Future Circular Collider Study

Overview and Design Status

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gratefully acknowledging input from FCC coordination group, global FCC design study team and all other contributors

http://cern.ch/fcc

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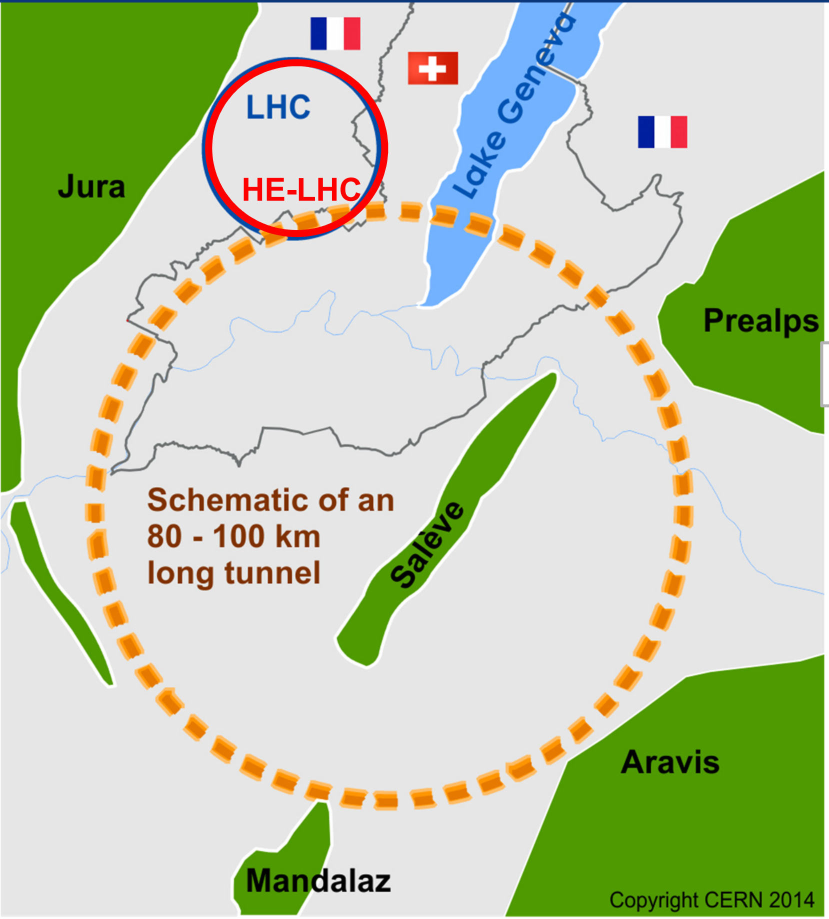
European Commission | Horizon 2020 European Union funding for Research & Innovation

photo: J. Wenninger

Future Circular Collider Study - Scope:

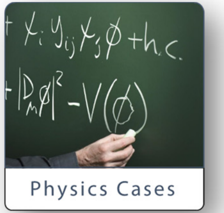


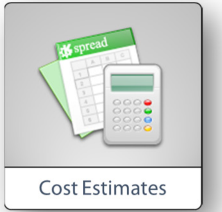
International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → long-term goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e^- from ERL





FCC study: physics and performance targets

FCC-ee:

- Exploration of 10 to 100 TeV energy scale via couplings with precision measurements
- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) ($m_{Z,}$ m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings)

➢ Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points

FCC-hh:

- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks

➢ Machine design for 100 TeV c.m. energy & integrated luminosity ~ $20ab^{-1}$ within 25 years

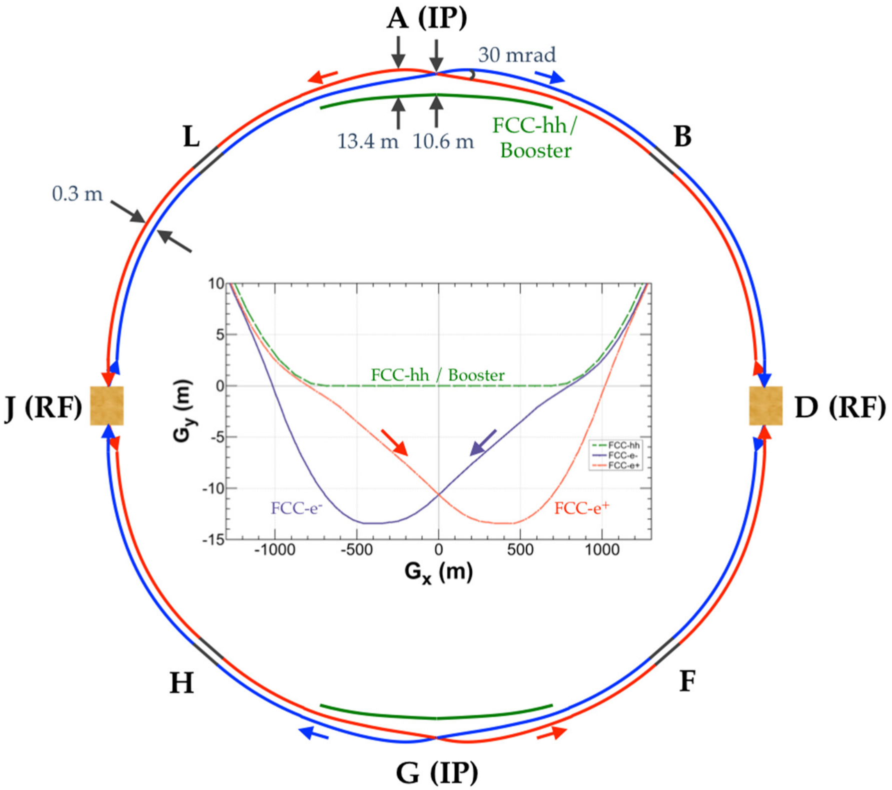
HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy ~ 27 TeV = 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC

➢ Machine design within constraints from LHC CE and based on HL-LHC and FCC technologies

FCC-ee basic design choices

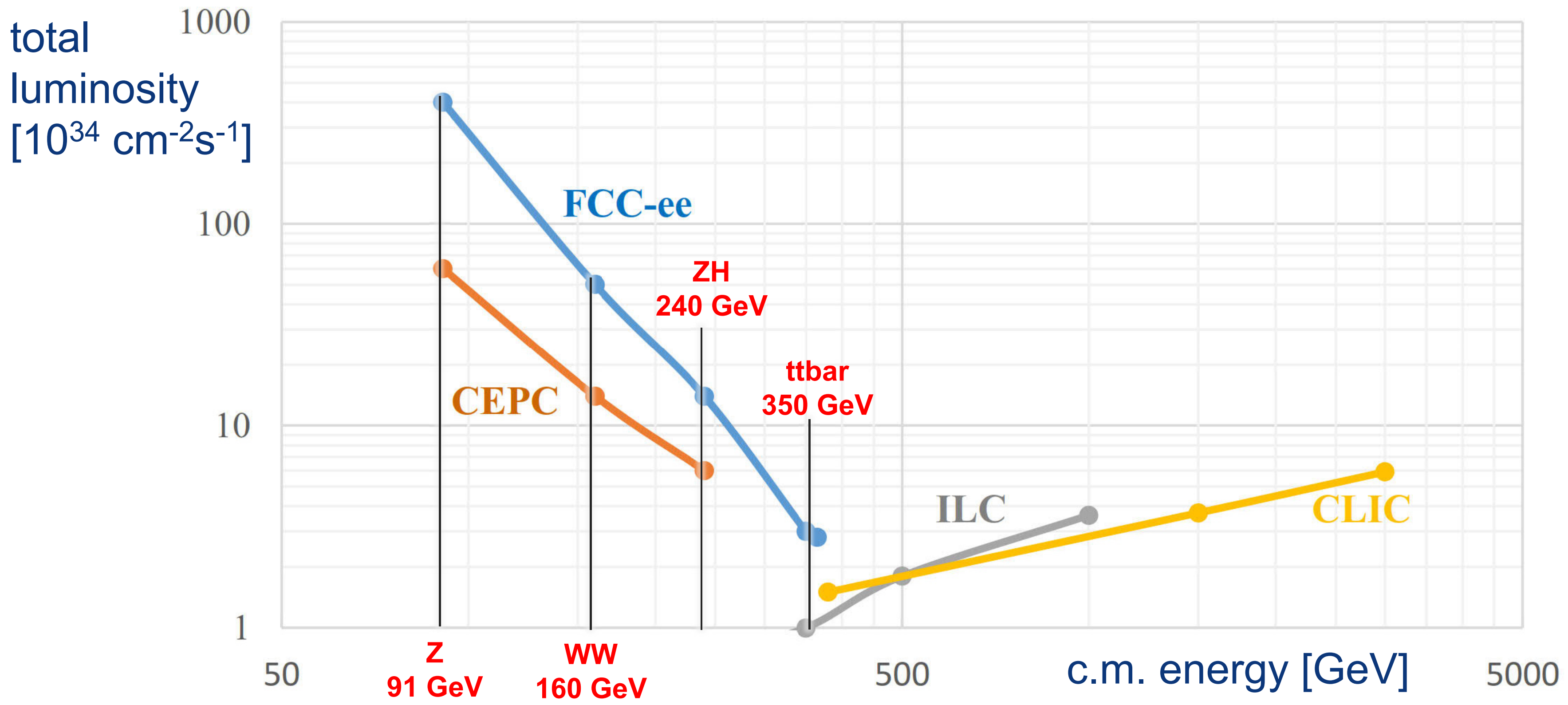
- **Double ring** e+ e- collider ~100 km
- **Follows footprint of FCC-hh**, except around IPs
- **Asymmetric IR layout and optics** to limit synchrotron radiation towards the detector
- **2 IPs, large** horizontal crossing angle **30 mrad, crab-waist optics**
- **Synchrotron radiation power 50 MW/beam** at all beam energies
- **Top-up injection** scheme for high luminosity
- Requires **booster synchrotron in collider tunnel**



