US Contributions to FCC
FCC-US Workshop

Tor Raubenheimer

April 24, 2023

FCC-ee Layout

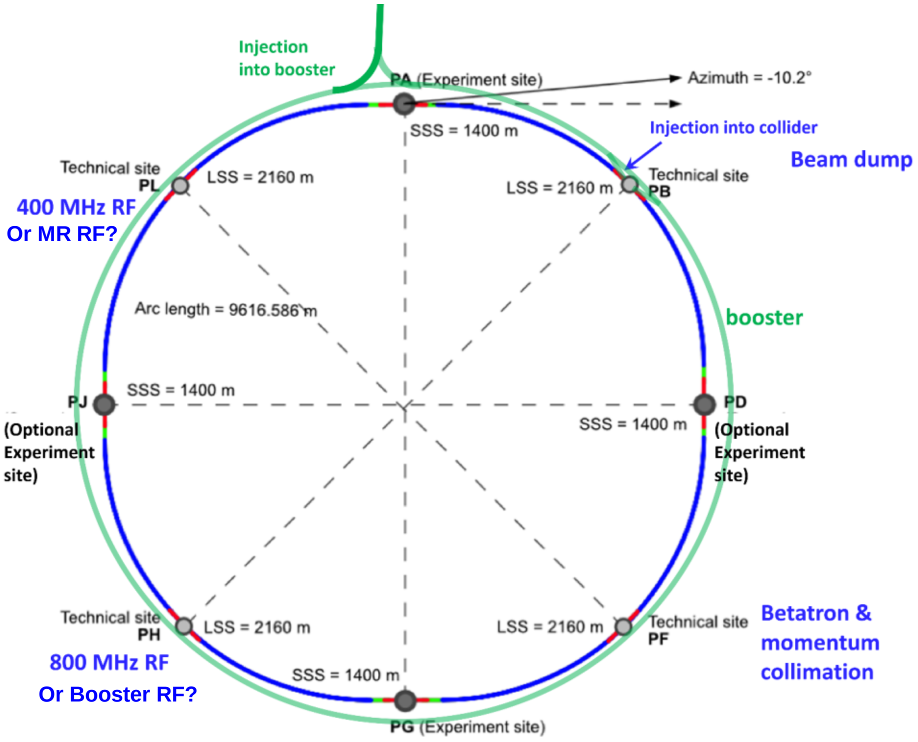
Double ring e+e- collider with 91 km circ.

Common footprint with FCC-hh, except around IPs

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 and 20 GeV e+/e- source and linac**



Present US Engagement in FCC Accelerator

- Physics and detector studies (numerous US universities and labs)
- high-field magnet development (FNAL, LBNL, NHFML)
- SRF development (800 MHz 5-cell cavity prototype, JLAB)
- FCC-ee accelerator design: optics and collective effects (SLAC)
- FCC-ee machine detector interface (SLAC, BNL, JLAB)
- FCC-ee interaction-region magnet systems (BNL)
- FCC-ee polarisation and precise energy calibration (FNAL, BNL, Cornell, UNM)
- FCC-EIC collaborations (BNL, JLAB)
- FCC tunnel safety (FNAL)
- FCC civil engineering - surface building design (FNAL)
- SRF 800 MHz bulk Nb cavities with high-Q – in preparation
- SRF cryomodule design – in preparation

Opportunities for increased engagement

Some R&D topics match to unique US technical expertise: bulk Nb SRF, compact SC IR magnets, …

Many other topics leverage US capabilities: beam physics, RF power sources, waveguides, and couplers, power convertors, HTS magnets, beam instrumentation and feedback, controls, ….

Other topics could engage US industry: 270 km vacuum chamber and associated components, dipole magnets for main ring and booster, supports and girders, ….

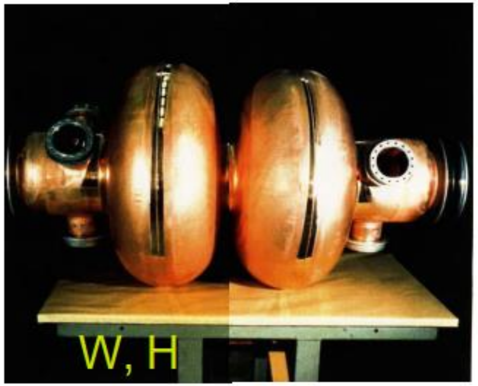
3 different types of SRF cavities for the FCC-ee RF baseline

