DYNAMIC APERTURE AND SEXTUPOLE TUNING STUDIES IN THE FCC-EE

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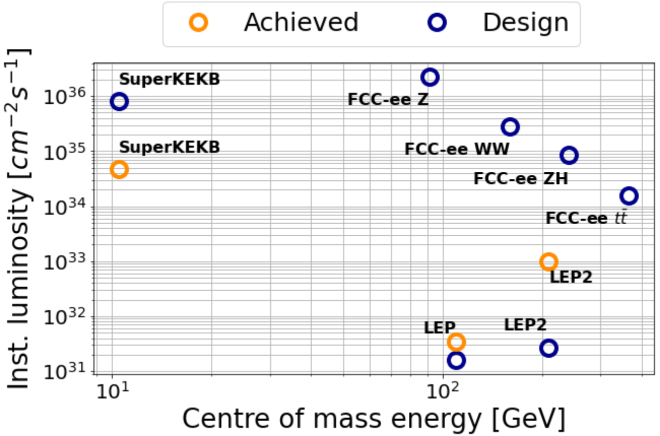
Introduction

- FCC-ee targets unprecedented luminosities
  - Numerous implications on layout, among those are
    - Small β^* resulting in large chromaticity generated by final focus quadrupoles
    - Top-up injection to increase integrated luminosity
    - Large energy spread due to beamstrahlung
  - Challenge is to find good chromaticity correction scheme with sufficient dynamic aperture (DA) and momentum aperture (MA) to avoid excessive particle loss



Sources: 1,2,3,4

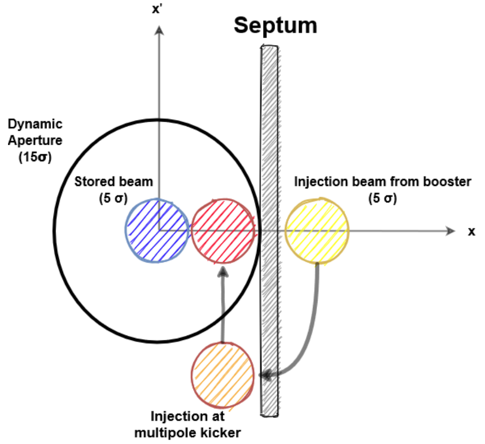
Required DA and momentum acceptance

- DA and MA requirements stem from:
  - Sufficiently large DA for top-up injection
  - MA to keep beam lifetime high ($\tau_{beam} > 20\ min$ at $t\bar{t}$)

- DA requirements from top-up injection estimated in

  M. Aiba et al., Top-up injection schemes for future circular lepton collider and

  K. Oide, 31st FCC-ee optics design meeting
  - For on-momentum injection, target DA larger than $15\ \sigma_x$
  - For off-momentum injection, DA at $\pm 1.8\ \%$ larger than $5\ \sigma_x$
    - Assuming $5\ \sigma_x$ stored beam and $5\ \sigma_x$ injected beam



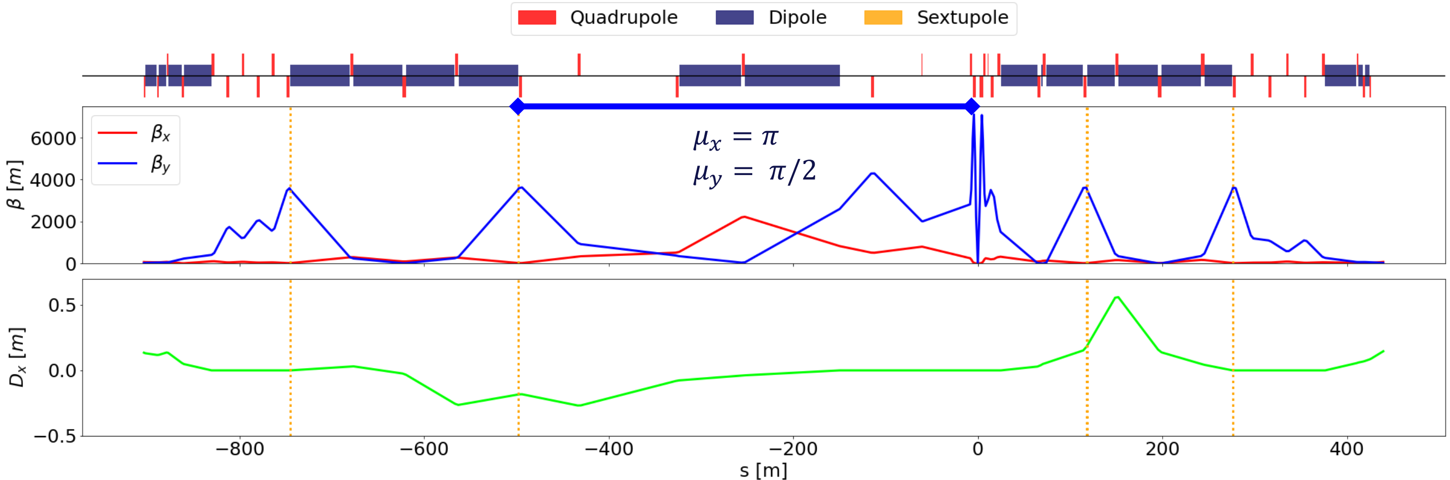
- MA follows large energy spread due to beamstrahlung and to keep reasonable beam lifetime
  - For lower energy modes $\delta_{acceptance} > 1.5\%$, whereas $t\bar{t}$ requires $\delta_{acceptance} > 2.8\%$ (References: *F. Zimmermann et al. IPAC14, MOXAA01*, *A. Bogomyakov et al. PRSTAB* ***17,*** *041004*, *K. Ohmi and F. Zimmermann, IPAC14, THPRI004*)

