Superconducting magnets for particle accelerators - 4

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CONTENTS

- Accelerator magnets
  - Limits to highest field in Nb-Ti
  - Hints on Nb_3Sn
- Hints on detector magnets
- Luminosity and operation
  - Luminosity definition and equation
  - Emittance, intensity and beam beam limit
  - Beta*
  - Integrated luminosity
  - The present situation in the LHC

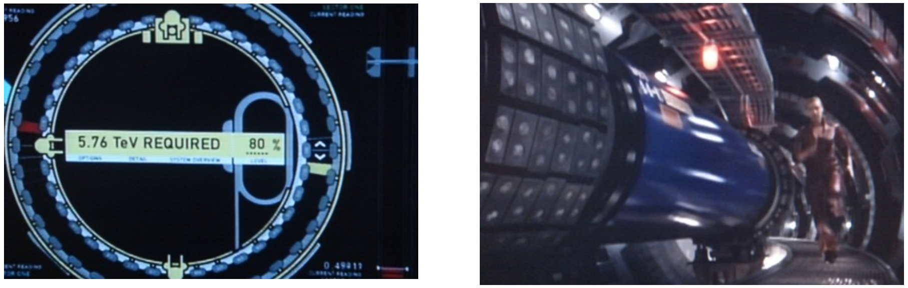
INTERLUDE: THE TERMINATOR-3 ACCELERATOR

We apply some concepts to the accelerator shown in Terminator-3 [Columbia Pictures, 2003]

- Estimation of the magnetic field

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

  - Energy = 5760 GeV
  - Radius ~30 m
  - Field = 5760/0.3/30 ~ 700 T (a lot !)

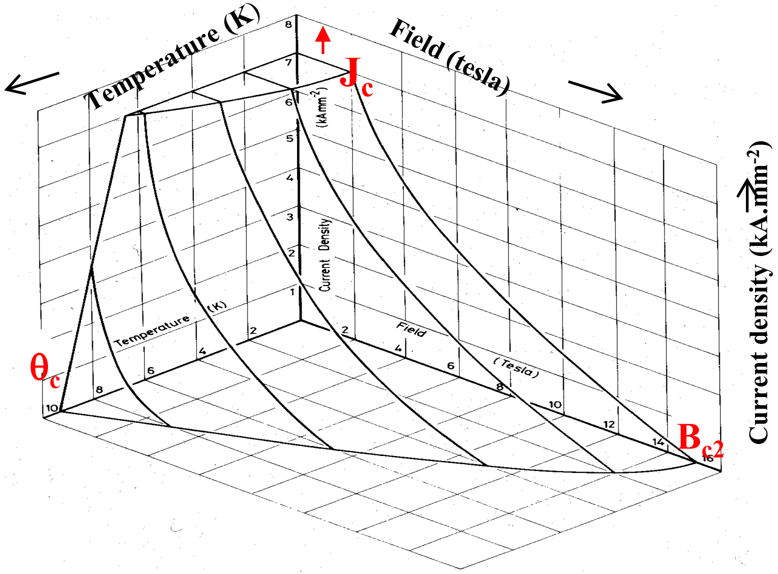


Energy of the machine (left) and size of the accelerator (right)

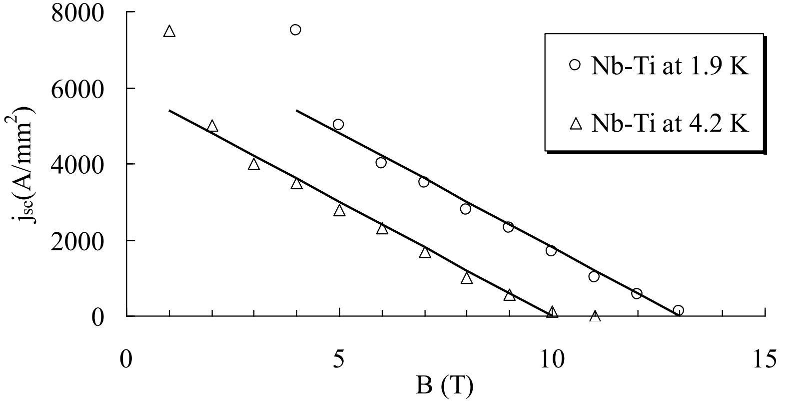
- Is it possible to have 700 T magnets ??

LIMITS TO HIGH FIELDS

- The material is superconductor as long as *B*, *j*, and temperature stay below the critical surface
  - The maximum current density ~ 10 000 A/mm^2, but this at zero field and zero temperature
  - In a magnet, the winding has a current density to create a magnetic field → the magnetic field is also in the winding → this reduces the current density
  - The obvious ultimate limit to Nb-Ti dipoles is 14 T at zero temperature and zero current density, and 13 T at 1.9 K
  - In reality, we cannot get 13 T but much less – around 8 T in the LHC – why ?



Critical surface for Nb-Ti



Section of the Nb-Ti critical surface at 1.9 and 4.2 K, and linear fit

LIMITS TO HIGH FIELDS

- We compute what field can be reached for a sector coil of width *w*
  - We characterize the critical surface by two parameters

$$j_c = \kappa c(B^*_{c2} - B)$$

and we added κ which takes into account that only a fraction (~¼) of the coil is made up to superconductor

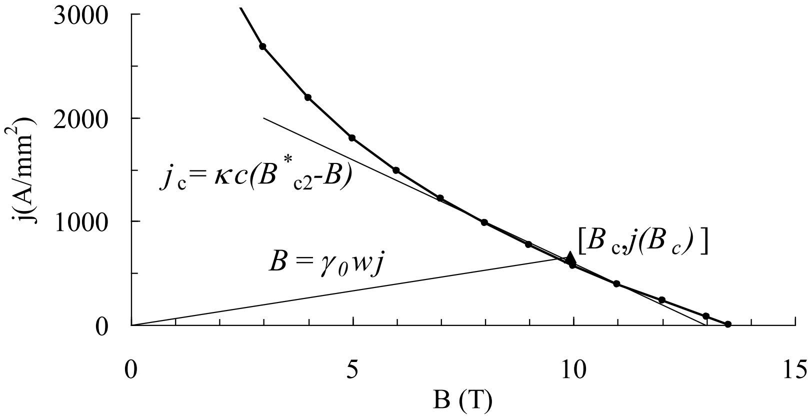
  - The relation between current density *j* and field *B* is $B = \gamma_0 wj$

