FCC ACCELERATOR STATUS and R&D

Tor Raubenheimer

FCC IS Workshop
December 5-9, 2022

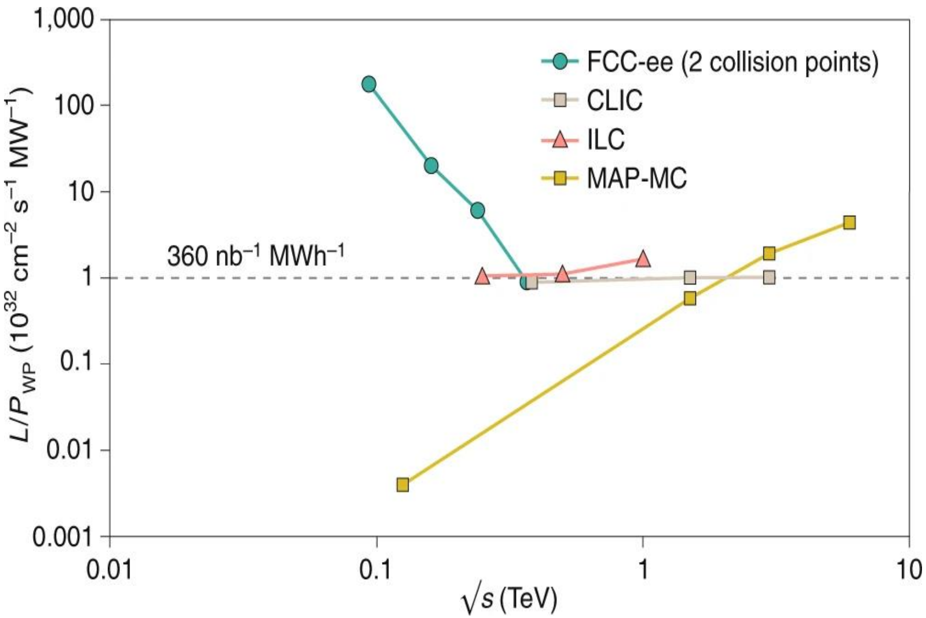
Introduction

- **FCC-ee fills need for a precision EW/Higgs factory while setting stage for a 100 TeV p-p collider in the future**
  - FCC infrastructure will support a century of physics
- **Very high luminosity precision study of Z and H**
  - 2×10^{36} $cm^{-2}s^{-1}$/IP at Z and 7×10^{34} $cm^{-2}s^{-1}$ at Zh
- **Low-risk technical solution** based on 60 years of e^+e^- circular colliders and particle detectors
  - R&D on components for improved performance but no need for "demonstration" facilities
- **Utility requirements** similar to CERN existing use

FCC-ee Luminosity

- **FCC-ee efficient $\mathcal{L}$ from Z to $t\bar{t}$**
  - Thanks to twin-aperture magnets, SRF, efficient RF power, top-off injection
- **Accumulate >2.5 ab^{-1} with ~0.5x10^{6} H produced per IP**
- **Accumulate >75 ab^{-1} with ~2x10^{12} Z produced per IP**
- **Run plan naturally starts at Z but is under discussion**

Luminosity vs. electricity consumption



Highest lumi per AC site power of all proposals
Electricity cost ~200 CHF per Higgs boson

Challenges and Drivers

- High beam energy → large circumference to reduce synchrotron radiation and strong luminosity dependance on energy
  - Large circumference → challenging tuning and tolerances and long runs for facilities
  - Tunnel radiation → may limit in-tunnel electronics
- High luminosity → strong beam-beam with beamstrahlung and reduced lifetimes
  - High beam current → large RF power with collective instabilities and collimation
  - Requires top-up injection and large dynamic aperture

Outline

- **Overall requirements and status**
- **Parameters**
- **Main e+/e- rings beam optics**
- **Collective effects, Dynamic aperture, Injection, Collimation, …**
- **SRF and Energy efficiency**
- **Full-energy booster and e+/e- injector**
- **R&D Issues**

Accelerator Design Status

- New ~90 km circumference placement with 8 access points
- Layout with 4 IP's that is consistent with upgrade to FCC-hh
- Optimizing allocation of straight sections
- New FCC-ee optics to optimize beam-beam
- 400 MHz and 800 MHz RF systems
- Starting tunnel integration studies for RF and Arc sections
- Full energy booster that will fit in FCC tunnel for top-up injection
- e+ / e- injector to fill booster 24 / 7

Basic Design Choices

Double ring e+e- collider

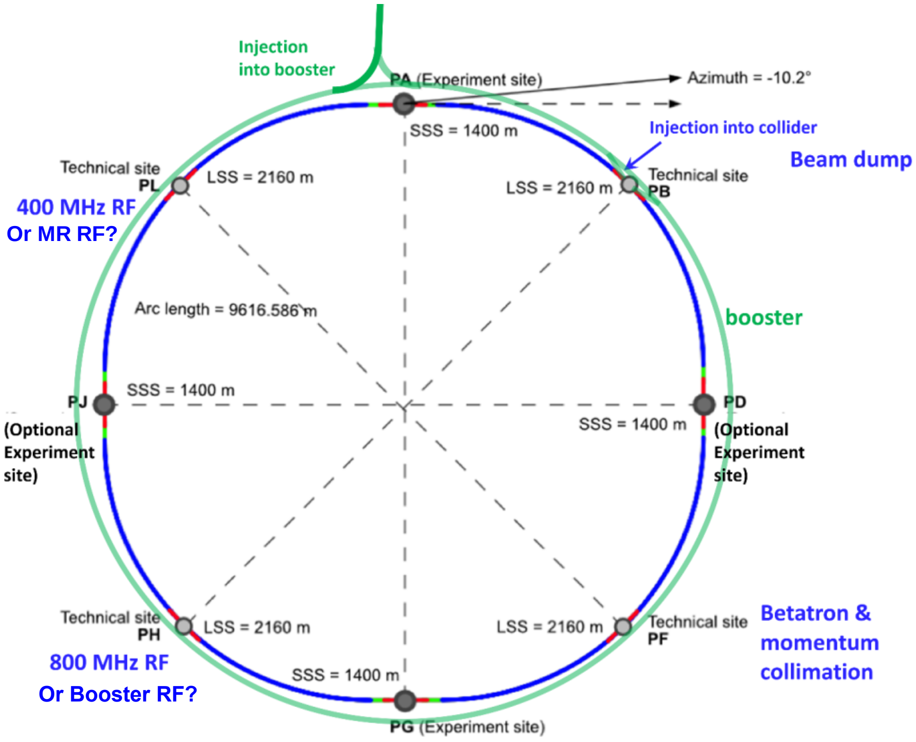
Common footprint with FCC-hh, except around IPs

Asymmetric IR layout and optics to limit synchrotron radiation towards the detector

Perfect 4-fold superperiodicity allowing 2 or 4 IPs; large horizontal crossing angle **30 mrad, crab-waist collision optics**

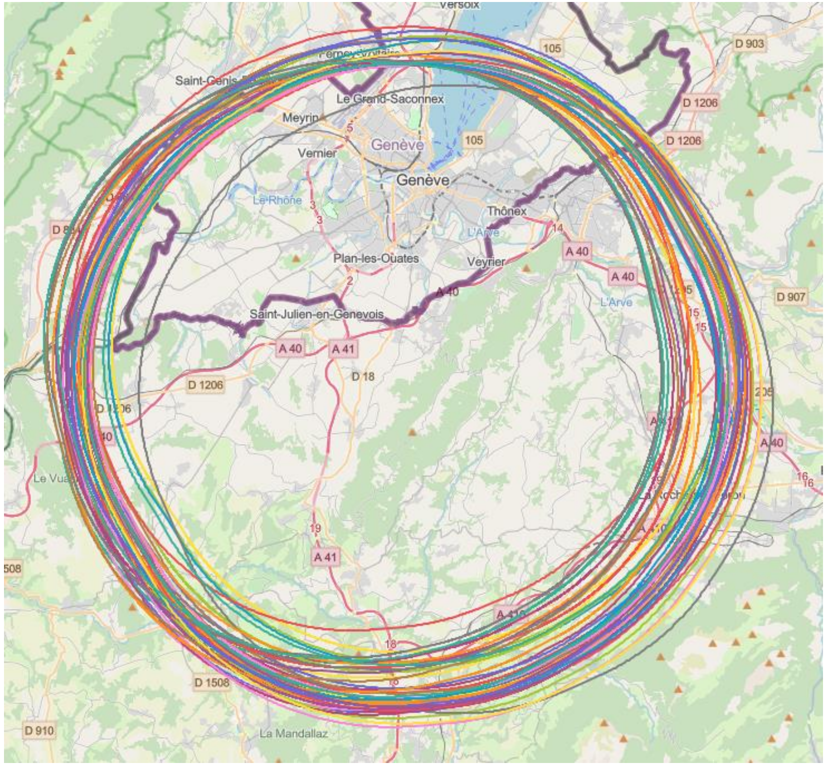
Synchrotron radiation power 50 MW/beam at all beam energies

