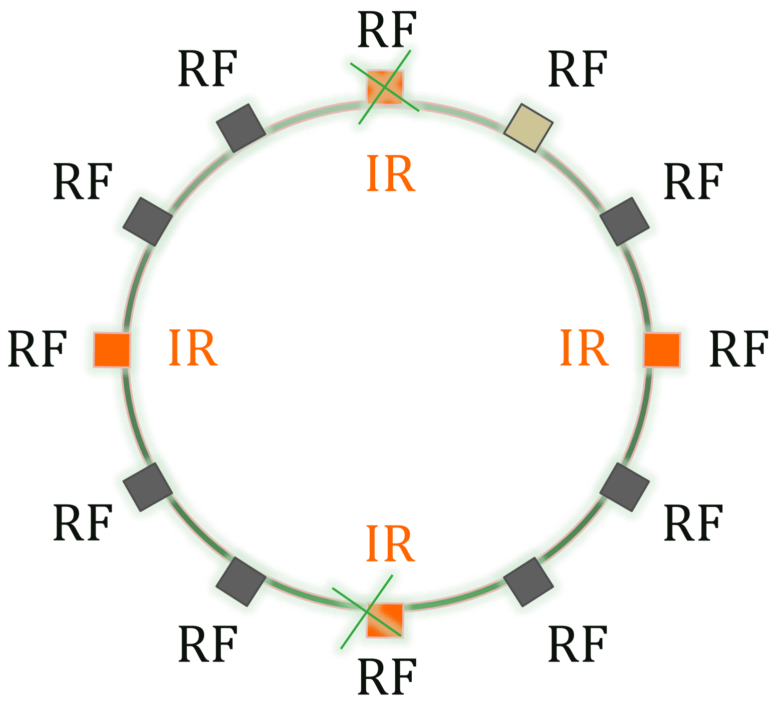
Tolerance studies and coupling for extreme low emittance in the Future Circular Collider FCC-ee (TLEP)

Sandra Aumon
CERN

On behalf of the FCC-ee Lattice Design team

FCC-ee lattice: 1m/2mm beta*

- Circumference: 100km
- 12 folds lattice
- 12 arcs (~6.8 km)
- 12 RF sections
- 4 and 2 IPs lattices with 0.5/1mm, 1m/2mm beta*
- L*=2m
- **Priority on 2IP lattices, 1m/2mm 120 and 175GeV**

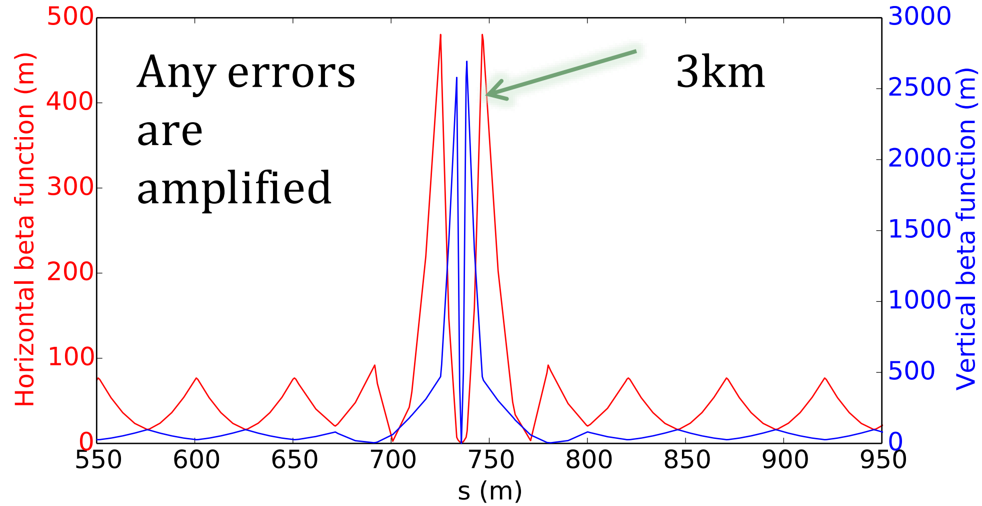


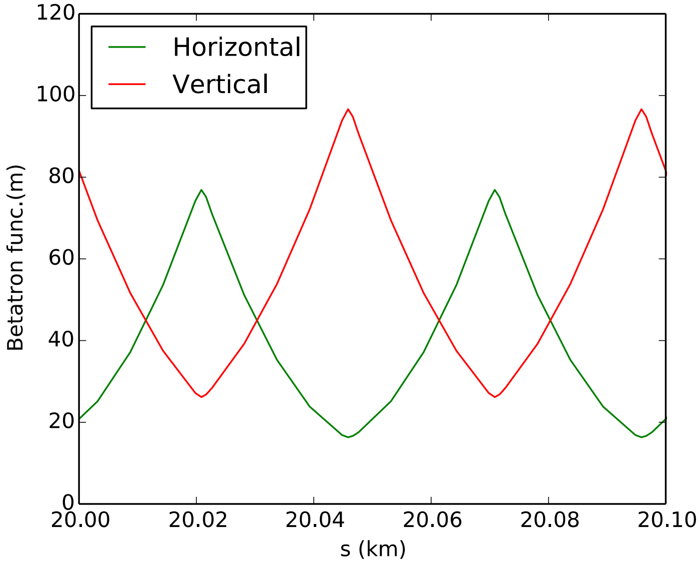
FCC-ee lattice

- 120 GeV
- 1m/2mm beta*, 2 Ips
- Tool: MADX

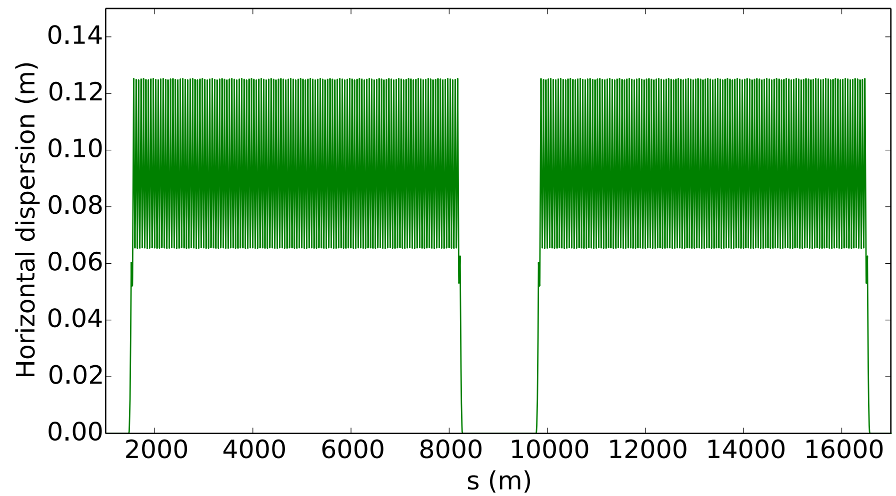
- Qx=419.08/ Qy=333.14
- DQx = -573.6506369
- DQy = -852.4978106

