Program on Technology Innovation: Superconducting DC Cable Workshop

Summary Report

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Technical Update, March 2006

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ABSTRACT

This report is a summary of discussions and conclusion from a workshop on the technology of superconducting DC transmission cables. The workshop was held at EPRI in Palo Alto, California on October 12, 13, and 14, 2005. The purpose of the meeting was to bring a small group of experts in technologies relevant to the development of such a cable and to enumerate potential issues, technical challenges, and a timetable for development. The first half of the workshop consisted of short technical presentations, each of which was followed by questions and discussions. The intent was to bring every participant to a fundamental level of familiarity with each of the separate technologies. This report summarizes those discussions. The synthesis of the various technologies, in particular their capacities and limitations, led to a general feeling for the likely range of superconducting DC cable power capacity and system length, the types and number of interface points between the DC cable and the AC power grid, and the need for support technologies such as vacuum and cryogenic systems.

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INTRODUCTION

Economic, environmental, and political forces will change the nature of energy use in the next decades. As a result, future generation and use of electricity is quite uncertain. Increased use of large generating facilities, such as nuclear or remote wind farms, forms one possibility while small distributed energy sources, e.g., renewable and hydrogen forms another scenario. Should large, 5 to 10 GW, power generation facilities become the norm in a couple of decades, then methods of transmitting power of this level over long distances will be required. One way to accomplish that goal is to use DC cables based on high-temperature superconductors. The technology to build such DC cables exists today. However, existing superconducting materials and other system components that are technically capable of meeting such a mission would not deliver a competitive alternative to existing technologies. Fortunately, a great deal of ongoing research in these areas promises to improve performance and reduce cost.

Looking to the future, EPRI convened a workshop on the technology of superconducting DC transmission cables. The purpose of the meeting was to bring a small group of experts in technologies relevant to the development of such a cable. Their goals were to enumerate potential issues and technical challenges and to discuss a timetable for development. The workshop lasted two full days, beginning midday Oct 12. The participants and the agenda for the workshop are listed in Appendix A, along with some of the assigned topics for the various speakers. The first half of the workshop consisted of short technical presentations, each of which was followed by questions and discussions. These presentations are included as Appendices B thru H. The intent of these presentations was to bring all participants to a fundamental level of familiarity with each of the separate technologies. Section 2 of this report summarizes some important facts from the presentations and, more importantly, the subsequent discussions.

Looking forward, EPRI wishes to establish a team that will work to define the DC cable system and establish developmental goals and time frames for progress. The initial task for the team is the syntheses of the technologies into a workable DC cable system that is functionally effective and interfaces safely with the rest of the power grid. This, of course, depends on the general feeling for the likely range of superconducting DC cable power capacity, cable length, and the types and number of interface points between the DC cable and the AC power grid.

Vision

Where are we going and how will we get there? What is the future of electric power and society's use thereof? It was these issues that were addressed by the initial workshop speaker, Chauncy Starr, the first president of EPRI. He provided both some encouragement and challenges to the attendees for the task ahead. He noted that the goals of the concept are truly long range. As such, the measure of success is one of advancement of the technology rather than the development of a commercial product.

The value of a large system is the ability to provide energy under difficult conditions thereby avoiding the enormous social costs of off-design events. Our objective is to make the system invulnerable to such conditions. This desire was a major contributor to the discussions that led to the EPRI SuperGrid project. The physical ability to move huge amounts of power over long distances in a secure way is critical to the future of the electric power grid. As we look back, experience shows us that there are often unexpected outcomes of research and applied science projects. It is important to have a long-range target, but it is critical in aiming toward it that we maintain a flexible program.

Superconducting cables are the key to high power transmission over long distances e.g. East Coast to Mid to West Coast to take the advantages of the different times of peak load. Such a capability will make an enormous difference to power flow e.g. from nuclear parks, hydro generation or perhaps even wind farms to load areas. It will accommodate power demand variations across the country and be particularly valuable to the Eastern Utilities.

The concept is to underground the cable. Tunneling is better than burying, because it reduces vulnerability; cost being a secondary issue as in the New York Metro tunnels. This characteristic is now being taken for granted as an asset. Superconductivity is the main part of the SuperGrid and the SCDC cable concept, but they are much less attractive if above ground or in a trench.

A major goal of this program must be to convince others that is not only viable, but also valuable. Some major advances must be made to accomplish this goal. If we knew where we were going we would just be making measurements along the way. Exploring a new area requires experimentation and flexibility.

The time scale on the development, application and acceptance of the SCDC transmission line is 20-30-40 years from now. It is in keeping with other historical changes in the power industry. It took 50 years for the energy industry to move from wood to coal. EPRI advanced turbines were 10 years in development and 10 years in acceptance. The successful EPRI FACTS program is now 20 years old. It takes 20 years to plan and realize new educational processes.

Electricity is now 40% of all energy consumed in the USA and is a lifeline for the existence of society as we know it. We can communicate the need and benefits of long length SCDC transmission to the public without difficulty over a 20-year period.

Finally, overhead and above ground electric transmission are inherently vulnerable to acts of man and nature. Tunnels are less vulnerable. Further, there are major problems of getting right of way approval for overhead lines and a fortune has been spent on EMF issues.

What is needed is not a simple superconducting DC cable, but a system that is a complement to the AC power grid. One cannot consider an SCDC in a vacuum, but rather must look at it as a part of the much larger machine that serves our society. The measure of a new technology must be how effectively it contributes to the overall performance of the electricity system.

Purpose

The workshop has several purposes. These include the following:

- Provide a technical foundation and action plan for EPRI to use in developing a conceptual design of a DC Superconducting (DCSC) cable system.
- Develop and qualify a team to participate in the conceptual design project.
- Assess and catalogue the knowledge base presently available to developers and consultants.

- Plan literature searches and other investigative activities of relevant technology areas
- Make a tentative plan for the overall scope of the program. (Effort, duration, budget needs, partners, etc.).

There was some discussion of the fact that there are several superconducting AC cable programs, including 3 in the US at the present time. The two tables below list the major cable programs worldwide as of 2004. These were not presented at the workshop, but are of value in setting the stage for the future DC cable effort.

Table 1-1 Listing of most existing superconducting cable projects, part 1.

Project/ Management	Innopower	China Acad. Sci.	KERI	KEPRI	SuperAce
Site	Puji Substation	Chang Tong	LG Cables	KEPRI/KEPCO	Yokasuka
Utility	Yunan Electric	None?	KEPCO	KEPCO	TEPCO Chubu E
Start Operation	April 2004	Dec 2004	July 2004	Summer 2005	March 2004
Type	AC	AC	AC	AC	AC
Phases	3	3	3	3	1
Voltage	35 kV	15 kV	22.9 kV	22.9 kV	77 kV
Current	2 kA	1.5 kA	1.2 kA	1.2 kA	1.0 kA
Length	33.5 m	75 m	30 m	100 m	500 m
Dielectric	Warm	Warm	Cold	Cold	Cold

Table 1-2 Listing of most existing superconducting cable projects, part 2.

Project/ Management	ConduMex	Tratos Cavi	SuperPower	AMSC	Ultera	Nexans
Site	CIDEC Lab	Pievi St. Stefano	Albany	Long Island	Columbus, Oh	? Spain ?
Utility	CFE	None	Niagara Mohawk	LIPA	AEP	EOn
Start Operation	Phase I: 2005	Spring 2005	2006	2006	2006	? 2007 ?
Type	AC	AC	AC	AC	AC	AC
Phases	1 ---> 3	3	3	3	3	1
Voltage	23 kV	45 kV	34.5 kV	138 kV	13.5 kV	10 kV
Current (kA	2 kA	2 kA	1.8 kA	2.4 kA	3 kA	1 kA
Length	10 ---> 100 m	50 m	350 m	660 m	200 m	30 m
Dielectric	Warm	Warm	Cold	Cold	Cold	Cold

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SUMMARIES AND COMMENTS ON PRESENTATIONS

This section provides a summary of the various presentations and more importantly some of the subsequent discussions in the workshop. The first session on grid connections caused more discussion than any other. This was because there was a great deal of catching up in the area by the various participants and because the earlier admonition that the SCDC cable was to be part of a complete power delivery system was well accepted and all wished to establish the limitations and requirements imposed by the AC grid.

Grid Connections by Bob Lasseter

When DC lines and cables are compared to conventional AC systems, a major concept in making a decision on a new line is the breakeven distance—the length where DC becomes less expensive than AC (i.e., when the cost of converters at each end of the line is overcome by the lower cost per unit length). This is a good concept in general, but establishing a similar figure of merit for SCDC cable will require considerably more information than is available today, and some unknown amount of research. It is not clear how the trade off will be sensitive to voltage, current and power levels.

The thyristor-based converters at each end of most DC links today are about 99.35 % efficient, their exact efficiency depending on the power level. These converters typically require a stiff AC system at the receiving end. There are two major types of converter, voltage source converters and current source converters. In addition to the type of converter it is possible to use devices other than thyristors as elements. The gate turnoff device (GTO) can be a very effective element of the converter, however GTO based converters are only about 98.4 % efficient. These are more likely to be elements in a converter that feeds power into a weak AC system.

There is a need to have a voltage drop (droop) along the line of a conventional DC cable to achieve control. One potential task for the initial part of the program is to assess the need for this or an equivalent in a superconducting DC cable.

One cost component in a superconducting cable is the copper that is needed to carry current when there is a fault. Since the DC cable will carry a very large current under normal conditions, it will be necessary to have a considerable cross-section of copper for safety. The cost of the converter terminals can be expected to be about the same for high-voltage, low-current as for low-voltage, high-current converters. However, some cost penalty should probably be assigned to new technology options because of the risks involved. So, a slightly higher terminal cost should be used for any breakeven comparison.

For point-to-point systems (systems with no tap on the DC line), current source converters are perfectly acceptable. However, for any long distance transmission system, taps to serve loads along the cable route must be expected. Many of these taps could be expected to be relatively small, which will limit the reliability of the cable system, since a small tap will probably have a low short circuit capacity, which increases the likelihood of commutation failures in an inverter and a temporary collapse of the power transfer in that region. This is discussed in some detail in an old EPRI study on HVDC Circuit Breaker applications. The result of this project (probably RP326) performed by IREQ in Canada under the direction of John Bowles was published in about 1978.

The load and thus the power flow will cycle. The SCDC cable must be able to follow such load variations. For a long-distance cable, which is probably the case for most DC superconducting cables, the current polarity could change over some cable sections as a result of daily or seasonal power flow changes. Such power reversals could be scheduled on a periodic basis. An assessment of the effects of polarity changes must be an early task for the program.

The fault performance of DC systems addressed in the presentation was based on current source systems and assumes the characteristics of high voltage overhead lines where the surge impedance is about 300 •. In such a system operating at 500 kV, the maximum instantaneous surge current for a DC line fault is about 1.7 kA. For a 25 kV cable with a surge impedance of 15 •, the maximum instantaneous surge current is also about 1.7 kA, but this might be only 8% of a 20 kA cable's current rating and it would be less than 2% for a 100 kA cable. For a ground fault in a converter terminal, the fault current contributed by the DC cable should be much below 2 PU current. For ground faults in the DC cable itself, the cable voltage can be clamped to ground at each end and the crowbar can be used to prevent the current from changing rapidly.

As a standard case, we should consider a 5 GW cable operating at +- 25 kV with 100 kA current.

There are 8~9 DC transmission links in North America. Worldwide, three high power DC transmission projects exist or are in construction, Itaipu, 3 Gorges and the US Pacific Intertie. Conventional thyristor valve technology is used, but these systems need a strong voltage source for commutation. Itaipu has a high power rating of 3.1 GW at 600kV, but a high voltage and comparatively low current of 2.5 kA compared to the 100 kA of an SCDC cable.

The operational case of a fault to earth (overhead line insulator flashover?) causes a transient drop in voltage and, in particular, a 2.0 PU current for 20ms before the rectifier regains control. In the case of an SCDC cable however a fault to earth would be a disastrous event with disruptive violence (an explosion and vaporization) severely damaging the cable and taking it out of operation for a long time period. The design must accommodate this eventuality. Can the peak current be reduced to 1.5 PU and can the duration be reduced.

DC systems with high current/low voltage provide an advantage over HVDC in that high current encourages many inverters distributed over the load region. This reduces the need to strengthen the local ac system. For HVDC the converters are built in series and cannot be broken into many converters with out major additional cost. The basic bipolar power module has a range between 30MW and 400 MW with typical rating around 100MW. The type of converters used can be current sourced converter (CSC), voltage sourced converter (VSC) or both.

One basic configuration is point-to-point transfer of power with many paralleled power modules at each end. For example if the power module is 100MW and the cable is carrying 5GW then there must be at least 51 power modules at each end to insure no loss of power with the failure of a power module. In this configuration power reversal can be achieved using CSCs or VSCs. For a system using CSCs keeping the current fixed but revering the voltage across the cable can reverse the power. CSCs can easy achieve voltage reversal in a few cycles but can act much slower depending on how fast the charge on the cable capacitance can be reversed and the tolerance of the cable to voltage reversal. A system using VSCs implies keeping the voltage across the cable fixed and reversing the current to reverse the power flow. Again the rate of change depends on the inductance of the cable and what the cable can tolerate.

When we consider longer cables with higher power levels we assume that there are many taps between the two ends resulting in a multi-terminal system. The driving force behind the many taps range from getting the right-of-way to the ability to insert power into the ac system without major reinforcement of the ac system such as adding local generation and/or ac transmission lines. The basic converter module for the ends and the taps need to have at least one extra power module in parallel to allow for loss of a module without degrading the dc system operation.

The class of converters (CSC or VSC) in the multi-terminal cases becomes more complex. The simplest is a mixed system with one-way power flow for large generation at one end to many ac load centers along the line. The generation need not be a single point but must have one-way power flow. The simplest solution is to use CSCs at the generation end and VSCs at all points where power is injected into the ac systems. This removes the problem of ac voltage support at the receiving ac system since VSCs can control the ac voltage as well and power injection. This allows for black start of a small ac system that do not have local generation. The down side is that VSC have losses approaching 10 times that of CSC.

Traditional multi-terminal dc systems using CSCs have major problems of complexity which limit them to 3 or 4 terminals. The basic problem results at each converter during transient events where the major complication is a current dependent dc voltage between terminals. Traditional CSC systems are complicated and need a carefully customized overall control scheme. It becomes increasingly difficult to determine which converter should assume voltage regulation following mode changes as system size increases (number of terminals). Superconducting cables change several key system characteristics and have a major impact on control options.   There is no longer a current dependent dc voltage drop. Voltage regulation sets a single voltage level for all the terminals. Transient changes in dc voltage propagate throughout the dc system and can be used for control in a fashion similar to the use of change in frequency on ac systems. This system has the advantage of much lower losses, but all the CSCs operating as inverters need stiff ac voltages. Perhaps this could be solved using forced commutated CSCs.

Multi-terminal systems have major problems with reversal of power flow on an arbitrary line segment. For example for a CSC based multi-terminal system the voltage needs to be reversed at all terminals making all rectifiers into inverters and all inverters into rectifiers. To change an individual converter, say from inverter to rectifier requires changing the connections of the CSC to the dc line. In CSCs the devices allow current flow in a single direction. There is development work at EPRI and some companies to development bi-directional current flow for CSCs. The situation is different for multi-terminal systems using VSCs. VSCs can operate as inverters or rectifiers with a simple control action which reverses the current direction in the converter. This requires current changes in the dc line up to double the converter's rated current. The technical and development challenges for a more general multi-terminal system push this level of flexibility well into the future.

Looking at the prospective 5GW SCDC cable, the adoption of a higher transmission voltage than 25kV significantly reduces the complexity of the converter, whilst not necessarily increasing the complexity of the cable and accessories.

The practicability issues of the integration of high-power SCDC link(s) into the existing lower power AC transmission and distribution systems and the operation and control of the link are key to the viability, usefulness and acceptance of the SCDC concept. It is likely to be necessary as part of the project to develop a plan to show how the AC network will radiate out from the remote DC/AC terminal(s). This has always been a point of attack on SC cables e.g. 'Why do we want to carry so much power, on one cable, to one place' and 'Even if we could, why do we want to put all our eggs in one basket, if it faults, we lose everything?'

The design and qualification test requirements for conventional DC cables are based almost entirely on the operating characteristics of the converter in normal and abnormal operation for both Voltage and Current commutated devices. A task for Brian Gregory will be to send available information on existing levels and their believed derivation to the team for comment and relevance to modern valve/bridge circuits.

The inverter needs something like 50% VARs compared with MVA rating to avoid commutation failures.

Normally one gets 2 PU fault current for about 20 milliseconds from a fault. After this, the flow is restored to 1 PU by the controls. There were comments that ABB has a control system that might reduce the fault current even faster than this. Peak fault current might be limited to 1.5 PU with the best technology and the duration might be as short as 10 milliseconds.

Discharge of stray capacitance of the line will increase the local current at the fault to a much higher level than seen by the rectifier, but this discharge will be brief.

Loss of a line carrying more than 1 GW is likely to cause cascading failure of the AC system so the system needs to be carefully designed, perhaps with multiple lines. Perhaps some energy storage should be included in the system design to accommodate cable loss.

We would like to have a short circuit ratio above 4, preferably 10. This ratio is defined as MVA short circuit on AC grid divided by DC power.

Some DC lines have an earth return or at least can operate in this mode as an option in case of loss of one pole. This solution is appropriate for conventional DC lines that operate at high voltage and low current. This is done today for currents of one to three thousand amperes and this requires careful engineering of the ground connections. It will not work with 100 kA where the voltage drop would be commensurate with the 25 kV design voltage.

Superconducting Basics and SCDC and Cryoresistive Cables by Paul Grant

We normally think of a conductor as a material that carries current from one place to another. Normal conductors have a finite conductivity (i.e., they resist the flow of current), whether it is varying or constant. This resistance leads to heating and thus power losses in the conductors. For all practical purposes, superconductors have an infinite conductivity. Thus, they should be able to carry a constant current with no losses. This condition is true so long as the current is constant. Under this condition, there is no voltage within the conductor; and thus no power transfer within the material. A varying current implies an inductive voltage as a minimum and often causes a varying magnetic field. This field induces voltages in various parts of the conductor and leads to a variety of other currents within the superconductor and any normal conductors included in the design. Limits on magnet field depend on its orientation with respect to the superconductor. Field calculations are needed to determine the magnetic field variations due to a) the lay angle of the tape and b) reverse lay of alternate layers.

One task for the program is to estimate the cost per GW-km and kWh delivered for a SCDC cable system. The converter costs are about the same (first order approximation) for the SCDC converter terminal as for present day HVDC systems. A 5-10 GW conventional DC link would require four overhead DC lines. Two SCDC cables could carry this much power. If the cable is not too expensive, the superconducting option should be competitive, especially considering the reduced needs for rights of way.

The losses associated with current transients are of significant concern. To some extent, current transients can be controlled for all normal power changes but not for those arising from common faults in the AC and DC systems. A converter terminal may have to be shut down instantaneously for many expected failures in the converter terminals. This is unavoidable. Also, power schedules most likely have to be adjusted to match daily fluctuations in the demand for power. Balancing these requirements is the need to build the minimum amount of conventional conductor material in the cable to reduce the capital cost of the SCDC cable system. This trade-off needs to be better understood so that the cost of the overall transmission system can be optimized.

Energy dissipation associated with faults on the DC cable system will be one of the major challenges for design of the cable system. Using data from the PEPCO SCDC cable, the following was found:

- Inductance and capacitance per meter of cable:
  1. $L=1.5*10^{-7}$H/m;
  2. $C=1.8*10^{-10}$F/m; Z=29 ohms
- Stored energy per 100 km of cable @ 25kV and 100kA:
  3. Inductive stored energy is 75MJ
  4. Capacitive stored energy is approximately 6kJ?

Keeping the DC current as unchanged as possible under all fault conditions will prevent over-voltages from developing in the cable system if the stored magnetic energy is converted to energy stored in the cable's capacitance to ground (or between the conductors). If a 100kA continuously rated crowbar switch at each end of the cable is used, the DC current can circulate for a long time through the shorted ends of the cable. The switch will have to be rated for the transient current arising as a result of discharge of the cable's capacitance, and the cable has to be able to survive these discharge currents. Of course, once a crowbar is applied, all of the power transfer through the cable will go to zero. Restart of the power transfer requires the crowbar switches to be "opened" (forced commutation of a thyristor switch may be needed for this) and the cable capacitance needs to be brought up to normal voltage again. Metal-oxide varistor energy absorbers will be needed to manage the transients most likely arising as a result of short duration current changes associated with the system's recovery phase. Such energy absorbers should be able to limit the over-voltages to less than 2 or 2.5 per unit of normal voltage. However, there will be short duration, possibly significant, current changes associated with these transients, which may push the cable into a quench situation at least along some segments of the cable close to the terminations. Some simulations need to be run to fully understand these phenomena.

The effect of cycling once an hour produces losses in a superconducting cable of 0.3 watts/meter at 100kA. This value drops to 0.01 W/meter if the cycling is only once a day. Dropping power 1% over 1 hr produces $4x10^{-7}$ watts/meter. We can assume that heat flow from external sources into the cable will be typically 1 watt/meter.

Ripple at 360 Hz is expected as major component on a DC system. Filters can be used to minimize the ripple with an optimization done on an economics basis. We estimate that a 1% amplitude (1 kA) will cause heating of 0.5 W/meter, at 2% it rises to 4 W/meter, and at 3% it rises even further to 13+ W/meter

We can conclude that, in a superconducting system, power demand variations are much better handled by voltage changes rather than current changes.

Recent superconductor costs are $50 to $75 per kA-meter (at 77 K, 0.1T, 1 microvolt/cm). As a comparison, for this voltage drop, the cost of aluminum is only $1.66 per kA-meter. However, the losses at such a resistance are too great in either case. As the voltage drop decreases to 0.1 microvolt/cm the cost of aluminum increases by a factor of 10, whereas the cost of the superconductor only increases by a factor of 1.5 or so.

The cost of losses and the value of "carbon credits" should be considerations for design of the system.

A mono-cable with a room temperature dielectric appears to be simple, but has prospective problems of high inter-cable perpendicular magnetic fields, high electromotive forces and difficulty in dealing with the central LN duct connections at straight joints and electrically insulated connections at feed/stop/anchor joints. Available information on the 'e-cable' needs to be studied.

One possibility for the cable study is to take existing SC BSCCO powder in silver tape technology as manufactured in long continuous lengths. However, looking to YBCO tapes is likely to lead to a lower cost cable at somewhat different operating conditions.

Supplier 'guaranteed' information or best estimates on the following are required from each of the commercial suppliers. See task in conclusions and recommendations of a "Design Criteria Document".

- Tape dimensions and tolerances.
- T_c, J_c and H_c and the mechanical strain relationship (tensile, compressive and bending)
- Mechanical stress-strain application limits, minimum bending radii.
- Hysteresis curve (bean model) for calculation of losses.
- Coefficients of thermal contraction with temperature.
- Specific heat capacity with temperature.
- Thermal resistivity with temperature (transverse and longitudinal).
- Ageing phenomena and effect on electrical and mechanical performance (if any)
- Material incompatibilities (if any)
- Corrosion susceptibilities (if any)
- Suppliers design information re: rating calculations for 40-year life (if any).

- Supplier's guaranteed and recommended service life, and/or ageing derating factors.
- The recommended tape-to-tape and tape-to-current leads connecting method.

Practical Aspects of Superconductivity for Applications by Bill Hassenzahl

Operational issues for the high temperature superconductor in an SC DC line are not much different from the related issues in existing low-temperature superconducting LTS applications. Because of the large number of LTS devices that have been constructed, the technology has become an engineering issue, rather than one of development.

There are many practical limits to the capabilities of superconducting materials and the devices they make practical. Perhaps the most significant issue is the ability to maintain the appropriate cryogenic operating condition during upset conditions. When the superconductor quenches, its current carrying capacity is negligible compared to copper or aluminum, so it is necessary to add a parallel conventional conductor for transient protection. One part of this is management of the stored inductive energy. This is particularly important for magnets. LTS magnets are designed to increase in temperature from 4 K to a maximum of 100~150K in 100 to 300 ms.

Extending this to superconducting AC cables, conventional material is needed for fault protection. An example of a 40kA, 5-cycle fault for a 1 kA cable was described. If the cable must recover superconductivity after the fault and a temperature rise of 1 K is allowed, then the cross section of the copper stabilizer must be about 4 cm^2. The question is how to extend this to a 100kA DC cable. A factor of 40 is much too conservative for a long distance cable system, since the surge impedance of a 25kV cable system will limit the instantaneous charge-discharge current to 1.7 kA, assuming a 15 • surge impedance of the cable. The travel time for a surge is about 300 km/ms so for a 150km cable, there is one millisecond available for measurements and control actions before a reflected wave travels from one end of the cable to the other end and back. Therefore, it should be possible to keep most instantaneous current changes to less than about 3 to 4 kA. This requires further studies to understand the tradeoffs between control system response and cable stresses.

Voltage excursions are a more likely cause for superconducting device failures, than loss of superconductivity. Voltage is a problem when electrical faults occur internally or externally.

Whereas there is a general need for normal conductor in the LTS devices, these materials generally include some normal conductor because it aides the fabrication processes, which include steps that are similar to that of the drawing and extrusion of copper wire. The fabrication of these materials allows an area ratio is 2.5 to 1 for the copper to superconductor (i.e., the superconductor is only about 30 % of the total area).

As the temperature is lowered, almost all materials decrease in dimension. Several power cable demonstrations have dealt with the expansion and contraction of the conductor with temperature change–but these were short lengths so the problem may yet be there and should not be underestimated.

The Pirelli Detroit Edison cable was designed to take a current overload for 30 minutes and had a significant quantity of silver in the tapes. More detailed information on this would be of value to the DC cable program.

Inverter Converter Designs for Existing DC by Stig Nilsson

The multi-terminal concept described in this presentation is assumed to be made up of primarily voltage source converters. However, it should be clear that for point-to-point power transmission systems involving basically one sending end and one receiving end converter (can be multiple parallel converters but at one site), current source converters might be preferred. For some systems where some converters are only used as rectifiers, hybrid systems with a mixture of current and voltage source converters should also be feasible.

In multi-terminal, long-distance cable transmission systems, power transfers between terminals can be assumed to change direction on a daily, weekly or seasonal basis. This is typically the case for the Pacific HVDC Intertie between Oregon and Los Angeles where the hydro system in the Northwest is used to generate power during the day and power is reduced to zero or reversed during the night to conserve water during low flow, late summer, or fall conditions. Similar kinds of requirements or restrictions will probably apply to most long distance power transmission systems.

The method of control of the converter and the types of elements, e.g., IGBTs vs. thyristors will affect the operational characteristics of a terminal. Specifically, pulse-width modulated (PWM), voltage source converters facilitate power flow control in a multi-terminal system and can be expected to perform with fewer constraints than typically are found in multi-terminal current-source converter systems.

The proposed low-transmission voltage of 25kV DC is more closely matched to the state of the art for series connection of gate-turn-off thyristor (GTO) or insulated gate bipolar transistor (IGBT) valves used in PWM converters, thereby reducing the problems of designing a multi-stack, series-connected converter system needed to withstand high transmission voltages. However, there are no significant converter design differences between 25kV and 50kV DC. In principle, it is easier to design a parallel-connected PWM converter system for high-current output than HV output with series/parallel devices.

Higher transmission voltages have advantages for long distance AC systems. These systems are used throughout the world and are unlikely to change. Thus, a low-voltage high-current SCDC link would have certain inefficiencies in transformer losses at the ends if terminated at existing HV AC transmission system voltages instead of closer to the loads at a medium voltage bus; for instance a 69kV to 138kV distribution station.

Redundancy is a critical issue associated with overall system performance. Thus, an SCDC 25kV 100kA cable system must be bi-polar with a spare parallel cable for N+1 redundancy and reliability. This will have some considerable impact on the magnetic field in the various cables, and thus on the detailed conductor design and layout.

The superconducting DC cable is unique in that there is essentially no resistance and AC losses are insignificant. The issue with losses discussed earlier is because the refrigeration system must remove the loss from a cryogenic environment requiring considerable extra power. Absence of resistance and AC losses could cause low-damped resonances and control issues in the DC line and the converter terminals.

Some failure modes in a converter terminal could lead to AC injection into the DC cable. This is an unacceptable failure mode.

The cable's resonant frequency is likely to be low and less than 60Hz because of high capacitance (low voltage and thin insulation) and high inductance (if separate monopoles). If concentric bi-poles are used the inductance will be significantly reduced. The reactances need to be determined for system design.

A multi-terminal, voltage-source converter system will significantly increase the short circuit currents resulting from a cable fault, which should be considered in the cable design.

Current continuity in the cable is essential under all operating conditions to avoid excessive L di/dt generated voltages. The electromagnetic energy stored in a SCDC cable carrying 100kA with 15mH/100km inductance is enormous at 75MJ. Dissipating this energy without damage to the cable or to the connected utility grids will be a significant aspect of future design assessments.

The cable terminal requires some protection against faults at the interface between the cable and the AC system. For example, a transition to an open circuit state of the converter or the ac system may require a crowbar device (a thyristor or a SMES) at the end of the cable.

Critical areas of the cable are the terminals and splices/joints. Extra thick insulation is needed to reduce risk of dielectric failure in these areas.

It may be of interest to combine the SCDC cable system with a cryogenic converter. It is not clear, however, that there is a benefit from using a cryogenic converter system. If a cryogenic converter system is developed and is found to be effective in other scenarios, then it would likely be useful in an SCDC cable because one transition from ambient to cold could be eliminated, thus reducing the losses due to thermal conductivity. However, increased time and complexity of performing valve maintenance may more than offset any reduction of losses.

The most likely research that would benefit future superconducting DC cables is in the area of higher current thyristors, IGBTs, and GTOs. An increase in the diameter of thyristors from 15 cm to over 30 cm can be envisaged.

If large quantities of power are to be delivered to one area, there will be the need in the receiving terminal(s) to have black-start capability.

Cable Designs by Brian Gregory

Conductor Ampacity

The prospective 100kA ampacity for a single SCDC cable is approximately 20-50 higher than the levels achieved to date by the largest conventional cables. Today the limits of passive, naturally-cooled, buried HV AC cables are 2-3 kA. Forced cooling allows up to 3-4 kA. In a conventional DC system the elimination of AC losses permits the ampacity to be increased by approximately 20%. Operators do not like the complexity of conventional force cooled cable systems and will generally only select them when natural cooling is unpalatable.

Insulation Design

Conventional DC systems operate a given insulation type at a higher volts-per-mil criterion than AC systems, a factor of 2 being a typical value. For example, a 161kV DC cable would have very similar dimensions to a 345kV AC cable. Nevertheless, the design of insulation for DC transmission is more complex than for AC. At the proposed SCDC system voltage of 25 kV the insulation thicknesses would be determined as much by mechanical requirements as electrical performance. The thicknesses could be quite small, being in the region of 3 to 6 mm. Consequently for mechanical robustness, there is no benefit in considering system voltage lower than 25 kV or perhaps lower than 50 kV.

Conventional AC cables insulated with hydrocarbon fluid impregnated paper or PPLP (polypropylene laminated paper) insulation are designed on the limiting value of stress at the conductor shield produced by the lightning impulse voltage. Consequently, they have a natural, built-in factor of safety of approximately 100% at normal operating voltage. The stress distribution is a capacitive one and follows a simple logarithmic distribution derived from Gauss's law in which the maximum stress occurs at the conductor shield.

Conventional AC cables insulated with extruded XLPE (cross-linked polyethylene) insulation are also designed based on the capacitive distribution. The limiting condition is different, being the magnitude of stress at the conductor shield under AC operating voltage. This also requires the addition of a calculated design margin to achieve a system service life of say 40 years.

The stress distribution in a conventional DC cable is quite different from that in an AC cable. At operating voltage, the stress distribution is influenced by the mobility of charge carriers, which in turn is influenced by the magnitude of the local electric stress and by the temperature distribution across the insulation. The position of highest stress changes from being at the inner conductor shield under no-load conditions to being at the outer insulation shield when under load.

The most onerous operating condition for a conventional DC cable connected to a current-source converter is the superimposition of a lightning impulse voltage on an opposite polarity DC U_o voltage. This is followed in severity by a) impulse, b) polarity reversal (specified qualification test voltage of ± $1.5U_o$) and c) load cycling at a constant $2U_o$ voltage.

For current-source based converters in an SCDC system, voltage reversal would be encountered if fast power reversal operations were needed. However, power reversal can be made without much transient change to the direct current, thus significantly decreasing the resulting heat losses in the SC conductor. For fault management, voltage transients up to 2 to 2.5 per unit DC voltage of any polarity should be considered. Assessment of this level of fault current for a high-power SCDC cable should be one of the early tasks in the program.

For voltage-source based converters in an SCDC system, the voltage polarity will be unchanged irrespective of power flow direction since, during a power flow reversal, the current polarity must reverse. Unless limiting measures are taken, the high current transient would generate significant heat in the SC conductor. Under fault conditions, it might be necessary to force a polarity reversal to drain the high stored energy in the cable's inductance, in which case over-voltages might be encountered including polarity reversal up to about 2 to 2.5 per unit.

Voltage stresses on the cables under fault conditions need further study before establishing their levels with some reasonable level of confidence.

The insulation of conventional DC cables becomes polarized in normal operation and upon grounding. It can take about 3 weeks for complete charge relaxation at normal room temperature.

Conventional XLPE cables have the additional problem of by-products present in the insulation from the factory cross-linking reaction, these being polar compounds. In service, the electrophoretic forces cause these species to migrate and form halos of trapped charge around the conductor and insulation shields. In an AC cable, the stress increase is small being about 5%.

If XLPE is used to insulate a conventional DC cable the stress increase could be very large e.g. 30-800%. Upon grounding the cable, the space charge would be retained at room temperature for periods of approximately 6 months. To accelerate the recovery it would be necessary to ground the XLPE insulation at typically 80^{o}C, this being an impractical restriction on service operation.

Modified types of XLPE insulation for conventional DC cables have been and are being developed to reduce the magnitude of the space charge, one type is used in ABB's 'DCLight' system.

The electrical and mechanical properties of prospective SCDC cable insulating materials will need to be quantified at LN temperatures.

For SCDC operation, uncross-linked PE insulation can be considered, thereby eliminating the by-products. Filled EPR (ethylene propylene rubber) insulation can also be considered, as although it contains similar cross-linking by-products to XLPE, the filler absorbs and limits the migration of the by-products.

The charge migration may not happen at 77K, helping to make extruded polymeric and elastomeric insulations more attractive by simplifying the stress distribution and reducing the maximum stress. Note: this may impact the choice of cold vs. warm dielectric cable constructions.

However, if space charge does build up, it is improbable that it will ever drain away at 77K, thereby permanently distorting the electrical stress level. Similarly, it is improbable that it will be possible to discharge the insulation rapidly by the application of a ground connection to the conductor. For this reason, it is thought that the more onerous operating conditions will be a) polarity reversal and b) the superimposition of impulse on DC system voltage.

Reliability

The reliability of the SCDC cable system is critical to its practicability and acceptance. SCDC system performance should be equal to or better than the high reliability exhibited by a conventional 400 kV cable system. The high reliability is designed-in because of the 400kV system down-side of an average time of about 30 days to repair and re-energize and, in severe cases, as much as 6 months. This needs to be compared to about 2 days to repair an overhead transmission line. On the other hand, the overhead line is likely to have more outages. So, some evaluation of loss of service and availability needs to be included in the SCDC analysis.

Cables are limited in length by the maximum permitted diameter of the shipping reel. Today, this means the cable length cannot exceed about 1km before having a joint/splice. This issue puts a premium on achieving a small cable size. Accessories are the weakest link in both conventional and SCDC cable systems as they have to be assembled under site conditions and not under controlled factory conditions. They take a long time to assemble and the materials and labor significantly increase the system cost. If superconducting cables have a central LN duct in the conductor then pressure-tight connections will be needed every km. This will make it more difficult to connect the conductor and to apply the insulation overall. The bottom line is that long cable reel lengths increase system reliability and reduce cost.

Factory Shipping Tests

Cables must be designed to achieve mechanical flexibility of the conductor, insulation and outer envelope during manufacture, shipping, installation and service operation. This requirement separates cables from all other items of electrical equipment. For an SCDC cable there is the additional requirement to withstand thermal contraction during cool-down to 77K.

One cannot fully test each reel of SCDC cable in the factory, this being a major issue.

In manufacture, every millimeter of the insulation over the length on the reel has to be perfect. It is highly desirable that factory shipping tests be performed on the insulation, including an overvoltage withstand test. SC cables which employ wet designs of LN impregnated paper, or PPLP insulation, cannot easily be tested without cooling the shipping reel to 77K, this being impractical for mass production.

The very significant risk exists in cable manufacture that the SC tapes may suffer unrecorded damage that will not become apparent until service failure results. To eliminate this risk it is highly desirable that the continuity and ‘resistance’ of the conductor be tested. This is not yet possible with any design of SCDC cable without cooling the conductor to 77K. A quality assurance method requires to be developed.

Design of the Cable and Cryogenic System

The challenge exists to produce a cable design that will overcome the SCDC problems by:

- Achieving robust metallic sheaths for the cryostat capable of withstanding high LN pressure whilst maintaining a hard vacuum and, depending on the cable design, a robust pressure-tight LN duct for the conductor.
- Reducing the complexity and operating risks of the service straight joints, which result from the need to connect a) the pressure retaining LN conductor ducts together and b) the vacuum tight and pressure retaining cryostat sheaths together.
- Reducing the complexity of both the service LN feed joints and anchor joints, by having to bring insulated LN ducts from conductor voltage through the joint insulation to ground voltage.

One possibility for investigation is to completely separate the construction of the SCDC cable from that of the cryostat system. A key advantage is that the cryostat pipe dimensions, LN flow rate and pressures can be optimized to achieve the maximum hydraulic cooling lengths with minimal restrictions from the cable construction. The cable would be manufactured as a conventional extruded self-contained ‘dry’ construction without built-in liquid nitrogen ducts or built-in cryostats, thus being of simple construction, small in diameter and of long length. The extruded insulation would be suitable for factory HV voltage testing. The outer cryostat pipe would be manufactured separately and assembled and tested on site to form a robust empty duct, as in conventional HPFF cable systems. The SCDC cable would be pulled into the cryostat pipe and jointed in a near-conventional way. The cryostat pipe would finally be closed, sealed, purged, and filled with the liquid nitrogen coolant.

Environmental Aspects

One very important issue in a conventional cable is the environmental impact of a hydrocarbon fluid leak from a fluid filled cable. This will not carry-over as a specific issue for the selection of coolant fluids in an SCDC cable system as liquid nitrogen and helium are constituents of the atmosphere and liquid hydrogen, although flammable, is an improbable pollutant.

Cryogenics and Vacuum by Bill Hassenzahl

A superconducting cable must operate in a cryogenic environment. This need implies several components for the system. One is a cryogenic refrigerator that can maintain the cold environment. The second is a way of assuring the operating temperature over a long distance with a minimum of equipment and the lowest possible cost. This latter requirement has two separable items, the first is a transport mechanism for the cryogenic coolant and the second is the need for a very low heat input to the cable along its length. This latter goal can only be accomplished by having a vacuum environment surround the cold, power-carrying portion of the cable. (Note: for AC cables with lengths of a kilometer or so, the heat flow into the cable is dominated by the power leads at the two ends and internal losses play a significant role. Thus, the optimization process is different.)

Results from an ‘e-pipe’ study for EPRI were used during the presentation as examples of what might be feasible and what typical values for refrigeration and vacuum could be used. Perhaps most critical is that the cable will be many tens of kilometers in length. This puts certain requirements on the various ancillary components, though it may have little effect on the cross-section of the high voltage portion of the cable.

Three cryogens come to mind for use in the cable: liquid nitrogen, gaseous helium and liquid (or gaseous) hydrogen. Liquid nitrogen was chosen for the e-pipe because it simplifies several portions of the cryogenic system. For the moment we assume that is the cryogen of choice. At some point in the SCDC program one should look at the other alternatives. In particular, liquid hydrogen may be particularly attractive eventually if the cables are part of the SuperGrid.

Heat flow into the cable along its length depends on: (roughly in order of importance) the type of thermal insulation, the dimensions of the cable, and the operating temperature. The total heat flow can be separated into radiation from the ambient environment, convection by gases in the space between the ambient outer wall and the cold cable, and conduction along supports for the cold cable.

These can be controlled to about 0.5 watts per meter of length of the cable.

The refrigerator that removes the heat must also accommodate the flow losses required to move the cryogen along the cable and the heat that flows to the cable through power leads. A conservative estimate of a total heat leak of 1 watt per meter was assumed for the ‘e-pipe’ and seems to be a reasonable value to use for the DC cable. This implies that the total heat load for a cable will be from ten to several hundred kW.

Several types of refrigerator can provide cooling at cryogenic temperatures. A few of them can be made for the loads expected for the DC cable. One way to compare them is by the amount of room-temperature electrical power required to remove a watt of heat at the operating temperature. The ratio is referred to as the specific power, and the inverse is the coefficient of performance (COP), which is a number that is always less than 1. The COP is determined by two components, the Carnot efficiency and the inherent thermodynamic efficiency of the refrigerator. The former depends on the operating temperature and the latter on the type of refrigerator and the total room temperature power. As a simple approximation, it requires about 20 W at room temperature to remove 1 W at 77 K and larger refrigerators have a better COP than smaller ones. Of interest is that the capital cost of the refrigerator is about $200 per cold watt.

Heat input is roughly continuous along the length of the cable, but the refrigerators will likely be discrete units spaced every few kilometers. To assure high availability, it will be necessary to provide some form of redundancy for these units and to assure that power is available to them independent of power flow within the cable itself.

Since a moderate vacuum is required, several approaches are possible. One is to have continuous pumping along the length via "getters" and another is to have discrete vacuum pumps every km or so. A trade study of vacuum systems and outer pipe dimensions is needed as part of the overall DC cable program. This study must look at longevity of the system. There is little experience with extended vacuum systems that operate for 20+ years.

Eventually one may wish to use hydrogen as the cryogenic fluid. There are several possible modes for using this material. It may be premature to consider it for the DC cable program.

Current Limiting in the Grid by Ben Damsky

The main purposes of fault current limiters are to reduce forces in conductors during short circuits and faults and to limit heating and, in the case of a superconducting cable, to accommodate thermal recovery of the superconducting elements. Significant work has been performed in the area of current limiting using high impedance transformers, explosive fuses, semiconductor systems, 'matrix fault' limiters and the electronic 'SSCL' limiter. Most of the "limiters" are designed to operate in an AC system where the zero crossing of the current makes circuit opening easier.

In the SCDC cable project it is first necessary to perform an outline system design study to determine the magnitude and duration of fault currents associated with, for example, a normal load current of 100kA. It will then be necessary to consider the practicability of controlling the fault current, what development will be required to achieve this and in what type of terminal equipment.

The interface between the SCDC cable and a converter at one or more of the tap locations might require some form of fast-acting current limiter or even a DC breaker. If a fault occurs within the converter or in the AC system in such a way that the controls of the converter can be used to limit the over-currents, no extra limiter device will be needed. However, if a fault occurs in such a way that the converter is left inoperable, the current flowing through the tap before the fault must be channeled into some other path or interrupted. If the total cable current is shunted into a crowbar switch, all other converters connected to the cable will also loose their power transfer capability, which might lead to blackouts in the systems connected to the cable. This would clearly be unacceptable.

To illustrate this, consider a 200 MW converter connected to a 25kV DC tap. In such a system, the rated current of the power leads would be 8kA. If the tap is suddenly disconnected, the 8kA DC current needs to be controlled in some way. Either the total power fed into the system must be reduced or the current must be funneled into some other tap, maintained for the time it takes for the affected converter to be returned to service, or brought to zero. Maintaining a constant current and voltage at the tap for 200 ms may be needed to enable the fault condition in the AC system to be removed and for the system to recover. An element capable of storing 40 MJ is one method of protection against this event. After the storage is full, the current needs to be reduced by 8 kA at the tap location, which might be an appropriate use of a current limiter. Depending on the location of the fault and the storage device and the topology of the cable, it may be possible to have one or a few storage devices connected to the cable to accommodate these rapid changes.

Equivalently, loads of 200 MW or more might turn on or off over short times, actions which would introduce a variation of a similar magnitude. Therefore, the ability to change loads rapidly is critical to the design of the SCDC cable system and its interface to the grid.

A long DC cable will likely have two parallel lines for redundancy if the power level and thus the criticality of the transmission are high. In a parallel line arrangement, breakers will be placed at connection links to allow transfer of power from one line to another. There could be a need to use this for shorts or when a segment is down for maintenance.

An improved MOV can operate with two series segments, one of which can be short circuited in the case of an over-voltage. The advantage is that the two series segments in normal operation each see moderate voltage which they can tolerate for long times without degradation. When one is short-circuited, the other clamps the line voltage at a lower level than could be achieved without the shorting of one segment.

3

DISCUSSION, ISSUES AND FUTURE TASKS

Some of the issues discussed during the workshop and possible tasks for future work on the Superconducting DC Cable program are presented here. At this time, the items in the list have not been prioritized. That will be one of the first steps in the development of a program for the development of this technology. Nevertheless, there are several items that certainly need to be addressed to establish the scope of any future effort. These are included in the discussion section below as well as being included in the list of tasks.

Discussion

At present, it is not clear how an SCDC cable would be integrated into the power grid. A first step in the program should be one or more system studies related to this interaction. Specifically, one must better understand the interactions between the AC-DC converters, the SCDC cable systems and the grid. Such simulations should be made assuming: a) relatively short distance city-in-feeds as one of the possible applications and b) a very long distance, complex power system for the other. The former would be a necessary step in selecting an appropriate site and type of SCDC cable for a demonstration at a reasonable power level. For example, assuming about 200MW and a 20 kA cable, the voltage will be rated 10kV. This would be relatively easy to accomplish with today's power semiconductor technology. Higher power transmission systems will presumably be somewhat higher voltage ratings for cable and probably a current rating of at least 100 kA. If the cable were to be rated 100 kV, it could be used to transfer 10 GW. However, the technology needs to be proven before this would be given serious consideration.

Another system study suggested includes exploring tradeoffs among cable design parameters including voltage, cold vs. warm electrical insulation, conduit size, number of poles per cable, and distances between joints, cryogenic and vacuum interface facilities.

Tasks

The following specific tasks were addressed during the workshop and are likely tasks for the early phases of the program. Some of these items will be natural components of the system studies mentioned above.

- Assess likely/ optimum power levels for the SCDC cable. Is one high-power line or several lower power lines better?
- Assess the minimum/optimum voltage for an SCDC cable.
- Assess the need for multiple taps on a SCDC cable
- Determine optimum power capacity for each single converter/rectifier
  - What is the optimum number of bipoles in each converter station?
  - Does this number favor multi-terminal cables?

- Determine the harmonic currents and voltages induced on the DC cable by different converter topologies. Need projected SCDC cable inductance and capacitance or their ranges to determine this.
- Evaluate the impact of harmonic currents and voltages on the performance of the superconductor in the DC cable. Establish a data set of losses as a function of frequencies (harmonics), conductors and cable design. Estimate the impact of changing power levels on DC cable losses and performance.
- Determine design impacts of power/voltage reversal on the DC cable.
- Determine the maximum likely fault current and the maximum fault duration on the DC cable. Values of 2 PU and 20 ms duration are typical. What are they likely to be for the SCDC cable?
- Determine the amount of stabilizer (copper) needed to protect the cable from such a fault. Is this value any different from the minimum needed for stability of the superconductor against transients.
- Determine the impact of currents introduced by the stray capacitance of the cable during a fault.
- Establish a database of properties/characteristics of materials and components to be used by the program. Essentially all items to be included; e.g., superconductors, converters (current and voltage source), power leads, AC grid characteristics, cryogenics, etc. In some programs, this is called a "Design Criteria Document". Such a document changes as the design progresses. So that specific components replace generic as they are selected.
- Determine the impact of loss of the DC cable on the AC system (source and load areas). How do losses affect overall grid stability?
- Is black-start capability important (or even possible), how much does it cost, and does it impair any other characteristics of the DC Cable?
- How does one accomplish power dispatch for a DC cable that has multiple connections and little voltage drop associated with current flow?
- What improvements are needed in YBCO superconductors to make them more effective for DC cable applications? Is the appropriate research proposed or in place? For example, will the use of nano particles provide adequate improvement in pinning for the conductor to accommodate the magnetic fields at the surface of a DC cable? Will such advances impact the losses in the conductor?
- A long-range question relates to the eventual costs of YBCO conductors. Will they ever be low enough for SCDC cables to be competitive? What is the measure for answering this question?
- Will any other superconductors be appropriate for an SCDC cable?
- Is it appropriate to focus on a specific material at this time and use it as a benchmark in the program?
- What SCDC cable capacity and length (size) is appropriate for a demonstration?
- Determine the need for redundancy (n+1) for DC cables. What are the effects of the magnetic field produced by one of the cables on the others?
- Some initial effort must be spent on the issue of terminal and splice insulation.

- Since there may be more than one eventual cable (or cable system design), a range of currents, voltages, and dimensions need to be addressed.
- Determine the impact of loss or addition of loads of 200 MW or more over short times. This would introduce a variation of a current in the line that might require electricity storage capability. How does this issue impact the design of SCDC cable system and its interface to the grid?
- Determine the value of a superconducting DC cable vis-à-vis a cryoresistive cable.

