ACCELERATOR PHYSICS AND TECHNOLOGY - EPISODE II

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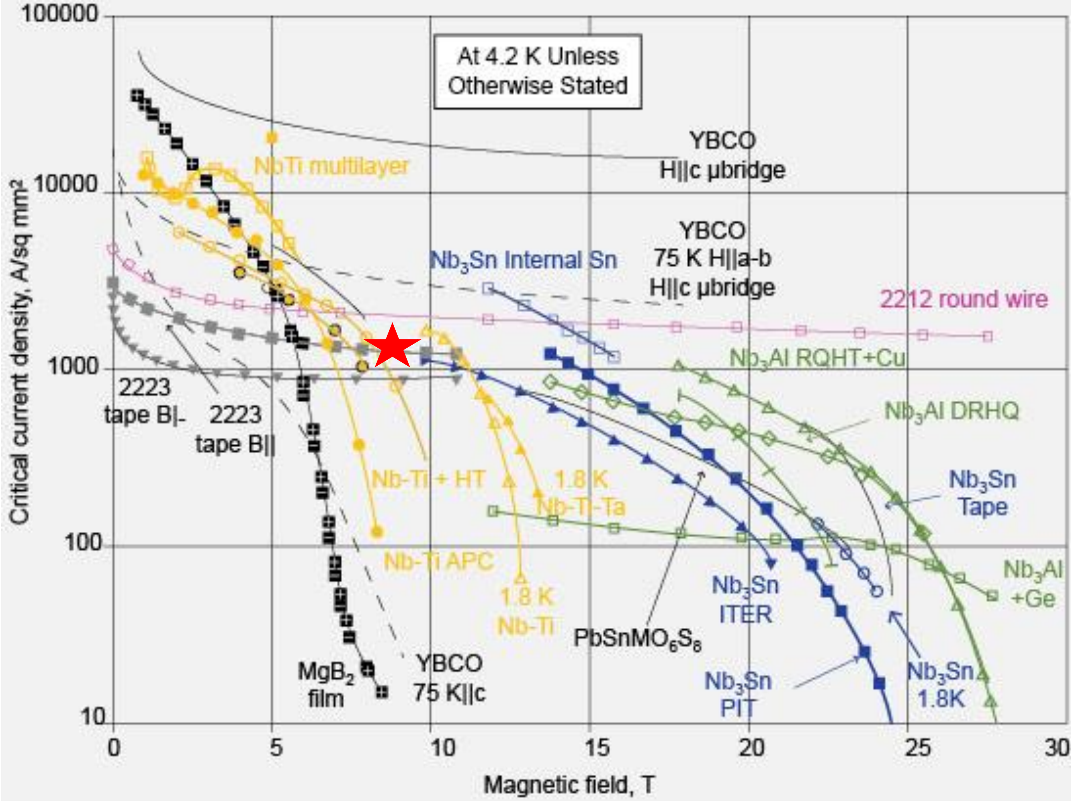
CONTENTS

- Limits of Nb-Ti magnets
- Towards larger fields: Nb_3Sn and HTS
- Limitations to current density: stress, protection

RECALL ON CRITICAL SURFACE

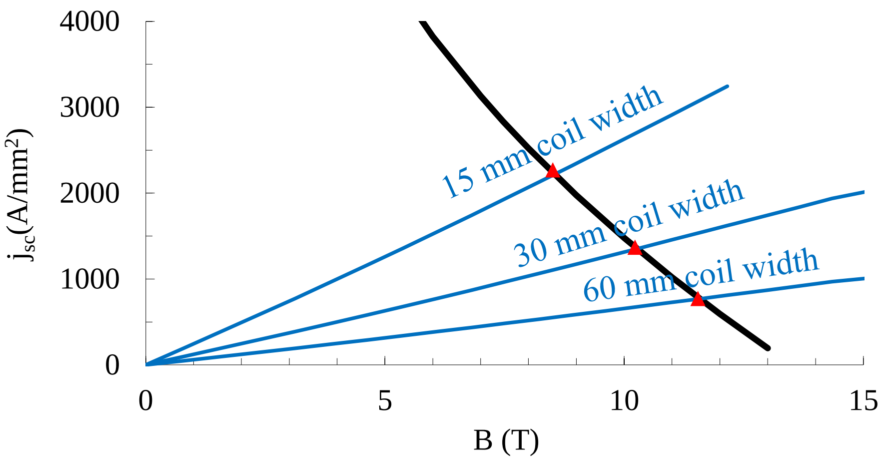
- Critical current density vs. field for different materials (semilog scale) at 4.2 K
  - To remember: more critical current density, less field



Critical current density in the superconductor versus field for different materials at 4.2 K [P. J. Lee, et al]

