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Dynamic aperture, ideal and with errors for FCC-ee

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Outline

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- FCC-ee will provide unprecedented luminosities

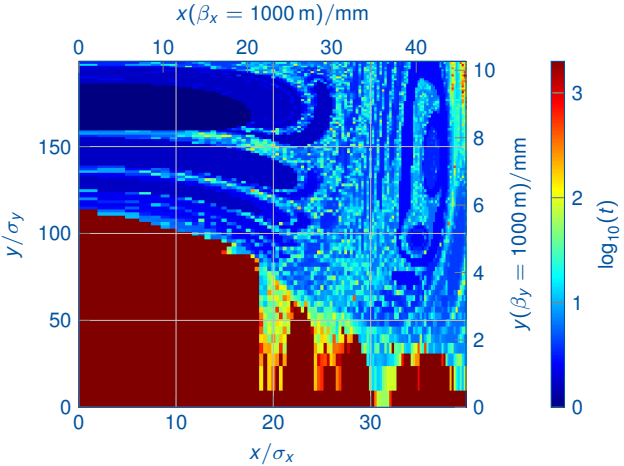
$\Leftrightarrow$ top-up injection into fully squeezed magnet optics required

- lossless injection guaranteed if:
  - dynamic aperture sufficiently large
  - momentum aperture sufficiently large
- studies of dynamic and momentum aperture with and without misalignment errors are presented

Outline

4D Dynamic Aperture

- tracking using MAD-X-PTC
- tracking done at 175 GeV
- 2000 turns, 4D case, no radiation
- region of stability up to $\sim 20\,\sigma_x/100\,\sigma_y$



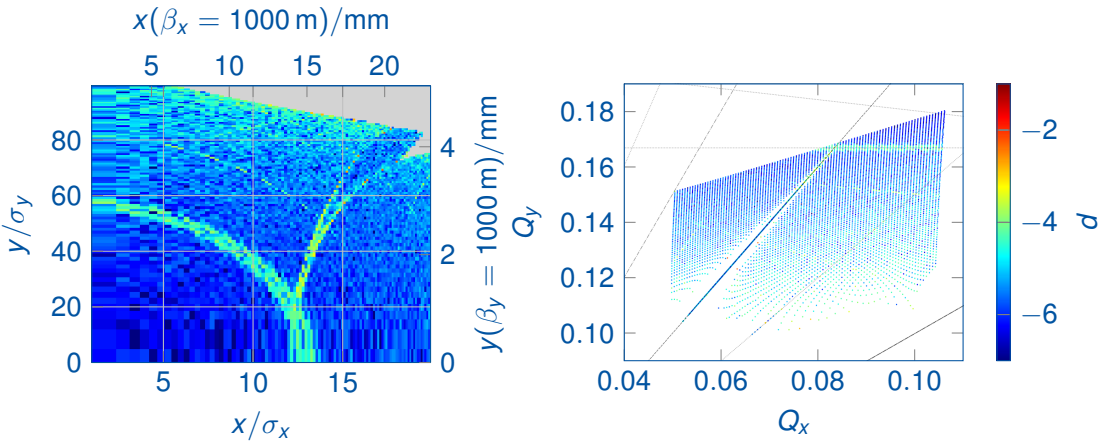
FMA of stable region (I)

- previously determined stable region up to $\sim 20\,\sigma_x / 100\,\sigma_y$
- apply frequency map analysis (FMA) to study of non-linear beam dynamics
- diffusion rate defined as $d = \log_{10}\left[\sqrt{\left(\nu_x^{(2)} - \nu_x^{(1)}\right)^2 + \left(\nu_y^{(2)} - \nu_y^{(1)}\right)^2}\right]$
- $\nu_i^{(1/2)}$ referring to tune determined from 1st / 2nd half of tracked turns using numerical analysis of fundamental frequencies (NAFF)
  NAFF: $\Delta\nu \approx 1/t^3$ FFT: $\Delta\nu \approx 1/t$

