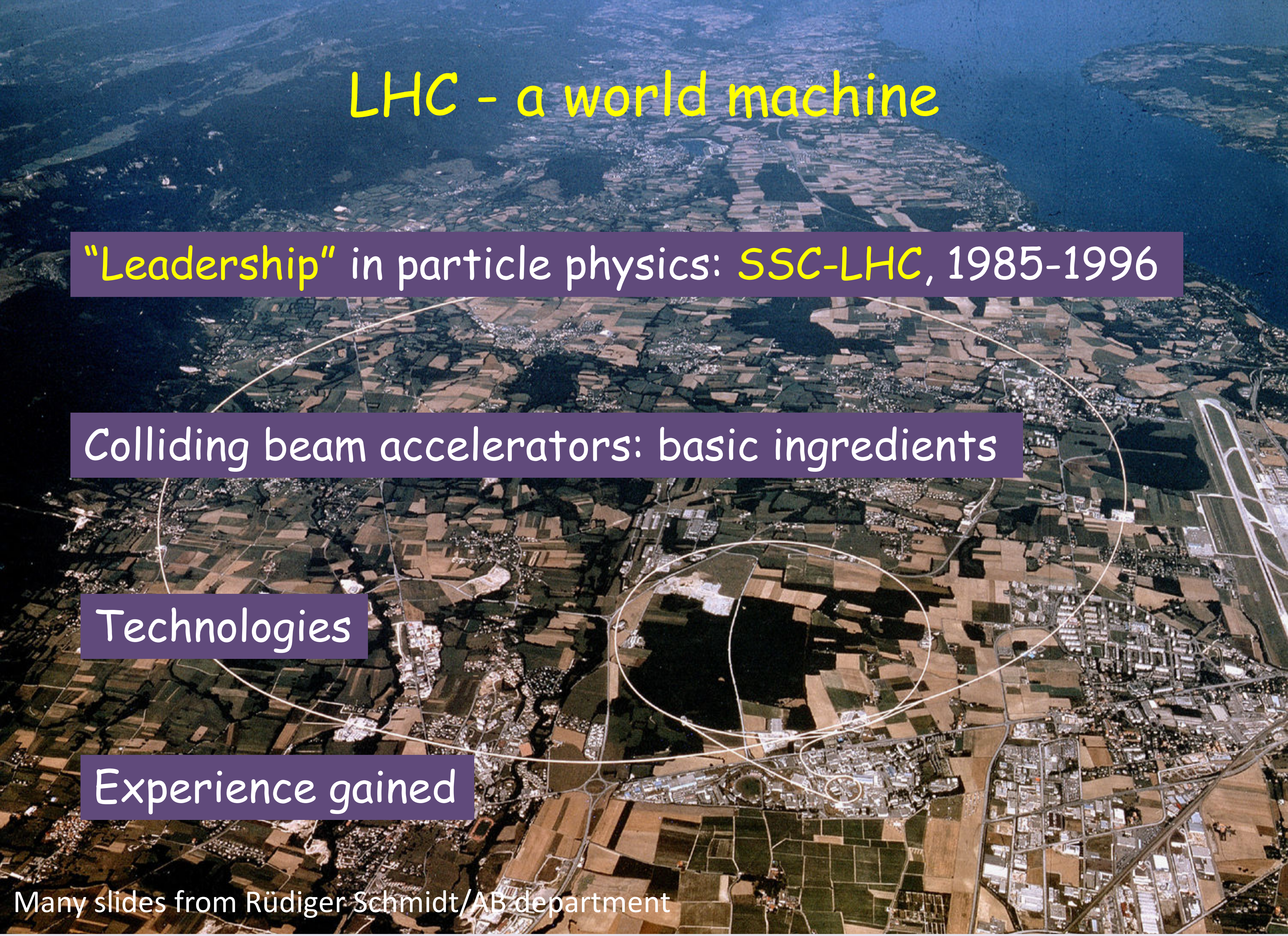
LHC - a world machine



“Leadership” in particle physics: SSC-LHC, 1985-1996

Colliding beam accelerators: basic ingredients

Technologies

Experience gained

Many slides from Rüdiger Schmidt/AB department

Early accelerators

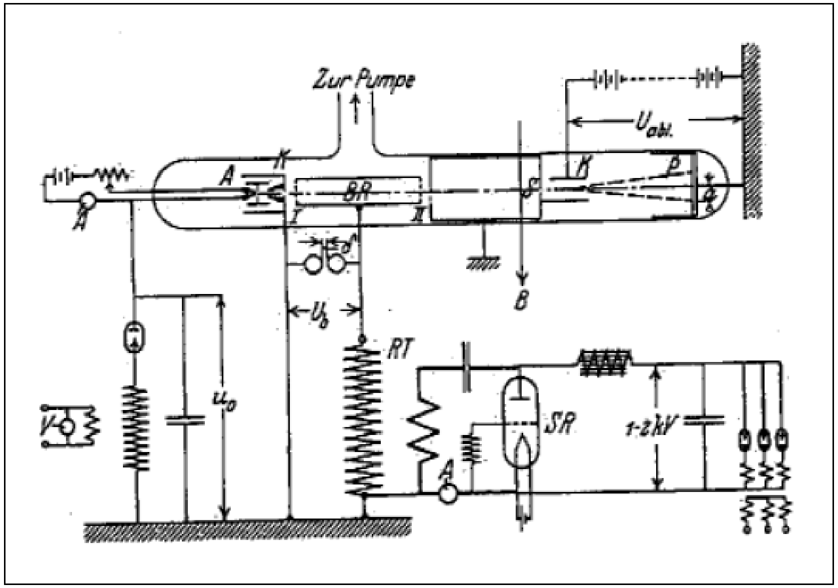
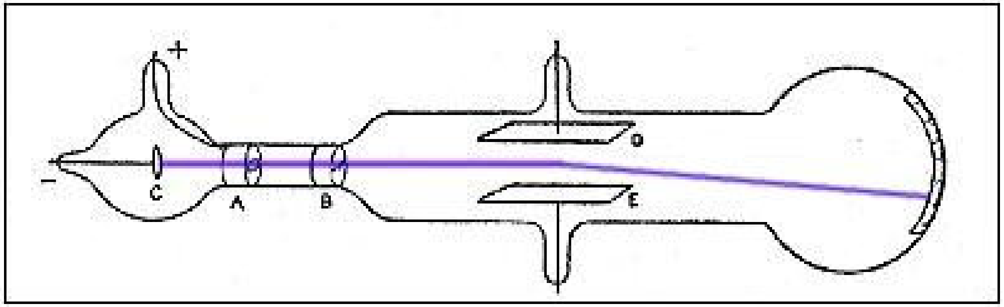


Figure 1: Wideröe's single drift tube linear accelerator.



J J Thomson

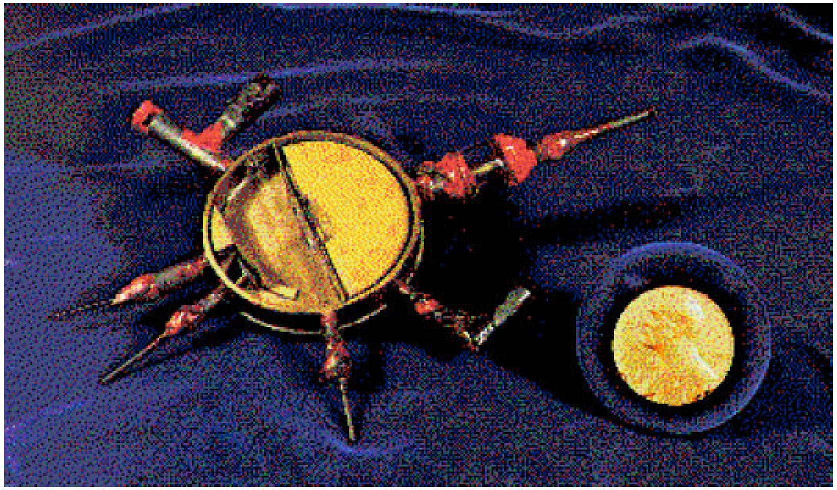
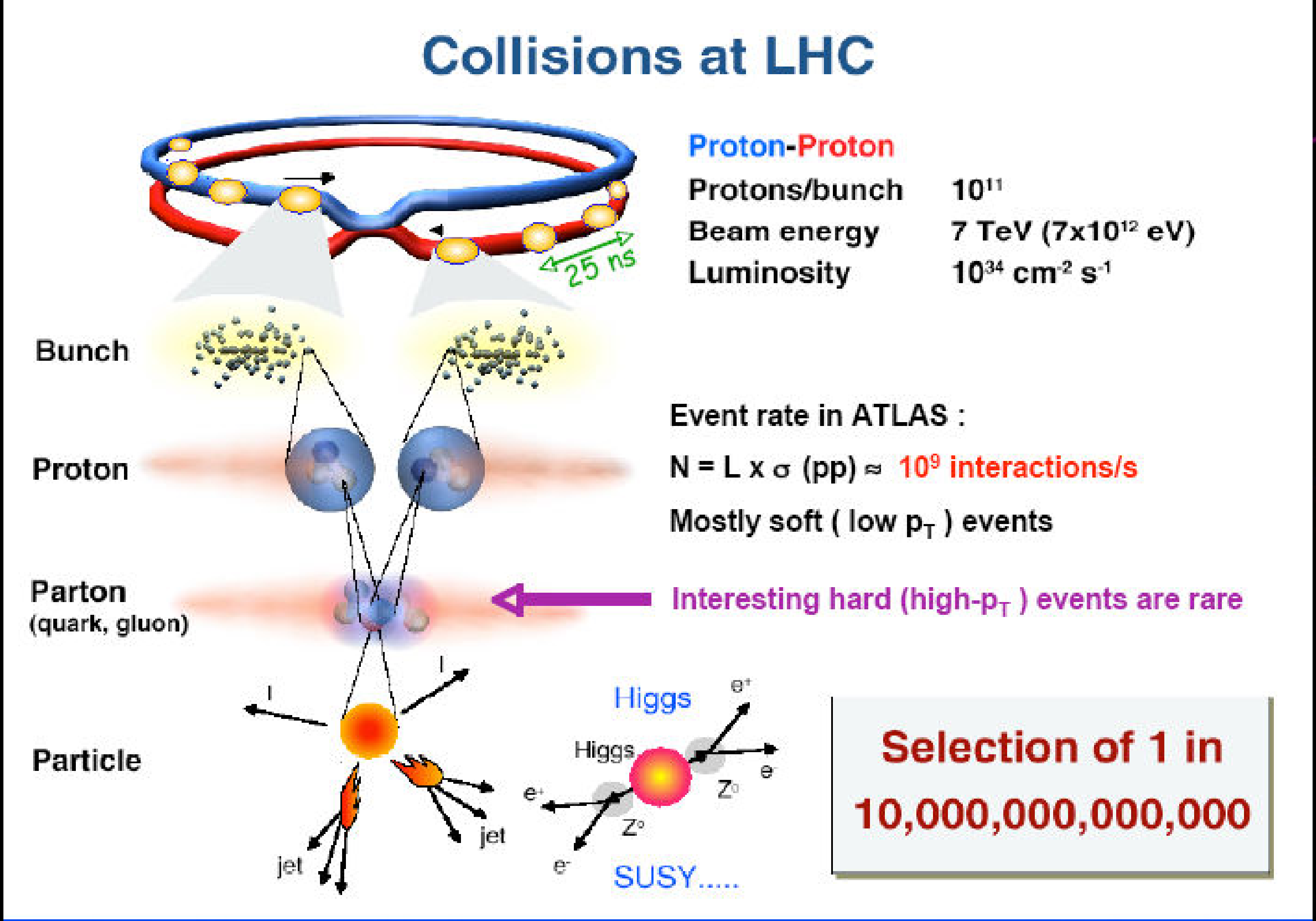


Figure 2: The first cyclotron with the Nobel Prize medal for comparison.

Particle Physics, accelerators and experiments

Accelerators bring matter to extremely high temperatures and experiments observe the properties of the decay products



Collisions at LHC

Proton-Proton

Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate in ATLAS :

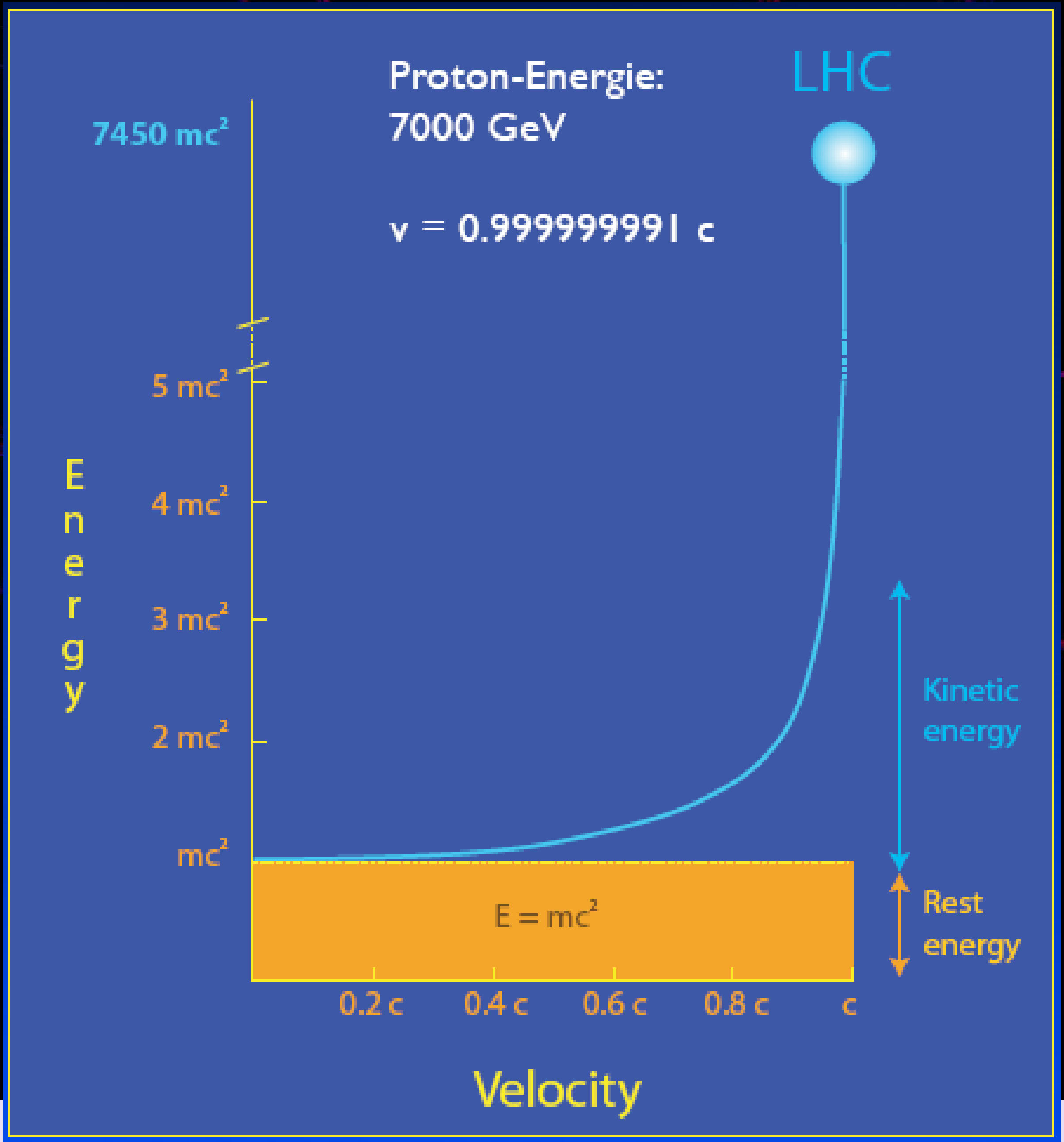
N = L x σ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

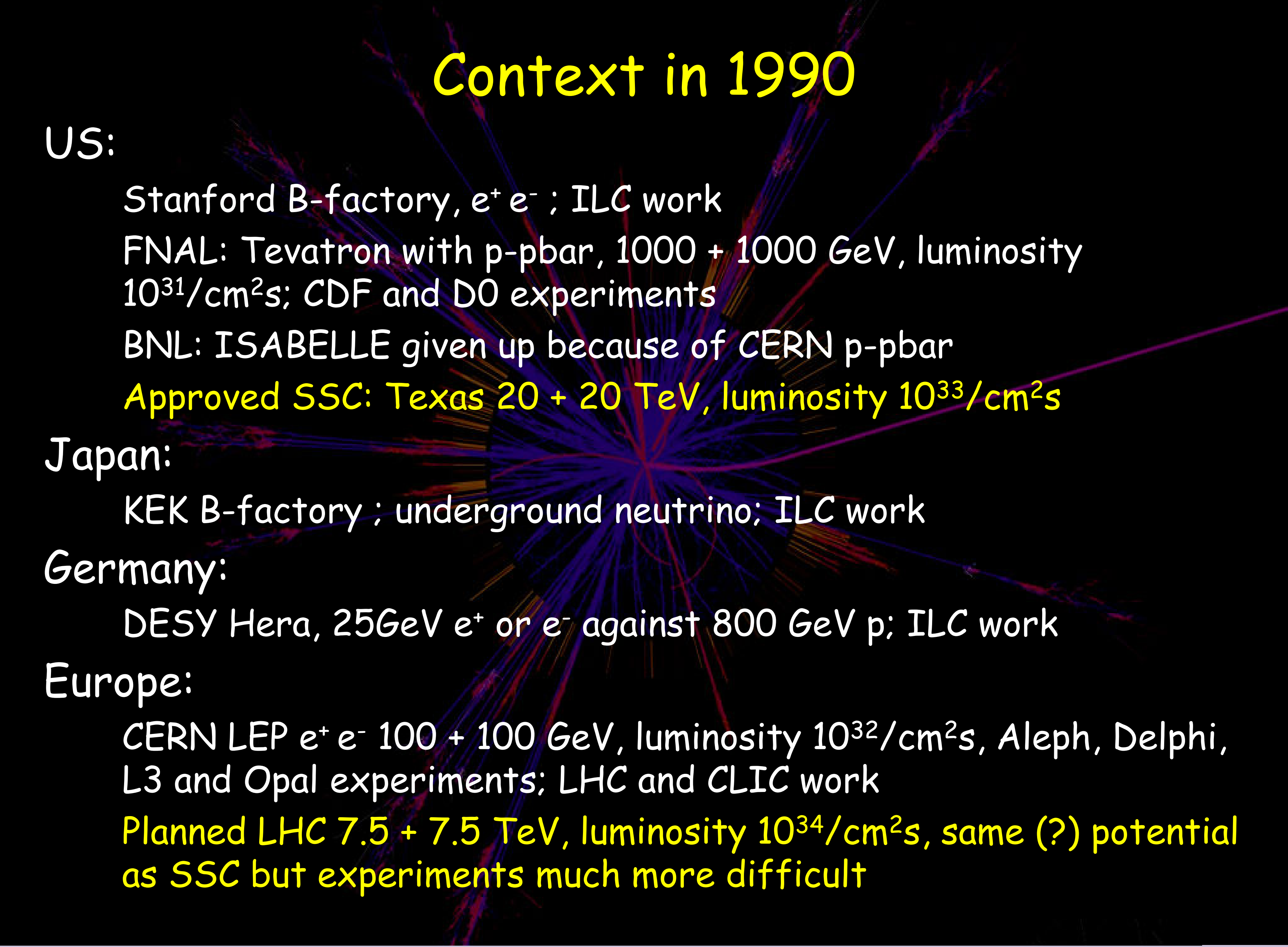
Interesting hard (high-p_T) events are rare

