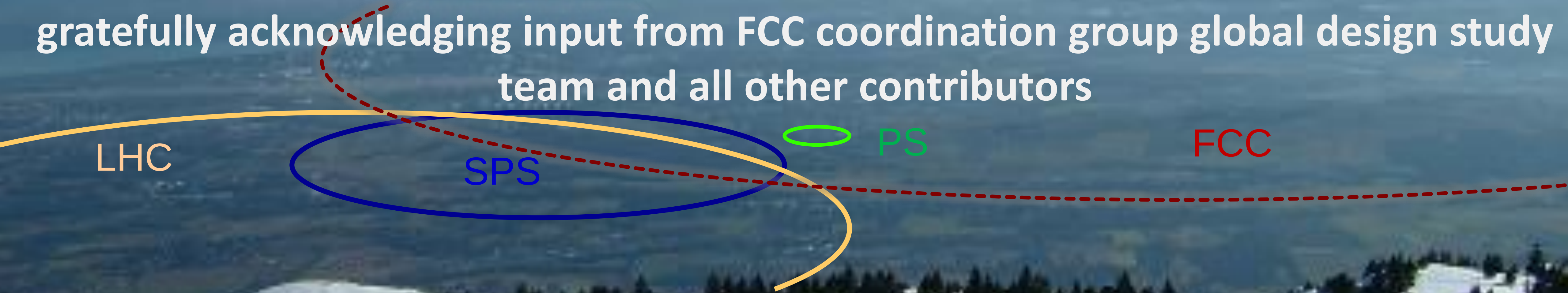
Future Circular Collider Study
Status and Plans

M. Benedikt and F. Zimmermann

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



FCC hh ee he

EuroCirCol

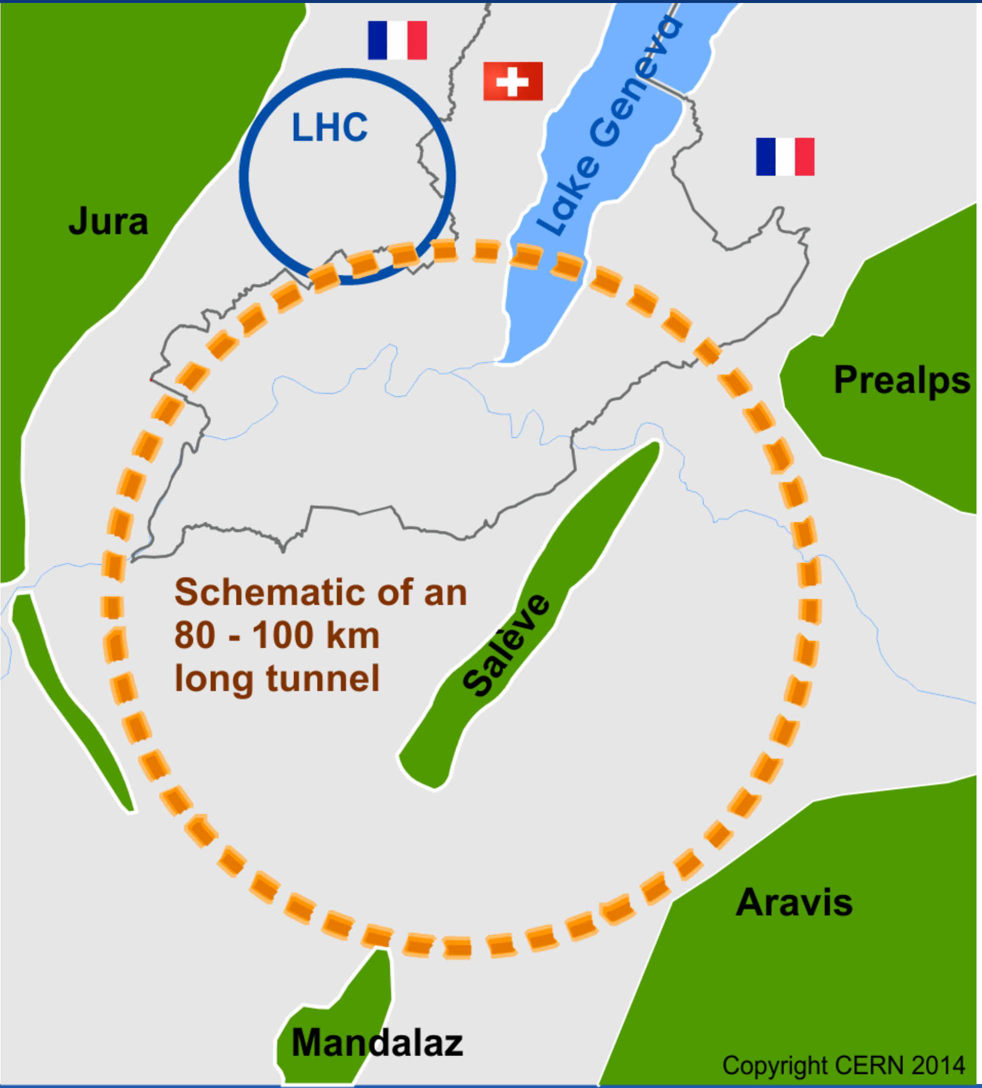
http://cern.ch/fcc

*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*

Contents

- Study status and major evolution since FCC week 2016 Rome
- FCC schedule considerations
- Further study planning towards Conceptual Design Report
- EASITrain H2020 training network

Scope of FCC Study

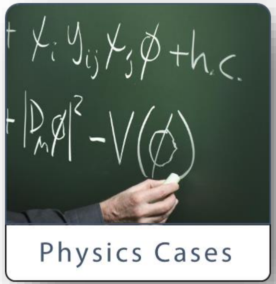


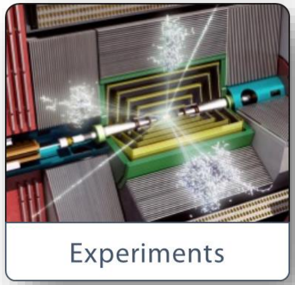
International FCC collaboration (CERN as host lab) to study:

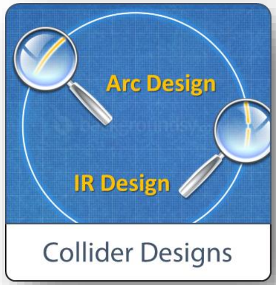
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

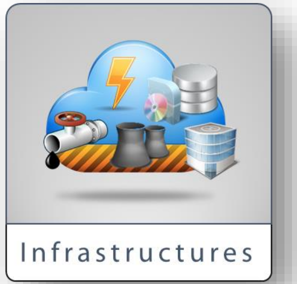
  ~16 T $\Rightarrow$ 100 TeV *pp* in 100 km

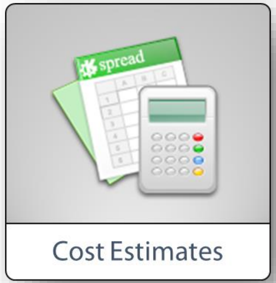
- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, e from ERL
- **HE-LHC** with *FCC-hh* technology
- **CDR for end 2018**











FCC-pp collider parameters

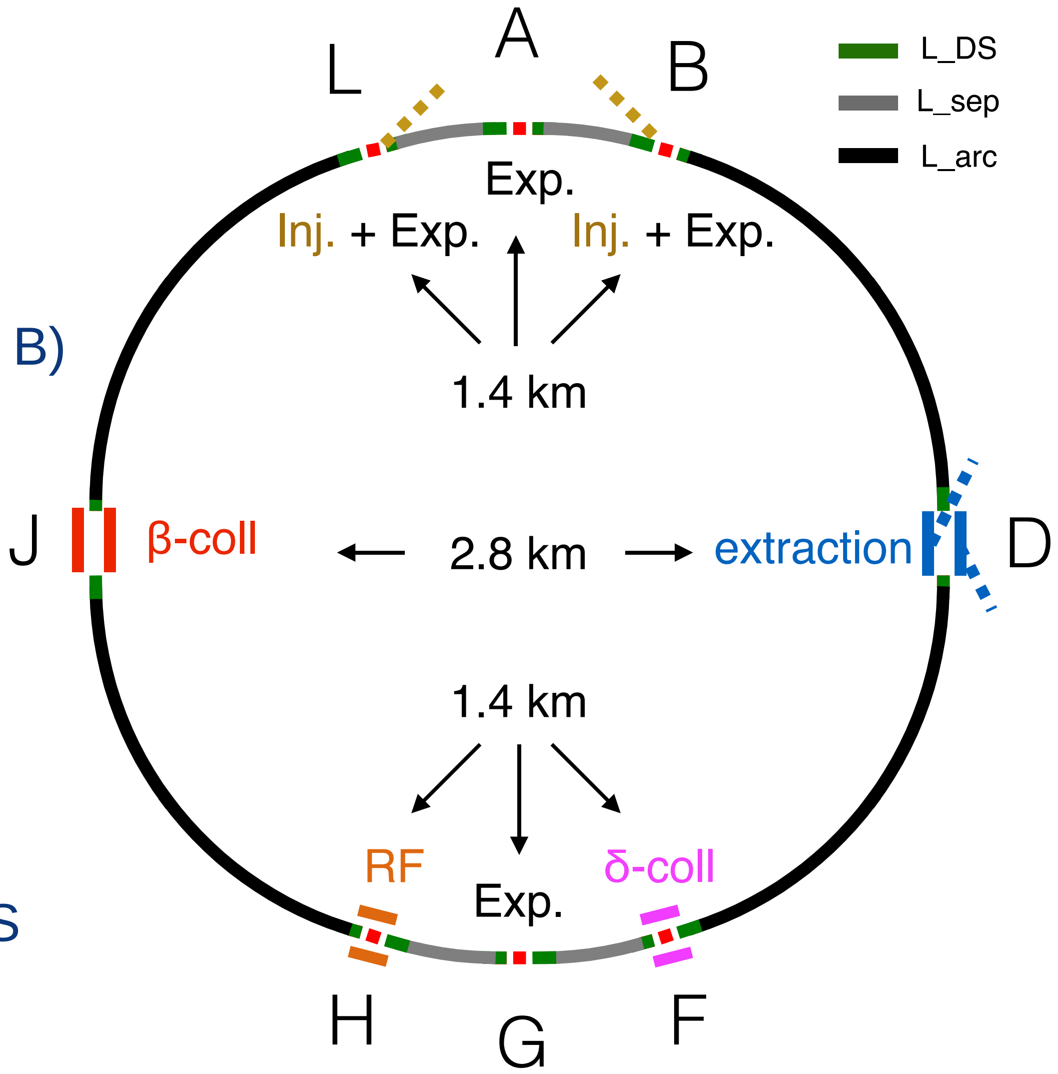
parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / 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	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

FCC-ee collider parameters

parameter	Z	W	H (ZH)	ttbar
cm collision energy [GeV]	91	160	240	350
beam current [mA]	1400	147	29	6.4
no. bunches	71000	7500	740	62
bunch intensity [10^{11}]	0.4	0.4	0.8	2.1
bunch spacing [ns]	2.5 / 5.0	40	400	5000
SR energy loss / turn [GeV]	0.036	0.34	1.71	7.72
total RF voltage [GV]	0.25	0.8	3.0	9.5
long. damping time [turns]	1280	235	70	23
horizontal beta* [m]	0.15	1	1	1
vertical beta* [mm]	1	2	2	2
horiz. geometric emittance [nm]	0.27	0.26	0.61	1.33
vert. geom. emittance [pm]	1.0	1.0	1.2	2.66
bunch length with SR & BS [mm]	4.1	2.3	2.2	2.9
luminosity [10^{34} $cm^{-2}s^{-1}$]	130	16	5	1.4

FCC-hh new 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



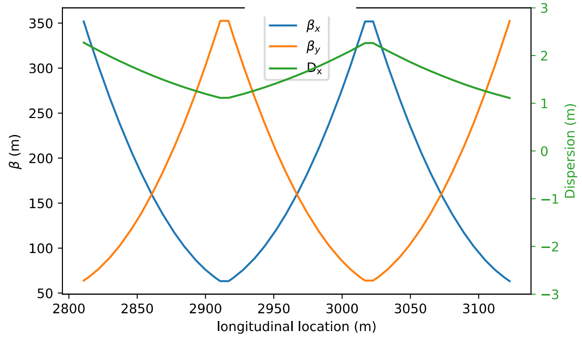
New features:

- **Overall length 97.75 km**
- **Economy length 2.25 km**
- Injections upstream side of experiments
- **Avoids mixing of extraction region and high-radiation collimation areas**

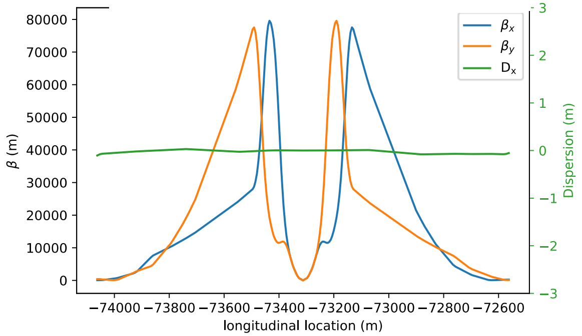
Taking this layout as fixed
(for CDR preparation)

