Future Hadron Colliders: Accelerator Challenges

SWHEPPS: Strategy Workshop on High-Energy Particle Physics in Switzerland, 9.6.2016

Bernhard Auchmann, PSI/CERN

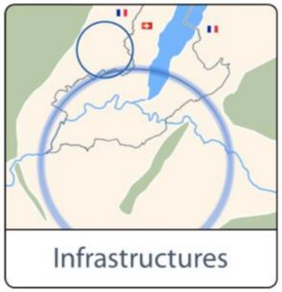
Main References

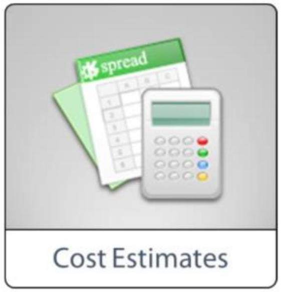
[1] FCC Week, April 11-15, 2016 in Rome:
http://indico.cern.ch/event/438866
[2] 1st Review of the EuroCirCol WP 5:
http://indico.cern.ch/event/516049

470 Participants; 48 parallel and
6 plenary sessions + poster session.

Overview

- Strategic motivation
- Ongoing Collider Studies: FCC-hh, HE-LHC, and SPPC
- Infrastructure
  - Injectors
  - Civil Engineering
  - Power Consumption
- R&D Programs
  - Magnet Systems
  - Superconductor
  - Synchrotron Radiation / Beam Vacuum
  - Beam Dump
  - Operational Cycle and Availability





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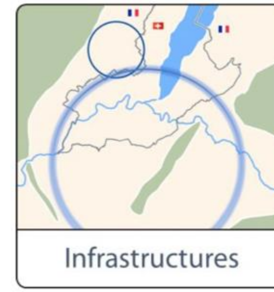

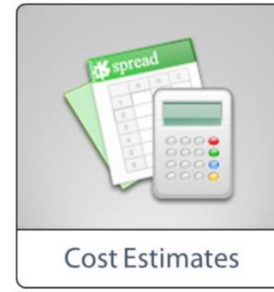

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FCC Design Study – Motivation

- **European Strategy for Particle Physics 2013:**
  "... *to propose an ambitious post-LHC accelerator project* ..., CERN should undertake design studies for accelerator projects in a global context, ... *with emphasis on proton-proton and electron-positron high-energy frontier machines* ... *coupled to a vigorous accelerator R&D programme*, including high-field magnets and high-gradient accelerating structures, ..."
- **US P5 (DOE/NSF) recommendation 2014:**
  "....A very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window...."
- **ICFA statement 2014:**
  ".... ICFA supports studies of energy frontier circular colliders and encourages global coordination....."
- **Update to the European Strategy for Particle Physics in 2019/20!**

[1] M. Benedikt, F. Gianotti.

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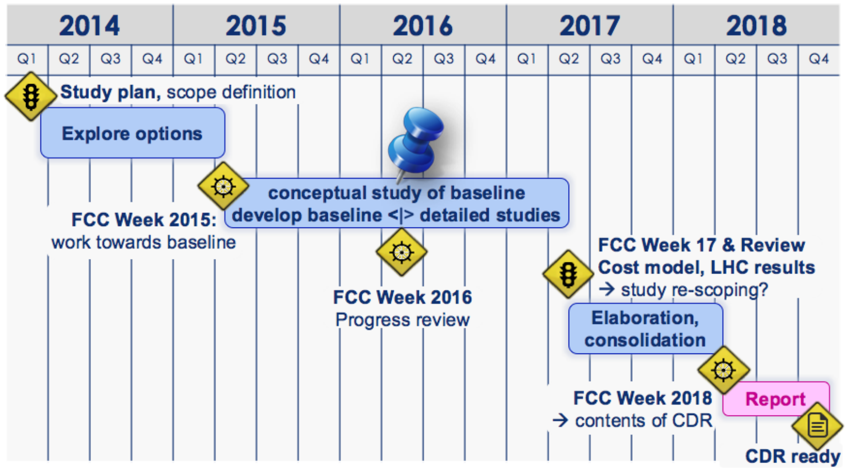
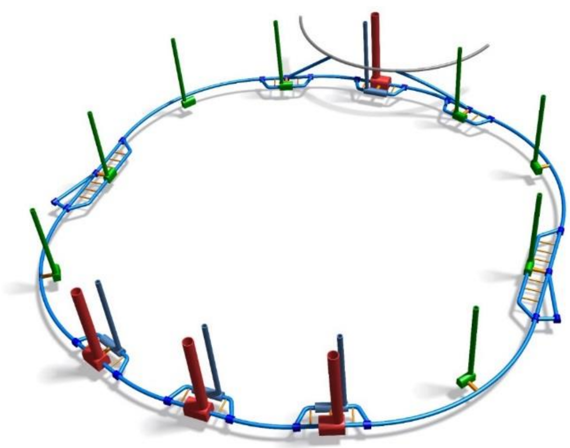
DOE .. Department of Energy, NSF .. National Science Foundation
ICFA .. International Committee for Future Accelerators

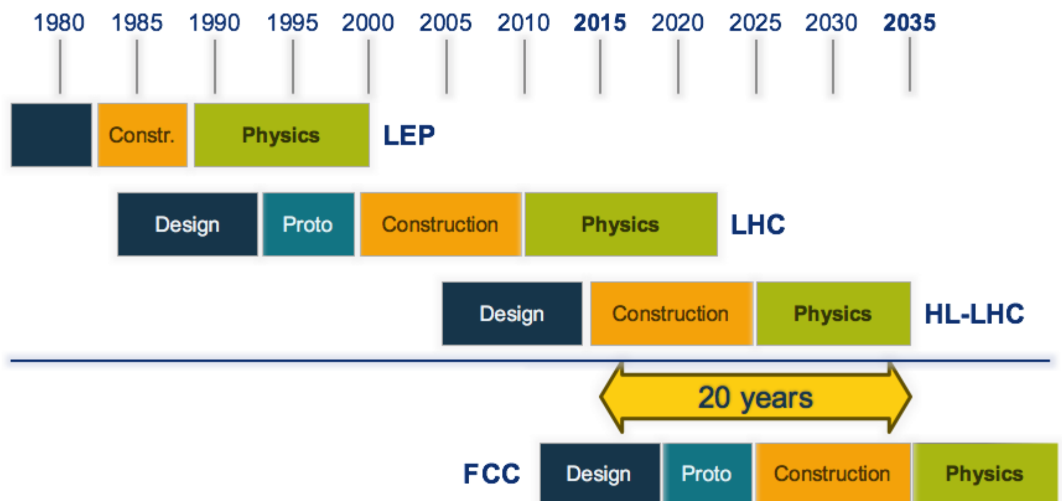
FCC Design Study – Milestones



- 74 institutes
- 26 countries + EC

Status: April, 2016





[1] M. Benedikt.

Now is the time to plan for the period 2035 – 2040

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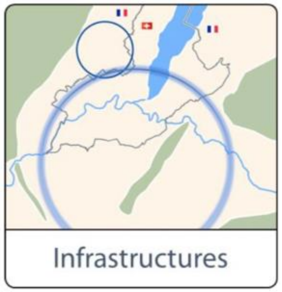

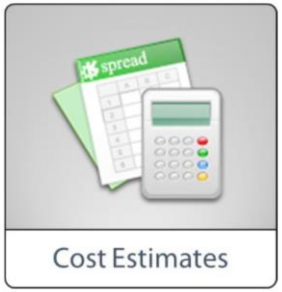

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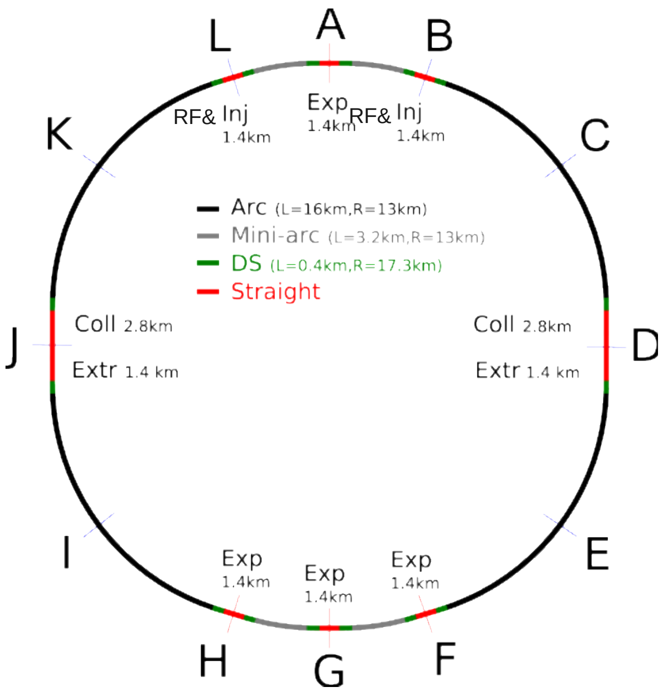
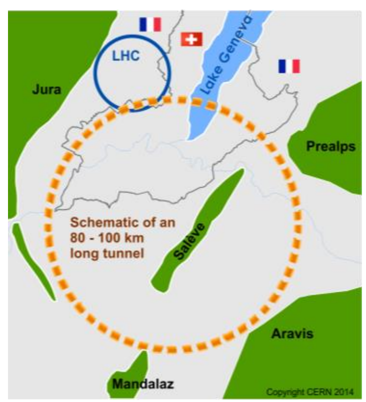
FCC-hh Layout and Parameters



parameter	FCC-hh		SPPC	HE-LHC* (*tentative)	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
dipole field [T]	16		20	16	8.3
circumference [km]	100		54	27	27
# IP	2 main & 2		2	2 & 2	2 & 2
beam current [A]	0.5		1.0	1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25	25
beta* [m]	1.1	0.3	0.75	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	12	>25	(5) 1
events/bunch crossing	170	<1020 (204)	400	850	(135) 27
stored energy/beam [GJ]	8.4		6.6	1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		58	3.6	(0.35) 0.18

nominal/ultimate

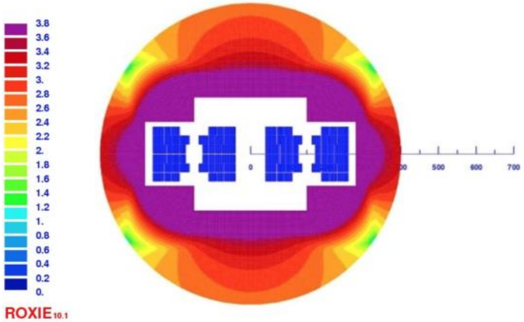
[1] M. Benedikt.