Selection of 1 in 10,000,000,000,000

Protons: energy transport and speed



Context in 1990



US:

- Stanford B-factory, $e^+ e^-$; ILC work
- FNAL: Tevatron with p-pbar, 1000 + 1000 GeV, luminosity $10^{31}/cm^2s$; CDF and D0 experiments
- BNL: ISABELLE given up because of CERN p-pbar
- Approved SSC: Texas 20 + 20 TeV, luminosity $10^{33}/cm^2s$

Japan:

- KEK B-factory ; underground neutrino; ILC work

Germany:

- DESY Hera, 25GeV e^+ or e^- against 800 GeV p; ILC work

Europe:

- CERN LEP $e^+ e^-$ 100 + 100 GeV, luminosity $10^{32}/cm^2s$, Aleph, Delphi, L3 and Opal experiments; LHC and CLIC work
- Planned LHC 7.5 + 7.5 TeV, luminosity $10^{34}/cm^2s$, same (?) potential as SSC but experiments much more difficult

SSC, LHC, Tevatron

“Green Field” solution

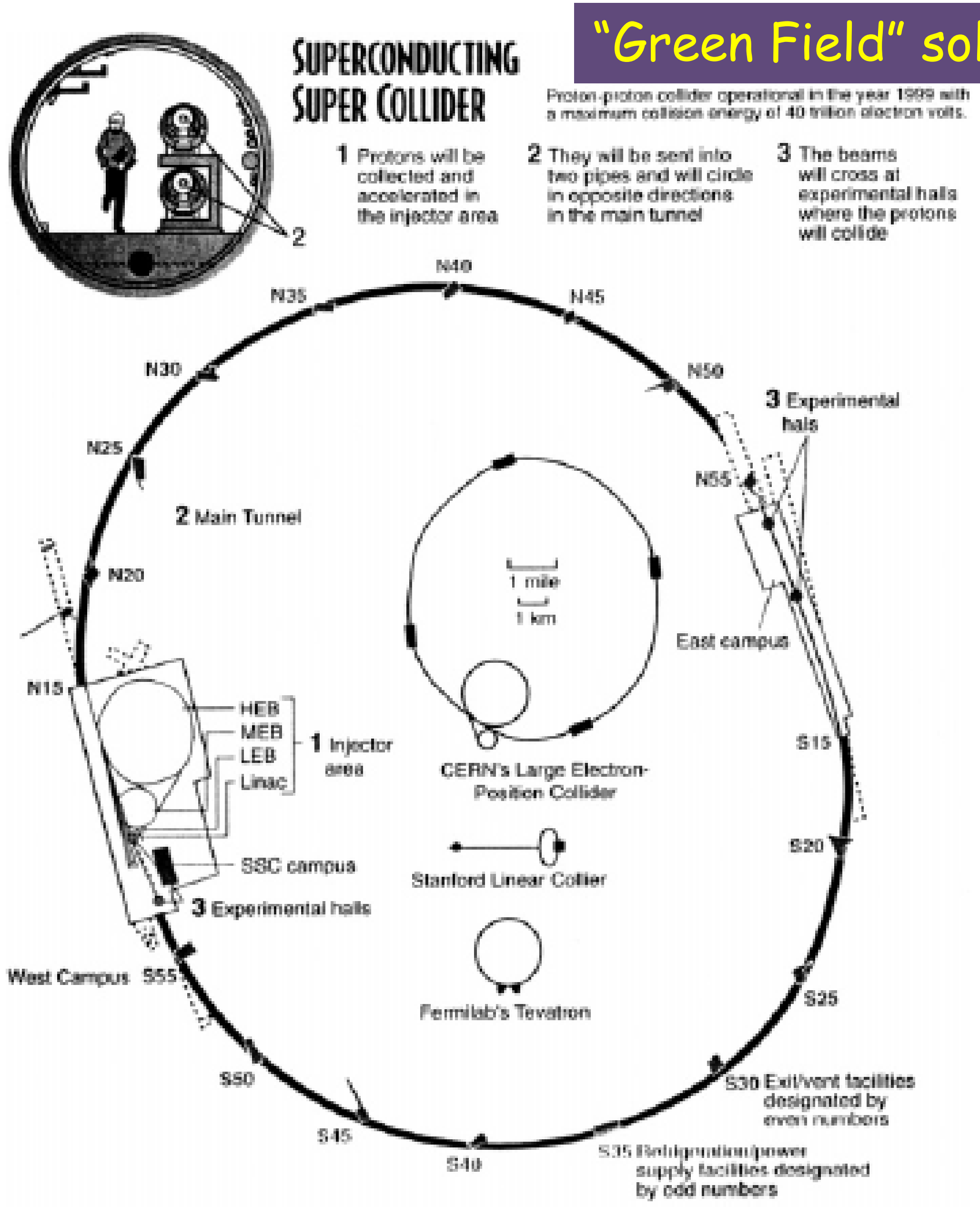


Fig. 1. Comparison of the planned size of the SSC with three large particle colliders then in operation. Courtesy of SSC Laboratory.

SSC approval 1987

Site selected 1988

Cost 3 → 4.4 10^9 $,

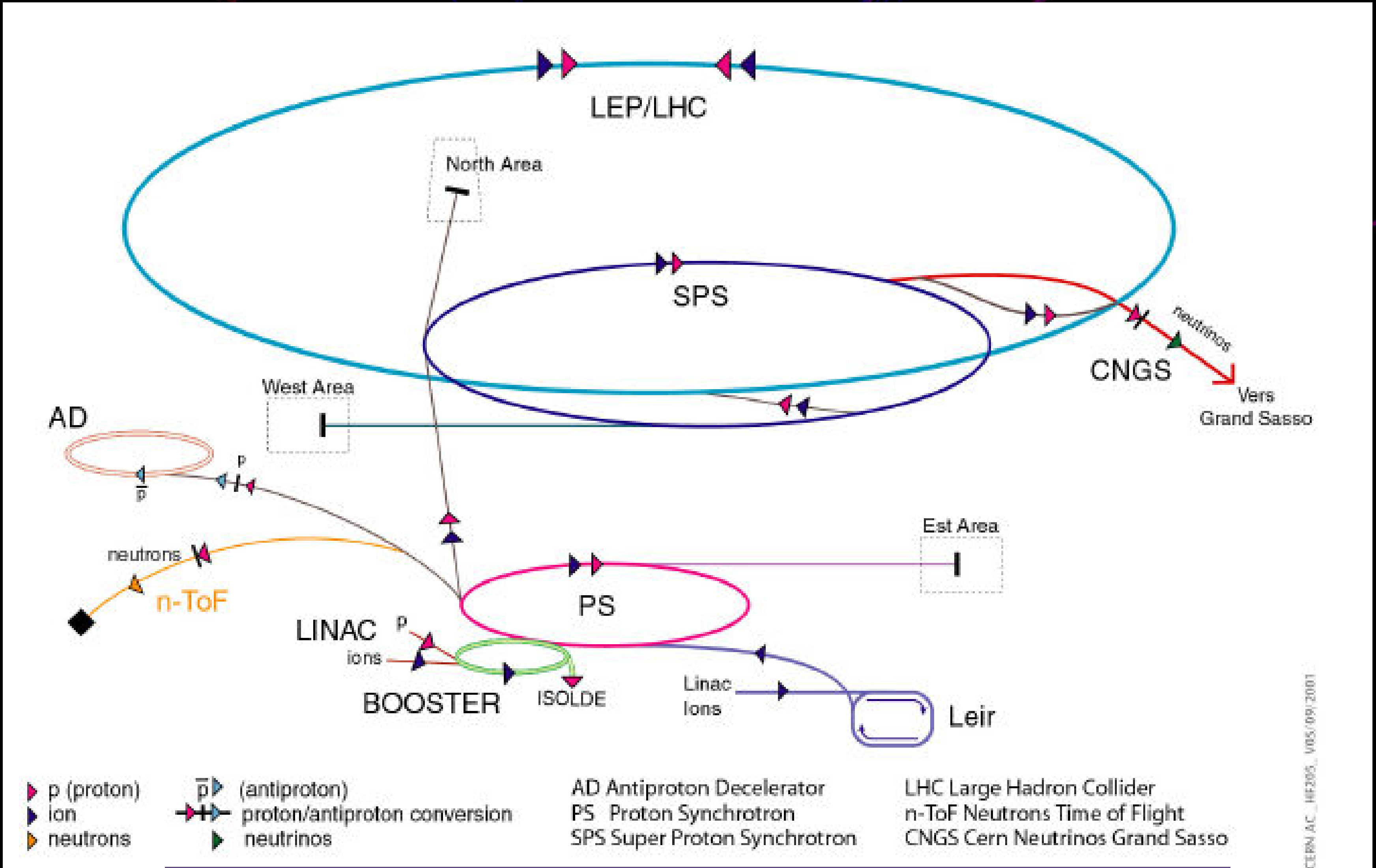
5.9 10^9 $ in 1989,

8.3 10^9 $ in 1991,

>10 10^9 $ in 1993→

Demise SSC: cost, insufficient foreign contributions, spin-offs exaggerated, other physics projects and end of cold war

Accelerators at CERN operating or approved LHC approval 1994-1996, ~20% extl. contributions



CERN: Use existing infrastructure and experience

LHC parameters

Parameters:

Proton beam energy: 7 TeV

L = 1.0 x 10^{34} cm^{-2} s^{-1}

Pb ion beam energy : 2.8 TeV/u

L = 1.0 x 10^{27} cm^{-2} s^{-1}

Installed in LEP tunnel

Chronology:

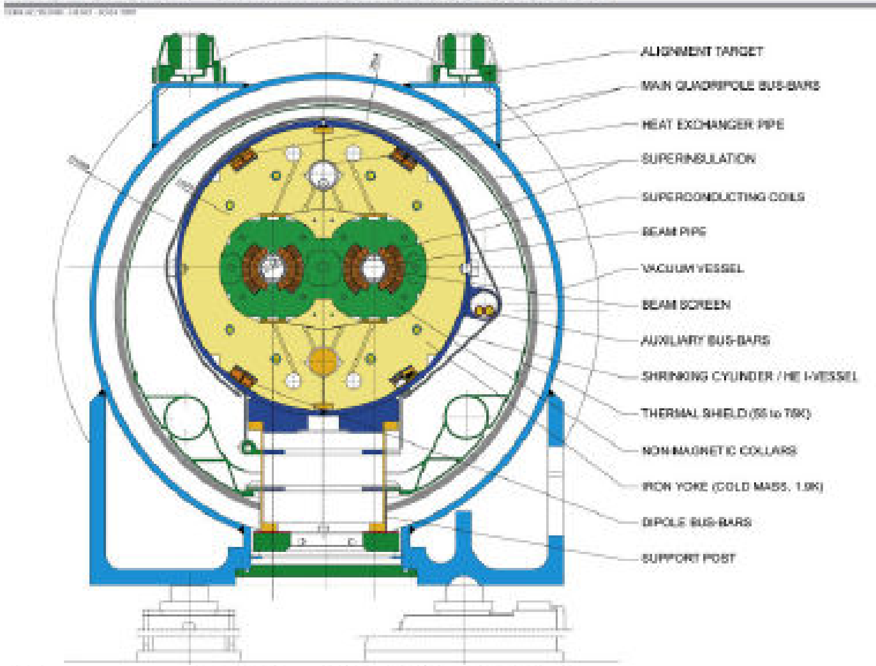
Design: 83 – 94
(considered since mid 70's)

Approval:

- 94 (two-stages 5 → 7TeV)
- 96 (single stage 7 TeV) with substantial NMS contributions

Operation: 2007 →

LHC DIPOLE : STANDARD CROSS-SECTION



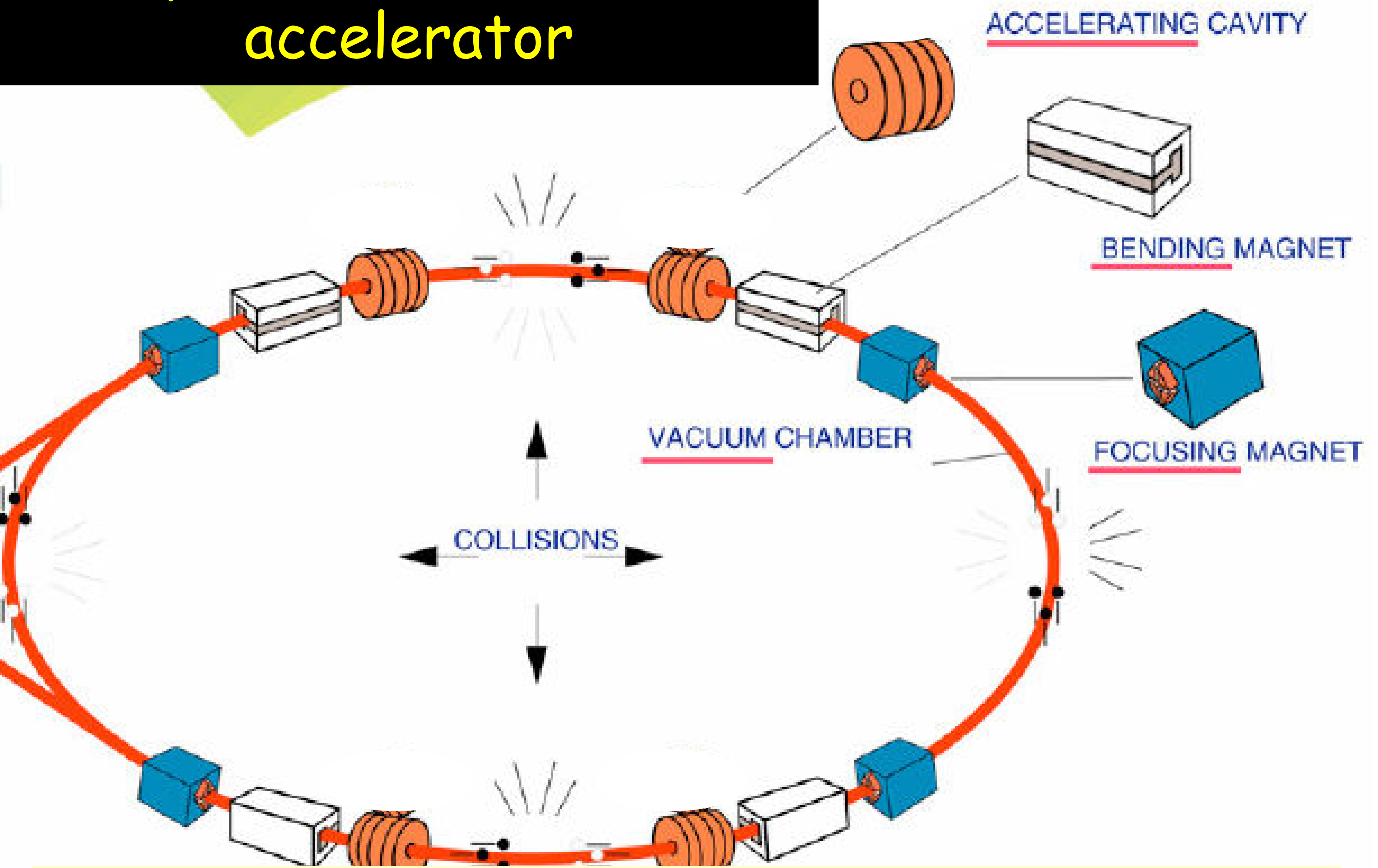
Dipole magnet: B = 8.3 T, 12 kA,
Nb-Ti sc 6-7μm filaments > cables,
1.9 K He II cooling, Δx = 194 mm b-b
cold mass: L = 16.5 m overall, 28 t

CERN: closer to technological limits and available resources

LHC: From first ideas to realisation

1976 : superconducting Large Storage Ring, LSR, study
1982 : First studies for the LHC project
1982,83 : W, Z detected at SPS proton antiproton collider
1984 : Nobel Price for S. van der Meer and C. Rubbia
1989 : Start of LEP operation (Z-factory) - Berlin wall
1994 : Approval of the LHC by the CERN Council
1996 : Final decision to start the LHC construction (-10% !)
1996 : LEP operation at 100 GeV (W-factory)
2000 : End of LEP operation (Higgs or not Higgs)
2002 : LEP equipment removed
2003 : Start of the LHC installation
2005 : Start of hardware commissioning
2008 : Commissioning with beam started → incident
2009 : Nov. Collisions at 3.5TeV???