Interaction Region





FODO cell



Method for tolerances and correction up to 120 GeV

1. Errors in lattice (up to 0.150mm for misalignments, 0.1mrad for rolls)
2. Orbit correction

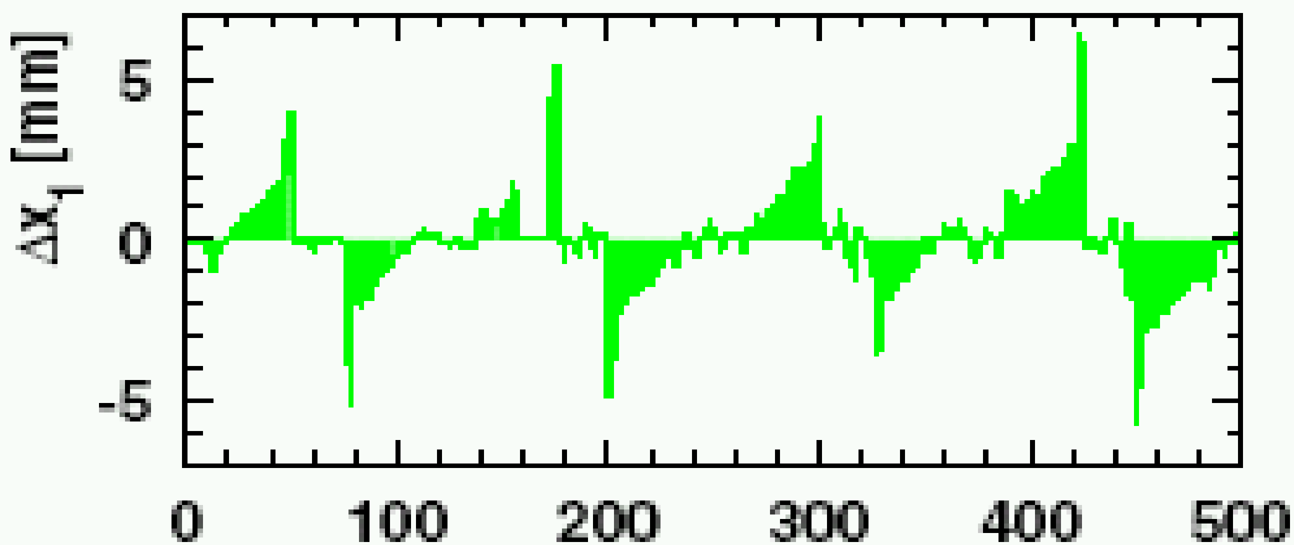
   -> Correct the orbit and H.&V dispersions
3. Chromaticity correction with sextupoles of the arcs (large strength)
4. Tune corrections
5. Re-matching of the optics due to beta-beating
6. Coupling correction & V. dispersion correction

Work in progress

7. Switch the synchrotron radiation in MADX:

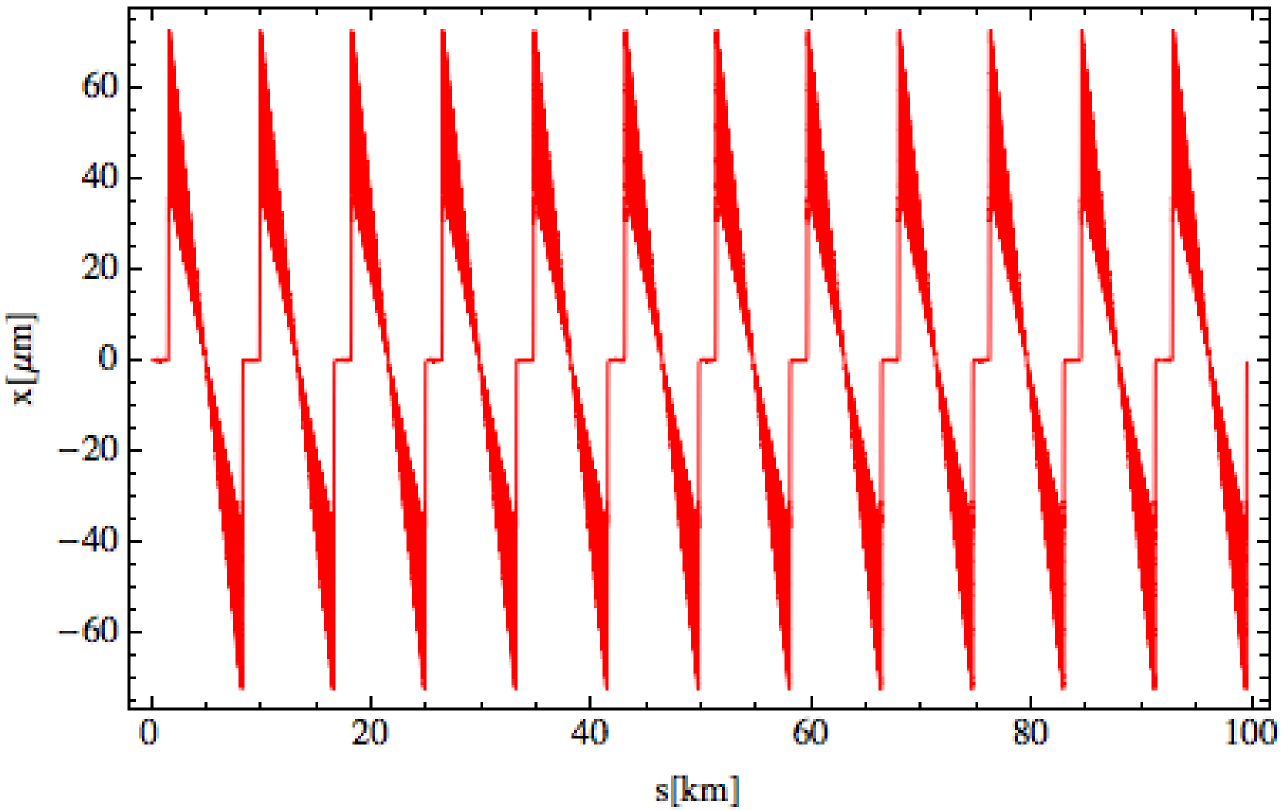
   - compute equilibrium emittances, final orbit with sawtooth effect

„Sawtooth Effect" at LEP



BPM Number

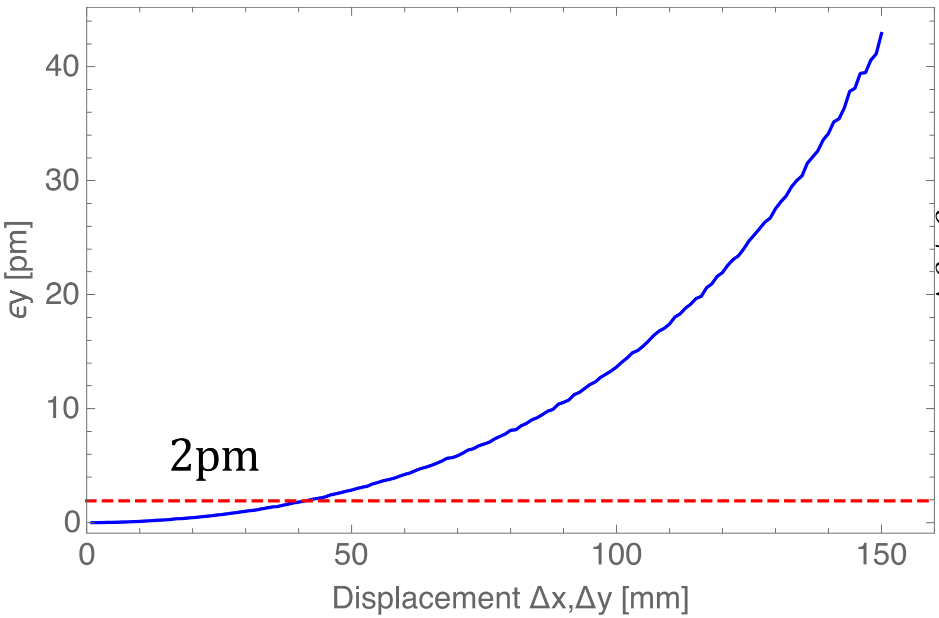
Sawtooth Effect in TLEP (120GeV)



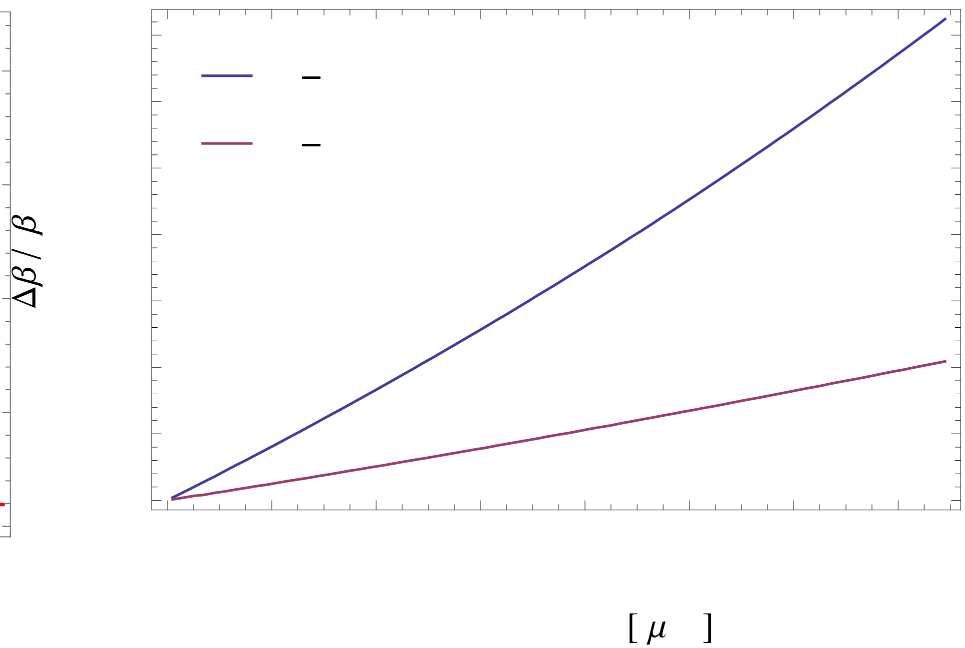
Correction of the linear lattice before switching the radiation.
(only Sawtooth effect remains)

