Accelerator summary

K. André, F. Zimmermann

Tuesday - FCC-ee baseline optics,
chair: Ilya Agapov/DESY, 8h30-10h00

- **Update on the GHC optics,** Katsunobu Oide/U Geneva
- **Top-up injection status and studies,** Yann Dutheil/CERN
- **Numerical tools for beam-beam effects**, Peter Kicsiny/CERN
- **Collimation studies for FCC-ee**, Giacomo Broggi/Sapienza

FCC-ee Alternative Optics,
chair Angeles Faus-Golfe/IJCLab, 10h30-12h00

- **Alternate Optics for the FCC-ee**, Kevin Andre/ESRF
- **GHC vs LCC design concepts and next steps for pre-TDR,** Ghislain Roy/CERN
- **Xsuite evolution for FCC studies,** Giovanni Iadarola/CERN
- **Nested magnets & ballistic optics for FCC-ee**, Cristobal Garcia/EPFL
- **Spin polarization in the EIC electron storage ring**, Yunhai Cai/SLAC

FCC accelerators: Tuning and Operations,
chair: Rogelio Tomas/CERN, 13h30-15h00

- **Correction & tuning strategies**, Jacqueline Keintzel/CERN
- **Optics tuning simulations for FCC-ee lattices,** Elaf Musa/DESY
- **Integrated simulations for calculation of tolerances,** Kyriacos Skoufaris/CERN
- **BBA for FCC-ee and Beam Test at KARA,** Christian Goffing/KIT
- **IR alignment and Xsuite migration,** Satya Sai J./U Geneva

Still Tuesday - FCC-ee collective effects,
chair: Lenny Rivkin / PSI, 15h30-17h00

- **Overview on collective effects for the main rings,** Mauro Migliorati/Sapienza
- **Main rings impedance budget,** Carlo Zannini/CERN
- **Impact of Collimators' Geometric Impedance on Beam Stability**, Dora Gibellieri/U Caen
- **Beam-Beam and Wakefield-Induced Collective Instabilities and Mitigation Strategies,** Roxana Soos/U Paris-Saclay
- **Electron-cloud effects and possible mitigations strategies,** Luca Sabato/EPFL
- **Beam-Beam effects in presence of errors: results and strategies,** Leon Van Riesen-Haupt/EPFL

20 talks on Tuesday

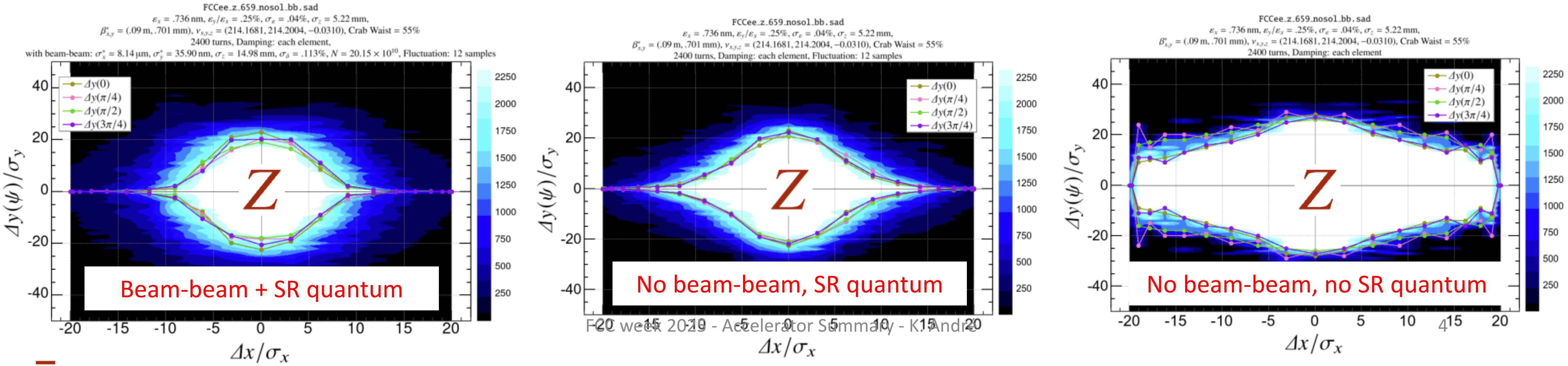
1st Session - FCC-ee accelerator: Baseline optics

- Update on GHC optics and lattice design
- Top-up injection status and studies
- Numerical tools for FCC-ee beam-beam studies
- Collimation studies for FCC-ee

K.Oide

Updates on the GHC optics and lattice design

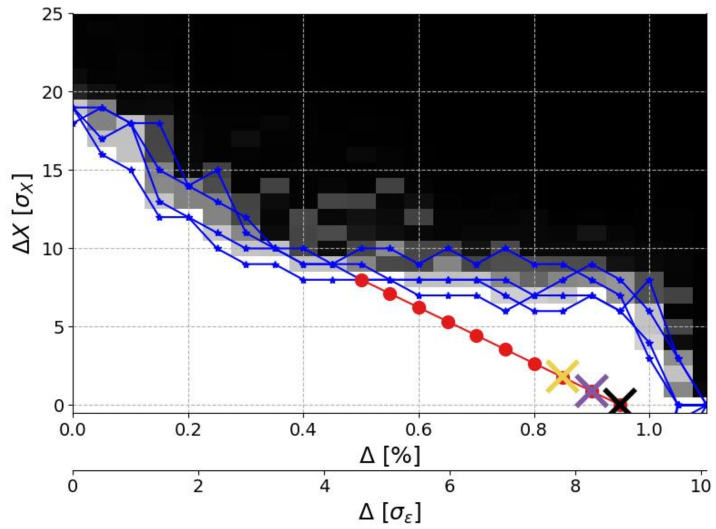
- β^*_x=9cm and Q'_x=12 to relax the X-Z beam-beam instability at Z.
- Extension of L* from 2.2 to 2.4m is possible for more radial space.
- A common technical straight section (TSS) for injection/extraction, collimation, and RF (Z/W) maintaining the ring super-periodicity.
- Extension of the available space for the cryomodules in the RF section for ttbar, still remains insufficient –swap 400MHz with 800MHz ?

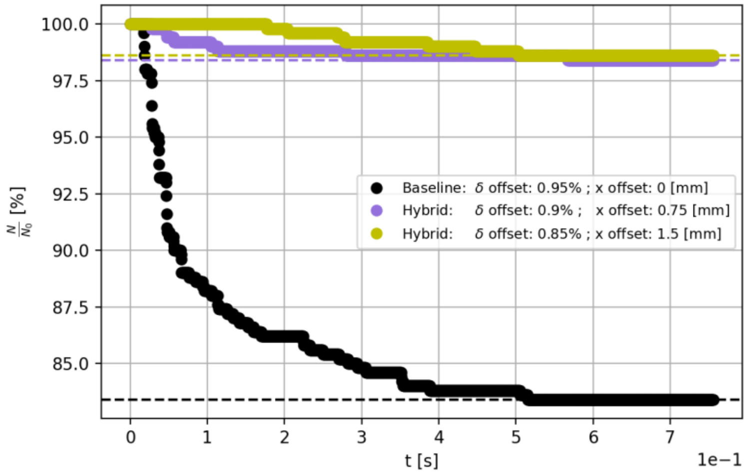


Y.Dutheil

Top-up injection status and studies

- Hardware:
  - Orbit π-bump comprising 2 kickers (might be extended to 4 for more flexibility).
  - Thin magnetic septum (2.8mm blade and 304µs flat-top)
- Particle tracking including beam-beam effects indicates that an hybrid injection maximizes the injection efficiency (w.r.t. on-axis).
- Initial bootstrapping simulations from low intensity indicate a vertical optics mismatch and ε_z increases with intensity.
- Preliminary injection losses simulations performed to set protection requirements.