Components of a classical accelerator

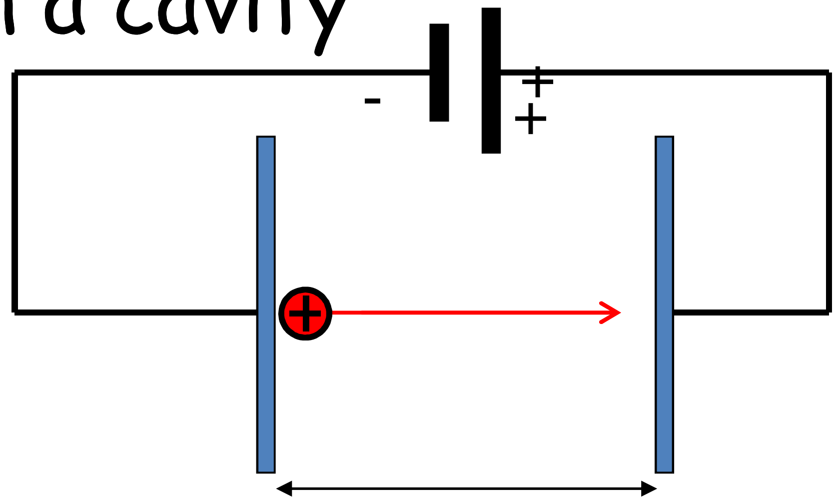


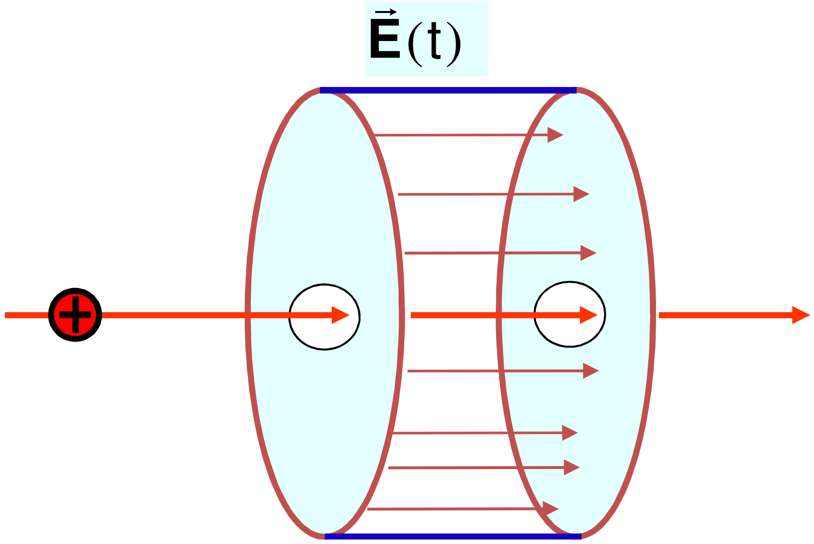
LHC: circular machine with energy gain per turn of some MeV

Acceleration in a cavity

U = 1000000 V
d = 1 m
q = e_0

ΔE = 1 MeV





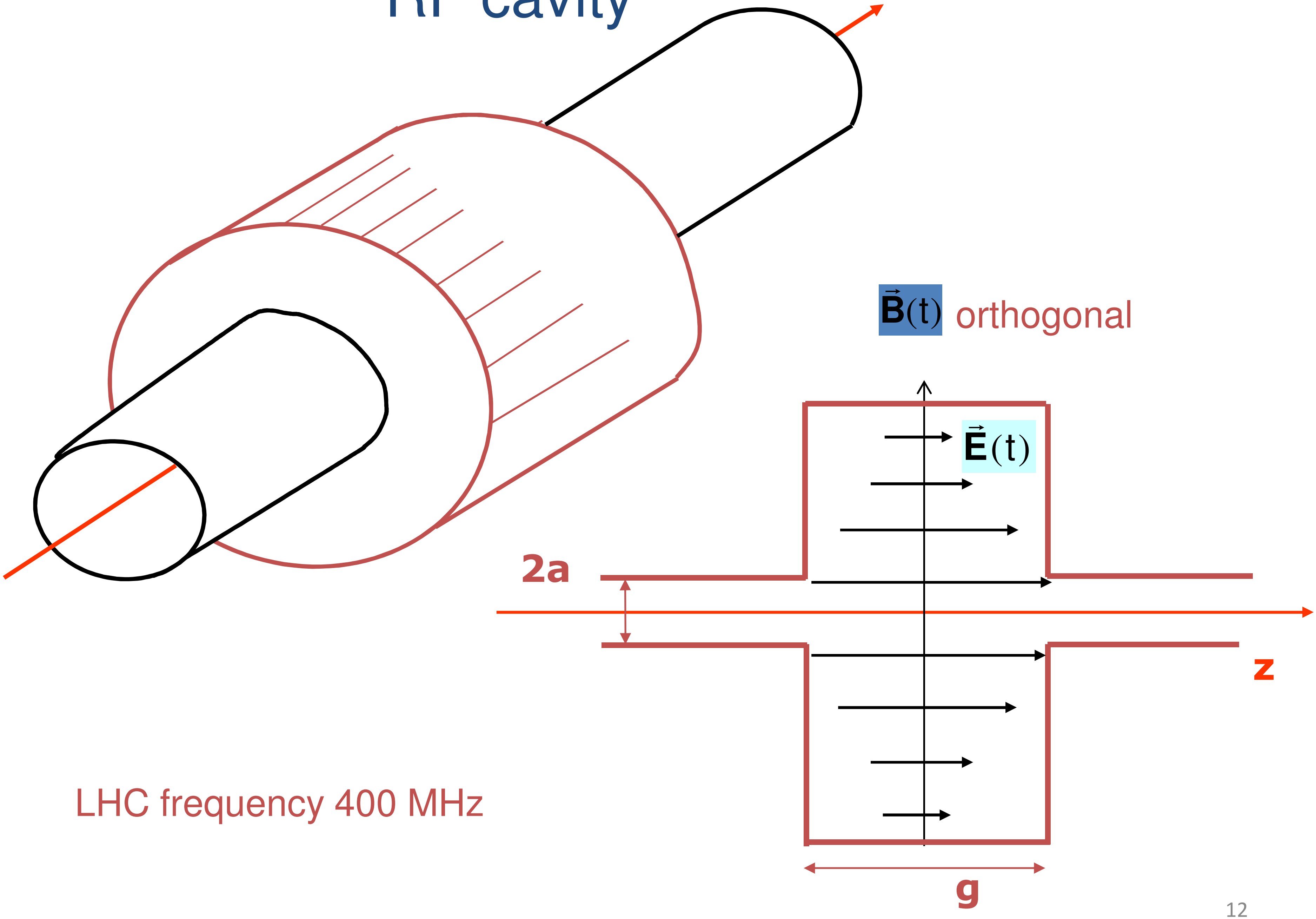
Time varying field

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

Maximum field about 20 MV / m

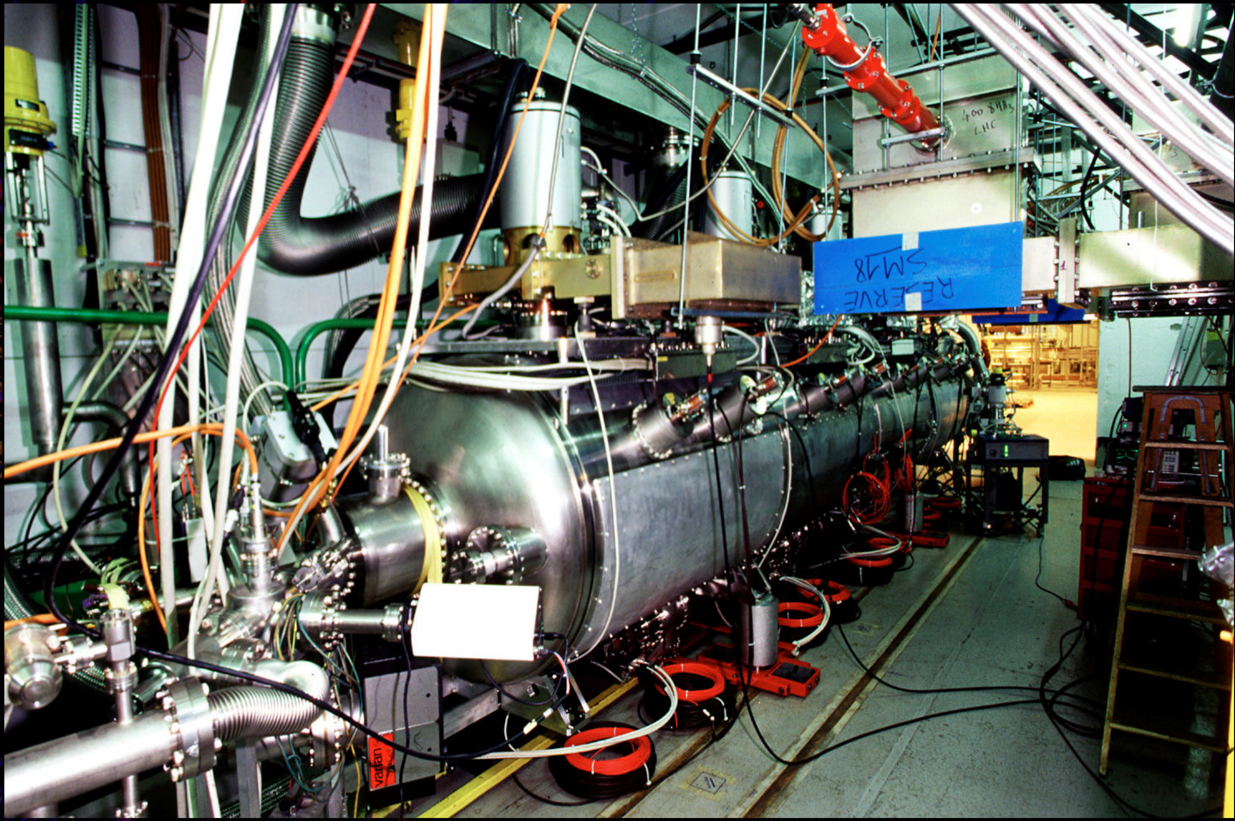
Consequence : bunched beam

RF cavity



LHC frequency 400 MHz

RF systems: 400 MHz



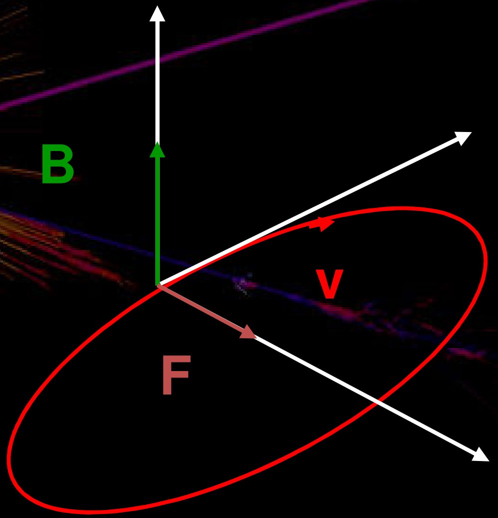
Power test of the first module

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



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

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

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

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

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

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:

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

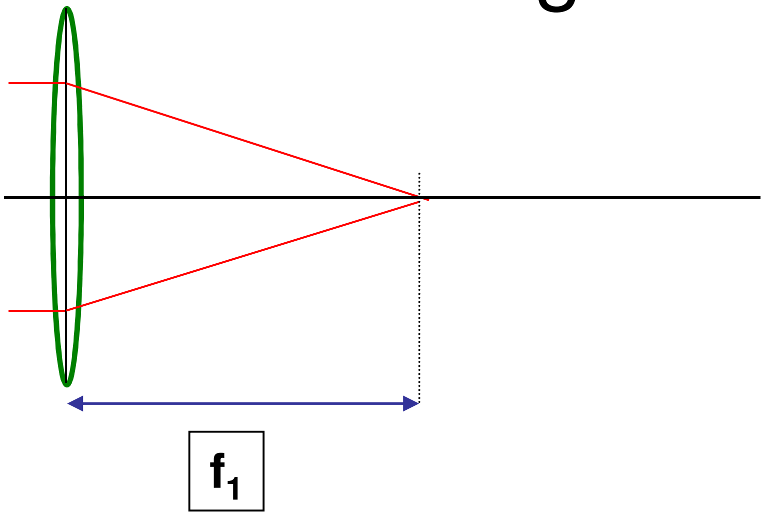
$F_{B\_field} = 3.986 \times 10^{-10} N$ $F_{E\_field} = 1.121 \times 10^{-12} N$

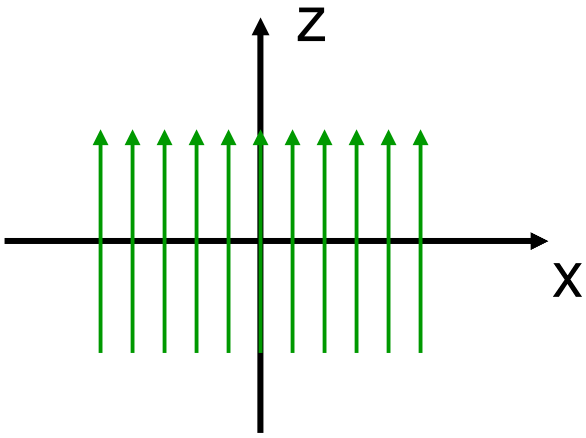
$$\frac{F_{B\_field}}{F_{E\_field}} = 355.469$$

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

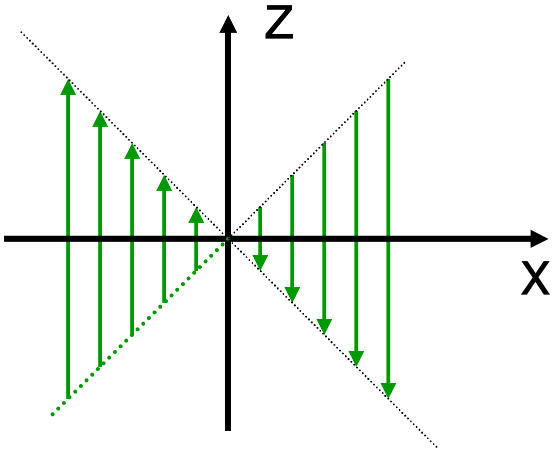
Radius of a proton in a B field with $\boxed{B = 8.3\,T \;:\; 7 \cdot 10^{12} \frac{eV}{c} \cdot \frac{1}{e_0 \cdot B} = 2.813 \times 10^{3}\, m}$

Focusing using lenses as for light





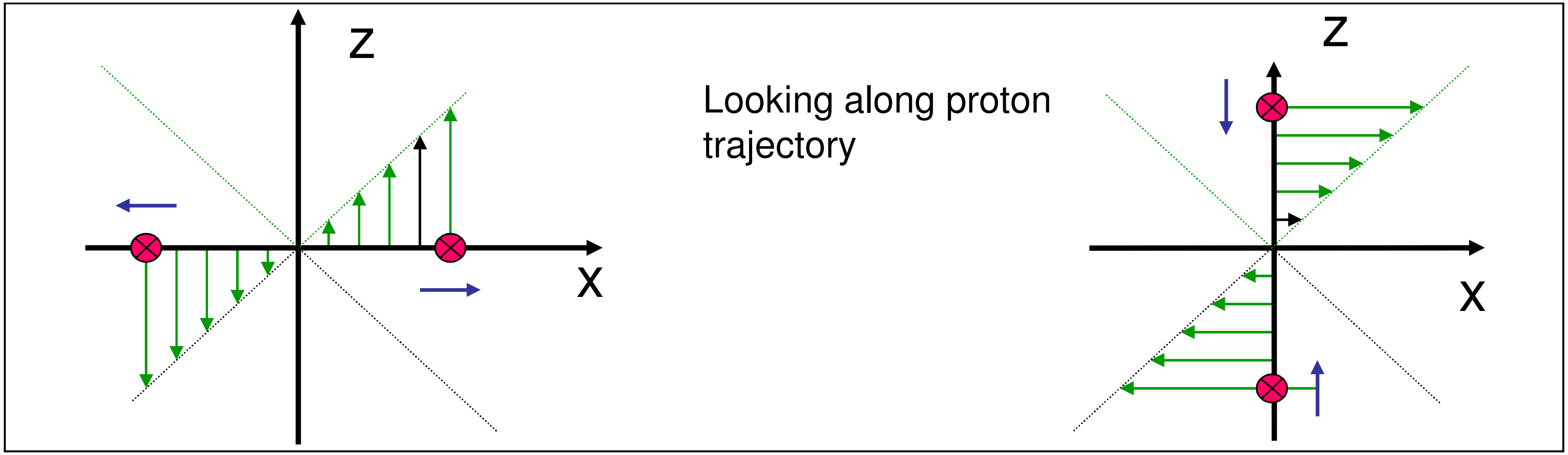
Dipolemagnet – B-field in aperture constant



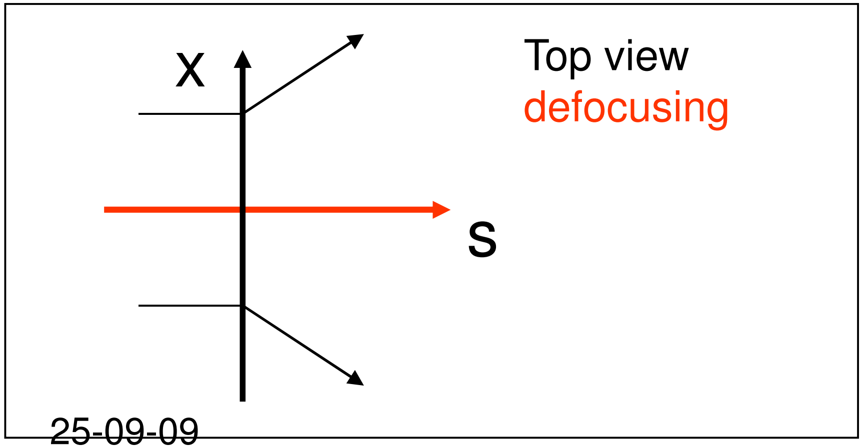
Quadrupolemagnet – B-field zero in centre, linear increase (as a lense)

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

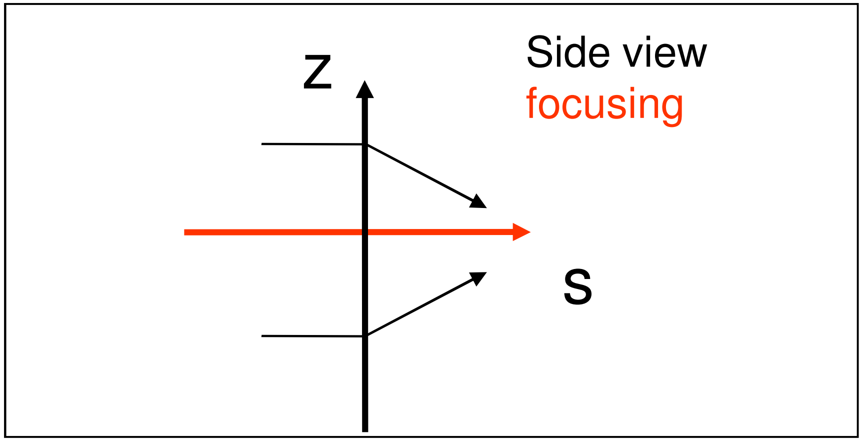
Assuming proton runs along s into the screen, perpendicular to x and z



