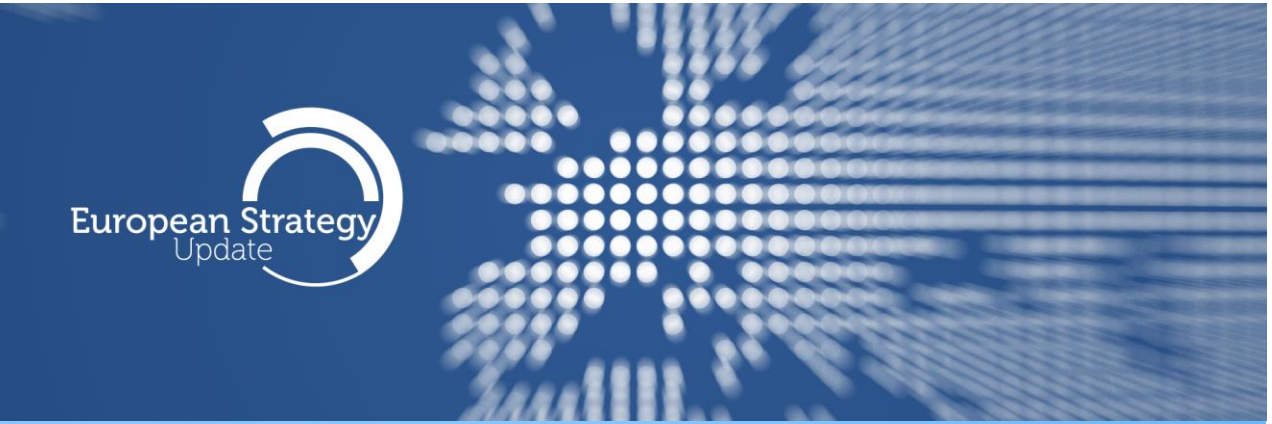
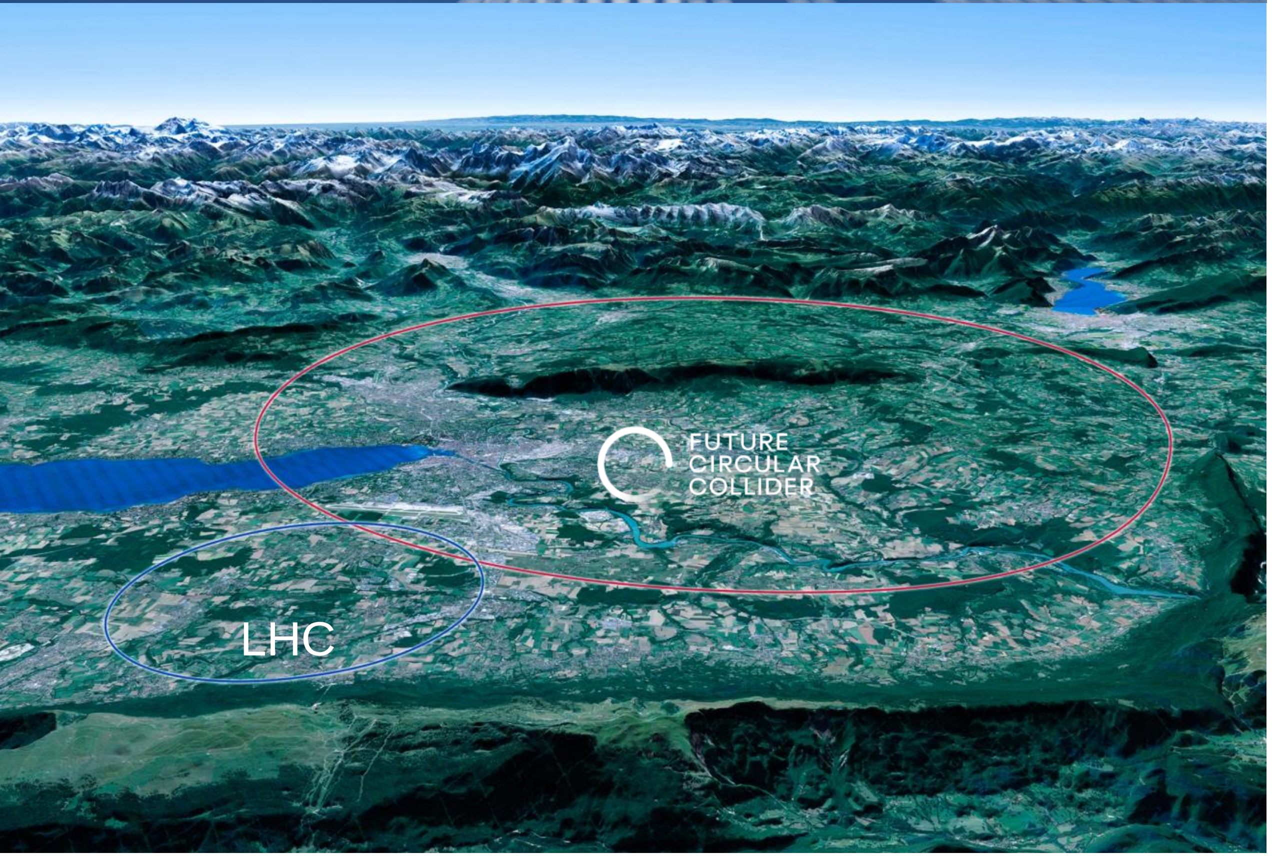
Lecture 21

Future Circular Collider (FCC-ee)
JAI Student Design Project 2022-2023

Professor Emmanuel Tsesmelis
Principal Physicist, CERN
Department of Physics, University of Oxford

Accelerator Physics Graduate Course
John Adams Institute for Accelerator Science
1 December 2022





CERN Scientific Priorities for the Future

Implementation of the recommendations of the **2020 Update of the European Strategy for Particle Physics**:

- Fully exploit the LHC & HL-LHC.
- Build a Higgs factory to further understand this unique particle.
- Investigate the technical and financial feasibility of a future energy-frontier 100 km collider at CERN.
- Ramp up relevant R&D.
- Continue supporting other projects around the world.

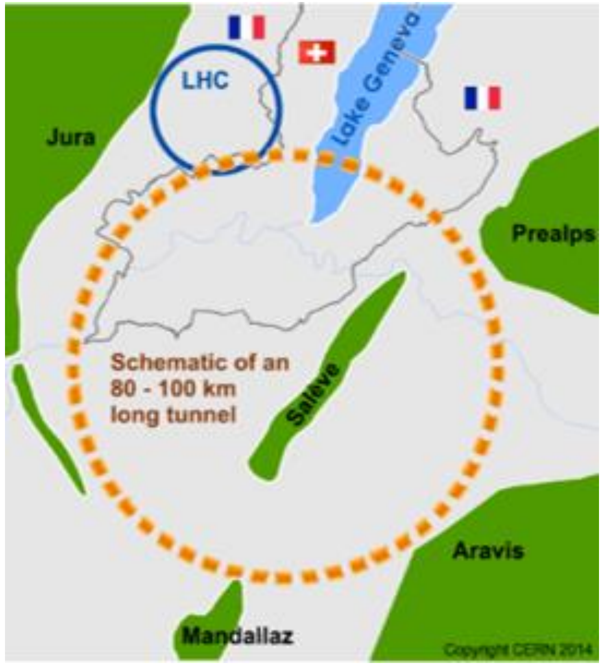
FUTURE
CIRCULAR
COLLIDER

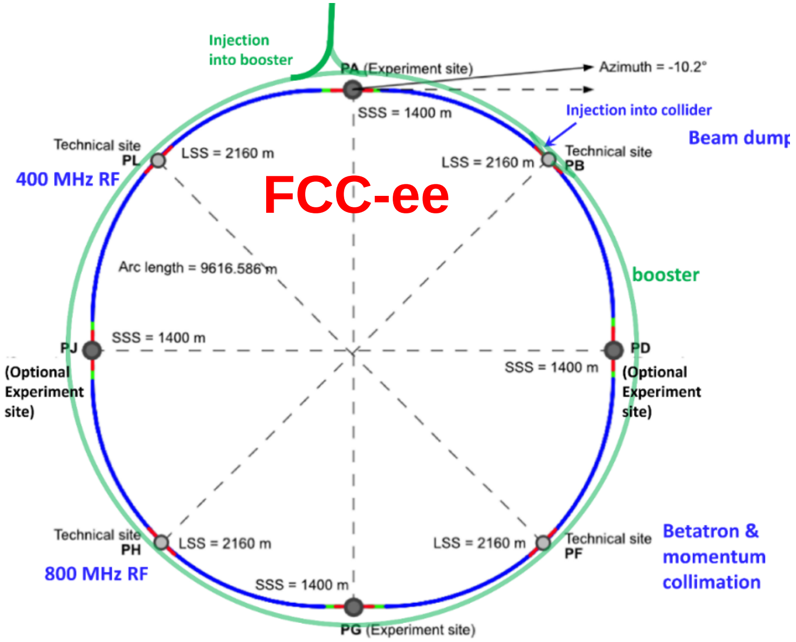
The FCC Integrated Programme

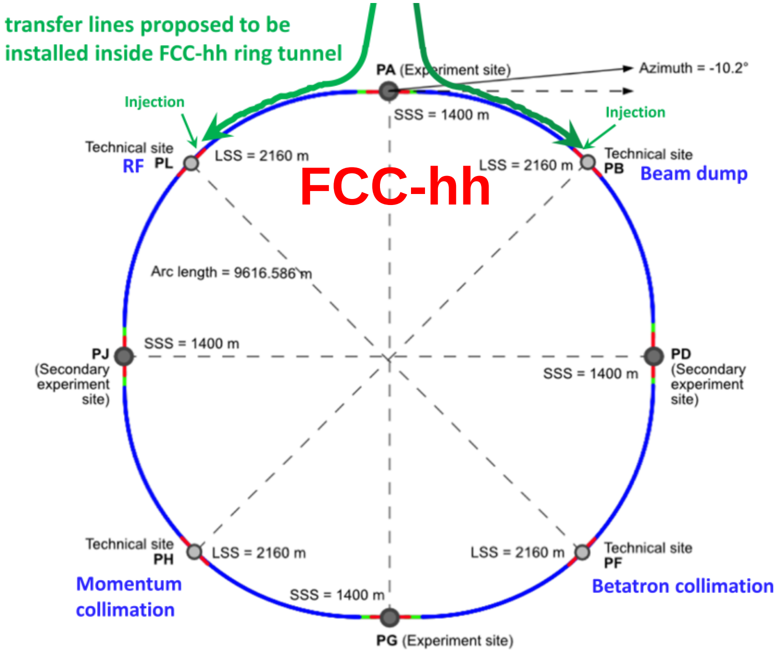
Inspired by Successful LEP – LHC Programmes at CERN

Comprehensive long-term programme maximising physics opportunities

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC programme







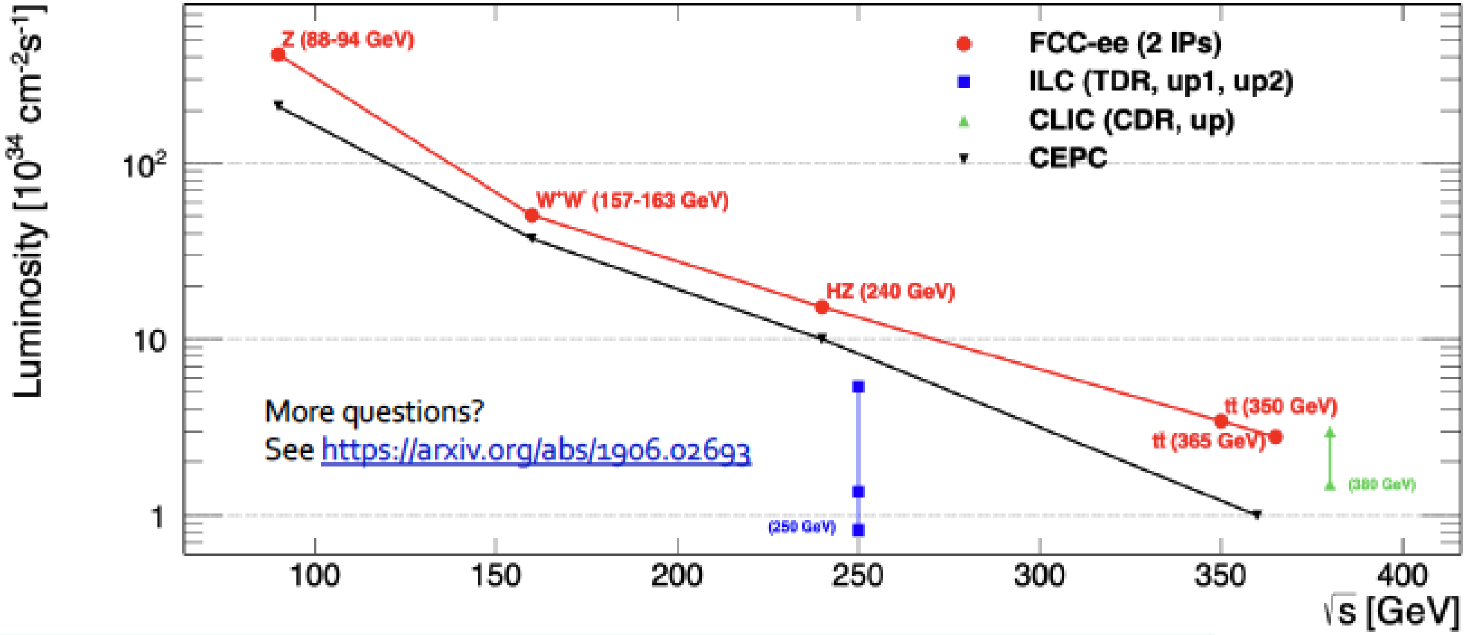
2020 - 2040

2045 - 2060

2070 - 2090++

FCC-ee Higgs and Electroweak Factory

- Great energy range for the SM heavy particles + highest luminosities + √s precision