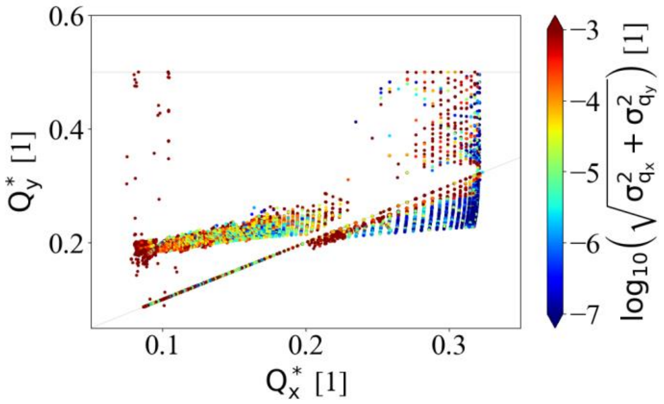


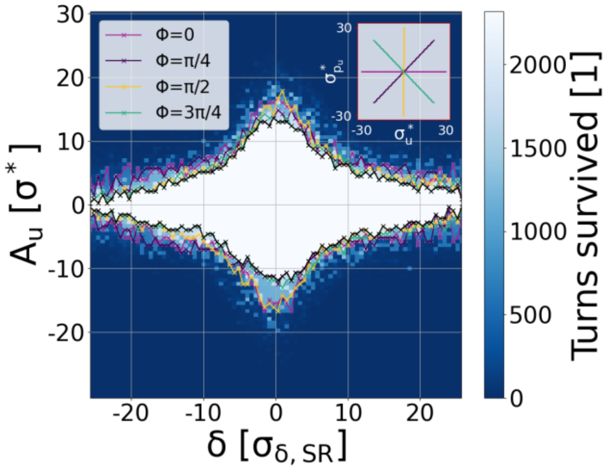
Numerical tools for FCC-ee beam-beam studies

- Xsuite used for self-consistent FCC-ee beam dynamics studies.
- Interest in highlighting correlation between beam lifetime (time consuming) and DA studies (comparatively fast computation).
- Standardized setups and submission scripts for DA/MA, FMA evaluation tools are being developed. -> xutil has started this process.

	Weak-strong 6D	Quasi-strong-strong 6D	Strong-strong 6D SG	Strong-strong 6D PIC	Beamstrahlung	Bhabha-scattering	Transverse wakefields	Longitudinal wakefields	Linear tracking	Lattice tracking	Open source	Runs on GPU
Xsuite												

Available	Not available

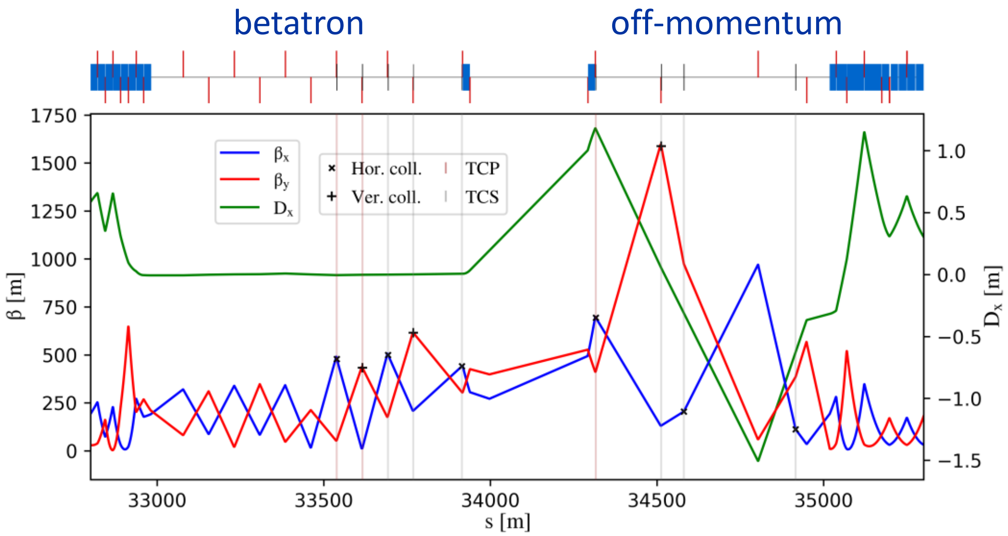


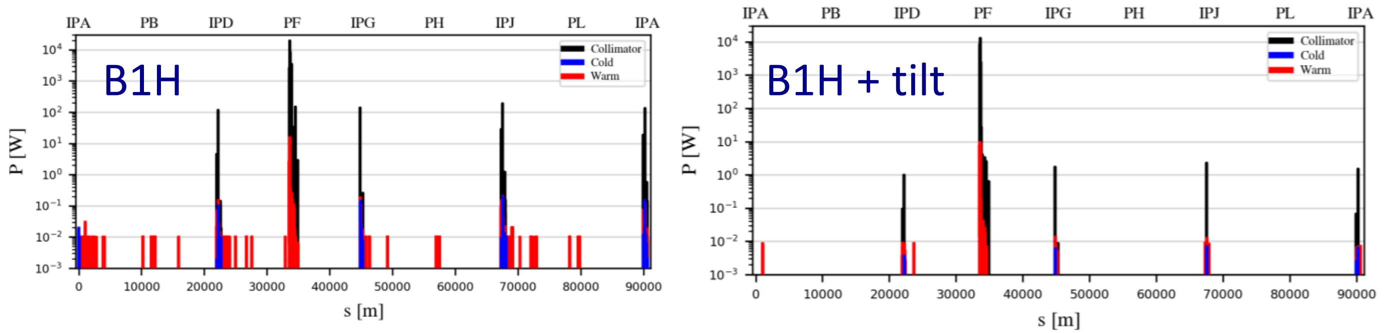


G.Broggi

Collimation studies for FCC-ee

- The collimation system consists of beam halo collimators with shower absorbers in between, synchrotron radiation collimators and local protection collimators.
- Use of the universal technical insertion conserving super-periodicity.
- Beam loss scenarios simulated for FCC-ee include: generic halo, beam-gas interactions, top-up injection, fast instabilities and more to be studied including their impacts on the particle detector (background).
- Xsuite-BDSIM benchmark at SKEKB accurately reproducing measured background trend.(beam-gas and Touschek scattering).





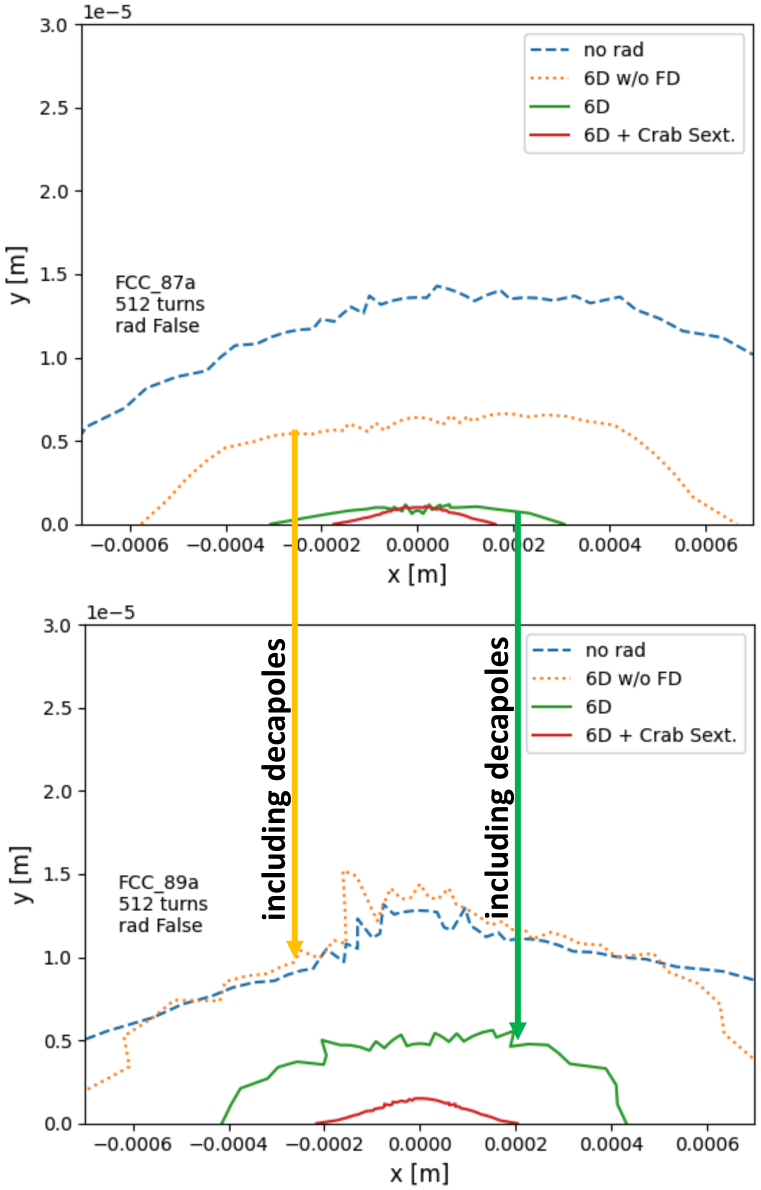
Beam halo losses w/o (left) and w/ (right) collimator angular alignment.

