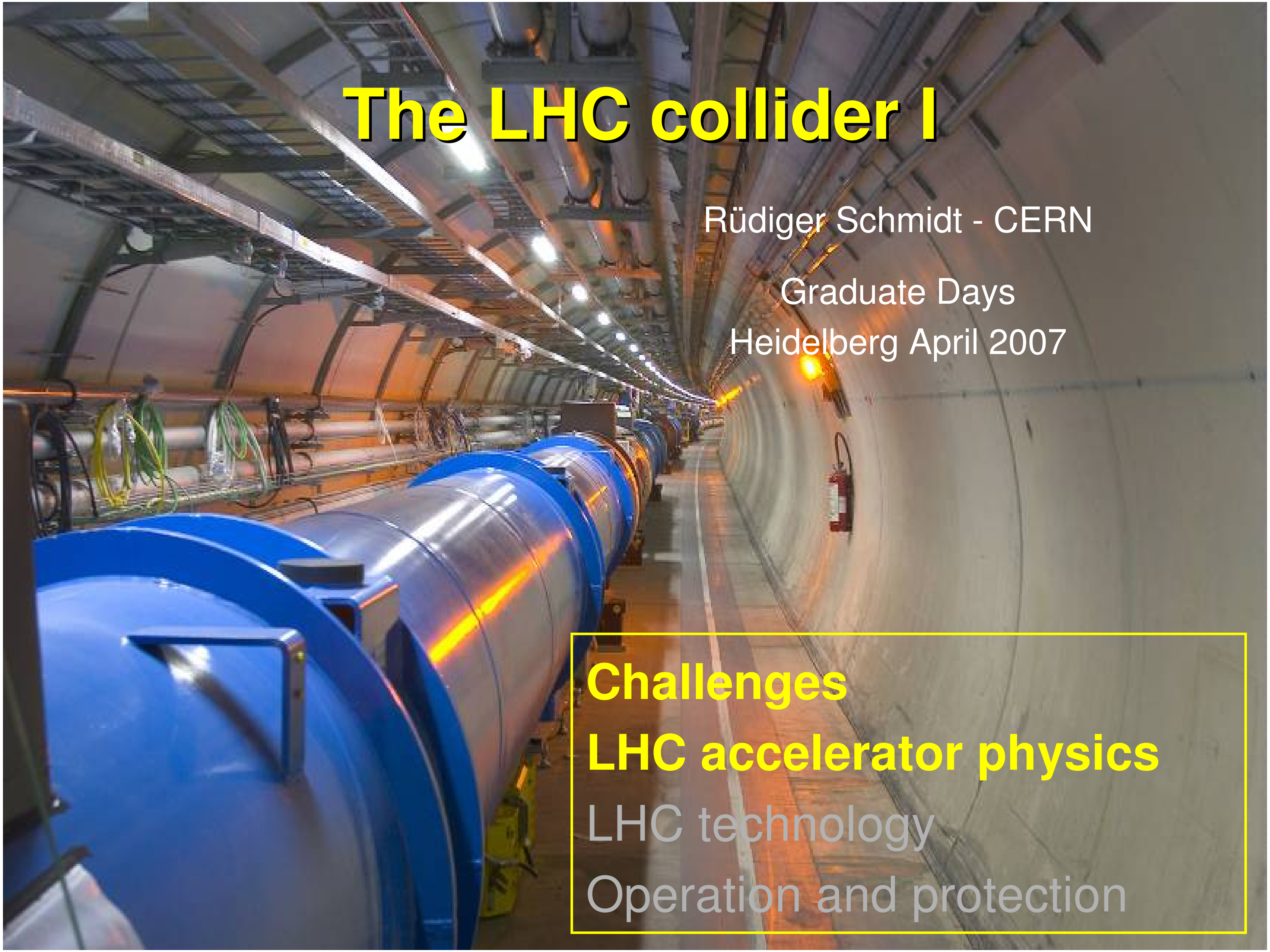


The LHC collider I

Rüdiger Schmidt - CERN

Graduate Days

Heidelberg April 2007

Challenges

LHC accelerator physics

LHC technology

Operation and protection

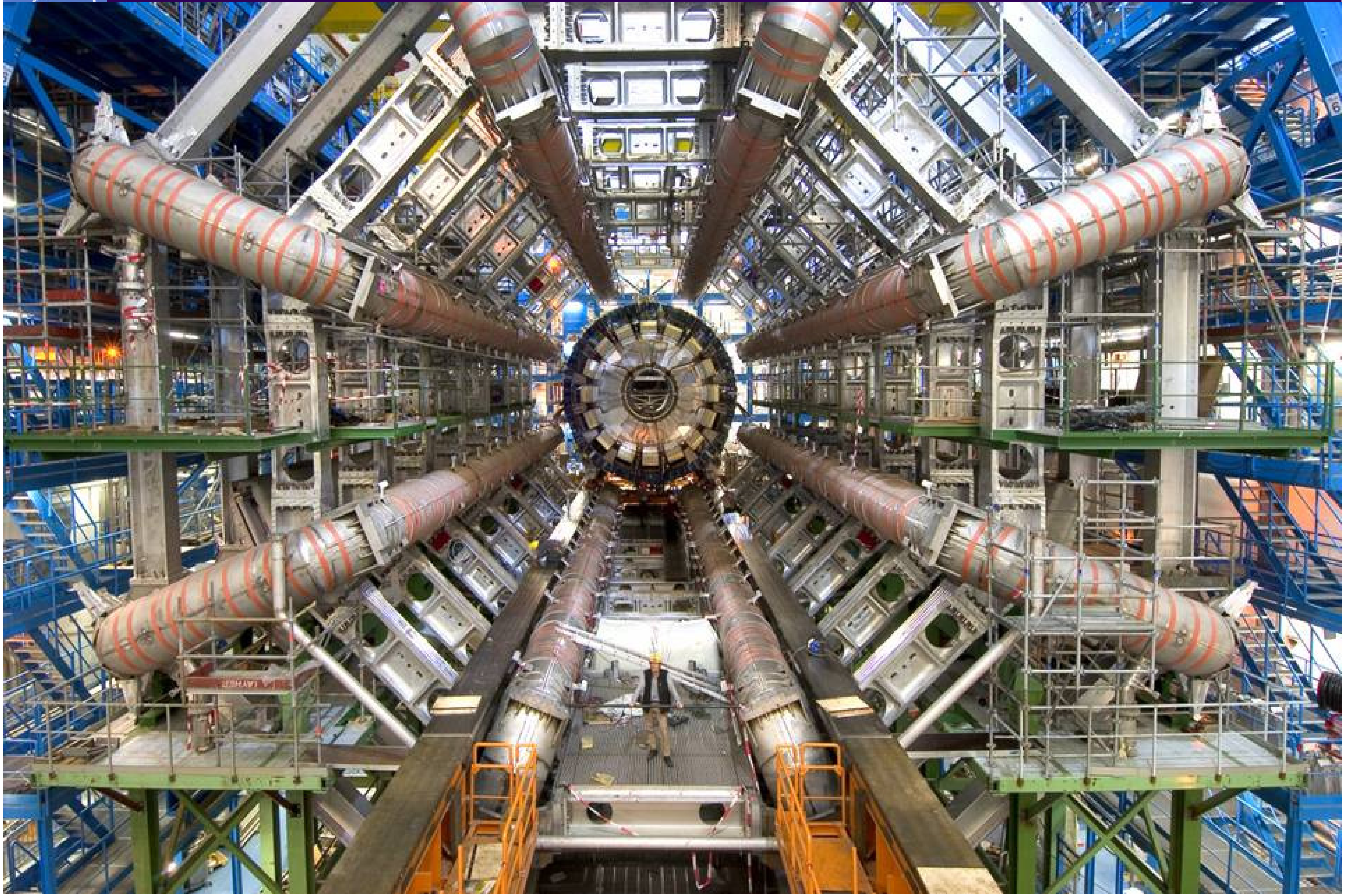
Energy and Luminosity

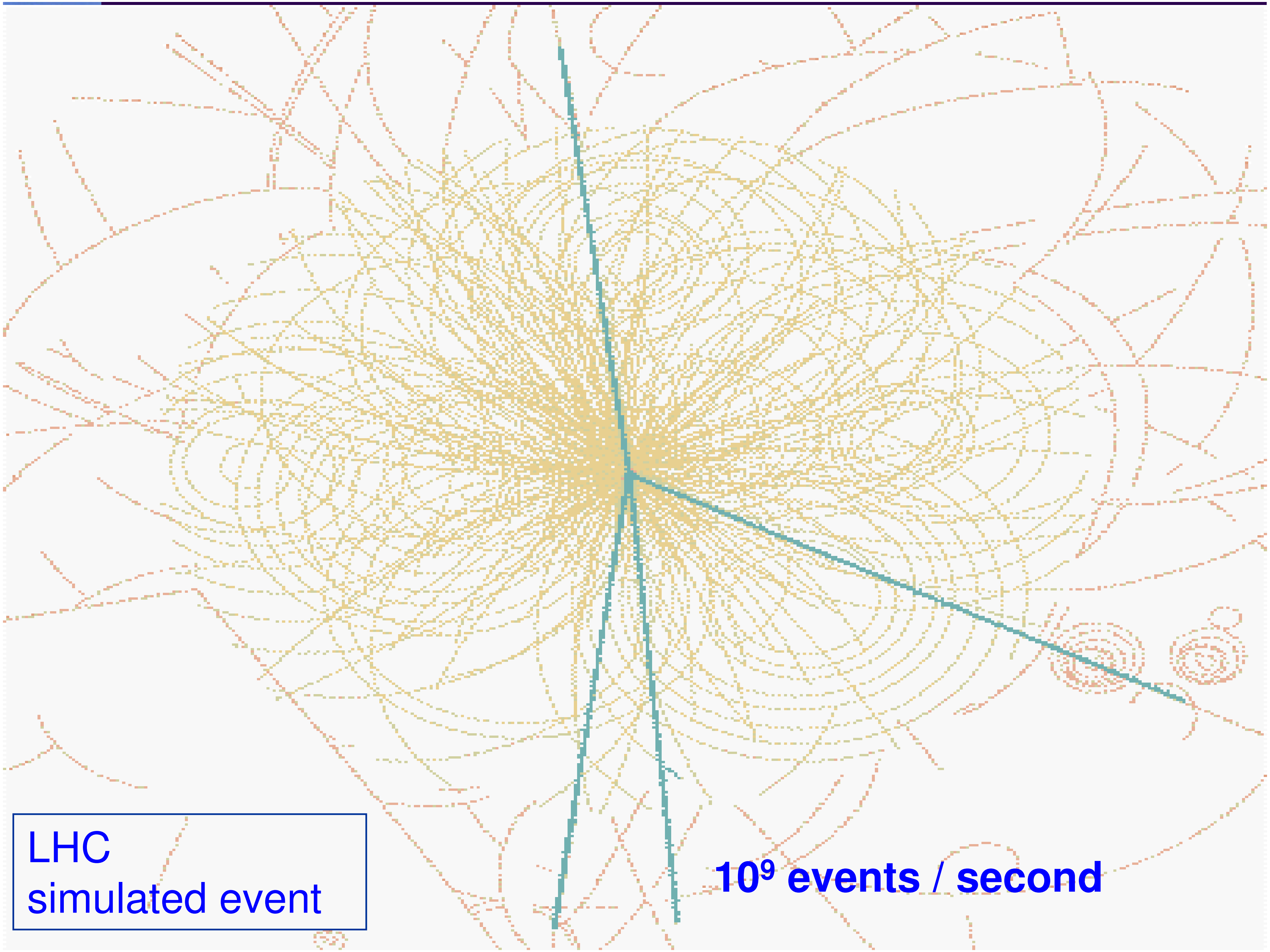
- Particle physics requires an accelerator colliding beams with a centre-of-mass energy substantially exceeding 1TeV
- In order to observe rare events, the luminosity should be in the order of 10^{34} [$cm^{-2}s^{-1}$] (challenge for the LHC accelerator)
- Event rate:

$$\frac{N}{\Delta t} = L[cm^{-2} \cdot s^{-1}] \cdot \sigma[cm^{2}]$$

- Assuming a total cross section of about 100 mbarn for pp collisions, the event rate for this luminosity is in the order of 10^9 events/second (challenge for the LHC experiments)
- Nuclear and particle physics require heavy ion collisions in the LHC (quark-gluon plasma ....)

ATLAS Detector





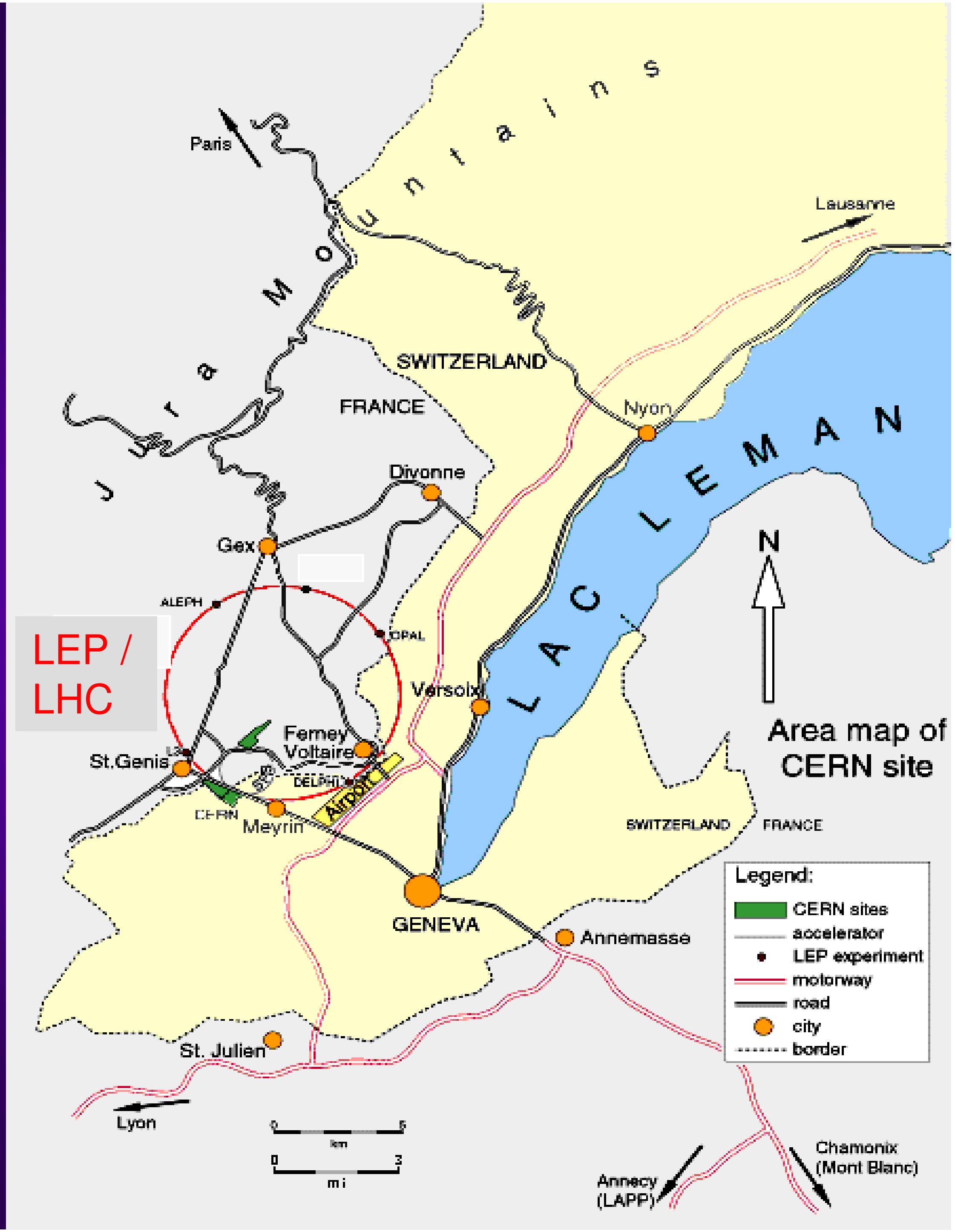
LHC
simulated event
10^9 events / second

CERN and the LHC

CERN is the leading European institute for particle physics

It is close to Geneva across the French Swiss border

There are 20 CERN member states, ~7 observer states, and many other states participating in research



er

LEP: e+e-

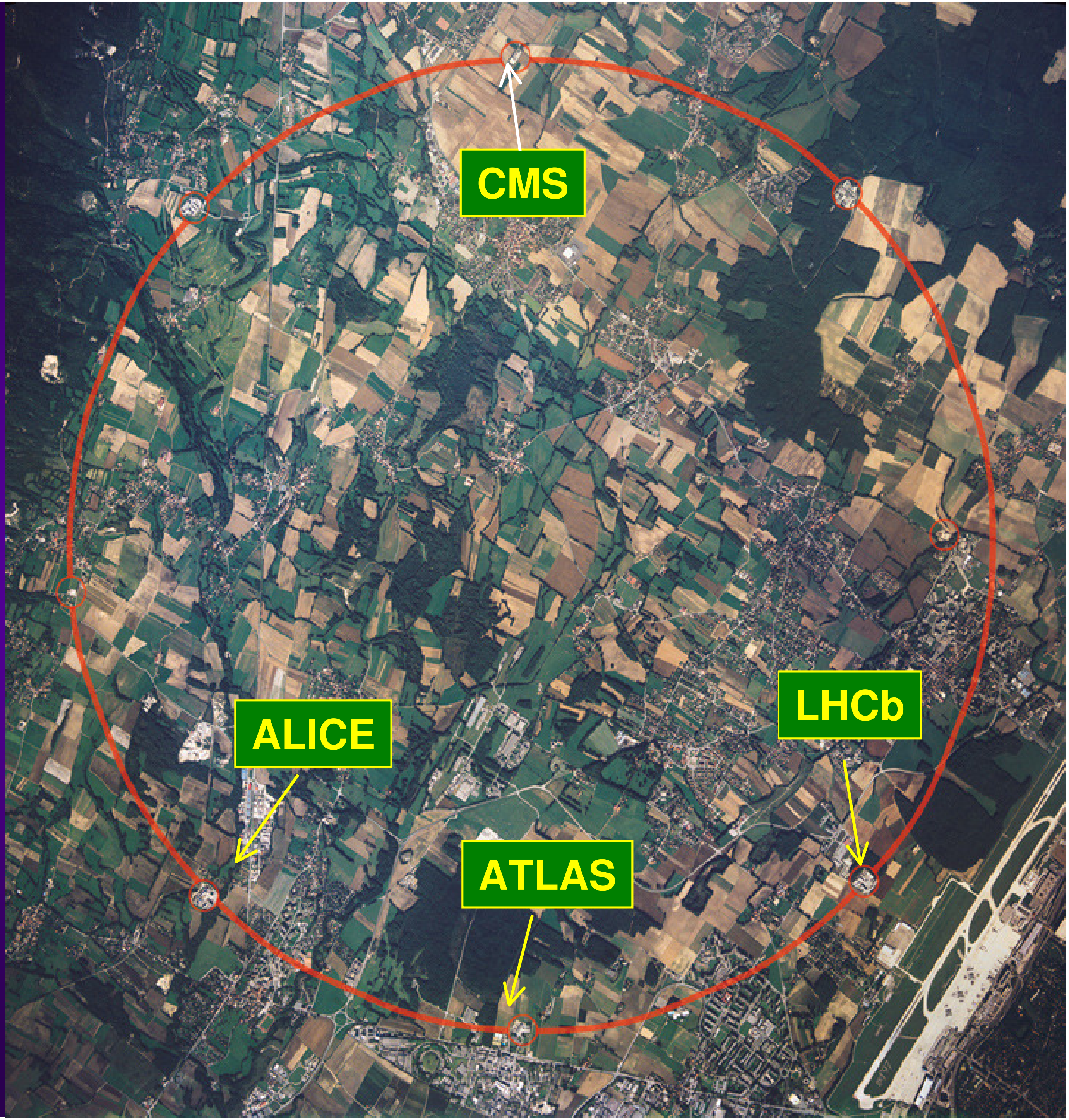
104 GeV/c (1989-2000)

Circumference 26.8 km

LHC proton-proton Collider

7 TeV/c in the LEP tunnel

LHC will also collide heavy ions



LHC: From first ideas to realisation

1982 : First studies for the LHC project

1983 : Z0 detected at SPS proton antiproton collider

1985 : Nobel Price for S. van der Meer and C. Rubbia

1989 : Start of LEP operation at 45 GeV (Z-factory)

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

1996 : LEP operation at 100 GeV (W-factory)

2000 : End of LEP operation

2002 : LEP equipment removed (second life for sc cavities ?)

2003 : Start of the LHC installation

2005 : Start of hardware commissioning

2007/8 : Commissioning with beam

The LHC is the largest machine that has ever been built, and probably the most complex one

To make the LHC a reality: Accelerators physics and ....

- Electromagnetism und Relativity
- Thermodynamics
- Mechanics
- Physics of nonlinear systems
- Solid state physics und surface physics
- Quantum mechanics
- Particle physics and radiation physics
- Vacuum physics

+ Engineering

Mechanical, Cryogenics, Electrical, Automation, Computing

Outline

- Accelerator Physics: An Introduction
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Lorentz Force

The force on a charged particle is proportional to the charge, and to the vector product of velocity and magnetic field:

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

For an electron or proton the charge is:

$$q = e_0 = 1.602 \cdot 10^{-19}\ [C]$$

Acceleration (increase of energy) only by electrical fields – not by magnetic fields:

$$\Delta E = \int_{s1}^{s2} \vec{\mathbf{F}} \cdot \mathbf{d}\vec{\mathbf{s}}$$

$$\frac{dE}{dt} = \vec{\mathbf{v}} \cdot \vec{\mathbf{F}}$$

$$\frac{dE}{dt} = q \cdot (\vec{\mathbf{v}} \cdot \vec{\mathbf{E}} + \vec{\mathbf{v}} \cdot (\vec{\mathbf{v}} \times \vec{\mathbf{B}})) = q \cdot \vec{\mathbf{v}} \cdot \vec{\mathbf{E}}$$

Acceleration

Acceleration of a particle by an electrical potential

$$U = \int_{s1}^{s2} \vec{\mathbf{E}} \cdot \mathbf{d}\vec{\mathbf{s}}$$

Energy gain given by the potential

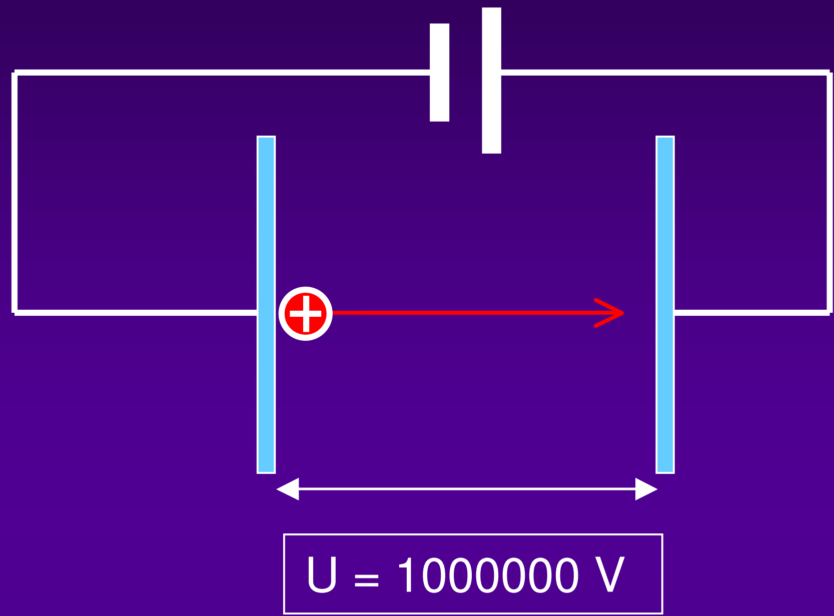
$$\Delta E = \int_{s1}^{s2} \vec{\mathbf{F}} \cdot \mathbf{d}\vec{\mathbf{s}} = \int_{s1}^{s2} q \cdot \vec{\mathbf{E}} \cdot \mathbf{d}\vec{\mathbf{s}} = q \cdot U$$

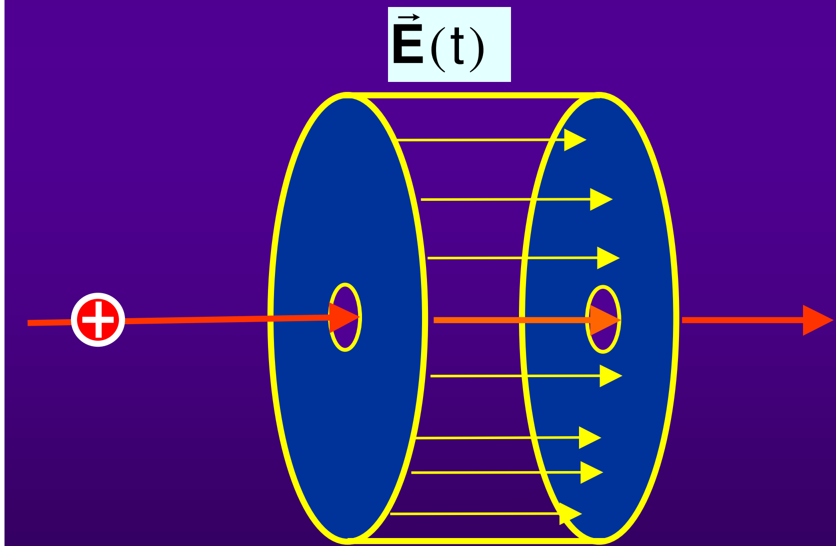
For an acceleration to 7 TeV a voltage of 7 TV is required

Acceleration with RF fields

U = 1000000 V
d = 1 m
$q = e_0$

$\Delta E = 1$ MeV





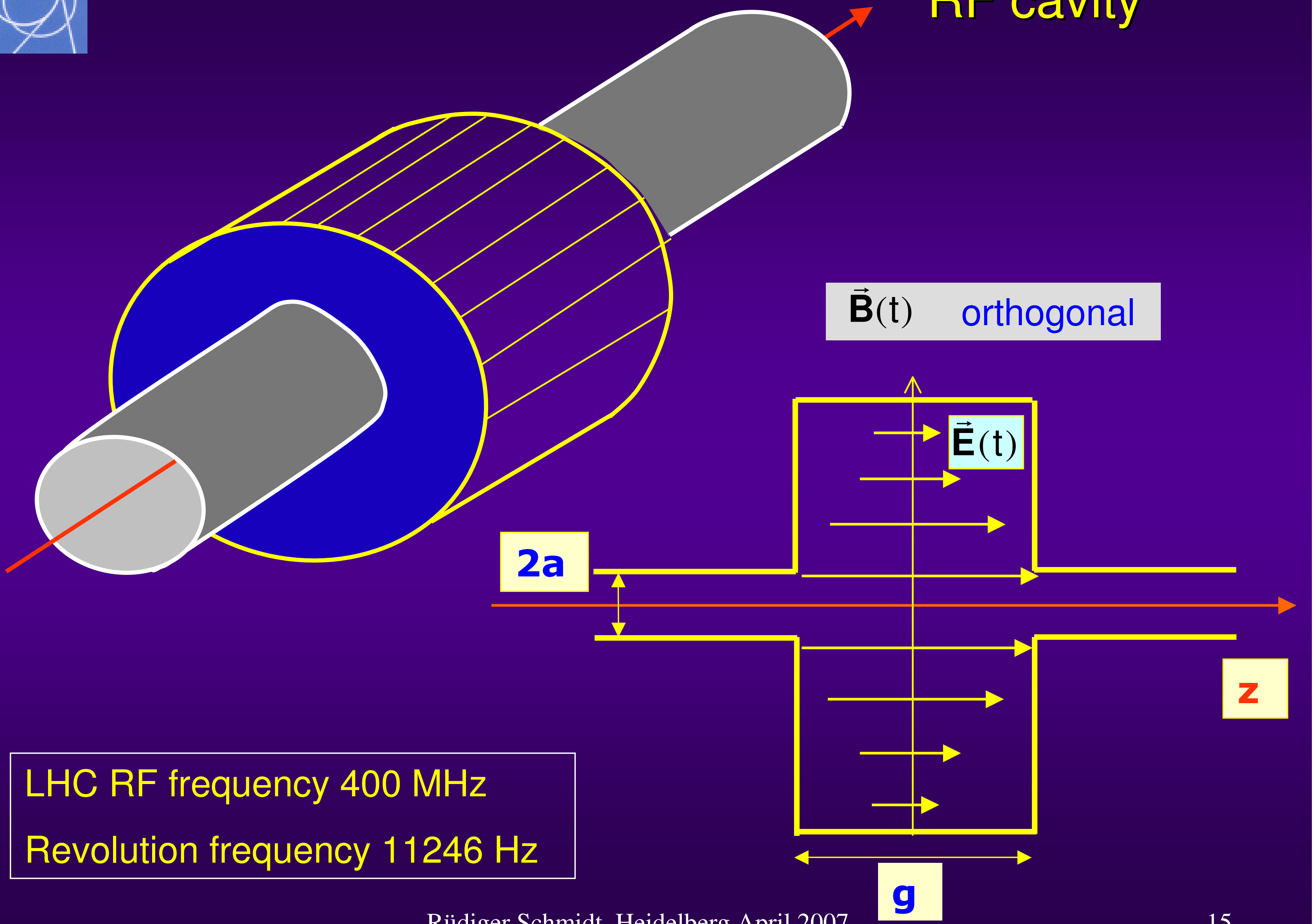
Time varying field

$$E_z(t) = E_0 \cdot \cos(\omega \cdot t + \varphi)$$

Maximum field about 20 MV / m

Consequence : bunched beam

RF cavity



LHC RF frequency 400 MHz

Revolution frequency 11246 Hz

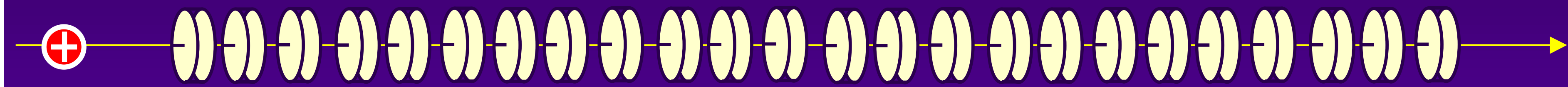
RF systems: 400 MHz

400 MHz system:

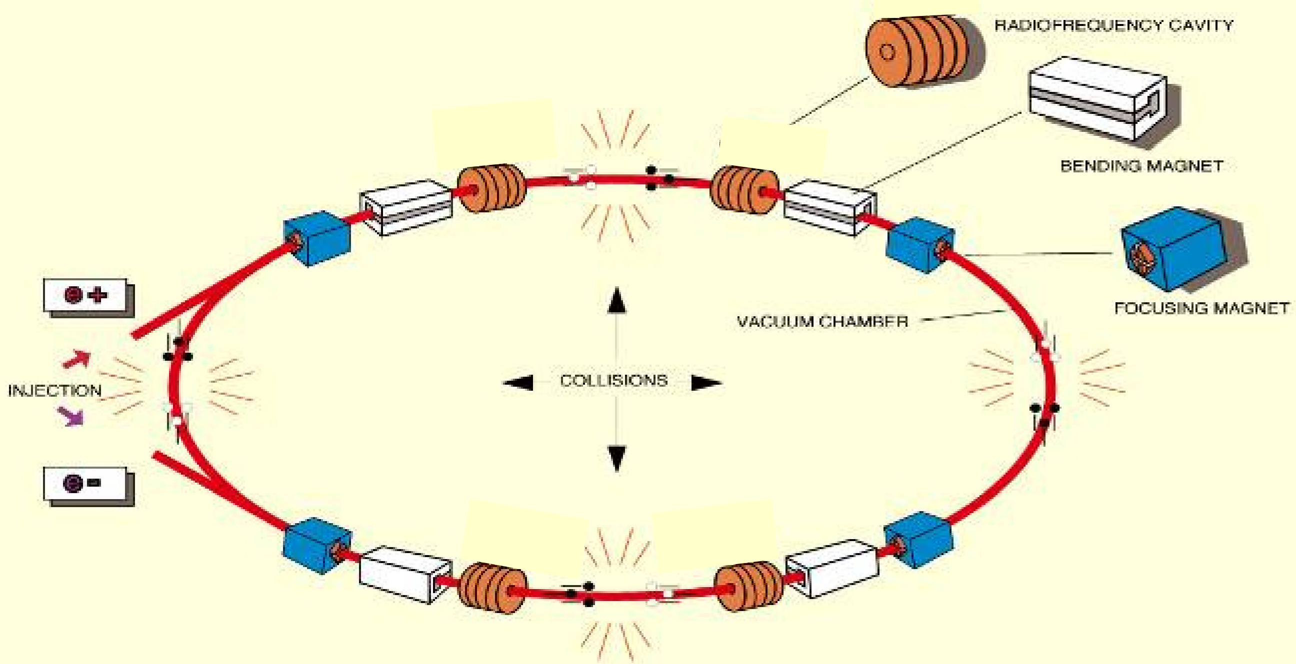
16 sc cavities (copper sputtered with niobium) for 16 MV/beam were built and assembled in four modules

To get to 7 TeV: Synchrotron – circular accelerator and many passages in RF cavities

LINAC (planned for several hundred GeV - but not above 1 TeV)



LHC **circular machine** with energy gain per turn some MeV
acceleration takes about 20 minutes



....requires deflecting magnets (dipoles)

Deflection by magnetic fields

For a charged particle moving perpendicular to the magnetic field the force is given by:

$$\mathbf{F} = m \cdot \mathbf{a} = q \cdot \mathbf{v} \cdot \mathbf{B}$$

The particle moves on a circle

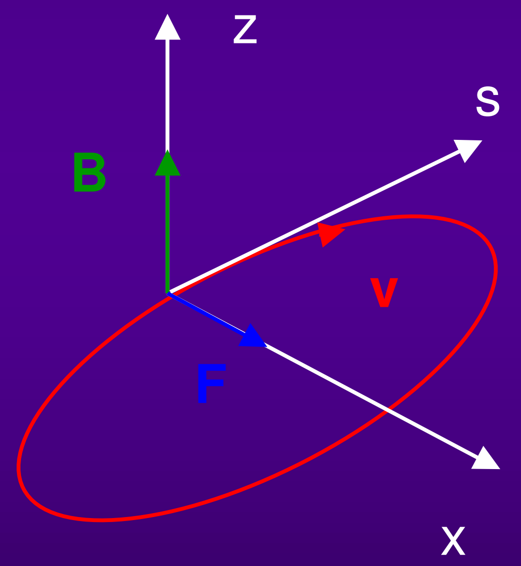
$$\mathbf{F}_{Lorentz} = q \cdot \mathbf{v} \cdot \mathbf{B}$$

$$\mathbf{F}_{Centrifugal} = m \cdot \mathbf{v}^2 / R$$

$$R = m \cdot \mathbf{v} / q \cdot \mathbf{B}$$

$$\text{with } \omega = \frac{v}{R} \text{ one gets: } \omega = \frac{q}{m} \cdot \mathbf{B}$$

$$\mathbf{B} = \frac{E}{R \cdot q \cdot c}$$

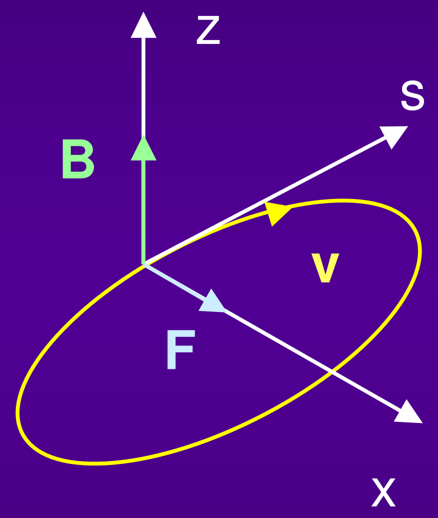


Particle deflection: Lorentz Force

The force on a charged particle is proportional to the charge, and to the vector product of velocity and magnetic field:

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

$$B = \frac{p}{e_0 \cdot R}$$



- Maximum momentum 7000 GeV/c
- Radius 2805 m fixed by LEP tunnel
- **Magnetic field B = 8.33 Tesla**
- Iron magnets limited to 2 Tesla, therefore superconducting magnets are required
- Deflecting magnetic fields for two beams in opposite directions

Force on a proton by an electric and magnetic field

An electrical field is assume, with a strength of: $E := 7 \cdot 10^6 \frac{V}{m}$

A transverse magnetic field is assumed with $B := 8.3T$

With the Lorentz Force $F = e_0 \cdot (E + c \cdot B)$ the force on the proton is given by:

$F_{B\_field} := e_0 \cdot c \cdot B$ $F_{E\_field} := e_0 \cdot E$

$F_{B\_field} = 3.986 \times 10^{-10} N$ $F_{E\_field} = 1.121 \times 10^{-12} N$

$$\frac{F_{B\_field}}{F_{E\_field}} = 355.469$$

For the gravitation: $F_G := g \cdot m_e$ $F_G = 8.933 \times 10^{-30} N$

Radius of a proton in a B field with $B = 8.3\,T \;\; : \; 7 \cdot 10^{12} \frac{eV}{c} \cdot \frac{1}{e_0 \cdot B} = 2.813 \times 10^3 m$

