The CERN future circular hadron collider

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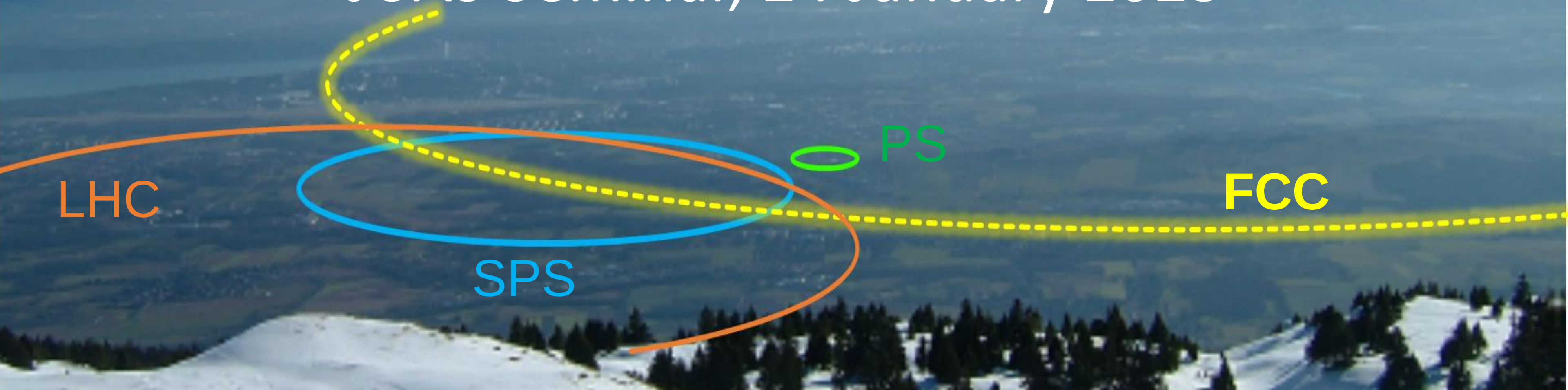

http://cern.ch/fcc

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photo: J. Wenninger

FUTURE CIRCULAR COLLIDER

Outline

- Why a hadron collider after LHC/HL-LHC
- FCC integrated study: strategy and plans
- Selected FCC-hh ring challenges
- Recent developments: new layout
- Outlook

Acknowledgements: W. Bartmann, M. Benedikt, J. Borburgh, R. Bruce, B. Goddard, G. Perez Segurana, T. Risselada, F. Zimmermann

Why a hadron collider after LHC/HL-LHC

- The 2013 Update of the European Strategy for Particle Physics (ESPPU) [1] stated, inter alia, that *"...Europe needs to be in a position to propose an* ***ambitious post-LHC accelerator project at CERN*** *by the time of the next Strategy update" and that "CERN should undertake design studies for accelerator projects in a* ***global context****, with emphasis* ***on proton–proton and electron-positron high-energy frontier*** *machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in* ***collaboration with national institutes, laboratories and universities world-wide***".

- The LHC discovered the Higgs, but now we are facing another challenging question: "what is next and where is it?".
  - Additional particles and interactions must extend the Standard Model (SM), to explain for example, the existence of dark matter (DM), neutrino masses and the observed matter/antimatter asymmetry.
  - The SM itself calls for a broader theoretical framework, to provide a rationale for the dynamical origin of electroweak (EW) symmetry breaking (EWSB) and to justify the otherwise unnatural fine tuning needed to prevent quantum corrections pushing the Fermi scale up to the Planck scale.

Why a hadron collider after LHC/HL-LHC

- **Setting the centre-of-mass energy**
  - The LHC and other experiments do not concretely point to any specific BSM scenario and mass scale today.
  - Rather general arguments support 100 TeV as a sensible target for FCC-hh.
  - There is clearly no upper limit to how high the community would like the energy to be. However, there is evidence that 100 TeV is necessary and sufficient to achieve crucial measurements and give clear yes/no answers to some of the important questions that might still be left open after the.
  - **Note that this center-of-mass energy is (almost) compatible with the magnet technology.**

- **Setting the luminosity goal**
  - Cross sections for the production of a state of mass M typically scale like $1/M^2$.
  - The FCC-hh luminosity should therefore increase w.r.t. the LHC by a factor of $(100/14)^2 \sim 50$, for its discovery reach to be sensitive to masses $100/14 \sim 7$ times larger than at the LHC.
  - The baseline FCC-hh integrated luminosity of 20–30 ab^{-1} exceeds what is obtained with this factor, if rescaled from 300fb^{-1}, the target of the nominal LHC luminosity (the HL-LHC target luminosity is 3000 fb^{-1}).
  - A further increase of the luminosity by a factor of 10 beyond these values would only extend the discovery reach by less than 20%.

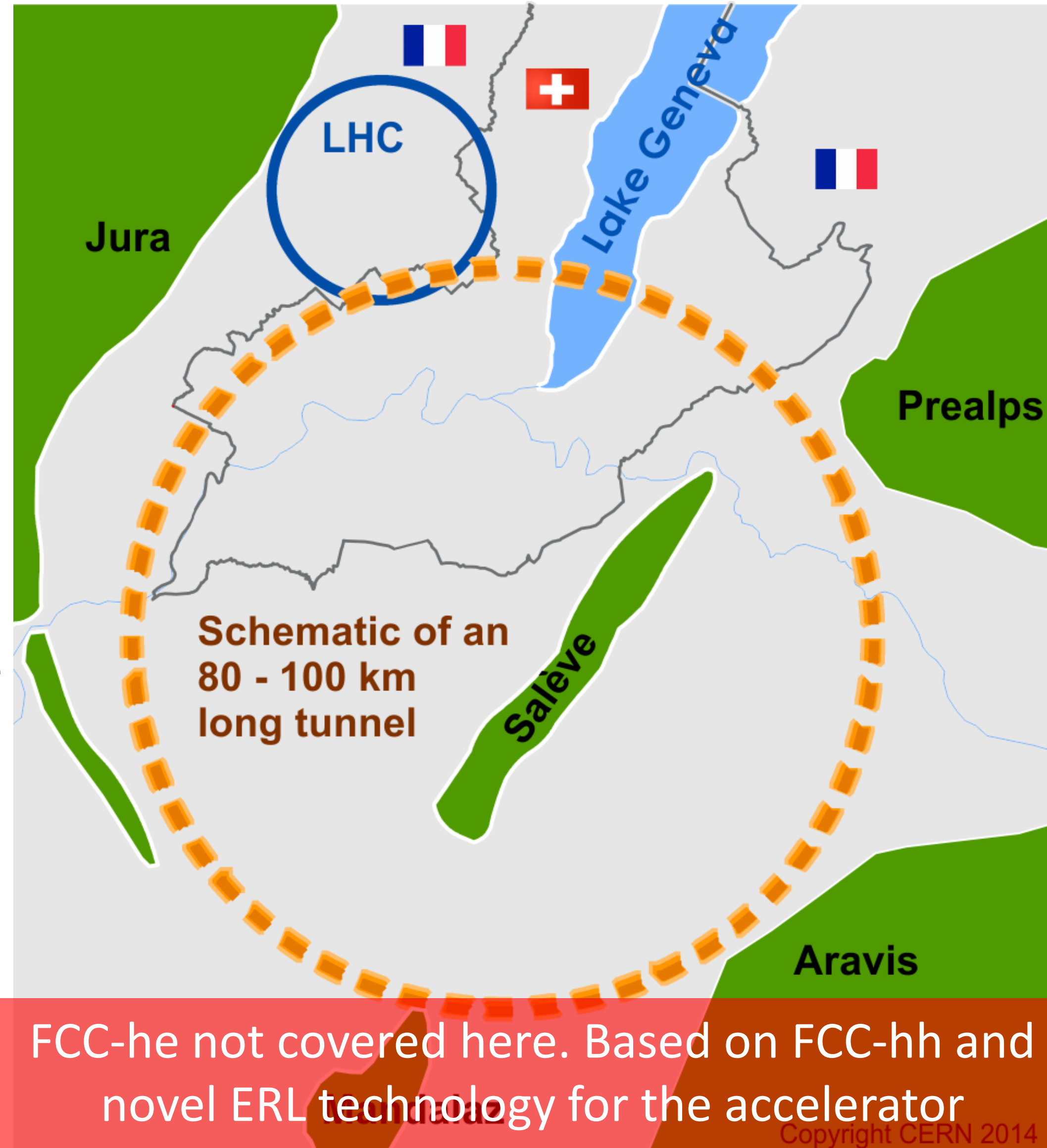
Future Circular Collider Study launched in 2014

international FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km infrastructure** in Geneva area
- ***e⁺e⁻* collider (*FCC-ee*) as a possible first step**
- *p-e* (*FCC-he*) option, HE-LHC …



FCC-he not covered here. Based on FCC-hh and novel ERL technology for the accelerator infrastructure for the electron beam

FCC CDR and Study Documentation

- **FCC-Conceptual Design Reports (completed in 2018):**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

    EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

- **Summary documents provided to EPPSU SG**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

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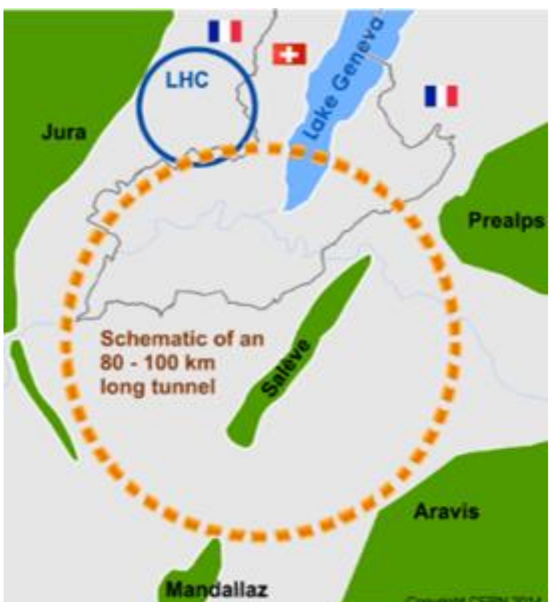
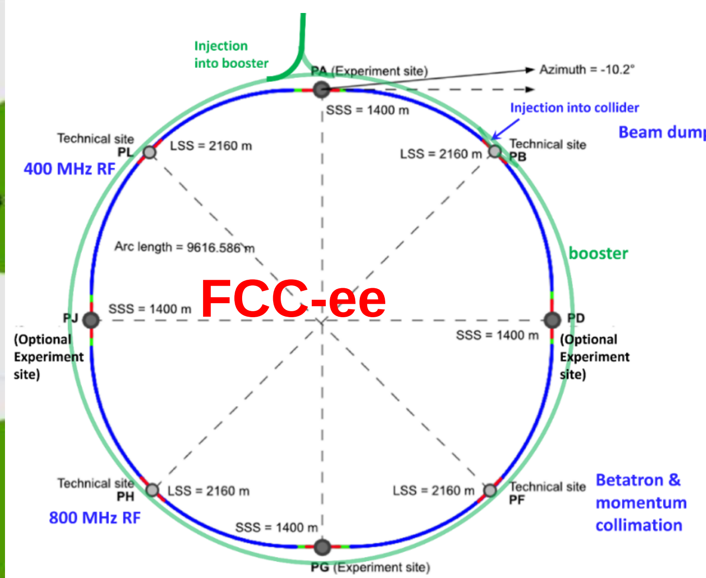
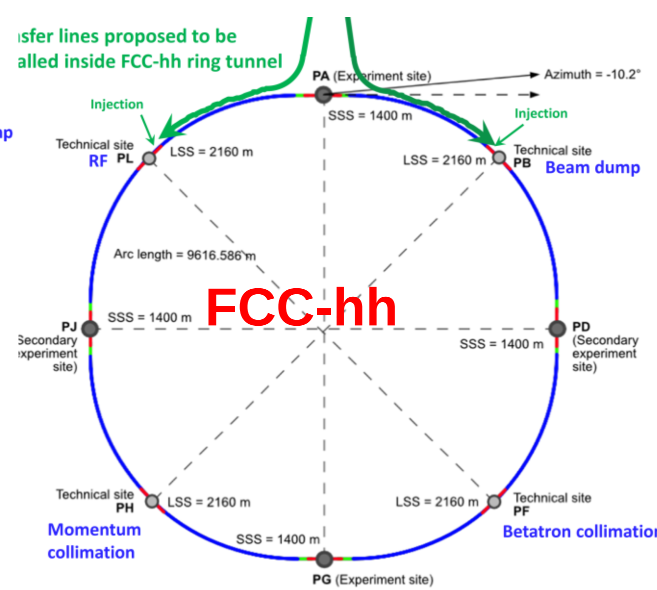
The FCC integrated program

Comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, reusing CERN's existing infrastructure
- FCC integrated program allows continuation of HEP after completion of the HL-LHC program

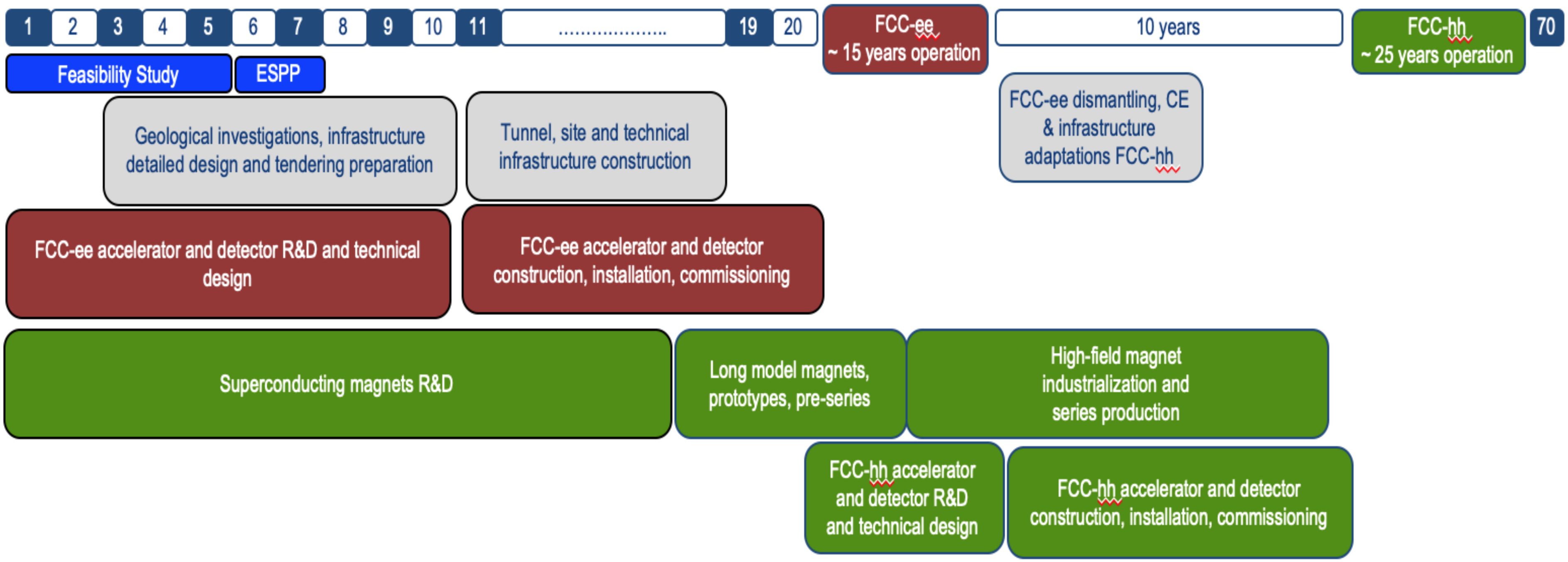






2020 - 2040 | **2045 - 2060** | **2070 - 2090++**

Timeline of the FCC integrated programme



- ❑ Feasibility Study: 2021-2025
- ❑ If project approved before end of decade → construction can start beginning 2030s
- ❑ FCC-ee operation ~2045-2060
- ❑ FCC-hh operation 2070-2090++

