FCC ACCELERATOR and OPERATIONS

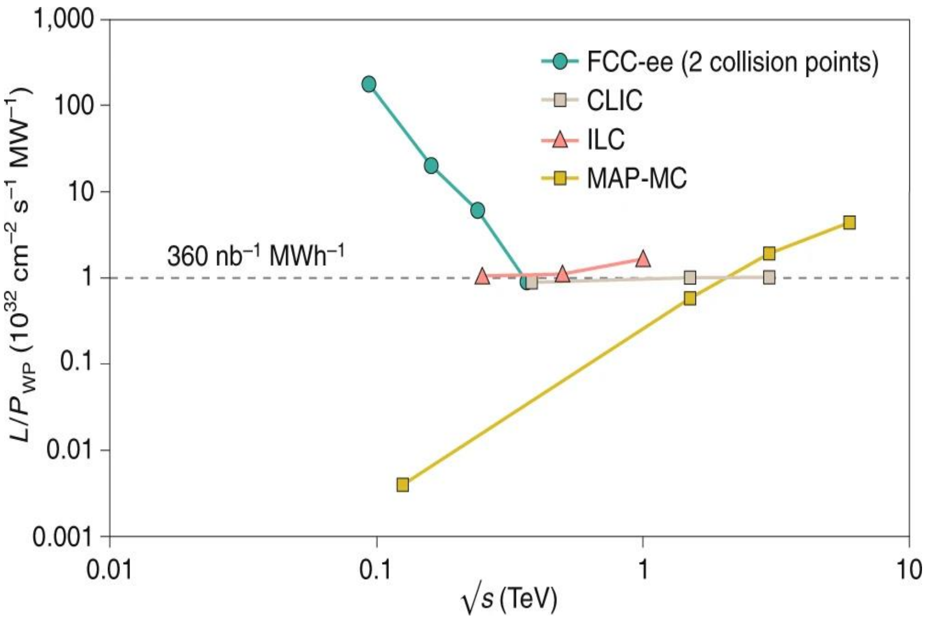
Introduction

- **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, …**
- **Full-energy booster and e+/e- injector**
- **MDI and integration**

Accelerator Design Status

- **New 91 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

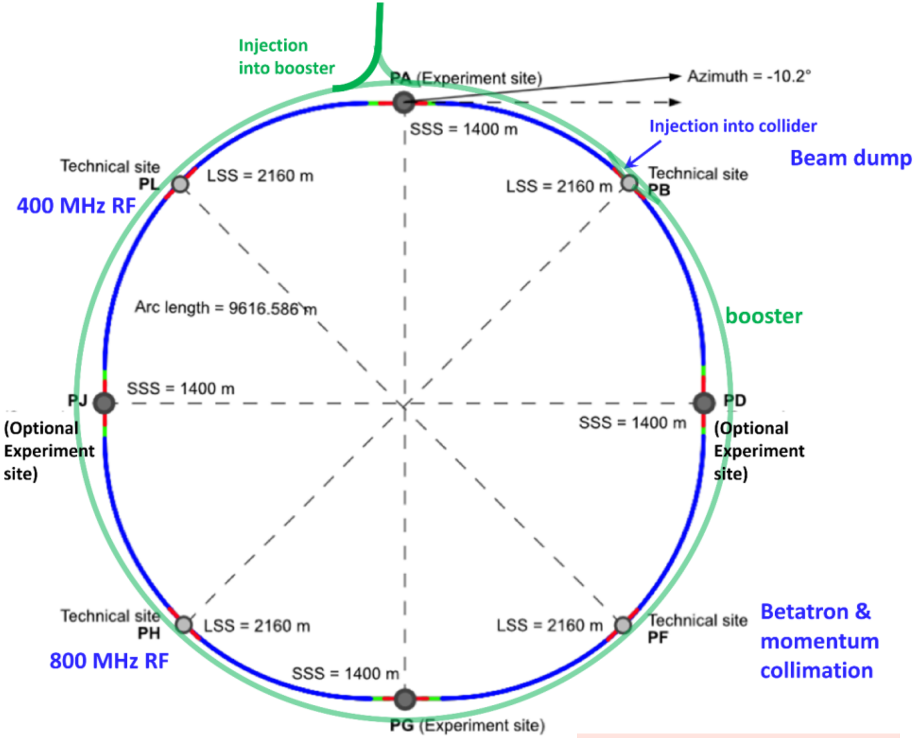
Common footprint with FCC-hh, except around IPs