Energy loss for charged particles by synchrotron radiation

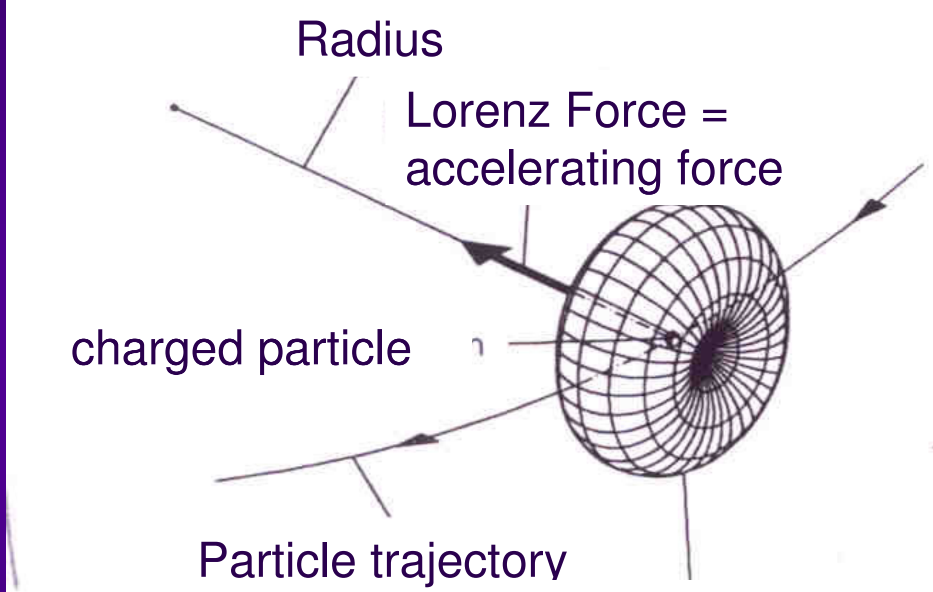


Figure from K.Wille

Power emitted for one particle: $$P_S = \frac{e_0^2 \cdot c}{6 \cdot \pi \cdot \varepsilon_0 \cdot \left(m_0 \cdot c^2\right)^4} \cdot \frac{E^4}{\rho^2}$$

with E = energy, m_0 = rest mass, e_0 = charge, and ρ = radius

Energy loss for charged particles electrons / protons in LEP tunnel

$E_{lep} := 100\text{GeV}$

$E_{lhc} := 7000\text{GeV}$

Energy loss for one particle per turn:

$U_{lep} = 3.844 \times 10^{9}\ \text{eV}$

$U_{lhc} = 8.121 \times 10^{3}\ \text{eV}$

Total power of synchrotronradiation:

Number of electrons in LEP: $N_{lep} := 10^{12}$

Number of protons in LHC $N_{lhc} := 10^{14}$

$P_{total\_lep} := N_{lep} \cdot P_{lep}$

$P_{total\_lhc} := N_{lhc} \cdot P_{lhc}$

$P_{total\_lep} = 1.278 \times 10^{7}\ \text{W}$

$P_{total\_lhc} = 2.699 \times 10^{3}\ \text{W}$

The power of the synchrotronradiation emitted at the LHC is very small, but the radiation goes into the supraconducting magnets at 1.9 K ... 20 K

...just assuming to accelerate electrons to 7 TeV

assuming LEP with electrons at 7 TeV: $\gamma_{lep} := \frac{7 \cdot 10^{12}}{m_e \cdot c^2} eV$

$$U_{lep} := e_0^{\,2} \cdot \frac{\gamma_{lep}^{\,4}}{3 \cdot \varepsilon_0 \cdot \rho}$$

$$U_{lep} = 9.23 \times 10^{16}\, eV$$

...better to accelerate protons

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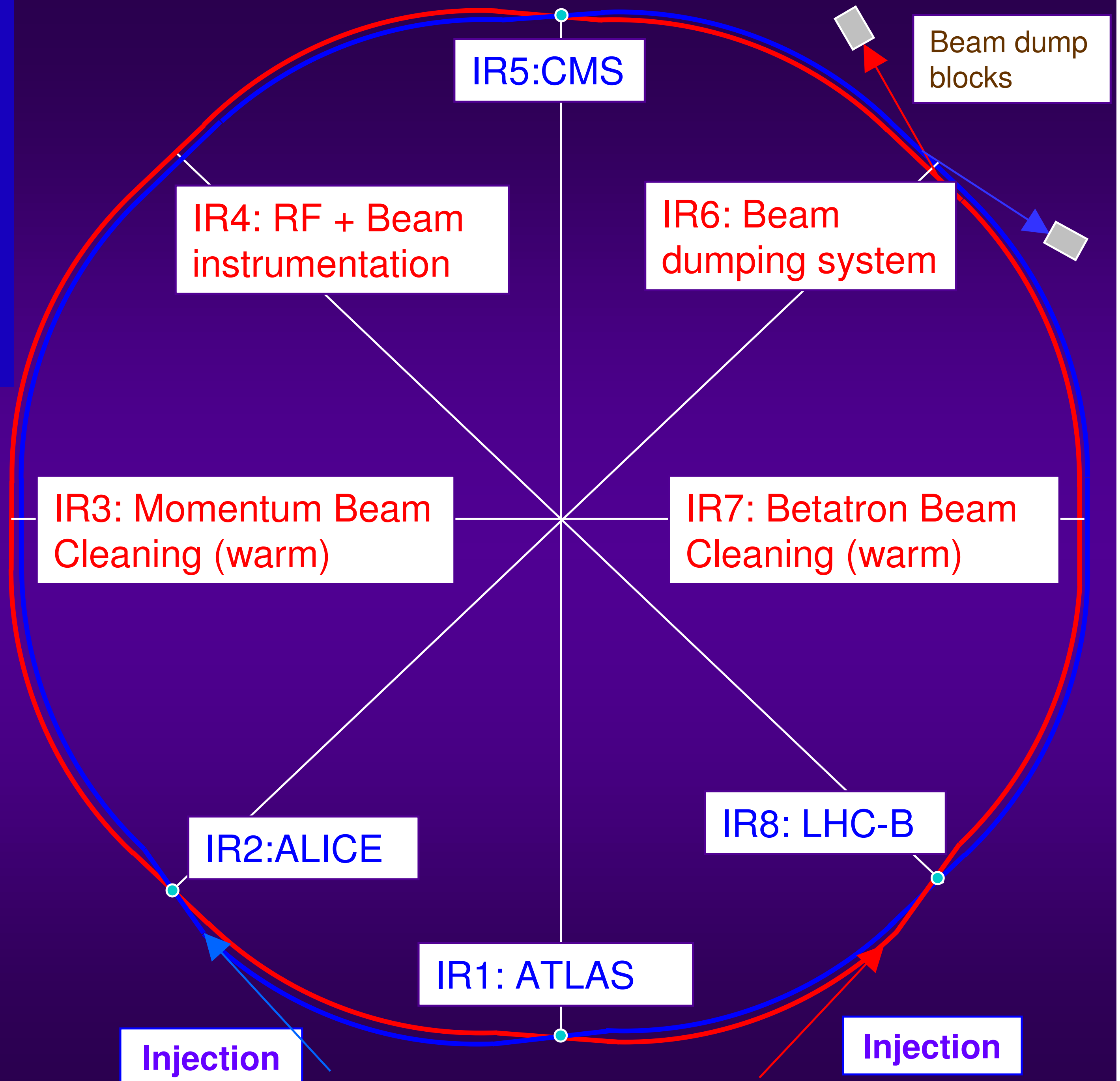
LHC Layout

eight sectors
eight arcs

eight long straight sections (insertions) about 700 m long



Main dipole magnets: making the circle

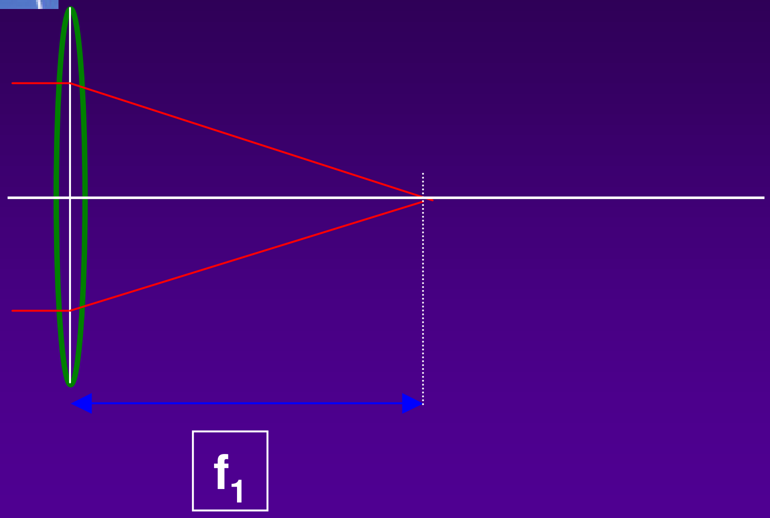
Beam transport

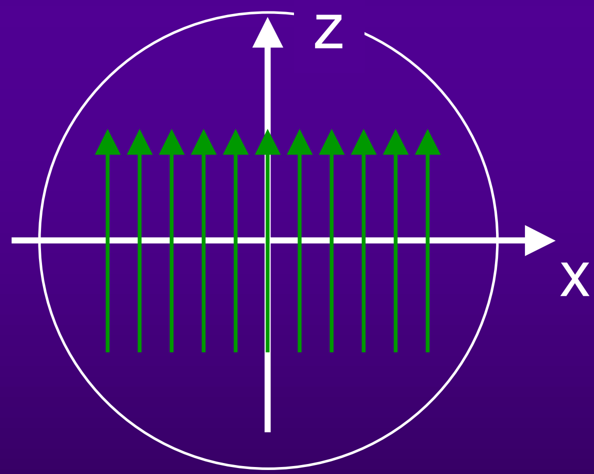
Need for getting protons on a circle: dipole magnets

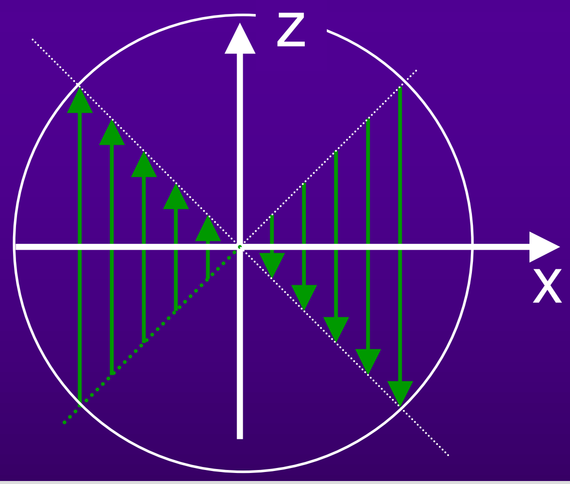
Need for focusing the beams:

- Particles with different injection parameters (angle, position) separate with time
  - Assuming an angle difference of 10^{-6} rad, two particles would separate by 1 m after 10^{6} m. At the LHC, with a length of 26860 m, this would be the case after 50 turns (5 ms !)
- Particles would „drop“ due to gravitation
- The beam size must be well controlled
  - At the collision point the beam size must be tiny
- Particles with (slightly) different energies should stay together

Focusing using lenses as for light







Dipolemagnet – B-field in aperture constant

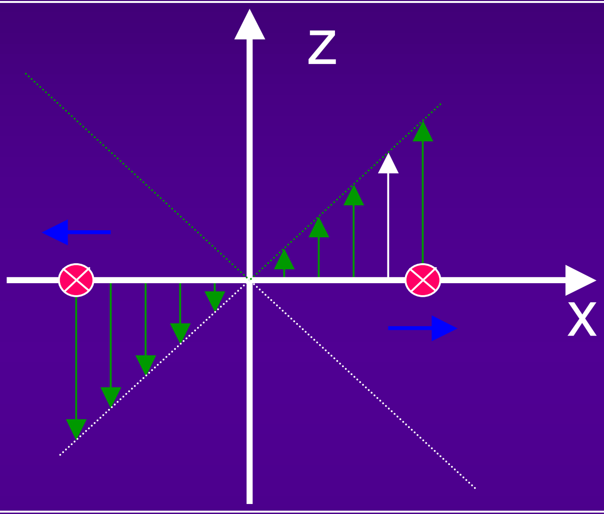
Quadrupolemagnet – B-field zero in centre, linear increase (as an optical lense)

From Maxwell equations:

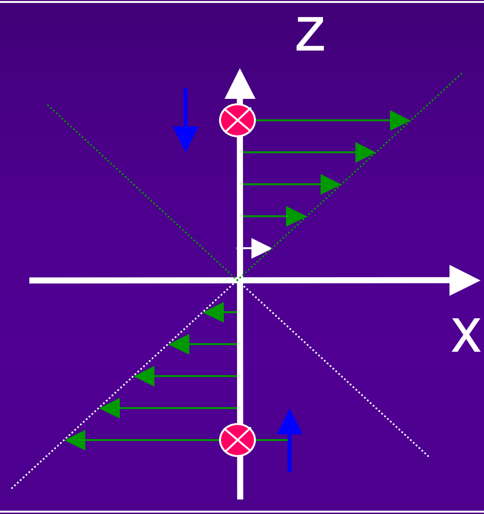
$$B_z(x) = \text{const} \cdot x$$

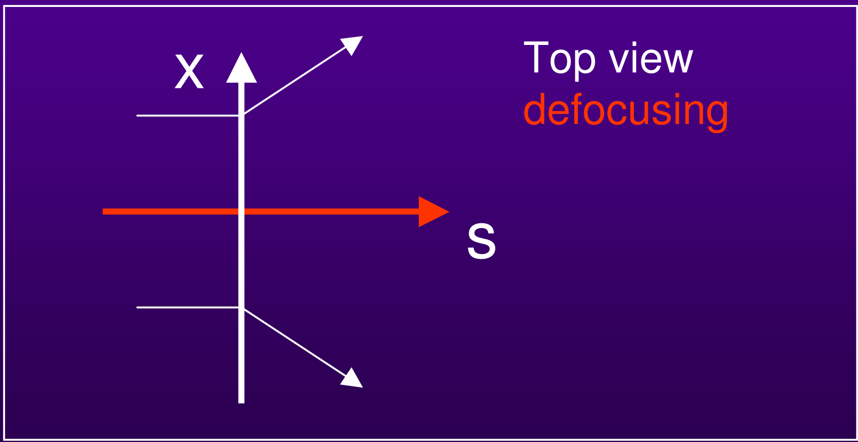
$$B_x(z) = \text{const} \cdot z$$

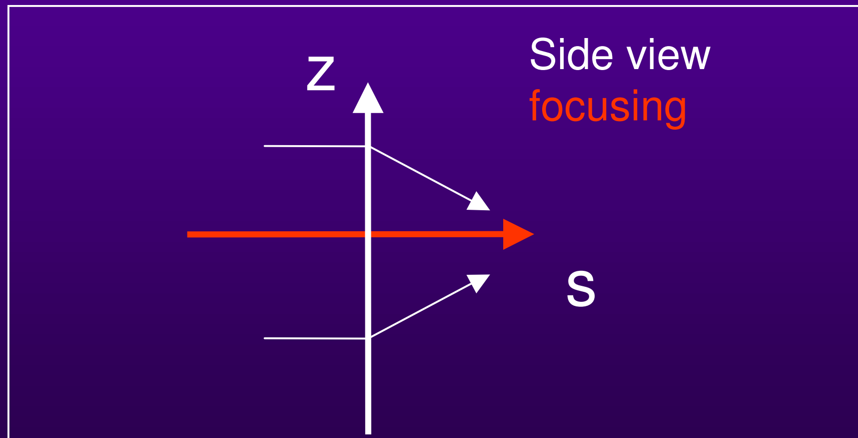
Assuming proton runs along s (=y), perpendicular to x and z



Looking along proton trajectory

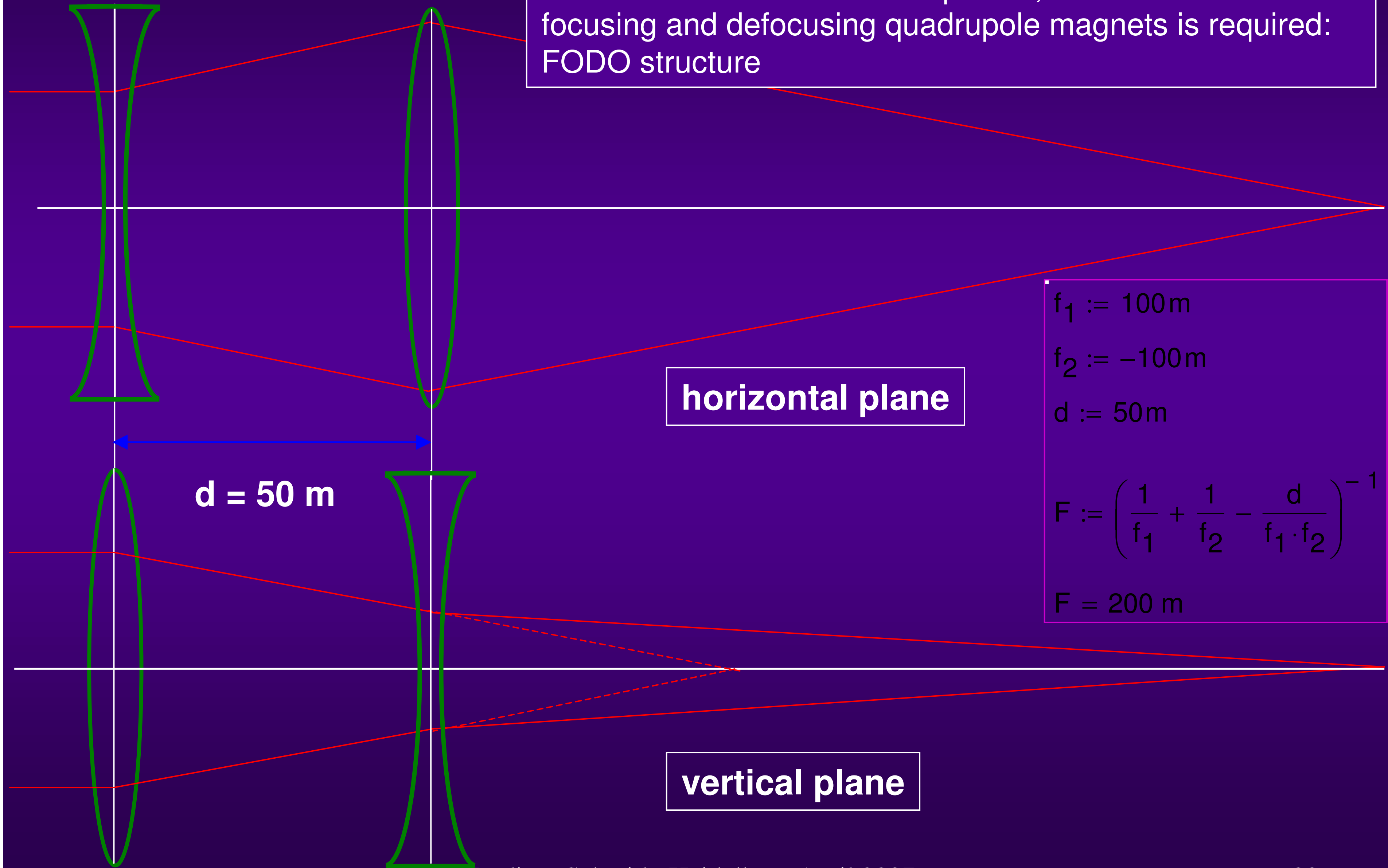






Focusing of a system of two lenses for both planes

To focuse the beams in both planes, a succession of focusing and defocusing quadrupole magnets is required: FODO structure



$f_1 := 100\,\mathrm{m}$

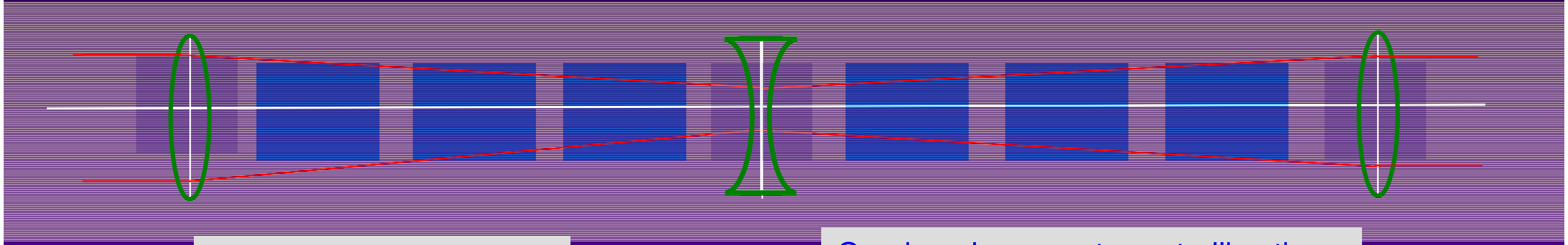
$f_2 := -100\,\mathrm{m}$

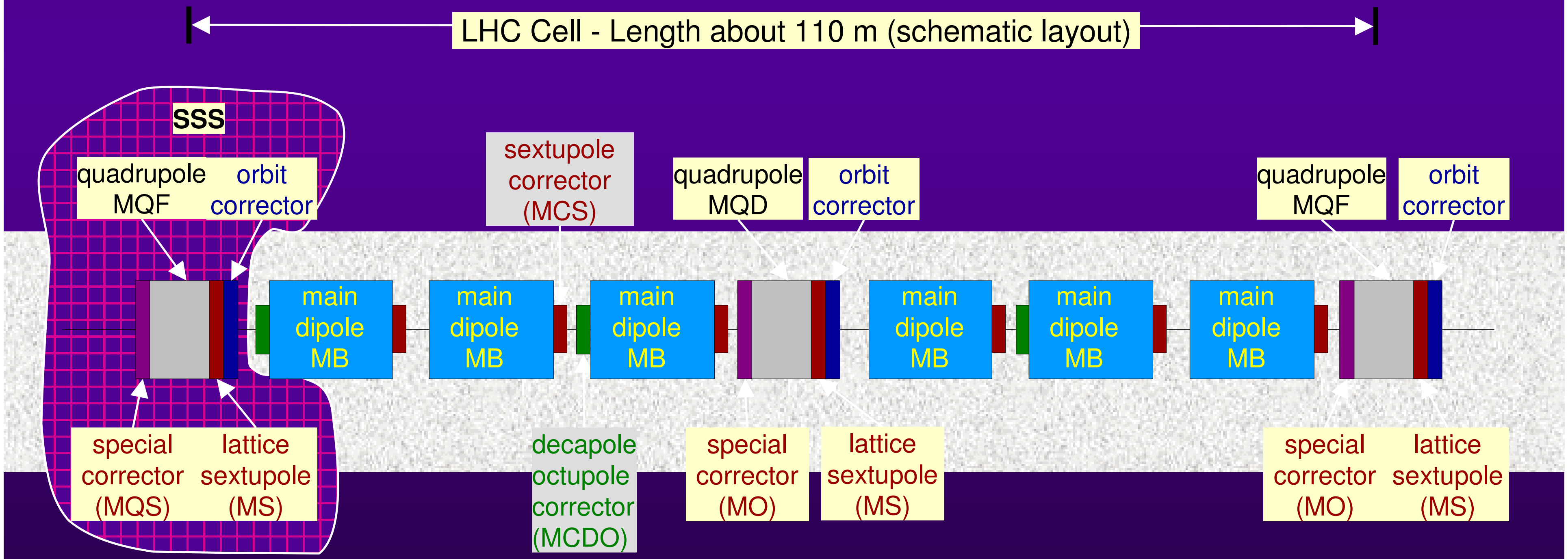
$d := 50\,\mathrm{m}$

$$F := \left(\frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \cdot f_2}\right)^{-1}$$

$F = 200\ \mathrm{m}$

A cell in the LHC arcs

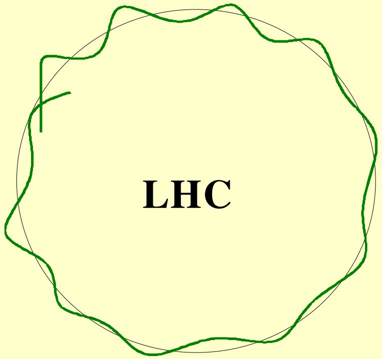




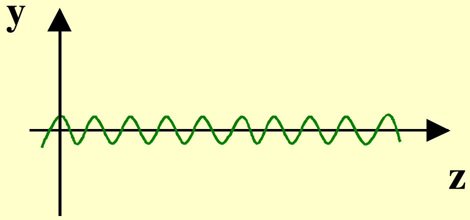
Magnets and beam stability

- Dipole magnets
  - To make a circle around LHC
- Quadrupol magnets
  - To keep beam particles together
  - Particle trajectory stable for particles with nominal momentum
- Sextupole magnets
  - To correct the trajectories for off momentum particles
  - Particle trajectories stable for small amplitudes (about 10 mm)
- Multipole-corrector magnets
  - Sextupole - and decapole corrector magnets at end of dipoles
- Particle trajectories can become instable after many turns (even after, say, 10^6 turns)

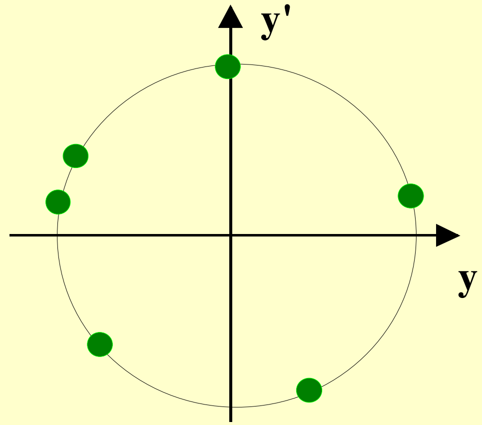
Particle stability and superconducting magnets - Quadrupolar- and multipolar fields



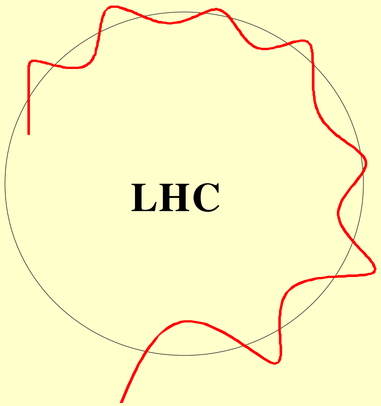
Particle oscillations in quadrupole field (small amplitude)



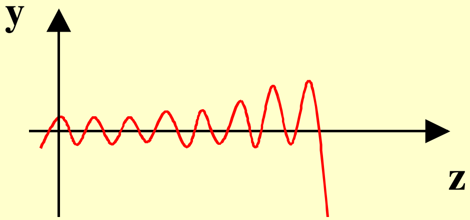
Harmonic oscillation after coordinate transformation



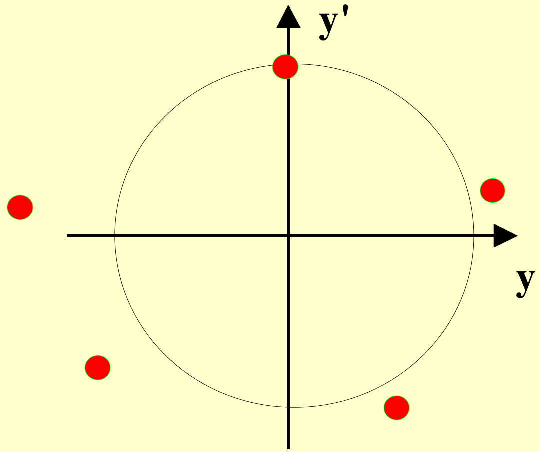
Circular movement in phase space



Particle oscillation assuming non-linear fields, large amplitude



Amplitude grows until particle is lost (touches aperture)



No circular movement in phasespace

Dynamic aperture and magnet imperfections

- Particles with small amplitudes are in general stable
- Particles with large amplitudes are not stable
- The dynamic aperture is the limit of the stability region
- The dynamic aperture depends on field errors - without any field errors, the dynamic aperture would be large

- The magnets should be made such as the dynamic aperture is not too small (say, 10 • the amplitude of a one sigma particle, assuming Gaussian distribution)

- The dynamic aperture depends also on the working point and on the sextupole magnets for correction of chromatic effects

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High luminosity by colliding trains of bunches

Number of „New Particles“ per unit of time:

$$\frac{N}{\Delta T} = L\left[cm^{-2} \cdot s^{-1}\right] \cdot \sigma\left[cm^{2}\right]$$

The objective for the LHC as proton – proton collider is a luminosity of about 10^{34} [$cm^{-2}s^{-1}$]

- LEP (e+e-) : 3-4 10^{31} [$cm^{-2}s^{-1}$]
- Tevatron (p-pbar) : ~ 10^{32} [$cm^{-2}s^{-1}$]
- B-Factories: > 10^{34} [$cm^{-2}s^{-1}$]

Luminosity parameters

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x \cdot \sigma_y}$$

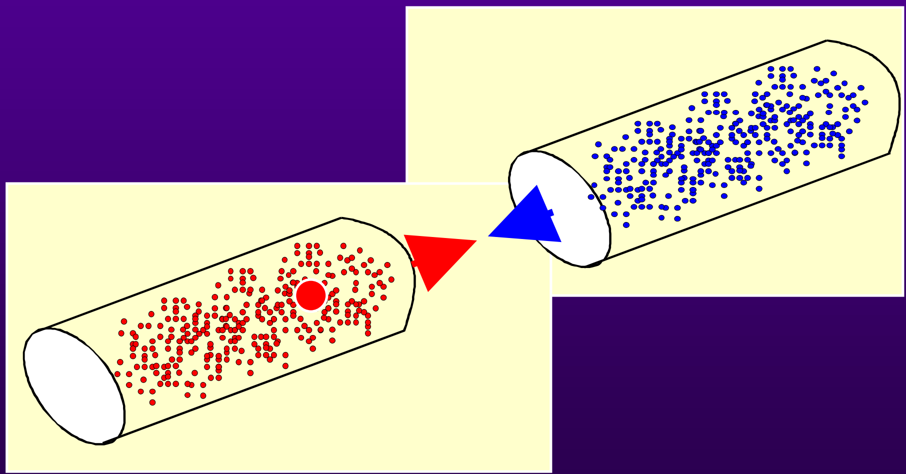
with :

$N =$ Number of protons per bunch

$f =$ revolution frequency

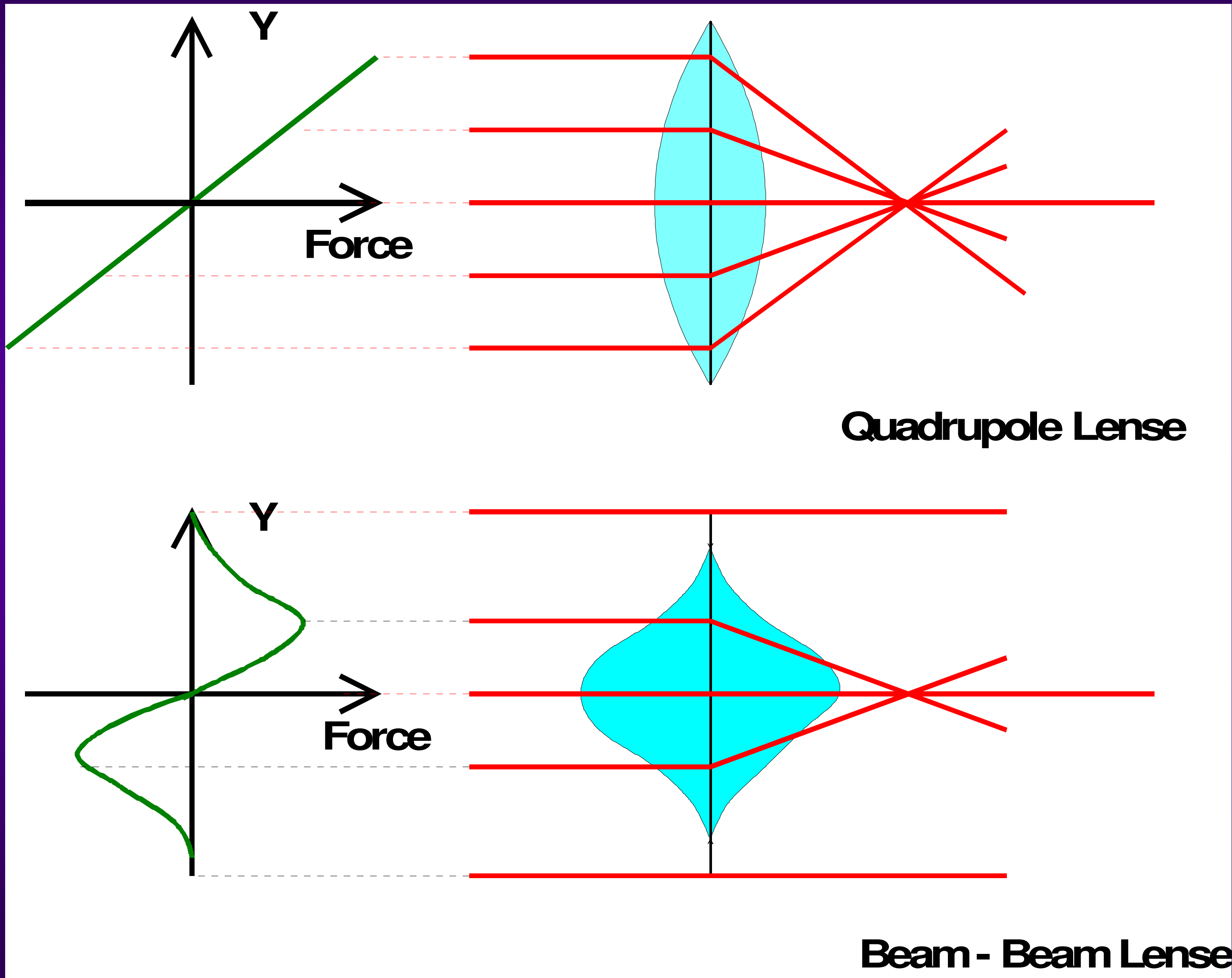
$n_b =$ number of bunches per beam

$\sigma_x \cdot \sigma_y =$ beam dimensions at interaction point



What happens with one particle experiencing the force of the em-fields or 10^{11} protons in the other beam during the collision ?

