

# FCC Feasibility Study & Path to Construction

IPAC'25, Taipei, 6 June 2025

Michael Benedikt and Frank Zimmermann, CERN  
on behalf of the FCC collaboration



Swiss Accelerator  
Research and  
Technology

<http://cern.ch/fcc>



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European  
Commission

Horizon 2020  
European Union funding  
for Research & Innovation

photo: J. Wenninger

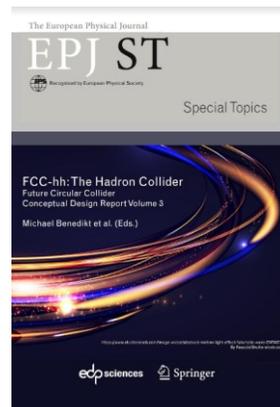
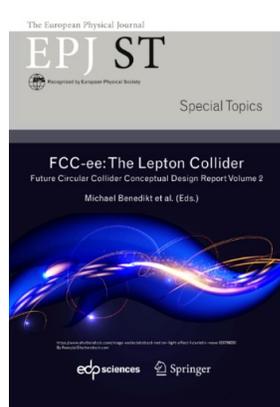
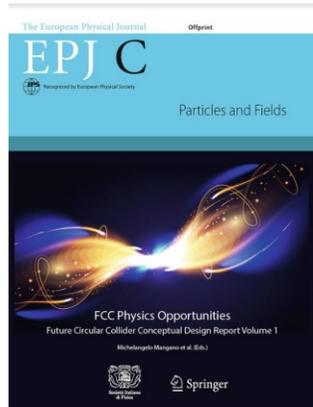
# Prehistory

Larger hadron collider (“VHE-LHC”) suggested at EuCARD Malta workshop in 2010 [[arXiv: 1111.7188](https://arxiv.org/abs/1111.7188)]

Circular e<sup>+</sup>e<sup>-</sup> Higgs factory (“LEP3”, “DLEP”) first proposed in 2011, after initial hints from LHC experiments [[arxiv:1112.2518](https://arxiv.org/abs/1112.2518)]. Concept driven forward in 2012–2013 (“TLEP”), as a community initiative.

2013 European Strategy for Particle Physics Update (ESPPU) → Launch of Future Circular Collider (FCC) study

→ Conceptual Design Reports (4 volumes) as input to ESPPU 2019/20



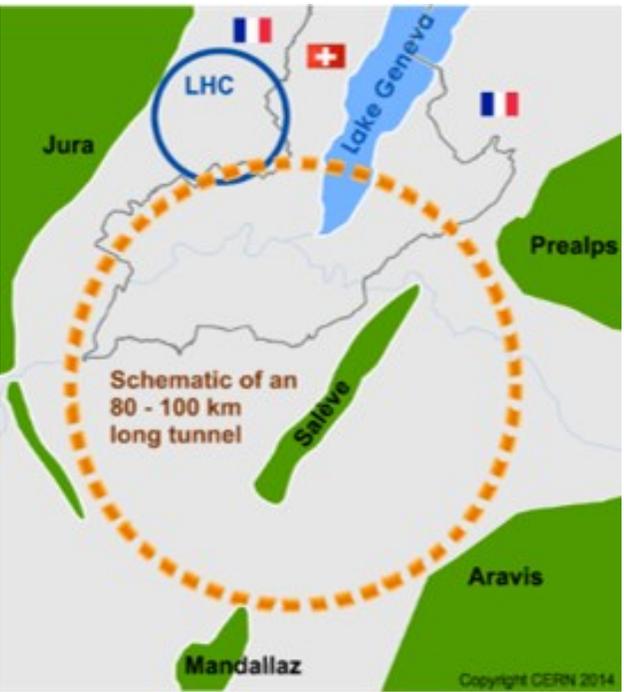
**Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC CDRs published in European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

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

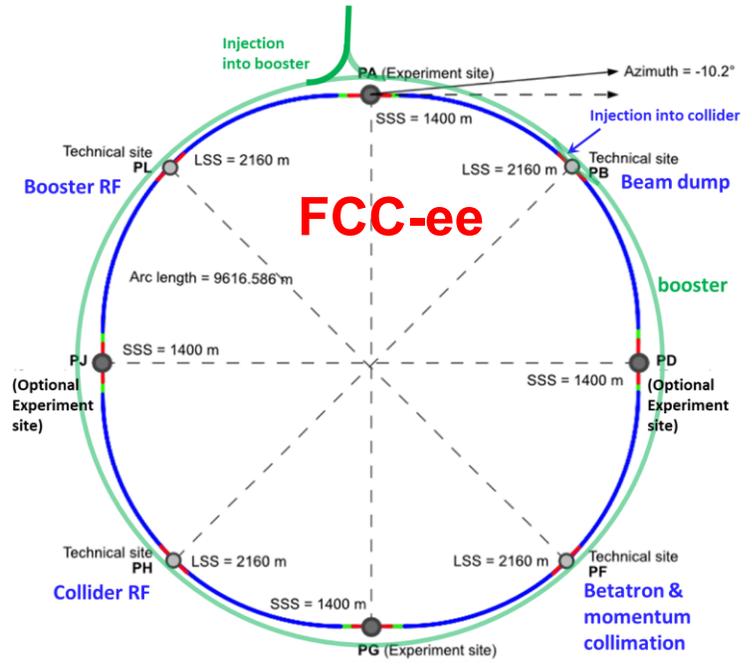
2020 Update of European Strategy for Particle Physics  
→ Launch of “Future Circular Collider Feasibility Study”

# FCC integrated program

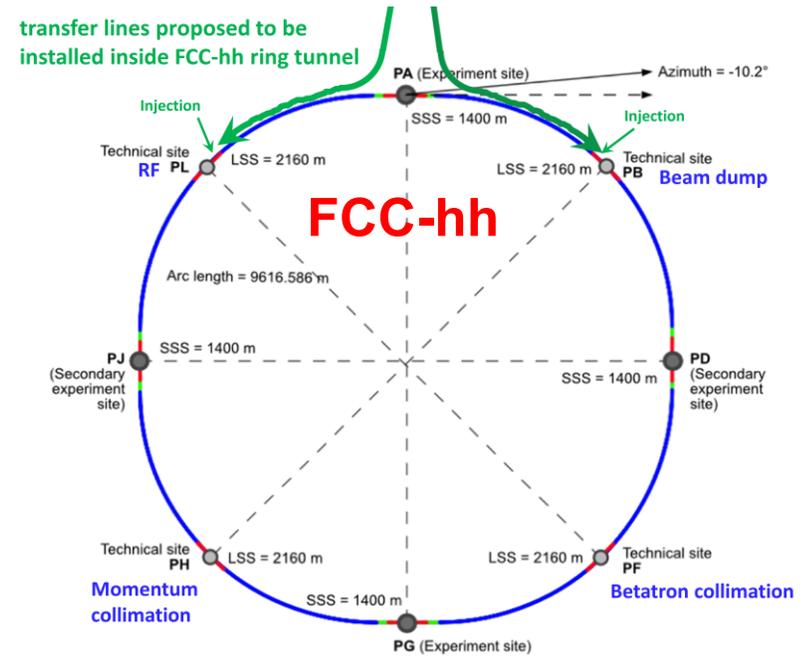
- stage 1: FCC-ee (Z, W, H,  $t\bar{t}$ ) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option
- highly synergetic and complementary programme maximising the physics opportunities
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



2020 - 2045



2045 - 2065

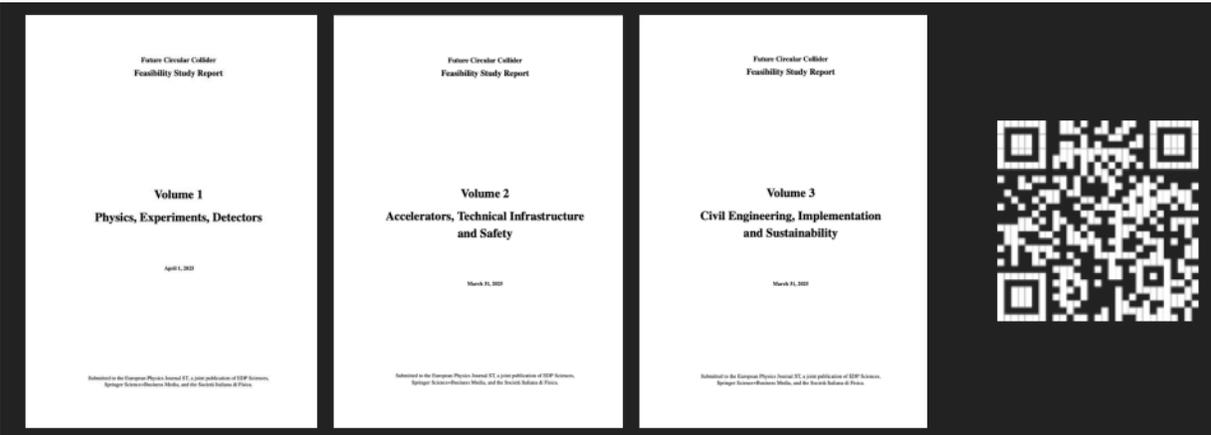


2070 -

# FCC Feasibility Study Report (FSR) delivered on 31 March 2025

## Structure: three volumes

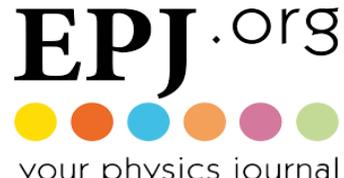
- **Vol. 1: Physics, Experiments & Detectors**
- **Vol. 2: Accelerators, Technical Infrastructures, Safety Concepts**
- **Vol. 3: Civil Engineering, Implementation & Sustainability**



These & other FCC input to 2025/26 ESPPU posted at <https://indico.cern.ch/event/1534205/>

## Input for 2025/26 Update of European Strategy for Particle Physics

prepared with Overleaf & to be published by EPJ (Springer-Nature) – FCCIS members



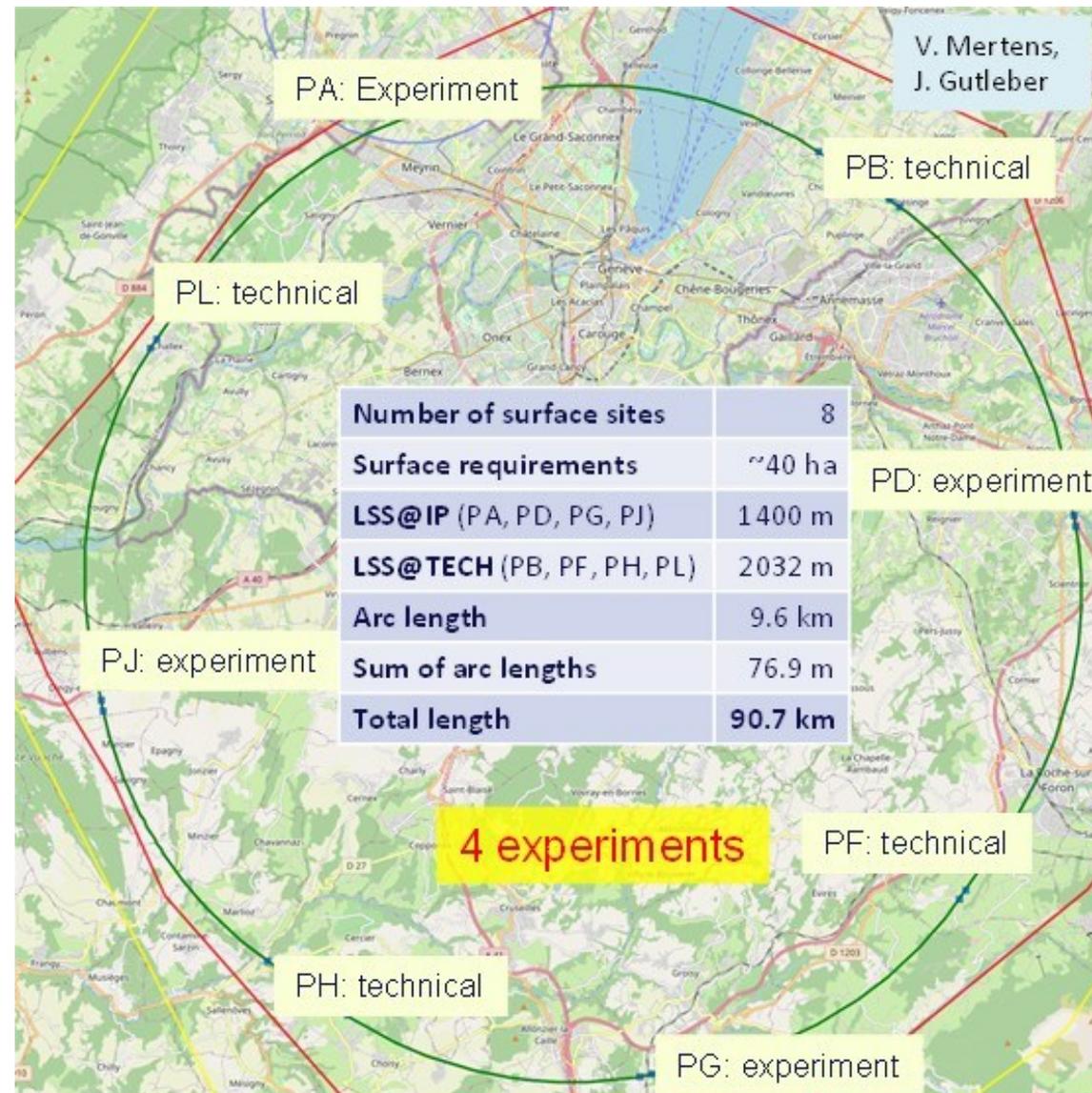
# Reference layout and implementation

**90.7 km ring, 8 surface points, 4-fold superperiodicity**

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

Reference layout was the basis for:

- **Surface sites optimisation and land reservation** with host states CH and FR
- **Environmental initial-state study**



# Surface site locations: 7 in France, 1 in Switzerland

Optimisation done with communes, land plot needs communicated to Host States



PA



PB



PD



PF



PG



PH

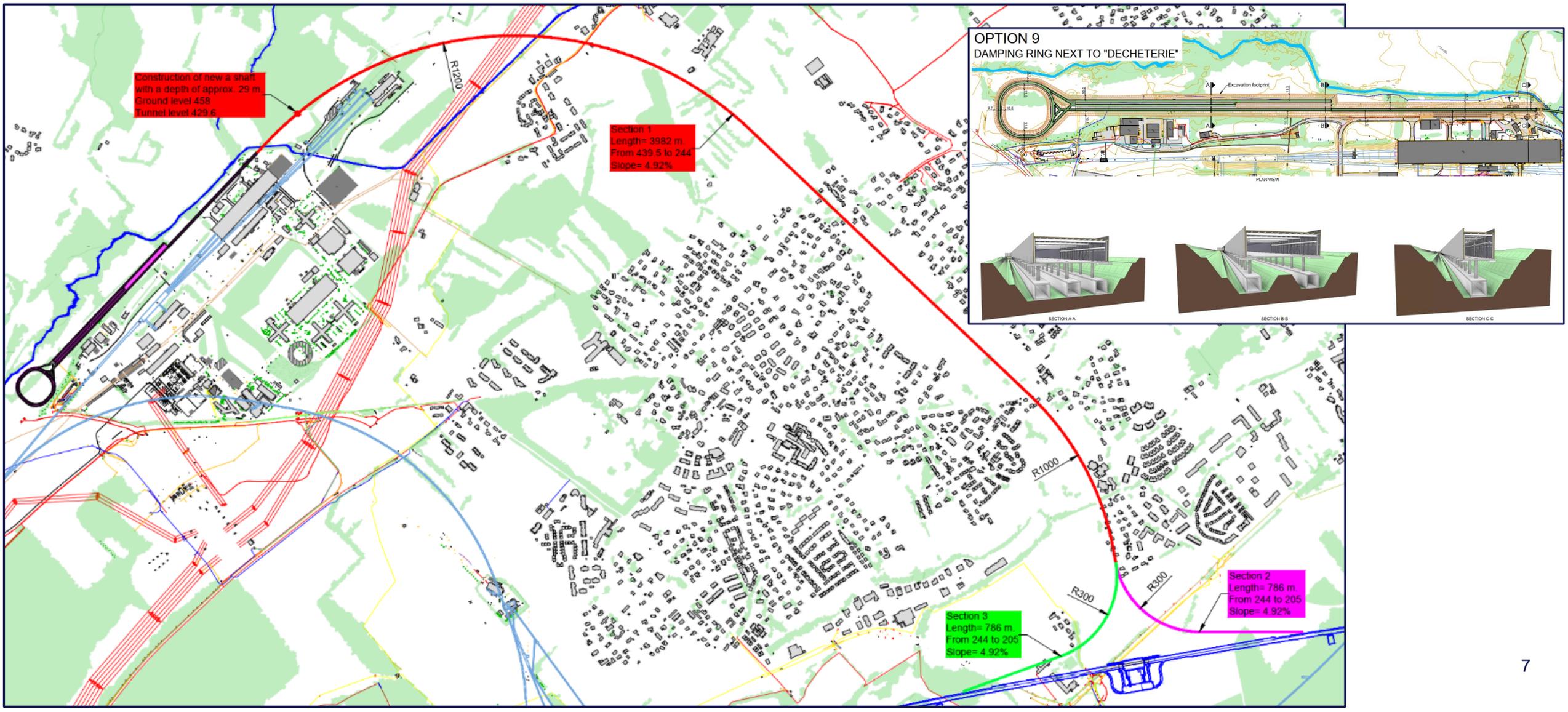


PJ



PL

# FCC-ee injector with HE Linac on CERN Préveessin site (“cut and cover” construction) Transfer Line to Collider PA & possible connection to “North Area” fixed targets



