Optimization studies and error budget for the ESRF upgrade lattice.

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Outline

PART 1: low emittance lattices

PART 2: highlights from PhD thesis

1. Optimization of lattices under design
2. Experimental results on correction of lattice errors in existing accelerators
3. Estimation of error tolerances

Luminosity and Brilliance

Colliders

Luminosity

R = L σ

$$\mathcal{L} = \frac{N^+N^-}{4\pi\sigma_y\sqrt{(\sigma_z \tan\frac{\theta}{2})^2 + \sigma_x^2}} f_c$$

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\epsilon_{\mathbf{x,y}}}$$

Light sources

Brilliance

B = photons/(s mm² mrad² BandWidth)

$$B_n = \frac{F_n}{4\pi^2(\varepsilon_x + \lambda_n/4\pi)(\varepsilon_y + \lambda_n/4\pi)}$$

$$\epsilon_{(\mathbf{x,y})} < \frac{\lambda}{4\pi}$$

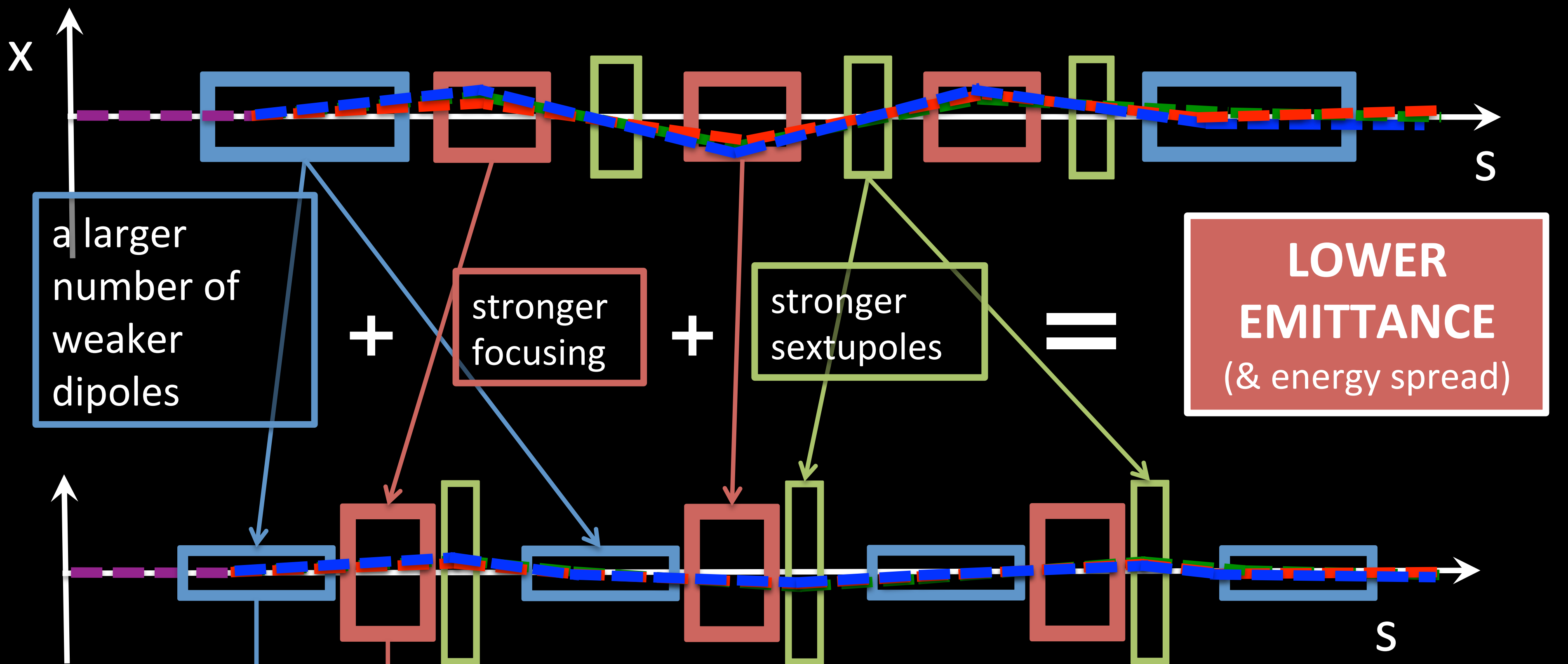
Diffraction limit,
at λ=10nm is 10 pmrad
(lower ε does not increase B)

Low horizontal and vertical emittance

Limited by accelerator magnetic lattice and errors

Limited by errors

How to reduce the lattice emittance



$$E_x \propto \frac{\beta_x D_x}{\rho} \qquad (@\,dipoles)$$

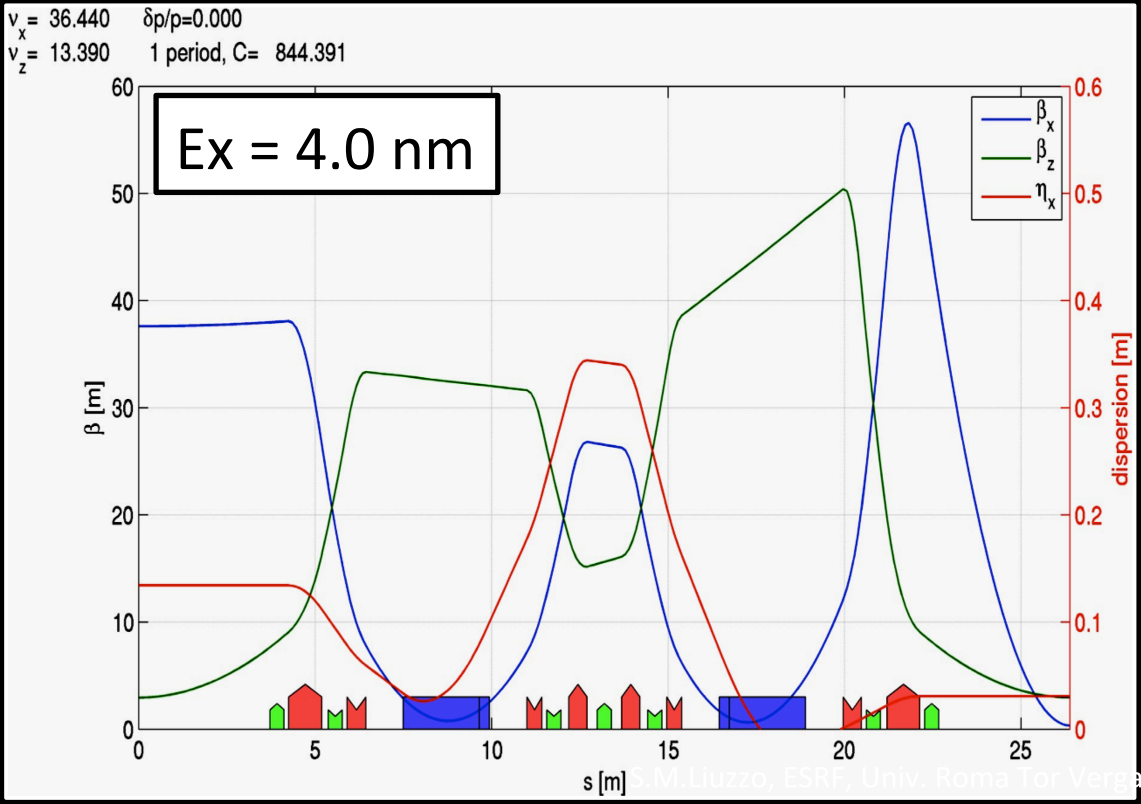
In the vertical plane no DIPOLES (usually): no synch. radiation emission.
equilibrium emittance is limited only by the statistical nature of radiation, emitted in a cone of 1/gamma aperture (in both planes).

Low horizontal emittance lattices

No radiation in the vertical plane, only dumping.

$$E_x \propto \frac{\beta_x D_x}{\rho} \qquad (@\,dipoles)$$

$$Chromaticity\ [>0] \propto -\beta_x K_1\ (@\,quads)\ + D_x K_2\ (@\,sext.)$$



ESRF present lattice (Double-Bend Achromat)

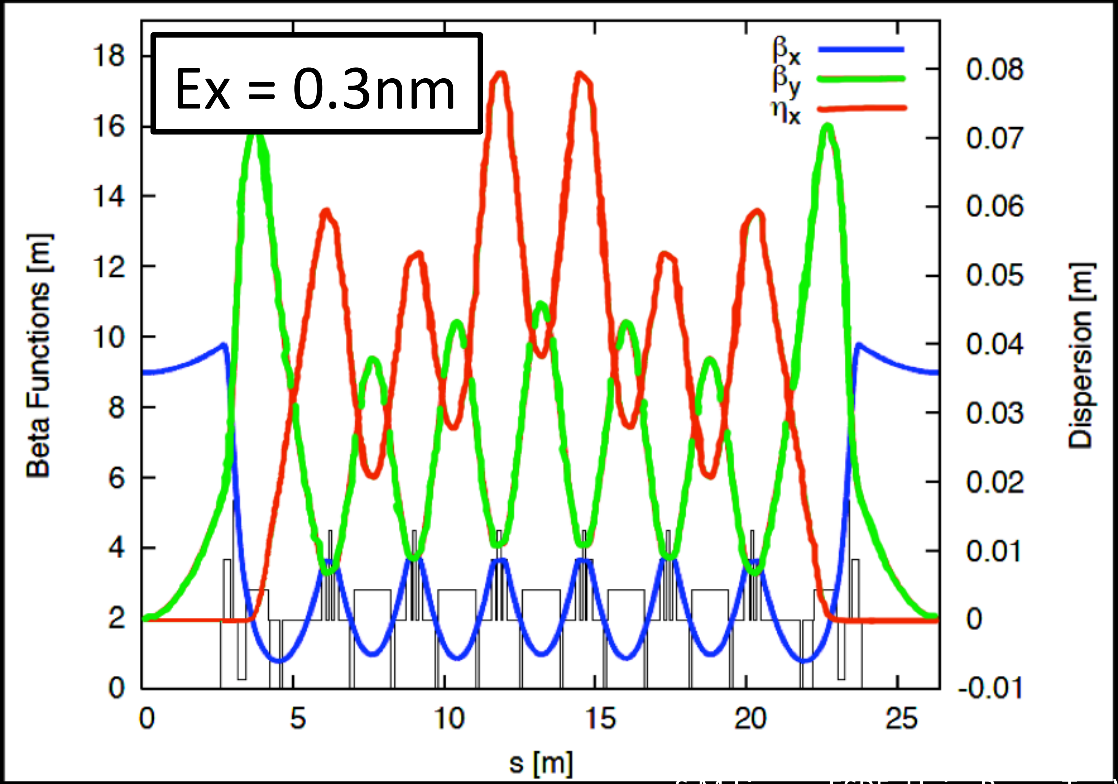
- Many 3rd gen. SR sources
- Strong focusing (large K_1)
- D_x, β_x~0 @ 2 dipoles
- Local dispersion bump (large D_x @ sext.) for chromaticity correction with **low** sextupole fields (K_2)

Low horizontal emittance lattices

No radiation in the vertical plane, only dumping.

$$E_x \propto \frac{\beta_x D_x}{\rho} \quad (@\,dipoles)$$

$$Chromaticity\ [>0] \propto -\beta_x K_1\ (@\,quads) \ + D_x K_2\ (@\,sext.)$$



MAX-IV lattice (Sweden)
(7-Bend Achromat)

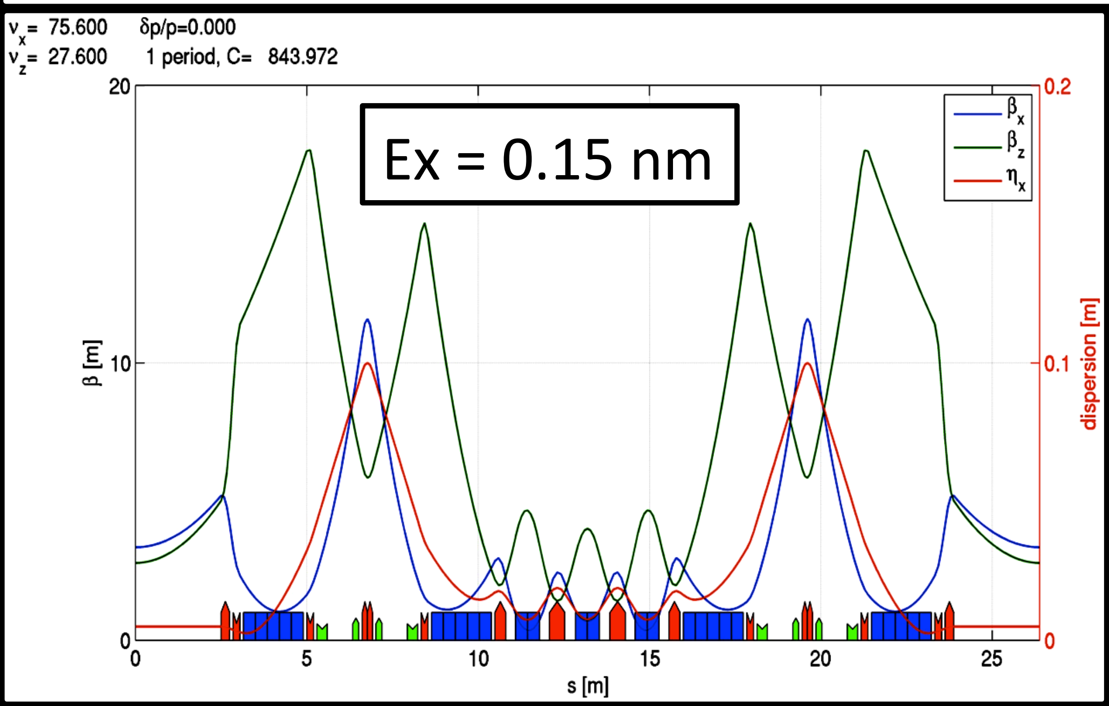
- Many recent low emittance lattice designs
- Strong focusing (large K_1)
- $D_x \neq 0$, $\beta_x \sim 0$ @ 7 dipoles
- No dispersion bump (small D_x @ sext.) for chromaticity correction with **high** sextupole fields (K_2)=> poor lifetime

Low horizontal emittance lattices

No radiation in the vertical plane, only dumping.

$$E_x \propto \frac{\beta_x D_x}{\rho} \quad (@\,dipoles)$$

$$Chromaticity\ [>0] \propto -\beta_x K_1\ (@\,quads) + D_x K_2\ (@\,sext.)$$

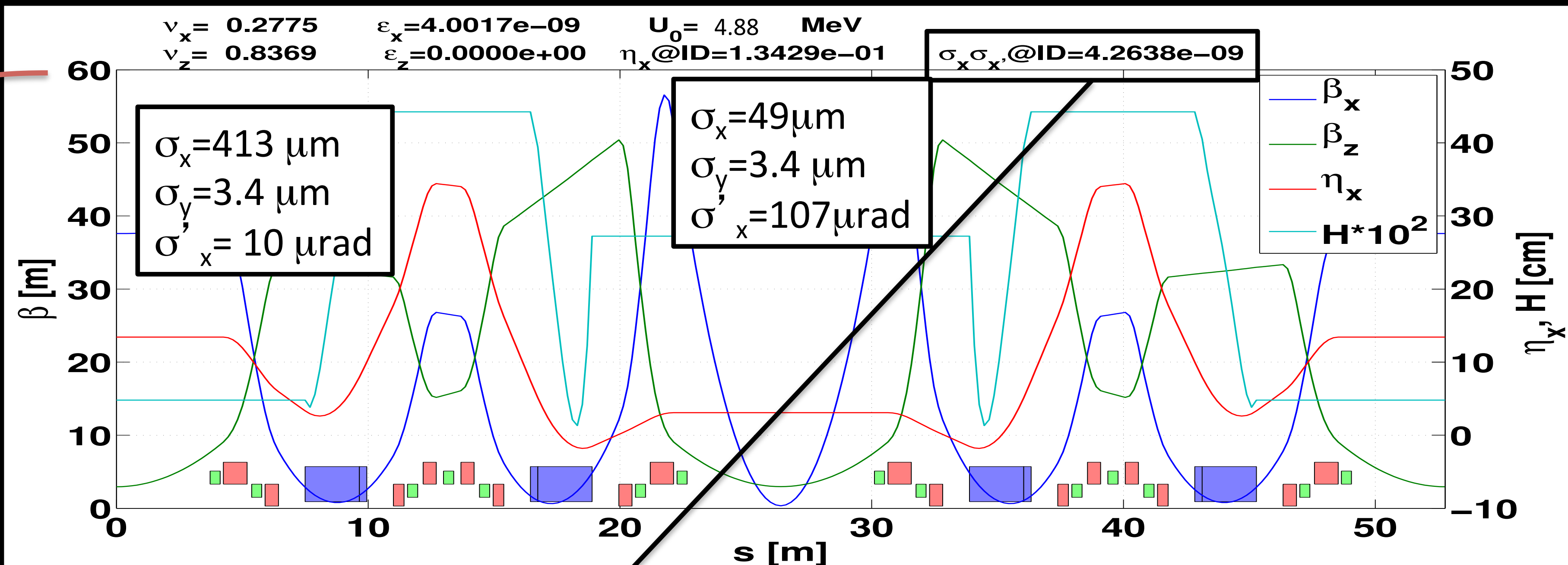


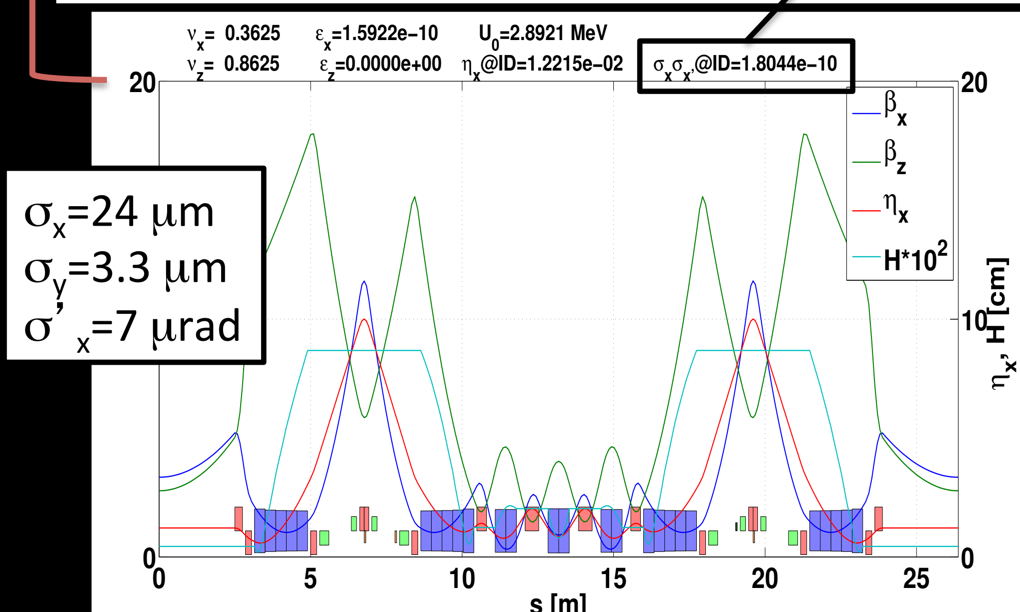
ESRF new lattice (Hybrid Multi-Bend)