Limitation: beam-beam interaction



Electromagnetic force on a particle in the counterrotating beam

Optimising luminosity by increasing N

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x \cdot \sigma_y}$$

Electromagnetic field of one beam act on other beam. Calculation by transforming into frame of test particle and calculate Lorentz Force :

$$F(r) = \frac{N \cdot e^2}{2\pi \cdot \varepsilon_0} \cdot \frac{(1+\beta^2)}{r} \cdot \left[1 - \exp(-\frac{r^2}{2 \cdot \sigma^2}) \right]$$

Bunch intensity limited due to this strong non-linear field to about N = 10^{11}

Beam beam interaction determines parameters

Number of protons per bunch limited to about **10^{11}**

Beam size given by injectors and by space in vacuum chamber

f = **11246 Hz**

Beam size **16 μm**, for β = 0.5 m

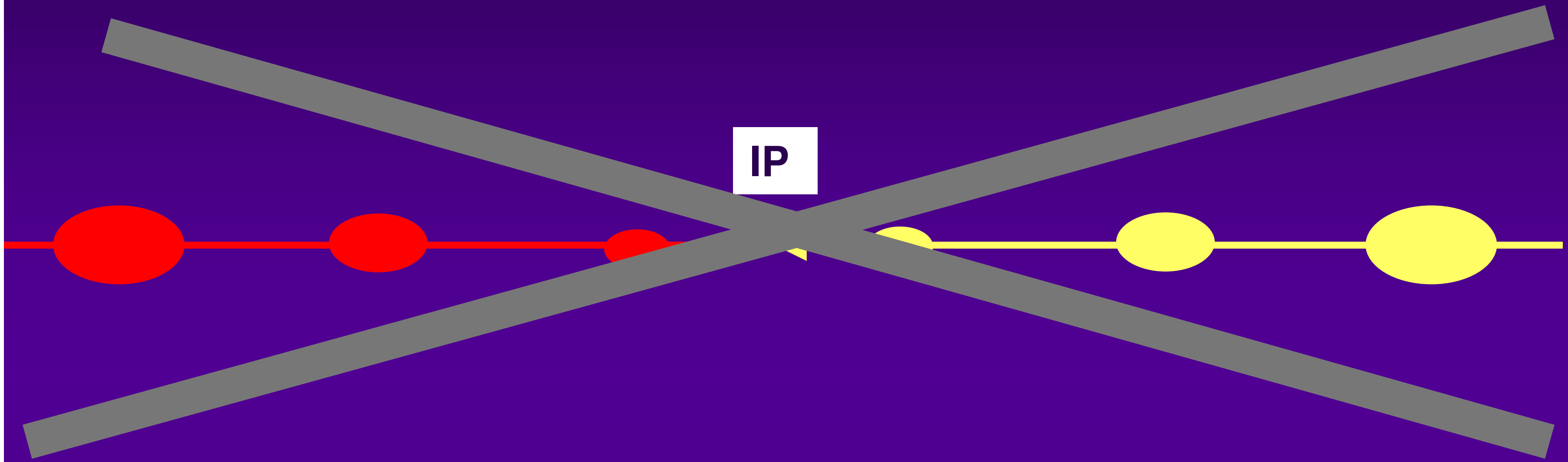
$$L = N^2 f \; n_b / 4\pi \sigma_x \sigma_y = 3.5 \; 10^{30} \; [cm^{-2} \, s^{-1}]$$

with one bunch

with **2808** bunches (every 25 ns one bunch)

$L = 10^{34} \; [cm^{-2} s^{-1}]$

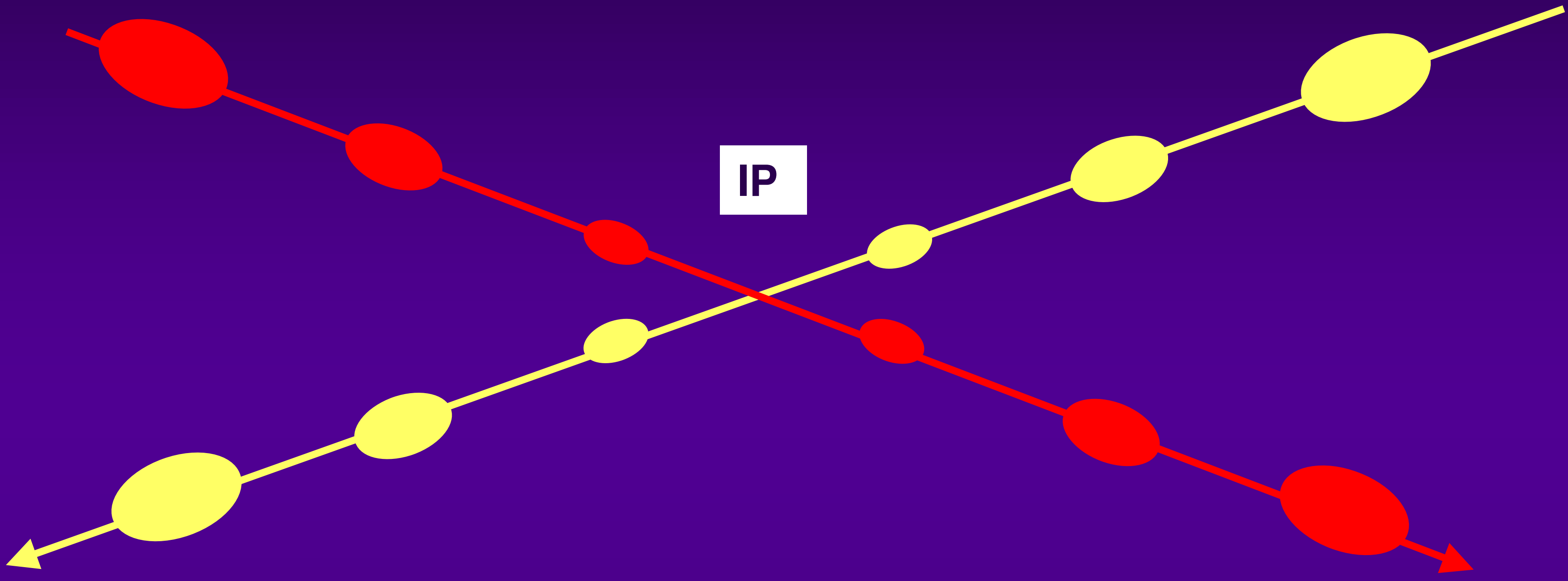
Large number of bunches



Bunch structure with 25 ns spacing

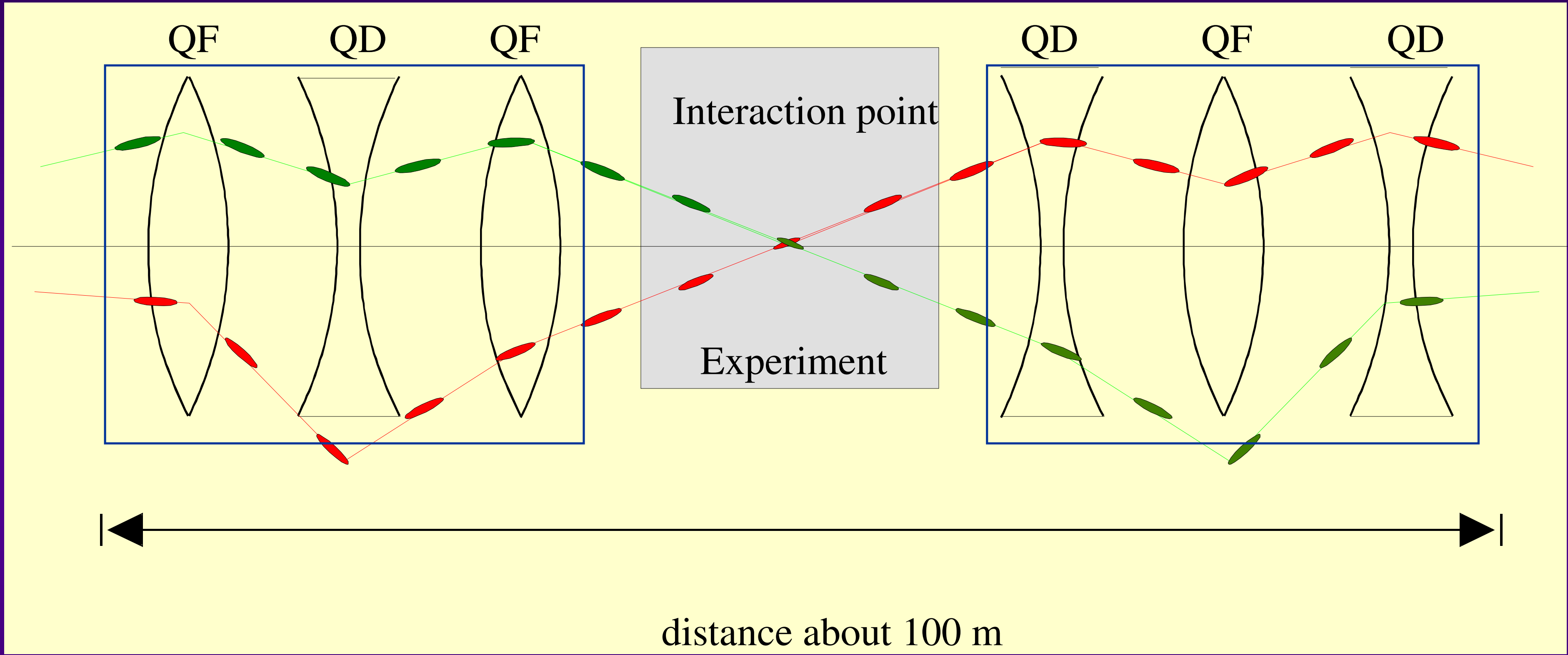
- Experiments: more than 1 event / collision, but should not exceed a number in the order of 10-20
- Limit number of collision points as far as possible
- Vacuum system: photo electrons

Large number of bunches



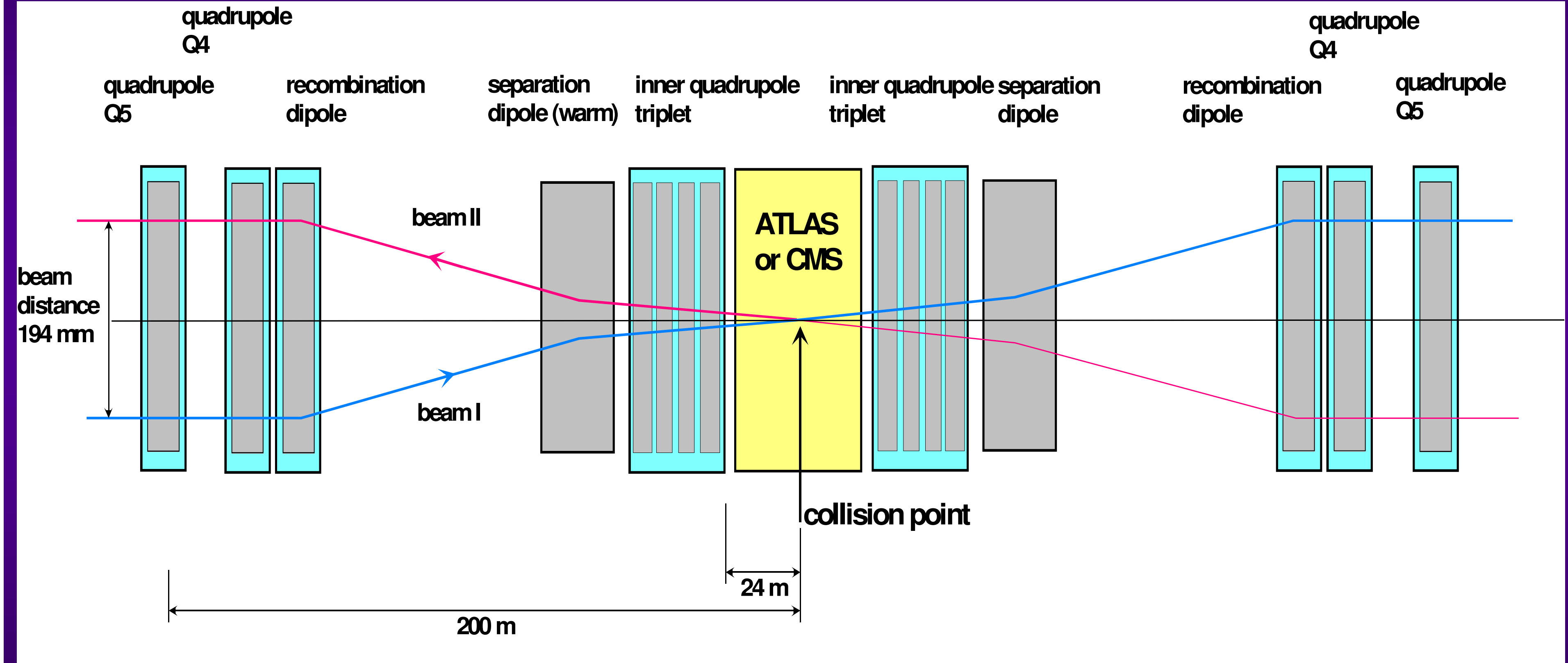
- **Crossing angle** to avoid beam beam interaction (only long range beam beam interaction present)
- Interaction Region quadrupoles with gradient of 250 T/m and 70 mm aperture

Crossing angle for multibunch operation



- Focusing quadrupole for beam 1, defocusing for beam 2
- High gradient quadrupole magnet triplet with large aperture (US-JAPAN)
- Total crossing angle of 300 µrad
- Beam size at interaction point 16 µm, in arcs about 0.3 mm

Layout of insertion for ATLAS and CMS



Example for an LHC insertion with ATLAS or CMS

Outline

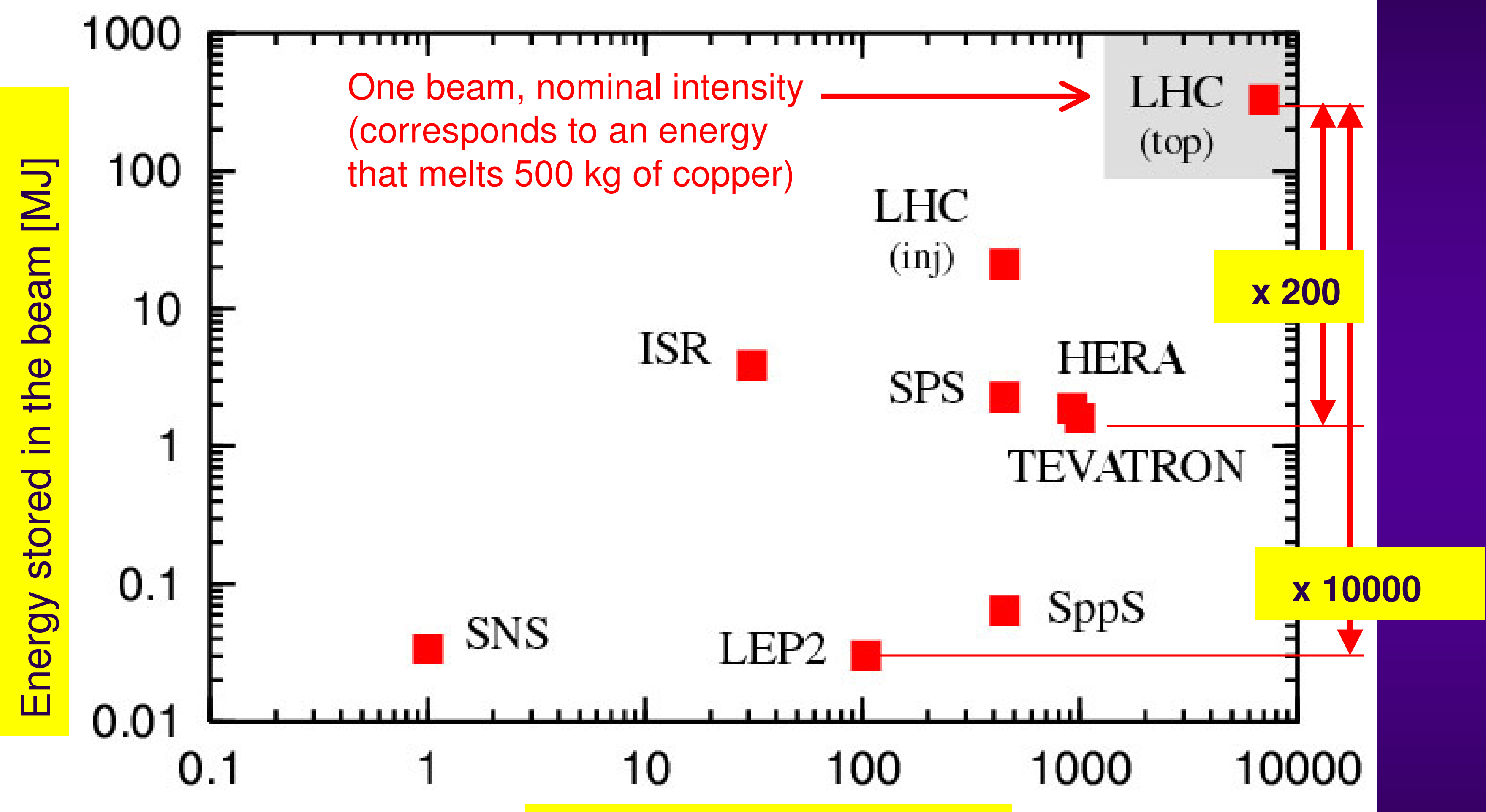
- Accelerator Physics: An Introduction
  - Why protons? Why in the LEP tunnel? Why superconducting magnets? Why "two" accelerators in one tunnel?
- LHC layout and beam transport
- The quest for high luminosity and the consequences
- **Wrapping up: LHC Parameters**
- The CERN accelerator complex: injectors and transfer
- LHC technology
- LHC operation and machine protection
- Conclusions

Very high beam current

Many bunches and high energy -
Energy in one beam about 330 MJ

- Dumping the beam in a safe way
- Beam induced quenches (when 10^{-7} of beam hits magnet at 7 TeV)
- Beam stability and magnet field quality
- Beam cleaning (Betatron and momentum cleaning)
- Synchrotron radiation - power to cryogenic system
- Radiation, in particular in experimental areas from beam collisions (beam lifetime is dominated by this effect)
- Photo electrons - accelerated by the following bunches

Challenges: Energy stored in the beam



courtesy R.Assmann

Transverse energy density: even a factor of 1000 larger

Momentum at collision	**7 TeV/c**
Momentum at injection	450 GeV/c
Dipole field at 7 TeV	8.33 Tesla
Circumference	26658 m

High beam energy in LEP tunnel

superconducting NbTi magnets at 1.9 K

Luminosity	**10^{34} cm^{-2}s^{-1}**	
Number of bunches	2808	
Particles per bunch	$1.1 \cdot 10^{11}$	
DC beam current	0.56	A
Stored energy per beam	**350**	**MJ**

Normalised emittance	**3.75**	**µm**
Beam size at IP / 7 TeV	15.9	µm
Beam size in arcs (rms)	300	µm

High luminosity at 7 TeV

very high energy stored in the beam

beam power concentrated in small area

Arcs: Counter-rotating proton beams in two-in-one magnets

Magnet coil inner diameter	**56**	**mm**
Distance between beams	194	mm

Limited investment

small aperture for beams

summarising the constraints….

Centre-of-mass energy must well exceed 1 TeV, LHC installed into LEP tunnel

- Colliding protons (and heavy ions)
- Magnetic field of 8.3 T with superconducting magnets

Luminosity of 10^{34} $cm^{-2}s^{-1}$

- Need for “two accelerators” in one tunnel with beam parameters pushed to the extreme – with opposite magnetic field

Economical constraints and limited space

- Two-in-one superconducting magnets

Outline

- Accelerator Physics: An Introduction
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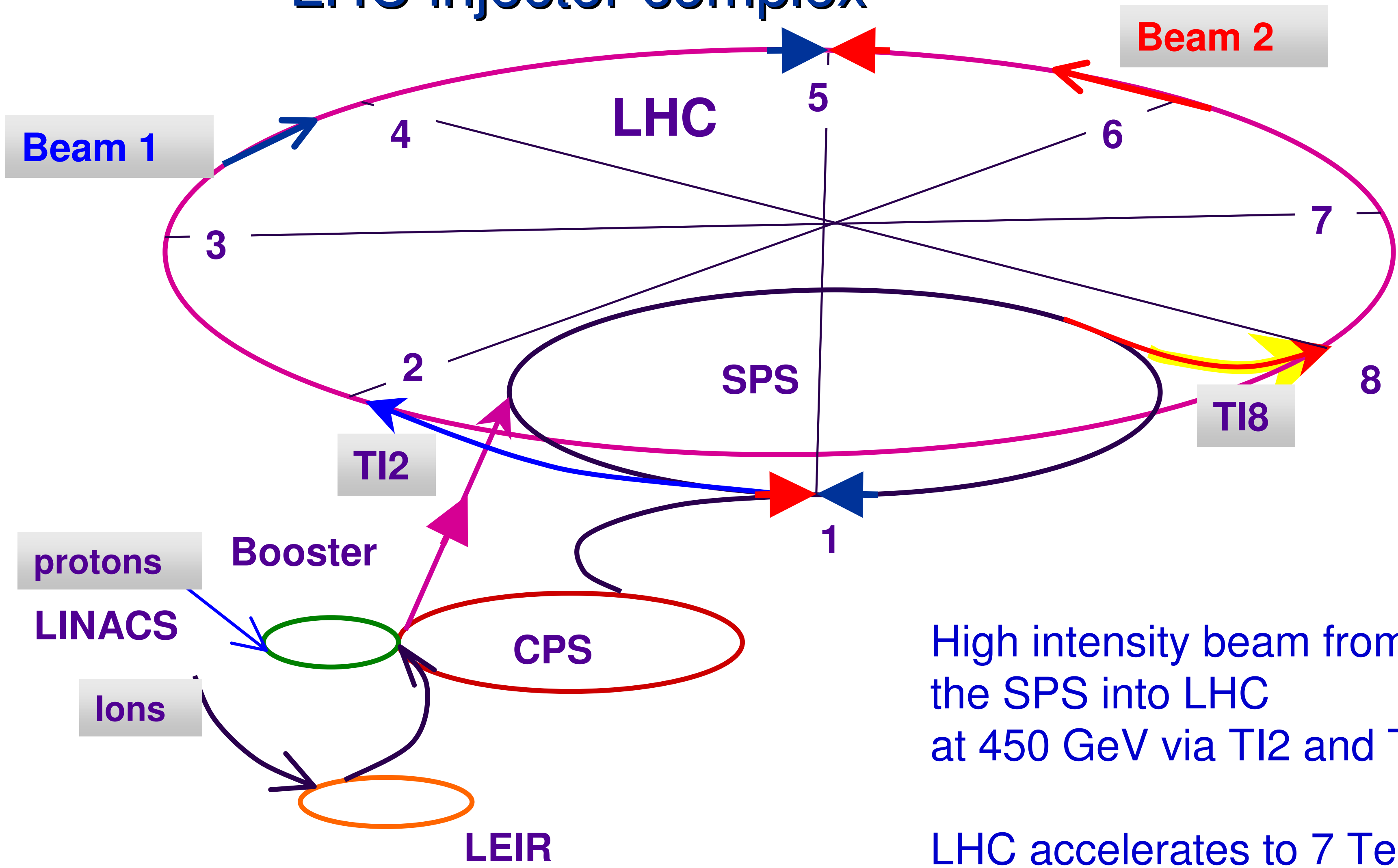
LHC injector complex



High intensity beam from the SPS into LHC at 450 GeV via TI2 and TI8

LHC accelerates to 7 TeV

Beam size of protons decreases with energy: $\sigma^2 = 1 / E$

Beam size large at injection

Beam fills vacuum chamber at 450 GeV

Getting beam into the LHC

Beam size of protons decreases with energy: $\sigma^2 = 1 / E$

- Beam size large at injection
- Beam “fills” vacuum chamber at 450 GeV

If the energy would be lower ...

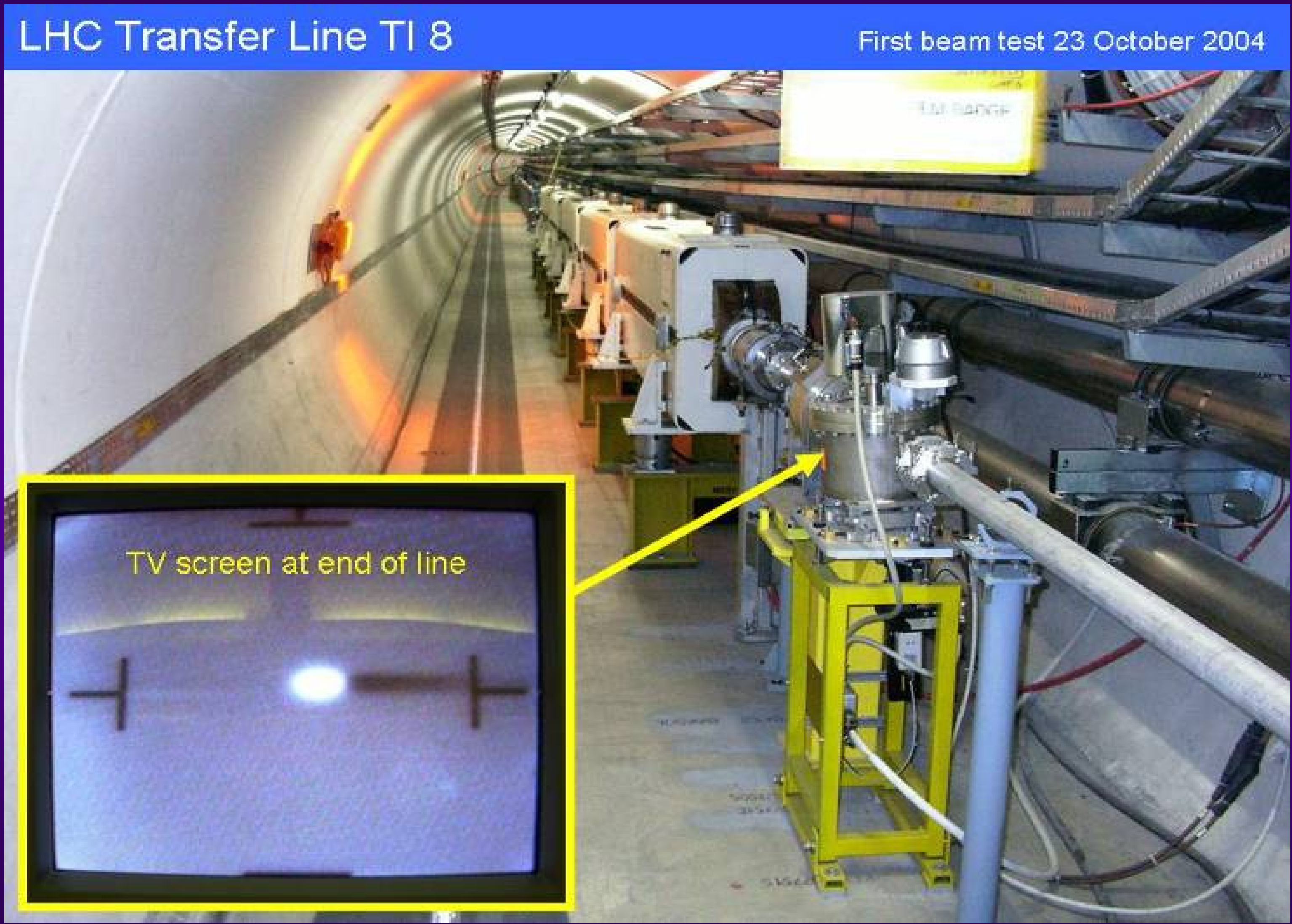
- larger vacuum chamber and larger magnets – increased cost
- magnets and power converter limitations (dynamic effects, stability, …)
- issues of beam stability

Injection from the SPS at 450 GeV, via two transfer lines, into the LHC

Injector Complex

- Pre-injectors: Linac, PS Booster and Proton Synchrotron deliver protons at 26 GeV to the SPS
- The SPS accelerates protons from 26 GeV to 450 GeV
- Both, the pre-injectors and the SPS were upgraded for the operation with nominal LHC beam parameters
- Already today, beams are available close to the nominal beam parameters required for the LHC
- The TI8 injection line has been commissioned

Results of Transfer Line TI8 test



The LHC collider II

Rüdiger Schmidt - CERN

Graduate Days

Heidelberg April 2007

Challenges

LHC accelerator physics

LHC technology

Operation and protection

summarising constraints and consequences….

Centre-of-mass energy must well exceed 1 TeV, LHC installed into LEP tunnel

- Colliding protons, and also heavy ions
- Magnetic field of 8.3 T with superconducting magnets
- Large amount of energy stored in magnets

Luminosity of 10^{34} $cm^{-2}s^{-1}$

- Need for “two accelerators” in one tunnel with beam parameters pushed to the extreme – with opposite magnetic dipole field
- Large amount of energy stored in beams

Economical constraints and limited space

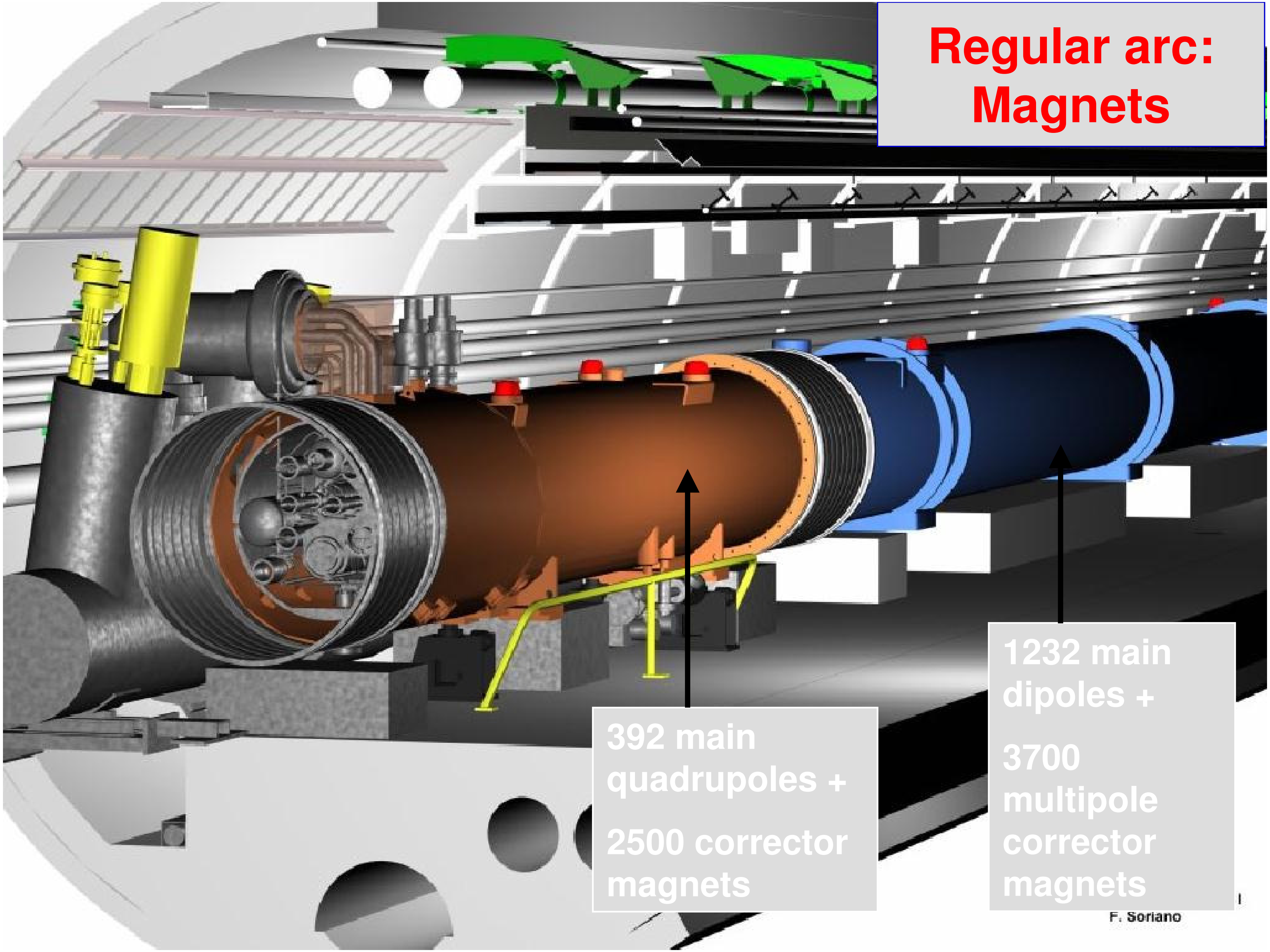
- Two-in-one superconducting magnets

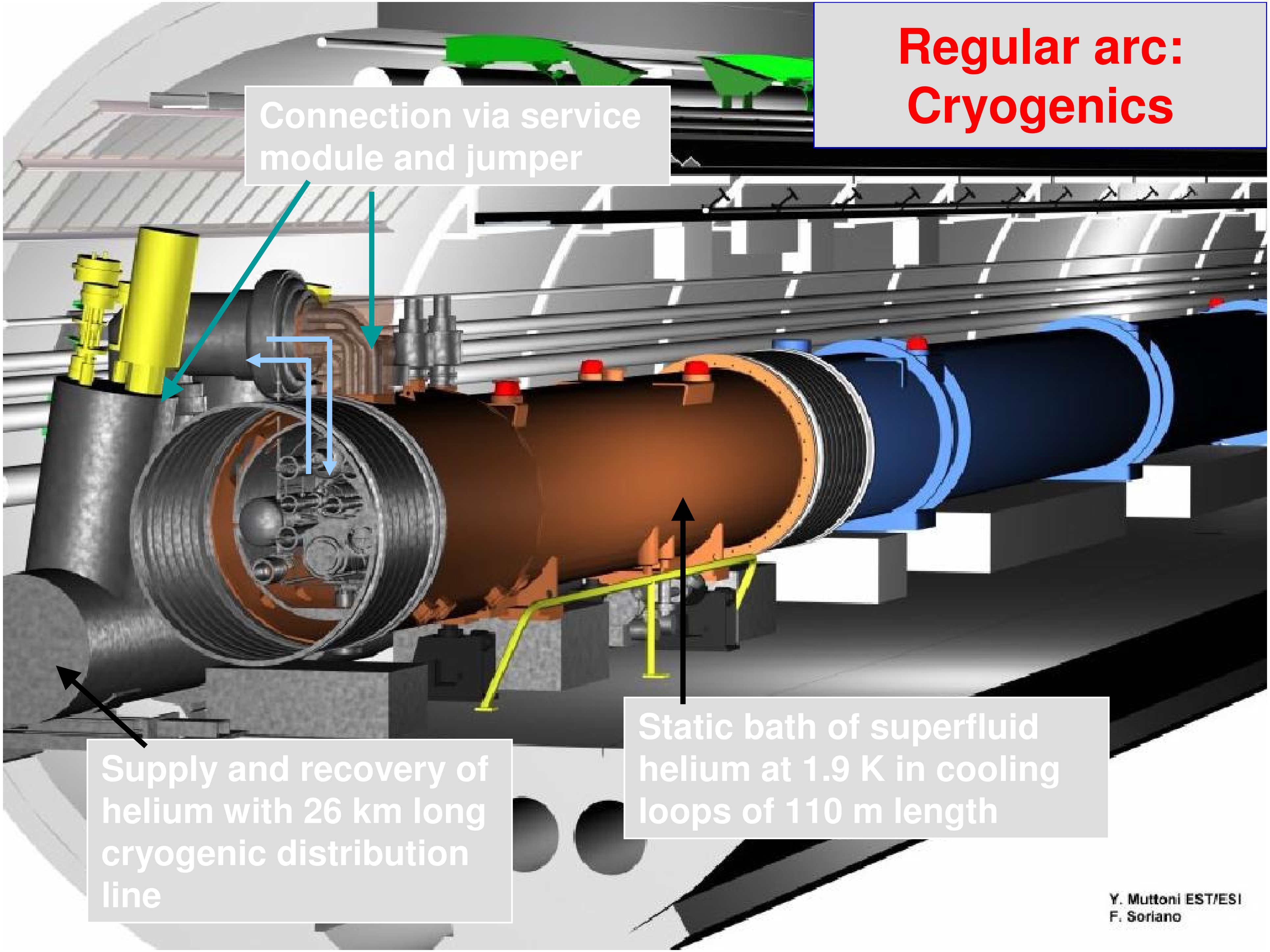
Outline

- Main systems in LHC arcs
- LHC main dipole magnets
  - **How does it work?**
  - **Superconductivity**
  - **From fabrication to installion**
- From magnets to electrical circuits
- Magnet operation and machine protection
- Beam operation and machine protection
  - **Risks**
  - **Beam dumping system**
  - **Collimation system**
  - **Strategy for Protection of the LHC machine**
- From construction to operation
- Conclusions

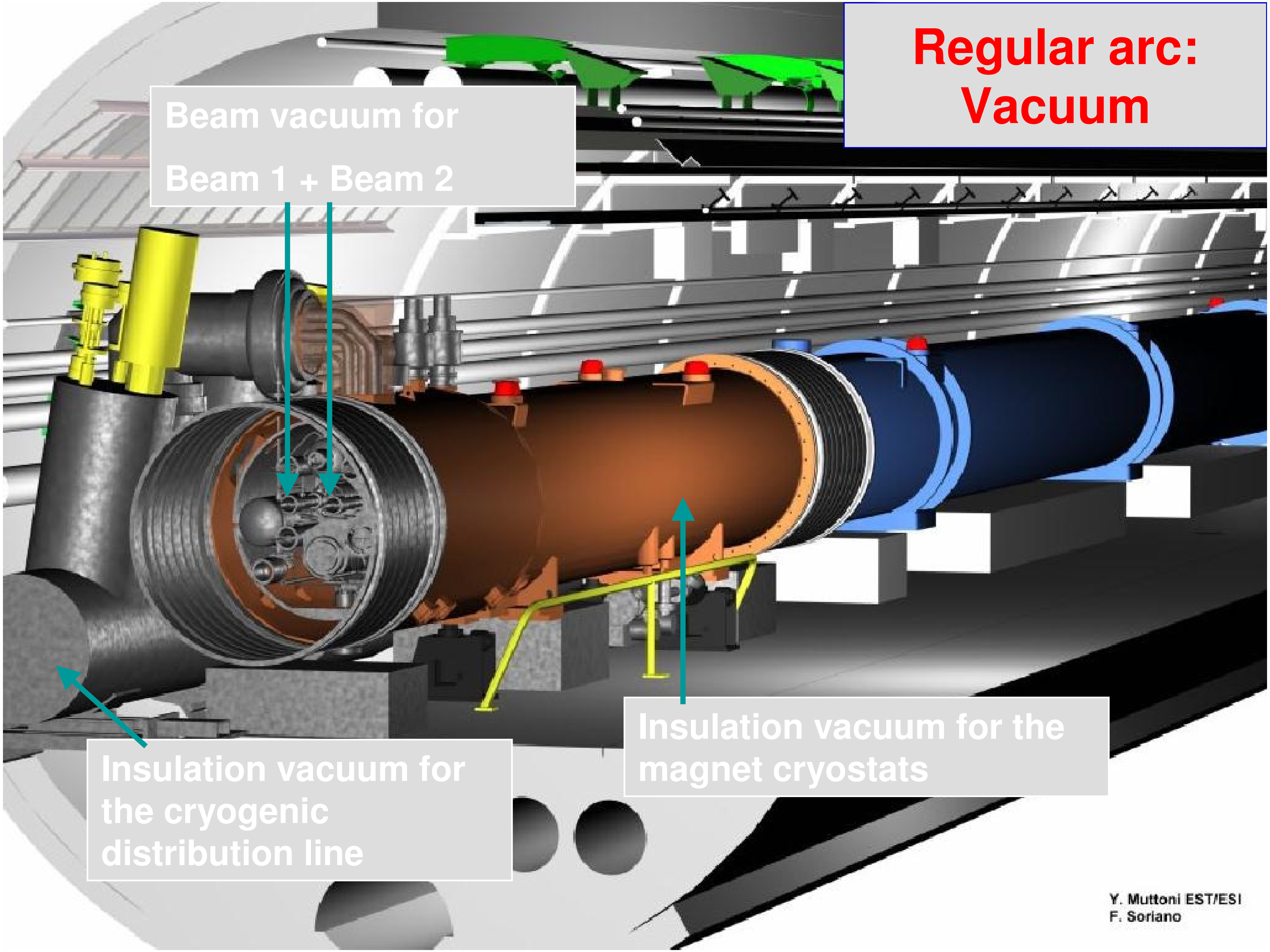
Main systems in LHC arcs

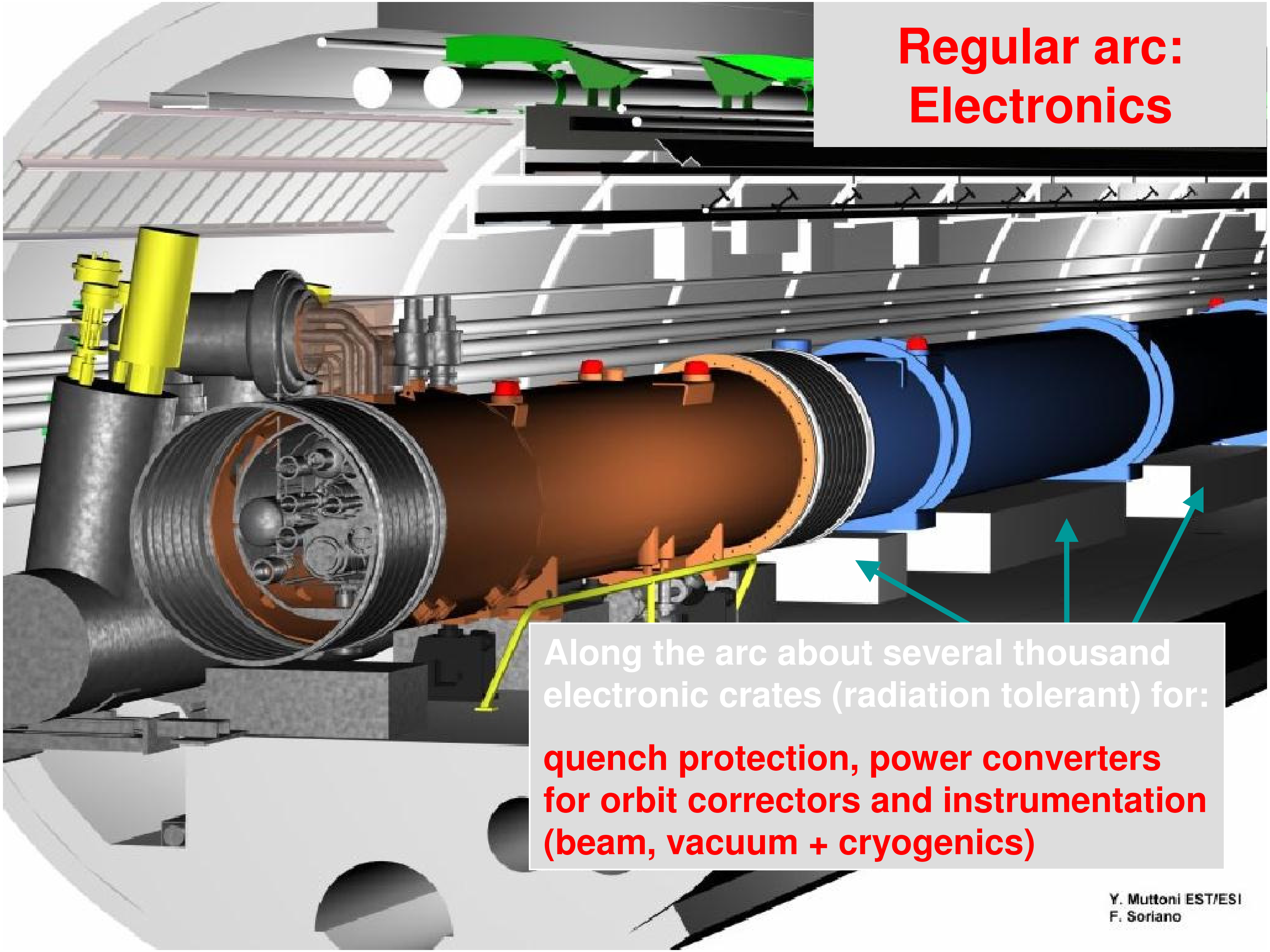
Regular arc: Magnets




Regular arc:
Cryogenics
Connection via service module and jumper
Supply and recovery of helium with 26 km long cryogenic distribution line
Static bath of superfluid helium at 1.9 K in cooling loops of 110 m length
Y. Muttoni EST/ESI
F. Soriano

