HIGH ENERGY LHC

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On behalf of the HE-LHC working group

R. Assmann, R. Bailey, O. Bruning, O. Dominguez Sanchez, G. De Rijk, M. Jimenez, S. Myers, L. Rossi, L. Tavian, E. Todesco, F. Zimmermann « First thoughts on a Higher Energy LHC » CERN ATS-2010-177

and of the participants to the Malta workshop

A 16.5+16.5 TeV proton collider in the LHC tunnel

- The idea
  - Installing a 16.5+16.5 TeV proton accelerator in the LEP tunnel

		LHC	HE LHC	ratio
Collision energy	(TeV)	7.0	16.5	2.4
Dipole field	(T)	8.3	20	2.4

  - Main ingredient: 20 T operational field dipoles
    - Proposal in 2005 for an LHC tripler, with 24 T magnets [P. McIntyre, A. Sattarov, "On the feasibility of a tripler upgrade for the LHC", PAC (2005) 634].
- Working group launched at CERN in May 2010
  - www.cern.ch/he-lhc
  - Report published in September R. Assmann, R. Bailey, O. Bruning, O. Dominguez Sanchez, G. De Rijk, M. Jimenez, S. Myers, L. Rossi, L. Tavian, E. Todesco, F. Zimmermann « First thoughts on a Higher Energy LHC » CERN ATS-2010-177
- Workshop in Malta October 2010
  - http://indico.cern.ch/internalPage.py?pageId=0&confId=97971
  - Proceedings: CERN Yellow report 2011-3

The view from the high energy physics community

- Discovery potential [J. Wells, CERN 2011-3]
  - The panorama is complex and LHC discoveries will shed more light but …
  - The energy frontier is always extremely interesting and for many processes cannot be traded with more luminosity at lower energy

> The results of the LHC will change everything, one way or another. There will be a new "theory of the day" at each major discovery, and the arguments will sharpen in some ways and become more divergent in other ways. Yet, the need to explore the high energy frontier will remain.

- Do we need new experiments ? [M. Nessi, CERN 2011-3]
  - Most of the electronics and inner detectors will be rebuild and upgraded already for the HL-LHC – so it will be for the HE-LHC
    - Modular and gradual approach is possible
  - Main questions to be answered 'soon' (in a few years)
    - Can we manage to keep the same magnets and structures, just replacing modules?
    - If a new detector is needed, will it involve new civil engineering?

THE INJECTION ENERGY

- Injection energy is important

		LHC	HE LHC	ratio
Collision energy	(TeV)	7.0	16.5	2.4
Dipole field	(T)	8.3	20	2.4
Injection energy	(TeV)	0.45	1.2	2.7
Dynamic range	(adim)	15.6	13.8	0.9
Aperture	(mm)	56	40	0.7

  - Keeping the same injection would avoid the need of new injectors and transfer lines but would bring the dynamic range from 15.6 to more than 40 – not considered as realistic
  - Injection at 1.2 TeV (or more) we keep the same dynamic range
  - Beneficial effect on the aperture
    - 2/3 of LHC aperture used by the beam
    - Higher injection energy → lower beam size $\sqrt{E}$ → 40 mm aperture possible
  - Aperture is very valuable asset – keep it as low as possible
    - Reduction from 56 mm to 40 mm allows 20% reduction of the cost and 30% less stored energy (with a coil of 80 mm thickness)