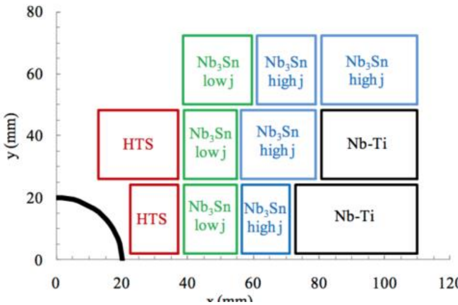


Parameter table delivered to EU.

HE-LHC

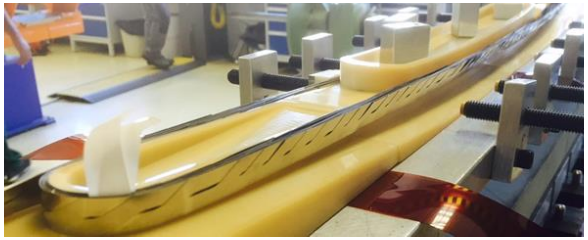
- High-energy hh collider in the LHC tunnel:
  - **baseline 16-T FCC technology for >25 TeV** or
  - 20 T LTS+HTS magnets for 33 TeV [3].

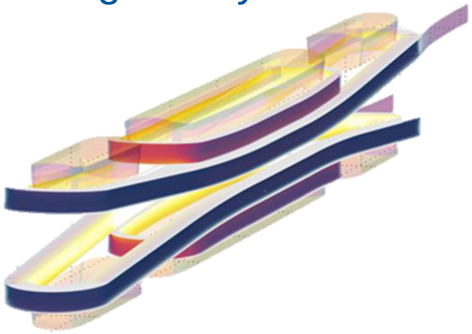




- 5-T HTS inserts are studied as part of FCC design study.

Feather-2 magnet, Roebel bar cable from REBCO tape [4].



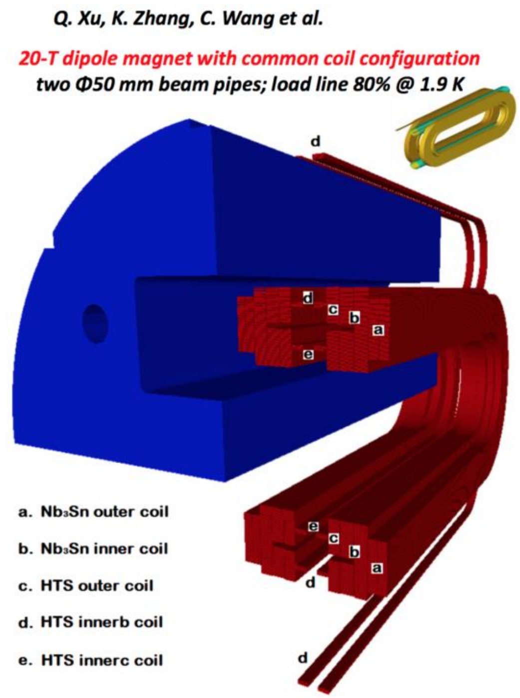


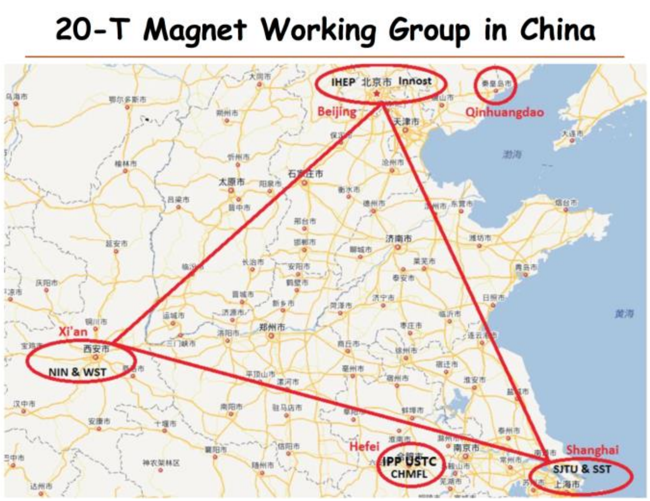
[3] L. Rossi, E. Todesco, Conceptual Design of 20-T Dipoles for High-Energy LHC, https://arxiv.org/pdf/1108.1619
[4] J. Van Nugteren and G. Kirby, CERN.

SPPC

- **AsiaHEP/ACFA 2016**:
  "… The past few years have seen a growing interest in a large radius circular accelerator ... ultimately for proton-proton collisions at the high-energy frontier. We encourage the effort lead by China in this direction, and look forward to ... the technical design ..."
- Pre-study, R&D and preparation work
  - Pre-study 2013-20
  - R&D 2020-30
  - Engineering Design 2030-35
  - Construction 2035-42
  - Data taking 2042 -

[1] Q. Xu.





The CEPC-SPPC ring sited in Qinhuangdao, 50 km and 100 km options .

ACFA .. Asia Committee for Future Accelerators
AsiaHEP .. Asia-Pacific High Energy Physics Panel

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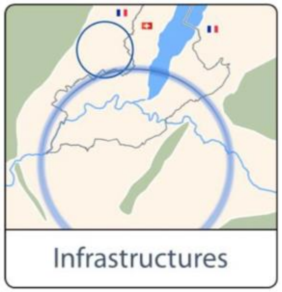
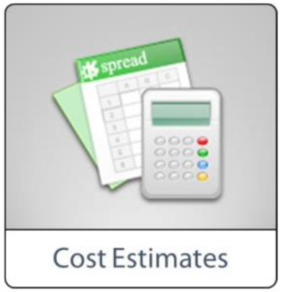




