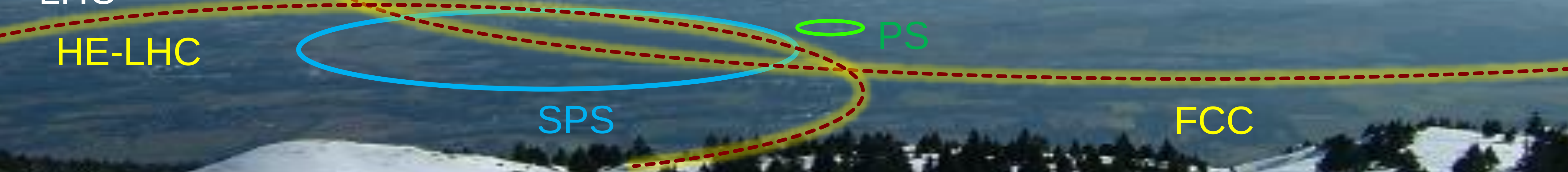
Future Circular Collider Study Status Overview

Michael Benedikt, CERN, for the FCC Collaboration

FCC Physics Workshop, 11 January 2018

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



http://cern.ch/fcc

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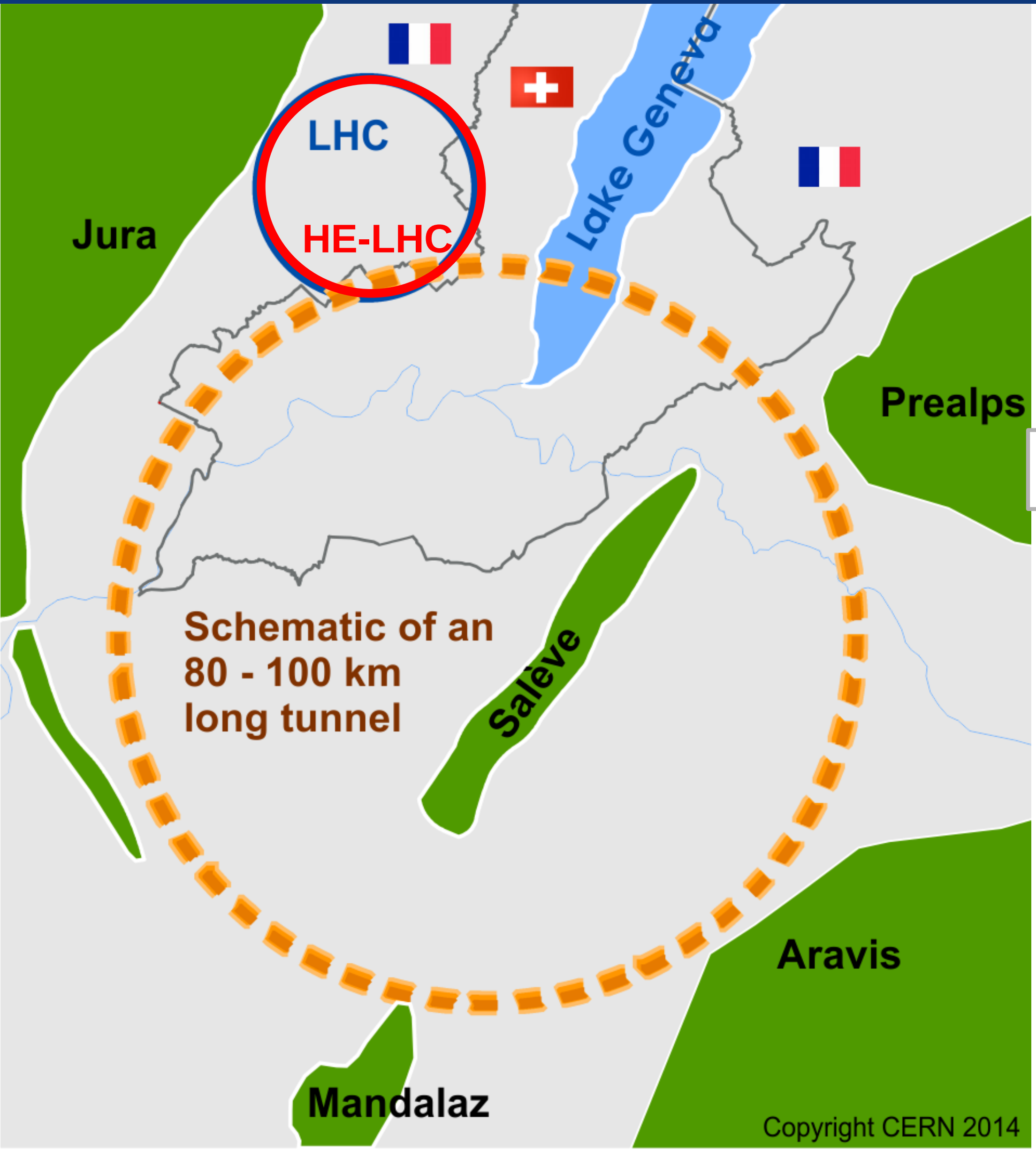
photo: J. Wenninger

Future Circular Collider (FCC) Study

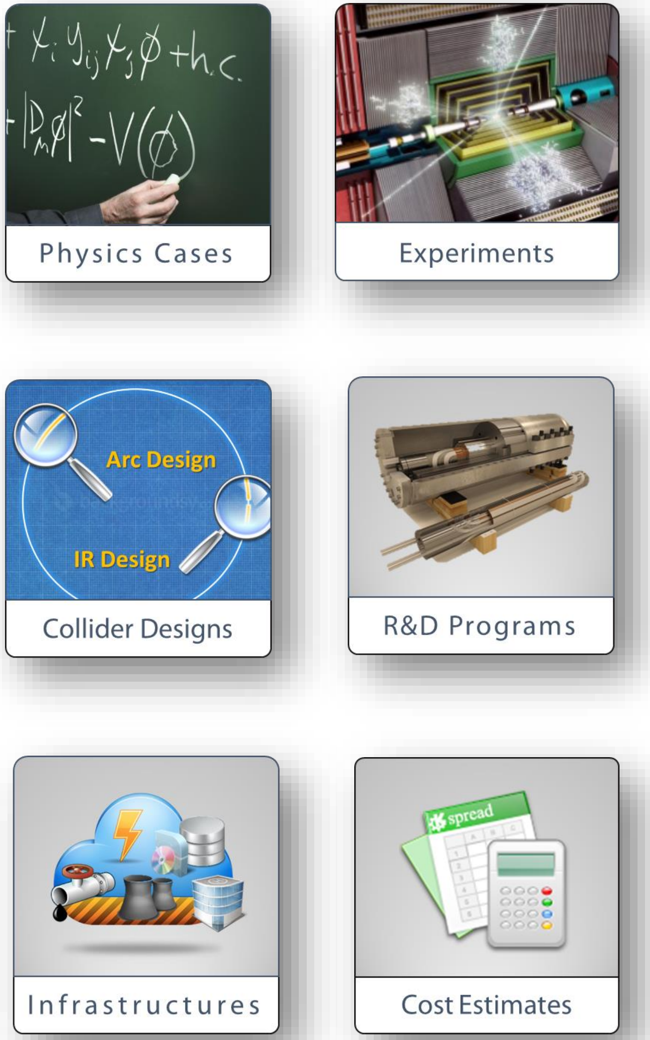


International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, 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_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 c.m. energy & integrated luminosity ~ 20ab^{-1} within 25 years

HE-LHC:

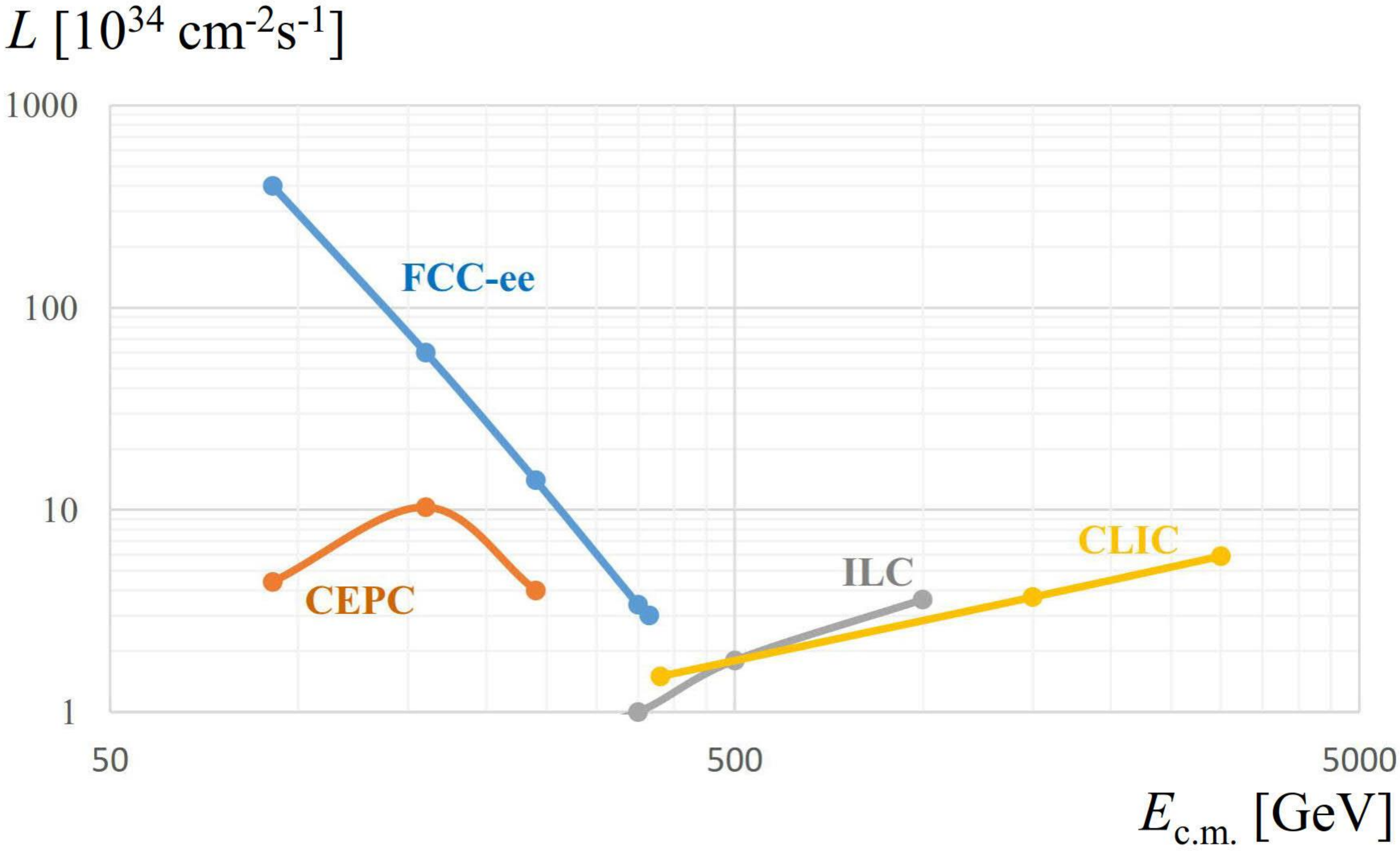
- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC

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

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar	
beam energy [GeV]	45	80	120	175	182.5
beam current [mA]	1390	147	29	6.4	5.4
no. bunches/beam	16640	1300	328	40	33
bunch intensity [10^{11}]	1.7	2.3	1.8	3.2	3.35
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.2
total RF voltage [GV]	0.1	0.75	2.0	8.8	10.3
long. damping time [turns]	1273	236	70	23	20
horizontal beta* [m]	0.15	0.2	0.3	1	1
vertical beta* [mm]	0.8	1	1	1.6	1.6
horiz. geometric emittance [nm]	0.27	0.84	0.63	1.34	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.7	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 7.5	3.15 / 5.3	2.75 / 3.82	2.76 / 3.78
luminosity [10^{34} $cm^{-2}s^{-1}$]	>200	>32	>7	>1.7	>1.5
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / 24	38 / 18	37 / 24	36 / 25

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	52 ab^{-1}/year		
W	32	8.3 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)	1.5	0.38 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

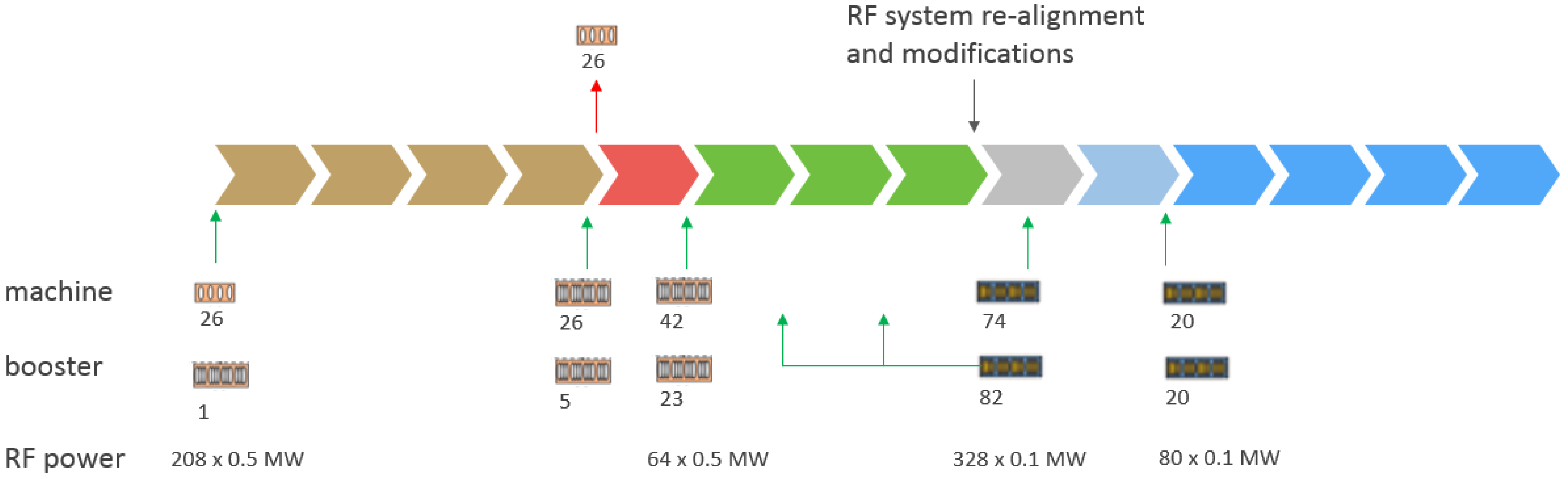
"Ampere-class" machine

	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 for FCC-ee & booster:

- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cav, ~1 MW source**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**

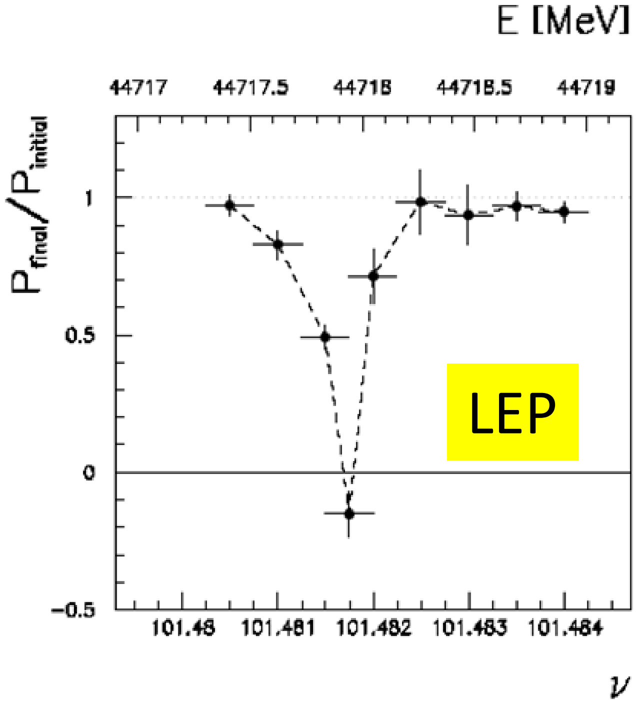


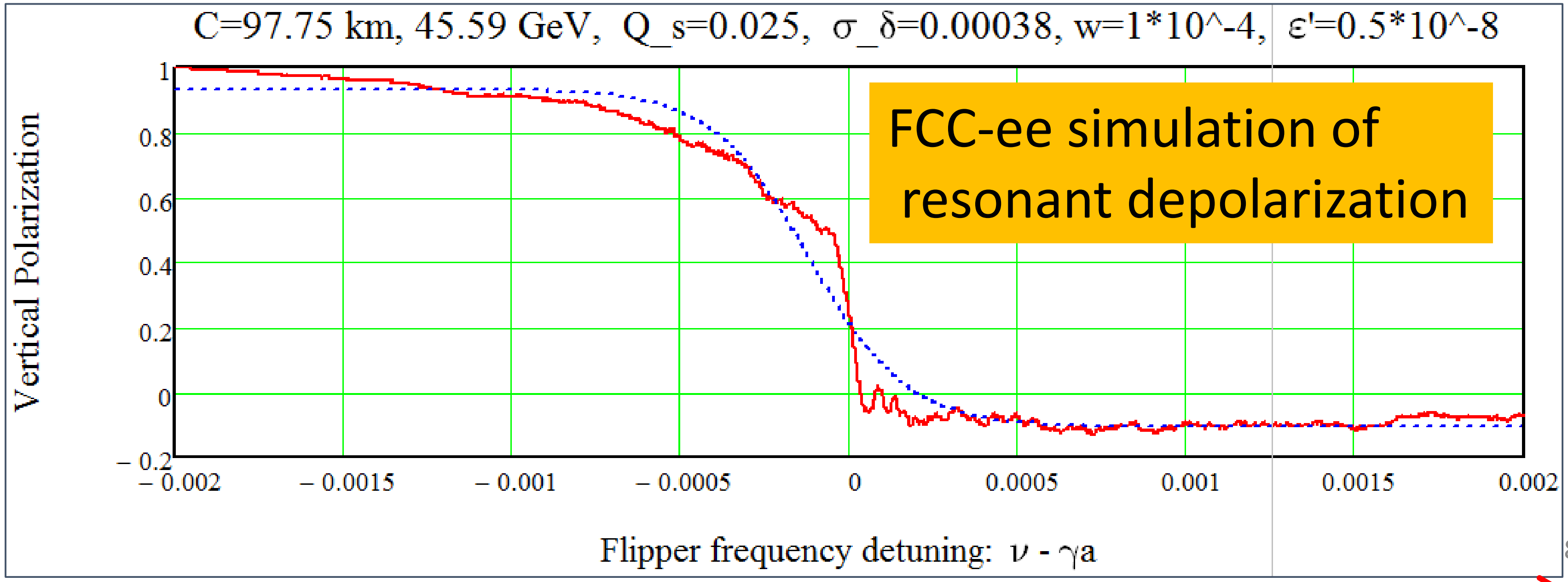
- LEP record: ~ 32 CM in one shutdown
- Possibly 1 year of long shutdown between ZH and ttbar operation.
- spread 800 MHz RF power & booster installation over the preceding shutdowns

Beam Polarization and Energy Calibration

- **Priority from Physics** : ΔE/E ~O(10^{-6}) around Z pole and WW threshold → **Z,W mass&width**
- **Exploit natural transverse beam polarization** present at Z and W, unique to e+e- circular coll's.
  - ➢ Required hardware (polarimeter, wigglers, depolarizer) is defined & integrated
  - ➢ Running mode with 1% non-colliding bunches and wigglers defined
- **Work in progress: errors from betatron motion in non-planar orbits, transverse impedance, RF asymmetries, optimum depolarizer set-up vs Qs at W, etc**

➔ On track to match goal of 100 (300) keV errors on ECM at Z (WW) energies.



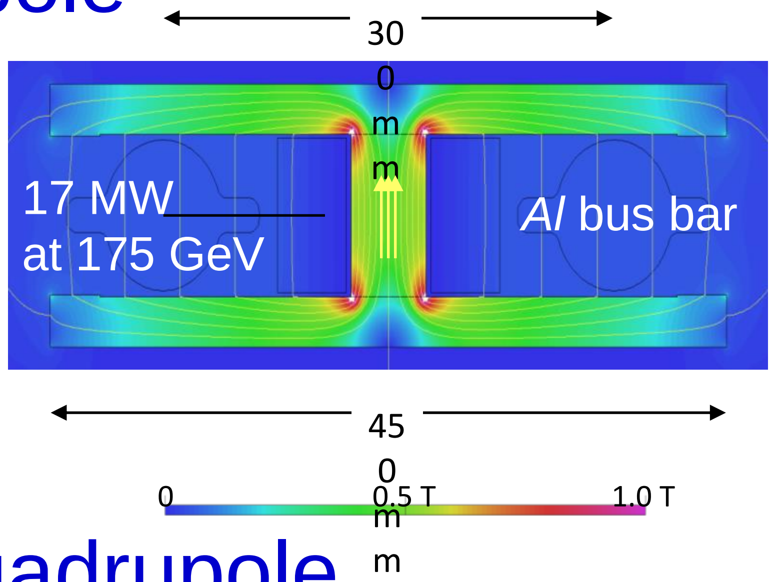


260 seconds sweep of depolarizer frequency

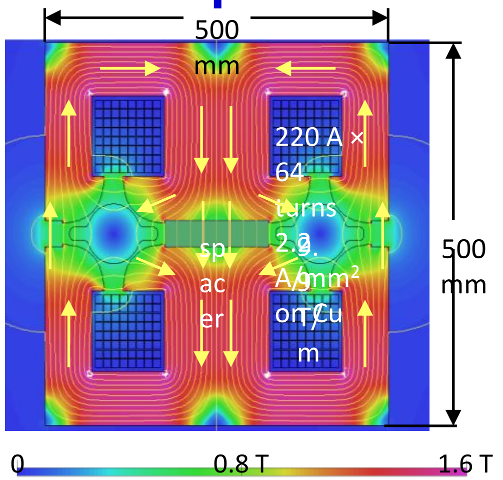
FCC-ee dual aperture main magnets

low-power low-cost designs - factor 2 power saving by dual aperture

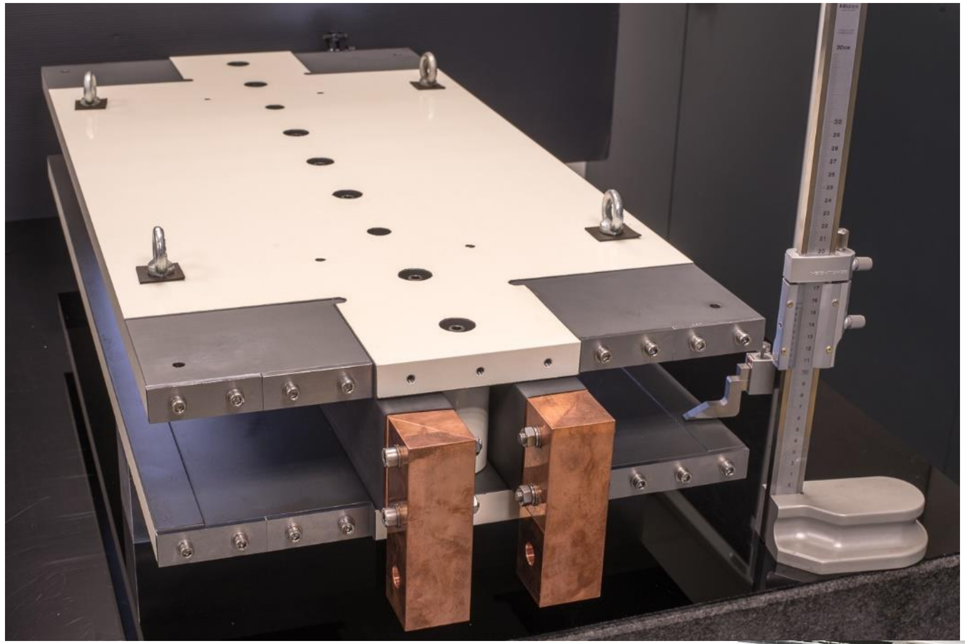
dipole



quadrupole



22 MW at 175 GeV with *Cu* coil



construction of main dipole and quadrupole models (~1 m units)

magnetic measurements ongoing

RF cavity development & FCC-eh ERL

5-cell 800 MHz cavity, JLAB prototype for FCC-ee (top mode) & FCC-eh; also single-cell cavities for all FCC's

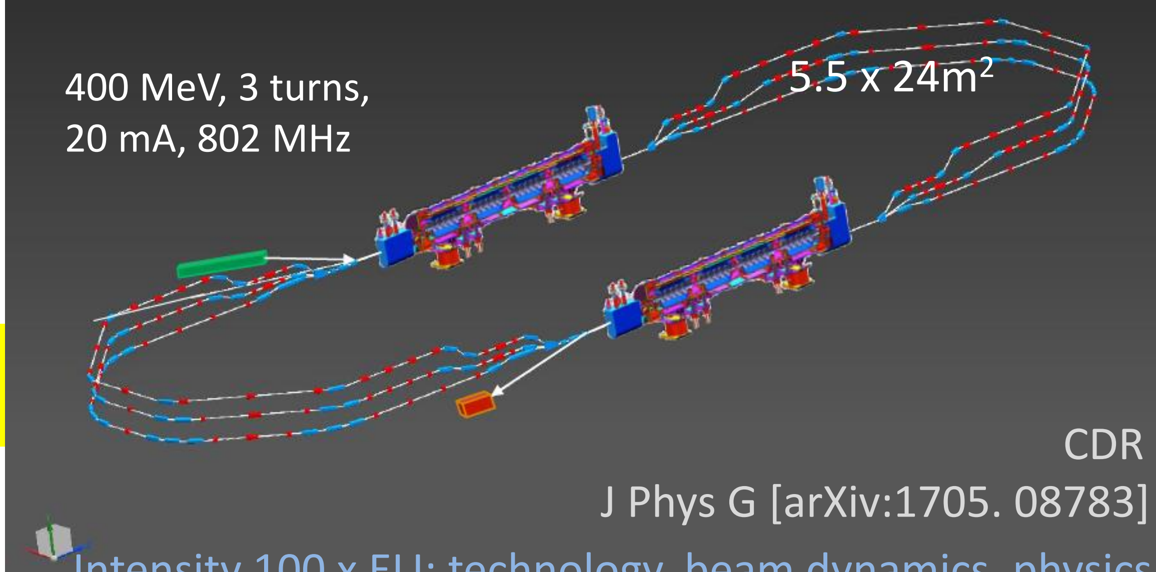
optimized for high current operation

M. Klein

FCC-eh: 60 GeV e^- from Energy Recovery Linac (ERL)

PERLE@Orsay ERL test facility

BINP, CERN, Daresbury/Liverpool, Jlab, Orsay +..



