The Large Hadron Collider

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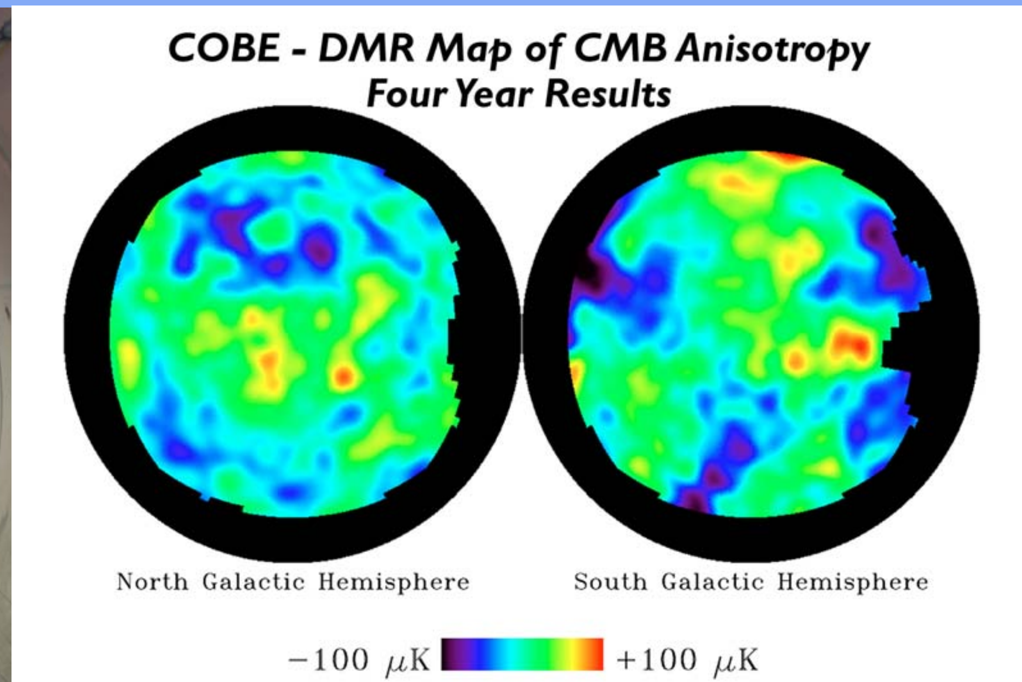
CERN



T

1.9 K

2.728 K

The coldest ring in the universe!

The Large Hadron Collider

This lecture.

LHC Technologies

- Magnets
- Cryogenics
- Radiofrequency
- Vacuum

Tomorrow.

LHC Accelerator Physics

- Intrabeam scattering
- Beam-beam interaction
- Coherent effects
- Electron cloud

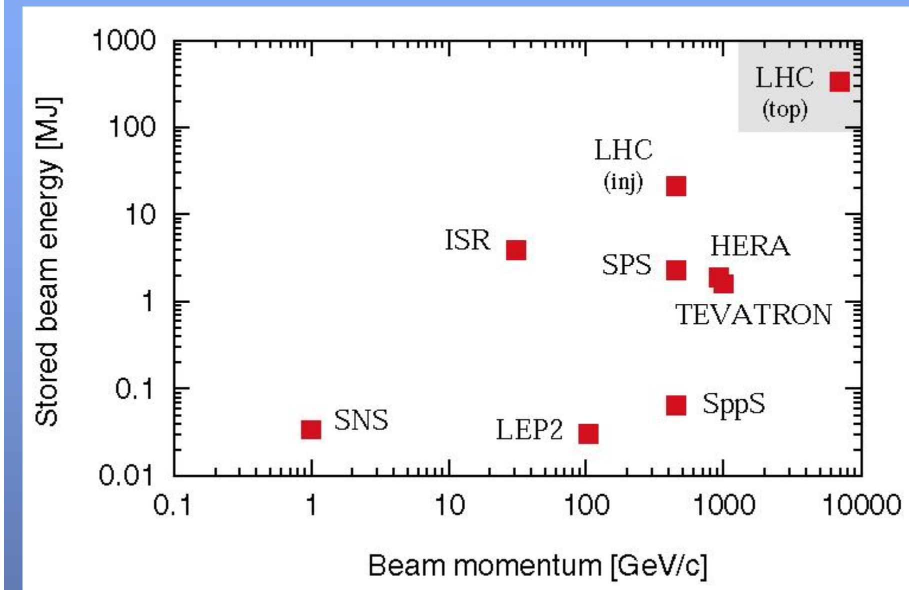
Introduction

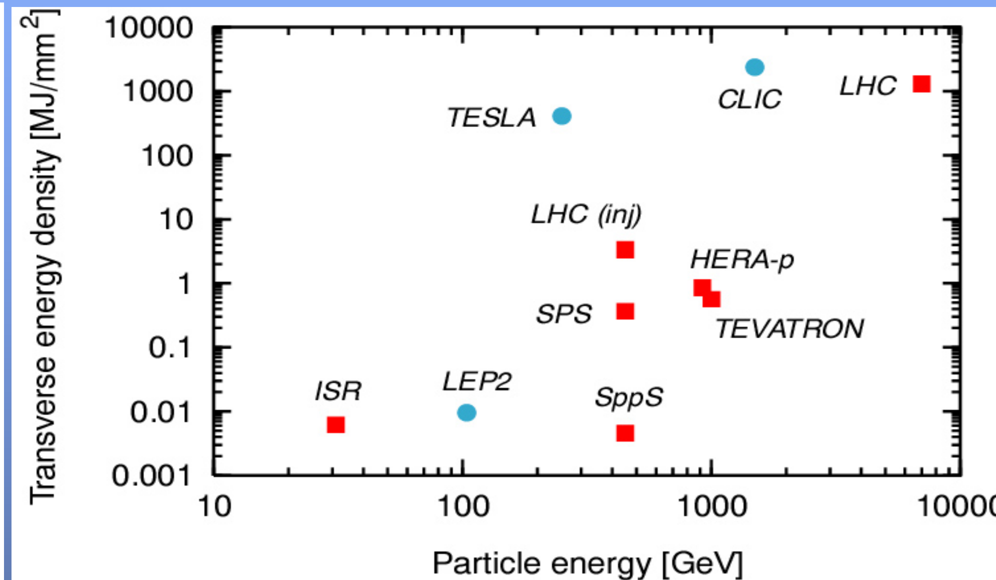
The Large Hadron Collider (LHC) at CERN is now in its final installation and commissioning phase. It is a two-ring superconducting proton-proton collider housed in the 27 km tunnel previously constructed for the Large Electron Positron collider (LEP). It is designed to provide proton-proton collisions with unprecedented luminosity (1034cm-2.s-1) and a centre-of-mass energy of 14 TeV for the study of rare events such as the production of the Higgs particle if it exists. In order to reach the required energy in the existing tunnel, the dipoles must operate at 1.9 K in superfluid helium. In addition to p-p operation, the LHC will be able to collide heavy nuclei (Pb-Pb) with a centre-of-mass energy of 1150 TeV (2.76 TeV/u and 7 TeV per charge). By modifying the existing obsolete antiproton ring (LEAR) into an ion accumulator (LEIR) in which electron cooling is applied, the luminosity can reach 1027cm-2.s-1.

Main parameters of LHC (p-p)

• Circumference	26.7	km
• Beam energy at collision	7	TeV
• Beam energy at injection	0.45	TeV
• Dipole field at 7 TeV	8.33	T
• Luminosity	10^{34}	$cm^{-2}.s^{-1}$
• Beam current	0.56	A
• Protons per bunch	$1.1x10^{11}$	
• Number of bunches	2808	
• Nominal bunch spacing	24.95	ns
• Normalized emittance	3.75	μm
• Total crossing angle	300	μrad
• Energy loss per turn	6.7	keV
• Critical synchrotron energy	44.1	eV
• Radiated power per beam	3.8	kW
• Stored energy per beam	350	MJ
• Stored energy in magnets	11	GJ
• Operating temperature	1.9	K

