The Large Hadron Collider

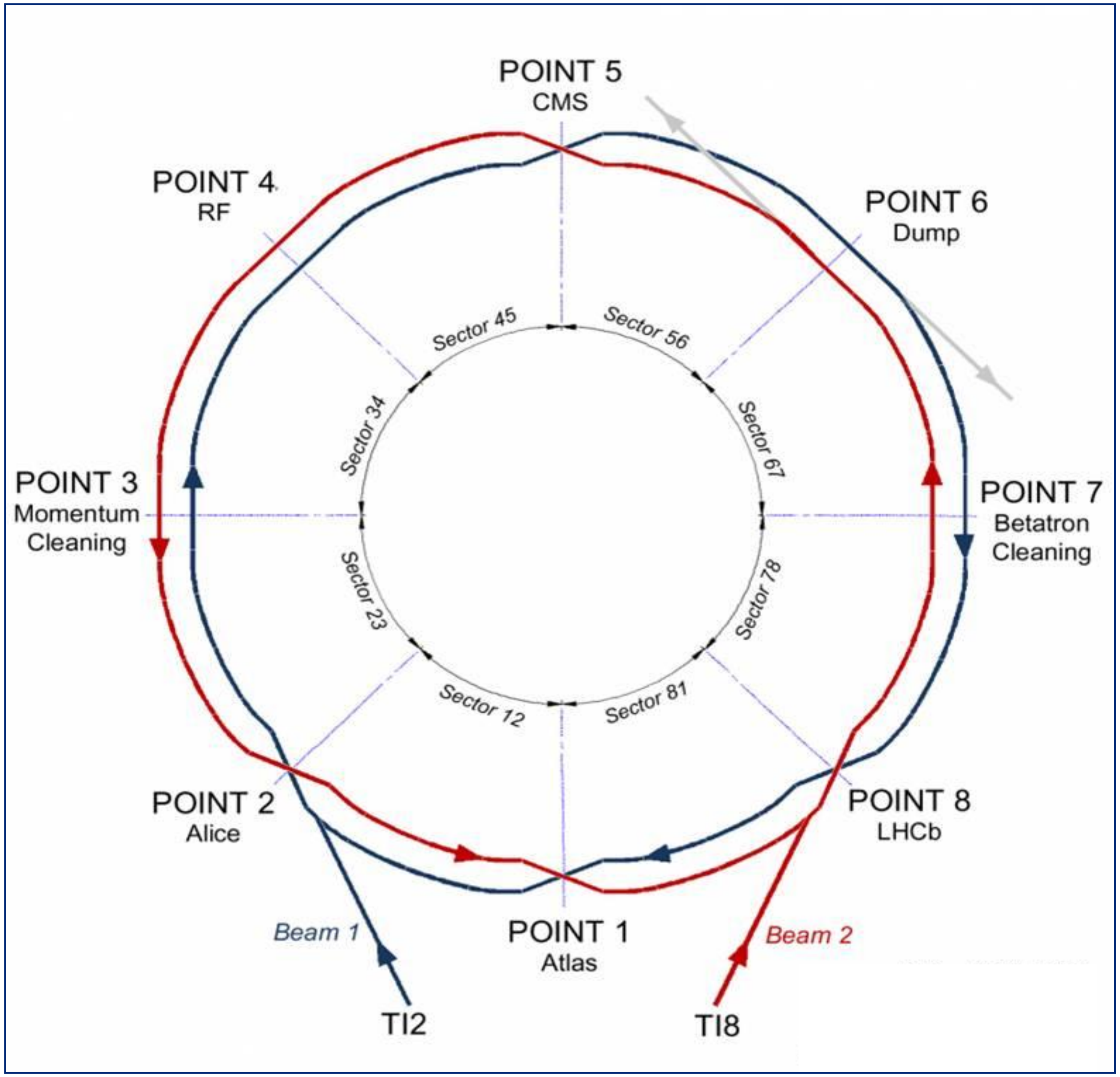
Philippe Lebrun
CERN, Geneva, Switzerland

African School of Physics 2010
Stellenbosch, South Africa, 1-21 August 2010

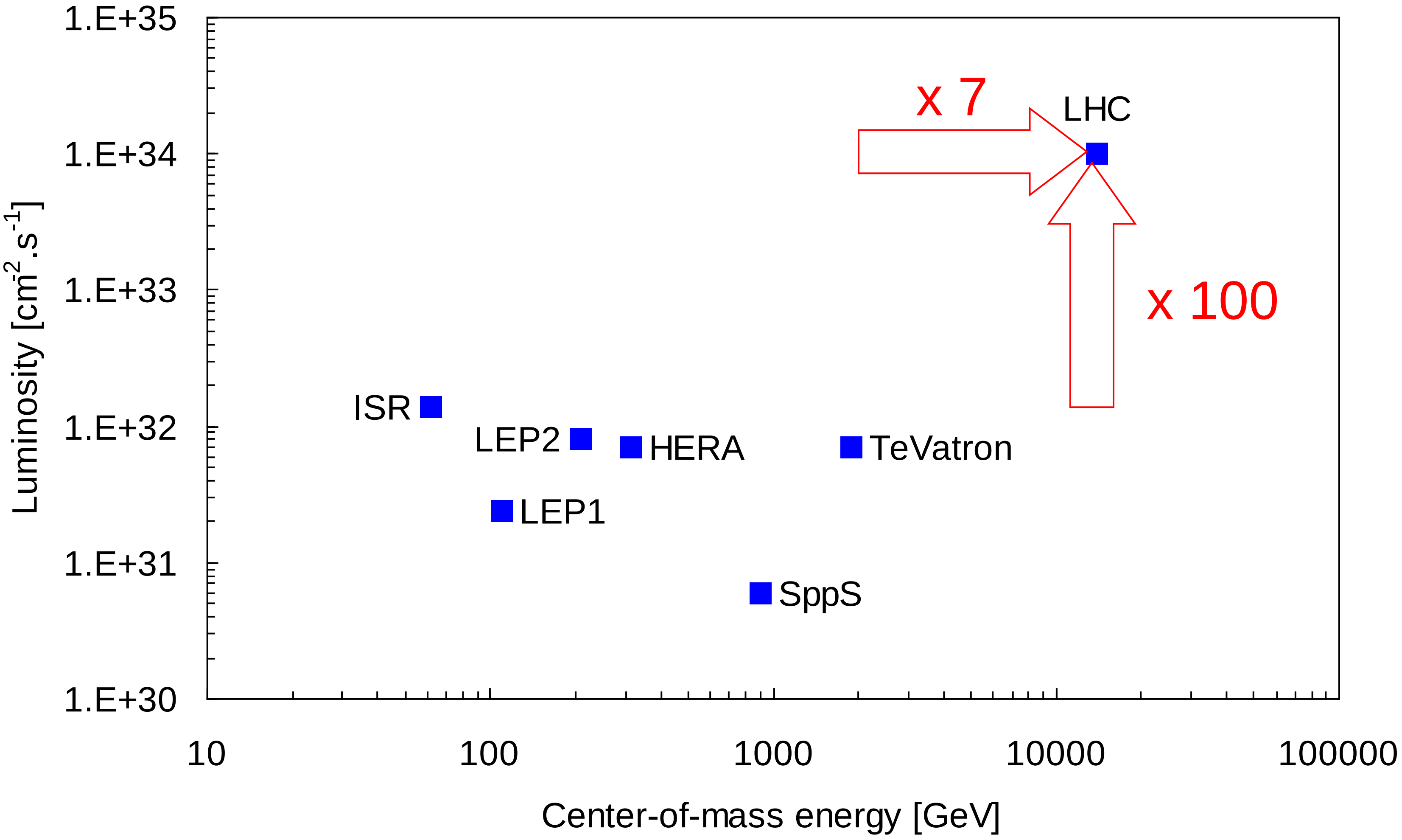
Contents

The largest scientific instrument in the world

Colliding counter-rotating beams of hadrons at the center of four large particle detectors



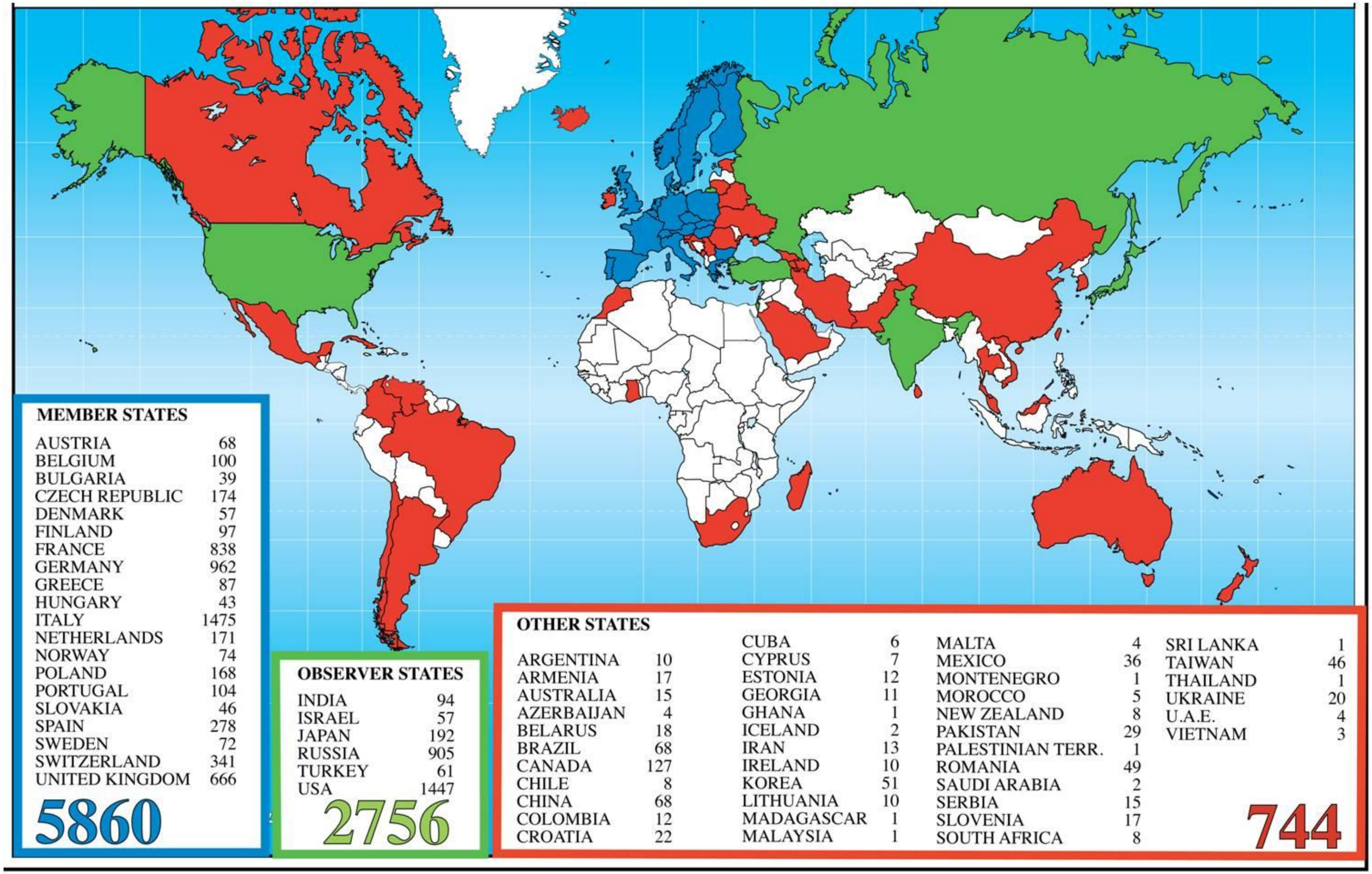
A new territory in energy and luminosity



Advanced technology at work

23 km of superconducting magnets cooled in superfluid helium at 1.9 K

A global project serving the world community of particle physicists



MEMBER STATES

AUSTRIA	68
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MALAYSIA	1
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SRI LANKA	1
TAIWAN	46
THAILAND	1
UKRAINE	20
U.A.E.	4
VIETNAM	3

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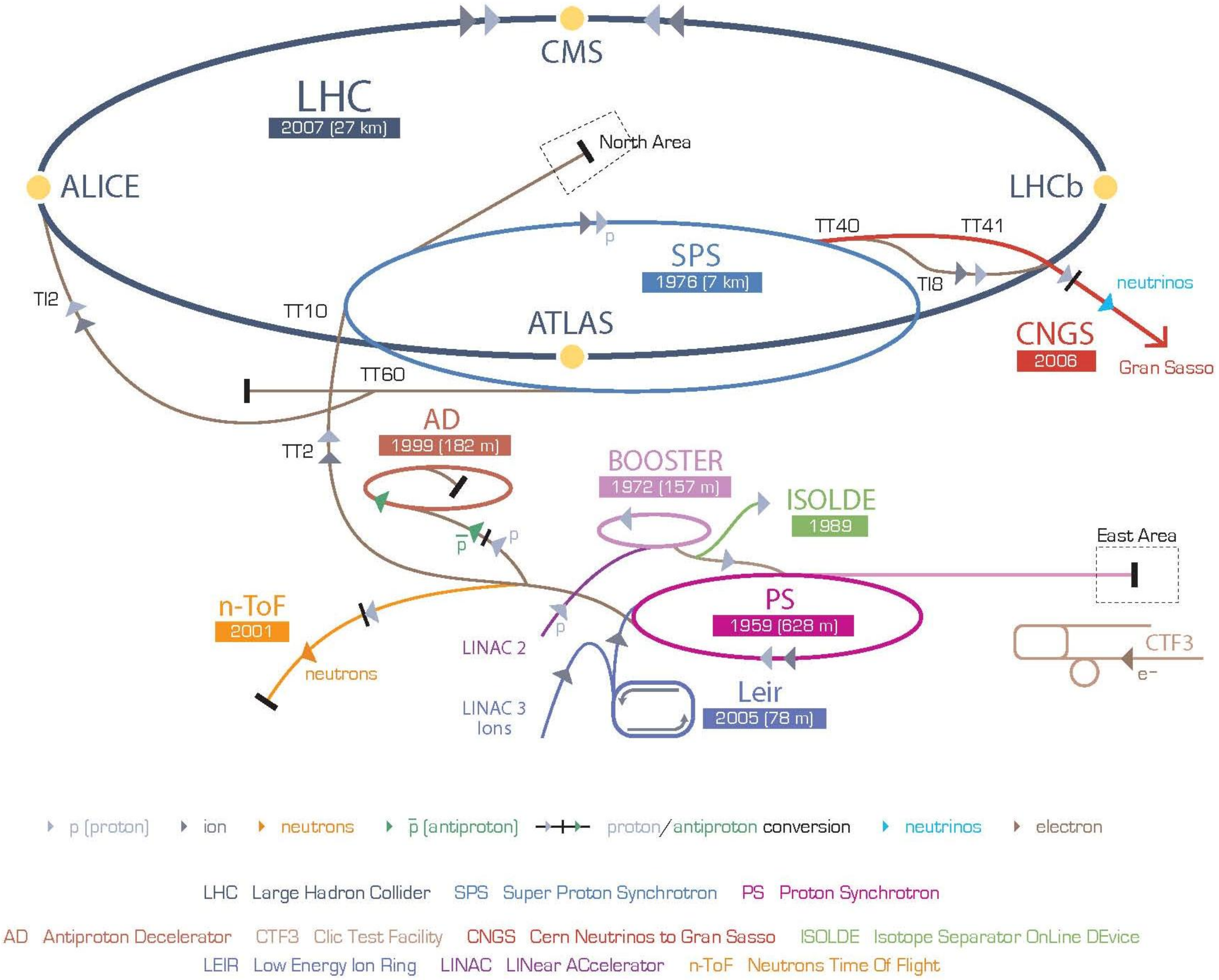
Making best use of CERN's infrastructure



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	0.58	A
Protons per bunch	1.15×10^{11}	
Number of bunches	2808	
Nominal bunch spacing	24.95	ns
Normalized emittance	3.75	μm.rad
Total crossing angle	285	μrad
Energy loss per turn	6.7	keV
Critical synchrotron energy	44.1	eV
Radiated power per beam	3.6	kW
Stored energy per beam	362	MJ
Stored energy in magnets	11	GJ
Operating temperature	1.9	K

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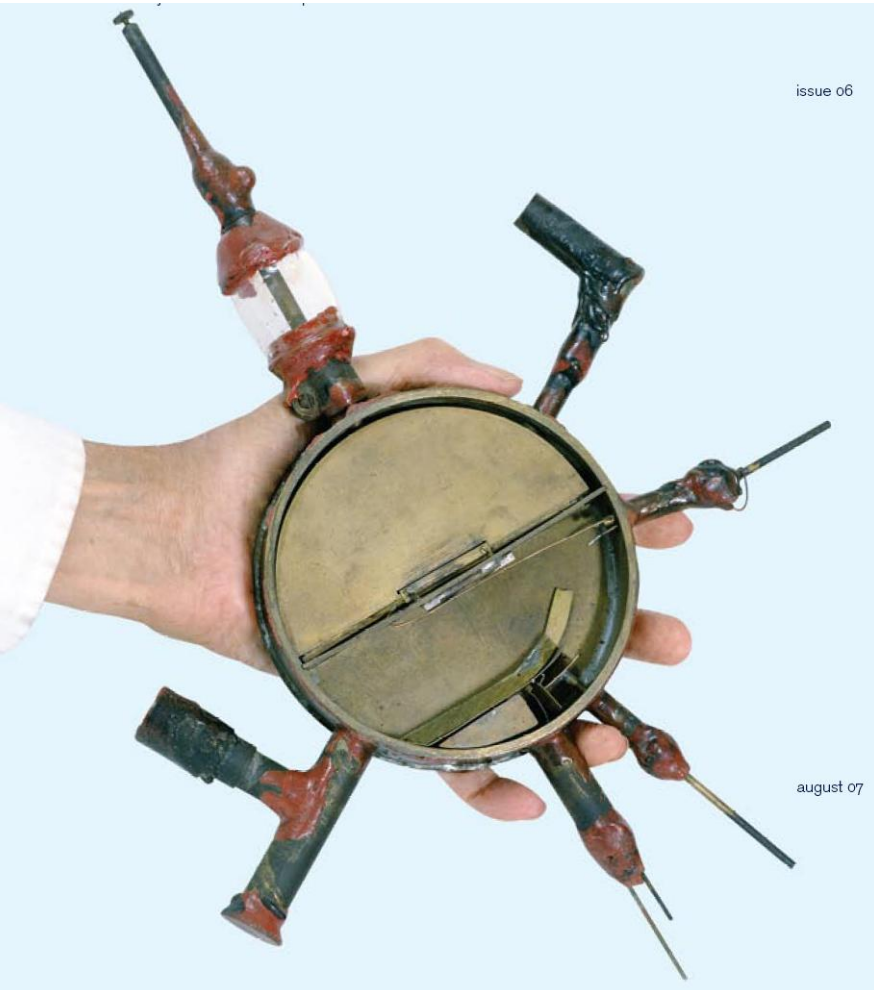
  - Dynamic aperture
- Technology
  - Superconducting magnets
  - Powering and protection
  - Cryogenics
  - Vacuum

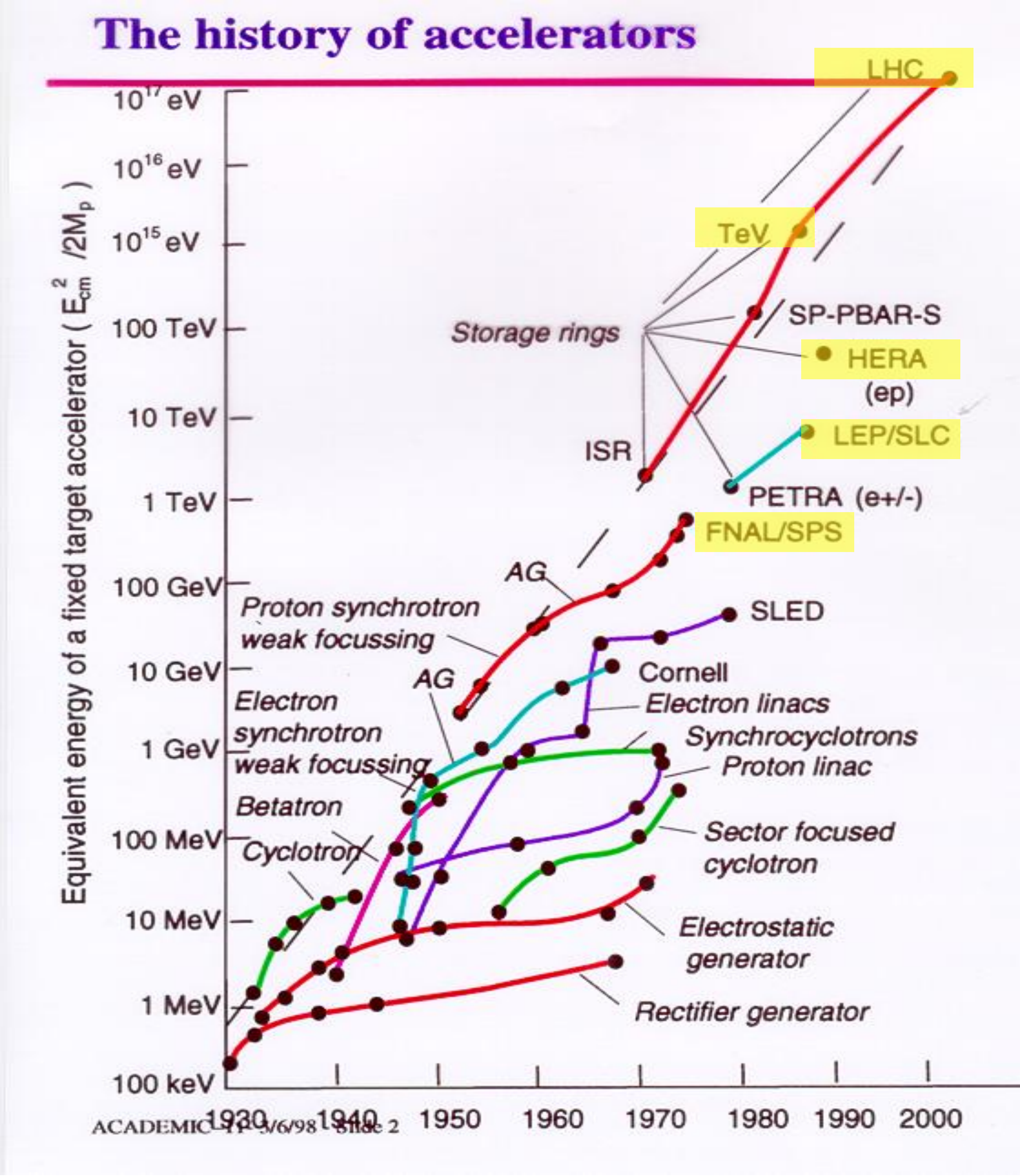
The first circular accelerator

Lawrence and Livingston’s 80 keV cyclotron (1930)

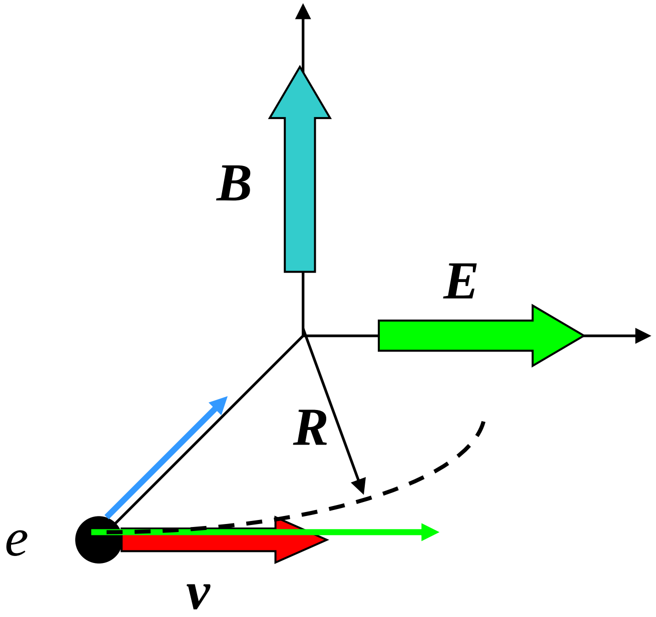
Ernest O. Lawrence



- sustained exponential development for more than 70 years
- progress achieved through repeated jumps from saturating to emerging technologies
- superconductivity, key technology of high-energy machines since the 1980s



Beam energy and bending field



Lorentz force on charged particle

$$\vec{F} = e\left(\vec{E} + \vec{v} \wedge \vec{B}\right)$$

Charge

Electric field

Velocity

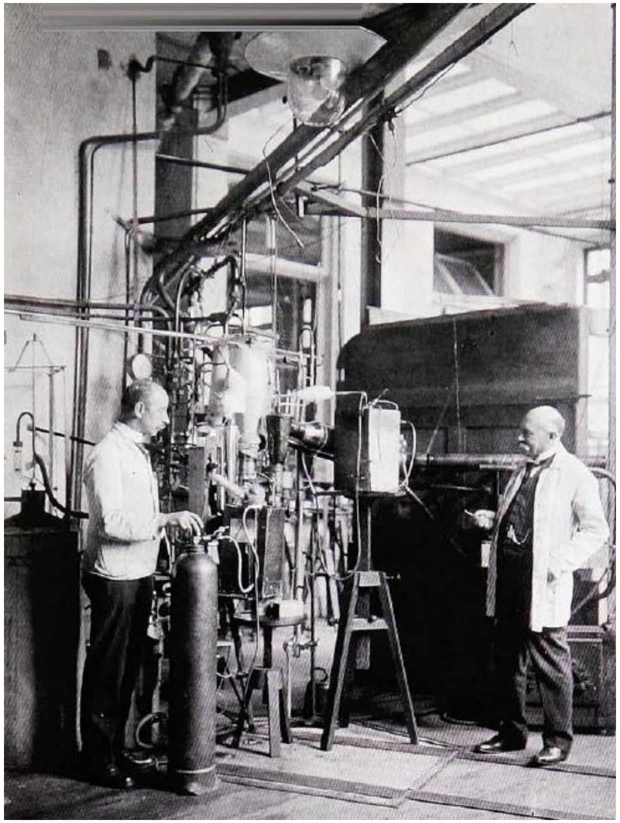
Magnetic field

In a circular accelerator

Particle momentum → $p = e\,B\,R$ ← Radius of curvature

$$p\left[GeV/c\right] \approx 0.3\,B\left[T\right]R\left[m\right]$$

The LHC needs a field of 8.33 T to bend 7 TeV beams along the curvature of the tunnel, with a radius of 2804 m

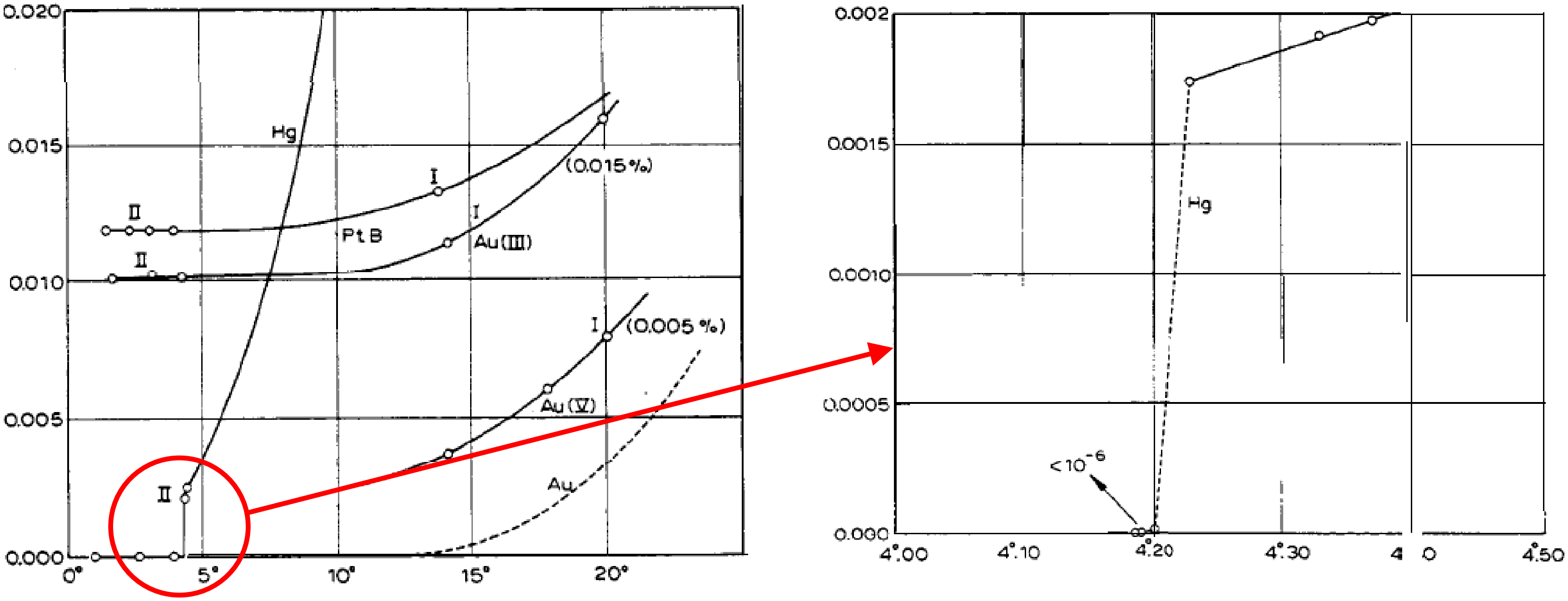


HEIKE KAMERLINGH ONNES

Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium

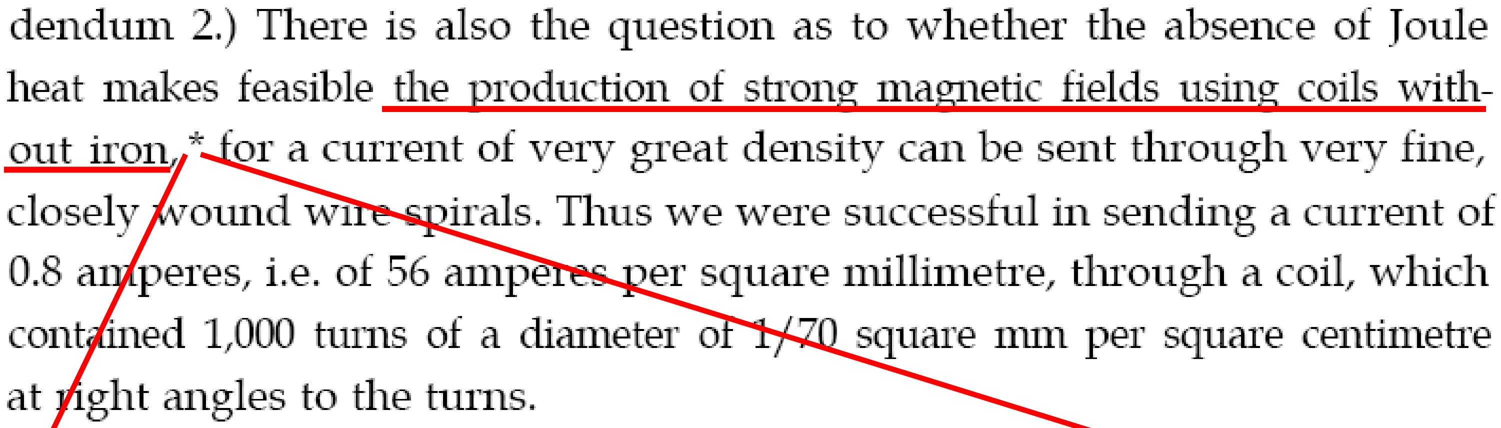
Nobel Lecture, December 11, 1913

Discovery of superconductivity (1911)

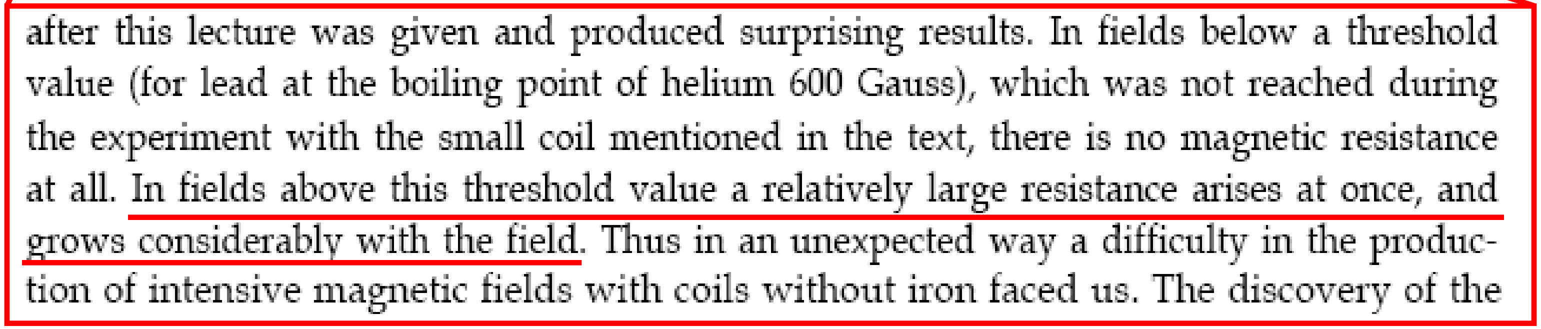


Thus the mercury at 4.2°K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity.