LIMITS IN NB-TI MAGNETS

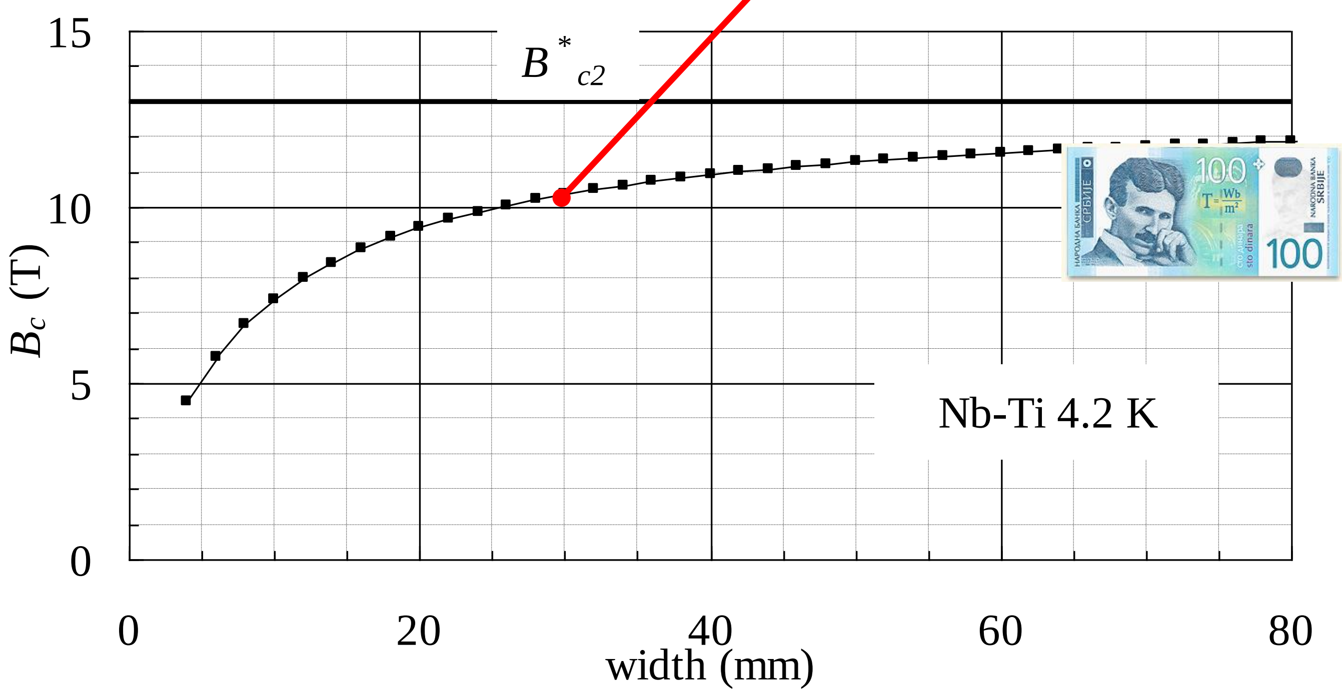
- Nb-Ti loses superconductivity at 13 T, 1.9 K – why 8 T is the limit ?
  - Cost
  - Stability
- We start with cost
  - Field is proportional to current density – so called loadline
    - At a certain point (B(j),j) crosses the critical surface – this is the limit
  - How to have more field ? Put more coil, and lower the loadline
  - But this is an expensive game !



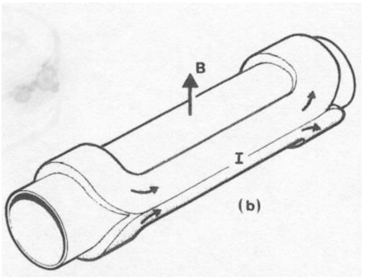
Critical surface for Nb-Ti: j versus B and magnet loadline

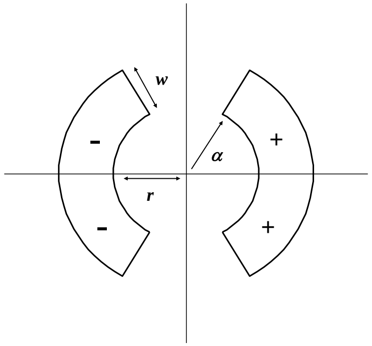
SUPERCONDUCTING MAGNET DESIG

- We have computed what field can be reached for a sector coil of width *w* for Nb-Ti – goes as ~$w/(1+w)$
  - There is a slow saturation towards 13 T
  - The last Tesla are very expensive in terms of coil, so we could go to 13 T, but we do not go: not for lack of physics but for lack of $$$
  - LHC dipole has been set on 30 mm coil width, giving ~10 T