New compared to CDR

400 MHz 1-cell cavities

Nb/Cu

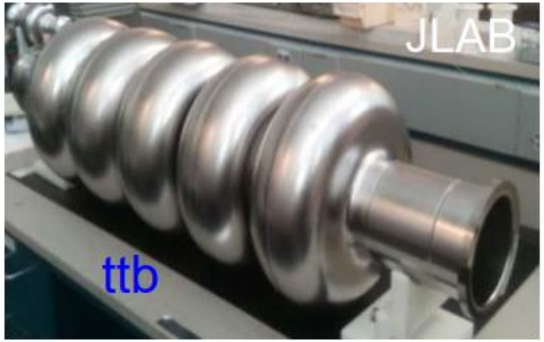
Removed after Z operation



400 MHz 2-cell cavities

Nb/Cu

2-cell is better for W working point
(reduced RF power per cav., improved HOM damping)



800 MHz 5-cell cavities

Bulk Nb

F. Peauger and O. Brunner

New RF parameters (February 2023)

Limiting parameters for RF

15-Feb-23	Z		W		H		ttbar2		
	Collider per beam	booster	Collider per beam	booster	Collider 2 beams	booster	Collider 2 beams	Collider 2 beams	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1050	1050	2100	2100	2100	9200	11300
Eacc [MV/m]	5.72	5.34	10.95	20.01	10.78	20.01	10.78	20.12	20.10
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.00	8.20	18.75	8.08	18.75	8.08	18.85	18.83
#cells	56	140	256	280	520	560	520	2440	3000
# cavities	56	28	128	56	260	112	260	488	600
# CM	14	7	32	14	65	28	65	122	150
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav * [W]	22	0.2	163	3	158	3	158	23	3
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.6E+04	2.7E+05	1.1E+06	7.7E+06	1.1E+06	1.5E+07	9.4E+06	3.8E+06	8.3E+07
Detuning [kHz]	8.939	5.126	0.472	0.141	0.096	0.014	0.031	0.032	0.003
Pcav [kW]	880	176	385	88	379	44	45	181	8
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	0.35	0.35	0.88	0.88	0.56	0.96	0.87
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005

* heat loads from power coupler and HOM couplers not included

one RF system per beam | common RF system for both beams

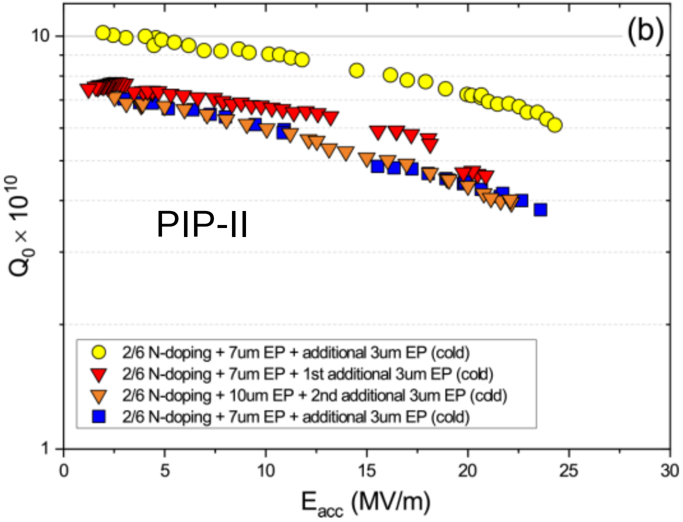
- **Cavity performances: 20 % margin on Eacc and Q0 between vertical test and operation**
- **In total: 365 cryomodules, 1460 cavities, 25% with Nb/Cu technology**

