HIGH-FIELD MAGNETS & FCC-hh SCENARIOS

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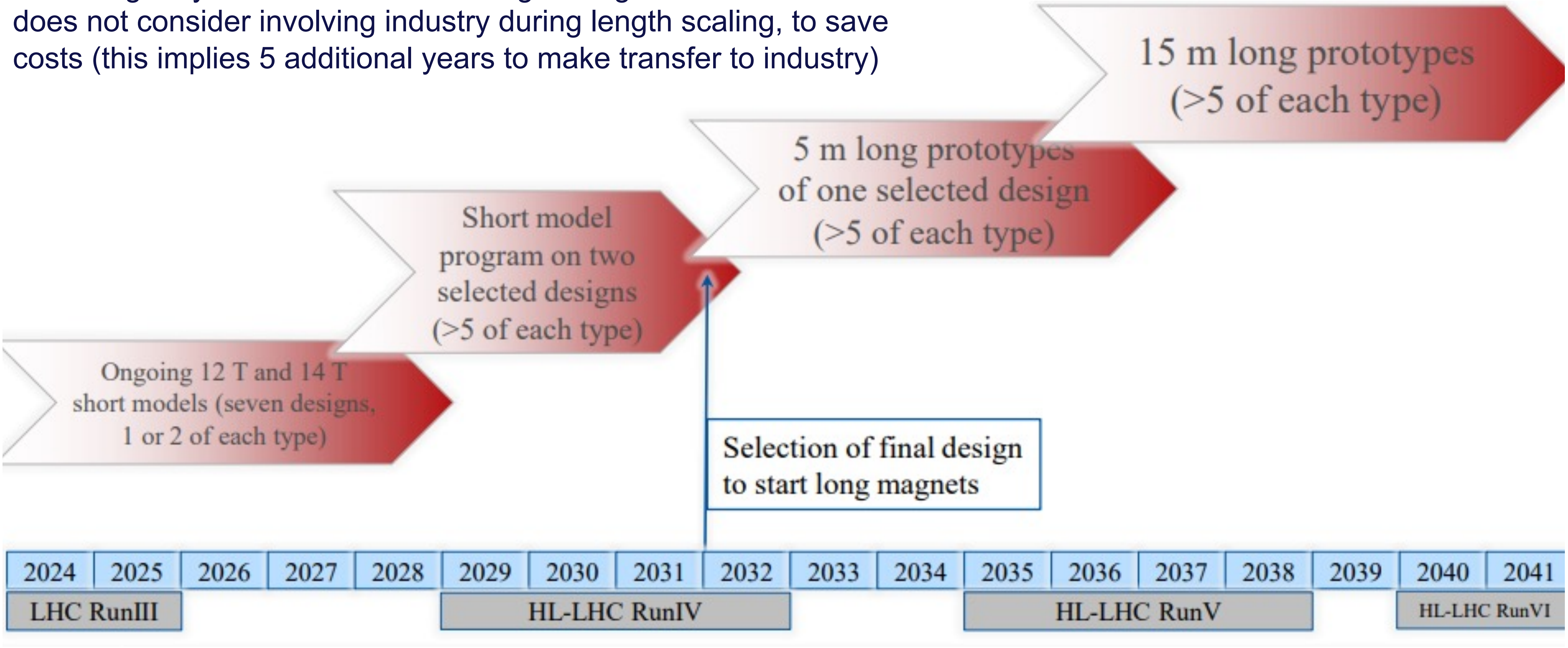
Warm thanks to Bernhard Auchmann, Amalia Ballarino, Michael Benedikt, Massimo Giovannozzi, Michelangelo Mangano, and Ezio Todesco

