Status of the FCC-hh Design Study

D. Schulte, CERN

For the FCC-hh collaboration

FCC Goal

FCC study develops a conceptual design of a new facility

FCC-hh defines infrastructure

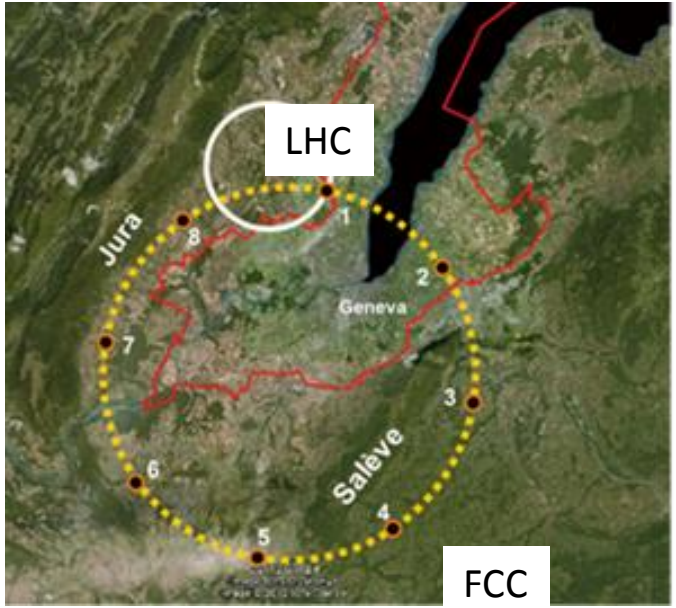
- 100 TeV proton-proton collisions, 20 ab^{-1}
- 7x LHC energy and 7x HL-LHC integrated luminosity
- Use existing infrastructure to generate beam
- New ~100km-long collider ring

Potential first stage **FCC-ee** offers electron-positron collisions from 90 GeV to 365 GeV

- Unprecedented electron-positron collision energies >208 GeV
- Much higher event rates at previously reached energies ($O(10^5)$ times as many Z as at LEP/LEP2)

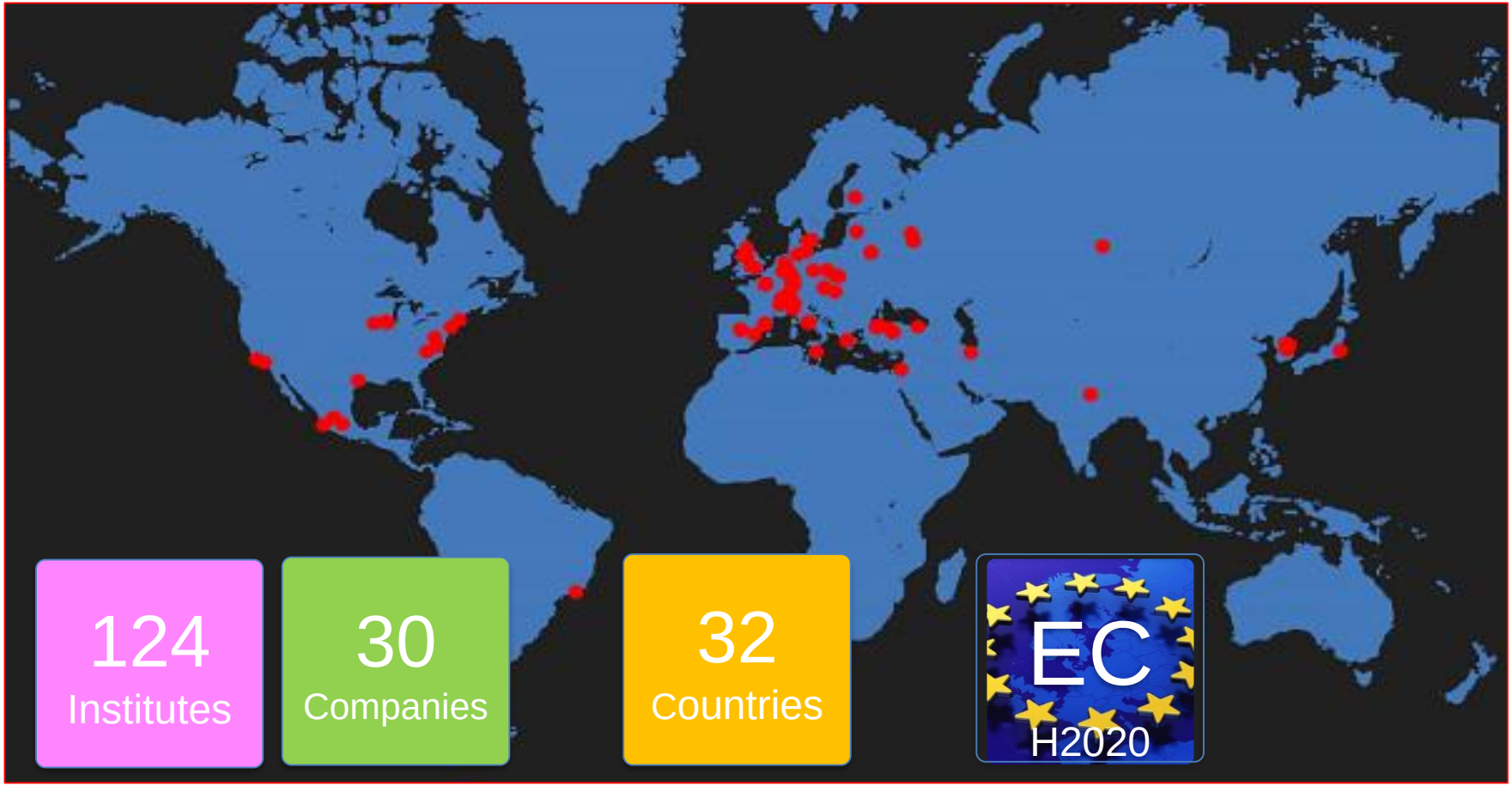
FCC-eh Proton-electron option is also possible

