# DYNAMIC APERTURE AND SEXTUPOLE TUNING STUDIES IN THE FCC-EE

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**FCCIS – The Future Circular Collider Innovation Study**. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754

# Introduction

- FCC-ee targets unprecedented luminosities
  - Numerous implications on layout, among those are
    - Small $\beta^*$ resulting 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

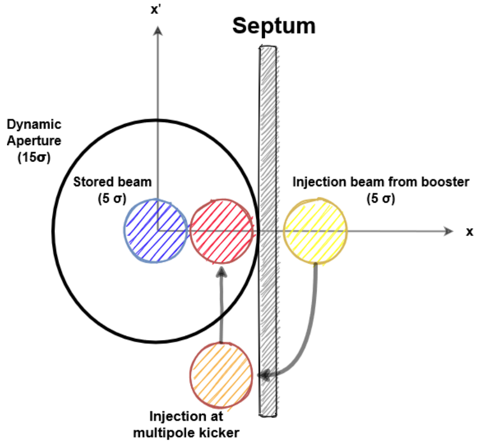
# Required DA and momentum acceptance

- 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, 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



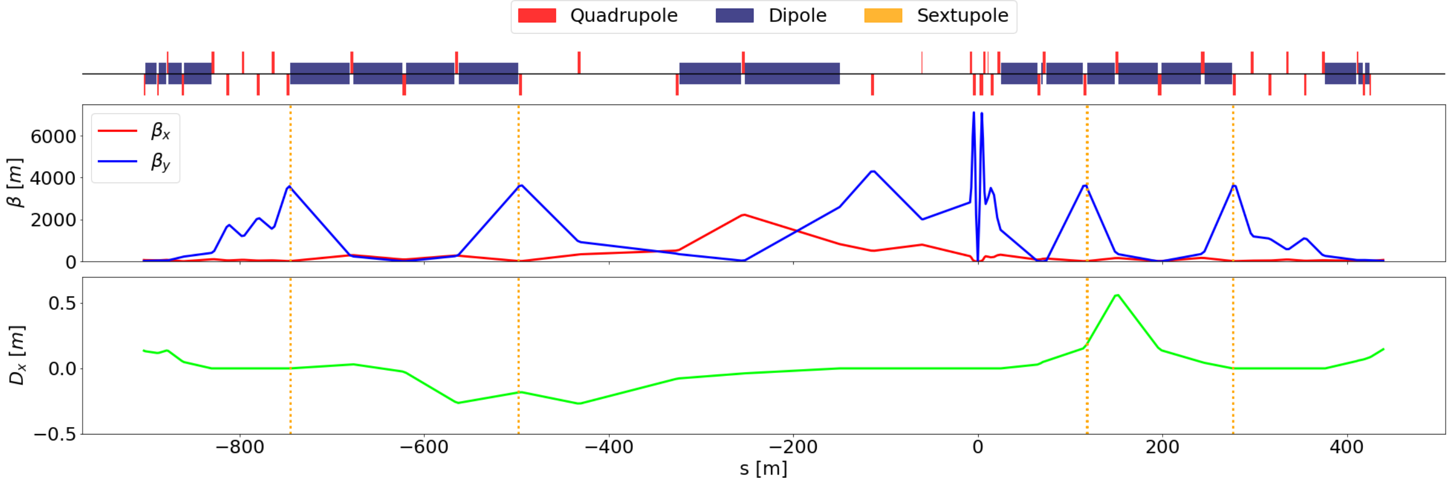

- MA follows large energy spread due to beamstrahlung and to keep reasonable beam lifetime
  - For lower energy modes $\delta_{acceptance} > 1.5\%$, whereas $t\bar{t}$ requires $\delta_{acceptance} > 2.5\%$ (References: *F. Zimmermann et al. IPAC14, MOXAA01*, *A. Bogomyakov et al. PRSTAB **17,** 041004*, *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 $\pi$
  - 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
  - Additional constraint from chromatic optics in IP (see *H. Sugimoto et al., IPAC2017, MOPIK076*)