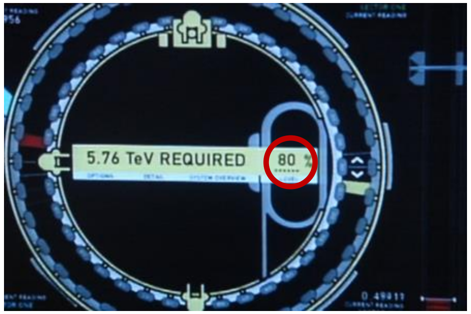


Field versus coil thickness for Nb-Ti at 1.9 K



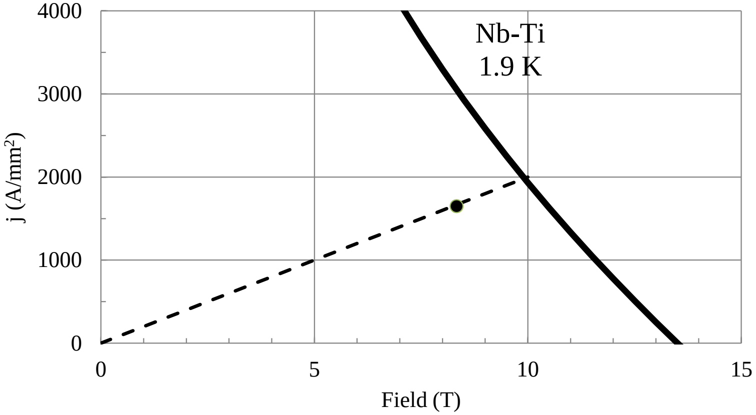


- Stability: one cannot work on the critical surface
  - Any disturbance producing energy (beam loss, coil movements under Lorentz forces) increases the temperature and the superconductivity is lost
  - A margin of ~20% is usually taken
    - So magnet work at 80% of loadline
    - LHC dipoles are giving 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
    - This corresponds to 2 K of margin



Margin of the main dipoles in four accelerators

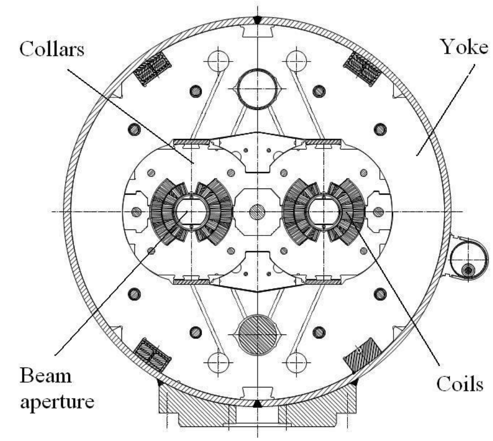
	Nominal			Actual		
	Temp. (K)	Field (T)	Margin	Temp. (K)	Field (T)	Margin
Tevatron	4.6	4.3	4%	4.6	4.2	6%
Hera	4.6	4.7	23%	3.9	5.3	23%
RHIC	4.5	3.5	30%	4.5	3.5	30%
LHC	1.9	8.3	14%	1.9	*7.8**	*19%*



IRON SHIELDING

- Final estimate of the transverse size of LHC main dipoles
  - Magnet aperture radius: 30 mm for the beam
  - Coil width: 30 mm to get 8 T
  - Collars
    - Lorentz forces need a mechanical st
  - Yoke
    - This is needed to shield : iron takes
      we have 8 T in 30 mm so we need
      30/2*8=120 mm of iron
  - Total about 500 mm diameter

  - For the Terminator-3 accelerator,
    we have 640 T in 30 mm,
    we would need 30/2*640~10 m of iron
    → no space in their tunnel