A

AGENDA/PRESENTATIONS/PARTICIPANTS

Agenda

Wednesday afternoon, Oct 12

Noon	Lunch	
12:15 PM	Welcome Insights	Starr
1:00 PM	Introductions	Eckroad
1:15 PM	Discuss goals and expected outcome of workshop	Eckroad
2:00 PM	Grid interconnection issues for DC cables	Lasseter
3:00 PM	Break	
3:15 PM	Continue discussions of DC cables	all
3:30 PM	Presentation on superconducting fundamentals SC Cable projects	Grant
4:15 PM	Presentation on practical issues for operation and protection of superconductors	Hassenzahl
5:00 PM	Close for the day	

Thursday Oct 13

7:30 AM	Continental breakfast	
8:00 AM	Inverter converter valve and station designs for SCDC cables	Nilsson
9:00 AM	Various designs for DC cables and insulation	Gregory
10:00 AM	Break	
10:15 AM	Cryo-resistance vs. superconductivity for DC cables	Grant
10:45 PM	Basics of vacuum and cryogen flow	Hassenzahl
Noon	Lunch	
1:00 PM	Fault current limiters	Damsky
2:00 PM	Discussion of future need for DC cables US and worldwide	All
3:00 PM	Address purposes of the workshop and reset workshop and program goals	All
4:00 PM	Work through goals	

Friday Oct 14

7:30 AM	Continental breakfast	
8:00 AM	Continue with discussion of goals emphasis on program for 2006 and beyond	All
10:00 AM	Break	
10:15 AM	Discuss future team(s) to carry out overall program Establish action items and time schedules.	All
11:15 AM	Wrap-up and plan near term effort, report, etc.	All
Noon	Lunch	

Attendees

Ram Adapa

Ben Damsky

Steve Eckroad

Aty Edris

Paul Grant

Brian Gregory

Bill Hassenzahl

Chauncey Starr

Walter Zenger

Bob Lasseter

Session/Presentation Guidelines

Wednesday afternoon, Oct 12

Goals and expected outcome of workshop • Important: Attendees are expected to define a discrete range of power, voltage & current for study and application (e.g., is anything below 5 GW [+/- 25 kV, 100 kA] worth considering [prototypes excepted]) • Attendees are expected to define the merits and demerits of several macroscopic SCDC cable designs (e.g., monaxial [RTD, separate poles, cables] vs. coaxial [CTD, two poles per cable]) • Presentations should be planned to take half the time allowed, the remainder to be taken up in questions and answers. One hour time slots should have 15 to 20 slides maximum. • Procedural issues o Note taking and collection o Presentations in PowerPoint and on media to Chair	Eckroad
Grid interconnection issues for DC cables • How are existing HVDC interconnections used and why? When does DC make sense and when not? o What portion are used for wheeling massive generation to load (e.g., Itaipu, Three Gorges)? o Inter-AC grid ties a la the Pacific HVDC and Neptune (how often, if at all, is the current flow reversed?) What should we plan on for SCDC o DC back-to-backs (Republic of Texas, Japan, how long, reversible??) o Opportunities within the present grid for DC (interties, ring busses) • Impedance issues for SCDC interties (optimum power, keeping in mind low voltage and high current is what SC is good at) • Fault handling in HVDC…issues presented by the higher current levels in SCDC	Lasseter
Superconducting fundamentals SC Cable projects • Definition of superconducting critical state parameters for HTSC wire (Tc, Jc, H* and frequency) and relevance to cable application • Characteristics, specifications and cost of present and soon to be available HTSC wire, including MgB_2, including maximum lengths and jointing. • Brief review of present HTSC cable projects • Revisit original Garwin-Matisoo and LASL LTSC cable projects	Grant
Practical issues for operation and protection of superconductors • Stabilization during faults and current overload o Transition of superconductors to the normal state o Enthalpy and heat transfer o Fault dissipation on "one way" transmission interties (parallel normal	Hassenzahl

conductor?) o Energy extraction o Voltage issues	

Thursday Oct 13

Inverter converter valve and station designs for SCDC cables • Issues surrounding “paradigm shift” from high voltage, low current to low voltage, high current (“DC Heavy”) • Ripple and harmonic filtering and suppression (will “resonance” be an issue given “zero” resistance? (high Q)) • Fault, overload and service issues re I/C design o Reversible I/C valves…off loading to surrounding AC grid(s) o High voltage transients (L di/dt) o Single pole servicing…practical aspects of servicing one pole…earth return during servicing? • Pump/Cryo-station power supply along route o Tap-offs? o Separate AC supply cable? • Comment on “Chowduri” paper (it’s mostly control issues, not SCDC…VSC, etc.) • Is there an opportunity to reduce discrete (thyristor, GTOs, etc.) part count by using the sc cryo-infrastructure for cooling, maybe for “specially designed” cryo-bipolars	Nilsson
Designs for DC cables and insulation • Almost all existing HVDC cables are submarine…where are the land uses…are they two poles per cable (a la Sumitomo submarine), two cables (one cable per pole, a la Empire Connection) or “hybrid” (Neptune) • Review the BICC DC HTSC cable design effort o What EU applications were to be targeted? • Advantages, disadvantages of past and proposed SCDC cable designs o Monaxial (RTD) (Garwin-Matisoo, Grant) o Coaxial CTD) (LASL, BICC) o AMSC “2-in-1” • Polarization issues in cold dielectrics	Gregory
Cryo-resistance vs. superconductivity for DC cables • Review past cryo-resistive cable efforts (e.g., CRIEPI) • Define “Jc” for normal metals and compare costs with HTSC	Grant

Basics of vacuum and cryogen flow • Pumped vs. “permanent” vacuum • Phase diagrams (pressure and flow rates) • “Head” issues…how far can you pump uphill…or come downhill? • What are the characteristics of nitrogen and other liquids • Refrigeration types and efficiencies • Cryogenic infrastructure o Sources of heat to be removed ▪ Radiative ▪ Hysteretic (ripple and harmonics) ▪ Flow friction • Intervals between recooling and re-pumping stations	Hassenzahl
Presentation on Fault Current Limiters • Conventional FCLs • Superconducting FCLs • Compare different FCL designs advantages and disadvantages o Response time o Fraction of limiting current o Efficiency o Effect of changed impedance on system during normal operation o Potential for use with advanced technologies such as SC AC and DC Cables	Damsky
Discussion of future need for DC cables US and worldwide	All
Address purposes of the workshop and reset workshop and program goals	All
Work through goals	

Friday Oct 14

Continue with discussion of goals emphasis on program for 2006 and beyond	All
Discuss future team(s) to carry out overall program **Establish action items and time schedules.**	
Wrap-up and plan near term effort, report, etc.	

B

GRID INTERCONNECTION ISSUES – LASSETER

Grid Interconnection Issues

DCSC Cable Workshop

EPRI

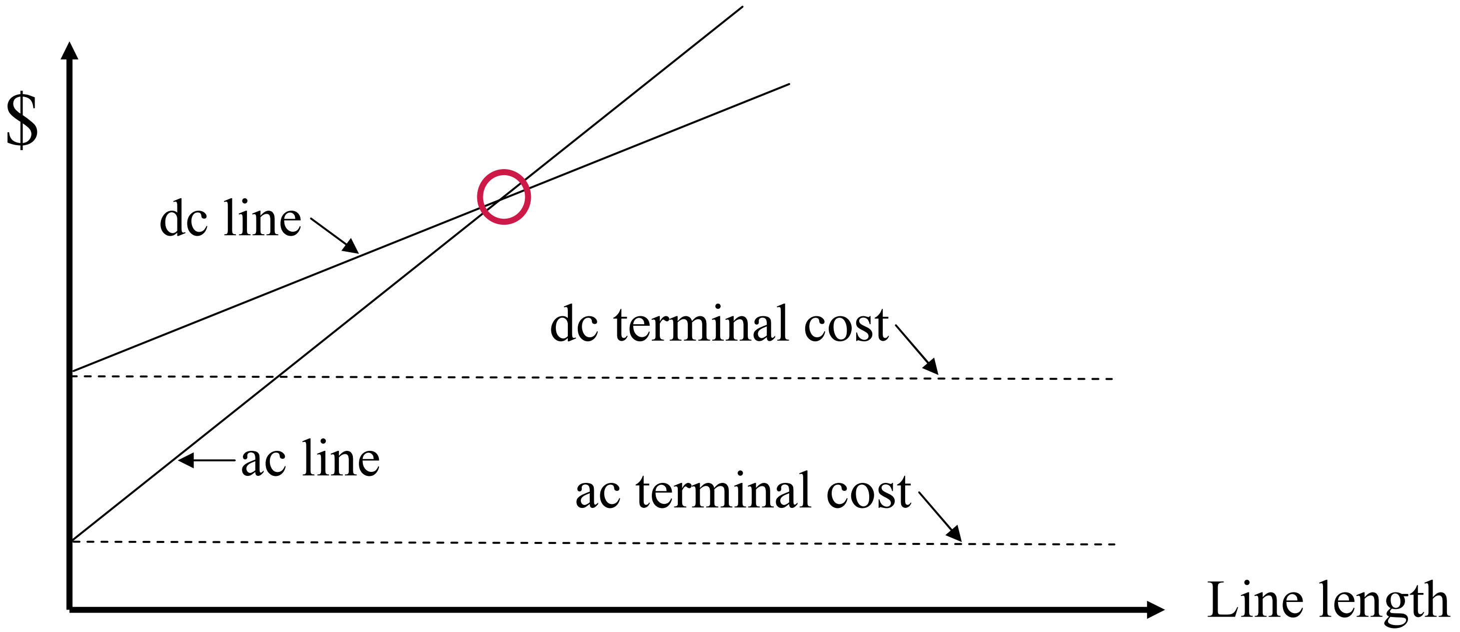
October 12-14, 2005

Bob Lasseter

University of Wisconsin-Madison

HVDC Applications

• Asynchronous	different ac networks
• Cable	> 2-3 miles
• Lowest cost	Breakeven distance



Other Application Issues

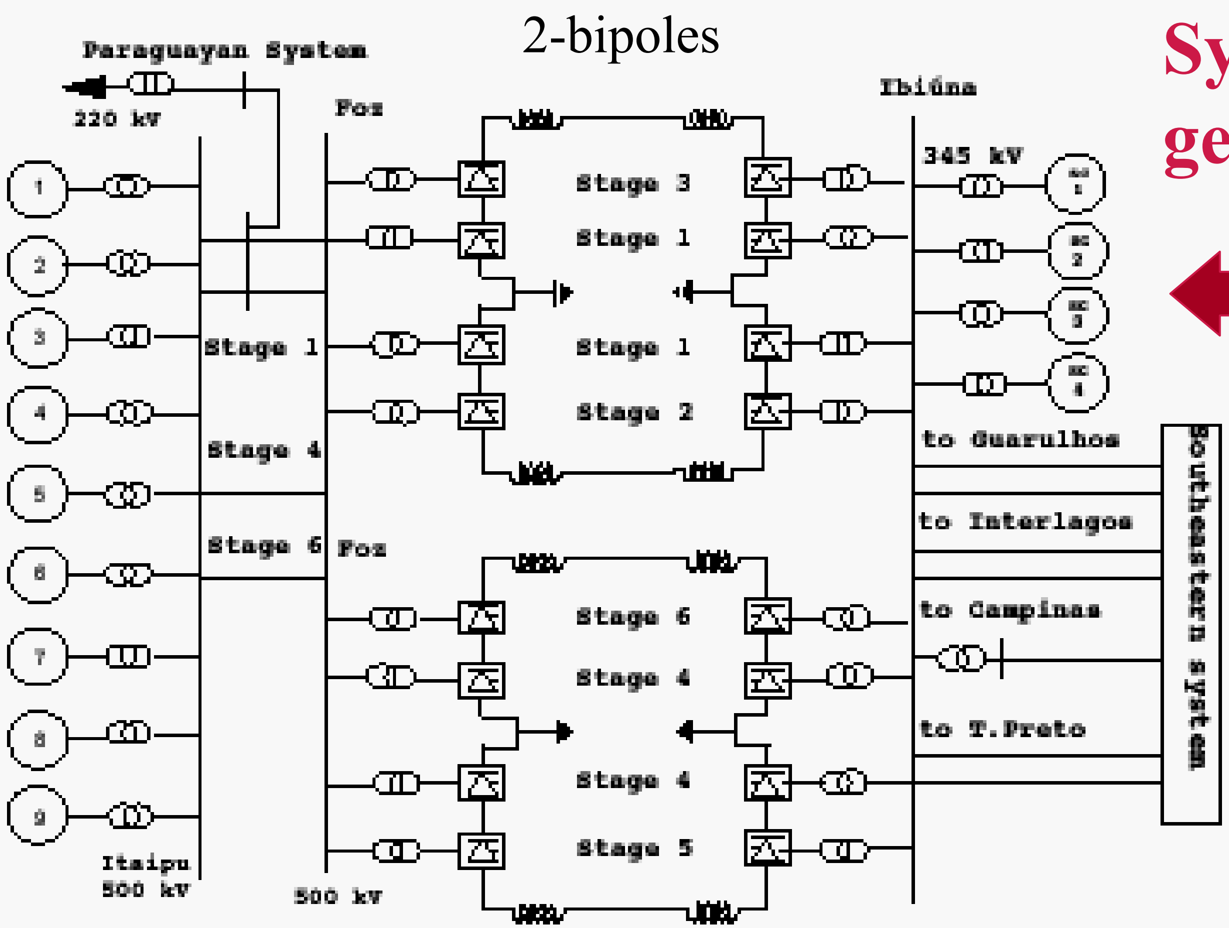
Positive

- Control of power flow from ac-1 to ac-2
- Low converter losses ~0.65%
- Redundancy; ~ series Thyristors

Negative

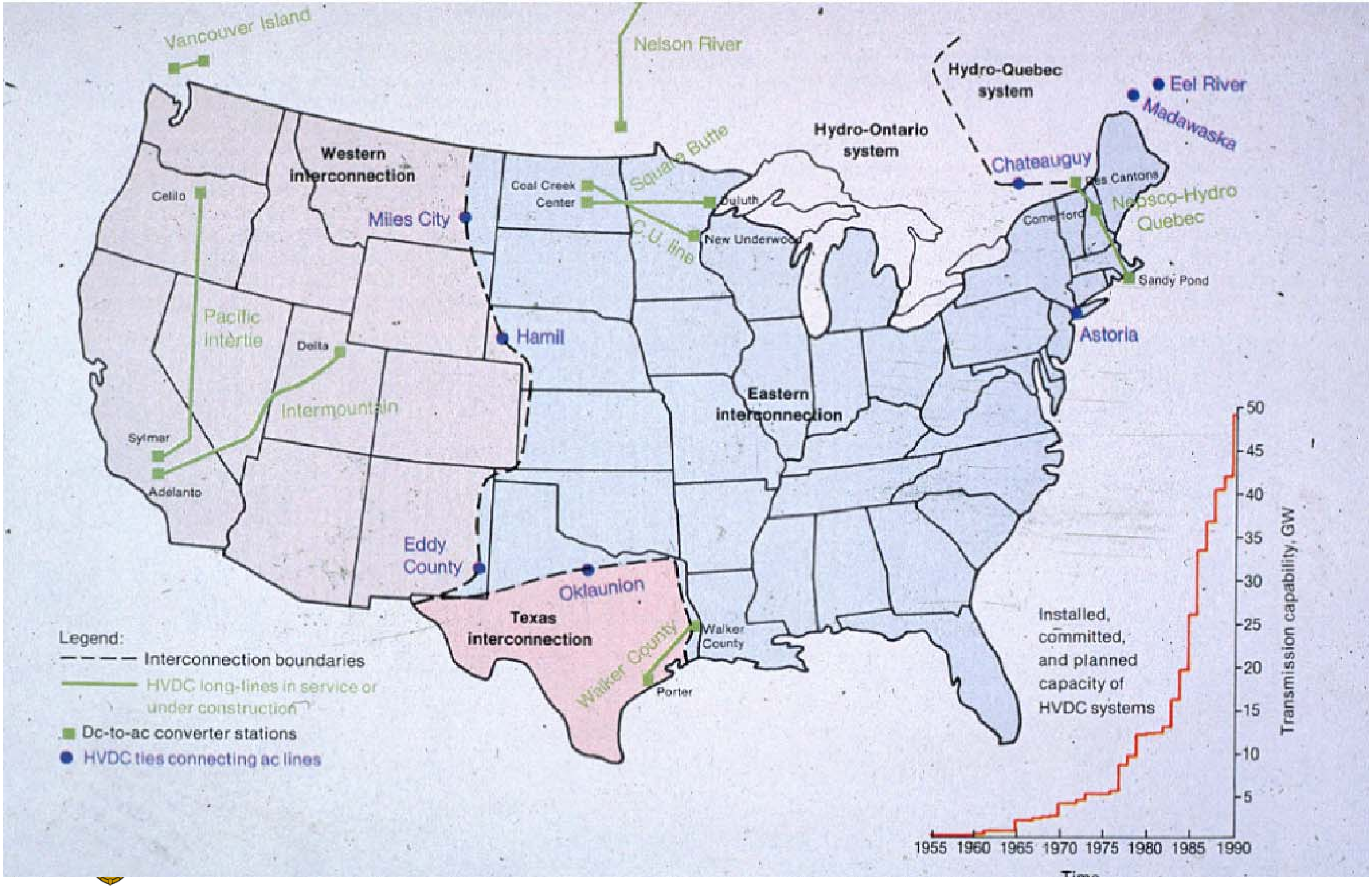
- Needs stiff ac voltage for thyristors at inverter
- Gate turn off devices have losses 3-10 times higher and difficult to place in series

Itaipu HVDC System
3.1 GW ± 600kV ~ 2.5 Ka



Synchronous generators

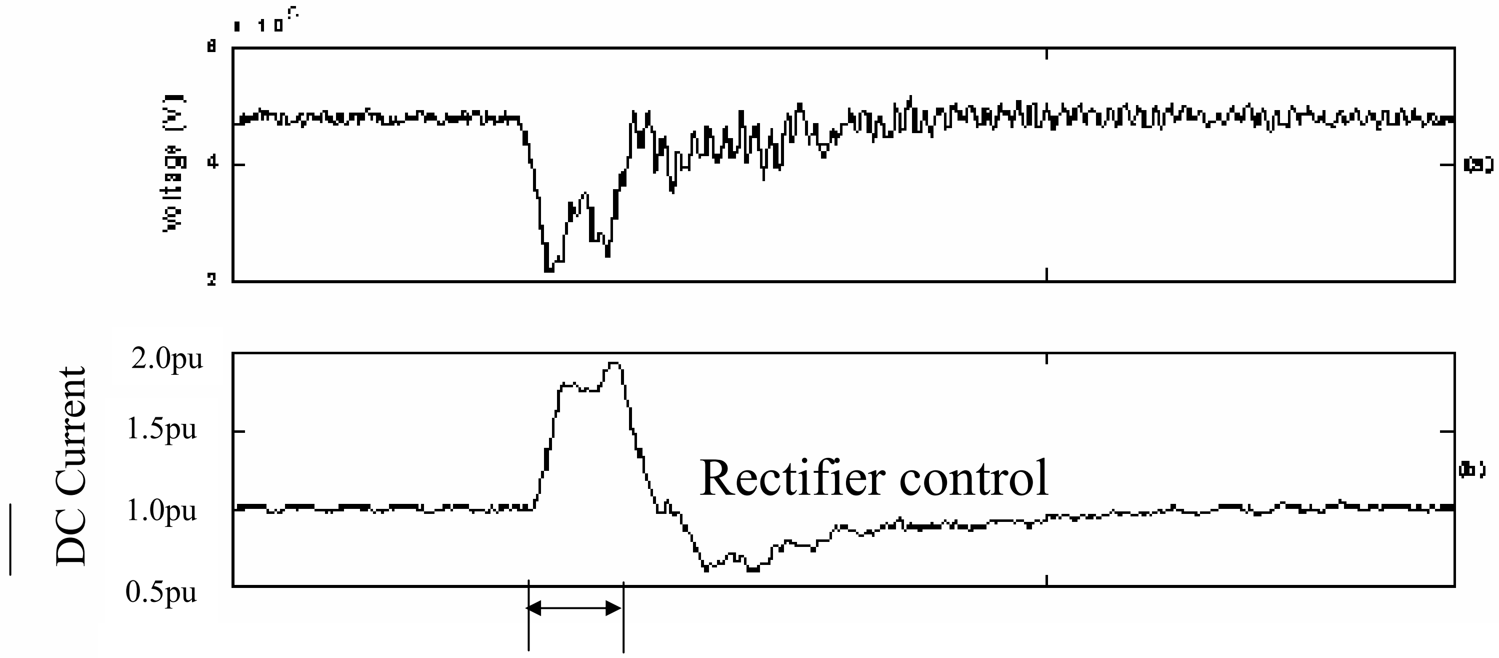
Figure 2. Itaipu HVDC System main circuit and evolution


Vancouver Island
Nelson River
Hydro-Quebec system
Eel River
Madawaska
Hydro-Ontario system
Square Butte
Western interconnection
Coal Creek Center
Duluth
C.U. line
New Underwood
Chateauguy
Des Cantons
Comerford
Nepsco-Hydro Quebec
Sandy Pond
Celilo
Miles City
Pacific Intertie
Delta
Hamil
Astoria
Intermountain
Eastern interconnection
Sylmar
Adelanto
Eddy County
Oklaunion
Texas interconnection
Walker County
Walker County
Porter
Legend:
Interconnection boundaries
HVDC long-lines in service or under construction
Dc-to-ac converter stations
HVDC ties connecting ac lines
Installed, committed, and planned capacity of HVDC systems
Transmission capability, GW
50
45
40
35
30
25
20
15
10
5
1955
1960
1965
1970
1975
1980
1985
1990
Time

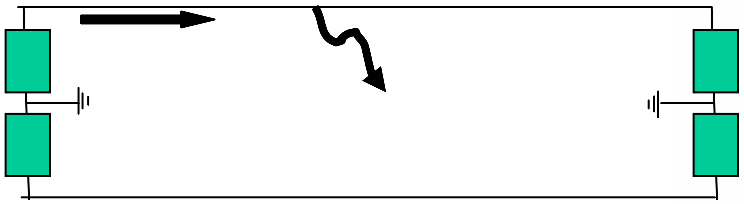
Long Transmission Systems

System	GWs	kV	kA converter	# bipoles
Itaipu	3.1x2	±600	2.6	2
3 Gorges	3.0x3	±500	3.0	2 Different locations
Pacific intertie	3.1	±500	2.0	4 Parallel units

DC Faults



~ 20msec



ac/dc interface issues

- Converter complexity
- Injected power levels
- Stiffness of ac system
- Changing load 24/7
- Ac system with loss of 5 GW

Converter complexity

5 GW cable: ± 25 kV at 100kA

- Thyristor current ratings max.~3.5 kA
- 28 or 30 rectifiers and 28 or 30 inverters
- Bipole size ~175 MW

Johnson,B.K., R.H. Lasseter, F.L. Alvarado, D.M. Divan, H. Singh, M.C. Chandorkar, and R. Adapa, "High-Temperature Superconducting dc Networks", IEEE Transactions On Applied Superconductivity, Vol. 4, No.3, pp.115-120, September 1994.

Converter complexity: 1 GW Unit

Voltage	Current	# bipoles/end
± 25 kV	20kA	6
± 50 kV	10kA	3
± 75 kV	6.6 kA	2
± 150 kV	3.5 kA	1

Injected power levels

5 GW cable: ±25kV at 100kA

AC transmission Power levels (ERPI's Red Book)

•345 kV	0.5 GW
•500 kV	1.0 GW
•765 kV	2.2 GW

- 1 GW at a substation is close to upper power limit
- Loss of a 1 GW line has the potential to start a cascading loss of the ac system.

Substation Stiffness

DC/AC interface (inverter)

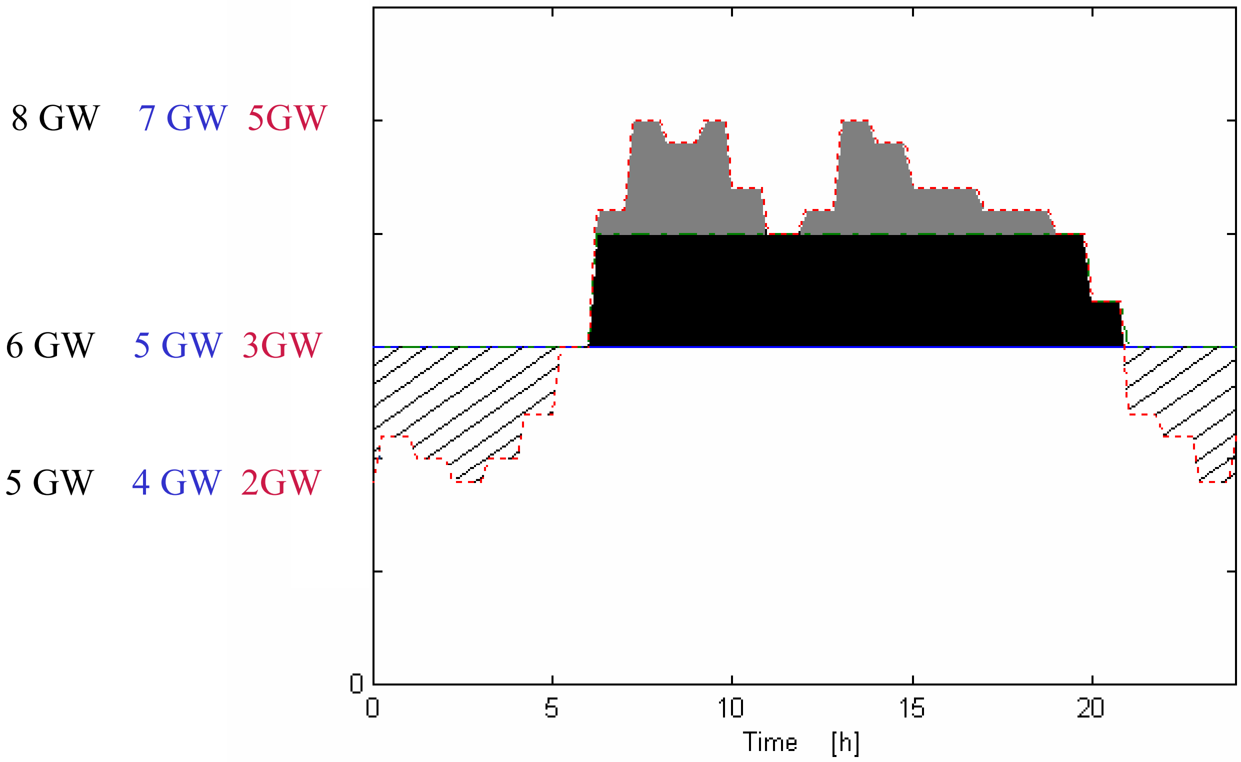
- Short circuit ratio

$$SCR = \frac{MVA_{sc}}{P_{dc}} \geq 3.5 - 4.0$$

- For a 1 GW cable the ac $MVA_{sc} \geq 3500$

Changing ac load 24/7

ISSUE: 24/7 load. **Do you regulate flow or track load locally?**



ac/dc interface issues

- Converter complexity } **no voltage droop**
- Injected power levels
- Stiffness of ac system

} **reduce injected power**

- Changing load 24/7
- Loss of cable

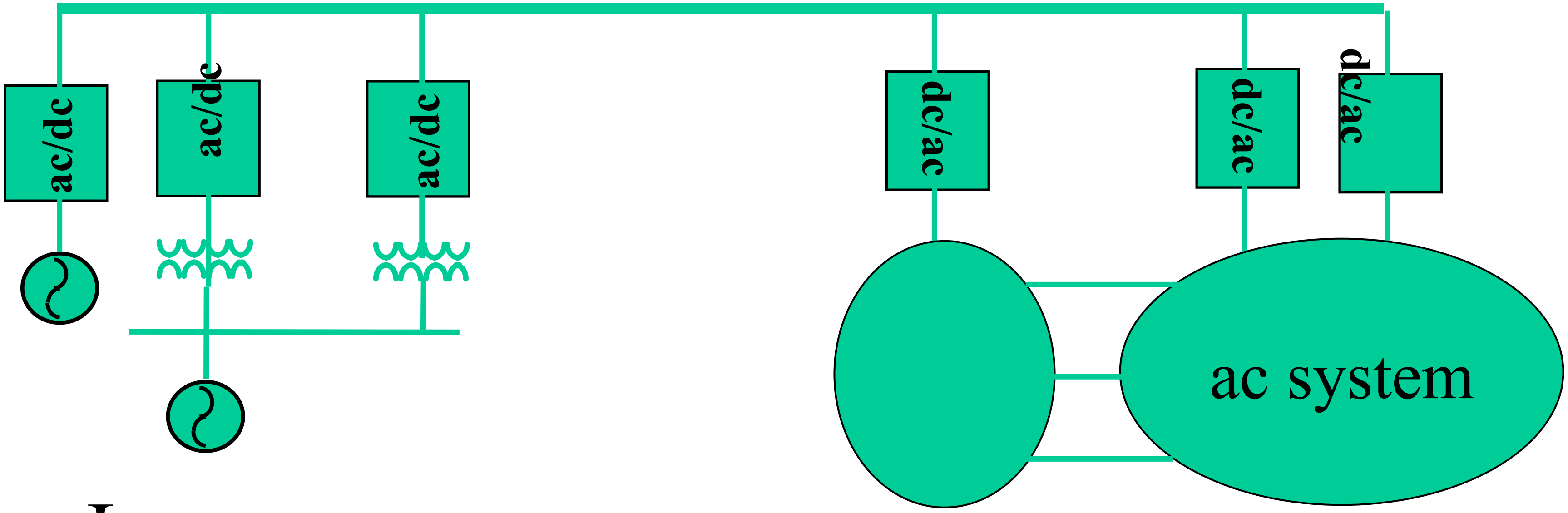
} **storage**

ac/dc interface issues

imply a multi-terminal dc system to deal with:

- Converter complexity
- Injected power levels
- Stiffness of ac system

3 GW 60 kA DC Cable/Multi Converters

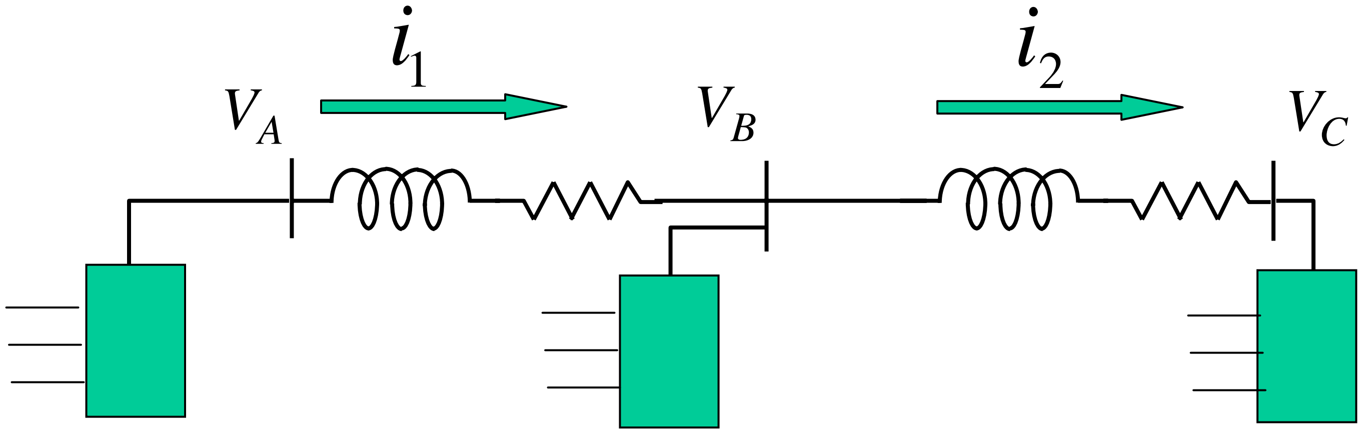


Issues

1. Multi-terminal problem
2. Paralleling 6 bipoles
3. Converter failure
4. Control of power flow

ac/dc Each block assumes 6 parallel bypoles

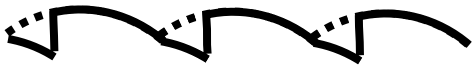
Traditional Multi-terminal HVDC



$$\langle V_{dc} \rangle = V(\alpha) - \frac{3}{\pi} X_{ac} I_{dc}$$

$V_A, V_B, \& V_C$ Function of currents i_1 & i_2

Thyristor Controlled Rectifier



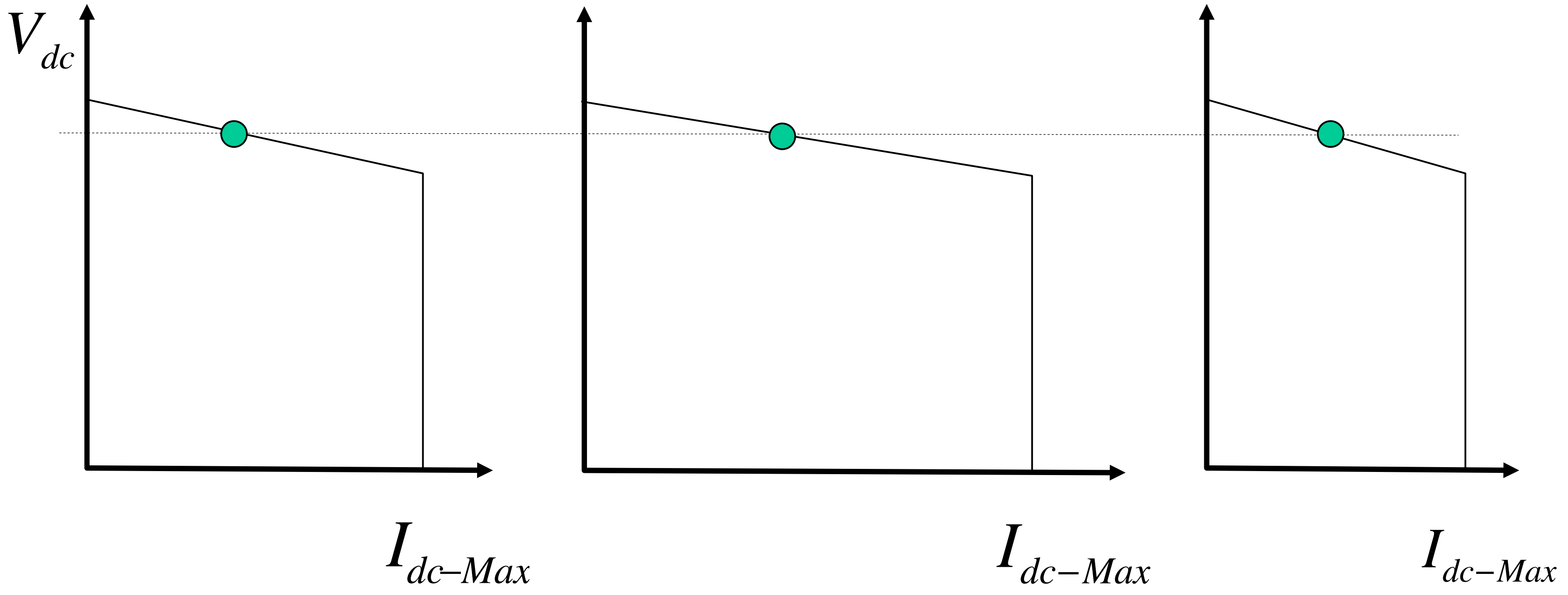
Superconducting Cable

No current dependent voltage drop in the cable provides for;

1. Multi-terminal operation
2. Paralleling converters/bipoles

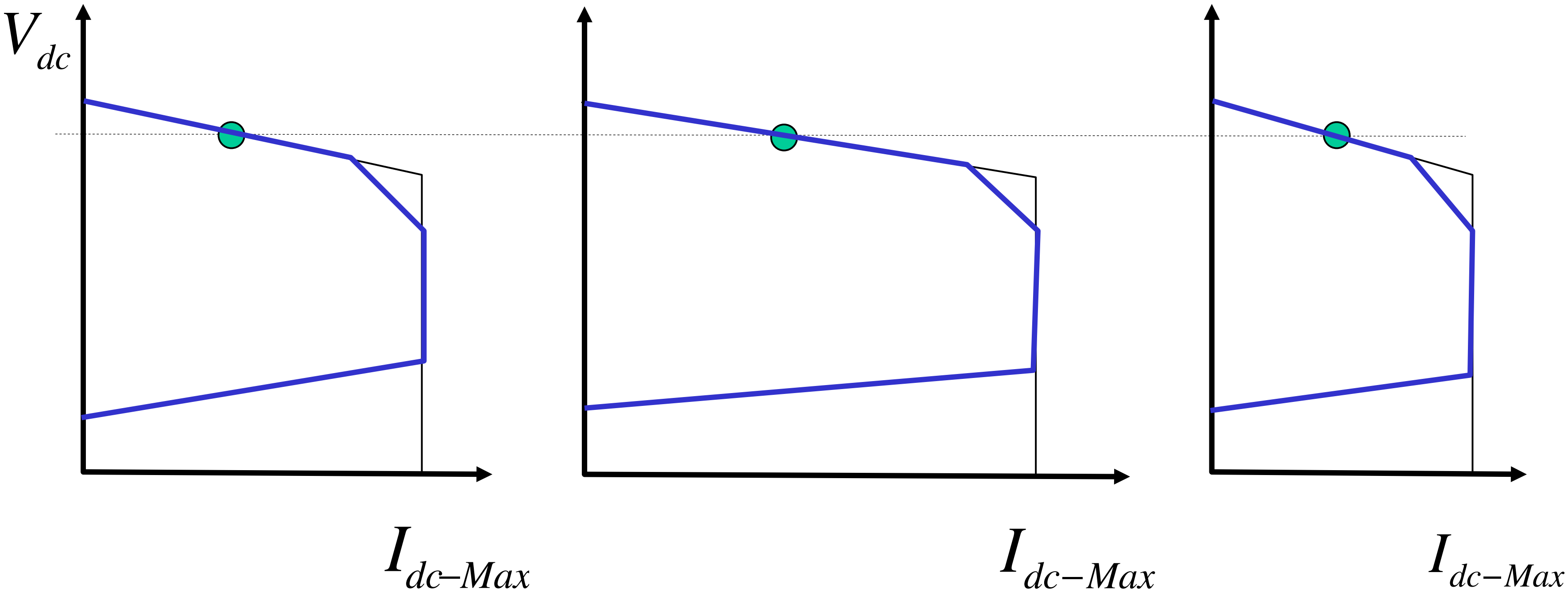
Power Dispatch on dc voltage

Thyristor Controlled Rectifier

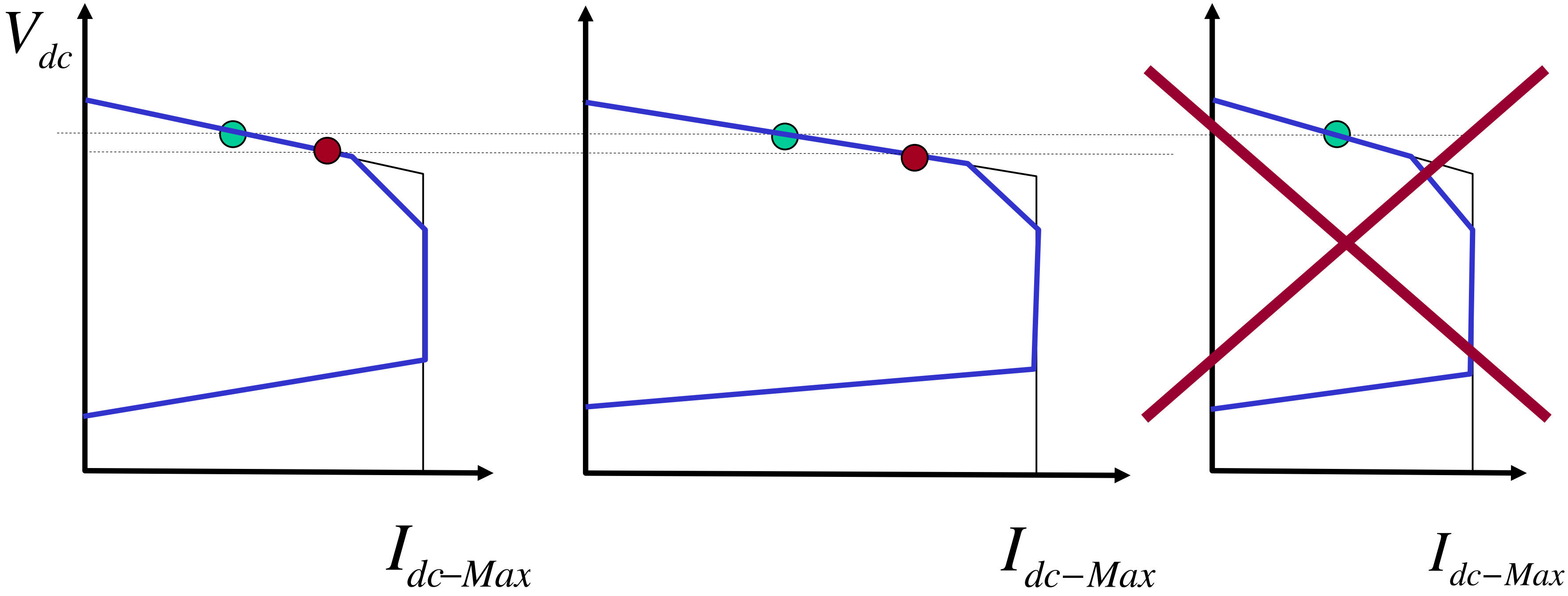


$$\langle V_{dc} \rangle = V(\alpha) - \frac{3}{\pi} X_{ac} I_{dc}$$

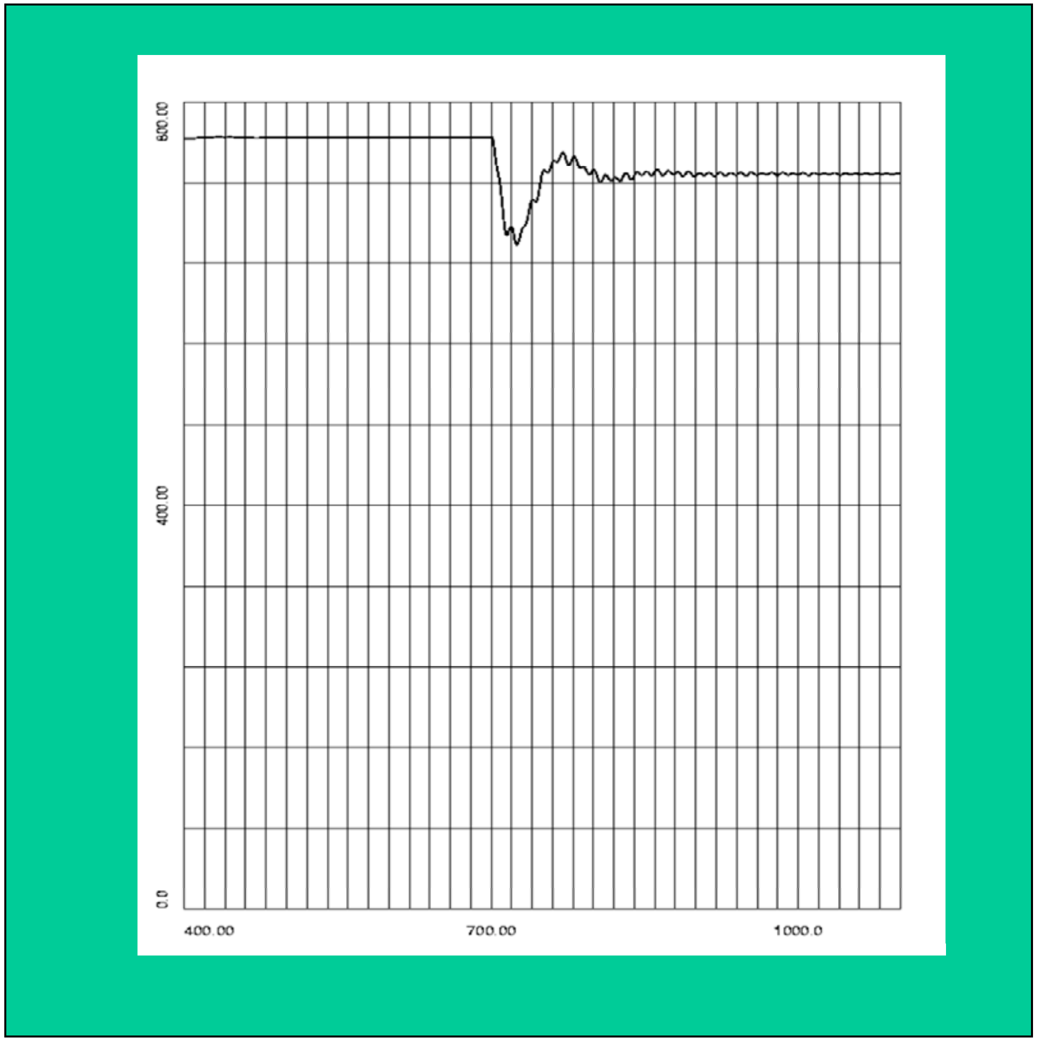
Power Dispatch on dc voltage



Loss of rectifier



DC voltage with loss of one Rectifier



Distributed Control

Rectifiers

- Share load
- Independent of number

Inverters

- Provides stable ac voltage to the load
- Automatic load shedding
- Independent of number

Coordination is achieved through dc voltage

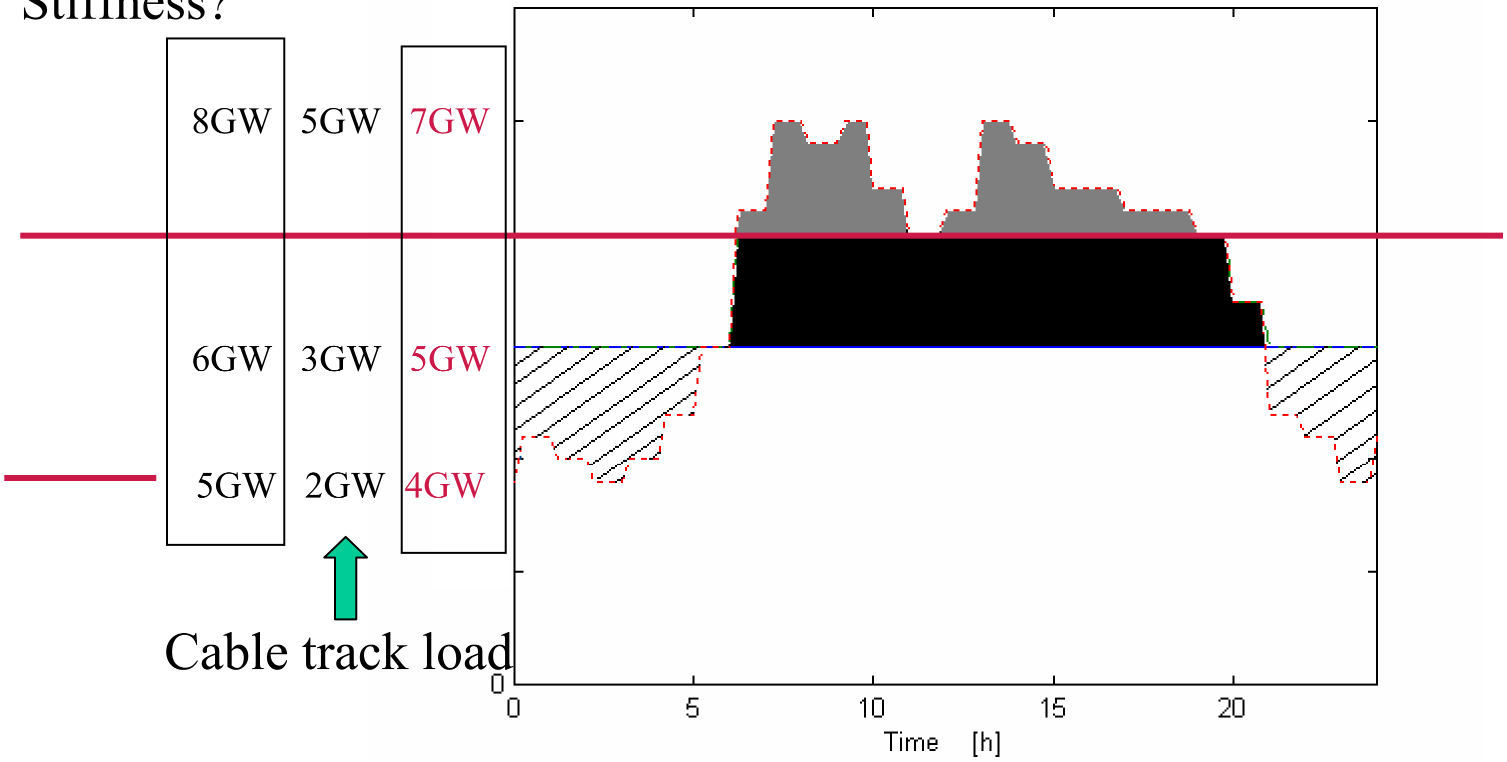
Reference:

Tang, W and R.H.Lasseter, "An LVDC Industrial Power Distribution System without Central Control Unit," PESC , Ireland, June 2000.

Return to AC System Load

ISSUE: 24/7 load. Do you regulate flow or track load locally/storage?

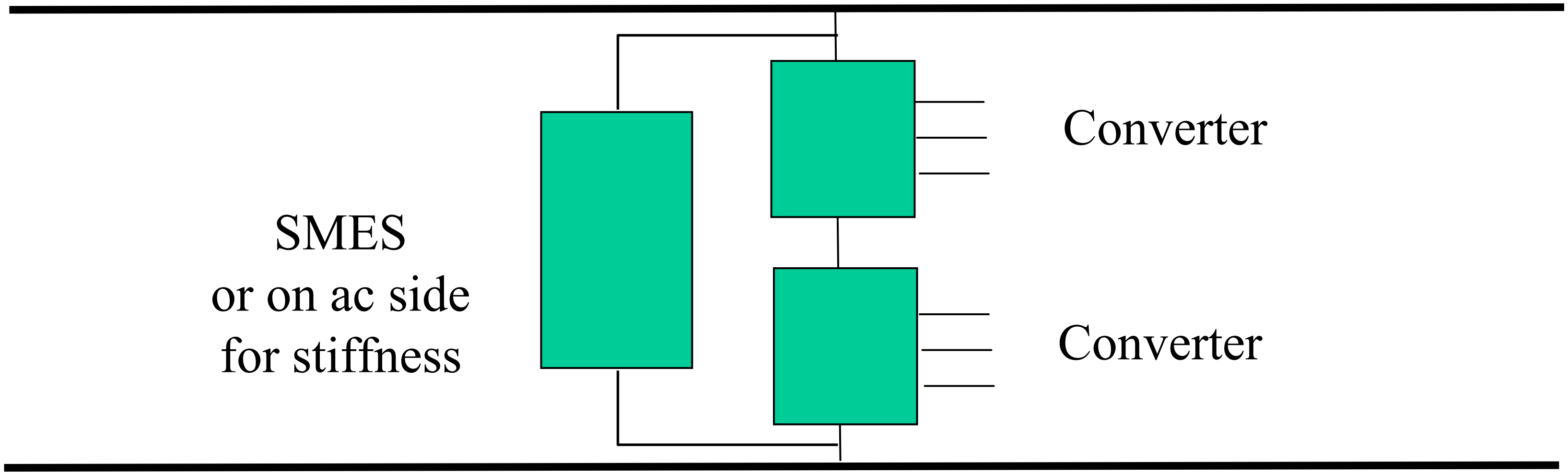
Stiffness?