Integrated FCC-hh lattice design

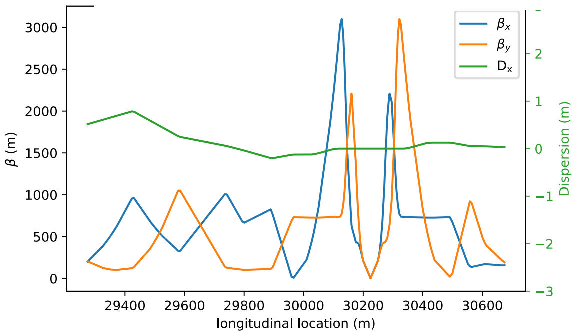
Arc



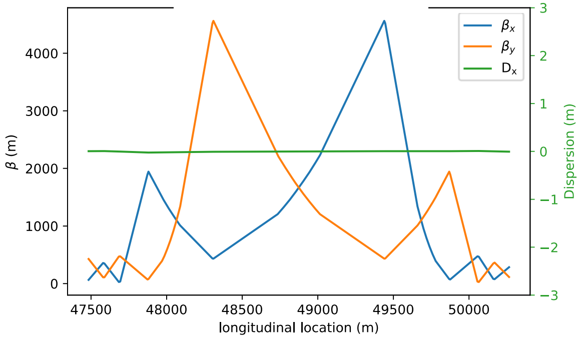
Main experiments



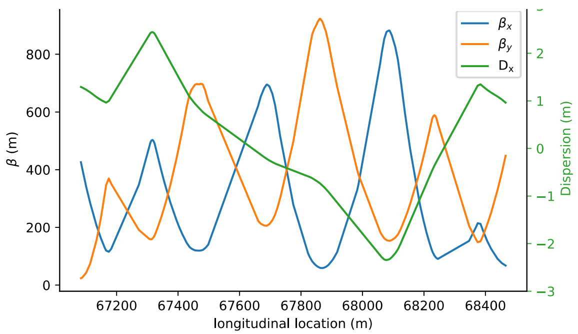
Special experiments



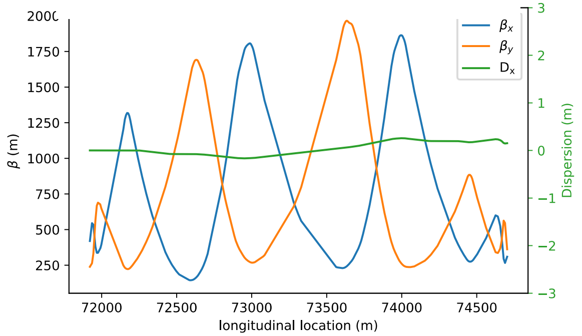
Extraction



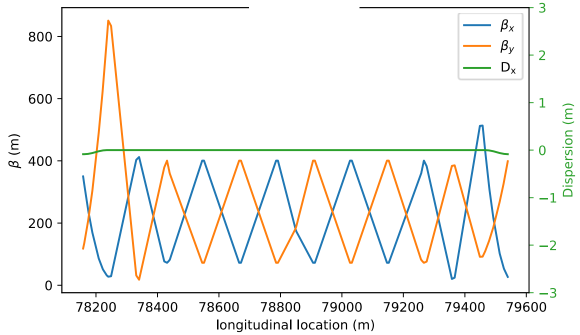
Momentum collimation



Betatron collimation



RF



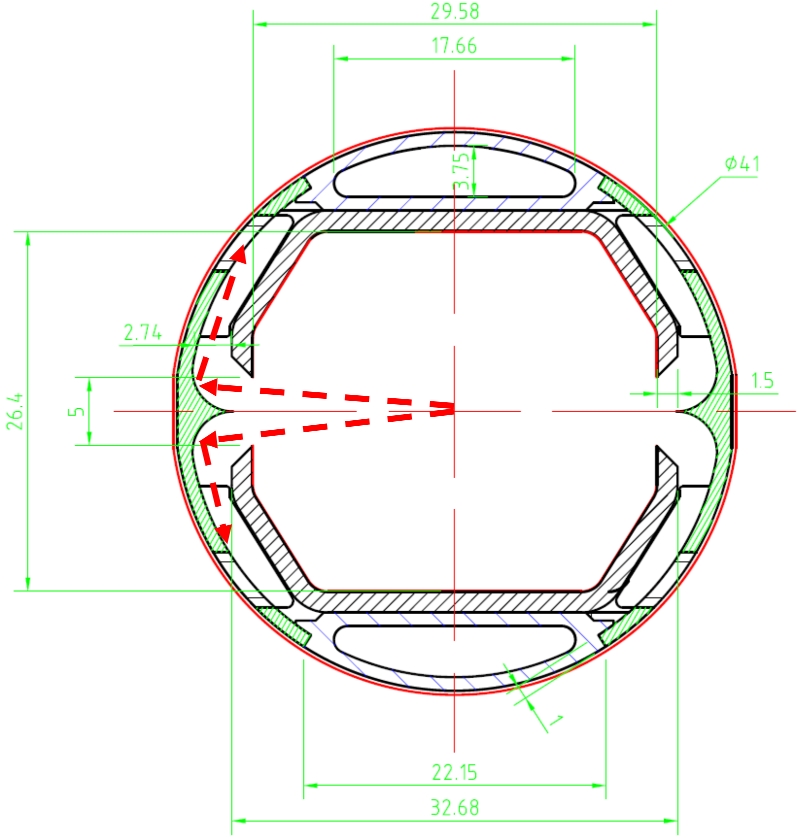
Full integrated lattice exists

- Lattice imperfection studies are progressing well, injection dyn. aperture OK, @collision ongoing
- Dynamic aperture optimization in iteration with magnet design (balancing errors at injection/collision)
- Tentative specifications for magnets correctors and alignment tolerances

Cryogenic beam vacuum system

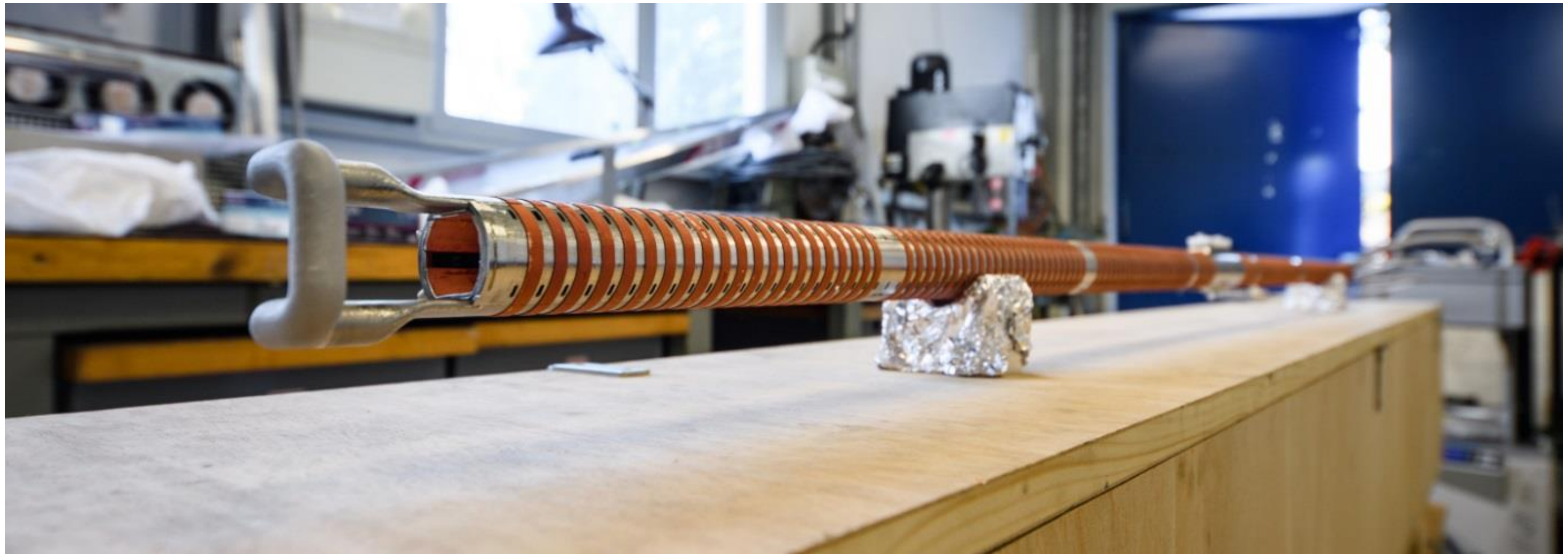
One of the most critical elements for FCC-hh

- Absorption of synchrotron radiation at ~50 K for cryogenic efficiency (5 MW total power)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.



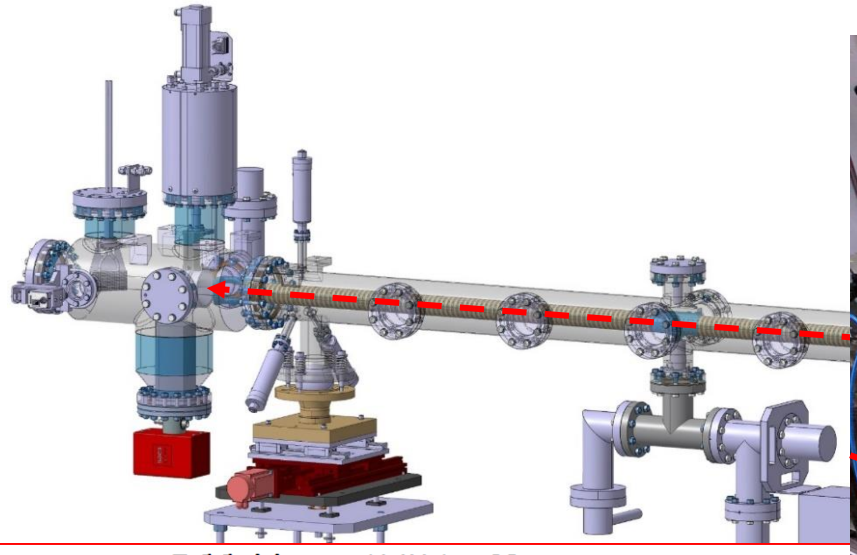
FCC Beamscreen prototype for test at ANKA:

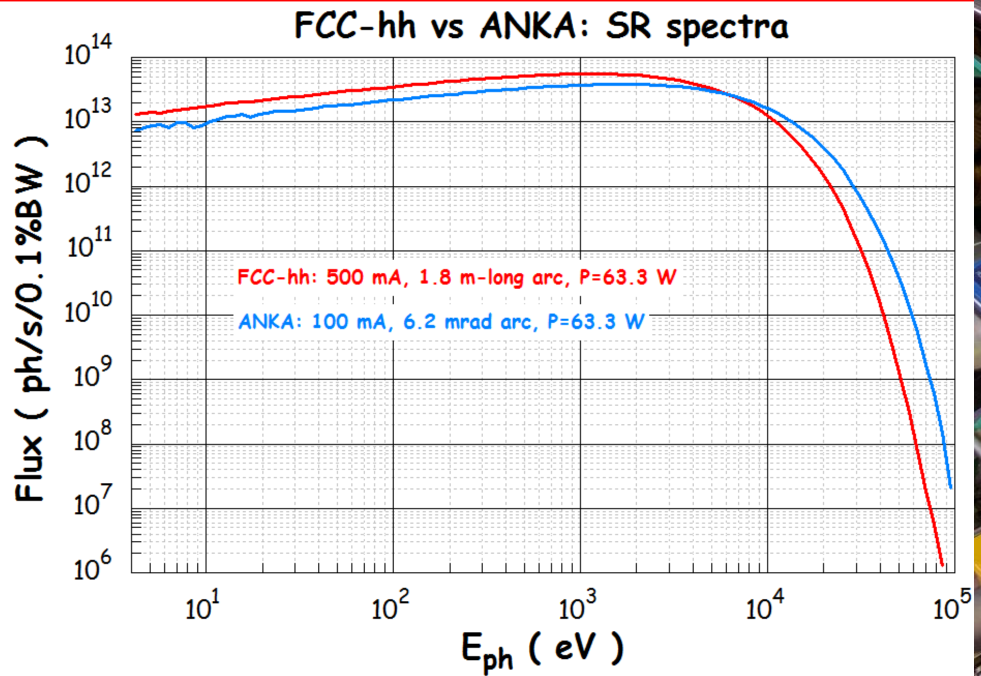
External copper rings for heat transfer to cooling tubes

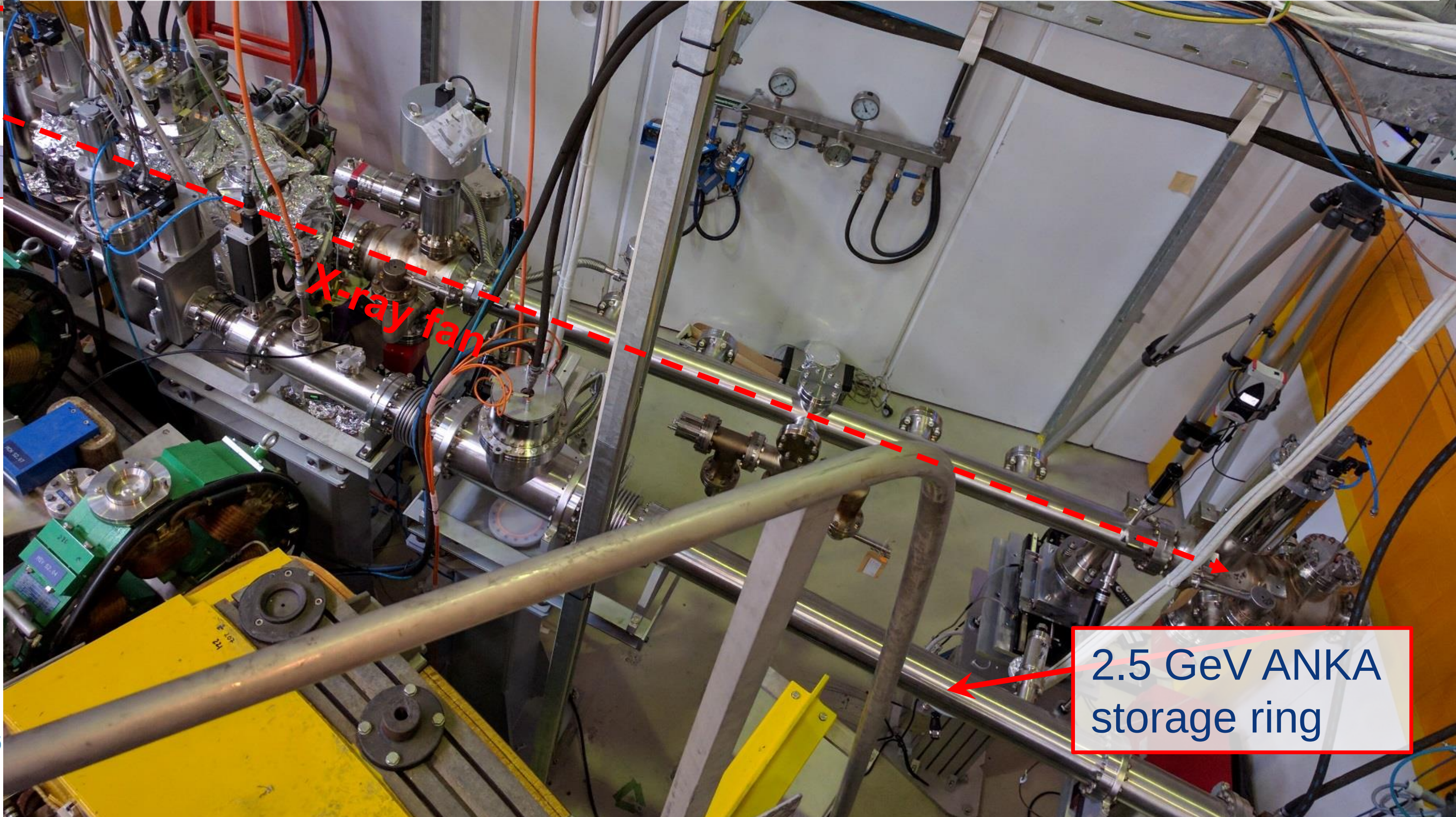


FCC-hh beam screen test @ ANKA

FCC-hh Beam-screen test Set-up at ANKA:
Complete system installed in the ANKA ring;
First beam scheduled in early June