What can happen if you do not shield your magnet

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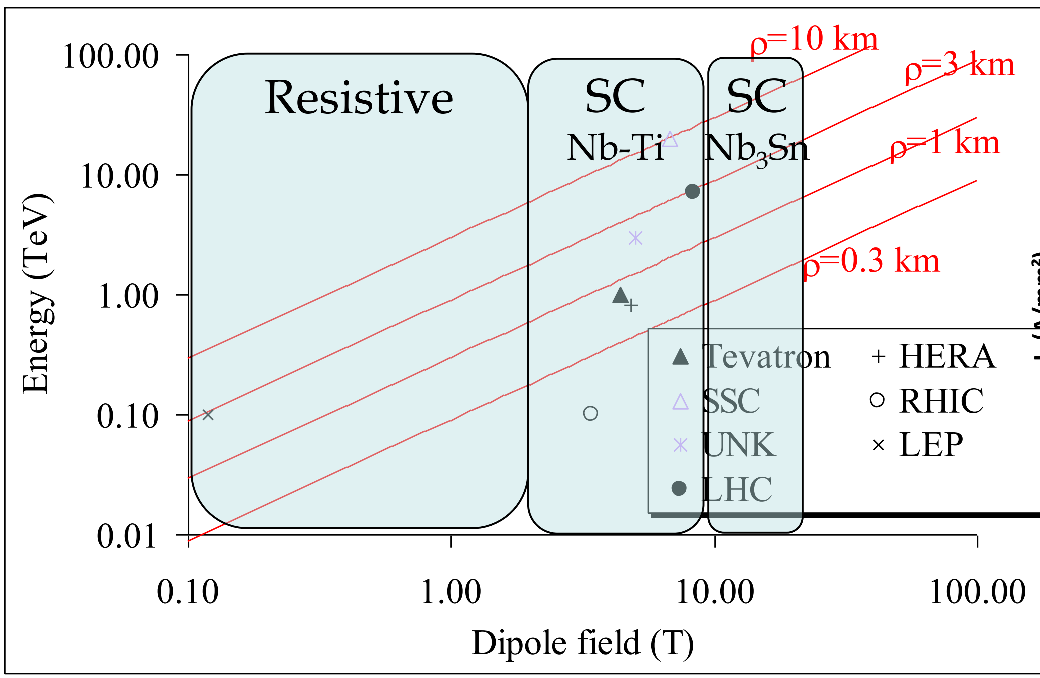
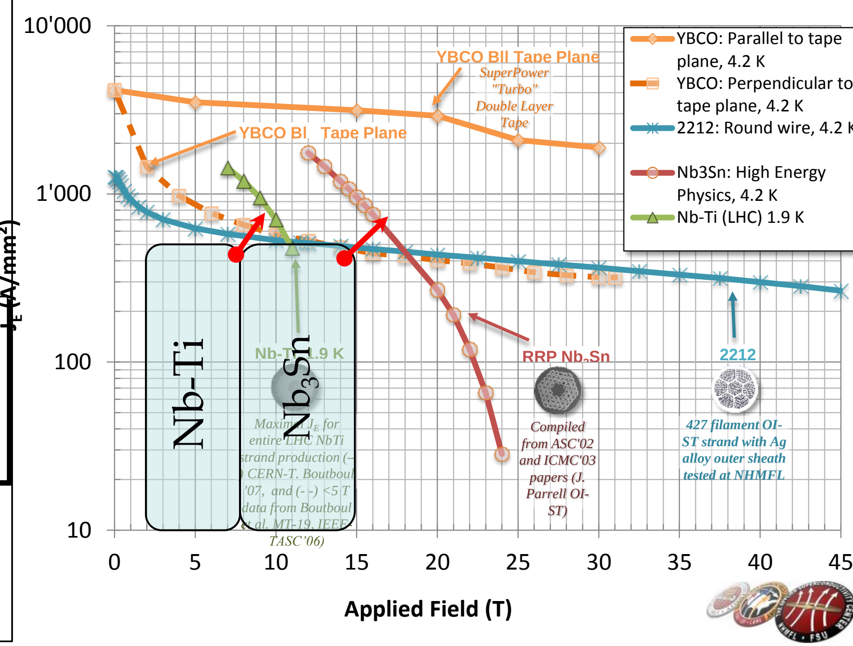
- Limits of Nb-Ti magnets
- Towards larger fields: Nb_3Sn and HTS
- Limitations to current density: stress, protection

TOWARDS LARGER FIELDS

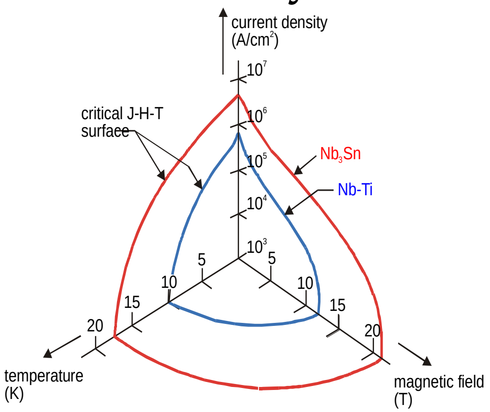
- Yesterday we have seen the Nb-Ti accelerator magnets are limited at 8 T
  - Critical surface – (cost and stability)
  - Nb_3Sn has a wider critical surface: covers up to ~15 T