PEAK LUMINOSITY

- Luminosity: twice the LHC

$$L=\gamma\frac{f_{rev}}{4\pi}\frac{n_b N^2}{\varepsilon\beta^*}F(\beta^*)$$

		LHC	HE LHC	ratio
Collision energy	(TeV)	7.0	16.5	2.4
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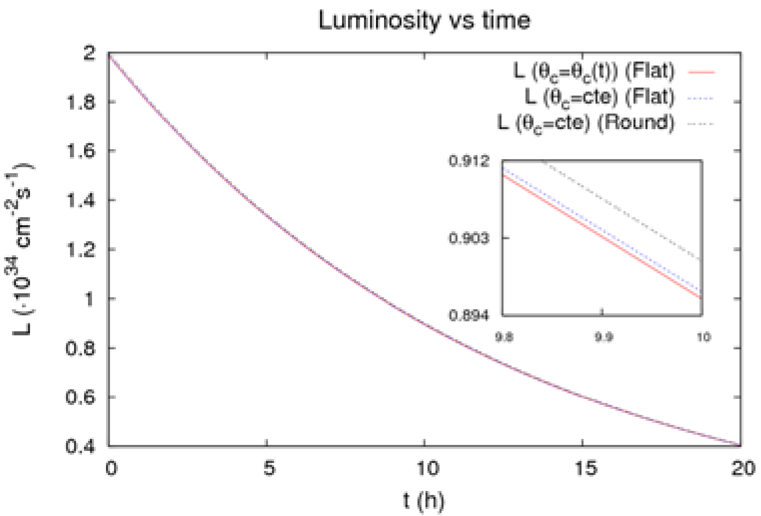
Dynamic range	(adim)	15.6	13.8	0.9
Aperture	(mm)	56	40	0.7
Luminosity	($cm^{-2}\,s^{-1}$)	1.0E+34	2.0E+34	2
Bunch intensity	(adim)	1.15E+11	1.30E+11	1.1
N. bunches	(adim)	2808	1404	0.5
Bunch spacing	(ns)	25	50	2.0
β*	(m)	0.55	0.4	0.7
Energy per beam	(MJ)	362	482	1.3

Luminosity parameters [F. Zimmermann et al. CERN 20111-3]

- A factor 2.4 comes for free (nearly …) from the energy
- Proposal of rebalancing: 50% less bunches n_b compensated by 15% larger bunch intensity N and 30% smaller β^*
  - ☺ Electron cloud becomes less critical (larger bunch spacing: 50 ns)
  - ☺ Smaller stored energy (not 2.4 the LHC, but only 30% more)
  - ☺ Smaller load due to synchrotron radiation (not 2.4^4=31 LHC, but only 17 LHC)
  - The smaller β^* and the larger intensity seem at hand

Integrated Luminosity and Synchrotron Radiation

- Luminosity: twice the LHC



Evolution of luminosity during a run [F. Zimmermann et al. CERN 20111-3]

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Energy per beam	(MJ)	362	482	1.3
SR power per ring	(kW)	3.6	63	17
Energy loss per turn	(keV)	6.7	207	30.9
Optimal run time	(h)	15	10	0.7

- Synchrotron radiation induces a strong reduction of emittance
  - Artificial transverse emittance blow-up can be needed to avoid reaching beam-beam limit
  - Optimal running time of the order of 10 h (still reasonable)
  - One should get about 0.8 fb^{-1} per day

SYNCHROTRON RADIATION AND HEAT LOADS

- Synchrotron radiation: scaled with 4th power of the energy
  - But we have less beam, so SR power is a factor 17 larger
  - Less than 2.4^4= 31, but still large

				LHC	HE-LHC bs2	ratio
Thermal shield	50-75 K	[W/m]	Heat inleaks	7.7	7.7	1.0
Heat intercept	4.6-20 K	[W/m]	Heat inleaks	0.2	0.2	1.0
Beam screen	4.6-20 K	[W/m]	Synchrotron radiation	0.33	**5.71**	**17.3**
	(LHC)	[W/m]	Image current	0.36	2.4	6.7
	40-60 K	[W/m]	Photo-electron cloud	0.90	1.50	1.7
	(HE-LHC)	[W/m]	Total	1.6	**9.6**	**6.0**
Cold mass	1.9 K	[W/m]	Heat inleaks	0.21	0.21	1.0
		[W/m]	Resistive heating	0.10	0.34	3.4
		[W/m]	Beam-gas scattering	0.05	0.03	0.6
		[W/m]	Total	0.36	0.58	1.6