Cable track load

Cable &
base load
generation

Load cable at 5 GW 24/7



SC Cable

Converter

SMES
or on ac side
for stiffness

Converter

SC Cable

1 GW Inverter

Provides local power with loss of cable

Grid Interconnection Issues

- Dc faults; (2pu current over 20 msec)
- Converter complexity (Multi-terminal)
- Injected power levels (Multi-terminal)
- Stiffness of ac system (Multi-terminal, ac storage or gate turn-off devices)
- Changing load 24/7 (Storage or track some of the load)
- Loss of cable (Storage)

C

SUPERCONDUCTIVITY & POWER CABLES – GRANT

Superconductivity & Power Cables

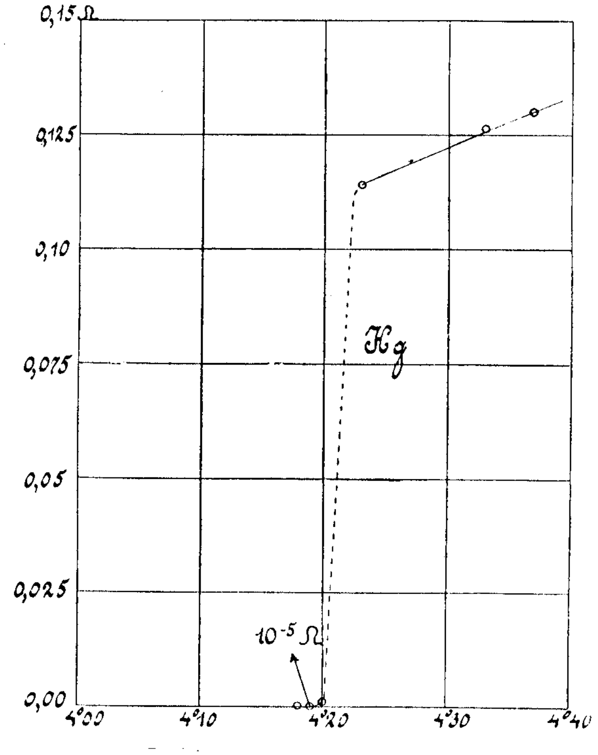
Paul M. Grant
Visiting Scholar in Applied Physics, Stanford University
EPRI Science Fellow (*retired*)
IBM Research Staff Member Emeritus
Principal, W2AGZ Technologies
w2agz@pacbell.net
www.w2agz.com

EPRI Workshop on SCDC Cables
12 - 14 October 2005, Palo Alto

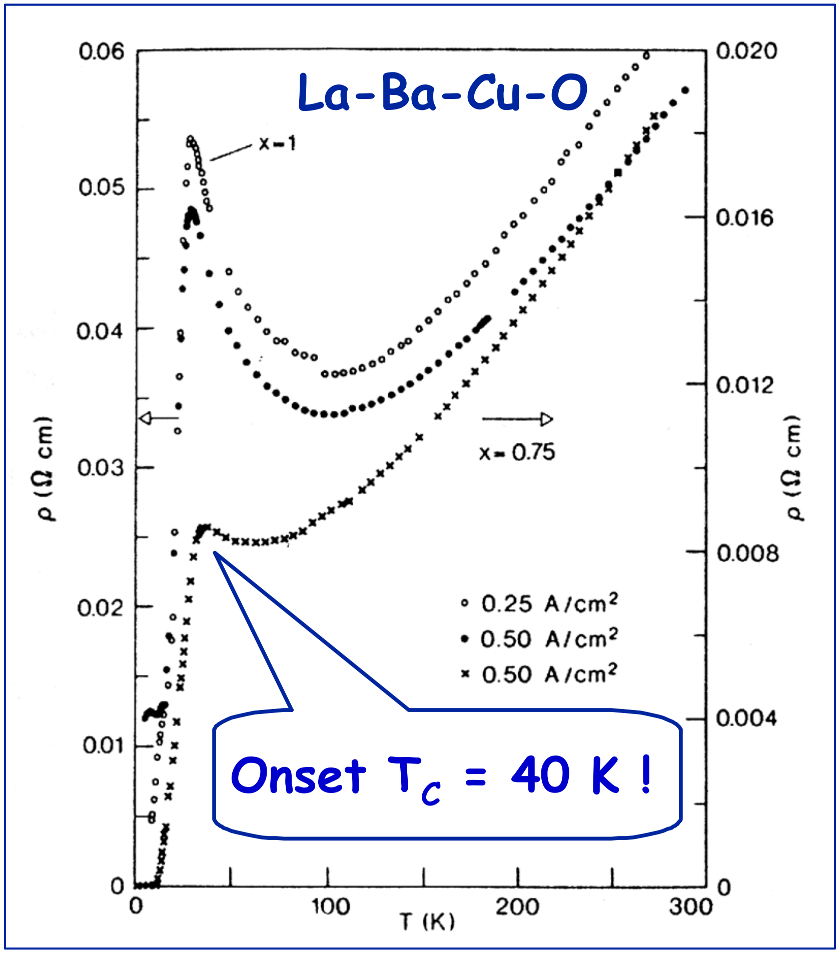
Outline

- Critical State Parameters (T_C, J_C, H^*, ω) relevant to power applications of superconductivity
- Properties of presently and soon to be available HTSC tapes and wires
- Brief overview of present HTSC cable projects
- Re-visit Garwin-Matisoo & LASL LTSC dc cable concepts
- Efficacy of cryo-resistive cables and HTSC wire costs (tomorrow)

The Discoveries



Leiden, 1911



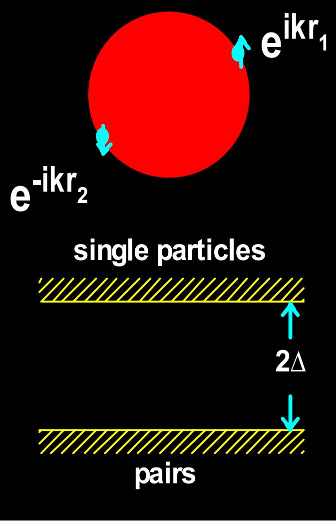
La-Ba-Cu-O

Onset T_c = 40 K !

Zürich, 1986

Superconductivity 101

Cooper Problem

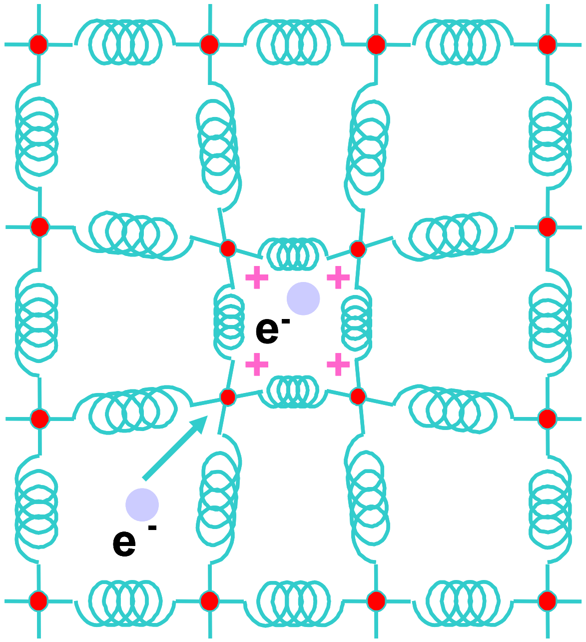


$H(k) + H(-k) + V(k)$

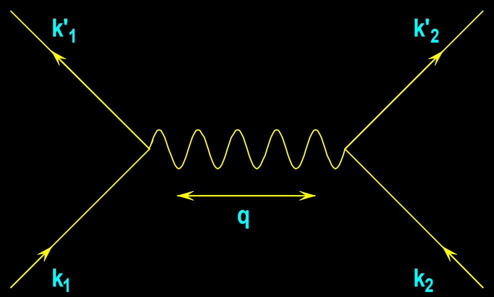
$V(k) = -V_0 \int_0^{k_f} dk\, e^{ik(r_1 - r_2)}$

$\psi(r_1 - r_2) = \phi(r_1 - r_2)\chi(s_1, s_2)$

$2\Delta \sim e^{-2/N(E_f)V_0}$



Fermion-Boson Feynman Diagram



$$T_C = 1.14\, \theta_D \exp(-1/\lambda)$$

$$\theta_D = 275 \text{ K},$$

$$\lambda = 0.28,$$

$$\therefore T_C = \underline{9.5 \text{ K}} \quad \text{(Niobium)}$$

GLAG

$$G[\phi] \approx \int d^3r[\frac{1}{2m^*}(-i\hbar\nabla + e^* A)\phi^*(i\hbar\nabla + e^* A)\phi + a\phi\phi^* + \tfrac{1}{2}b\phi\phi^*\phi\phi^*]$$

$$-(i\partial\nabla - A)^2 f + f(1 - f^2) = 0$$

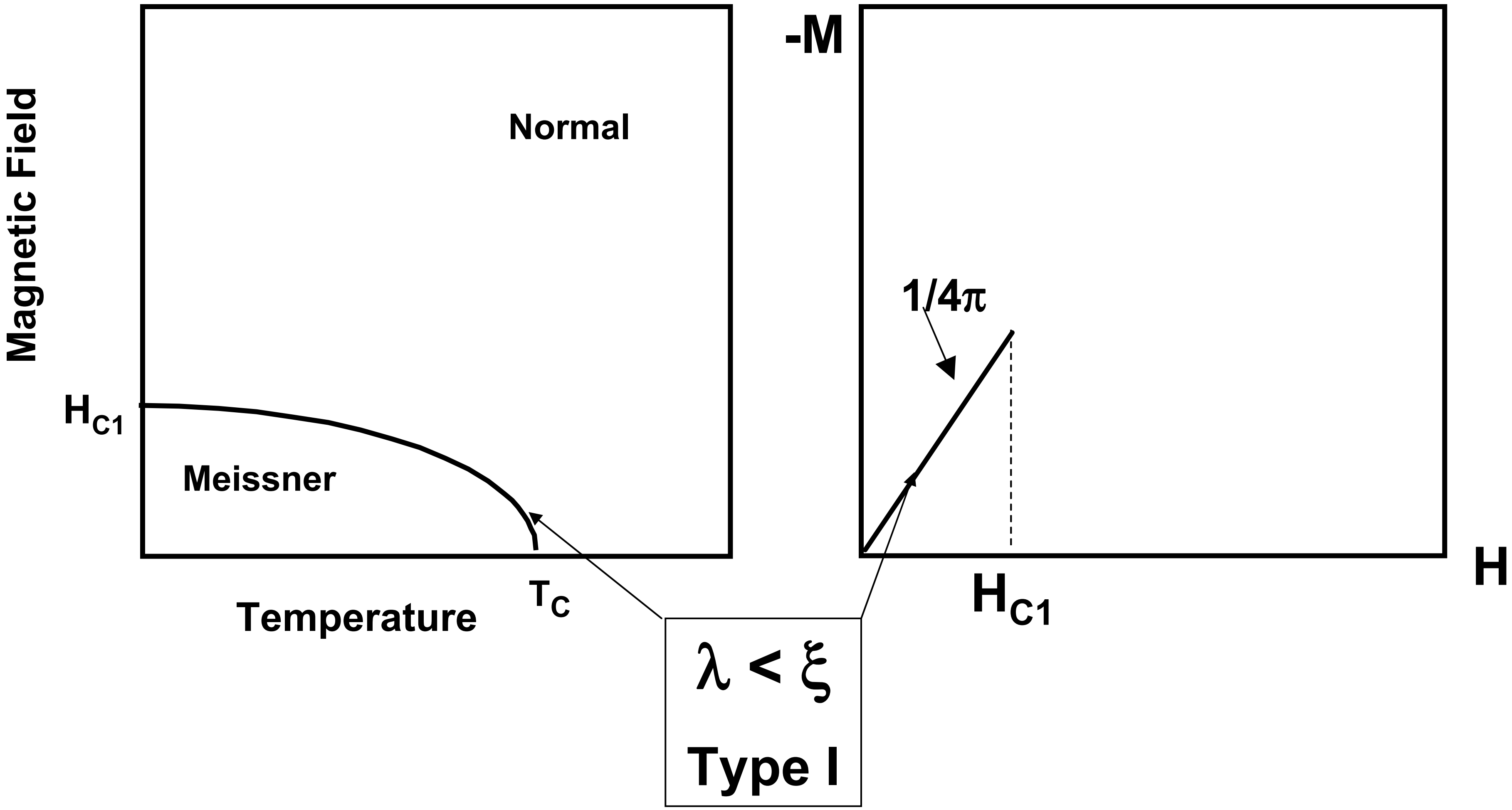
$$\kappa^2\nabla \times (\nabla \times A) + \tfrac{1}{2}i(f^*\nabla f - f\nabla f^*) + Af^2 = 0$$

$$\phi = (|a|/b)^{1/2} f$$

$$A = (\Phi_0 / 2\pi\xi)A$$

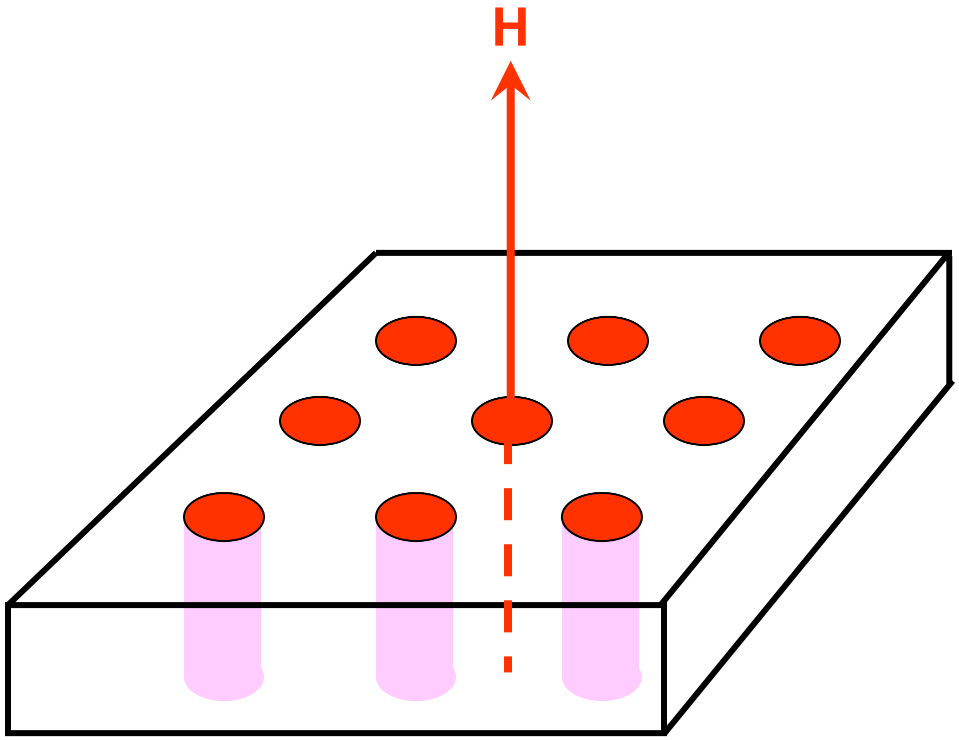
$$\boxed{\kappa = \lambda_L / \xi}$$

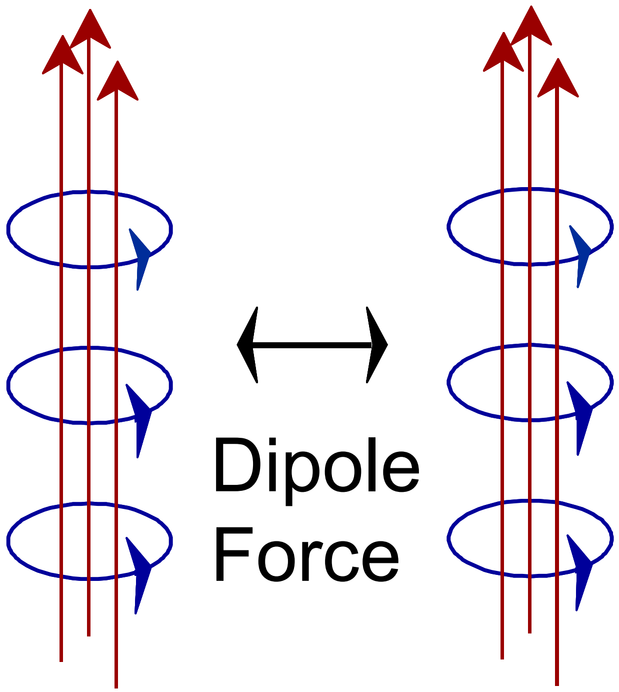
The Flavors of Superconductivity



Abrikosov Vortex Lattice

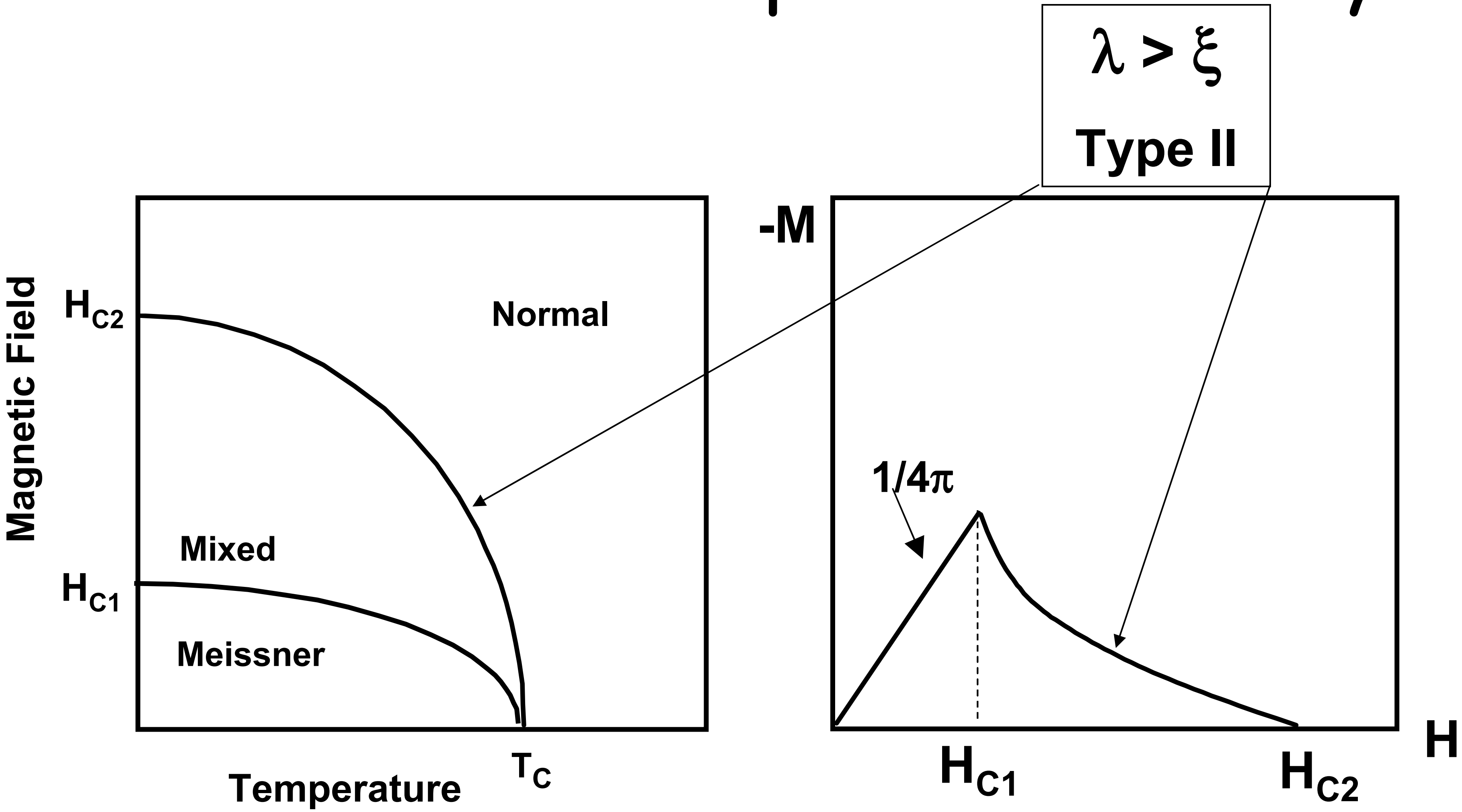
$\lambda > \xi$





Dipole Force

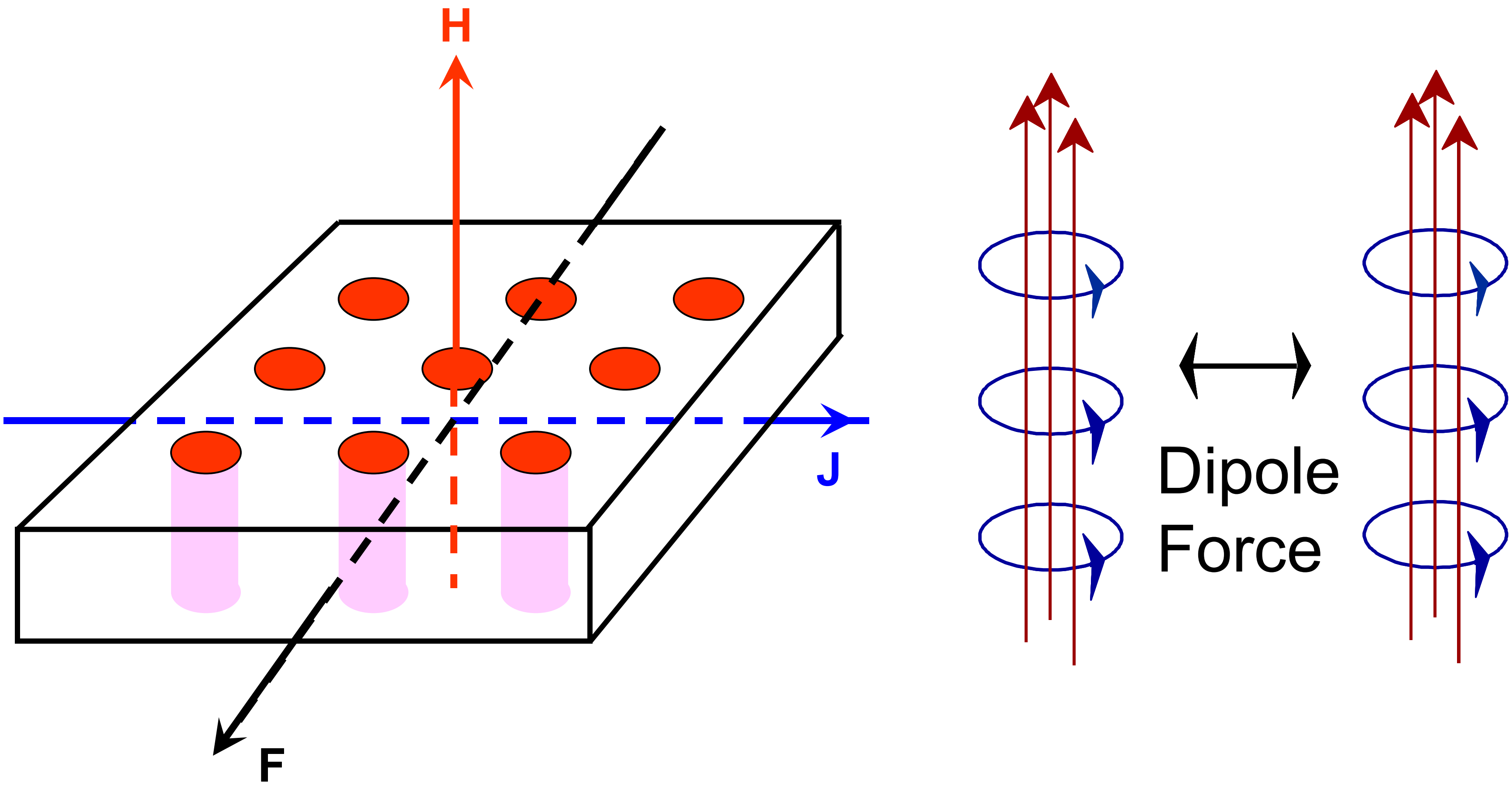
The Flavors of Superconductivity



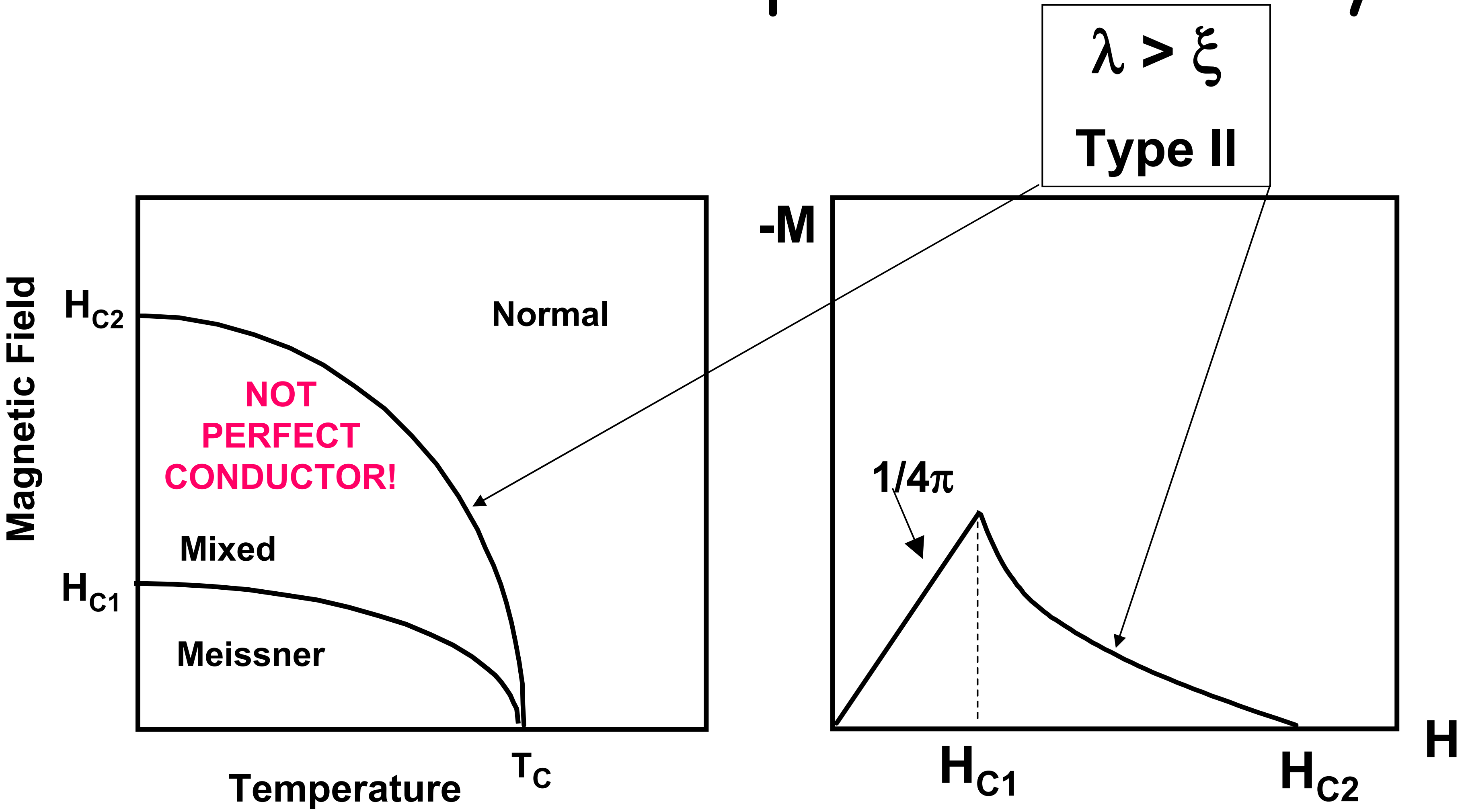
$\lambda > \xi$

Type II

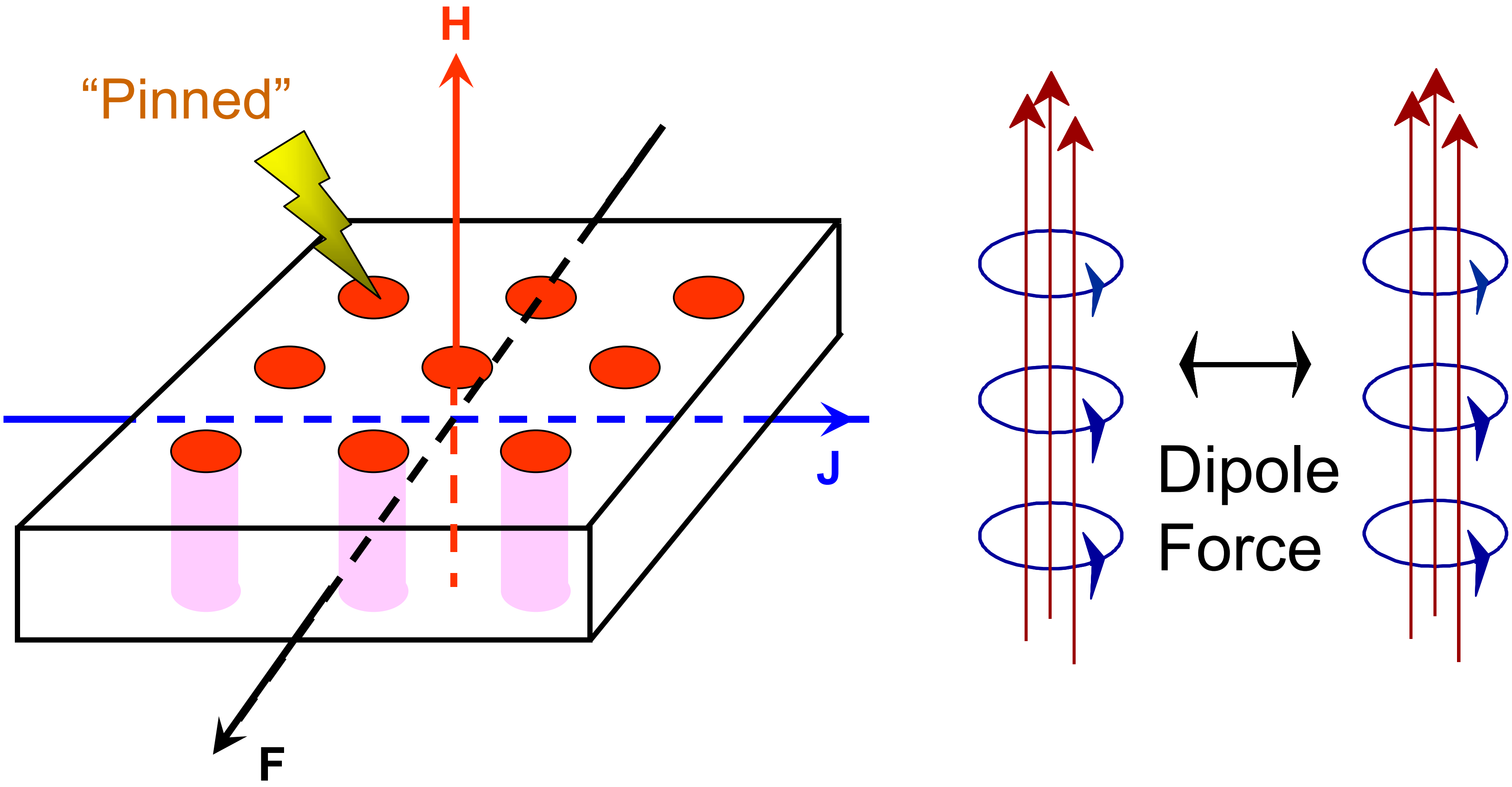
Abrikosov Vortex Lattice



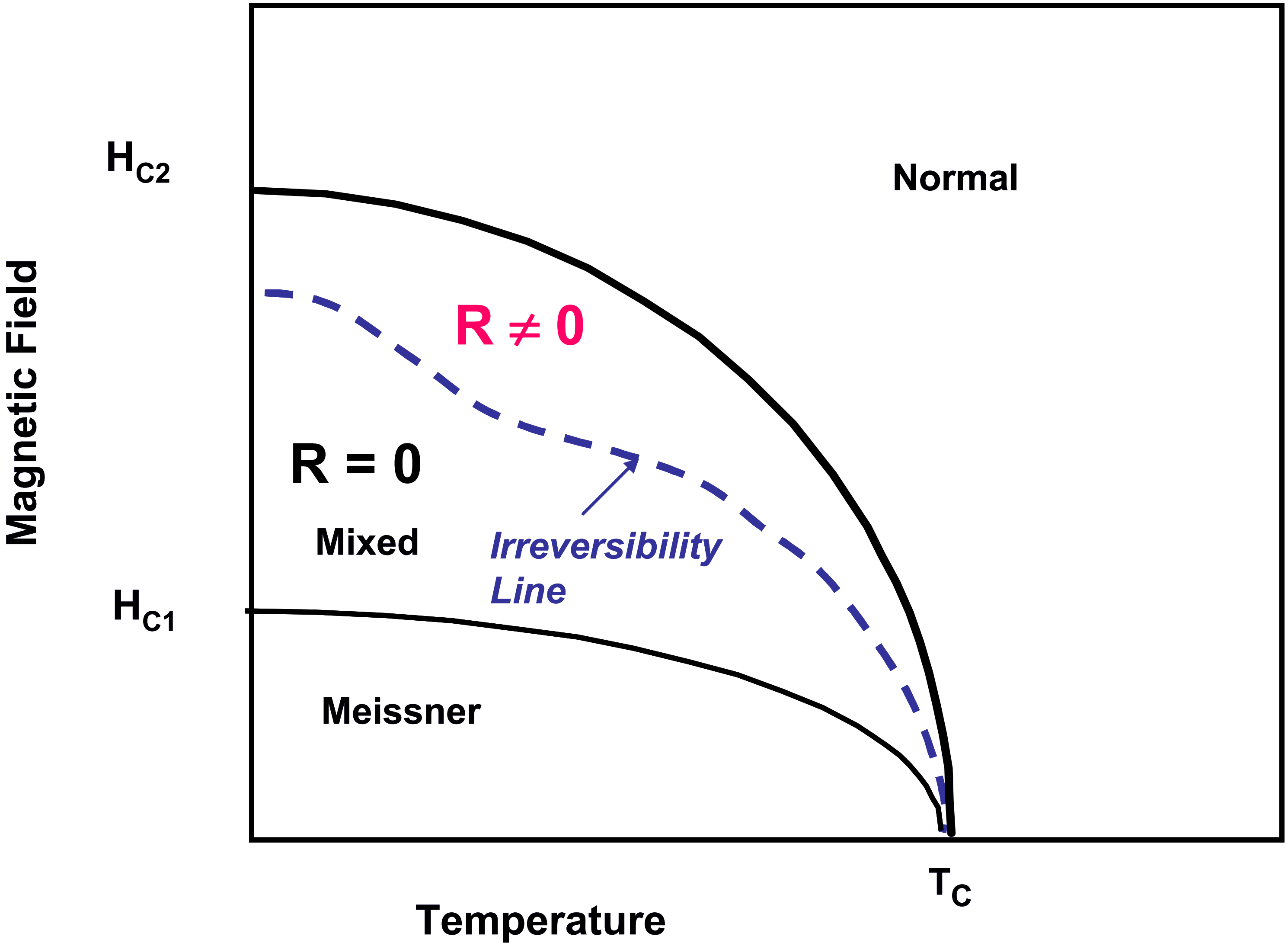
The Flavors of Superconductivity



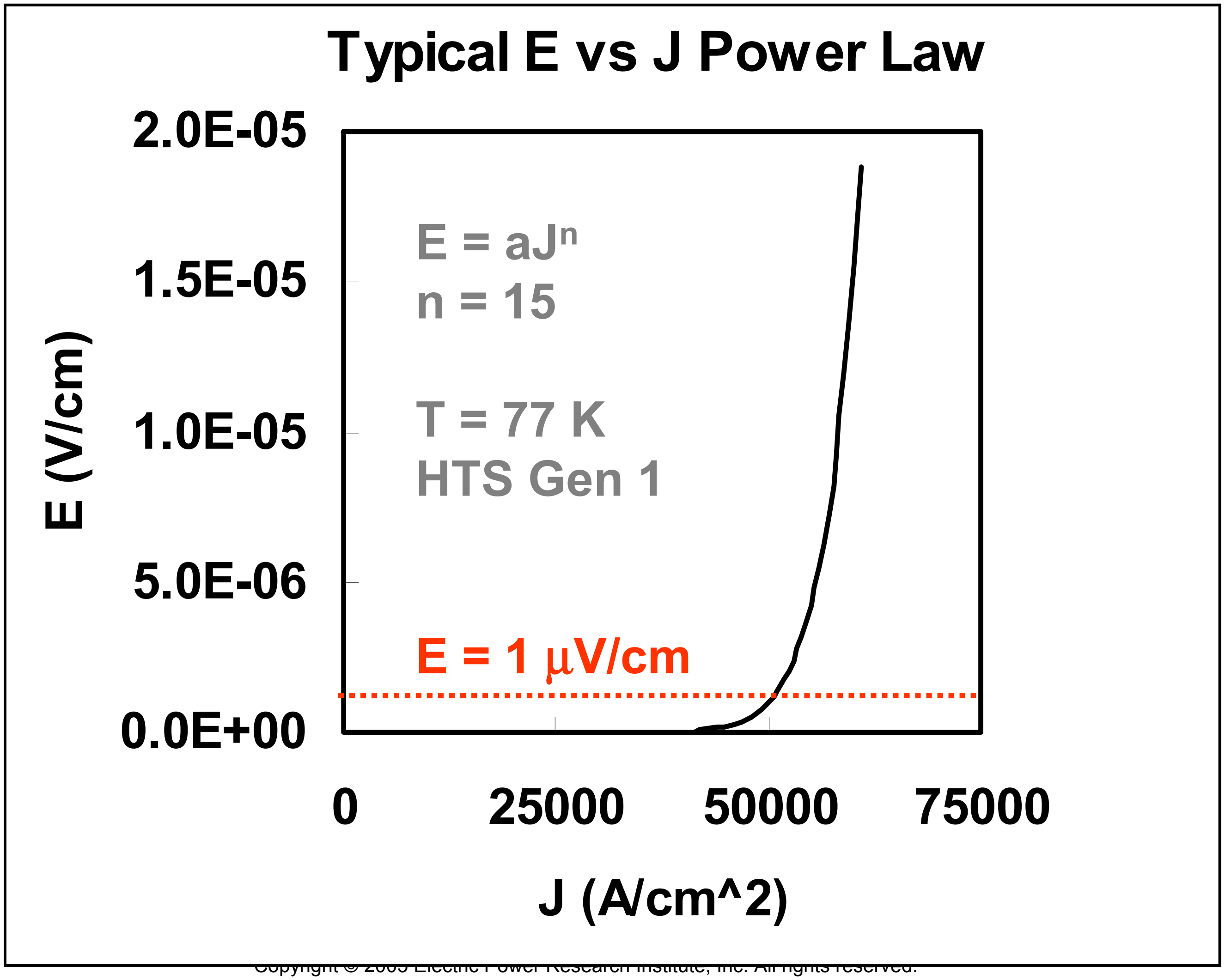
Abrikosov Vortex Lattice



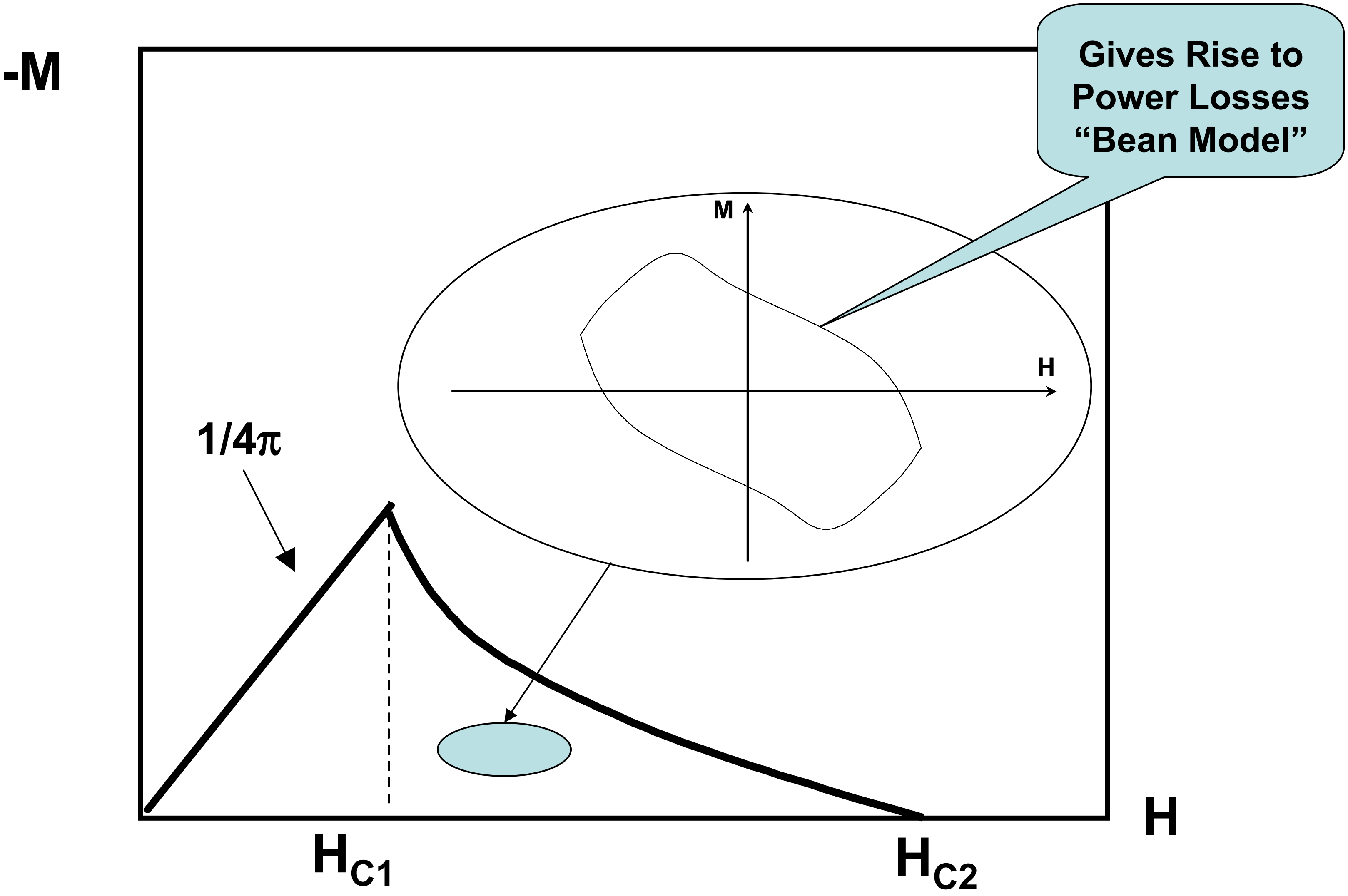
The Flavors of Superconductivity



No More Ohm's Law

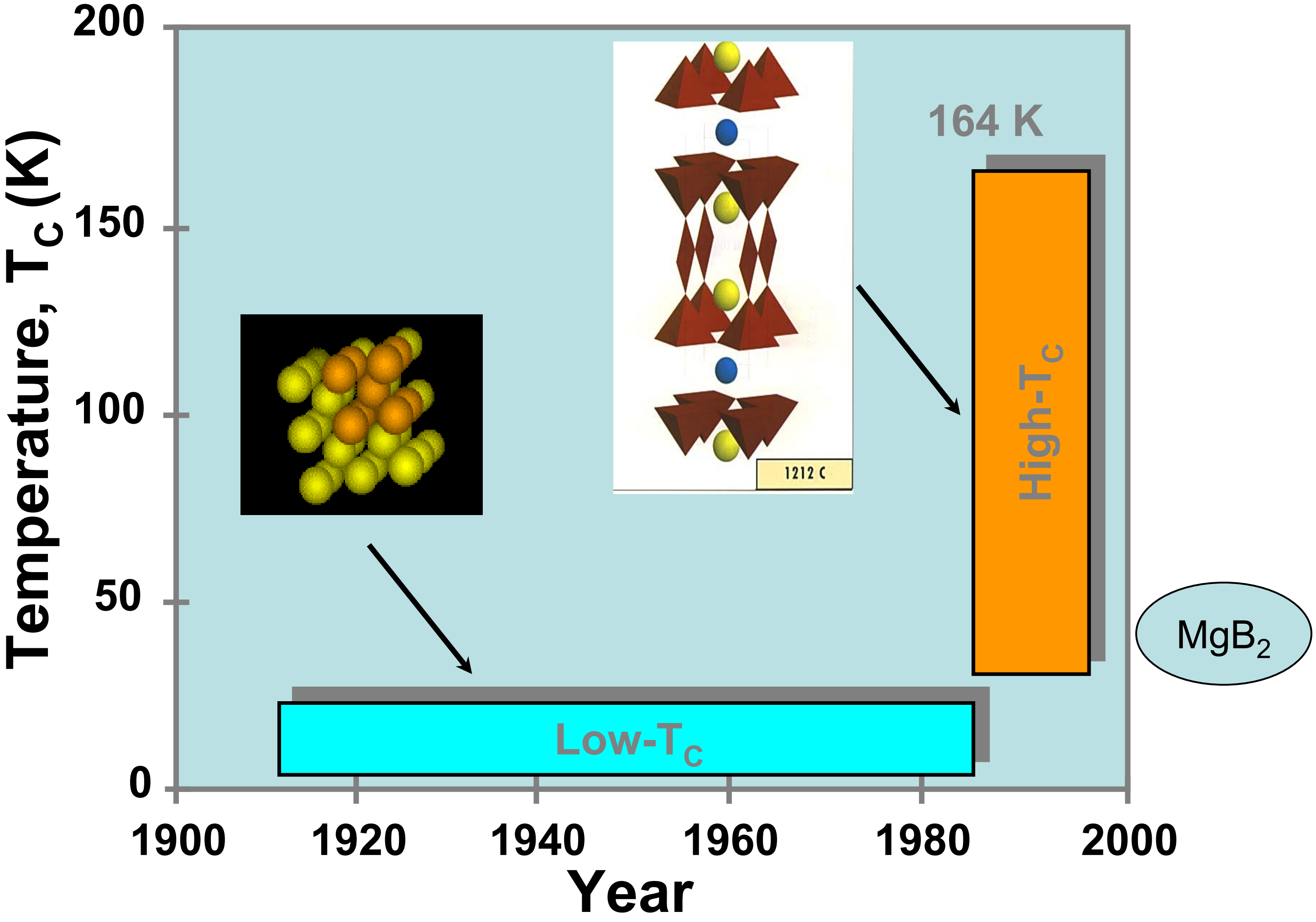


ac Hysteresis

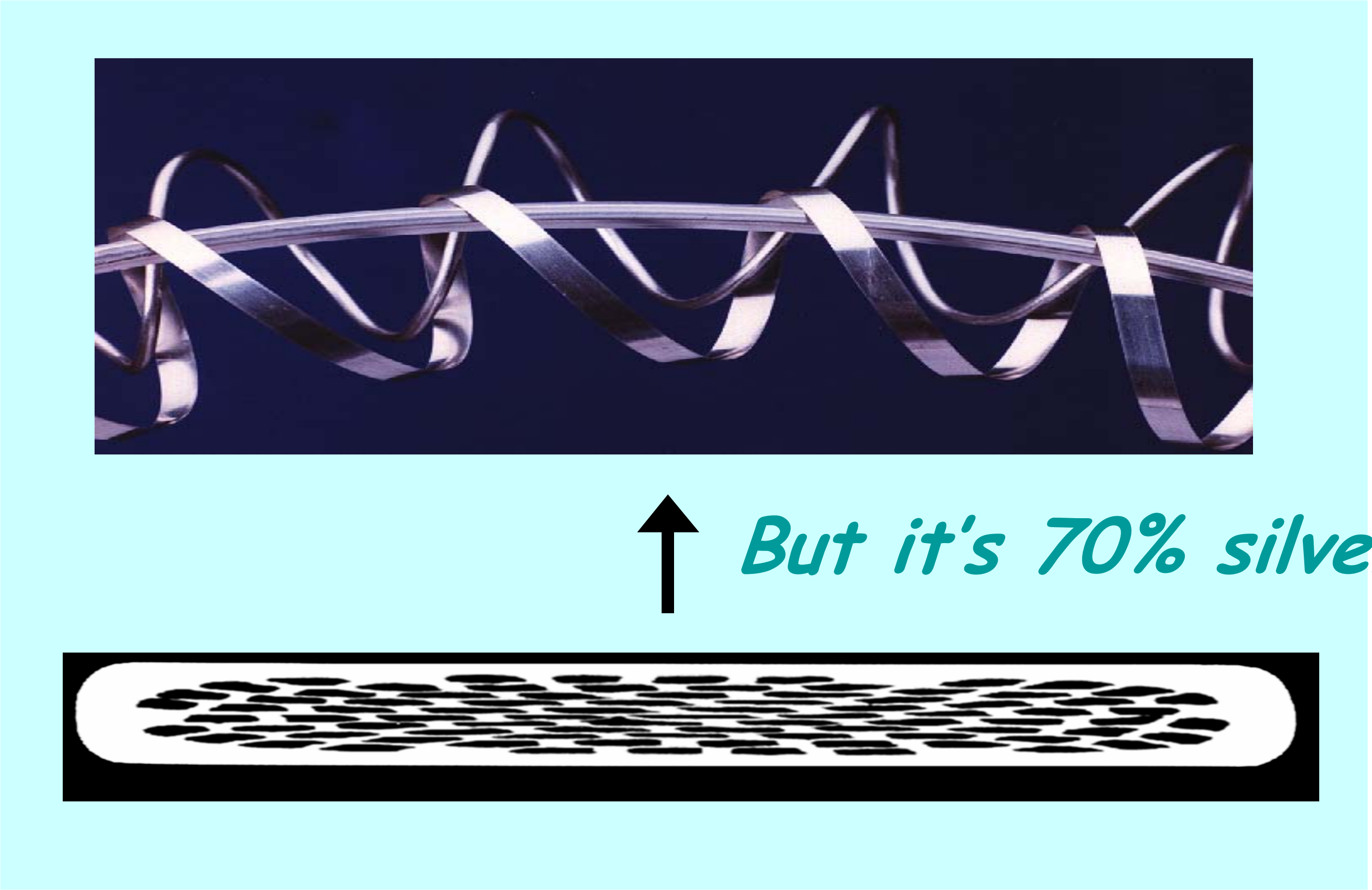


Gives Rise to Power Losses "Bean Model"

T_c vs Year: 1991 - 2001

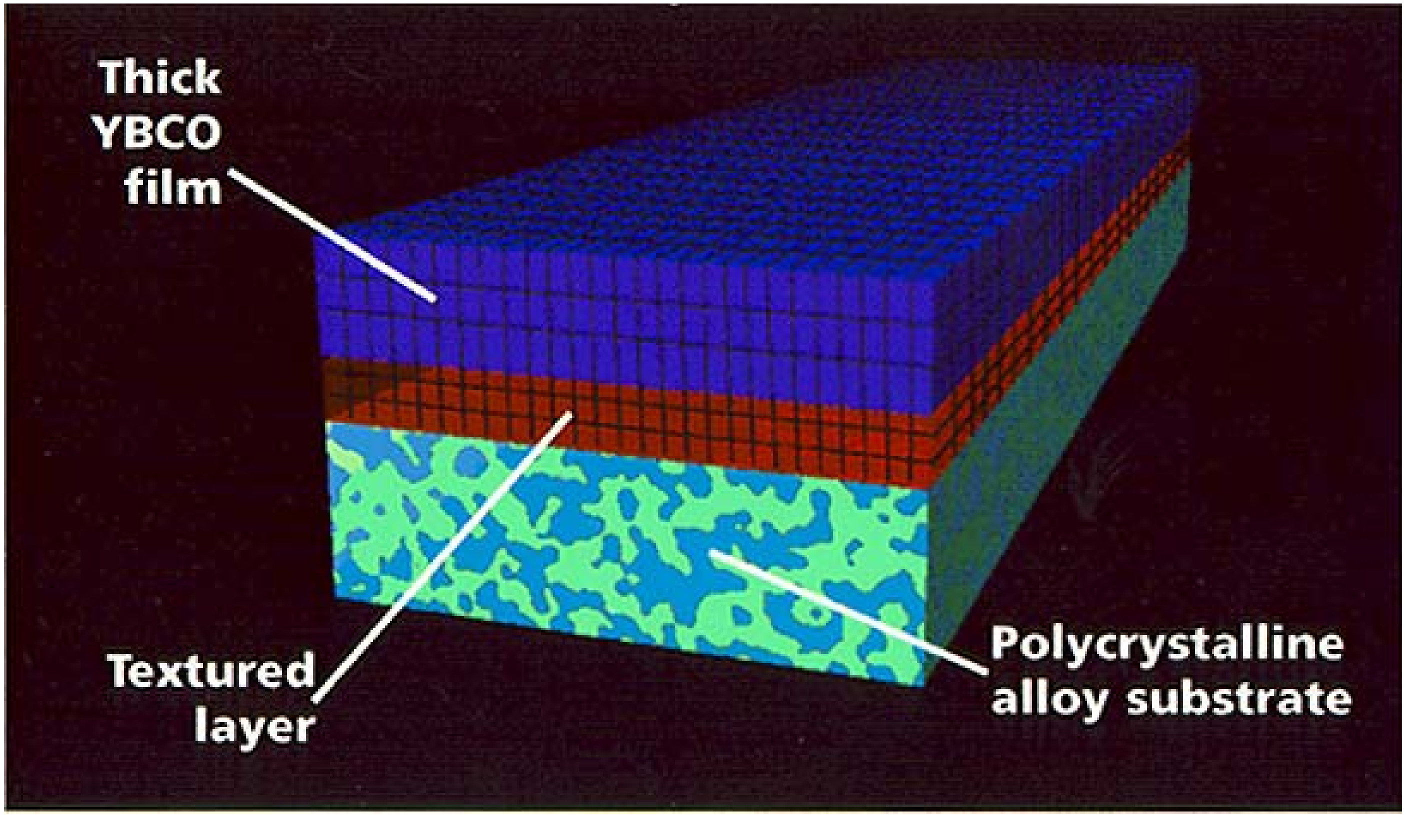


HTSC Wire Can Be Made!