More questions?
See https://arxiv.org/abs/1906.02693

				E_{CM} errors:
Z peak	E_{cm} ~ 91 GeV	5×10^{12} e+e- → Z	LEP x 10^5	<100 keV
WW threshold+	$E_{cm} \geq 161$ GeV	$> 10^8$ e+e- → WW	LEP x 10^3	<300 keV
ZH threshold	E_{cm} : 240 GeV	10^6 e+e- → ZH	Never done	2 MeV
$\bar{t}t$ threshold	E_{cm} ~ 350 GeV	10^6 e+e- → $\bar{t}t$	Never done	5 MeV

P. Janot

Physics Opportunities with FCC-hh

- With 30 ab^{-1} @ 100 TeV in 25 years
  - 2×10^{10} Higgs bosons (180 × HL-LHC)
    - 2×10^{7} Higgs pairs, 10^{8} ttH events
  - 10^{12} top pairs (300 × HL-LHC)
  - 5×10^{13} W, 10^{13} Z (70 × HL-LHC)
  - 10^{5} gluino pairs im m_{gluino} ~ 8 TeV
  - …

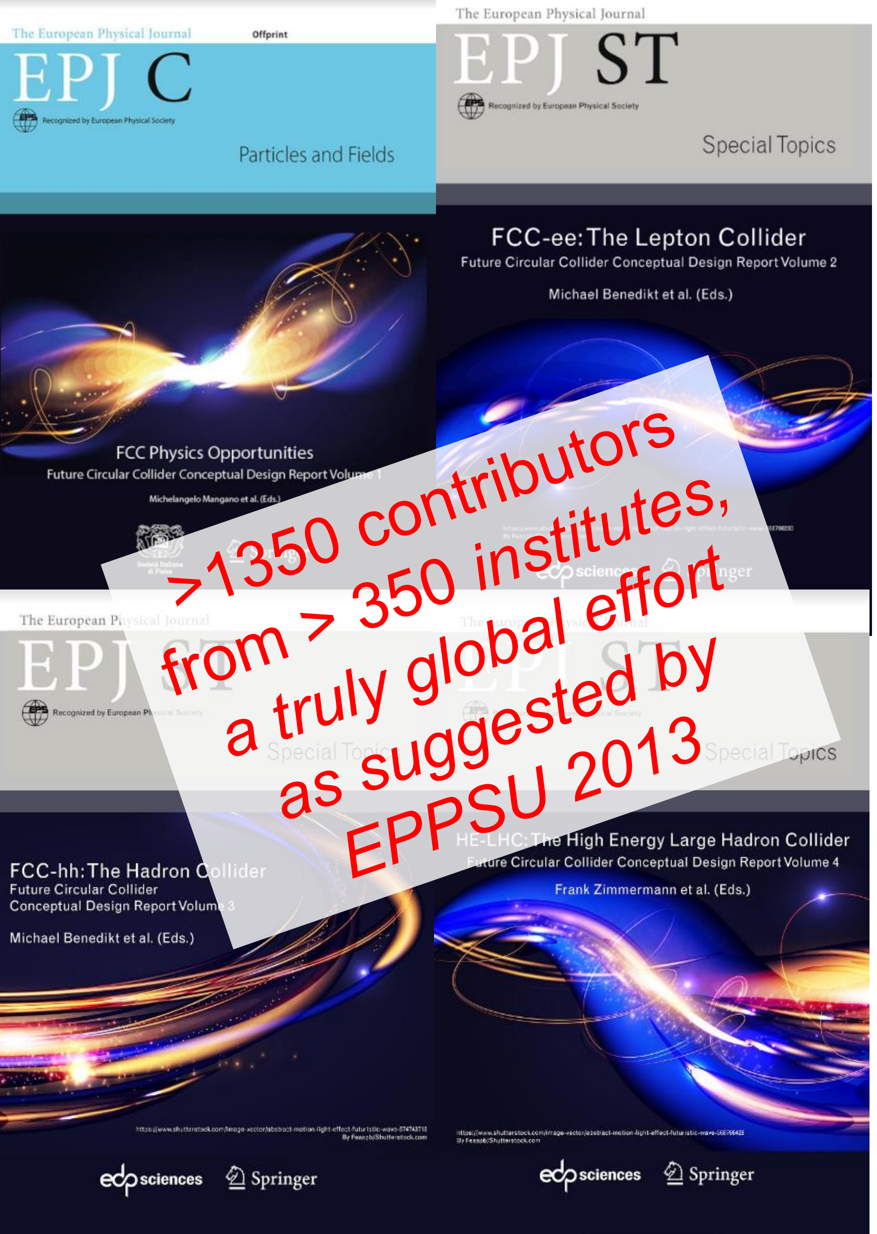
- High precision study of H and top
  - Exploration of EWSB in all details
    - Higgs self-coupling to 2-3%
  - Rare or BSM decays
    - BR(H → invisible) to 2.5×10^{-4} (DM!)
    - $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$ to 0.5%
      - ➔ FCC-ee standard candle essential

- Sensitivity to heavy new physics
  - With indirect precision probes
    - e.g., with cross-section ratios
    - e.g., with high-p_T final states
  - Trade statistics for systematics
    - Further improved by FCC-ee synergies
  - High-energy phenomena (VBS, DY)

- Direct particle observation
  - Mass reach enhanced by ~5 wrt LHC
    - New gauge bosons up to 40 TeV
    - Strongly interacting particles up to 15 TeV
    - Natural SUSY up to 5-20 TeV
    - Dark matter up to 1.5-5 TeV
      - ➔ Possibility to find or rule out thermal WIMPs as Dark Matter candidates

P. Janot

FCC Conceptual Design Report and Study Documentation



>1350 contributors from > 350 institutes, a truly global effort as suggested by EPPSU 2013

- **FCC-Conceptual Design Reports:**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

    EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 ,

    EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

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

FCC Feasibility Study

FCC Feasibility Study

FCC Feasibility Study (FS) will address a recommendation of the 2020 update of the European Strategy for Particle Physics (ESPP):

- “Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.
- Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”

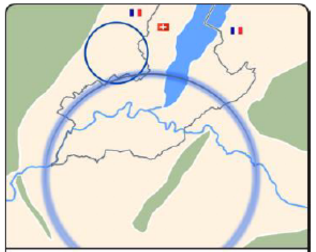
2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

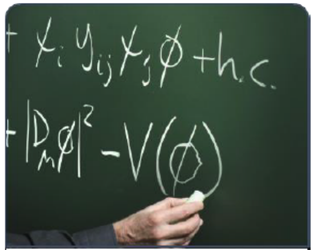
by the European Strategy Group

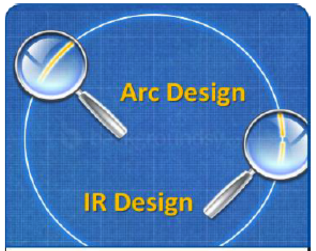
High-level Goals of Feasibility Study

High-level goals of Feasibility Study

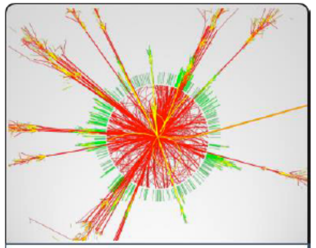
- optimisation of placement and layout of the ring and related infrastructure, and demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval, with a focus on identifying and surmounting possible showstoppers;
- optimisation of the design of the colliders and their injector chains, supported by targeted R&D to develop the needed key technologies;
- development and documentation of the main components of the technical infrastructure;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, environmental aspects and energy efficiency;
- identification of substantial resources from outside CERN’s budget for the implementation of the first stage of a possible future project;
- consolidation of the physics case and detector concepts for both colliders.

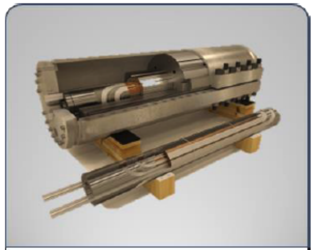

Infrastructures


Physics Cases



Collider Designs


Experiments


R&D Programs

Cost Estimates

FUTURE
CIRCULAR
COLLIDER

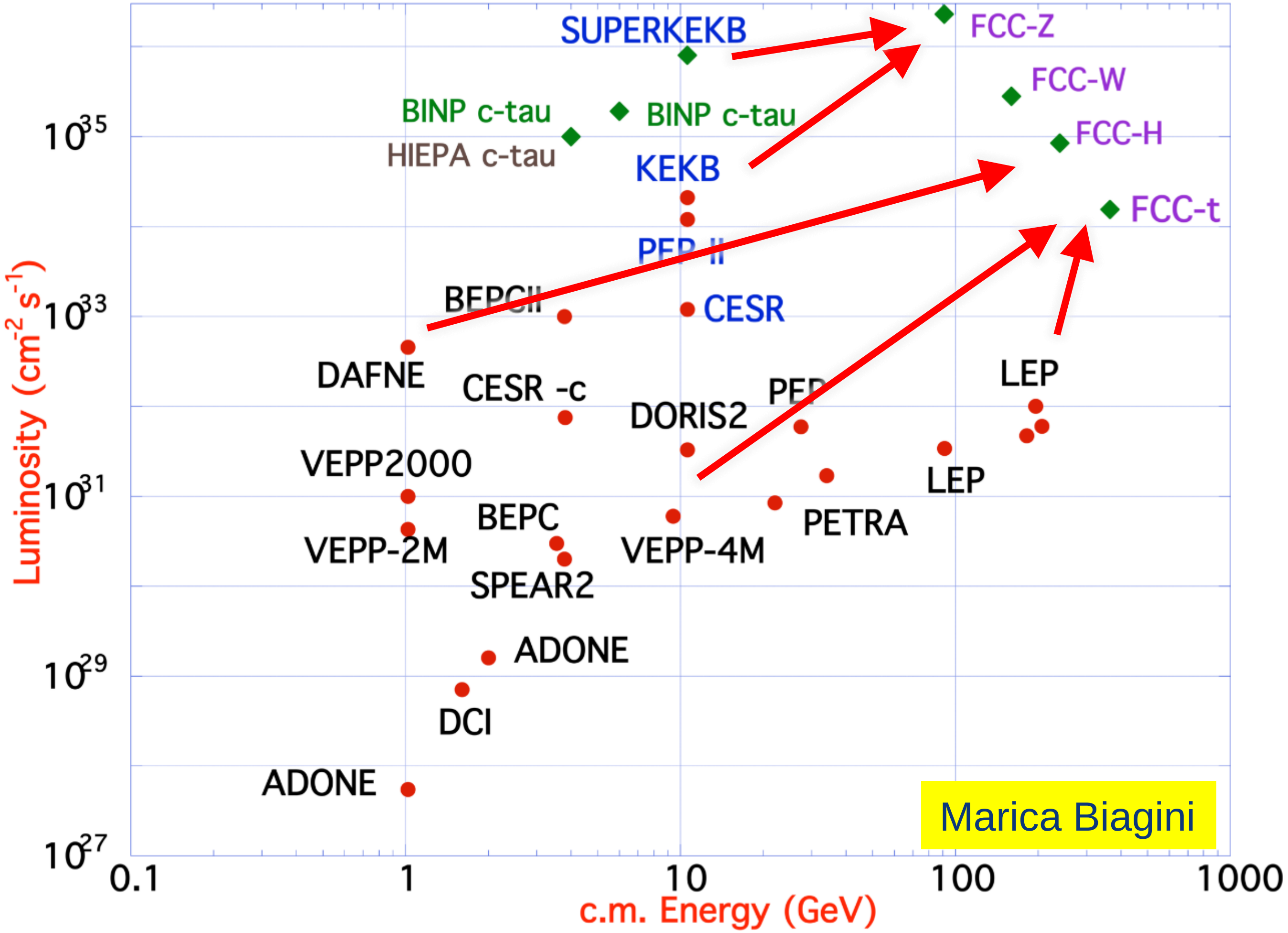
Stage 1: FCC-ee Collider Parameters

K. Oide, D. Shatilov,

Parameter [4 IPs, 91.2 km,T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity $[10^{11}]$	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP $[10^{34}$ cm^{-2}s$^{-1}]$	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

FCC-ee Design Concept

Based on lessons and techniques from past colliders (last 40 years)



B-factories: **KEKB & PEP-II:**
double-ring lepton colliders,
high beam currents,
top-up injection

DAFNE: crab waist, double ring

S-KEKB: low β_y*, crab waist

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

combining successful ingredients of several recent colliders → highest luminosities & energies