CERN Accelerator Complex

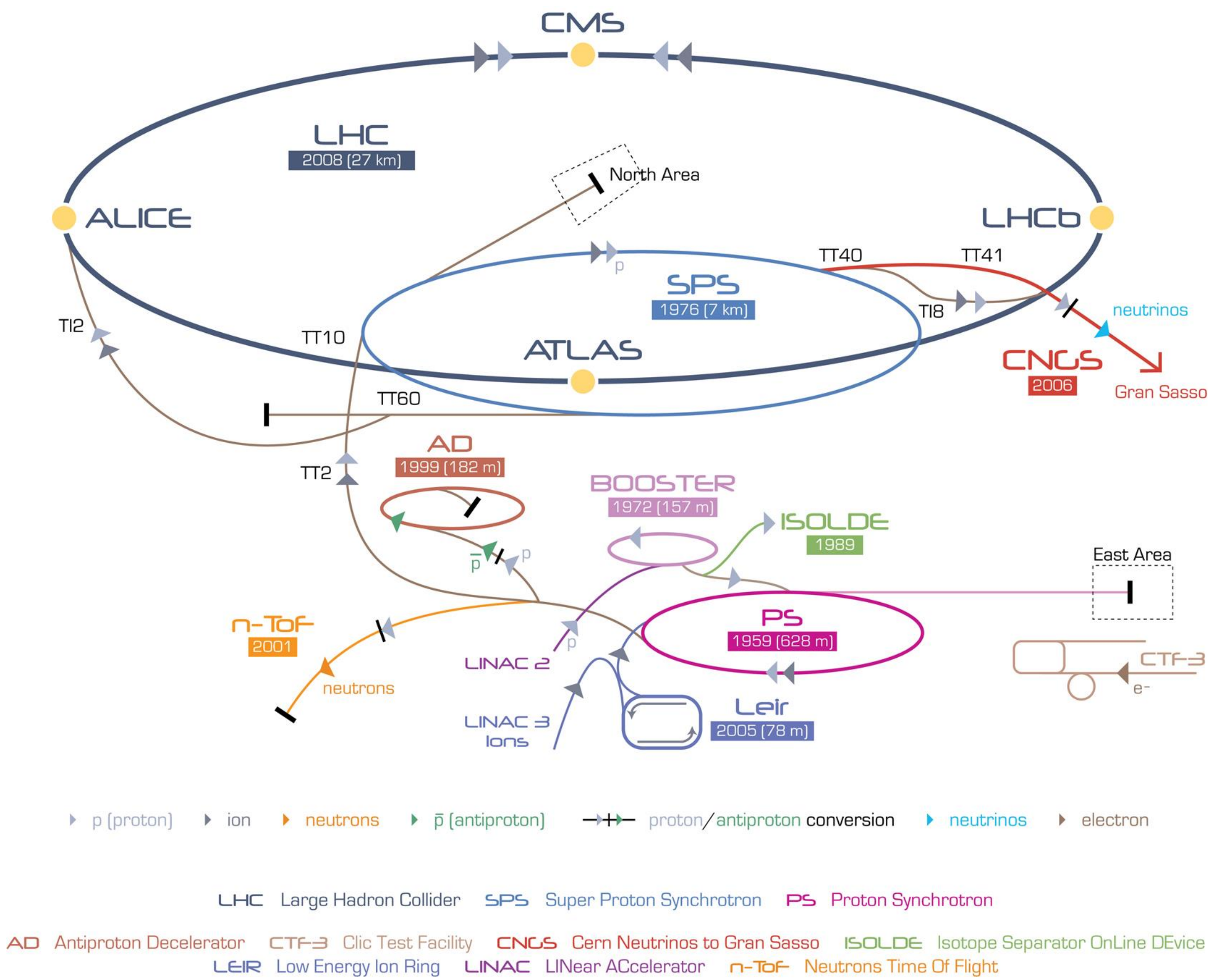
Linac 2: 50 MeV

PSB: 1.4 GeV

PS: 25 GeV

SPS: 450 GeV

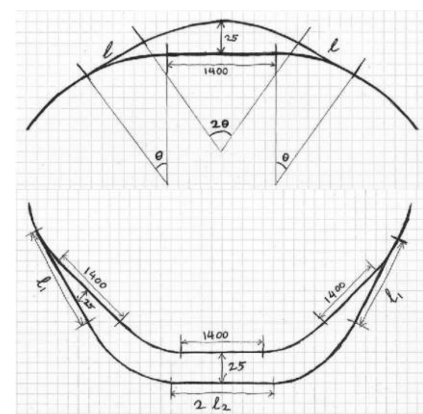
LHC: 6.5 TeV



FCC-hh Injector

Several options under study:

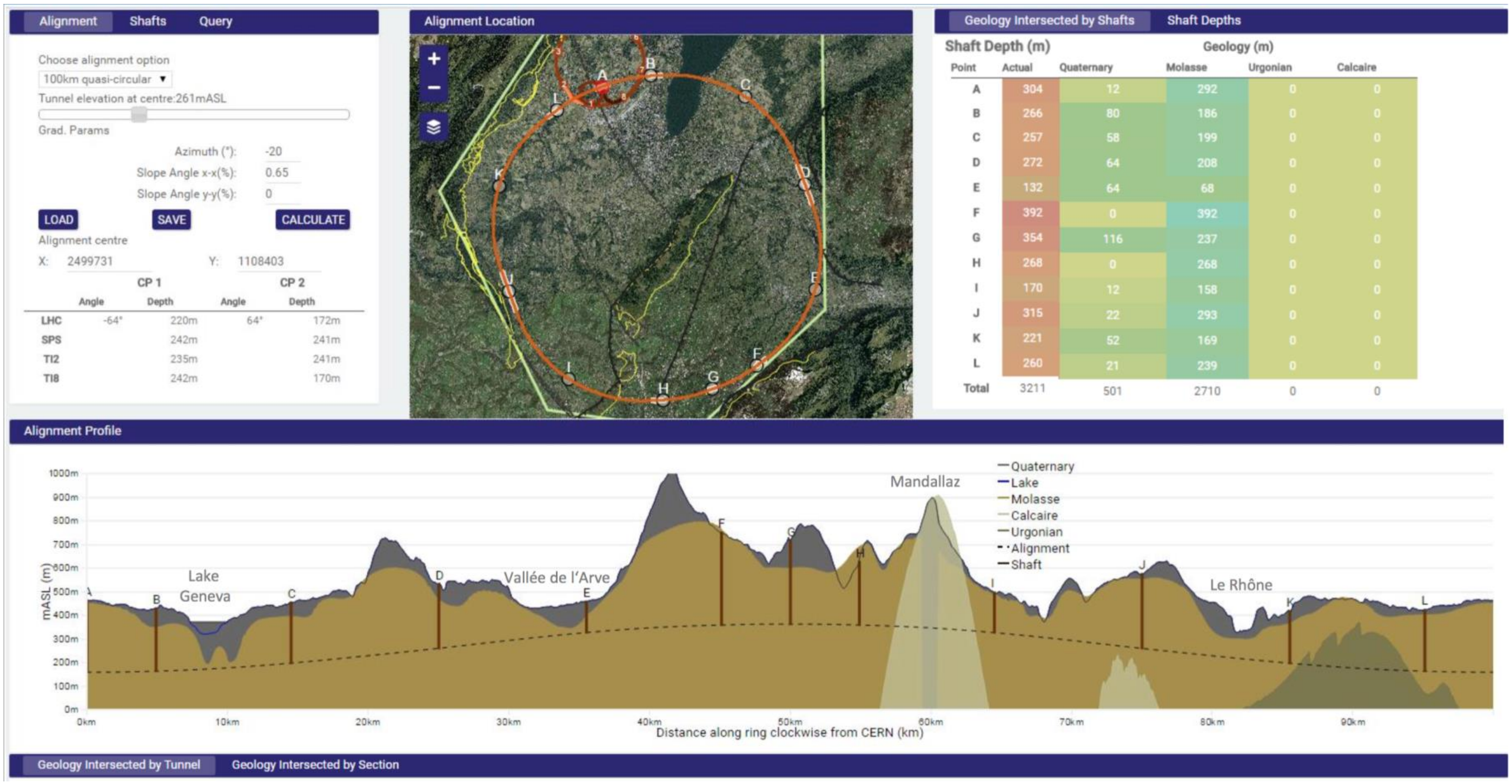
- LHC at 3.3 TeV with >5x faster ramp rate.
  - Extraction in Points 2 and 8 (now ALICE, LHCb).
  - 4 km of superconducting-magnet transfer lines.
  - Availability and operational cost as question marks.
- SPS+ at >1 TeV, 7 km with ~6-T fast-ramping superconducting magnets
  - Challenging but feasible magnet system.
- HE Booster in FCC tunnel
  - injection to booster from current SPS.
  - super-ferric magnet system (superconducting cable in iron-dominated magnet) to reduce power consumption.
- Other options
  - Super-ferric booster in LHC tunnel.
  - Injection at 450 GeV from SPS
- Experiments in LHC to learn about operation with large energy swing.



[1] L. Stoel.

FCC Civil Engineering

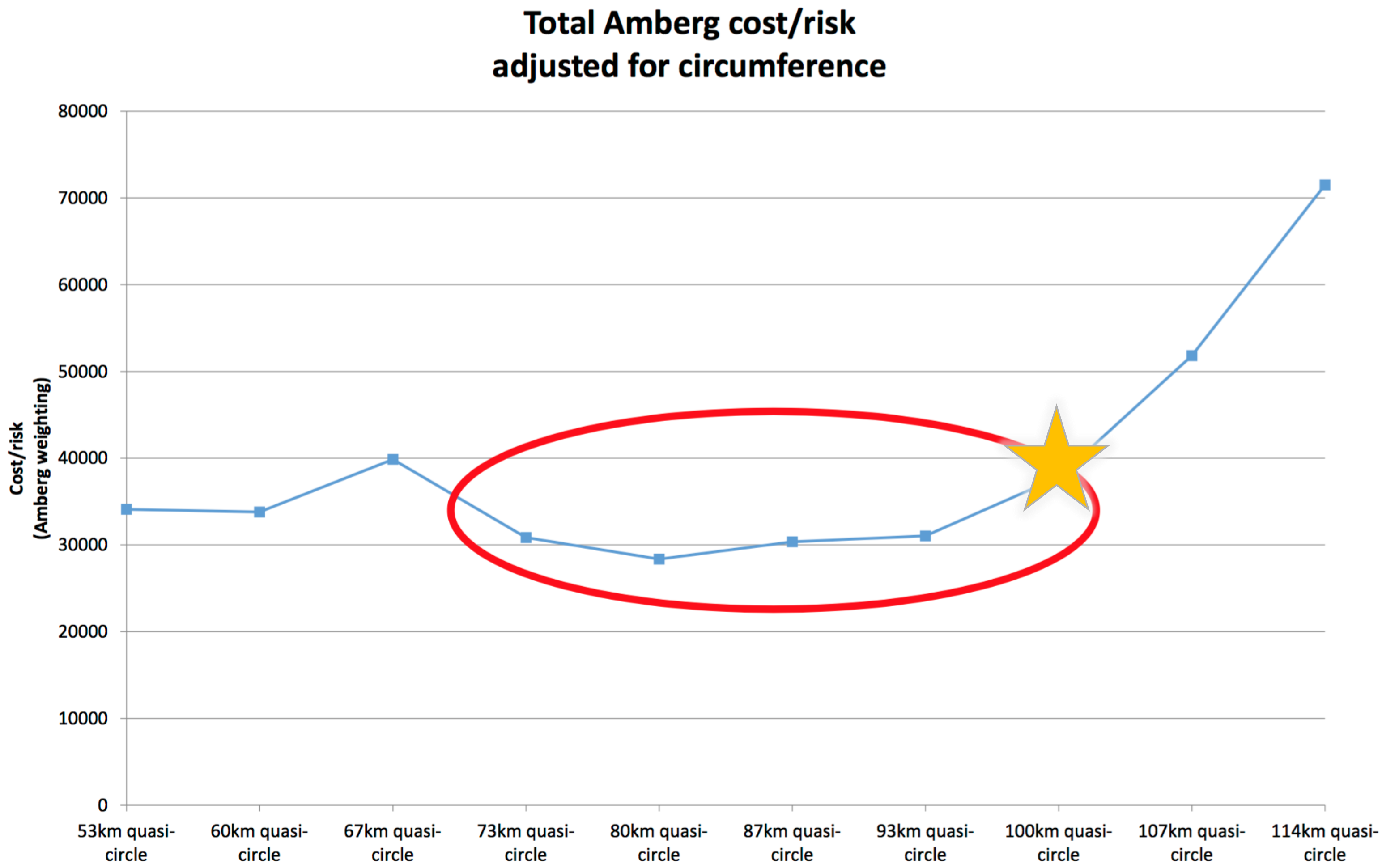
- Tunnel optimization tool wrt. cost and risk.



