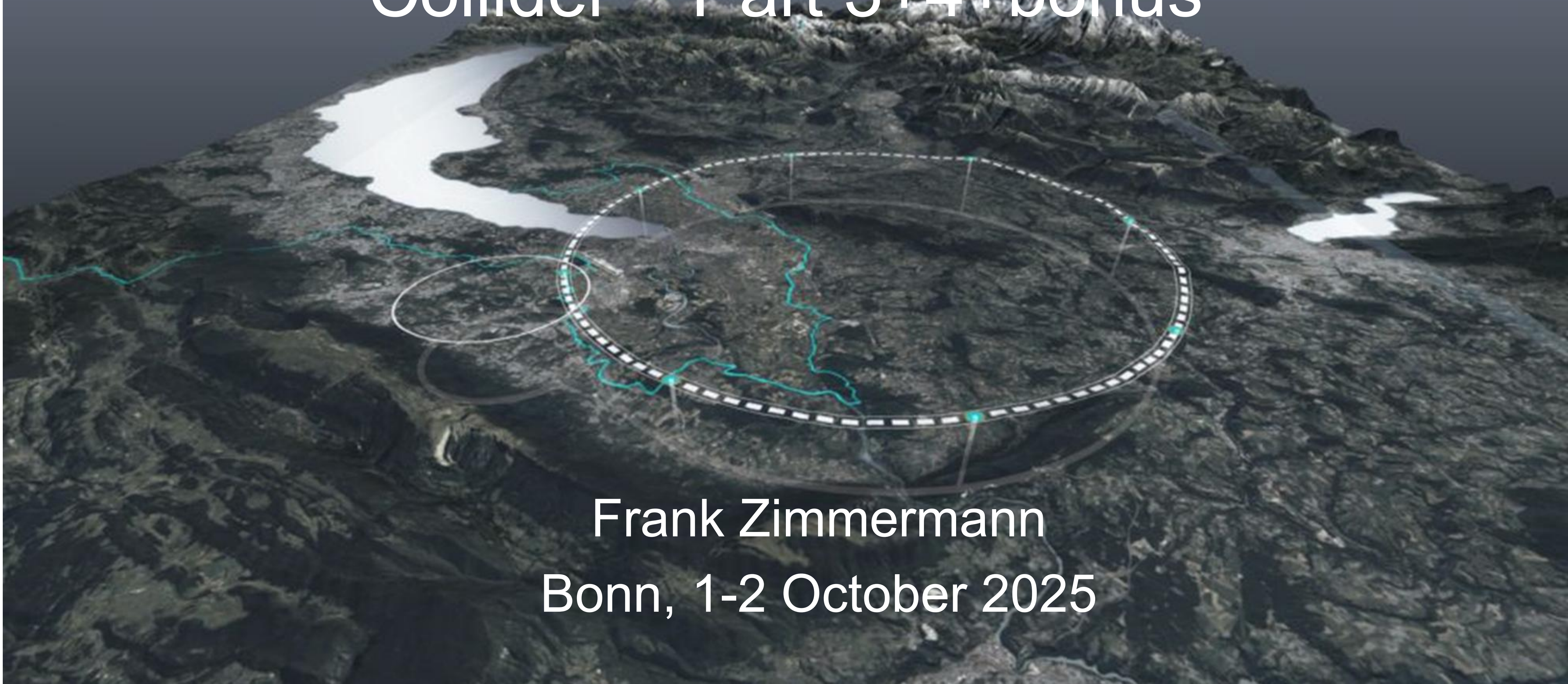
Lectures on the Future Circular Collider – Part 3+4+bonus



Frank Zimmermann

Bonn, 1-2 October 2025

Lecture 3 – injector & polarisation

3.1 top-up

3.2 booster

3.3 injector complex

3.4 injector – positron production

3.5 energy calibration – polarisation

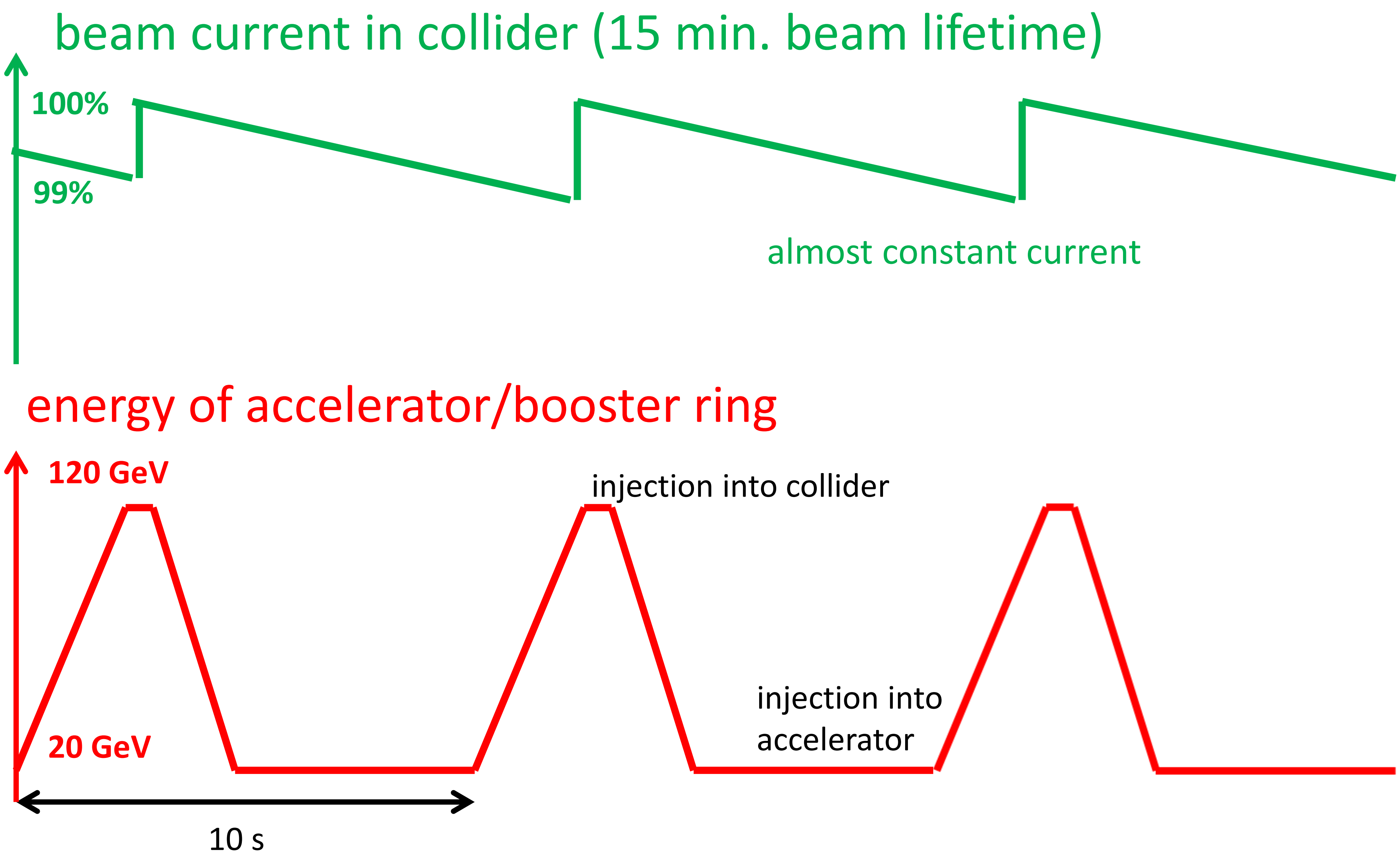
3.6 polarised sources

FCC-ee top-up injection

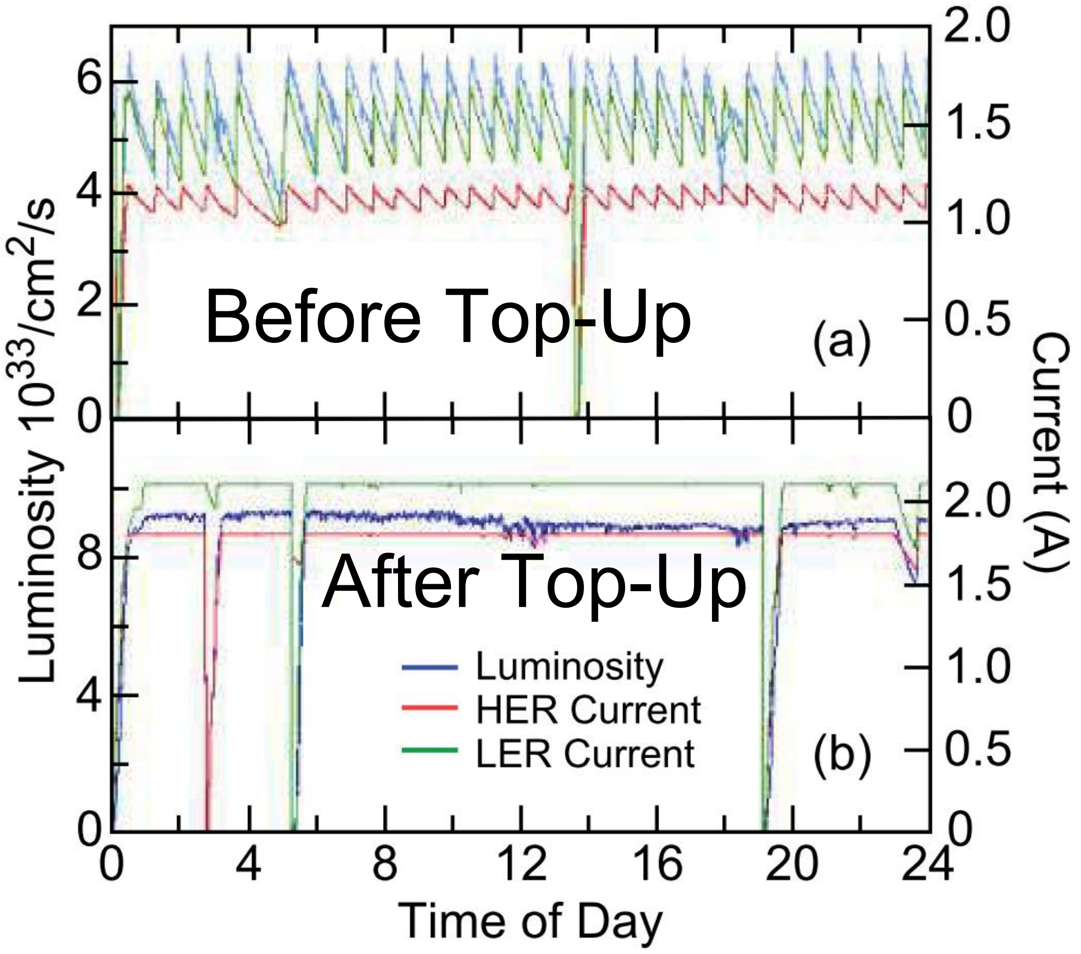
beside the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection to sustain the extremely high luminosity

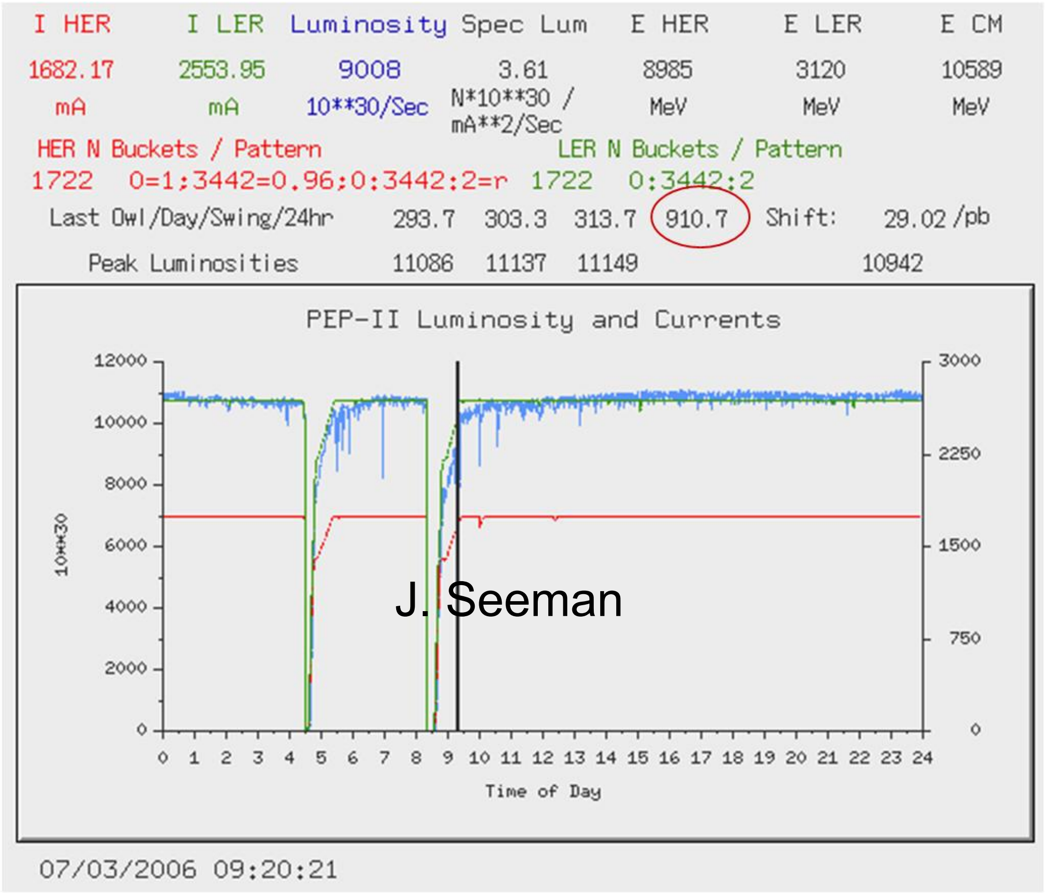
- same size of RF system, but low power (~ MW)
- top up frequency ≈0.1 Hz
- booster injection energy ≈ 20 GeV
- bypass around the experiments

top-up injection: schematic cycle



top-up injection at the PEP-II B factory, around yr 2000





J. Seeman

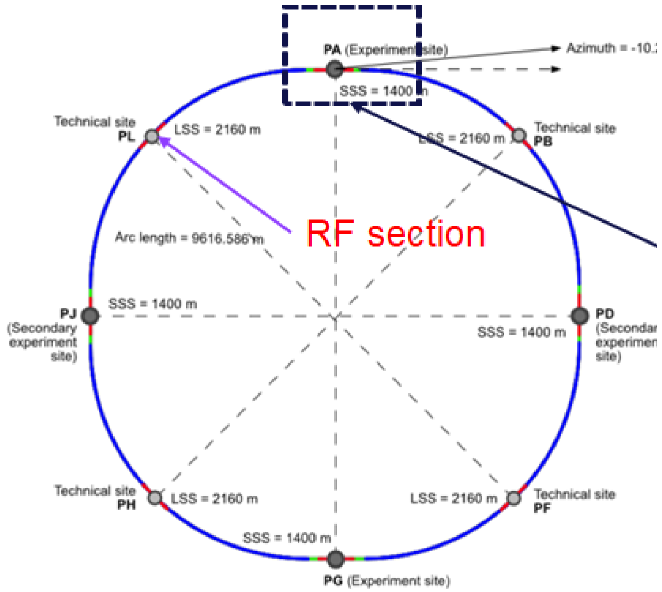
average luminosity ≈ peak luminosity

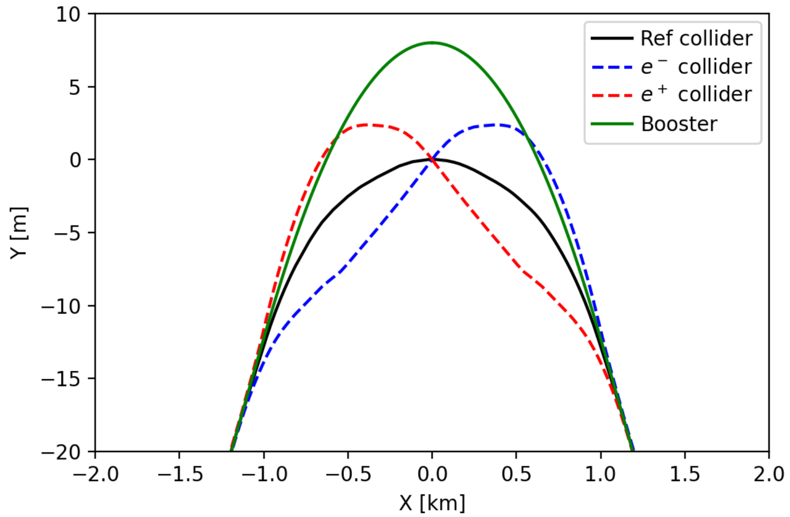
similar results from KEKB

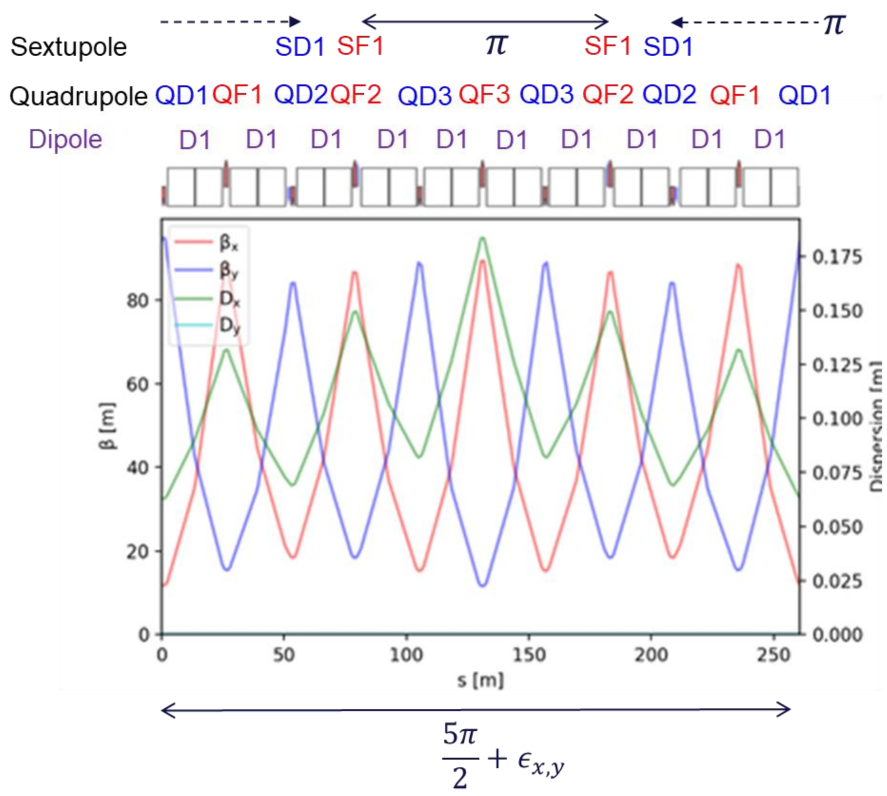
3.2 booster

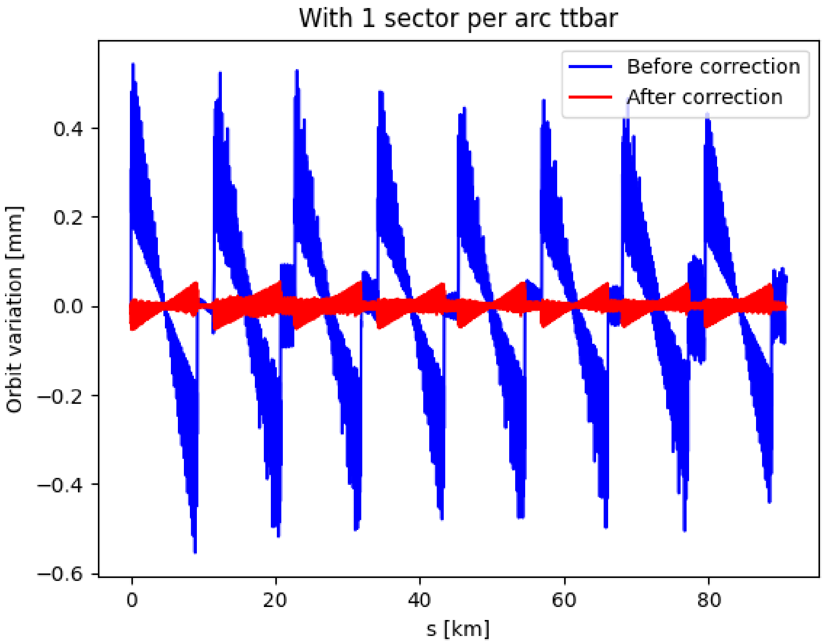
- also a storage ring
- similar to collider, installed in the same 90 km tunnel
- no low-beta insertions, but bypasses around the experiments
- only ~1% of collider beam current, →1% of RF power
- fast ramping
- low dipole field at 20 GeV injection energy, ~60 G

booster bypass around the detectors





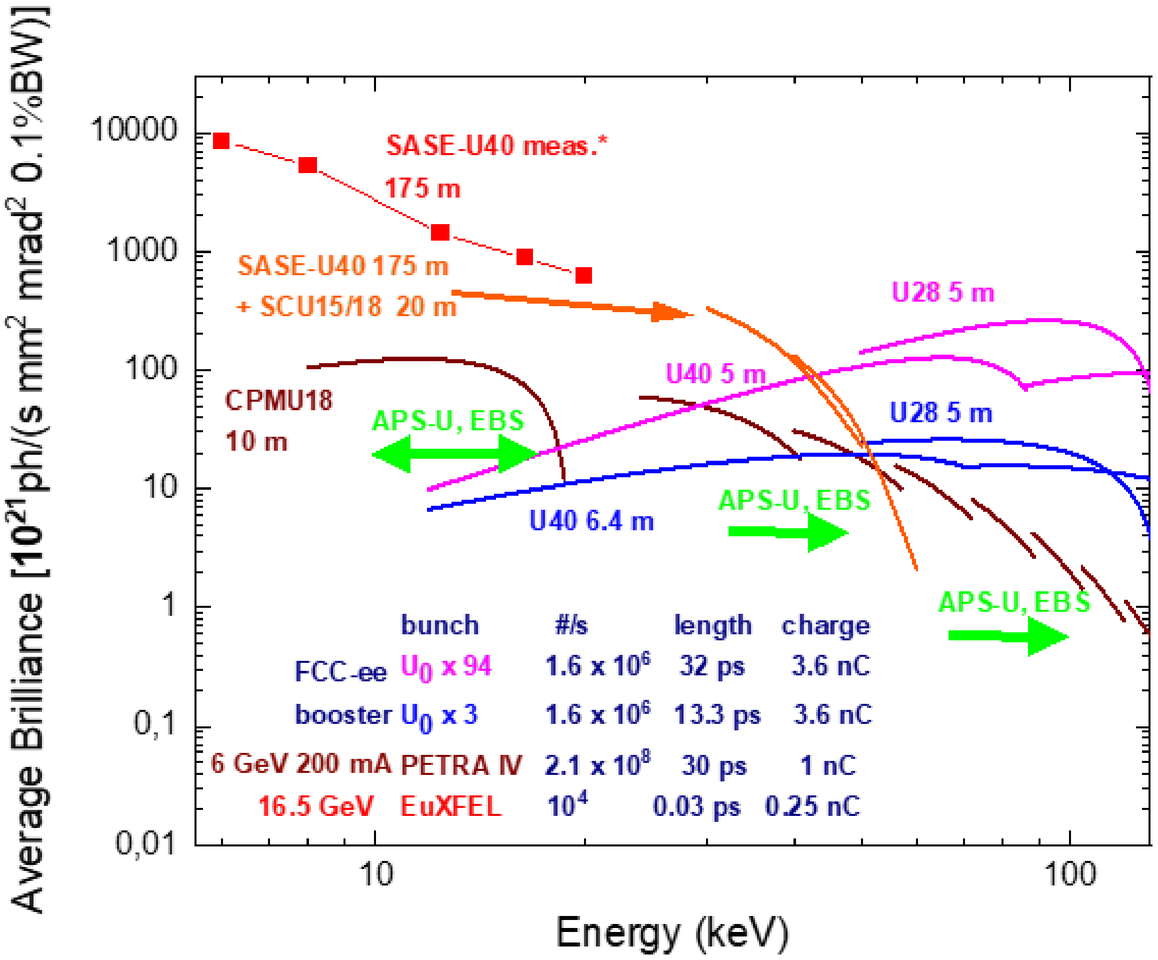


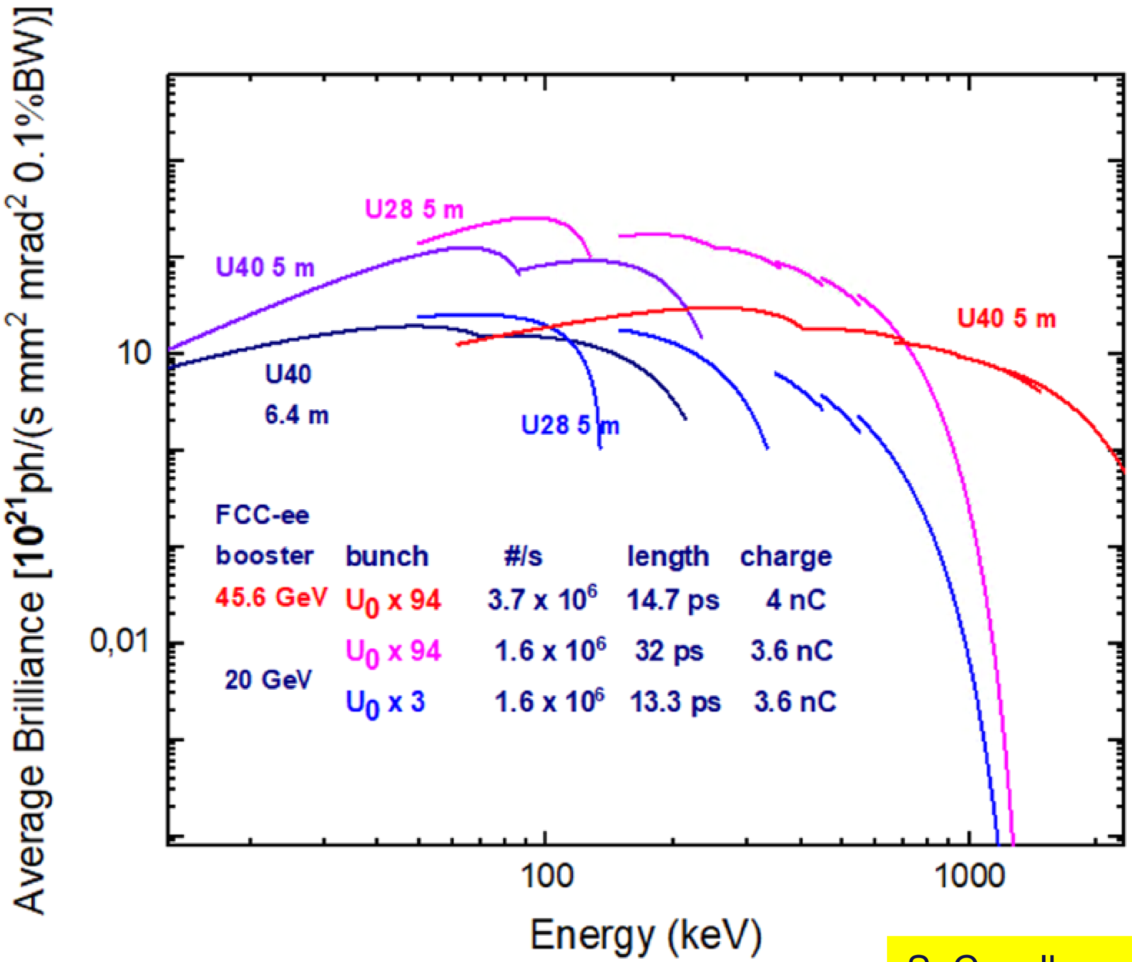


at ttbar: tapering using horizontal orbit correctors

A. Chance

FCC-ee booster as unique ultimate photon source





S. Casalbuoni

case for ≥20 GeV storage-ring light source: PRAB **28**, 024401 (2025); arXiv:2505.11022

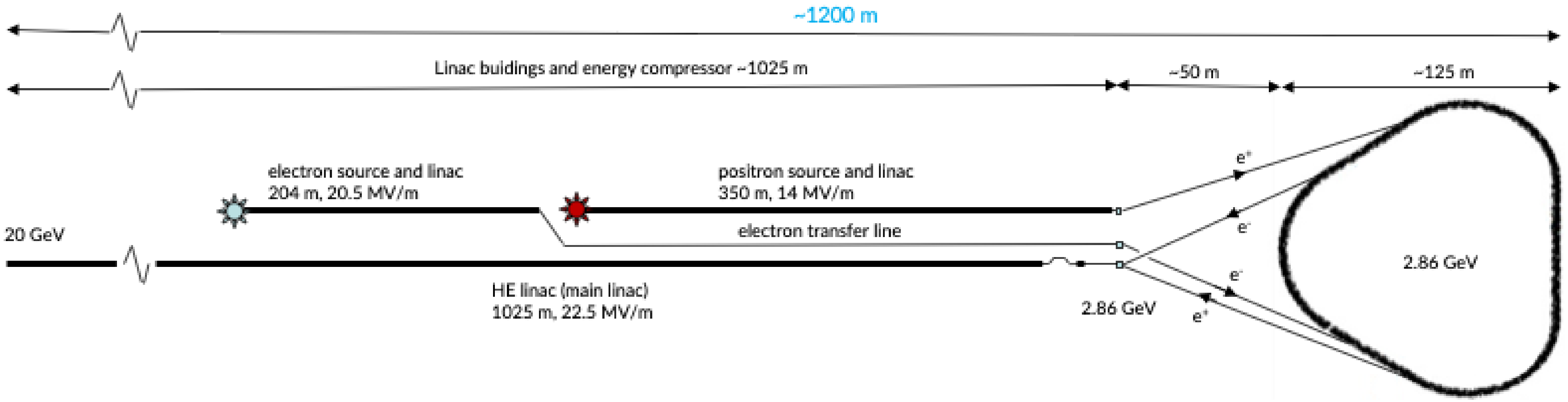
"we argue that achieving further significant emittance reduction and increase in radiation brightness is only possible by increasing the beam energy"

I. Agapov
S. Antipov

3.3 injector complex

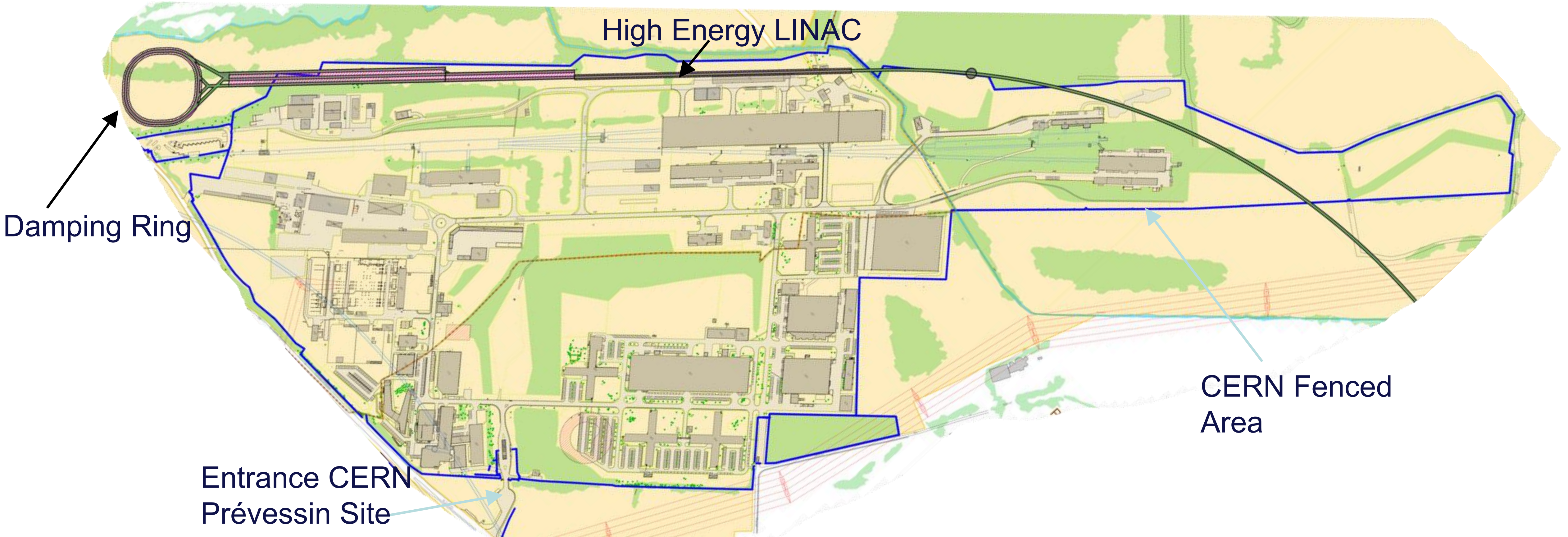
FCC-ee injector concept

- **three warm copper S-band linacs (3 GHz), well established technology**
  - moderate RF gradient ~22.5/20.5 MV/m
  - 100 Hz repetition rate
  - 1-4 bunches per rf pulse
  - more efficient RF structures, precision-machined (PSI), efficient RF power



Optimised injector implementation at Prévessin site

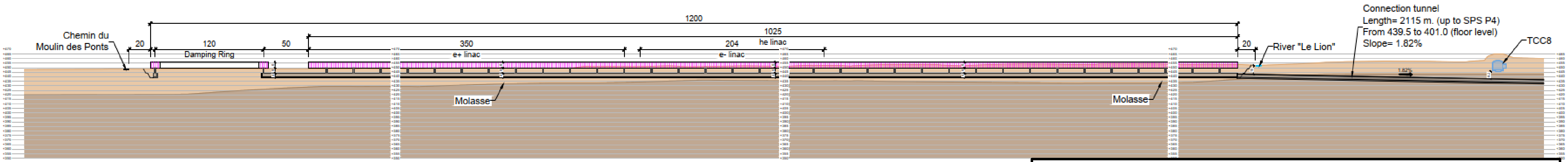
- Better integration with existing CERN Prévessin Site & strongly reduced visible impact from outside.
- Ideal connection to existing experimental halls.
- Good conditions for construction (see next slide).
- CERN dedicated land, small part outside fenced area but with same urbanistic classification as enclosed Prevessin Site



injector construction concept

OPTION 9

DAMPING RING NEXT TO "DECHETERIE"