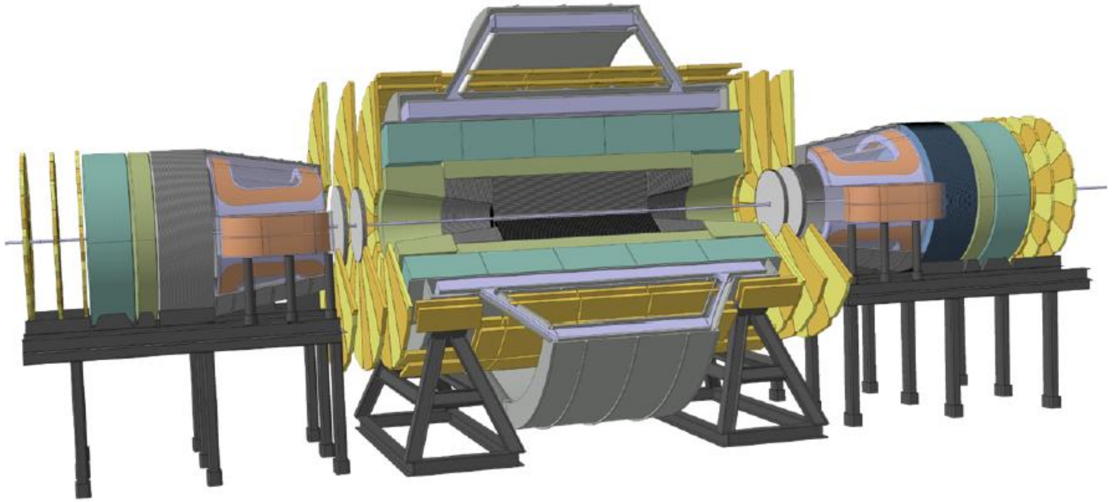
FCC-hh detector – new reference design

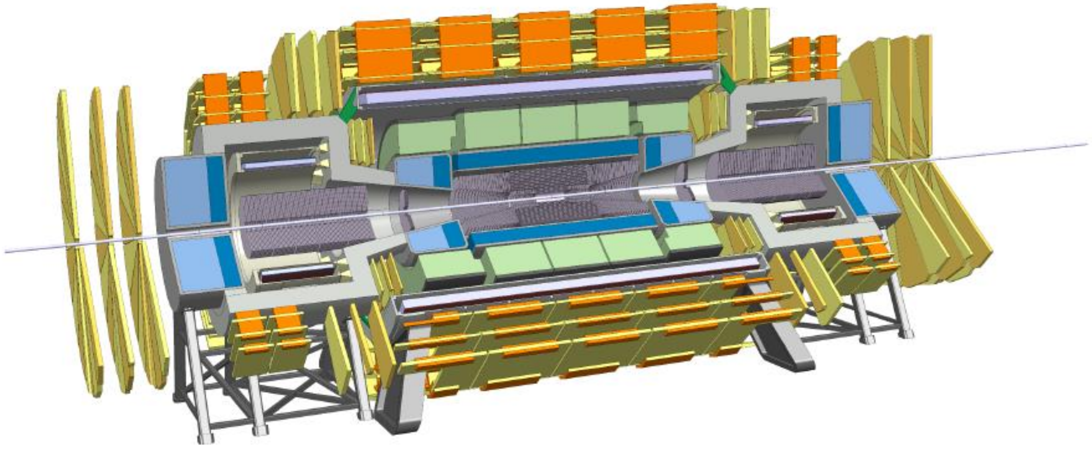
6T, 12m bore solenoid, 10Tm dipoles, shielding coil

→ 65 GJ Stored Energy
→ 28m Diameter
→ >30m shaft
→ Multi Billion project

4T, 10m bore solenoid, 4T forward solenoids , no shielding coil

→ 14 GJ Stored Energy
→ Rotational symmetry for tracking !
→ 20m Diameter (≈ ATLAS)
→ 15m shaft
→ ≈ 1 Billion project





Implementation - new footprint baseline

Alignment | Shafts | Query

Choose alignment option: V4variation_v2017-2

Tunnel elevation at centre:322mASL

Grad. Params

Azimuth (°): -23.5

Slope Angle x-x(%): 0.3

Slope Angle y-y(%): 0.08

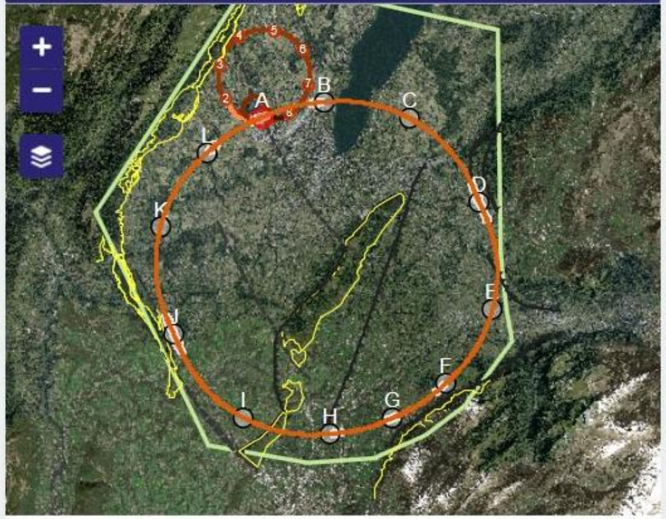
LOAD | SAVE | CALCULATE

Alignment centre

X: 2499941 Y: 1107760

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	37°	49m	-40°	83m
SPS		121m		126m
TI2		121m		126m
TI8		51m		118m

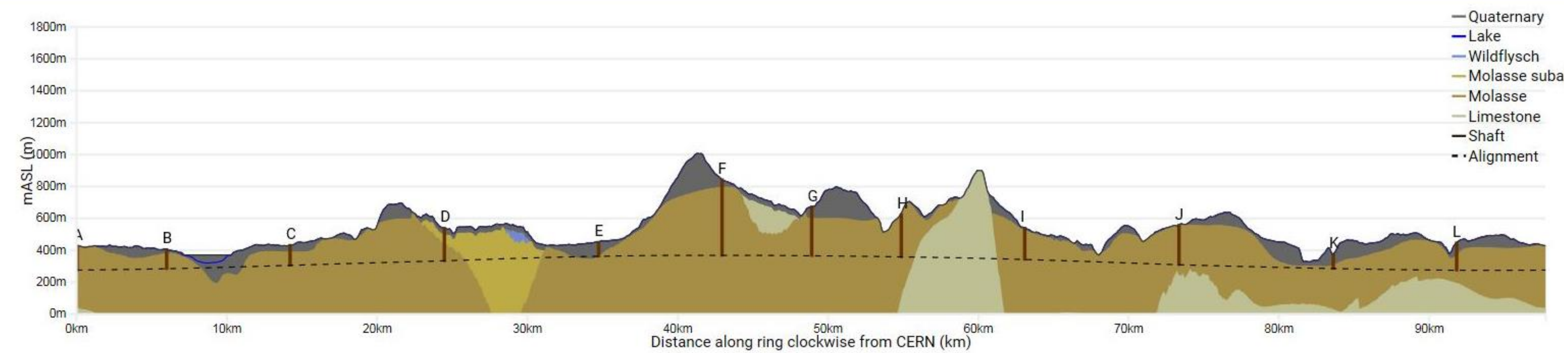
Alignment Location



Geology Intersected by Shafts | Shaft Depths

	Shaft Depth (m)	Geology (m)					
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Limest
A	152	0	0	0	152	0	
B	121	0	0	26	95	0	
C	127	0	0	44	83	0	
D	205	66	0	40	100	0	
E	89	0	0	89	0	0	
F	476	0	0	49	427	0	
G	307	0	0	73	234	0	
H	266	0	0	0	266	0	
I	198	0	0	11	187	0	
J	248	0	0	1	247	0	
K	88	0	0	70	18	0	
L	172	0	0	89	83	0	
Total	2449	66	0	492	1892	0	

Alignment Profile



Geology Intersected by Tunnel | Geology Intersected by Section

Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc.

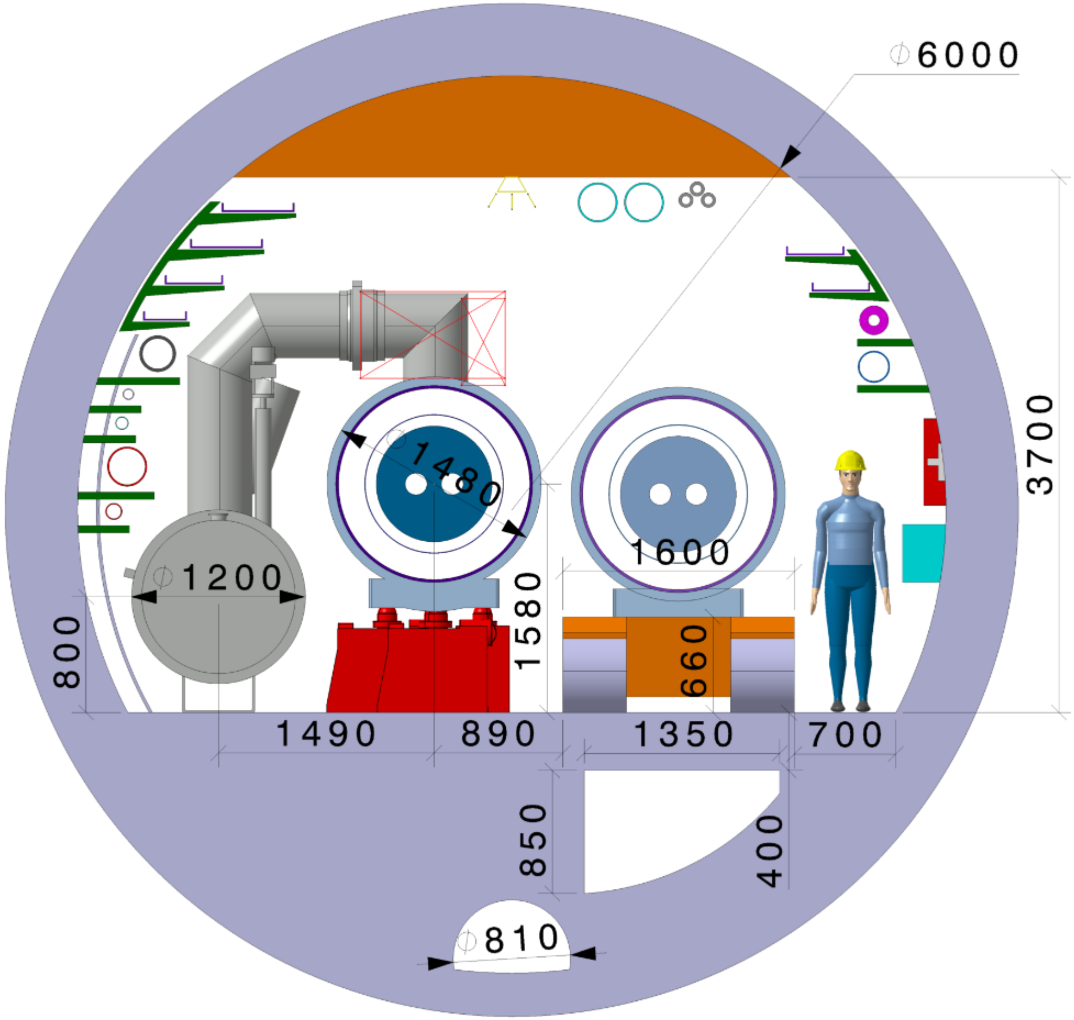
Tunneling

- Molasse 90%, Limestone 5%, Moraines 5%

Shallow implementation

- ~ 30 m below lakebed
- Reduction of shaft length and technical installations
- One very deep shaft **F** (RF or collimation), alternatives being studied, e.g. inclined access