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

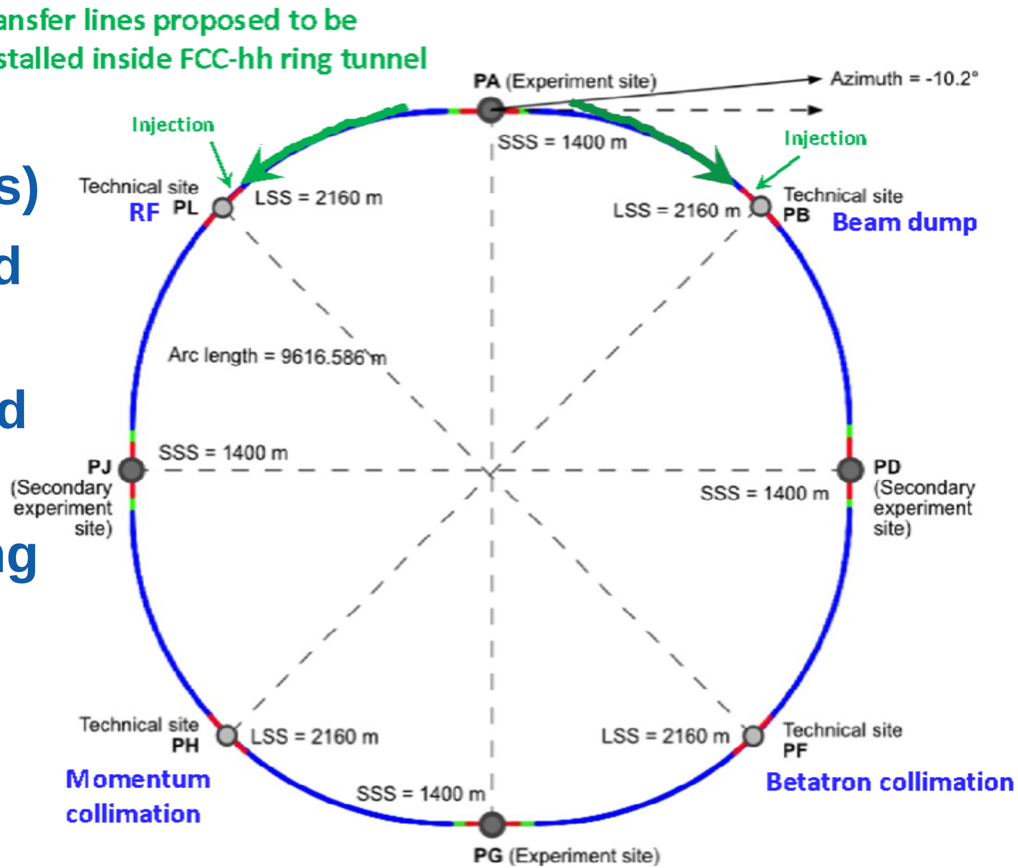
Top-up injection scheme for high luminosity
Requires **booster synchrotron in collider tunnel**