Regular arc: Vacuum

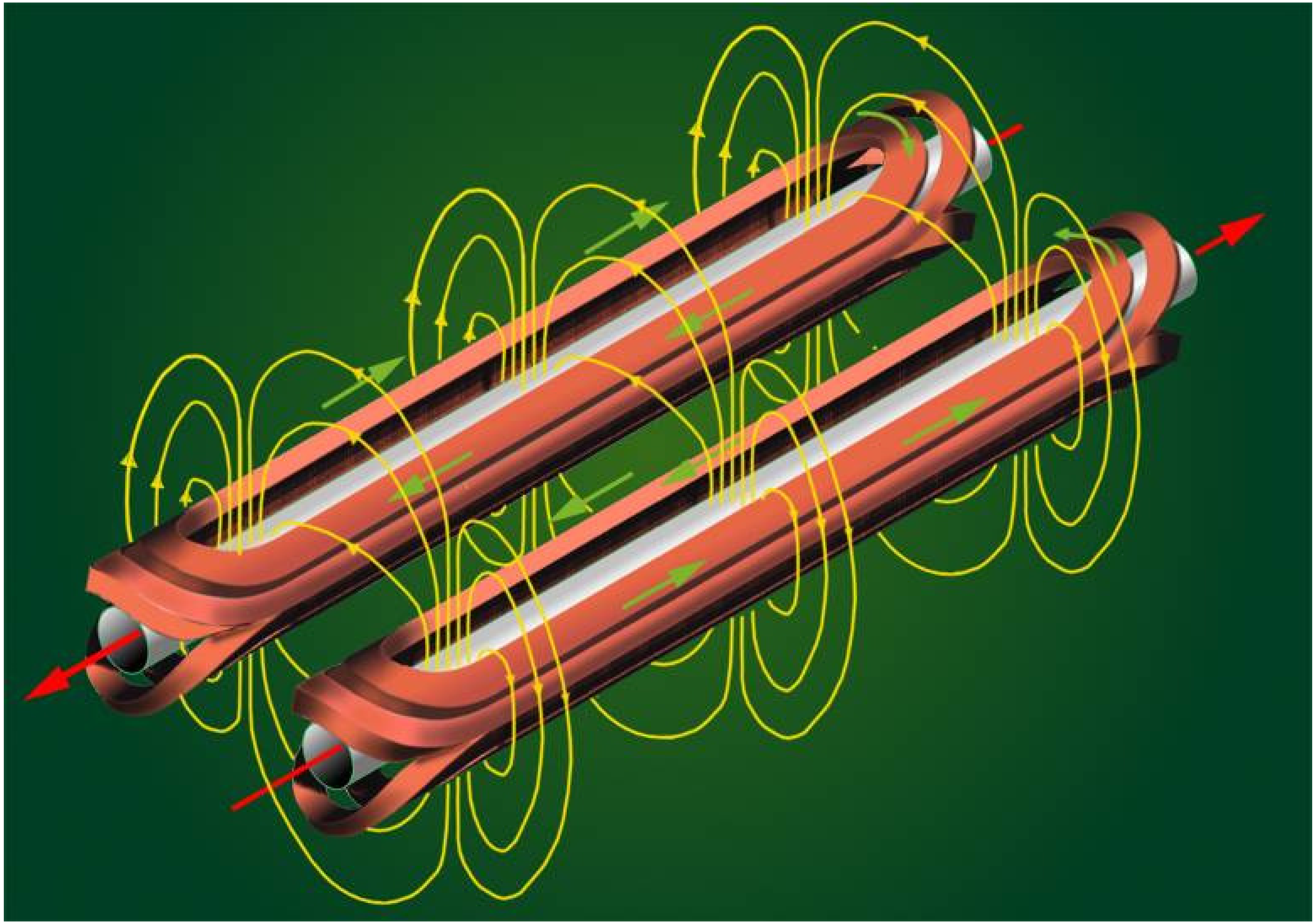



Regular arc:
Electronics
Along the arc about several thousand electronic crates (radiation tolerant) for:
quench protection, power converters for orbit correctors and instrumentation (beam, vacuum + cryogenics)
Y. Muttoni EST/ESI
F. Soriano

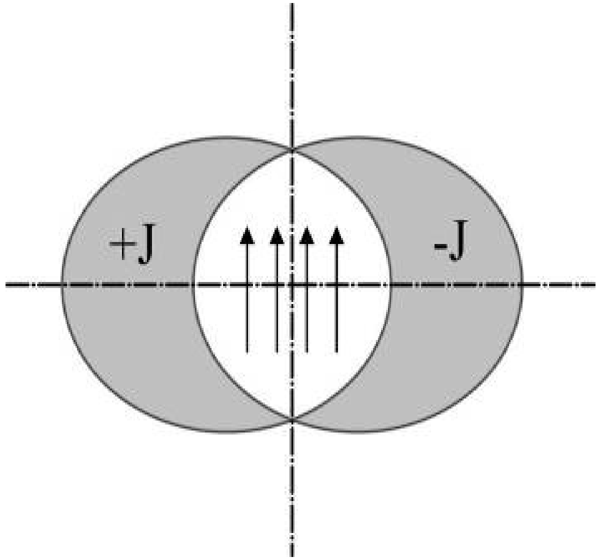
Dipole magnets for the LHC

1232 Dipolmagnets
Length about 15 m
Magnetic Field 8.3 T
Two beamtubes with an opening of 56 mm

Coils for Dipolmagnets



Dipole field – approximate cosine teta current distribution



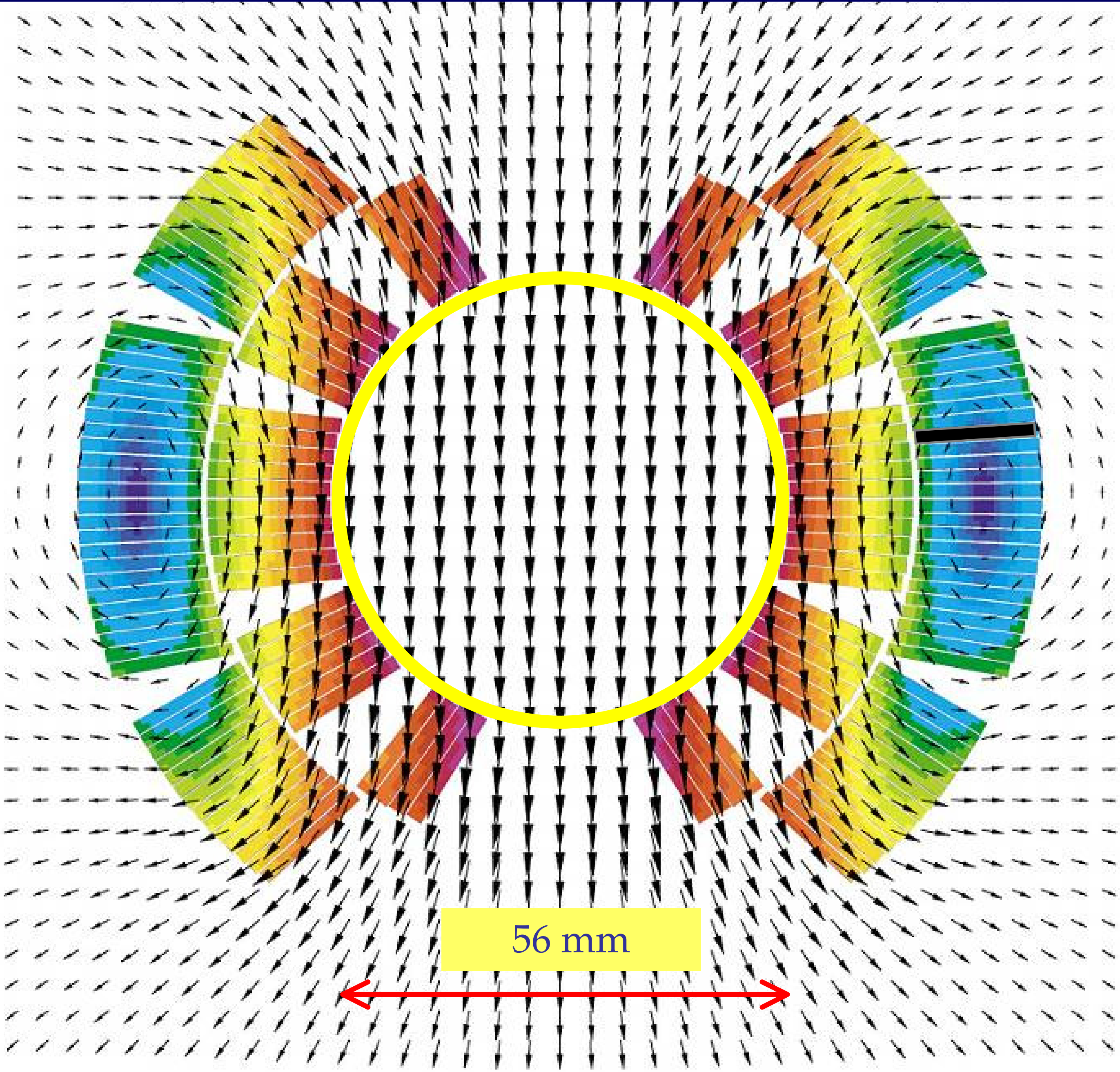
Intersecting ellipses generate uniform field

Such configuration follows:

$$J_s = J \cdot \cos(\theta)$$

In practice the above current distributions are approximated by real conductors, so the field contains also higher order harmonics

Dipole coil cross section



Superconducting cable for 12 kA

15 mm / 2 mm

Temperature 1.9 K cooled with Helium

Force on the cable:

F = B * I0 * L

with

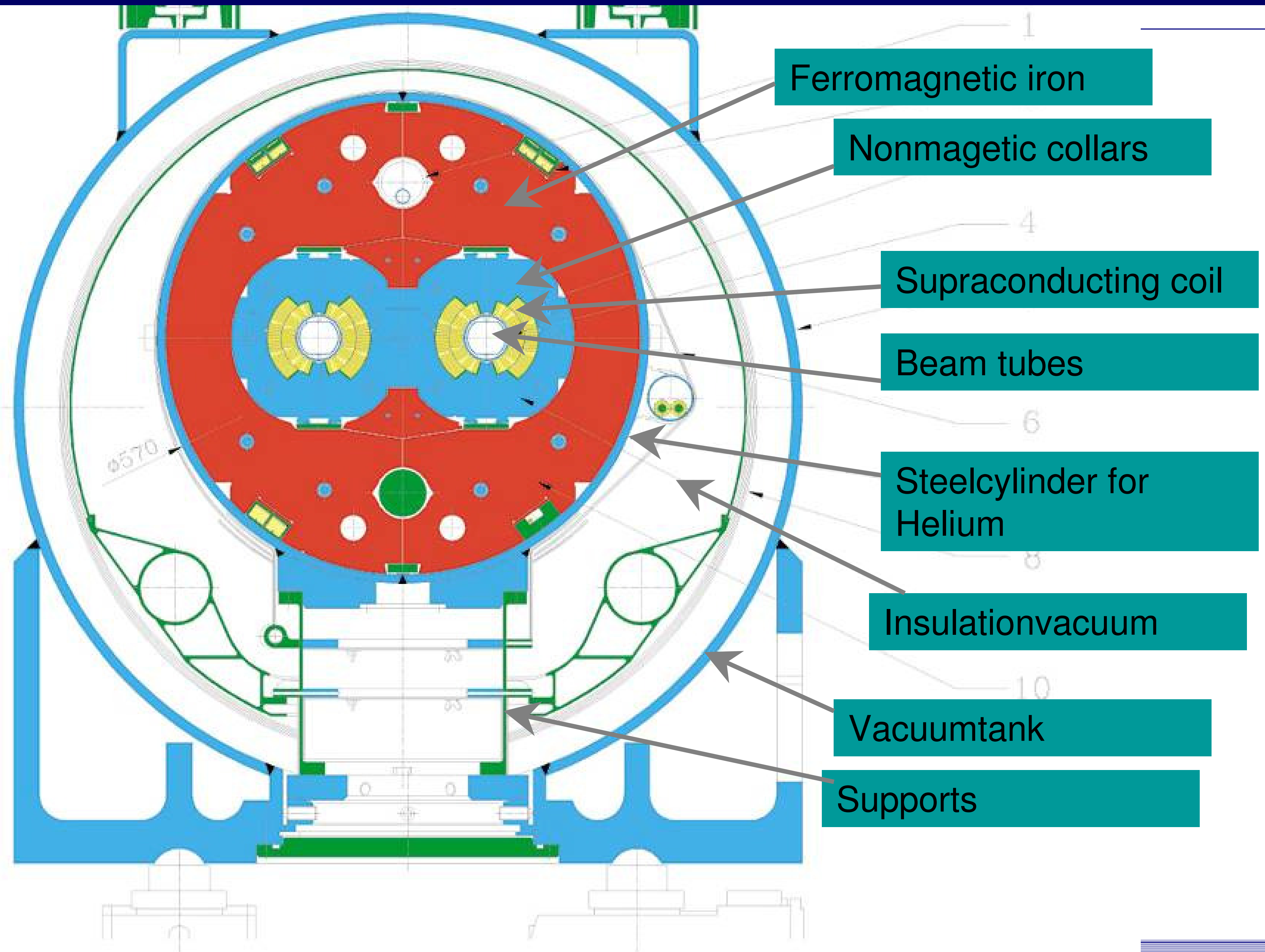
B = 8.33 T

I0 = 12000 Ampere

L = 15 m

F = 165 tons

Dipole magnet cross section

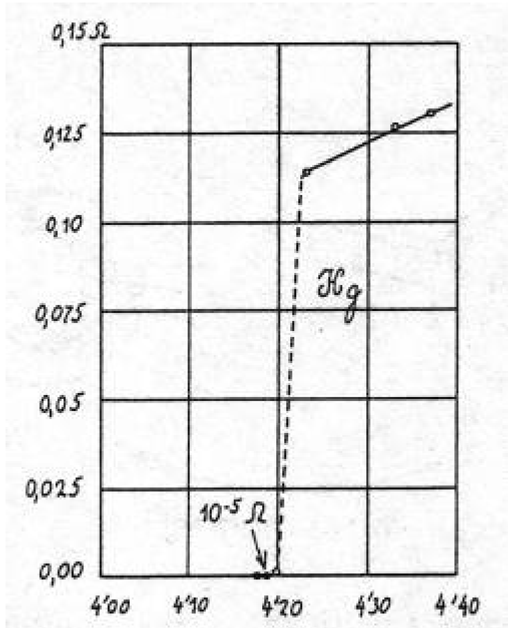


Discovery of superconductivity

- **1908 -- Kamerlingh Onnes liquifies Helium**

1911 -- R-T
for Mercury

?



*"…. Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive **state** …."*

Copyright A.Verweij

Magnetic field - current density - temperature

Superconducting

material determines:

Tc critical temperature

Bc critical field

Production process:

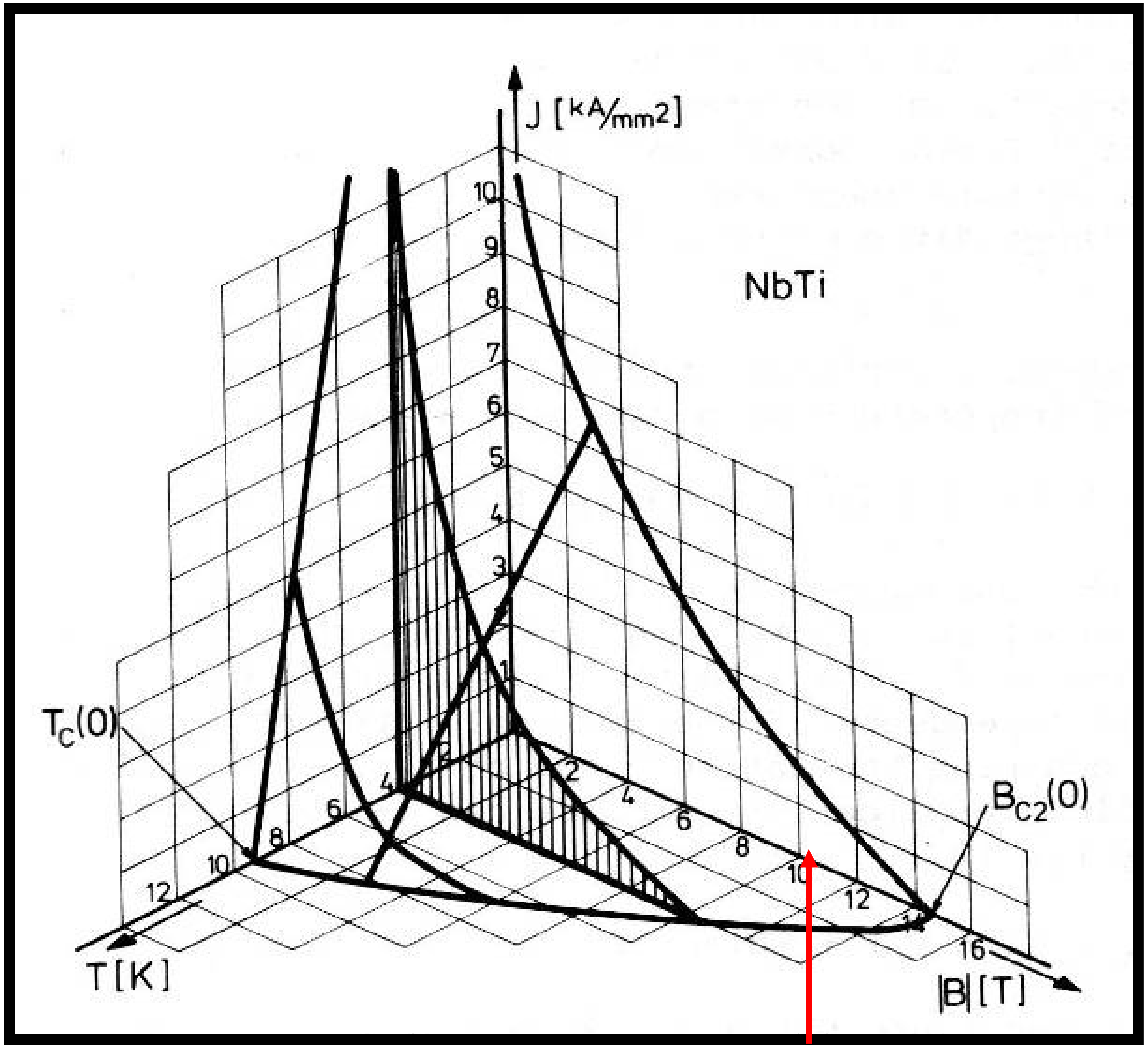
Jc critical current density

Lower temperature ⇒ increased current density

Typical for NbTi:

2000 A/mm2

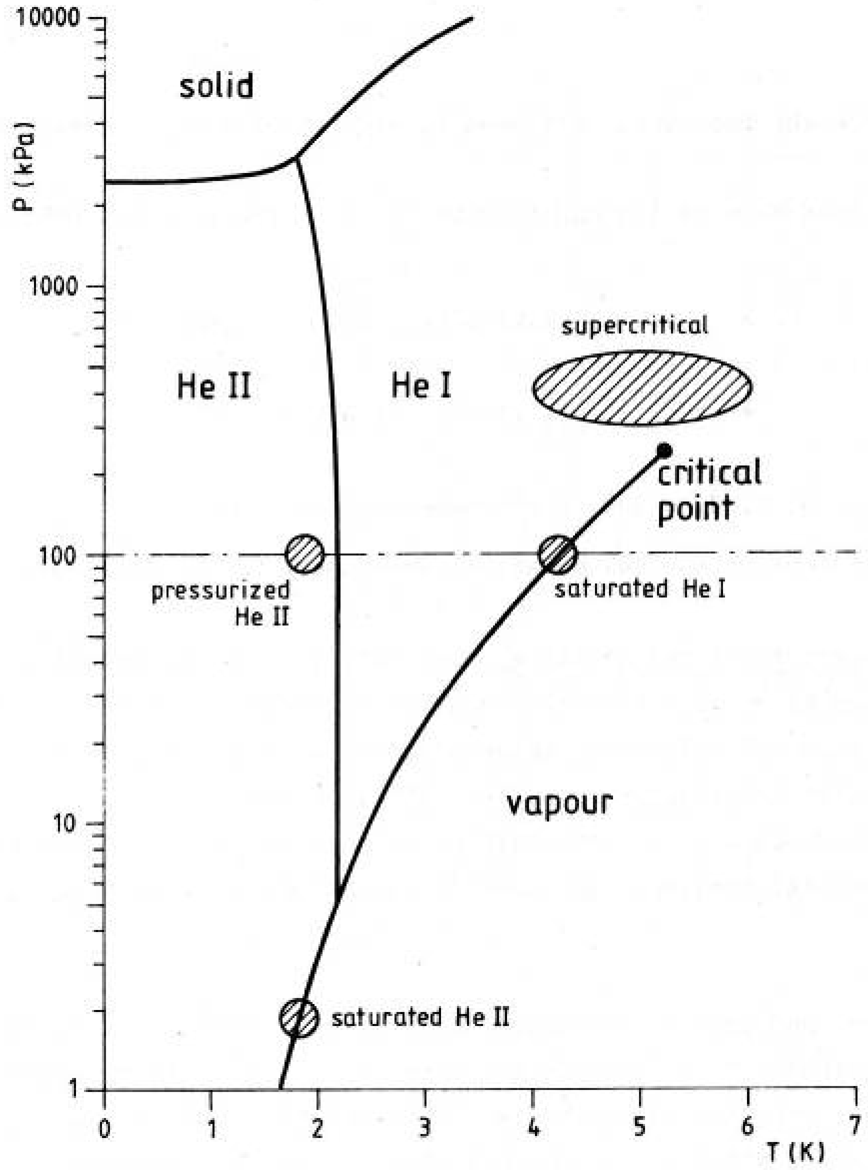
@ 4.2K, 6T



LHC: for 10 T operation at less than 1.9 K required

Copyright A.Verweij

Helium:
Phasediagram



$T > T_{\lambda}$: He I

$T < T_{\lambda}$: He II
(superfluid Helium)

T_{λ}=2.17 K

LHC:

T = 1.9 K
P ≈ 1.2 bar

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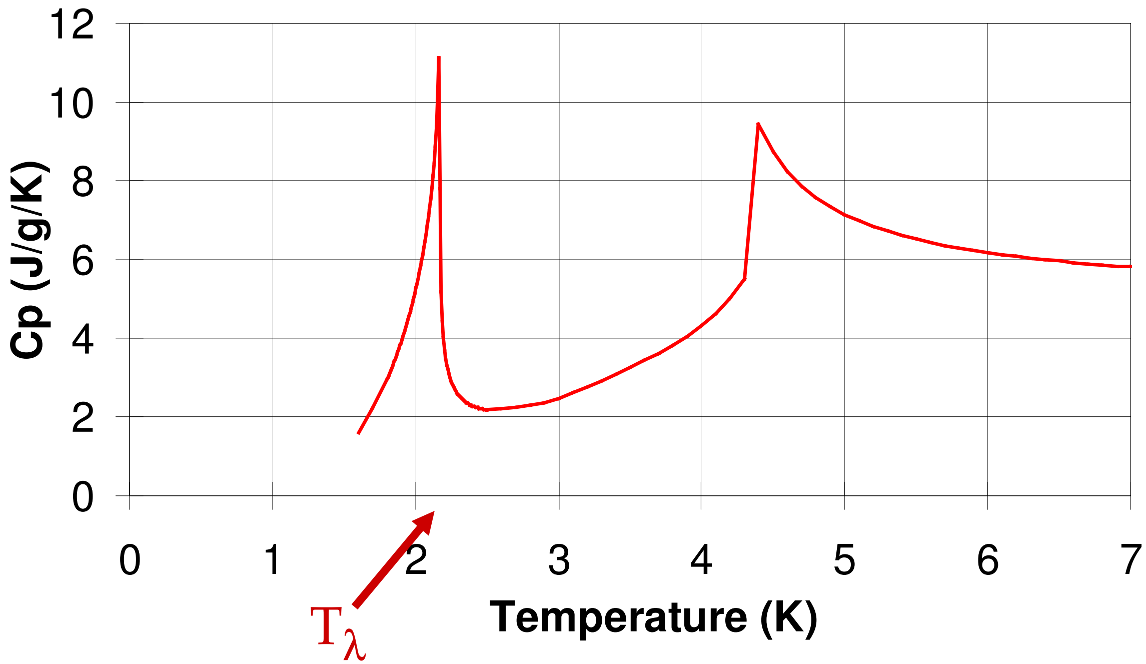
Helium Parameter

Specific heat of Helium as function of T

Phasetransition at 2.18 Kelvin

Superfluid Helium (He II)



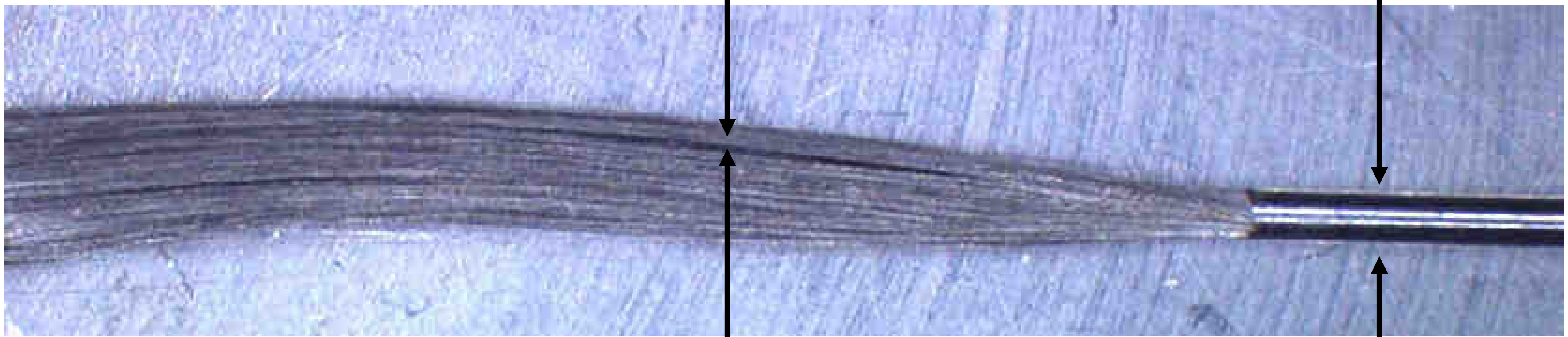
	He II, 1.9K	He I, 4.2K	Water, 300K	SC @ 8T, 1.9K	SC @ 8T, 4.2K
thermal cond.	~100,000	0.02	1	~400	~400
viscosity	0.01 – 0.1	3	1000		
Cp	4	5		0.0001	0.0004

Copyright A.Verweij

Superconducting wire

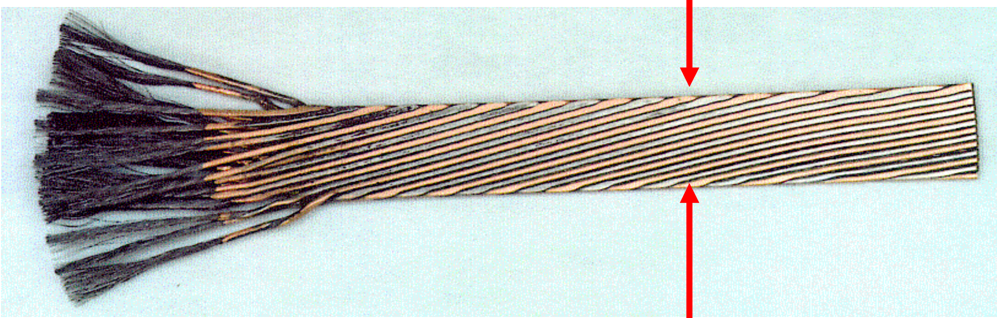
Filament diameter ∅6 µm

Wire diameter ∅1 mm



Typical value for operation at 8 T and 1.9 K: 800 A

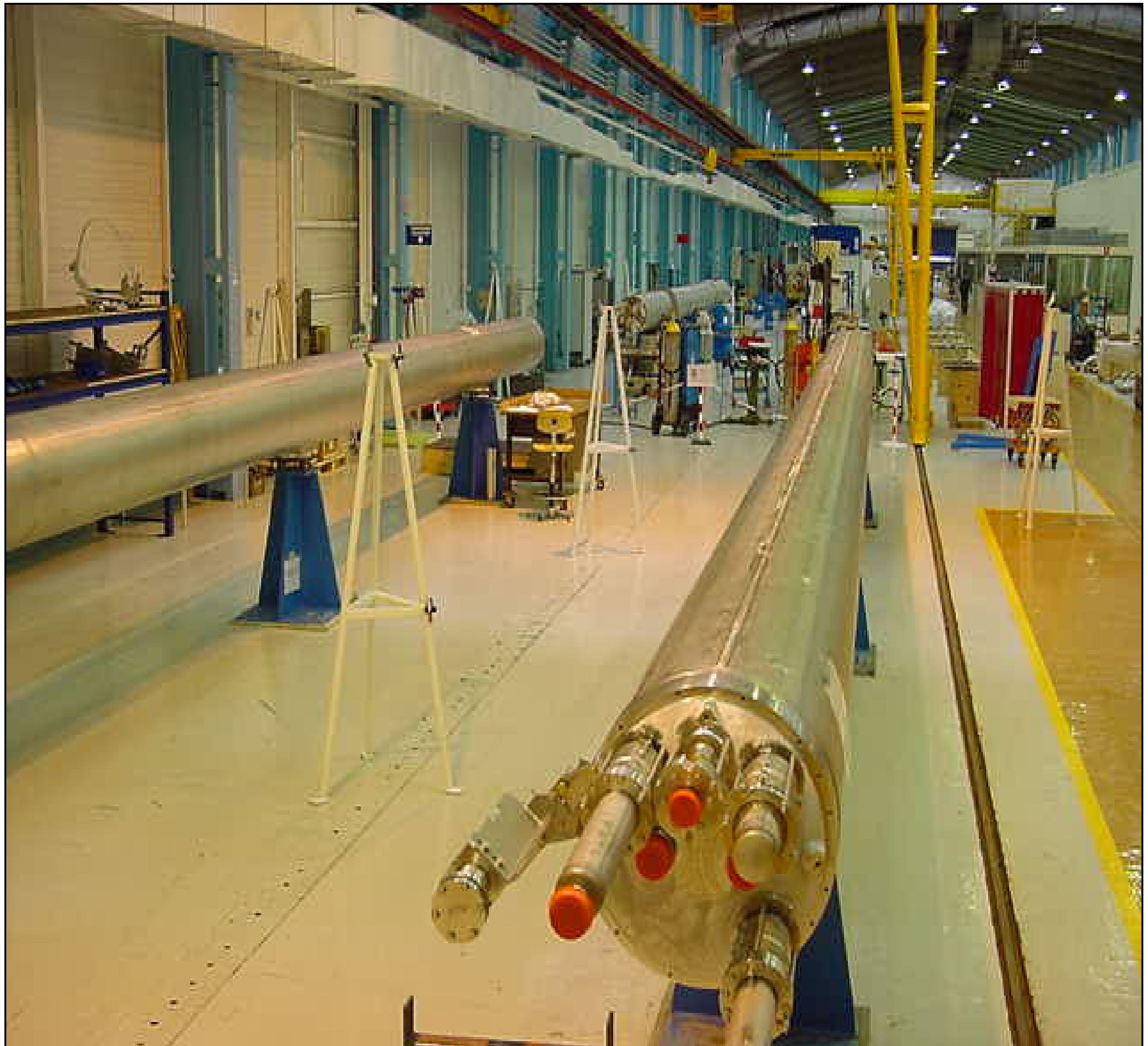
width 15 mm



Rutherford cable

Copyright A.Verweij

Fabrication of superconducting dipoles



Dipole assembly in industry

Cryostating and measurements (main dipoles and other magnets)

SMA18 cryostating hall at CERN for installing dipole magnets into cryostats

SM18: 12 measurement stations are prepared for cold tests of possibly all superconducting magnets

First cryodipole lowered on 7 March 2005

Only one access point for 15 m long dipoles, 35 tons each

Transport in the tunnel with an optical guided vehicle

about 1600 magnets to be transported for 15 km

at 3 km/hour

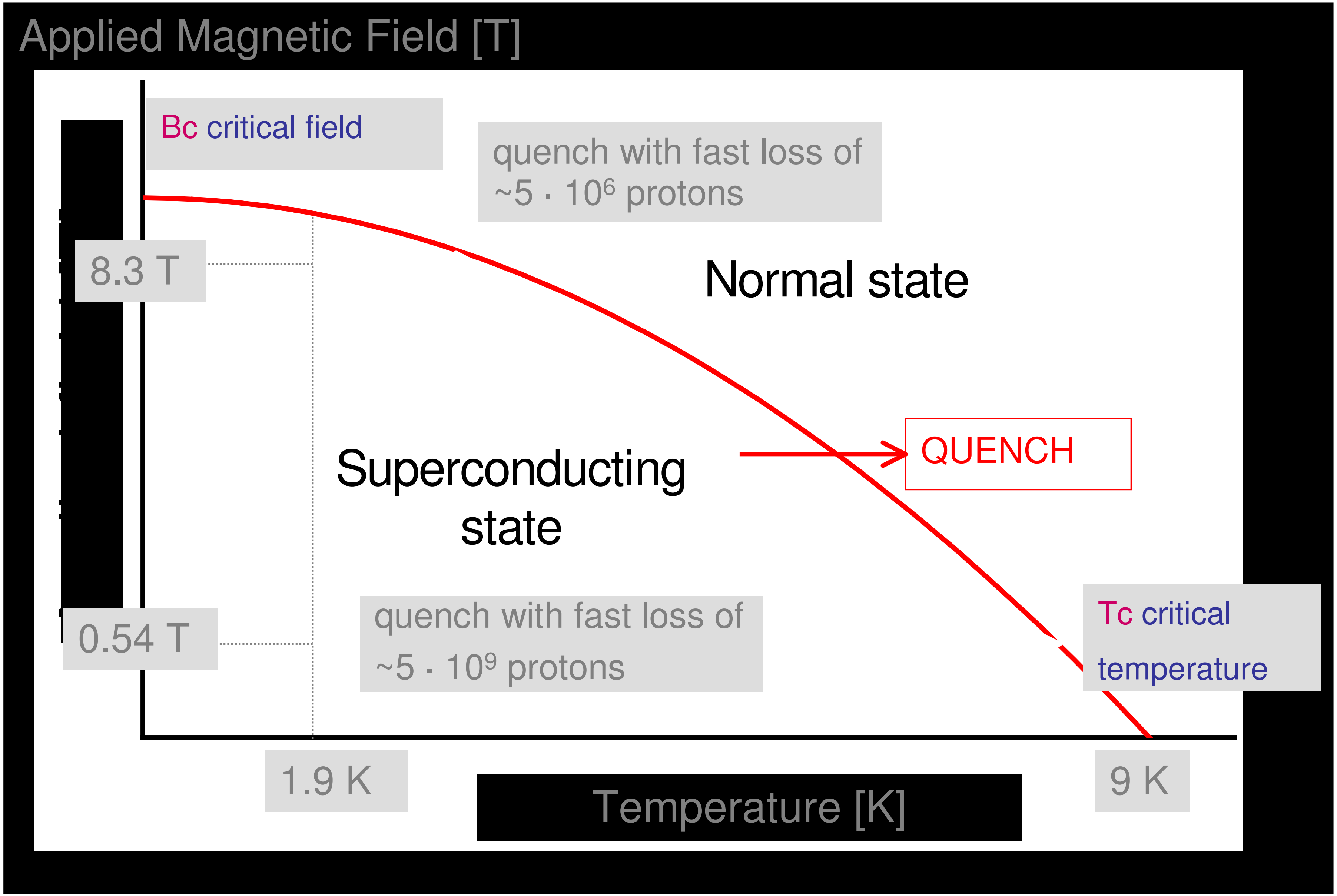
Transfer on jacks

Challenges for dipole production

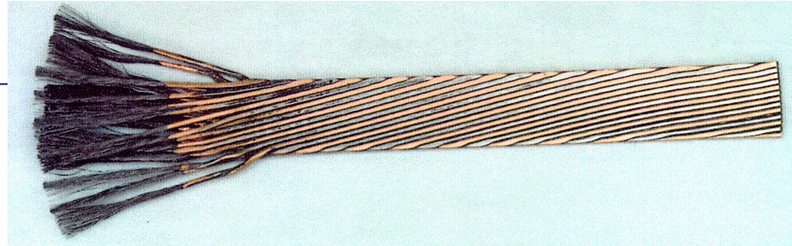
- The field quality must be excellent (relative field errors much less than 0.1 %, positioning of collars to some 10 μm)
- The geometry must be respected – and the magnet must be correctly bent (banana shape)
- All magnets had to be produced in time, delivered to CERN, installed in the cryostats, cold tested, and finally installed into the LHC tunnel

- The magnets must reach without quenching a field of at least 8.3 Tesla, and possibly 9 Tesla

