Appendix C: A digression on costs and two case studies

Ezio Todesco
European Organization for Nuclear Research (CERN)

Lectures based on University of Milano Bicocca courses in 2016-2018

Thanks to L. Bottura and G. de Rijk for proposing and supporting this initiative

All the units will use International System (meter, kilo, second, ampere) unless specified

CONTENTS

- Previous digressions in these lectures
  - Appendix A: A digression on beam optics, from stable motion to chaos
  - Appendix B: A digression on Maxwell equations and scales in atomic physics
- Coming today and next week
  - Appendix C: A digression on costs, and two case studies
  - Appendix D: A digression on manufacturing techniques of magnet components

CONTENTS

- Cost as enabling factor for technologies: two oversimplified cases
  - Power line
  - Large aperture solenoid (MRI-like)

- Two case studies
  - A conceptual design: a 640 T dipole as shown in Terminator III
  - A sensitivity analysis: how to squeeze some more field from LHC dipoles (Fresca dipole)

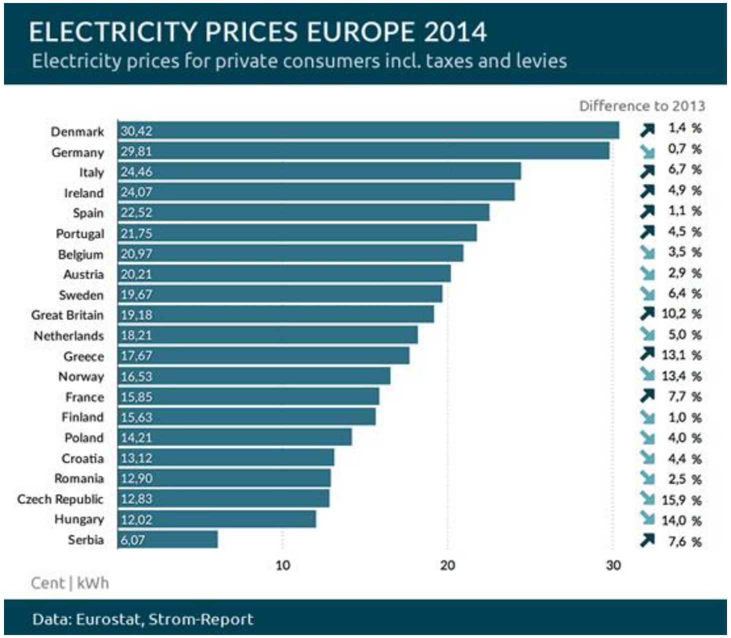
QUESTIONS

- If superconductivity exists and works, why do we still have resistive power lines ?

- Here we will address some issues related to costs using oversimplified models
  - Even though the simplifications we use are huge, one can learn something on cost as an enabling factor of a technology

ENERGY PRICE

- Electricity is the most versatile form of energy in our society, easy to transport (but not to store)
- Prices of electricity for private use range between 0.1-0.3 $/kWh
  - 1 kWh = 1000 J/s × 3600 s = 3.6 MJ
  - One LHC dipole has 2 kWh stored energy



[from http://strom-report.de/strompreise/#strompreise-europa]

ELECTRICITY PRICE

- A human being has a power of ~150 W
  - At the gym, we can lift 15 kg in 1 s for 1 m: 15×9.8×1/1 = 150 W
  - Infact, in one day you have about 86 000 s, this means you produce/consume 12 MJ, that is 3 kcal (6 BigMac – 1.5 LHC dipole)

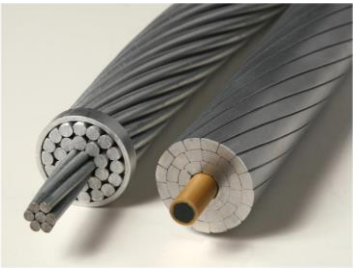
  - Considering that a human being can make 150 W, in our society electricity price corresponds to paying ~3 cents per hour a person … that's cheap

ALUMINIUM VERSUS COPPER

- The two main conductors are Al and Cu
- Different features:
  - Density: 2700 kg/m^3 for Al, 8900 kg/m^3 for Cu
  - Cost: 1.5 $/kg for Al, 4.5 $/kg for Cu

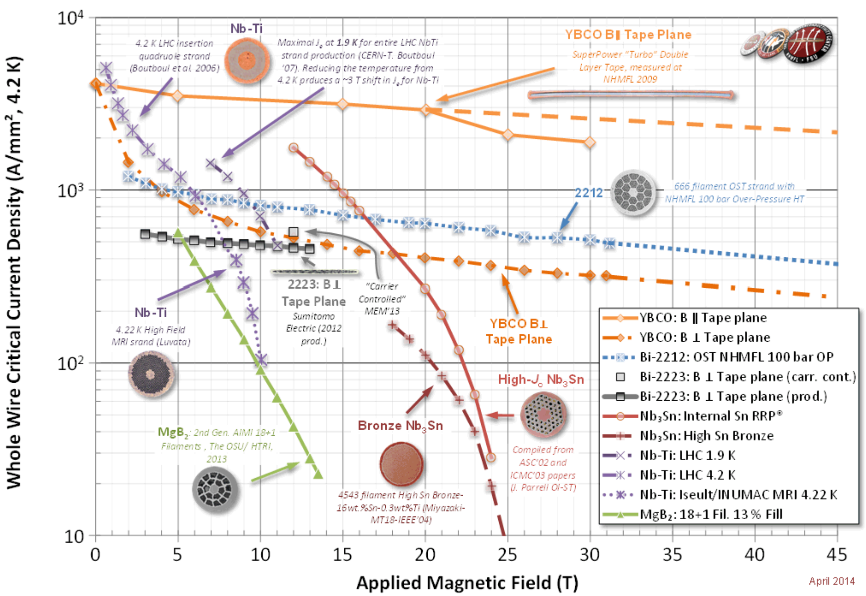
    (source www.metalprices.com)
  - Resistivity at 300 K: 2.7×10^{-8} Ω m for Al, 1.7×10^{-8} Ω m for Cu

    (many sources, see Y. Iwasa, "Case studies in superconducting magnets", Springer, or J. Ekin, "Experimental techniques for low temperature measurements", Oxford Univ. press)
  - What counts for electricity is the volume: the difference in volumetric price is a factor ten in favor of Al
  - That's why Al is used when large quantities are needed (power lines)
  - The lower mechanical strength is compensated by adding some stainless steel
- Limits to current density
  - 1 A/mm^2 without active cooling
  - 5 A/mm^2 with cooling



COST OF SUPERCONDUCTORS

- There are orders of magnitudes in the price of conductors and superconductors
- Price is a primary factor to enable a technological switch
  - Nb-Ti for accelerator magnets is 200 $/kg
  - Nb_3Sn lower cost is 800 $/kg (low current density for ITER)
  - HTS are more than one order of magnitude w.r.t. Nb_3Sn



[P. Lee famous plot, http://fs.magnet.fsu.edu/~lee/plot/plot.htm]

COST IN \$/kA m

- Price of superconductors is also given in \$/kA m
  - At the end, this is what is interesting to make power lines or magnets (Ampere turns)
  - One has to associated a current density *j*

$$p_{kAm} = p_{kg} \frac{\rho}{j\left[A/mm^2\right]} 10^{-3}$$

- Example of Nb-Ti, j = 500 A/mm^2
  - To carry 1 kA one needs 2 mm^2
  - One meter of this wire has a volume of 2×10^{-6} m^3
  - For Nb-Ti it has a weight of 12 g, and a cost of 2.4 \$/kA m

- Example of Al, 1 kA can be carried out by 1000 mm^2
  - One meter of this wire has a volume of 10^{-3} m^3
  - For Al it has a weight of 2.7 kg, and a cost of 4.0 \$/kA m

- For Nb-Ti, the 500 times larger ability of carrying current density is more than compensating the 200 times larger price

EXAMPLE: A POWER LINE

- What counts is the price per kA m, and Nb-Ti is cheaper than Al
  - Notwithstanding the much larger price (200 $/kg versus 1.5 $/kg), the current density is more than 100 times larger and therefore in terms of material is competitive
  - Much higher prices for other materials must be compensated by a corresponding increase in the current density, and today this is not the case for Nb_3Sn or HTS

- For a power line there are two additional factors
  - Losses on large distances can be reduced to very small fraction of total energy by using a higher voltage
    - Infact, losses are dominated by the last kilometer distribution, that are at lower voltage
  - Superconductivity would require diffused cryogenic installations whose cost in non negligible

