# ACCELERATOR OVERVIEW

gratefully acknowledging the contributions of the FCC Accelerator Pillar
as well as the rest of the FCC team

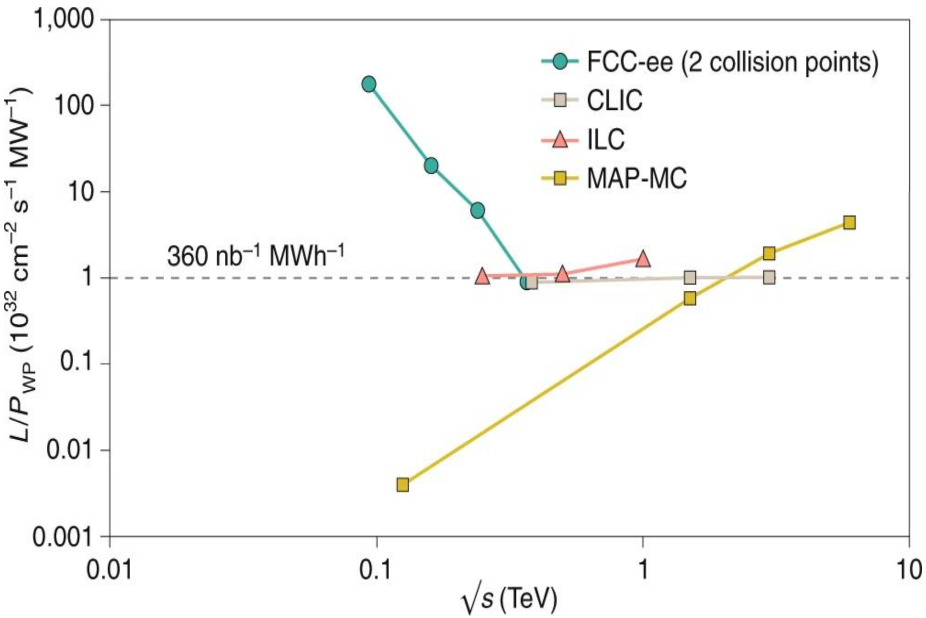
# Introduction

- **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**
  - $2\times10^{36}$ $cm^{-2}s^{-1}$/IP at Z and $7\times10^{34}$ $cm^{-2}s^{-1}$ 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**

# Outline

- **Overall requirements and status**
- **Parameters**
- **Main e+/e- rings beam optics**
- **Collective effects, Dynamic aperture, Injection, Collimation, …**
- **Full-energy booster**
- **E+/e- injector**
- **Technical systems**

- **Many, many topics with significant progress – touch on a few**

# Accelerator Design Goals

1. **Establish a baseline with robust technology consistent with placement studies for mid-term review in fall of 2023**
   - The baseline is a refinement of the CDR design complemented with more complete specifications and studies

2. **Establish a list of alternative technologies that could have significant impact on cost or performance**
   - Develop timelines to demonstrate these alternatives and move to baseline

3. **Iterate on the baseline for the completion of the Feasibility Study in 2025**

# 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

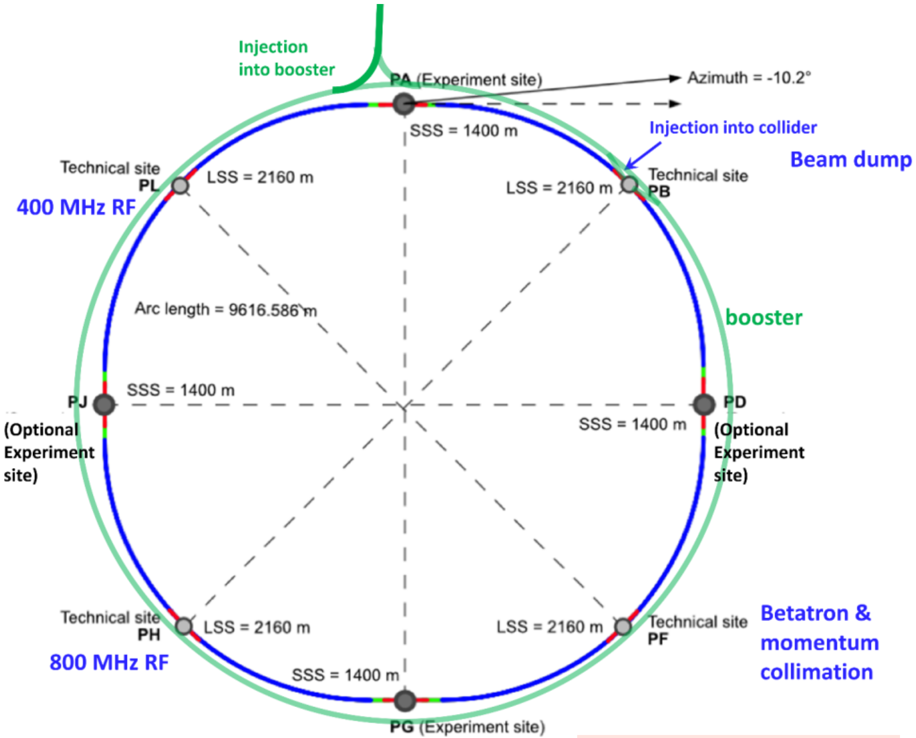
**Common footprint with FCC-hh**, except around IPs

**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

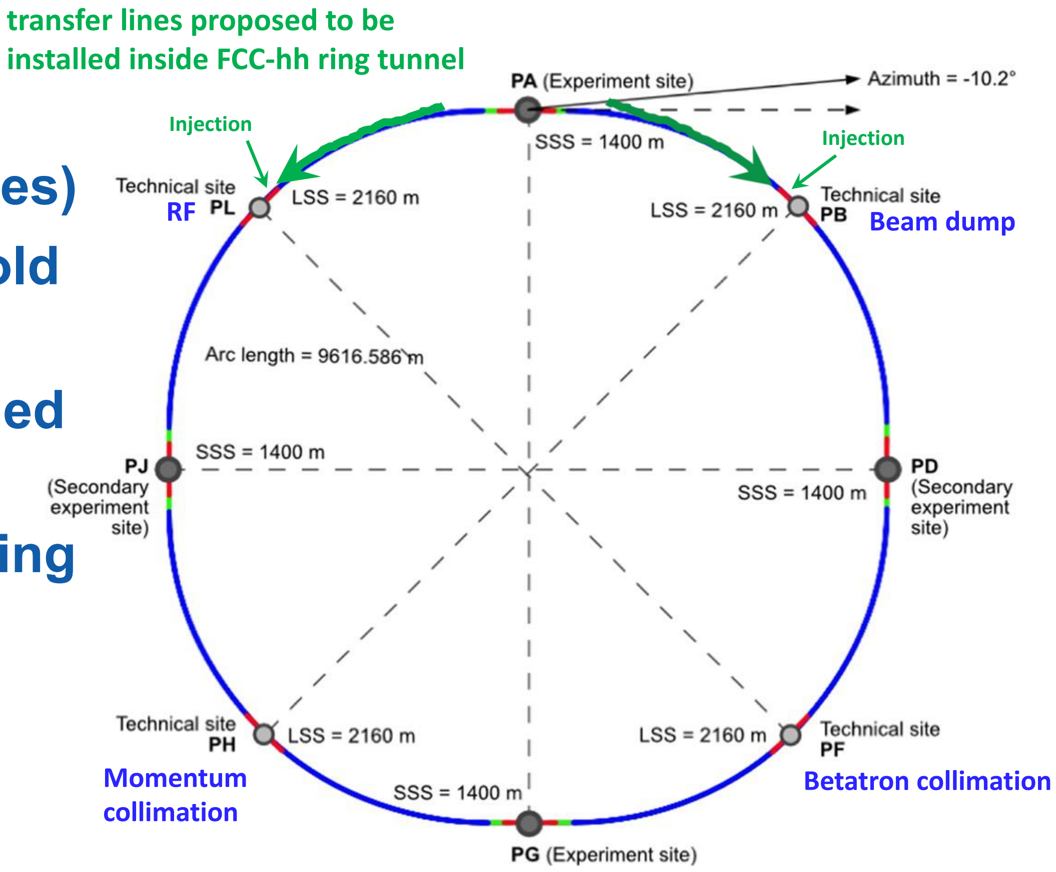
**Top-up injection** scheme for high luminosity
Requires **booster synchrotron in collider tunnel**