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

High Q_0 SRF Systems – US expertise

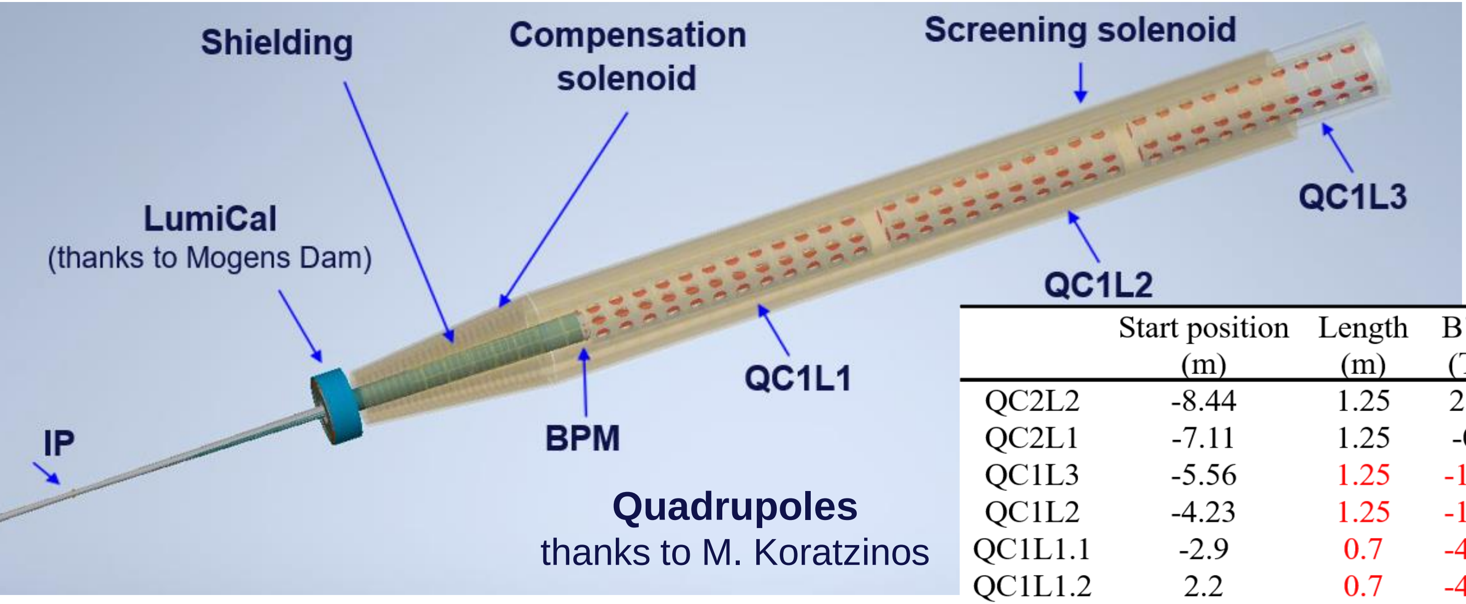
- **LCLS-II developed new N_2 doping approach → is operating cryomodules at 1.3 GHz with $Q_0 = 2.7 \times 10^{10}$ at 16 MV/m**
- **PIP-II is developing high Q cavities at 650 MHz**



- **LCLS-II-HE will build 23 cryomodules with Q0 = 2.7×10^{10} and >21 MV/m**

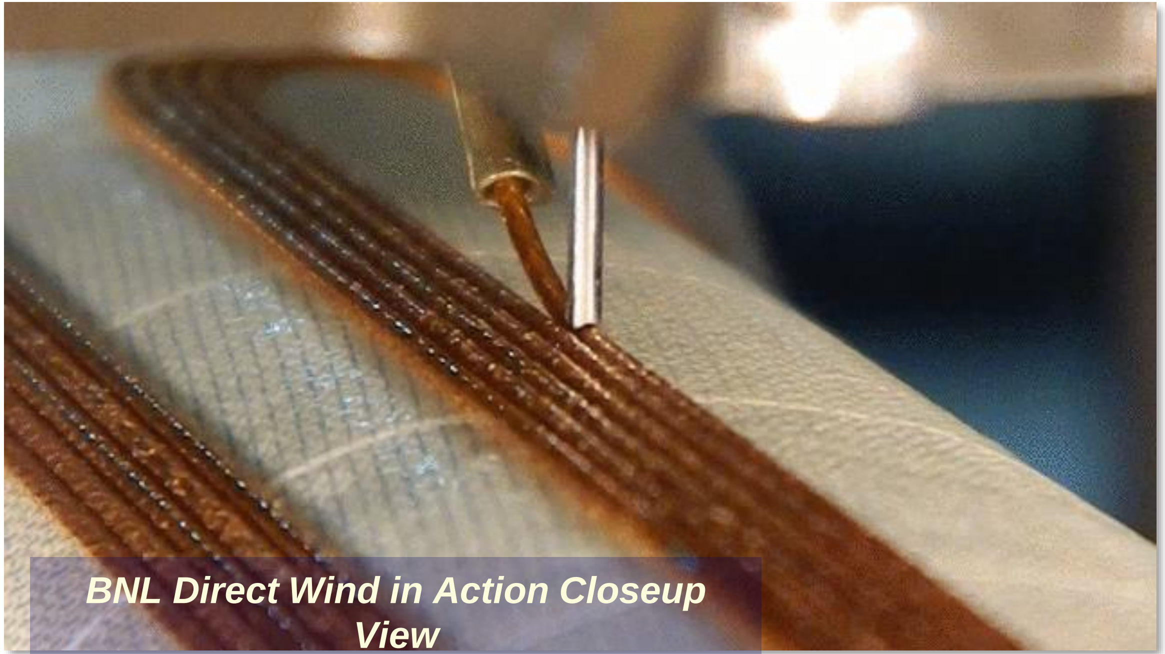
- **Complicated integration with SC quadrupoles, solenoids, IR chamber, LumiCal, shielding, and diagnostics**