First idea of superconducting magnets (H. K. Onnes 1913)


dendum 2.) There is also the question as to whether the absence of Joule heat makes feasible the production of strong magnetic fields using coils without iron,* for a current of very great density can be sent through very fine, closely wound wire spirals. Thus we were successful in sending a current of 0.8 amperes, i.e. of 56 amperes per square millimetre, through a coil, which contained 1,000 turns of a diameter of 1/70 square mm per square centimetre at right angles to the turns.

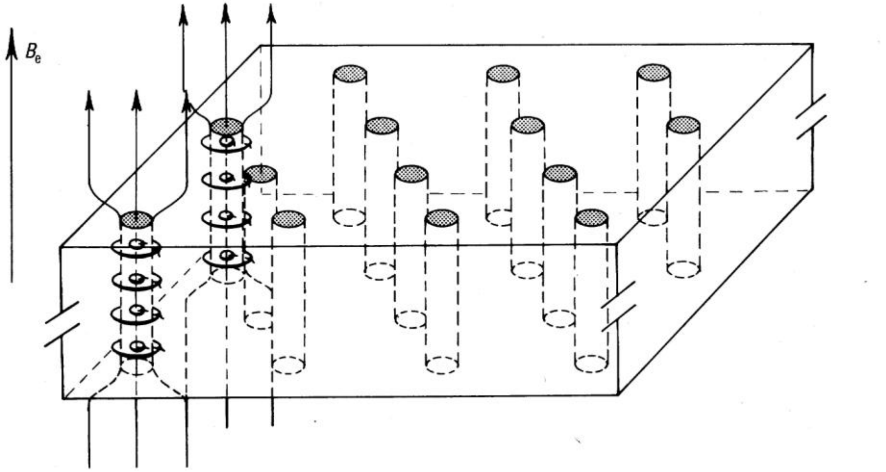
critical field of superconductors!

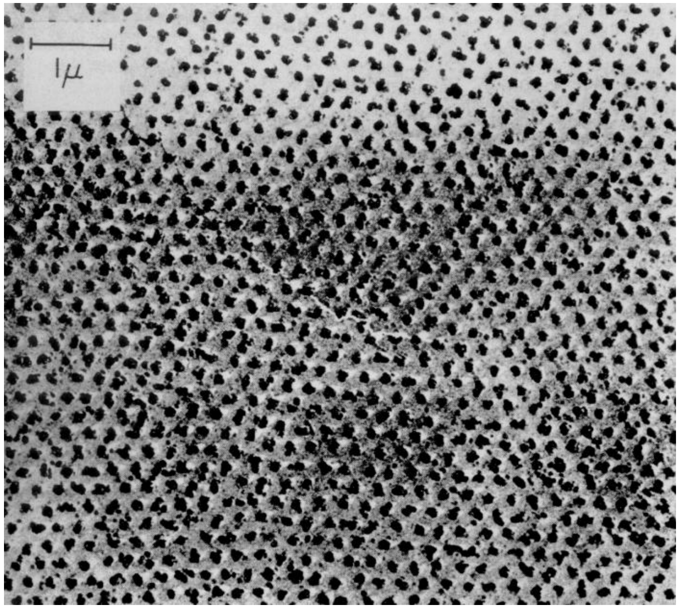

after this lecture was given and produced surprising results. In fields below a threshold value (for lead at the boiling point of helium 600 Gauss), which was not reached during the experiment with the small coil mentioned in the text, there is no magnetic resistance at all. In fields above this threshold value a relatively large resistance arises at once, and grows considerably with the field. Thus in an unexpected way a difficulty in the production of intensive magnetic fields with coils without iron faced us. The discovery of the

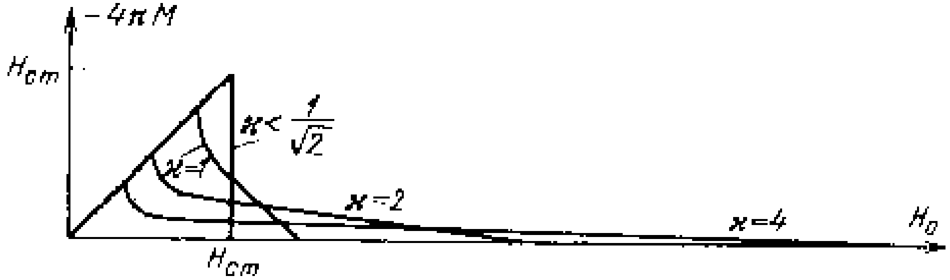
Vortex lattice of type-II superconductors (1954)

Field penetrates locally without destroying superconductivity in bulk

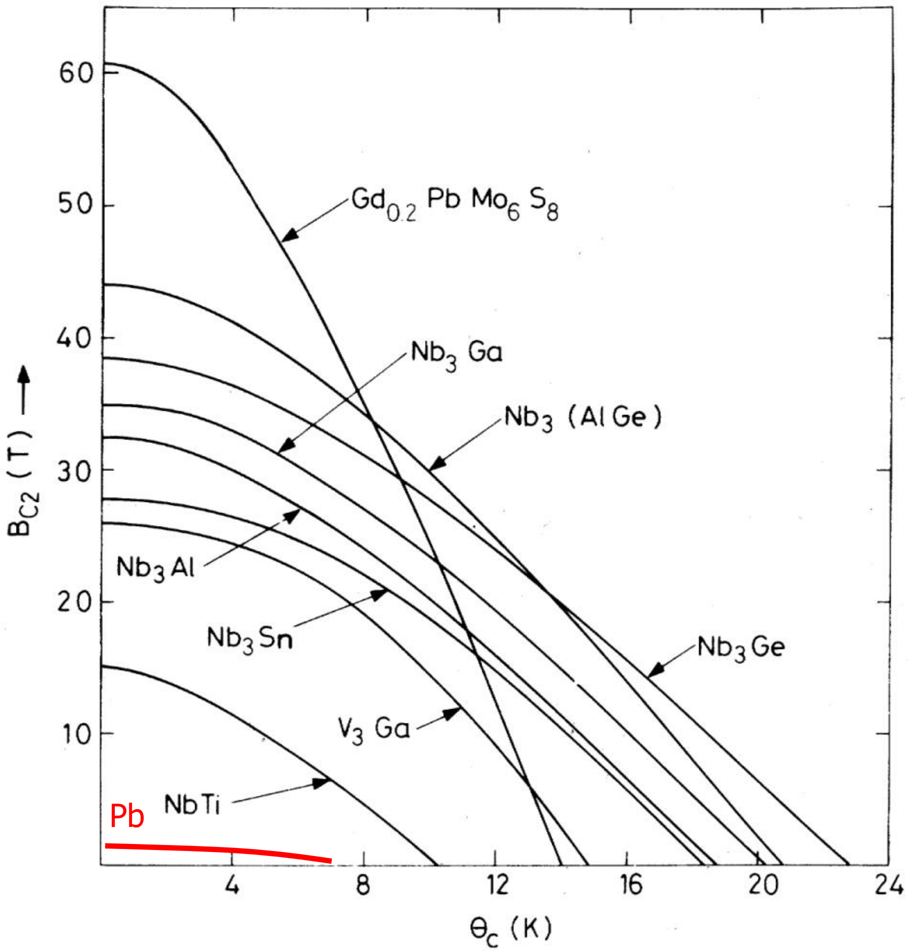
Alexei Abrikosov



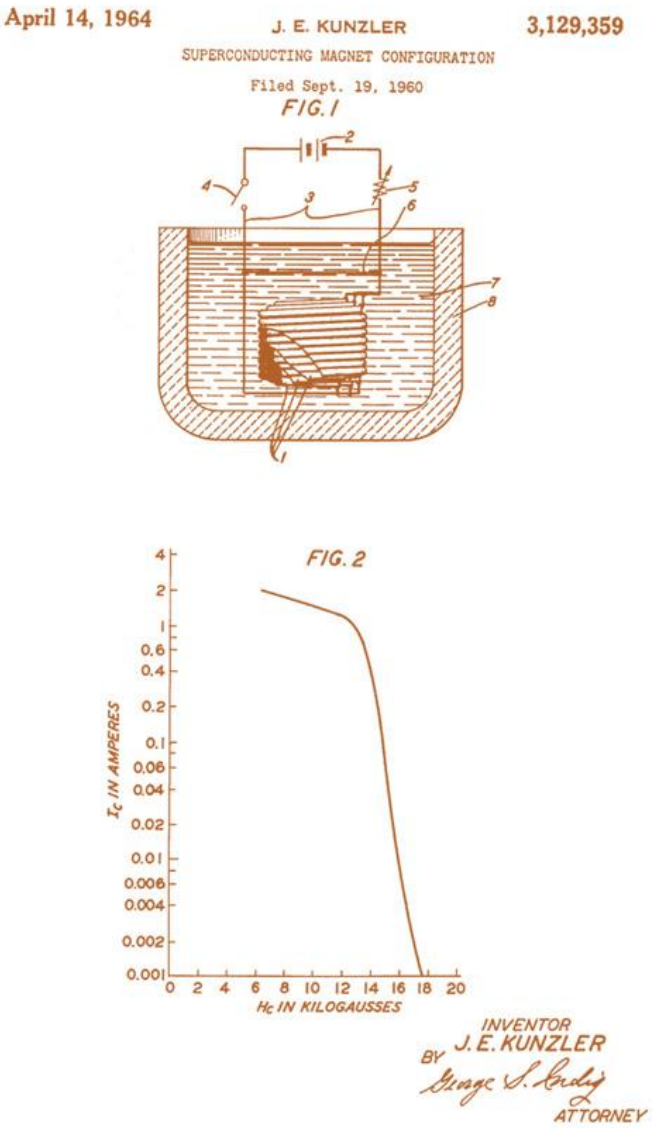




Upper critical field of type II superconductors is compatible with magnet applications



First « high-field » superconducting magnet (1960)



April 14, 1964 J. E. KUNZLER 3,129,359

SUPERCONDUCTING MAGNET CONFIGURATION

Filed Sept. 19, 1960

FIG. 1

FIG. 2

INVENTOR
J. E. KUNZLER
BY George S. Indig
ATTORNEY

Patent filed in 1960 by J. Kunzler, of Bell Laboratories (registered in 1964)

1.5 T reached with magnet wound from molybdenium-rhenium alloy wire

Discovery of Nb-Ti alloys (1961)

PHYSICAL REVIEW VOLUME 123, NUMBER 5 SEPTEMBER 1, 1961

Superconducting Solid Solution Alloys of the Transition Elements

J. K. Hulm and R. D. Blaugher
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

(Received April 19, 1961)

The solid solution alloys formed by the incomplete *d*-shell metals in groups 4, 5, 6, and 7 have been tested for superconductivity down to 1°K. For alloys formed between neighboring elements in a given *row* of the periodic table, two transit
proximately equal to 4.7 and 6.4, respe
upper maximum is absent. Similar max
rows of the periodic table, thus confirn
normal density-of-states function, $N(0)$
these peaks lying at about the same com
ent work. The relationship of T_c to $N($
data are also presented for alloys comp
In this case, the form of the relationshi

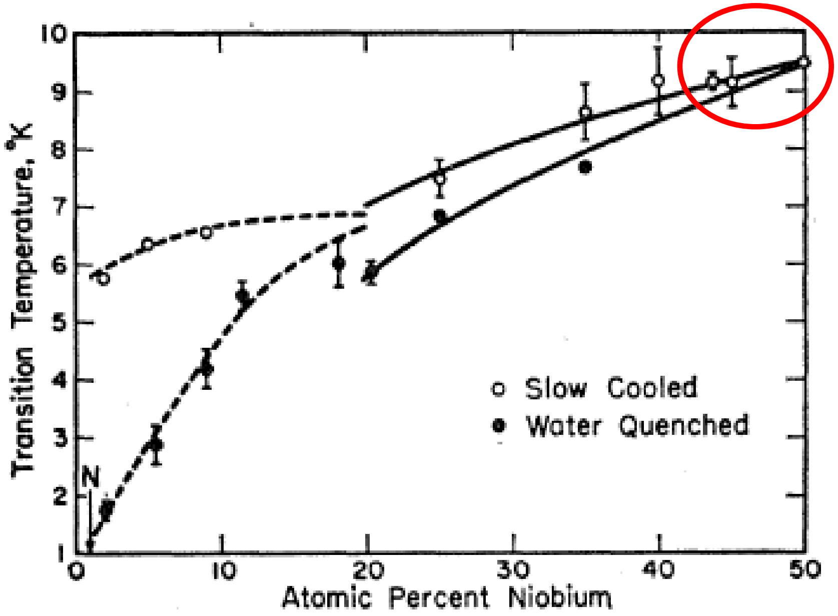


Fig. 6. Transition temperature versus composition for titanium-niobium alloys prepared by different types of heat treatment.

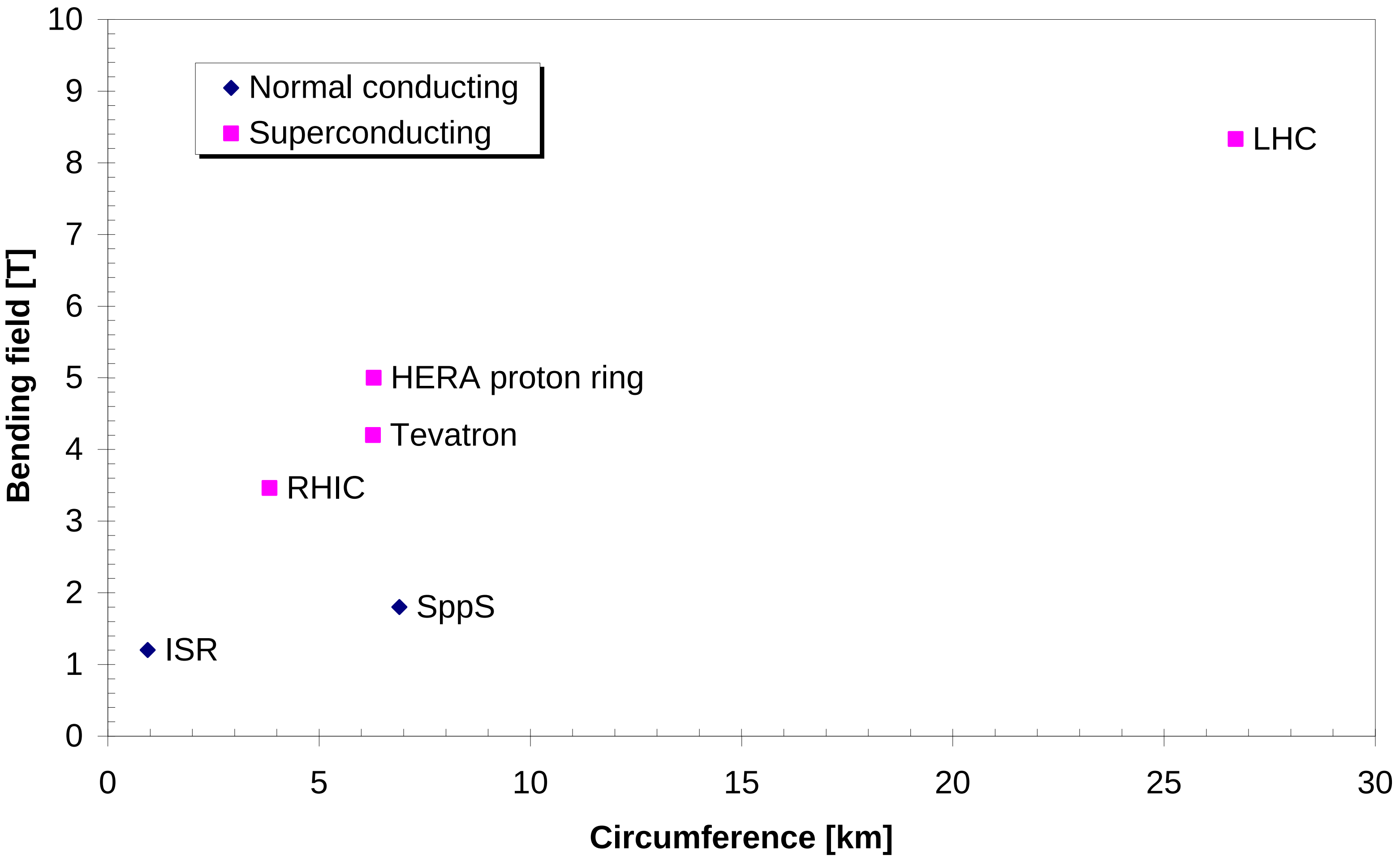
High-energy circular accelerators using superconducting magnets

HERA proton ring at DESY, Germany (1992)

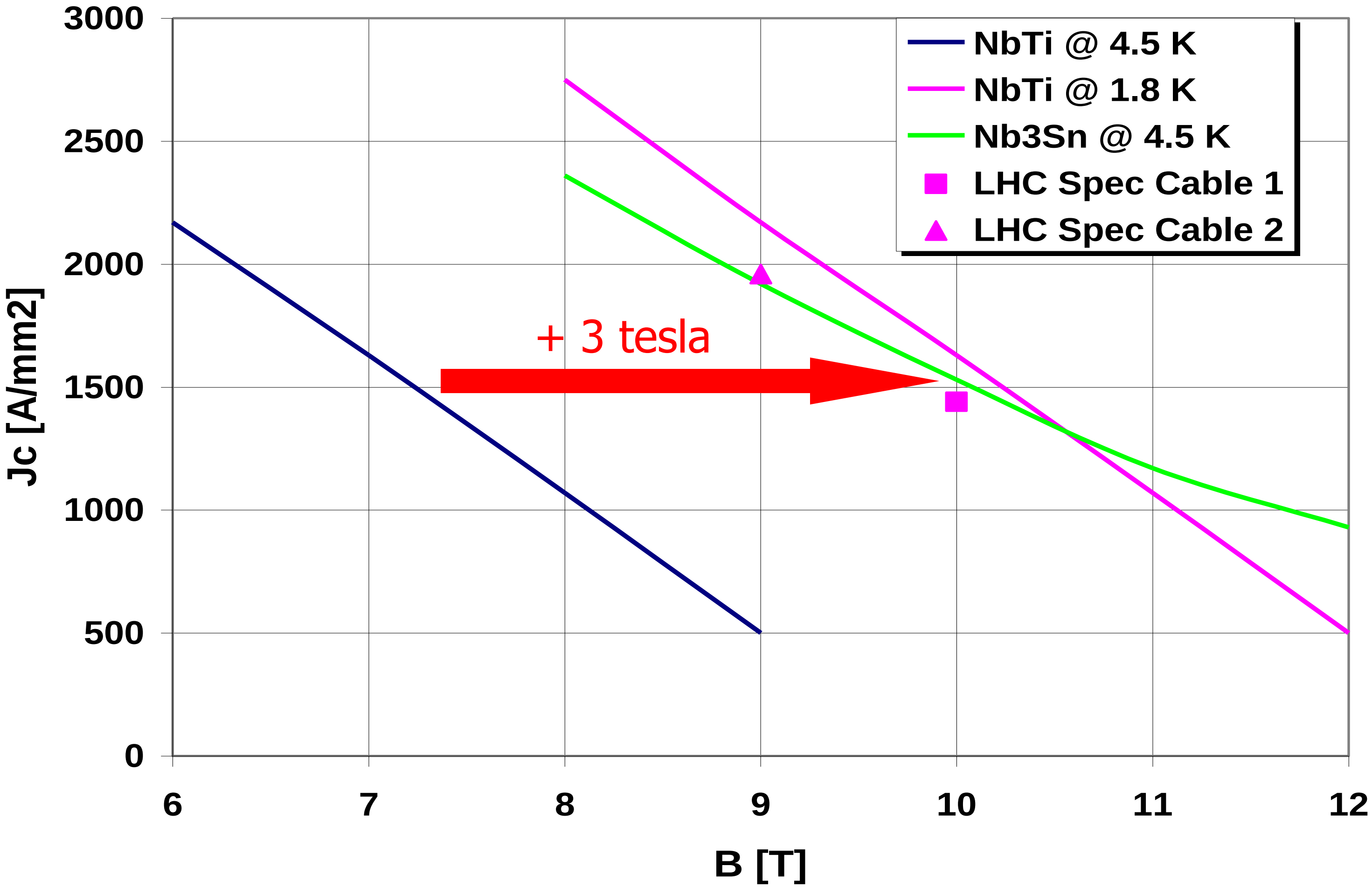
The Tevatron at Fermilab, USA (1983)

RHIC at Brookhaven National Lab, USA (2000)

Circumference & bending field of hadron colliders



Rationale for LHC basic technical design



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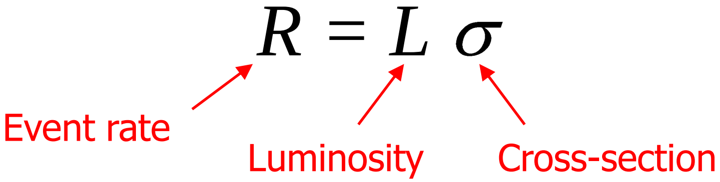
Event rate and luminosity



$$R = L\ \sigma$$

Event rate

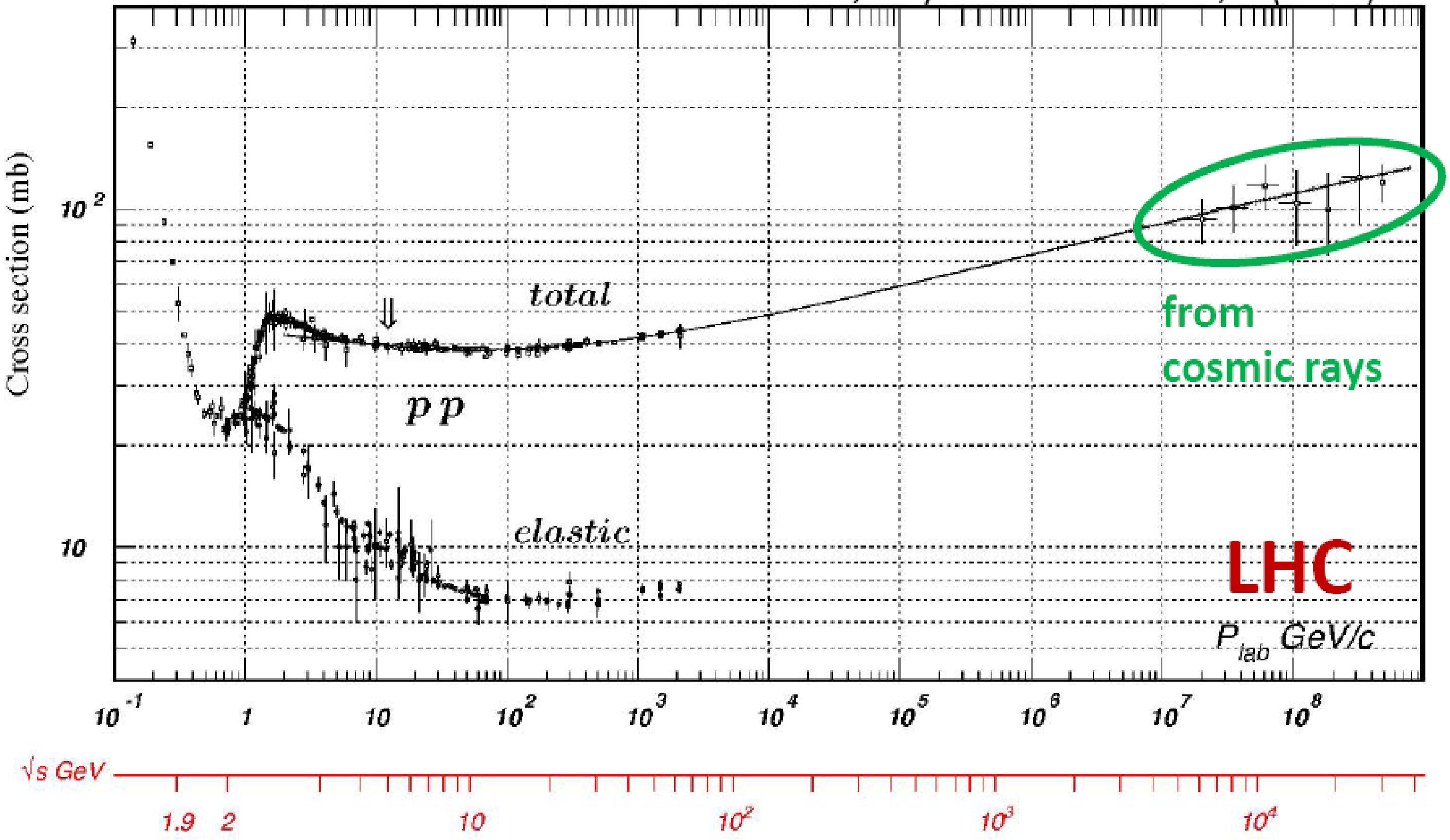
Luminosity

Cross-section

$\sigma_{TOT} \sim 100$ mbarn $= 10^{-25}$ cm^2

$\sigma_{inelastic} \sim 60$ mbarn $= 6\ 10^{-26}$ cm^2

C. Amsler *et al.*, Physics Letters **B667**, 1 (2008)



Luminosity with colliding beams

Number of bunches

Number of particles per bunch

Revolution frequency

Relativistic factor

$$L = \frac{N_b^2 \; n_b \; f_{rev} \; \gamma}{4 \, \pi \, \varepsilon_n \, \beta^*} F$$

Geometric factor linked to crossing angle

Normalized emittance

Beta function at collision point

- To maximize luminosity
  - increase bunch number, bunch population
  - reduce emittance, beta function at collision point
  - cross at small angle

limits?

Beam stored energy

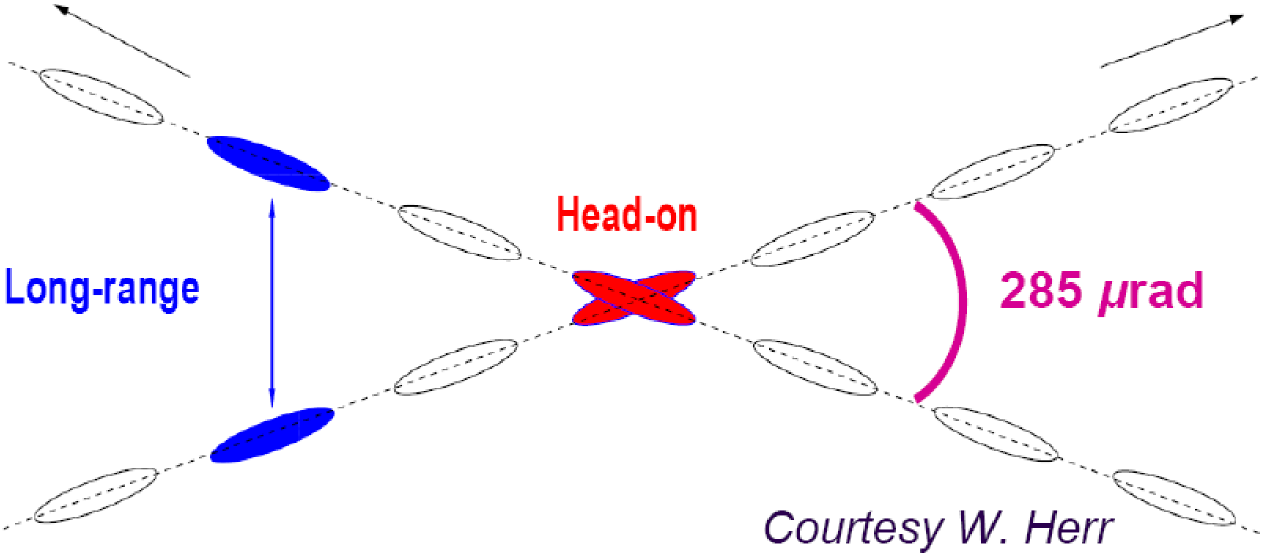
- Energy stored in circulating beam

$$E_{beam} = m_0\, c^2\, \gamma\, N_b\, n_b$$

With 2808 bunches of 1.1 10^{11} protons at 7 TeV, E_{beam} = 362 MJ, equivalent to 80 kg TNT!