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Feasibility study goals and roadmap

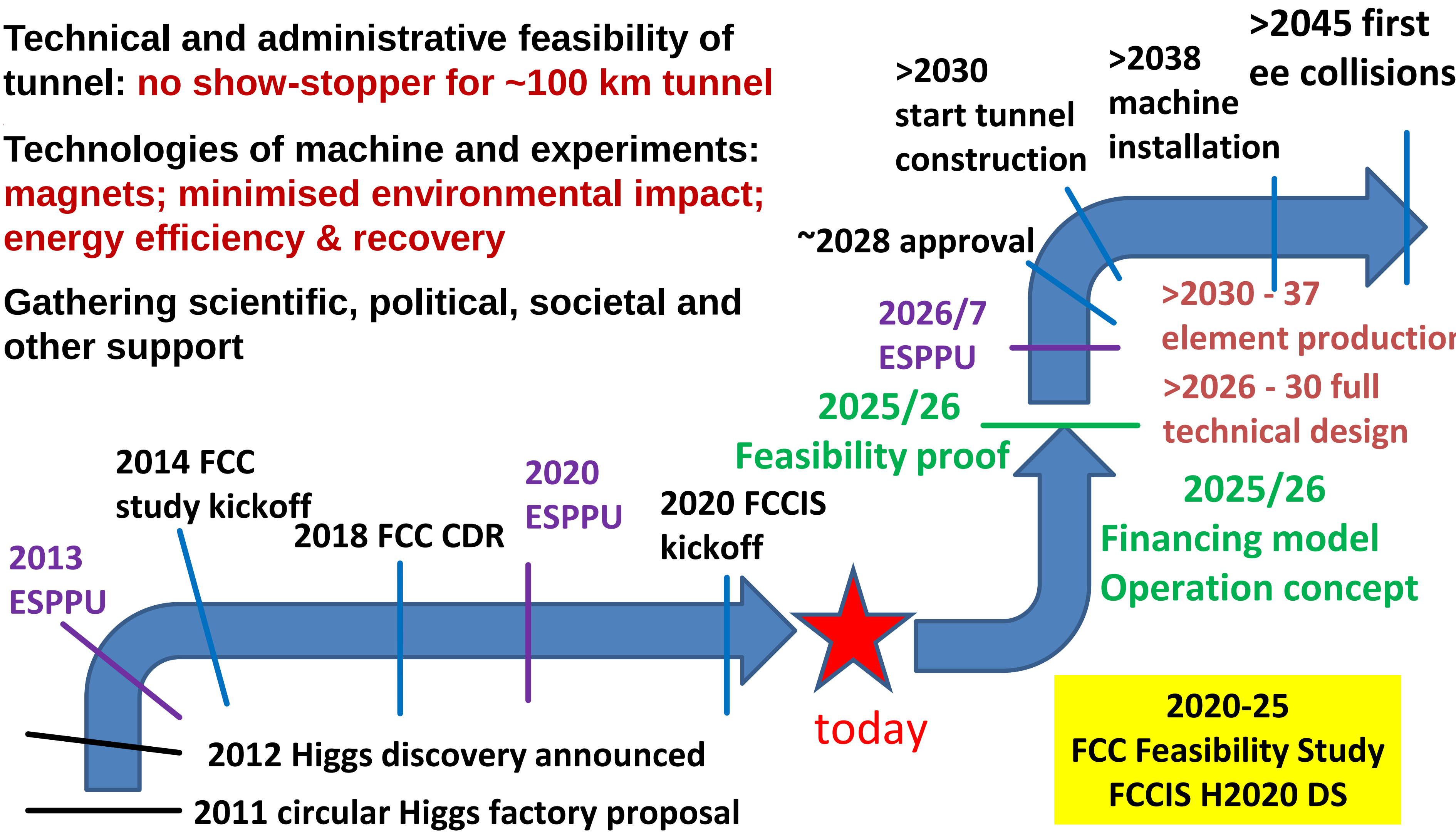
Highest priority goals:

Financial feasibility

Technical and administrative feasibility of tunnel: no show-stopper for ~100 km tunnel

Technologies of machine and experiments: magnets; minimised environmental impact; energy efficiency & recovery

Gathering scientific, political, societal and other support



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Status of Global FCC Collaboration

increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

141 Institutes

30 Companies

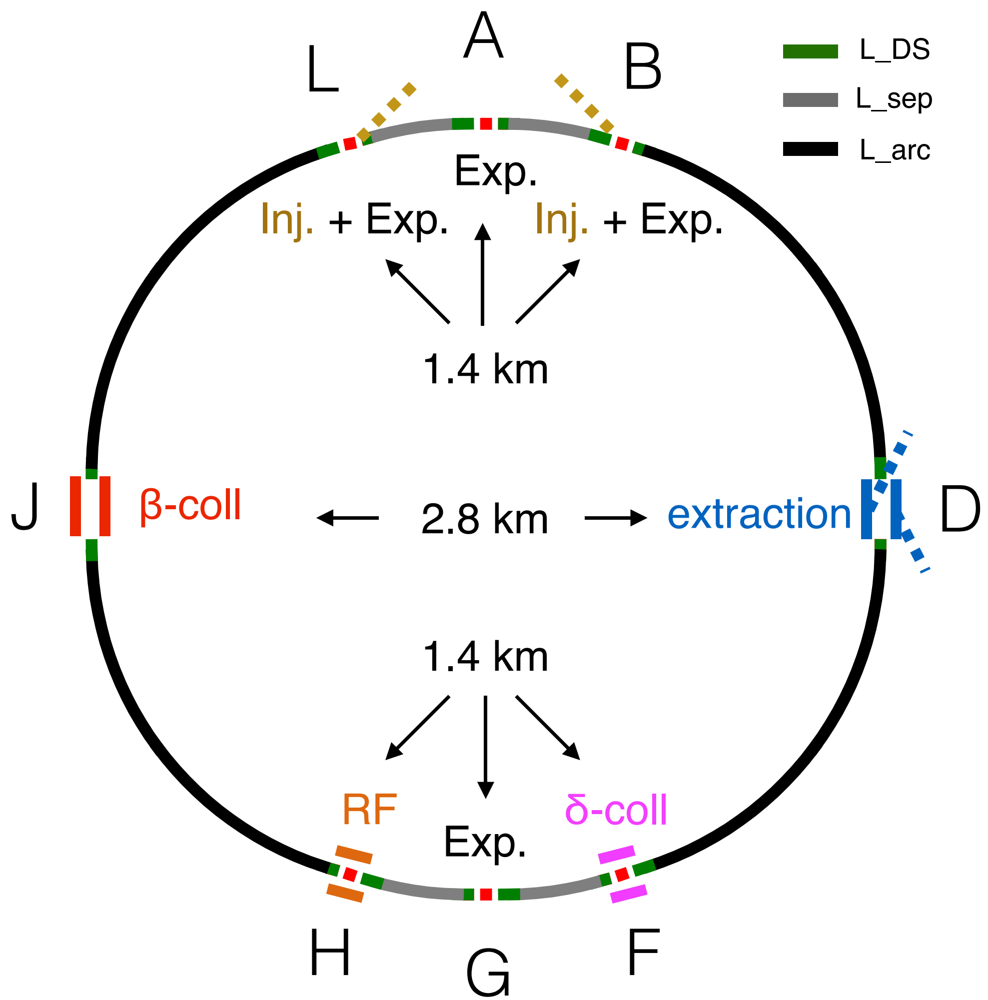
34 Countries

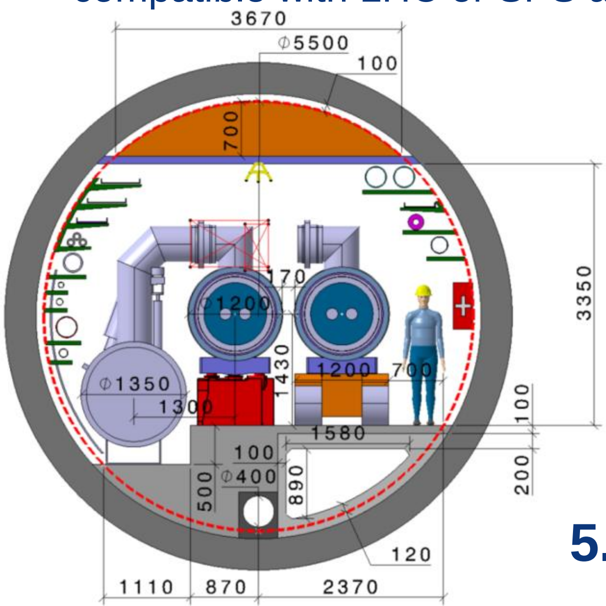
EC H2020

FCC-hh layout

- two high-luminosity experiments (A & G)
- two other experiments combined with injection (L & B)
- two collimation insertions
  - betatron cleaning (J)
  - momentum cleaning (F)
- extraction insertion (D)
- clean insertion with RF (H)
- compatible with LHC or SPS as injector

circumference: 97.75 km

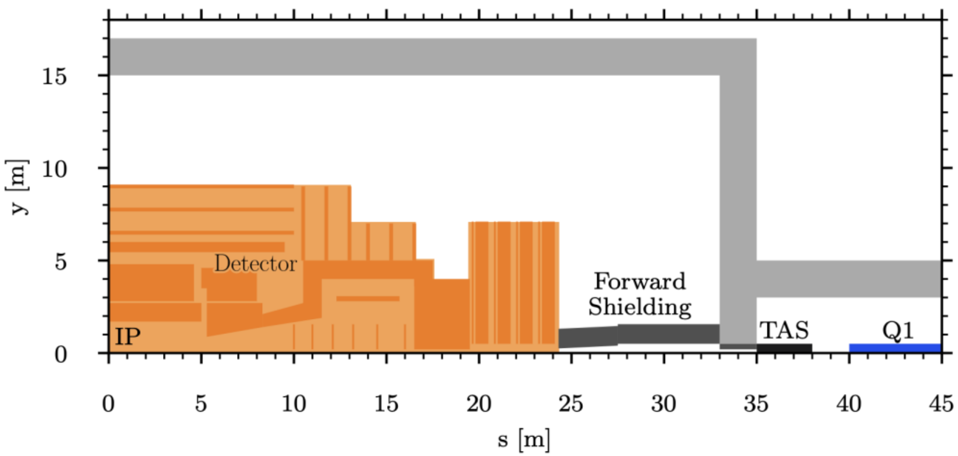


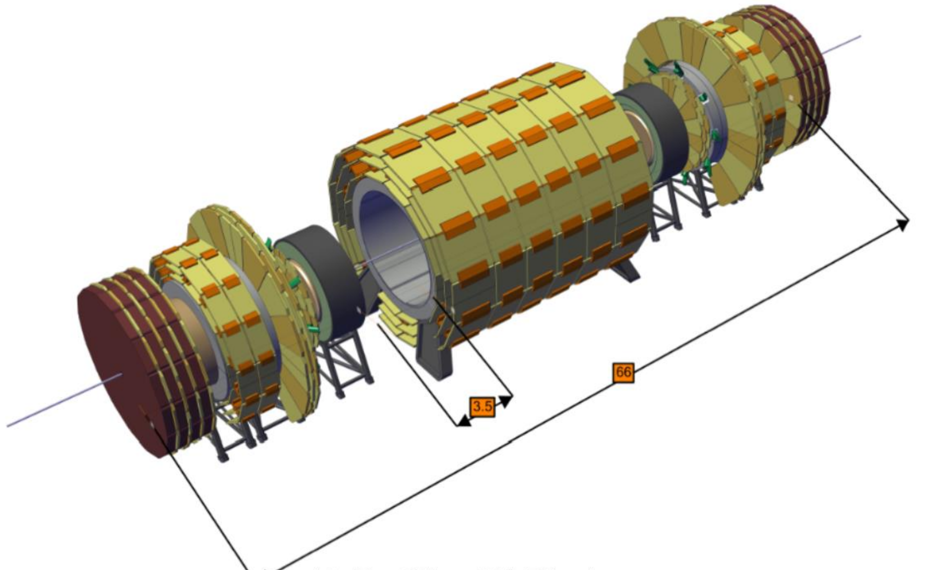


5.5 m inner diameter

High-luminosity interaction regions

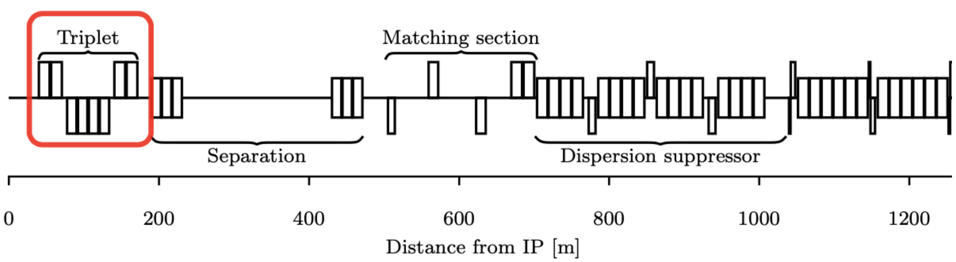
Essential input: size of experimental cavern (determines distance IP first triplet quadrupole)



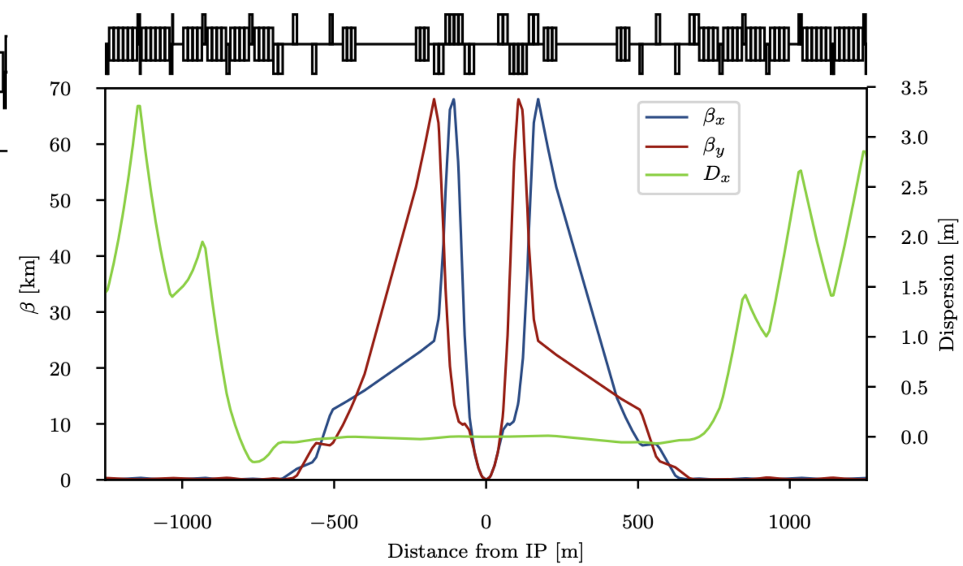


H. Da Silva, W. Riegler

Insertion layout



High-luminosity optics
for β*=30 cm
70 km beta peak!