EXAMPLE: A POWER LINE

- Let us consider a power line of 100 km carrying 100 MW
  - We will show that losses can be made negligible
- Overhead power lines rated according to the voltage
  - Low voltage below 1 kV
  - Medium voltage 1 – 70 kV urban and rural areas
  - High voltage 70-230 kV
  - Ultra-high voltage over 230 kV up to 800 kV
- High voltage means low current, and low losses
  - Note that we make a DC example, even though power lines are AC
  - With 500 kV, one needs to carry 200 A : $500\times1000\times200 = 100$ MW
  - Assume a conductor with 0.1 A/mm^2 (to minimize losses)
  - 2000 mm^2 needed, corresponding to 200 m^3 of conductor
  - Resistivity is $2.7\times10^{-8} / 2\times10^{-3} \times 10^{5} = 1.35\ \Omega$
  - Losses are $R\, I^2 = 1.35 \times 200^2 = 54$ kW less than 1 per mil of the 100 MW

EXAMPLE: A POWER LINE

- Losses are dominated by the last km of the power line, where the high voltages cannot be used
- Even though resistive losses cannot be a cost driving factor, there are several other aspects that can push for some specific applications of superconductivity to power lines
  - In particular large current densities of superconductivity allow much more compact devices – this can be an enabling factor for cases in which space has a large cost: for instance underground power line in dense metropolis
  - See for a review on possible advantages H. Thomas, et al. “Superconducting transmission lines” *Renewable and Sustainable Energy Reviews* **55** (2016) 59-72
- The compactness of superconductivity makes it an interesting option for all applications where weight/space has a large cost: for instance the motor windings in wind turbines, see A. B. Abrahmsen, et al. “Large superconducting wind turbine generators” *Energy Procedia* **24** (2012) 60-67

CONTENTS

- Cost as enabling factor for technologies: two oversimplified cases
  - Power line
  - Large aperture solenoid (MRI-like)

- Two case studies
  - A conceptual design: a 640 T dipole as shown in Terminator III
  - A sensitivity analysis: how to squeeze some more field from LHC dipoles (Fresca dipole)

EXAMPLE: A MRI MAGNET

- Let us consider a MRI (Magnetic Resonance Imaging) magnet with 1 m diameter, 2 m long, 4 T operational field

  - We assume is a vertical dipole (not a solenoid) to use our formulas for accelerator magnets

$$B = 6.9 \times 10^{-4} w(mm)\, j(A/mm^2)$$

  - Therefore for 4 T, with 5 A/mm^2 we need a coil width of w=1200 mm
  - Let us consider an aperture r=500 mm

EXAMPLE: A MRI MAGNET

- B=4 T j= 5 A/mm^2 r= 500 mm w=1200 mm

- Conductor volume V=11 m^3

$$V = L\frac{2}{3}p(w^2 + 2rw)$$

- Let us assume a cable surface A with N turns
  - Total length of conductor is

$$l_c = 4LN$$

  - Resistance is

$$R = \frac{r}{A} l_c \qquad V = Al_c$$

  - Dissipated power is

$$P = RI^2 = \frac{r}{A} l_c j^2 A^2 = r l_c j^2 A = r j^2 V$$

  - Let us take copper to minimize losses: P=1.7×10^{-8}×(5×10^6)^2×11=4.6 MW

EXAMPLE: A MRI MAGNET

- Summary of the resistive magnet: operational current of 5 A/mm^2
  - Large coil thickness of 1200 mm
  - Volume of coil is 11 m^3, this gives 100 tons of Cu and 450 k$ of material
- Dissipated power is 4.6 MW, assuming a 50% availability during the year (5000 hours) this makes 23 GWh, for a cost of 4.5 M$/y

- Let us make a further attempt to optimize:
  - We divide by 3 the current density, and by 10 the dissipated power
  - Current density is 1.6 A/mm^2, coil thickness goes to 3800 mm, total size of the magnet is 8 m – pretty large
  - Operational cost is 0.45 M$/y
  - But copper volume is 75 m^3, 3 M$ cost for the conductor only … not to speak about the large infrastructure

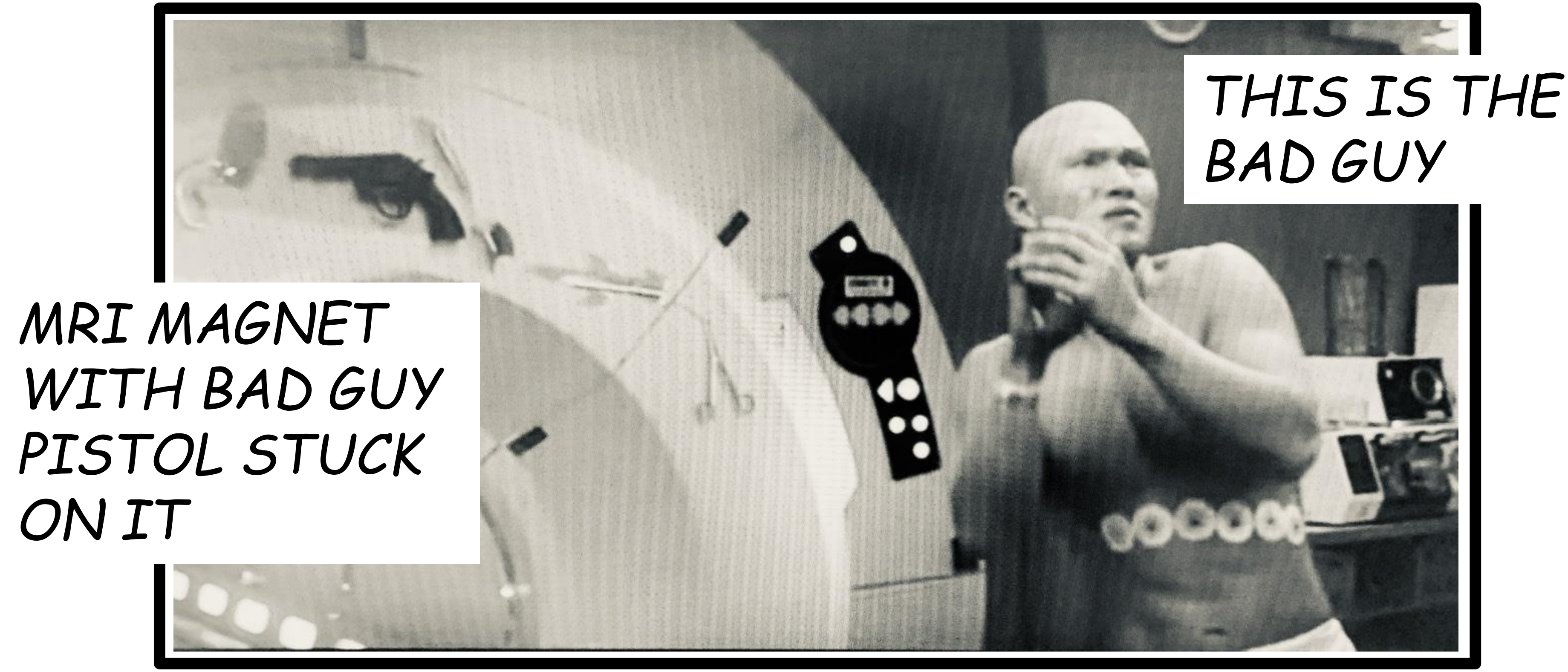
EXAMPLE: A MRI MAGNET

- Let us explore the superconductive option with Nb-Ti
- We can have 400 A/mm^2, i.e. produce the 4 T field with only 15 mm coil width
  - The total volume is 0.065 m^3, for a superconductor mass of 500 kg
- In case of Nb-Ti this is 100 k$ of material
  - Cheaper than copper, even in the 5 A/mm^2 option
  - But operational cost only related to cryogenics (local in this case, ie close to the magnet – one does not need to cool a 100 km line), instead of 4 M$/year …
- Once more, cost is critical !

- An essential feature of superconductivity is the ability to use very high current density without paying the associated losses

TALKING ABOUT MRI …

- James Bond switching on and off an MRI magnet during a fight
  - Die another day(L. Tamahori, Eon productions, 2002)
  - Well, MRI do not switch on and off in a fraction of second …



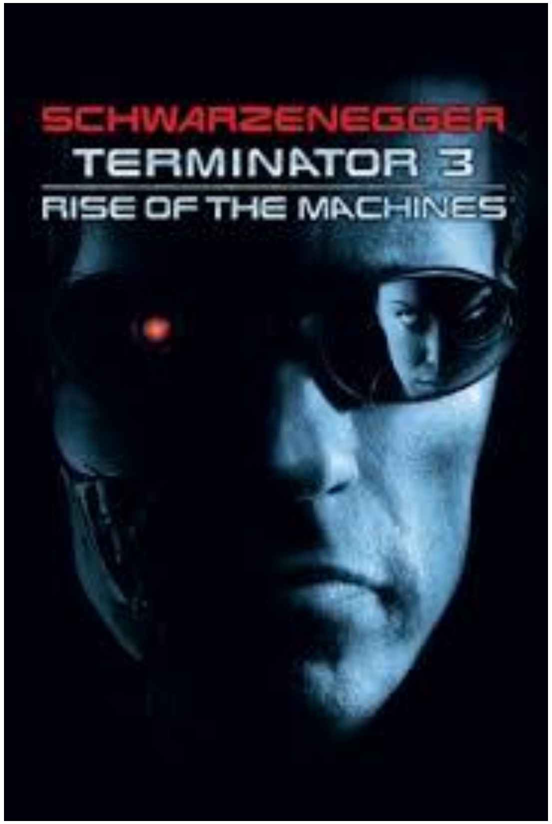
SOMETHING MORE FROM HOLLYWOOD

- The man with golden gun (G. Hamilton, Eon productions, 1974)
  - James Bond explaining to the M. Scaramanga how solar energy can be stored in superconducting magnets operating in liquid helium
  - Well, magnetic field is not the best place to store energy …
- Live and let die (G. Hamilton, Eon productions, 1973)
  - James Bond using a magnetic watch to open a closet and to unzip the clothes of a spy
  - Well, I let you make the computations…
- X-Men 2 (B. Singer, 20th Century Fox, Marvel ent. et al, 2003)
  - Magneto escaping from his plastic prison using the iron in the blood of the guard
  - I'm not able to comment this …
- At the end, the accelerator shown in Terminator is not one of the most impossible devices …