Looking along proton trajectory



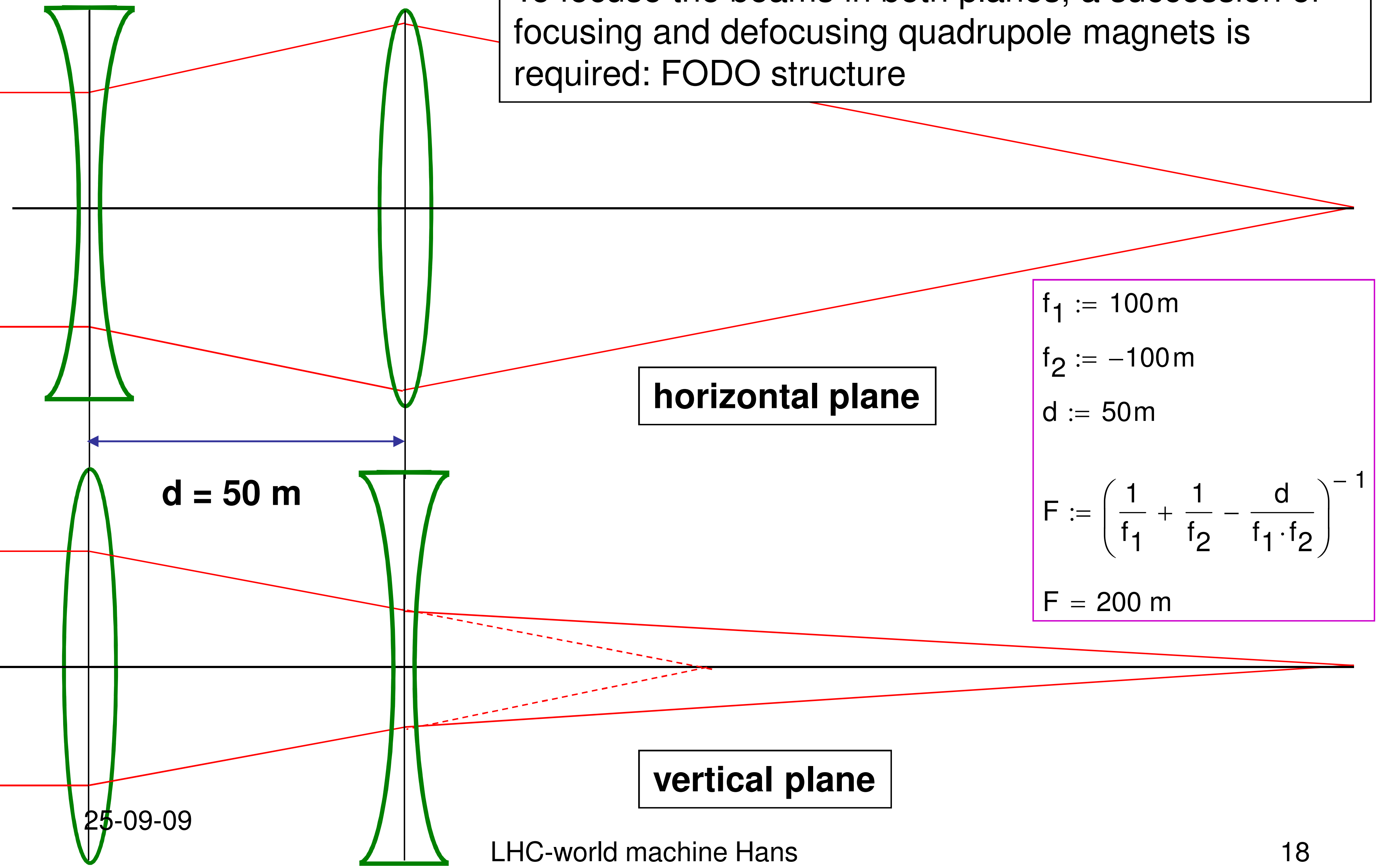
Top view
defocusing



Side view
focusing

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



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

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

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

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

$F = 200\ \mathrm{m}$

..just assuming to accelerate electrons to 7 TeV (synchrotron radiation)

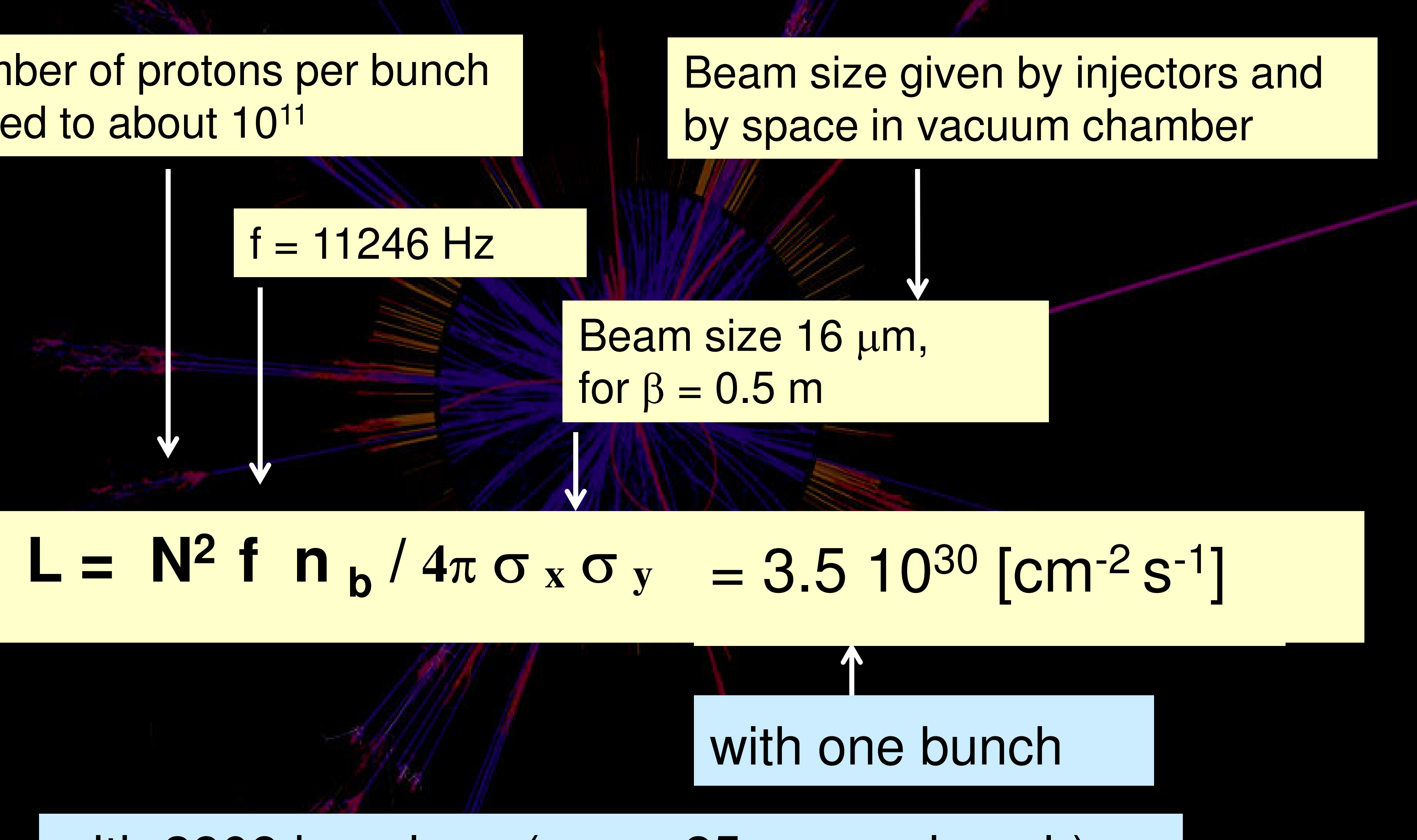
assuming LEP with electrons at 7 TeV: $\gamma_{lep} := \frac{7 \cdot 10^{12}}{m_e \cdot c^2} eV$

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

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

...better to accelerate protons

Beam-beam interaction determines parameters other beam like "quadrupole"



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 $\beta = 0.5$ m

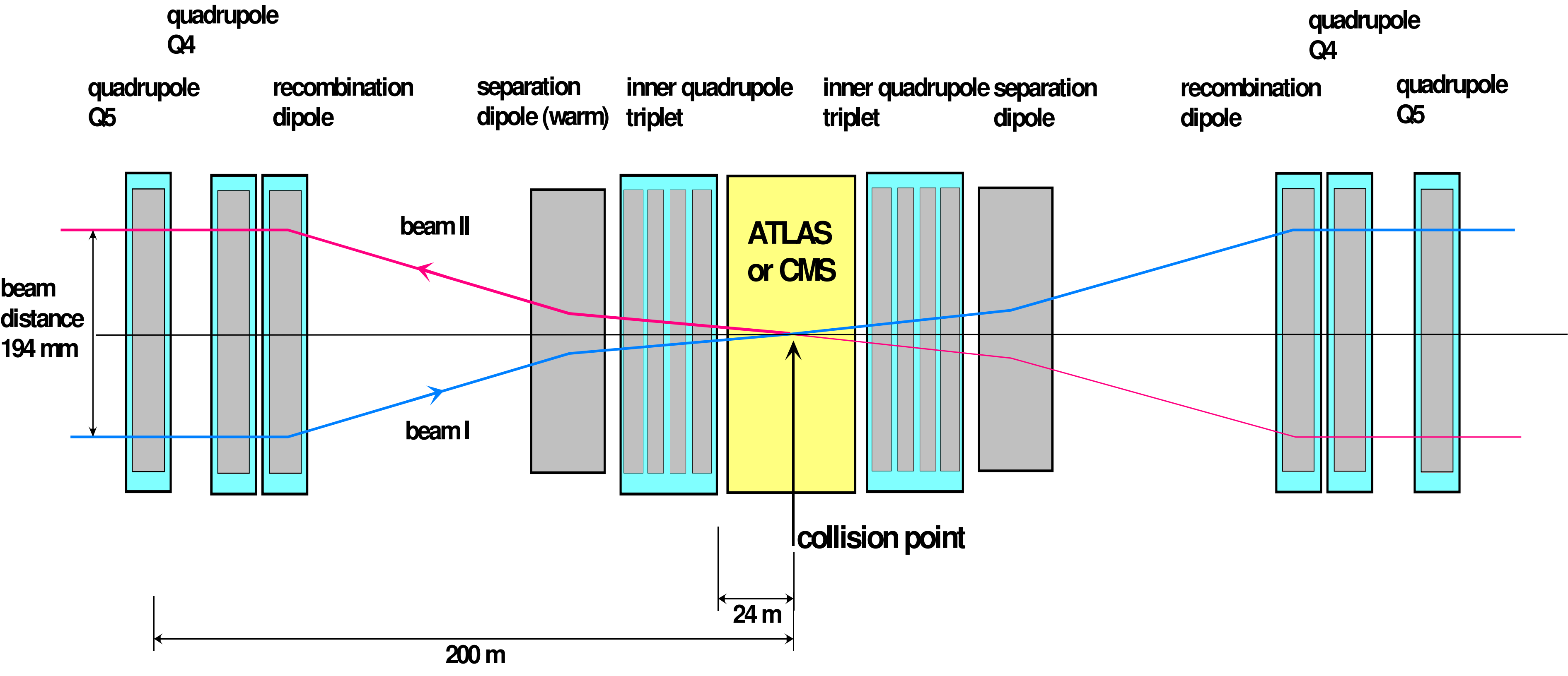
$$L = N^2 f\ n_b / 4\pi \sigma_x \sigma_y = 3.5\ 10^{30}\ [\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$$

with one bunch

with 2808 bunches (every 25 ns one bunch)

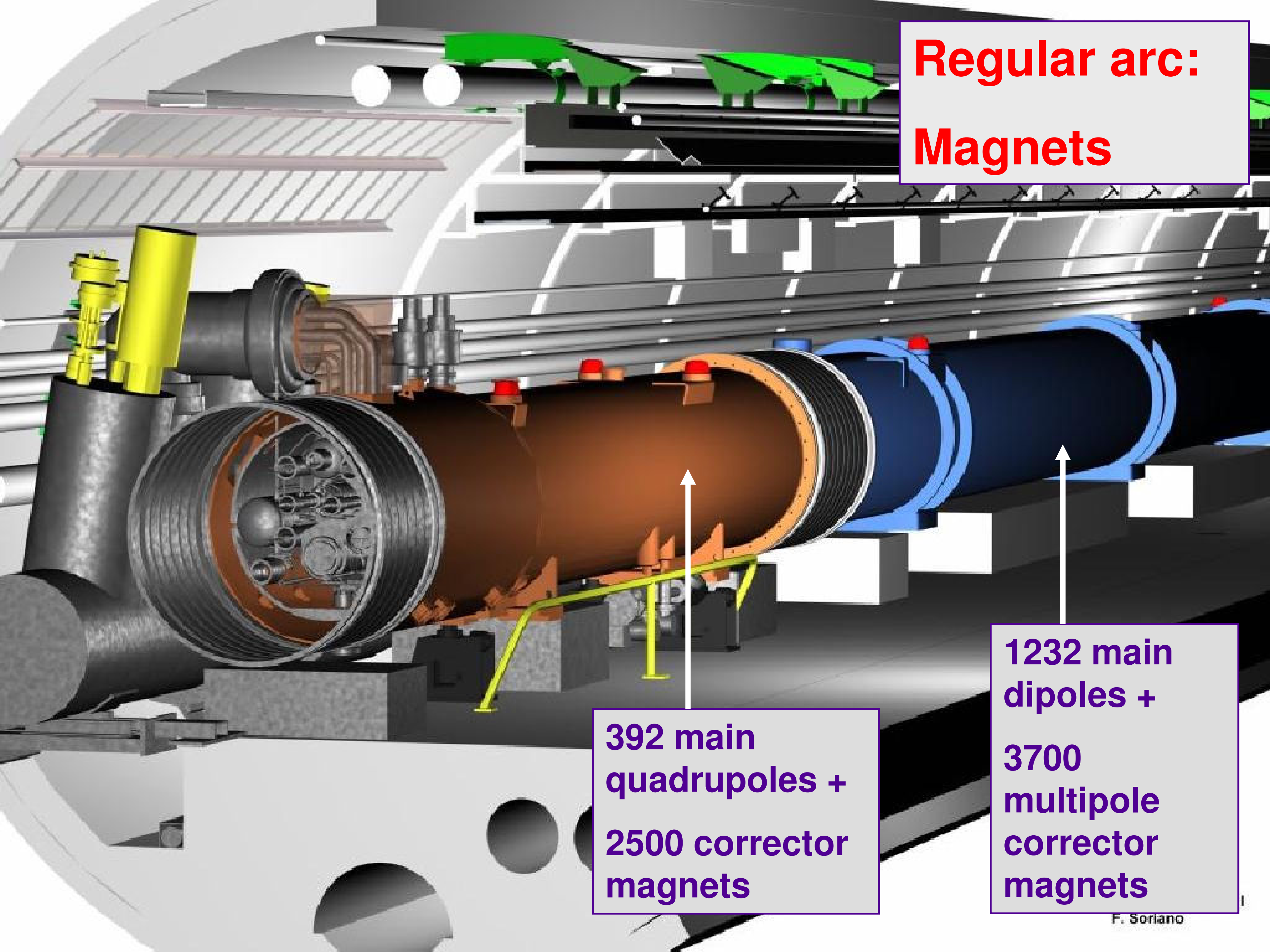
$$L = 10^{34}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$