M. Boscolo,
M. Koratzinos,
B. Parker



	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

IR Magnets

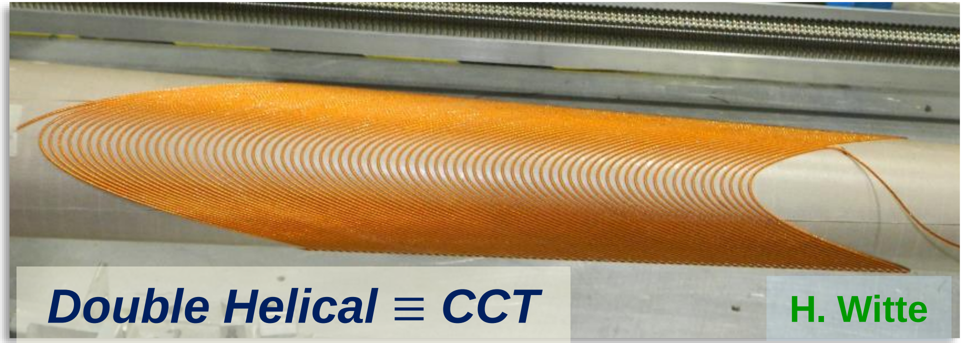


BNL Direct Wind in Action Closeup View

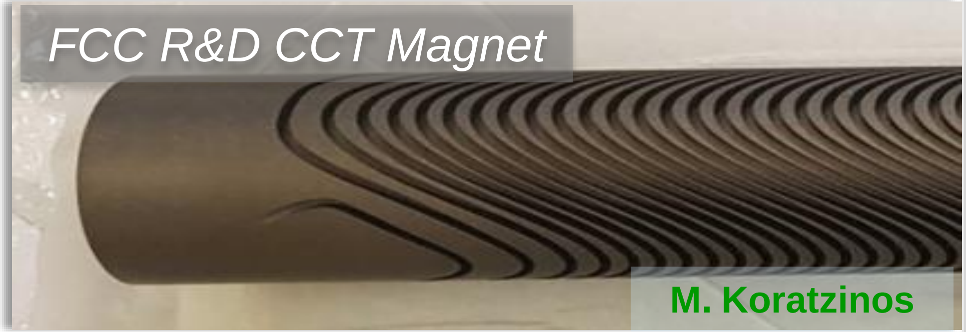
- Challenging IR magnets embedded in the detector with 2.2 meter L*
- Similar requirements to Linear Colliders
- Small aperture with modest pole-tip field
- Design and requirements have significant impact on detectors