A FEW WORDS ON THE MOVIE

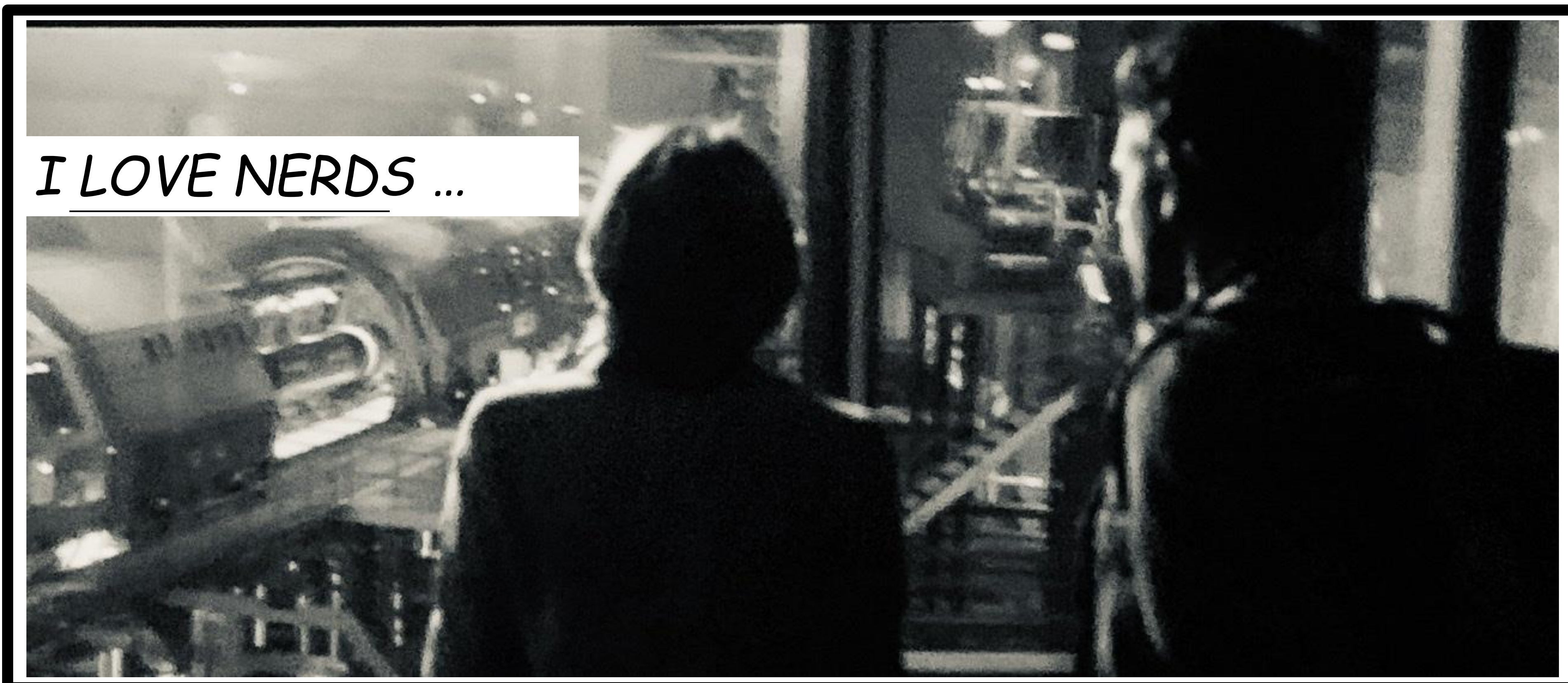
- Terminator: the rise of the machines (J. Mostow, Intermedia and C2 pictures, 2003)
  - Third episode of the Terminator saga
- Three main elements
  - Human beings losing control over machines
    - Golem (Jewish tradition, around 1500)
    - Frankenstein (M. Shelley, 1818)
    - Matrix (L. Wachowski and L. Wachowski, 1999)
  - Enhanced human beings, or human-like machines

    ... in the cyberpunk tradition
    - Blade Runner (R. Scott, 1982)
    - Robocop (P. Verhoeven, 1987)
  - Travelling in time
    - The time machine (H. G. Wells, 1895)
    - La jetée (C. Marker, 1962)
    - Back to the future (R. Zemeckis, 1985)
    - 12 monkeys (T. Gilliam, 1995)



TERMINATOR III DIGEST

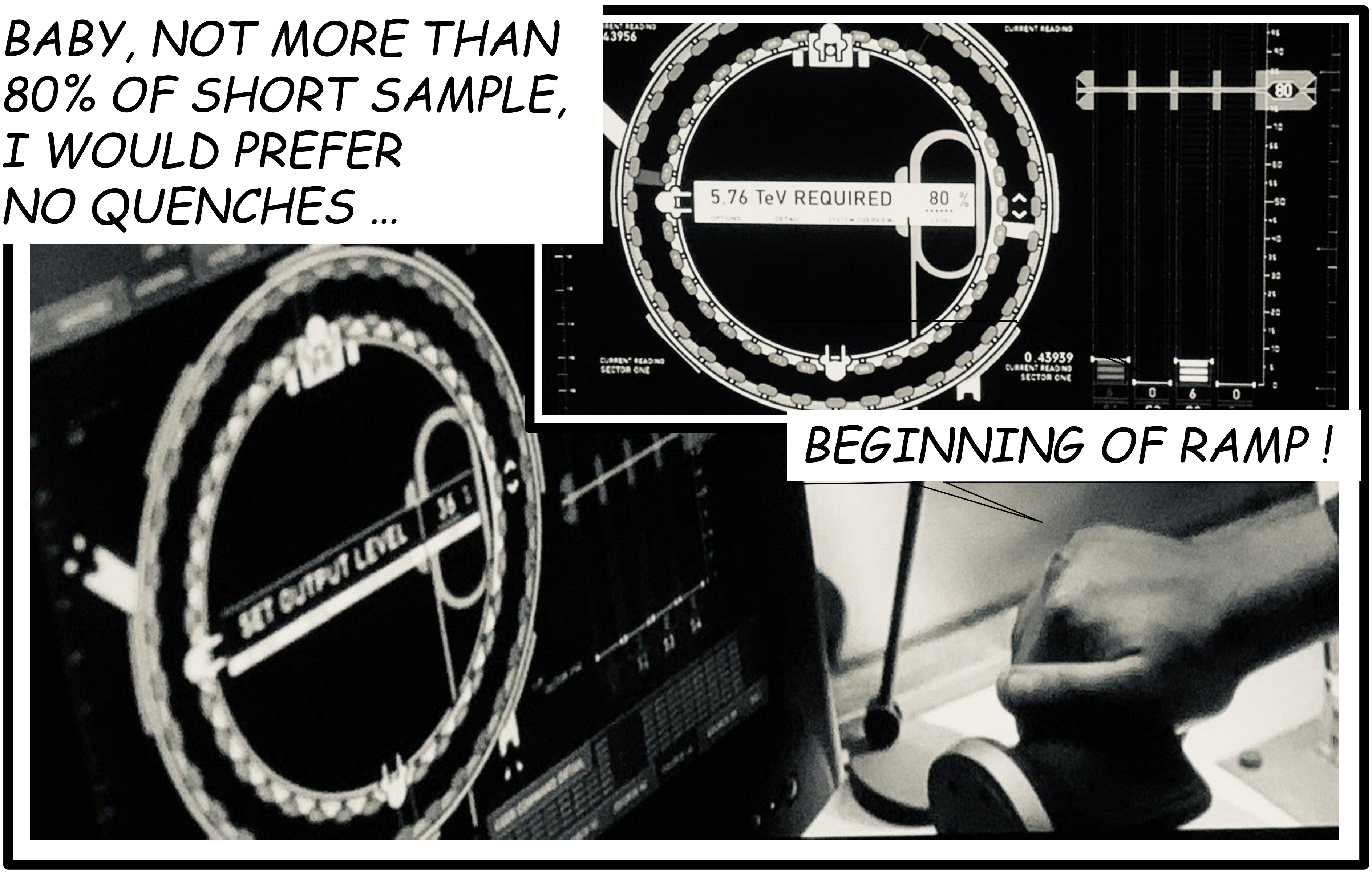
A 5.76 TeV ACCELERATOR!! WITH THIS SIZE
THE MAGNETS SHOULD MAKE 600 T!