Heat loads in the LHC and one option for HE LHC [D. Delikaris, L. Tavian CERN 2011-3]

- Heat loads
  - The term coming from synchrotron radiation is dominant – on the beam screen we have 6 times larger loads than in the LHC
    - Different options of beam screen temperature: 40-60 K is appealing
  - Cold mass heat load is only 50% larger (related to MB current)
- Not yet possible to tell is LHC cryogenics can be reused
  - It will be 20 years old, but …

Beam screen, injection, dump

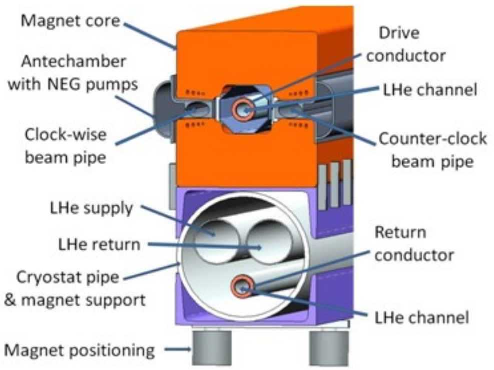
- Magneto resistance of the beam screen: increase of about a factor 2 w.r.t. LHC (due to higher field) [E. Metral, CERN 2011-3]
  - Impedances scale with √ of magneto resistance → 40% larger impedance should not be an issue for the beam stability

- Injection lines (in case of injection at 1.3 TeV) [B. Goddard et al. , CERN 2011-3]
  - Completely new layout needed – more space needed (60 m between quads) also for injection protection devices

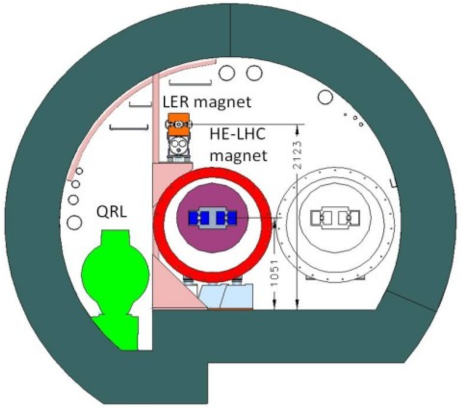
- Dump [B. Goddard et al. , CERN 2011-3]
  - Dump possible with a similar layout as in the LHC – upgrade of dilution or of the dumping block needed

INJECTORS

- Option for the injectors [R. Garoby, CERN 2011-3]
  - Low Energy Ring (LER) in the LHC tunnel: 2 T superferric dipoles
    - Option1 – bypass of experiments
    - Option2 – going through experiments
    - Injection in one go
    - No additional work for transfer lines
  - Superconducting SPS (S-SPS): 5-6 T dipoles
    - Not occupying precious space in the LHC tunnel
    - No problem of experiments bypass
    - Higher cost
  - Issue: LHC injectors still working in 2025-2040?



LER magnets [H. Piekartz, CERN 2011-3]