(w thickness of the coil, γ_0 is a constant)

and the field that can be reached is given by $B_c = \gamma_0 wj_c = \gamma_0 w\kappa c(B^*_{c2} - B_c)$

$$B_c = B^*_{c2}\frac{\kappa c\gamma_0 w}{1+\kappa c\gamma_0 w}$$

  - The larger coil, the smaller j_c, the larger *B*

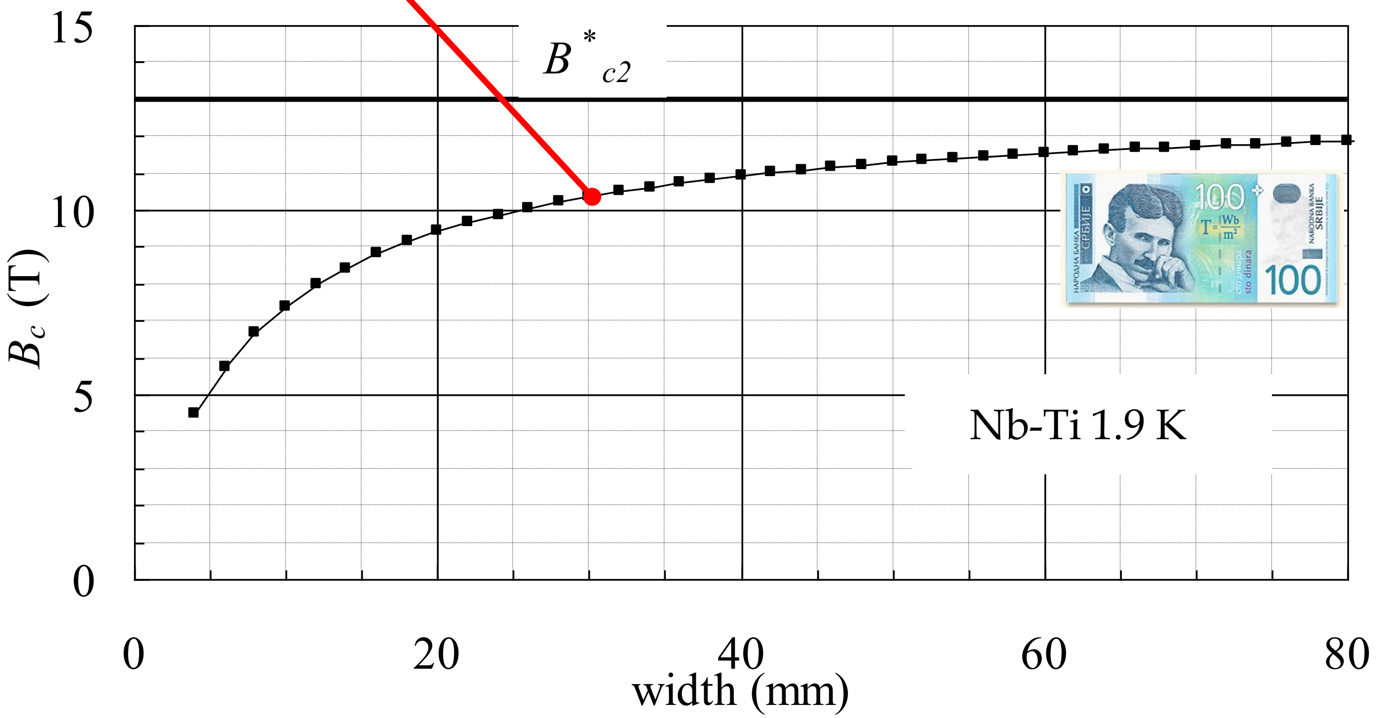


Critical surface for Nb-Ti: j versus B and magnet loadline

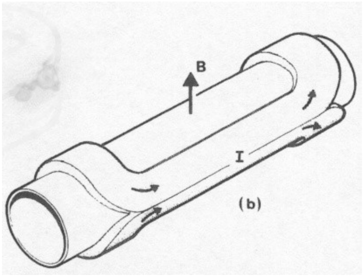
LIMITS TO HIGH FIELDS

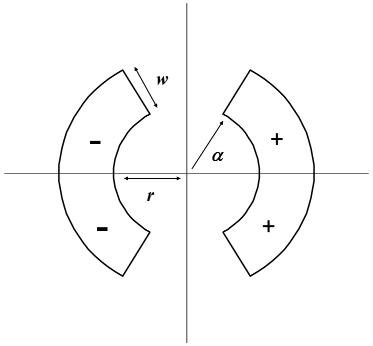
- We have computed what field can be reached for a sector coil of width *w* for Nb-Ti
  - There is a slow saturation towards 13 T
  - The last Tesla are very expensive in terms of coil
  - LHC dipole has been set on 30 mm coil width, giving ~10 T