Point	Shaft Depth (m) Actual	Geology (m) Quaternary	Molasse	Urgonian	Calcaire
A	304	12	292	0	0
B	266	80	186	0	0
C	257	58	199	0	0
D	272	64	208	0	0
E	132	64	68	0	0
F	392	0	392	0	0
G	354	116	237	0	0
H	268	0	268	0	0
I	170	12	158	0	0
J	315	22	293	0	0
K	221	52	169	0	0
L	260	21	239	0	0
Total	3211	501	2710	0	0

[1] J. A. Osborne

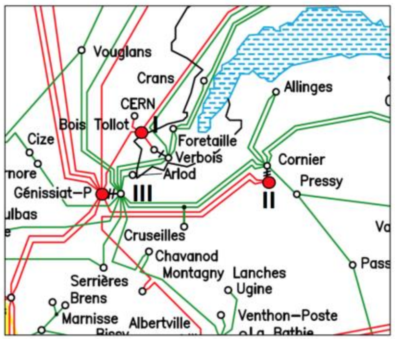
FCC Civil Engineering

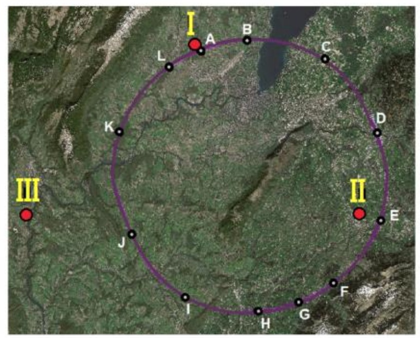


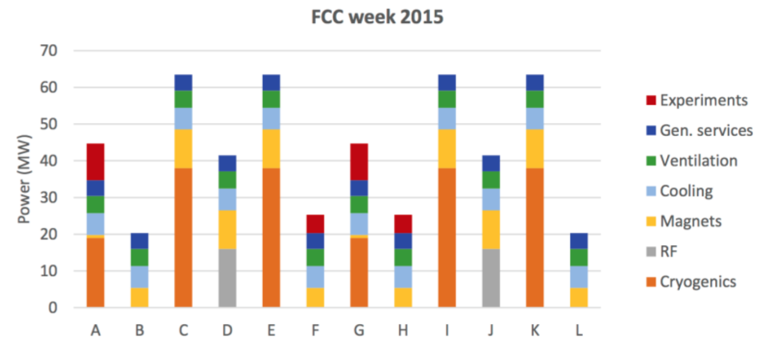
[1] J. A. Osborne

Power Consumption

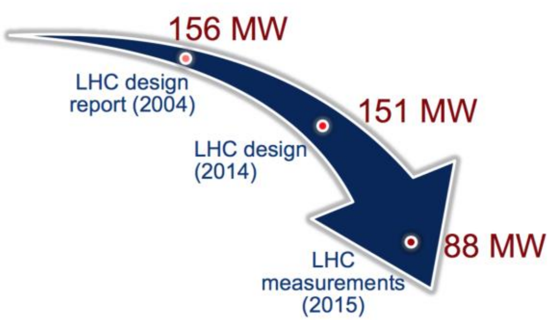
- Target power consumption: 500 MW (~3.2x LHC target).
- Three 400 kV powering substations in the region.



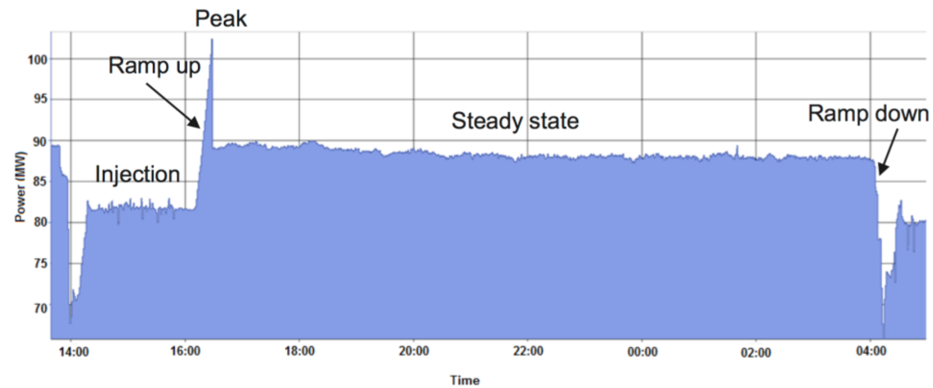




- LHC experience used to refine estimates.



LHC Physics run



[1] D. Bozzini, M. Mylona.

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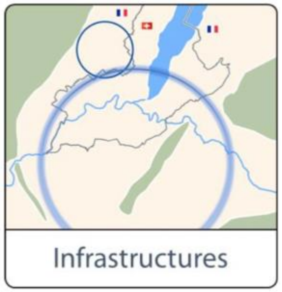

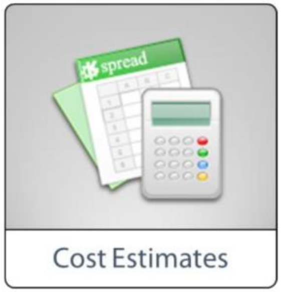

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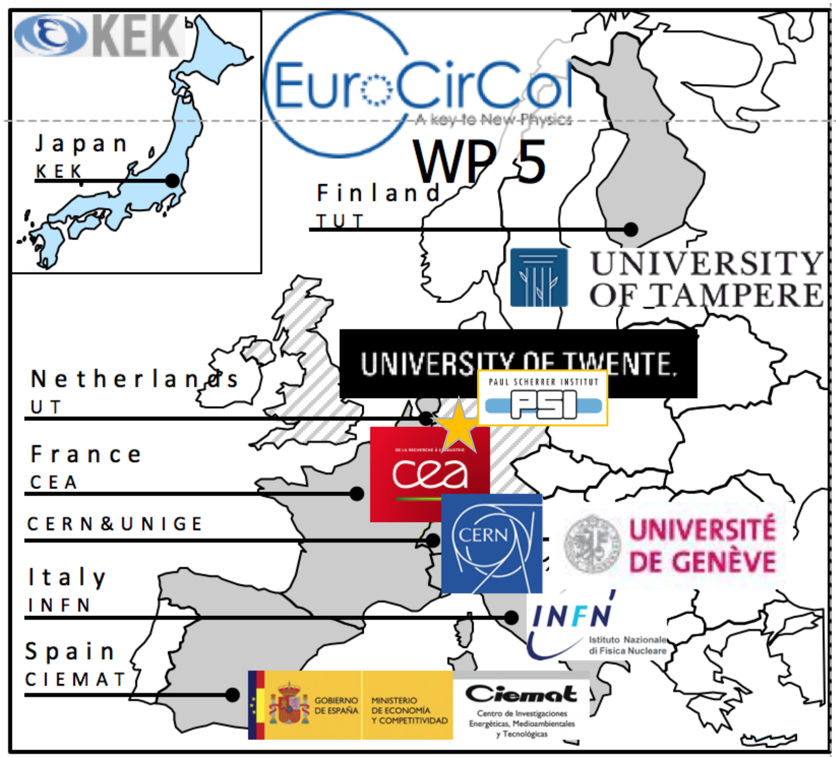
EuroCirCol WP5

- The European Circular Energy-Frontier Collider Study
- European Union’s H2020 Framework Programme under grant agreement no. 654305.
- Task WP5: **Construction design of a 16-T FCC main dipole.**
- Ongoing: survey of design options
- Next steps:
  - Detailed technical design.
  - Refined cost model.
- PSI joins EuroCirCol effort with CHART/FCC funding.