FCC-ee IR Magnet R&D

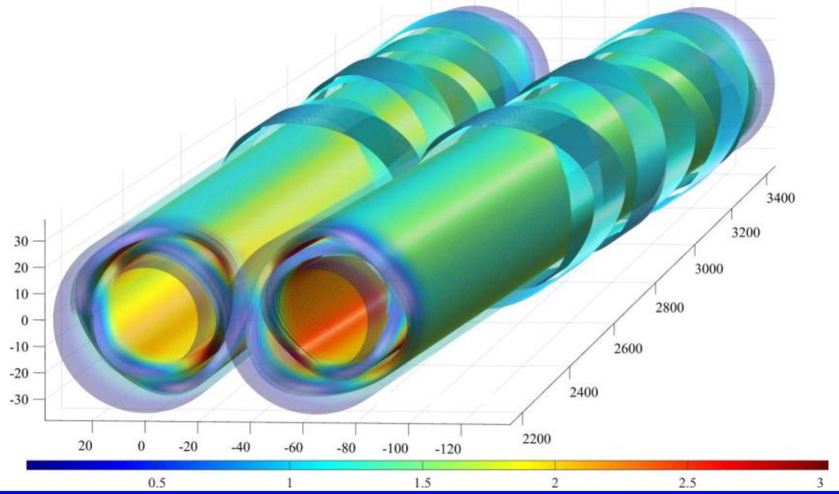
- **Many similarities with EIC IR**

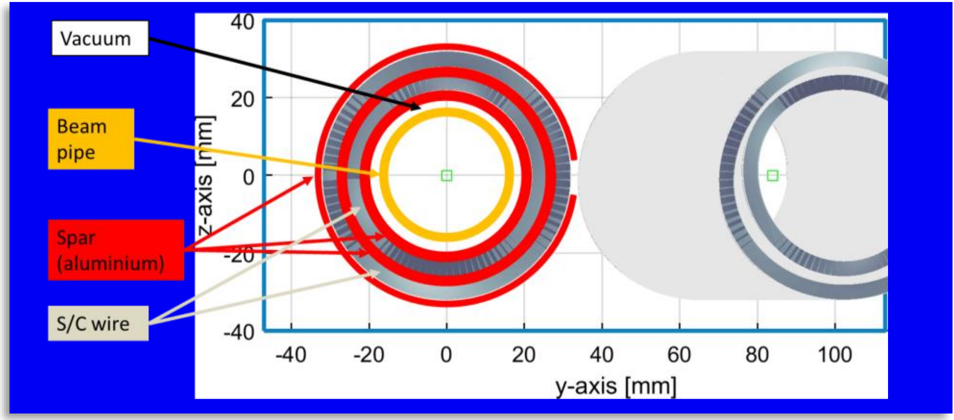


Direct Wind Tapered Double Helical Coil



Grooved Double Helical Coil Support





Baseline FCC-ee Coils and Beam Pipe

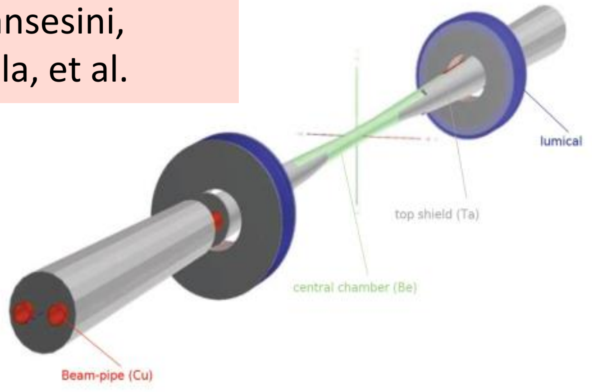
FCC-ee IR Mockup

IP chamber: critical for performance, MDI

1) 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

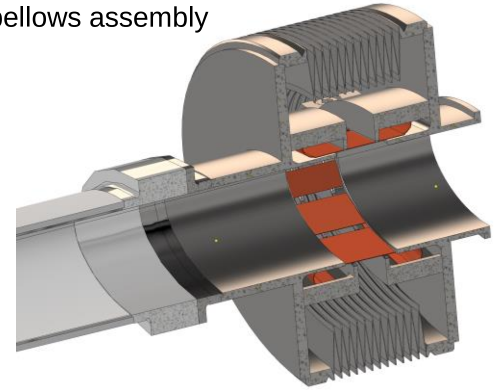
2) Elliptical vacuum chamber with remote vacuum connection, first quadrupole QC1, cryostat, beam pipe and quadrupole and cryostat support, vibration & alignment sensors

M. Boscolo,
F. Fransesini,
F. Palla, et al.

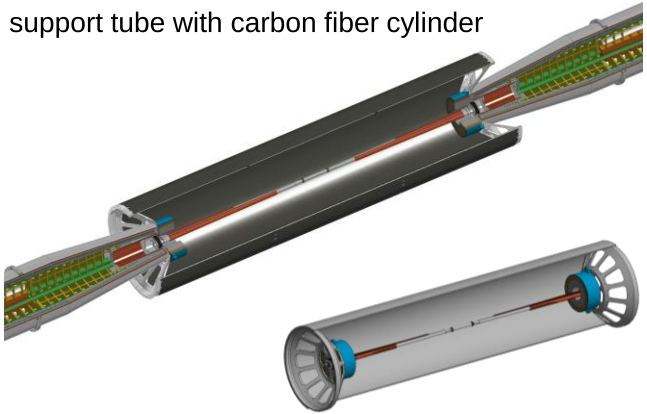


SLAC NATIONAL ACCELERATOR LABORATORY
INFN LNF Istituto Nazionale di Fisica Nucleare
LAPP Laboratoire d'Annecy de Physique des Particules
CERN
INFN Istituto Nazionale di Fisica Nucleare Sezione di PISA