120GeV-1m/2mm-2IPs

Emittance before coupling correction
Misaligned Quadrupoles



Beta-beating introduced by
sextupoles



The coupling comes from off center orbit in the sextupoles for the chromaticity correction (first order)

Preliminary results for coupling correction

- Correct non-diagonal element of the transport Rmatrix Re13 at the BPMs (given by MADX) – the others (Re23 etc..) are going down automatically.
- Building a Response matrix 3990x(2x3990)
- Computation of the response matrix parallelized+inversion (20 hours CPU)

$$M = \begin{array}{c} \\ \text{bpm}_1 \\ \vdots \\ \text{bpm}_n \\ \vdots \\ \text{bpm}_{2x3990} \end{array} \overset{\quad J_1 \;\cdots\; J_n \;\cdots\; J_{3990}}{\begin{bmatrix} \Delta Re_{13} \\ \\ \Delta D_y \end{bmatrix}}$$

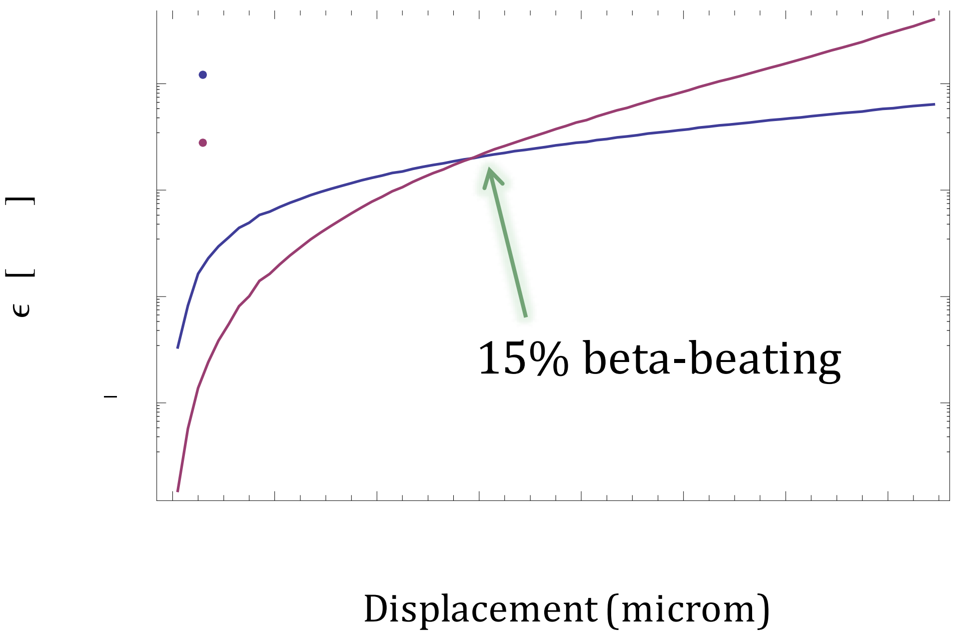
To be inverted

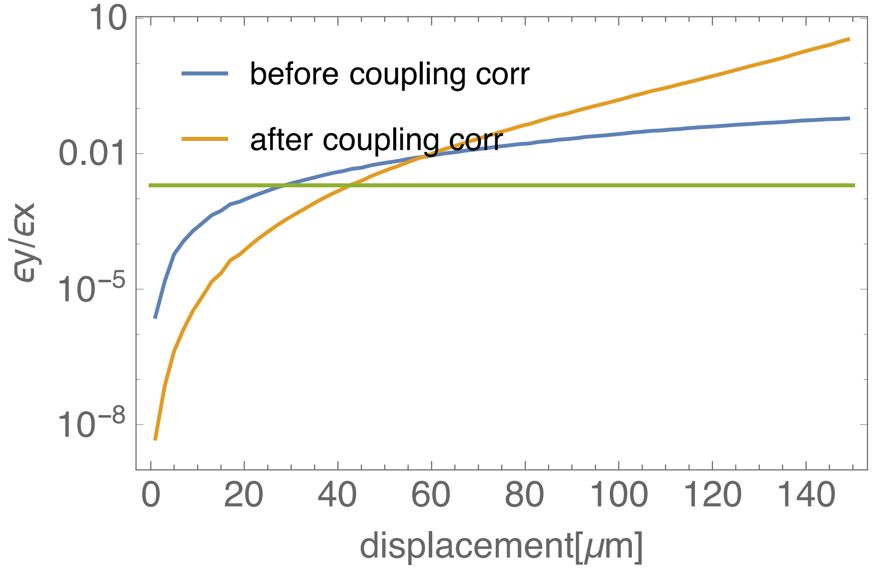
To correct $$\begin{bmatrix} \Delta Re_{13} \\ \Delta D_y \end{bmatrix}_{bpm} = M J_{skew}$$

Javier Alabau Gonzalo for CLIC damping ring

Preliminary results for coupling correction

120 GeV -1m/2mm beta*

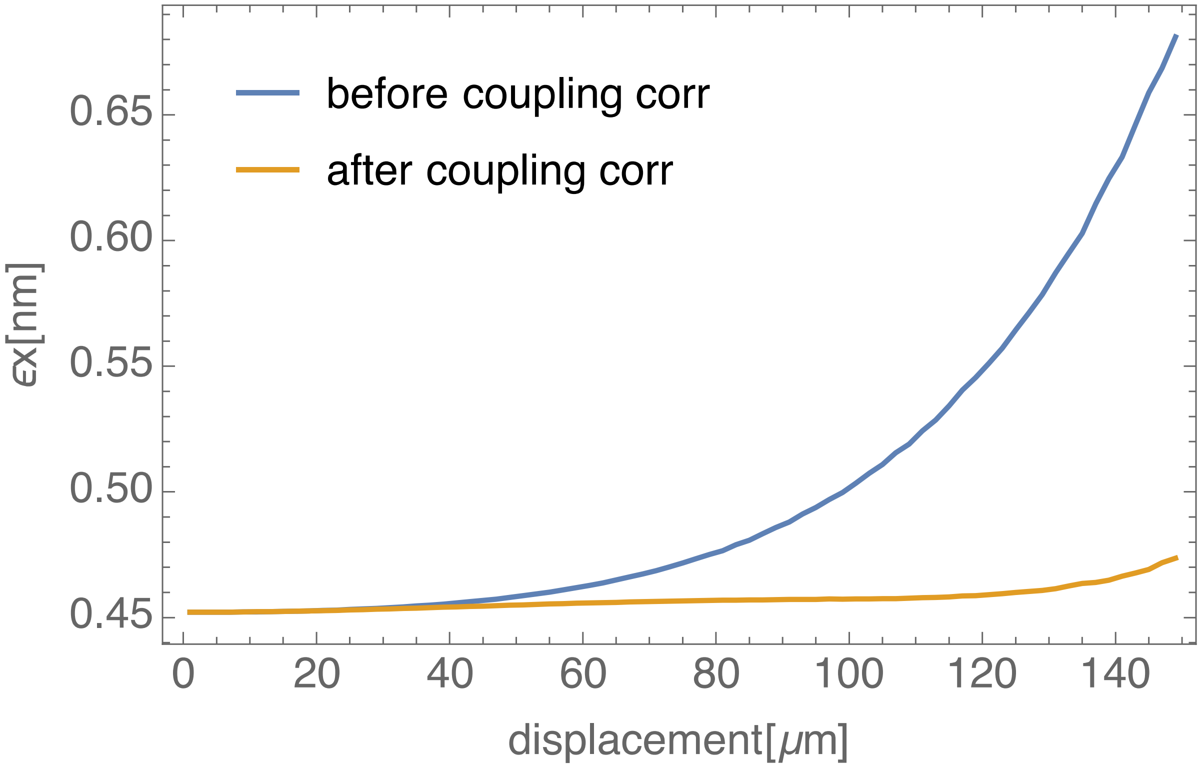




- 0.060 mm tolerance for quadrupole tolerance
- Above 0.060mm, coupling correction counter-productive