LET'S RAMP THE MAGNETS:
THE TERMINATOR WILL STICK
ON THEM AS A SOUVENIR
ON THE FRIDGE !

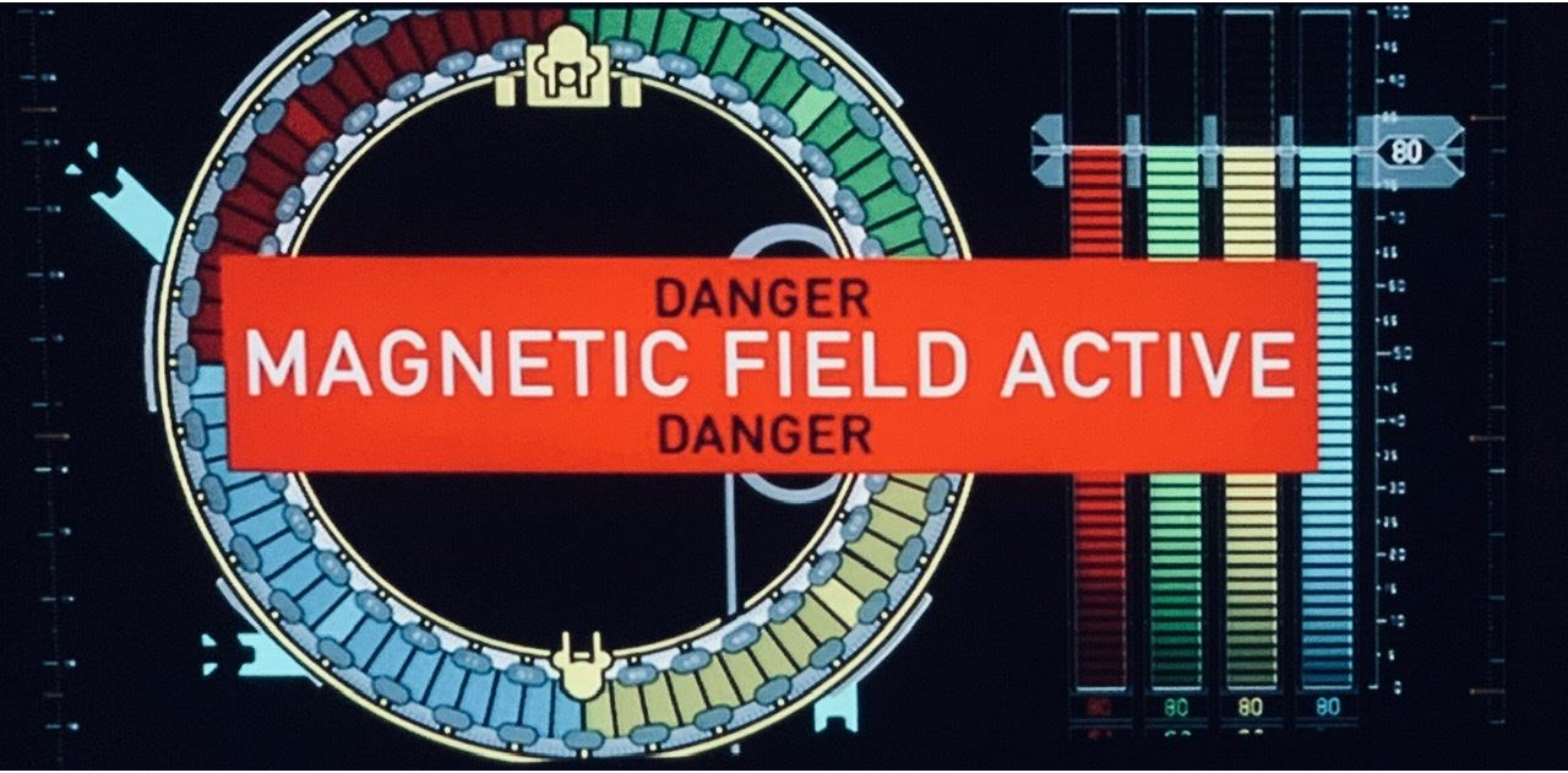
THIS WOULD NEVER
WORK IN THE LHC ...

TERMINATOR III DIGEST



TERMINATOR III DIGEST

TERMINATOR III DIGEST



…. IT WORKS !!!

DIE YOU ***** …

MAGNETIC FIELD AND CURRENT DENSITY ESTIMATE

- Curvature radius of the order of 30 m (circumference of 200 m)
- Energy is 5760 GeV
  (see Unit 1)

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

  - Field required is 5760/9=640 T

- Magnet length is much shorter than in LHC (2 m)
- Magnet cryostat has the same size of LHC (1 m)
  - Not clear if this is a collider (double aperture) or a single aperture
    - We assume it is a single aperture with 50 mm aperture (25 mm radius)
  - Magnet size cannot be larger than 800 mm (diameter)
  - Coil width cannot be larger than 250 mm, so let us assume a w=0.25 m (a very large coil width)
  - This leaves 125 mm for the mechanical structure

MAGNETIC FIELD AND CURRENT DENSITY ESTIMATE

- 640 T given by 250 mm coil width (see Unit 4)

$$B_1 = 6.9\times 10^{-4}\, w\left[\mathrm{mm}\right] j\left[\mathrm{A/mm^2}\right]$$

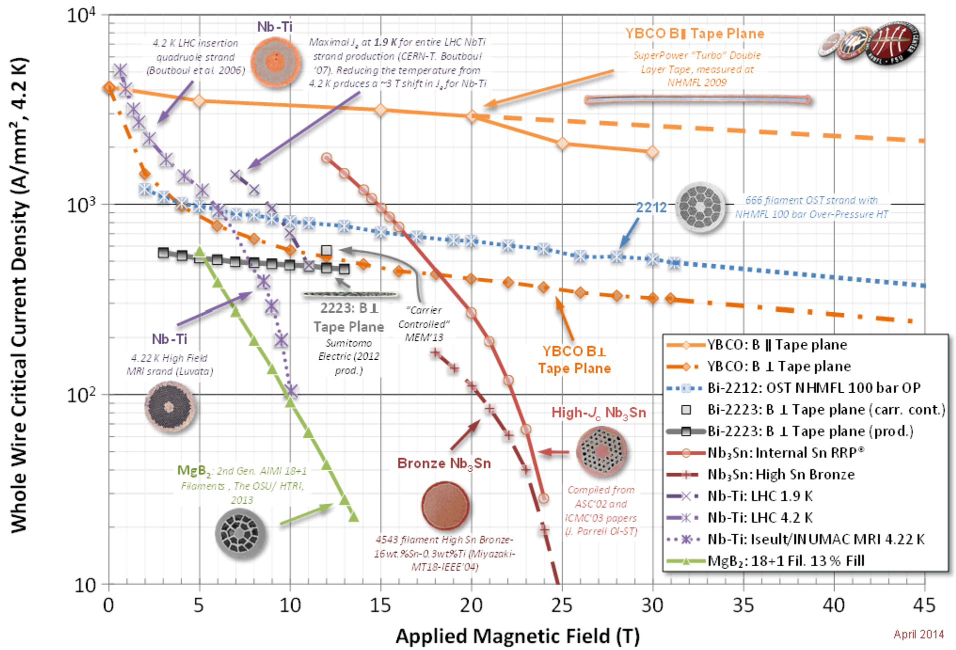
  - In the LHC we have 30 mm coil width and 400 A/mm^2, giving 8 T
  - We need to increase 80 times the field, we increase 8 times the coil length, so the current density must increase by a factor 10
  - Overall current density is 4000 A/mm^2
  - We are a factor ten above typical values in accelerator magnets
- Iron cannot help much …
  - With r=25 mm, w=200 mm if we place the iron directly in contact with the coil we have R_I=225 mm and the field enhancement due to iron is
  - (25×225)/225^2=11%