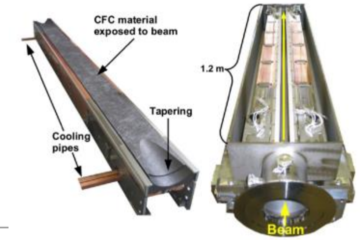


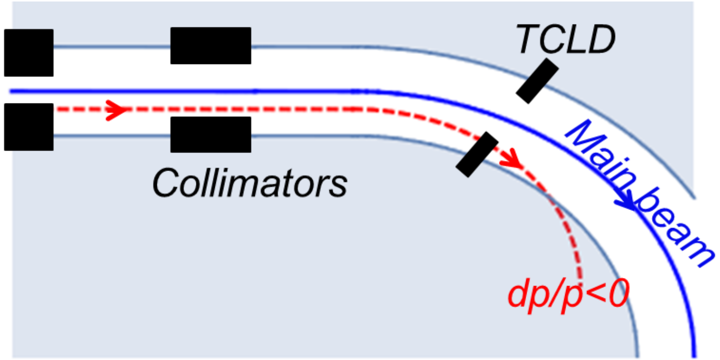
Collimation system

- Clean unavoidable regular losses, passive machine protection, optimize background and radiation dose
- Keep impedance within limits
- Main design loss scenarios
  - Unavoidable off-momentum losses of unbunched beam at start of ramp: 1% loss over 10 s
  - Extraction and injection kicker pre-fire
  - Betatron cleaning 0.2 h beam lifetime during 10 s or "steady-state" 1 h beam lifetime
  - **0.2 h lifetime and 8.3 GJ stored energy => 11.6 MW beam loss power**

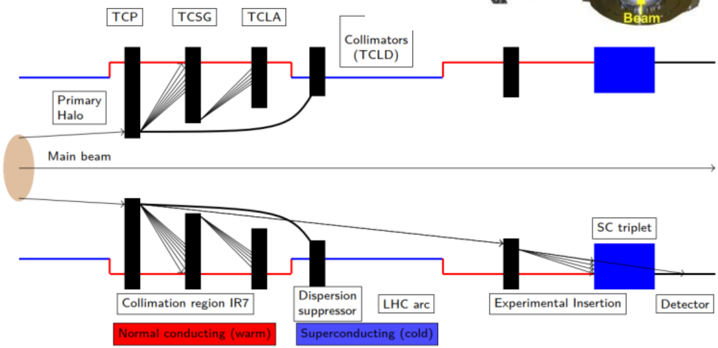
8.3 GJ = kinetic energy of an empty Airbus A380 cruising at 880 km/h

- The FCC-hh collimation system is a scaled up version of the HL-LHC/LHC system (NIM, A 894 (2018) 96-106)
- Multi-stage system to intercept and absorb the losses





- Dispersion suppressor collimators (TCLD) intercept off-energy particles
- scattered out of primary (mainly) in collimation insertion
- created in collisions at IPs

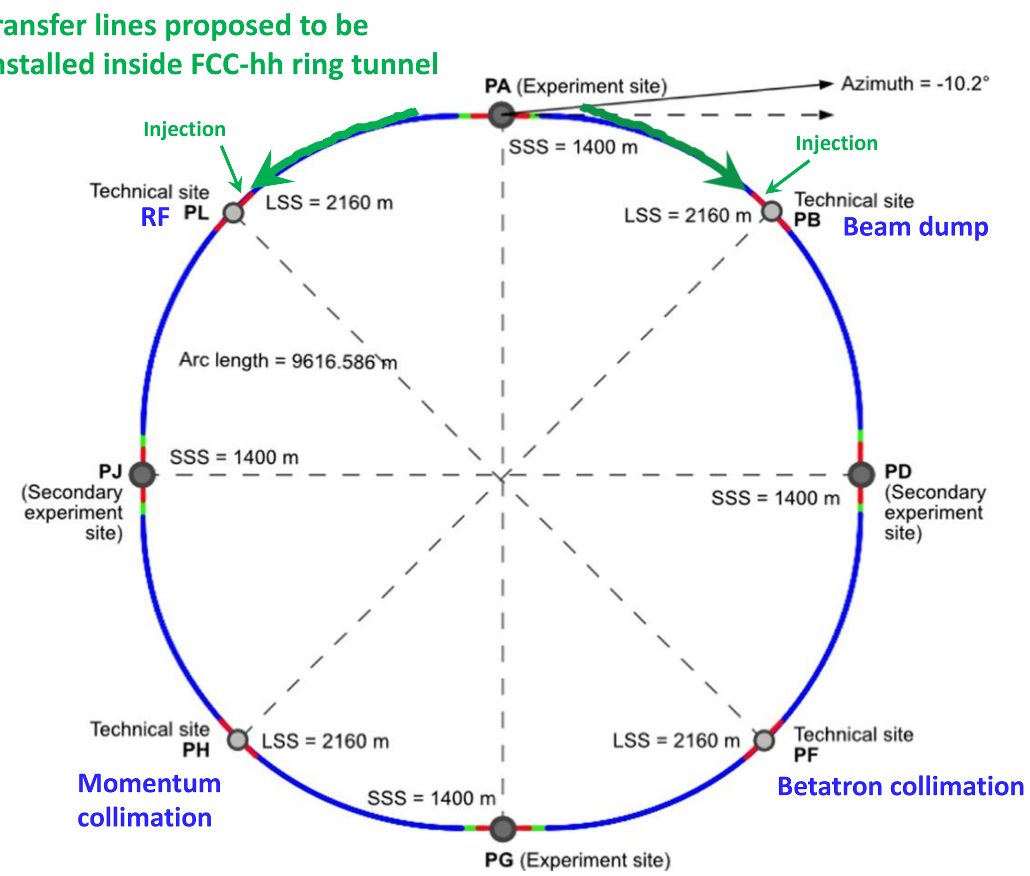


FCC-hh (pp) collider parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

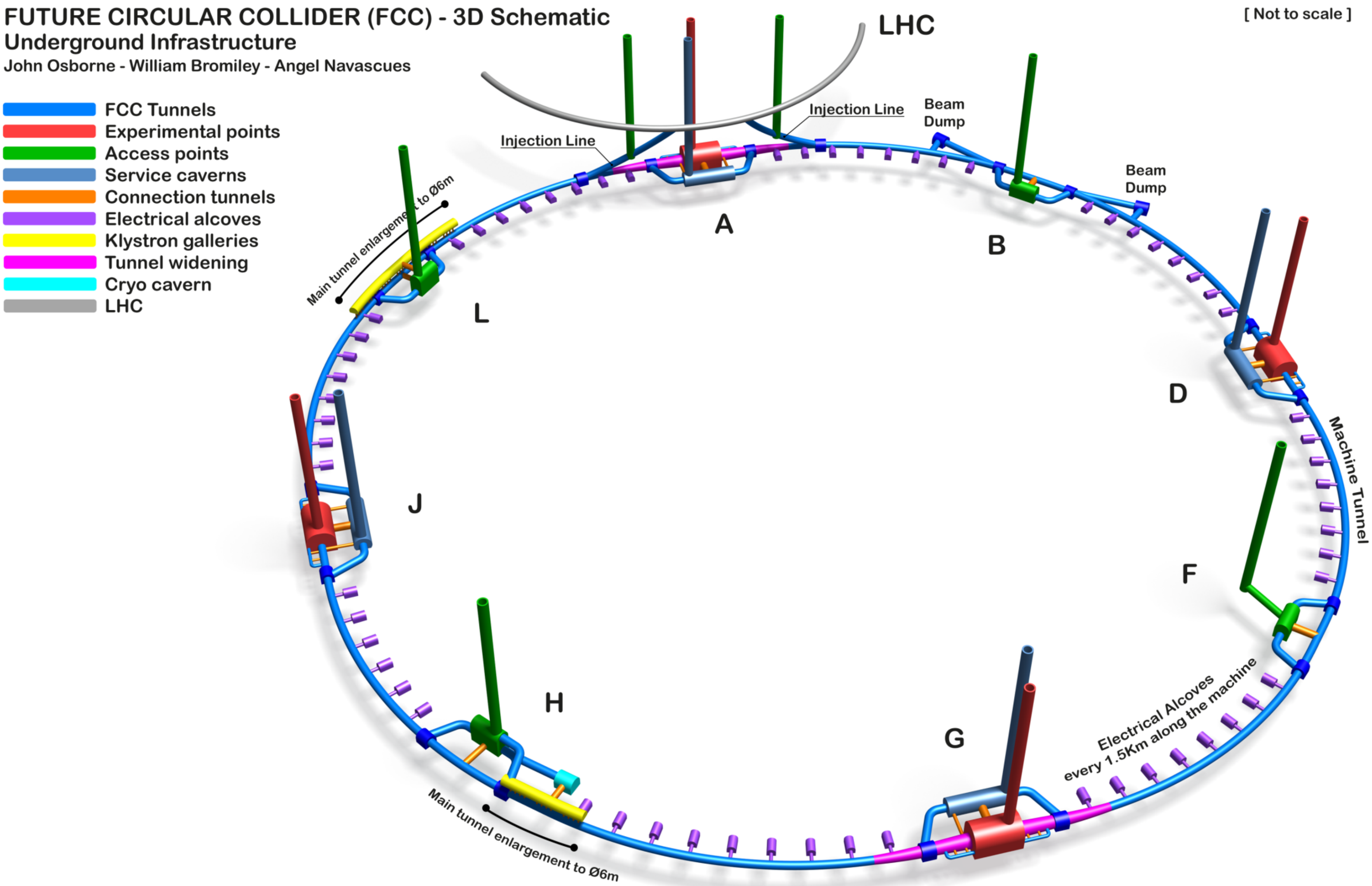
Recent developments: new layout

- **Exact four-fold symmetry**
- Four experiments (A, D, G, & J)
- Two collimation insertions
  - betatron cleaning (F)
  - momentum cleaning (H)
- Extraction insertion + injection (B)
- RF insertion + injection (L)
- **Last part of transfer lines in the ring tunnel, using normal-conducting magnets**
- Compatible with LHC or SPS as injector



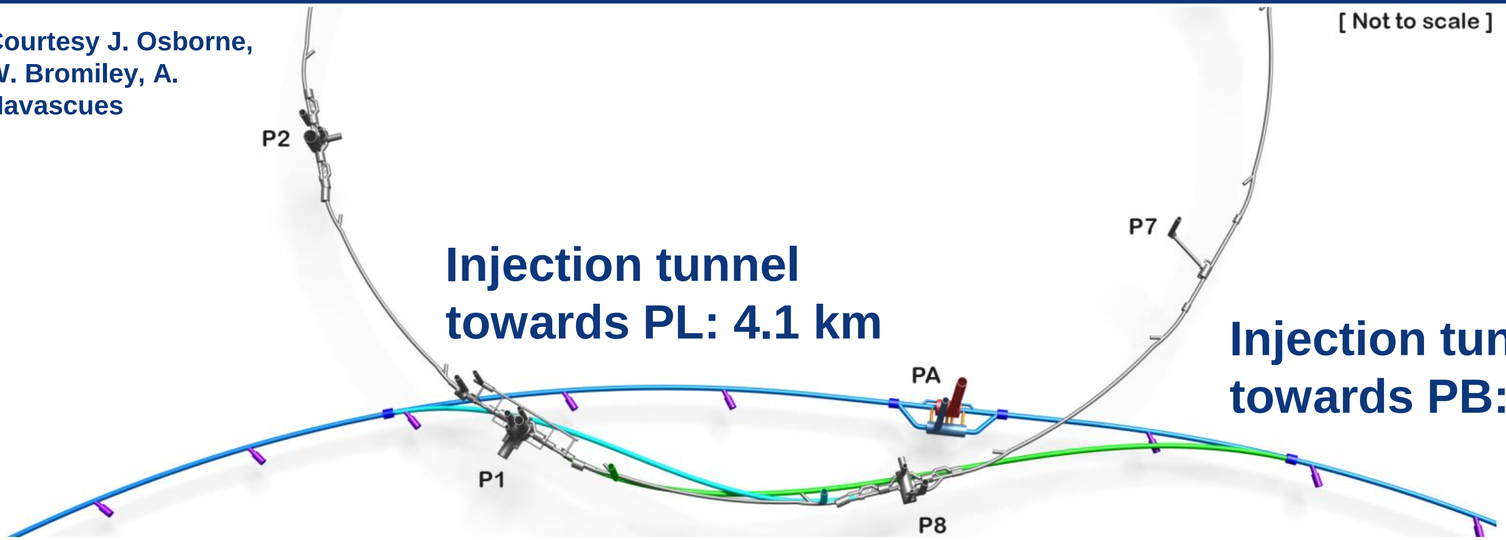
- **Number of arc cells: 42**
- **Cell length: 215.3 m**
- **Length of experimental straight sections: 1400 m**
- **Length of technical straight sections: 2032 m**
- **Length of circumference: 90.7 km**