Beam momentum & stored energy of colliders

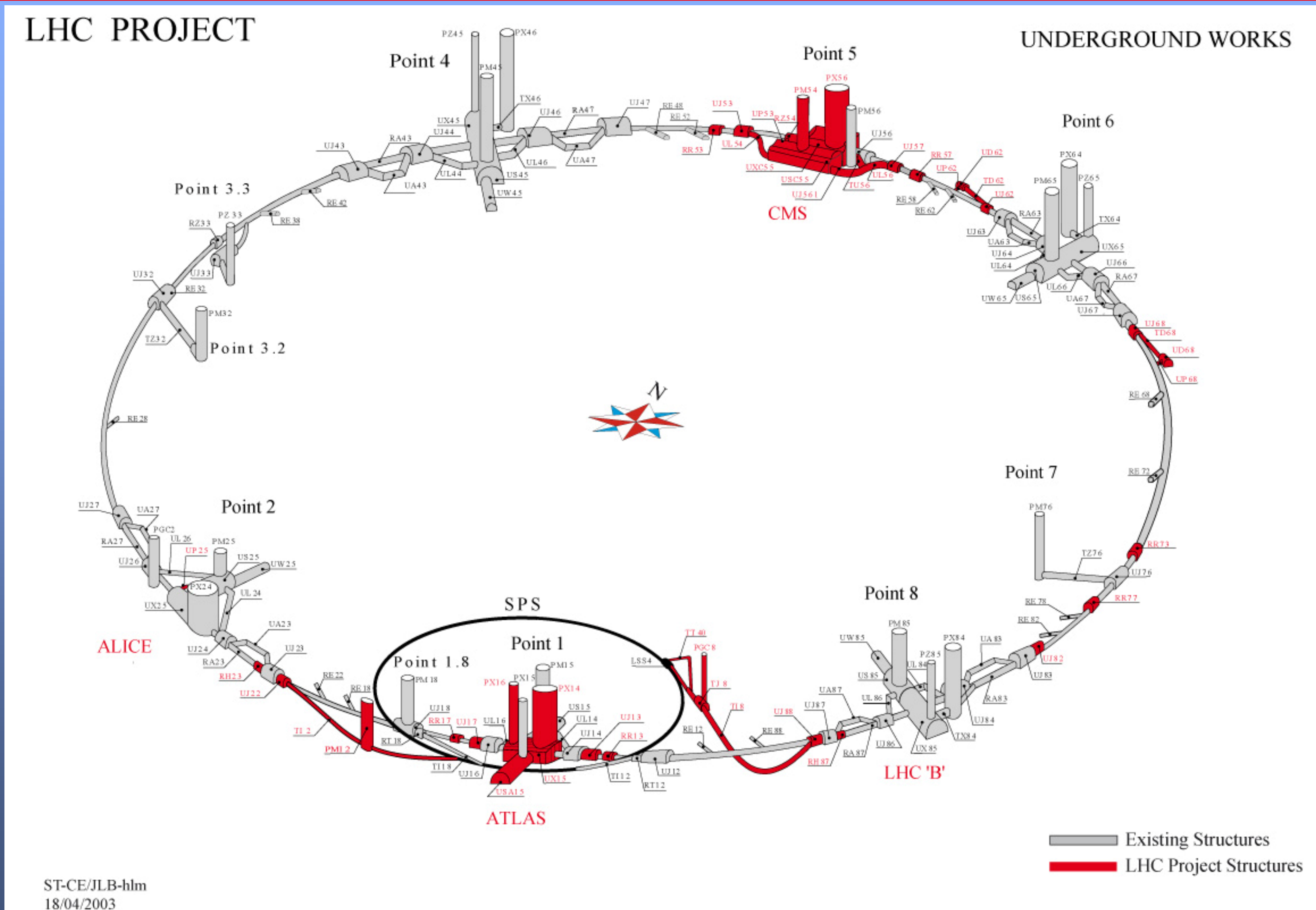




Energy stored in the accelerator beam, as a function of beam momentum. At less than 1% of nominal intensity LHC enters new territory.

Stored energy density as a function of beam momentum. Transverse energy density is a measure of damage potential and is proportional to luminosity.

Schematic layout of the LHC



Lattice Layout

The regular LHC lattice was designed to maximize the amount of bending power in the arc by making the dipoles as long as reasonably possible. This minimizes the amount of dead space between interconnects as well as the number of dipoles to be manufactured, tested and interconnected. After careful optimization, the dipole length was chosen to be 14.2 m (magnetic), 15 m overall with 23 regular lattice periods per arc. Each period is 106.9 m long and is made up of six dipoles and two short straight sections each of 6.6 m length containing the main quadrupoles and lattice correctors. The two apertures of ring 1 and ring 2 are separated by 194 mm. Both dipole apertures are connected in series whereas the quadrupoles are powered in two families, all focusing quadrupoles of rings one and two in series and likewise for the defocusing quadrupoles.

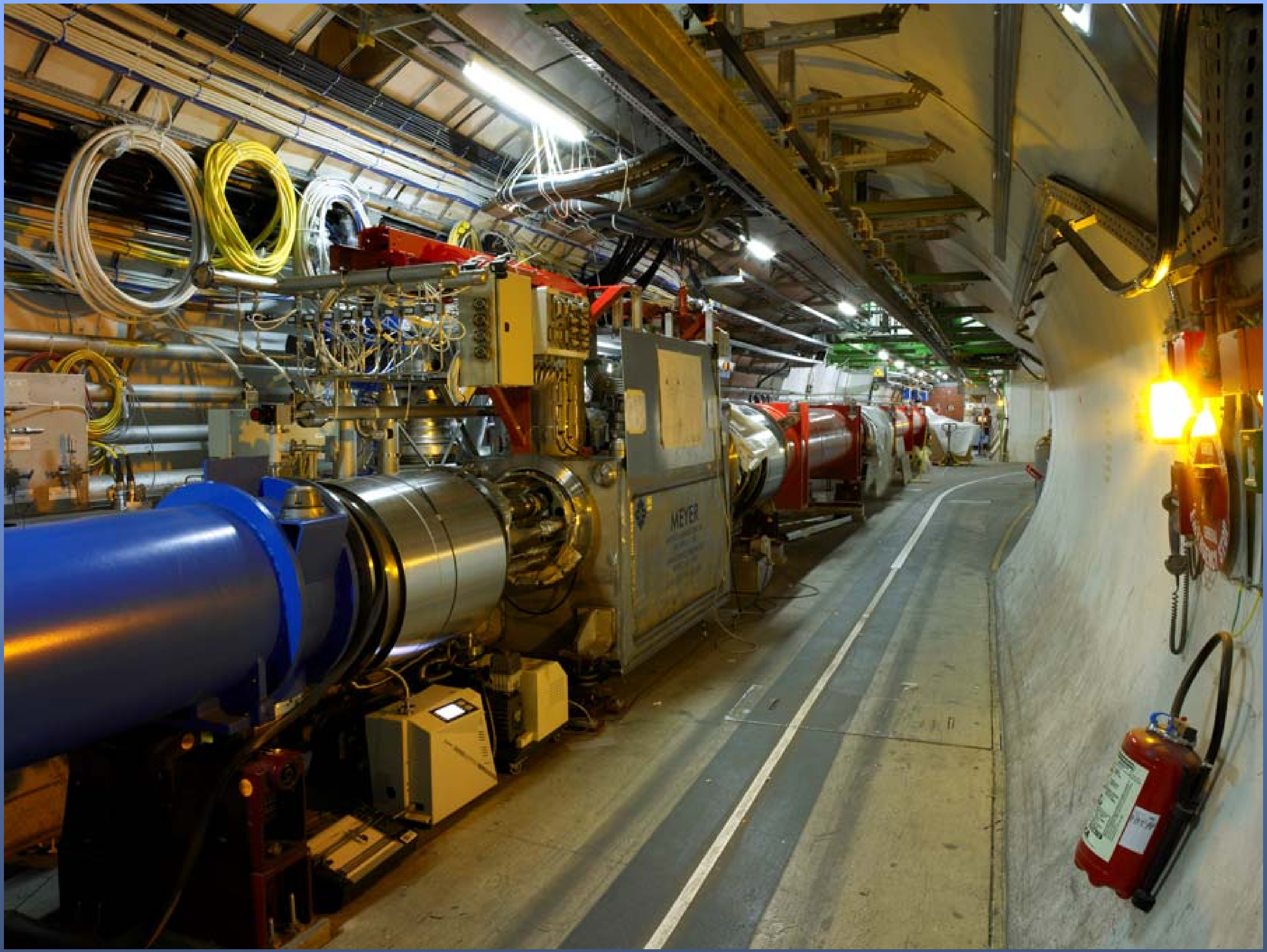
The transition from the regular arc contains a dispersion suppressor consisting of two perturbed lattice periods. The purpose of the dispersion suppressor is threefold:

- adapt the LHC reference orbit to the geometry of the tunnel,
- cancel the horizontal dispersion generated in the arc and by the separation and recombination dipoles,
- help with the matching of the beams between the arcs and straight sections.

Lattice Layout

- A generic design of a dispersion suppressor can be made using standard arc cells with missing dipoles and dipoles of different length to those in the arc. However, due to the constraints imposed by the geometry of the existing tunnel and the economy of having only one standard dipole length, the dispersion can only be fully cancelled by individual powering of the quadrupoles in the dispersion suppressor cells. These quadrupoles also provide additional parameters for matching the insertion optics.
- The short straight sections in the arcs contain the main quadrupoles and also the correction sextupoles for chromaticity control and the orbit correction dipoles. Depending on their location, they can also contain trim normal or skew quadrupoles or Landau damping octupoles.
- The optics of the long straight sections differ according to their functionality. At Points 1 and 5 in the high luminosity insertions the small beta (0.5 m) at the collision point is generated with the help of a quadrupole triplet assembly. At points 2 and 8, the optics at the 450 GeV injection level must allow beam injection whereas at top field the beams must be focused to a moderate beta. At the utility insertions the optics is tailored to their functionality. Details of the optics in the various insertions can be found elsewhere*.