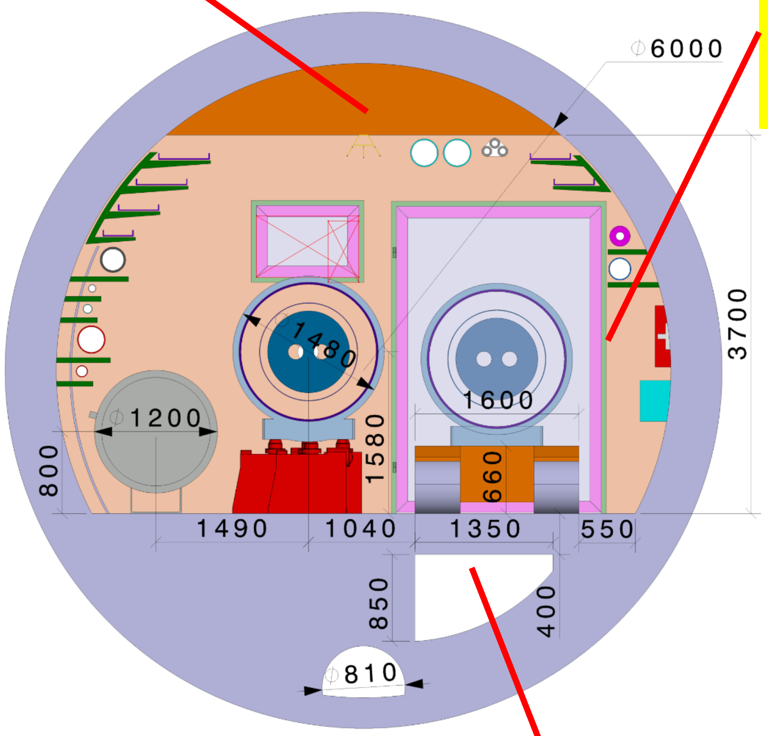
FCC-hh integration



Basic layout following LHC concept

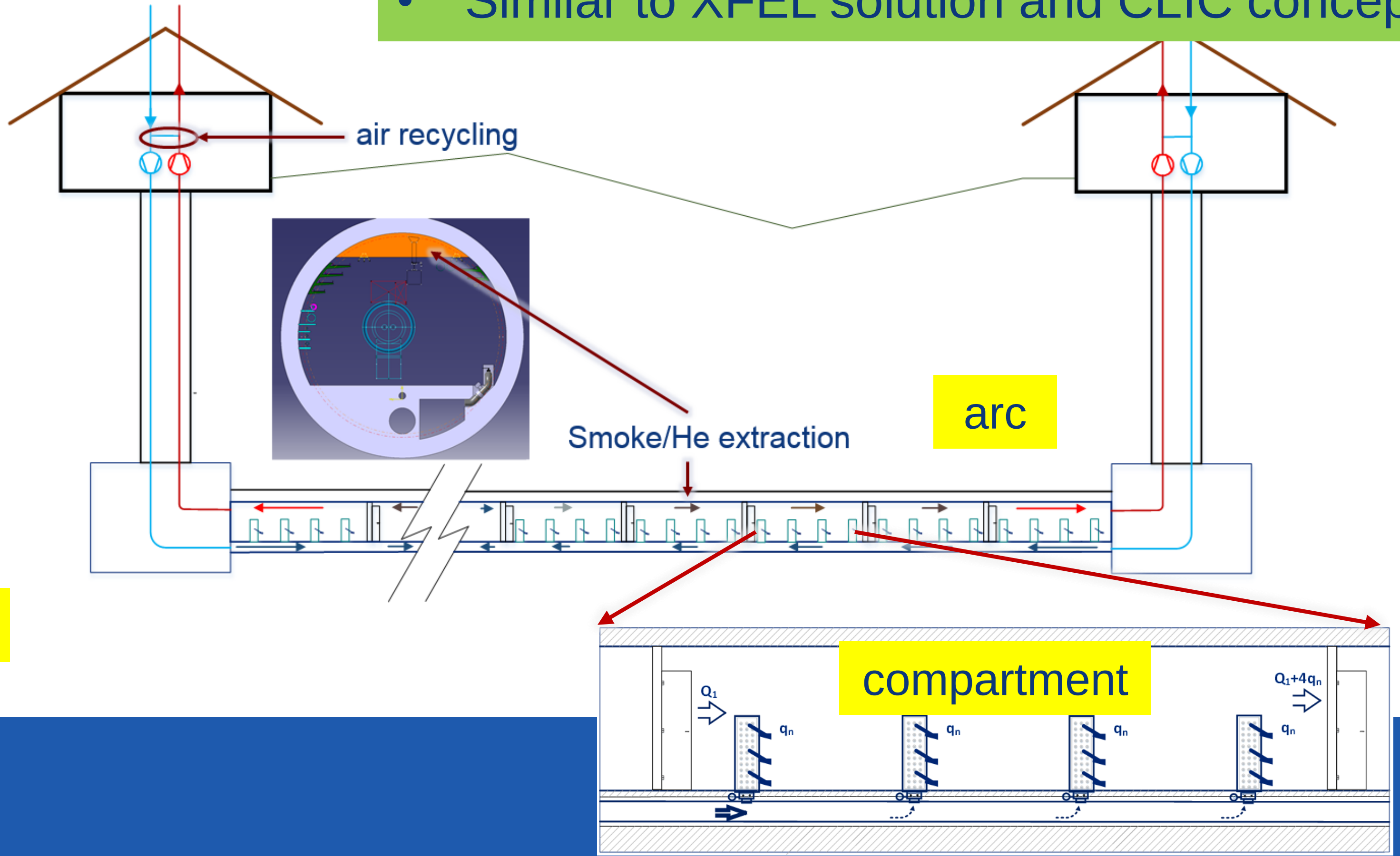
- **6 m inner tunnel diameter**
- Main space allocation:
  - 1200 mm cryo distribution line (QRL)
  - 1480 mm installed cryomagnet
  - 1600 cryomagnet magnet transport
  - >700 mm free passage.

FCC-hh tunnel safety concept



Working hypothesis for safety concept:

- Longitudinal compartments separated by automated fire doors, with individual control of ventilation and smoke/He extraction.
- Similar to XFEL solution and CLIC concept

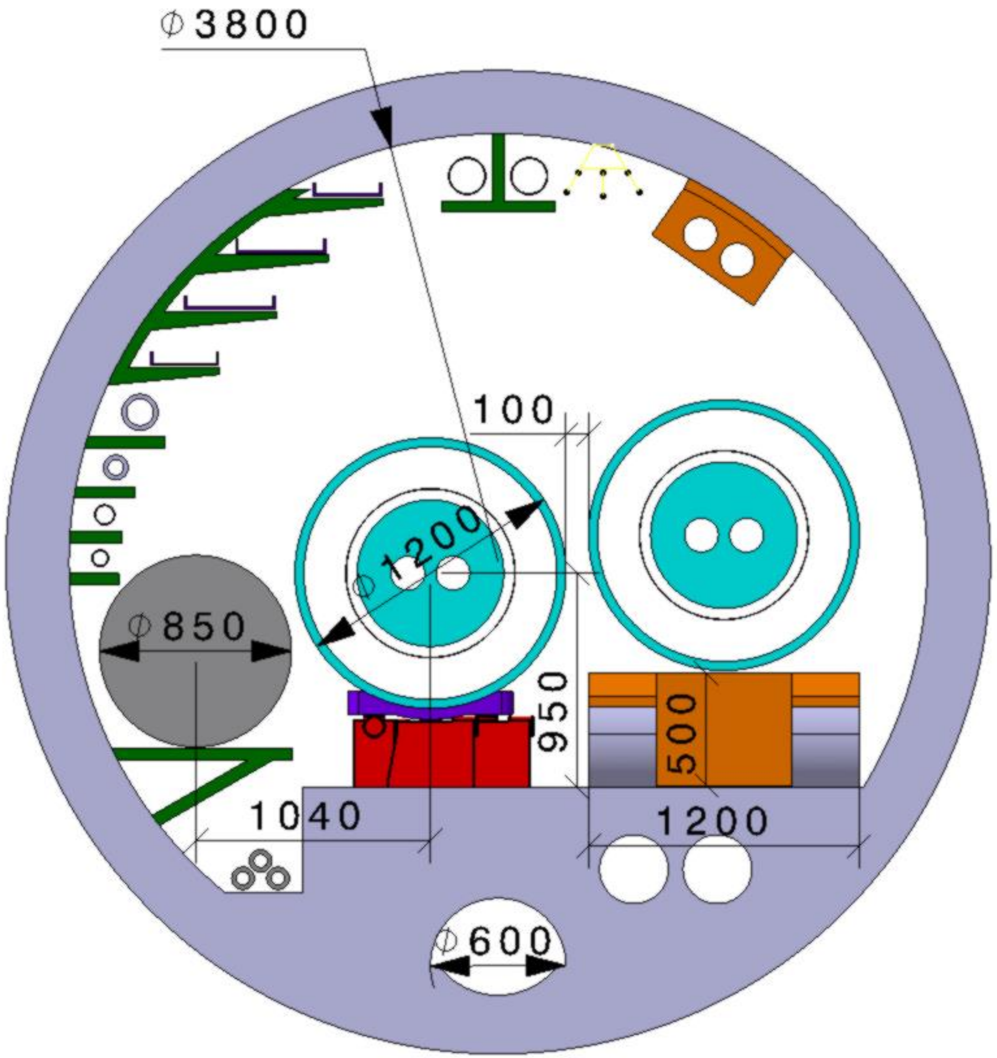


HE-LHC integration aspects

Present working hypothesis for HE LHC design:

No major CE modification on machine tunnel and caverns

- Similar geometry and layout as LHC machine and experiments
- Due to 16 T dipole field and increased cryogenic load, magnet cryostat and cryo distribution line (QRL) larger than for LHC.
- Challenges for tunnel integration and QRL & 16 T cryostat design.
- **Maximum magnet cryostat external diameter compatible with LHC tunnel: 1200 -1250 mm**
- **Classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**



16 T cryo-dipole integration approach

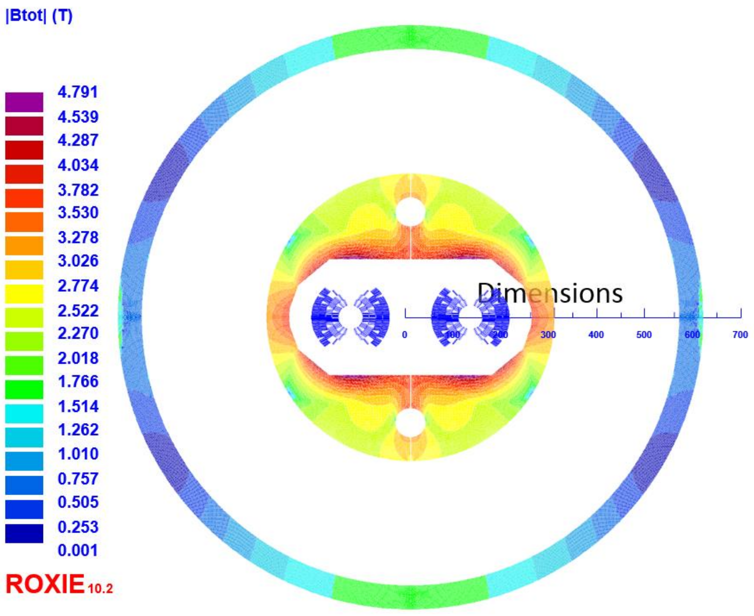
Design strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

- Goal is reduction of external diameter to ~1200 mm
- Options und consideration:
  - Allow stray-field and/or cryostat as (partial) return-yoke
  - Active compensation with (simple) shielding coils
  - Optimization of inter-beam distance (compactness of coils)
  - *(QRL integrated in magnets, → negative impact on integral field because of longitudinal space required for service module (5%))*

→ Smaller diam. also relevant for FCC-hh cost optimization

→ Design optimization for specific project after decision

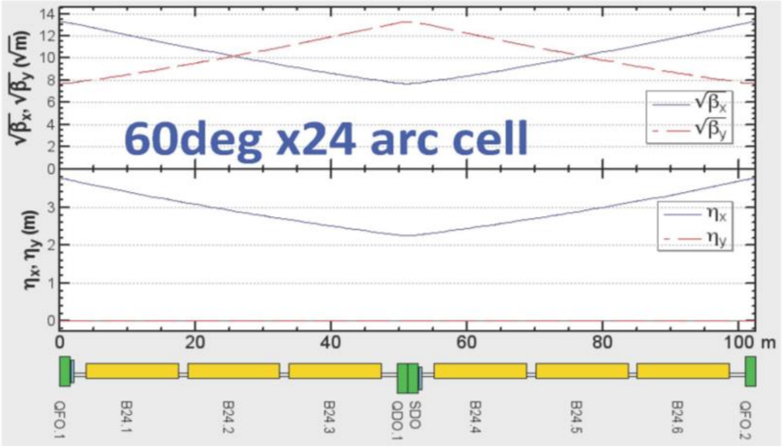
Example magnetic cryostat coldmass 40t, total mass 62t

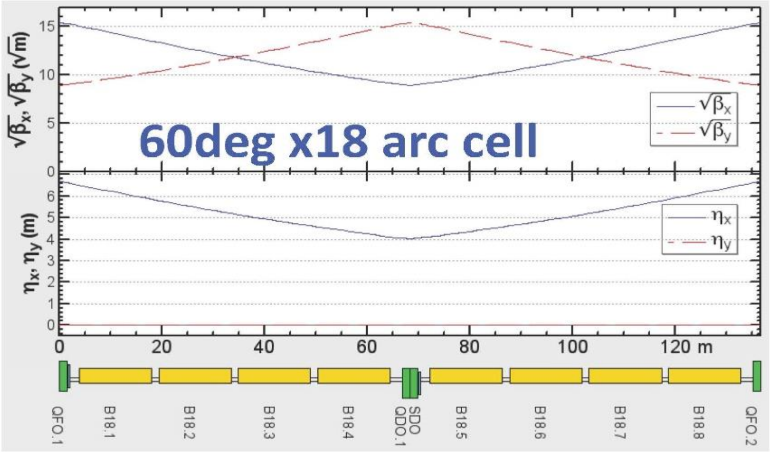


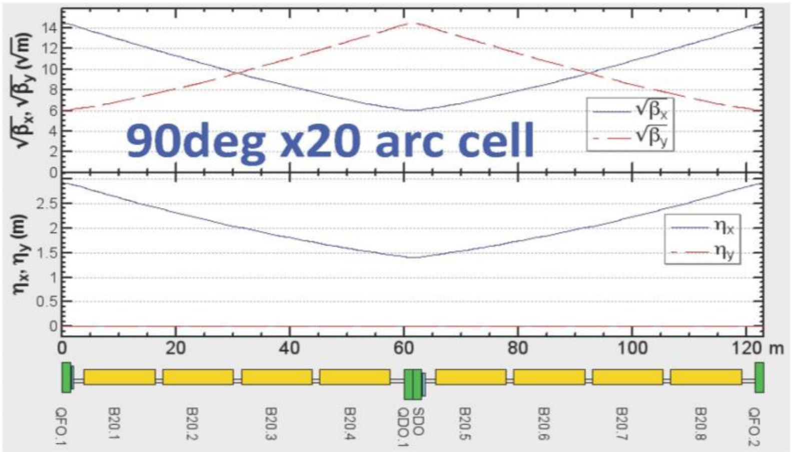
Only magnetic elements shown

Description	ID in mm	OD in mm
Iron yoke	-	600
Aluminium shrinking cylinder	600	740
Stainless steel He tight shell	740	760
Al radiation shield	934	940
Vacuum vessel (magnetic steel)	1120	1220

HE-LHC optics design work







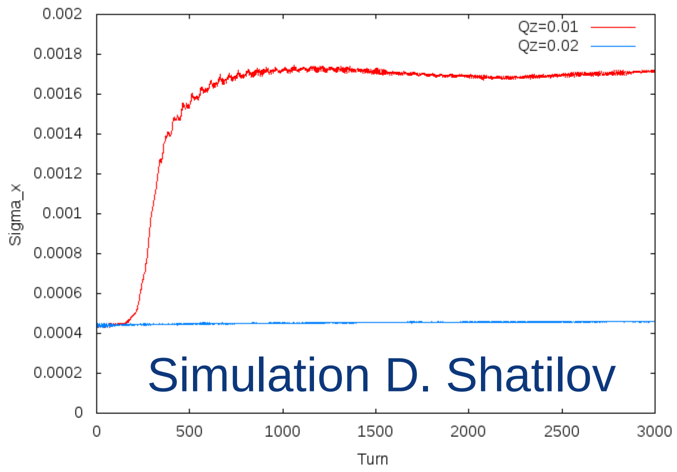
Studying various arc-cell options, optimizing dipole field, quadr. & sext. strengths, geometry & dynamic aperture, aperture requirements, injection energy, etc.