CDR

J Phys G [arXiv:1705. 08783]

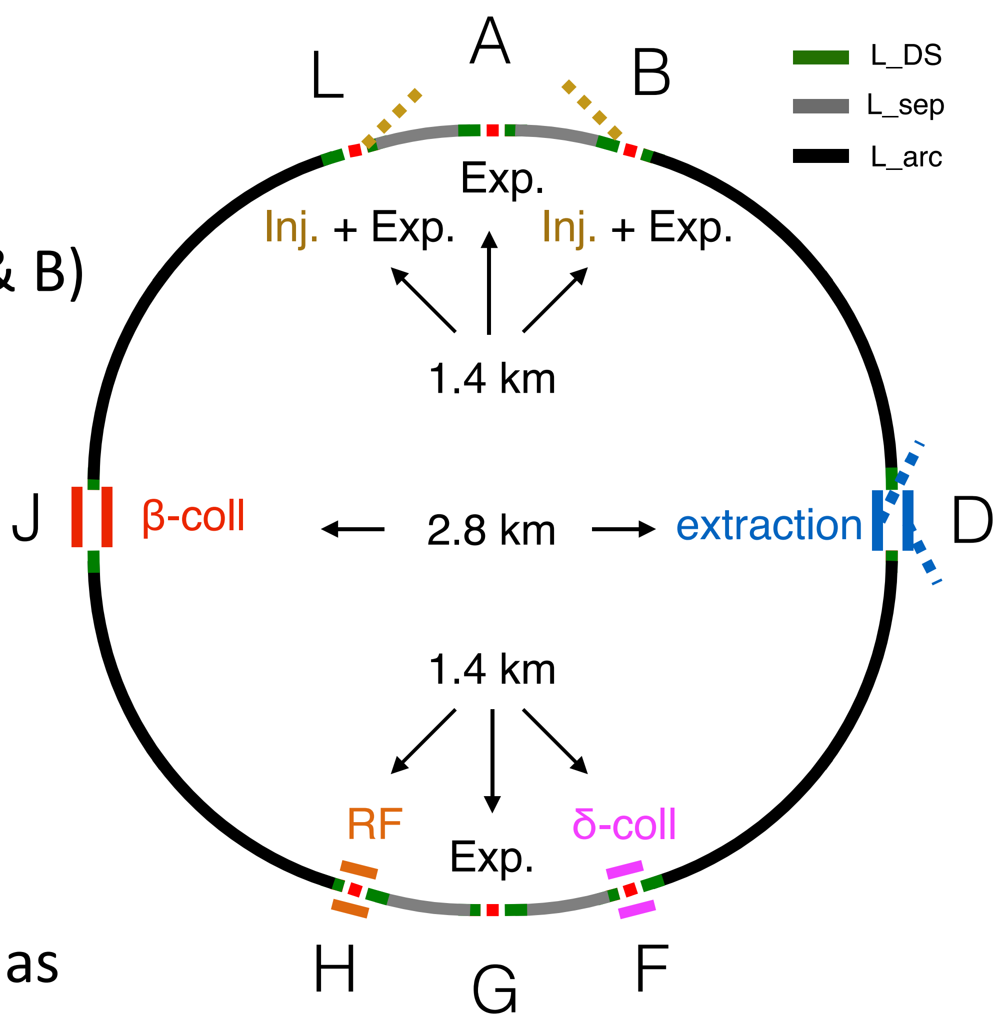
Intensity 100 x ELI: technology, beam dynamics, physics

Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [µm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

FCC-hh layout and optics

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



- **Circumference 97.8 km**
- Injections upstream side of experiments
- **Avoids mixing of extraction region and high-radiation collimation areas**
- **Beam dynamics studies confirm design goals**
- Focus on optimization of collimation system and extraction system

FCC-hh detector – new reference design

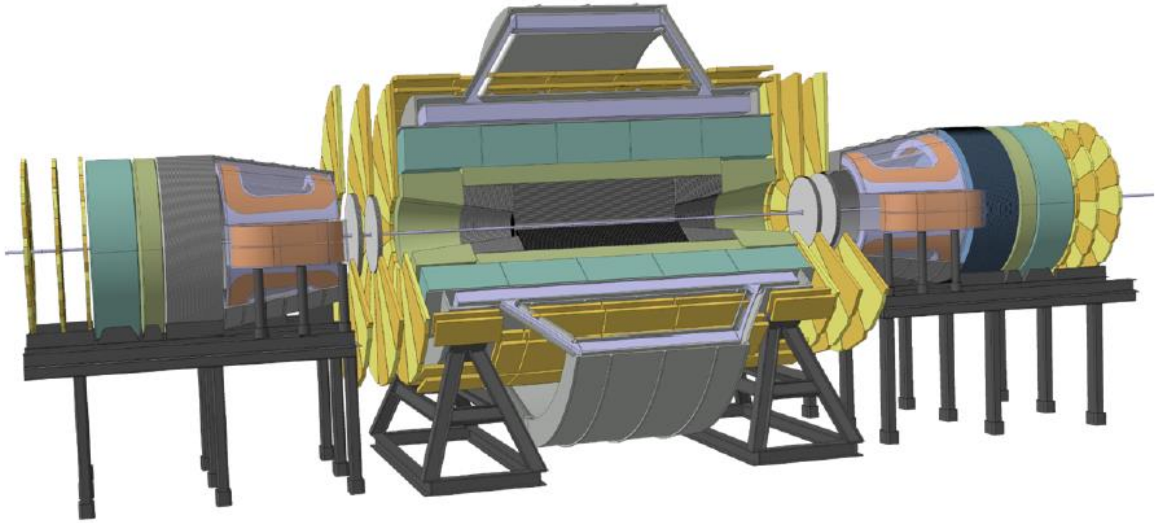
6 T, 12 m bore solenoid, 10 Tm dipoles, shielding coil

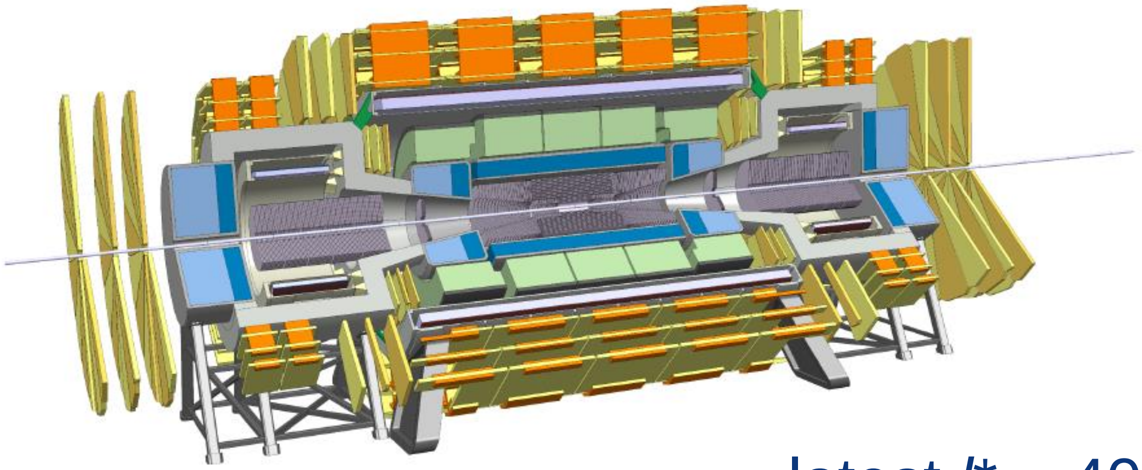
- 65 GJ stored energy
- 28 m diameter
- >30 m shaft
- multi billion project

→

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

- 14 GJ stored energy
- rotational symmetry for tracking!
- 20 m diameter (~ ATLAS)
- 15 m shaft
- ~1 billion project



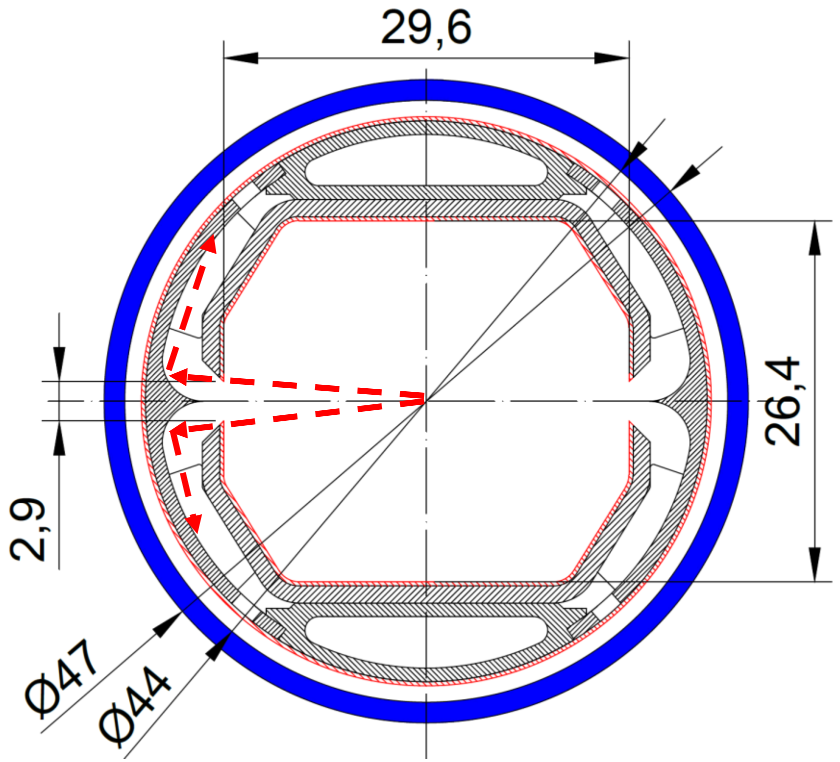


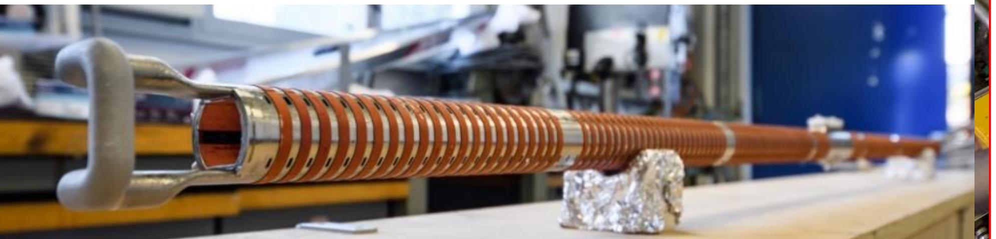
latest l^* = 40 m

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**

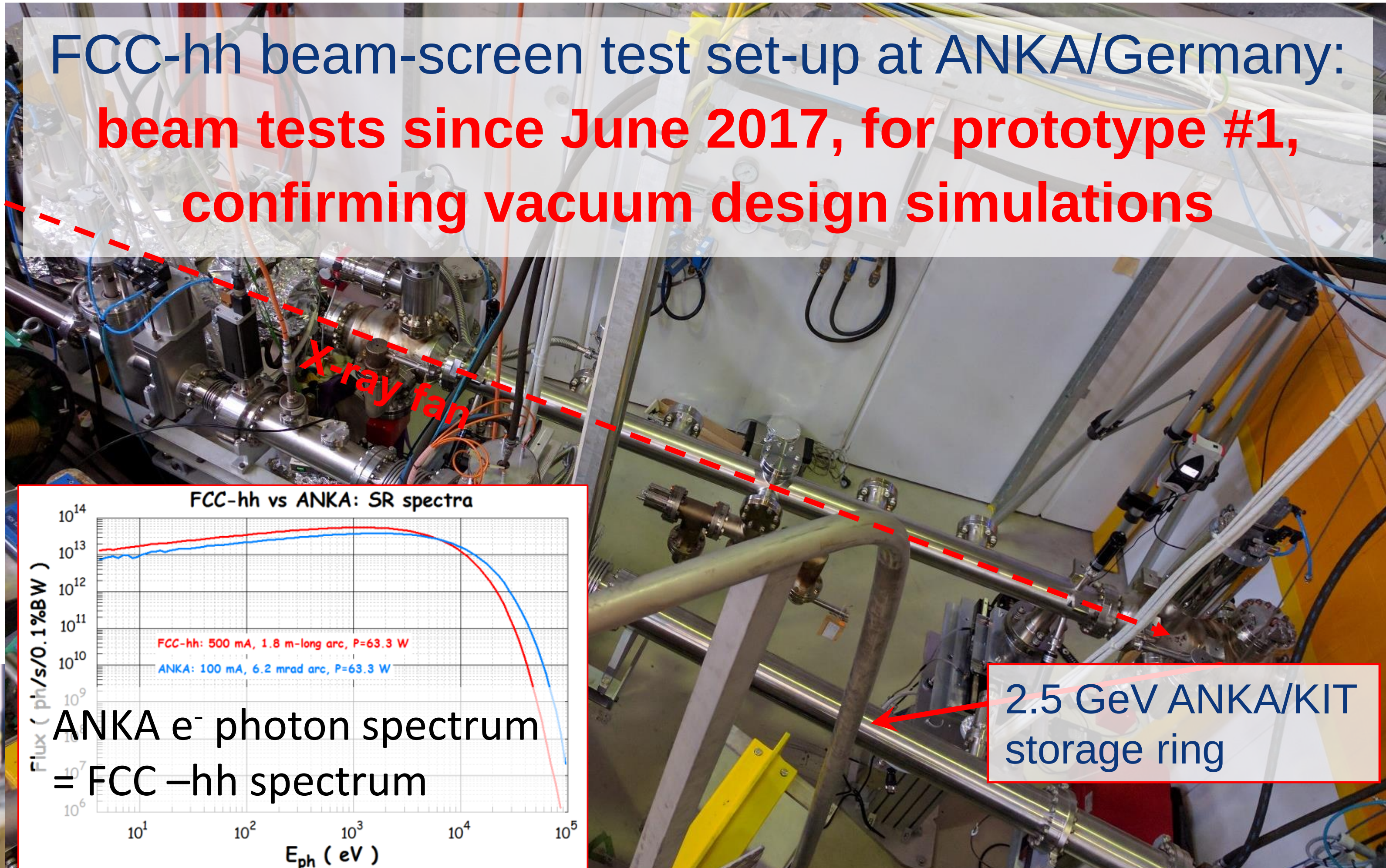
- **Absorption of synchrotron radiation at ~50 K** for cryogenic efficiency (5 MW →100 MW cryoplant)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.





