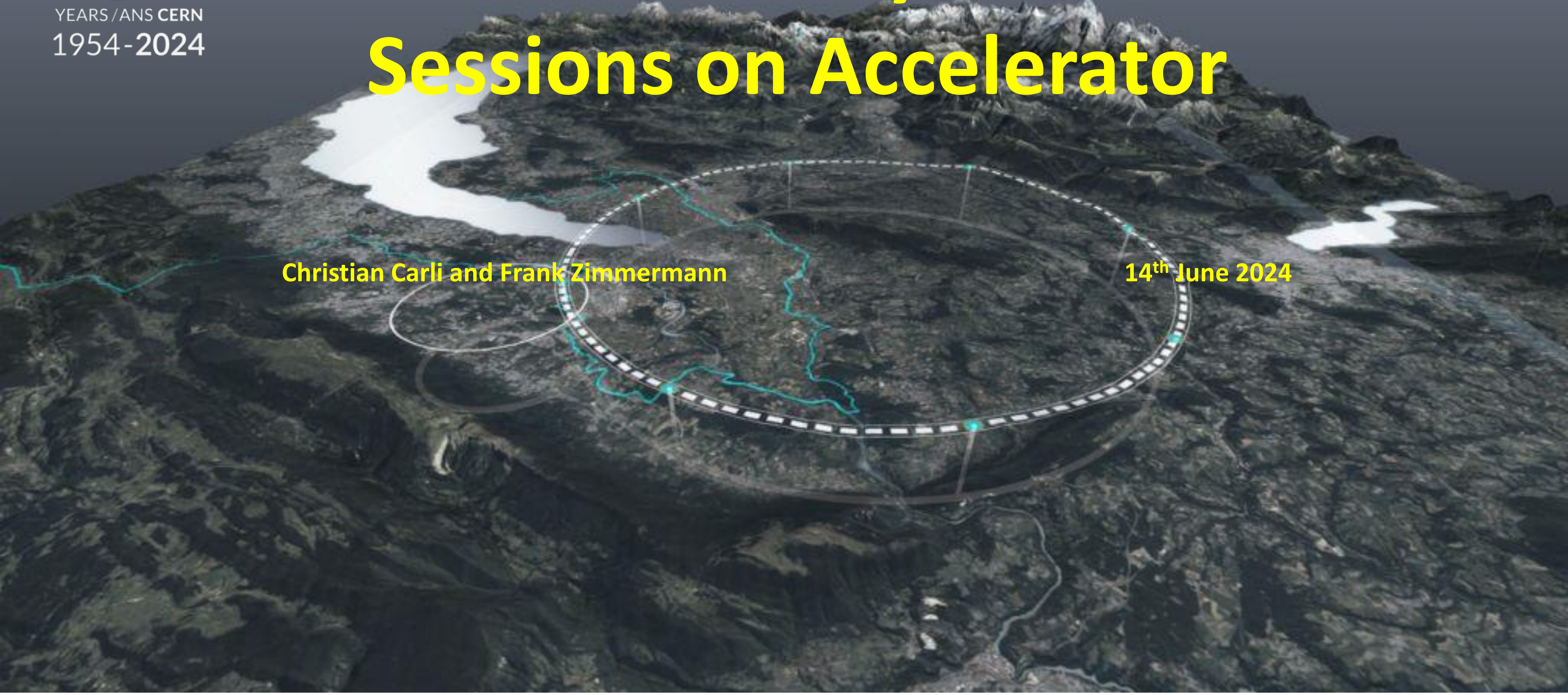
FCC Week, 10th to 14th June 2024

Summary of Sessions on Accelerator



Christian Carli and Frank Zimmermann

14th June 2024

YEARS / ANS CERN 1954-2024

FUTURE CIRCULAR COLLIDER Innovation Study

EuroCirCol A key to New Physics

EASITrain

iFAST

E-JADE

EAJADE

CHART Swiss Accelerator Research and Technology

http://cern.ch/fcc

CERN

Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **iFAST**, grant agreement 101004730, **FCCIS**, grant agreement 951754; **E-JADE,** contract no. 645479; **EAJADE**, contract number 101086276; and by the Swiss **CHART** program

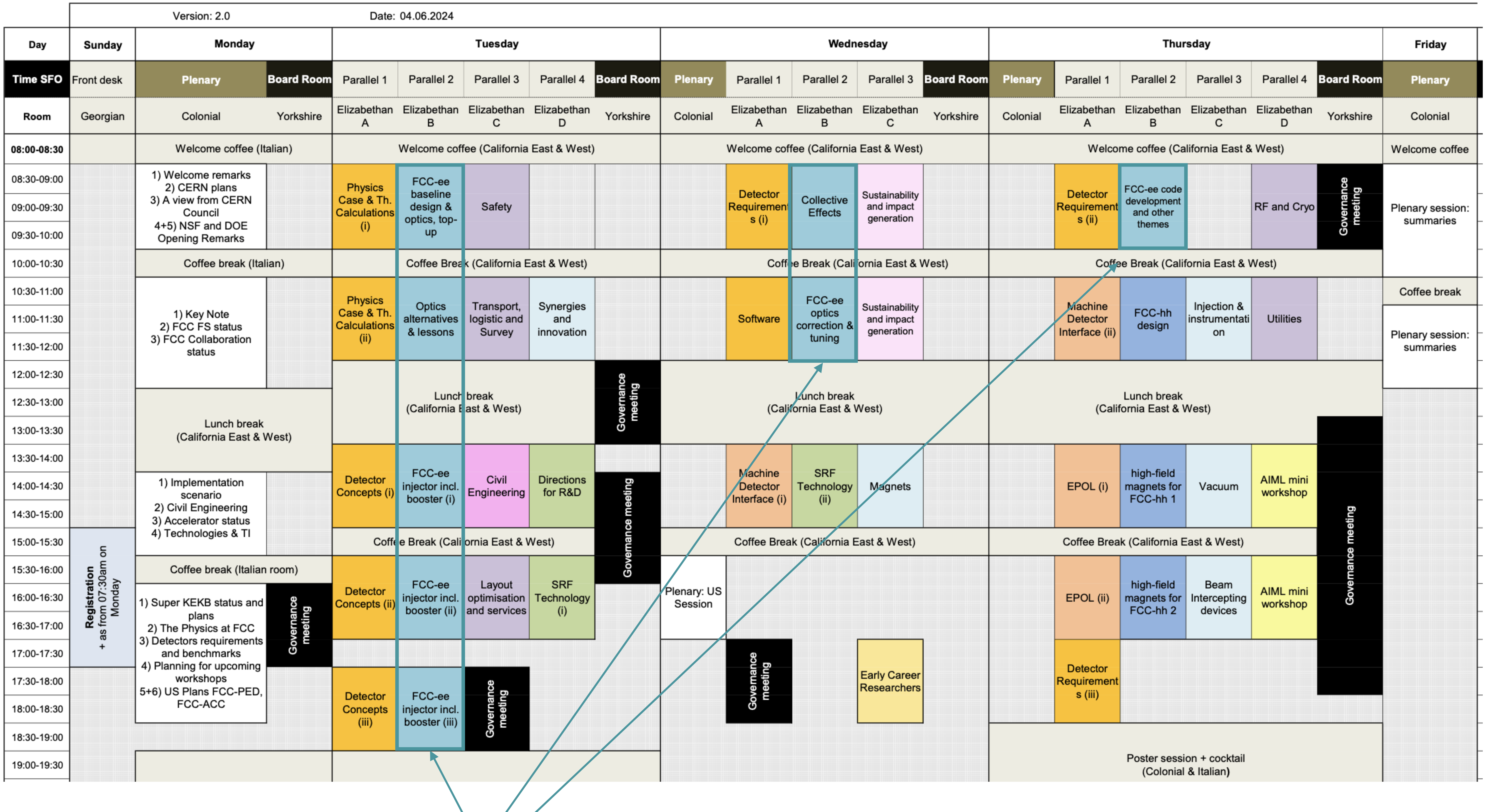
photo: J. Wenninger

European Commission

Horizon 2020 European Union funding for Research & Innovation

FCC week 2024

FUTURE CIRCULAR COLLIDER



- Sessions covered by this summary on accelerator
- Rich program with many interesting talks and thorough studies
- Selection (subjective) of highlights

Lattice Design

- Baseline Lattice GHC (K. Oide)
  - Local correction of chromatic effects from IP in vertical plane only
  - Same X-poles for crab waist and local correction of vertical
  - Many incremental improvements over the last months
  - Chromaticity correction in arcs with X-pole pairs (many different strengths) with π phase advance

- Local Chromaticity Correction LCC Lattice (P. Raimondi)
  - Local correction of perturbations (chromatic effects, anharmonicities …)
  - Local correction of chromatic effects from IP in both planes
  - Dedicated crab-waist X-poles
  - Arc cells with with nested X-poles and no multiple of π phase advance between

- Nested Magnet Lattice (L. van Riesen-Haupt)
  - Combined function magnets to reduce dipolar field and synchrotron radiation loss
  - HTS coils for flexibility – very different optics at low and high energy
  - Change of geometry between high and low energy settings

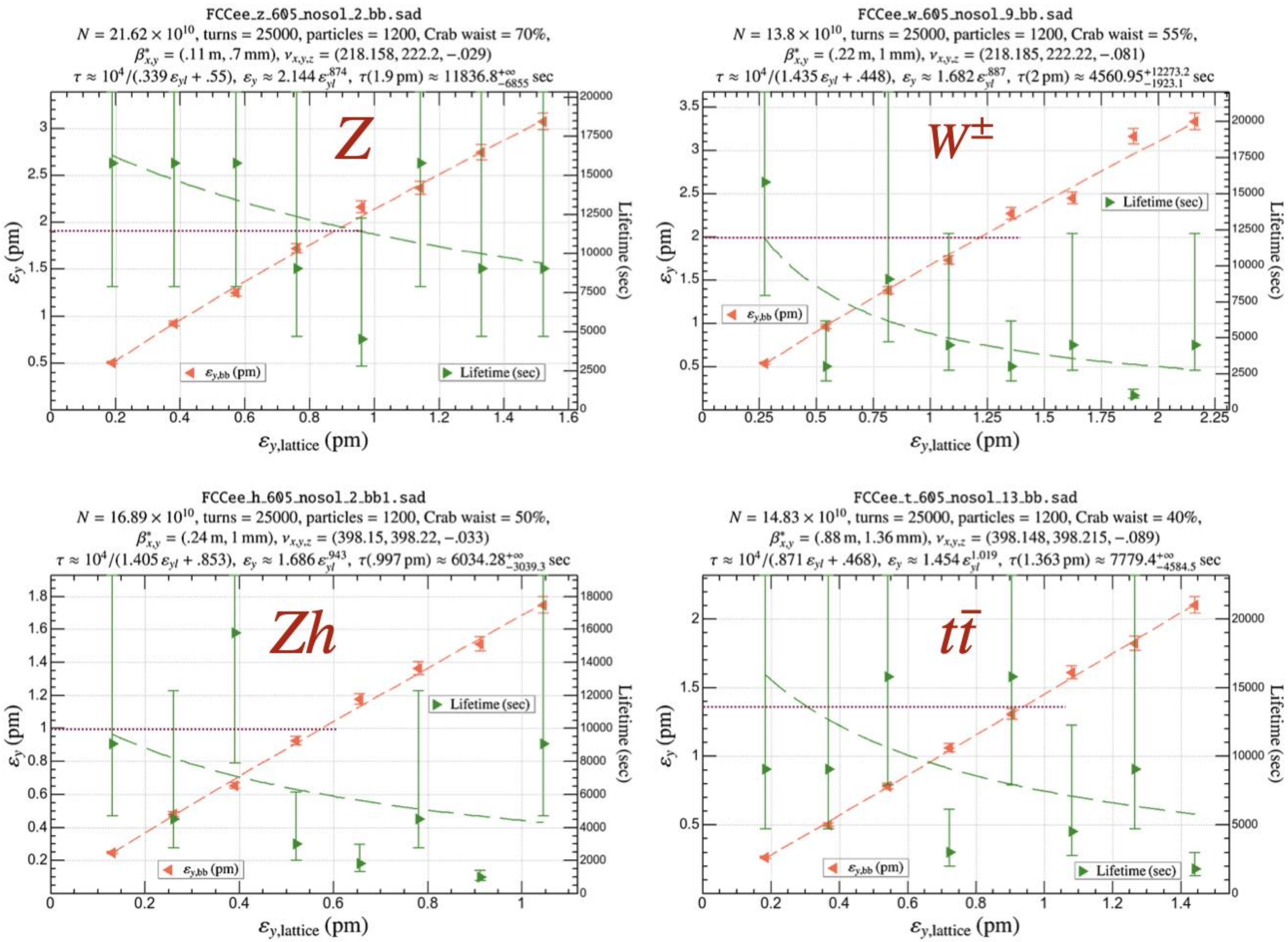
- Combination of different approaches to converge on lattice?
  - Speculation: arc cells proposed by P. Raimondi and GHC IR design? …

Lattice Design

FUTURE CIRCULAR COLLIDER

Lifetime & beam blowup with lattice + beam beam & beamstrahlung

FUTURE CIRCULAR COLLIDER



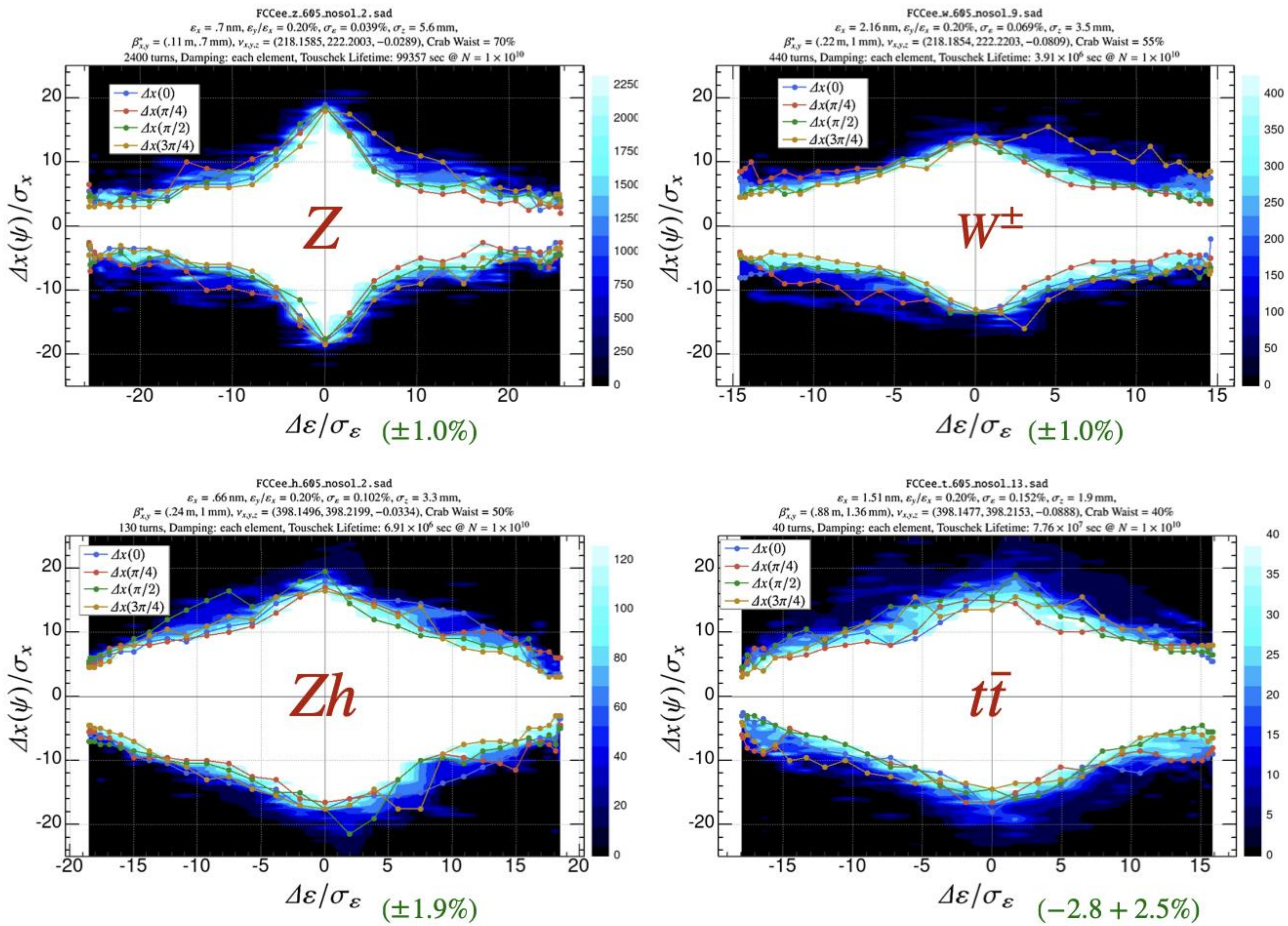
- The vertical emittance after collision (red) and the lifetime (green) against the lattice vertical emittance for each collision energy.
- The purple horizontal dashed line shows the goal vertical emittance at collision, where the vertical emittance of the strong beam is set at.
- SR in all elements, weak-strong beam-beam (BBWS), beamstrahlung are included.
- No machine error is included.
- These results, and also the DA, have been reproduced by independent simulations by P. Kicsiny: https://indico.cern.ch/event/1335891/contributions/5632544/attachments/2745020/4776609/pkicsiny_fccee_optics_meeting_2023_11_02.pdf , **except the lifetime.**
- Using SAD/BBWS on HPC-BATCH. Each plot takes 2 to 3 hours (higher energy needs more time for radiation).