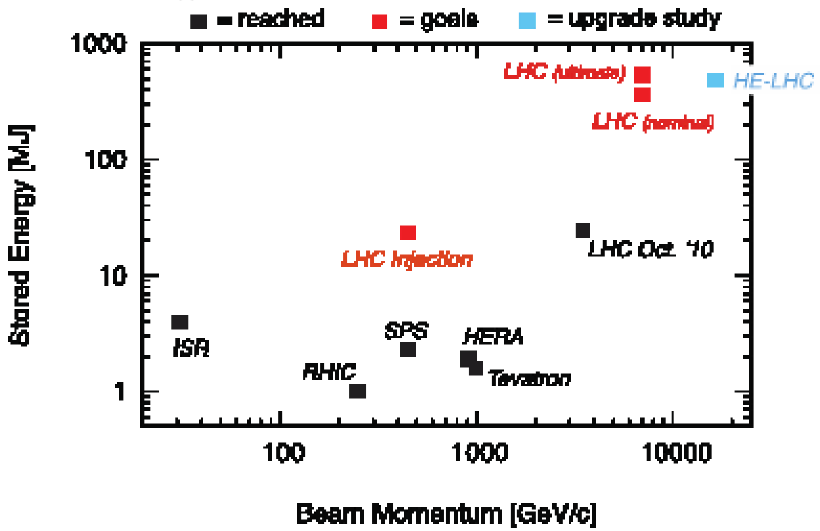


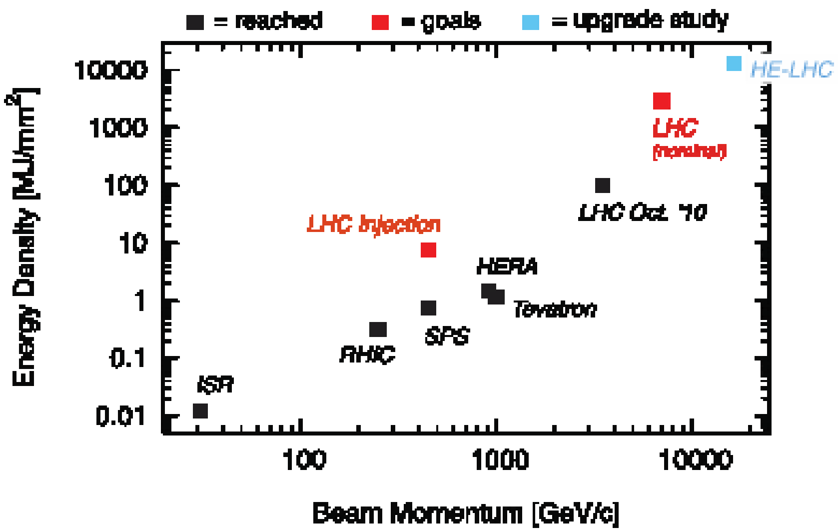
HE-LHC and LER in the LEP tunnel [H. Piekartz, CERN 2011-3]

	S-SPS	LER-1	LER-2
Cost (M€)	1800	550	270

PROTECTION AND COLLIMATION

- Several aspects to be considered
  - Efficiency: degraded by factor 3-6 w.r.t. LHC – will be addressed by with future upgrades
  - Robustness: energy density a factor 2.6 larger than acceptable
    - Either larger emittance, or more robust materials, or review of limits
  - Larger apertures at 16.5 TeV to avoid too small gaps and large impedance



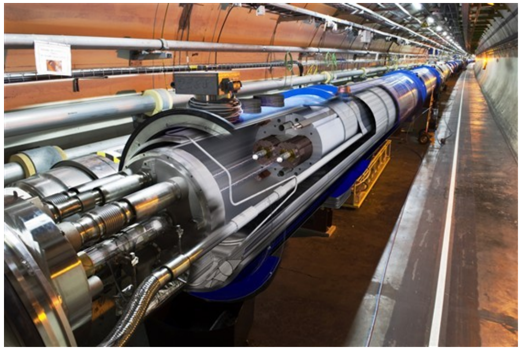


Stored energy vs beam energy (left) and energy density versus beam energy (right) [R. Assman. CERN 2011-3]

Magnets: Dipoles Main Constraints

- Design is driven by
  - Transverse space in the tunnel → transverse size of the magnet
    - 570 mm diameter for the cold mass in the LHC
    - We assume 800 mm diameter for the HE-LHC
    - Coil must be reasonably compact
  - Cost: we need Nb_3Sn and HTS
    - Cost of Nb_3Sn ~4 times Nb-Ti
    - Cost of HTS ~ 4 times Nb_3Sn