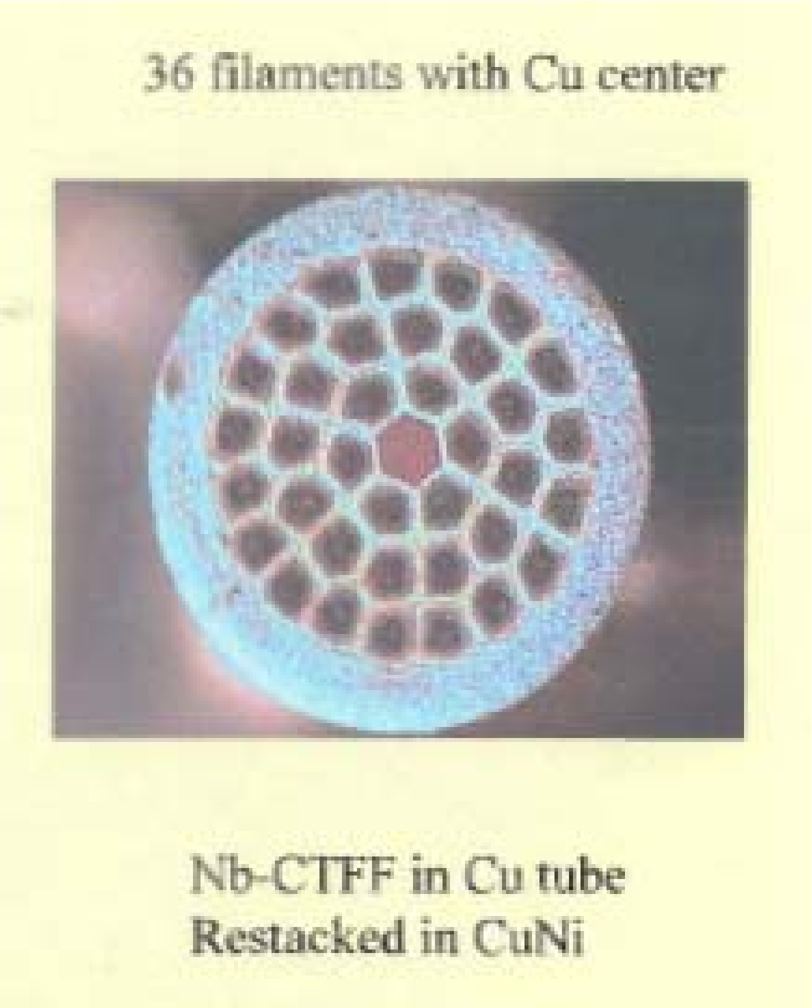


But it's 70% silver!

Coated HTSC Conductors
Generation II Wire



MgB_2 Wire



- “Discovered” in 2001
- One month later we have several meters of wire
- Today kilometer lengths are available for sale

Finished Cable

Puji Substation, Kunming, China

HTSC Cable Projects Worldwide – Past , Present and Future

Two IBM Physicists (1967)

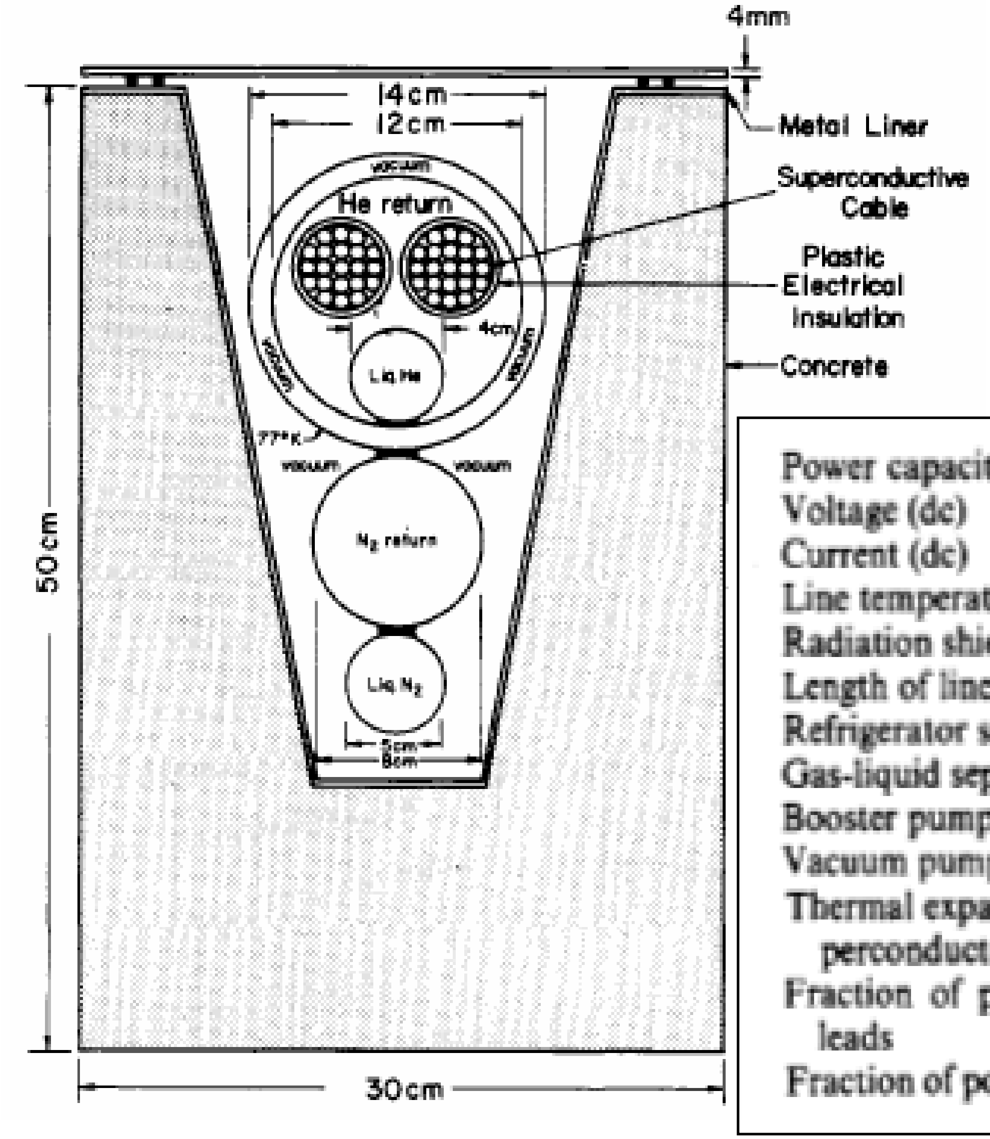
Superconducting Lines for the Transmission of Large Amounts of Electrical Power over Great Distances

R. L. GARWIN AND J. MATISOO

- Nb_3Sn (T_C = 18 K) @ 4.2 K
- 100 GW (+/- 100 kV, 500 kA)
- 1000 km
- Cost: $800 M ($8/kW) (1967)

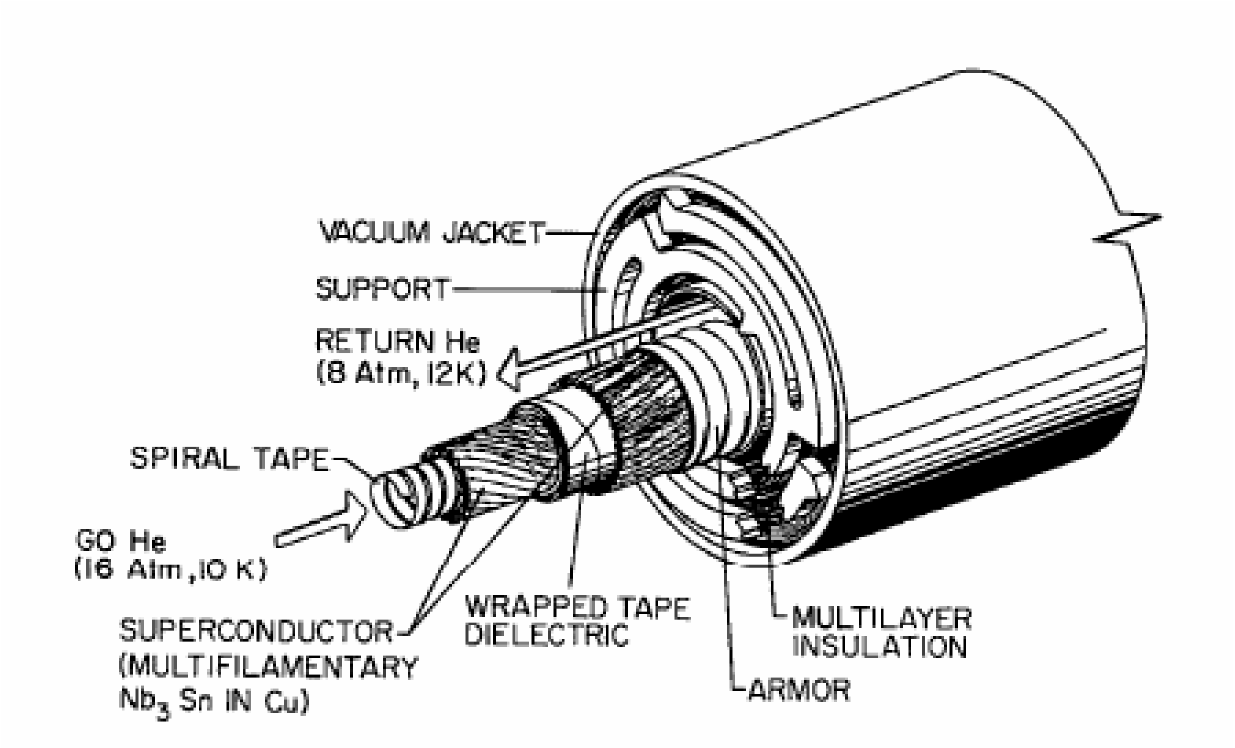
$4.7 B Today!

G-M Specs



Power capacity	100 GW (10^{11} W)
Voltage (dc)	200 kV (2×10^5 V)
Current (dc)	0.5×10^6 A
Line temperature	4.2°K (liquid helium)
Radiation shield	77°K (liquid nitrogen)
Length of line	1000 km
Refrigerator spacing	20 km
Gas-liquid separator spacing	50 m
Booster pump spacing	500 m
Vacuum pump spacing	500 m
Thermal expansion bellows 1.5 m long (superconductors wound helically) spacing	500 m
Fraction of power dissipated in line and leads	$<10^{-7}$
Fraction of power used for refrigeration	$<10^{-3}$

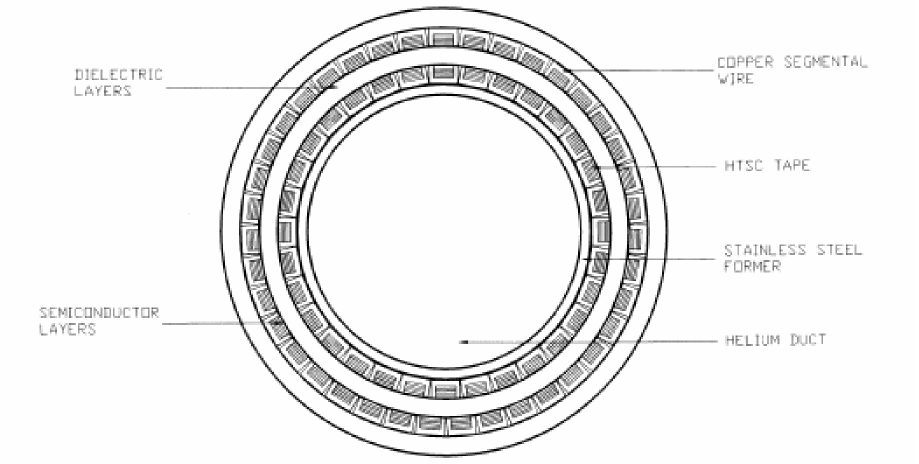
LASL SPTL (1972-79)



Specifications

- 5 GW
  (+/- 50 kV, 50 kA)
- PECO Study
  (100 km, 10 GW)

BICC HTSC dc Cable (1995)



Prototype Specs

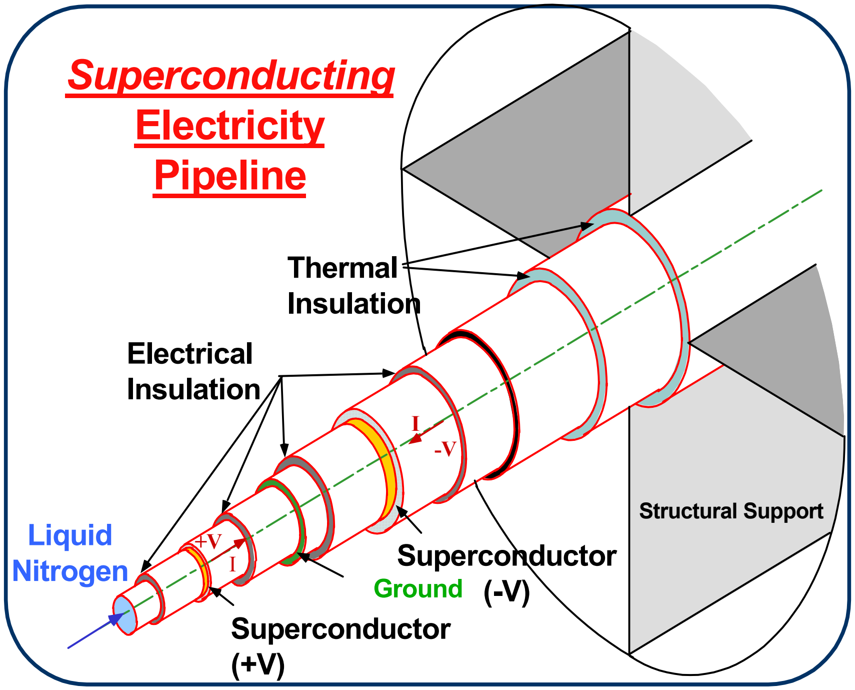
- 400 MW
  - +/- 20 kV, 10 kA
- Length: 1.4 m
- Diameter: 4 cm
- He (4.2 – 40 K)

Design Target

- 400 MW, 100 km
- Flowing He, 0.2 kg/s, 2 MPa, 15 – 65 K
- Cooling Losses: 150 kW

e-Pipe

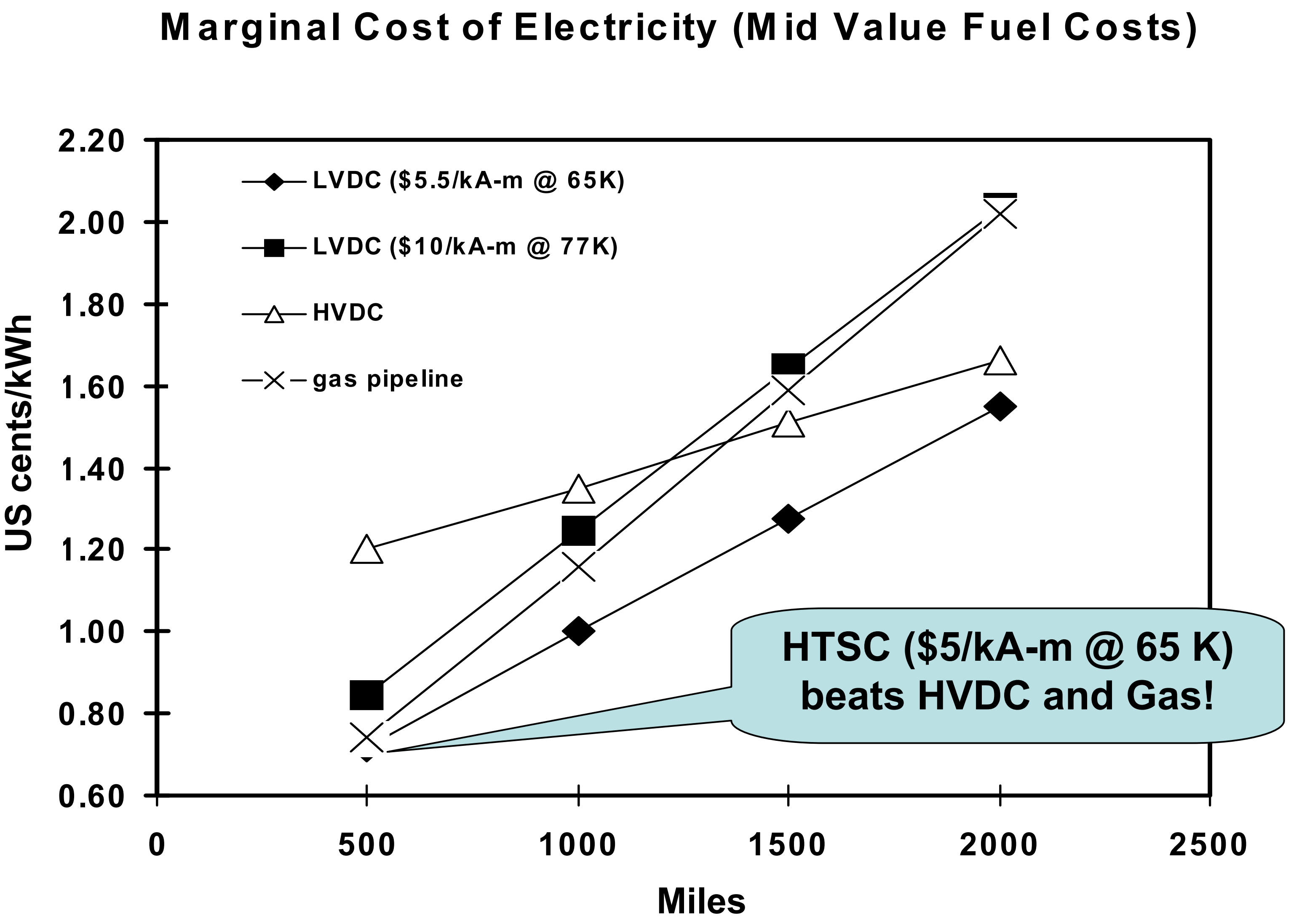

CYPRUS
Nicosia
Mediterranean Sea
Beirut
LEBANON
Damascus
Golan Heights
SYRIA
Latakia
Hims
Euphrates
Mosul
Irbil
Kirkuk
Tigris
Baghdad
IRAQ
Al Hillah
Al Kut
An Nasiriyah
Al Basrah
Haifa
ISRAEL
Jerusalem
Gaza Strip
Amman
West Bank
JORDAN
Al Aqabah
Alexandria
Cairo
EGYPT
Gulf of Suez
Gulf of Aqaba
Tabuk
Ha'il
Hafar al Batin
KUWAIT
Kuwait
Tehran
Qom
Bakhtaran
Arak
Dezful
Esfahan
Ahvaz
Abadan
Bandar-e Bushehr
Persian Gulf
Dhahran
Manama
BAHRAIN
QATAR
Doha
Riyadh
SAUDI ARABIA
Medina
Yanbu al Bahr
Luxor
Aswan
Tropic of Cancer
Administrative Boundary
Hala'ib
Jiddah


Superconducting Electricity Pipeline
Thermal Insulation
Electrical Insulation
Liquid Nitrogen
+V
I
I
-V
Superconductor (+V)
Superconductor
Ground
(-V)
Structural Support

e-Pipe Specs (EPRI, 1997)

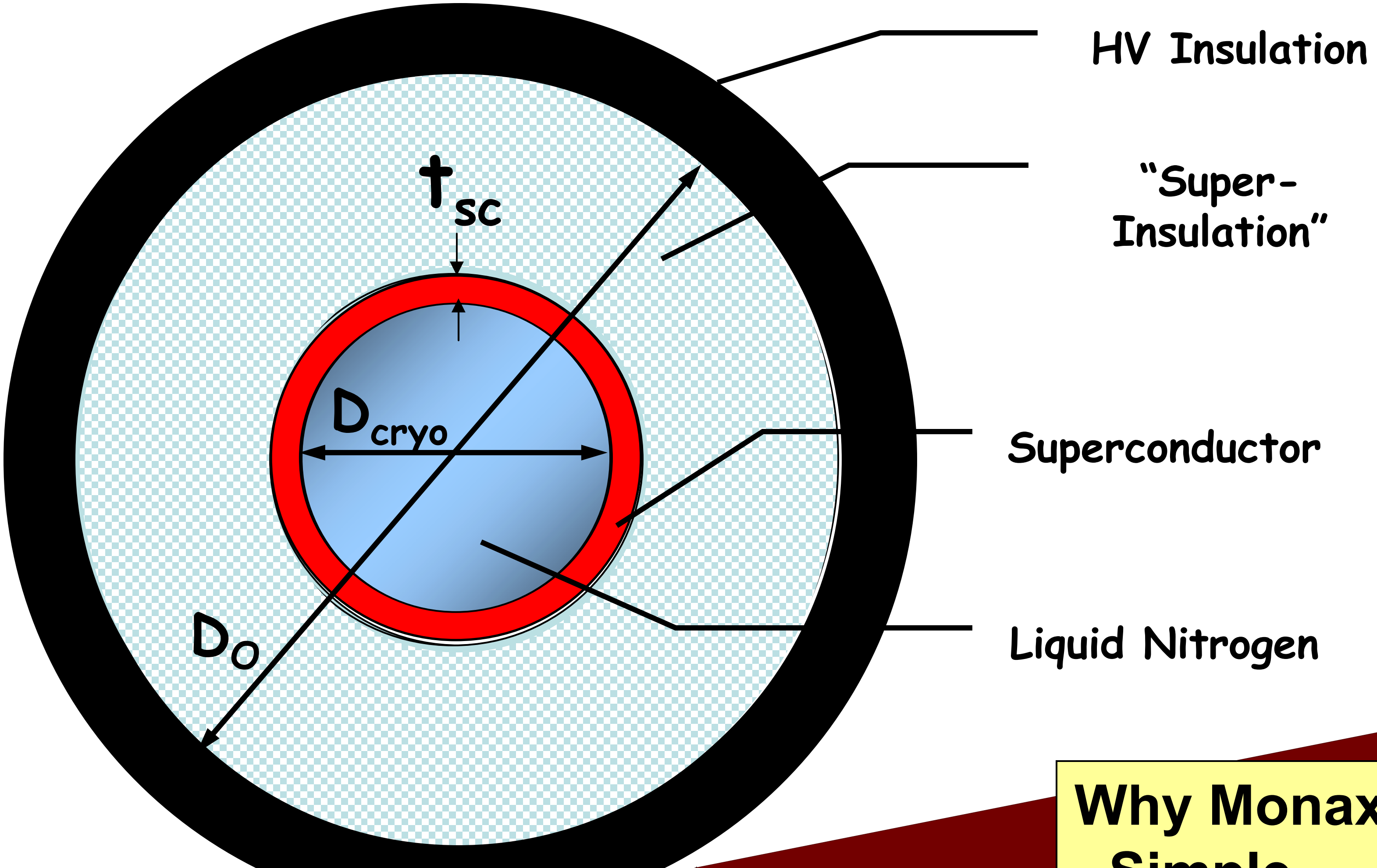
Capacity	5 GW (+/- 50 kV,50 kA)
Length	1610 km
Temperature Specs: - 1 K/10 km @ 65 K - 1 W/m heat input	- 21.6 kliters LN_2/hr - 100 kW coolers - 120 gal/min
Vacuum: - 10^{-5} – 10^{-4} torr	- 10 stations - 10 km spaced - 200 kW each

e-Pipe/Gas/HVDC Cost Comparison



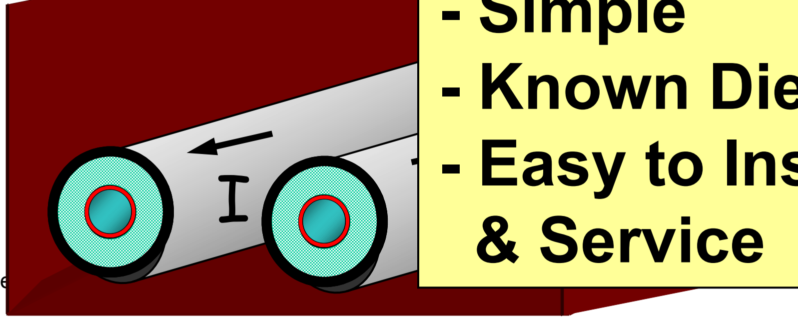
HTSC ($5/kA-m @ 65 K) beats HVDC and Gas!

HTSC dc Cable



Garwin – Matisoo

Revisited !



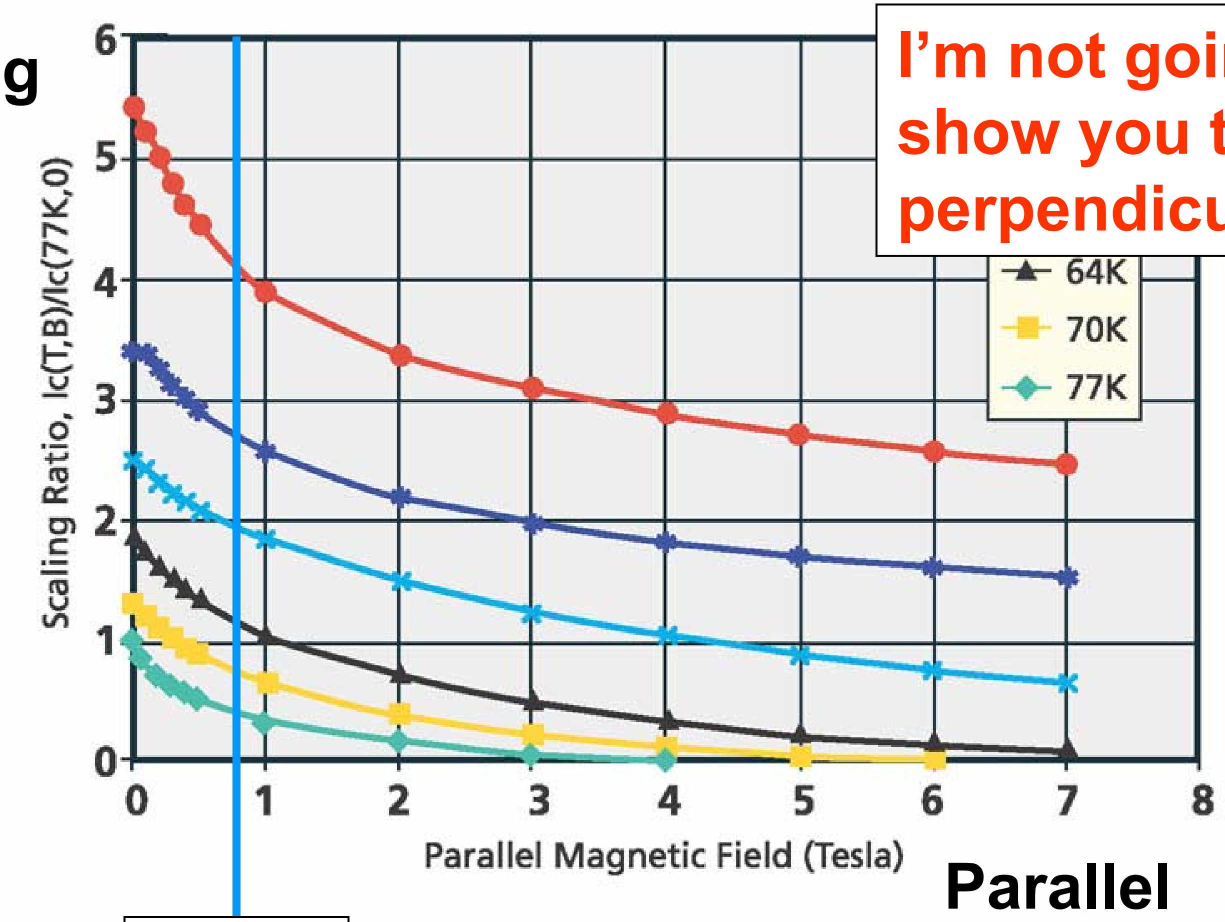
Why Monaxial?
- **Simple**
- **Known Dielectric**
- **Easy to Install & Service**

SCDC Cable Parameters

- Power = 5 GW
- Voltage = 25 +/- kV
- Current = 100 kA
- Jc = 25000 A/cm^2
- Dcryo = 5 cm
- A* = 3.629 cm^2
- t(sc) = 0.243 cm
- R* = 1.075 cm
- B = 0.8 T

AMSC Tape Jc(T, B)

De-rating Factor



I'm not going to show you the perpendicular data!

Parallel

0.8 T

High Amplitude Transient Current Losses (ac & energize)

"Bean Model"

$$H = 4 \times 10^{-9} I_0^2 F \quad \text{W/cm}$$

Io (A)	F (Hz)	H (W/m)
100,000	~~60~~	2.4×10^5
100,000	1/hour	0.3
100,000	1/day	0.01

Possibly could reverse line in one hour!

Small Amplitude Losses (Load Fluctuations)

$$H = \frac{4 \times 10^{-10} (\Delta I)^3 F}{J_c R^2} \quad \mathrm{W/cm}$$

Load Fluctuation Losses over a 1 hour period

Δ (%)	ΔI (A)	ΔP (MW)	H (W/m)
1	1000	50	4×10^{-7}
10	10000	500	4×10^{-4}
20	20000	1000	3×10^{-3}
30	30000	1500	1×10^{-2}

OK, as long as changes occur slowly!

Small Amplitude Losses (Load Fluctuations)

$$H = \frac{4 \times 10^{-10}(\Delta I)^3 F}{J_c R^2} \quad \mathrm{W/cm}$$

…and sometimes even when they're fast!

Consider 1 MW worth of customers coming in and out every millisecond, (*e.g., 10,000 teenagers simultaneously switching 100 W light bulbs on and off*) resulting in ΔI = 20 A, but a heat load of only 10 μW/m

Small Amplitude Losses (Ripple)

$$H = \frac{4 \times 10^{-10}(\Delta I)^3 F}{J_c R^2} \quad \mathrm{W/cm}$$

3-Phase Converter: F = 360 Hz

Δ (%)	ΔI (A)	ΔP (MW)	H (W/m)
1	1000	50	0.50
2	2000	100	3.99
3	3000	150	13.46
4	4000	200	31.91
5	5000	250	62.32

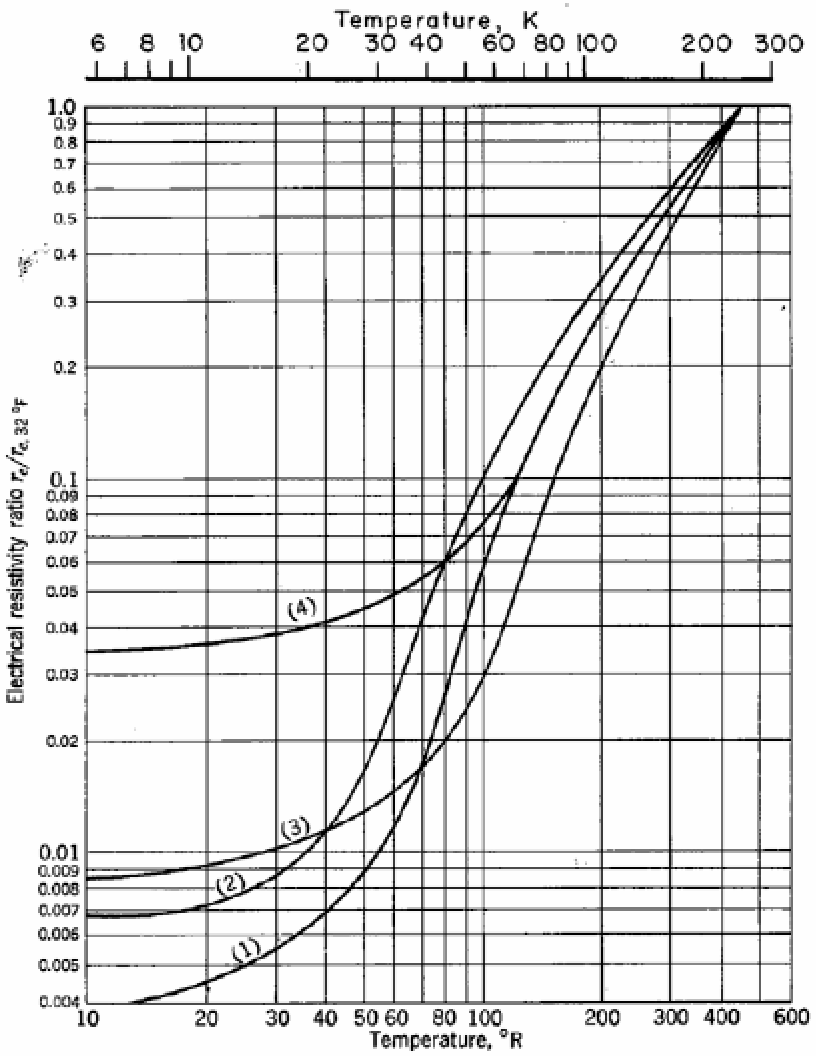
HTSC Wire C/P

- 2010 AMSC “Long Length” Quote:
  - 50 – 75 \$/kA×m (77 K, 0.1 T, 1 μV/cm)
  - Gen 1 or 2 ? Doesn’t matter !

- MgB_2 2006 “12 km” Projection:
  - 1.50 \$/kA×m (20 K, 0.2 T, 1 μV/cm)

Temperature Dependence of the Resistivity of Metals

Electrical Resistivity Ratio for Several Materials at Low Temperatures: (1) Copper; (2) Silver; (3) Iron; (4) Aluminum (Stewart and Johnson 1961).



"J_C's" of Common Metals (77 K)

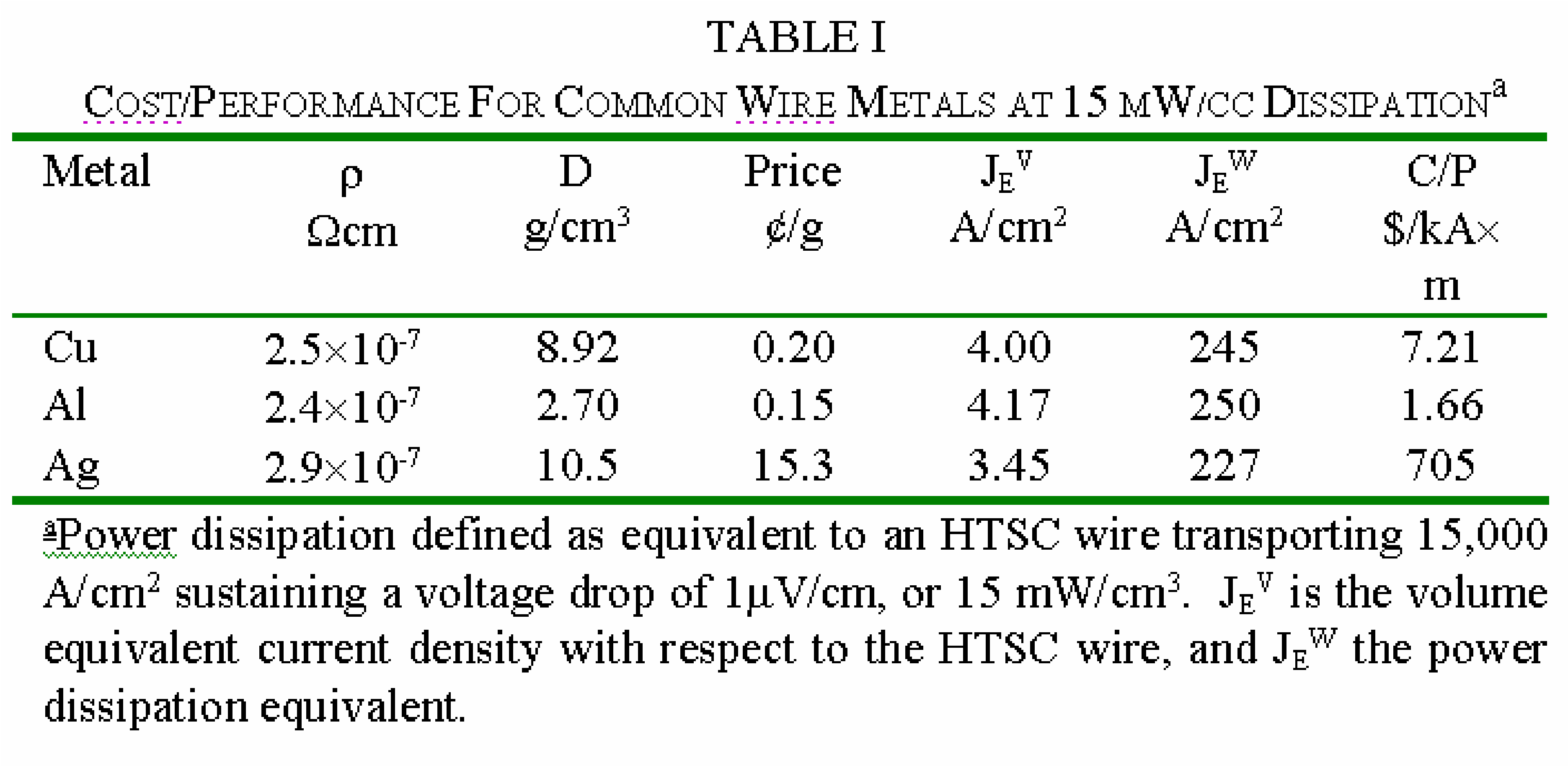


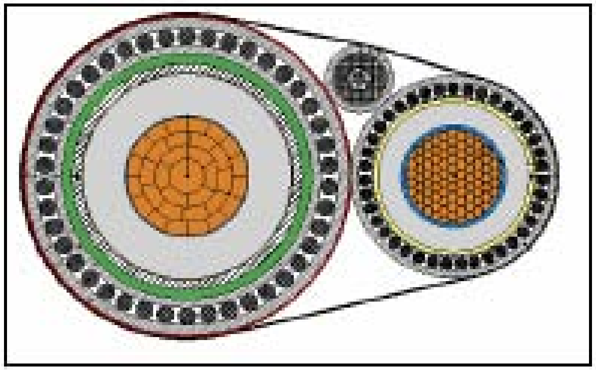
TABLE I

COST/PERFORMANCE FOR COMMON WIRE METALS AT 15 mW/cc DISSIPATION[a]

Metal	ρ Ωcm	D g/cm^3	Price ¢/g	J_E^V A/cm^2	J_E^W A/cm^2	C/P $/kA× m
Cu	2.5×10^{-7}	8.92	0.20	4.00	245	7.21
Al	2.4×10^{-7}	2.70	0.15	4.17	250	1.66
Ag	2.9×10^{-7}	10.5	15.3	3.45	227	705

[a] Power dissipation defined as equivalent to an HTSC wire transporting 15,000 A/cm^2 sustaining a voltage drop of 1μV/cm, or 15 mW/cm^3. J_E^V is the volume equivalent current density with respect to the HTSC wire, and J_E^W the power dissipation equivalent.

NEPTUNE
Regional Transmission System™



HVDC Cable Cross-Section

Pirelli (GS)
Energy Cables

$190 M

Sayerville, NJ → Levittown LI, NY

- 600 MW (+/- 250 kV, 1200 A)
- 65 miles (105 km)
- $400 M
- 2007

Financials

40 yrs @ 4%:	$ 20M
LOM:	1 M
NOI (100%):	5 M

T 77 K	C/P $/kA×m	Cost ($M)
Cu	7	1.8
HTSC	100	25.1

EMPIRE CONNECTION

Specifications

2-1000 MW HVDC Bipolar Circuits

- Circuit 1: 130 miles, Greene County → Bronx County
- Circuit 2: 140 miles, Albany County → New York County
- Each Circuit: +/- 500 kV, 1000 A Bipolar (2 cables ea.)

Financials

$750 M ($400 M "VC", $350 M "Futures")

- Loan Payment (4%, 40 yrs, 750 M$) = 35 M$/yr
- Labor, Overhead, Maintenance = 5 M$/yr
- Tariff = 0.5 ¢/kWh
- Profit (NOI) @ 50% Capacity = 4 M$/yr
- Profit (NOI) @ Full Capacity = 48 M$/yr

Why didn't it go forward?

HTSC Cost = $87 M

See Muller articles on www.w2agz.com/scdc.htm

Bakun HEP

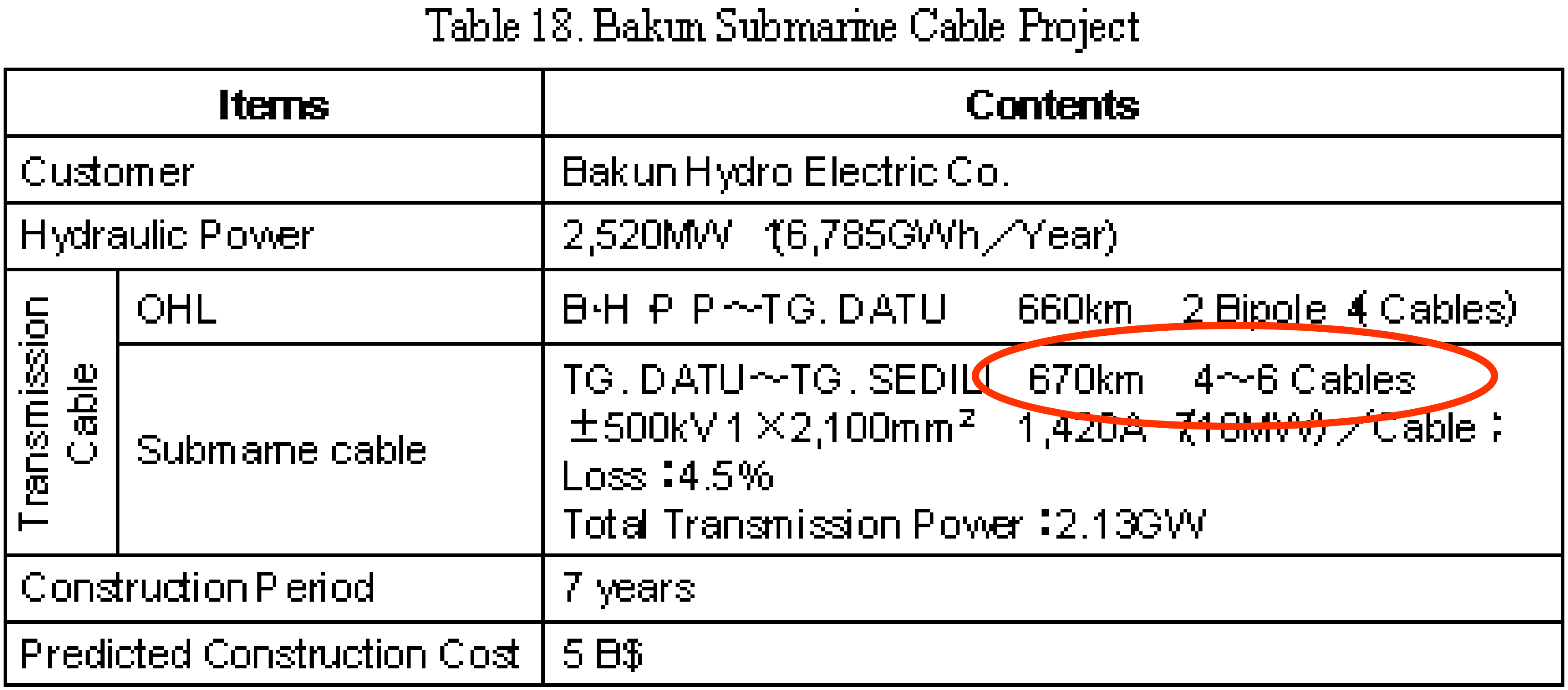


Table 18. Bakun Submarine Cable Project

Items		Contents
Customer		Bakun Hydro Electric Co.
Hydraulic Power		2,520MW (16,785GWh／Year)
Transmission Cable	OHL	B·H P P～TG. DATU 660km 2 Bipole (4 Cables)
	Submarine cable	TG. DATU～TG. SEDILI 670km 4～6 Cables ±500kV 1×2,100mm² 1,420A (710MW)／Cable ; Loss :4.5% Total Transmission Power :2.13GW
Construction Period		7 years
Predicted Construction Cost		5 B$

T 77 K	C/P $/kA×m	Cost ($M)
Cu	7	4.7
HTSC	100	67

©Eureka Cartography, Berkeley, CA

D

APPLIED SUPERCONDUCTIVITY ISSUES/SOLUTIONS – HASSENZAHL

Applied Superconductivity Issues and Solutions

For

EPRI DC Line Workshop 10/12-15/2005

By

W. V. Hassenzahl

Advanced
Energy
Analysis

ASC Outline

- Perfect Conductors
- Practical Conductors
- Critical currents, fields, and temperatures
- AC losses
- QUENCH or what happens when a superconductor goes normal
  - Device and superconductor interaction.
  - Voltage, current, energy and temperature
- Issues

Advanced Energy Analysis

Perfect Conductors

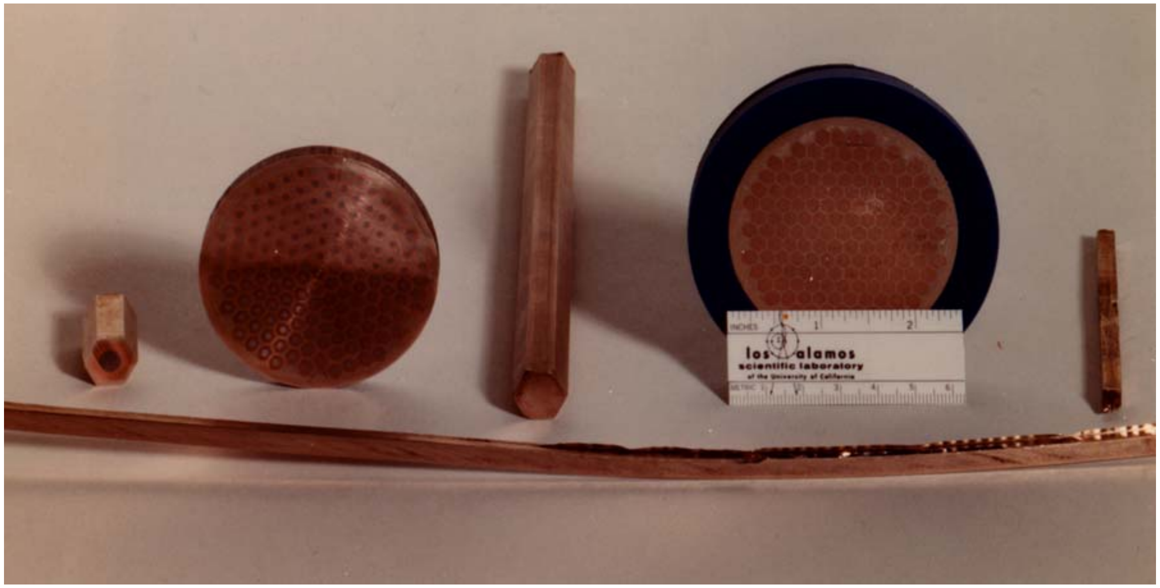
- Some materials under certain conditions have no measurable resistance! Constraints include the following:
  - Low temperature (Below a critical value)
  - Allowable magnetic field
  - Direct current
- Many materials are superconducting but only a few have “everything” going for them.
  - Workable critical temperature
  - Inherently high critical current density
  - Low sensitivity to magnetic fields
  - Simple and inexpensive to fabricate
  - Low (acceptable) strain sensitivity

Advanced Energy Analysis

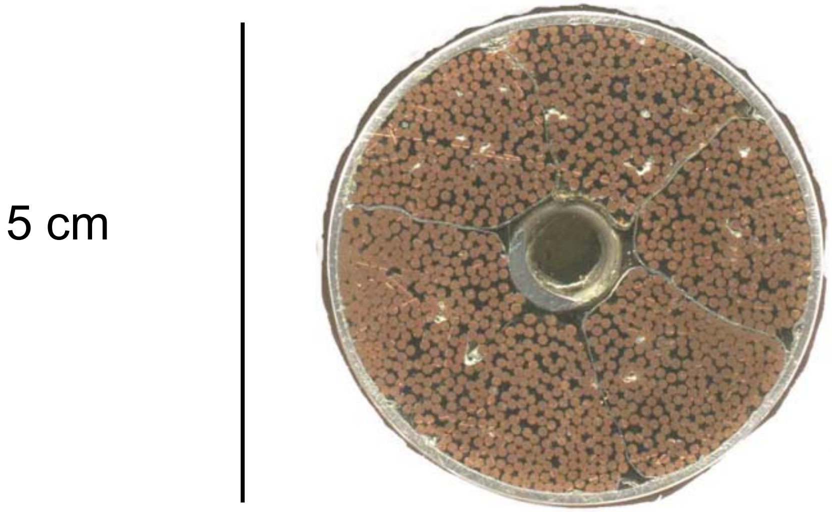
Practical Conductors

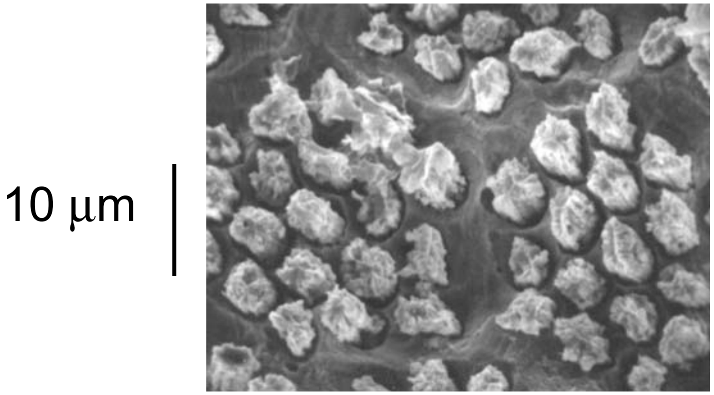
- Composite conductor with superconductor, structural material, and normal conductor.
- Detailed requirements depend on the application: magnet, cable, transformer, FCL, etc.
- Conductor geometry depends on materials, processes, total current, cooling, etc.