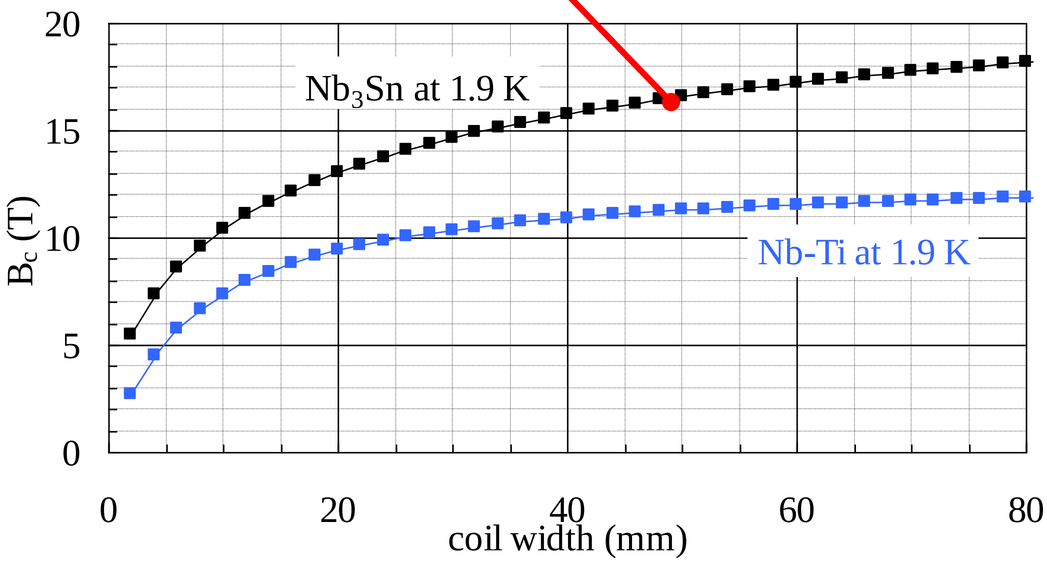


TOWARDS LARGER FIELDS

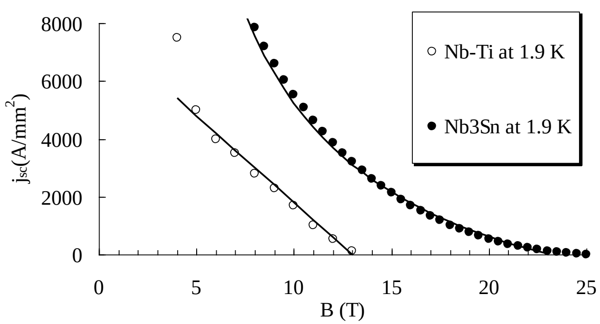
- Nb_3Sn has a wider critical surface
  - But the material is more difficult to manufacture
  - It has never been used in accelerators, but tested successfully in short models and used in solenoids
  - With Nb_3Sn one could go up to 15-18 T (-20%)
  - World record is 13.5 T (D20,HD2, Berkeley)