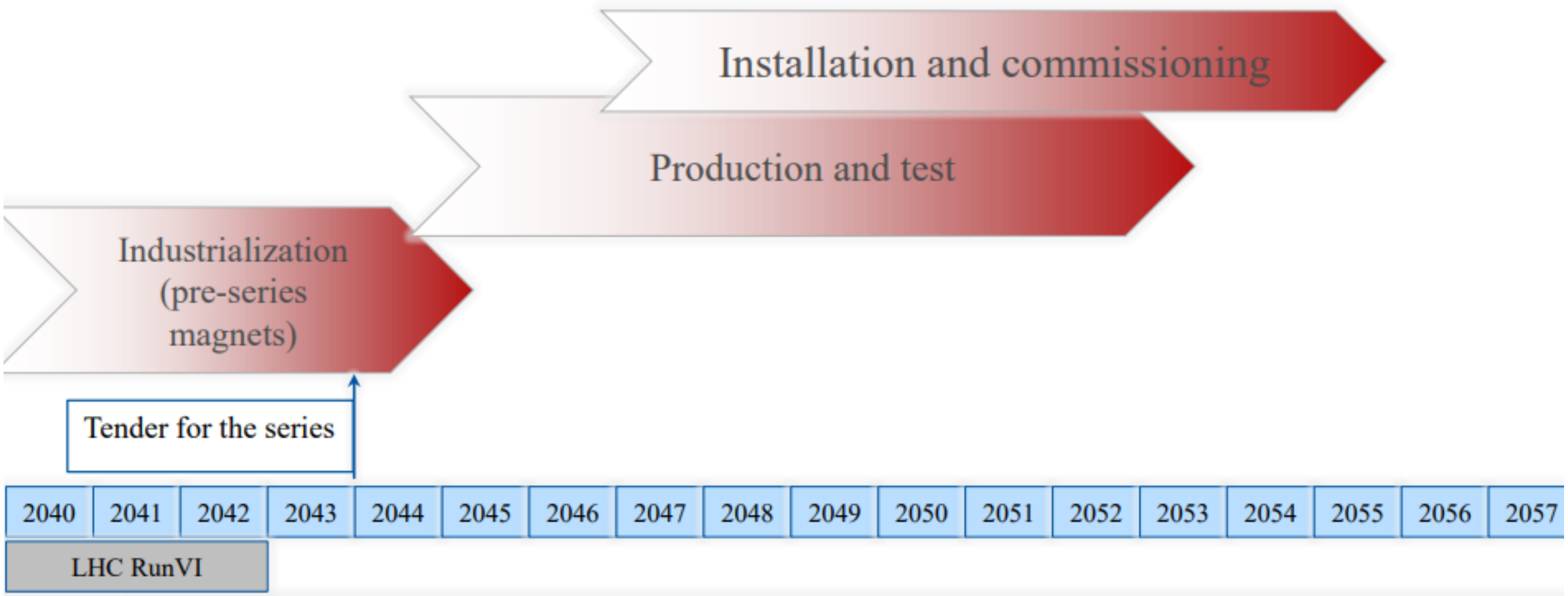
14 T Nb_3Sn "accelerated" roadmap: short models & scaling in length

assuming 10 years to make the scaling in length from 1.5 to 15 m
does not consider involving industry during length scaling, to save costs (this implies 5 additional years to make transfer to industry)



E. Todesco, B. Auchmann

14 T Nb_3Sn "accelerated" roadmap: Industrialization, production, & commissioning



this roadmap indicates 2055 as possible date for FCC-hh start

E. Todesco, B. Auchmann

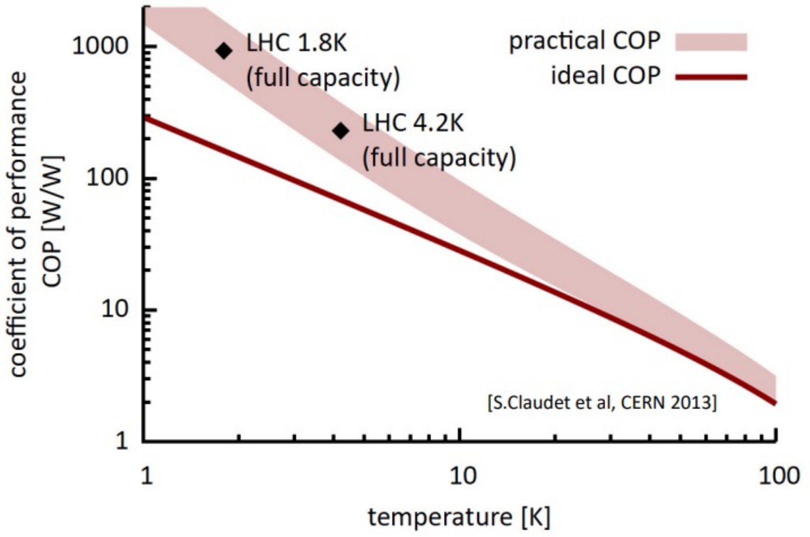
FCC-hh power consumption

FCC-hh CDR (2020): magnet system (16 T) at 1.9 K to save conductor cost, and beamscreen temperature of 50 K for intercepting synchrotron radiation
• Cryogenics responsible for half of ~580 MW power consun
• Magnet ramp losses buffered into He-II bath with minimal temperature excursions thanks to lambda peak in He-II heat capacity.