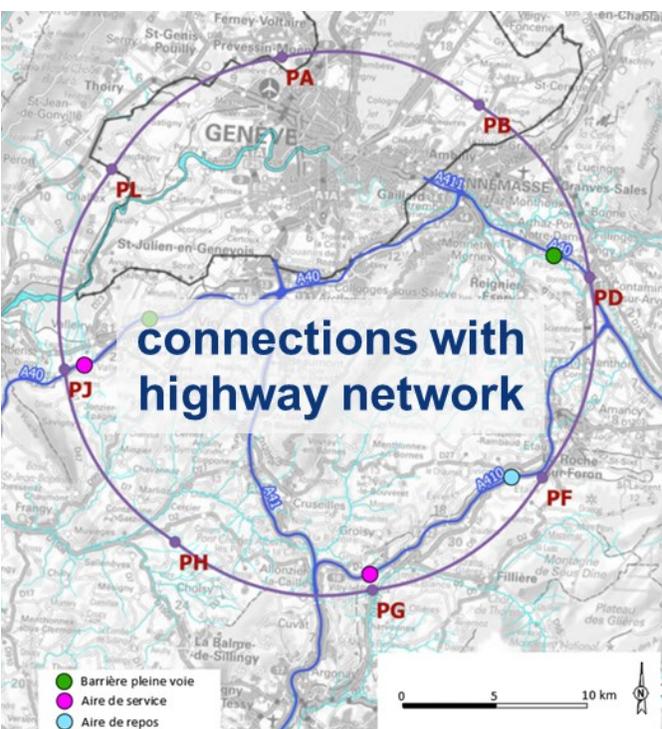
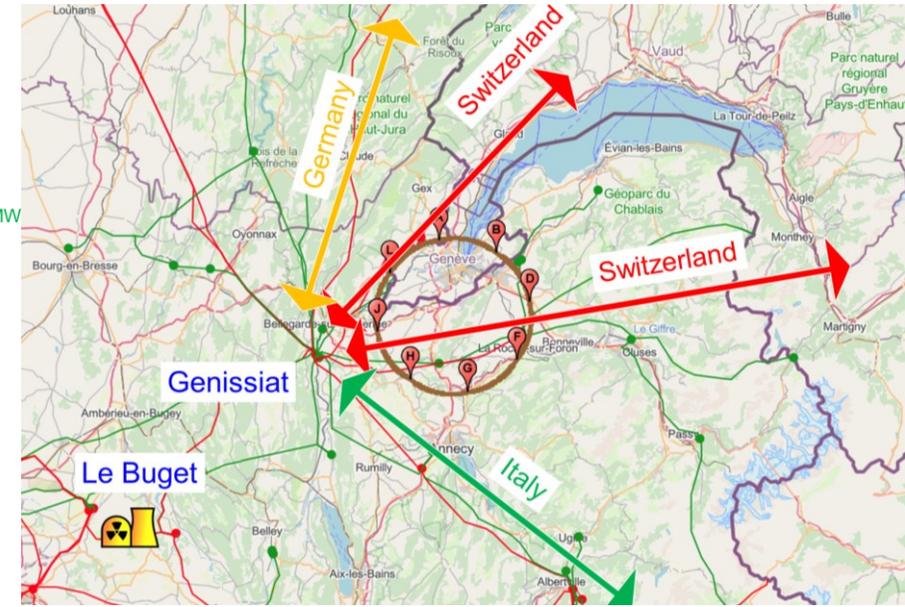
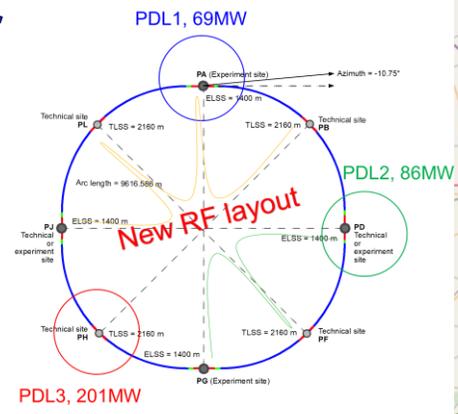
# Resource needs & connections to regional infrastructure

**Electricity consumption 1.1 – 1.8 TWh/year**

Three supply points

- Two new substations from existing HV grid
- Reuse of present CERN station

Feasibility confirmed with RTE (FR operator)



**Road access**

developed for all 8 surface sites

Four possible highway connections defined

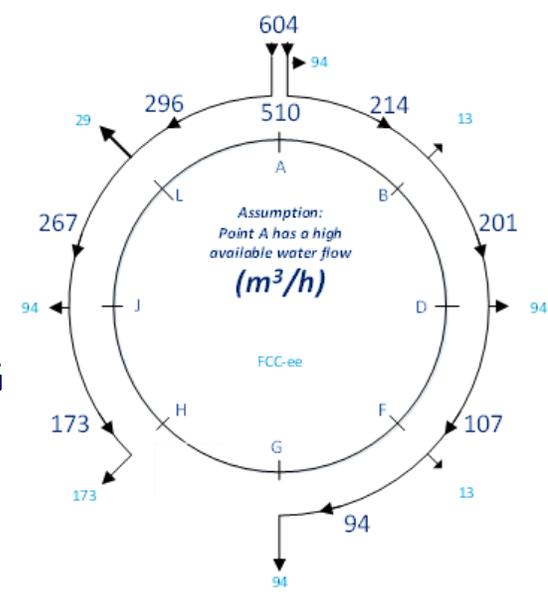
Less than 4 km of new roads required

**Raw water need:**

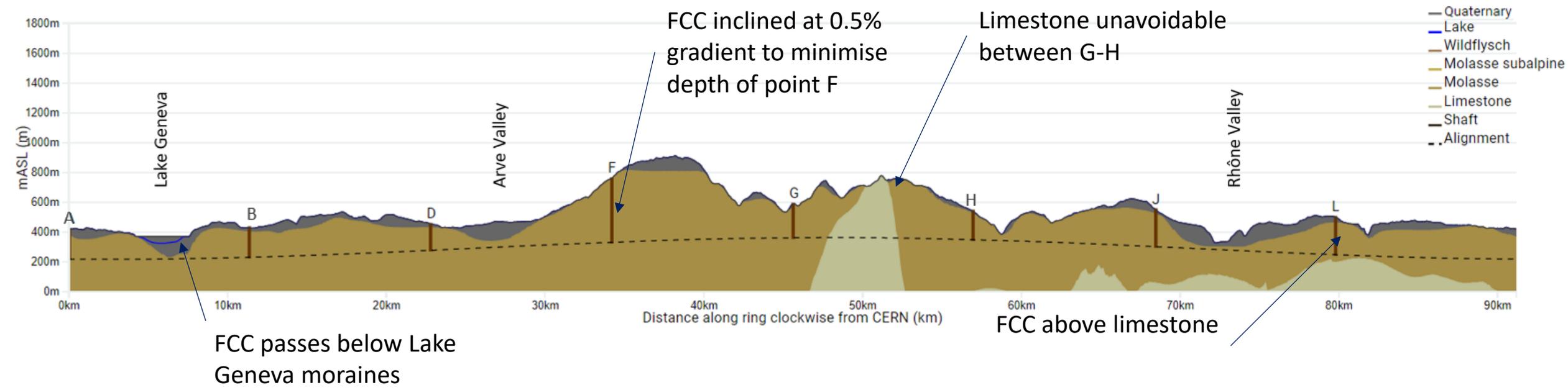
1 – 3 million m<sup>3</sup>/year

Water supply from lake Geneva via existing SIG supply to CERN

Distribution via tunnel



# simplified longitudinal profile of FCC tunnel and geology



**Tunneling mainly in moraine layer (soft rock), well suited for fast, low-risk TBM construction.**

**6 million m<sup>3</sup> excavated volume → 8.5 million m<sup>3</sup> excavation material on surface**

**CE Designs of all underground structures developed**

**Average shaft depth ~240 m**

**To fix the vertical position of the tunnel, interfaces between geological layers must be known**

# FCC – Initial Sub-Surface Investigations

28 boreholes and 80 km of seismics planned between October 2024 and December 2025

## Site investigation results provide:

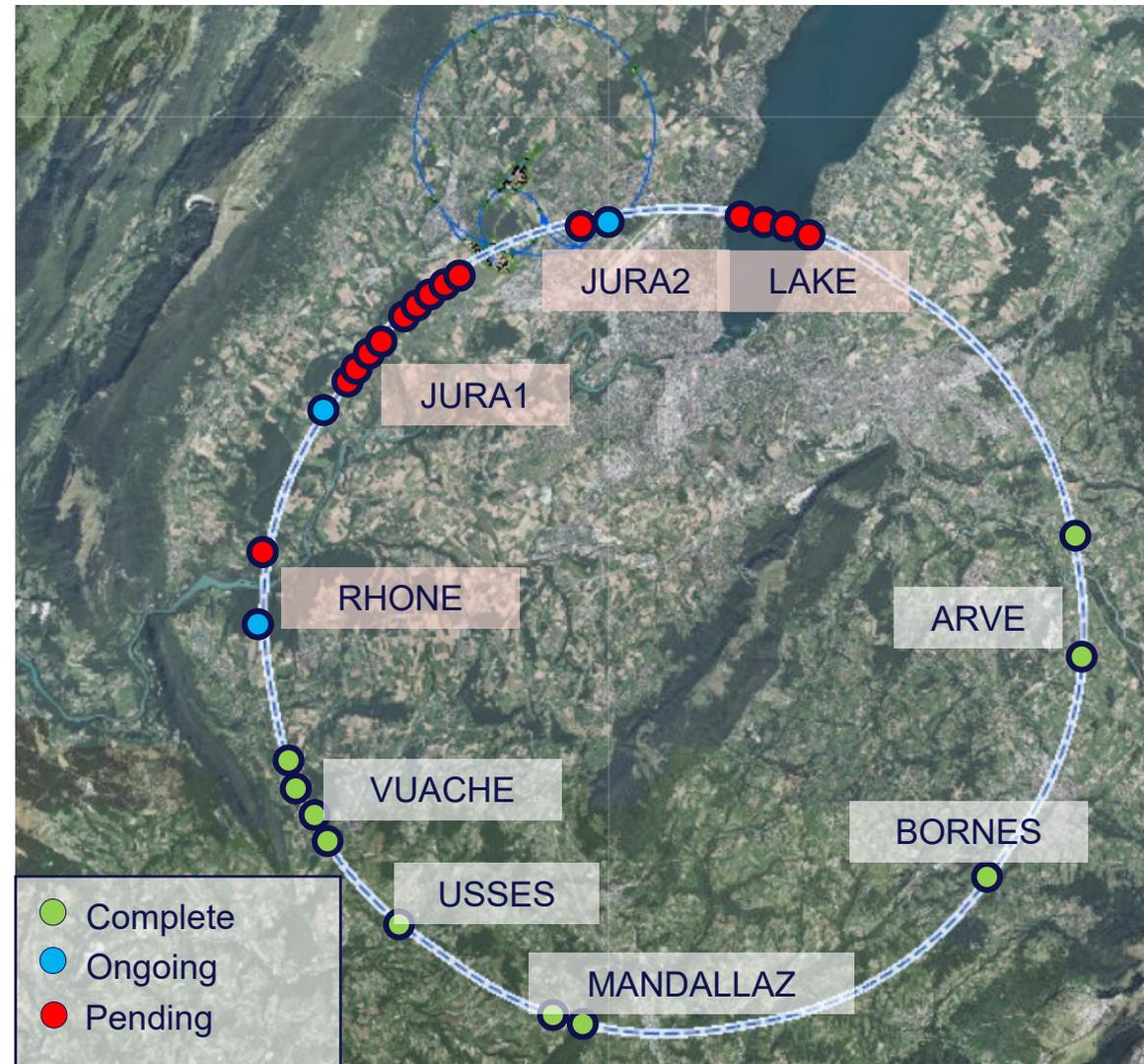
- Locations of geologic interfaces, **permitting to fix vertical position and inclination of tunnel**

## Southern work package status mid May 2025

- Geophysics acquisition & interpretation completed (40 km)
- All drillings completed (logging and testing ongoing)
- Preliminary results positive, confirming 3D geol model
- Limestone passage Mandallaz less extensive

## Northern work package status mid May 2025

- 3 drill sites in France currently active, 2 more to start soon
- Still pending permits for the works in Switzerland



# Stage 1: $e^+e^-$ collider FCC-ee

## Consolidated main parameters

## FCC-ee functional layout

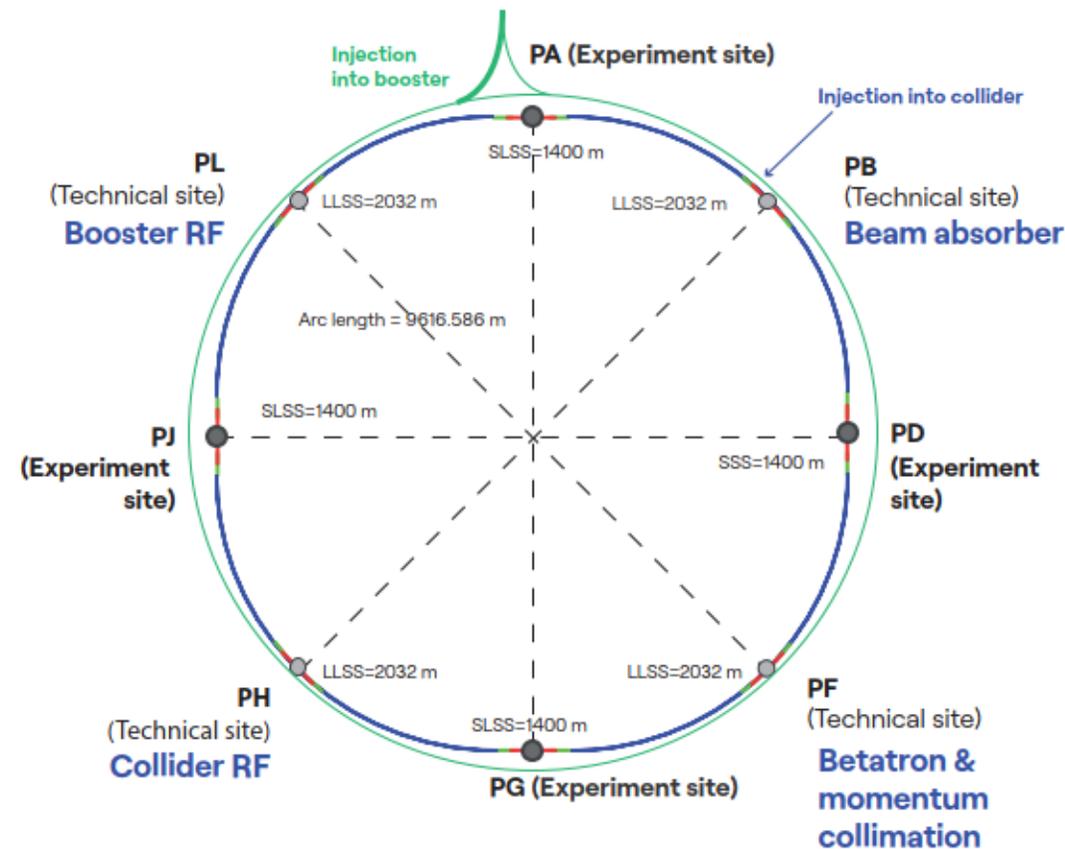
parameter	Z	WW	H (ZH)	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1294	135	26.8	5.1
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	145	20	7.5	1.4
total integrated luminosity / IP / year [ $\text{ab}^{-1} / \text{yr}$ ]	17	2.4	0.9	0.17
beam lifetime [min]	21	13	9	10