Critical surface for Nb-Ti and Nb_3Sn

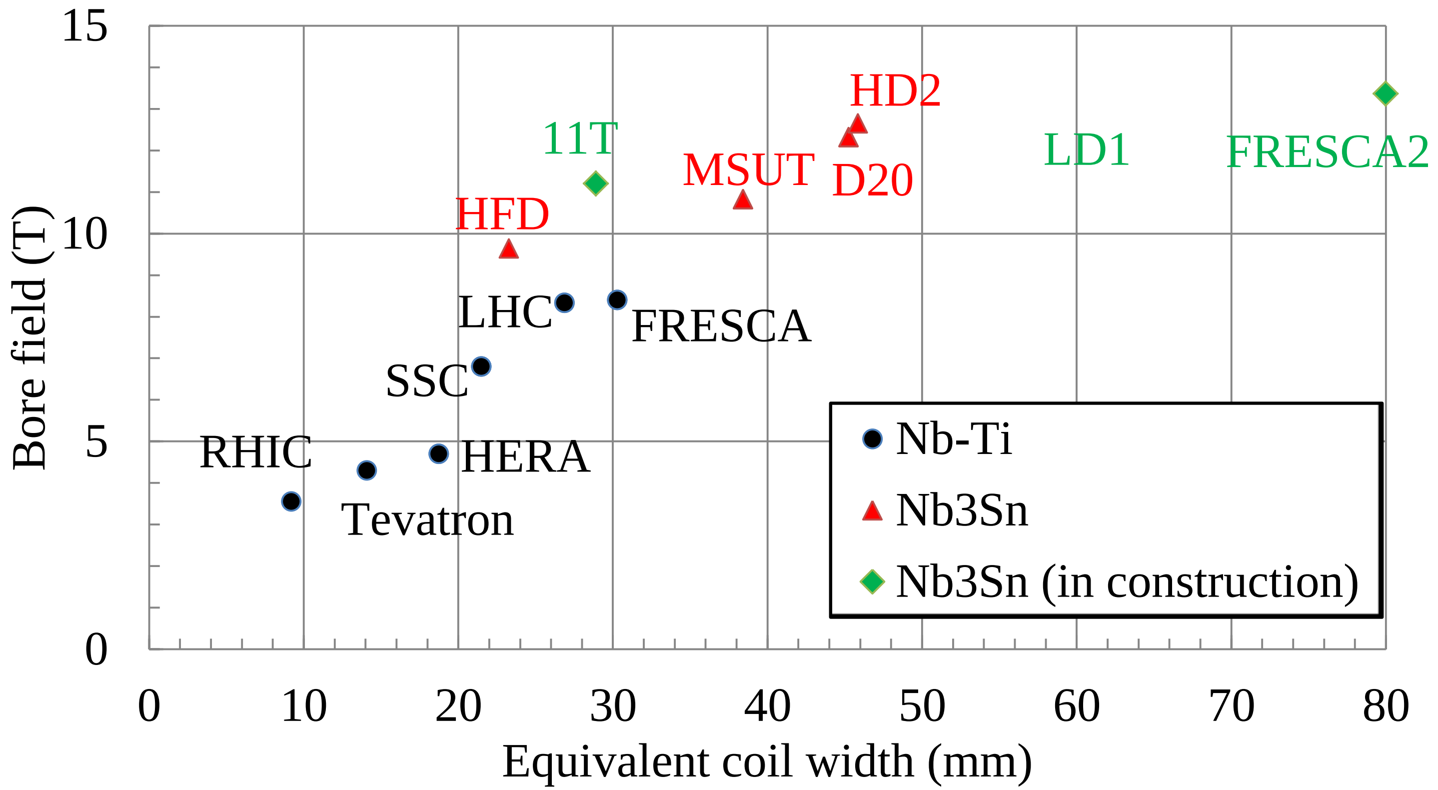


Field versus coil thickness for Nb-Ti and Nb_3Sn at 1.9 K



TOWARDS LARGER FIELDS

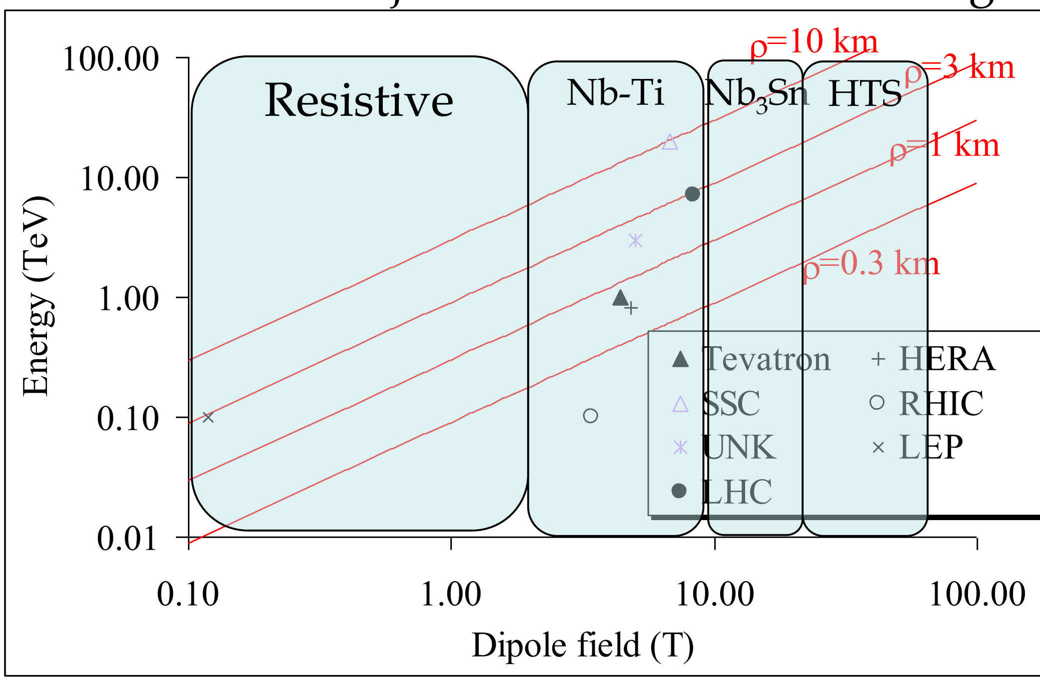
- Summary of accelerator dipoles, Nb-Ti and Nb_3Sn, built and planned

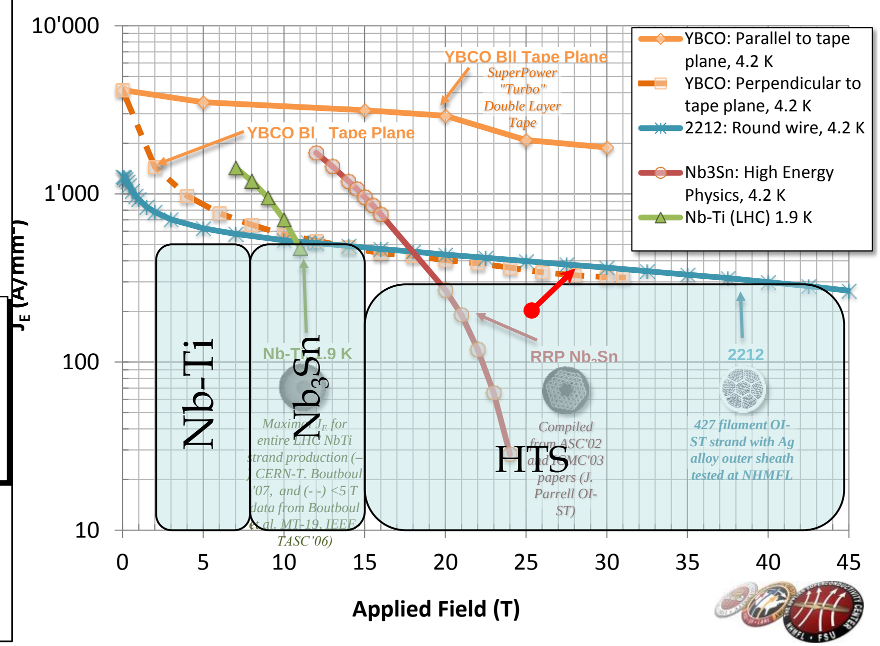


Bore field in dipoles: operational for Nb-Ti and maximum achieved for Nb3Sn

TOWARDS LARGER FIELDS

- Nb_3Sn is limited at 15 T
  - HTS materials have the amazing feature of having a critical surface with very low slope dj/dB
  - Today they are at 300-400 A/mm2 in the range 15-40 T
    - We just need 20% more and huge spaces will be opened!