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

beam tests since June 2017, for prototype #1, confirming vacuum design simulations



Worldwide FCC Nb_3Sn program

Main development goals:
- **J_c increase (16T, 4.2K) > 1500 A/mm^2 i.e. 50% increase wrt HL-LHC wire**
- **Potentials for large-scale production and cost reduction**

- **Procurement of state-of-the-art conductor:**
  - Bruker-OST– European/US
- **Conductor development with regional industry:**
  - CERN/KEK – Japanese contribution. Japanese **industry** (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku Univ. and NIMS).
  - CERN/Bochvar High-technology Research Inst. – Russian contribution. Russian **industry** (TVEL) and laboratories
  - CERN/KAT – Korean **industrial** contribution
- **Characterization of conductor & research with universities:**
  - **Technical Univ. Vienna, Geneva University, University of Twente**
  - **Applied Superconductivity Centre** at Florida State University

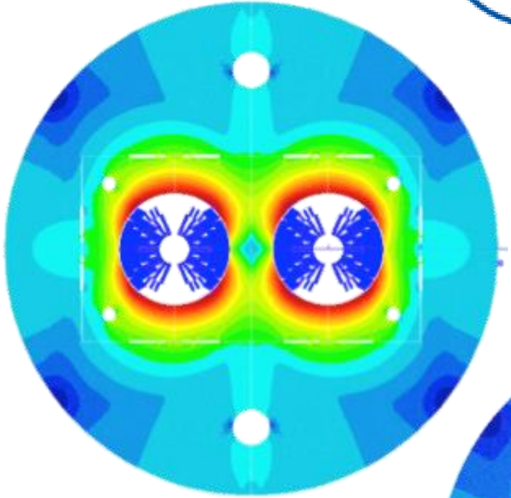
16 T dipole design activities and options

H2020

EuroCirCol

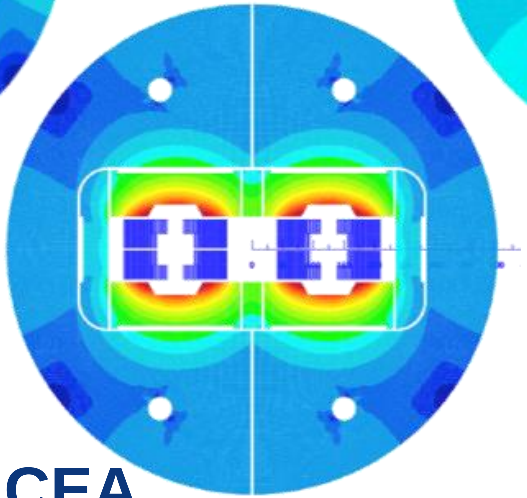
A key to New Physics

Cos-theta



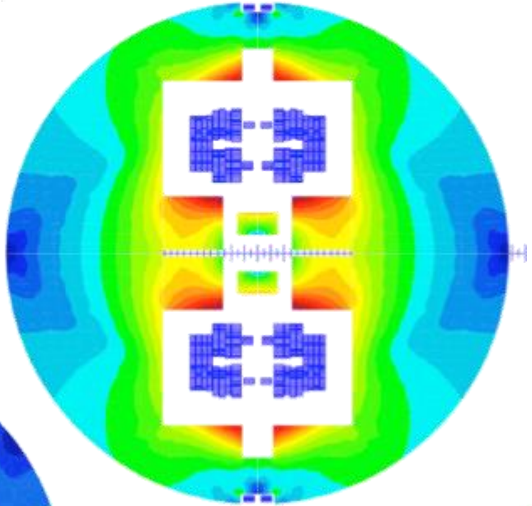
INFN

Blocks



CEA

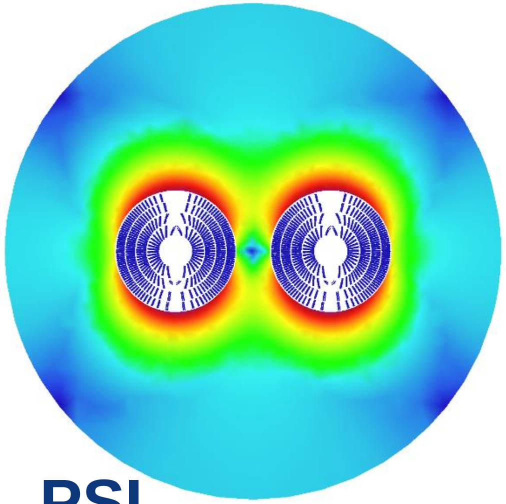
Common coils



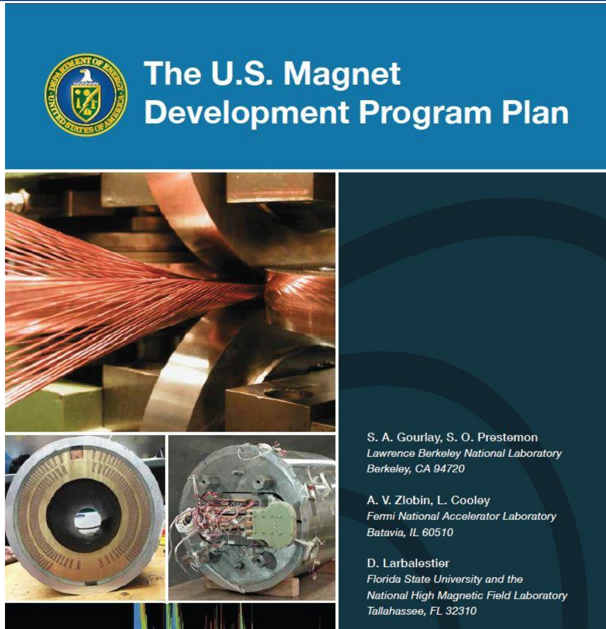
CIEMAT

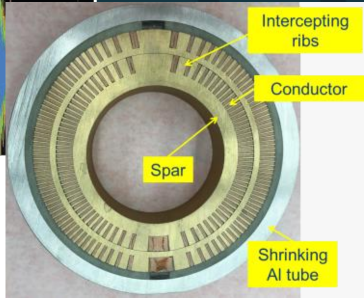
Swiss contribution

Canted Cos-theta

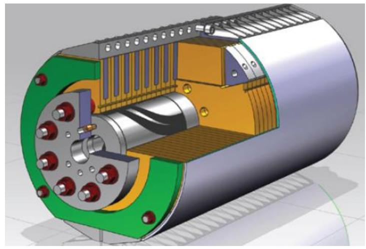


PSI





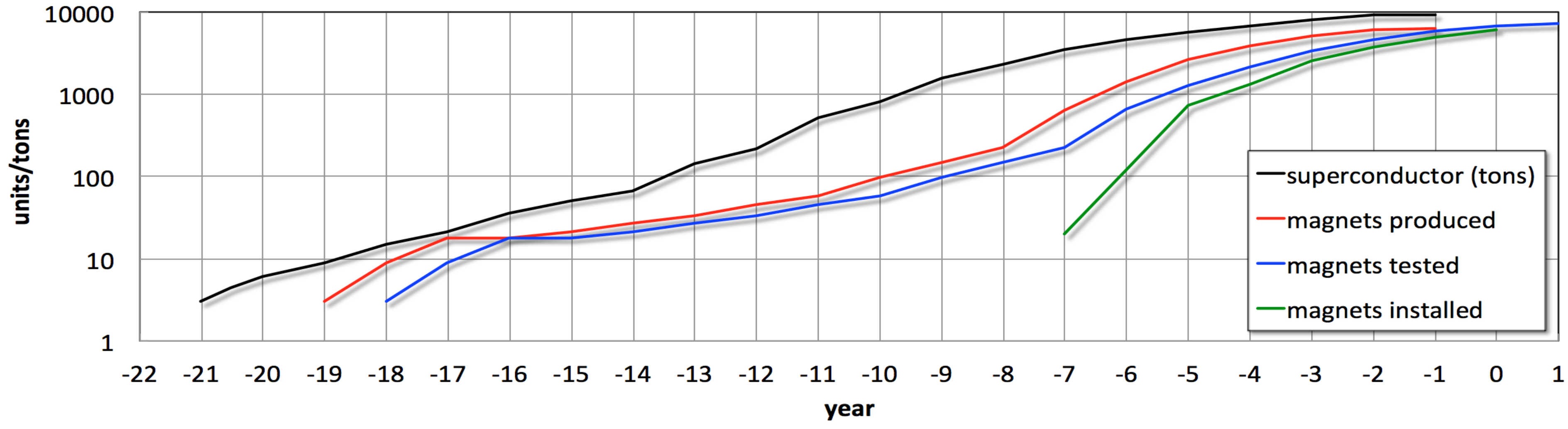
LBNL



FNAL

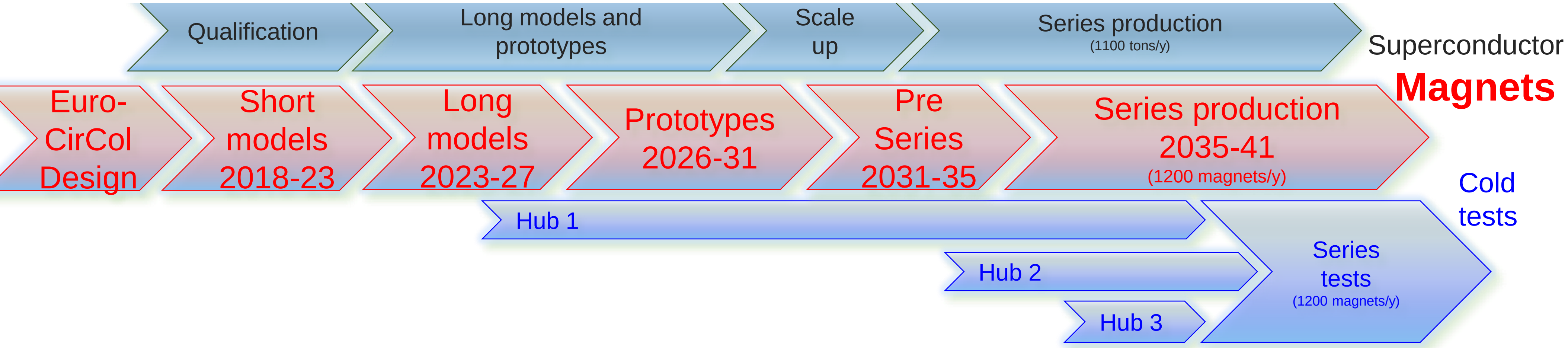
Short model magnets (1.5 m lengths) will be built from 2017 - 2022

16 T magnet R&D schedule



total duration of magnet program:

~20 years

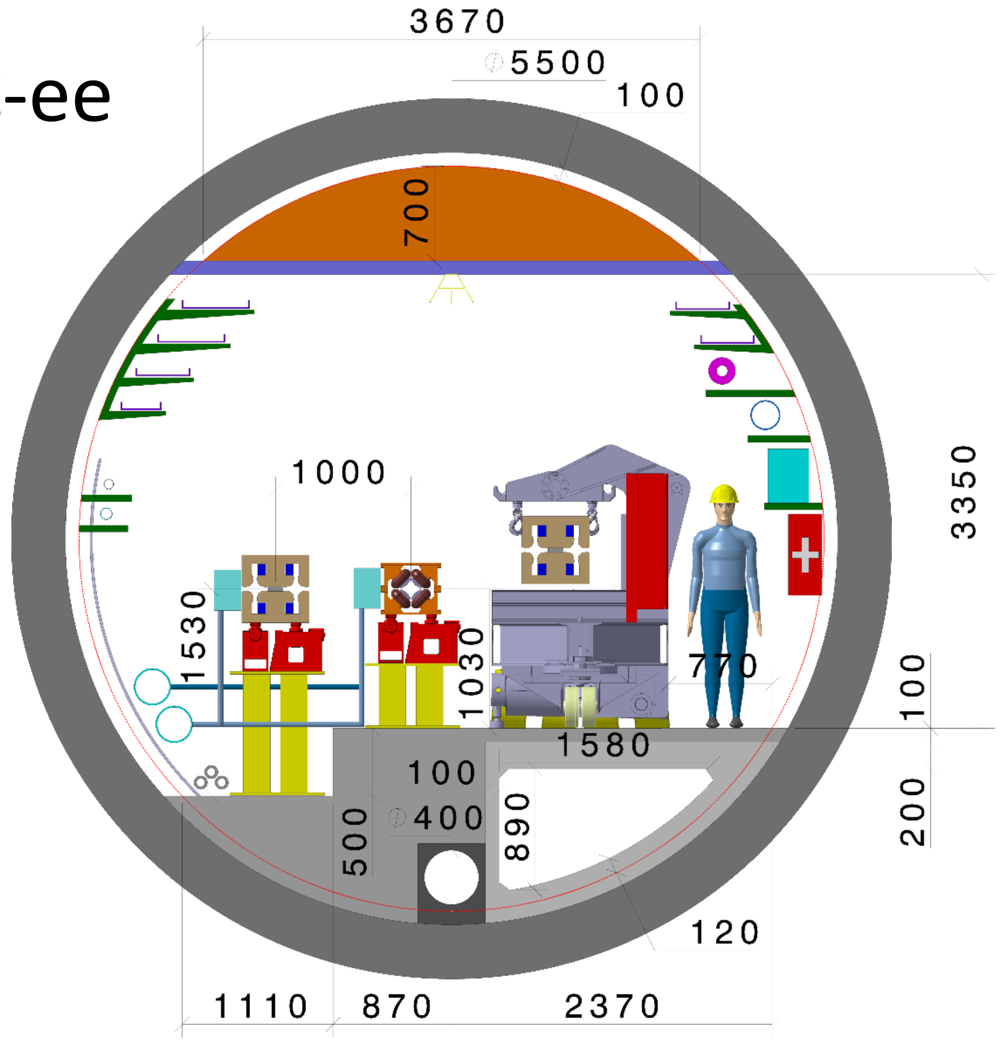


would follow HL-LHC Nb_3Sn program with long models at industry from 2023/24

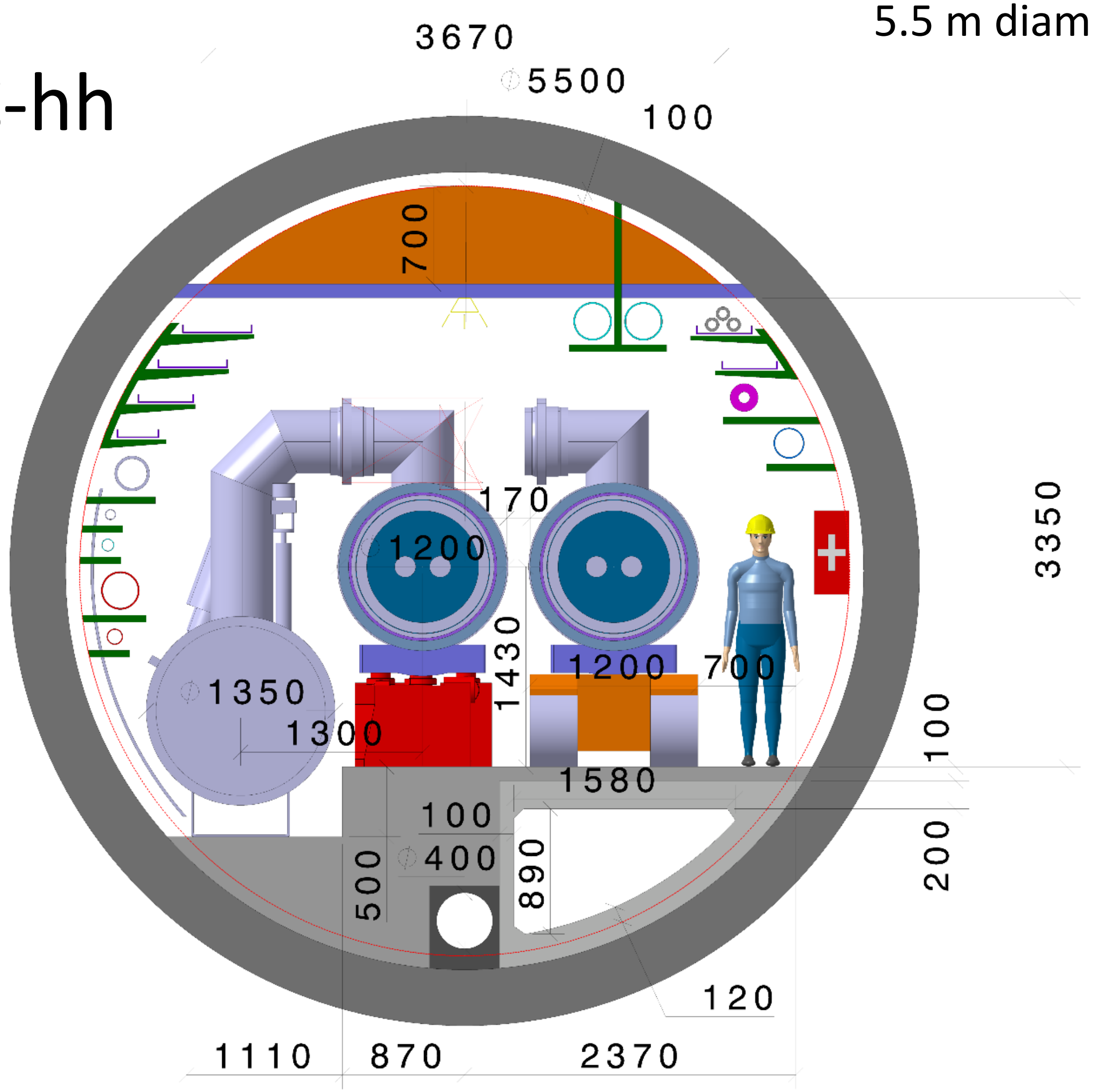
FCC tunnel integration

5.5 m diameter

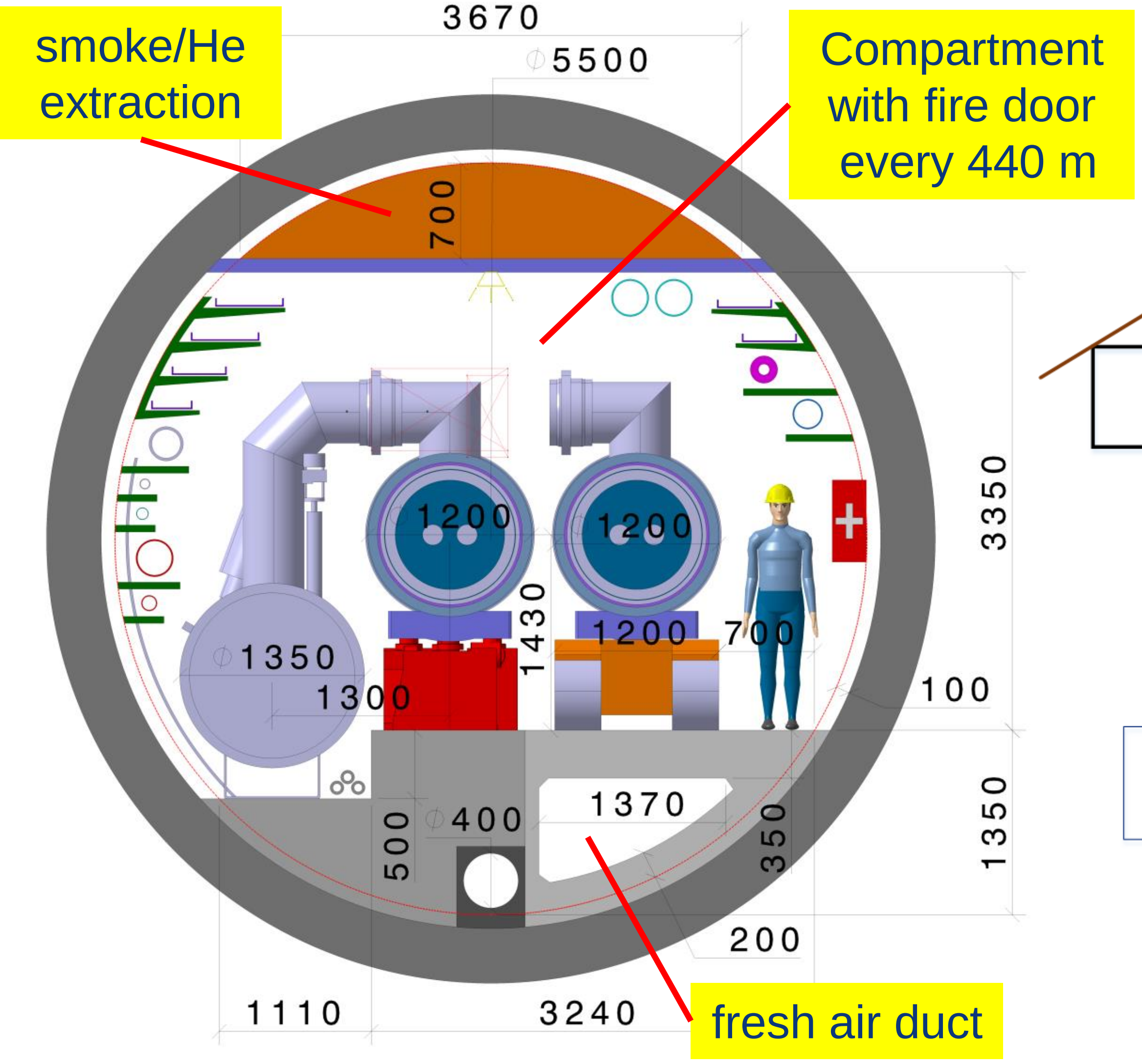
FCC-ee



FCC-hh

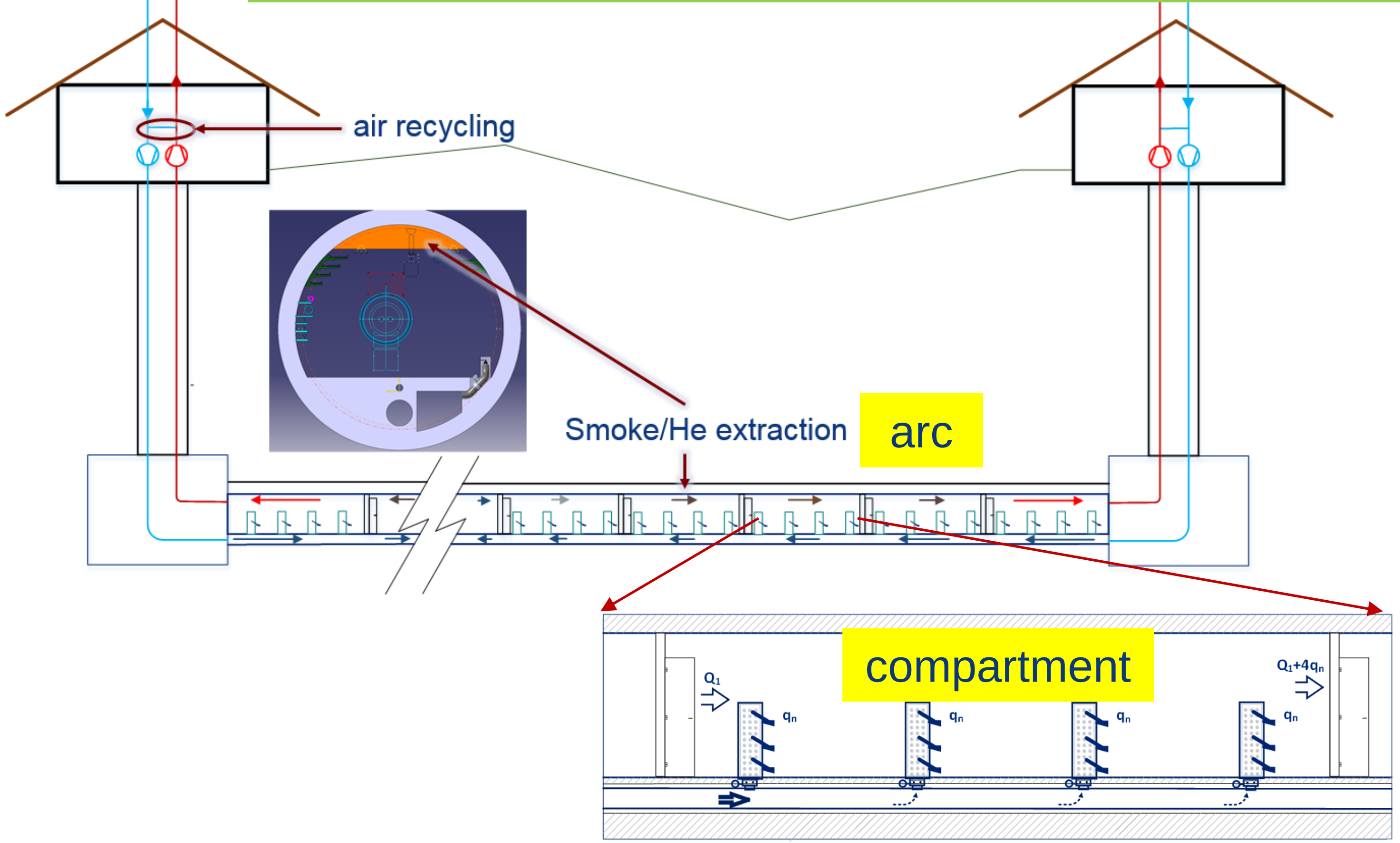


FCC integration and safety concept



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



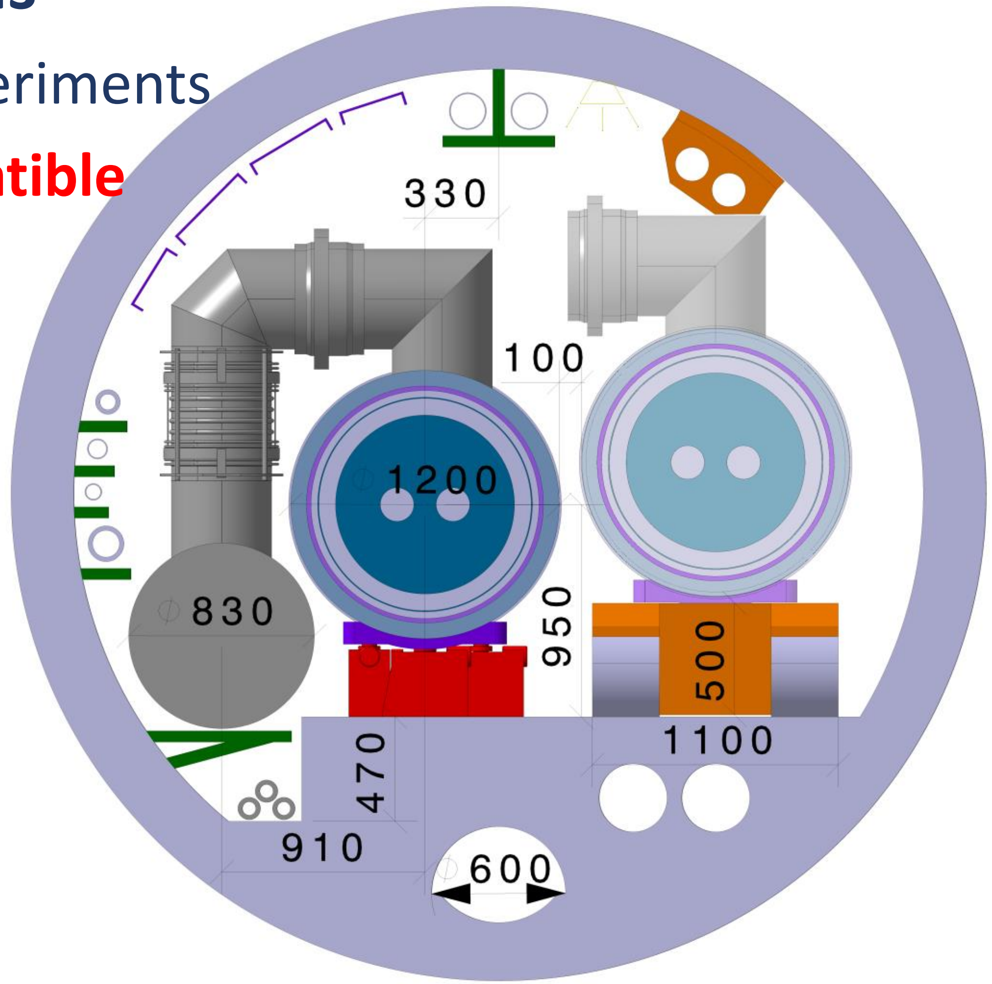
HE-LHC integration aspects

Working hypothesis for HE LHC design:

No major CE modifications on tunnel and caverns

- Similar geometry and layout as LHC machine and experiments
- **Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **Classical cryostat design gives ~1500 mm diameter!**

LHC tunnel diameter 3.8 m



Strategy: develop optimized 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

- **Allow stray-field and/or cryostat as return-yoke**
- **Optimization of inter-beam distance (compact)**

→ **Smaller diameter also relevant for FCC-hh cost**

16 T cryo-dipole integration approach

Design evolution

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

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

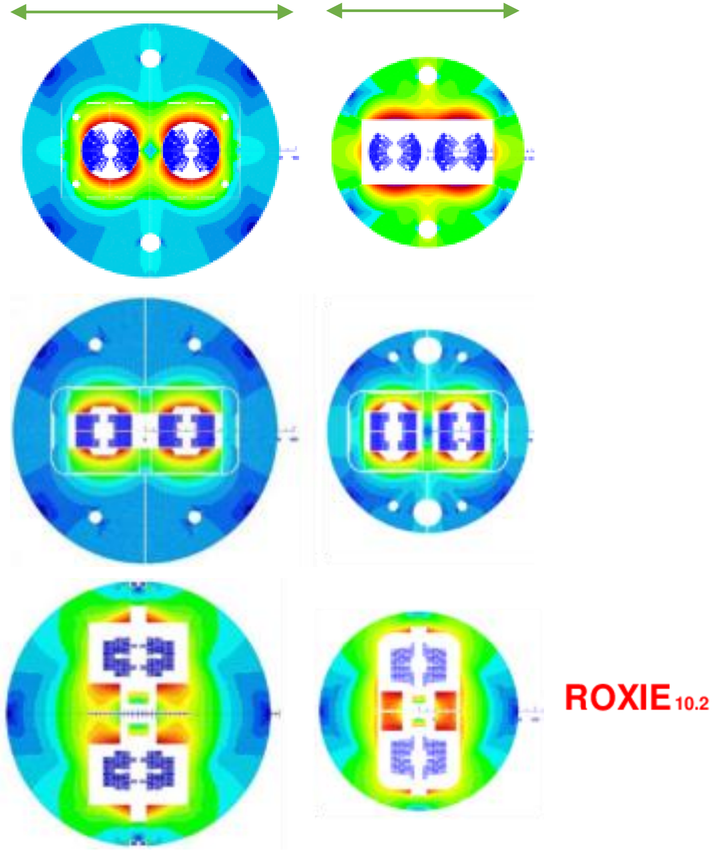
cold mass 40t
total mass 62t

800 mm 600 mm

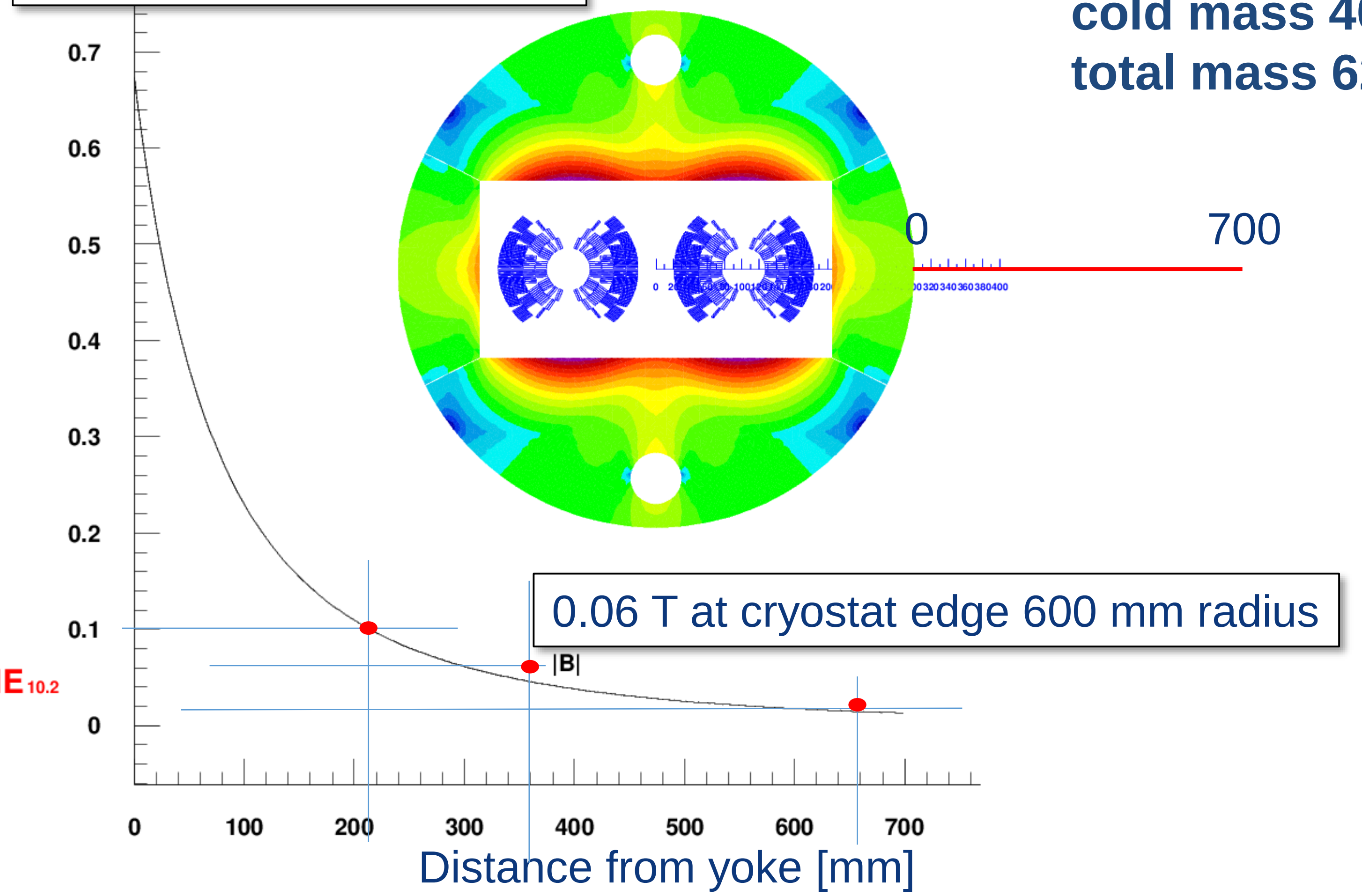
Cosine-theta (baseline)

Block-type coils

Common-coils



2015 2017



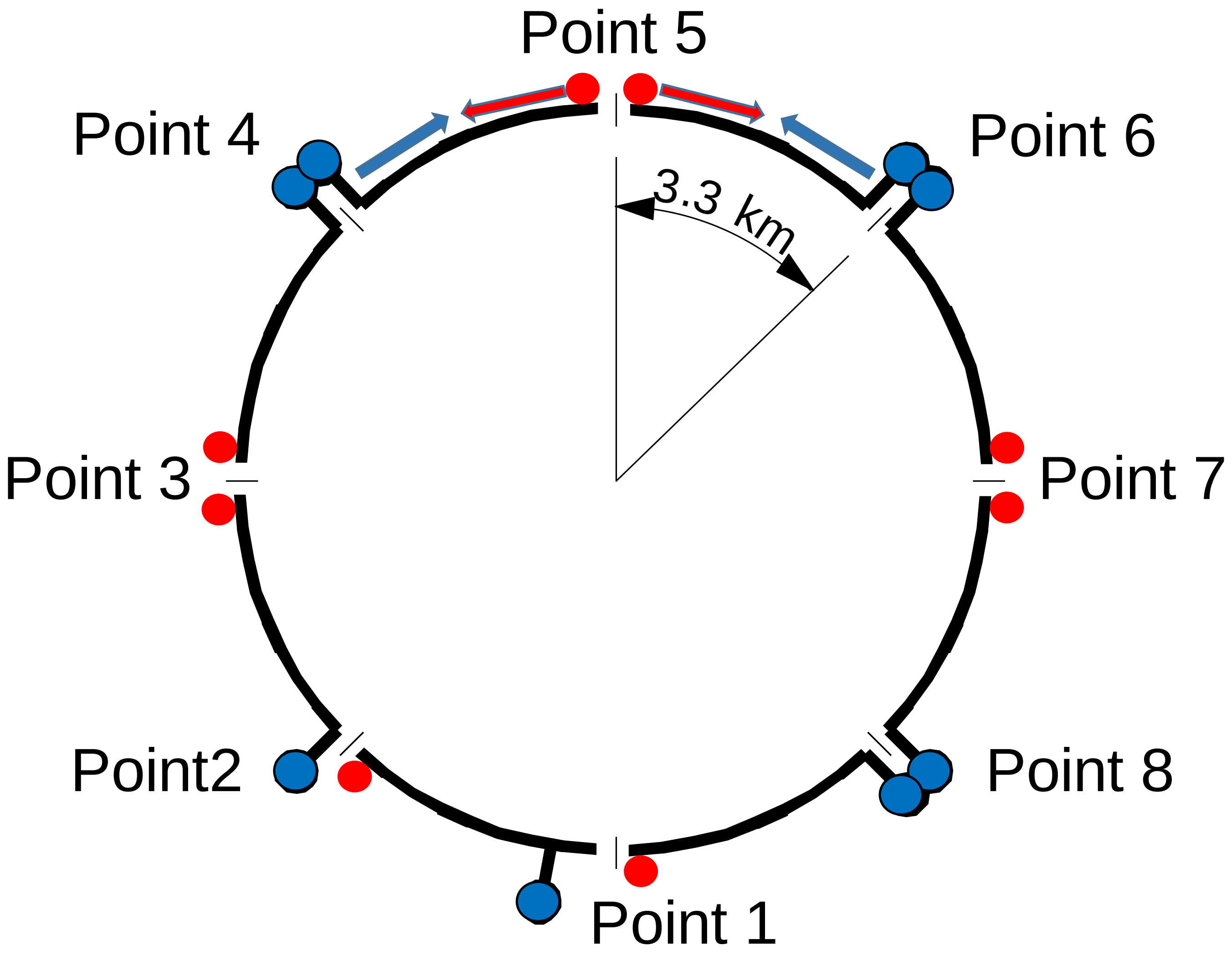
HE-LHC cryogenic layout

Higher heat load and integration limitations (Cryo-line diameter) requires installation of

- **8 additional 1.8 K refrigeration units wrt. LHC**
  - 2.3 kW @ 1.8 K (~ LHC size)
  - P elect: ~500 kW per unit

- **8 new higher-power 4.5 K cryoplants**
  - 28 kW @ 4.5 K (including 2.3 kW @ 1.8 K)
  - P elect: ~6500 kW per cryoplant (cf. 4200 kW for LHC cryoplant)

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

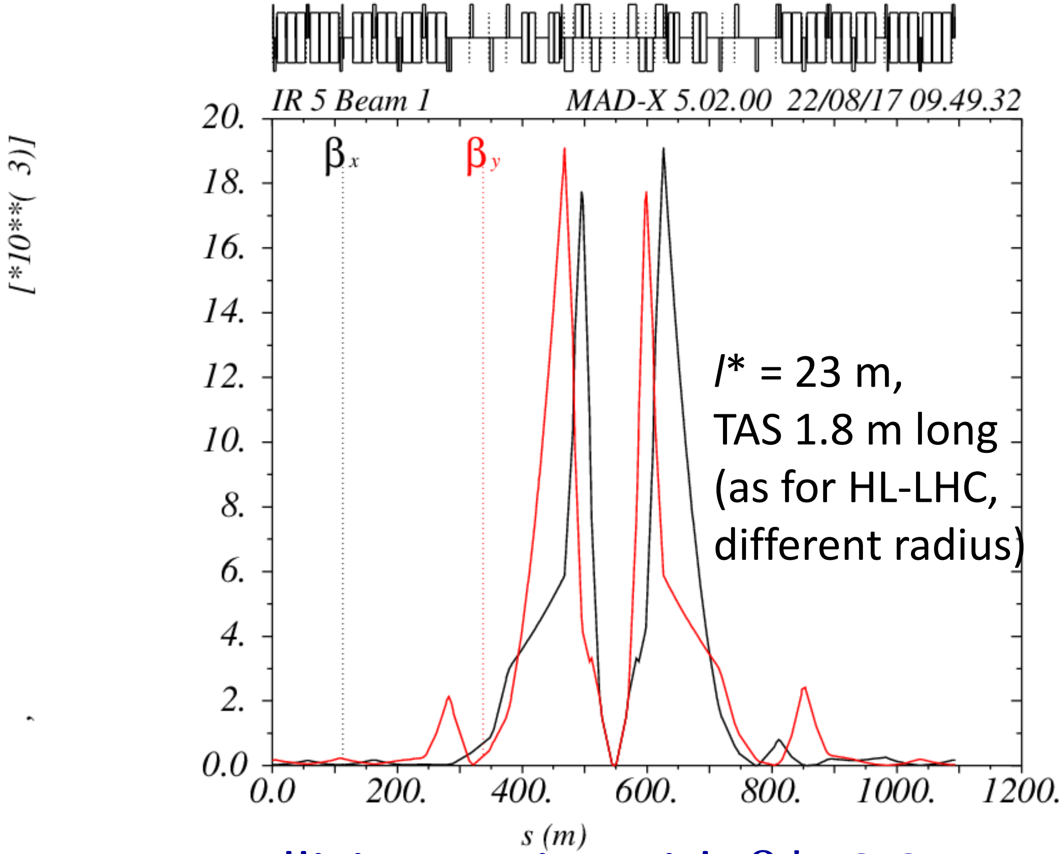


HE-LHC IR optics & triplet shielding

triplet lengths: HE-LHC: 56 m (13.5 TeV)