4 years  
 $6 \times 10^{12}$  Z  
 LEP  $\times 10^5$

2 years  
 $> 10^8$  WW  
 LEP  $\times 10^4$

3 years  
 $> 2 \times 10^6$  H

5 years  
 $2 \times 10^6$   $t\bar{t}$  pairs



# FCC-ee collider performance

## double ring collider

- many bunches, high current, like LHC and B factories, different from LEP

## top-up injection

- standard at modern light sources, like SLS
- used at recent  $e^+e^-$  colliders, PEP-II (USA), KEKB (Japan), BEPCII (China)

## crab-waist collision scheme

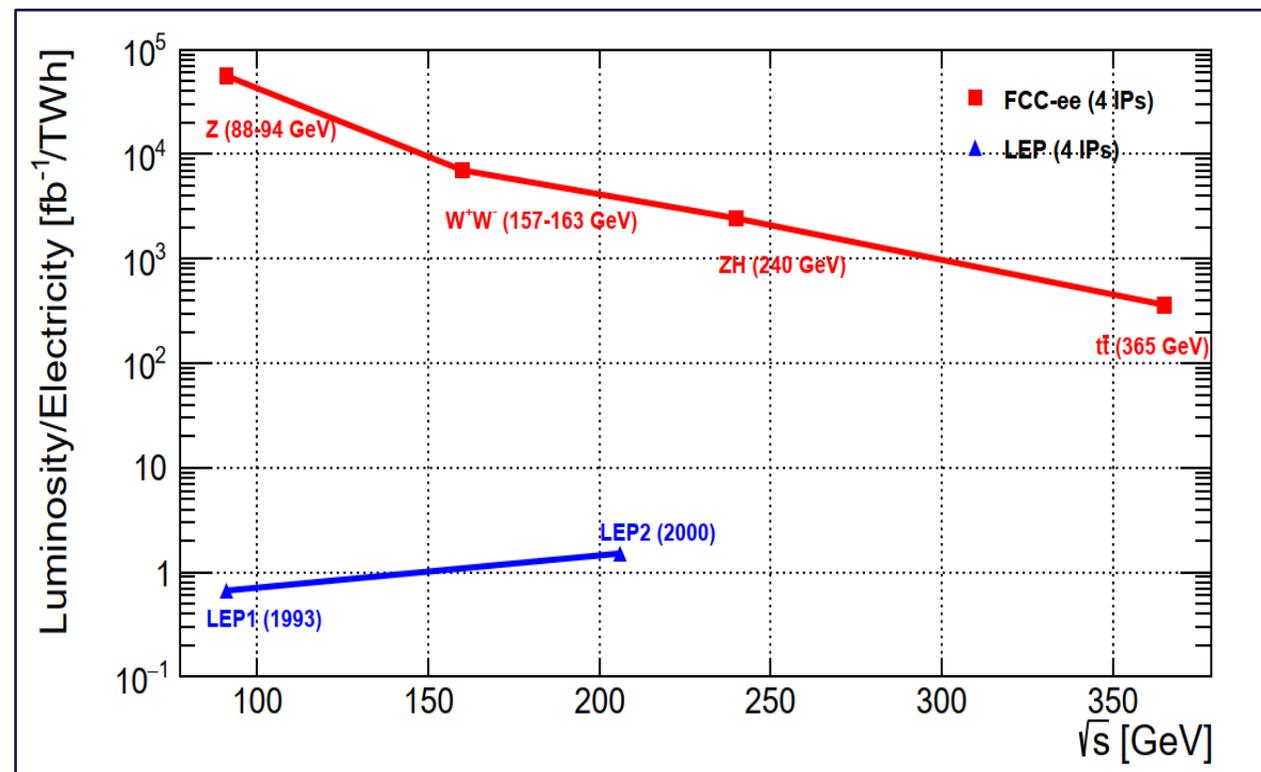
- successfully demonstrated at DAΦNE (Italy) and SuperKEKB (Japan)

## superconducting radiofrequency system

- Nb/Cu 400 MHz SC cavities pioneered at former CERN LEP
- bulk Nb 800 MHz SC cavities similar to ESS (Sweden), EuXFEL (Germany)
- revolutionary highly efficient RF power sources
- new operation scheme for flexible energy switching & reduced complexity

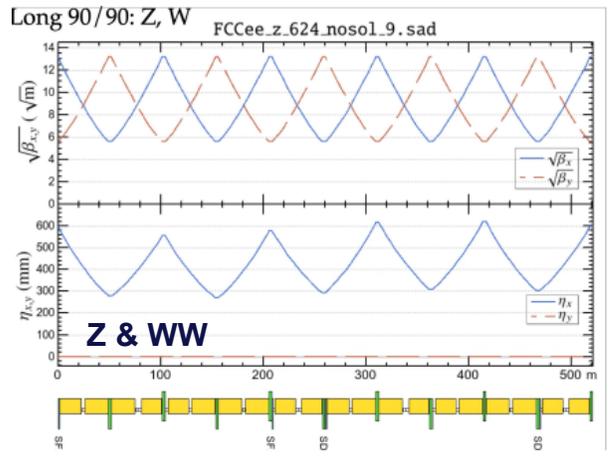
Combining concepts from past and present lepton colliders results in a giant step in efficiency:

→  $10^4 - 10^5 \times$  luminosity/energy of LEP  
 → sustainable physics

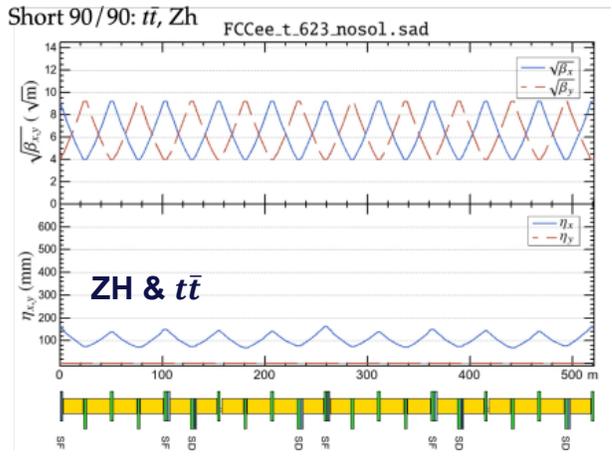


# FCC-ee optics baseline GHC

arc

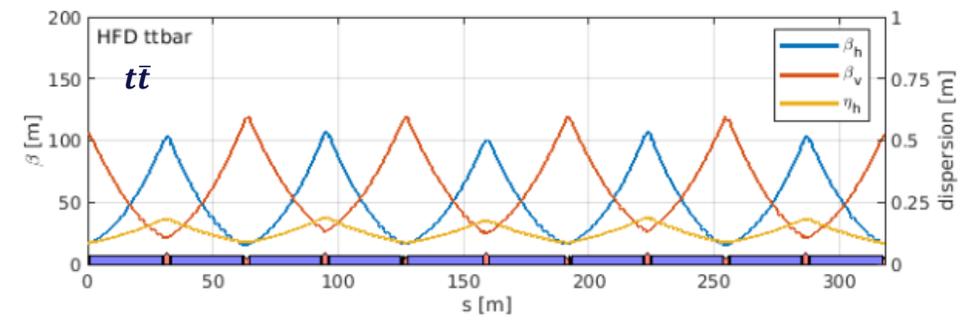


K. Oide et al.

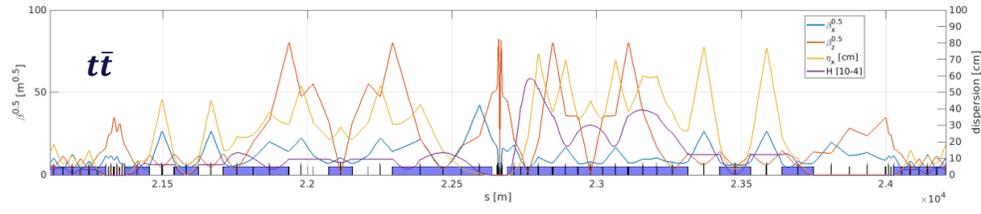
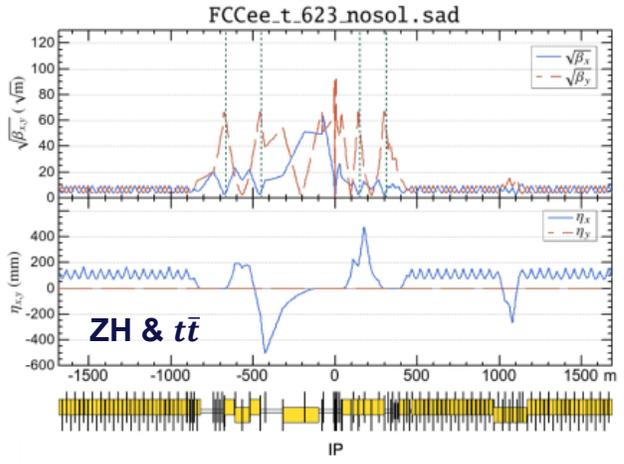
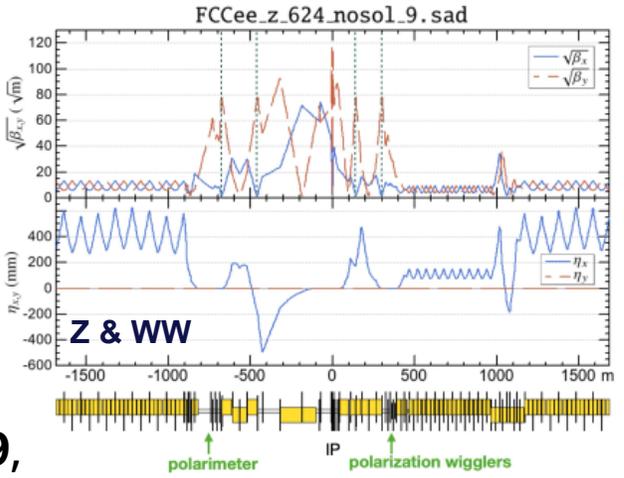


# alternative LCC

P. Raimondi, S. Liuzzo, et al.



experimental straight

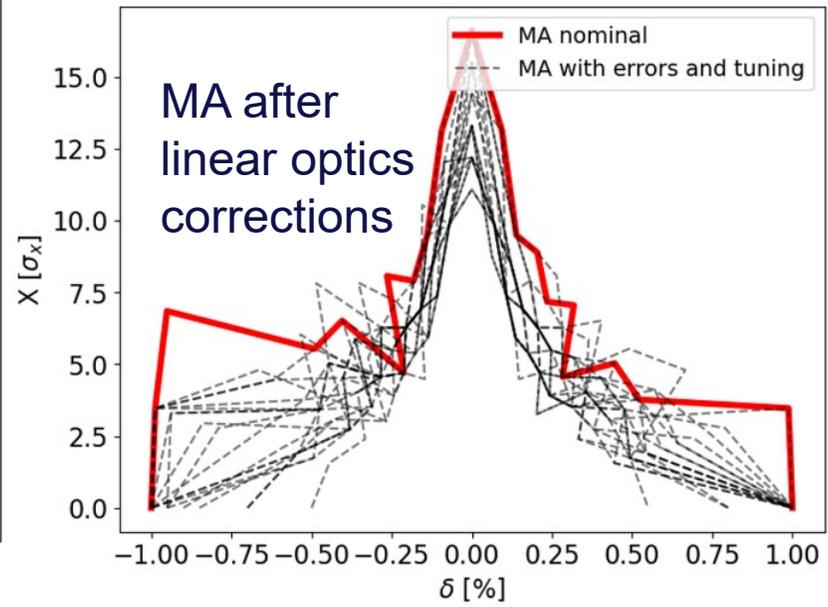
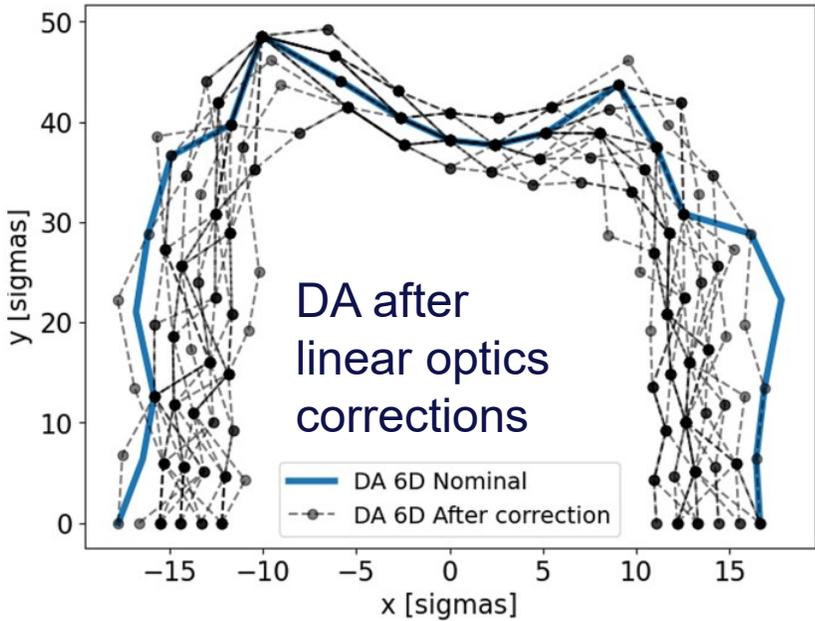


PRAB 19,  
111005 (2016)

PRAB 28,  
021002 (2025)

→ March 2026: Decision on Optics G. Roy, S. Kostoglou

# dynamic aperture & arc tolerances

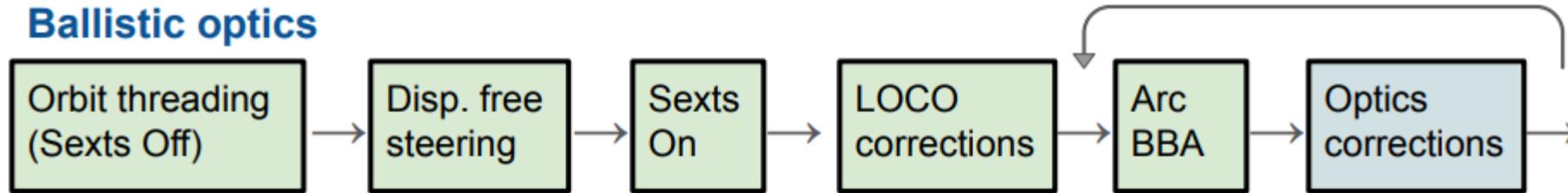


Element	$\sigma_{x/y}$ [ $\mu\text{m}$ ]	$\sigma_{\theta/\psi/\phi}$ [ $\mu\text{rad}$ ]	$\Delta k/k$ [ $10^{-4}$ ]
Arc quads & sext.	50	50	2
Dipoles	1000	1000	2
Girders	150	150	-
BPMs-to-quad	100	-	-