June 11, 2024, K. Oide 5

K. Oide, GHC optics and collider parameters

Lattice Design

Dynamic aperture (z-x)



- The momentum acceptance is larger than ±1%, which is the minimum requirement for synchrotron injection (following remarks by Y. Dutheil).
- Some DA(MA)s still seem immature, for instance at Z. However, the beam-beam lifetime looks OK.

June 11, 2024, K. Oide 7

K. Oide, GHC optics and collider parameters

Lattice Design

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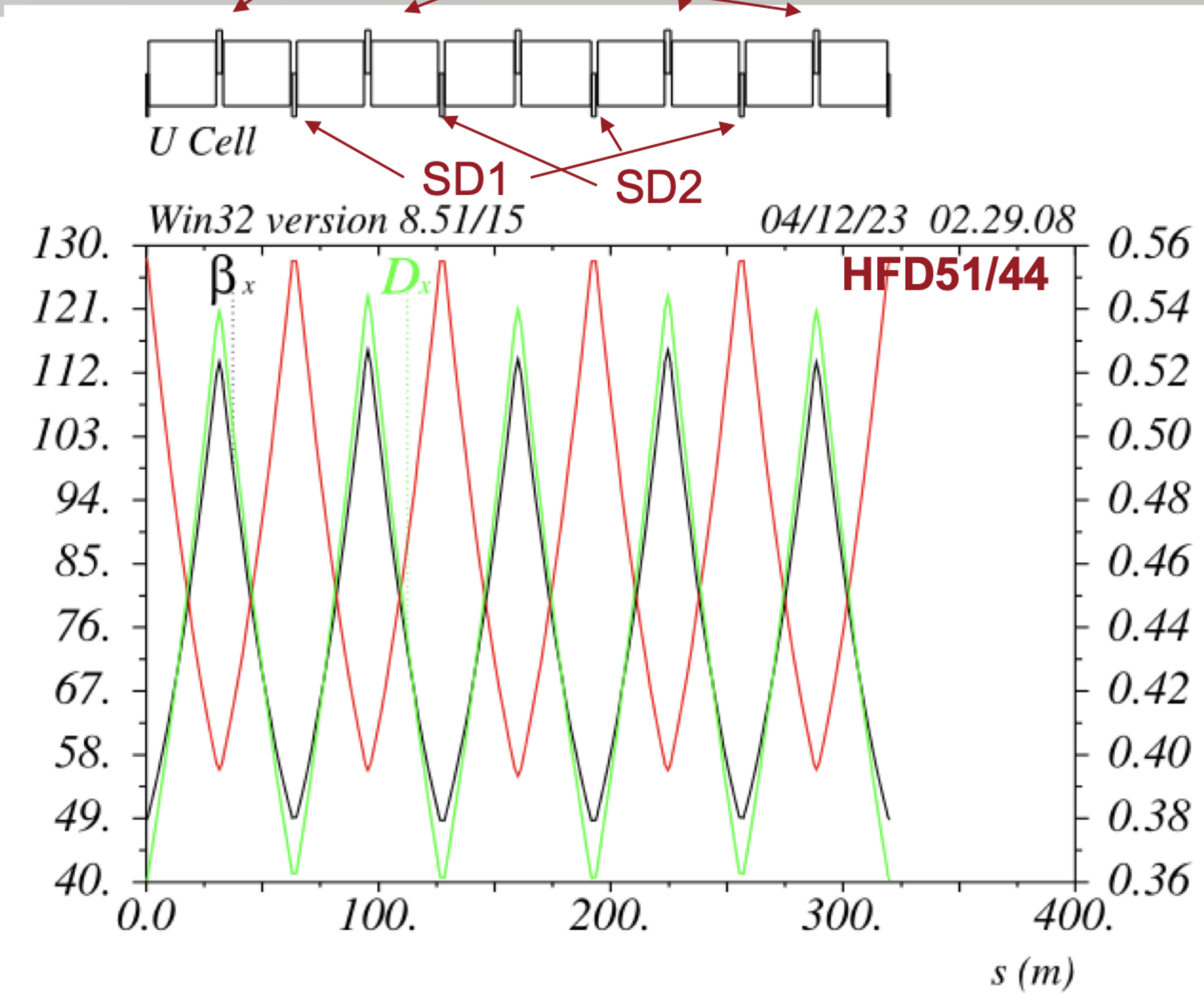
Lattice Design

FUTURE CIRCULAR COLLIDER

HFD_51/44 **Z mode** SLAC



Given the additional degree of freedom from the 4 sexts families, good tunes working points do exist almost continuously.

HFD_51/44 delivers:
Ex = 0.70nm Alphac =3.30e-5
(Ex = 0.69nm Alphac =2.94e-5 for full ring)

Muy has been chosen as best compromise between chromaticities, detunings and sensitivitiy to collective effects.

Peak betas are very similar to the HFD100/74 (Long9090 FODO has twice larger betas wrt Short9090)

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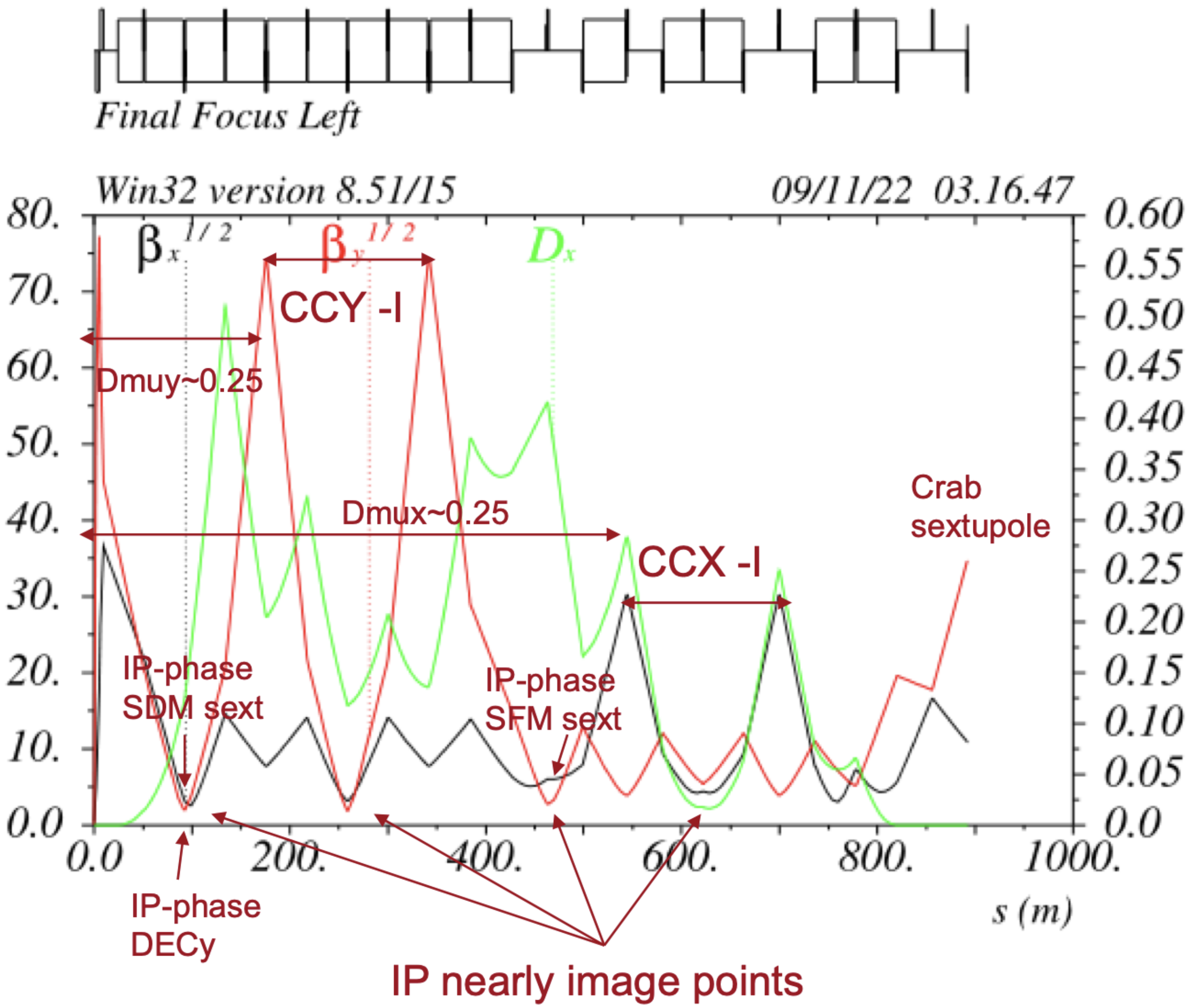
P. Raimondi, Local Chromatic Correction Arc & Final Focus FCC Optic

Lattice Design

FUTURE CIRCULAR COLLIDER

Final Focus chromatic and geometric aberration tuning knobs

SLAC



Main aberrations tuning knobs:

1) Main Sextupoles SDy and SFx
2) SDy&SDx phase advance wrt IP
3) IP-phase sextupoles SDM and SFM
4) Etaxp@ CCSY and CCSX
5) Decapoles y (&x)
6) Phase advance between –I sextupole pairs

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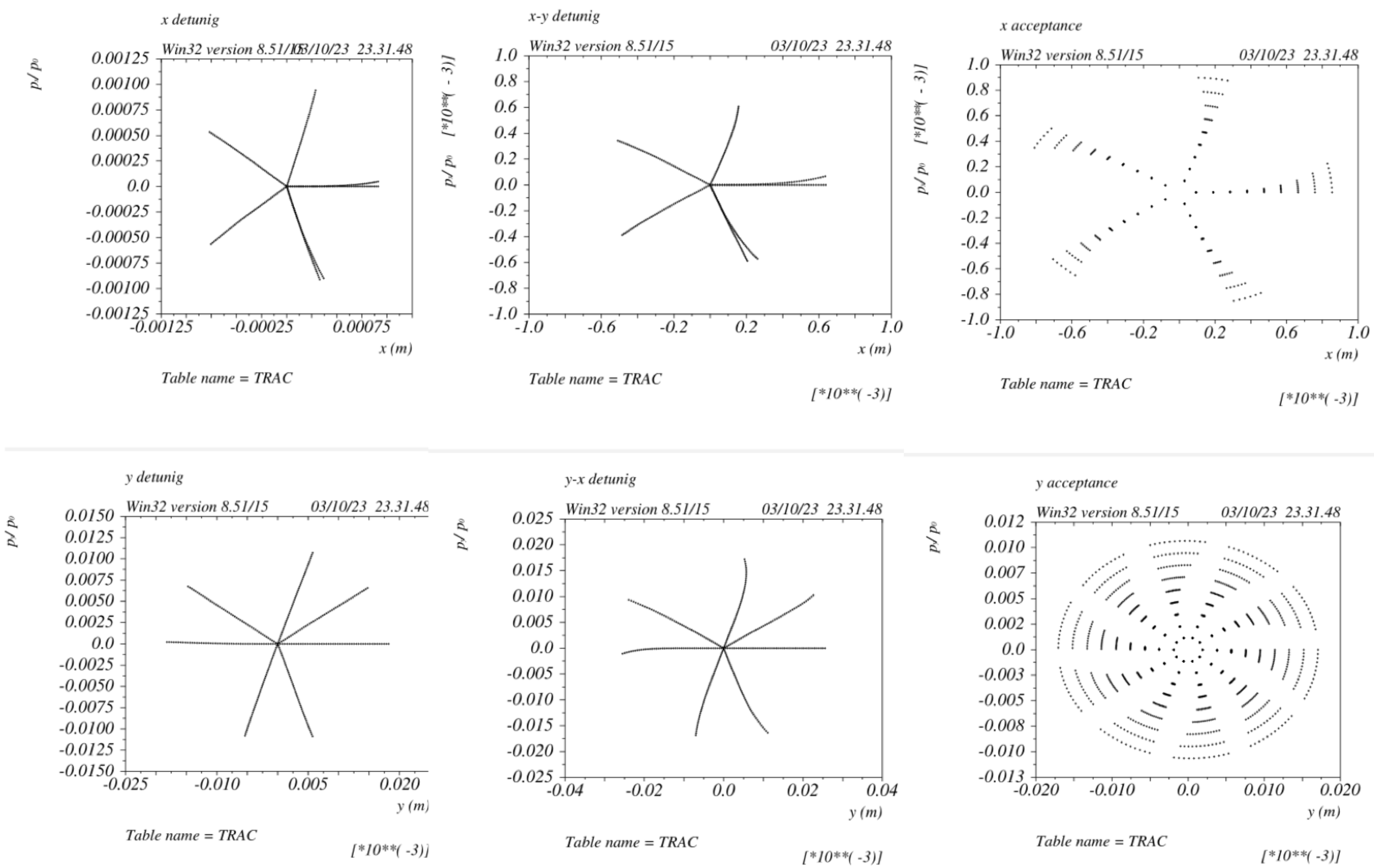
P. Raimondi, Local Chromatic Correction Arc & Final Focus FCC Optic

Lattice Design

FUTURE CIRCULAR COLLIDER

Full ring transverse DA

v_67 ttbar optic



On energy dynamic is linear. "Resonances" are virtually not existing.
Extremely favourable dynamics to minimize BeamBeam degradation (DS)

The quest/dream for a "quasi" time-independent trajectory is at reach!

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P. Raimondi, Local Chromatic Correction Arc & Final Focus FCC Optic

Lattice Design

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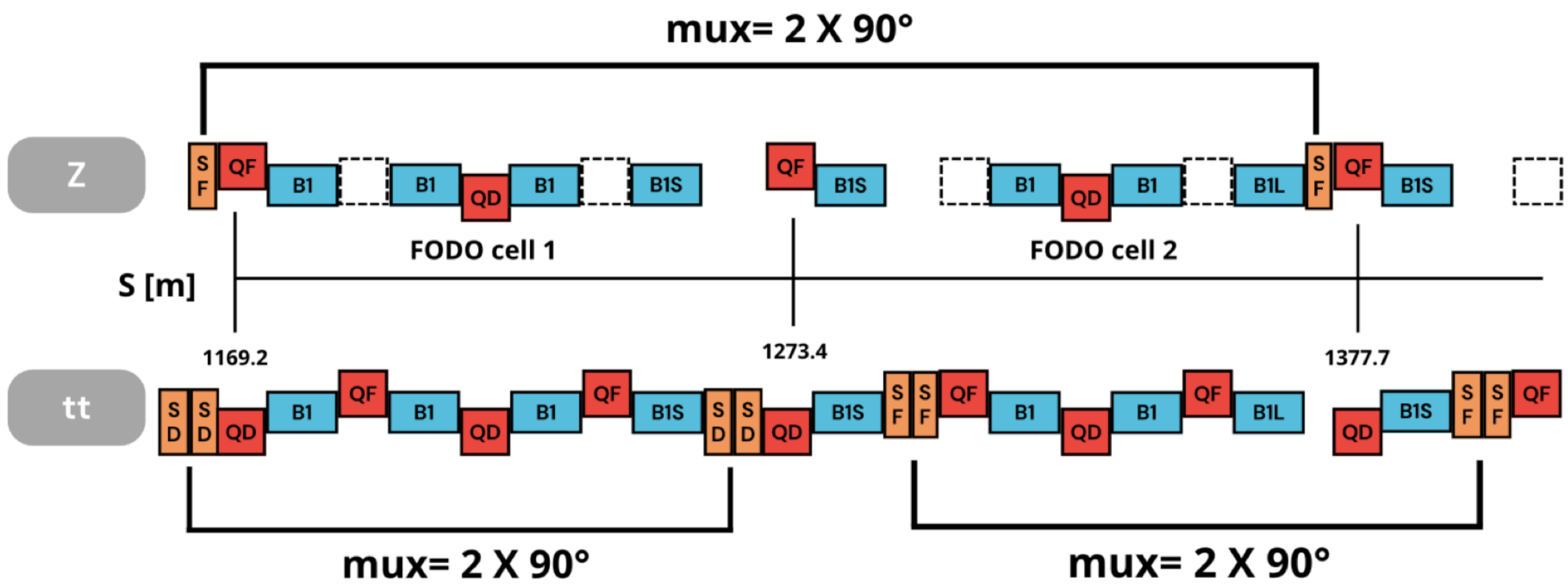
Lattice Design