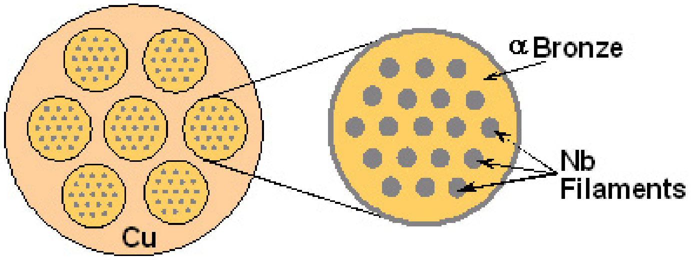
Practical Conductors Nb-Ti



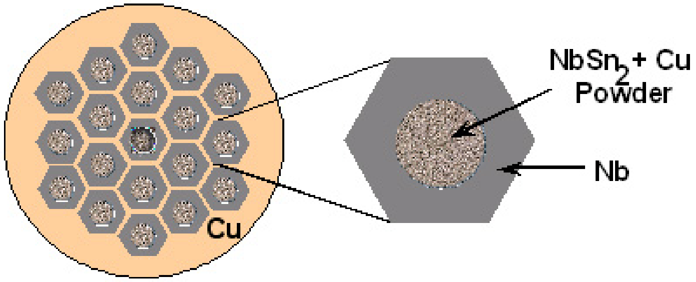
Practical Conductors Nb_3Sn



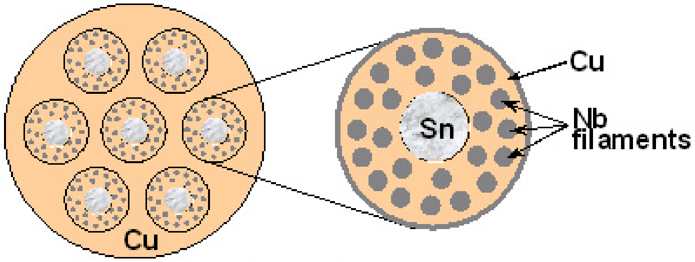




Bronze process

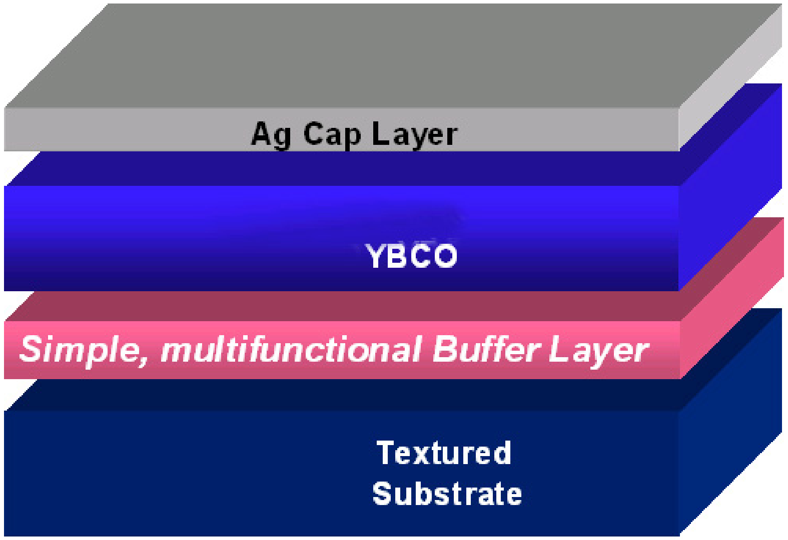


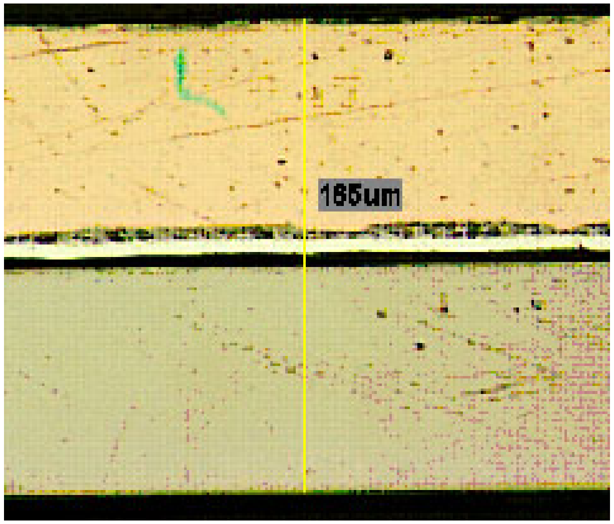
Powder-in-tube process

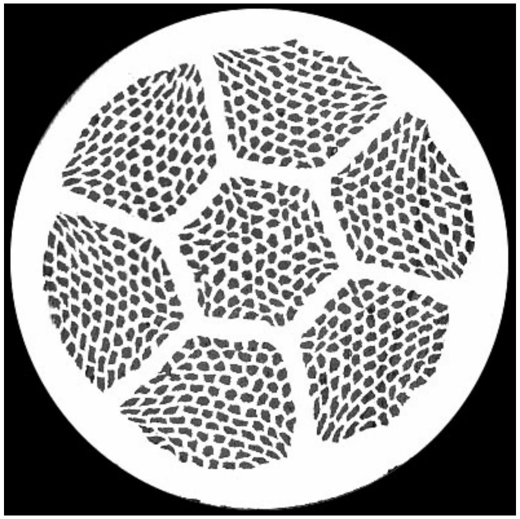


Internal Sn Process

Practical Conductors HTS







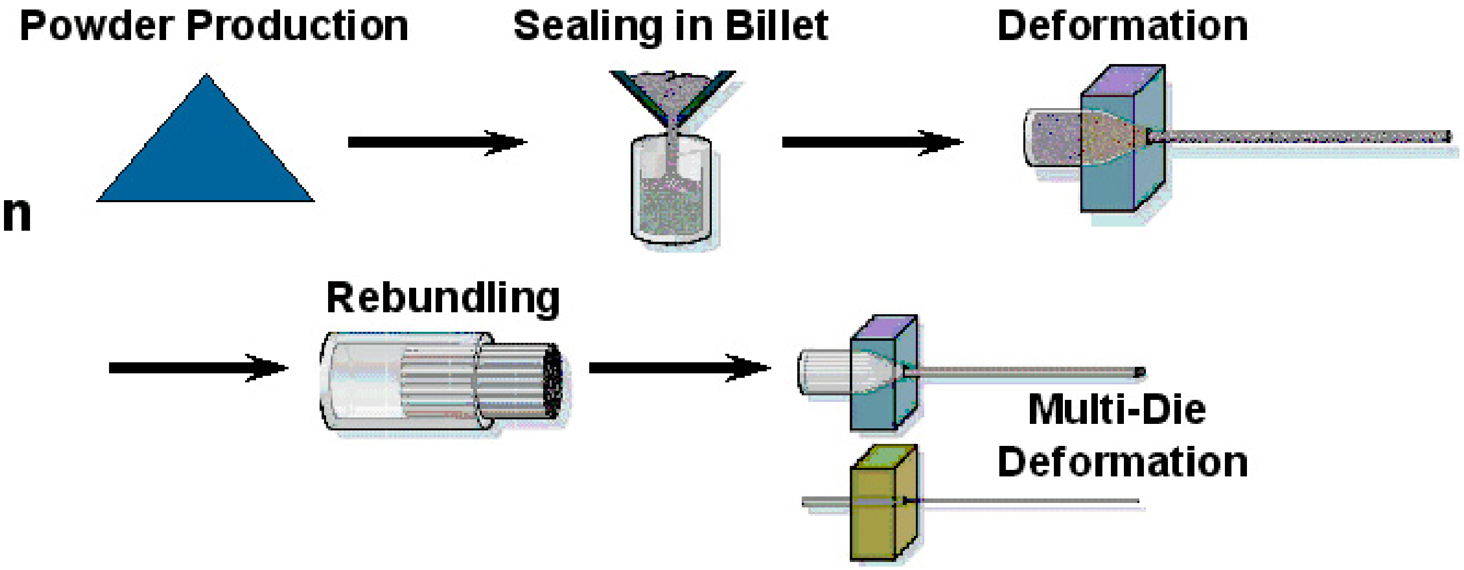
BSCCO 2212

BSCCO 2223

Practical Conductors

BSCCO Fabrication

Part 1:
Precursor Fabrication



Powder Production

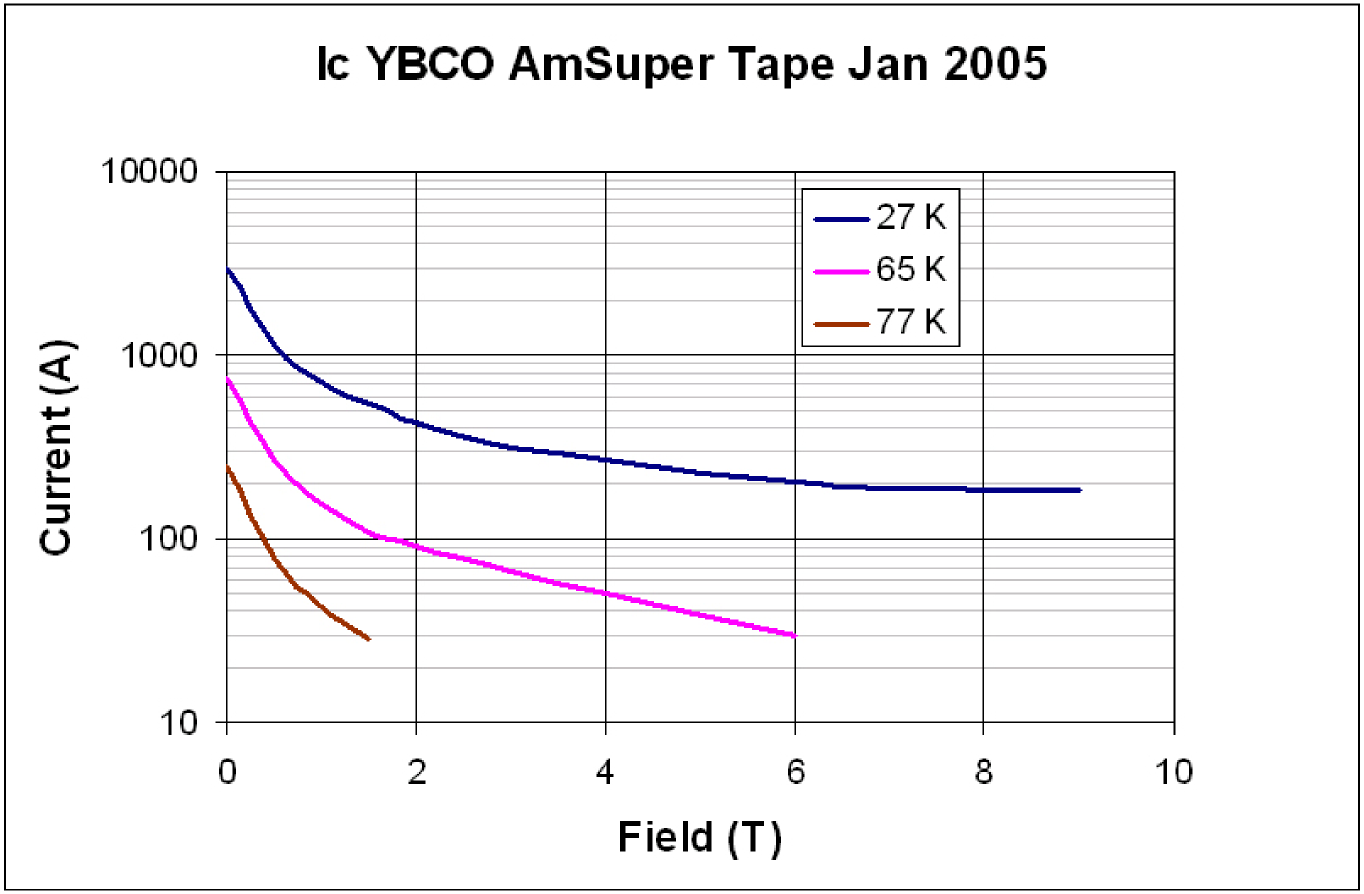
Sealing in Billet

Deformation

Rebundling

Multi-Die Deformation

Critical Currents



Advanced
Energy
Analysis

AC Losses

QUENCH

- The transition from superconducting to normal state of a superconductor that is carrying current.
- It is possible to discuss the QUENCH of a superconductor alone. Not very interesting because high resistance and high current density suggest the use of fuse theory.
  - Fuse currents of a 16 Gauge wire ambient
    - Copper 120 A
    - Steel 35 A
    - Fuse Wire 20 A
  - A 16 gauge Nb-Ti wire at 4.2 K and 5 T carries 3800 A
- Poof end of discussion!

QUENCH

- So add a normal metal “stabilizer” to carry current when a transition occurs.
  - How much do you need?
  - Depends on time to decrease current (Fault clearing)
    - Usually dictated by external circuit components
  - Depends on the allowable temperature rise.
  - Depends on material properties
    - Electrical conductivity
    - Specific heat
- Will use Nb-Ti based system because theory and experiment are in agreement

QUENCH

- Consider a magnet (or any other device) with a cable type conductor as in slide 5.
  - The magnet stores a certain amount of energy.
  - The magnet has a maximum safe terminal voltage.
  - The temperature and size of a normal zone will increase due to joule heating
  - Heat transfer to cryogen is too slow to affect process
- To determine the heating we use the following relation, where C and ρ depend on temperature.

$$CdT = j^2 \rho dt \longrightarrow \int_{T_o}^{T} \frac{C}{\rho} dT = \int_0^t j^2 dt$$

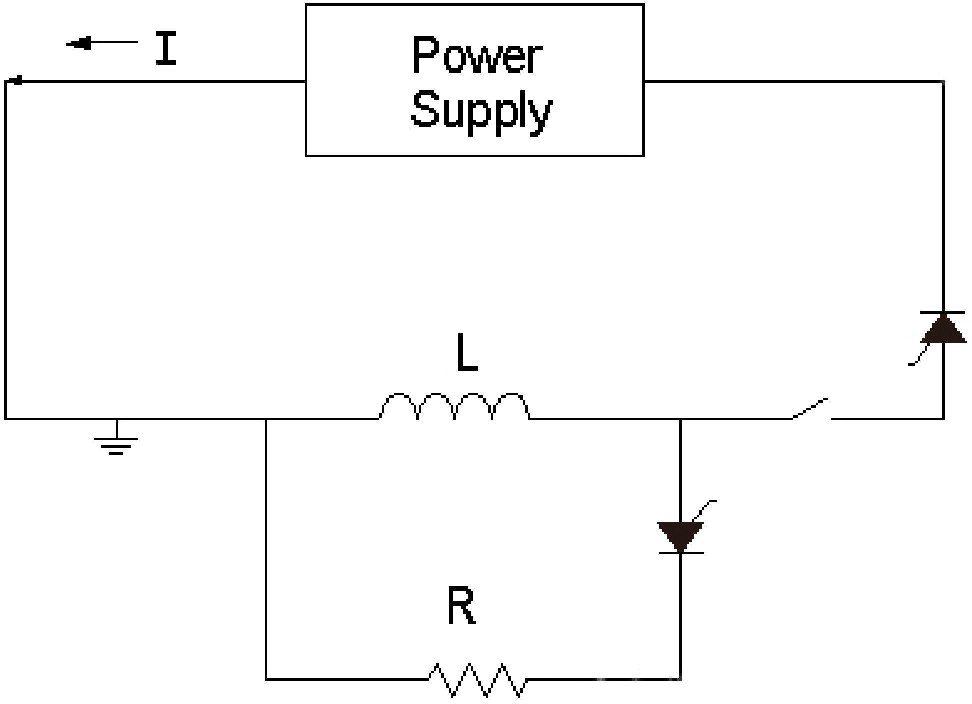
Advanced
Energy
Analysis

QUENCH

- Two cases to consider for the magnet
  - The normal region increases is size, i.e., it propagates likely in three directions.
  - The normal zone is small and does not propagate, i.e., no internal voltage. This will probably be the usual case for high-temperature superconducting systems (TBD)
- Let us consider a type of magnet that has little stabilizer. This characteristic is driven by issues separate from the stabilizer cost.
  - We choose Hadron accelerator Dipoles. Thousands have been made and are being used every day.

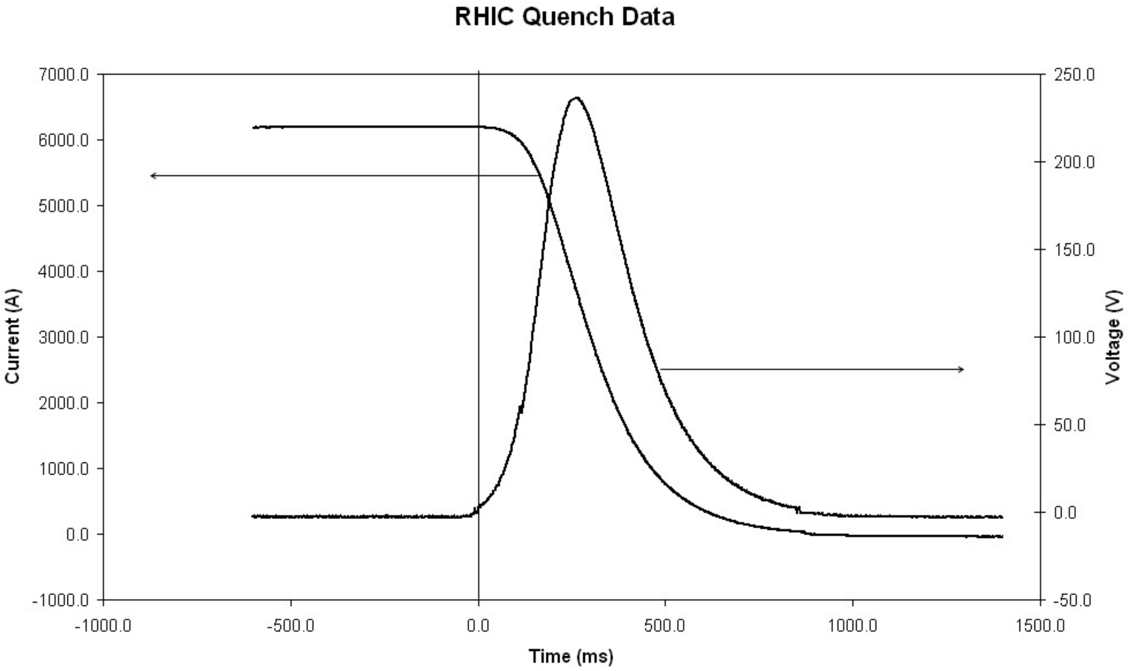
QUENCH

- Typical test circuit and procedure
- Normal region is detected
- Switch is opened
- V, I, and dI/dt are recorded.
- Internal voltage is from L di/dt



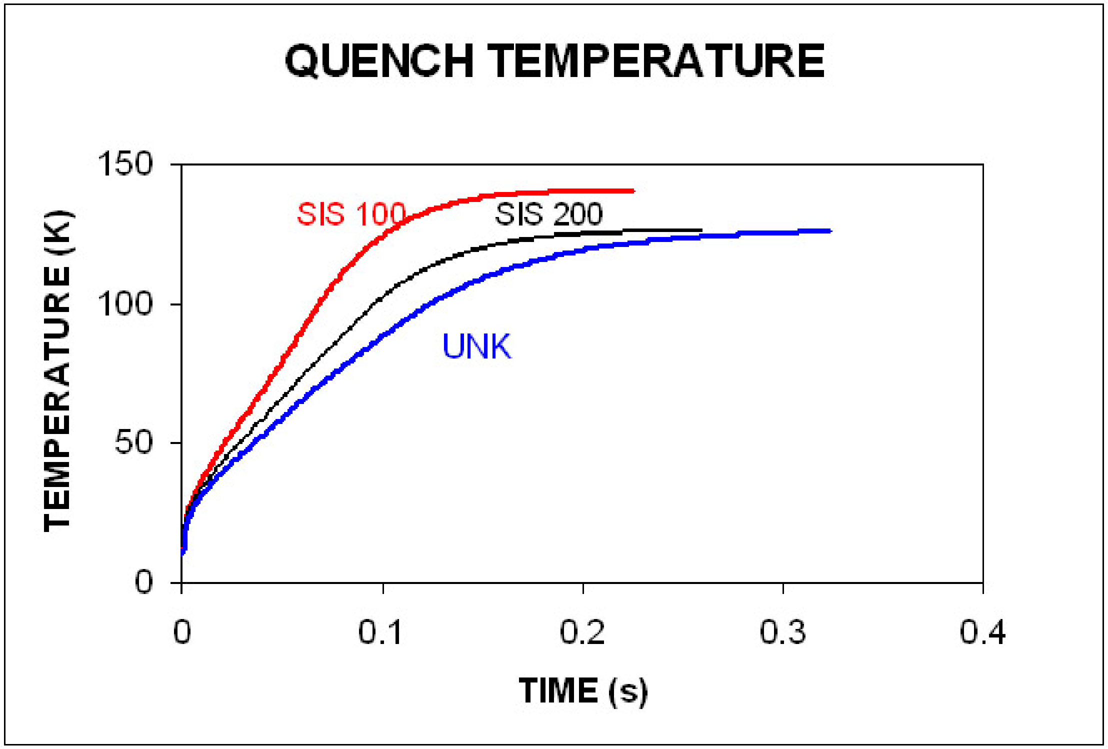
QUENCH

- Relativistic Heavy Ion Collider (RHIC) type dipoles
- Uses Rutherford Cable as in Slide 5.



QUENCH

- Temperature is difficult to measure, but it can be calculated fairly closely and verified in some instrumented models.



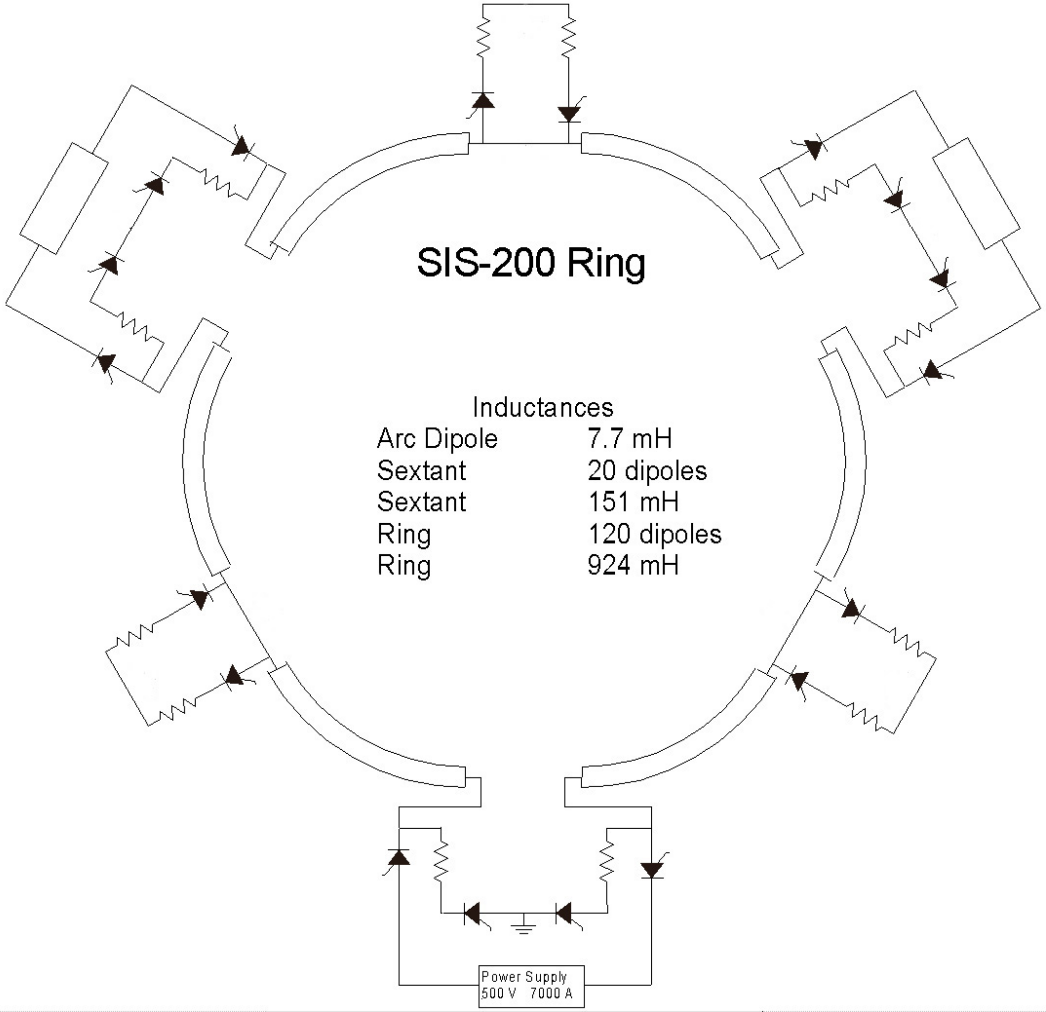
Advanced
Energy
Analysis

QUENCH

- So you should be asking how does a magnet relate to an electric power system.
    - Simple, the accelerators are rings consisting of hundreds or thousands of these magnets.
    - Recall, the magnet has a maximum safe terminal voltage.
    - But the ring must also have a limitation on maximum voltage.
    - Various schemes are possible to limit the overall voltage

QUENCH Protection

- Simplified ring circuit with energy extraction capabilities.



Inductances

Arc Dipole	7.7 mH
Sextant	20 dipoles
Sextant	151 mH
Ring	120 dipoles
Ring	924 mH

Protection of an AC Cable

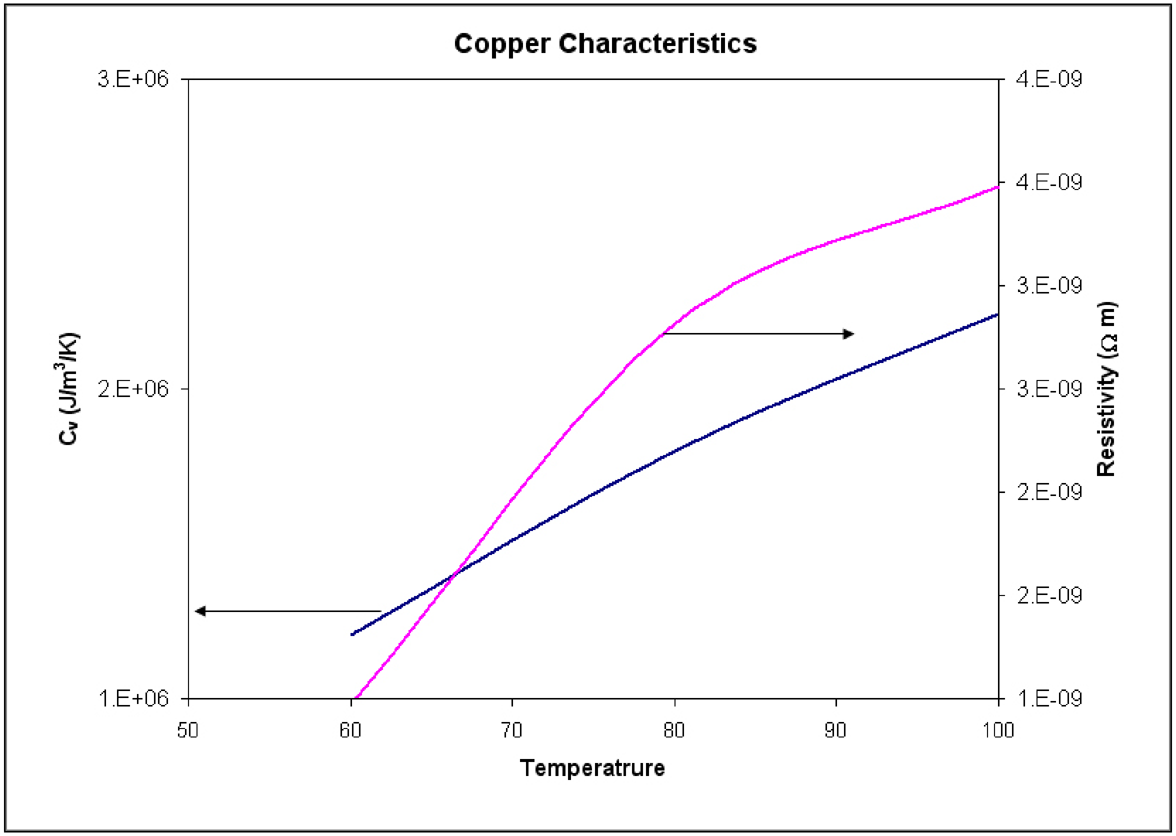
- Most HTS AC cable designs have a normal conductor in parallel.
  - Its dimensions are chosen on the basis of
    - Anticipated fault conditions—current and duration.
    - Cooling schemes or allowable temperature rise
    - Recovery time
- Consider a cable that can be subjected to a 5-cycle 40,000 A fault. Operating current is not important. Temperature rise cannot exceed 1 K.
  - Superconductor goes normal along the entire length of the cable in milliseconds.
  - Use RMS values rather than addressing short term local conditions.

Advanced Energy Analysis

Protection of an AC Cable

- Governing Equation relates temperature rise to heating and material (copper) characteristics
- Copper area depends on temperature
  - from 3.3 cm2 at 65 K
  - to 4.5 cm2 at 80 K

$$\Delta T = \frac{Q}{V \cdot C_V} \approx \frac{I^2 \cdot \Delta t}{\sigma \cdot A^2 \cdot C_V}$$



Advanced
Energy
Analysis

Issues

- If it wasn't clear, in terms of protection, current, voltage, energy, and temperature are your adversaries.
- What happens if there are recurring faults?
- What are the long term (minutes+) impacts of a fault?
- Are there cooldown issues related to stress on and motion of the conductors?
- Will recurring transitions damage the conductor?
- Can we extrapolate all, some, any experience with LTS devices to HTS systems?

E

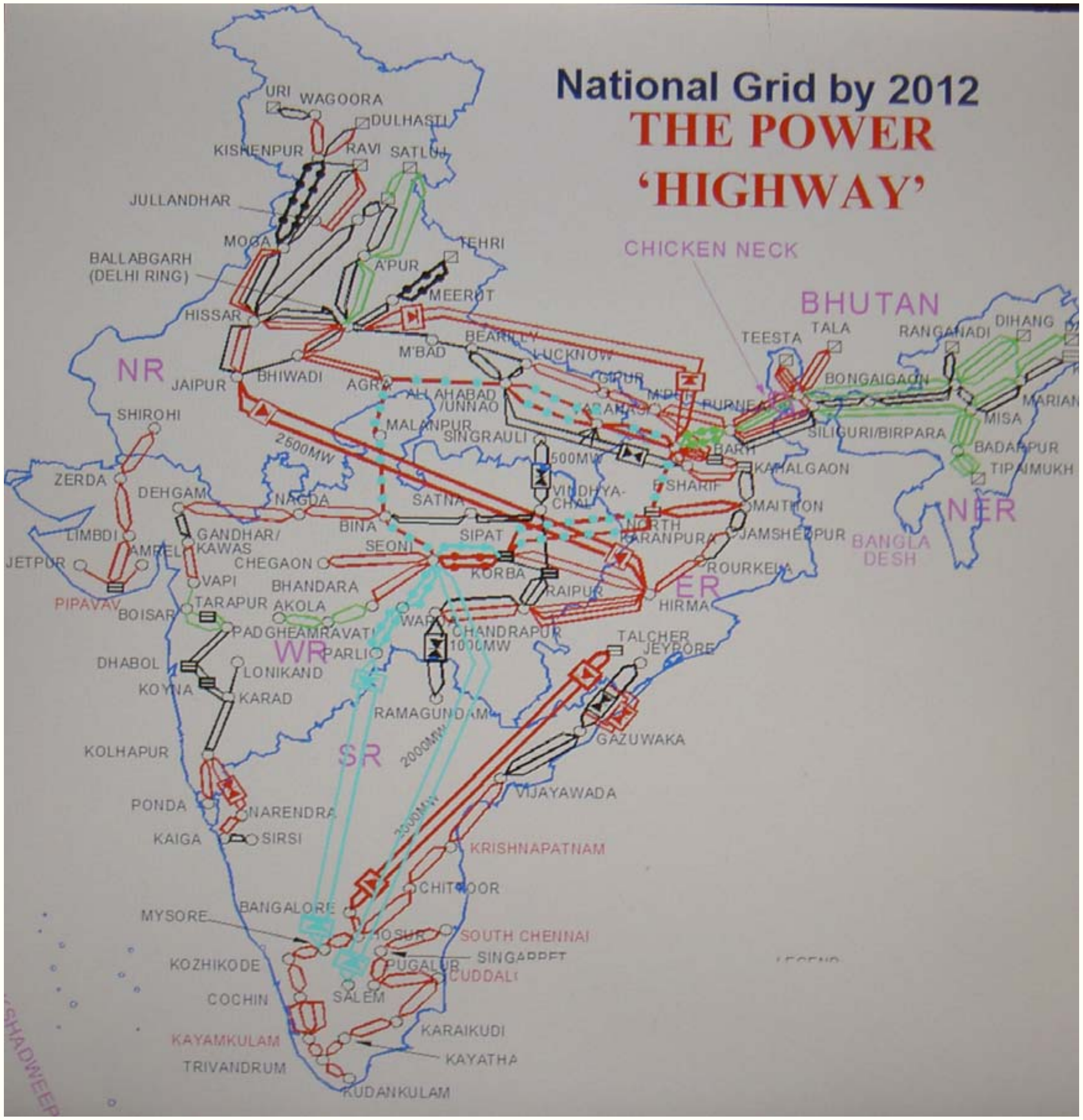
INVERTER-RECTIFIER DESIGN FOR SCDC CABLES – NILSSON

Inverter-Rectifier Valve and Station design for SCDC Cable System

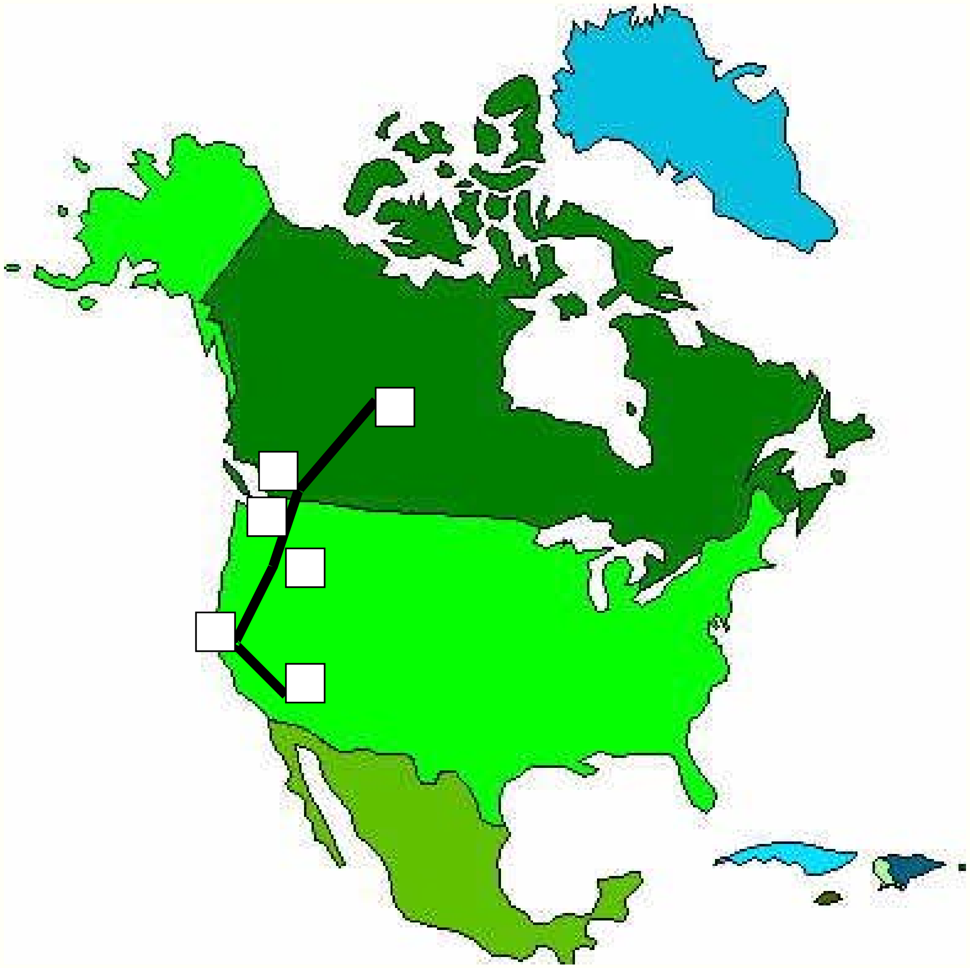
- by
- Stig Nilsson
- Exponent
- EPRI DCSC Workshop
- October 12-14, 2005

Issues

- Issues surrounding “paradigm shift” from high voltage, low current to low voltage, high current (“dc Heavy”)
- Ripple and harmonic filtering and suppression (will “resonance” be an issue given “zero” resistance? (high Q))
- Fault, overload and service issues re I/C design
- Reversible I/C valves…off loading to surrounding ac grid(s)
- High voltage transients (L di/dt)
- Single pole servicing…practical aspects of servicing one pole…earth return during servicing?
- Pump/Cryostation power supply along route
- Tap-offs?
- Separate ac supply cable?
- Comment on “Chowduri” paper (it’s mostly control issues, not SCDC…VSC, etc.)
- Is there an opportunity to reduce discrete (thyristor, GTOs, etc.) part count by using the sc cyro-infrastructure for cooling, maybe for “specially designed” cryo-bipolars


National Grid by 2012
THE POWER
'HIGHWAY'
CHICKEN NECK
BHUTAN
NR
WR
SR
ER
NER
BANGLA
DESH
URI
WAGOORA
DULHASTI
KISHENPUR
RAVI
SATLUJ
JULLANDHAR
MOGA
TEHRI
BALLABGARH
(DELHI RING)
A'PUR
MEERUT
HISSAR
BEARILLY
M'BAD
LUCKNOW
JAIPUR
BHIWADI
AGRA
ALLAHABAD
/UNNAO
MALANPUR
SINGRAULI
GIPUR
M'PUR
PURNEA
SHIROHI
2500MW
500MW
VINDHYA-
CHAL
TEESTA
TALA
RANGANADI
DIHANG
BONGAIGAON
MARIANI
MISA
SILIGURI/BIRPARA
BADARPUR
TIPAIMUKH
BARH
KAHALGAON
MAITHON
JAMSHEDPUR
ROURKELA
SHARIF
NORTH
KARANPURA
ZERDA
DEHGAM
NAGDA
BINA
SATNA
LIMBDI
AMRELI
GANDHAR/
KAWAS
SEONI
SIPAT
KORBA
JETPUR
CHEGAON
VAPI
BHANDARA
TARAPUR
AKOLA
RAIPUR
HIRMA
PIPAVAV
BOISAR
PADGHE
AMRAVATI
WARDHA
CHANDRAPUR
1000MW
TALCHER
JEYPORE
DHABOL
LONIKAND
PARLI
KOYNA
KARAD
RAMAGUNDAM
GAZUWAKA
KOLHAPUR
2000MW
VIJAYAWADA
PONDA
NARENDRA
KAIGA
SIRSI
3000MW
KRISHNAPATNAM
CHITTOOR
MYSORE
BANGALORE
HOSUR
SOUTH CHENNAI
KOZHIKODE
SINGARPET
PUGALUR
CUDDALORE
COCHIN
SALEM
KAYAMKULAM
KARAIKUDI
TRIVANDRUM
KAYATHAR
KUDANKULAM
LAKSHADWEEP
LEGEND

SC-HVdc Link from Alberta Tar Fields to Southern California



Approximate Surge Impedance Loading of AC Lines

System Voltage (kV)	115	138	161	230	345	500	765
SIL (MW)	35	50	70	140	420	1000	2300

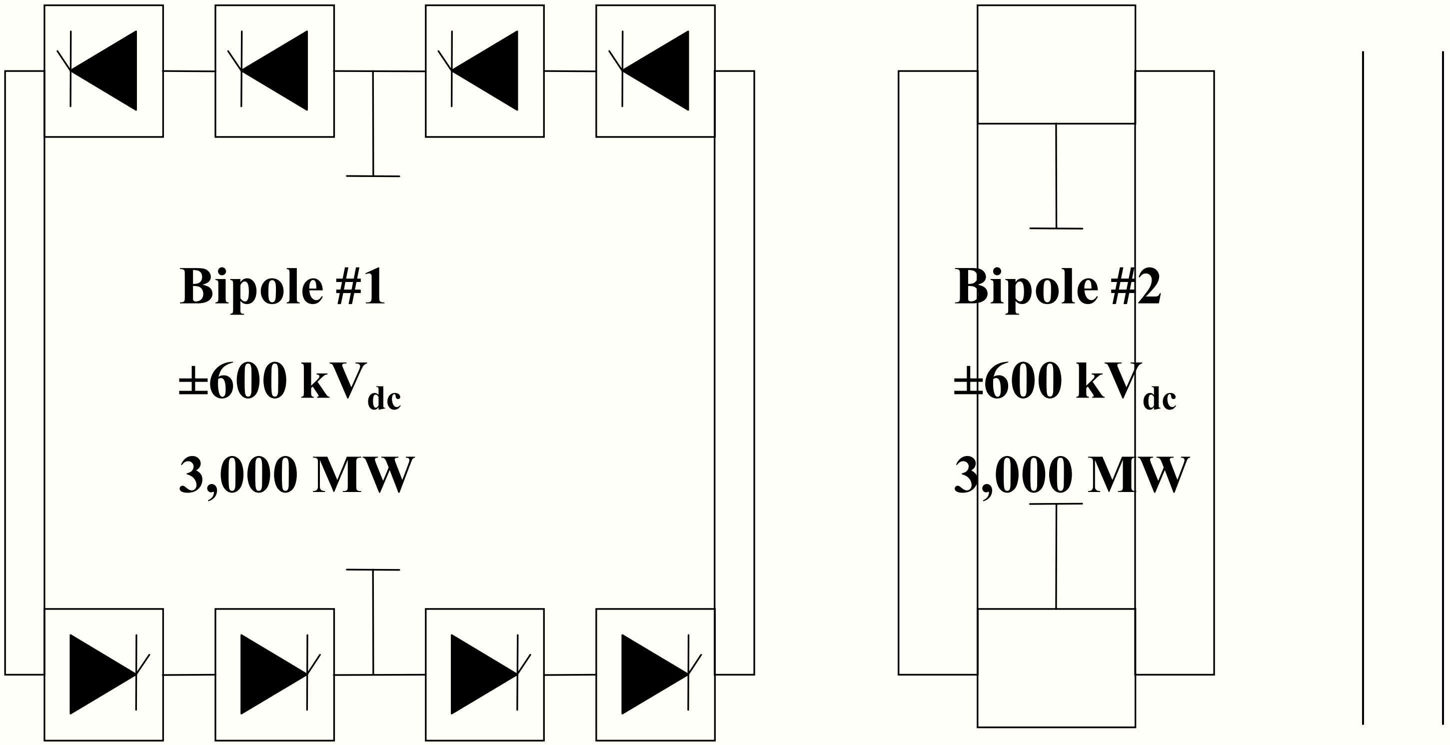
SCDC cable systems

- **Feeding into 500 to 765 kV stations**
- **Three transformers typically needed before reaching distribution system levels**
  - Losses significant
- **25kV to 500kV step up transformers costly and large for 2000 to 3000 MW banks**
- **Generators well matched for 20 to 25 kV dc systems**
  - Almost 1:1 ratio for transformers

Issues surrounding “paradigm shift” from high voltage, low current to low voltage, high current (“dc Heavy”)

- **Present day systems current source converters**
    - Exception – ABB’s HVdc Light with about a 2% loss penalty over CS systems
- **High voltage, high power, long distance transmission**
    - 500 to 600 kV, 2 to 3 kA
- **Back to back systems**
    - Typically 200 MW or above
    - High current designs
    - Low to medium voltage
- **Multiterminal systems – three terminal systems**

Itaipu – Sao Paulo HVdc Link



Bipole #1

±600 kV_{dc}

3,000 MW

Bipole #2

±600 kV_{dc}

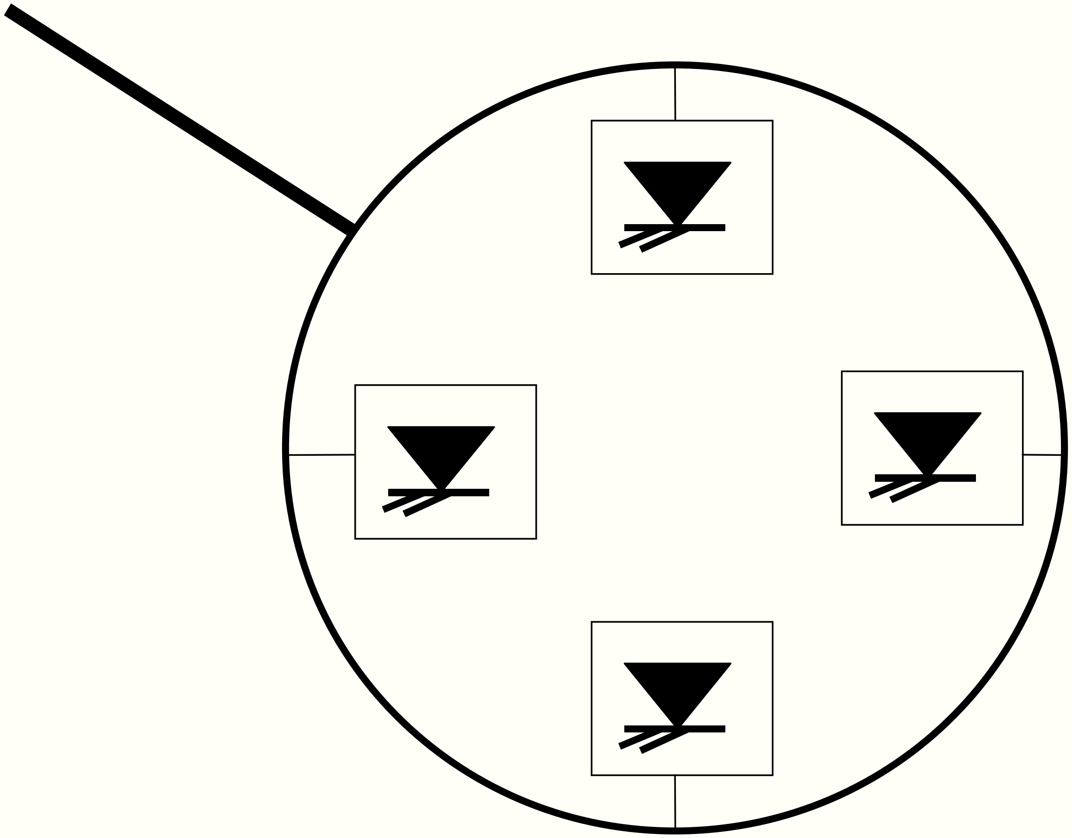
3,000 MW

765kV
parallel
ac lines

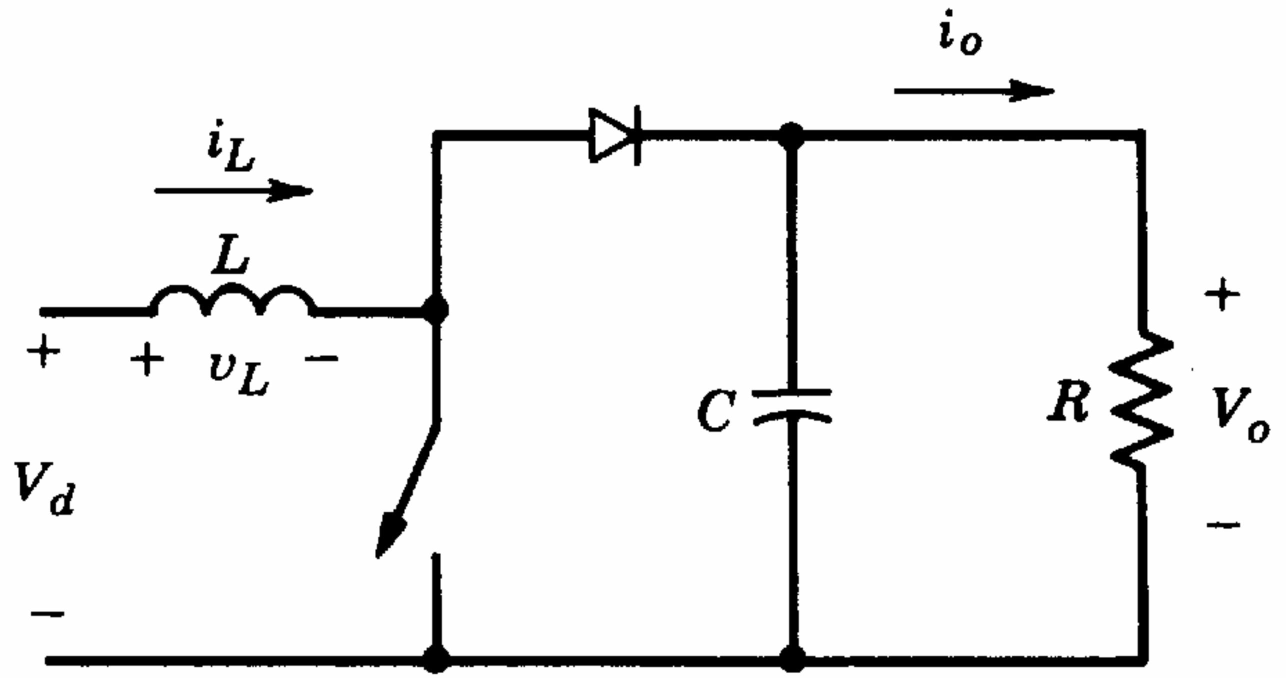
Single pole servicing…practical aspects of servicing one pole…earth return during servicing?