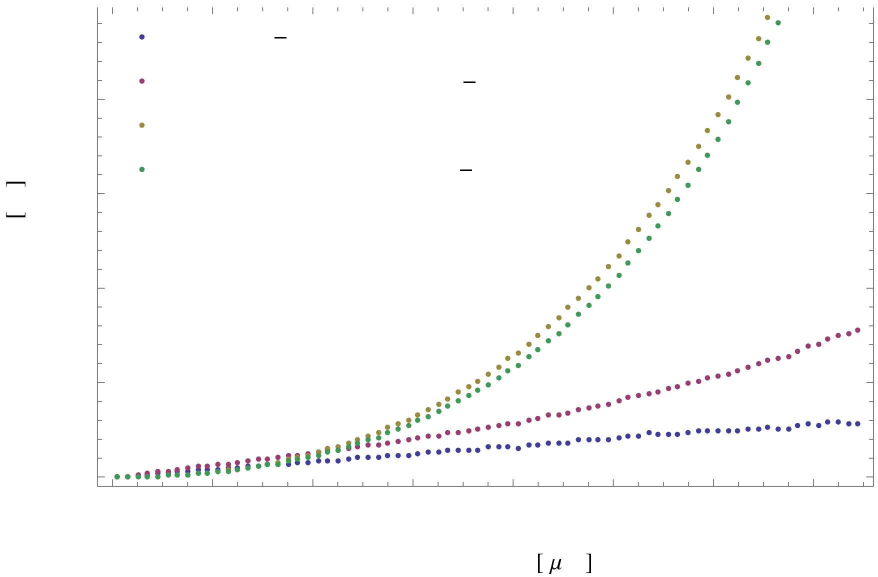
120GeV-1m/2mm-2IPs

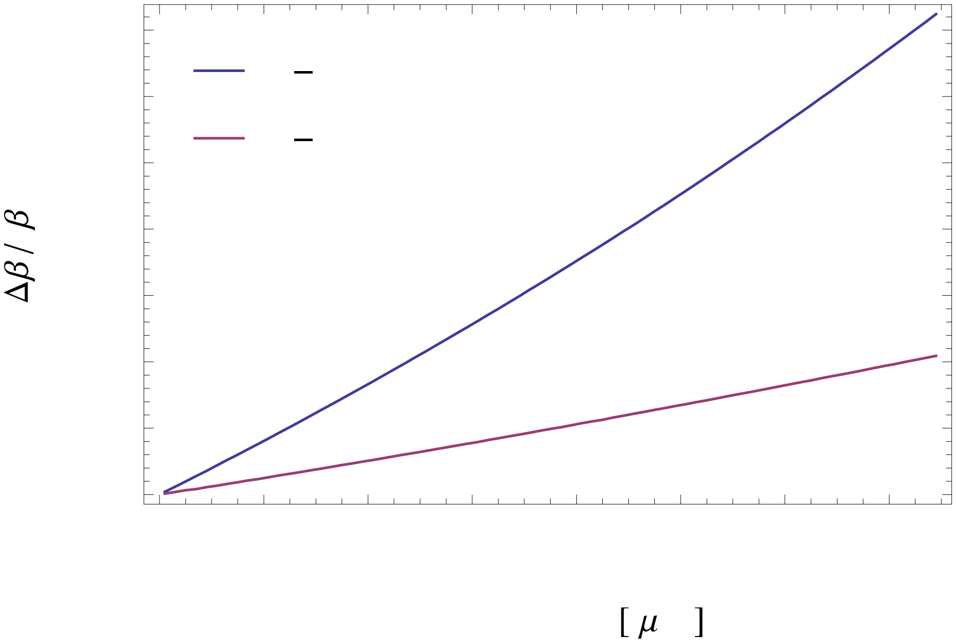
Horizontal Emittance



Preliminary results
for coupling correction

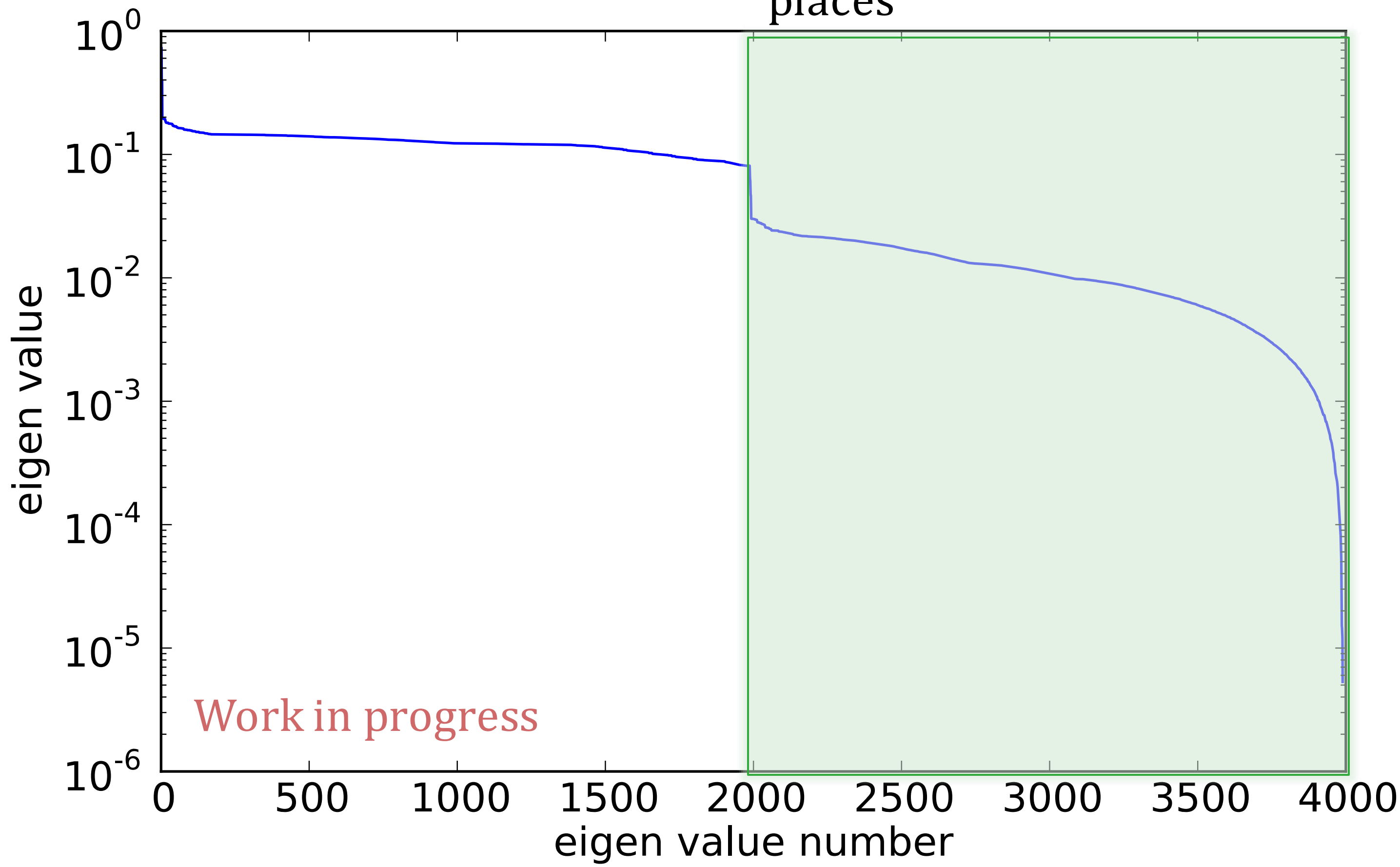
- Very likely explanation:
  optics mismatch, vertical dispersion mismatch,
  skews combination/optimization