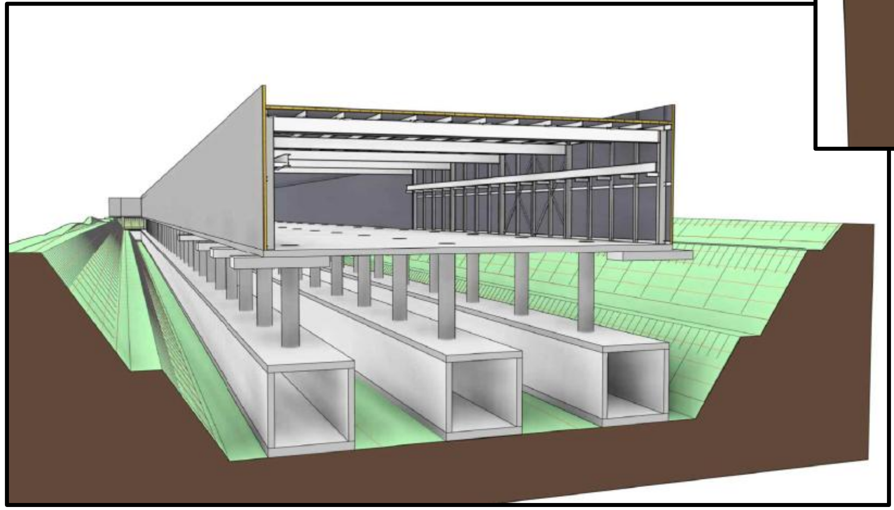


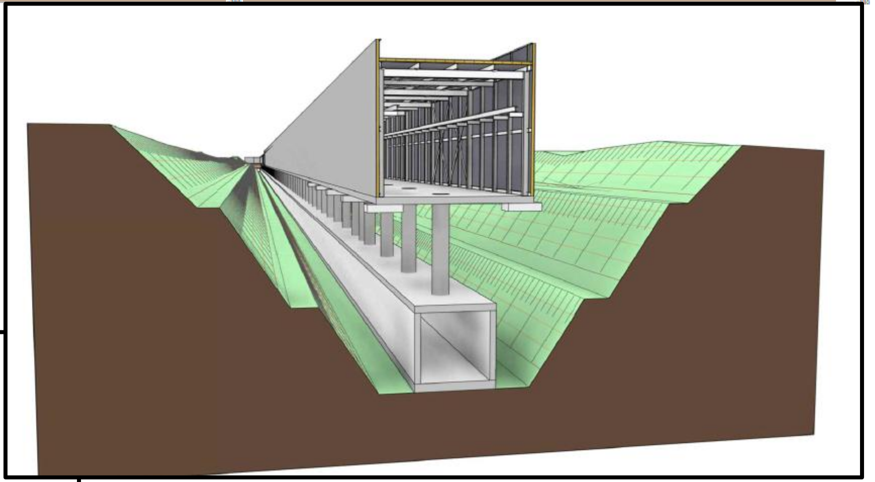
LONGITUDINAL PROFILE

Longitudinal Section

- Less than 5 m elevation change over the 1200 m of terrain provides **ideal conditions for "cut and cover" technique**
- Most efficient and cheapest way of building shallow underground construction
- Excavated material largely re-used as backfill above the tunnel
- Accounts also for radio-protection requirements

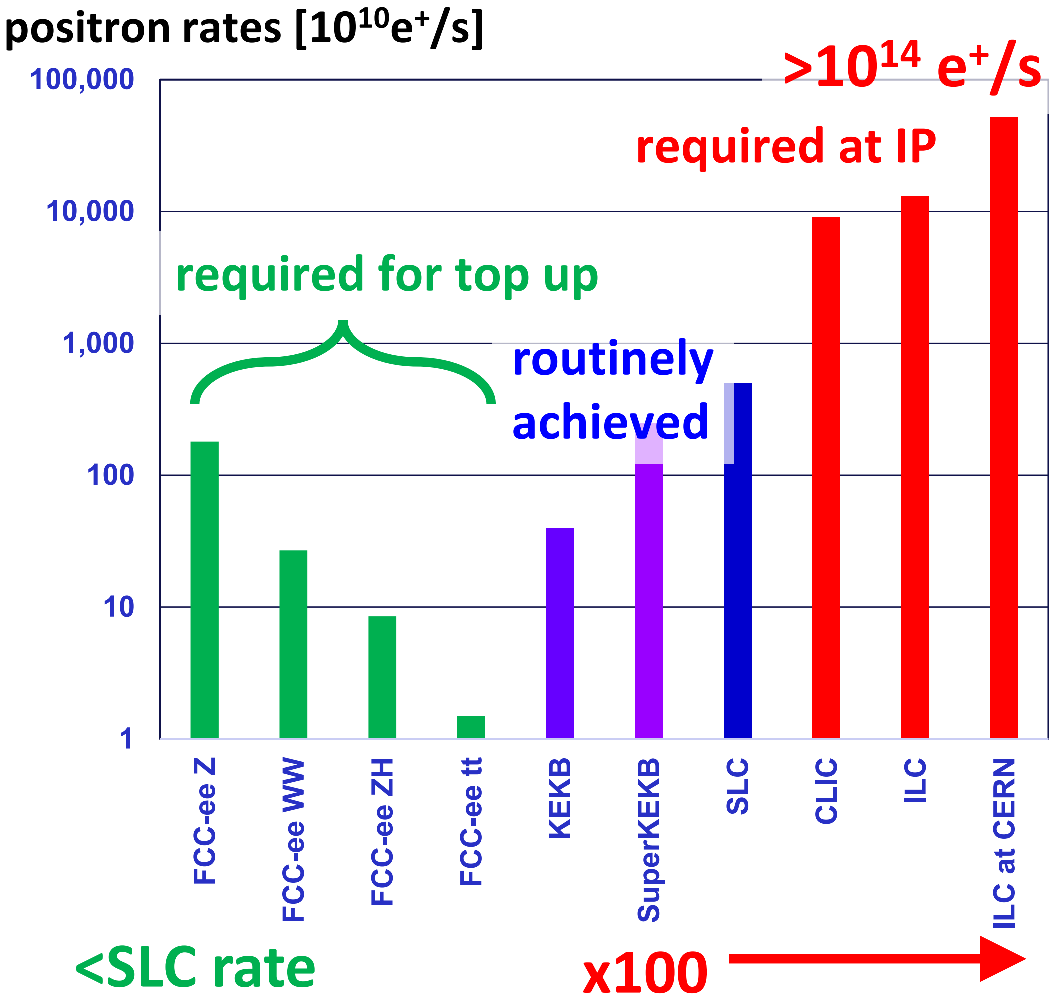
HE LINAC Line +
Electron and Positron Lines



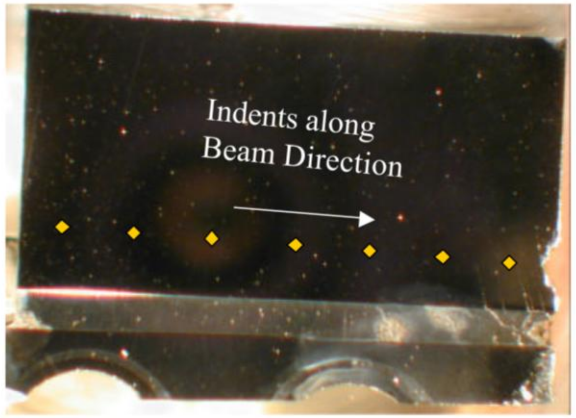


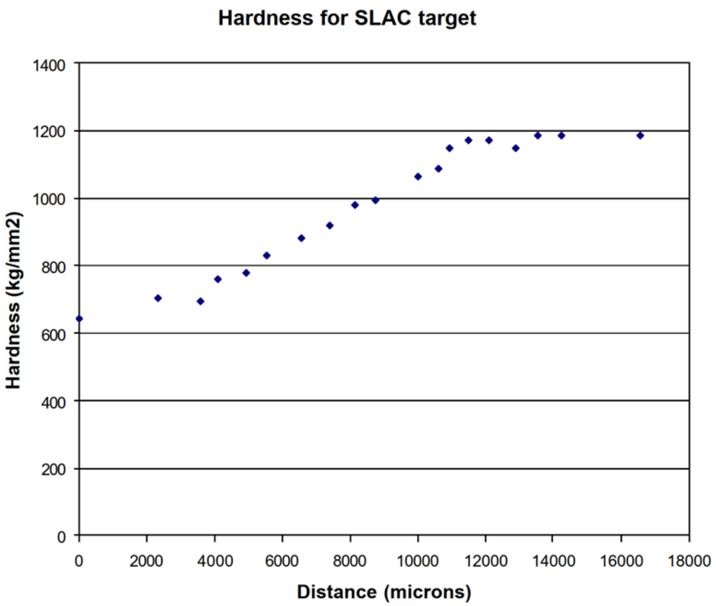
HE LINAC Line

3.4 injector – positron production

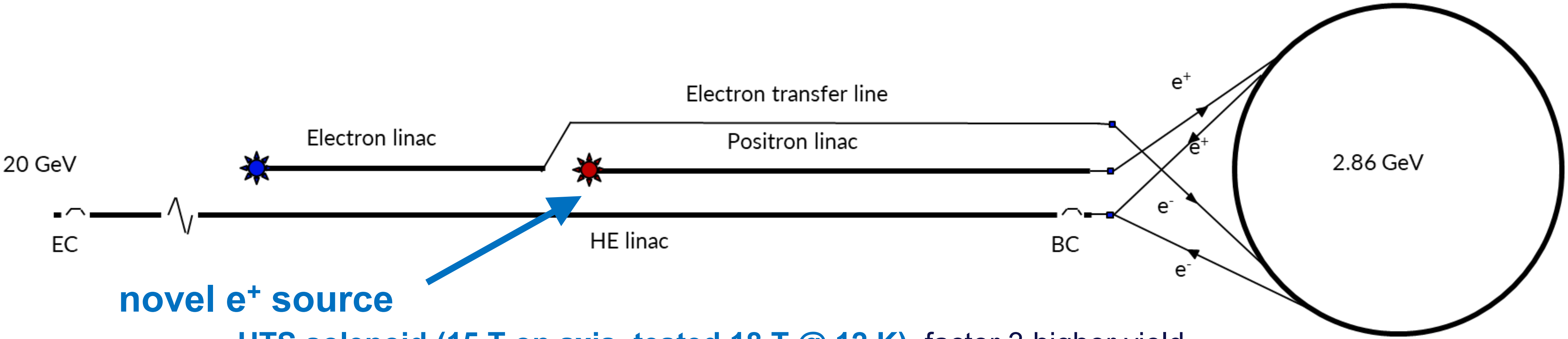


SLC e+ target failed after 5 years of operation



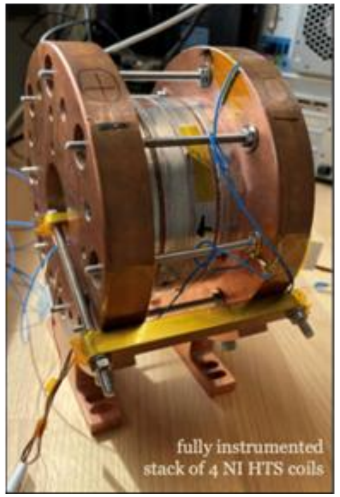


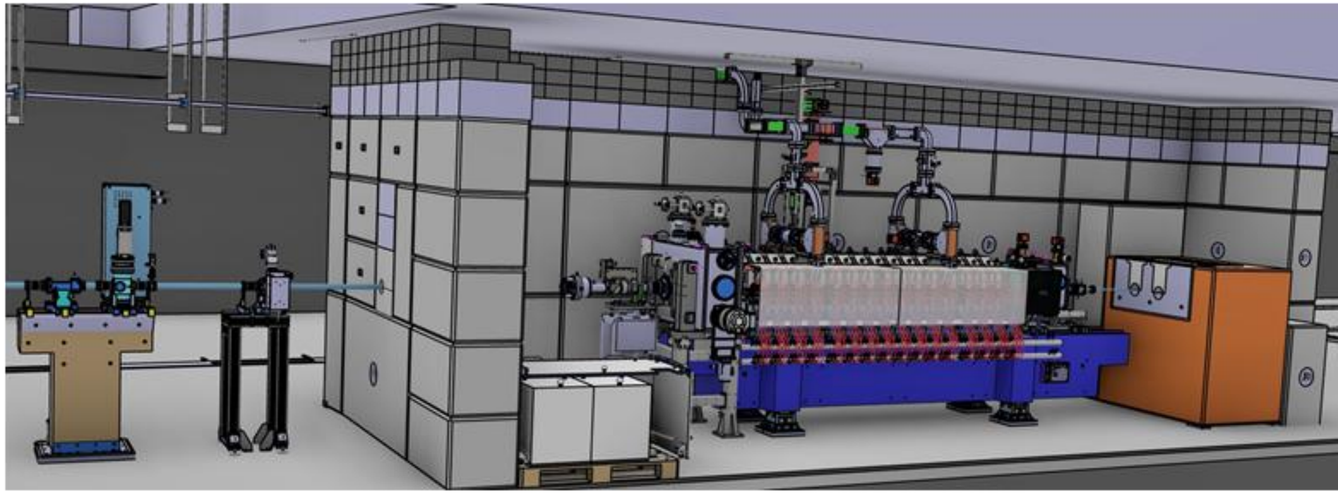
FCC-ee positron source & prototype



novel e^+ source

- **HTS solenoid (15 T on axis, tested 18 T @ 12 K)**, factor 3 higher yield
- proof-of-principle beam tests at PSI SwissFEL from 2026





3.5 energy calibration - polarisation

at Z and W: frequent resonant-depolarisation measurements with non-colliding bunches

- ✓ much better resolution than at LEP, few tens of keV
- ✓ measurement of energy spread
- ✓ extrapolation from average to individual IPs
- ✓ OR: injecting polarised beam

spin tune $Q_{\text{spin}} = \gamma a_e$, a_e the anomalous magnetic moment of the electron ($a_e \approx$ 0.00116)

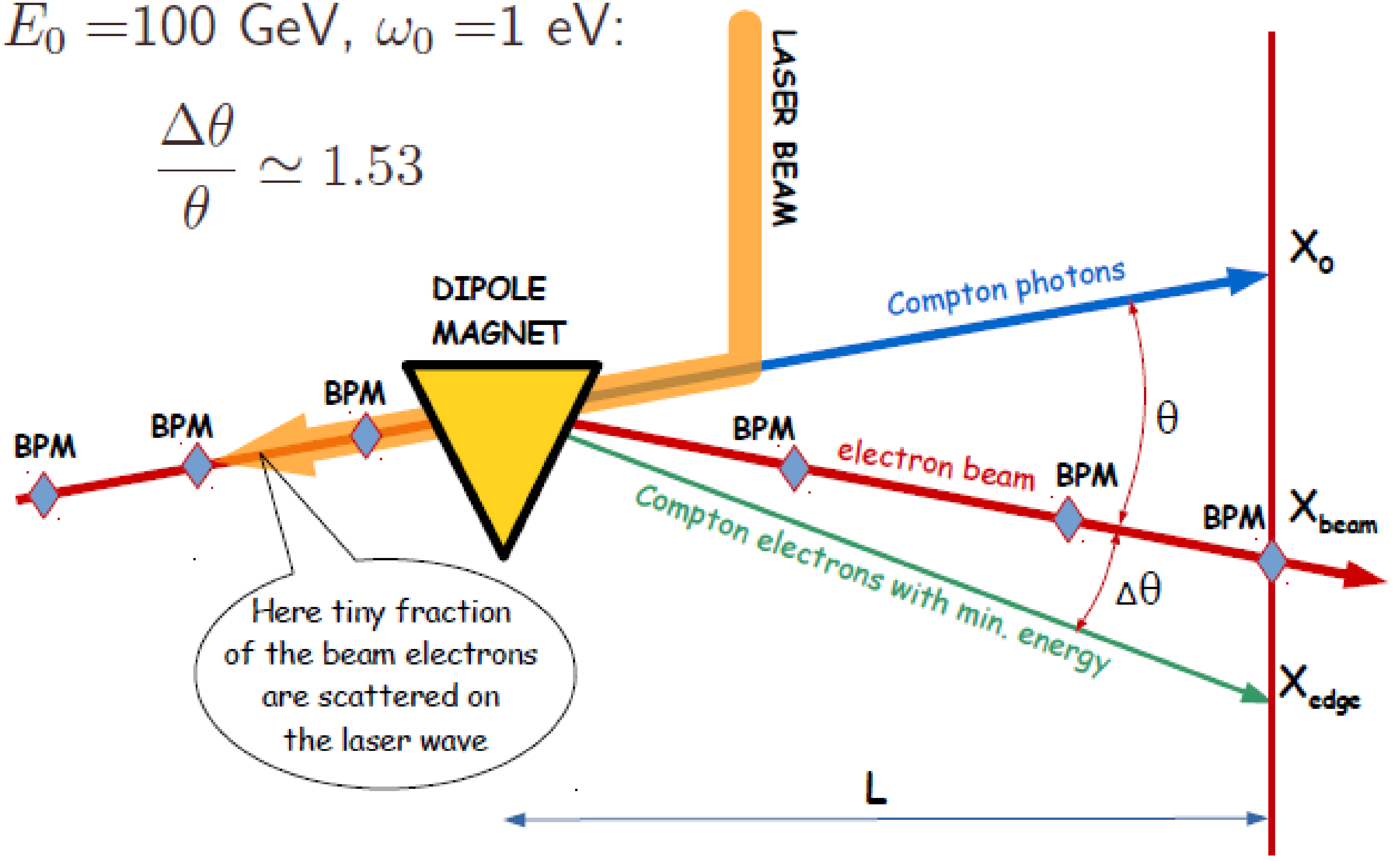
at higher energies, H and $t\bar{t}$:

- ✓ use physics measurements
- ✓ other? (laser back scattering / spectrometer?)
- ✓ OR: injecting polarized beam

Spectrometer with laser calibration (suggestion)

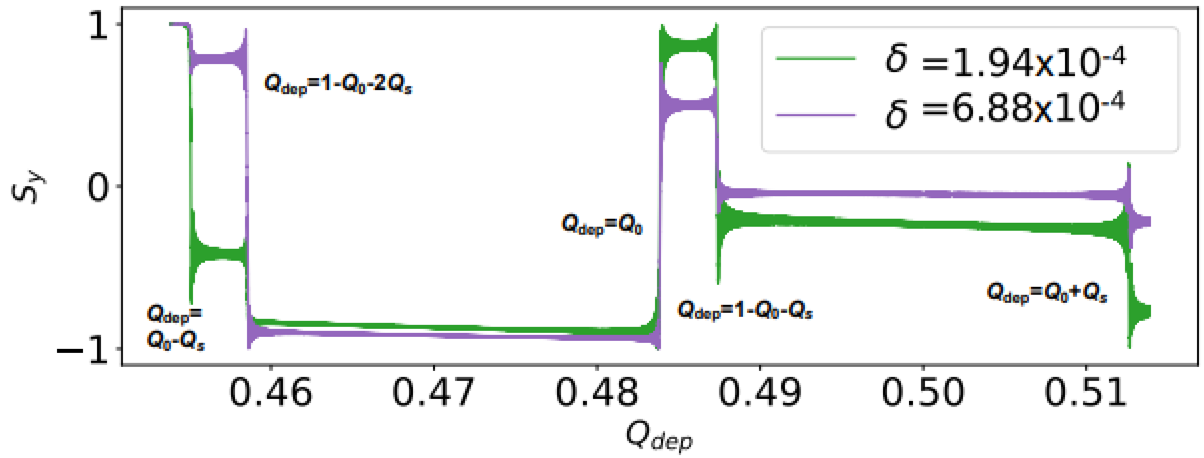
$E_0 = 100$ GeV, $\omega_0 = 1$ eV:

$$\frac{\Delta\theta}{\theta} \simeq 1.53$$

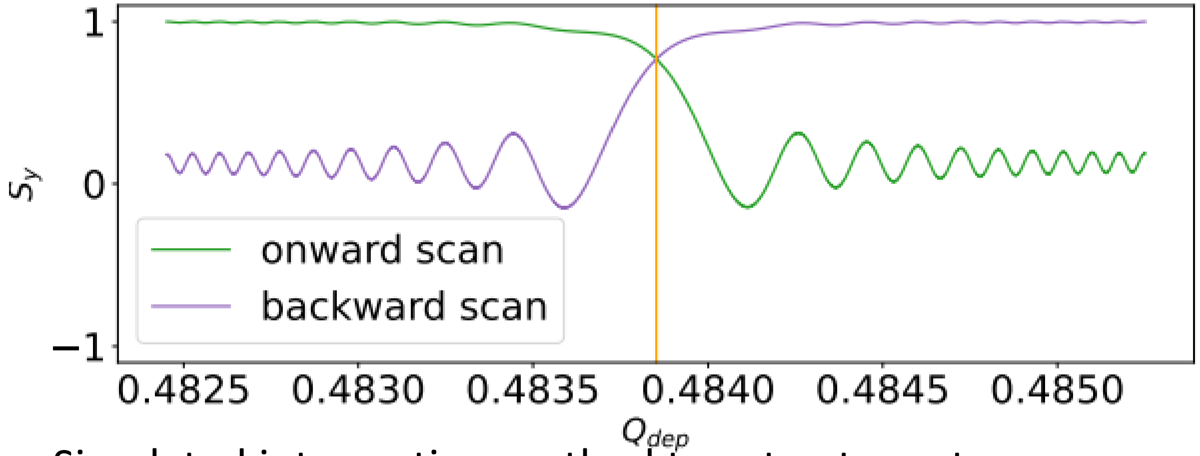


Access to the beam energy: $E_0 = \frac{\Delta\theta}{\theta} \times \frac{m^2}{4\omega_0}$

resonant depolarisation



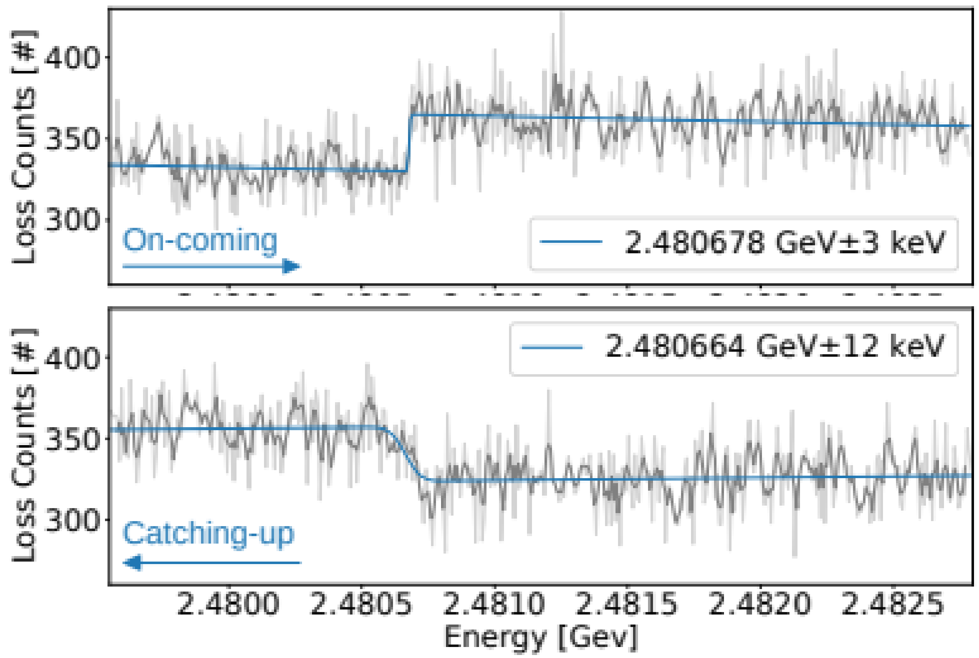
Simulated RDP scans for single particles undergoing synchrotron oscillations



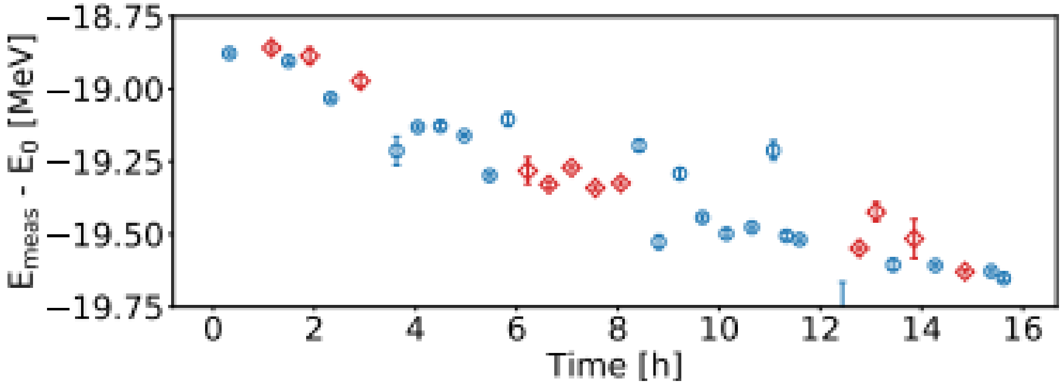
Simulated intersection method to extract exact resonance frequency

Kiel, Keintzel, Z.; 2025

Experiments at KARA, Keintzel et al..; 2024



Scan results for increasing (top) and decreasing depolariser frequency (bottom). The different shape of the fitted function is consistent with a downward drift in beam energy



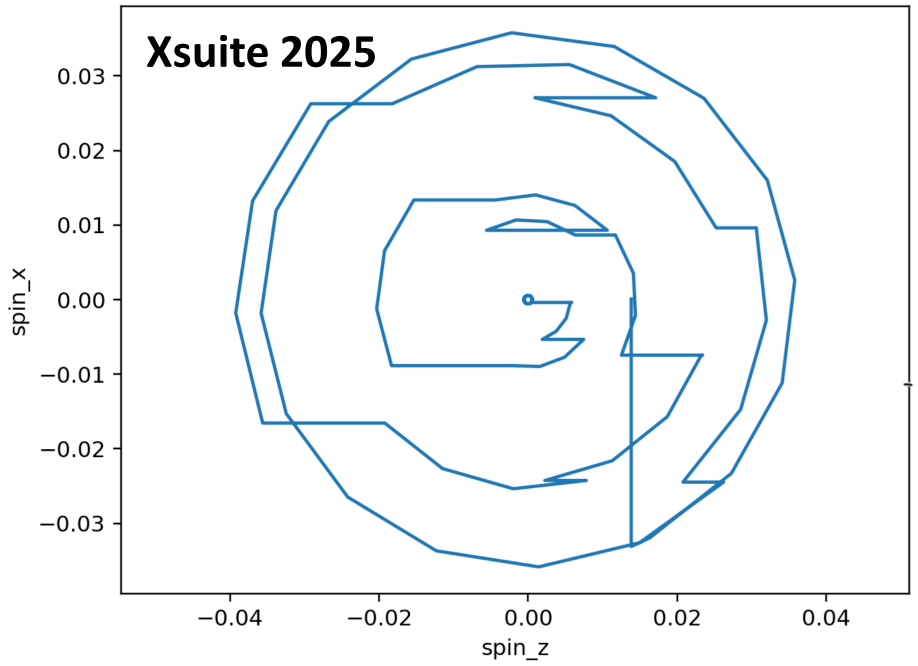
KARA beam energy drift with respect to 2.5 GeV over 16 h from RDP scans of various speed & either scan direction

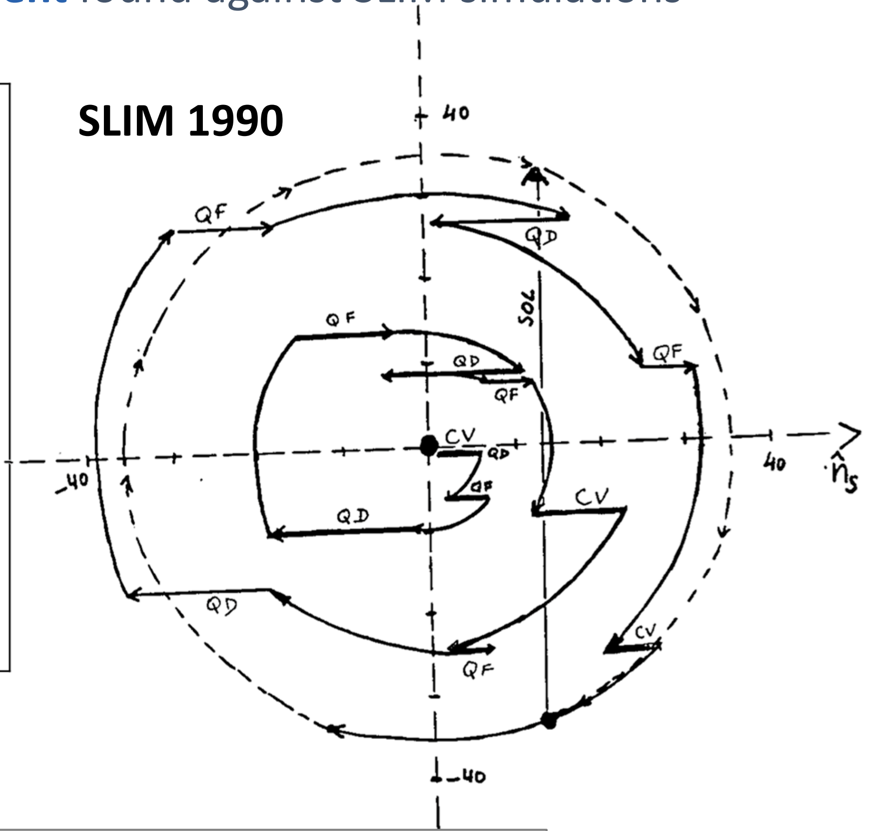
<u>spin tracking</u> newly implemented in Xsuite !

collaboration with BNL EIC project

tests,
benchmarking,
and first simulation studies ongoing

Benchmarking case of **LEP1** with orbit bumps to compensate precession in the experimental solenoids → **good agreement** found against SLIM simulations





Compensation of Integer Spin Resonances Created by Experimental Solenoids

Alain Blondel

L. P. N. H. E., Ecole Polytechnique, 91128 Palaiseau Cedex, France

22 April 1990

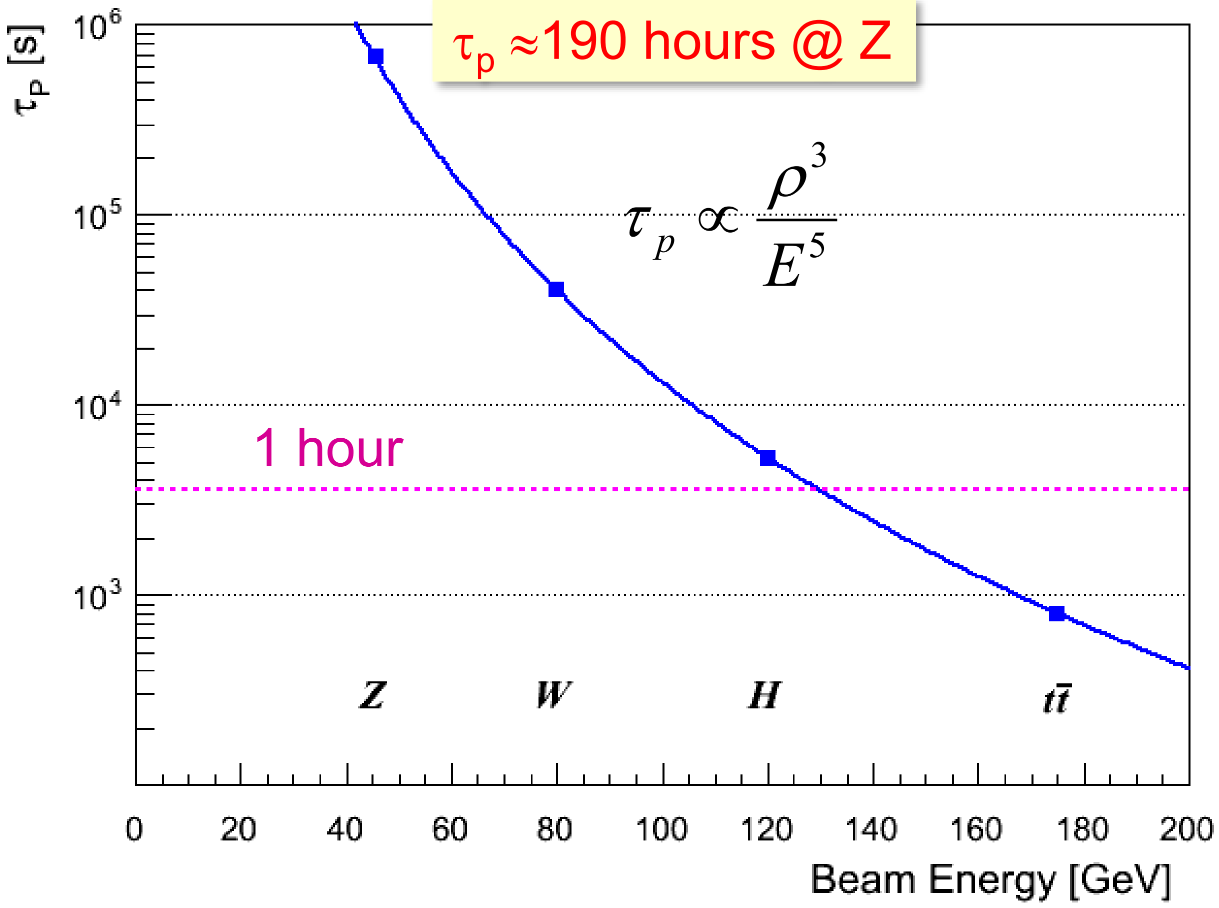
10 mrad

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

3.6 polarised sources
self polarisation in storage ring (Sokolov-Ternov effect)

transverse polarization build-up (Sokolov-Ternov) is slow at *FCC-ee* (large bending radius ρ)

build-up is ~40 times slower than at LEP



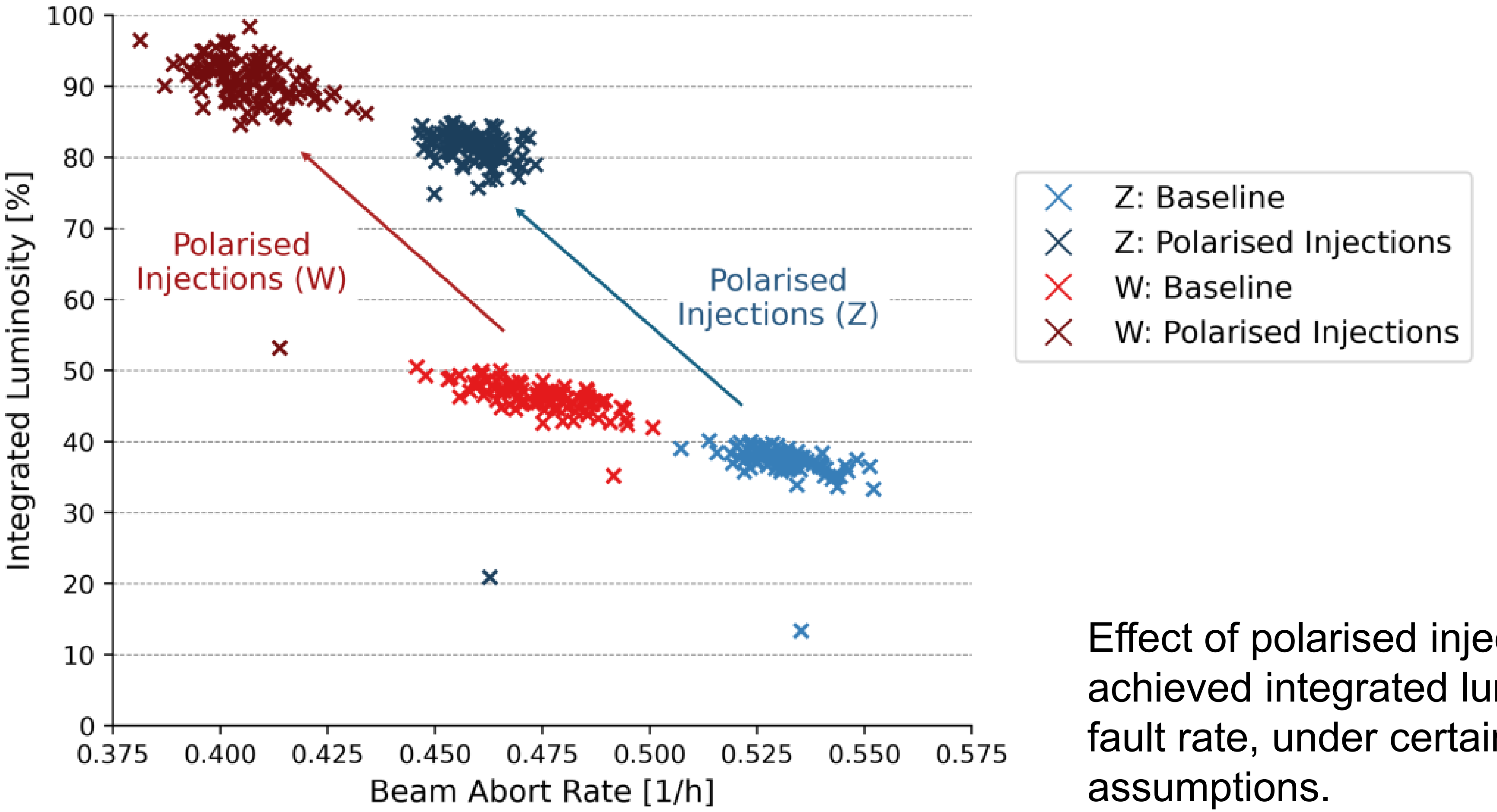
wigglers may lower τ_p to ~12 h, limited by $\sigma_E \leq$ 60 MeV and power

due to power loss the wigglers can only be used to pre-polarize some bunches (before main injection)

→ ≈ OK for energy calibration (few % P sufficient)

J. Wenninger

concern : availability - after each beam abort need to inject & then prepolarise pilot bunches



Effect of polarised injections on achieved integrated luminosity and fault rate, under certain assumptions.