Operational margin of a superconducting magnet



Power into superconducting cable after a quench



Cross section : $A_{sc} := 10 \cdot mm^2$

Current : $I_{sc} := 10000 \cdot A$

Length of superconductor : $L_{sc} := 1 \cdot m$

Copper resistance at 300 C: $\rho_{cu} := 1.76 \cdot 10^{-6} \cdot ohm \cdot cm$

$$P_{sc} := \rho_{cu} \cdot I_{sc}^2 \cdot \frac{L_{sc}}{A_{sc}} \qquad P_{sc} = 1.76 \times 10^5 \, watt$$

Specific temperature of copper at 300 C : $cv_{cu} := 3.244 \cdot \frac{joule}{K \cdot cm^3}$

Temperature increase of copper $\delta T := \frac{P_{sc}}{A_{sc} \cdot L_{sc} \cdot cv_{cu}}$

Temperature increase within one second: $\delta T = 5.425 \times 10^3 \, \frac{K}{s}$

Quench - transition from superconducting state to normalconducting state

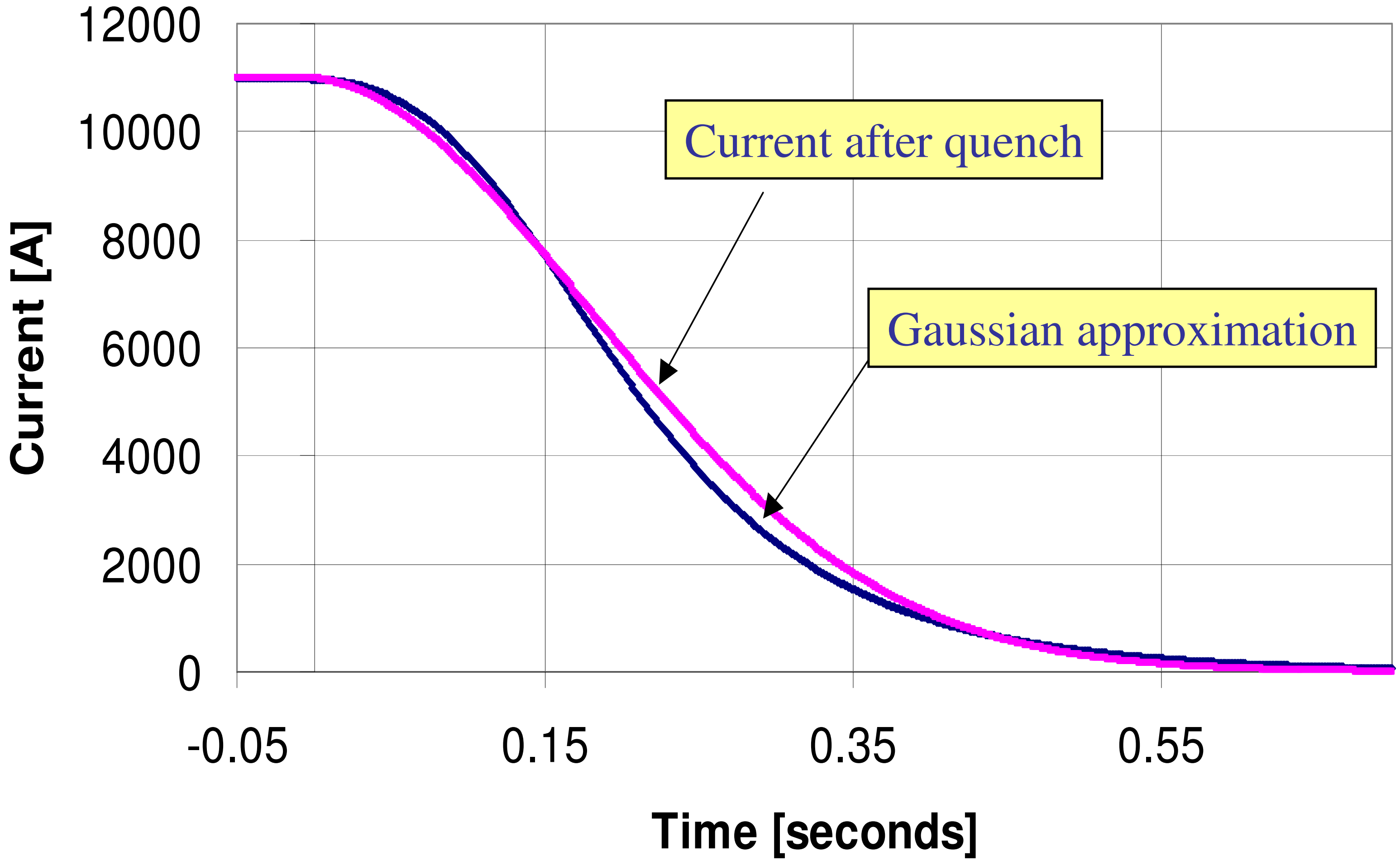
- Quenches are initiated by an energy in the order of mJ (corresponds to the energy of 1000 protons at 7 TeV)

- Movement of the superconductor by several µm (friction and heat dissipation)
- Beam losses
- Failure in cooling

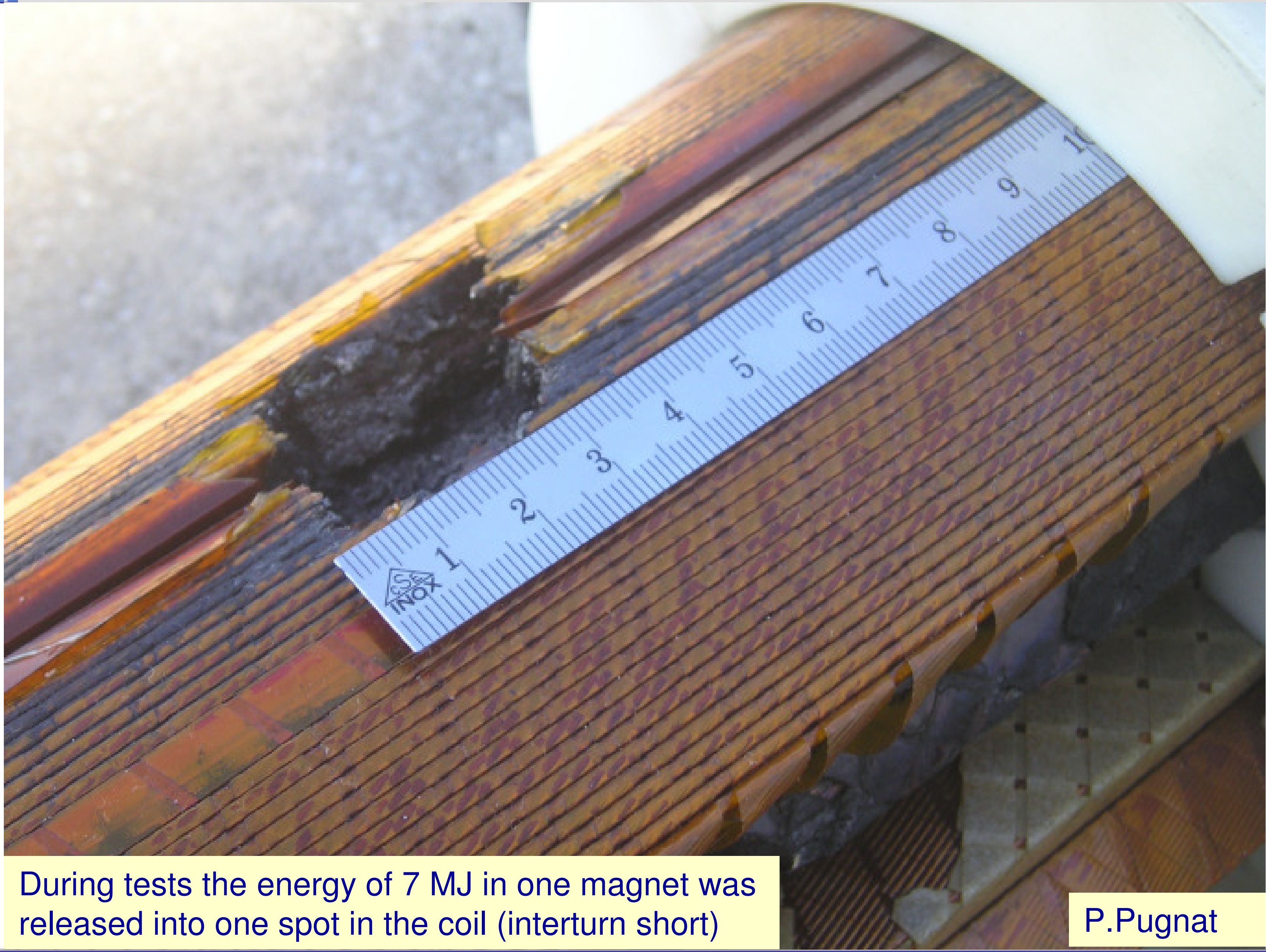
- To limit the temperature increase after a quench
  - **The quench has to be detected**
  - **The energy is distributed in the magnet by force-quenching the coils using quench heaters**
  - **The magnet current has to be switched off within << 1 second**

Current after a quench

Current in a dipole magnets after a quench, when heaters are fired (7 TeV) - 7 MJ within 200 ms into magnet



If this does not work…



During tests the energy of 7 MJ in one magnet was released into one spot in the coil (interturn short)

P.Pugnat

From magnets to electrical circuits

Magnet inventory: about 10000 magnets

Powered in series

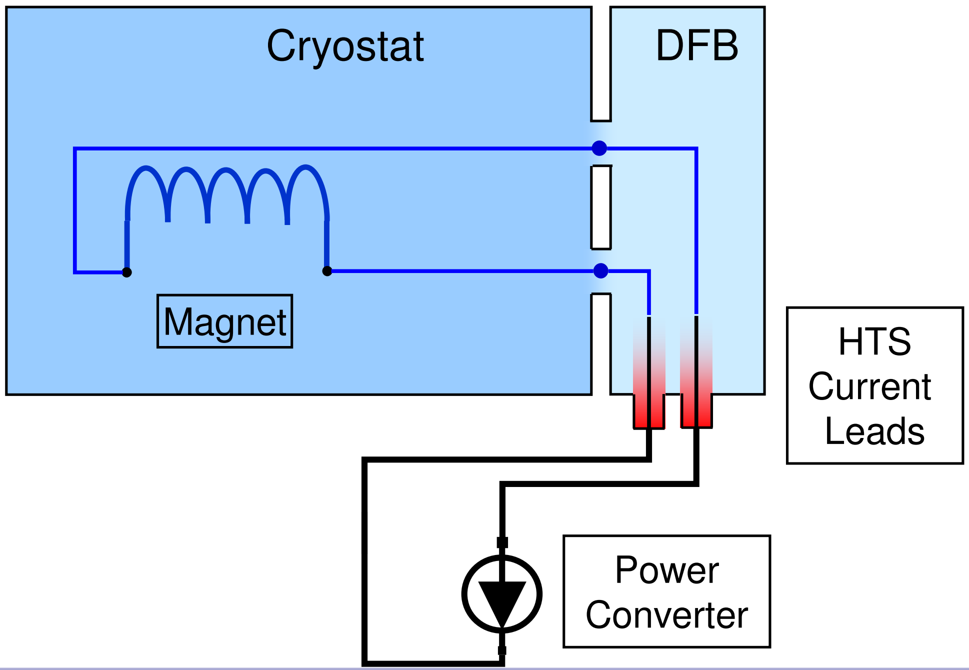
- **Main dipole magnets (13 kA)**
- **Focusing and defocusing arc quadrupole magnets (13 kA)**
- **Lattice sextupole magnets in arcs (600 A) to correct the trajectories for off-energy particles**
- **Multipole and other correctors in arcs (trim quadrupoles, sextupoles, decapoles, octupoles, 600 A) to correct field imperfections, to suppress instabilities, etc.**

Powered individually

- **752 arc orbit corrector magnets powered individually (60 A) to ensure that the beam follows the design orbit (within about 0.5 mm)**
- **Correctors to adjust beam parameters (trim quadrupoles, orbit correctors, etc., 80 – 600 A) in arcs and insertions**
- **Insertion main dipole and quadrupole magnets (4 – 8 kA) to ensure beam crossing / to increase the interbeam distance / to focus beams for experiments etc.**

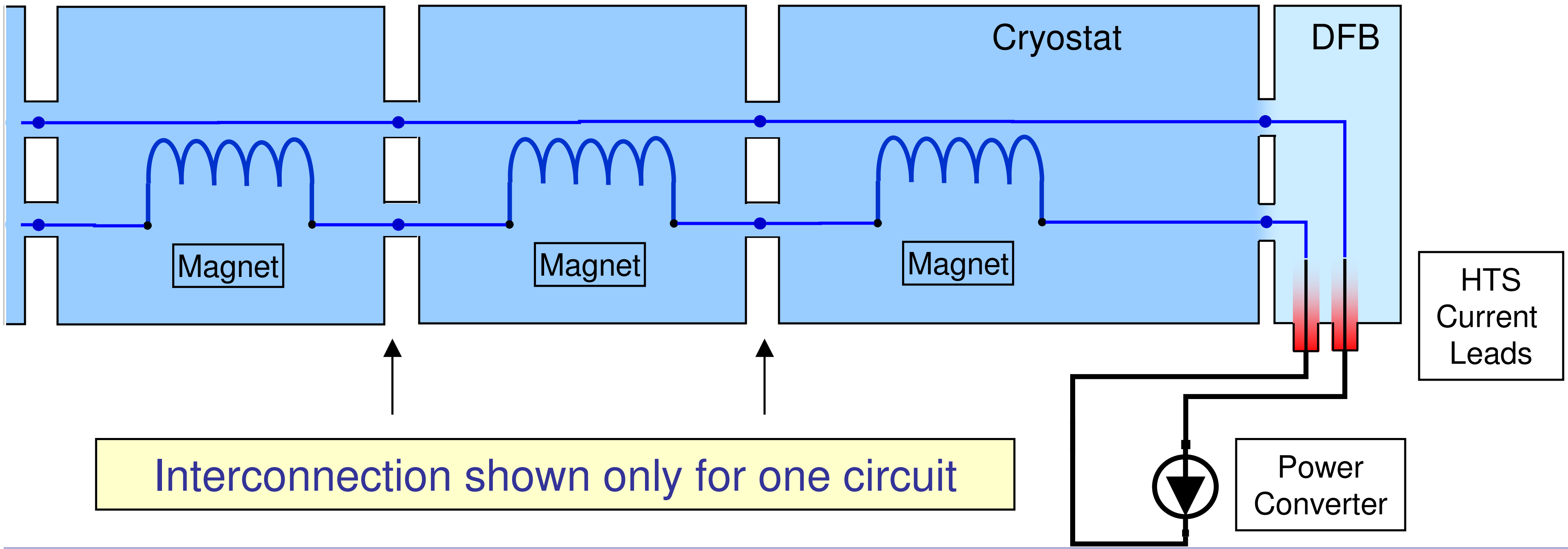
From superconducting magnet to electrical circuit

- The magnet needs to be cooled at 1.9K or 4.5K
  - Installed in a cryostat
- The magnet needs to be powered
  - Power converter at room temperature to supply the current
- The magnet must be connected
  - By superconducting cables inside the cryostat
  - By normal conducting cables outside the cryostat
- The superconducting cables must be connected to normal conducting cables
  - Connection via current leads inside special cryostat (DFB)



Interconnection of magnets inside cryostat

- Cryostated magnets with length 15 m for dipoles, 5 m for SSS
- Many cryostated magnets interconnected to make the 3 km long continuous arc cryostat
- All superconducting bus bars need to be connected for each interconnect
- Magnet in the center of the arc still powered from DFB
- Only 60 A orbit correctors powered locally

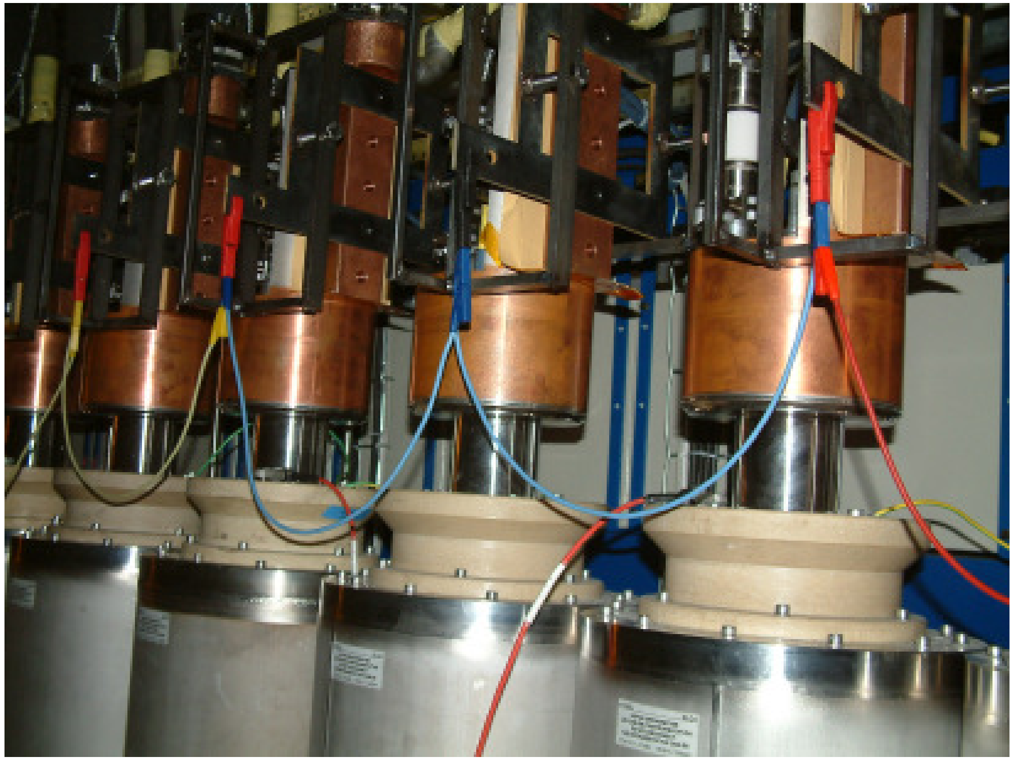


Power converters and water cooled cables

Power converter 6 kA

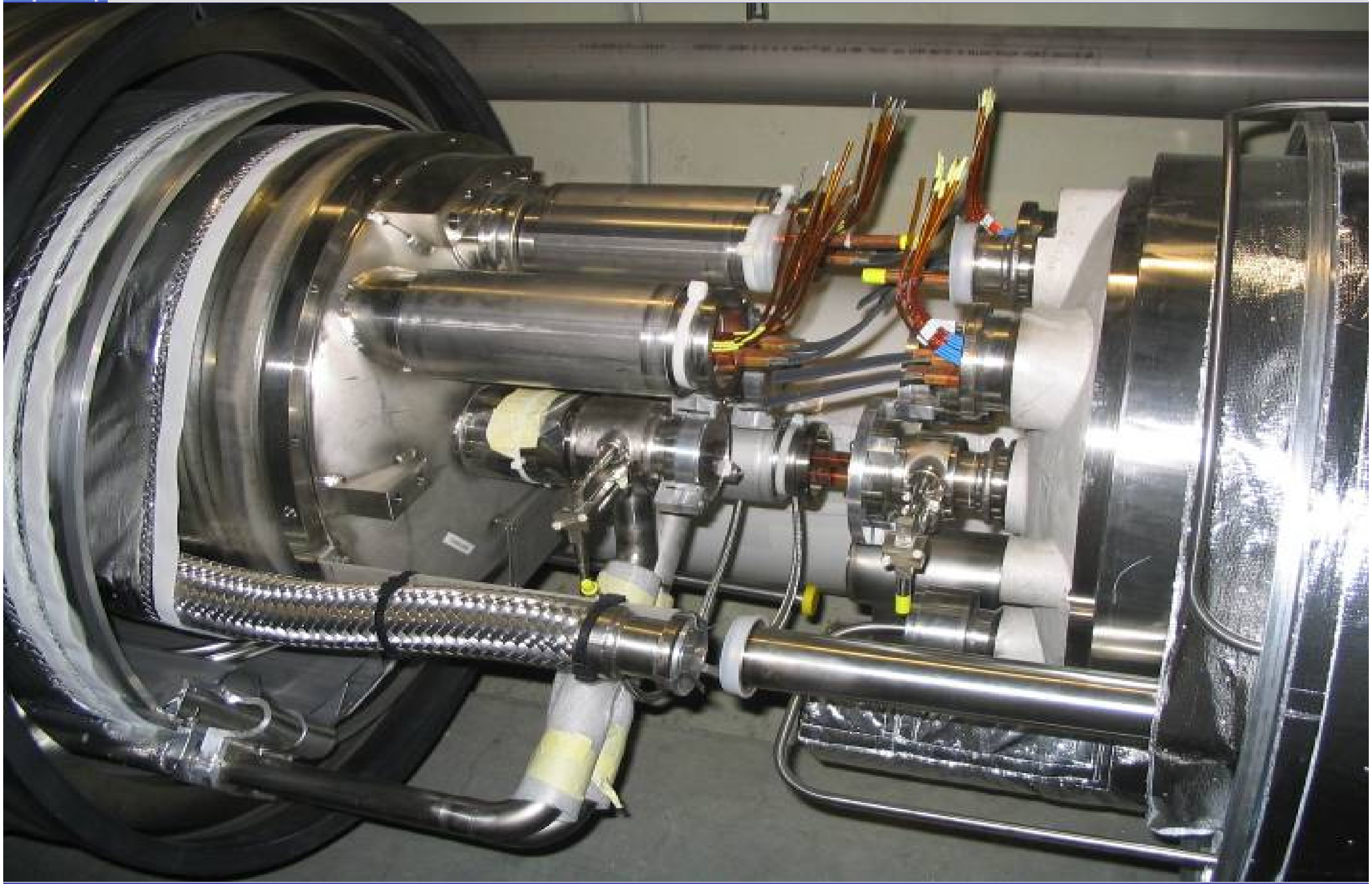
Water cooled cables 13 kA

DFBs with current leads - feeding current from warm to cold

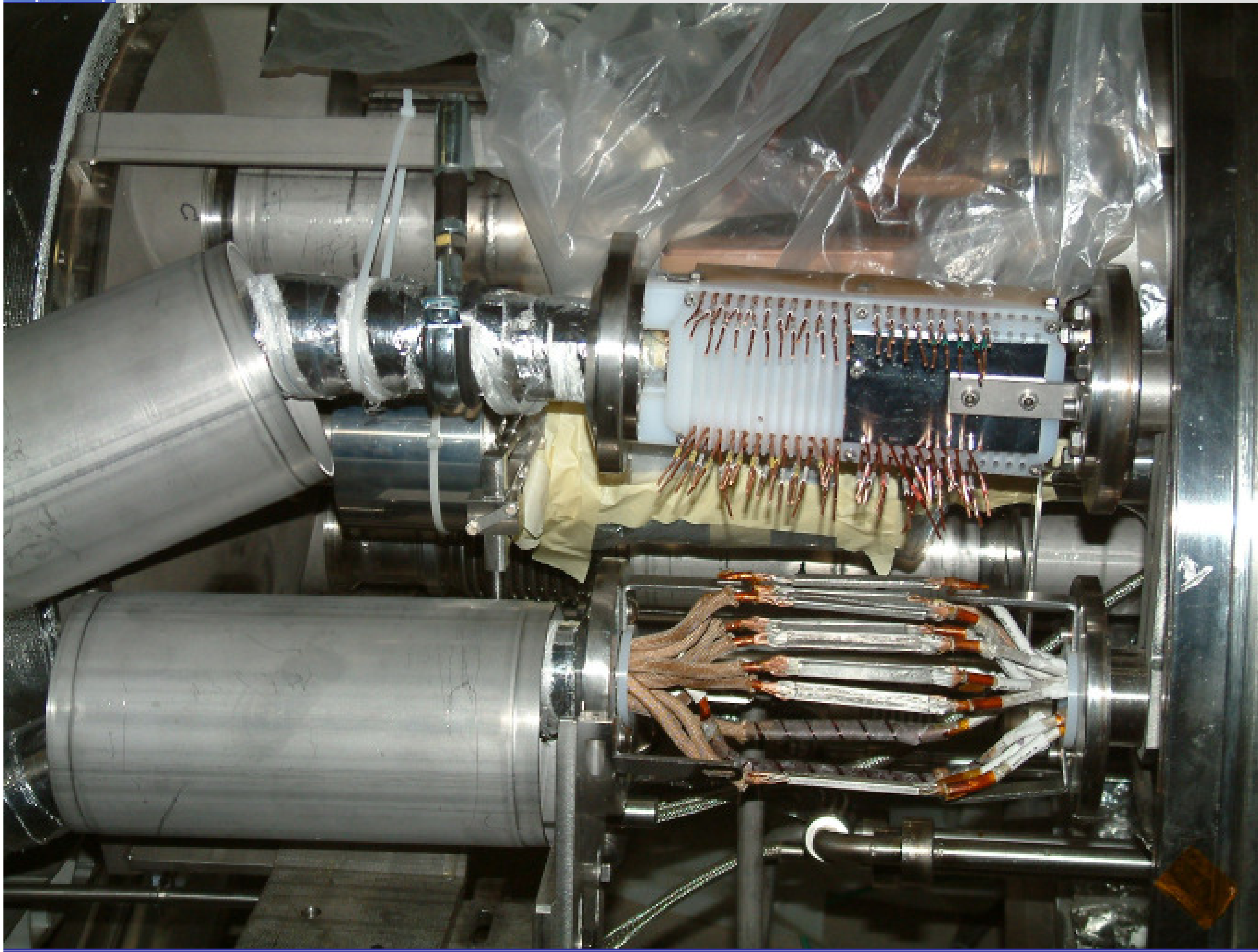


DFB and HTS current leads

Interconnecting busbars



One out of 1700 interconnections (19/3/2007)



600 A bus bars (NLine)

6 kA bus bars

Magnet operation and machine protection

Energy stored in LHC main dipole magnets

$$E_{dipole} = 0.5 \bullet L_{dipole} \bullet I^2_{dipole}$$

Energy stored in one dipole is 7.6 MJoule

For all 1232 dipoles in the LHC: 9.4 GJ

- Too much energy for one electrical circuit
  - **charging the energy requires too much voltage**
  - **discharging the energy is even more critical**
- Subdivide LHC powering into 8 sectors
- 154 main dipole magnets in series for one sector
- Stored energy in other magnets much less, but failure could also lead to damage

What does this mean?

10 GJoule……

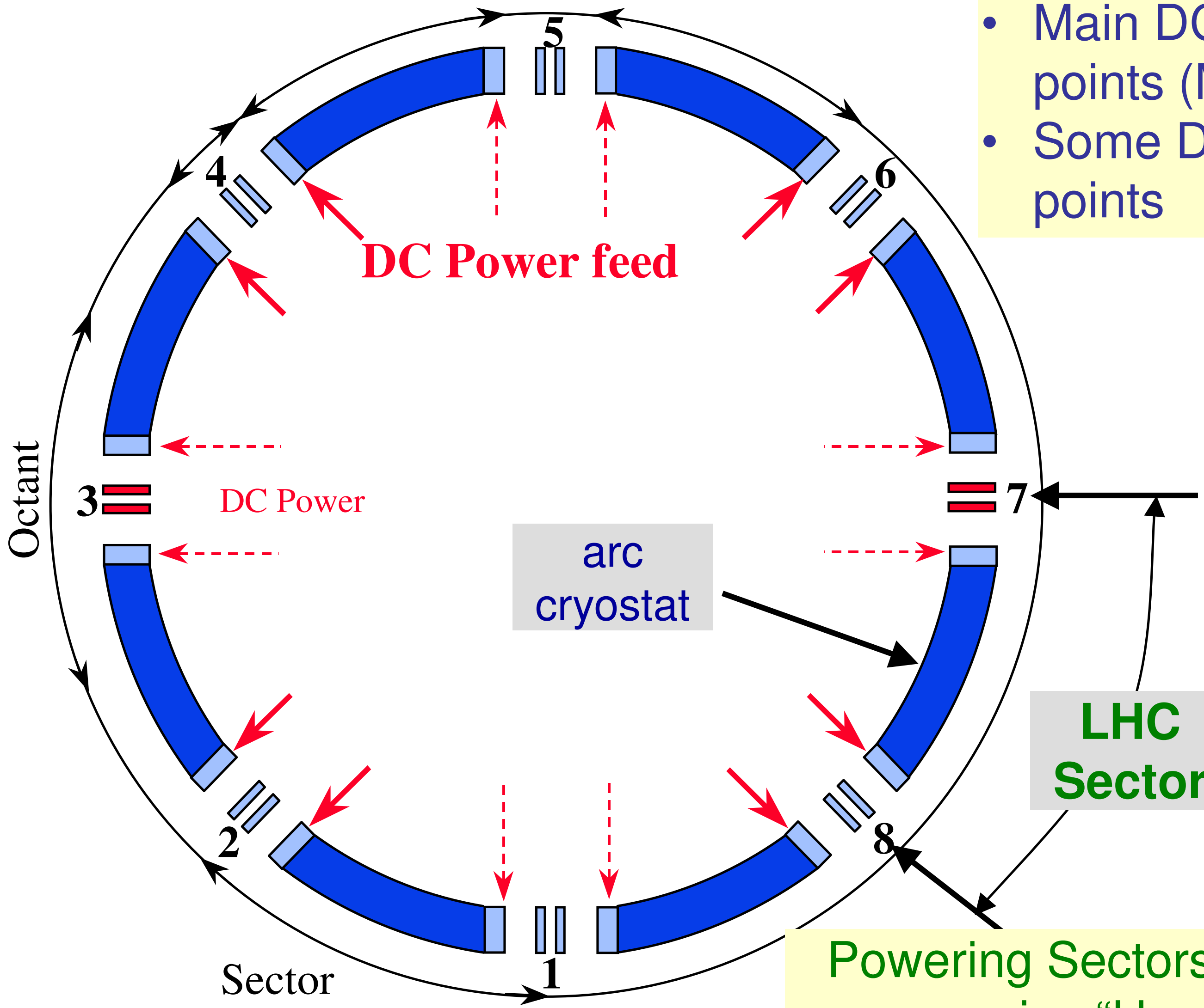
- corresponds to the energy of 1900 kg TNT
- corresponds to the energy of 400 kg Chocolate

- corresponds to the energy for heating and melting 12000 kg of copper

- corresponds to the energy produced by of one nuclear power plant during about 10 seconds

Could this damage equipment: How fast can this energy be released?

LHC Powering in 8 Sectors

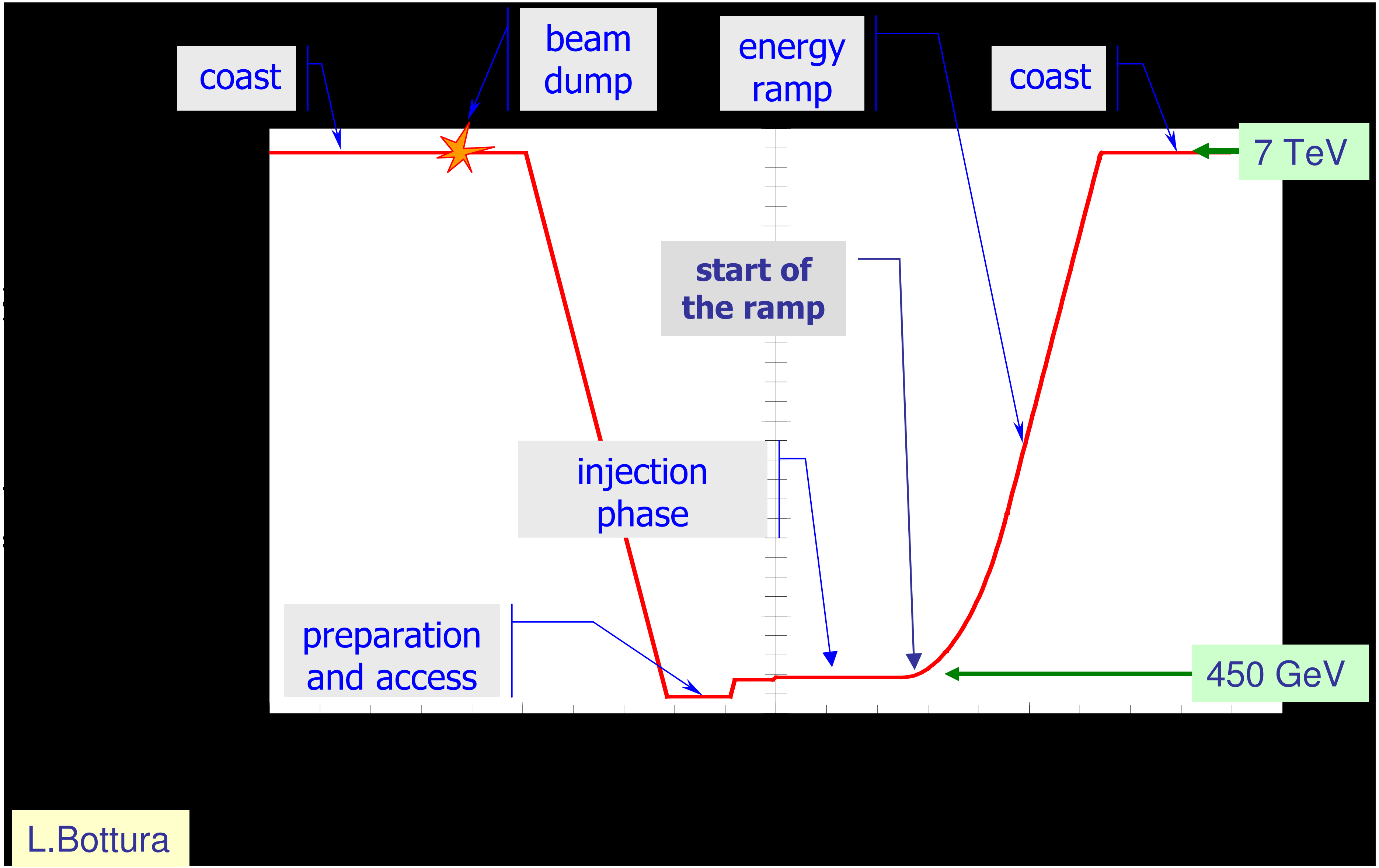


- Main DC power feed at even points (MB, MQ)
- Some DC power feed at odd points

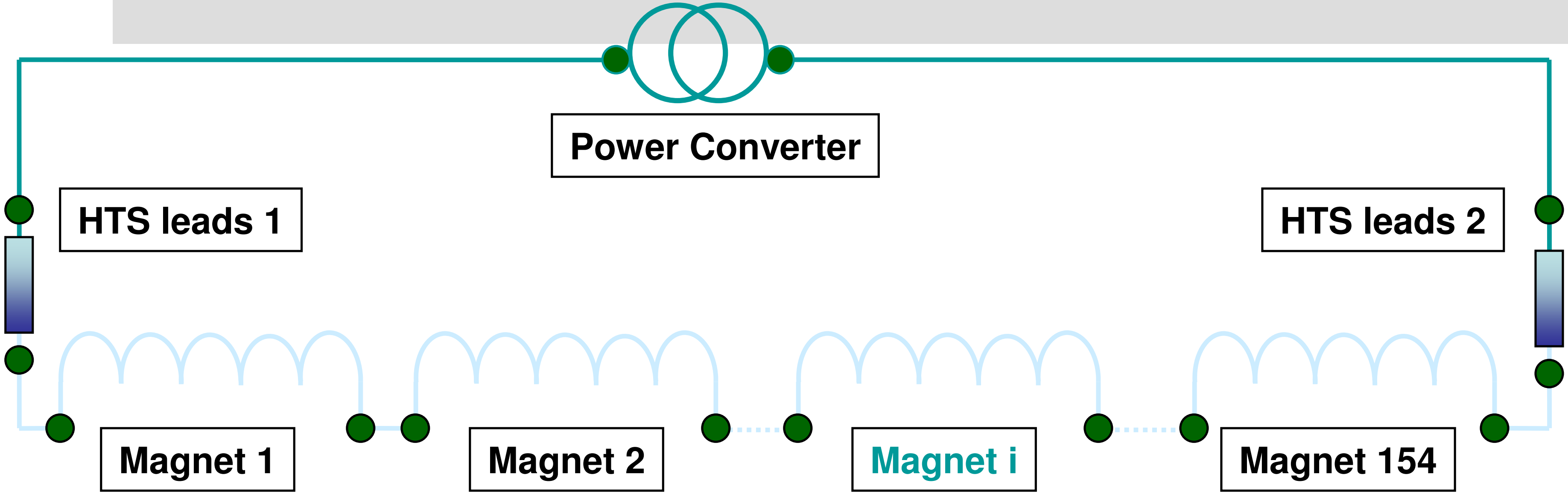
Powering Sectors allow for progressive "Hardware Commissioning" started two years before beam

P.Proudlock

Charging the energy: LHC magnetic cycle

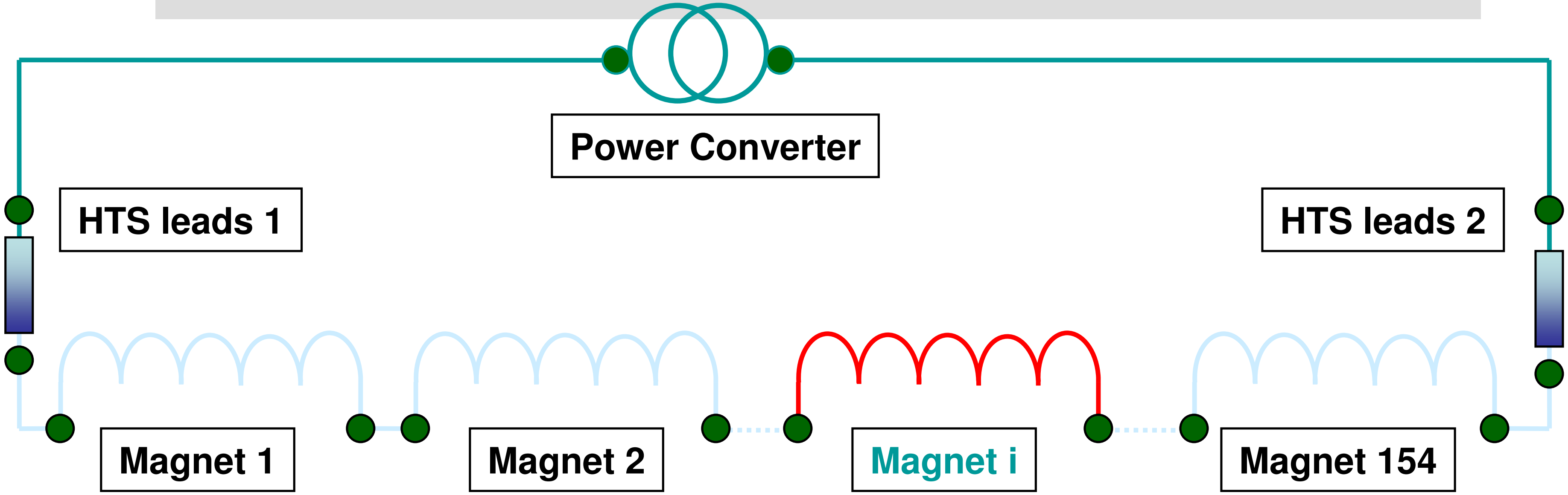


Ramping the current in a string of dipole magnet



- LHC powered in eight sectors, each with 154 dipole magnets
- Time for the energy ramp is about 20-30 min (Energy from the grid)
- Time for discharge is about the same (Energy back to the grid)