- Strong focusing (large K_1)
- D_x, β_x~0 @ 7 dipoles
- 2 Local dispersion bumps (large D_x @ sext.) for chromaticity correction with low sextupole fields (K_2)
- Ex = 0.15nm

The whole lattice is composed of 32 cell as the above

ESRF current vs upgrade lattice





- Stronger focusing, smaller beta functions
- smaller dispersion
- Combined function magnets
- 2 dispersion bump per cell
- 2->7 dipoles per cell
- less energy loss

Highlights from the thesis 1

1. Optimization of the ESRF upgrade lattice dipole fields to obtain a smaller emittance
2. Study and correction of the residual variation of tune with amplitude
3. Measurements for a new correction technique to minimize vertical and horizontal emittance
4. Error budget estimations using LET

ATMATCH OPTIMIZER

ATMATCH OPTIMIZER

Low emittance tuning

Low emittance tuning

Accelerator Physics Codes

Optics (β α γ tune,…) and tracking are computed by all codes

Code name

- MADX
- MAD8
- Accelerator Toolbox
- OPA
- Tracy
- elegant Genetic algorithm
- Beta ESRF
- Geant4Beamline Interaction with matter
- SAD
- Acceleraticum
- MADX-PTC Normal form analysis
- …

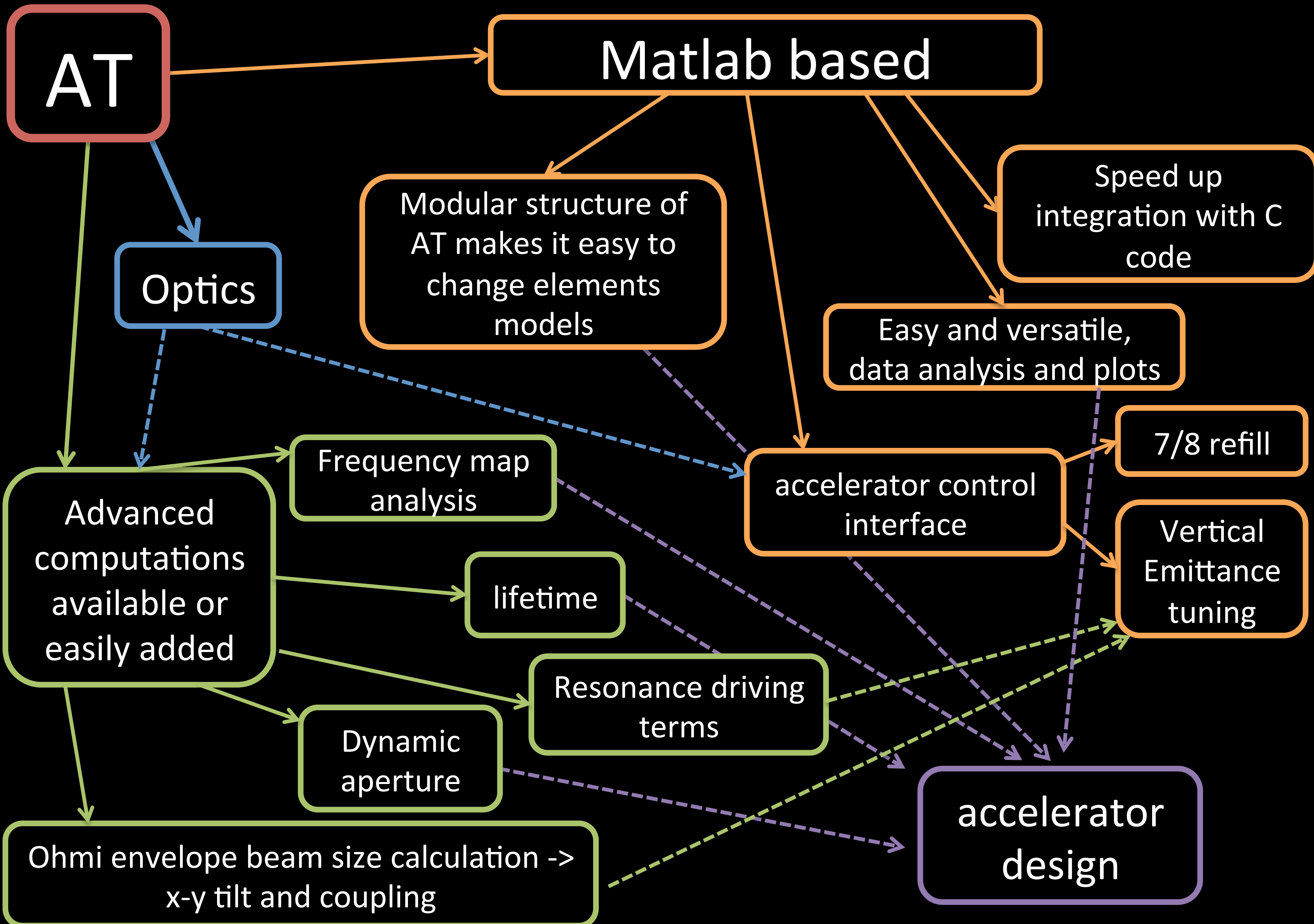
@ ESRF

Code name

- MADX
- MAD8
- AT
- OPA
- elegant
- Beta
- (G4BL)
- MADX-PTC
- …

Lattice input conveters, both directions

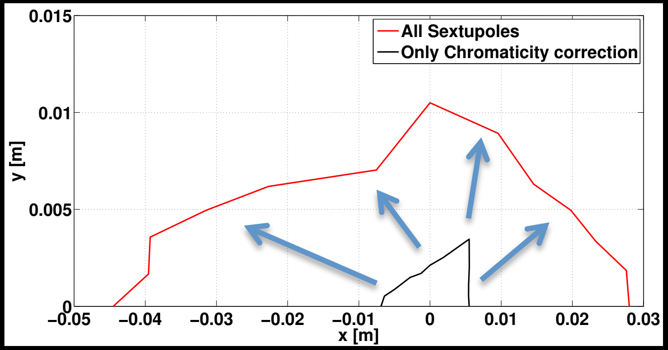
Codes are written in: Fortran, C, Matlab, C++


AT
Matlab based
Optics
Modular structure of AT makes it easy to change elements models
Speed up integration with C code
Easy and versatile, data analysis and plots
7/8 refill
accelerator control interface
Vertical Emittance tuning
Frequency map analysis
Advanced computations available or easily added
lifetime
Resonance driving terms
Dynamic aperture
accelerator design
Ohmi envelope beam size calculation -> x-y tilt and coupling

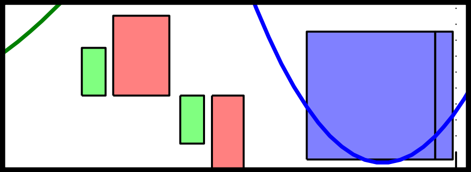
MATCHING AND OPTIMIZATION NOT PRESENT IN AT

DEVELOPED a function to :

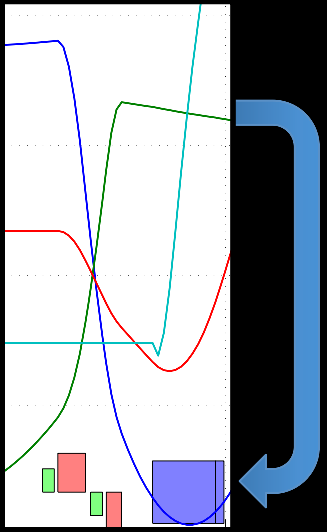
- determine magnet strengths that provide the wished optics.
- Injection bump, beta at the injection, beta at the ID, dispersion at the setxupoles
- Need to optimize parameters, such as Dynamic Aperture and Emittance
- Perform computations to manipulate the lattice, orbit bumps, lattice design specifications



Larger Dynamic apertures



Dipole field >=0.85T
Qaud. Gradient <100 T/m
Get, smaller emittance



Optics -> magnets
tunes, chromaticity,
Low beta @ID

ATMATCH: AT general purpose fitting routine.

AT Lattice
(cell array of structures)

- Element name
- Quadrupole, Sextupole
- Integration method
- Length
- Position
- Errors
- Multipole expansion
- …

Variables
(array of structures)

- Field to change in AT
- Limits

or

- Function (conditions!)
- Limits

Constraints/ objectives
(array of structures)

- function of the AT lattice
- Wished value limits
- Weight

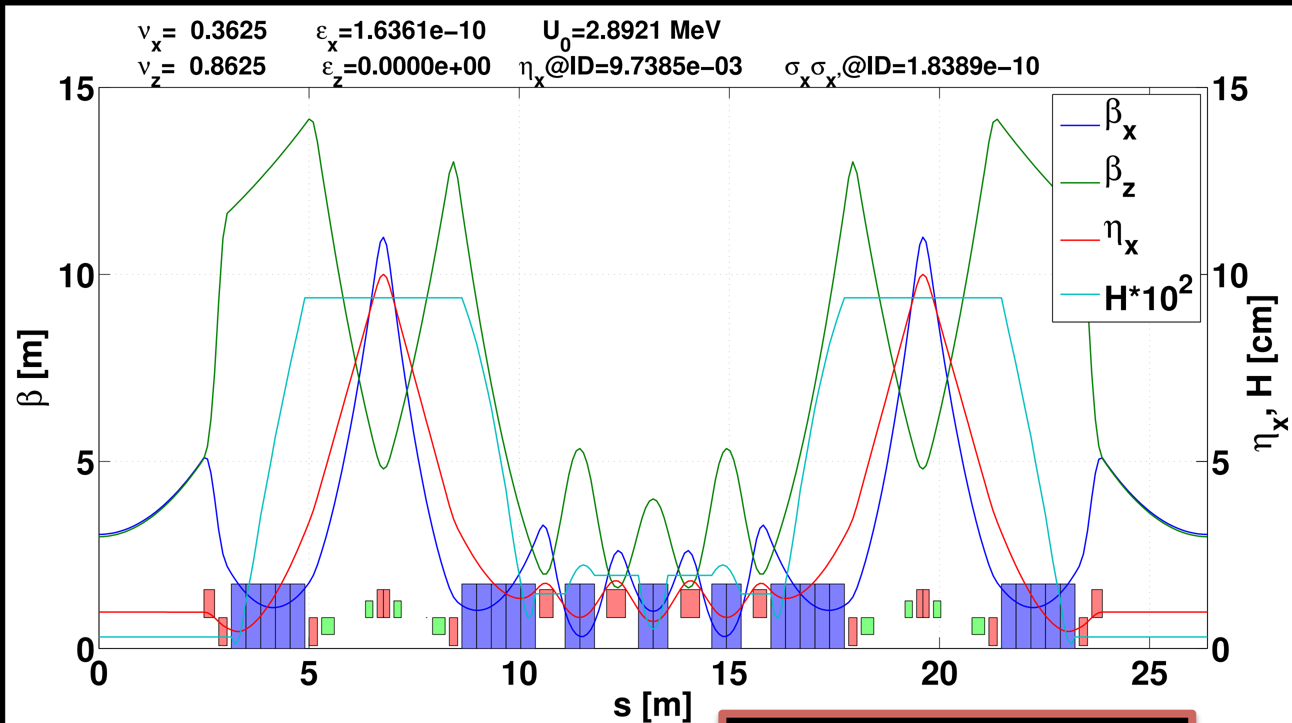
ATMATCH

LOOP

change Variables ⇨ new AT Lattice ⇨ compute Constraints

The optimizer is provided within Matlab: fminsearch, lsqnonlin,…

ESRF upgrade emittance optimization



Cell is symmetric:
Vary the dipole fields to minimize the horizontal emittance:

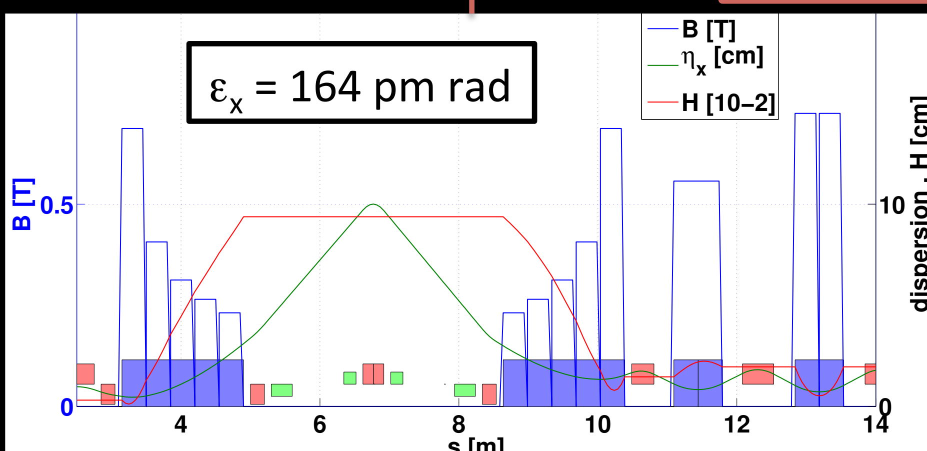
- Fixed total angle
- Fixed total length
- Fixed key optics

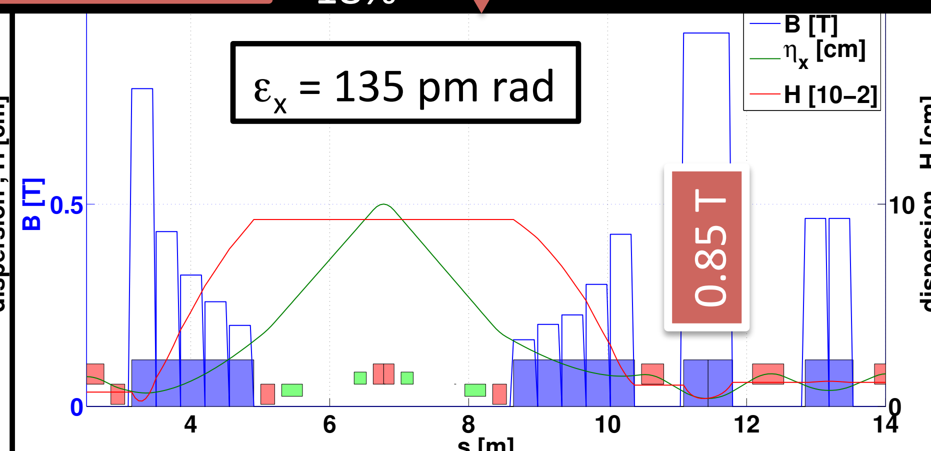
$$E_x \propto \frac{\beta_x D_x}{\rho} \qquad (@\,dipoles)$$

Stronger bending where small beta and dispersion

ATMATCH OPTIMIZER

-18%





Variation of dispersion at sextupoles

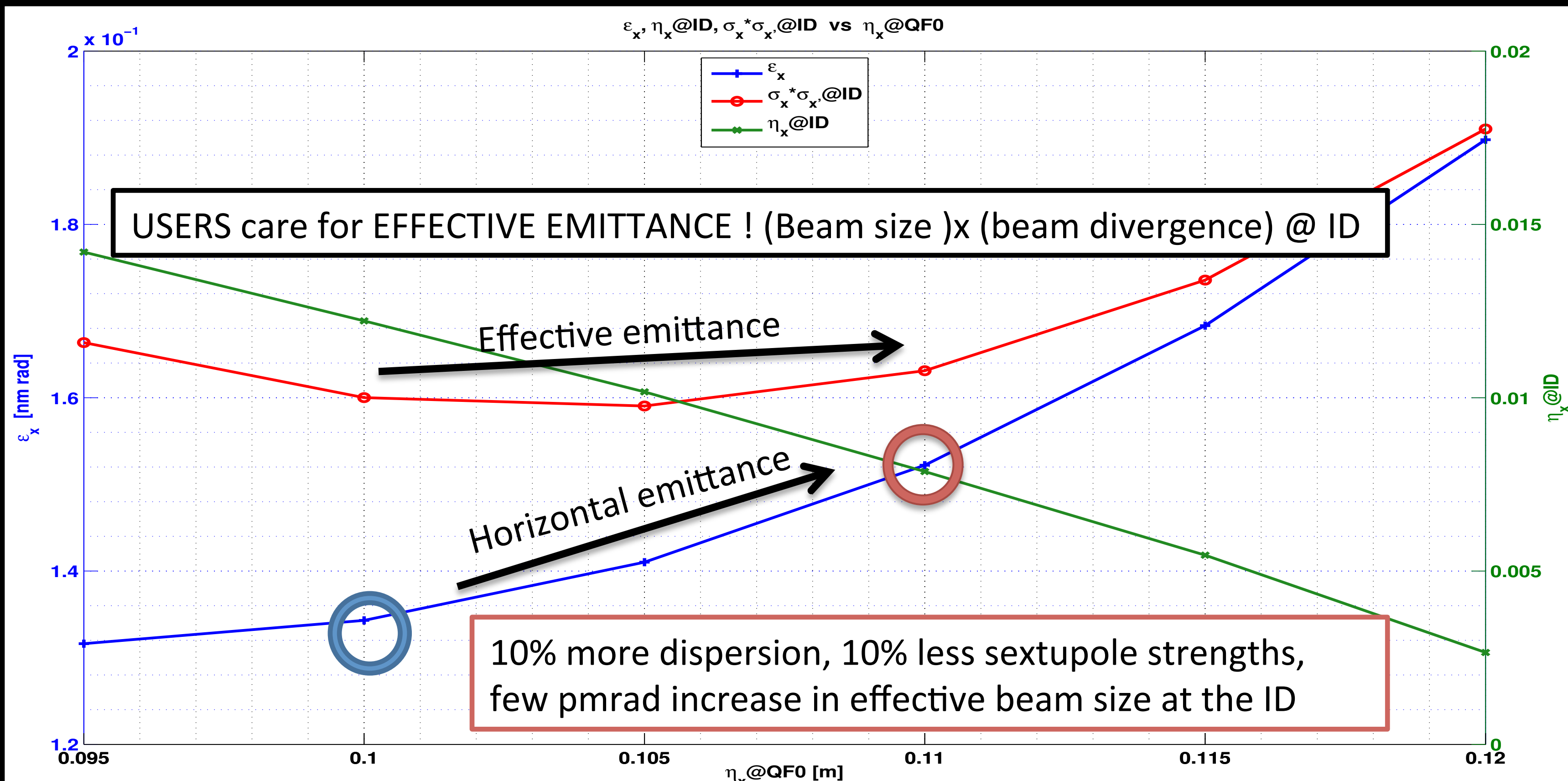
$$\sigma_x = \sqrt{\epsilon_x \beta_x + (\eta_x \delta)^2}$$

$$\sigma_{x'} = \sqrt{\frac{(1+\alpha_x^2)\epsilon_x}{\beta_x} + (\eta_x' \delta)^2}$$

$$\varepsilon_{\text{eff}} = \sigma_{x'} \sigma_x$$

$$\textit{Chromaticity}\ [>0] \propto -\beta_x K_1\ (@\textit{quads})\ + D_x K_2\ (@\textit{sext.})$$

All optics Fixed. Varying dispersion at sextupoles. EFFECTIVE Emittance at Insertion Devices (ID) is optimized as before using ATMATCH.