Y. Papaphilippou, *Detecting Chaos in Particle Accelerators through Frequency Map Analysis Method*, Chaos 24 (2014) 024412, 2014

J. Laskar, *Frequency map analysis and particle accelerators*, Proceedings of the 2003 Particle Accelerator Conference, 2003, pp. 378-382 Vol.1

FMA of stable region (II)



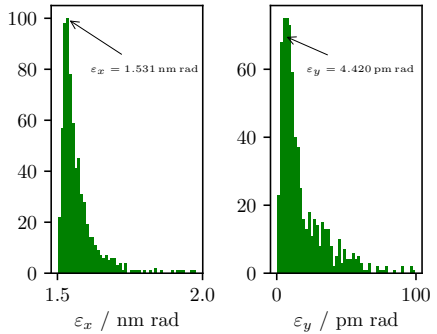
- reasonable choice of working point
- first interaction with resonances for amplitudes of $\sim 12\,\sigma_x$

Outline

Misalignments and corrections

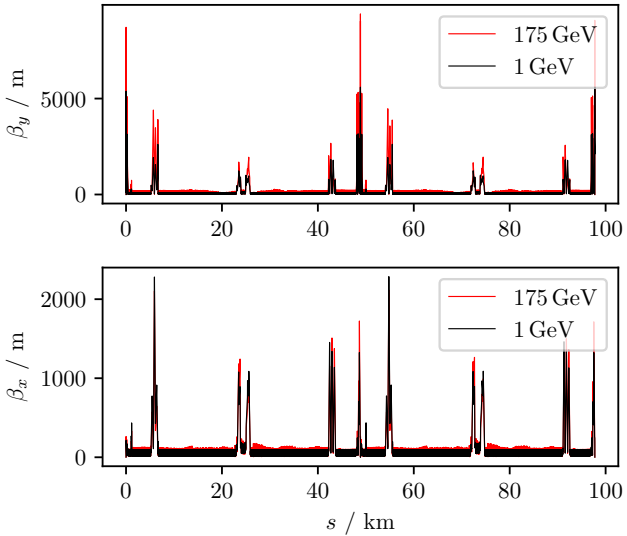
- misalignments introduced and corrected (comp. previous presentation by T. K. Charles: *Optics Correction and Emittance Performance for FCC-ee at 175 GeV*)
- misalignment assigned to quadrupoles / sextupoles with Gaussian random number generater truncated at 2.5 σ
- corrections performed at 1 GeV
- after corrections are applied, energy is increased to 175 GeV and tapering applied
- emittance determined using `EMIT` module in MAD-X

	σ_x	σ_y	σ_θ
arc quadrupoles	100 µm	100 µm	100 µrad
IP quadrupoles	50 µm	50 µm	50 µrad
sextupoles	100 µm	100 µm	



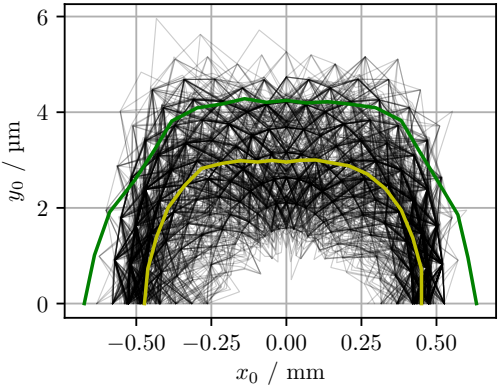
Beta beat after correction

- at 1 GeV, where corrections are performed:
  - beta beat under control
- transition to 175 GeV and turning on radiation:
  - beta beat is at a much higher level
  - reason was a bug in tapering procedure