Table 9.1. Power requirements of accelerator subsystems for the highest performance operation period during the luminosity production phase at the flat top of the cycle.

Subsystem	Electrical needs (approx. MW)
Cryogenics	276 (ca. 250 with further optimisations)
Radiofrequency	26
Magnets	80
Cooling and ventilation	30
General services	40
Four experiments	42
Data centres for four experiments	18
Injector complex	68
Total	**580** (ca. 550 with further optimisations)

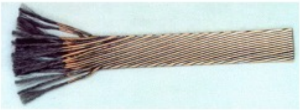
Power-consumption could be significantly reduced:
• Reducing magnetic field requirement from 16 to 14 T lower SR power and also makes SC coils more compact
• 4.5 K magnet temperature improves cryogenic efficiency
• in parallel beam screen temperature increased, to ~70 K.
• Ramp losses need to be minimized and buffered in dedicated locations along the cryo circuit.
• An addt' low-cryogen-inventory option under study, where a heat-exchange pipe is routed directly through/along the coils of an otherwise dry coldmass.
• The HFM Programme prepares a number of demonstrator magnets to be tested at 1.9 K and 4.5 K.



HTS ReBCO Option at 20 K

- Higher magnet temperature further improves power consumption for static and beam-induced losses.
- Higher fields and collision energies could be envisaged but main cryo load for FCC-hh is synchrotron radiation (SR) on the beam screen.
- SR power scales $\propto B^4$!
- Higher collision energy enabled by HTS cannot be more power efficient than energies attainable with LTS.
- In addition, increased ramp losses may (at least) in part cancel the improved cryogenic efficiency at 20 K.

Effective filament size: Nb-Ti 4-5 μm,
Nb3Sn 20-50 μm,
ReBCO **2-12 mm**



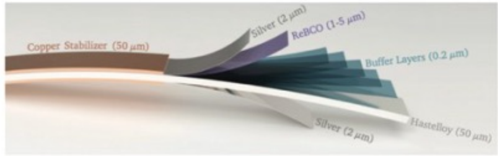
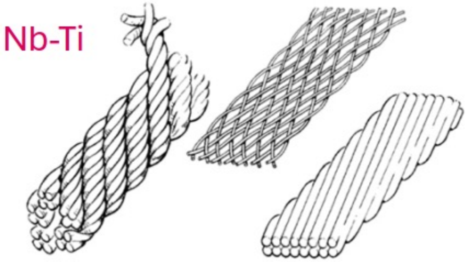


Figure 1.7. *Material composition of ReBCO coated conductor. For visual clearness the tape is cut in half along its length such that the inside becomes visible. In reality the copper and the silver layers fully surround the hastelloy substrate carrier.*