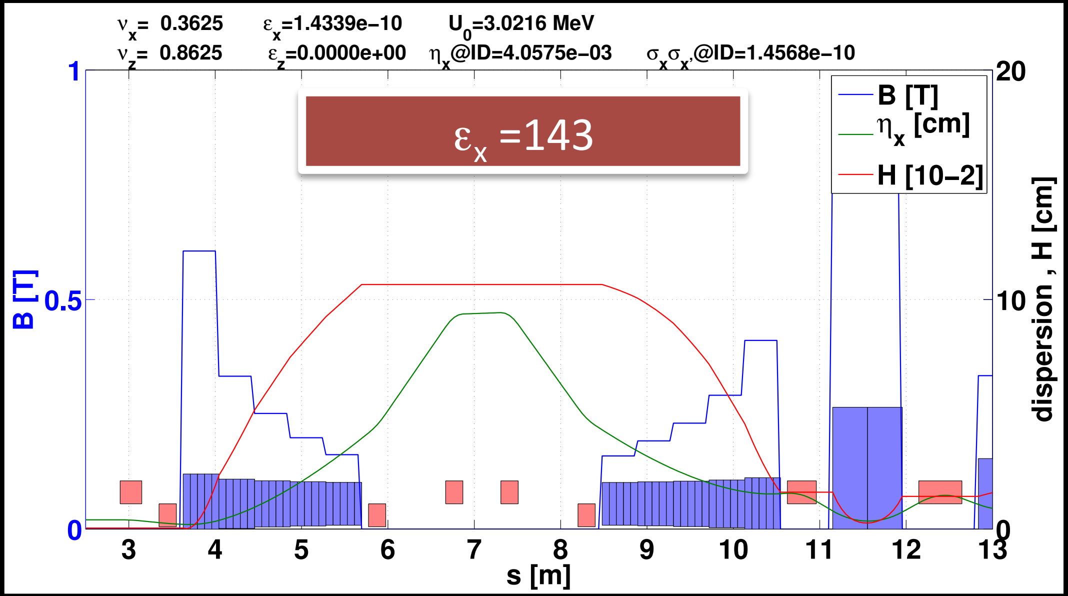


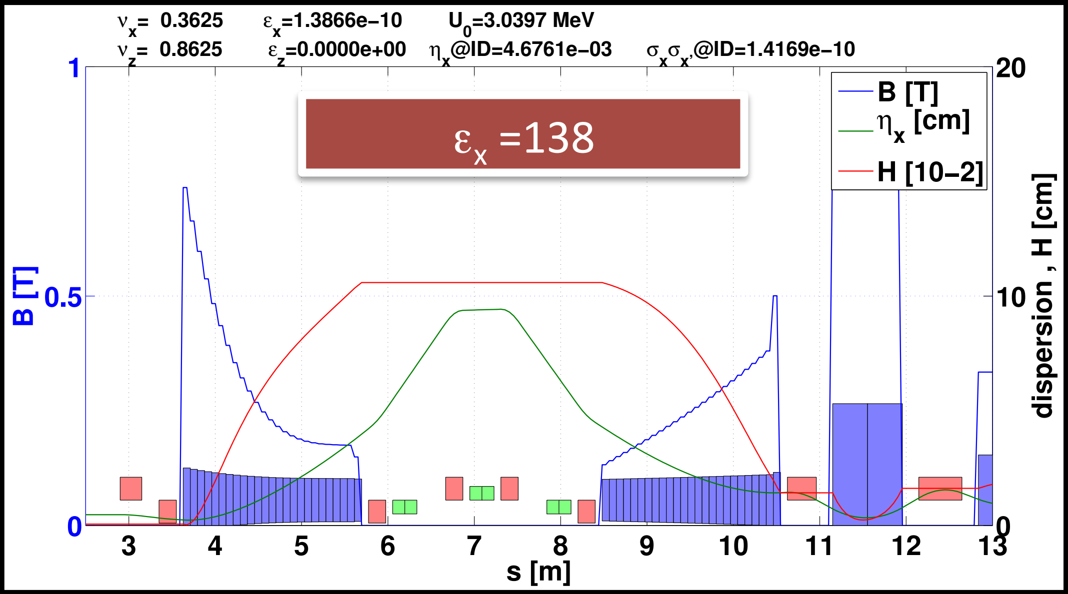
Higher emittance

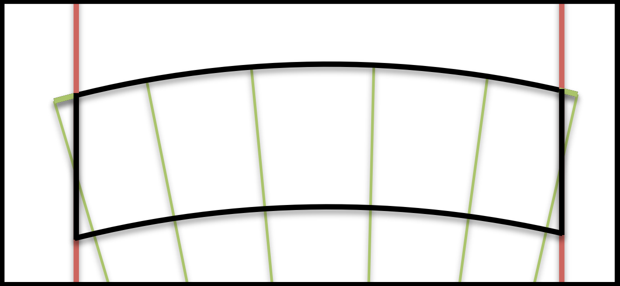
Higher dispersion @ ID

Higher Dispersion BUMP (WEAKER SEXTUPOLES)

Longitudinal dipole field profile





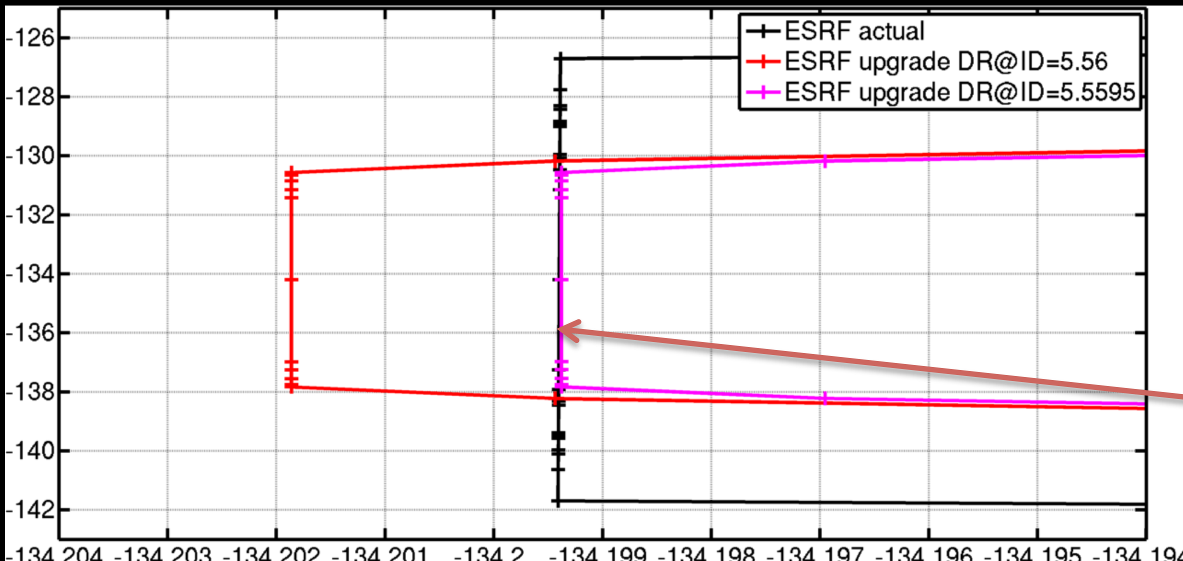


Optics constant!
Emittance minimized with 3rd order polynomial profile.
Constant fields for radiation dipoles. Fixed position of radiation sources.

Where H is small, large dipole field. Small emittance.

ATMATCH code written and developed for this study and the following

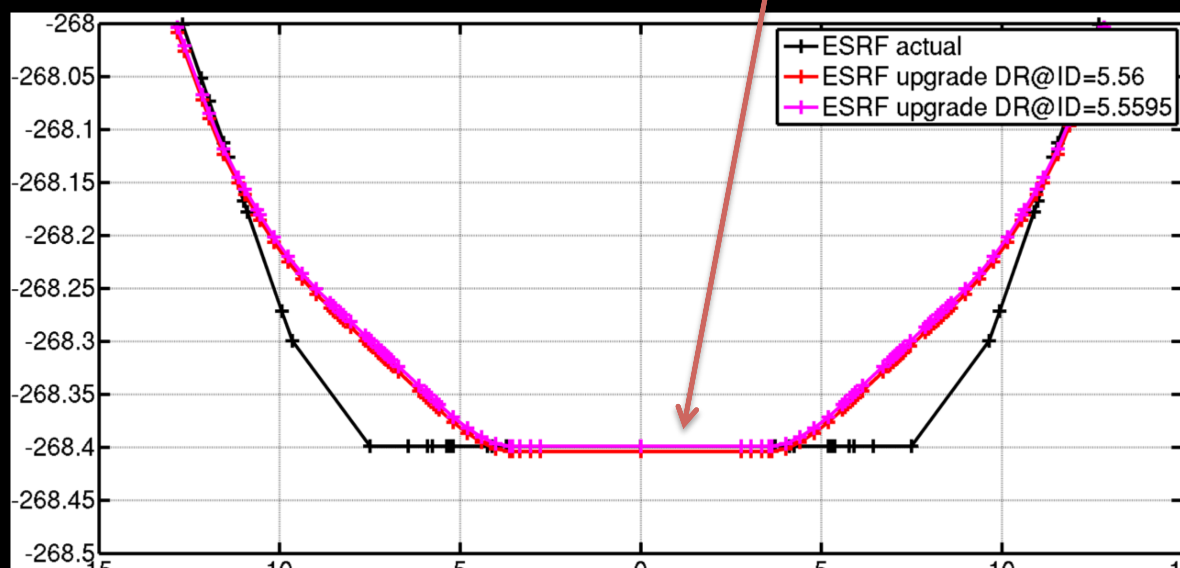
Fit ID position



Automated fit of ID source point positions varying the length of a drift space (or a combination)

Changed drift

Length of drift between sextupoles in the dispersion bump or length of ID straight section changed to fit discrepancy



Highlights from the thesis 2

1. Optimization of the ESRF upgrade lattice dipole fields to obtain a smaller emittance
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ATMATCH OPTIMIZER