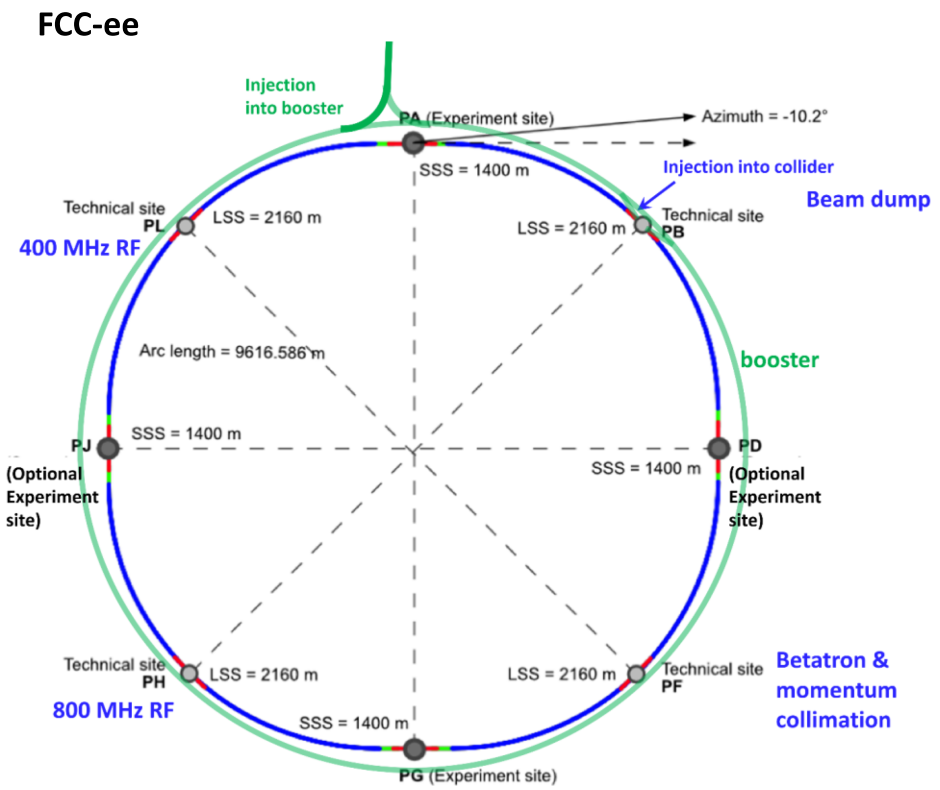

K. Oide, J. Gutleber

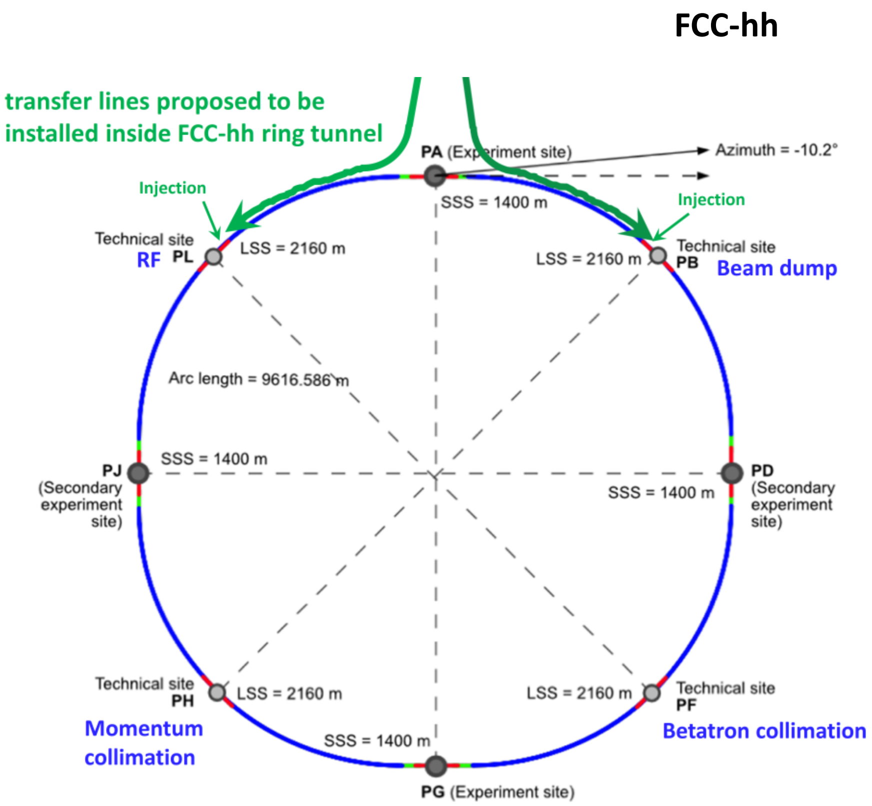
# 100 TeV FCC-hh

- 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

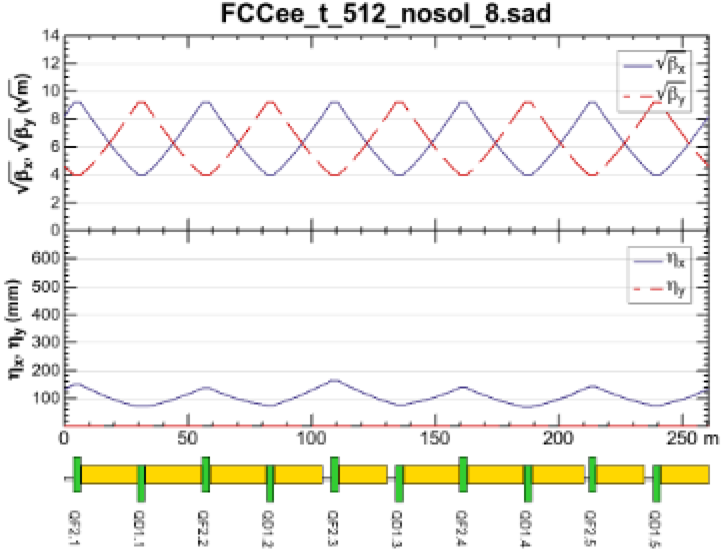


| Parameter [4 IPs, 91.1 km, $T_{rev}$=0.3 ms] | Z | WW | H (ZH) | ttbar |
|---|---|---|---|---|
| beam energy [GeV] | 45 | 80 | 120 | 182.5 |
| beam current [mA] | 1280 | 135 | 26.7 | 5.0 |
| number bunches/beam | 10000 | 880 | 248 | 40 |
| bunch intensity [$10^{11}$] | 2.43 | 2.91 | 2.04 | 2.37 |
| SR energy loss / turn [GeV] | 0.0391 | 0.37 | 1.869 | 10.0 |
| total RF voltage 400 / 800 MHz [GV] | 0.120 / 0 | 1.0 / 0 | 2.08 / 0 | 2.5 / 8.8 |
| long. damping time [turns] | 1170 | 216 | 64.5 | 18.5 |
| horizontal beta* [m] | 0.1 | 0.2 | 0.3 | 1 |
| vertical beta* [mm] | 0.8 | 1 | 1 | 1.6 |
| horizontal geometric emittance [nm] | 0.71 | 2.17 | 0.64 | 1.49 |
| vertical geom. emittance [pm] | 1.42 | 4.34 | 1.29 | 2.98 |
| horizontal rms IP spot size [μm] | 8 | 21 | 14 | 39 |
| vertical rms IP spot size [nm] | 34 | 66 | 36 | 69 |
| beam-beam parameter $\xi_x$ / $\xi_y$ | 0.004 / 0.159 | 0.011 / 0.111 | 0.0187 / 0.129 | 0.093 / 0.140 |
| rms bunch length with SR / BS [mm] | 4.38 / 14.5 | 3.55 / 8.01 | 3.34 / 6.0 | 1.95 / 2.75 |
| luminosity per IP [$10^{34}$ cm$^{-2}$s$^{-1}$] | 182 | 19.4 | 7.26 | 1.25 |
| total integrated luminosity / year [ab$^{-1}$/yr] | 87 | 9.3 | 3.5 | 0.65 |
| beam lifetime rad Bhabha + BS [min] | 19 | 18 | 6 | 9 |

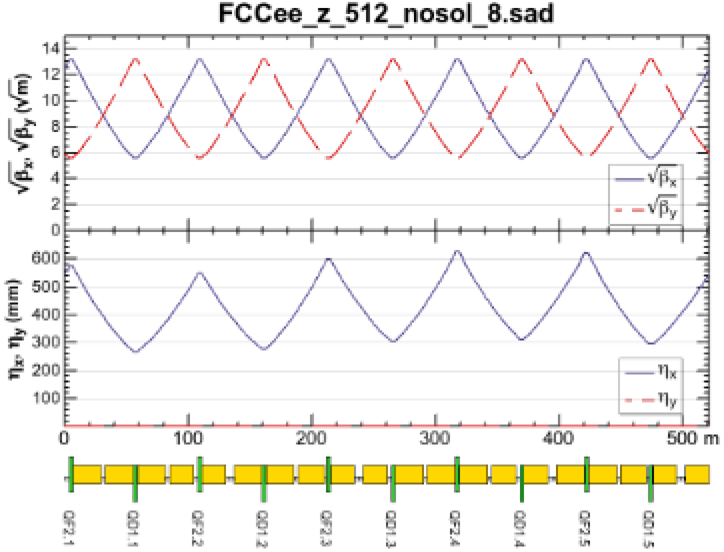
# FCC-ee Arc optics

- **New configuration for arc optics with long ~100 m cells at Z & W and short ~50 m cells at Zh and t-tbar**
  - Reduces $\varepsilon_x$ at high E and increases $\alpha_c$ at low E