$$B_c = B^*_{c2}\frac{\kappa c\gamma_0 w}{1+\kappa c\gamma_0 w}$$



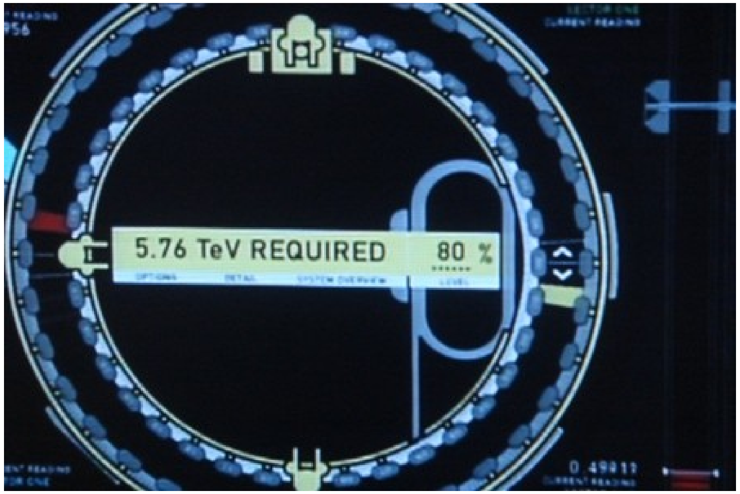
Field versus coil thickness for Nb-Ti at 1.9 K





LIMITS TO HIGH FIELDS

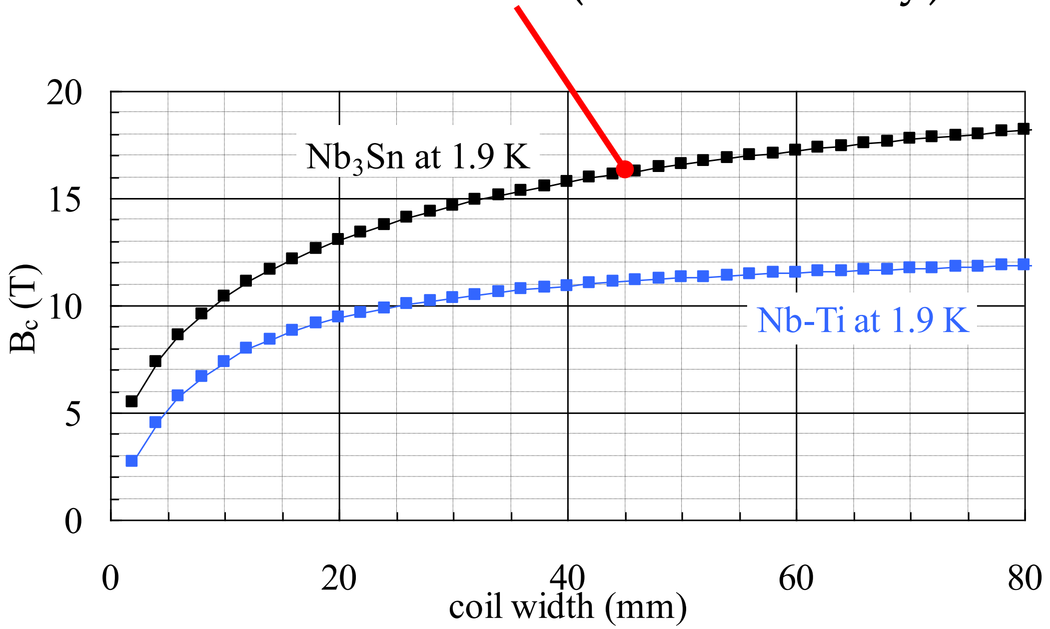
- One cannot work on the critical surface
  - Any disturbance producing energy (beam loss, coil movements under Lorentz forces) increases the temperature and the superconductivity is lost
    - In this case one has a transition called quench – the energy must be dumped without burning the magnet
    - The energy in the LHC dipoles is 8 MJ !
  - A margin of ~10-20% is usually taken, i.e. you work at 80-90%
    - LHC dipoles are giving the maximum field 10 T given by a reasonable amount of coil (30 mm) for Nb-Ti at 1.9 K
    - With a 20% operational margin one gets ~ 8 T which is the baseline value



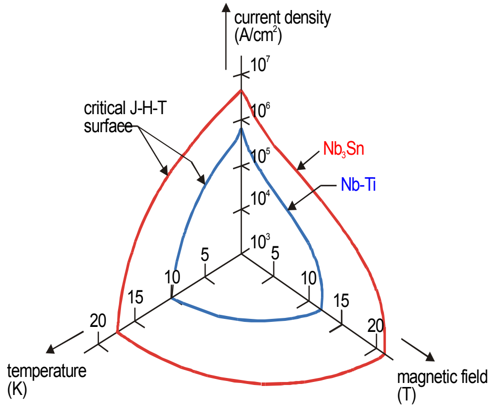
Operational limit of 20%
[Terminator-3, Columbia Pictures, 2003]

LIMITS TO HIGH FIELDS: HINTS ON Nb_3Sn

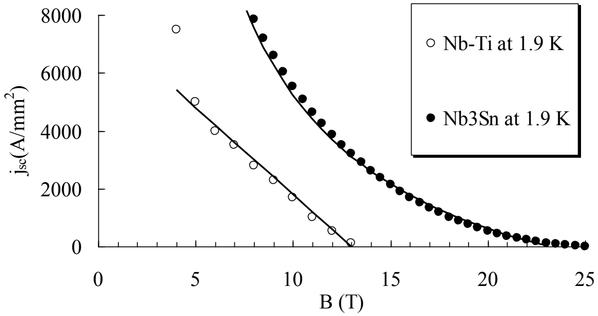
- Nb_3Sn has a wider critical surface
  - But the material is more difficult to manufacture
  - It has never been used in accelerators, but tested successfully in short models and used in solenoids
  - With Nb_3Sn one could go up to 15-18 T
  - World record is 16 T (HD1, Berkeley)