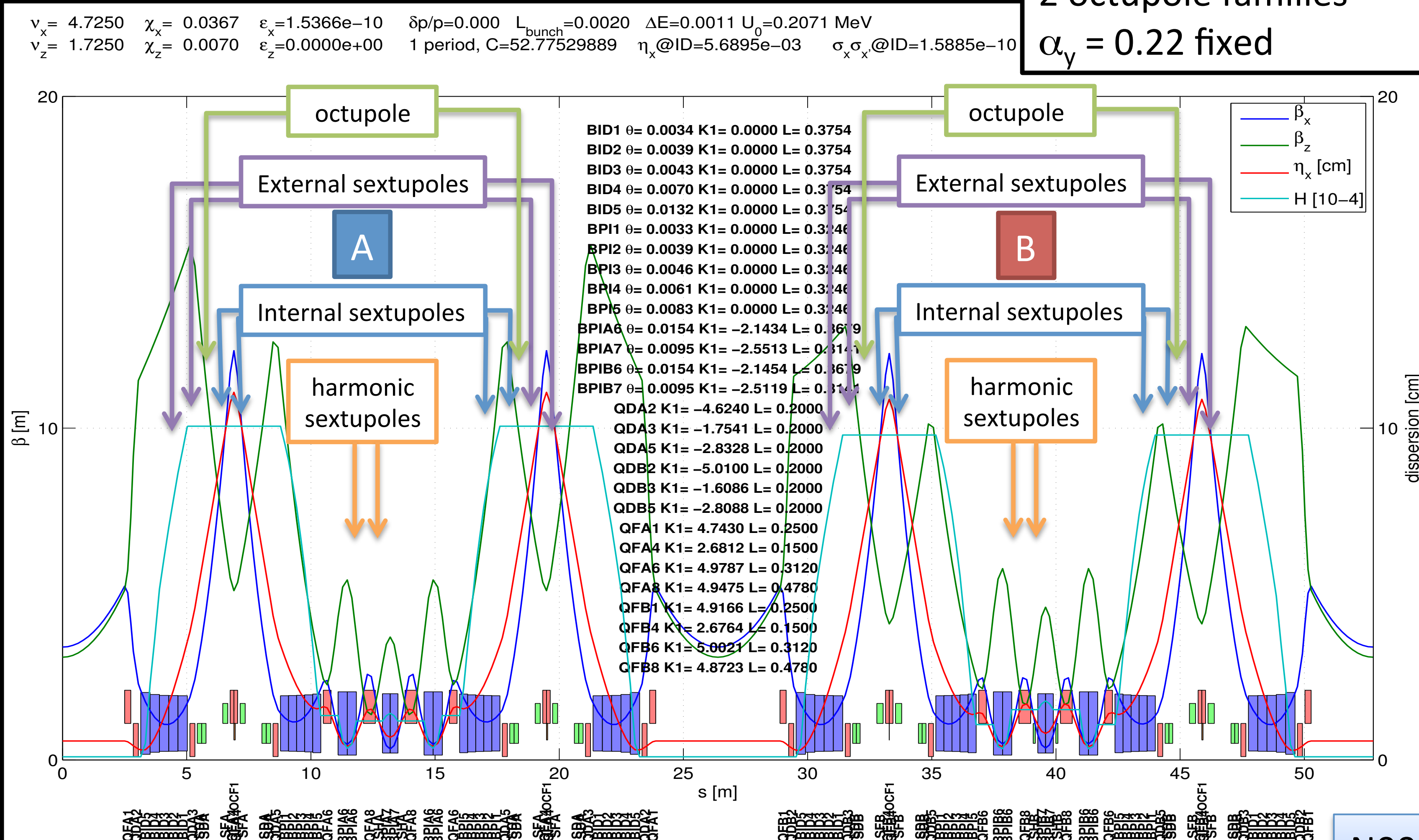
ATMATCH OPTIMIZER

Low emittance tuning

Low emittance tuning

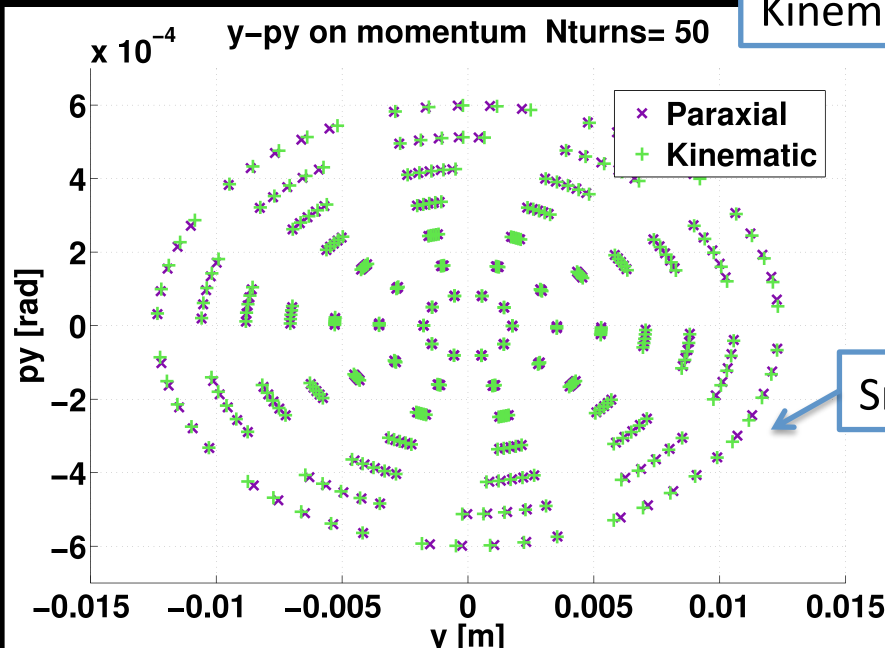
ESRF upgrade lattice non-linear optics

10 sextupole families
2 octupole families
α_y = 0.22 fixed

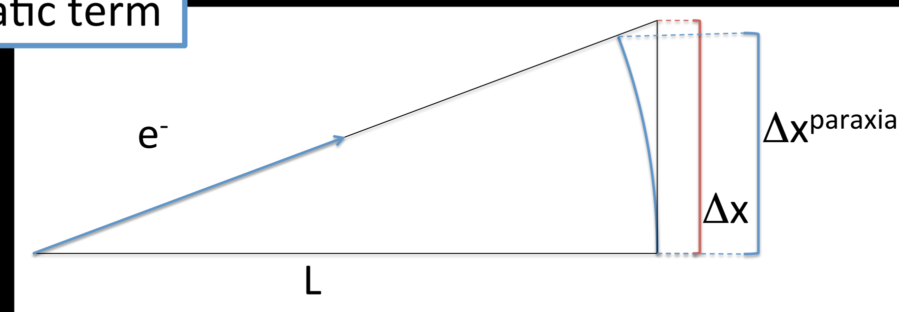


N004

Fringe fields and kinematic term



Kinematic term

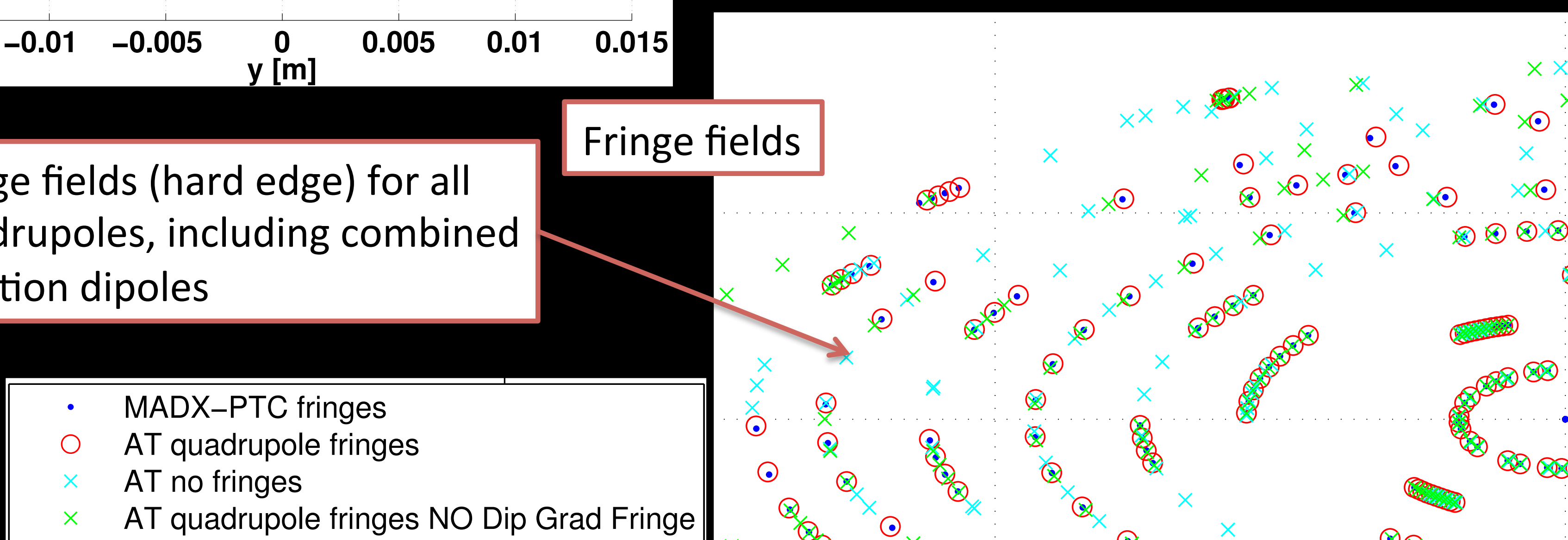


Small additional detuning at large amplitudes

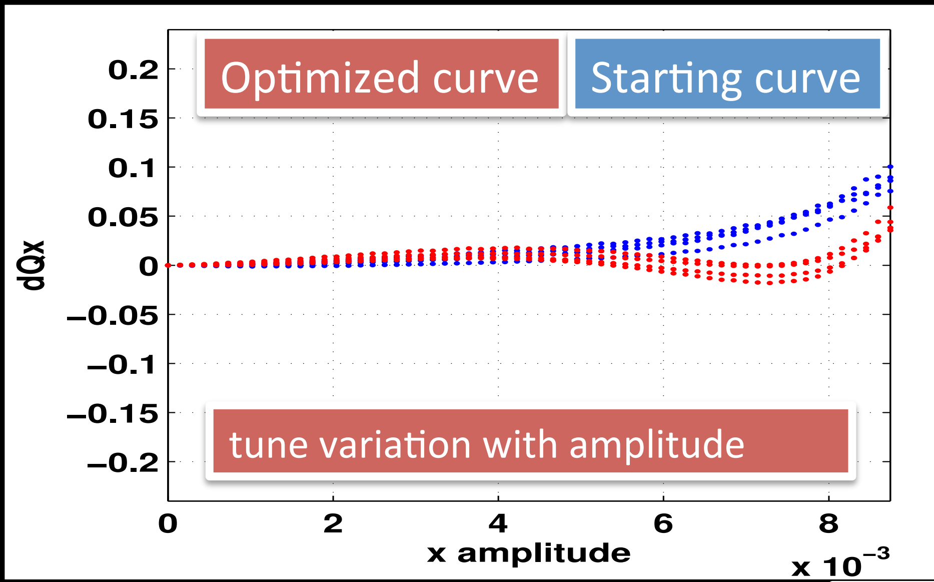
Larger effects for colliders, ex. SuperB, Tau-charm,…

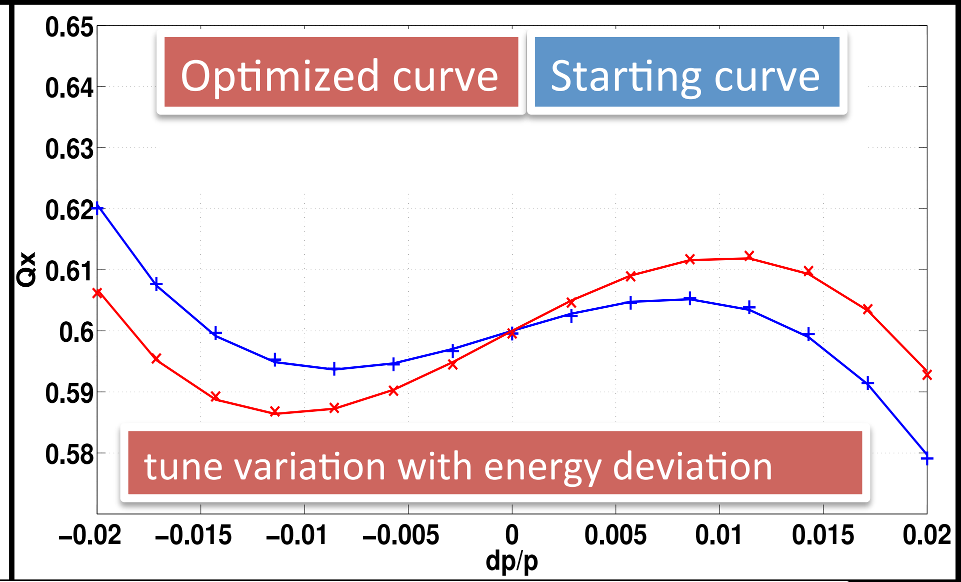
Fringe fields

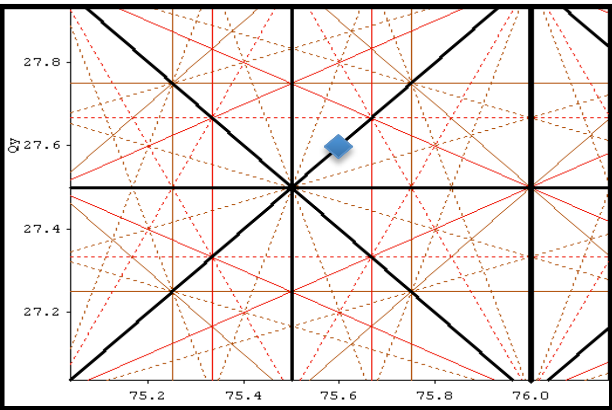
Fringe fields (hard edge) for all quadrupoles, including combined function dipoles

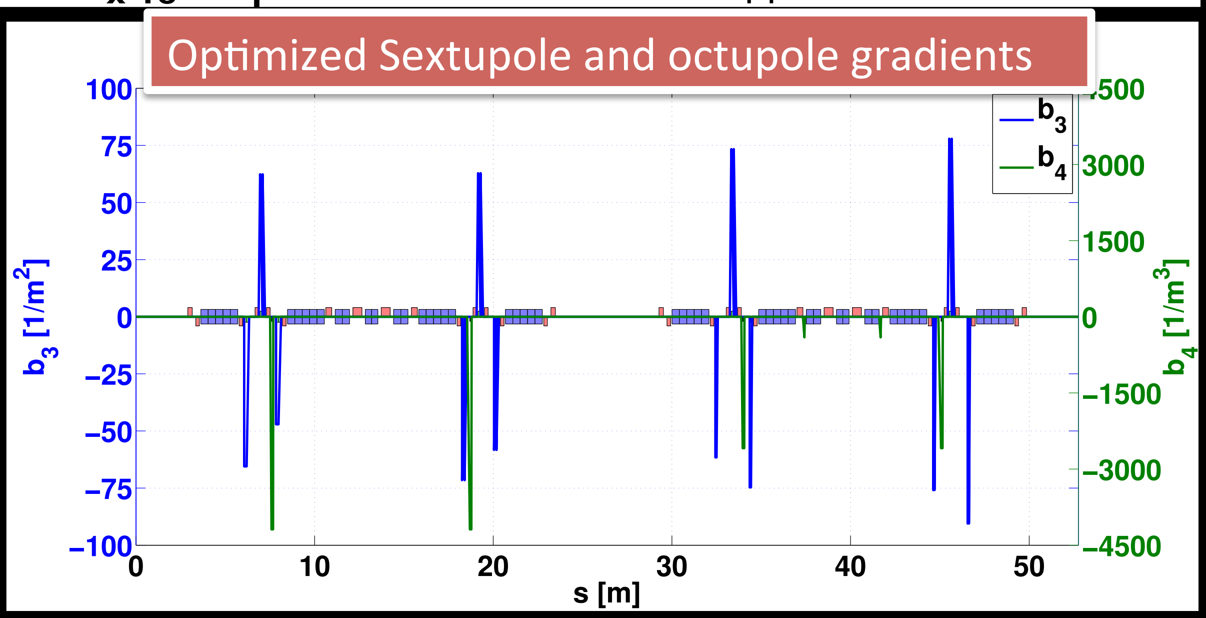


Mitigation of tune variation with amplitude









Moving in the tune space particles may be trapped in resonances and lost.

Highlights from the thesis 3

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ATMATCH OPTIMIZER

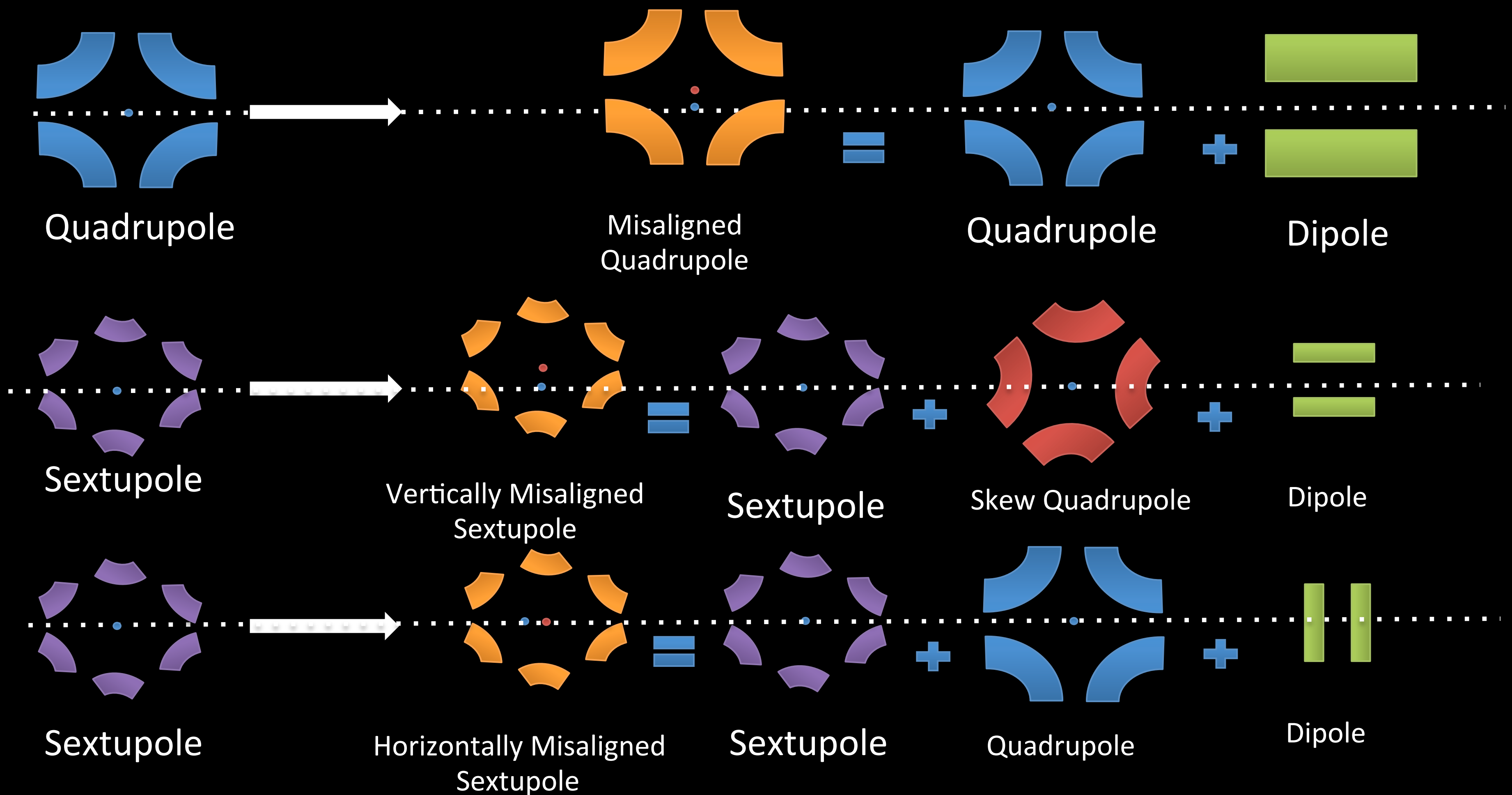
ATMATCH OPTIMIZER

Low emittance tuning

Low emittance tuning

Misalignments

Real accelerators are not perfectly aligned. Unwanted fields are present in the lattice:



Effect of misalignments: vertical emittance

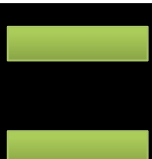
Focusing

Quadrupole

Coupling

Skew Quadrupole

Orbit and Dispersion



Dipole

Reference

ε_x= 2 nm rad

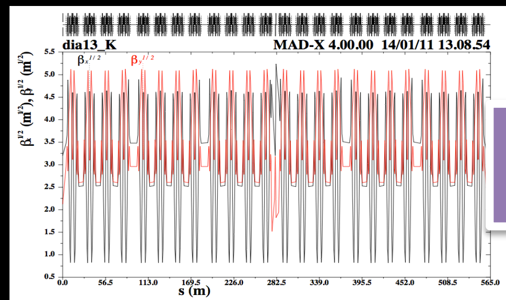
ε_y= 0 pm rad

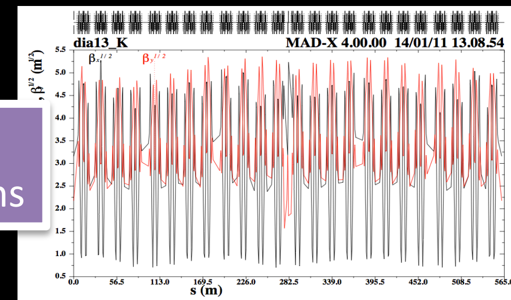
With errors

ε_x= 2.1 nm rad

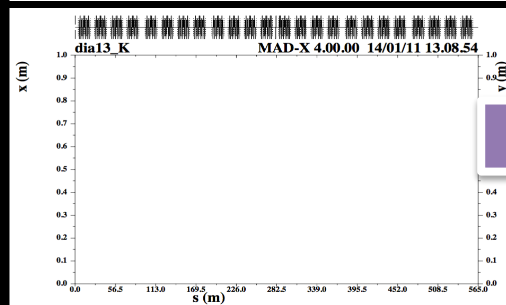
ε_y= 100 pm rad

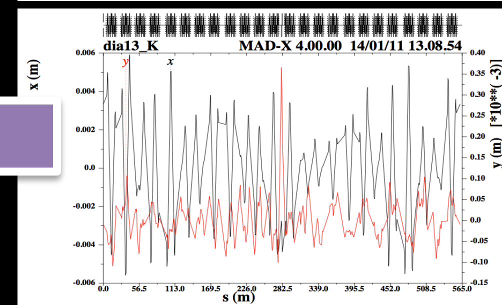
Beta functions



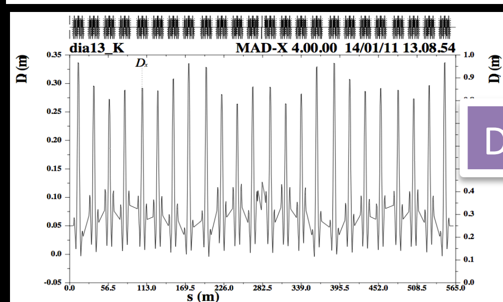


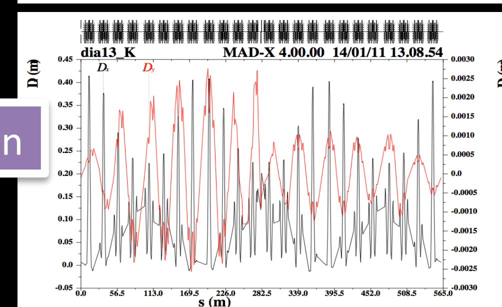
Orbit





Dispersion



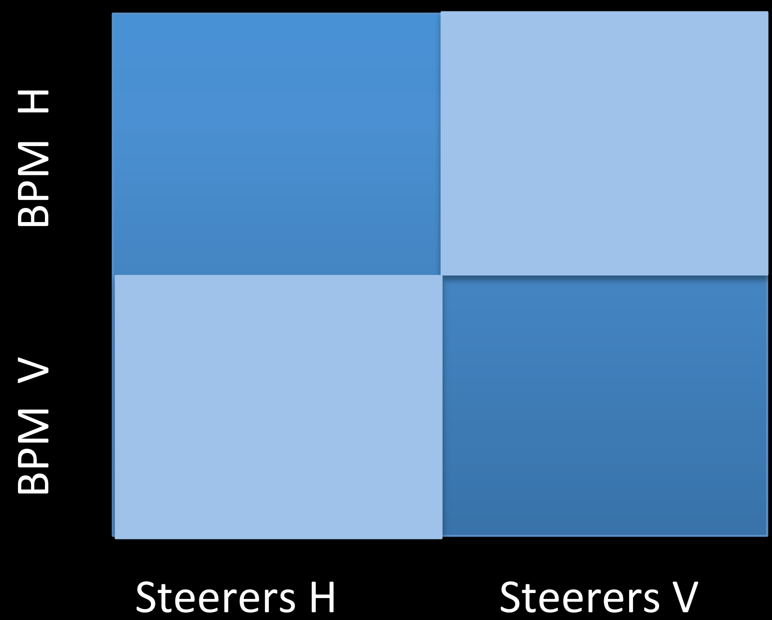


To correct, equivalent fields need to be adjusted along the lattice: CORRECTORS

Orbit and dispersion correction

How to compute the values of the correctors to reduce the unwanted orbit and dispersion?

