Future Circular Collider Study
Overview and Design Status

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19TH HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY

Corfu, Greece

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

http://cern.ch/fcc

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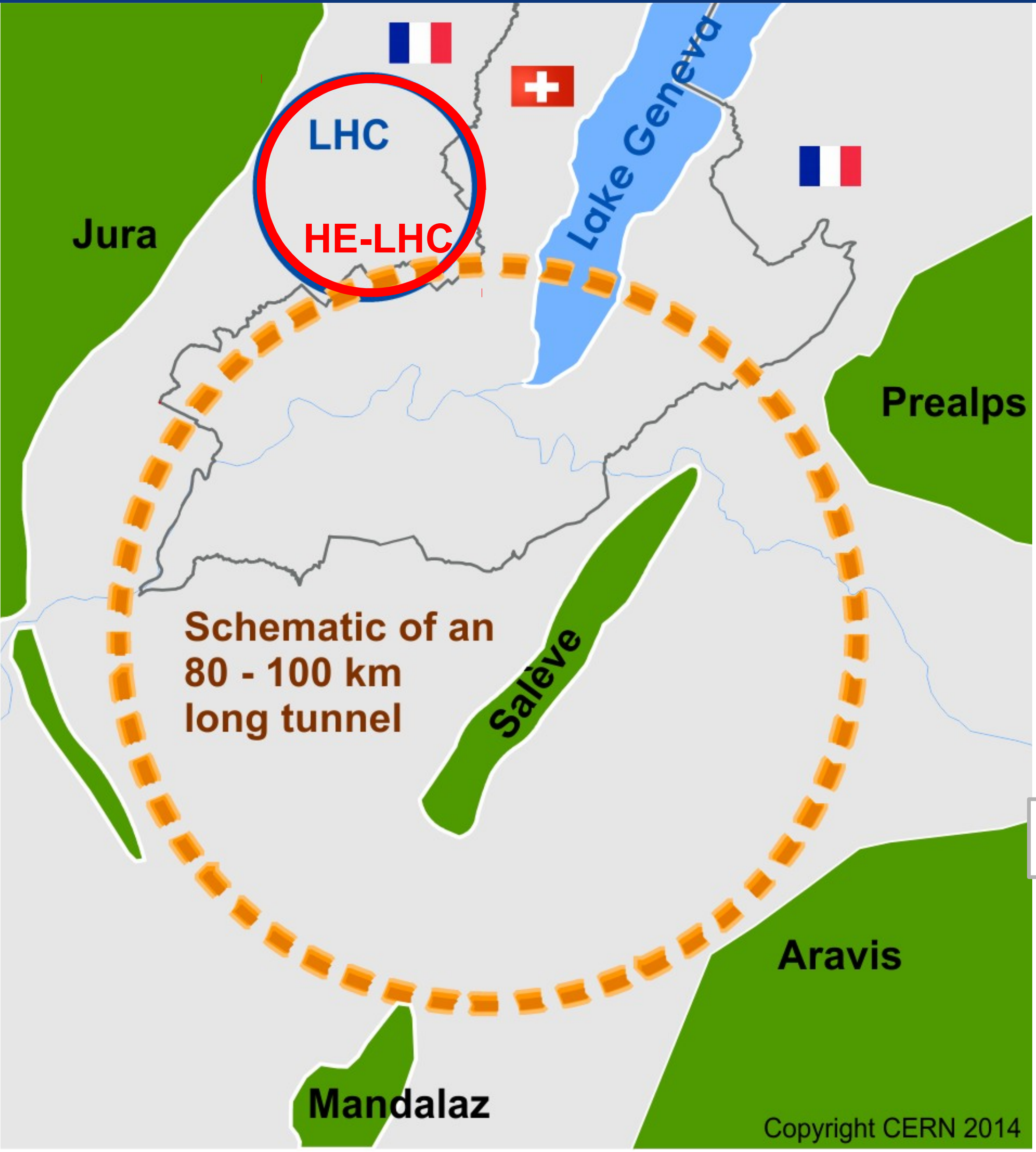
European Commission | Horizon 2020 European Union funding for Research & Innovation

photo: J. Wenninger

Future Circular Collider Study

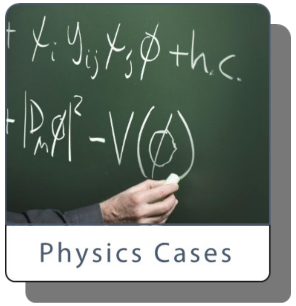


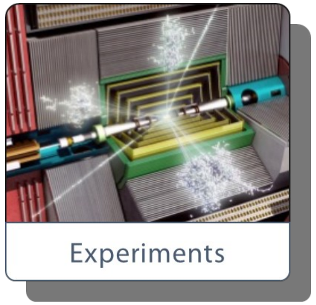
International FCC collaboration (CERN as host lab) to study:

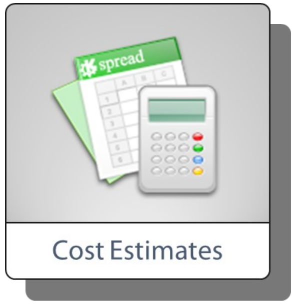
- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- ***pp*-collider (*FCC-hh*)** long-term goal, defining infrastructure

~16 T ⇒ 100 TeV *pp* in 100 km

- **HE-LHC** with *FCC-hh* technology







FCC Study: Physics & 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
  (m_Z, m_W, m_{top}, $\sin^2\theta_W^{eff}$, R_b, α_{QED} (m_Z), α_s (m_Z m_W m_τ), 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 CM energy & integrated luminosity ~ 20 ab^{-1} in 25 years

HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- CM 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

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Higgs Couplings

Christophe Grojean
ECFA-EPS Special Session
Ghent, July 2019

 # Higgscouplings whose sensitivity improves by 2/5/10 compared to HL-LHC

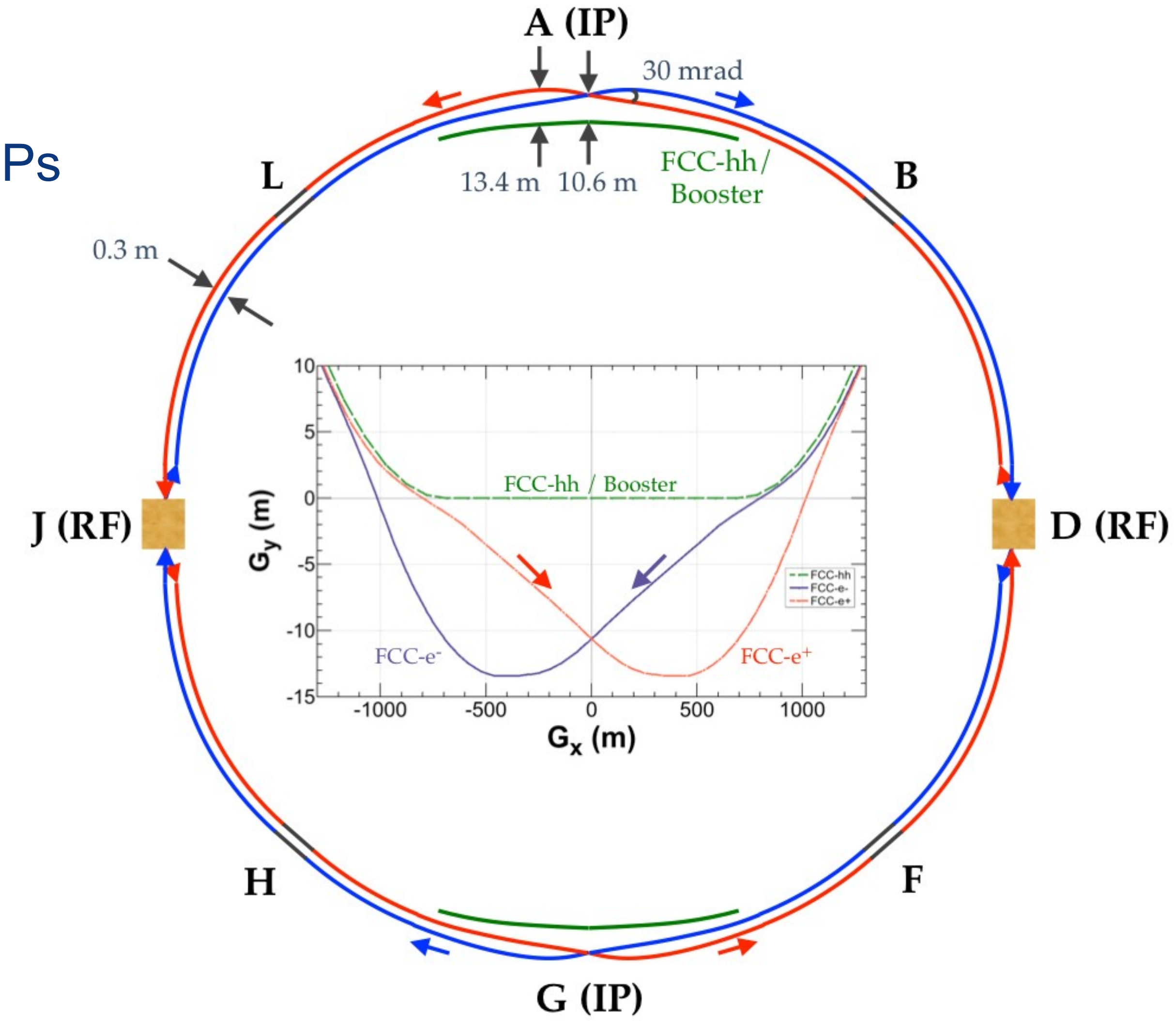
B. Heinemann for Higgs@FC WG

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2nd/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

All future colliders have rich potential to outperform (HL-) LHC in Higgs physics
Extensive reach in BSM discoveries