1970s, Nb-Ti



Paul Scherrer Institute PSI

Present, ReBCO

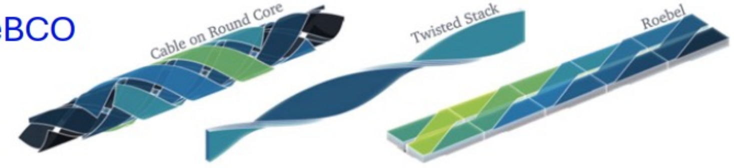


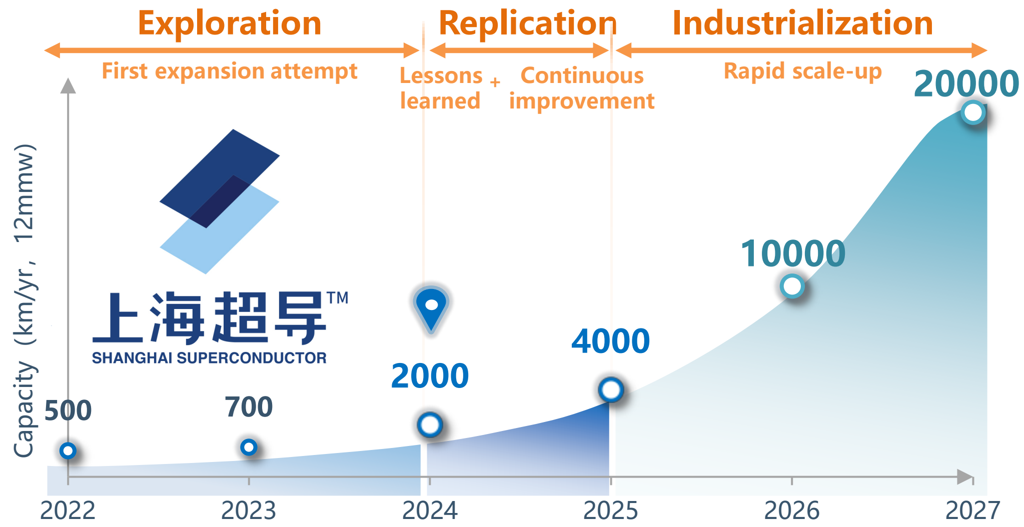
Figure 1.10. *Three different geometries for assembling a cable with ReBCO coated conductor. Also refer to Table 1.2.*

[M. Wilson, Pulsed Superconducting Magnets' CERN Academic Training May 2006]
[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. PhD thesis, UTwente, 2016.]

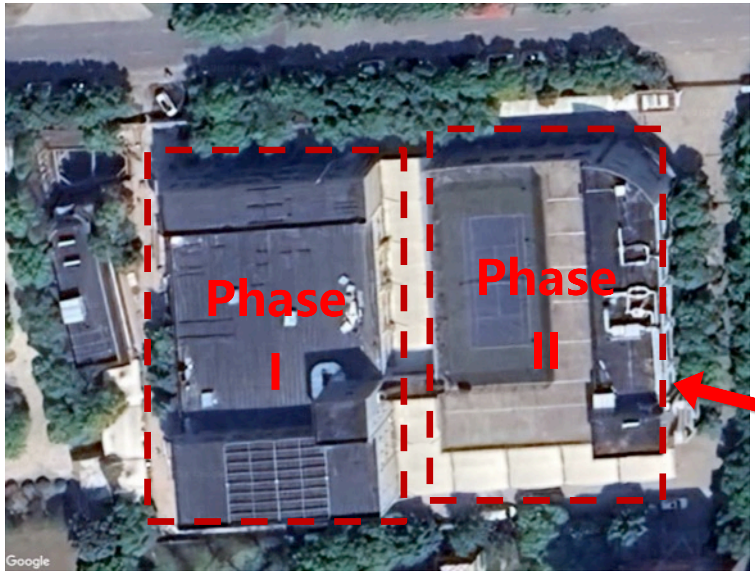
HFM is in the progress to set max. ramp-loss targets to guide the magnet R&D. The goals are to based on:
1. An HTS accelerator at 20 K should operate more sustainably than an LTS accelerator at 4.5 K at equivalent magnet field (e.g., 14 T). 2. **The cryogenic installation + magnet should fit into the FCC-ee tunnel.** Initial estimates indicate a **4-8x increase in ramp losses wrt. Nb_3Sn state of the art,** which may fall within the above Target (1). Work in progress …

ReBCO production plan in China – Shanghai Superconductors

2022 Q1: completion of fundraising
2022 Q2: expansion project initiated
2023 Q3: moving to new site
2024 Q1: Output at 1200 km/yr (12mmw)
2024 Q2: Capacity at 2000 km/yr (12mm-w), Phase I project complete.
2024 H2: Output at 2000 km/yr (12mmw), Phase II in renovation, and Phase III siting finalized.