HE-LHC Proton-proton option in LHC tunnel with FCC-hh technology



Consistent with implementation at CERN

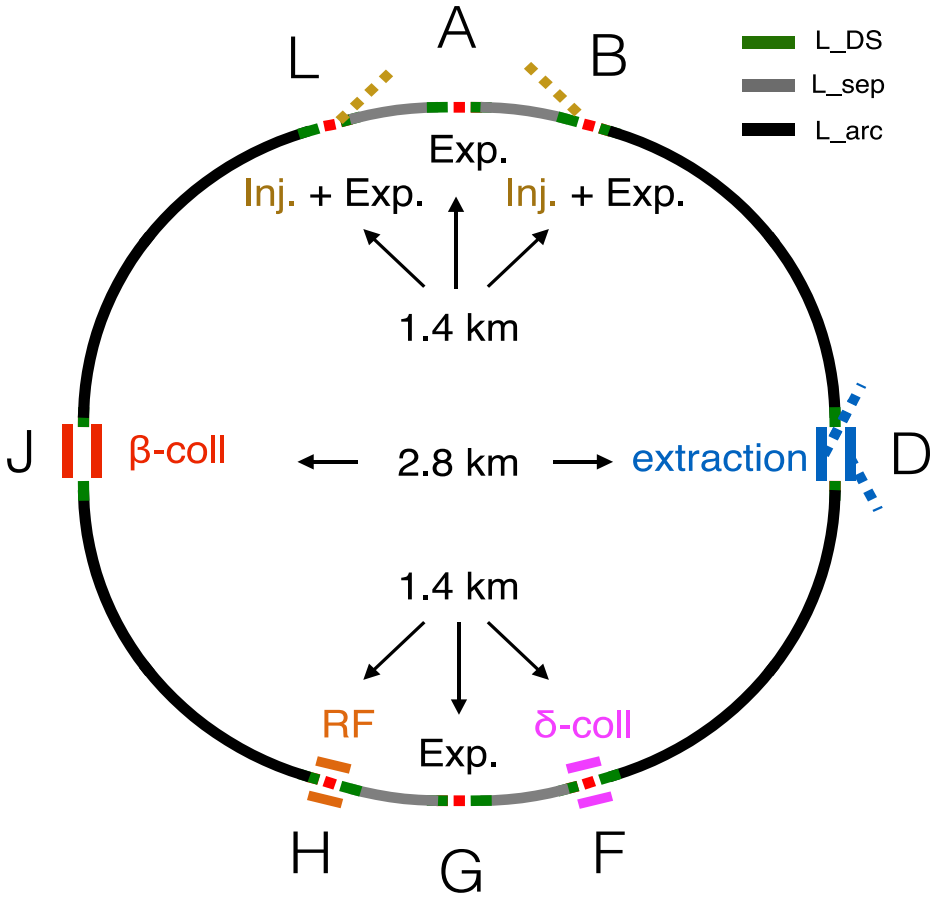
FCC Collaboration



FCC-hh Layout

Layout for CERN site

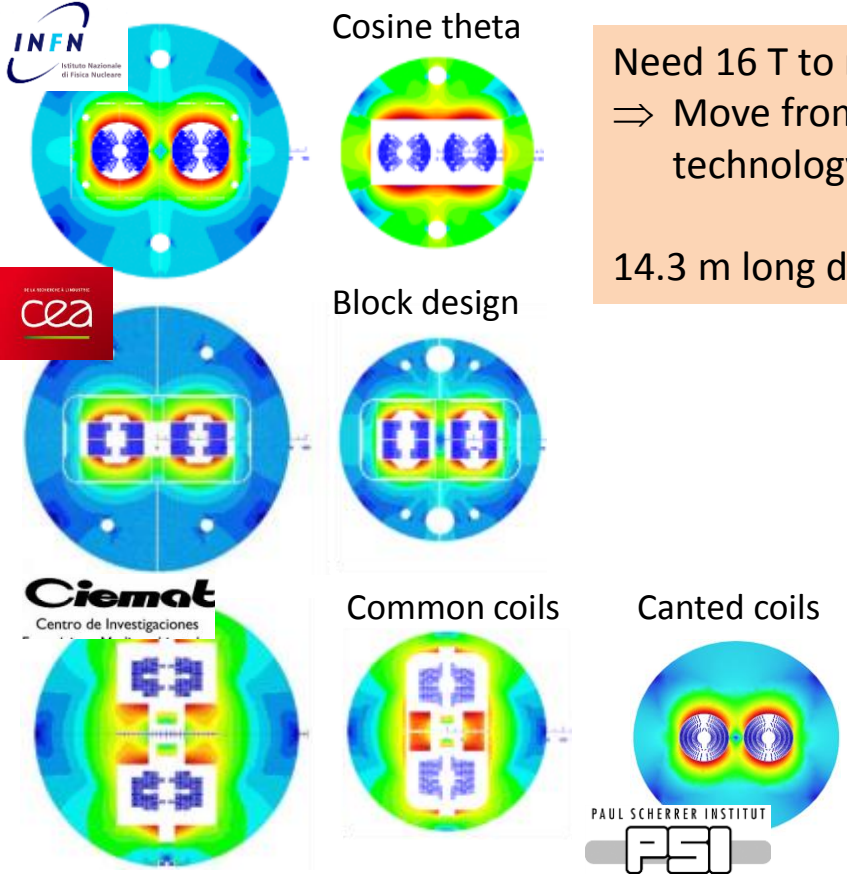
- Two high-luminosity experiments (A and G)
- Two other experiments combined with injection at 3.3 TeV (L and B)
- Two collimation insertions
  - Betatron cleaning (J)
  - Momentum cleaning (E)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Circumference 97.75km
- Can be integrated into the area
- Can use LHC or SPS as injector



Hadron Collider Parameters

	LHC / HL-LHC	HE-LHC (tentative)	FCC-hh Initial	FCC-hh Ultimate
Cms energy [TeV]	14	27	100	100
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1 / 5	16	5	20-30
Machine circumference	26.7	26.7	97.75	97.75
Arc dipole field [T]	8	16	16	16
Bunch charge	1.15 / 2.2	2.2	1	1
Bunch distance [ns]	25	25	25	25
Background events/bx	27 / 135	440	170	<1020
Bunch length [cm]	7.5	7.5	8	8

Magnet Development



Need 16 T to reach 50 TeV /beam
⇒ Move from NbTi (LHC technology) to Nb_3Sn

14.3 m long dipoles

Magnet is key cost driver
- Improve cable performance
- Reduce cable cost
- Improve fabrication of magnet
- Minimise amount of cables
- Push lattice filling factor

Safety margin from 18% to 14%
Reduced inter-beam distance from 250 to 204 mm
Stray field up to 0.1 T
⇒ Total conductor (incl. copper) from O(10 kt) to 7.6 kt