      → grading of material is necessary
  - Margin
    - We ask to work with 20% margin from critical surface, i.e., we have to design a magnet for 25 T



	Operational field (T)	Operational current (kA)	Operational margin (%)
Tevatron	4.4	4.3	~26%
Hera	4.7	5.0	~31%
RHIC	3.5	5.5	~33%
SSC	*6.7*	*6.6*	*~15%*
LHC	8.3	11.8	~16%

LHC 'Energy Upgrade' proposed in [O. Bruning, et al.,LHC Project Report **626** (2002)]
24 T dipole for LHC tripler proposed in [P. McIntyre, A. Sattarov, PAC 2005, 634]
This proposal: [L. Rossi, E. Todesco, CERN 2011-3]

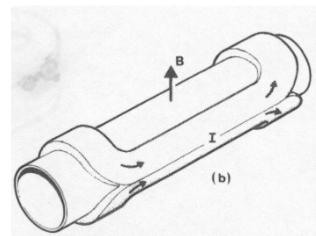
MAGNETS: DIPOLE COIL

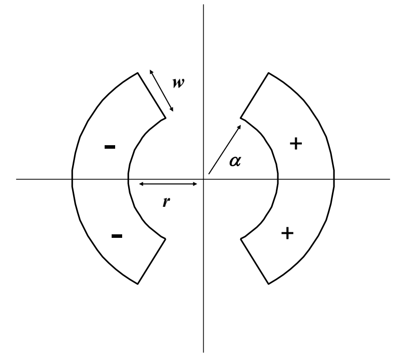
- First choice: current density – keep the same as the LHC

$$B\ [\mathrm{T}] \sim 0.0007 \times \textit{coil width}\ [\mathrm{mm}] \times \textit{current density}\ [\mathrm{A/mm^2}]$$

LHC: 8 [T]~ 0.0007 × 30 × 380

		LHC	HE LHC	ratio
Collision energy	(TeV)	7.0	16.5	2.4
Dipole field	(T)	8.3	20	2.4
Coil width	(mm)	31	80	2.6
Current density	(A/mm^2)	380	380	1

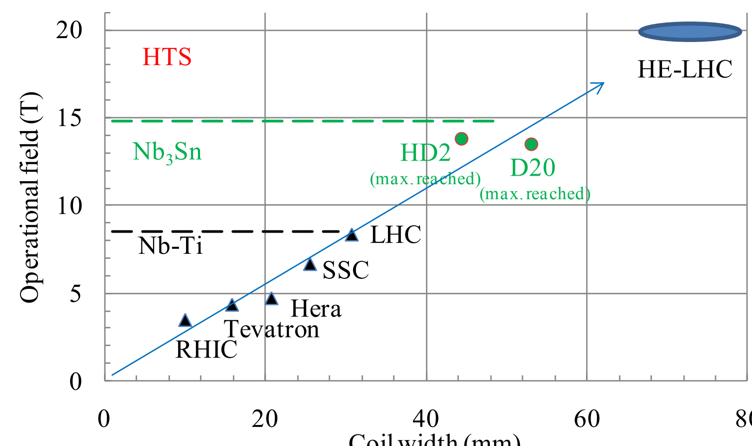




- Accelerators used current density of the order of 350–400 A/mm^2
  - This provides ~2.5 T for 10 mm thickness
  - 80 mm needed for reaching 20 T

w.r.t. McIntyre design at 800 A/mm^2

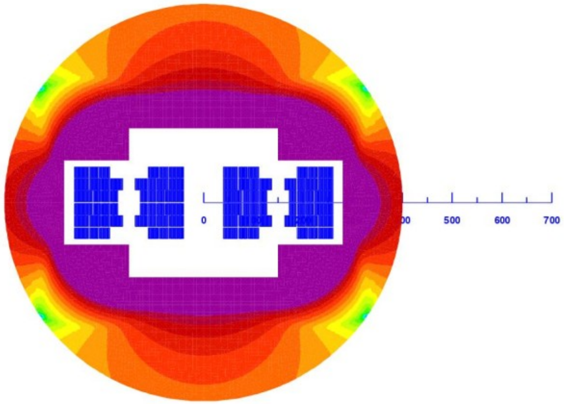
- Stress increases only by 2.4
- Coil size is still manageable