FCC-ee Basic Design Choices

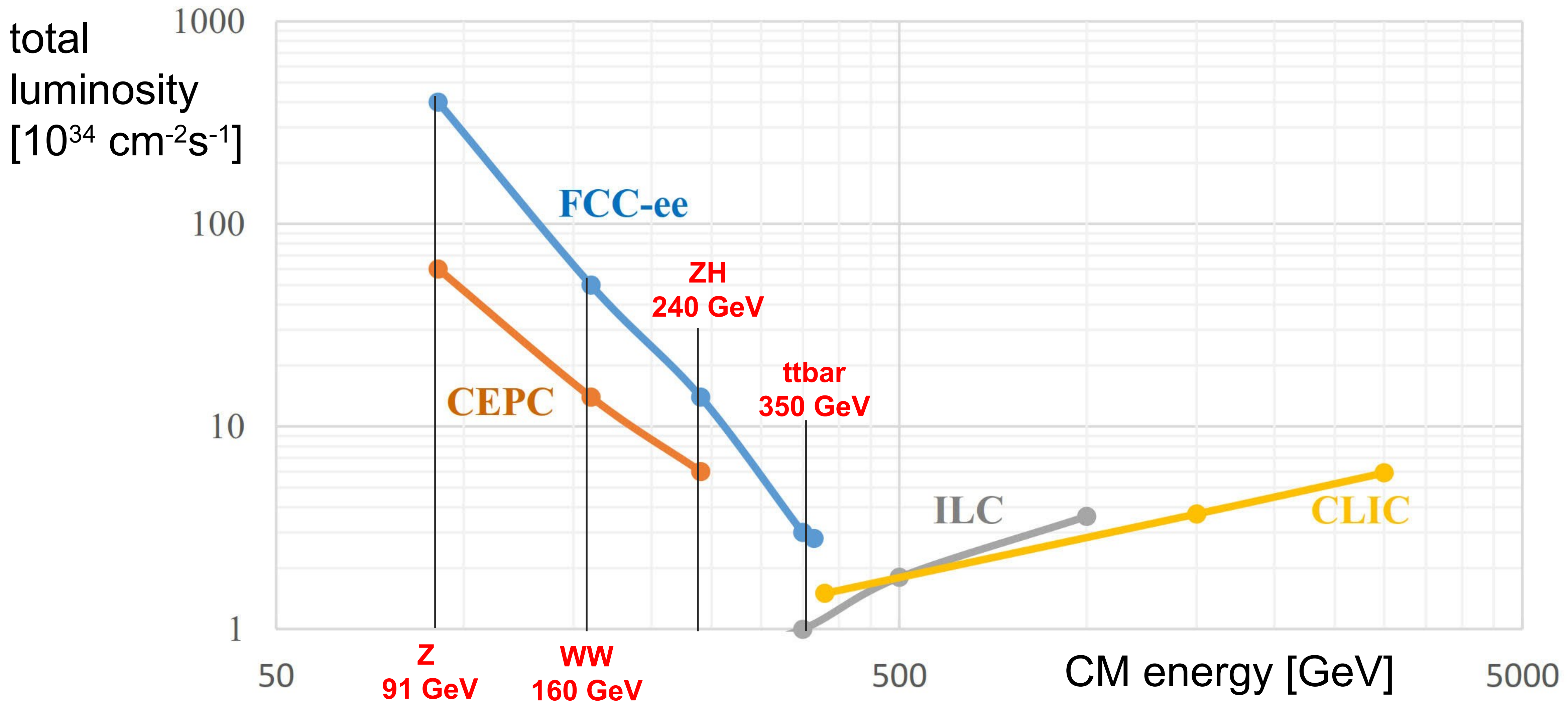
- **Double ring** e+ e- collider ~100 km
- **Common footprint with FCC-hh**, except around IPs
- **Asymmetric IR layout and optics** to limit synchrotron radiation towards the detector
- **2 IPs, large** horizontal crossing angle **30 mrad, crab-waist optics**
- **Synchrotron radiation power 50 MW/beam** 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 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	48 ab^{-1}/year		
W	25	6 ab^{-1}/year	**10 ab^{-1}**	**2**
H	7.0	1.7 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	0.34 ab^{-1}/year	**1.5 ab^{-1}**	**4**

programme duration: 15 years ***- including machine mod***

e 1 (*Z*, *W*, *H*): 9 years, Phase 2 (top): 6 years

FCC-ee RF Staging Scenario

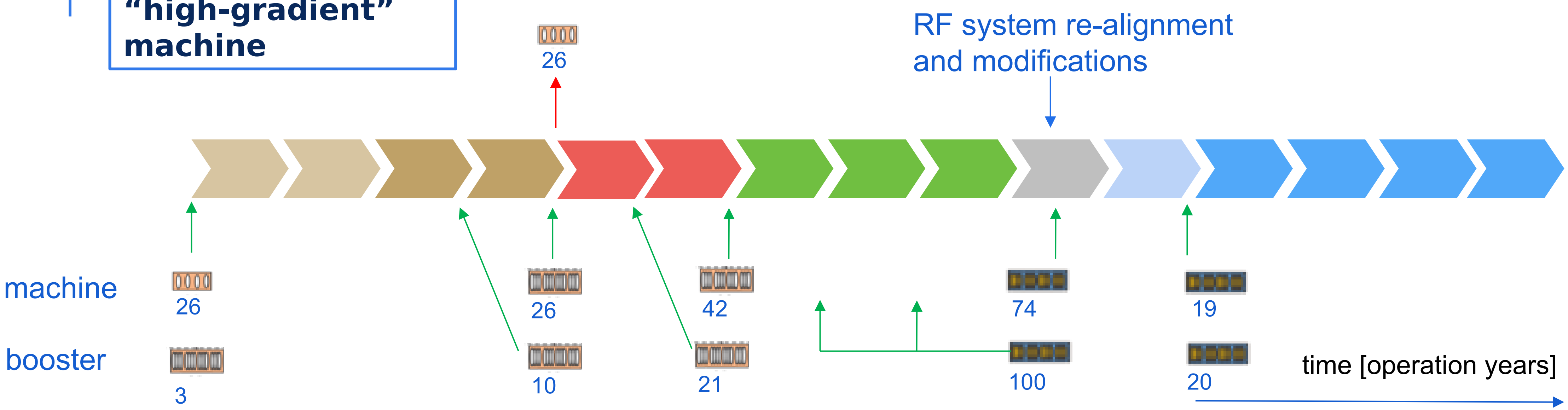
WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

"Ampere-class" machine

"high-gradient" machine

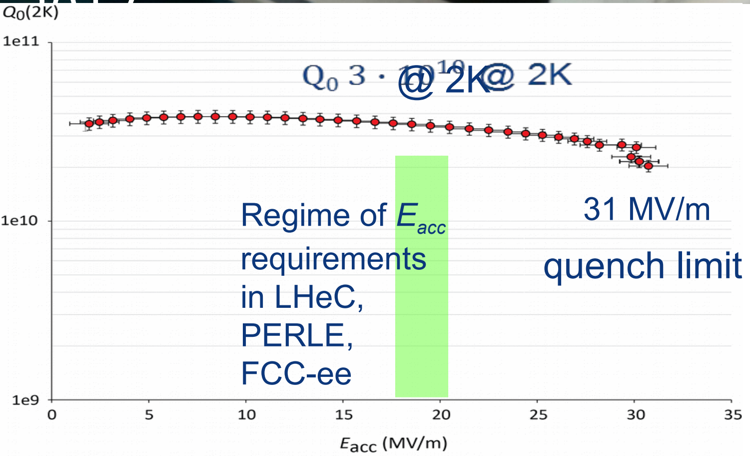
Three sets of RF cavities to cover all options for FCC-ee & Booster:

- **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)**



Progress with SCRF cavity R&D Programme

5-cell 800 MHz cavity, JLAB prototype for both FCC-ee (t-



Seamless 400 MHz single-cell cavity formed by

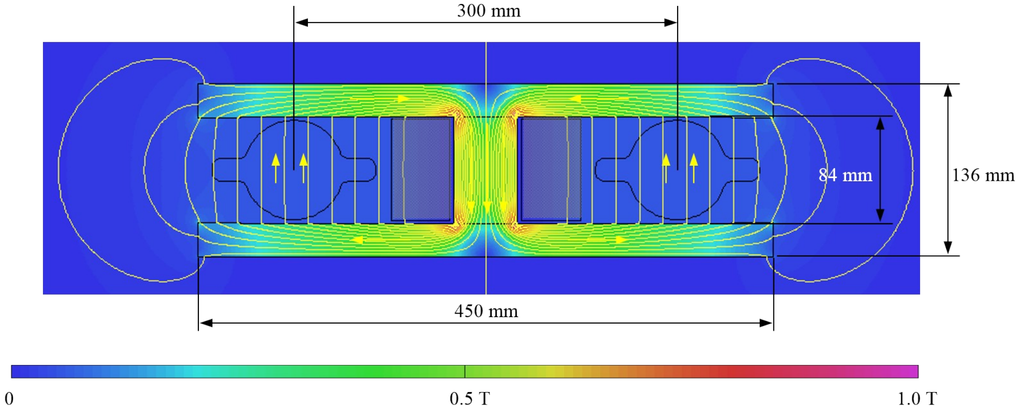
Tooling fabricated and successfully tested with an Aluminium cavity.

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

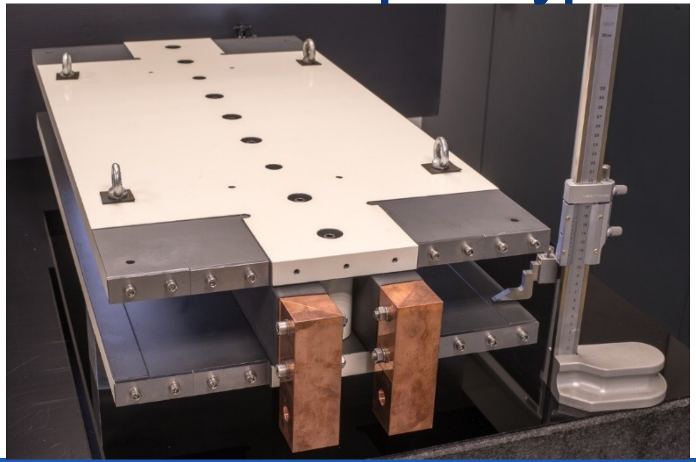
High strain rate technology using shockwaves in water from HV discharge. EHF investigated for half-cells and seamless Nb and Cu cavities.

Prototypes of FCC-ee Low-power Magnets

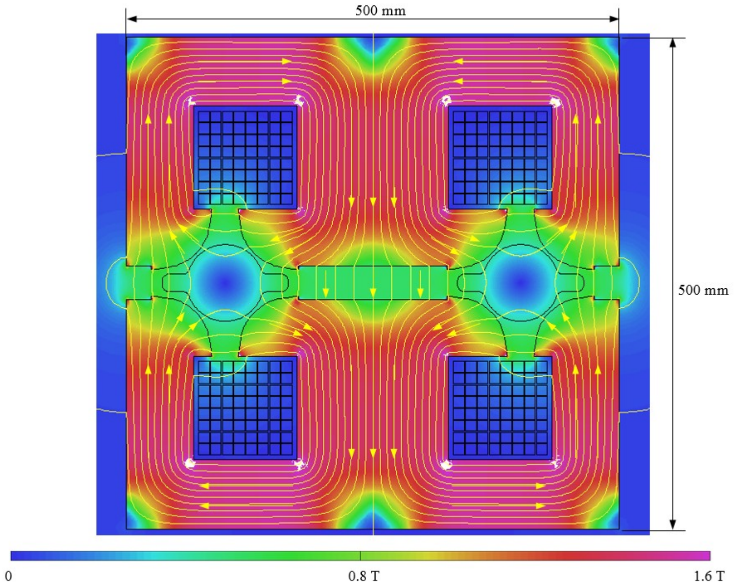
Twin-dipole design with 2X power saving
16 MW (at 175 GeV), with Al busbars