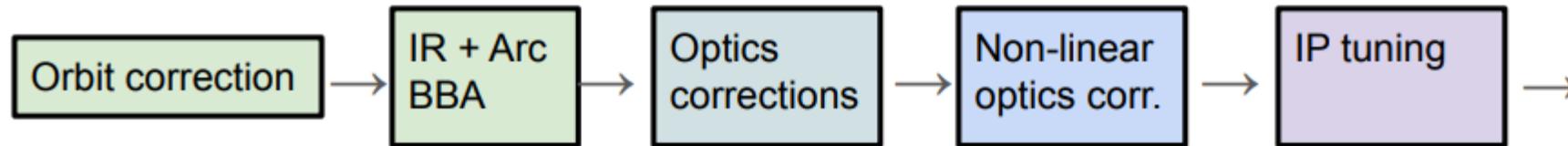
Arc alignment and strength tolerances

# optics commissioning sequence

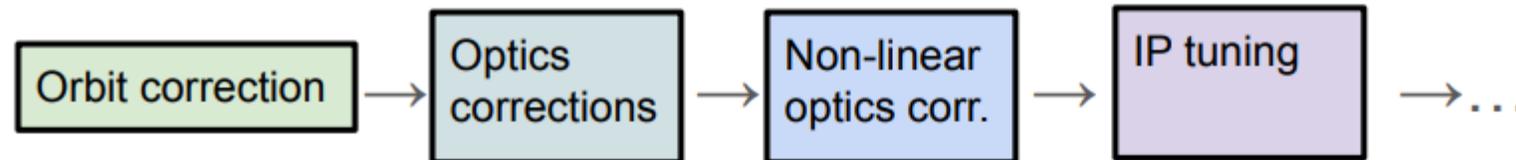
## Ballistic optics



## Relaxed optics (various iterations decreasing $\beta^*$ )



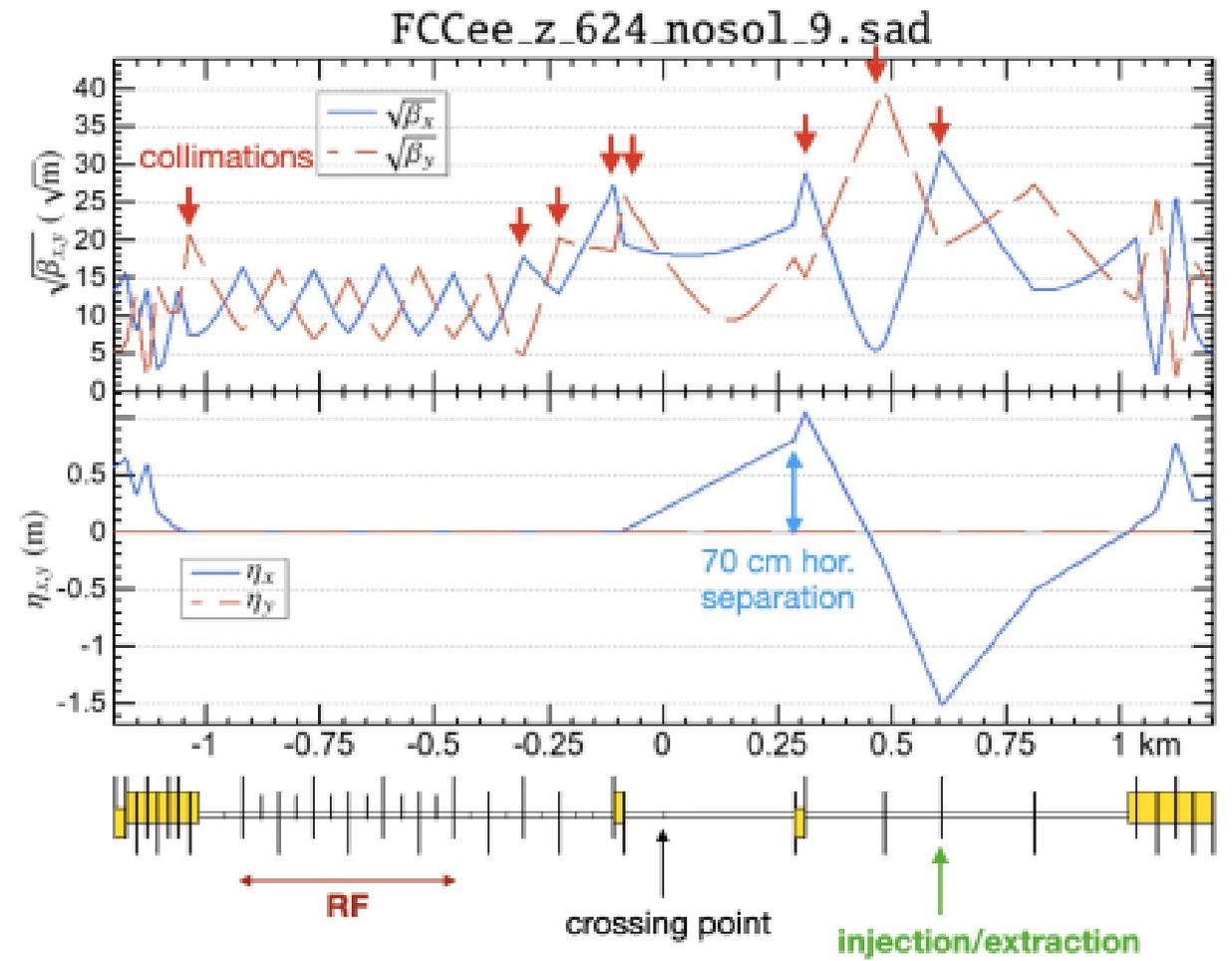
## Baseline optics



# universal optics for technical straights

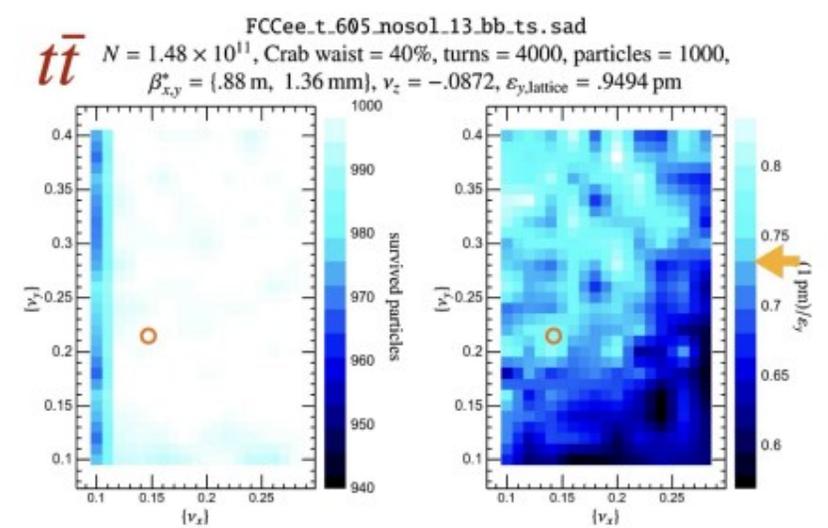
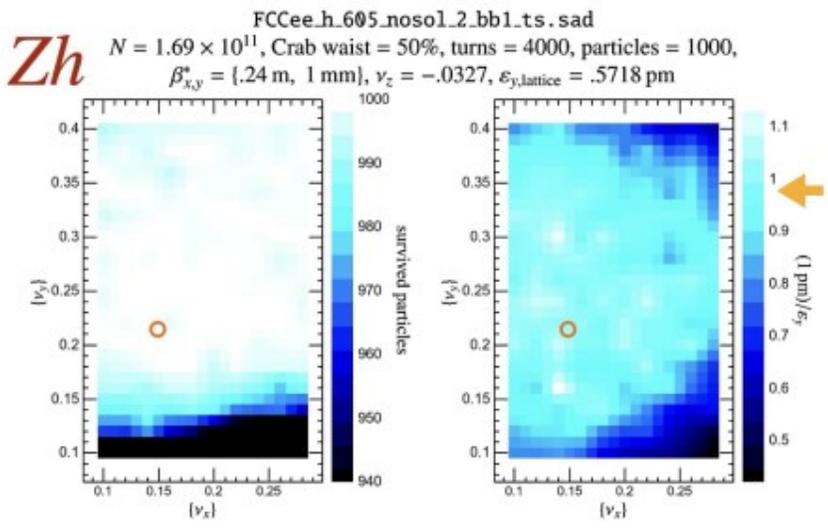
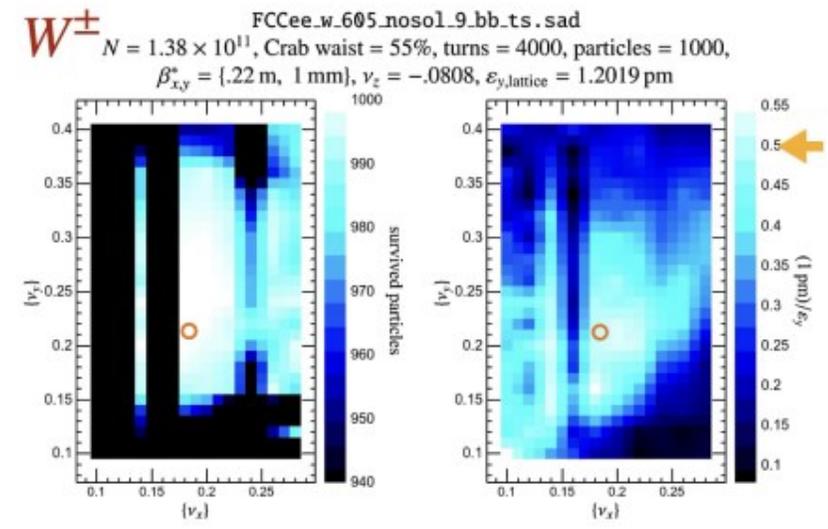
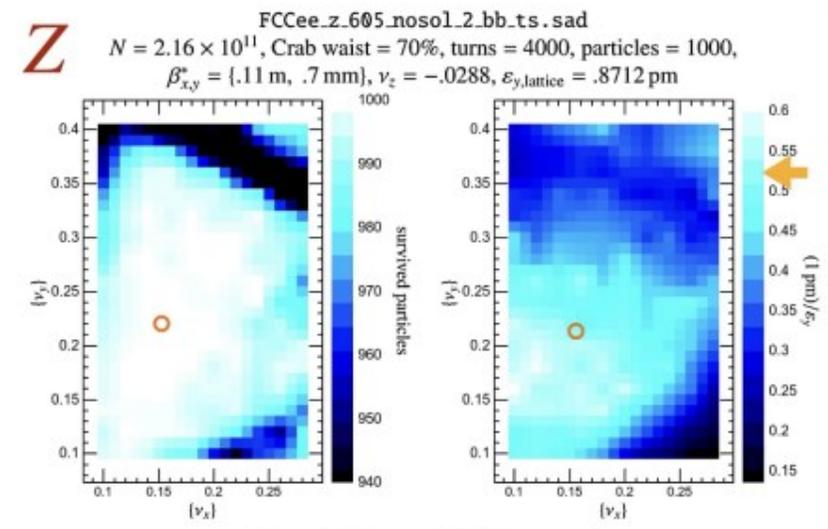
K. Oide

for all technical insertions in Z/W operation: RF, injection/extraction, & collimation



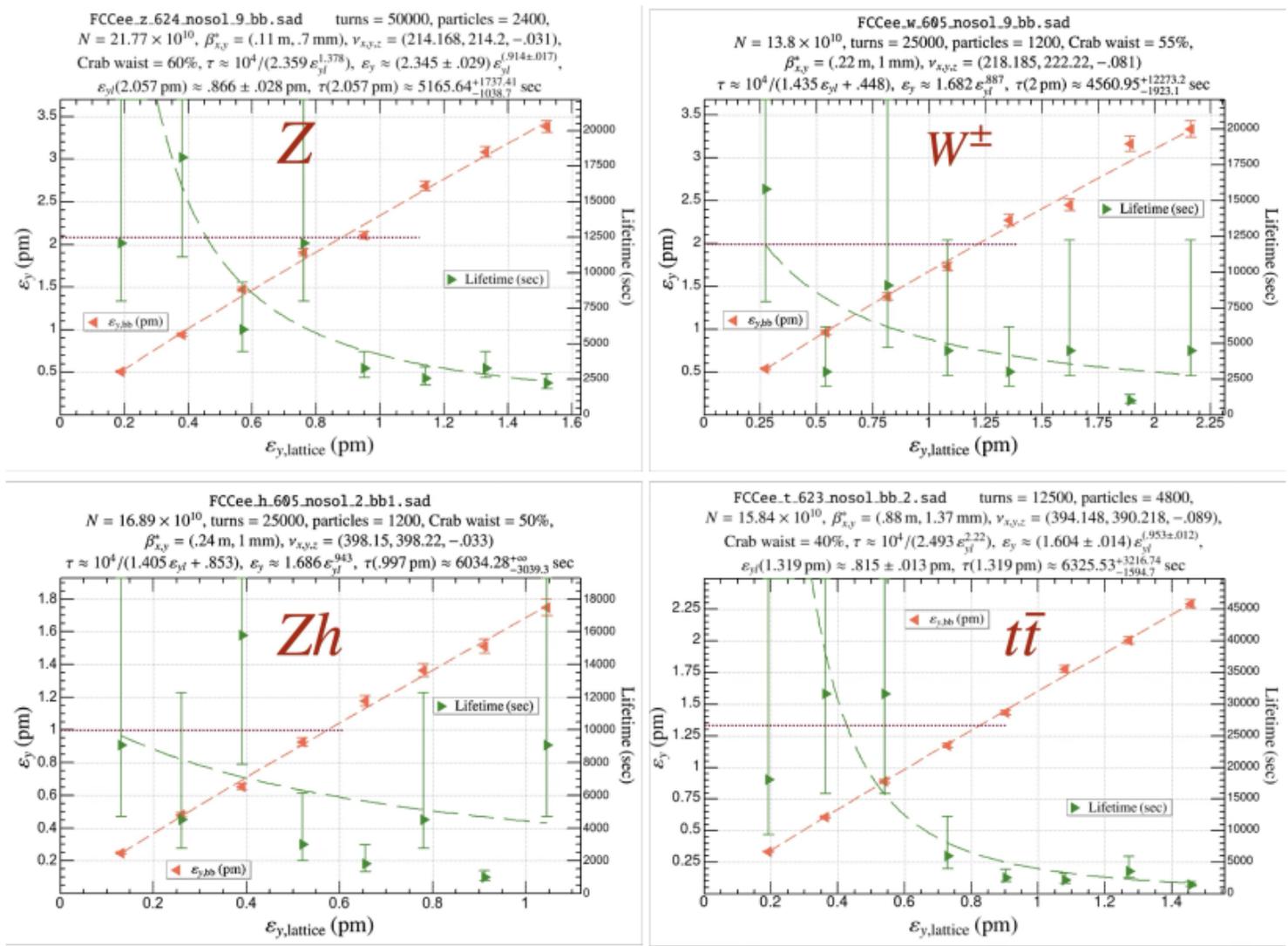
maintaining perfect superperiodicity

# beam-beam performance with full lattice



tune scan of the beam-beam effect with the full lattice

# vertical bare lattice emittance required with beam-beam



results of beam-beam tracking with lattice and beamstrahlung for each energy

# FCC design with Xsuite



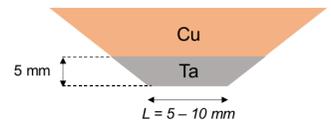
G. Iadarola

tutorials in form of Jupyter notebooks

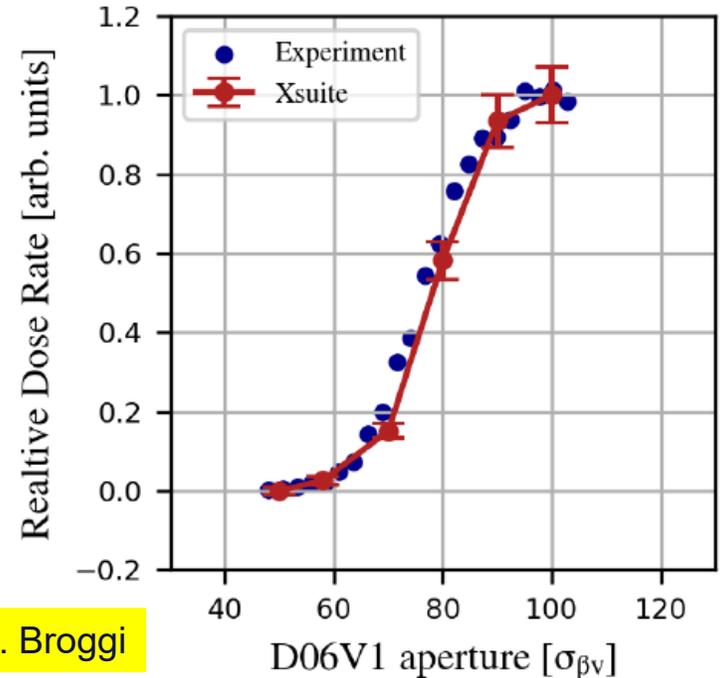
# + SuperKEKB benchmarks

G. Broggi, J. Salvesen, G. Iadarola, H. Sugimoto, K. Oide

Touschek & beam-gas scattering for different collimator settings, including collimator-matter interaction