Overall FCC-hh layout



FCC-hh layout and transfer lines

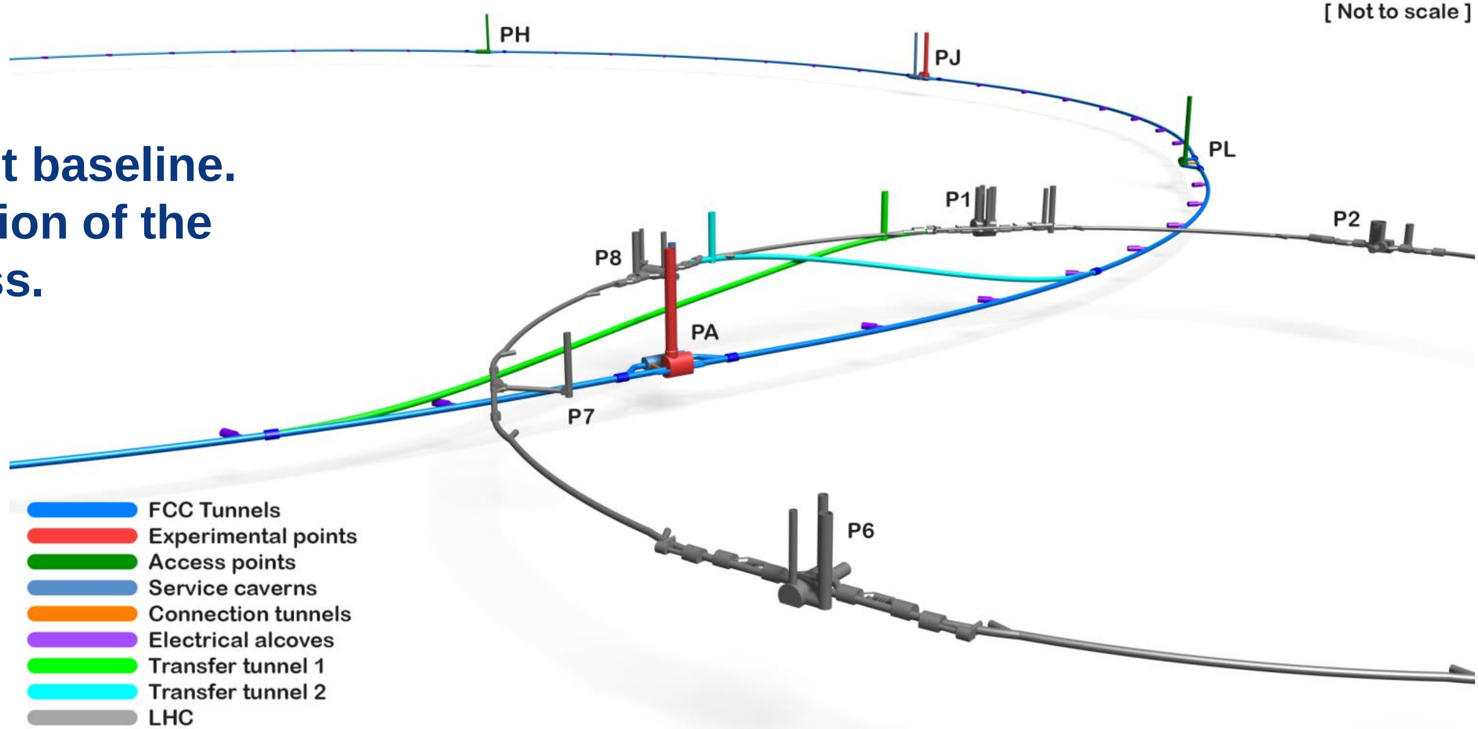
Courtesy J. Osborne, W. Bromiley, A. Navascues



Injection tunnel towards PL: 4.1 km

Injection tunnel towards PB: 6.1 km

This is the current baseline. Further optimisation of the design in progress.



Outlook

- A sound baseline for FCC-hh ring exists (heavily driven by LHC design).
- Strong support for a hadron collider at the energy frontier.
- Long time before any concrete decision is taken. Therefore:
  - A new layout has been proposed
  - Optimise by moving away from the LHC paradigm
  - **Innovate**

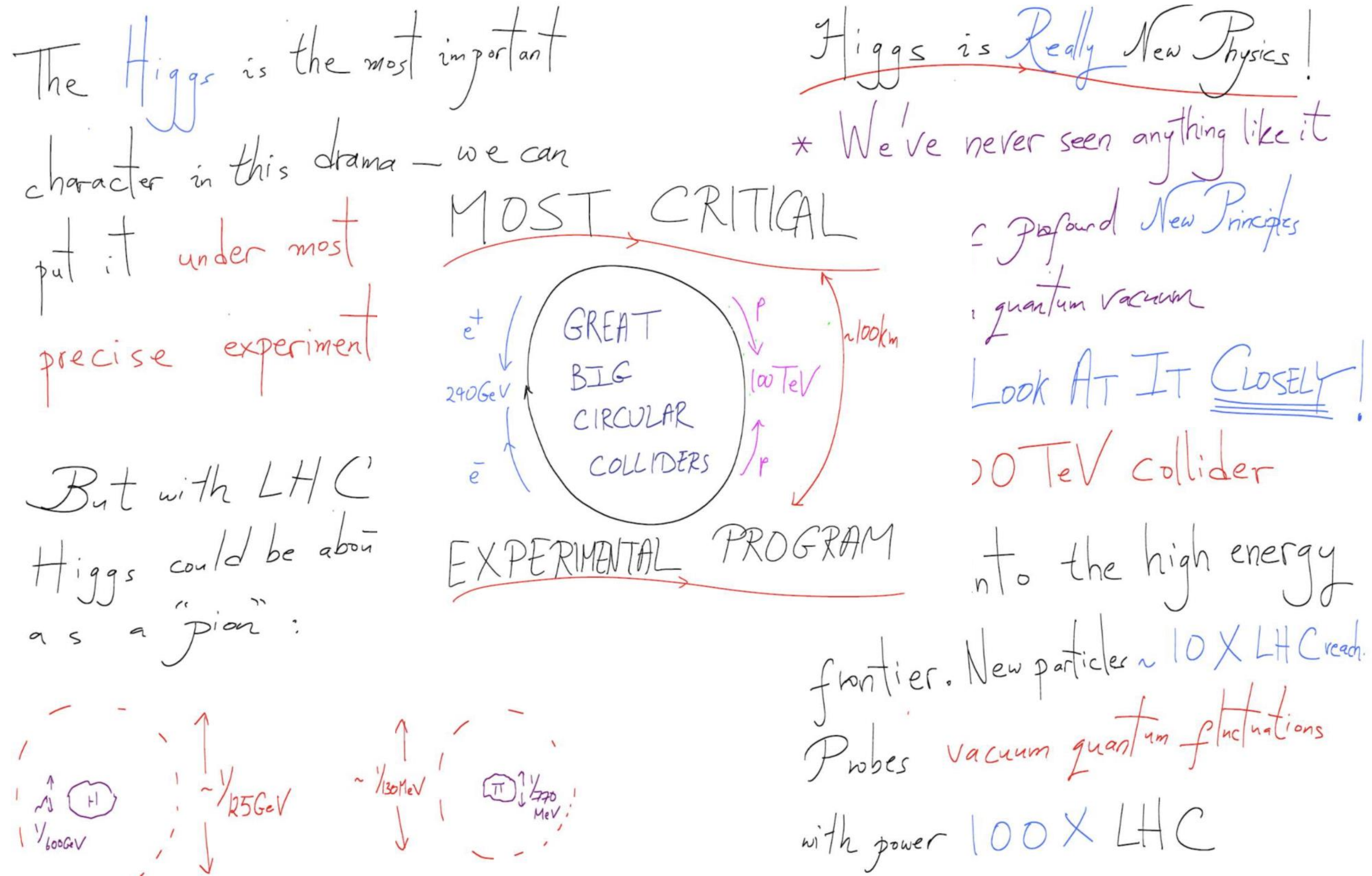
Plenty of creative and exciting work for generations of accelerator physicists!

Thanks a lot for your attention!!!

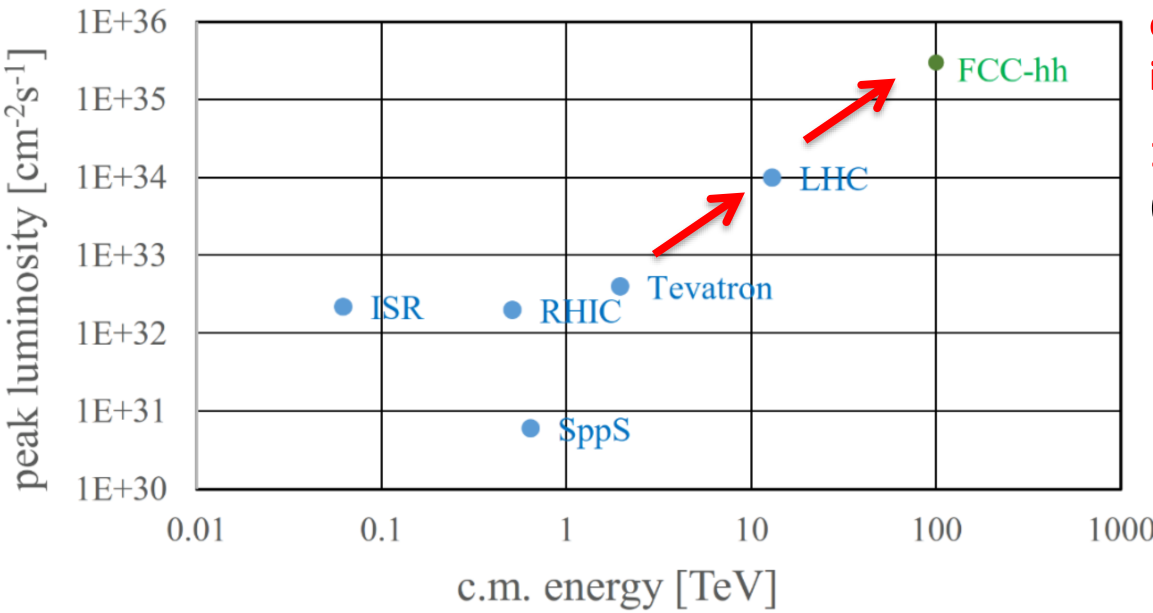
Back up slides

Why a hadron collider after LHC/HL-LHC

Nima Arkani-Hamed: “FCC and the Future of Fundamental Physics”, FCC Week 2019.



FCC-hh: performance



order of magnitude performance increase in **energy & luminosity**

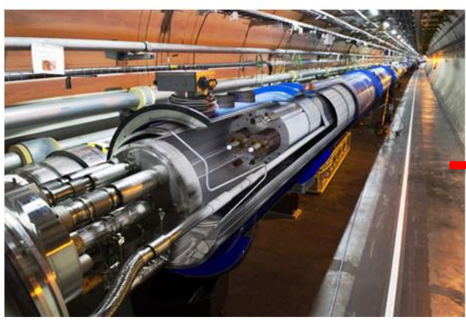
100 TeV cm collision energy
(vs 14 TeV for LHC)

20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)

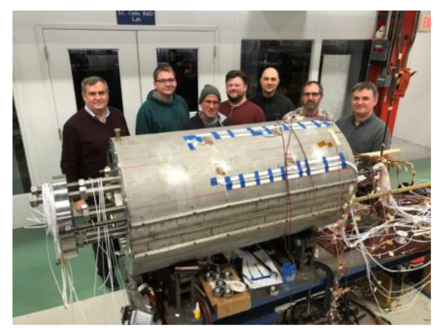
similar performance increase as from Tevatron to LHC