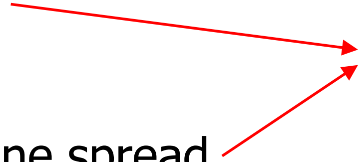
$$L = \frac{N_b\, f_{rev}}{4\,\pi\, m_0\, c^2 \varepsilon_n\, \beta^*}\, F\, E_{beam} = \frac{1}{4\,\pi\, m_0\, c^2}\, \underbrace{f_{rev}}_{\text{Set by machine circumference}}\, \overbrace{\frac{N_b}{\varepsilon_n}}^{\text{Set by injector chain}}\, \overbrace{\frac{F}{\beta^*}}^{\text{Set by collision optics}}\, E_{beam}$$

Beam-beam effects



Courtesy W. Herr

- Particle trajectories in one beam perturbed by e-m field of the other
- Head-on crossing
  - Excites betatron resonances
  - Generates tune spread
- Long-range
  - Additional non-linear tune spread
  - Minimum crossing angle > beam divergence at collision point



tune footprint must not cross low-order resonances

Head-on beam-beam tune shift

Number of collision points

~ 0.01

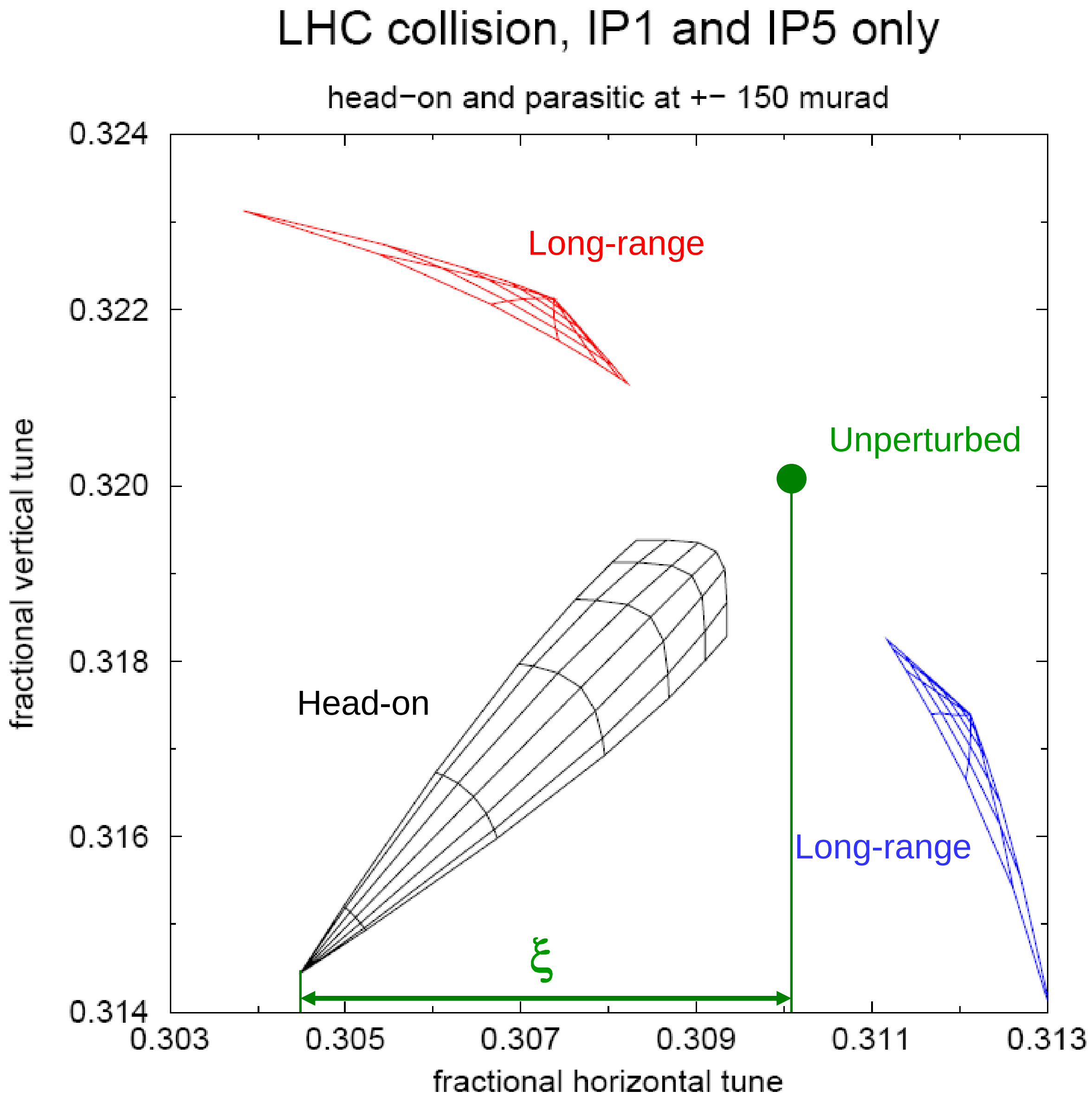
Should not exceed 0.015
(empirical limit)

$$\xi_{total} = \frac{k\ N_b\ r_p}{4\ \pi\ \varepsilon_n} F < \xi_{\max}$$

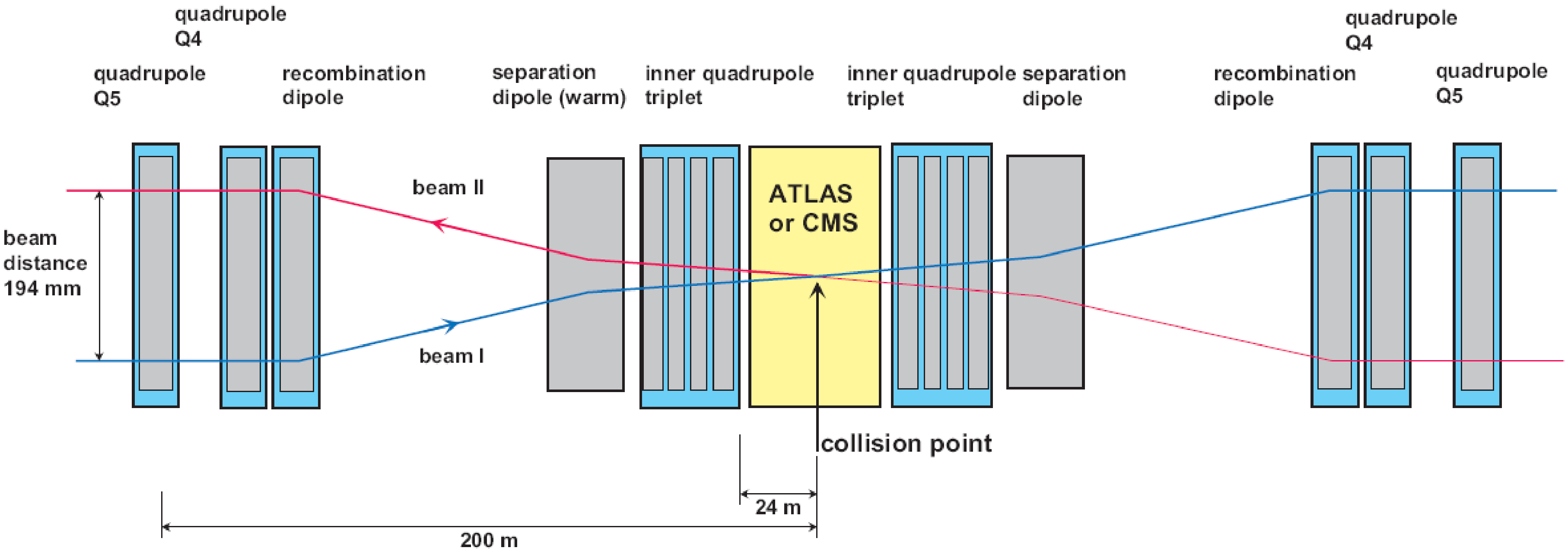
- Strategy to maximize luminosity
  - Operate at beam-beam limit
  - Maximize number of bunches, bunch population
  - Decrease beta at collision point

$$L = \frac{\xi_{total}\ N_b\ n_b\ f_{rev}\ \gamma}{k\ r_p\ \beta^*}$$

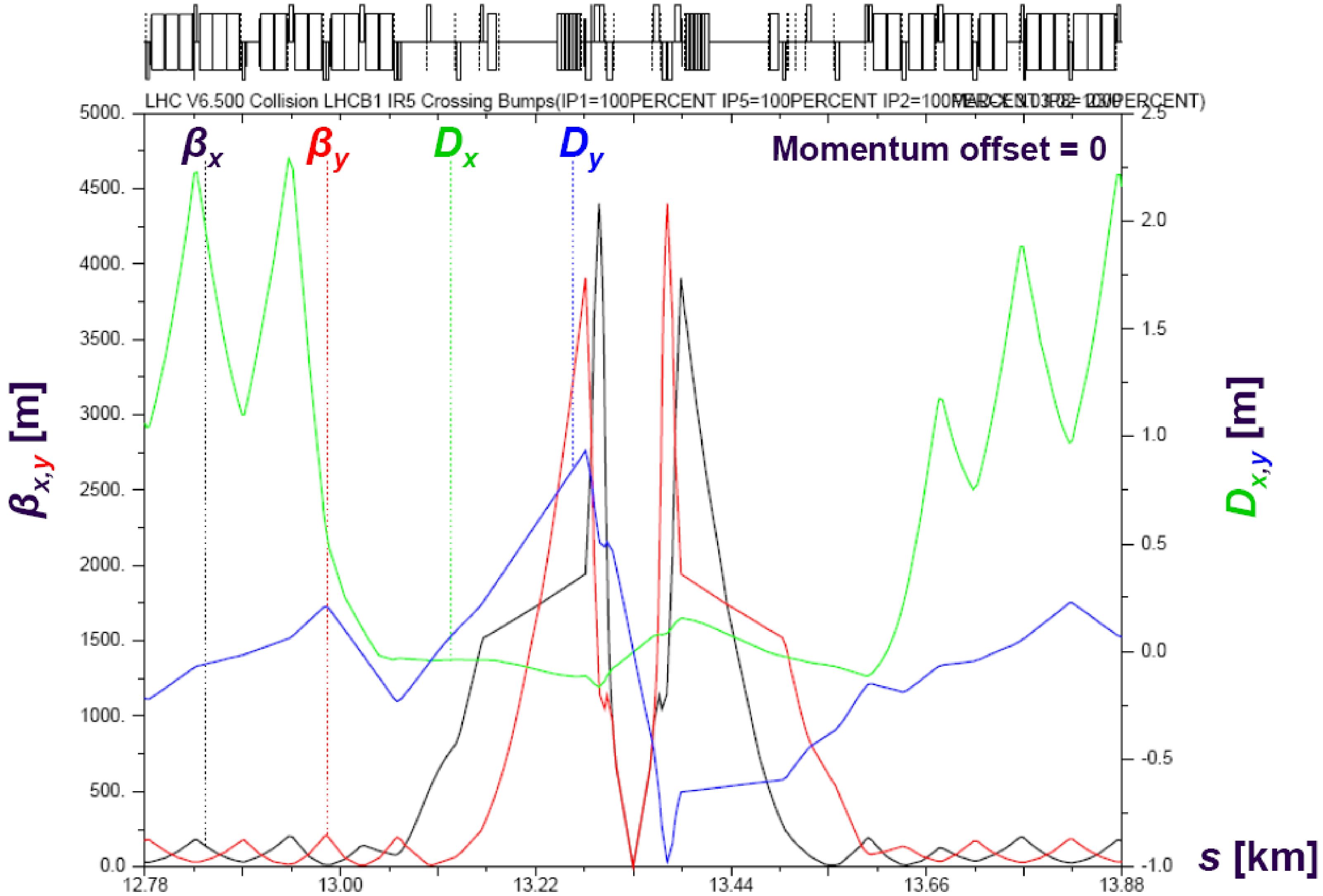
Beam-beam tune footprint



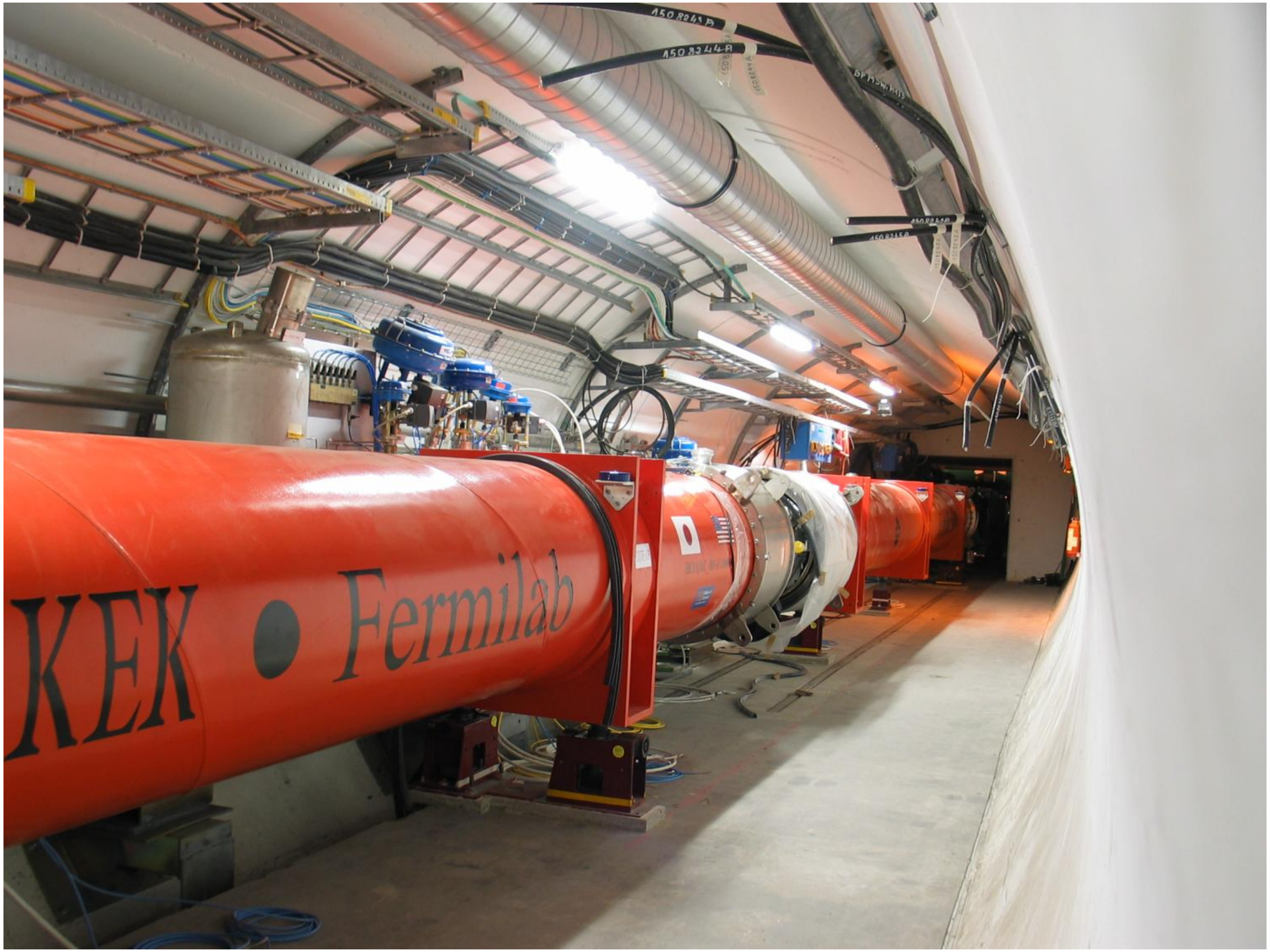
Layout of high-luminosity collision region



High-luminosity insertion optics



High-luminosity insertion
Inner triplet installed at LHC point 5



Luminosity lifetime

- Luminosity will decay with time due to degradation of beam intensity and emittance, by several processes
  - intra-beam scattering, i.e. multiple Coulomb scattering between particles in the same bunch
  - nuclear scattering of particles by residual gas molecules
  - the collisions themselves

~ 45 hours initially, 29
h as N_{total} and L decay

$$\tau_{nuclear} = \frac{N_{total}}{k\, L\, \sigma_{total}}$$

- Overall

$$\frac{1}{\tau_L} = \frac{1}{\tau_{IBS}} + \frac{2}{\tau_{gas}} + \frac{1}{\tau_{nuclear}}$$

~ 15 h, at least
one fill per day

~ 80 h

~ 100 h, must be large
w.r.t. to other processes

~ 29 h

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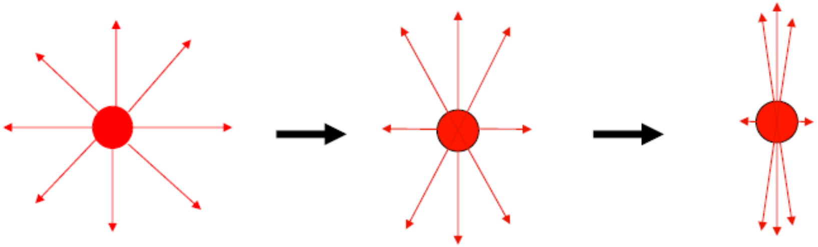
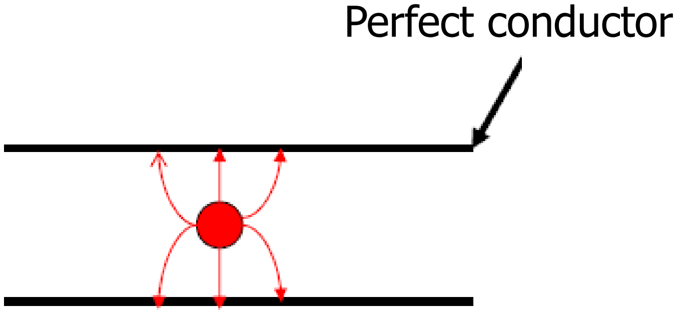
Beam impedance





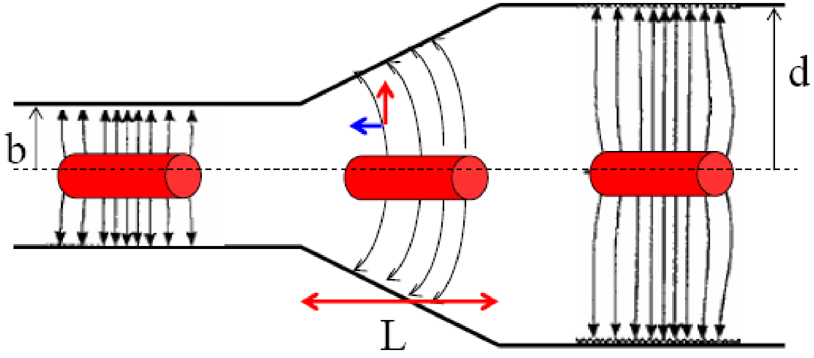
In case of resistive wall or change of cross-section, there is an interaction between the (charged) beam and the wall

⇒ energy dissipation (heating)

⇒ beam instabilities

This interaction can be described by an impedance $Z(\omega)$

Resistive wall or change of cross-section



Low transverse impedance for beam stability

- Transverse impedance

  $Z_T(\omega) \sim \rho\, R / \omega\, b^3$

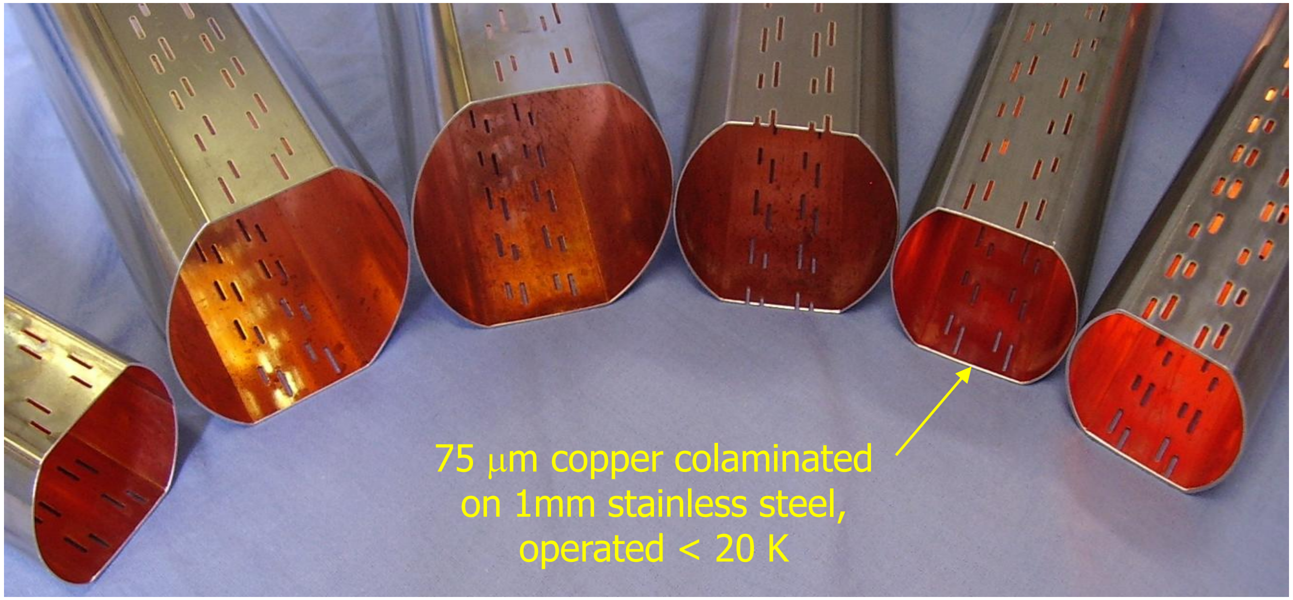
  ρ wall electrical resistivity

  R average machine radius

  b half-aperture of beam pipe

- Transverse resistive-wall instability
  - dominant in large machines with small aperture
  - compensated by beam feedback, provided growth is slow enough (~ 100 turns)
  - maximize growth time $\tau \sim 1/Z_T(\omega)$ i.e. reduce $Z_T(\omega)$

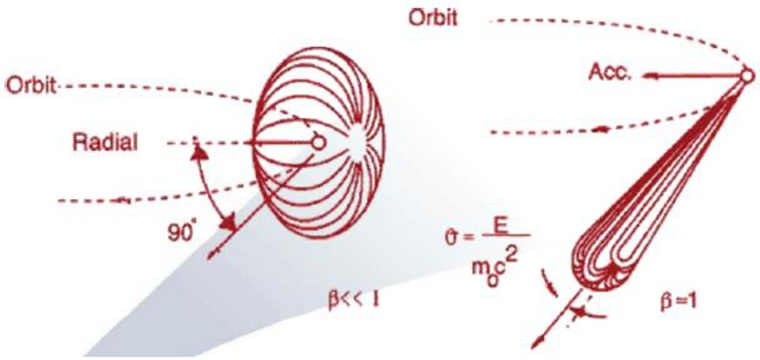
⇒ *low ρ, i.e. low-temperature wall coated with >0.05 mm copper*



75 µm copper colaminated
on 1mm stainless steel,
operated < 20 K

Synchrotron radiation

- Charged particle beams bent in a magnetic field undergo centripetal acceleration and emit e-m radiation
- When beams are relativistic, radiation is emitted in a narrow cone



- Radiated power

Free space impedance

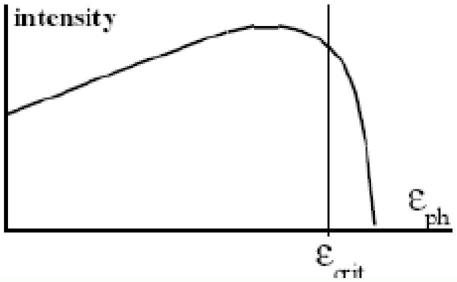
$$P_{syn} = \frac{Z_0\, e^2\, c\, \gamma^4}{3\, R} \boxed{N_b\, n_b\, f_{rev}}$$

~ beam current

Bending radius

- Critical photon energy

$$u_c = \frac{3}{2} \hbar\, c\, \frac{\gamma^3}{R}$$

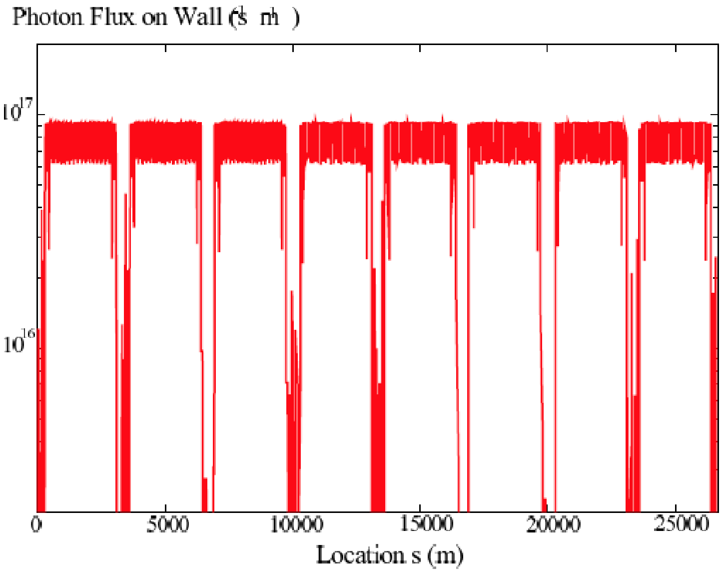


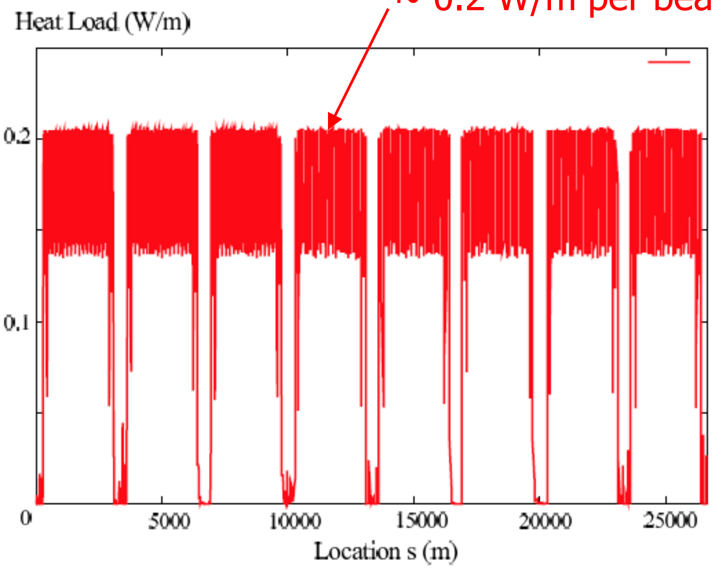
Synchrotron radiation

parameter	450 GeV	7 TeV
total power / beam	0.066 W	3886 W
energy loss per turn	0.11 eV	6.7 keV
average photon flux per metre and second	0.4×10^{16}	6.8×10^{16}
photon critical energy	0.01 eV	43.13 eV
longit. emittance damping time	5.5 yr	12.9 h
transv. emittance damping time	11 yr	26 h

large at low T

UV, easy to screen

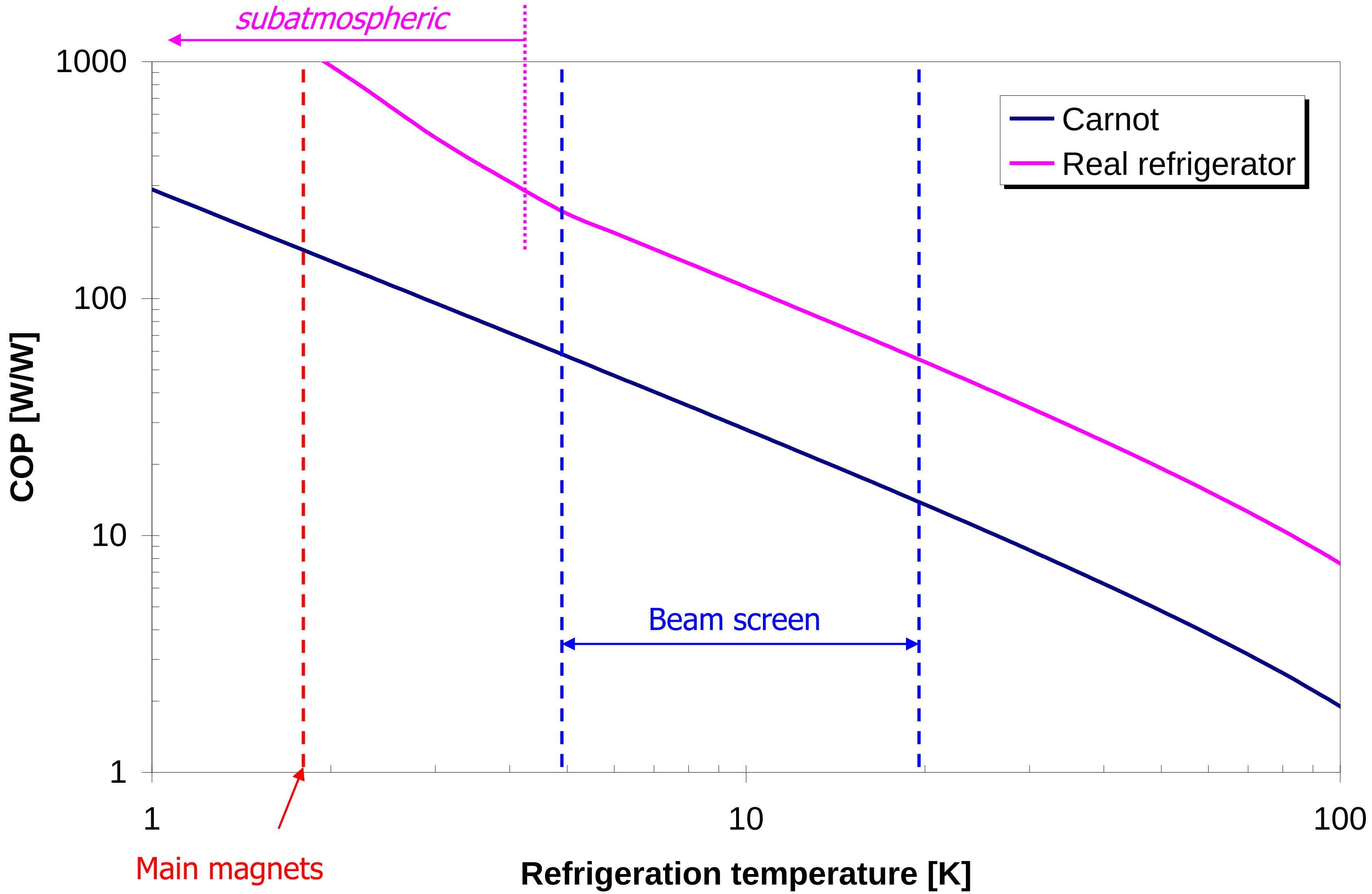




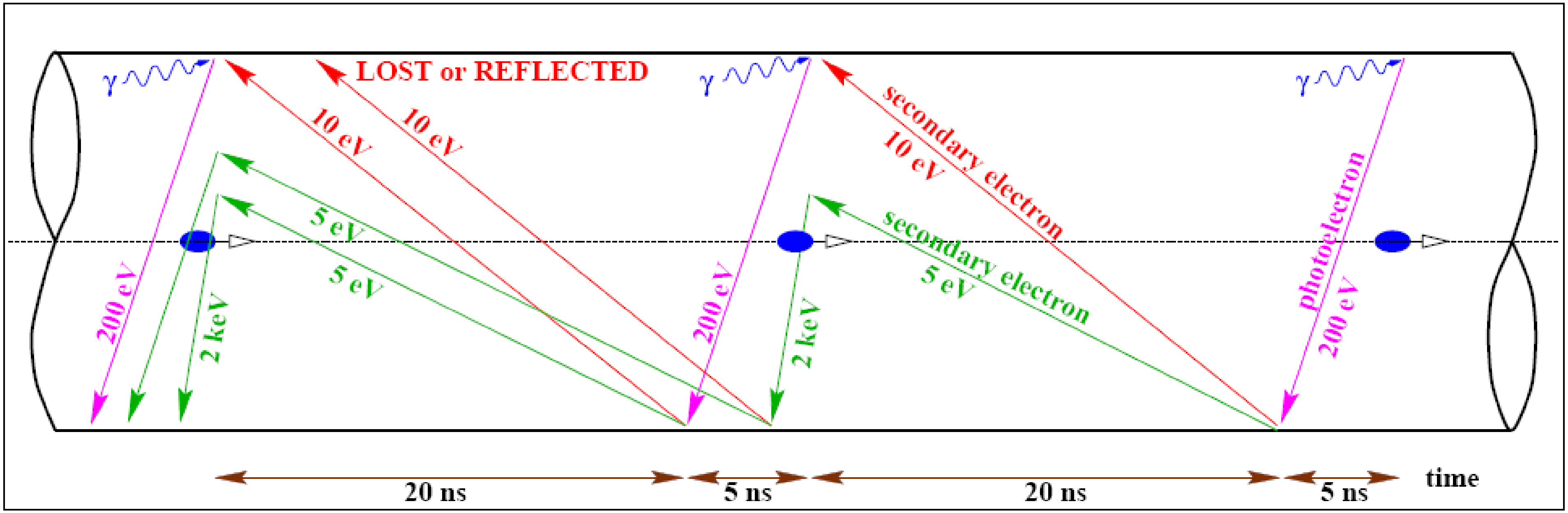
~ 0.2 W/m per beam

COP of cryogenic refrigeration & beam screen

Intercepting beam-induced heating at higher temperature



The electron cloud effect

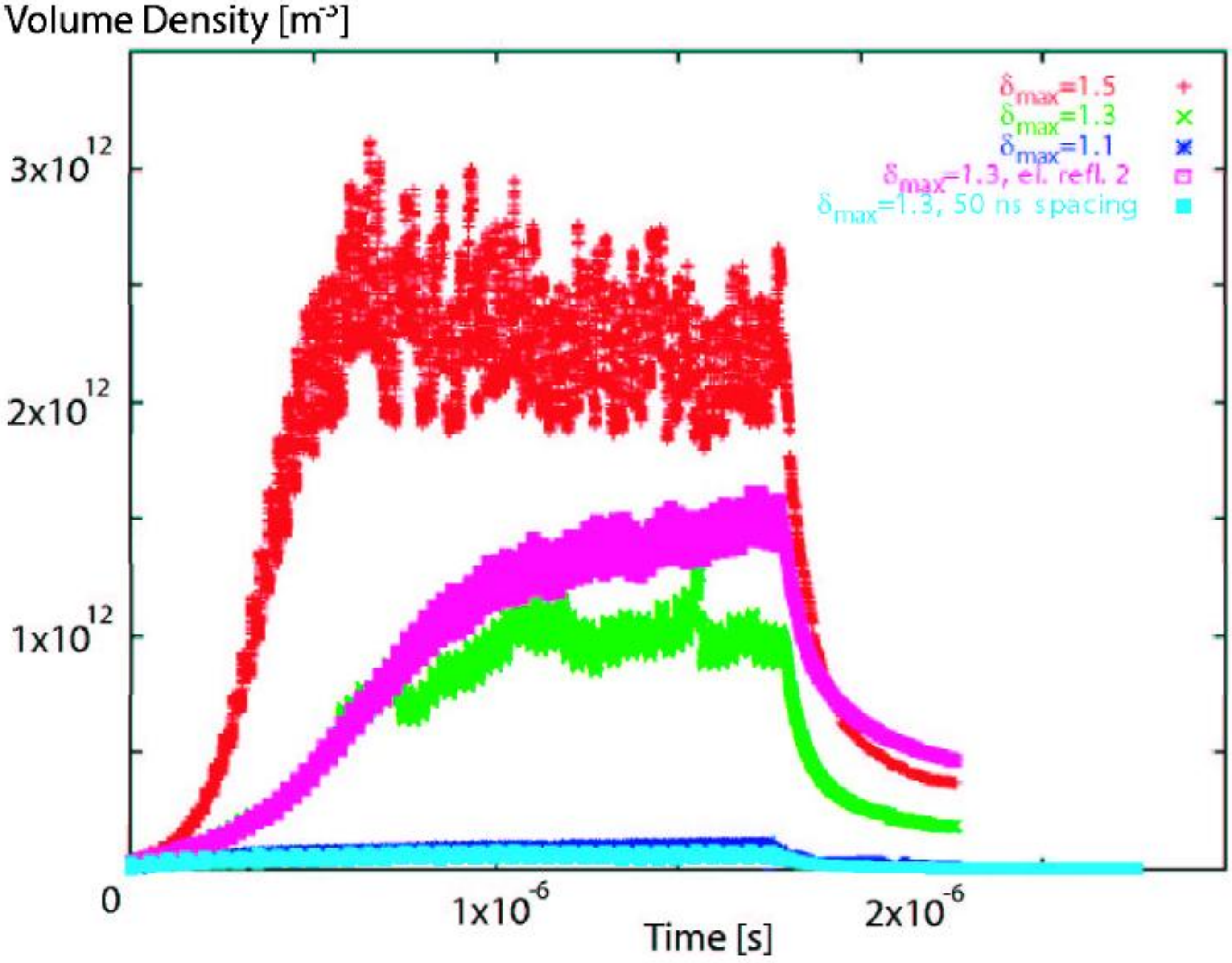


Resonant acceleration of electrons extracted from the wall (photo-electrons and secondary electrons), by the electrical field of the successive bunches.