Quench - Emergency discharge of energy …



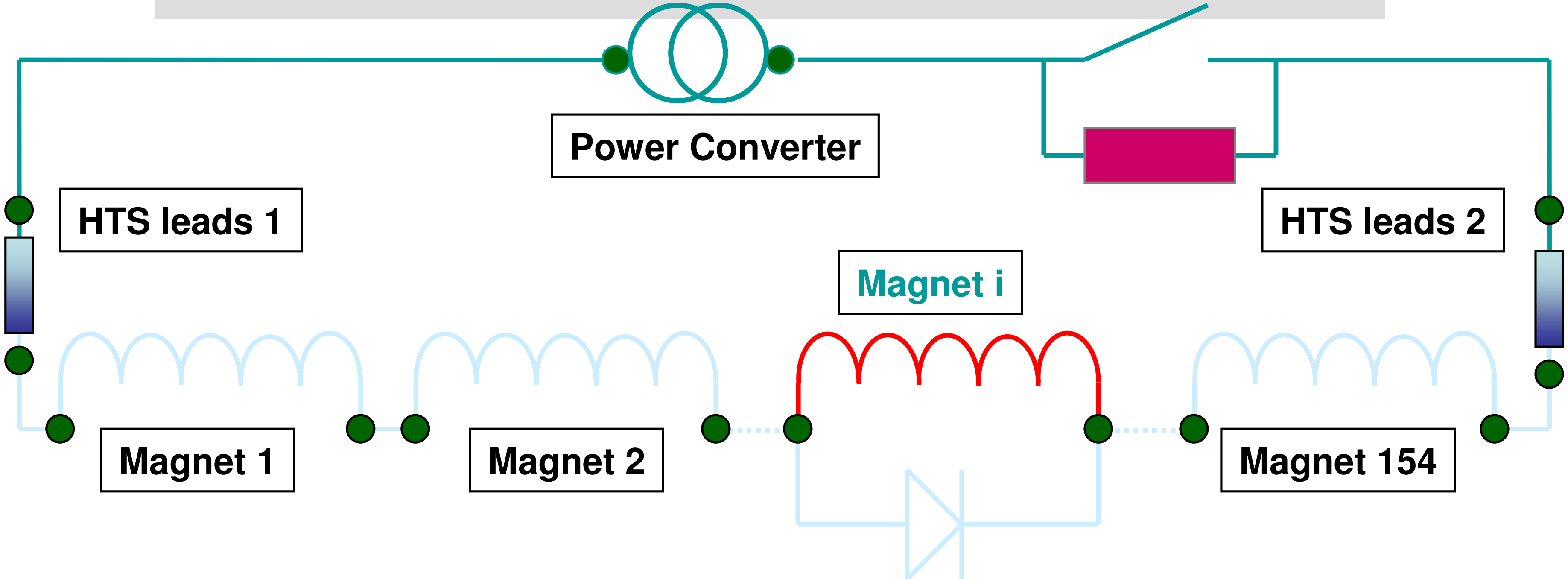
- assume one magnet quenches
- assume the magnets in the string have to be discharged in, say, 200 ms

$$U_{discharge\_1} := \frac{L_{dipole} \cdot I_{dipole}}{0.2s} \qquad U_{discharge\_154} := \frac{154 L_{dipole} \cdot I_{dipole}}{0.2s}$$

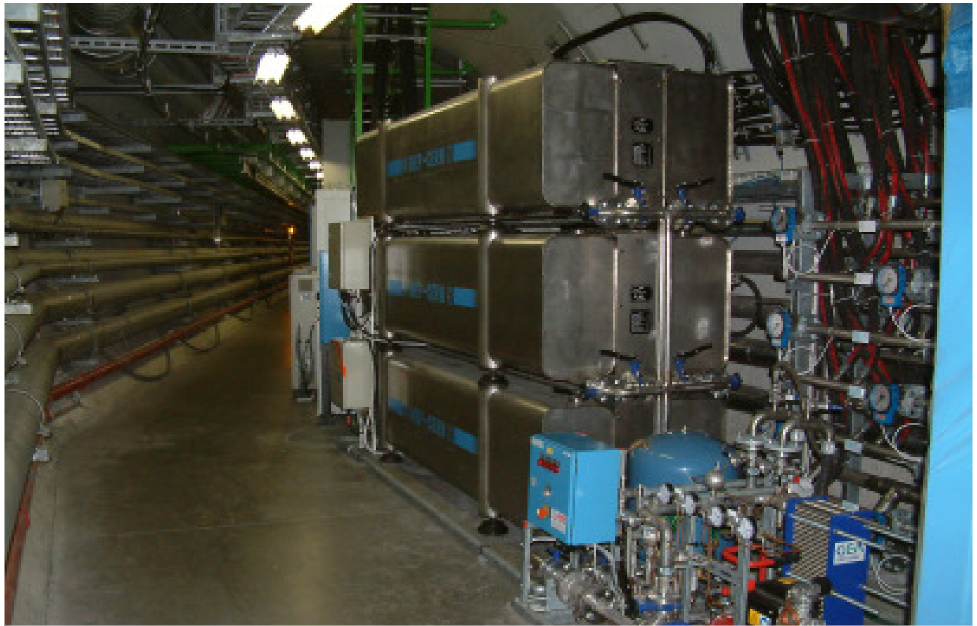
$$U_{discharge\_1} = 6.426 \times 10^{3} V \qquad U_{discharge\_154} = 9.896 \times 10^{5} V$$

Discharge with about 1 MV: not possible

.....and how it being done in the LHC



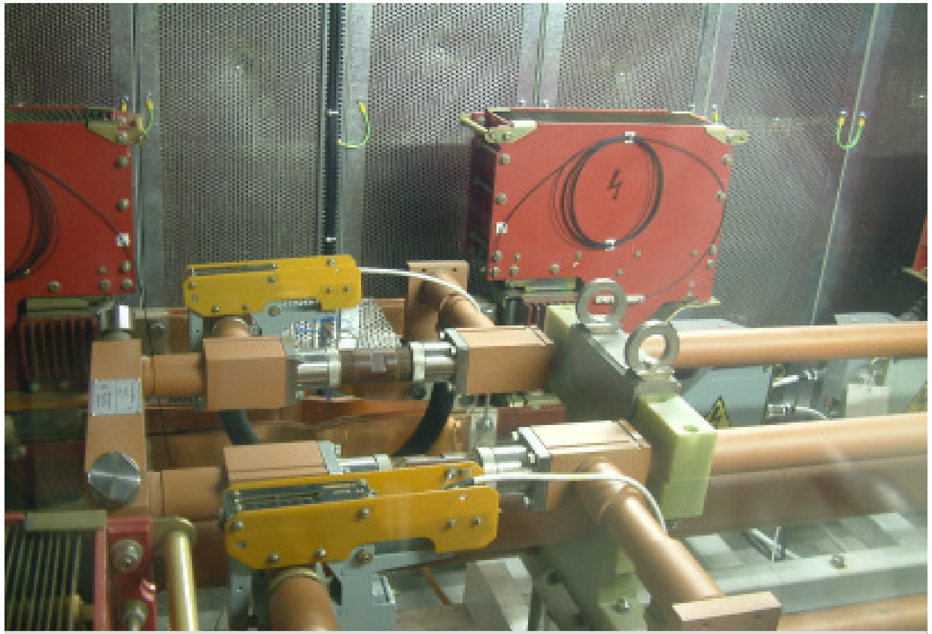
- when one magnet quenches, quench heaters are fired for this magnet
- the current in the quenched magnet decays in about 200 ms
- the current in all other magnets flows through the bypass diode that can stand the current for about 100-200 seconds



Energy extraction resistors MB

Energy extraction switch house 13 kA

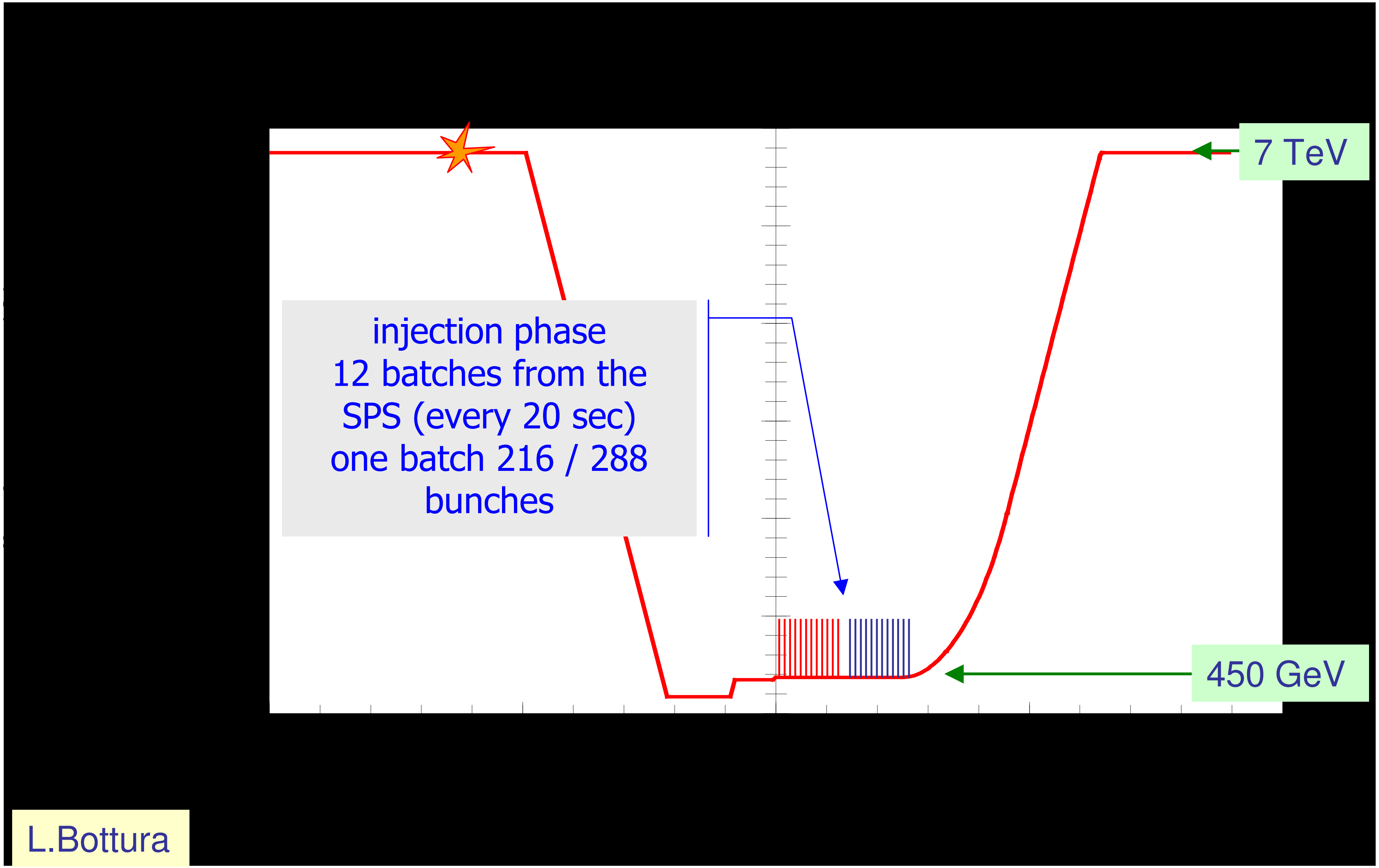
Diode for 13 kA



Energy extraction switch 13 kA

Beam operation and machine protection

LHC magnetic cycle - Beam injection



Regular (very healthy) operation

Assuming that the beams are colliding at 7 TeV

Single beam lifetime larger than 100 hours…..

- **corresponds to a** loss of about 1 kW / beam
- **far** below the cooling power of the cryogenic system**, even if all particles would be slowly lost at 1.9 K**
- **losses should be** either distributed across the machine **or** captured in the warm cleaning insertions

Collision of beams with a luminosity of **10^{34} cm^{-2}s^{-1}**

- lifetime **of the beam** dominated by collisions
- 10^9 protons / **second lost per beam** / **per experiment (in IR 1 and IR 5 - high luminosity insertions) - this is about** 1.2 kW
- large heat load **to close-by superconducting quadrupoles**
- heavy shielding **around the high luminosity IPs**

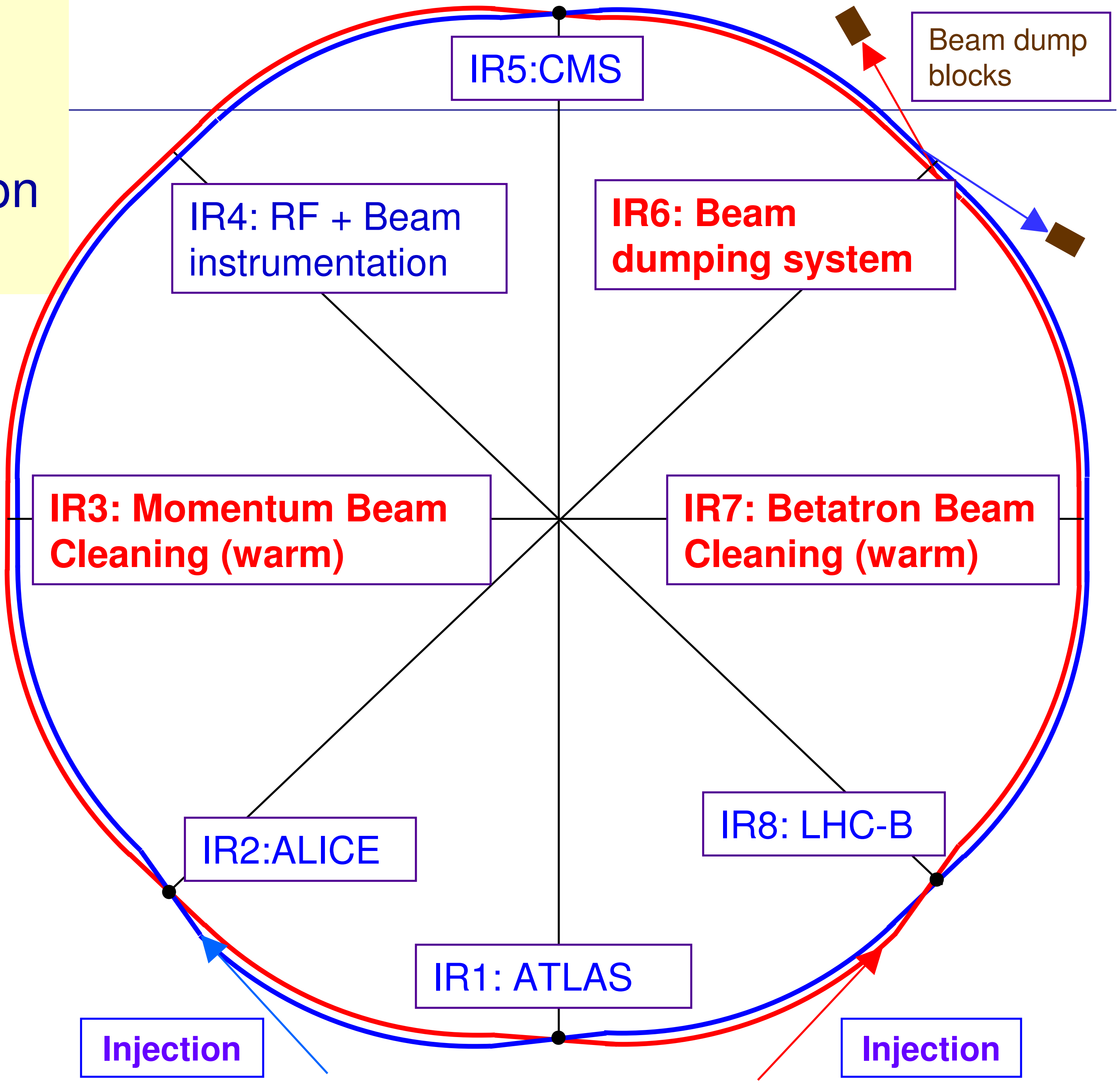
End of data taking in normal operation

- Luminosity lifetime estimated to be approximately 10 h (after 10 hours only 1/3 of initial luminosity)
- Beam current somewhat reduced - but not much
- Energy per beam still about 200-300 MJ
- Beams are extracted in beam dump blocks

- The only component that can stand a fast loss of the full beam at top energy is the beam dump block - all other components would be damaged
- At 7 TeV, fast beam losses with an intensity of about **5% of one "nominal bunch** (from 2808)" could damage superconducting coils

LHC ring

3 insertions for machine protection systems



Beam losses into material

- Proton losses lead to particle cascades in materials
- The energy deposition leads to a temperature increase
- For the maximum energy deposition as a function of material there is no straightforward expression
- Programs such as FLUKA are being used for the calculation of the energy deposition

Magnets could quench…..

- **beam lost - re-establish condition takes several hours**

The material could be damaged…..

- **melting**
- **losing their performance (mechanical strength)**

Repair could take several weeks or more

Damage of material for impact of a pencil beam

Maximum energy deposition in the proton cascade (one proton) $E_{max\_Cu} := 1.5 \cdot 10^{-5} \frac{J}{kg}$

Specific heat of copper is $c_{Cu\_spec} = 384.5600 \frac{1}{kg} \frac{J}{K}$

To heat 1 kg copper by, say, by $\Delta T := 500K$, one needs: $c_{Cu\_spec} \cdot \Delta T \cdot 1kg = 1.92 \times 10^{5} J$

Number of protons to deposit this energy is: $\frac{c_{Cu\_spec} \cdot \Delta T}{E_{max\_Cu}} = 1.28 \times 10^{10}$

copper

Maximum energy deposition in the proton cascade (one proton) $E_{max\_C} := 2.0 \cdot 10^{-6} \frac{J}{kg}$

Specific heat of graphite is $c_{C\_spec} = 710.6000 \frac{1}{kg} \frac{J}{K}$

To heat 1 kggraphite by, say, by $\Delta T := 1500K$, one needs: $c_{C\_spec} \cdot \Delta T \cdot 1kg = 1.07 \times 10^{6} J$

Number of protons to deposit this energy is: $\frac{c_{C\_spec} \cdot \Delta T}{E_{max\_C}} = 5.33 \times 10^{11}$

graphite

SPS experiment: Beam damage at 450 GeV

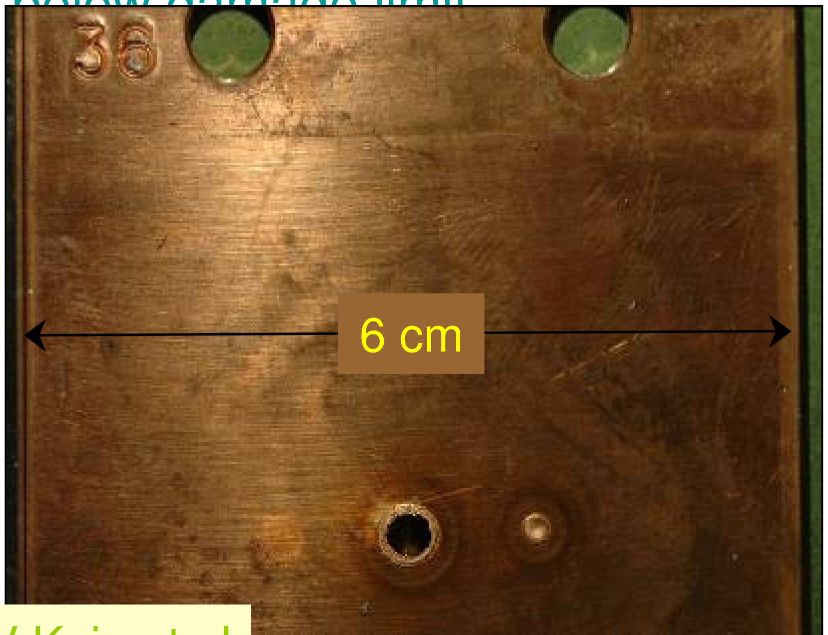
Controlled SPS experiment

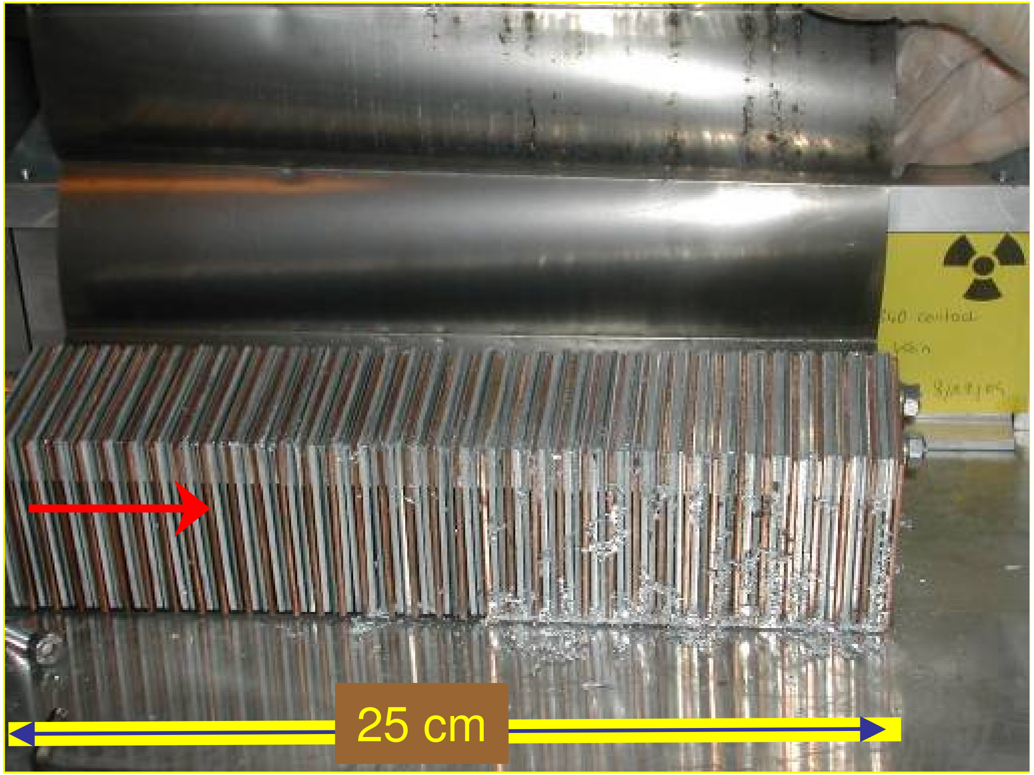
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

above damage limit

- $2 \cdot 10^{12}$ protons

below damage limit

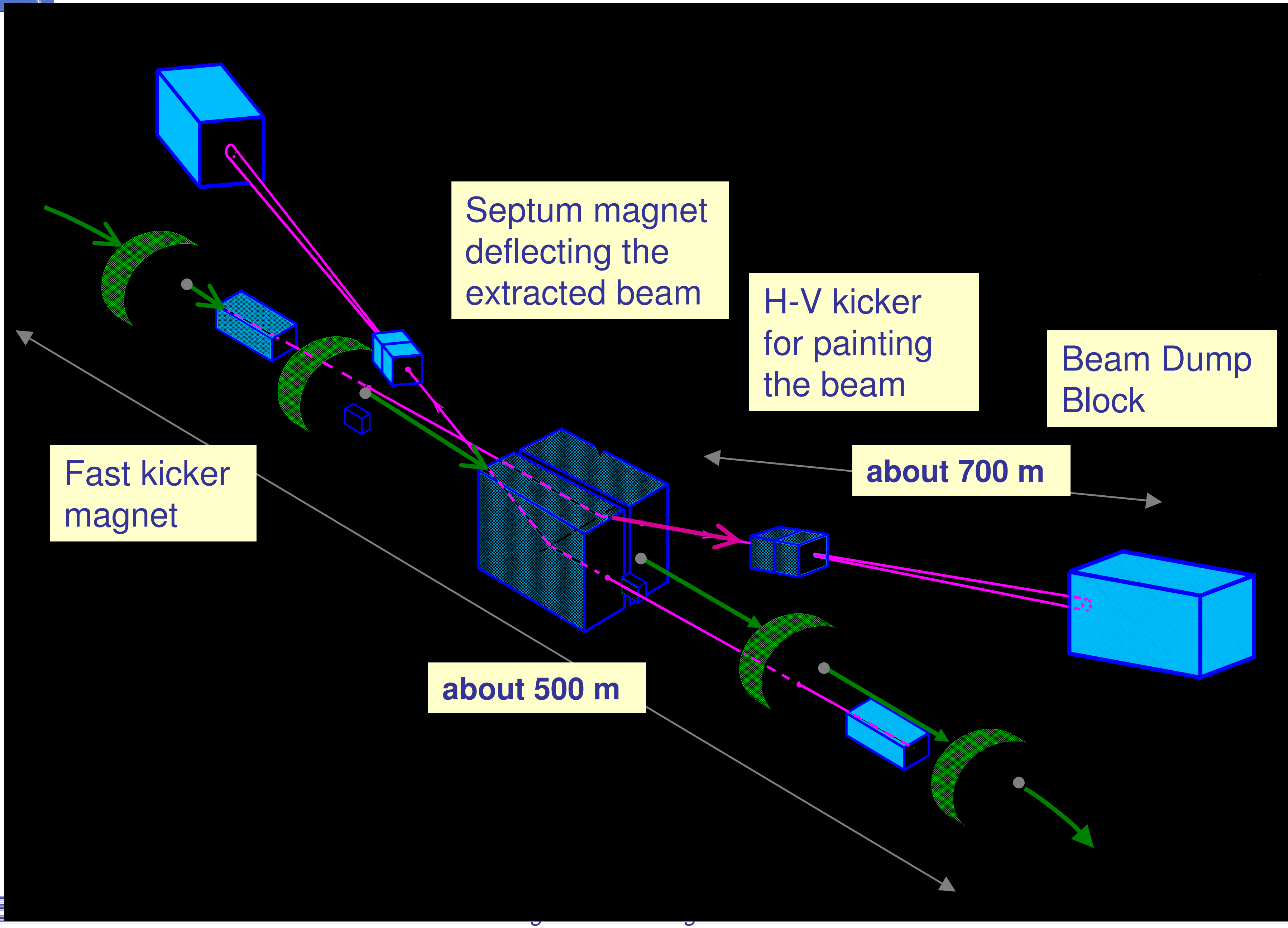




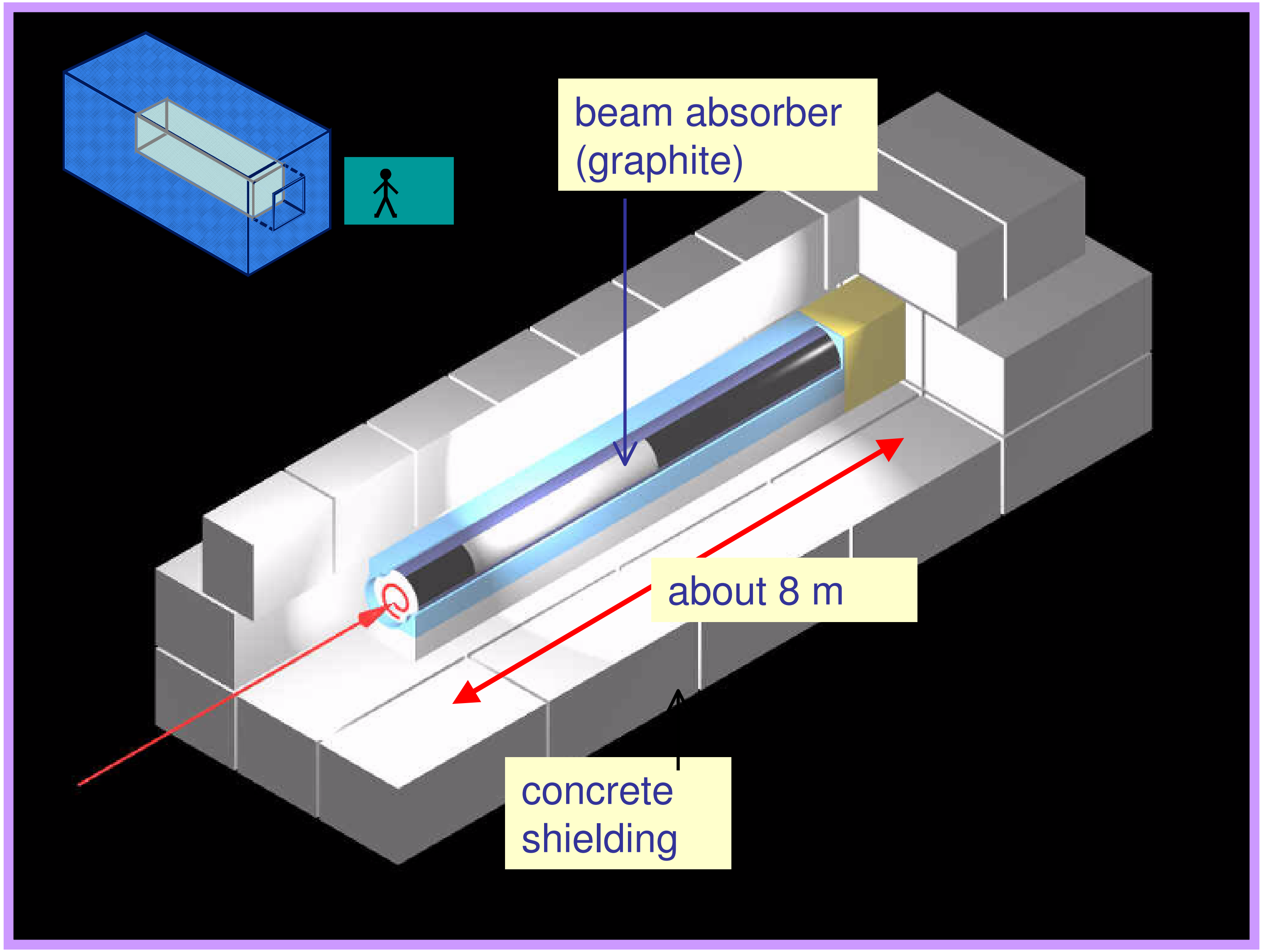
0.1 % of the full LHC beams

V.Kain et al

Schematic layout of beam dump system in IR6



Beam Dump Block - Layout



L.Bruno

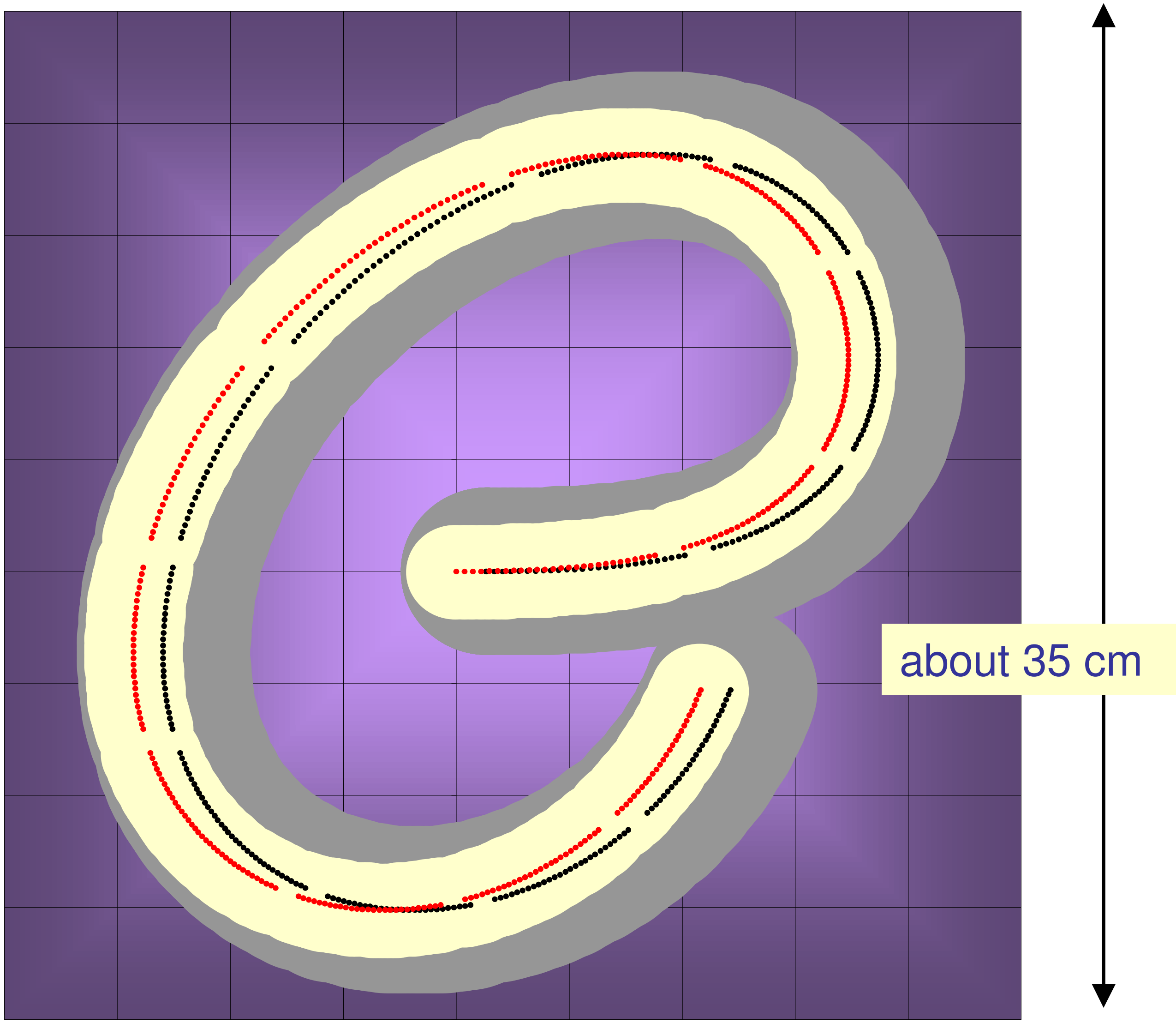
Beam on Beam Dump Block

initial transverse beam dimension in the LHC about 1 mm

beam is blown up due to long distance to beam dump block

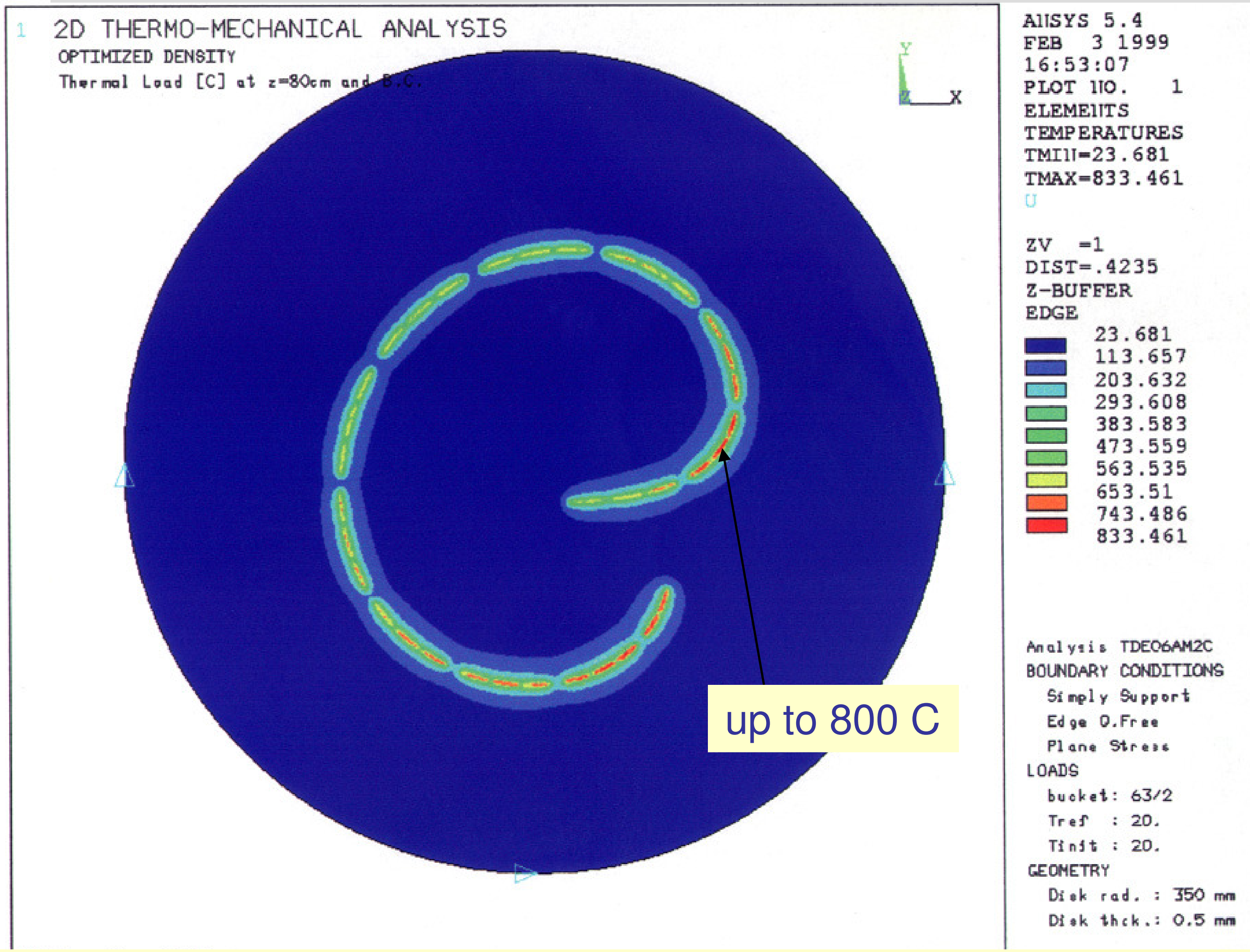
additional blow up due to fast dilution kickers: painting of beam on beam dump block

beam impact within less than 0.1 ms



M.Gyr

Temperature of beam dump block at 80 cm inside



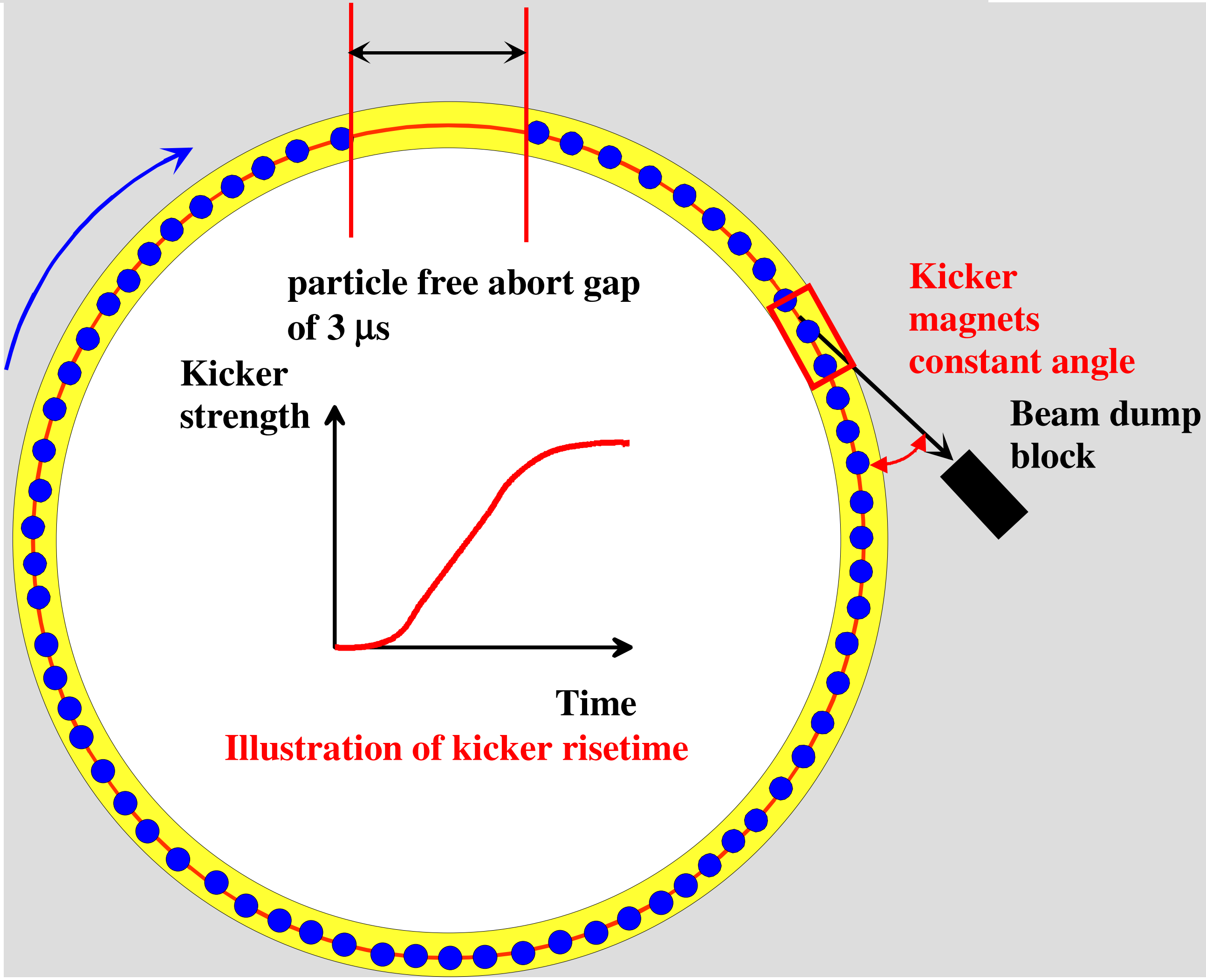
L.Bruno: Thermo-Mechanical Analysis with ANSYS