FCC-ee RF Staging Scenario

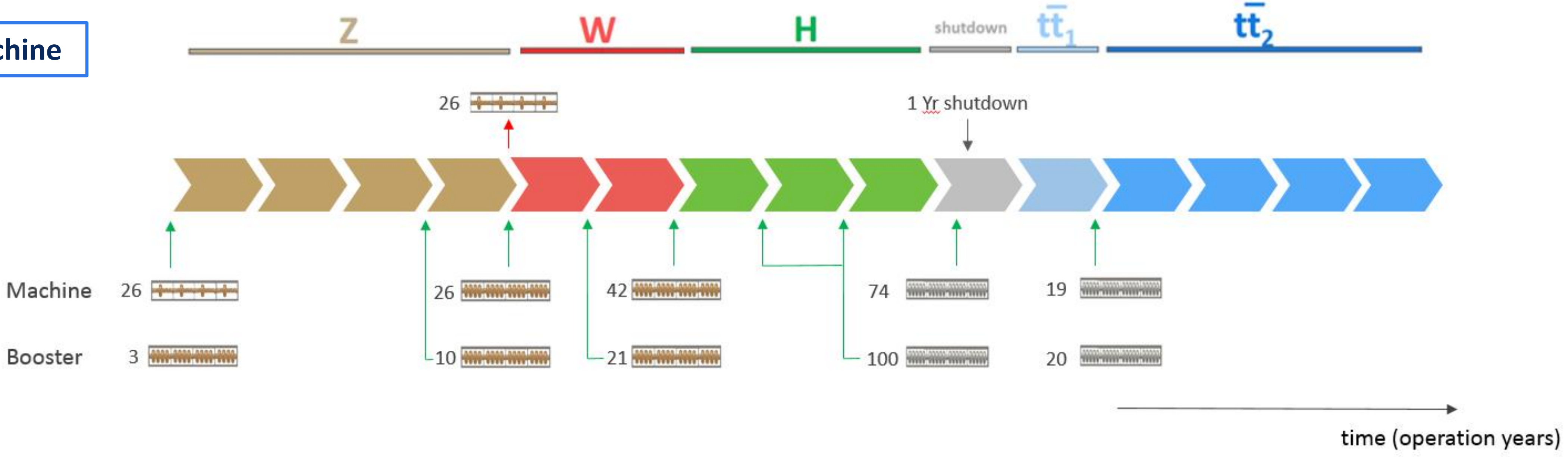
“Ampere-class” machine

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

“high-gradient” machine

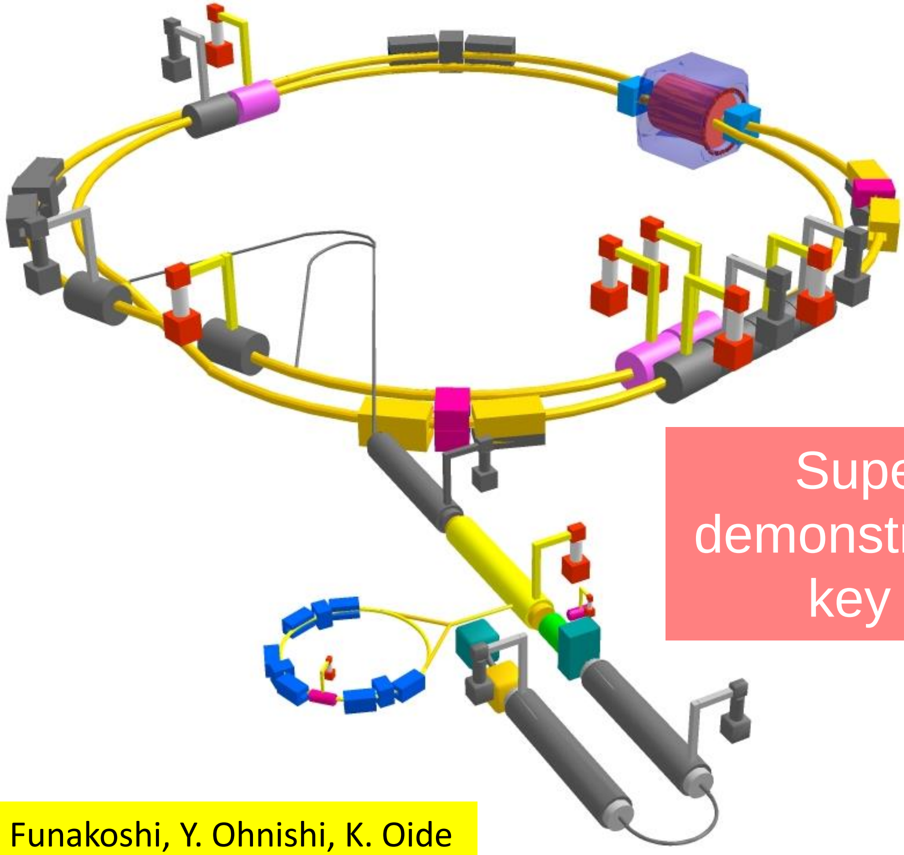
three sets of RF cavities to cover all options for FCC-ee & booster:

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



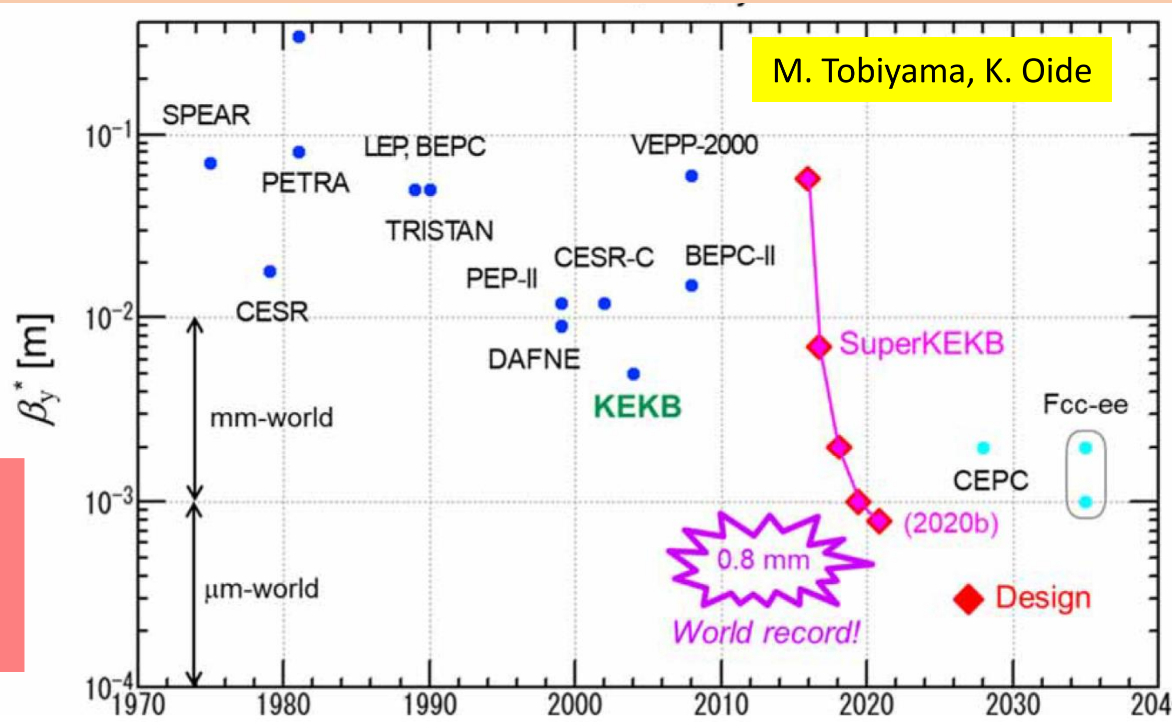
SuperKEKB – Pushing Luminosity and β*

Design: **double ring e^+e^- collider as *B*-factory** at 7(e^-) & 4(e^+) GeV; **design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$; β_y^* ~ 0.3 mm; nano-beam – large crossing angle** collision scheme **(crab waist w/o sextupoles)**; **beam lifetime ~5 minutes**; **top-up** injection; **e^+ rate up to ~ 2.5 10^{12} /s** ; **under commissioning**



SuperKEKB is demonstrating FCC-ee key concepts

Y. Funakoshi, Y. Ohnishi, K. Oide



M. Tobiyama, K. Oide

β_y^* = 0.8 mm achieved in both rings – using the FCC-ee-style "virtual" crab-waist collision scheme

Potential EIC – FCC collaboration

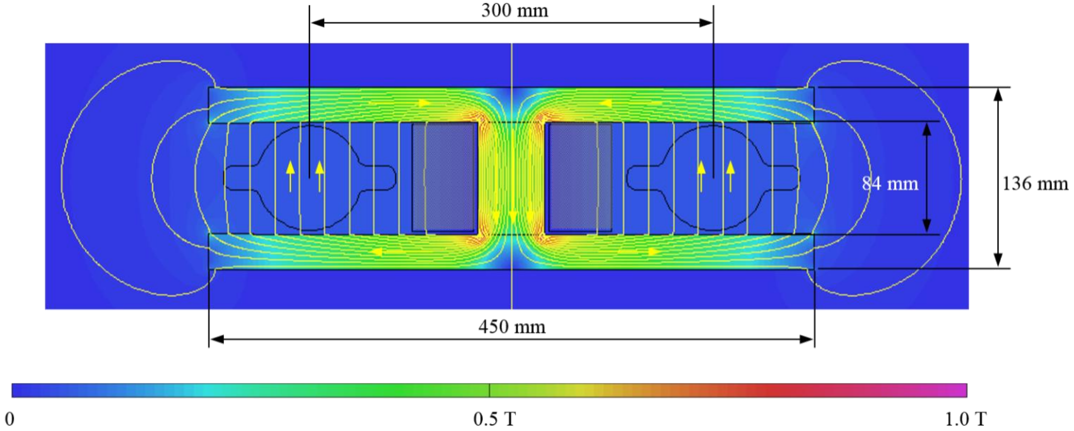
NSLS-II, EIC & FCC-ee beam parameters

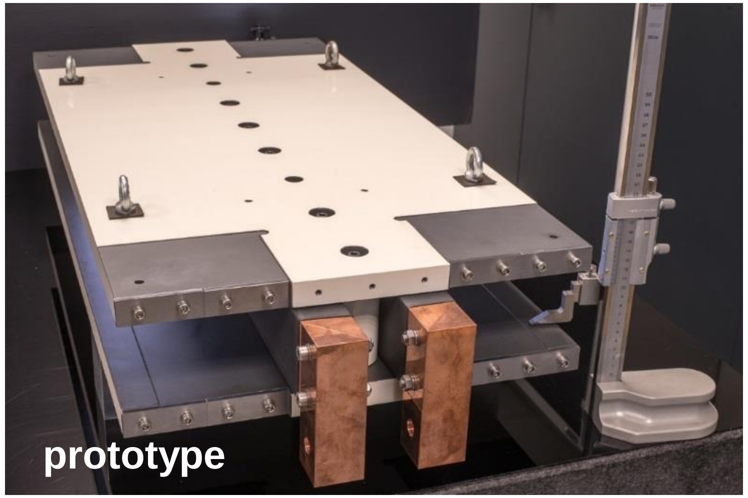
	NSLS-II	EIC	FCC-ee-Z
Beam energy [GeV]	**3**	**10 (20)**	**45.6**
Bunch population [10^{11}]	**0.08**	**1.7**	**1.7**
Bunch spacing [ns]	**2**	**10**	**15, 17.5 or 20**
Rms bunch length [mm]	4.5 - 9	**2**	**3.5 (SR)**
Beam current [A]	0.5	**2.5 (0.27)**	**1.39**
RF frequency [MHz]	500	591	400

Similarity of several parameters strongly suggests collaboration to exploit synergies in areas such as beam instrumentation, SRF, vacuum system with SR handling, etc.

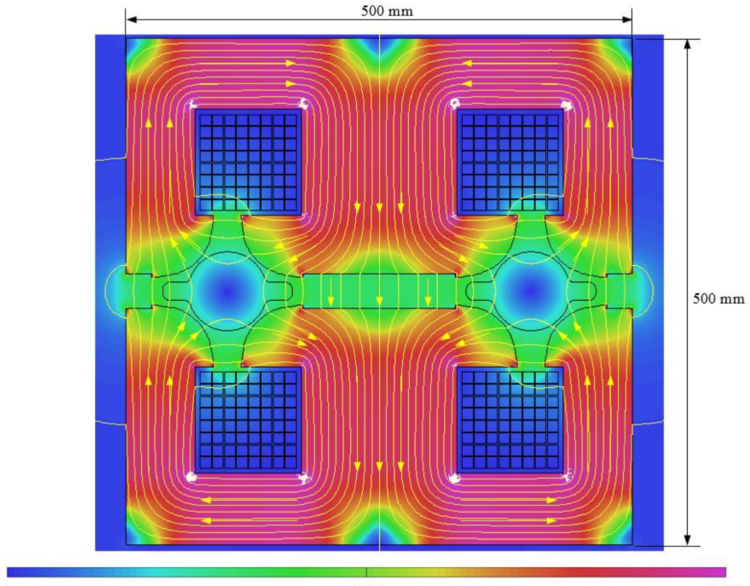
Prototypes of FCC-ee Low-power Magnets

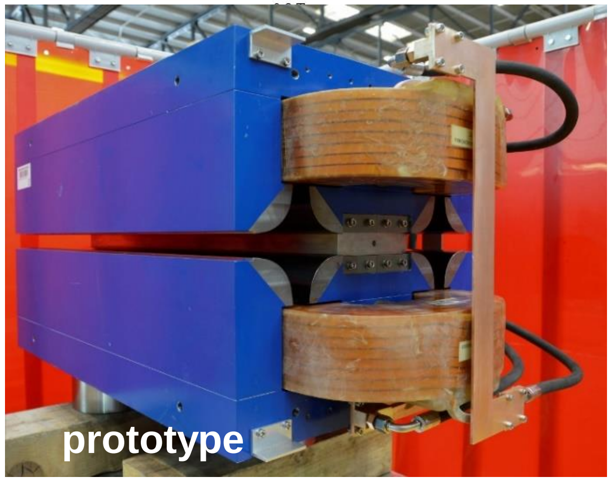
Twin-dipole design with 2× power saving 16 MW (at 175 GeV), with Al busbars