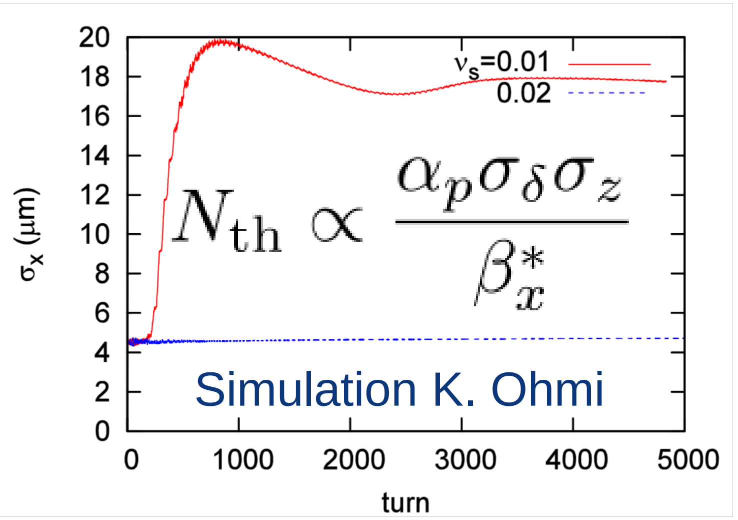
	24 x 60 deg	18 x 60 deg	20 x 90 deg
dipole length, m	13.56	14.1	12.39
number of dipoles	1280	1280	1424
dipole field, T	16.3	15.68	16.04
cell quad gradient, T/m	289.5	215.9	340.0

FCC-ee new optics baseline

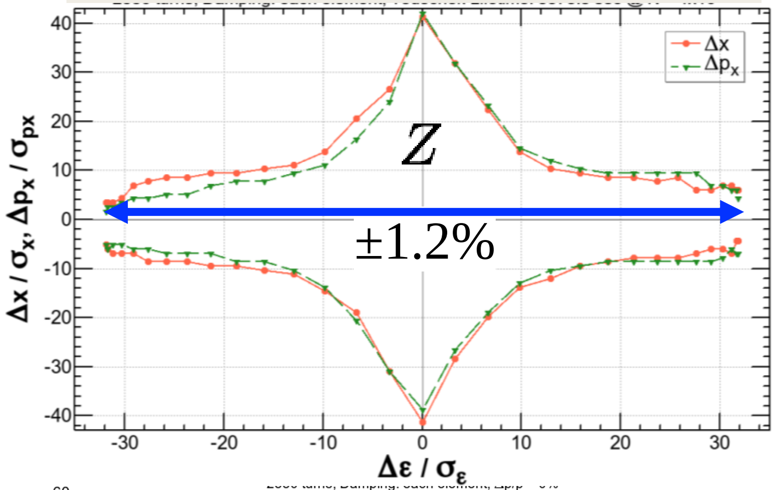
Motivations for optics changes since Rome:

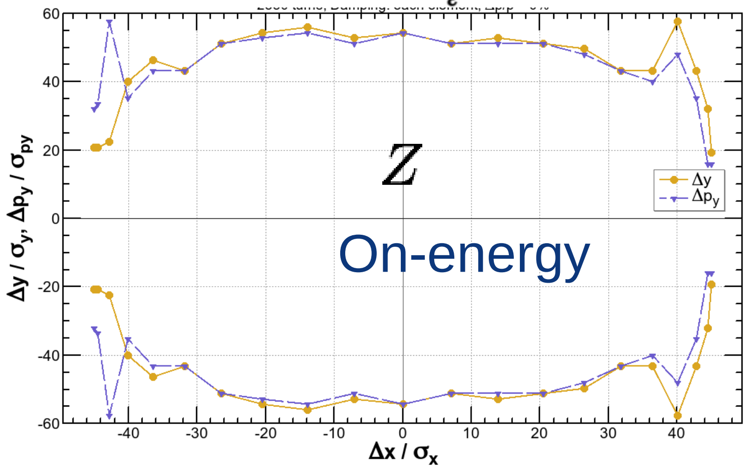
- Mitigation coherent beam-beam instability at Z working point
  - Smaller βx*
  - 60°/60° cell in the arc (larger emittance and momentum compaction), also mitigates microwave instability
- Fitting ee layout to the footprint of the new FCC-hh layout
- Adapt optics for the "Twin Aperture Quadrupole" scheme for arc quadrupoles





Dynamic aperture studies
45.6 GeV, $\beta^*_{x,y}$ = (0.15 m, 1 mm)

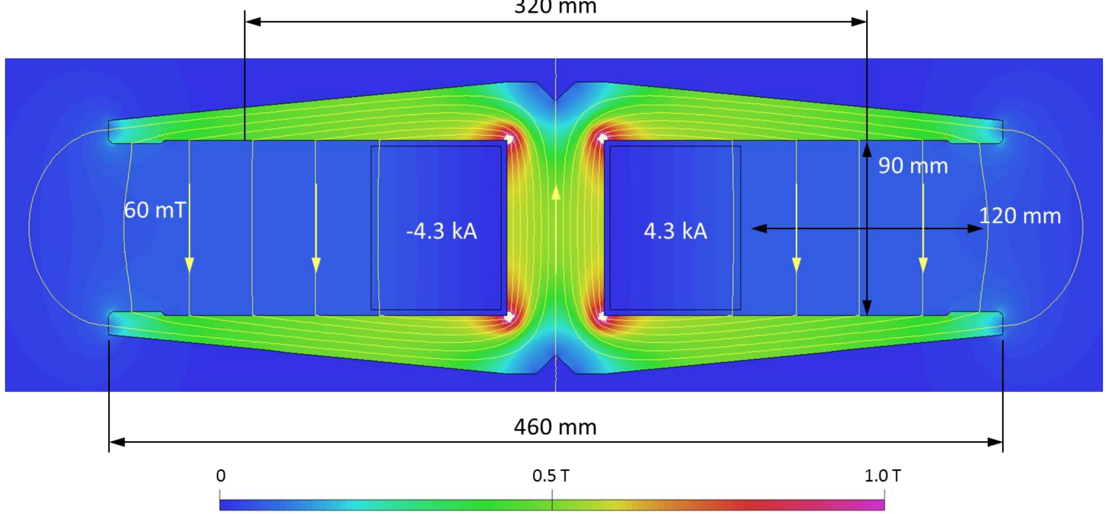




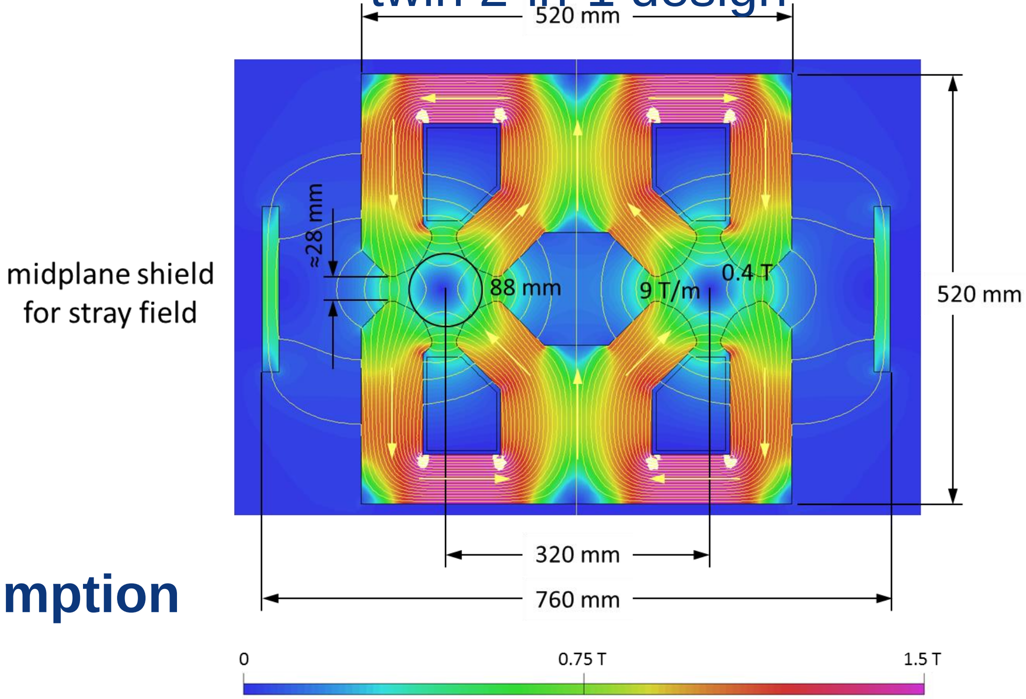
FCC-ee dual aperture main magnets

Prototyping launched of main dipole and quadrupole magnets (~1 m units)