Phase I @ Shanghai	Phase II @ Shanghai	Phase III @ Shanghai
2,000km/yr	4,000km/yr	20,000km/yr
~7,000m²	~9,600m²	~40,000m²+peripheral facilities



Phase II

Phase I

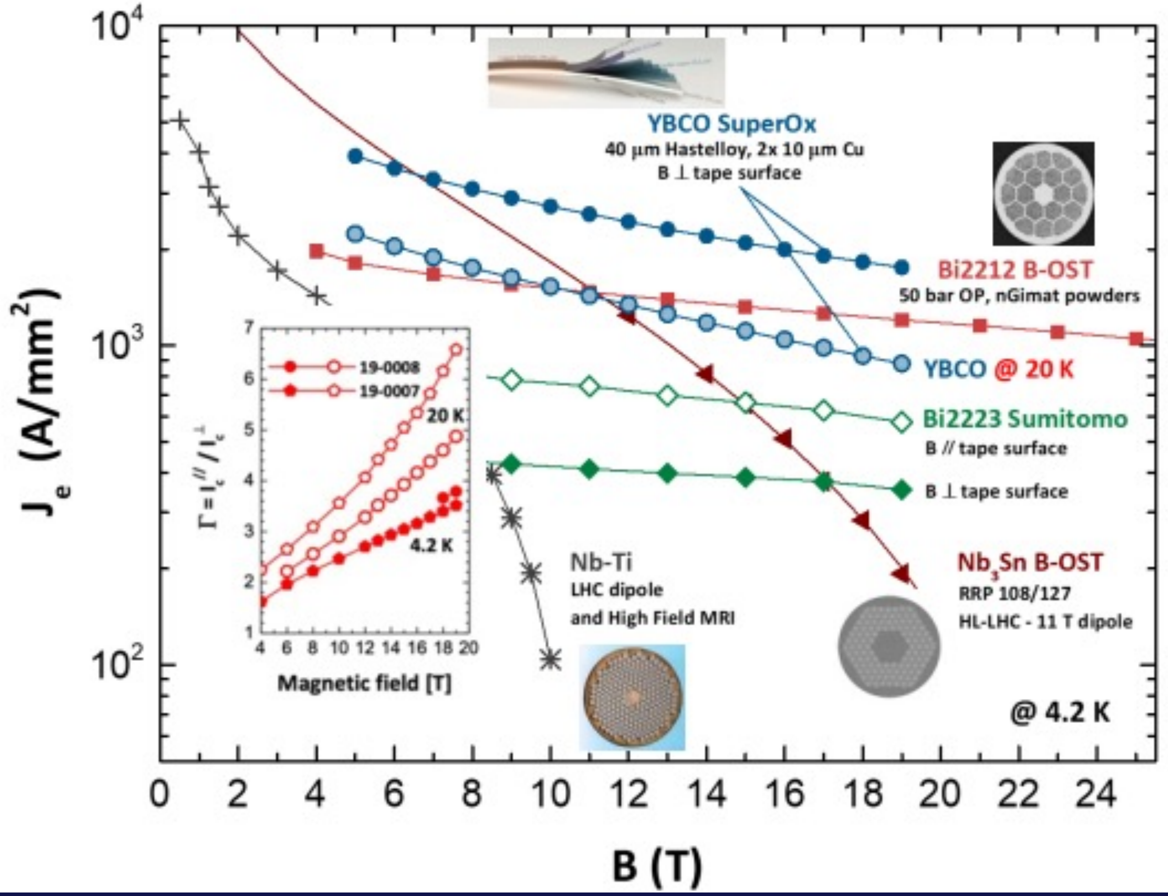
Staff
280+

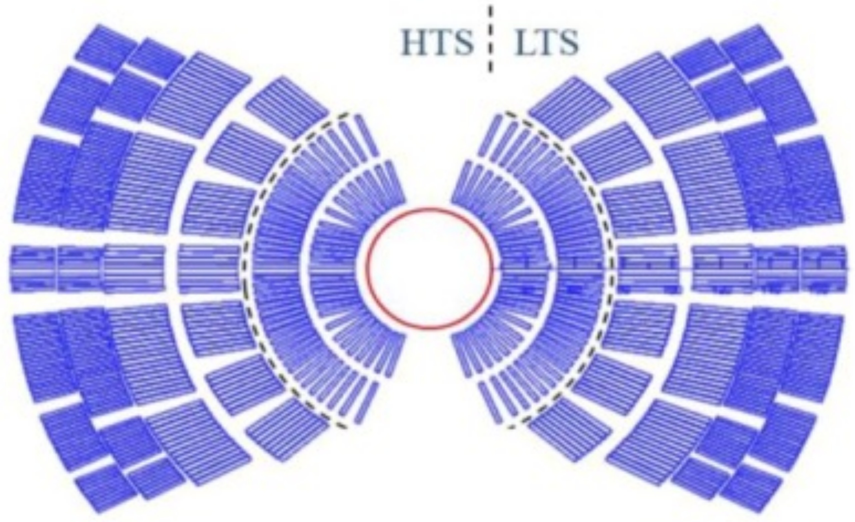
>5x rest of the world

A. Ballarino, Bai Song

Bi-2212 as alternative

- technically mature HTS material
- a filamented conductor like LTS, Bi-2212 may best be utilized at 4.5 K, in a hybrid configuration with Nb3Sn low-field layers





Hybrid design for 20 T magnet
[P. Ferracin, et al, IEEE TAS 33 (2023) 4002007]

Assumptions for FCC-hh scenarios & possible parameter range

With present layout of the FCC, and after diligent optimization (by Massimo, Gustavo, and Thys), the following energies can be reached according to the dipole field:

Dipole field [T]	c.m. energy	Comment
12	72	not far above peak field of HL-LHC Nb_3Sn quadrupoles