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



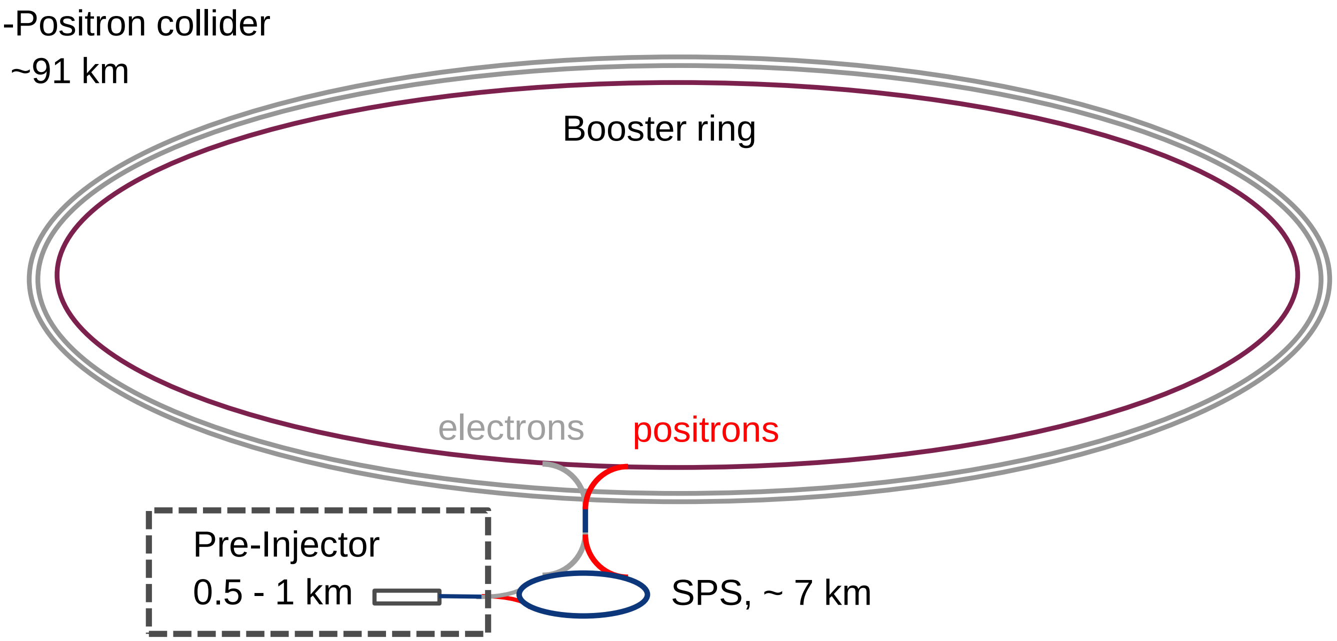


FCC-ee Pre-Injector Complex

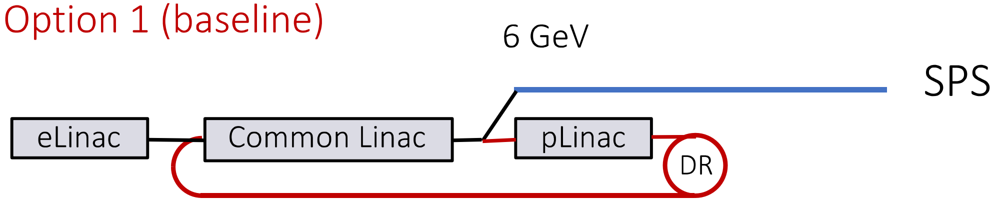
- The e+ creation by high-energy electrons hitting a target results in a large energy spread and transverse emittance.
- A damping ring (DR) is required to reduce the e+ emittance by about 3 orders of magnitude and to minimize the damping time.
- The DR consists of 2 straight sections housing in total 4 wigglers of 6.64 m length each. One of the straight sections also contains 8.56 m of drift space reserved for injection/extraction and the opposite section hosts two LHC-type 400 MHz superconducting cavities of 1.5 m. length (3.5 m with cryostat).

FCC-ee Pre-Injector Complex

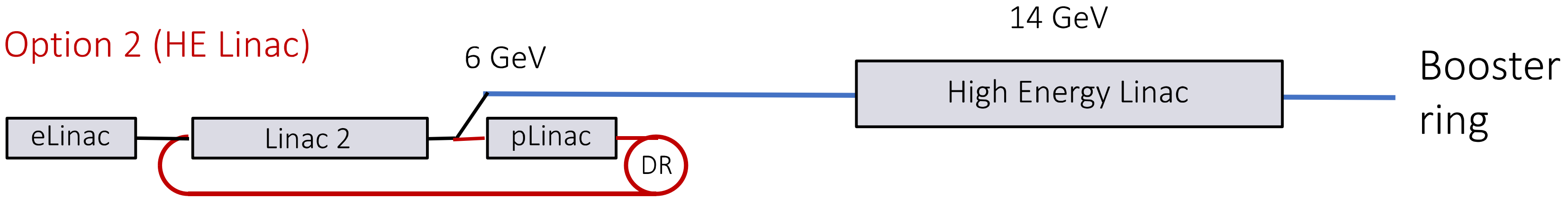
- Pre-injector: e-/e+ linacs up to 6 (20) GeV, 1.54 GeV Damping Ring.
- Pre-Booster Ring (SPS or new ring) (6–20 GeV).
- Booster Ring (20 → 45 GeV).
- The main 6 GeV linac feeds the positron source. The positrons are produced with 6 GeV e- beam.



Option 1 (baseline)

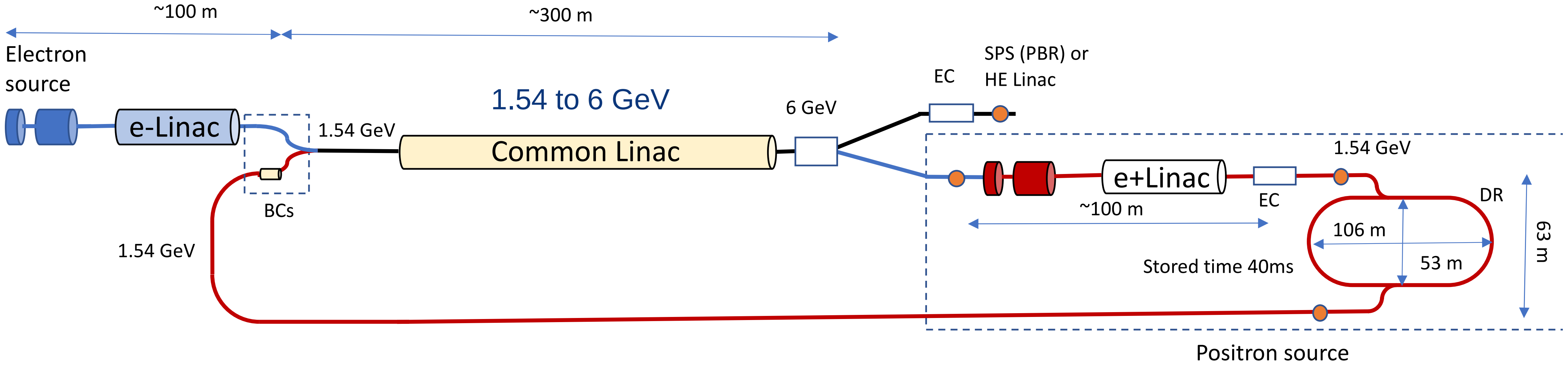


Option 2 (HE Linac)



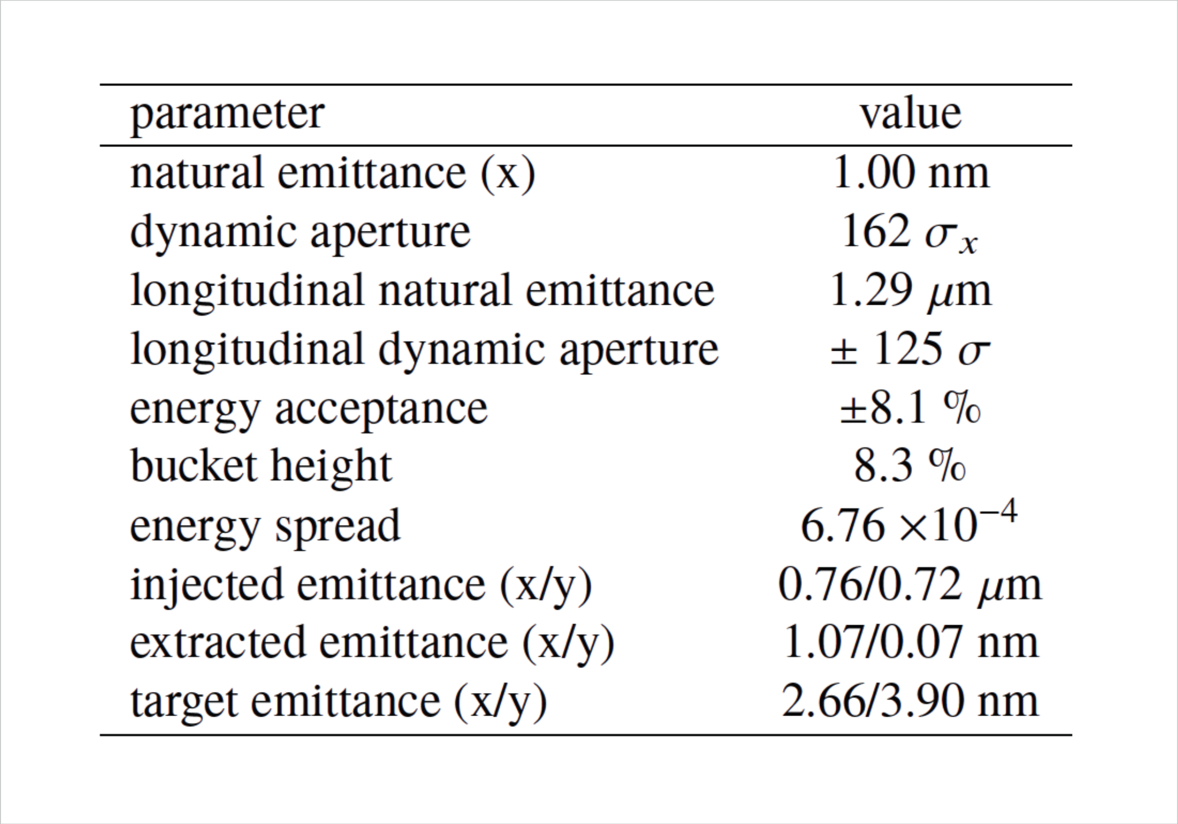
FCC-ee Pre-Injector Layout (6 GeV Option)

More details: talk on linac studies by Simona Bettoni



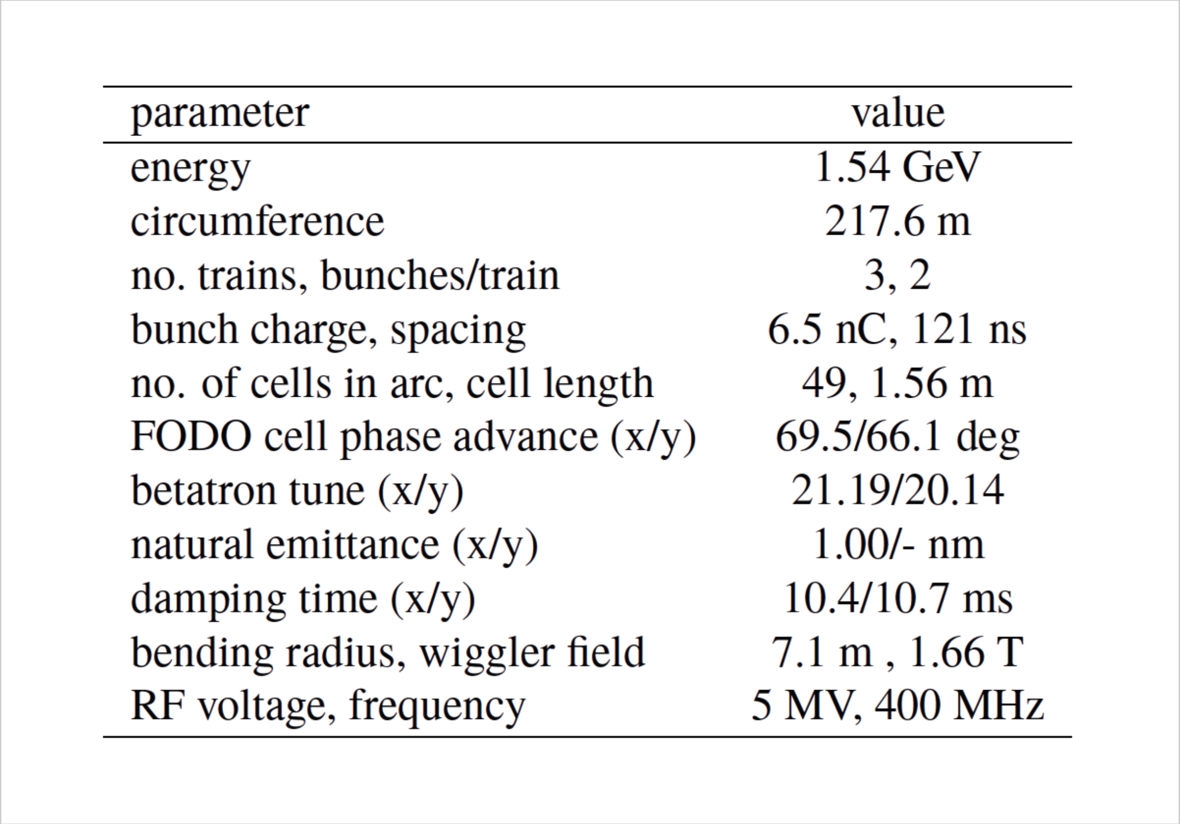
- Linac efficiencies optimised: electron/positron beam with same energy, main and drive electron beam with same final energy.
- Specifications are fulfilled for the electron bunch (beam dynamics simulations for the e- linac and common linac well advanced).
- e+ linac: several options of the capture section, RF design well advanced 2 GHz, 200 Hz, large iris aperture, beam dynamics on-going.
- DR provides the damping of the positron beam and delays extraction to allow single species operation for the common linac.