Field versus coil thickness for Nb-Ti and Nb_3Sn at 1.9 K



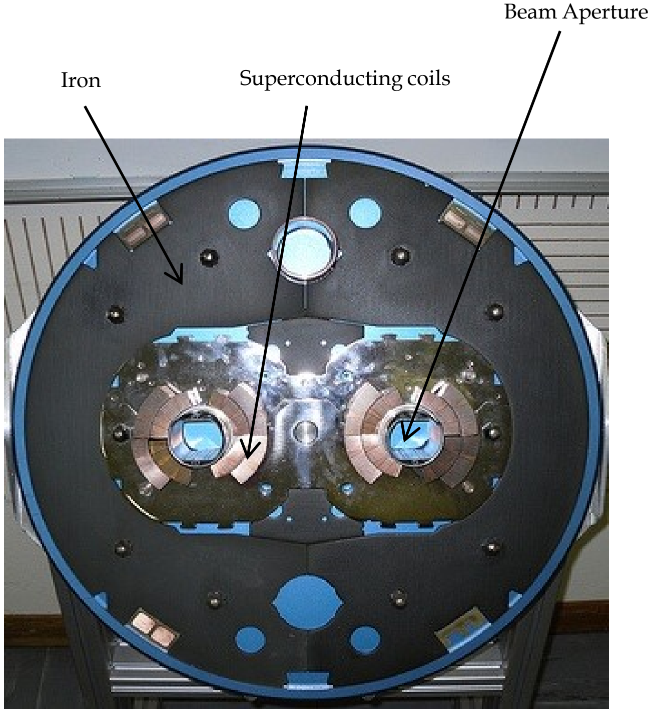
Critical surface for Nb-Ti and Nb_3Sn



SHIELDING

- The coils are surrounded by iron to avoid to have magnetic field outside the magnets
  - The iron can take at least 2 T, then it saturates

The iron lady got stuck on a magnet whose field is not shielded
[Terminator-3, Columbia Pictures, 2003]



LHC dipole cross-section

- For the LHC case: 28 mm aperture radius * 8 T ~ 120 mm iron at 2 T
  - For the Terminator-3 field is 700 T, aperture could be ~ 50 mm, one would need 700/2*50 ~ 17 m of iron ! - that’s why their magnets are not shielded

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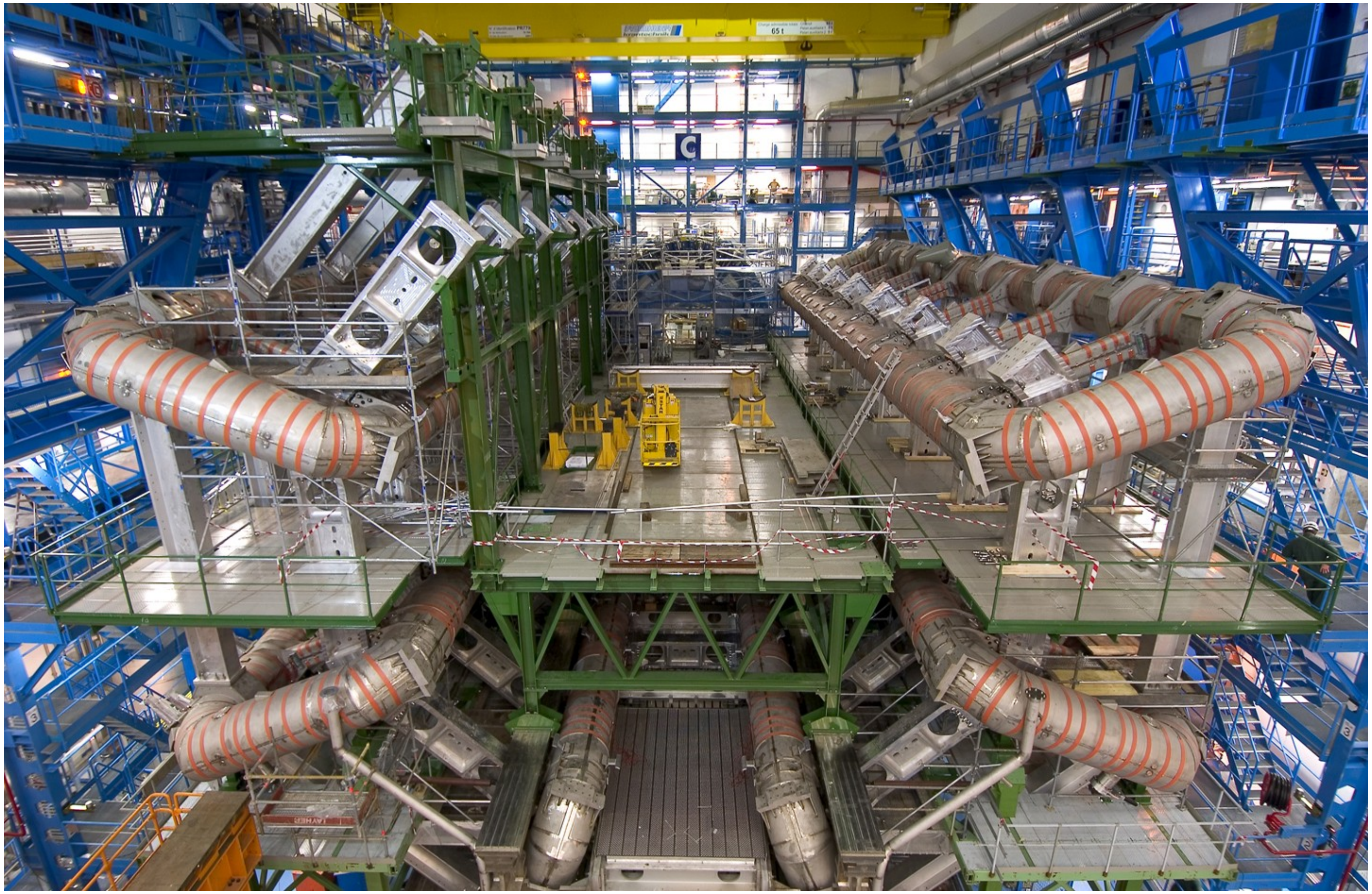
DETECTOR MAGNETS

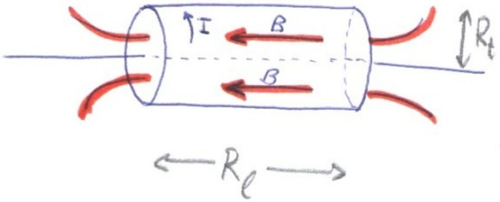
- The beam is small … why are detectors so large ?