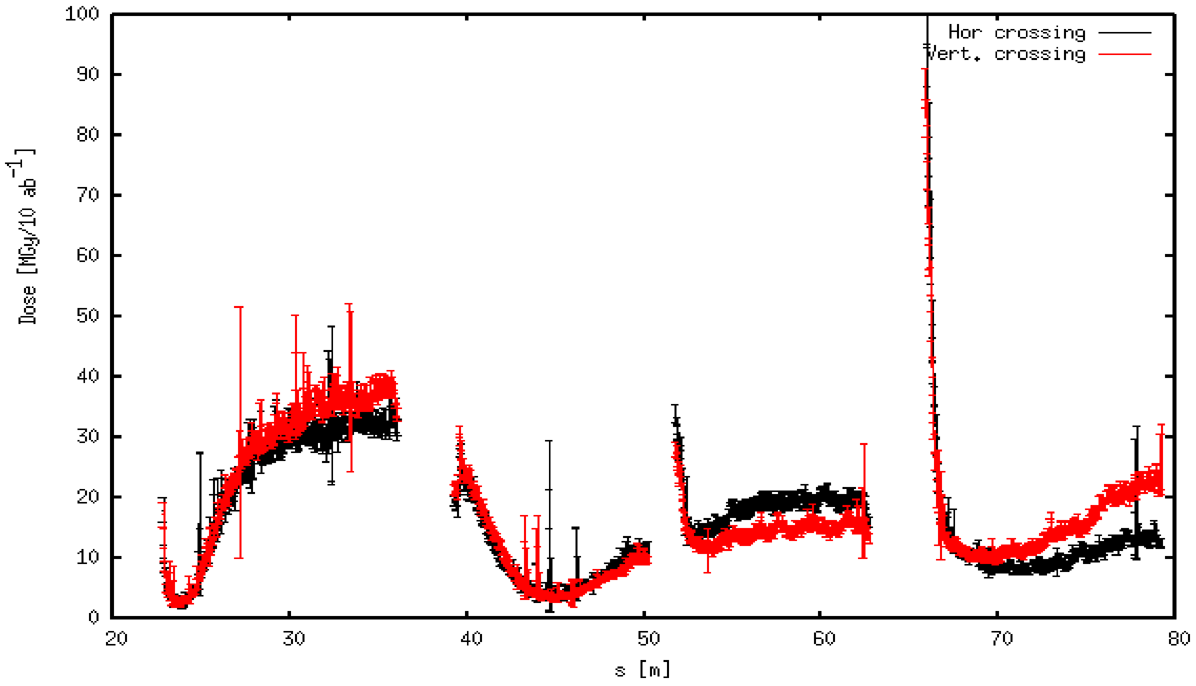
HL-LHC: 41. 8m, present LHC: 30.4 m

ca. 11 m space for crab cavities



collision optics with β^*=0.25 m

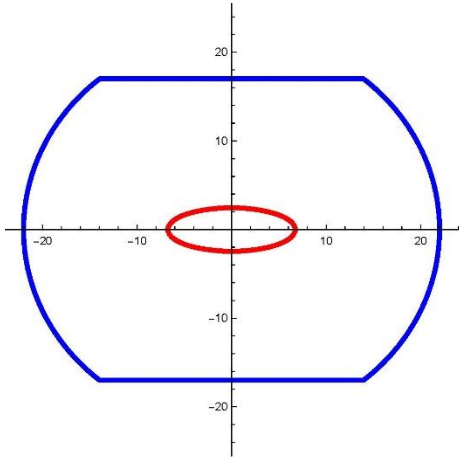
- **Triplet quadrupoles with 2 cm inside tungsten shielding**
- **For 10 ab^{-1} total luminosity: 30-40 MGy peak radiation (peak at Q3 can be reduced with shielding)**



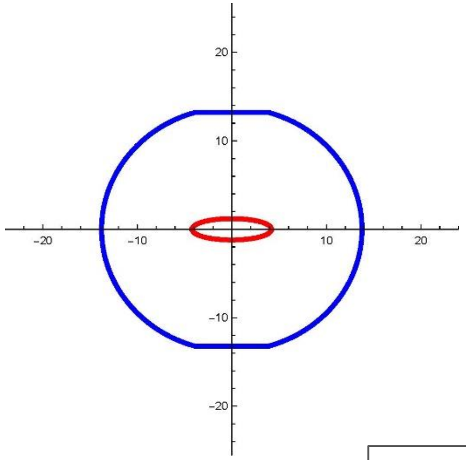
Work on collimation insertions ongoing

Horizontal beam size (6σ) in arcs (QF) at injection

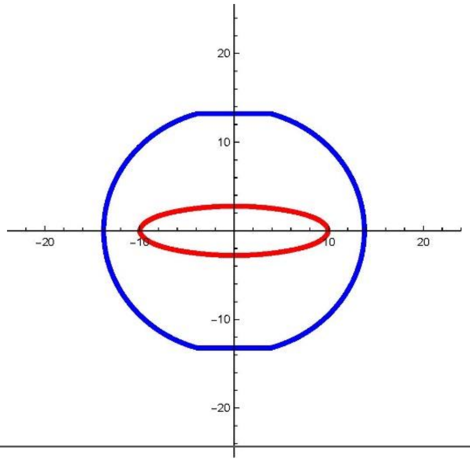
HL-LHC



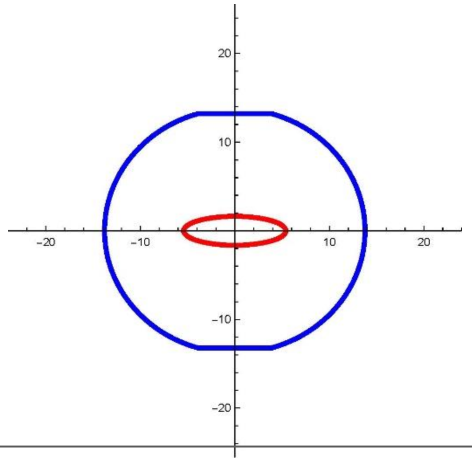
FCC-hh 3.3 TeV



HE-LHC 450 GeV

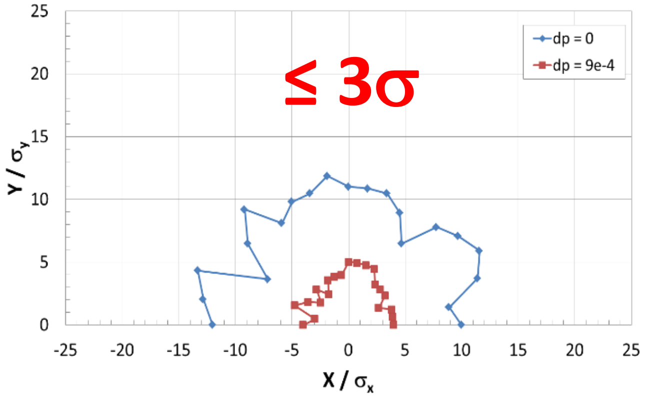


HE-LHC 1.3 TeV

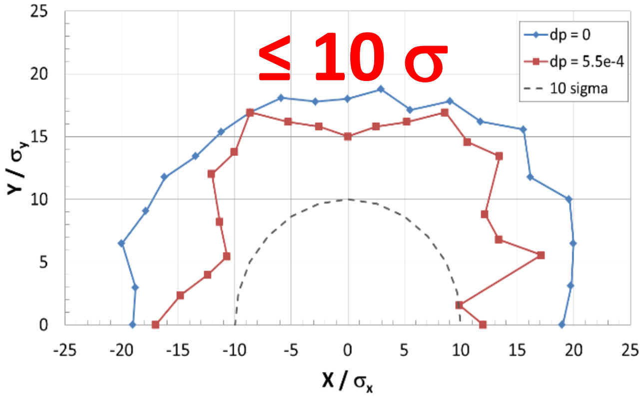


Dynamic aperture studies with systematic field errors of compact dipole b3 component already corrected in each dipole

450 GeV, systematic field errors in arc dipoles, b5 @ 30%, b3 (x2) correctors, 1024 turns, 14 MV



1.3 TeV, systematic field errors in arc dipoles, b5 @ 30%, b3 (x2) correctors, 1024 turns, 10.5 MV



Various studies ongoing:

- Arc optics: aperture vs. top energy
- Magnet design optimization
- Impedance/stability at injection
- **Performance (intensity) vs. injection energy**

HE-LHeC and FCC-he ep collisions

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

Oliver Brüning[1], John Jowett[1], Max Klein[1,2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool

CE tunnel implementation study

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

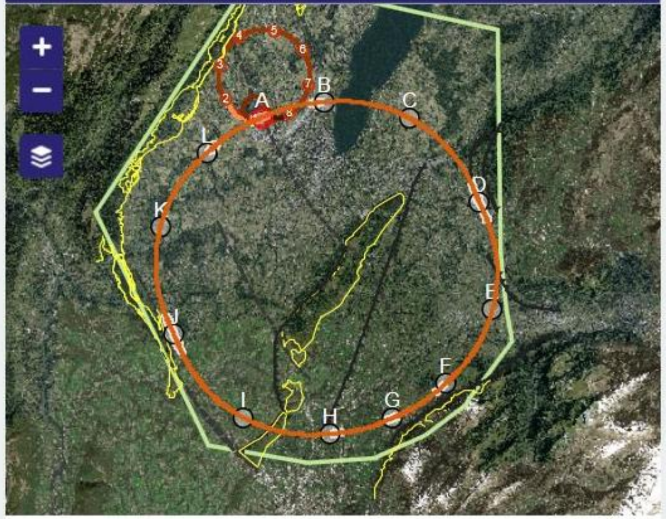
LOAD | SAVE | CALCULATE

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

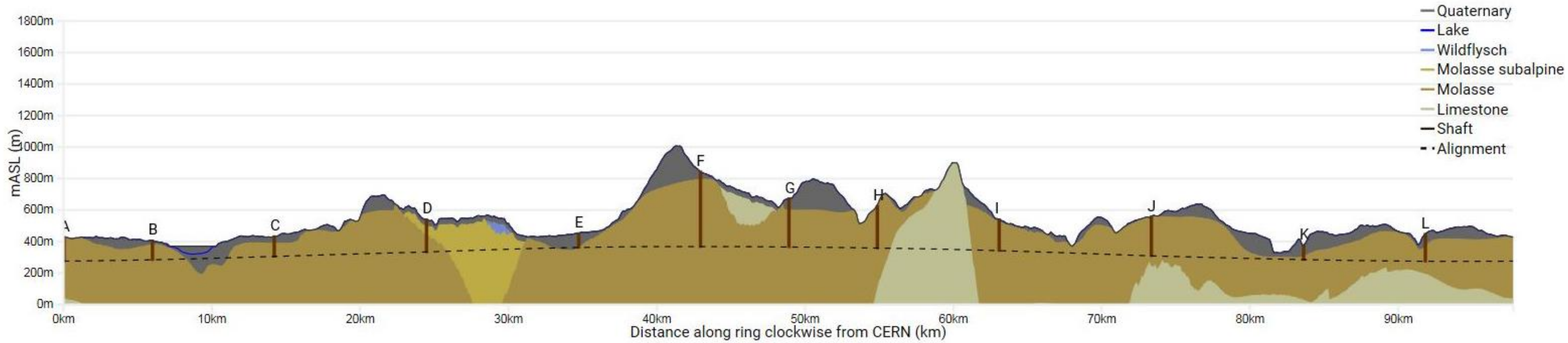
Alignment Location



Geology Intersected by Shafts | Shaft Depths

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

Alignment Profile



Geology Intersected by Tunnel | Geology Intersected by Section

84.6% | 5.2% | 5.5% | 4.7%

Optimisation criteria:

- tunneling rock type,
- shaft depth accessibility
- surface points, etc.