- **Earth return used in almost all dc systems but in the US only for emergency operation**
  - Grounding electrodes and ground resistance for Pacific Intertie about 3 ohms
    - For 3kA this is 9 kV which for a 500kV system is trivial
    - For a 100kA system, it is 30kV which is not feasible for a 25kV system
      - Electrodes can be improved but environmental concerns will probably block implementation of such a system
- **SCDC systems must have a third conductor or each cable must be bipolar with a redundant cable in case of failure of the first**

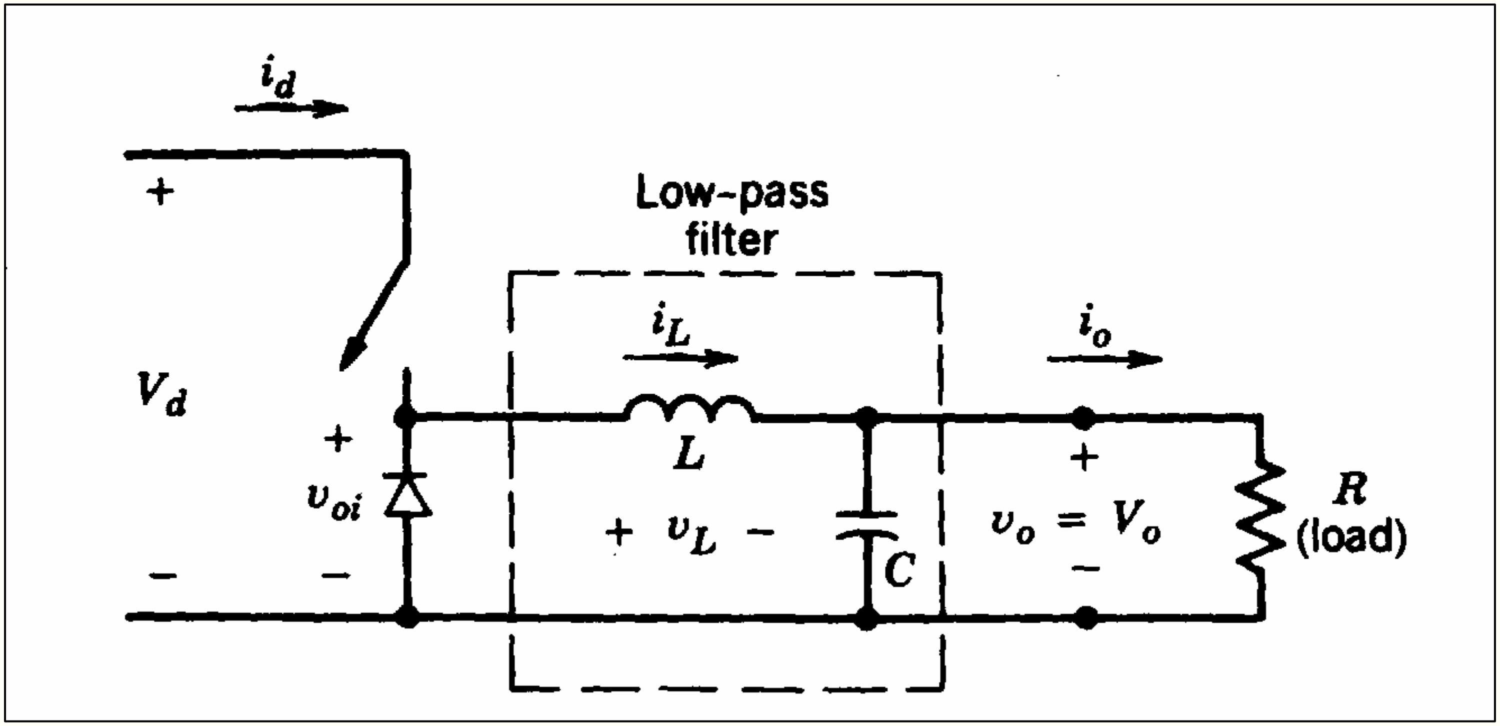
Topology of Receiving System for Connection to Superconducting HVdc Cable



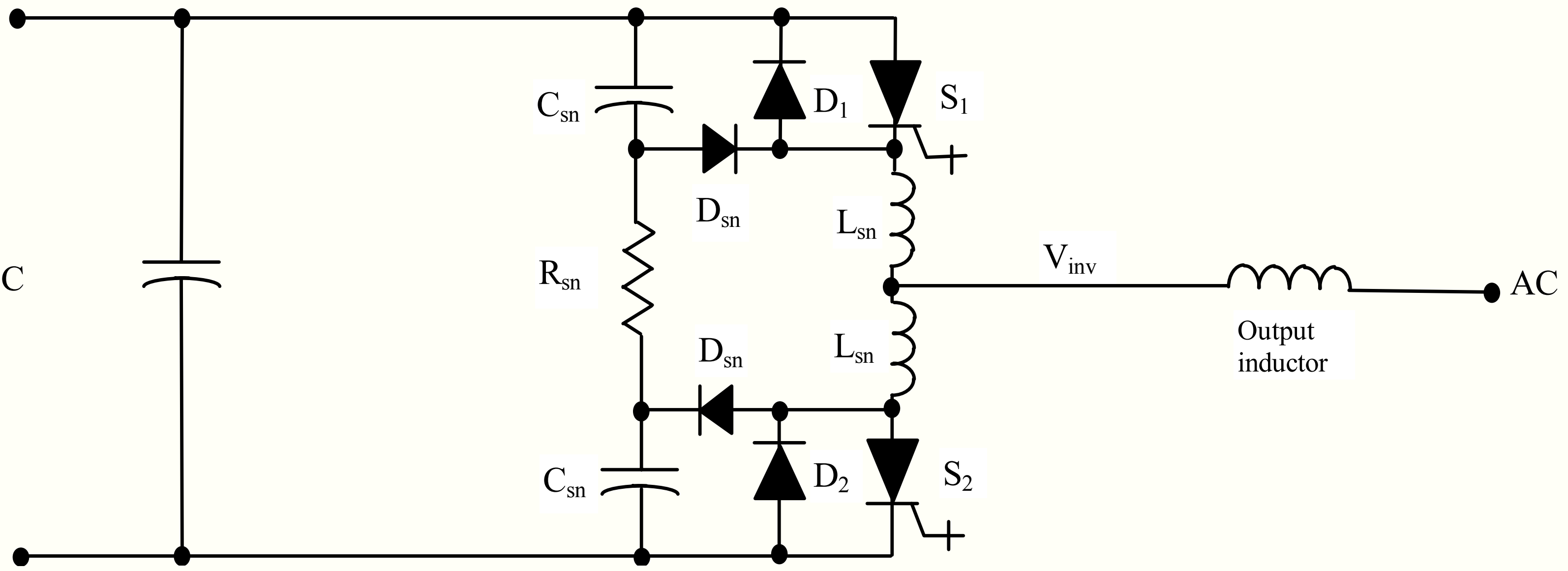
Boost Converter



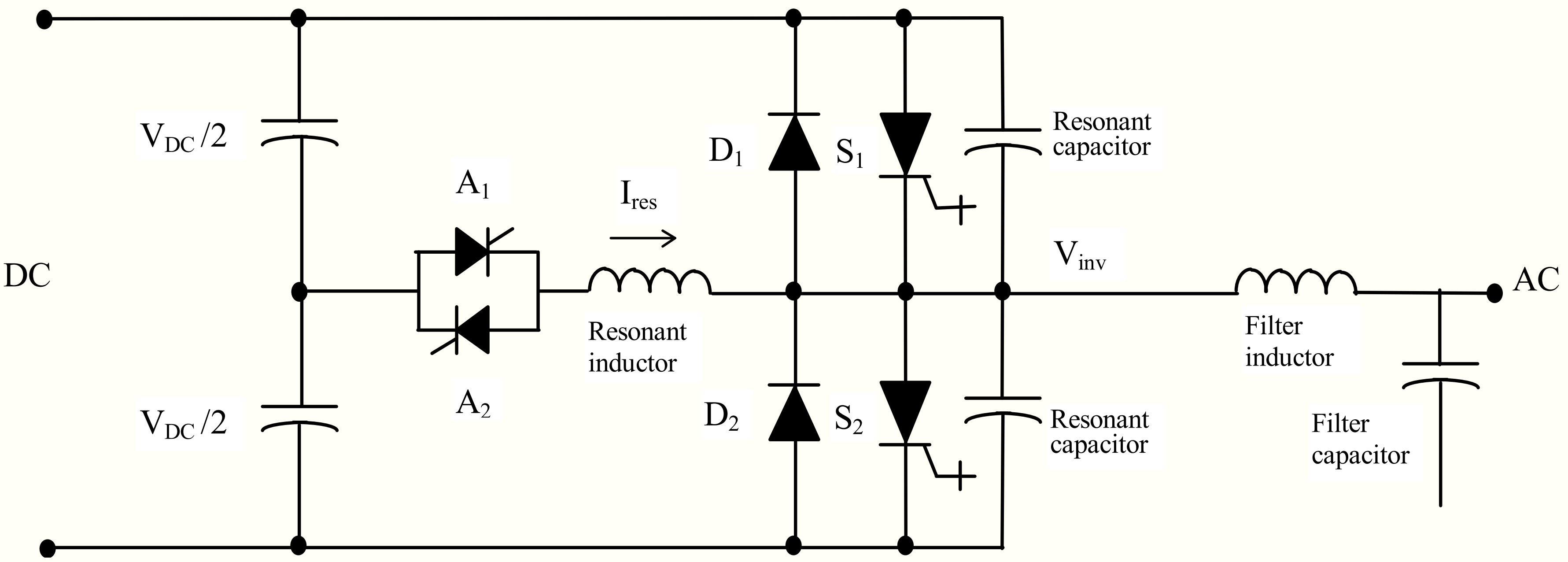
Buck Converter



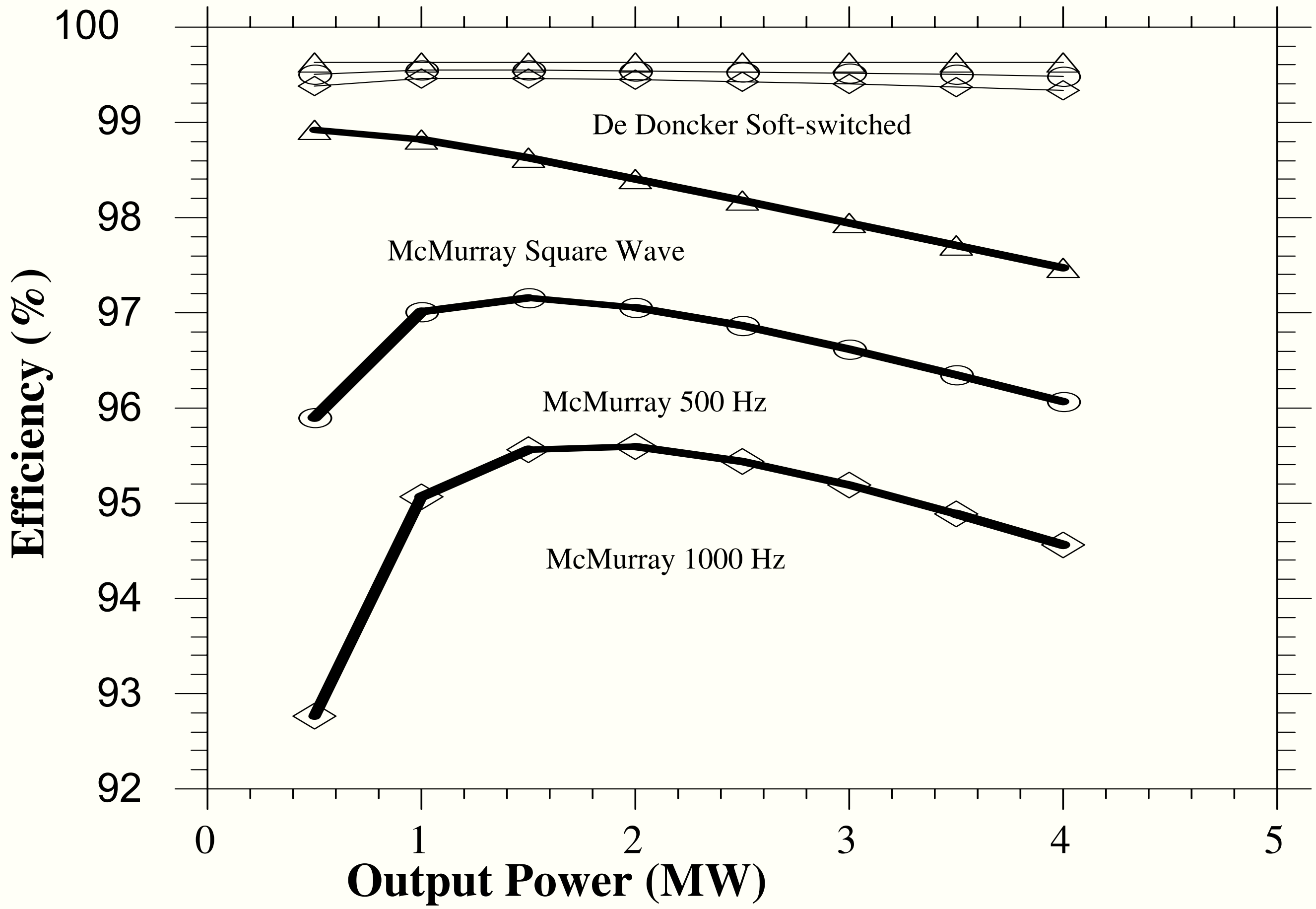
Hard Switched VSI Leg



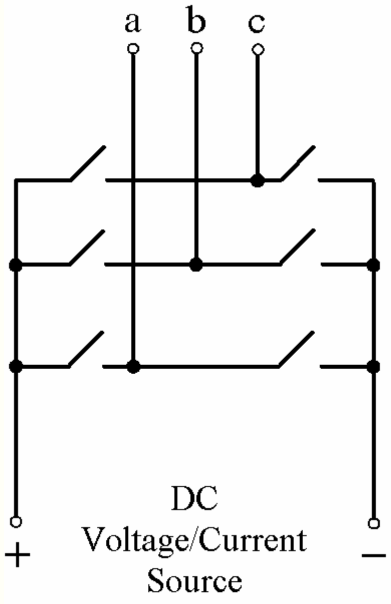
Soft Switched ARCP VSI leg

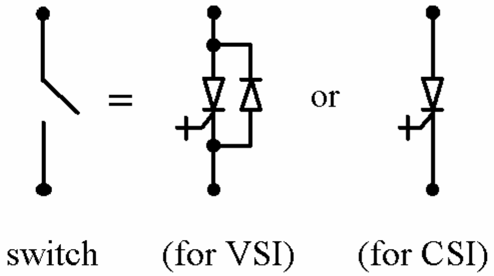


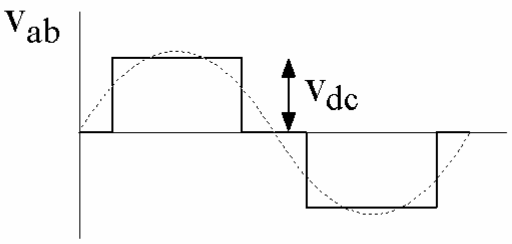
Efficiency


100
99
98
97
96
95
94
93
92
Efficiency (%)
0
1
2
3
4
5
Output Power (MW)
De Doncker Soft-switched
McMurray Square Wave
McMurray 500 Hz
McMurray 1000 Hz

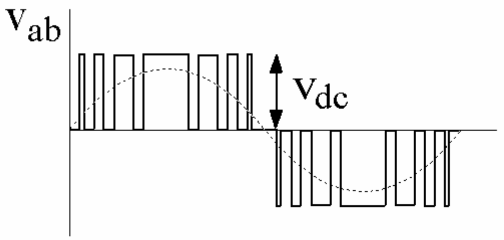
Converter Fundamentals







Fundamental-frequency switching



PWM switching

Semiconductor Technologies

- **Thyristors – CSI**
- **Gate turn off thyristors – symmetrical (CSI) or unsymmetrical (VSI)**
- **IGCT (GTO with special gate drivers) – VSI**
  - PWM less than 1 kHz
- **IGBT (insulated gate bipolar transistor) – VSI**
  - PWM up to appr. 2 kHz
  - ABB – up to 1780A

SCDC cable systems

- **Taps required to build a grid requires multiterminal systems**
- **Multiterminal current source converter systems difficult to control**
- **Voltage source converter systems conceptually would work like an ac ssytem**
    - Inverters control power infeed
    - Rectifiers act like sinks providing a constant output voltage
    - Droop needed for power sharing between rectifiers

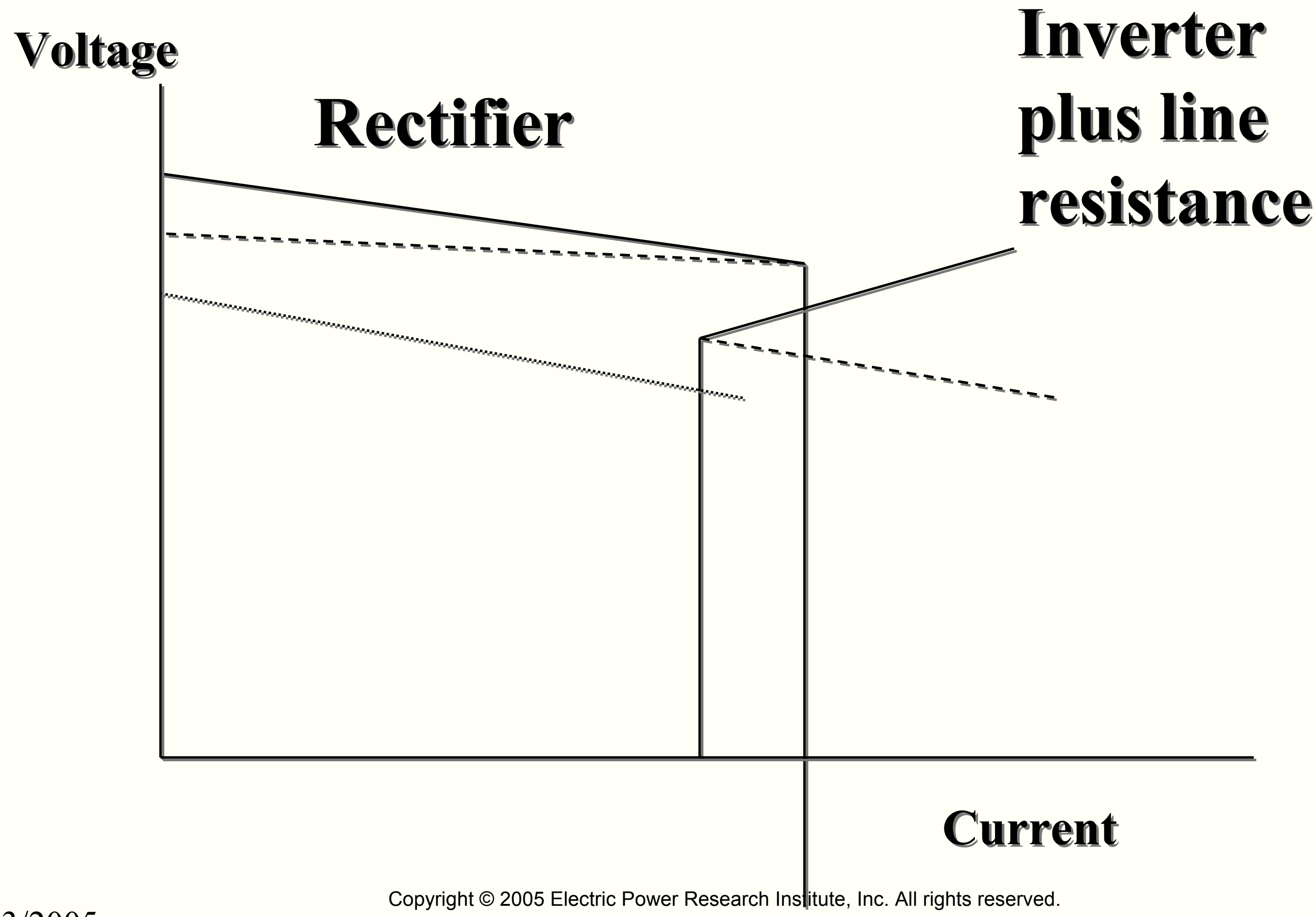
Reversible I/C valves…off loading to surrounding ac grid(s)

- Reversible valves mainly a concept for taps in current source rectifier/inverter systems
- Useful and may be required for stable operation of a small tap on a high power dc link

Converter technologies

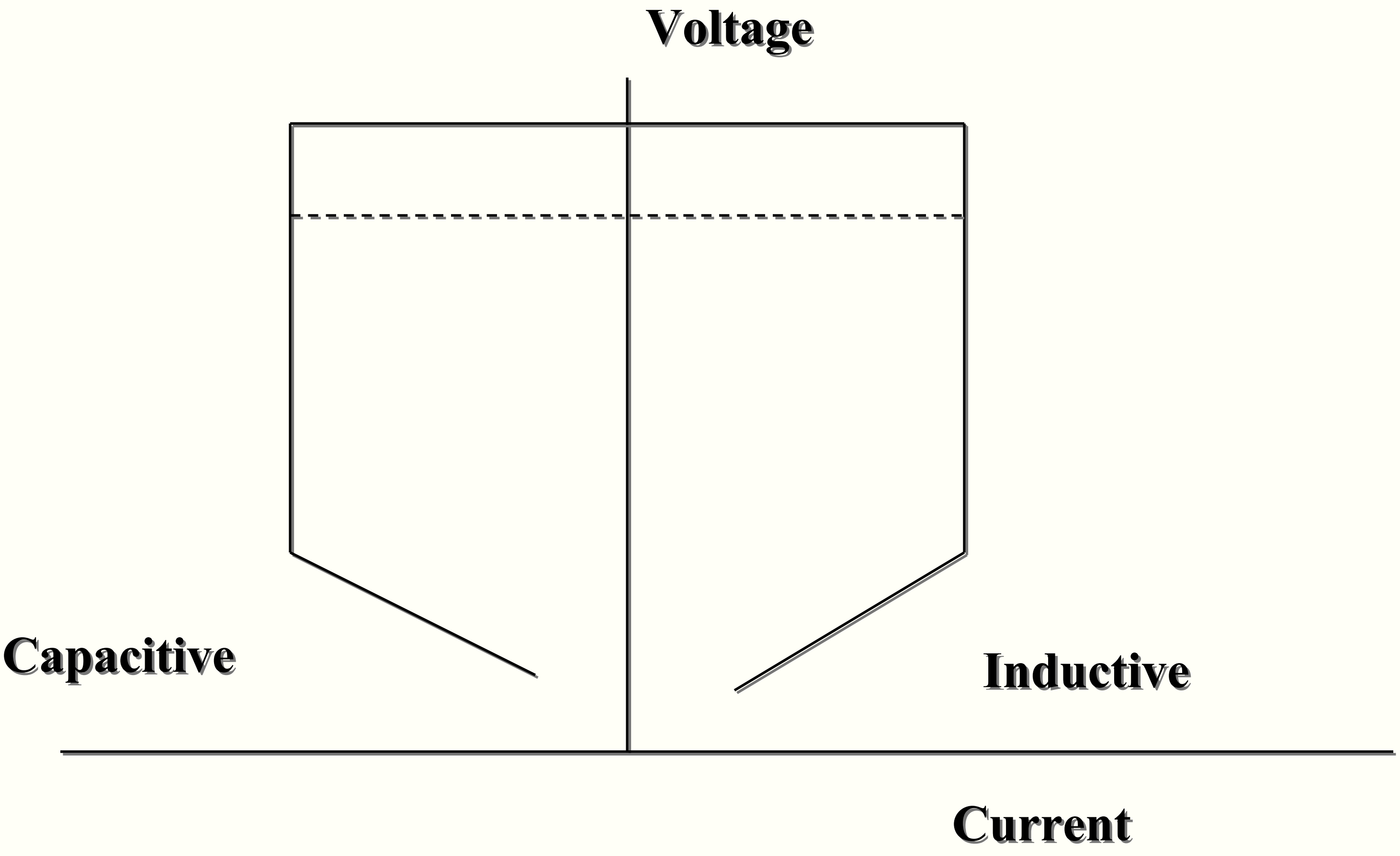
- **CSI**
  - 12 – pulse
  - Large filters
  - Reactive power requirement
  - Inverter sensitive to voltage disturbances
    - Commutation failures
  - Requires support from ac system for commutations
  - Power – limited by shipping
- **VSI**
  - PWM
  - Small filters
  - Self-commutated
  - Active and reactive power control relatively independent
  - Valve sensitive to overcurrents
    - Can limit current injection into ac system
  - Black start capability
  - +/- 150kV; 555MW

DC System Control - CSI



Foz do Iguaçu Converter Station

DC Systems - VSI



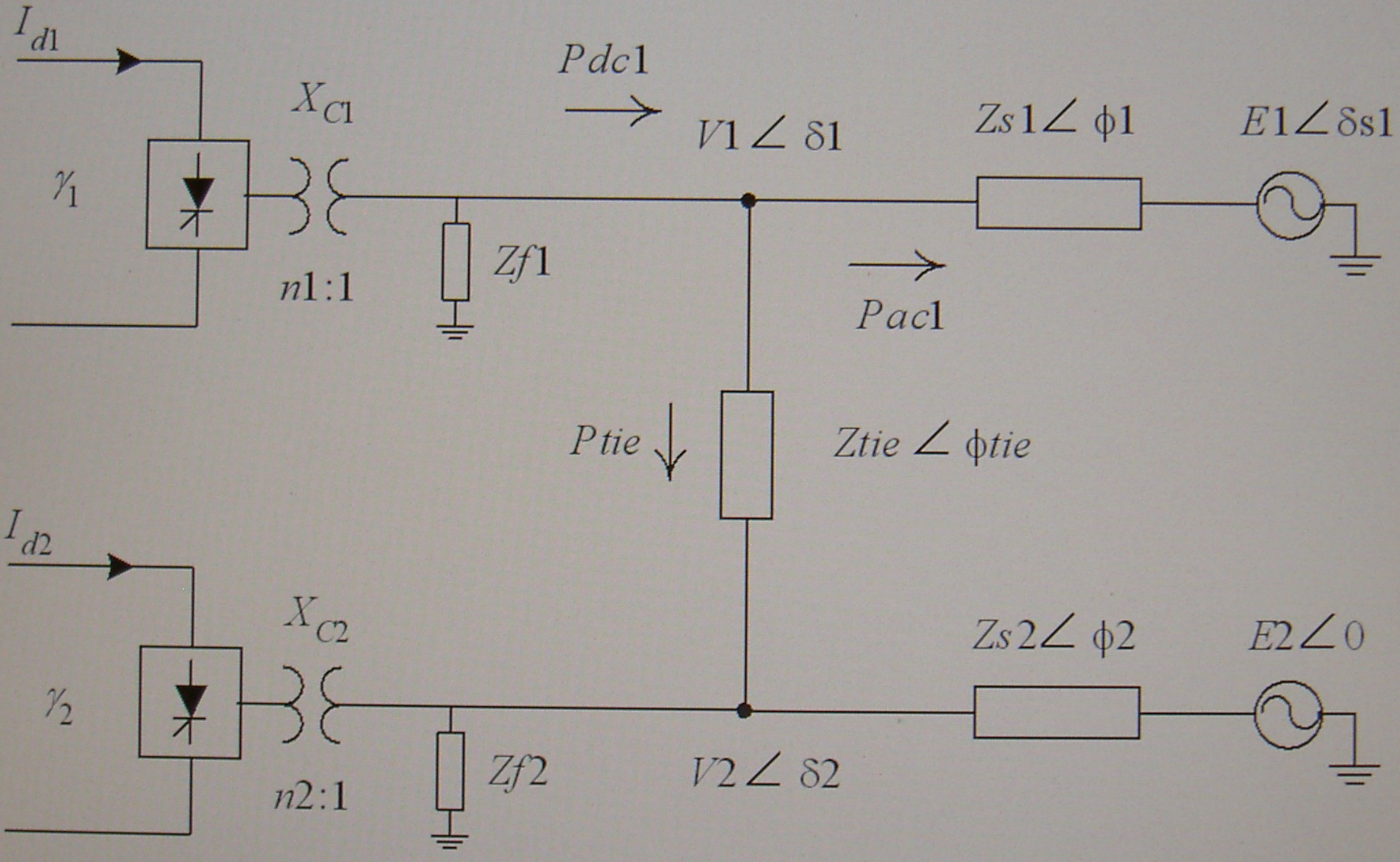
Shoreham converter station (Cross Sound Cable)
80m x 25m x 11m (Length x Width x Height)

Ripple and harmonic filtering and suppression (will "resonance" be an issue given "zero" resistance? (high Q))

- **Zero resistance is a dc characteristic**
- **AC losses provides damping**
- **Ac injection into dc cable under steady state conditions not acceptable**
- **VSI with PWM operation requires small dc filters for effective damping**
- **High cable capacitance and cable inductance leads to low cable resonance frequency << 60 Hz**
  - Long delay between injection of power at the sending end before it is noticeable at the receiving ends
  - Stability of the ac/dc system could be an issue

Fault, overload and service issues re I/C design

- **Ac system faults will**
    - Lead to loss of power injection a the rectifier terminals
        - Possibly inject 60 Hz into the cable
        - Drop in dc current unless current recirculation can be used
    - Lead to load rejection at the inverter ends
        - Drop in dc current unless current recirculation can be used
    - Recovery from faults may have to be slow to avoid loss dissipation in the cable
    - Multiple infeeds at both rectifier and inverter ends can lead to undesirable interactions between terminals
        - Magnifies the effect of ac system disturbances on the dc cable


I_{d1}
$Pdc1$
X_{C1}
$V1\angle\delta1$
$Zs1\angle\phi1$
$E1\angle\delta s1$
γ_1
$Zf1$
$n1:1$
$Pac1$
$Ptie$
$Ztie\angle\phi tie$
I_{d2}
X_{C2}
$Zs2\angle\phi2$
$E2\angle0$
γ_2
$Zf2$
$n2:1$
$V2\angle\delta2$

High voltage transients (L di/dt)

- **100kA, 25 kV DC line fault –**
  - 15 mH for 100km is 75MJ
  - 18 micro-F for 100kM is 6kJ
  - Open ended cable will be catastrophic
  - Crowbars needed at both ends of the cable in case of overvoltage
- **Current continuity must be preserved under all conditions**

Pump/Cryostation power supply along route

- **Cooling systems critical for the operation of the SCDC cable**
- **Loss of power to cooling systems is a possibility**
  - Small taps using VSI to feed cooling systems is possible if power can be supplied using non-superconducting elements of the cable
  - Taps are a risk of failure
  - Local ac power with diesel backup may be more reliable
    - Avoid 1977 ConEd blackout problems
      - Backup power is needed and redundant cooling systems required

sc cyro-infrastructure for cooling, maybe for “specially designed” cryo-bipolars

- Superconducting device technologies can be developed
- Semiconductors a small part of the total parts count
- Device replacement is required so cryogenic converters will suffer from availability problems
- High current devices easier to build than high voltage devices
- 6 inch thyristor devices and larger can be made
- Limitation is right now high current IGBTs

F

CABLE SYSTEM TECHNOLOGY – GREGORY

EPRI:

DC HTSC Long Length Cable System

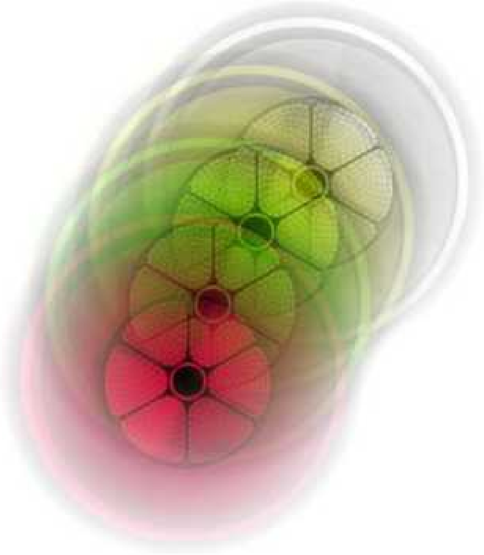
12th- 14th October 2005

Palo Alto

Cable System Technology

- Background
- AC and DC cables
- DC HTSC cables

Brian Gregory



Cables are used when no other solution is acceptable:

Despite lower DC costs, majority of applications are AC

- Dense populations (New York, Singapore)
- Climatic risks to OH lines (typhoons-Hong Kong)
- Wide river and sea crossings
- Within OH line in areas of scenic beauty (to gain public acceptance)
- Power system interconnectors
    - Between countries: **DC**
    - Between different system frequencies : **DC**

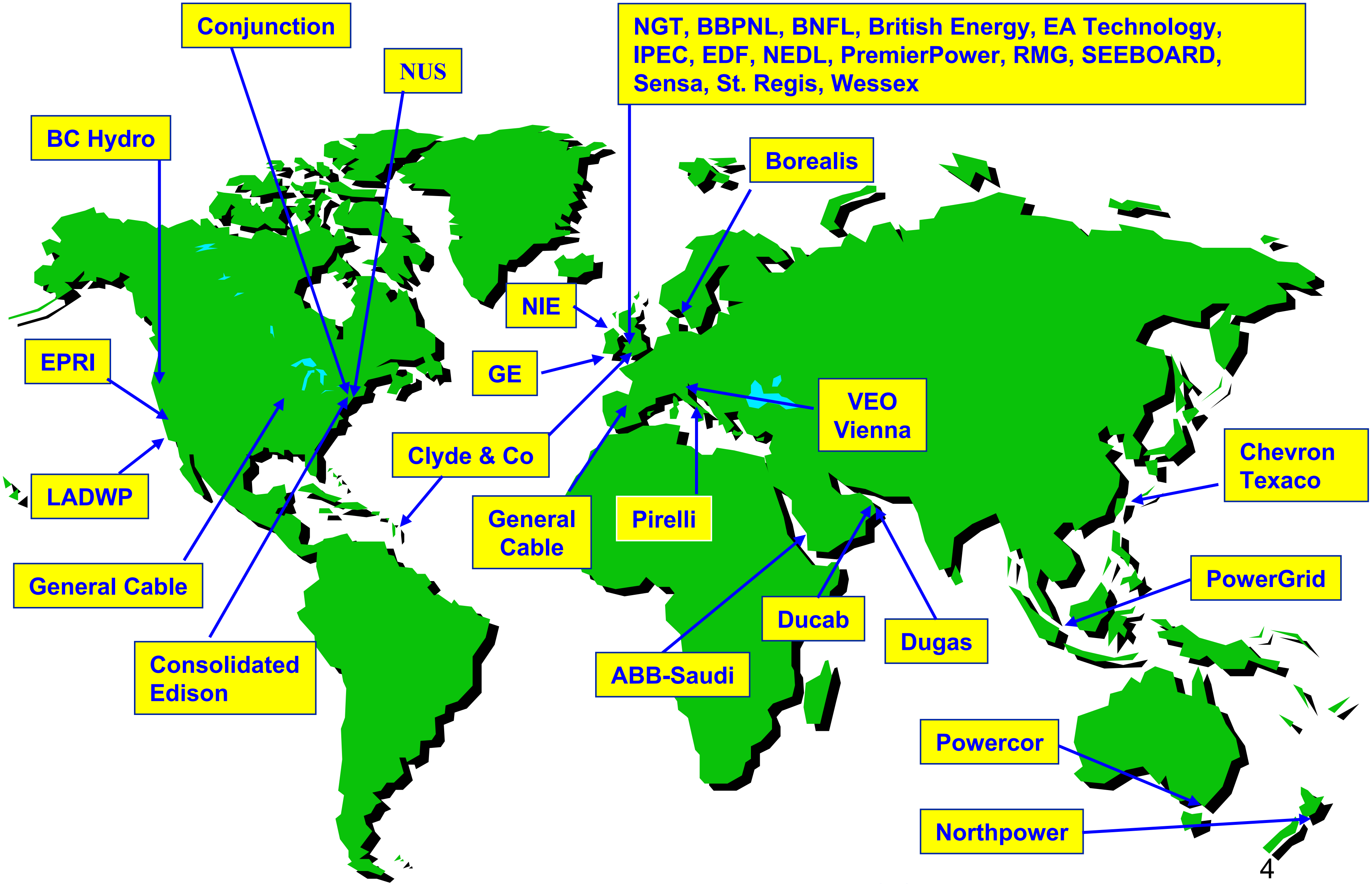
Cable Reliability is the Essential Parameter for Transmission

Mechanical flexibility differentiates cables from all other insulated equipment

- Cables are buried deep in the ground
- In a hostile environment
- Underneath the water table
- At risk from dig-in damage by builders, farmers, other utilities
- At risk from vehicle load damage

- Inaccessible for maintenance
- Designed for 40 year life
- Repairs take 4 to 12 weeks of electricity outage time
- Cables are very expensive
- AC cables have high capacitance
- AC cables need special bonding

Cables are Used in Areas of High Population Density



DC Cable Systems are Predominantly Subsea Links

Oct. 13, 2005

CCI *Cable Consulting International*

Cable Types: AC Transmission

BG's Experience

- Cable Types

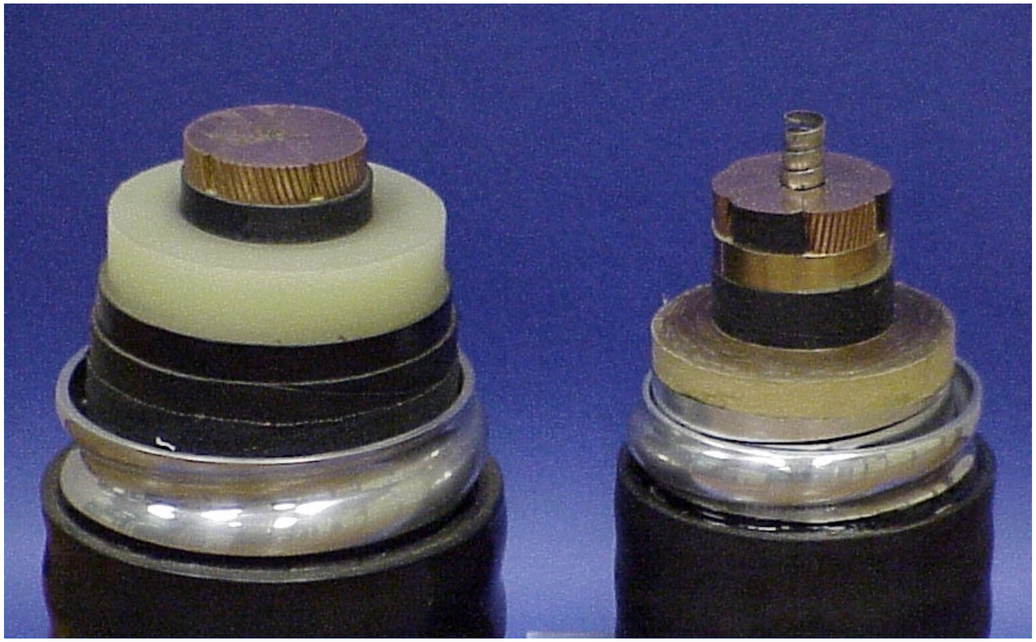
XLPE cable systems:	400kV
XLPE subsea cable systems 90KV:	110km
FF PPL tape cable systems:	**500kV**
FF paper tape cable systems:	**525kV**
GF paper cable system:	**132kV**
MIND systems (paper + compound)	66kV

- Cooling Types
  - Naturally cooled
  - **Integrally sheath water cooled**
  - Separate pipe cooled: a historical 'special' application
  - Internal oil cooling: experimental demonstrators
  - Internal water cooling: experimental demonstrator

Became unpopular: maintenance problems

State of the Art for EHV AC Systems

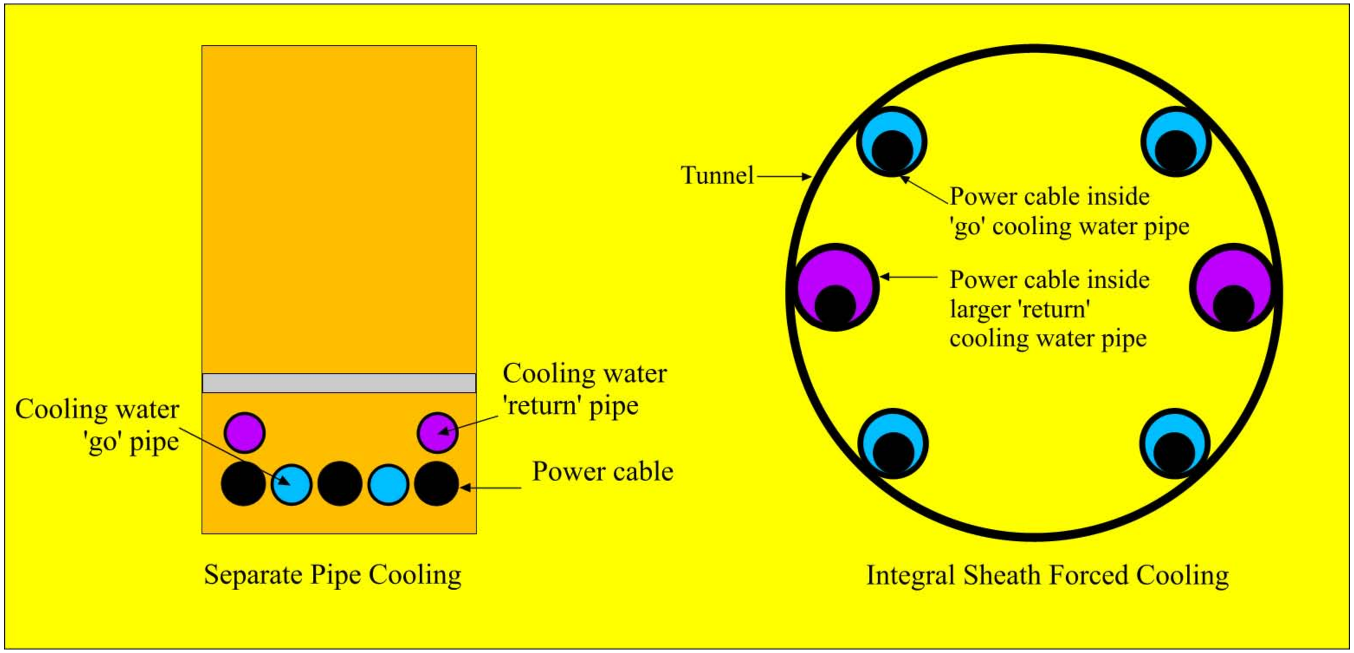
400kV Cable Systems with Joints



- **Extruded XLPE**
- Immature product, but gaining acceptance
- 5 years service in limited applications
- Mixed experience to date
- Environmentally friendly
- Reduced risk of fire spread
- Reduced maintenance

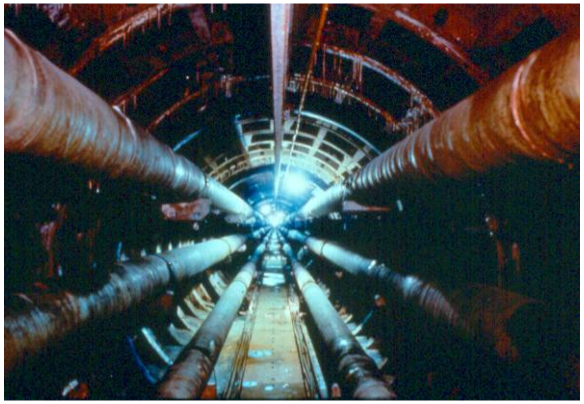
- **Fluid filled paper and PPL**
- Mature product
- 40 years service
- 25 years of proven reliable service
- **Risk of fluid leaks**
- Fire risk in tunnels and buildings
- **Maintenance on hydraulic system**

Forced Cooling



Cooling by water circulation requires the installation of pumping and heat exchange stations.

Forced air cooling is also possible where cables are erected on steelwork and a draft of air is pushed through the tunnel
either with fans or by natural chimney ventilation.

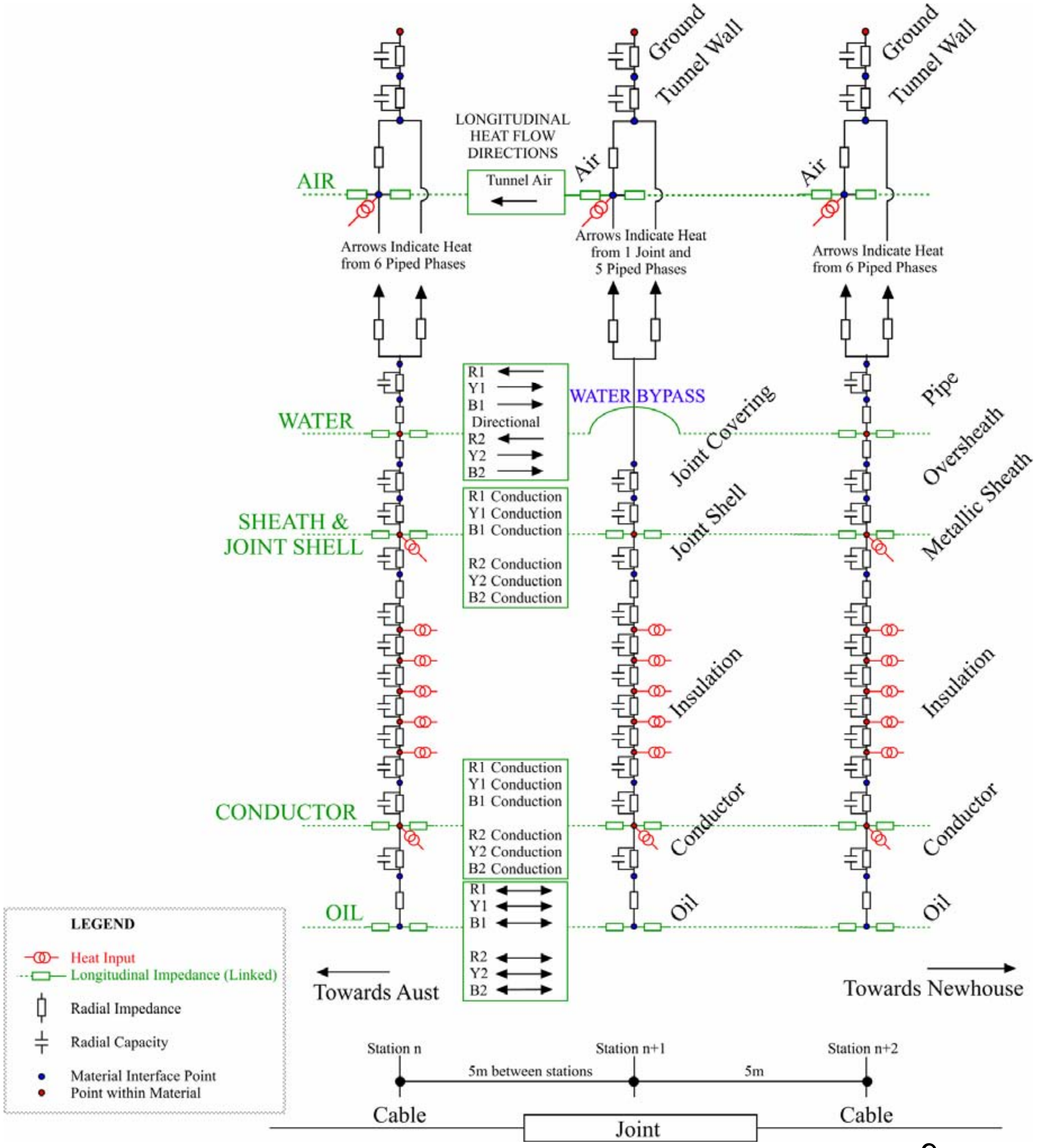


400kV Severn Tunnel

Cooling Systems are Complex:

400kV Severn Tunnel Thermal Model of Joint and Adjacent Cable

	Number of Model Sections
Aust Yard	10
Aust Shaft	9
Tunnel	735
Newh Shaft	6
Newh Yard	7+
Total	767 per cable, 6 cables



DC Cables

BG’s Experience

• 266kV DC FF land cable Kingsnorth-Willsden	1968
• 100kV DC MI Cross Channel: improved connector strength	1975
• 250kV DC GF Cook Straight NZ: Improved connector and gas sealing	1976
• 1000kV DC EPRI EL 3973 (FF cable and accessory designs)	1975~85
• Underground DC transmission study, Heyer, PEC	1983
• 270kV DC FF land cable from Sellindge to Folkestone	1984
• DC system designs and MI cable bids for subsea links:	1990’s
– 250kV Moyle, Isle of Man, Bass Straight, Euro-Viking Cable	
• Development programmes for DC cables with new insulation materials	
– PPL	1990
– XLPE, EPR	1998
• EPRI technology review of DC extruded cables, CCI	2004

Prospective long length land applications are defeated by:

- **Converter costs**
- **Inefficiency of non-pressure MI type (low operating temperature)**
- **Inefficiency of transmission class XLPE (space charge stress increase)**

Superconducting Cable Experience
BG’s Experience

- BICC, Rogers and Slaughter niobium-tin LTSC demonstrator, 1970’s
- Brookhaven LTSC niobium-tin 1980’s
- HTSC: BICC Worldwide Cables Technology Board
  - UK consortium study on applications
  - Research at Erith started 1990
  - Transmission cable application studies 1992
  - Manufacture of BISCCO PIT 1992
  - DC demonstrator BICC Ceat Cavi + Ensaldo
  - Bids for European projects for demonstrator ~1996

400kV AC Cables are Supplied to Site in Short Lengths of Less than 1km: Many joints are Needed

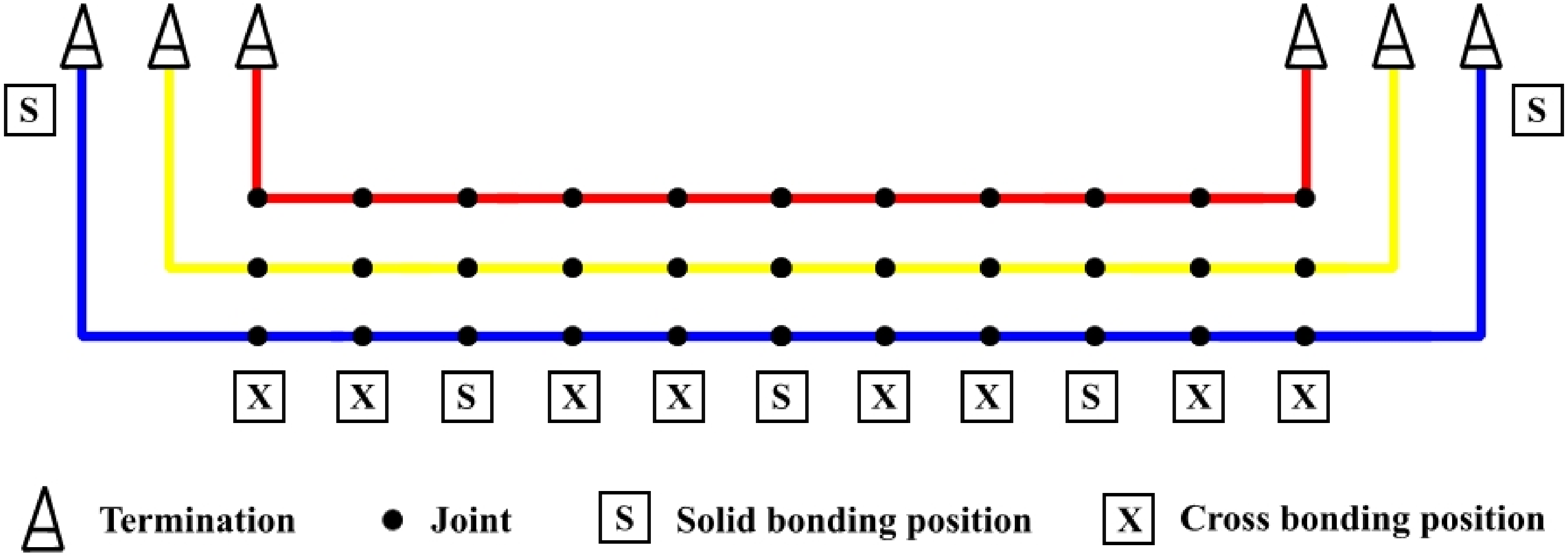
- Drum diameter is limited by bridge height
- Drum weight is limited by the road and ground strength

We need to make HTSC cables longer,   5km?