2nd Session - FCC-ee accelerator: Alternative optics

- Alternate optics for the FCC-ee
- GHC vs LCC design concepts and next steps for pre-TDR phase
- Xsuite evolution for FCC studies
- Nested magnets and ballistic optics for the FCC-ee
- Spin polarization in the EIC electron storage ring

Alternate optics for the FCC-ee

- Beam parameters: comparable to GHC, **smaller** energy loss per turn for LCC.
- Number of magnets: at ttbar the LCC optics has **less** magnets with **smaller** gradients.
- Dynamic Aperture: **larger** DA on- and off-energy for the LCC optics, especially **vertically** (@Z).
- Work needed to perform tuning studies and to adapt the straight sections to compare with the GHC lattice.



G.Roy

GHC vs. LCC design concepts and next steps for the pre-TDR phase

- Presentation of the comparison exercise: arcs, insertions, hardware, …
- Active “FCC-ee Layout and Optics Design working group”
- Ambitious timeline post FCC Week 2025:

Summer 2025:
Repository re-organized and ready; optics layout; naming conventions

September 2025:
Beam optics with technical insertions, complete layouts.

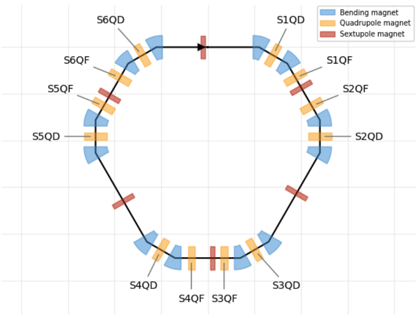
December 2025:
Optics comparison report; geometry frozen for Civil Engineering

March 2026:
Decision on Optics – review from expert panel ?

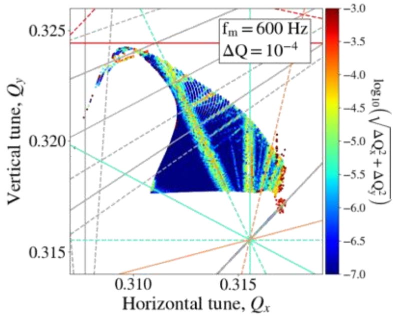
FCC Week 2026:
First Technical Design of Optic

Xsuite evolution for FCC studies

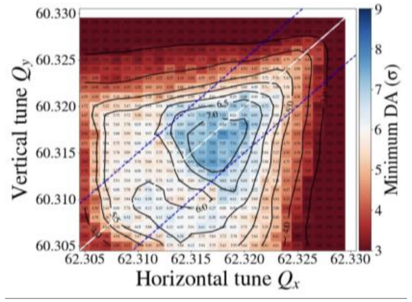
- Xsuite considered a workhorse for FCC-ee beam dynamics studies
- Alleviate extendibility and integration issues from legacy tools, offers python interface and supports single/multi-threaded CPU and GPU.
- Xsuite capabilities comprise: Optics and lattice design, imperfections and correction, interface with MAD-NG, RF-Track, BDSIM/FLUKA, collective effects and recently polarization tracking (analytical & stochastic).



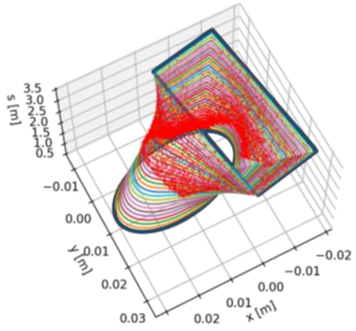
Lattice Design



Beam-Beam Effects



Tracking (dynamic aperture)



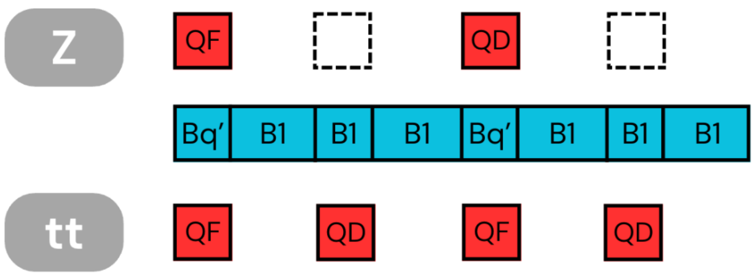
Collimation

C.Garcia-Jaimes

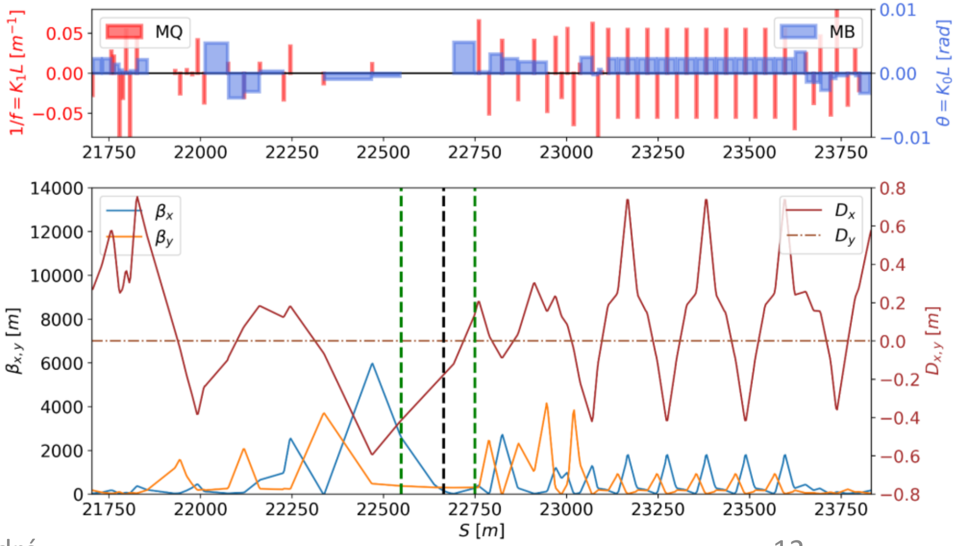
Nested magnets and ballistic optics for the FCC-ee

- Nested magnets for Z and ttbar:
  - Fully integrated in the GHC lattice.
  - Compatibility issues between Z and ttbar has been resolved.
- Ballistic optics for the Z energy
  - Turn off quadrupoles and sextupoles 200m around the IP → Significant increase of the DA and relaxed magnet sensitivities.
  - Further work needed to improve the MA and beam lifetime (sextupole optimization).