Xsuite-simulated response of Belle-II diamond detector:



G. Broggi

# spin tracking newly implemented in Xsuite !

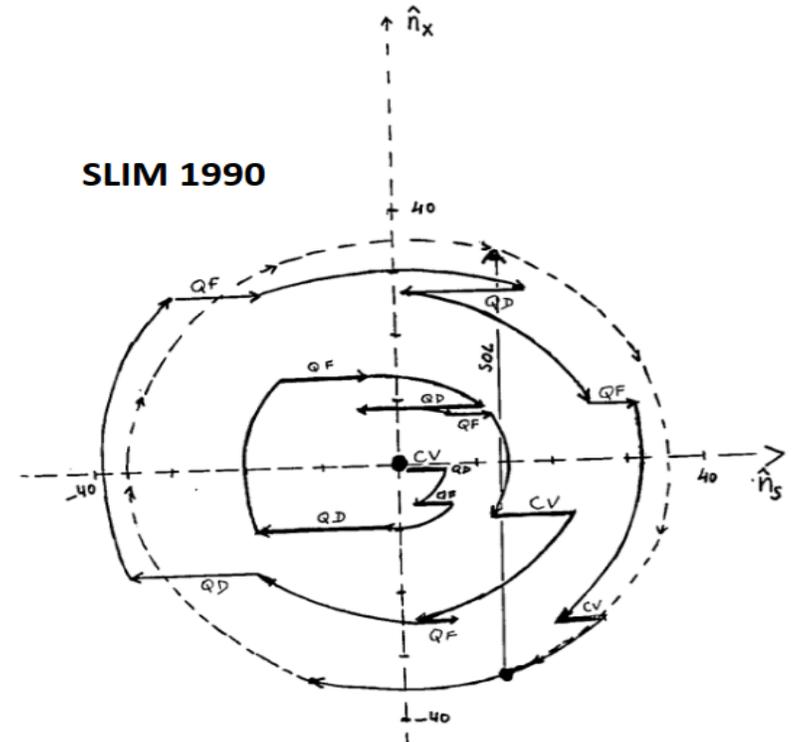
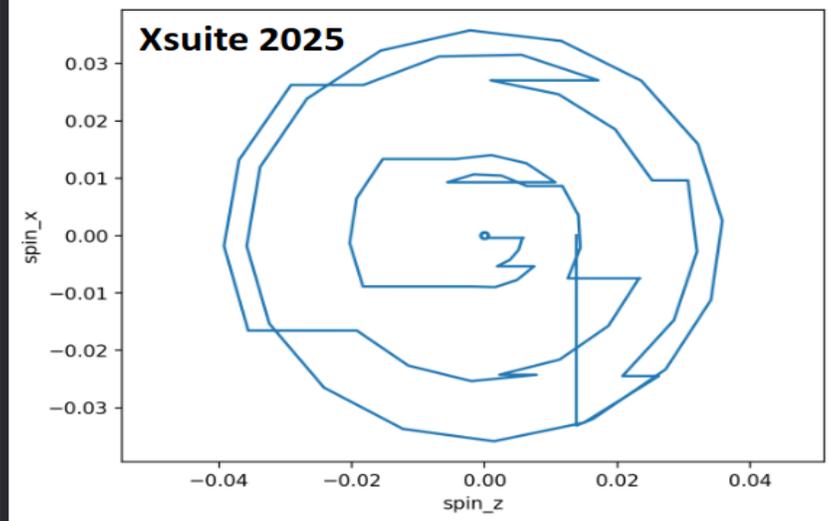
collaboration with BNL EIC project

tests,  
benchmarking,  
and first simulation  
studies ongoing



...and against 35-year-old SLIM simulation

Studied the case of LEP1 with orbit bumps to compensate precession in the solenoids



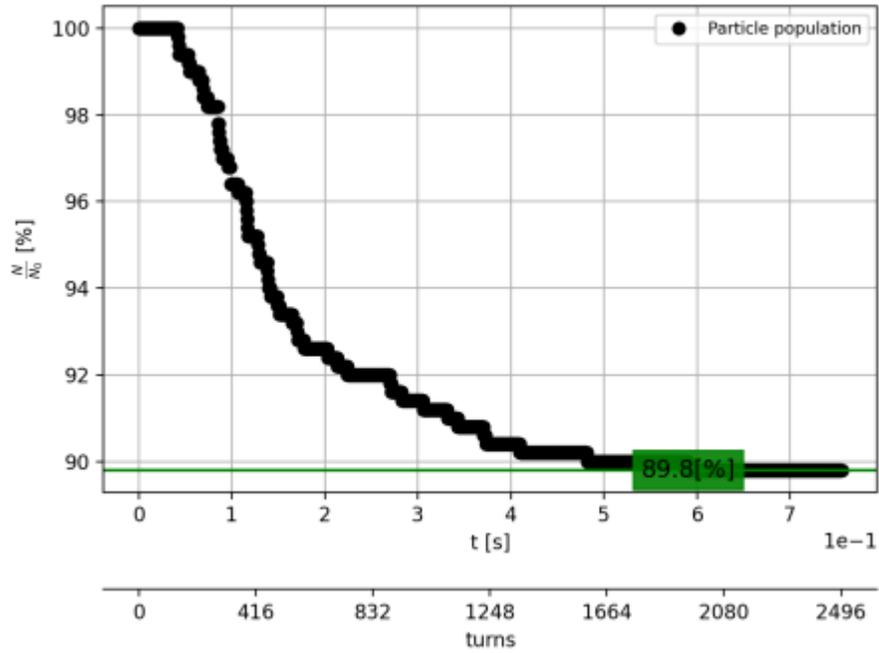
Compensation of Integer Spin Resonances Created by Experimental Solenoids

Alain Blondel  
L. P. N. E. E., Ecole Polytechnique, 91128 Palaiseau Cedex, France  
22 April 1990

G. Iadarola,  
K. Hock,  
Y. Wu,  
J. Keintzel,  
J. Wenninger

Many thanks to J. Wenninger and Y. Wu for their input and guidance!

# top-up injection



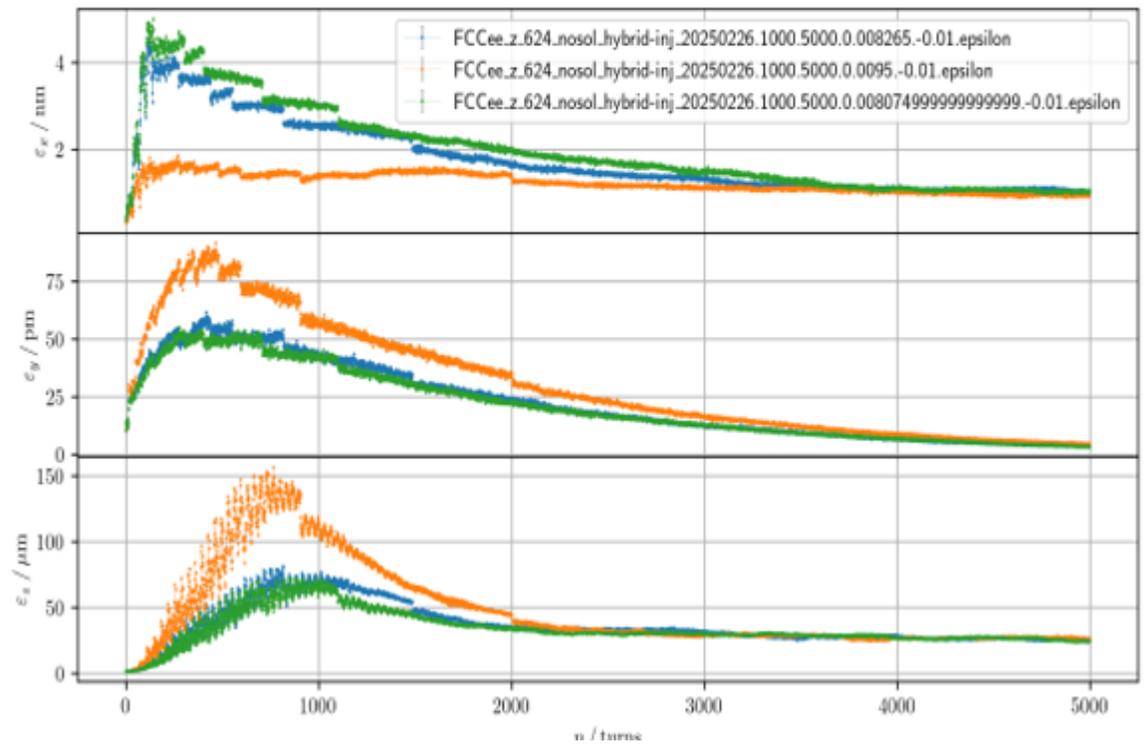
injection efficiency ~90%  
including beam-beam, beamstrahlung and chromatic matching

w/o beam-beam 100%

# hybrid injection

## Emittances

Vertical size reduction with momentum difference reduction

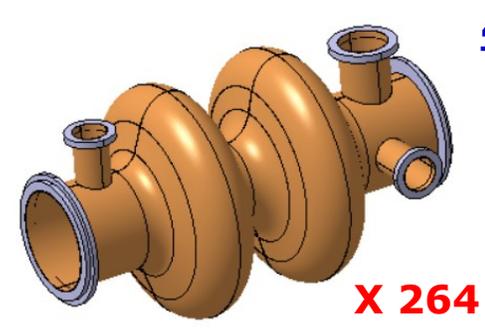


$\delta = 0.0095, 0.008265, 0.008075$

$z \equiv -0.01$  m: optimum  $z$  might be different



# superconducting RF system – key technology, R&D

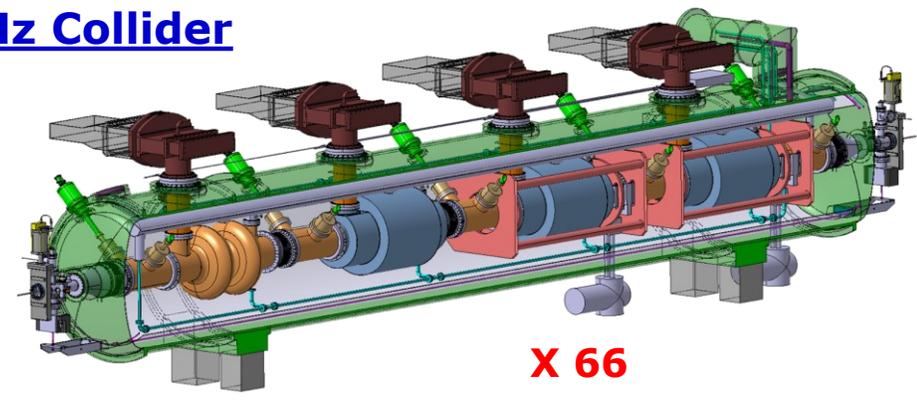


X 264

## 400 MHz Collider

### Superconducting elliptical cavity

- 400 MHz, 2-cell, copper Nb coated
- 1.5 m. long



X 66

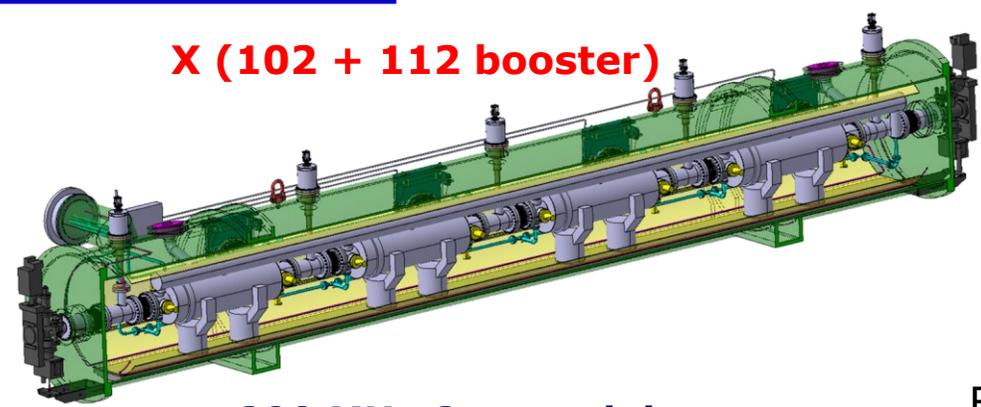
## 400 MHz Cryomodule

## 800 MHz Collider + Booster

X (408 + 448 booster)



X (102 + 112 booster)

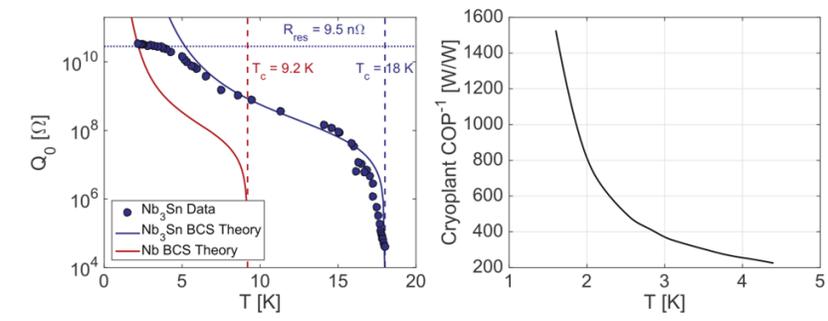


## 800 MHz Cryomodule

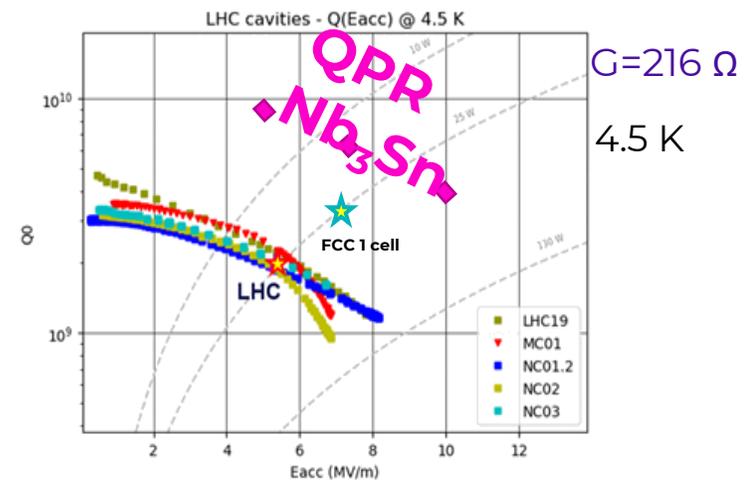
### Superconducting elliptical cavity

- 800 MHz, 6-cell, bulk Nb
- Nb<sub>3</sub>Sn if R&D is successful

## Nb<sub>3</sub>Sn on Cu coating



Move from Nb @2K to Nb<sub>3</sub>Sn @4.5 K would reduce cryogenic power by factor 3