90°/90° : $t\bar{t}$, *Zh*




Long 90°/90° : *Z*, *W*

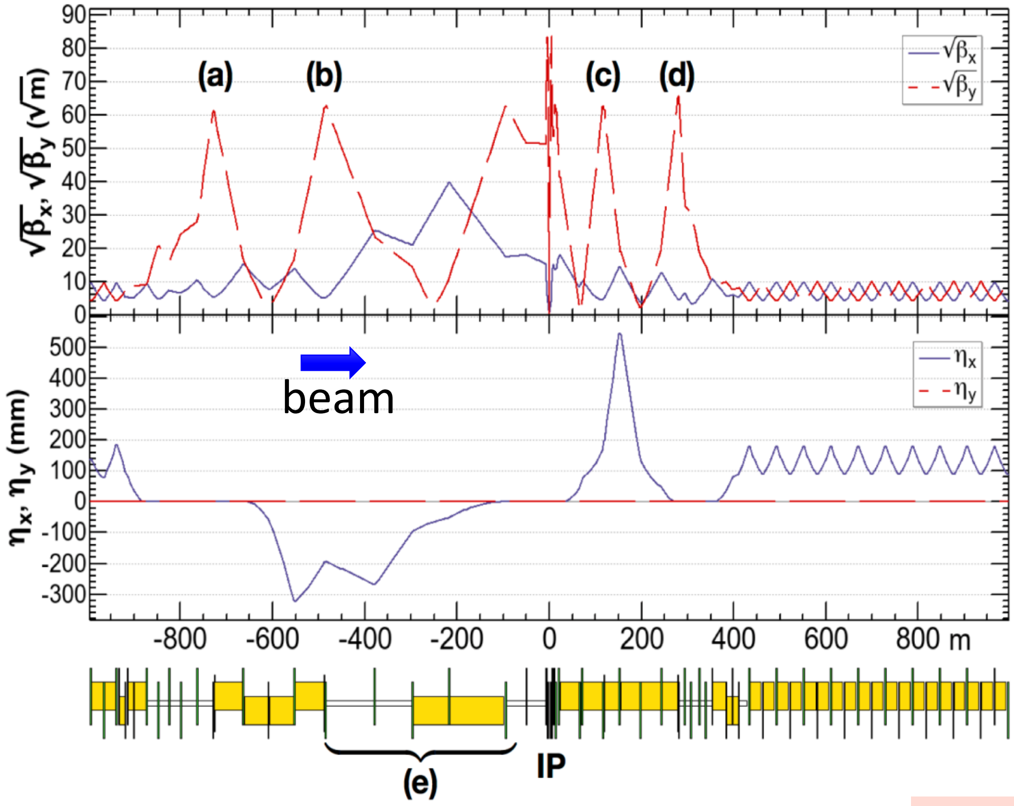



K. Oide

# 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**

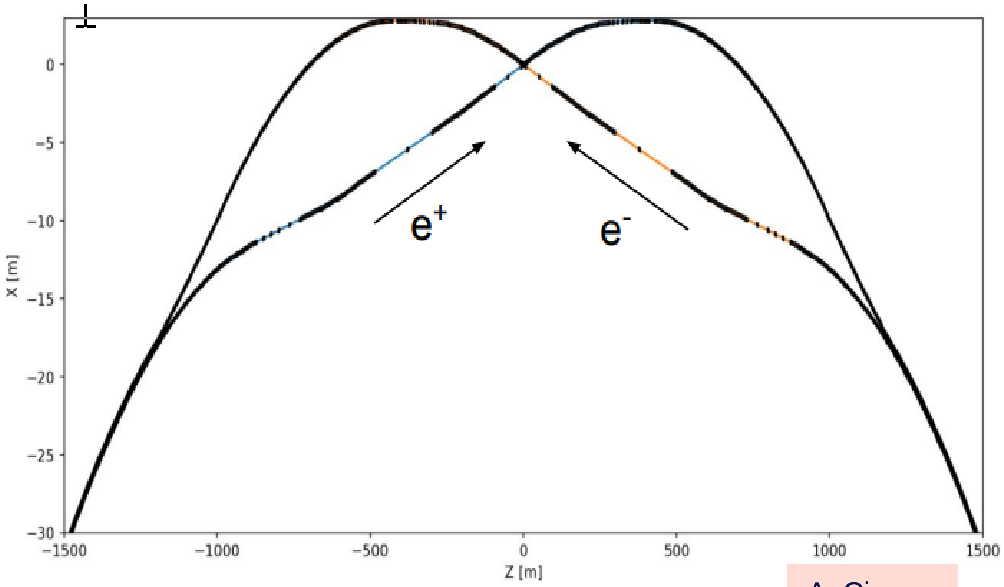
CDR optics, ttbar 182.5 GeV




K. Oide

# FCC-ee IR geometry

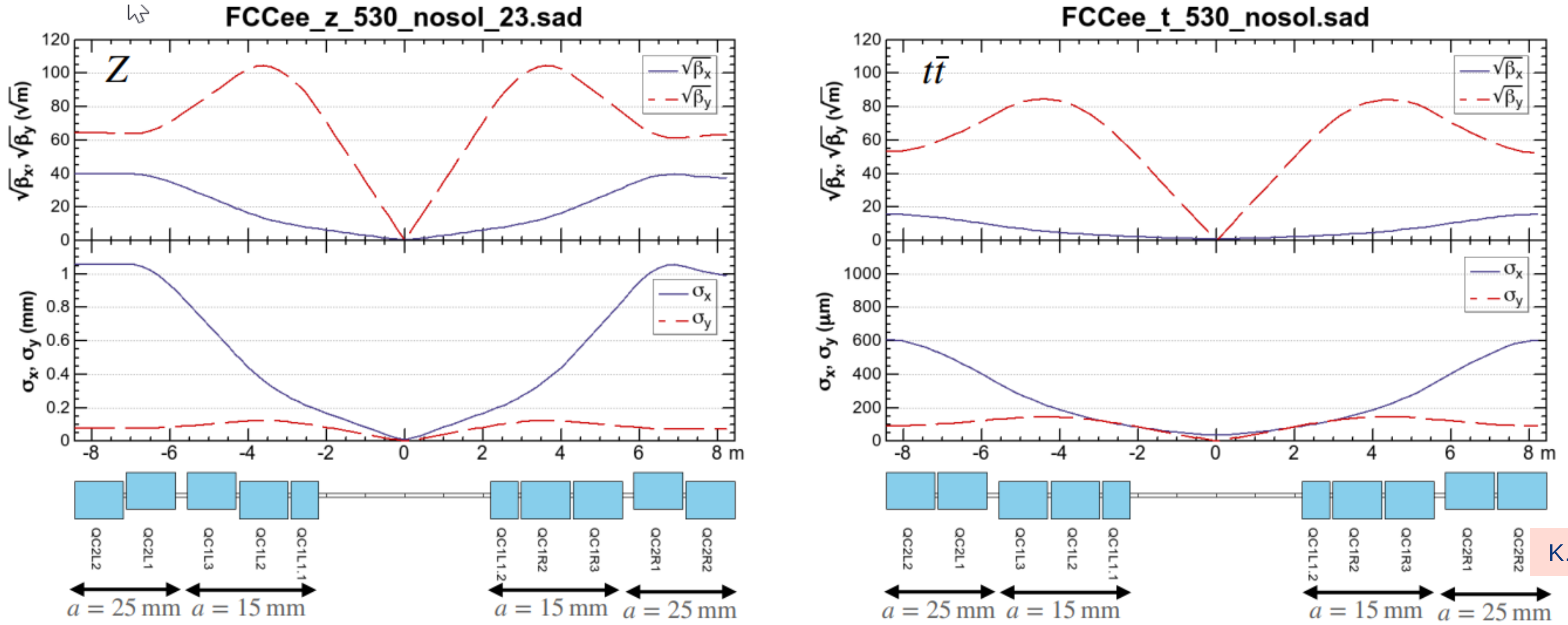
- **FCC-ee and FCC-hh IP's moved to same location to reduce IR tunnel width**
- **Asymmetric IR layout is chosen to minimize the incoming synchrotron radiation**
    - Photon $E_{crit}$ < 100 keV from magnets within ~500 m of IP
    - Collimators and masks further protect detectors
    - Optimization is ongoing as part of MDI effort




A. Ciarma

# FCC-ee IR quadrupole optics

- **Final quadrupole configuration is optimized for different working points from the Z to t-tbar**