Nested magnet arc design



Ballistic lattice



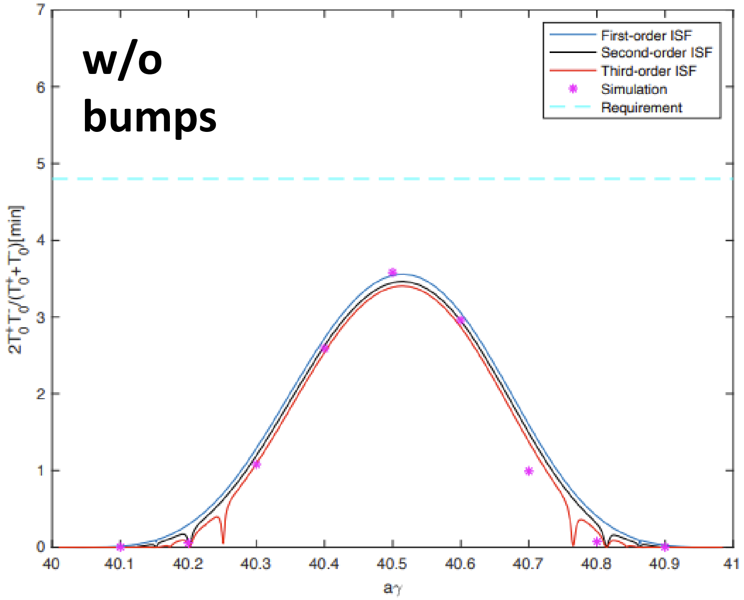
Y.Cai

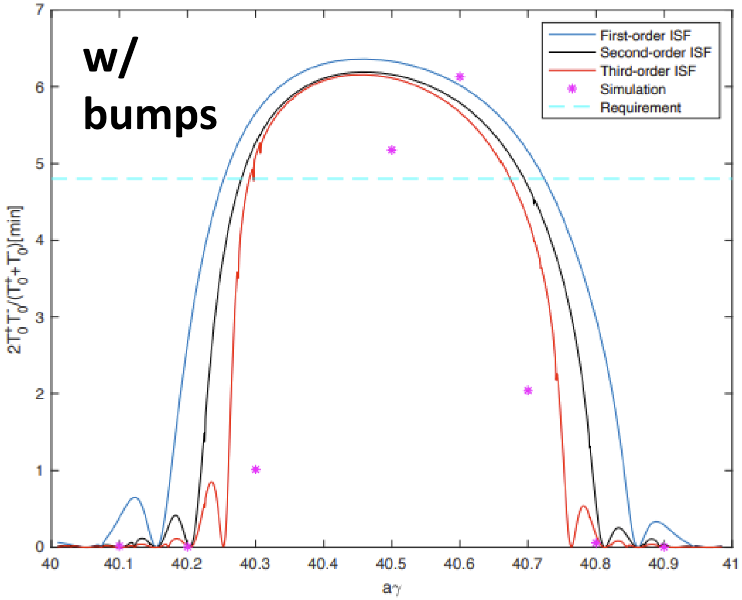
Spin polarisation in the ESR of EIC

- Developed normal forms up to arbitrary order for orbital motion and spin precession analytical solution. Good agreement with tracking.
- Semi-local spin matching scheme: Four orthogonal vertical bumps to match the spin longitudinally along the spin closed orbit.

✓ Equilibrium polarization is nearly doubled.

✓ Almost no impact on the dynamic aperture.



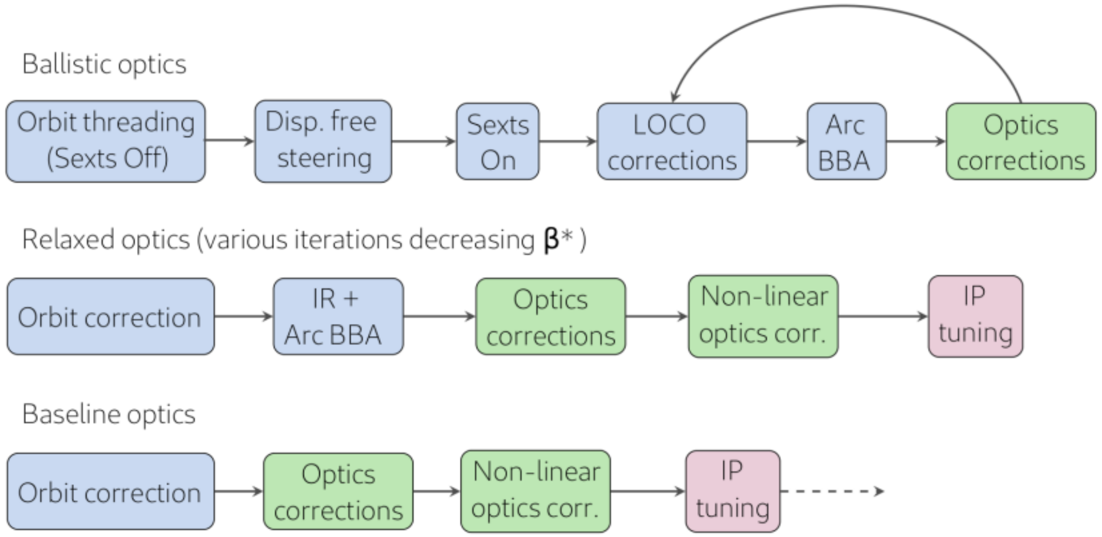


3^{rd} Session - FCC-ee accelerator: Tuning and operations

- Correction and tuning strategies for FCC-ee
- Optics tuning simulations for FCC-ee lattices
- Integrated simulations for calculation of tolerances
- BBA for FCC-ee and beam test at KARA
- IR alignment and Xsuite migration

Correction and tuning strategies for FCC-ee

- Commissioning and tuning strategy developed and progressing.
- Good global optics tuning performance (w/o IR errors nor multipole errors), efficient IP tuning knobs, small errors in the IR cause blow-up.
- SKEKB: complexity and manufacturing errors in the IR lead to degradation of the optics, impacting DA but also injection efficiency.
- Studies focused on using GHC at Z; plan to look at the other beam energies and perform the same studies for the LCC lattice.

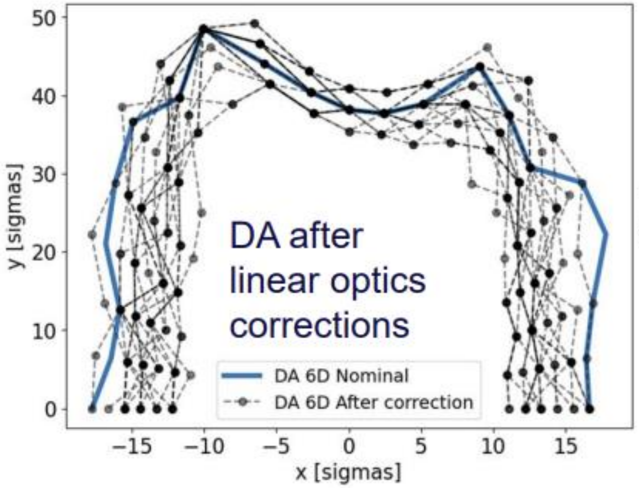


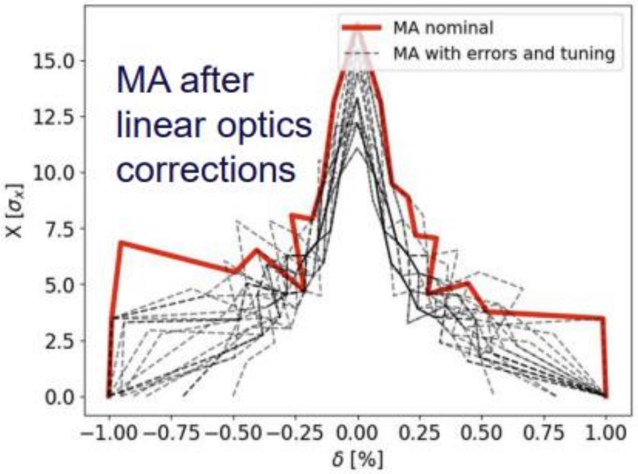
Element	Transv. Tol.	Rot. Tol.	Field. Tol.
Arc quad.	50µm	50µrad	2e-4
Arc sext.	50µm	50µrad	2e-4
Dipoles	1000µm	1000µrad	2e-4
Girders	150µm	150µrad	-
BPM-quad.	100µm	-	-

E.Musa

Optics tuning simulations for FCC-ee lattices

- Developed a correction procedure
  - With tuning simulations for the ballistic and nominal GHC optics
- Comparison of correction procedure in favor of TbT compared to LOCO because it focuses on the phase advance between BPMs.
- Improved correction when having BPMs attached to quadrupoles.