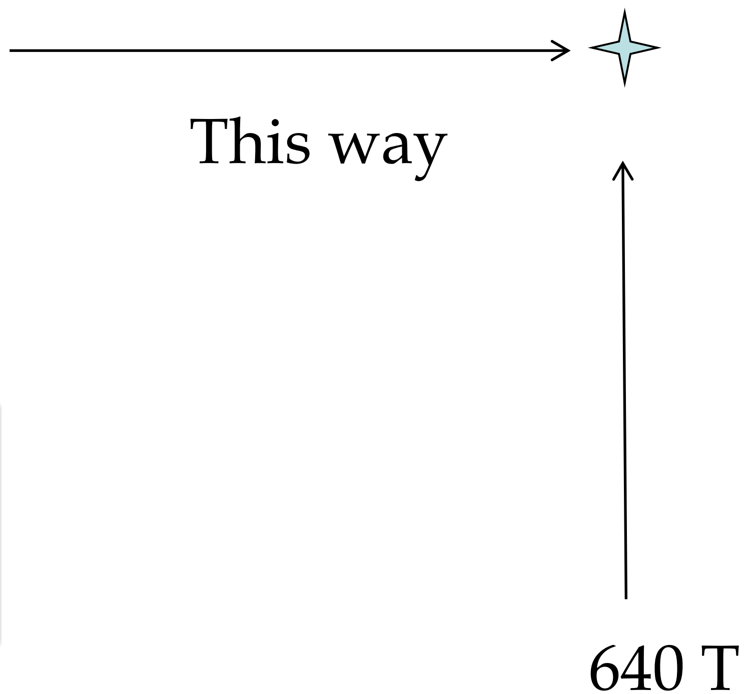
  (See Unit 9)
  - At these field it is totally saturated … let us neglect its contribution

MAGNETIC FIELD AND CURRENT DENSITY ESTIMATE

- Field of 640 T, coil width of 250 mm
  - Current density of 4000 A/mm^2
  - At 80% of short sample, therefore conductor should have 5000 A/mm2 overall current density at 800 T
  - 15000 A/mm^2 superconductor current density at 800 T, assuming 1/3 of sc

(see Unit 5)





LORENTZ FORCES

- Accumulation of stress in the midplane (see Unit 10)

$$s_q(MPa) = \frac{j(A/mm^2)B(T)r(mm)}{2000}$$

  - On the border of the aperture: σ_θ=4000×25×640/2= 32 GPa
  - Using the Fessia-Regis corrective factor,

$$s_{q\max} = \frac{jBr}{2}\max_{0<x<w}\frac{2(r+x)^3+r^3-3(r+x)^2(r+w)}{3wr(r+x)}$$

  - We get to 4.5 times larger value, i.e. 150 GPa
- Stress in the radial direction
  - It is about 1.5 times the magnetic pressure
  - σ_r=1.5×640^2/2/(4π10^7)= 240 GPa

- Therefore the superconductor should be able to withstand order of 250 GPa, without degradation
- … and the structure as well

COIL ENERGY DENSITY AND PROTECTION

- Estimate of stored energy
  - 640 T over an aperture of 25 (aperture)+125 (half coil width) mm
  - 23 GJ, or 12 GJ/m (it is 0.5 MJ/m in the LHC dipoles)

  - Coil area of 0.31 m^3
  - Energy density of 70 GJ/m^3 = 70 J/mm^3

(see Unit 12 and 13)

  - Protection limit given by coil enthalpy is 0.5 J/m^3 so this is impossible unless extracting 99.5% of the energy

COIL ENERGY DENSITY AND PROTECTION

- So let us consider the energy extraction
  - Short magnet of 2 m length – stored energy of 23 GJ
    - (this is 23 times the energy of all the 1232 LHC dipoles !)
  - Assume a very large cable, 30 mm width, 3 mm thickness
    - This has 90 mm^2, with 4000 A/mm^2 current density, so the magnet current is 360 kA, and inductance is 2×23 000 / 360^2 = 0.35 H

$$\Gamma(T_{max}) \equiv A^2 \nu \int_{T_0}^{T_{max}} \frac{c_p(T)}{\rho_{Cu}(T)} dT$$

  - What is the $\Gamma(T_{max})$ of a cable with 90 mm^2 surface?
    - Let us scale the plot, multiplying 10^{17} for the $(90\times10^{-6}\ \mathrm{m}^2)^2$ and taking half of Cu
    - This gives $\Gamma(T_{max})$ = 400 MA^2 s
    - Condition for protection is

$$\Gamma(300K) > \Gamma_q = \frac{U}{R_d} = \frac{UI_0}{V_{max}}$$

    - Therefore the resistance should be $R_d > U/\Gamma(300\mathrm{K}) = 23\times10^9/400\times10^6 = 60\ \Omega$
    - So to have energy extraction the magnet should withstand

$V_{max}=R_d I_0=60\times360$ kV = 22 MV

COIL ENERGY DENSITY AND PROTECTION

- An alternative path for protection
  - How about developing an electromagnetic coupling with the structure so that the whole magnet takes the heat ?
  - The magnet volume is $2\times0.4^2\times\pi= 1\ m^3$
  - Therefore the energy density is $23\ GJ/m^3 = 23\ J/mm^3$
  - Still too large … no way

- Summary of the requirements

- Conductor
  - Current density in the superconductor: >15000 A/mm^2 at 800 T
  - Filament size: 5 μm (scale with inverse of current density)
  - Cable with <5% degradation at 250 Gpa

- Structure
  - Structure able to withstand 250 GPa, with a thickness of 125 mm

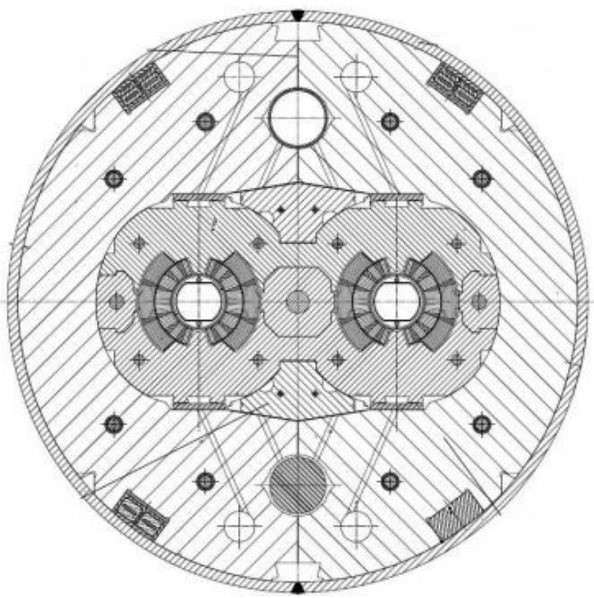
- Protection
  - Development of insulation able to withstand 50 MV, occupying not more than 20% of the coil volume

CONTENTS

- Cost as enabling factor for technologies: two oversimplified cases
  - Power line
  - Large aperture solenoid (MRI-like)

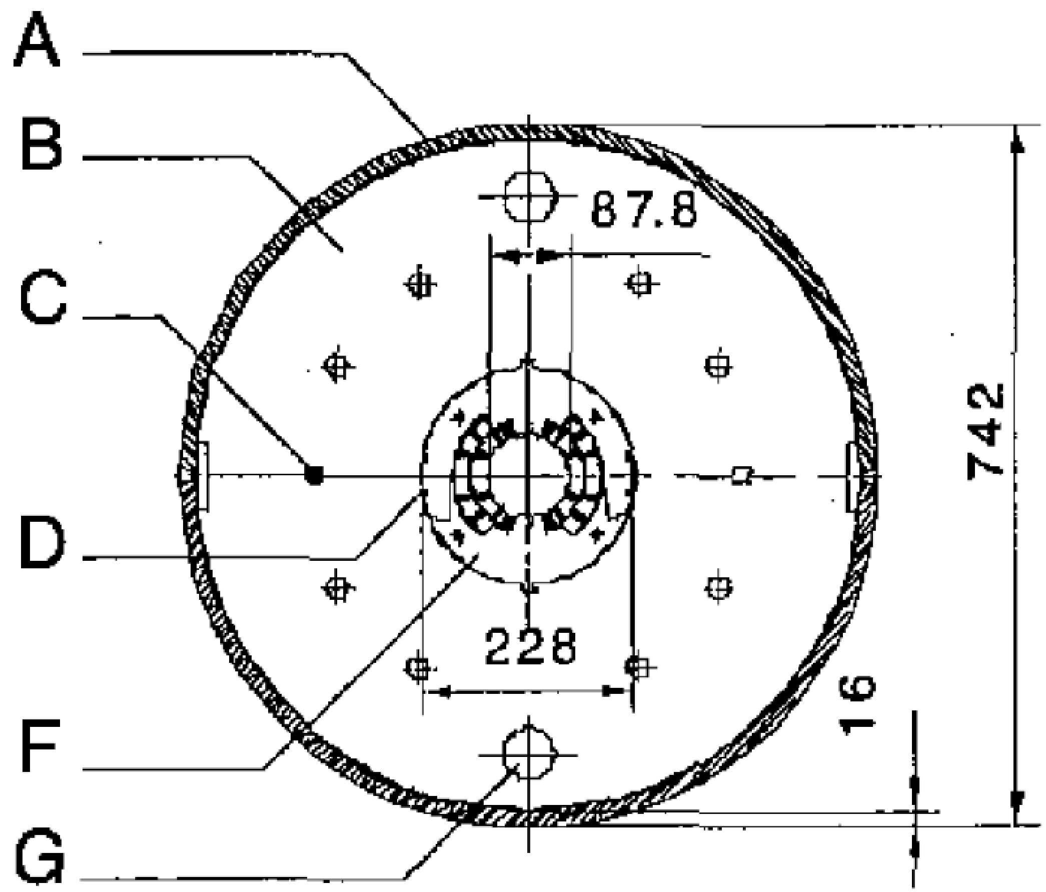
- Two case studies
  - A conceptual design: a 400 T dipole as shown in Terminator III
  - A sensitivity analysis: how to squeeze some more field from LHC dipoles (Fresca dipole)

LHC DIPOLE VERSUS FRESCA DIPOLE



LHC main dipole

(R. Perin, D. Leroy, S. Russenschuck D. Perini, P. Fessia, et many al.)