Jack Heron

better: inject already polarised pilot bunches

polarised e- gun | well established technology

spin transport through linac, transfer lines, booster to collider

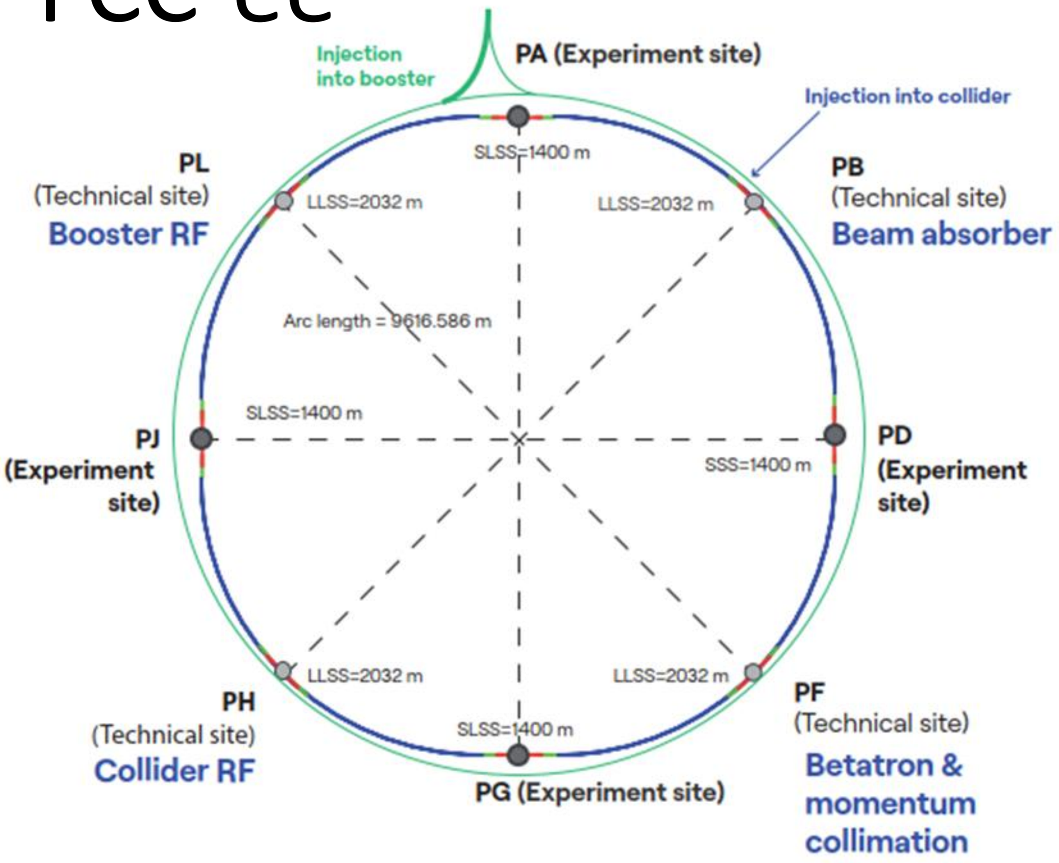
- large synergies with the US EIC project

polarised e+?

- using polarised e- to produce e+ may yield a few % polarisation
- polariser ring

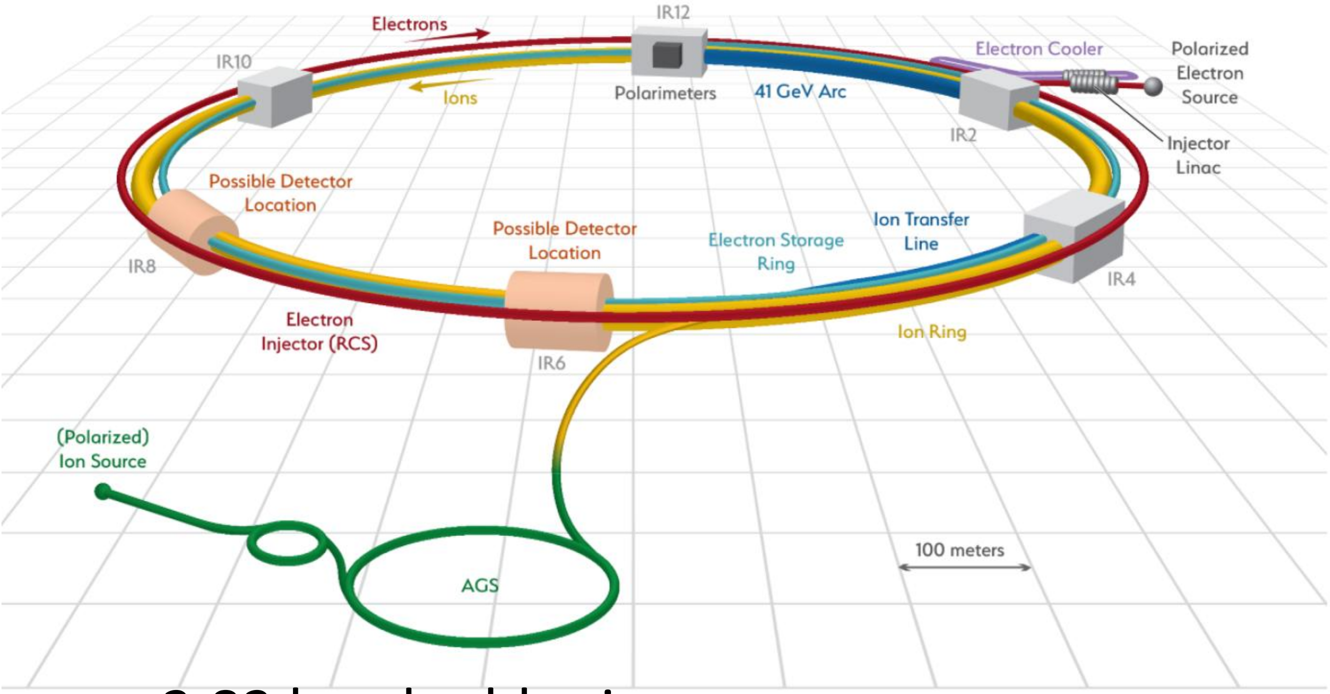
FCC & EIC similarities

FCC-ee



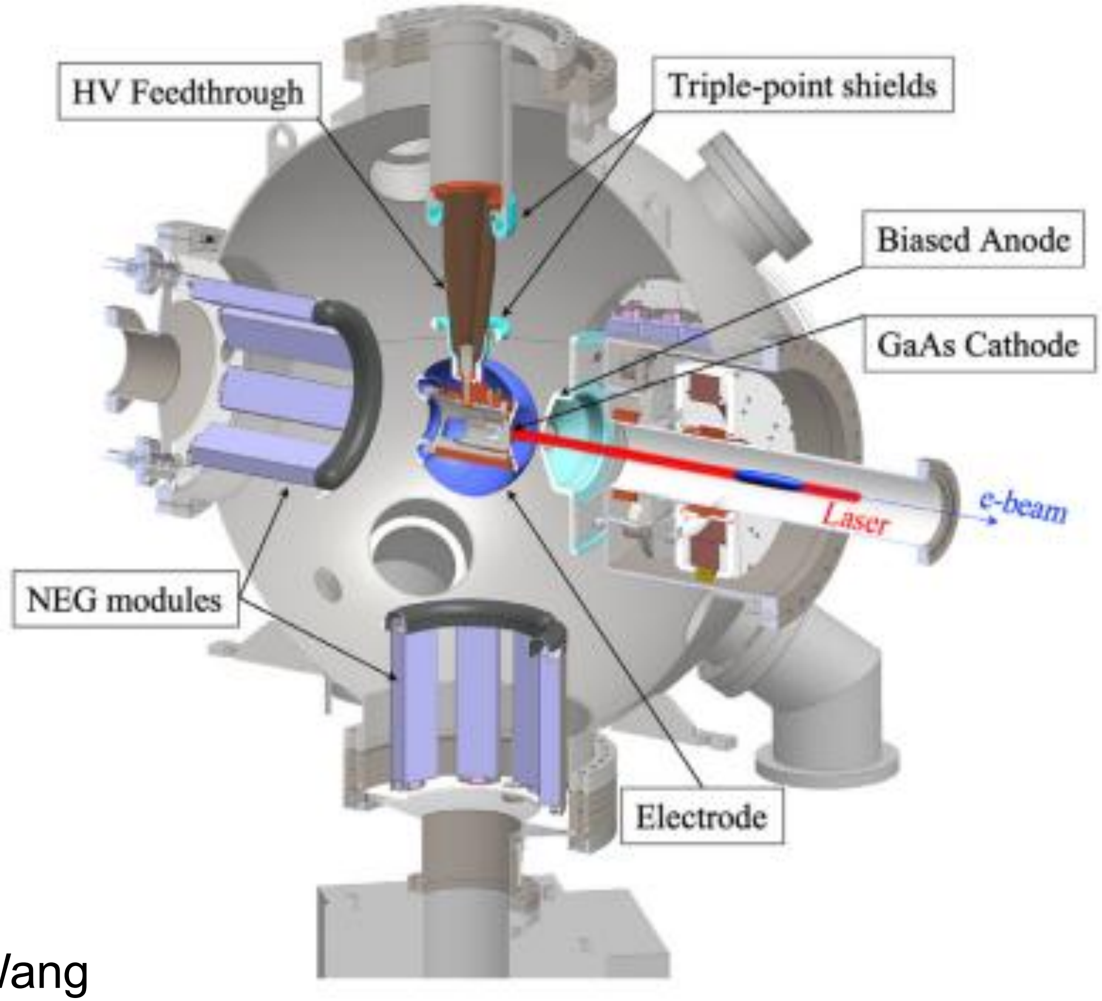
90.7 km double ring, full-energy $e^{\pm}$ injection,
> 1 A beam current (at the Z),
injection rate Hz, every min. into same bucket,
polarised $e^{\pm}$ pilot bunches

EIC



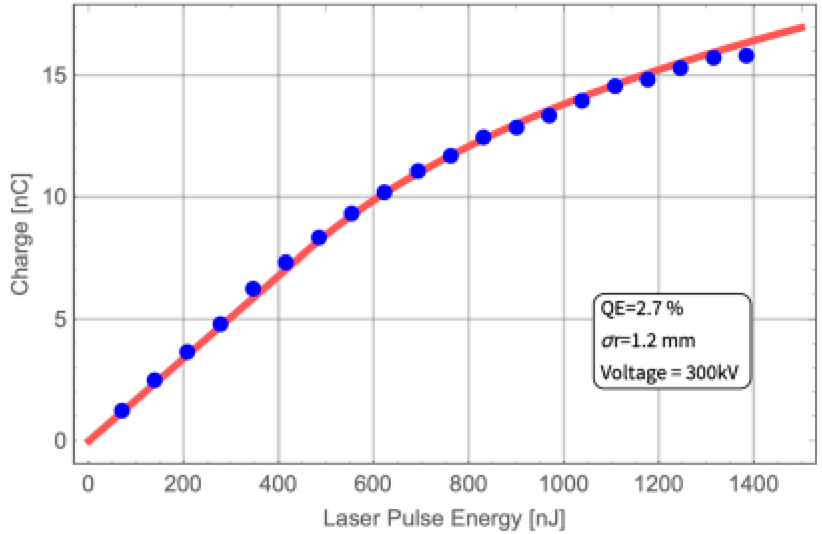
3.83 km double ring,
full-energy e^{-} injection,
> 2 A beam current (at 10 GeV)),
injection rate 1 Hz,
every 1 or 3 min into same bucket,
polarised e^{-}pilot bunches

polarised electron gun



E. Wang

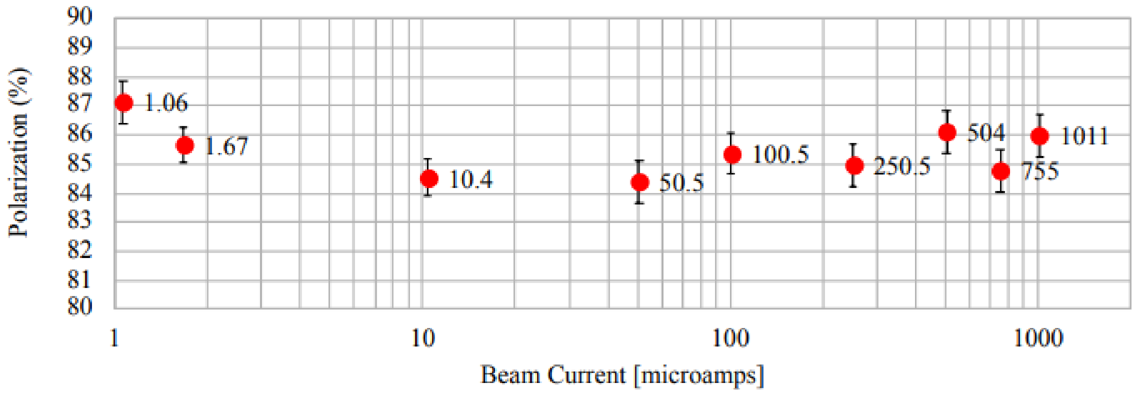
Cross-sectional view of the BNL HVDC gun for EIC polarised e- source (7 nC required) **300-350 kV**



Space charge limit for the EIC polarized gun with a 6 mm diameter laser spot. Blue dots are measurement and the red curve is the fitted curve

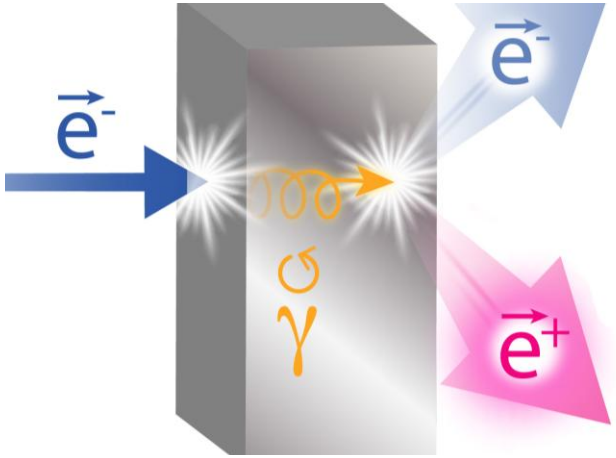
GaAs/GaAsP strained-superlattice photocathode at JLAB

J. Grames

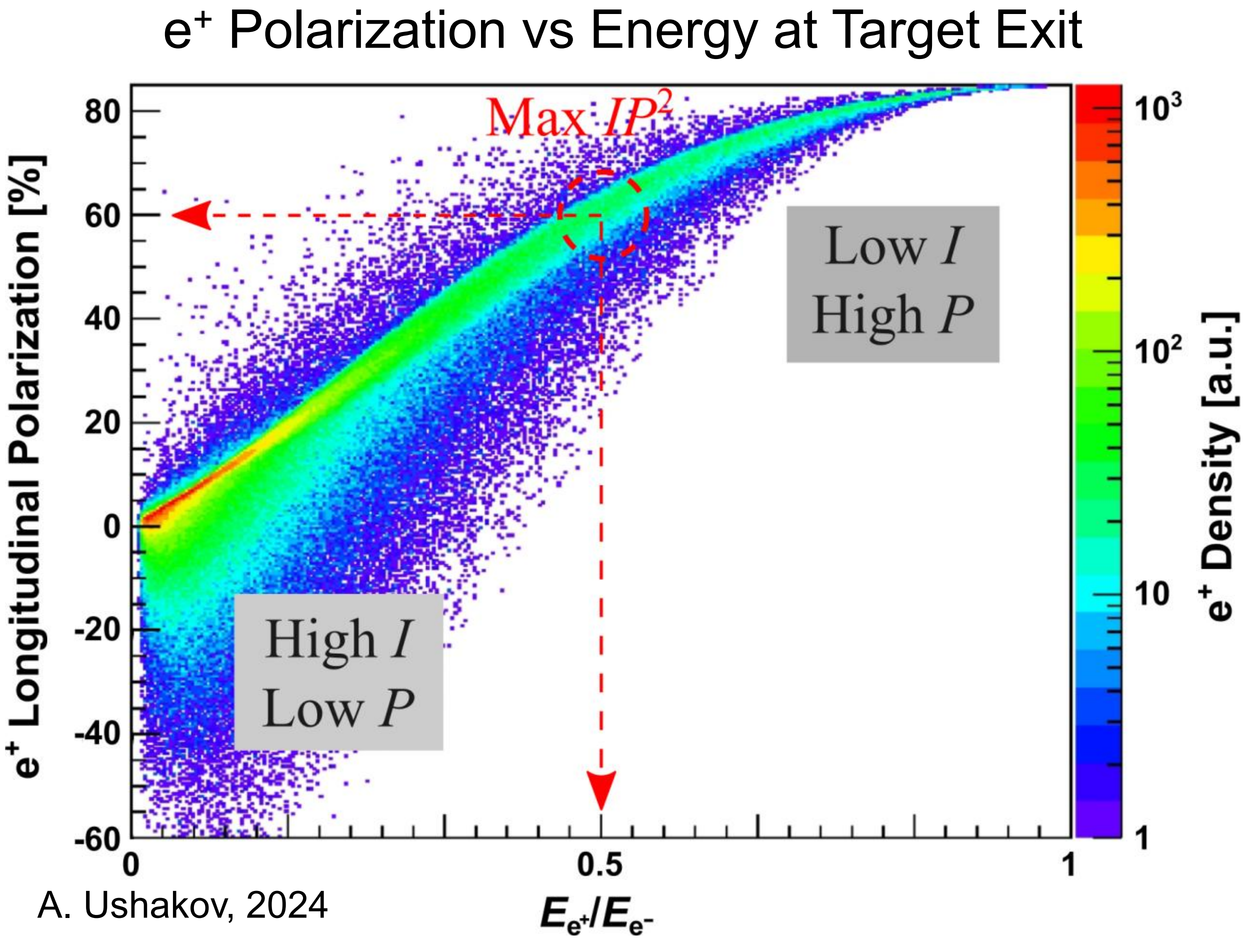


Spin polarization measurements of a GaAs/GaAsP photocathode demonstrate high spin polarization spanning three decades of beam current from 1 μA to 1 mA

polarised positrons: generation w. polarised e^- beam



Ce^+BAF project



A. Ushakov, 2024

For max Figure-of-Merit ($FoM = IP^2$, where I is e^+ current and P is e^+ polarization):

- Optimal e^+ energy at target exit is about half of e^- drive beam energy.
- e^+ polarization at half of e^- energy is ~60%.
- 4 mm is an optimal thickness of W target for 120 MeV e^- beam

S. Habet et al., "Characterization and optimization of polarized and unpolarized positron production", Tech. Rep. JLAB-ACC-23-3794, Feb. 2023. doi:10.48550/arXiv.2401.04484

a few percent e^+ polarisation attainable for FCC-ee

Ivan Koop, 2016

polariser ring for positrons at FCC-ee

- Optimal energy is about 1 GeV. It is large enough to suppress the Touschek and small enough not radiate too much SR.

$$\left.\begin{aligned} \tau_{ST}^{-1} &\sim B^3 E^2 \frac{\rho}{R} \\ \langle \dot{E} \rangle &\sim B^2 E^2 \frac{\rho}{R} \end{aligned}\right\} \rightarrow \quad \Delta E_{\text{Polarization}} = \langle \dot{E} \rangle \tau_{ST} \sim \frac{1}{B}$$

- SLAC was operating successfully 1.2 GeV damping ring for years!

- From polarization point of view it is preferable to use the high field bends instead of asymmetric field wigglers. Currently we rely on use of B=5.5 T identical short dipole magnets (about 15^0each) .

- But SC wigglers are better developed. Could also be an option!

Energy, E	1	GeV
Circumference, C	22	m
Average radius, R	3.5	m
Bending radius, ρ	0.6	m
Bending field, B	5.5	T
Energy loss / turn, U_0	145	keV
Momentum spread, σ_p	0.00155	
Number of e± per bunch, N	10^{10}	
Number of bunches, N_b	16	
Total beam current, I	350	mA
SR powrer	50	kW
Polarization time (Sokolov-Ternov), τ_{ST}	127	s
Polarization degree	70	%
Injection/Ejection time periodicity, T_0	10	s

Here we assume that every bunch spends in a ring $T_0 \cdot N_{b=}$=160 s before extraction.

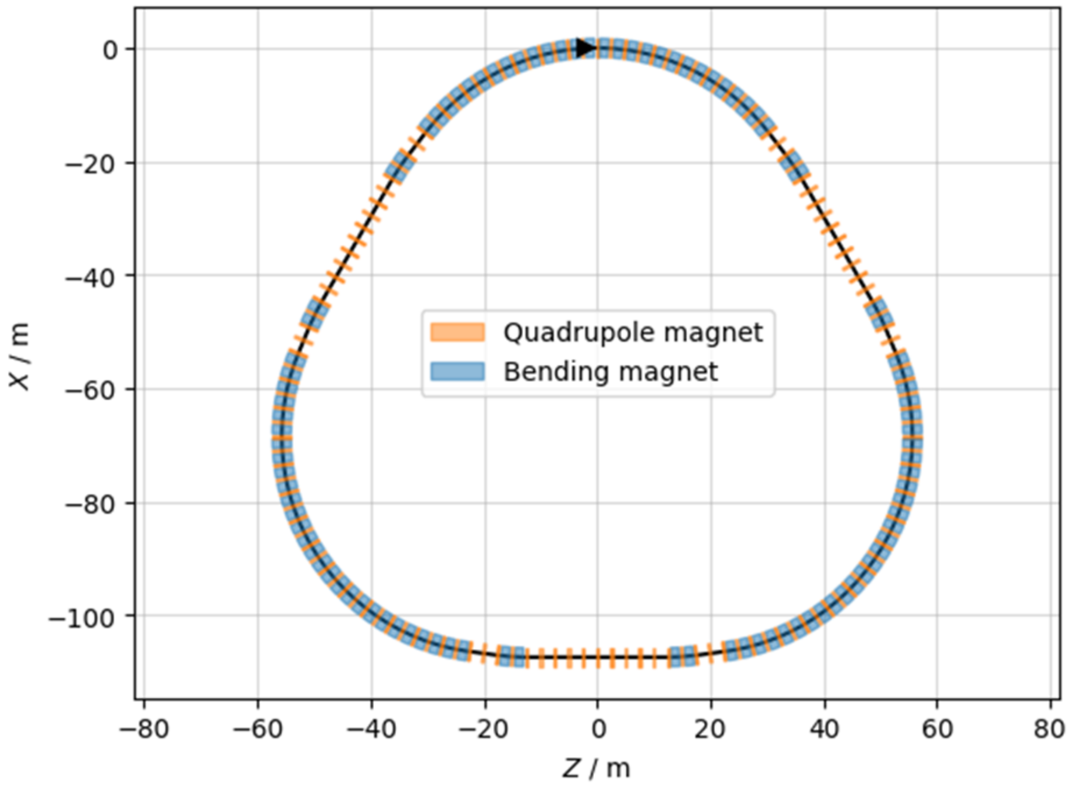
So, the polarization degree is high enough, in the order of 70%!

Every 10 s one bunch is assumed to be extracted for the energy calibration purposes only.

Use of high bending field is energetically beneficial to obtain certain polarization degree.

Ivan Koop

DR-scale polariser ring, 2025



three new polariser ring designs

Parameters	Design 1	Design 2	Design 3
Circumference [m]	345.3	348.97	237.0
Arc cell	FODO : $\pi/3$	FODO : $\pi/2$	FODO : $\pi/3$
Natural hor. emittance [nm.rad] (WGL on/off)	19.56 / 40.21	5.45 / 11.40	35.26 / 52.78
Bunch length [mm]	9.44	6.50	7.98
Damping times $\tau_{x,y}$ [ms]	12.71, 12.57	13.14, 13.09	5.63, 5.52

polarisation build up time ~0.3-1.0 h

- Polarization build up by the Sokolov-Ternov effect* :

$$\tau_{pol}^{-1} = \bar{w}^{\uparrow} + \bar{w}^{\downarrow} = \frac{5\sqrt{3}}{8} \cdot \frac{e^2\hbar}{4\pi\varepsilon_0(mc^2)^2} \cdot \gamma^5 \cdot \frac{1}{C}\int \frac{1}{|\rho(s)|^3}\, ds$$

$$P_{eq} = \frac{\bar{w}^{\uparrow} - \bar{w}^{\downarrow}}{\bar{w}^{\uparrow} + \bar{w}^{\downarrow}} = -\frac{8\sqrt{3}}{15} \cdot \frac{\int \frac{1}{\rho(s)^3}\, ds}{\int \frac{1}{|\rho(s)|^3}\, ds}$$

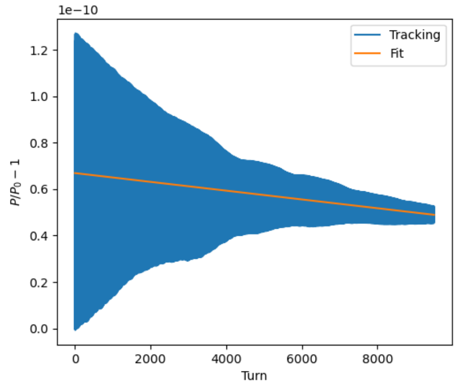
$\bar{w}^{\uparrow}$, $\bar{w}^{\downarrow}$: spin-flip transition rates due to synchrotron radiation

$\bar{w}^{\uparrow} \neq \bar{w}^{\downarrow} \Rightarrow$ net polarization builds up over time

Asymmetric Wigglers

$$\langle B^3 \rangle = \frac{B_1^3 L_1 + B_2^3 L_2}{L_1 + L_2} \neq 0 \quad \Rightarrow \quad \text{Efficient polarization}$$

machine w/o errors



Depolarization time from fit $\tau_{depol} \approx 6 \times 10^8\, s$

Siddhi Keskar, Christian Carli

Lecture 4 – FCC-ee technologies

4.0 Motivation

4.1 SRF cavities

4.2 cryogenics

4.3 RF power sources

4.4 CC vs LC

4.5 vacuum system, photons, NEG, shielding

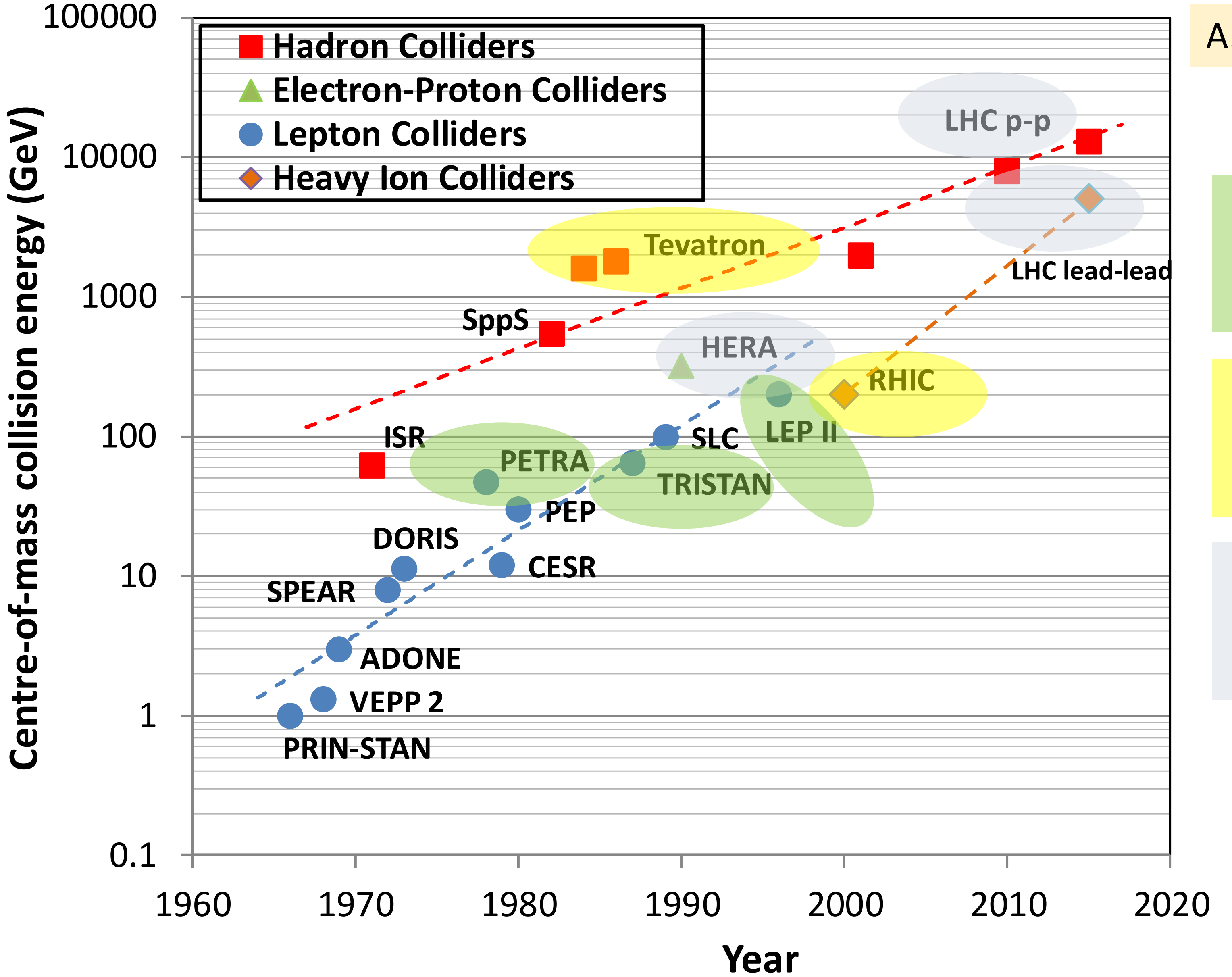
4.6 collimation

4.7 beam diagnostics

4.8 HTS magnets – 4.9 FCC-hh

4.0 Motivation

colliders constructed & operated



A. Ballarino

Colliders with superconducting RF system

Colliders with superconducting arc magnet system

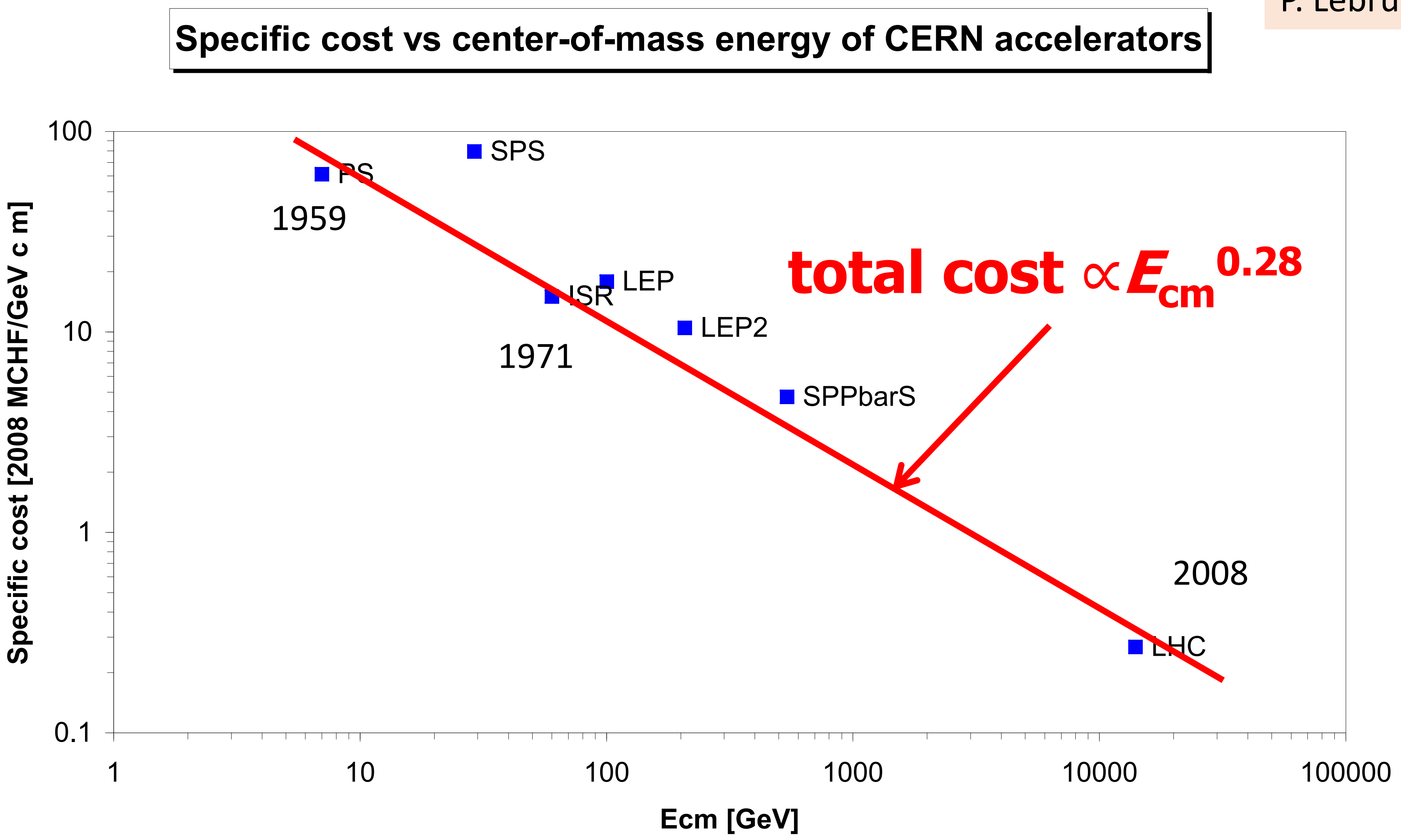
Colliders with superconducting magnet & RF

