Futuri Acceleratori pp

Lucio Rossi – CERN
High Luminosity LHC Project Leader

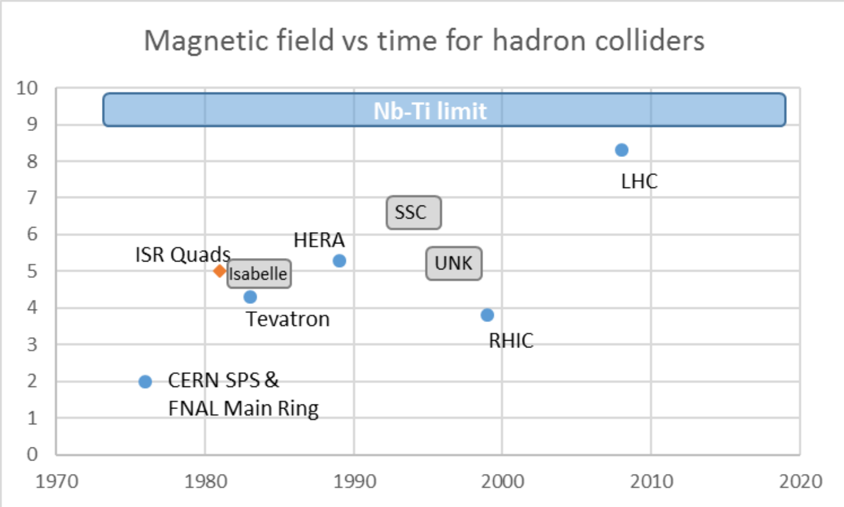
Thnaks to L. Bottura, M. Benedikt, F. Zimmermann and D. Tommasini

Panorama of energy frontier Hadron Colliders

- LHC : 2008 (2010) – 2024 - Operating
- HL-LHC : 2026 – 2040 – Under construction
- A few projects at the – far – horizon
- FCC 100 km – 100 TeV
  - Design Study launched 2013
- HE-LHC 26.7 km – 28 TeV
  - Inside the FCC study
- Chinese SppC (100 km; 70-150 TeV); pre-DS

Hadron Colliders are ruled by: $E_{beam} = 0.3\ R * B$ (TeV; km; T)

< 10 y to double field: 2 T MR→ 4 T Tevatron
> 20 y to double again in SC: → 8 T of LHC

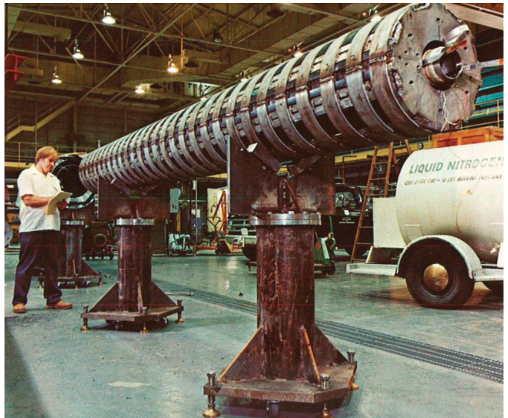


Consideration on LHC

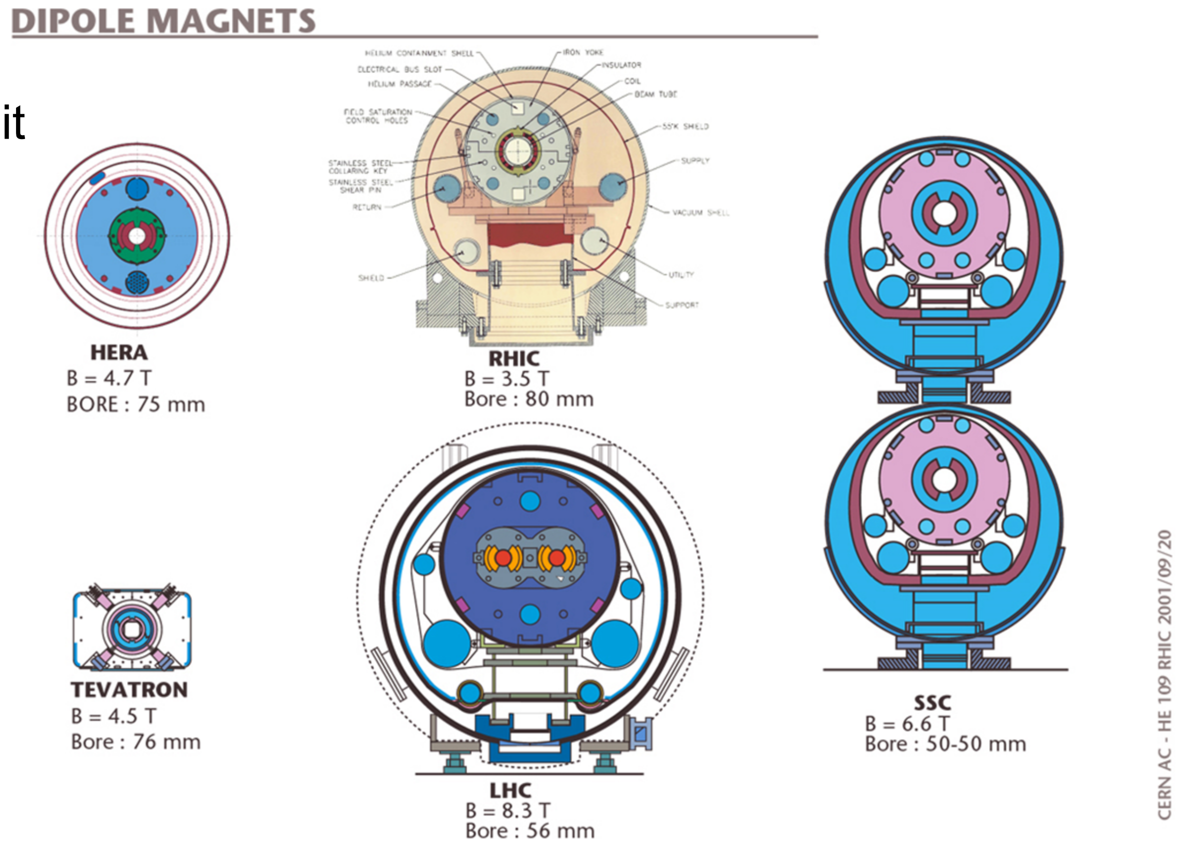
- Designed for 8.33 T (14 TeV c.o.m.) with margin to go to 9 T (15 TeV c.o.m)
- Today operating at **7.75 T** (13 TeV)
- **8.33 T in 2021 possibly**
- **9 T may be in 2026/2030 with HiLumi but very difficult (trade off with loss of lumi)**

Hadron Collider Magnets: Hall of fame

LHC has been the summit of > 40 y developements with SC Nb-Ti magnets.



4.5 T full size dipole prototype for Isabelle (BNL, 1975)



The 25 y LHC construction time line

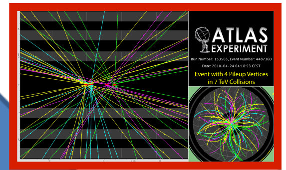
9 T - 1 m single bore

10 T-1m Nb3Sn dipole

9 T -10 m long protoype

9 T-15 m final protoype

Last LHC dipole



1985 1987 1990 1994 2000 2006 2010

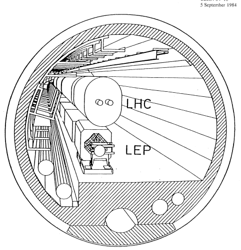
S

Striking: only 4 y to make a design «near to final». The conductor was almost there! (thanks to SSC)