Dipole:
twin aperture yoke, single busbars as coils



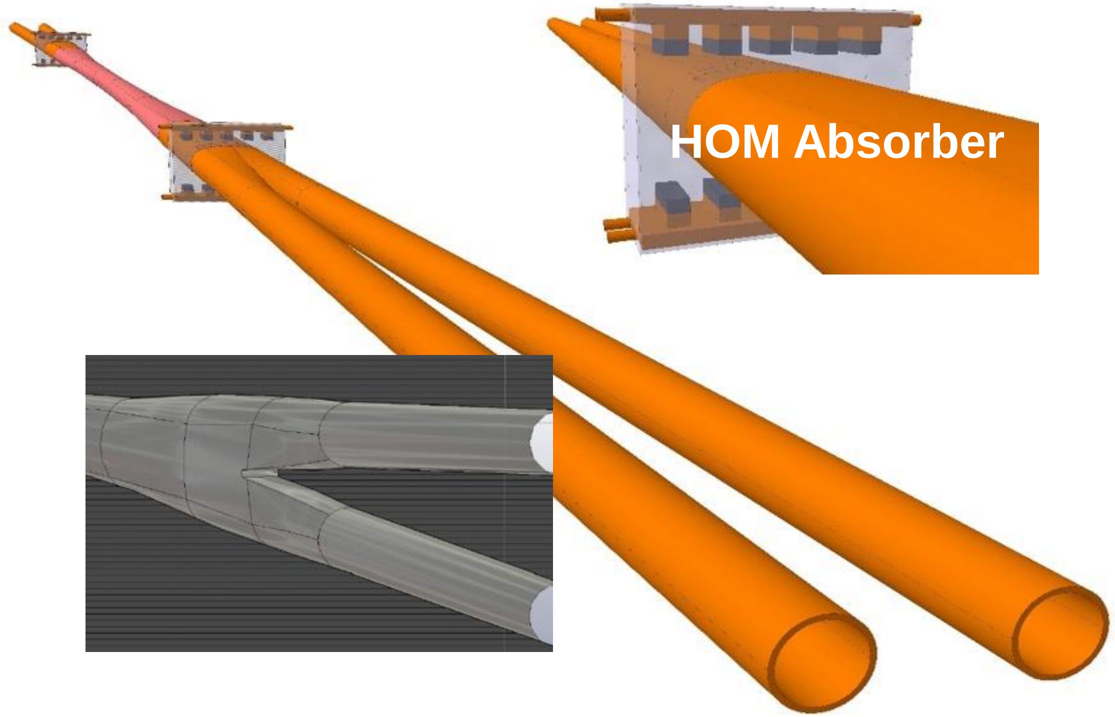
Quadrupole:
twin 2-in-1 design

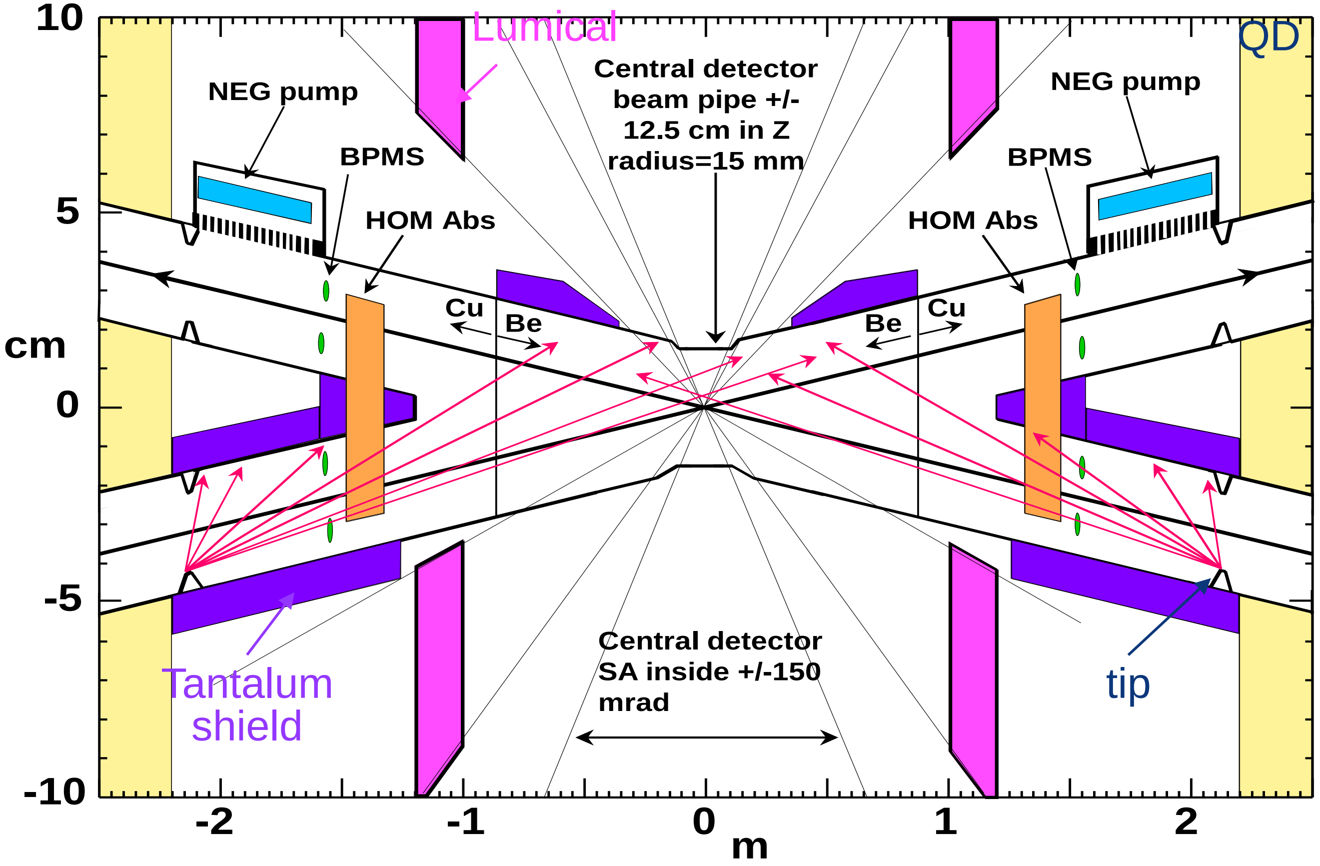


- **Considerable savings in Ampere-turns and power consumption by novel dual aperture designs**
- **Power consumption twin quad: 22 MW at 175 GeV with Cu coil (half of single-aperture quads) and power consumption twin dipole: = 17 MW at 175 GeV with Al bus bar**

FCC-ee MDI optimisation

- Detailed IR design, beam pipe diameter 3 cm throughout, symmetric final focus, L* = 2.2 m
- Ta shield 1 cm, SR mask tips, 5μm Au in central section to cope with SR at high energy
- Design of HOM absorber to avoid trapped modes in central chamber





FCC-ee RF staging scenario

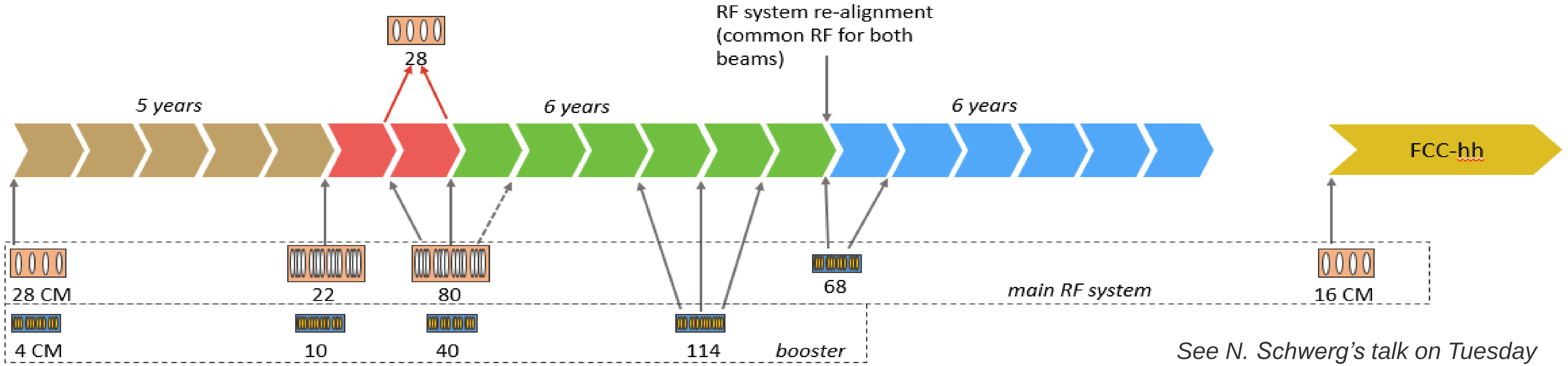
"Ampere-class" machine

	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

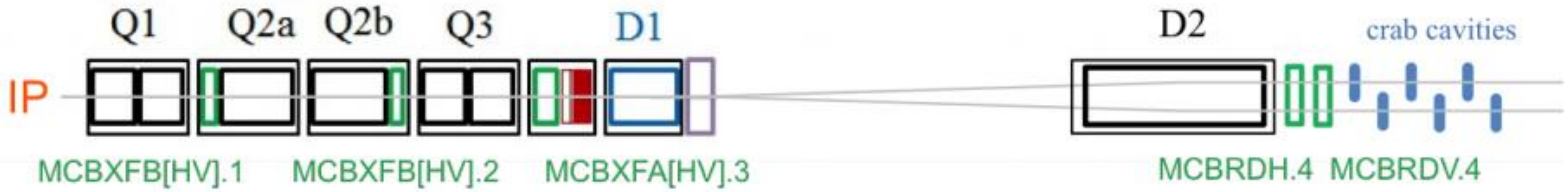
Three sets of RF cavities to cover all options FCCee & Booster:

- Installation sequence comparable to LEP (≈30 CM/shutdown)
- high intensity (Z, FCC-hh): 400 MHz mono-cell cav, ≈ 1MW source
- high energy (H, t): 400 MHz four-cell cavities, also for W machine
- booster and t machine complement: 800 MHz four-cell cavities
- Adaptable 100MW, 400MHz RF power distribution system



See N. Schwerg's talk on Tuesday

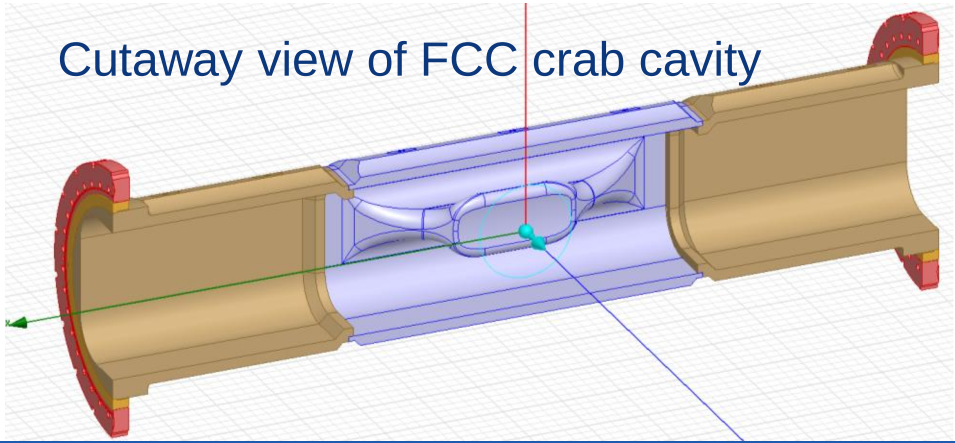
Nb/Cu crab cavity for FCC-hh / HE-LHC



Schematic layout:
E. Cruz-Alaniz,
Nov. 2016, Barcelona

- **Performance of both HE-LHC and FCC-hh phase 2 based on crab cavities!**
  - **Development of compact Nb/Cu SC crab cavity based on ridged waveguide resonator**
  - **Low longitudinal and transverse impedances, provides natural damping for HOMs**
  - **Compatible with 200 mm inter-beam distance**

Cutaway view of FCC crab cavity

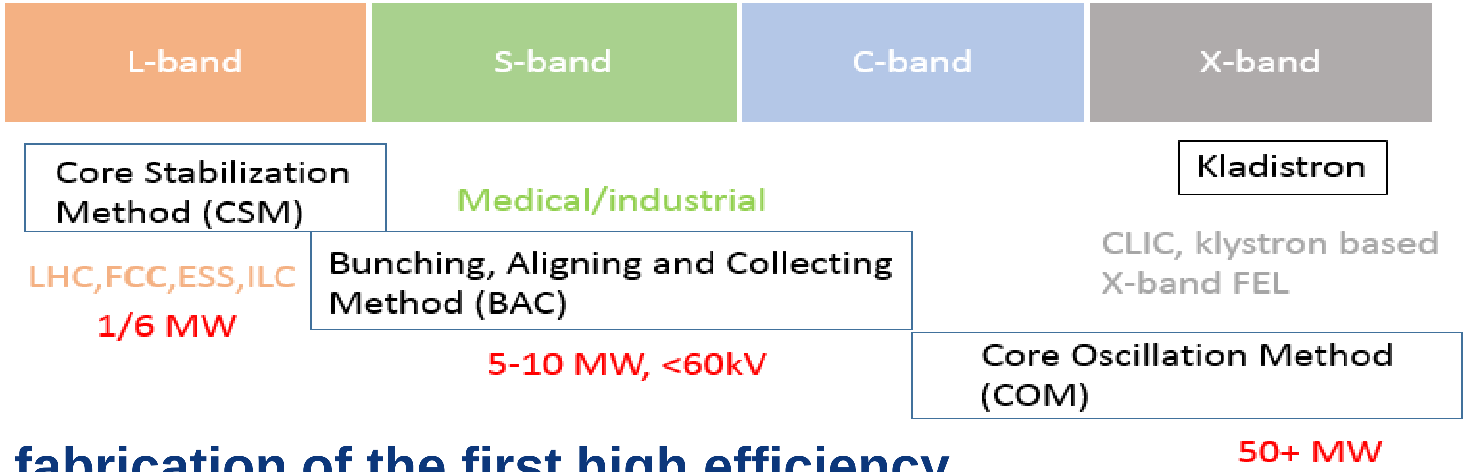


Wide
Open
Waveguide

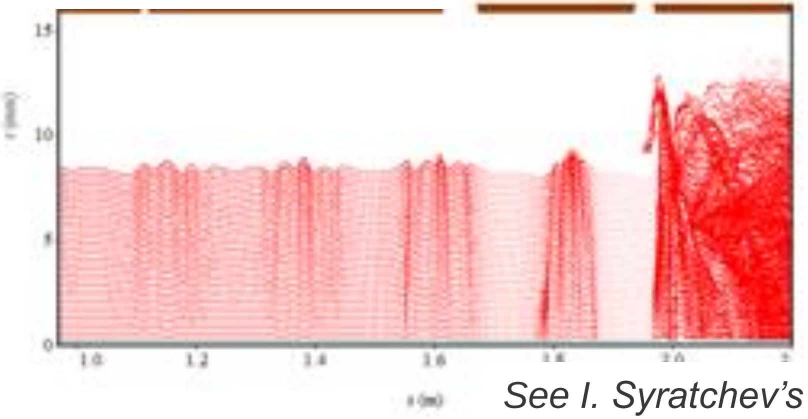
	FCC-hh
RF frequency [MHz]	400
Total voltage V [MV]	18 (uncertainty ±20%)
Available length [m]	20
Beam separation [mm]	250 (maybe 204 soon)
Average beta in the ring [m]	(339+67)/2 = 203
Beta* [m]	0.3
Crossing angle [urad]	89
Beta at CC location [m]	10100 ÷ 10900

Efficient klystron technology

- **Development of new klystron bunching technologies to increase RF power production efficiency to almost 90%, was initiated at CERN in 2013 (HEIKA), essential for FCC-ee**