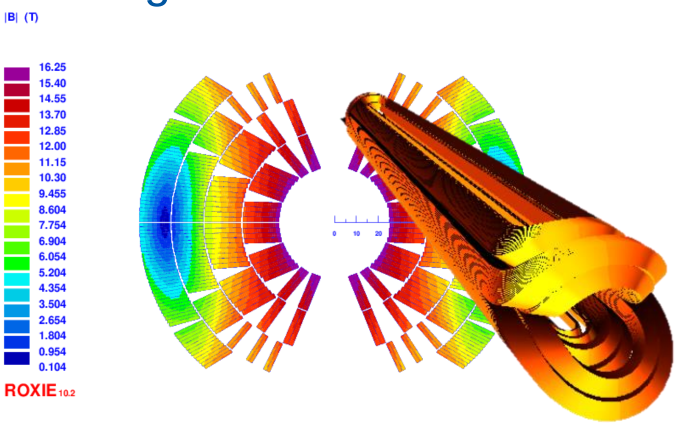


[2] D. Tommasini, http://cern.ch/fcc/eurocircol.

Magnet Types

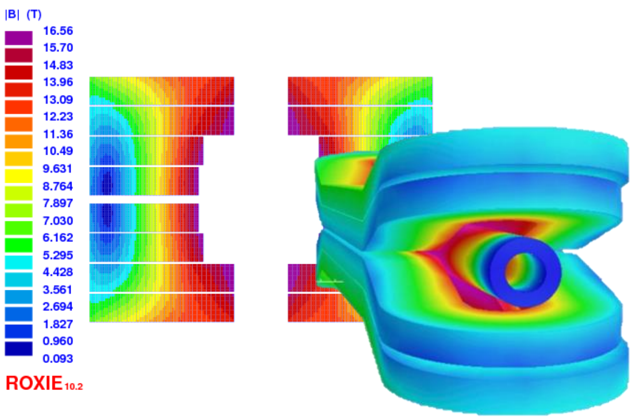
Cosine Theta Coil

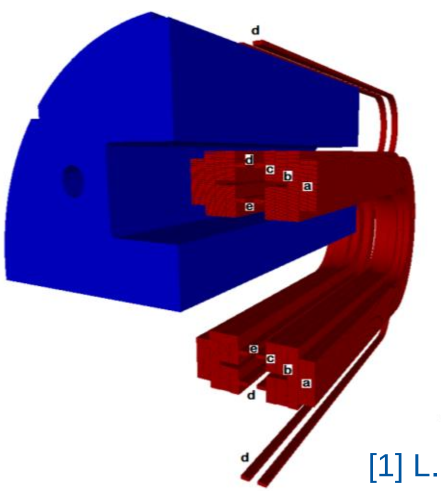
Highest efficiency. Difficult stress management and coil end design.



Block Coil

On paper simpler end design.
Slightly lower efficiency.



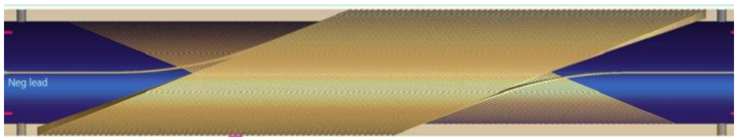


Common Coil

Simple coil ends.
Higher stored energy.
Slightly lower efficiency.

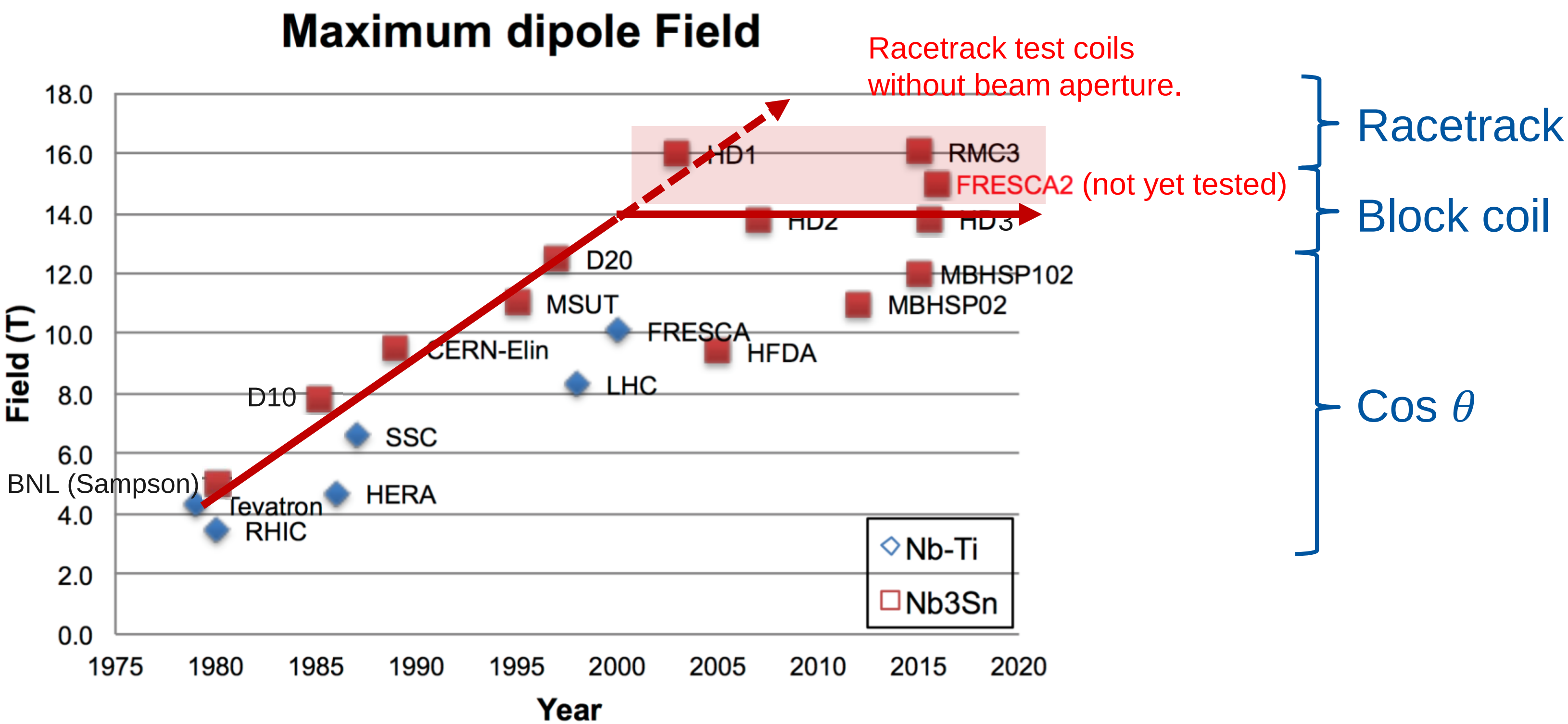
Canted Cosine Theta (Tilted Helices)

Simple manufacturing, low coil stress.
Lowest efficiency.



[1] L. Brouwer, S. Caspi, [2] M. Duharte, S. Farinon, C. Lorin, J. Munilla, M. Sorbi, F. Toral, Q. Xu

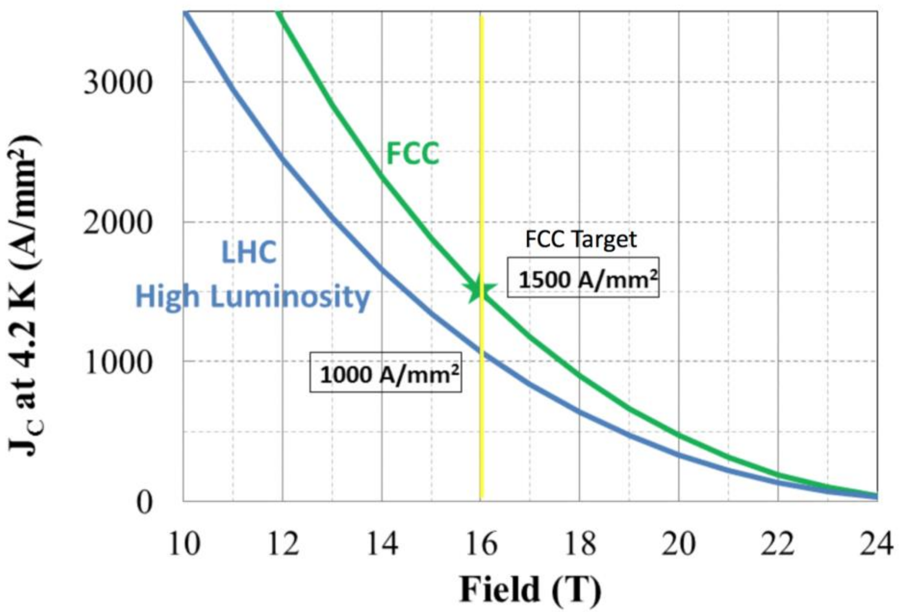
Historical View



[1] G. de Rijk

Still a long and hard road ahead for 14.3-m-long 16-T dipole.
(Longest Nb_3Sn magnet to date: LARP LQ quad with 3.7 m.)