Governed by:

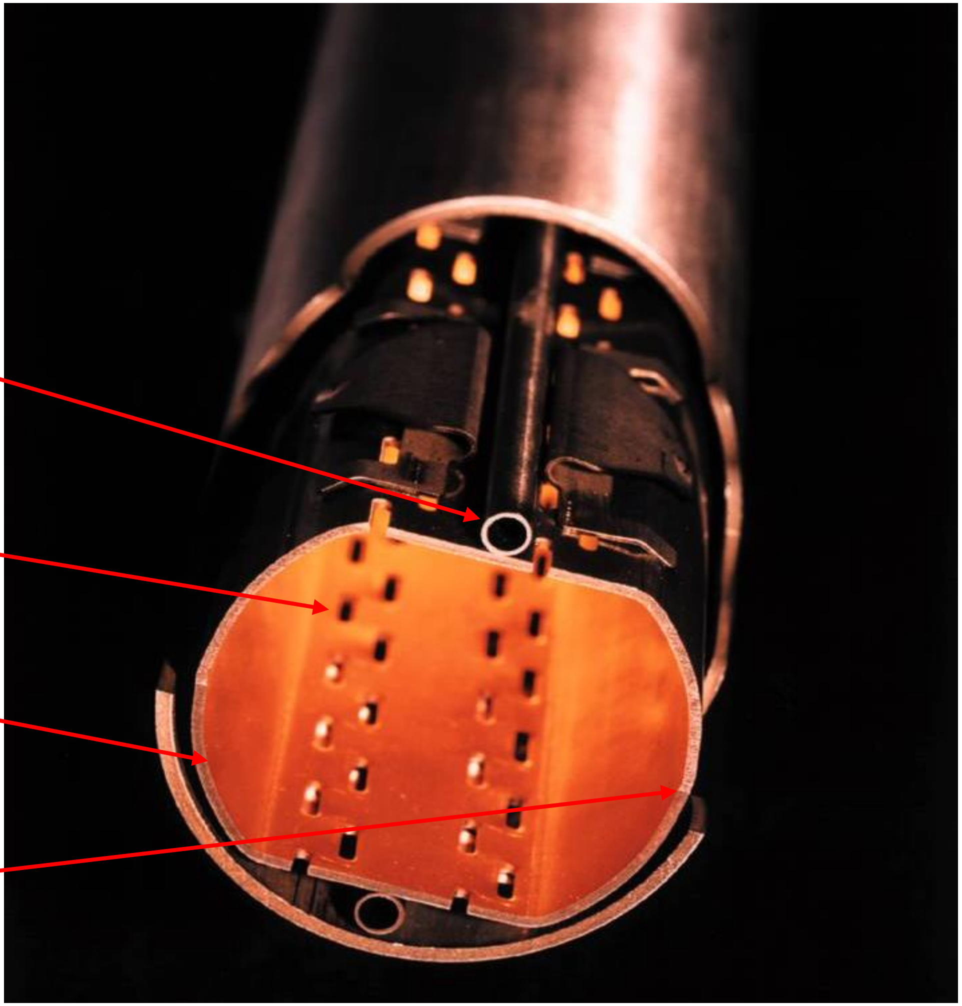
- photon irradiation of the wall ⇒ *low reflectivity surface*
- bunch repetition rate ⇒ *increase bunch spacing*
- secondary electron yield ⇒ *low-SEY surface and beam cleaning*

Simulated build-up of electron cloud, for different values of SEY

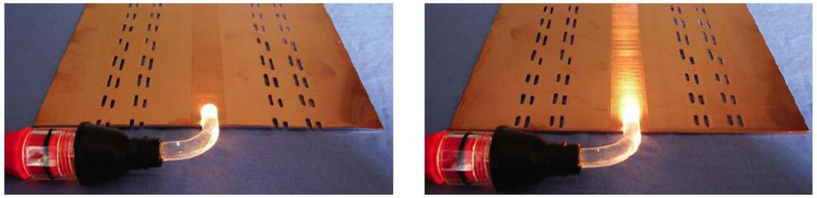


The beam screen

A multi-function component required by beam physics

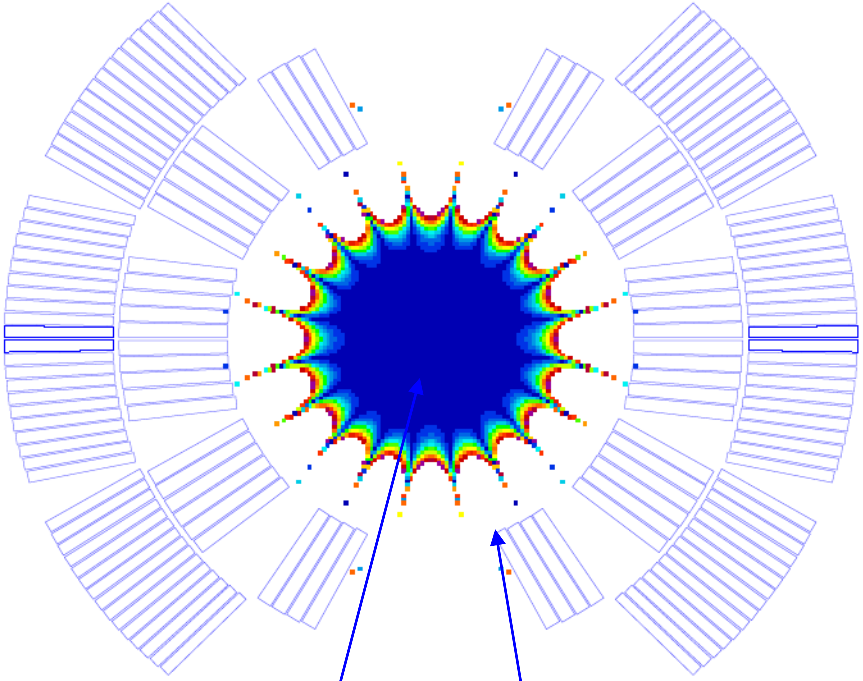


- Interception of beam-induced heat loads at 5-20 K (supercritical helium)
- Shielding of the 1.9 K cryopumping surface from synchrotron radiation (pumping holes)
- High-conductivity copper lining for low beam impedance
- Low-reflectivity sawtooth surface at equator to reduce photoemission and electron cloud



Contents

Field quality in superconducting magnets



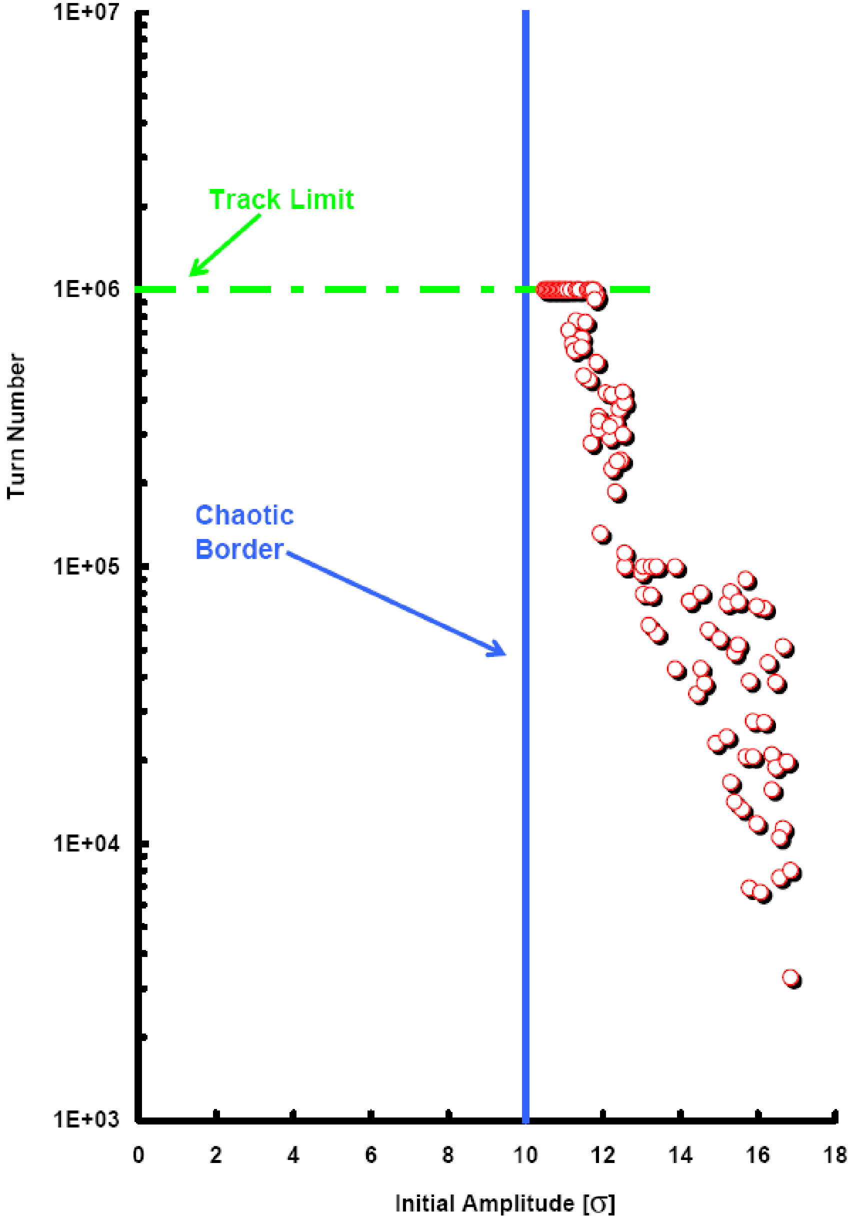
« Good field » region
ΔB/B < 10^{-4}

Magnet
« aperture »

$$B_y + iB_x = B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_{ref}} \right)^{n-1}$$

- In superconducting magnets, the field quality is determined by the positioning precision of a finite number of conductors and not by the geometry of the iron yoke, so it can never be as good as in conventional "iron-dominated" magnets
- As a consequence, the « good field » region is substantially smaller than the magnet aperture
- Dynamic aperture = aperture inside which particle orbits are stable
- Dynamic aperture estimated by computer « tracking » of particle orbits around virtual machines with distributed random and systematic imperfections
- Tracking results are used to define maximum systematic and random deviations of each field multipole

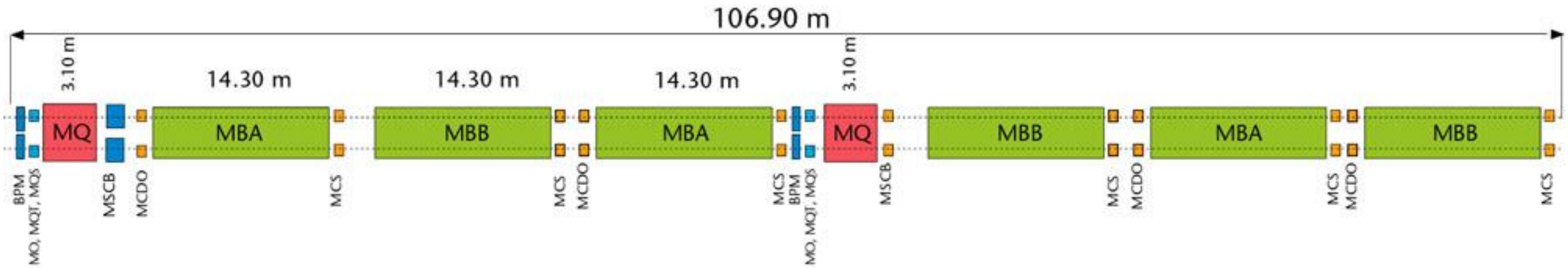
Dynamic aperture from tracking simulations



From tracking simulations to real d.a.

Source or Uncertainty	Impact	D.A. in σ
Target for tracking 10^5 turns		12
Finite mesh size	-5%	
Linear Imperfections[a]	-5%	
Amplitude ratio x_i/y_i plane	-5%	
Extrapolation to 4 10^7 turns	-7%	9.4
Time dependent multipoles	-10%	
Ripple	-10%	7.5
safety margin	-20%	6.0

Schematic layout of one LHC cell (23 periods per arc)



MQ: Lattice Quadrupole
MO: Landau Octupole
MQT: Tuning Quadrupole
MQS: Skew Quadrupole
MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
BPM: Beam position monitor
MBA: Dipole magnet Type A
MBB: Dipole magnet Type B
MCS: Local Sextupole corrector
MCDO: Local combined decapole and octupole corrector

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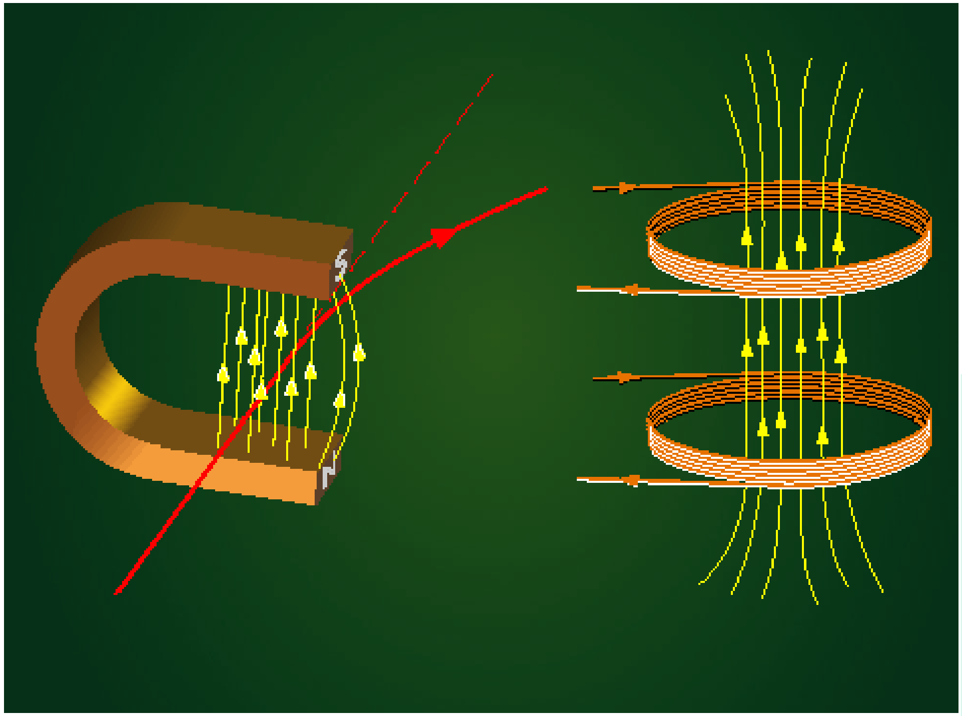
  - Vacuum

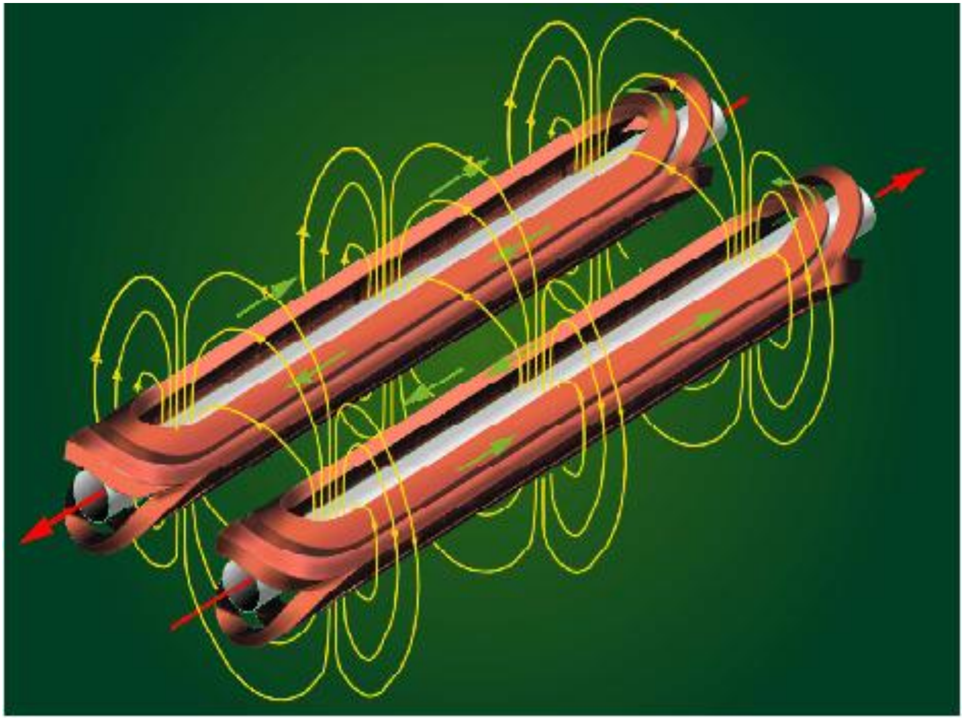
Superconducting accelerator magnets



In a superconducting magnet, the field level and geometry is basically given by the current distribution in the coils

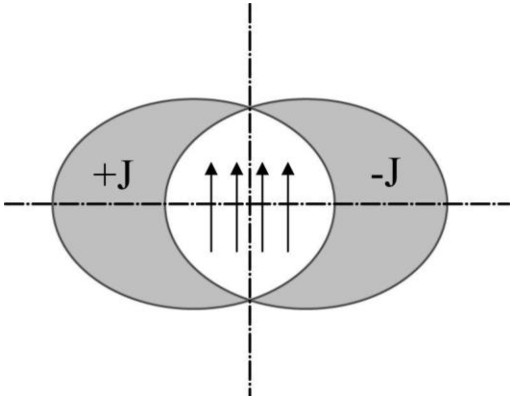
To match the geometry of the beam tubes, the coils are saddle-shaped & elongated

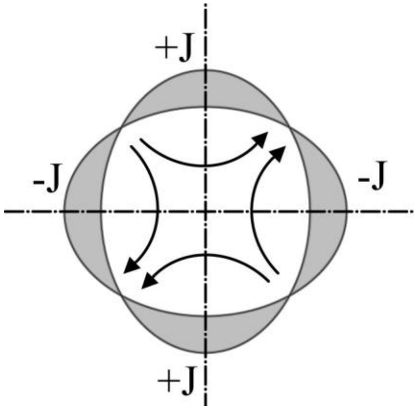
In the LHC, two sets of coils create opposite fields in the neighbouring apertures



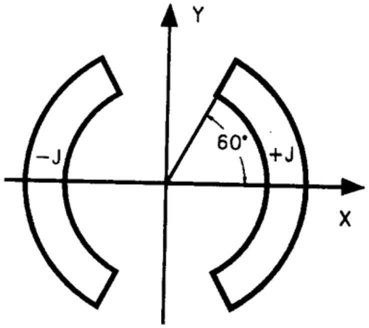
Current distributions

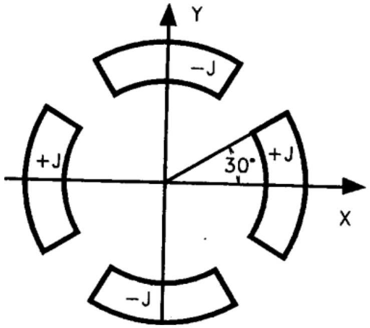
Two intersecting ellipses with uniform current density generate uniform dipole and quadrupole fields ⇒ **"cos θ"** geometry

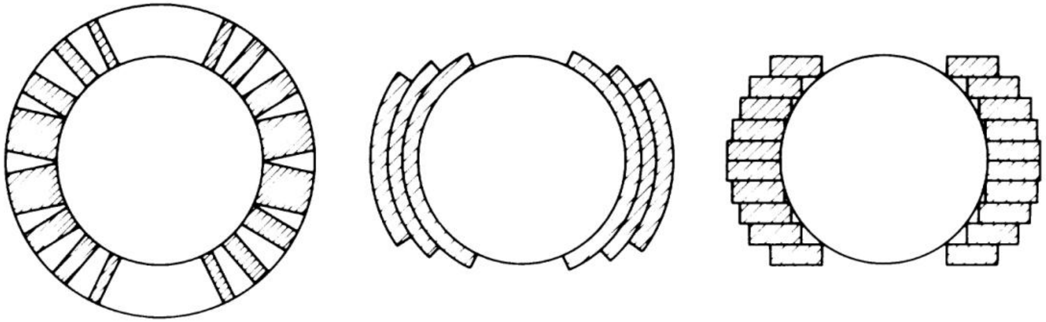




In practice, this can be approximated by current sheets, leading to "**block**" or "**layer**" coil designs





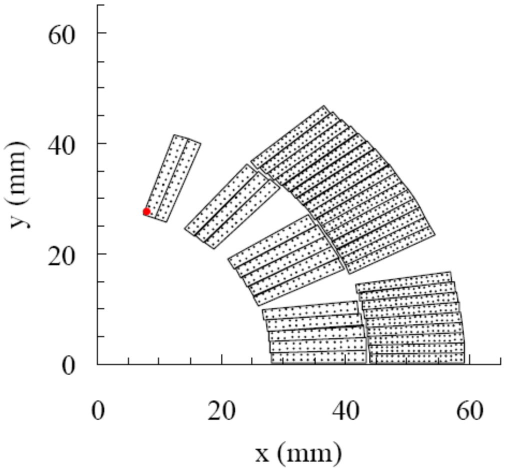


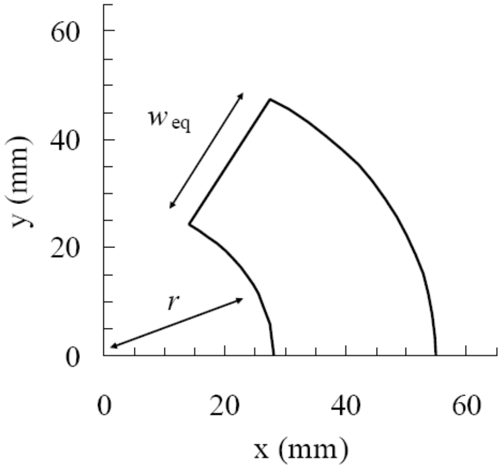
Field of single-layer dipole coil

Average current density in coil

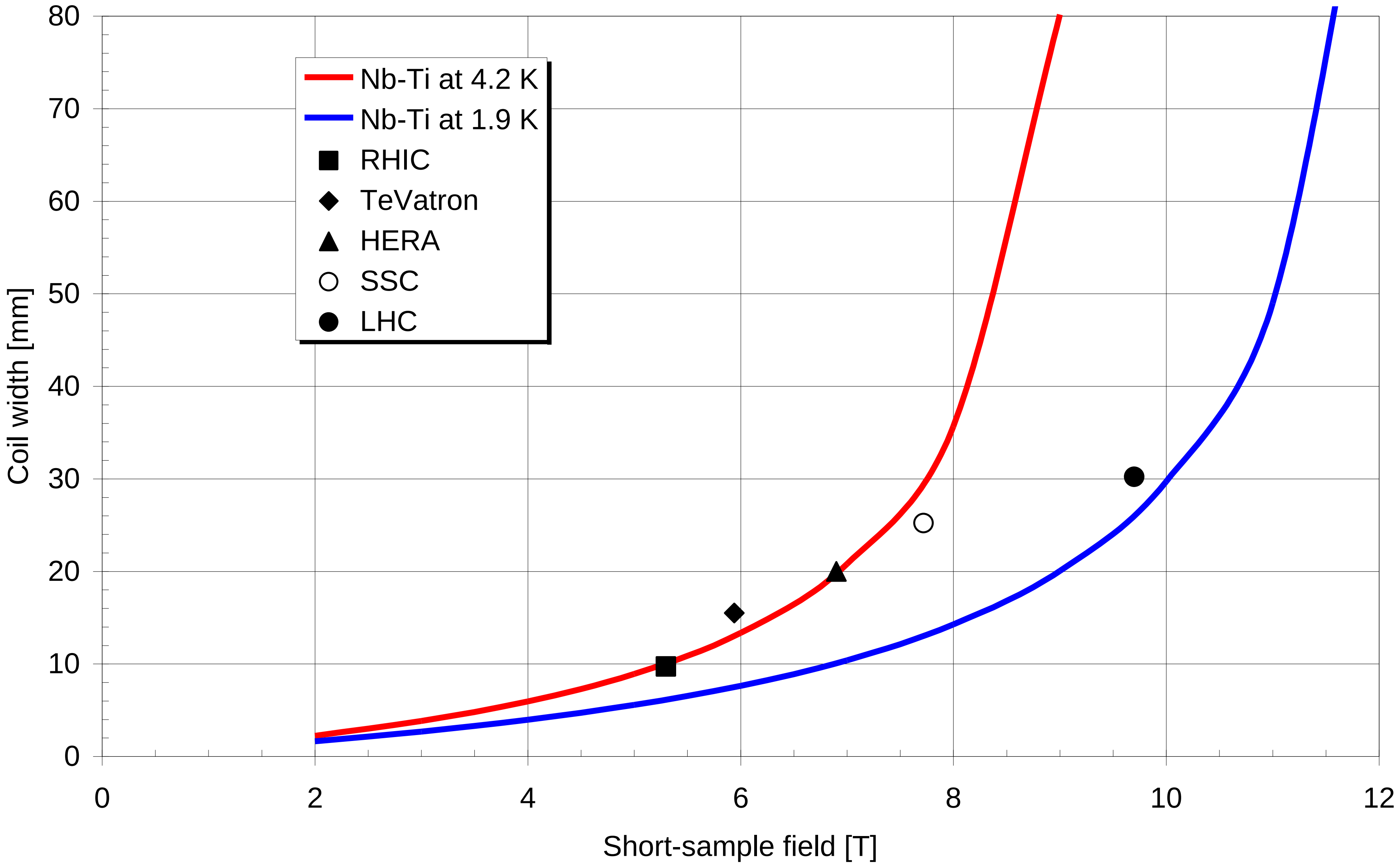
$$B = \frac{\mu_0 \sqrt{3}}{\pi} \; j_{tech} \; w$$

Coil width

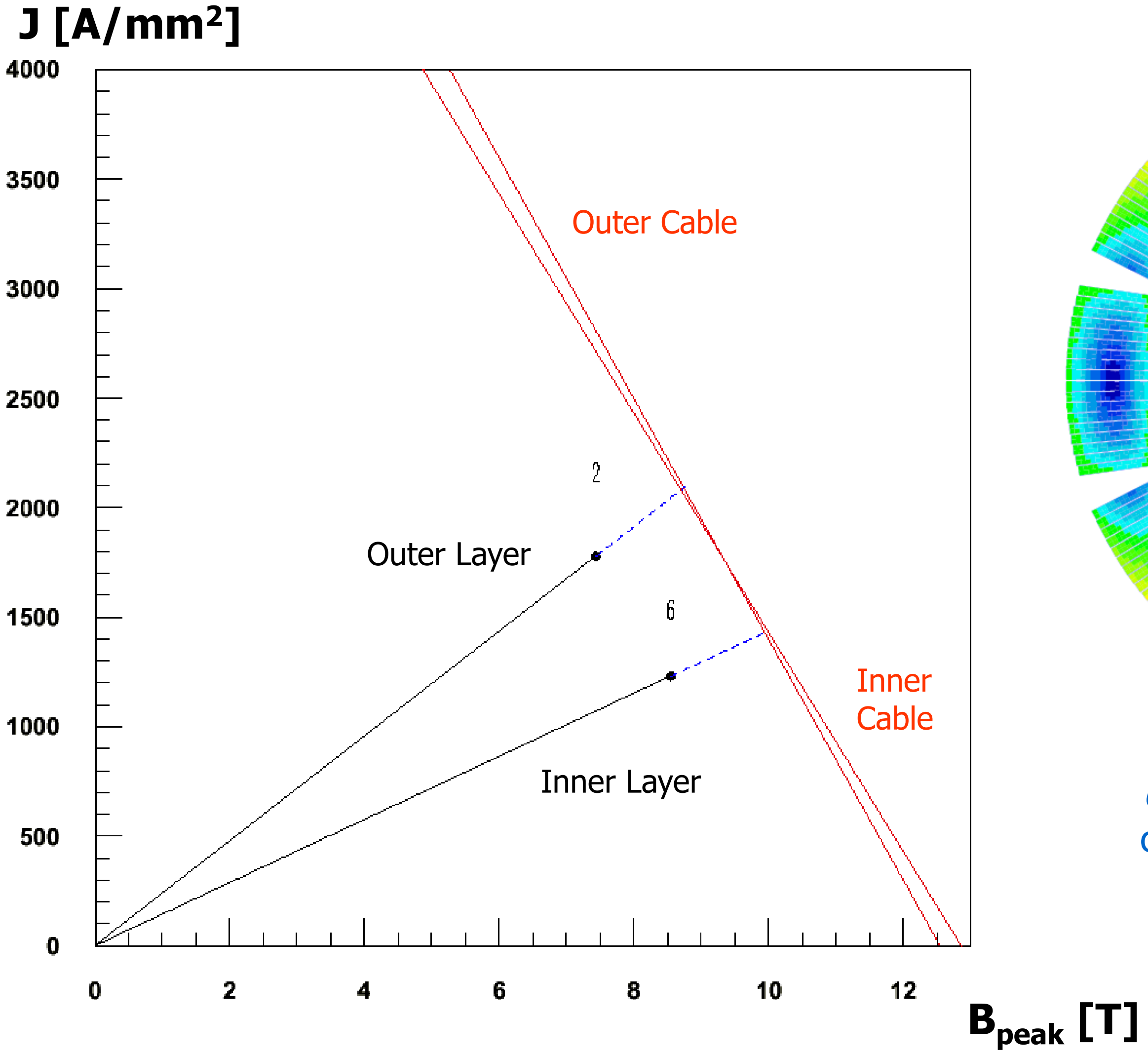


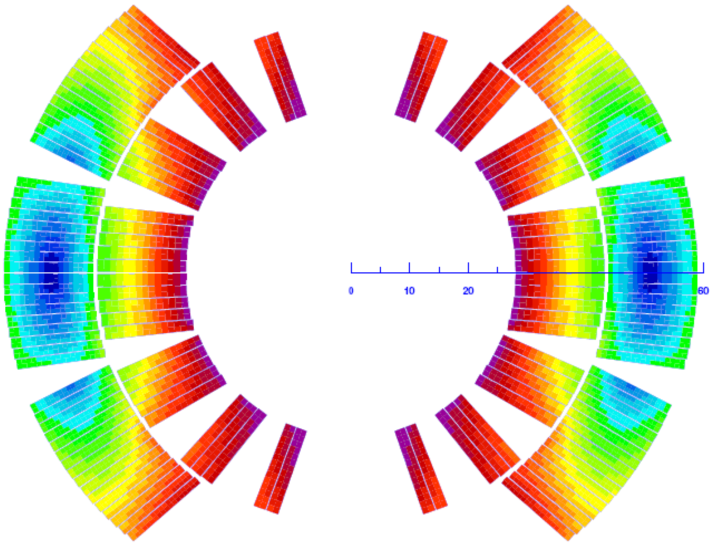


Superconducting cos θ dipoles in Nb-Ti Coil width vs field



Load lines of LHC main dipole

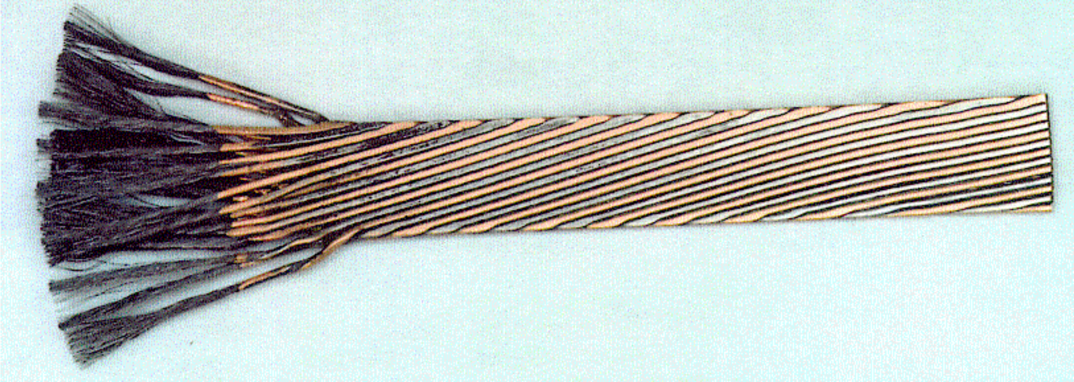




Current grading permits the outer cable, which sees a lower field, to operate at higher current density