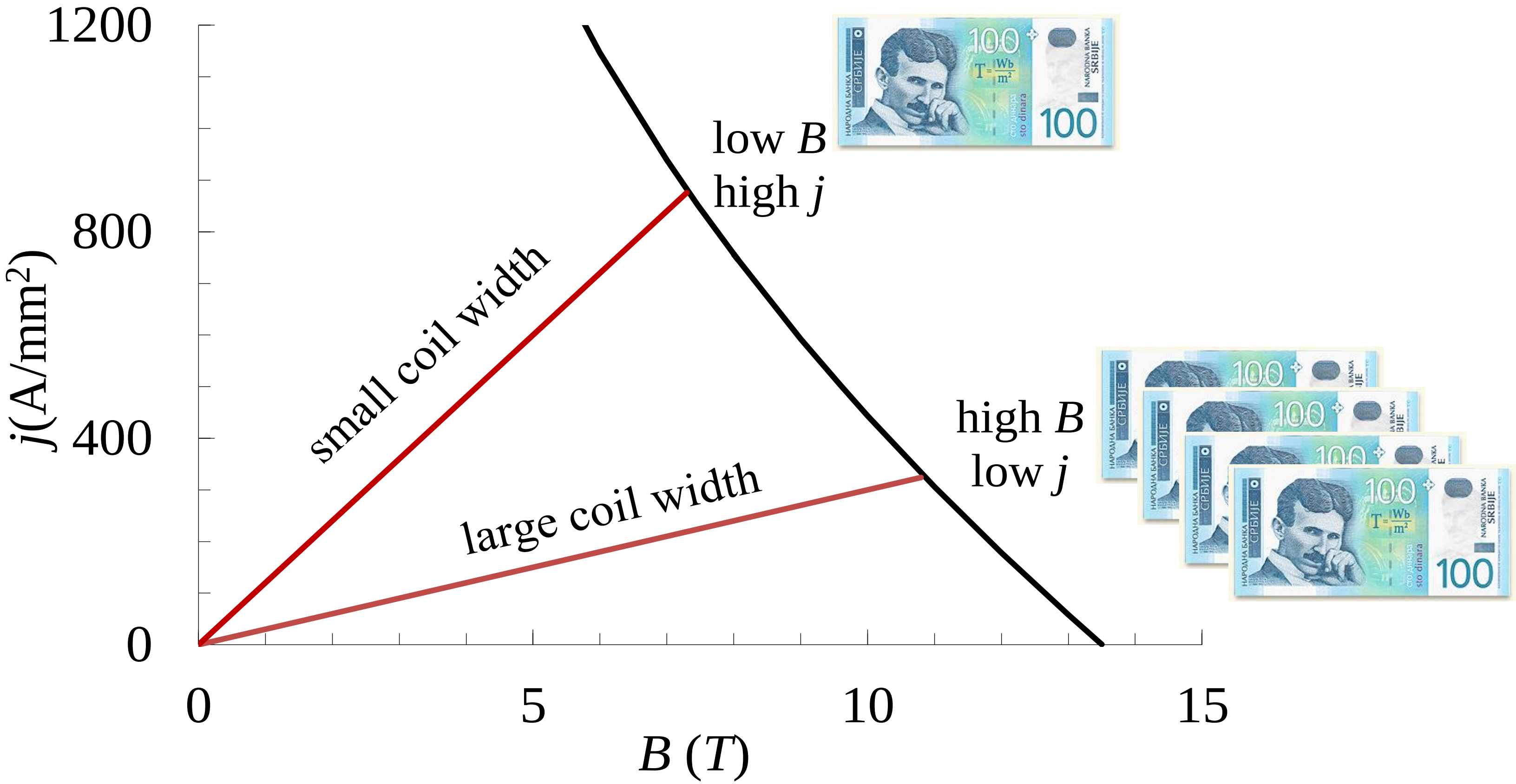


A) Shrinking Cylinder B) Yoke C) Alignment Key
D) Collar Key F) Collars G) Heat Exchanger Hole

Fresca dipole (G. Spigo, D. Leroy, A. Verweij)

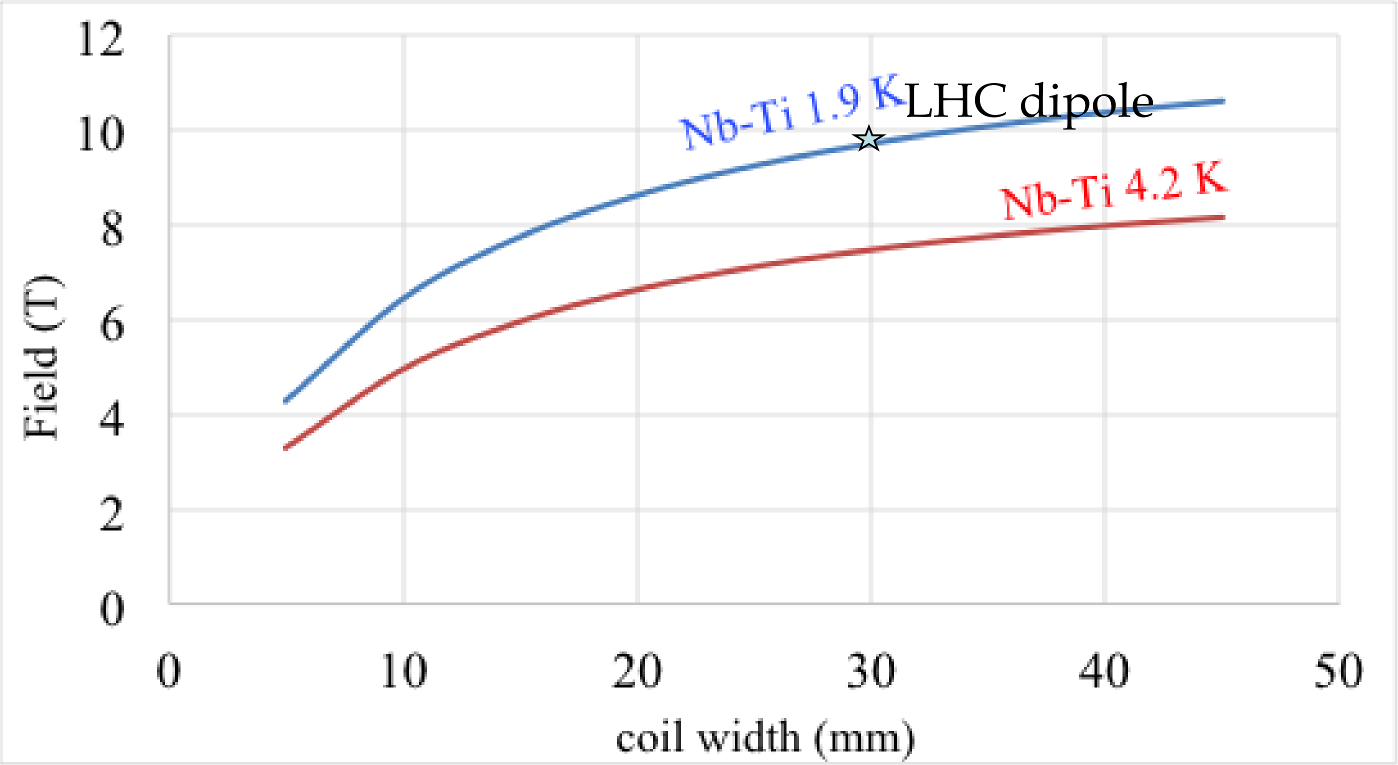
HOW TO SQUEEZE MORE FIELD FROM THE LHC DIPOLES

- As quoted in Unit 8, the short sample field versus the coil width has an implacable law, that make the last teslas very expensive



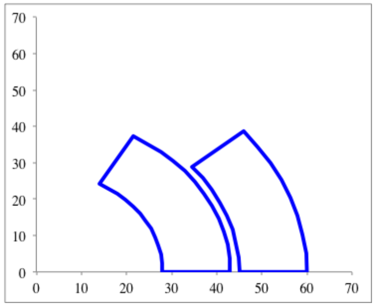
HOW TO SQUEEZE MORE FIELD FROM THE LHC DIPOLES

- LHC dipole, with its 30 mm coil width and 9.7 T short sample field, is considered to be the ultimate field reachable with Nb-Ti
  - However, the world record for accelerator like dipoles belong to Fresca – that managed to squeeze few more tenths of tesla out of Nb-Ti