Response Matrix M



SVD (pseudo inverse) of M to calculate Correction $\vec{\theta}$

Orbit correction

$$\vec{x} = M\vec{\theta}$$

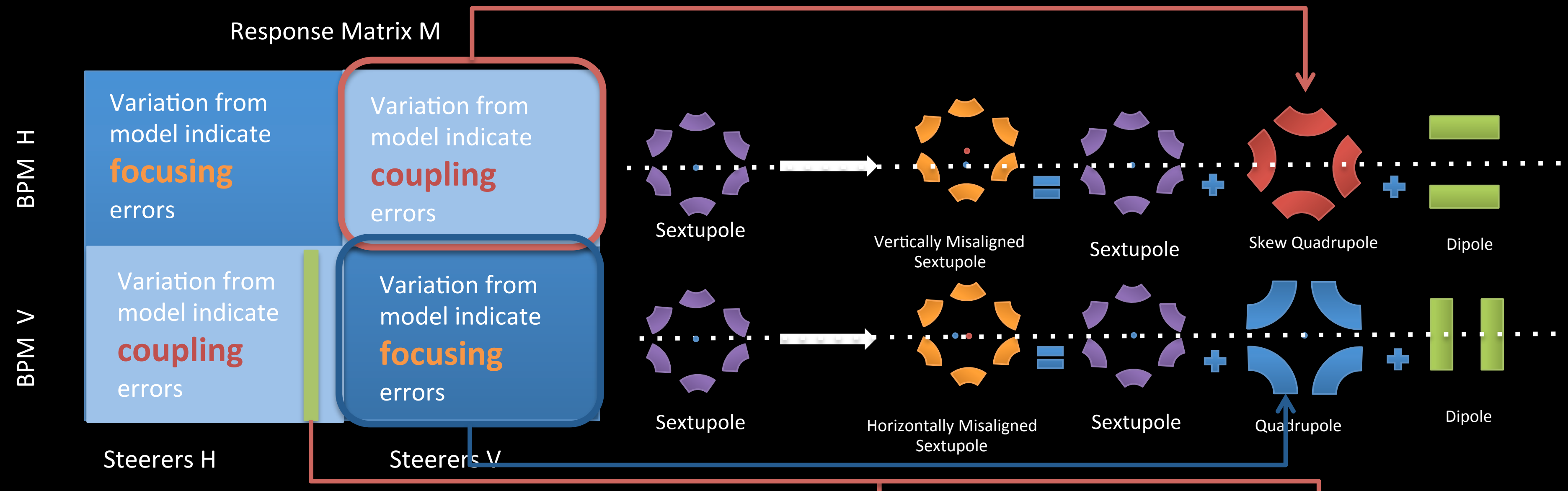
$$M_{ij} = \frac{\partial x_i}{\partial \theta_j}$$

Dispersion response matrix (deviation from reference)

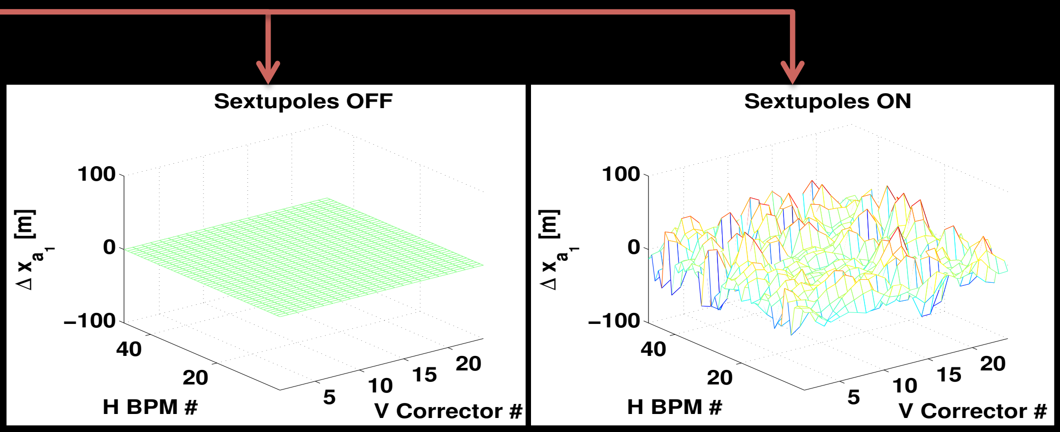
$$\vec{\eta} = M^{disp}\vec{\theta}$$

$$M^{disp}_{ij} = \frac{\partial \eta_i}{\partial \theta_j}$$

Using the sextupoles off axis effects: LET



Introduce additional 224 normal quads (for focusing) and 224 skew quads (for coupling) by conveniently steering the beam off-axis inside the 224 sextupole magnets (with orbit steerers, i.e. dipoles).



Pro: optics further corrected without installing additional magnets
Con: larger orbit distortion

ESRF: 224 BPM, 96 steerers , 64 skew quad, 32 quad
+ 224 SEXTUPOLES as normal and skew quads

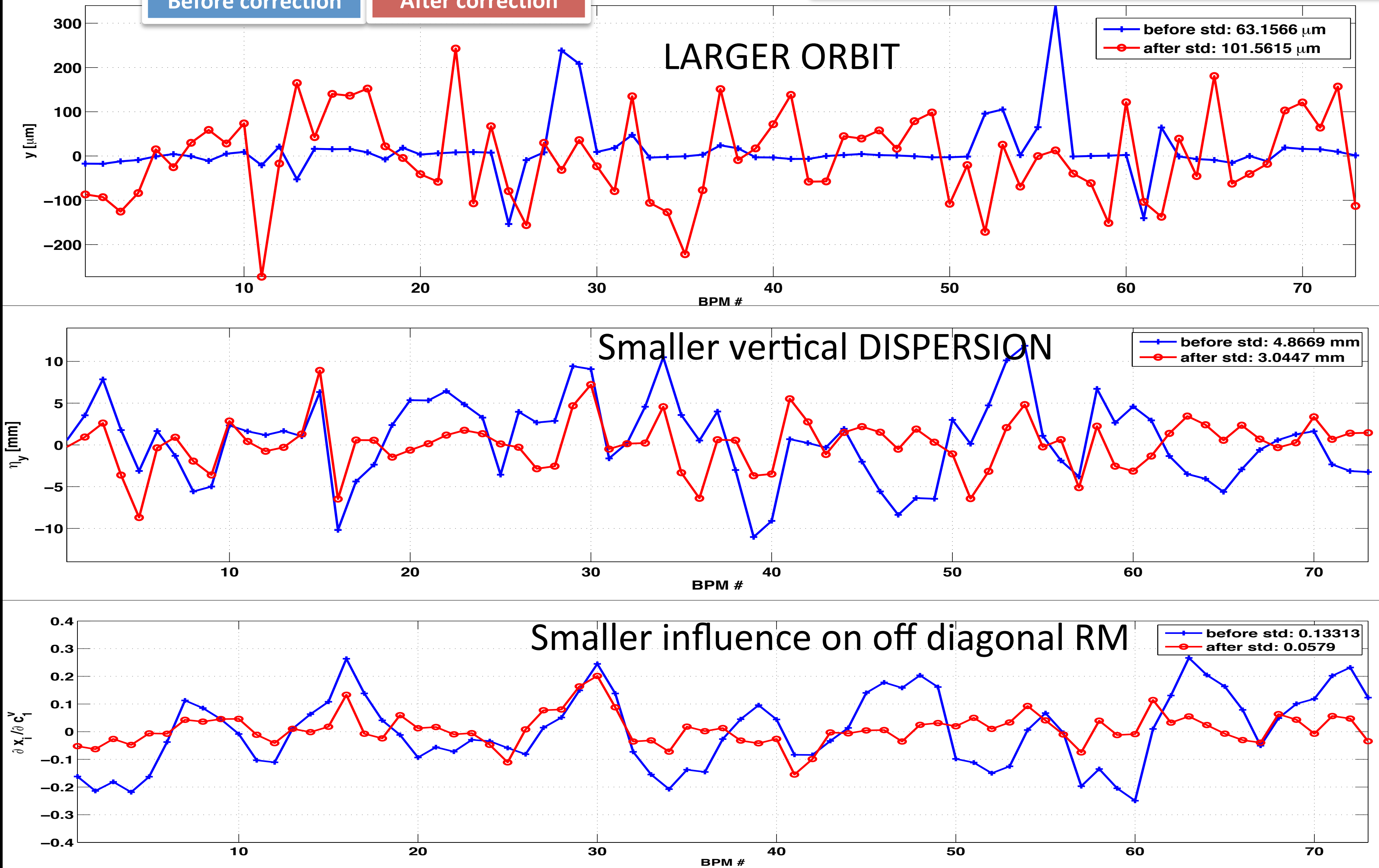
SLS measurements

Vertical steerers only

σ_y from 16 μm to 7 μm

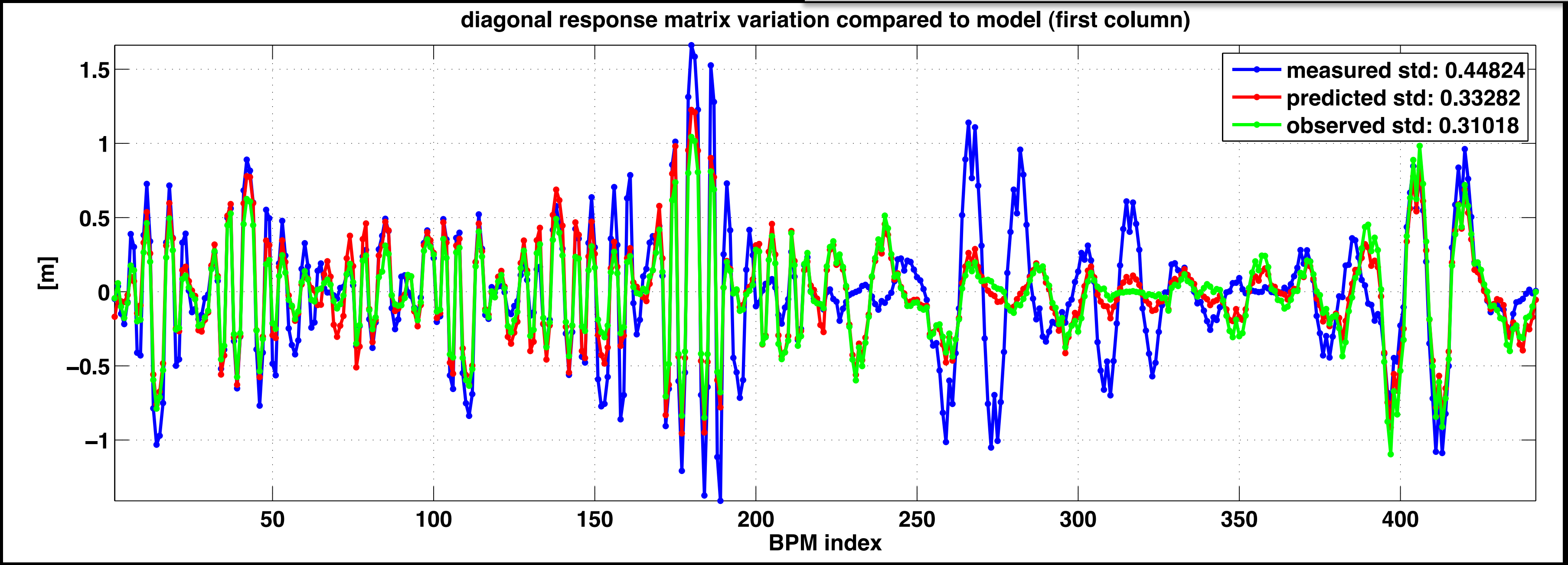
Before correction

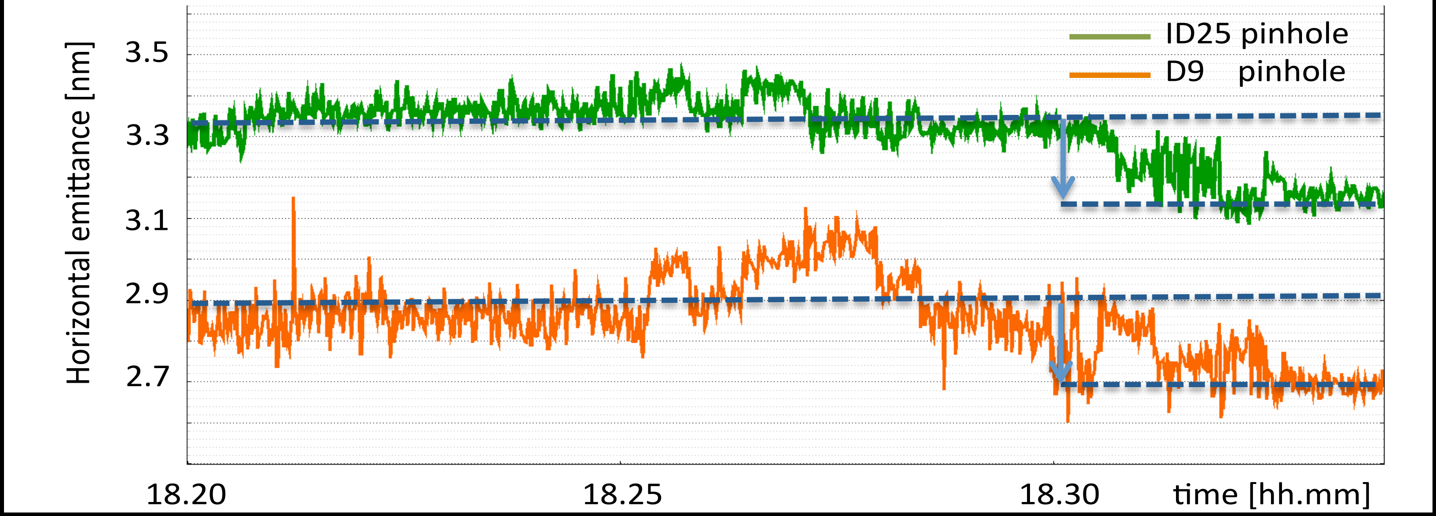
After correction



Horizontal Steerers

Correction of horizontal dispersion and beta-beating using horizontal steerers only



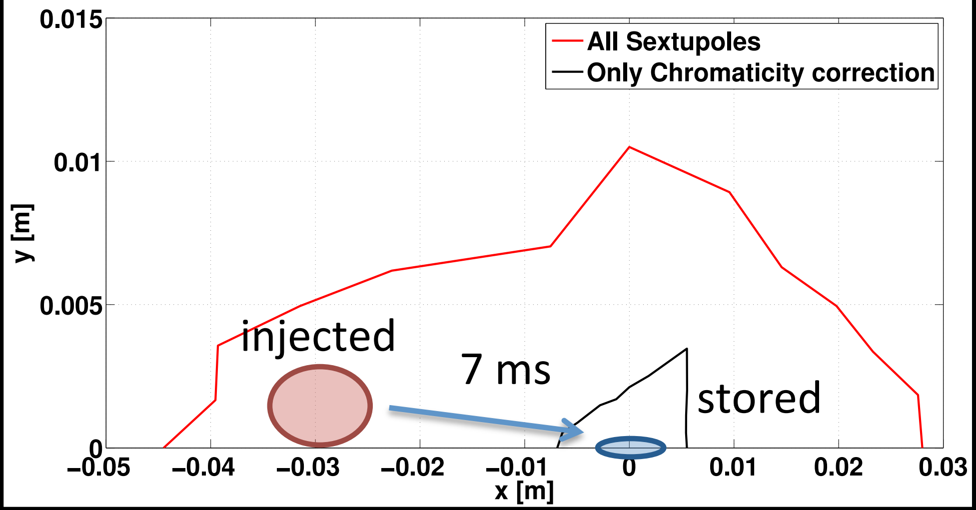


Measurements at ESRF

Highlights from the thesis 4

1. Optimization of the ESRF upgrade lattice dipole fields to obtain a smaller emittance — ATMATCH OPTIMIZER
2. Study and correction of the residual variation of tune with amplitude — ATMATCH OPTIMIZER
3. Measurements for a new correction technique to minimize vertical and horizontal emittance — Low emittance tuning
4. Analysis of the influence of errors on low emittance lattices. — Low emittance tuning

Dynamic aperture and lifetime



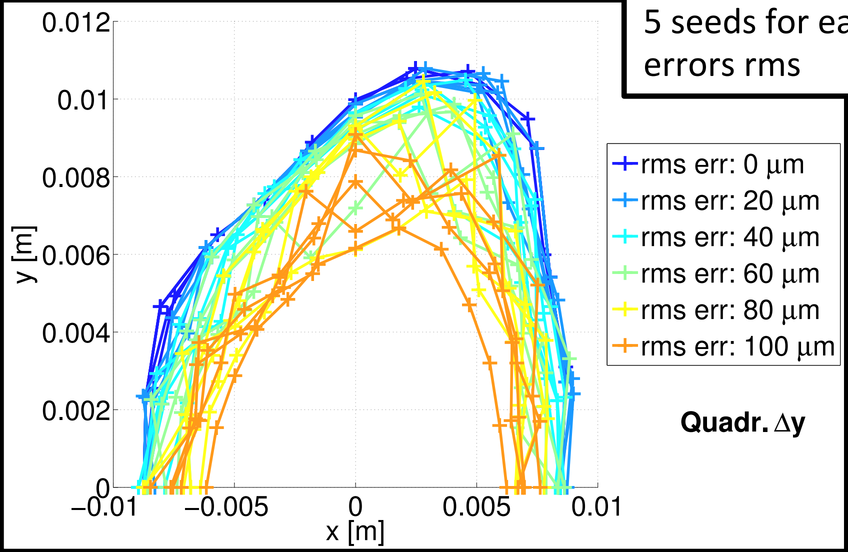
Dynamic aperture:
Region of transverse space where tracked particles survive at least a given number of turns (512 here).
Need sufficient dynamic aperture to inject the beam off axis in a region where it may survive.

Dynamic aperture may be improved by an accurate choice of non-linear fields: sextupoles and octupoles

Dynamic aperture Is reduced by the effect of errors and only partially recovered by the use of a correction scheme (LET).