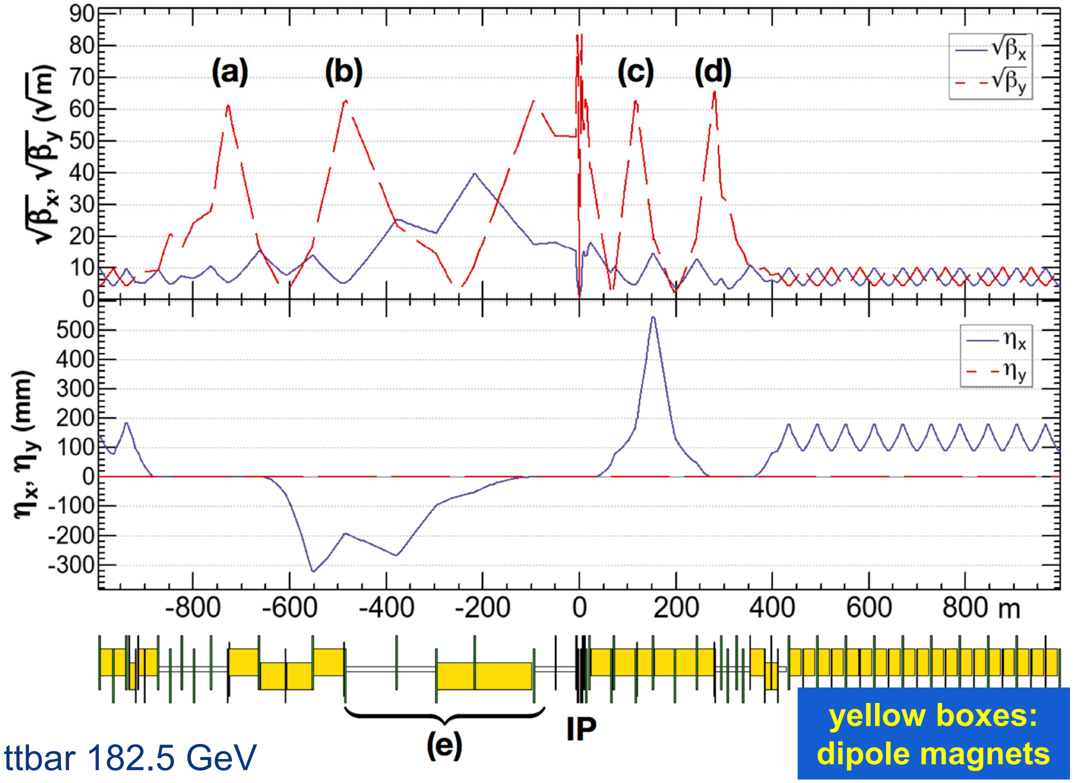
FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

Lepton collider luminosities



FCC-ee asymmetric crab-waist IR optics



ttbar 182.5 GeV

- **Asymmetric IR optics** to suppress synchrotron radiation toward the IP, **$E_{critical}$ <100 keV from 450 m from IP (e)**
- **4 sextupoles (a – d) for local vertical chromaticity correction combined with crab waist,** optimized for each working point.
- **Common arc lattice** for all energies, **60 deg for Z, W and 90 deg for ZH, tt** for maximum stability and luminosity

FCC-ee operation model

working point	luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	25	7 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.4	0.36 ab^{-1}/year	**1.5 ab^{-1}**	**4**

total program duration: 14 years - ***including machine modifications***

phase 1 (*Z, W, H*): 8 years, phase 2 (top): 6 years

FCC-ee RF staging scenario

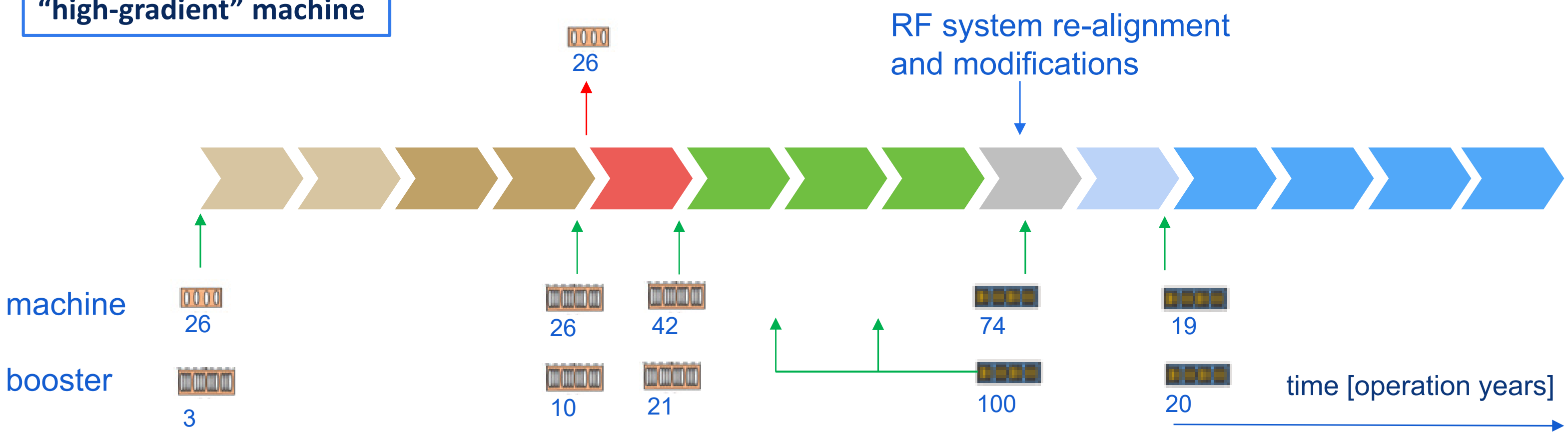
“Ampere-class” machine

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

“high-gradient” machine

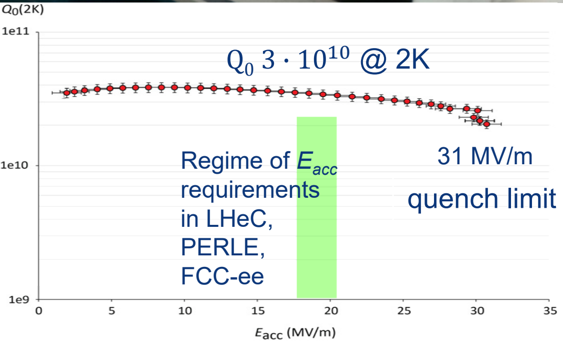
three sets of RF cavities to cover all options for FCC-ee & booster:

- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**
- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**

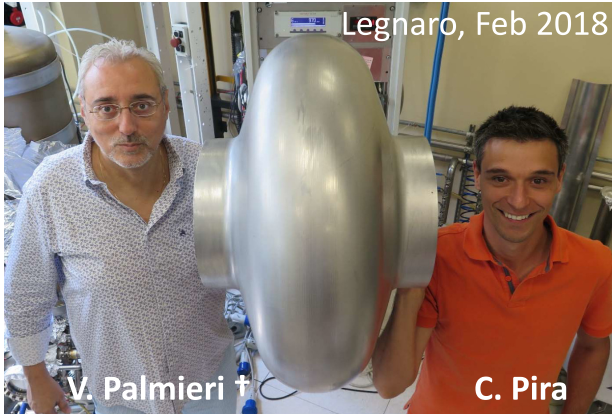


SRF cavity development program (examples)

5-cell 800 MHz cavity, JLAB prototype for both FCC-ee (t-tbar) & FCC-eh ERL (PERLE)



Seamless 400 MHz single-cell cavity formed by spinning at INFN-LNL



Tooling fabricated and successfully tested with an Aluminium cavity.

† We're saddened about the sudden death of Vincenzo Palmieri few weeks ago.

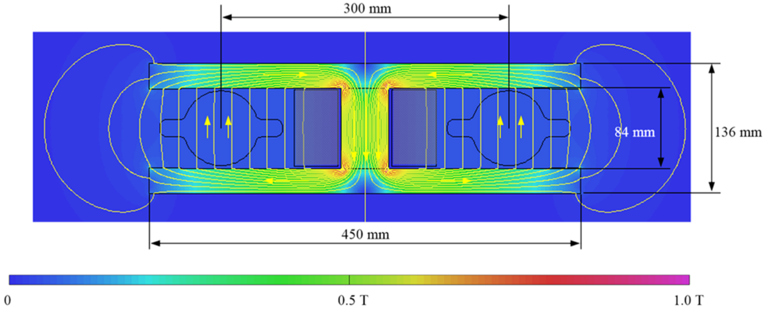
CERN half-cells formed using Electro-Hydro-Forming (EHF) at Bmax.

EASITrain

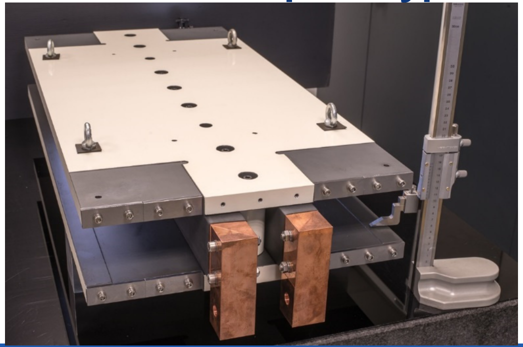
High strain rate technology using shockwaves in water from HV discharge. EHF investigated for half-cells and seamless Nb and Cu cavities.

