

# Status and plans for FCC-hh optics studies

Massimo Giovannozzi  
CERN, BE Department  
FCC Week 2021, 30 June 2021



<http://cern.ch/fcc>

Work supported by the **European Commission** under the **HORIZON 2020** projects **EuroCirCol**, grant agreement 654305; **EASITrain**, grant agreement no. 764879; **ARIES**, grant agreement 730871, **FCCIS**, grant agreement 951754, and **E-JADE**, contract no. 645479

photo: J. Wenninger

- The CDR baseline
- Current activities
- Some innovation
- Outlook

Acknowledgements: W. Bartmann,  
M. Benedikt, R. Bruce, J. Gutleber,  
V. Mertens, T. Risselada, F.  
Zimmermann



**FCC  
WEEK  
2021**  
28 June – 2 July

ONLINE EVENT  
Register Here:  
<https://indico.cern.ch/e/fccw2021>

 FUTURE  
CIRCULAR  
COLLIDER

FCCIS - The Future Circular Collider Innovation Study.  
This H2020 Research and Innovation Action project  
receives funding from the European Union's H2020  
Framework Programme under grant agreement no. 950754.

- The CDR baseline
- Current activities
- Some innovation
- Outlook



# FCC WEEK 2021

28 June – 2 July

**ONLINE EVENT**  
Register Here:  
<https://indico.cern.ch/e/fccw2021>

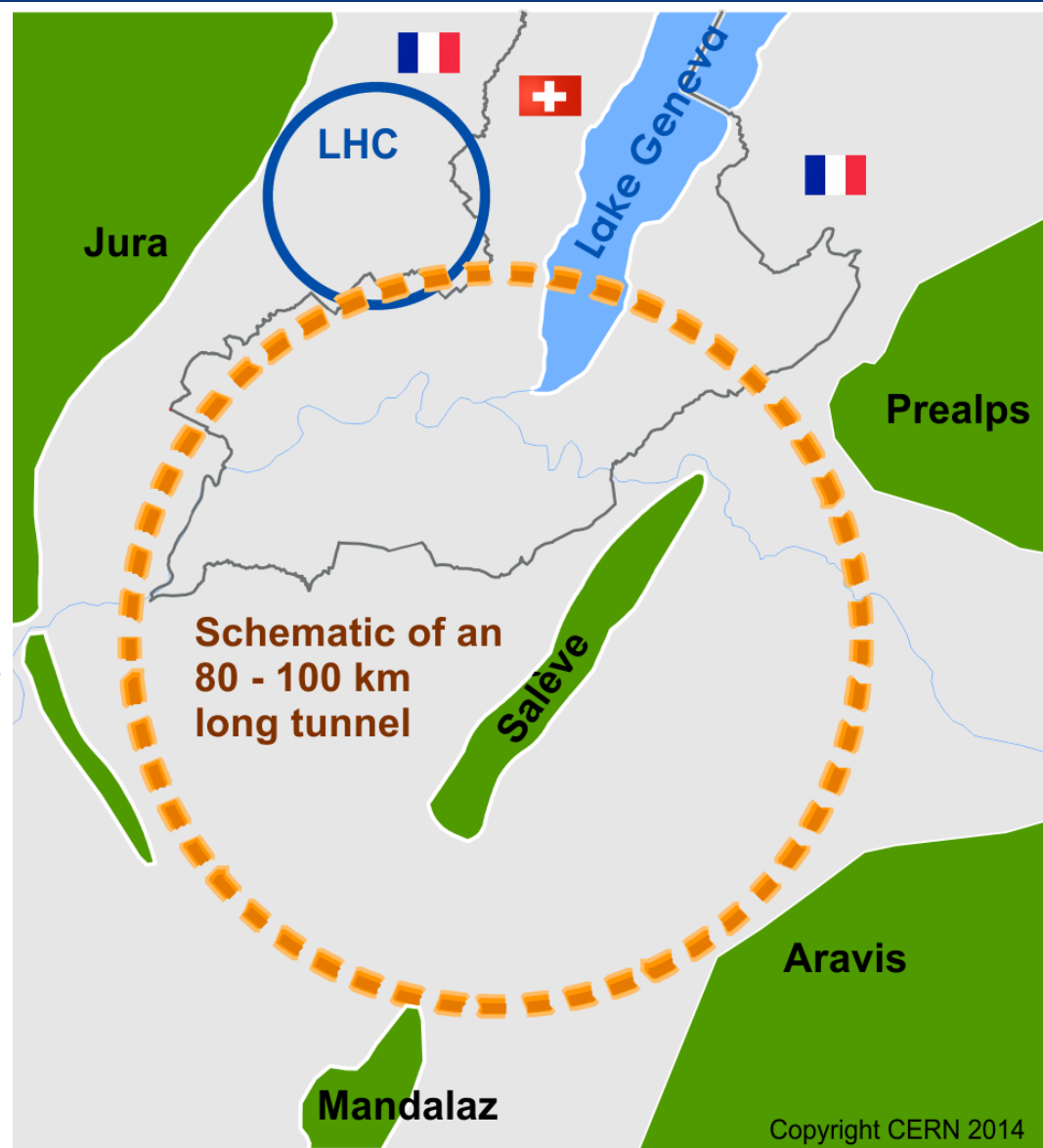


FCCIS - The Future Circular Collider Innovation Study  
This H2020 Research and Innovation Action project  
receives funding from the European Union's H2020  
Framework Programme under grant agreement no. 951754.

# Future Circular Collider Study launched in 2014

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

- **$pp$ -collider (*FCC-hh*)**  
→ defining infrastructure  
requirements
- $\sim 16\text{ T} \Rightarrow 100\text{ TeV } pp$  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-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](#)

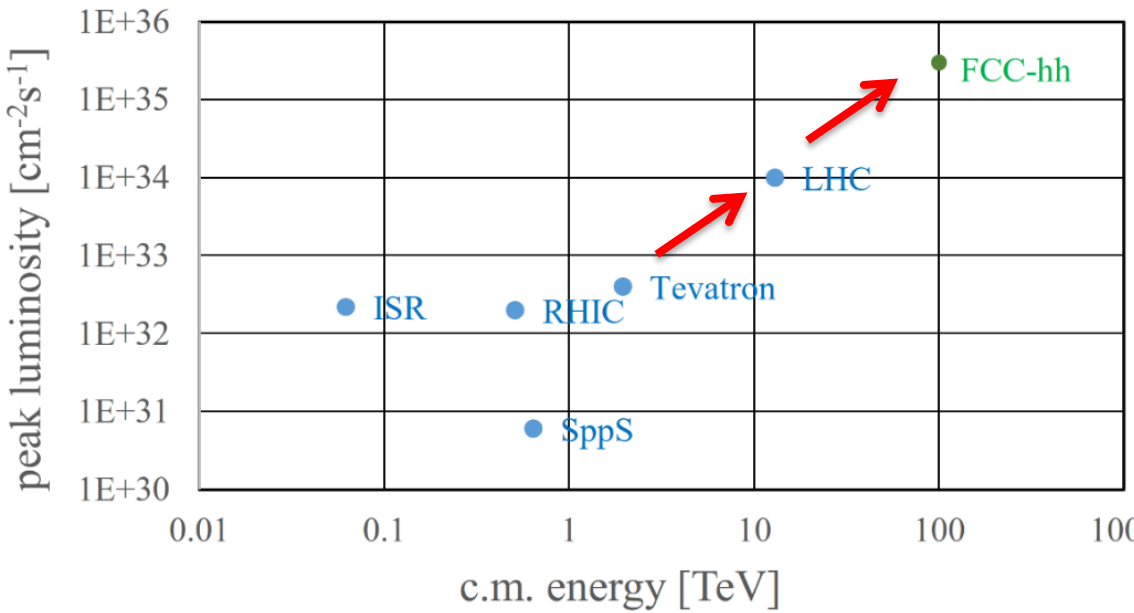
- **Summary documents provided to EPPSU SG**

- **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
- Accessible on <http://fcc-cdr.web.cern.ch/>

# FCC-hh (pp) collider parameters

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

# FCC-hh: performance



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

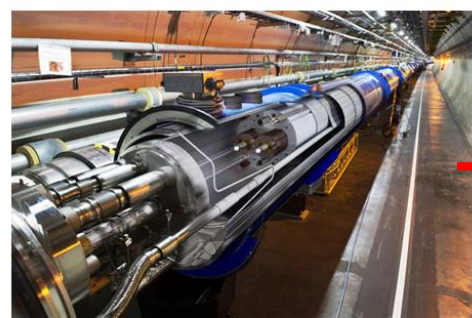
**100 TeV cm collision energy (vs 14 TeV for LHC)**

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

similar performance increase as from Tevatron to LHC

**key technology: high-field magnets**

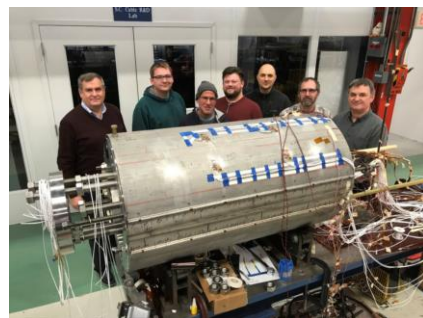
from LHC technology 8.3 T Nb-Ti



via HL-LHC technology



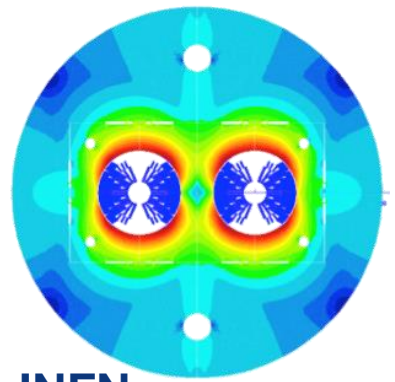
FNAL demonstrator 14.5 T  $\text{Nb}_3\text{Sn}$