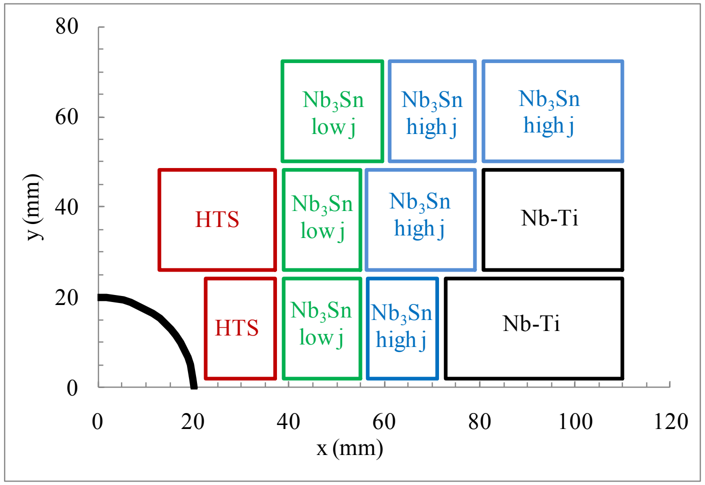
Operational field versus coil width in accelerator magnets

Stored energy is critical

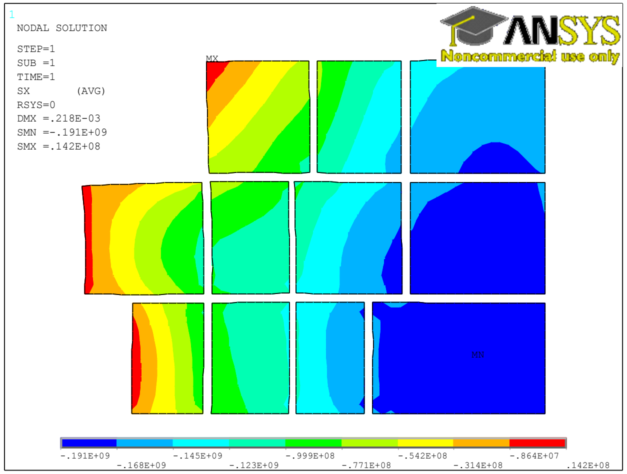
		LHC	HE LHC	ratio
Collision energy	(TeV)	7.0	16.5	2.4
Dipole field	(T)	8.3	20	2.4
Coil width	(mm)	31	80	2.6
Current density	(A/mm^2)	380	380	1.0
Operational current	(A)	11.8	13.8	1.2
Distance between beams	(mm)	192	300	1.6
Length	(m)	14.3	14.3	1.0
Stored energy	(MJ)	7	100	14
Stress	(MPa)	70	180	2.6



Sketch of the double aperture magnet with the iron yoke – Coils are in blue



Coil grading (one quarter of coil shown)



Stress in the coil at 20 T operational field [A. Milanese]

COST

- Acrobatic estimate (prices for 2025 …)
  - Nb_3Sn 4 times more expensive than Nb-Ti
  - HTS 4 times more expensive than Nb_3Sn

	($/kg)	m^3	Kg	M$	%
Nb-Ti	200	0.12	960	0.19	5%
Nb_3Sn - h	800	0.16	1300	1.0	28%
Nb_3Sn - l	800	0.10	850	0.7	18%
Bi 2212	3000	0.07	620	1.9	49%
Total		0.45	3730	3.8	