Low-power low-cost design for FCC-ee magnets

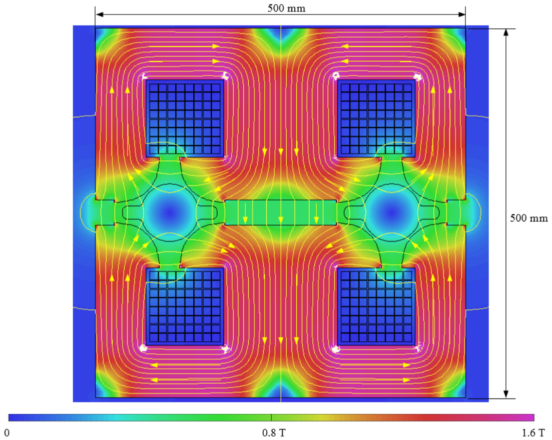
Twin-dipole design with 2× power saving
16 MW (at 175 GeV), with Al busbars



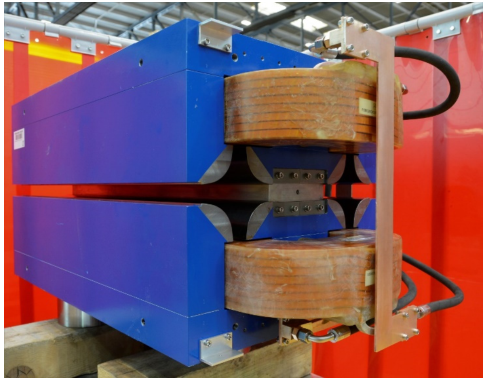
first 1 m prototype



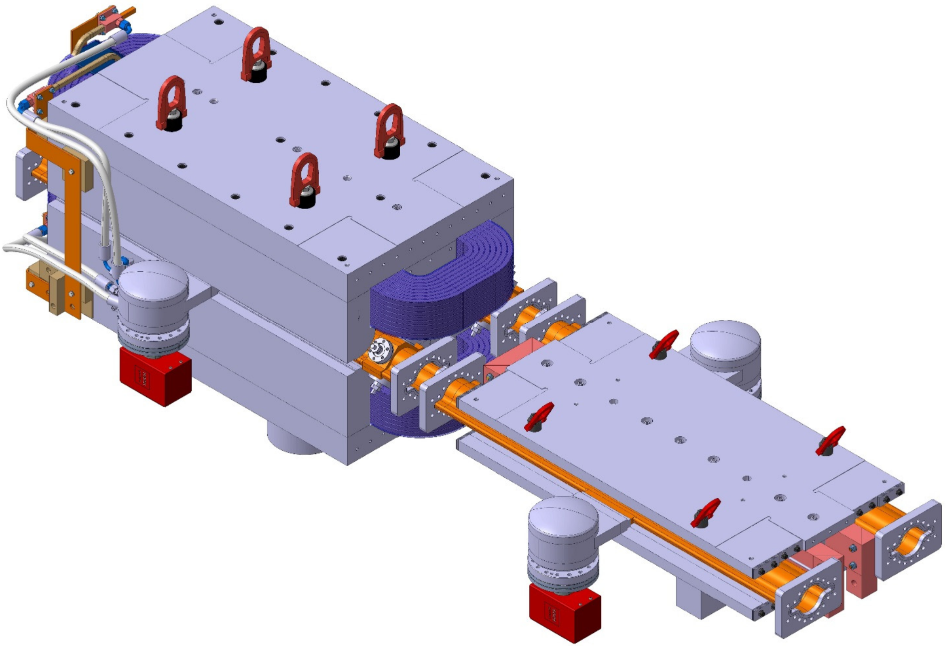
twin F/D quad design with 2× power saving
25 MW (at 175 GeV), with Cu conductor



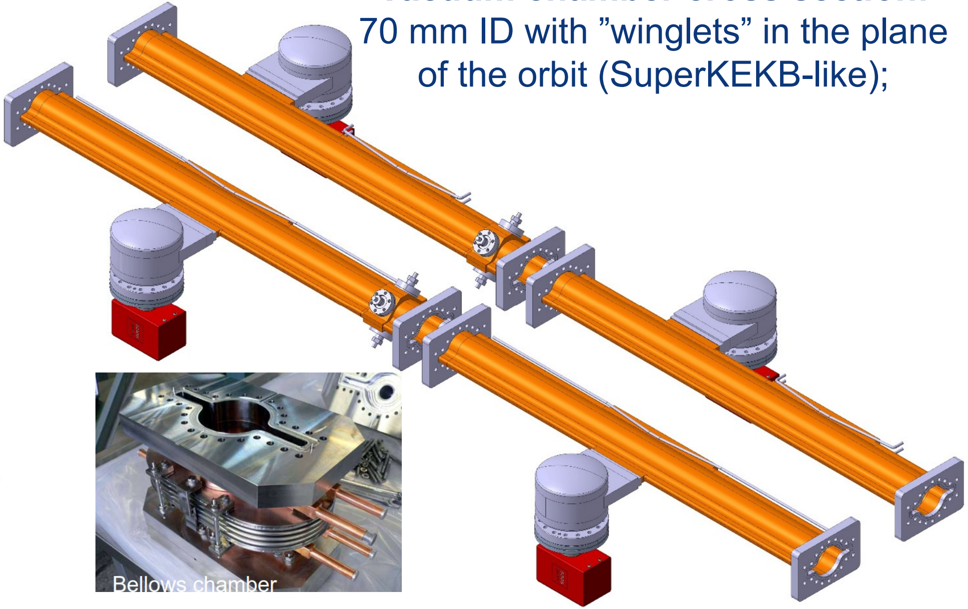
first 1 m prototype



FCC-ee arc vacuum prototyping & integration

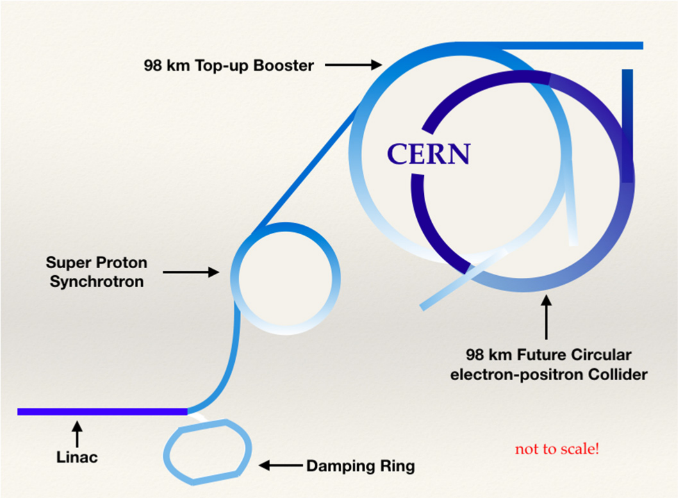


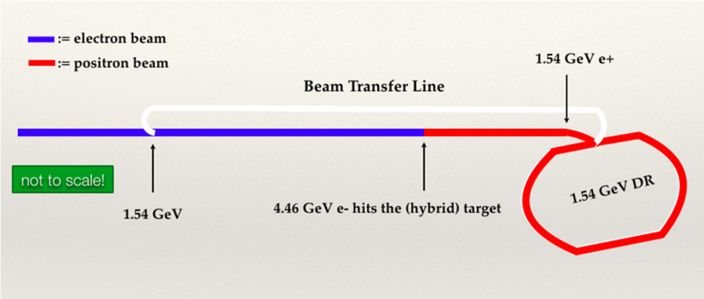
Vacuum chamber cross section:
70 mm ID with ”winglets” in the plane of the orbit (SuperKEKB-like);



- The chambers feature **lumped SR absorbers with NEG-pumps** placed next to them.
- **Construction of chamber prototypes in coming months and integration with twin magnets**

FCC-ee injector layout





- SLC/SUPERKEKB-like 6 GeV linac accelerating **1** or **2** bunches with repetition rate of **100-200 Hz**
- **Same linac** used for positron production @ **4.46 GeV** Positron beam emittances reduced in DR @ **1.54 GeV**
- Injection @ **6 GeV** into of Pre-Booster Ring (SPS or new ring) and acceleration to 20 GeV
- Injection to main Booster @ **20 GeV and interleaved** filling of e+/e- (below **20 min** for full filling) and continuous top-up

FCC-pp collider parameters

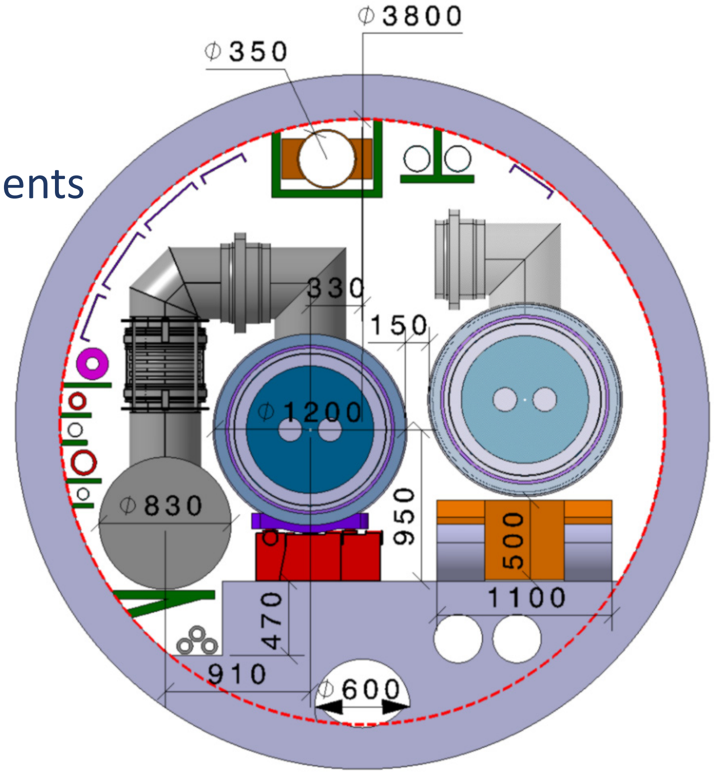
parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.1	1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	2.2	1.15
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	28	5 (lev.)	1
events/bunch crossing	170	1000	800	132	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