Complication 2: Z vs tt Layout



- **tt lattice** requires arc cells **half the length** of those in **Z lattice**
  - Results in **flipping of polarity** of focusing quadrupoles
- Also **change in dipole** field in quadrupoles **to preserve partitions**
  - Results in a **different geometric layout** of design orbit

L. van Riesen-Haupt, Nested Magnet Optics for FCC-ee

Lattice Design

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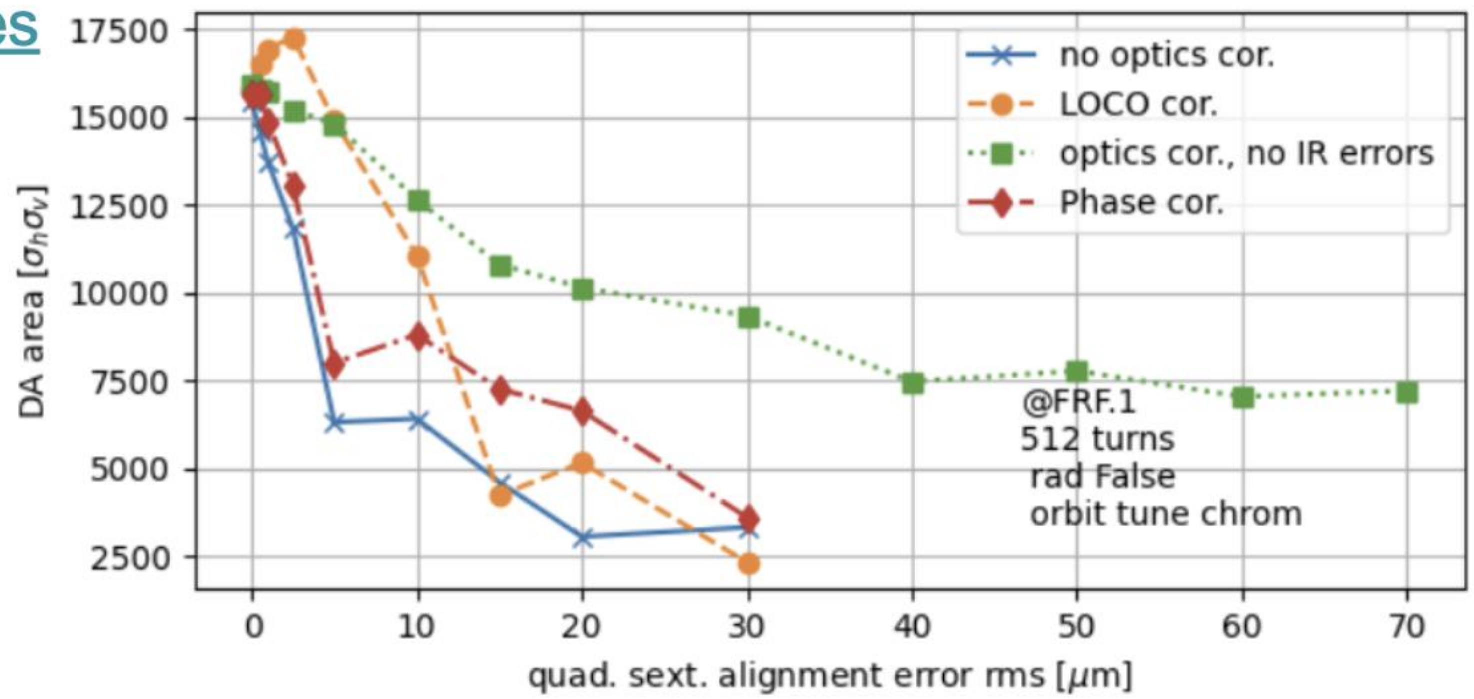
FCC-ee Optics Correction and Tuning

- Status of the FCCee optics tuning studies (R. Tomas and J. Keintzel)
  - Overview of recent work of FCC-ee optics tuning WG
    - Active community with regular meetings with participants from many institutes
  - Procedure(s) require to ramp up X-poles interleaved with orbit and optics corrections
  - Dynamic aperture and beam life-time during and after completion of tuning procedures to be watched at
  - Recent result: Precise correction of betatron phases important
  - Many studies and a lot of progress,
    - Still thorough studies needed to come to credible scenario for running and commissioning

- Parallel Beam Base Alignment (pBBA) studies (X. Huang)
  - Modulation of quadrupole or X-pole strengths
  - Offset between beam and magnet determined from Induced Orbit Shift (IOS)
    - Different algorithms to deduce beam w.r.t. magnet offset

DA after optics tuning simulations with sextupole ramp-up

S. Liuzzo's slides



GHC Z lattice

Severe reduction of DA with IR errors →Dedicated alignment system might be needed.

Mild reduction of DA when errors only applied to arcs up to 70 μm and likely beyond.

Phase advance correction does not show significant improvement for DA…

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R. Tomas and J. Keintzel, Status of optics correction studies

FUTURE CIRCULAR COLLIDER

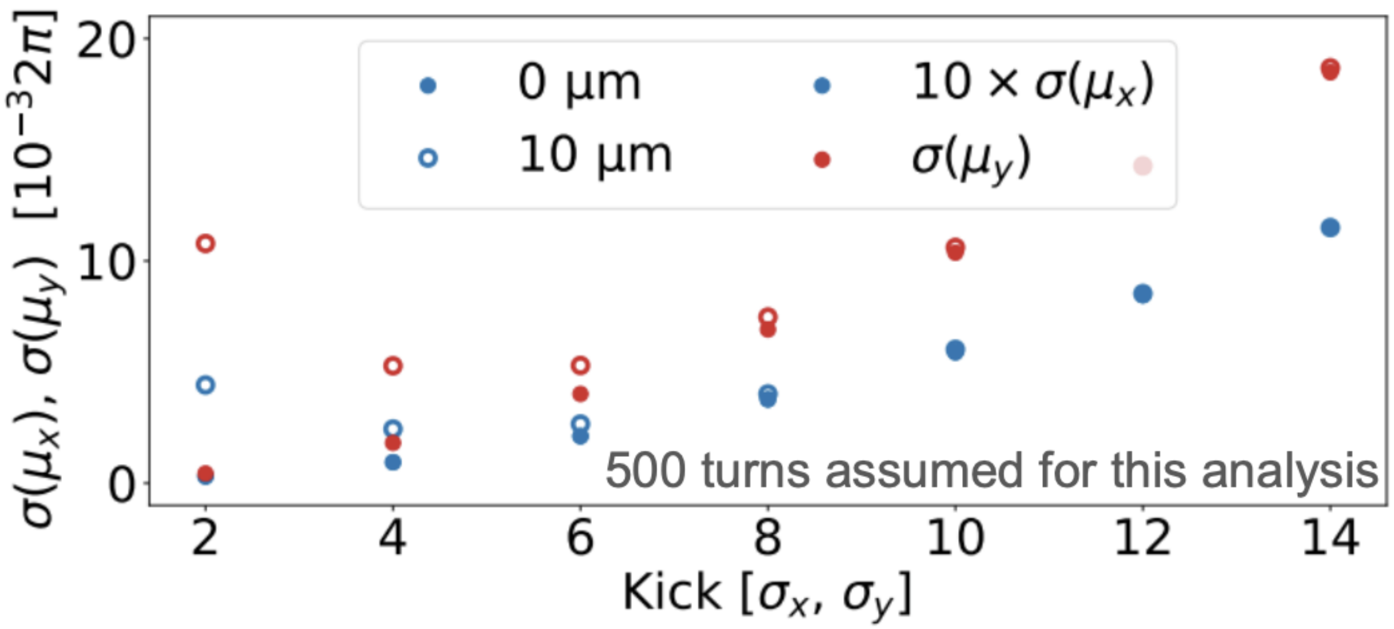
Measuring the phase advance with Turn-by-Turn BPMs

Even with 0 μm BPM noise kick amplitudes of 4σ or larger exceed target resolution of 10^{-3} 2π rad in arc BPMs.

→AC dipoles to excite for about 50000 turns at ≈2σ amplitude with BPMs of <10 μm TbT noise is needed (could be with ≈60 bunches @ Z, A. Lechner et al.).

Further studies needed, specially for IR BPMs, target resolution of 10^{-4} 2π rad.

J. Keintzel et al. IPAC22 and FCC BI slides



BPM Parameter	Requirement
Orbit resolution	0.1 μm
TxT resolution	< 10 μm

E. Howling et al. ATDC #2

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R. Tomas and J. Keintzel, Status of optics correction studies

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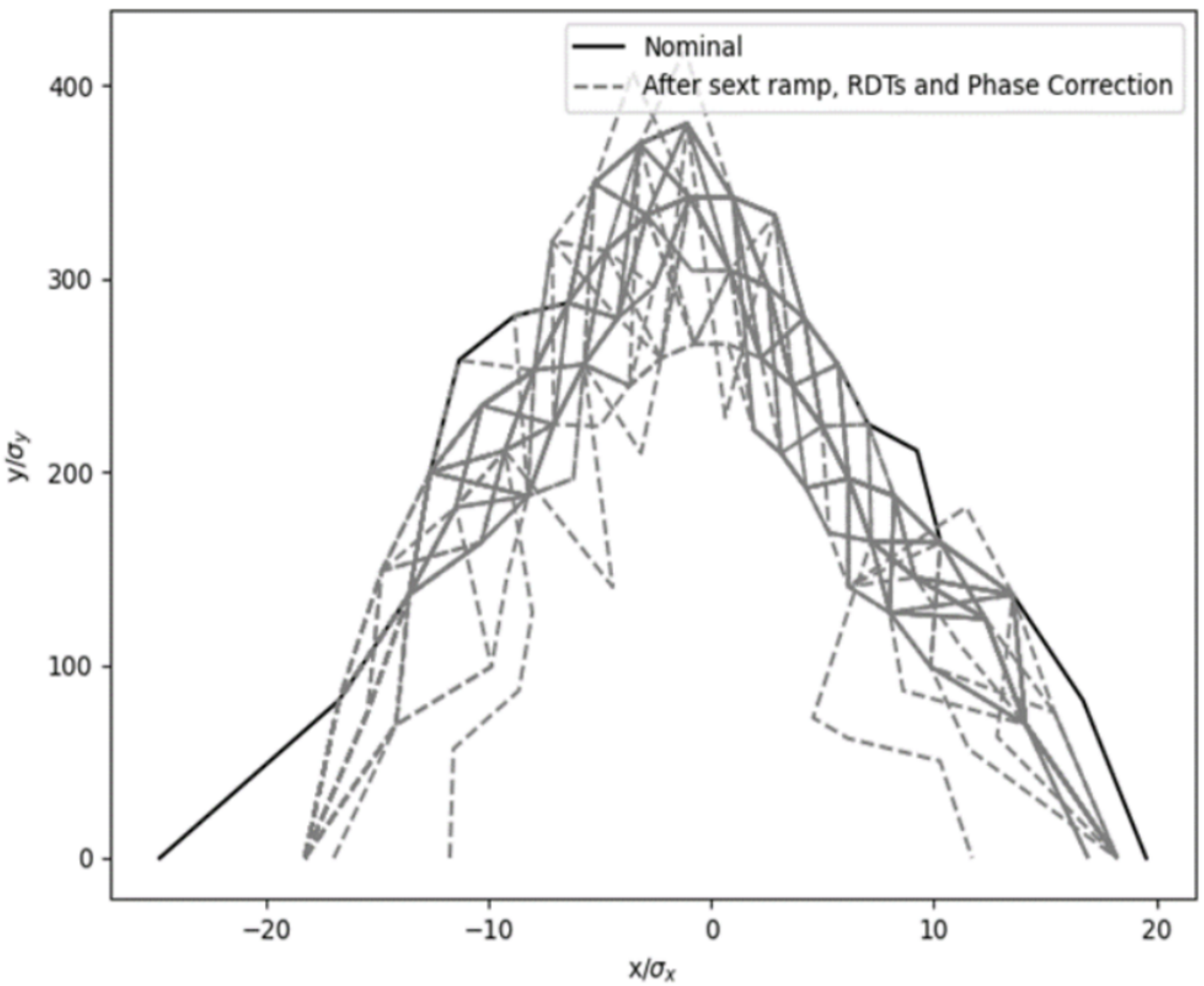
DA after optics tuning simulations: 100 µm in arcs



E. Musa's slides

See E. Musa's poster on Thu poster session!

Mild reduction of DA when errors only applied to arcs up to **100 µm**.

Phase advance and RDT correction were key in these simulations to improve DA.

Including errors also in the IR ongoing

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R. Tomas and J. Keintzel, Status of optics correction studies

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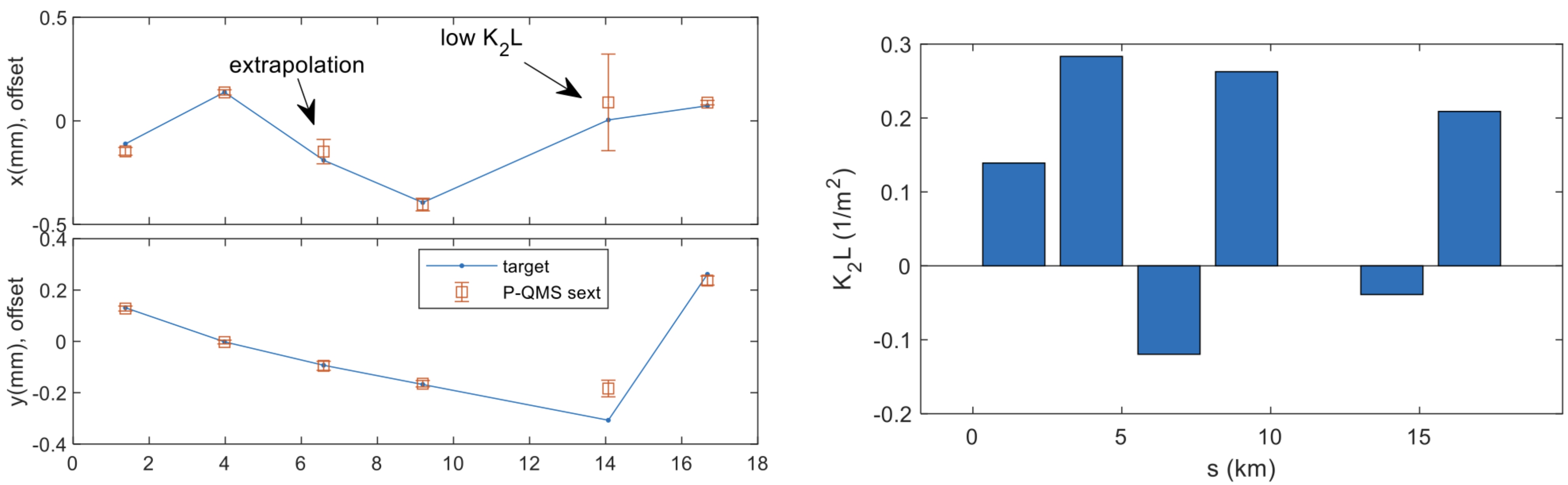
FUTURE CIRCULAR COLLIDER

Comparison of sextupole BBA with target

SLAC

- Sextupole centers found by BBA agree with target
  - Error sigmas are estimated by repeating simulation 10 times
  - Large error sigma occur when
    - The center lies outside of the scanned range
    - The sextupole modulation strength is low
- The typical error bar is ~20 um for $K_2L \sim 0.2\ m^{-2}$.