Iterations with lattice designers for field quality

Short models in 2018 – 2023
Prototypes 2026 -- 2032

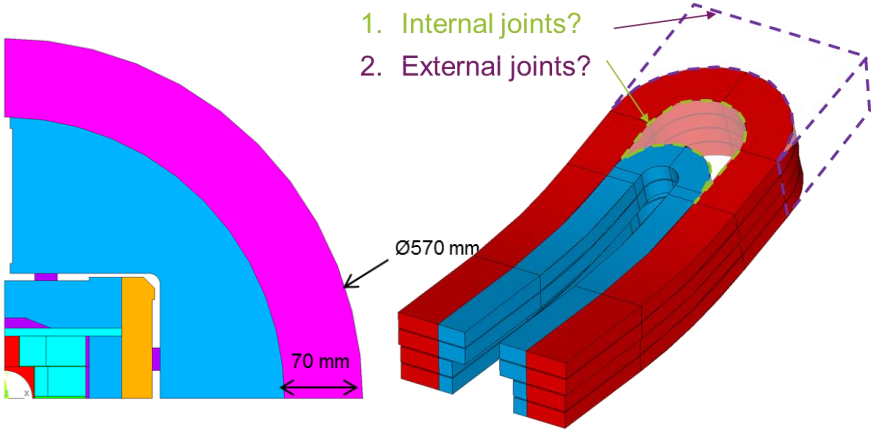
Magnet Models

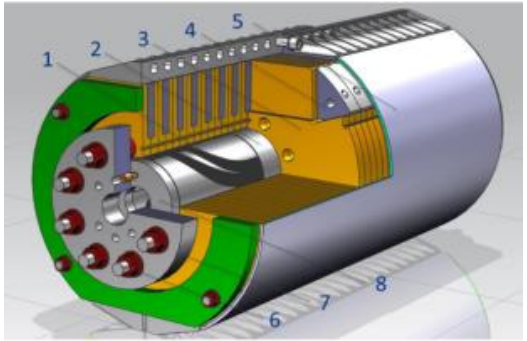
With today's state of the art conductors:

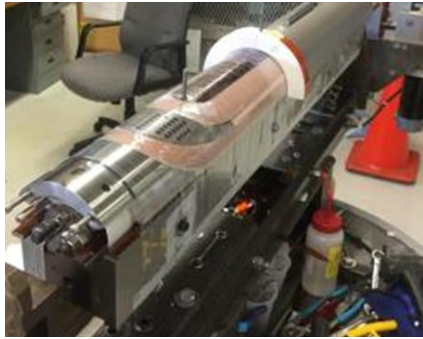
- 15 T achievable at 14 % margin
- 17 T at short sample

- Cos-theta and common-coil model magnet programs are under preparation

15 T dipole demonstrator
60-mm aperture
4-layer graded coil







Conductor

New activity with many collaborators started in 2017 with ambitious targets

FCC Conductor Development Workshop at CERN, 5-6 March 2018

Participants

Switzerland: CERN

Japan: KEK, Furukawa Electric, Jastec

Russia: Bochvar Institute of Inorganic Materials JSC VNIINM, TVEL

Korea: Kiswire

China: Western Superconducting Technologies Co., Ltd.