bellows assembly



support tube with carbon fiber cylinder

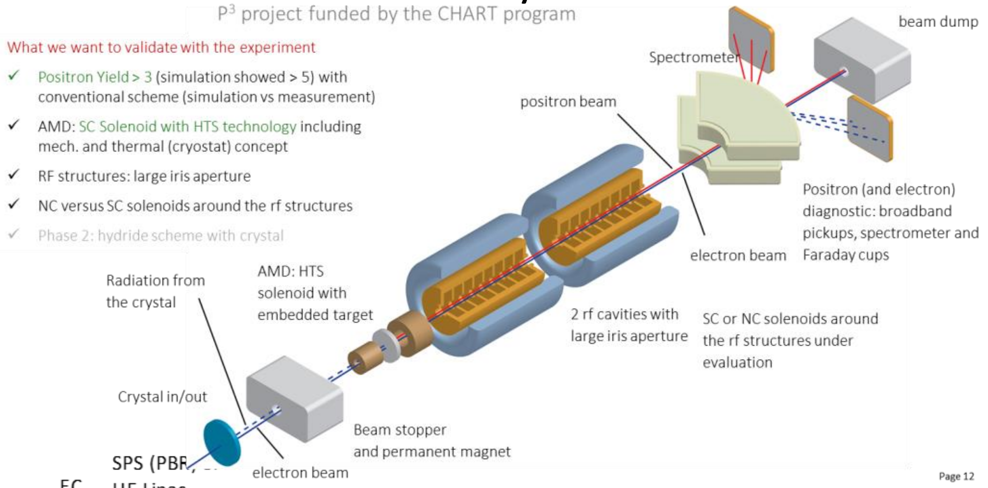


FCC-ee Pre-Injector R&D

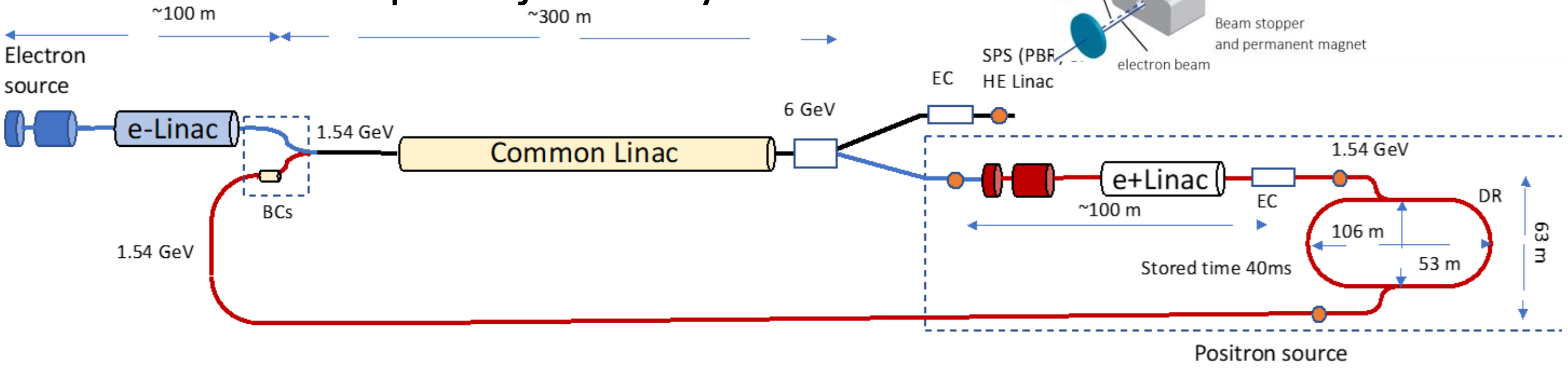
Collaboration between PSI and CERN with external partners: CNRS-IJCLab (Orsay), INFN-LNF (Frascati), KEK/SuperKEKB as observer, INFN-Ferrara – radiation from crystal

e+ requirements ~2x SLC

P^3: PSI e^+ production experiment with HTS solenoid at SwissFEL planned for 2024/25



Latest FCC-ee pre-injector layout

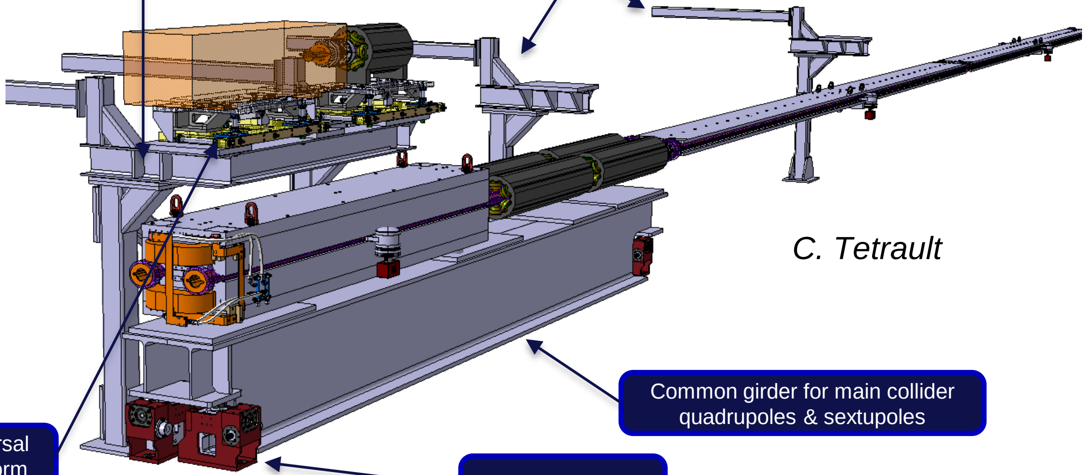


20 GeV linac to Booster

P. Craievich, A. Grudiev, C. Milardi, A. De Santis, et al.

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
  - 6000 11-meter twin-bore dipoles and 3000 3-meter twin-bore quadrupoles plus the booster



FCC-ee Vacuum System

Present design similar to that presented in the CDR:

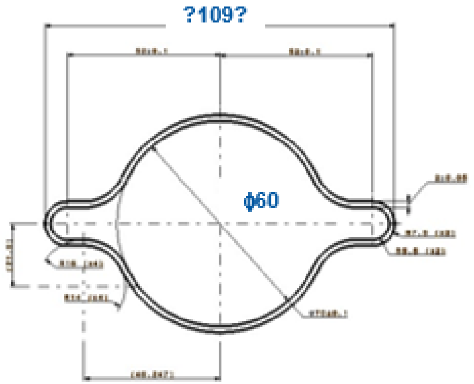
Geometry: Tube with two winglets
2 mm thick, 60 mm ID

Material: Copper
- Good thermal conductivity and low electrical resistivity
- Shielding for the X-Ray synchrotron radiation fan and minimizing the irradiation of machine and tunnel components

Surface treatment: NEG coating
- Distributed pumping speed
- Low SEY
- Quick vacuum conditioning

Lumped SR photon absorber:
Distanced by about 5.8 m

Lumped pump: no need for a systematic installation in vicinity of the absorbers →1 or 2 per cell



Vacuum chamber prototype cross-section

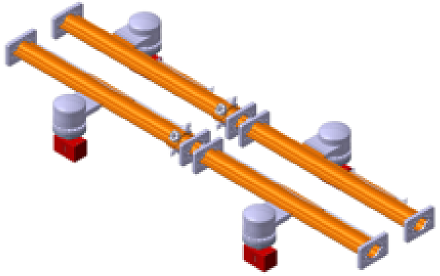
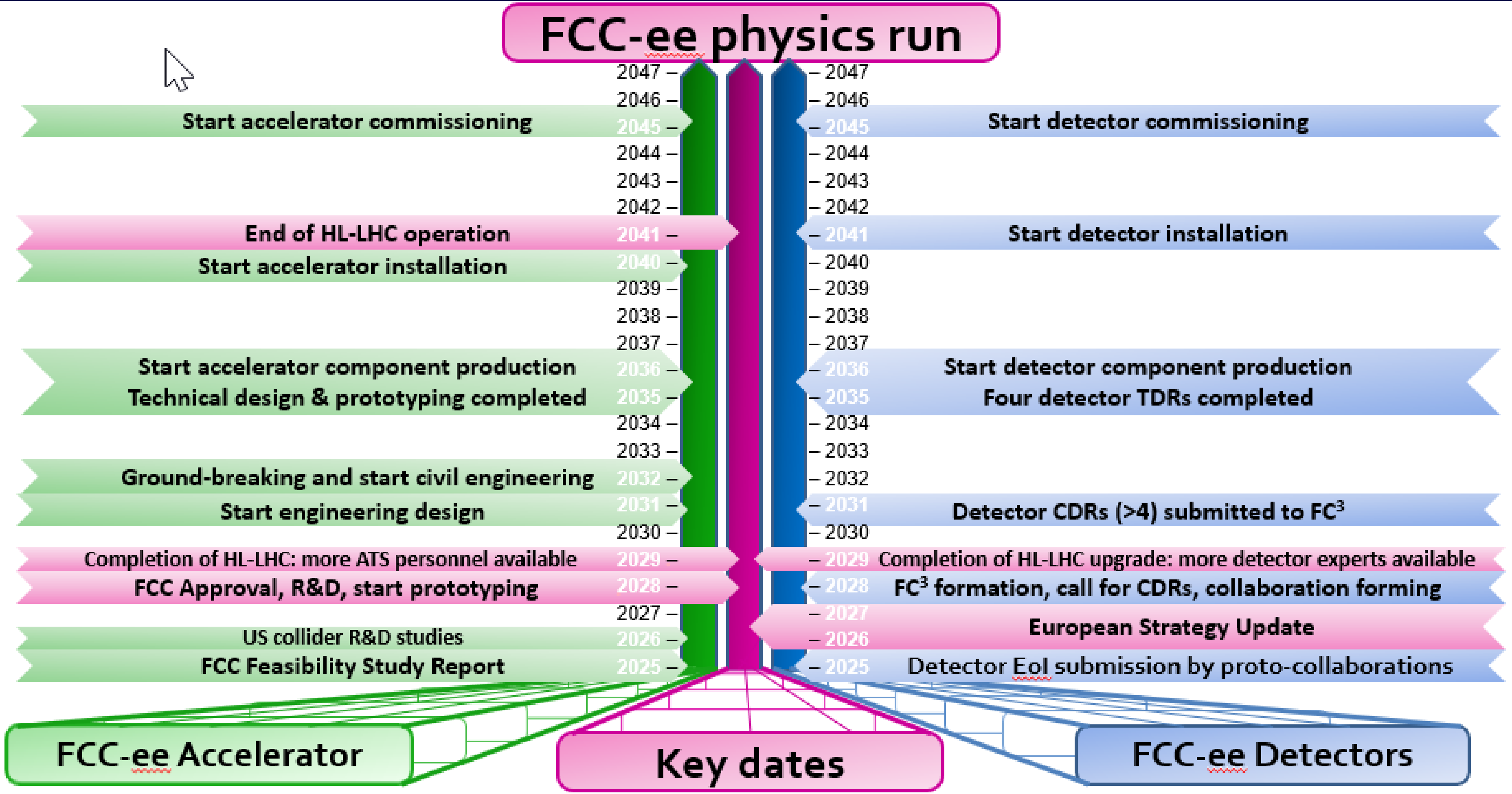