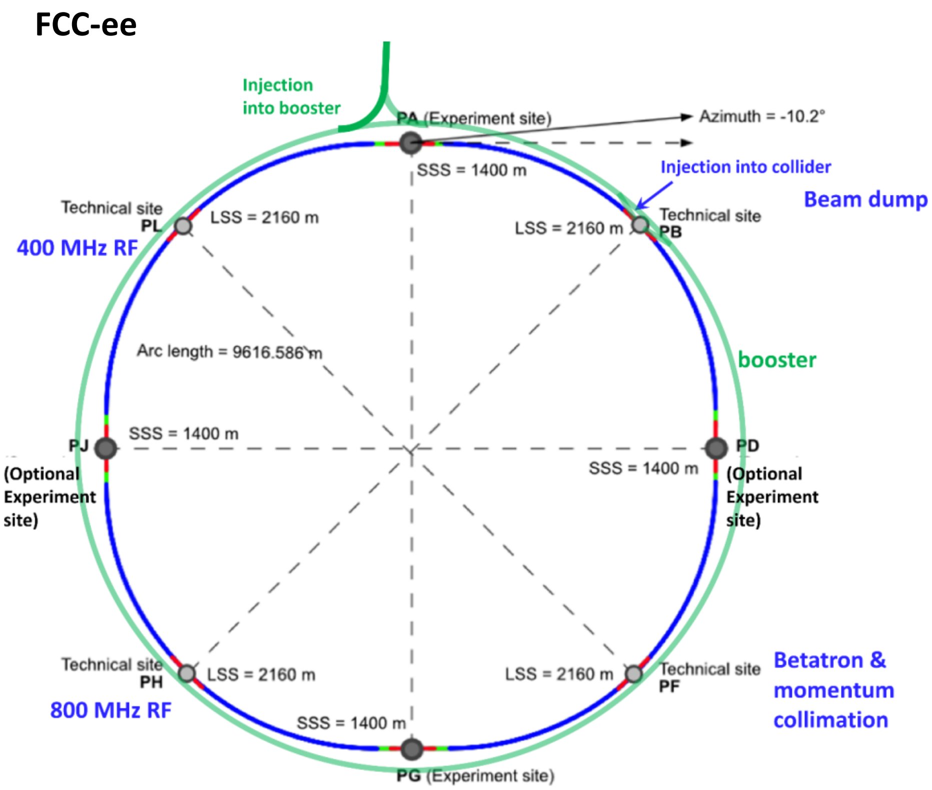
K. Oide, J. Gutleber

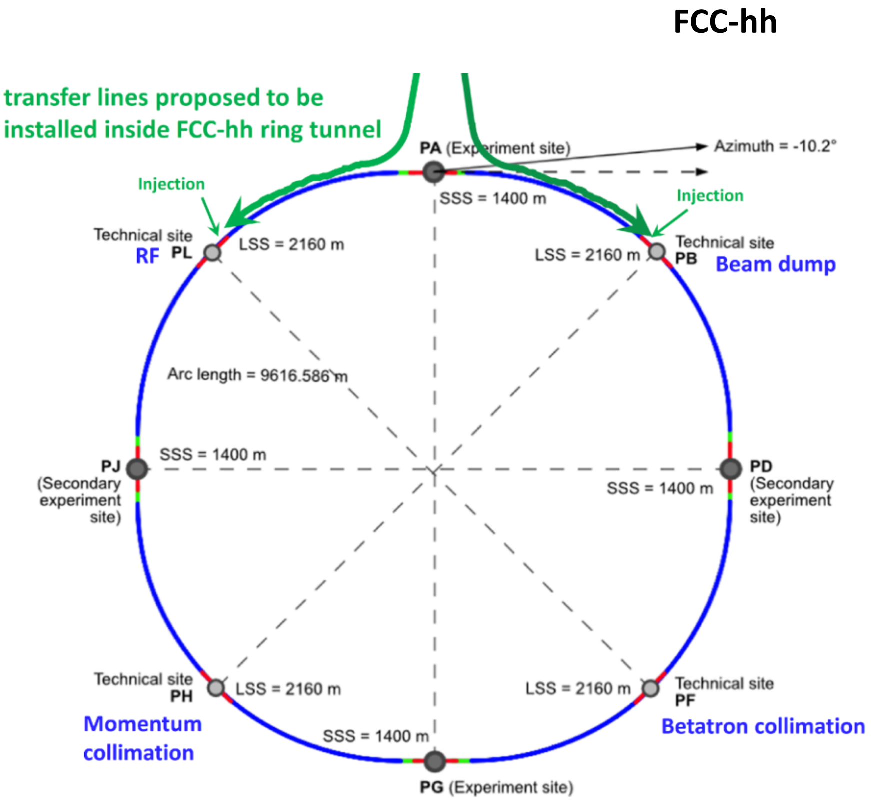
100 TeV FCC-hh

- 16T CF dipoles (or 17T SF dipoles)
- Layout like LHC but with four-fold symmetry (up to 4 IP's)
- Compatible with LHC or upgraded SPS as Injector
- Portion of transfer lines in the ring tunnel
- Circumference of 91.1 km
- 400.8 MHz RF 121800 harmonic consistent with SPS & LHC and multiple uniform bunch spacings



FCC-ee layout consistent with FCC-hh





FCC-ee Parameters

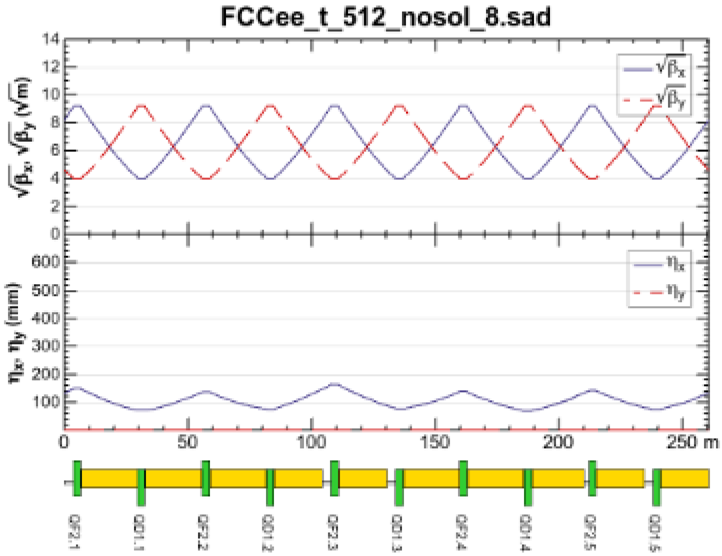
K. Oide, D. Shatilov

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
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	1.95 / 2.75
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
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 $\xi_x/\xi_y{}^a$		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)	[sec]	–		1065	4062
Lifetime (lum)	[sec]	1129	1070	596	744