*LHC Design Report, CERN-2004-03. (2004)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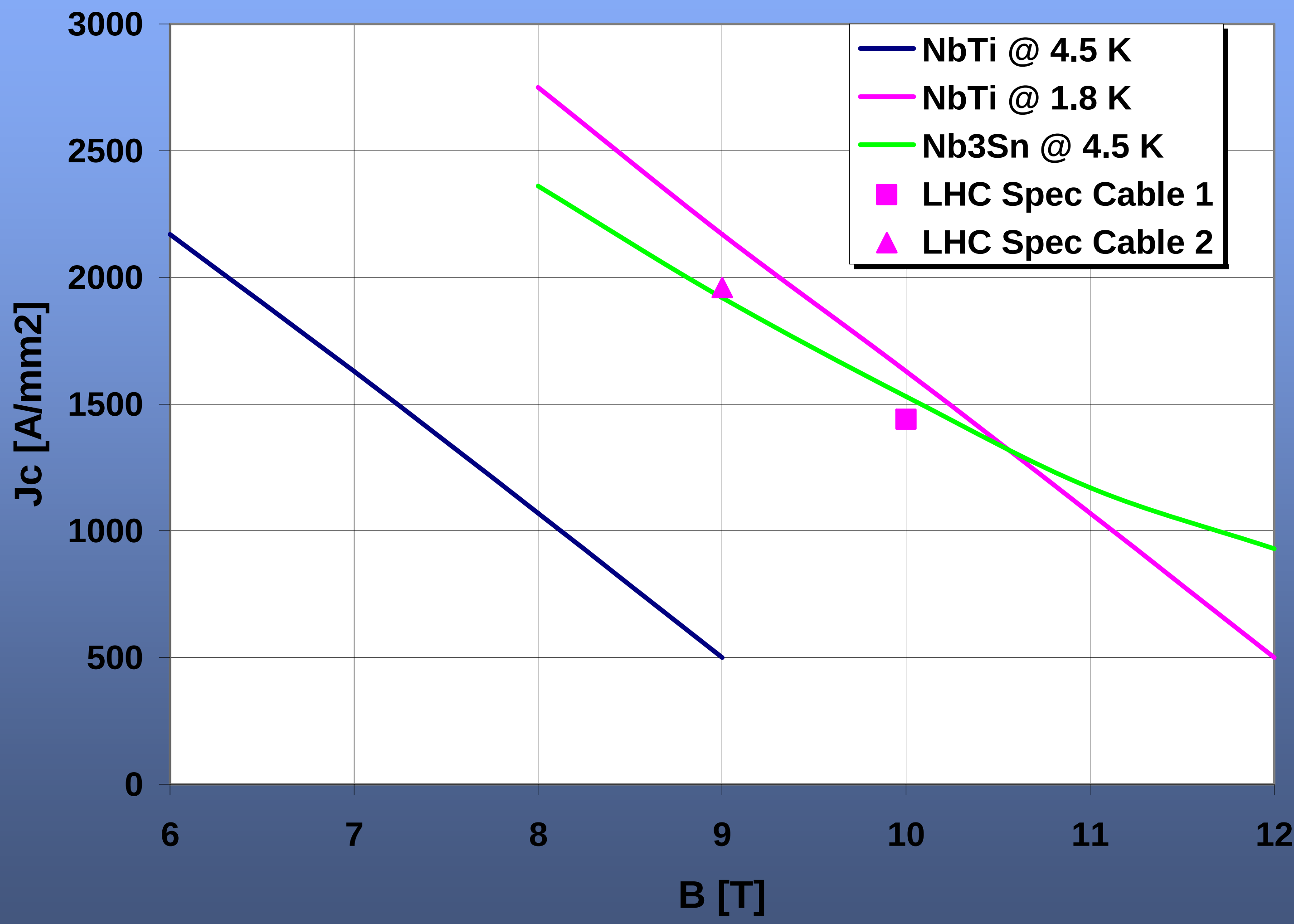
Magnets

- The LHC contains more than 7000 superconducting magnets ranging from the 15 m long main dipoles to the 10 cm long octupole/decapole correctors inside the dipole cold masses as well as more than 100 conventional warm magnets not counting the 500 or so conventional magnets in the two 2.6 km long transfer lines between the SPS and the LHC. The most challenging are the superconducting dipoles and the quadrupoles in the arcs, dispersion suppressor and matching regions.

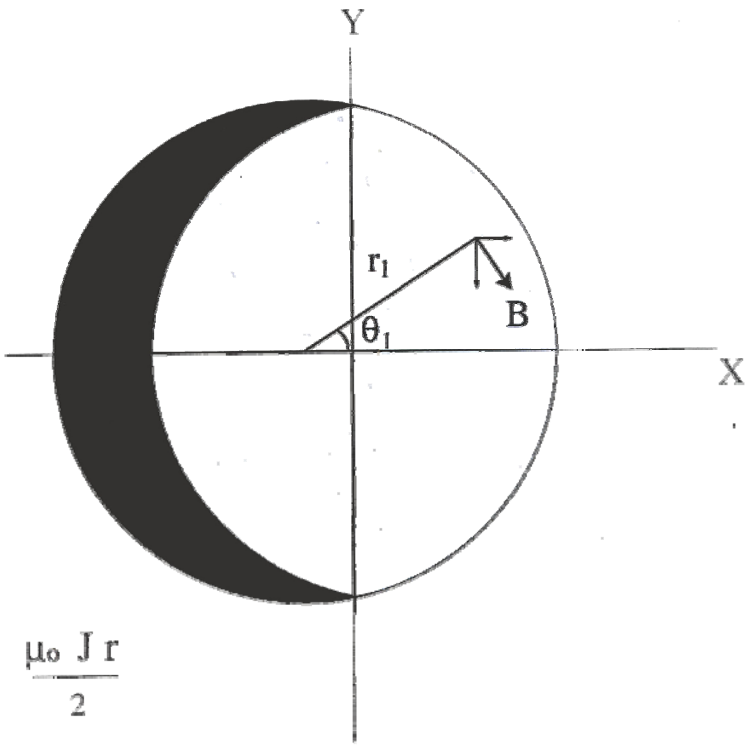
- The three large superconducting accelerators operating today, the Tevatron (FNAL), HERA (DESY) and RHIC (BNL) all use magnets made with classical Nb-Ti superconductor cooled with supercritical helium at a temperature slightly above 4.2 K. In each case, the nominal field is below or around 5 T. In order to increase the field to above 8 T, two possibilities exist today.

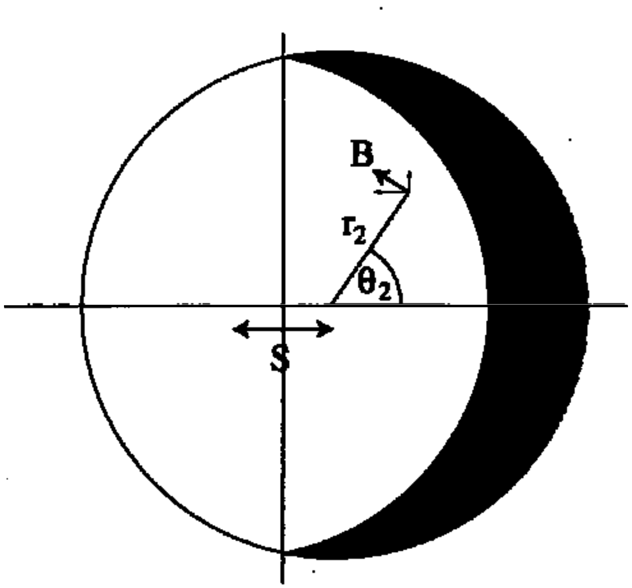
Critical Current Density of Technical Superconductors



Superconducting magnets in the LHC

Type	Number	Function
MB	1232	Main dipoles
MQ	392	Arc quadrupoles
MBX/MBR	16	Separation & recombination dipoles
MSCB	376	Combined chromaticity & closed orbit correctors
MCS	2464	Sextupole correctors for persistent currents at injection
MCDO	1232	Octupole/decapole correctors for persistent currents at injection
MO	336	Landau damping octupoles
MQT/MQTL	248	Tuning quadrupoles
MCB	190	Orbit correction dipoles
MQM	86	Dispersion suppressor & matching section quadrupoles
MQY	24	Enlarged-aperture quadrupoles in insertions
MQX	32	Low-beta insertion quadrupoles