key technology: high-field magnets

from
LHC technology
8.3 T Nb-Ti



via
HL-LHC technology



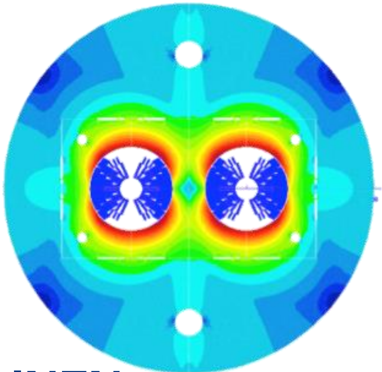
FNAL demonstrator
14.5 T Nb_3Sn

16 T dipole design activities and options

EuroCirCol
A key to New Physics

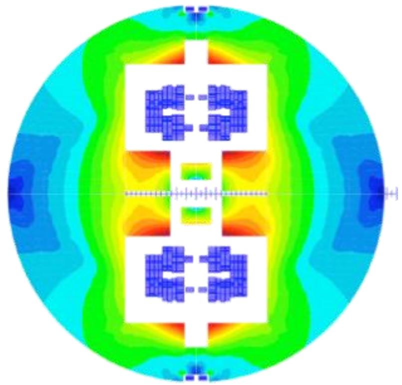
Swiss contribution

Cos-theta



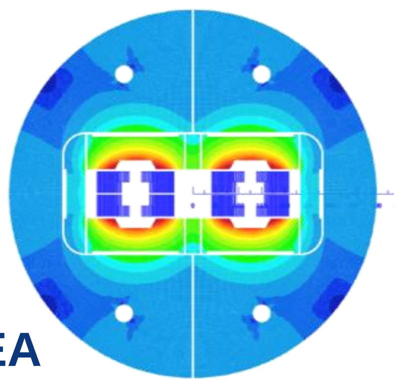
INFN

Common coils



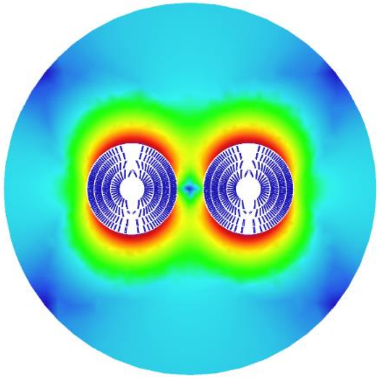
CIEMAT

Blocks



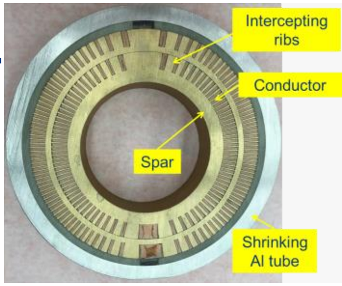
CEA

Canted Cos-theta

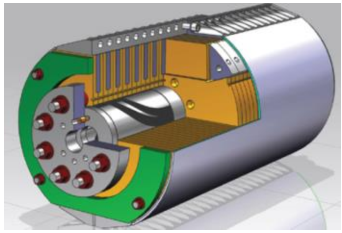


PSI

LBNL

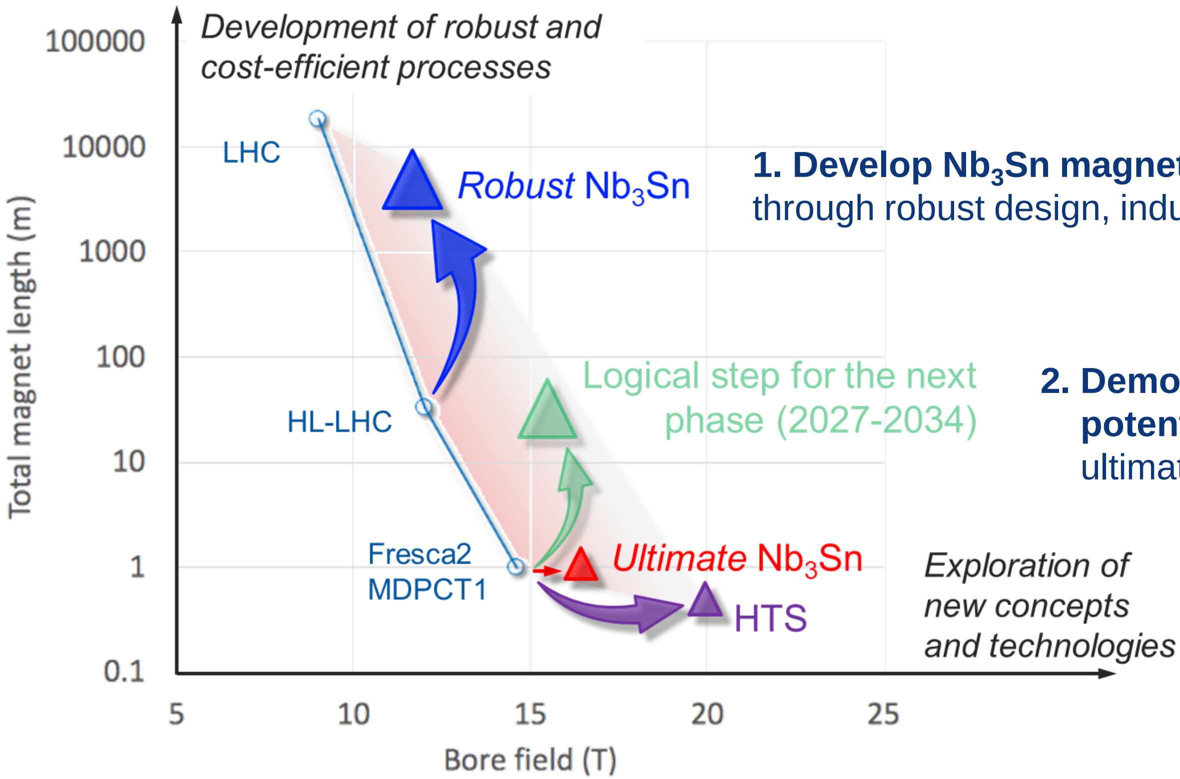


FNAL



Short model magnets (1.5 m lengths) will be built until ~2025

High Field Magnet program goals until 2027

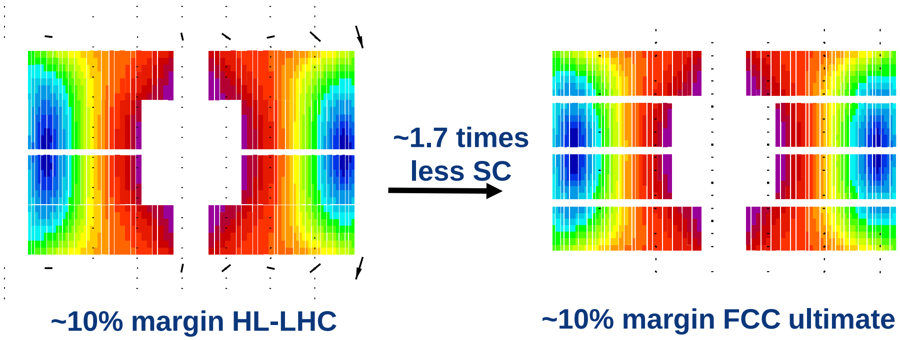


1. **Develop Nb_3Sn magnets for collider-scale production**, through robust design, industrial processes and cost reduction
2. **Demonstrate Nb_3Sn full potential** in terms of ultimate performance
3. **Provide a proof-of-principle for HTS magnet technology**

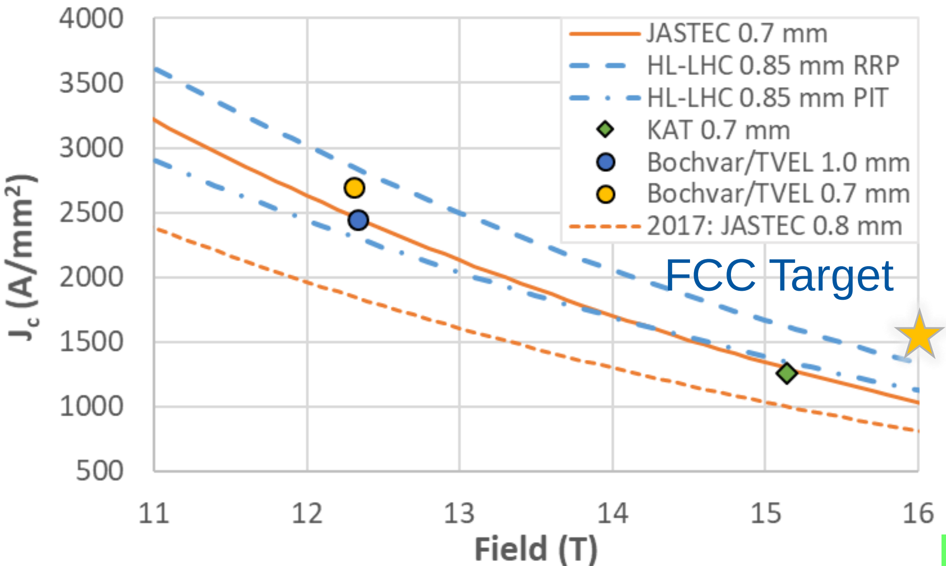
Worldwide FCC Nb3Sn program

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



After 1-2 years development, **prototype Nb_3Sn wires from several new industrial FCC partners already achieve HL-LHC J_c performance**



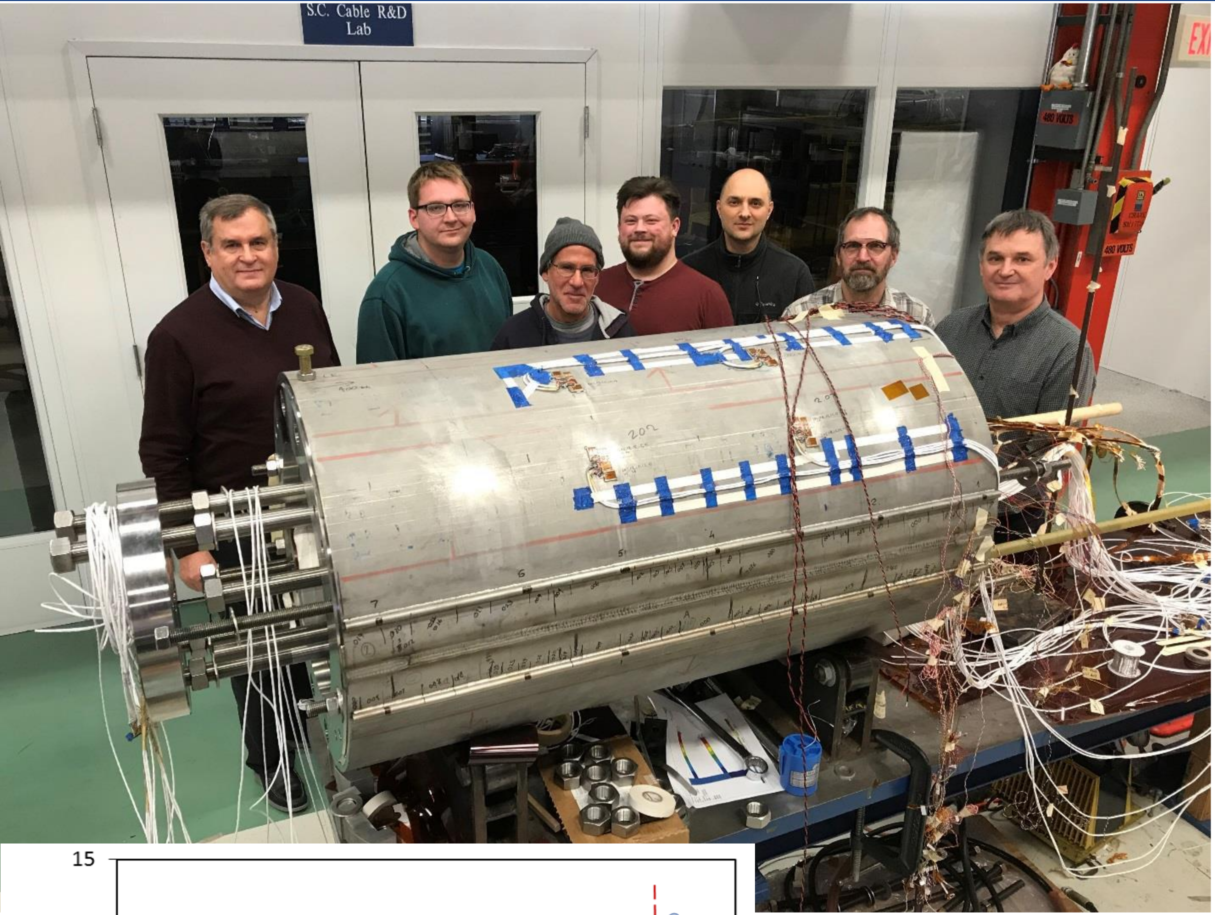
FCC conductor development collaboration:

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

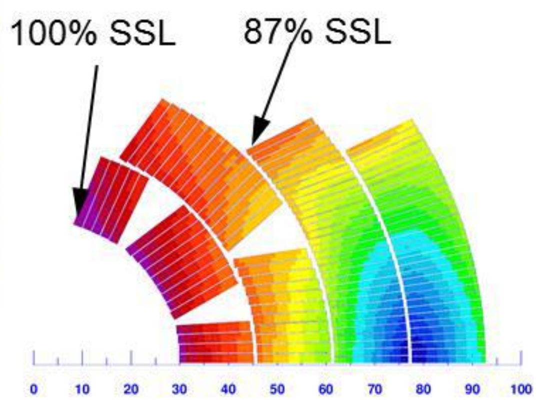
2019/20 results from US, meeting FCC J_c specs:

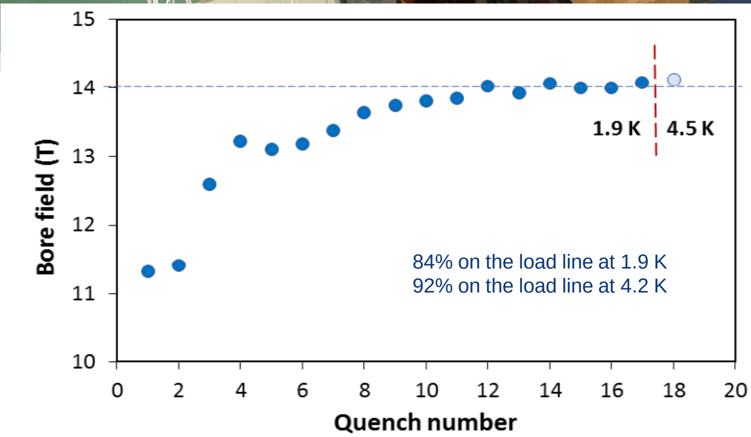
- **Florida State University:** high-J_c Nb_3Sn via Hf addition
- **Hyper Tech /Ohio SU/FNAL**: high-J_c Nb_3Sn via artificial pinning centres based on Zr oxide.

US – MDP: 14.5 T magnet tested at FNAL



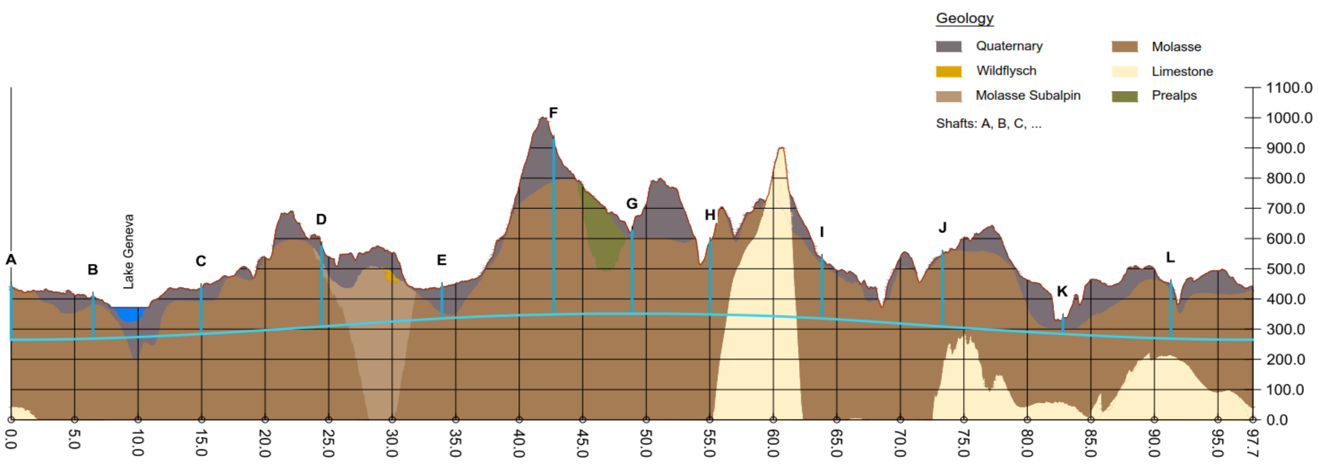
60-mm aperture
4-layer graded coil

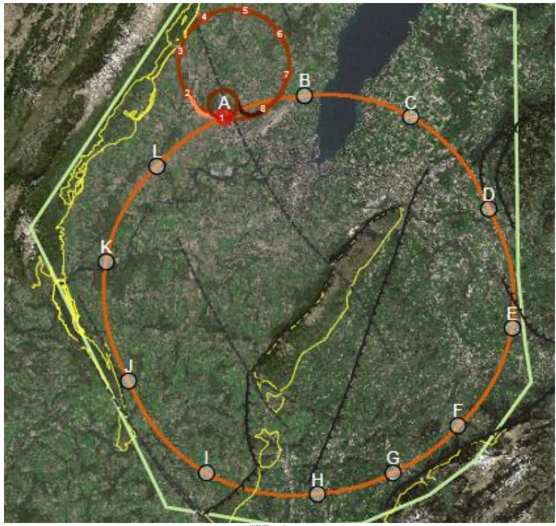




- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T

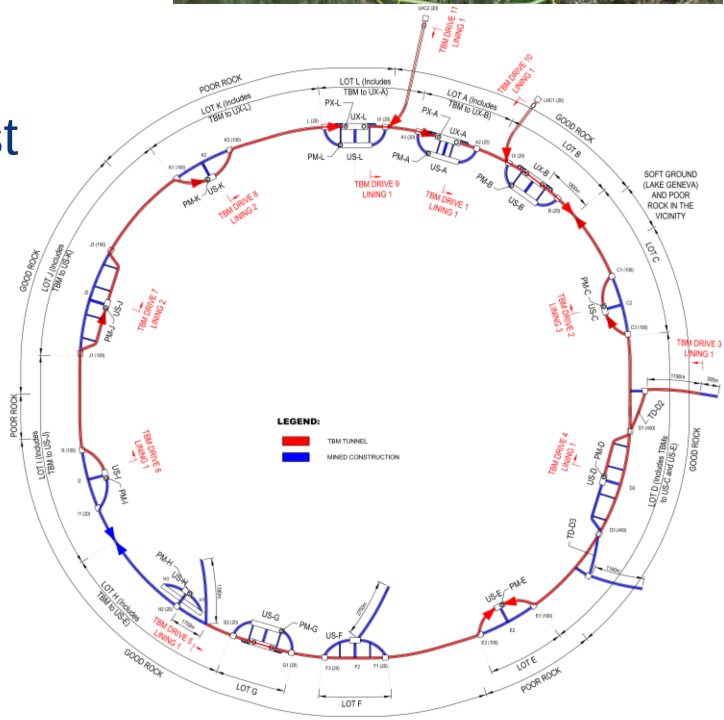
FCC implementation - footprint baseline





Current baseline position based on:

- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)
- **90 – 100 km circumference**
- **12 surface sites with few ha area each**