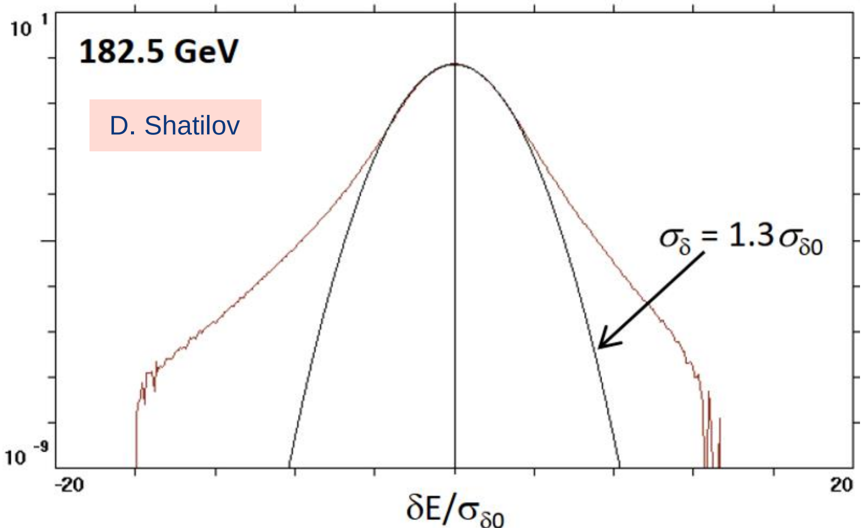



K. Oide

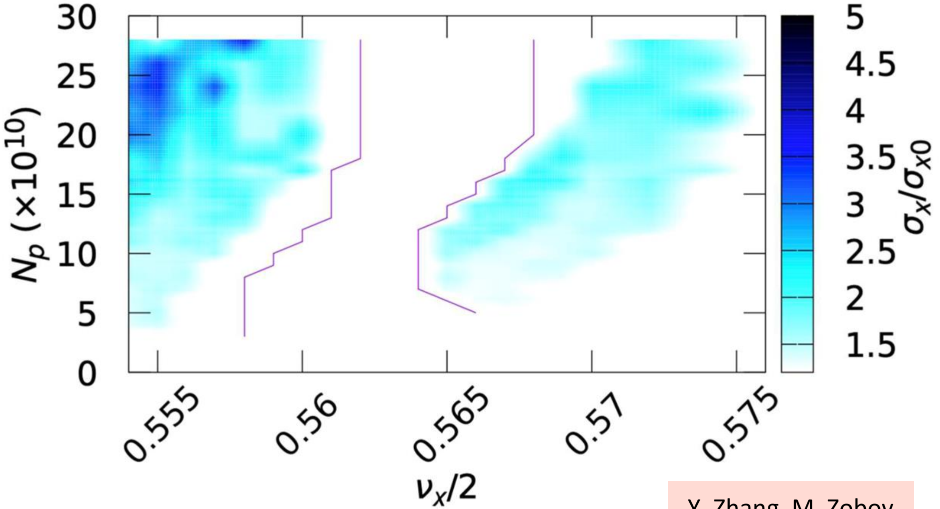
# FCC-ee Beam-Beam

- **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 $\alpha_c$



# FCC-ee Optics correction and tuning

- **Developed model for correcting orbit and optics due to errors in the arcs which is complicated due to large size of the rings**
  - Correction is effective at correcting $\varepsilon_y$ and optics which is generated in the arcs but is not sufficient to restore dynamic aperture
  - Need to develop and model IR optics tuning knobs

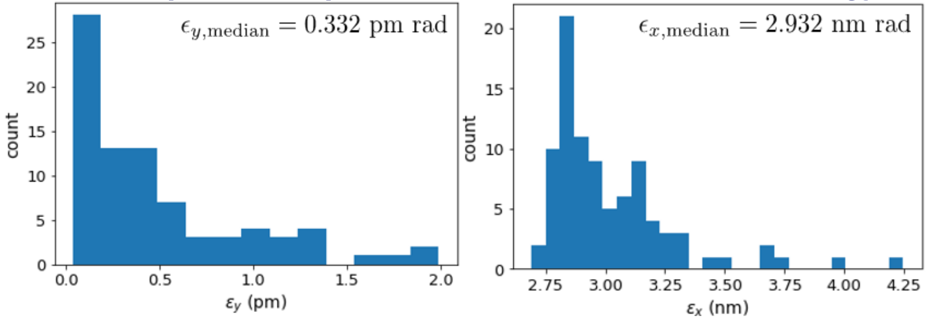
**Sextupoles set to 10% of their design strength**

- Orbit correction
- Combined coupling and dispersion correction (Python)
- Beta-beating correction applied (Python)
- Sextupole strengths increased by 10%

*Iterated over many times.*

Constant checking of the tunes and orbit avoids running into resonances, or failure to find the closed orbit.

**ttbar (182.5 GeV) 4IP lattice, after correction strategy**




**RMS misalignment and field errors tolerances:**

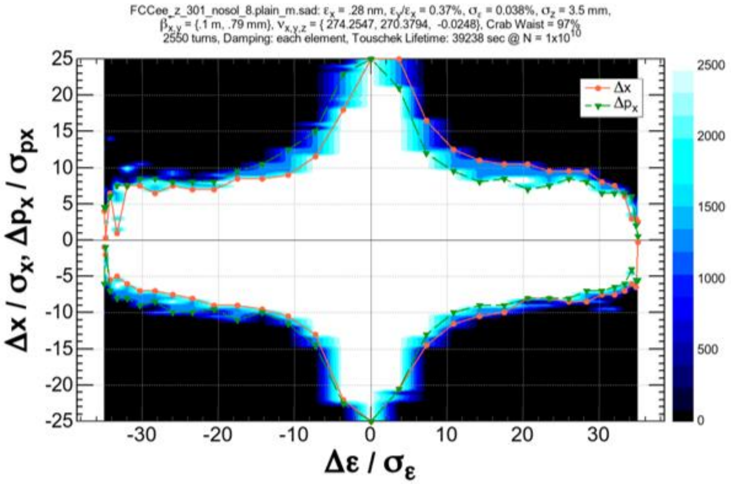
| Type | $\Delta$X ($\mu$m) | $\Delta$Y ($\mu$m) | $\Delta$PSI ($\mu$rad) | $\Delta$S ($\mu$m) | $\Delta$DTHETA ($\mu$rad) | $\Delta$DPHI ($\mu$rad) |
|---|---|---|---|---|---|---|
| Arc quadrupole* | 50 | 50 | 300 | 150 | 100 | 100 |
| Arc sextupoles* | 50 | 50 | 300 | 150 | 100 | 100 |
| Dipoles | 1000 | 1000 | 300 | 1000 | - | - |
| Girders | 150 | 150 | - | 1000 | - | - |
| IR quadrupole | 100 | 100 | 250 | 250 | 100 | 100 |
| IR sextupoles | 100 | 100 | 250 | 250 | 100 | 100 |

* misalignments relative to girder placement

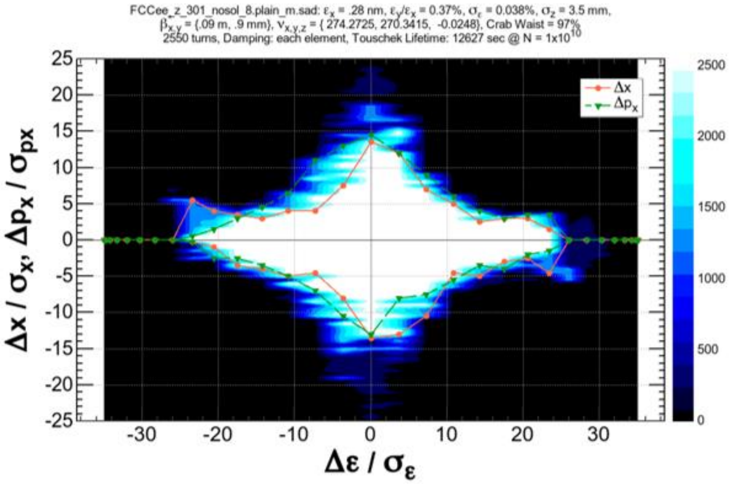
# FCC-ee Dynamic Aperture

- **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

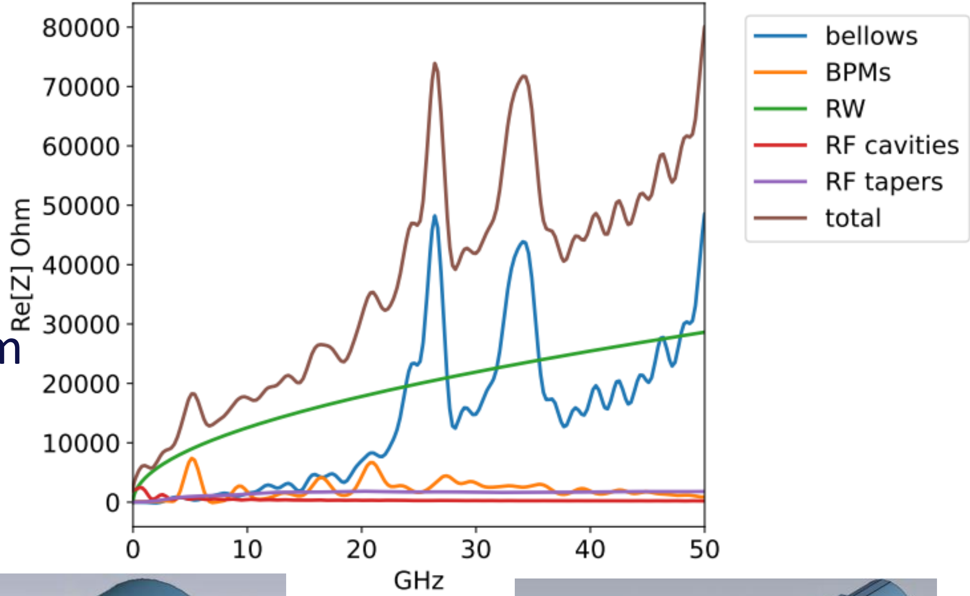


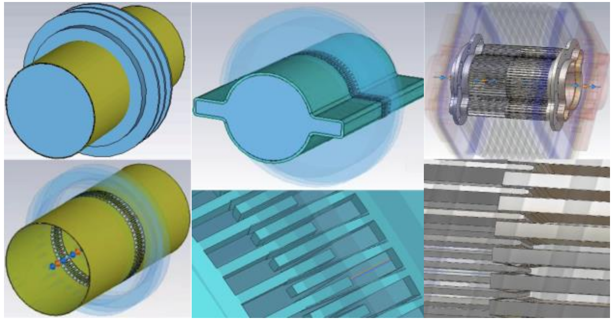

Errors + corrections (“seed 1”)

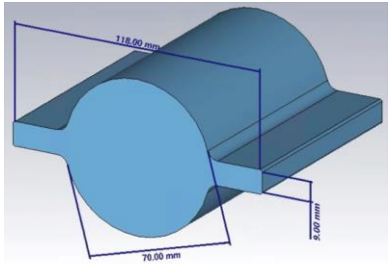


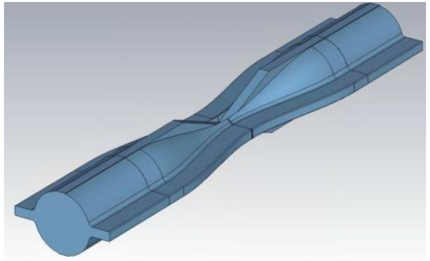
# FCC-ee Impedance modeling

- **Impedance modeling is a critical step in evaluating performance limits of modern accelerators**
    - Developing budget with vacuum chamber, bellows, BPMs, RF, and collimators