Chromaticity correction schemes

- Two chromaticity correction schemes in FCC-ee
  - Local correction of vertical chromaticity in the IR
    - Crab sextupoles integrated in the local chromaticity correction scheme (LCCS)
  - Sextupoles in arcs to correct ring chromaticity
    - Two options studied interleaved scheme and non-interleaved scheme

Local chromaticity correction in IR

- Local chromaticity scheme based on *K.Oide, Final focus system with odd-dispersion scheme* and presented in K. Oide et al., *PRAB* ***19,*** *111005 (2016)*
  - Two sextupoles separated by phase advance of π
  - Inner sextupole in dispersive region to correct Q'_y from final focus quadrupoles
  - Strength of outer sextupole set to cancel geometric contribution, reduced to generate crab waist
  - Phase from IP to first arc sextupole subject to optimization



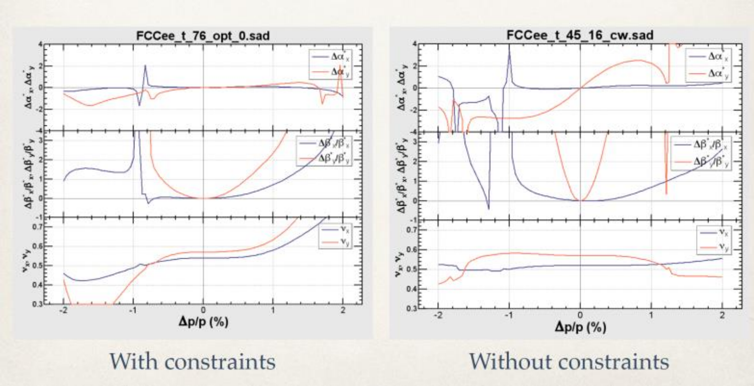
Arc sextupoles and constraints

- Set arc sextupoles to correct $Q'_{x,y}$ of the ring to target values while achieving sufficient DA and MA (natural $Q'_{x,y}$ after LCCS: -500 units)

  - Additional constraint from chromatic optics in IP (see H. Sugimoto et al., IPAC2017, MOPIK076)

$$\frac{1}{\beta^*_{x,y}}\frac{\partial \beta^*_{x,y}}{\partial \delta} = \mp \sum_i \frac{\beta^i_{x,y} D^i_x}{2\sin(2\pi Q_{x,y})} k^i_2 \cos\left(2\left|\mu^*_{x,y} - \mu^i_{x,y}\right| - 2\pi Q_{x,y}\right)$$

  - May be extended to other elements such as collimators



K. Oide, KEK Seminar, Jun. 2016

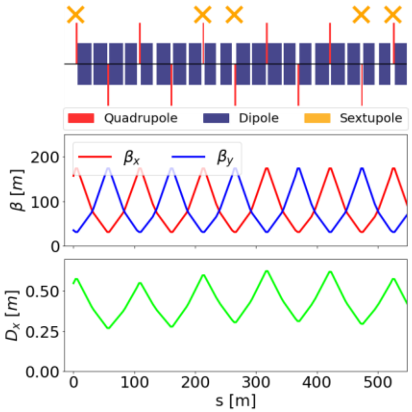
- Correction schemes to follow the arc cell layout
  - Currently, FODO lattice is used due larger filling factor thus lower ΔE_{turn}, other options such as DBA studied in