14	84	Nb_3Sn or HTS
17	102	HTS
20	120	HTS

Increasing the c.m. energy beyond ~100 TeV, **we will assume that the synchrotron-radiation power could not increase, beyond a total of about 4 MW** (which must be removed from inside the cold magnets)

On the other hand, **when decreasing the beam energy, one can hold either the synchrotron-radiation power** (increasing current up to HL-LHC values) **or the beam current constant**. Also, the **pile-up might need to be limited, e.g. to ~1000 events/crossing**. We thus consider three scenarios for 12 T (0.5 A and 1.12 A beam current, the latter without or with pile-up levelling).

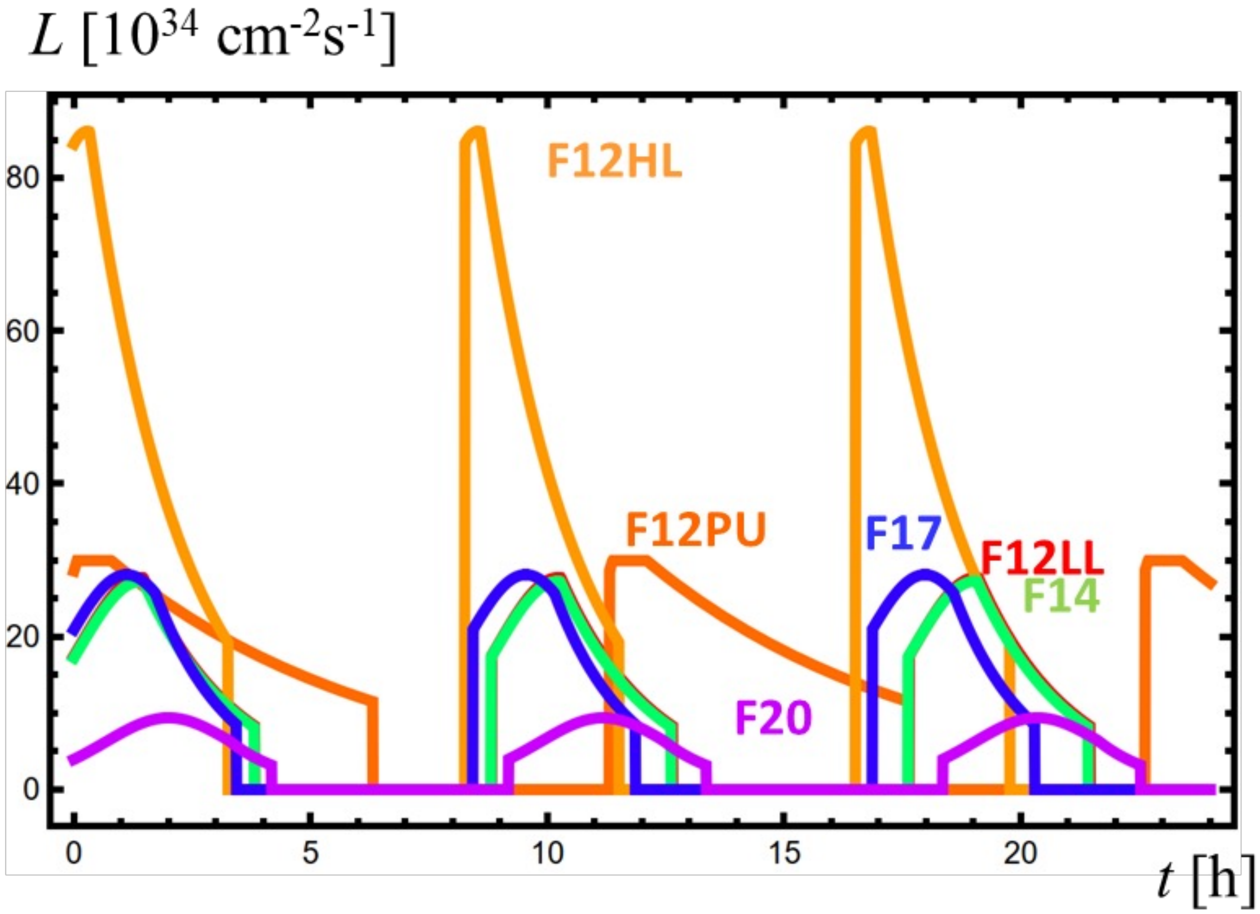
Finally, **further overall lowering the synchrotron radiation power, by reducing the number of bunches, in order to restrict the total power consumption of the future FCC-hh, would decrease peak and integrated luminosity by the same factor.**