Austria: TU Wien

Germany: Technische Universität Bergakademie Freiberg

Italy: Columbus Superconductors

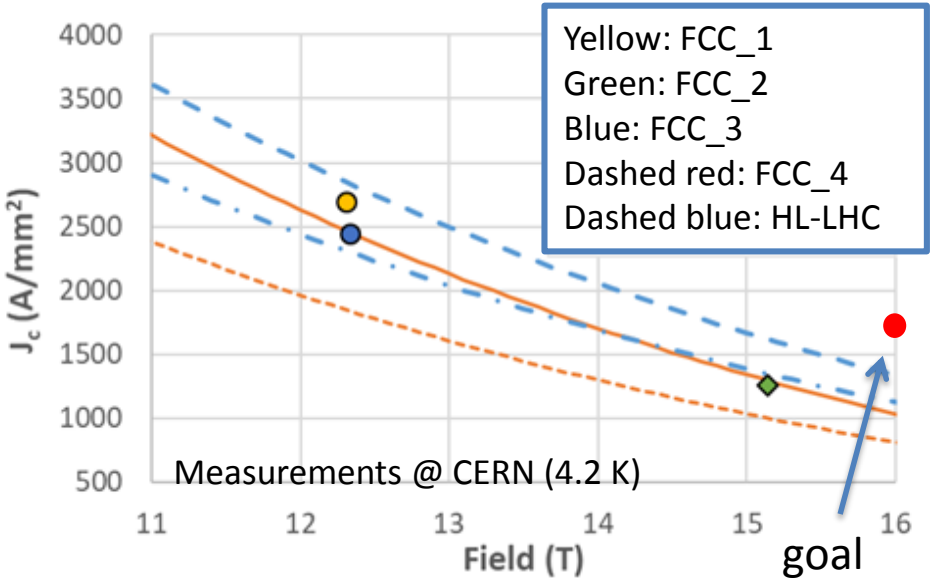
Finland/USA: Luvata Special Products

Italy: SPIN

Switzerland: Université de Genève

7 companies, two universities and two national research institutes

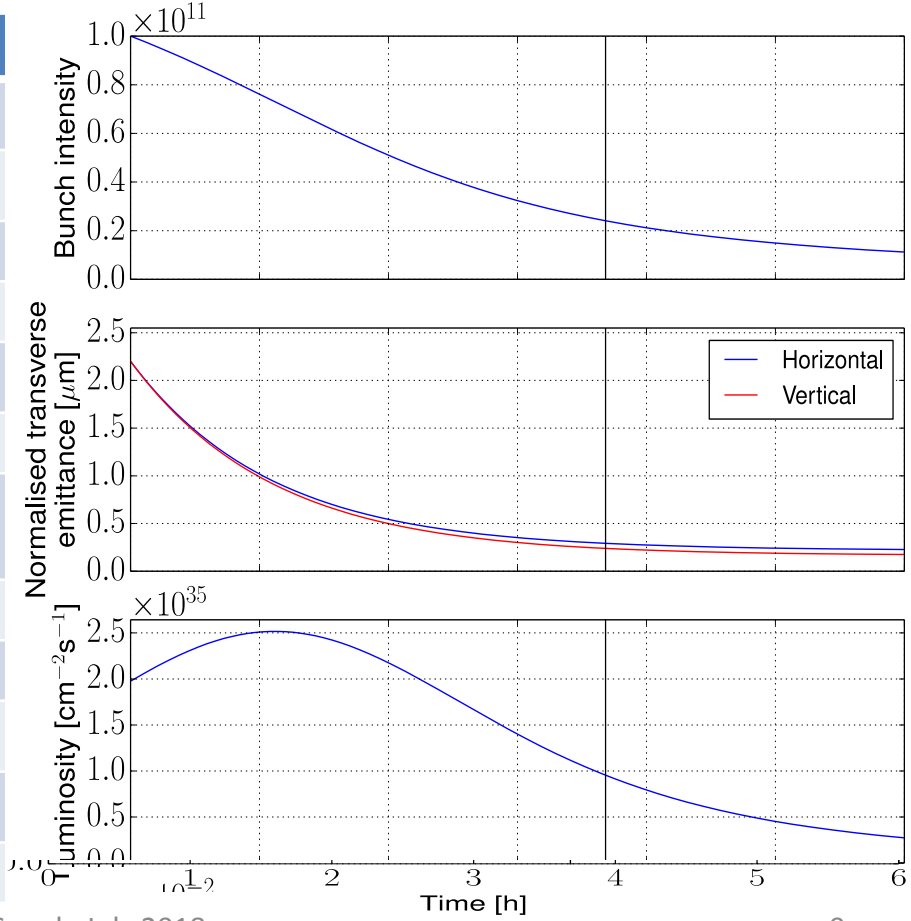
Wire diameter	mm	~ 1
Non-Cu Jc (16 T, 4.2 K)*	A/mm²	≥ 1500
Unit length	km	≥ 5
Cost	€/kA m**	≤ 5



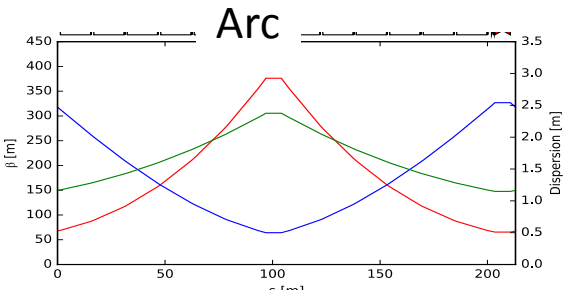
First wires almost reached HL-LHC requirements

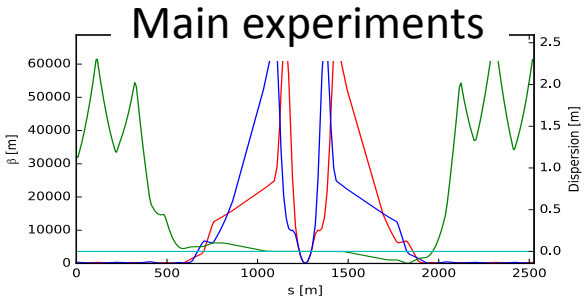
Beam Parameters

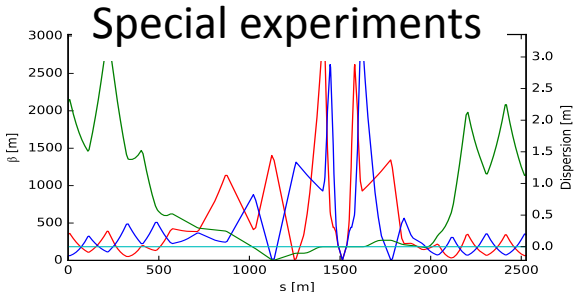
	Initial	Ultimate
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20-30
Background events/bx	170	<1020
Bunch distance Δt [ns]	25	
Bunch charge N [10^{11}]	1	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8	3.5
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4