Many Straight Joints are Required

- This 400kV 12km long AC circuit has 36x1 km drum lengths
- It needs 33 joints
- Each joint is a point of higher risk

If DC HTSC cable is shipped in 3 x 4km lengths, only 4 joints are needed on a bi-pole circuit



Reliability depends on each part of the cable system
Joints are the most vulnerable part
DC HTSC CHALLENGES

- System design (each circuit is unique), **RELIABILITY AND AVAILABILITY OF COOLING?**

- Cable design: electrical stress, type of metallic and jackets **LN AND VACUUM CONTAINMENT**
- Cable manufacturing quality (machine, materials, men) **CAN'T FACTORY TEST HTSC Cable**

- Installation type (buried, duct, tunnel)
- Installation method (bond pulled, nose pulled)
- Cable protection (cement and cover tiles?)

- **Joint design: CONDUCTOR CONNECTION, INSULATION, FORCES**
  - **ACCESS FOR LN AND VACUUM?**
  - **LN PRESSURE SECTIONALISING?**

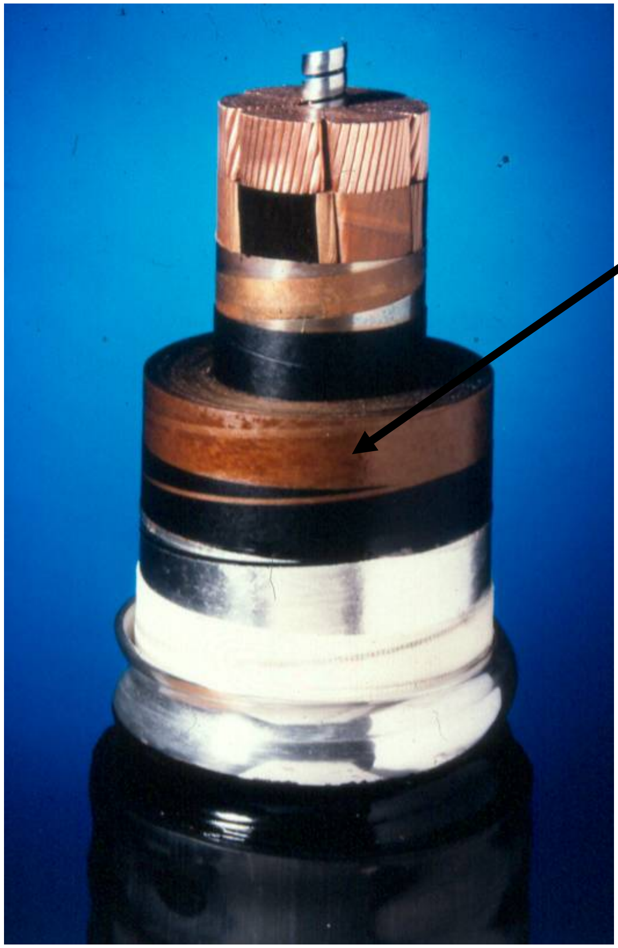
- **Joint manufacturing quality (machine, materials, men)**
- **Jointer training and skill** **MORE COMPLEX**
- **Joint assembly (need site room, good lighting, clean, dry, humidity control)**
- **Joint protection from:**
  - **Water**
  - **Cable contraction forces**
  - **Ground movement**
  - **Traffic loads**

300kV AC and above transmission

600kV DC

AC Paper Insulated Fluid Filled Cable

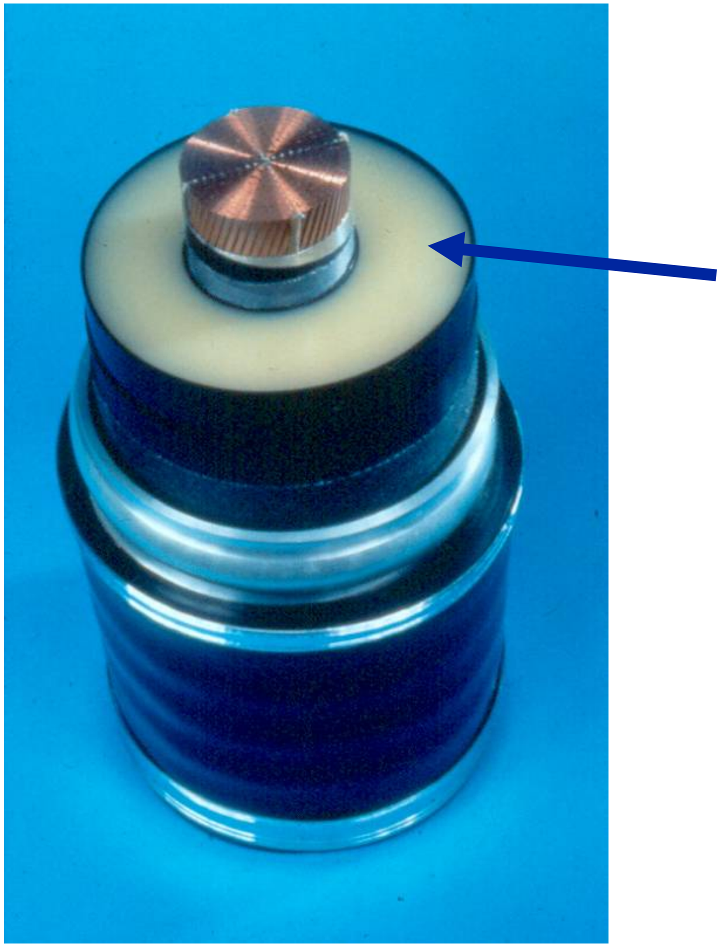
The most efficient type of DC cable



- A natural 200% performance margin exists on ac voltage applications, because impulse designed.
- Insulation is 50% paper tapes and 50% thin fluid (oil)
- Fluid is the most important part
- Fluid is pressurised (5.3bar)
- Insulation has self-healing properties
- Straight joints share the cable fluid
- Risk of leaks is environmentally unacceptable

- **DC insulation: design stresses of twice AC are used, so only half insulation thickness is needed.**
- **DC conductor sizes are smaller.**
- **Only two cables needed instead of three**

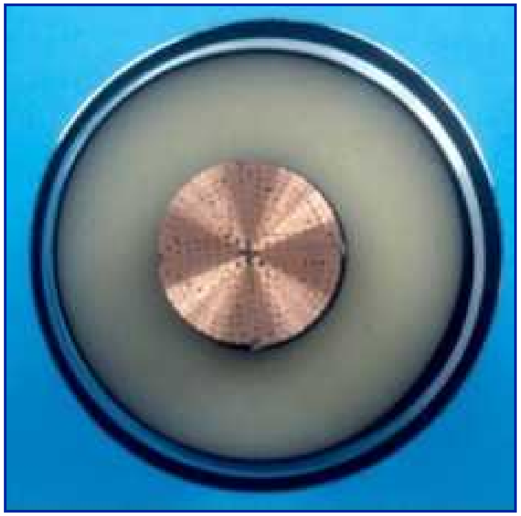
AC XLPE Cable



The newest type

- **Has no natural performance margin on ac voltage**
- Insulation is extruded polyethylene
- Polyethylene is chemically crosslinked
- Insulation is vulnerable to manufacturing problems:
    - Screen/shield protrusions
    - Particles
    - Gas bubbles
- Jointing cables reliably is difficult as there is no insulating fluid
- DC: very high insulation resistance, holds charge, so is difficult to discharge
- DC: polar species migrate towards shields, stress increased 30-800%, cant be drained cold

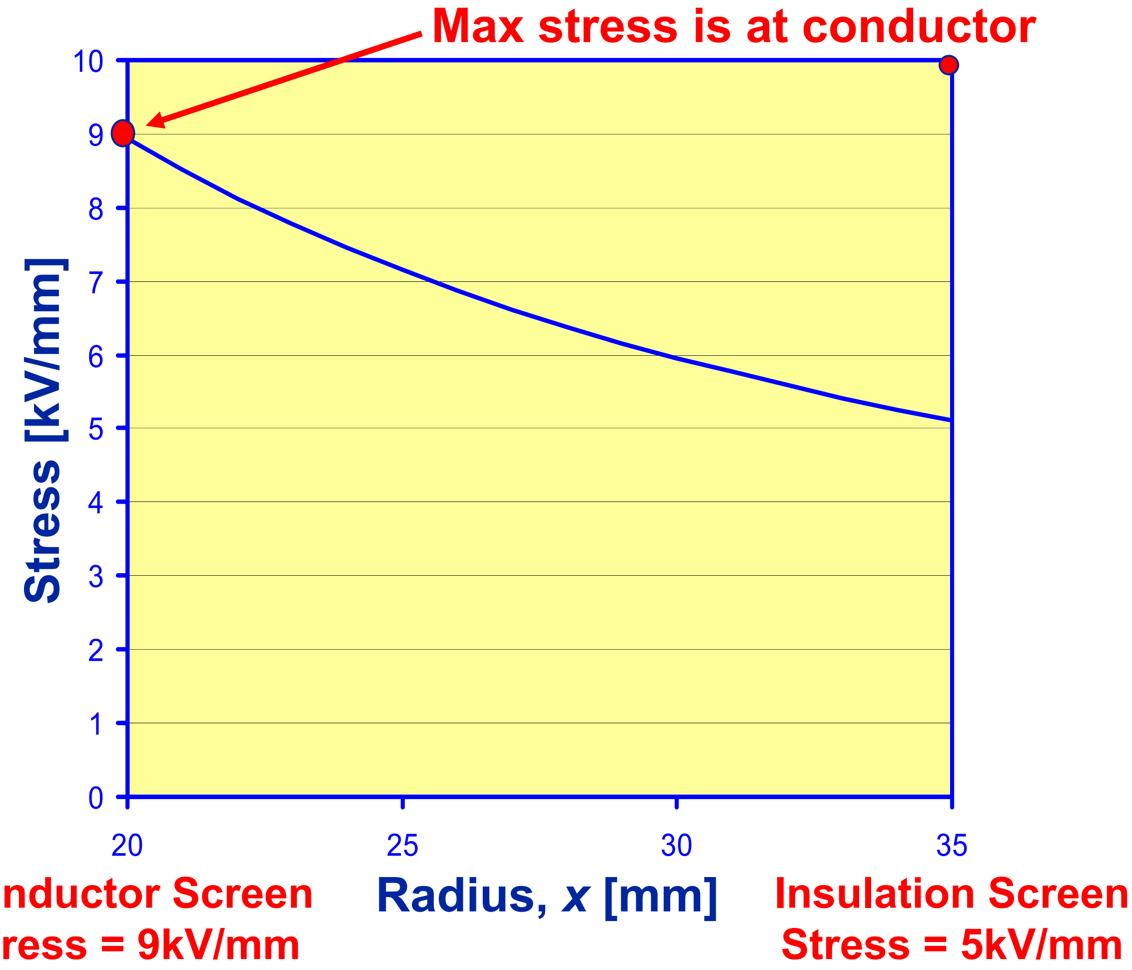
Stress Distribution on AC Voltage and Impulse Voltage: The stress is not a constant value because of the circular shape



Stress at radius *x*

$$E_x = \frac{V}{x \ln(R/r)}$$

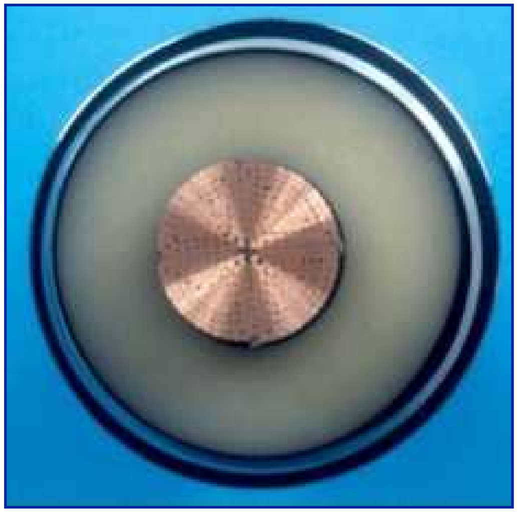
R = insulation radius
r = conductor screen radius
x = variable radius



Conductor Screen Stress = 9kV/mm

Insulation Screen Stress = 5kV/mm

Stress Distribution on DC Voltage: Is similar to AC case when cold, but ‘stress’ inversion occurs when hot, due to increased charge mobility

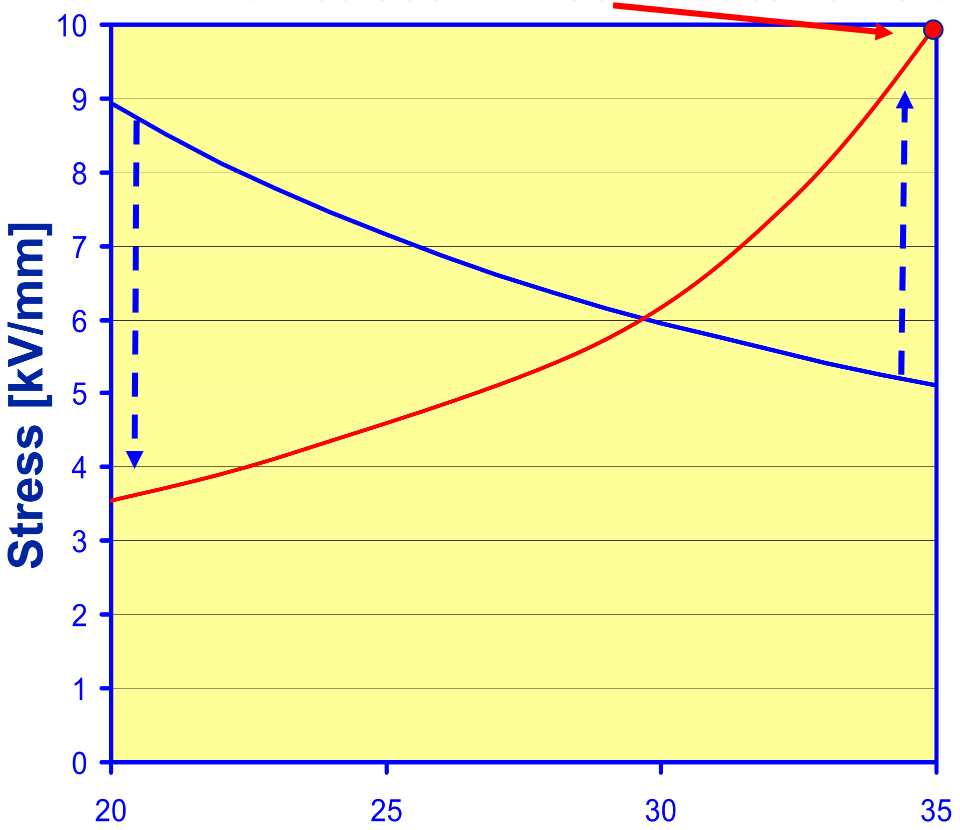


Stress at radius x

$$E_x = \frac{V}{x \ln(R/r)}$$

R = insulation radius
r = conductor screen radius
x = variable radius

Max stress moves to outer shield



Conductor Screen Stress = 9kV/mm

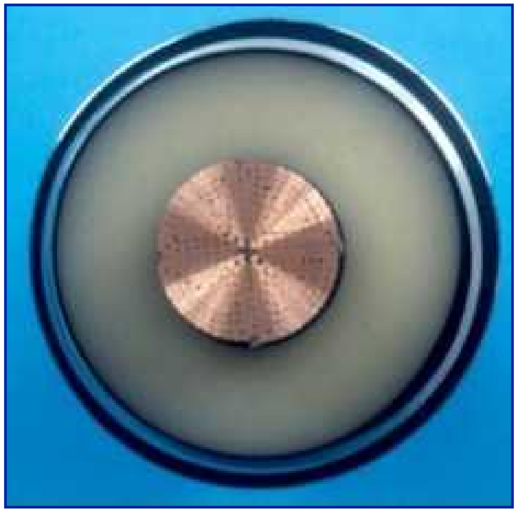
Radius, *x* [mm]

Insulation Screen Stress = 5kV/mm

Insulation Design for DC Cable

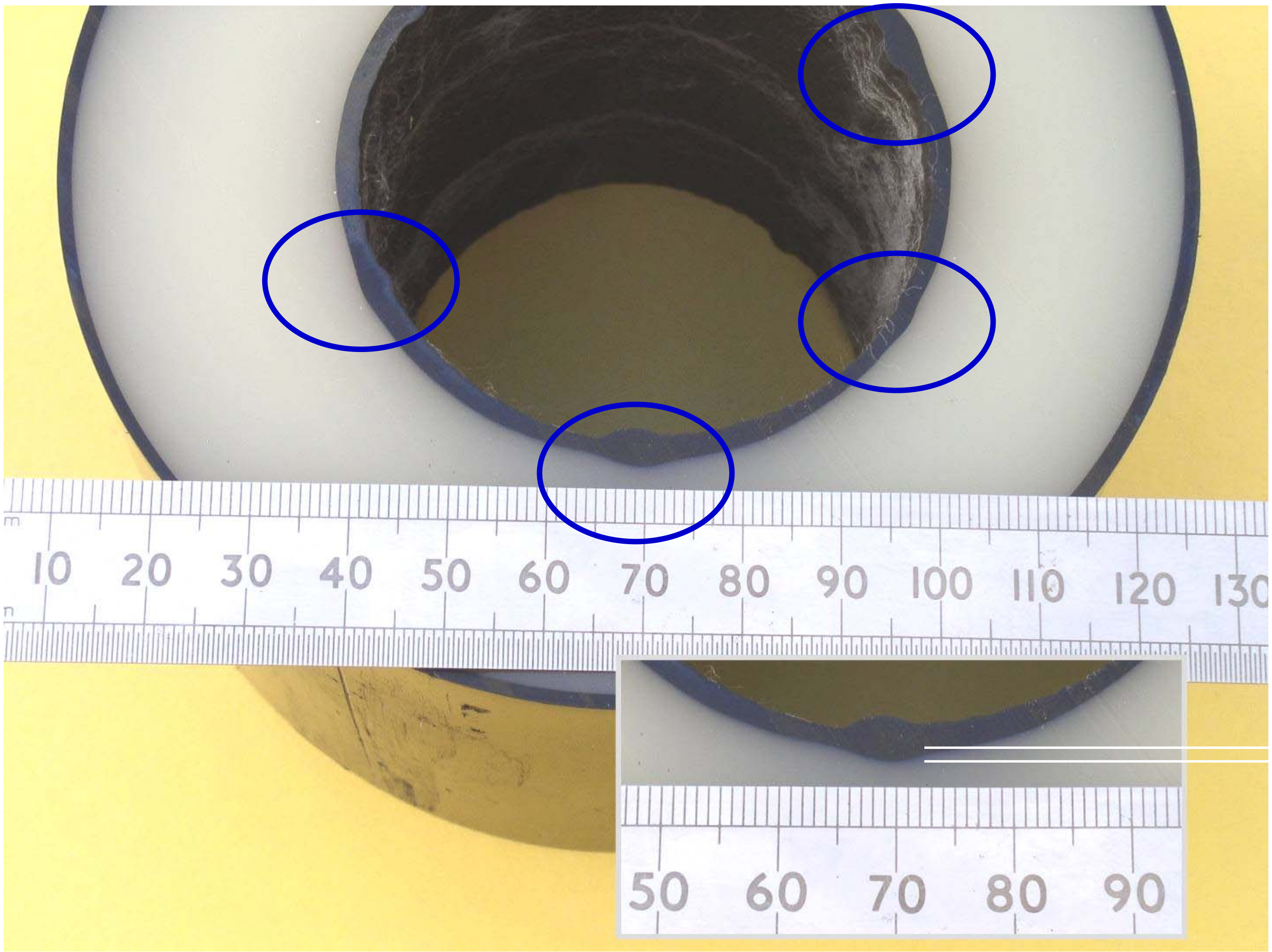
More complex than AC, but is known technology

Effect of 77K temp ?



- PD repetition rate greatly reduced: gives higher design stress
- Formulae and material parameters for stress distribution are more complex: stress inversion
- Worst case is impulse on opposite polarity DC, as stresses add as a scalar quantities; due to commutation failure
- Rapid polarity reversal also has to be qualification tested as insulation holds charge when conductor is at zero potential.
- For extruded insulation only, space charge needs to be minimized by material and process development; difficult at transmission voltages.

Every mm in a km of cable of insulation has to be perfect; made by factory processes, materials and people who are not!



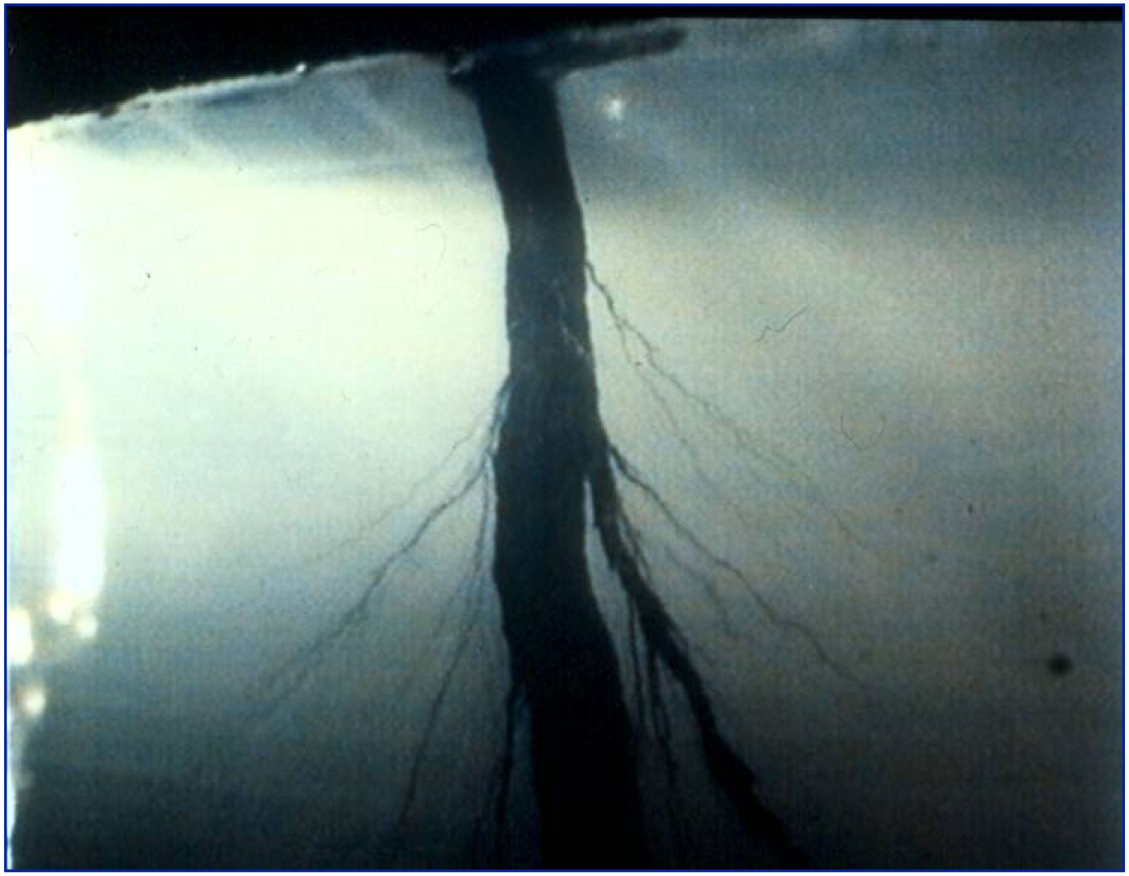
0.8mm

Milliken segmental conductor

Incipient trees growing from particles in ‘clean’ XLPE cable at factory shipping acceptance test

- **Copper particles 3~4mm long**
- **Tips of tree branches growing outwards**
- **Resulted in HV failure, so OK?**

Large defects can be found at the factory HV test if stress is high enough



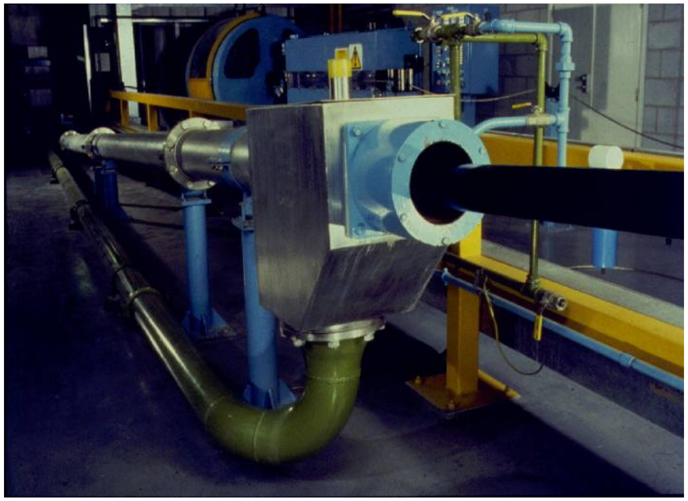
- **Growing inwards from core screen**
- **Main fault channel 4mm wide**
- **Fine incipient trees radiating out**

HTSC Cable:

Cold Dielectric cable uses LN as part of the dielectric and so cannot be voltage tested in the factory – a very major disadvantage

DC HTSC Cable: Factory Test Solution for Investigation

Use of ‘In-Line Ultrasonic NDT Monitoring’

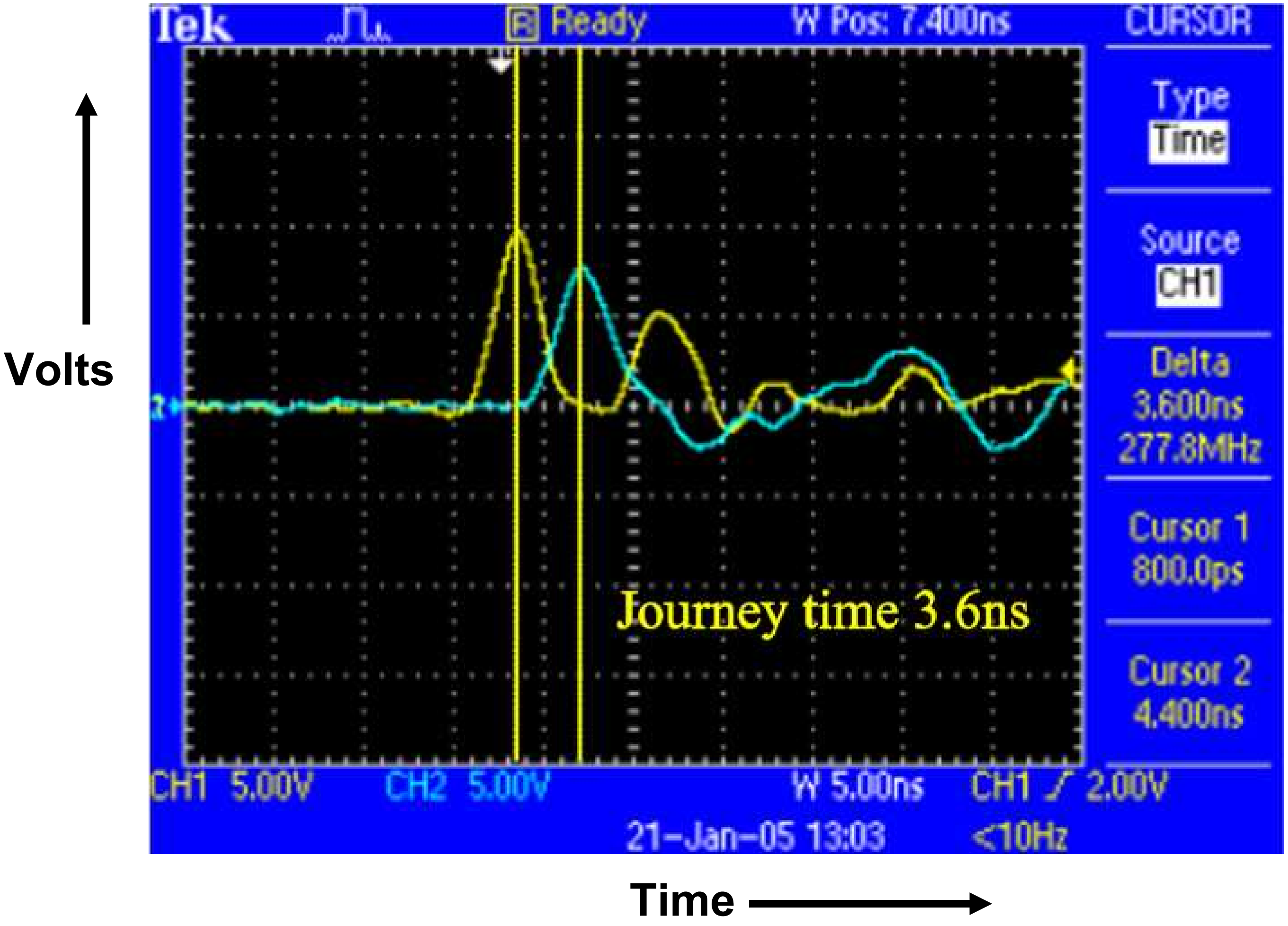


Monitor detects:

- Layer geometries
- Screen Interface defects
- Insulation defects
- Conductor defects

DC HTSC Cable: Factory Test Solution for Investigation

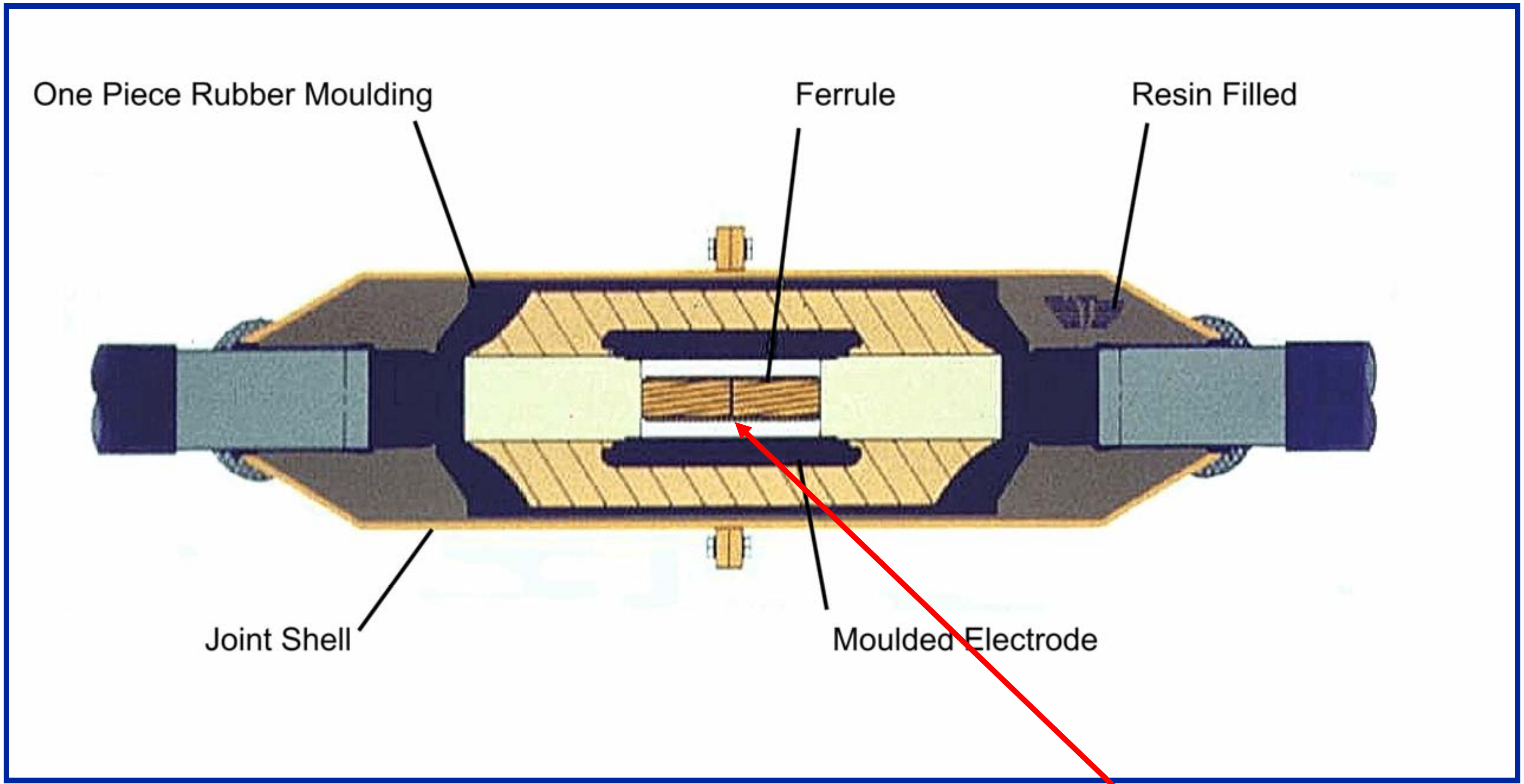
Use of electrical or optical time domain reflectometry to test conductor assembly



Journey time 3.6ns

DC HTSC Accessories

are much more complex than cables and are not assembled in controlled factory conditions



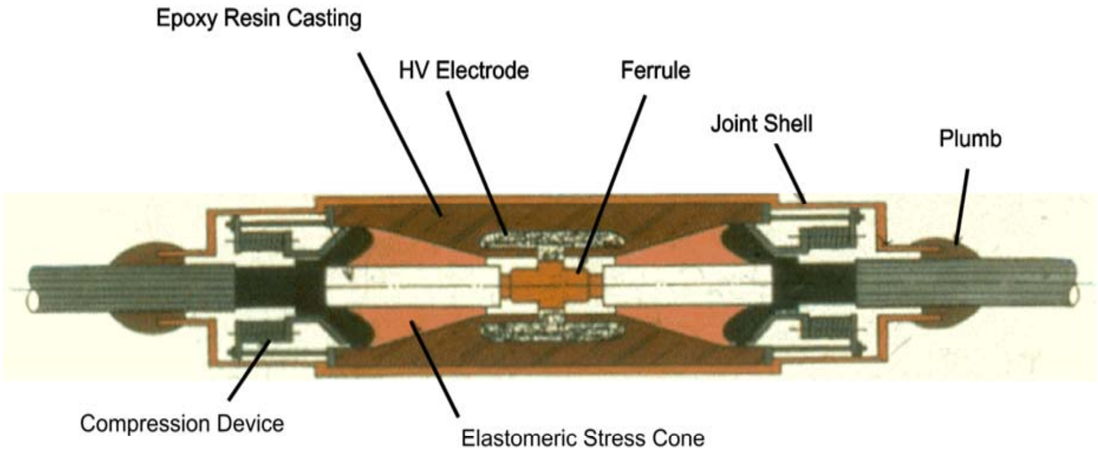
HTSC Warm Dielectric cable design: it is very difficult to join and seal the central duct and contain the pressurized LN

Prefabricated Composite Straight Joint

DC HTSC WD and CD Cables:

Special sectionalizing feed joints will need to be developed that;

1. **Withstand LN pressure**
2. **Withstand differential thermomechanical force**
3. **Do not exhibit charge effects in the stressed feed channels: electrophoresis**

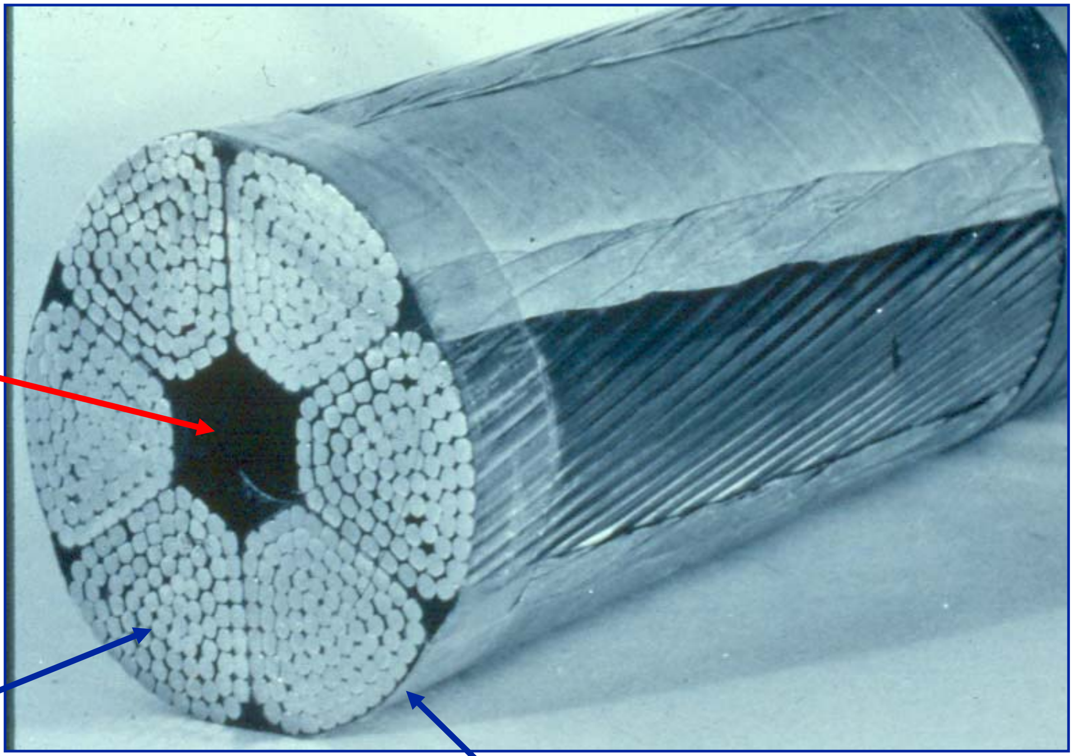


Pre Fabricated Joint

HTSC Cable: Design Solution for Investigation

A 'Dry-Dry', Warm Dielectric cable design

- No LN duct in conductor mandrel
- Possibly eliminate mandrel
- Or use for other purposes



Stranded copper support mandrel and smoothing conductor

HTSC conductor applied onto mandrel

Advantages of ‘Dry-Dry’ DC HTSC Cable Design

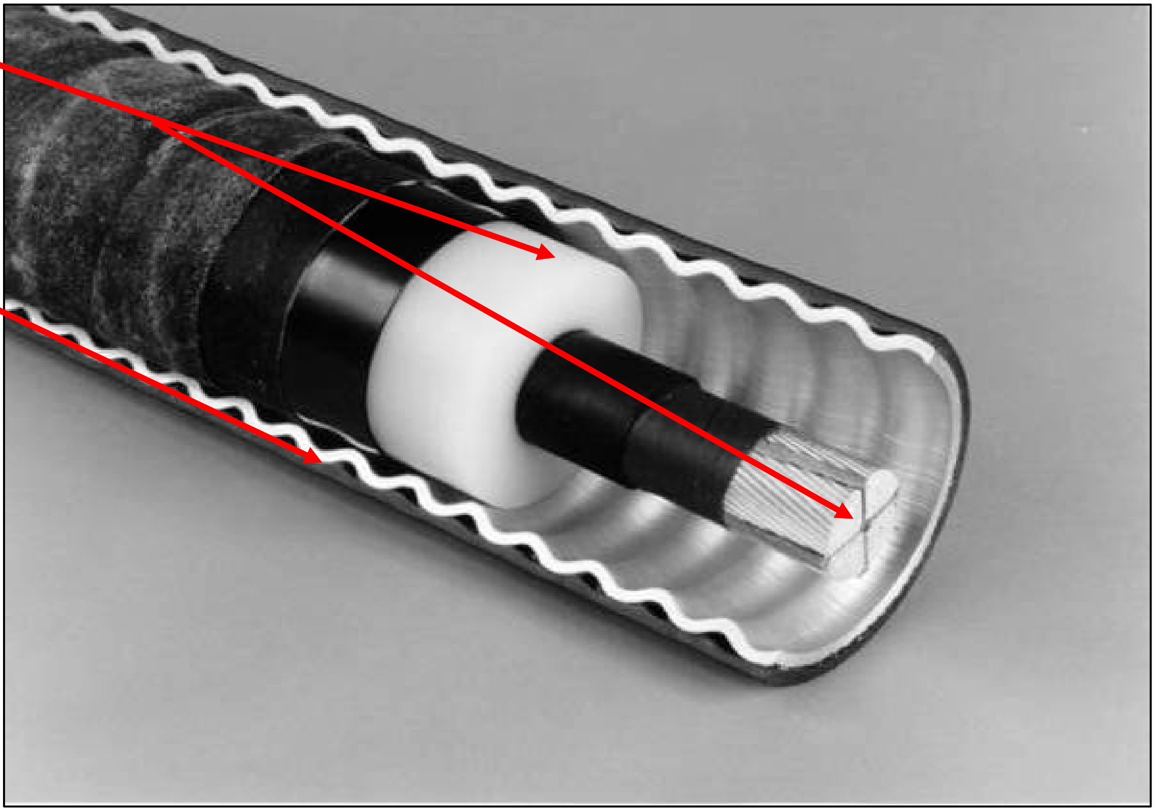
Type	HTSC Terminology	LN Pressure in		Vacuum Cryostat
		Conductor Duct	Cable Sheath	
Dry-Dry	CD	No	No	No
Wet-Dry	WD	Yes	No	Yes
Wet-Wet	CD	Yes	Yes	Yes

CD : cold dielectric

WD : warm dielectric

DC HTSC Cable: Design Solution for Investigation

- Completely 'Dry-Dry' no LN
- No internal LN pressure
- No vacuum filled cryostat

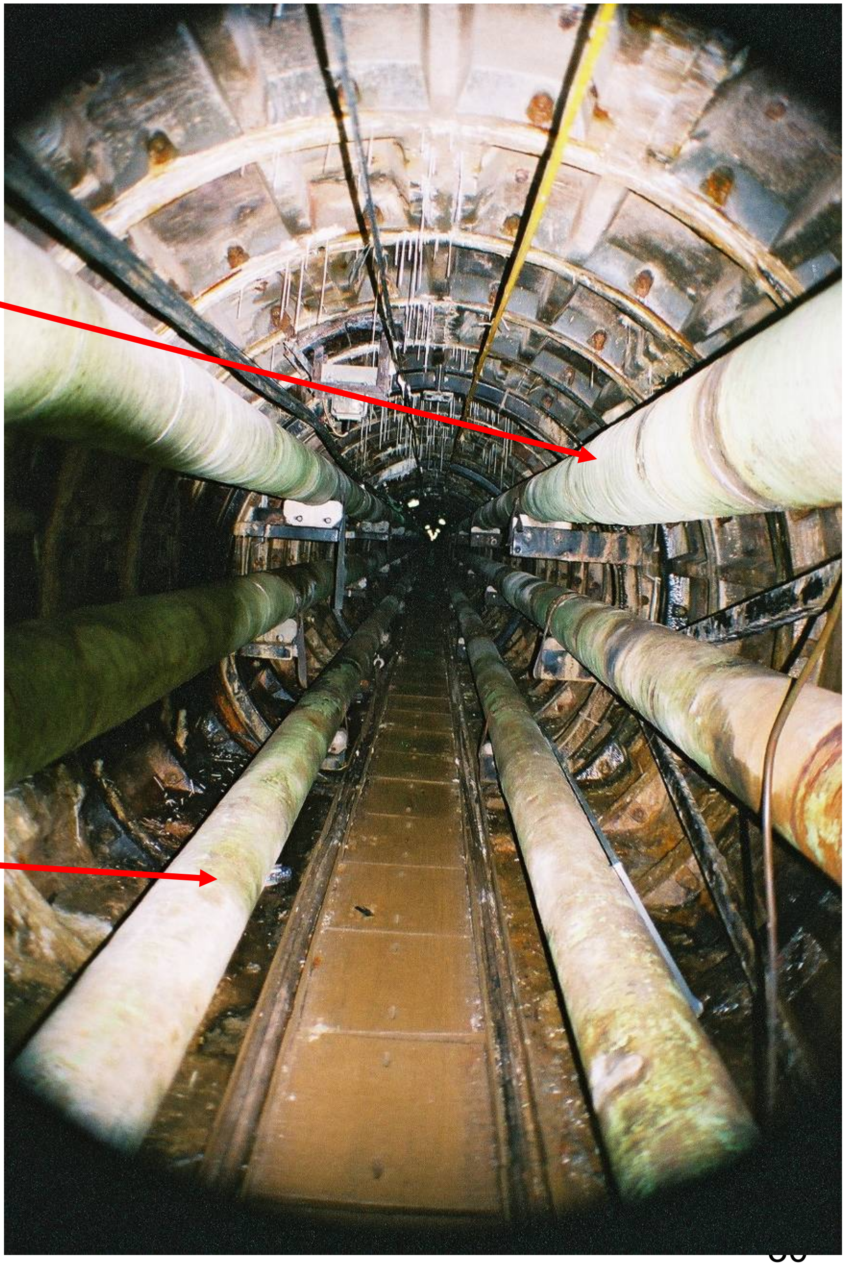


<u>Advantages</u>

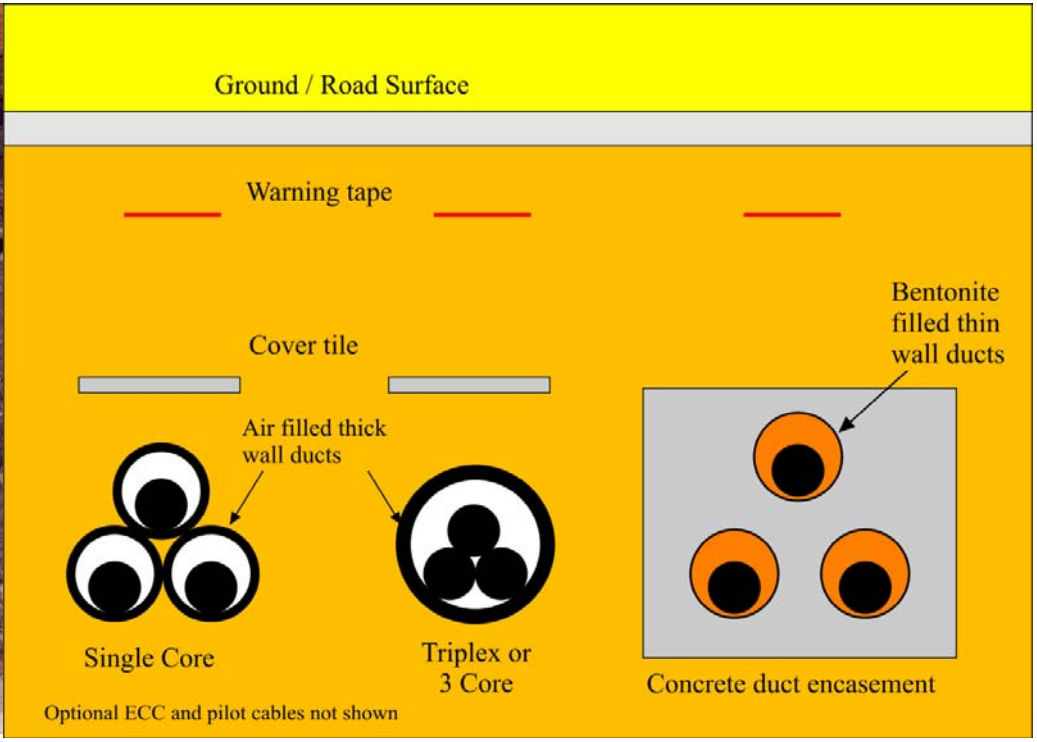
- Cable is self contained
- Simple; close to normal cable construction
- Lowest cost cable
- Lowest system risk
- Smallest cable diameter
- Longer cable on reel
- Fewer joints
- Joints are simpler
- Coolant and electrical systems are separated