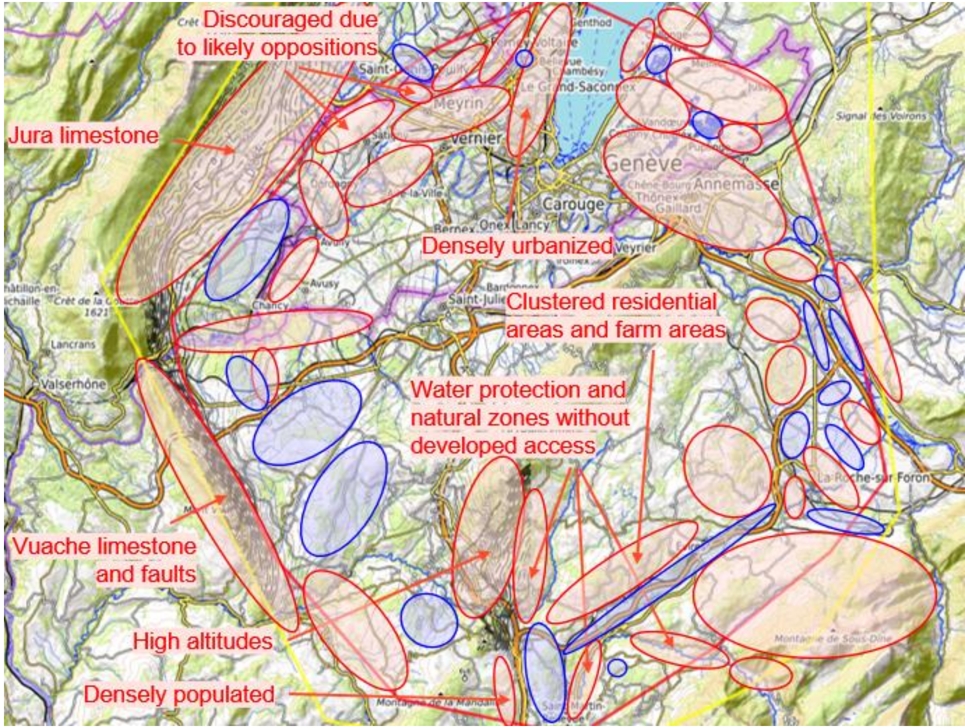
Top-up injection scheme for high luminosity
Requires **booster synchrotron in collider tunnel**



Accelerator Placement Optimization

J. Gutleber, V. Mertens

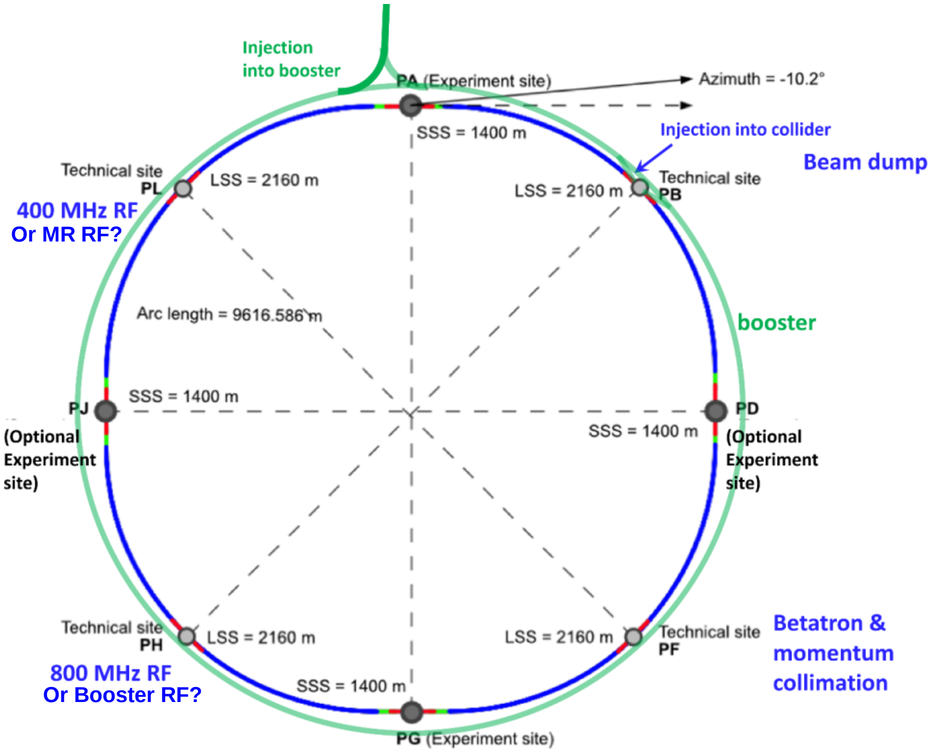


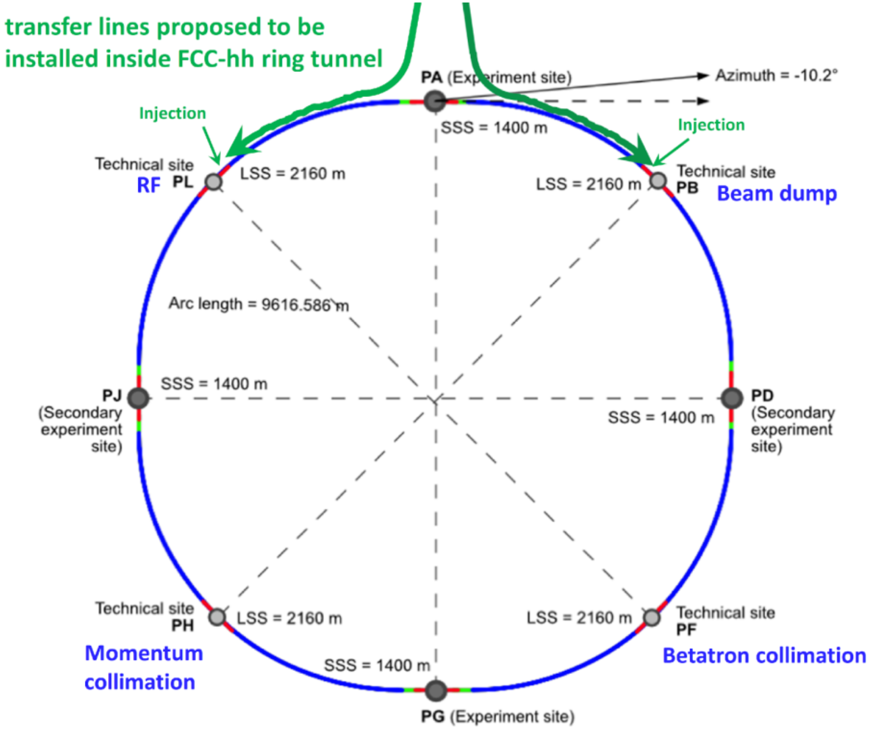


Placement Impact

- **New PA31 layout proposed in 2021**
- **PA31-1.0 had a 91.2 km circumference**
- **Needed to modify to have matched harmonic number for injector chain → 91.1 km (Dec. 2021)**
- **Further circumference reduction needed to support surface sites leading to 90.8 km optics (Summer 2022)**
- **Settling on 90.7 km circumference with a harmonic number of 121,200 at 400.79 MHz which supports surface sites as well FCC-hh injector chain**

FCC-ee layout consistent with FCC-hh





FCC-ee Parameters

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	90.836848			
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	$[10^{11}]$	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	$[10^{-6}]$	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.94 / 2.74
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.1 / 9.2
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	400.793257			
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y [a]		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	$[10^{34}/\text{cm}^2\text{s}]$	182	19.4	7.26	1.25
Lifetime (q + BS + lattice)	[sec]	840	–	< 1065	< 4062
Lifetime (lum)	[sec]	1129	1070	596	741

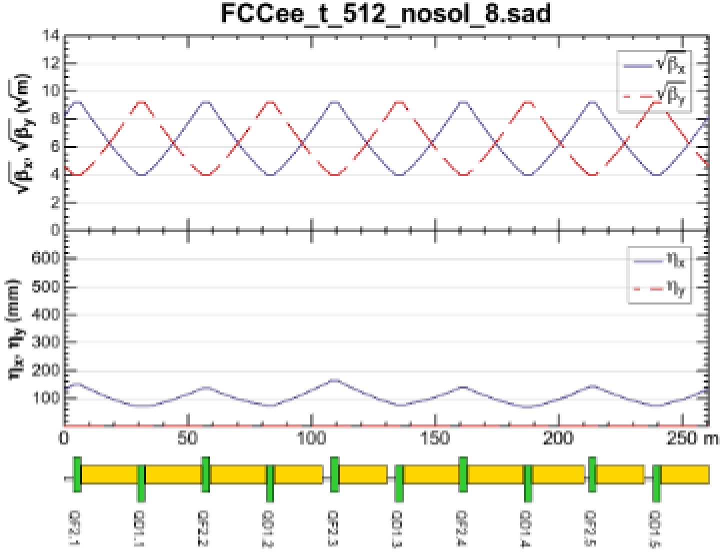
[a] incl. hourglass.