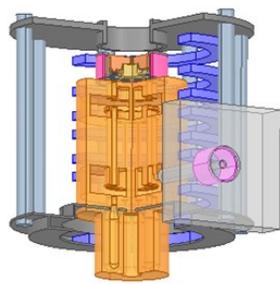


Equivalent to a Q of  $9 \times 10^9$  @5 MV/m @4.5 K  
 Almost 1 order of magnitude better than LHC!  
 Room for improvement

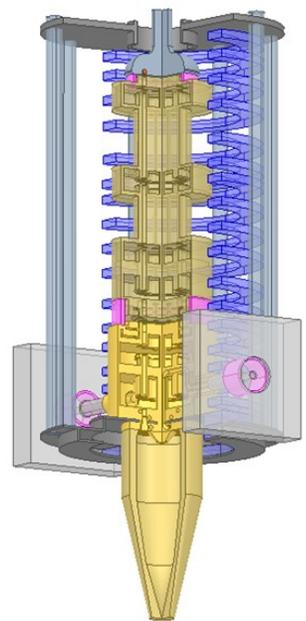
# efficient RF power source

## MB tristron – compact !

MB Tristron (concept)



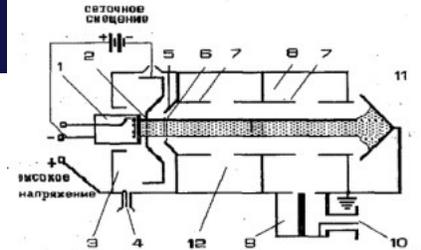
MB TS Klystron (design)



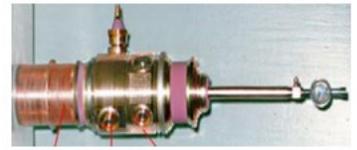
TH2167 HE klystron (prototype)



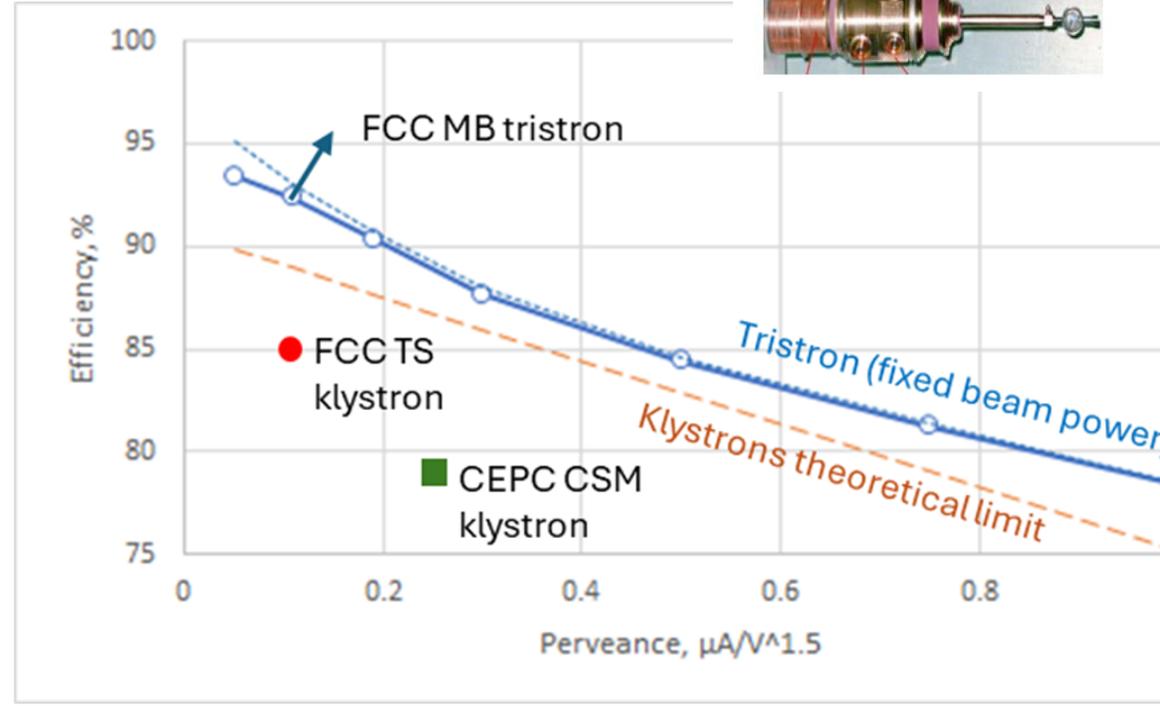
I. Syratchev



Tristron (A.D. Sushkov et. al. 1967)  
MB Prototype tested in 1997, V. Tsarev:



## MB tristron – efficient !



- **Very efficient: >90%**, Low Voltage: <50kV
- **Compact: ~ 1m<sup>3</sup>, Cost effective** (w.r.t. klystron)



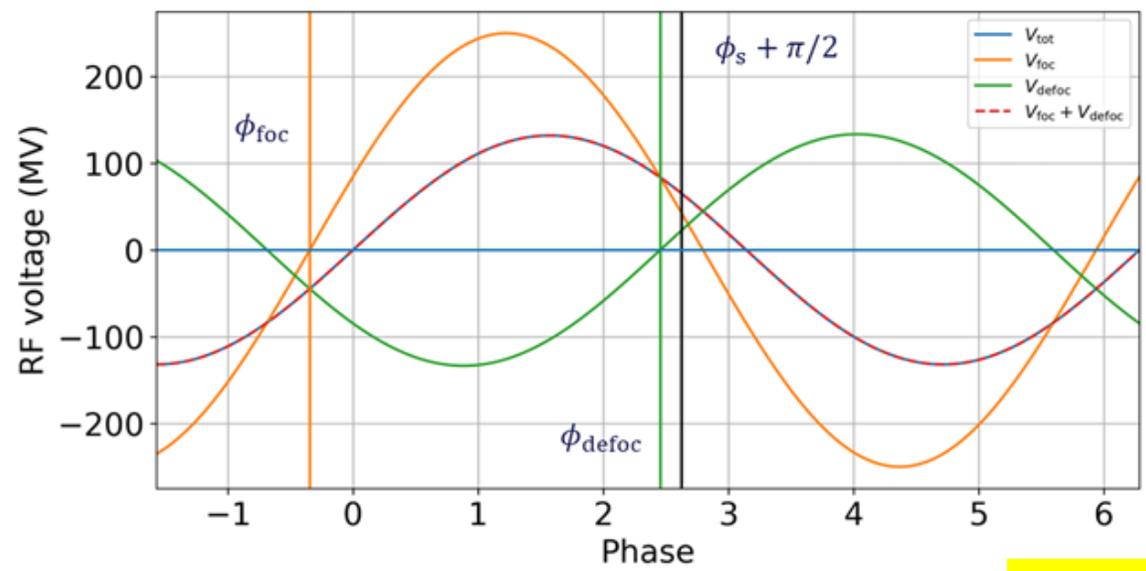
# Different running modes

	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1283	0.079
W	80	135	1.05
H	120	26.7	2.1
t $\bar{t}$	182.5	5	11.67

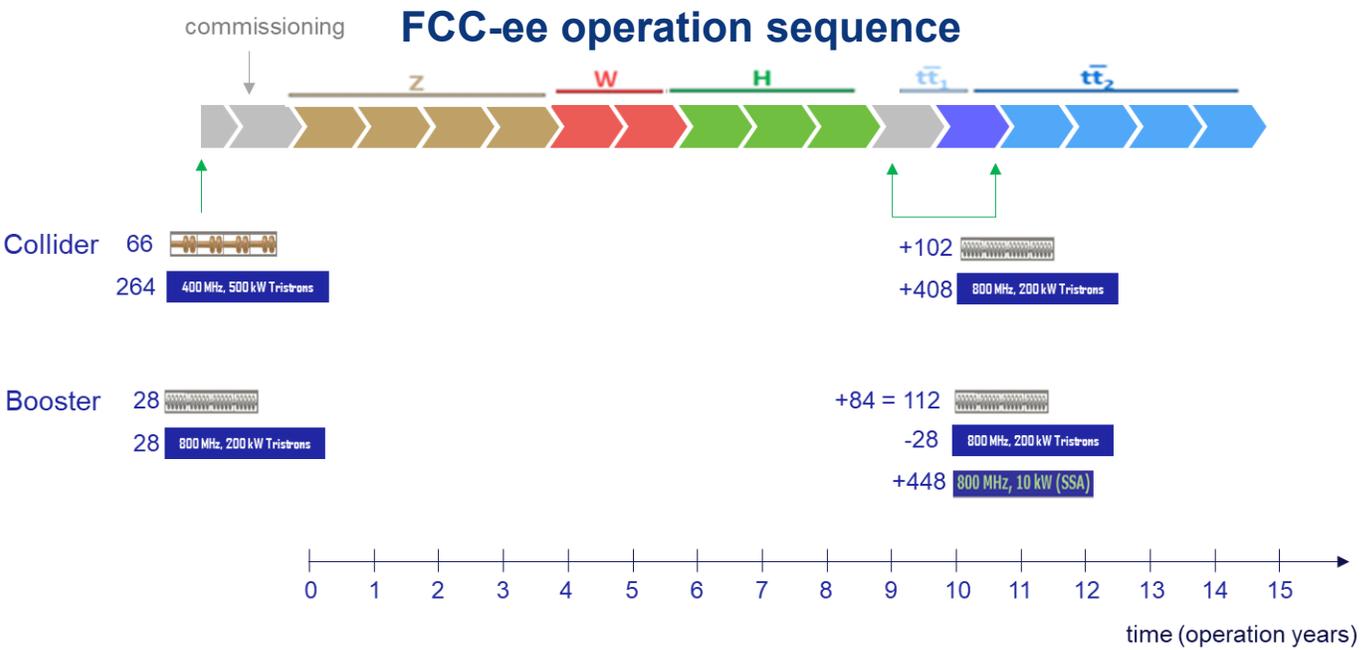
Reverse phase operation (RPO) mode allows increasing RF cavity voltage (Y. Morita et al., SRF, 2009)

- Experimentally verified with high beam loading in KEKB (Y. Morita et al., IPAC, 2010)
- Baseline solution for EIC ESR (e.g., J. Guo et al., IPAC, 2022)

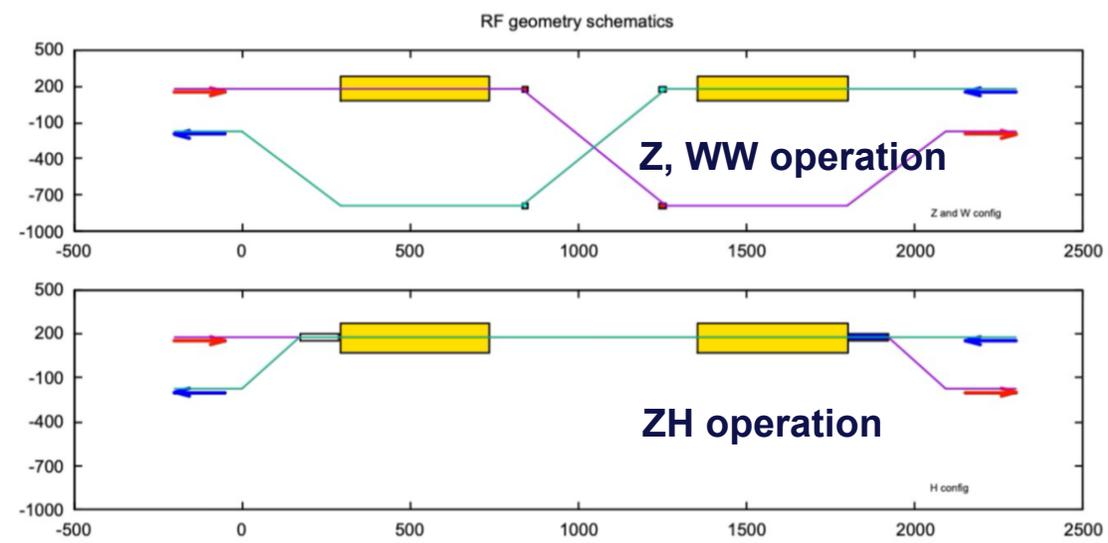
# RF reverse phase operation



# FCC-ee operation sequence and SRF concept

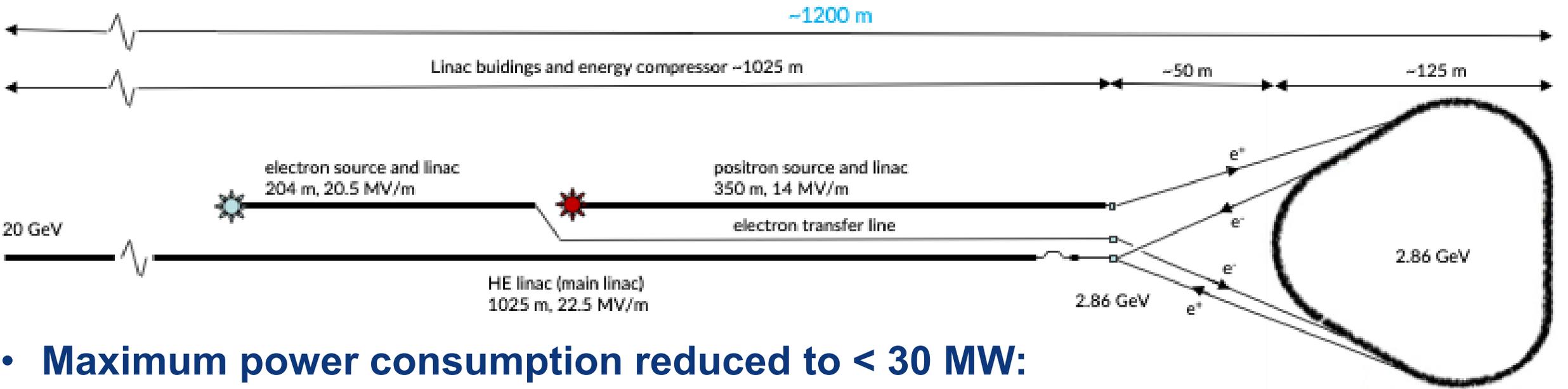


## 400 MHz RF layout and beam switching



- **2-cell 400 MHz SRF system for Z, W and ZH**, entire system installed at operation start  
Constant cavity coupling thanks to **reverse phase operation at Z**
  - **Flexibility for switching between Z, WW, ZH operation**
  - Suppression of the single-cell 400 MHz system
  - Reduced R&D, installation, commissioning, etc...
- **6-cell 800 MHz SRF system for  $ttbar$  operation in collider, and for booster at all modes**

# Optimised FCC-ee injector design

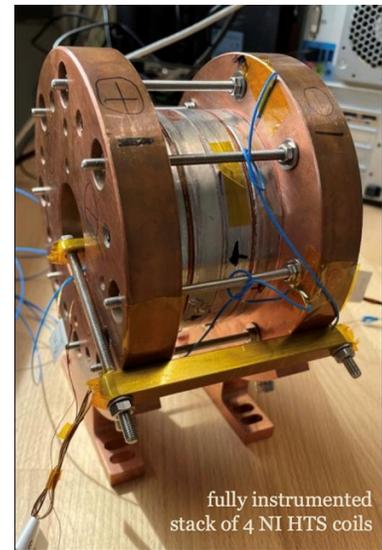


## • Maximum power consumption reduced to < 30 MW:

- new accelerating structures with higher shunt impedance;
- lower gradient (29.5 MV/m → 22.5/20.5 MV/m);
- lower repetition rate (200/400 Hz → 100 Hz).