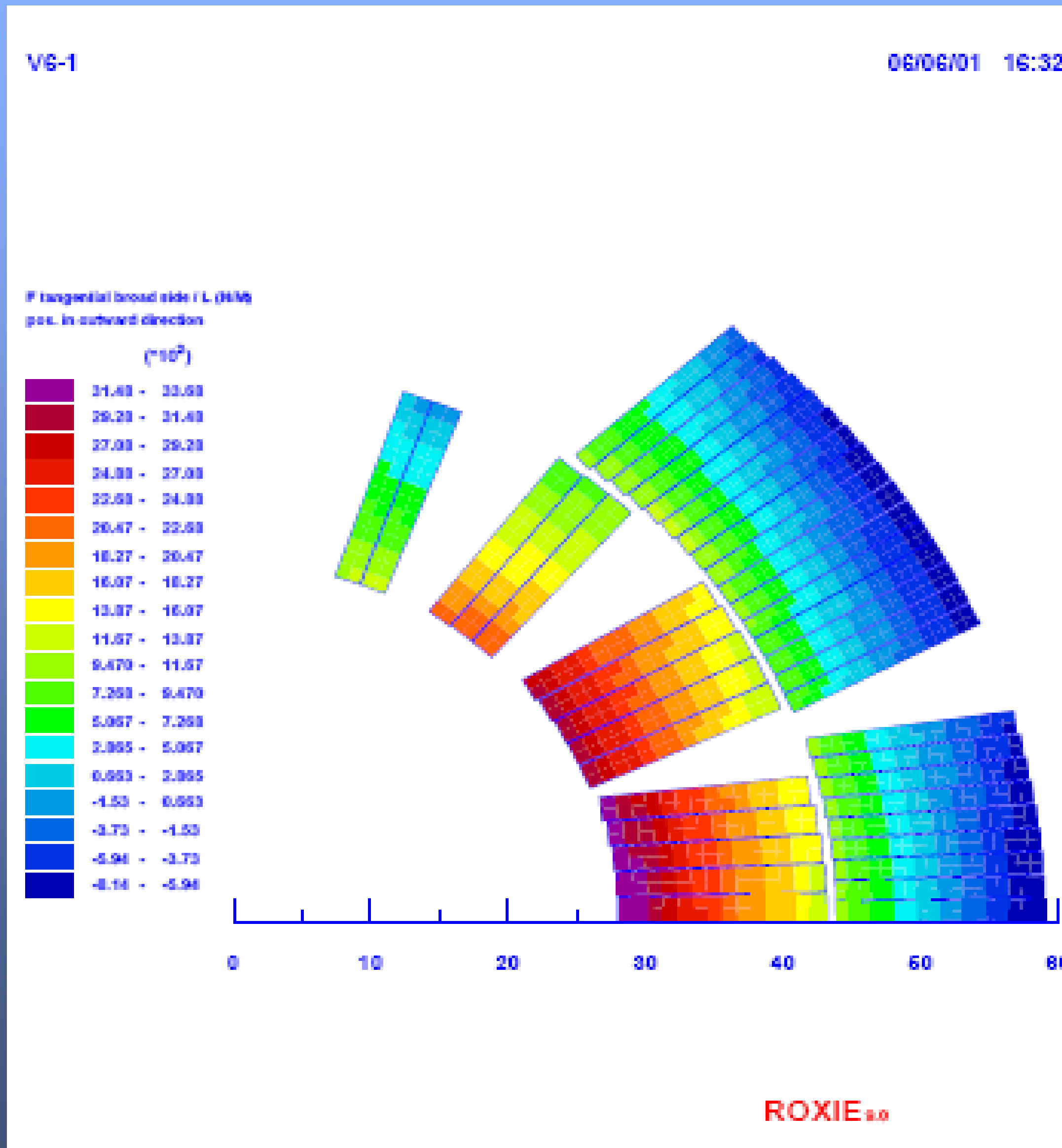




$$B = \frac{\mu_0 J r}{2}$$

$$B_Y = \frac{\mu_0 J}{2}\left\{-r_1 \cos\theta_1 + r_2 \cos\theta_2\right\} = -\frac{\mu_0 J s}{2}$$

$$B_X = \frac{\mu_0 J}{2}\left\{r_1 \sin\theta_1 - r_2 \sin\theta_2\right\} = 0$$


V6-1
06/06/01 16:32
F tangential broad side / L (N/M)
pos. in outward direction
(*10^2)
31.40 - 33.60
29.20 - 31.40
27.00 - 29.20
24.80 - 27.00
22.60 - 24.80
20.47 - 22.60
18.27 - 20.47
16.07 - 18.27
13.87 - 16.07
11.67 - 13.87
9.470 - 11.67
7.269 - 9.470
5.067 - 7.269
2.865 - 5.067
0.663 - 2.865
-1.53 - 0.663
-3.73 - -1.53
-5.94 - -3.73
-8.14 - -5.94
0
10
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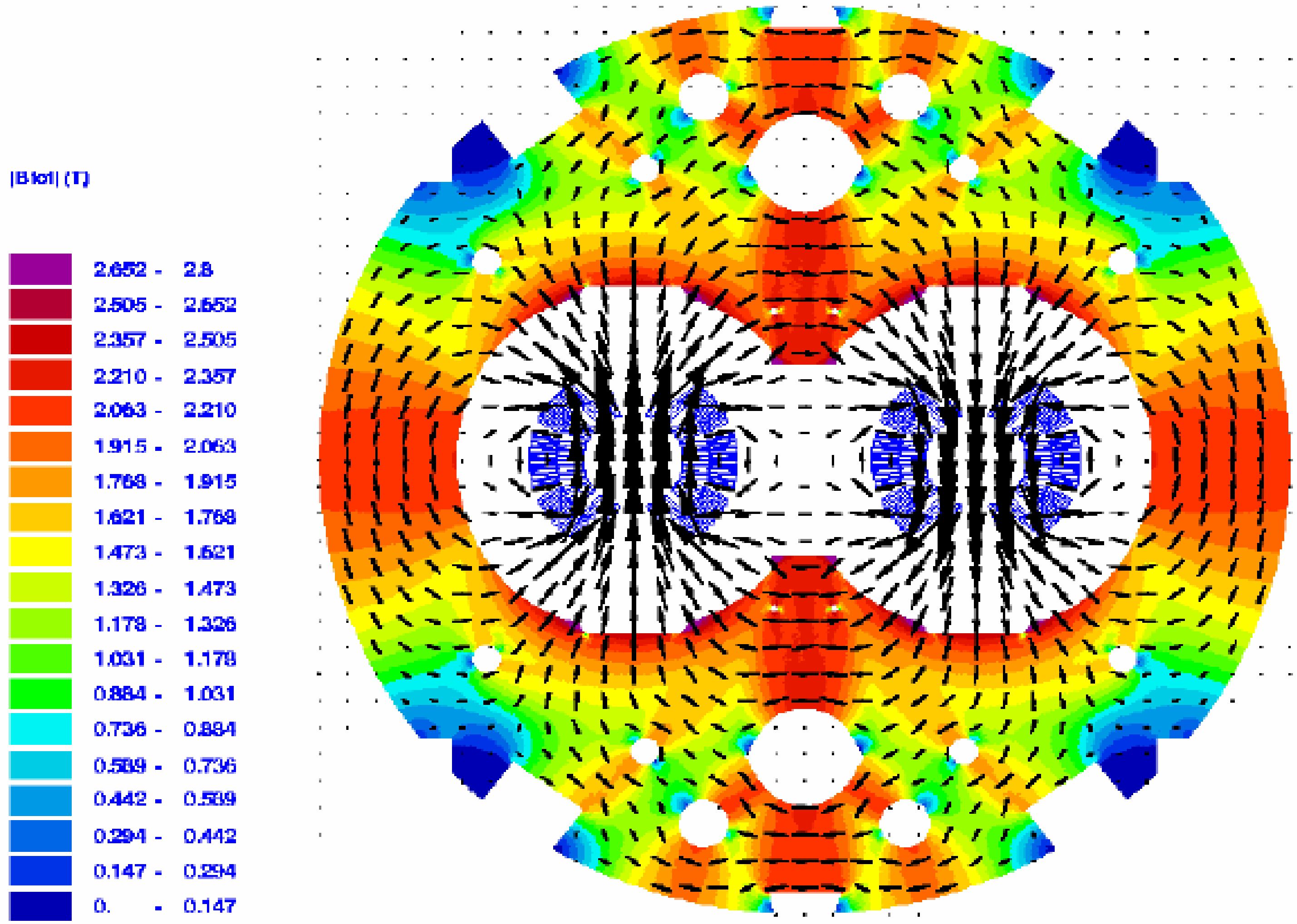
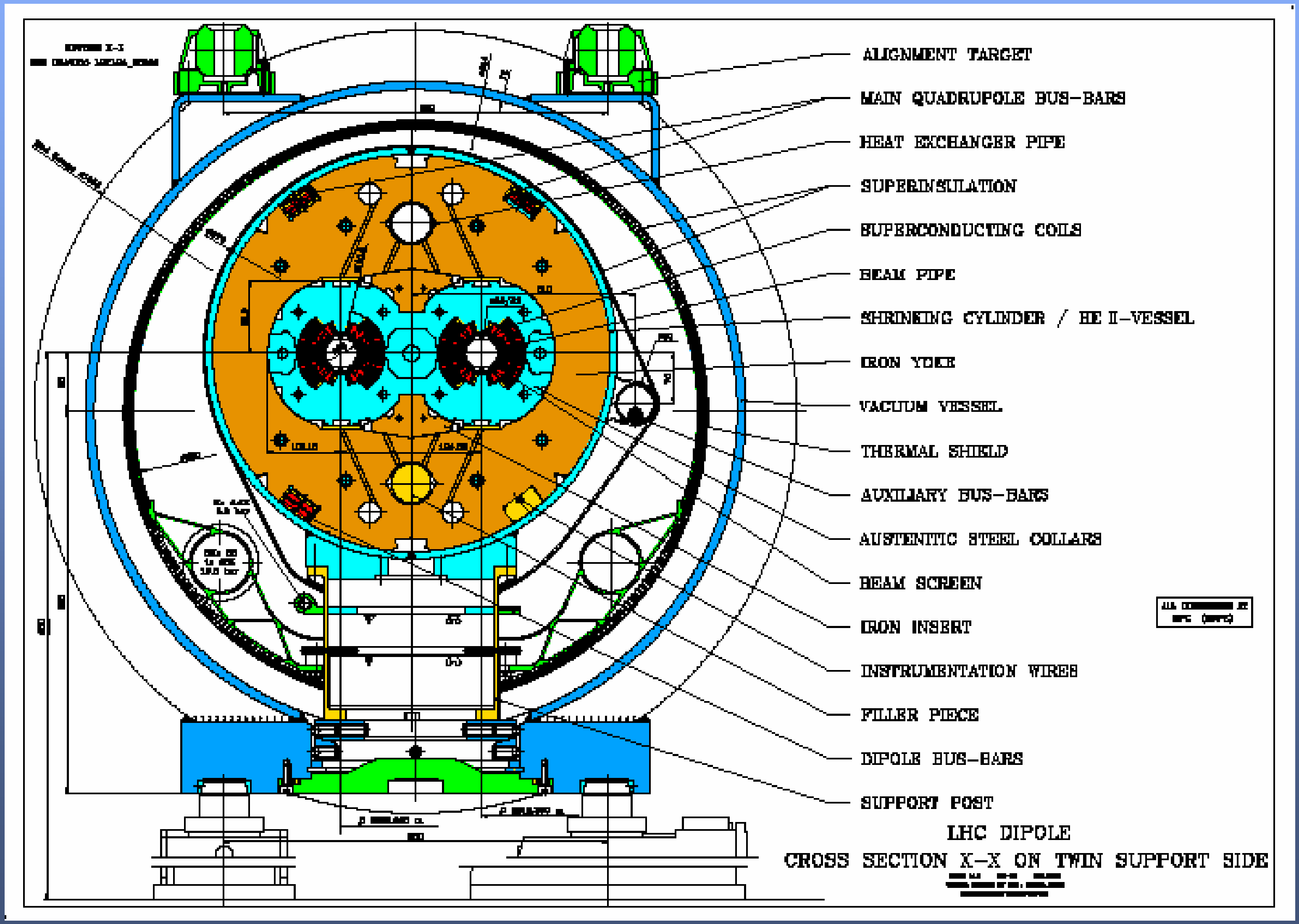
ROXIE

