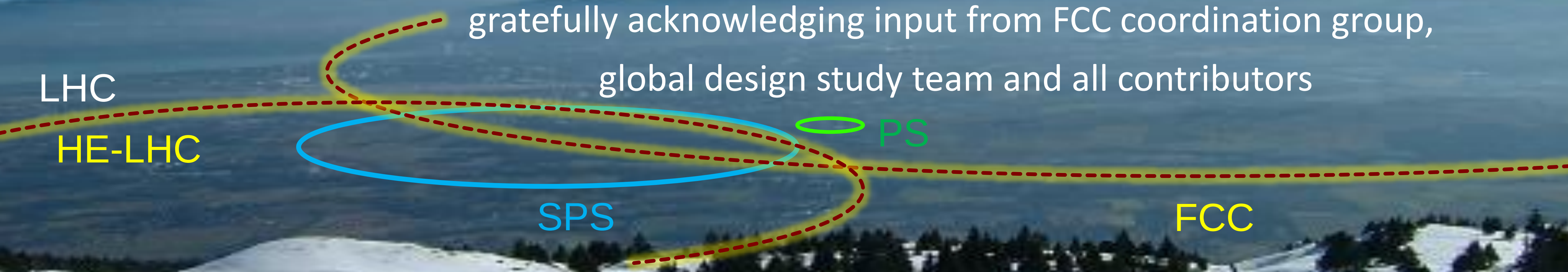
Future Circular Collider Study
Status update from FCC week Berlin

Michael Benedikt, CERN, for the FCC Collaboration

PECFA, CERN, 17 November 2017

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



FCC hh ee he

EuroCirCol A key to New Physics

EASITrain

ARIES

E-JADE

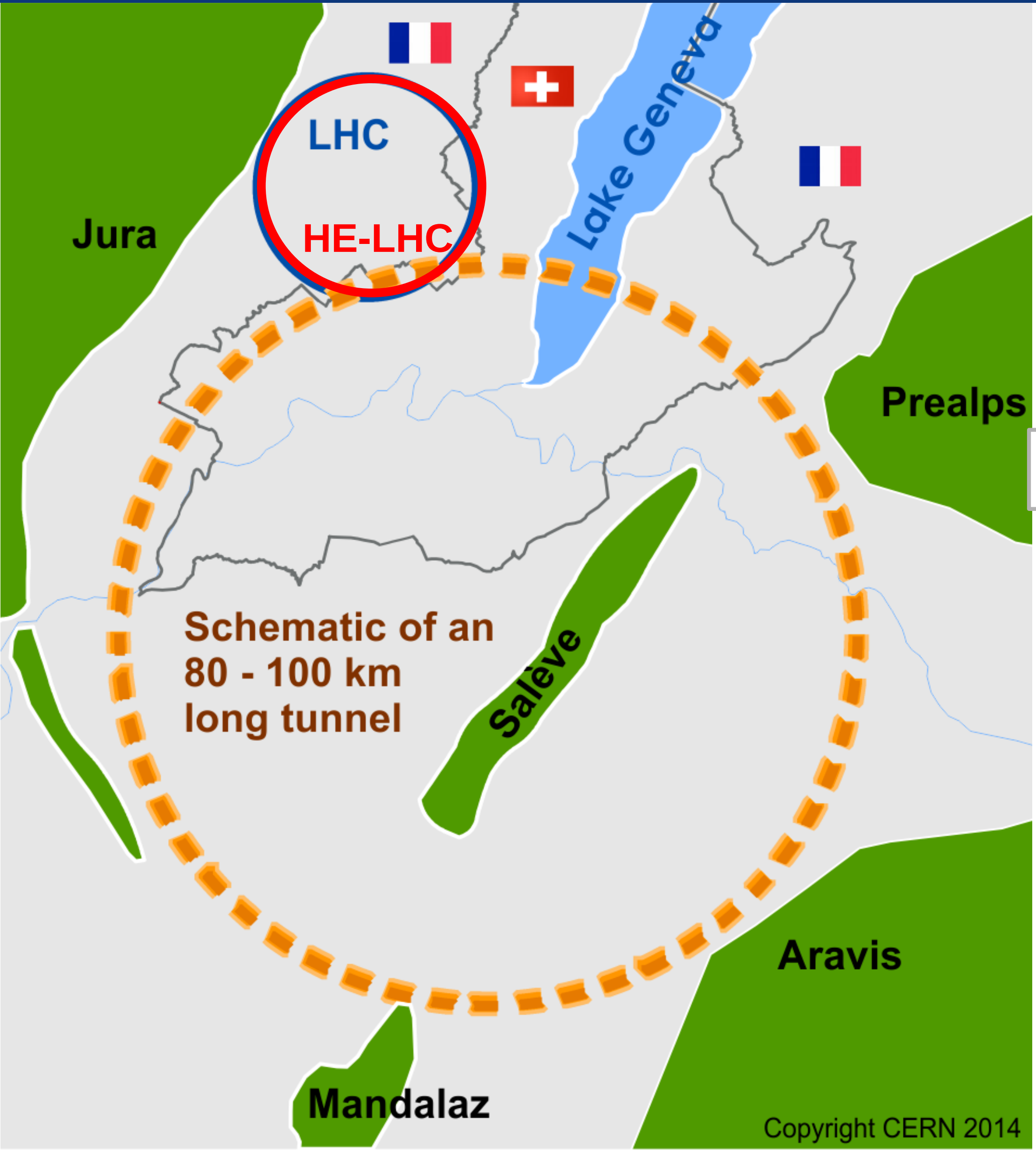
http://cern.ch/fcc

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **ARIES**, grant agreement 730871; and **E-JADE,** contract no. 645479*

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

photo: J. Wenninger

Future Circular Collider (FCC) Study

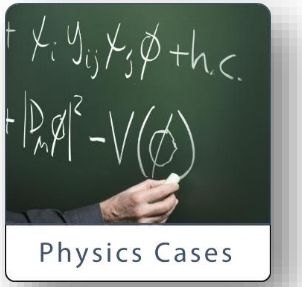


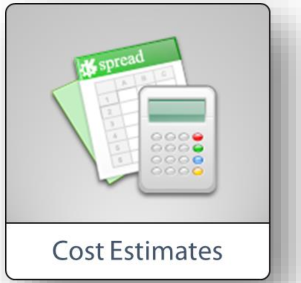
International FCC collaboration (CERN as host lab) to study:

- ***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 $\sim$ 20ab^{-1} within 25 years

HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy = 27 TeV $\sim$ 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 physics

- First FCC physics workshop at CERN in January 2017 (>200 participants)
- Second FCC physics workshop at CERN: 15-19 January 2018, CERN
- HL-LHC and HE-LHC physics workshop started October 2017 until end 2018

Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

M. Mangano (ed.)

- **Volume 1: SM processes** (238 pages)
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages)
- **Volume 3: beyond the Standard Model phenomena** (189 pages)
- **Volume 4: physics with heavy ions** (56 pages)
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