first 1 m prototype



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



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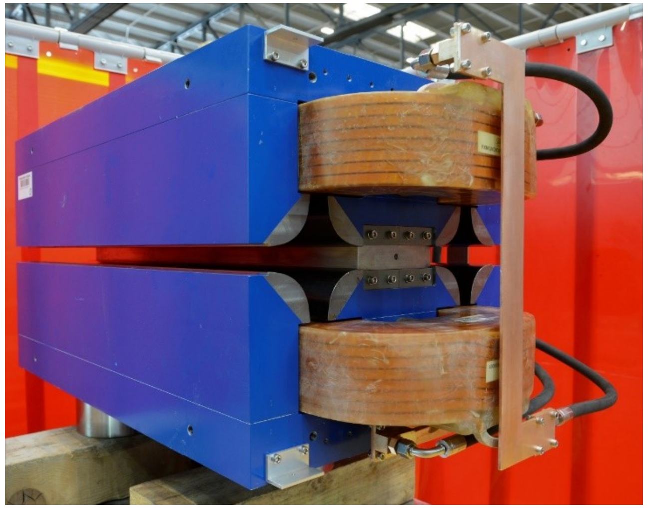
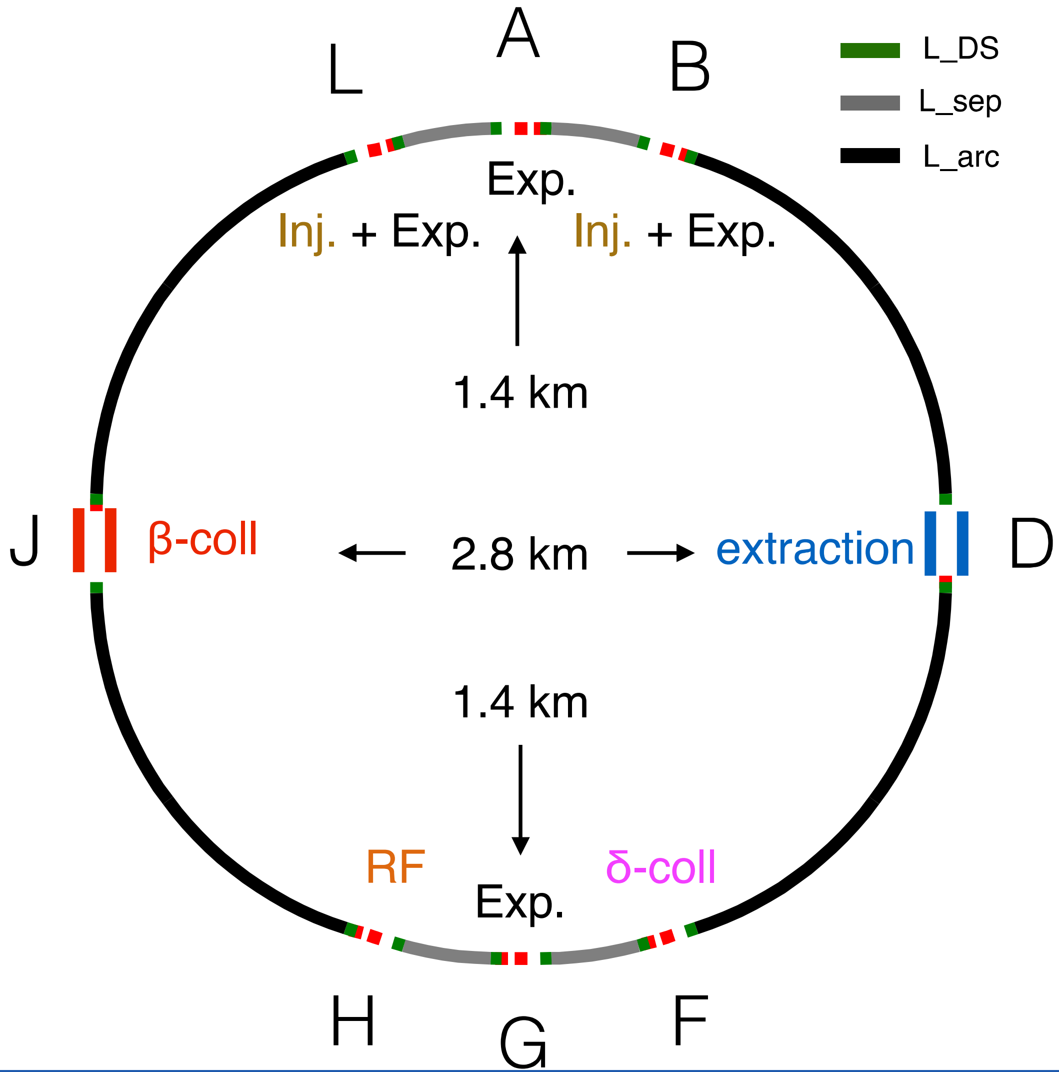


FCC-pp Collider Parameters

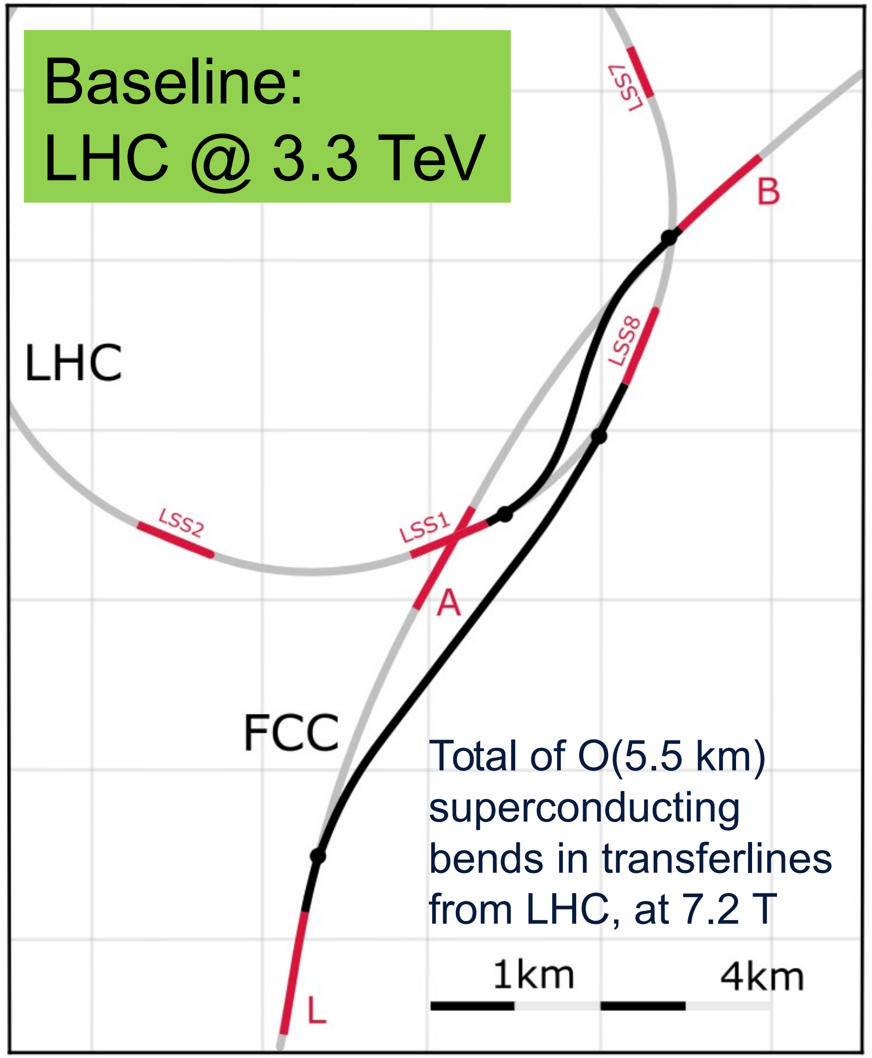
parameter	FCC-hh		HE-LHC	HL-LHC	LHC
Collision energy cms [TeV]	100		27	14	14
Dipole field [T]	16		16	8.33	8.33
Circumference [km]	97.75		26.7	26.7	26.7
Beam current [A]	0.5		1.27	1.1	0.58
Bunch intensity [10^{11}]	1	1	2.5	2.2	1.15
Bunch spacing [ns]	25	25	25	25	25
Synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.1	0.33	0.17
Long. emit. damping time [h]	0.54		1.8	12.9	12.9
Beta* [m]	1.1	0.3	0.45	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	16	5 (lev.)	1
Events/bunch crossing	170	1000	460	132	27
Stored energy/beam [GJ]	8.4		1.4	0.7	0.36

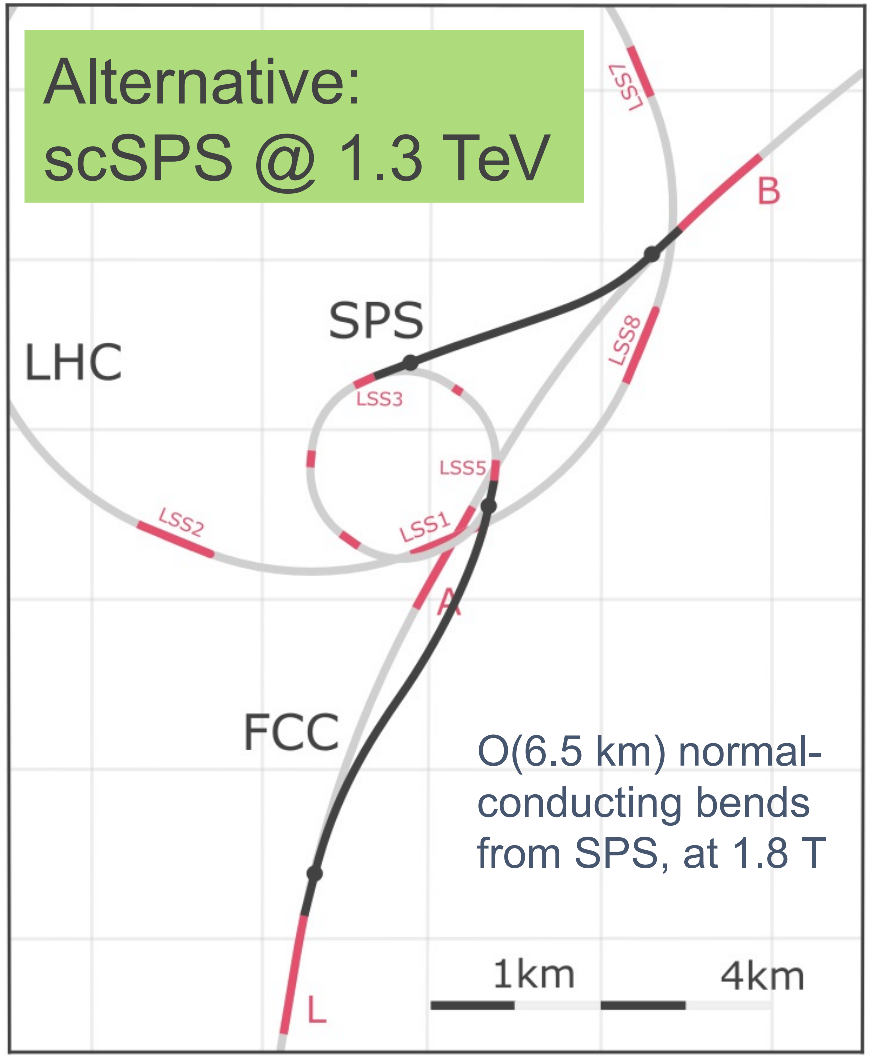
FCC-hh Lay-out and Optics



- **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

FCC-hh Injector Options and Transfer Lines





Current baseline:

- **Injection energy 3.3 TeV LHC**
- **Field-swing FCC-hh like LHC**

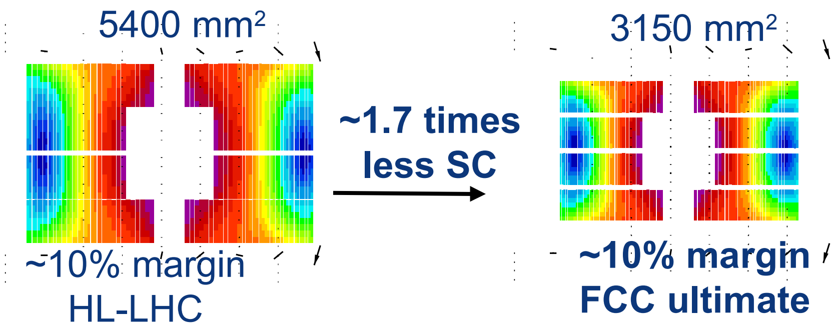
Alternative options:

- **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)**

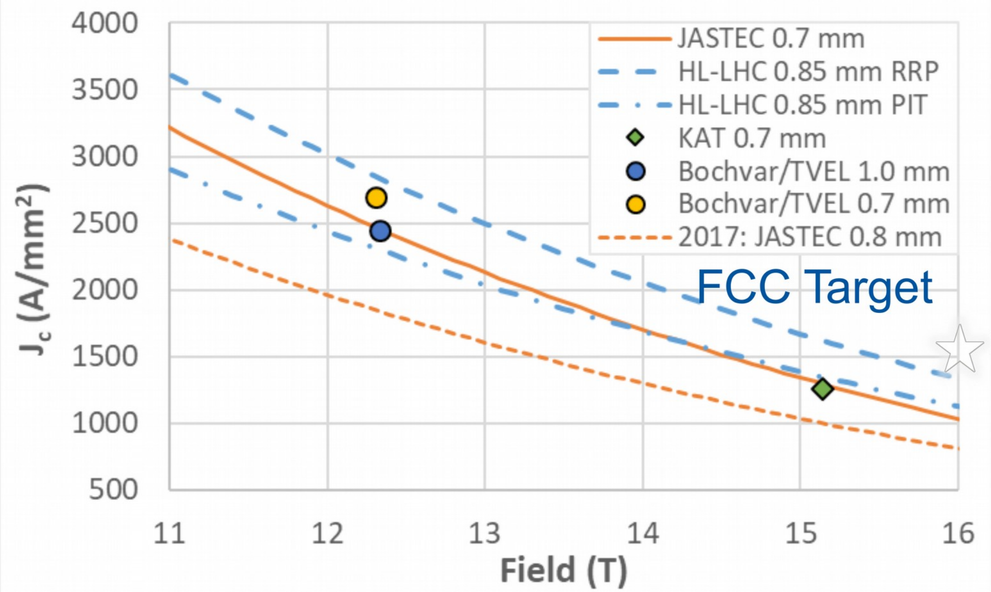
Worldwide FCC Nb_3Sn Programme

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**



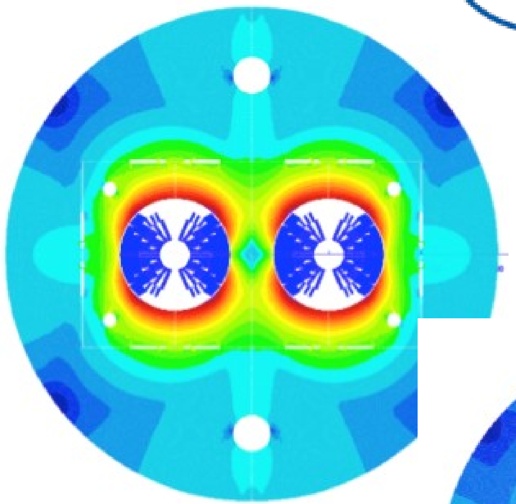
Conductor activities ongoing for FCC:

- **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 Freiburg, Germany**

16 T Dipole Design Activities and Options

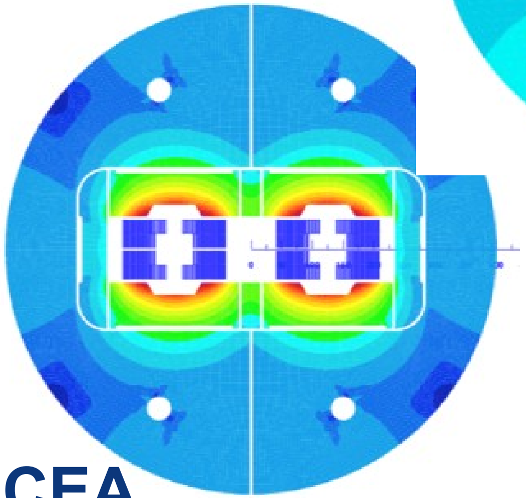
H2020 EuroCirCol
A key to New Physics

Cos-theta



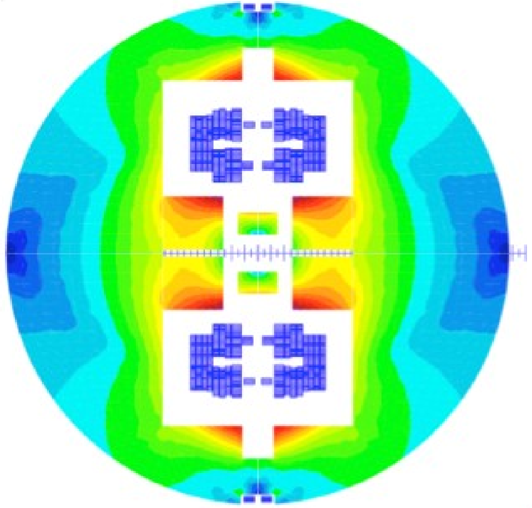
INFN

Blocks



CEA

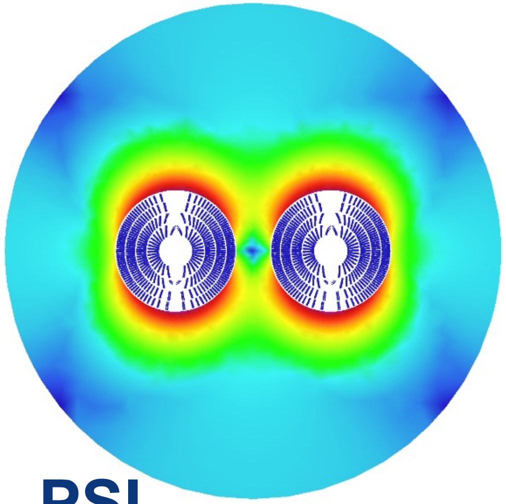
Common coils



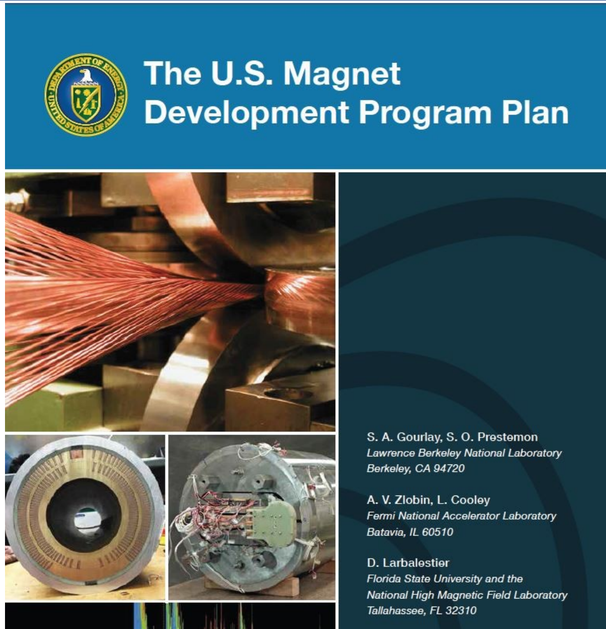
CIEMAT

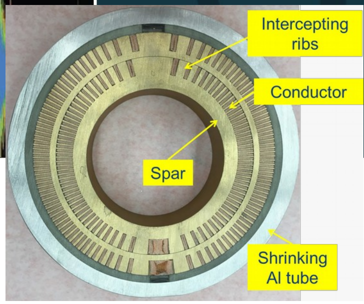
Swiss contribution

Canted Cos-theta

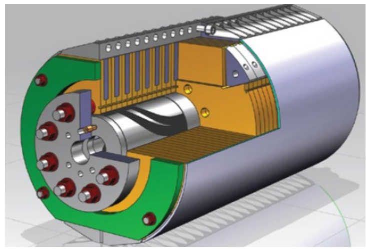


PSI





LBNL

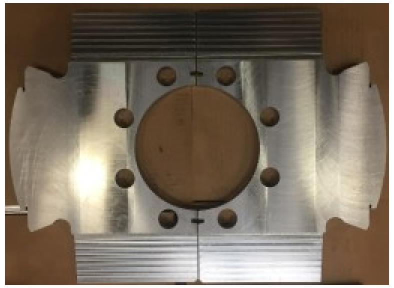


FNAL

Short model magnets (1.5 m lengths) will be built from 2019 – 2023

Russian 16 T magnet programme coordinated by BINP.

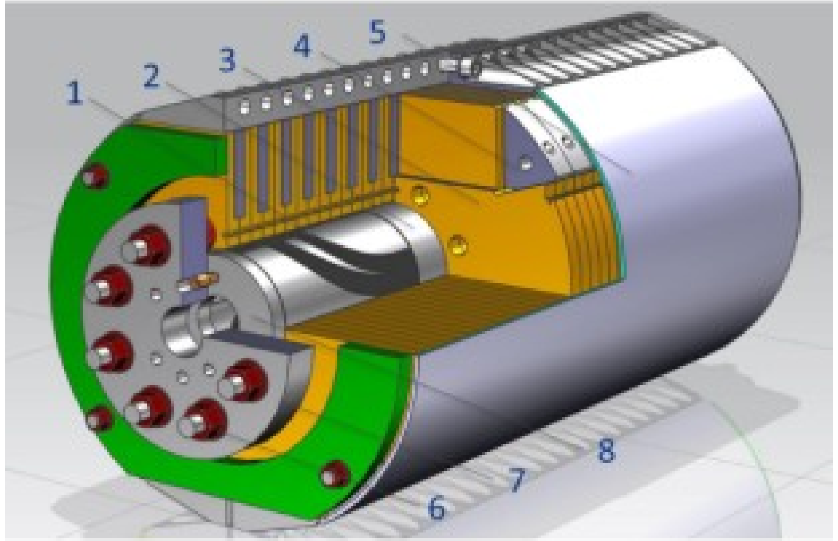
15 T Dipole Demonstrator (US-MDP)



Iron Laminations

AL I-Clamps

Fillers



StSt Skin

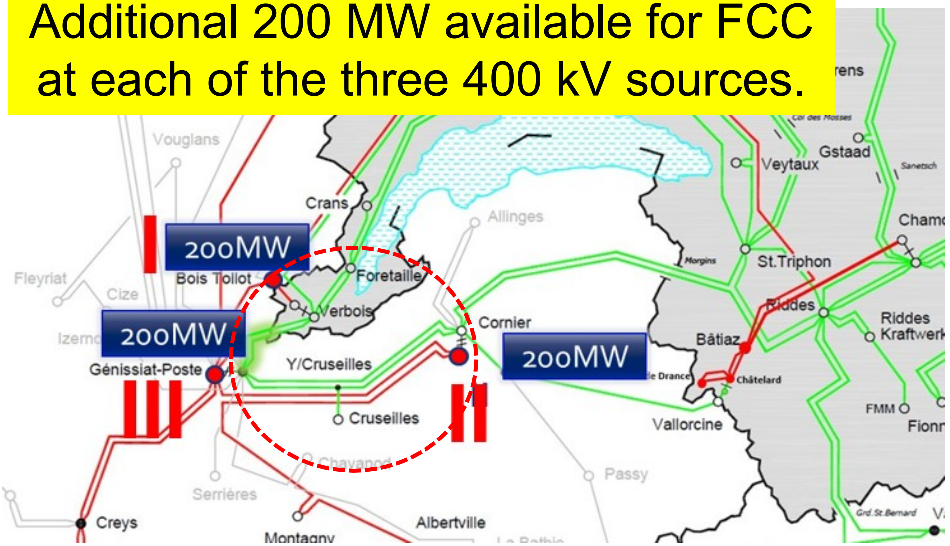
End Plates

Axial Rods

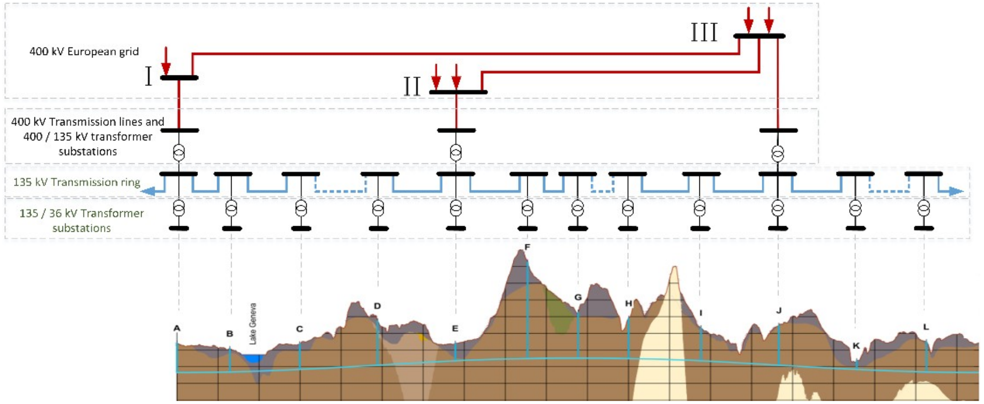
- **Magnet assembly nearly completed at FNAL, electrical tests ongoing**
- **First magnet test in coming weeks**

Supply and Distribution of Electrical Energy

Additional 200 MW available for FCC at each of the three 400 kV sources.