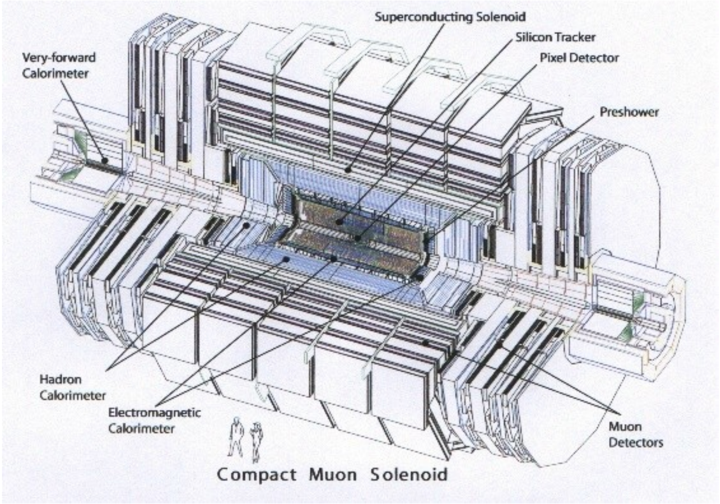
The toroidal coils of ATLAS experiment

DETECTOR MAGNETS

- Detector magnets provide a field to bend the particles generated by collisions (not the particles of the beam !)
  - The measurement of the bending radius gives an estimate of the charge and energy of the particle
- Different lay-outs
  - A solenoid providing a field parallel to the beam direction (example: LHC CMS, LEP ALEPH, Tevatron CDF)
    - Field lines perpendicular to *(x,y)*



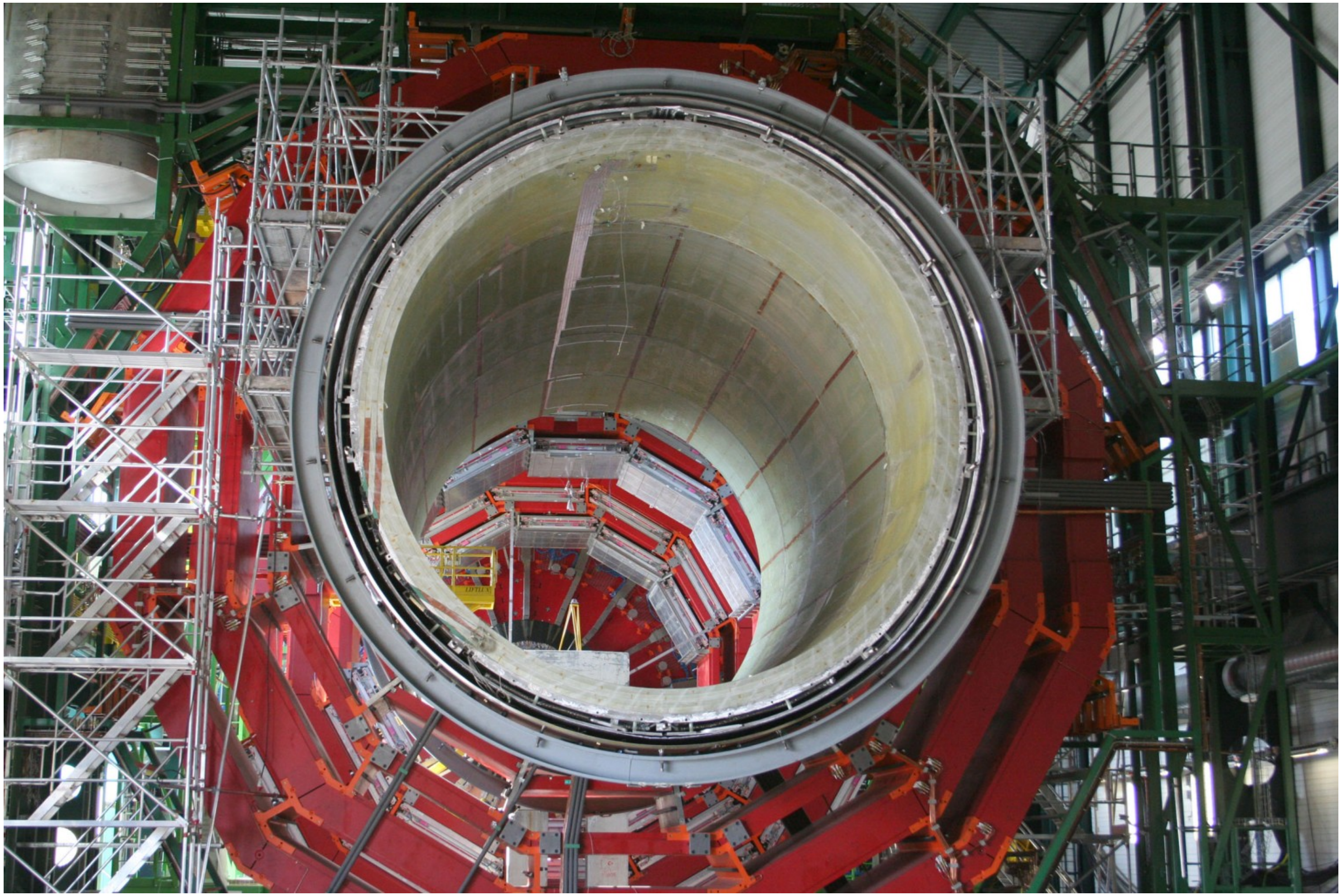
Sketch of a detector based on a solenoid