X. Huang (SLAC)

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X. Huang, Beam-based alignment simulations for FCC-ee
better results for quadrupole offsets

Injectors and Injection

FUTURE CIRCULAR COLLIDER

- Top-up injection scheme into the collider (Y. Dutheil)
  - Aim at on-axis injection with energy offset
  - Possibly small horizontal betatron oscillations in case of thick septum and small momentum acceptance
- Collider Filling Schemes (H. Bartosik)
  - Z-mode (and W mode) filling with say only 1/10th of the collider bunches topped up per booster cycle (each transferred bunch with maximum 1/10th of the intensity in the collider)
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- Preinjector (P. Craievich)
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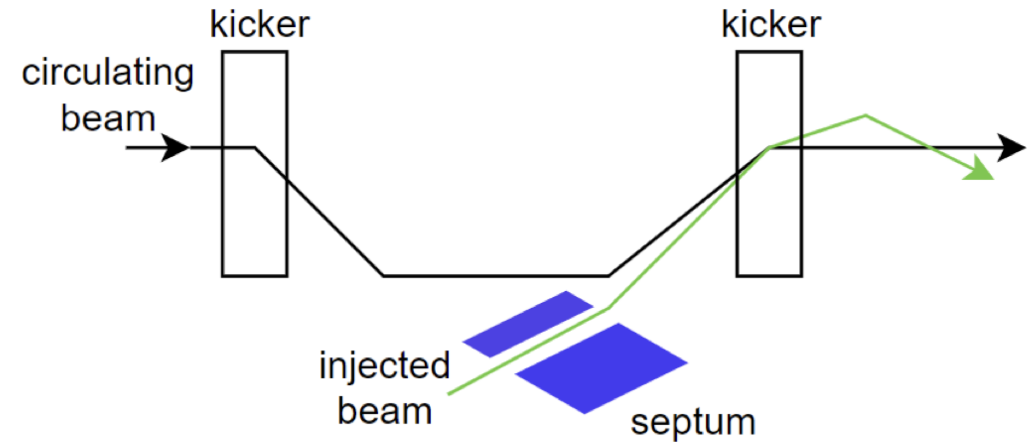
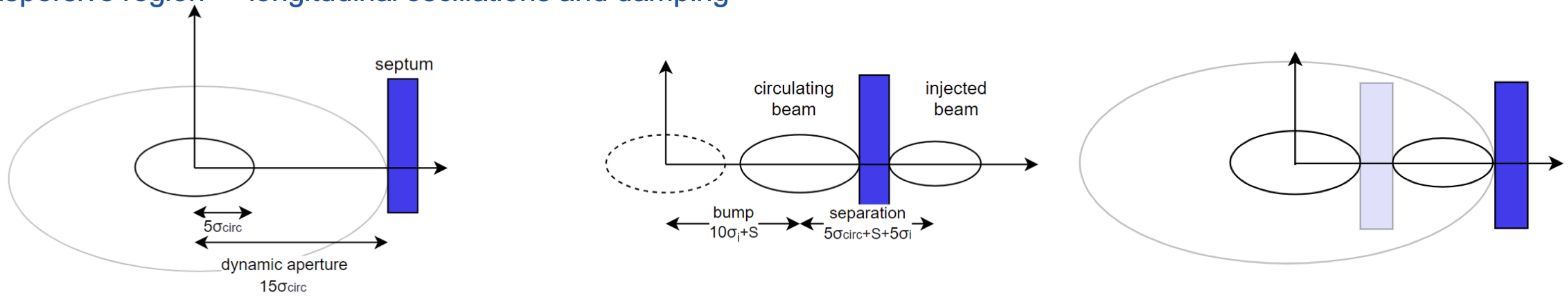
  - Many optimization – damping ring at 2.86 GeV, positron production, energy and bunch compressors

Injectors and Injection

Introduction to top-up injection: conventional concept

- Dipole kickers magnets create a closed bump to bring the stored beam trajectory close to the injection system (see G. Favia and J. Borburgh on Thu)
- Two kickers are placed with 180° phase advance between them (π-orbit-bump)
- The bump is constant for up to a single turn while off before and after
- Beam separation at the injection septum
  - Off-axis means the separation exists in the transverse space -> betatron oscillations and damping
  - On-axis means the separation exists in momentum at a dispersive region -> longitudinal oscillations and damping



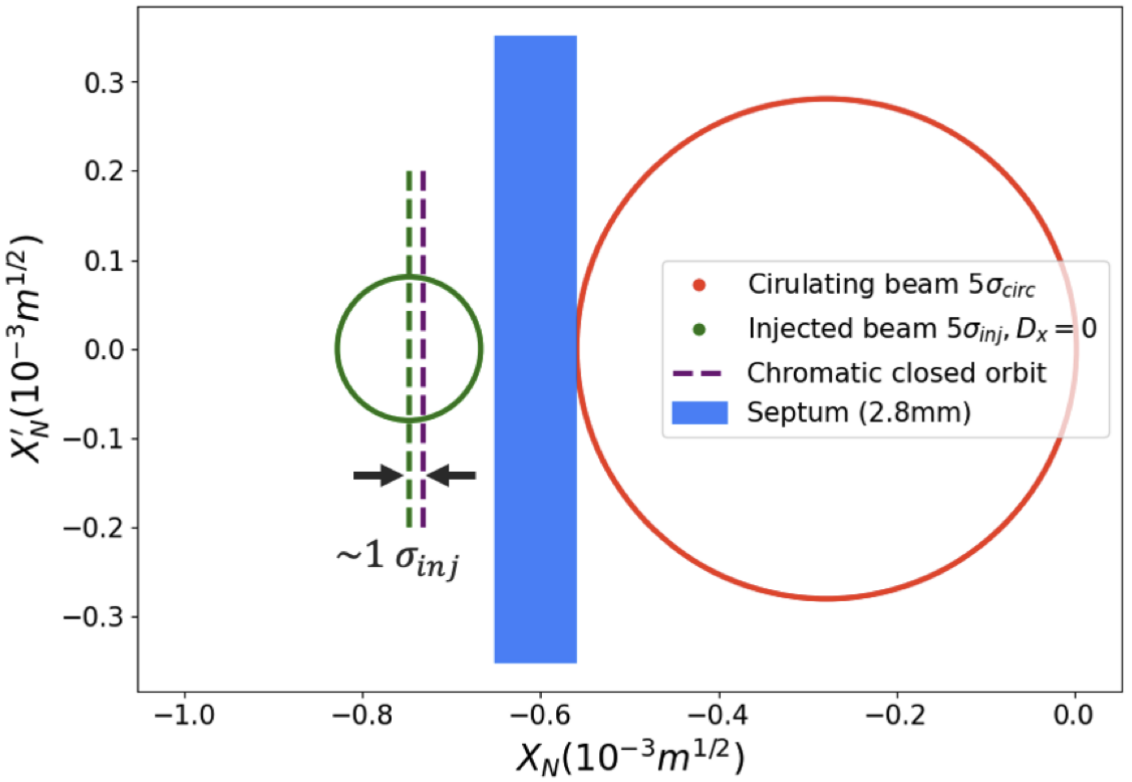


[1] P. Hunchak, 2021 FCCIS WP2 Workshop ,link

Y. Dutheil: Top-up injection scheme into the collider

Baseline scheme: optimisation with hybrid on-off axis injection scheme

- Limitations to the energy offset of the injected beam
  - RF acceptance
  - Dynamic aperture
- Small betatron offset of a few sigma remains acceptable [1]
- Hybrid optimization reduces momentum offset at the expense of
  - $D_s\delta < 5\sigma_{cir} + S + 5\,\sigma_{inj}$
    -> Offset = $5\sigma_{cir} + S + 5\,\sigma_{inj}$ - $D_s\delta$
- Betatron oscillation damping is slower than longitudinal
  - Z-mode longitudinal damping time is ~0.3 s
  - Z-mode considering injections every ~3 s



- Taking the orbit with an energy offset of 1% as an example

  Distance between injected beam and off energy orbit

  ~ 1.5 mm ≡ ~1 σ_{inj}

1] K. Andre, SR power deposition from injected beam, 161st FCC-ee Optics Design Meeting,

Y. Dutheil: Top-up injection scheme into the collider

Injectors and Injection

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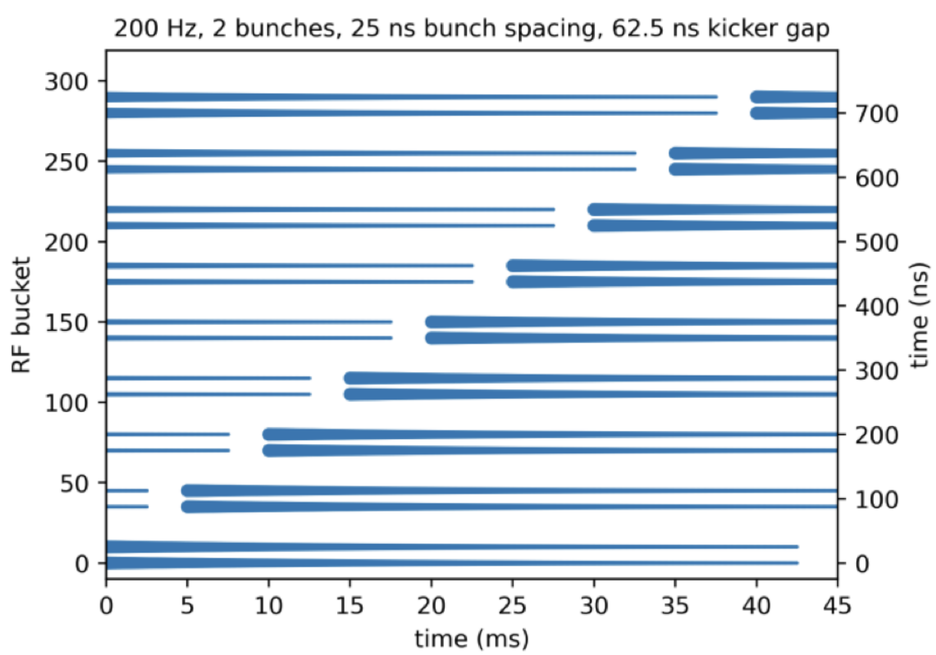
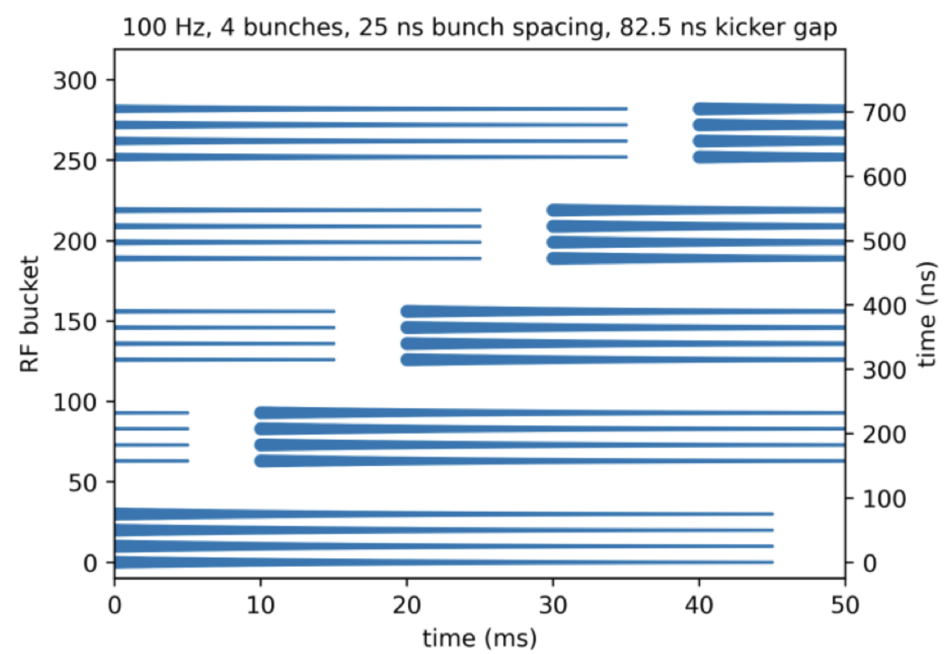
Injectors and Injection

FUTURE CIRCULAR COLLIDER

Pre-injector

- CDR scheme is based on Linac producing 2 bunches (25 ns spacing) at 200 Hz
  - **Damping ring at 1.54 GeV used for e^+ only**
  - Staggered injection, storage for ~42.5 ms (4 damping times), staggered extraction (first in first out)
- New proposal with Linac producing 4 bunches (25 ns spacing) at 100 Hz
  - **Damping ring at 2.86 GeV used for both e^+ and e^-** (see presentation of P. Craievich)



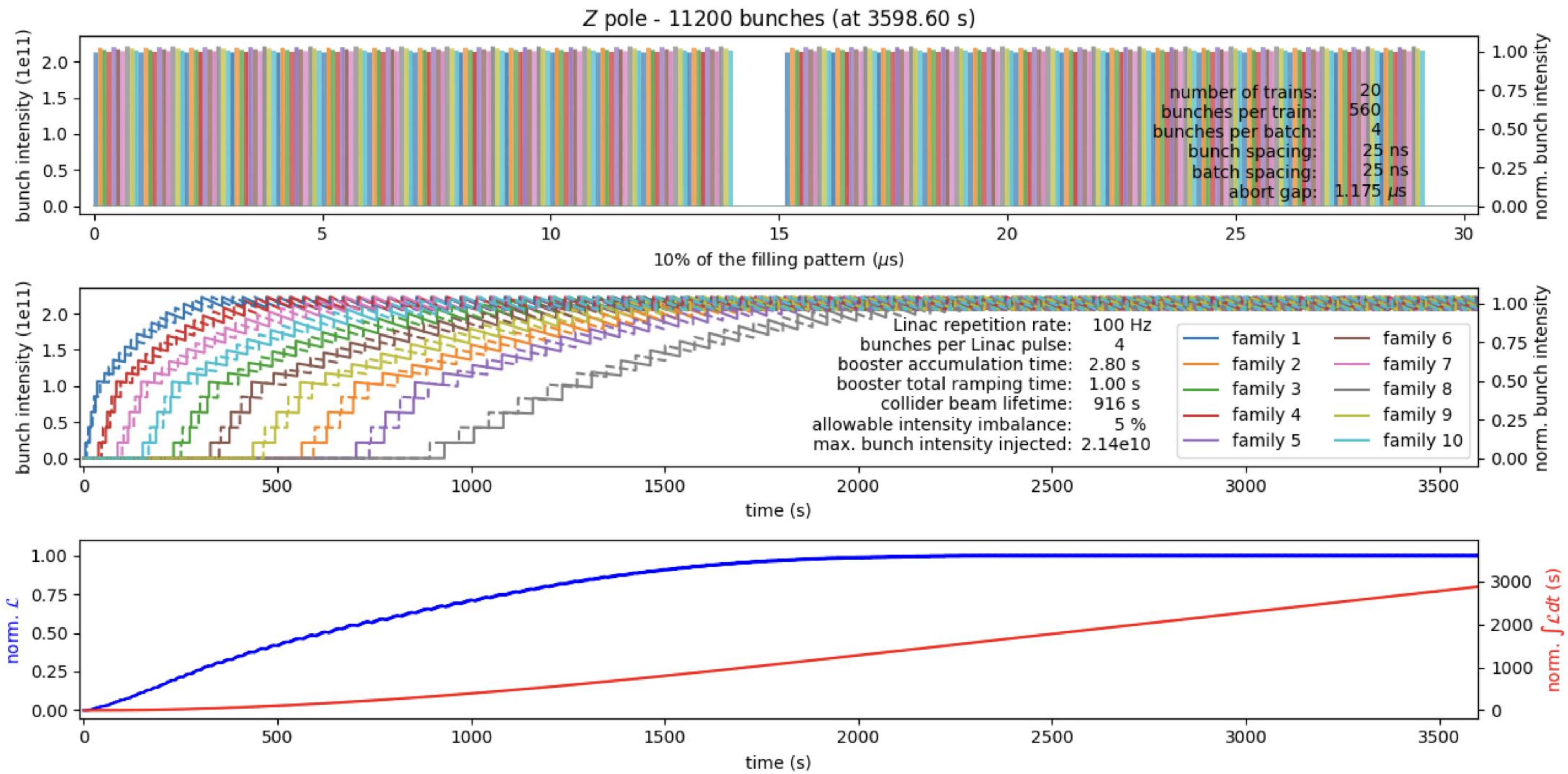


H. Bartosik: Collider Filling Scheme

Injectors and Injection

FUTURE CIRCULAR COLLIDER

Potential e-cloud mitigation scheme



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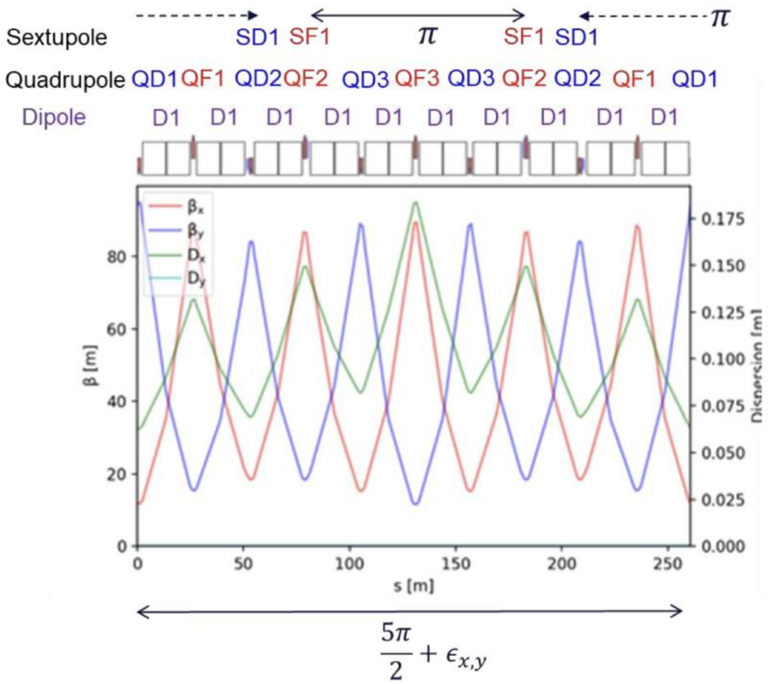
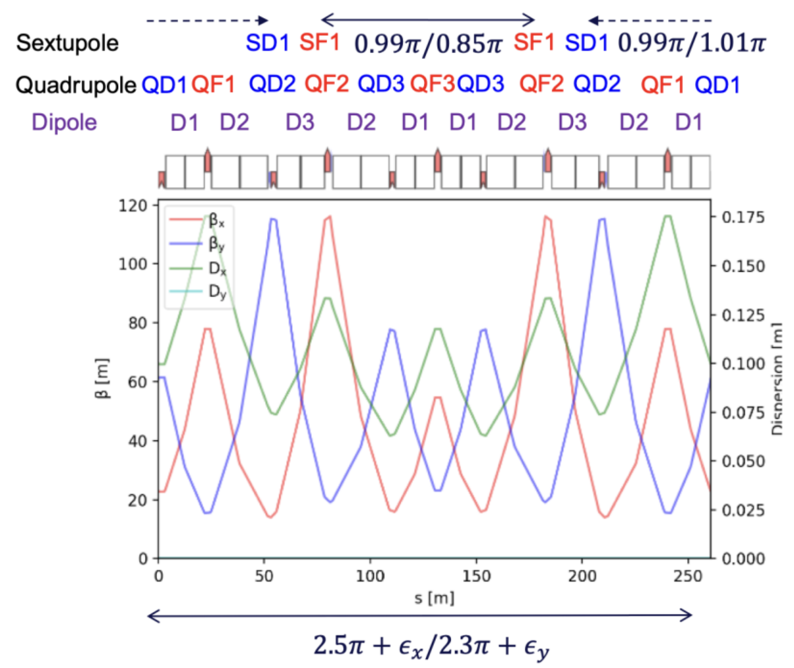
Baseline optics: FODO



- Made of about 5 FODO cells of 52 m.
- 6 quadrupole families with about the same strength
  - to have a phase advance of π between the pair of sextupoles
  - To adjust the tune of the arc cell to get the target global tune.
- 1 dipole corrector + 1 BPM per quadrupole:
  - Horizontal when QF
  - Vertical when QD
- Cell length adjusted to follow the collider arc periodicity.