Dynamic aperture with misalignments & residual beta beat

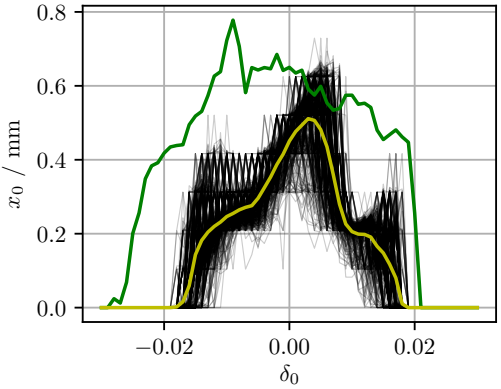
- (semi) corrected machines for 1000 seeds
- displayed are 580 seeds yielding more than 0.25 mm $\approx 6\,\sigma_x$ at IP
- tracking for 100 turns corresponding to 4 longitudinal damping times
- tracking including radiation damping and quantum excitation
- average horizontal aperture corresponds to $\sim 11.3\,\sigma_x$



Momentum aperture with misalignments & residual beta beat

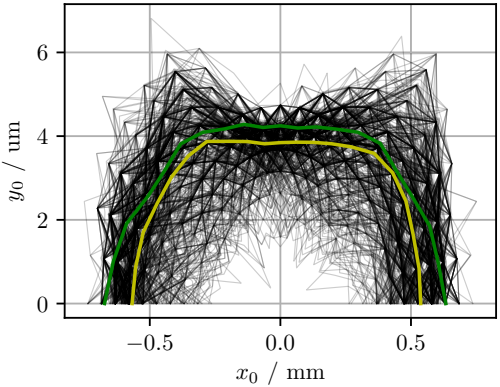
- (semi) corrected machines for 1000 seeds
- displayed are 580 seeds yielding more than 0.25 mm $\approx 6\,\sigma_x$ at IP
- tracking for 100 turns corresponding to 4 longitudinal damping times
- tracking including radiation damping and quantum excitation
- momentum aperture incl. 80 % beta-beat: ± 1.7 %

$\Rightarrow$ sufficient for beam storage



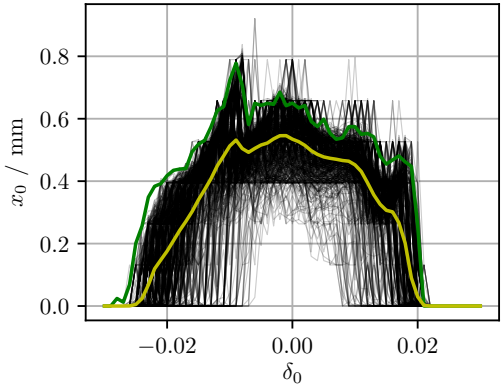
Dynamic aperture with misalignments

- corrected machines for 1000 seeds
- displayed are 675 seeds yielding more than 0.25 mm $\approx 6\,\sigma_x$ at IP
- tracking for 100 turns corresponding to 4 longitudinal damping times
- tracking including radiation damping and quantum excitation
- average horizontal aperture corresponds to $\sim 13.5\,\sigma_x$

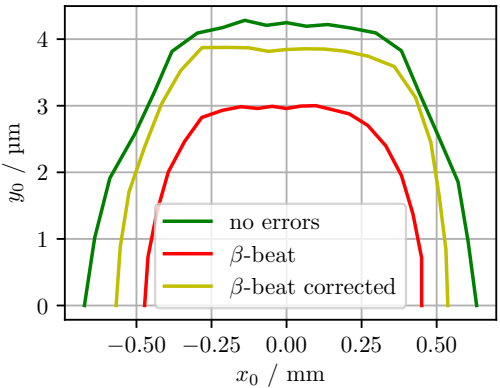


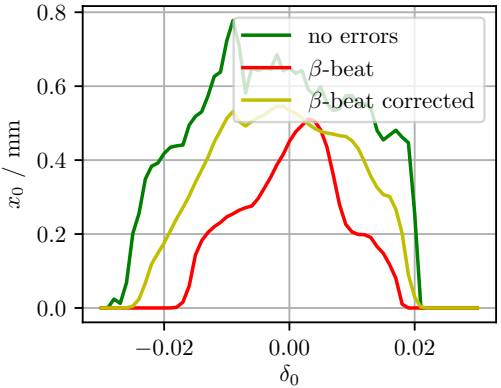
Momentum aperture with misalignments

- corrected machines for 1000 seeds
- displayed are 675 seeds yielding more than 0.25 mm $\approx 6\,\sigma_x$ at IP
- tracking for 100 turns corresponding to 4 longitudinal damping times
- tracking including radiation damping and quantum excitation
- momentum aperture: $-2.5\,\%/2.1\,\%$