Sketch of the CMS detector in the LHC

  - A series of toroidal coils to provide a circular field around the beam (example: LHC ATLAS)
    - Field lines of circular shape in the *(x,y)* plane

DETECTOR MAGNETS

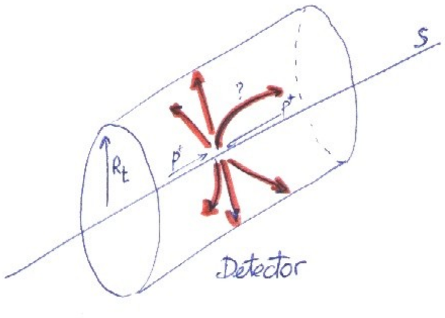


The solenoid of CMS experiment

DETECTOR MAGNETS

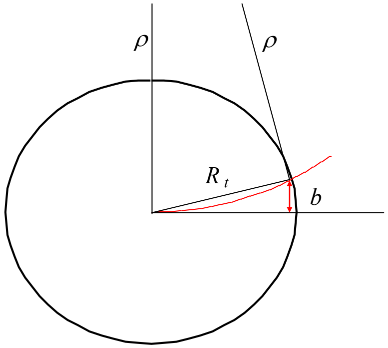
- Detector transverse size
  - The particle is bent with a curvature radius

$$E = eB\rho$$



  - B is the field in the detector magnet
  - R_t is the transverse radius of the detector magnet
  - The precision in the measurements is related to the parameter b
  - A bit of trigonometry gives

$$b = \frac{R_t^2}{2\rho} = \frac{e}{2}\frac{R_t^2 B}{E}$$



  - The magnetic field is limited by the technology
  - If we double the energy of the machine, keeping the same magnetic field, we must make a 1.4 times larger detector …

DETECTOR MAGNETS

- Detector transverse size
  - B is the field in the detector magnet
  - R_t is the transverse radius of the detector magnet
  - The precision in the measurements is $\propto 1/b$

$$b = \frac{R_t^2}{2\rho} = \frac{e}{2}\frac{R_t^2 B}{E}$$

$$b \sim 0.15\frac{R_t^2 B}{E[\mathrm{GeV}]}$$

- Examples
  - LEP ALEPH: E=100 GeV, B=1.5 T, R_l=6.5 m, R_t=2.65 m, b=16 mm
    - that's why we need sizes of meters and not centimeters !

- The magnetic field is limited by technology
  - But fields are not so high as for accelerator dipoles (4T instead of 8 T)
  - Note that the precision with BR_t^2 – better large than high field …

- Detector longitudinal size
  - several issues are involved – not easy to give simple scaling laws

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LUMINOSITY AND OPERATION

- The energy is not the only relevant parameter: the other is the frequency of collisions (how many data?)
  - The number of collisions (events) per second is given by the luminosity times the cross-section of the event

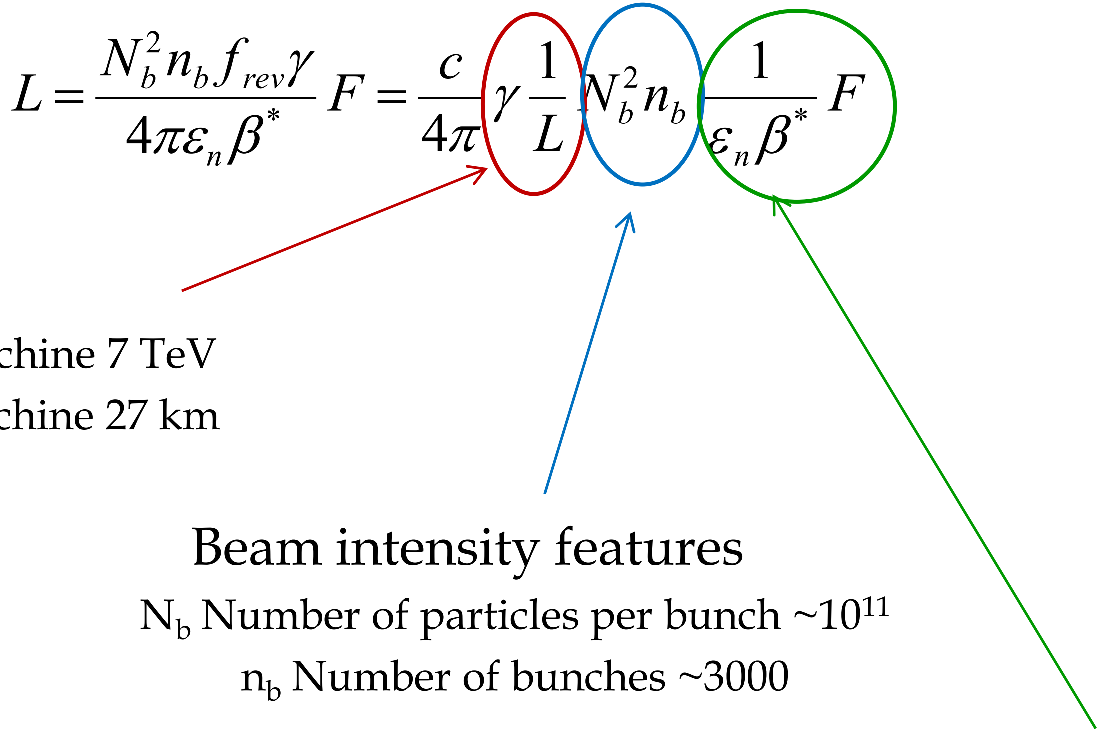
$$N_{event}\left[s^{-1}\right]=L\left[cm^{-2}s^{-1}\right]\sigma_{event}\left[cm^{-2}\right]$$

  - The cross-section depends on the type of event ("surface of the particle")
  - The luminosity depends on the accelerator and on the beam – it is a parameter of the whole machine

- One needs large luminosities to have more statistics!
  - But the detectors must be able to swallow all these events!