SVD decomposition
Eigen values

Optimization of the number of eigenvalues & skews & places

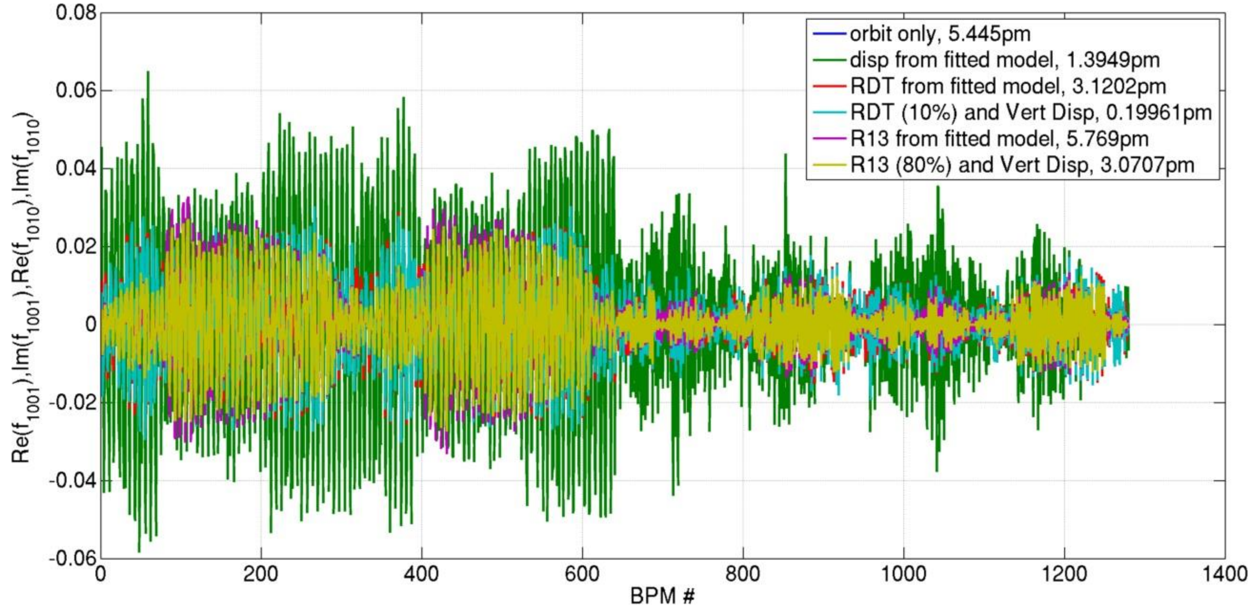


Resonance Driving Term method from ESRF

$$m_{w,c} = \frac{\sqrt{\beta_x^{(c)}\beta_y^{(c)}}e^{i(\Delta\phi_{w,x}^{(c)} - \Delta\phi_{w,y}^{(c)})}}{4(1 - e^{2\pi i(Q_u - Q_v)})}$$

$$m_{w,c} = \frac{\sqrt{\beta_x^{(c)}\beta_y^{(c)}}e^{i(\Delta\phi_{w,x}^{(c)} + \Delta\phi_{w,y}^{(c)})}}{4(1 - e^{2\pi i(Q_u + Q_v)})}$$

$$\begin{pmatrix} \vec{f}_{1001} \\ \vec{f}_{1010} \end{pmatrix}_{\text{meas}} = -\mathbf{M}\vec{J}_c,$$

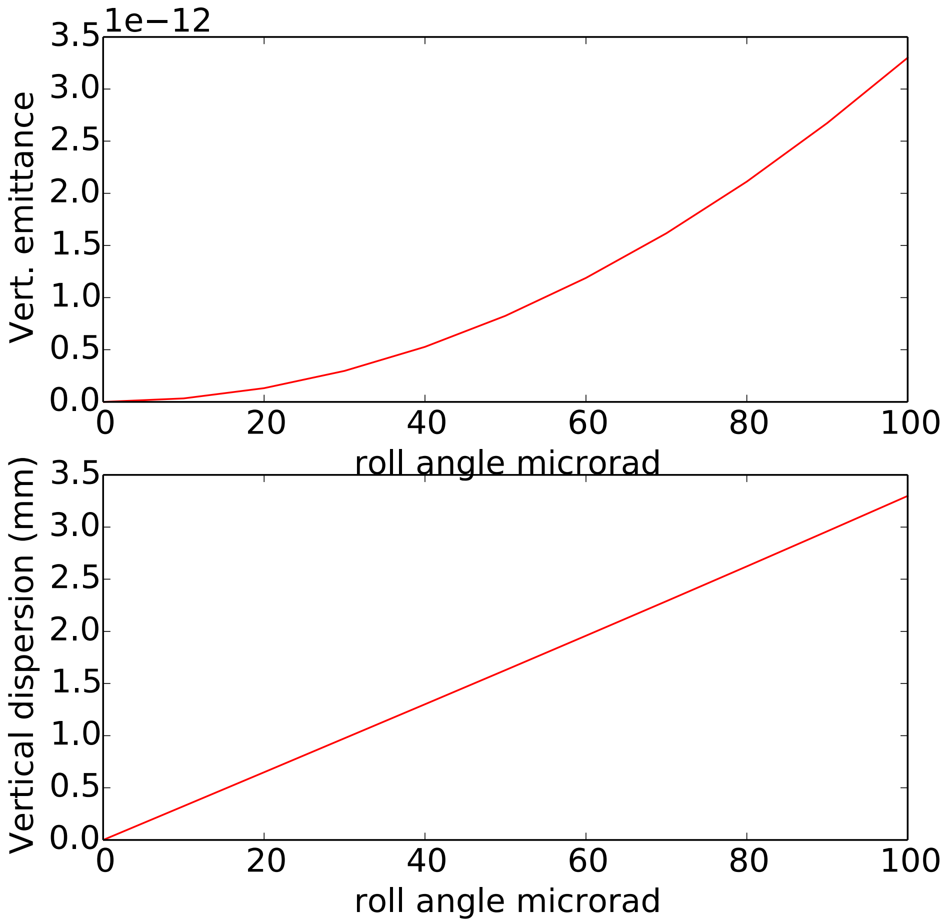


Linear!

Courtesy S. Liuzzio

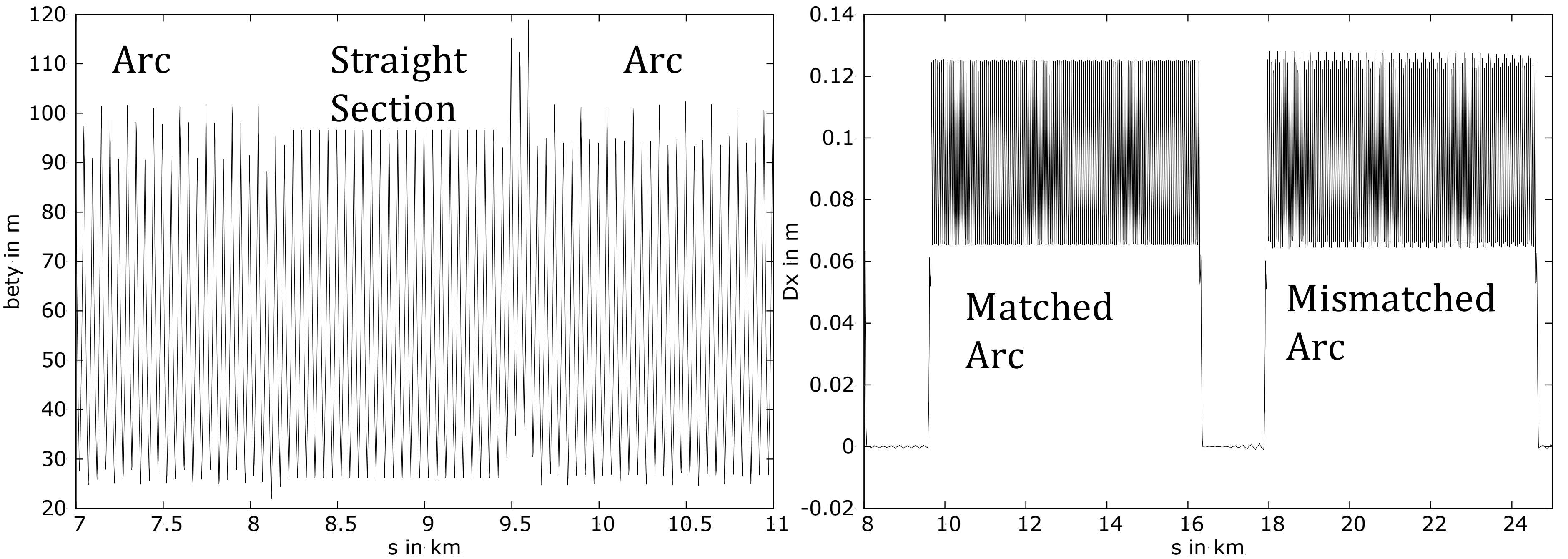
Rolls angle in quadrupoles

- 120 GeV – 1m/2mm beta*
- Before coupling correction
- More relax situation than quadrupole misalignments