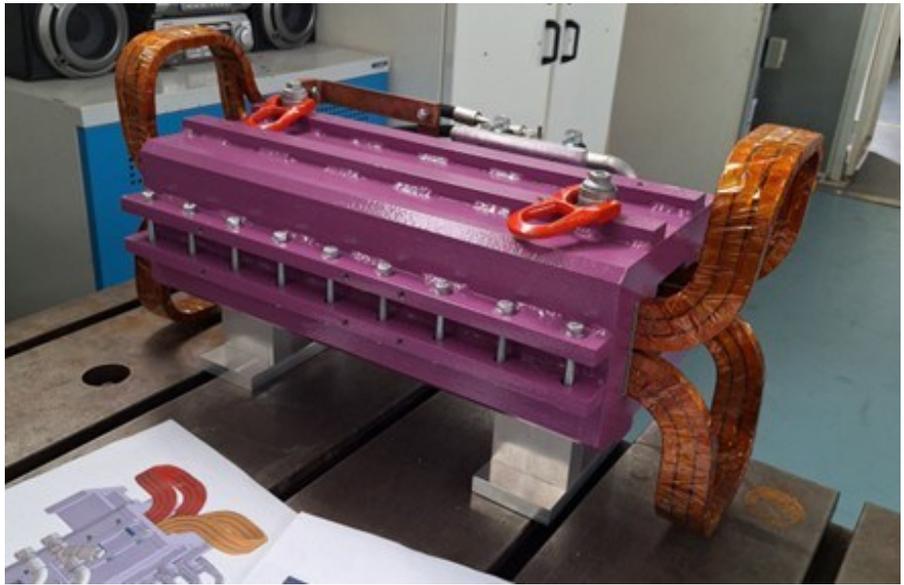
## • Novel positron source

- HTS solenoid (15 T on axis, tested 18 T @ 12 K)
- proof-of-principle beam tests at PSI SwissFEL from 2026

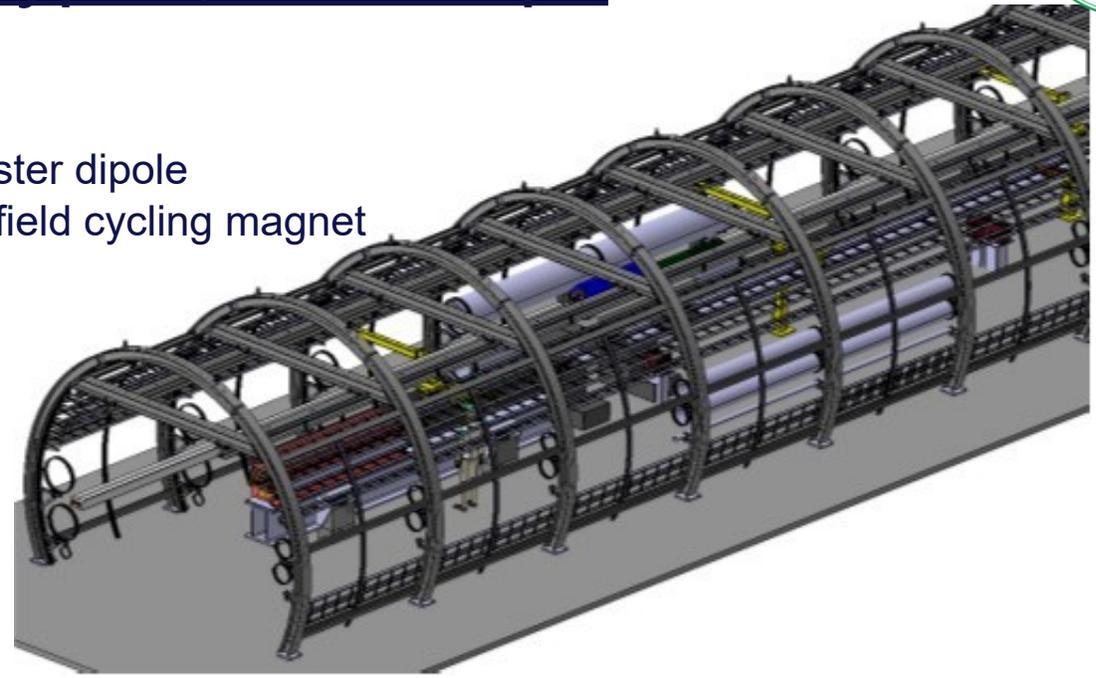




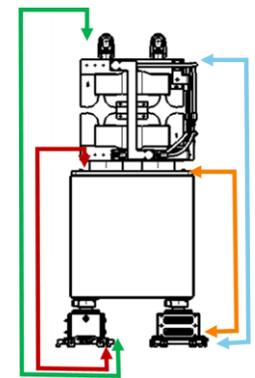
# arc magnets, girders, prototypes, mock-ups



Booster dipole  
low-field cycling magnet



**Arc half-cell =**  
the most repeated  
component of  
mechanical  
hardware in the  
tunnel: → 77 km  
over 90 km are  
arc cells



Vibration studies with girder on PSI jacks



**Goal:** → arc half-cell mock-up to test aspects related to:

- Transport
- Integration
- Assembly
- Stability inspection
- Fabrication, machining capabilities, etc.
- Installation
- Alignment
- Maintenance
- Safety

**Interaction Region mock-up**  
under construction in Frascati

central chambers, back  
from e-beam-welding in UK ;  
will be used for paraffin test



# other FCC-ee science opportunities

large circumference, high energy, abundant positron production, low-emittance beams, high-power beamstrahlung, injector complex

→ FCC-ee offers unique opportunities for various other fields of physics and science

## Examples:

- production of **true muonium**
- creation of a **Bose-Einstein condensate of positronium**
- **high(est)-energy photons**, Compton imaging, nuclear research etc.
- **spatially coherent photon beams**, possibly down to **0.1 Å wavelengths**
- **higher average and peak brightness** than any existing or planned light source
- **radioactive isotope production**
- **neutron source**

## **Other Science Opportunities at the FCC-ee**

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<sup>11</sup>ETH Zürich, Zürich, Switzerland

<sup>12</sup>University of the Bundeswehr Munich, Neubiberg, Germany

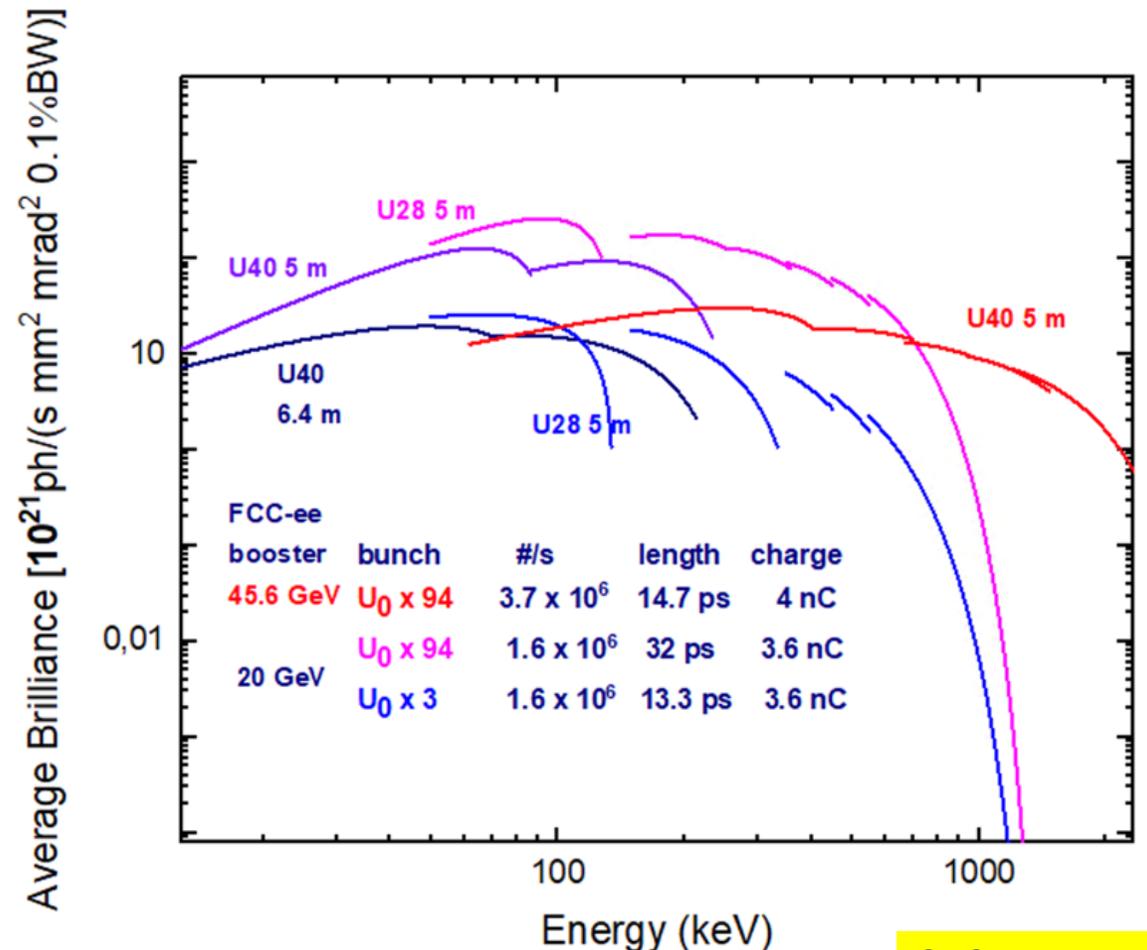
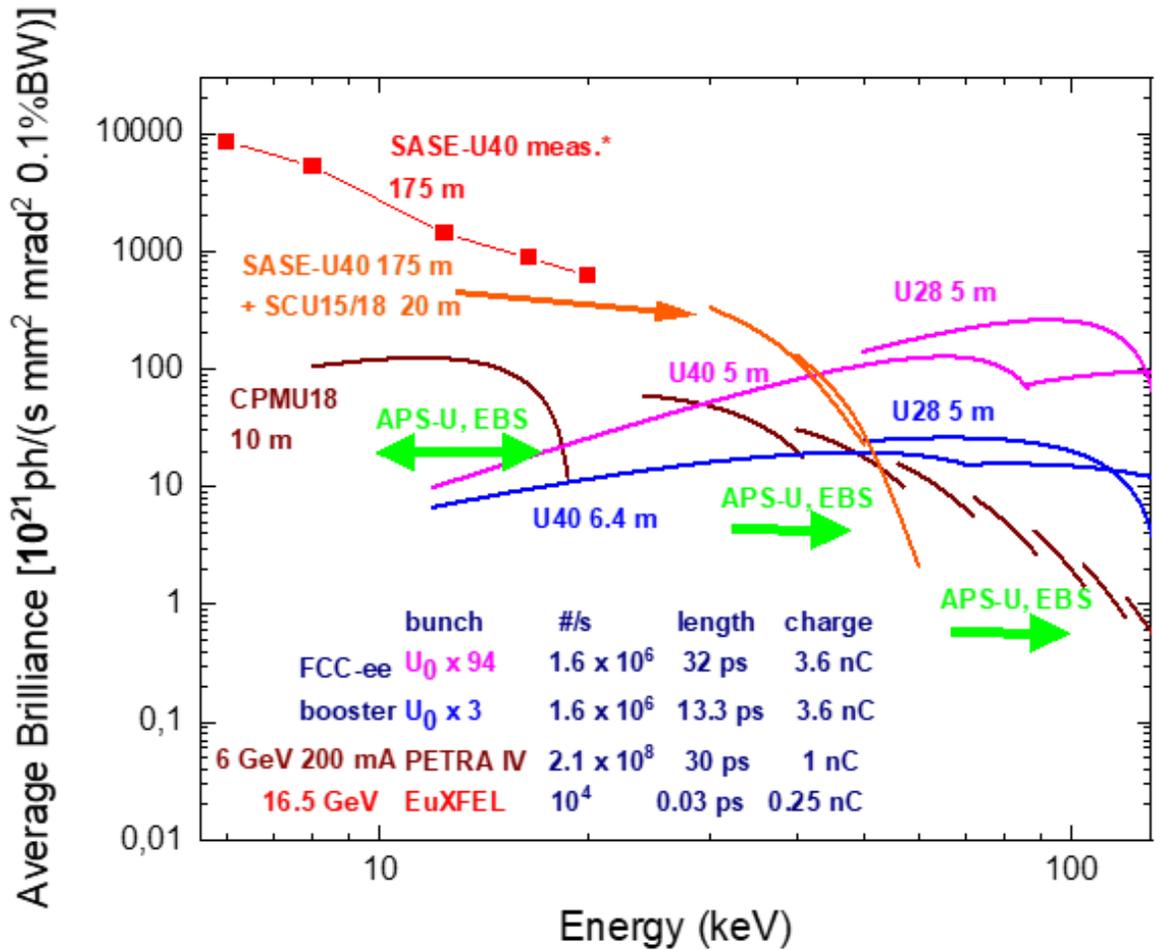
<sup>13</sup>INFN Milano, Milano, Italy

<sup>14</sup>IJCLab, Orsay, France

..

CERN-FCC-ACC-2025-0005,  
doi: [10.17181/CERN.BSP4.H8ED](https://doi.org/10.17181/CERN.BSP4.H8ED)

# FCC-ee booster as unique ultimate photon source



S. Casalbuoni

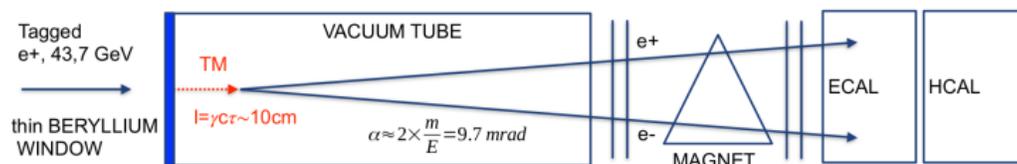
case for  $\geq 20$  GeV storage-ring light source: PRAB 28, 024401 (2025); arXiv:2505.11022 (last month!)

*“we argue that achieving further significant emittance reduction and increase in radiation brightness is only possible by increasing the beam energy”*

I. Agapov  
S. Antipov

# producing true muonium – a world’s first !?!

assuming  $\Delta E \sim 44$  MeV, one can expect to produce around 1 TM atom per  $4.4 \times 10^{13}$  positrons.

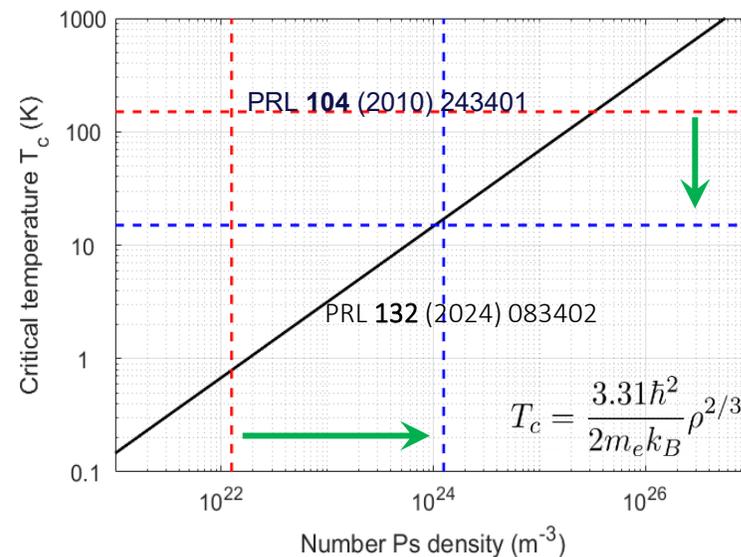


Simplified layout of the experimental set-up

with estimated rates the properties of the bound state could be studied

# Bose-Einstein condensate of Ps – also world’s first

A positronium density of  $10^{15} \text{mm}^{-3}$  is necessary for forming a BEC. Current  $e^+$  sources cannot reach that !



When a Ps-BEC annihilates, a coherent burst of gamma rays is emitted.

A proposed way to build a 511 keV gamma ray laser!