K. Oide, Nov. 2022

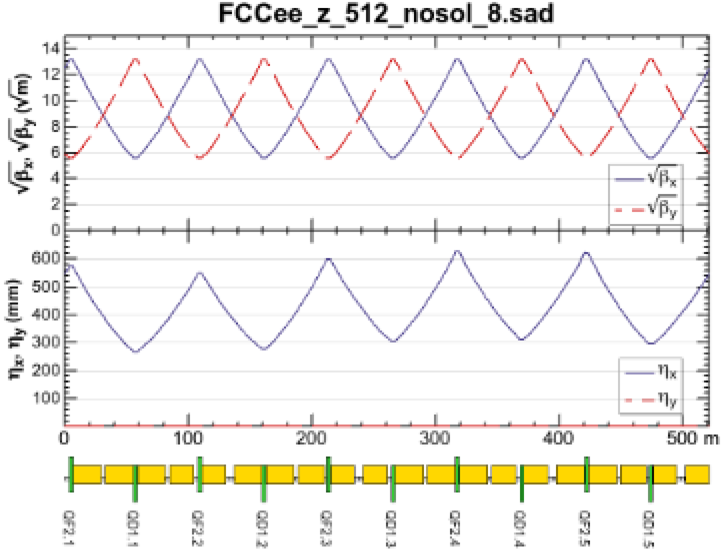
FCC-ee Arc FODO optics

- **Configuration for arc optics with long ~100 m cells at Z & W and short ~50 m cells at Zh and t-tbar**
  - Reduces ε_x at high E and increases α_c at low E

90°/90° : $t\bar{t}$, Zh



Long 90°/90° : Z, W

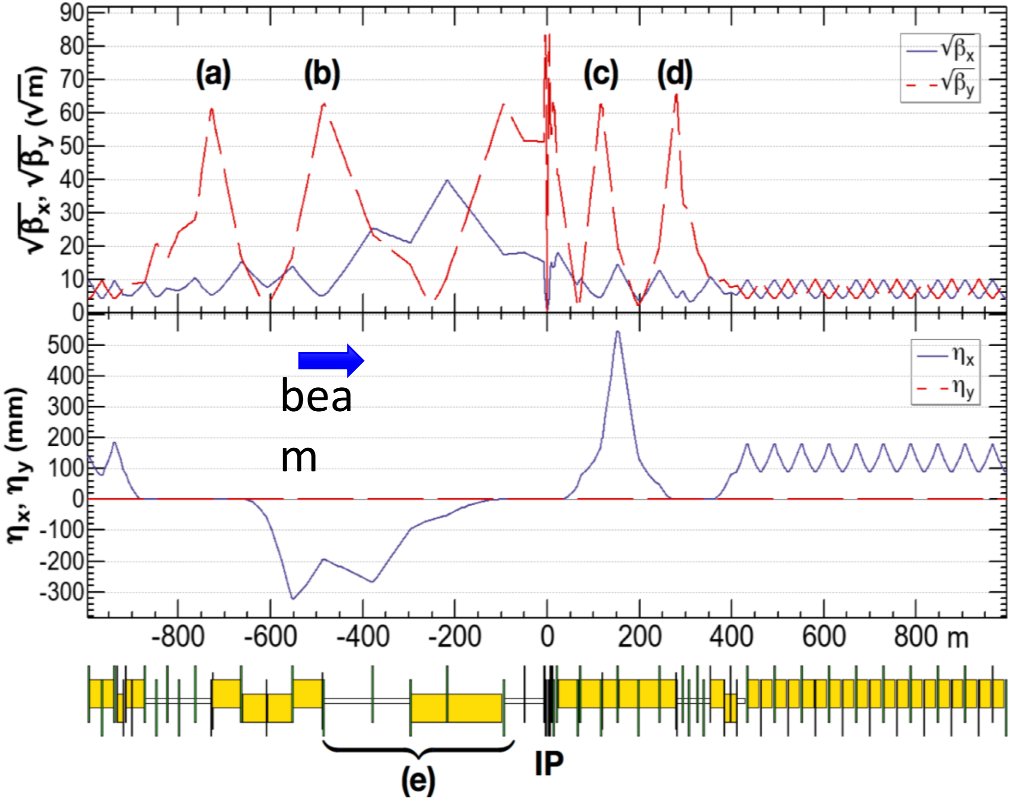


K. Oide

FCC-ee IR optics

- **Novel 'virtual' crab waist combining local vertical chromaticity correction**
    - Crab waist was demon-strated at DAFNE
    - Crab waist is also being used at SuperKEKB
- **Optimized optics configurations for each of the 4 working points**

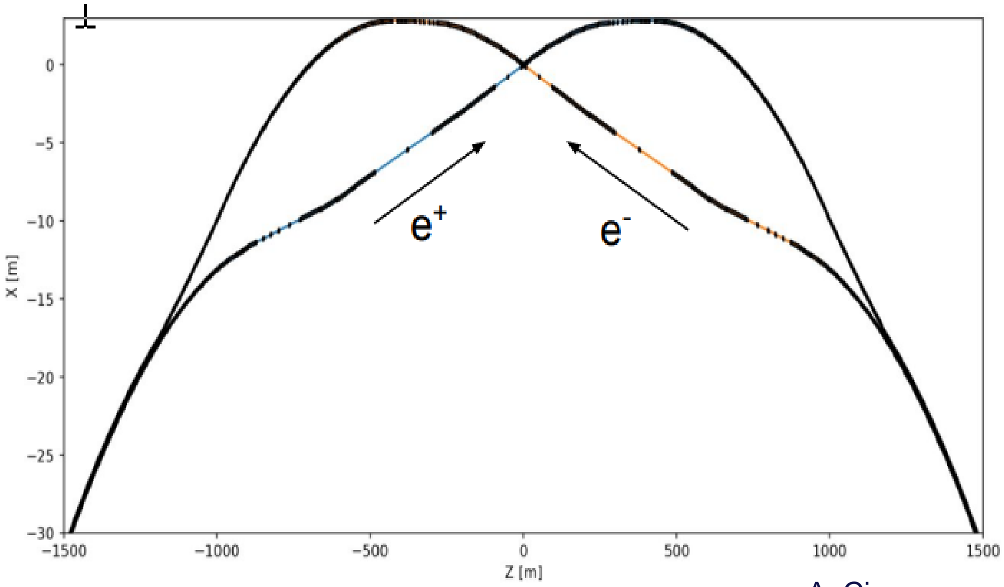
CDR optics, ttbar 182.5 GeV



K. Oide

FCC-ee IR geometry

- **FCC-ee and FCC-hh IP's moved to same location to reduce IR tunnel width**
- **Asymmetric IR layout is chosen to minimize the incoming synchrotron radiation**



A. Ciarma

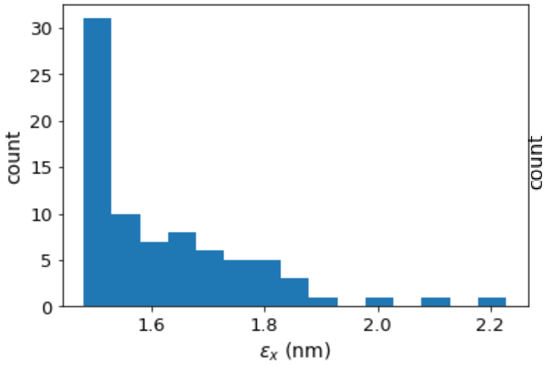
- Photon E_{crit} < 100 keV from magnets within ~500 m of IP
- Collimators and masks further protect detectors
- Optimization is ongoing as part of MDI effort

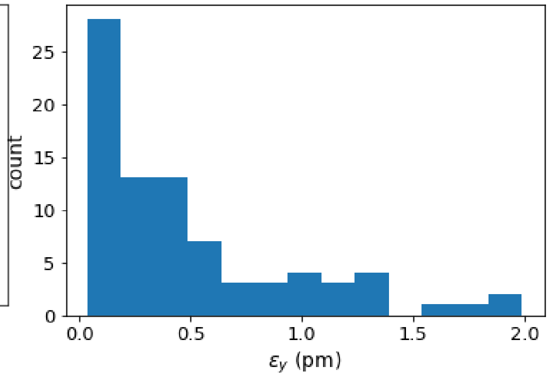
FCC-ee Tuning and Correction

- **Extensive studies on emittance tuning and dynamic aperture**
  - Emittance tuning looks good given a ‘reasonable’ set of errors
  - Working to develop beam-based alignment models to combine with mechanical alignment specifications
  - Sets requirements on diagnostics but eases installation and stability requirements

T. Charles

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	0	0	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	-
IR quadrupole	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$

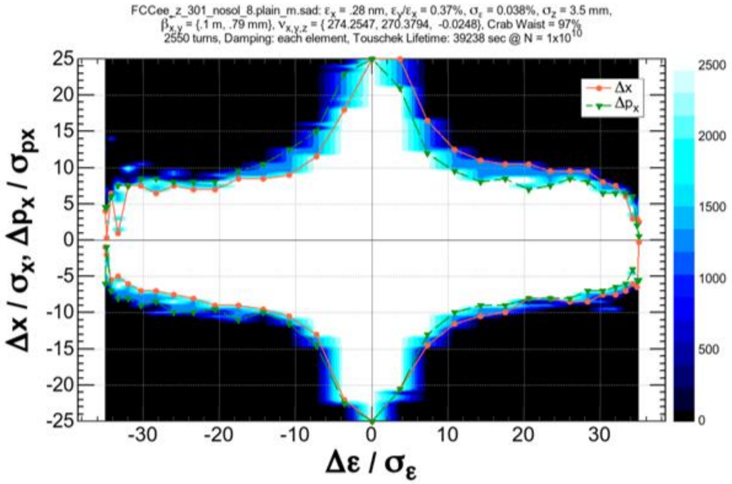




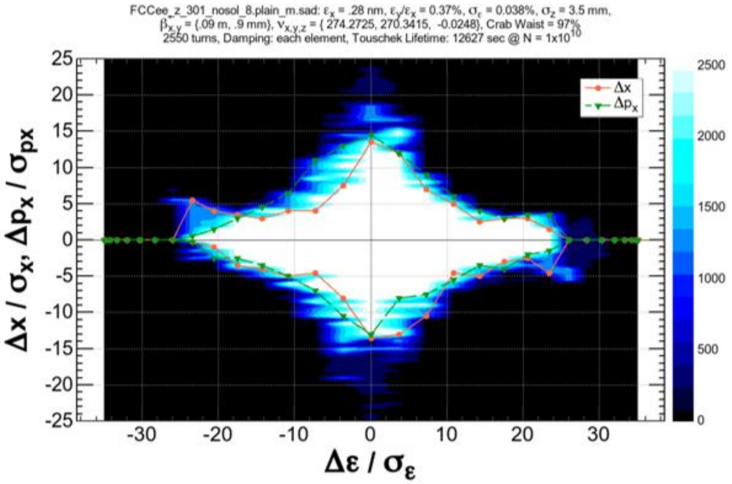
FCC-ee Dynamic Aperture

- **Large dynamic aperture is needed for top-up injection and lifetime due to high beamstrahlung energy tails**
  - Dynamic aperture optimized with ~150 families of sextupoles
  - Aperture is good without errors but still need to improve error correction