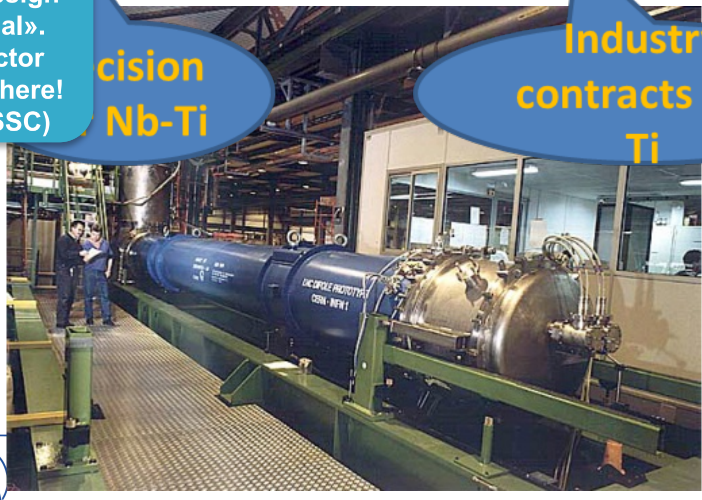
cision Nb-Ti

Industry contracts Nb-Ti

LHC start-up



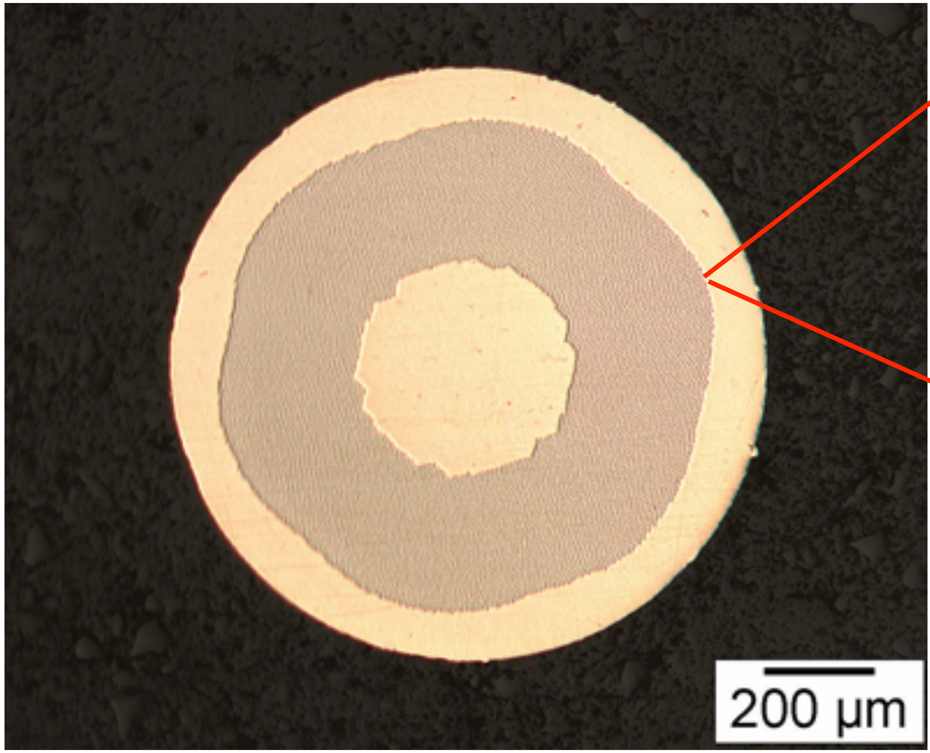
LARGE HADRON COLLIDER
IN THE LEP TUNNEL

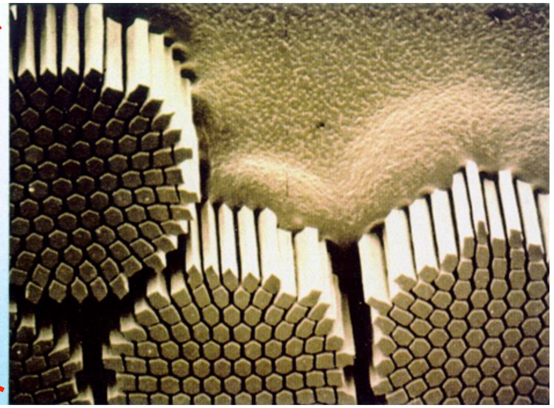


HiLumi HL-LHC PROJECT

CERN

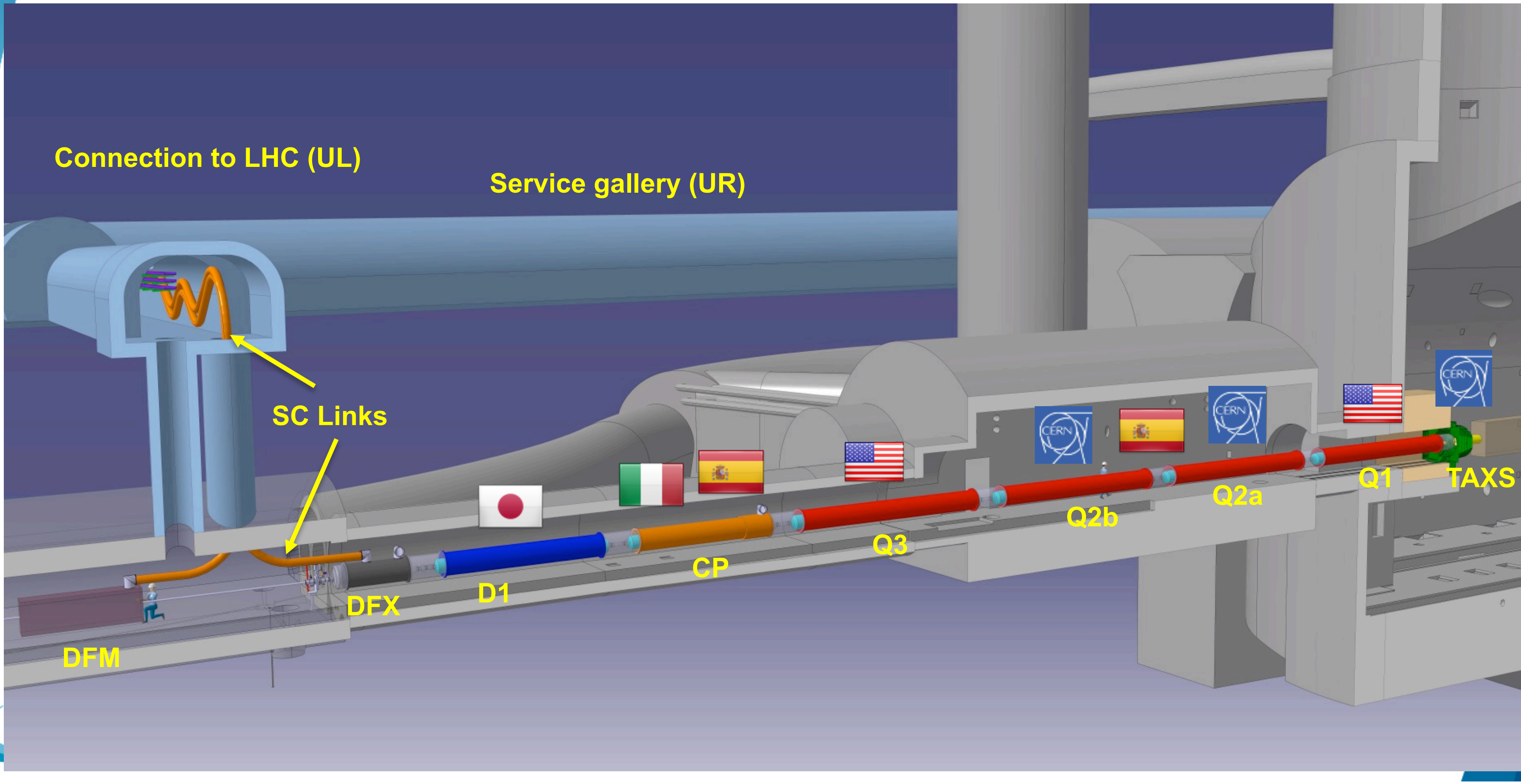
The key factor: superconductor (but not the only factor!)



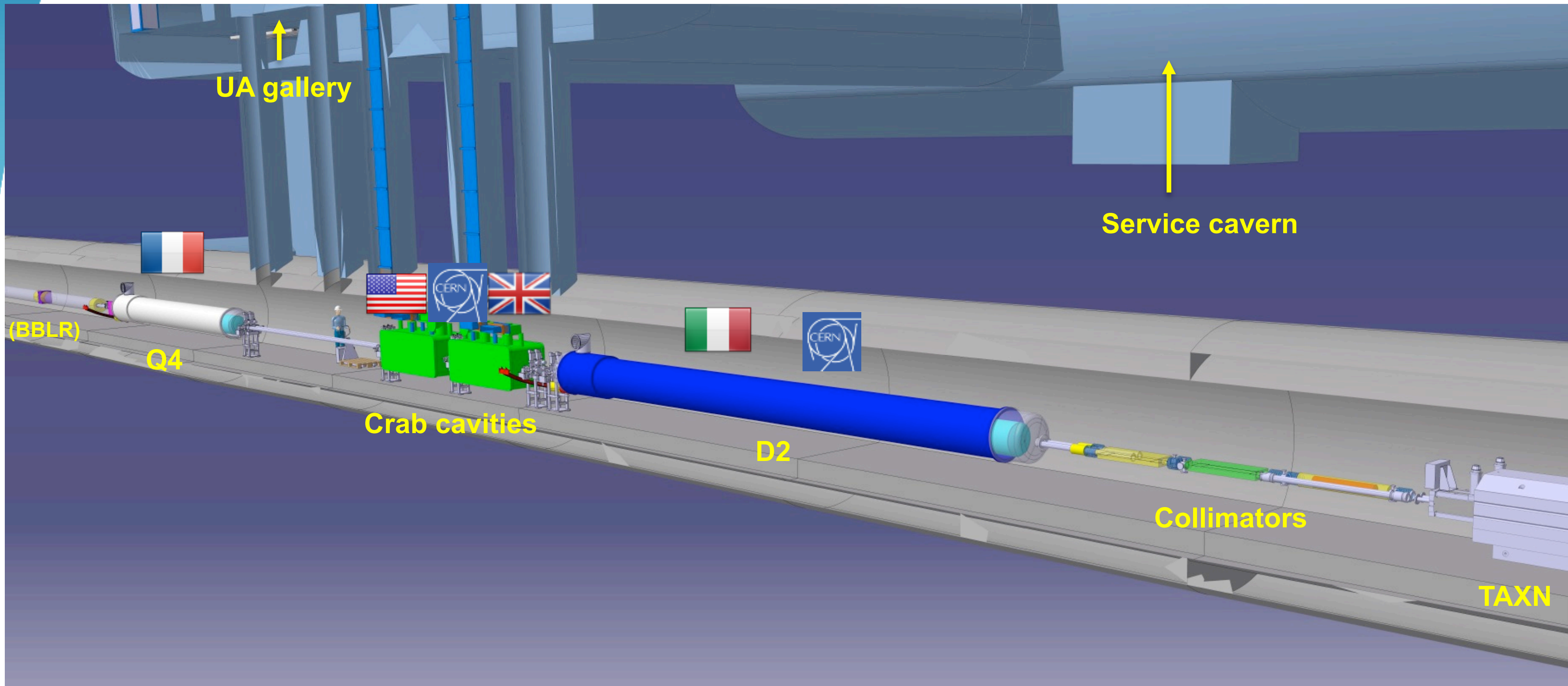


Developing SC is the key in SC accelerators.
The perfection of LHC superconductor is such that we basically «forget» the SC effects and is the base of the repeatibility and optimal performance of the collider