LUMINOSITY AND OPERATION

- Equation for the luminosity



$$L = \frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n\beta^*} F = \frac{c}{4\pi}\gamma\frac{1}{L} N_b^2 n_b \frac{1}{\varepsilon_n\beta^*} F$$

Machine features

Energy of the machine 7 TeV

Length of the machine 27 km

Beam intensity features

N_b Number of particles per bunch ~10^{11}

n_b Number of bunches ~3000

Beam geometry features

Size of the beam at collision

LUMINOSITY AND OPERATION

$$L=\frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}F=\frac{c}{4\pi}\gamma\frac{1}{L}N_b^2 n_b\frac{1}{\varepsilon_n\beta^*}F$$

- The beam-beam limit

$$\xi=\frac{r_p}{4\pi}\frac{N_b}{\varepsilon_n}<0.02$$

  - N_b Number of particles per bunch ε_n transverse size of beam
  - One cannot put too many particles in a “small space”
  - Otherwise the Coulomb interaction when the beam collide make the beam unstable

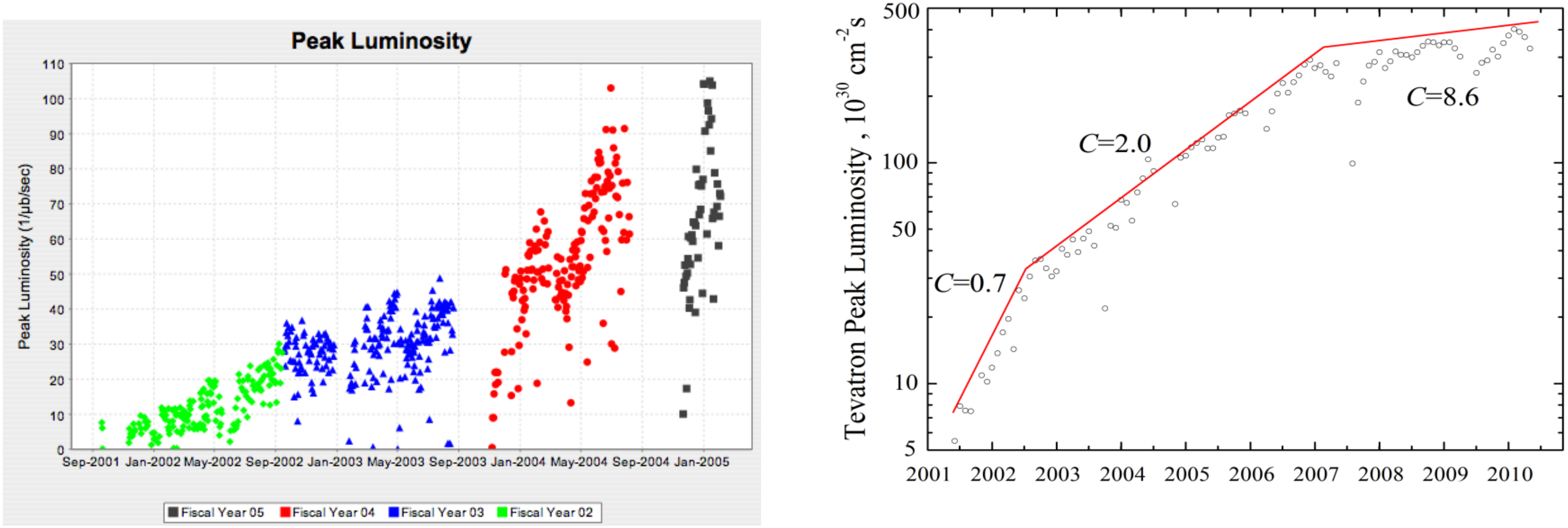
- The stored energy

$$E\propto N_b n_b\gamma$$

  - The higher the energy, the most challenging is the protection of the machine
    - A beam lost makes holes! Collimators protect the machine
  - For the LHC the beam has a total energy of 350 MJ

LUMINOSITY AND OPERATION

- Achieving the nominal performances is a long process!!
  - It usually takes years …



Increase in luminosity in Tevatron Run II [V. Shiltsev]