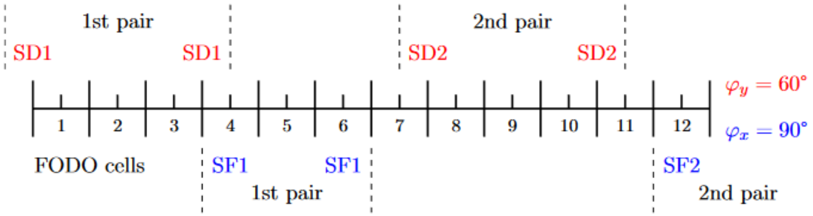
$$\frac{1}{\beta^*_{x,y}}\frac{\partial \beta^*_{x,y}}{\partial \delta} = \mp \sum_i \frac{\beta^i_{x,y} D^i_x}{2\sin(2\pi Q_{x,y})} k^i_2 \cos\left(2\left|\mu^*_{x,y} - \mu^i_{x,y}\right| - 2\pi Q_{x,y}\right)$$

  - May be extended to other elements such as collimators

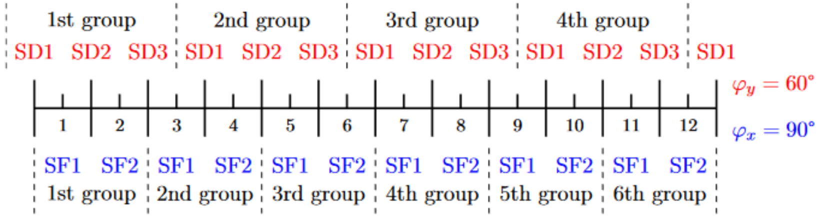
- Correction schemes to follow the arc cell layout
  - Currently, FODO lattice is used due larger filling factor thus lower $\Delta E_{turn}$, other options such as DBA studied in *B. Härer, Lattice design and beam optics calculations for the new large-scale electron-positron collider FCC-ee*

# Interleaved and non-interleaved sextupole schemes

- In the non-interleaved scheme, sextupoles of same family are separated by –*I* transform
  - No sextupoles in-between pair, resulting in lower number and requiring more strength



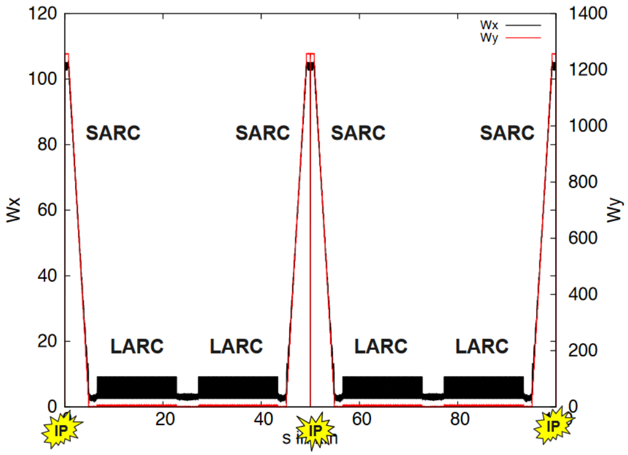

- In the interleaved scheme, sextupoles at every quadrupole, thus breaking cancelation
  - Allows for larger number of sextupoles, reducing required strength, but cancelation broken

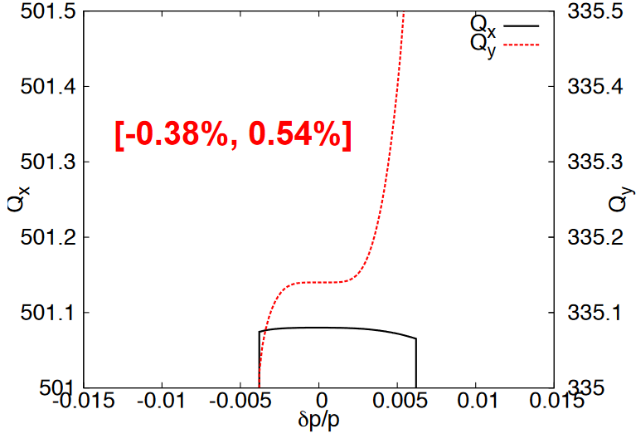



*From B. Härer, Lattice design and beam optics calculations for the new large-scale electron-positron collider FCC-ee*

# Studies on interleaved scheme

- In the CDR phase, interleaved schemes were studied (see _B. Härer, Lattice design and beam optics calculations for the new large-scale electron-positron collider FCC-ee_ and _B.Härer, 35th FCC-ee optics design meeting_)
  - Racetrack layout with $C = 100km$ and two-fold symmetry
    - Early design of the IR straight without LCCS was used
    - Chromaticity of doublet corrected by short arcs next to IR, ring chromaticity by sextupoles in long arcs
    - Up to six sextupole families studied and correction accounting for terms up to $Q_{x,y}^{(4)}$
      - MA for $t\bar{t}$ below $0.5\%$
      - Later studies with LCCS found MA of $\pm 1.1\%$