advances by new technologies and new materials

(important example SC)

cost / sustainability

P. Lebrun, RFTech 2013



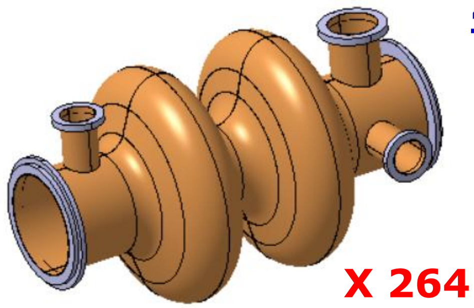
new concepts and new technologies

cost per collision energy greatly reduced

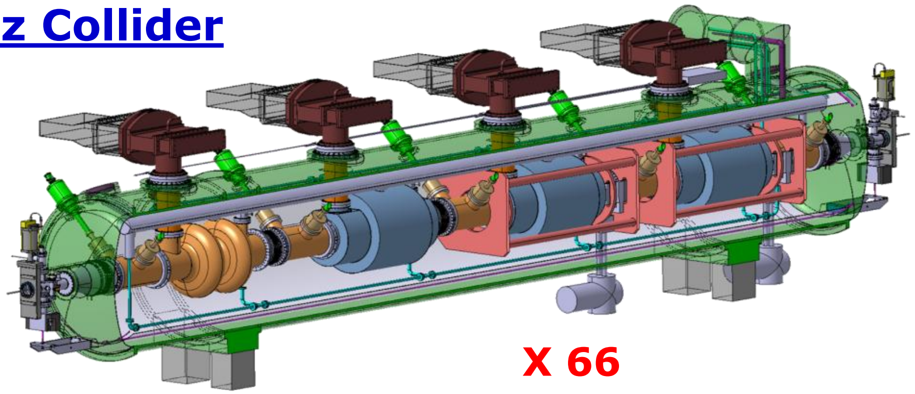
4.1 SRF cavities

superconducting RF system

400 MHz Collider



X 264



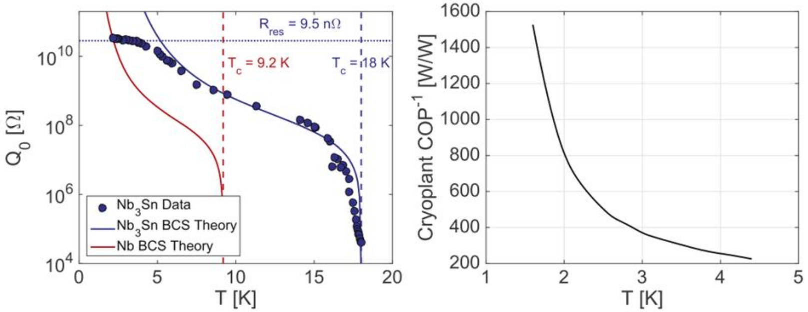
X 66

Superconducting elliptical cavity

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

400 MHz Cryomodule

Nb_3Sn on Cu coating

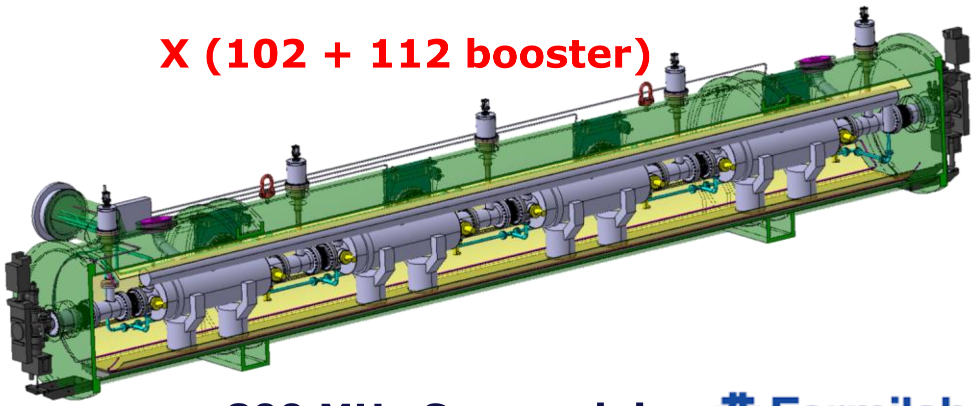


Move from Nb @2K to Nb_3Sn @4.5 K would reduce cryogenic power by factor 3

800 MHz Collider + Booster

X (408 + 448 booster)

X (102 + 112 booster)



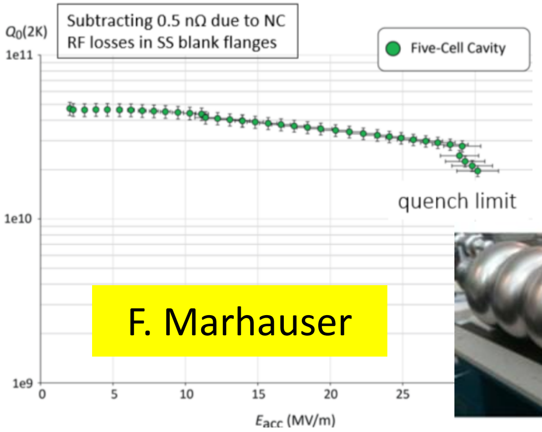
Superconducting elliptical cavity

- 800 MHz, 6-cell, bulk Nb
- Nb_3Sn if R&D is successful

800 MHz Cryomodule

Fermilab

Jefferson Lab



F. Marhauser

5-cell 800 MHz, bulk Nb prototype (2018)

FCC-ee different running modes

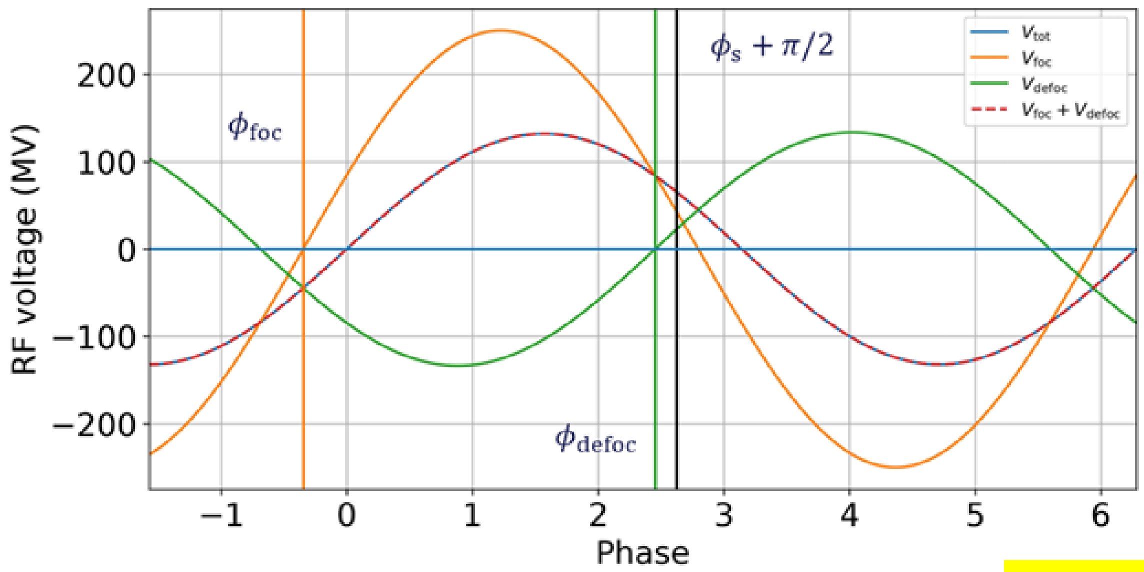
	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	**1294**	**0.079**
W	80	135	1.05
H	120	**26.7**	**2.1**
$t\bar{t}$	182.5	**5**	**11.3**

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)

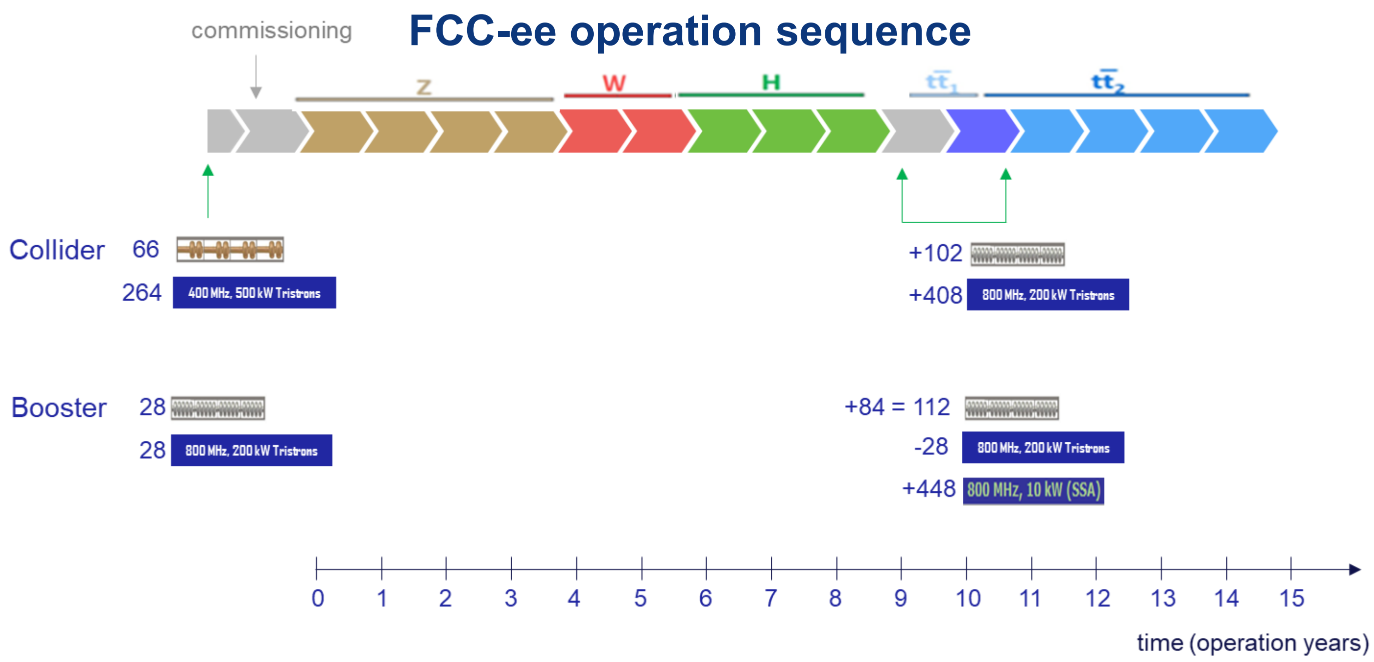
RF reverse phase operation

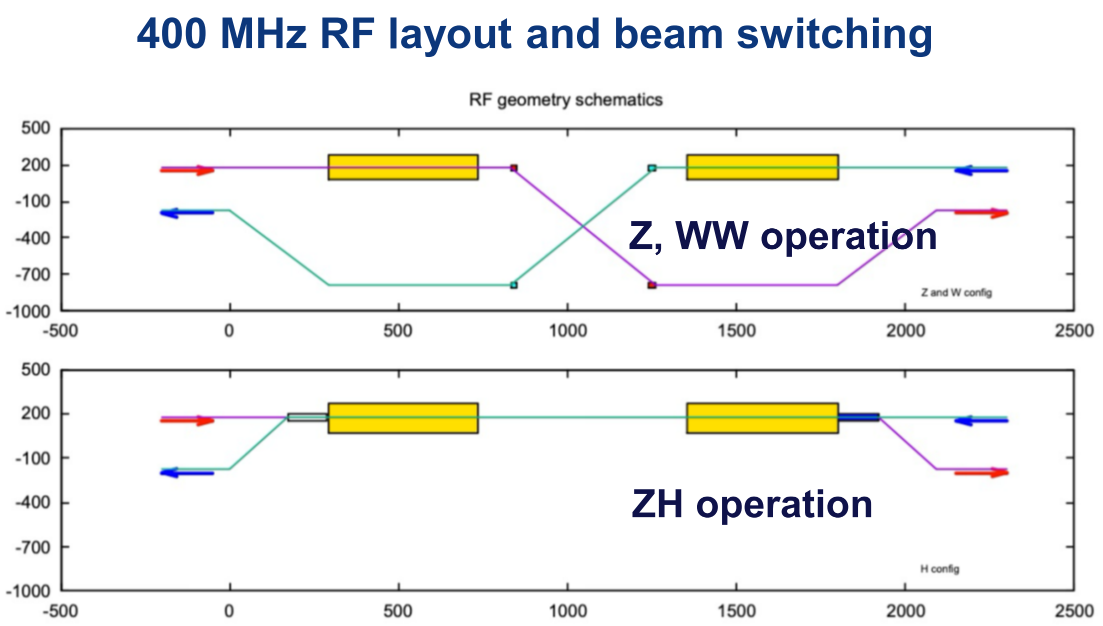
at the Z pole



I. Karpov

FCC-ee operation sequence and SRF concept





- **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**
- **6-cell 800 MHz SRF system for ttbar operation in collider, and for booster at all modes**

cryo power, Q value, total power

$$Q = \omega E_{\mathrm{stored}} / P_{\mathrm{dissipated}}$$

$$P_{\mathrm{dissip}} = \frac{U_a^2}{\left(\frac{R}{Q}\right) Q}, P_{\mathrm{beam}} = U_a I_b .$$

$$\begin{aligned} P_{\mathrm{grid}} &= P_{\mathrm{cryo}} + P_{\mathrm{RF}} \\ &= \mathrm{COP} \cdot P_{\mathrm{dissip}} + \frac{1}{\eta_{\mathrm{RF}}} \Delta P_{\mathrm{beam}} . \end{aligned}$$

(from M. Seidel, ORE)

4.2 cryogenics

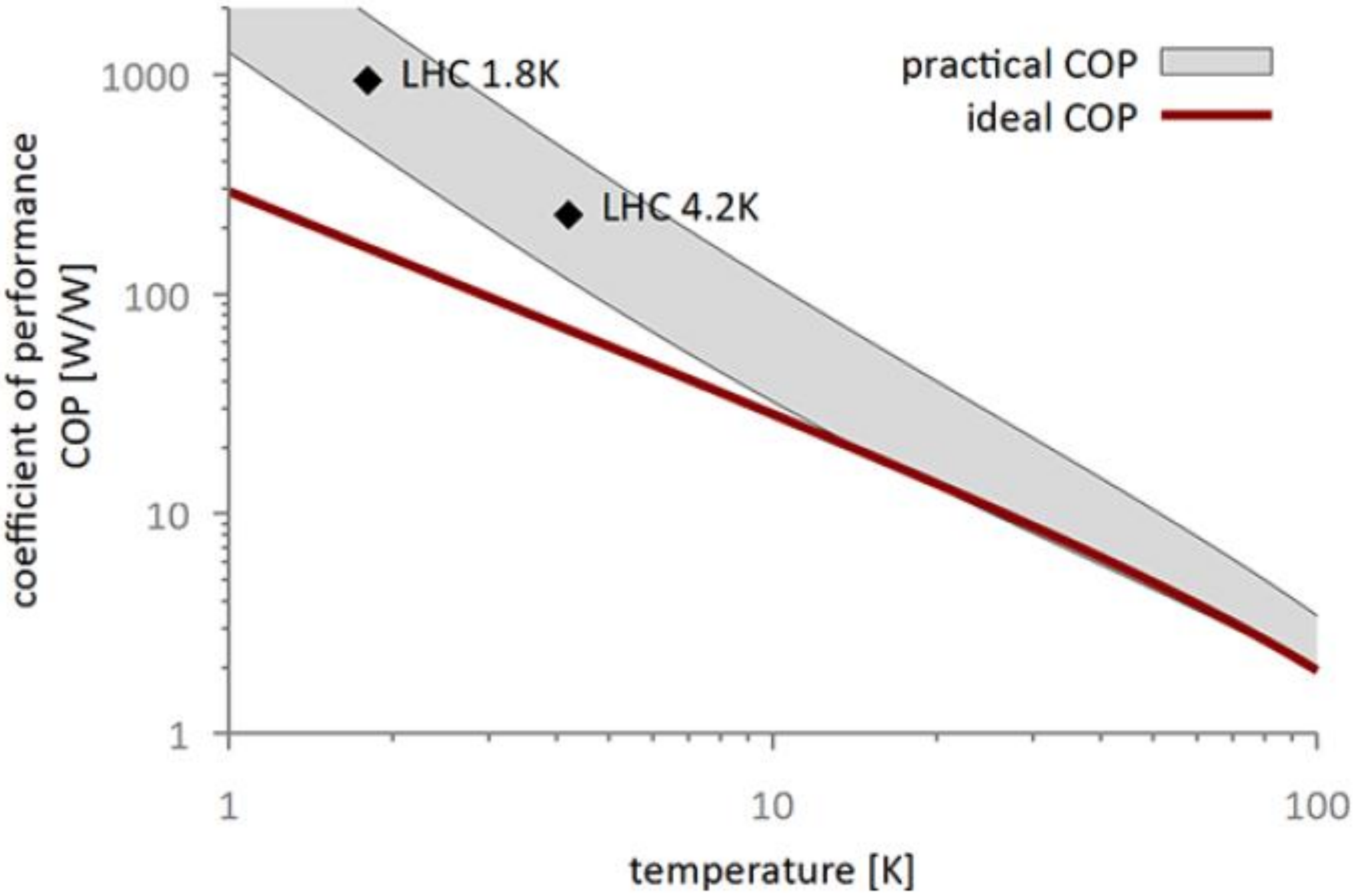
cryogenic efficiency

coefficient of performance (COP) relates applied work to the removed heat

ideal COP (Carnot):

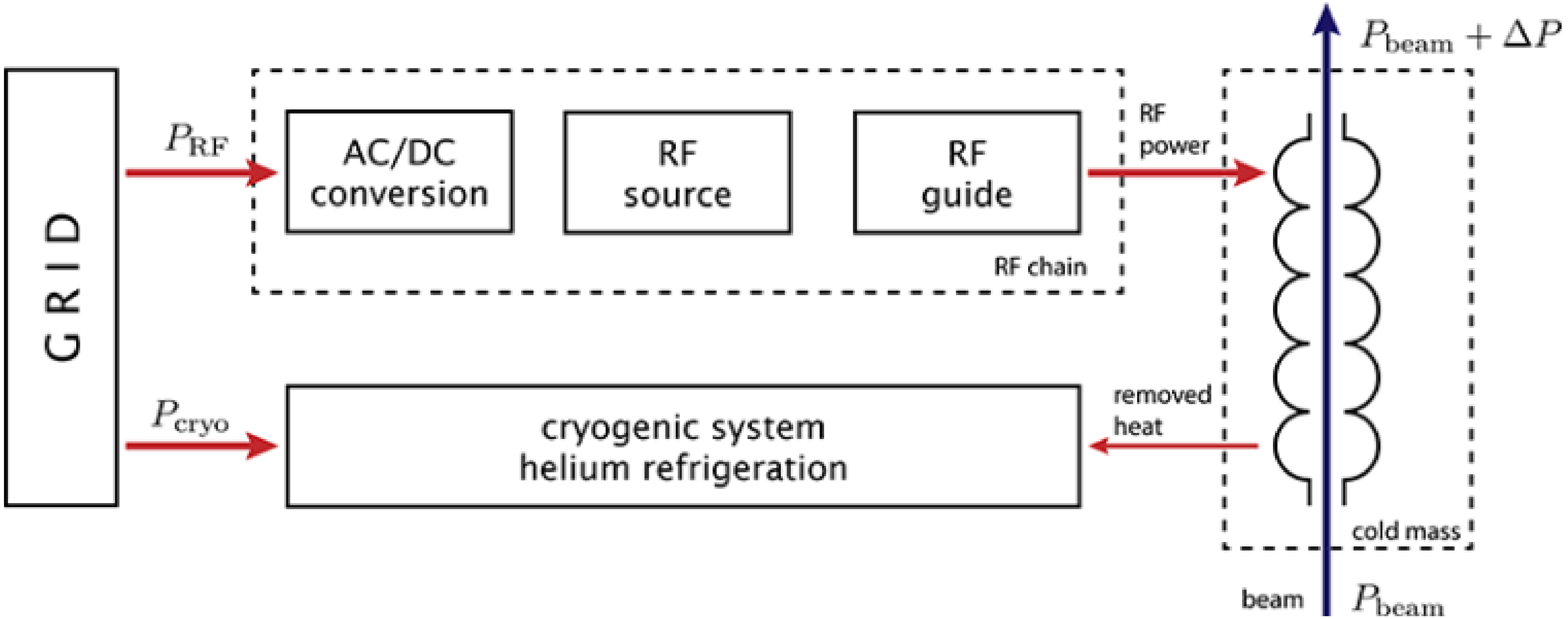
$$\mathrm{COP} = \frac{W_c}{Q_{\mathrm{in}}} = \frac{T_0 - T}{T}$$

Carnot efficiency = maximum possible thermal efficiency for any heat engine operating between two temperatures



The best possible COP factor derived from Carnot efficiency is shown together with a range of practically achievable COP. The two points from LHC are taken from Claudet et al. (2013). (M. Seidel, ORE)

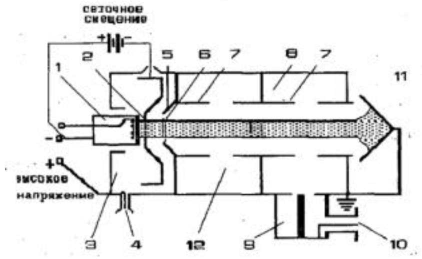
Basic power flow for the FCC-ee SRF system



(from M. Seidel, ORE)

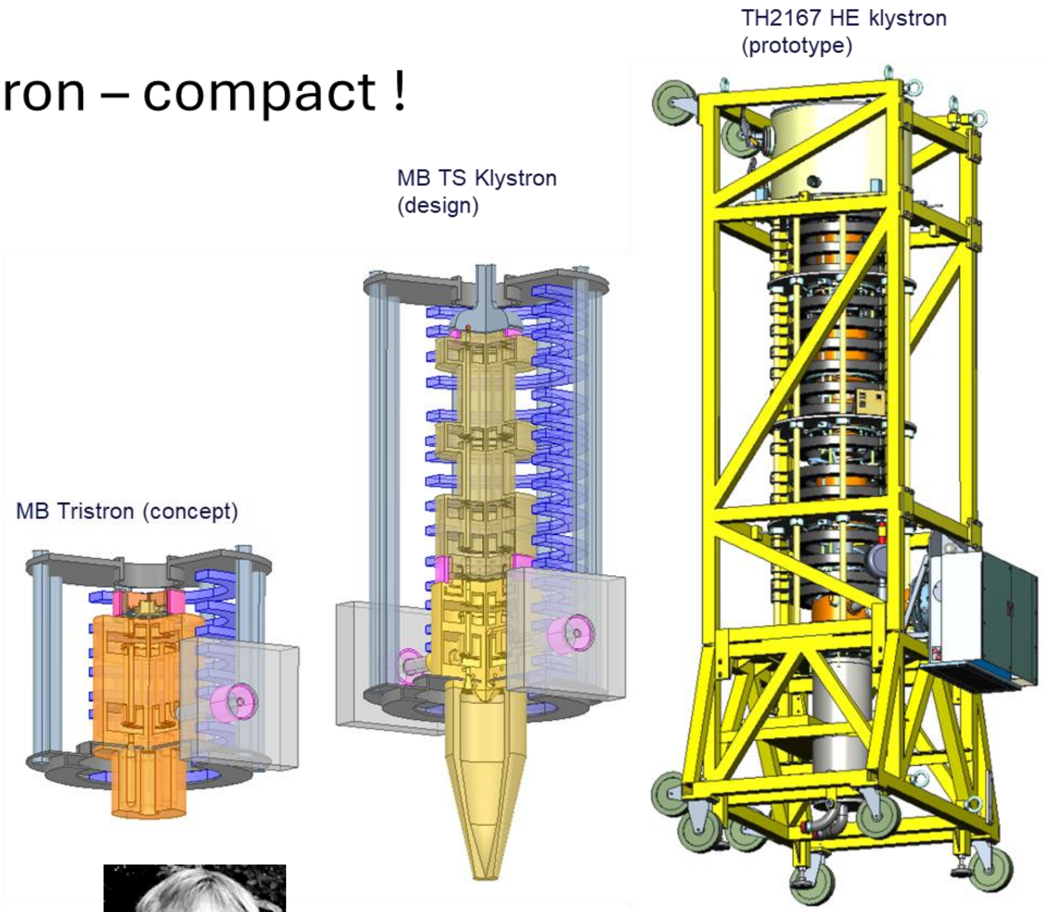
4.3 RF power sources

efficiency!

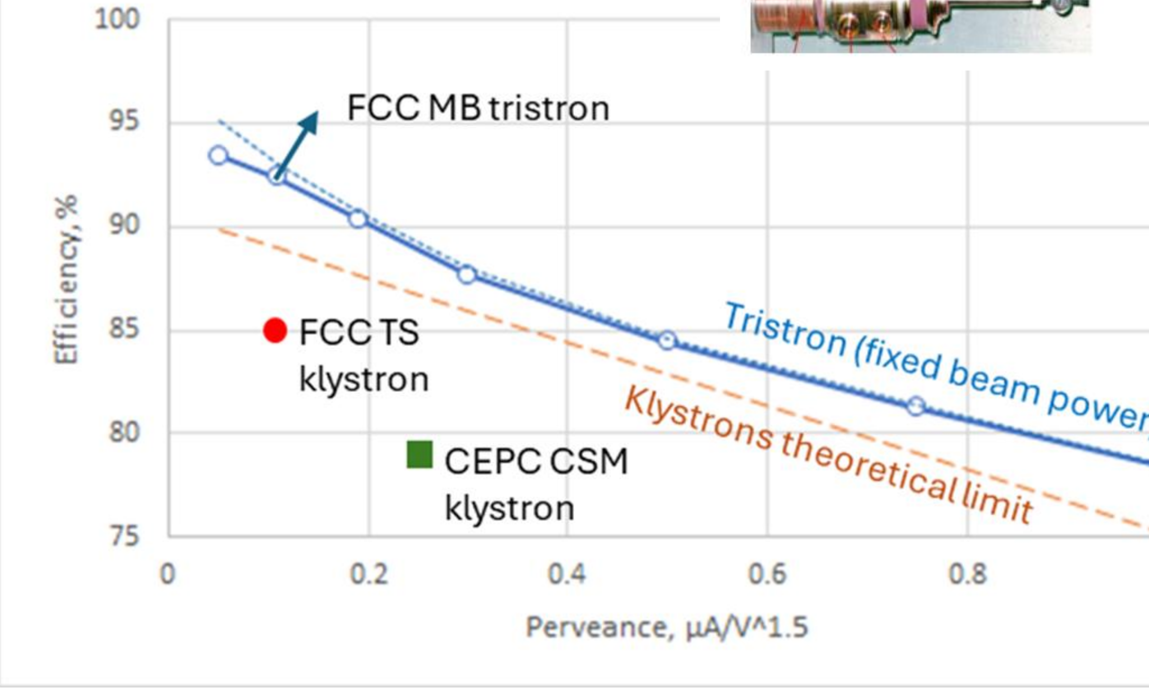


Tristron (A.D. Sushkov et. al. 1967)
MB Prototype tested in 1997, V. Tsarev:

MB tristron – compact !



MB tristron – efficient !