Layout of insertion for ATLAS and CMS compress to ~16 µm



Example for an LHC insertion with ATLAS or CMS

Regular arc: Magnets



392 main quadrupoles +

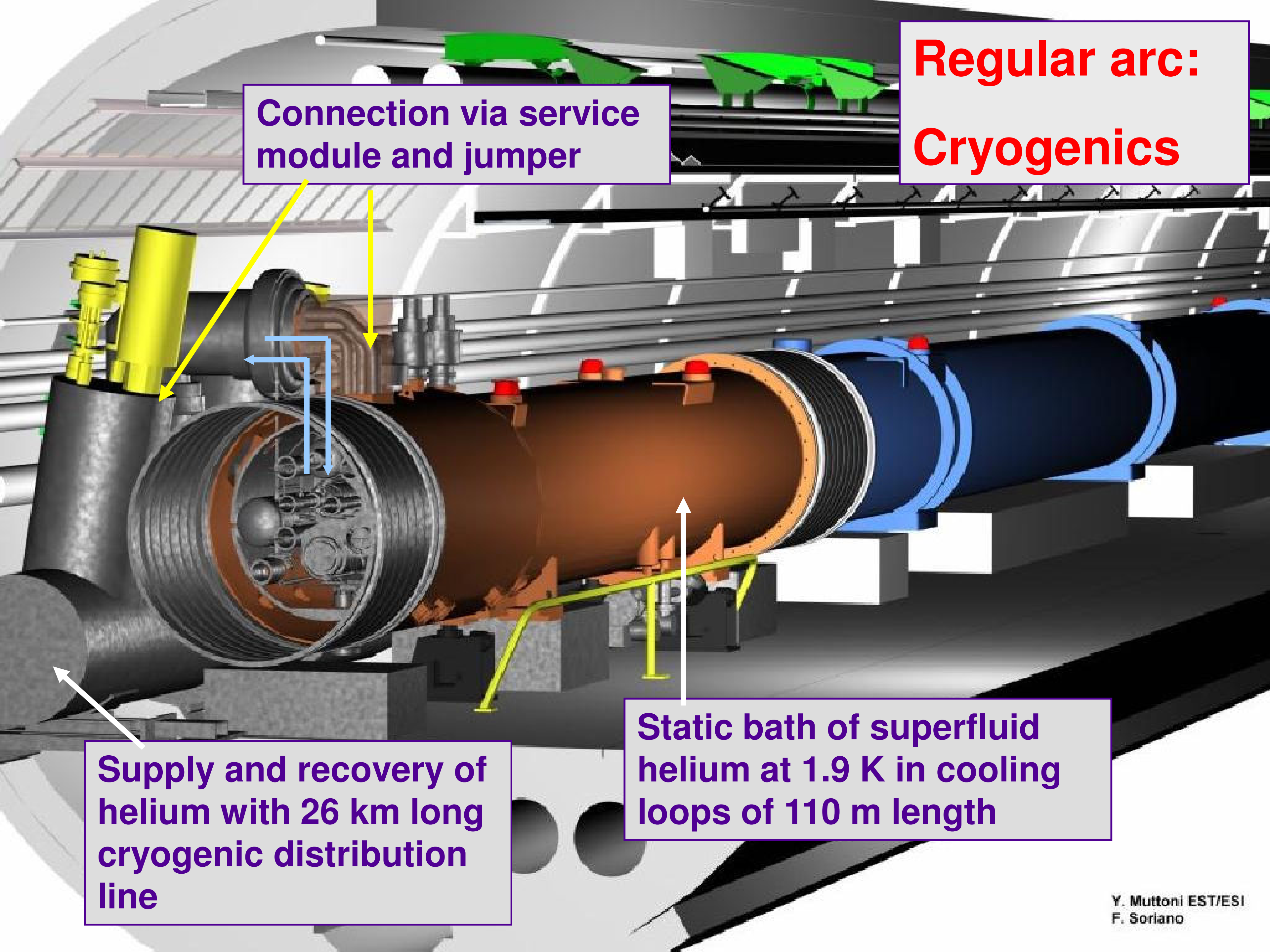
2500 corrector magnets

1232 main dipoles +

3700 multipole corrector magnets

F. Soriano

Regular arc: Cryogenics

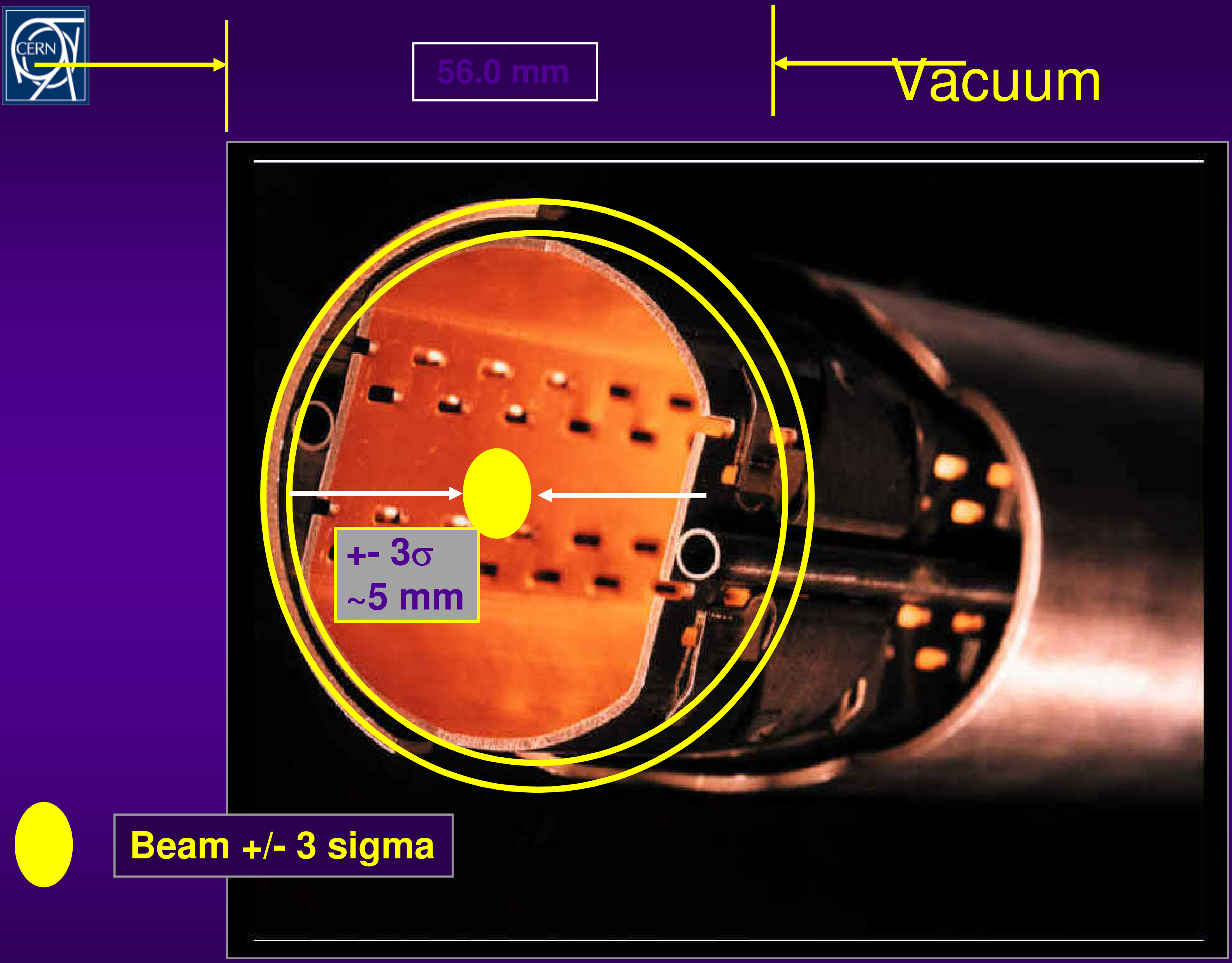


Connection via service module and jumper

Static bath of superfluid helium at 1.9 K in cooling loops of 110 m length

Supply and recovery of helium with 26 km long cryogenic distribution line

Y. Muttoni EST/ESI
F. Soriano



56.0 mm

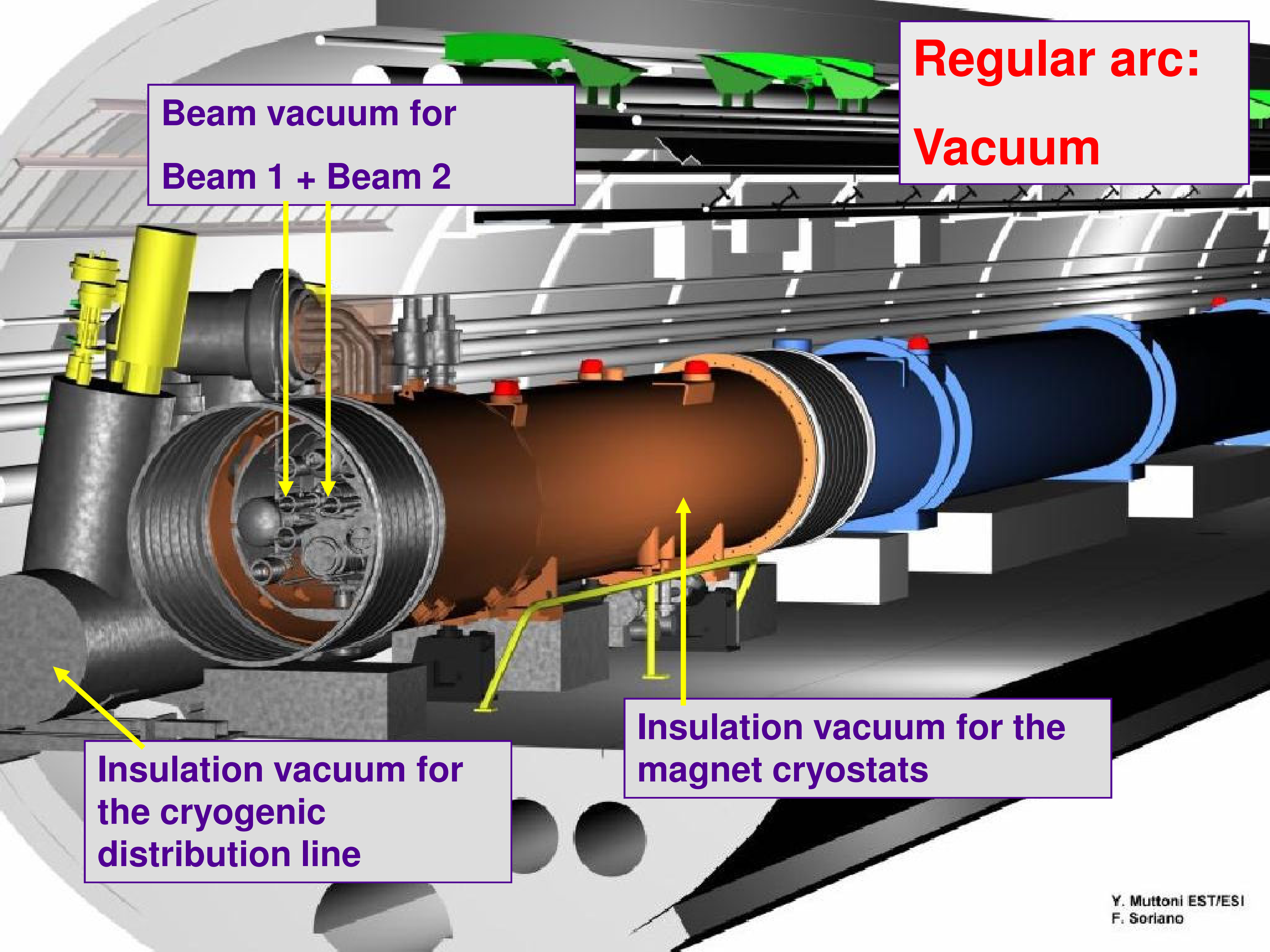
Vacuum

+- 3σ
~5 mm

Beam +/- 3 sigma

Beam in vacuum chamber with beam screen at 450 GeV

Regular arc: Vacuum



Beam vacuum for Beam 1 + Beam 2

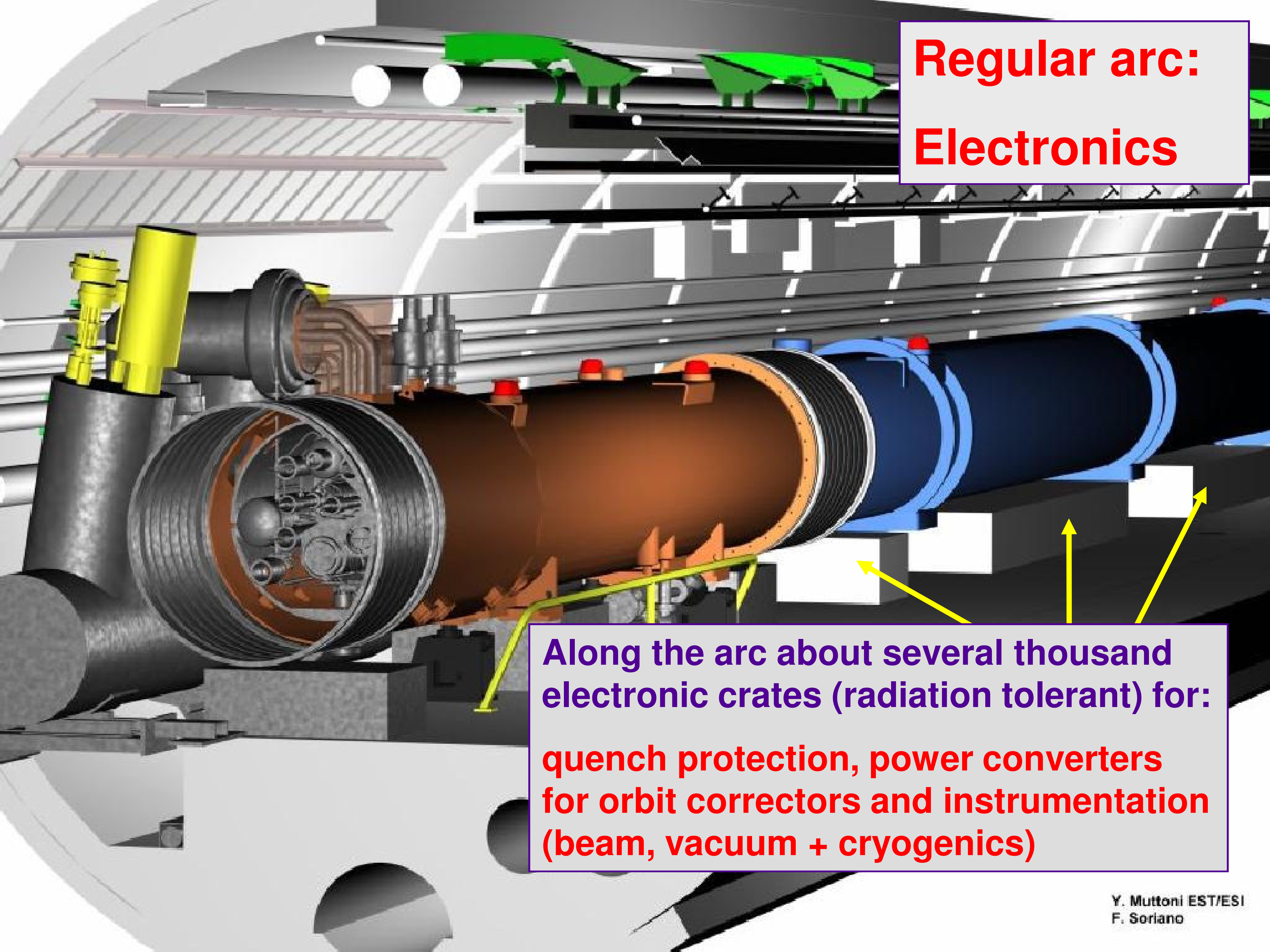
Insulation vacuum for the magnet cryostats

Insulation vacuum for the cryogenic distribution line

Y. Muttoni EST/ESI
F. Soriano

Regular arc:

Electronics

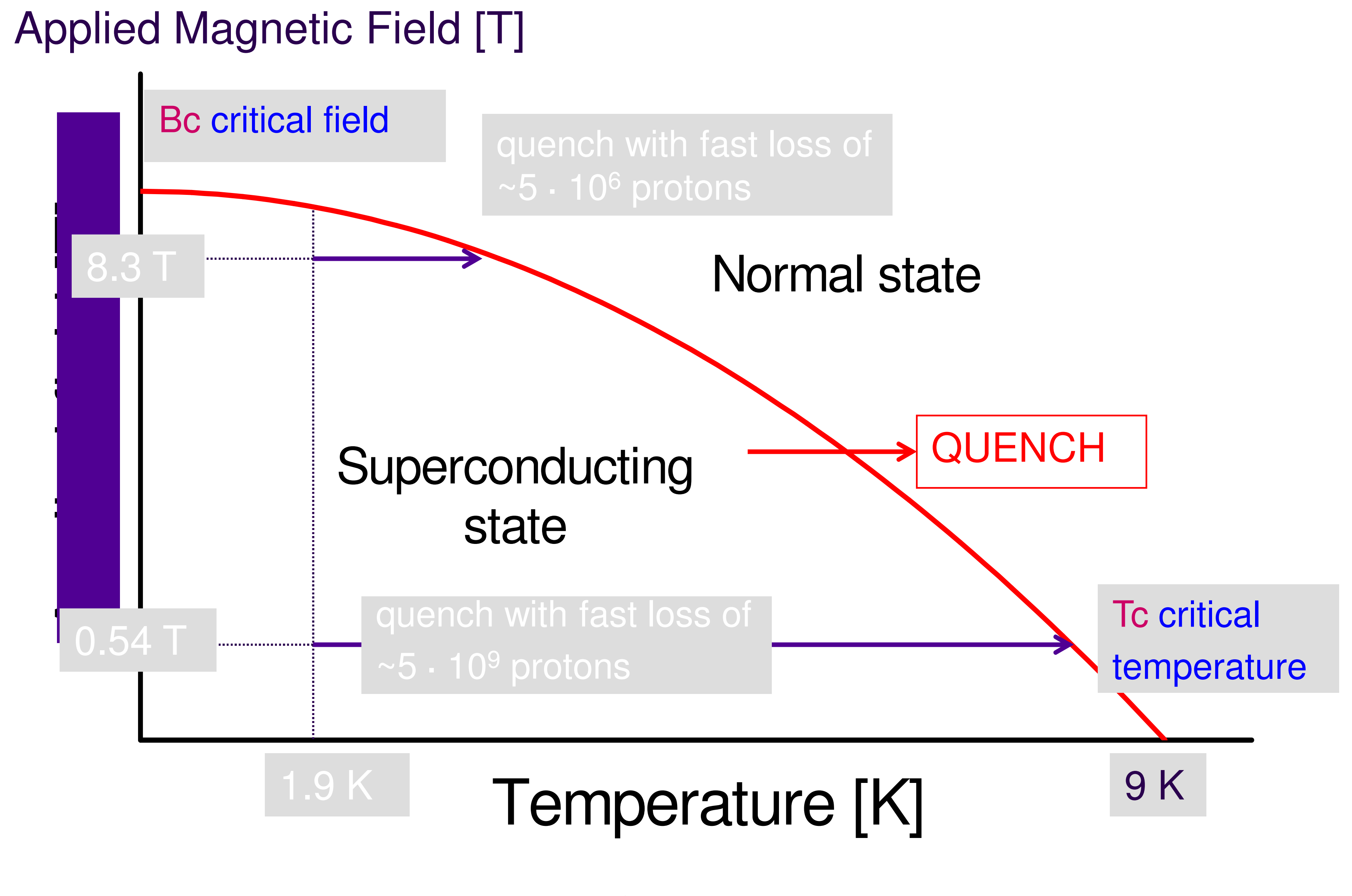


Along the arc about several thousand electronic crates (radiation tolerant) for:

quench protection, power converters for orbit correctors and instrumentation (beam, vacuum + cryogenics)

Y. Muttoni EST/ESI
F. Soriano

Operational margin of a superconducting magnet



Applied Magnetic Field [T]