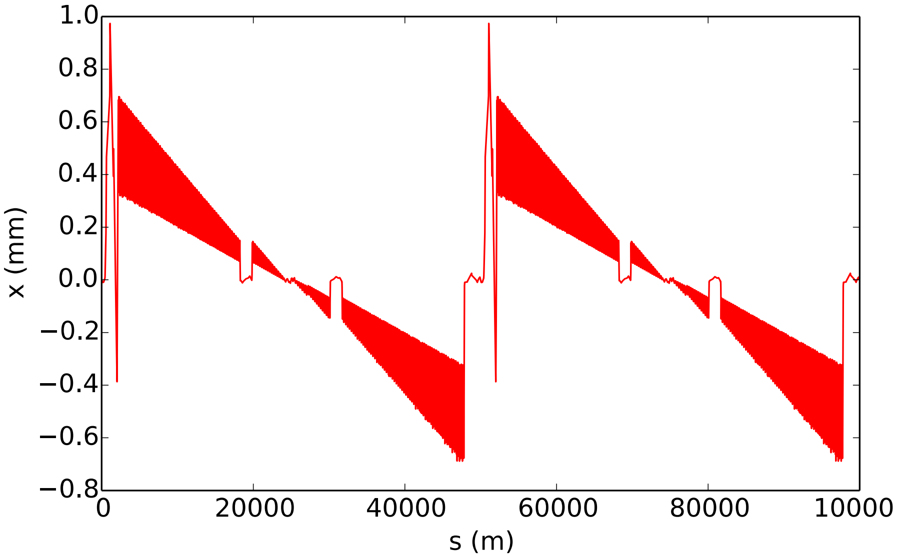


Matching of FCC-ee optics

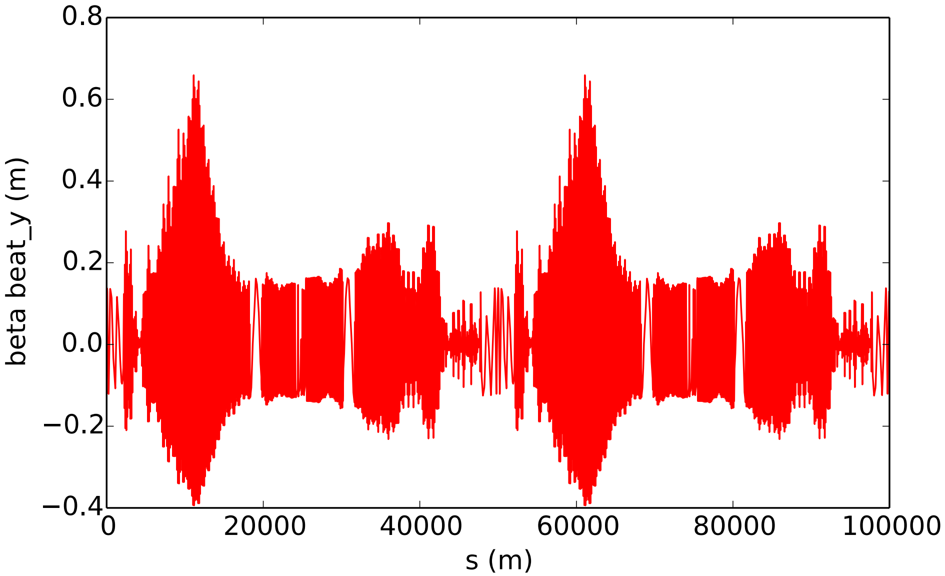
- Use Dispersion suppressor/matching sections to rematch in straight sections and arcs. (ARC- Dispersion Suppressor – Matching section -SS – FF – IP)
- Do not touch the quads of the arcs (4000 quads in the machine)
- Work in progress



Racetrack lattice 120GeV – no tapering



Non linear beta_beat



120GeV -2 Ips – 2mm beta* - 2RF sections
Strong beta beat sur sawtooth – need to be tapered

Conclusions – Next steps

- Challenging machine in terms of tolerances
  toward linear collider requirements for tolerances
- Beta-beating and vertical dispersion spoil the vert. emittance during the coupling correction

  - Re-matching of the machine (Resp. matrix based on ideal machine)
  - Improve SVD decomposition for response matrix (exclude certain eigenvalues)
  - skews in Dispersion Suppressor section less efficient.

- Comparison with RDT method (A. Franchi et al., PRSTAB 14.0034002) – Able to measure
- Tolerance for a Racetrack lattice - local chromaticity correction at the IPs (Katsunobu Oide) – Tunnel fitting with the FCC-hh machine

Thank you for your attention!