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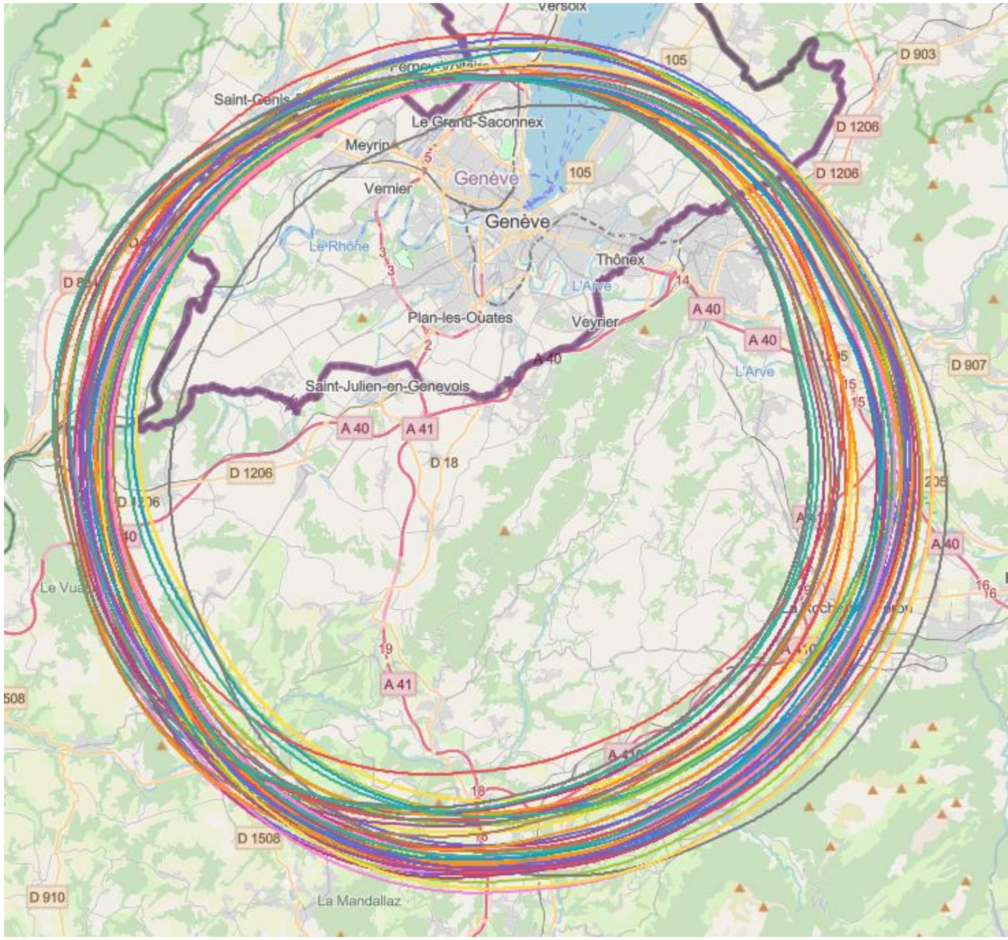
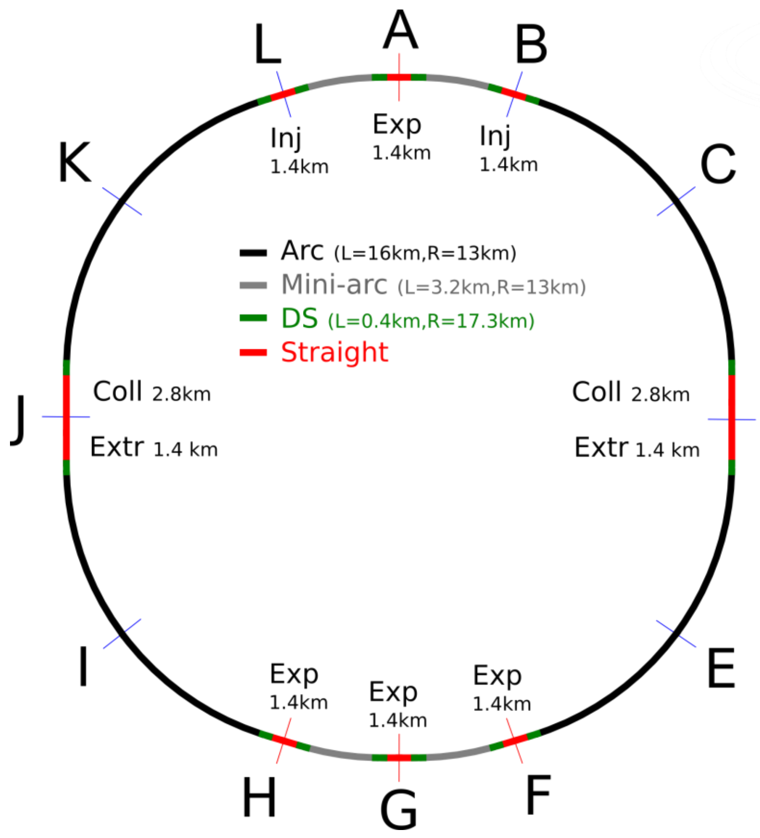
Collider placement optimisation

- Overall layout and placement optimisation process across both host states
- Following the "avoid-reduce-compensate" directive of European and French regulatory frameworks
- Process integrates diverse requirements and constraints:
    - performance permitting world-leading scientific research
    - technical feasibility of civil engineering and subsurface constraints
    - territorial constraints on surface and subsurface
    - nature, accessibility, technical infrastructure, and resource needs & constraints
    - economic factors including development of benefits for, and synergies, with the regional developments
    - …
- Collaborative effort of technical experts at CERN, consultancy companies and government notified bodies

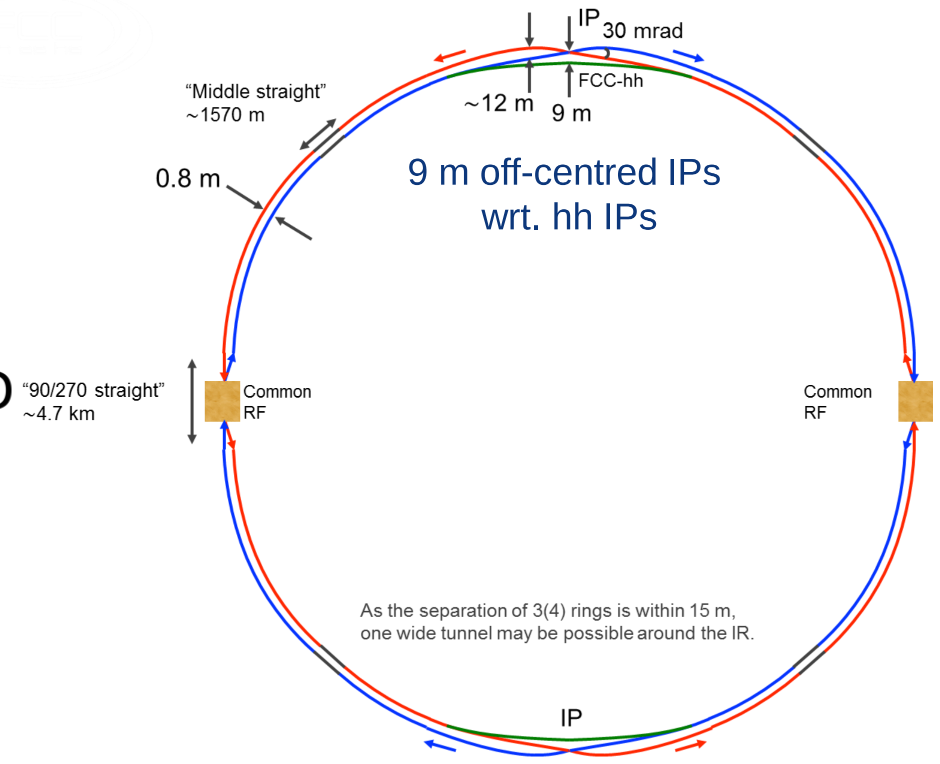


FCC consistent machine layouts

FCC-hh



FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

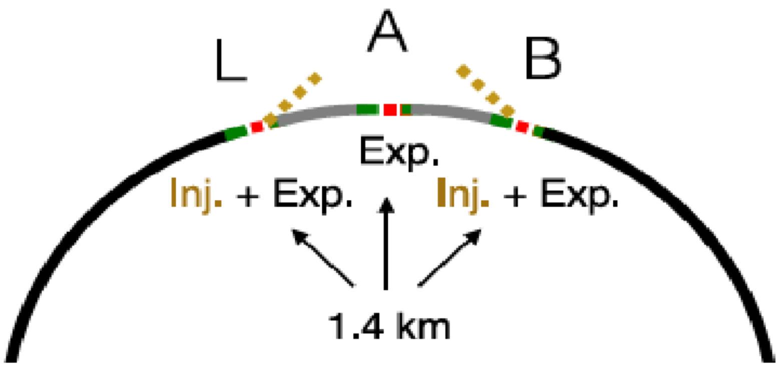


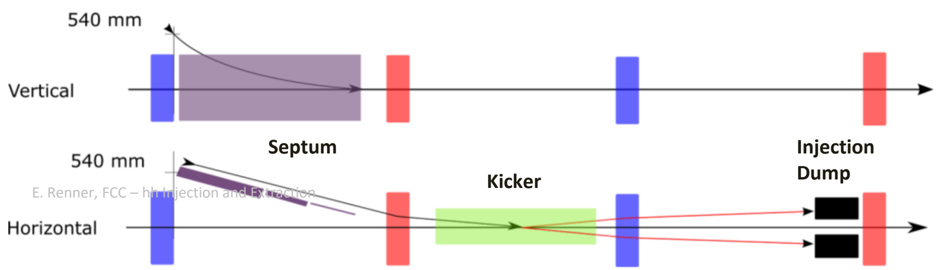
Closed optics solutions for full ring for both machines available

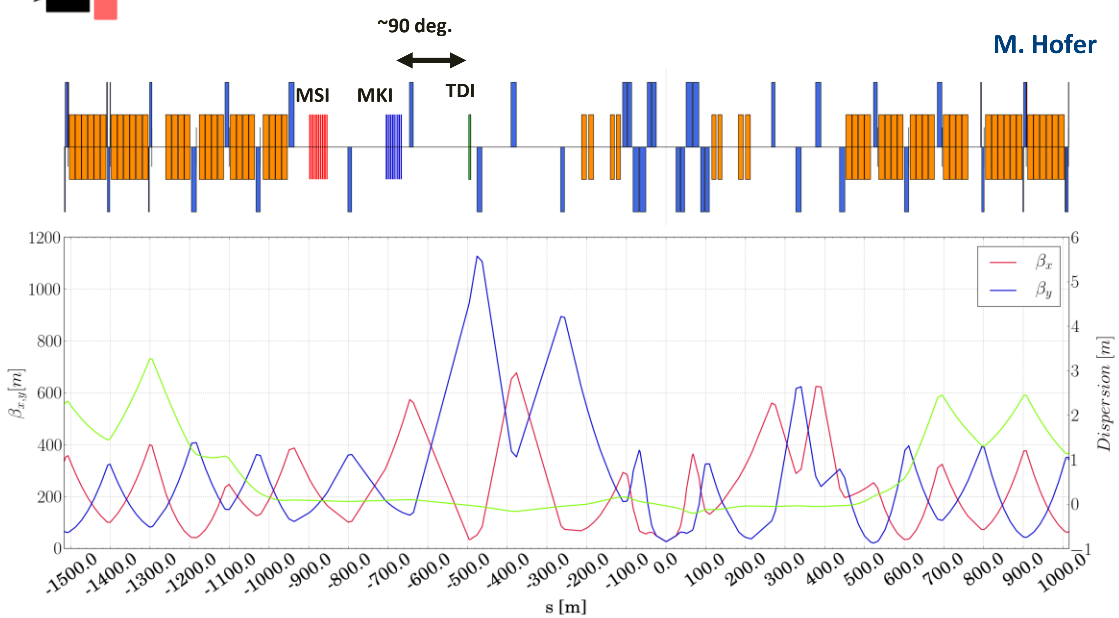
Injection system

A. Chmielinska, FCC-hh Injection and Extraction

- Combined with side experiments (IPB and IPL) – 1.4km, ~0.7km for injection
- Baseline: Injection from HEB (LHC) at 3.3 TeV
- 1.3 TeV option studied as well
- Double plane injection



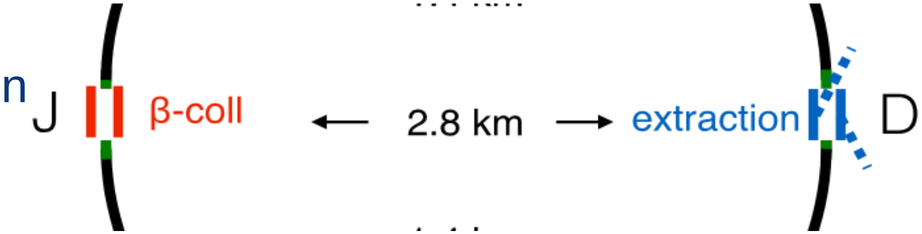




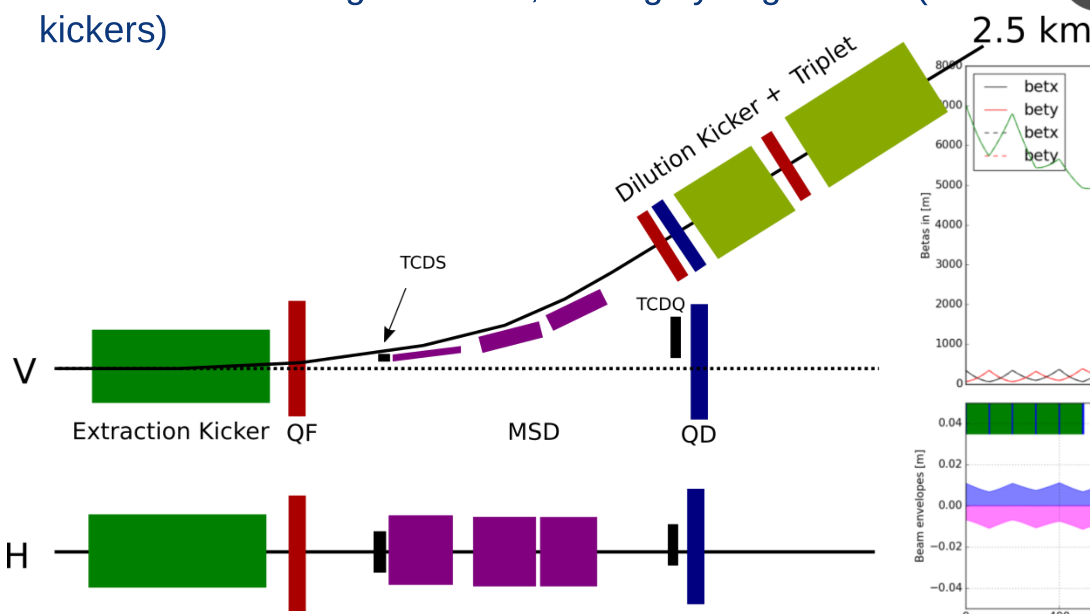
	Septa (nc Lamb.)	Kicker
System Length [m]	104	40
Deflection [mrad/Tm]	9.8/92	0.18/2
Number of Modules	21	18
Flux Field [T]	0.7-1.2	0.062