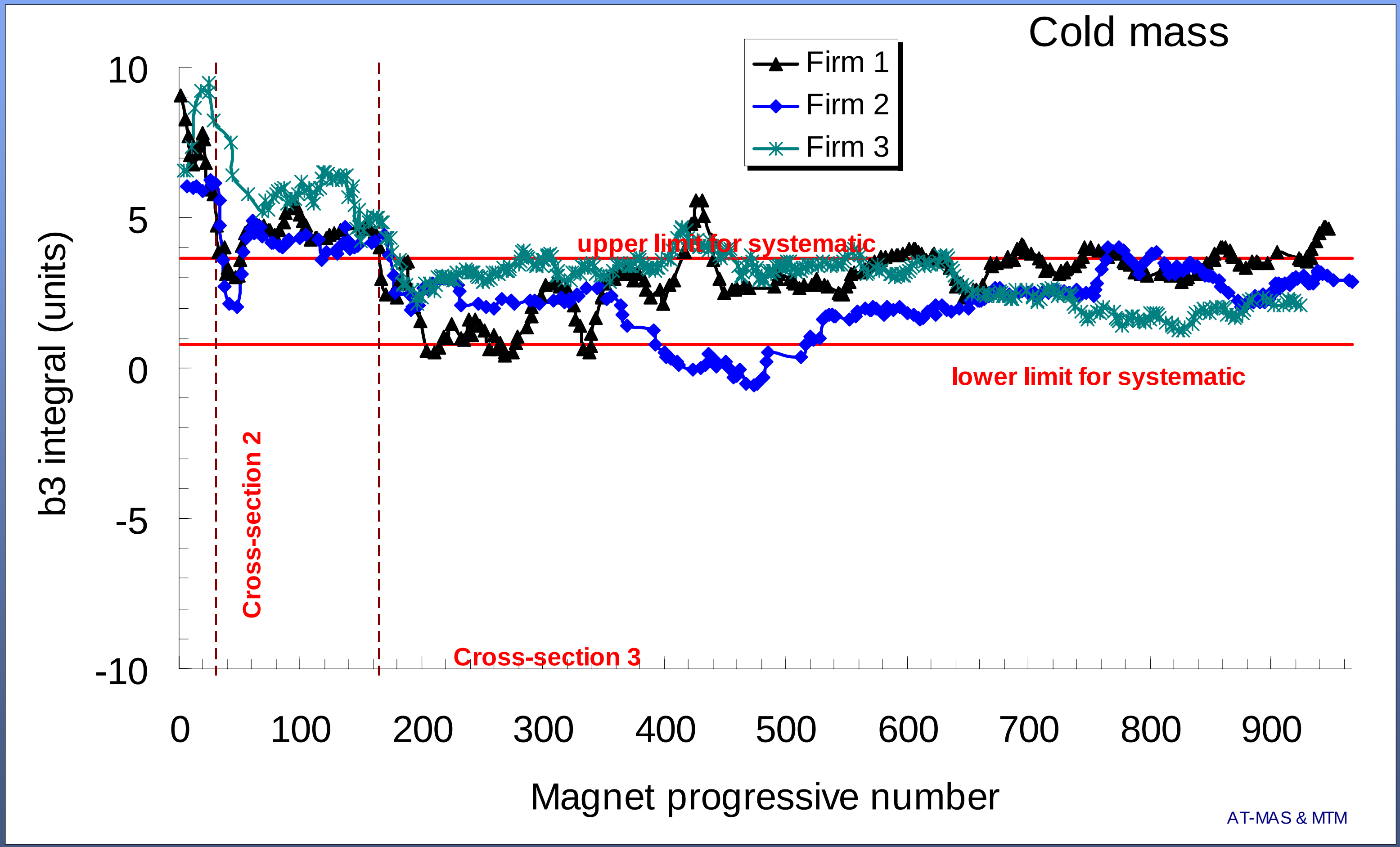
Dipole magnetic flux plot



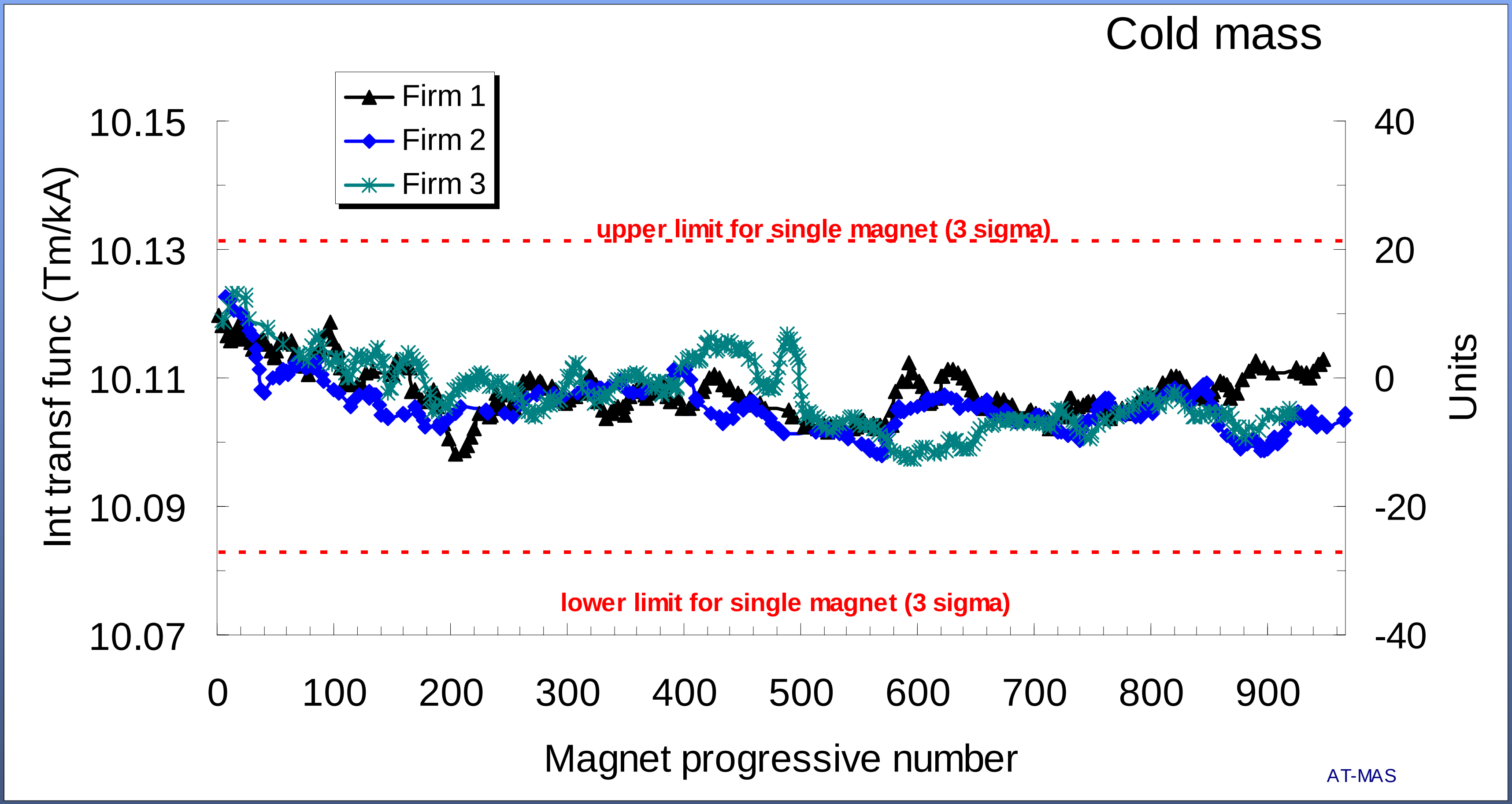
Cross-section of LHC Cryodipole



Dipole: b3 integral field



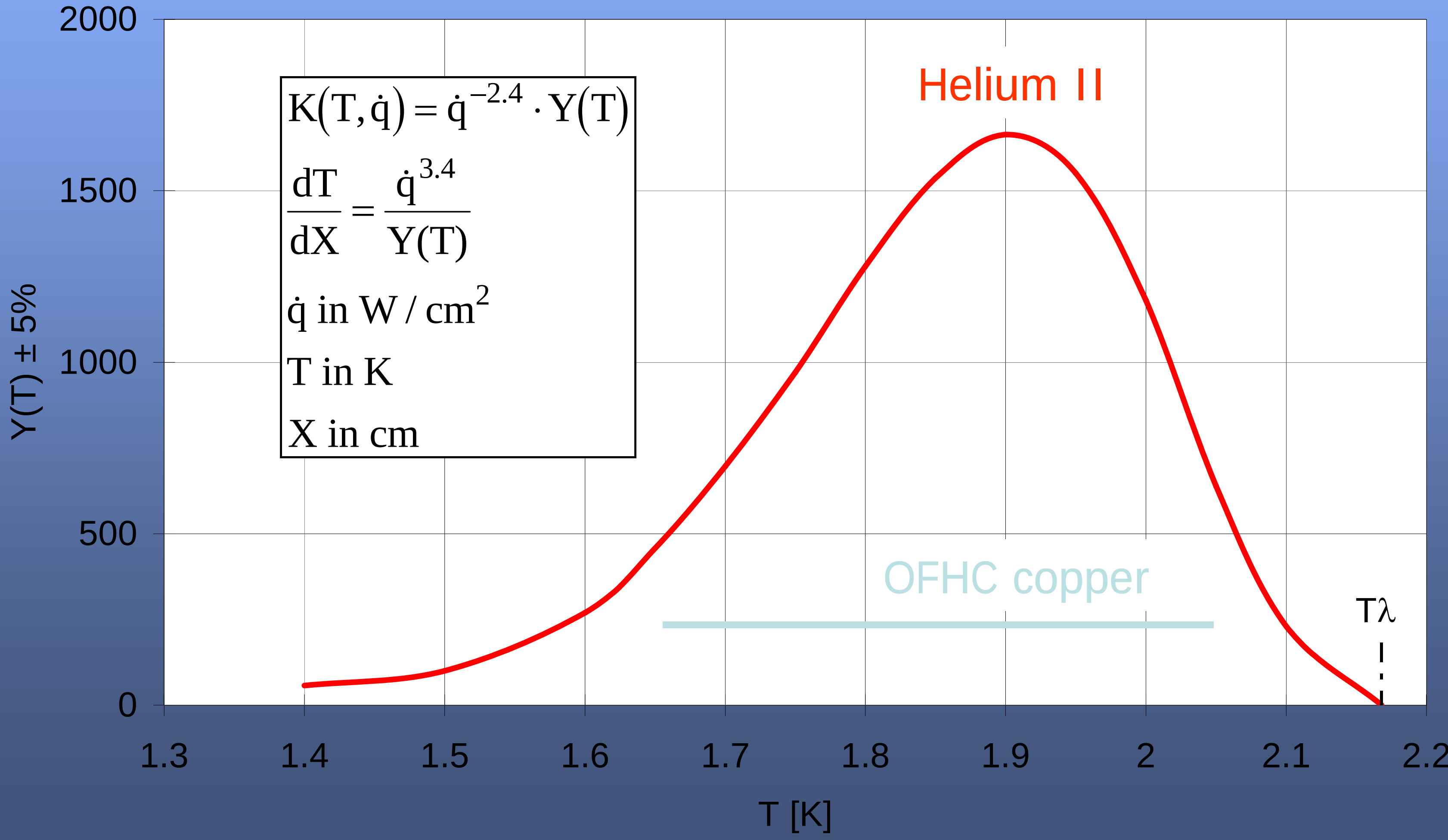
Dipole: integral field



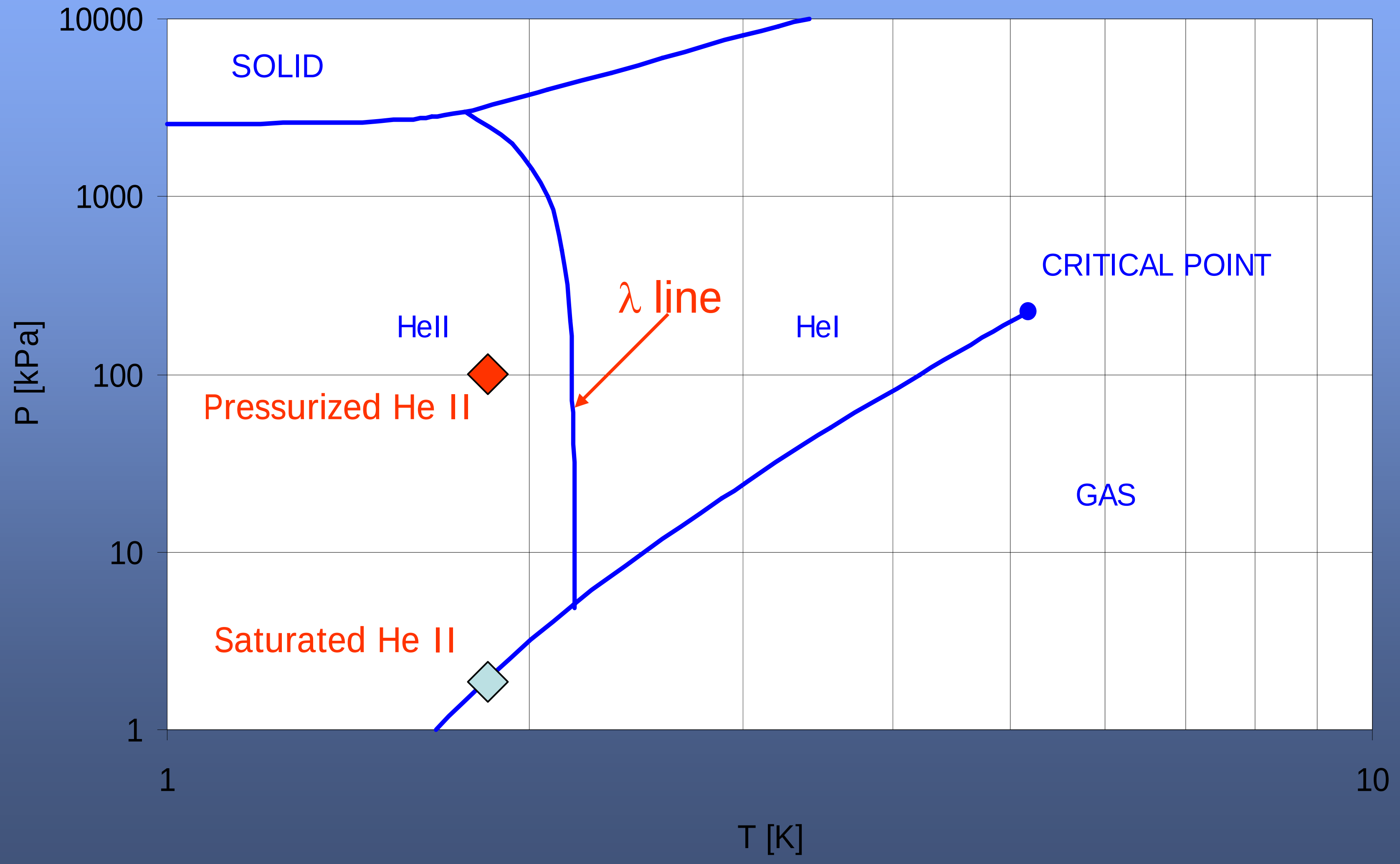
Cryogenics

The LHC magnets are cooled with pressurized superfluid helium, which has some interesting properties that make it a unique engineering material. Best known is