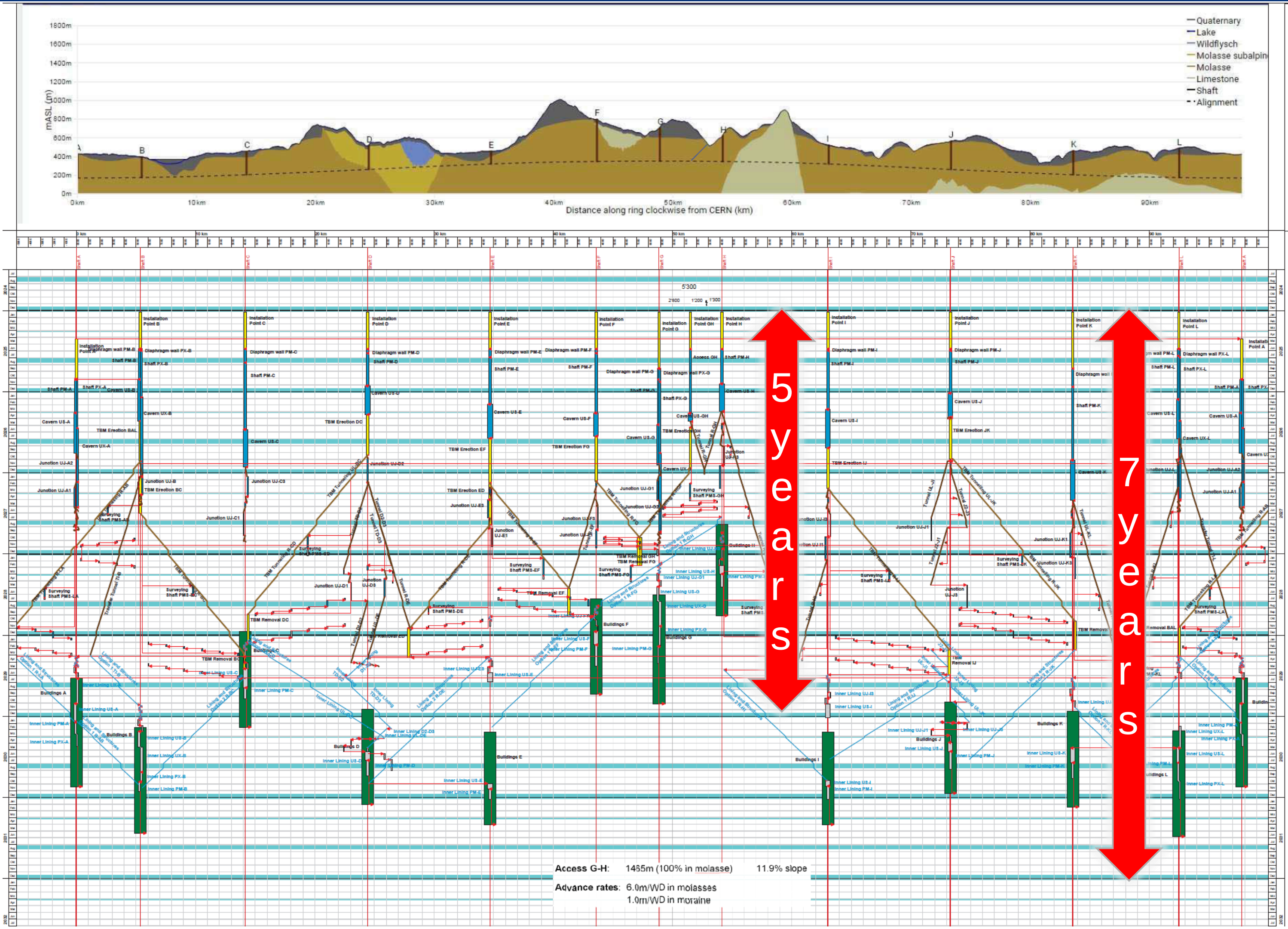


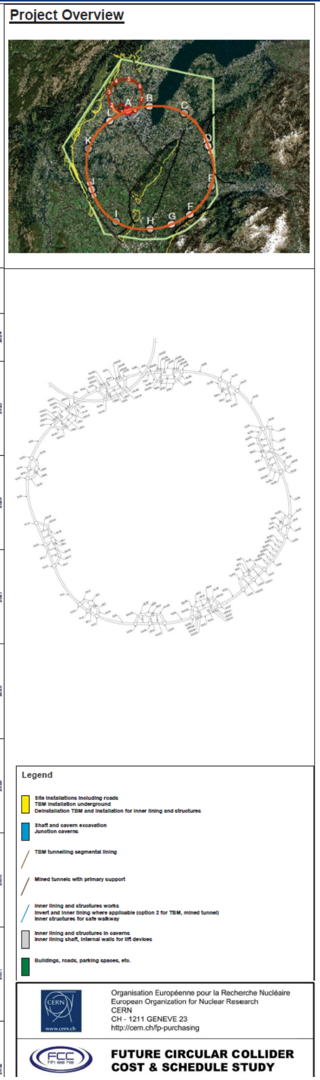
- **Towards fabrication of the first high efficiency CSM tube**
- **Presently negotiations with industry for protoype production for end 2018**
- **Single beam, 1.4 MW, 0.8 GHz, 134 kV, 12.55 A**
  85.7% efficiency in simulations



See I. Syratchev's talk on Tuesday

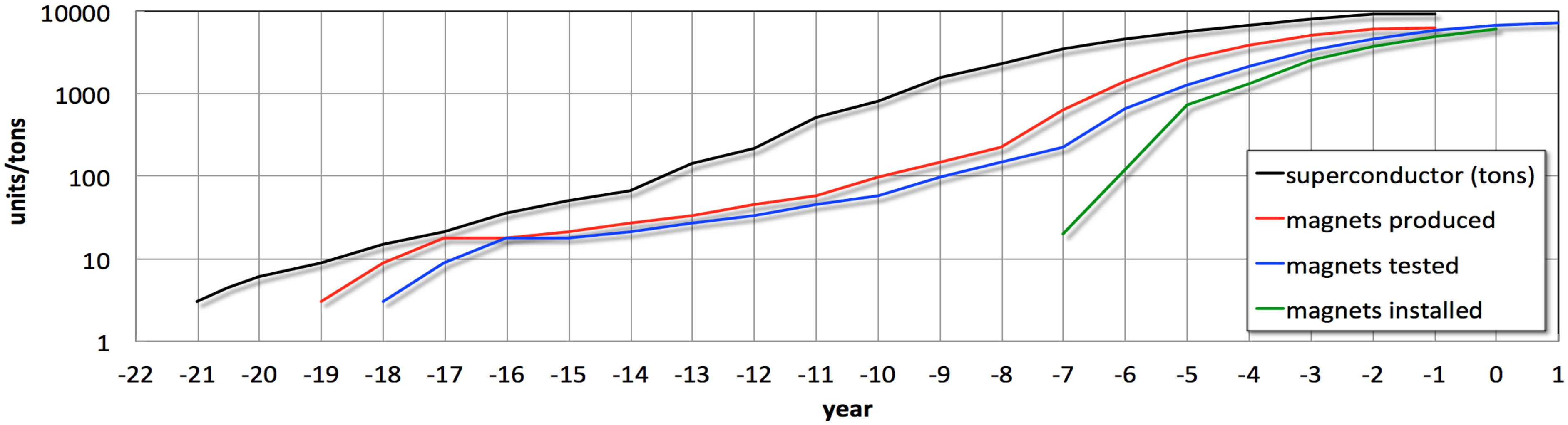
CE schedule studies





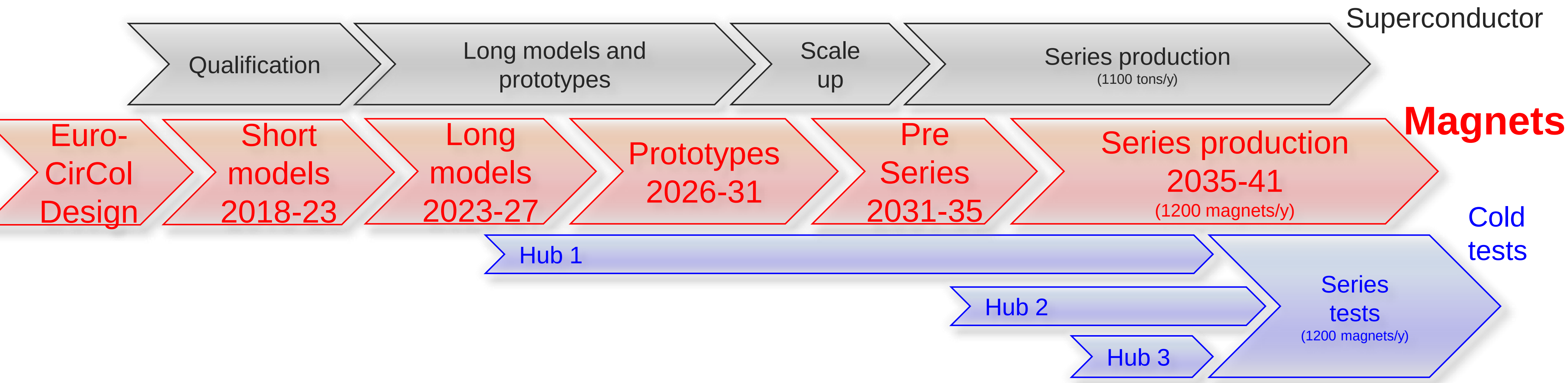
- CE and schedule studies with consultants
- First sectors can be available after 4.5 to 5 years for Technical Infrastructure install.
- Total CE duration about 7 years
- Next steps: combination with logistics considerations for TI and machine installation for overall schedule optimization

16 T magnet R&D schedule



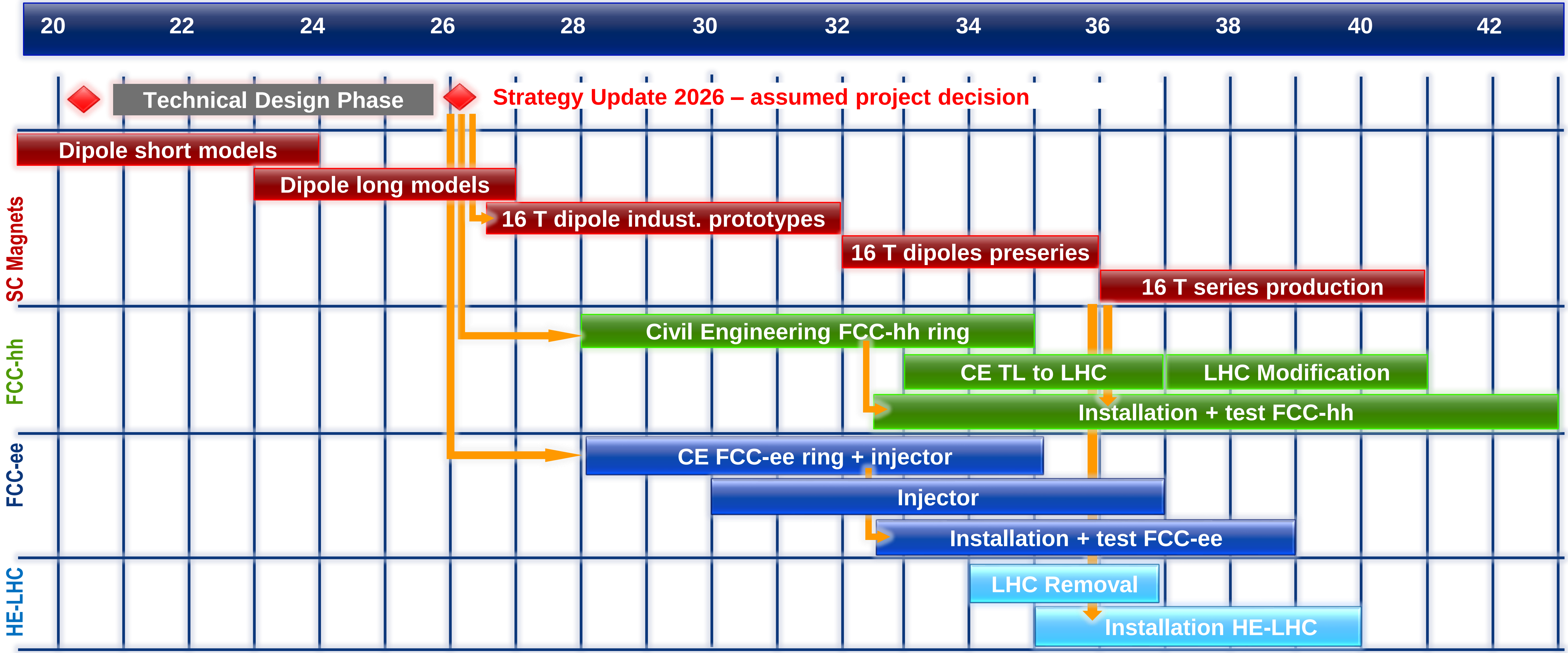
Total duration of magnet program:

~20 years

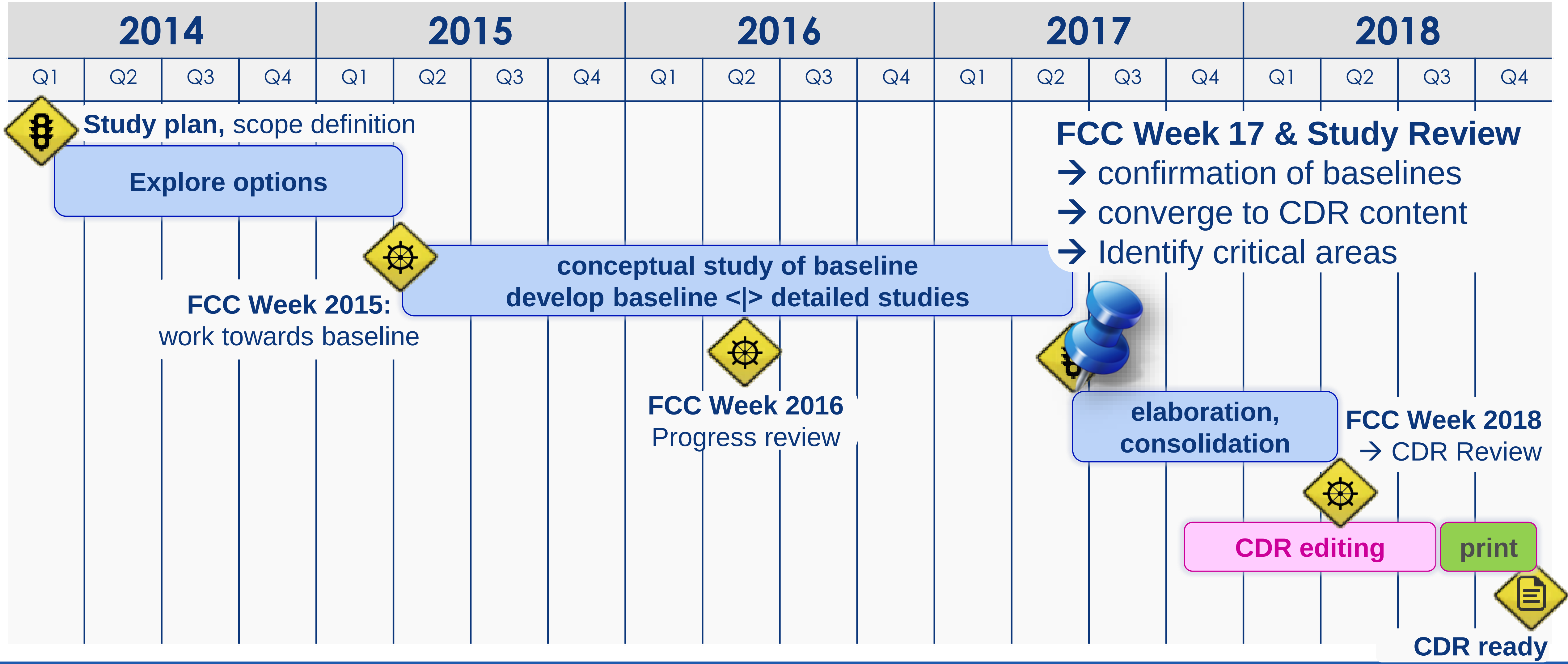


Would follow on HL-LHC Nb3Sn program with long models with industry from 2023/24

Draft Schedule Considerations



CDR Study Timeline



FCC Advisory Committee

- **IAC composition to cover all study areas, 17 members**
- **Important role as expert review committee for study and CDR preparation**