DC HTSC Cable in Tunnel: Design Solution for Investigation

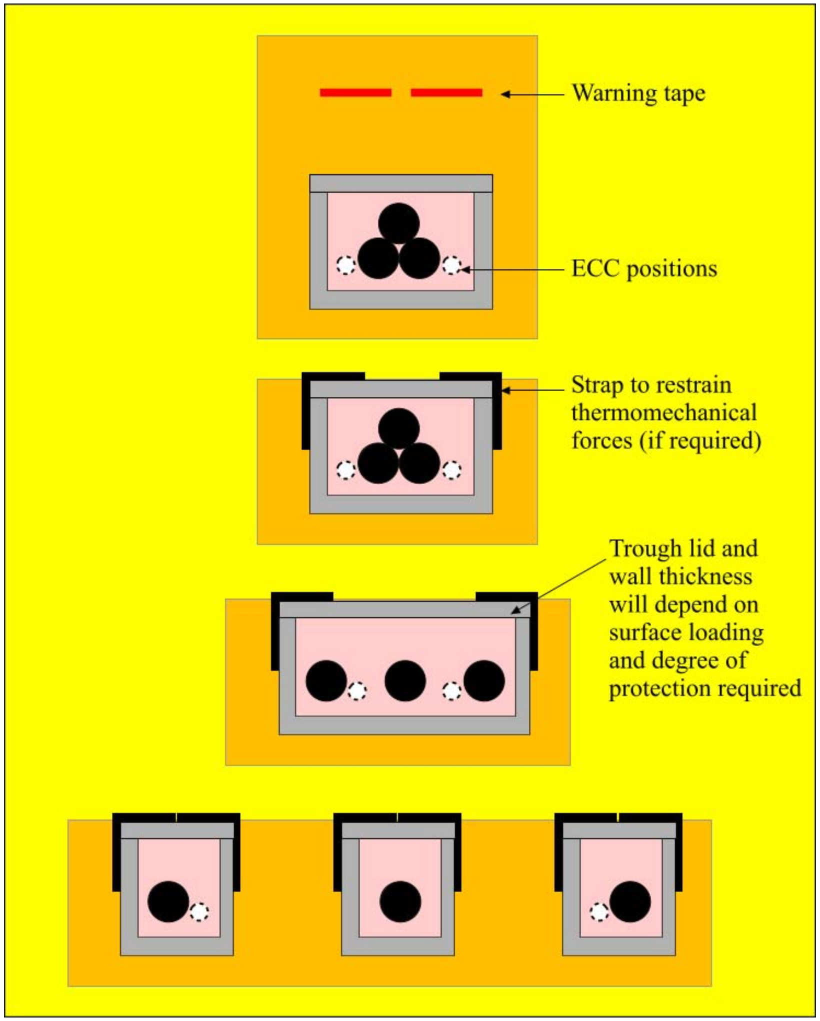
- Pre-assemble LN cryostat pipe, either rigid or flexible
- Pressure test cryo-pipes
- Pull-in the HTSC cable
- Joint cable lengths
- Voltage test the cable in major section lengths
- Close the cryo-pipes
- N_2 gas-up: cool down and LN fill
- LN feed is into cryo-pipes not cable
- Cryo-pipe is accessible for monitoring and re-evacuation through system life
- Cryo-pipes can be re-cabled to:
    - replace section of faulted cable
    - fit DC HTSC cable with a higher Tc when available



DC HTSC Cable Cryostat in Buried Pipes : Design Solution for Investigation

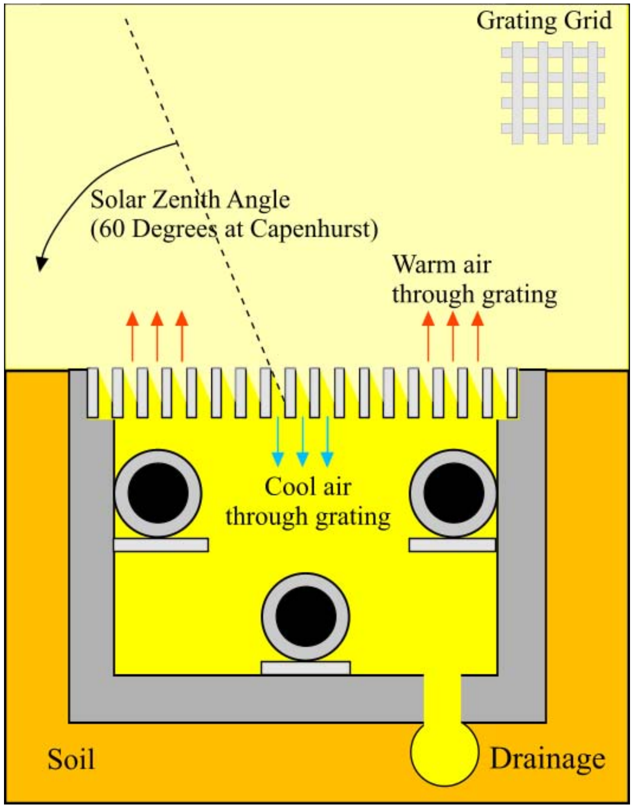


DC HTSC Cable Cryostat Pipes in Surface Troughs : Design Solution for Investigation



500kV Cables in China

DC HTSC Cable Cryostat Pipes in Accessible Cable Chase : Design Solution for Investigation



400kV cables in UK

Summary: DC HTSC Long Length Cable System

Challenges:

- Development is needed of a factory method for 100 % voltage and current testing of cable
- Development of insulation is needed to withstand thermomechanical forces
- Accessory design, assembly and reliability is difficult
- LN pressures and flows are high; imposing limitations on cable and joints

Way forward:

- Maximize cable lengths to minimize joint numbers
- Dry-Dry cable design is small, long length, self-contained and can be voltage tested
- Design and install cable separately from LN cooling and cryogenic system
- Perform design study to optimize the voltage, current, cooling system, cable size and lengths

G

CRYOGENICS AND VACUUM FOR SCDC CABLES – HASSENZAHL

Advanced
Energy
Analysis

Cryogenics and Vacuum Issues for Superconducting DC Cables

For

EPRI DC Line Workshop 10/12-15/2005

By

W. V. Hassenzahl

ASC Outline

- Assumptions
- Heat Sources in a cable
- Example previous EPRI study
- Thermal insulation schemes
- Refrigeration/Refrigerators
- Pressure drop and vacuum issues in a long cable
- The Boiling Curve and liquid characteristics

Advanced
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Analysis

Assumptions

- Cable is DC superconducting (or cryoresistive)
  - Temperature is below 77 K
  - Current level is above 50 kA
  - Cable is at least 100 kilometers long*
    - Will include some comments and references to short AC cables

* This will be a later discussion topic?

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Analysis

Heat Sources in a cable

- Terminations—Power Leads
  - Loss depends on Current level.
- Penetrations—intermediate power points (later)
- Cryogen entry and exit areas (later)
- Radiation
- Convection in low pressure (vacuum) enclosure
- Conduction through supports/constraints
- Cryogen frictional flow losses (pressure drop)

Terminations

- The region where current enters the cold environment must be made of a normal electrical conductor. (Typically copper)
  - Good electrical conductors also conduct heat well
- Nevertheless these materials are resistive and generated heat.
- It is possible to optimize the termination to accommodate operating conditions
  - Average current as a fraction of nameplate

Terminations

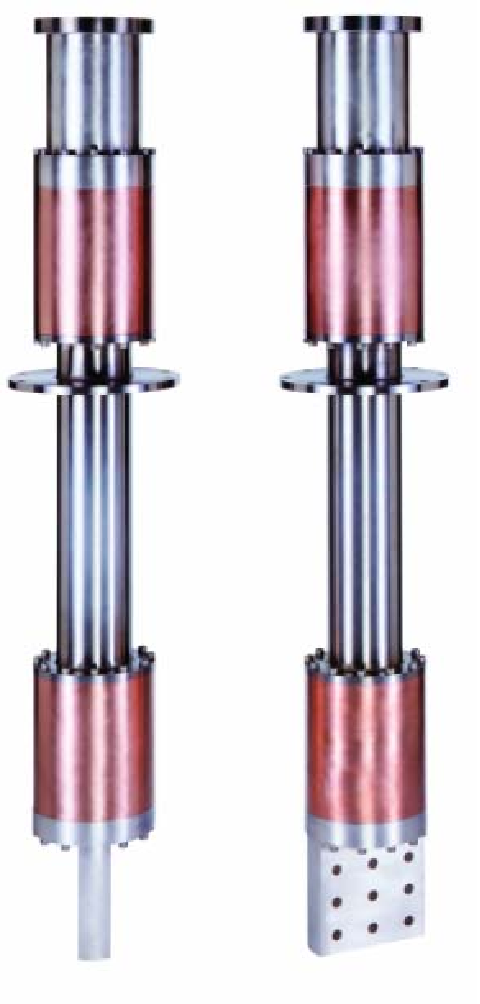
- Heat flow from 300 K to 77 K is about 50 W per lead per 1000 amperes

$$W = [L_0(T_2^2 - T_1^2)]^{1/2} \cdot I \qquad L_0 = 2.45\text{x}10^{-8}\ \text{W}\ \Omega\ \text{K}^{-2}$$

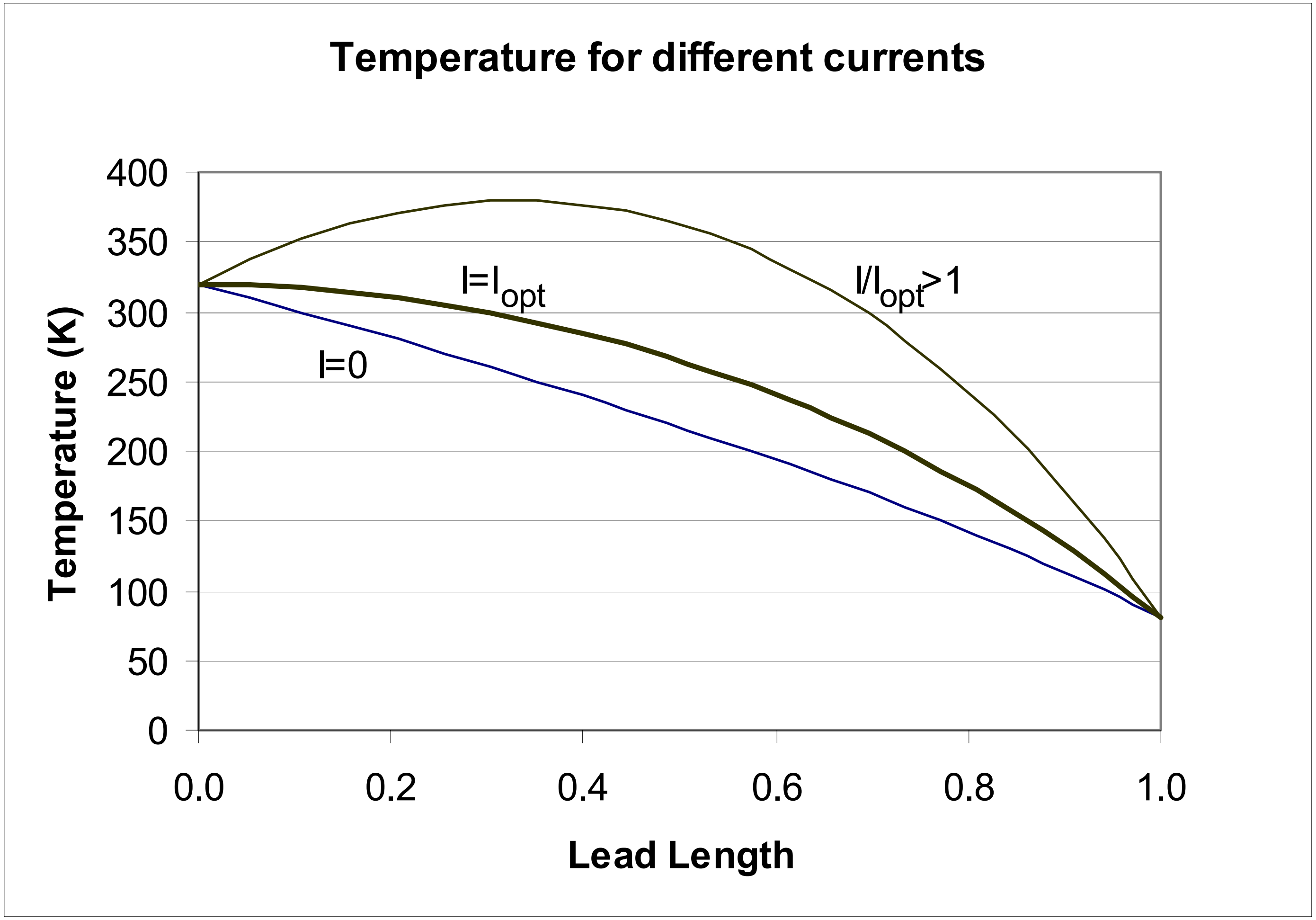
  - Even good electrical conductors are resistive and generate heat.
  - Electrical conductors also conduct heat.
- It is possible to optimize the leads to accommodate operating conditions
  - Specifically the average operating current as a fraction of nameplate

Lead Characteristics

- Total heat into cryogenic environment is independent of:
  - Normal conductor used
  - Length of lead
  - Diameter of lead
  - Lead length and lead diameter are related
- Low conductivity materials (e.g., brass) provide thermal inertia and thus a bit of safety.



Lead Heat Flow



Vapor Cooled Leads

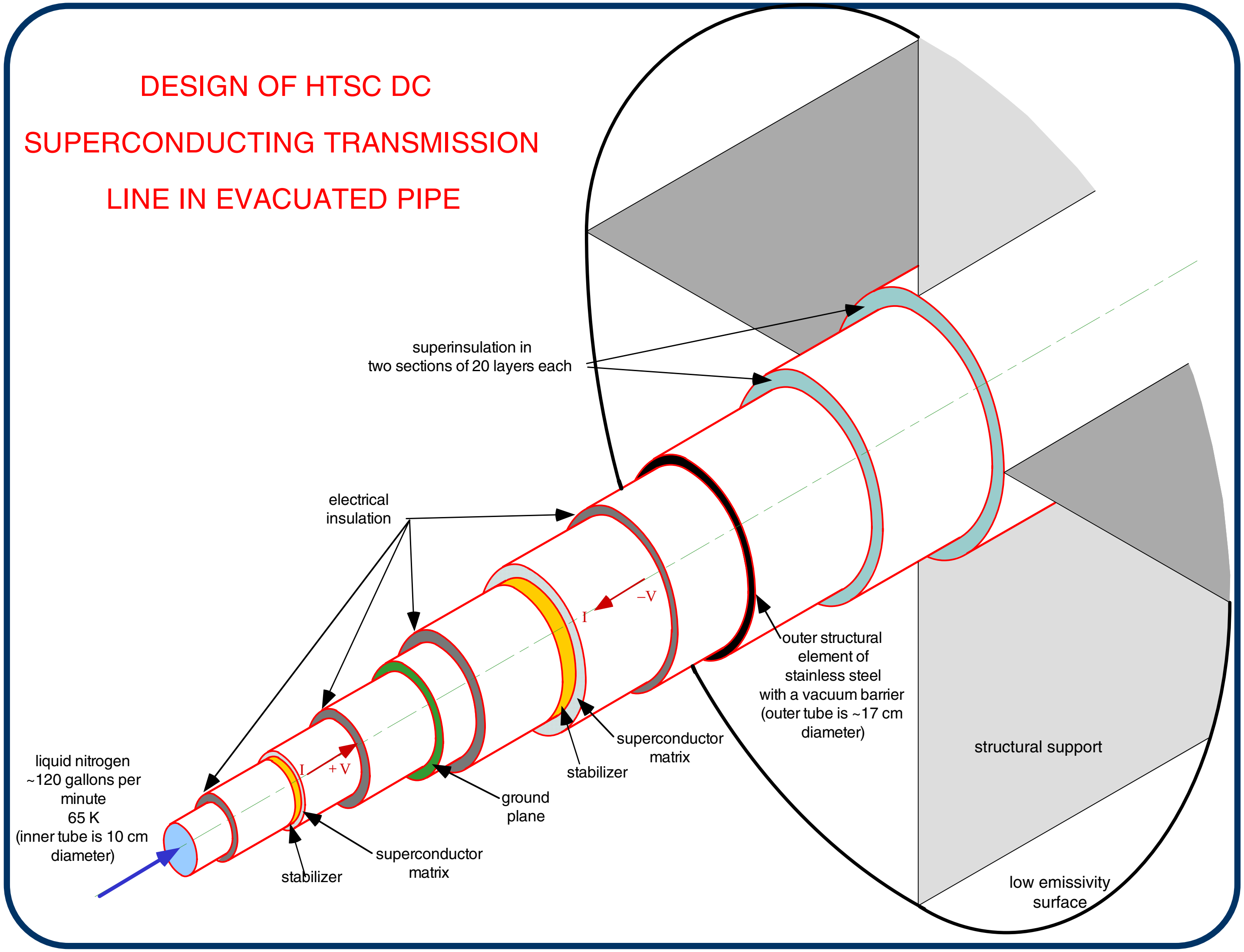
- The above discussion needs to be refined if the leads are to have cold gas cooling.
  - Vapor-cooled leads may or may not be appropriate for DC Cables.
  - Systems with sufficient heat input other than from the leads can use boiloff gas to absorb some of the heat in the lead. Gas generally flows within the lead-requires plumbing.
  - Access to cryogens may impact lead reliability.
  - Voltage may be an issue at top or bottom of lead-requires voltage insulation in piping.

DC Cable Example

DESIGN OF HTSC DC

SUPERCONDUCTING TRANSMISSION

LINE IN EVACUATED PIPE



Radiation

- Simple physical law for radiation Stefan/ Boltzman equation
  - $W=\sigma\varepsilon A\ (T^4_{ambient}-T^4_{cond})$
  - Emissivity affected by surface preparation $0<\varepsilon<1$
  - $\sigma=5.67x10^{-12}Wcm^{-2}K^{-1}$
  - A is the effective area and depends on geometry
  - If ε is 0.3 the radiation is about 40 W/m
  - Even at 0.03 the load is 4 W/m
- Bad news

Radiation

- Superinsulation in the form of multiple layers of aluminized mylar insulation (MLI) can be used to further reduce the radiation heat load.
  - Heat in flux is inversely proportional to the number of layers.
  - If the acceptable limit is 0.1 W/m, then need 40 layers.
  - Typical bats of this type of insulation are 20 layers thick and usually two are needed.

Thermal Conduction

- Gravity supports and positioning spacers between the ambient shell and the cryogenic components conduct heat.
  - Simple conduction process
  - Complications
    - Thermal conductivity varies with temperature
    - Dimensions/loads change with temperature

- Sho

Convection

- Gaseous convection via residual gas (it isn't a perfect vacuum) carries heat to the cryogenic components.
  - Two regimes of convection (Conceptually)
    - At low pressures the molecules travel directly from the ambient wall to the cold wall without intermediate collisions. Heat flow is proportional to pressure.
    - At higher pressures there are intermediate collisions between molecules. Heat flow is less than proportional to pressure.
  - Analyzing convection in the presence of superinsulation is "impossible". Revert to empirical procedures.

Vacuum

- First we need some definitions
  - Start with 1 atmosphere (1 atm.)
  - 760 mm mercury = 1 atm.
  - 760 torr = 1 atm.
  - 10^{-3} torr = 1 micron of mercury

Advanced
Energy
Analysis

Vacuum

- Experiments indicate that at about 10^{-4} torr the combined convection and radiation heat leak is about 0.75 W/m^2. (This is the cold surface area.)
- Improving the vacuum to 10^{-5} torr would reduce the heat load to about 0.5 W/m^2. Not worth the trouble.
- Achieving 10^{-4} torr for the DC cable is non trivial.
  - Gas gets trapped in the superinsulation and diffusion is slow
  - Not all vacuum pumps are effective at this pressure.
  - Pressure depends on the nearness of the pump
  - Some “getters” are available for local vacuum maintenance.

Vacuum

- A likely scenario is to have external vacuum pumps separated by a km or so and to have local Non Evaporable Getters (NEGs) distributed at short intervals.
- The vacuum can severely degrade at long distances from a vacuum pump.
  - The amount of degradation depends on the areas and length of the flow paths to the pump, the temperature, and the molecular weight of the gas to be removed.
  - This is expressed via a “conductance” parameter.

$C \propto \left(\frac{T}{M}\right)^{1/2} \cdot \frac{D^3}{L}$

$$C \propto \left(\frac{T}{M}\right)^{1/2} \cdot \frac{D^3}{L}$$

Vacuum

- Each vacuum pump is defined by a pumping speed S.
- Each section of the path to the vacuum pump has a conductance C.
- Both of these quantities have the same dimensions (liters/second)
- One can then calculate the effective pumping speed at any location away from the pump.
- S_{eff} must be adequate to maintain the desired vacuum.

$$\frac{1}{S_{\text{eff}}} = \frac{1}{S} + \frac{1}{C_1} + \frac{1}{C_2} \cdots$$

Conduction

- This is not a significant source of heat into the Cable!

Frictional heating loss

- As the cryogen is pumped along the length of the cable.
  - Friction with the walls heats the fluid.
  - Friction causes a pressure drop.
- The smaller the mass flow the less frictional heating.
- However, there is less mass to absorb the heat from the other sources. Thus:
  - There is a trade off among a variety of parameters
    - Mass flow.
    - Cryogen temperature.
    - Temperature increase between refrigeration stations.
    - Pressure drop.

Total heat input

Heat Source	Heat Input (W_t/m)
Radiation and Gaseous Convection	0.50
Support Conduction	0.05
Viscous heating (pumping loss)	0.20
Miscellaneous, including leads	0.20
ac losses	0.05
Total	**1.00**

Refrigeration

- Cables are power (cold) hogs and have refrigeration loads higher than for other SC technologies.
  - DC vs. AC
    - Dc's high current means large heat input at the terminations
    - DC implies no AC losses
- Several types of cryogenic refrigerator are possible for cables.
  - The type of refrigerator is not the issue
  - The refrigerator characteristics of importance are
    - Room temperature power (Read that as Efficiency)
    - Reliability/Availability
    - Cost
    - Physical dimensions

Refrigeration

- Refrigeration systems require energy to transfer heat from a low temperature to a high temperature.
- There is an ideal thermodynamic limit for the process, the Carnot limit.
- All refrigerators require some additional energy due to various inefficiencies.
- Two quantities are used to describe the relation between the cooling capacity and the room temperature power.
  - “Coefficient Of Performance” (COP).
  - Specific Power (SP).

Refrigeration

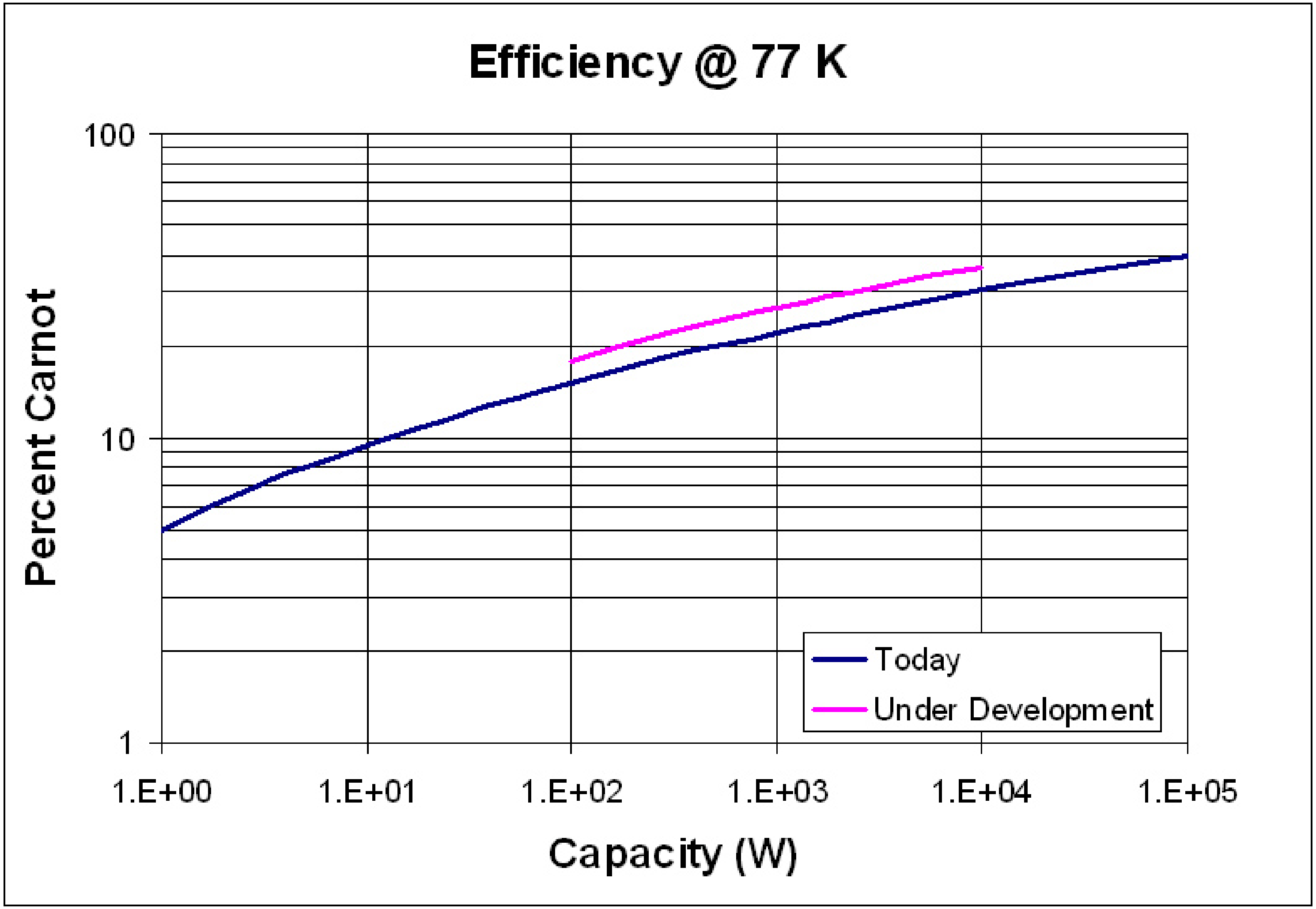
$$\dot{Q}_{Cold} = P_{External} \cdot COP = \frac{P_{External}}{SP}$$

$$COP_{Carnot} = \frac{T_{Cold}}{T_{External} - T_{Cold}}$$

$$\eta_{Ref} = \frac{COP}{COP_{Carnot}}$$

- Refrigerators can be best compared on the basis of the items listed two slides back
- There is a clear trade off between cost and efficiency

Refrigeration



Advanced Energy Analysis

Cost Goals for SC Cryogenics

Capital Costs	**GOAL**	**Current Status**
•30K	~$100/cold watt	~$300/cold watt
•50-60K	~$ 70/cold watt	~$150/cold watt
•70-77K	~$ 20-40/cold watt	~$100-$240/cold watt
Operating Input Power		
•30K	45-60 W input /cold W (15-20% Carnot)	70 W/cold W (12% Carnot)
•50-60K	17-23 W input /cold W (20-25% Carnot)	35 W/cold W (13% Carnot)
•70-77K	20 W input /cold W (17.5-30% Carnot)	26 W/cold W (10-25% Carnot)

H

CURRENT LIMITING IN THE SUPERGRID – DAMSKY

The Role of Current Limiting In the SuperGrid

Ben Damsky

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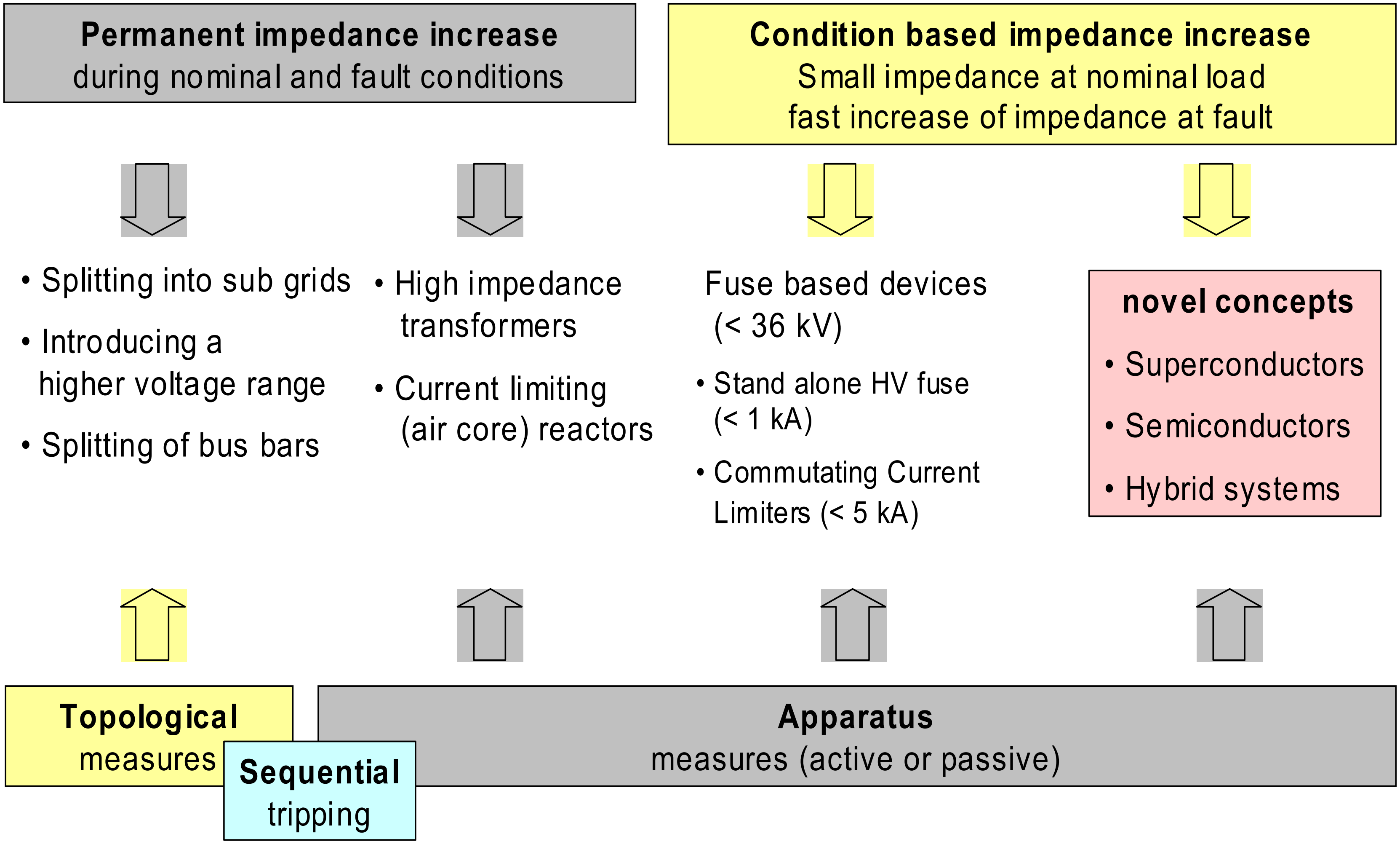
Palo Alto

October 13, 2005

Why Use Current Limiting for the SuperGrid

- Reduction of the short-circuit forces on cables designed for low thermal conductivity.
- Reduction of cable heating from a fault and subsequent thermal recovery time.

Fault Current Limiting Methodologies



Permanent impedance increase
during nominal and fault conditions

Condition based impedance increase
Small impedance at nominal load
fast increase of impedance at fault

- Splitting into sub grids
- Introducing a higher voltage range
- Splitting of bus bars

- High impedance transformers
- Current limiting (air core) reactors

Fuse based devices (< 36 kV)

- Stand alone HV fuse (< 1 kA)
- Commutating Current Limiters (< 5 kA)

novel concepts

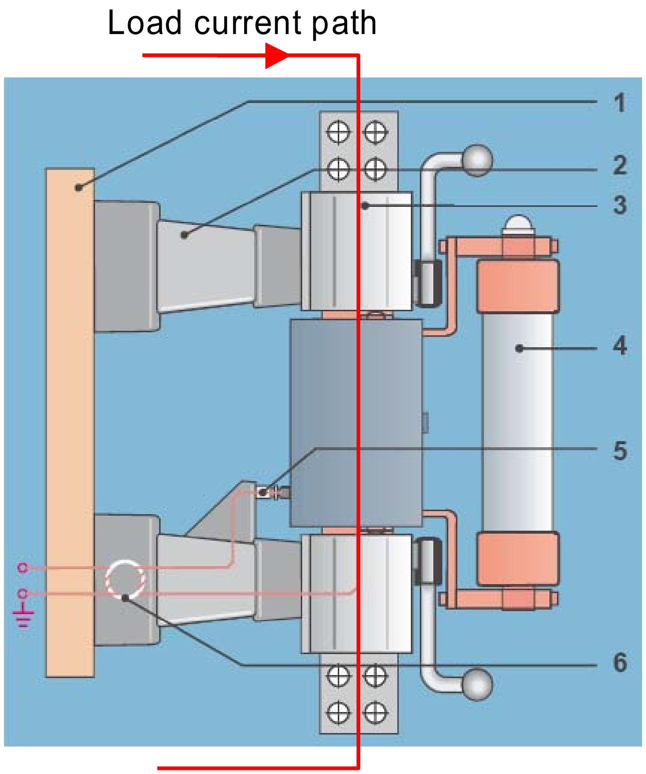
- Superconductors
- Semiconductors
- Hybrid systems

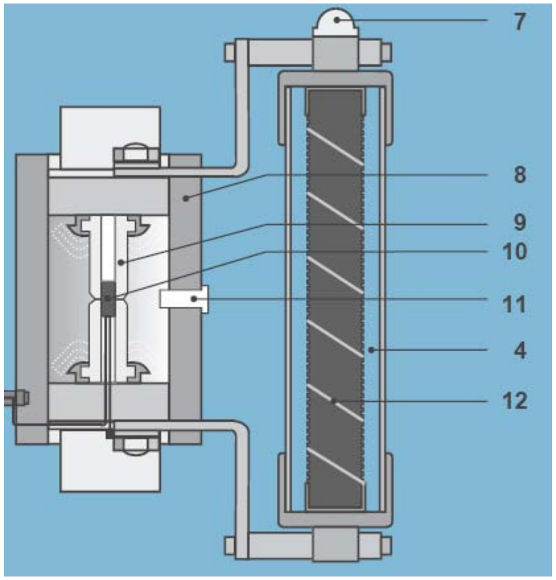
Topological
measures

Sequential
tripping

Apparatus
measures (active or passive)

Explosive Fuses Provide Higher Current Ratings





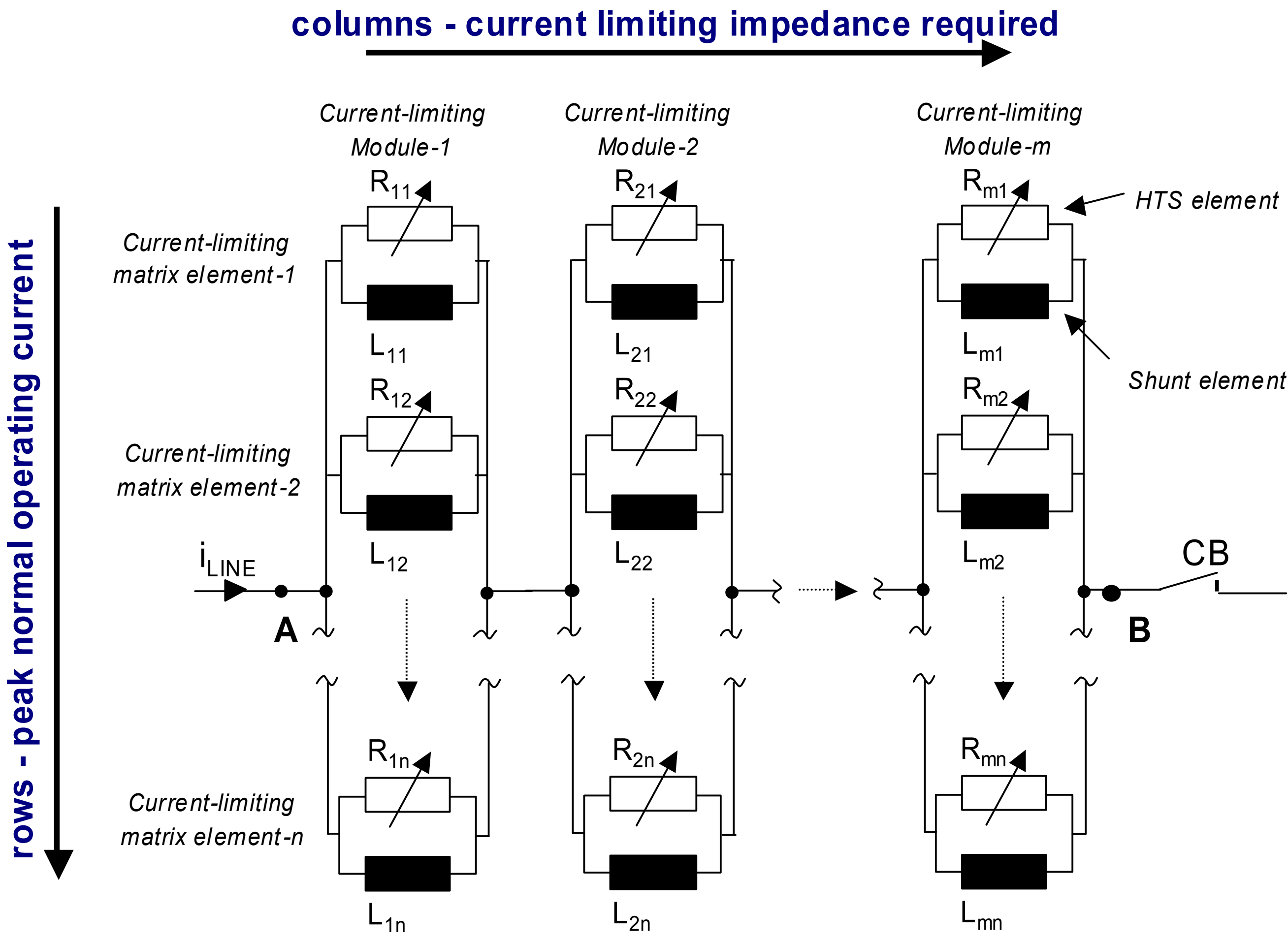
I_S-limiter insert holder with insert for 12 kV, 2000 A

1 Base plate
2 Insulator
3 Pole head with clamping device
4 Fuse
5 Telescopic contact
6 Insulator with pulse transformer

I_S-limiter insert

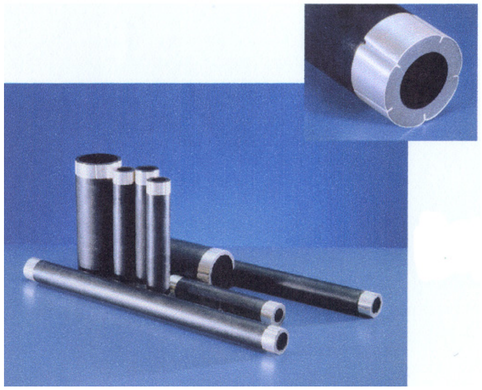
4 Fuse
7 Fuse indicator
8 Insulating tube
9 Bursting bridge
10 Charge
11 Main conductor indicator
12 Fuse element

Matrix Fault Current Limiter

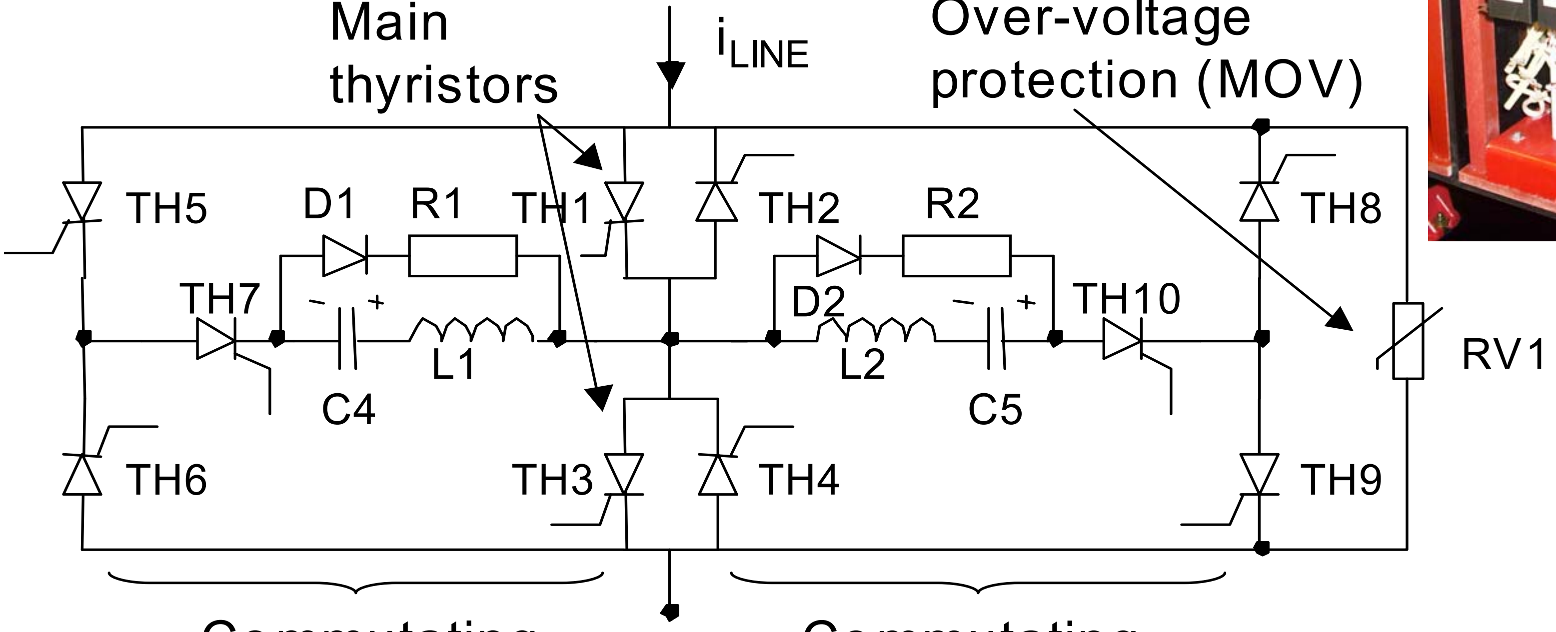


columns - current limiting impedance required

rows - peak normal operating current



Schematic of SSCL module using ultra fast electronics



Main thyristors

Over-voltage protection (MOV)

Commutating circuit

Commutating circuit

Pre-Prototype MFCL

Bushings

Valves, connections for Liquid Nitrogen Fill

Cryocooler

Cryostat

Photo: SuperPower

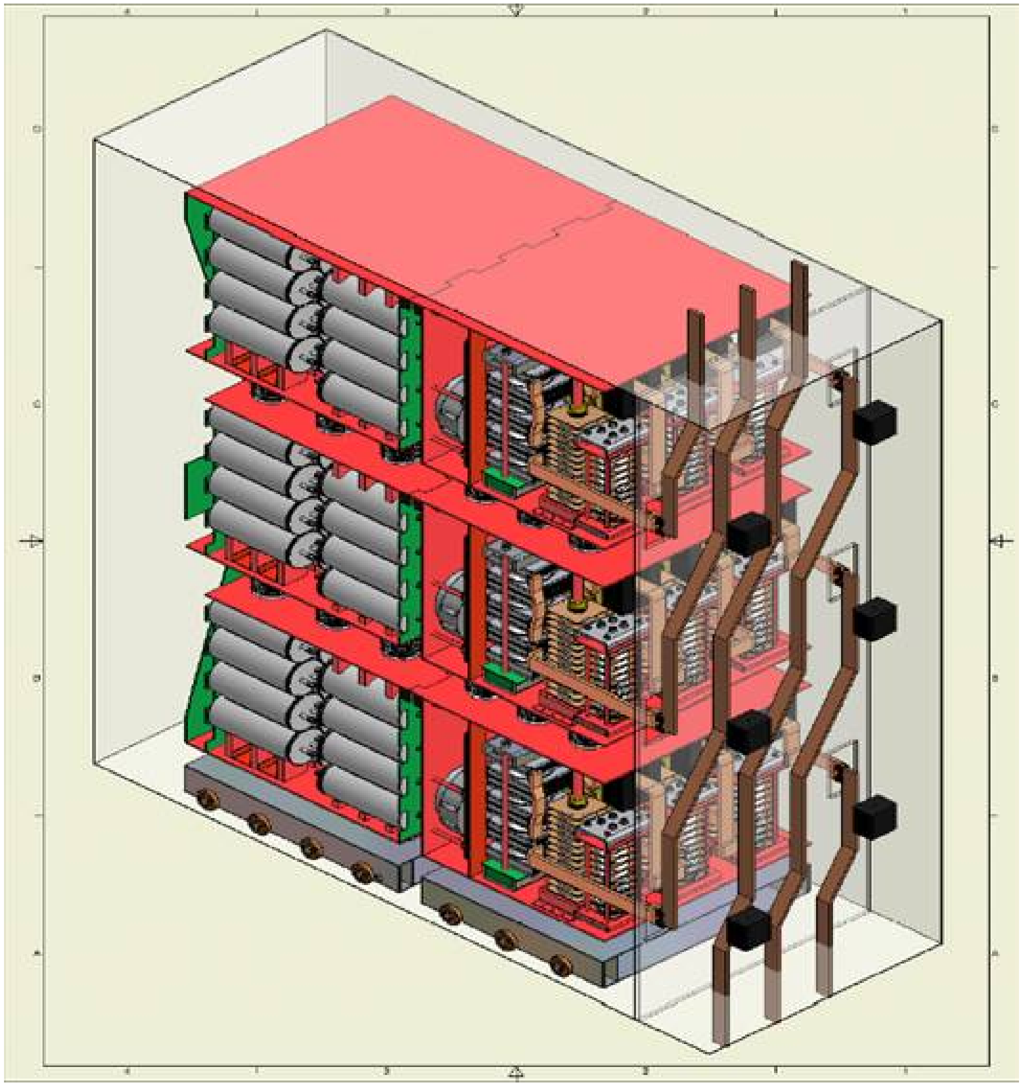
Single-Phase Unit for Non-grid R&D Testing

Requirement	Value
Line-to-line voltage	15kV
Line-to ground voltage	8.66kV
Load Current	800Arms
Prospective Fault Current (Asymmetrical)	25kA
Fault Duration	3 cycles
Cryostat Temperature	74K to 77K

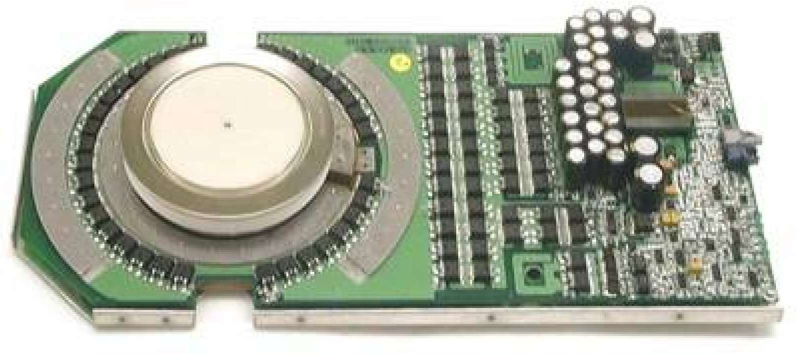
Medium Voltage

SSCL

Medium Voltage SSCL, uses two carts



69 kV SSCL, DOE Funding



New phase of work

Move to turn-off device

Eliminate the need for the commutation capacitor

ETO device is strong candidate

ETO is based on GTO

6 inch GTO now available with 6 kA rating

Special aspects of the SuperGrid

For a DC system, insertion of inductance is not as good as resistance

DC system controls can turn off the fault current; the question is how fast this can be done

Expect Supergrid cable ratings will be in the range of 10 to 20 kA continuous

Comparison of Overall Systems

Explosive fuse:

Has a control system; aging of components is a potential issue

SCCL:

Simple in operation and control is passive

Has a “Fail-Safe” design

SSCL:

Many parts and an elaborate control system

Allows flexibility and added functions, but has more opportunities for failure

Comments on System Availability

Explosive fuse:

Should have high availability

SCCL:

Should have high availability if cryo cooling system of the cable is used

SSCL:

DC converters and FACTS devices only achieve 96% availability

Air cooling and conservative ratings should improve this number

Comparison of Systems: Repeated Operations

Explosive Fuse:

Simple design requires manual exchange of cartridge. Gatling gun design is possible.

SFCL:

Simple design requires a long thermal recovery. This will not be acceptable for 1000 MW systems.

SSCL:

Readily repeats if components sized properly

Comparison of Cooling Aspect

Explosive fuse:

Cooling not used today; adding cooling could improve current rating

SFCL:

Requires cryogenic cooling with cost and reliability issues, but this can be provided by the cable cooling system

Recovery time is an issue

SSCL:

Uses a simple fan: low cost and power and easy to include redundancy

Recovery time set by capacitor recharging – a few seconds

Comparison of Systems: Current Capacity

Explosive Fuse:

Currents higher than 1 kA are a problem

SMFCL:

Matrix concept allows flexibility in current and voltage

SSCL:

New 6 inch devices should allow 3 kA, higher ratings impossible until bigger devices available

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