Bc critical field

quench with fast loss of $\sim 5 \cdot 10^6$ protons

8.3 T

Normal state

Superconducting state

QUENCH

0.54 T

quench with fast loss of $\sim 5 \cdot 10^9$ protons

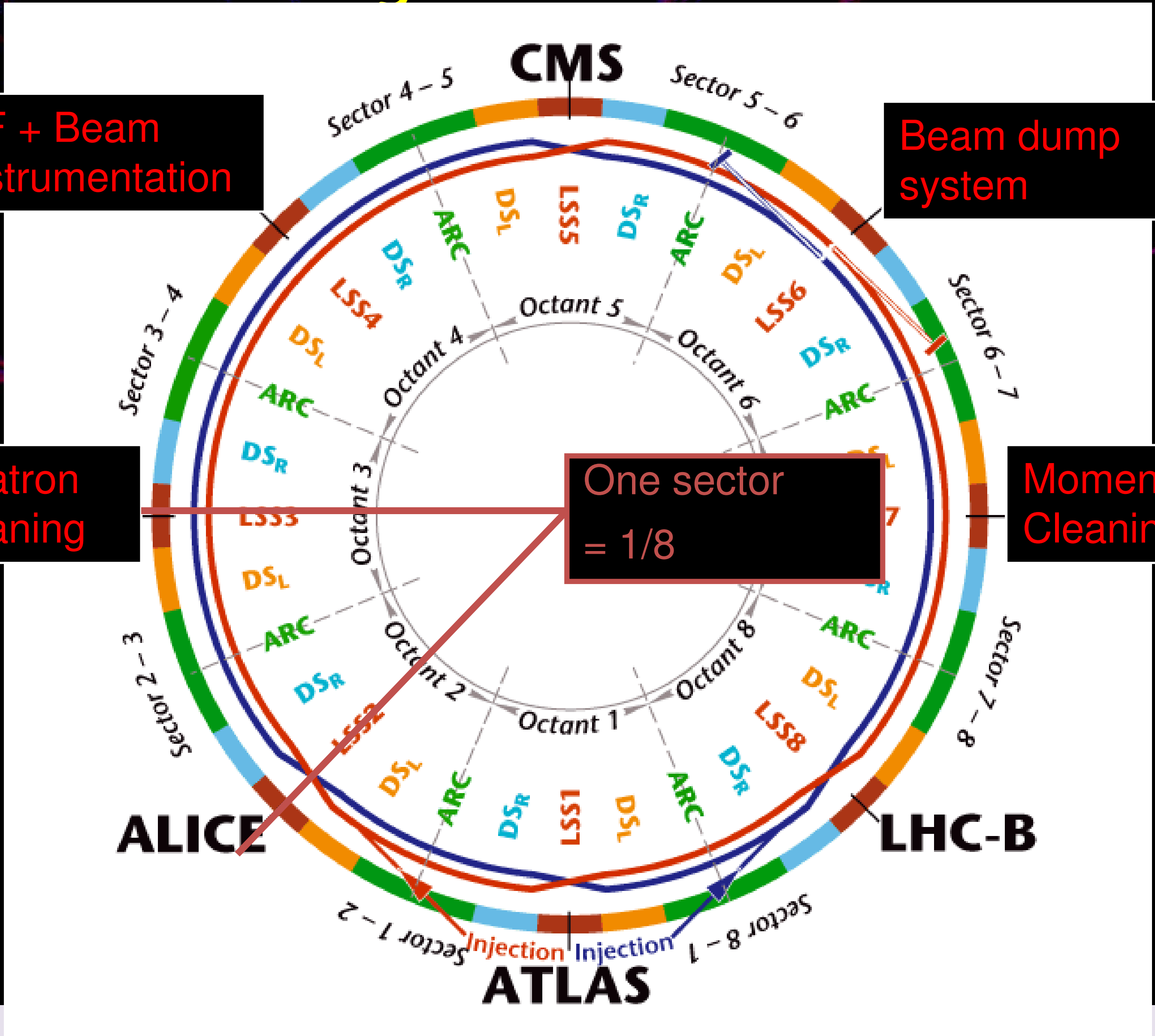
Tc critical temperature

1.9 K

Temperature [K]

9 K

Layout of the LHC ring: 8 arcs and 8 long straight sections



RF + Beam instrumentation

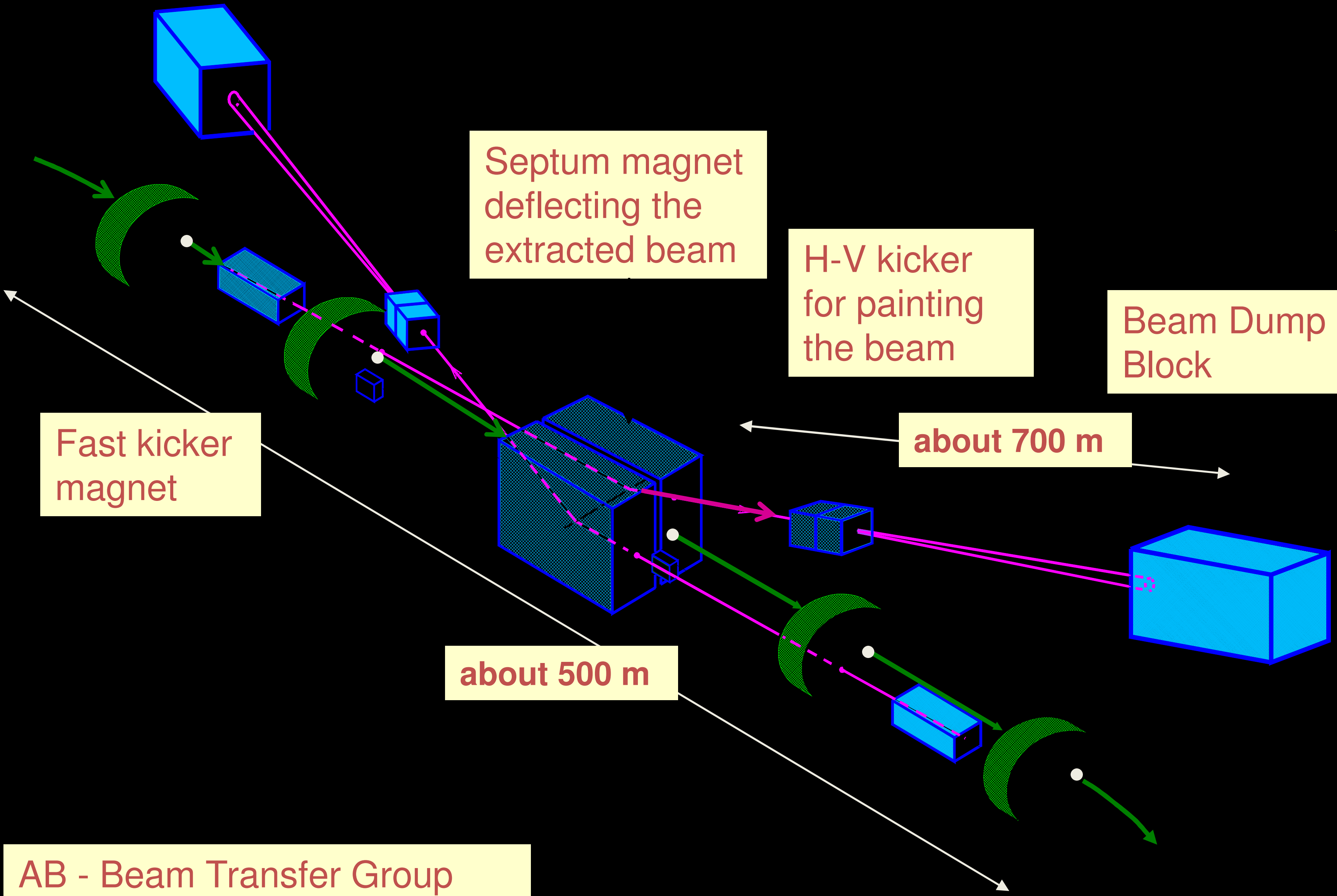
Beam dump system

Betatron Cleaning

Momentum Cleaning

One sector = 1/8

Schematic layout of beam dump system in IR6



Septum magnet deflecting the extracted beam

H-V kicker for painting the beam

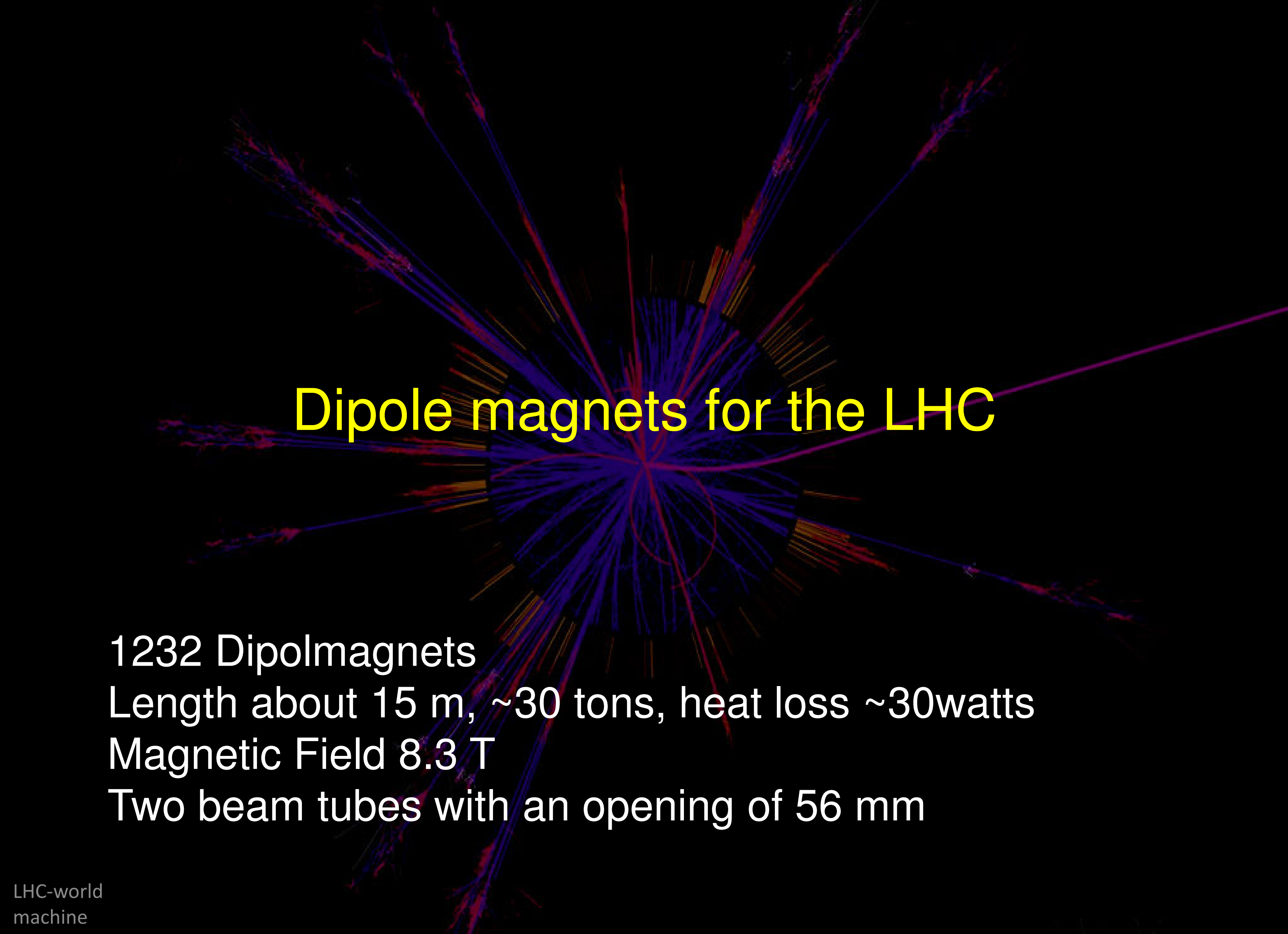
Beam Dump Block

about 700 m

Fast kicker magnet

about 500 m

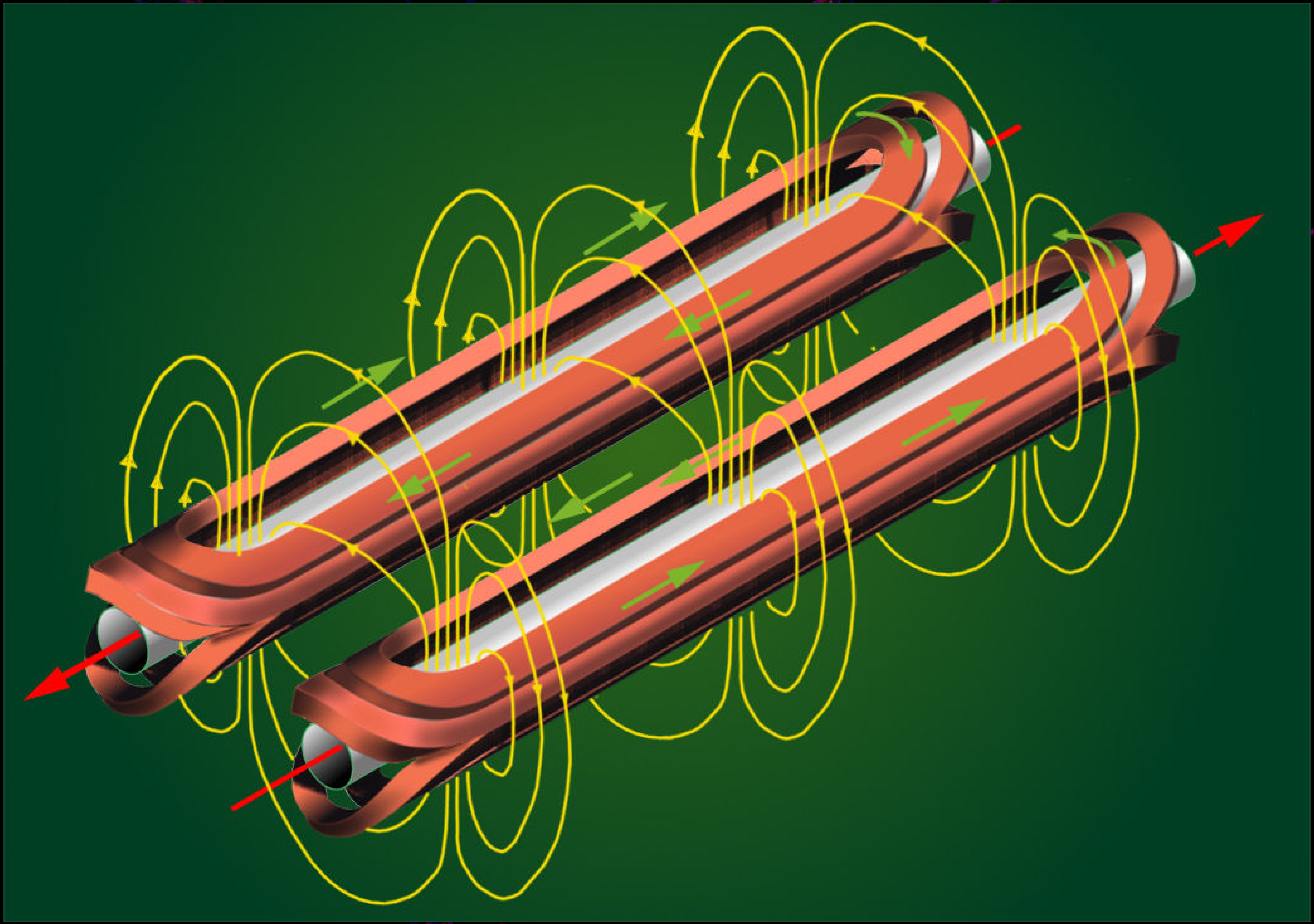
AB - Beam Transfer Group



Dipole magnets for the LHC

1232 Dipolmagnets
Length about 15 m, ~30 tons, heat loss ~30watts
Magnetic Field 8.3 T
Two beam tubes with an opening of 56 mm

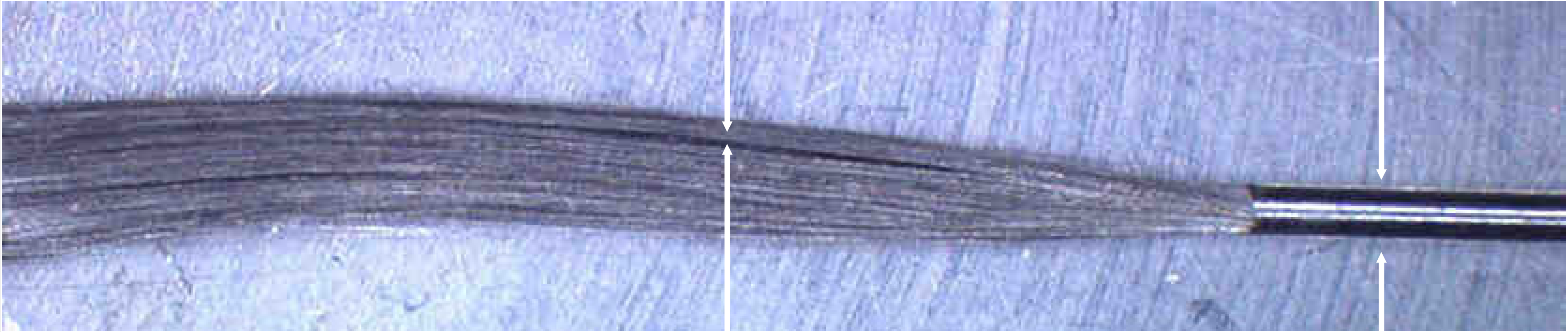
Coils for Dipolmagnets



Supraconducting filaments, wire and cable

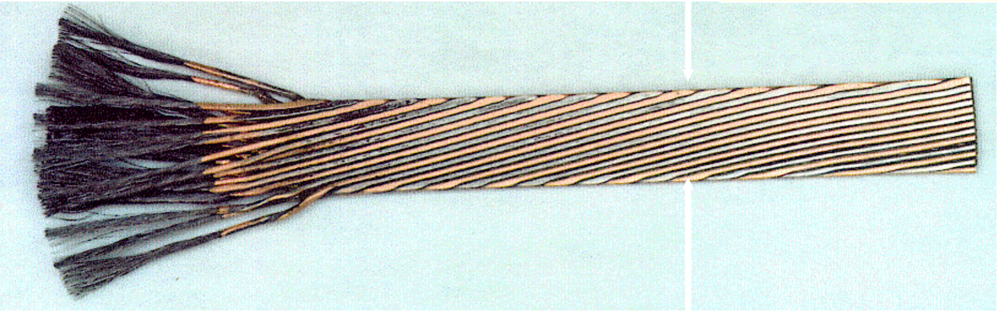
∅6 μm

∅1 mm



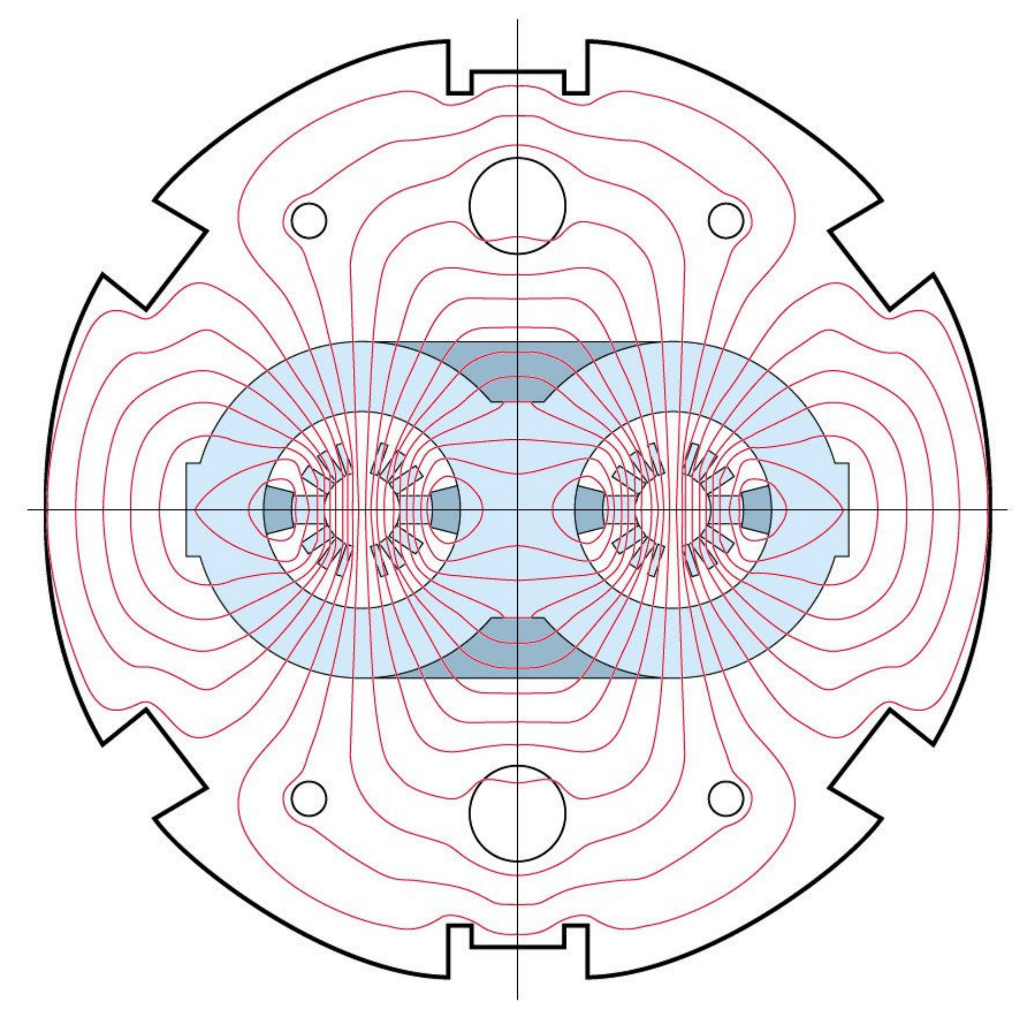
Typical value for operation at 8 T and 1.9 K: 800 A