published as CERN yellow report CERN-2017-003-M

Physics at FCC-ee

P. Janot et al.

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164,

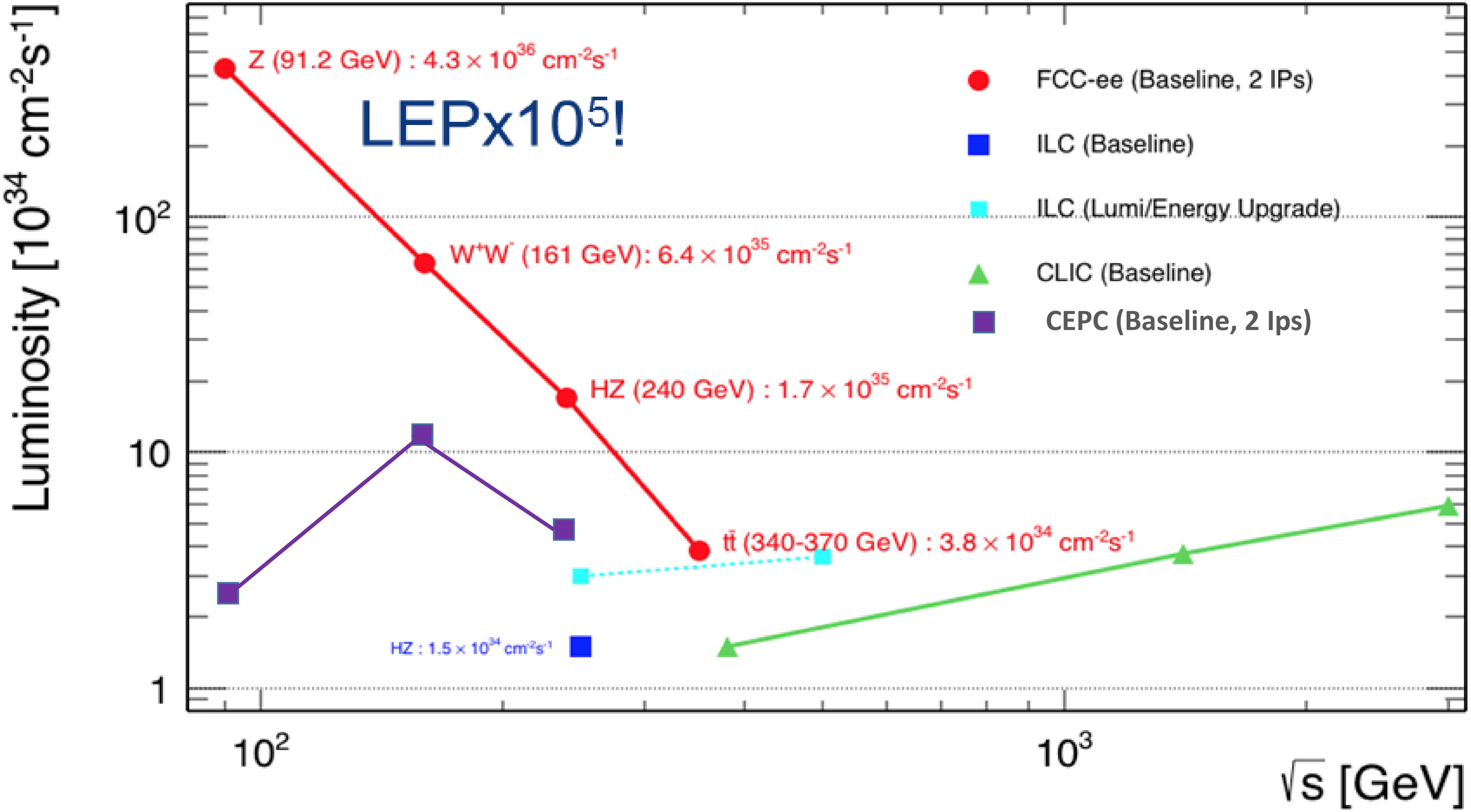
https://link.springer.com/article/10.1007%2FJHEP01%282014%29164

https://arxiv.org/abs/1308.6176

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	2000	393	48	39
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7	2.8
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.21
total RF voltage [GV]	0.1	0.44	2.0	9.5	10.9
long. damping time [turns]	1281	235	70	23	20
horizontal beta* [m]	0.15	0.2	0.3	1	1
vertical beta* [mm]	0.8	1	1	2	2
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.34	1.45
vert. geom. emittance [pm]	1.0	1.0	1.3	2.7	2.7
bunch length with SR / BS [mm]	3.5 / 12.1	3.3 / 7.6	3.1 / 4.9	2.5 / 3.3	2.5 / 3.2
luminosity [10^{34} $cm^{-2}s^{-1}$]	>200	>30	>7	>1.5	>1.3
beam lifetime rad Bhabha / BS [min]	70 / >200	500 / 20	42 / 20	39 / 24	39 / 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	30	7.8 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)	1.3	0.34 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

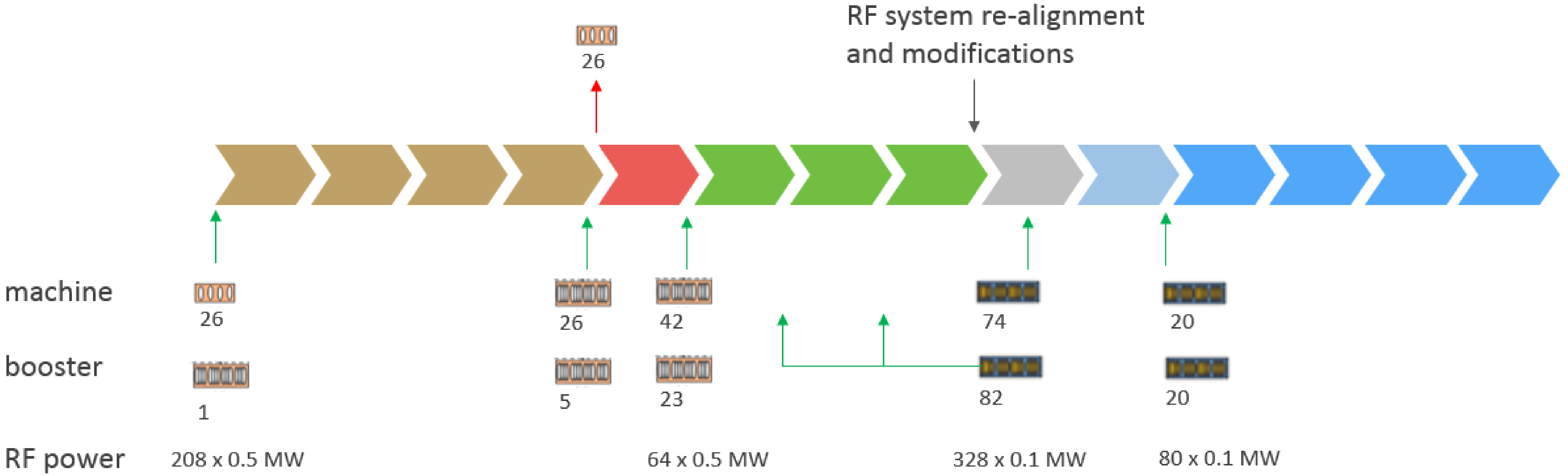
"Ampere-class" machine

	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

SRF 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

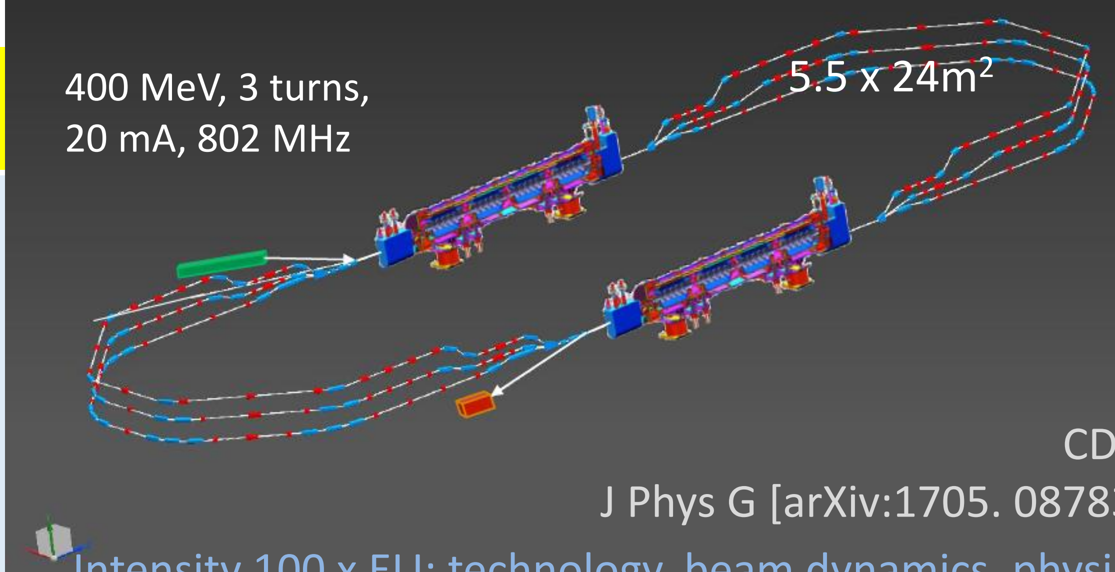
FCC-eh: 60 GeV e^- from Energy Recovery Linac (ERL)