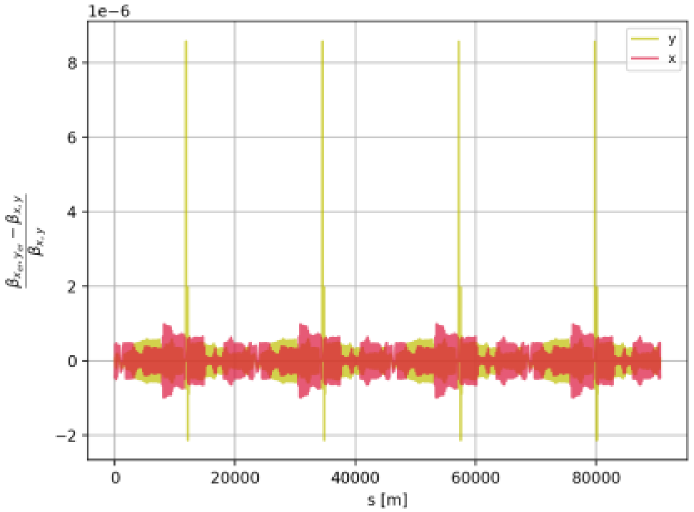


Element	$\sigma_{x/y}$ [µm]	$\sigma_{\theta/\psi/\phi}$ [µrad]	$\Delta k/k$ [10^{-4}]
Arc quads & sext.	50	50	2
Dipoles	1000	1000	2
Girders	150	150	-
BPMs-to-quad	~~100~~ 10	-	-

Arc alignment and strength tolerances

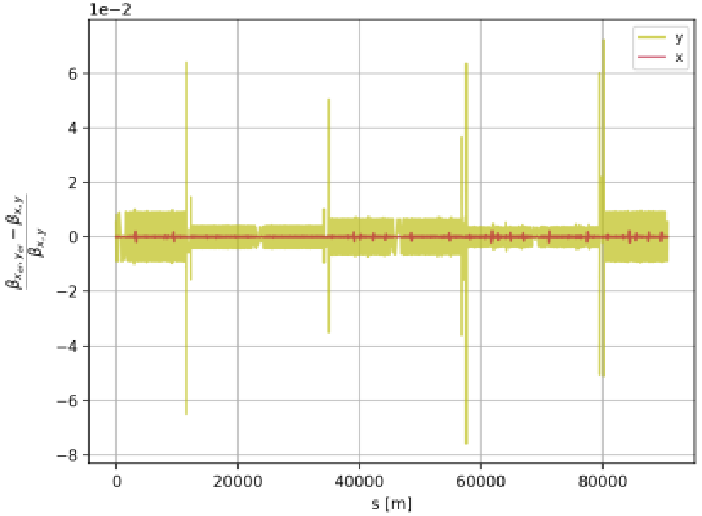
Integrated simulations for calculation of tol.

- Reduced sextupole strengths during commissioning: ballistic optics gives a larger lifetime –LCC presents a 350 turns lifetime with sextupoles turned off.
- Injection performance about 90%, optics aberrations from beam-beam interaction, tolerances are low -> iterations needed.
- Impact of ground motion: correlated and uncorrelated motions.
- Magnetic field errors tolerances are challenging.



Beta-beating from **uncorrelated** ground motion

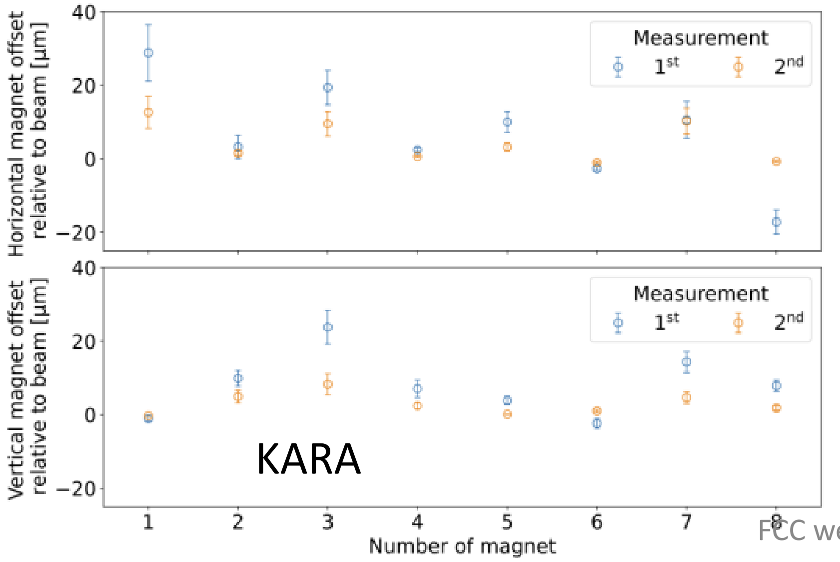
Xutil repository

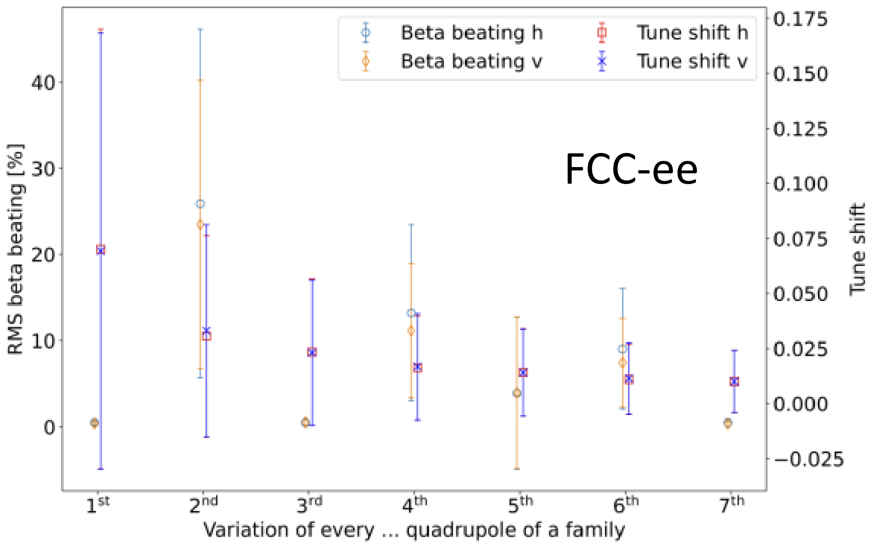


Beta-beating from **correlated** ground motion

BBA for FCC-ee and beam test at KARA

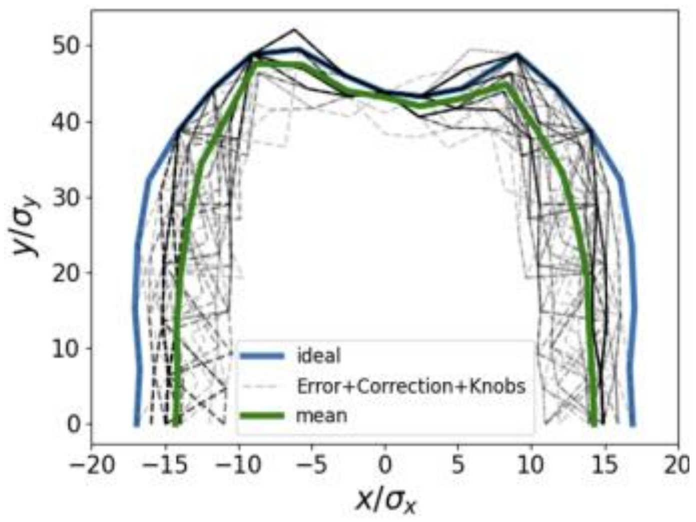
- Parallel BBA with focus on arc quadrupoles to reduce the mechanical tolerances for quadrupoles and sextupoles.
- Studies performed for GHC and LCC relaxed optics:
  - Promising results to achieve the target of 10 to 20 micrometers accuracy
  - Magnet selection is important *e.g.* beta-beating and tune change
- Proof-of-principle at KARA