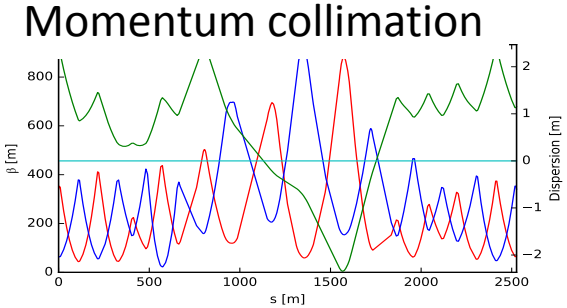


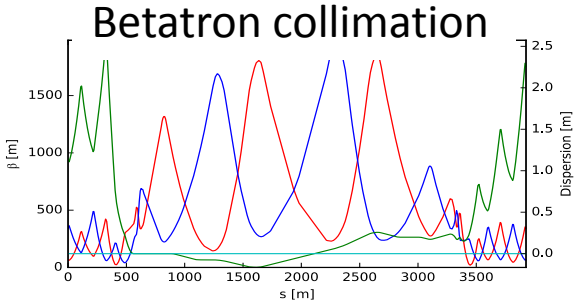
Integrated Lattice

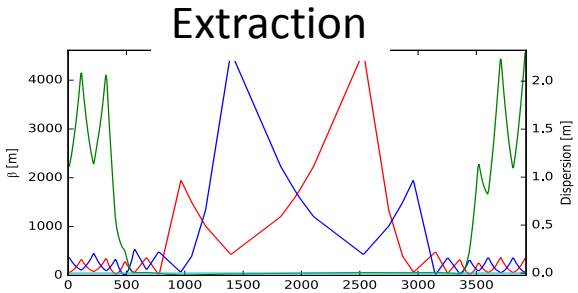


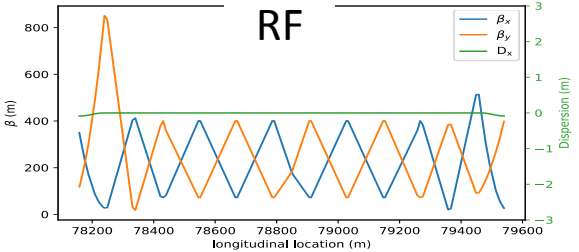










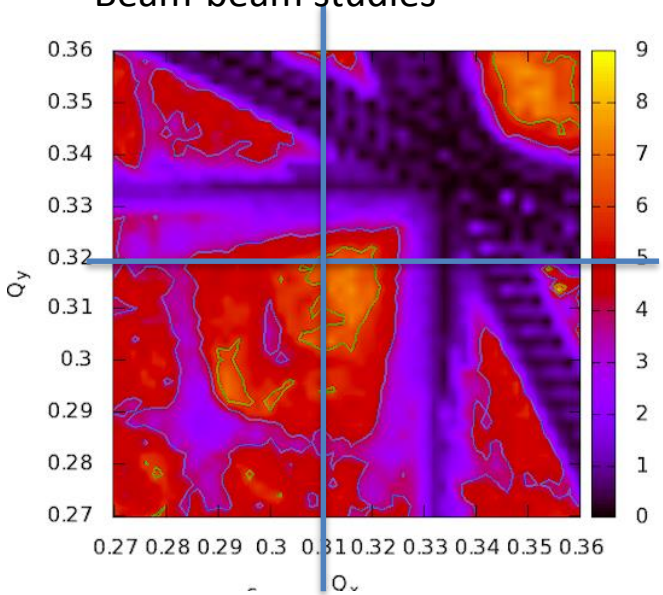


Full integrated lattice exists

- large amount of work (code, matching, tuning, …)
- some small issues remain to be solved
- some proposals for improved desgins to be integrated

Beam Dynamics

Beam-beam studies



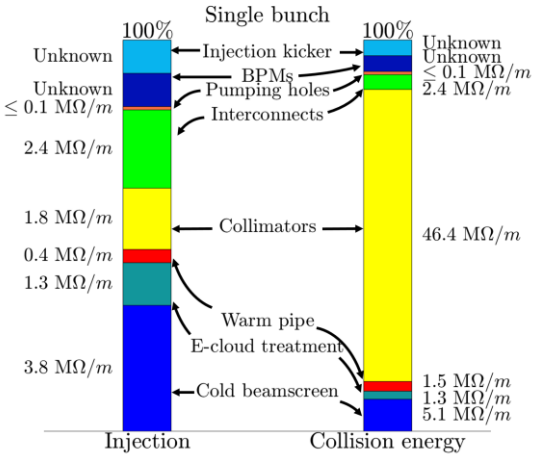
Lattice design, integration of octupoles for stability etc. corrector design, dynamic aperture studies, …

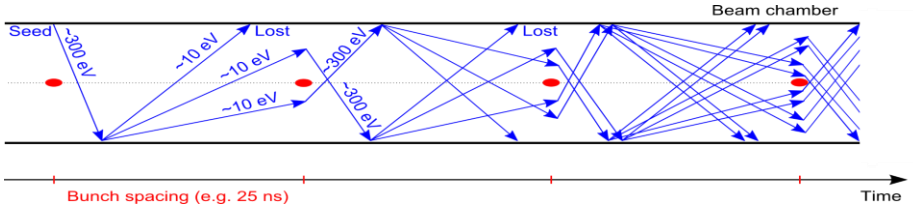
Beam dynamics studies validate the design

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Instabilities:
Impedances, octupoles, electron lens, feedback, ..
Electron cloud, coatings, …

Beam handling:
Collimation, injection, extraction, …





FCC-hh Technology Example

30 W/m synchrotron radiation (LHC: 1 W/m)
Make it small to make magnet cheap

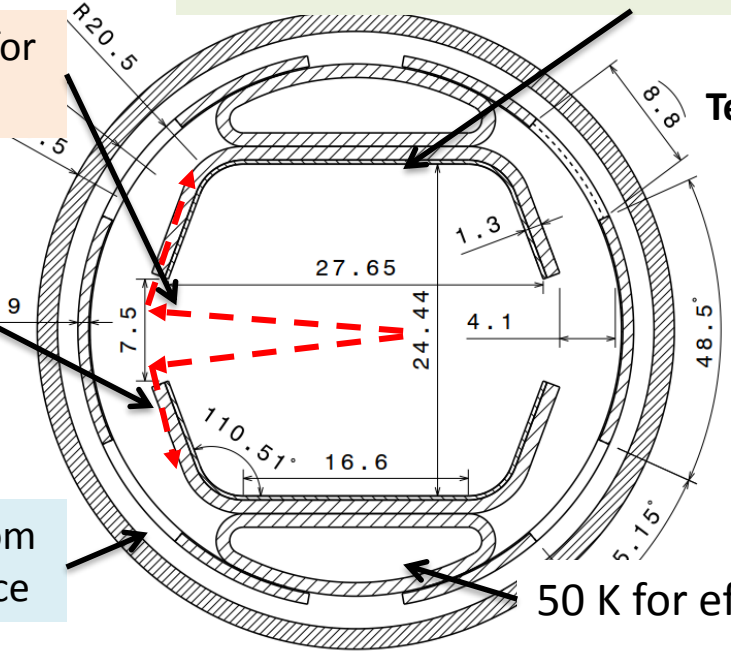
Magnet aperture 50 mm (LHC 56 mm)