# 16 T dipole design activities and options

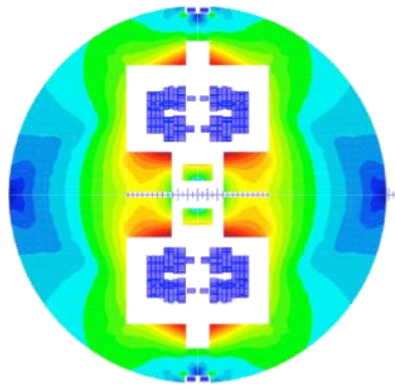


Cos-theta



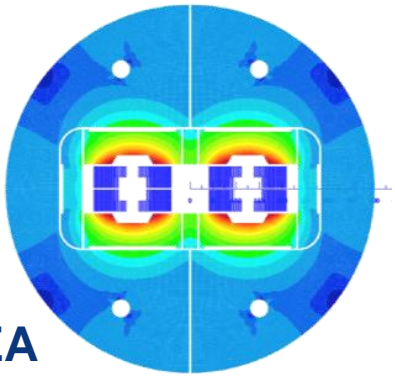
INFN

Common coils



CIEMAT

Blocks

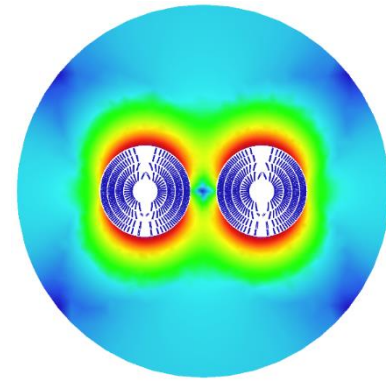


CEA

Swiss contribution

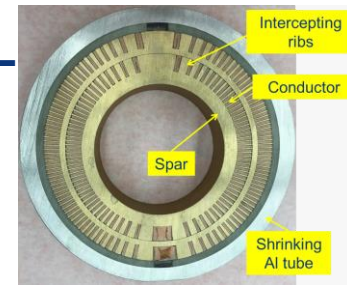


Canted Cos-theta

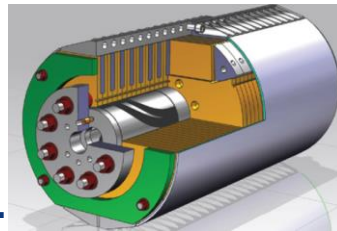


PSI

LBNL

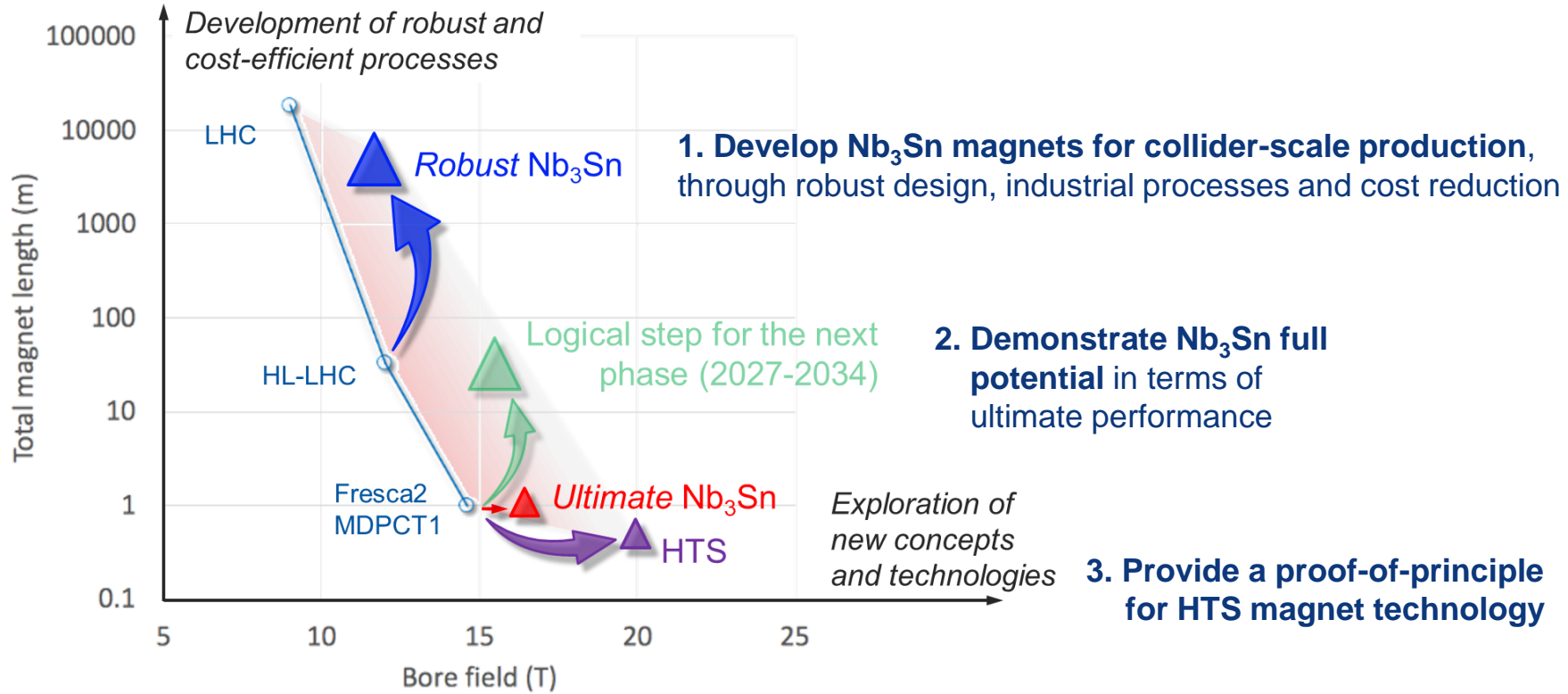


FNAL



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

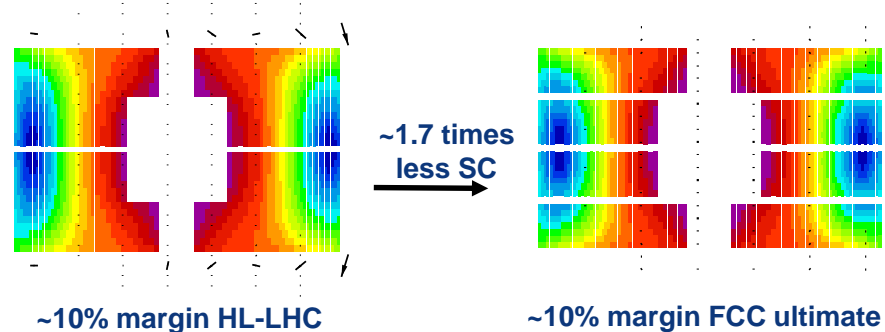
# High Field Magnet program goals until 2027



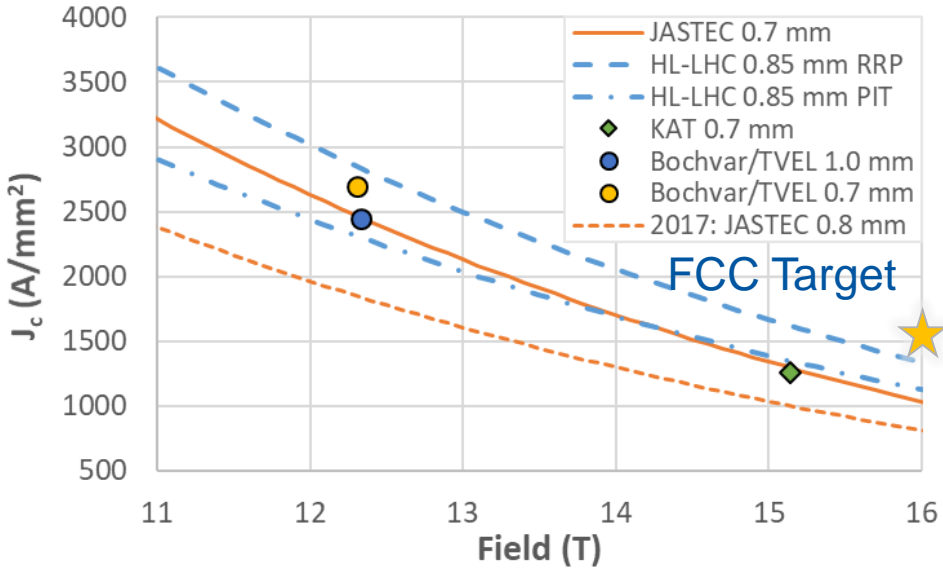
# Worldwide FCC Nb<sub>3</sub>Sn program

Main development goal is wire performance increase:

- $J_c$  (16T, 4.2K) > 1500 A/mm<sup>2</sup> → 50% increase wrt HL-LHC wire
- Reduction of coil & magnet cross-section



After 1-2 years development, **prototype Nb<sub>3</sub>Sn wires from several new industrial FCC partners already achieve HL-LHC J<sub>c</sub> performance**