High Luminosity LHC -1 New Triplets IT QUADs

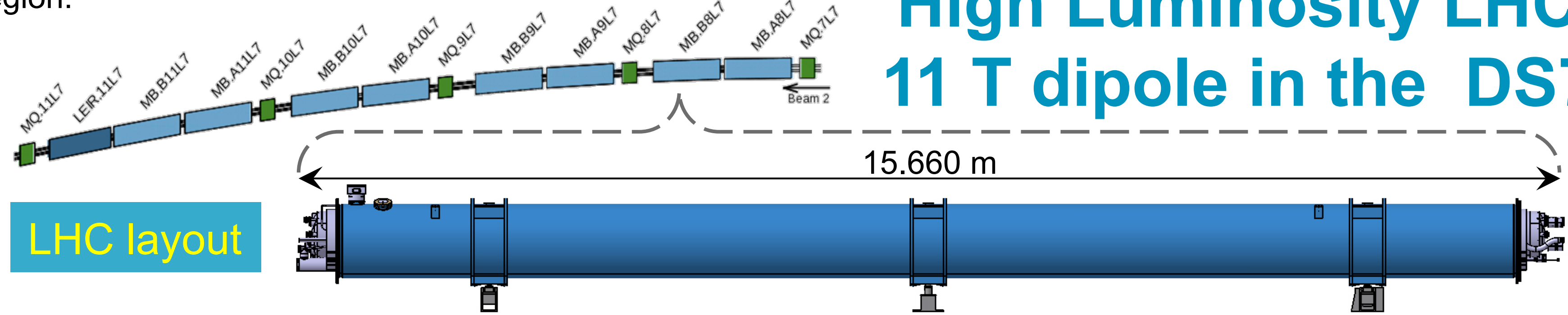


High Luminosity LHC – 2 New Matching section

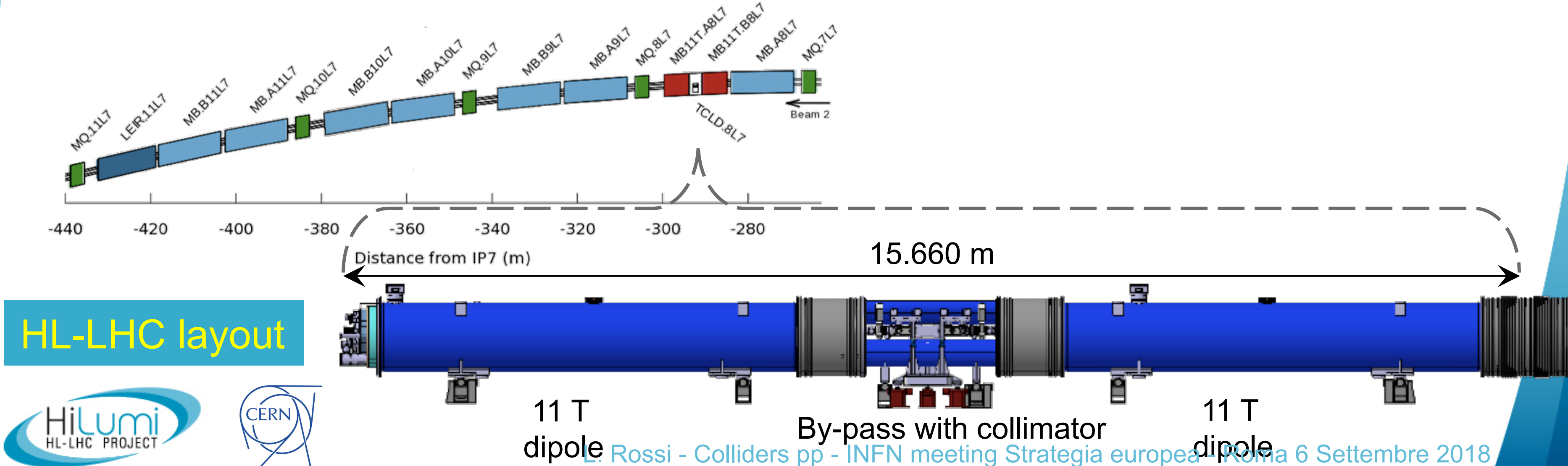


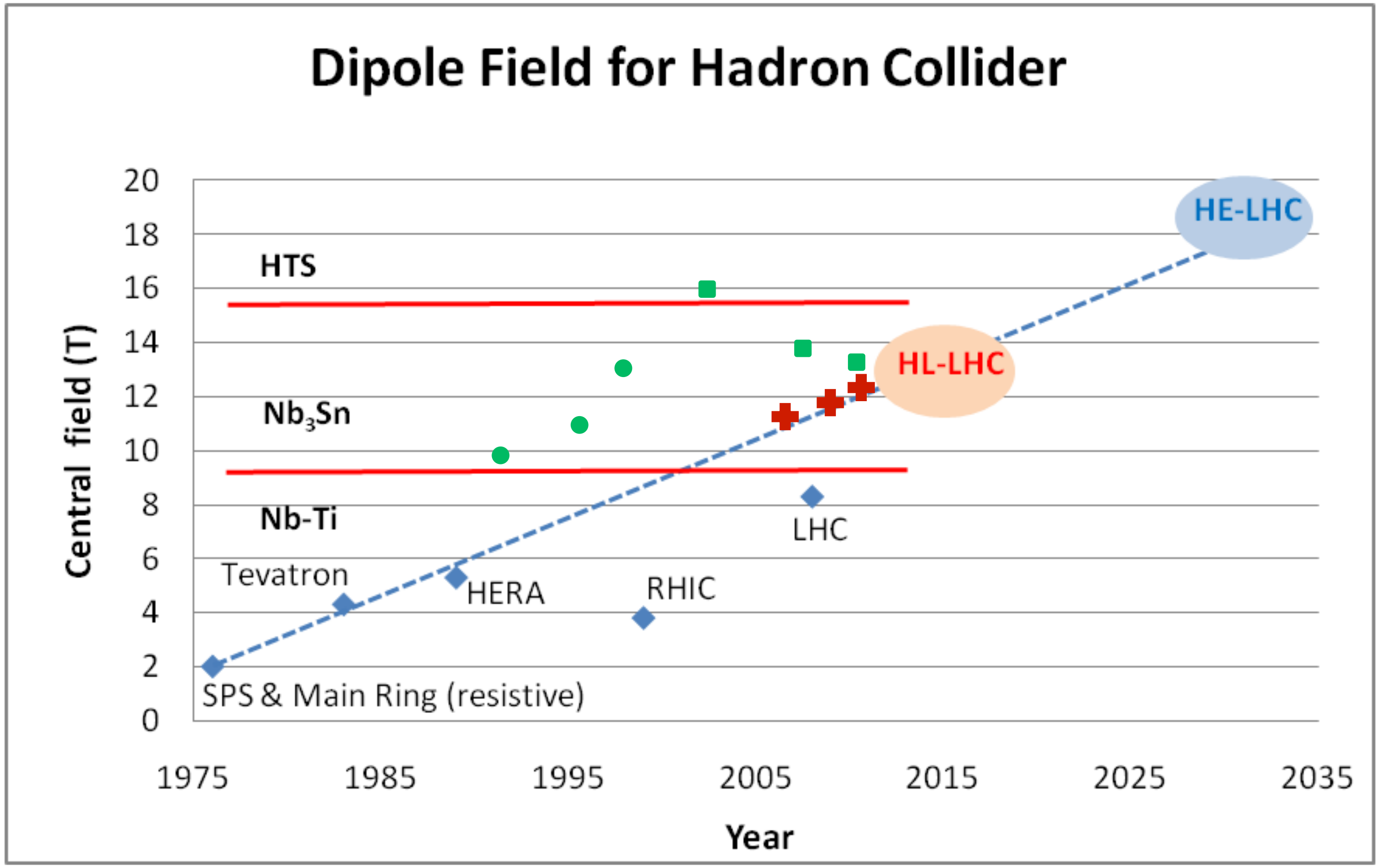
High Luminosity LHC 11 T dipole in the DS7

Present layout of the DS region:



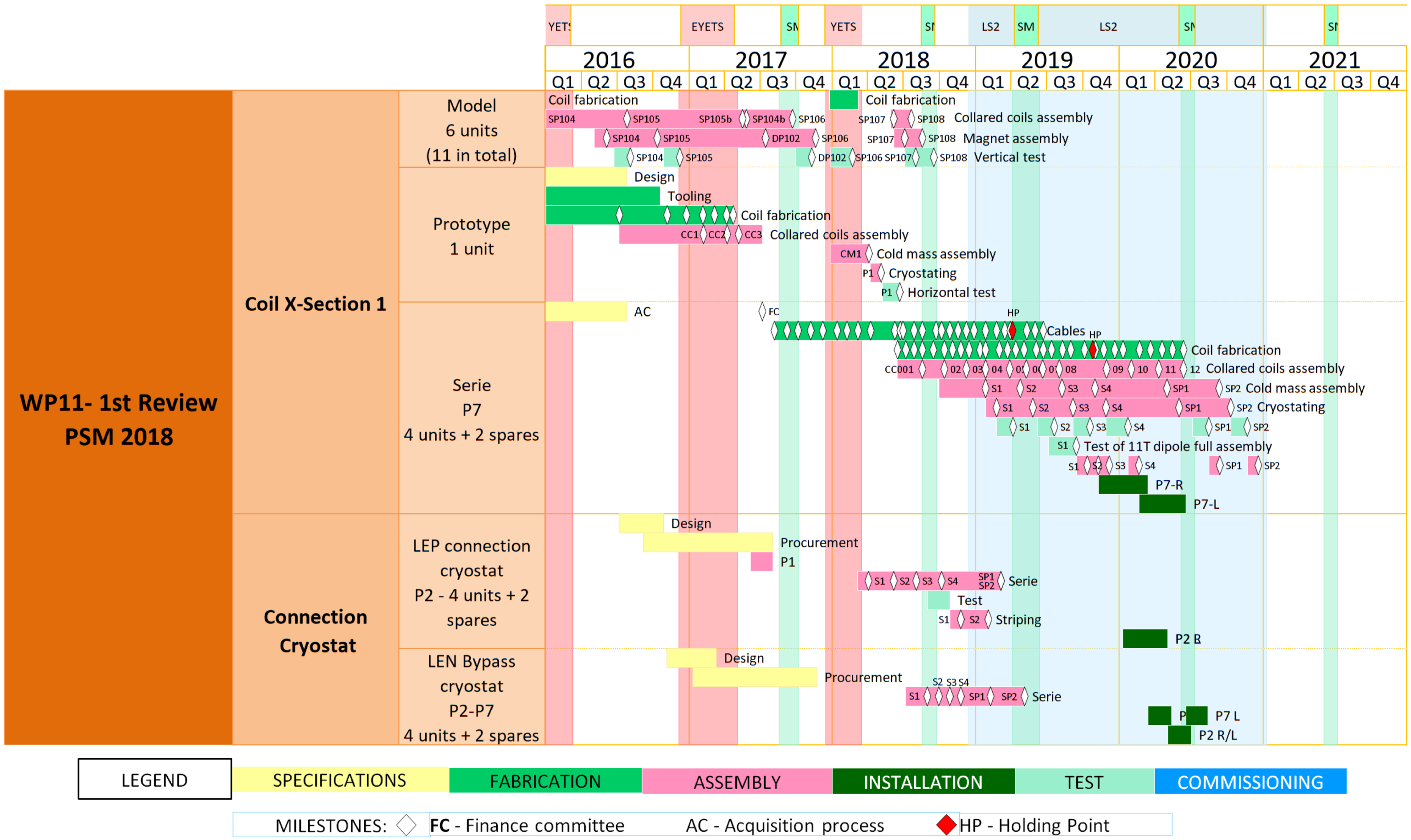
New layout with one collimator and two 11T dipoles:



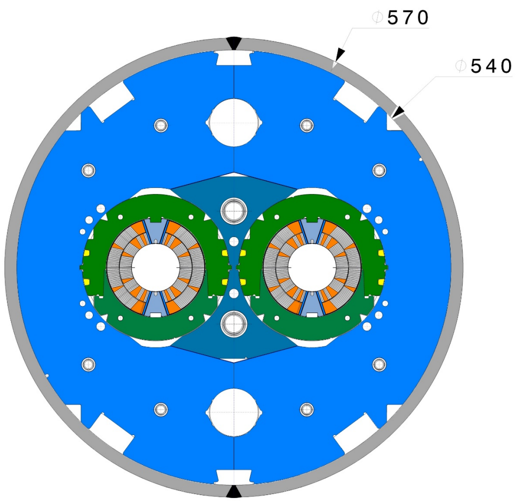


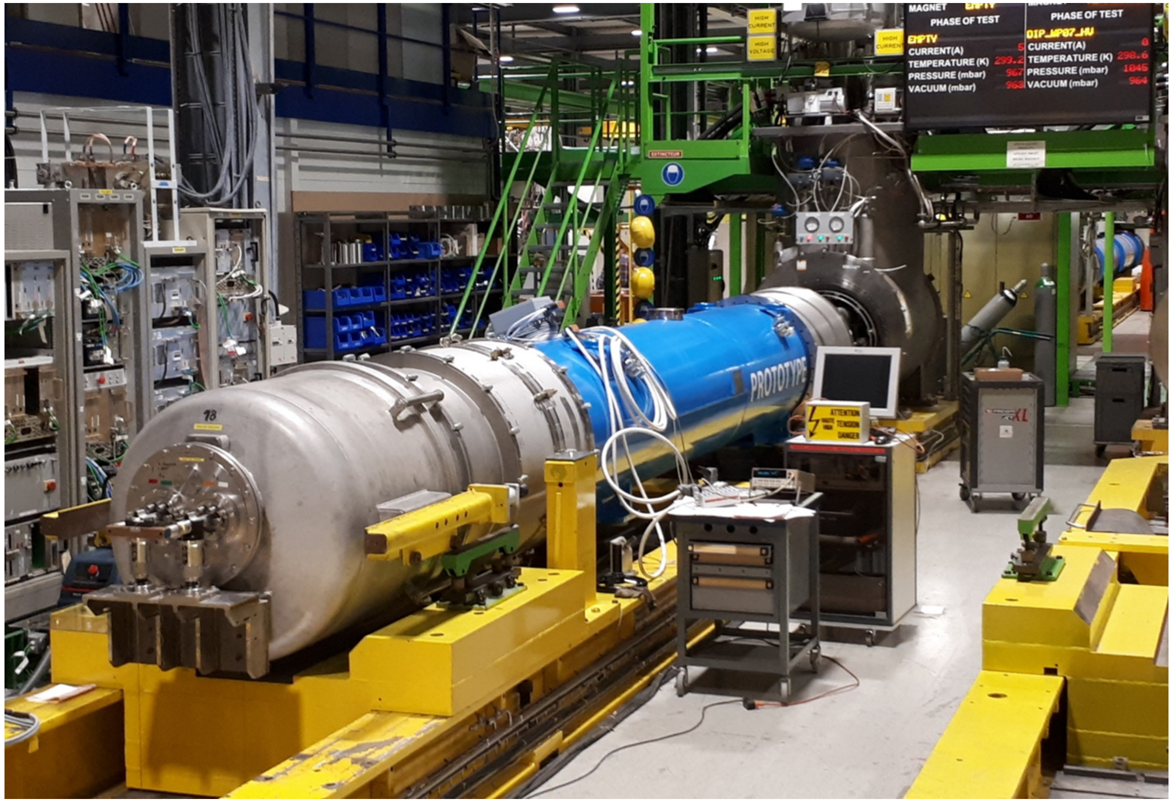
◆ Nb-Ti operating dipoles; ● Nb3Sn cosϑ test dipoles ■ Nb3Sn block test dipoles ✚ Nb3Sn cosϑ LARP QUADs