No error



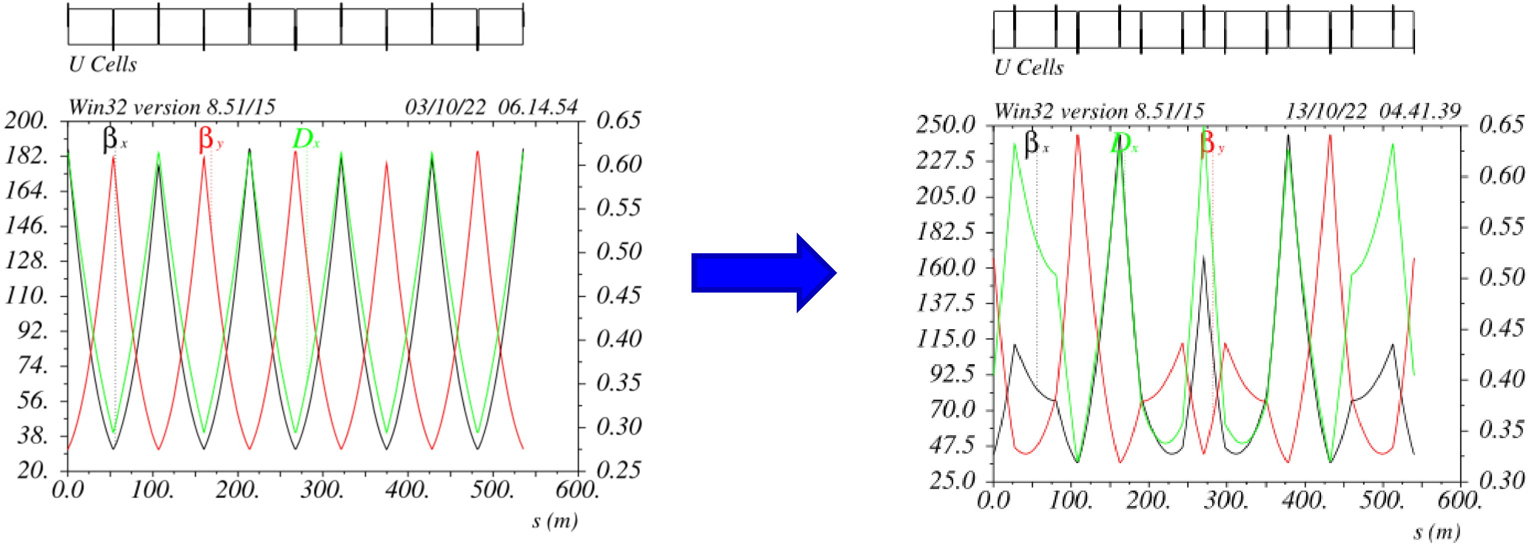
Errors + corrections (“seed 1”)



Alternate Ring Optics

P. Raimondi

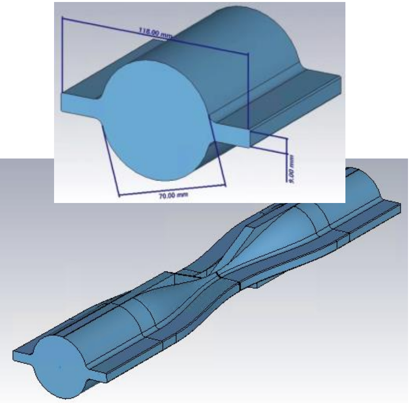
- **Nominal arc cells are 90-degree FODO cells**
  - Consider cell concepts from LC damping rings or light sources that may have better chromatic behavior → better DA

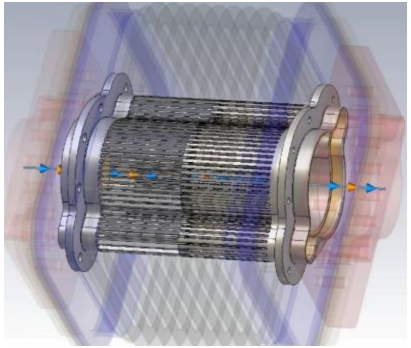


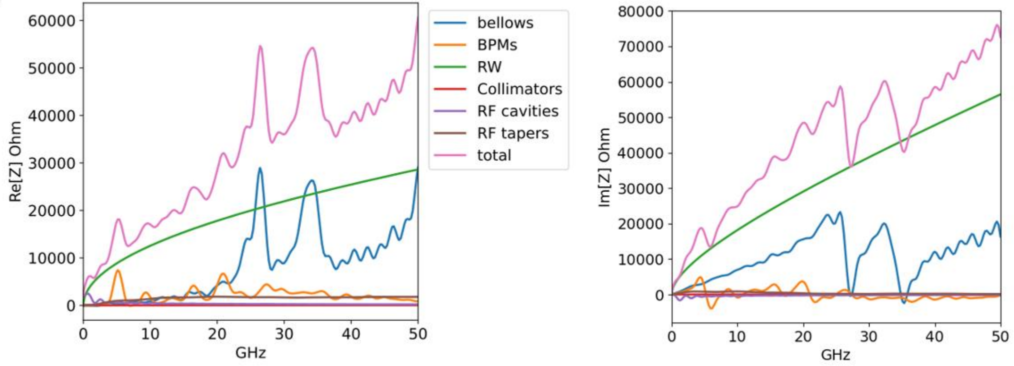
FCC-ee Collective effects

INFN SAPIENZA Università di Roma | Dipartimento di Scienze di Base e Applicate per l'Ingegneria

- **Single bunch instabilities calculated with impedance, beam-beam, and ring optics but there is complicated interplay**
  - Building detailed impedance model: vacuum chamber, RF, bellows, BPMs, collimators working with Super KEKB, EIC, ….
  - Longitudinal wake and beam-beam constrains tunes
  - Beam-beam stabilizes the transverse mode-coupling instability



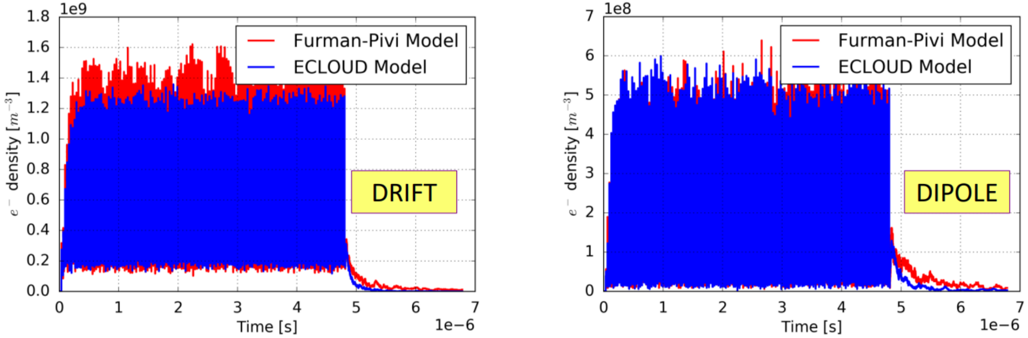




FCC-ee Long-range Collective effects

- **Multibunch instabilities constrain bunch spacing**
  - Requires low SEY and n_γ on vacuum chamber to avoid significant e-cloud
  - Damped RF cavities and electron cloud limits Δt ≥ 15 ns – ongoing studies
- **Large ring circumference limits feedback gain**
  - Developing integrated simulations for collective effects with feedback

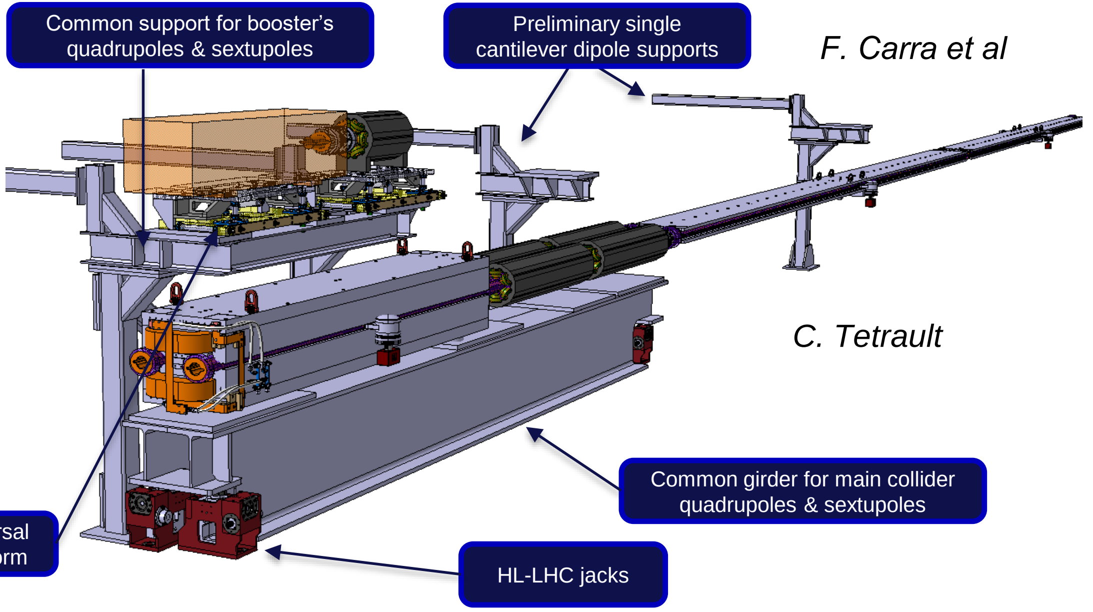
SEY =1.1 , $n'_{(\gamma)}$ =1e-6 m^{-1} , bunch spacing: 32 ns