	FCC International Advisory Committee			
Chair	**Dissertori**	Guenther	ETHZ	CH
Physics Experiments	**Diemoz**	Marcella	INFN	IT
	Egorychev	Victor	ITEP	RU
	Herten	Gregor	U. Freiburg	GE
	Quigg	Chris	FNAL	US
	Parker	Andrew	U. Cambridge	UK
Accelerator Design	**Assmann**	Ralph	DESY	GE
	Biscari	Caterina	ALBA-CELLS	ES
	Fischer	Wolfram	BNL	US
	Shiltsev	Vladimir	FNAL	US
Technology and Infrastructure	**Lebrun**	Philippe	JUAS	FR
	Minervini	Joe	MIT	US
	Mosnier	Alban	CEA	FR
	Ross	Marc	SLAC	US
	Seidel	Mike	PSI	CH
	Watson	Tim	ITER	ITER
	Yamamoto	Akira	KEK	JP

Study reviews towards CDR

- **FCC week for presentation of information, followed by executive review session to discuss key issues.**
- **FCC week Berlin & 29/30 June @ CERN.**
- **FCC week 2018 (9-13 April 2018, tbc.) + mid-May @CERN.**

FCC Week Program

Tuesday (30.5)				Wednesday (31.5)					Thursday (1.6)			
FCC-hh machine design review Design (1)	Conductor Development Program (1)	*FCC-ee physics & experiment review Run plan and SM precision measurements*	SRF Recent designs and progress	FCC-hh machine design: SppC and selected topics	16 T magnets review EuroCirCol (1)	*FCC-hh review Physics potential of FCC-hh*	FCC-ee review Optics & instrumentation		Special technologies Beam vacuum	I&O review CE, electricity, ventilation, logistics, transport	FCC-ee Beam dynamics	*FCC-hh experiment review Calorimetry & trigger*
R. Aleksan (CEA)	A. Ballarino (CERN)	G. Iacobucci (UNIGE)	R. Rimmer (JLAB)	A. Faus-Golfe (CNRS)	E. Todesco (CERN)	J. Lykken (FNAL)	J. Seeman (SLAC)		F. Perez (ALBA)	C. Prasse (FIML)	B. Holzer (CERN)	B. Heineman (DESY)
Coffee Break				Coffee Break					Coffee Break			
FCC-hh machine design review Design (2)	Conductor Development Program (2)	*FCC-ee physics & experiment review Higgs, top and flavour*	SRF Materials	FCC-hh machine design: Selected topics	16 T magnets review EuroCirCol (2)	Common experiment software	FCC-ee review Machine Detector Interface		Special technologies Other directions for R&D	16 Tesla magnets US Programme	FCC-ee review Injector	*FCC-hh experiment review Physics performance*
F. Cerutti (CERN)	C. Senatore (UNIGE)	D. Bortoletto (UOXF)	V. Palmieri (INFN LNL)	O. Boine-Frankenheim (TU Darmstadt)	A. Zlobin (FNAL)	P. Allport (Uni Birmingham)	K. Oide (KEK)		A. Ryazanov (Kurchatov)	P. Vedrine (CEA)	I. Papaphilippou (CERN)	A.Etienvre (CEA)
Lunch				Lunch				International Advisory Committee (closed session)	Lunch			EuroCirCol mid-term review (closed session)
								G. Dissertori (ETH)				R. Aleksan (CEA)
FCC-hh machine design review Beam performance and specifications	Conductor Development Program (3)	*FCC-ee physics & experiment review Direct discovery & detectors*	SRF review RF system concepts and requirements	Special technologies review FCC-hh beam handling	16 T Magnets Models & Technology ERMC-RMM-Wound Conductor	*FCC-hh experiment review Detector requirements & concepts*	FCC-ee review Energy calibration & polarization	Economic impact of CERN colliders (1)	Special technlogies Other Magnets	I&O review Cryogenics	*FCC-he review Accelerator & interation region*	Comon detector technologies
M. Migliorati (INFN)	D. Larbalestier (Florida State Uni)	L. Linssen (CERN)	J. Zhai (IHEP)	M. Sullivan (SLAC)	S. Gourlay (LBL)	D. Charlton (Uni Birmingham)	E. Levichev (BINP)	M .Florio (Uni Milano)	E. Fischer (GSI)	D. Delikaris (CERN)	R. Assmann (DESY)	G. Tonelli (INFN)
Coffee Break				Coffee Break					Coffee Break			
FCC-hh machine design review Injectors	Conductor: Electromechanical characterization	*FCC-ee physics & experiment review Synergies & complementarities*	SRF review Directions for R&D	Special technologies review Recent design & progress	Other Magnets	*FCC-hh experiment review Magnet & tracking*	FCC-ee review Collective effects & top-up injection	Economic impact of CERN colliders (2)	I&O review Operation, reliability, safety	16 Tesla magnet review Status towards the CDR	FCC-eh: Physics	HE LHC design
P. Spiller (GSI)	M. Eisterer (TU Vienna)	J. Ellis (Uni London)	S. Posen (FNAL)	S. Casalbuoni (KIT/ANKA)	T. Ogitsu (KEK)	N. Wermes (Uni Bonn)	M. Biagini (INFN)	M .Florio (Uni Milano)	Ll. Mirales (CERN)		M. D'Onofrio	A. Seryi (JAI)

Review Information

- **All sessions marked in red are earmarked for review**
- **Also EuroCirCol mid-term review integrated in FCC week 2017**
  Reviewer: Prof. O. Kester

Conceptual Design Report

1 – PHYSICS

Physics opportunities across all scenarios

2 Hadron Collider Summary

3 – Hadron Collider Comprehensive
- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experiment
- eh

4 Lepton Collider Summary

5 – Lepton Collider Comprehensive
- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experiment

6 High Energy LHC Summary

7 – High Energy LHC Comprehensive
- Accelerator
- Injectors
- Infrastructure

Refs to FCC-hh, HL-LHC, LHeC

- **Required for end 2018, as input for European Strategy Update**
- **Common physics summary volume**
- **Three detailed volumes FCChh, FCCee, HE-LHC**
- **Three summary volumes FCChh, FCCee, HE-LHC**

CDR planning

2017	Jun	ToC & Volume layout definition | Jun
	Jul	
	Aug	
	Sep	Guidelines, tools ready, editorial teams operational | Sep
	Oct	VOLUME EDIT STARTS | Oct
	Nov	
	Dec	
2018	Jan	
	Feb	
	Mar	
	Apr	Contents review by IAC (FCCWeek) | Apr 9-13
	May	Review session with IAC | May 15
	Jun	END OF VOLUME EDIT | June 30
	Jul	Overall editing: Proofread, homogenization, cross-referencing, polishing
	Aug	END of Final edit | Aug 31
	Sep	
	Oct	PRINT FINISHED | Oct 26

- **Editing package "Overleaf"**
- **During summer nomination of editors and author groups**
- **FCC CDR available for publication in November 2018.**

H2020 EASITrain ITN

European Advanced Superconductivity Innovation and Training Network

- **Selected for funding by EC in May 2017**
- **15 Early Stage Researchers (not yet PhD) paid for 36 months.**
- **Start: 1. October 2017, Duration: 48 months**
- **Timeline and events:**
  - Kick-off meeting: 5. – 6. September 2017 at CERN
  - All job applications until 1. October 2017
  - All jobs filled until 31. December 2017
  - Introduction Workshop at CERN, 11. – 23. March 2018
  - EASISchool 1 in Vienna, Austria, 19. – 31. August 2018

EASITrain Topics

- SC wires at low temperatures for magnets (Nb_3Sn, MgB_2, HTS)
- Superconducting thin films for RF and beam screen (Nb_3Sn, Tl)
- Electrohydraulic forming for RF structures
- Turbocompressor for Nelium refrigeration
- Magnet cooling architectures

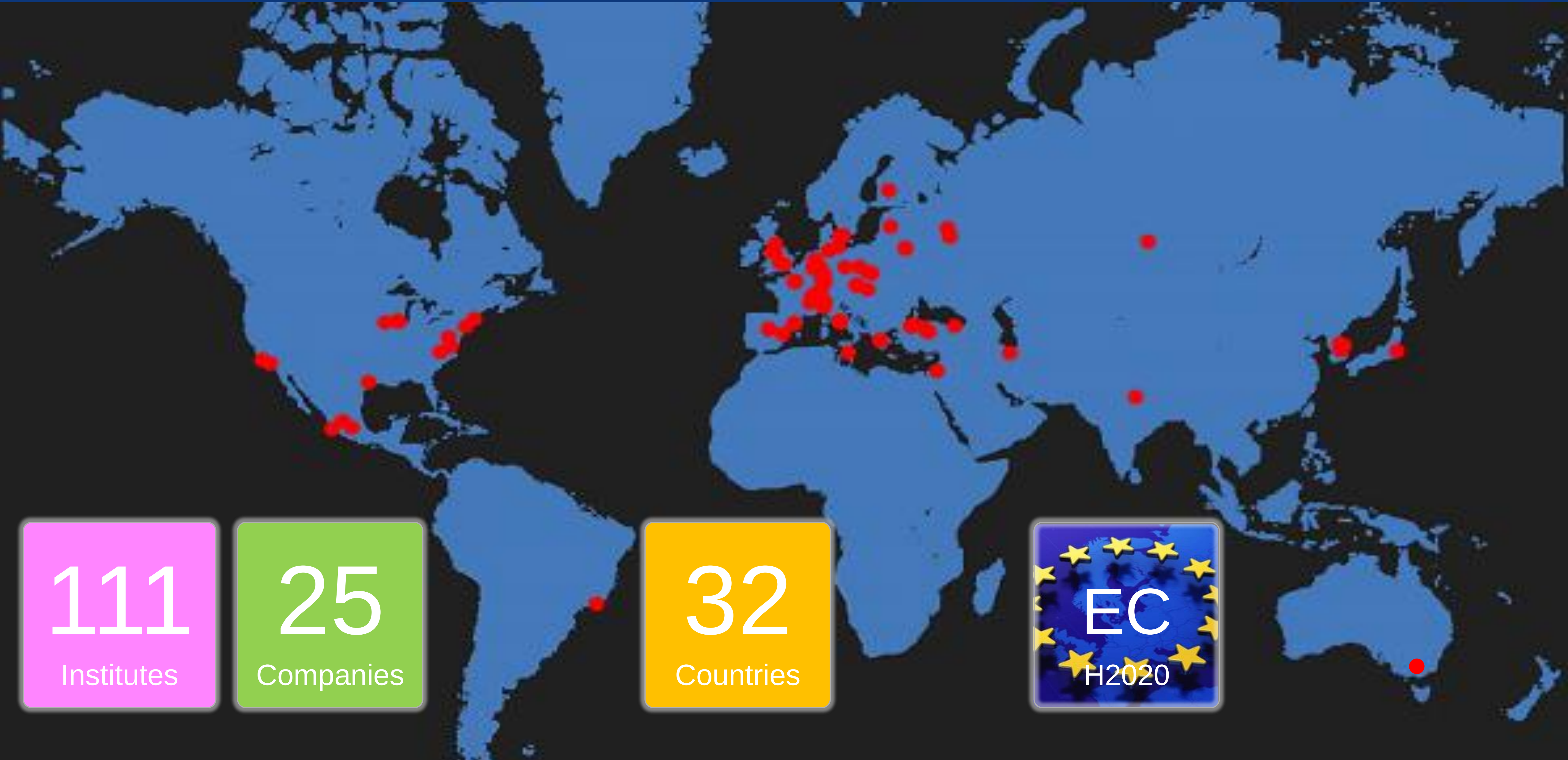
13 Beneficiaries

BRUKER, cea, Columbus Superconductors, HZB Helmholtz Zentrum Berlin, SPIN, Universität Stuttgart, INFN, Technische Universität Dresden, TU Wien Technische Universität Wien, Universität Siegen, WU Wirtschaftsuniversität Wien Vienna University of Economics and Business, I-CUBE, CERN

12 Partners

Bmax power to shape, ASG Superconductors, Bilfinger Babcock Noell GmbH, CemeCon The Tool Coating, IEEE Advancing Technology for Humanity, Criotec Impianti S.r.l., MAN Diesel & Turbo, Terra Mater Factual Studios, Red Bull Media House, research instruments, Sigmaphi Magnets and Beam Transport, Università degli Studi di Genova, Air Liquide

Collaboration & Industry Relations



Summary and outlook 2017/18

- Consolidate design baselines for FCC-hh, FCC-ee, HE-LHC
- Comprehensive parameter document for FCC-eh was recently published
- 2018 FCC physics workshop: 15-19 Jan. 2018, CERN
  (FCC physics WS in Jan. 2017 (>200 participants)).
- Advance further on HW developments (magnets, SRF, special technologies)
- Develop implementation scenarios, schedules and cost estimates
- Define author/contributor teams for CDR core parts
- Prepare, assemble and edit CDR contributions
- FCC Week in spring 2018 will review CDR draft contents
- Presentation of printed CDR at the end of 2018

Have an interesting and productive week!