Nb_3Sn Conductor Goals

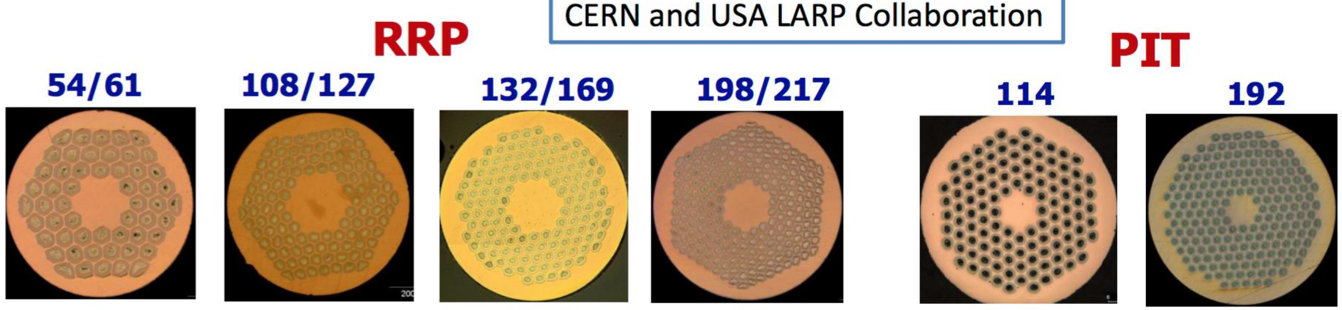


		Nb_3Sn
Wire diameter	mm	~ 1
Non-Cu Jc (16 T, 4.2 K)*	A/mm²	≥ 1500
$\mu_0\Delta M$(1 T, 4.2 K)	mT	≤ 150
$\sigma(\mu_0\Delta M)$ (1 T, 4.2 K)	%	≤ 4.5
Deff	μm	≤ 20
RRR	-	≥ 150
Unit length	km	≥ 5
Cost	Euro/kA m**	~ 5

*Je ~ 600 A/mm²
*Cu:non Cu ~ 1

** 16 T, 4.2 K

CERN and USA LARP Collaboration



[1] A. Ballarino, [2] B. Bordini

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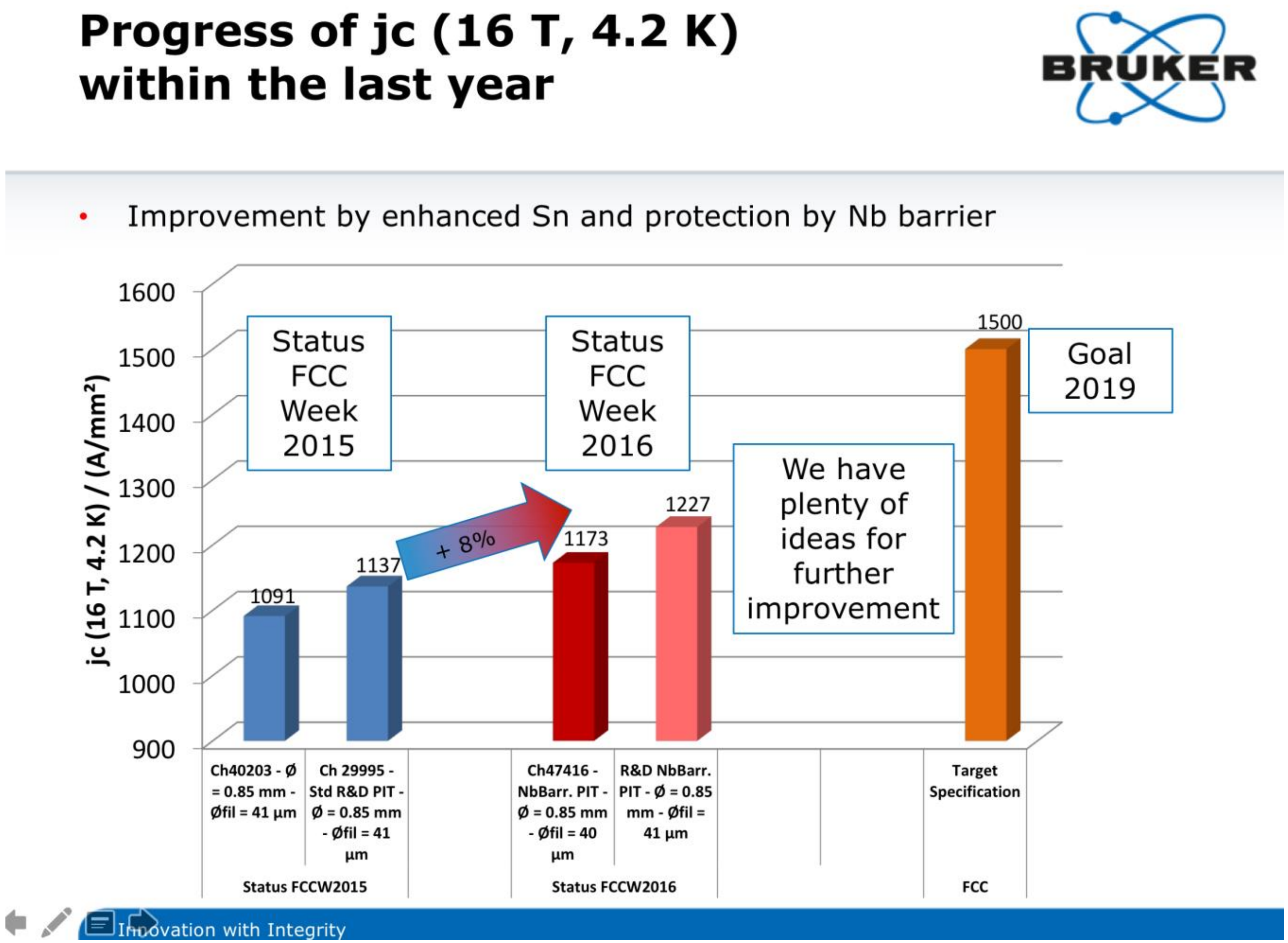
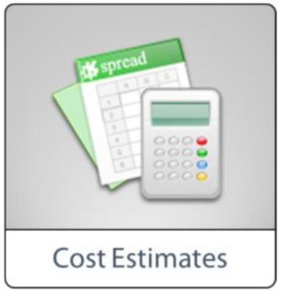
Progress as Reported by Industry



[1] K. Schlenga.

Conductor Cost

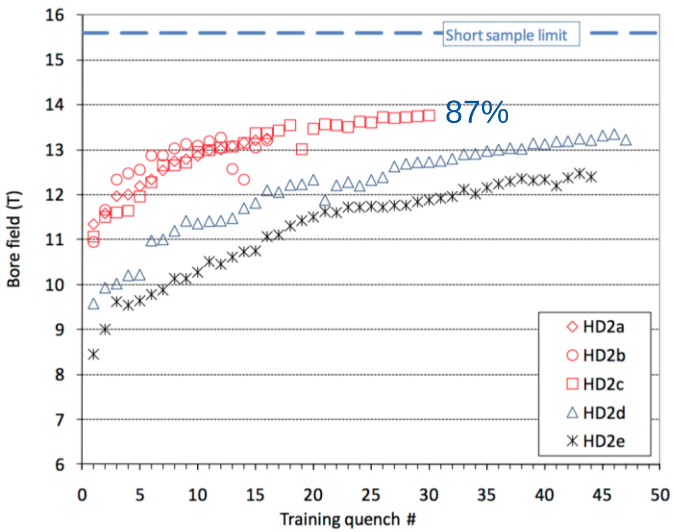


- LHC: conductor cost 1/3 of magnet cost.
- FCC: expected conductor cost >1/2 of magnet cost.
- Problem: for required Nb_3Sn conductor, FCC *is* the market.
- To reach target cost of 5 $kA^{-1}m^{-1}$ need to find savings >2/3 of current cost.
- Cost drivers:
  - Capital investment for large-scale production
  - Billet size
  - Competition

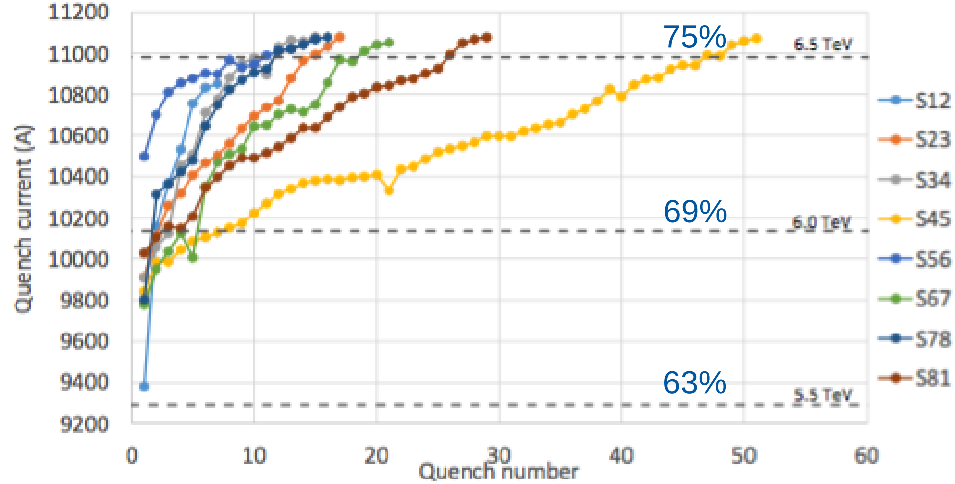
  } Determined by volume of demand.
  - Raw-material cost, out of our control
    - Hedge large variations (over past 10 years x4 in Nb, x7 in Sn, x5 in Cu).
  - Process cost
  - **Conductor performance** – active R&D
    - increase by artificial pinning, smaller grain size, etc.
  - **Unit length** / production waste
    - 1 km UL produces ~30% scrap. (Current designs have ~5 km UL!)
  - **Performance margins**

[1] A. Ballarino, L. Cooley, I. Pong, K. Schlenga, D. Schoerling

Necessary Design Margins



Training of HD2 up to 87% of short-sample limit [5].