B. Härer, Lattice design and beam optics calculations for the new large-scale electron-positron collider FCC-ee

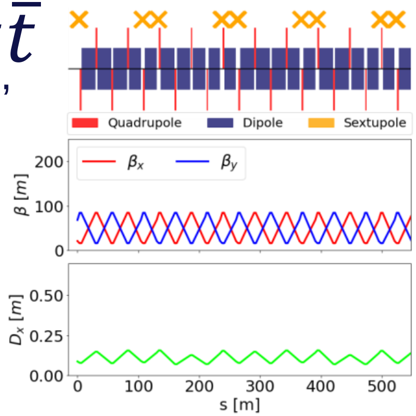
Arc optics and layout

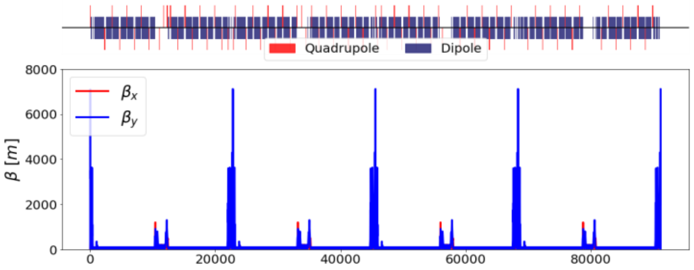
- Baseline FCC-ee arc uses FODO cells with variable cell length
  - For Z and W, cell length of ~100m and phase advance of $90^\circ/90^\circ$
  - Quadrupole will be installed in the gaps, reduced cell length to 50m for H and $t\bar{t}$, keeping phase advance of $90^\circ/90^\circ$
- Chromaticity correction by families of non-interleaved sextupole pairs
  - During CDR phase, interleaved schemes with up to 6 families were studied (see B. Härer, CERN-THESIS-2017-073 and 35th FCC-ee optics design meeting), but DA/MA didn't meet requirements
- Note: currently, lattice with perfect 4-fold periodicity is studied
  - Collimation and Inj./Extraction to be integrated

Z



$t\bar{t}$



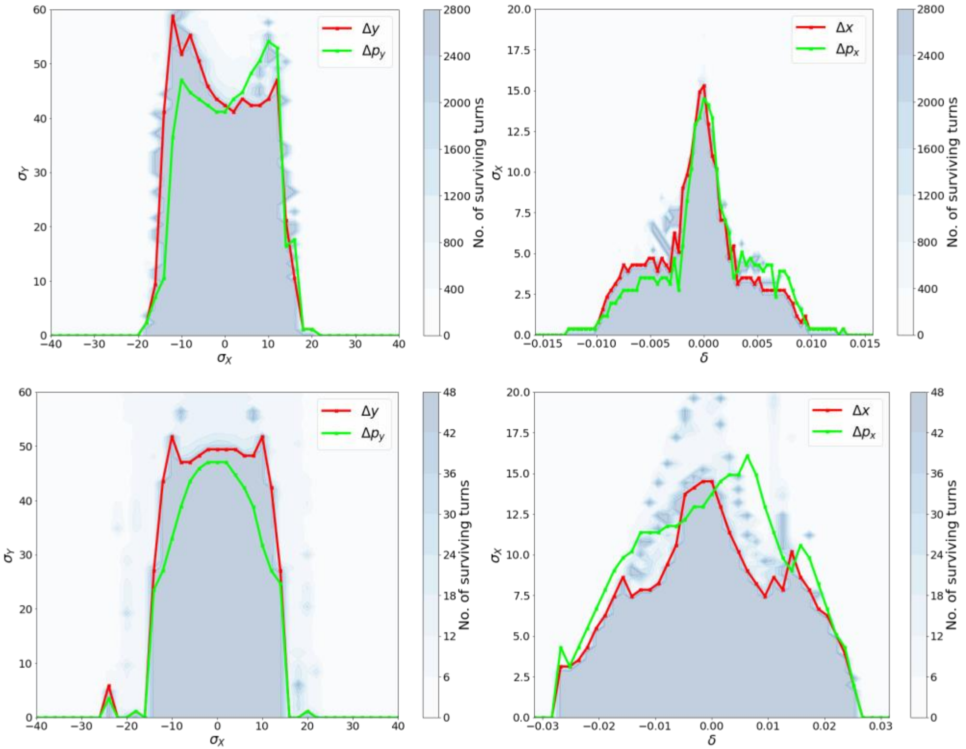


Studies on non-interleaved scheme

- Correction scheme in the baseline lattices is a non-interleaved scheme (see FCC-ee CDR and K. Oide et al., *PRAB* **19,** *111005 (2016)*)
  - Optimization using Downhill Simplex algorithm with the DA/MA area as figure of merit
  - Tracking for 2 times long. damping time 45 turns ($t\bar{t}$) / 2500 turns (Z), including tapering & SR
  - Using all 75 (Z)/ 146 ($t\bar{t}$) sextupole pairs as independent variables (keeping lattice periodicity)