HFD – or local chromaticity correction

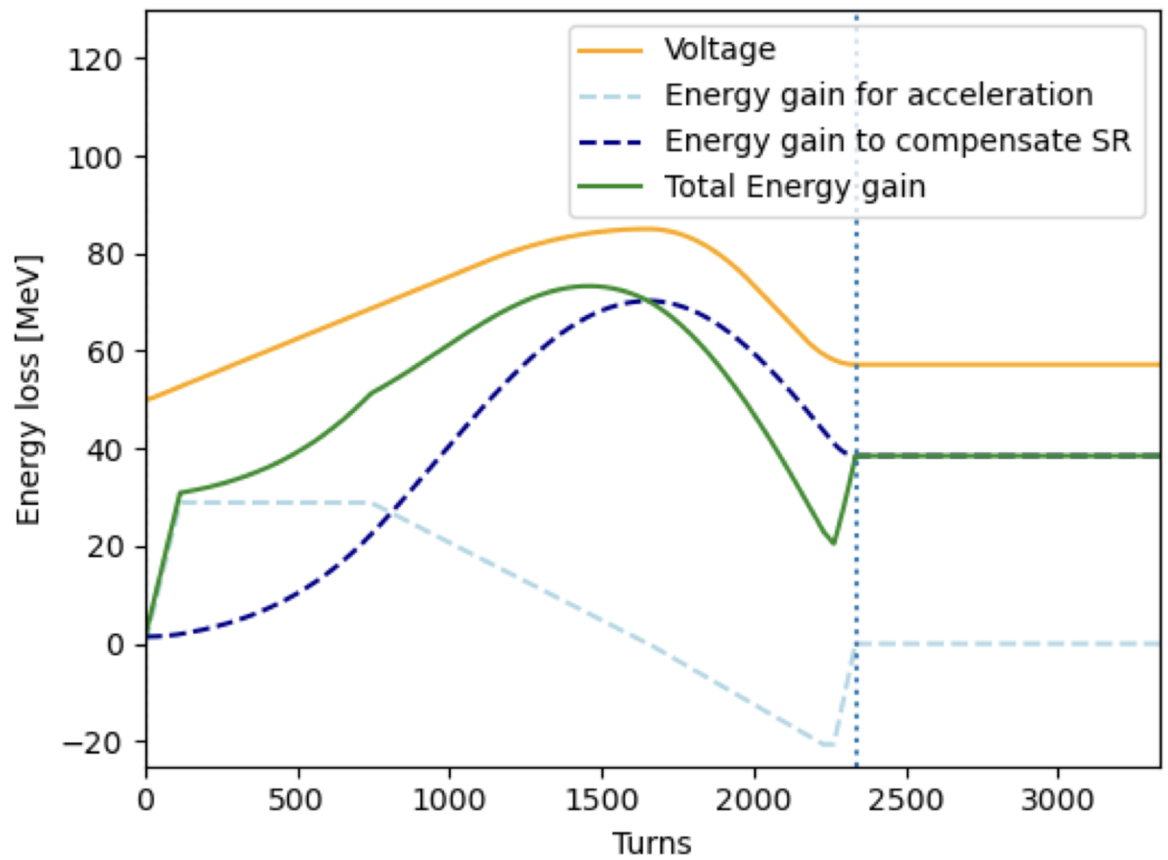


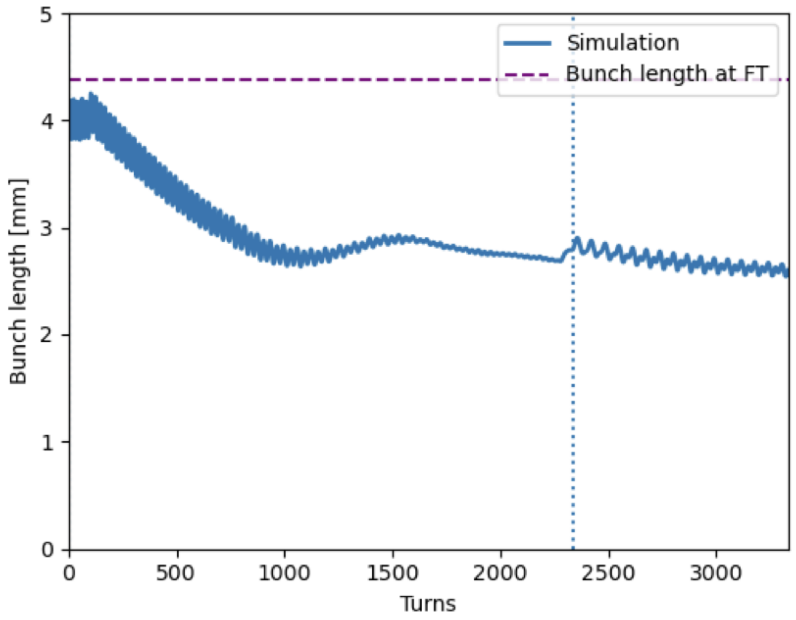
- Variation of the dipole length: 3 families BUT same field (no need of additional powering).
- 6 families
  - to have an optimum phase advance between the pair of sextupoles to minimize anharmonicity
  - To adjust the tune of the arc cell to get the target global tune.
  - The horizontal and vertical tunes are slightly different.
- 1 dipole corrector + 1 BPM per quadrupole:
  - Horizontal when QF
  - Vertical when QD
- Cell length adjusted to follow the collider arc periodicity.

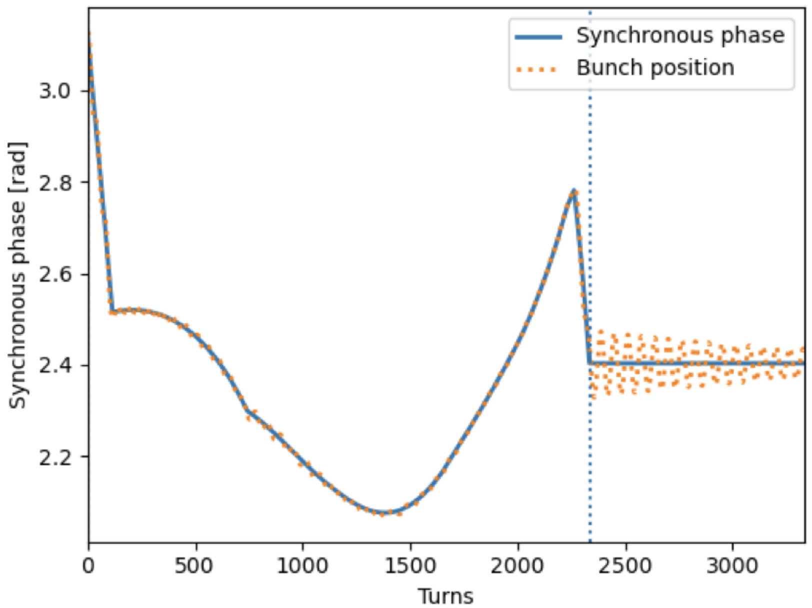
H. Ghribi: High-energy Booster Overview

Injectors and Injection

1. Ramp design for the Z mode







A. Vanel: RF-based Optimazation of the Booster Cycle

Injectors and Injection

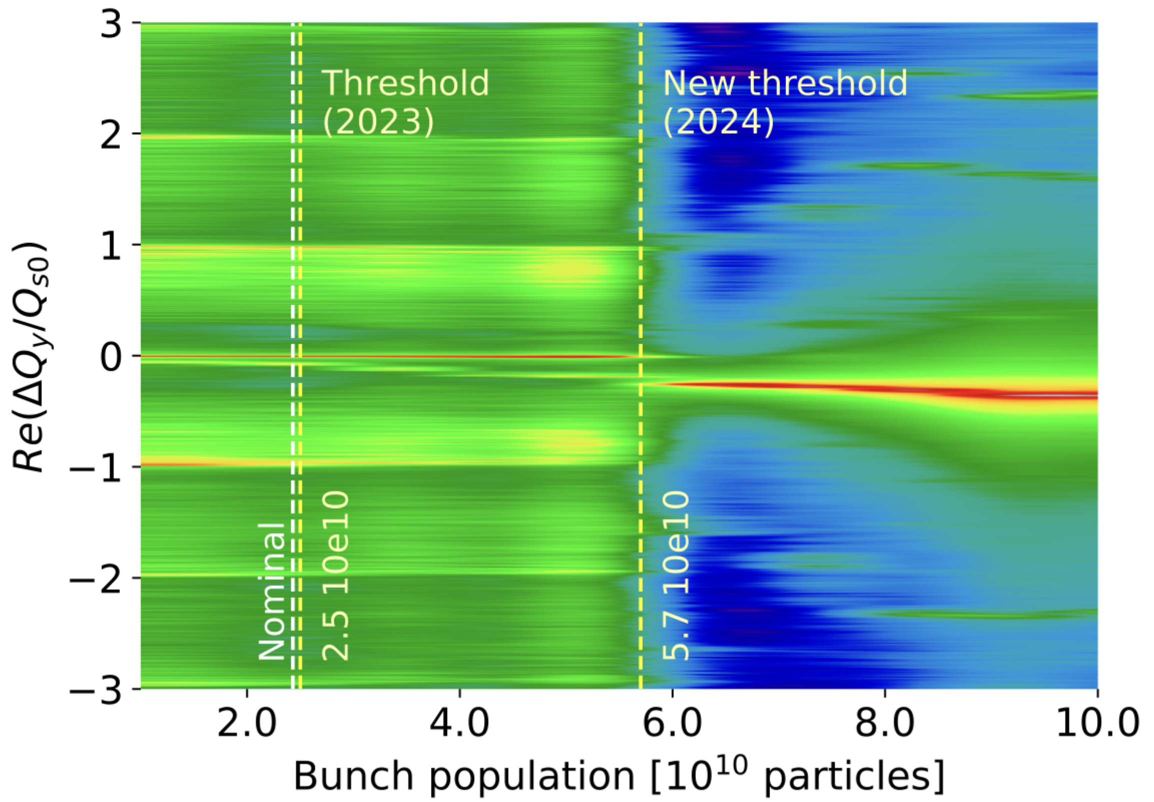
TMCI

New baseline (2024) - No margin - No transverse damper

Now, if we update the booster parameters table with :

- Decreased momentum compaction
- Increased beam pipe diameter
- Beam pipe material set to copper

⇒ TMCI threshold is more than doubled !



Modes scan as a function of bunch population at injection energy (E =20 GeV) for the PA31.3 baseline (2024), $t\bar{t}$ operation and a 30 mm radius copper beam pipe.

A. Ghribli: FCCee High Energy Booster - Updates on collective effects studies

Injectors and Injection

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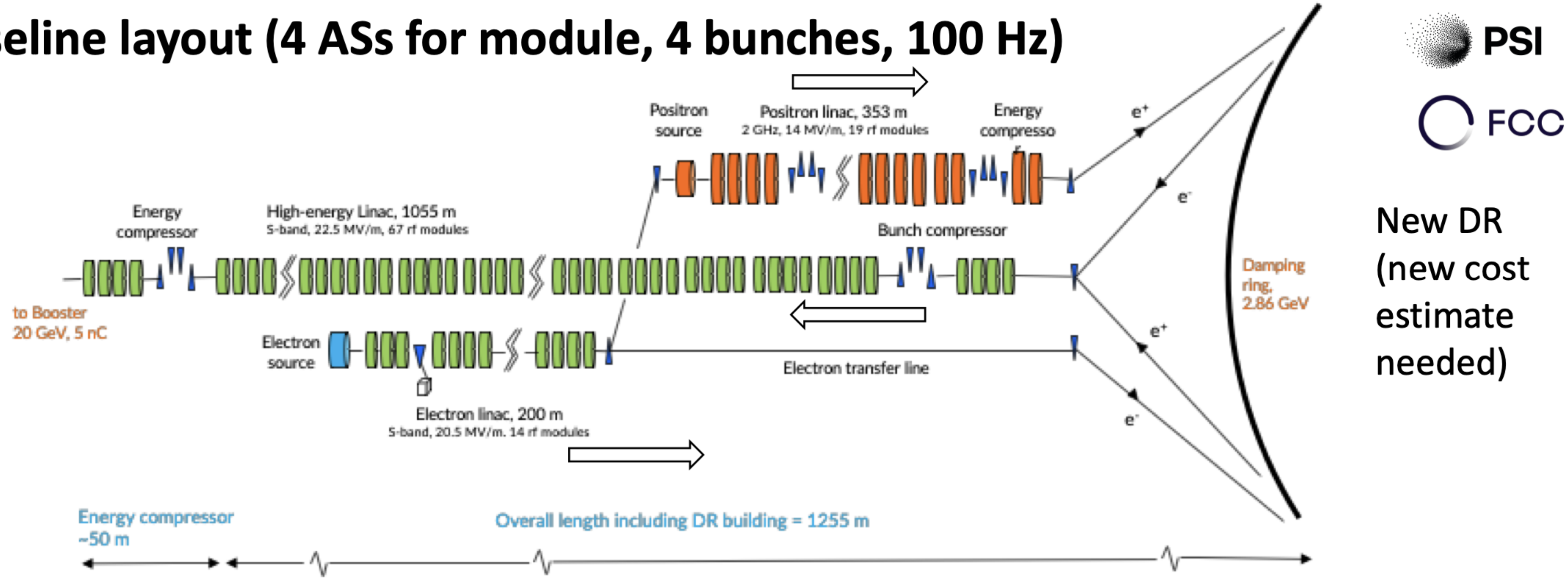
- Top-up injection scheme into the collider (Y. Dutheil)
  - Aim at on-axis injection with energy offset
  - Possibly small horizontal betatron oscillations in case of thick septum and small momentum acceptance
- Collider Filling Schemes (H. Bartosik)
  - Z-mode (and W mode) filling with say only 1/10th of the collider bunches topped up per booster cycle (each transferred bunch with maximum 1/10th of the intensity in the collider)
    - Mitigation of machine protection issues at transfer, and of intensity dependent effects in Booster
  - Collider filling by bringing groups of bunches (say 1/10th of the total) to nominal intensity
    - Avoids all bunches with intermediate intensities to mitigate positron e-cloud
- High-energy Booster Overview (A. Ghribi)
  - Cu vacuum chamber with larger 30 mm radius cures instabilities (impedance budget to be confirmed)
  - Re-design with same optics for all energies, same circumference than collider
  - Reduced intensities and four bunches per pre-injector cycle
  - Ramp with overshoot to enhance damping (presentation by A. Vanel)
- Preinjector (P. Craievich)
  - Re-design with four bunches per pulse, no common Linac, max. repetition rate 100 Hz
  - Many optimization – damping ring at 2.86 GeV, positron production, energy and bunch compressors

Injectors and Injection

New baseline layout (4 ASs for module, 4 bunches, 100 Hz)



New DR (new cost estimate needed)

- The present positron yield would allow positrons to be generated at a lower electron beam energy (more details in the Iryna's talk) → Higher energy DR (2.86 GeV), no common linac with 2x repetition rate, no large arc.
- More stable electron and positron bunches at beginning of the HE linac.
- DR for both species with flat emittances (and polarized positrons?), first consideration in Antonio's talk
- Linac cost, length and power consumption optimizations presented for the previous layout are still valid BUT higher power consumption and costs for DR (to be estimated).