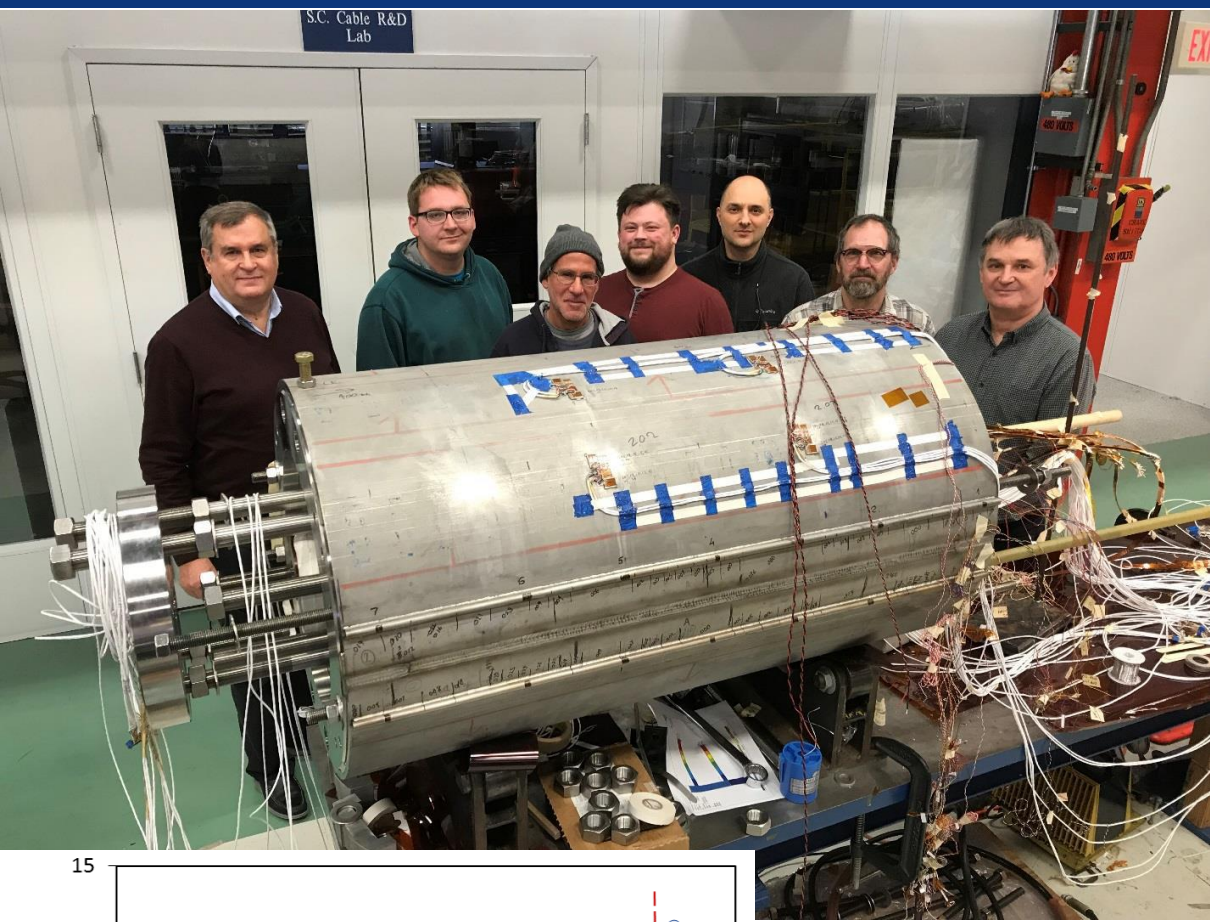
## FCC conductor development collaboration:

- 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**

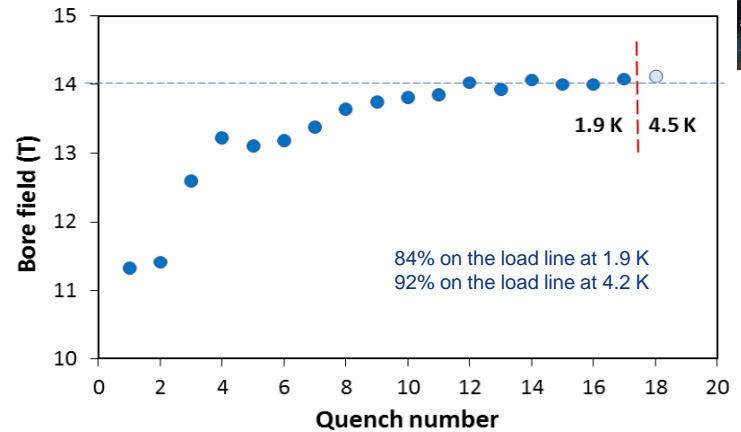
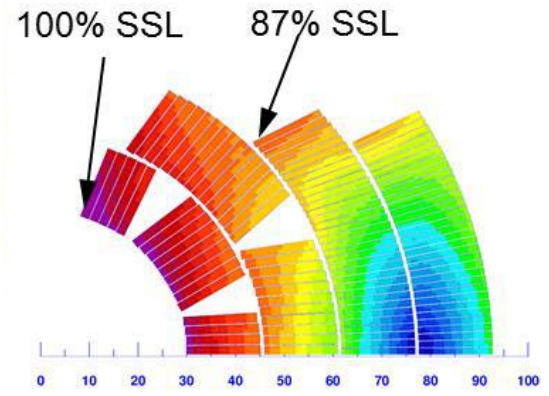
## 2019/20 results from US, meeting FCC J<sub>c</sub> specs:

- Florida State University: high-J<sub>c</sub> Nb<sub>3</sub>Sn via Hf addition
- Hyper Tech /Ohio SU/FNAL: high-J<sub>c</sub> Nb<sub>3</sub>Sn via artificial pinning centres based on Zr oxide.

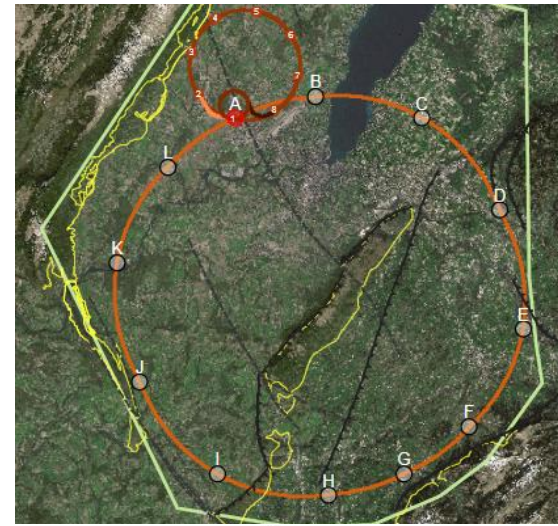
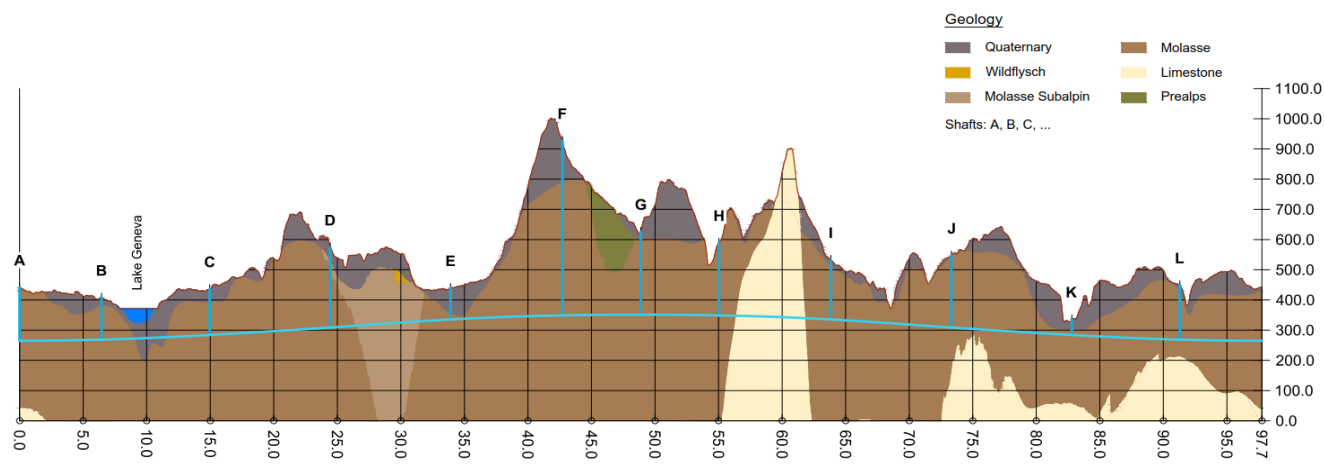
# US – MDP: 14.5 T magnet tested at FNAL



60-mm aperture  
4-layer graded coil

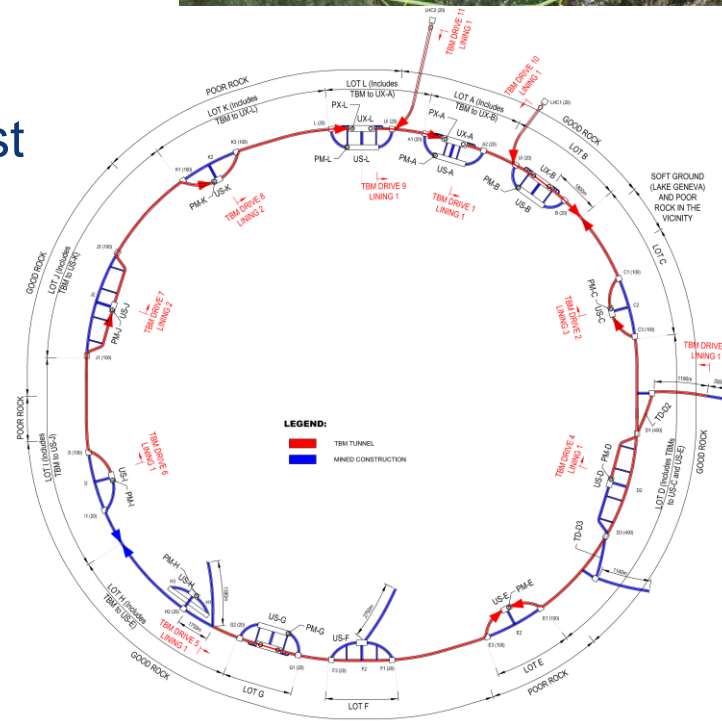


- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T



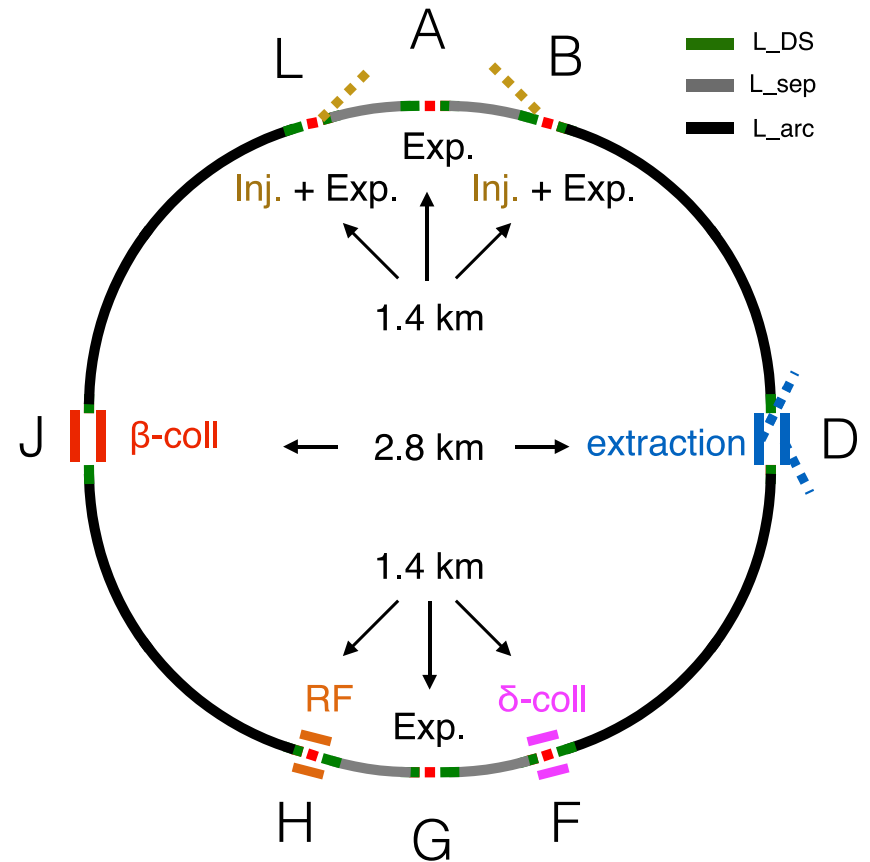
## Current baseline position based on:

- 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**



# FCC-hh layout

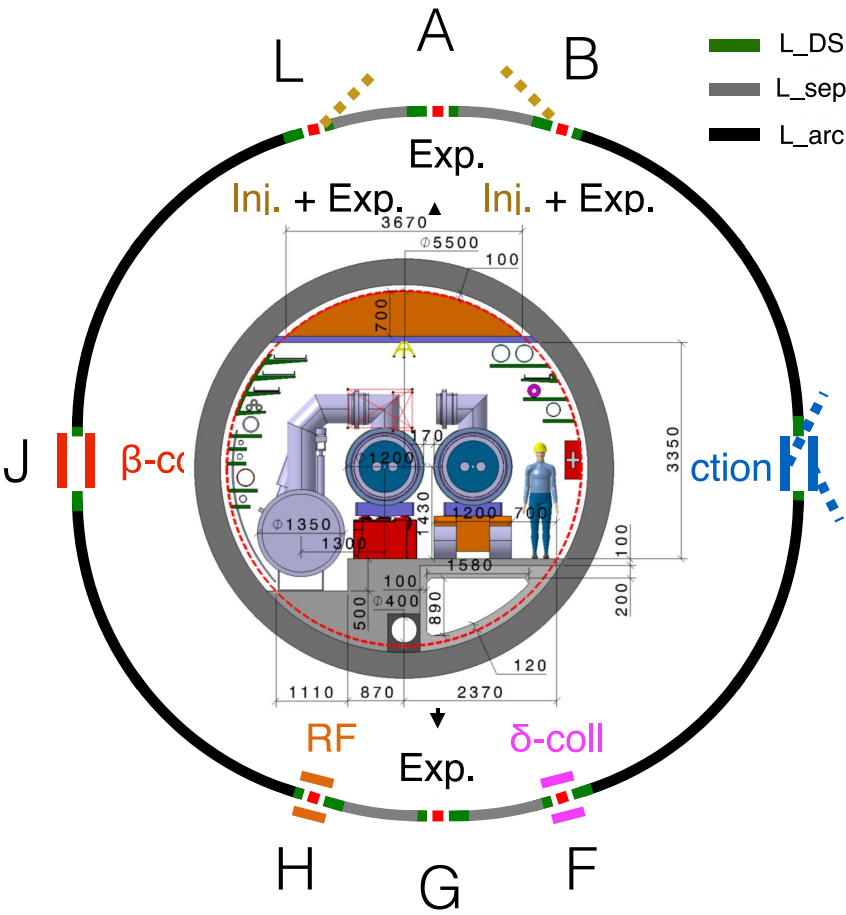
- Two high-luminosity experiments (A & G)
- Two other experiments combined with injection (L & B)
- Two collimation insertions
  - betatron cleaning (J)
  - momentum cleaning (F)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Compatible with LHC or SPS as injector



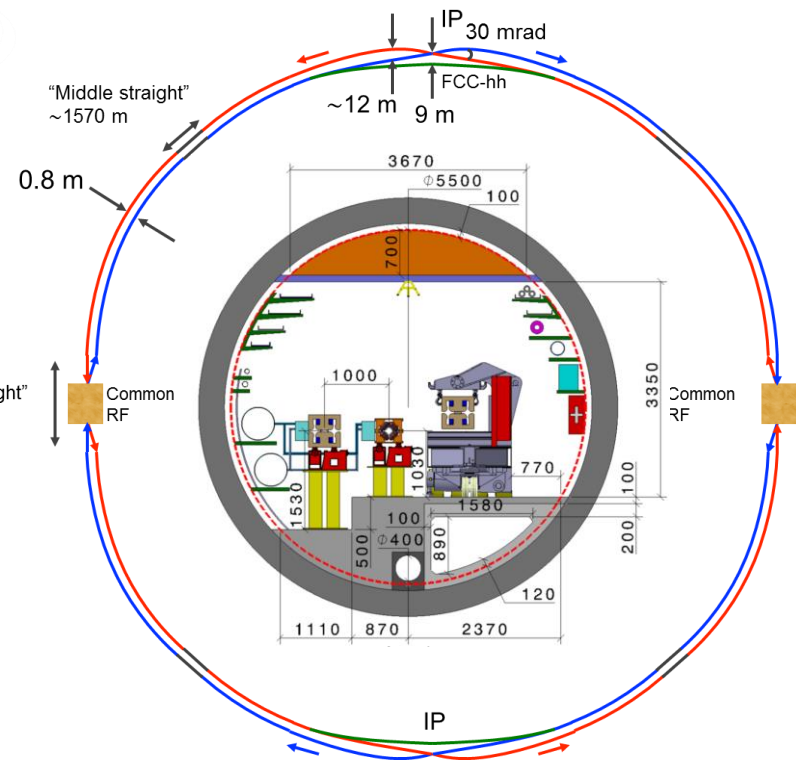
**circumference: 97.75 km**

# FCC consistent machine layouts

## FCC-hh

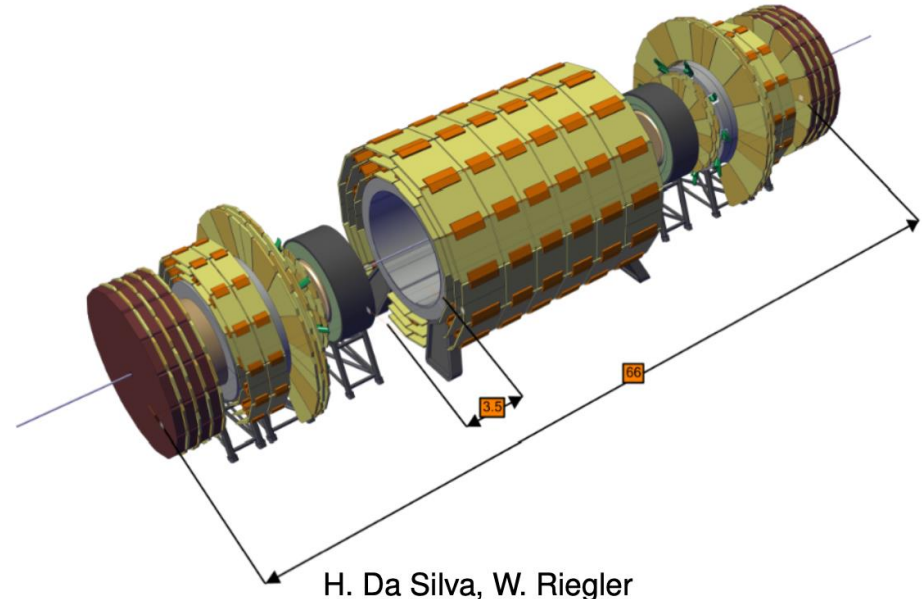
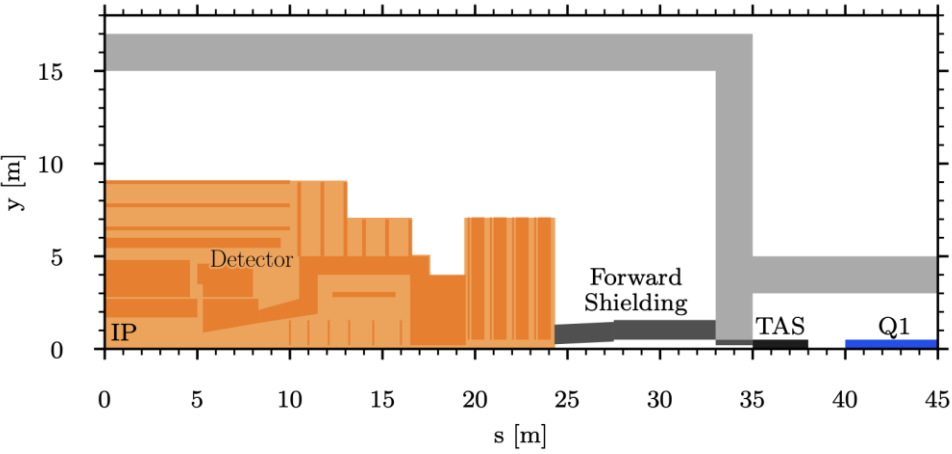


## FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

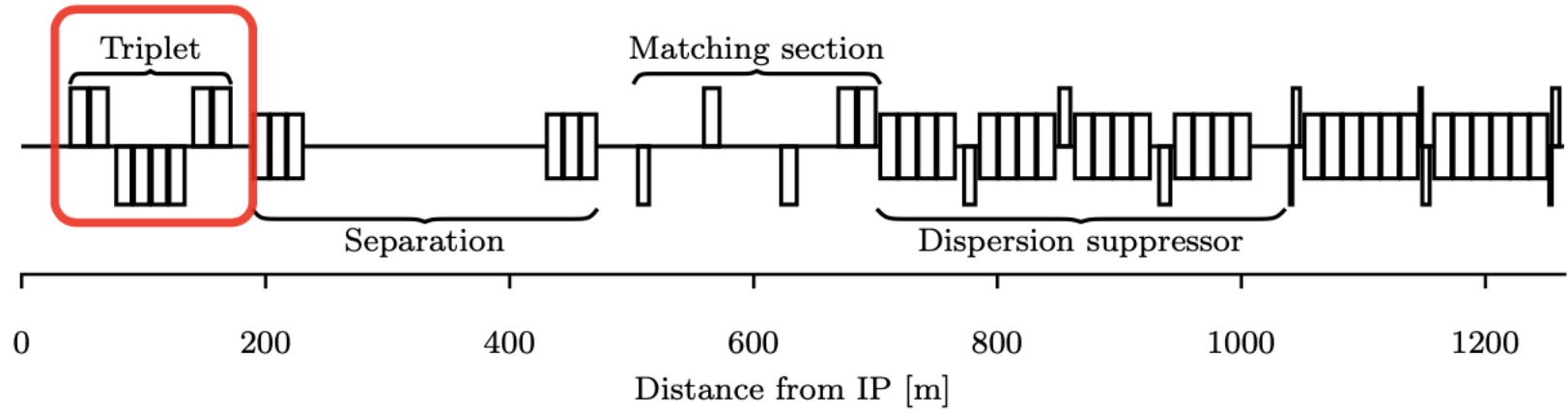


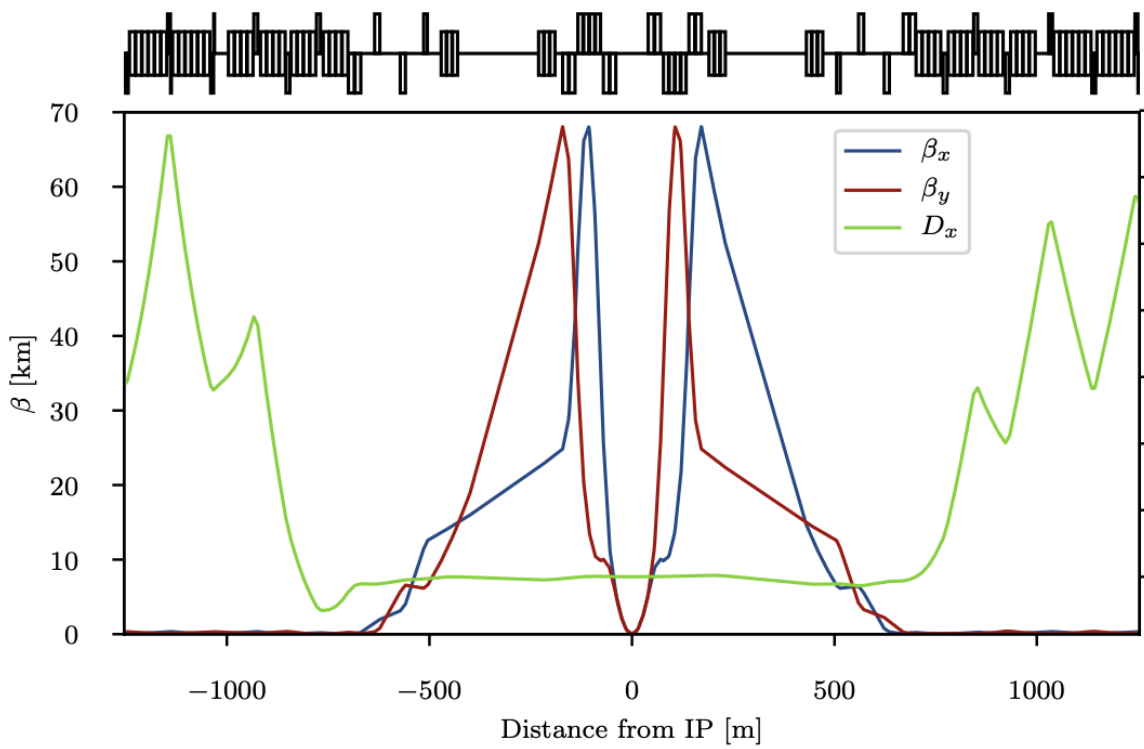
Optics solutions for full ring for both machines available

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



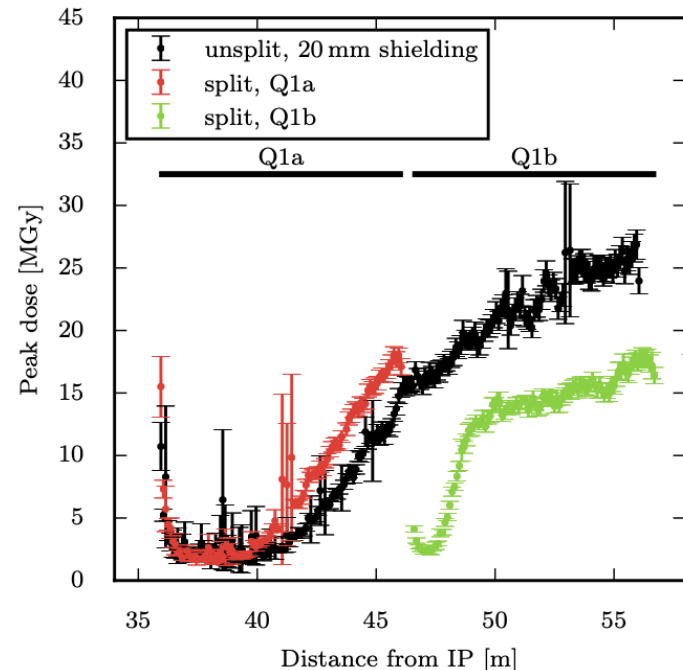
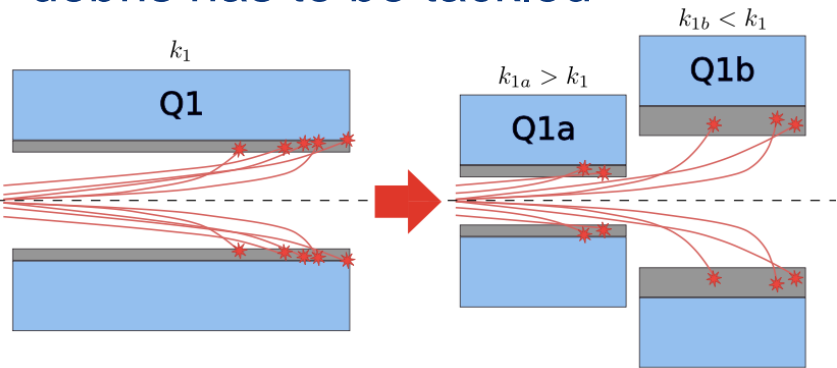
- Insertion layout





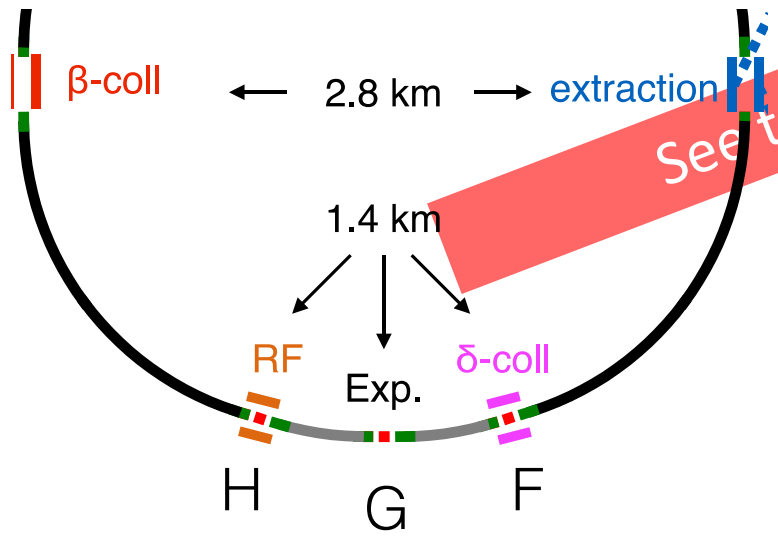
High-luminosity optics for  $\beta^*=30$  cm  
70 km beta peak!

Energy deposition in the Q1 due to luminosity debris has to be tackled



# Collimation system

- Roles of collimation system: clean unavoidable regular losses, passive machine protection, optimize background and radiation dose
- At the same time, keep the impedance within limits
- Collimation system is hosted in two insertions: one for betatron- and one for momentum-collimation



See talk by R. Bruce!!

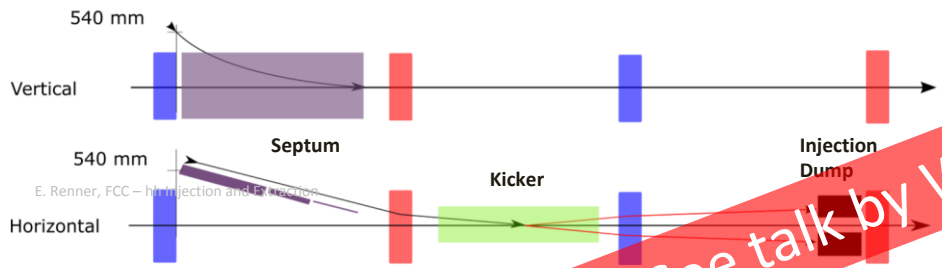
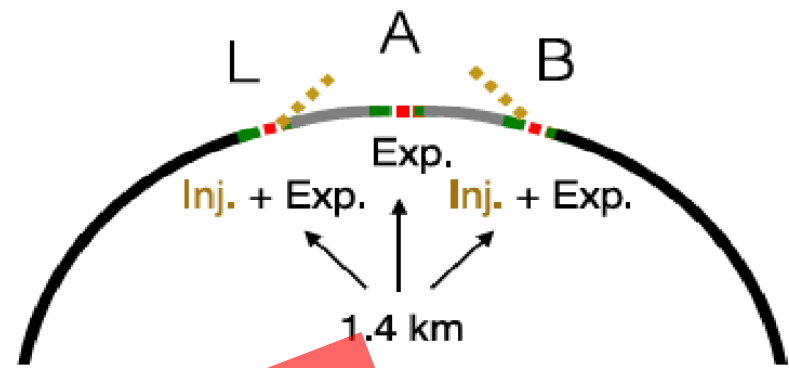
8.3 GJ = kinetic energy of an empty Airbus A380 cruising at 880 km/h