FCC-ee Pre-Injector Complex



parameter	value
natural emittance (x)	1.00 nm
dynamic aperture	162 σ_x
longitudinal natural emittance	1.29 μm
longitudinal dynamic aperture	± 125 σ
energy acceptance	±8.1 %
bucket height	8.3 %
energy spread	6.76×10^{-4}
injected emittance (x/y)	0.76/0.72 μm
extracted emittance (x/y)	1.07/0.07 nm
target emittance (x/y)	2.66/3.90 nm

Damping Ring Design Parameters



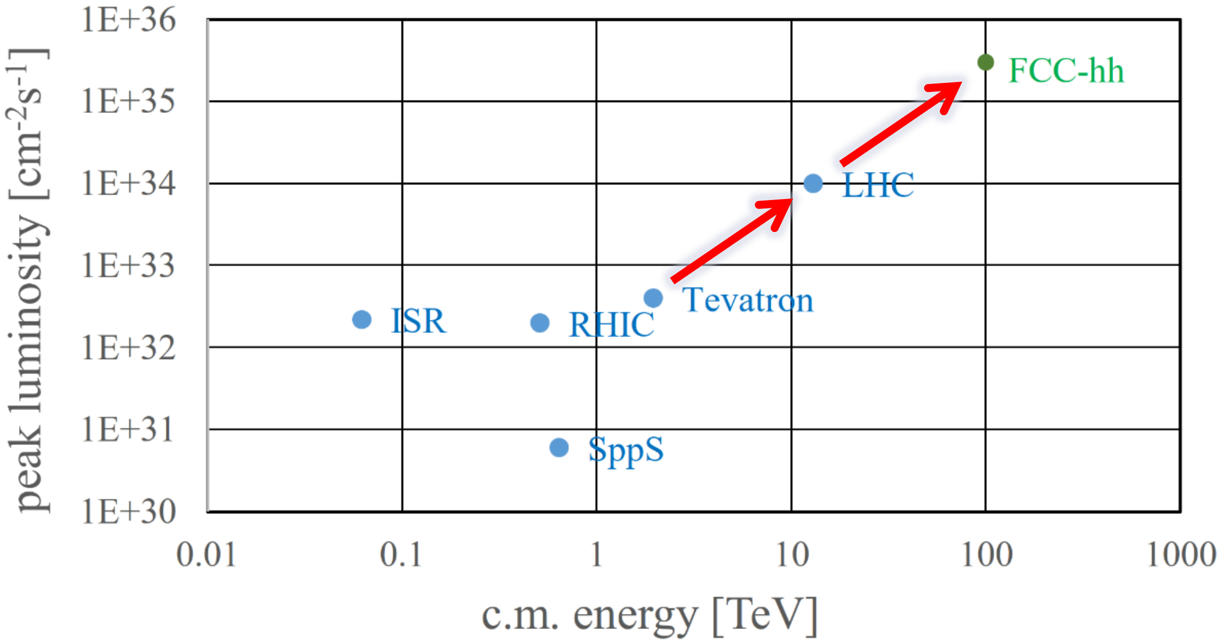
parameter	value
energy	1.54 GeV
circumference	217.6 m
no. trains, bunches/train	3, 2
bunch charge, spacing	6.5 nC, 121 ns
no. of cells in arc, cell length	49, 1.56 m
FODO cell phase advance (x/y)	69.5/66.1 deg
betatron tune (x/y)	21.19/20.14
natural emittance (x/y)	1.00/- nm
damping time (x/y)	10.4/10.7 ms
bending radius, wiggler field	7.1 m , 1.66 T
RF voltage, frequency	5 MV, 400 MHz

Damping Ring Performance

Stage 2: FCC-hh (pp) Collider Parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	~17 (~16 comb.function)		8.33	8.33
circumference [km]	91.2		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36

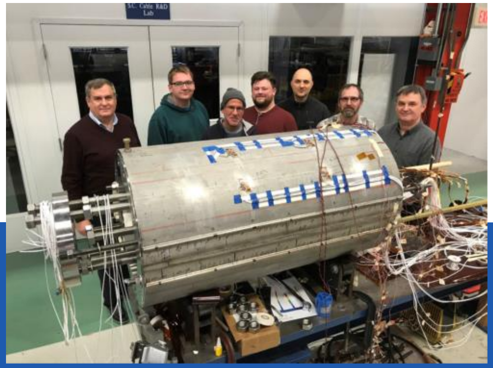
FCC-hh: Highest Collision Energies



- **Order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- Similar performance increase as from Tevatron to LHC
- **Key technology: high-field magnets**

from
LHC technology
8.3 T NbTi dipole

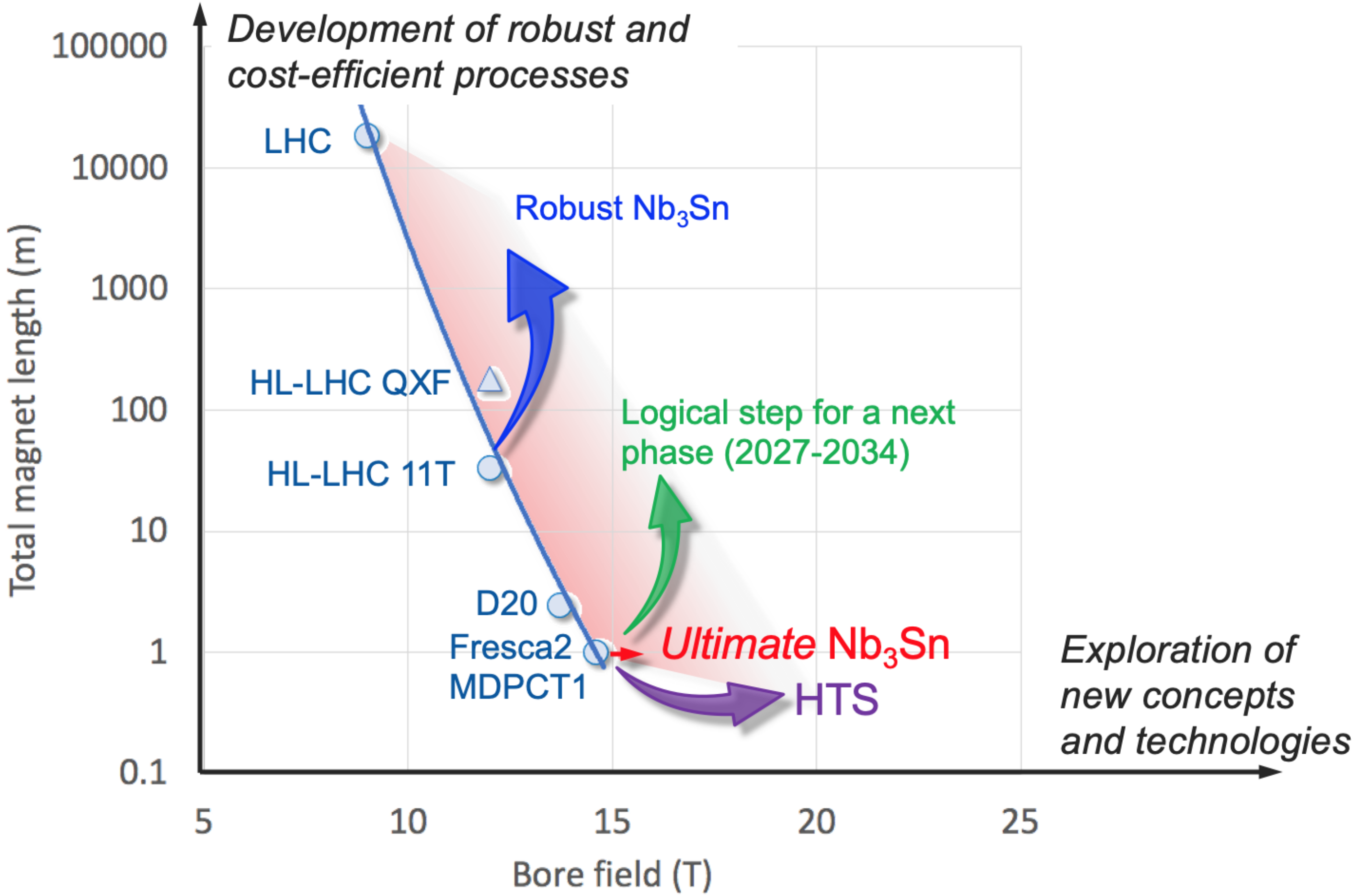
via
HL-LHC technology
12 T Nb_3Sn quadrupole



FNAL dipole demonstrator
14.5 T Nb_3Sn

High-field Magnet R&D: First steps towards FCC-hh

In parallel to FCC Study, HFM development programme as long-term separate R&D project



Main R&D activities:

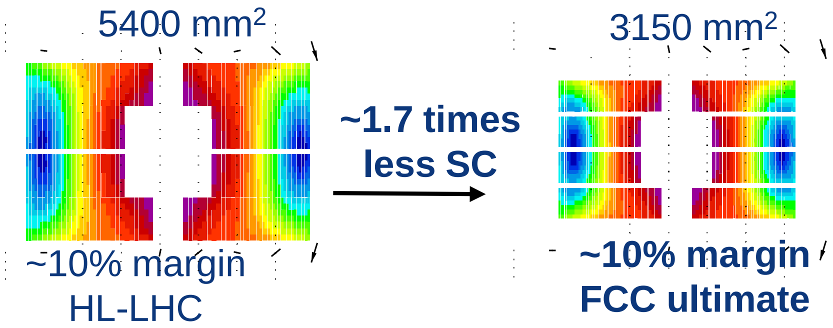
- ☐ materials: goal is ~16 T for Nb_3Sn, at least ~20 T for HTS inserts
- ☐ magnet technology: engineering, mechanical robustness, insulating materials, field quality
- ☐ production of models and prototypes: to demonstrate material, design and engineering choices, industrialisation and costs
- ☐ infrastructure and test stations: for tests up to ~ 20 T and 20-50 kA

Global collaborations already established during FCC CDR phase.

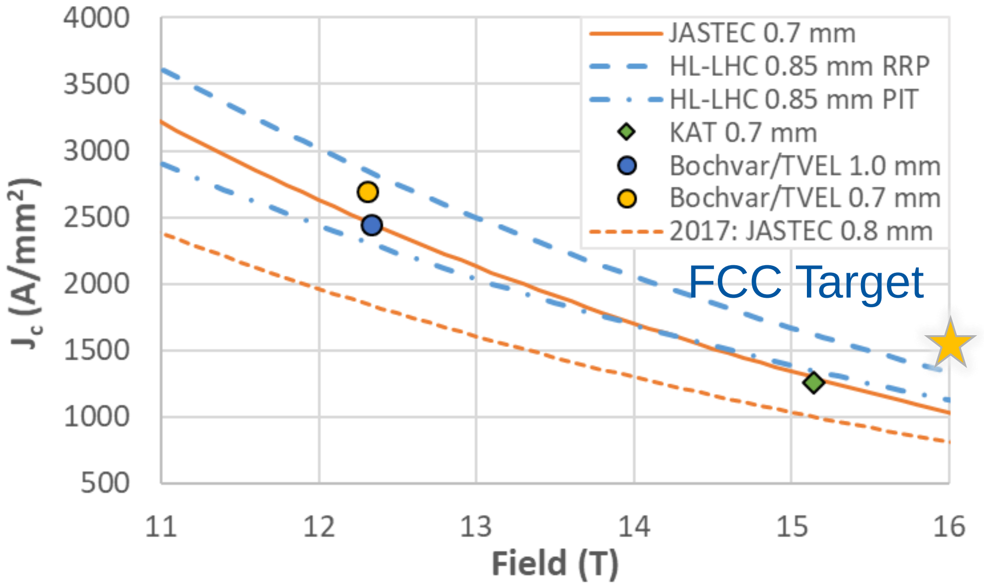
World-wide FCC Nb_3Sn Programme

Main development goal is wire performance increase:

- **J_c (16T, 4.2K) > 1500 A/mm^2 →50% increase wrt HL-LHC wire**
- **Reduction of coil & magnet cross-section**



After 1-2 years development**, prototype Nb_3Sn wires from several new industrial FCC partners already achieve HL-LHC J_c performance**



FCC conductor development collaboration:

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

2019/20 results from US, meeting FCC J_c specs:

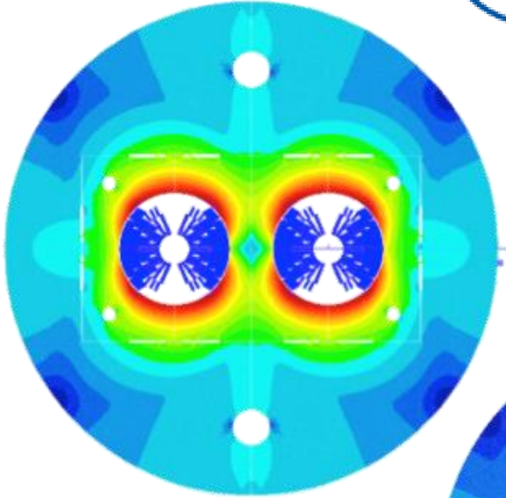
- **Florida State University:** high-J_c Nb_3Sn via Hf addition
- **Hyper Tech /Ohio SU/FNAL**: high-J_c Nb_3Sn via artificial pinning centres based on Zr oxide.