- 3.8 M$ of conductor per LHC-like magnet (15 m, 2-in-1)
  - 4.6 M$ including manufacturing (hypothesis: the same as LHC except coil construction increased by 50%)
- 1200 dipoles → 5500 M$
  - About five times the LHC for 2.5 times the field

The New Tunnel Option

- Option 1:
  - 3000 LHC magnets at 8.3 T (no HTS no Nb3Sn) in 52 km tunnel
  - Magnet cost: 3000 M$
- Option 2:
  - 1600 magnets with NB-Ti and Nb_3Sn at 15 T (no HTS) in a 33 km tunnel
  - Magnet cost: 4200 M$
- Plus
  - Tunnel cost
  - Infrastructures, which can be as costly as the tunnel
  - Experiments
  - Permits for sites, …

CONCLUSIONS

- From a point of view of beam dynamics, the HE-LHC does not present hard showstoppers

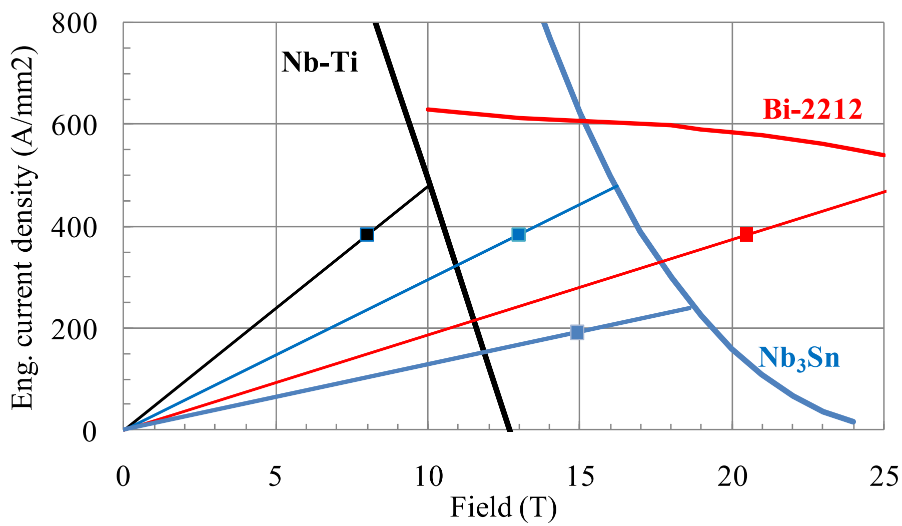
- The main challenge is the 20 T magnet
  - Available technology today is up to 15 T
  - Cost
  - Stored energy and protection

- Main critical choices
  - Timeline for R&D on magnets
  - 20 T or 15 T ?
  - Injector options
  - Can we use the experiments layouts with upgrade of detectors?

Reserve slides

Guidelines for the coil

- What material can tolerate 380 A/mm[2] and at what field ?
  - For Nb-Ti: LHC performances - up to 8 T
  - For Nb_3Sn: 1500 A/mm^2 at 15 T, 4.2 K – up to 12 T
    - With lower current density 190 A/mm^2/m we can get to 15 T
  - Last 5 T made by HTS - we ask for having ~380 A/mm^2
    - Today in Bi-2212 we have half, i.e., ~200 A/mm^2



Engineering current density versus field for Nb-Ti and Nb_3Sn (lines) and operational current (markers)

MAIN OPEN ISSUES

- HTS
  - Critical current: reach 400 A/mm^2 operational current in HTS
    - With 200 A/mm^2 as today, one would reach ~17.5 T
  - Manufacturing of dipoles
    - We start to have experience on solenoids, much less on dipoles
- Building an hybrid coil
  - Different curing for Nb-Ti, Nb_3Sn, HTS
- Protection
  - Very large stored energy
  - Hybrid coil
- Stresses
  - 200 MPa are at the limit of Nb_3Sn