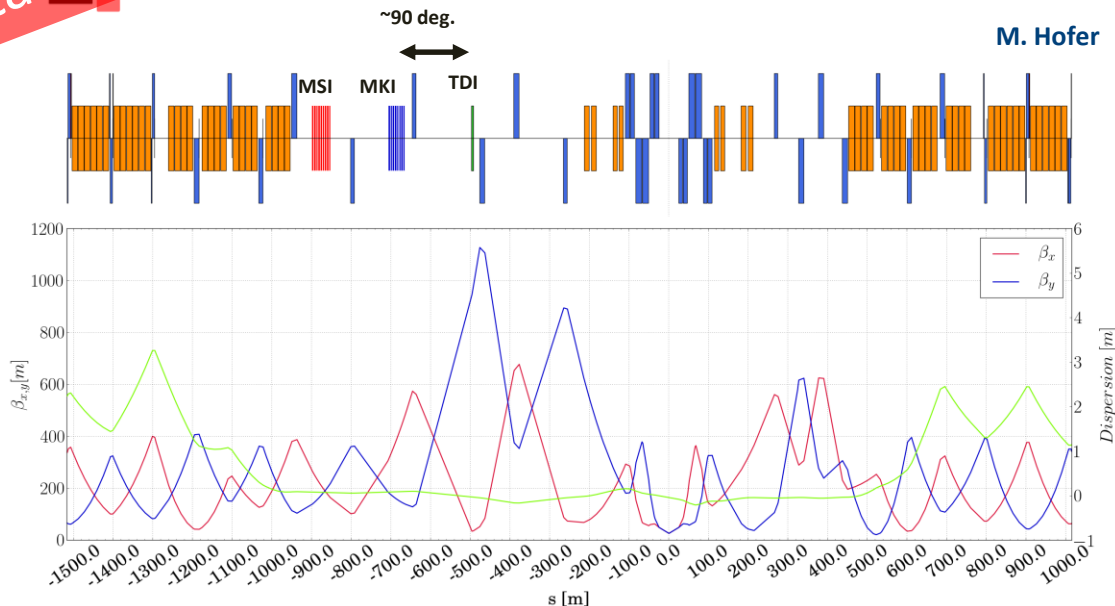
# Injection system

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



See talk by W. Bartmann!!!

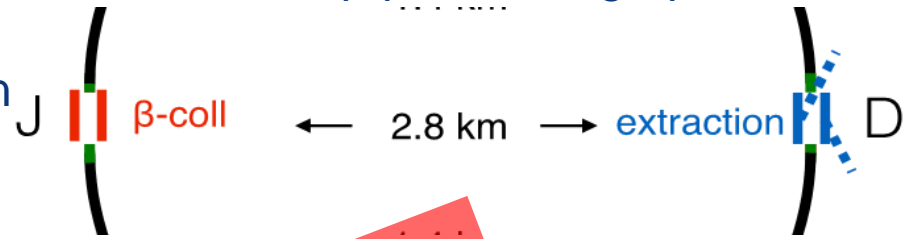


M. Hofer

	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

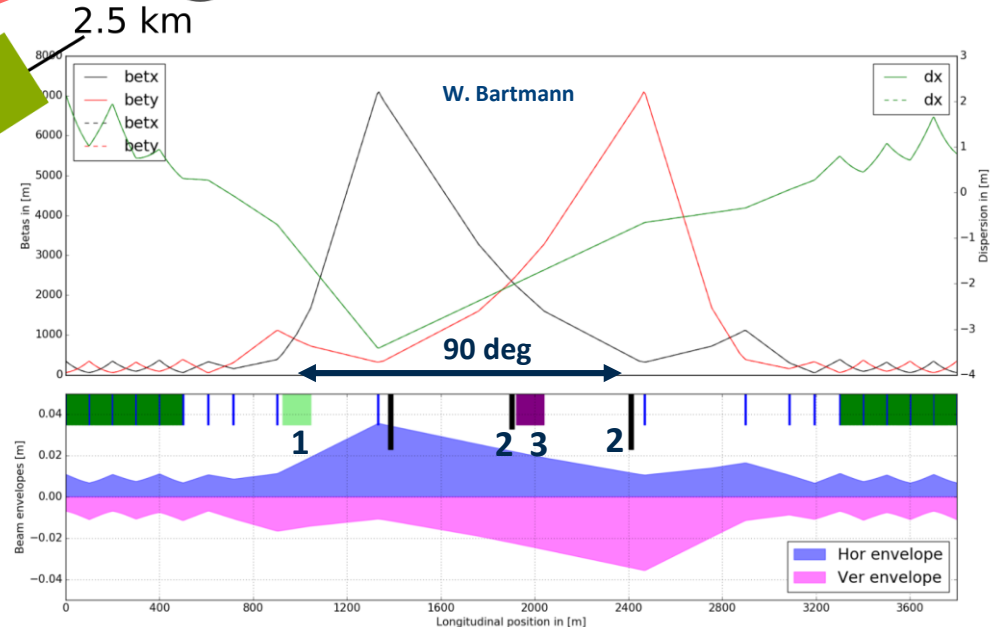
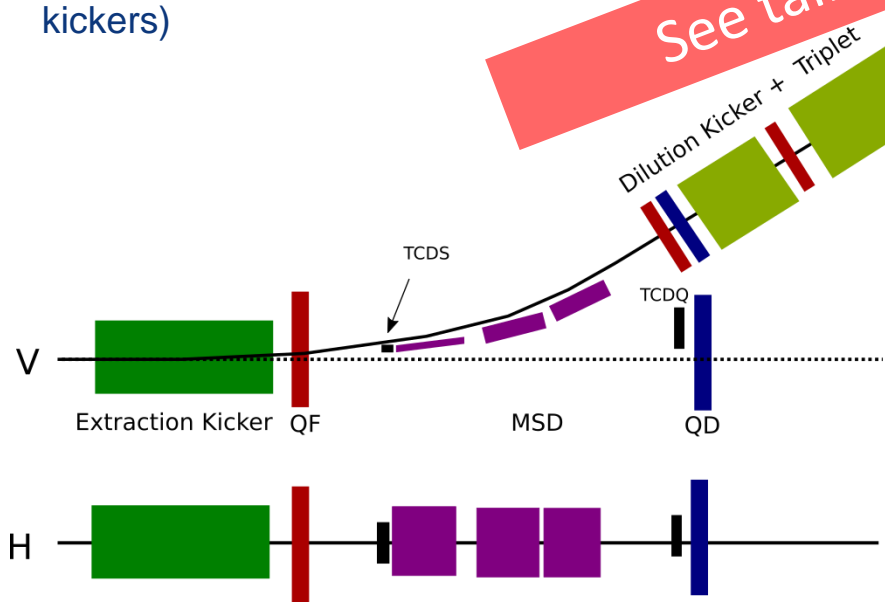
# Extraction system

- 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  $\sim 70$ m
- Septa Layout requires single plane extraction (vertical)
- Reduced kicker segmentation, still highly segmented (150 kickers)

See talk by W. Bartmann!!!



- The CDR baseline
- Current activities
- Some innovation
- Outlook



# FCC WEEK 2021

28 June – 2 July

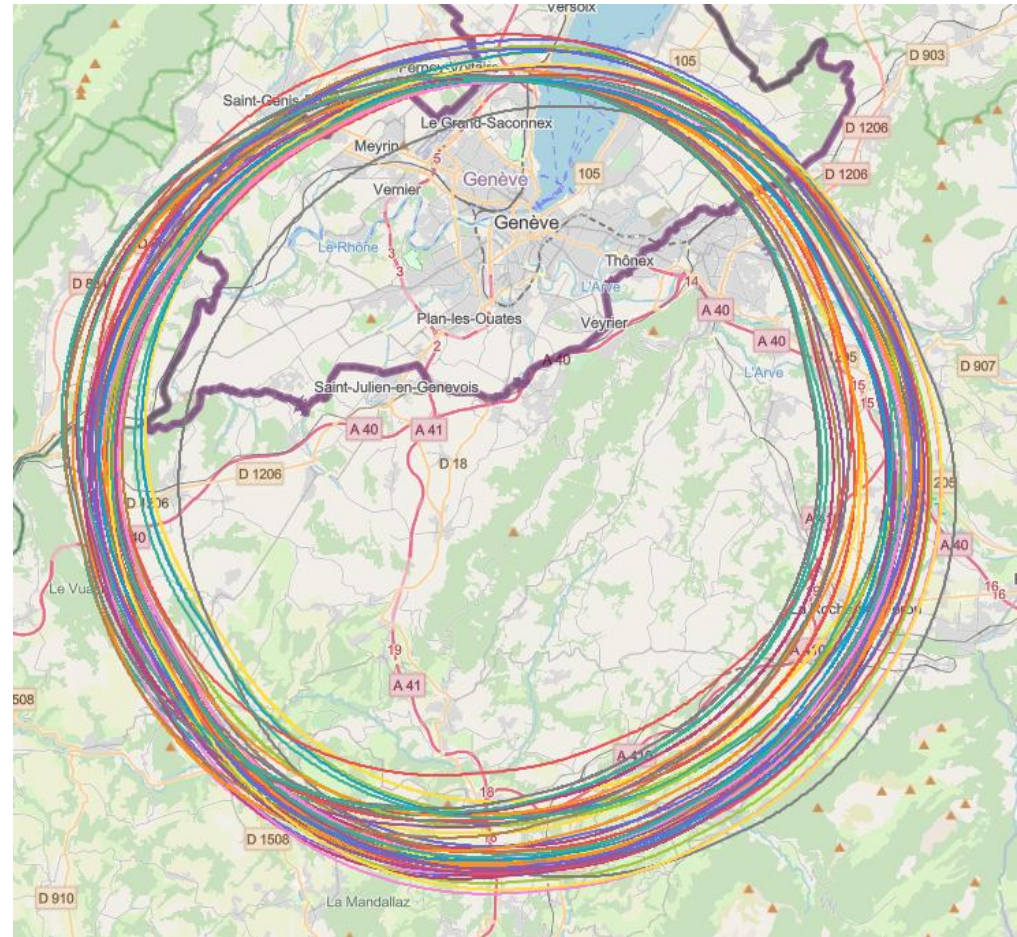
ONLINE EVENT  
Register Here:  
<https://indico.cern.ch/e/fccw2021>



FCCIS - The Future Circular Collider Innovation Study  
This H2020 Research and Innovation Action project  
receives funding from the European Union's H2020  
Framework Programme under grant agreement no. 951754.