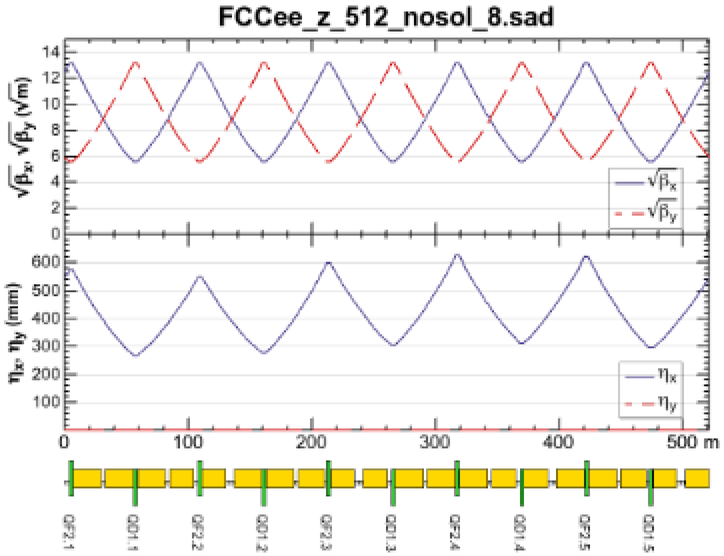
FCC-ee Arc FODO optics

- **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

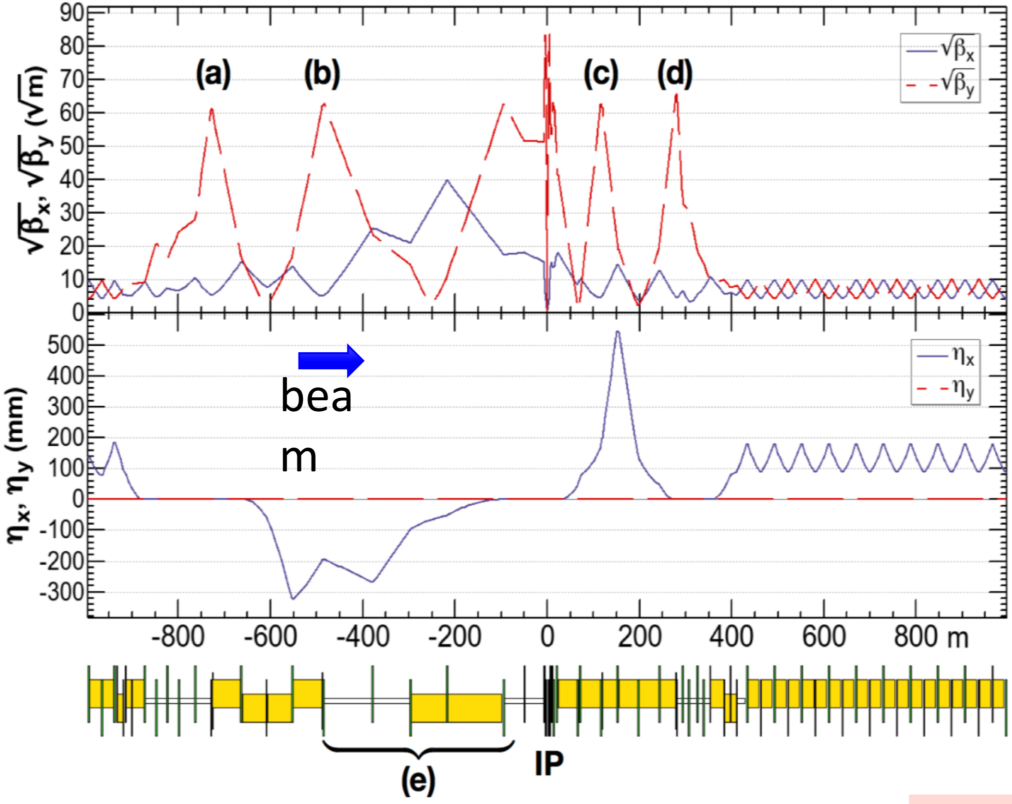


K. Oide

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**

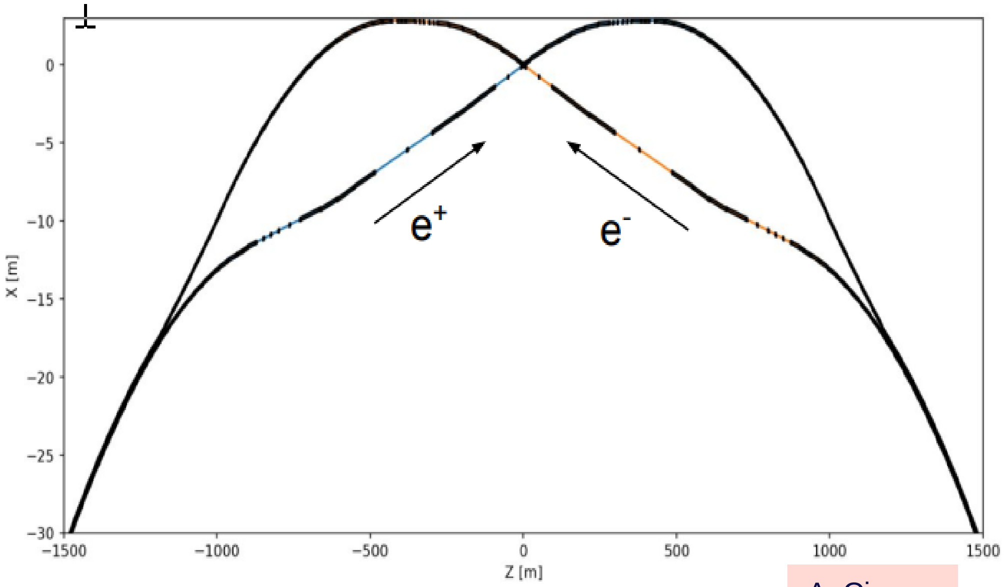
CDR optics, ttbar 182.5 GeV



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**



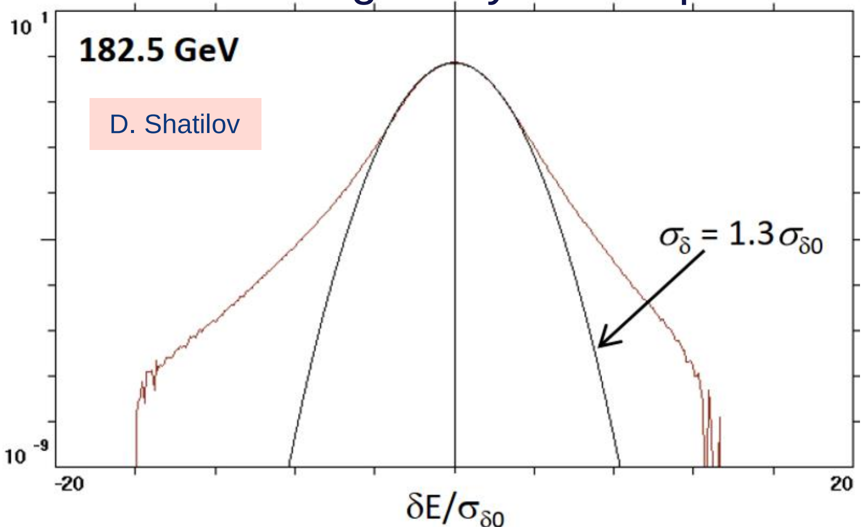
  - Photon E_{crit} < 100 keV from magnets within ~500 m of IP
  - Collimators and masks further protect detectors
  - Optimization is ongoing as part of MDI effort