# FCC-ee Collective effects

- **Single bunch instabilities can be calculated based on 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**

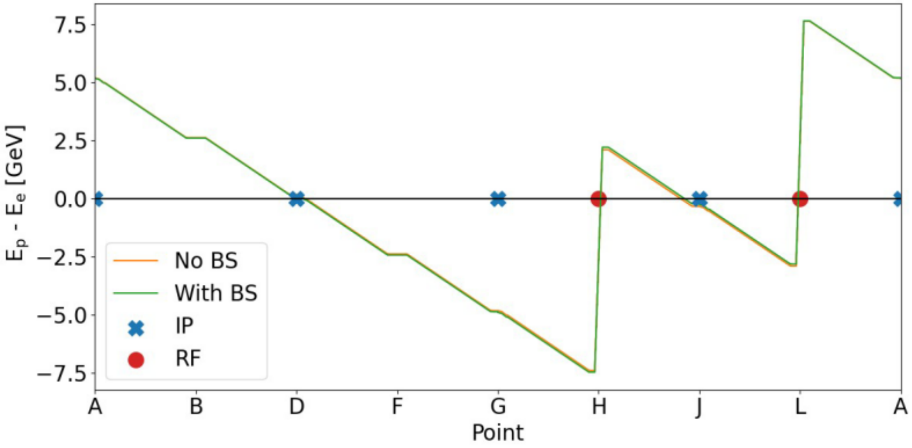
# FCC-ee SRF Systems

| 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 RF placement

- **Optimizing the RF placement to minimize center-of-mass energy variation and reduce infrastructure requirements**
  - The two best access points for SRF are PL and PH
  - A single RF region reduces the c-o-m energy variation between IP's to ~7 keV for Z operation
  - t-tbar requires 2 RF regions and the beam energy will vary by ±4 GeV

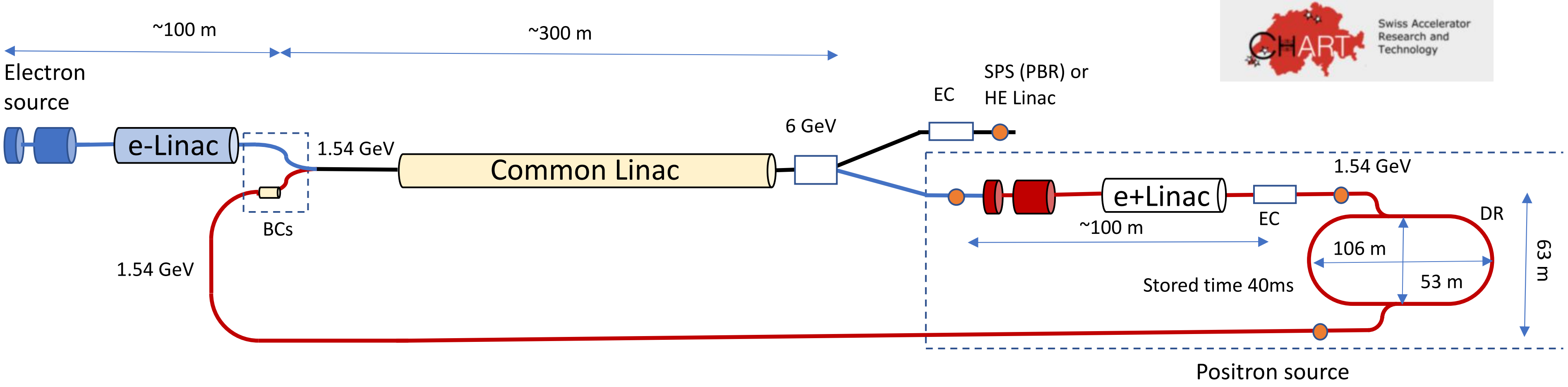
Boost: + for e+; - for e-




J. Keintzel

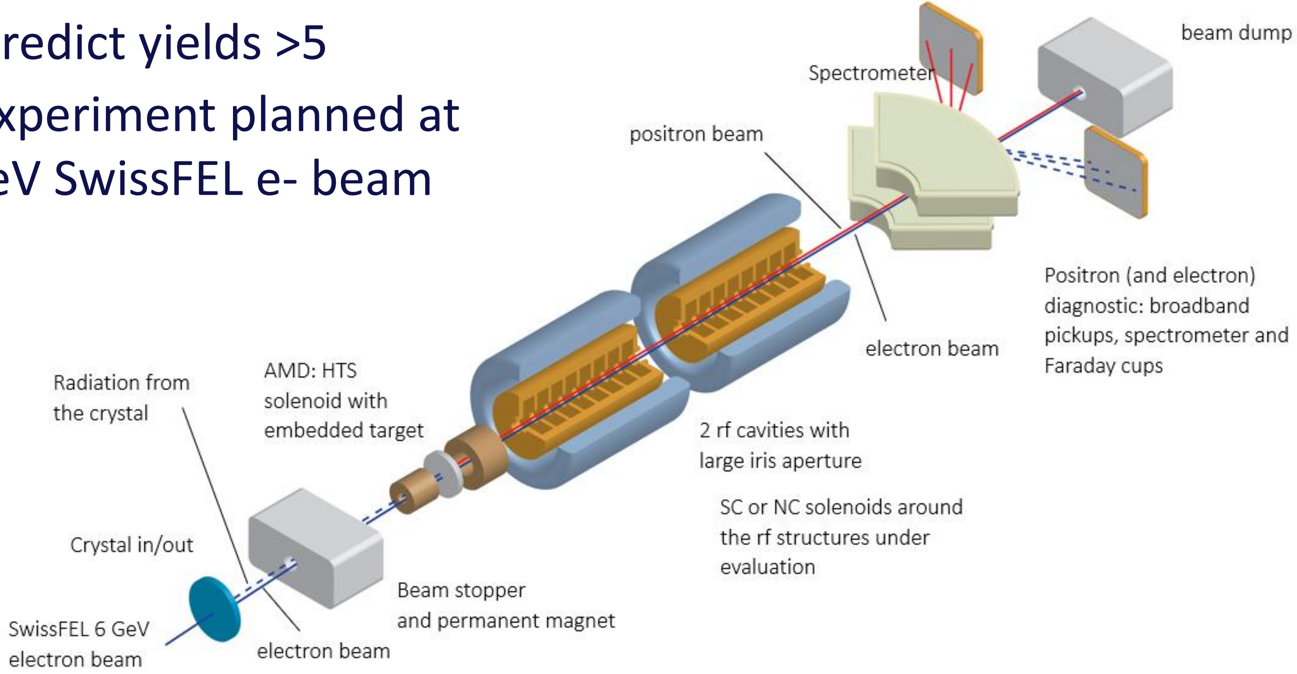
# FCC-ee Injector

- **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 Injector positron source

- **Positron rates much lower the LC designs (~2x SLC e+ source)**
  - e+ source based on HTS solenoid
  - Simulations predict yields >5
  - Verification experiment planned at PSI using 6 GeV SwissFEL e- beam



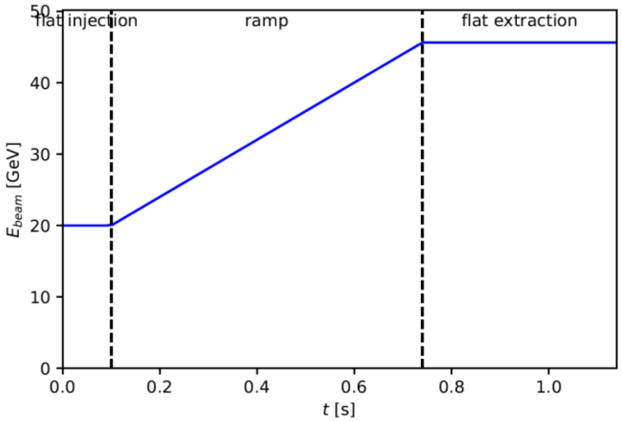
# FCC-ee Injector

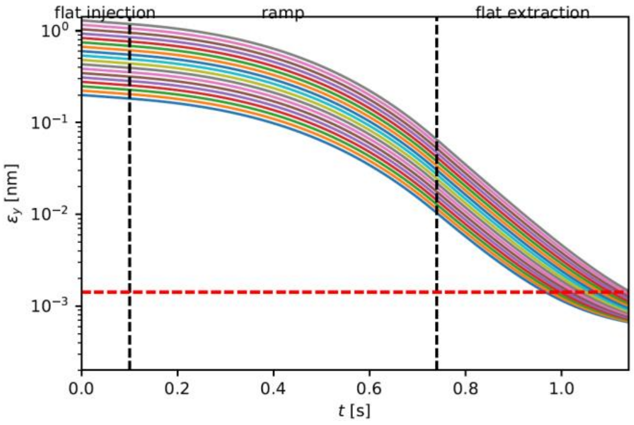
- **Injector requirements**

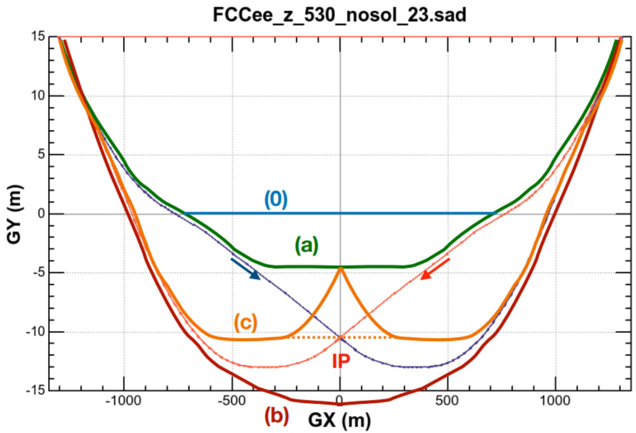
| | Baseline | HE Linac | Unit |
|---|---|---|---|
| Ring for injection | SPS/PBR | BR | |
| Injection energy | 6 | 20 | GeV |
| Bunch population both species | 3.47 (5.55) | 3.12 (5.0) | 1E10 (nC) |
| Repetition rate | 200 | 200 | Hz |
| Number of bunches | 2 | 2 | |
| Bunch spacing | 17.5-100 | 17.5-100 | ns |
| Normalized emittance (x, y) (rms) | 50, 50 | 50, 50 | mm.mrad |
| Bunch length (rms) | ~1 | ~1 | mm |
| Energy spread (rms) | <0.1 | <0.1 | % |