11 T dipole schedule. It is for LS2: 2019!



First 11 T prototype (full size) on test @ CERN

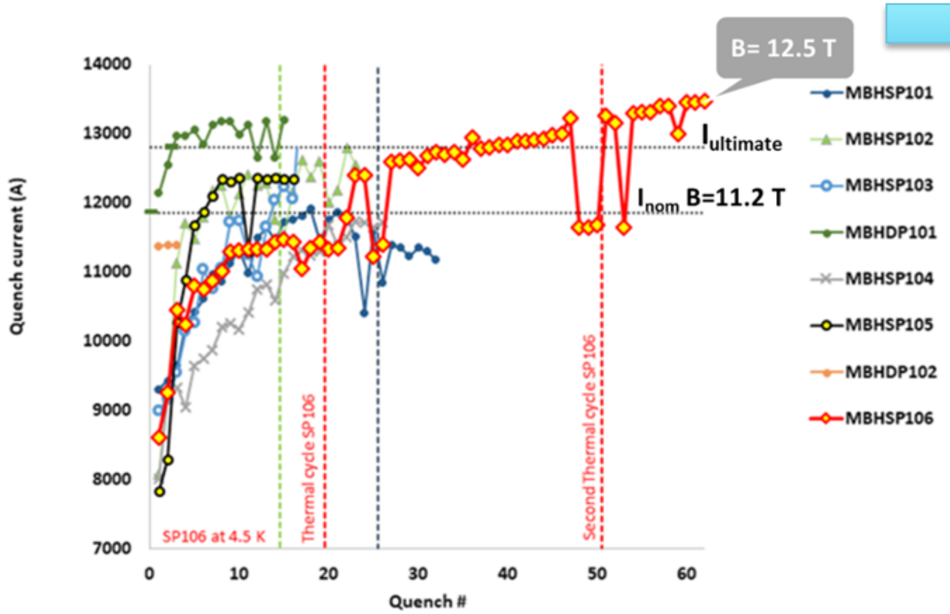




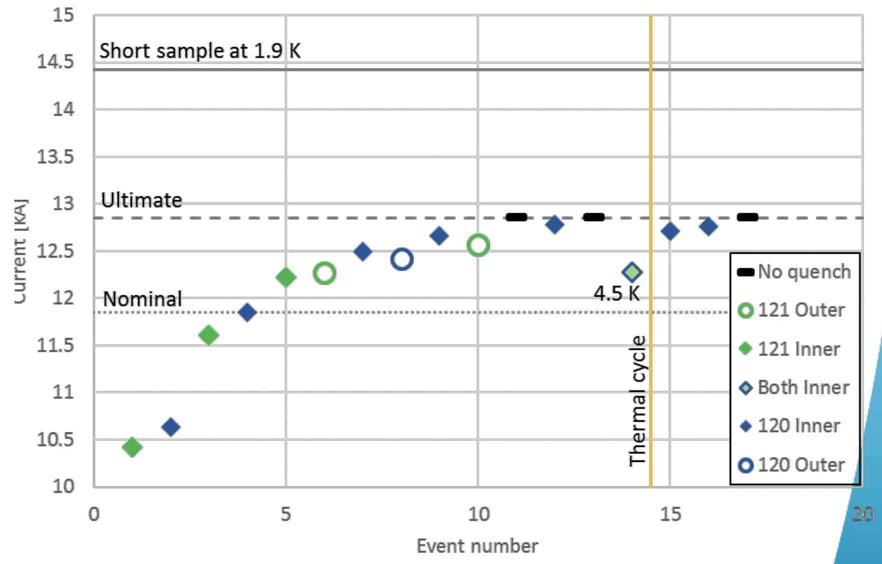
Result not positive (<10 T)
Magnet under rework to test second aperture alone

Review of 11 T results

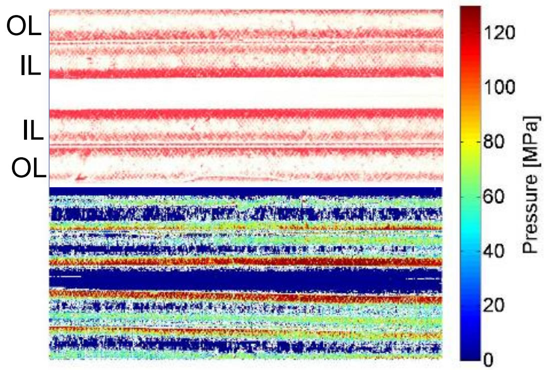
Results on short models before test of long proto



Result of the first «new design» to cure «erratic» behaviour (July 2018)

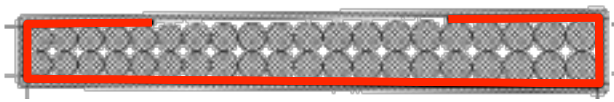


What was done?

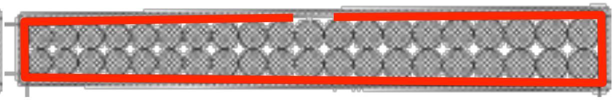


120 MPa stress gradient on the mid-plane in MBHSP105b

50 % Mica open gap
6.9 mm

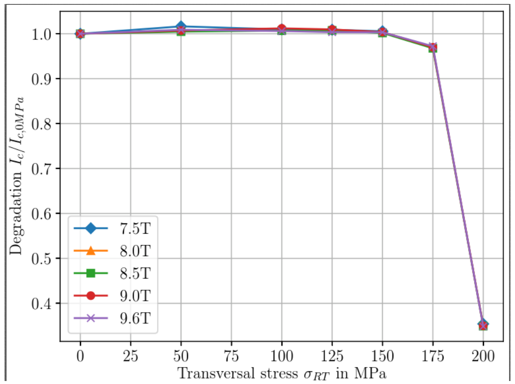


6 % Mica open gap
0.9 mm

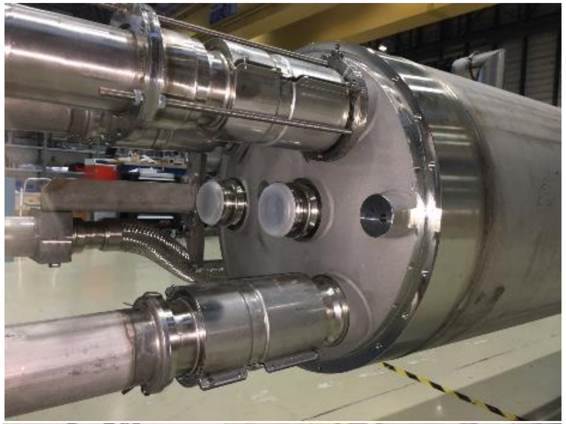


Nb3Sn is a brittle material! See figure at right!
More careful analyis and measurement of the conductor stress and properties of coils

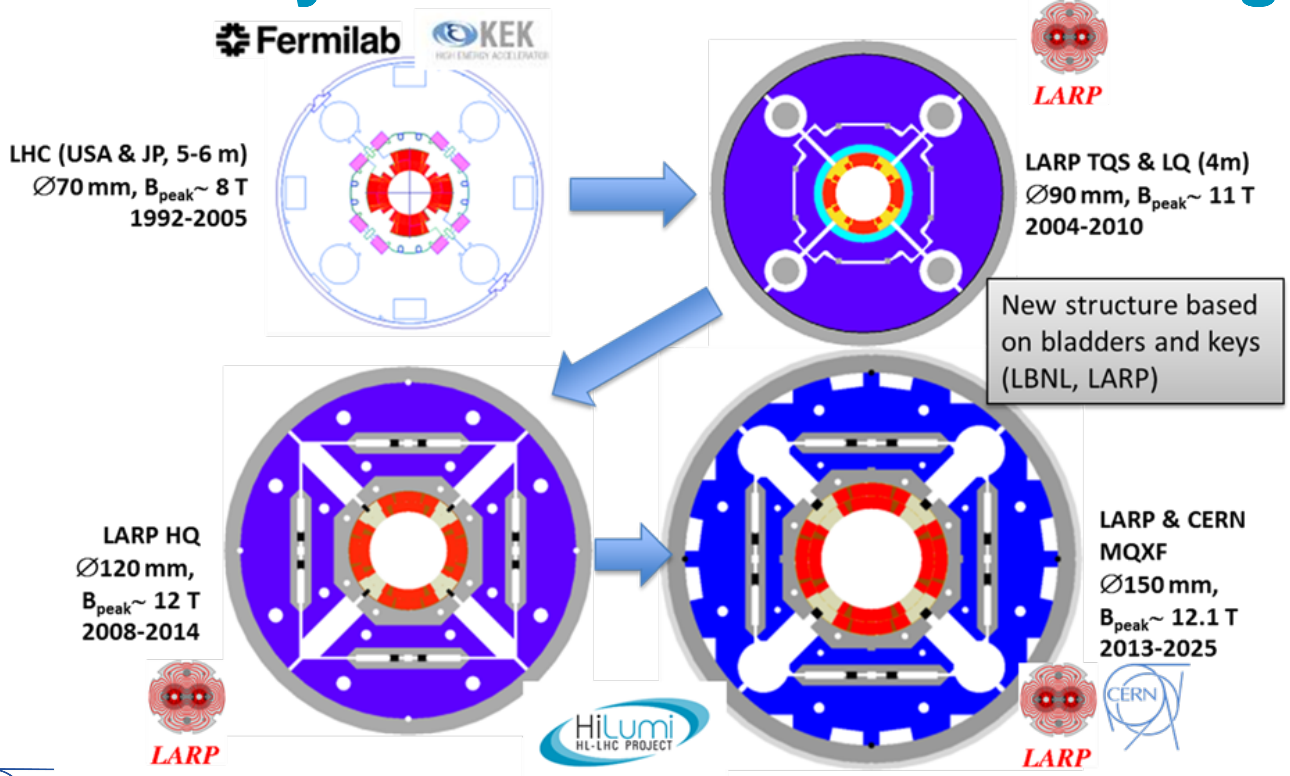
1. A. New insulation thickness; B. new insulation (Mica) geometry
2. C. More controlled procedure of collaring (crical operation to prestress coils



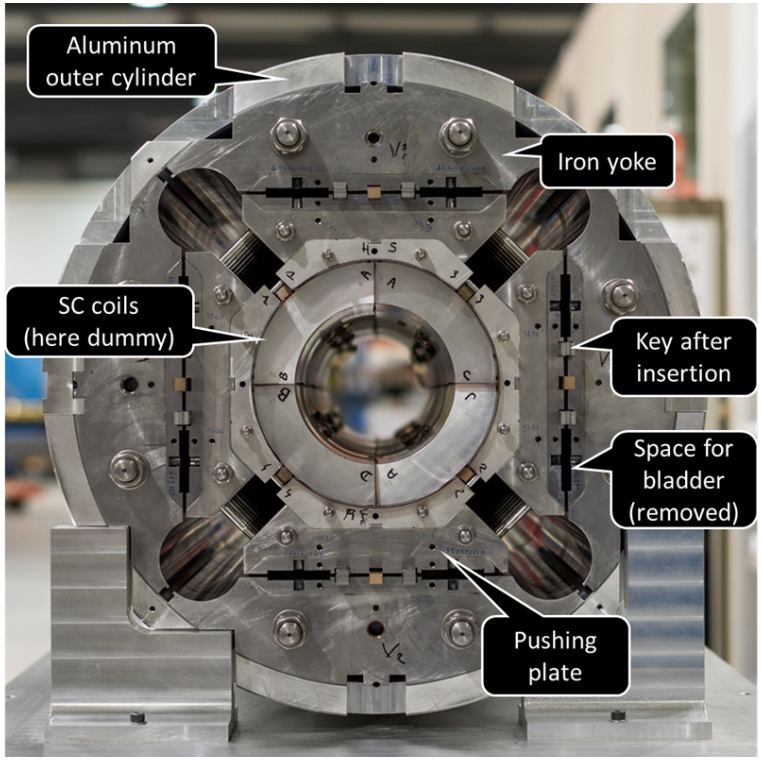
Now 11 T in full swing for production great care in QA given the sensitivity of Nb3Sn

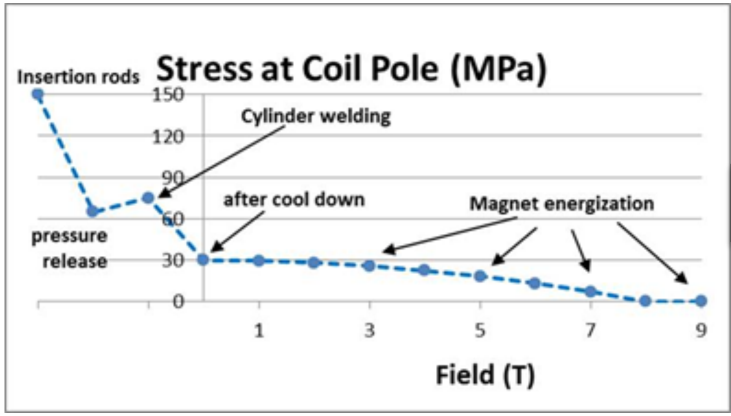


IT quadrupole. Increase in field btu also in size wrt LHC. Very relevant also for FCC magnets

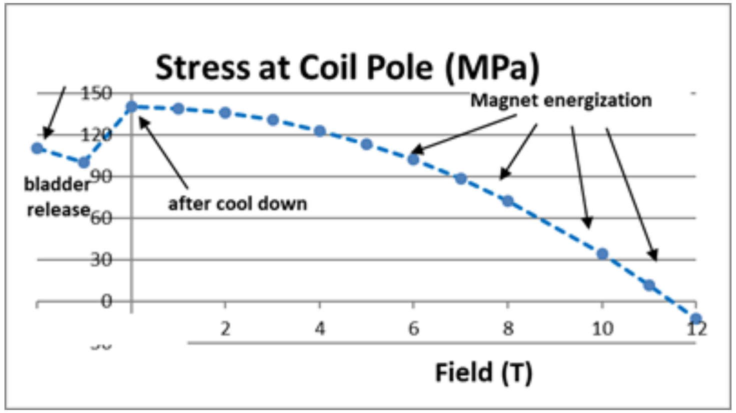


New Keys&Bladders of IT Quads concept allows to better control stress: 15 y of development…