Requirement for clean beam dump

Beam dump must be synchronised with particle free gap

Strength of kicker and septum magnets must match energy of the beam

« Particle free gap » must be free of particles



Lifetime of the beam with nominal intensity at 7 TeV

Beam lifetime	Beam power into equipment (1 beam)	Comments
100 h	1 kW	Healthy operation
10 h	10 kW	Operation acceptable, **collimation must absorb large fraction of beam energy** (approximately beam losses = cryogenic cooling power at 1.9 K)
0.2 h	500 kW	**Operation only** possibly for **short time**, collimators must be very efficient
1 min	6 MW	Equipment or operation **failure** - operation not possible - **beam must be dumped**
<< 1 min	> 6 MW	**Beam** must be **dumped VERY FAST**

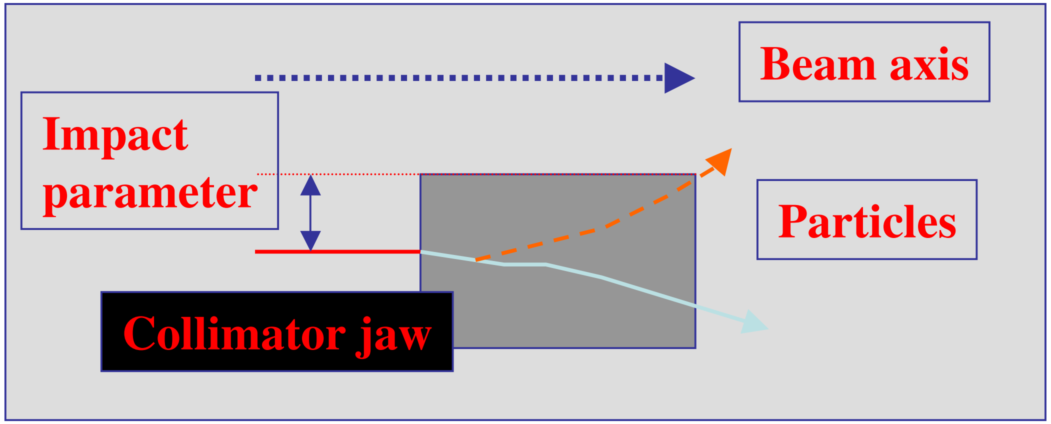
Failures will be a part of the regular operation and MUST be anticipated

Basic concept of two stage collimation

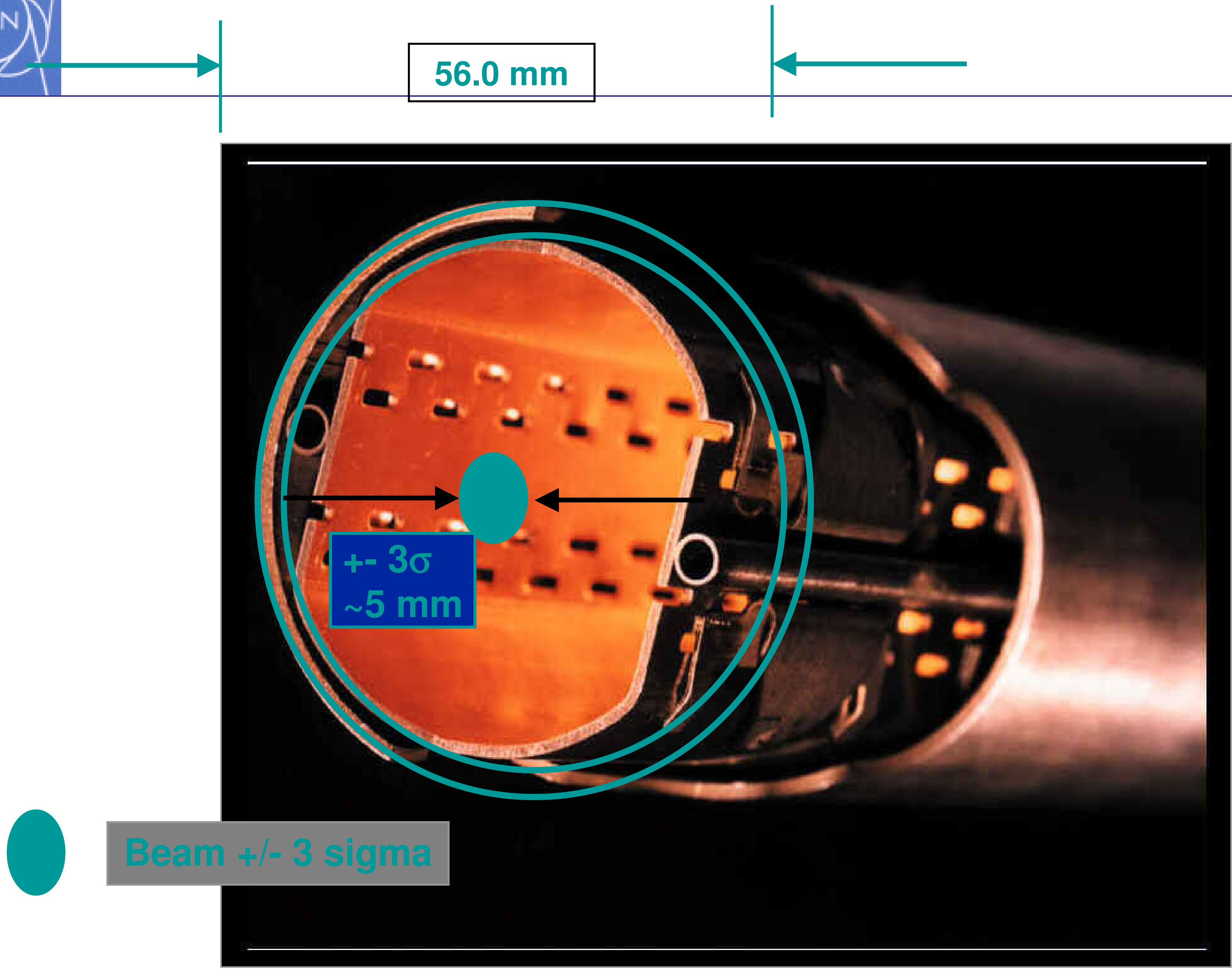
Jaws (blocks of solid materials such as copper, graphite, ….) very close to the beam to absorb **more than 99.9 % of protons** that would be lost

Primary collimators: Intercept primary halo
Impact parameter: ~ 1 μm
Scatter protons of primary halo
Convert primary halo to secondary off-momentum halo

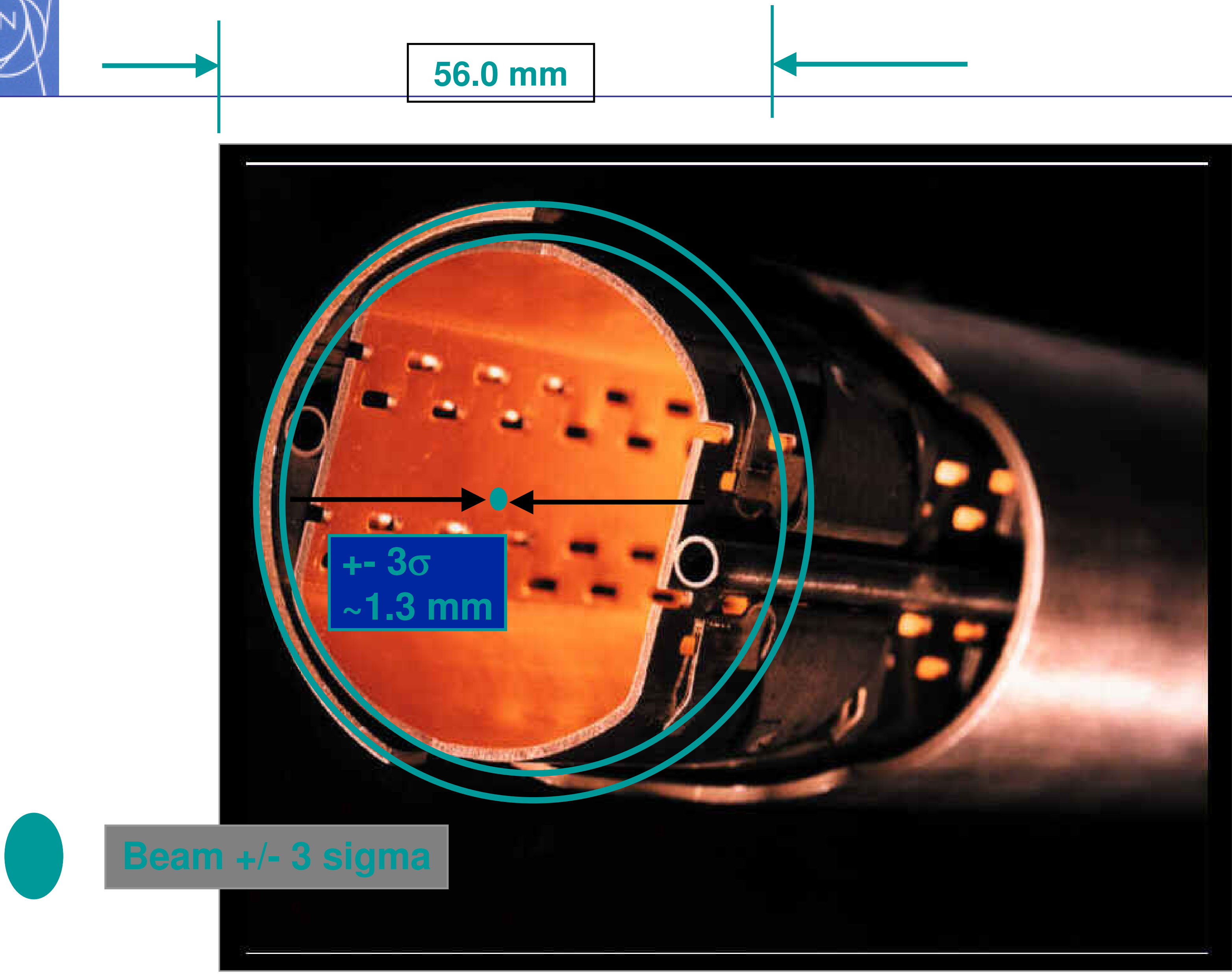
Secondary collimators: Intercept secondary halo
Impact parameter: ~ 200 μm
Absorb most protons
Leak a small tertiary halo



R.Assmann

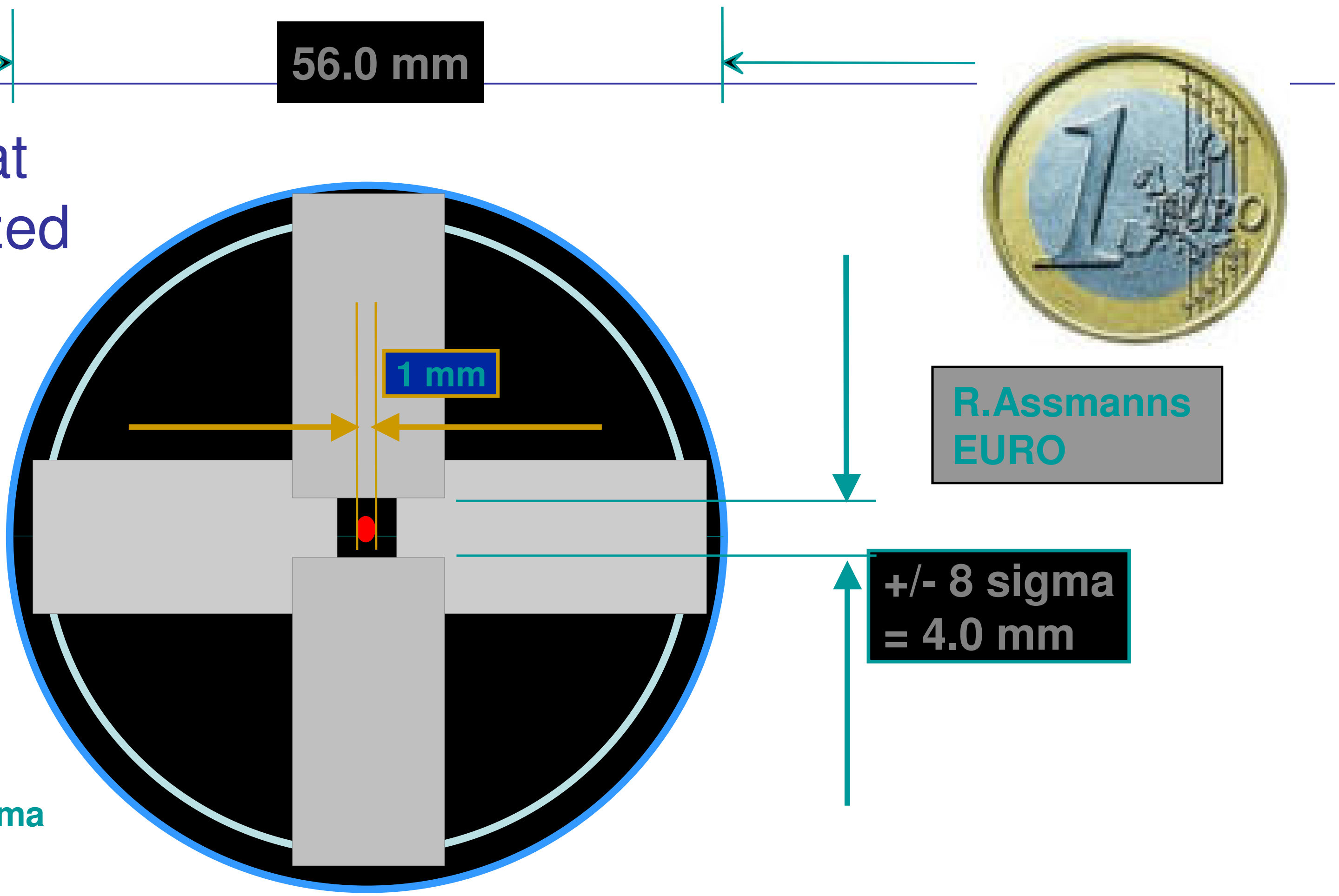


Beam in vacuum chamber with beam screen at 450 GeV



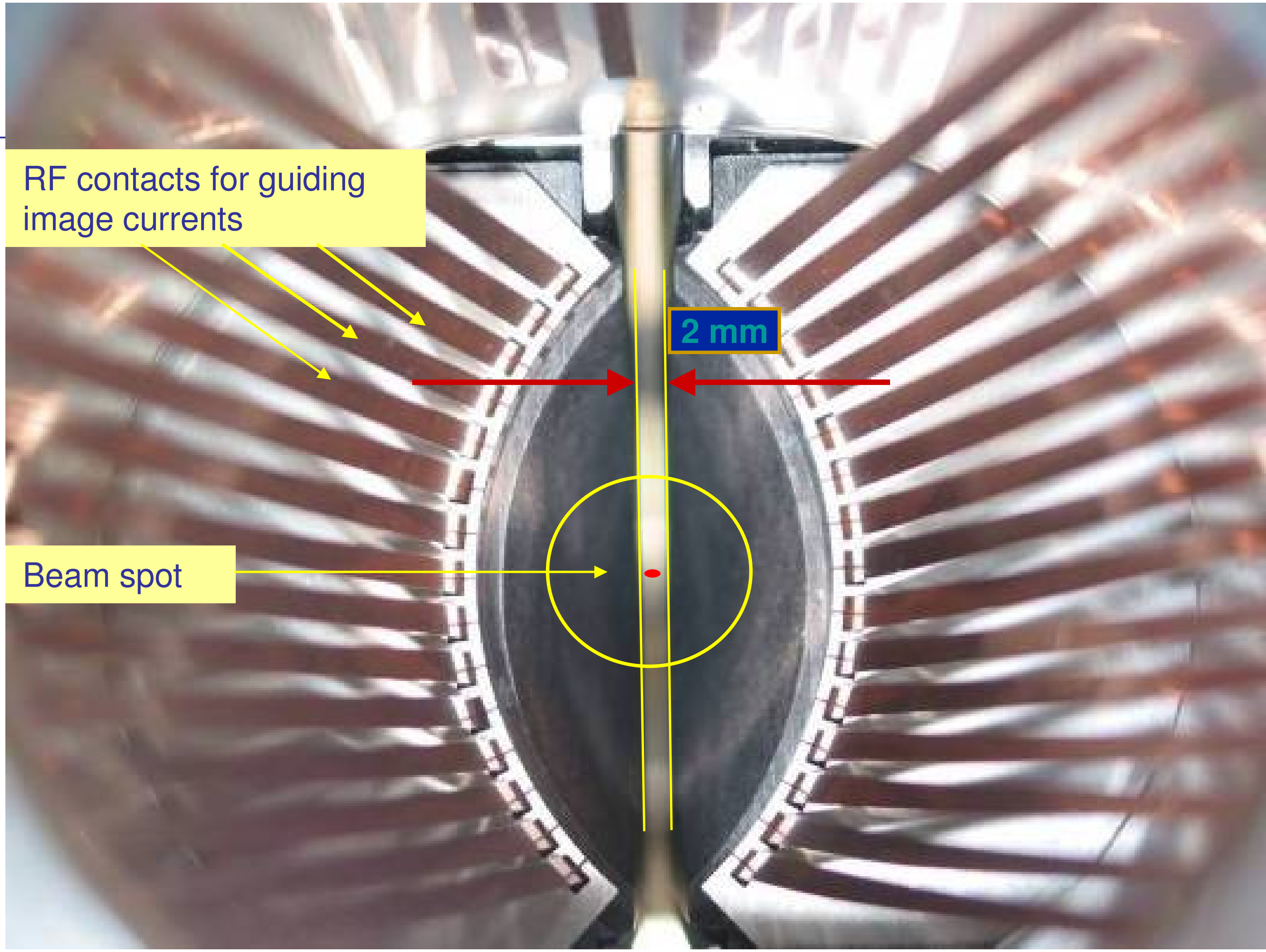
Beam in vacuum chamber with beam screen at 7 TeV

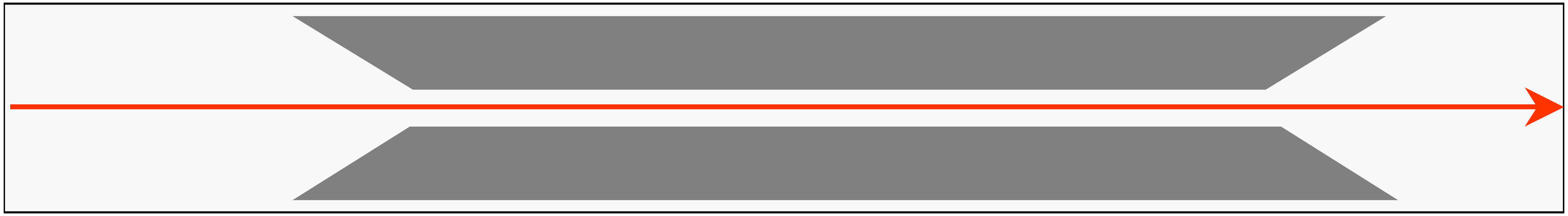
Collimators at 7 TeV, squeezed optics



Example: Setting of collimators at 7 TeV - with luminosity optics

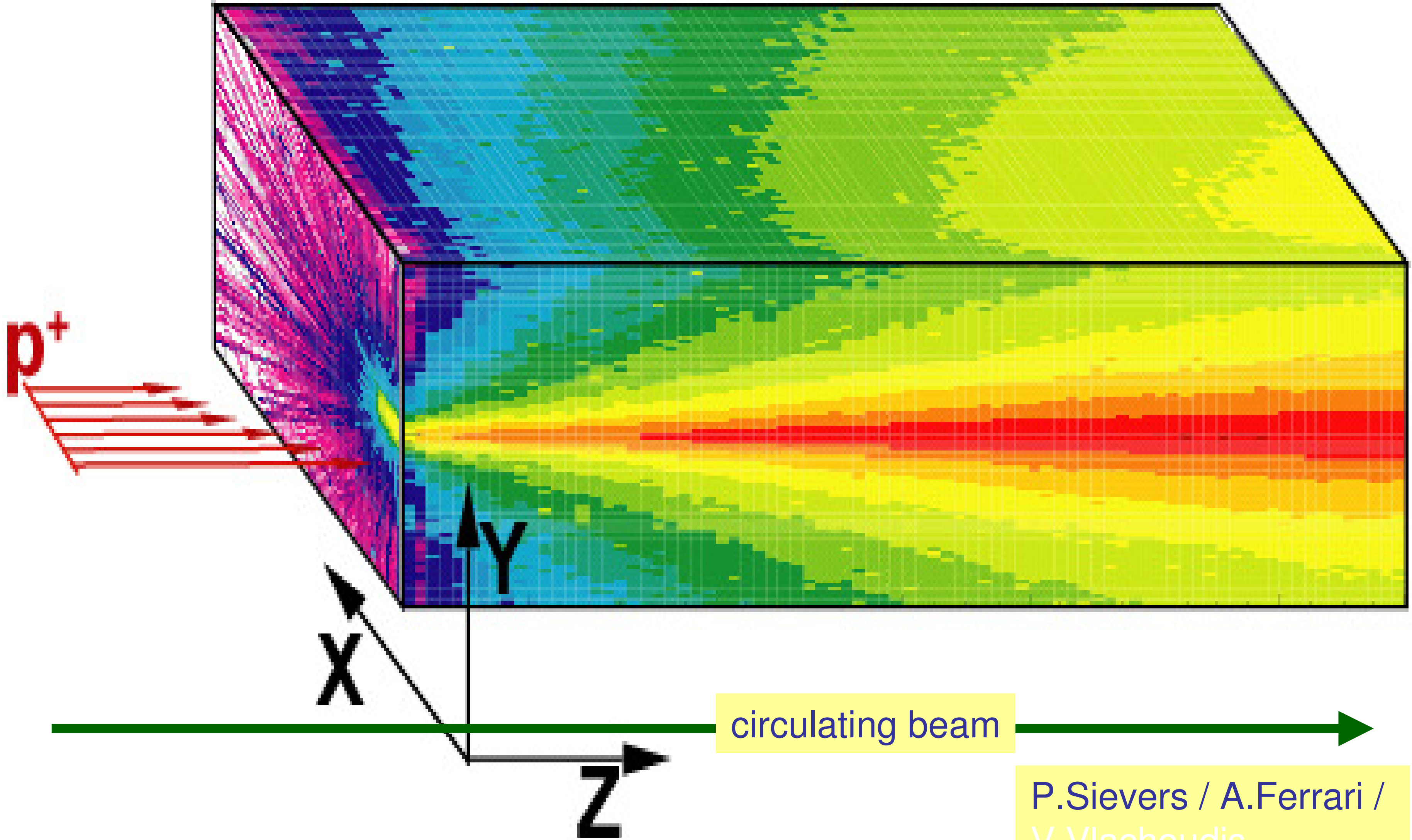
Beam must always touch collimators first !


RF contacts for guiding image currents
2 mm
Beam spot



Accidental kick by the beam dump kicker at 7 TeV

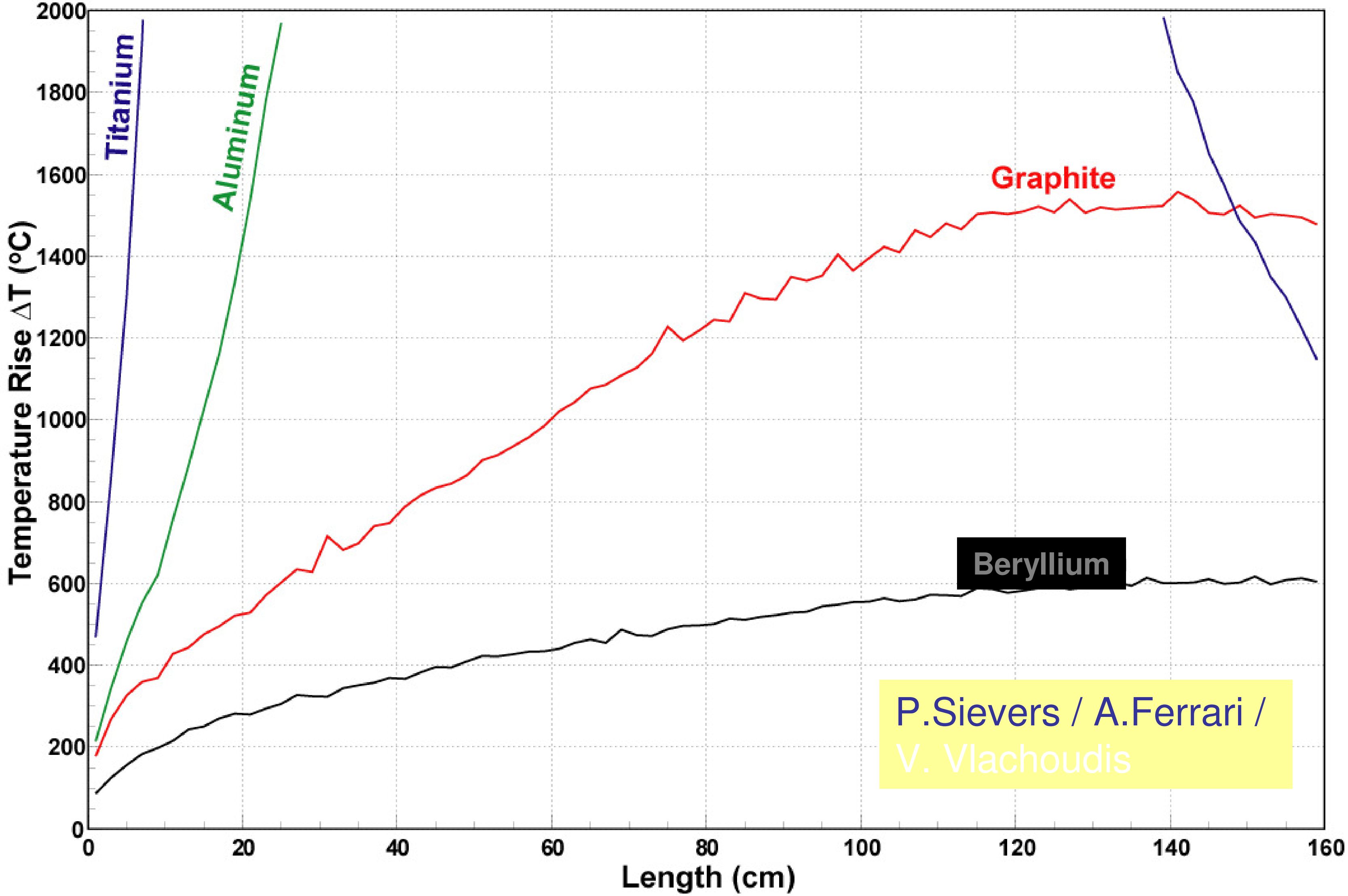
part of beam touches collimators (about 20 bunches from 2800)



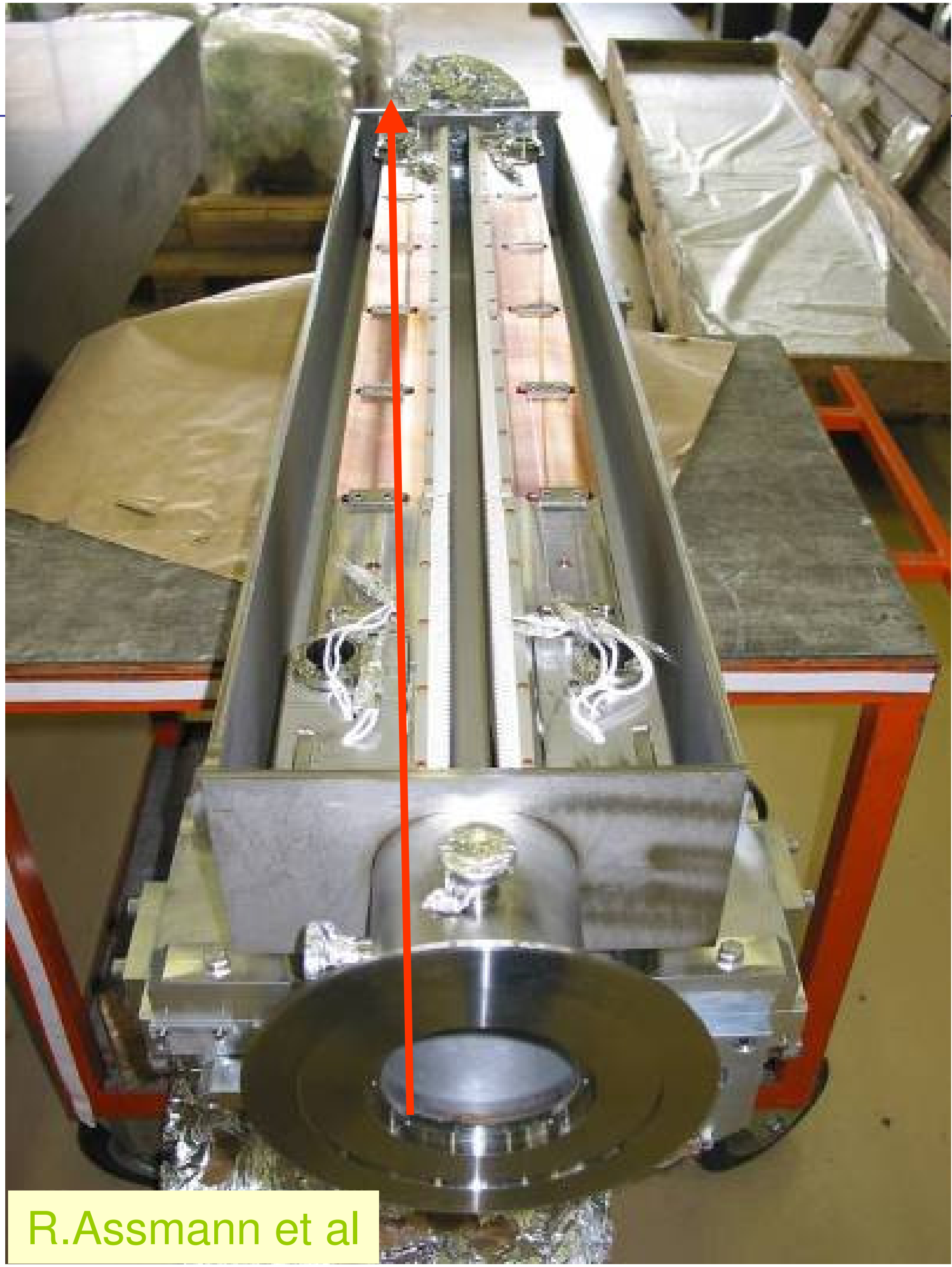
P.Sievers / A.Ferrari / V.Vlachoudis

Accidental kick by the beam dump kicker at 7 TeV

part of beam touches collimators (about 20 bunches from 2808)



The LHC Phase 1 Collimator

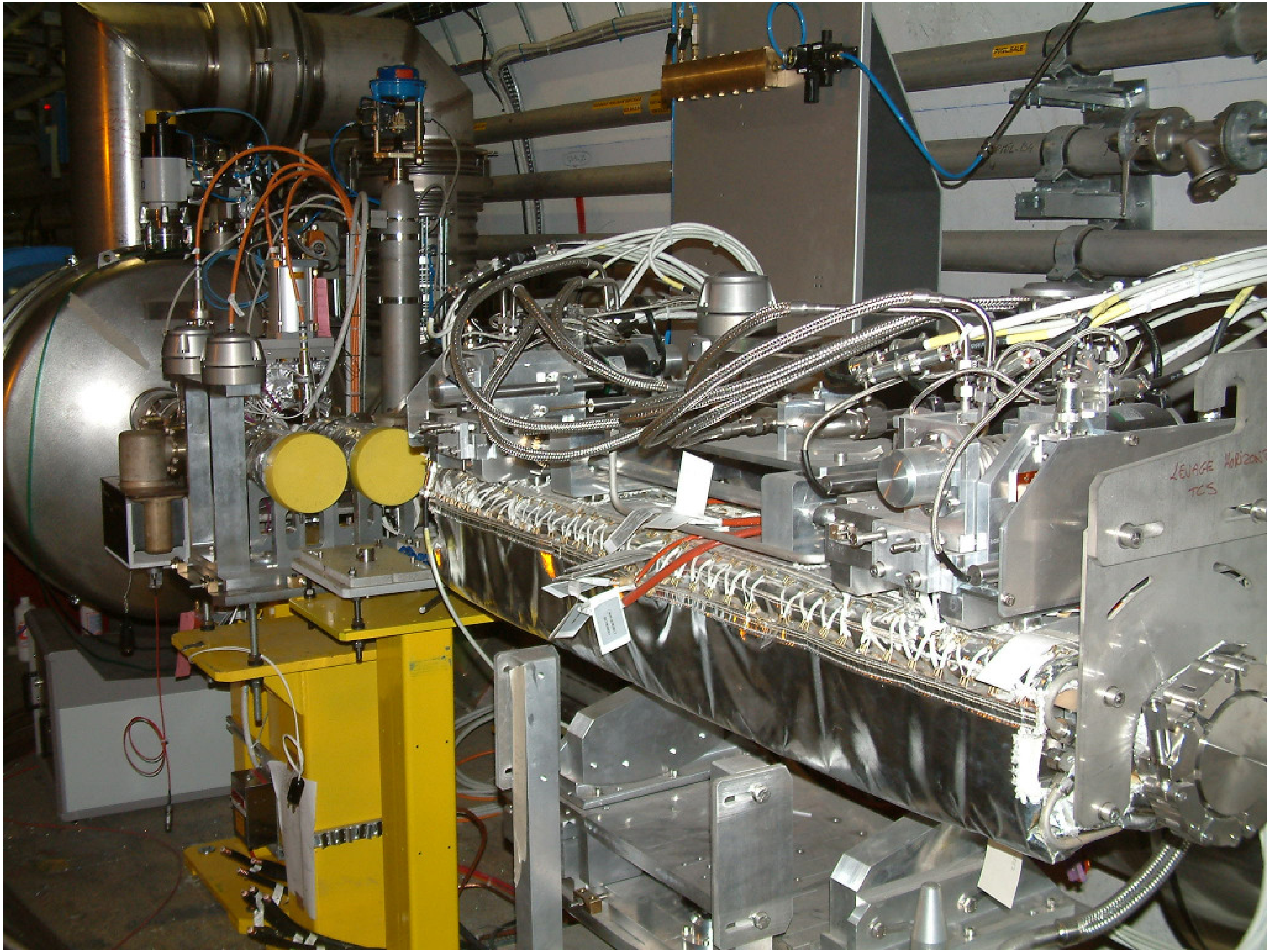


Vacuum tank with two jaws installed

Designed for maximum robustness:

Advanced Carbon Composite material for the jaws with water cooling!