# 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

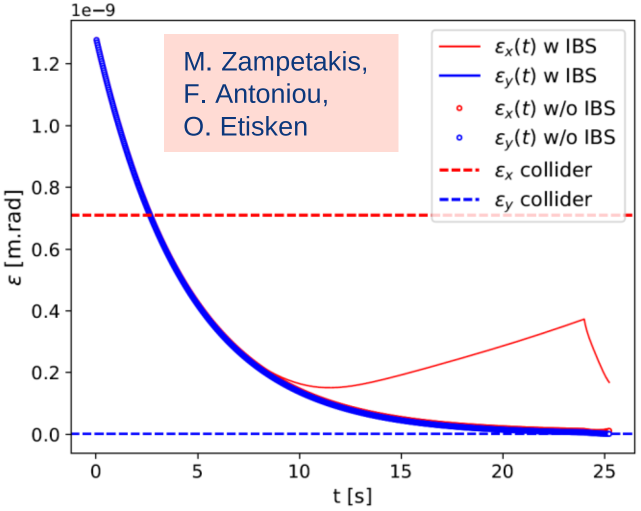


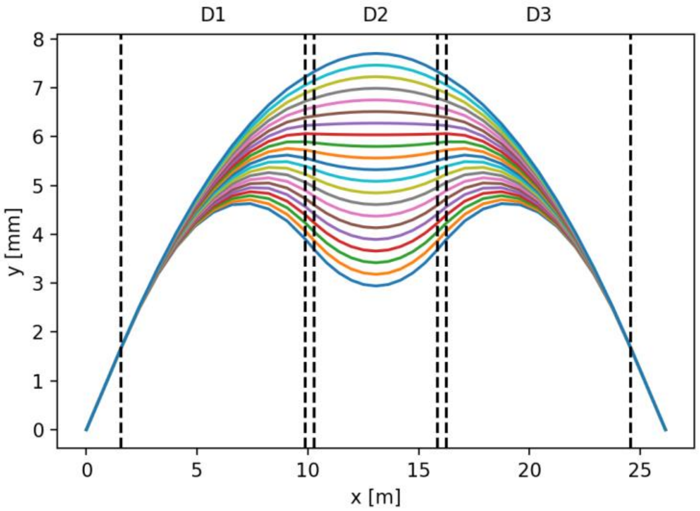



# FCC-ee Full-energy booster

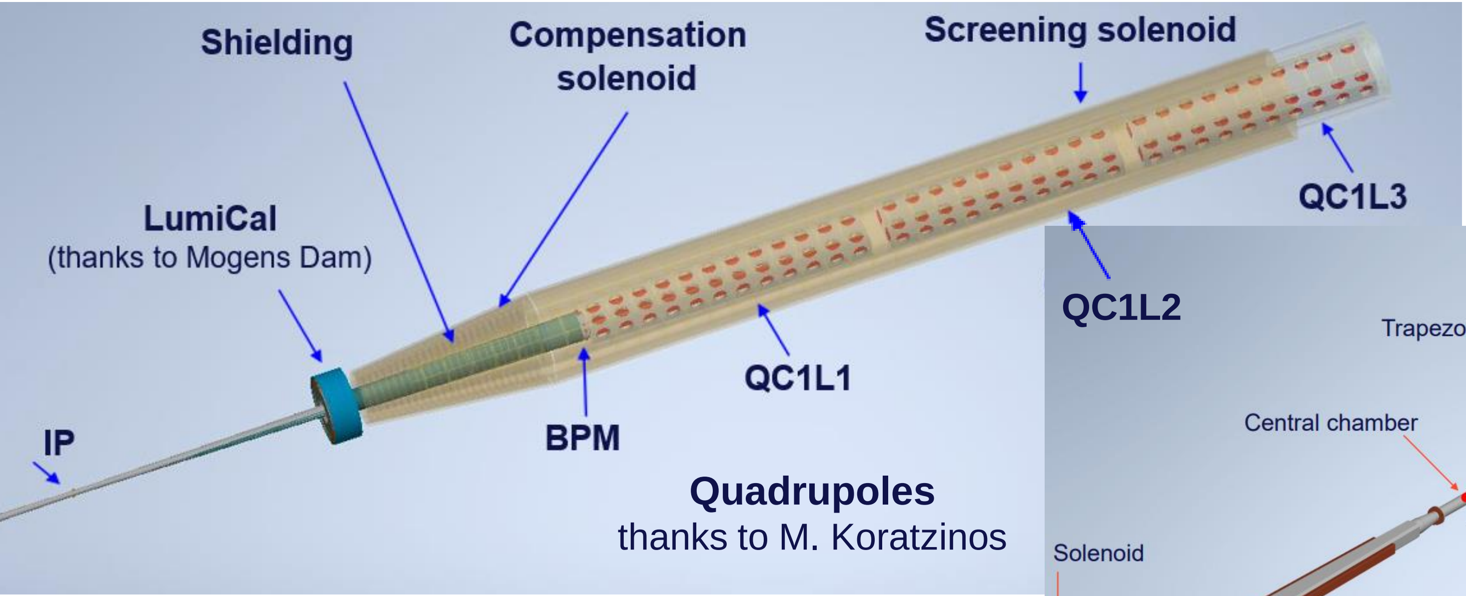
- **Challenges for booster with Z operation**
  - Long accumulation time at Z or roughly 25 s (10,000 bunches at 400 Hz)
  - Effects like IntraBeam Scattering may cause variation from bunch to bunch
  - Options being explored are to increase damping during accumulation or perhaps increase time at full energy to damp away transients

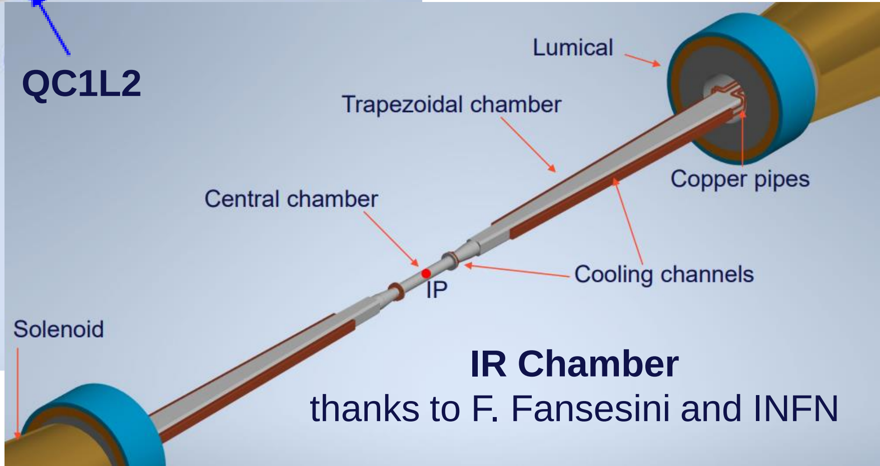


# FCC-ee MDI and IR design

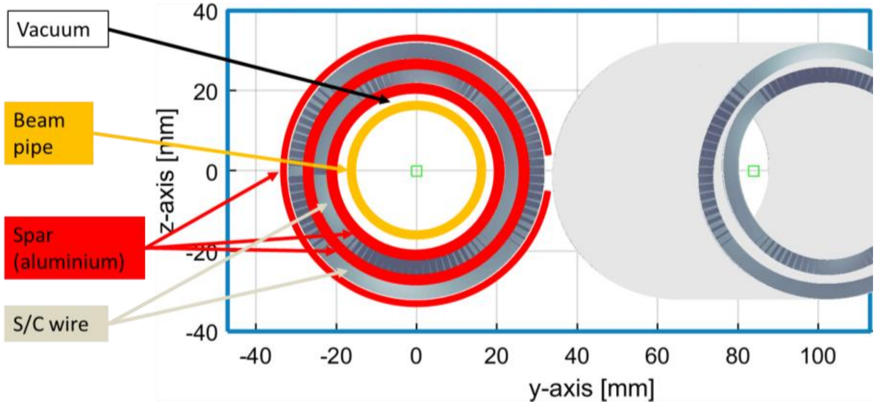
- **Complicated integration with SC quadrupoles, solenoids, IR chamber, LumiCal, shielding, and diagnostics**