LUMINOSITY AND OPERATION

- Achieving the nominal performances is a long process!!
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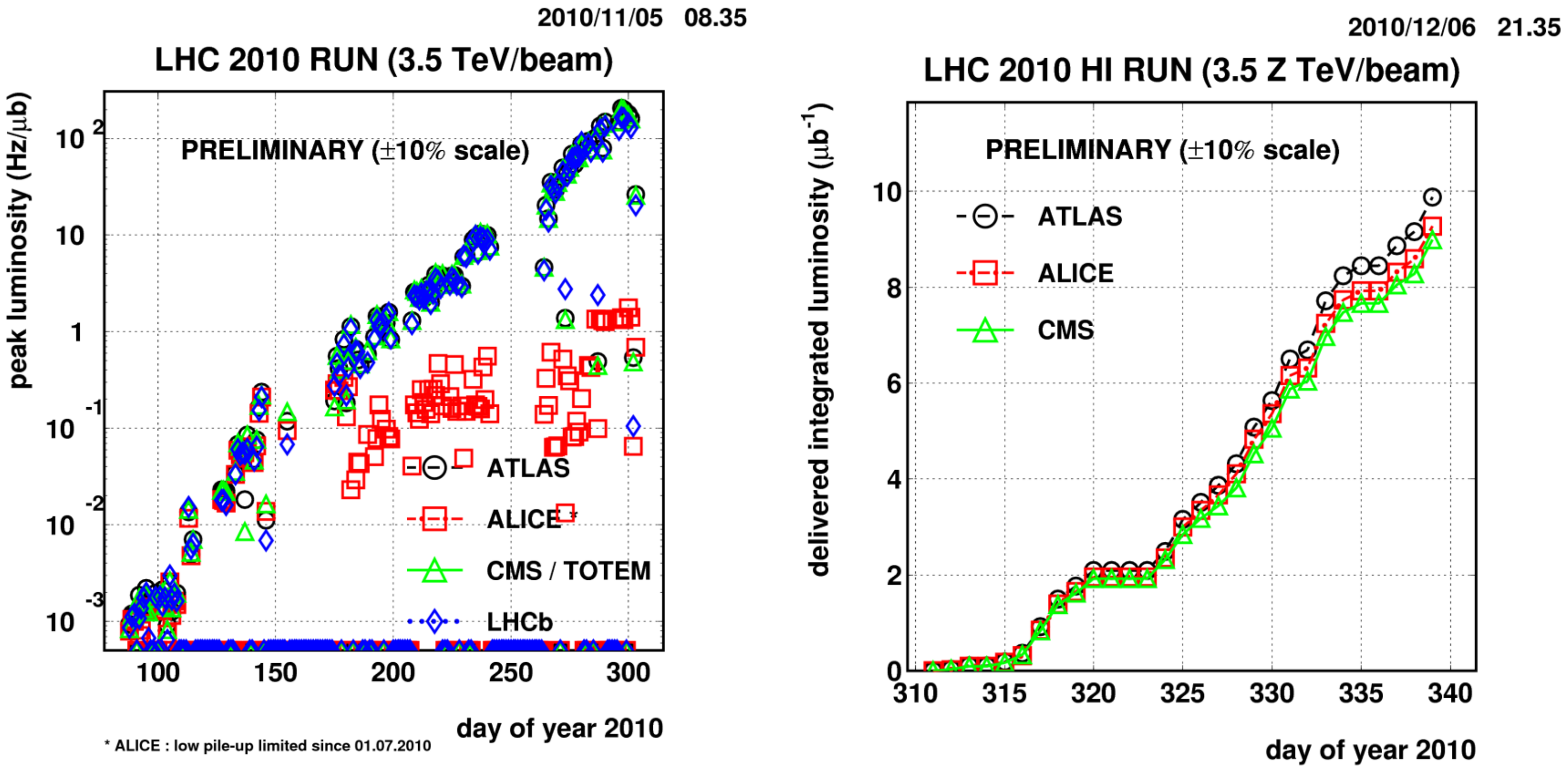
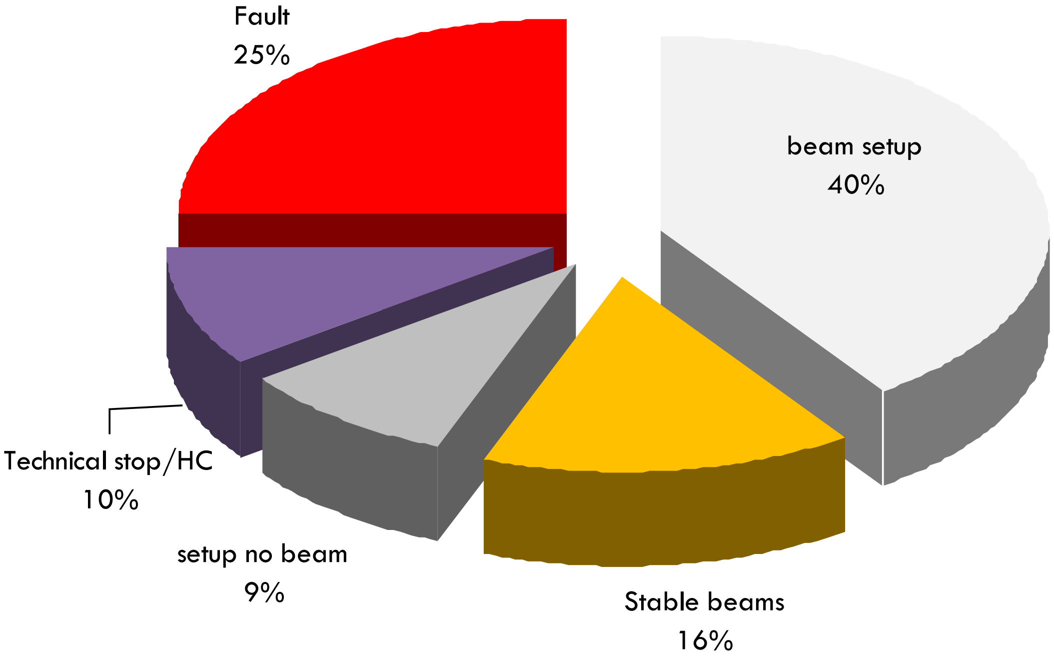


Increase in luminosity in LHC 2010 [M. Lamont, M. Ferro Luzzi]

LUMINOSITY AND OPERATION

- Achieving peak luminosity is not everything: one has to do it continuously
  - In 2010 we had 1/6 of the time used for making collisions – not bad



Time dedicated to beam in 2010 [W. Venturini Delsolaro]

LUMINOSITY AND OPERATION

- Where are we today?

$$L=\frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}F=\frac{c}{4\pi}\gamma\frac{1}{L}N_b^2 n_b\frac{1}{\varepsilon_n\beta^*}F$$

	Nominal	2010	Loss w.r.t. nominal	Reason
N_b	1.15×10^{11}	1.2×10^{11}	0.9	Better than expected - injectors can put many protons!
n_b	2808	400	7.0	Above 400 one start to see electron cloud - to be cured with scrubbing
γ	7000	3500	2.0	Limited to 3.5 TeV for interconnection problems (2010 incident)
ε	3.75	2.5	0.7	Much better than expected - injectors can give smaller beams!
β	0.55	3.5	6.4	Limited to 3.5 m, but 2 m reached
L			54	

- Total reached in 2010: around a factor 50 less than nominal
- Very good for first year! But the hard part has to come …