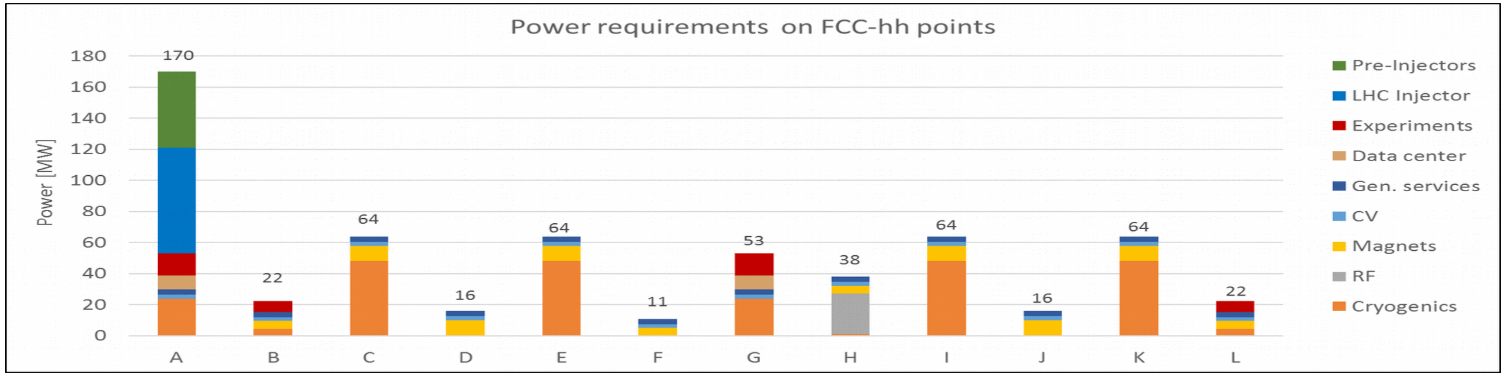


---- 400 kV ---- 230 kV

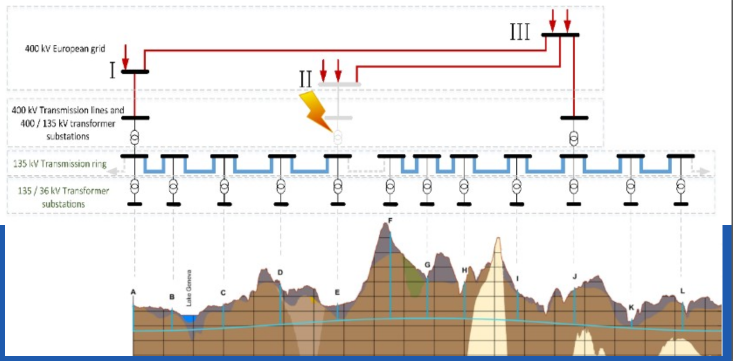


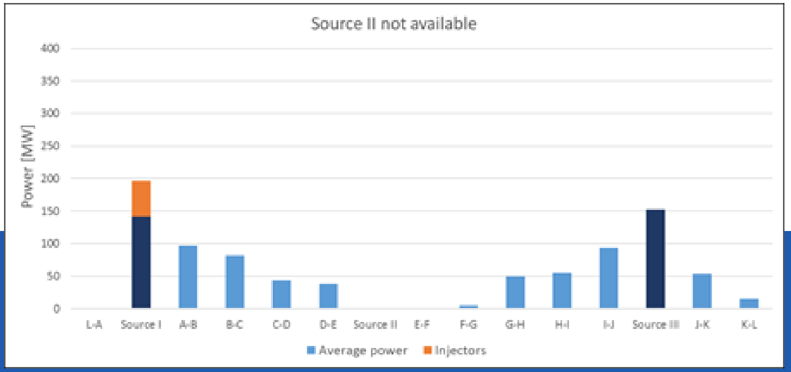
3 x 400 kV connections
+ 135 kV underground power distribution (NC)

Per-point power requirements as input for infrastructure-optimized conceptual design. (Peak FCC-ee 260 - 340 MW, total FCC-hh 550 MW)

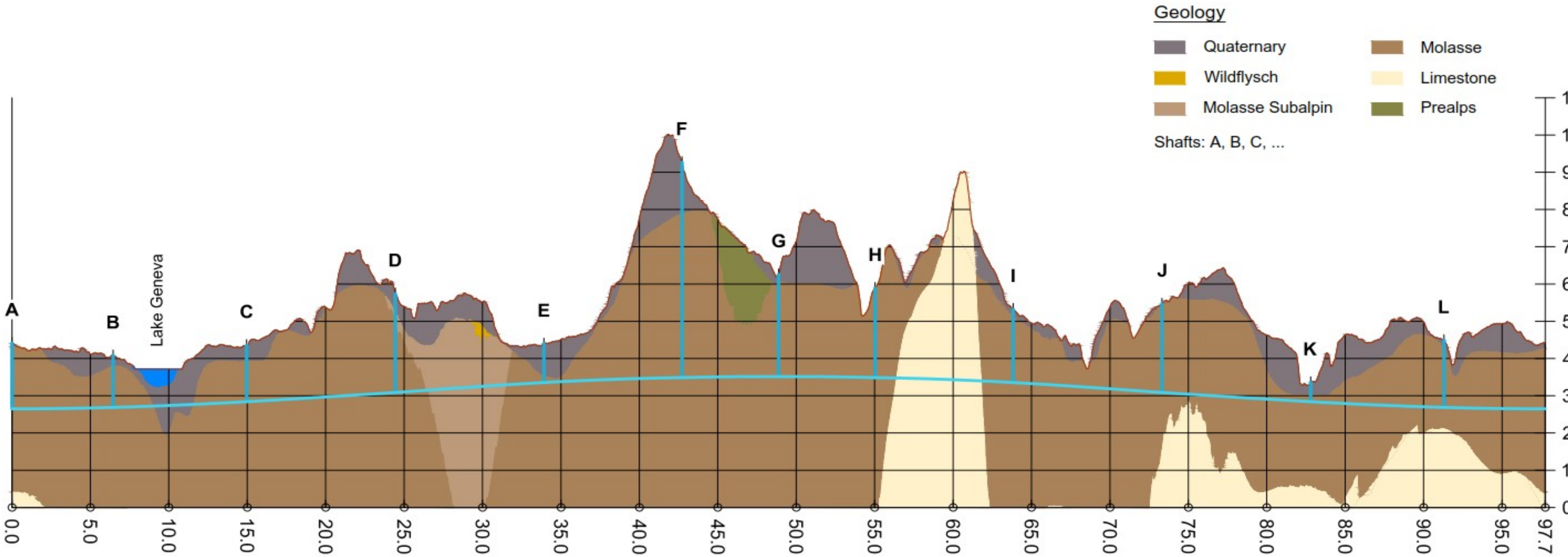


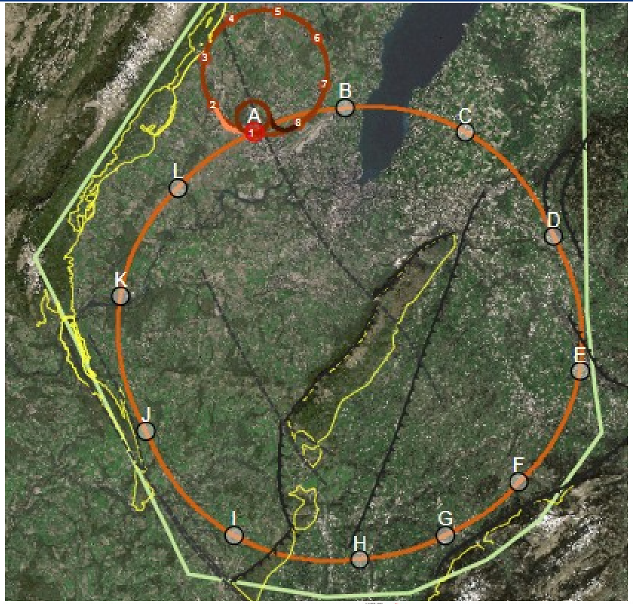
If one power source goes down fall back to „degraded mode“: FCC remains cold, vacuum preserved, controls on, RF off, no beam (“standby”). All FCC points supplied from 2 other 400 kV points, through the power transmission line.

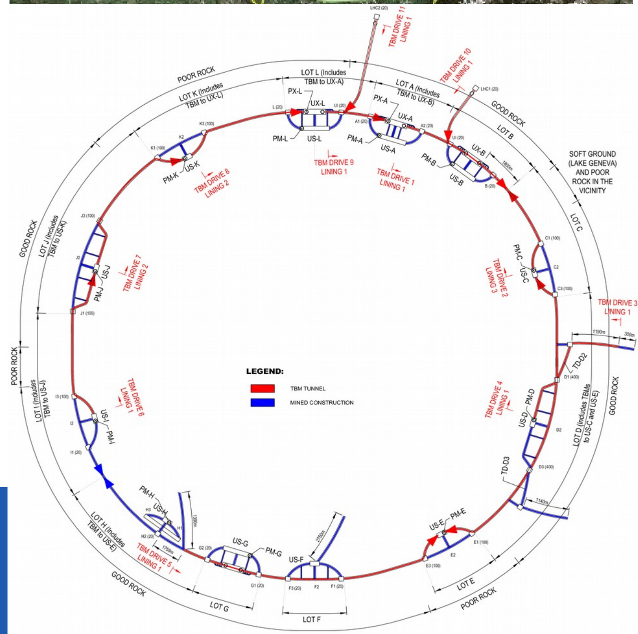




FCC Implementation - Baseline Footprint







Present baseline position was established considering:

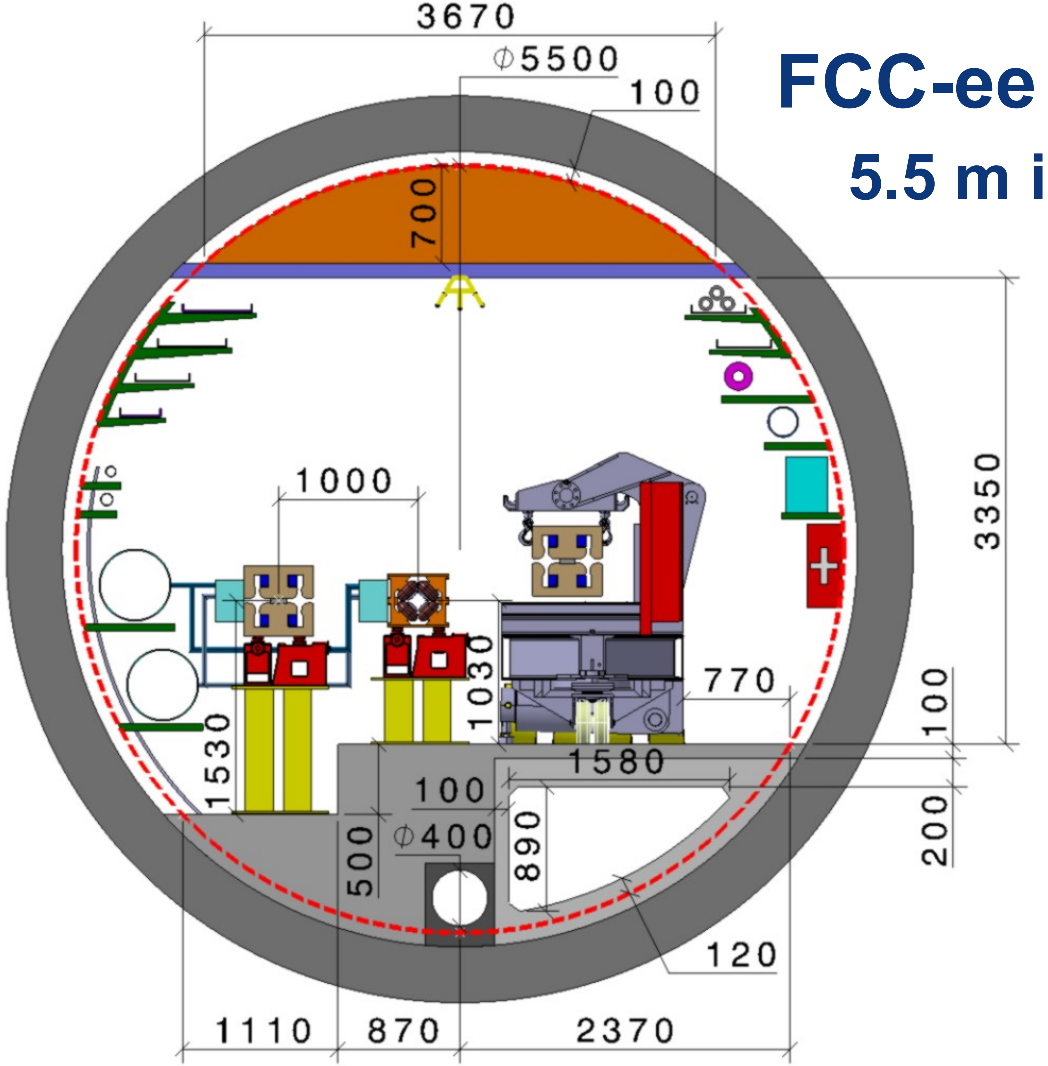
- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

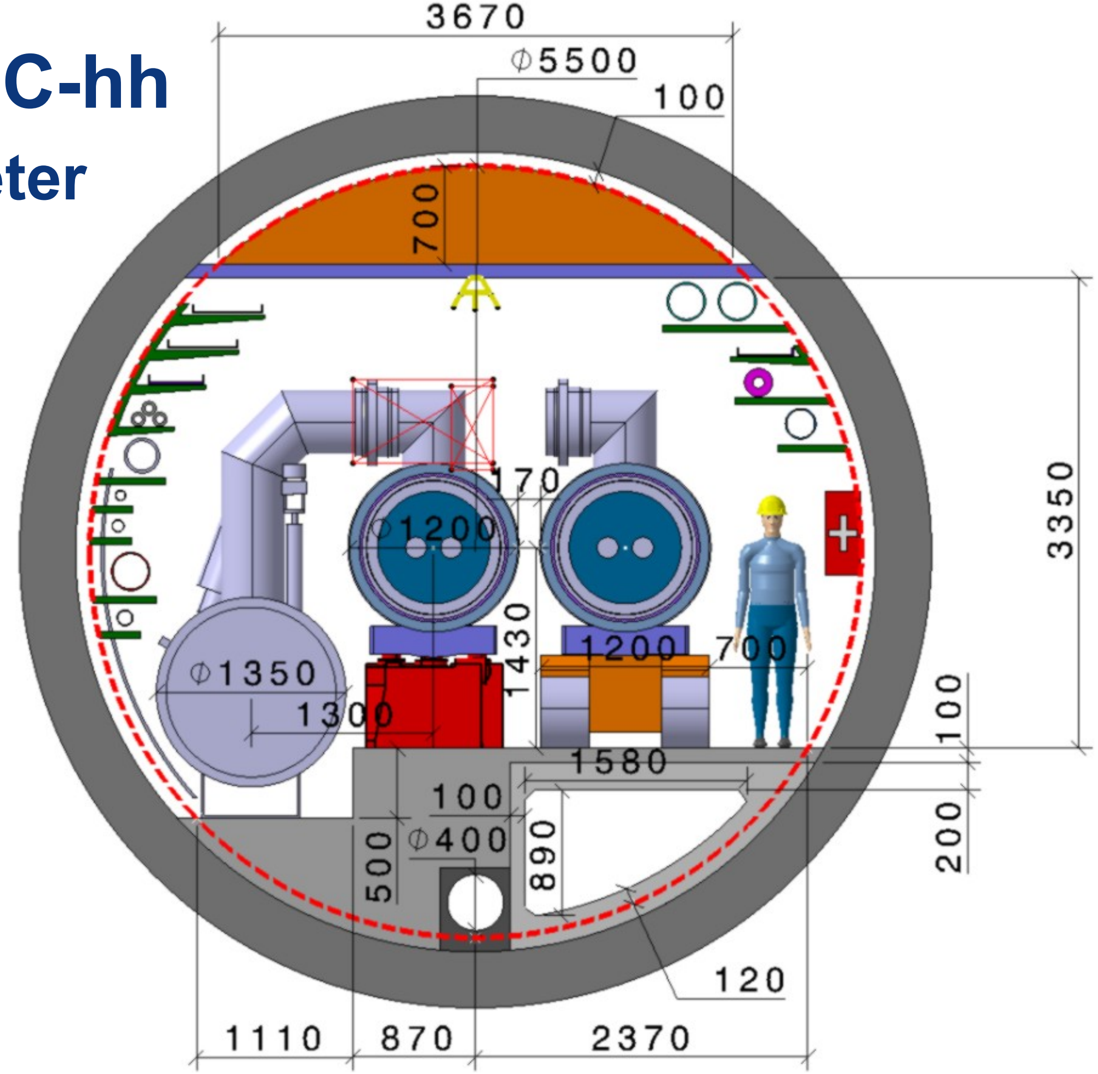
Next step: review of surface site locations and machine layout