PERLE@Orsay ERL test facility

FCC-he studies on H+BSM+SM physics;
$Q^2 < 10\ TeV^2$, 1 ab^{-1}

work on detector, IR, LHeC reference, technology,…

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



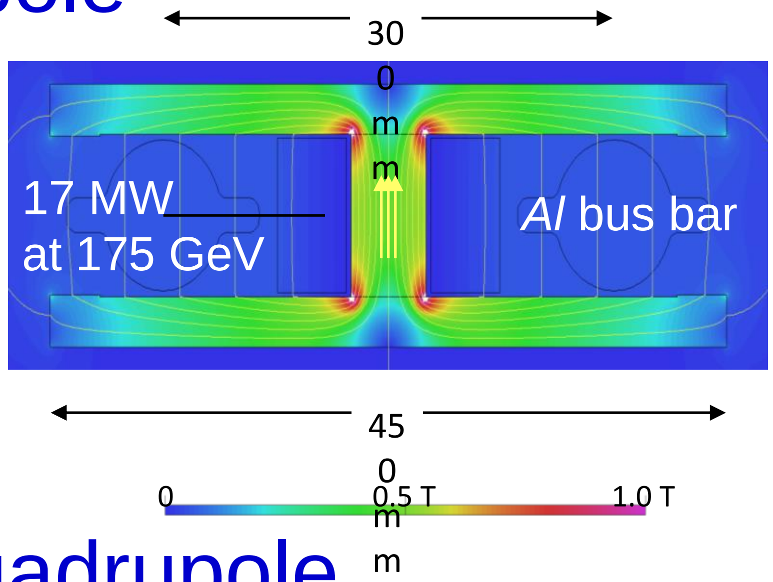
CDR
J Phys G [arXiv:1705. 08783]

Intensity 100 x ELI: technology, beam dynamics, physics

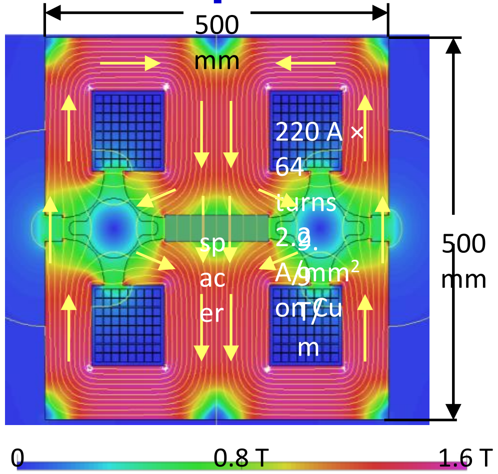
FCC-ee dual aperture main magnets

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

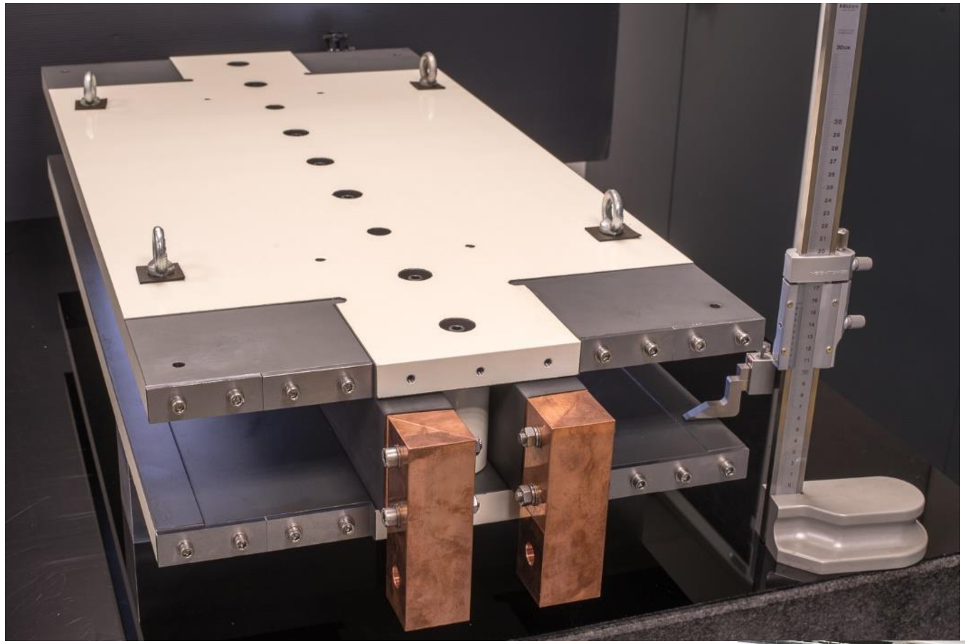
dipole



quadrupole



22 MW at 175 GeV with *Cu* coil



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

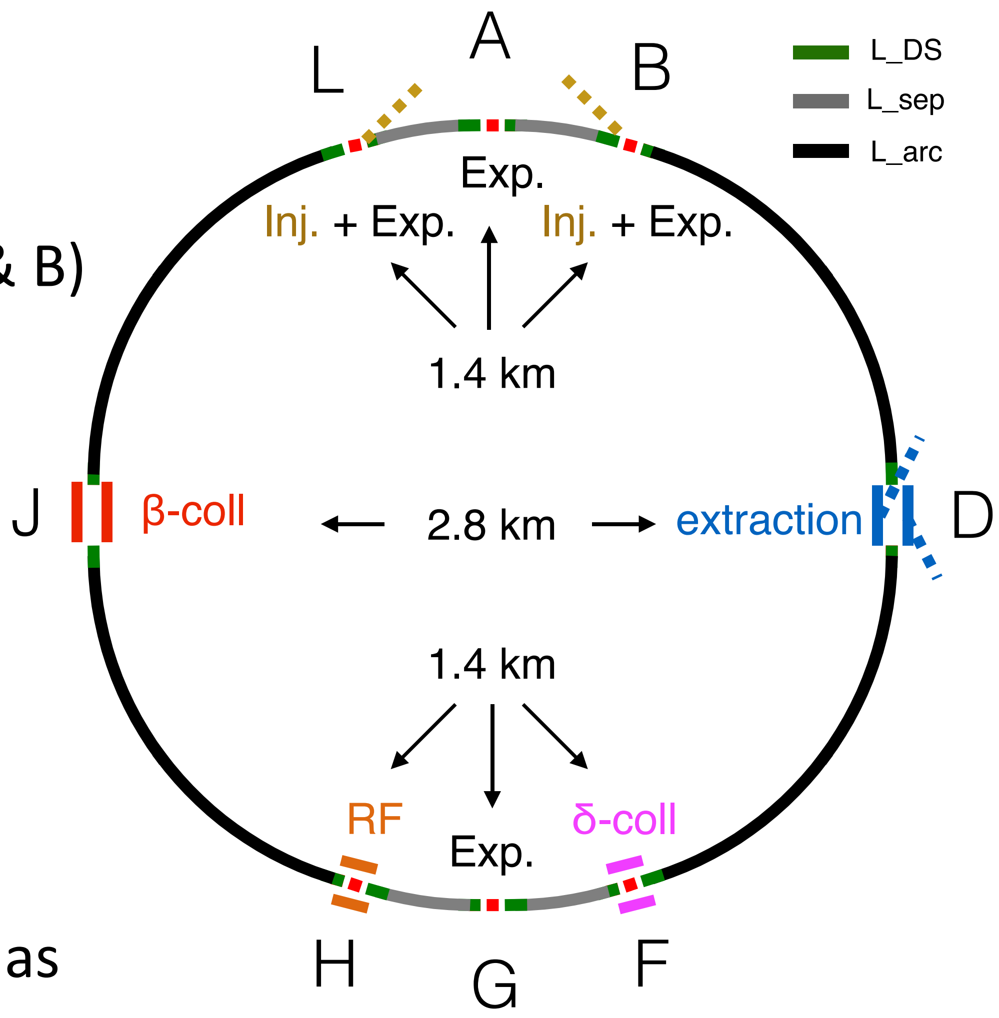
magnetic measurements ongoing

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

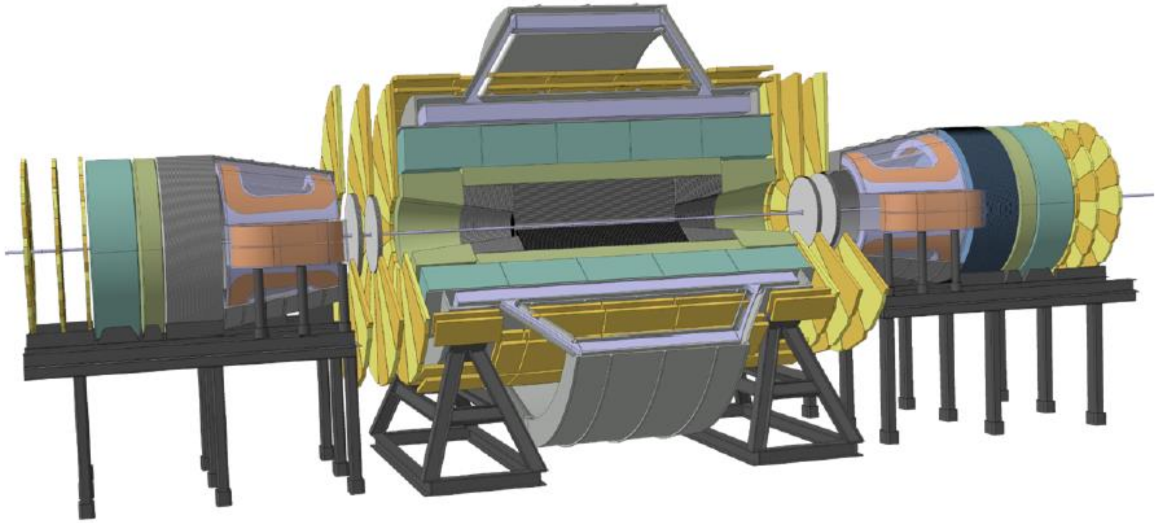


- **Circumference 97.8 km**
- Injections upstream side of experiments
- **Avoids mixing of extraction region and high-radiation collimation areas**
- **Beam dynamics studies confirm design goals**
- Focus on optimization of collimation system and extraction system