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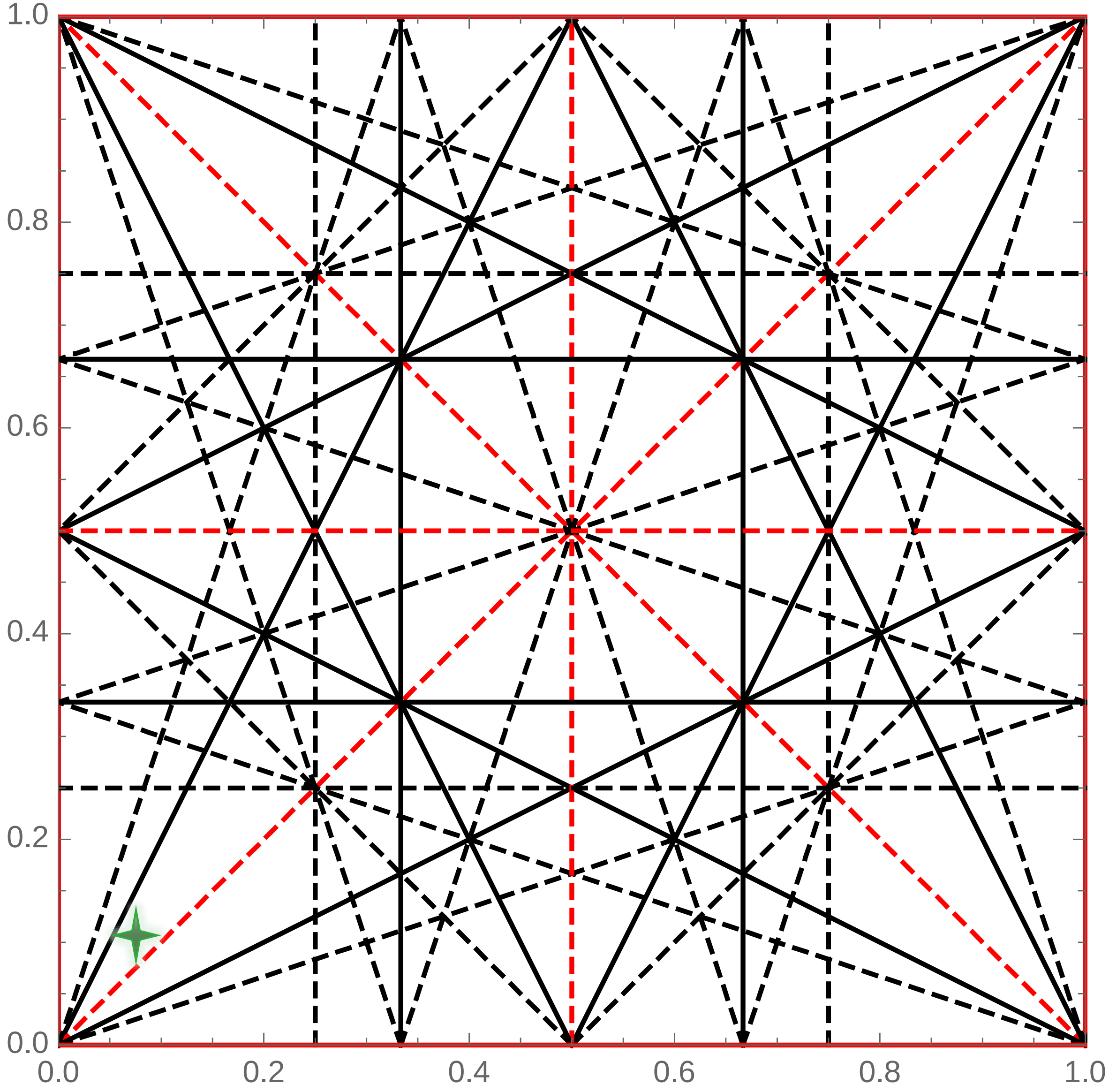
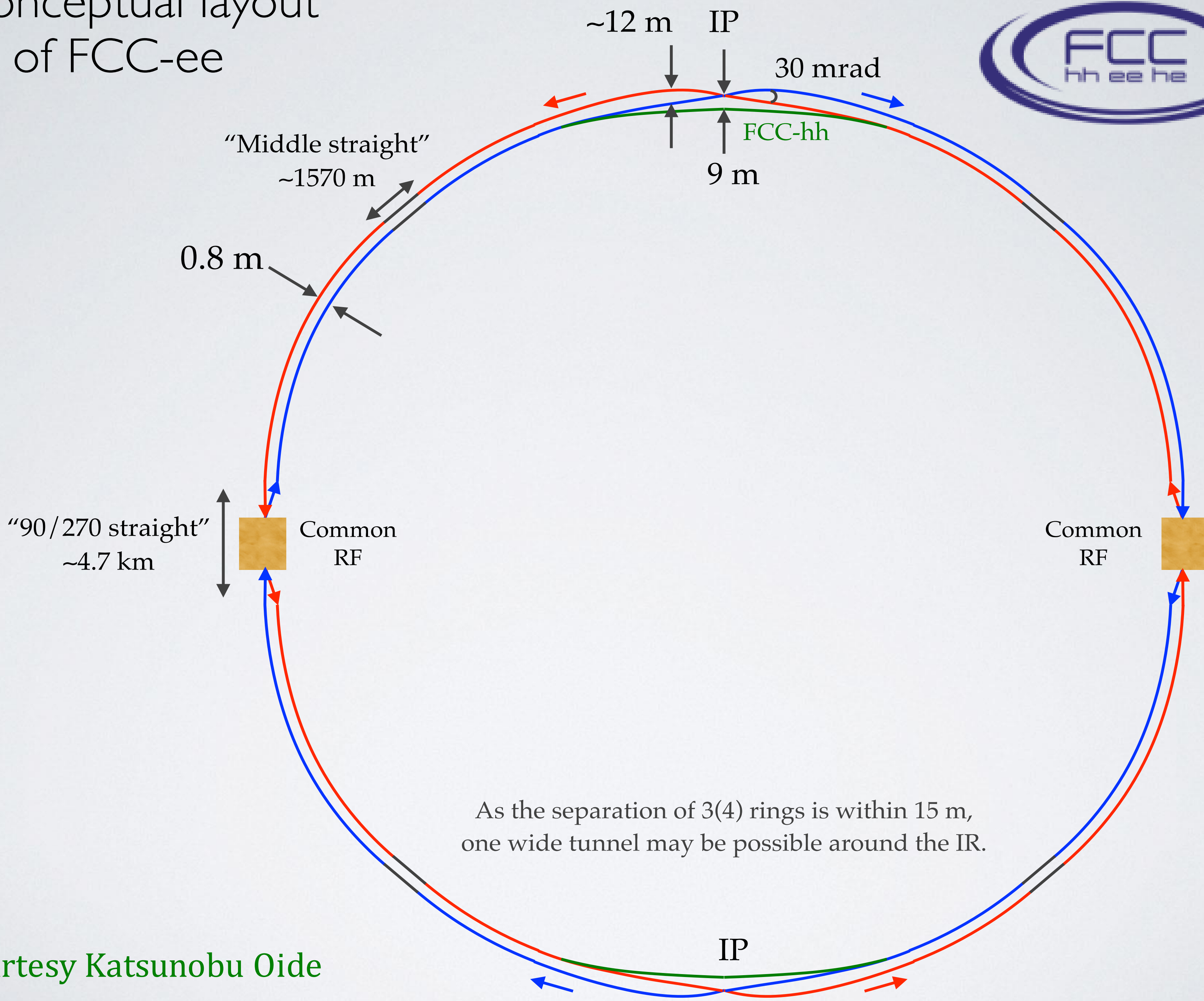

1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0

A conceptual layout of FCC-ee

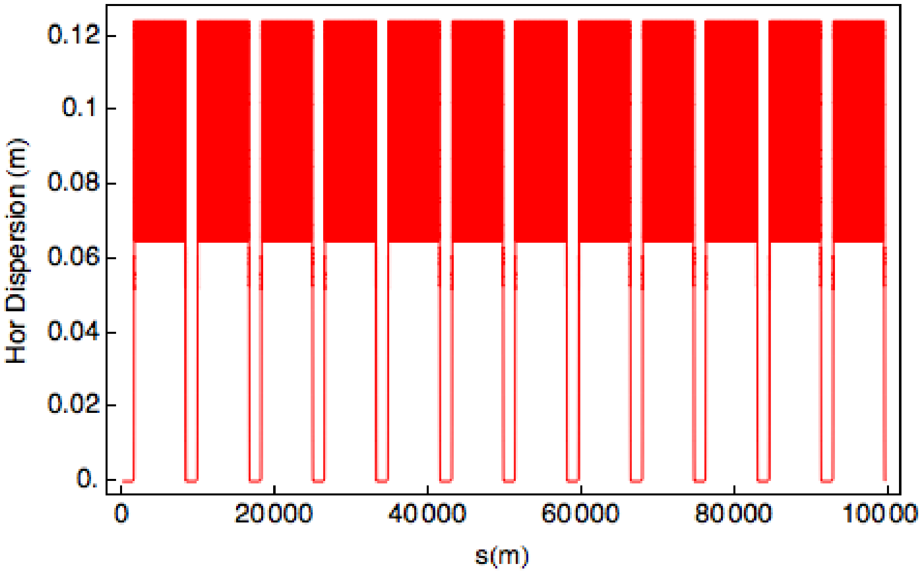


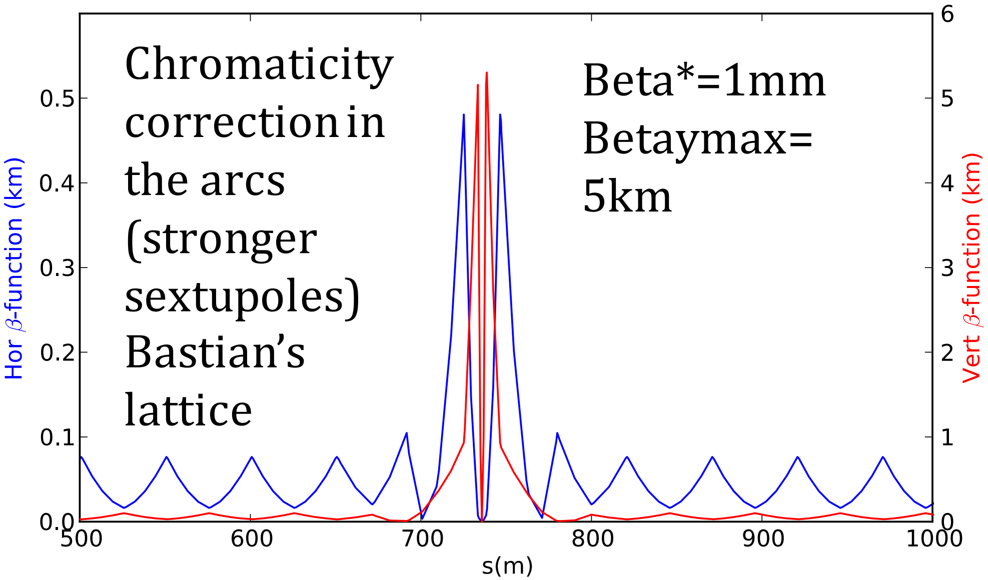
As the separation of 3(4) rings is within 15 m, one wide tunnel may be possible around the IR.