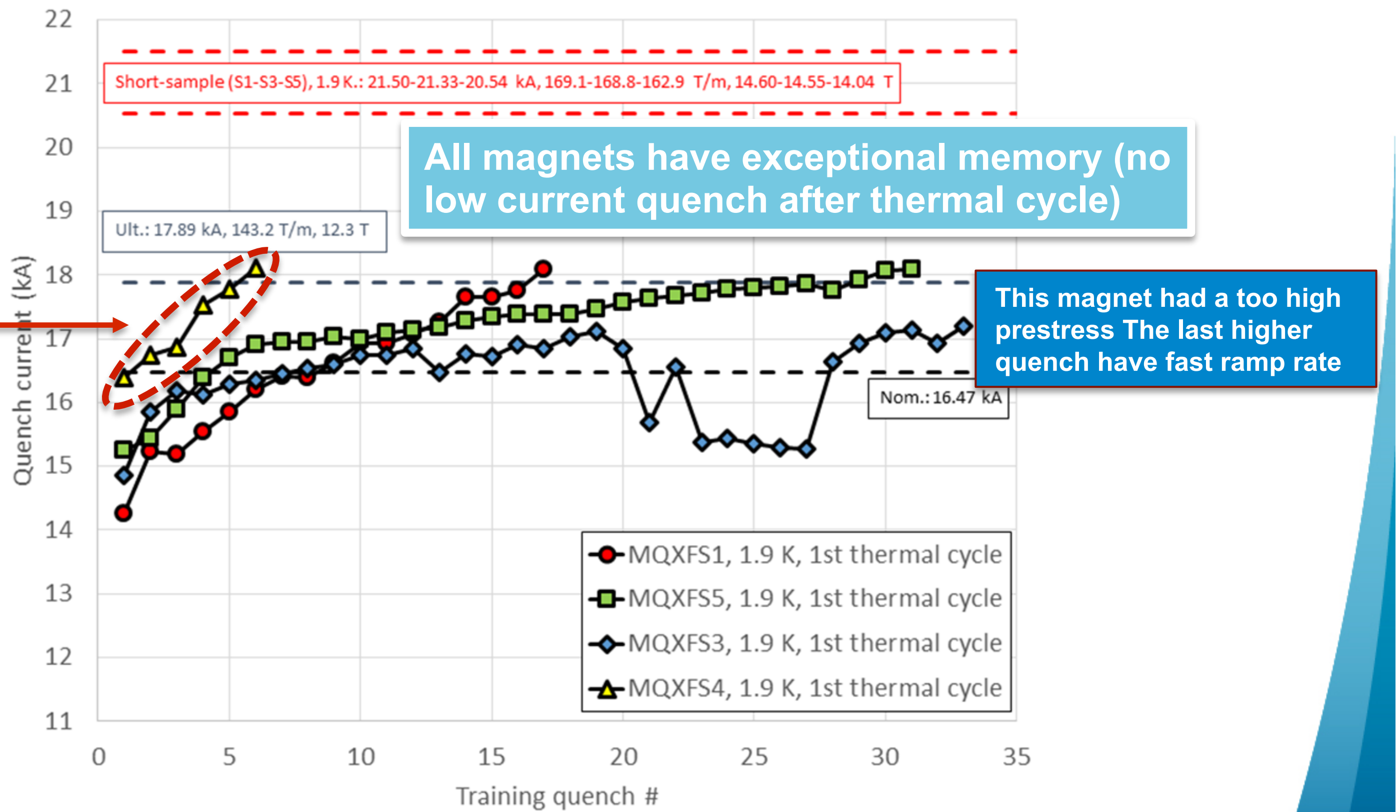
LHC dipole



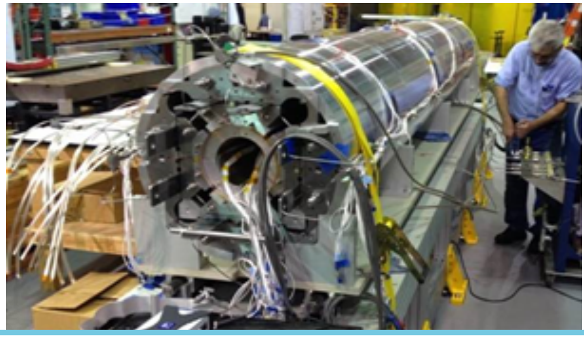
HL-LHC IT Quad

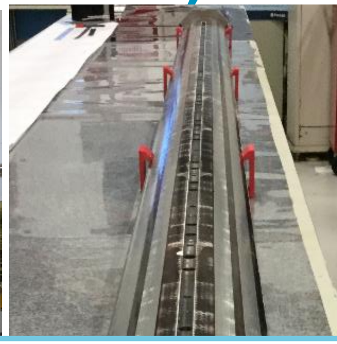
Result of IT quadrupoels

Best HF magnet ever tested in terms of behaviour (not max field) Final conductor, final prestress procedure

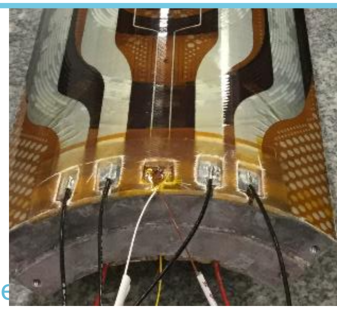


Construction of the 1st and 2nd long (7.5 m!) IT Quad in full swing (also in USA)





Making long magnets in Nb_3Sn is not granted but we are confident for Hilumi: the project is big but not enormous (about 30 magnets of 4.2, 5.5 and 7.2 m length)



A step between HL-LHC and a HE-LHC?

- Report under editing (by O. Bruning) in 2018.
- Pushing to 15 TeV (ultimate dipole field of 9 T): not impossible, in the HiLumi time, sensible less availability, trade off with less lumi maybe not convenient, TBD
- Pushing the energy using 11 T as middle cell dipole (1/3) gaining 11% energy: 15.5-16.6 TeV (nominal-ultimate field).
  - Most probably not convenient in terms of cost, personnel resources,time (big installation) and very difficult for optics. I think is impossible to «touch» only the magnets. And needs at least a design revision of the HiLumi 11 T.
  - Not for tomorrow, not easy, not cheap, not «transparent» for other CERN development, not a terrific gain…

Personal opinion

FCC-hh and HE-LHC parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC 2018
collision energy cms [TeV]	100		27	14	13
dipole field [T]	16		16	8.33	7.74
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.49
bunch intensity [10^{11}]	1	1	2.2	2.2	1.1
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	2.3
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.11
long. emit. damping time [h]	0.54		1.8	12.9	16.1
beta* [m]	1.1	0.3	0.45	0.15 (min.)	0.30
normalized emittance [μm]	2.2		2.5	2.5	2.0
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	16	5 (lev.)	2.0
int. luminosity / year [fb^{-1}]	250	1000	500	250	50?
events/bunch crossing	170	1000	440	132	60
stored energy/beam [GJ]	8.4		1.3	0.7	0.28

parameter	FCC-hh$_{nominal}$	FCC-hh$_{initial}$	HE-LHC	HL-LHC	LHC 2017
allocated physics time ***T*** [days]	160	160	160	160	160
peak luminosity $\hat{L}$ [10^{34} cm^{-2}s^{-1}]	30	5	16	5 (levelled) [7.5 ult.]	1.5 (levelled)
availability ***A*** [%]	70	70	75	80 [85 ult.]	82
average turnaround t_{ta} [h]	4	5	5	4 [4]	5 (w/o faults)
(optimum) run time t_{run} [h]	3.7	11.6	5.3	8-13 [6.5]	~10
nominal luminosity / day L_{av} [fb^{-1}]	9.0	2.2	4.2	1.9 [2.3]	0.4
time-fraction in physics t_{phys} [%]	**34**	**49**	**39**	**54** [53]	**55**
int. luminosity L_{int} [fb^{-1} / year]	**1000**	**250**	**500**	**250** [310 ult.]	**60**

$$t_{\text{phys}} \approx A \frac{t_{run}}{t_{run} + t_{ta}} \qquad L_{\text{int}} \approx A\, T\, L_{\text{nominal per day}}$$

these hadron machines feature two high-luminosity experiments and up to two lower-luminosity (or special) interaction points

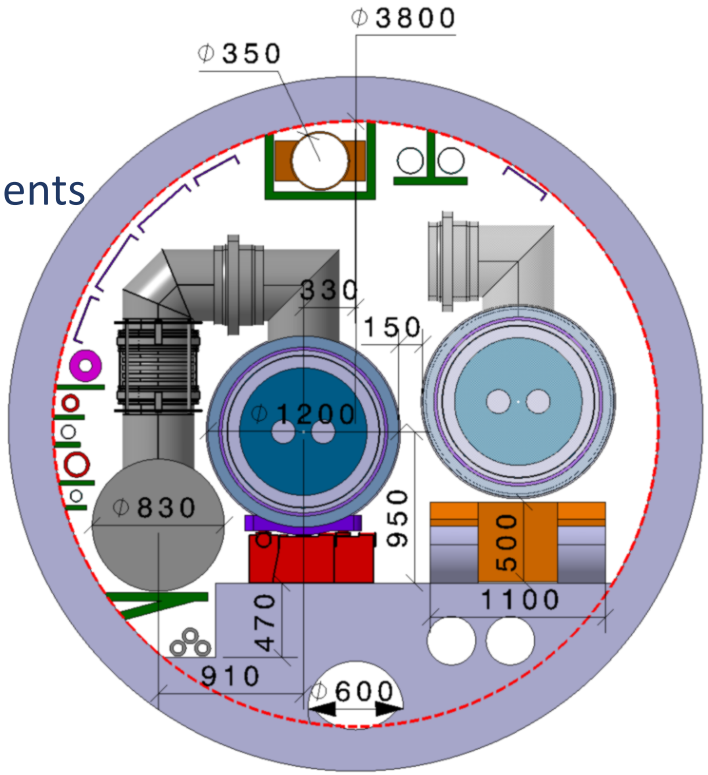
HiLumi HL-LHC PROJECT CERN

HE-LHC integration aspects

Working hypothesis for HE LHC design:

No major CE modifications on tunnel and caverns

- Similar geometry and layout as LHC machine & experiments
- **Maximum magnet cryostat diameter ~1200 mm**
- **Maximum QRL diameter ~830 mm**

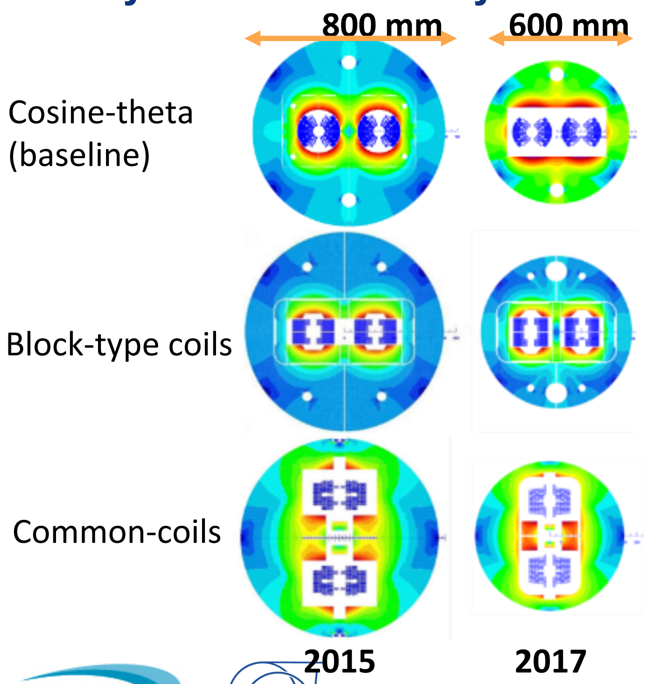


Integration and design strategy:

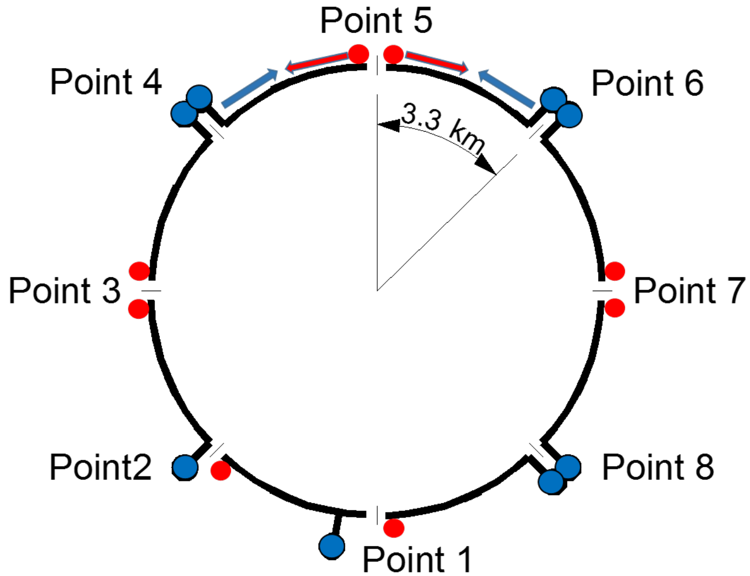
- Development of optimized 16 T magnet, compatible with HE LHC requirements
- New cryogenic layout to limit QRL dimension

16 T dipole design evolution: to save and to keep compatible with HE-LHC

- Coil optimization and margin 18 → 14%
- Inter-beam distance 250 → 204 mm
- Stray-field < 0.1 T at cryostat



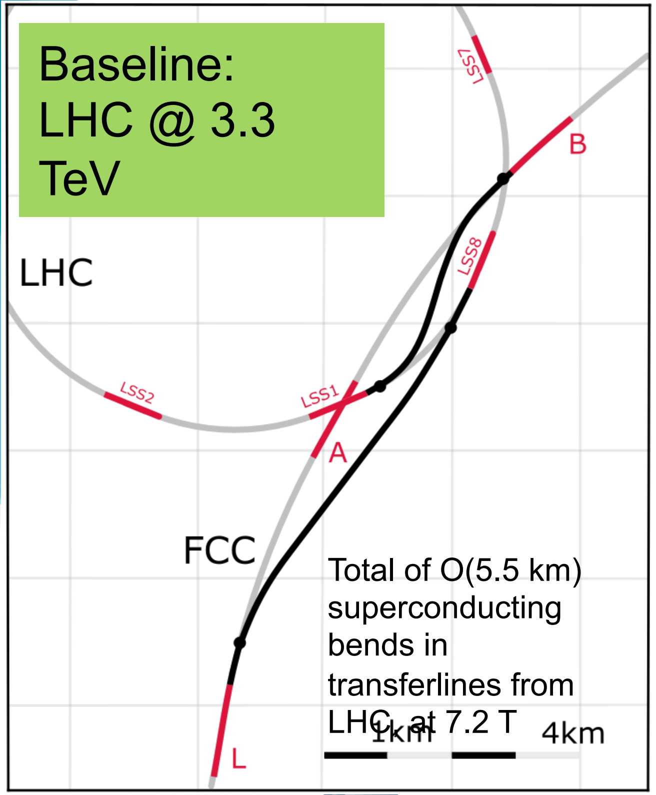
Half-sector cooling instead of full sector (as for LHC) to limit cross section of cryogenic distribution line

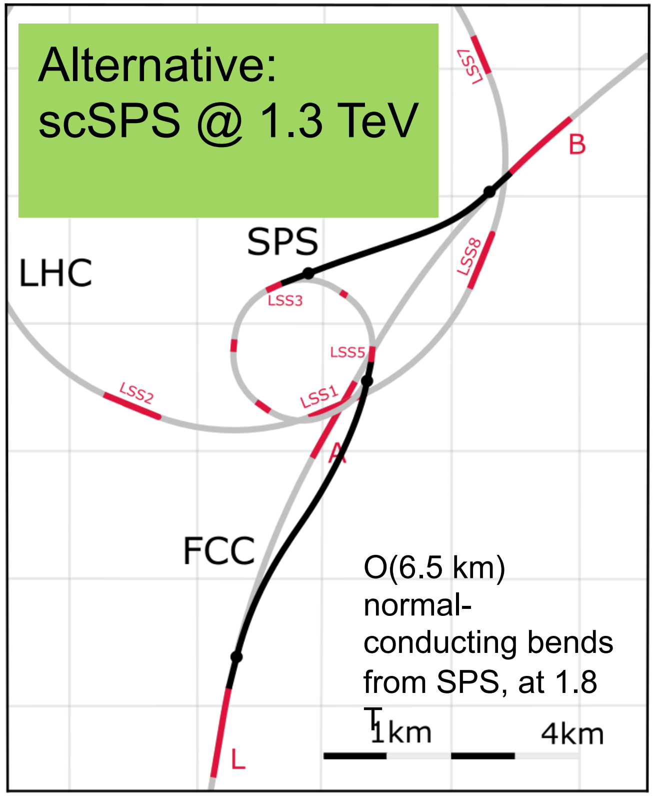


higher heat load and integration limitations:

- **8 additional 1.8 K refrigeration units wrt. LHC**
- **8 new higher-power 4.5 K cryoplants**

FCC-hh injector options: a 1.3 TeV injection may allow smaller cheaper HE magnets



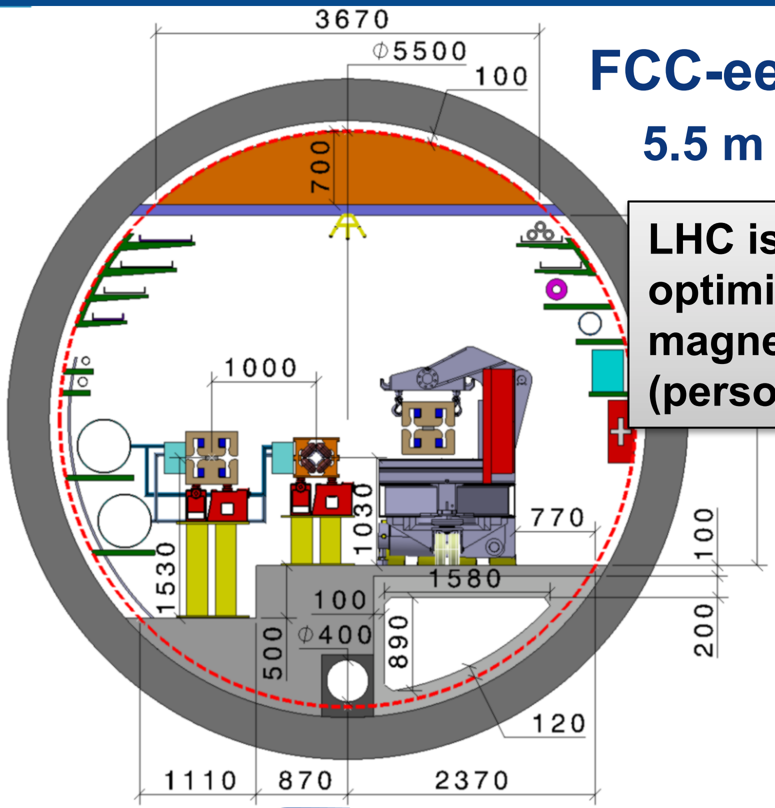


Current baseline:
- **Injection energy 3.3 TeV LHC**

→ Field-swing FCC-hh like LHC

Alternative options:
- **Injection from $SPS_{upgrade}$ around 1.3 TeV**
- **$SPS_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp, cf. SIS 300 design**
- **$SPS_{upgrade}$ would also be an ideal injector for HE LHC (as alternative to the 450 GeV SPS)**

FCC – tunnel integration in arcs

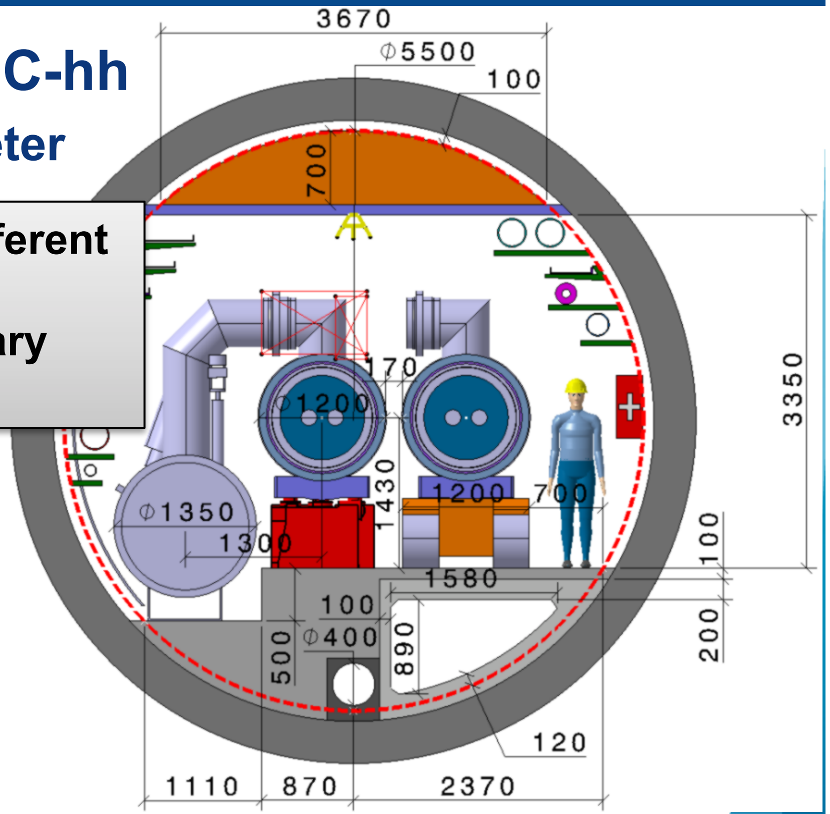


FCC-ee

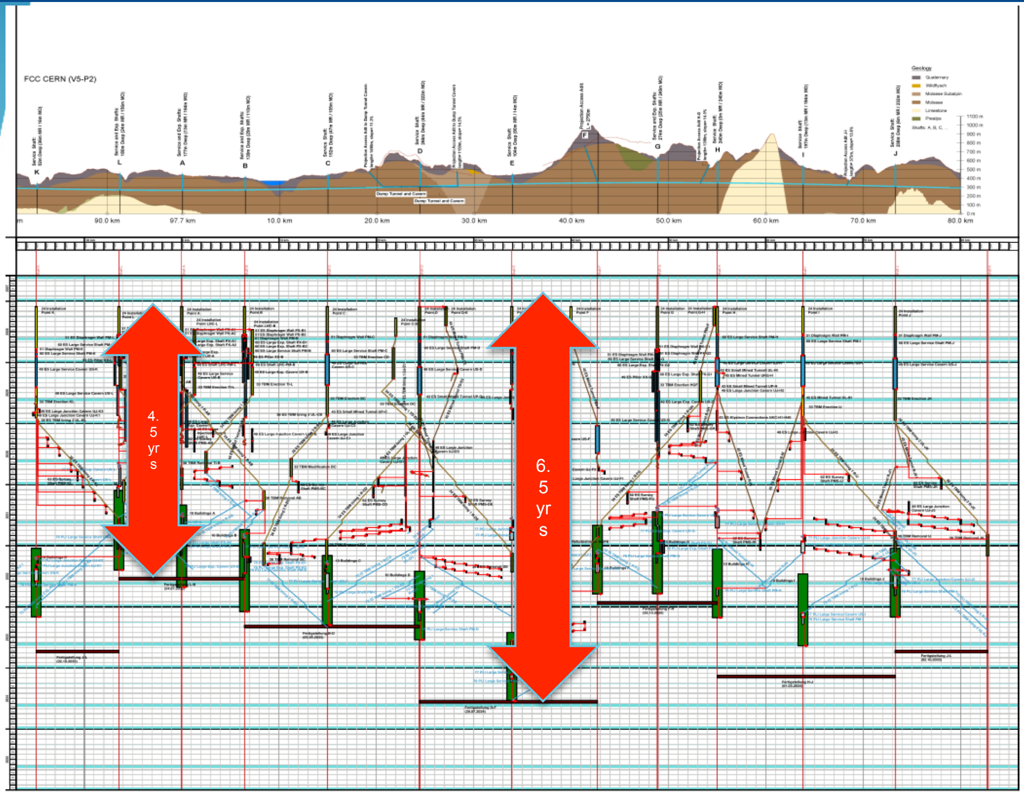
FCC-hh

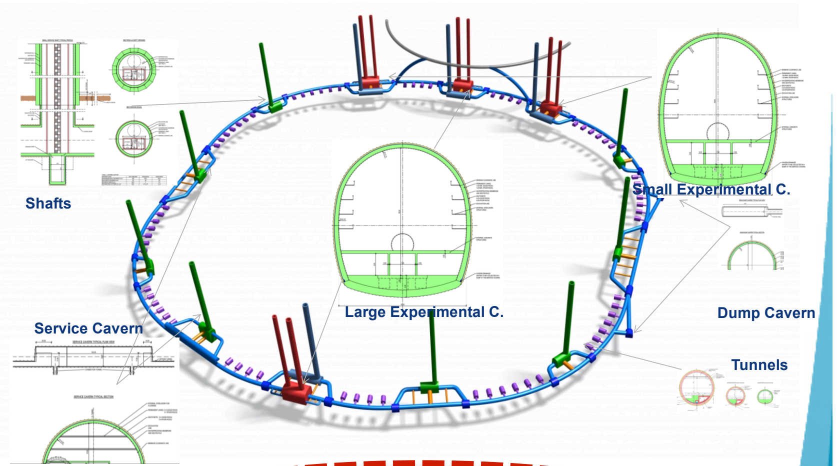
5.5 m inner diameter

LHC is 3.8 m! A different optimisation of the magnets is necessary (personal opinion)