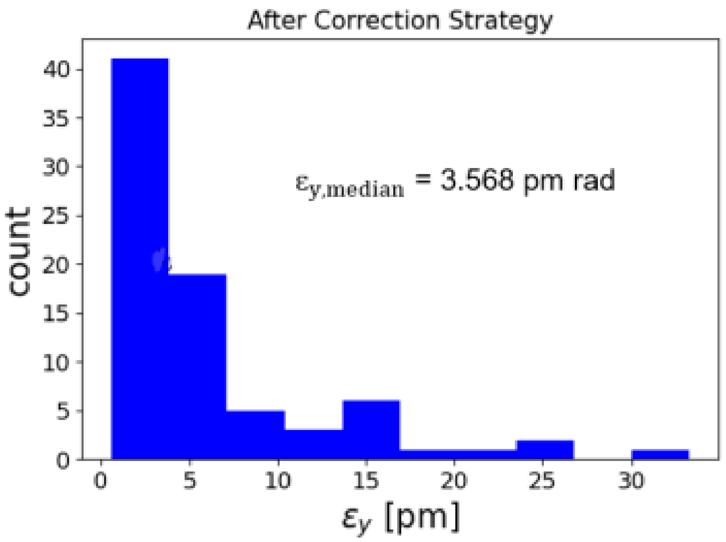


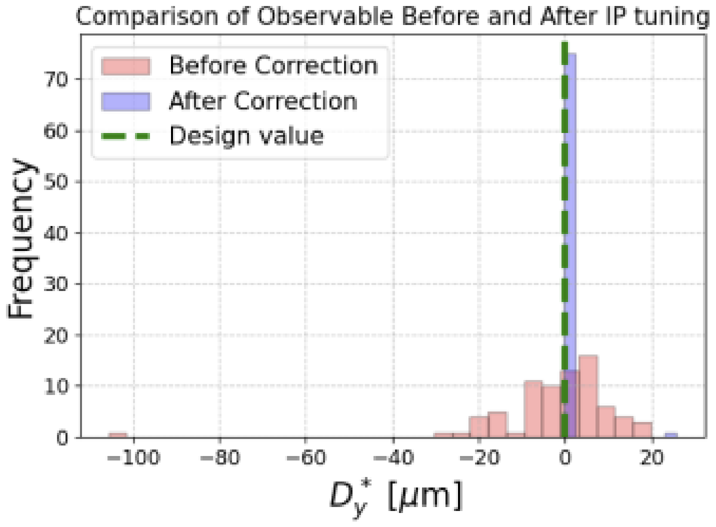


IR alignment and Xsuite migration

- Global correction combined with IP tuning knobs are efficient at recovering the IP optics parameters. The median of the vertical emittance over 100 seeds remains twice larger than the design.
- The errors in the final focus doublet largely dominates the tuning of vertical emittance.
- Efforts on-going to integrate tuning and correction algorithms within Xsuite.





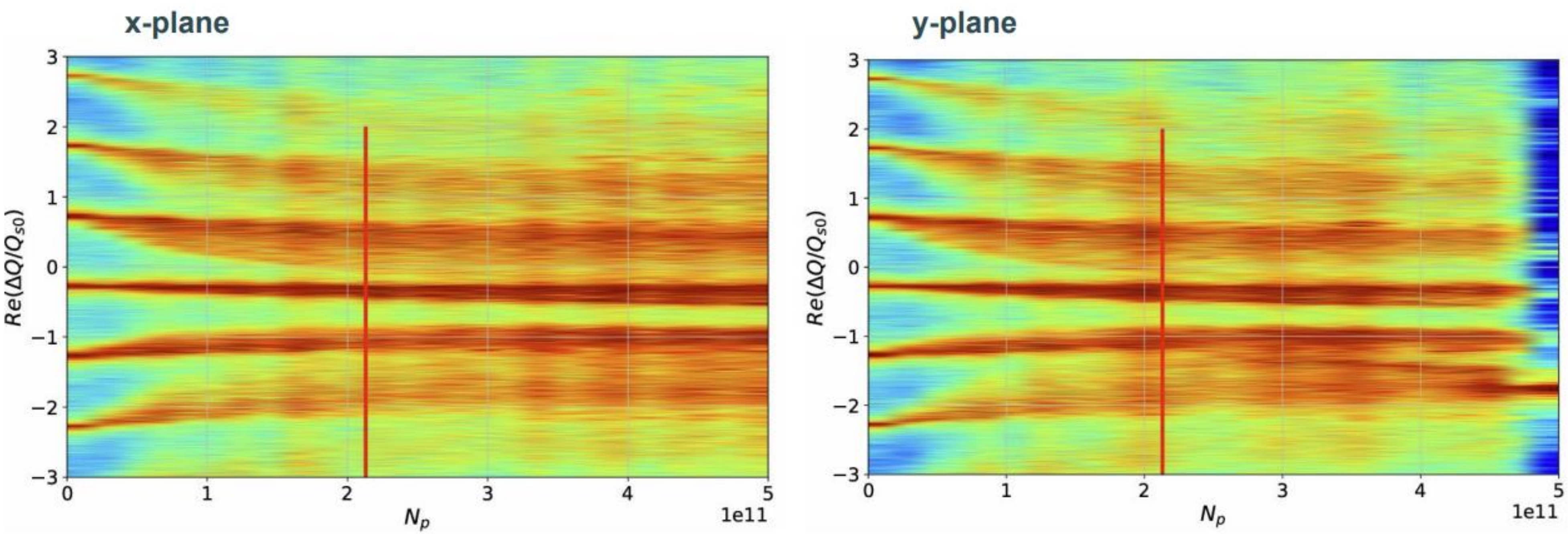


4^{th} Session - FCC-ee accelerator: Collective effects

- Overview on collective effects for the main rings
- Main rings impedance budget
- Impact of collimators geometric impedance on beam stability in the FCC-ee
- Beam-beam and wakefield-induced collective instabilities for FCC-ee at Z energy
- Electron-cloud effects and possible mitigation strategies
- Beam-beam effects in presence of errors

Overview on collective effects for the main rings

- With the current impedance model, the vertical plane shows an instability threshold close to the nominal beam intensity.
- **Feedback system and chromaticity help**, but vertical instability remains critical.
- Still missing several impedance sources and updated of some devices is needed.
- Interplay with beam-beam and beamstrahlung must be considered in the future.



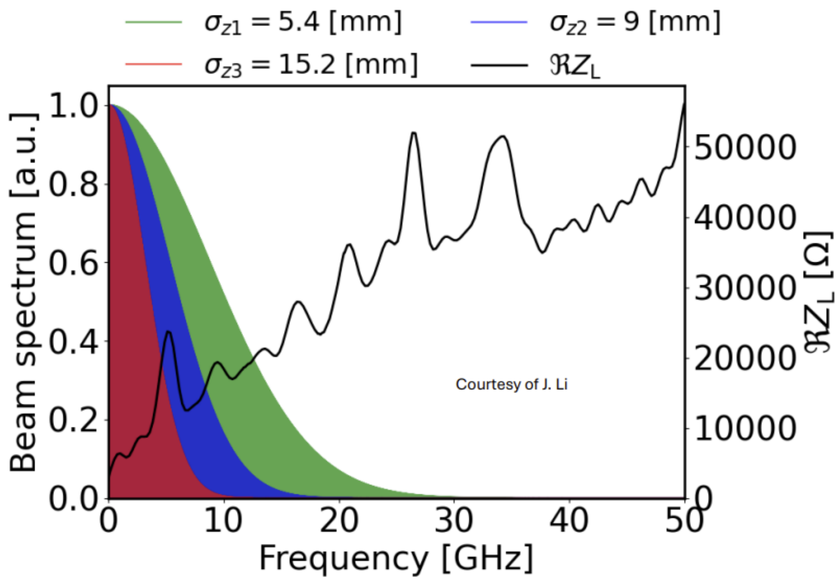
Wake with reduced collimators' geometric contribution.