FCC-hh detector – new reference design

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

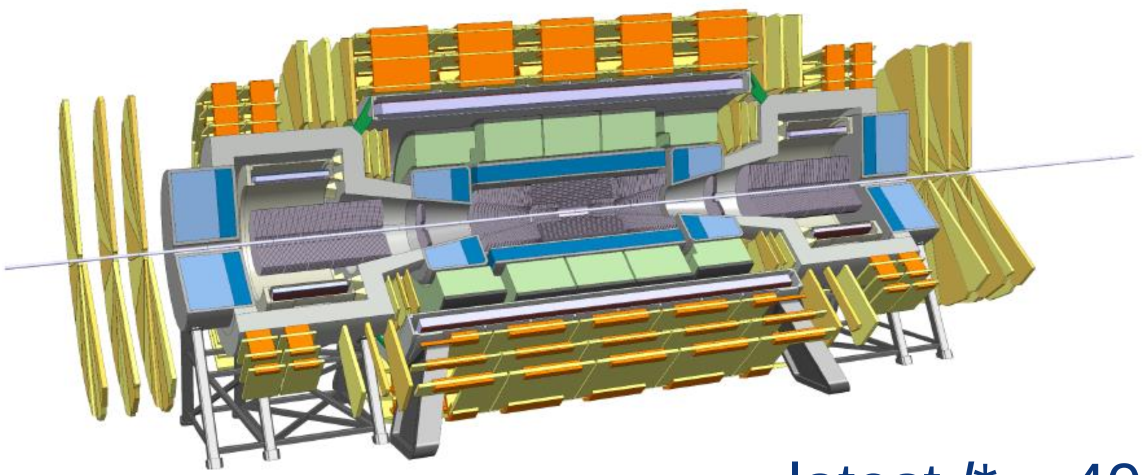
- 65 GJ stored energy
- 28 m diameter
- >30 m shaft
- multi billion project



→

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

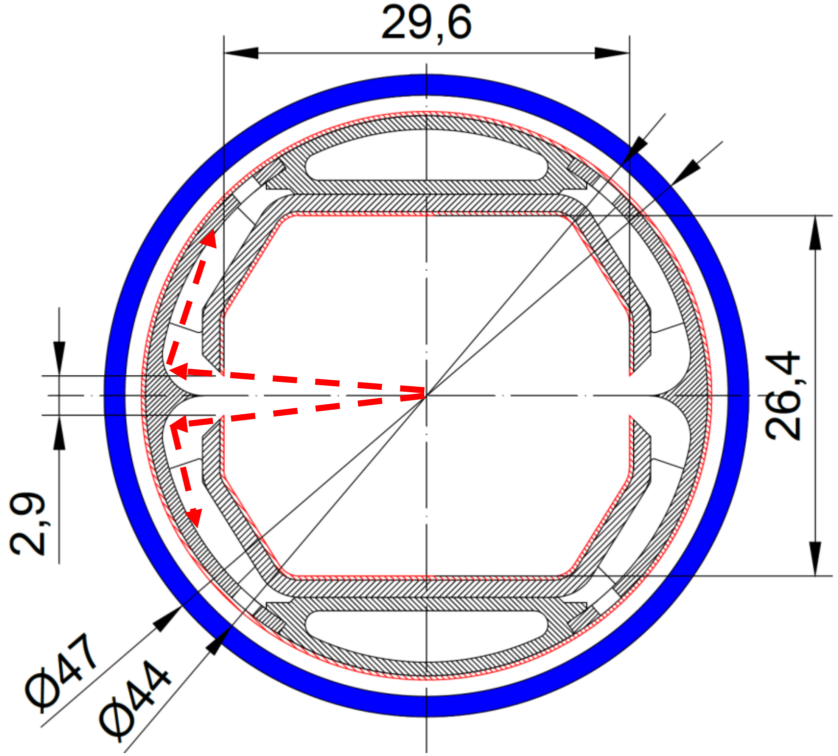


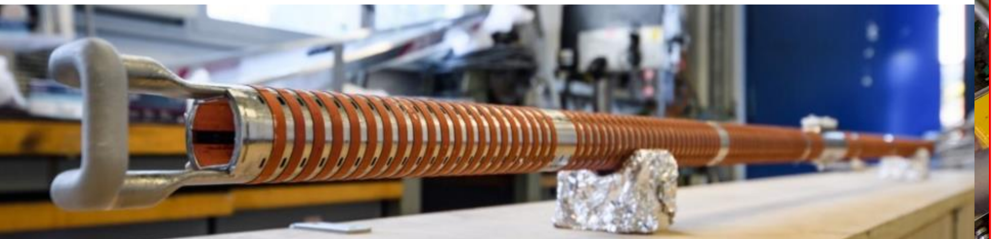
latest l^* = 40 m

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**

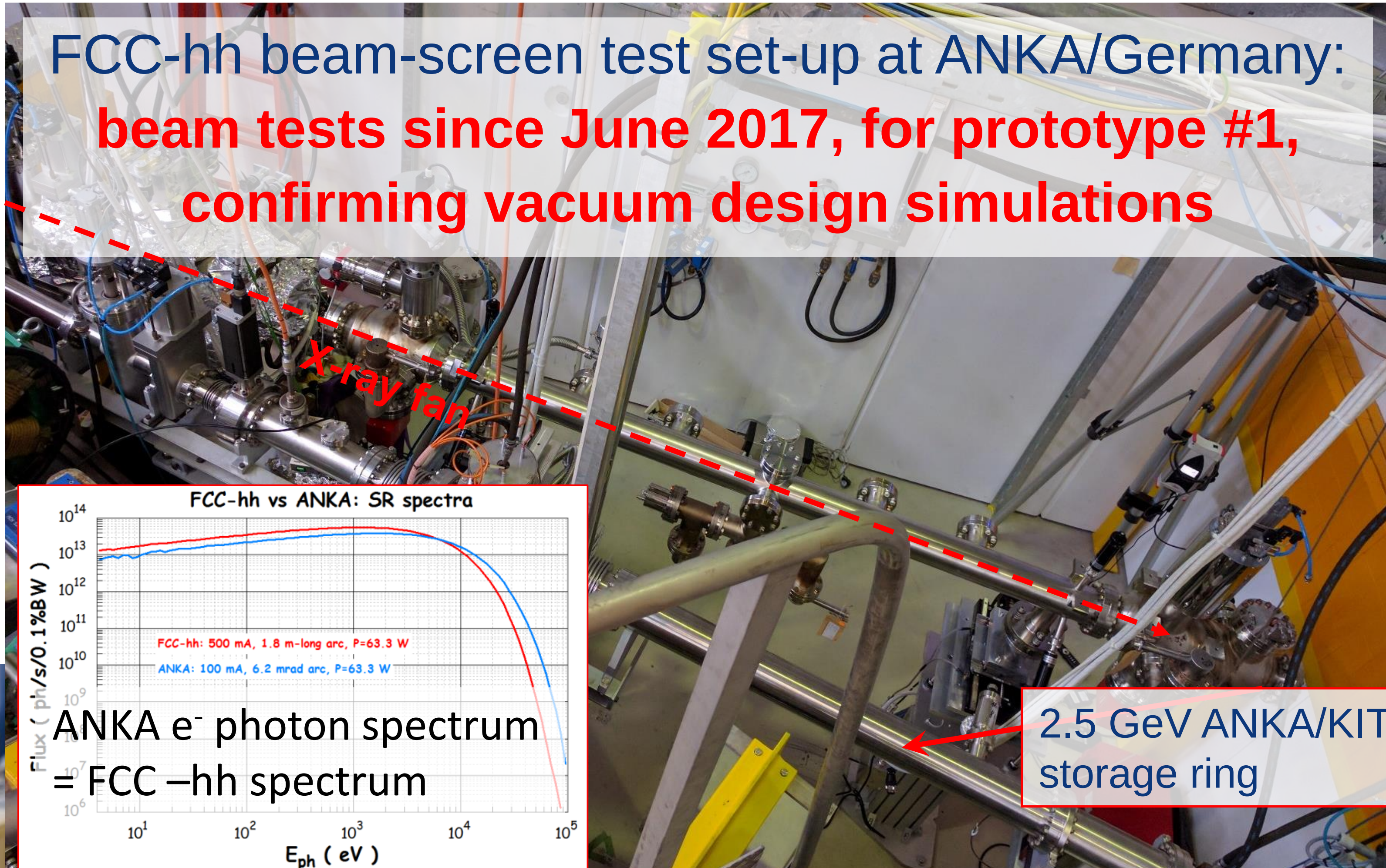
- **Absorption of synchrotron radiation at ~50 K** for cryogenic efficiency (5 MW →100 MW cryoplant)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.