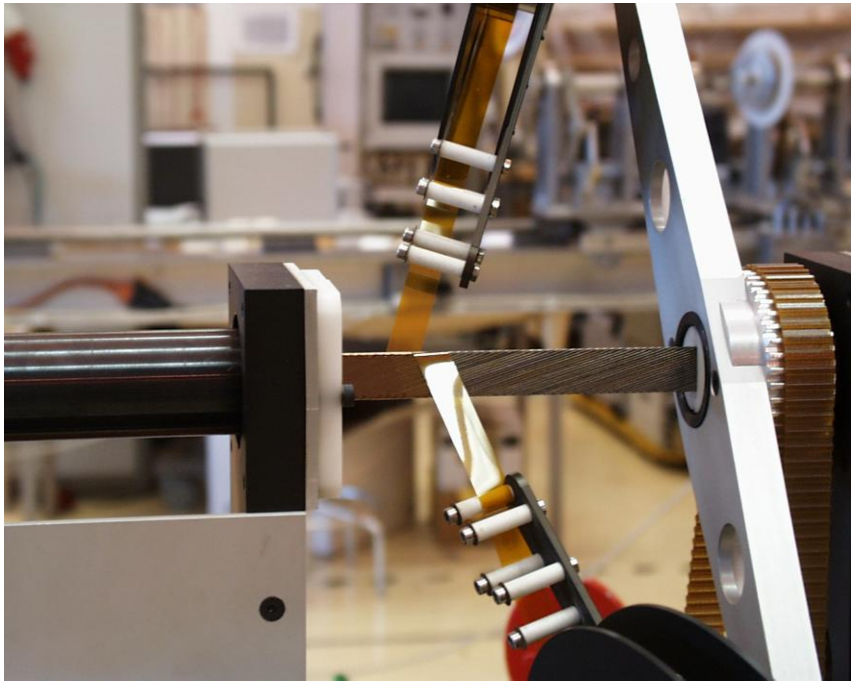
Inter-layer splice in graded coil

7500 km of high-performance superconducting cable



Cable with etched strands showing Nb-Ti filaments

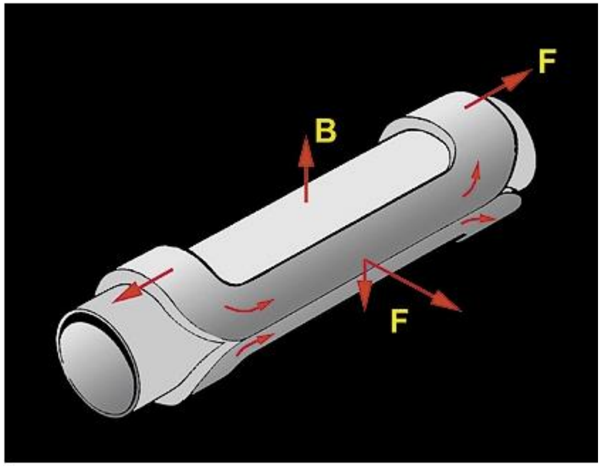
Cable insulation by double polyimide wrap

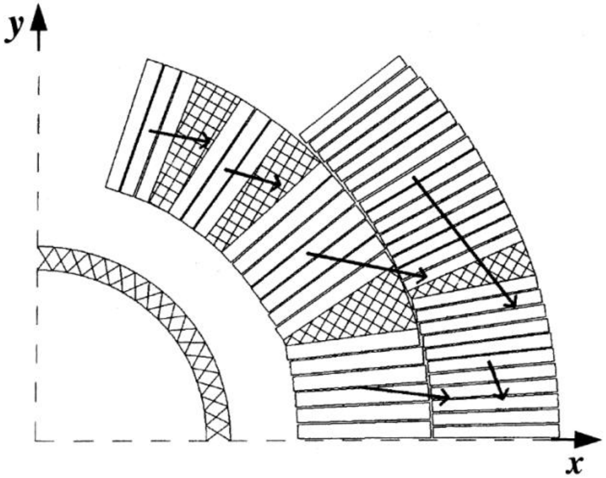


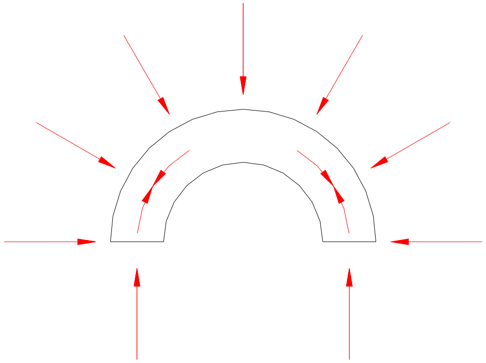
	Inner Cable	**Outer Cable**
Number of strands	28	36
Strand diameter	1.065 mm	0.825 mm
Filament diameter	7 µm	6 µm
Number of filaments	~ 8900	~ 6520
Cable width	15.1 mm	15.1 mm
Mid-thickness	1.900 mm	1.480 mm
Keystone angle	1.25	0.90
Transposition length	115 mm	100 mm
Ratio Cu/Sc	≥ 1.6	≥ 1.9

Manufacturing of superconducting coils

Electromagnetic forces







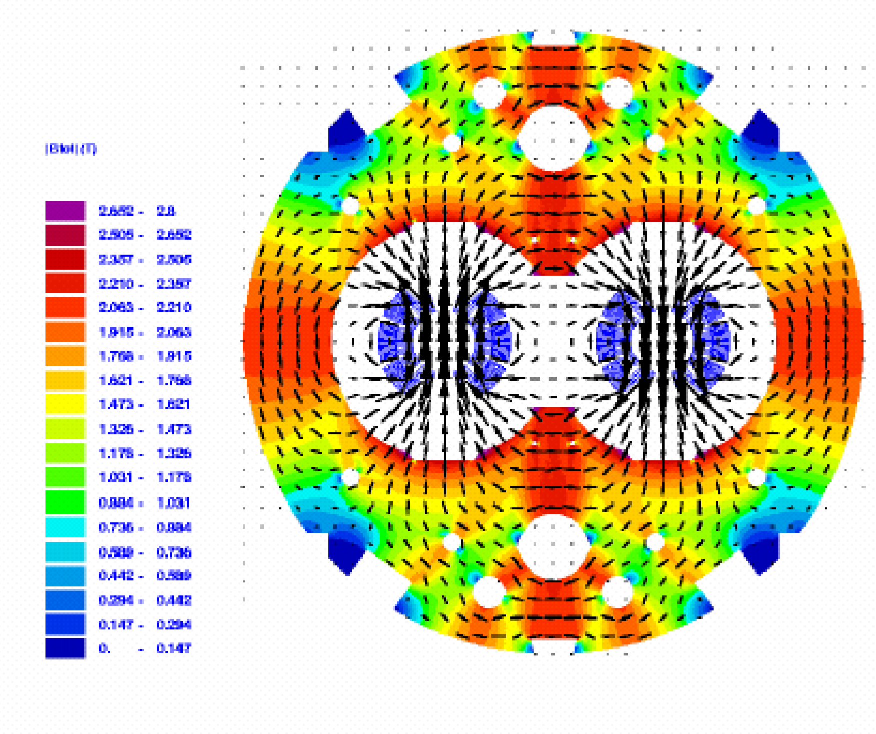
High magnetic field acting on high current generates large **electromagnetic forces** at right angle, which cannot be resisted by the mechanical strength of the conductor: saddle-shaped coils of accelerator magnets are not self-supporting

B = 10 T, I = 10 kA ⇒ 10^5 N/m per turn !

⇒ "**roman arch**" coil geometry to contain the azimuthal component

⇒ external **support structure** against the radial component

Twin-aperture dipole magnet



Limited transverse space in tunnel ⇒ compact cross-section

Flux closure within twin magnet yoke ⇒ magnetically efficient design, limited stray field

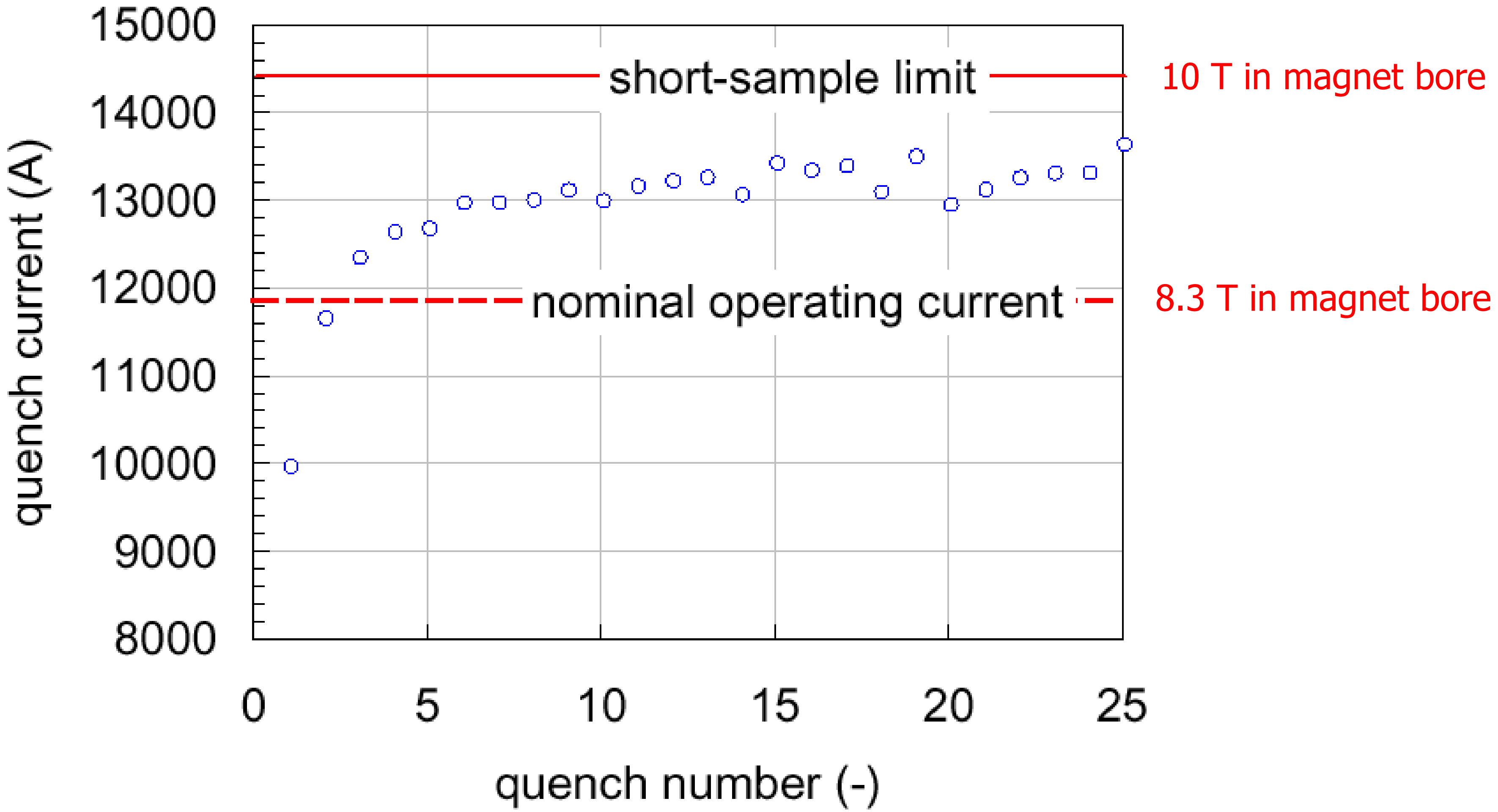
Stainless steel collars resting on iron yoke inside preshrunk cylindrical shell ⇒ rigid structure

Assembly of dipole cold masses

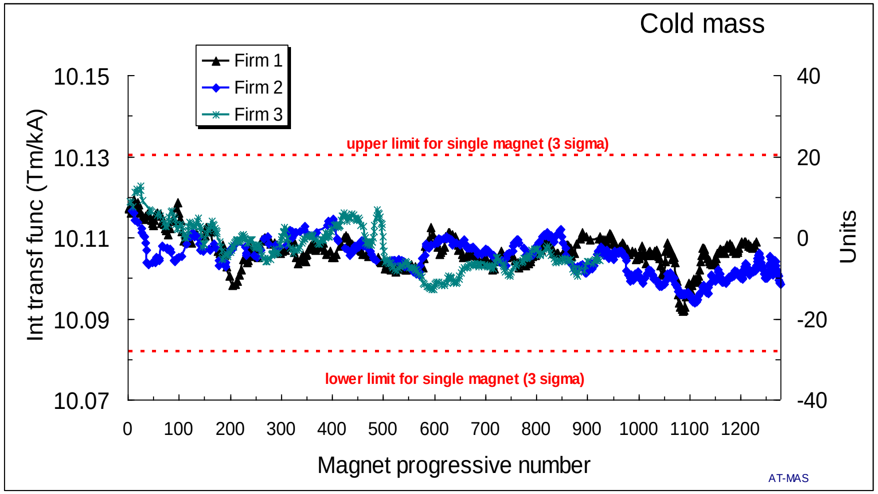
Final assembly of cryomagnets at CERN

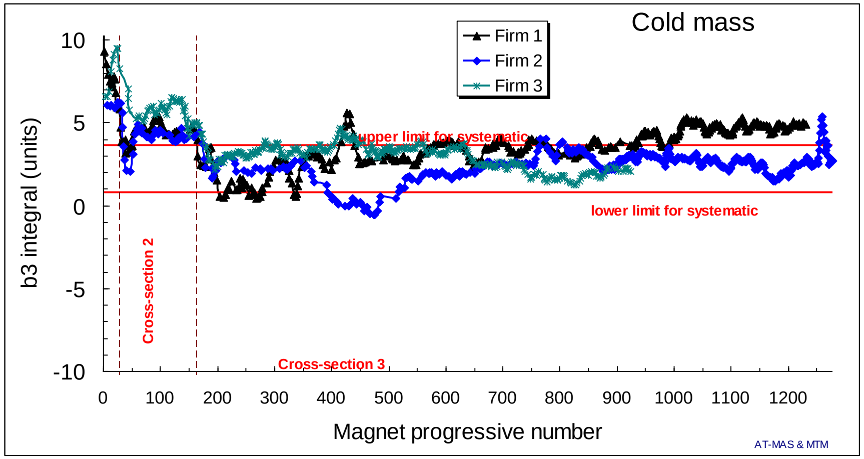
Cryogenic tests of magnets

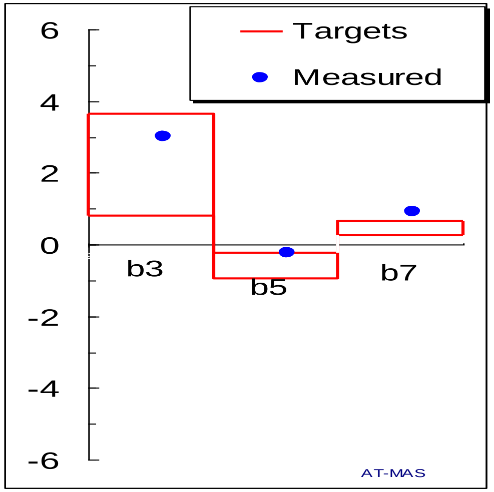
Training of superconducting magnets

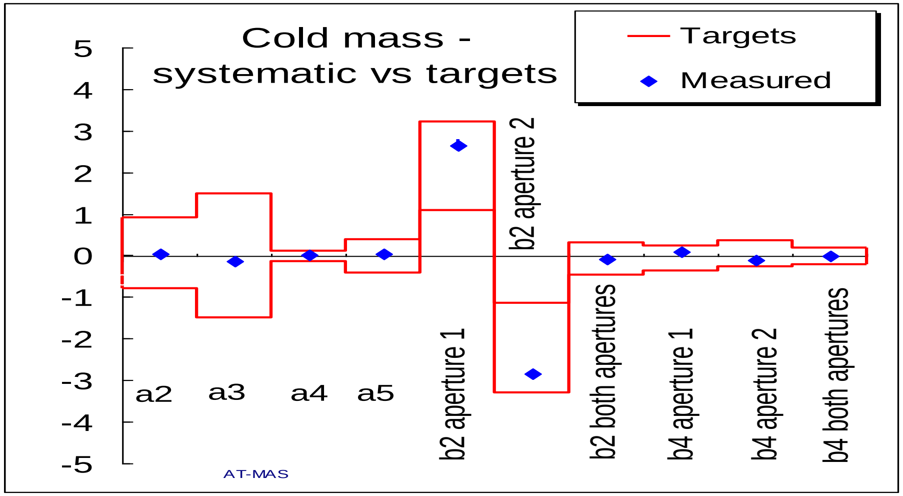


Dipole field quality in series production

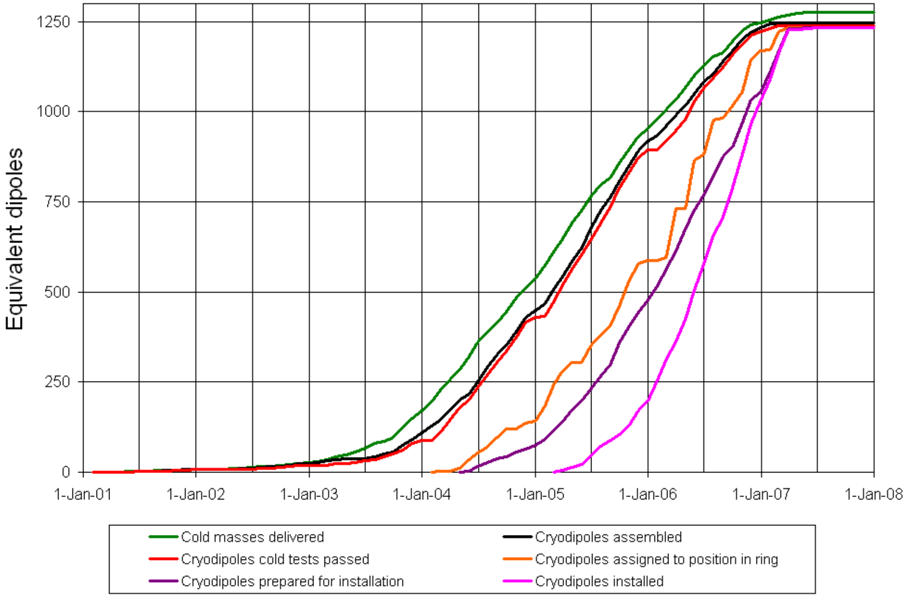


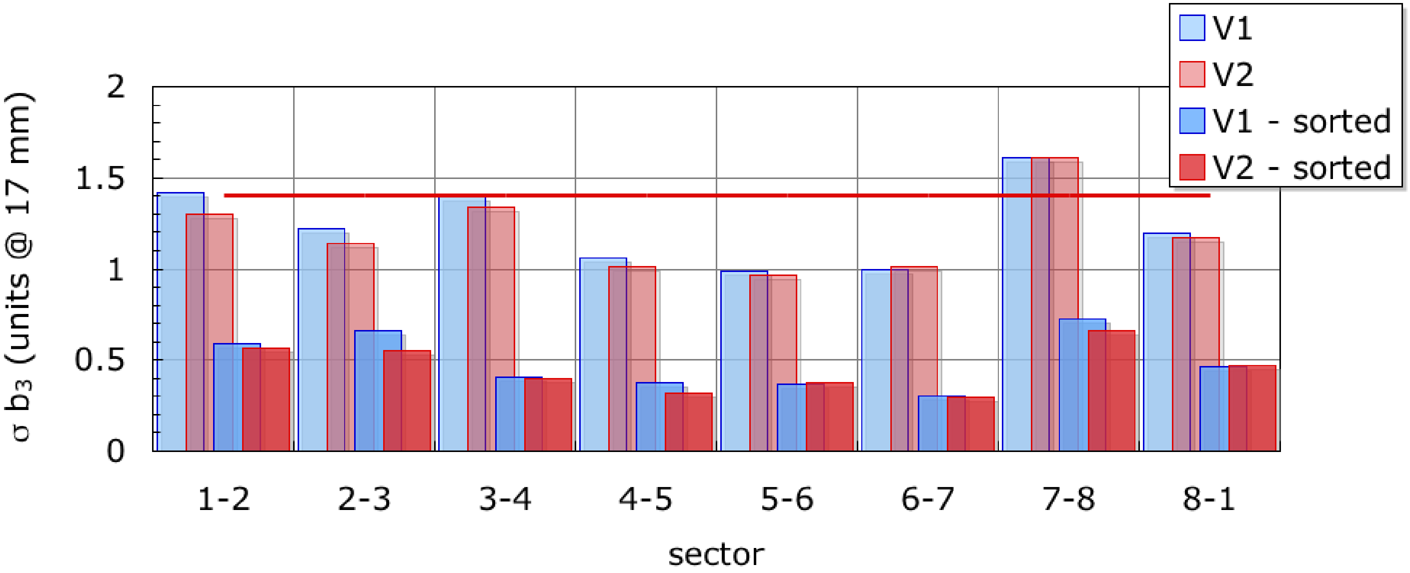




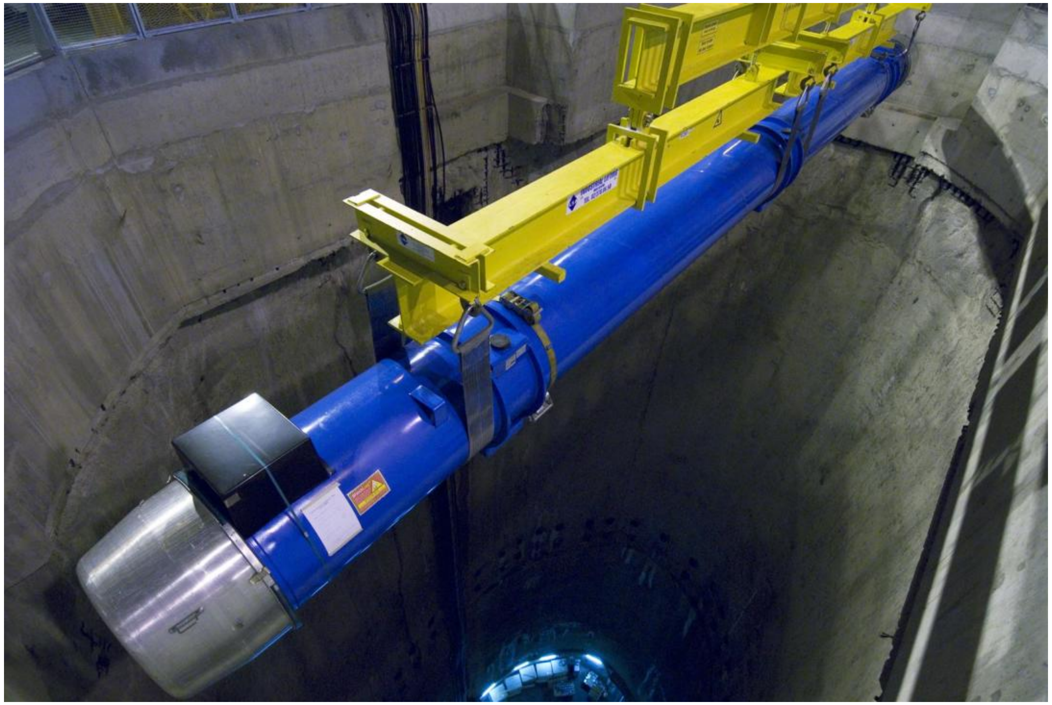


Buffer storage allows sorting, reduces dispersion

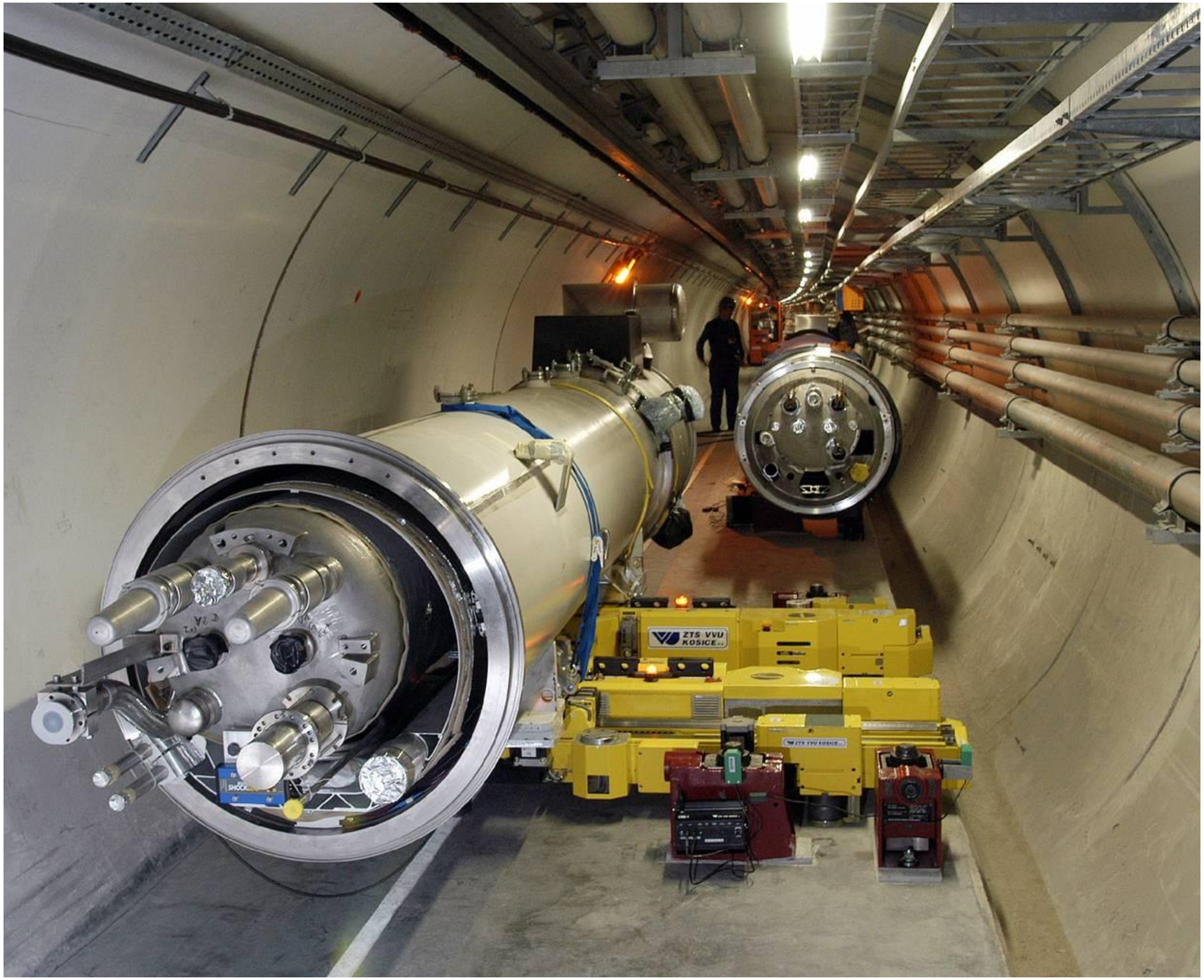




Lowering of magnets in tunnel



Cryomagnet installation in tunnel



Interconnections in tunnel

65’000 electrical joints

Induction-heated soldering

Ultrasonic welding

Very low residual resistance

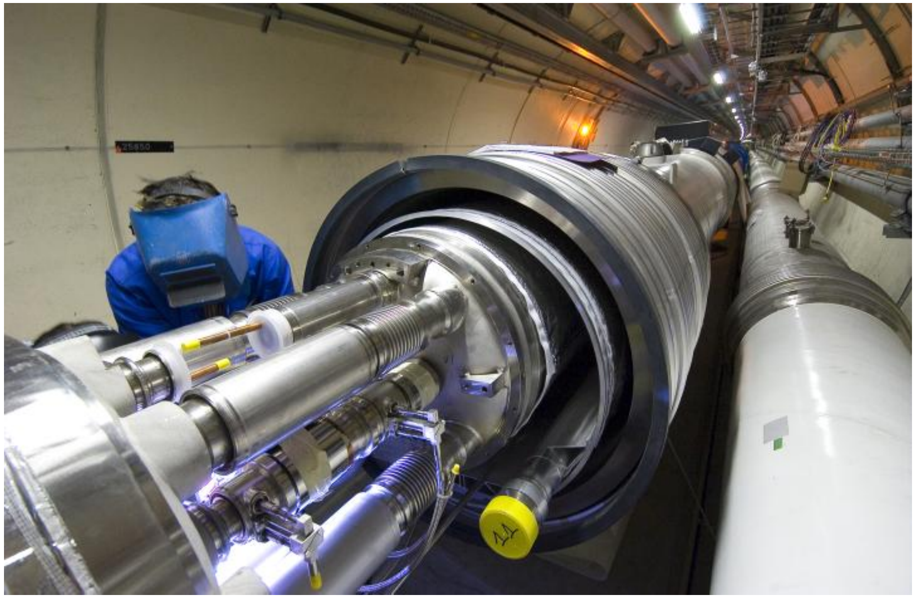
HV electrical insulation

40’000 cryogenic junctions

Orbital TIG welding

Weld quality

Helium leaktightness



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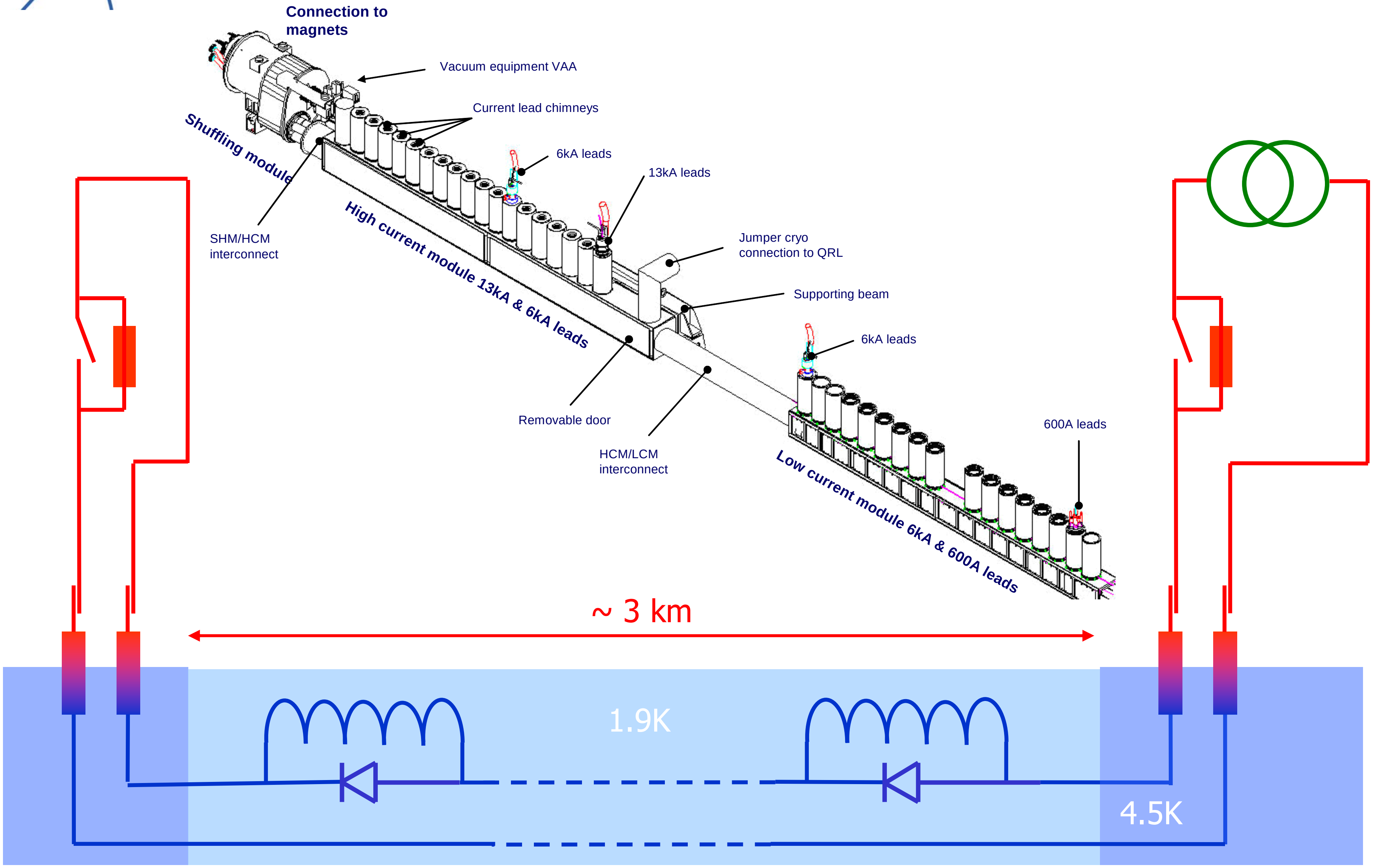
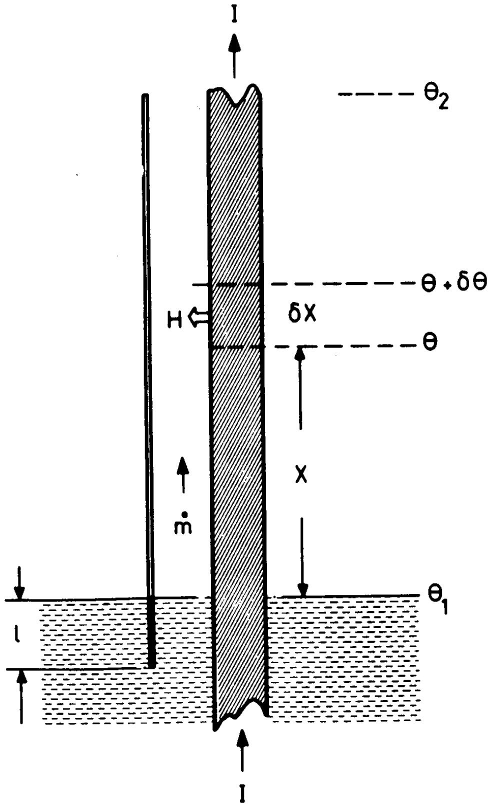
Arc electrical feedbox