Fatih Yaman, STFC
Luca Sabato, EPFL
FCC IS and CHART

FCC-ee Accelerator Layout

- **The arc cells are repeated 2000 times around the ring**
  - Critical to understand and optimize the layout for cost, installation, alignment, operation, and maintenance
  - Includes placement of the main rings and the Booster
- **The RF regions are also tightly constrained**
  - Optimize cryomodule lengths and waveguides



FCC-ee SRF Systems

- **Baseline uses established SRF technologies in use at CERN**
- **800 MHz for booster and 400 MHz at Z, W, Zh while adding 800 MHz at t-tbar**
  - Z with very high current → 120 MV of low frequency (400 MHz) single-cell cavities with RF dedicated to e+ or e-
  - Upgrade to 2-cell cavities at W with 1 GV in each ring
  - Increase to 2.1 GV shared between e+ and e- at Zh
  - Add 9 GV of 5-cell 800 MHz to e+ and e- rings along with a total of 11 GV 800 MHz for the booster
- **Consider more aggressive options as alternates in future**

FCC-ee SRF Systems

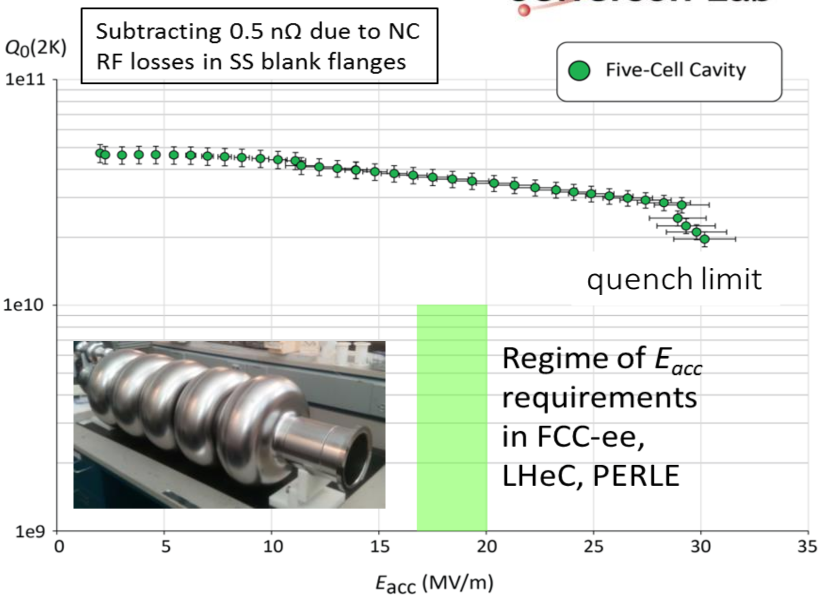
24th May 2022	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1000	1000	2480	2480	2480	9190	11670
Eacc [MV/m]	5.72	6.23	11.91	24.26	11.82	25.45	11.82	24.52	25.11
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	8.93	22.73	8.86	23.85	8.86	22.98	23.53
#cells	56	120	224	220	560	520	560	2000	2480
# cavities	56	24	112	44	280	104	280	400	496
# CM	14	6	28	11	70	26	70	100	124
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	19	0.5	174	7	171	8	171	51	8
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.6E+04	3.2E+05	1.2E+06	8.9E+06	1.5E+06	1.2E+07	8.3E+06	4.9E+06	5.3E+07
Detuning [kHz]	8.939	4.393	0.430	0.115	0.123	0.031	0.025	0.040	0.005
Pcav [kW]	880	205	440	112	352	95	62	207	20
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9937
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9875.14
cos phi	0.32	0.27	0.36	0.36	0.74	0.74	0.70	0.90	0.85
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.005	0.010	0.010	0.001

FCC-ee SRF R&D

- **400 MHz Cu/Nb cavities with Q_0 of >3e9 at 12 MV/m and 4.5K**
  - Require strong damping of single-cell cavities to reduce HOMs at Amp-level current
  - Coupler design for ~MW RF power
  - Compact cryomodule design for W, Zh, and t-tbar
- **800 MHz Nb cavities with Q_0 of >3e10 at 25 MV/m and 2K**
  - Require strong damping of HOMs in 5-cell cavities for 100 mA
  - Recently increased Q_0 spec from 2e10 to >3e10
  - Coupler design for 250 kW RF power
  - Compact cryomodule design for t-tbar

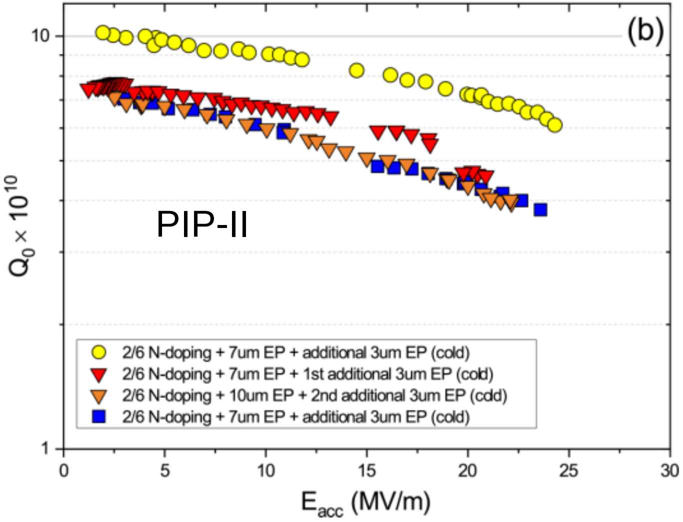
FCC-ee 400 and 800 MHz SRF Systems

- **R&D is on-going around the world on high Q_0 cavities**
- **400 MHz is based on thin-film coatings of Cu cavities while 800 MHz are bulk Nb**
- **LHC is pushing the 400 MHz development of HiPIMS sputtering**
- **Jlab tested a bare 800 MHz cavity**



High Q_0 SRF Systems

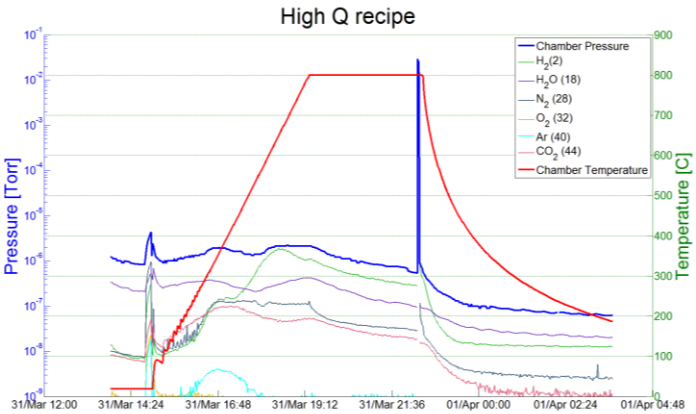
- **LCLS-II developed new N_2 doping approach → is operating cryomodules at 1.3 GHz with Q_0 = 2.7x10^{10} at 16 MV/m**
- **PIP-II is developing high Q cavities at 650 MHz**

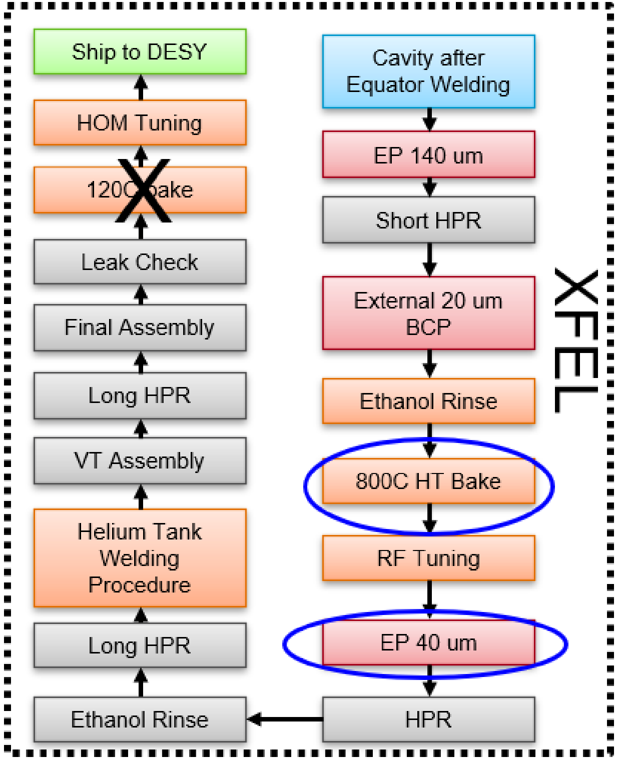


- **LCLS-II-HE has built two cryomodules with Q0 = 2.7x10^{10} and >21 MV/m**

Developing High Q Cavities

- **Development of cavities is guided by theory but still very much an exploration**
- **LCLS-II developed 2/6 N_2 recipe; LCLS-II-HE 2/0 and 3/60 recipes; ILC low-T bake; PIP-II mid-T bake**