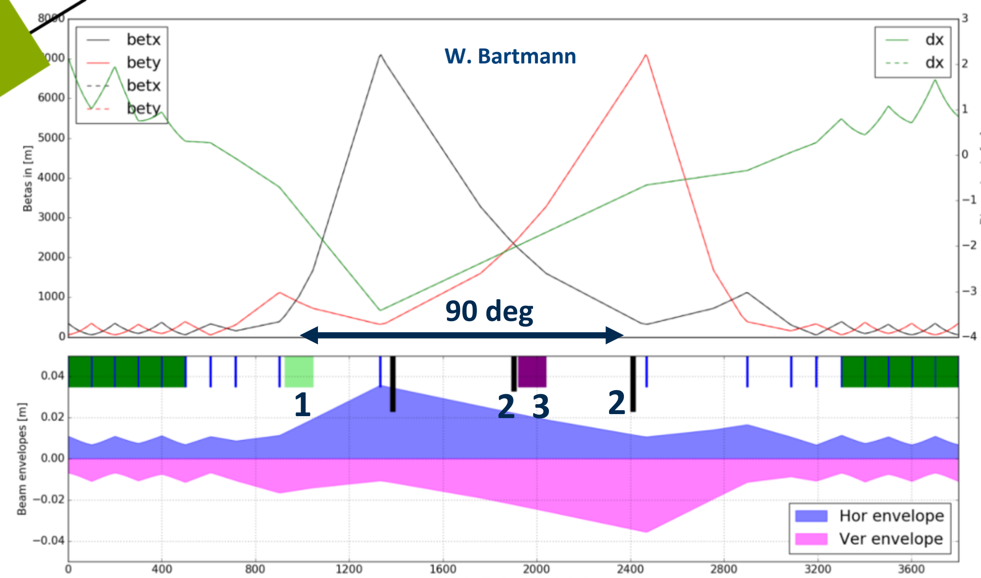
Extraction system

- IPD, 2.8 km for extraction of both beams
- 2.5 km dump line with dilution kicker system to create sweep pattern at graphite beam dump
- Design mainly driven by machine protection
  - Safely extract 8.5 GJ beam
  - Reduce failure probabilities
  - Avoid downtime in case of failure



- Based on novel septa: SuShi (3.2 T) and Truncated CosTheta (4 T). Total system length ~70m
- Septa Layout requires single plane extraction (vertical)
- Reduced kicker segmentation, still highly segmented (150 kickers)

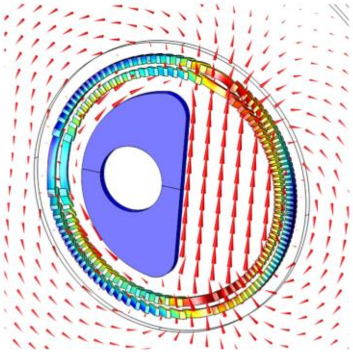


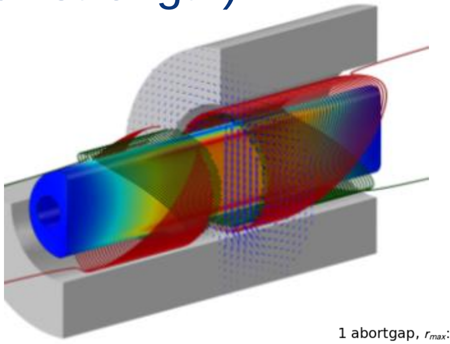


Extraction system

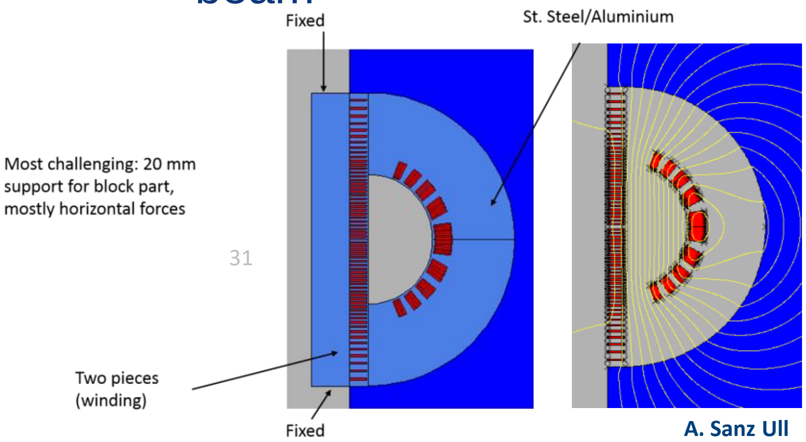
- SuShi
  - 3.2 T
  - Apparent septum blade: 25 mm
  - It can potentially be reduced to 20mm using Nb-Ti for the shield (reduced kick strength)

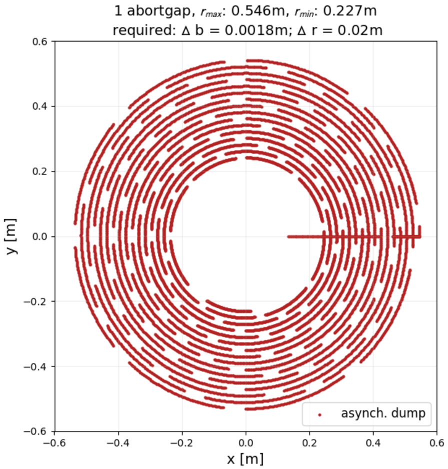
Barna et al. (2019). NbTi/Nb/Cu Multilayer Shield for the Superconducting Shield (SuShi) Septum. ***IEEE Transactions on Applied Superconductivity*, *29*** **(1)**.





- Truncated Cos-Theta
  - 4 T
  - 35mm app. septum blade
  - Very flexible geometry for larger separation of circulating and extracted beam



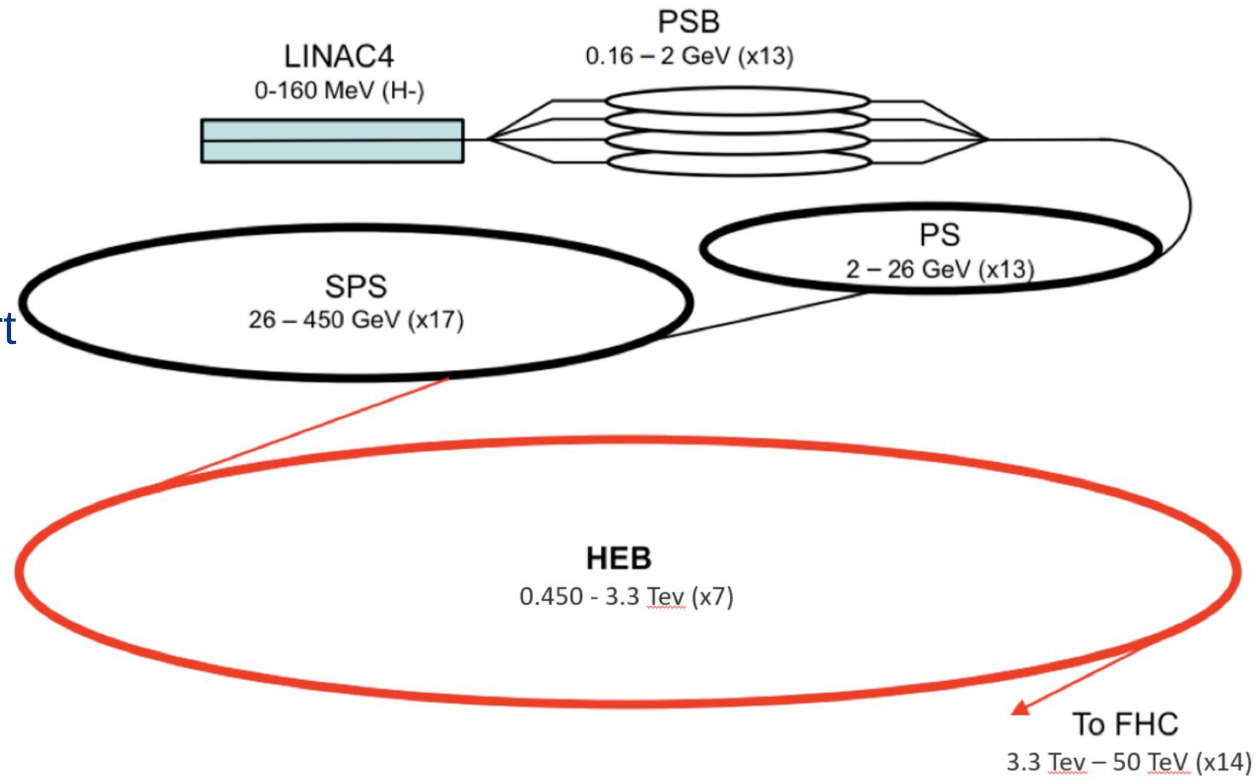


Dilution pattern on the dump block

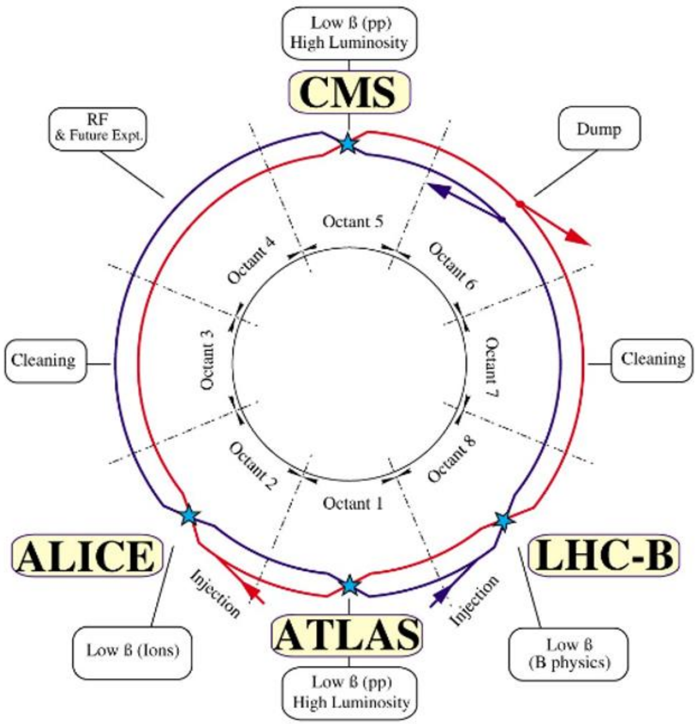
FCC-hh injector

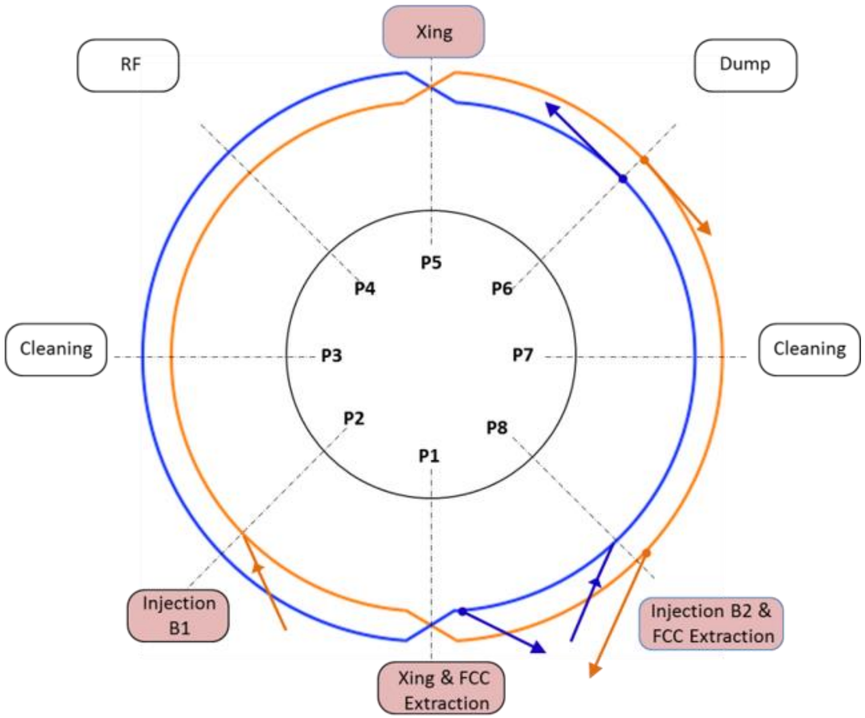
- High Energy Booster (HEB) requirements
  - Inject at 3.3 TeV,
    - 1.3 TeV has been studied as low-energy option, but presently excluded by FCC-hh collider.
  - Deliver required beam parameters:
    - Intensity, emittance, spacing.
  - Fill FCC-hh as quickly as possible,
    - Target 30 minutes (LHC experience shows that this is reasonable).

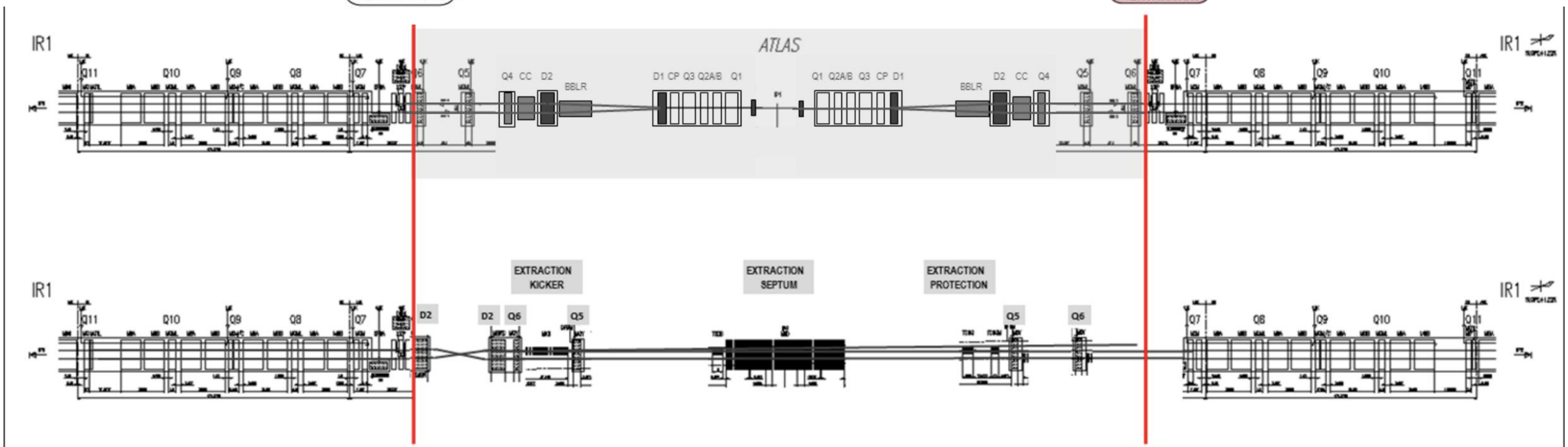
- Re-use existing CERN proton complex as far as possible:
- Assume post HL-LHC performance,
- Keep the main project effort focused on the 100 km collider(s).
- Options studied based on existing tunnels:
  - SPS: 6.9 km
  - LHC: 26.7 km
  - FCC: 100 km