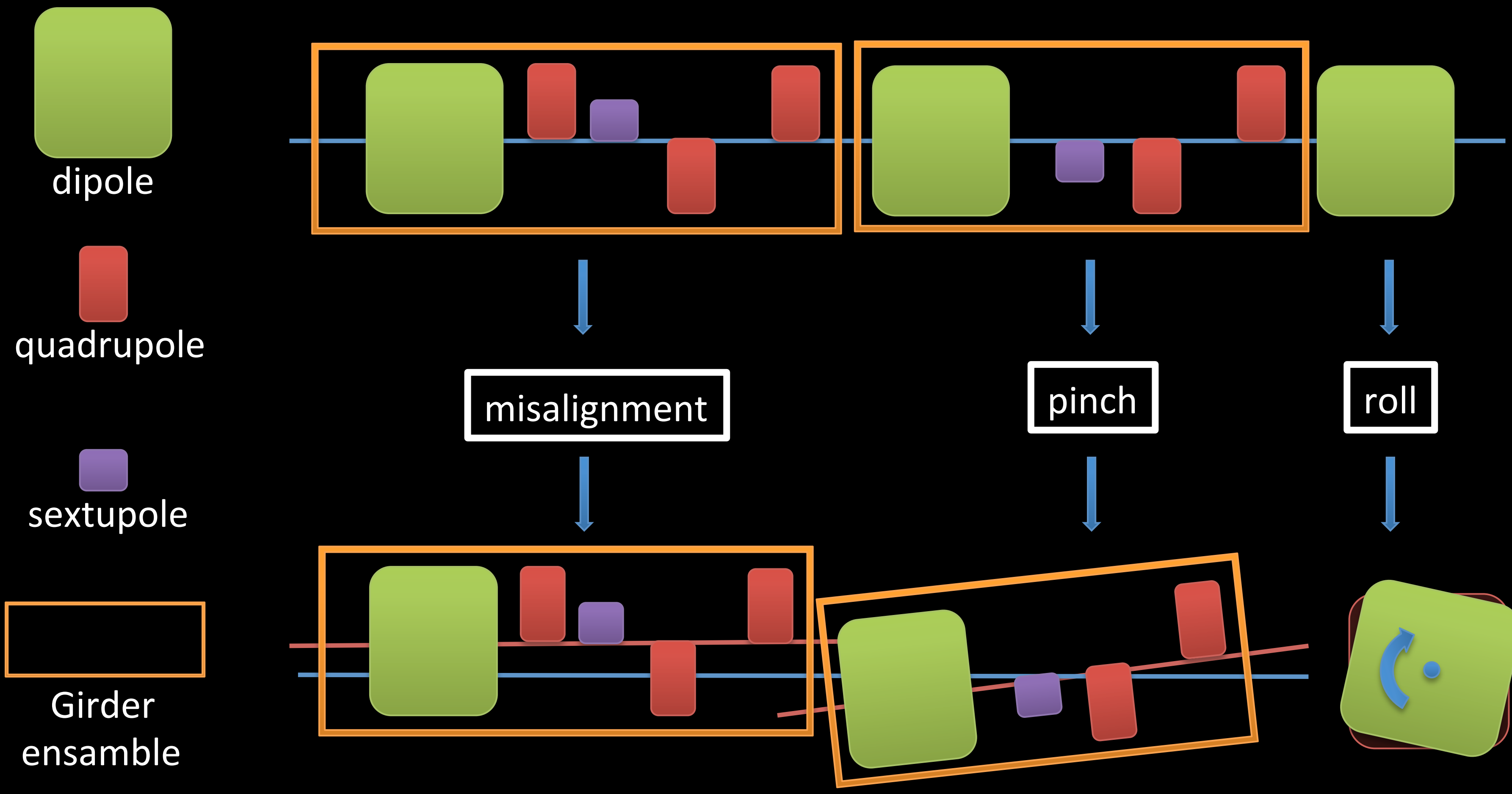
What is the maximum tolerable error?

5 seeds for each errors rms

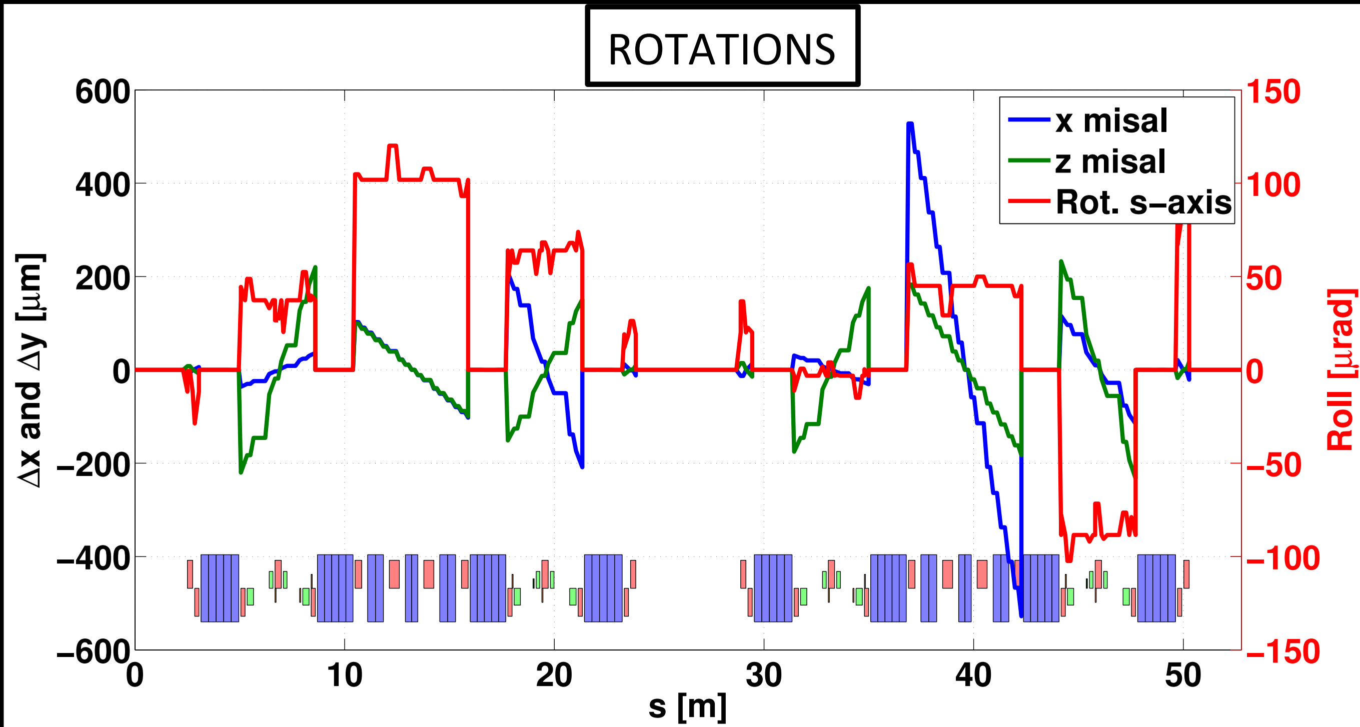


Errors studied

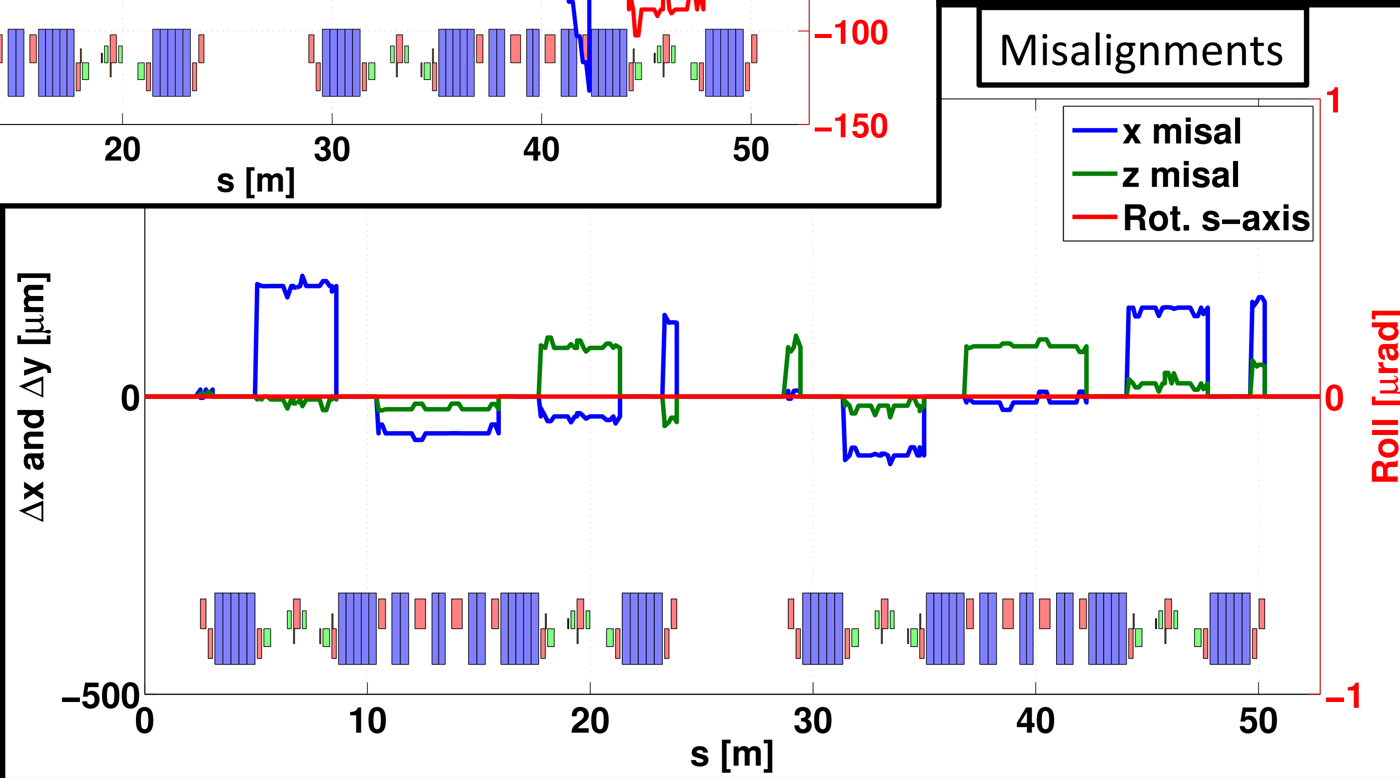
- Misalignments (quad, sext, girders)
- Rotations about z (quad, girders)
- Integral field errors (dipoles, quad, sext)
- All are taken from a truncated Gaussian (2 sigma)



Error application examples



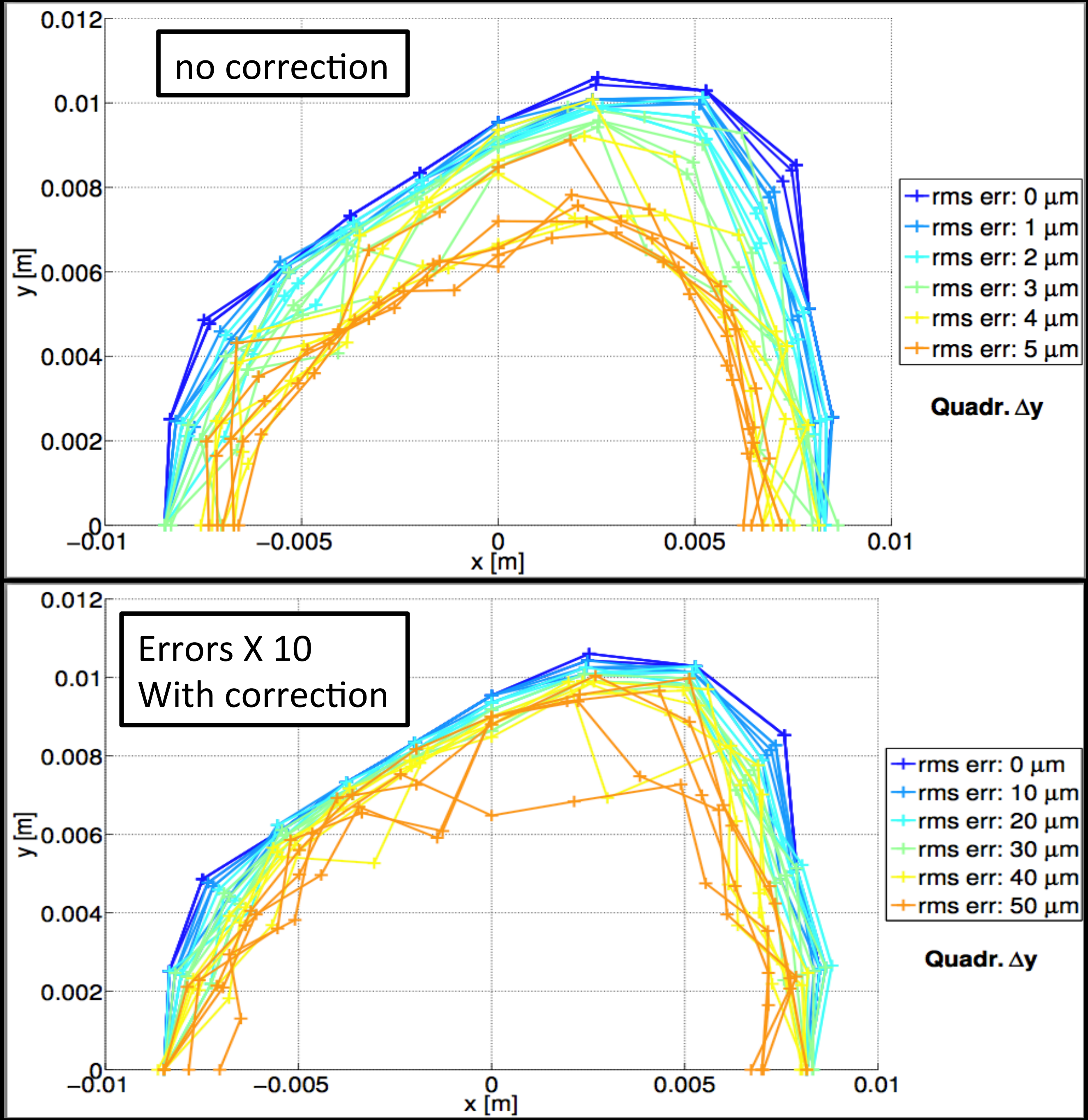
Girder Errors are 10X single magnet errors



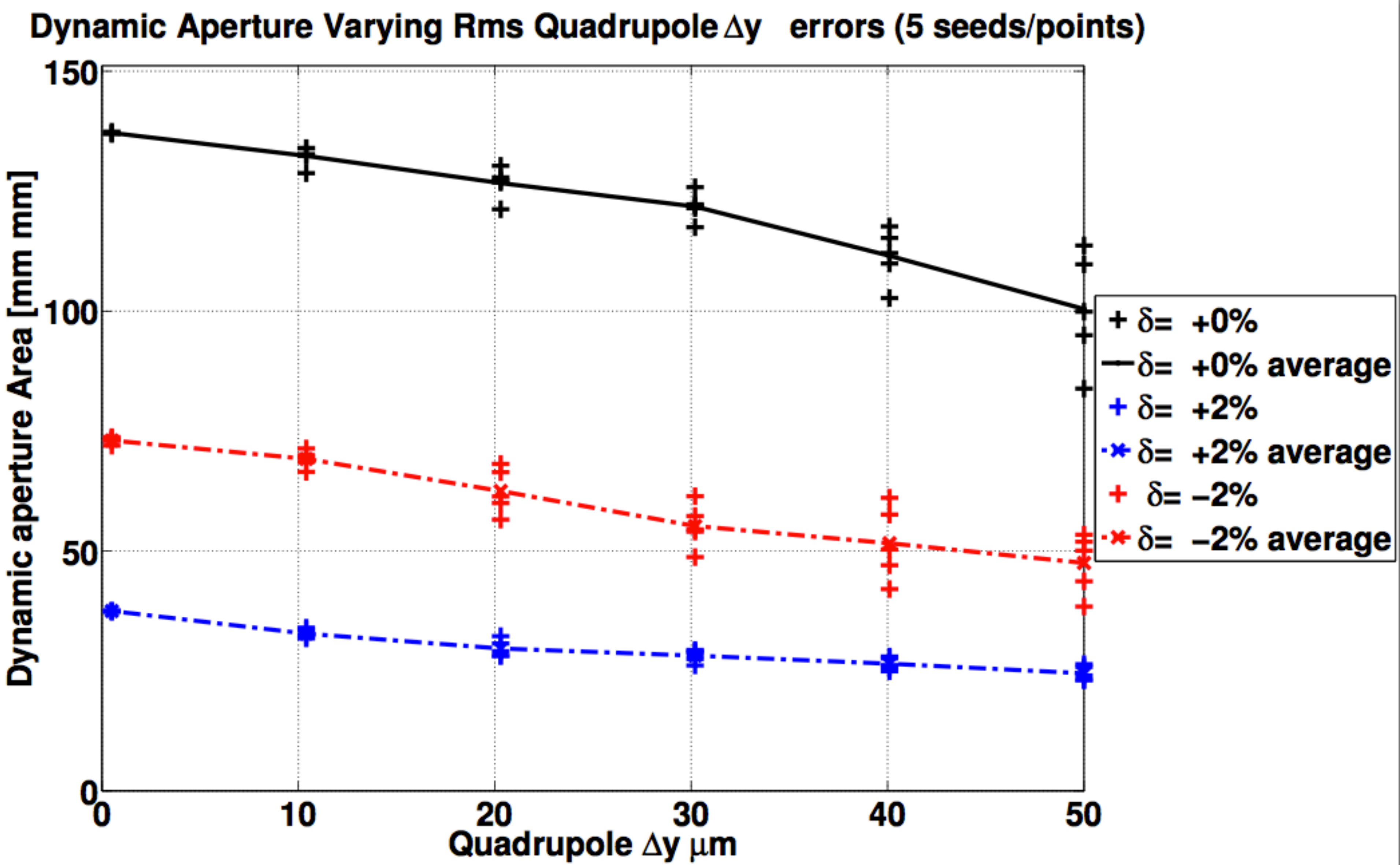
Additional care is taken to properly assign errors for SLICED DIPOLES