Sustainability compared with other Higgs factories

Patrick Janot

https://indico.cern.ch/event/1178975/

P. Janot and A. Blondel, *Who is the greenest? - The environmental footprint of future Higgs boson studies*, arXiv 2208.10466 (2022); https://arxiv.org/abs/2208.10466

TWh / year for the "Higgs factory" centre-of-mass energy

$\sqrt{s}$ = 240 GeV for CEPC/FCC-ee, 250 GeV for ILC/C3, 380 GeV for CLIC

CLIC	ILC	C3	FCC-ee	CEPC
0.8	0.9	0.9	1.1	2.0

Energy consumption in MWh / Higgs

CLIC	ILC	C3	CEPC	FCC-ee
30	20	21	10	3.3

becomes 2 MWh / Higgs for FCC-ee with 4 IPs

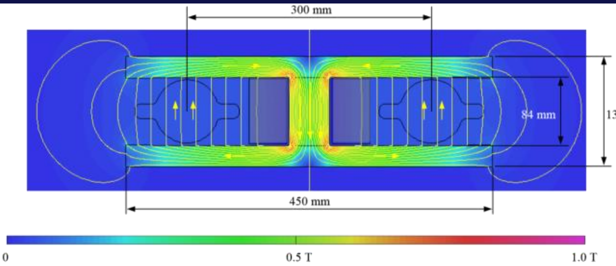
Present carbon footprint for electrical energy in tons CO_2 / Higgs

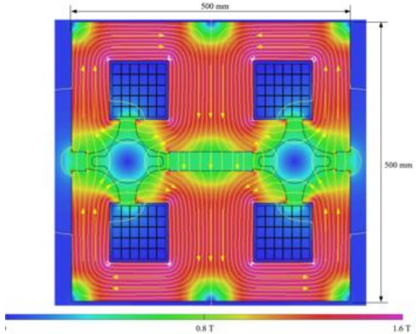
CLIC@CERN	ILC@KEK	C3@FNAL	CEPC@China	FCC-ee@CERN
2.1	7.8	8.5	6.1	0.24

0.14 ton CO_2 / Higgs for FCC-ee with 4 IPs

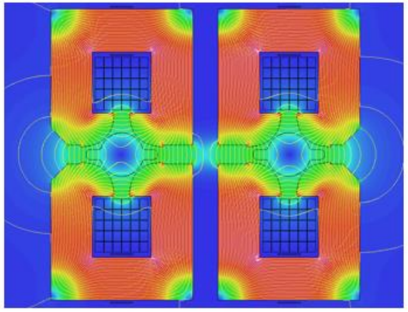
FCC-ee Power Consumption

- **Roughly 300 MW operating at Higgs**
  - Complete power accounting
- **High efficiency RF sources (150 MW) 80 → 90%**
- **High Q RF Cavities (20 MW)**
- **Magnet systems (40 MW)**
  - Dipole quite efficient
  - Quadrupole and sextupole magnets simplified and power reduced with smaller bore or HTS
  - Cable losses may be reduced with in-tunnel PS
- **Efficient cooling and ventilation (40 MW)**





CDR cross-section



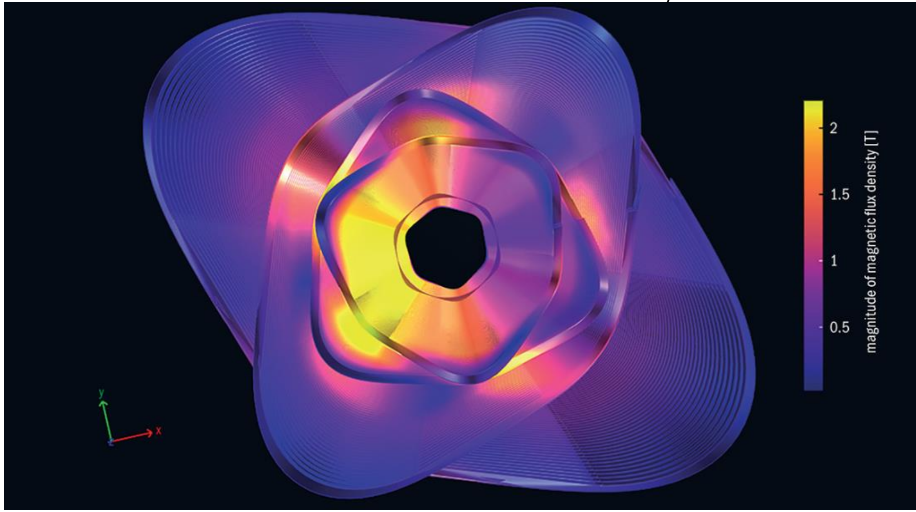
Modified cross-section

HTS Arc Quadrupole / Sextupole / Dipole

Swiss Accelerator Research and Technology

- **Develop HTS magnets for arc quadrupole / sextupoles**
  - Reduce power consumption with nested quadrupole and sextupole
  - Cryo-coolers for compact installation
  - Add weak dipoles to reduce SR power by 10% at Z and 20% at Higgs
- **HTS4 R&D program supported by CHART led by M. Koratzinos**
  - Produce a 1-m protype section leveraging HTS development as part of CHART
  - Understand radiation environment and magnet and cooler radiation damage

CERN Courier, Nov. 2022



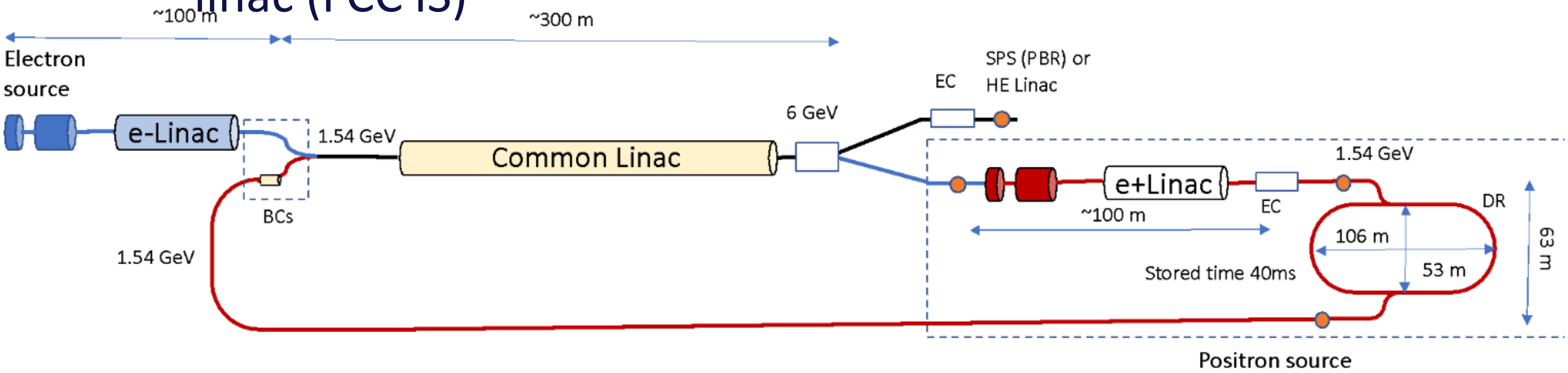
Full Energy Booster

- **Booster ramps from 20 GeV to Main Ring energy**
  - Accumulate electrons or positrons for injection to Main Ring
  - Accumulation times of ~25 seconds at Z
  - Damp beams and transients to Main Ring equilibrium values
  - Alternate injection of e- and e+ to maintain +/- 3 to 5% charge
- **Layouts are being developed with IP Bypasses, Inj/Ext, and RF**
  - Arc cell structure mirrors Main Ring
  - Laminated magnet concepts are being considered
  - Developing integrated model of arc structure including both Main Rings and Booster
  - Collective effects, dynamic aperture and tolerances are being studied

FCC-ee Pre-Injector

P. Craievich, A. Grudiev

- **Design concept being developed with PSI**
  - High brightness e- source and efficient e+ source with damping ring to generate pairs of 6 GeV bunches at 200 Hz (for Z)
  - Acceleration to Booster at ~20 GeV in SPS (CDR) or high energy linac (FCC IS)