FCC-hh injector baseline: re-use LHC



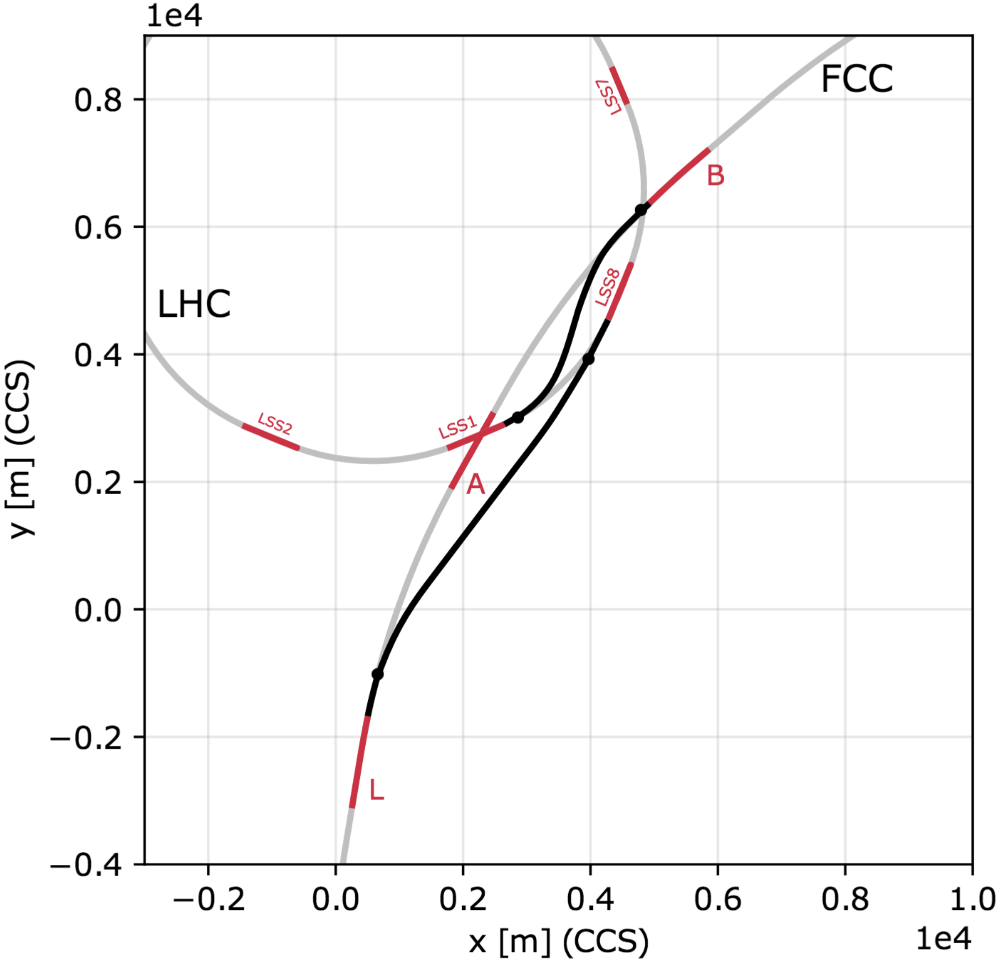




FCC-hh injector baseline: re-use LHC

- LHC Straight sections:
  - •IR1: **new extraction system** and beam crossing, plus **decommissioning** of ATLAS
  - •IR2: injection to inside ring plus **decommissioning** of ALICE and crossing
  - •IR3: no changes to momentum collimation
  - •IR4: no changes to RF system
  - •IR5: decommissioning of CMS, plus beam crossing
  - •IR6: no changes to beam dump
  - •IR7: no changes to betatron collimation
  - •IR8: injection to inside ring plus **new extraction** plus decommissioning of LHCb and crossing

Transfer from LHC P1 and P8 (11.7 km with 7 T dipoles)



FCC-hh injector baseline: re-use LHC

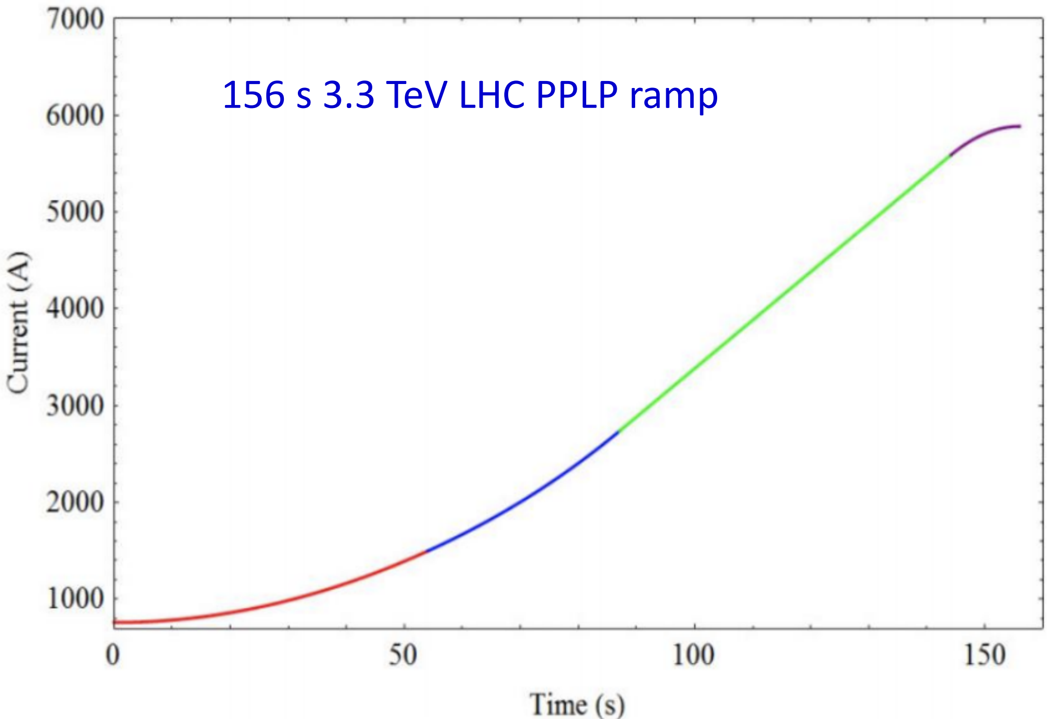
- Present LHC ramp up to 3.3 TeV would take 8′30″, total FCC filling time >1.5 hours.

- With dipole/quadrupole power converter upgrades and a ramp at 50 A/s, 3.3 TeV ramp takes 156 sec.

- PPLP scheme instead of PELP essential to fully profit from increased ramp rate (tested in 2017, used in LHC in 2018).

- Time to ramp down from 3.3 TeV driven by one-quadrant main quadrupole power converters. With upgrade, ramp down time shortened to 100 s.

- Overall FCC filling time (on paper) is then 46 minutes, for 4 LHC fills and ramps.



FCC-hh injector: alternatives

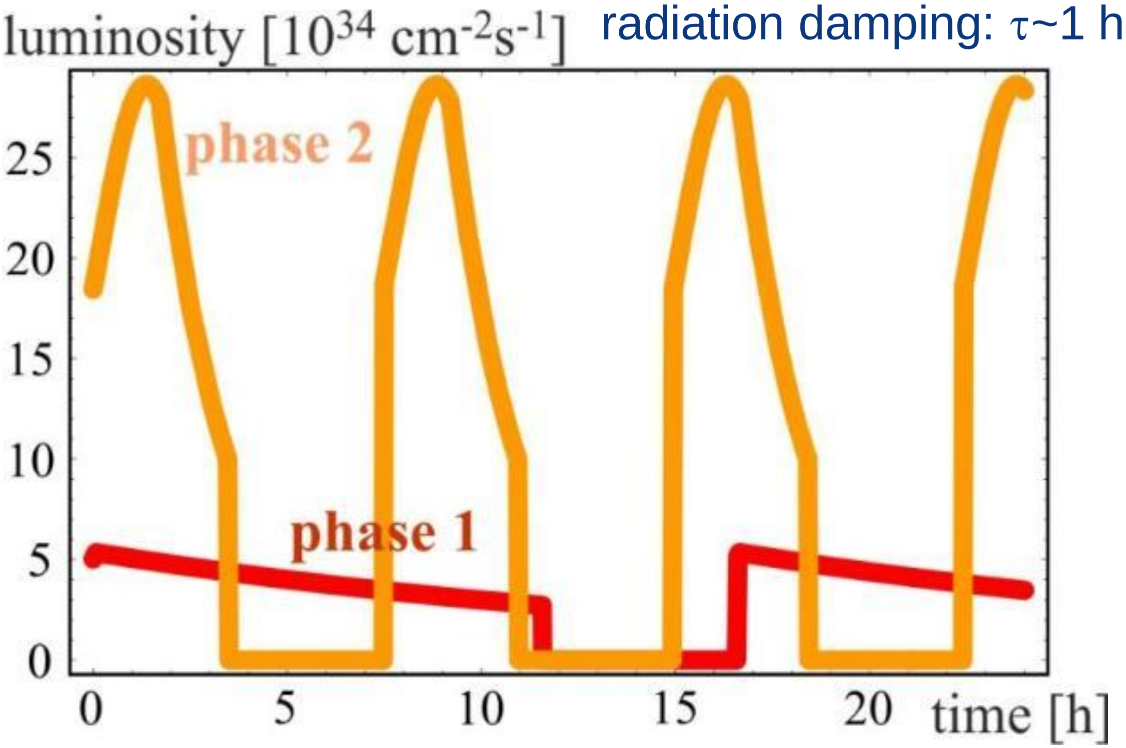
- 100 km superferric, 3.3 TeV HEB (in FCC-hh tunnel)
- Features
  - 1.1 T dipoles (for 70% filling factor)
  - Single aperture + polarity reversal, or simple twin aperture
  - Needs to be superferric: 50 kA SC cable (100 MW peak power if resistive)
  - Ramp-up time 120 s (limited by RF)
  - FCC filling in 32 minutes (injectors)
- Critical points
  - By-pass tunnels around 4 experiments - ∫15 km (FCC-ee)
  - Very high stored energy of 670 MJ
  - Issue of beam loss du to cross-talk between HEB and FCC-hh?
  - Integration into FCC tunnel still to demonstrate

- 3.3 TeV superconducting 26.7 km HEB in LHC tunnel
- Features
  - Dedicated HEB: more suitable than re-purposed LHC.
  - More robust, less complex magnets will be used: 4 T dipoles (4 K cos q – RHIC, Tevatron, FAIR SIS200/300)
  - Simplified LHC lattice, with insertions as per reused-LHC
  - Ramp-up time about 50 s (limited by RF system)
  - FCC filling time about 39 minutes (injectors)

FCC-hh luminosity over 24 h

If everything discussed before works as expected, this is what the experimentalists should get…

radiation damping: τ~1 h



PRST-AB 18, 101002 (2015)

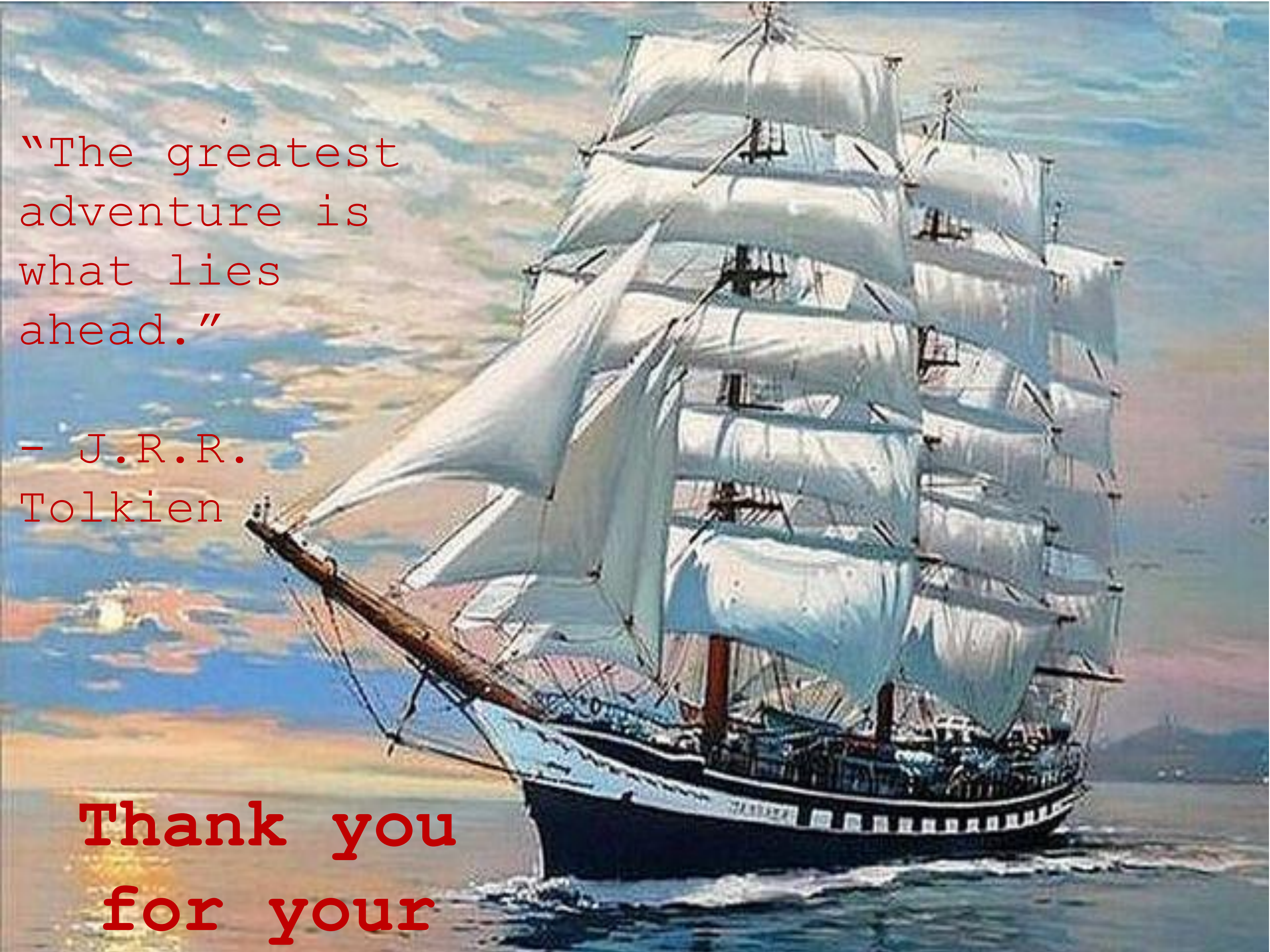
for both phases:

beam current 0.5 A, unchanged!

total synchrotron radiation power ~5 MW.

phase 1: β^*=1.1 m, ξ_{tot}=0.01, t_{ta}=5 h, 250 fb^{-1} / year

phase 2: β^*=0.3 m, ξ_{tot}=0.03, t_{ta}=4 h, 1000 fb^{-1} / year


"The greatest adventure is what lies ahead."
- J.R.R. Tolkien
Thank you for your