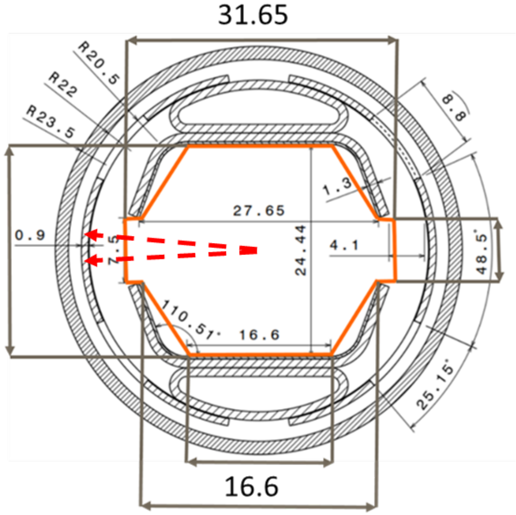
CE schedule studies

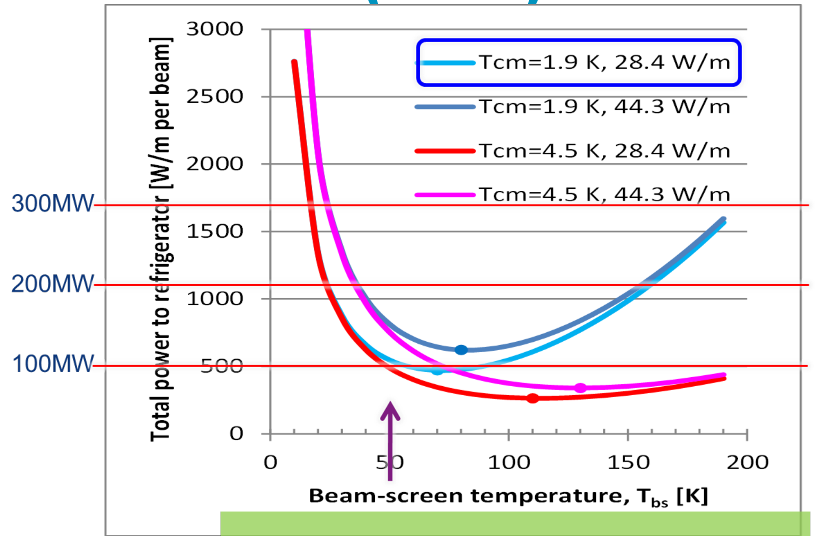


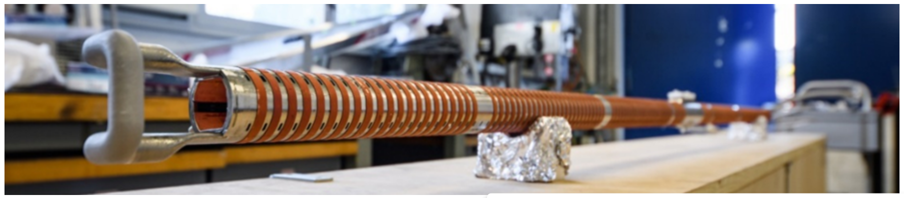


- Total construction duration 7 years
- First sectors ready after 4.5 years

Beam screen design with the synchrotron radiation (non) issue







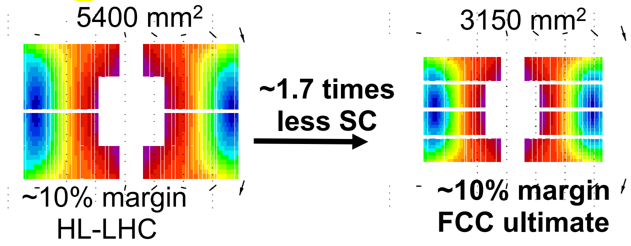
- **Optimum beam screen operation temperature 40 - 60 K**
- **Electrical power for beam screen cooling ~100 MW .**

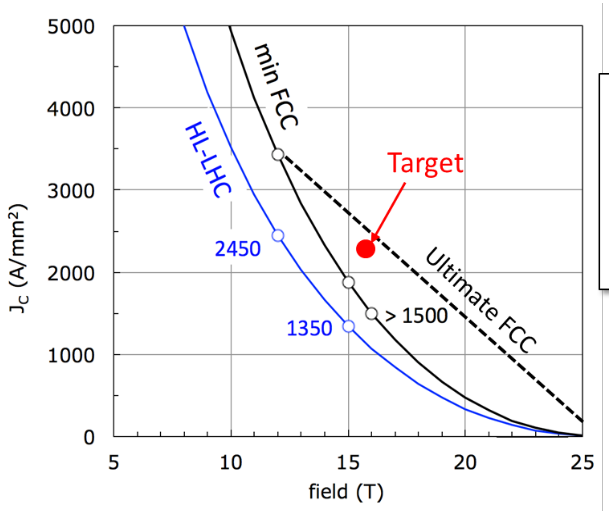
This shows that there is no real technical show-stopper, if one is able to build reliable and reasonable cost magnets

The critcal point to reach 16 T: superconductor! Worldwide FCC Nb_3Sn program

Main development goal is wire performance increase:

- J_c (16T, 4.2K) > 1500 A/mm² → 50% increase wrt HL-LHC wire
- Reduction of coil & magnet cross-section





D_{strand}: 0.7…1 mm
J_C (16 T, 4.2 K) > 1500 A/m
M (1 T,4.2 K) <150 mT
(D_{fil} < 20 μm)
RRR > 150
UL > 5 km
Cost(16 T, 4.2 K) < 5 USD/

This is difficult

Conductor activities for FCC started in 2017:

- **Bochvar Institute** (production at **TVEL**), **Russia**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT**, **Korea**
- **Columbus**, **Italy**
- **University of Geneva**, **Switzerland**
- **Technical University of Vienna**, **Austria**
- **SPIN**, **Italy**
- **University of Freiberg**, **Germany**

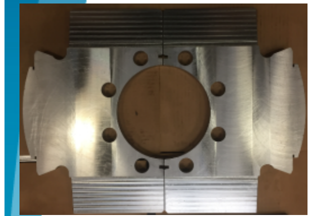
In addition, agreements under preparation:

- **Bruker**, **Germany**
- **Luvata Pori**, **Finland**

U.S. MAGNET DEVELOPMENT PROGRAM

15 T dipole demonstrator (US-MDP)

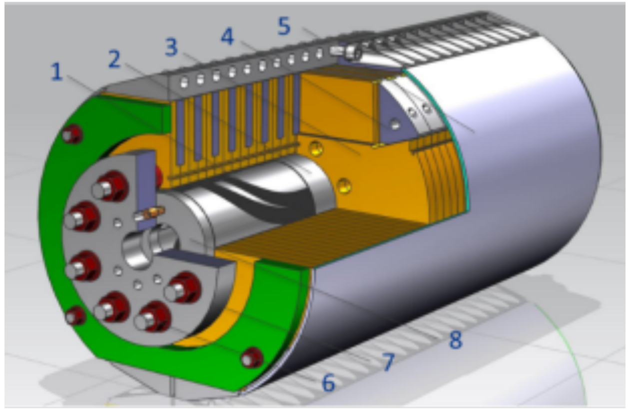
U.S. DEPARTMENT OF ENERGY | Office of Science

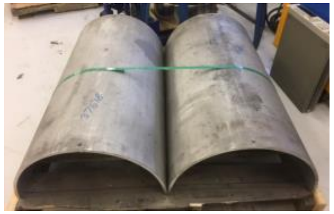


Iron Laminations

AL I-Clamps

Fillers





StSt Skin

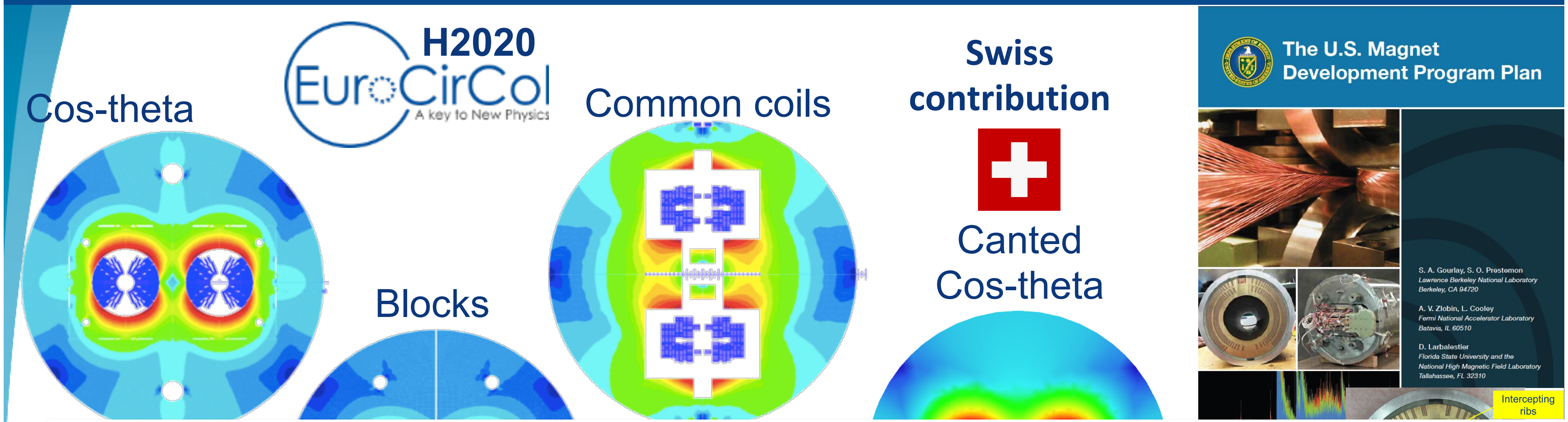
End Plates

Axial Rods

- All coil parts, structural components and tooling are available at FNAL
- Coil fabrication and the work with mechanical structure are in progress
- First magnet test in September 2018

HiLumi HL-LHC PROJECT CERN

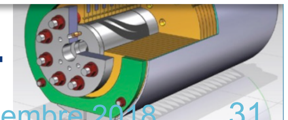
16 T dipole design activities and options



Very good: gaining resources and supports by various labs…
But it is wise? Isn't there a better use of the limited HEP resources ? Why not choose a design and concentrate on it? … All types can work if properly engineered
This is a personal opinion but seems to me evident...