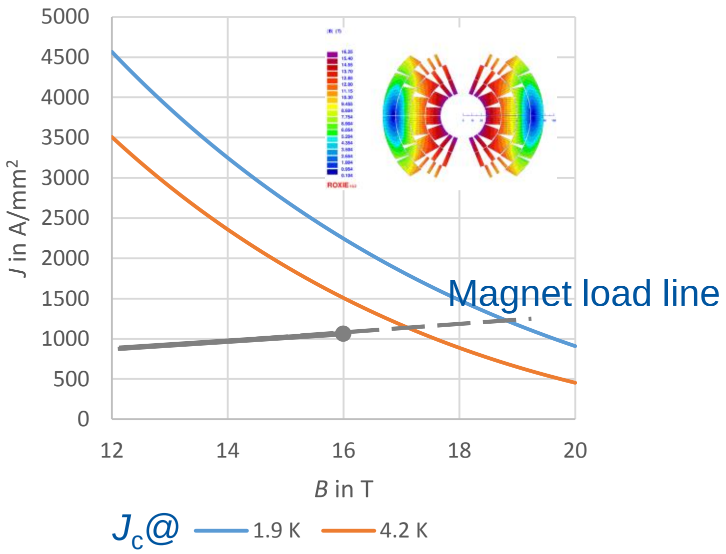


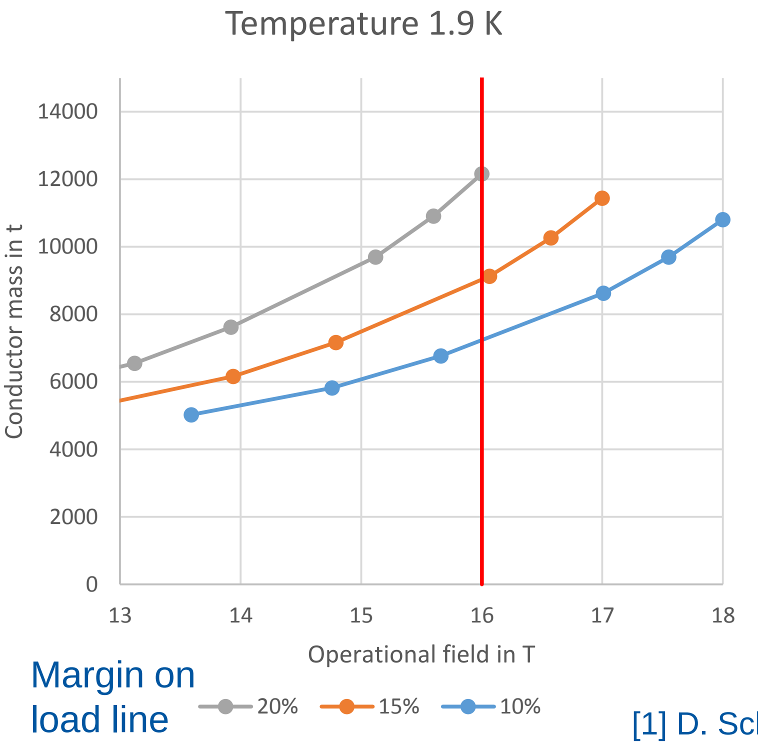
Re-training in LHC to 6.5 TeV [6].

Excessive training constitutes an energy limitation of the collider.
How much margin at nominal current?

[5] G. Apollinari, S. Prestemon, A. V. Zlobin, Progress with High-Field Superconducting Magnets for High-Energy Colliders, Annu. Rev. Nucl. Part. Sci. 2015.65:355-377.
[6] M. Pojer, M. Solfaroli, http://cern.ch/hcc, 2015.

Loadline Margin and Conductor Use



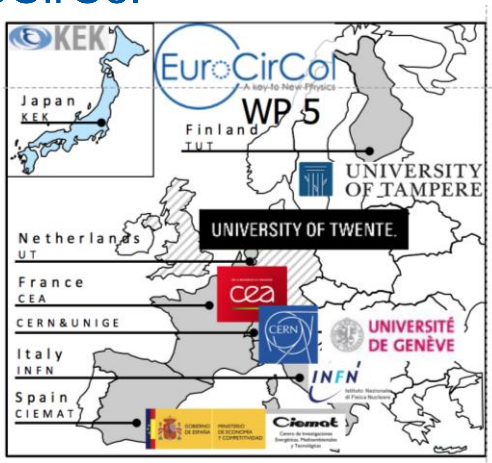


[1] D. Schoerling

- 20% vs. 10% margin at 16 T, 1.9 K, implies 2/3 higher conductor cost.
- Baseline target: 14%.

US/European Programs on Magnet R&D

EuroCirCol



CERN FCC technology program,

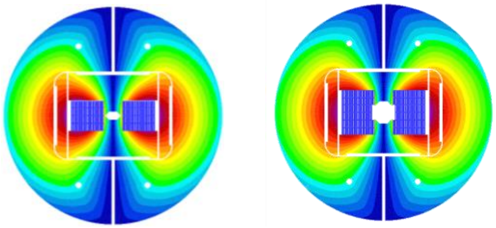
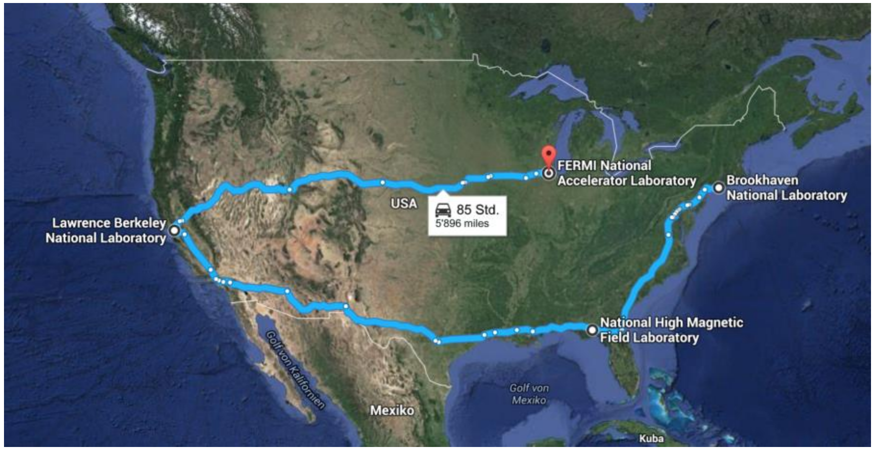
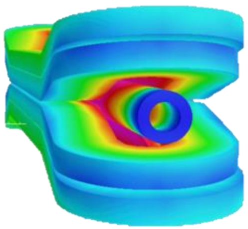


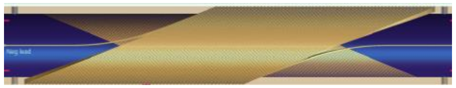
CHART contribution at PSI.

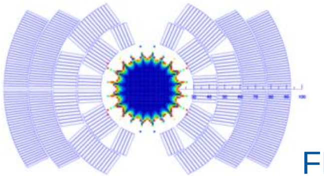
US Labs' High-Field Magnet Programs



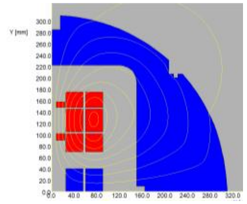


LBNL





FNAL



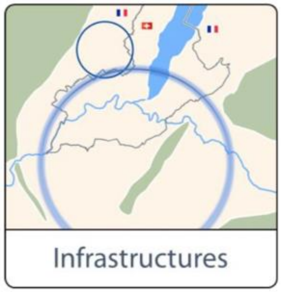
BNL

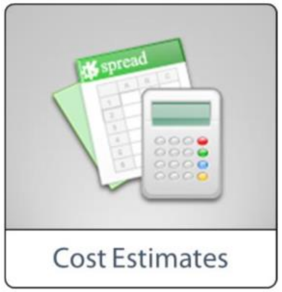
Further efforts for EU/US coordination under way.

[5] http://cern.ch/fcc/eurocircol, 2016.

Overview

- Strategic motivation
- Ongoing Collider Studies: FCC-hh, HE-LHC, and SPPC
- Infrastructure
  - Injectors
  - Civil Engineering
  - Power Consumption
- R&D Programs
  - Magnet Systems
  - Superconductor
  - Synchrotron Radiation / Beam Vacuum
  - Beam Dump
  - Operational Cycle and Availability





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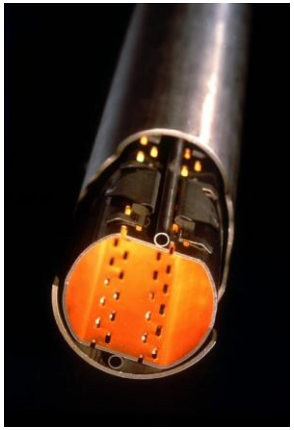
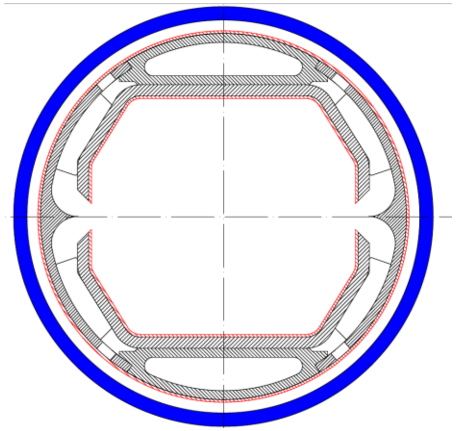
Synchrotron Radiation and Vacuum



- Arc synchrotron-radiation heat load, $\sim\frac{E^4}{R^2}$, increases from 0.17 W/m (LHC) to 28.4 W/m (FCC-hh).