Cryogenic current leads



Heat transfer processes at work

- Solid conduction
- Joule heating
- Convective cooling by He vapor

Metals are good electrical AND thermal conductors (Wiedemann-Franz-Lorentz law)

Optimal sizing of current lead results from compromise between heat conduction and Joule heating

Superconductors do not follow WFL law

They are perfect electrical conductors with low thermal conductivity

They can make excellent current leads… up to their transition temperature!

⇒ niche application for "high-temperature" superconductors

Current leads using HTS superconductor

	Resistive (WFL)	HTS (4 to 50 K) Resistive (> 50 K)
Heat inleak to liquid helium	1.1 W/kA	0.1 W/kA
Exergy loss	430 W/kA	150 W/kA
Electrical power of refrigerator	1430 W/kA	500 W/kA

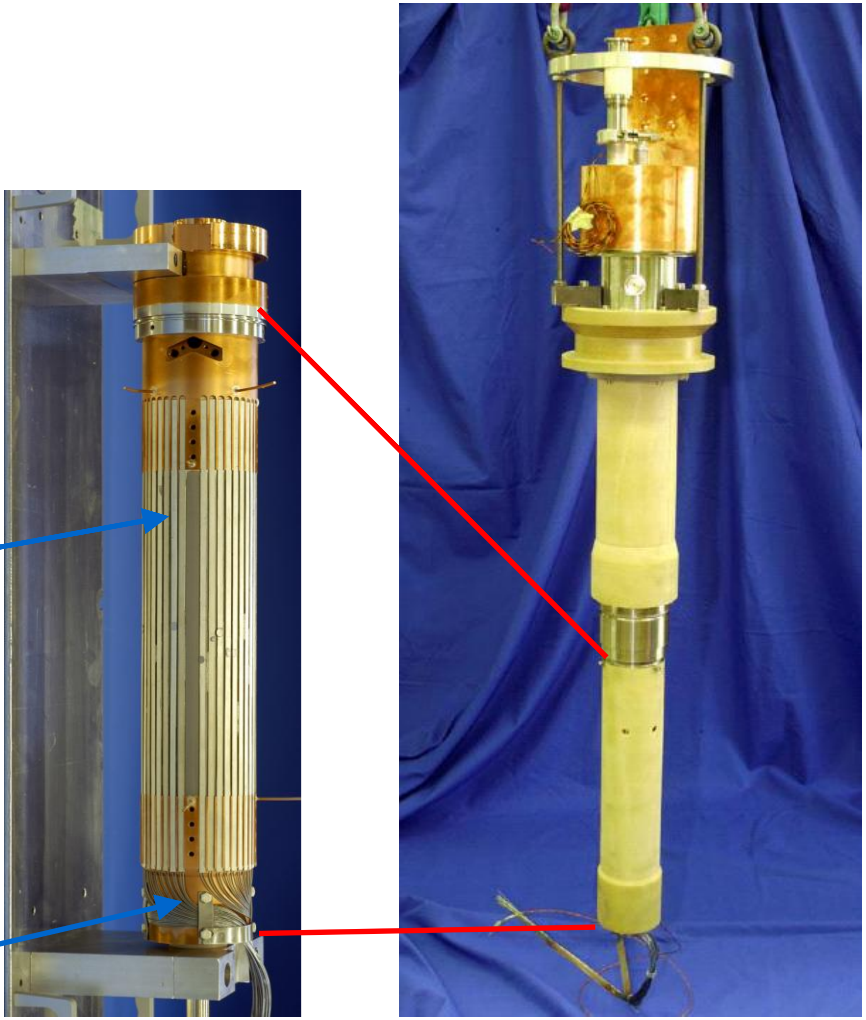
Sum of currents into LHC ~ 1.7 MA, i.e. need current leads for 3.4 MA total rating (in and out)

Economy ~ 3400 W in liquid helium ~ 5000 l/h liquid helium

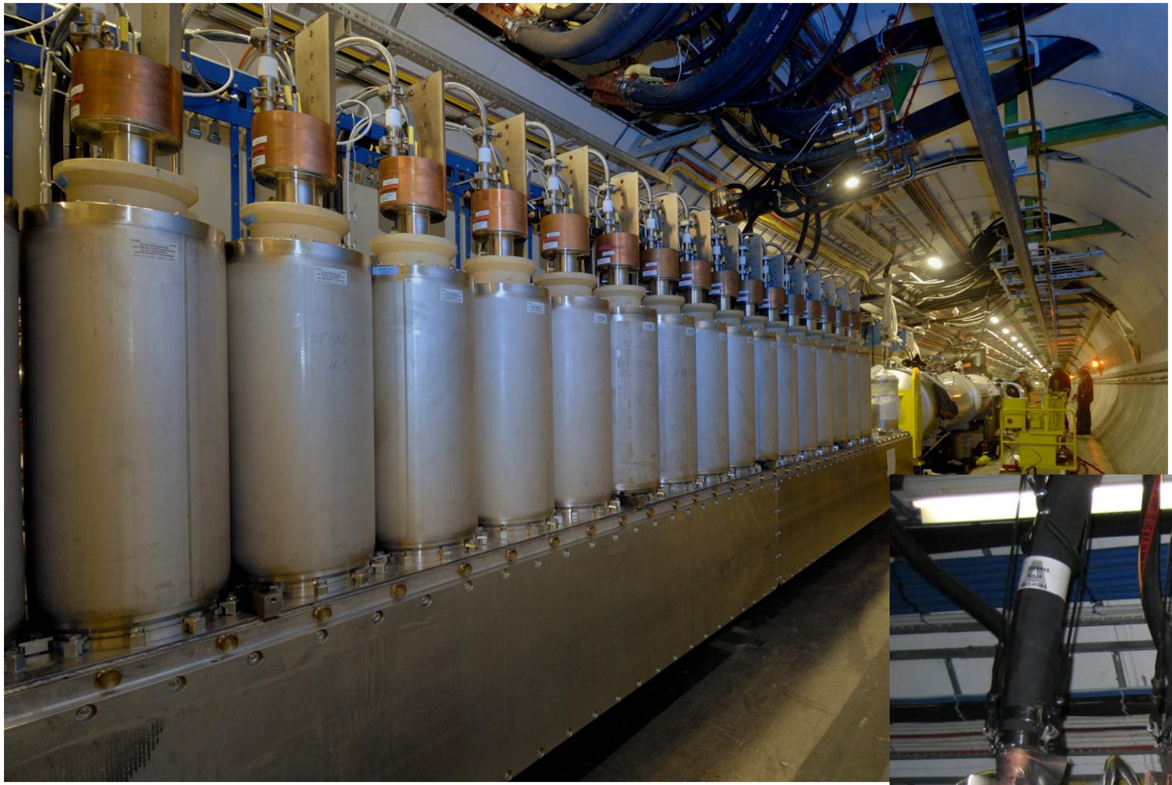
⇒ *capital: save extra cryoplant*

⇒ *operation: save ~ 3.2 MW*

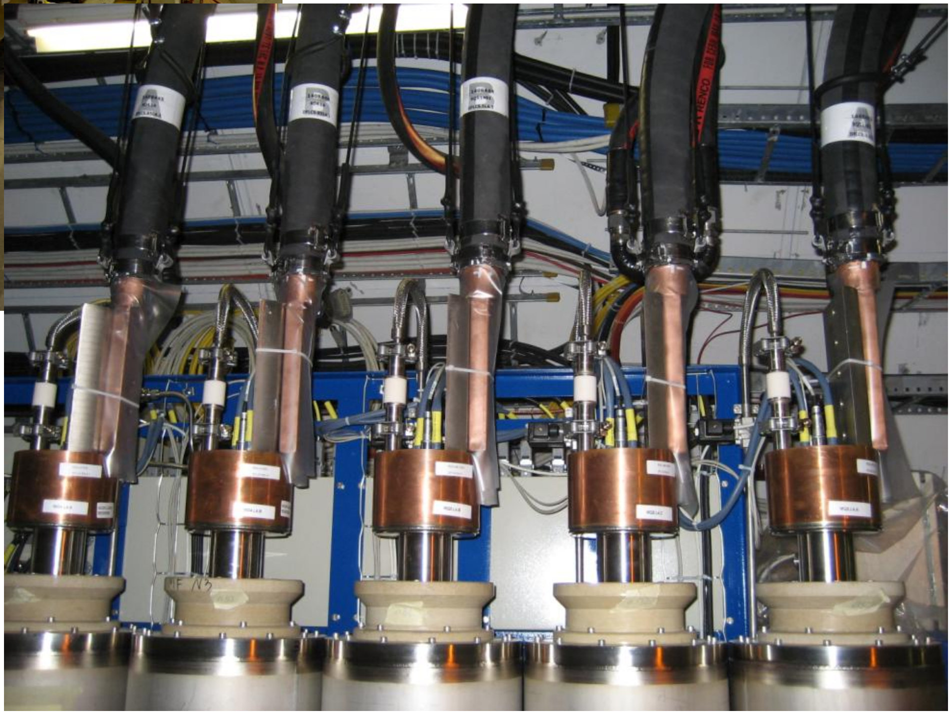
13 kA HTS current lead for LHC



HTS current leads in the LHC tunnel

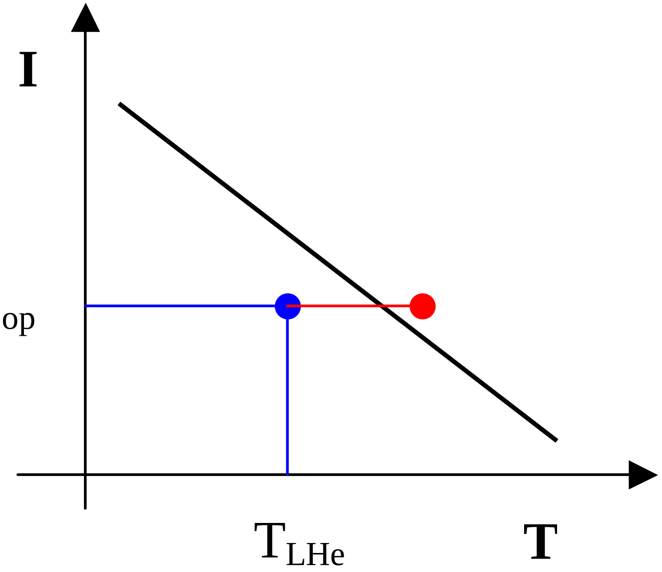


6 & 13 kA leads on
electrical feed-box



Water-cooled cables
on current lead lugs

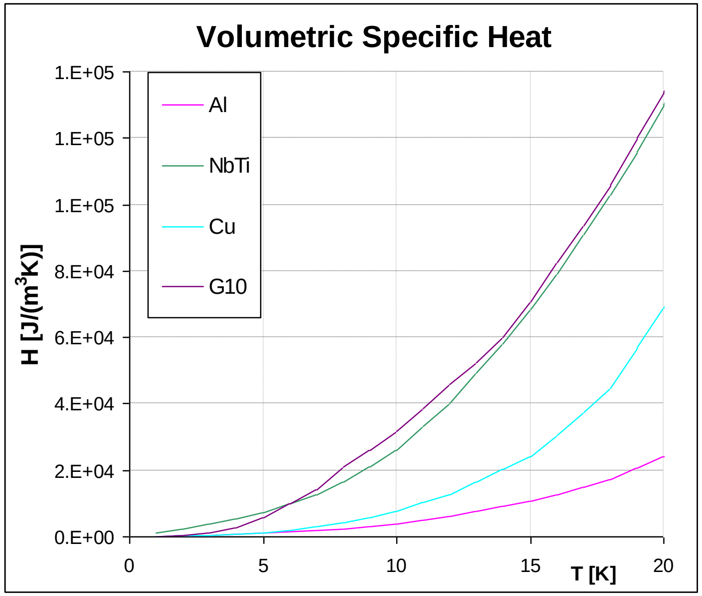
Superconductors are basically unstable!



Heat capacity of materials drops at low temperatures

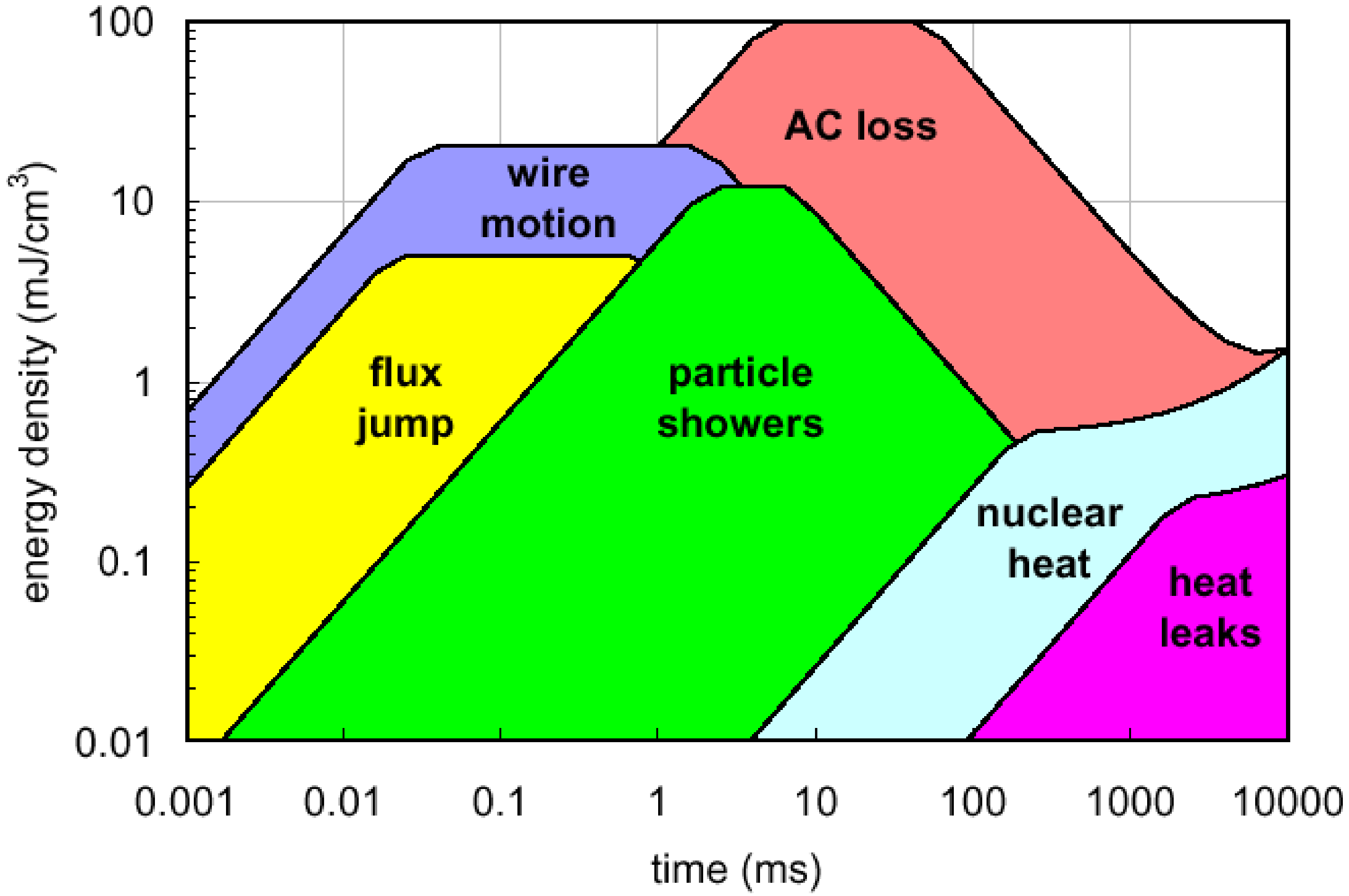
$\Delta T = \Delta E/\gamma C$

ΔE of few μJ on a superconducting strand in the cable generates ΔT pushing the operating point beyond the critical surface $\Rightarrow$ *resistive transition ("quench")*

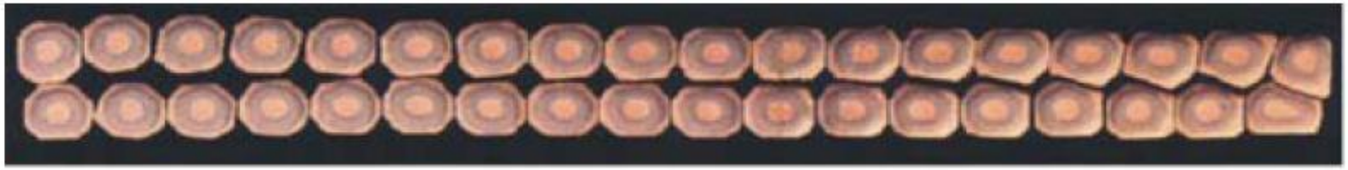

Volumetric Specific Heat

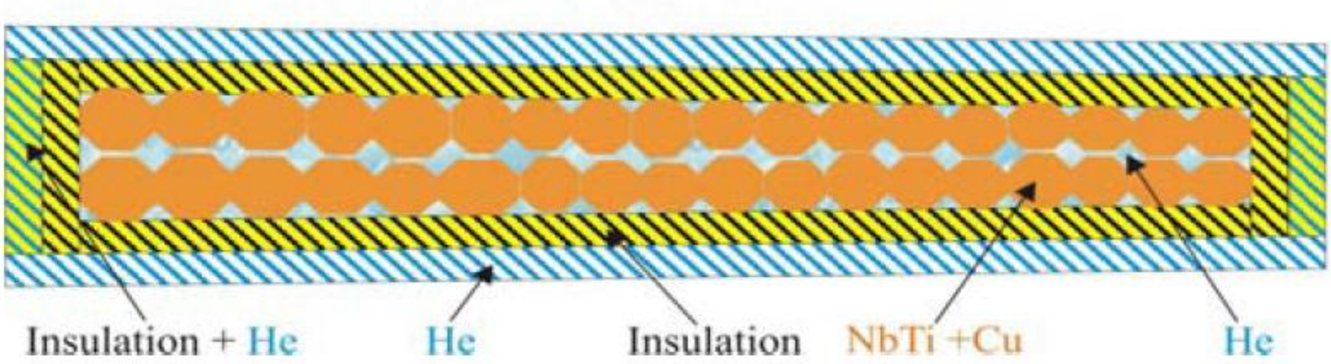
Temperature margin of superconductor	~ 1.5 K
Specific quench energy	~ 10 mJ/cm^3
Energy stored inductively in magnet	6.9 MJ
Energy stored in beam	360 MJ

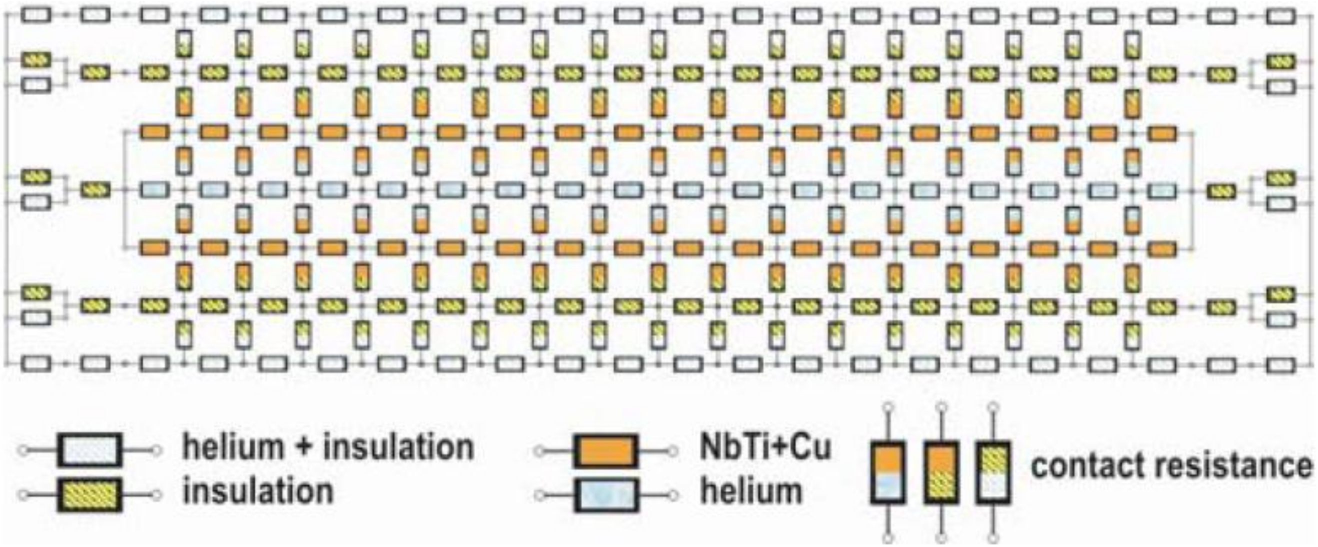
Perturbation spectrum of superconductor



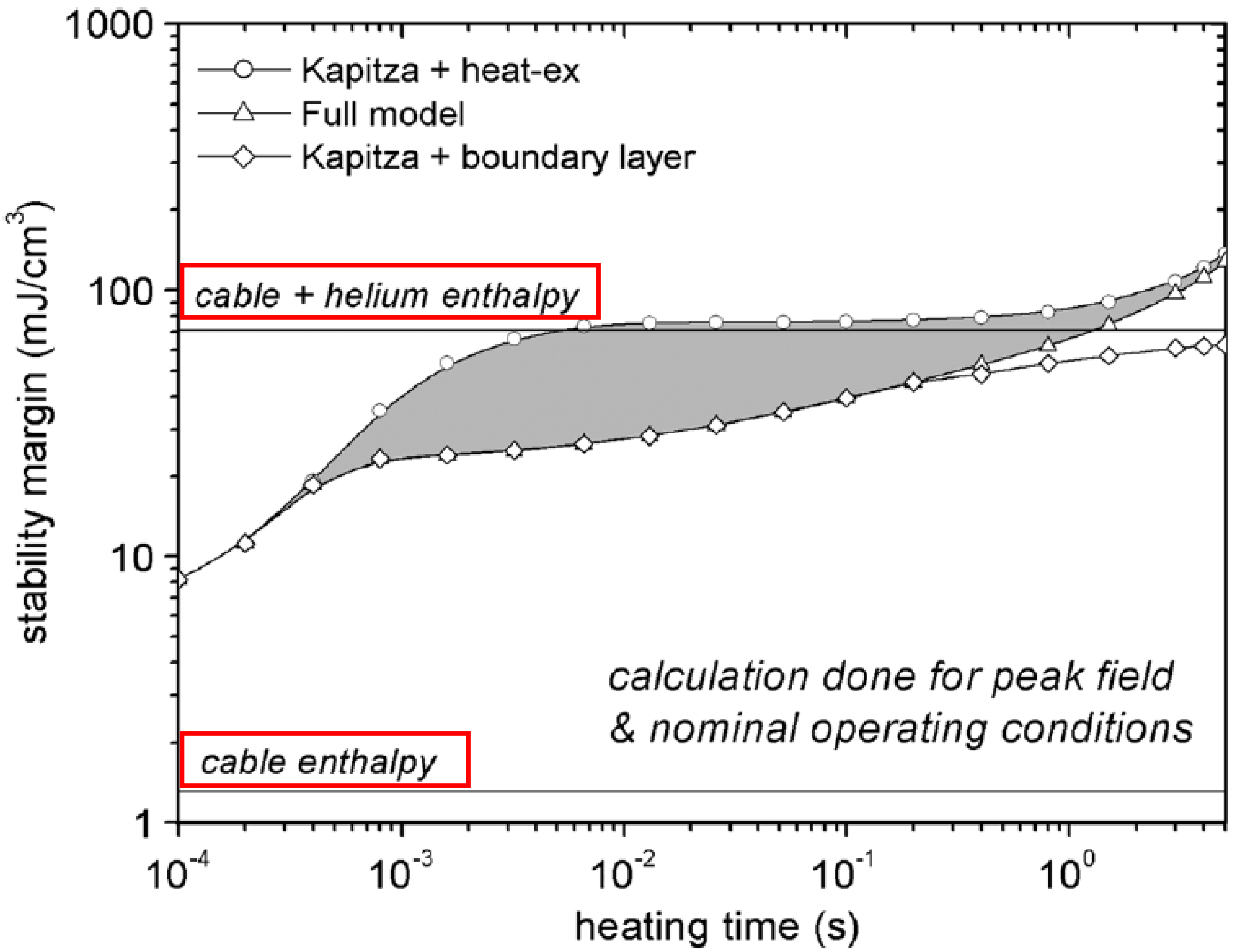
Network model of superconducting cable







Transient stability of superconducting cable



Hot spot temperature after a quench

Assume that quenched section is heated only by Joule effect and adiabatic (no conduction)

$$J^2(t)\rho(T)dt = \gamma C(T)dT \qquad \int_0^\infty J^2(t)dt = \int_{T_{op}}^{T_m} \frac{\gamma C(T)}{\rho(T)}dT \qquad J_0^2 T_d = U(T_m)$$

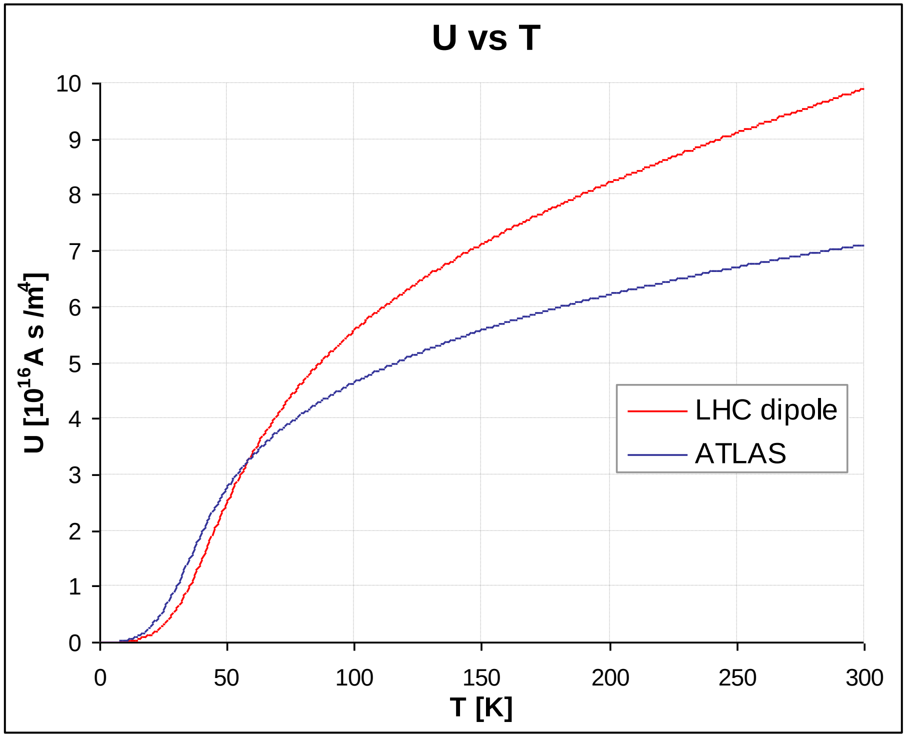
MIITs

To avoid too high hot spot temperature, speed up the quench propagation by any means

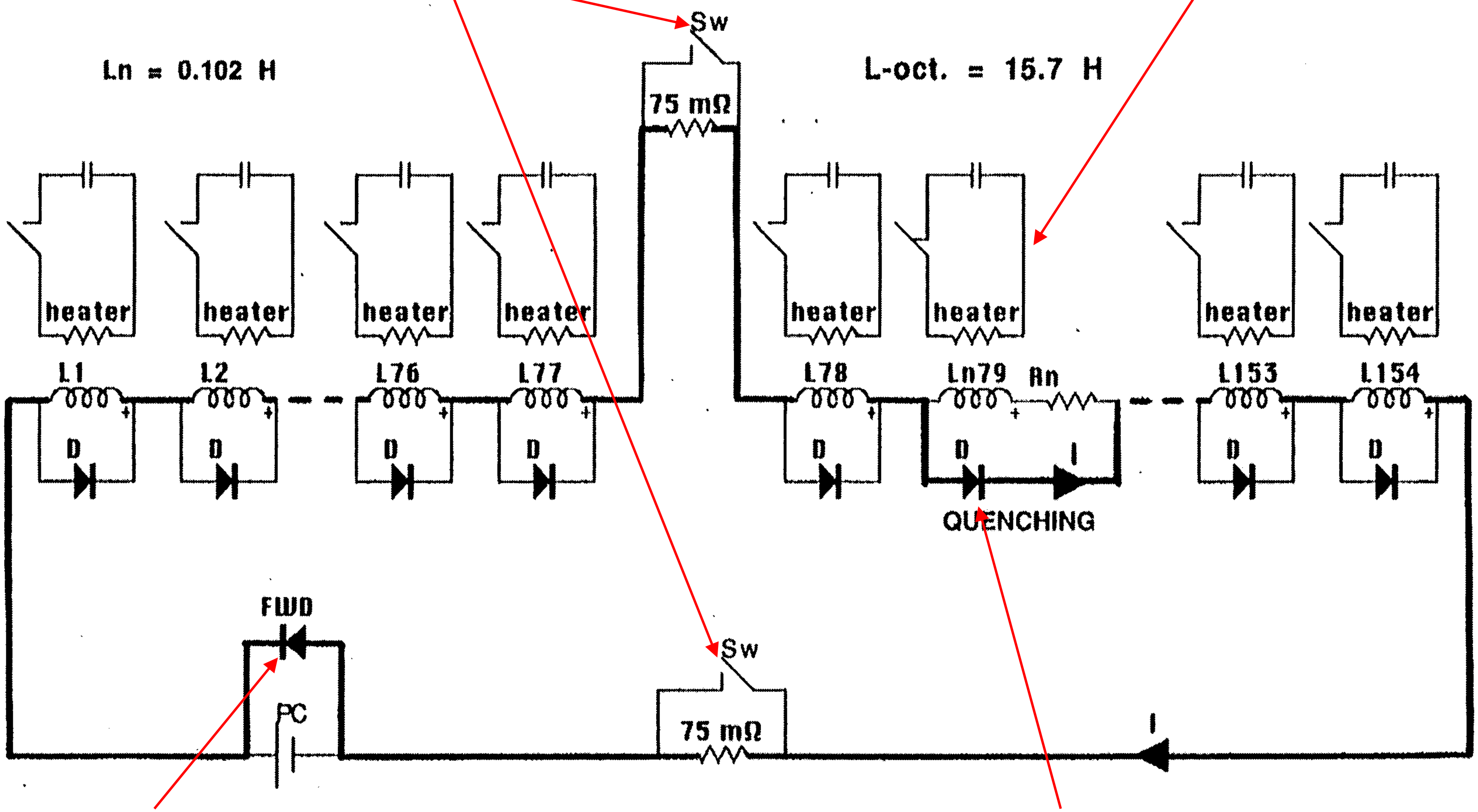
1) **Heater**: must be activated fast and reliably (20 ms)

2) “**Quench-back**” inductively propagated

This goes against having LHe in good contact with the conductor (i.e. against stability)!