# Collider placement optimisation

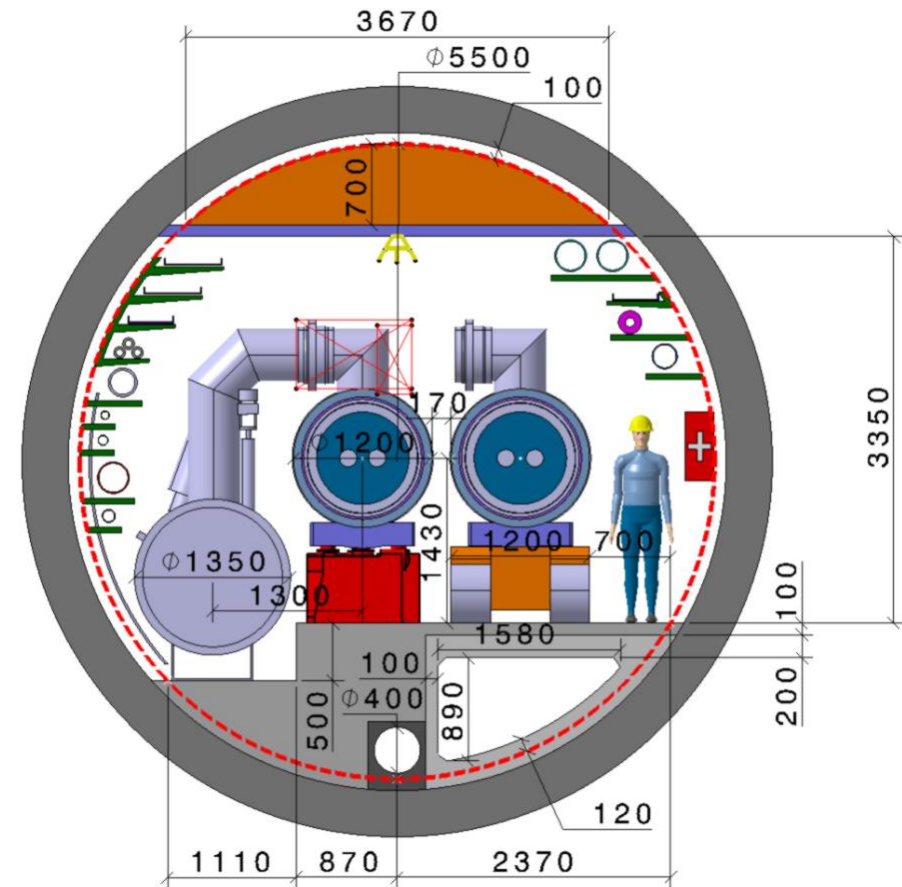
- Overall layout and placement optimisation process across both host states
- Following the "avoid-reduce-compensate" directive of European and French regulatory frameworks
- Process integrates diverse requirements and constraints:
  - performance permitting world-leading scientific research
  - technical 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

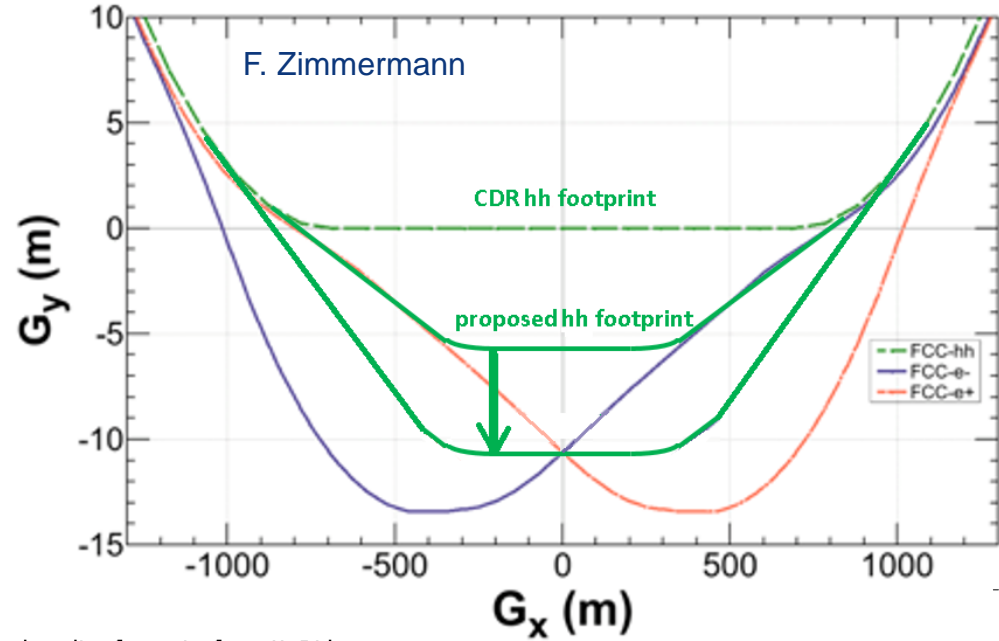
# Collider placement optimization and FCC-ee symmetry

- The search for optimal placement implies analysis of different layouts and geometries:
  - Different length of the insertions
  - Change in arcs (number of cells and cell length).
- For a limited number of promising candidates optics should be computed to ensure feasibility.
- Compatibility with FCC-ee layout should be ensured: four IPs has implications on FCC-hh layout and geometry.
  - Review functionalities of insertions
  - Review transfer lines (geometry, injection point).
  - Look for the possibility of integrating part of the transfer lines in the ring tunnel.



In case transfer lines should be installed in the main ring tunnel changes should be studied, e.g. new geometry of the cryogenic jumpers or increased tunnel cross section.

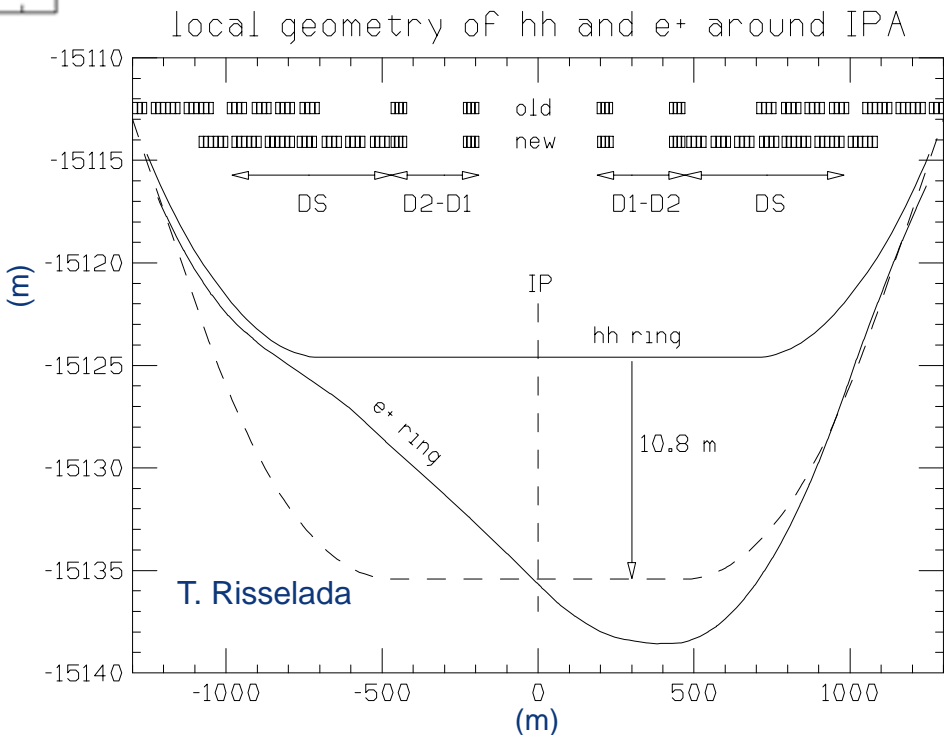
# Layout optimisation of high-luminosity insertions



baseline footprint from K. Oide

- Implementation of an improved layout with FCC-ee and FCC-hh IPs with same transverse positions
- Advantages
  - Size of detector cavern reduced
  - Possibility to re-use FCC-ee detector for FCC-hh
  - Tunnel width reduced over 2 x 500 m

- CDR
  - FCC-hh footprint compatible with FCC-ee injector



- The CDR baseline
- Current activities
- Some innovation
- Outlook



# FCC WEEK 2021

28 June – 2 July

ONLINE EVENT  
Register Here:  
<https://indico.cern.ch/e/fccw2021>

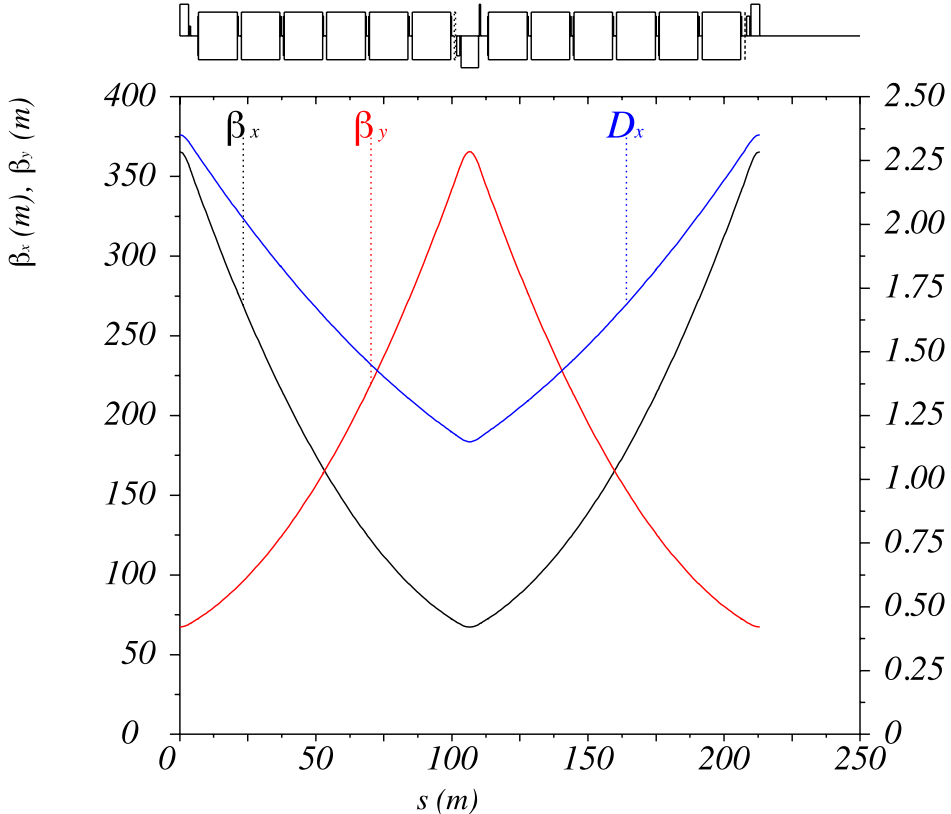


FCCIS - The Future Circular Collider Innovation Study  
This H2020 Research and Innovation Action project  
receives funding from the European Union's H2020  
Framework Programme under grant agreement no. 951754.