→ Beam-screen temperature must be higher (40-60 K instead of 5-20 K at LHC) for cryo efficiency. Cooling channel diameter must increase.

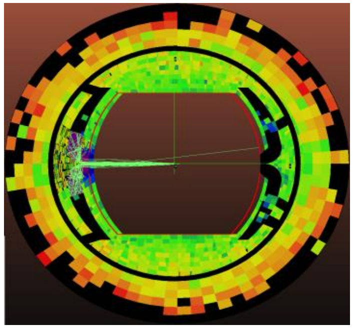


→ Higher temperature implies higher equilibrium vapour pressure.

→ Increased pumping slots.

- Studies:
  - SYNRAD and MOLFLOW simulations done.
  - Optimized impedance.
  - Lower SEY by laser ablation.
  - Avoidance of UFOs.
  - Test in ANKA beam line.

[1] F. Perez



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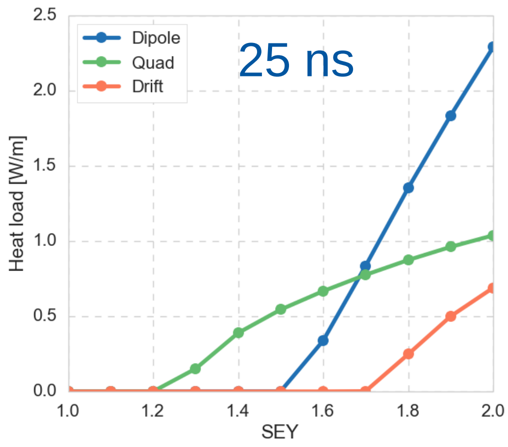
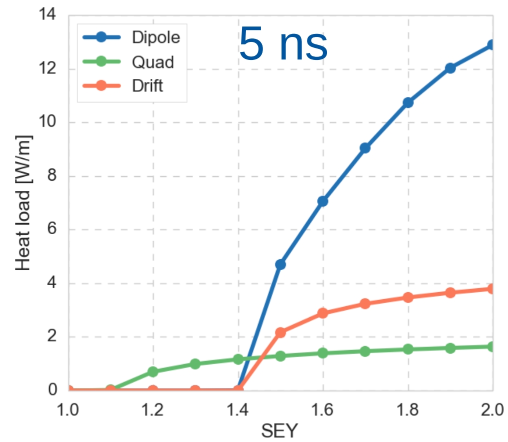
Bunch Spacing

- Production of 5 ns bunch spacing
  - Today by debunching and modulation at 200 MHz in PS.
  - Considered a “dirty” option:
    - beam from extraction-kicker gap lost in ring.
    - no bunch-to-bucket transfer.
  - “Clean” option Superconducting Proton Linac to replace PS Booster.
- Estimated integrated luminosity per day equivalent to that in the 25-ns scenario.
- Heat load from electron-cloud under control if SEY ≤ 1.1.
- Studies needed for instability limits.
- More machine-development studies at LHC to come.





[1] E. Shaposhnikova, X. Buffat, L. Mether

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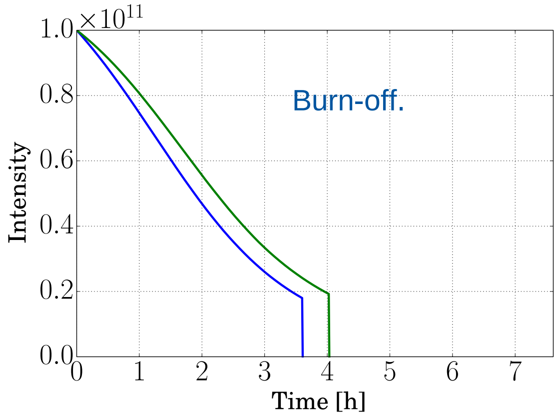
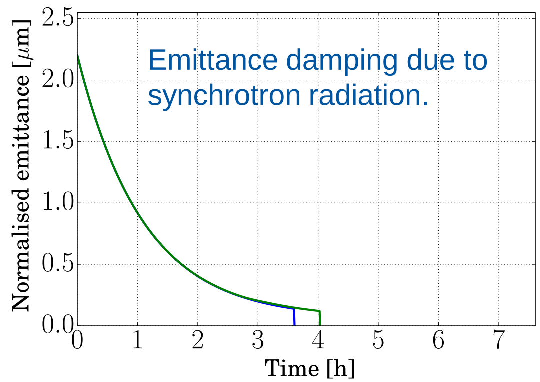
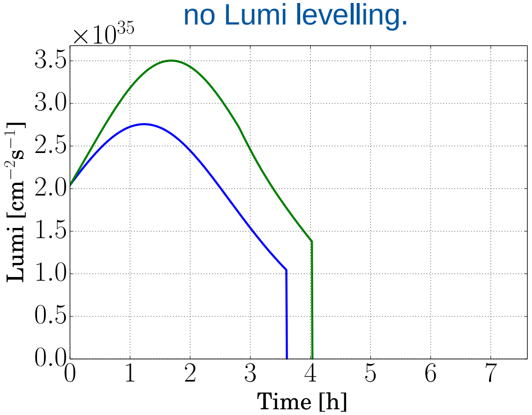
Operational Cycle and Availability

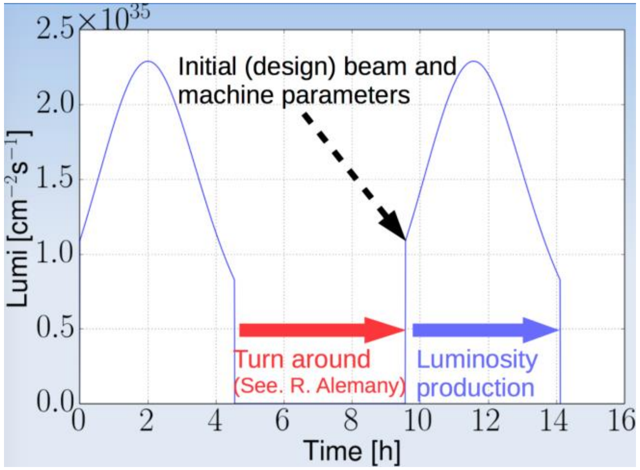
Stable beams and turnaround time of equal length!
Need to drastically improve turnaround time.

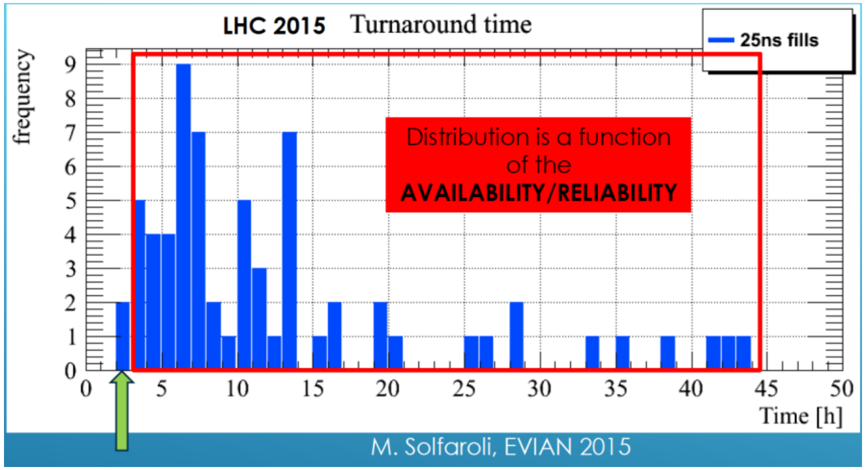
Nominal and ultimate beam and machine parameters, no Lumi levelling.









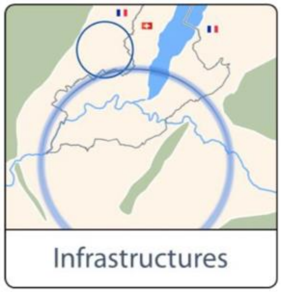


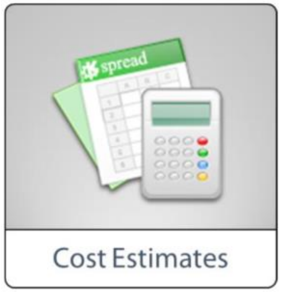
theoretical value

[1] D. Schulte, X. Buffat, R. Alemany Fernandez,
[6] M. Solfaroli, 6th Evian Workshop: https://indico.cern.ch/event/434129/

Summary

- Baseline parameters of FCC-hh (and ee) are fixed.
- Infrastructure layout fixed, cost- and schedule estimates under way.
- Magnet R&D is picking up momentum. US to get more involved.
- Numerous accelerator technologies are being studied anew – positive impact expected for LHC and HL-LHC.
- Authoritative cost estimates for the overall project only in 2018.





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