Six scenarios

1) A machine based on 12 T dipoles, with a beam current of 0.5 A as considered for the 16 T FCC-hh machine (F12LL).
2) A machine based on the same 12 T technology close to deployment, but with a higher beam current of 1.1 A, as considered for the HL-LHC (F12HL).
3) The same case as F12HL but limiting the pile up not to exceed a value of 1000 (F12PU).
4) A machine based on 14 T dipoles, and 0.5 A current (F14).
5) A machine based on High Temperature Superconductor (HTS) dipole magnets with a field of 17 T, just exceeding 100 TeV c.m., still with 0.5 A (F17).
6) A machine also based on High Temperature Superconductor (HTS) dipole magnets with a field of 20 T, and a beam current of 0.2 A, so that the synchrotron-radiation power is limited to about 2 MW / beam (F20).

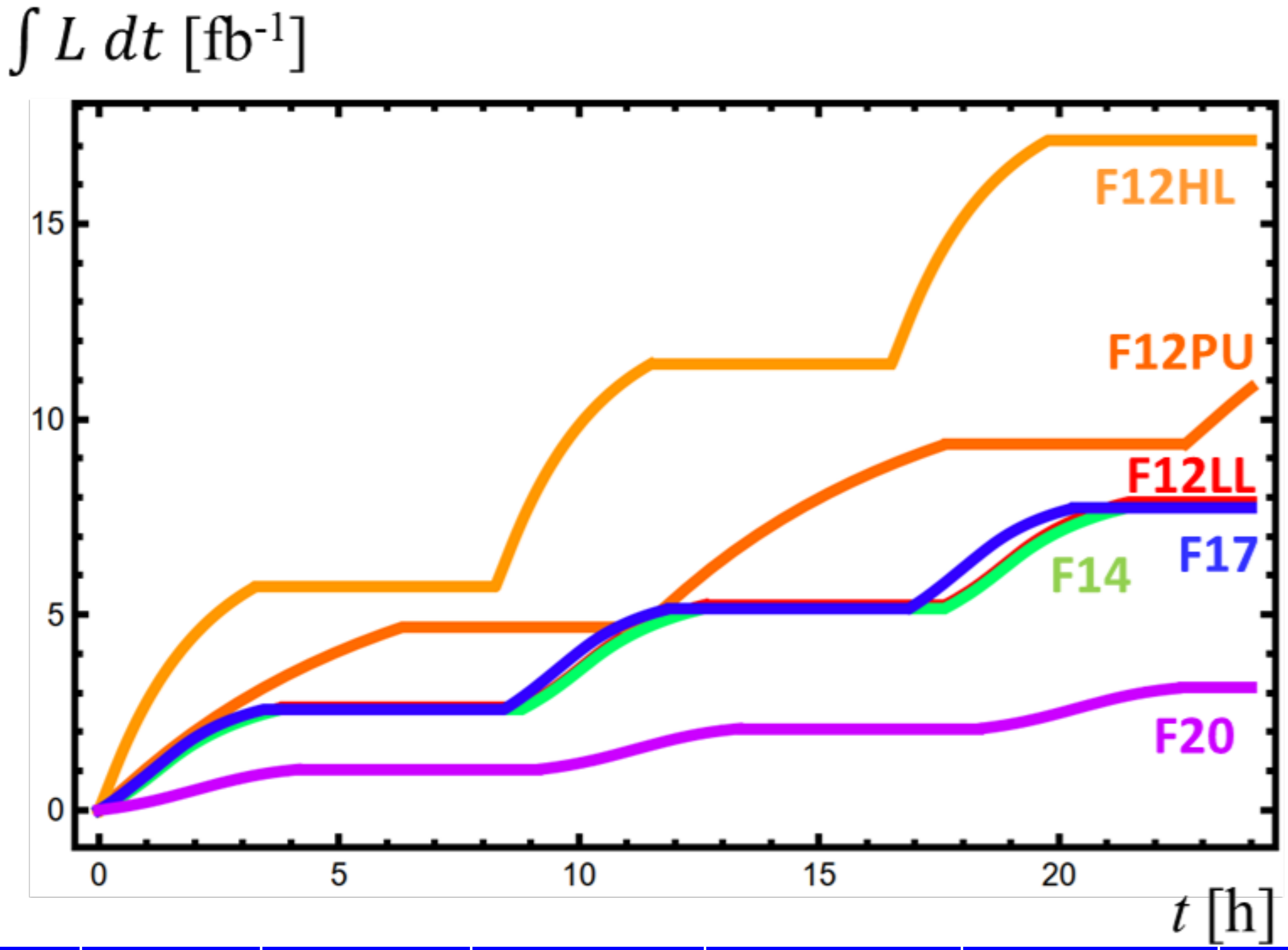
Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
c.m. energy	TeV	72	72	72	84	102	120	14
dipole field	T	12	12	12	14	17	20	8.33
beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
bunch popul.	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
bunches/beam		9500	9500	9500	9500	9500	9500	(2760) 2808
rf voltage	MV	30	30	30	35	43	50	(16) 16
longit. emit.	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
norm. tr. emit.	μm	2.5	2.5	2.5	2.5	2.5	2.5	(2.5) 3.75
IP beta*	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
initial σ^*	μm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min) 16.7