FCC – Tunnel Integration in Arcs

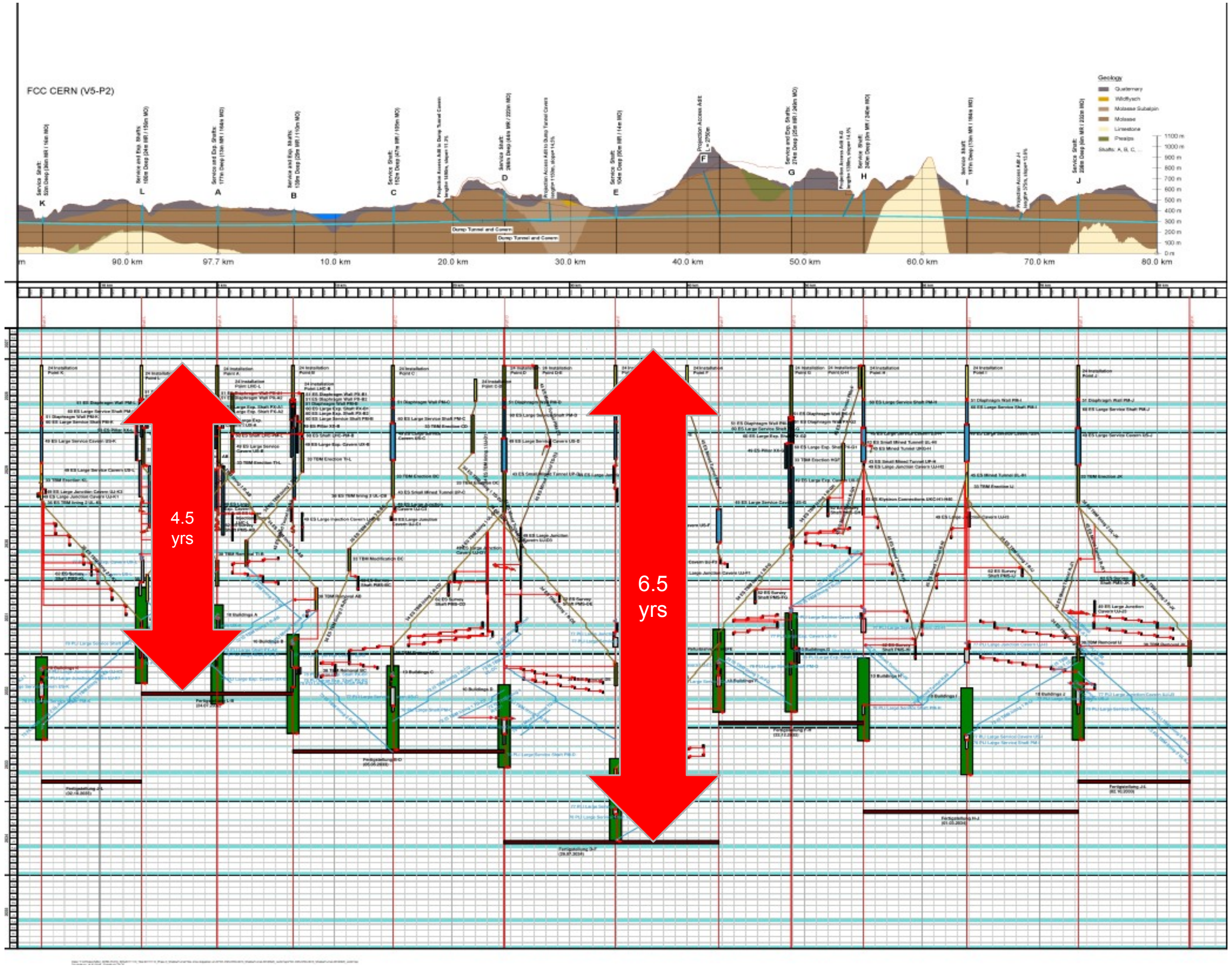
FCC-ee **FCC-hh**

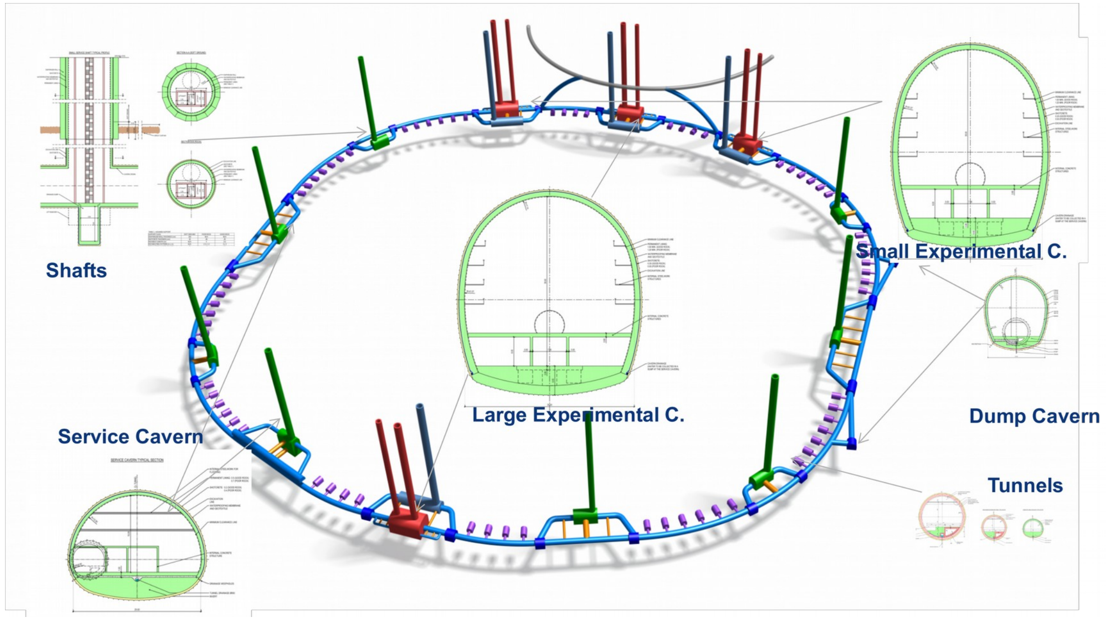
5.5 m inner diameter





CE Schedule Studies





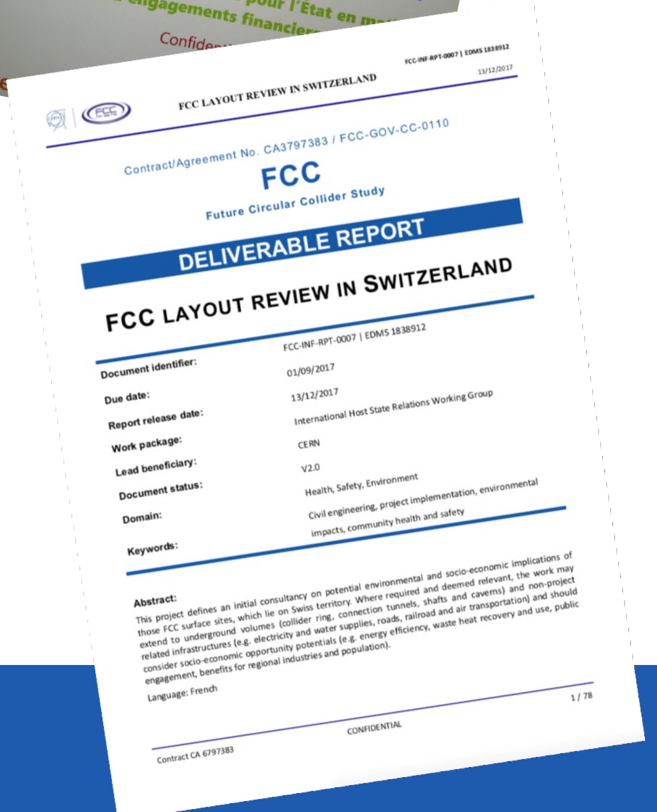
- Total construction duration 7 years
- First sectors ready after 4.5 years

FCC Work with Host States

General Secretariat of the Region Auvergne-Rhône-Alpes and notified body “Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement”

Working group with representatives of Federation, Canton and State of Geneva and representation of Switzerland at the international organisations and consultancy companies

- Administrative processes for project preparatory phase developed.
- First review of tunnel placement performed.
- Requirements for urbanistic, environmental, economic impact, land acquisition and construction permit related processes defined.
- **For 2019, common optimization of collider tunnel and surface site infrastructure planned.**


FCC LAYOUT REVIEW IN SWITZERLAND

Contract/Agreement No. CA3797383 / FCC-GOV-CC-0110

FCC

Future Circular Collider Study

DELIVERABLE REPORT

FCC LAYOUT REVIEW IN SWITZERLAND

Document identifier:	FCC-INF-RPT-0007 | EDMS 1838912
Due date:	01/09/2017
Report release date:	13/12/2017
Work package:	International Host State Relations Working Group
Lead beneficiary:	CERN
Document status:	V2.0
Domain:	Health, Safety, Environment
Keywords:	Civil engineering, project implementation, environmental impacts, community health and safety

Abstract:
This project defines an initial consultancy on potential environmental and socio-economic implications of those FCC surface sites, which lie on Swiss territory. Where required and deemed relevant, the work may extend to underground volumes (collider ring, connection tunnels, shafts and caverns) and non-project related infrastructures (e.g. electricity and water supplies, roads, railroad and air transportation) and should consider socio-economic opportunity potentials (e.g. energy efficiency, waste heat recovery and use, public engagement, benefits for regional industries and population).

Language: French

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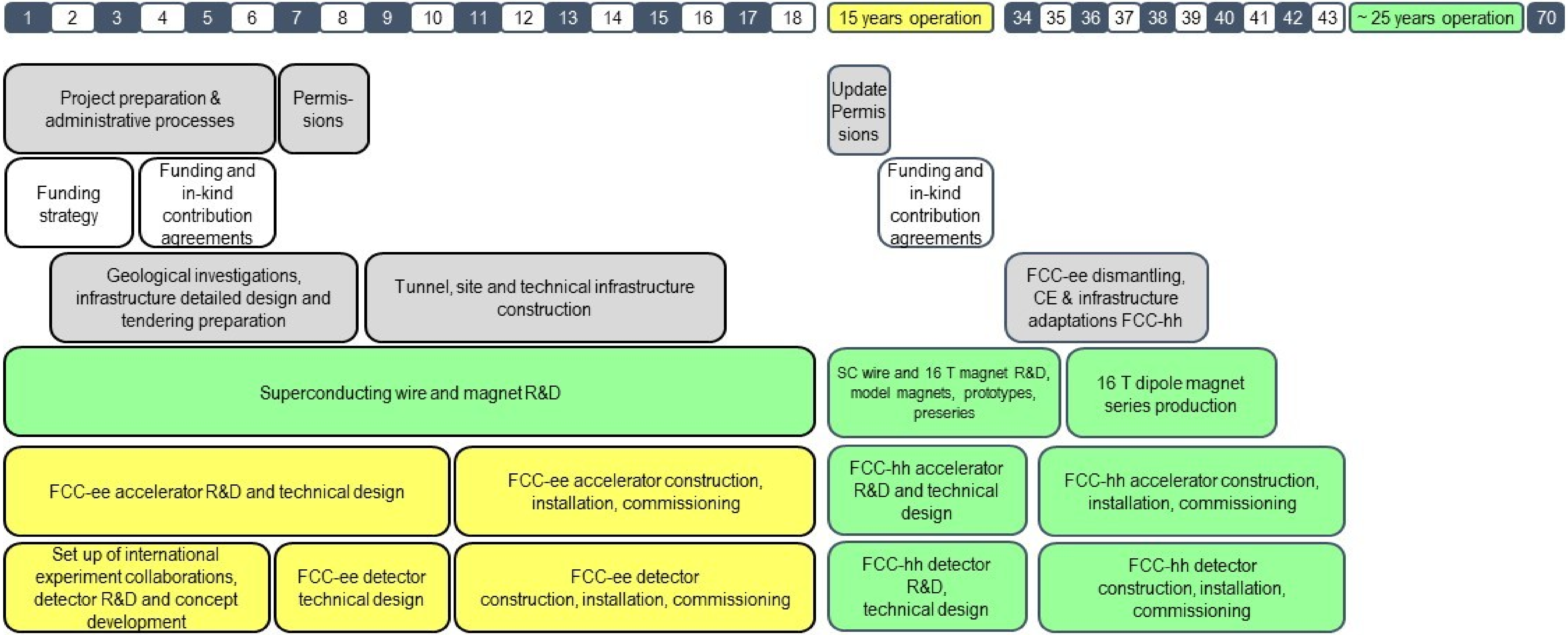
Contract CA 6797383 CONFIDENTIAL

FCC Integrated Project Technical Timeline



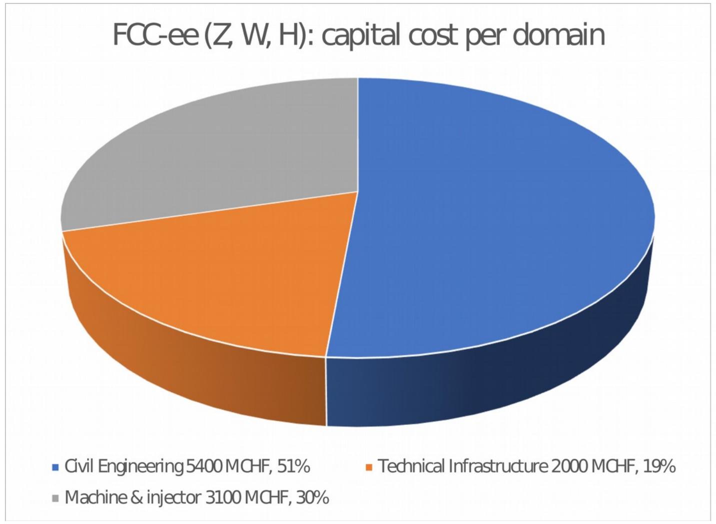
Input to Cost Estimates

- Consultants cost study for complete CE construction (including access roads, spoil transport and removal cost (normalized with ~10 large European tunnel projects).
- Machine technical designs as available.
- Scaling from LEP & LHC costs, HL-LHC & LIU activities.
- Further input from other machines and research centres, e.g. SuperKEKB injector linac, etc.

FCC-ee Cost Estimate

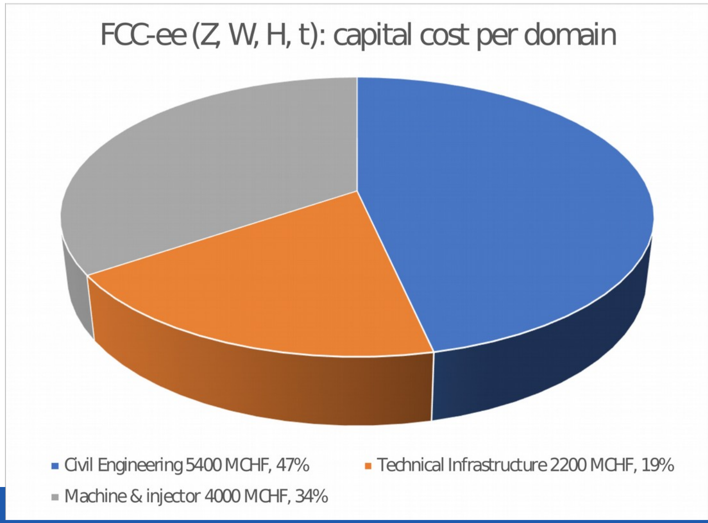
Total construction cost Phase 1 (Z, W, H) amounts to 10,500 MCHF

- 5,400 MCHF for civil engineering (51%)
- 2,000 MCHF for technical infrastructure (19%)
- 3,100 MCHF accelerator and injector (20%)