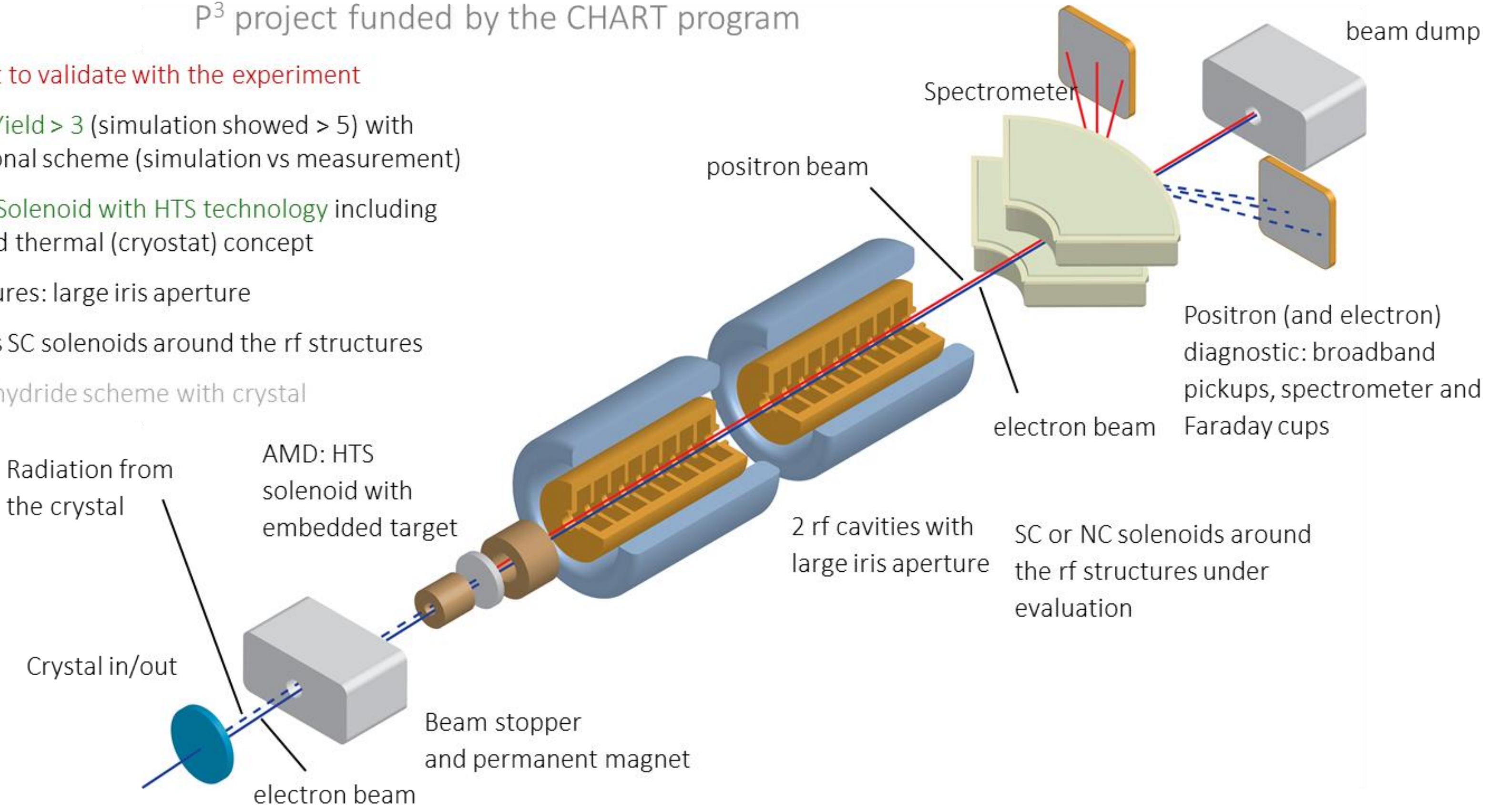


FCC-ee Pre-Injector R&D

P[3] project funded by the CHART program

What we want to validate with the experiment

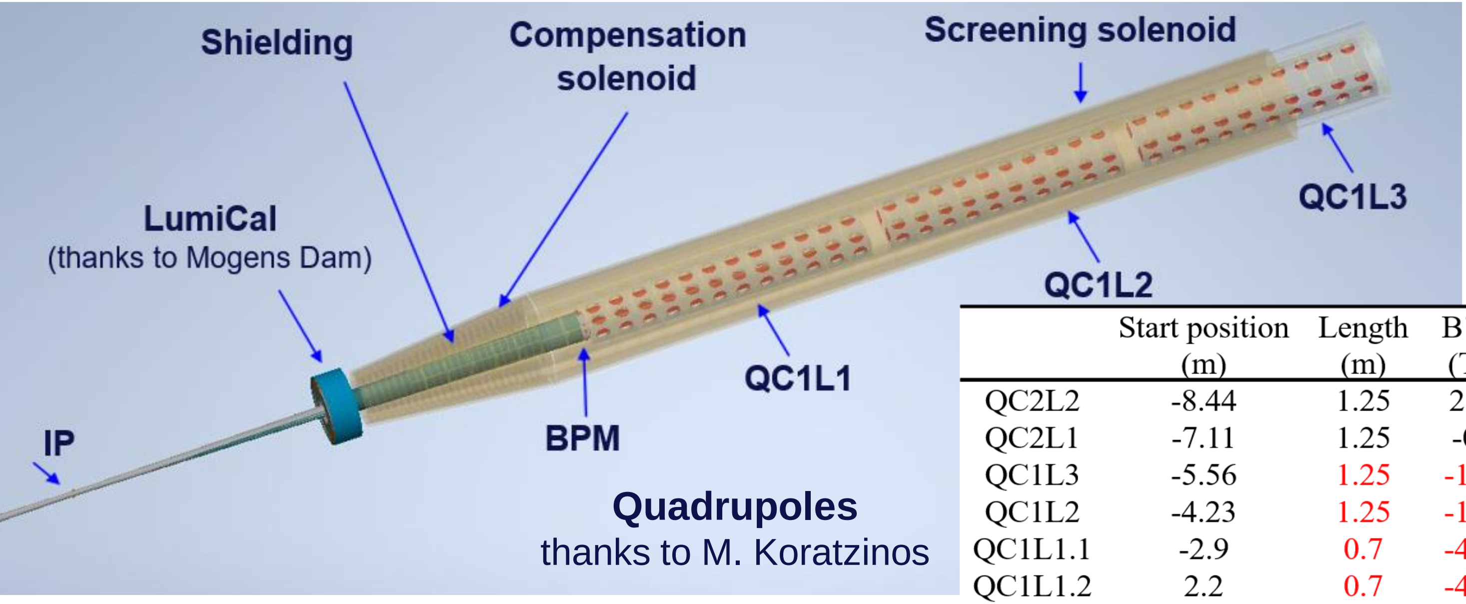
- ✓ Positron Yield > 3 (simulation showed > 5) with conventional scheme (simulation vs measurement)
- ✓ AMD: SC Solenoid with HTS technology including mech. and thermal (cryostat) concept
- ✓ RF structures: large iris aperture
- ✓ NC versus SC solenoids around the rf structures
- ✓ Phase 2: hydride scheme with crystal



FCC-ee MDI and IR design

- **Complicated integration with SC quadrupoles, solenoids, IR chamber, LumiCal, shielding, and diagnostics**

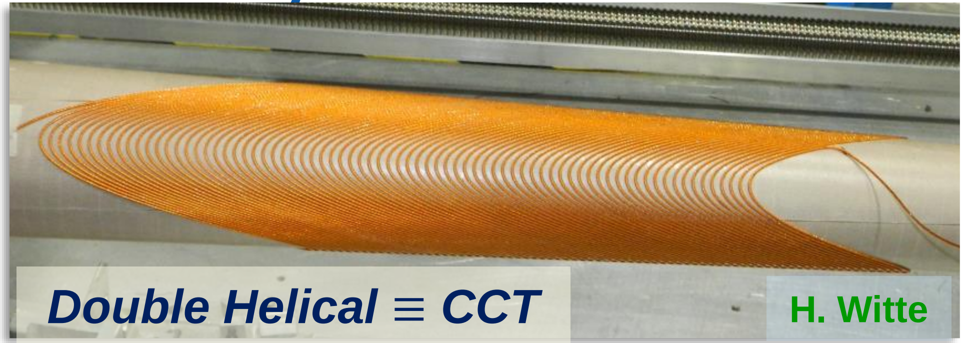
M. Boscolo,
M. Koratzinos,
B. Parker, et al



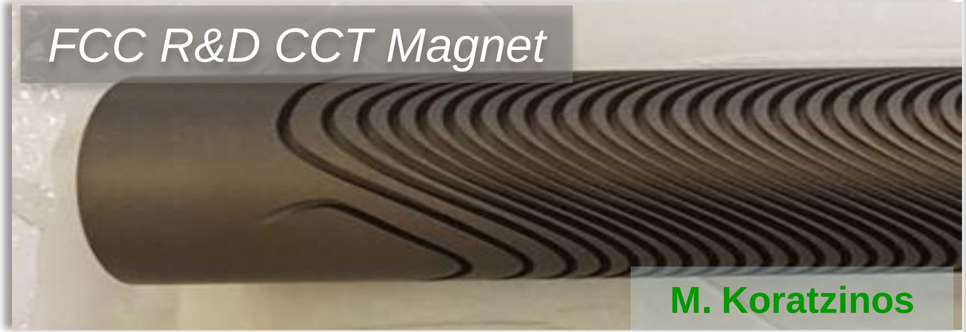
	Start position (m)	Length (m)	B' @Z (T/m)	B' @W (T/m)	B' @ H (T/m)	B' @ tt (T/m)
QC2L2	-8.44	1.25	25.05	43.82	61.30	69.50
QC2L1	-7.11	1.25	-0.18	0.00	7.32	56.85
QC1L3	-5.56	1.25	-19.35	-34.38	-53.08	-99.98
QC1L2	-4.23	1.25	-18.57	-32.94	-53.07	-99.98
QC1L1.1	-2.9	0.7	-40.95	-70.00	-99.71	-95.39
QC1L1.2	2.2	0.7	-40.95	-70.00	-99.71	-95.39
QC1R2	2.98	1.25	-25.44	-37.25	-51.94	-100.00
QC1R3	4.31	1.25	-19.54	-39.51	-53.65	-91.87
QC2R1	5.86	1.25	14.64	16.85	-2.65	37.19
QC2R2	7.19	1.25	19.50	44.32	67.52	94.43