width 15 mm

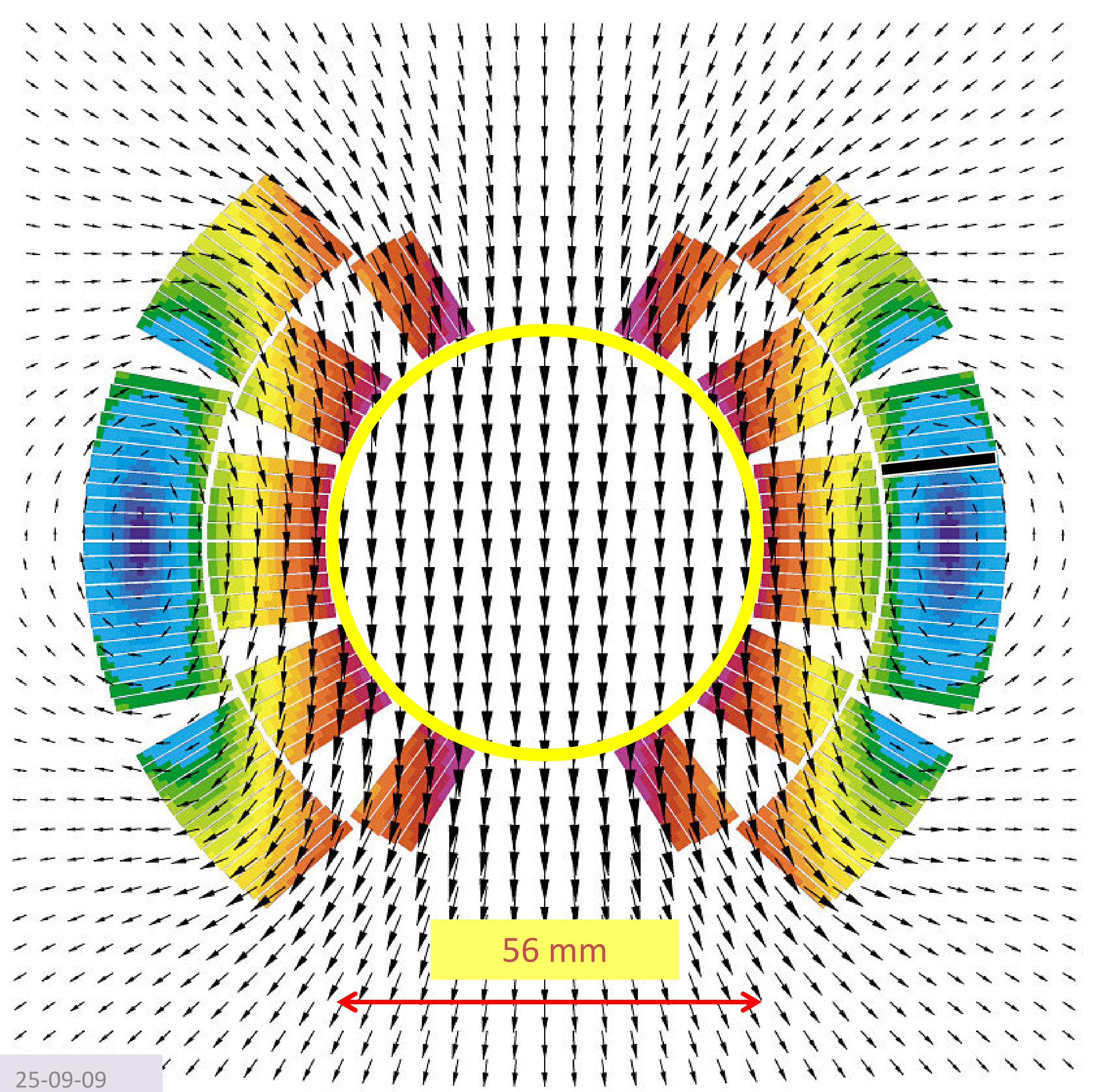


Rutherford cable

Two - in One Magnet



Computed magnetic flux map at B_0=10 Tesla



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

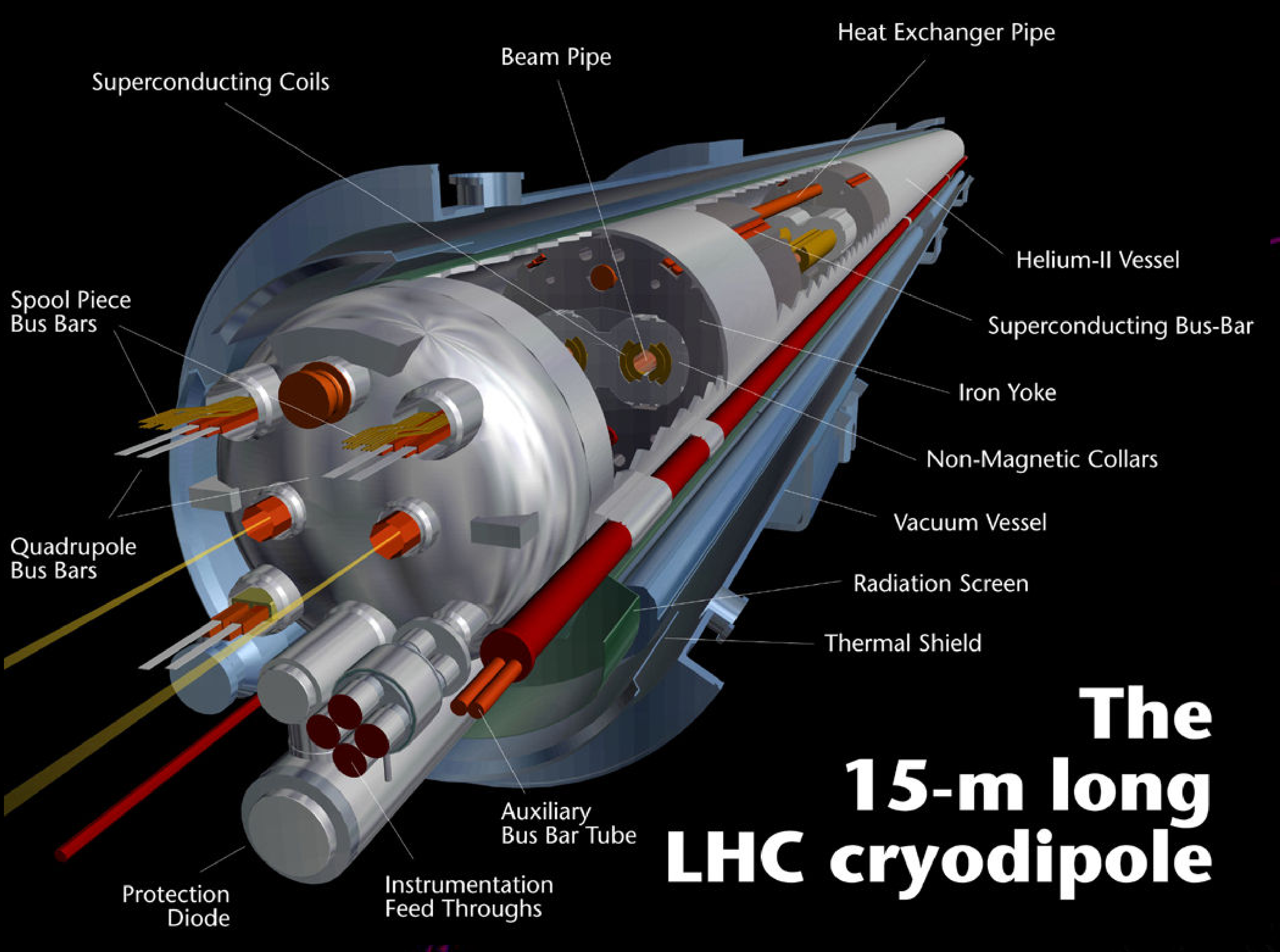
B = 8.33 T

I0 = 12000 Ampere

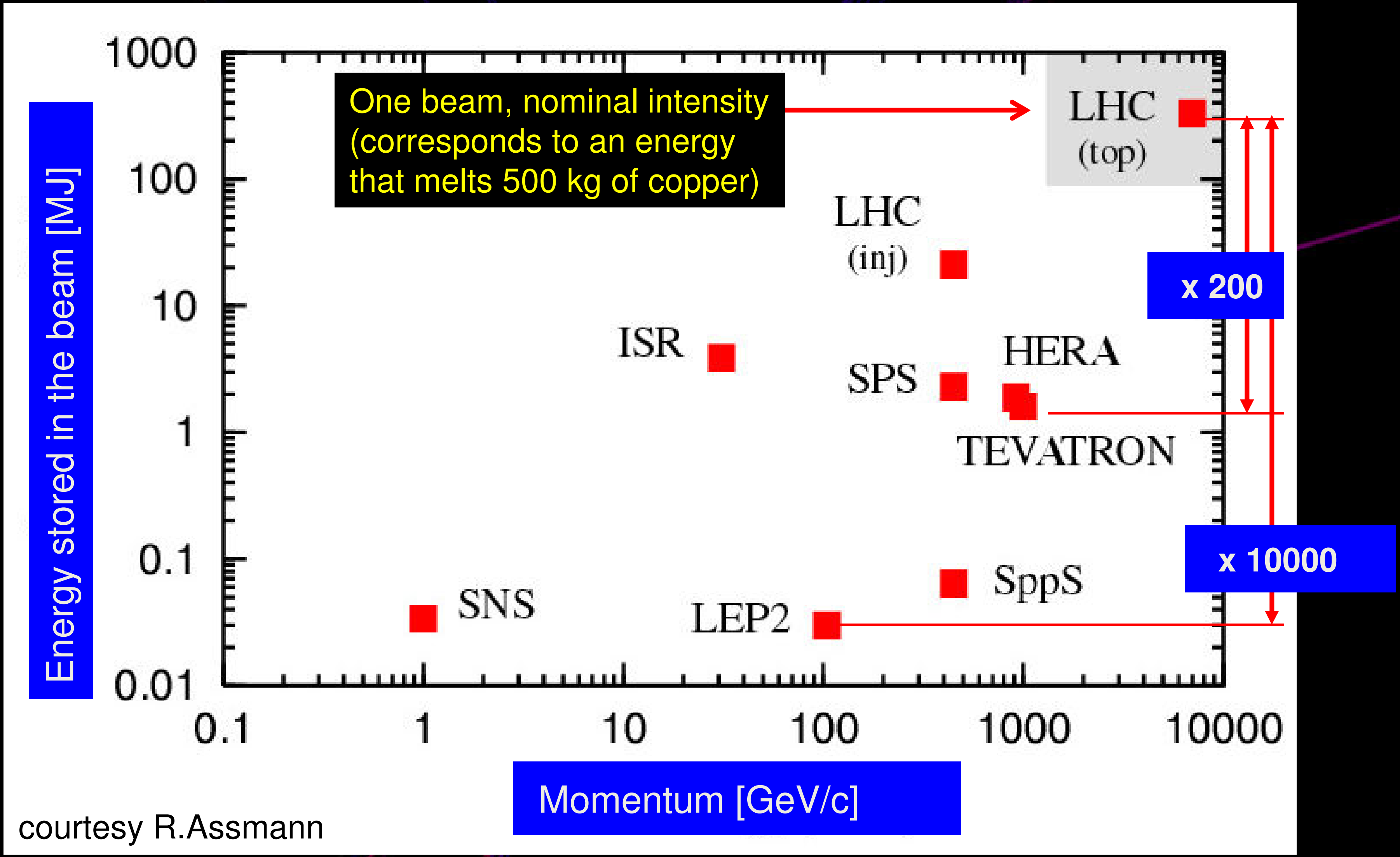
L = 15 m

F = 165 tons

The Dipolmagnet in a cryostat



Challenges: Energy stored in the beam



One beam, nominal intensity (corresponds to an energy that melts 500 kg of copper)

courtesy R.Assmann

Energy stored in LHC magnets

Approximation: energy is proportional to volume inside magnet aperture and to the square of the magnet field

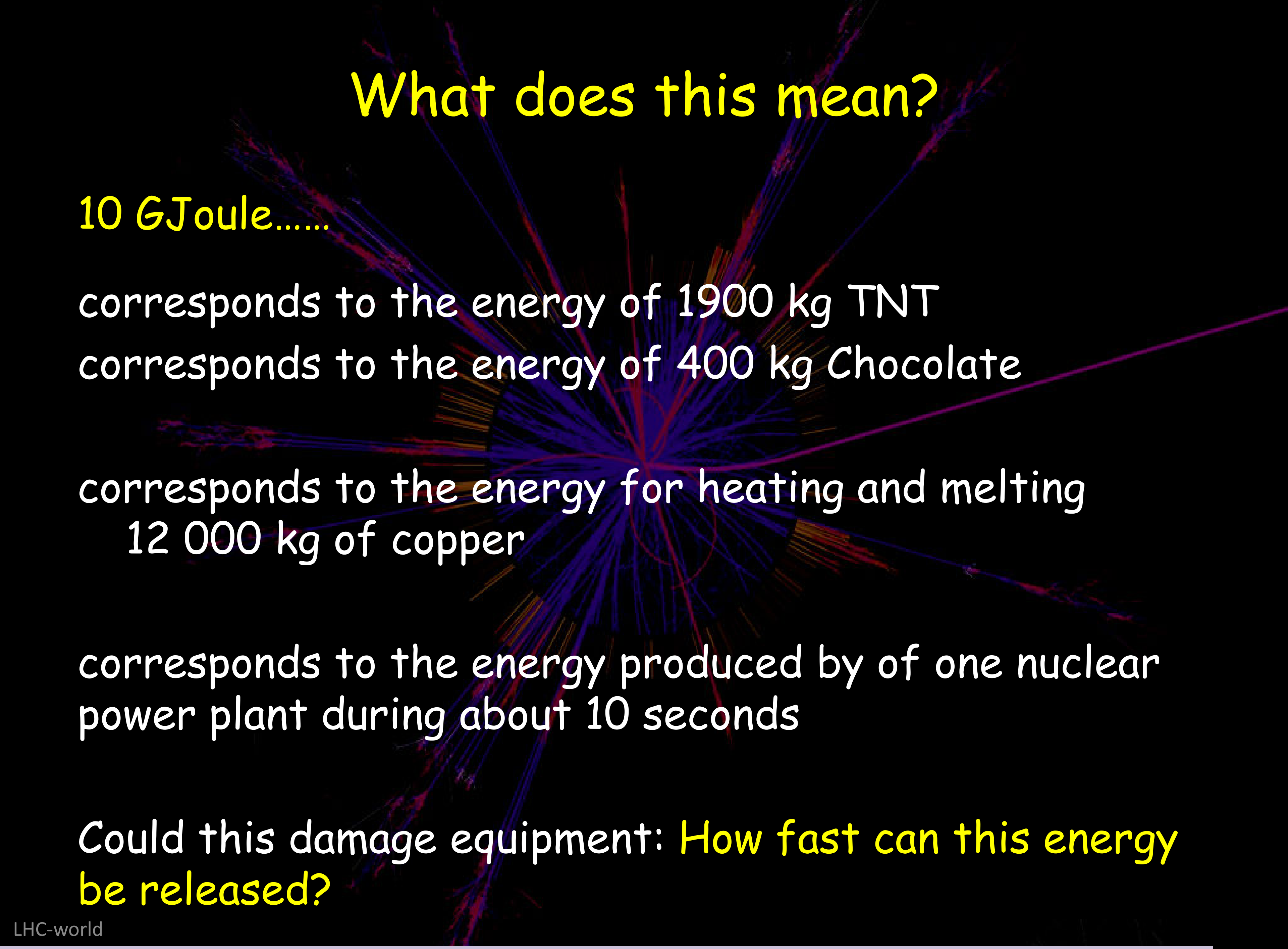
Energy stored in twin dipole magnet: $E_{stored} := 2\,\dfrac{B_{dipole}^{\;2}\cdot length\cdot r_{dipole}^{\;2}\cdot\pi}{\mu_0}$

about 5 MJ per magnet

Accurate calculation with the magnet inductance:

For all 1232 dipoles in the LHC: 9.4 GJ

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 12 000 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?