LHC magnet circuit protection scheme



Dissipate energy of magnet string by inserting discharge resistor in circuit

Fire heater to spread the quench over maximum coil volume and limit temperature

Free-wheeling diode across power converter

Diode bypasses quenched magnet during current discharge in string

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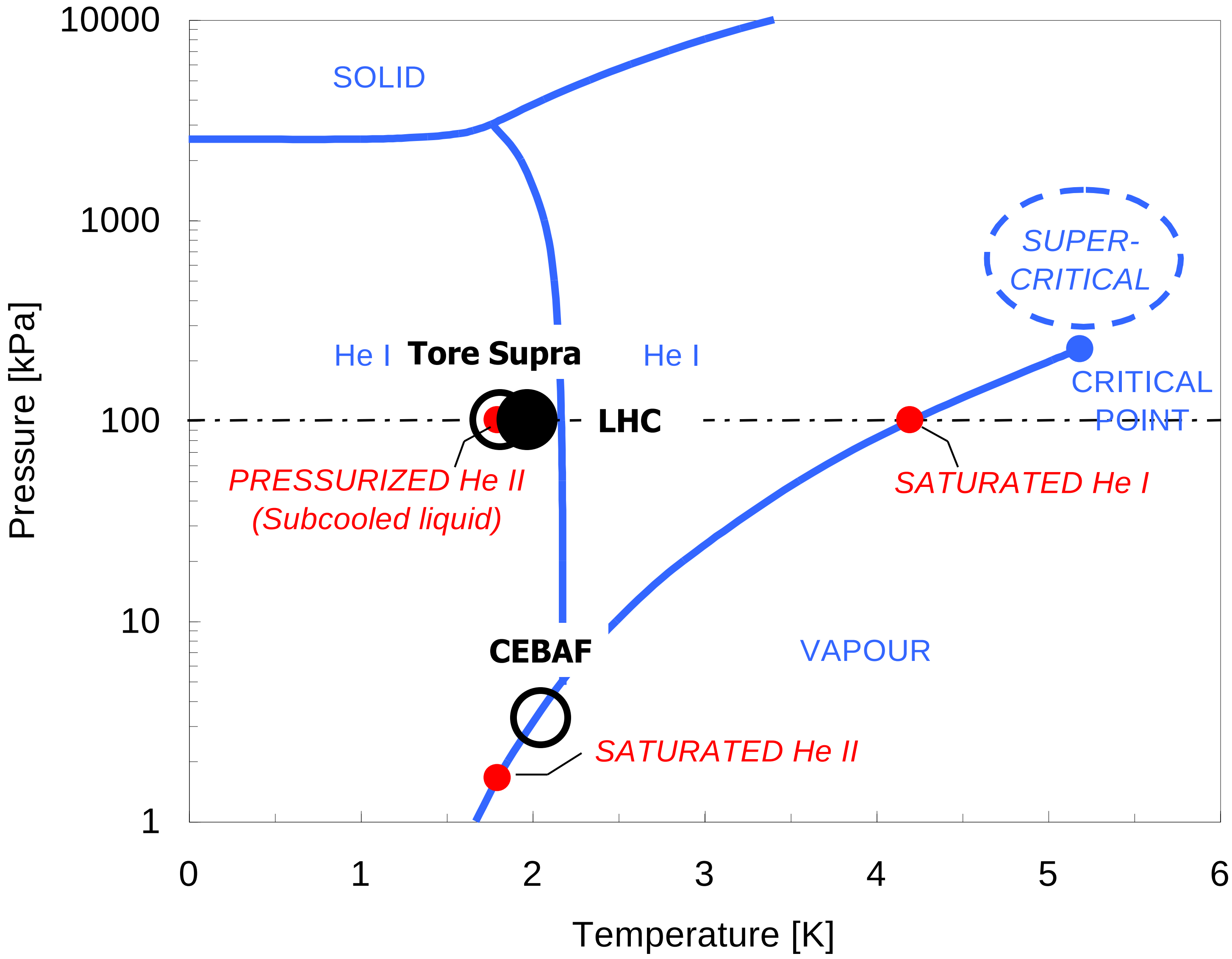
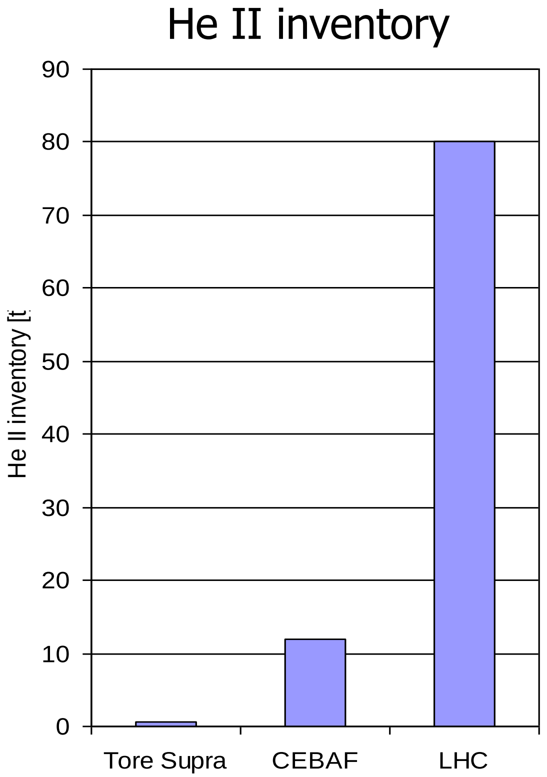
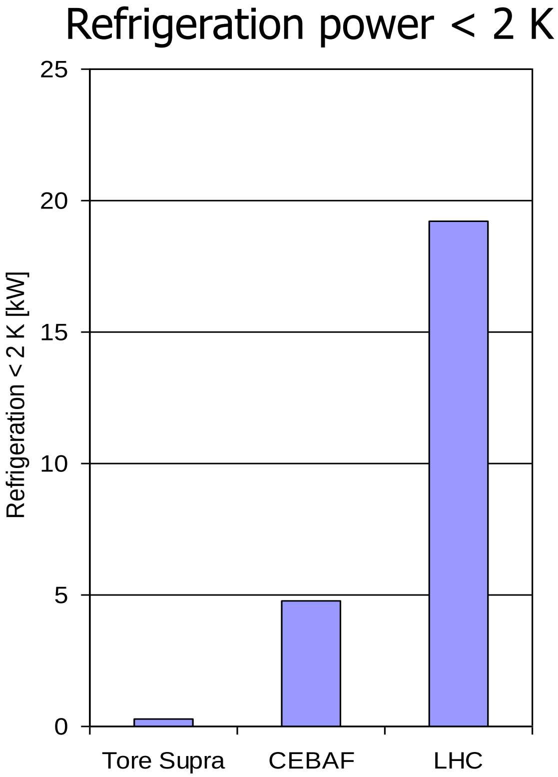
Cooling with superfluid helium

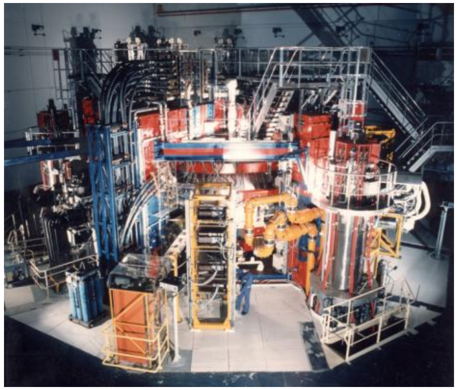


Large-scale superfluid helium systems





Tore Supra tokamak,
Cadarache (France)

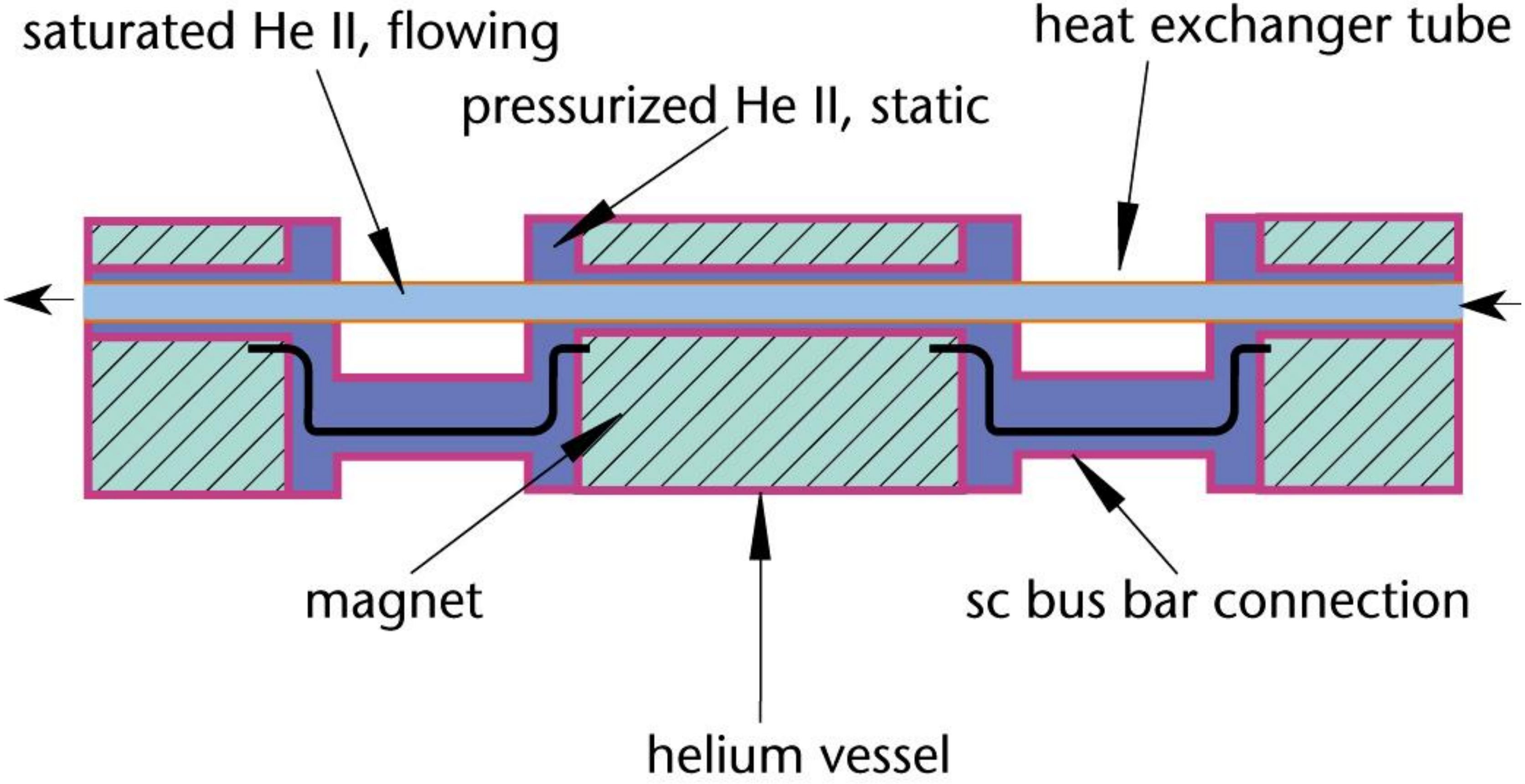


CEBAF accelerator,
Newport News (USA)

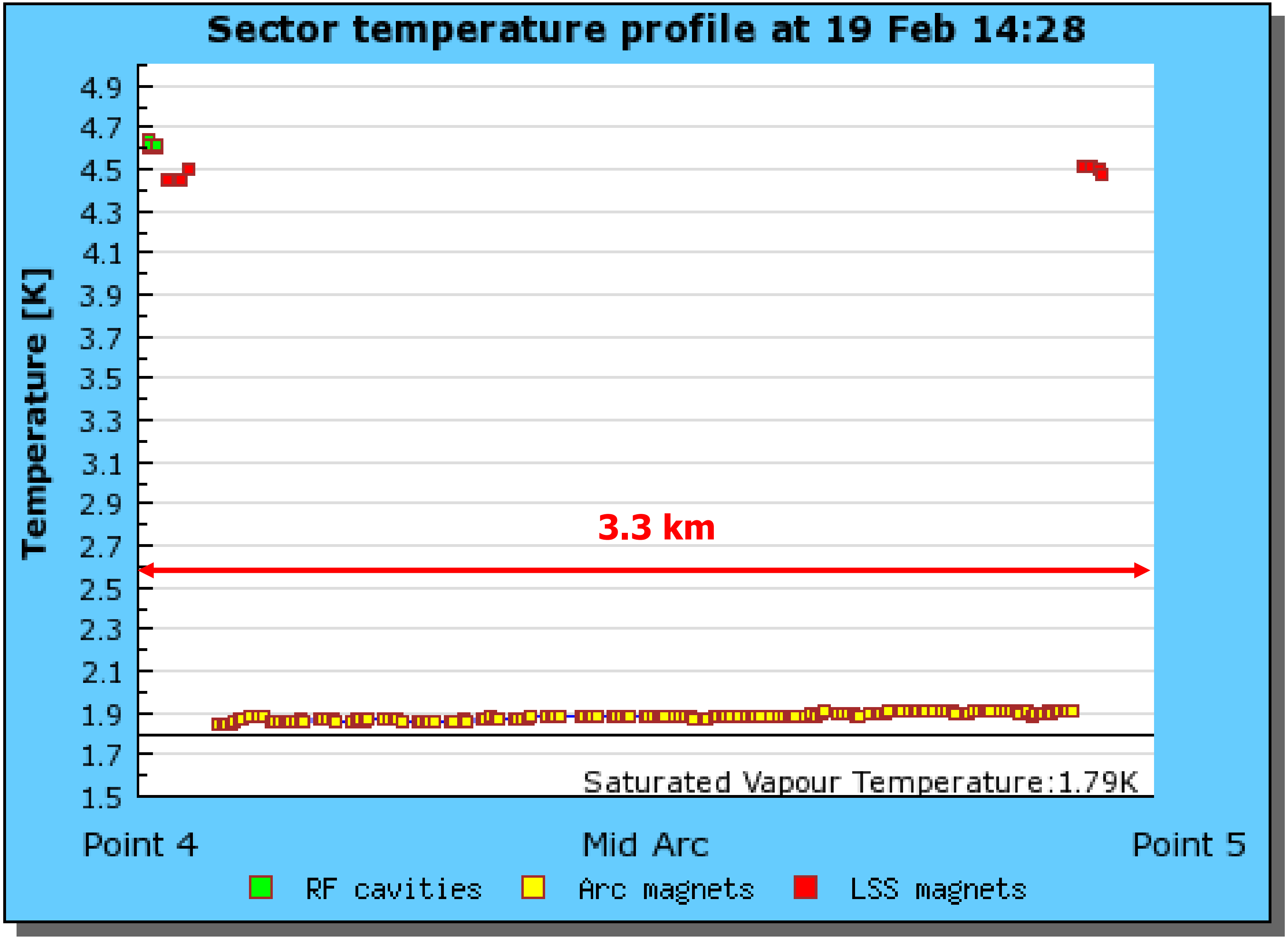
Thermophysical properties of He II

- Temperature < 2.17 K
- Low effective viscosity
  - 100 times lower than water at normal boiling point
- Very high specific heat
  - 10^5 times that of the conductor by unit mass
  - $2x10^3$ times that of conductor by unit volume
- Very high thermal conductivity
  - 10^3 times that of OFHC copper, cryogenic grade
  - Peaking at 1.9 K
  - Still, insufficient for transporting heat over large distances across small temperature gradients

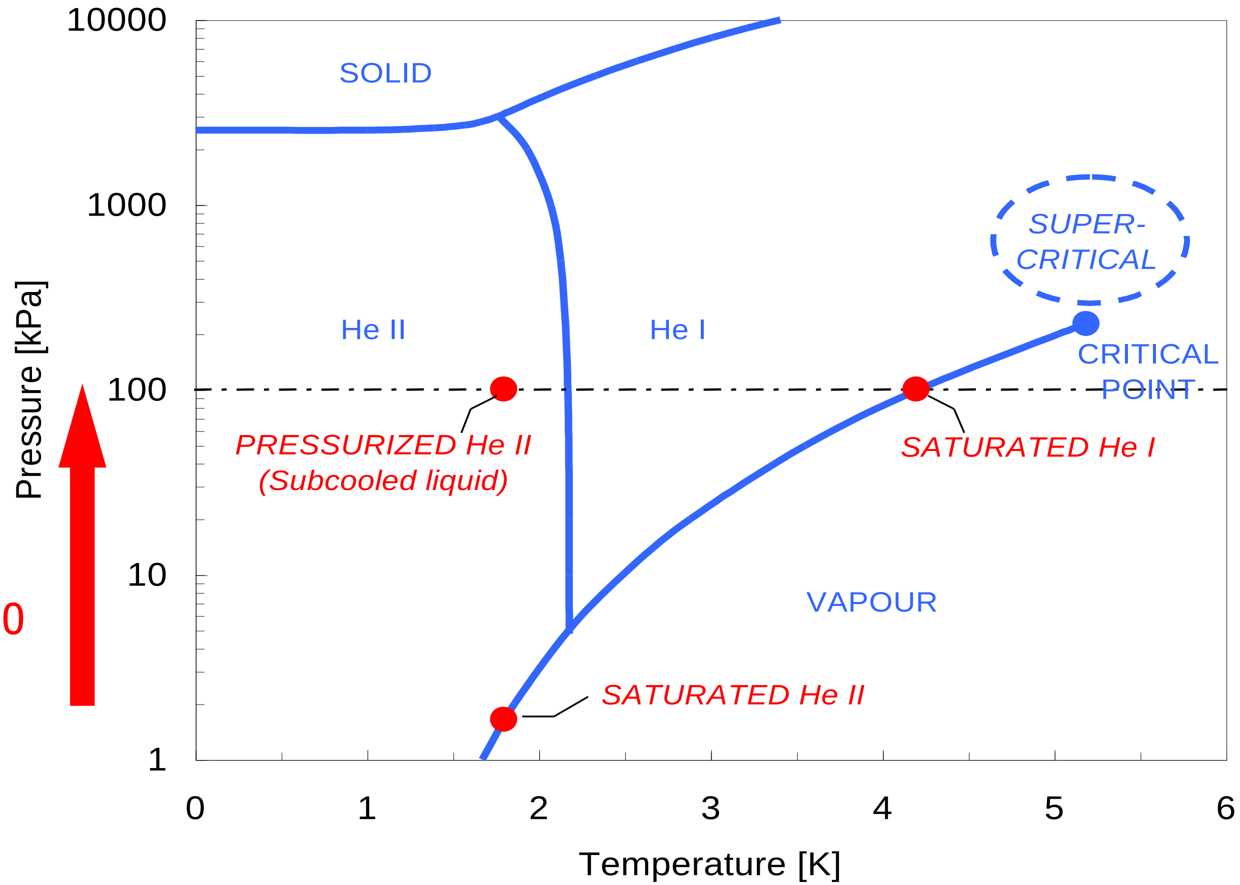
LHC magnet string cooling scheme



Cryogenic operation of LHC sector



Challenges of high-power 1.8 K refrigeration



Pressure ratio > 80

- Compression of large mass flow-rate of He vapor across high pressure ratio

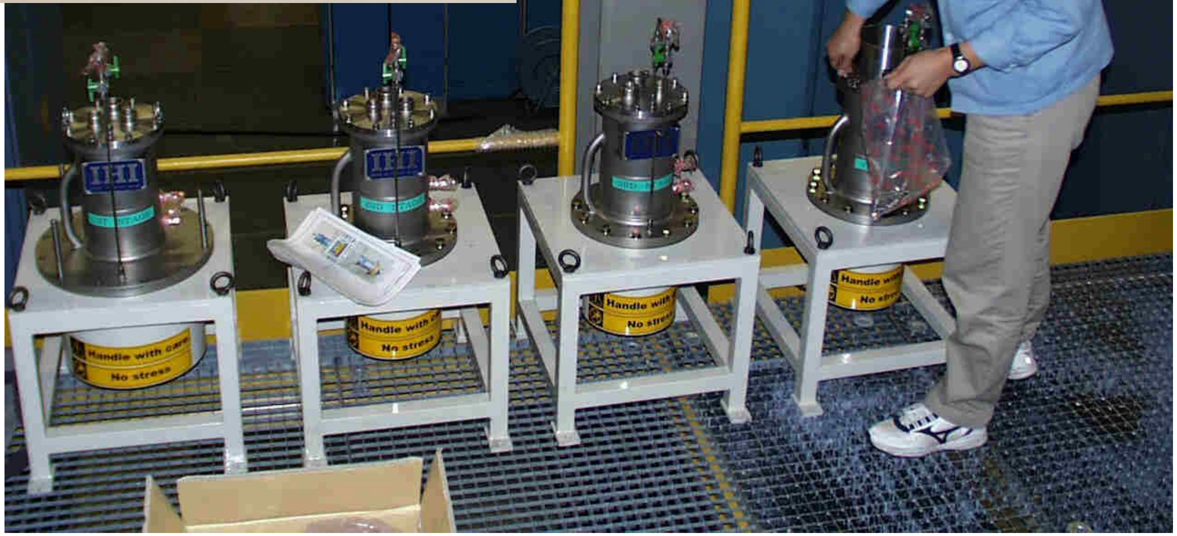
⇒ intake He at maximum density, i.e. cold

- Need contact-less, vane-less machine ⇒ hydrodynamic compressor
- Compression heat rejected at low temperature ⇒ thermodynamic efficiency

Cold compressors for 1.8 K refrigeration

Axial-centrifugal impeller

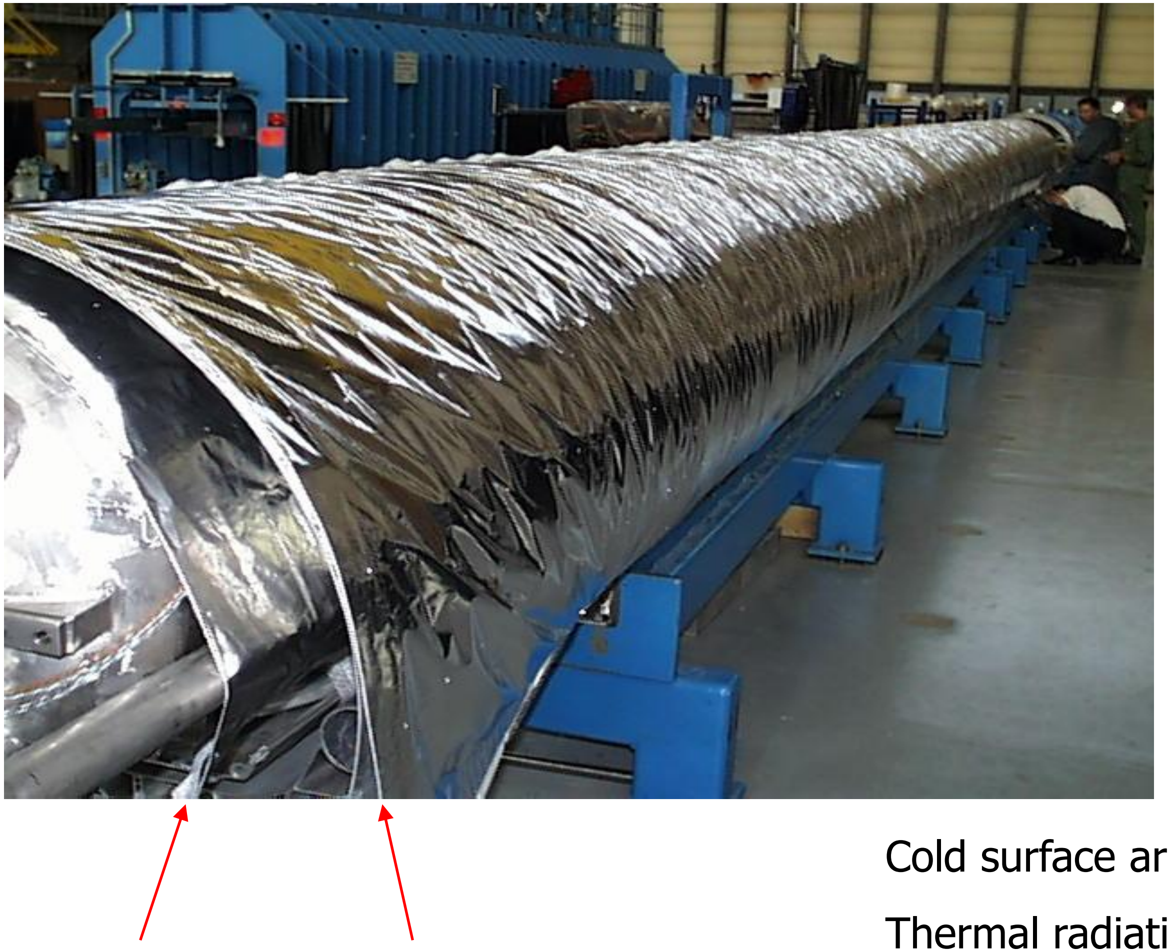
Cartridge 1st stage



4 cold compressor stages

Thermal insulation techniques

Multi-layer reflective insulation



10 layers around cold mass at 1.9 K

30 layers around thermal shield at 50-75 K

Cold surface area in LHC ~ 9 hectares!