I. Syratchev

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

power considerations

continually supplying circulating beam with

P_{SR}=100 MW power (SR losses) requires

wall-plug power $P_{wall}=P_{SR}/\eta_{RF}$

with η=conversion efficiency wall-plug → beam

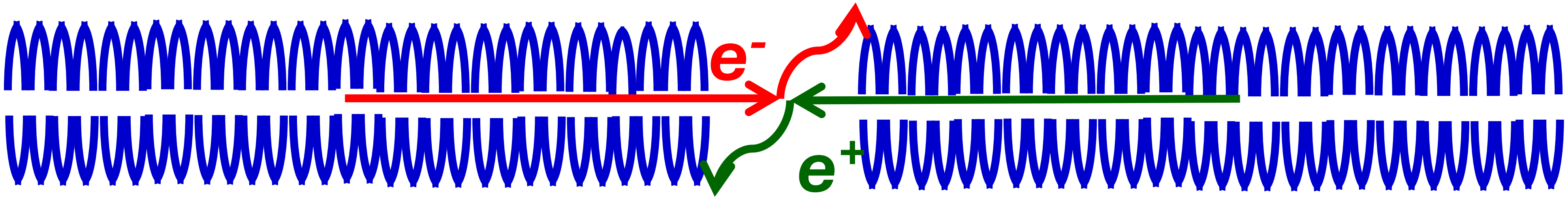
FCC target: $\eta_{RF} \geq 75\%$

note: cw RF systems for storage rings are
more efficient than those for pulsed linacs

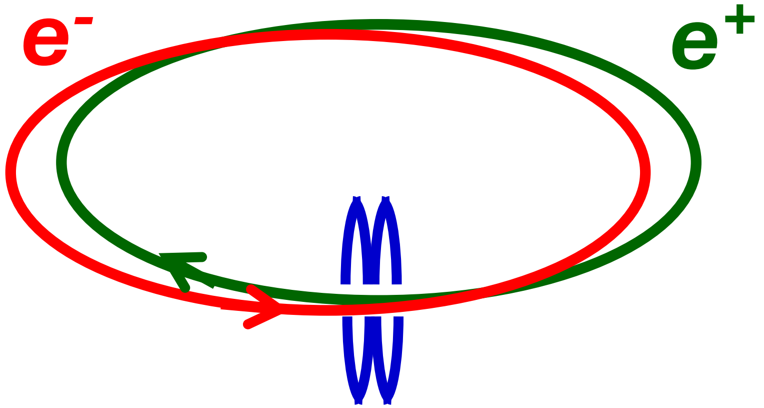
4.4 LC vc CC

energy transmitted to beam per collision

ILC: long RF sections w 2 x 125 GV voltage



- **both beams lost after single collision**
- **RF must supply full beam energy for each collision**



FCC-ee

- **beams collide many times, e.g. 4x / turn**
- **RF compensates SR loss (~1% E_{beam} / turn)**

difference in #collisions / (beam energy) ~ 300x

collider luminosity & wall-plug power

$$L \approx n_{IP} \frac{f_{rev} n N^2}{4\pi\sigma_x\sigma_y} \approx \frac{1}{4\pi} \mathrm{P}_{\mathrm{wall}} \mathrm{N}\eta \frac{1}{\left(\frac{\Delta \mathrm{E}_{\mathrm{beam}}}{\mathrm{IP}}\right)} \frac{1}{\sigma_x \sigma_y}$$

FCC-ee:

- higher bunch charge *N* (FCC-ee ~10x ILC charge / bunch)
- several IPs (n_{IP}=4)
- 3-4 times higher wall-plug power to beam efficiency η
- ΔE_{beam}/IP ~300 (instead of 1)

→ total factor 10x4x300~12000

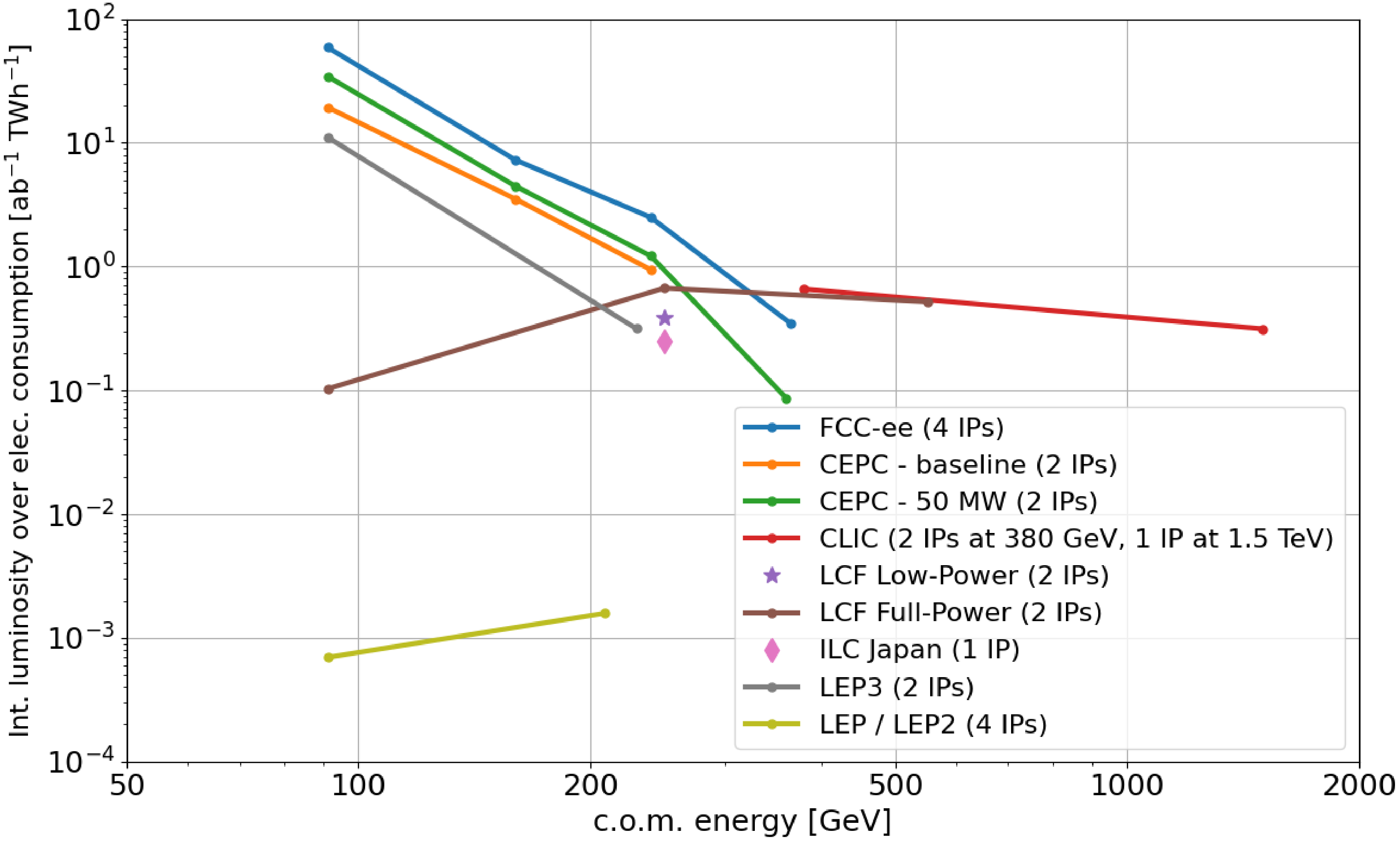
ILC:

- ~200x smaller IP spot size (smaller emittances and β^*'s)

→ for equal wall plug power *FCC-ee-H* has ~50x times more luminosity than *ILC-H*

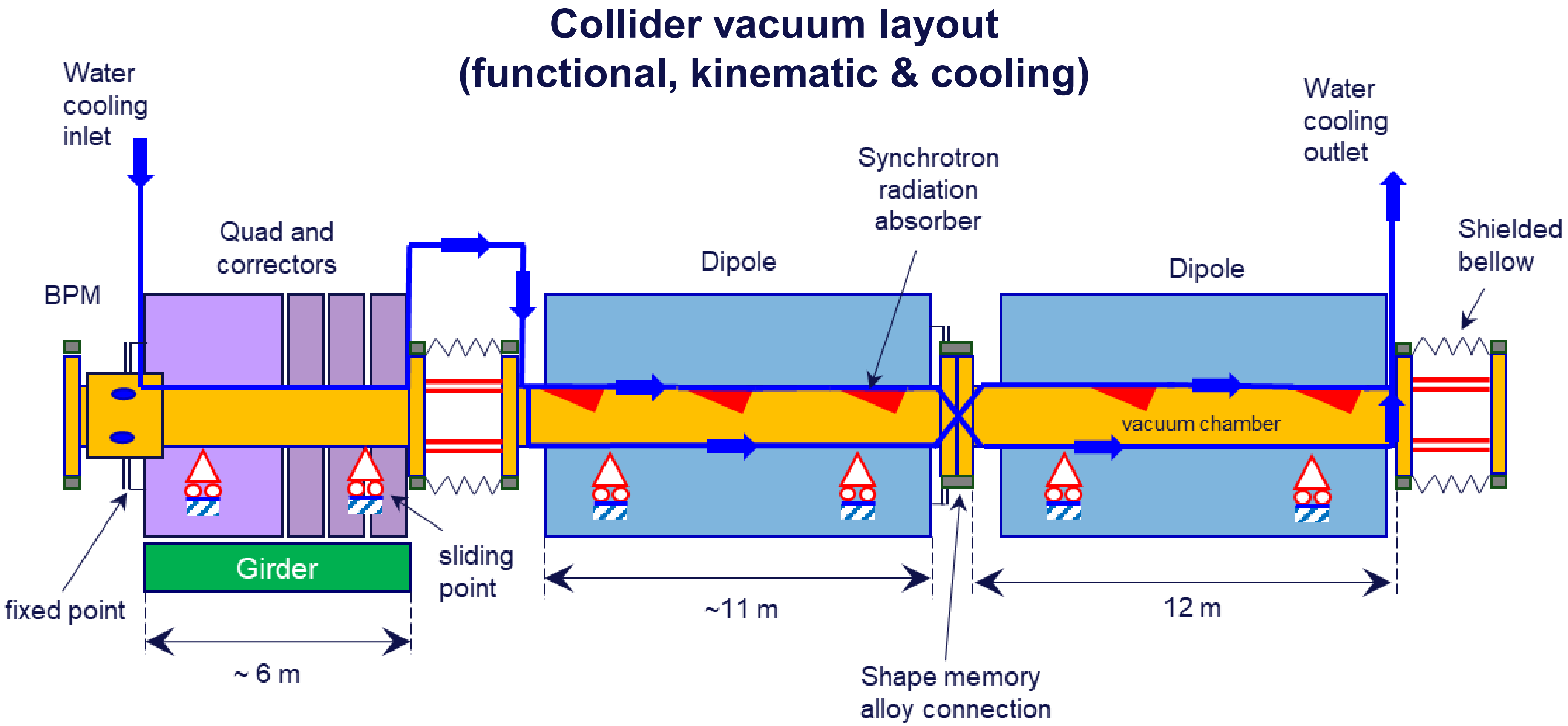
collider luminosity per wall-plug power

European Strategy Symposium, June 2025



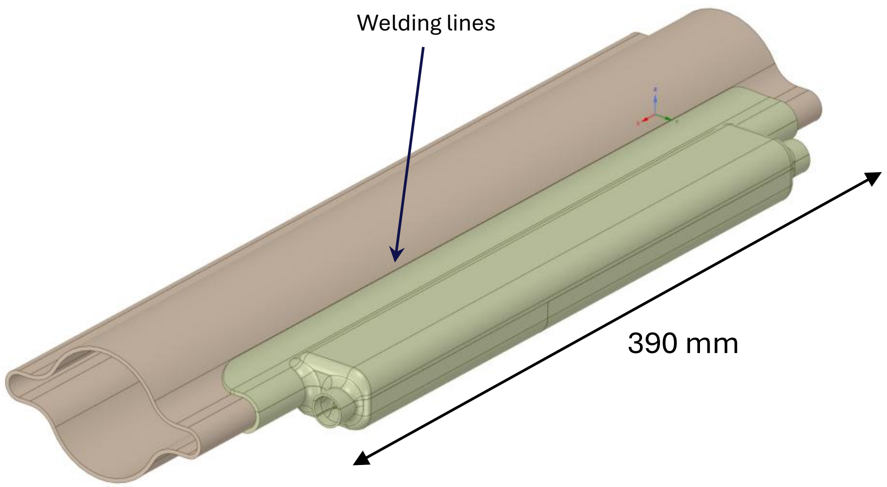
4.5 vacuum system

M. Morrone



- Synchrotron radiation absorbers are installed in dipoles, shielding also the interconnections and quad/correctors.

SR absorber

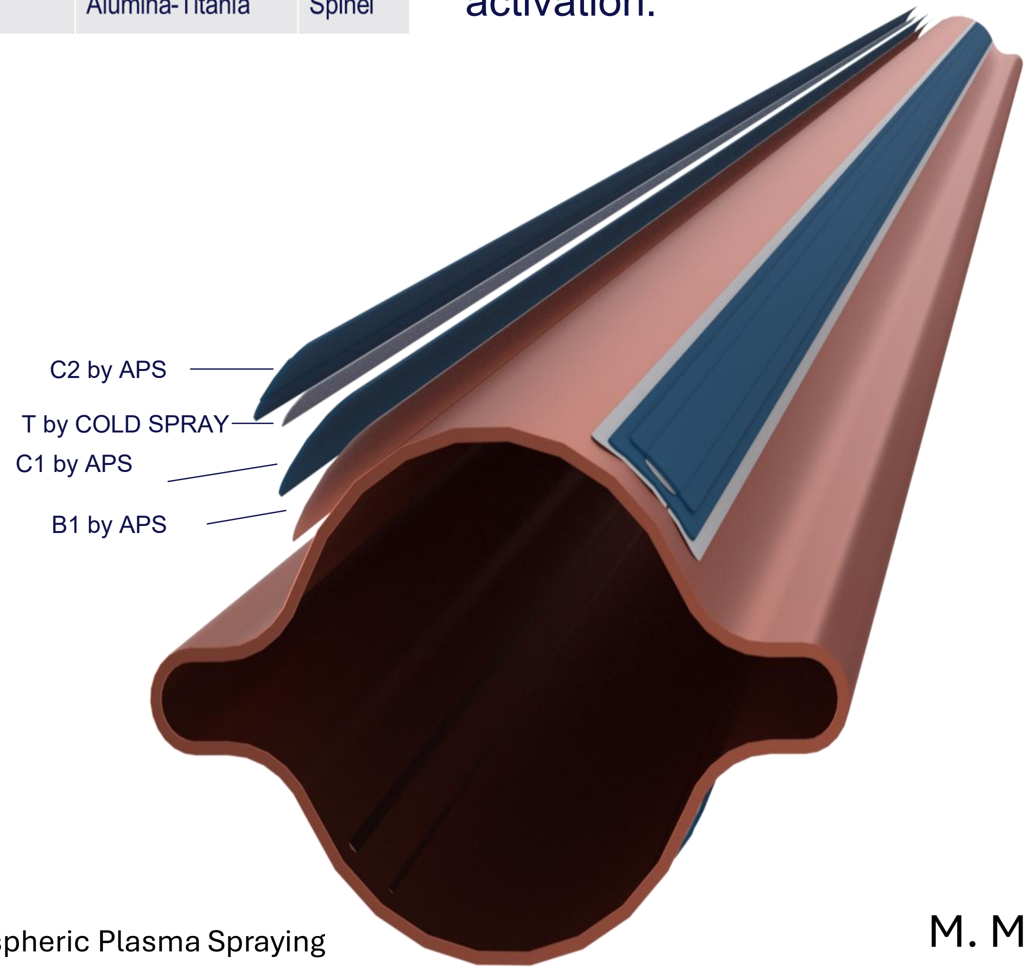


- High local heat deposition (~ 3.5 kW on average and 4.5 kW max) to be absorbed by each absorber → an efficient cooling system is needed.
- A high heat transfer can be achieved by twisted tape cooling channels (to increase turbulence) thanks to 3D printing .
- 5 absorber per half arc cell distanced 5-6 m are considered
- Sawtooth profile to reduce photon reflection and photoelectron generation.

bake out system

Layer	Thickness µm		Material	
B	100		NiCr20	
C1	300	500	Alumina-Titania	Spinel
T	200		Ti grade 4	
C2	500		Alumina-Titania	Spinel

Thin (up to 1.3 mm) and permanent rad-hard heating element is required to heat the collider vacuum chamber to 230 °C +/- 20 °C for NEG activation.

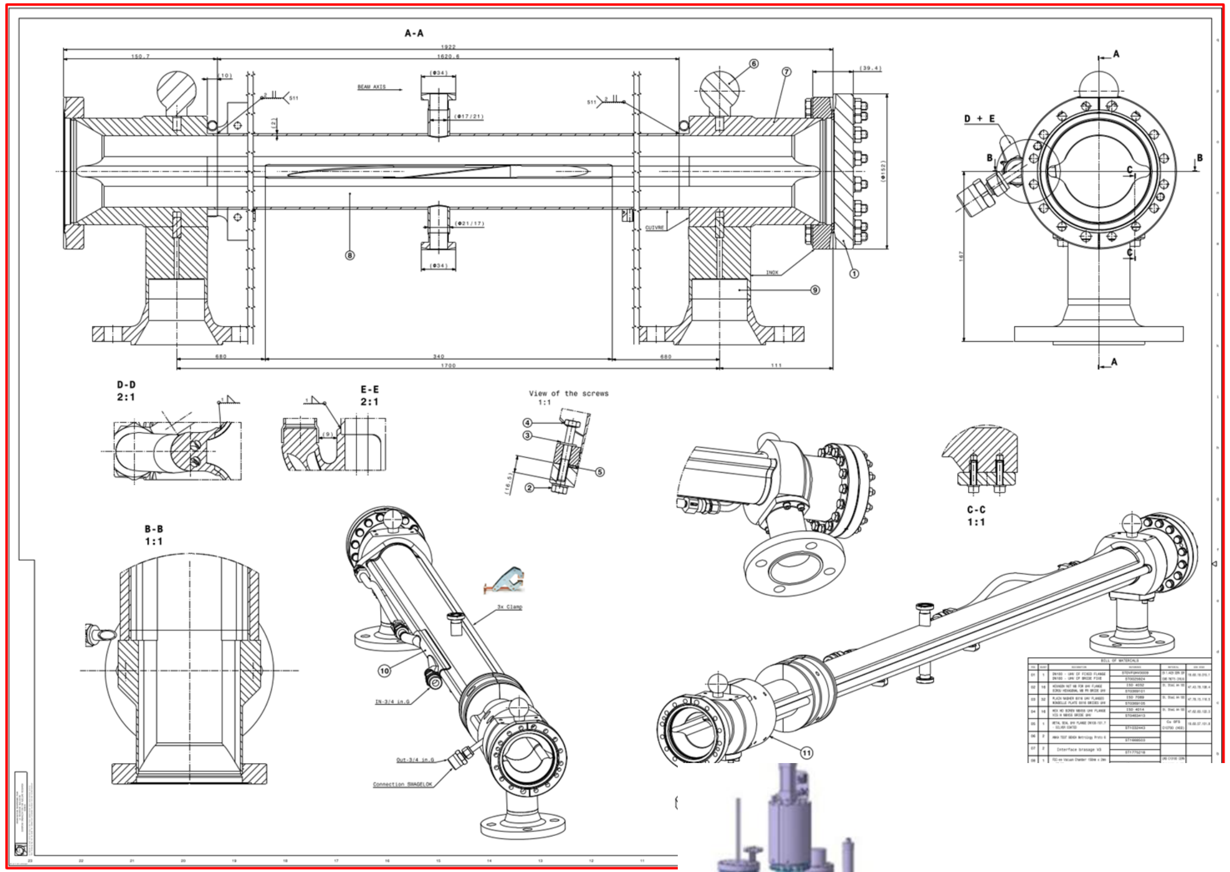


APS = Atmospheric Plasma Spraying

M. Morrone

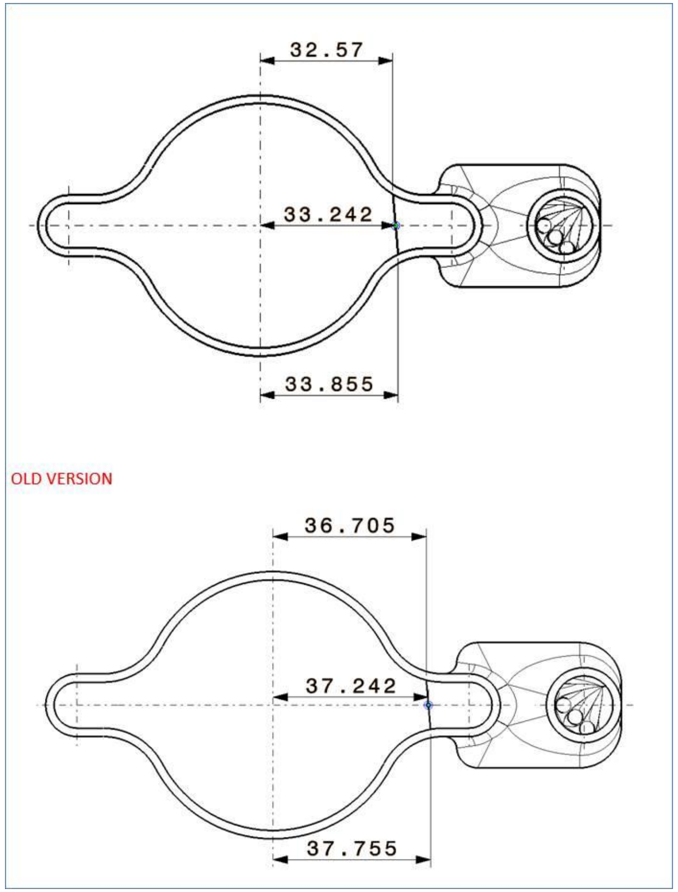
collider vacuum system with photon stop

2m-long extruded prototype chamber with SR absorber

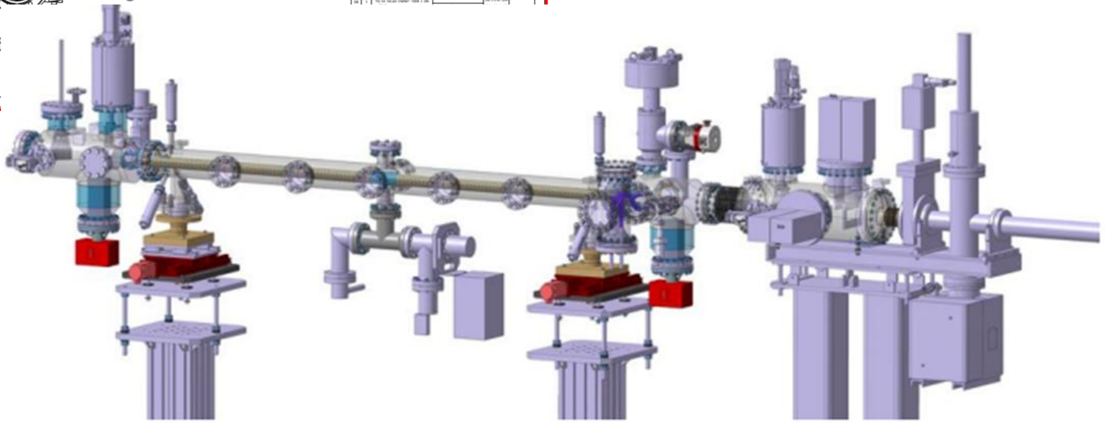


BESTEX crane moving test chamber (above) & BESTEX layout (below)

new absorber version with edge 4 mm closer to the beam axis



supports allowing direct installation at KIT (Karlsruhe) BESTEX for test with KARA SR, inc angular adjustments and theodolites for laser tracker

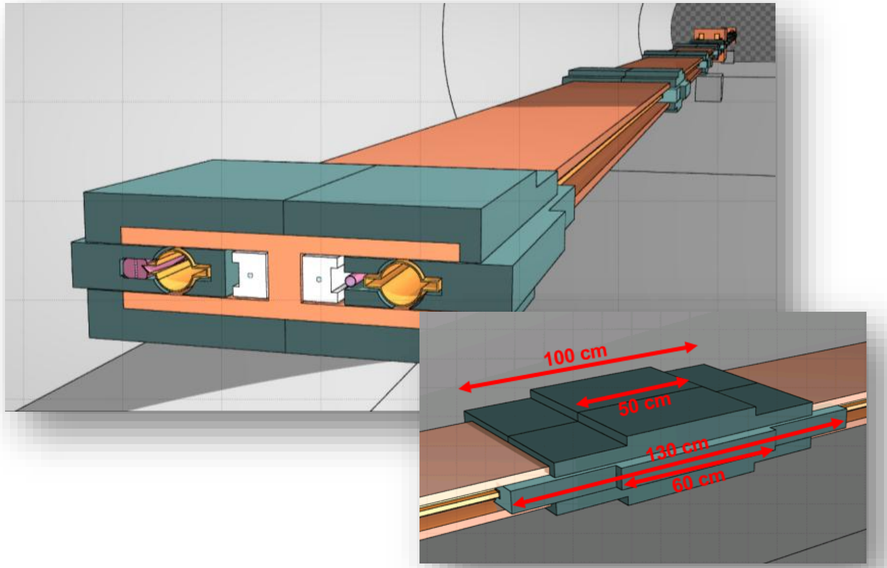


R. Kersevan

radiation shielding for FCC arcs

Shielding material for full ring (arcs)	
Shielding weight per stopper	400 kg
Photon stoppers per 20 dipole	10
# dipoles	2580
Total weight	10320 tons

Ionizing dose in tunnel is a concern for equipment: the **SR photon stoppers** in dipoles need to be ***enclosed by*** **top/bottom shielding plates** and **horiz. shielding inserts**



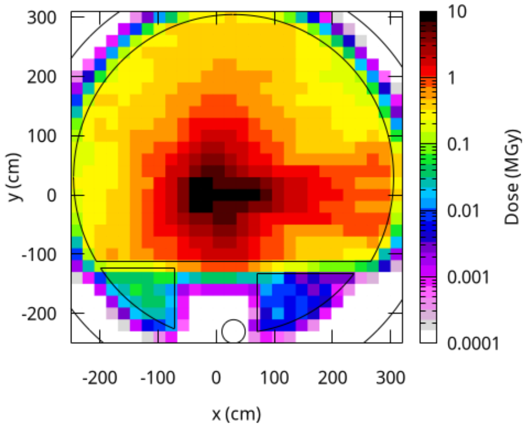
Progress since FCC Week 2024:

- **Converged on material choice for shielding**
  - Discarded W-alloys (18-19 g/cm^3) due to cost
  - Selected Pb94Sb6 (10.88 g/cm^3) as baseline material (reasonable pricing, common shielding material in industry, acceptable from RP perspective)
- **Optimization of shielding geometry**
  - Shape/dimensions adjusted to reduce photon leakage
  - With enhanced shielding efficiency, confident that we can achieve target dose levels for most cable trays (<100 kGy for full FCC-ee era, including ttbar)

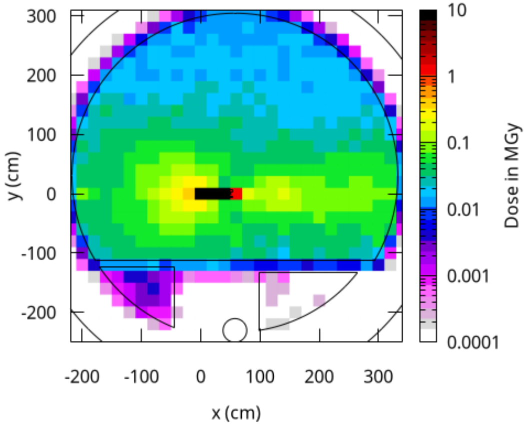
Technical points to be addressed in pre-TDR phase (until 2027): shielding integration and tolerances, supports, assembly procedures, ...

A. Lechner

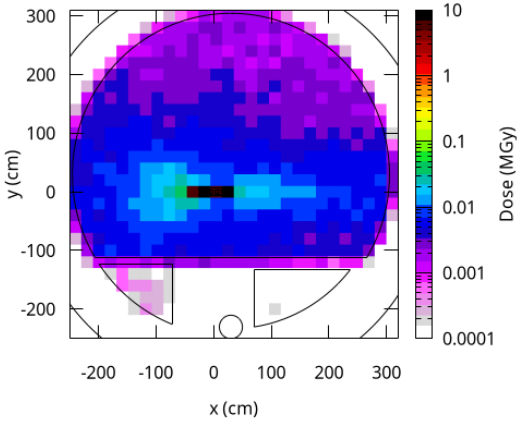
No shielding



With shielding (FCC week 2024)



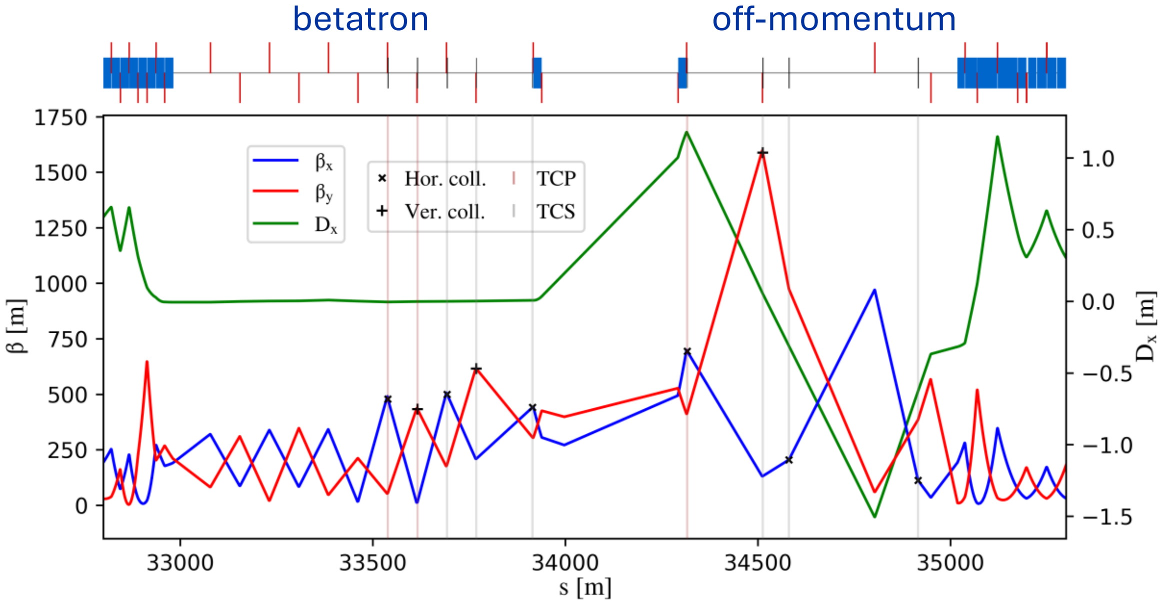
With shielding (Oct 2024)

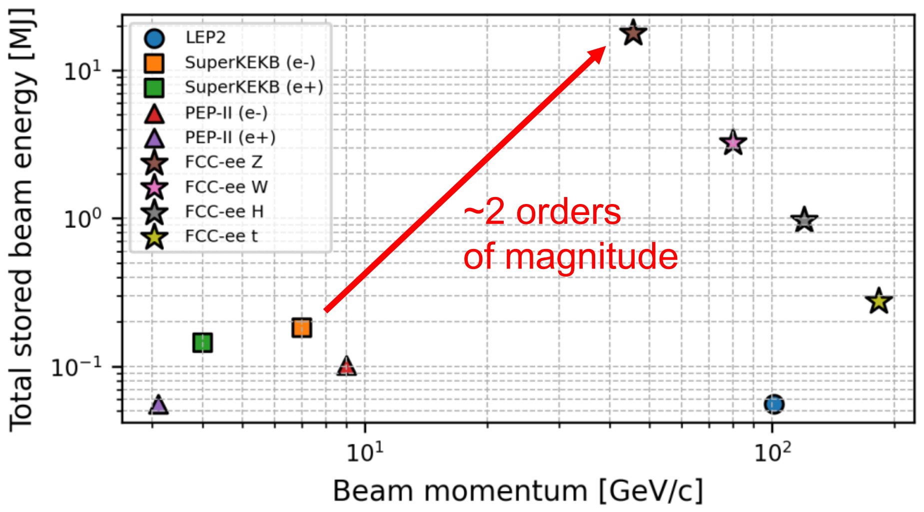


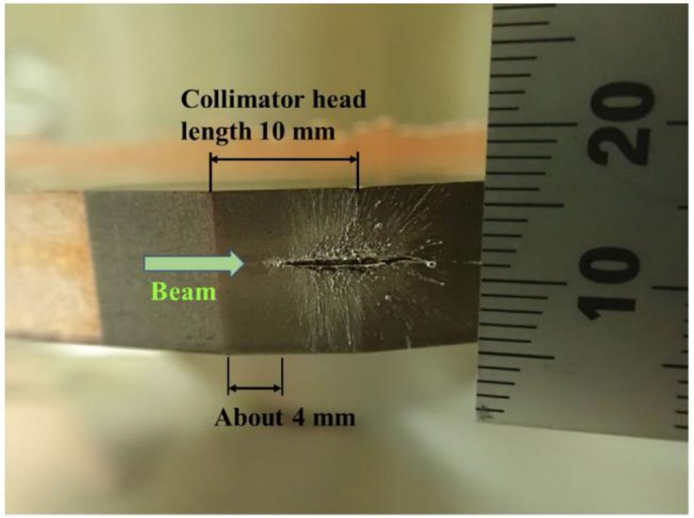
4.6 collimation

FCC-ee (*Z*) beam halo collimator parameters and settings

Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]	δ_{cut} [%]
TCP.H.B1	H	C-based	25	9.5	5.6	-
TCP.V.B1	V	C-based	25	50	1.4	-
TCS.H1.B1	H	Mo-based	30	10.5	6.2	-
TCS.V1.B1	V	Mo-based	30	65	2.2	-
TCS.H2.B1	H	Mo-based	30	10.5	6.5	-
TCS.V2.B1	V	Mo-based	30	65	3.6	-
TCP.HP.B1	H	C-based	25	18	12.5	1.1
TCS.HP1.B1	H	Mo-based	30	28	11.0	3.5
TCS.HP2.B1	H	Mo-based	30	28	8.3	1.3







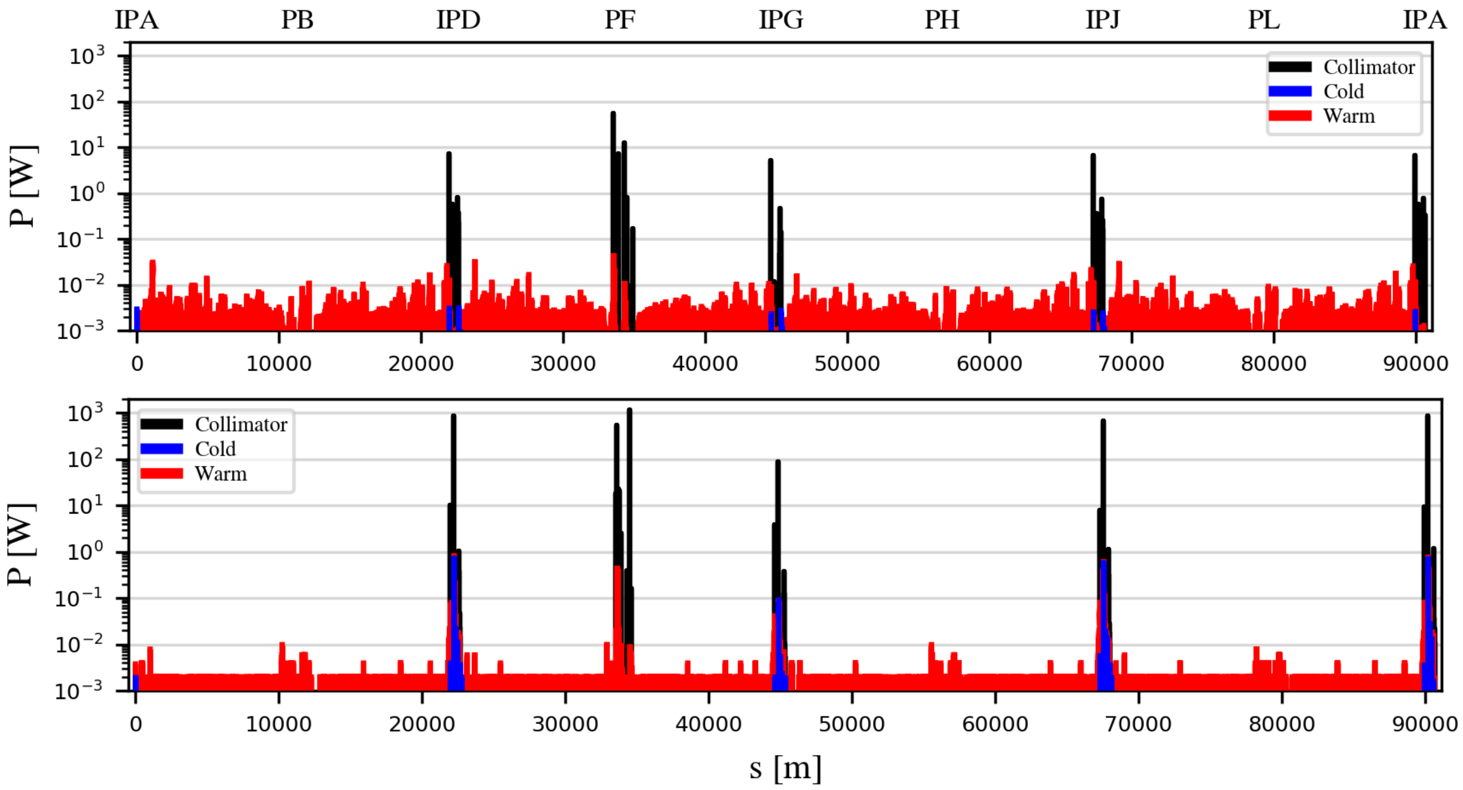
Damage to coated collimator jaw due to accidental beam loss in SuperKEKB – T. Ishibashi (talk)

G. Broggi

Beam-gas losses for the Z mode

*1h beam conditioning at full nominal current (1.27 A): pressure is expected to condition down further (up to a factor ~100) over time

- A scattering routine to simulate beam-gas interactions
- Based on realistic pressure and gas composition profile provided as input



Beam-gas bremsstrahlung

- Estimated lifetime after only 1h of beam conditioning*: **274 min**
- Expected to increase to > 100 h in a fully conditioned machine

Beam-gas Coulomb scattering

- Estimated lifetime after only 1h of beam conditioning*: **41 min**
- Expected to increase to > 10 h in a fully conditioned machine

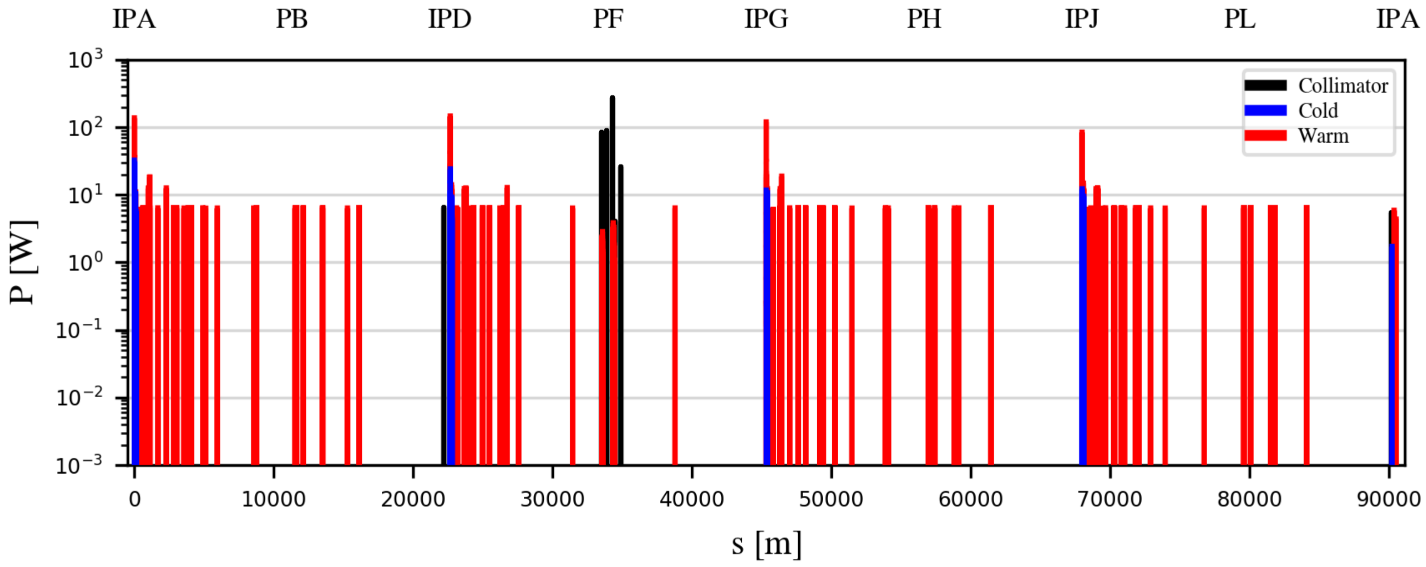
- At the FCC-ee beam energies, bremsstrahlung is expected to dominate beam-gas-induced lifetime degradation
  - BUT, under particular machine conditions, such as limited DA, even small angular deflections from a single Coulomb scattering event can be sufficient to drive particles beyond the DA limit

G. Broggi

Beam-beam losses for the Z mode

*quantum + lattice + BS + lum.