D. Shatilov, M. Migliorati

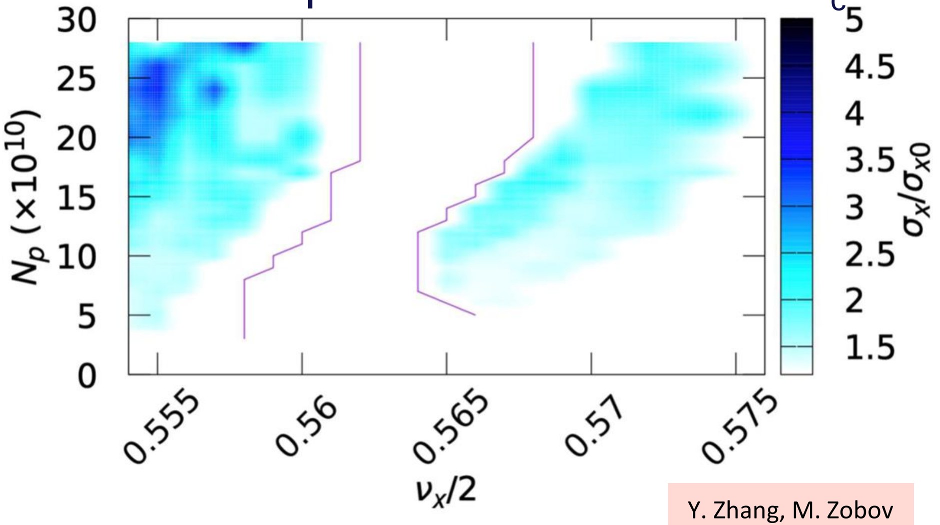
FCC-ee Beam-Beam

- **Beam-beam at high luminosity drives the ring parameters**
- **Updating beam-beam calculations and developing impedance model for the ring based on vacuum components**

Beamstrahlung → Dynamic aperture



BB and impedance → Tunes and α_c



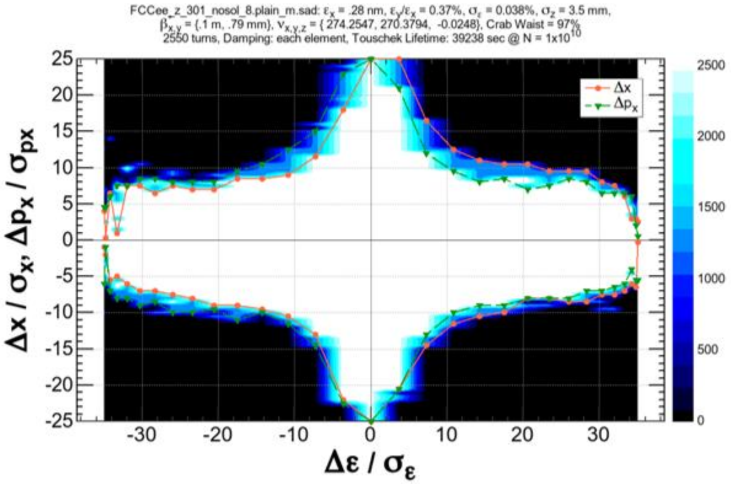
Y. Zhang, M. Zobov

K. Oide, M. Hofer, D. Shatilov

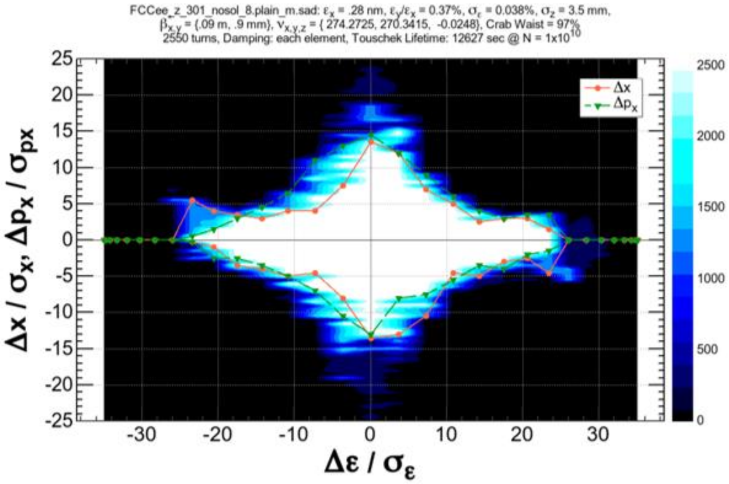
FCC-ee Dynamic Aperture

- **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”)



FCC-ee Collective effects

- **Single bunch instabilities calculated with impedance, beam-beam, and ring optics but there is complicated interplay**
  - Longitudinal wake and beam-beam constrains tunes
  - Beam-beam stabilizes the transverse mode-coupling instability
  - Longitudinal wake also likely modifies the mode-coupling instability
- **Multibunch instabilities constrain bunch spacing**
  - Requires low SEY on vacuum chamber
  - Damped RF cavities and electron cloud limits $\Delta t \geq 15$ ns
- **Large ring circumference limits feedback gain**
  - Developing integrated simulations for collective effects with feedback