Dynamic apertures

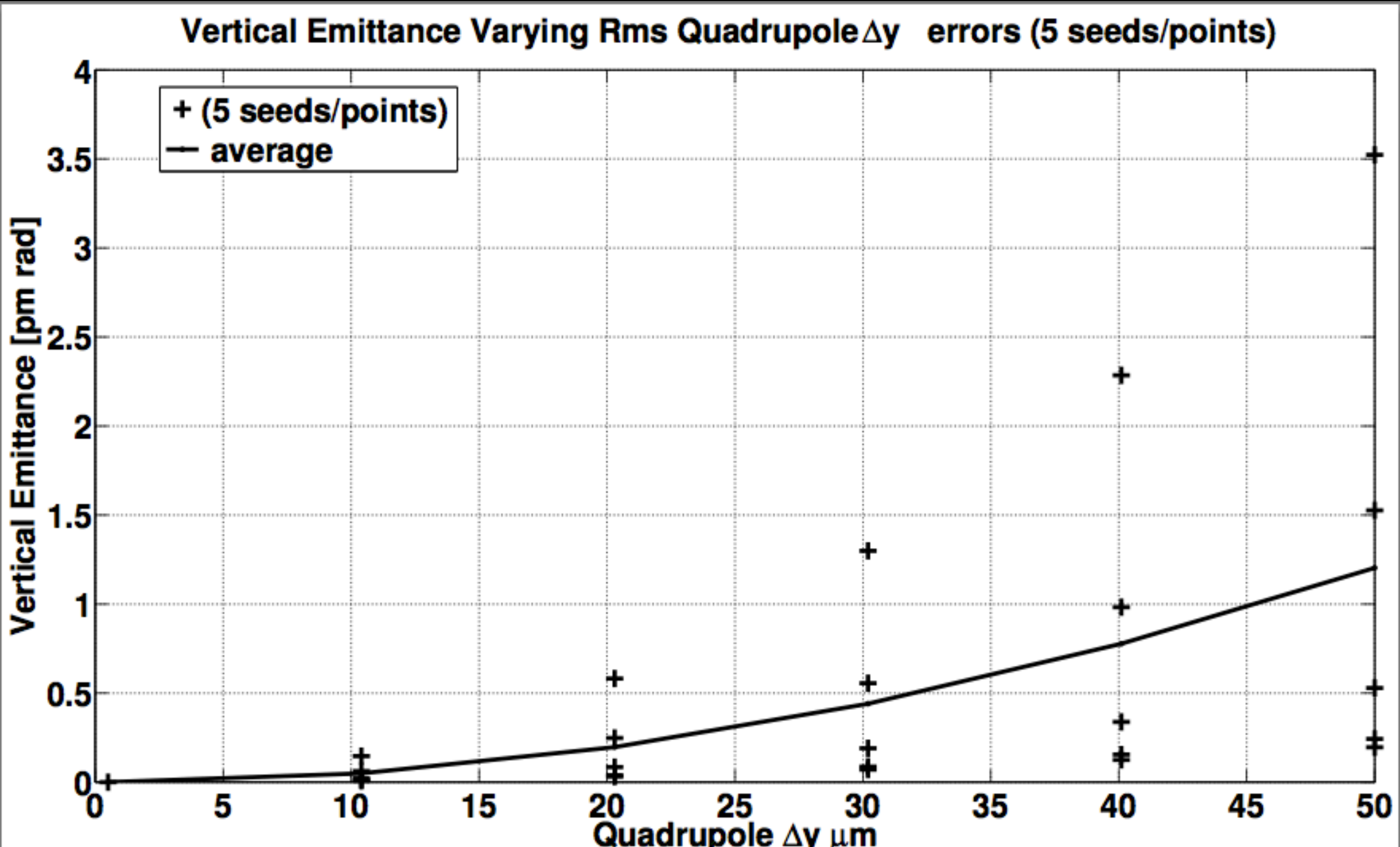
5 seeds for each rms
Quadrupole vertical displacement value analyzed



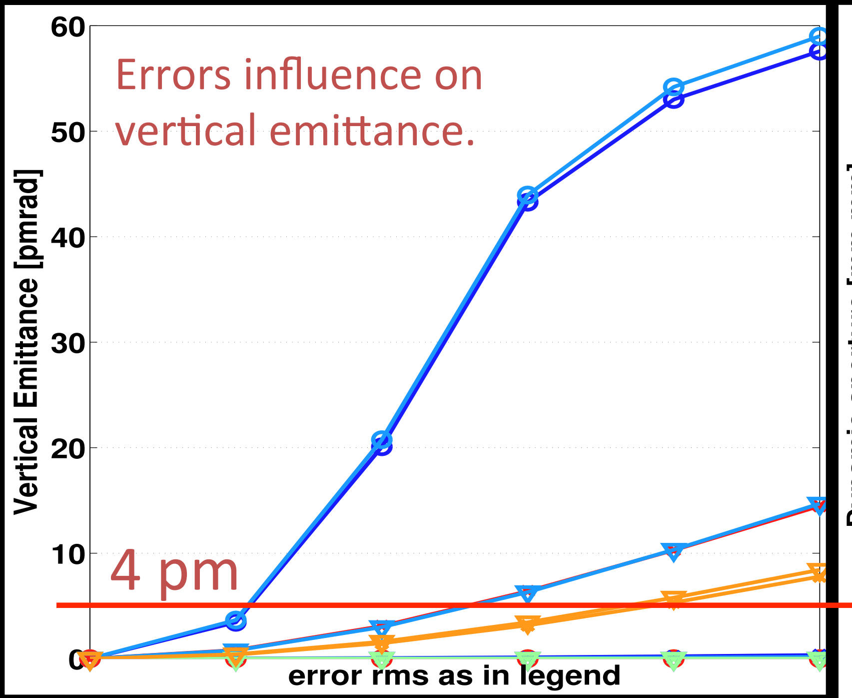
Dynamic aperture area vs quadrupole DY

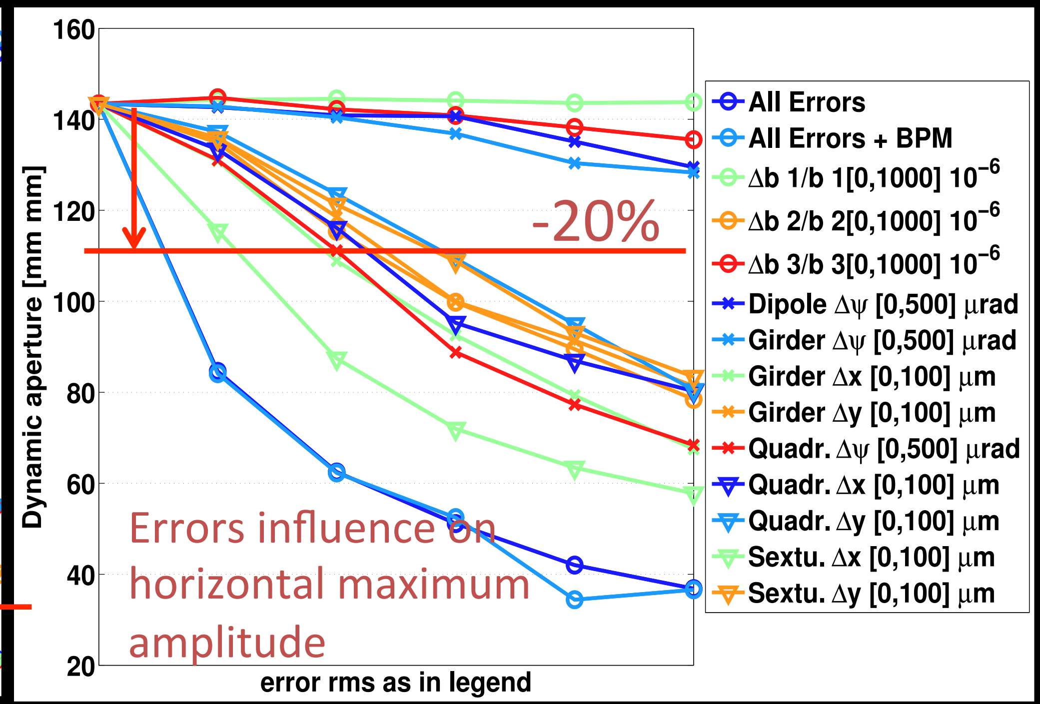


Vertical emittance vs quadrupole DY



Comparison between various error sources

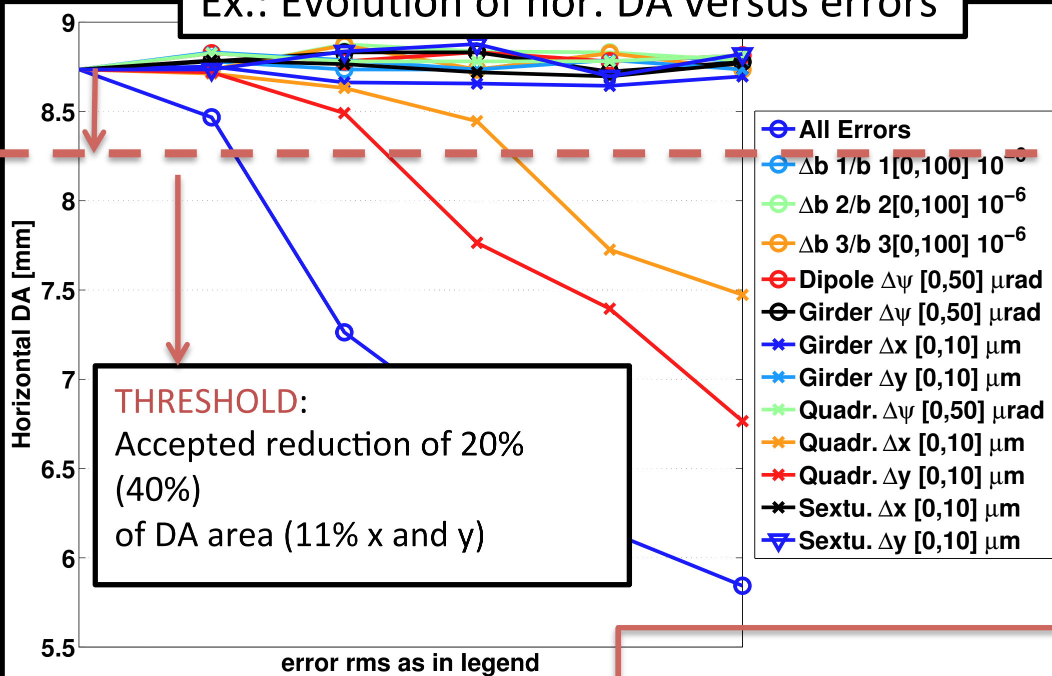




Thresholds:
20% reduction of dynamic aperture (with injection section approx: D.A.(mm)x2) and acceptance,
+-4pm variation of emittance

Errors influence no correction

Ex.: Evolution of hor. DA versus errors



THRESHOLD:
Accepted reduction of 20% (40%)
of DA area (11% x and y)

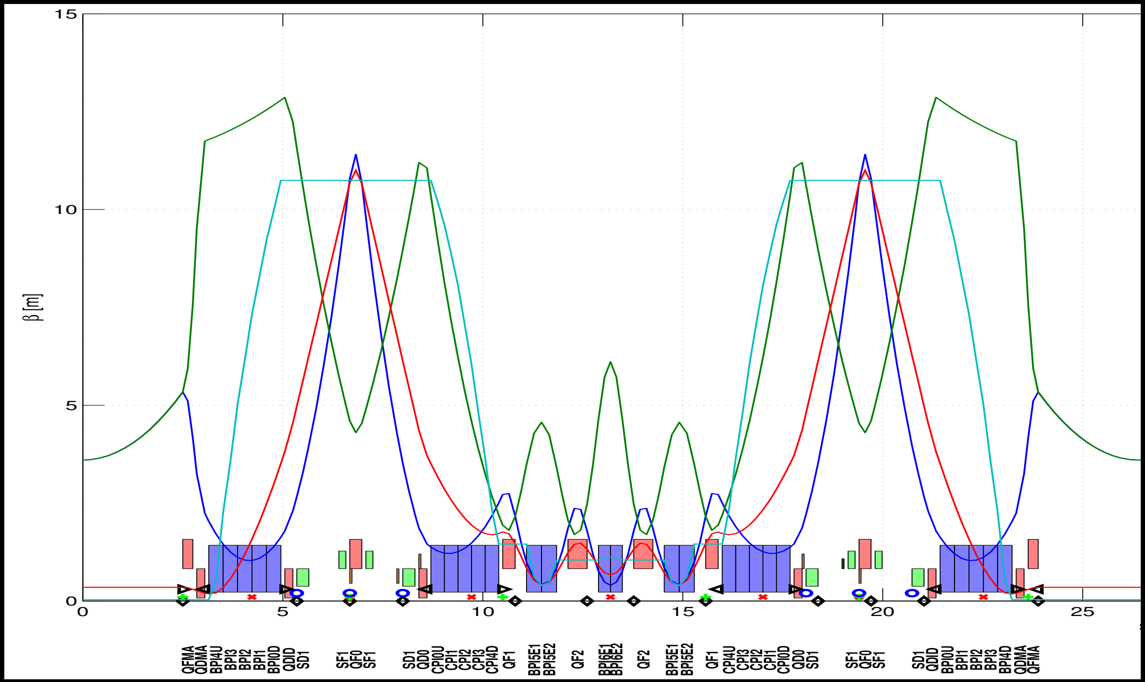
Large influence for off energy dynamics

List of tolerable errors

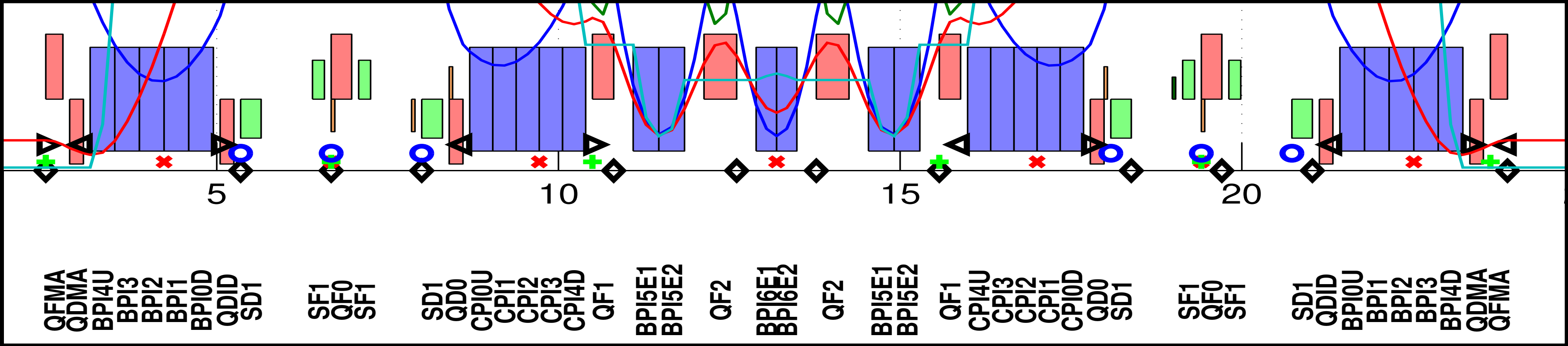
	dynamic aperture				emittance		acceptance		
error	H	V	+2%	−2%	ϵ_x	ϵ_y	H	V	min
AllErrors	50.5	34.6	**8.1**	9.9	84.3	32.9	21.4	15.3	8.1 %
$\Delta b_1/b_1$	**100.0**	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0 10^{-6}
$\Delta b_2/b_2$	**100.0**	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0 10^{-6}
$\Delta b_3/b_3$	**100.0**	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0 10^{-6}
DipoleΔψ	50.0	50.0	**46.4**	50.0	50.0	50.0	50.0	50.0	46.4 μrad
GirderΔψ	50.0	50.0	**47.4**	50.0	50.0	50.0	50.0	50.0	47.4 μrad
GirderΔx	10.0	10.0	**2.0**	5.5	10.0	10.0	10.0	10.0	2.0 μm
GirderΔy	10.0	10.0	9.9	**5.3**	10.0	10.0	10.0	10.0	5.3 μm
QuadrupoleΔψ	**50.0**	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0 μrad
QuadrupoleΔx	10.0	7.3	**1.3**	2.1	4.1	10.0	4.7	3.4	1.3 μm
QuadrupoleΔy	9.3	6.7	**1.3**	1.4	5.1	3.4	4.1	2.9	1.3 μm
SextupoleΔx	**10.0**	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0 μm
SextupoleΔy	**10.0**	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0 μm

NO CORRECTION

Correction scheme



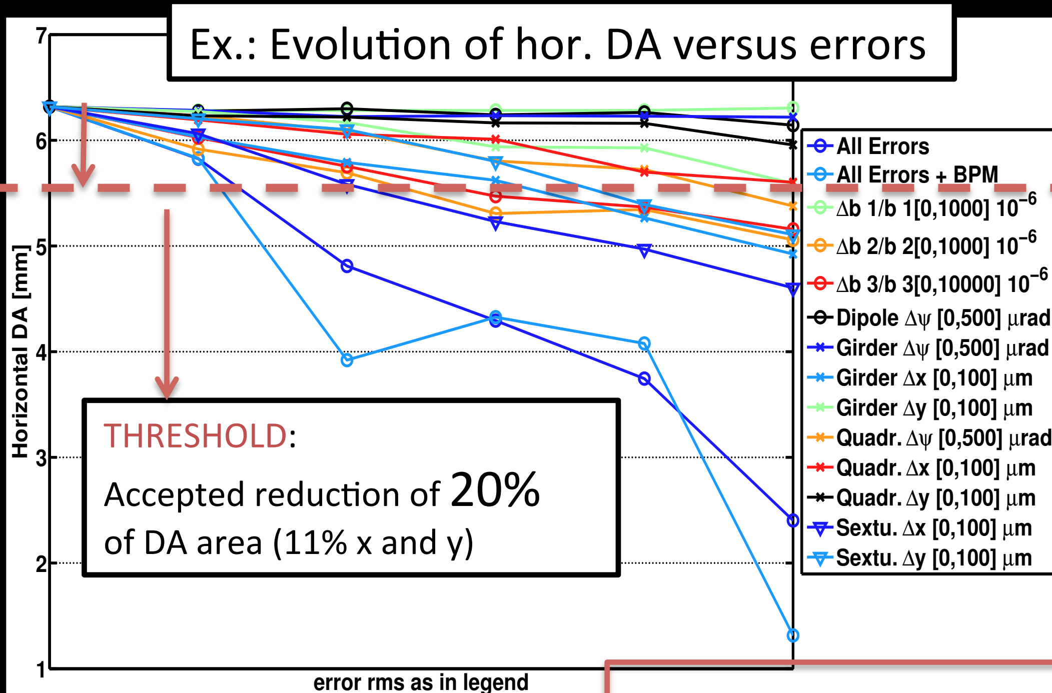
- Red crosses are H correctors
- Green crosses are vertical correctors
- Blue circles are skew quadrupole correctors
- Triangles are star and end of hipotetical girders
- Magnets are merged or considered solidal even if model is split
- No injection section

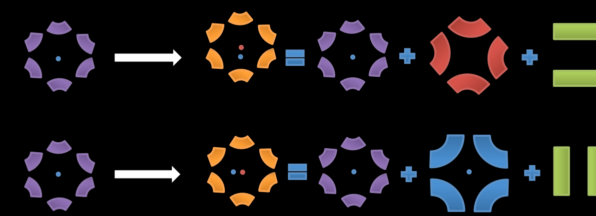


Correction:

- 10 steps ramp to error set correcting only orbit, horizontal and vertical.
- Horizontal correctors for horizontal orbit, horizontal dispersion, beta beating
- Vertical correctors for vertical orbit
- Skew quadrupoles for coupling and vertical dispersion
- Quadrupoles for beta beating
- Retune of the lattice to the working point (set to 0.58, 0.62).
- All quantities to be corrected are evaluated at the BPMs.
- The correction is reiterated several times.