its very low bulk viscosity which allows it to permeate the smallest cracks. This is used to advantage in the magnet design by making the coil insulation porous and enabling the fluid to be in contact with the strands of the superconductor. It also has a very large specific heat, 100,000 times that of the superconductor per unit mass and 2000 times per unit volume.

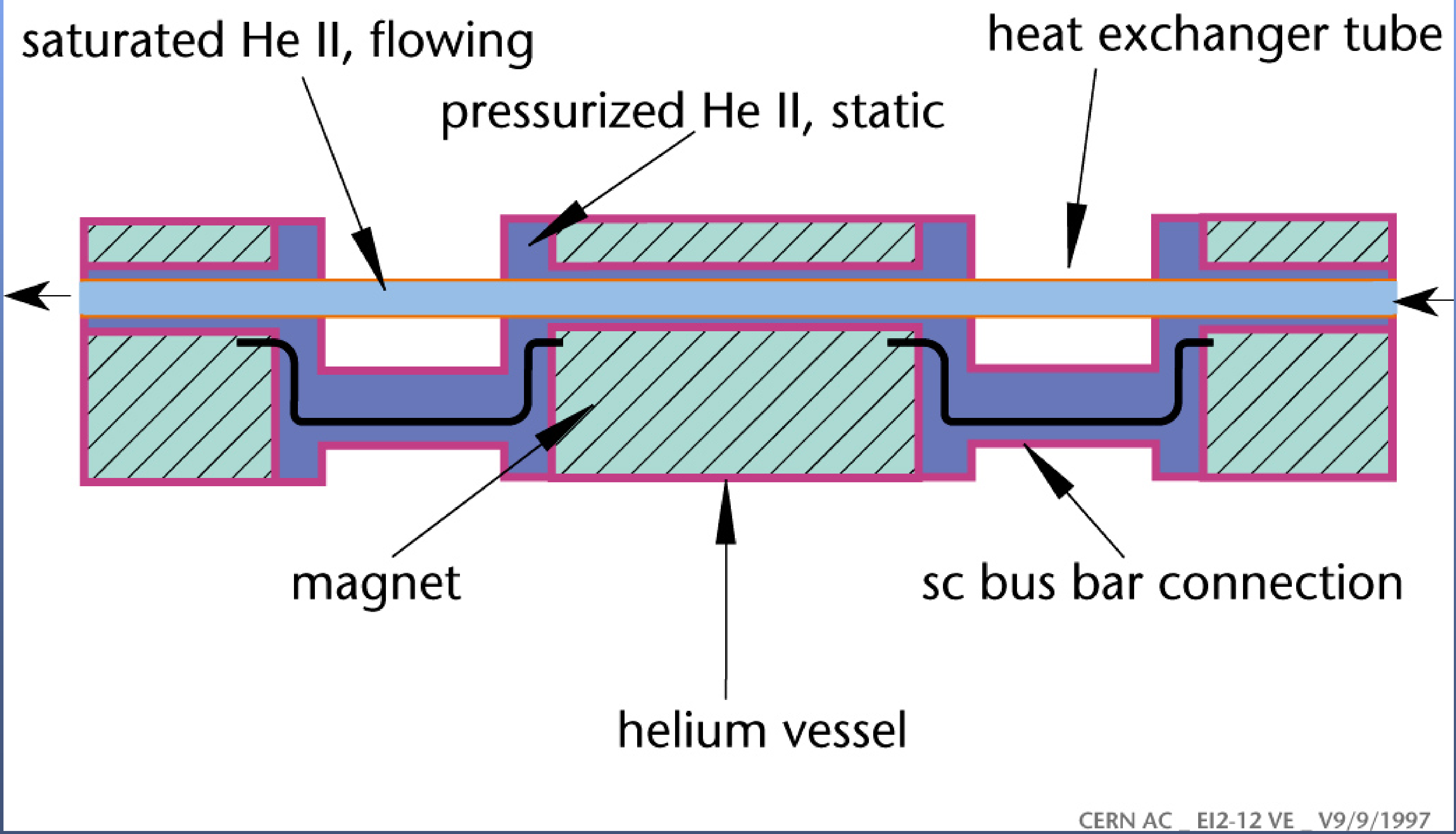
Equivalent Thermal Conductivity of He II