Comparison of dynamic / momentum aperture





- with 80 % beta-beat, dynamic / momentum aperture sufficient for beam storage
- dynamic / momentum aperture due to misalignments large enough for storage / injection

Conclusion & Outlook

- dynamic and momentum aperture have been studied including misalignments
- for misalignments including 50 µm rms of IP quadrupoles

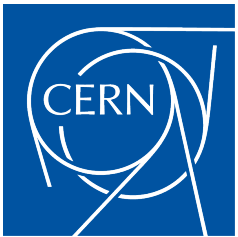
$\Rightarrow$ dynamic and momentum aperture sufficiently large for both beam storage and injection ($13.5\,\sigma_x$, $-2.5\,\%/2.1\,\%$)

- in the case of considerable beta beat in the order of 80 % and including 50 µm misalignment of IP quadrupoles:
  - dynamic aperture still larger than $10\,\sigma_x$
  - momentum aperture only reduced to $\pm 1.7\,\%$

  $\Rightarrow$ sufficient for beam storage
- next steps in this study include:
  - adapt correction script to perform yet another correction at 175 GeV
  - different misalignment amplitudes as well as
  - multipole field errors will have to be studied

Thank you for your attention...

Acknowledgements:
P. Skowronski, F. Zimmermann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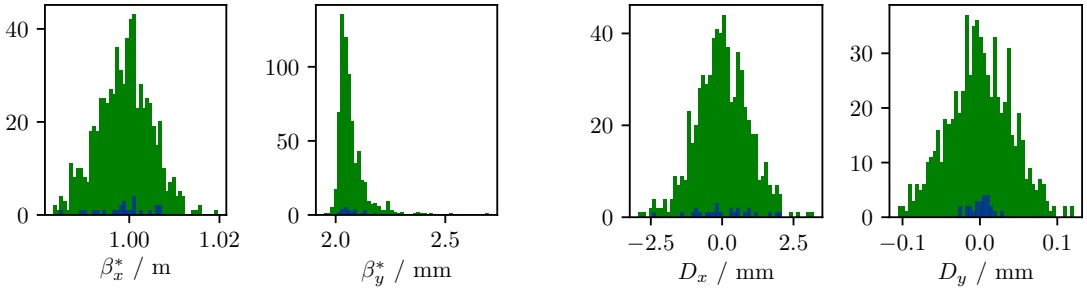
Back up slides

Correction procedure by S. Aumon

1. assign errors, switch off sextupoles
2. orbit correction
3. pure coupling correction
4. rematch hor. dispersion
5. loop over
   - 5.1 dispersion free steering w/o sextupoles (D_y correction)
   - 5.2 coupling correction
6. save closed orbit at start of machine
7. switch on sextupoles in loop over
   - 7.1 orbit correction
   - 7.2 coupling correction
   - 7.3 beta beat, hor. dispersion correction
   - 7.4 coupling, ver. dispersion correction

from: S. Aumon, "Status of Tolerance Studies for FCC-ee at 175 GeV", Low Emittance Rings Workshop 2018, CERN, 2018

β-function and dispersion at IP



- out of 1000 seeds, 690 converged meaning (arbitrary):
  $\varepsilon_x < 3.0\,\text{nm rad}$, $\varepsilon_y < 100\,\text{pm rad}$
- 25 seeds yield vertical emittance smaller than 2.5 pm rad (blue)

Example of one corrected error seed

- 100 µm arc quadrupole and sextupole misalignment
- perfect IP quadrupole misalignment