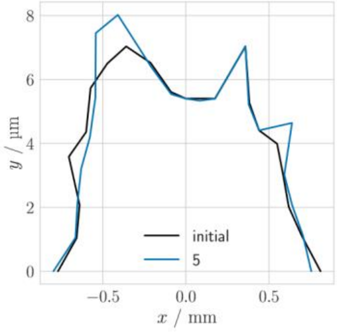
Z

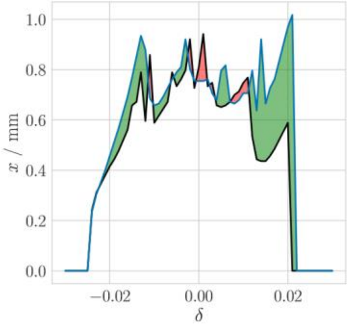
$t\bar{t}$

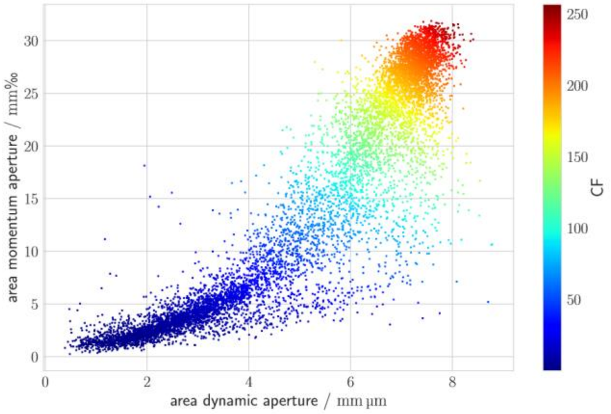


Further optimization using PSO

- Use of genetic algorithms to optimize DA is established practice in light source community (see 1,2,3,4,5,6,7,8,9)
  - Particle swarm optimization (PSO) to improve DA has been studied in the FCC-ee (see *T. Tydecks, 78th FCC-ee Optics Design Meeting*, FCC-ee CDR, and example code)
  - Initialization of a population of given size, evaluate objective function, and update individual particle based on global best solution and past best solution of individual
  - Shown promising improvements, MA area increased by 18%



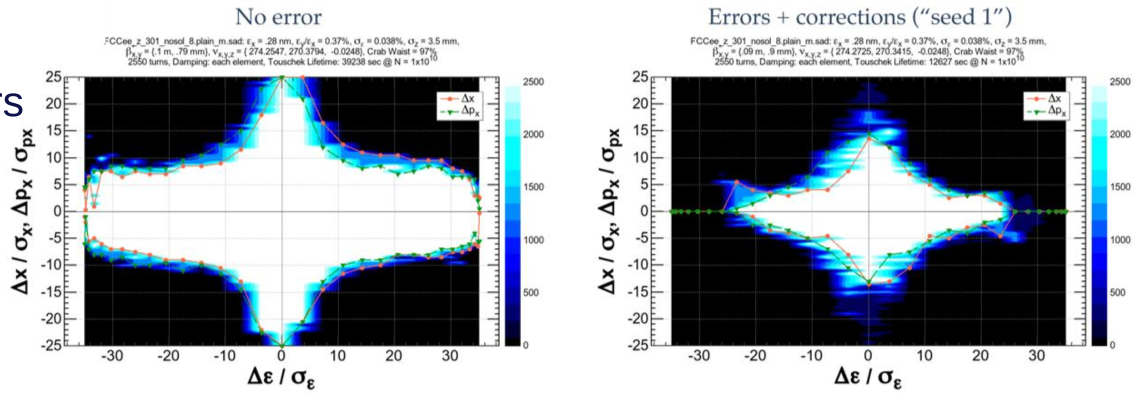




Issues and next steps

- Goals met so far only without errors/corrections included
  - Significant loss of DA when errors are included (see e.g. T. Charles and L. van Riesen-Haupt, 135th FCC-ee optics design meeting, K. Oide, FCCIS WP2 Workshop 2021, T. Tydecks, FCC-week 2018), how much can be restored by reoptimization of sextupoles remains to be studied

- Investigate solutions to reduce complexity
  - Reduced number of independent sextupole pairs
  - Schemes to reduce higher order chromaticity and amplitude detuning and impact on DA/MA
  - Tolerable deviation from perfect periodicity by optics errors



Outlook

- Size and performance requirements make FCC-ee a challenging machine in terms of DA
  - Sufficient DA for top-up injection and large MA to keep particle after emission of beamstrahlung photons
    - Secondary constraints from chromatic optics in the IP
  - Different chromaticity correction schemes studied in the past
    - Non-interleaved correction scheme with LCCS in IRs meets DA requirements and is used in the baseline lattices
  - Open questions:
    - Maximum achievable DA and MA in presence of errors
    - Required number of sextupole knobs and tuning time/complexity in operation

Thanks for your attention!