HE-LHC integration aspects

Working hypothesis for HE LHC design:

No major CE modifications on tunnel and caverns

- Similar geometry and layout as LHC machine & experiments
- **Maximum magnet cryostat diameter ~1200 mm**
- **Maximum QRL diameter ~830 mm**

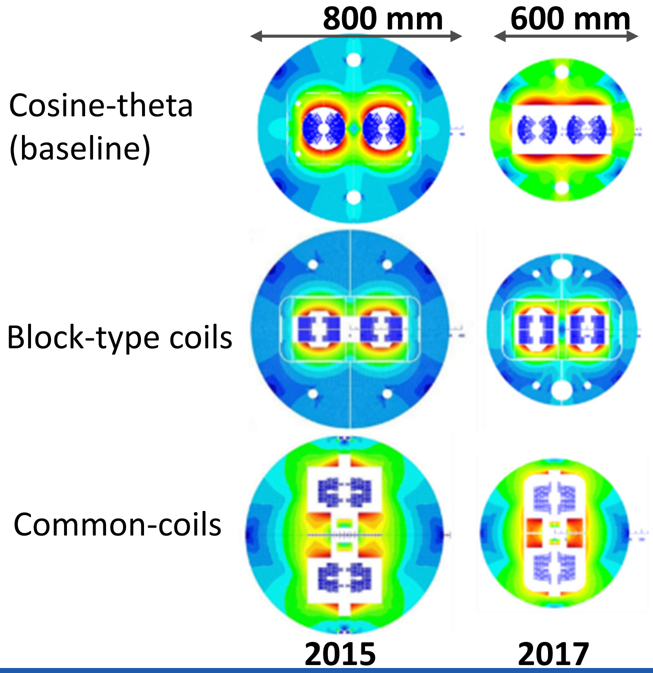


Integration and design strategy:

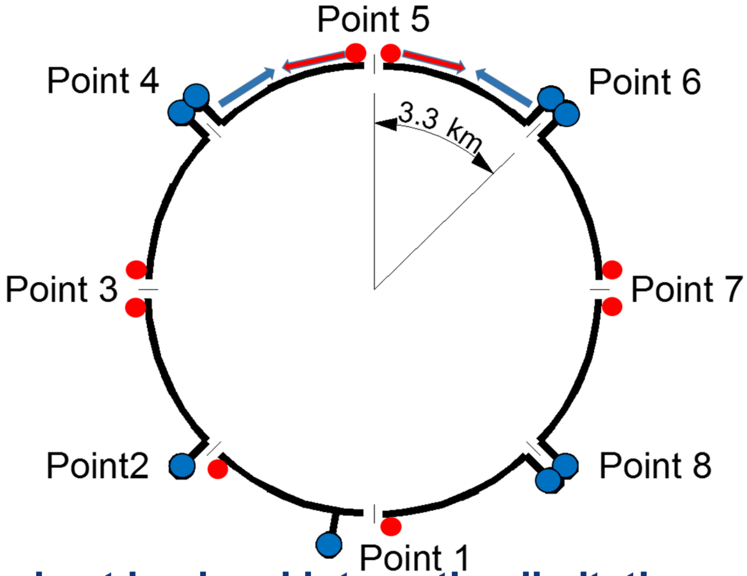
- Development of optimized 16 T magnet, compatible with HE LHC requirements
- New cryogenic layout to limit QRL dimension

16 T dipole design evolution

- Coil optimization and margin 18 → 14%
- Inter-beam distance 250 → 204 mm
- Stray-field < 0.1 T at cryostat



Half-sector cooling instead of full sector (as for LHC) to limit cross section of cryogenic distribution line

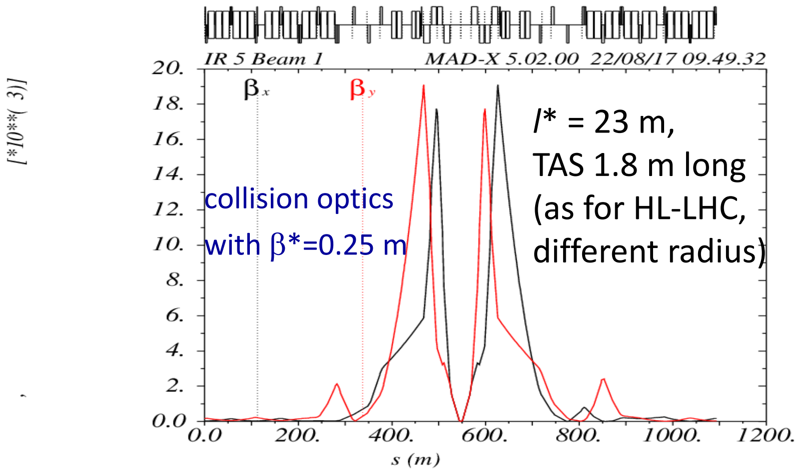


higher heat load and integration limitations:

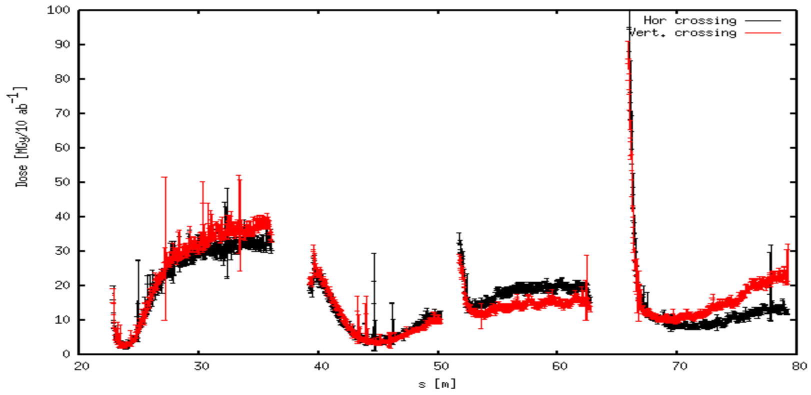
- **8 additional 1.8 K refrigeration units wrt. LHC**
- **8 new higher-power 4.5 K cryoplants**

HE-LHC IR optics & triplet shielding

- **triplet lengths: HE-LHC: 56 m** (13.5 TeV)
- **HL-LHC: 41. 8m, present LHC: 30.4 m**
- **ca. 11 m space for crab cavities**

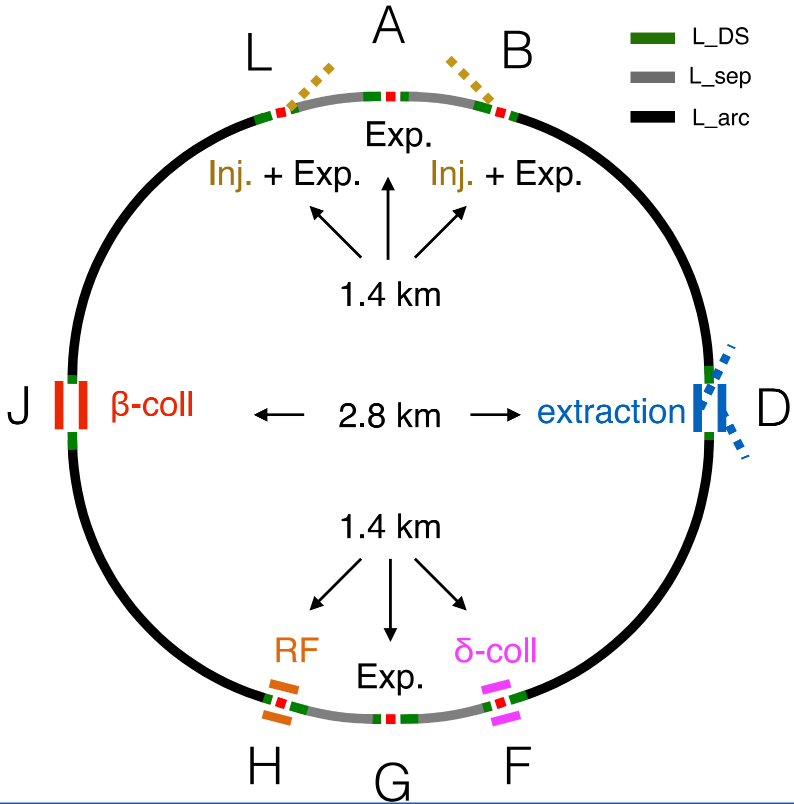


- **Triplet quadrupole design with 2 cm inner tungsten shielding**
- **For 10 ab^{-1} integral luminosity: ~40 MGy peak dose** (peak at Q3 can be reduced with shielding)