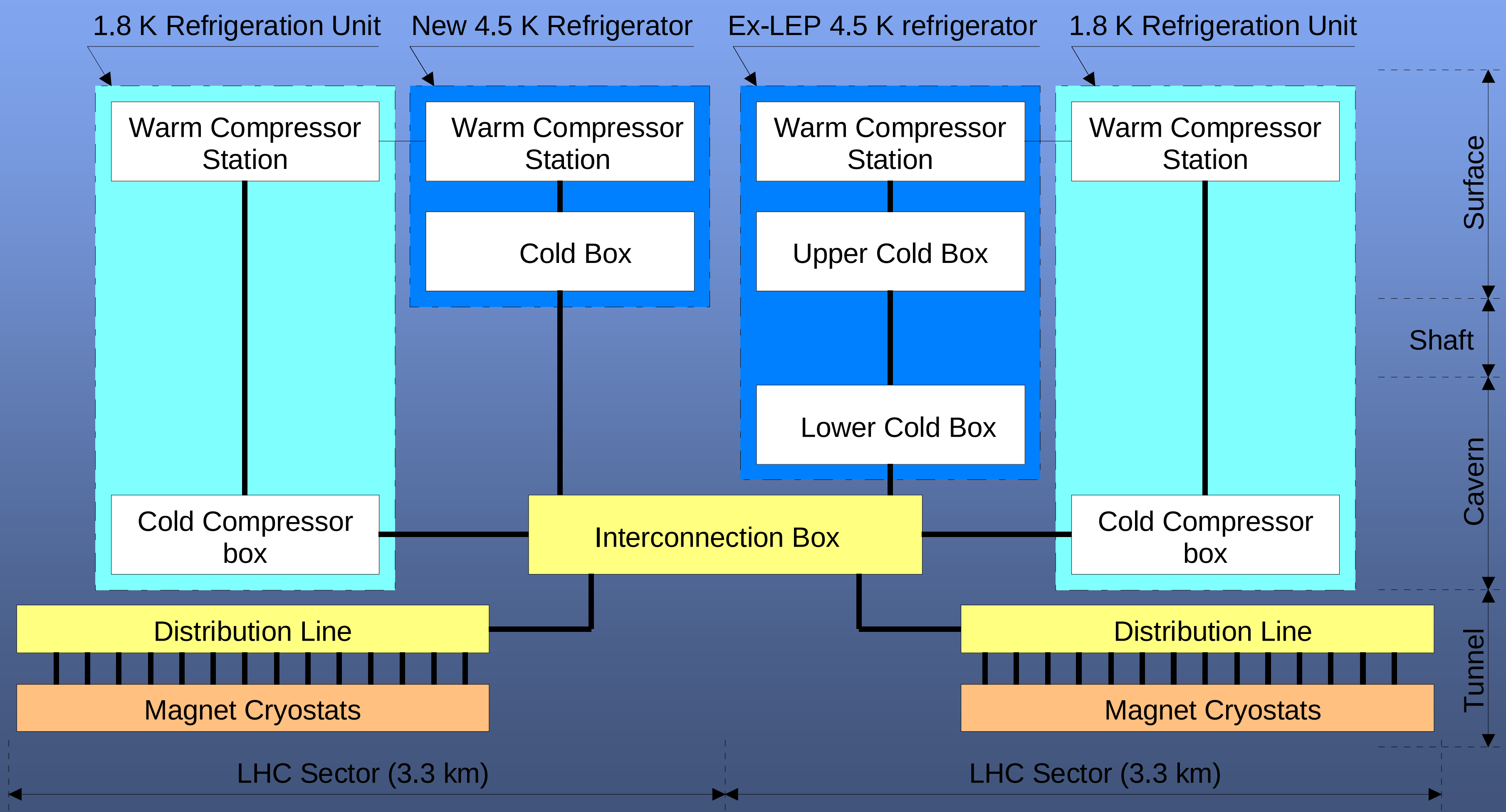
Phase Diagram of Helium



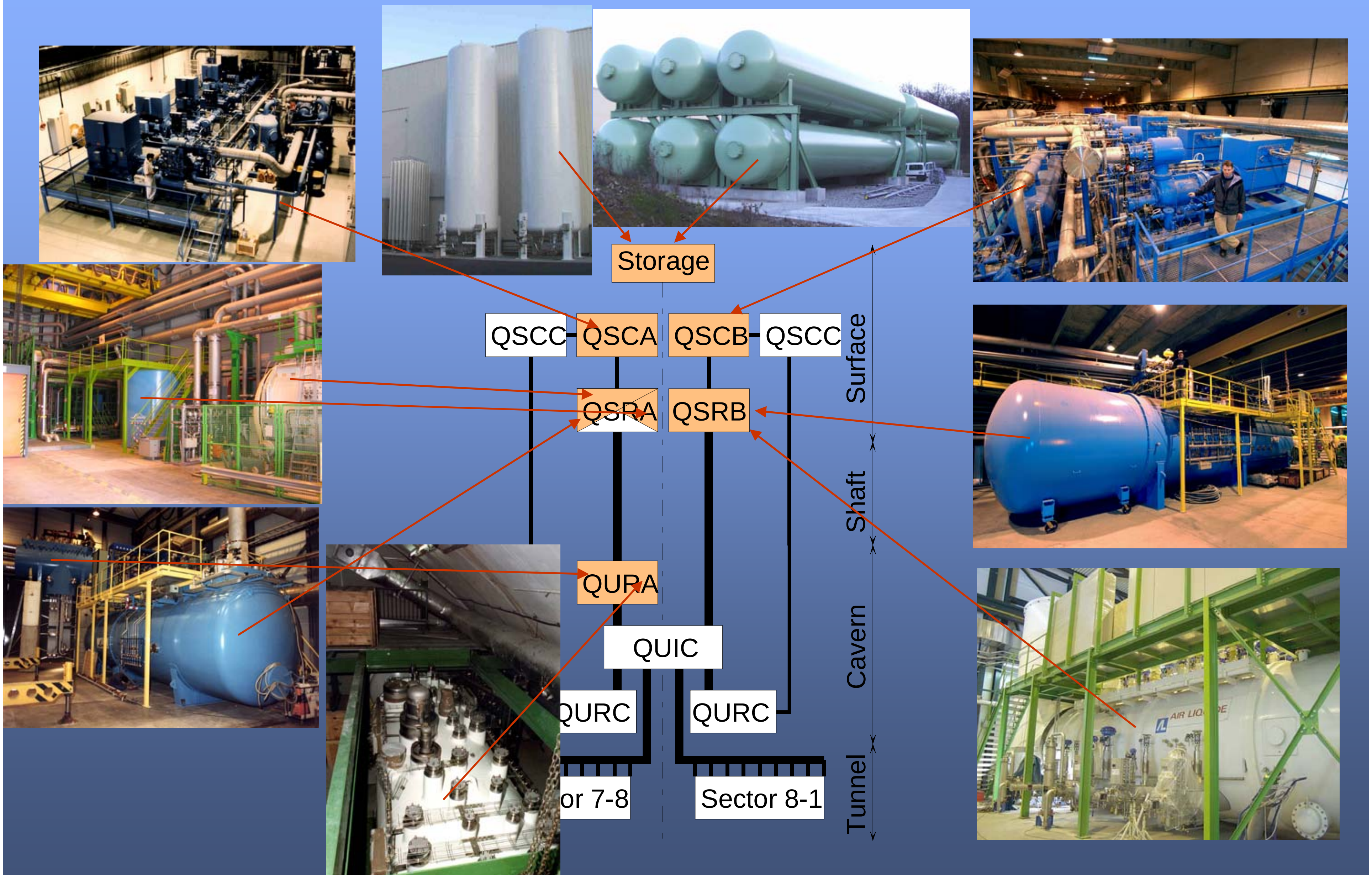
LHC magnet string cooling scheme



Cryogenic Architecture at LHC Even Point



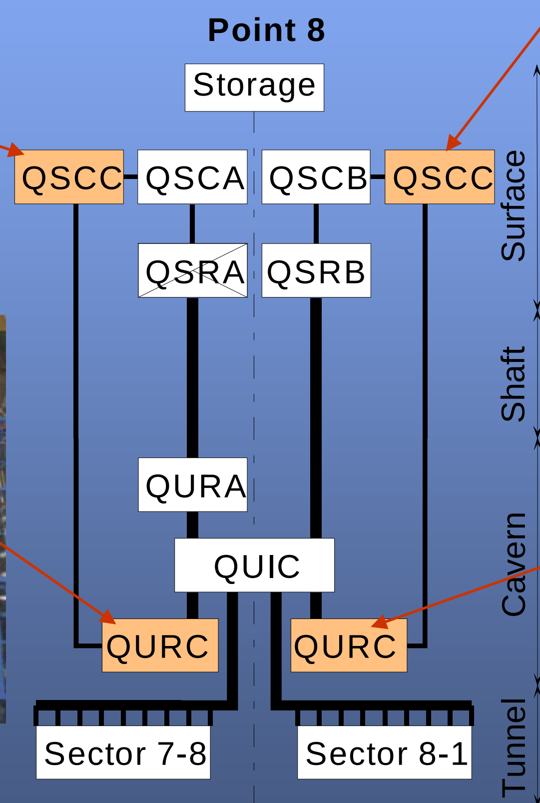
Infrastructure and refrigerators at 4.5 K