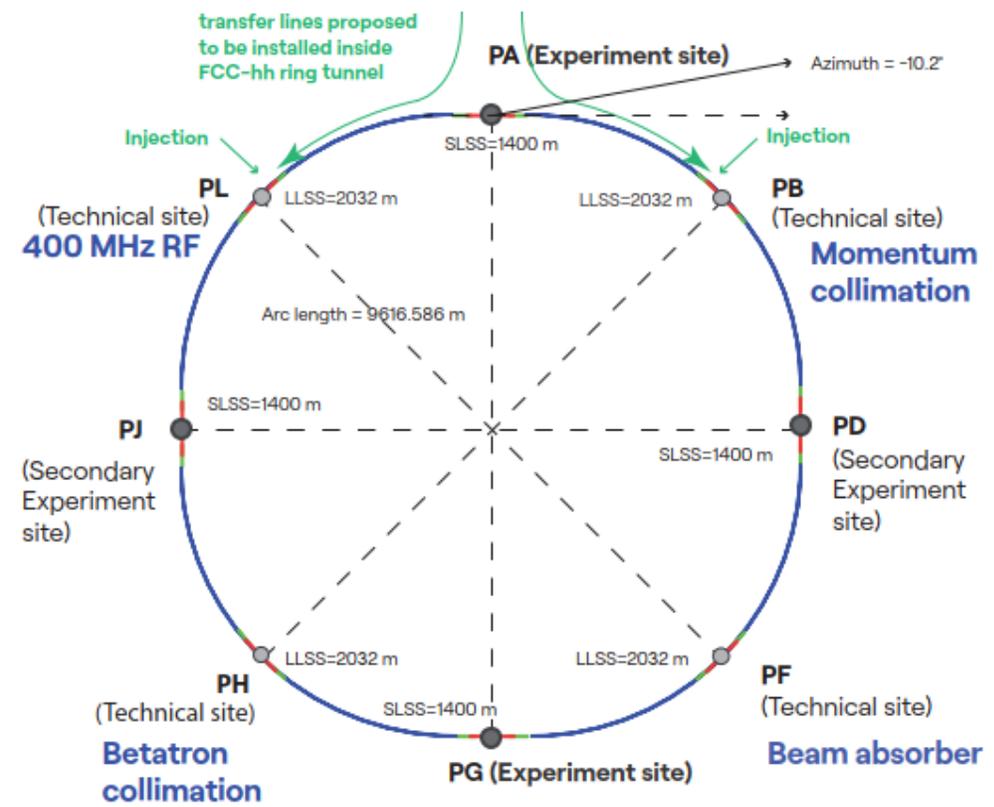
# Stage 2: hadron collider FCC-hh

- Parameter optimization to lower electricity consumption (~max. consumption of FCC-ee)
- Magnetic field considered realistic with today's technologies (Nb<sub>3</sub>Sn, ~14T, 1.9 K)

## Main parameters FSR 2025

parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	<b>85</b>	<b>100</b>	14
dipole field [T]	<b>14</b>	<b>16</b>	8.33
circumference [km]	<b>90.7</b>	<b>97.8</b>	26.7
beam current [A]	<b>0.5</b>	<b>0.5</b>	1.1
synchr. rad. per ring [kW]	<b>1200</b>	<b>2400</b>	7.3
peak luminos. [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	<b>30</b>	<b>30</b>	5 (lev.)
events/bunch crossing	<b>1000</b>	<b>1000</b>	132
stored energy/beam [GJ]	<b>6.5</b>	<b>8.3</b>	0.7
integr. luminosity / IP [ $\text{fb}^{-1}$ ]	<b>20000</b>	<b>20000</b>	3000

## FCC-hh functional layout



# New FCC-hh baseline and power consumption

## Technical system choices and areas for optimisation:

- Accelerator optics design to increase arc dipole filling factor and maximize beam energy
- Cold mass either at 1.9 K with superfluid He (studied in CDR, cf. LHC) or with 4.5 K with forced flow
- Temperature of beam vacuum system (beam screen)
- Cryogenics “eco mode” during shutdowns

	FCC-hh 90.7km Nb <sub>3</sub> Sn 14T	FCC-hh 90.7km Nb <sub>3</sub> Sn 14T
Magnet temperature	1.9 K	4.5 K
Yearly electricity consumption	< 2.5 TWh	< 2.0 TWh

- **Significant reduction of electrical power consumption (close to factor 2!) compared to CDR version 2019.**
- **Potential for further reduction, to be addressed with design optimisation and R&D on 4.5 K operation in next phase.**
- **Long term R&D towards accelerator magnets based on high-temperature superconductor materials, targeting higher fields and reduced electricity consumption**

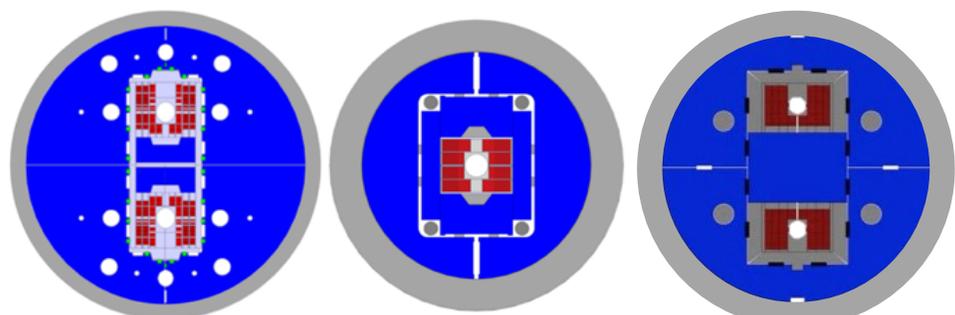
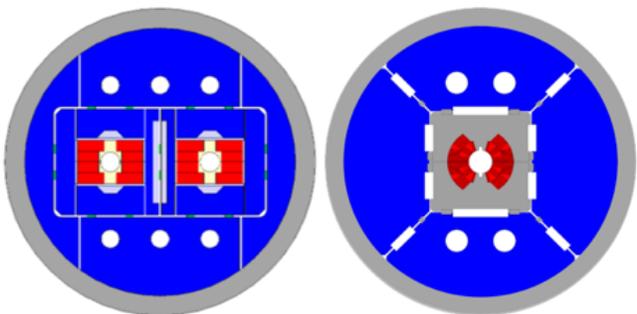
# FCC-hh High-Field Magnet Nb<sub>3</sub>Sn and HTS R&D ongoing

## Nb<sub>3</sub>Sn:

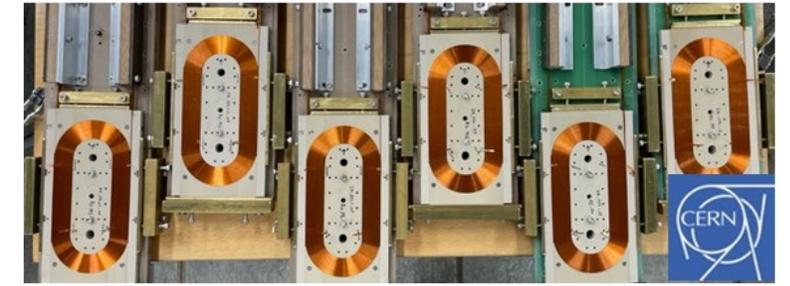
- 12- and 14-T short demonstrators
- Different coil geometries
- tests scheduled for 2026

## HTS R&D in various domains:

- REBCO and IBS Conductor R&D
- Racetrack coil developments



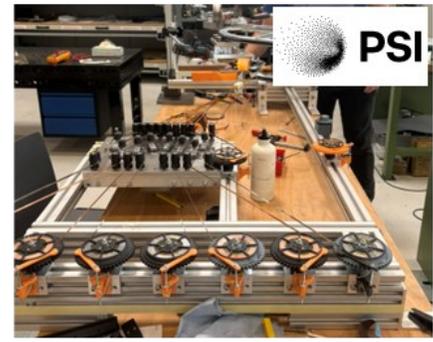
REBCO coated-conductor R&D line at KIT.



Insulated tape-stack coils for assembly in common-coil config at CERN.



Iron-based SC powder synthesis and R&D tape fabrication at CNR SPIN

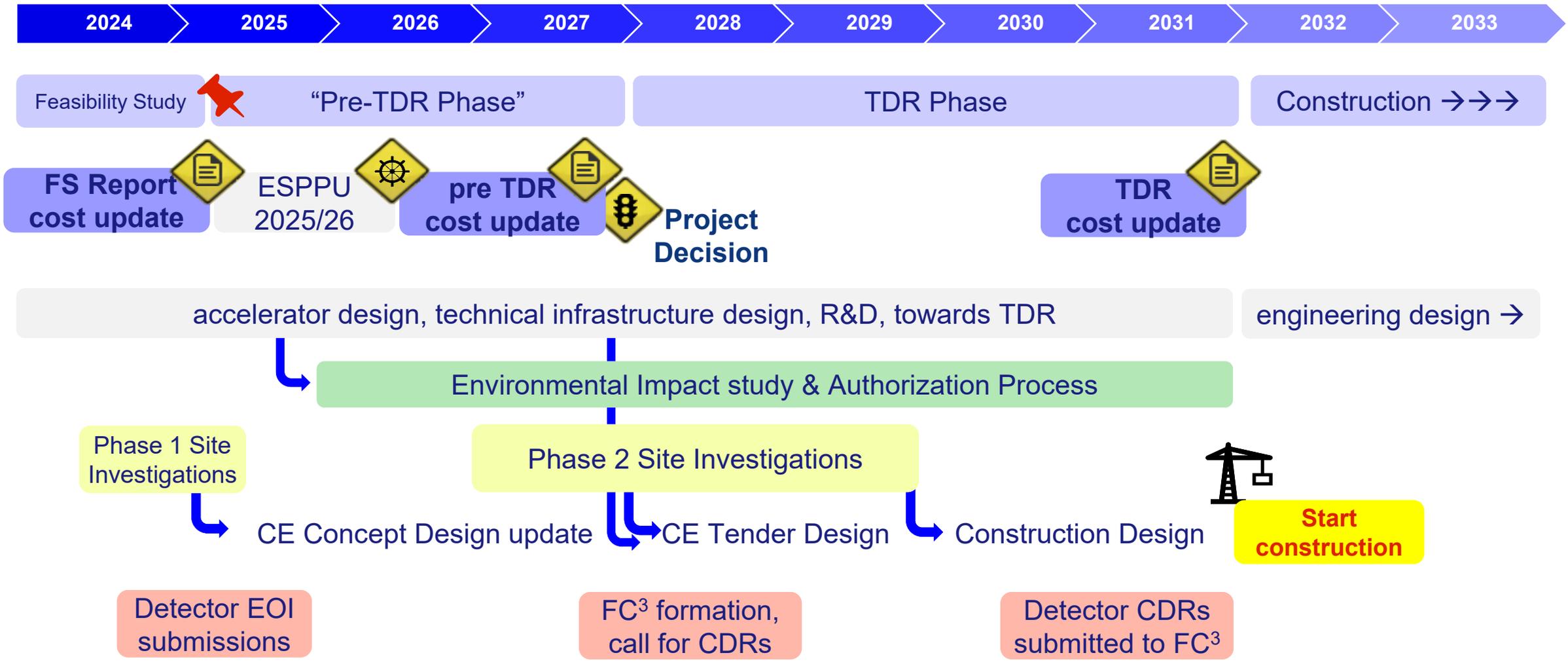


Fabrication of racetrack from solder-impregnated tape-stack cable at PSI.



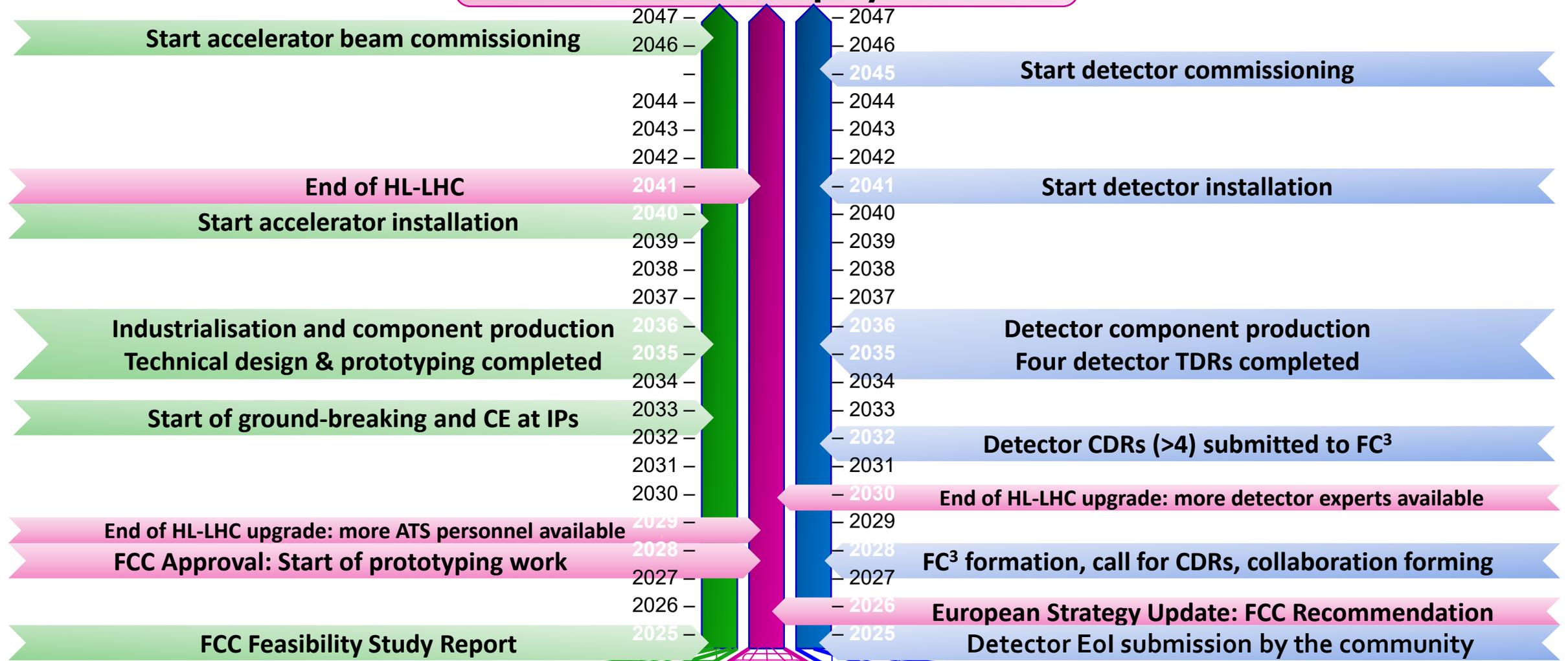
CEA process development for metal-insulated racetrack coils.

# Timeline till start of FCC construction



FC<sup>3</sup> = Future Circular Collider Committee

# Start of FCC-ee physics run



FCC-ee Accelerator

Key dates

FCC-ee Detectors

# Status of the FCC Global Collaboration

Increasing international collaboration is a prerequisite for success:

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

## 38 Participating Countries

- Austria – Belgium – Brazil – Canada – Chile – Colombia – Czech Republic – Denmark – Estonia – Finland – France – Georgia – Germany – Greece – Hungary – India – Iran – Italy – Japan – Latvia – Malta – Mexico – Netherlands – Norway – Pakistan – Poland – Portugal – Republic of Korea – Romania – Serbia – Spain – Sweden – Switzerland – Thailand – Türkiye – Ukraine – United Kingdom – United States of America

in Asia: India (2), Iran (2), Japan (3), Pakistan (1), South Korea (11), Thailand (4), and Türkiye (18)

FCC “IFNC” also contains Taiwan

## FCC Feasibility Study:

Aim is to further increase the collaboration, on all aspects, in particular on Accelerator and Physics/Experiments/Detectors

161  
Institutes

38  
Countries  
+  
CERN





**614 participants, 557 on site, 56 public sessions, 230 oral presentations, 33 posters, several outreach events: Wheel of Science, the Higgs Boson and our Life, Pint of Science, Code of the Universe, Industry & Technology Day**

*! Save the date !*



# Conclusions

- **FCC Feasibility Study concluded**; Feasibility Study Report submitted to the ESPP, as requested by CERN Council.
- Coherent baseline design for FCC integrated programme, including well-advanced territorial implementation scenario, in line with **CE construction start by 2032/33**.
- FCC-ee design level enables moving towards technical design and prototyping phase, aligned with overall schedule, and towards preparing input for potential **project decision by 2027/28**.
- Solid **long-term dual (Nb<sub>3</sub>Sn & HTS) R&D program** established for high-field magnets, as basis for FCC-hh.
- **Many thanks to the entire FCC collaboration for making all this possible!!!**

thank you for your attention

感谢您的关注

ご清聴ありがとうございました