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

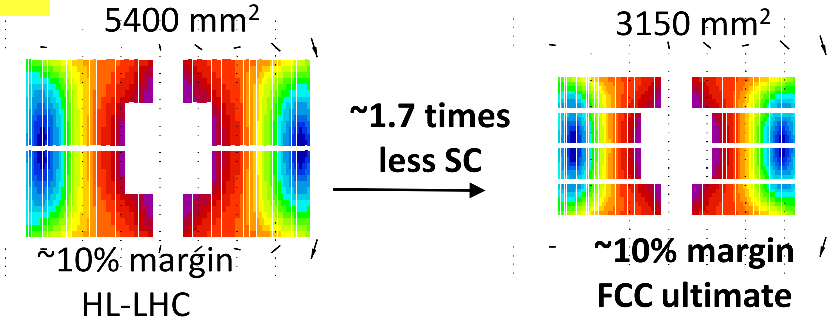
beam tests since June 2017, for prototype #1, confirming vacuum design simulations



Worldwide FCC Nb_3Sn program

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

Impact on coil section and conductor mass

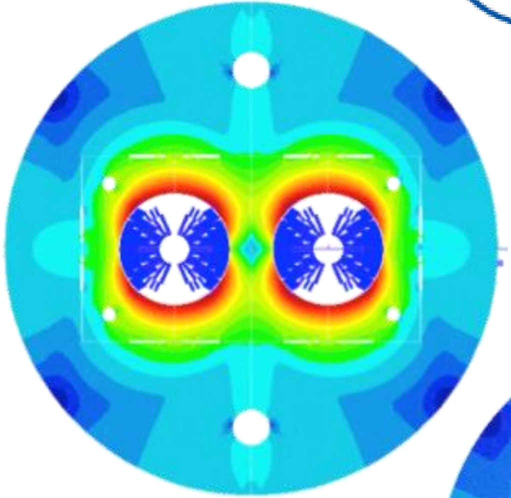


- **Procurement of state-of-the-art conductor:**
  - **Bruker-OST**– **European/US**
- **Conductor development with regional industry:**
  - **CERN/KEK** – **Japanese** contribution. Japanese **industry** (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku Univ. and NIMS).
  - **CERN/Bochvar High-technology 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