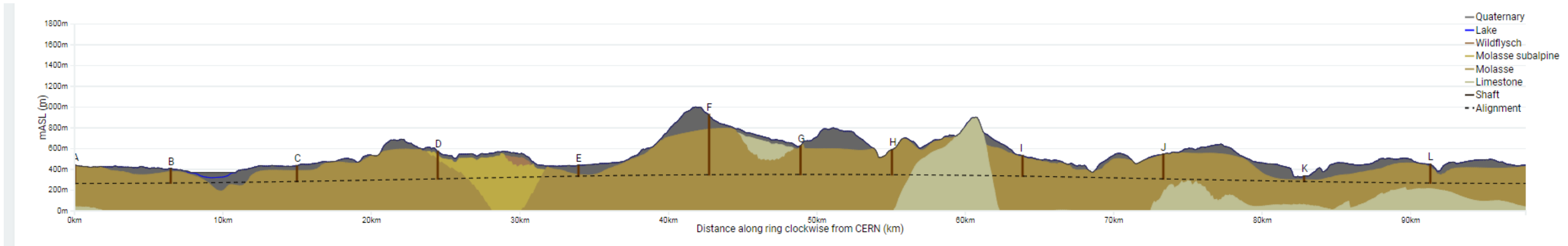
Tunneling:

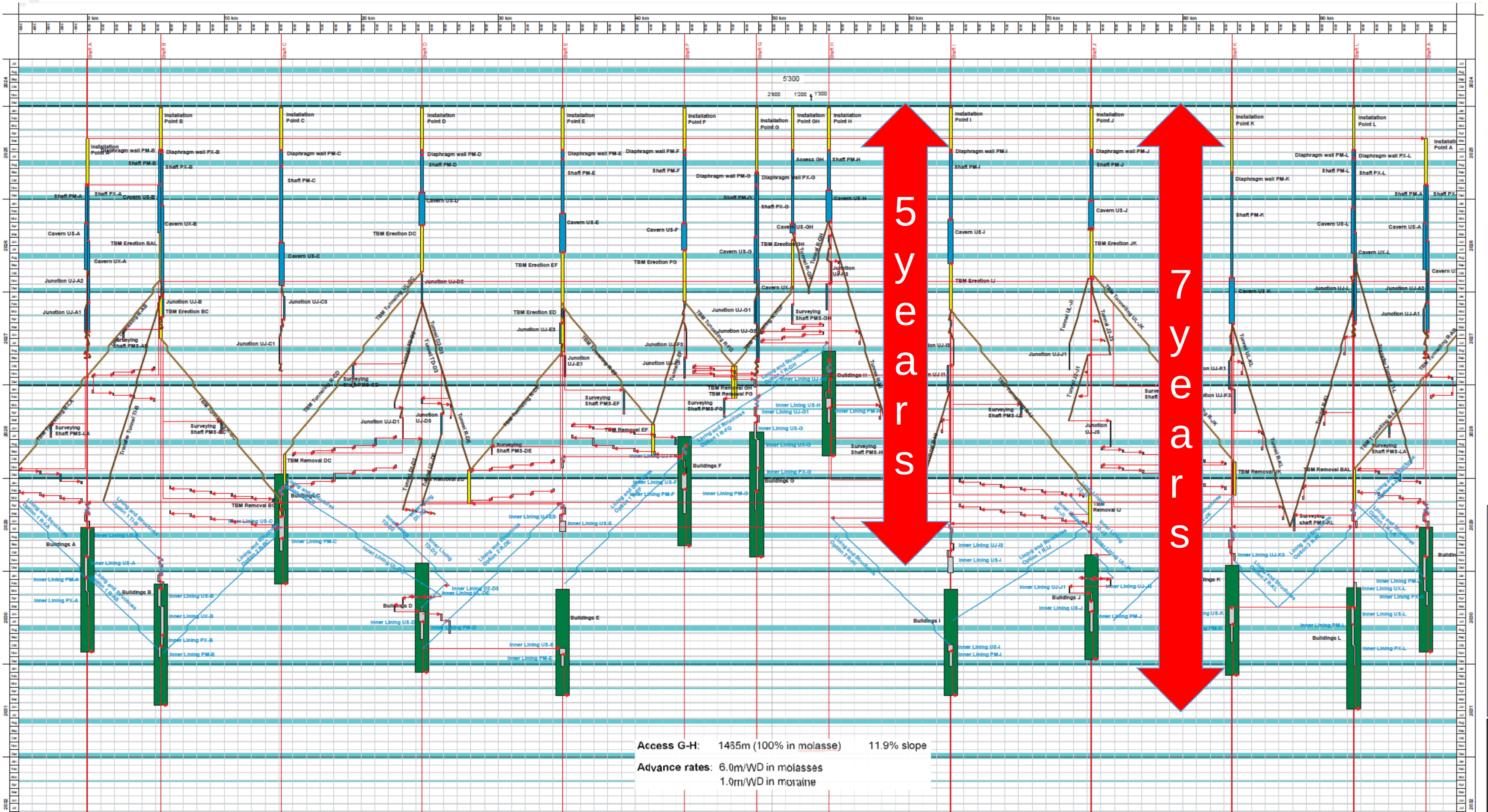
- Molasse 90%,
- Limestone 5%,
- Moraines 5%

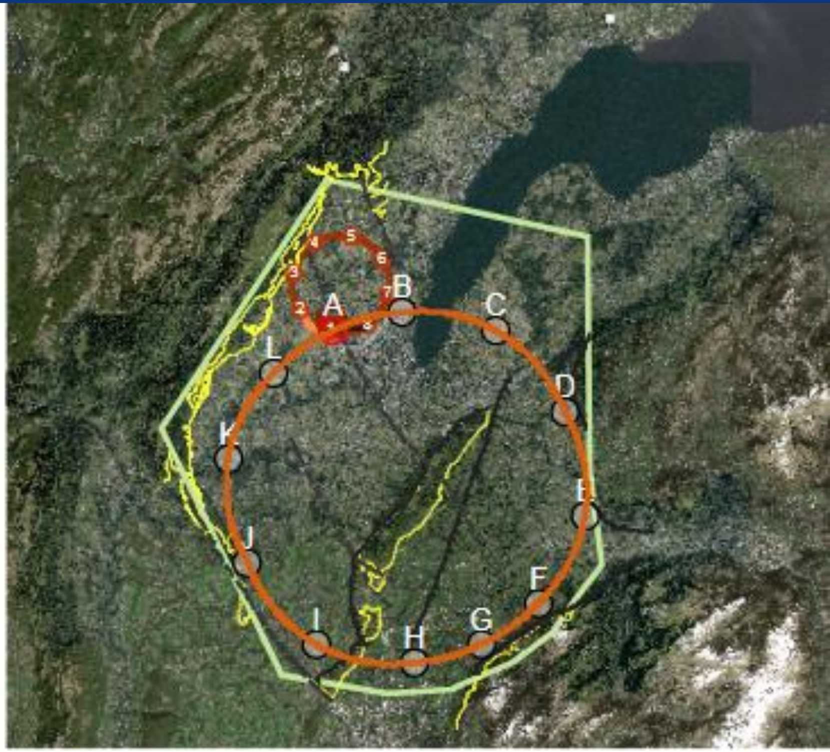
Implementation:

- 90-100 km fits well geological situation in Geneva basin
- Shallow variant, 30 m below lake-bed
- Connected with LHC or SPS

CE schedule study

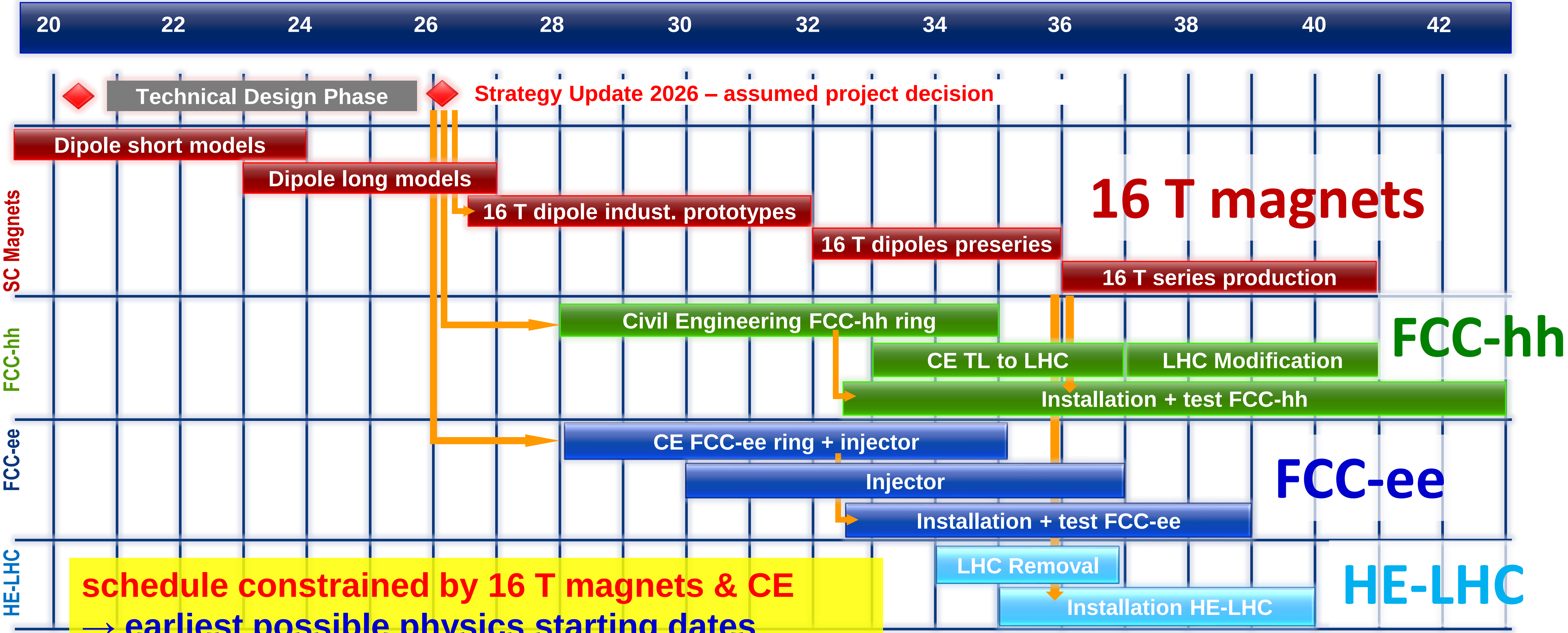






- **CE & schedule studies with consultants**
- ***first sectors available after 4.5 to 5 years for Technical Infrastructure installation***
- **total CE duration ~7 years**

Technical Schedule for each the 3 Options



schedule constrained by 16 T magnets & CE

→ earliest possible physics starting dates

- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

FCC Collaboration & Industry Relations

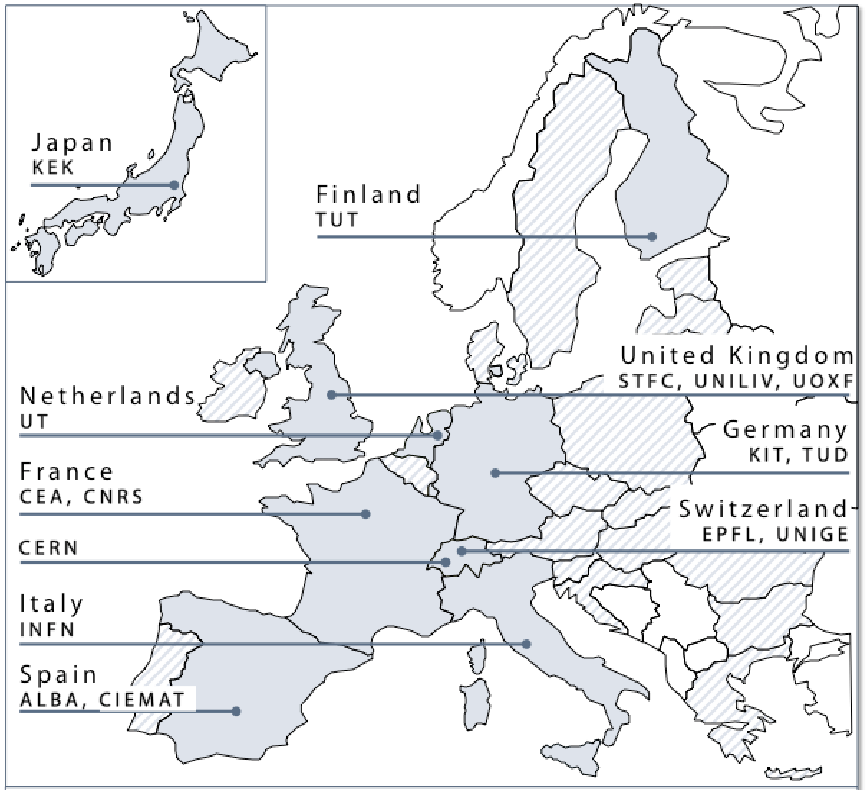
113 Institutes

25 Companies

32 Countries

EC H2020

EU H2020 Design Study EuroCirCol



EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

European Union Horizon 2020 program

- Support for FCC-hh study
- 3 MEURO co-funding
- Started June 2015, ends in May 2019

Scope:

FCC-hh collider

- Optics Design (arc and IR)
- Cryogenic beam vacuum system design including beam tests at ANKA
- 16 T dipole design, construction folder for demonstrator magnets

EASITrain Marie Curie Training Network

European Advanced Superconductivity Innovation and Training Network

➢ **selected for funding by EC in May 2017, started 1 October 2017**

- 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

Horizon 2020 program

Funding for 15 Early Stage Researchers over 3 years & training

13 Beneficiaries

12 Partners

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

CDR summary volumes will be available by end 2018, as input for European Strategy Update 2019/20

Summary

- FCC-ee:
  - Accelerator conceptual design is ready for CDR
  - Complete concept for phased collider operation and RF staging developed
  - Civil engineering, tunnel implementation and integrations studies completed for CDR
- FCC-hh:
  - Accelerator conceptual design is ready for CDR
  - Complete concept for FCC-hh beam handling & machine protection developed
  - Civil engineering, tunnel implementation and integrations studies completed for CDR
- HE-LHC
  - Accelerator conceptual design converging towards baseline for CDR
  - Challenging optimization due to CE boundary conditions (integration, lengths straights,…)
  - Injector studies to clarify feasibility of injection from 450 GeV SPS; trade off between energy reach & injection energy
- Key technologies:
  - Nb_3Sn based 16 T magnets, broad international development program in place
  - Successful tests of beam-screen vacuum system at ANKA/KIT Karlsruhe
  - Fabricated prototype SC cavities (Nb/Cu) for FCC-hh/FCC-ee/FCC-eh; also dual-aperture magnet prototypes for FCC-ee
- International FCC collaboration is growing steadily, focusing now on CDR preparation as input for European Strategy Update


FCC WEEK 2018
Future Circular Collider Conference
AMSTERDAM, Netherlands
09 - 13 APRIL
fccw2018.web.cern.ch