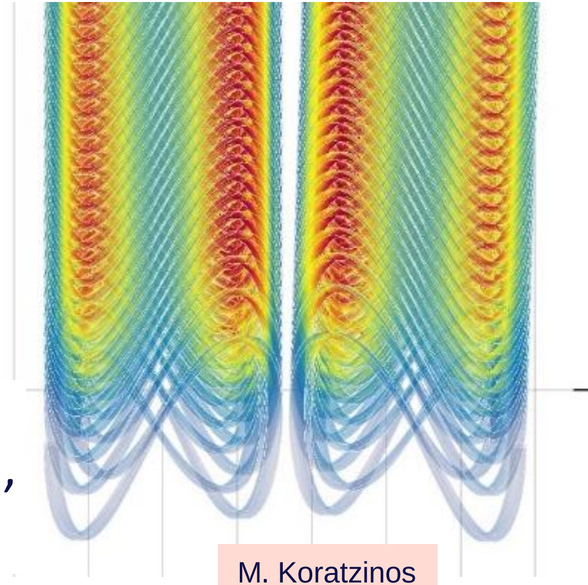


# FCC-ee IR magnets

- **Canted-Cosine-Theta magnets w/ fringe fields fully compensated**
  - Elegant 2-layer design for inner quadrupoles
  - Working to fit within 100 mrad stay-clear cone
  - Integration with supports, solenoids, trim coils, shielding, cryostat, etc needs to be developed
  - Prototype built and warm-tested
  - External review of concept April, 2022



M. Koratzinos

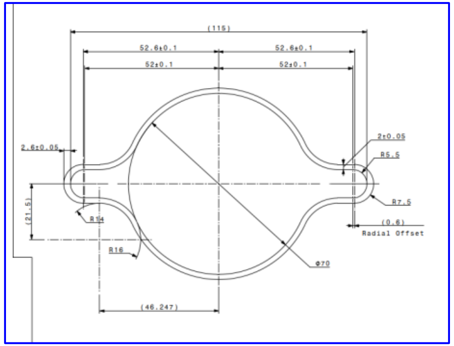
FUTURE CIRCULAR COLLIDER

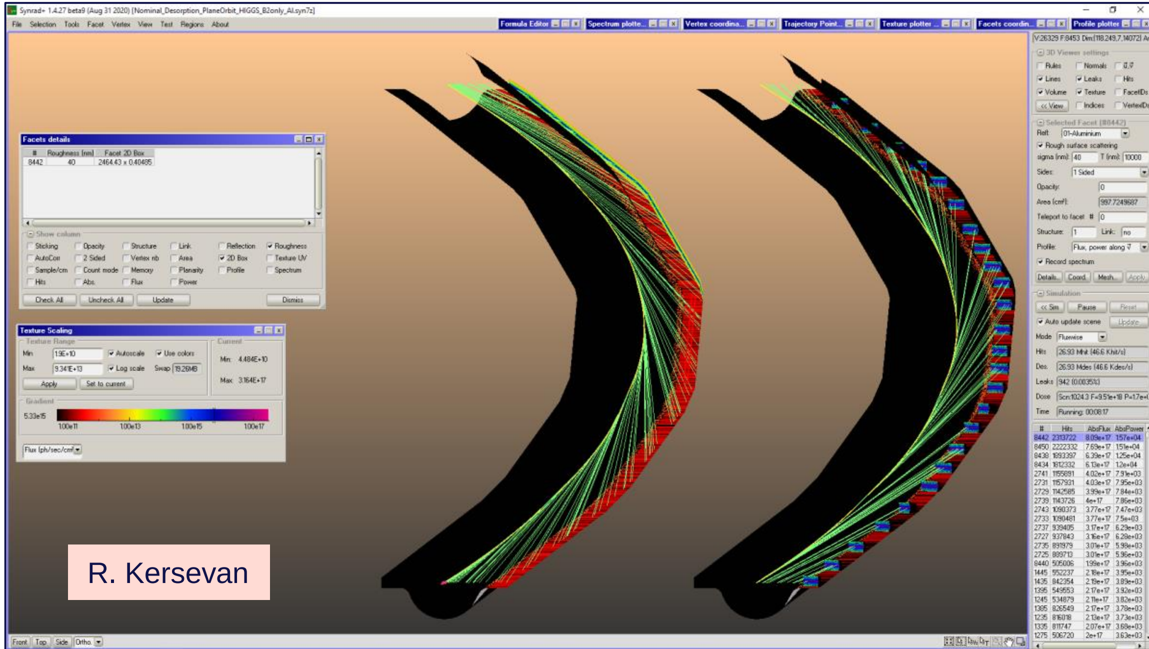
Pre-engineering design review and roadmap discussion for FCC-ee IR magnets

4 Apr 2022, 14:00 → 5 Apr 2022, 19:00 Europe/Zurich

# FCC-ee Vacuum system

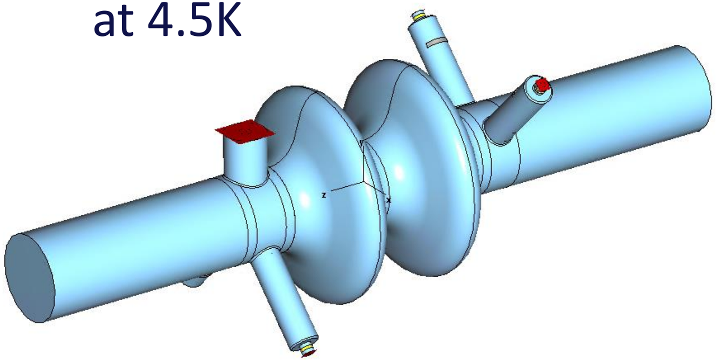
- **Specifying vacuum system**
  - Consider discrete absorbers space every <6 m or continuous absorbers along chamber wall
  - NEG coated Cu vacuum chamber
  - Need shielding to minimize tunnel radiation levels



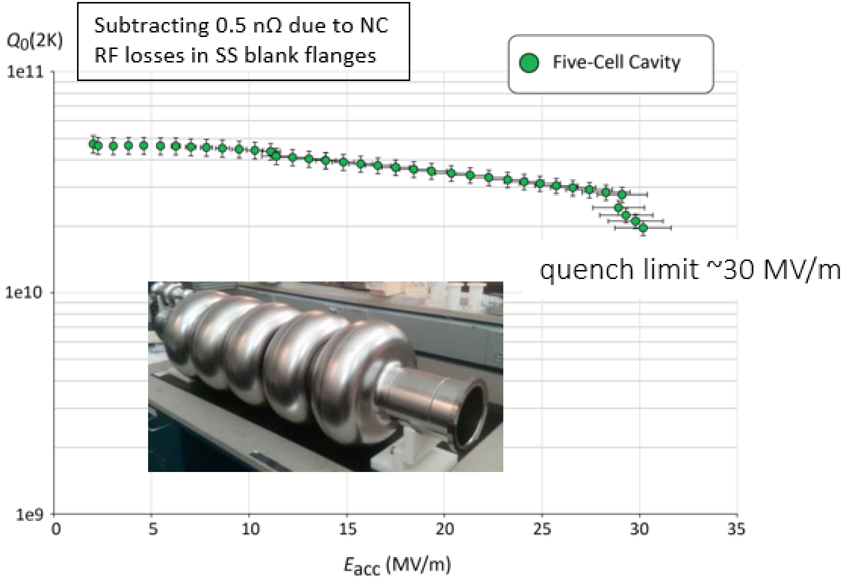
# FCC-ee SRF Technology

- **SRF technology building on LHC studies and collaborative R&D**
    - 5-cell 800 MHz cavity without damping built and tested at 2K by Jefferson lab with excellent results
    - 400 MHz cavities based on LHC studies of Cu-coated Nb cavities at 4.5K



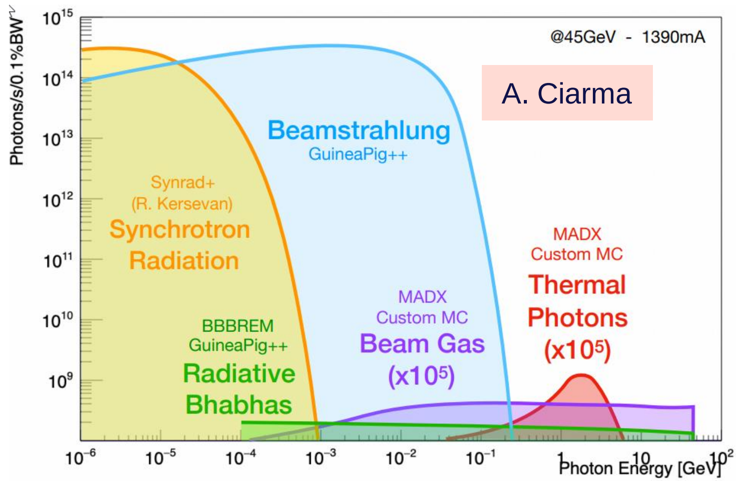
Model for 2-cell 400 MHz synergistic with LHC

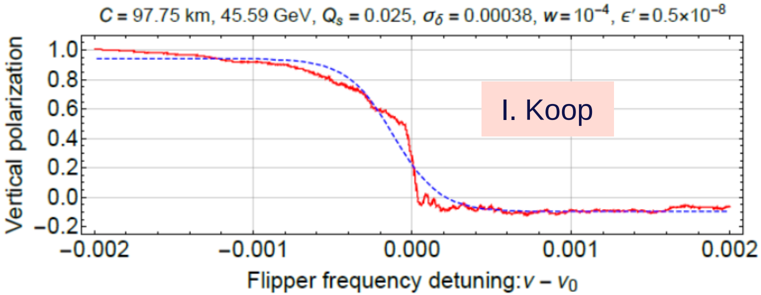
Jlab test of 5-cell 800 MHz



# FCC-ee Diagnostic examples

- **Roughly 400 kW of beamstrahlung at Z operation**
  - Can signal be used to optimize collisions?
- **Center-of-mass energy calibration at Z << 100 keV**
  - Plan to use resonant depolarization of pilot bunches similar to LEP