16 T Dipole Design Activities and Options

H2020

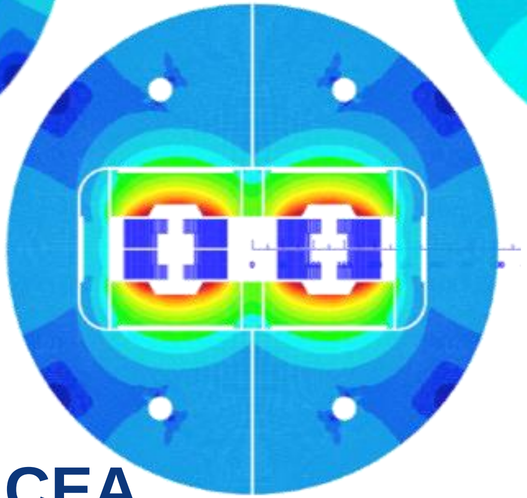
EuroCirCol
A key to New Physics

Cos-theta



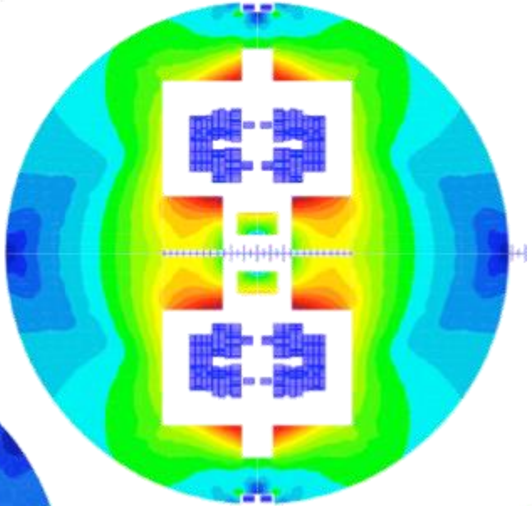
INFN

Blocks



CEA

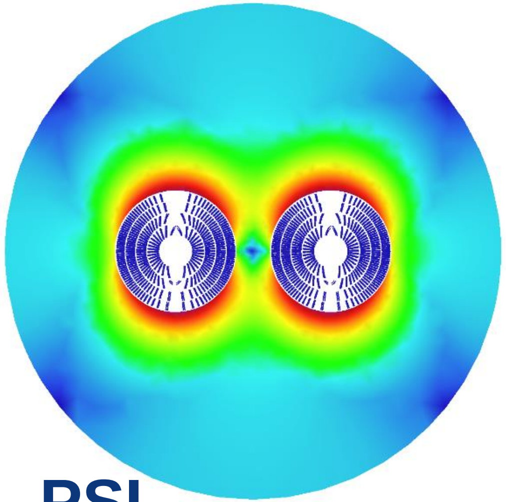
Common coils



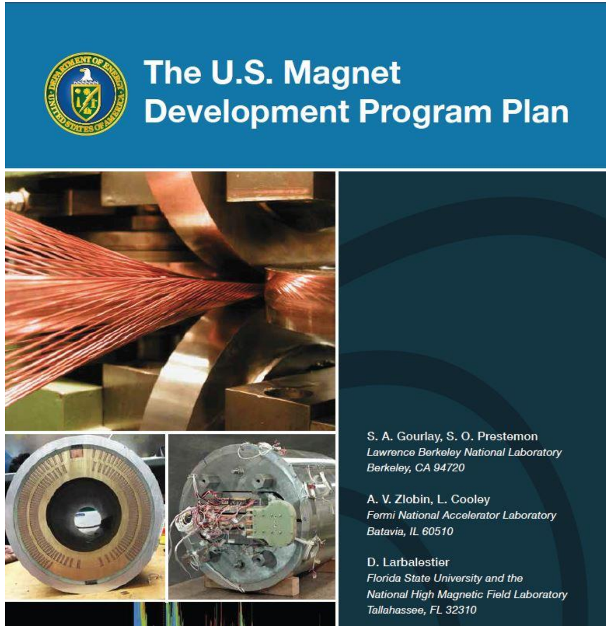
CIEMAT

Swiss contribution

Canted
Cos-theta



PSI

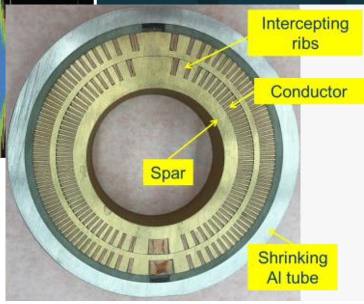


The U.S. Magnet
Development Program Plan

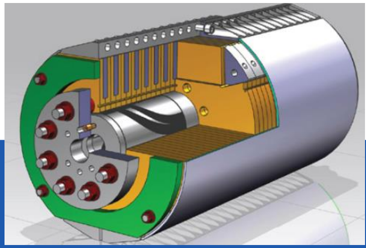
S. A. Gourlay, S. O. Prestemon
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory
Batavia, IL 60510

D. Larbalestier
Florida State University and the
National High Magnetic Field Laboratory
Tallahassee, FL 32310



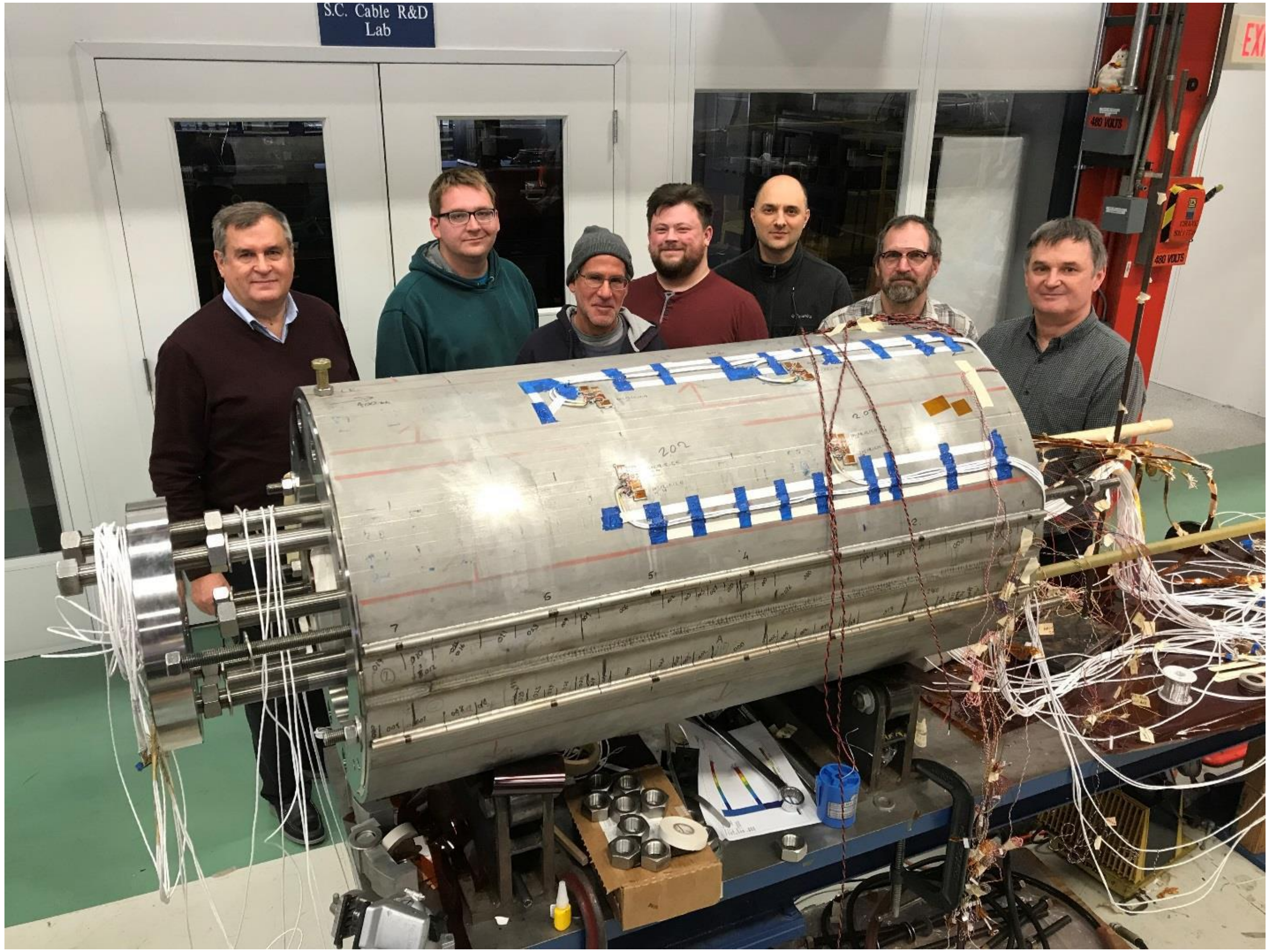
LBNL

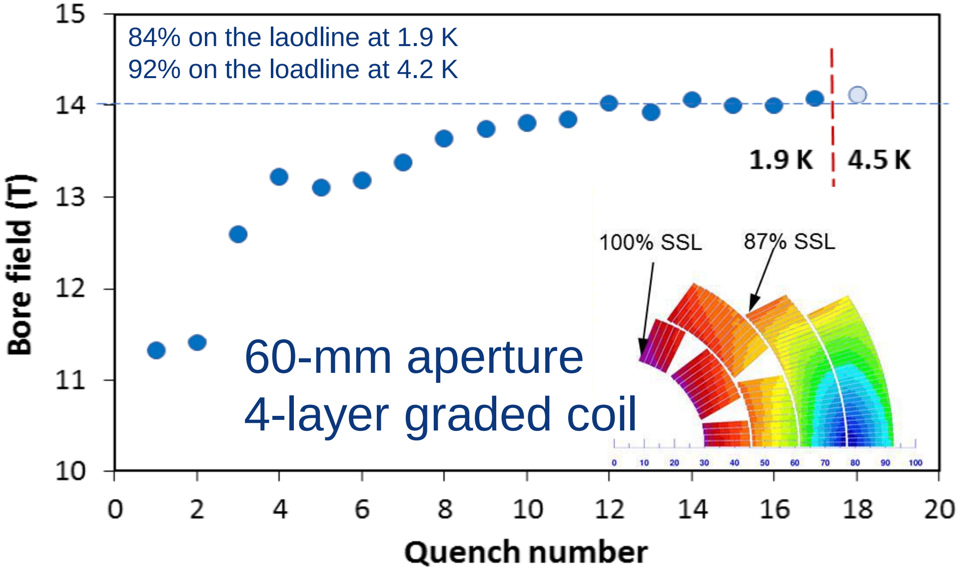


FNAL

Short model magnets (1.5 m lengths) will be built until 2025

US – MDP: 14.5 T Magnet Tested at FNAL



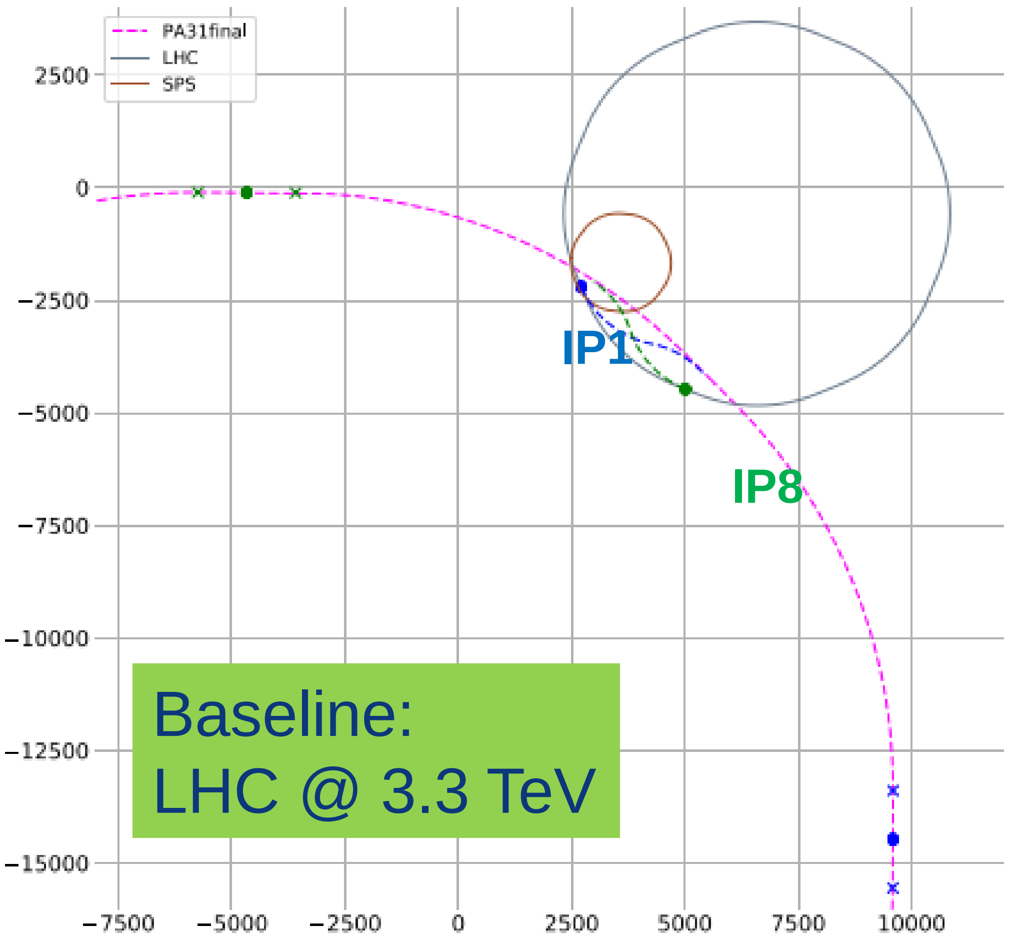


- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T

FCC-hh Hadron Injector Lines for New Layout

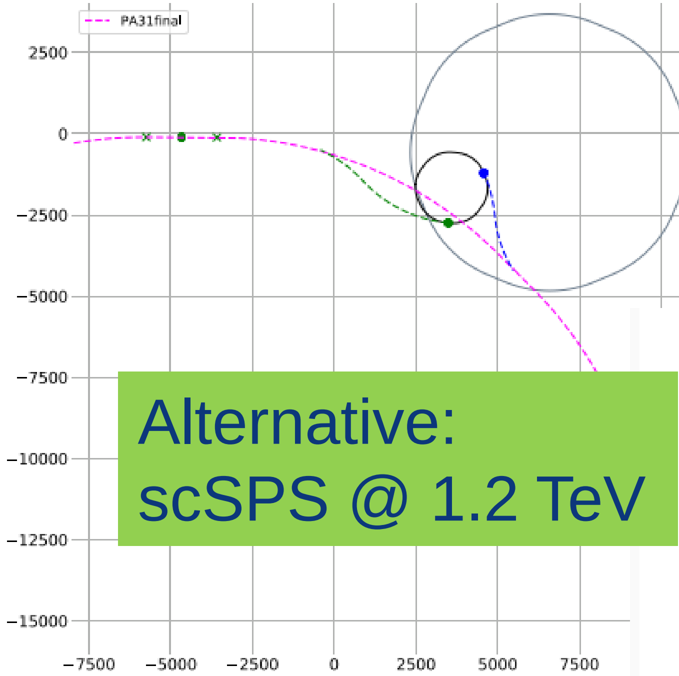
injection from LHC

Top view of LHC-FCC transfer lines in CCS coordinates [m]



Baseline:
LHC @ 3.3 TeV

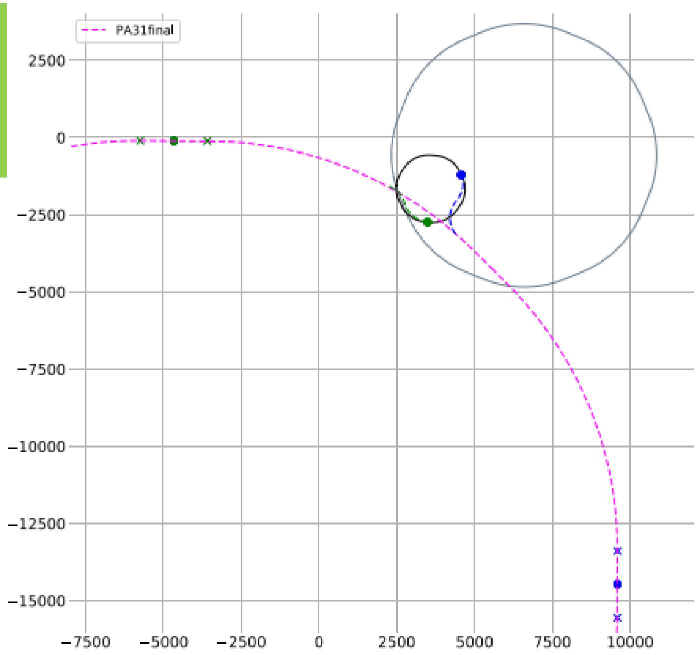
Top view of SPS-FCC transfer lines in CCS coordinates [m]