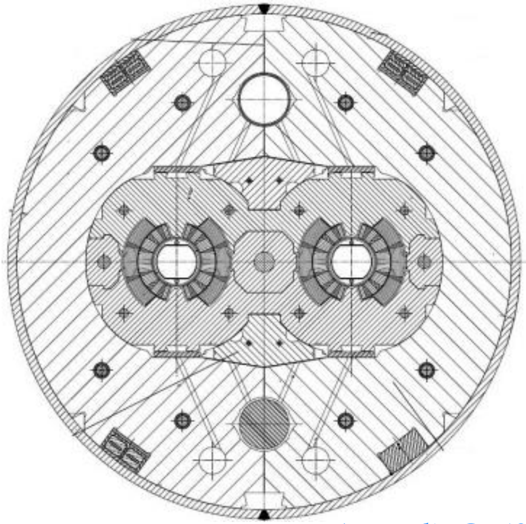
HOW TO SQUEEZE MORE FIELD FROM THE LHC DIPOLES

- Here we will discuss the use of the sensitivity equation applied to the LHC dipoles, in the direction pursued by Fresca dipole
- We start with the LHC dipole
  - Aperture 28 mm
  - Coil width: two layers of 15.4 mm width insulated cable
  - Insulated cable surface: 33.24 mm^2 (inner) 26.78 mm^2 (outer)
  - Turns: 15 (inner layer), 25 (outer layer)



- Equivalent coil width (ignoring grading)
  - Equation given in Unit 8, slide 18
  - A=4×15×33.24+4×25×26.78
  - w_{eq}=26.9 mm

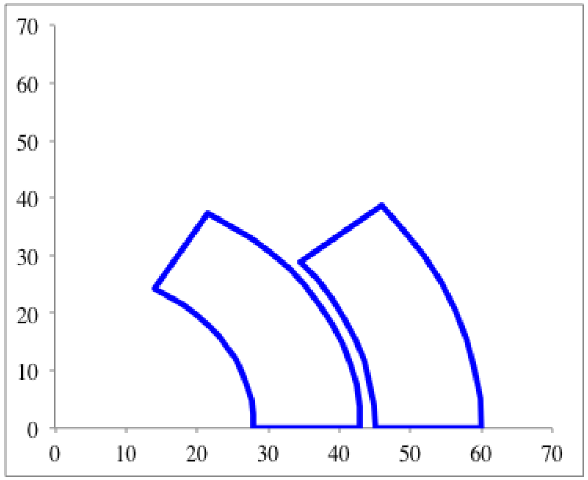
$$w_{eq} = r\left(\sqrt{1+\frac{3A}{2\pi r^2}} - 1\right)$$



HOW TO SQUEEZE MORE FIELD FROM THE LHC DIPOLES

- Here we will discuss the use of the sensitivity equation applied to the LHC dipoles, in the direction pursued by Fresca dipole
- We start with the LHC dipole
  - Aperture 28 mm
  - Coil width: two layers of 15.4 mm width insulated cable
  - Insulated cable surface: 33.24 mm^2 (inner) 26.78 mm^2 (outer)
  - Turns: 15 (inner layer), 25 (outer layer)
  - Grading: 33.24/26.78=1.24 (25% larger current density in the outer layer)
- Equivalent coil width (including grading)
  - Equation given in Unit 8, slide 18
  - $A=4\times15\times33.24+4\times25\times26.78\times1.24$
  - $w_{eq}=29.6$ mm

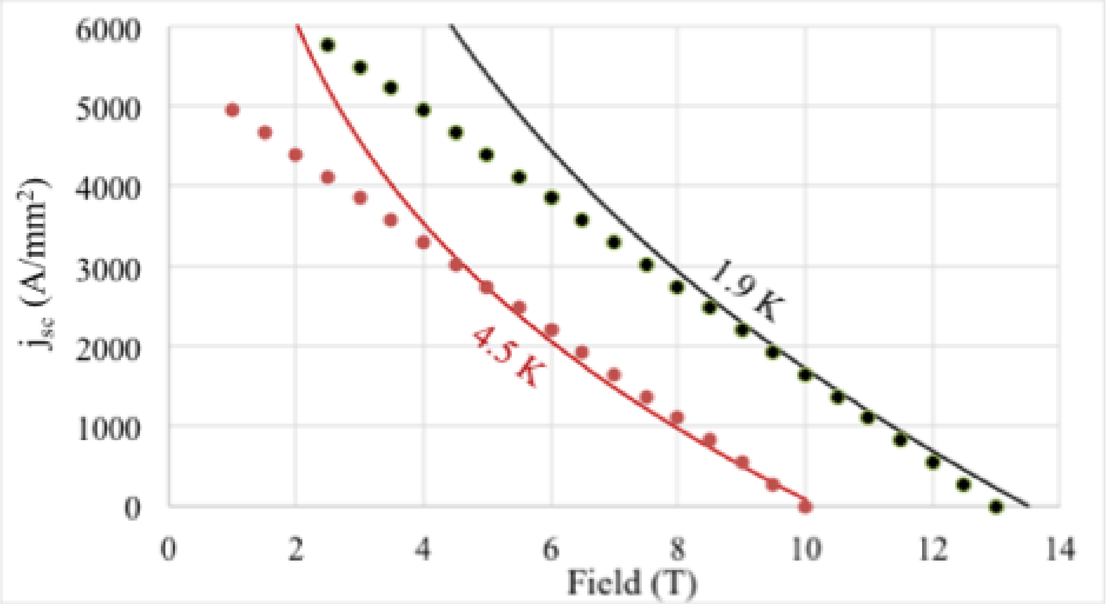
$$w_{eq} = r\left(\sqrt{1+\frac{3A}{2\pi r^2}}-1\right)$$



HOW TO SQUEEZE MORE FIELD FROM THE LHC DIPOLES

- Critical surface parameters (Unit 8, slide 6)
  - Slope of the critical surface at 1.9 K: s=550×10^6 A/m^2/T= 550 A/mm^2/T
  - Linear approximation of critical field at 1.9 K: b(1.9 K)=13 T

$$j_{sc,c}(B) = s(b(T) - B),$$



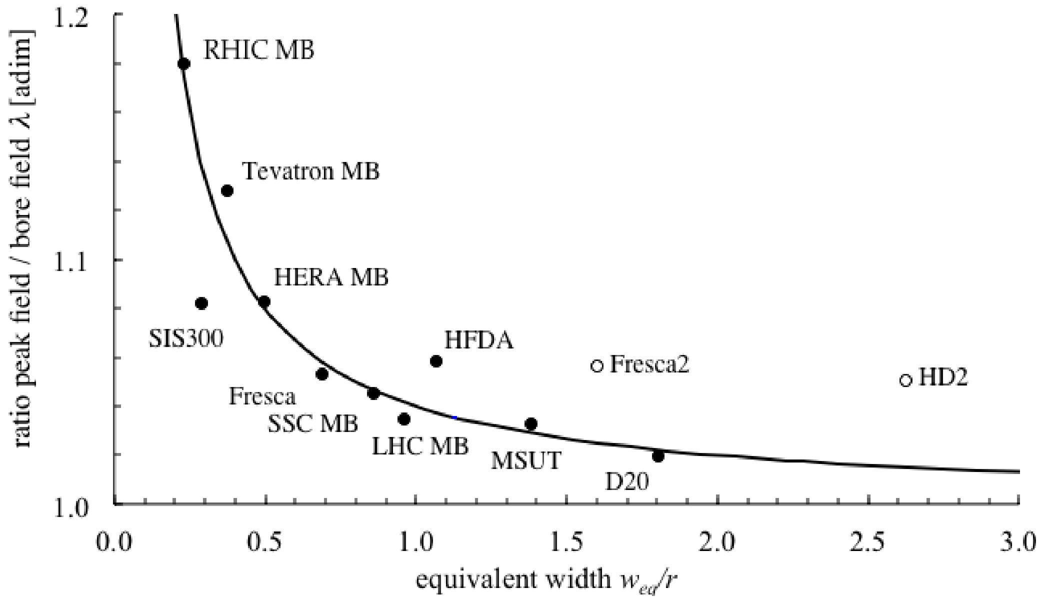
HOW TO SQUEEZE MORE FIELD FROM THE LHC DIPOLES

- Fraction of superconductor in the insulated cable (Unit 8, slide 8)
  - ν: ratio between area of superconductor and area of insulated cable
  - Inner cable: 28 strands, 1.065 mm diameter, 1.65 Cu/No_Cu – this gives A_{sc}=28×1.065^2×4/π/(1+1.65)=9.41 mm^2
  - Inner cable insulated surface 33.24 mm^2
  - Fraction of superconductor: 9.41/33.24=0.24
  - Outer cable cable: 36 strands, 0.825 mm diameter, 1.95 Cu/No_Cu – this gives A_{sc}=36×0.825^2×4/π/(1+1.95)=6.52 mm^2
  - Outer cable insulated surface 26.78 mm^2
  - Fraction of superconductor: 6.52/26.78=0.28