- Xsuite allows to set-up complex combined-effects simulations: beam-beam + collimation
  - ➢ Beam-beam kicks, radiative Bhabha, beamstrahlung in 4 IPs + detailed aperture and collimator model
  - ➢ Common technical insertion optics shows significant advantages
    - Absence of strong-vertical emittance blow-up previously observed (BB'24 talk)
    - Beam lifetime* in agreement with expectations: ~14 min vs. ~17 min without aperture and collimators
      - Primary collimator openings: 9.5σ (H plane), 50σ (V plane)



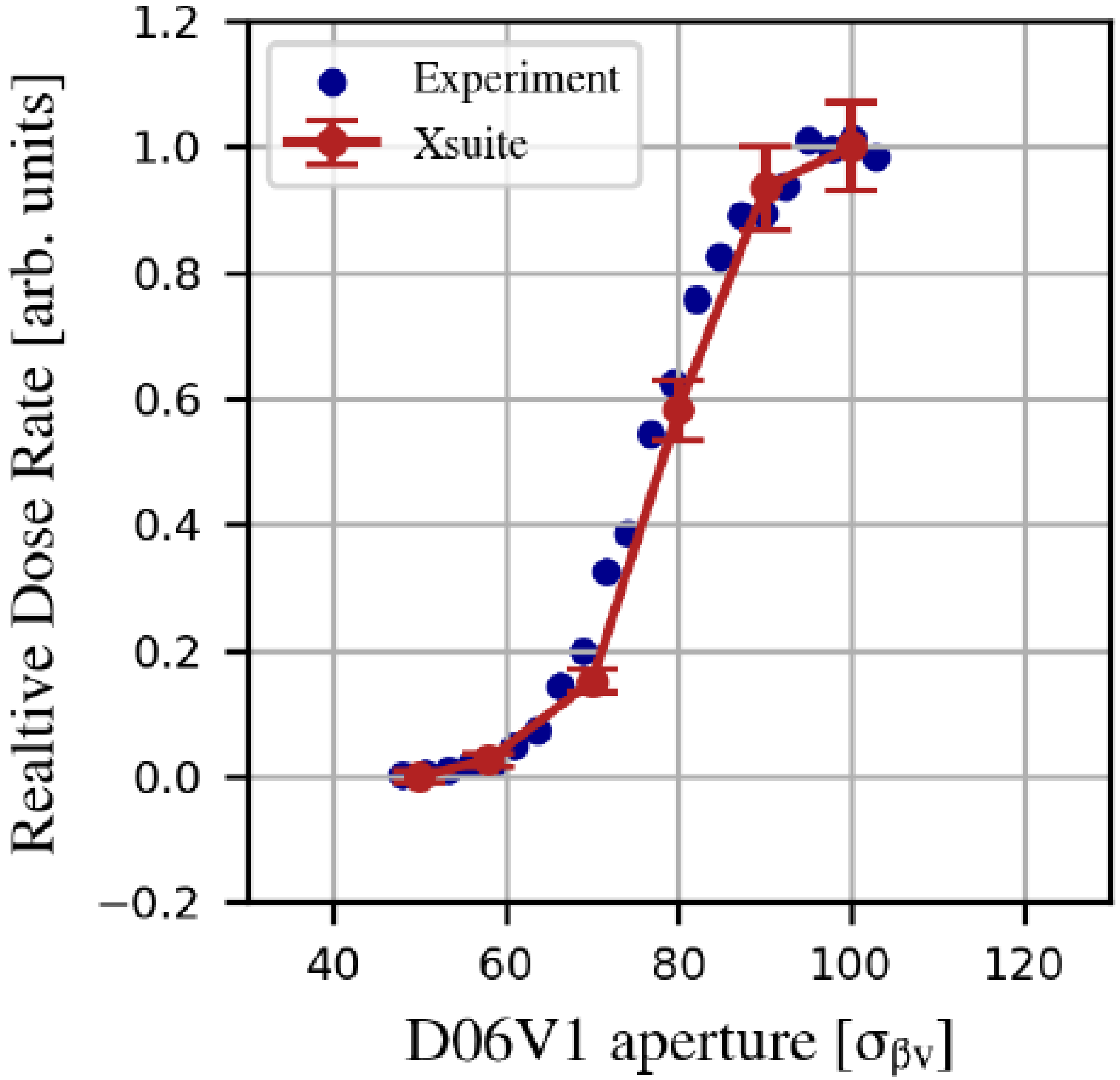
- Beam-beam losses intercepted by the collimation system in PF
- Beam-beam losses outside PF mostly on elements downstream of the IPs
  - ○ Local losses that cannot be intercepted in PF on a second turn
  - ○ Physics-debris-like collimators downstream of the IPs ?

G. Broggi

SuperKEKB benchmarks

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

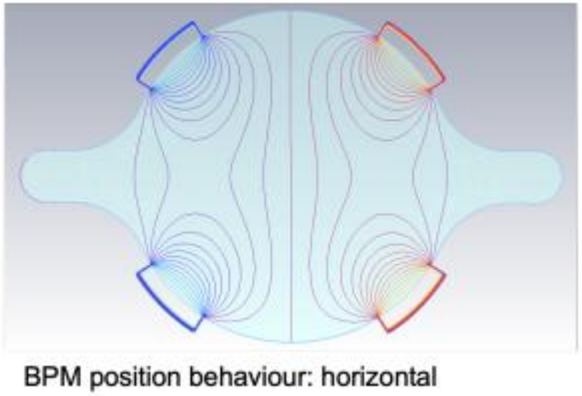
Xsuite-simulated response of Belle-II diamond detector:

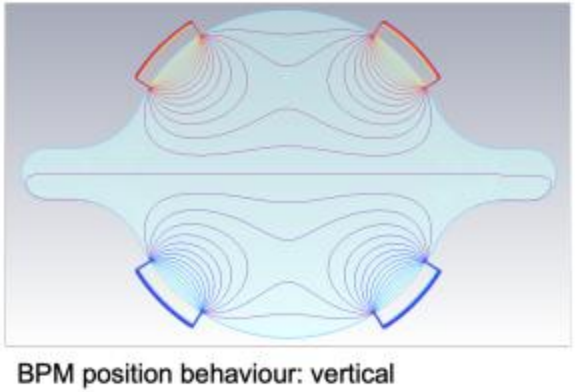


G. Broggi

4.7 beam diagnostics – beam position

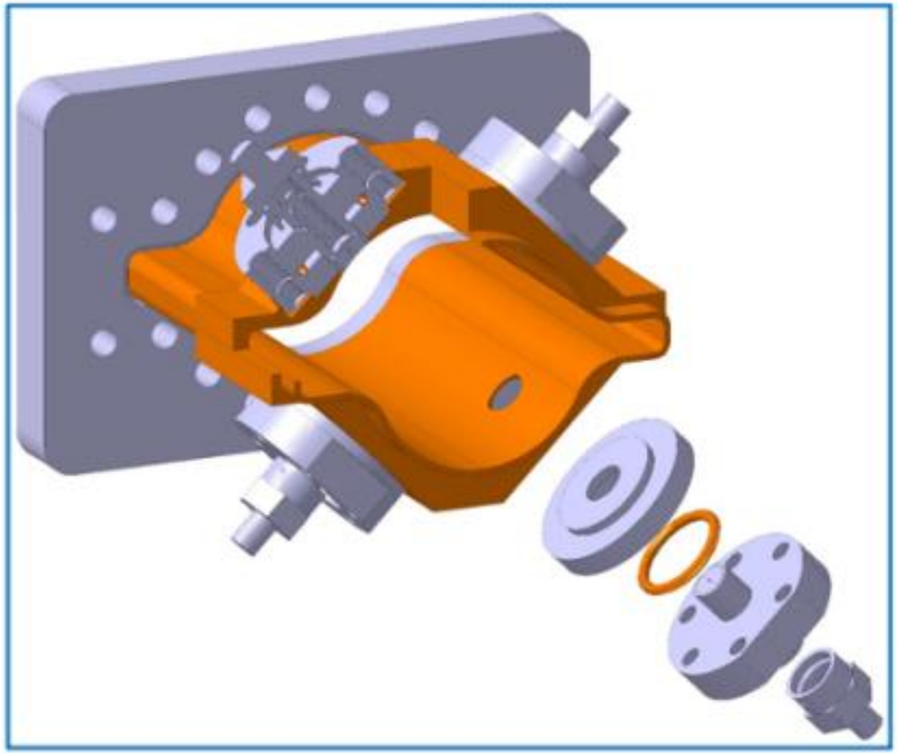
FCC-ee needs a total of approximately 7000 beam position monitors (BPMs)





Lines of constant beam displacement of a button BPM, horizontal (left), vertical (right).

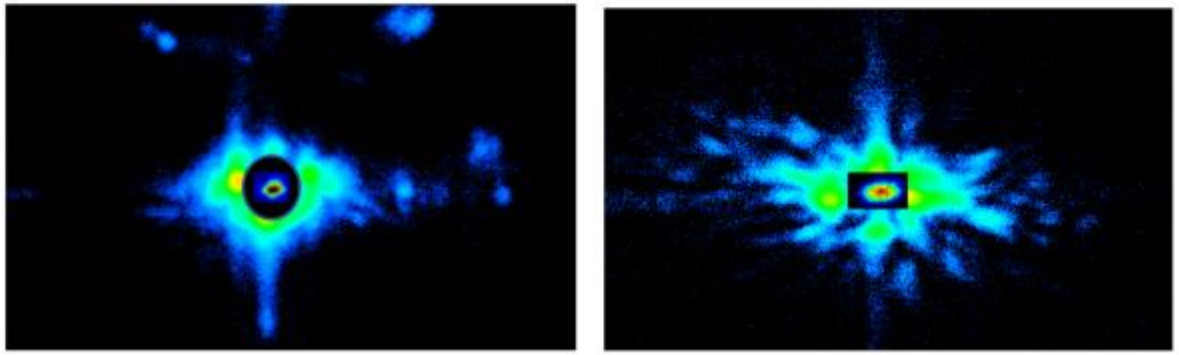
developing new manufacturing processes for BPM body with a copper vacuum chamber and button RF UHV feedthrough



Manufacturing R&D for FCC-ee BPM pickups

M. Wendt

beam size measurement

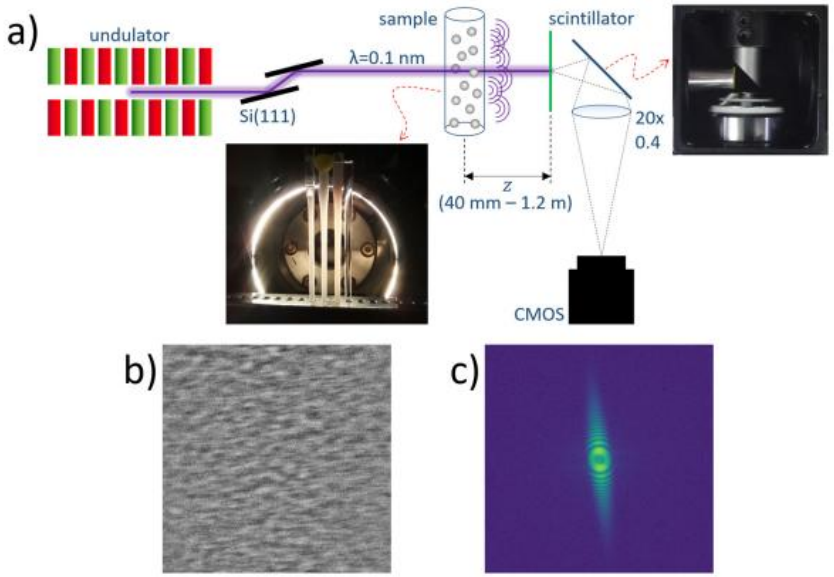


(a) HER, $I_{beam} = 0.57\,\mathrm{mA}$ (b) LER, $I_{beam} = 0.61\,\mathrm{mA}$

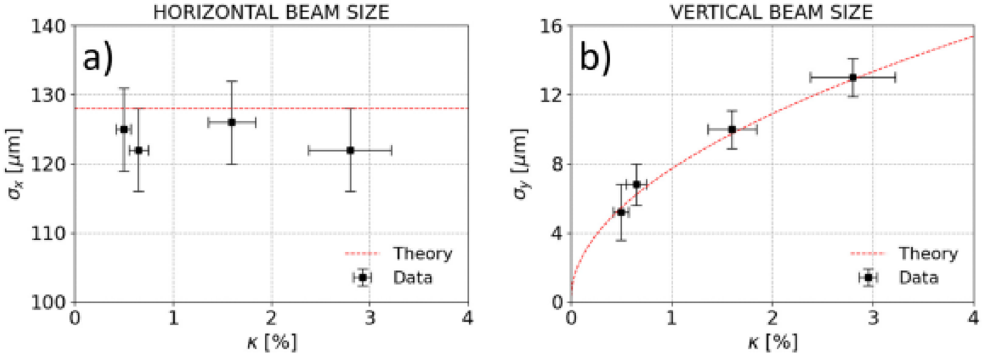
beam halo measurement at SuperKEKB using a diamond mirror for SR extractio

development of poly-crystal Diamond mirror for the SR monitor of FCC ee derived from the SuperKEKB SR monitor; halo measurement using coronograph

novel interferometric technique to perform full 2D beam size measurements: Heterodyne Near Field Speckles (HNFS) formed by interfering the weak spherical waves scattered by nanoparticles suspended in water with the intense X-ray beam



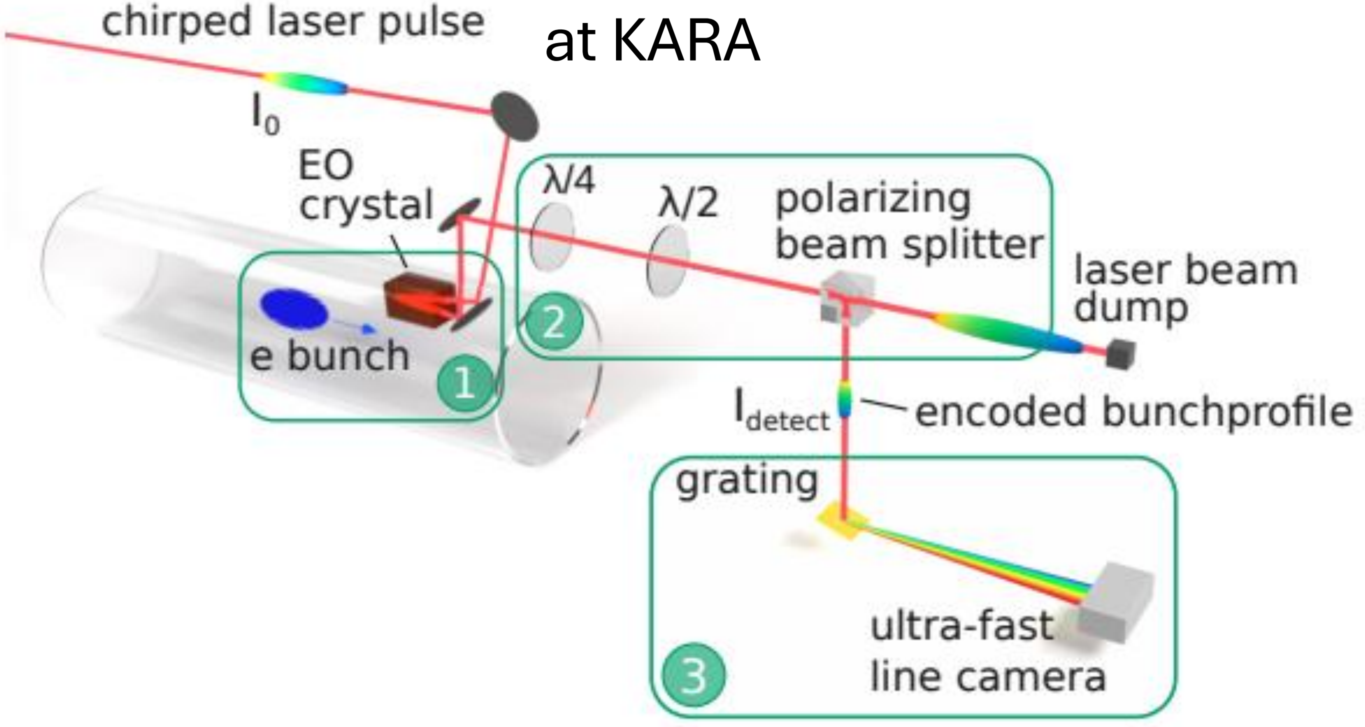
HNFS setup at ALBA (a). Measured X-ray speckles (b) and power spectrum (c) with 12.4 keV photons.



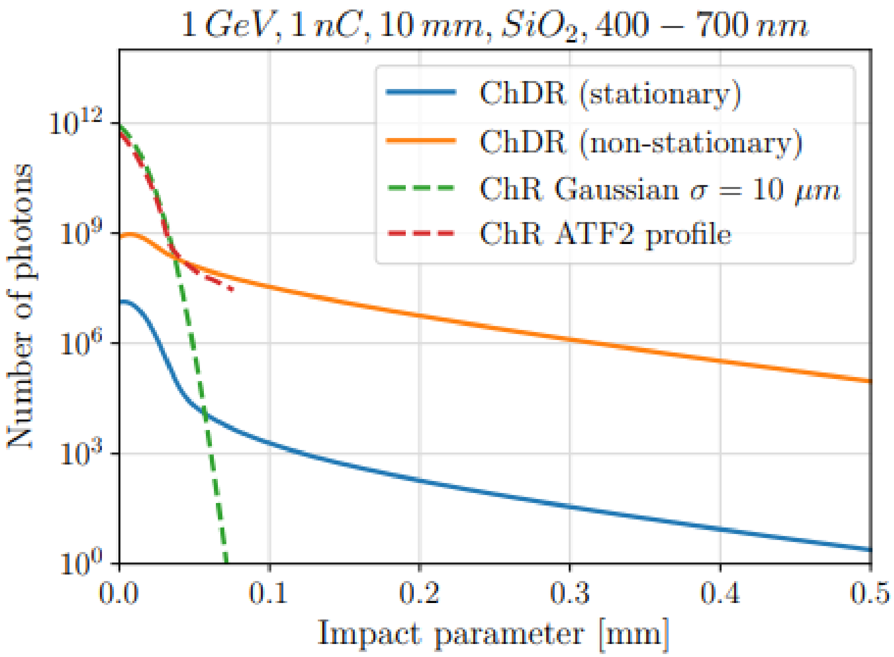
M. Wendt

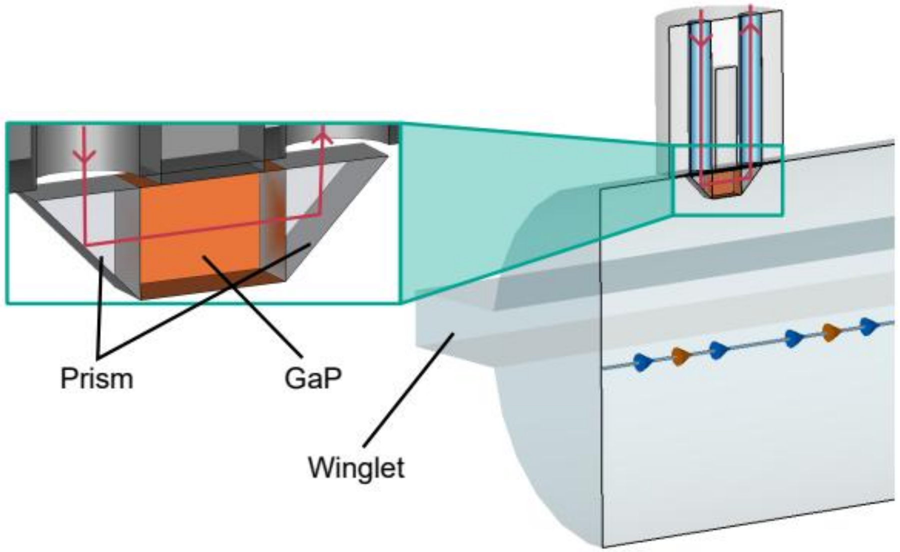
bunch length measurement

Principle of the EO bunch profile monitor at KARA



Cherenkov radiation





Concept of an adapted EO monitor design for FCC-ee
- The modified laser path through the crystal allows measurements of longer bunches

M. Wendt

CHART HTS4 project etc.

4.8 HTS magnets for FCC-ee

HTS solenoid for e^+ source (3x increase in yield e+/e-)

final focus sextupoles

final doublet quadrupoles

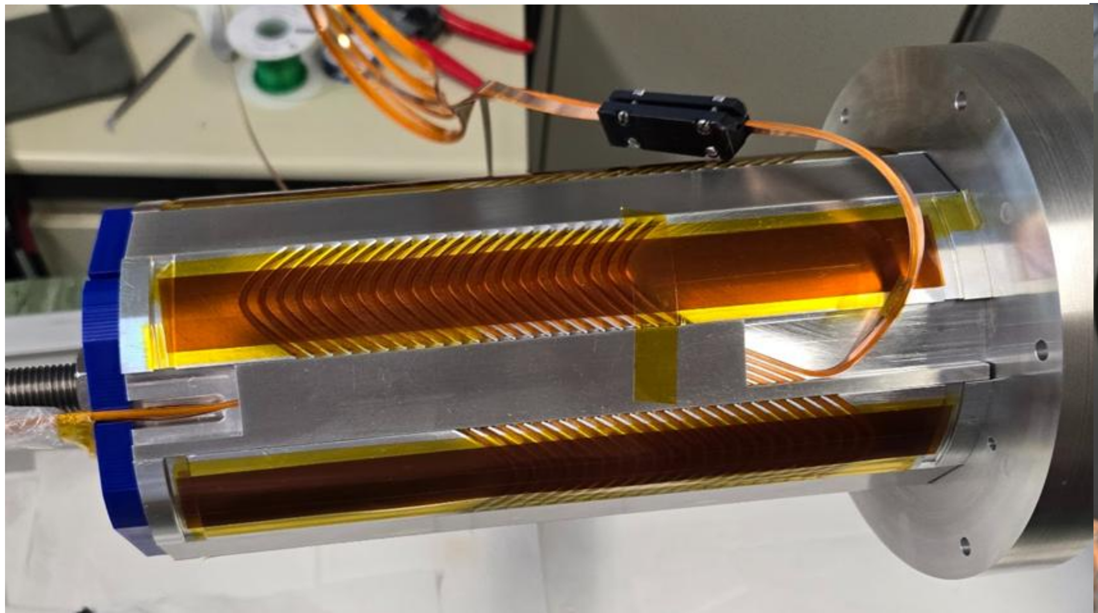
arc sextupoles

arc quadrupoles

Coil technology:

- HTS tape coated by **in-house** coating line
- **Automated coil winding**
- All coils have **reached I_c in LN2** without quenches

two HTS sextupole demonstrator magnets



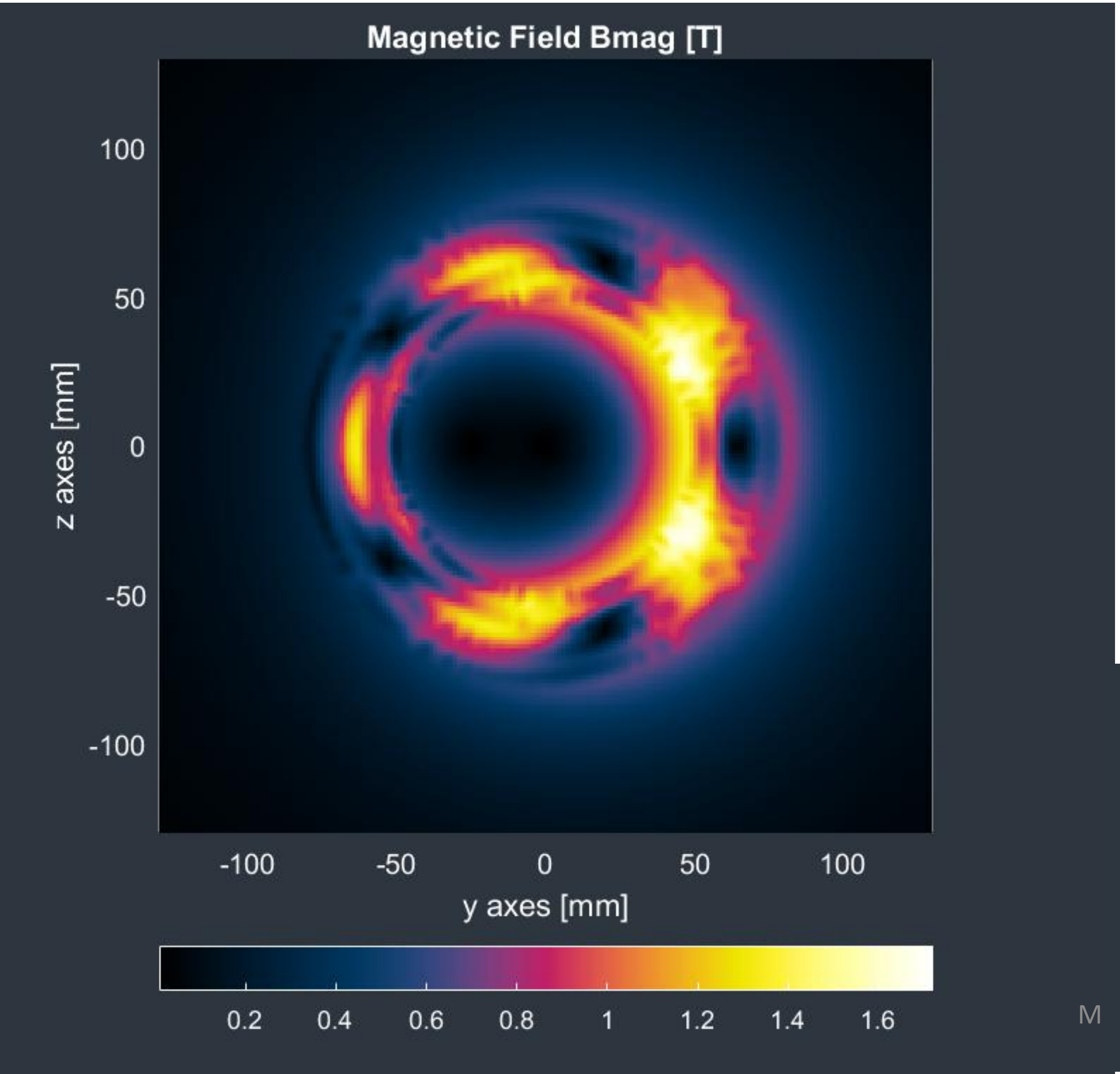
M. Koratzinos

HTS magnet strengths & fields

- SSS quad: 12T/m
- SSS sextupole: 800T/m2
- Nested quad and sextupole: Combined max. field: 1.7T
- FF quad: 100T/m; 2.7T peak field
- Crabbing sextupole: 8000T/m2; 10T! Maximum field. This magnet is very short and very strong.

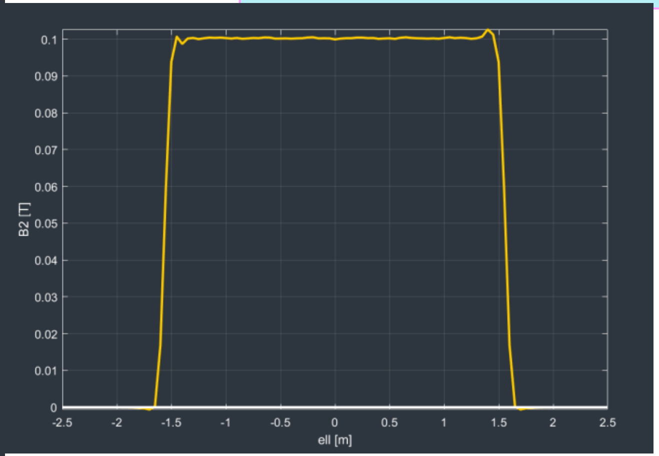
Magnetic analysis

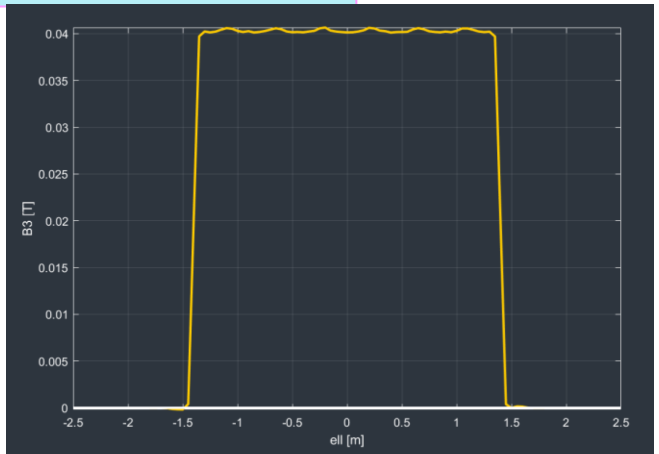
Quad and sextupole at full strength



- This is a low field application (1.7T max) gradients: 10T/m; 800T/m^2
- There is no problem attaining the performance with today's HTS tapes
- The question is only related to cost: the higher the performance, the lower the length of HTS tape needed, the lower the cost

B2 @10mm: 0.1T; B3 @10mm: 0.04T

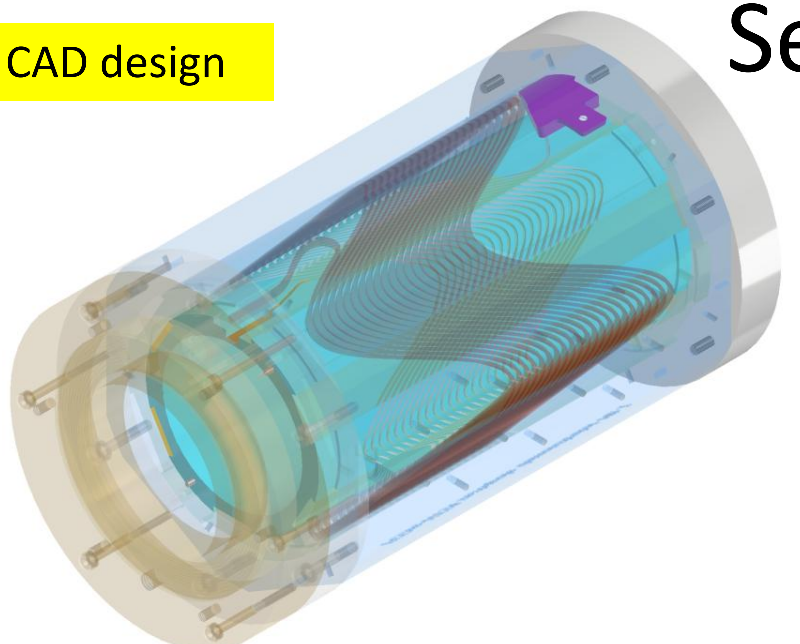




M

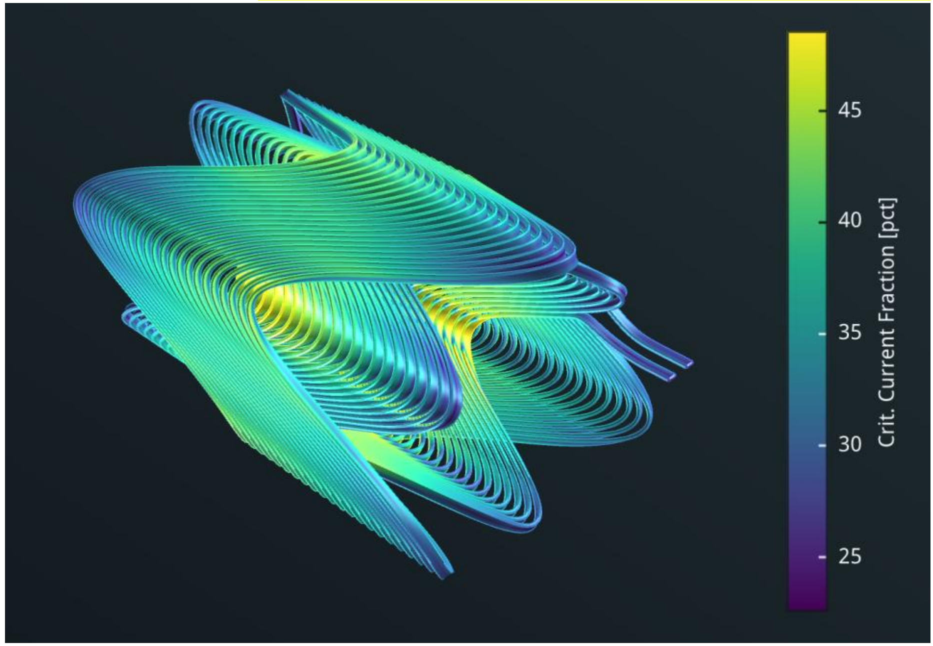
Sextupole demonstrator

CAD design



Specifications:
Type: CCT
Aperture: 90mm
Current: 260A
Temperature: 40K
Field gradient: 1000T/m2
Max. field @conductor:1.5T
Crit. Current fraction: 49%
Temp. margin: 14K