Refrigeration units at 1.8 K

Air Liquide

IHI Linde

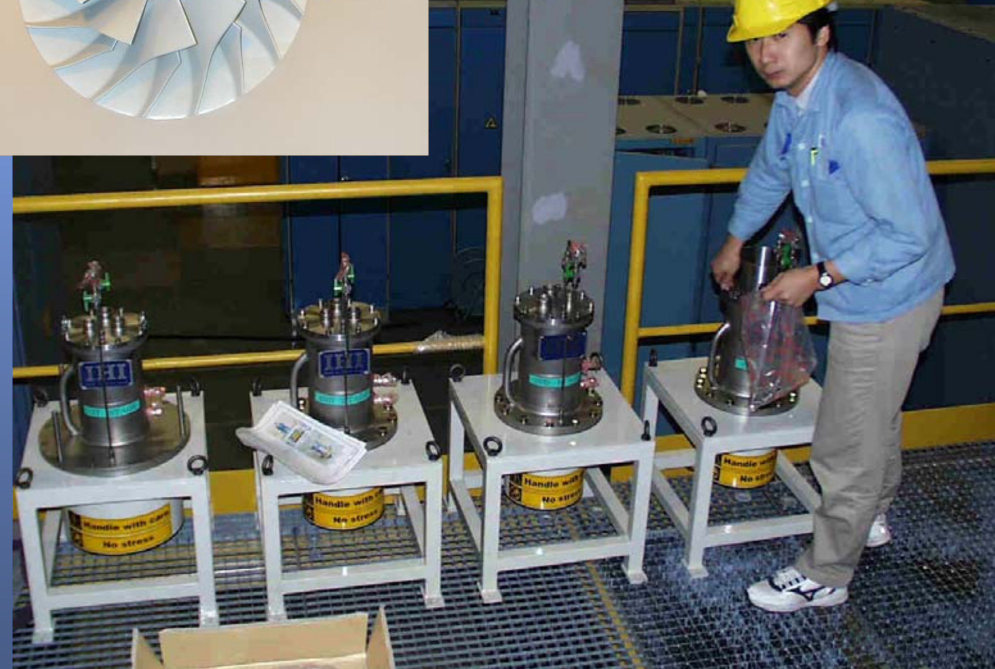


Cold compressors for 1.8 K refrigeration units

IHI-LINDE

Impeller

1st stage



The four stages

Radiofrequency Acceleration System

The RF system is located at Point 4. Two independent sets of cavities operating at 400 MHz (twice the frequency of the SPS injector) allow independent control of the two beams. The superconducting cavities are made from copper on which a thin film of a few microns of Niobium is sputtered onto the internal surface. In order to allow for the lateral space, the beam separation must be increased from 194 mm in the arcs to 420 mm. In order to combat intrabeam scattering each RF system must provide 16 MV during coast whilst at injection 8 MV is needed. For each beam there are 8 single cell cavities, each providing 2 MV, with a conservative gradient of 5.5 MV/m.

The cavities are grouped into two modules per beam, each containing four cells. Each cavity is driven by an independent RF system, with independent klystron, circulator and load. Although the RF hardware required is much smaller than LEP due to the very small synchrotron radiation power loss, the real challenges are in controlling beam loading and RF noise.

Four-Cavity Module during assembly

400 MHz Klystron

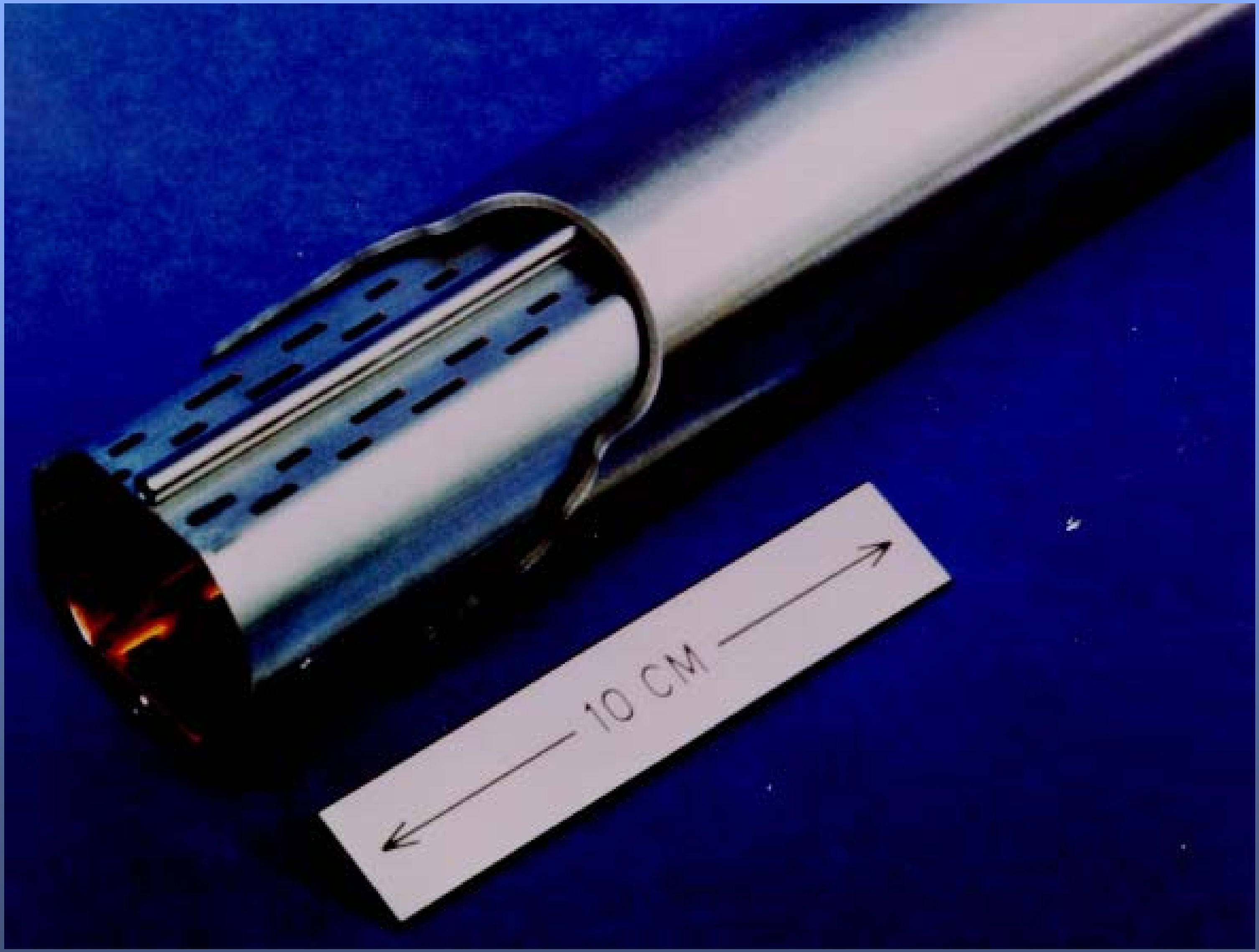
Vacuum System

The LHC presents several original requirements compared with classical vacuum systems. It has to ensure adequate beam lifetime in a cryogenic system where heat input to the 1.9 K helium circuit must be minimized and where significant quantities of gas can be condensed on the vacuum chamber. The main heat sources are:

- Synchrotron light radiated by the beam at high energy (0.2 W.M-1 per beam, with a critical energy of about 44 eV;
- Image currents (0.2 W.M-1 per beam);
- Energy dissipated by the development of electron clouds.
- Energy loss by nuclear scattering (30 mW.M-1 per beam).

In order to remove the heat from all these processes but the last with high thermodynamic efficiency, the 1.9 K cold bore of the magnets is shielded with a beam screen cooled to between 5 and 20 K. This beam screen is perforated with about 4% of the surface area to allow the cold bore of the magnets at 1.9 K to act as a distributed cryopump, allowing gas to be condensed on the cold bore surface protected against desorption by bombardment with synchrotron radiation photons.

LHC Beam Screen



Warm Vacuum System

For roughly 3 km of the 27 km circumference, mainly in the long straight sections, the vacuum chambers are at room temperature, requiring a low residual pressure without the benefit of the distributed cryopumping. As a spin-off of the development of sputtering technology for superconducting cavities a new getter material (TiZrV) has been developed which can be sputtered on the internal surface of the copper vacuum chambers and can be activated at the very low temperature of 200 degrees (conventional getters require activation at 600 degrees).

When activated, the chamber wall itself becomes a distributed pump, producing very low residual pressure and at the same time a very low secondary emission yield, preventing the buildup of an electron cloud.

All warm chambers, including those inside the detectors, are treated in this way.

Installation and Commissioning

- Last week, machine installation passed the half-way mark. Magnet installation will finish in March 2007 and the ring will be closed by August.
- There will be a low energy run in November 2007 where stable beams will be given to the detectors at 900 GeV (cm) whilst ramping studies will take place during machine studies.
- The first long physics run at 14 TeV will be in 2008.