Illustration of vacuum chambers with absorbers and pumps

The whole vacuum system shall be designed with a cost-effective and sustainable approach.



US DOE project key dates might differ somewhat from the FCC project milestones shown above.

Possibly: CD0 ~2029, CD1 ~2030/31, CD2 ~2033/34, scope-specific CD3a ~2032-34, full CD3 2036/37, CD4~2046/47.

Planning US Engagement

- **Working to develop an R&D budget request for P5**
  - Expect that OHEP will establish a funding path for FCC-ee accelerator and detector R&D and we're developing a placeholder to provide guidance
- **FCC-US meeting is an opportunity to start thinking about details**
  - Focus on technologies other than SRF right now: IR magnets, collimation, backgrounds, beam physics, ...
- **Lots more detail will be discussed at FCC Week 2023**
  - Join us there!

FCC-ee US Engagement Summary

- **US has been engaged in the FCC-ee design**

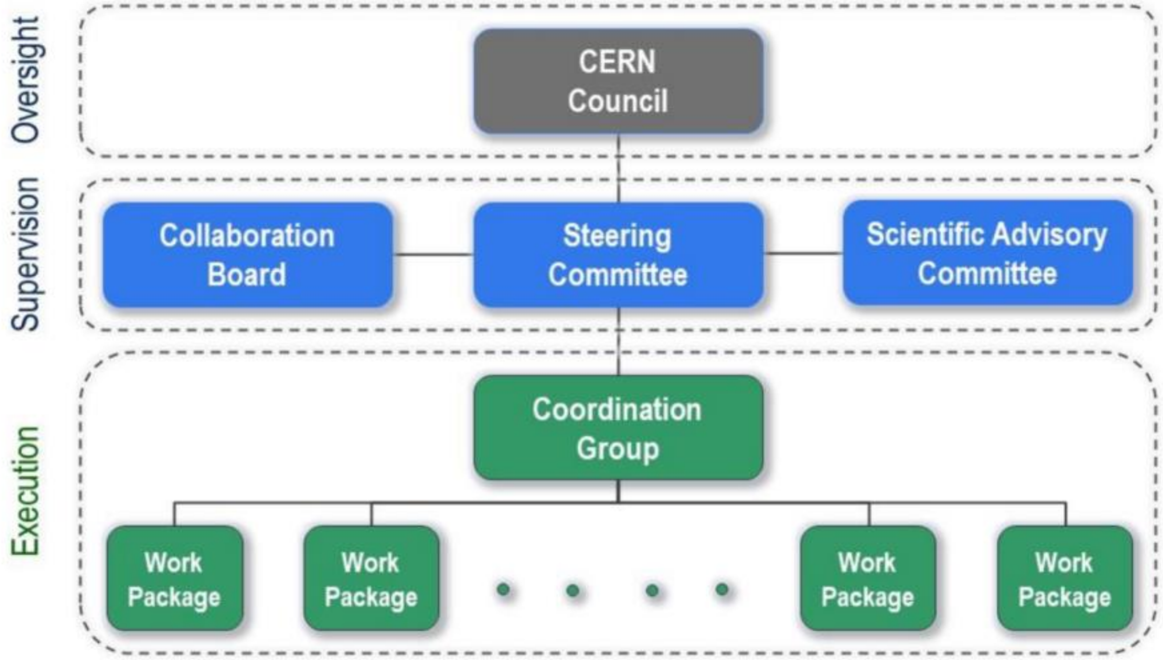
- **Many opportunities for engagement in R&D stage which will continue into 2030's – many synergies with EIC**

- **A decision on FCC-ee will be presumably made on 2027 timescale → increased engagement with R&D, engineering, and fabrication**

- **Assuming the project moves ahead, the US contribution could be B$-scale**

Thank you
for your attention.

Management and Advisory



Lia Merminga (FNAL) is member of Steering Committee
Andy Lankford (UC Irvine) is vice-Chair of Collaboration Board
Tor Raubenheimer (SLAC) is co-convener of Accelerators Work Package and member of Coordination group
Michiko Minty (BNL) is member of Scientific Advisory Committee