Laser treatment / carbon coating against ecloud

Extract photons for great vacuum

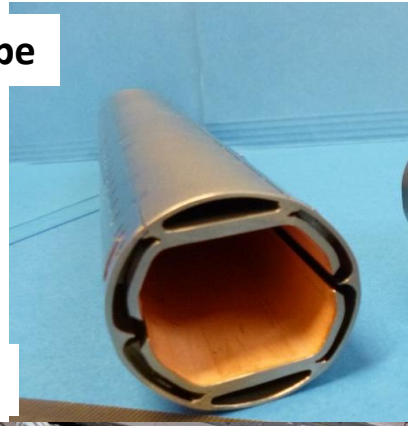
Strong to withstand quench

Hide pumping holes from beam for low impedance

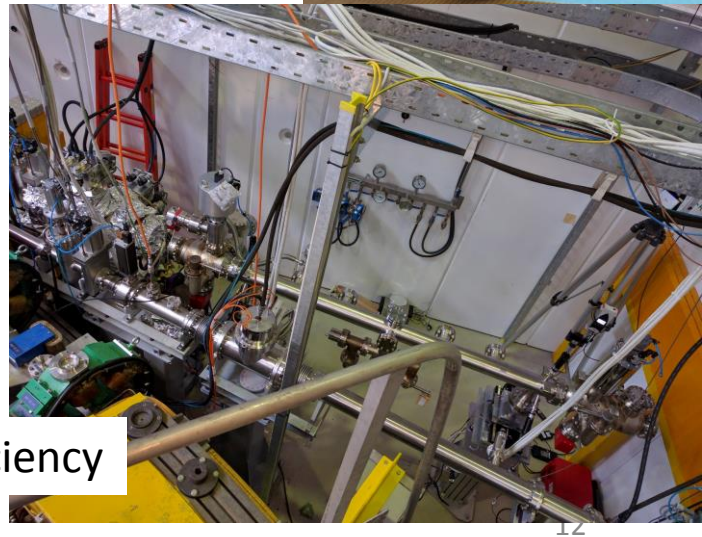


50 K for efficiency

Prototype



Test station in ANKA

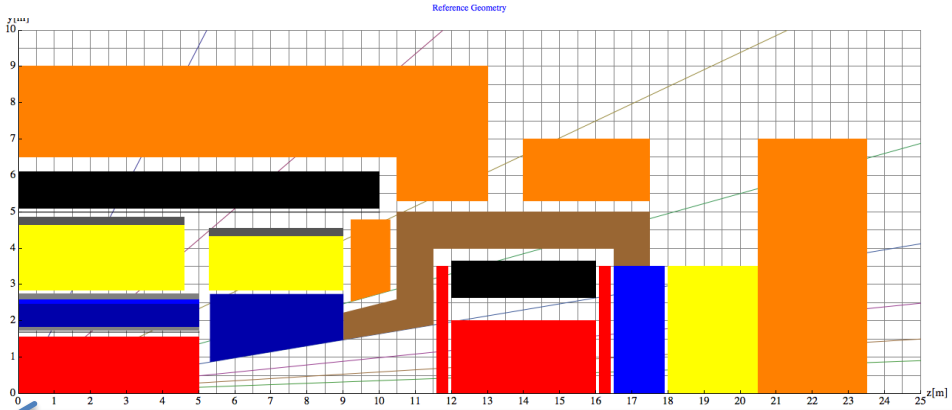


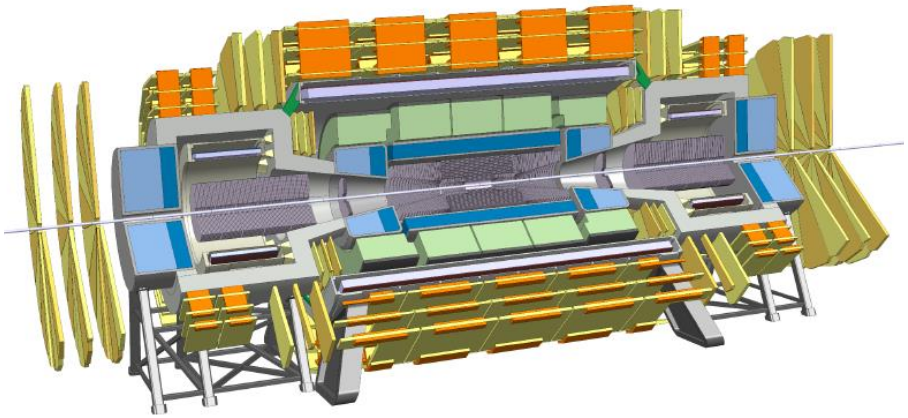
FCC-hh MDI

Tracking
Ecal
HCAL
Magnets and cryostat
Muons

Uses forward solenoid

Alternative option with forward dipole considered





Add. protection
TAS
Triplet

Hall half length: 33m
Tunnel before triplet: 7m

L^*=40 m

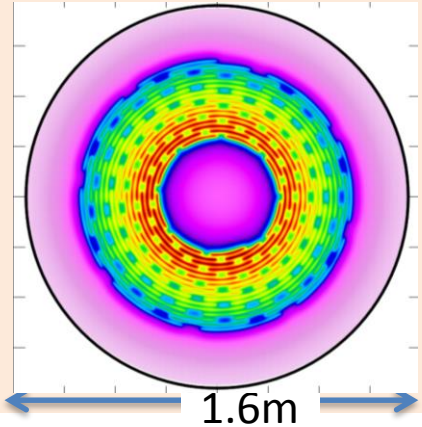
Detector half length 23.5m
Space to open 9.5m

FCC-hh Beam Losses

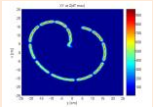
8 GJ kinetic energy per beam

- Boing 747 at cruising speed
- 2000 kg TNT
- 400 kg of chocolate
  - Run 25,000 km to spent calories
- O(20) times LHC