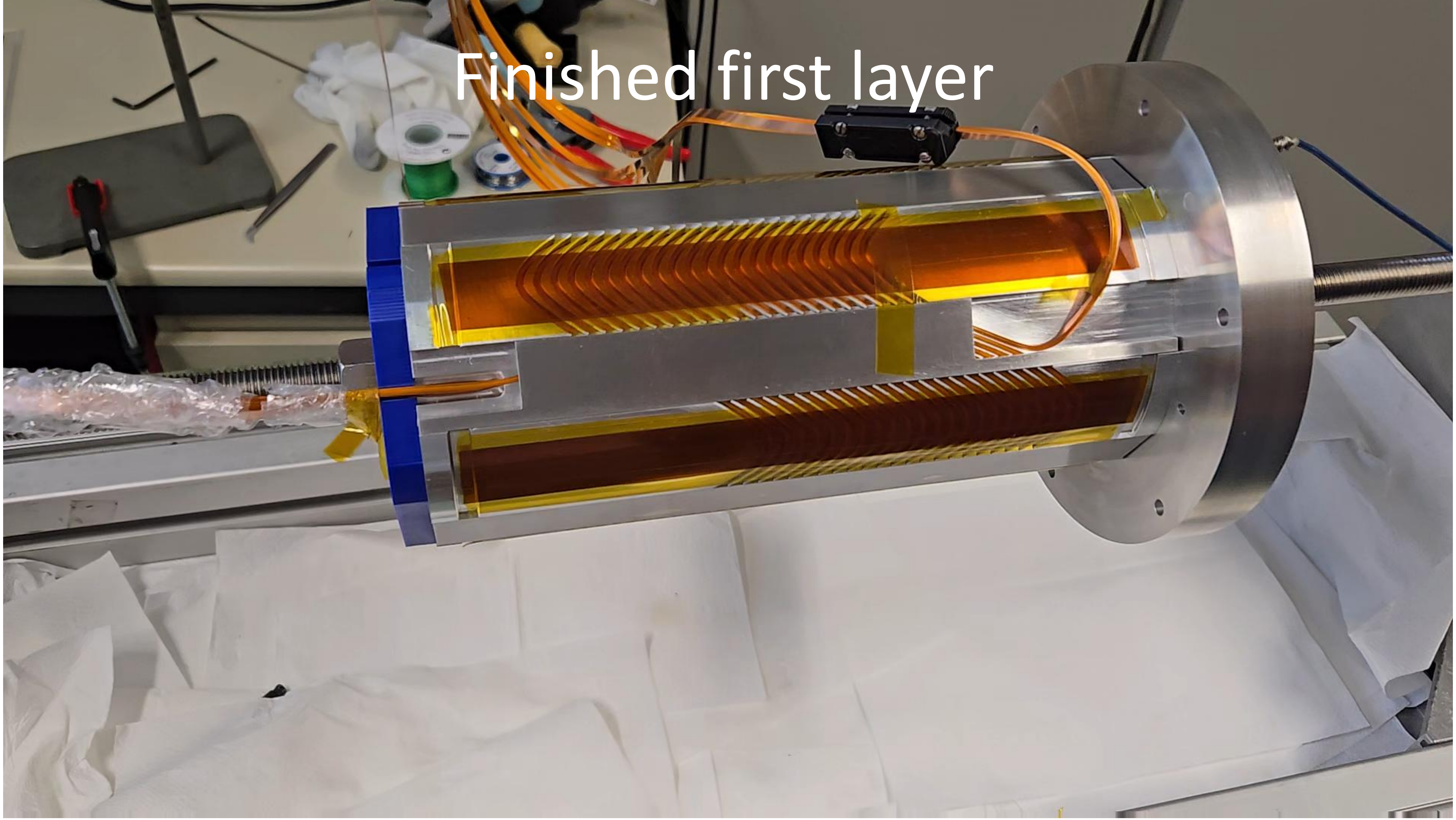
Critical current fraction at 40K

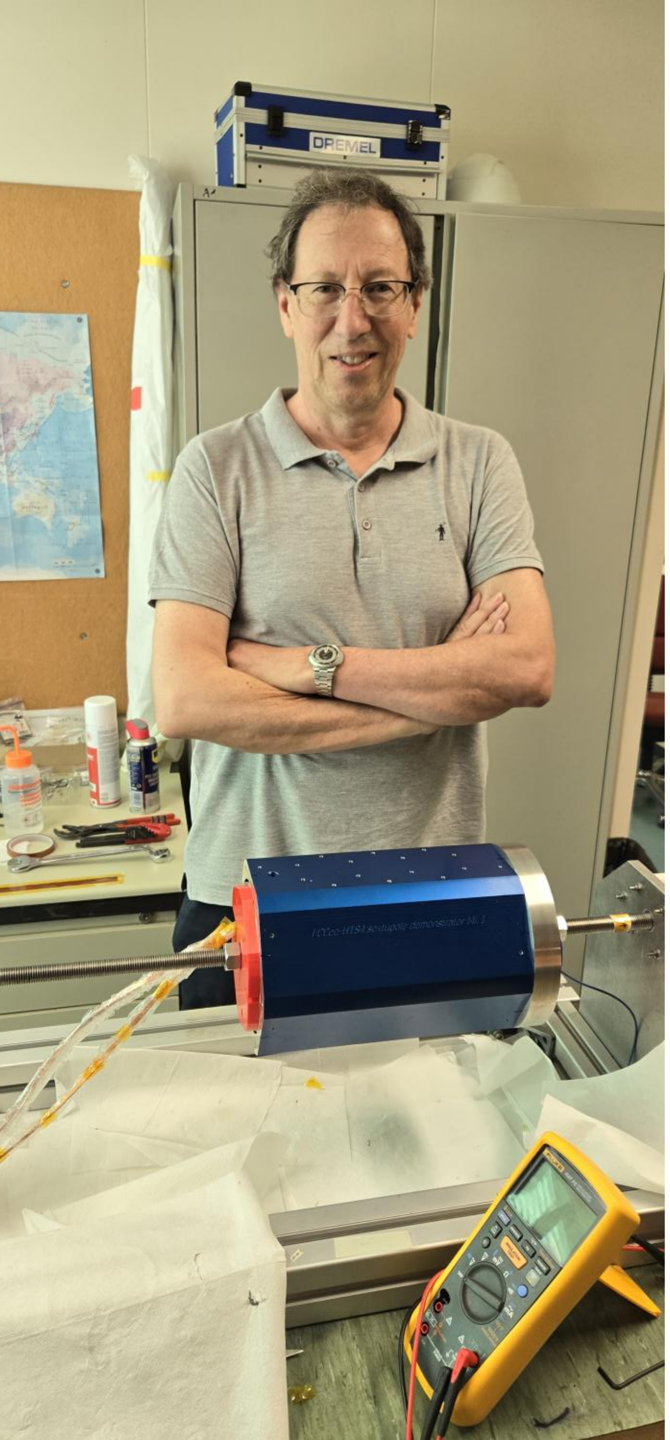


Aluminium formers

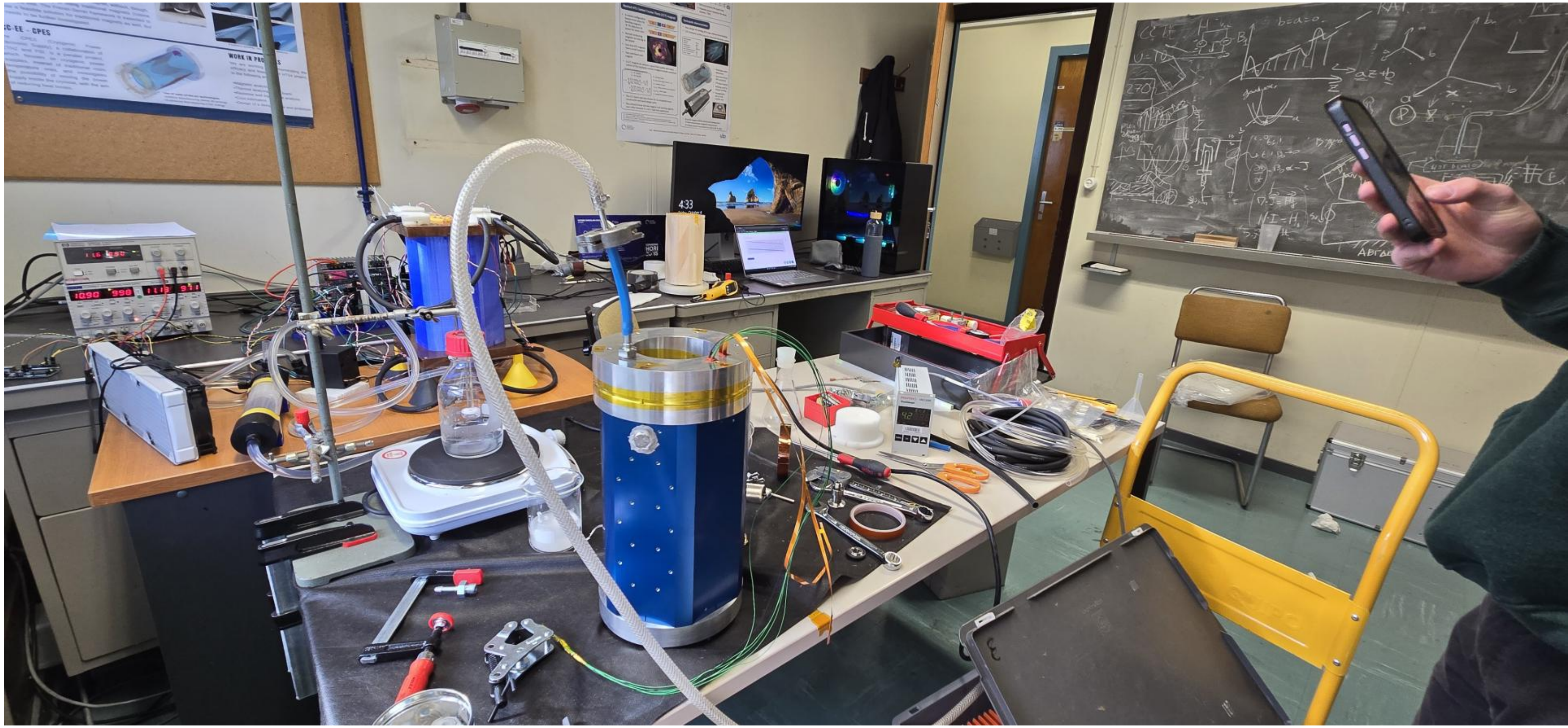
CT alternative

Finished first layer





Finishing and impregnation



4.9 FCC-hh baseline design & power consumption

Technical system choices and areas for optimisation:

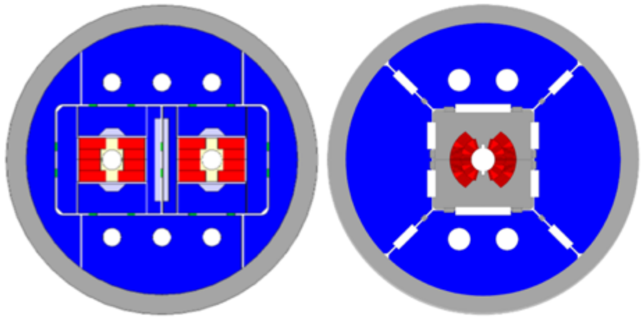
- Accelerator optics design to increase arc dipole filling factor and maximize beam energy
- Cold mass either at 1.9 K with superfluid He (studied in CDR, cf. LHC) or with 4.5 K with forced flow
- Temperature of beam vacuum system (beam screen)
- Cryogenics “eco mode” during shutdowns

	FCC-hh 90.7km Nb_3Sn 14T	FCC-hh 90.7km Nb_3Sn 14T
Magnet temperature	**1.9 K**	4.5 K
Annual electrical energy consumption	**< 2.5 TWh**	< 2.0 TWh

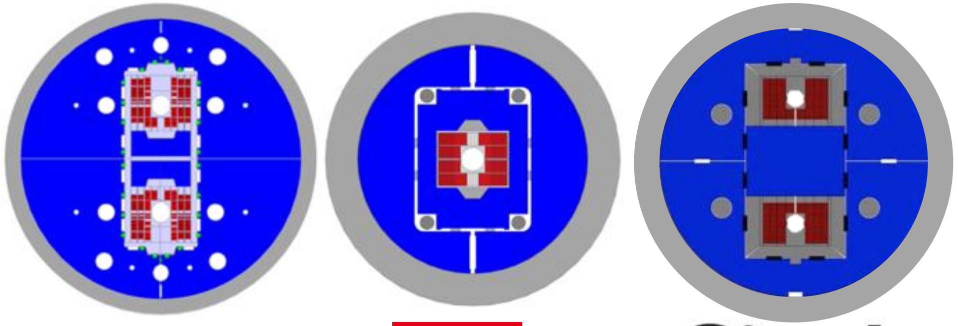
- **Significant reduction of electrical power (factor ~1/2 compared with 2019 CDR)**
- **Potential for further reduction, e.g. with R&D on 4.5 K operation, in next phase**
- **Long term R&D towards accelerator magnets based on high-temperature superconductor materials, targeting higher fields and even lower energy consumption**

FCC-hh High-Field Magnet Nb_3Sn and HTS R&D in Europe

Nb_3Sn:
- 12- and 14-T short demonstrators
- Different coil geometries
- tests scheduled for 2026



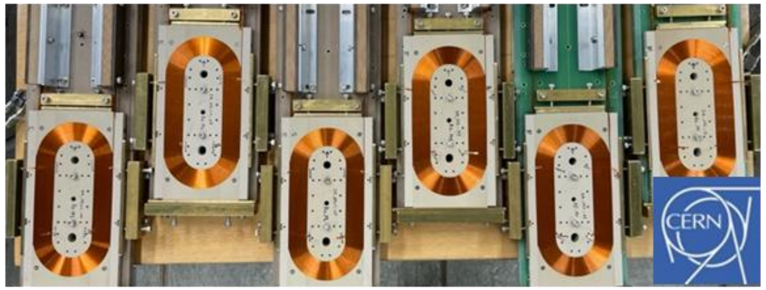
CERN CERN INFN Istituto Nazionale di Fisica Nucleare



PSI cea Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

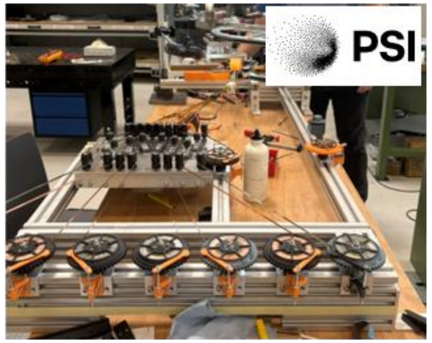
HTS R&D in various domains:
- REBCO and IBS Conductor R&D
- Racetrack coil developments

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.

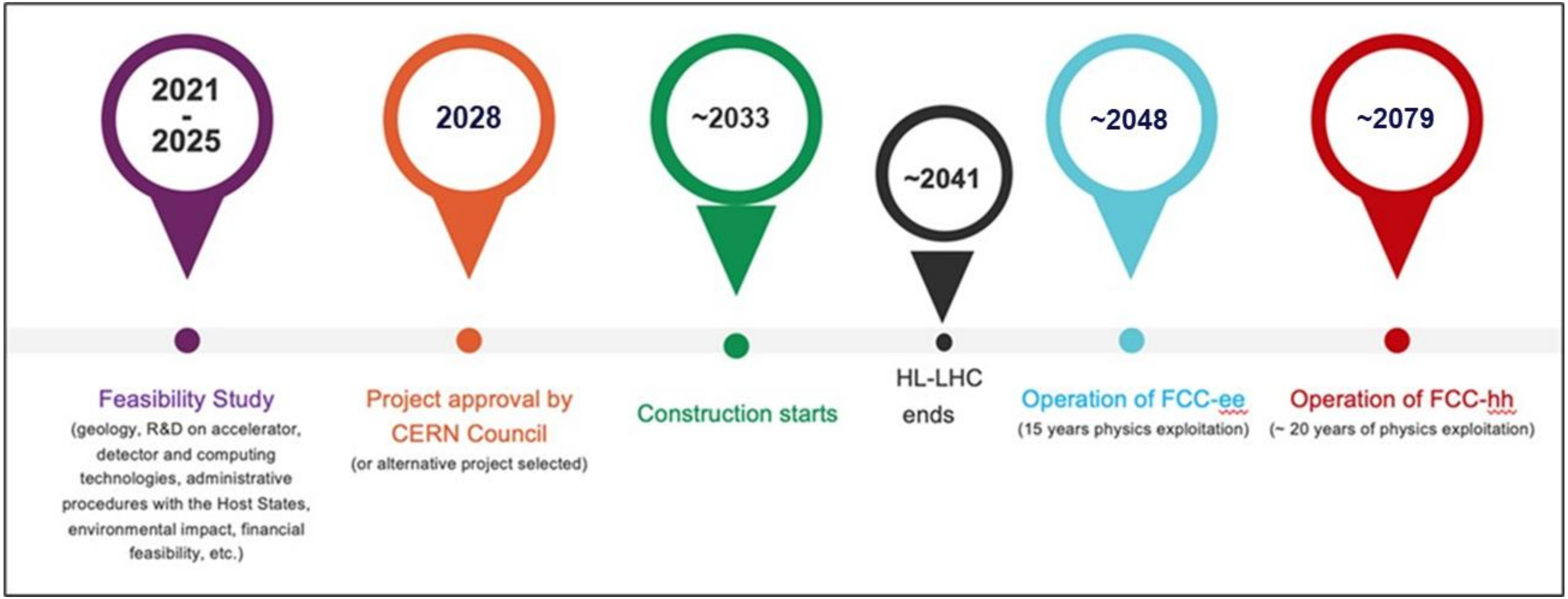
CEA process development for metal-insulated racetrack coils.

B. Auchmann, E. Todesco

bonus lecture

FCC status, preparation towards implementation and timeline

FCC integrated program – timeline



Ambitious schedule taking into account:

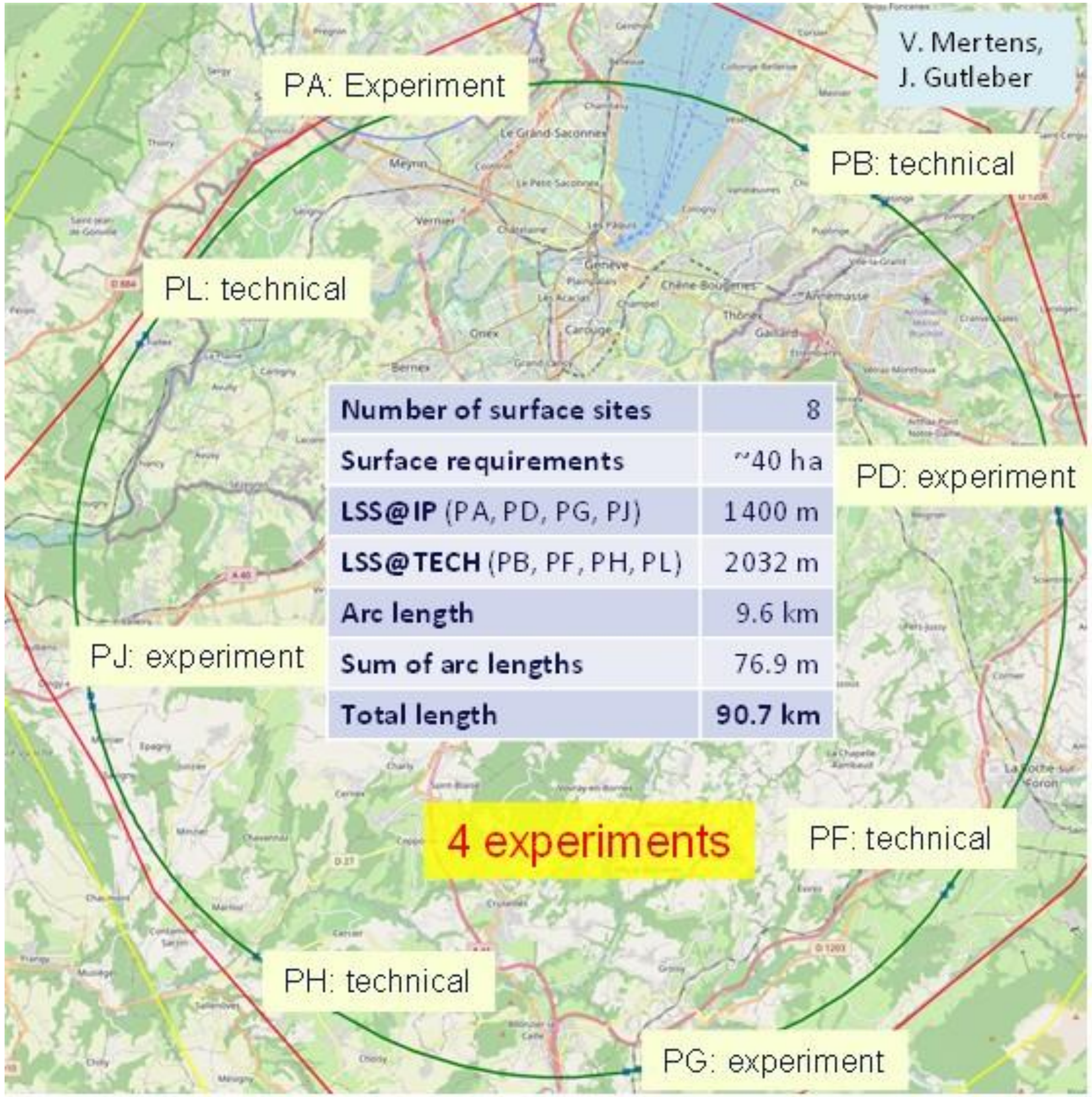
- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until 2041
- ❑ **constraints imposed by present assumptions in funding model**
- ❑ **project preparatory phase with adequate resources immediately after Feasibility Study**

Reference layout and implementation:PA31 - 90.7 km

Layout chosen out of ~ 100 initial variants, based on several criterias:

- **geology,**
- **surface constraints** (land availability, urbanistic, etc.),
- **environment,** (protected zones),
- **infrastructure** (electricity, transport),
- **machine performance**

“Avoid-reduce-compensate” principle of EU and French regulations.

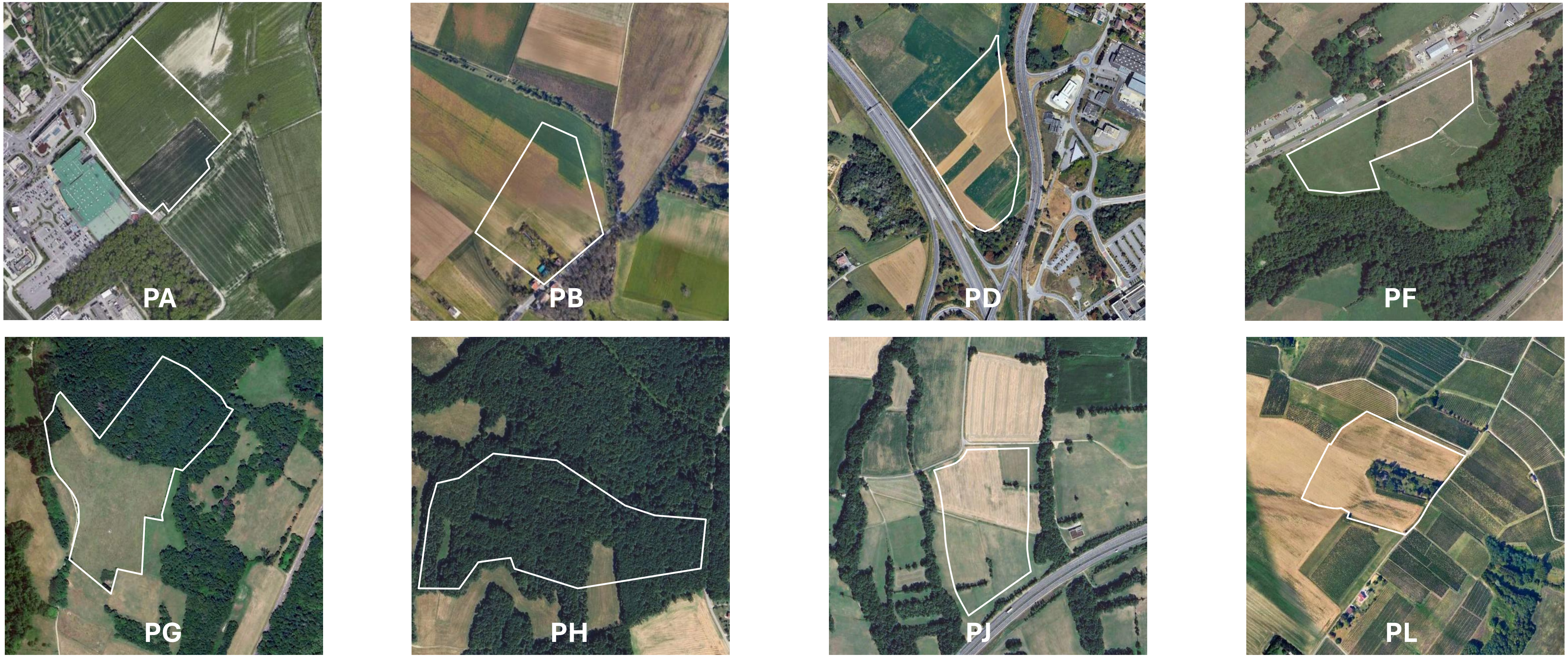


Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

Overall lowest-risk baseline:
90.7 km ring, 8 surface points,
4-fold symmetry

Surface site locations 7 FR and 1 CH

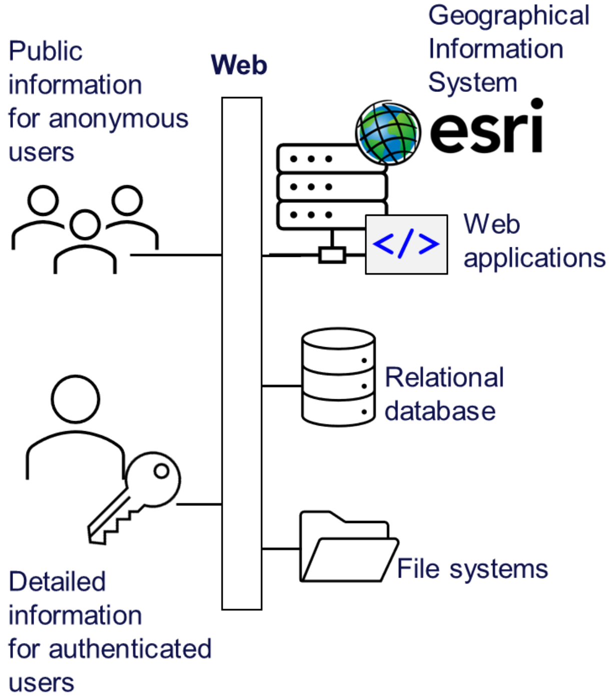
Optimisation done with communes



- land plot needs communicated to Host States,
- process in FR: «prise en consideration», landplot in CH owned by Canton of Geneva

Environmental initial state analysis

Environmental information system



- The environmental **initial state analysis** at the eight surface site locations (~600 ha covered) **did not reveal principal showstoppers for the project**.
- **Basis for detailed optimisation of surface sites**.
- **Reference for the environmental impact assessment**.
- Web-based report will be available end September 2025

Territorial dialogue and public participation

First cycle of public information meetings completed (April 2024 – March 2025)

11 sessions reached over 1,500 people in France & Switzerland

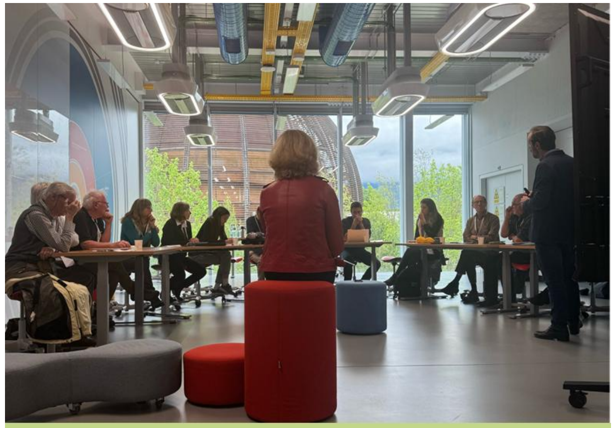
Dialogue Website

During 2025:

Second cycle of **public information meetings**.

Presence days in municipalities affected by surface sites to enable discussion with habitants.

Meetings with stakeholders of the territory.



- *First dialogue and exchange meeting with local environmental associations, 5 may, 2025*

During 2026:

Formal public participation process planned in France (Debat Public) and Switzerland (public concertation).

Resource needs & connections to regional infrastructure

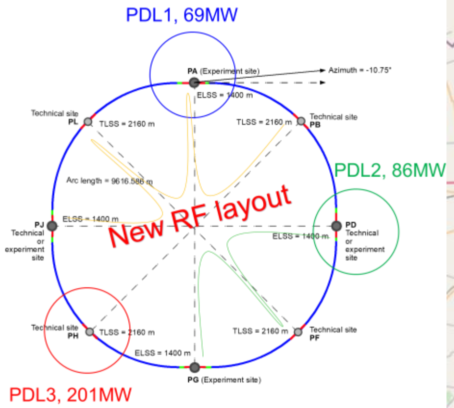
Electricity consumption 1.1 – 1.8 TWh/year

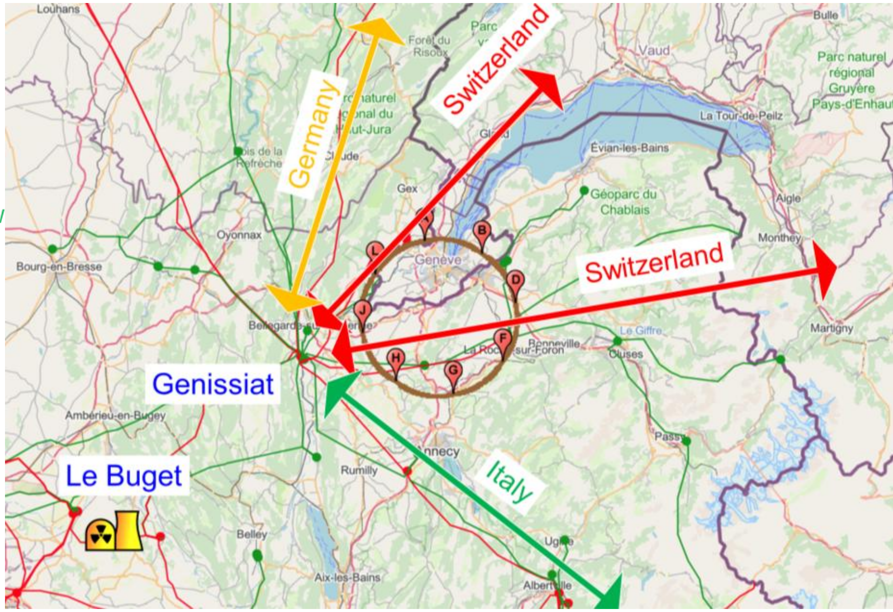
Three supply points

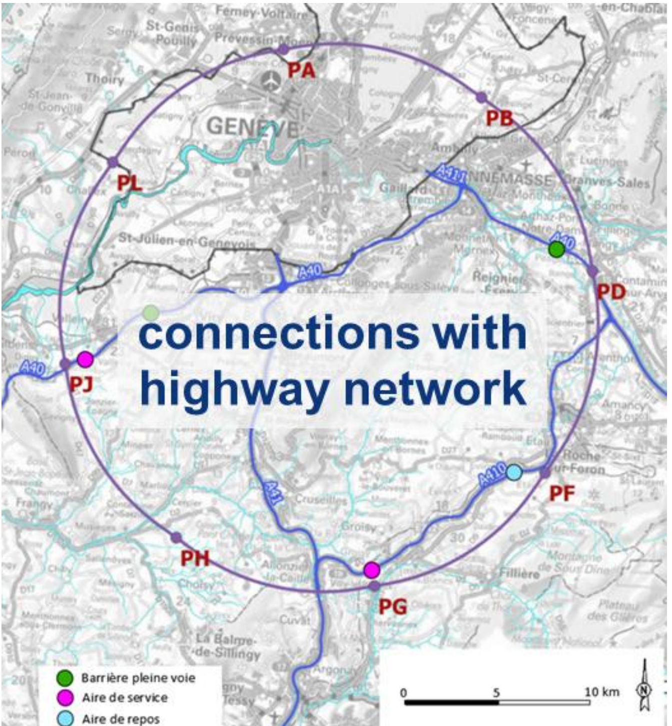
- Two new substations from existing HV grid

- Reuse of present CERN station

Feasibility confirmed with RTE (FR operator)







Road access
developed for all 8 surface sites

Four possible highway connections defined

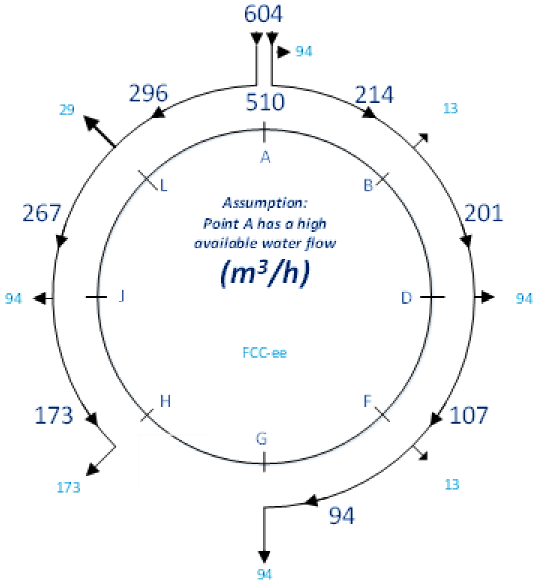
Less than 4 km of new roads required

Raw water need:

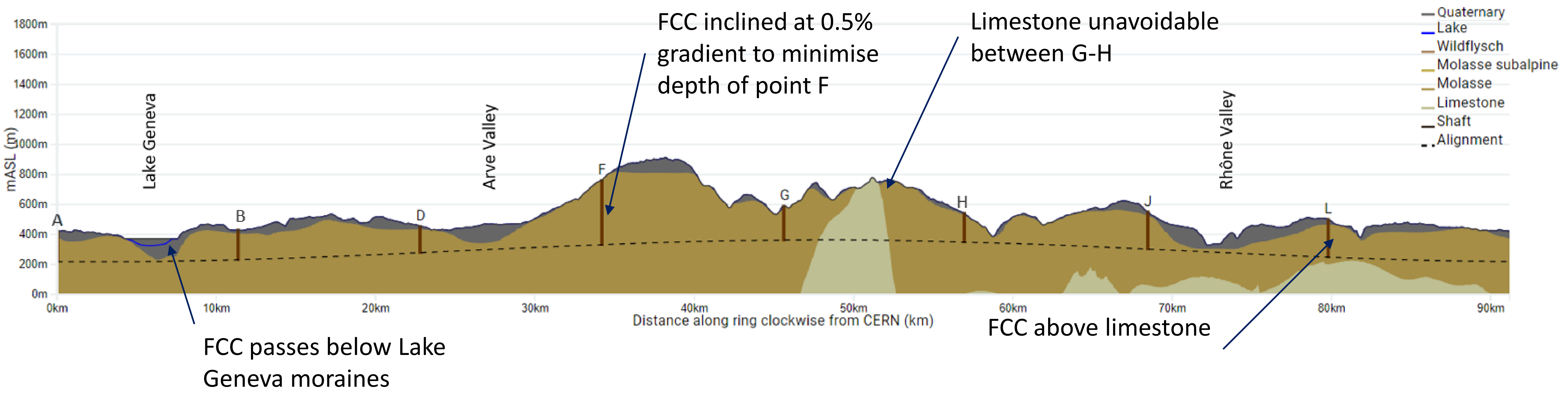
1 – 3 million m^3/year

Water supply from lake Geneva via existing SIG supply to CERN

Distribution via tunnel



Optimum placement of FCC tunnel and geology



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

6 million m^3 excavated volume → 8.5 million m^3 excavation material on surface

CE Designs of all underground structures developed

Average shaft depths ~240 m

To fix the vertical position of the tunnel, interfaces between geological layers have to be known

Reuse of excavated materials: OpenSkyLab project

- Develop a quality-managed processes to transform excavated materials into fertile soil
- Permit reuse in renaturalisation, agriculture, etc.
- Additives as compost etc. in various mixtures
- Location: 1 ha field, LHC P5 CMS Cessy (FR)
- Applicable to entire alpine molasse region!