Alternative:
scSPS @ 1.2 TeV

injection from scSPS
NC (left) or
SC transfer lines (below)

Top view of SPS-FCC transfer lines in CCS coordinates [m]



tunnel lengths:
- LHC, SC, 3.2/3.5 km
- SPS, NC, 4.6/3.2 km
- SPS, SC, 1.5/2.1 km

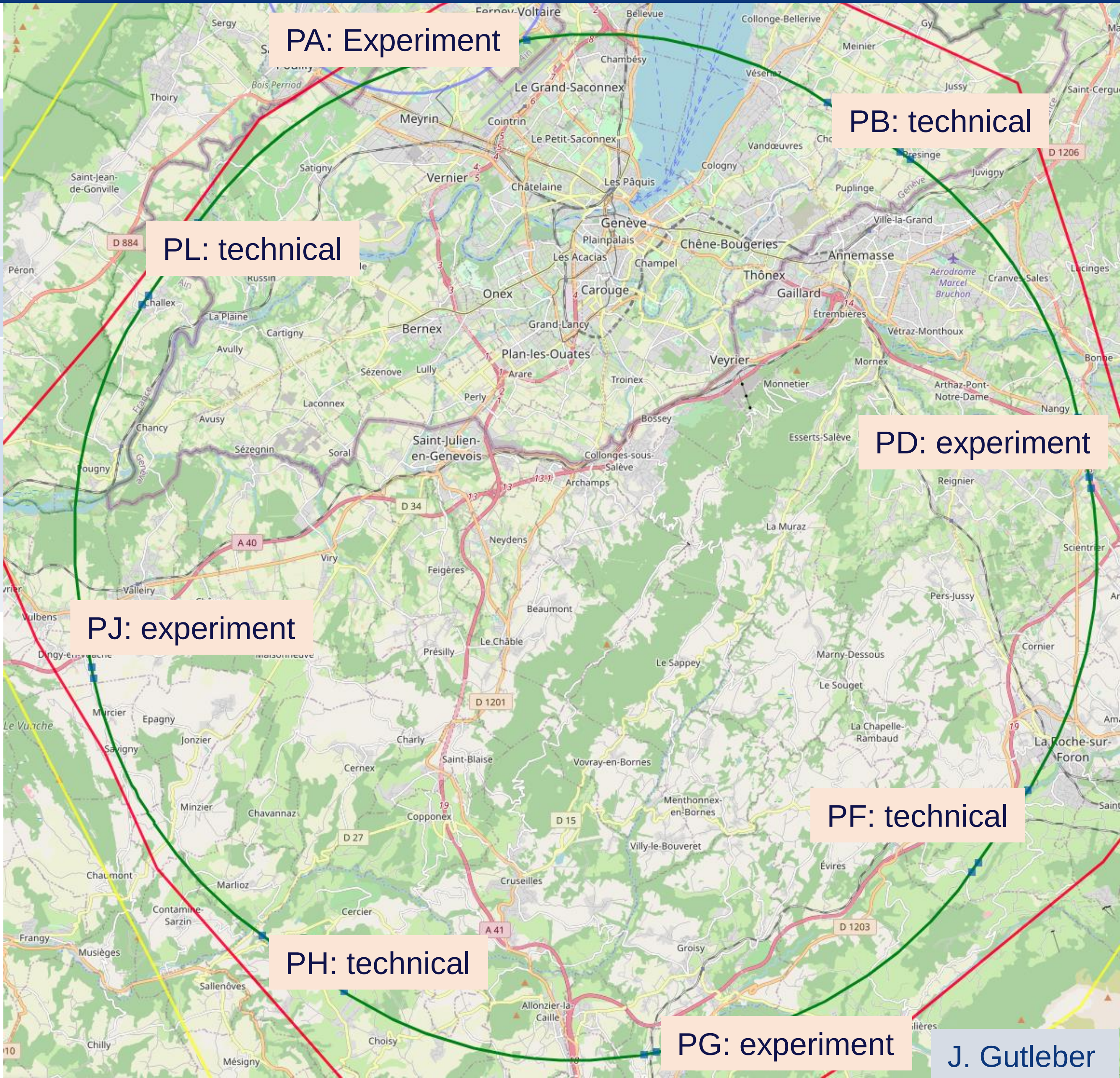
FUTURE CIRCULAR COLLIDER

Optimised Placement and Layout

8-site baseline “PA31”

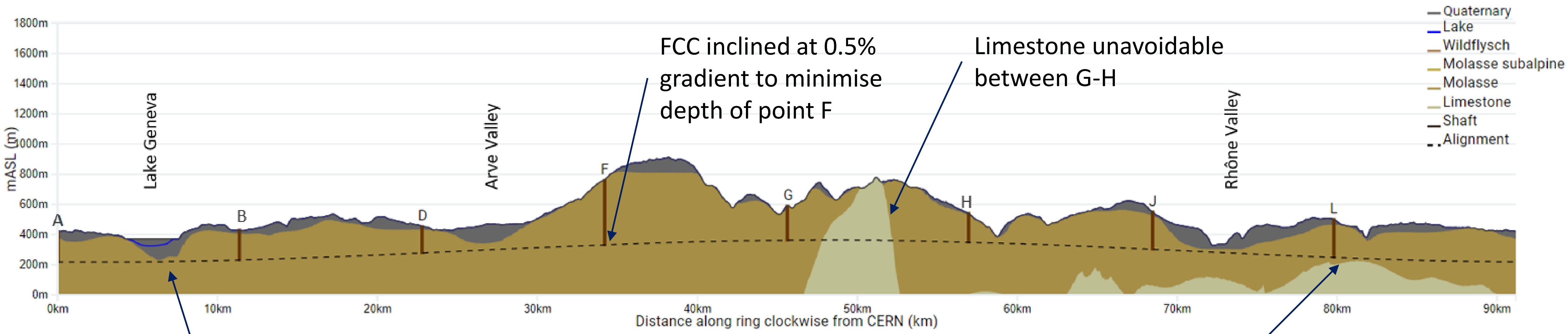
Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2143 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**91.1 km**

- 8 sites – less use of land, <40 ha instead 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP



J. Gutleber

FCC Long Section – PA31-1.0



FCC inclined at 0.5% gradient to minimise depth of point F

Limestone unavoidable between G-H

FCC passes below Lake Geneva moraines

FCC passes above limestone

Shaft depth:

A: 202 m

B: 200 m

D: 177 m

F: 399 m

G: 228 m

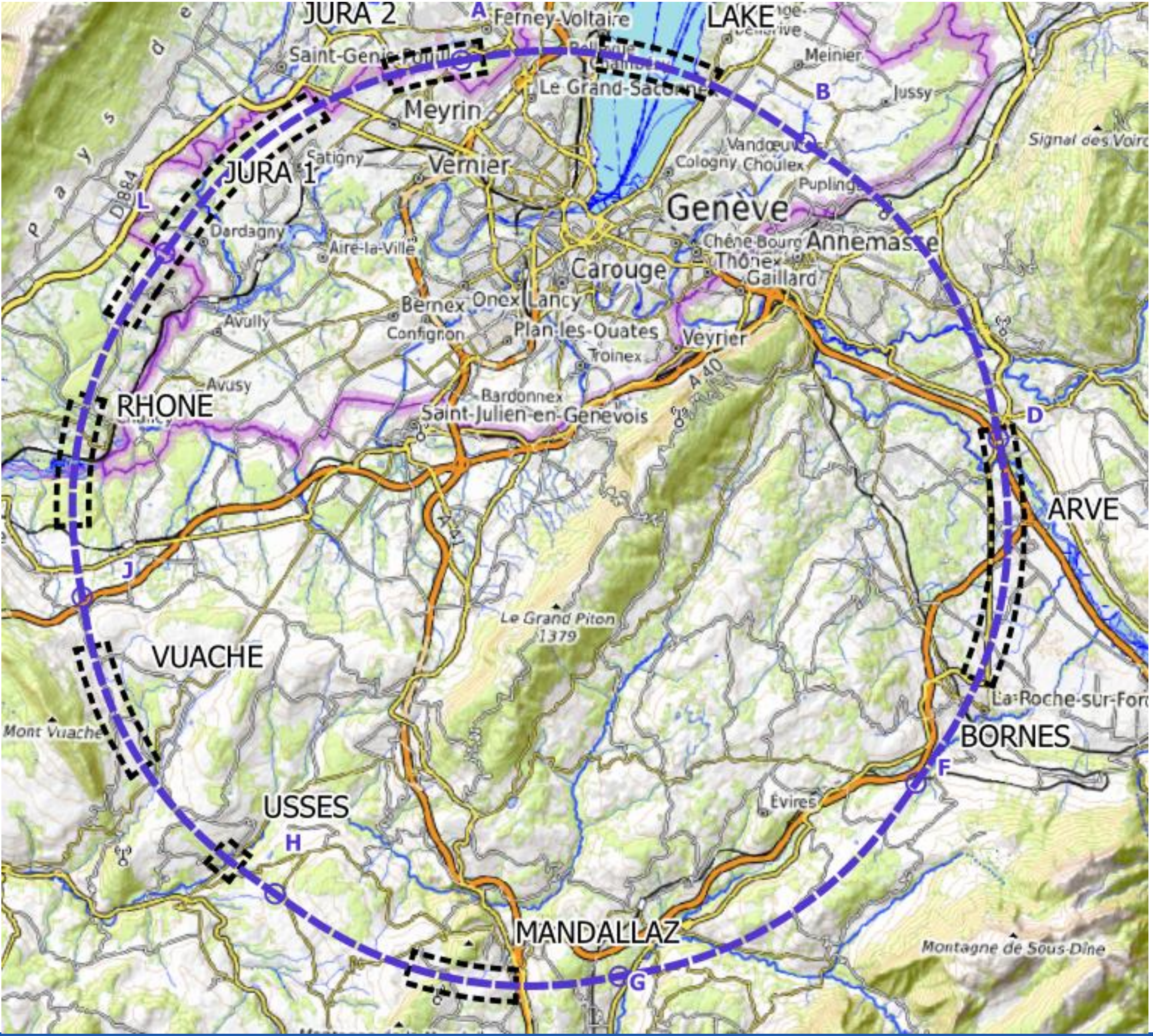
H: 139 m

J: 251 m

L: 253 m

John Osborne

Plans for High-risk Area Site Investigations



JURA, VUACHE (3 AREAS)
Top of limestone
Karstification and filling-in at the tunnel depth
Water pressure

LAKE, RHÔNE, ARVE AND USSES VALLEY (4 AREAS)
Top of the molasse
Quaternary soft grounds, water bearing layers

MANDALLAZ (1 AREAS)
Water pressure at the tunnel level
Karstification

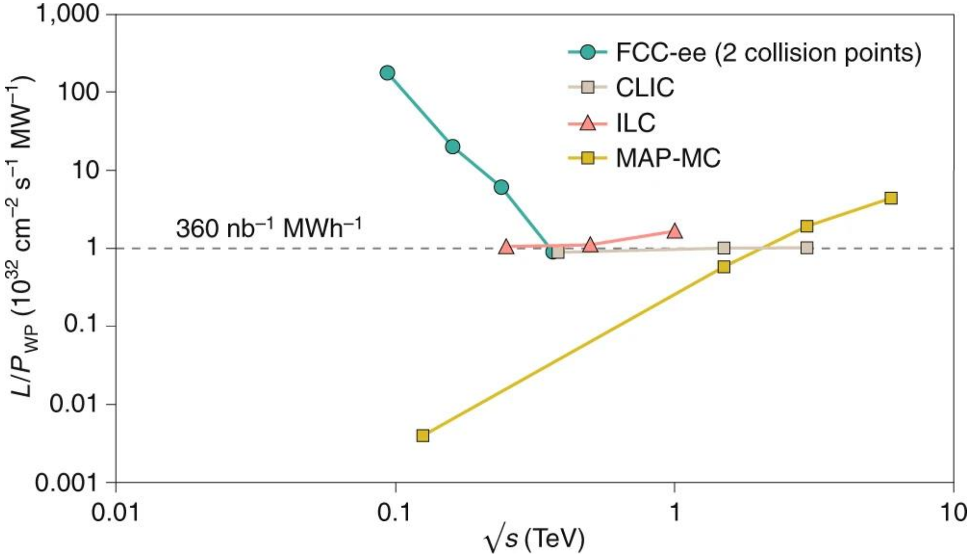
BORNES (1 AREA)
High overburden molasse properties
Thrust zones

Site investigations planned for 2024 – 2025:
~40-50 drillings, 100 km of seismic lines

Sustainability and Carbon Footprint Studies

highly sustainable Higgs factory

luminosity vs. electricity consumption



Thanks to twin-aperture magnets, thin-film SRF, efficient RF power sources, top-up injection

optimum usage of excavation material

int'l competition "mining the future®"

https://indico.cern.ch/event/1001465/

FCC-ee annual energy consumption ~ LHC/HL-LHC

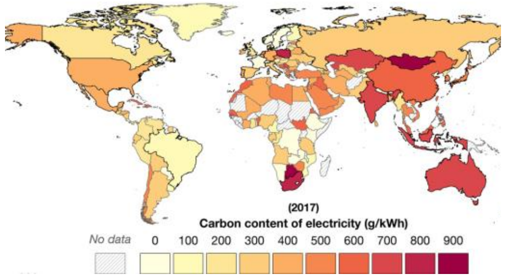
120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880					69	199872	MWh
Energy consumption / year	365	8760						1.52	TWh
Average power								174	MW