Complement cost for Phase 2 (ttbar) amounts to 1,100 MCHF

- 900 MCHF for RF, 200 MCHF for associated technical infrastructure



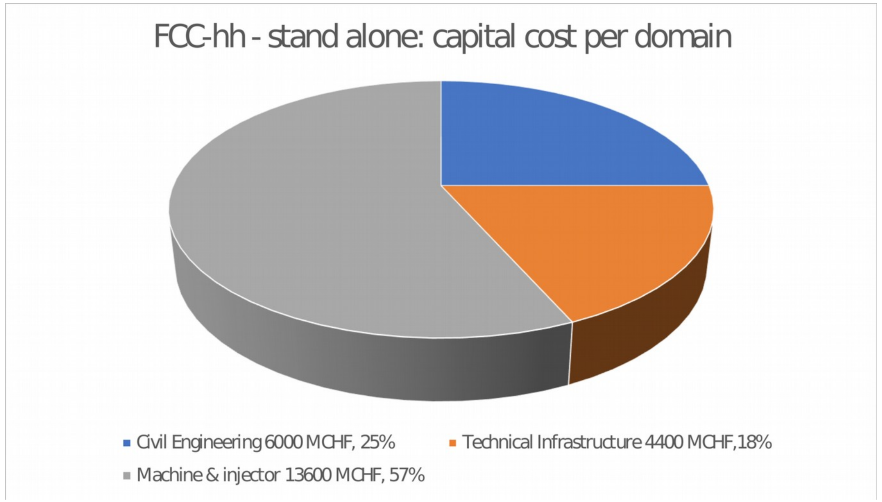
FCC-hh Cost Estimate

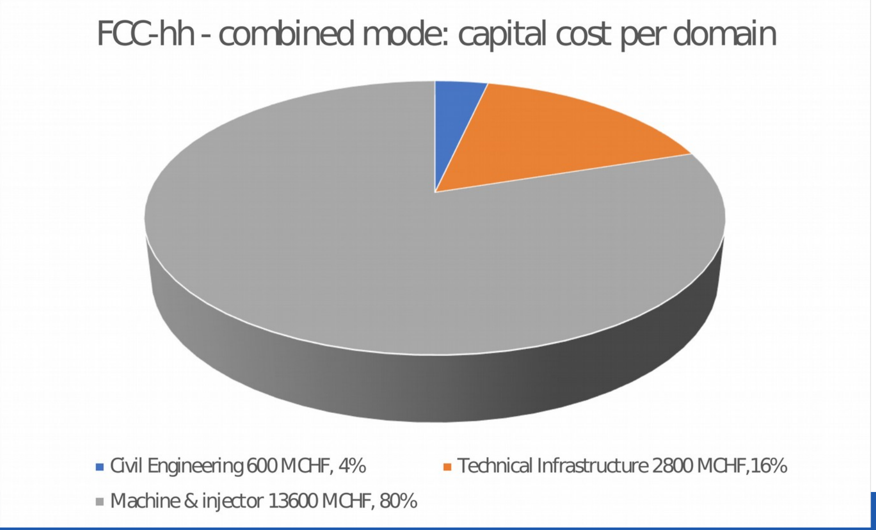
Total construction cost in “stand-alone” is 24,000 MCHF

- 13,600 MCHF accelerator and injector (57%)
  - Major part corresponds to the 4,700 Nb_3Sn 16 T main dipole magnets, totalling 9,400 MCHF, at cost target of 2 MCHF/magnet.
- 6,000 MCHF construction cost for surface and underground civil engineering (25%)
- 4,400 MCHF for technical infrastructures (18%)

Total construction cost in “combined mode” following FCC-ee is 17,000 MCHF.

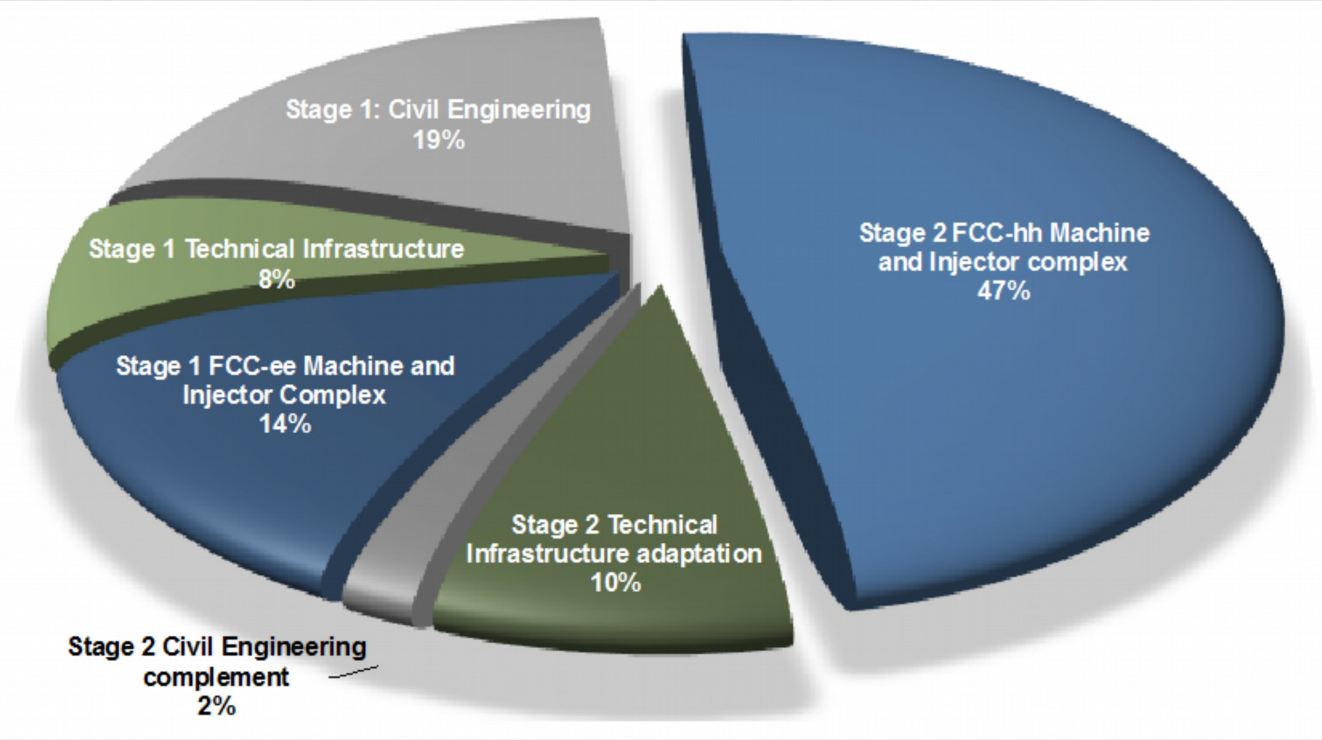
- CE and TI from FCC-ee re-used
- 600 MCHF for additional CE structures:
  - Two experiment caverns for the lower luminosity experiments
  - Beam dump tunnels and the two transfer lines from LHC
- 2,800 MCHF for additional TI, driven by cryogenics infrastructure





FCC-integrated Cost Estimate

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



FCC CDR and Study Documentation

- **FCC-Conceptual Design Reports:**
  - **Vol 1 – Physics, Vol 2 – FCC-ee, Vol 3 – FCC-hh, Vol 4 – HE-LHC**
  - Preprints available since 15 January 2019 on http://fcc-cdr.web.cern.ch/
  - CDRs submitted to **European Physical Journal C (Vol 1) and ST (Vol 2 - 4)**

- **Summary documents provided to EPPSU SG in December 2018**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

Status of Global FCC Collaboration

From Greece
AUTH, Thesaloniki
HOU, Patras
UOA, Athens
UPATRAS, Patras

136 Institutes

25 Companies

34 Countries

EC H2020

Final meeting of EuroCirCol DS (H2020 financed)

Some key topics:

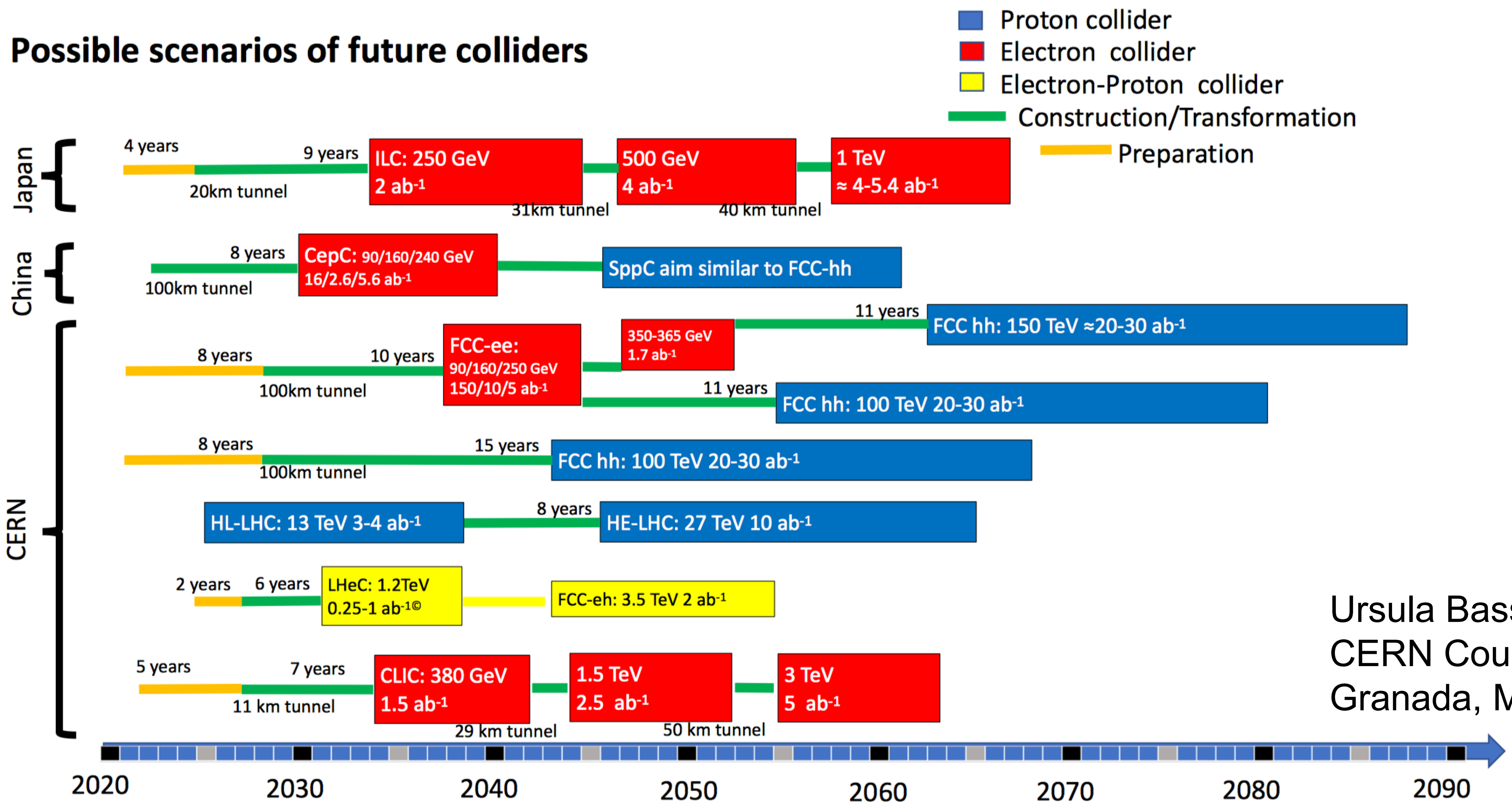
FCC physics

Studies on Tunnel Implementation and subsequent machine adaptation

R&D progress on SRF and SCM

FCC-ee :
Injector chain
MDI/IR optimization
Machine optimisation

Future of HEP



Ursula Bassler
CERN Council President
Granada, May 2019

Conclusions

- The FCC study focuses on high-performance energy frontier circular colliders for the post-LHC era.
- First phase of FCC conceptual design studies is completed with established baseline machine designs and performance matching the demanding physics requirements, documented in four Conceptual Design Reports.
- Worldwide R&D programmes 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.
- Next step, in parallel to ESU process, is development of a specific implementation scenario, accompanied by machine optimization, physics studies and technology R&D.