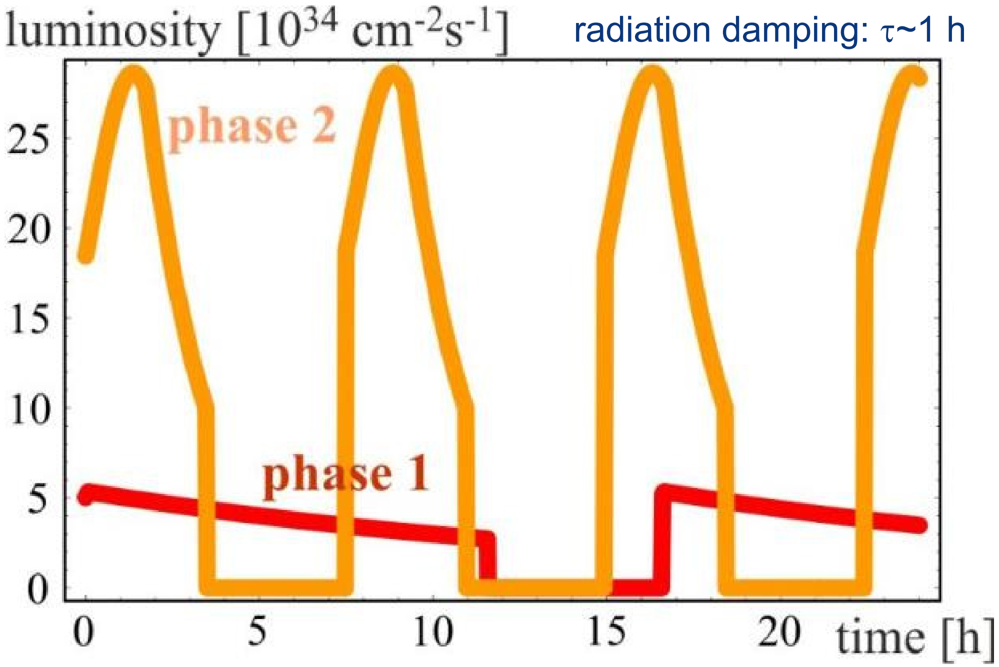
General optics design work ongoing for HE LHC with focus on injection (energy), field quality, physical & dynamic aperture, protection.

FCC-hh layout and optics



- **circumference 97.8 km**
- **two high-luminosity experiments (A & G)**
- **two other experiments (L & B)** combined with **injection upstream** of experiments
- **two collimation insertions**
  - betatron cleaning (J)
  - momentum cleaning (F)
- **Extraction/dump insertion (D)**
- **RF insertion (H)**
- **integrated optics for full ring established,** beam dynamics studies confirm design goals

FCC-hh operation phases and luminosity



Phase 2: Interplay of radiation damping, luminosity burn-off, controlled transvers blow-up

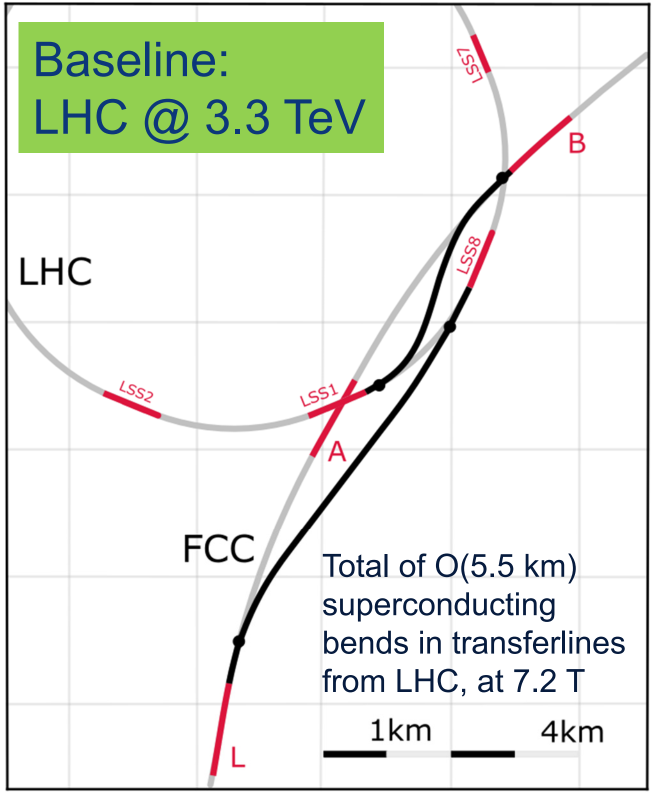
phase 1:
β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h
250 fb^{-1} / year

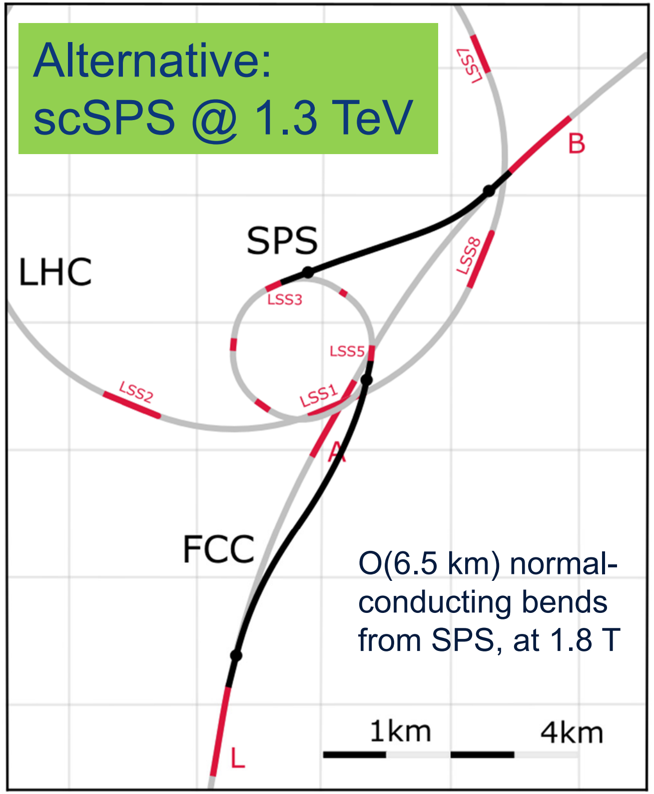
phase 2:
β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h
1 ab^{-1} / year

Transition via operation experience, no HW modification

Total integrated luminosity over 25 years operation:
O(20) ab^{-1}/experiment
consistent with physics goals

FCC-hh injector options and transfer lines





Current baseline:

- **Injection energy 3.3 TeV LHC**

→ Field-swing FCC-hh like LHC

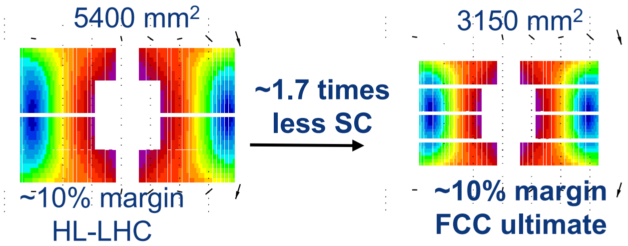
Alternative options:

- **Injection from $SPS_{upgrade}$ around 1.3 TeV**
- **$SPS_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp, cf. SIS 300 design**
- **$SPS_{upgrade}$ would also be an ideal injector for HE LHC (as alternative to the 450 GeV SPS)**

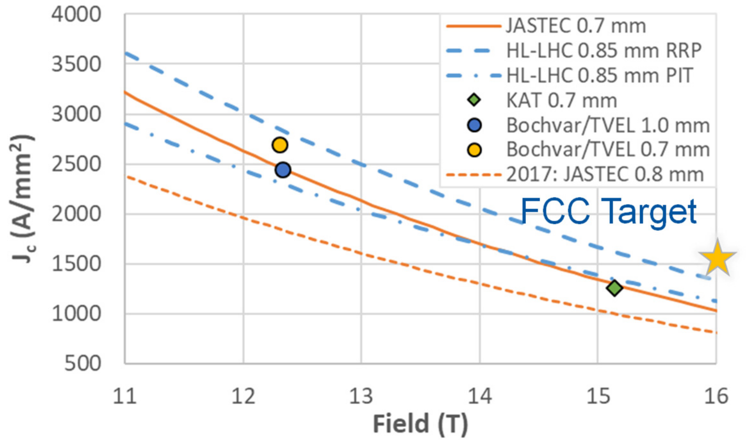
Worldwide FCC Nb_3Sn program

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 only one year development, **prototype Nb_3Sn wires from several new industrial FCC partners already achieve HL-LHC performance**



Conductor activities for FCC started in 2017:

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

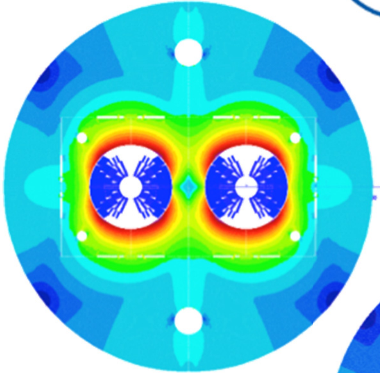
In addition, agreements under preparation:

- **Bruker**, **Germany**
- **Luvata Pori**, **Finland**

16 T dipole design activities and options

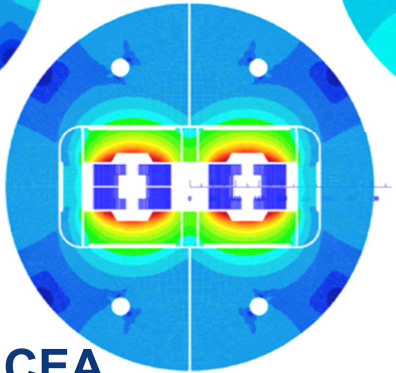
H2020 EuroCirCol
A key to New Physics

Cos-theta



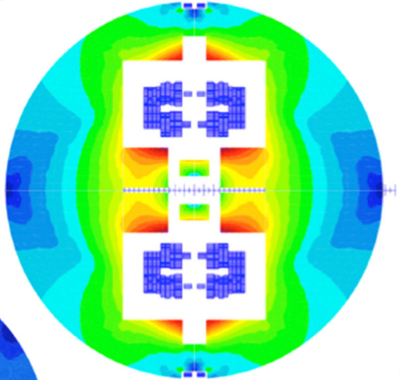
INFN

Blocks



CEA

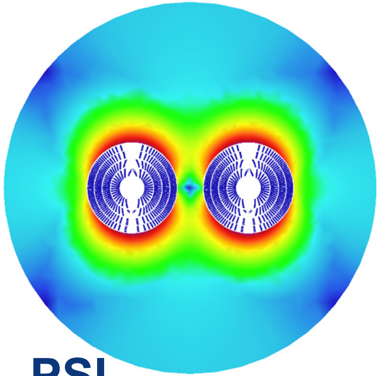
Common coils



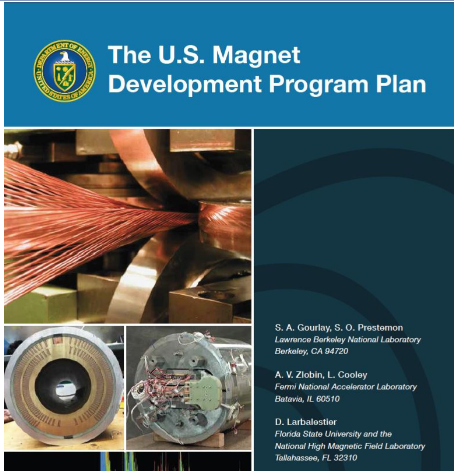
CIEMAT

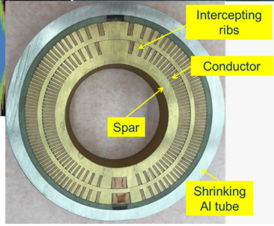
Swiss contribution

Canted Cos-theta

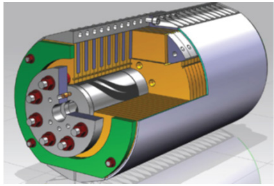


PSI





LBNL



FNAL

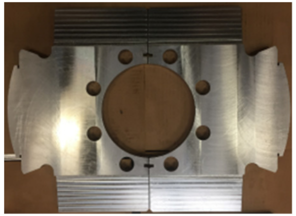
Short model magnets (1.5 m lengths) will be built from 2018 – 2022

Russian 16 T magnet program launched by BINP recently.

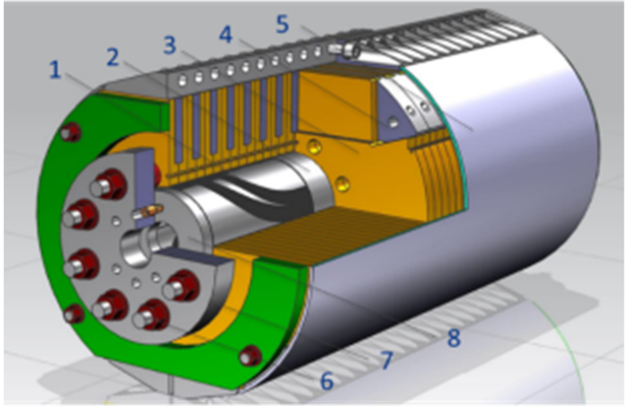
15 T dipole demonstrator (US-MDP)

U.S. MAGNET DEVELOPMENT PROGRAM

U.S. DEPARTMENT OF ENERGY | Office of Science


Iron Laminations


AL I-Clamps

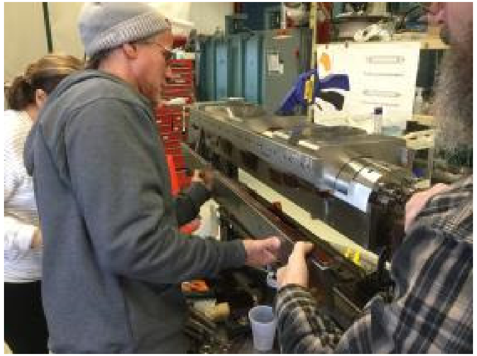



StSt Skin


End Plates


Fillers


Axial Rods

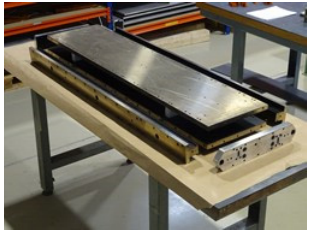


- **All coil parts, structural components and tooling are available at FNAL**
- **Coil fabrication and the work with mechanical structure are in progress**
- **First magnet test in September 2018**

16 T ERMC construction at CERN


First ERMC coil winding


Coil Reaction Tool


Coil Impregnation Tool

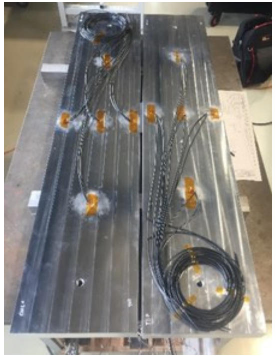

Aluminum shell


Magnet yoke

Coil fabrication

- Winding of the first coil has been completed
- Preparation for reaction on-going
- All tooling for coil production ready

- **Magnet assembly**
  - components and tooling ready
  - Dummy assembly to characterize the structure behavior on-going.

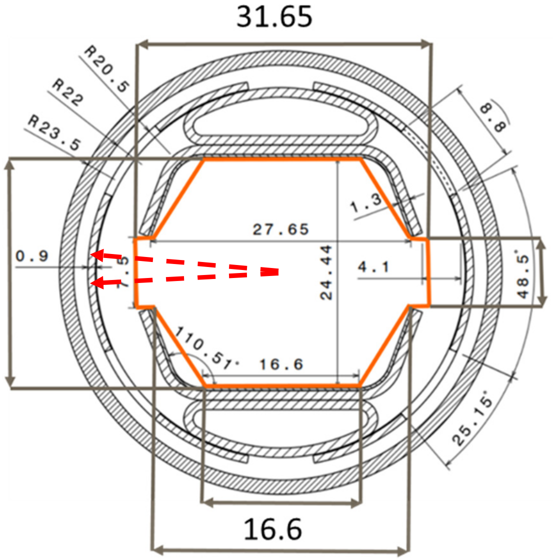

Dummy coils

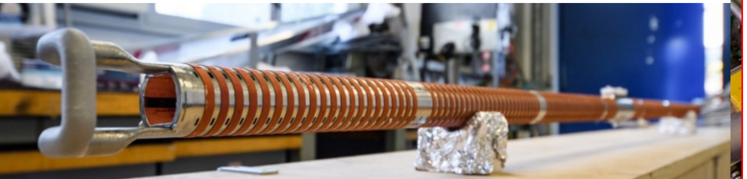

Axial rods

FCC-hh cryogenic beam vacuum system

synchrotron radiation **(~ 30 W/m/beam (@16 T field)** (cf. LHC <0.2W/m) **~ 5 MW total load in arcs**

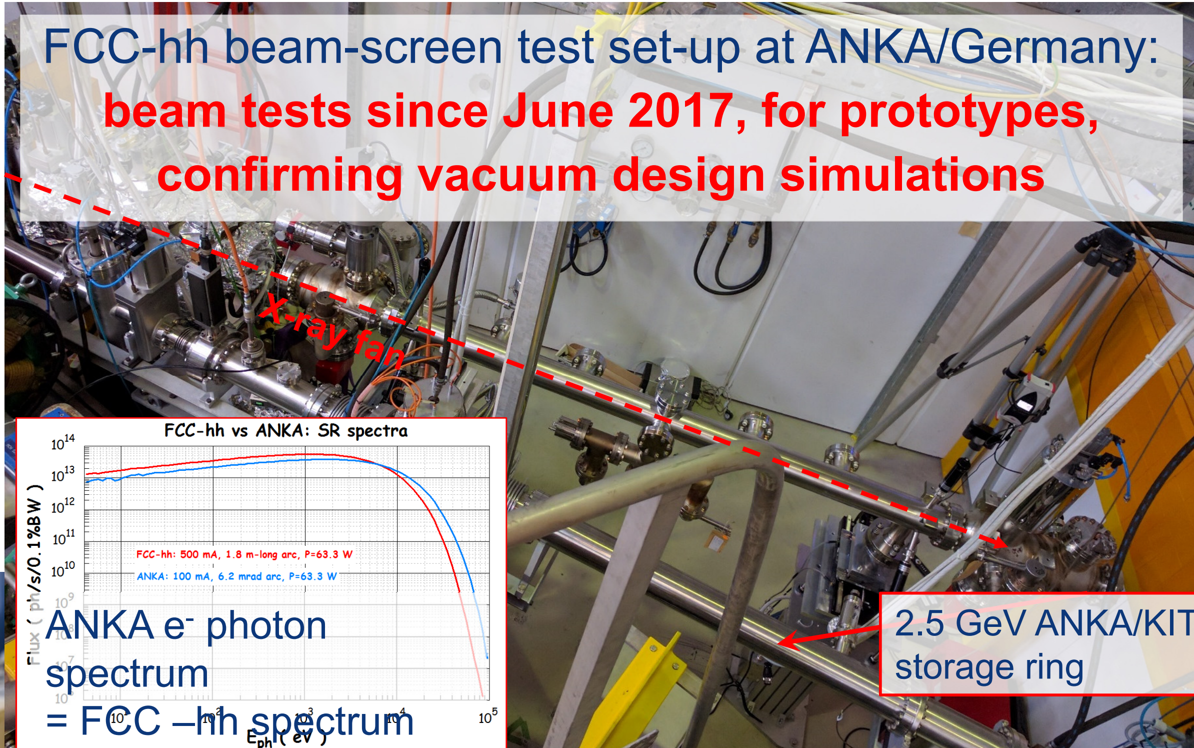
- **absorption of synchrotron radiation at higher temperature (> 1.8 K)** for cryogenic efficiency
- provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.