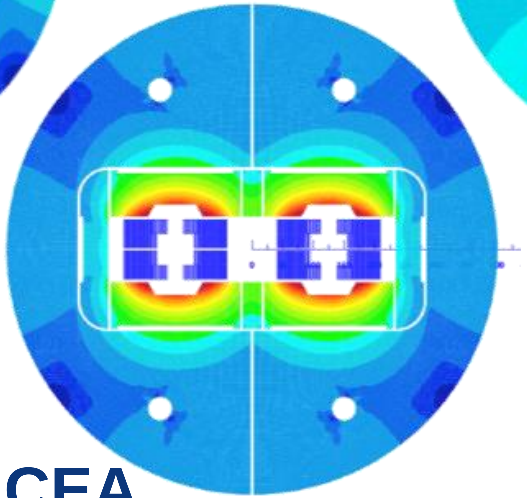
H2020 EuroCirCol
A key to New Physics

Cos-theta



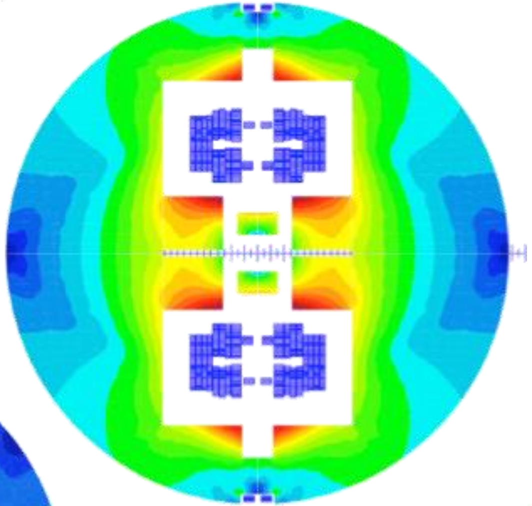
INFN

Blocks



CEA

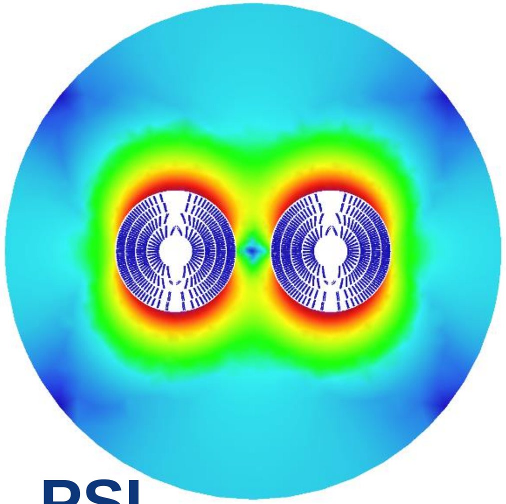
Common coils



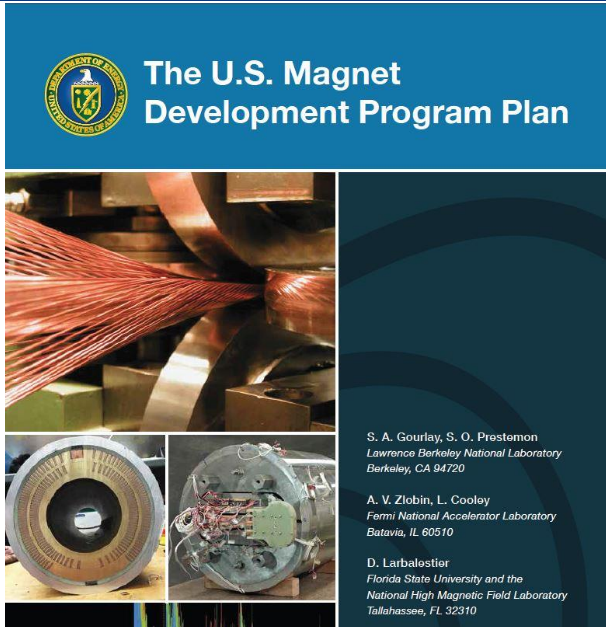
CIEMAT

Swiss contribution

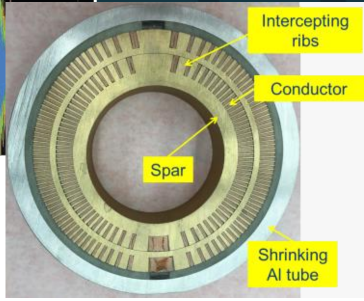
Canted Cos-theta



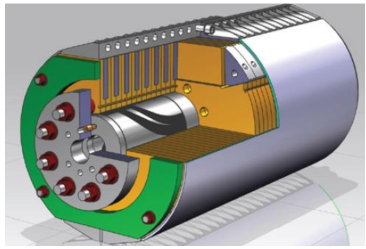
PSI



LBNL



FNAL



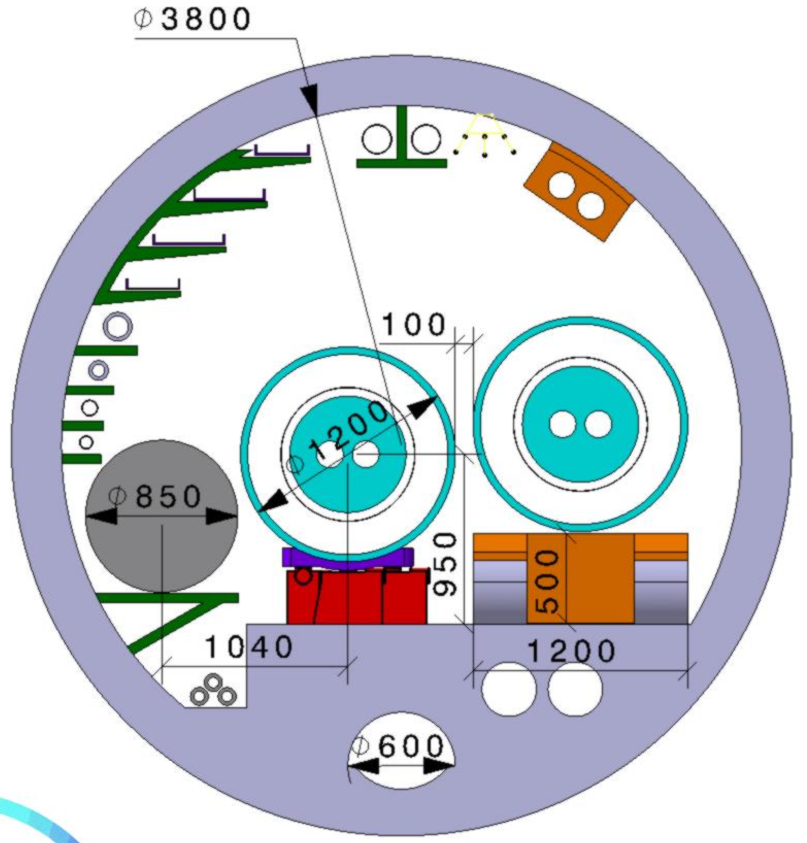
Short model magnets (1.5 m lengths) will be built from 2017 - 2022

HE-LHC integration aspects

Working hypothesis for HE LHC design:

No major CE modifications on tunnel and caverns

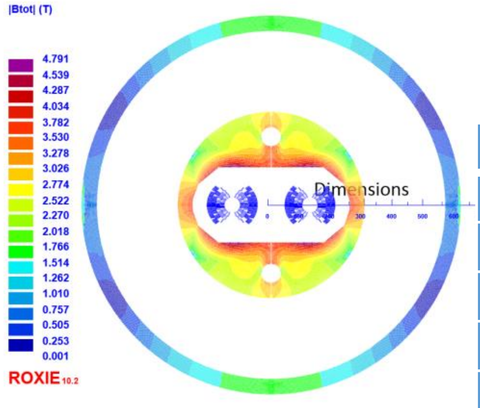
- Similar geometry and layout as LHC machine and experiments
- **Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **Classical cryostat design gives ~1500 mm diameter!**



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)**

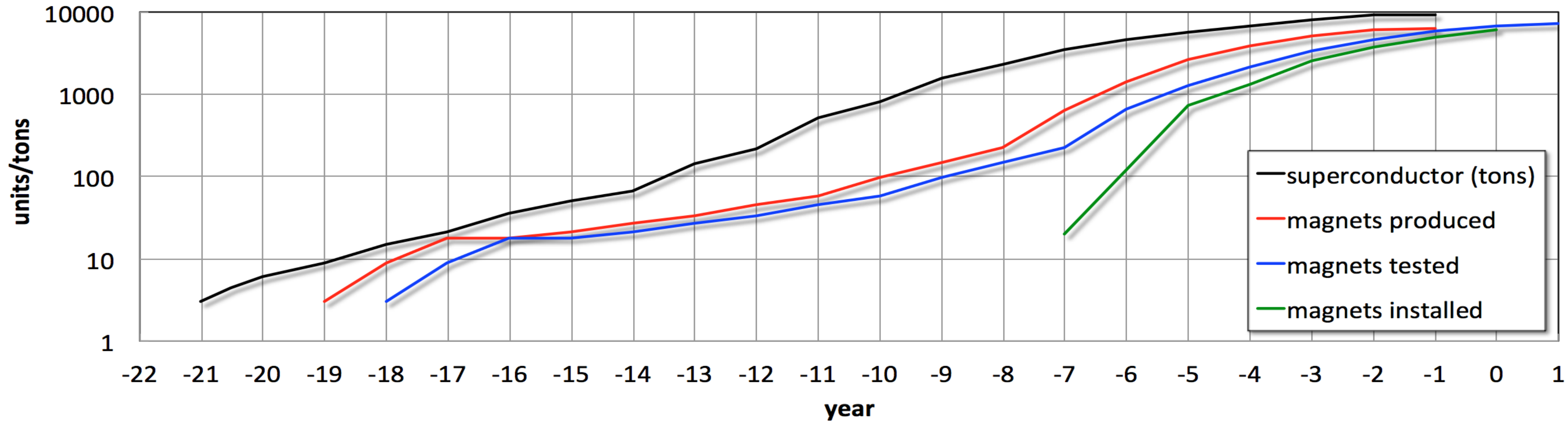
→ **Smaller diameter also relevant for FCC-hh cost**



Only magnetic elements shown

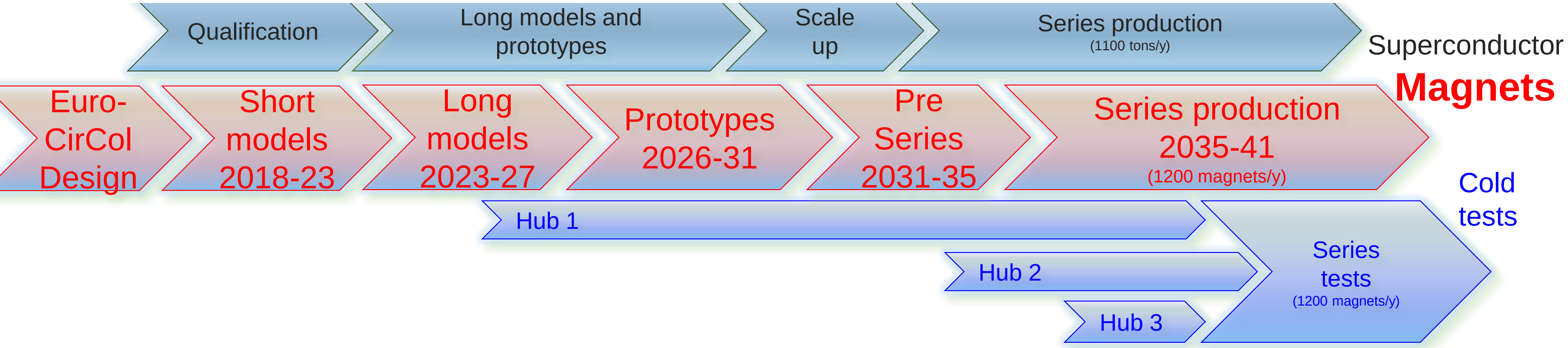
Description	OD in mm
Iron yoke	600
Aluminium shrinking cylinder	740
Stainless steel He tight shell	760
Al radiation shield	940
Vacuum vessel (magnetic steel)	1220