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Paolo Craievich, (Unlimited) Injector complex: status and outlook

Intensity dependent Effects

- Beam-beam studies (P. Kicsiny)
  - Beam-beam module implemented in X-Suite
    - Soft-Gaussian approximation, Beamstrahlung and radiative Bhabha-scattering
    - Flip-flop effect studied

- Collective Effects in Collider (M. Migliorati)
  - Collimators most important Impedance Source (resistive wall, geometric not yet evaluated)
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  - TMCI Instability (mode 0 and -1)
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- Circulant Matrix Method (R. Soos)
  - Preparation in View of fast Analysis of Instabilities due to Impedance and Beam-Beam
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- Electron Cloud studies (L. Sabato)
  - Multipacting and Photoemission

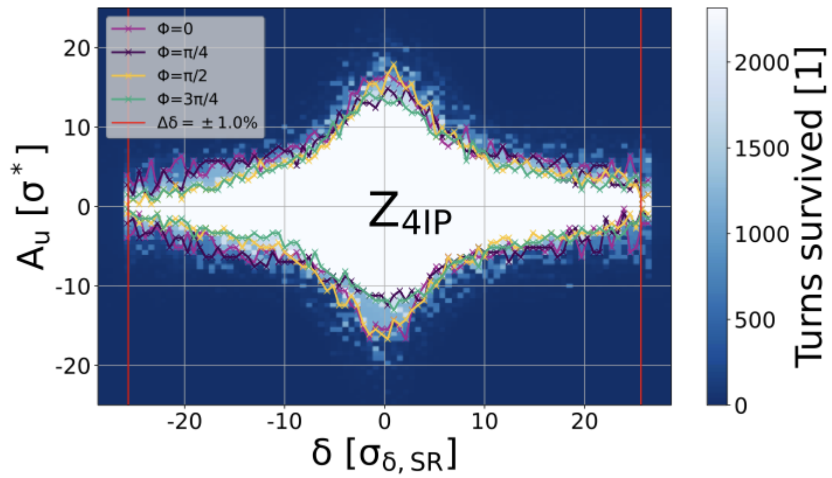
Intensity dependent Effects

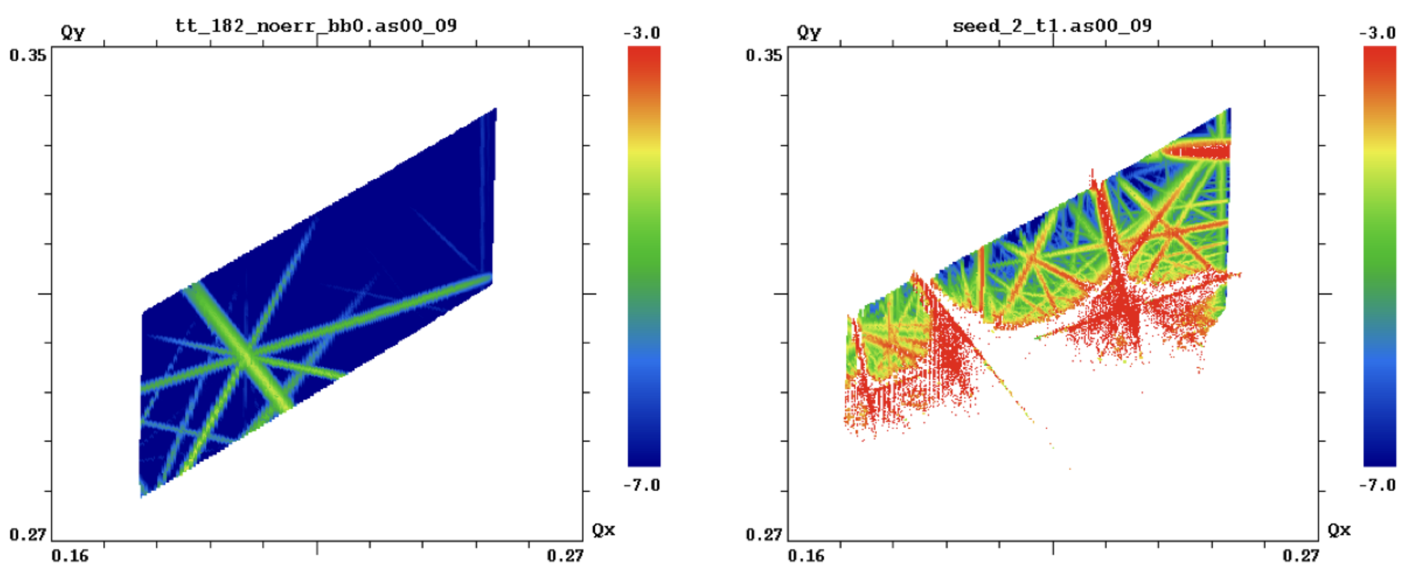
FCC 11 June 2024 | FCC Week 9

Dynamic aperture

w/o errors
- Negligible reduction from beam-beam
- Compares well with SAD results from K. Oide [12]

$$u \in \{x, y\} \qquad A_u = \sqrt{\left(\frac{u}{\sigma_u^*}\right)^2 + \left(\frac{p_u}{\sigma_{p_u}^*}\right)^2}$$





D. Shatilov [13]

w/ errors & corrections
- More lattice induced resonances are seen with beam-beam due to large amplitude detuning
- Full lattice needs to be optimized with beam-beam included
- Tools are ready, requires work with tuning working group to establish correction strategies

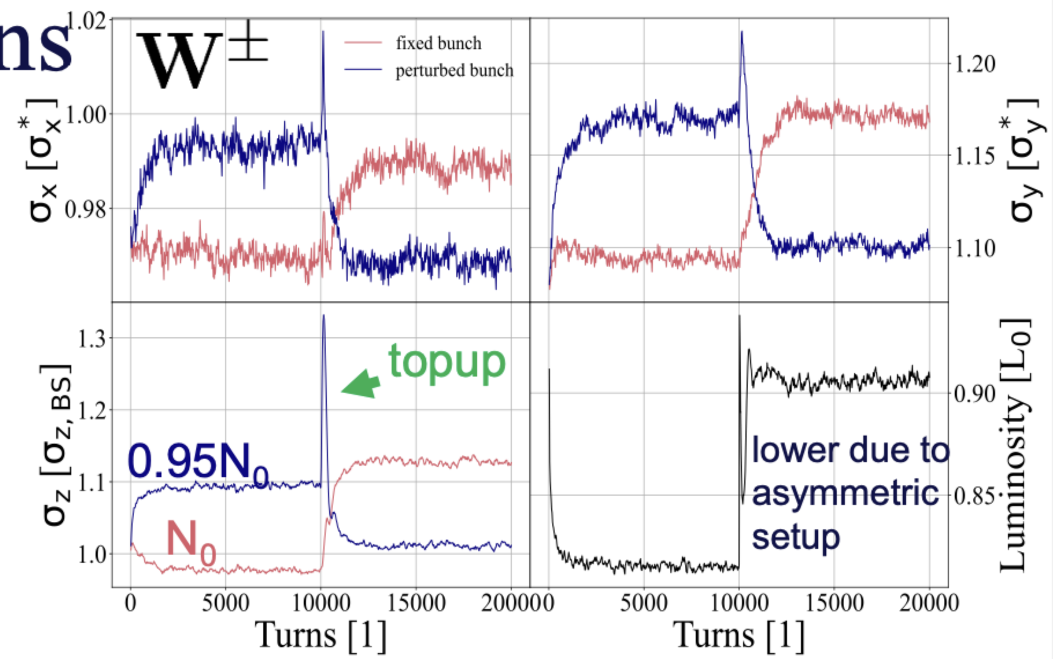
P. Kicsiny: Beam-Beam Studies for FCC-ee

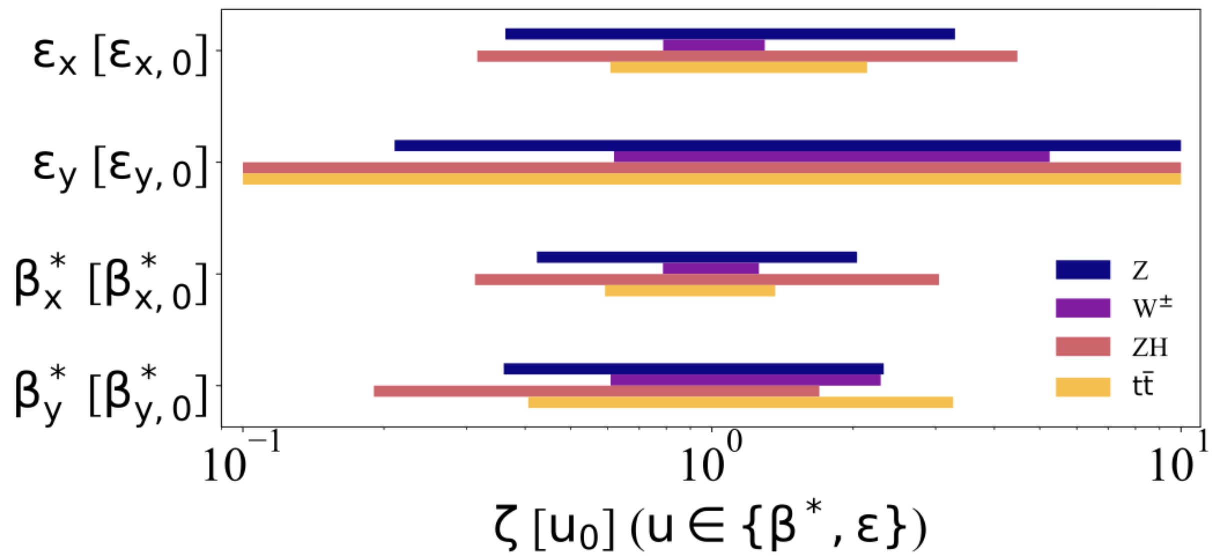
Intensity dependent Effects

Top-up injection & asymmetry scans

Longitudinal top-up simulated with Xsuite

- Perturbed bunch init. with 95% intensity
- Track till equilibrium & top-up
- Luminosity lower than in symmetric case (L_0) due to vertical blowup
  - Should be avoided (e.g. working point optimization)





- Evaluate asymmetries in emittance/beta leading to 50% vertical blowup
- Derived coarse tolerances for machine tuning

P. Kicsiny: Beam-Beam Studies for FCC-ee

Intensity dependent Effects

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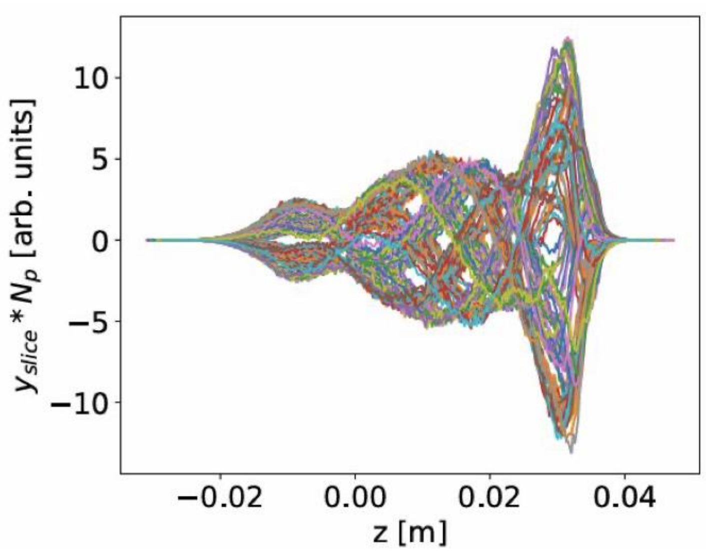
Intensity dependent Effects

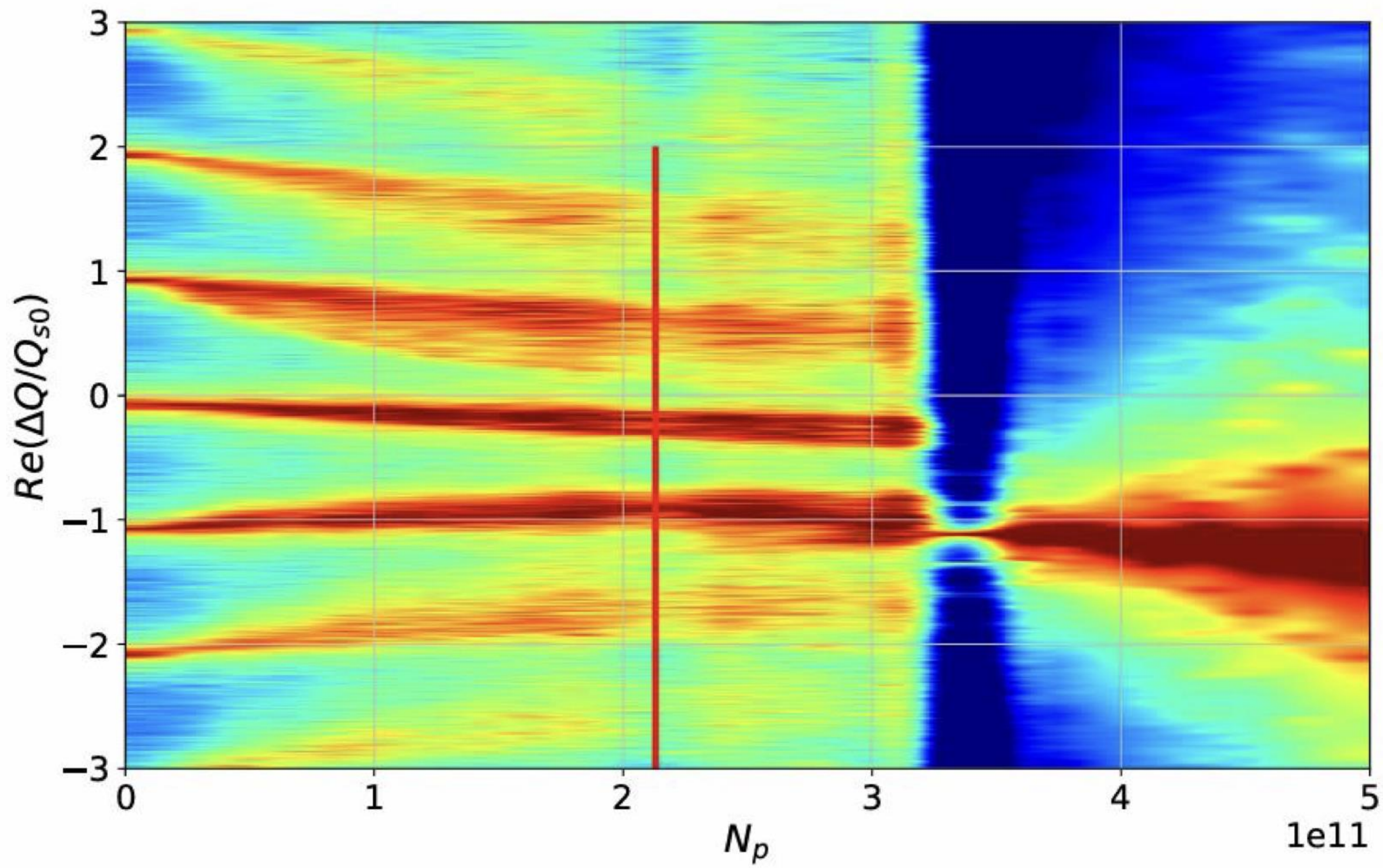
FUTURE CIRCULAR COLLIDER

Collective effects in transverse plane: TMCI

chromaticity = 5
feedback system on (4 turns)

Intra-bunch motion at
$N_p = 3.4 \times 10^{11}$





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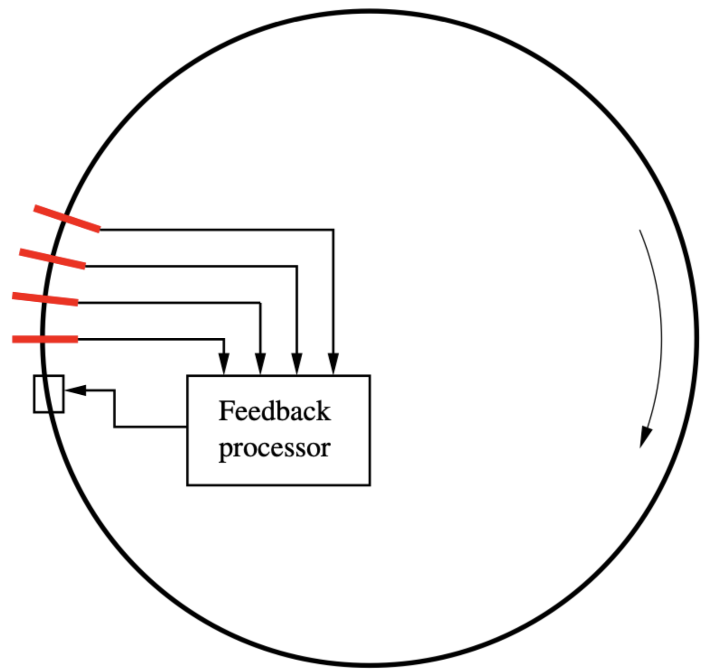
M. Migliorati: FCC-ee single beam collective effects

Intensity dependent Effects

Spatial Sampling — General Comments



- Feedback processor must:
  - Remove bunch-by-bunch DC offset (closed orbit) from each pickup signal;
  - Calculate correction kick from a linear combination of the resulting signals;
  - At least two non-degenerate pickups are needed, 3–4 probably provide a good balance between complexity, robustness, and performance.
- Phase advance from pickup to pickup does not need to be identical;
- Avoid cases where pickups are at $n\pi$;
- Avoid large swings in beta function from pickup to pickup.