initial *L*	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
ΔE / turn	MeV	1.3	1.3	1.3	2.4	5.3	10.1	0.0067
SR power/beam	kW	650	1450	1450	1200	2670	2020	(7.3) 3.6
tr.ε damp'g time	h	0.68	0.68	0.68	0.43	0.24	0.15	25.8
init *p*-burnoff time	h	5.1	2.3	6.9	5.1	4.0	8.4	(15) 40

Luminosity over 24 h



Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
initial *L*	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
opt. run time	h	3.8	3.3	6.3	3.8	3.4	4.2	(18-13) ~10

Ideal integrated luminosity per day



Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
ideal $\int L\,dt$ /day	fb^{-1}	7.9	17.1	10.8	7.7	7.7	3.1	(1.9) 0.4
$\int L\,dt$ / year	fb^{-1}	950	2000	1300	920	920	370	240 (55)

Options – not reviewed or approved by any management

Staging scenarios for FCC-hh to reduce initial cost ?

– 1. missing dipole scheme as proposed for SPS and LHC, and studied for HE-LHC, e.g. with initially two 12 T dipoles per cell, later adding 14 T dipoles in empty slots

– 2. lower field 12 T complete machine, later 20 T magnets

Top-up injection ?

– higher efficiency & higher integrated luminosity

– may allow reducing power consumption (beam current and β^*) at constant instantaneous luminosity

– needs a "fast" cycling full-energy full-field proton injector

This Wednesday the results of an election were announced

Will Mark Thomson make CERN great again ?