FCC-ee IR Magnet R&D

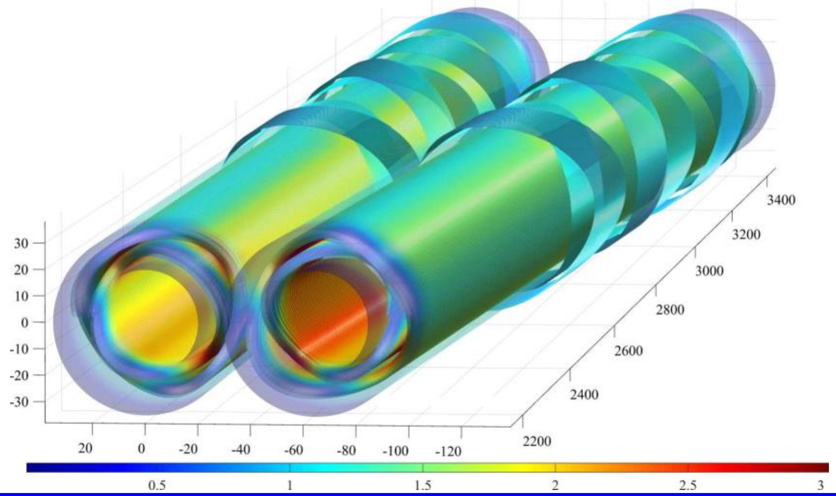
- **Many similarities with EIC IR**

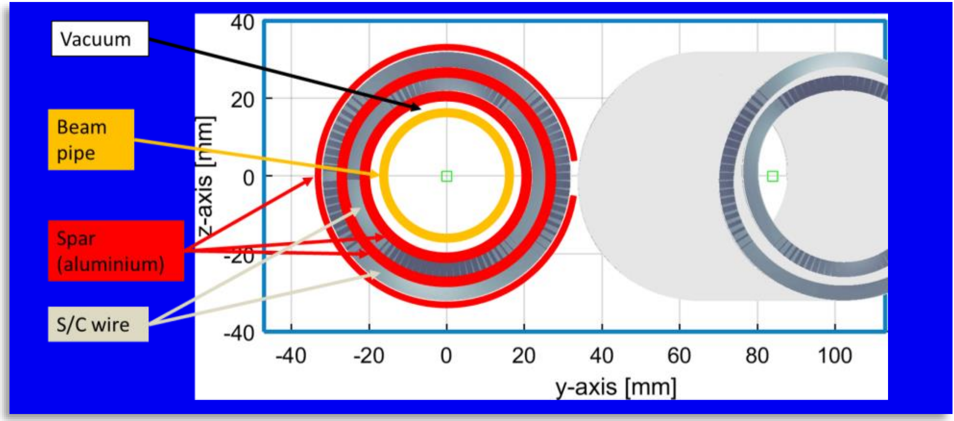


Direct Wind Tapered Double Helical Coil



Grooved Double Helical Coil Support





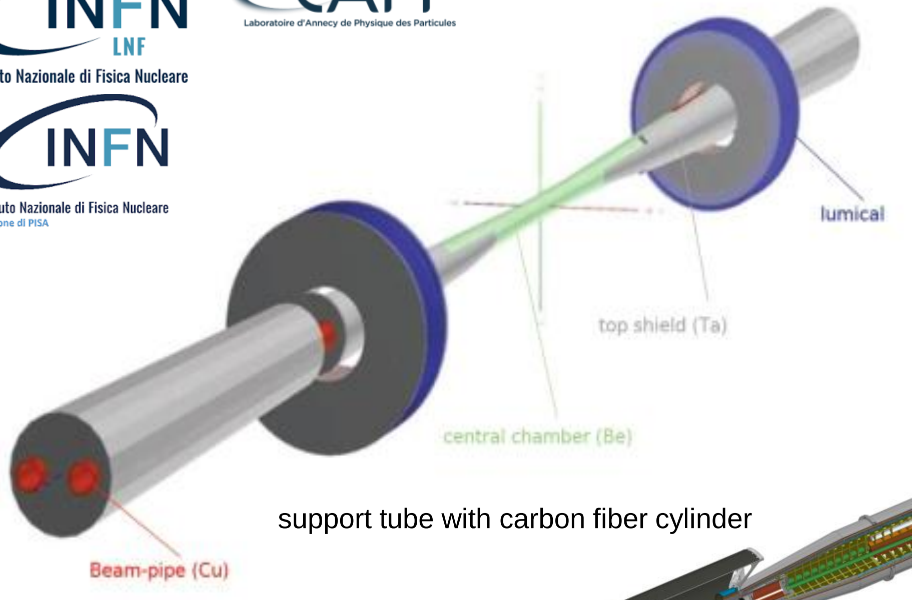
Baseline FCC-ee Coils and Beam Pipe

FCC-ee IR Mock-up

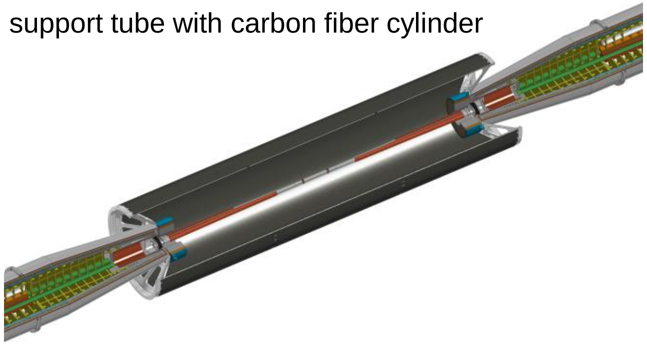
IP chamber: critical for performance, MDI

<u>Step 1:</u> **Central IP vacuum chamber** (test cooling and vacuum systems), **AlBeMet162 & steel transition** (shape of transition, EBW process), **Bellows** (vacuum and thermal tests), **Welding** (EBW for elliptical geometry), **C-fibre support structure**

<u>Step 2:</u> **Trapezoidal vacuum chamber with remote vacuum connection**, **first quadrupole QC1, cryostat,** beam pipe and quadrupole and **cryostat support**, **vibration & alignment sensors**

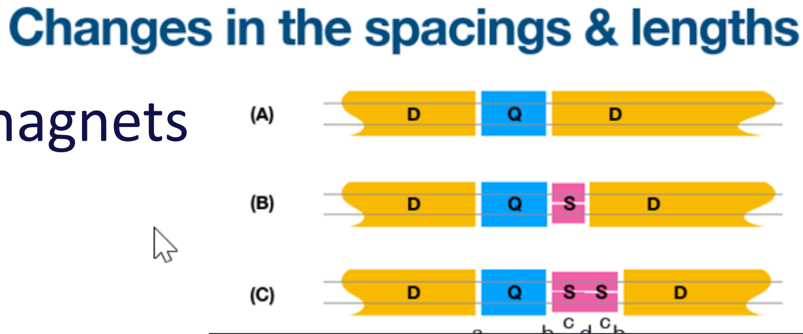


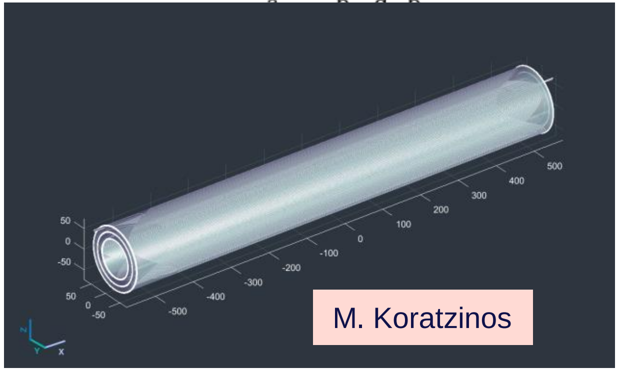
support tube with carbon fiber cylinder



FCC-ee Alternative technologies

- **Developing technologies with significant potential impact in parallel to baseline, e.g.**
  - HTS arc quadrupole/sextupole magnets
  - High efficiency RF sources
  - Radiation hard electronics
  - HE linac as a pre-booster
  - Positron target using crystal channeling
  - Advanced cooling tower design
  - Advanced cryogenic design
  - …





Combined function HTS magnet

Synergistic Programs

- **Collaborators around the world**

147 Institutes

30 Companies

34 Countries

- **Many synergies with other large accelerator projects**
  - Super KEKB (KEK)
  - CEPC (China)
  - Electron Ion Collider (BNL / Jlab)
  - PIP-II (Fermilab)
  - Synchrotron radiation facilities (world-wide)

FCC accelerator summary and timeline

- **Finalizing layouts with correct circumference**
- **FCC-ee baseline parameters are established**
  - Main ring substems, full-energy booster, and injector all being defined
- **Technical systems making good progress**
  - Vacuum, magnets, SRF, cryogenics, diagnostics, integration, …
  - Already most efficient Higgs solution but working to improve overall η
  - Extensive world-wide R&D program
- **Luminosity requires all systems work together in large facility**
  - Still many challenges in developing robust integrated design
- **Will have baseline established in 2023 and optimize further to complete feasibility study at end of 2025**

Thank you for your attention.