D. Teytelman: Transverse Feedback Options for FCC-ee

Intensity dependent Effects

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Intensity dependent Effects

FUTURE CIRCULAR COLLIDER

Xsuite and Circulant Matrix Model simulations for FCC-ee beam-beam and wakefield effects.

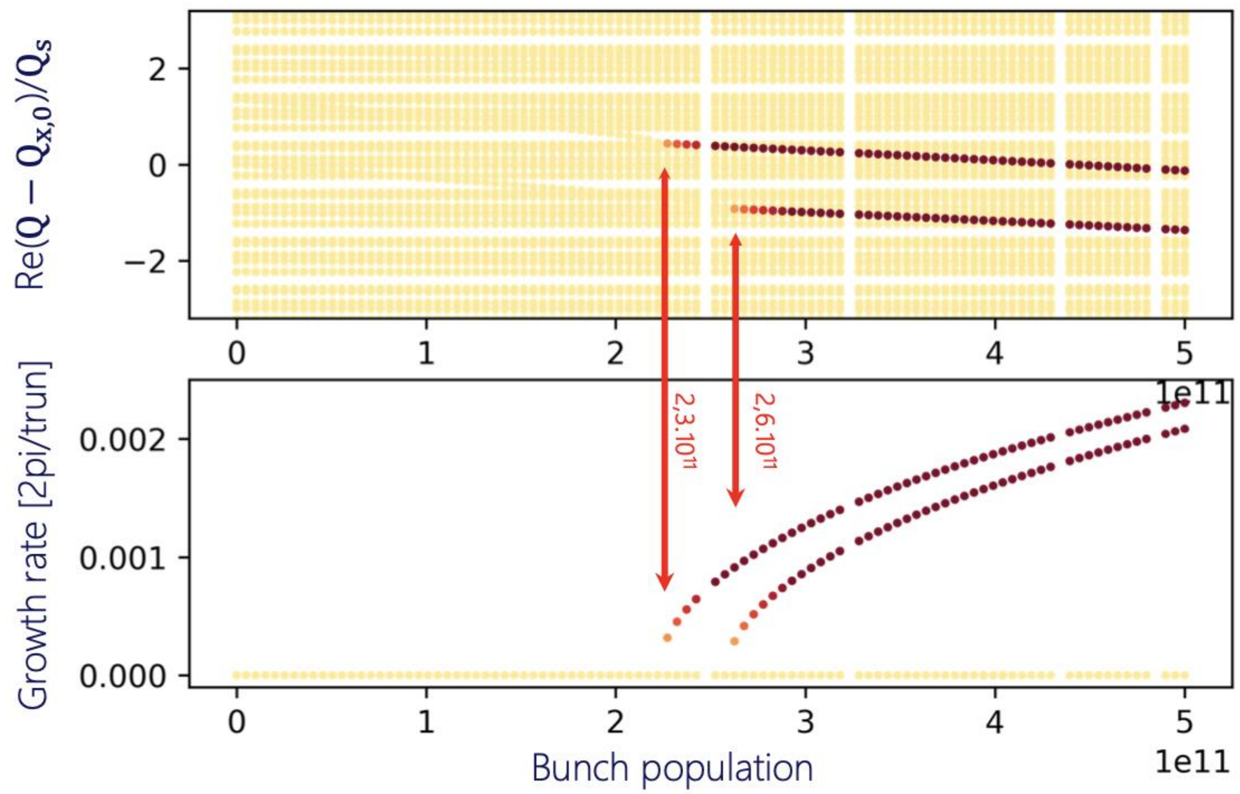
Roxana SOOS 12/06/24 30

Introduction | Simulation tools | Simulations of beam-beam | **Simulations of wakefields**

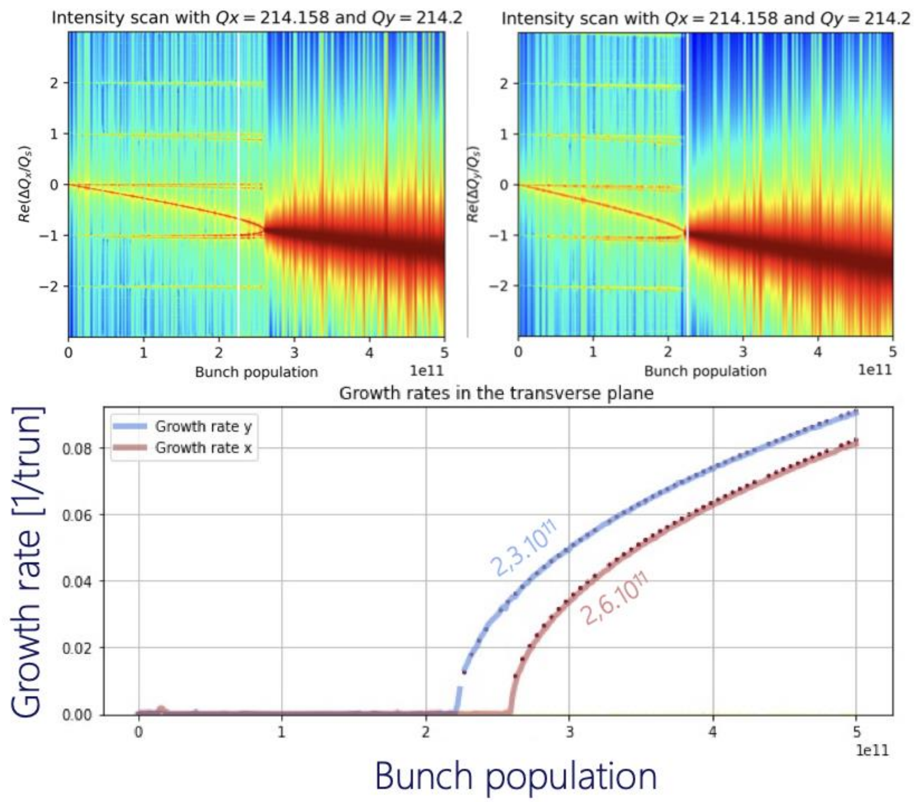
Transverse mode coupling instability simulations

Transverse wakefields for FCC-ee at Z energy; **perfect agreement!**

Intensity scan with CMM



Intensity scan with Xsuite - PyHT



Bunch length without beamstrahlung (5.2mm), L = 90.66 km , linearized RF, no longitudinal wakes.

R. Soos: Xsuite and Circulant Matrix Model simulations for FCC-ee beam-beam and wakefield effects

Intensity dependent Effects

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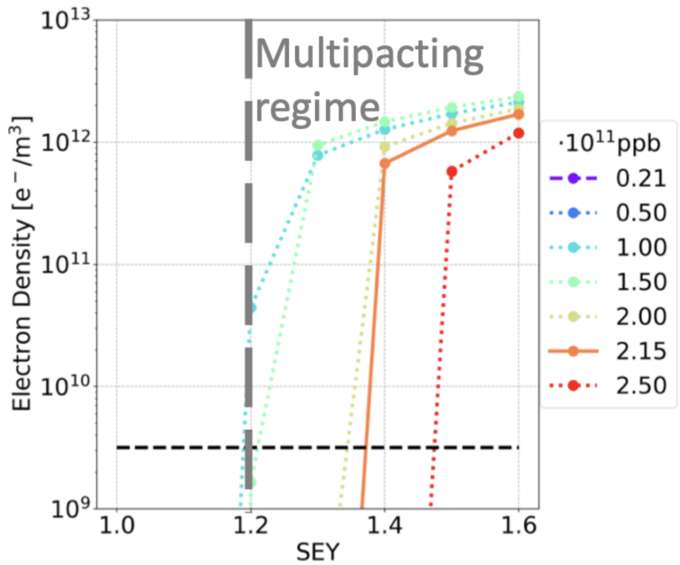
- Electron Cloud studies (L. Sabato)
  - ☐ Multipacting and Photoemission

Intensity dependent Effects

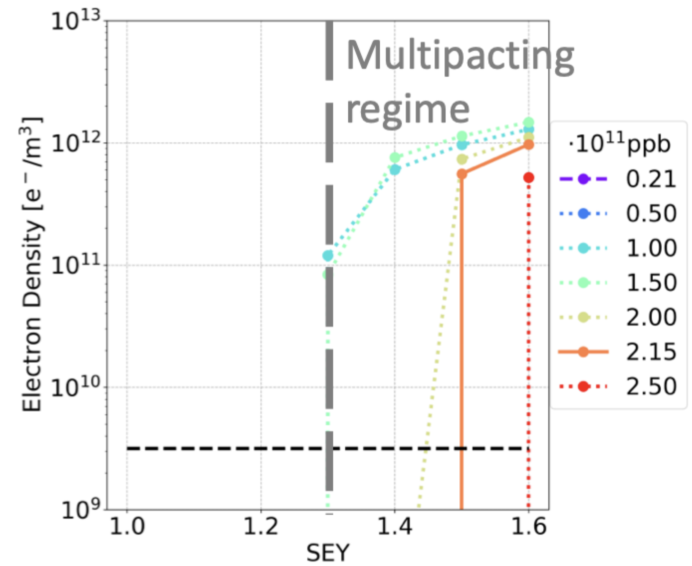
E-Cloud Build-Up Studies: Drift Space

Find the material propriety constraints to avoid e-cloud avalanche multiplication (multipacting)

Filling scheme 1



Filling scheme 2



The bunch intensities 1.00e11 and 1.50e11 ppb are the most critical cases

	Filling Scheme 1	Filling Scheme 2
SEY threshold (nominal intensity)	1.3	1.4
SEY threshold (all intensity below nominal one)	1.1	1.2

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L. Sabato: Electron Cloud Studies for the FCC-ee

Code Development

- Xsuite (G. Iadarola)
  - Synchrotron Radiation, Beam-Beam
  - Interfaces for Beam-Matter Interaction, Electron Cloud, Wake Fields
  - Can now model SuperKEKB IR
- BLAST-WarpX (A. Formenti)
  - Beam-beam Studies
  - PIC, different Geometries
  - Fast and flexible, first FCC-ee Simulations
- Bmad-Julia (G.Hoffstaetter)
  - Open Source Toolkits and Programs
  - Digital Twins
  - Machine Learning
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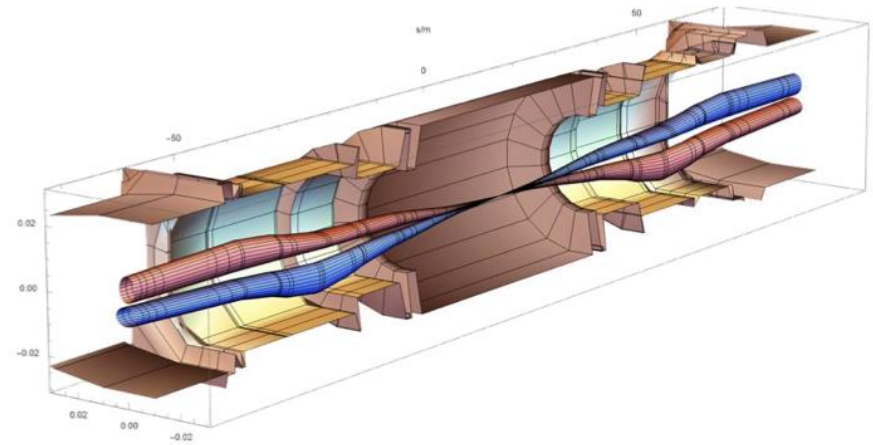
  - Resistive-wall wake field for arbitrary chamber geometries
  - FCC-ee detuning wake field cancelled by deforming circular chamber

Code Development

FUTURE CIRCULAR COLLIDER

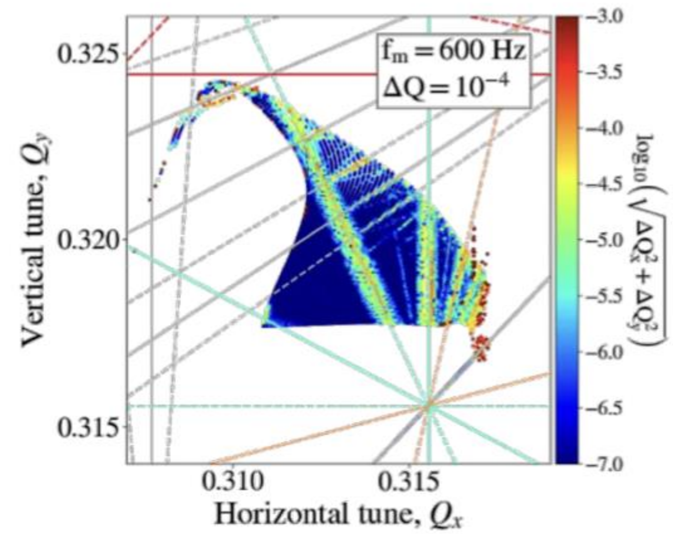
Introduction

Coming from **long tradition** in the **development of software tools for beam physics**



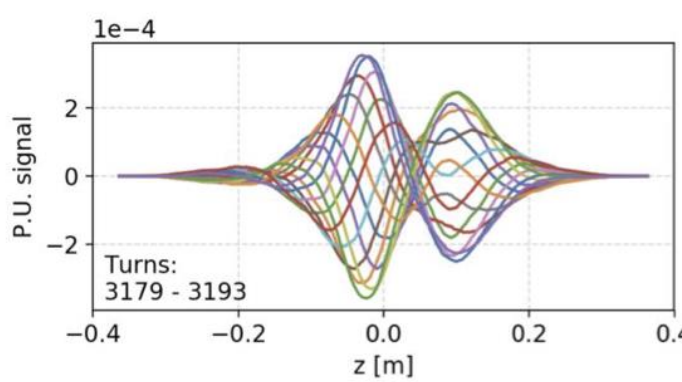
Powerful **tools** provided to the user community:

- **MAD-X**, standard for lattice description, optics calculation and design, tracking
- **Sixtrack**, a **fast-tracking program** used mainly for long **single-particle simulations**
- **Sixtracklib**, a **C/C++library for single-particle tracking** compatible with Graphics Processing Units (GPUs)
- **COMBI**, for the simulation of **beam-beam** effects using **strong-strong modelling**
- **PyHEADTAIL**, a **Python** toolkit for **collective effects** (impedance, feedbacks, space charge, and e-cloud).