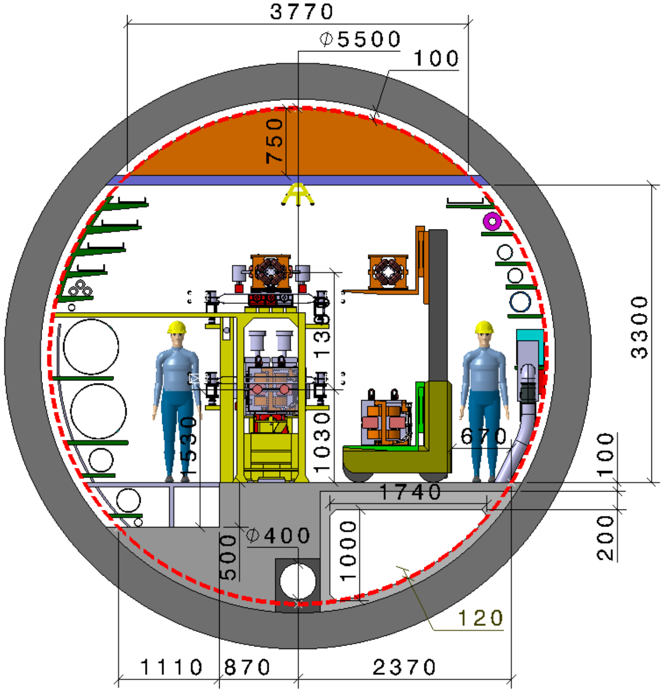

- **Beam size and position diagnostics are critical to achieving and maintaining small vertical emittances**

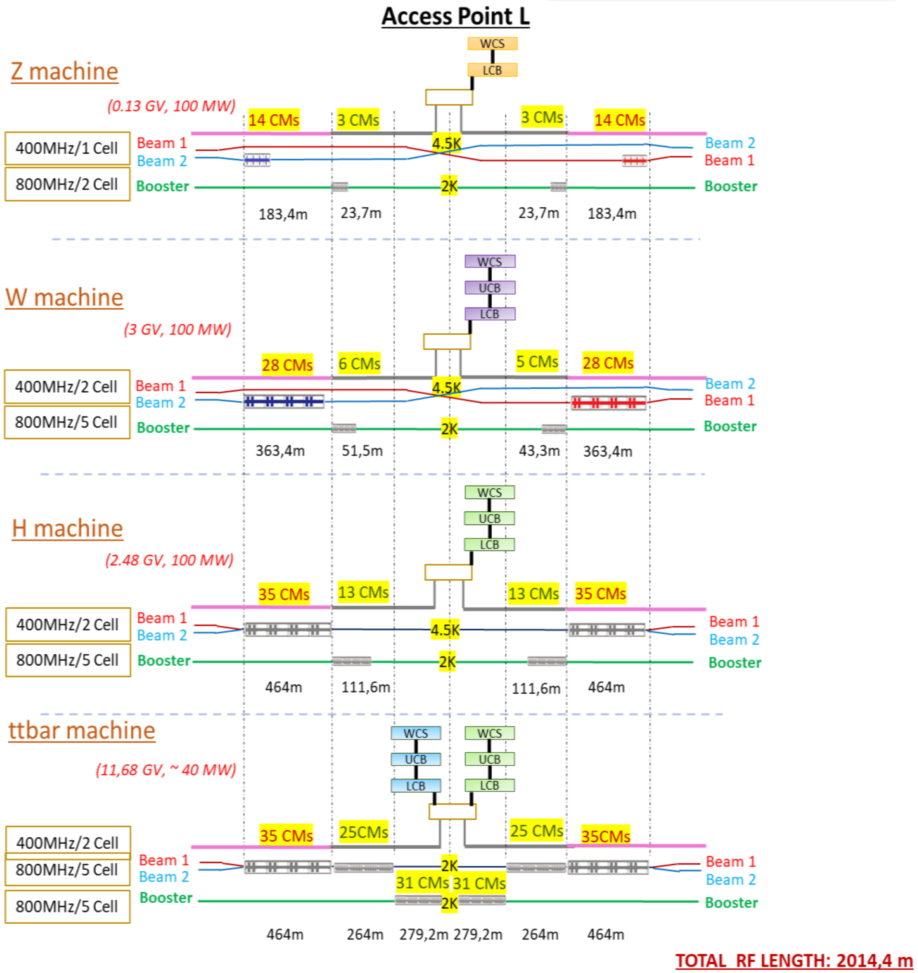
F. Valchkova-Georgieva, J-P. Corso



# FCC-ee Integration

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

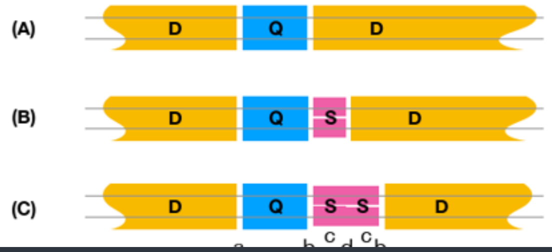


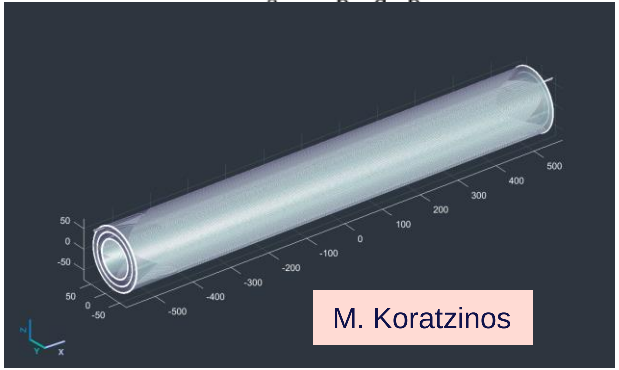



# FCC-ee Alternative technologies

- **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

| Day | Monday | Tuesday | | | | Wednesday | | | Thursday | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Room | Plenary | Parallel 1 | Parallel 2 | Parallel 3 | Parralel 4 | Parallel 1 | Parallel 2 | Parallel 3 | Parallel 1 | Parallel 2 | Parallel 3 | Parallel 4 |
| | Campus Cordeliers | CICSU Jussieu | | | | Campus Cordeliers | | Réfectoire Cordeliers | Campus Cordeliers | | | Réfectoire Cordeliers |
| Time | FARABOEUF | Room 105 | Room 107 | Room 109 | Room 116 | ROUSSY | PASQUIER | | FARABOEUF | PASQUIER | ROUSSY | |
| 09:00-09:30 | | FCCee accelerator FCCIS WP2 | Phy Programme/ Performance | FCCIS WP4 Socio Econom | | FCC hh accelerator | PED: EPOL | FCCIS WP3 Placement | PED/ACC: FCCee EPOL | RF Points for FCC-ee | Technology | |
| 09:30-10:00 | Plenary session | | | | | | | | | | | |
| 10:00-10:30 | | Chairperson | Chairperson | Chairperson | | Chairperson | Chairperson | Chairperson | Chairperson | Chairperson | Chairperson | |
| 10:30-11:00 | *Coffee break* | *Coffee break* | | | | *Coffee break* | | | *Coffee break* | | | |
| 11:00-11:30 | Plenary session | FCCee accelerator FCCIS WP2 | Phy Programme/ Performance | SRF Directions for R&D | | Technology | PED: Detector Concepts | Civil Engineering | PED/ACC: FCCee MDI | Electricity and Cooling | Technology | |
| 11:30-12:00 | | | | | | | | | | | | |
| 12:00-12:30 | Chairperson | Chairperson | Chairperson | Chairperson | | Chairperson | Chairperson | Chairperson | Chairperson | Chairperson | Chairperson | |
| 12:30-14:00 | *Lunch break* | *Lunch break* | | | | *Lunch break* | | | *Lunch break* | | | |
| 14:00-14:30 | Plenary session | FCCee injector FEB | Phy Programme/ Performance | Technology SRF | ISC meeting CLOSED | FCCee accelerator | PED: Detector Concepts | FCCIS WP5 Collaboration | PED/ACC: FCCee MDI | Transport & logistics, Safety | | |
| 14:30-15:00 | | | | | | | | | | | | |
| 15:00-15:30 | | Chairperson | Chairperson | Chairperson | F. Gianotti | Chairperson | Chairperson | Chairperson | Chairperson | Chairperson | | |
| 15:30-16:00 | Chairperson | *Coffee break* | | | | *Coffee break* | | | *Coffee break* | | | |
| 16:00-16:30 | *Coffee break* | FCCee injector FEB | Phy Programme/ Performance | Technology SRF | ISC meeting CLOSED | FCCee accelerator | TI Geodesy and survey | FCCIS WP5 Communication | | | | France, special session |
| 16:30-17:00 | Plenary session | | | | | | | | | | | |
| 17:00-17:30 | | Chairperson | Chairperson | Chairperson | F. Gianotti | Chairperson | Chairperson | Chairperson | | | | Chairperson |

# 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.