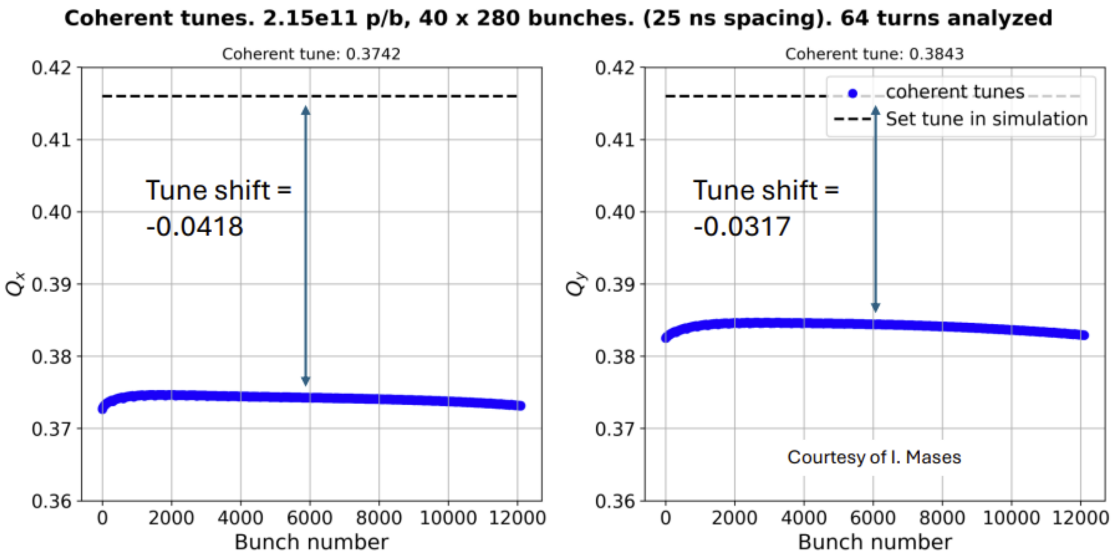
Chromaticity = 20
Feedback system on 4 turns

C. Zannini

Main rings impedance budget

- FCC-ee is challenging due to the combination of a large beam pipe and short bunches resulting in a **crosstalk between different accelerator elements**.
- **Impedance beam induced power** has a significant impact on the energy loss per turn from **~4% to ~20% depending on bunch length** (in collision or not).
- **Bunch-by-bunch tune shifts** must be taken into account to define the filling strategy and the overall impedance budget.
- Stability at nominal working point looks critical due to coupled bunch instability.



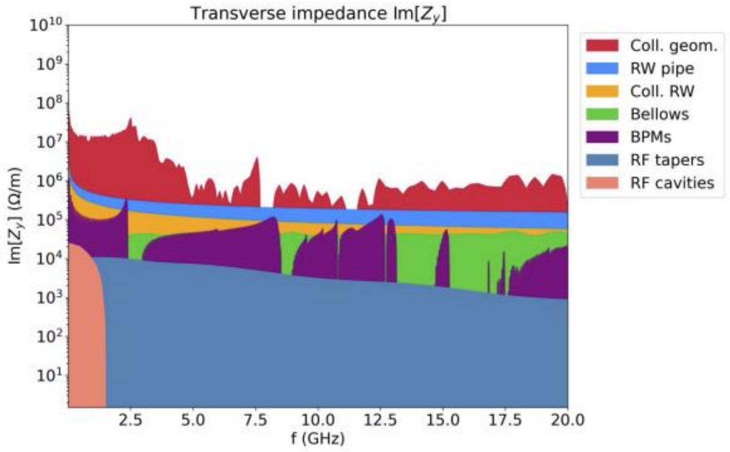


D. Gibellieri

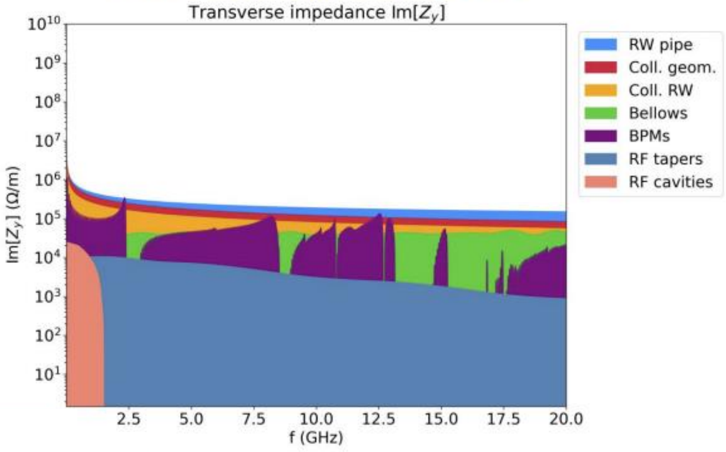
Impact of collimators geometric impedance on beam stability in the FCC-ee

- Impedance/Wake model development for critical design decisions:
  - Ensured model flexibility to facilitate impedance and wakefield updates in optics, material choices, coating thickness, geometries.
  - Enabled impedance assessments for different scenarios.
- The design of the collimator system is critical and the taper optimization reduced the geometrical impedance.
- The radiative wall impedance linked to optics design favor maximum collimator aperture (particularly vertically).

Horizontal and vertical collimator taper angle of 15 degrees

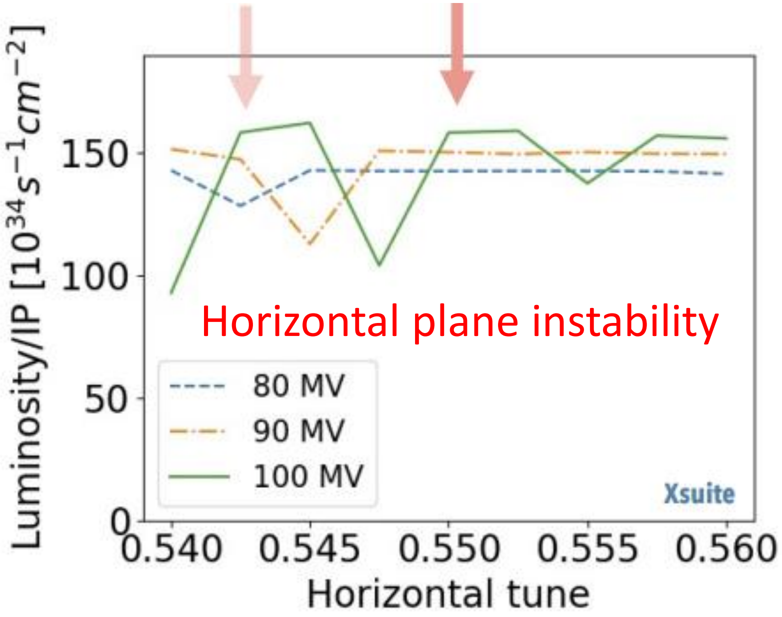


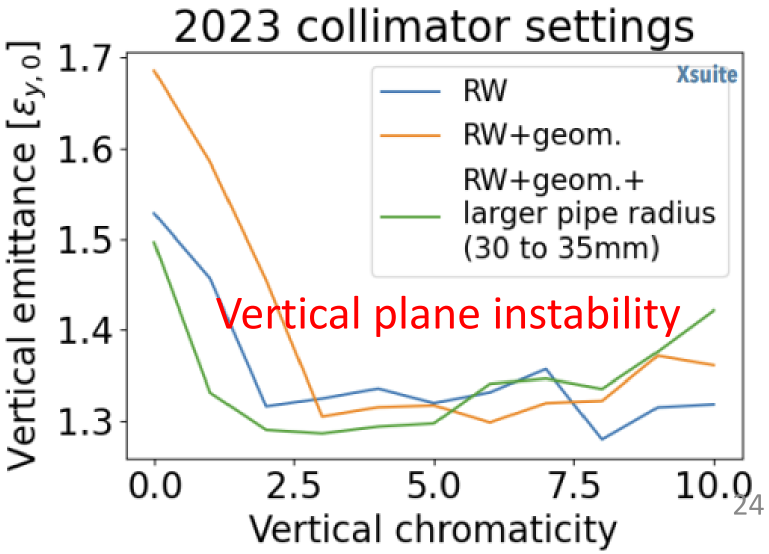
Horizontal collimator taper angle of 15 degrees and vertical taper angle of 2.5 degrees