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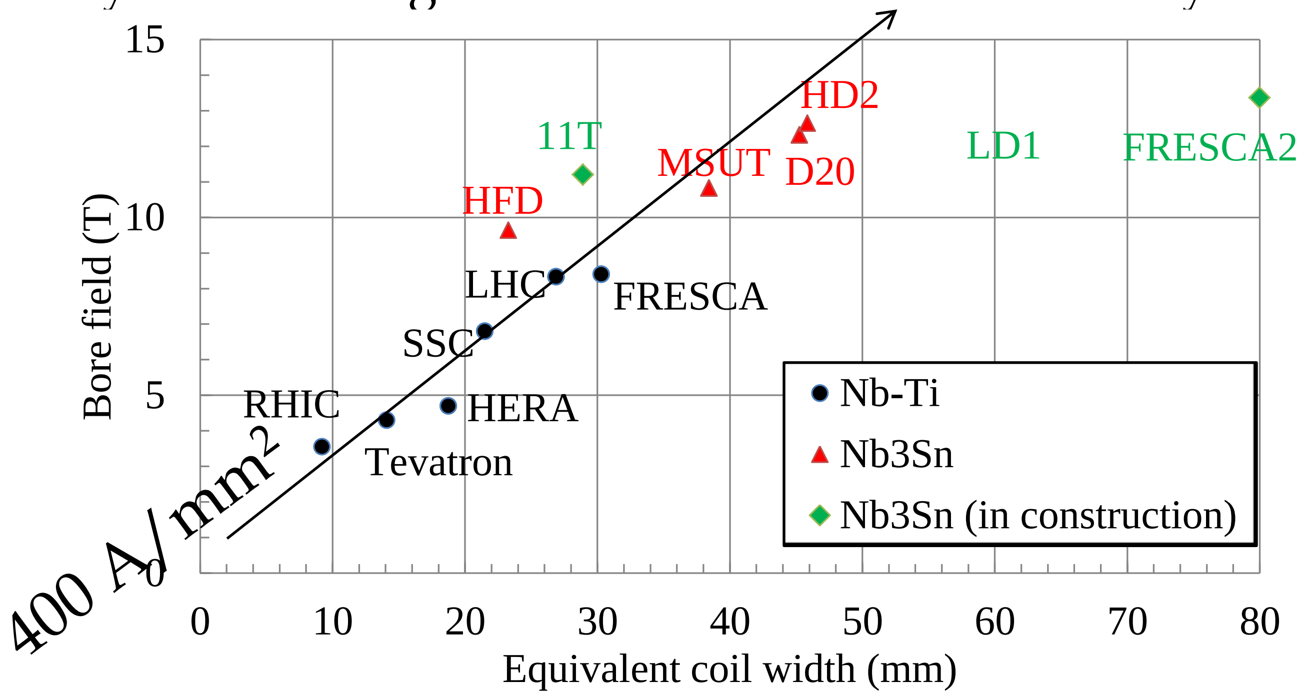
- What's behind this plot ?
  - Electromagnet:

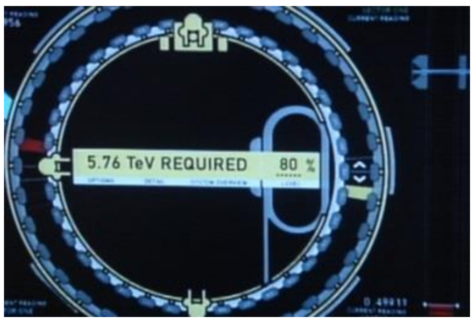
$$B[T] \approx 7 \times 10^{-4}\, j[A/mm^2]\, w[mm]$$

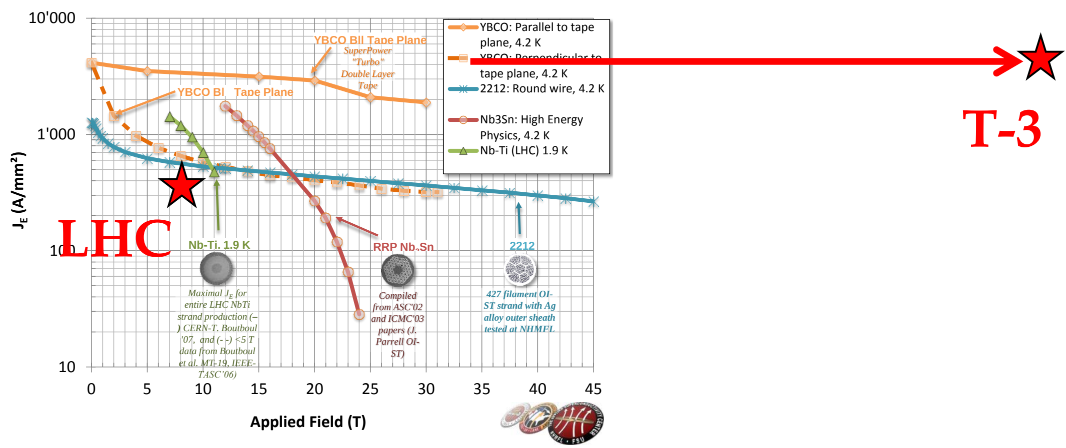
  - Why most of magnets have similar current density ?