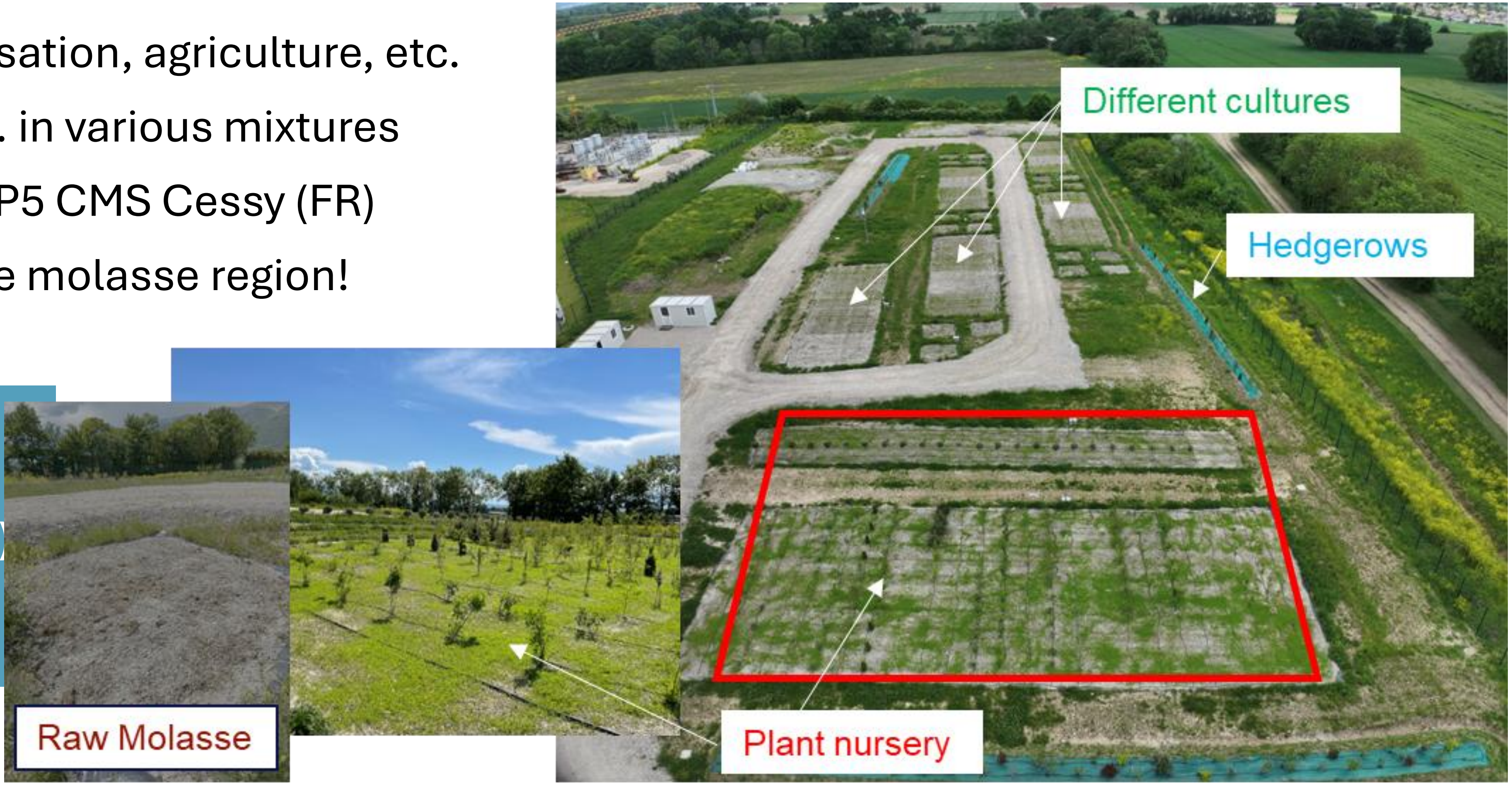
<u>Estimate of reuse quantities:</u>

40% refill of quarries (~ 7.5 Mt)

25% reconstituted soil (~ 4 Mt)

30% deposit (~ 5 Mt)

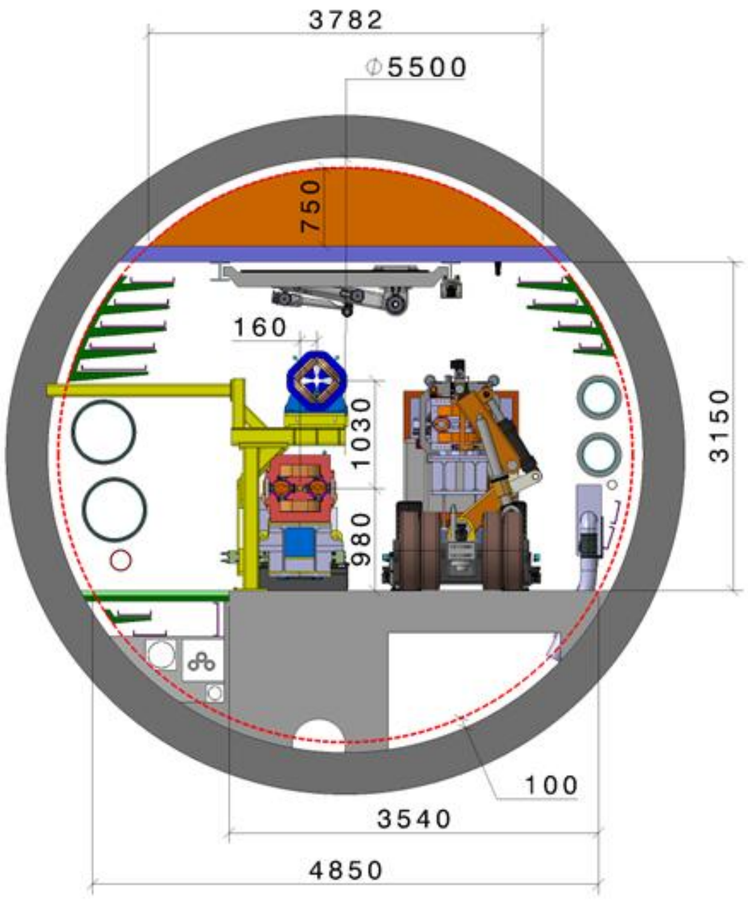
5% other reuse



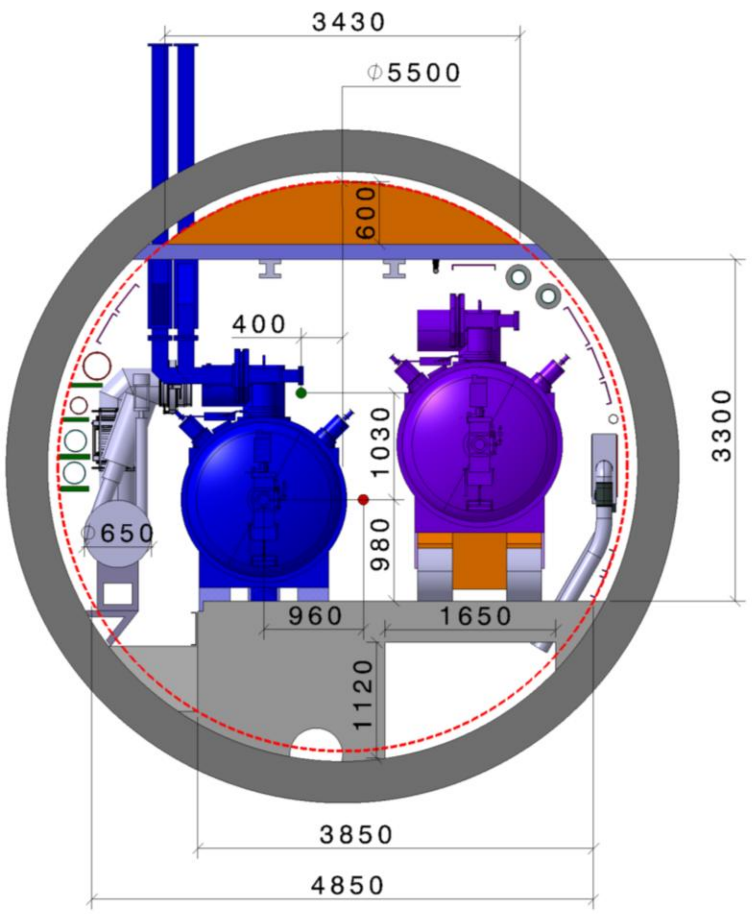
hepia Haute école du paysage, d'ingénierie et d'architecture de Genève · brgm Géosciences pour une Terre durable · EDAPHOS ENGINEERING · BOKU UNIVERSITY · microhumus · MONTAN UNIVERSITÄT LEOBEN · BECC · wsp

FCC – main tunnel integration – 5.5 m inner diameter

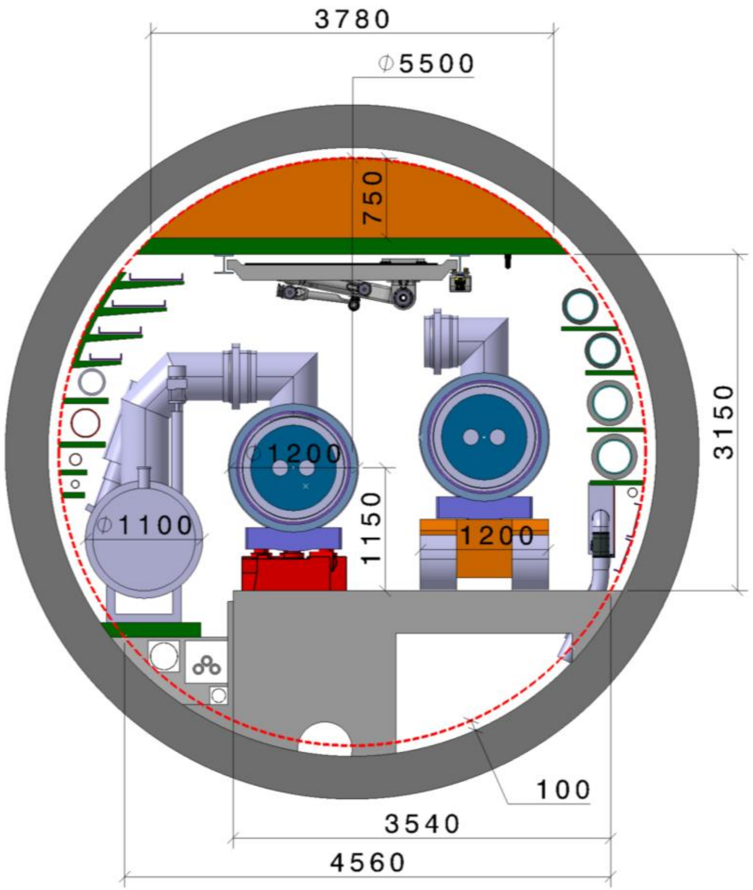
FCC-ee arc



FCC-ee 400 MHz RF section

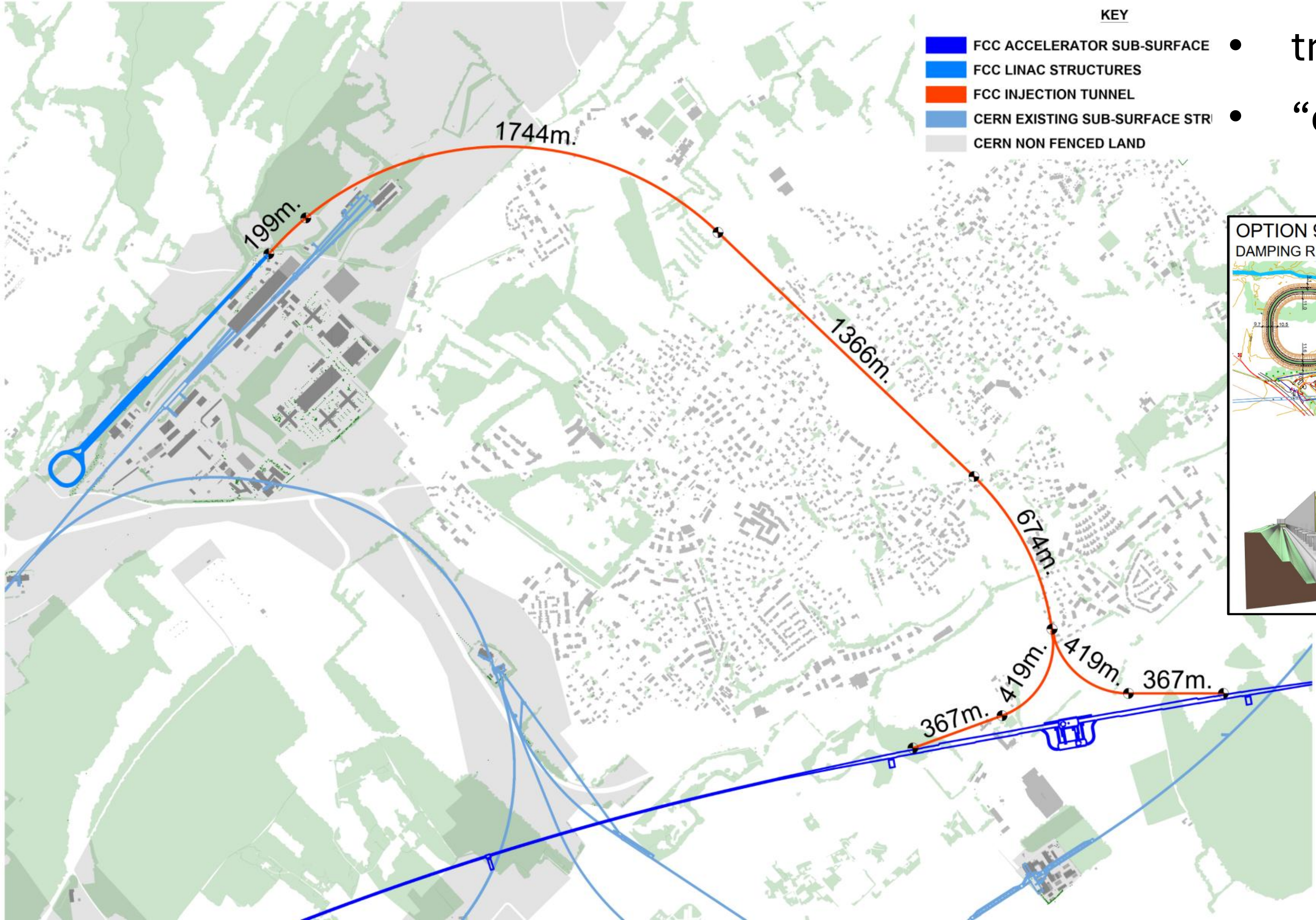


FCC-hh arc

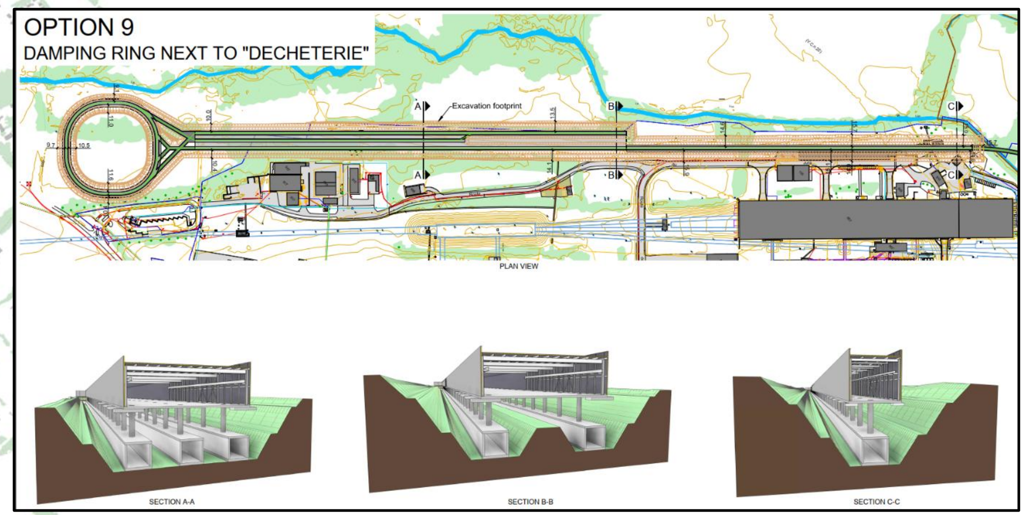


Integration & logistics studies for installation, safety concept reviewed, to confirm 5,5 m

FCC-ee injector with HE Linac

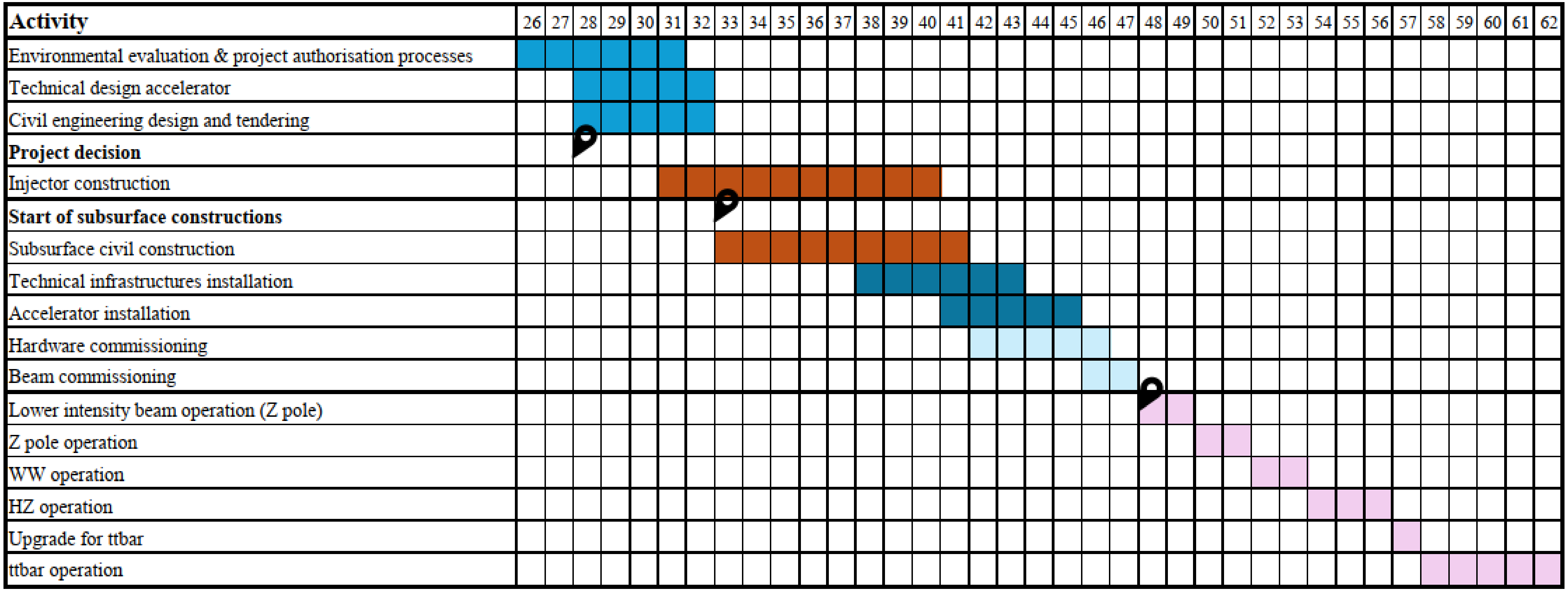


- Located on CERN Prévessin site
- possible connection to North Area to enable non-collider physics
- transfer line to FCC PA (LHC P8)
- “cut and cover” construction



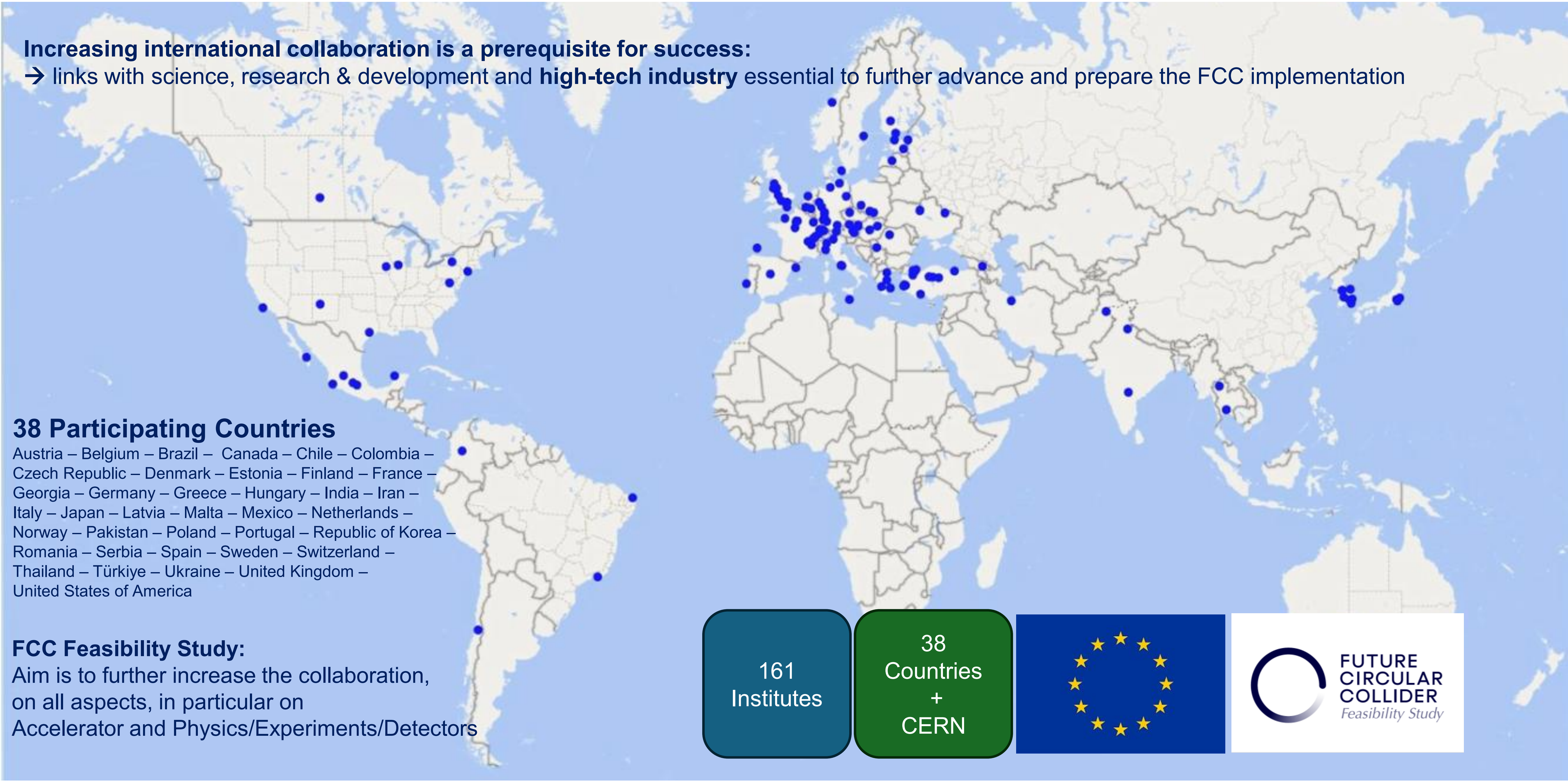
- Since MTR overall parameter optimization to reduce electrical power to < 30 MW

FCC-ee construction schedule



- **2028** — **assumed project approval by CERN Council**
- **01/2033 – 06/2041** — **CE construction work**
- **07/2039 – 12/2043** — **technical infrastructure installation**
- **07/2041 – 06/2045** — **accelerator installation**
- **07/2046** — **start of beam commissioning and operation**
- **01/2048** — **nominal beam operation**

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

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

FUTURE CIRCULAR COLLIDER
Feasibility Study

JS National Academies Report, 11 June 2025

Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider research and development program to enable the construction of a demonstrator of the key new technologies and their integration.

- **A collider with approximately 10 times the energy of the Large Hadron Collider (LHC) is crucial for addressing the big questions of particle physics and making discoveries.**
- Developing a U.S.-hosted muon collider—an unprecedented machine requiring considerable research, development, and a feasibility demonstrator—would solidify U.S. leadership in particle physics and drive accelerator innovation.

Recommendation 2: The United States should participate in the international Future Circular Collider Higgs factory currently under study at CERN to unravel the physics of the Higgs boson.

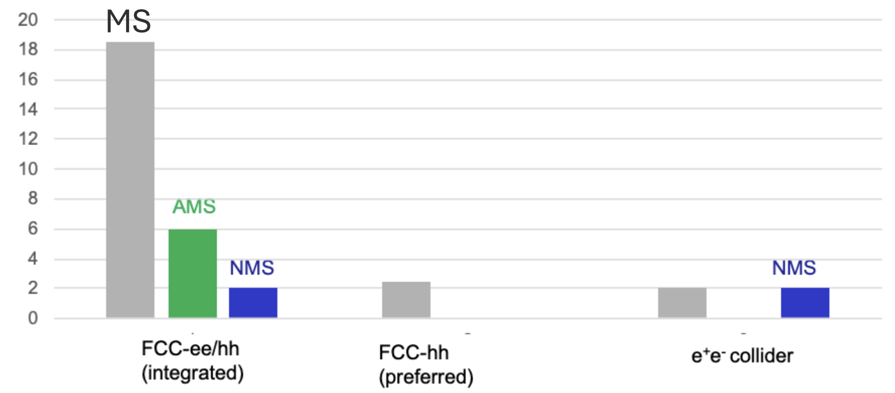
- **Determining whether the Higgs is elementary or has substructure has huge ramifications for the future of particle physics.**
- **Active participation in a Higgs factory is crucial for the U.S. particle physics community.**

European Strategy Update

National inputs to the ESPP

Publicly available at: https://indico.cern.ch/event/1439855/contributions/
Summary compiled by European Strategy Group

Preferred option

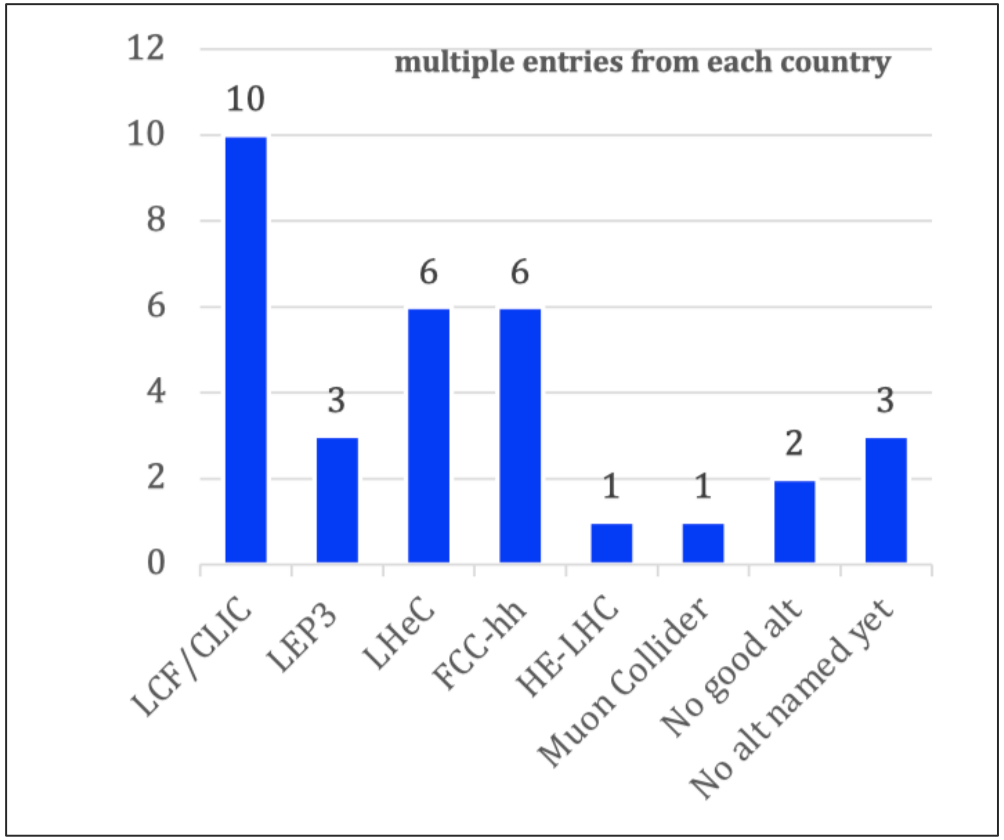


FCC-ee/hh (integrated)	MS: Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Israel, Italy, Norway, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden, Switzerland, (United Kingdom) AMS: Brazil, Croatia, Lithuania, Pakistan, Slovenia, Ukraine NMS: Canada, USA
FCC-hh preferred (but accept ee first)	Czech Republic, Serbia, (United Kingdom)
e^+e^- collider	MS: Austria, Bulgaria NMS: Australia, Japan

K. Jakobs, CERN Council, 20th June 2025

11

Alternative if preferred option not feasible



EU / European Commission & the FCC

edited by Mario Draghi, and officially handed over to Ursula von der Leyen in September 2024

European Competitiveness Report, September 2024 :

"One of CERN's most promising current projects, with significant scientific potential, is the construction of the Future Circular Collider (FCC): a 90-km ring designed initially for an electron collider and later for a hadron collider…"

https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en

CERN 70th anniversary

"….No European country alone could have built the world's largest particle collider. CERN has become a global hub because it rallied Europe and this is even more crucial today.

I am proud that we have financed the feasibility study for CERN's Future Circular Collider (FCC)*. …."*

Ursula von der Leyen, President of the European Commission

European Commission's proposal for next Multiannual Financial Framework (MFF) 2028–34 & European Competitiveness Fund (ECF), 16 July 2025

The published fact sheet for Horizon Europe for 2028-34 mentions "**moonshots**" – an evolution of the EU Missions – **prominently featuring the Future Circular Collider (first in the shortlist!).** Funding of up to 20% of the total cost !?!

https://commission.europa.eu/document/download/a0ecf3f6-a964-4e00-9cb3-4be28833b386_en?filename=MFF_HORIZON%20EUROPE_v9.pdf

further reading

FCC Feasibility Study Report (FSR)

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

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

I. Agapov[1], E.E. Alp[2], K. Andre[3], S. Antipov[1], A. Apyan[4], G. Arduini[3], L. Bandiera[5], H. Bartmann[3], H. Bartosik[3], M. Benedikt[3], S. Bettoni[7], J.M. Byrd[2], M. Calviani[3], A. Camper[8], C. Carli[3], S. Casalbuoni[9], A. Chance[10], P. Craievich[7], P. Crivelli[11], B. Dalena[10], M. Dickmann[12], M. Doser[3], I. Drebot[13], C. Duchemin[3], K. Dupraz[14], S.J. Freeman[3,15], A. Frasca[3,16], F. Gunsing[11,17], J. Jäckel[18], B. King[19], M.W. Krasny[20], A. Lechner[3], C.A. Lindstrøm[8], A. Mazzolari[5,6], C. Milardi[21], E. Musa[1], R. Negrello[5,6], F. Nguyen[22], K. Oide[23], Y. Papaphilippou[3], G. Paternò[5], V. Petrillo[24], K. Piotrzkowski[25], B. Rienäcker[16], G. Schnell[26,27], C. Schroer[1], I. Schulthess[1], L. Serafini[13], V. Shiltsev[28], M. Stampanoni[7,11], A. Variola[29], T. Watson[3], H.-U. Wienands[2], M. Wing[30], and F. Zimmermann[*3]

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[13]INFN Milano, Milano, Italy
[14]IJCLab, Orsay, France

CERN-FCC-ACC-2025-0005,
doi: 10.17181/CERN.BSP4.H8ED