CEA

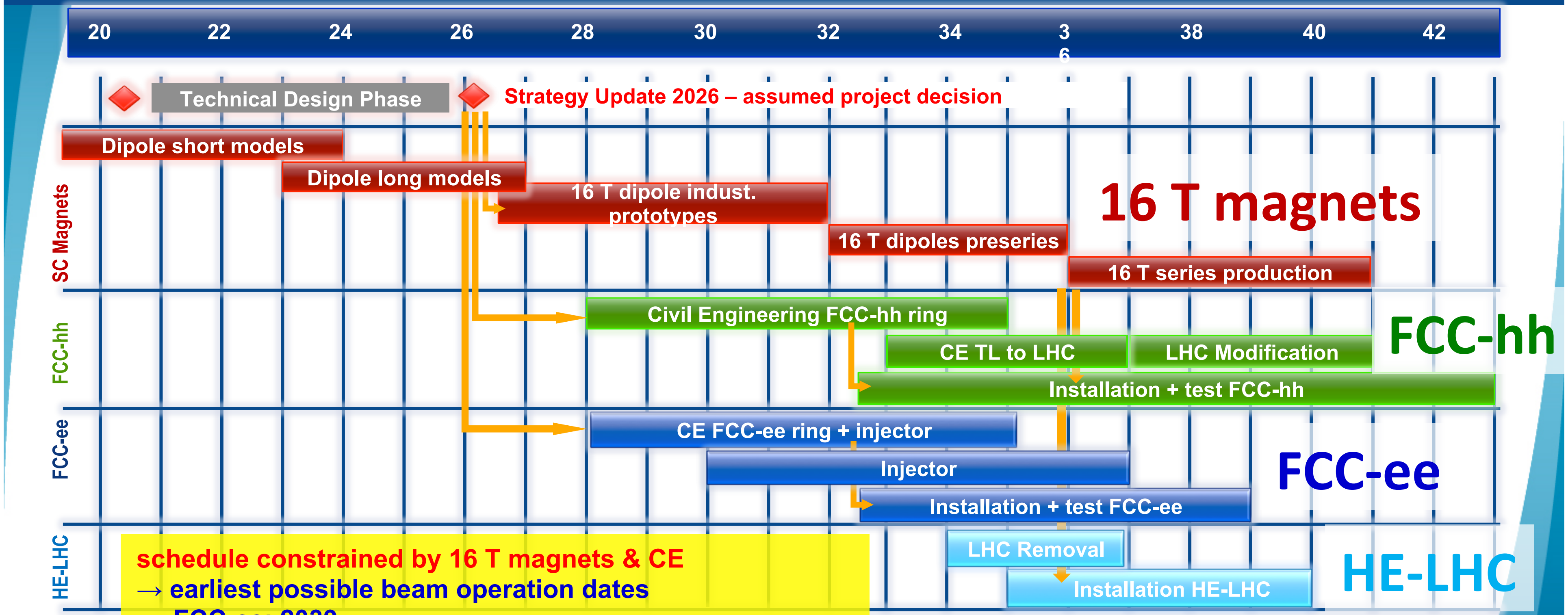
FNAL



Short model magnets (1.5 m lengths) will be built from 2018 – 2022

Russian 16 T magnet program launched by BINP recently.

Technical Schedule for each of the 3 options

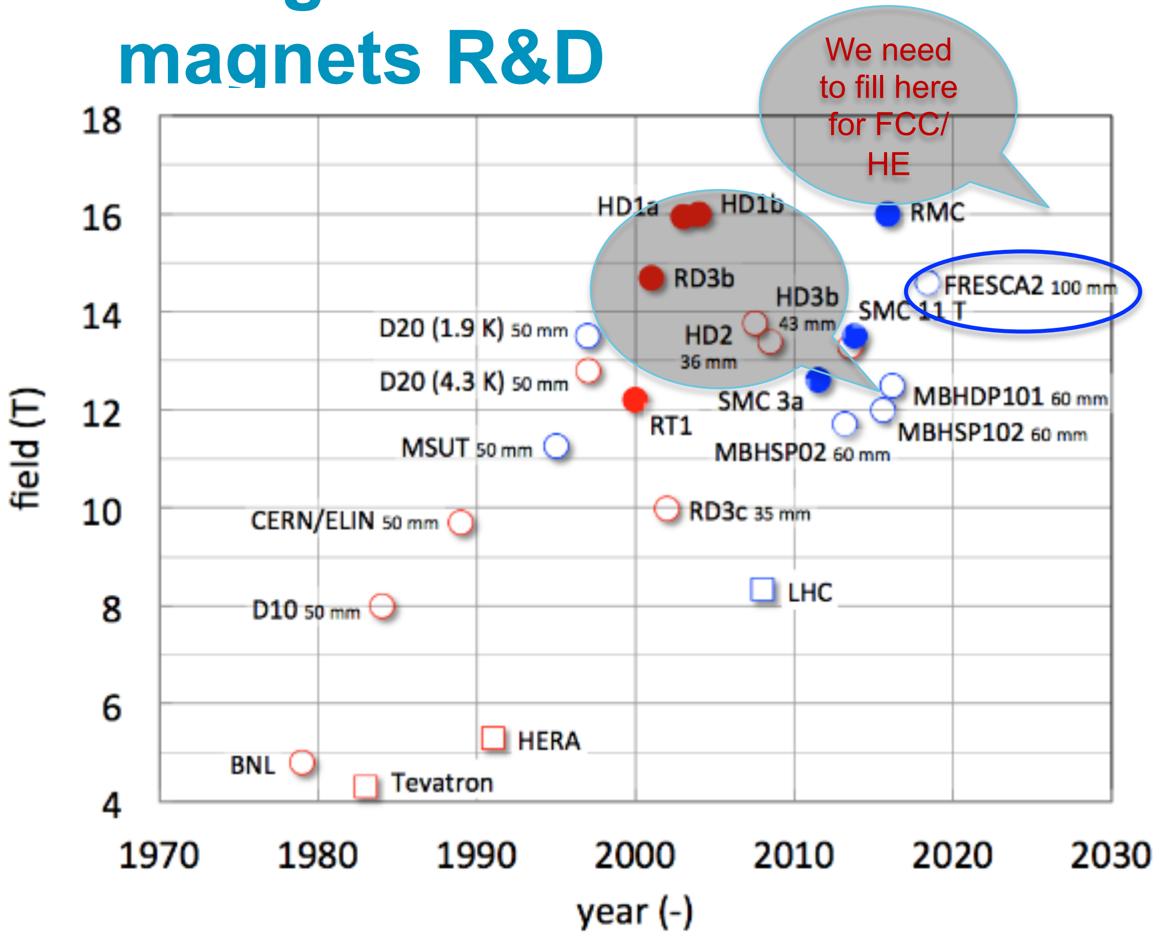


schedule constrained by 16 T magnets & CE

→ earliest possible beam operation dates

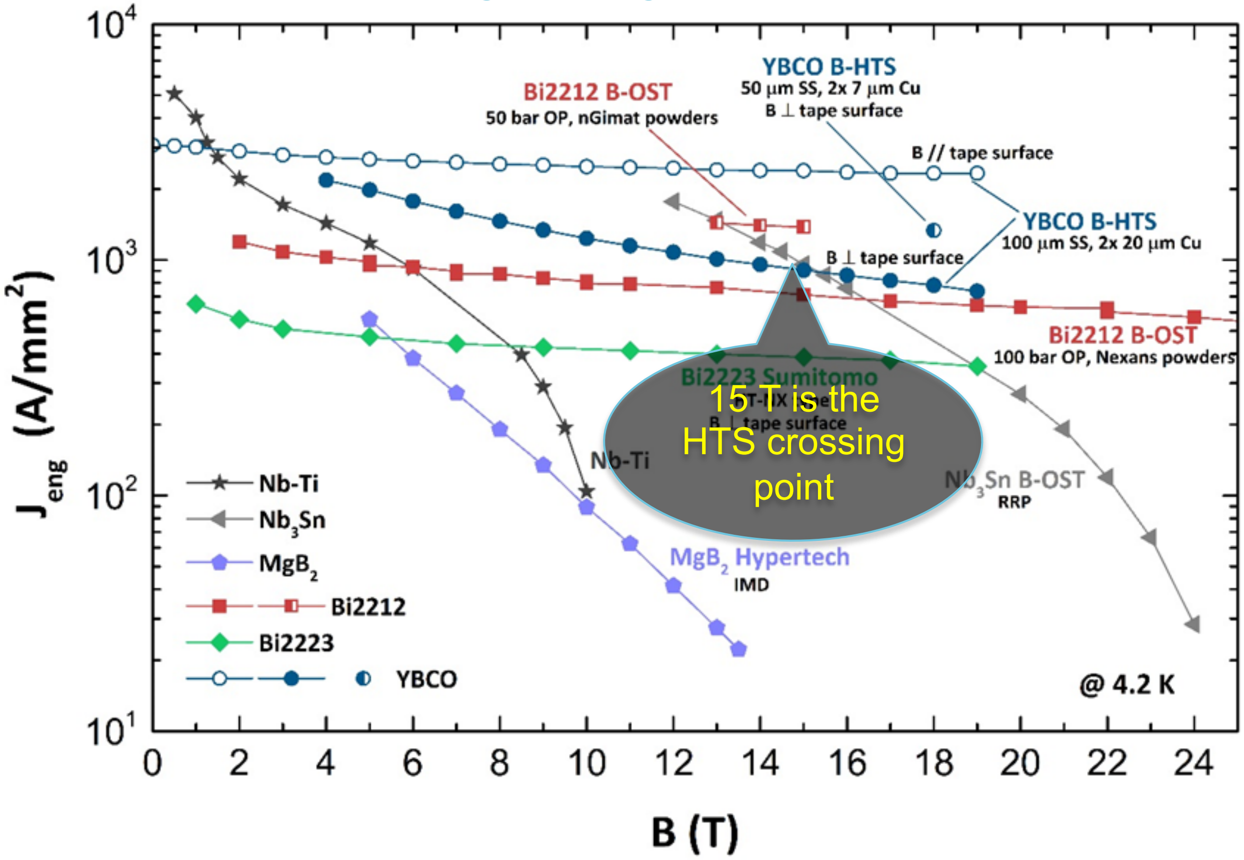
- **FCC-ee: 2039**
- **FCC-hh: 2043**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

Progress in magnets R&D



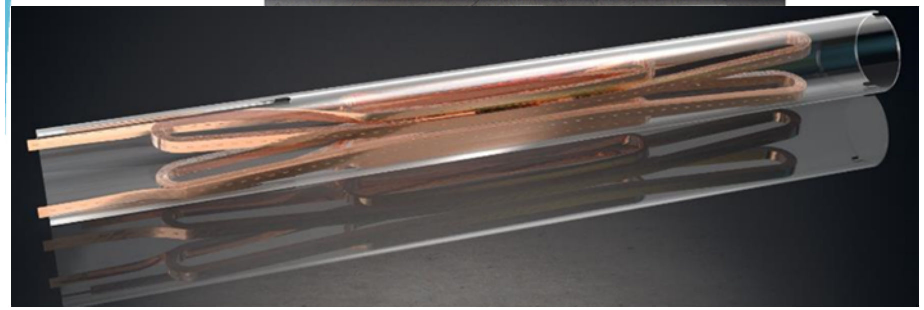
2018: FRESCA2
(14.6 T at 1.9 K, 100 mm)

And the HTS ? Only way to reach 16-25 T



Comments on HTS

Working on new type of cables and magnets: reached 3.5 T, expected 7 T in January 2019



HTS situation and perspective

- Very expensive (5 times than Nb3Sn)
- Magnets are easier: great stability, no training!
- May work in He gas at 20 K: big advantage for power consumption and easier system…
- Basic R&D for 5-10 years to reach maturity is needed. Last 3 y has doubled performance! A solenoid of 32 T has been tested successfully.
- **We would not be alone… plenty of Institute (and companies) work on HTS**
- **This is the ground for basic focus R&D.**

Conclusion

- The program for FCC/He is very well structured
- Maybe a better focus on some objectives and a reduction of those objectives may make the program more feasible.
- A 14 T dipole (**an HE-LHC of 24 TeV c.o.m**.) based on existing HiLumi superconductor – improved – **is really feasable today**.
- The 16 T is still a long way to be demonstrated**: it can, but it needs FOCUS** and requires true synergy not just sum of various labs effort;
- HE-LHC needs a different optimization for the magnet system and collider than FCC (**but the SAME technology R&D**) (personal opinion).
- If there is an intermediate step (LHeC, or a lepton collider) that pushes 5-10 years back the post-LHc pp collider, then HTS is probably the best solution.
- Embracing too large and unfocused R&D (generic High Field magnets) maybe not the best choice now for a project ready in the '30s…

Thanks

A of credits to : Luca Bottura, Frank Zimmermann, Michael Benedikt and Davide Tommasini