HOW TO SQUEEZE MORE FIELD FROM THE LHC DIPOLES

- Guess of ratio between peak field and bore field (Unit 8, slide 8)
  - λ=1+0.04×28/29=1.039
  - Therefore, peak field is 4% larger than bore field

$$\lambda(w,r) \sim 1+\frac{ar}{w_{eq}}$$

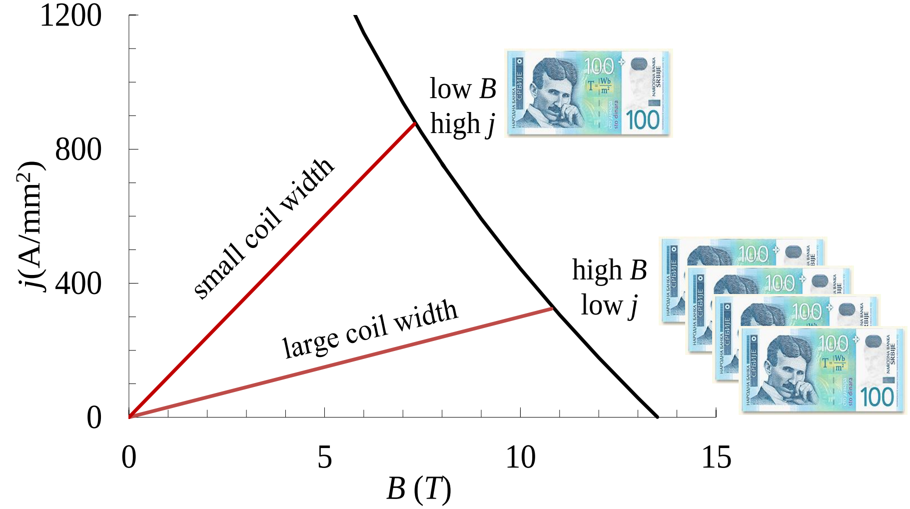


HOW TO SQUEEZE MORE FIELD FROM THE LHC DIPOLES

- Short sample estimate, no iron (Unit 8, slide 11, 12 and 24)
  - Estimate of the factor X
  - Where γ_c=6.6×10^{-7} T/A/m
  - X=6.6×10^{-7}×0.28×550×10^{6}×0.030=3.04
  - As we knew, we are in the regime of large coils
  - B_{ss}=13×3.04/(1+1.04×3.04)=9.50 T

$$X ° g_c ksw$$

$$B_{ss} = b \frac{X}{1+/X}$$

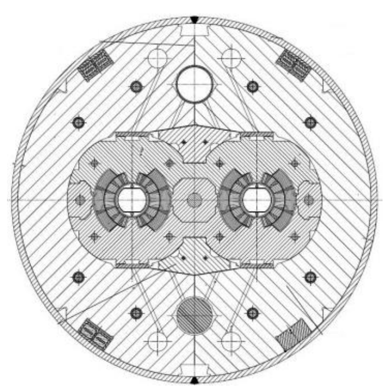


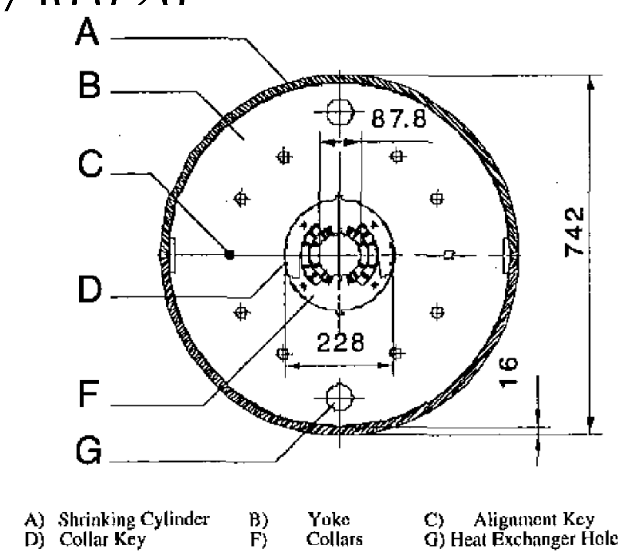
HOW TO SQUEEZE MORE FIELD FROM THE LHC DIPOLES

- Short sample estimate, with iron (Unit 8, slide 11, 12 and 24)
  - r: aperture radius
  - w coil width
  - R_I: radius of iron (obviously, R_I must be smaller than $r+w$)
  - Increase of transfer function due to iron: $$\frac{\Delta B_1^{iron}}{B_1} = \frac{\mu - 1}{\mu + 1}\frac{(r+w)r}{R_I^2} \approx \frac{(r+w)r}{R_I^2}$$
  - Therefore for LHC dipole (neglecting saturation)
    - Radius of iron is 98 mm
    - $\Delta B_1/B_1=(28+31)\times 28/98^2=0.17$
    - Therefore increase of 17% of field due to iron
  - Recomputing X including this increase: $$X \equiv g_c k s w \left(1 + \frac{\Delta B_1}{B_1}\right)$$
    - $X=6.6\times 10^{-7}\times 0.28\times 550\times 10^6\times 0.030\times 1.17=3.56$
  - And new short sample field is
    - $B_{ss}=13\times 3.56/(1+1.04\times 3.56)=9.84$ T (9.7 T computed with proper codes)

FROM LHC DIPOLE TO FRESCA

- Three main changes
  - Bare cable width is increased from 15.1 mm to 16.74 mm (+10.9%)
    - This increase reflects in the short sample with a factor $1/(1+\lambda X)=1/4.8$ (see Unit 8, slide 29) , therefore we gain 1.9% in short sample
  - Aperture is increased by nearly a factor two (from 28 mm to 43.9) – therefore ratio peak field/bore field improves from 1.039 (LHC dipole) to $\lambda=1+0.04\times 43.9/35=1.050$
    - This increase reflects in the short sample with a factor $X/(1+\lambda X)=3.6/4.8$ (see Unit 8, slide 29) , therefore we lose 0.8% in short sample
  - Iron contribution increases from 0.17 to 0.26
  - $\Delta B_1/B_1=(43.9+33)\times 43.9/114^2=0.26$





FROM LHC DIPOLE TO FRESCA

- New estimate
  - Equivalent coil width increases by 11% (15.1 mm to 16.7 mm bare cable, projected to equivalent coil width from 29.6 mm to 32.8 mm
  - Iron contribution increases from 0.17 to 0.26

    $\Delta B_1/B_1=(43.9+33)\times 43.9/114^2=0.26$

$$X \equiv \gamma_c k s w \left(1+\frac{\Delta B_1}{B_1}\right)$$

  - $X=6.6\times 10^{-7}\times 0.28\times 550\times 10^{6}\times 0.033\times 1.26=4.23$
  - Ratio peak field/bore field gets worse from 1.040 (LHC dipole) to $\lambda=1+0.04\times 43.9/35=1.050$
  - And new short sample field is
    - $B_{ss}=13\times 4.23/(1+1.05\times 4.23)=10.11$ T (10.15 T computed with proper codes)
    - Therefore, with a 10% increase in the width, and the enhanced contribution of iron, the final increase of the short sample field is 2.5%

SUMMARY

- Price is an important variable in the applications of superconductivity (as in most applications)
  - Price per volume of superconductors is 300 times larger than Al for Nb-Ti, and much larger for Nb_3Sn and HTS

- The main atout of superconductivity is to carry large current densities, and therefore provide compact devices, without having to pay for dissipated power
  - From 1-5 A/mm^2 to 100-500 A/mm^2 – it is a factor 100
    - For Nb-Ti, the larger current density roughly compensates the higher price
    - So the price per kA m is comparable

- Why 100-500 A/mm^2 and not more ?
    - Limits in the critical surface, instabilities (already shown) plus stresses induced by Lorentz forces in magnets and protection

SUMMARY

- With this range of prices and properties (current densities), superconductivity can replace resistive devices in some cases
  - Power lines: when compact devices are needed (example, power lines in metropolis, where the size becomes an issue)
  - Motors: when compact devices are needed (when weight is an issue)
  - For high field magnets, superconductivity allows not only to have compact devices but also saving on operational costs
    - NMR (Nuclear Magnetic Resonance) is a spectroscopy method to method to probe matter: physics, chemistry, material science, biology
    - MRI (Magnetic Resonance Imaging) is a special case of NMR, applied to biology
    - Accelerator magnets

900 MHz NMR magnet of 21.2 T

CONCLUSIONS

- We discussed the possibility of building a 600 T magnet as shown in a blockbuster science fiction movie
  - Using the equations derived for magnetic design, mechanical structure and protection we outlined the directions to explore to get to this target
- We showed how to use the equations discussed for the magnetic design to get a few more tenths of tesla in Nb-Ti magnets with two layers coils, showing how Fresca managed to break the 10 T barrier
  - This is another application of the analytical approach, that can be used to make accurate sensitivity analysis containing an "insight" on the main mechanisms