J.-P. Burnet, FCC Week 2022

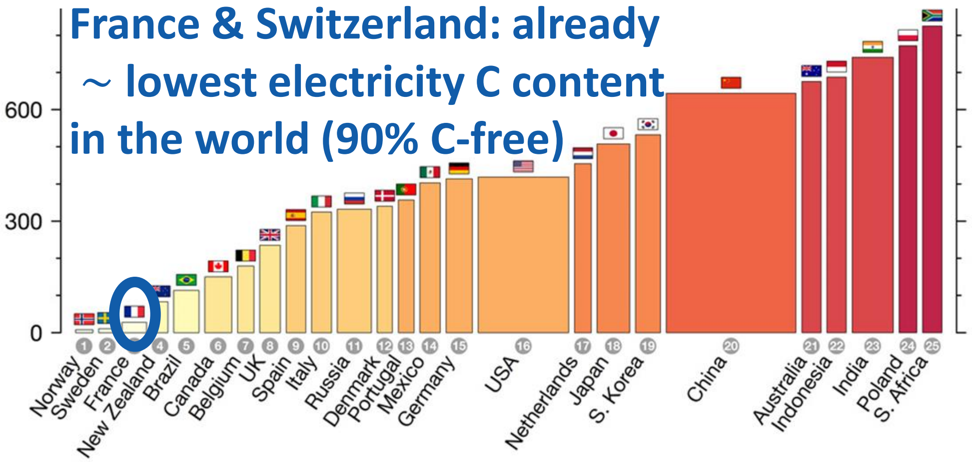
incl. CERN site & SPS

CERN Meyrin, SPS, FCC	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Energy consumption (TWh/y)	1.82	1.92	2.09	2.54

powered by mix of renewable & other C-free sources



https://www.carbonbrief.org/


France & Switzerland: already ~ lowest electricity C content in the world (90% C-free)

FUTURE CIRCULAR COLLIDER

Status of Global FCC Collaboration

Increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

147 Institutes

30 Companies

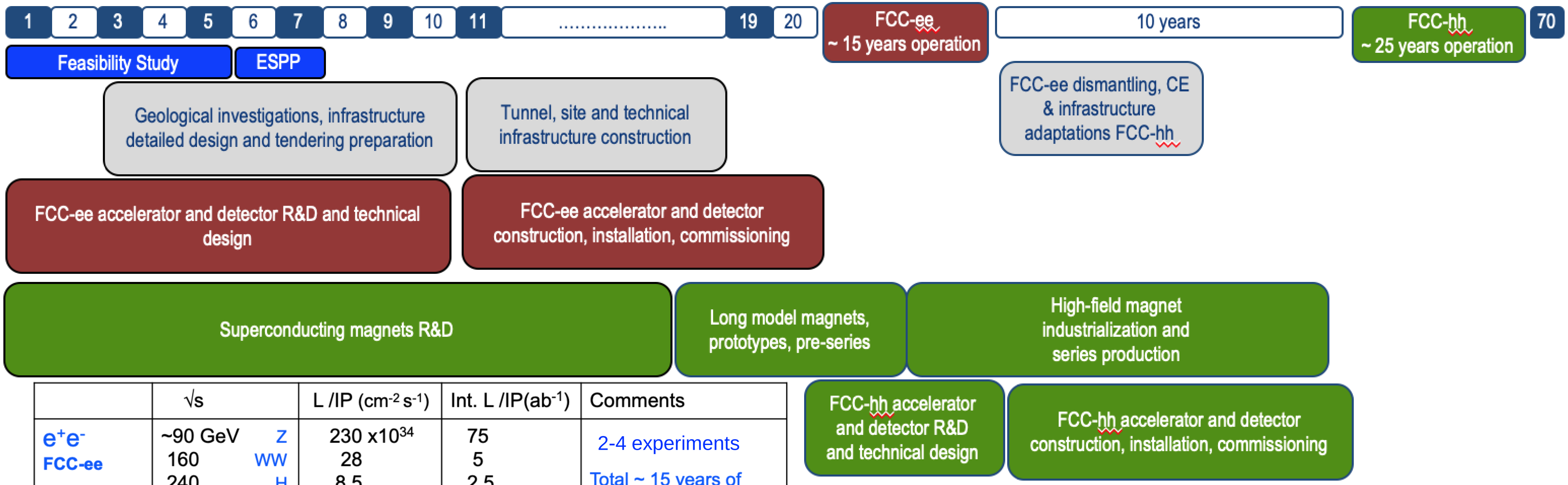
34 Countries

EC H2020

FUTURE
CIRCULAR
COLLIDER

Timeline of the FCC Integrated Programme

Technical schedule



1 2 3 4 5 6 7 8 9 10 11 ………………… 19 20

FCC-ee
~ 15 years operation

10 years

FCC-hh
~ 25 years operation

70

Feasibility Study

ESPP

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

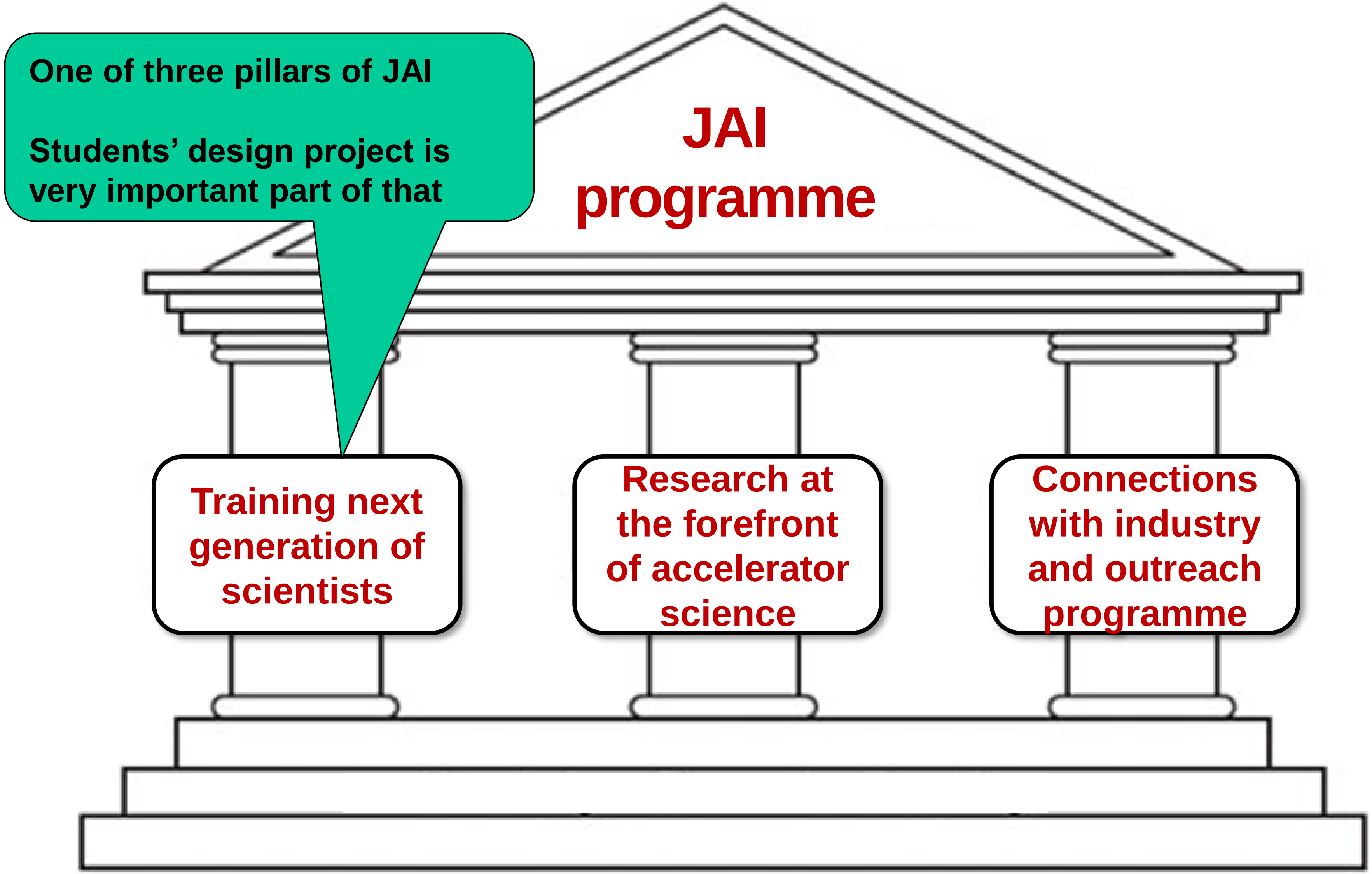
	√s	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	230 $\times 10^{34}$ 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep **Fcc-eh**	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb **Fcc-eh**	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

- ☐ Feasibility Study: 2021-2025
- ☐ If project approved before end of decade → construction can start beginning 2030s
- ☐ FCC-ee operation ~2045-2060
- ☐ FCC-hh operation 2070-2090++

F. Gianotti

JAI Training

Foundation of the JAI Programme

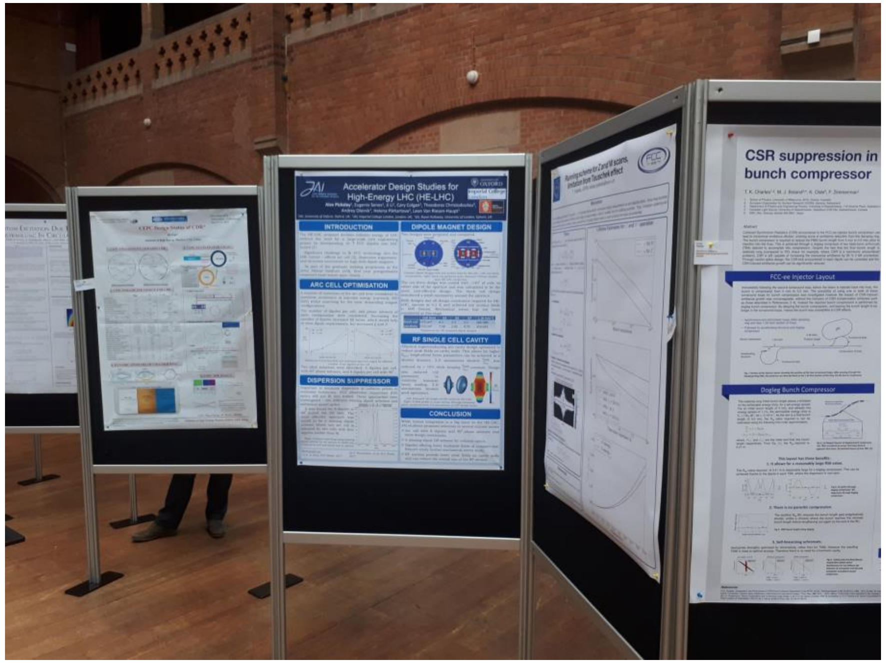


One of three pillars of JAI

Students’ design project is very important part of that

Accelerator Design Project 2017-2018

- **Accelerator Design Studies for the High-Energy LHC (HE-LHC) for 2017-2018**
  - **The aim of the 2017-2018 JAI student project work was to prepare a design for HE-LHC.**
  - **Design work consisted of study of the lattice, magnet systems and RF cavities.**
  - **Student presentations made at CERN in June 2018 (together with visits to accelerator facilities).**



HE-LHC Student Poster at FCC Week Amsterdam, April 2018

Accelerator Design Project

- **Accelerator Design Study for**
  - **Electron SPS: 2020-2021**
  - **FCC-ee Booster: 2021-2022**
  - **Design work consisted of study of the lattice, magnet systems and RF cavities.**
- **Student visits and presentations at CERN planned in June 2022.**

“The design project significantly contributes to the value of a PhD at the JAI and is a very effective learning tool ... it played an essential role in helping me to find a postdoc.”

“To me, the design project was by far the best part of the course. It puts the material taught into context and bridges the gap between lectures ... and a DPhil project ... .”

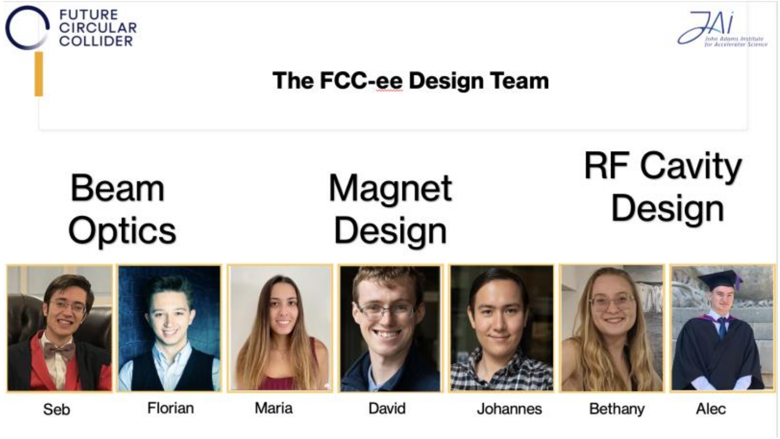
John Adams Institute for Accelerator Science

eSPS
Preliminary Design Report

Part of a JAI First-year Graduate Student Design Project 2020-2021

Majid Ali & Robert Murphy
Royal Holloway, University of London
Emily Archer, Pablo Arrutia, Joseph Bateman & Cameron Robertson
University of Oxford
Rebecca Taylor
Imperial College London
1st July 2021

eSPS Design Report published on CDS **(DOI 10.17181/CERN.Q29A.V5M6)** and students delivered JAI Seminar.



FUTURE CIRCULAR COLLIDER

The FCC-ee Design Team

Beam Optics | Magnet Design | RF Cavity Design

Seb, Florian, Maria, David, Johannes, Bethany, Alec

FCC-ee Design Report published on CDS (10.17181/CERN.GSBF.JG2K) & students delivered JAI Seminar

FCC-ee Damping Ring Student Design Project Plan

- **Optics Studies**
  - **Study various lattice options.**

- **Magnet Design**
  - **Optimise dipole and quadrupole magnets.**

- **RF System**
  - **Design of RF system.**

- **Overall parameter tables and sub-system inventory**

FUTURE
CIRCULAR
COLLIDER

Thank you