Courtesy Katsunobu Oide

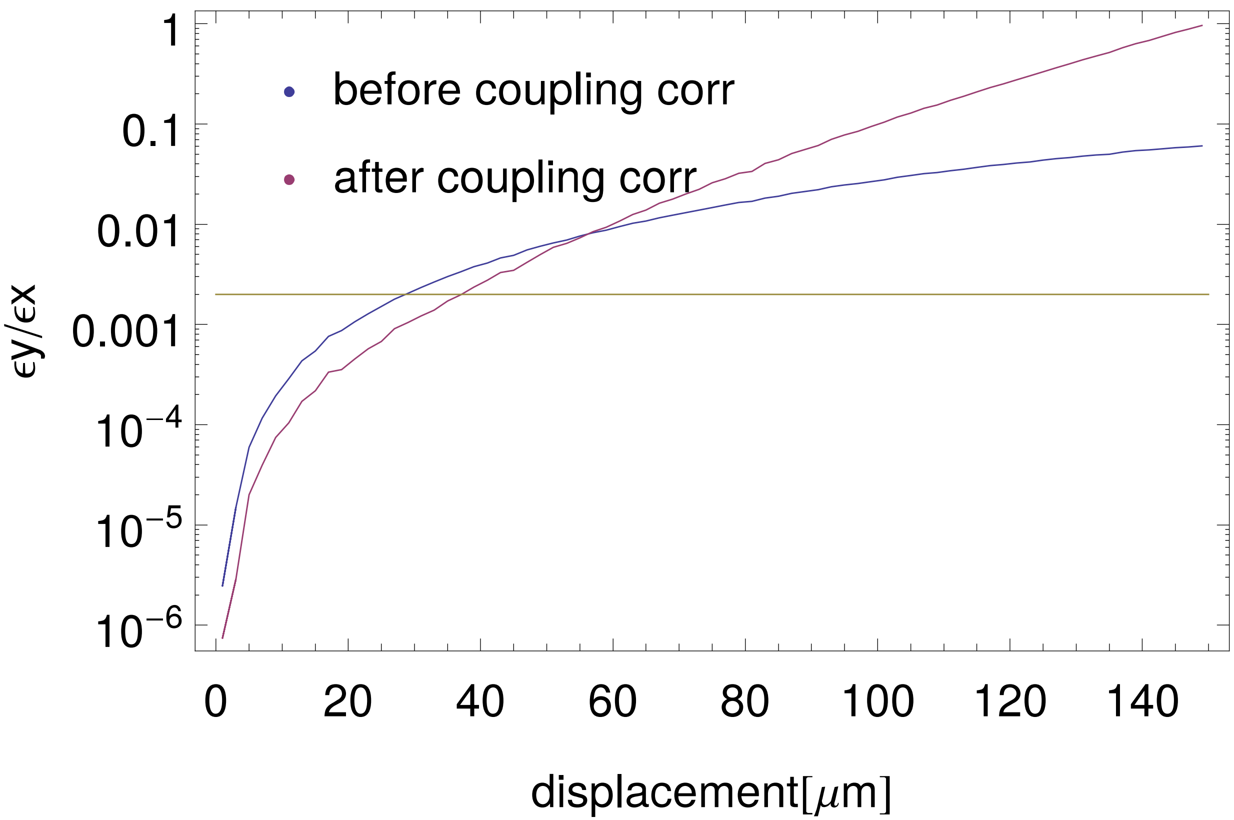
Optics at the IR

- Optics for 120GeV (H) and 175GeV (ttb)
- From Bastian Haerer's presentation, tuning of the cell length and phase advance to get the correct emittances.
- 2 lattices with 2 scheme of chromaticity correction (in the arc or around the IPs)

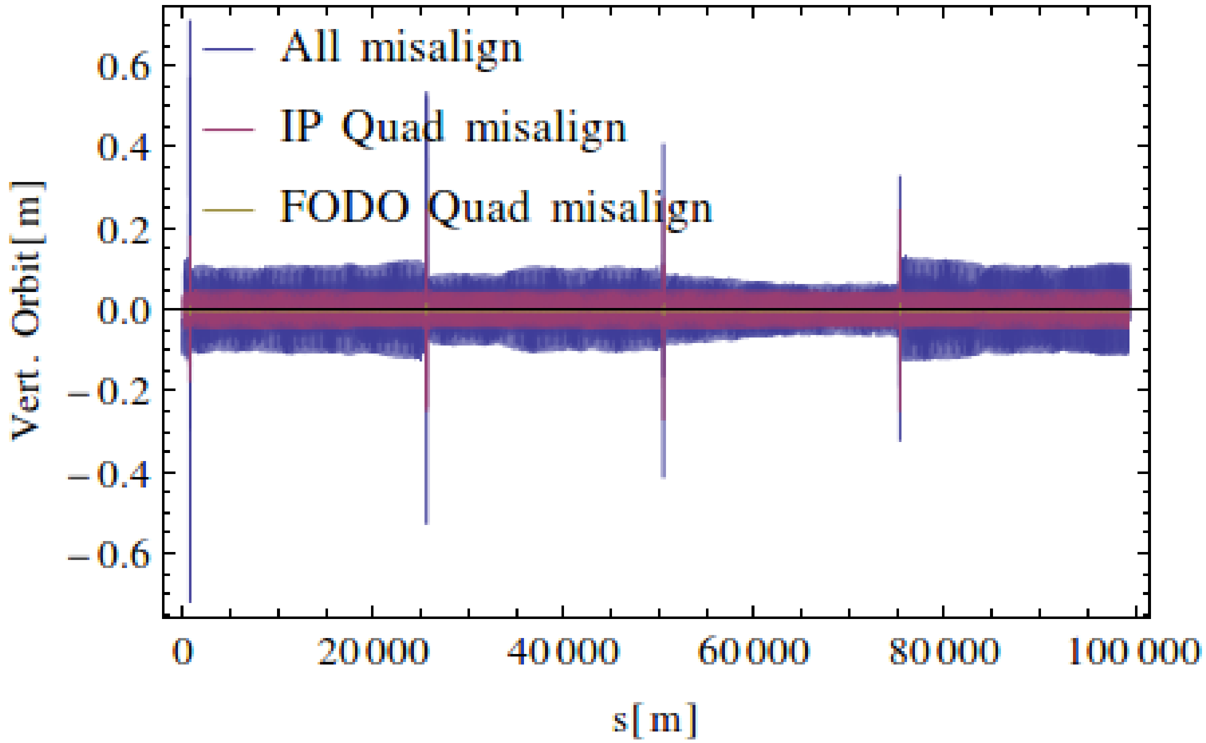




Only Coupling



Influence quadrupoles of IPs



Main challenges: parameter list

	Z	W	H	tt
Beam energy [GeV]	45.5	80	120	175
Beam current [mA]	1450	152	30	6.6
Bunches / beam	16700	4490	1330	160
Bunch population [10^{11}]	1.8	0.7	0.46	0.83
Transverse emittance ε - Horizontal [nm] - Vertical [nm]	 29.2 0.06	 3.3 0.007	 0.94 0.0019	 2 0.002
Momentum comp. [10^{-5}]	18	2	0.5	0.5
Betatron function at IP β* - Horizontal [mm] - Vertical [mm]	 500 1	 500 1	 500/1000 1/2	 1000 1/2
Energy loss / turn [GeV]	0.03	0.33	1.67	7.55
Total RF voltage [GV]	2.5	4	5.5	11

- Lattice design & optimization for 4 different energies
- Lattices with 2 and 4 IPs
- **Coupling ratio V.emit/H.emit ~0.2 & 0.1%**
- Challenging chromaticity correction scheme (chromaticity carried 90% by IR, 10% Arc) – B. Haerer and A. Bogomyakov

Average synchrotron radiation power per turn

$$P = \frac{cC_\gamma \beta^3 E^4}{2\pi R\rho} \longrightarrow P_{175}/P_{45} \approx 200$$

Emittance tuning in electron storage rings

L.C. Teng "Minimizing the Emittance in Designing the lattice of an Electron Storage Ring", 1984.

$$\epsilon_x = \frac{C_g}{J_x}\gamma^2\theta^3 F \qquad F_{FODO} = \frac{1}{2\sin\psi}\frac{5+3\cos\psi}{1-\cos\psi}\frac{L}{l_B}$$

L: cell length

l_B: dipole length

ψ : phase advance/cell

To match the baseline parameters, **Bastian Haerer** tuned cell length- phase advance per cell (90/60 degrees)

Energy (GeV)	Cell length (m)
45	300
80	100
120	50
175	

Emittance tuning in electron storage rings

Alignment errors, rolls angle and coupling spoil the vertical emittance and compromise the coupling of 1/1000 (2/1000)

-> <u>Coupling and Dy should be under control.</u>

$$\epsilon_y = 2\frac{J_z}{J_y}\left\langle \frac{D_y^2}{\beta_y} \right\rangle \sigma_\delta^2$$