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**

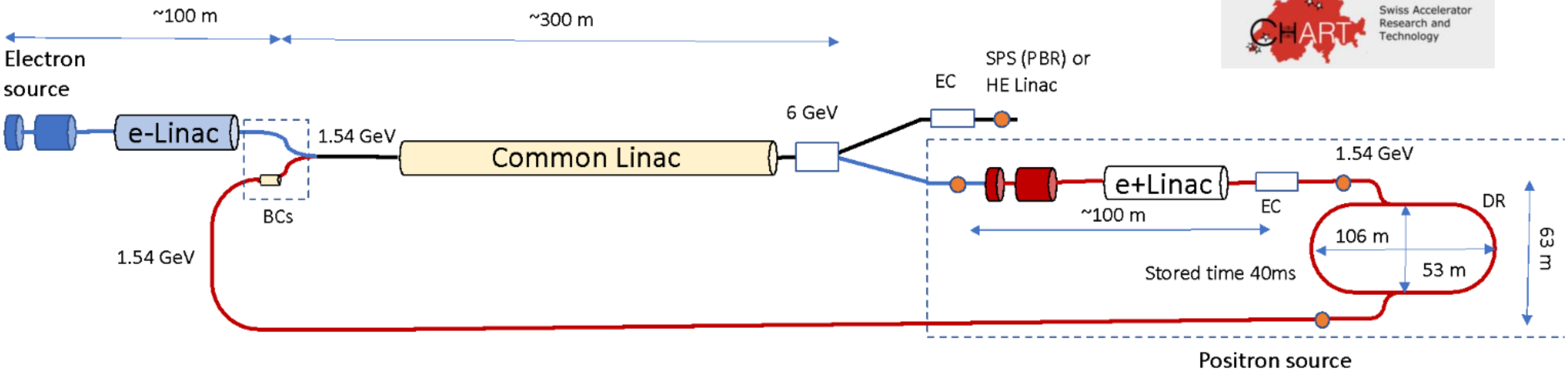
F. Peauger and O. Brunner

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

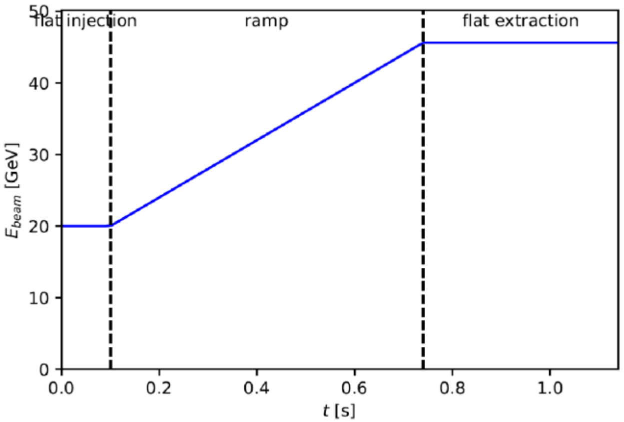
FCC-ee Injector

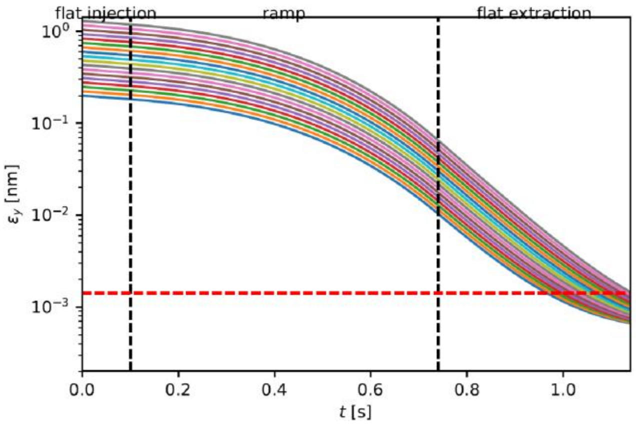
- **Design concept being developed with PSI**
  - High brightness e- source and efficient e+ source with damping ring to generate pairs of 6 GeV bunches at 200 Hz (for Z)
  - Acceleration to Booster at ~20 GeV in SPS or high energy linac

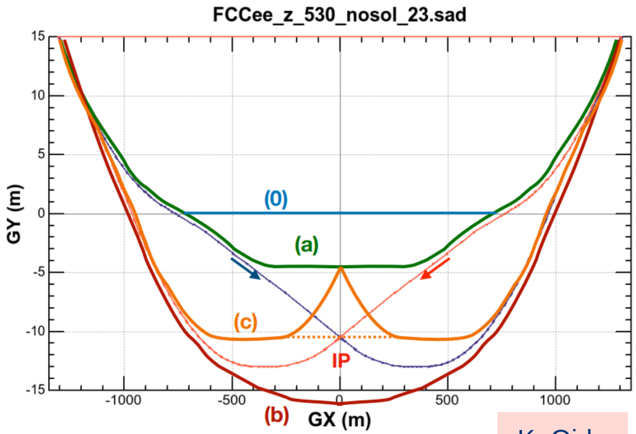


FCC-ee Full-energy booster

- **Full-energy booster will enable top-up injection**
  - Ramps from 20 GeV to main ring energy in a second
  - Damps incoming emittance from Injector to match main rings
  - Layout matches main ring cell structure although location in IR uncertain