# Studies on non-interleaved scheme

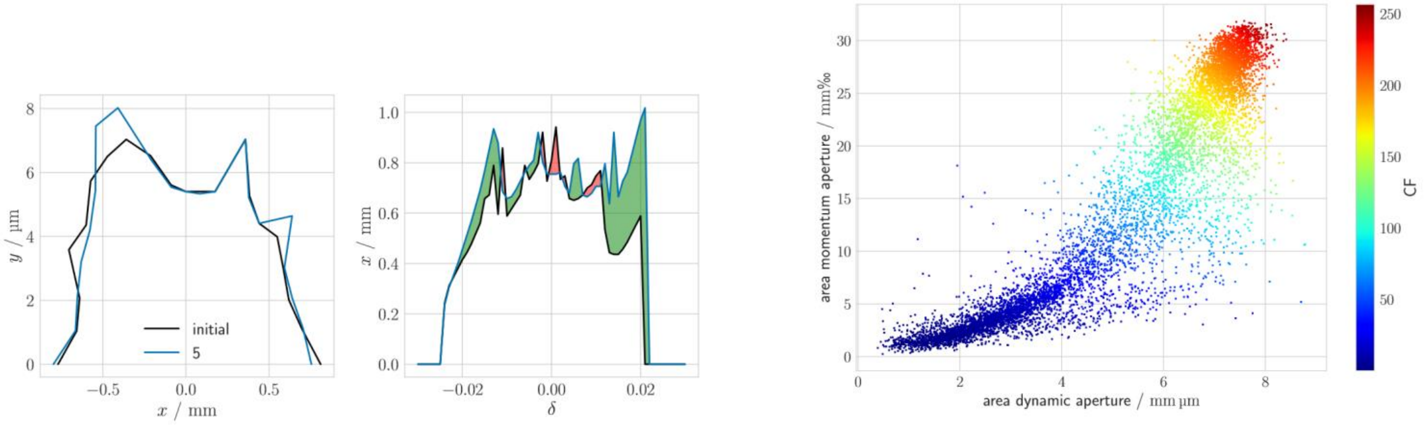
- Correction scheme in the baseline lattices is a non-interleaved scheme (see FCC-ee CDR and K. Oide et al., *PRAB* **19,** *111005 (2016)*)
  - Optimization using Downhill Simplex algorithm with the DA/MA area as figure of merit and all sextupole pairs as independent variables (keeping lattice periodicity)

| Operation mode | No. of sextupole pairs | |
|---|---|---|
| | 2-IP V18.1 layout (CDR) | 4-IP V22.1 layout (FCCFS) |
| Z (45.6 GeV) | 208 | 75 |
| $t\bar{t}$(182.5 GeV) | 294 | 146 |

- Target DA and MA were achieved or exceeded with this scheme
  - 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
  - Necessity of large number of independent sextupole pairs to be investigated

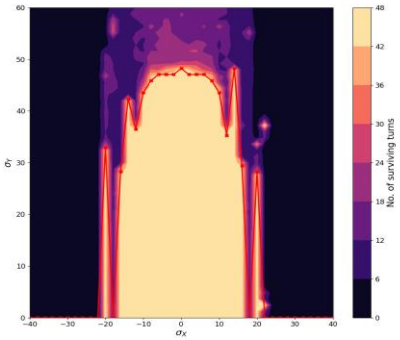
# Further optimization using PSO

- 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%

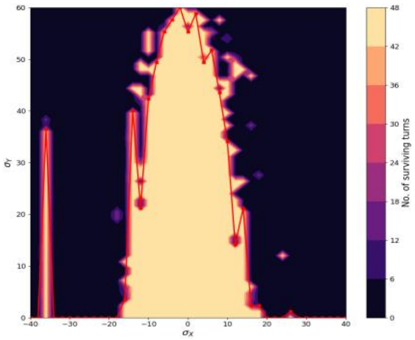


# Ongoing studies

- Reference implementation for sextupole tuning only available in SAD
  - Currently trying to port it for use with other codes and algorithms (Downhill simplex, PSO, NSGA-II,..)
    - A first prototype is developed here
  - Second to that, flexible definition of sextupole circuits
  - First study done for V22.1 $t\bar{t}$-lattice, reducing the number of circuits by a factor 2
    - Pair two focusing pairs to one circuit, and similar for defocussing
    - Further tweaking of Penalty function, weighting etc. required




DA using all sextupole knobs




DA with reduced number of circuits

# 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!