Beam-beam and wakefield-induced collective instabilities and mitigation

- The Circulant Matrix Model allows a rapid parameter sensitivity scan of the coherent <x-z> instability. -Chromaticity is a good candidate, but limitation to the lifetime must be established.
- Transient beam loading associated with 2cell cav seems acceptable in terms of <x-z> instability.
- Currently no mitigation technique was found to cope with <x-z> instability during non-uniform bootstrap injection.
- In the vertical plane, the TMRI is the dominant beam-beam and impedance driven instability, mitigated with chromaticity ~16.





L. Sabato

Electron-cloud effects and possible mitigation strategies

- The material constraints in order to avoid e-cloud avalanche multiplication are extremely tight with the baseline parameters.
- Using filling schemes with non-uniform bunch spacing the e-cloud formation process could be mitigated,
  - the total number of bunches could be increased, to decrease the bunch population, while keeping the surface requirements achievable, reducing the severity of other collective effects (beam-coupling impedance and beam-beam).

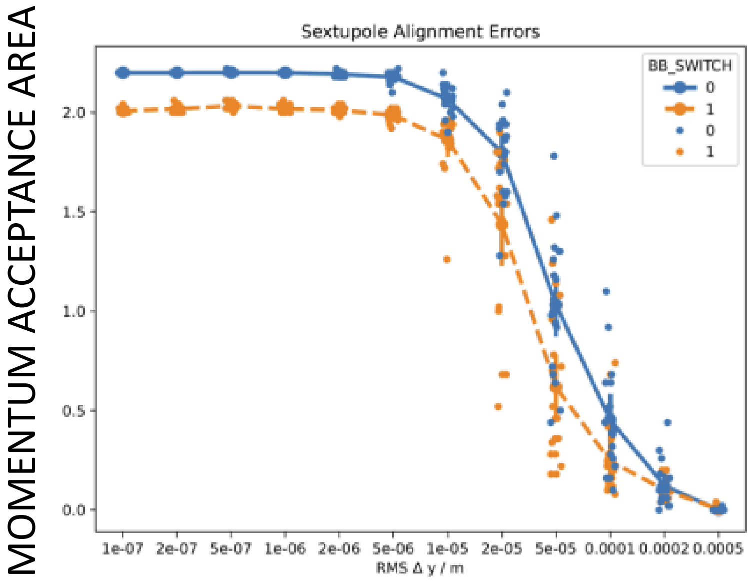
Element	Field	Bunch population	Uniform 25 ns	5b+20e 11,200 2.15×10^{11} ppb	6b+19e 13,440 1.79×10^{11} ppb	7b+18e 15,680 1.54×10^{11} ppb	8b+17e 17,920 1.34×10^{11} ppb	10b+15e 22,400 1.08×10^{11} ppb
Drift Space	-	nominal	1.4	1.4	>1.6	>1.6	>1.6	1.4
		below	1.2	1.4	>1.6	>1.6	>1.6	1.4
Dipole	15.2 mT	nominal	1.4	1.3	1.3	1.4	1.3	1.2
		below	1.0	1.2	1.3	1.4	1.3	1.2
Quadrupole	1.45 T/m	nominal	1.1	1.3	1.2	1.2	1.2	1.2
		below	1.0	1.3	1.2	1.2	1.2	1.2
Sextupole	72.5 T/m^2	nominal	1.1	1.5	1.4	1.3	1.2	1.2
		below	1.0	1.5	1.4	1.3	1.2	1.2

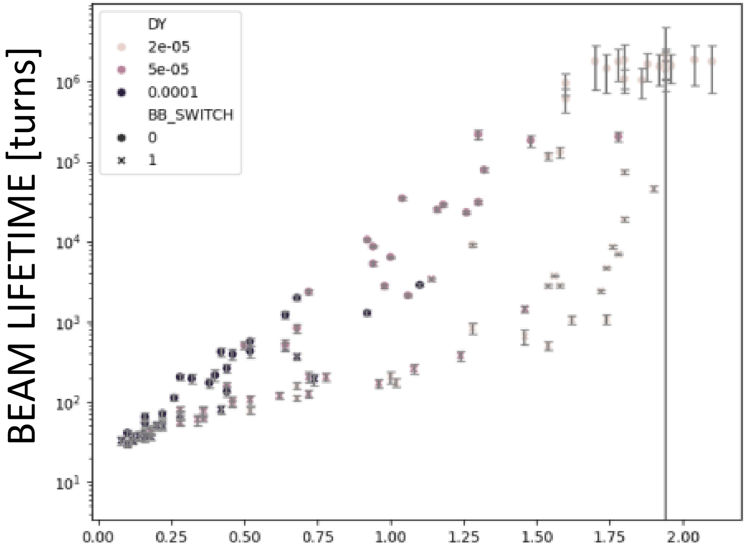
SEY requirements for various elements of the lattice, filling pattern and at constant beam current.

L. Van Riesen-Haupt

Beam-beam effects in presence of errors

- Developments in simulation tools and comprehensive benchmarking and testing.
- First simulations to probe combined effects:
  - Introduction of effects one-by-one to study and understand their individual behaviors
  - Misalignments, multipole errors, IP perturbations
  - First indications for tolerances and input for tuning teams
- Define new and explore established indicators to describe dynamics
- First exploration of correlations between figure of merit, with the long term target to add all effects in dedicated tuned lattices.





FCC-ee collider parameters for the GHC lattice. May 20, 2025.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658499		90.658526[a]	
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0390	0.370	1.86	9.99
SR power / beam	[MW]	50			
Beam current	[mA]	1281	135	26.8	5.0
Colliding bunches / beam		12000	1852	292	60
Colliding bunch population	[10^{11}]	2.02	1.35	1.74	1.57
		74	2.25	0.75	1.69
		84	1.96	1.05	1.39
		64	1.17	0.56	0.81
		Long 90/90		90/90	
		28.55		7.31	
		73		144	
		/ 0.7	220 / 1	240 / 1	900 / 1.4
		/ 214.200	218.179 / 222.241	394.150 / 390.221	394.148 / 390.218
		/ +5	0 / +3	0 / 0	0 / 0
		/ 0.1133	0.070 / 0.106	0.102 / 0.180	0.158 / 0.192
		/ 15.0	3.42 / 5.19	3.18 / 5.56	1.86 / 2.26
		5 / 0	1.00 / 0	2.10 / 0	2.10 / 9.18
		121200			
		400.788075		400.787954	
		310	0.0807	0.0338	0.0873
Long. damping time	[turns]	1168	217	65.5	19.2
RF acceptance	[%]	1.20	3.32	2.14	2.94
Energy acceptance (DA)	[%]	±1.0	±1.0	±2.0	-2.8/+2.5
Beam crossing angle at IP θ_x	[mrad]	±15			
Crab waist ratio	[%]	55	45	45	40
Beam-beam ξ_x/ξ_y[b]		0.0018 / 0.0955	0.0132 / 0.131	0.0108 / 0.130	0.067 / 0.140
Piwinski ang. $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma_x^*$		27.6	3.5	6.5	0.87
Lifetime (q + BS + lattice)	[sec]	4500	3600	4600	9400
Lifetime (lum)[c]	[sec]	1320	960	600	650
Luminosity / IP /10^{34}	[/cm^2s]	141	20	7.5	1.43

Thanks to all the speakers and thank you for your attention !