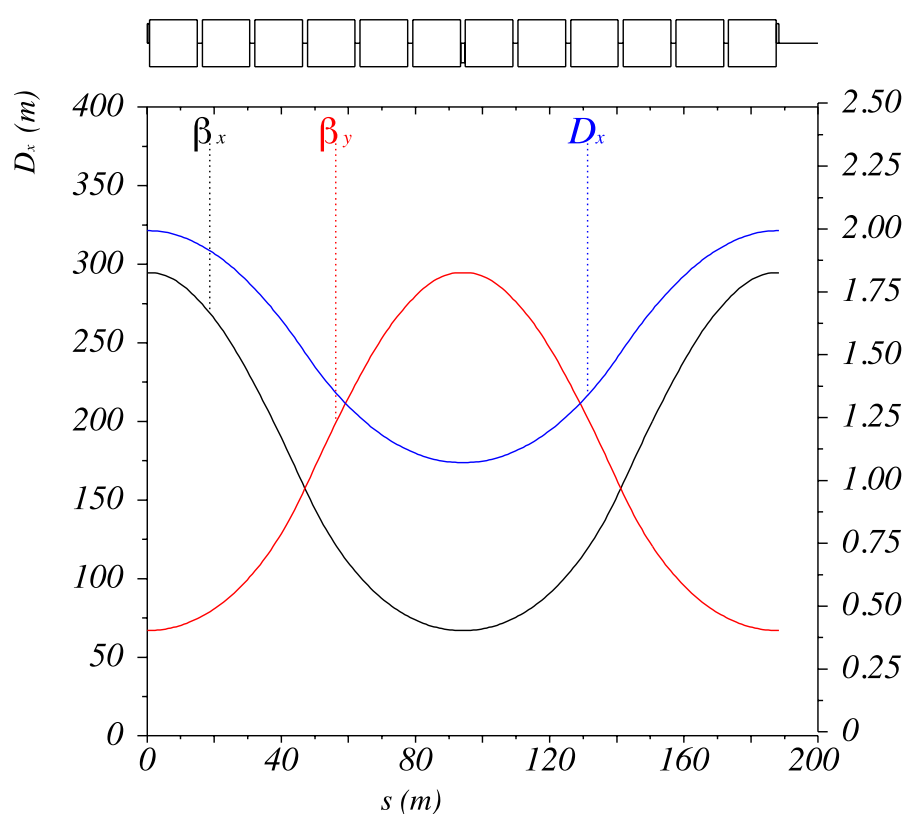
# A combined-function optics for FCC-hh?

- The use of combined-function (dipole-quadrupole) might be an interesting option for FCC-hh.
- Possible advantages
  - Increase filling factor
  - Simplify production (a single magnet type for the arcs)

Nominal FCC-hh FODO cell



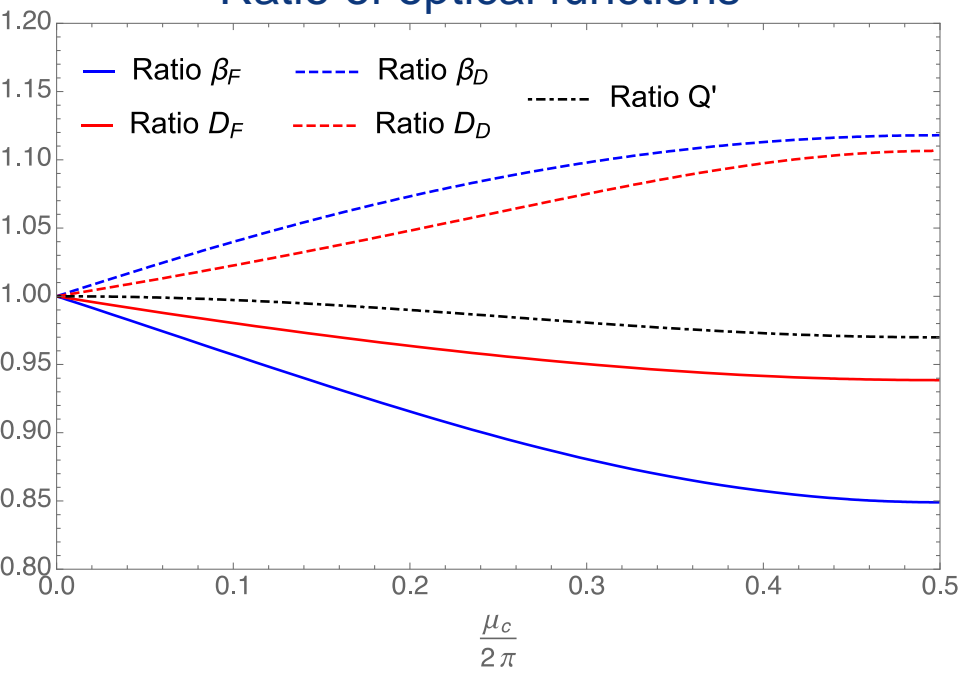
FCC-hh combined-function cell



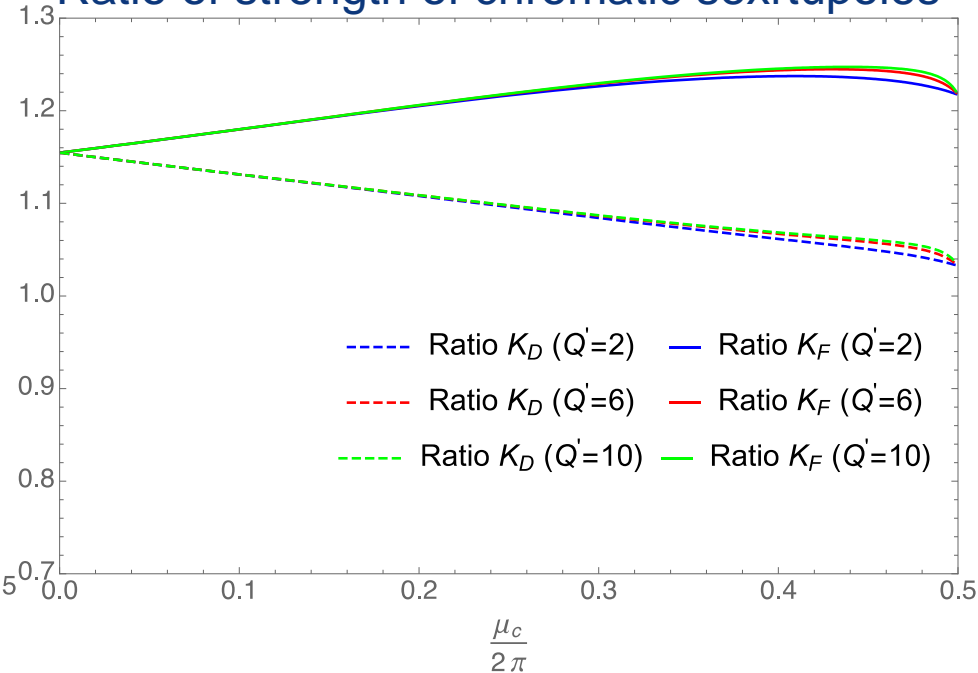
# A combined-function optics for FCC-hh?

- Some advantage of the combined-function cell with respect to the FODO one in terms of optical parameters.
- Marginal increase in the strength of the chromatic sextupoles.
- No issue for designing superconducting combined-function magnets (already in use in JPARC transfer lines, and will be used in D2 separation dipoles in HL-LHC).
- Next steps
  - Study dispersion suppressor
  - Study correctors systems for combined-function cell in view of modularity

Ratio of optical functions



Ratio of strength of chromatic sextupoles



- The CDR baseline
- Current activities
- Some innovation
- Outlook



# FCC WEEK 2021

28 June – 2 July

ONLINE EVENT  
Register Here:  
<https://indico.cern.ch/e/fccw2021>



FCCIS - The Future Circular Collider Innovation Study  
This H2020 Research and Innovation Action project  
receives funding from the European Union's H2020  
Framework Programme under grant agreement no. 951754.

- A sound baseline for FCC-hh ring exists (heavily driven by LHC design).
- We are from the time of any concrete decision. Therefore:
  - Consolidate, e.g.
    - Keep the ring layout synchronous with the developments of the FCC-ee ring
  - Optimise, e.g.
    - Overall layout of collimation and extraction insertions
    - Overall optimisation of dispersion suppressor layout
  - Innovate, e.g.
    - **Numerical simulation tools to include synchrotron radiation effect (tracking with nonlinear magnetic imperfections and synchrotron radiation). Strong synergy with FCC-ee activities!**
    - High-field magnets technology
    - Advanced beam screens (**HTS coatings, see next talks**)
    - Novel materials for collimator's jaw
    - Halo manipulation (crystal collimation, Hollow Electron Lens)
    - Nonlinear beam manipulations
    - **Novel optics concepts**
    - ...

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

**Thank you for your attention!**