Bore field in dipoles: operational for Nb-Ti and maximum achieved for Nb3Sn

- The Terminator-3 accelerator has 640 T with 200 mm (?) coil width→ 5000 A/mm^2 overall *j* (~10 times larger than usual accelerator magnets) able to withstand 640 T





- Surprise: even though we had a material with such a nice *B* vs *j* performance we would not be able to exploit it
- Going to very large current densities pose several issues

(i) Stability (ii) Stress (iii) Protection

We will deal only with protection to give an example

LIMITATIONS to CURRENT DENSITY: PROTECTION

- In case of an irreversible resistive transition (quench) we have a dangerous situation
  - Superconductors are very bad conductors above the transition
  - That's one of the reasons for having copper in the cable
  - Joule effect (proportional to j^2) heats the coil

$$\rho(T)\left[j(t)\right]^2 dt = c_p(T)dT \qquad \int_0^{\infty}\left[I(t)\right]^2 dt = A_{Cu}A\int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)}dT$$

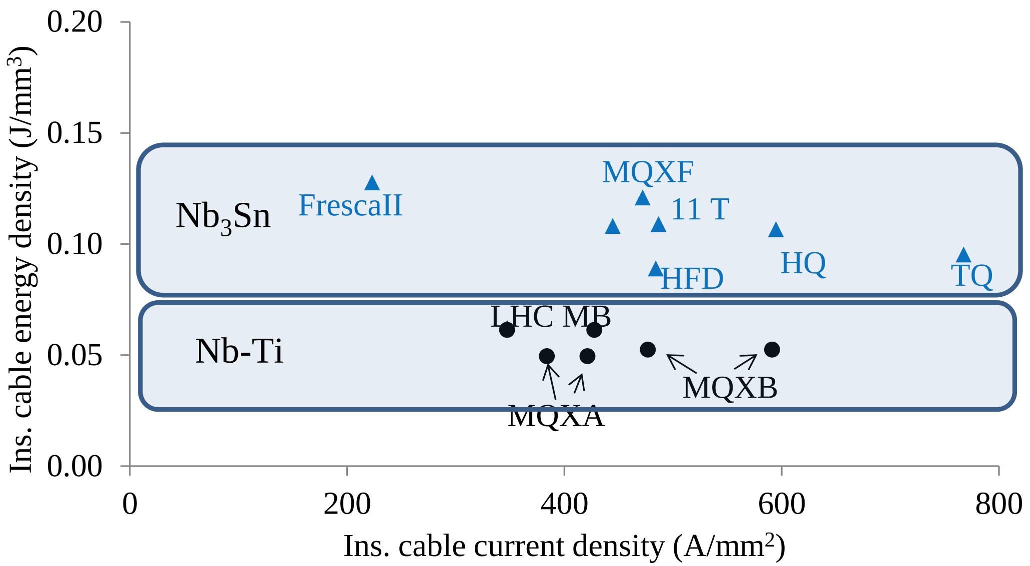
- If the current is not dumped rapidly enough the cable melts
  - Order of magnitude of time to dump the current: 0.1-0.5 s
- It is a RL circuit, time constant $\tau=L/R$
  - Where R is the resistance of the magnet – we should make it quench everywhere to increase R and lower τ

LIMITATIONS to CURRENT DENSITY: PROTECTION

- Best situation: all magnet quenches so energy is spread everywhere
  - Specific heat vary a lot in the range 2-300 K – very non linear problem
  - Enthalpy of a typical cable from 2 to 300 K is 0.6 J/mm^3
  - So energy density in the magnet must be smaller than this limit
    - If we want to make a magnet with given aperture and field, too small coil gives too large energy density → physical limit
- Nb-Ti typically operate at 0.06 J/mm^3
  - This is 1/10, meaning that 3 times larger current density reaches the enthalpy limit
- For Nb_3Sn typically we are at twice this value (0.1 J/mm^3)
- With these numbers, one has to react in 50 – 100 ms
  - (first thing: switch power off)

LIMITATIONS to CURRENT DENSITY

- The Terminator-3 accelerator has 640 T over 50 mm aperture with 200 mm coil width
  - Exercise: rough estimate of energy density
    - $B^2/2\mu$ over a circle of radius (50+200)/2 mm → 11.GJ/m of energy
    - Coil area: sector of thickness 200 mm over a radius of 25 mm → 0.08 m²
    - This gives 130 J/mm³ l, 250 times larger then the enthalpy limit (perhaps the most sci-fi number of the movie)



CONCLUSIONS

- Several factors limiting the highest fields
  - Superconducting properties –ability to tolerate magnetic field in the coil
    - Limit at 13 T for Nb-Ti, 25 T for Nb_3Sn
    - HTS opens towards 50 T
- Necessity of margin
  - You cannot work on the critical surface – but how much to step back?
- The cost to exploit the last Tesla of a superconductor is large
  - In terms of size, money (cost of superconductor)
  - That's why practial limits for Nb-Ti is 8 T and for Nb_3Sn is 15 T