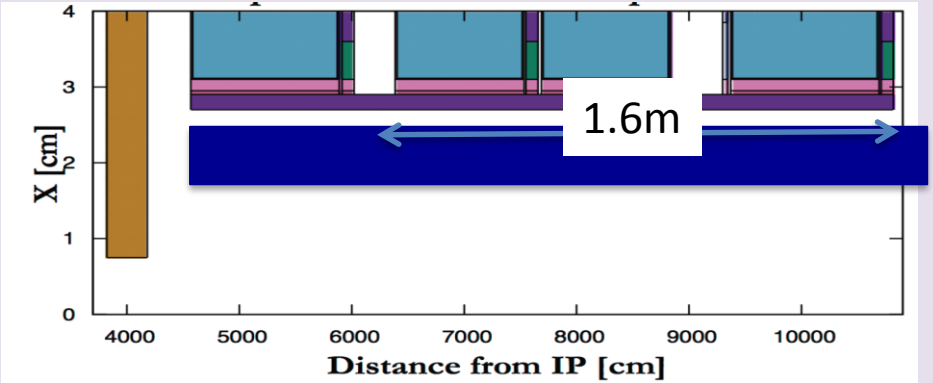
FCC-hh beam dilution pattern at dump



LHC beam dilution pattern at dump



Designed shielding to cope with the 500 kW collision debris per experiment

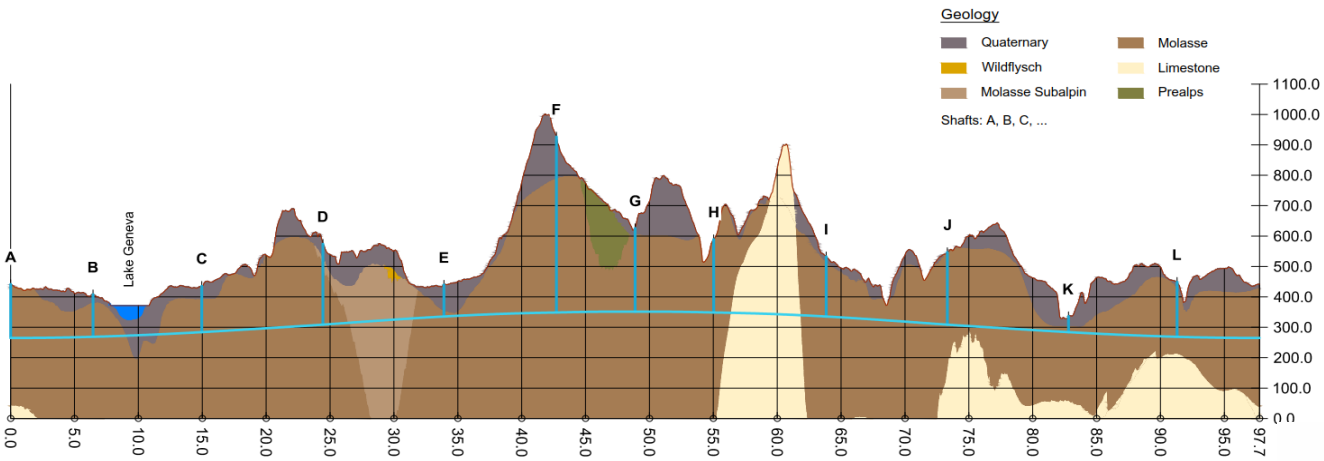


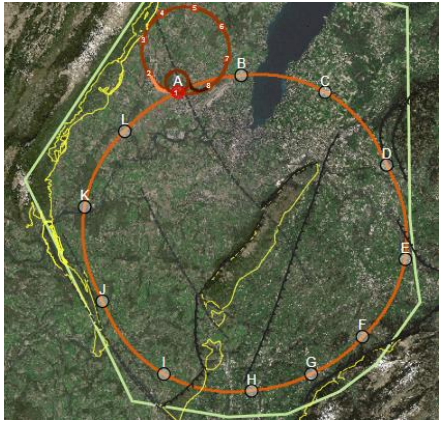
Triplet design allows for thick shielding

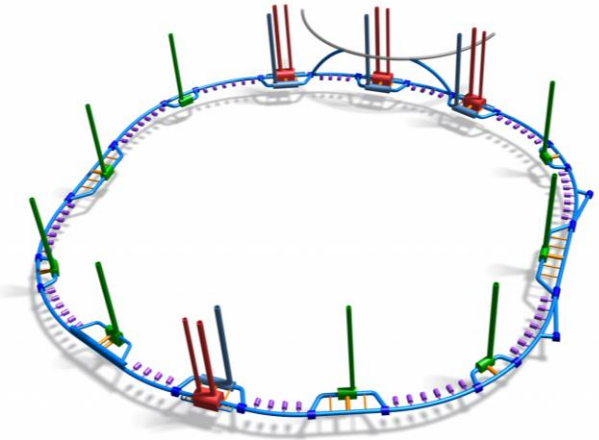
Collimation system design

- Designed system that can cope with the losses
- Detailed studies and optimisation of performance
- Also reduction of impedance

Site and Infrastructure Planning







Detailed studies of site, civil engineering, power availability
Planning of project implementation

Use of LHC or SPS as injector is possible

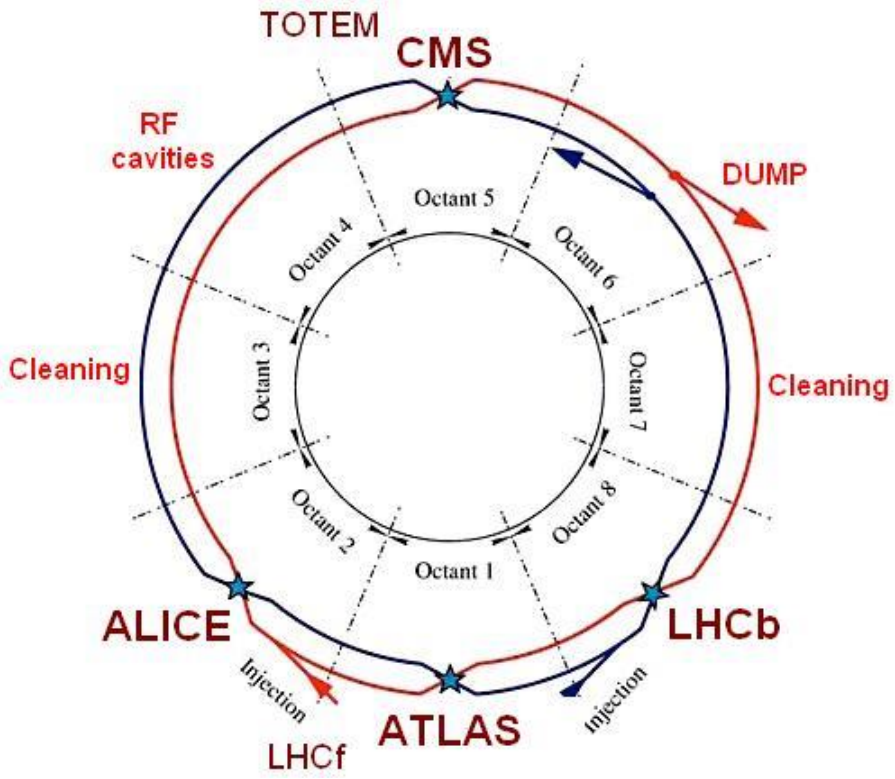
HE-LHC

Physics goals:

- 2 x LHC collision energy in LHC tunnel using FCC-hh magnets
  - I. e. cms energy > 27 TeV
  - Required some iterations of the design
- Target integrated luminosity ≥ 10 ab^{-1} over 20 years

Strategy:

- Use FCC-hh magnets & FCC-hh vacuum system
- Use HL-LHC crab cavities & long-range wire compensation
- Use HL-LHC/LIU parameters (25 ns baseline)
- No major modifications of LHC tunnel



HE-LHC Challenges and Optics

Challenges:

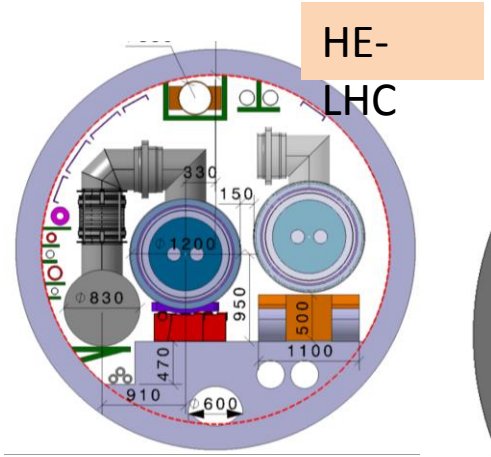
- LHC tunnel is small
- Insertions are short
- But seem able to cope with this

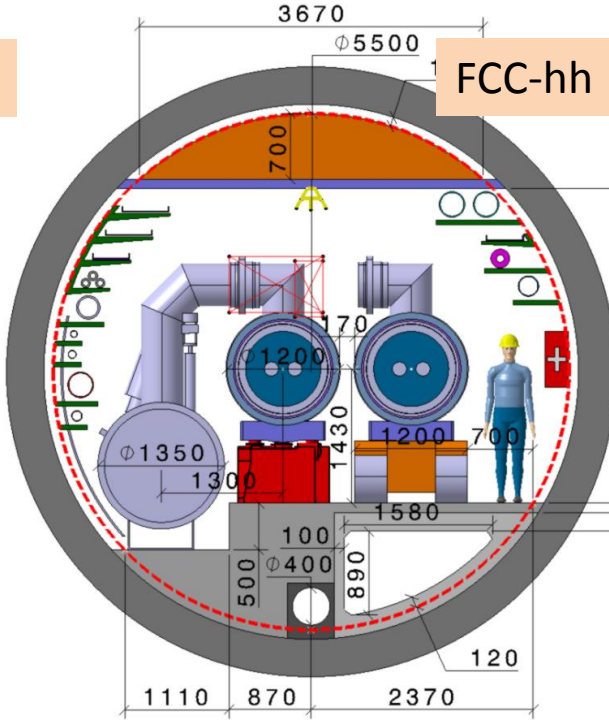
Two arc lattice options considered

- First has higher energy (27.3 TeV)
- Second has better dynamic aperture

Injector (SPS) likely needs upgrade with superconducting magnets (from 0.45 to 1.3 TeV)

Insertions design requires new approaches (e.g. superconducting magnets in collimaiton section?)





FCC Schedules

CDR concise summary volumes (FCC-hh, FCC-ee, HE-LHC)

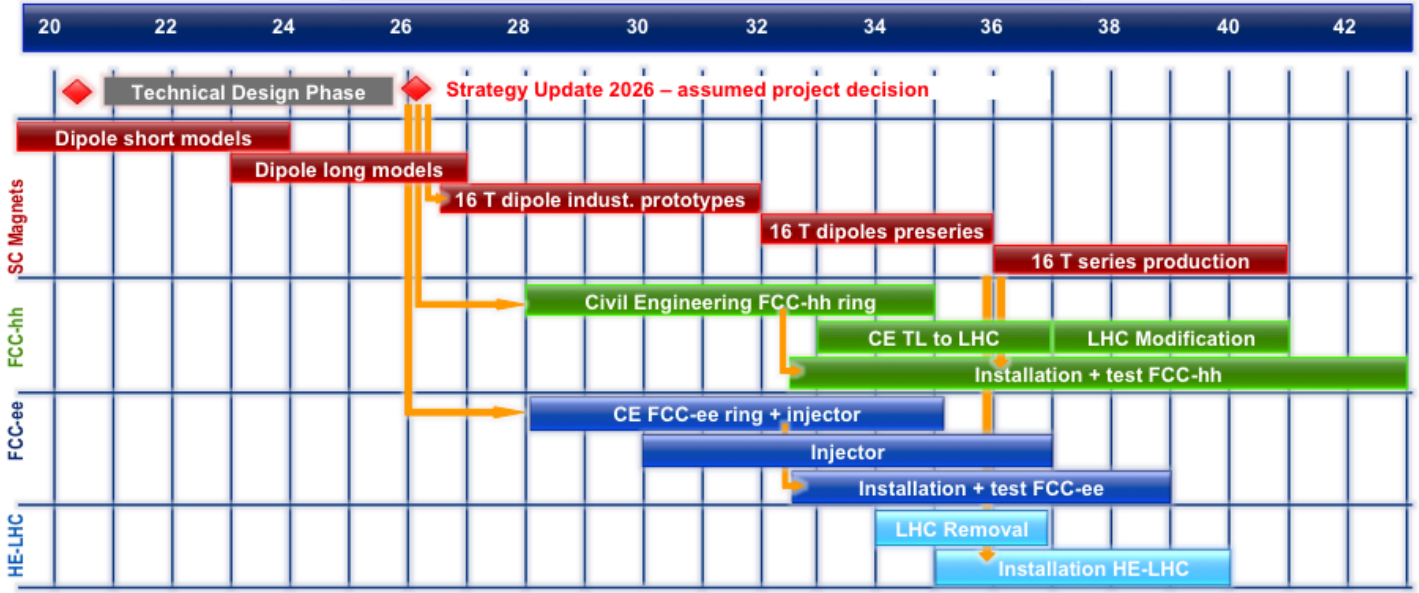
- Print-ready by November 2018

CDR technical volumes

- Proof reading and approval February to March 2019

Preliminary technically limited schedule

M. Benedikt



Conclusion

- FCC studies advances quickly is all areas
  - Collider concept designs ready, CDR is being edited
    - Including HE-LHC
- Good progress on all key technologies
  - In particular worldwide R&D programme in place, on Nb_3Sn superconductor, high-field magnets, and on highly-efficient SC RF
- International FCC collaboration growing steadily, focusing now on completing the CDRs as input for European Strategy Update
- R&D programme towards a technical design

Reserve

Beam Parameters and Luminosity

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Beam physics

Interaction region design

Power consumption
Beam stability
Damage potential

Beam dynamics studies show this will work

	Initial	Ultimate
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20-30
Background events/bx	170	<1020
Bunch distance Δt [ns]	25	
Bunch charge N [10^{11}]	1	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8	3.5
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4

Beam Parameters During a Fill

Synchrotron radiation is important at 50 TeV

- 5 MW for both beams
- 30 W/m per beam in the arc

⇒ Need to protect magnets from heat

⇒ Significant damping (1 h transverse damping time)

Beam burns off rapidly
Fast turn-around is key
LHC with modified magnet powering