Developed over decades, providing **powerful features** in their respective domains

- Nevertheless, **limitations also became apparent**…



4

G. Iadarola: X-Suite Integrated Beam Physics Simulation Framework

Code Development

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Code Development

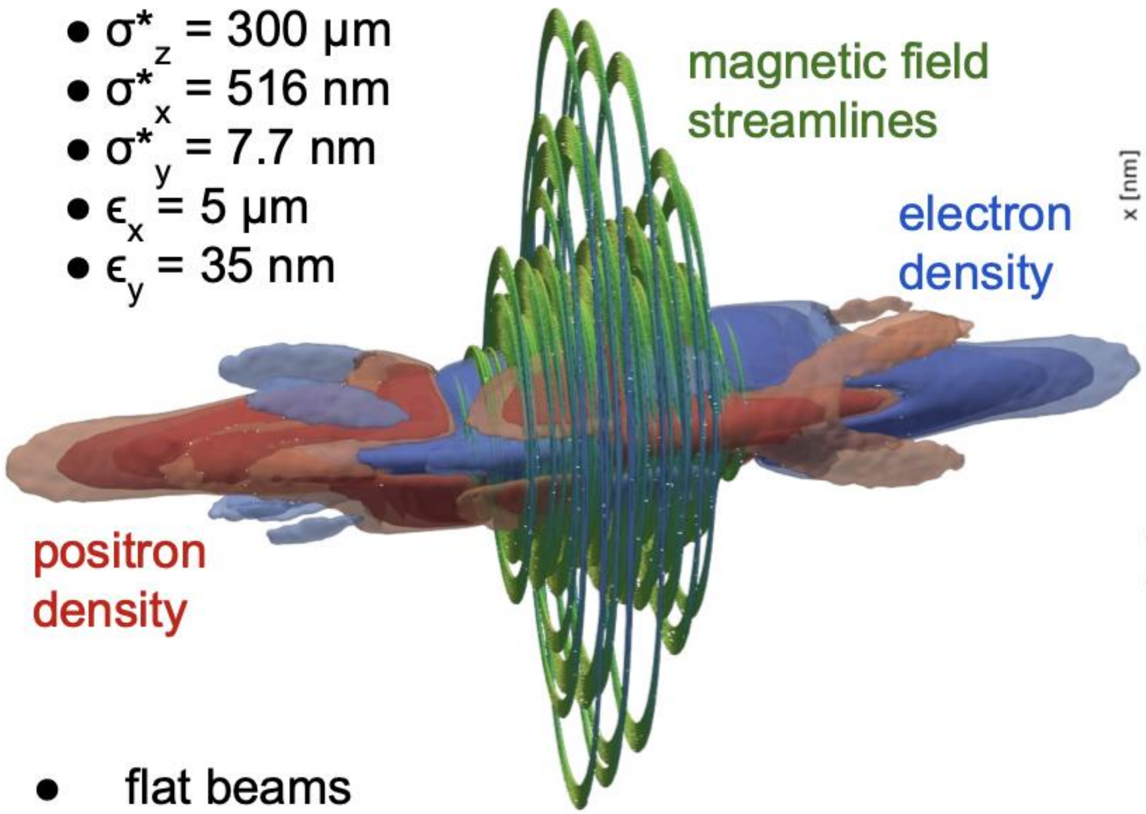
FUTURE CIRCULAR COLLIDER

Excellent agreement with flat ILC beams

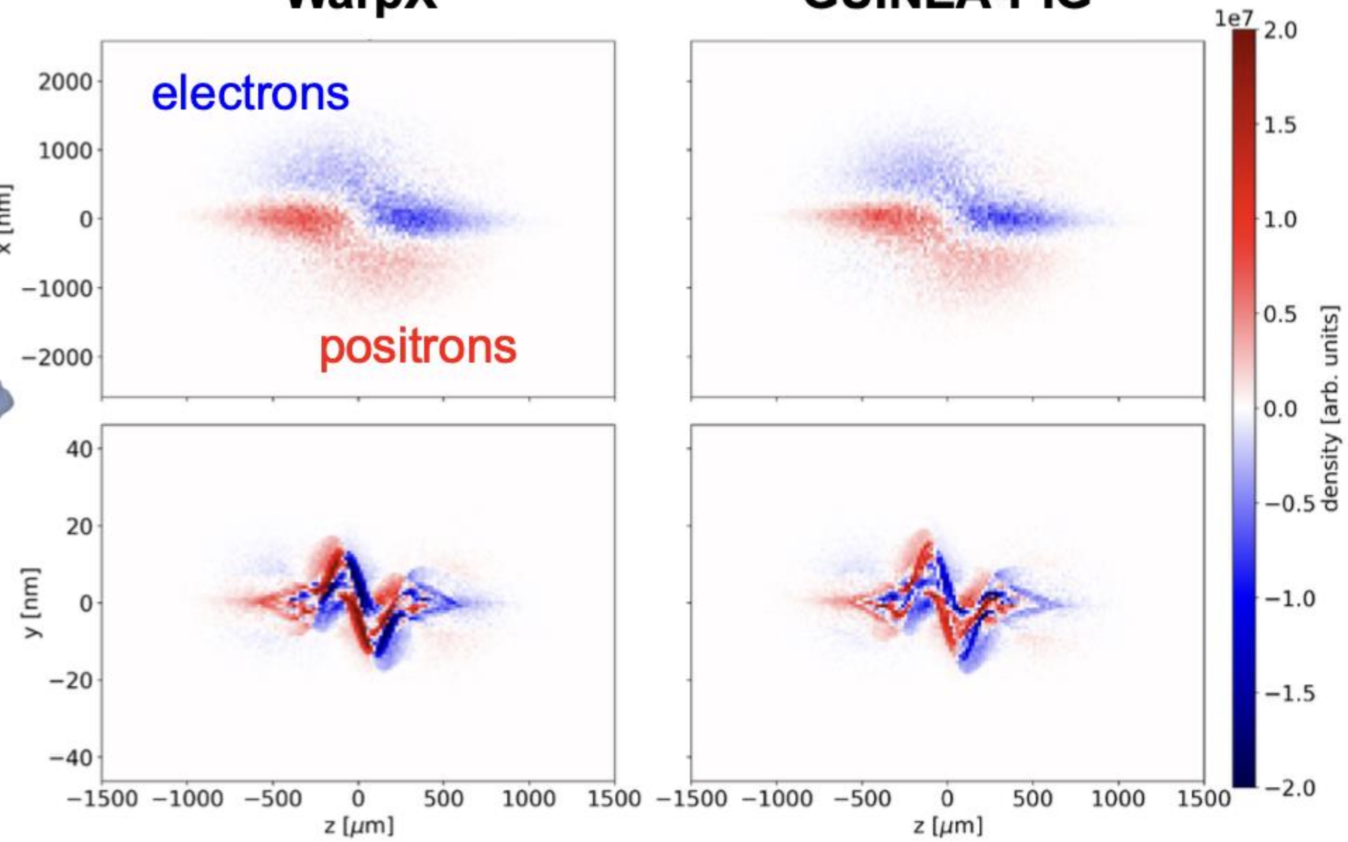
main parameters

- E_{COM} = 250 GeV
- N = 2 10^{10}
- σ^*_z = 300 μm
- σ^*_x = 516 nm
- σ^*_y = 7.7 nm
- ϵ_x = 5 μm
- ϵ_y = 35 nm

The International Linear Collider: Report to Snowmass 2021



snapshot of the beams' ***density integrated along the missing coordinate*** during collision



- flat beams
- significant disruption D_x = 0.30, D_y = 24.39
- negligible coherent pairs

offsets along x and y ~$\sigma_{x,y}$/10 to induce the kink instability and mitigate stochastic discrepancies

A. Formenti: New simulation tools for beam-beam collisions at the interaction point

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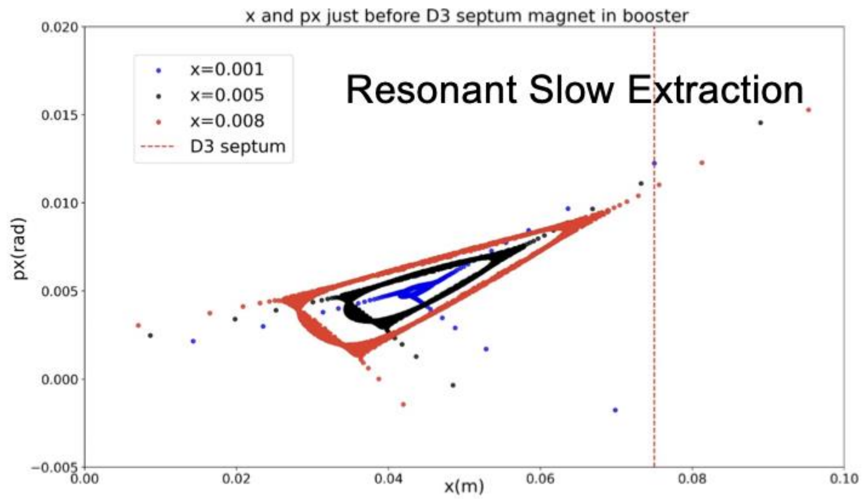
Code Development

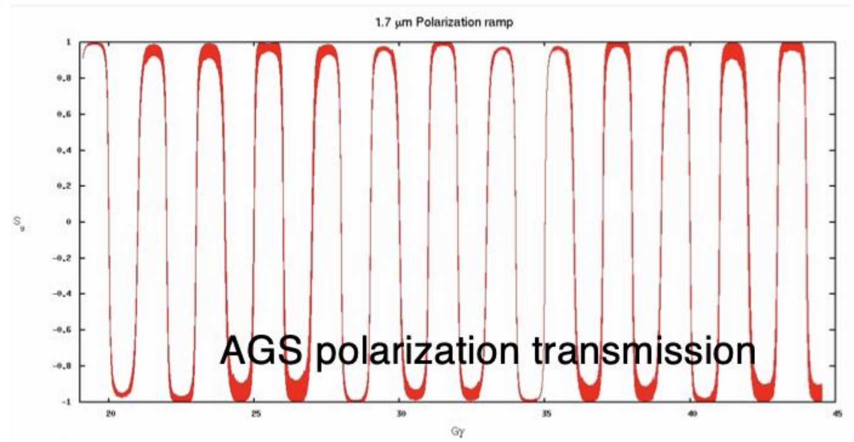
Slow Extraction and AGS Polarization

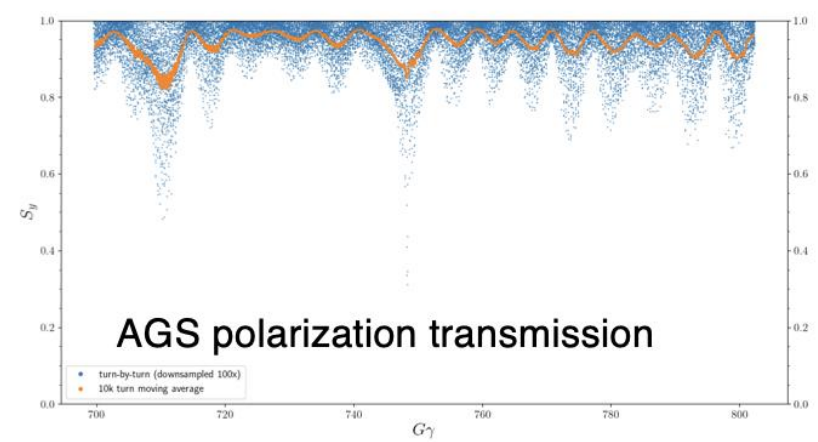
Bmad used for:

- Booster -> NSRL slow extraction
- AGS polarization transmission

-- Eiad Hamwi, Cornell







Brookhaven National Laboratory

CLASSE

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Georg Hoffstaetter: Bmad for the FCC andBmad-Julia collaboration for Machine Learning

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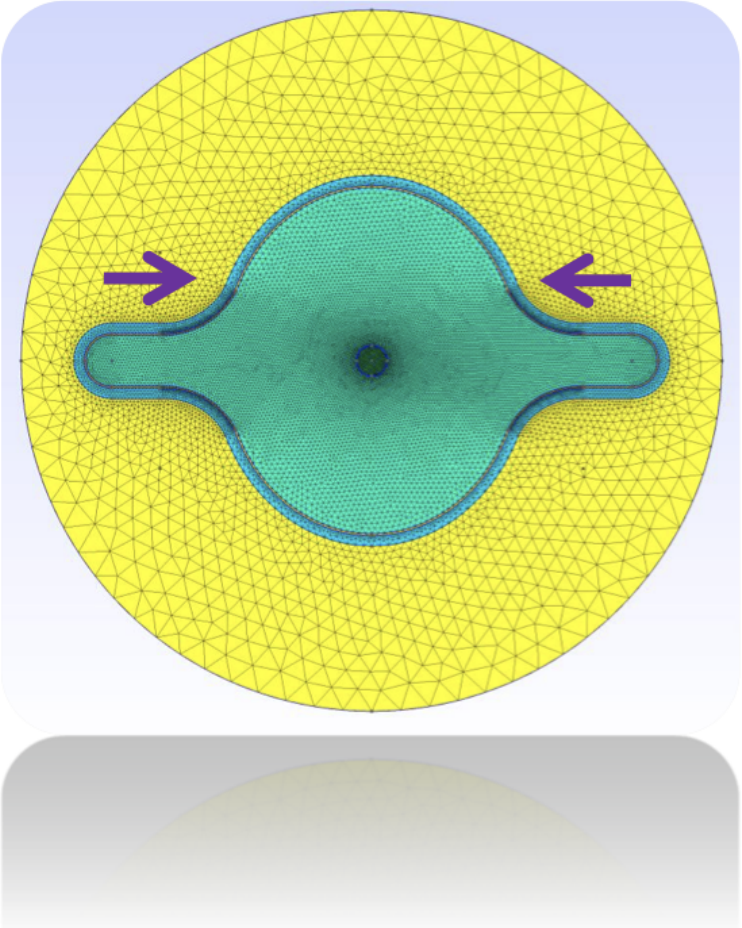
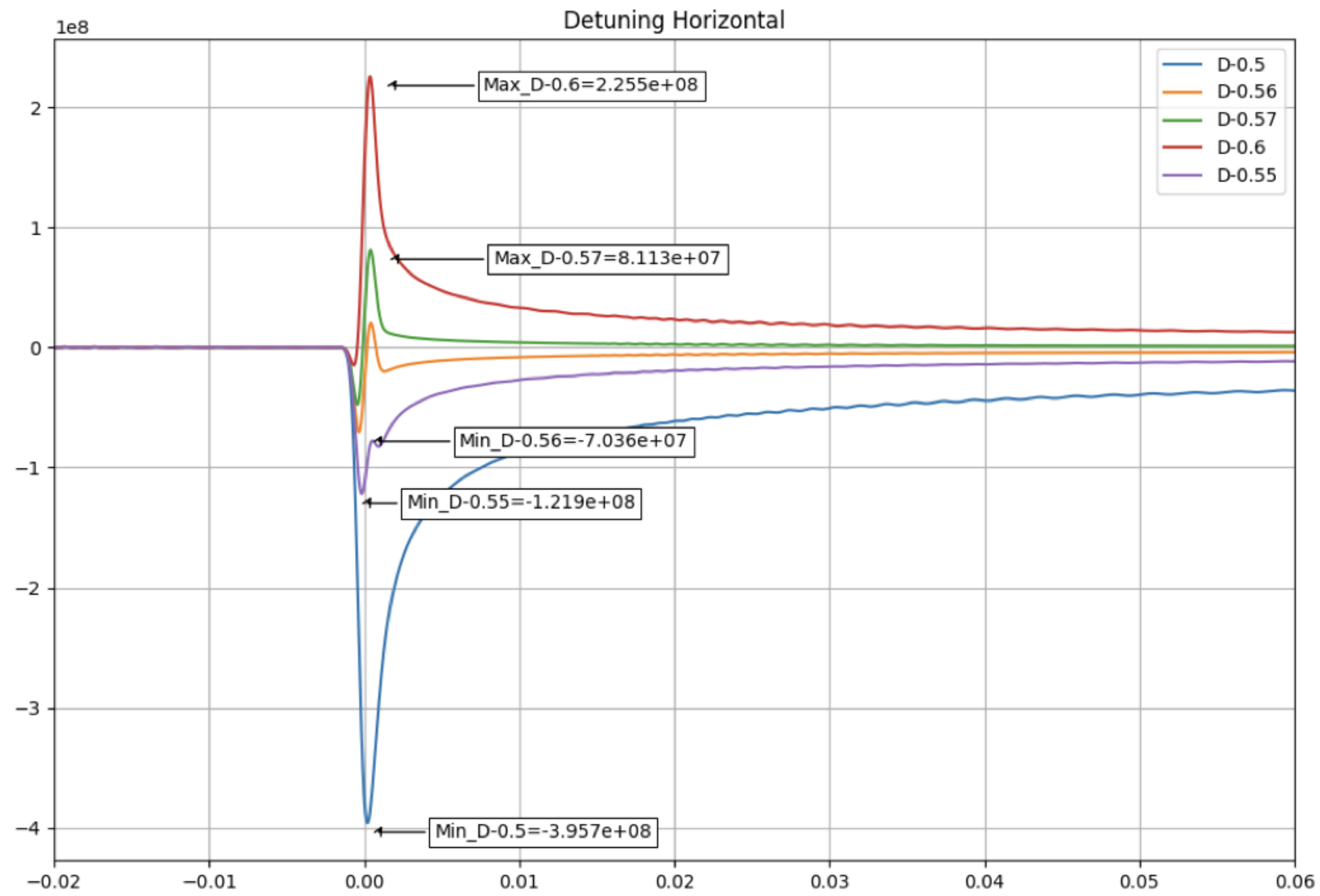
FCC main Ring

Minimizing Detuning impedance

Best ~ 560 – 570 μm (each side)





DESY. | VACI SUITE STATUS | Ali Rajabi, 2024 Page 27

A. Rajabi: VACI Suite updates, FCC Booster and Main Ring optimization

Thanks for your Attention