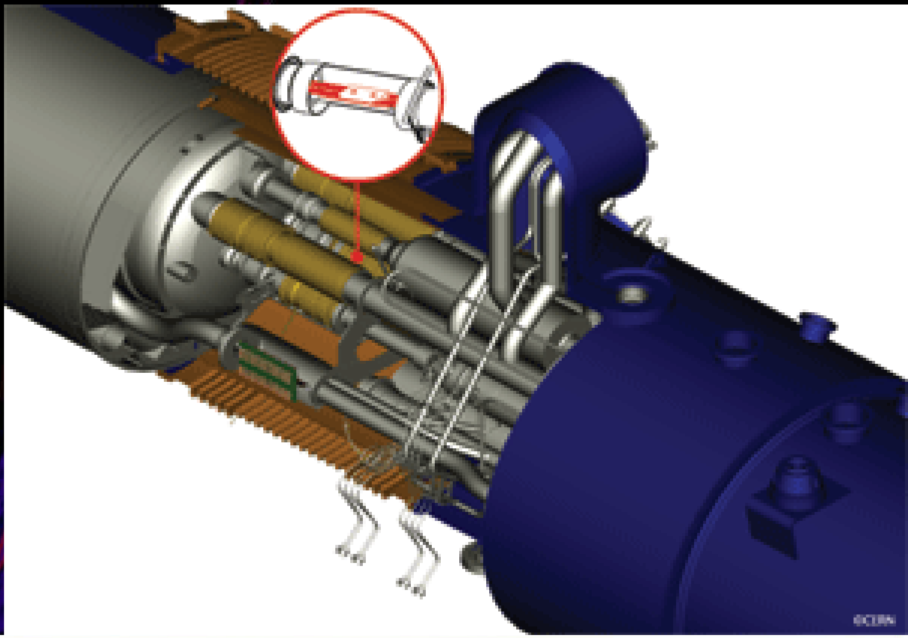
LHC magnet assembly at CERN

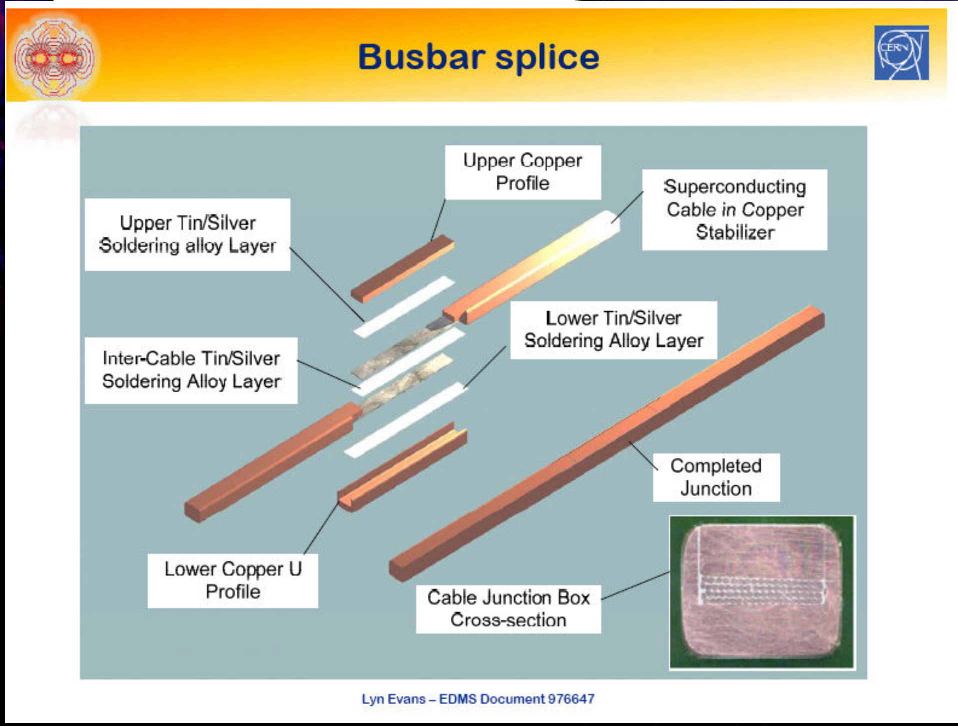
The "Incident"

LHC Status

Lyn Evans

RRB 10th November 2008





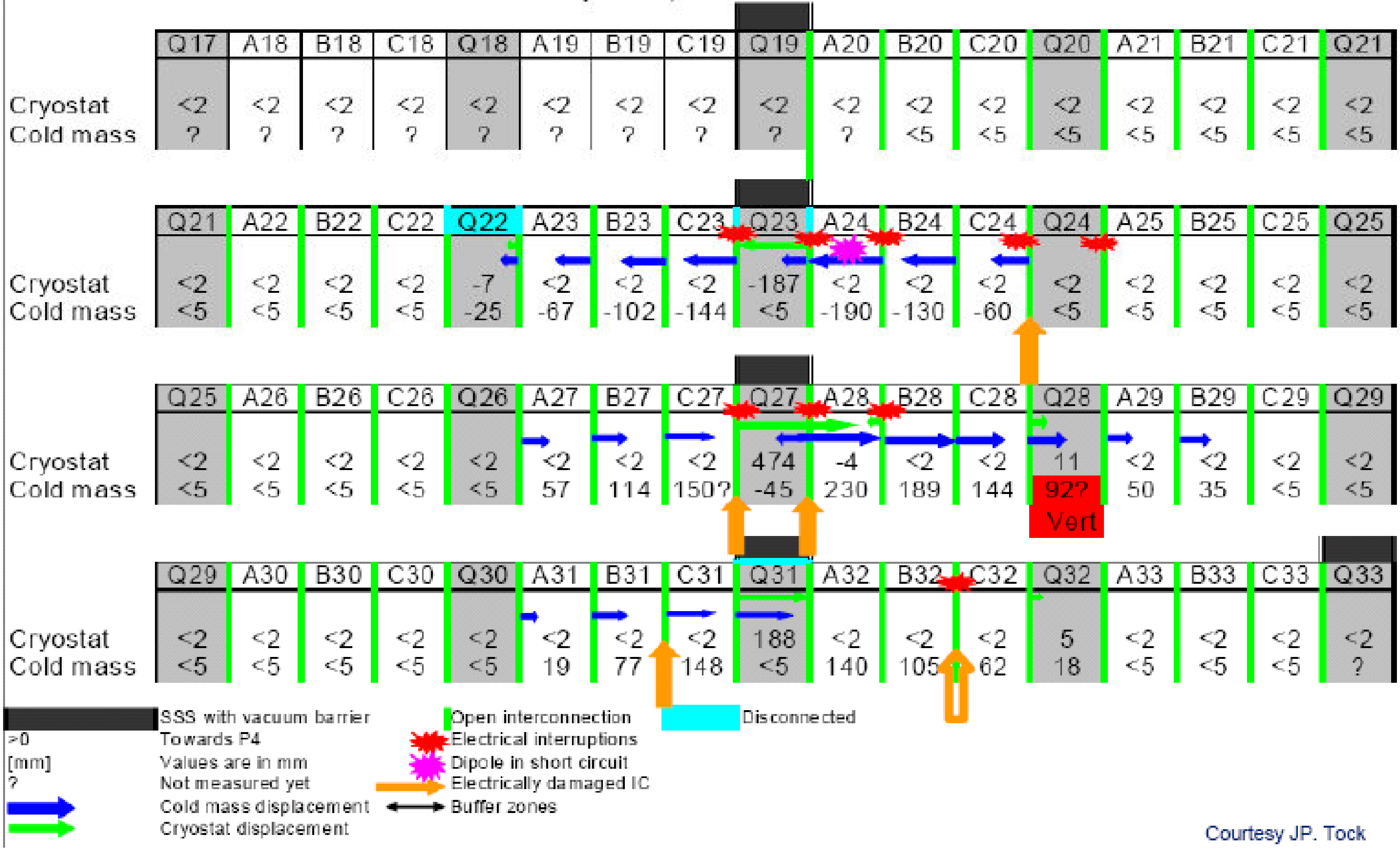
Busbar splice

Lyn Evans – EDMS Document 976647

Cryostat and cold masses longitudinal displacements

Displacements status in sector 3-4 (From Q17R3 to Q33R3) : P3 side

Based on measurements by TS-SU, TS-MME and AT-MCS



	Q17	A18	B18	C18	Q18	A19	B19	C19	Q19	A20	B20	C20	Q20	A21	B21	C21	Q21
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Cold mass	?	?	?	?	?	?	?	?	?	?	<5	<5	<5	<5	<5	<5	<5

	Q21	A22	B22	C22	Q22	A23	B23	C23	Q23	A24	B24	C24	Q24	A25	B25	C25	Q25
Cryostat	<2	<2	<2	<2	-7	<2	<2	<2	-187	<2	<2	<2	<2	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	-25	-67	-102	-144	<5	-190	-130	-60	<5	<5	<5	<5	<5

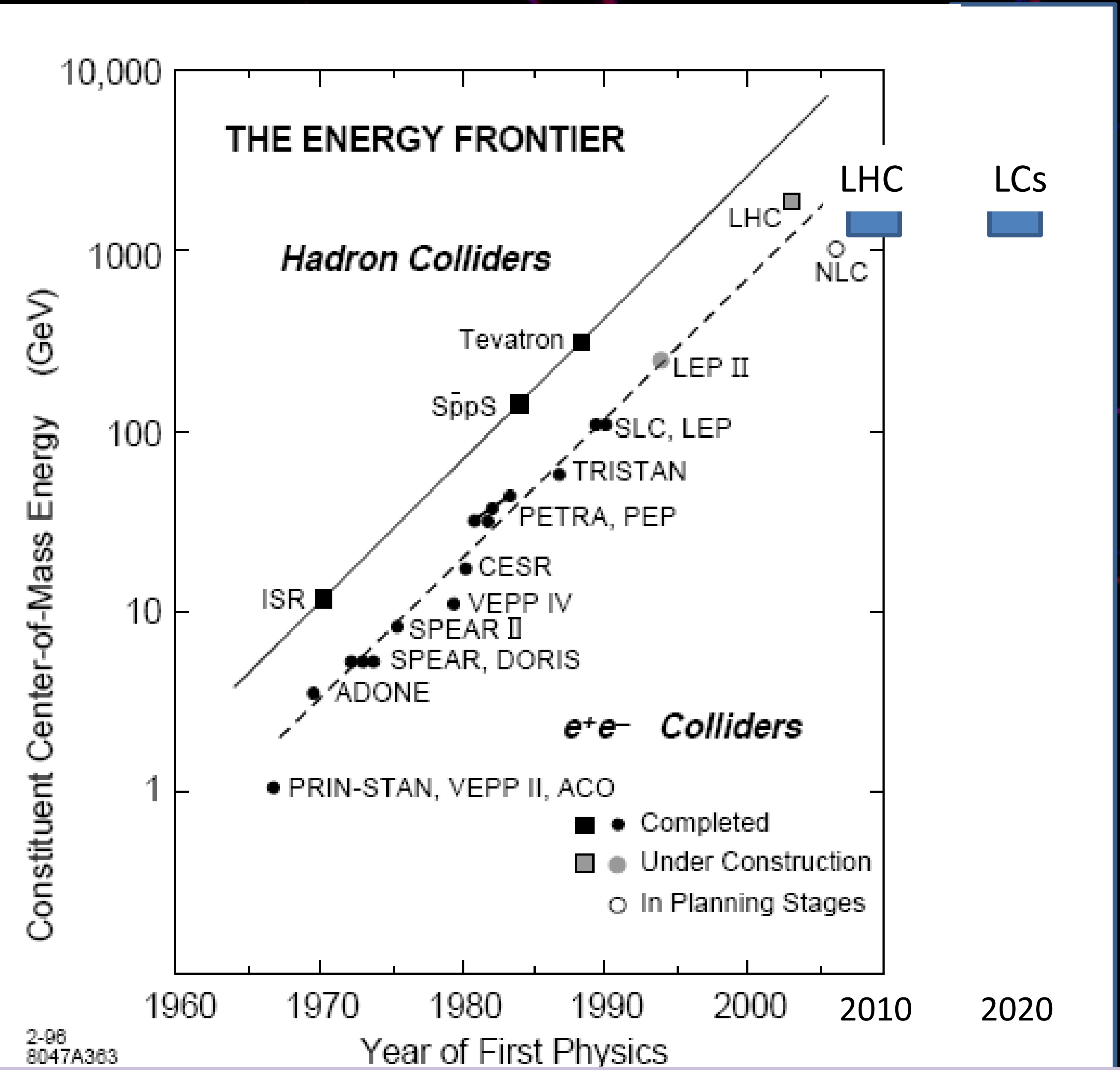
	Q25	A26	B26	C26	Q26	A27	B27	C27	Q27	A28	B28	C28	Q28	A29	B29	C29	Q29
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	474	-4	<2	<2	11	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	<5	57	114	150?	-45	230	189	144	92? Vert	50	35	<5	<5

	Q29	A30	B30	C30	Q30	A31	B31	C31	Q31	A32	B32	C32	Q32	A33	B33	C33	Q33
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	188	<2	<2	<2	5	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	<5	19	77	148	<5	140	105	62	18	<5	<5	<5	?

■	SSS with vacuum barrier
>0	Towards P4
[mm]	Values are in mm
?	Not measured yet
➡	Cold mass displacement
➡	Cryostat displacement
▌	Open interconnection
✷	Electrical interruptions
✷	Dipole in short circuit
➡	Electrically damaged IC
↔	Buffer zones
▭	Disconnected

Courtesy JP. Tock

Energy frontier-constituents vs. time



Exponential growth ended with Tevatron

ILC or CLIC far from exponential and LHC too

New ideas needed

LHC - the world machine today

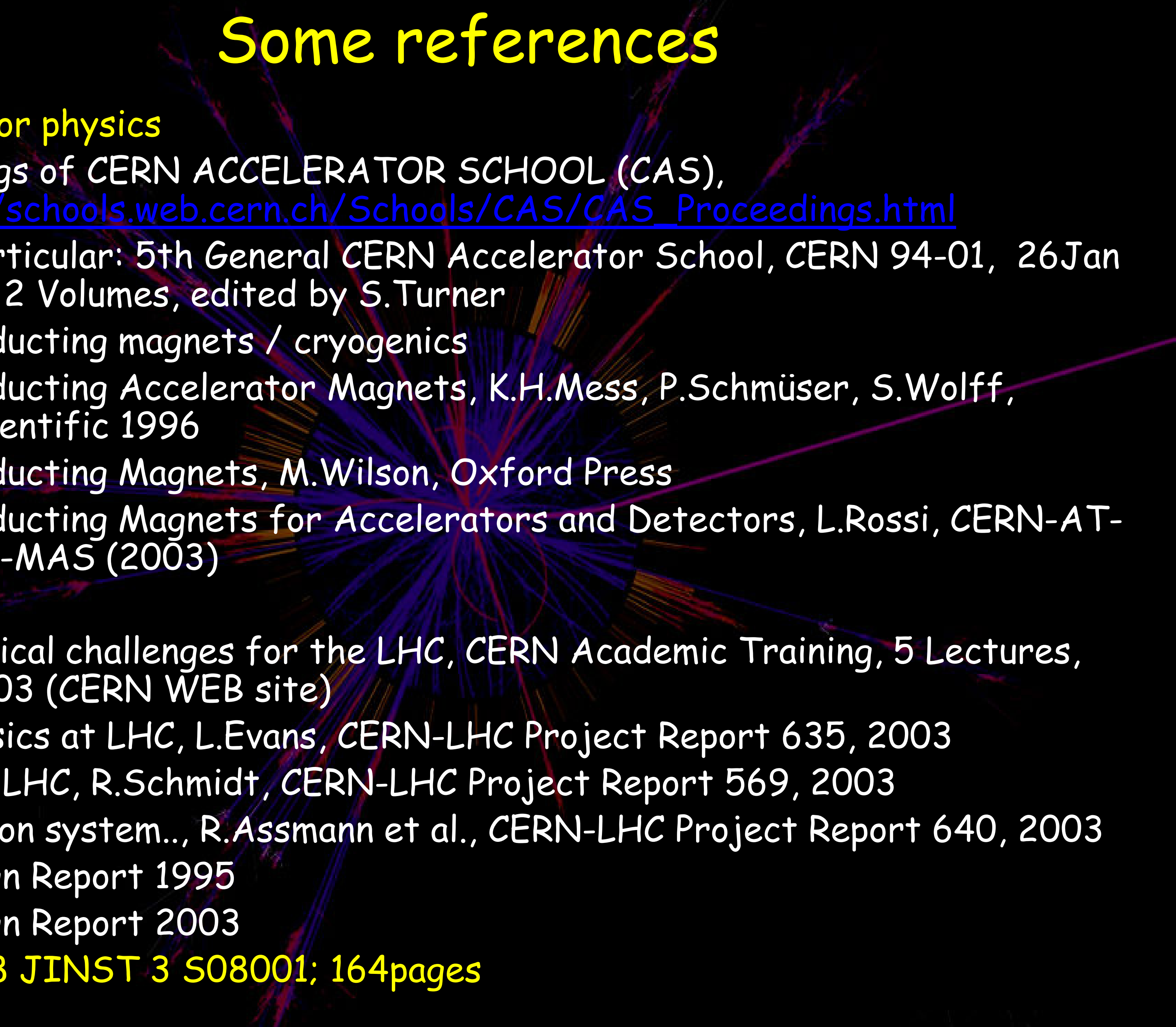
Marvellous global community tool – problems in details

Engineering management w.r.t “networked”, “collaborative”

Technologies: “next step” of factor 10 not in view - ??

Accelerators are the domain of physicists

Some references



Accelerator physics

Proceedings of CERN ACCELERATOR SCHOOL (CAS), http://schools.web.cern.ch/Schools/CAS/CAS_Proceedings.html

In particular: 5th General CERN Accelerator School, CERN 94-01, 26Jan 1994, 2 Volumes, edited by S.Turner

Superconducting magnets / cryogenics

Superconducting Accelerator Magnets, K.H.Mess, P.Schmüser, S.Wolff, World Scientific 1996

Superconducting Magnets, M.Wilson, Oxford Press

Superconducting Magnets for Accelerators and Detectors, L.Rossi, CERN-AT-2003-002-MAS (2003)

LHC

Technological challenges for the LHC, CERN Academic Training, 5 Lectures, March 2003 (CERN WEB site)

Beam Physics at LHC, L.Evans, CERN-LHC Project Report 635, 2003

Status of LHC, R.Schmidt, CERN-LHC Project Report 569, 2003

...collimation system.., R.Assmann et al., CERN-LHC Project Report 640, 2003

LHC Design Report 1995

LHC Design Report 2003

LHC 2008 JINST 3 S08001; 164pages