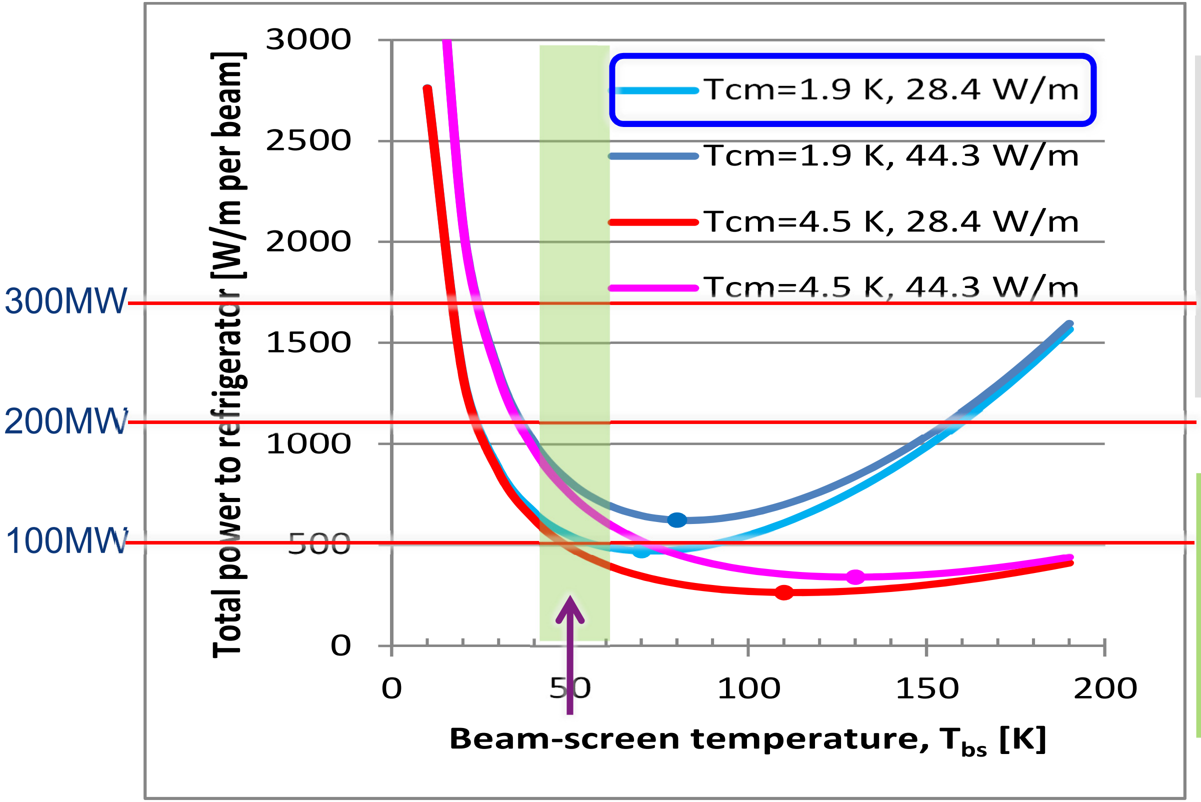


FCC-hh beam-screen test set-up at ANKA/Germany:

beam tests since June 2017, for prototypes, confirming vacuum design simulations



Cryoplants – energy efficiency

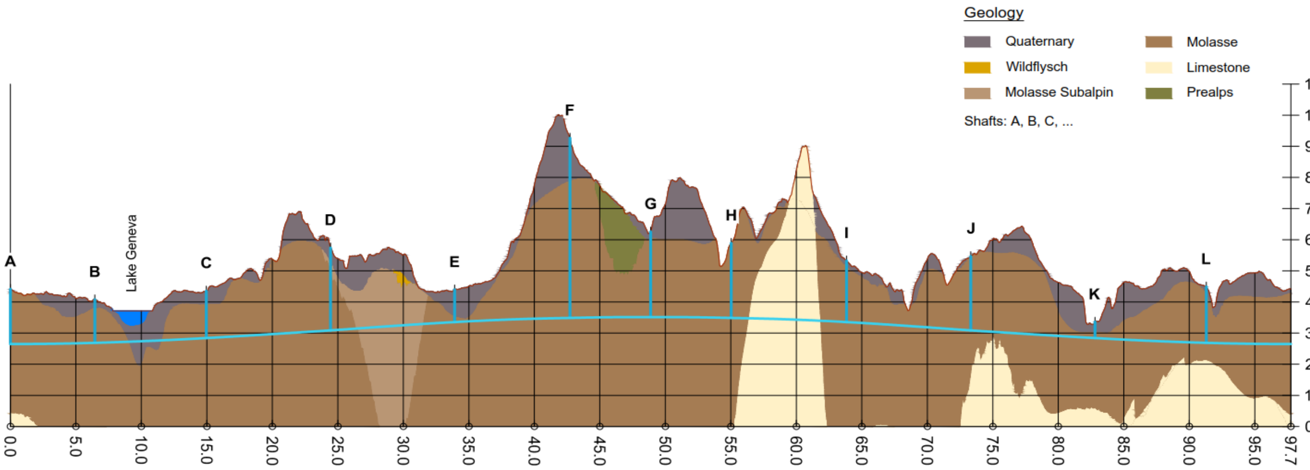


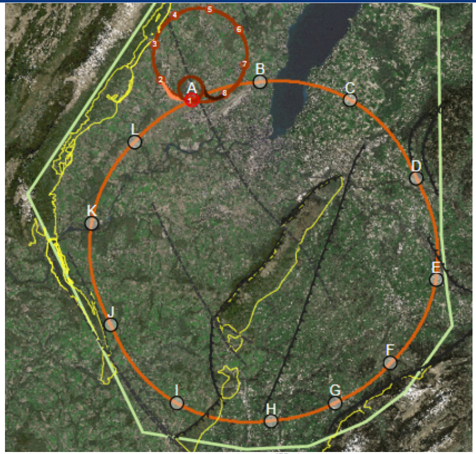
BS temperature choice is overall optimisation of:

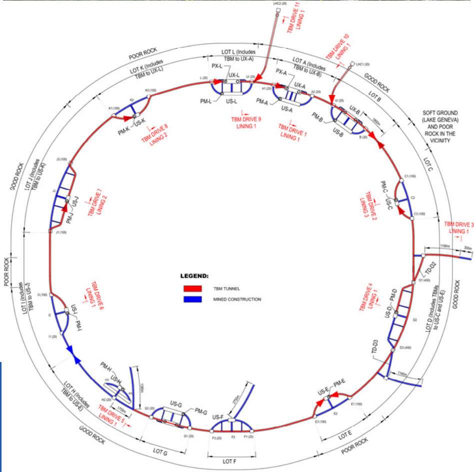
- **Cryoplant power consumption**
- **Vacuum system performance**
- **Impedance and beam stability**

- **Optimum beam screen operation temperature 40 - 60 K**
- **Electrical power for beam screen cooling ~100 MW .**

FCC implementation - footprint baseline





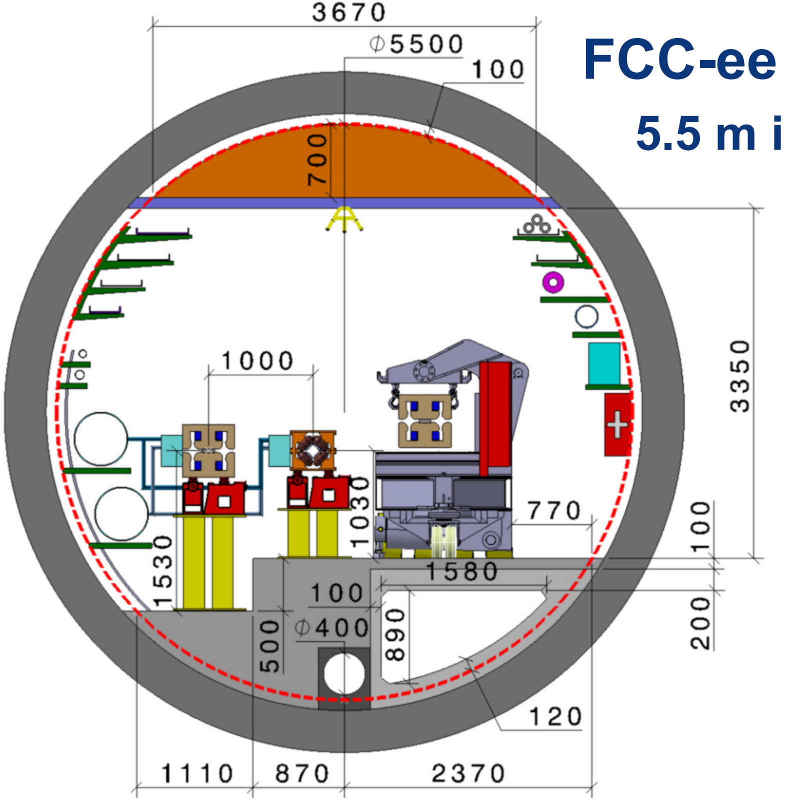


Present baseline position was established considering:

- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

next step: review of surface site locations and machine layout

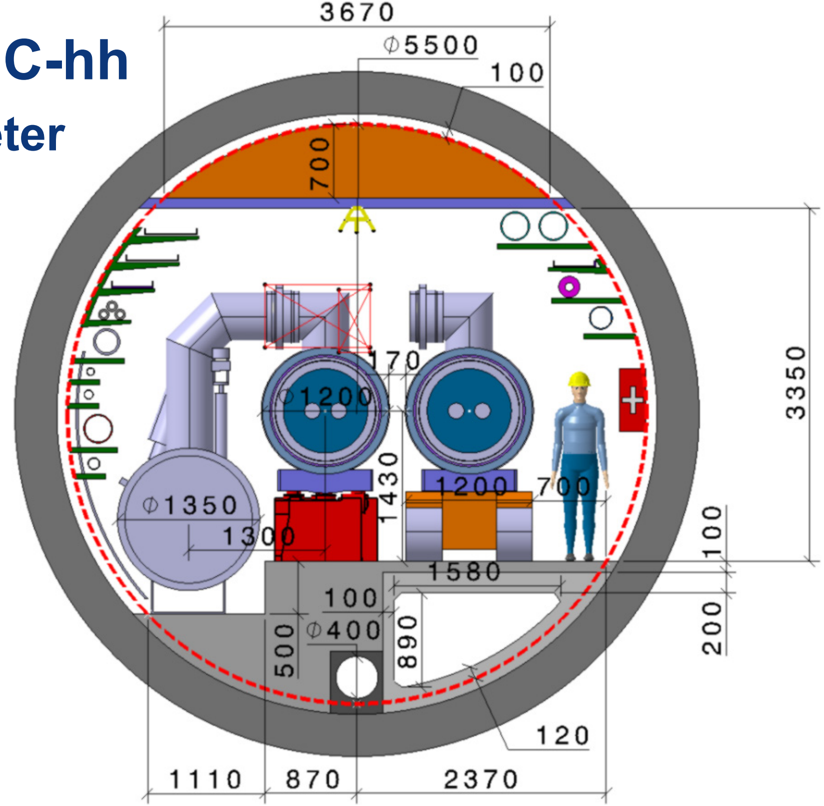
FCC – tunnel integration in arcs



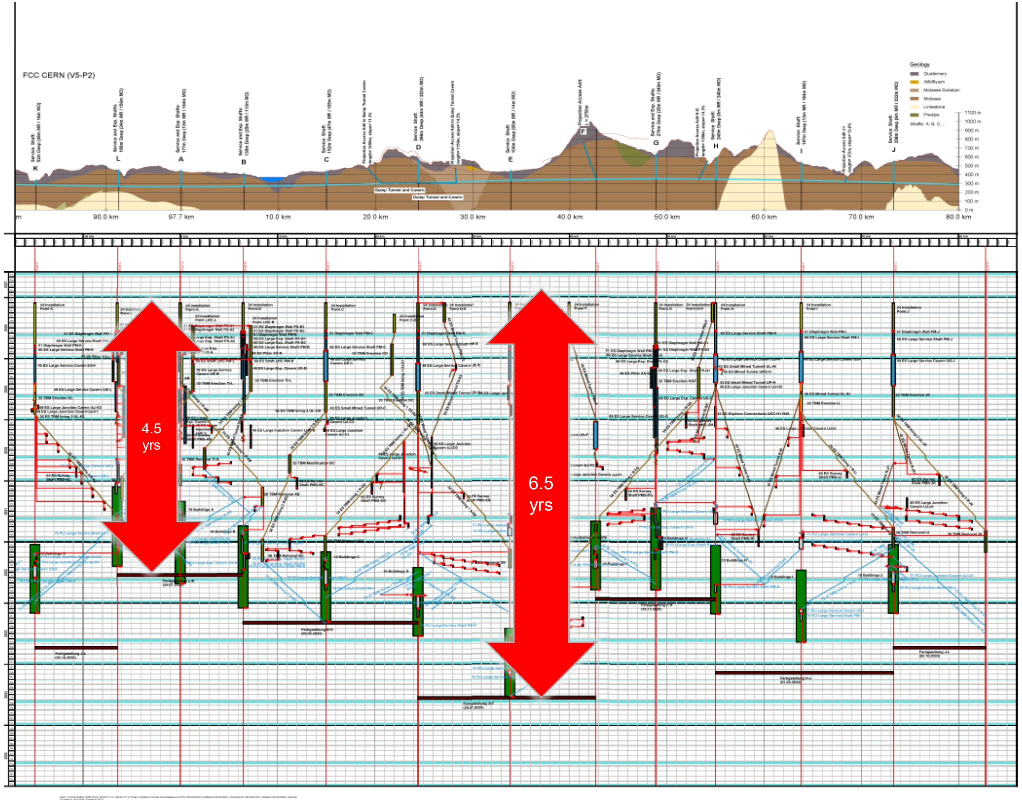
FCC-ee

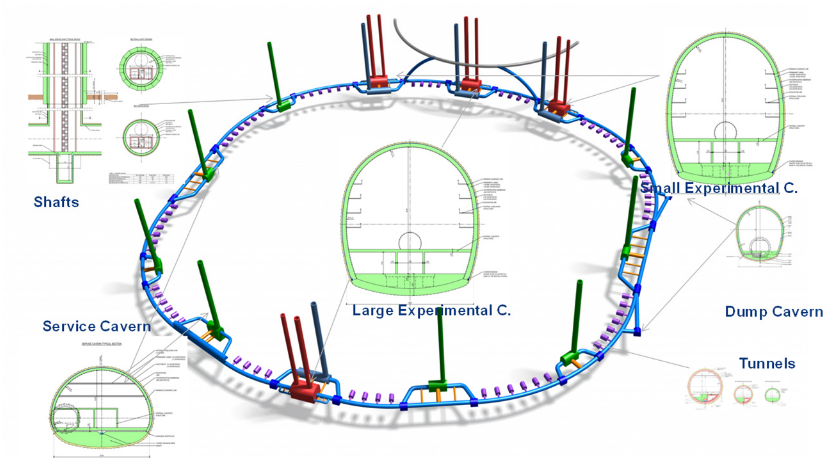
FCC-hh

5.5 m inner diameter



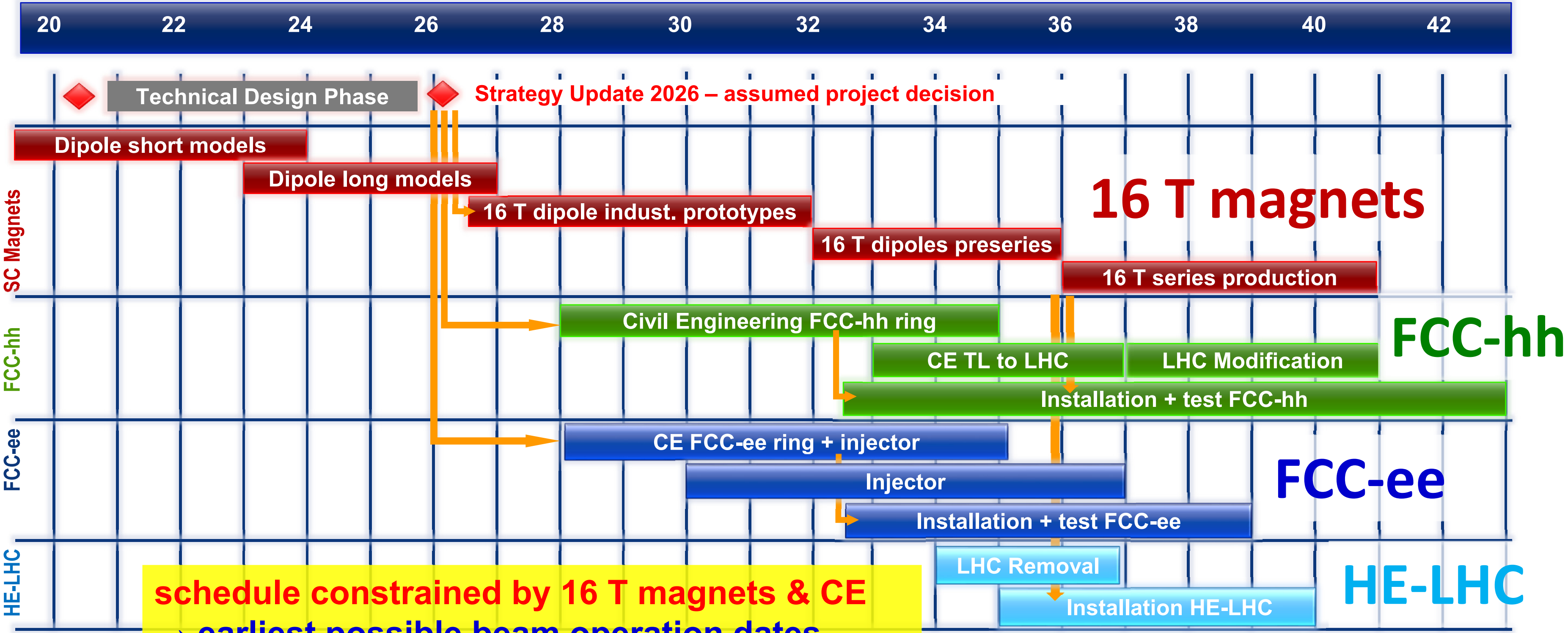
CE schedule studies





- Total construction duration 7 years
- First sectors ready after 4.5 years

Technical Schedule for each of the 3 options



schedule constrained by 16 T magnets & CE
→ earliest possible beam operation dates
- **FCC-ee: 2039**
- **FCC-hh: 2043**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

Global FCC Collaboration

124 Institutes

30 Companies

32 Countries

EC H2020

Conclusions

- The FCC study focuses on high-performance energy frontier circular colliders for the post-LHC era
- Baseline machine designs established with performance matching the demanding physics requirements
- Present focus is on completion of the conceptual design reports as input for European Strategy update
- Worldwide R&D programs in place on Nb_3Sn superconductor, high-field magnets and highly-efficient SC RF
- International FCC collaboration is growing steadily, there are many R&D opportunities and all the community is invited to join