First collimator in the tunnel


LEVAGE HORIZONT
TCS

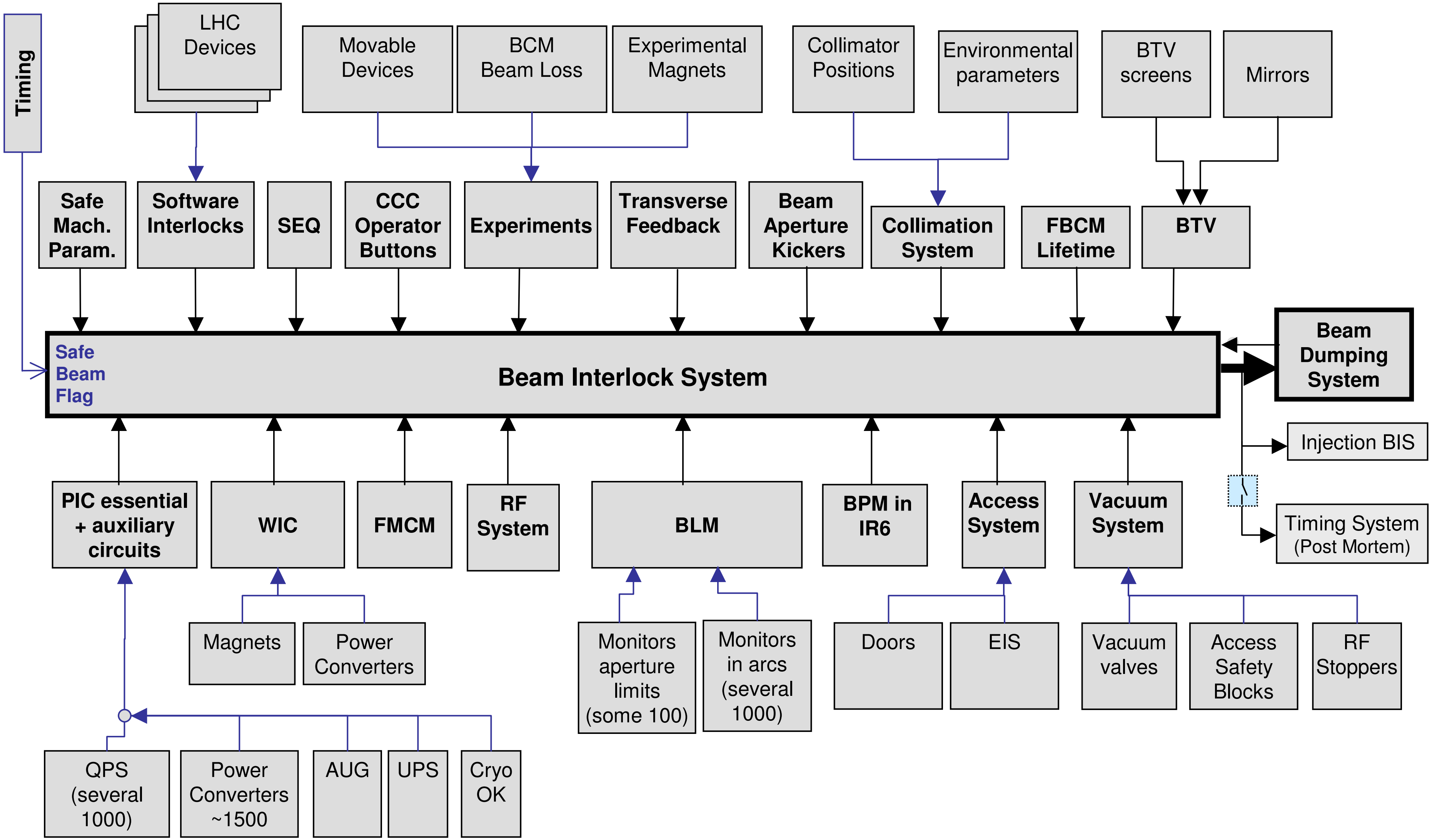
Optimisation of Beam Cleaning system

- Requirements for collimation system take into account failure scenarios and imperfect operation
  - Worst case is the impact of about 20 bunches on the collimator due to pre-firing of one dump kicker module
- Material for collimator: low Z material is favoured
- Impedance to be considered - conducting material is favoured
- more exotic materials are considered: copper loaded graphite, beryllium, partially plated copper ….

Single turn beam loss during injection and beam dump	**Passive protection** • Avoid such failures (high reliability systems - work is ongoing to better estimate reliability) • **Rely on collimators and beam absorbers**
Multiple turn beam loss due to many types of failures	**Active Protection** • Failure detection (from beam monitors and / or equipment monitoring) • Issue beam abort signal • **Fire Beam Dump**

In case of **any failure** or **unacceptable beam lifetime,** the **beam** must be **dumped immediately,** safely into the **beam dump block**

Beam Interlock System



Beam Loss Monitors

Primary strategy for protection: Beam loss monitors at collimators and other aperture limitations continuously measure beam losses

- Beam loss monitors indicate increased losses => MUST BE FAST

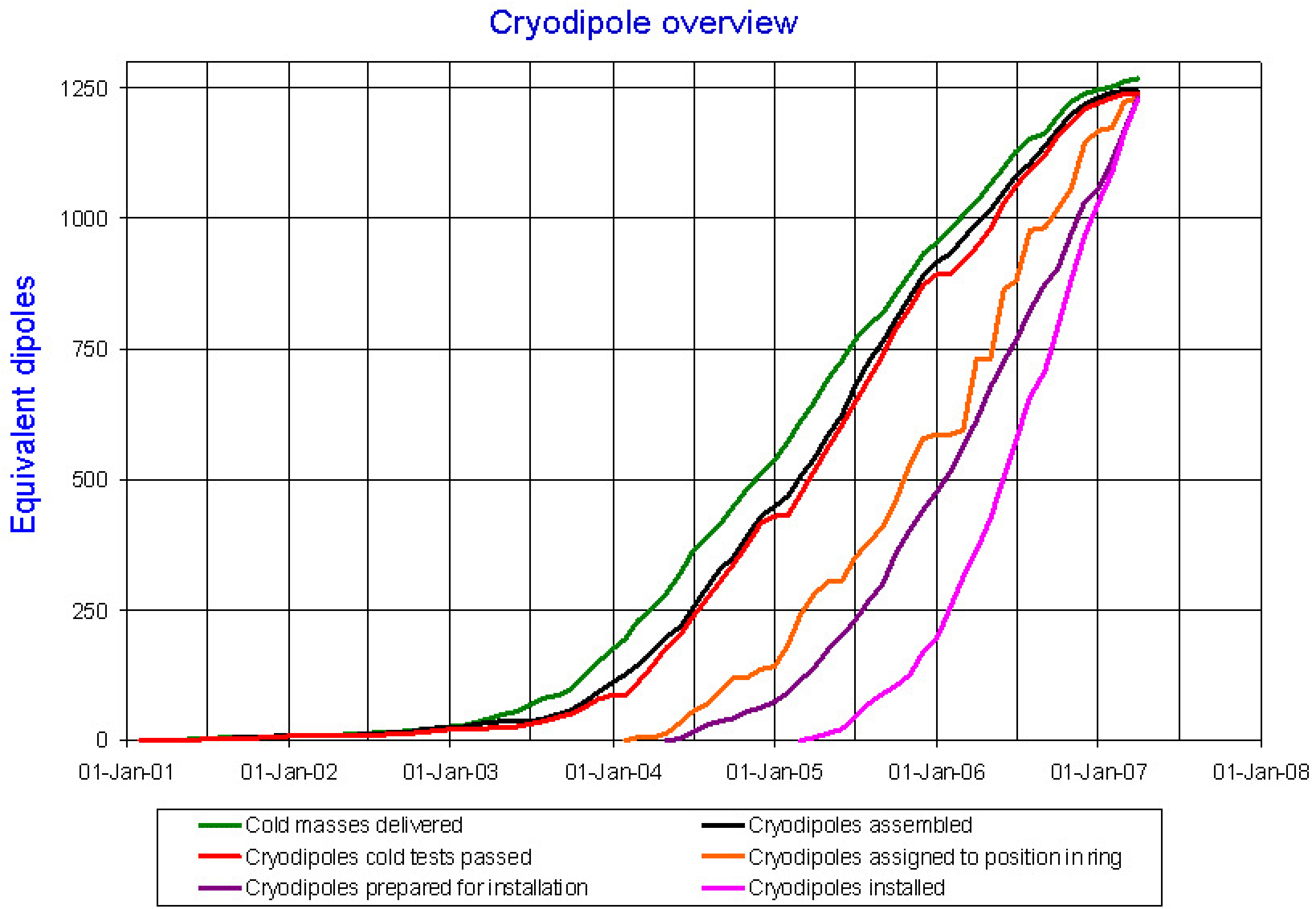
When beam losses exceed threshold

- Beam loss monitors break Beam Permit Loop
- Beam dump sees “No Beam Permit” => dump beams

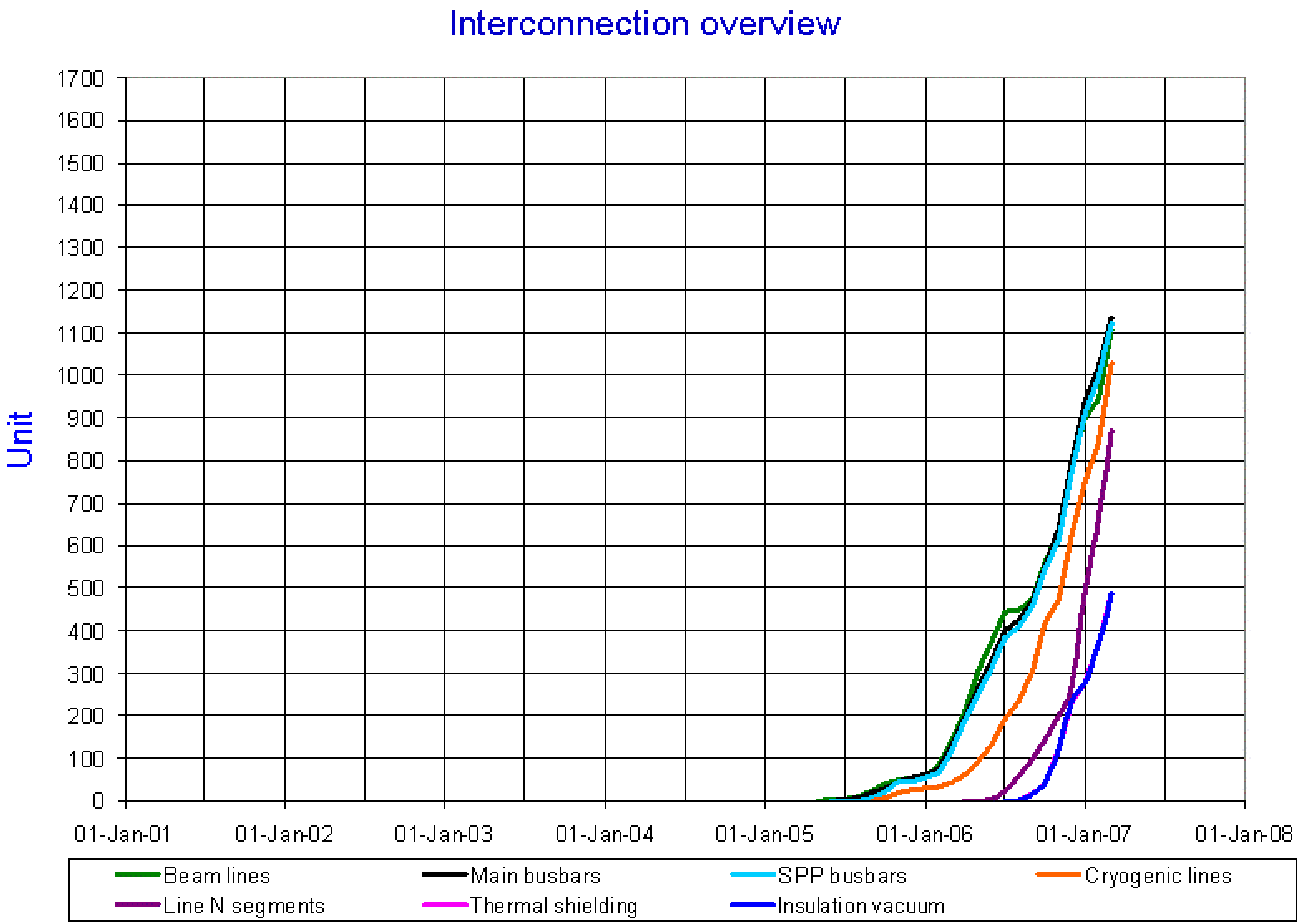
From construction to operation

LHC Progress Dashboard

Cryodipole production finished



Interconnections in progress

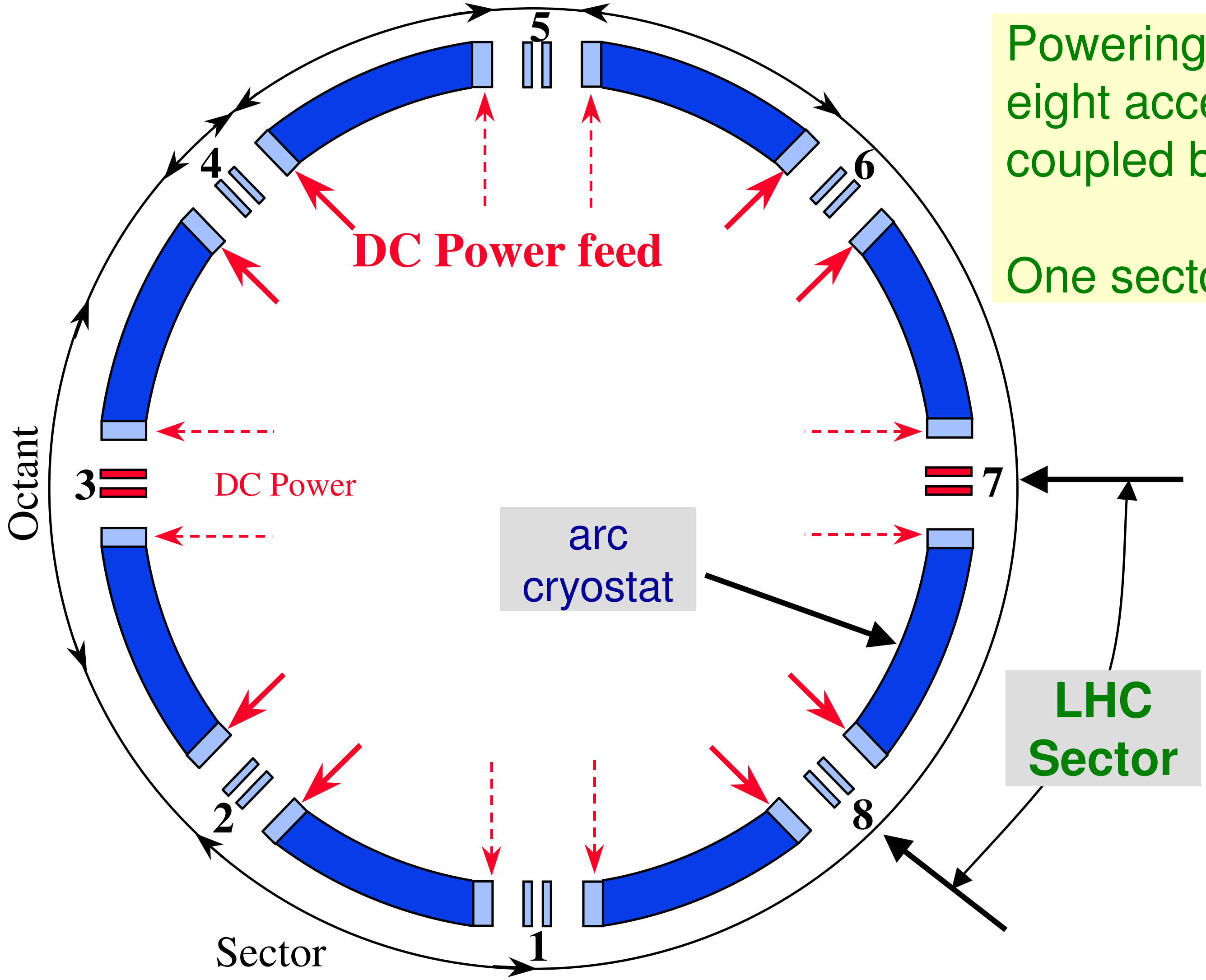


Commissioning of all technical systems that do not require beam: "**Hardware commissioning**"

- about 10000 magnets (most of them superconducting)
- 26 km cryogenic distribution line
- 26 km cryogenic magnets
- 4 vacuum systems, each 27 km long
- > 1600 magnet powering circuits with power converters (60A to 13000kA)
- quench protection and powering interlock systems
- commissioning of about 90% of the investement

> 10000 electronics crates for operation and protection

LHC Powering in 8 Sectors



Powering individual sectors: eight accelerators, only coupled by the beam.

One sector 1.5•mass of HERA

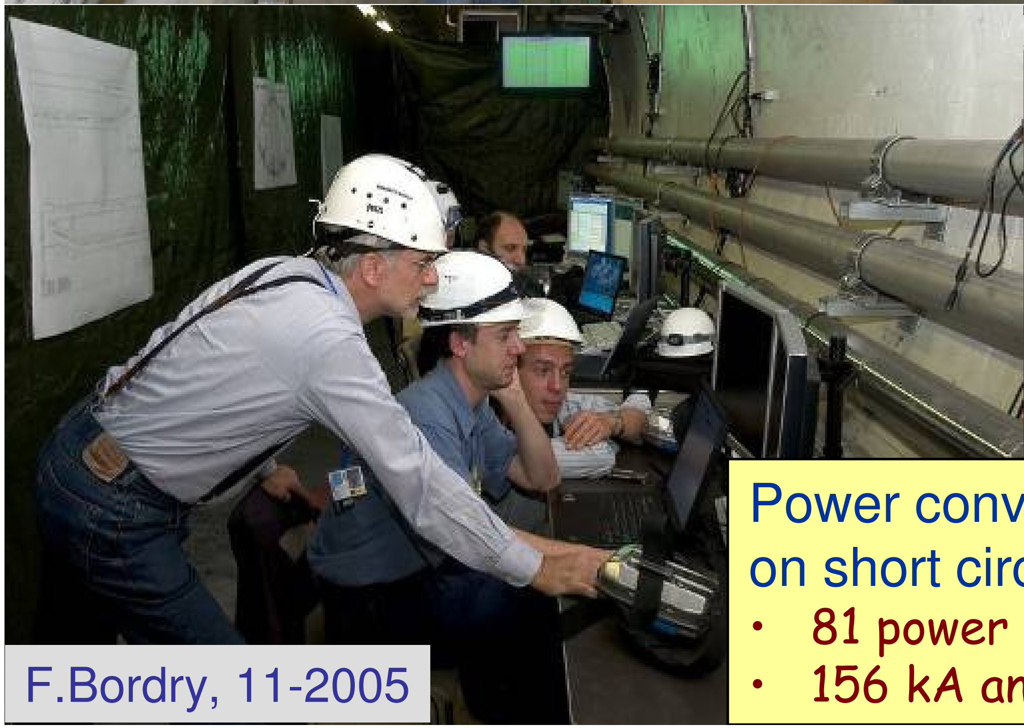
P.Proudlock

Hardware commissioning sequence

- Commissioning power converters on short circuit (including cooling and ventilation, controls, others, …)

When all magnets installed and interconnected

- Pumping vacuum system to nominal pressure
- Cooling down sector to 1.9 (4.5) Kelvin
- Connection of power converter to magnets via current leads
- Commissioning of the power converter + interlock system + magnet protection system (low current)
- Commissioning of magnet powering + magnet protection system (high current)
- Powering of all magnets in a sector to nominal current



Power converters installed and commissioning on short circuits in tunnel

- 81 power converters in UA83
- 156 kA and 1.2 MW dissipated: PCs and Cables

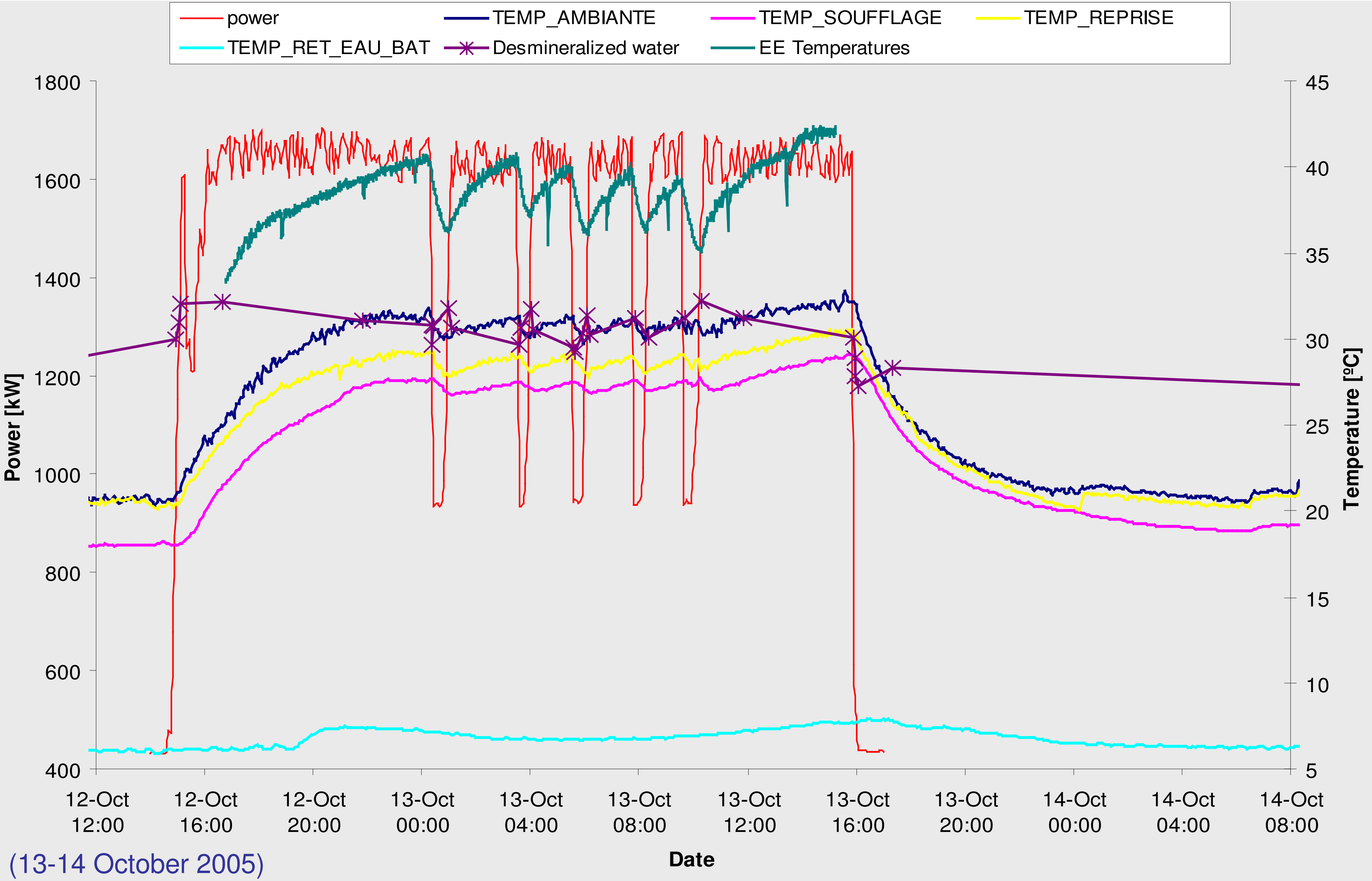
F.Bordry, 11-2005

High current power converter

Location: UA83 (Beginning)
Equipt type: LHC2-4-6-8kA
SP1 T°C: 46°
% conf.: 90%
Date: 2005-10-13 11h00

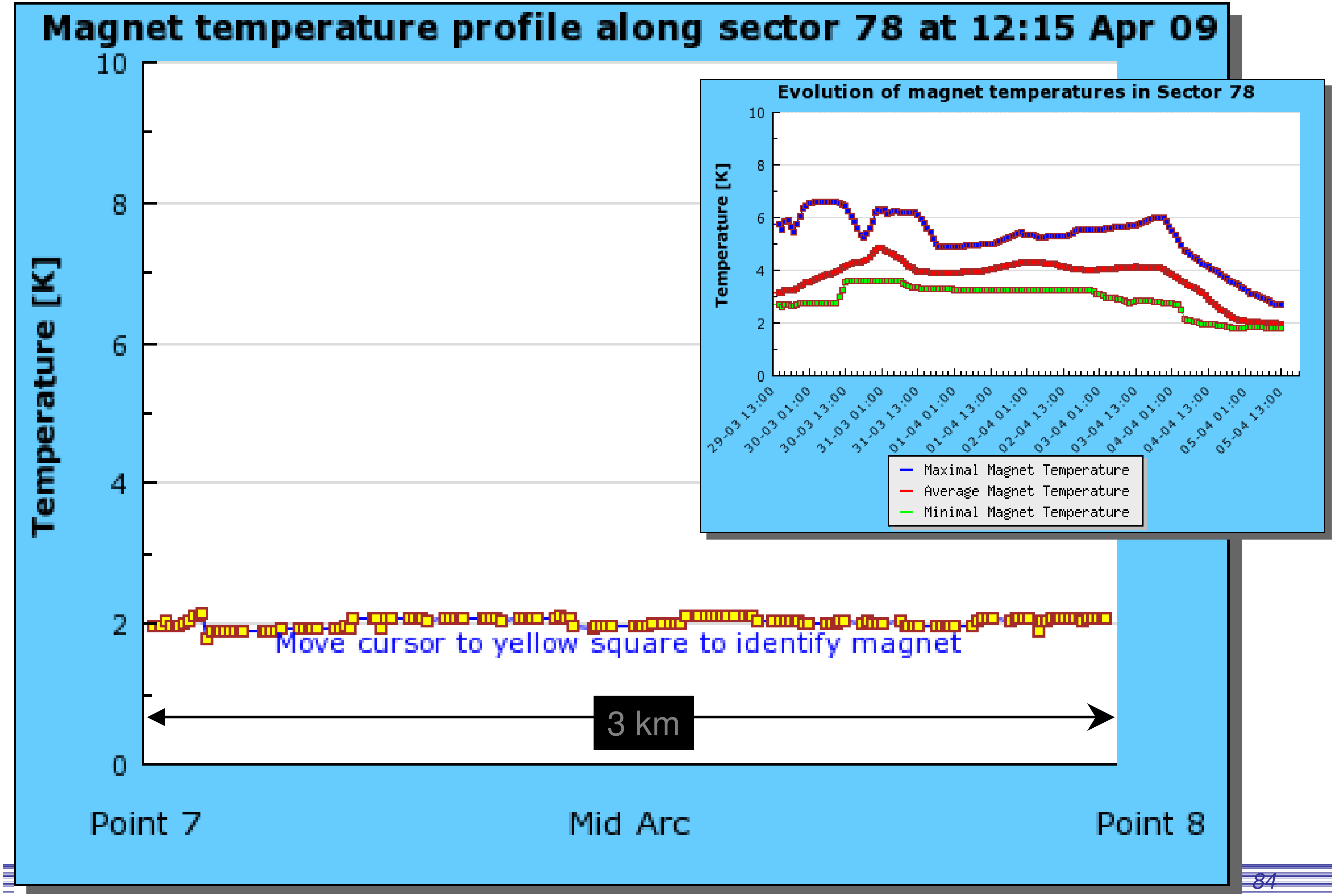
F.Bordry, 11-2005

24h endurance test of power converters and electrical network

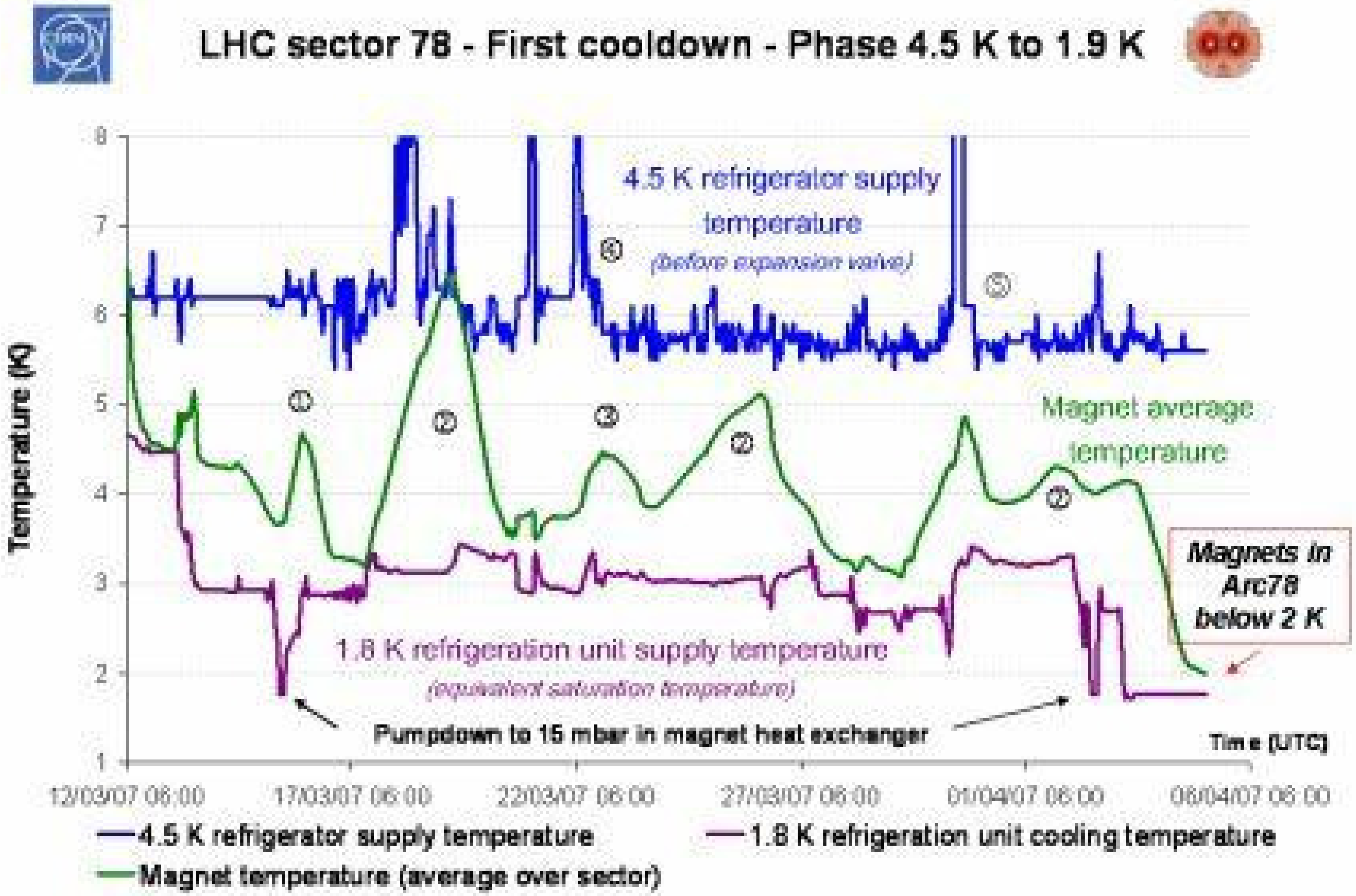


(13-14 October 2005)

Cooldown of sector 7-8



Cooldown details



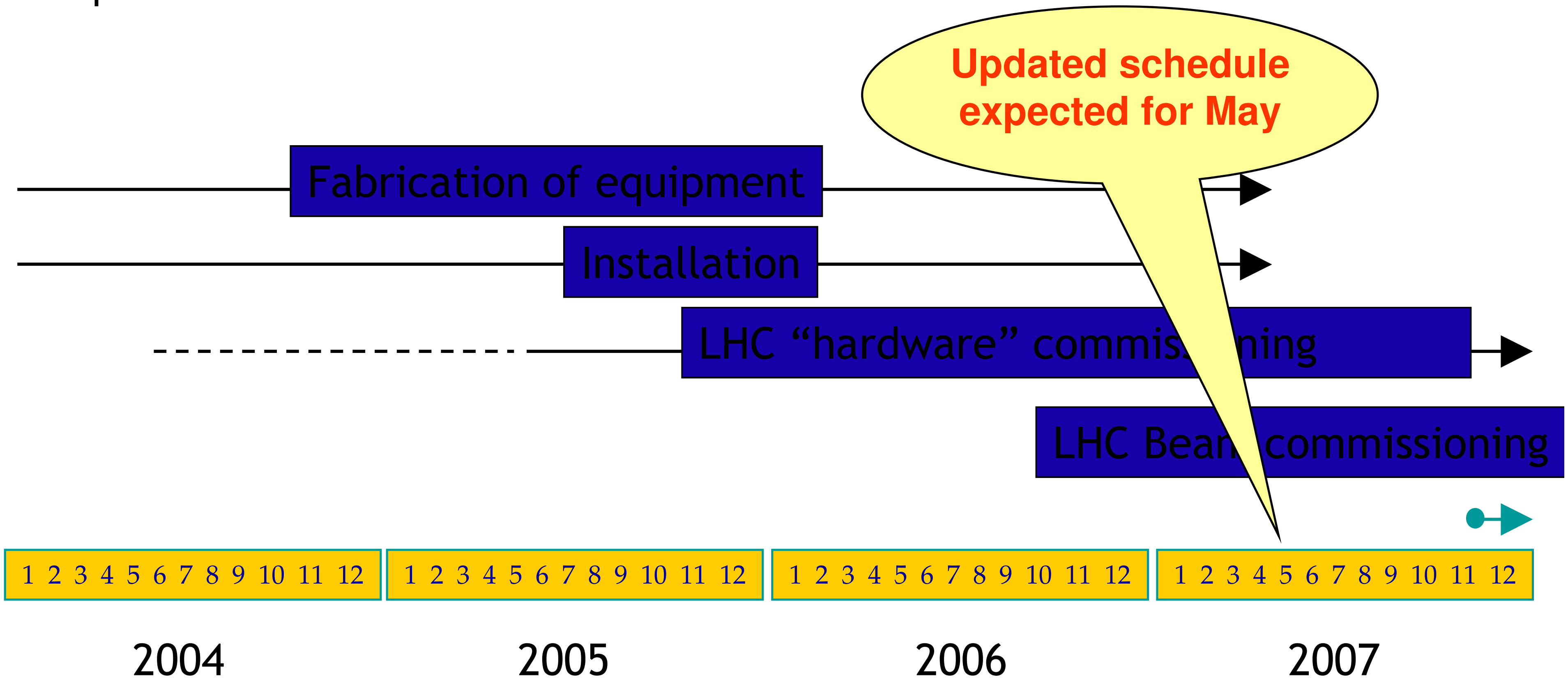
① Tuning of cold compressors & turbines with temporary stop of magnet cooling
② Stop of active cooling in weekend with only on call activity limited to secure hardware
③ Stop of magnet cooling for logic improvement in 1.8K refrigeration unit
④ Random emergency stop in cryogenic surface building with stop of sector 78 cooling
⑤ micro-electrical stop followed by utility stops

Status summary

- Magnet production completed
- Installation and interconnections in progress, few magnets still to be put in place
- Cryogenics
  - **one sector being cooled down**
  - **large part finished and operational (e.g. cryoplants)**
  - **QRL being installed and partial commissioning started**
- Powering system: commissioning started
  - **power converters installed and commissioning on short circuits in tunnel, 80% done**
- Other systems (RF, Beam injection and extraction, Beam instrumentation, Collimation, Interlocks, Controls)
  - **essentially on schedule for first beam in 2007/8**
- Injector complex ready

Recalling LHC challenges

- Enormous amount of equipment
- Complexity of the LHC accelerator
- New challenges in accelerator physics with LHC beam parameters pushed to the extreme



It would be wonderful to always report on smooth progress, but this is not the case…..and unrealistic

- The LHC is a machine with unprecedented complexity
- The technology is pushed to its limits
- The LHC is a ONE-OFF machine
- The LHC was constructed during a period when CERN was asked to substantially reduce the personel
- Problems came up and were solved / are being solved: dipole magnets, cryogenics distribution line, collimators, inner triplet, ….

In my view, such project can only be successful not because of the absence of problems, but because problems are detected and adressed with competent and dedicated staff and collaborators

Conclusions

- The LHC is a global project with the world-wide high-energy physics community devoted to its progress and results
- As a project, it is much more complex and diversified than the SPS or LEP or any other large accelerator project constructed to date

Machine Advisory Committee, chaired by

Prof. M. Tigner, March 2002

- No one has any doubt that it will be a great challenge for both **machine to reach design luminosity** and for the **detectors to swallow it**.
- However, we have a **competent and experienced team**, and **30 years of accumulated knowledge** from previous CERN projects has been put **into the LHC design**

L.Evans, Project Leader

Acknowledgement

The LHC accelerator is being realised by CERN financed by the CERN member states, in collaboration with institutes from many countries over a period of more than 20 years

Main contribution come from the USA, Russia, India, Canada, special contributions from France and Switzerland

Industry plays a major role in the construction of the LHC

Thanks for the material from:

R.Assmann, L.Bottura, L.Bruno, R.Denz, A.Ferrari, B.Goddard, M.Gyr, P.Proudlock, L.Rossi, S.Russenschuck, P.Sievers, G.Stevenson, A.Verweij, V.Vlachoudis

……..and thanks to the organisers for inviting me giving this presentation

Some references

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