Thermal radiation from 290 K (black-body) ~ 400 W/m^2 = 4 MW/ha

Heat flux from 290 K across 30 layers MLI ~ 1 W/m^2 = 10 kW/ha

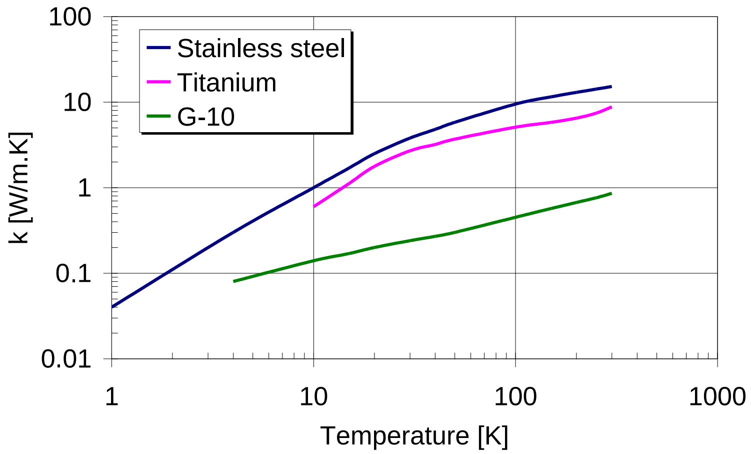
Thermal insulation techniques

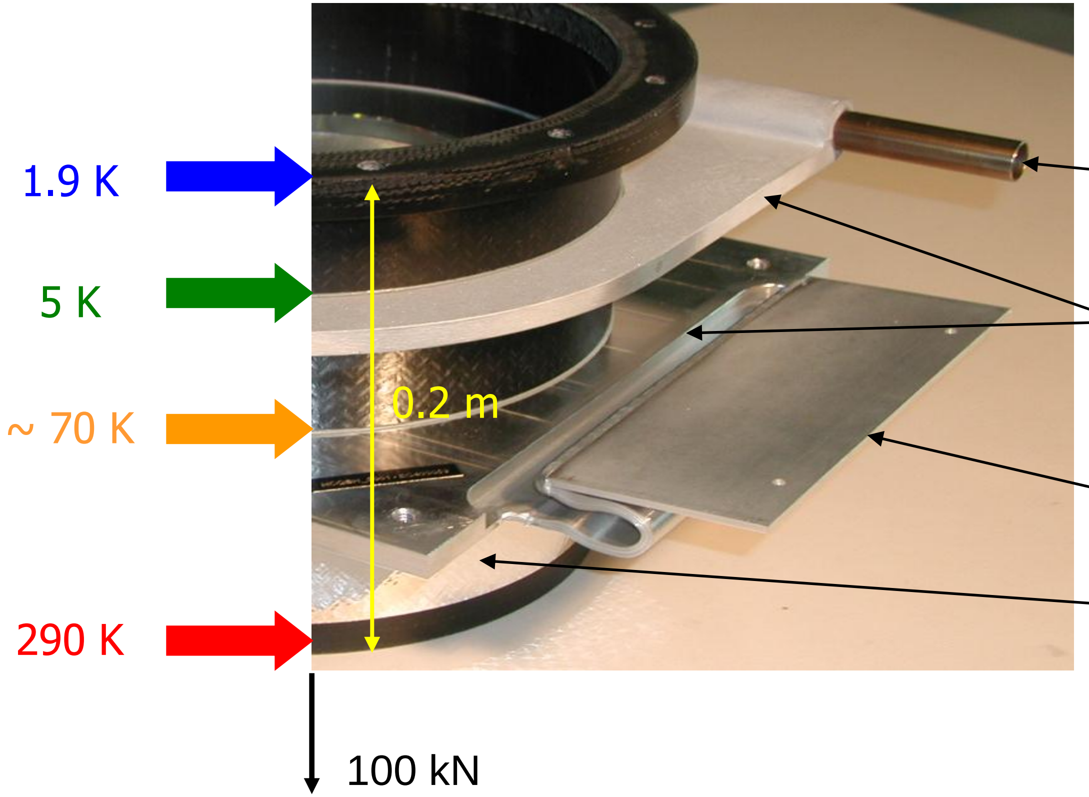
Low-conduction non-metallic support posts

LHC cold mass to be supported = 37’500 tons

Conduction length = support height ~ 0.2 m

At a compressive stress of 50 N/mm^2, this requires a total support cross-section of 7.5 m^2, representing a large thermal conduction path





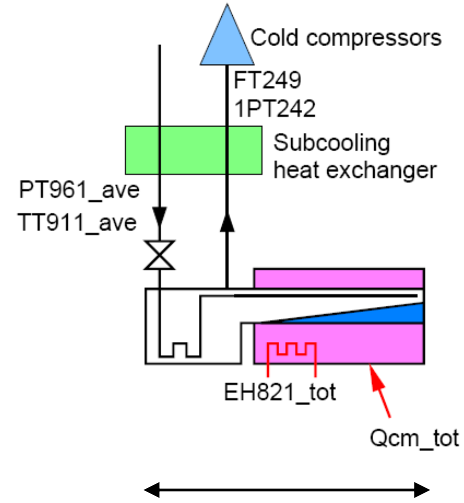
5 K cooling line (SC He)

Aluminium intercept plates glued to G-10 column

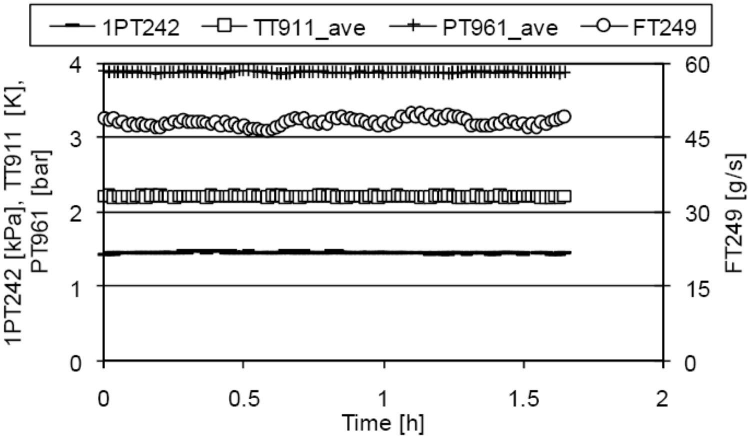
Aluminium strips to thermal shield at 50-75 K

Reflecting layer on section exposed to 300 K radiation

Heat inleak measurements on full sectors confirm thermal budget



LHC sector (3.3 km)



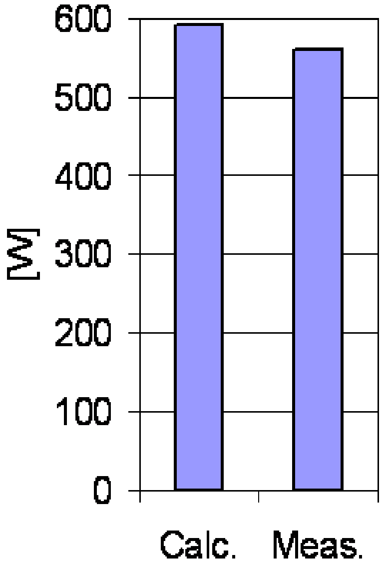
Temperatures and pressures stabilized, flow-rate integrated

Measured

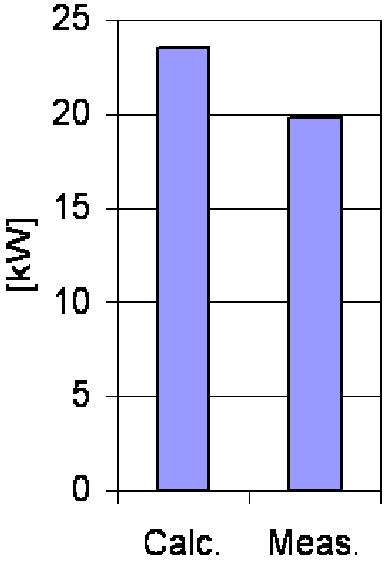
$$\dot{Q} = \dot{m}\,\Delta h(P, T)$$

He property tables

Total S7-8 @ 1.9 K



Total @ 50-75 K



Contents

- The LHC in a nutshell
- Performance
  - Energy
  - Luminosity
  - Collective effects
  - Dynamic aperture
- Technology
  - Superconducting magnets
  - Powering and protection
  - Cryogenics
  - Vacuum

Beam vacuum lifetime

- Dominated by nuclear scattering of protons on residual gas
- Lifetime of 100 h required to
  - Limit decay of beam intensity
  - Reduce energy deposited by scattered protons to ~ 30 mW/m

Scattering cross-section

$$\frac{1}{\tau_{gas}} = -\frac{1}{N}\frac{dN}{dt} = v \sum_i \sigma_i \; n_i$$

Gas density

Proton velocity

Sum over gas species

- Partial pressure

$$P_i = n_i \; k_B \; T$$

Proportional to temperature
for given gas density

Beam vacuum lifetime

Gas species	Nuclear scattering cross-section [mbarn]	Gas density for 100 h lifetime [m^{-3}]	Pressure at 5 K for 100 h lifetime [Pa]
H_2	95	9.8 E14	6.7 E-8
He	126	7.4 E14	5.1 E-8
CH_4	566	1.6 E14	1.1 E-8
H_2O	565	1.6 E14	1.1 E-8
CO	854	1.1 E14	7.5 E-9
CO_2	1320	0.7 E14	4.9 E-9

Vacuum in presence of beam

- Without beam

Outgassing rate

$$P = \frac{Q}{S}$$

Dynamic pressure

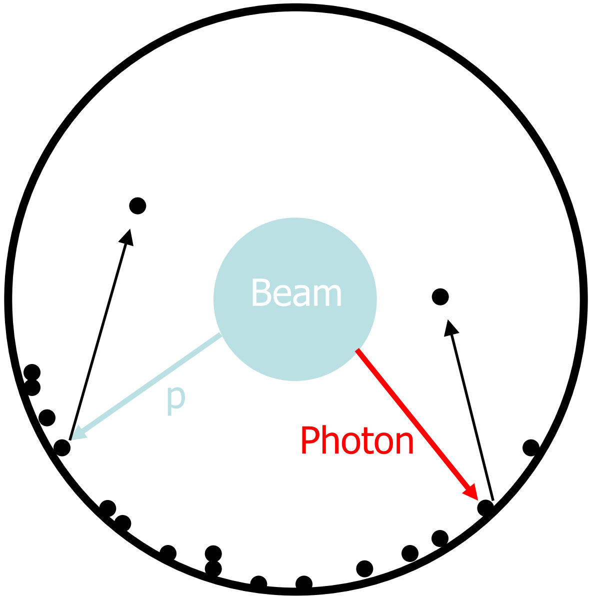
Pumping speed

- With beam

Photon/electron/ion desorption yield

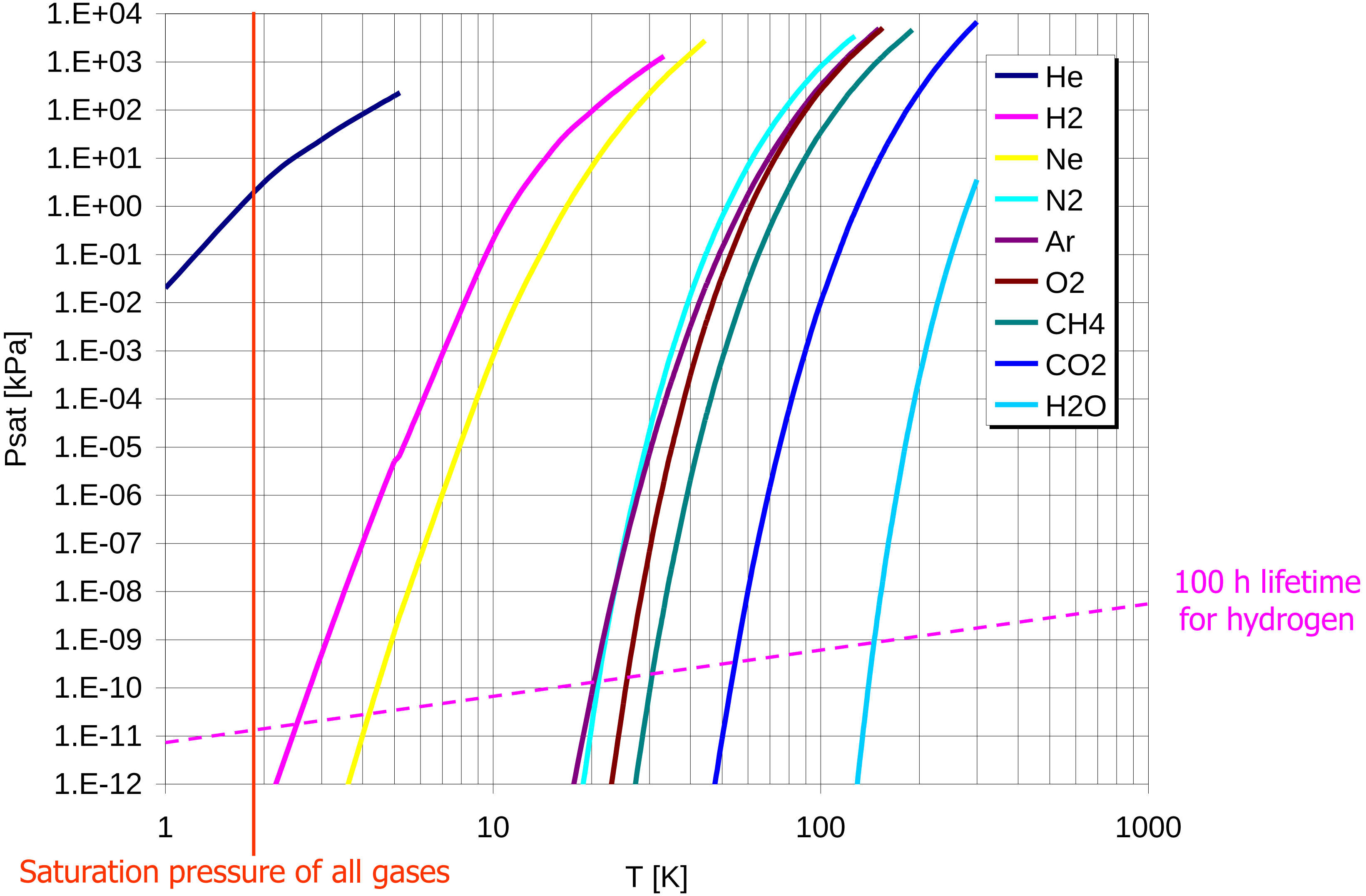
Photon/electron/ion flux

$$P = \frac{Q + \eta\,\dot{\Gamma}}{S}$$



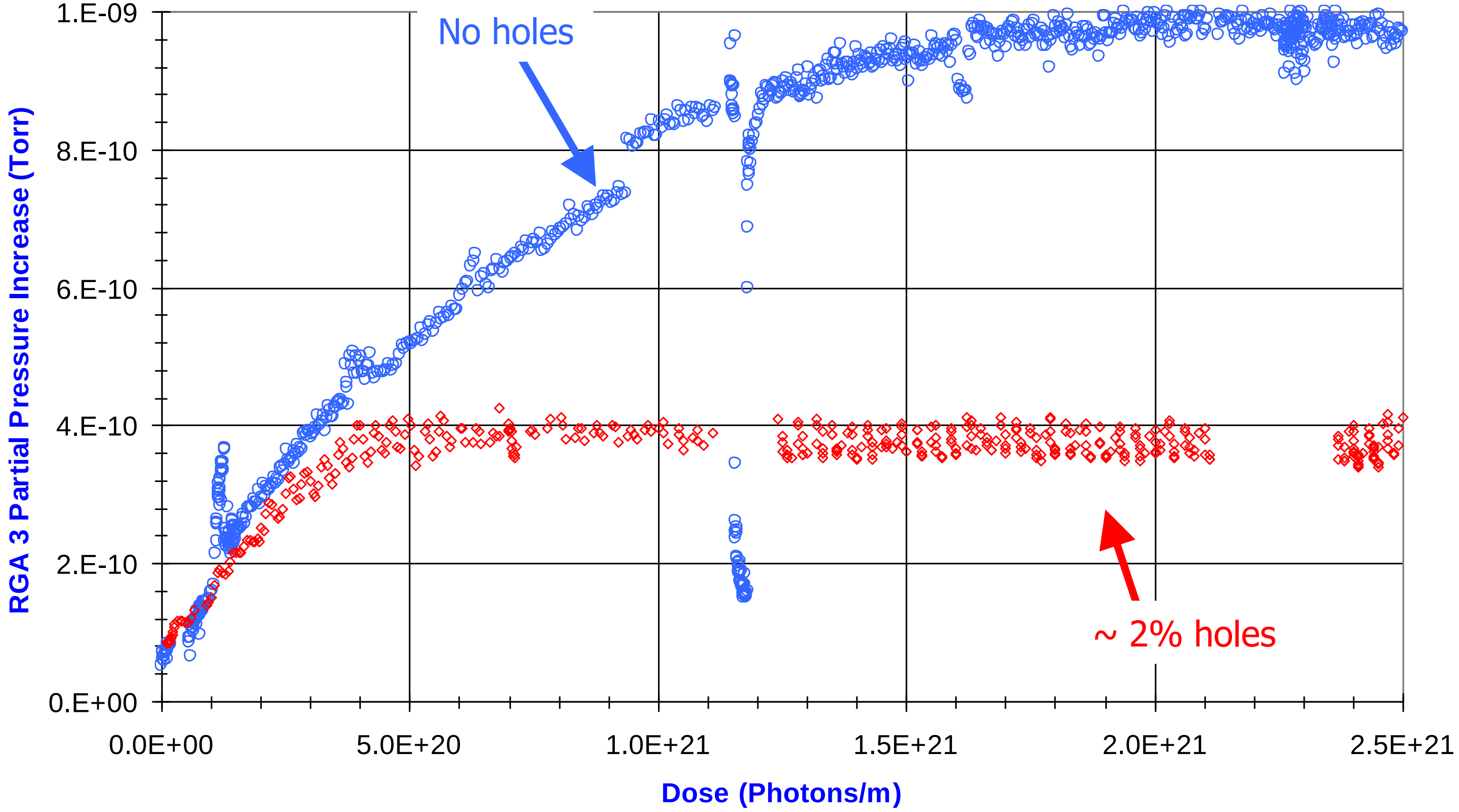
Condensed gas molecules

Cryopumping of beam vacuum at 1.9 K

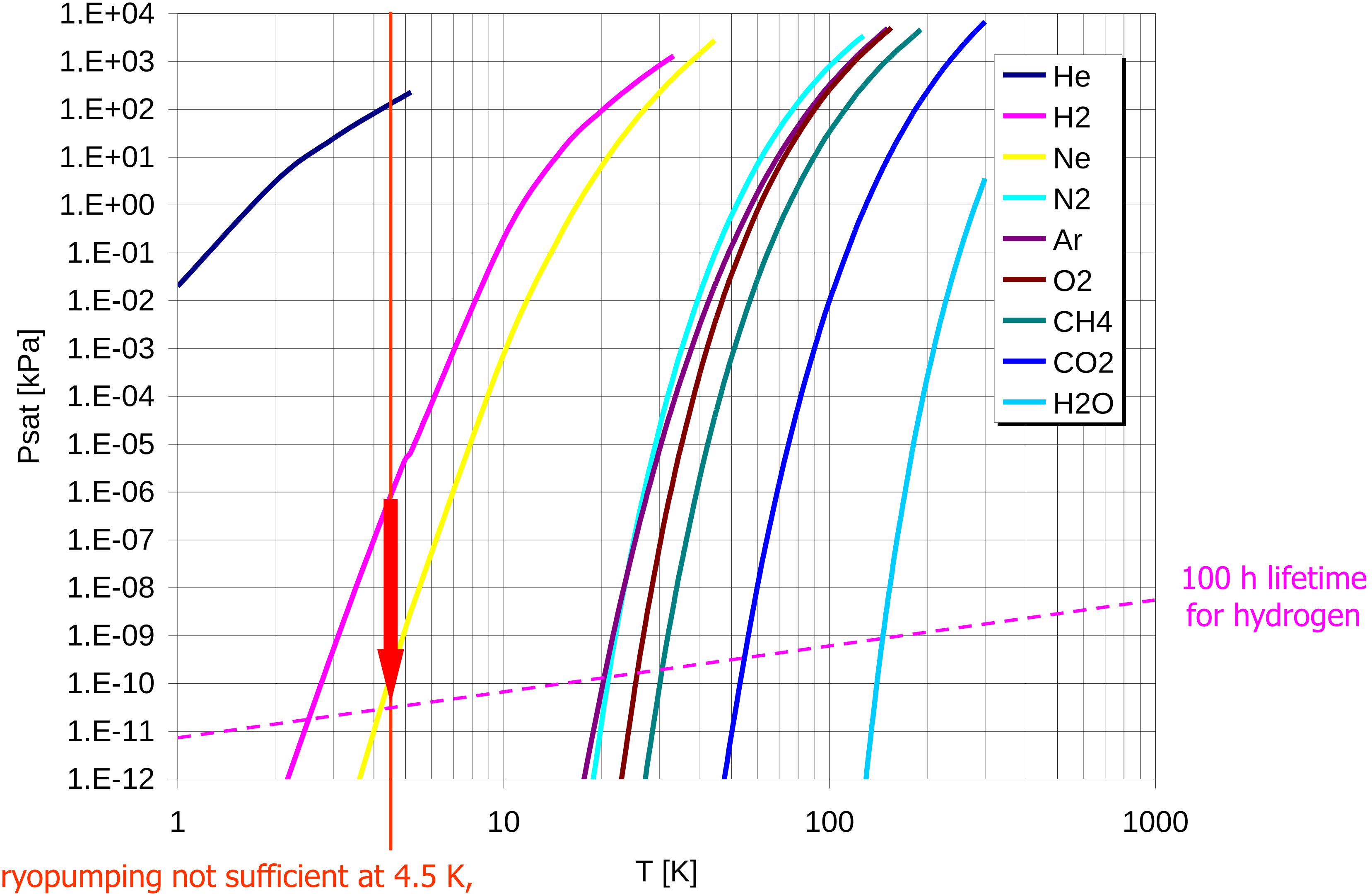


Saturation pressure of all gases except helium vanish at 1.9 K

Pumping desorbed gas through the beam screen

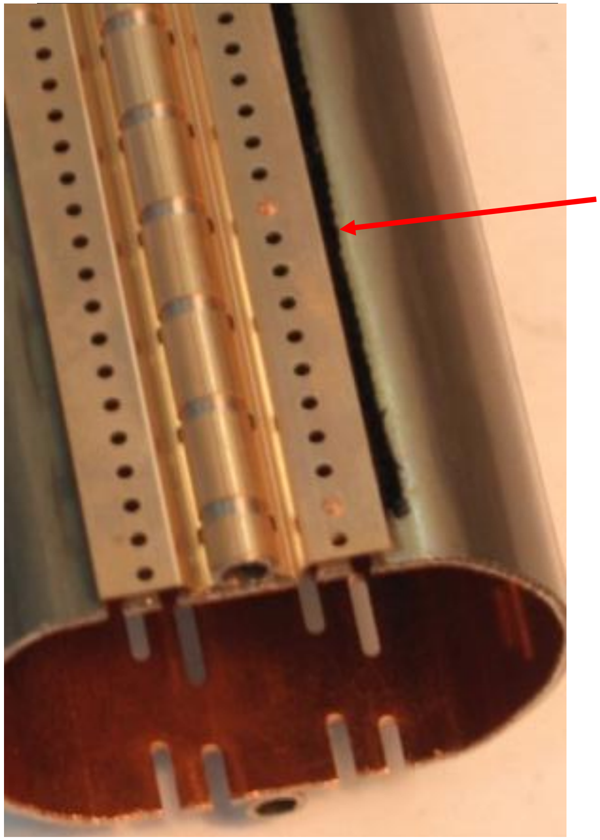


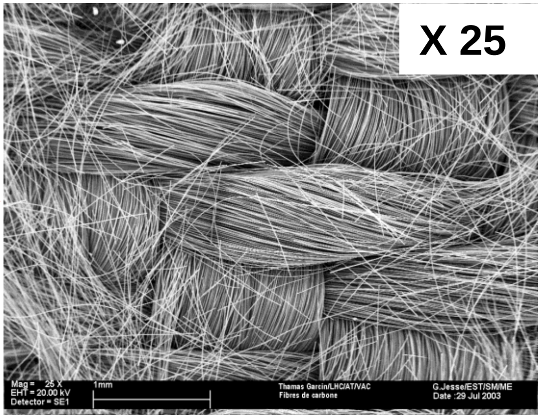
Cryosorption of beam vacuum at 4.5 K

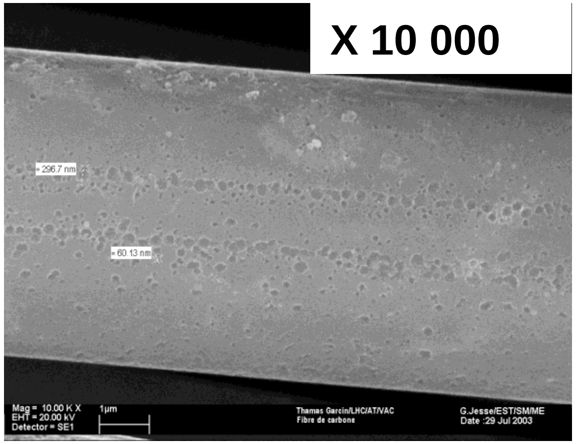


Cryopumping not sufficient at 4.5 K, use cryosorption

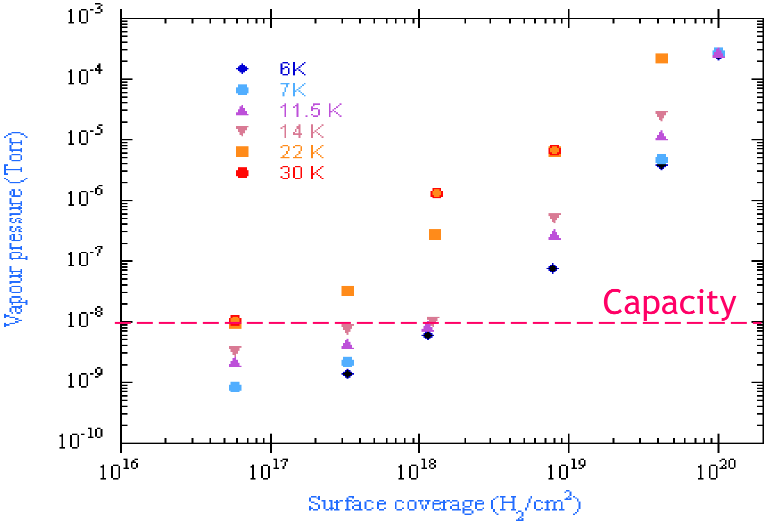
Cryosorber





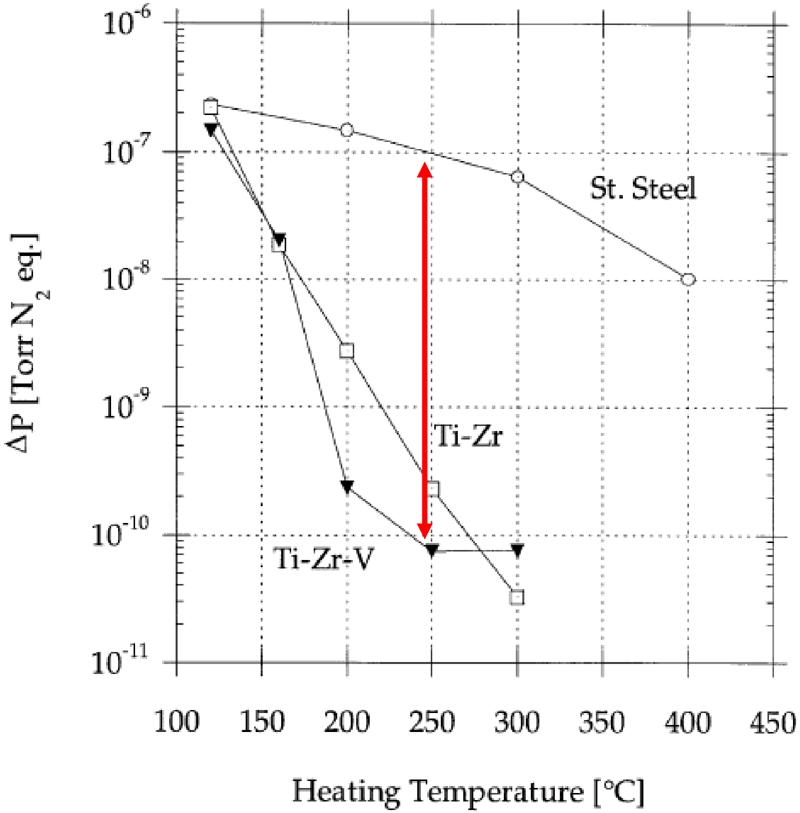


Carbon fiber mesh on the beam screen, to pump hydrogen
Capacity sufficient for regeneration only during annual shutdown

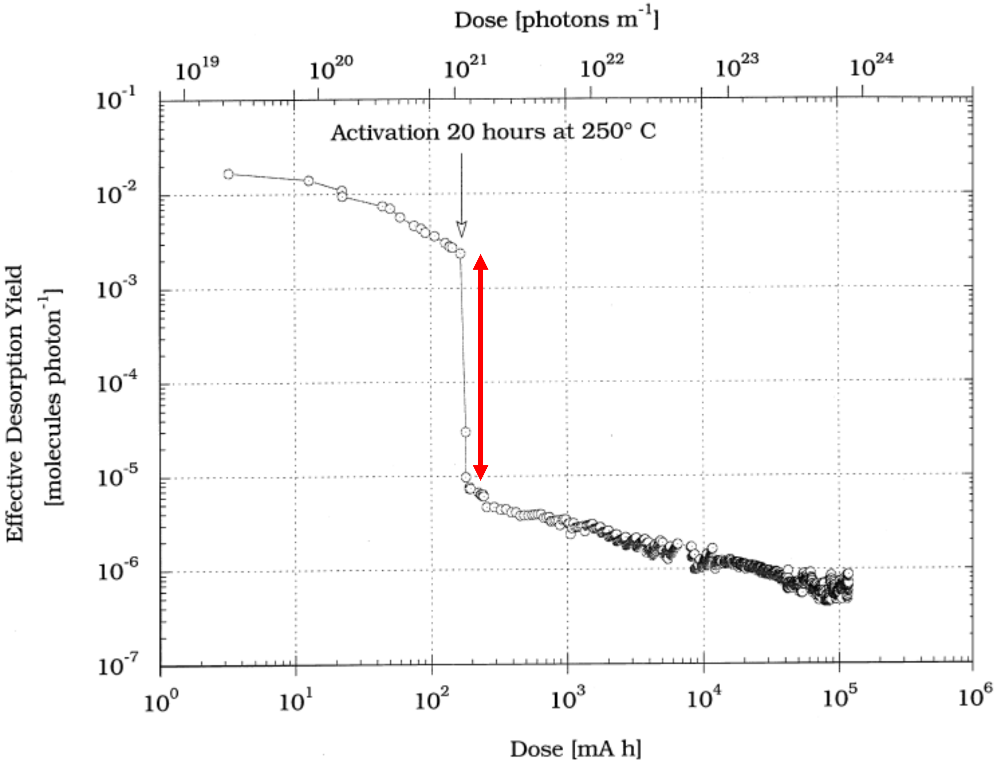


Non-evaporable getter coated vacuum chambers

Distributed pumping integrated into beam pipe

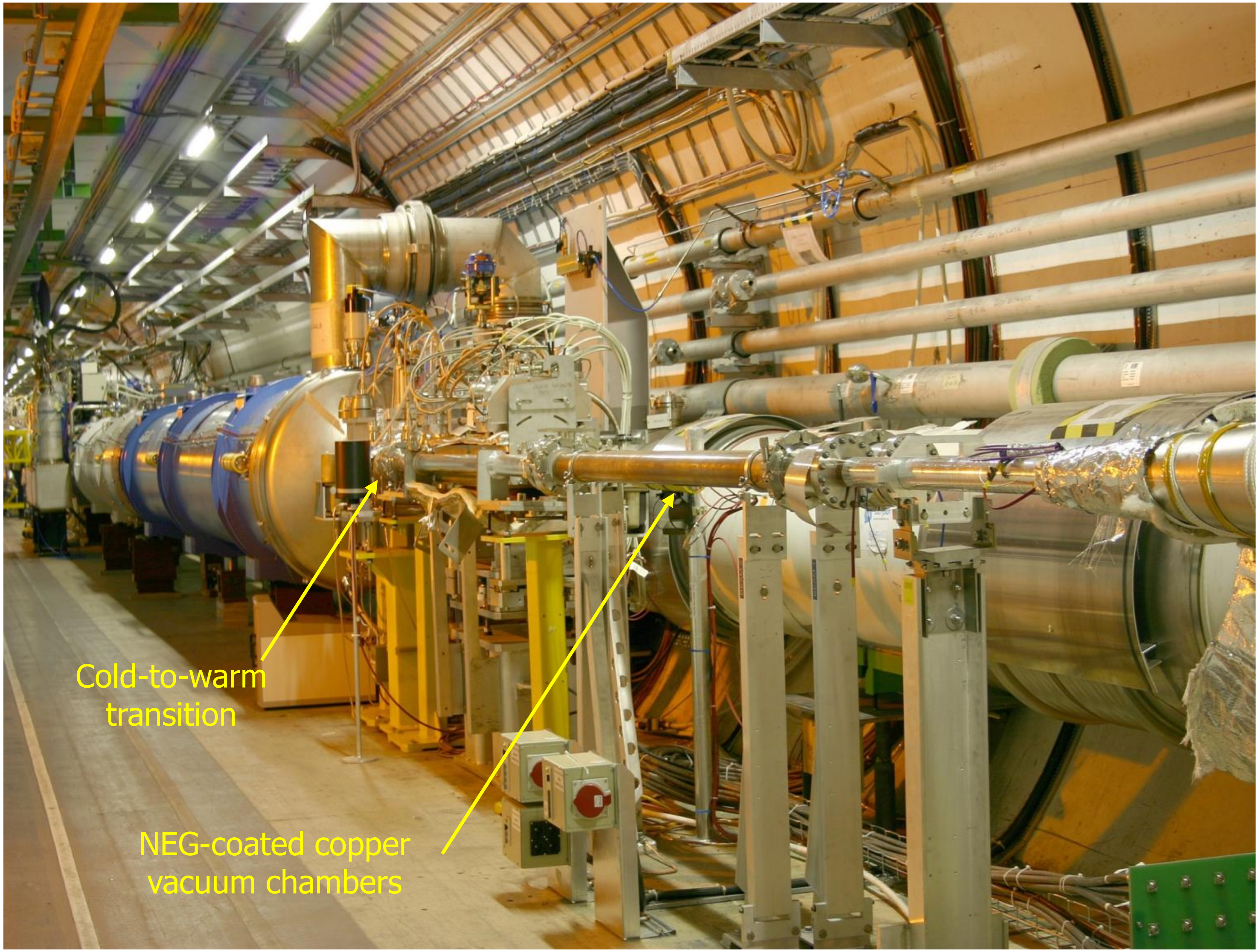


Pressure increase by 500 eV electron bombardment of surface at 20º C, after heating for 2 hours



Effective molecular desorption yield as a function of photon dose, on TiZrV NEG coating of stainless steel chamber

Beam vacuum in long straight sections



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