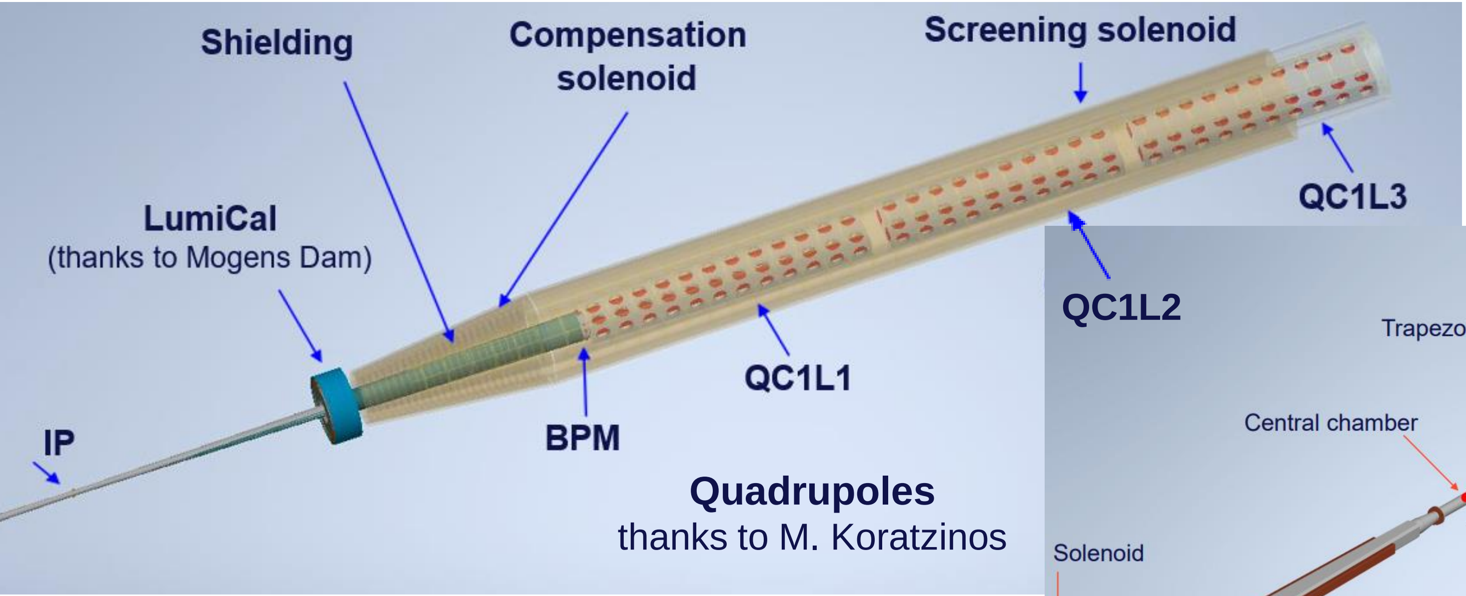


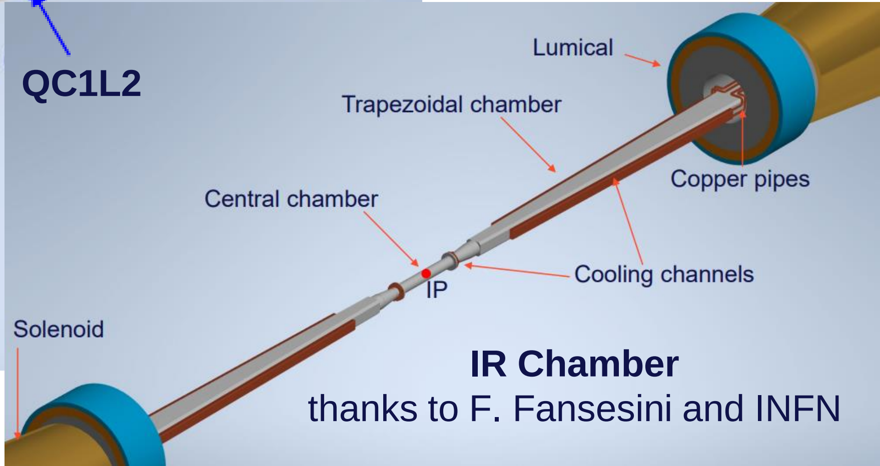


K. Oide

FCC-ee MDI and IR design

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

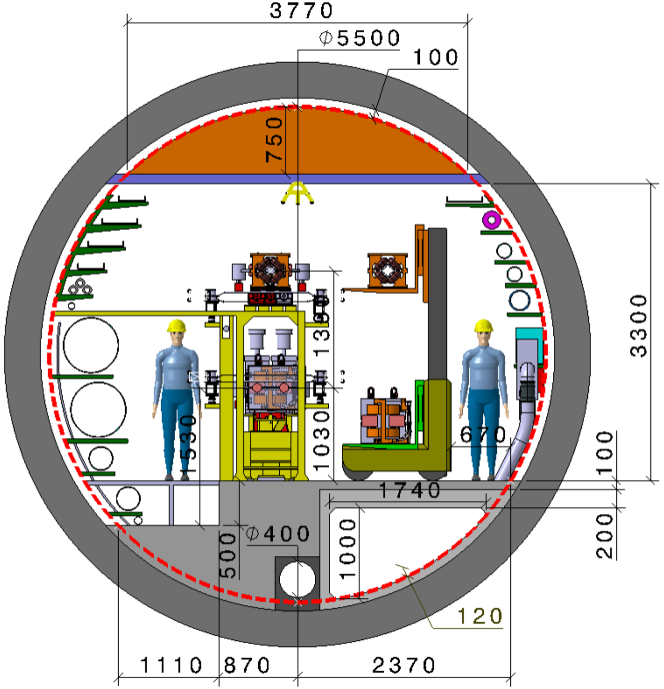


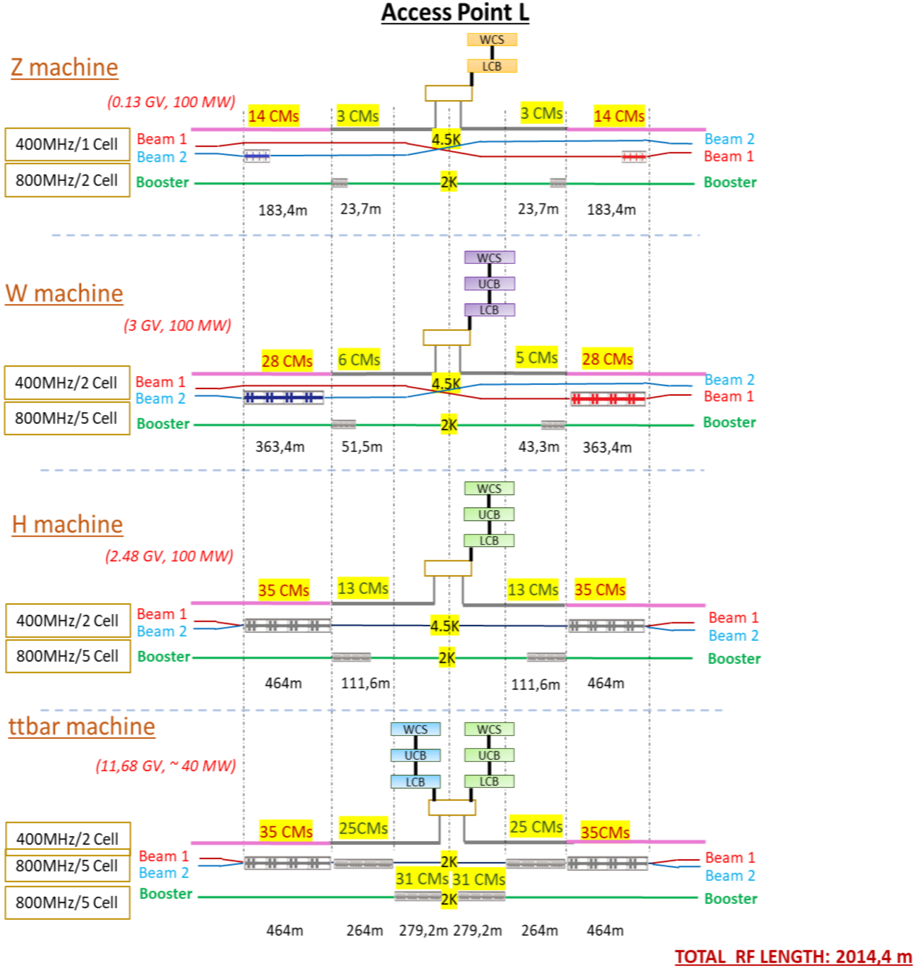


F. Valchkova-Georgieva, J-P. Corso

FCC-ee Integration

- **Working on integration of RF regions and Arc cell**

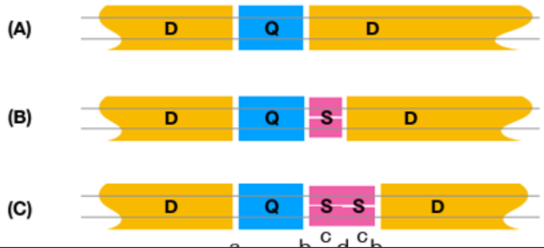


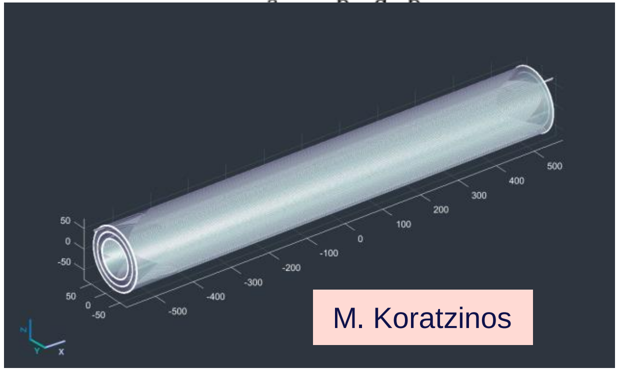


FCC-ee Alternative technologies

- **Developing technologies with significant potential impact in parallel to baseline, e.g.**
    - HTS arc quadrupole/sextupole
    - HE linac as a pre-booster
    - High Q_0 damped SRF cavities
    - High efficiency RF power sources
    - Positron target using crystal channeling
    - Advanced cooling tower design
    - ...

Changes in the spacings & lengths





Combined function HTS magnet

FCC accelerator summary and timeline

- **Finalizing layouts with correct circumference**
- **FCC-ee baseline parameters are being established**
  - Main ring substems, full-energy booster, and injector all being defined
- **Technical systems making good progress**
  - Vacuum, magnets, SRF, cryogenics, diagnostics, integration, …
- **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.