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

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

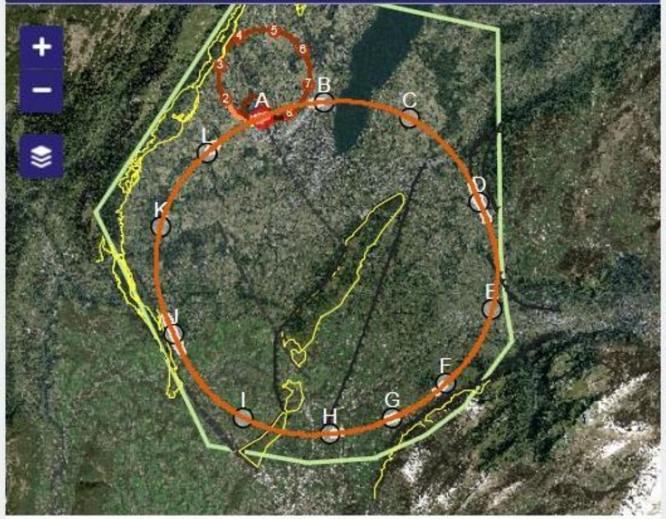
LOAD | SAVE | CALCULATE

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

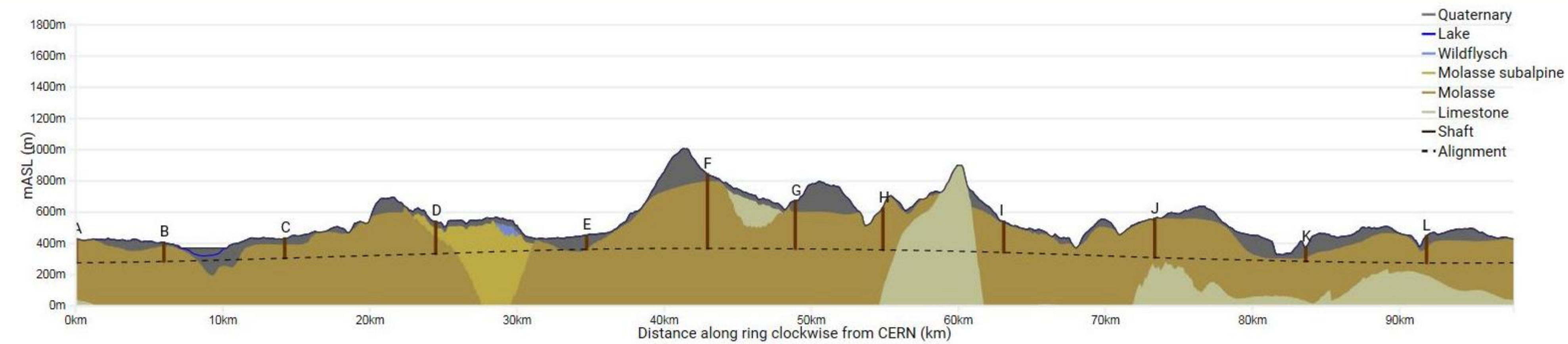
Alignment Location



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.

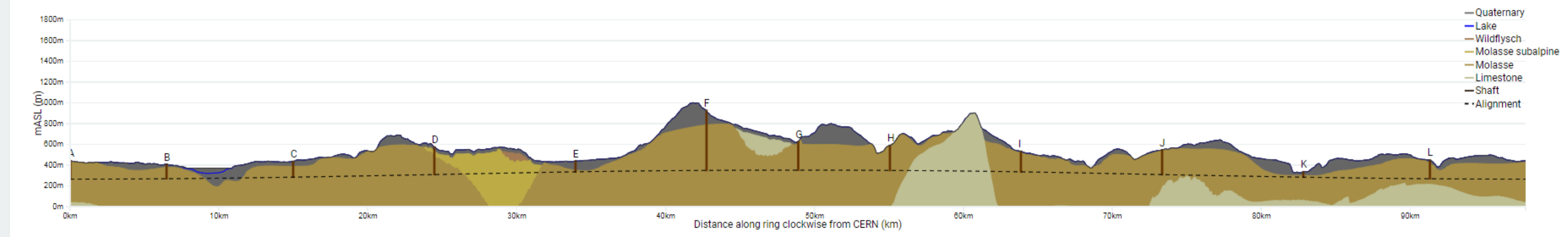
Tunneling:

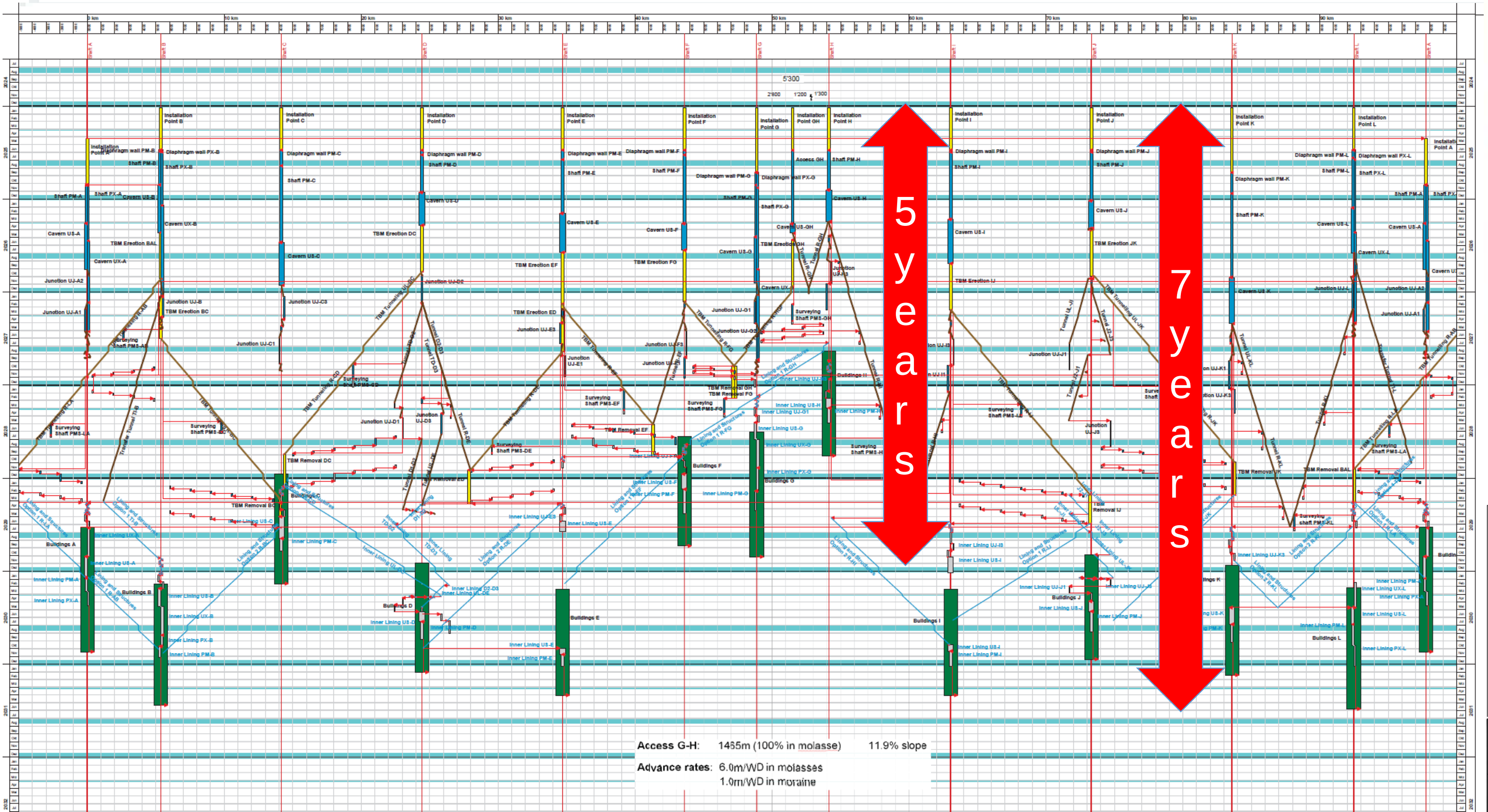
- Molasse 90%,
- Limestone 5%,
- Moraines 5%

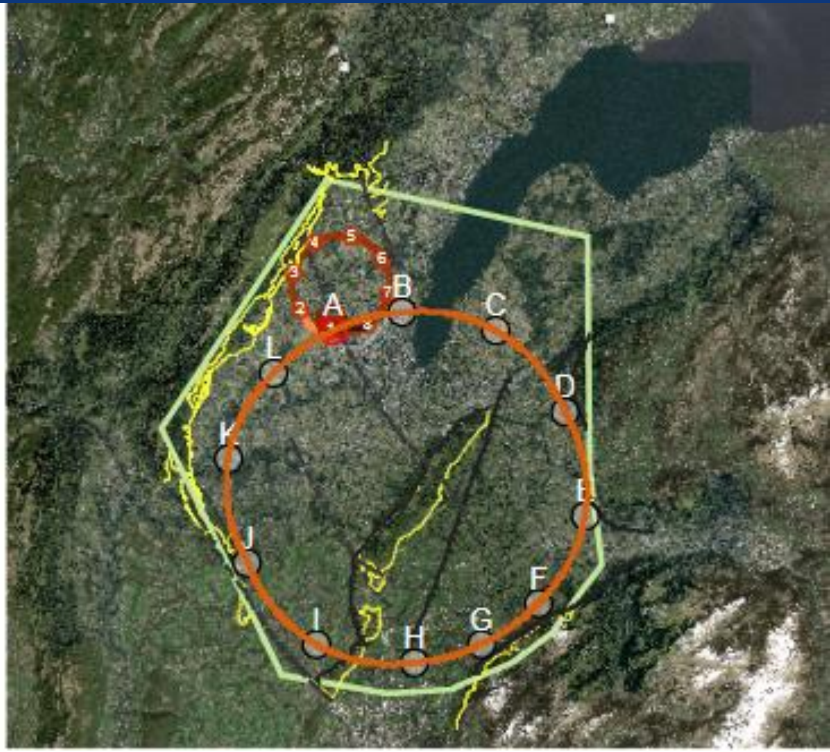
Implementation:

- 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

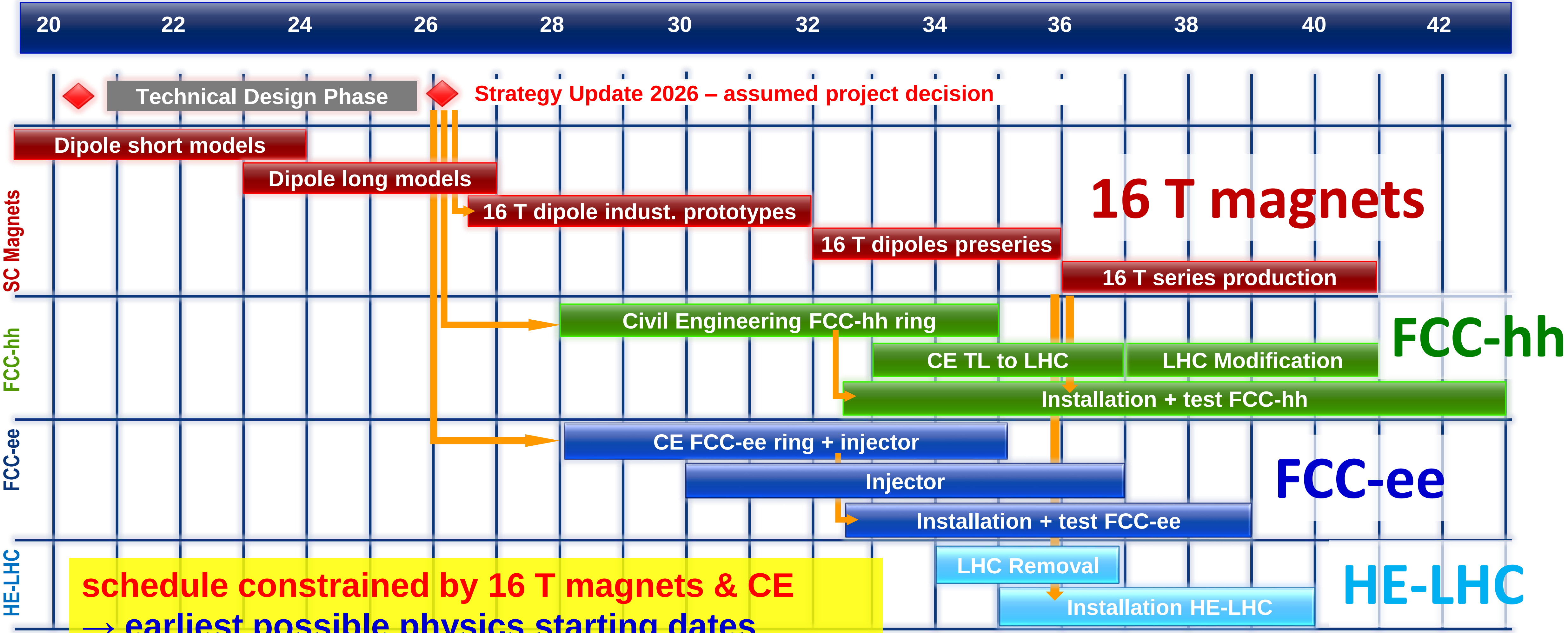






- **CE & schedule studies with consultants**
- ***first sectors available after 4.5 to 5 years for Technical Infrastructure installation***
- **total CE duration ~7 years**

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)**

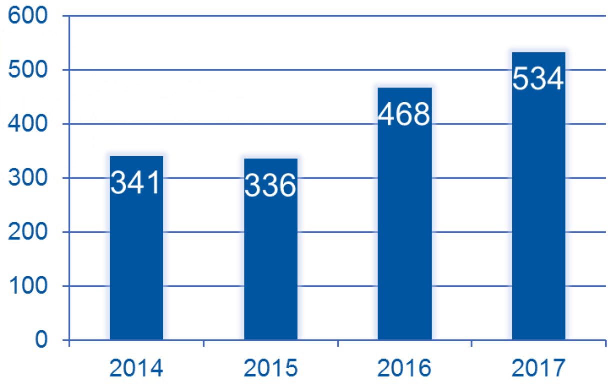
FCC Collaboration & Industry Relations

113 Institutes

25 Companies

32 Countries

EC H2020

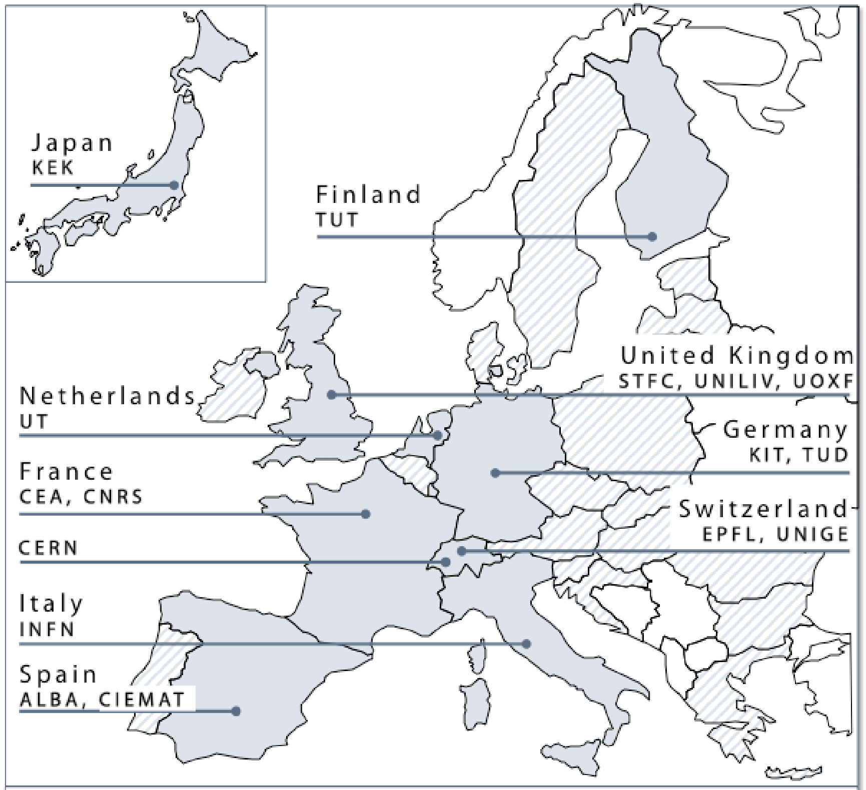


> 500 participants, 147 institutes
a lot of young people
(>35% younger than 35)

EU H2020 Design Study EuroCirCol

UNIVERSITY OF TWENTE. INFN TAMPERE UNIVERSITY OF TECHNOLOGY

cea CNRS dépasser les frontières CERN UNIVERSITY OF OXFORD



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

TECHNISCHE UNIVERSITÄT DARMSTADT

KIT Karlsruher Institut für Technologie

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF LIVERPOOL

UNIVERSITÉ DE GENÈVE

ALBA

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

MANCHESTER 1824

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

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, I-CUBE, CERN

12 Partners

Bmax, 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, Università degli Studi di Genova, Air Liquide

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 study status

- Fast advancement of the FCC study in all areas
- Accelerator designs of FCC-hh and FCC-ee machine ready for CDR
- Worldwide R&D programme on high-field magnets and Nb_3Sn superconductor and SRF in place
- EU support for EuroCirCol and EASITrain ITN
- International FCC collaboration is growing steadily, focusing now on writing the CDRs as input for European Strategy Update

also 2018 FCC Physics Workshop, 15-19 January 2018, CERN