Errors influence





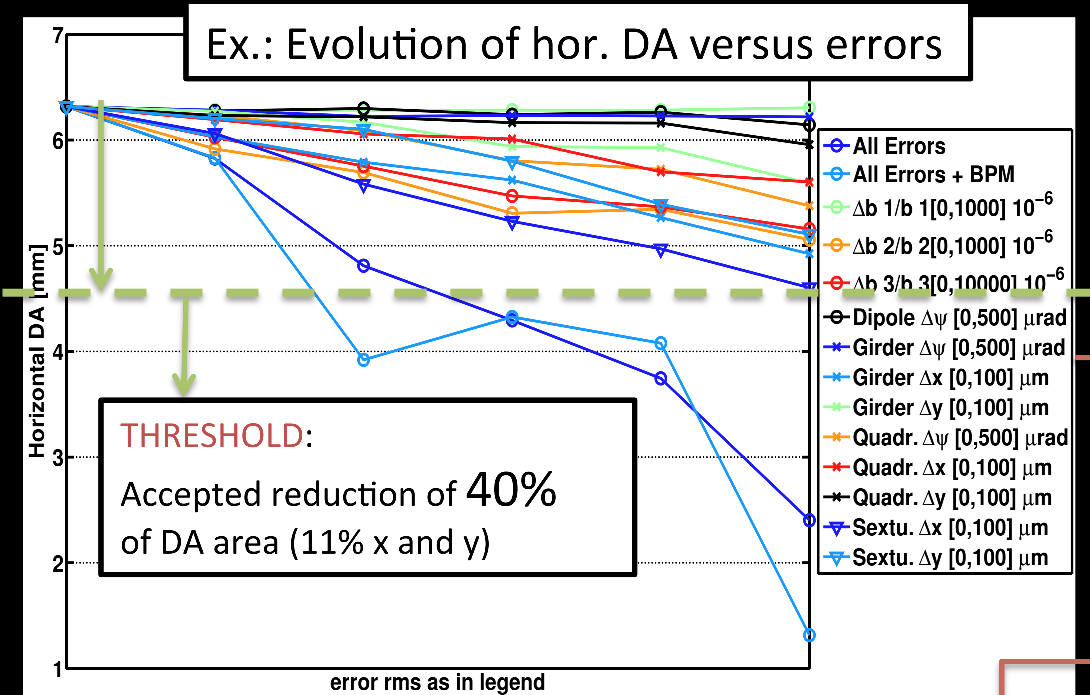
Large influence for off energy dynamics

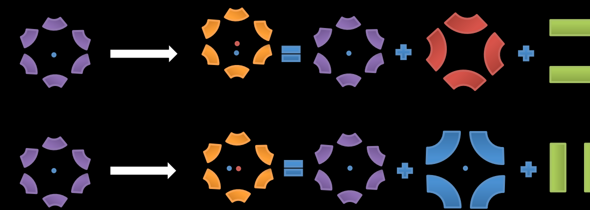
List of tolerable errors

	dynamic aperture				emittance		acceptance		
error	H	V	+2%	−2%	ϵ_x	ϵ_y	H	V	min
AllErrors	31.6	21.9	10.7	11.5	23.6	21.5	11.9	**8.8**	8.8 %
AllErrors + BPM	34.2	21.7	11.3	11.3	23.2	21.2	12.1	**8.7**	8.7 %
$\Delta b_1/b_1$	**1000.0**	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0 10^{-6}
$\Delta b_2/b_2$	1000.0	930.3	**316.2**	625.9	1000.0	1000.0	652.7	395.4	316.2 10^{-6}
$\Delta b_3/b_3$	**1000.0**	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0 10^{-6}
DipoleΔψ	**500.0**	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0 μrad
GirderΔψ	500.0	500.0	**393.2**	500.0	500.0	500.0	500.0	500.0	393.2 μrad
GirderΔx	100.0	68.8	30.6	**28.6**	100.0	100.0	38.2	29.8	28.6 μm
GirderΔy	100.0	84.7	**35.3**	43.1	86.0	68.1	47.4	40.4	35.3 μm
QuadrupoleΔψ	493.7	333.1	**125.1**	183.3	288.3	230.4	178.5	146.7	125.1 μrad
QuadrupoleΔx	100.0	81.5	**30.5**	38.7	100.0	100.0	43.4	35.1	30.5 μm
QuadrupoleΔy	100.0	93.4	**37.7**	46.0	56.8	46.7	52.6	43.2	37.7 μm
SextupoleΔx	74.5	39.3	21.0	22.2	100.0	100.0	24.3	**16.9**	16.9 μm
SextupoleΔy	100.0	87.8	**26.1**	42.2	80.6	65.1	57.8	42.3	26.1 μm

Correction with LET

Errors influence





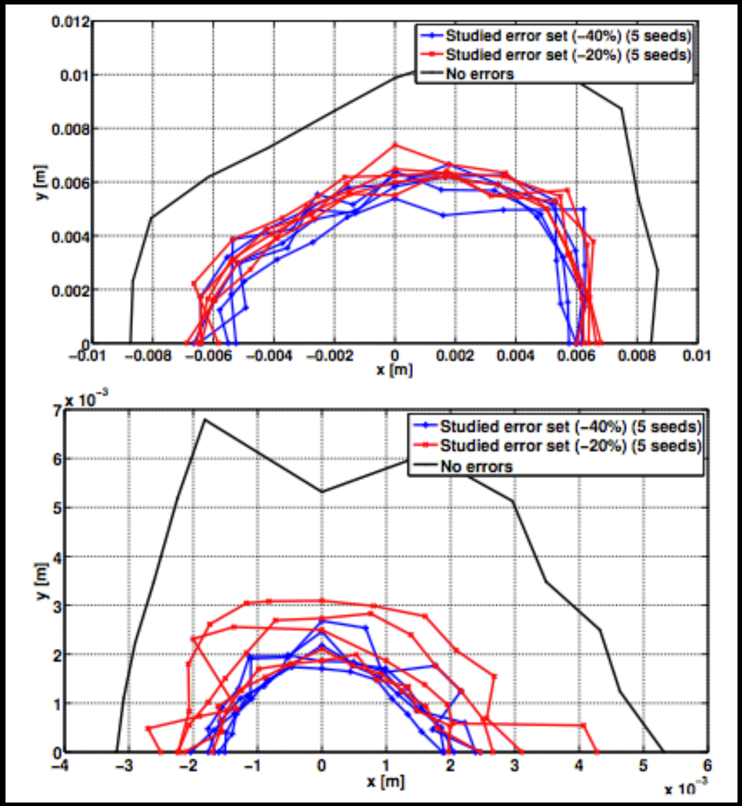
Large influence for off energy dynamics

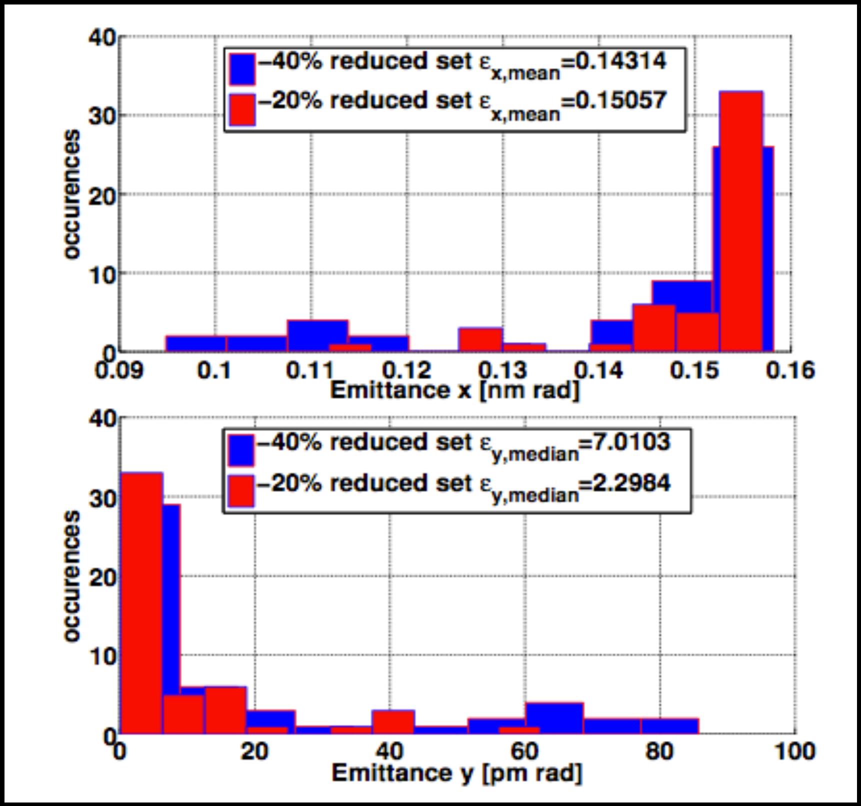
List of tolerable errors

	dynamic aperture				emittance		acceptance		
error	H	V	+2%	−2%	ϵ_x	ϵ_y	H	V	min
AllErrors	96.9	48.7	20.3	23.3	23.6	21.5	27.6	**16.6**	16.6 %
AllErrors + BPM	96.9	42.0	21.6	22.8	23.2	21.2	28.6	**16.4**	16.4 %
$\Delta b_1/b_1$	**1000.0**	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0 10^{-6}
$\Delta b_2/b_2$	1000.0	1000.0	907.6	1000.0	1000.0	1000.0	1000.0	**685.5**	685.5 10^{-6}
$\Delta b_3/b_3$	**1000.0**	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0 10^{-6}
DipoleΔψ	**500.0**	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0 μrad
GirderΔψ	**500.0**	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0 μrad
GirderΔx	100.0	100.0	89.2	55.1	100.0	100.0	91.4	**49.9**	49.9 μm
GirderΔy	100.0	100.0	90.4	88.5	86.0	68.1	100.0	**60.2**	60.2 μm
QuadrupoleΔψ	500.0	500.0	323.9	364.9	288.3	**230.4**	468.9	246.3	230.4 μrad
QuadrupoleΔx	100.0	100.0	100.0	77.8	100.0	100.0	100.0	**58.4**	58.4 μm
QuadrupoleΔy	100.0	100.0	97.2	81.5	56.8	**46.7**	100.0	65.8	46.7 μm
SextupoleΔx	100.0	85.7	63.5	39.5	100.0	100.0	63.5	**32.2**	32.2 μm
SextupoleΔy	100.0	100.0	77.9	91.1	80.6	**65.1**	100.0	73.5	65.1 μm

Correction with LET

Dynamic aperture, and emittances for tolerated errors budget.





2 set of tolerable errors defined changing the accepted reduction in emittance and DA:

- Multiple errors influence more the DA than single errors.
- Set with larger (double) tolerances (blue), gives about the same DA and larger emittances.

The definition of alternative corrector and BPM distribution is envisioned. Longitudinal motion and multipole have been addressed in other analysis not shown here.

Conclusions

Two codes have been presented:

- ATMATCH for the optimization of low horizontal emittance lattices (general purpose)
- LET for the tuning to ultra low vertical emittance and the correction of horizontal emittance

- The ATMATCH Code developed for the optimization of accelerator lattices, is now used in various light sources around the world (UK (Diamond), France (SOLEIL, ESRF), Spain (ALBA), THAILAND, CHINA, Australia, USA, …). It has been used in the thesis to optimize the ESRF upgrade lattice emittance, non-linear dynamics, and fix ID positions.

- The LET technique proved to be effective in using sextupoles off axis fields for the correction of vertical and horizontal emittance at DIAMOND, SLS and ESRF.

- The LET technique has been used to estimate a preliminary error budget for the ESRF upgrade lattice

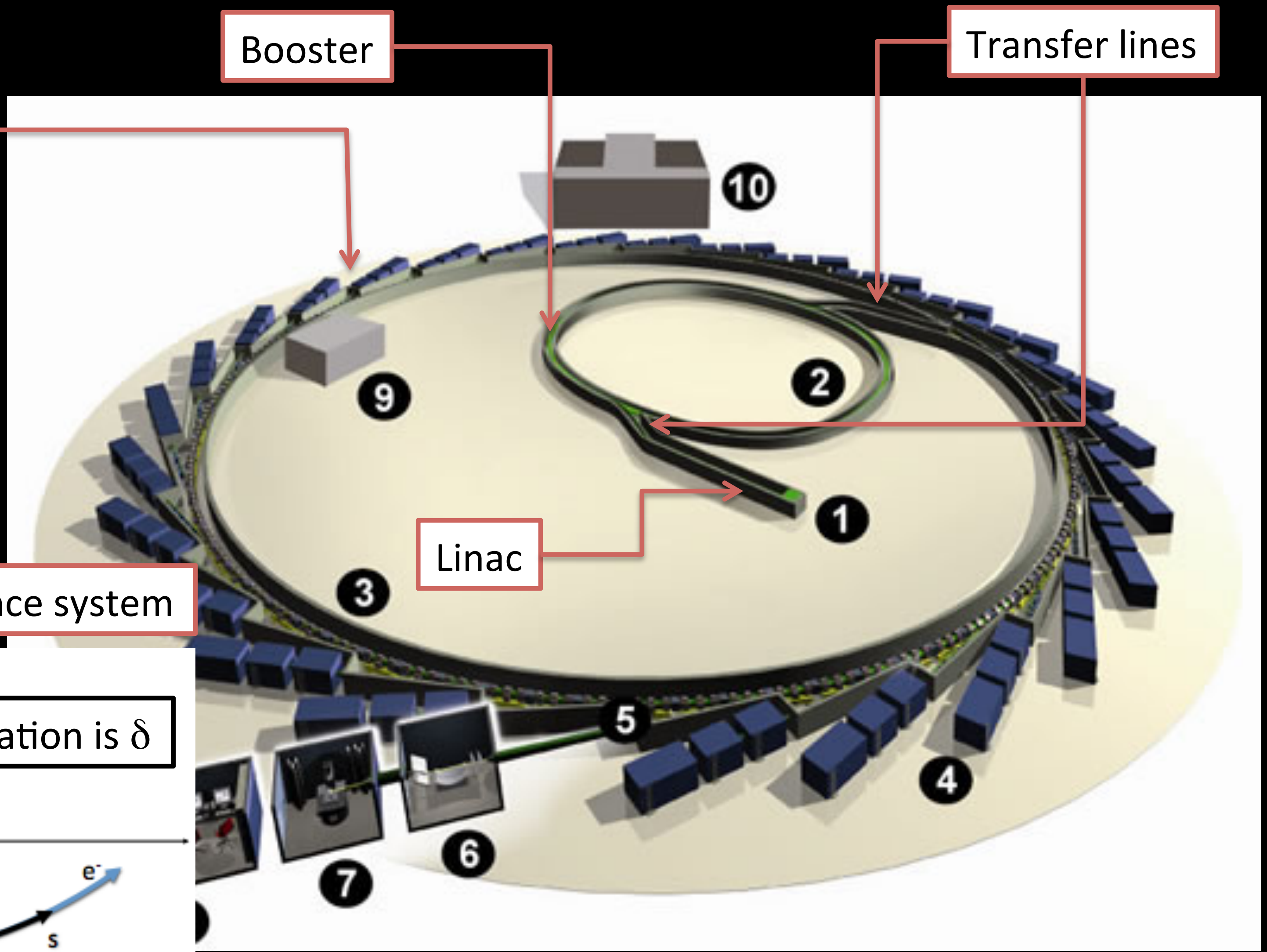
Data from atmatch guide download, september 2013

END

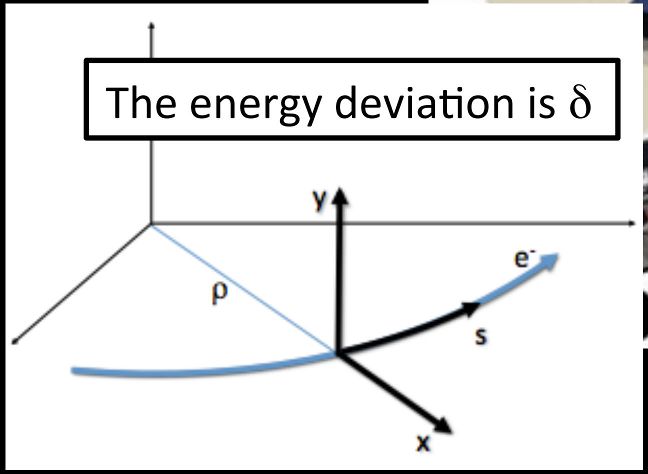
BACK UP

Additional slides on:
accelerator physics theory

Accelerator layout terminology



Curved reference system



Brilliance

Light Sources

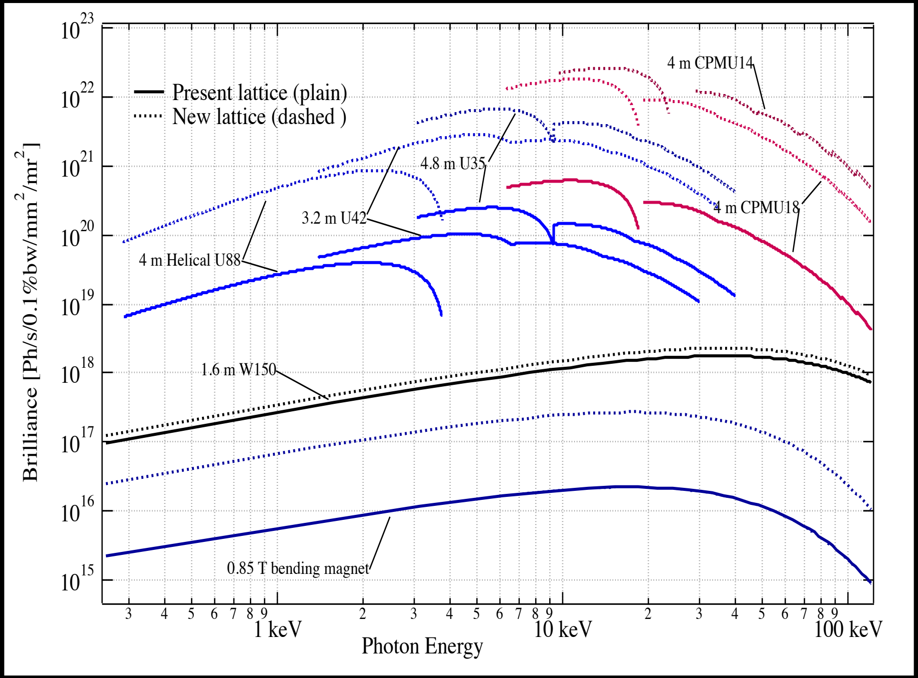
Brilliance

B = Photons/(s mm² mrad² BandWidth)

$$B_n = \frac{F_n}{4\pi^2(\varepsilon_x + \lambda_n/4\pi)(\varepsilon_y + \lambda_n/4\pi)}$$

$$\epsilon_{(\mathbf{x},\mathbf{y})} < \frac{\lambda}{4\pi}$$

Diffraction limit,
at λ=10nm is 10 pmrad
(lower ε does not increase B)



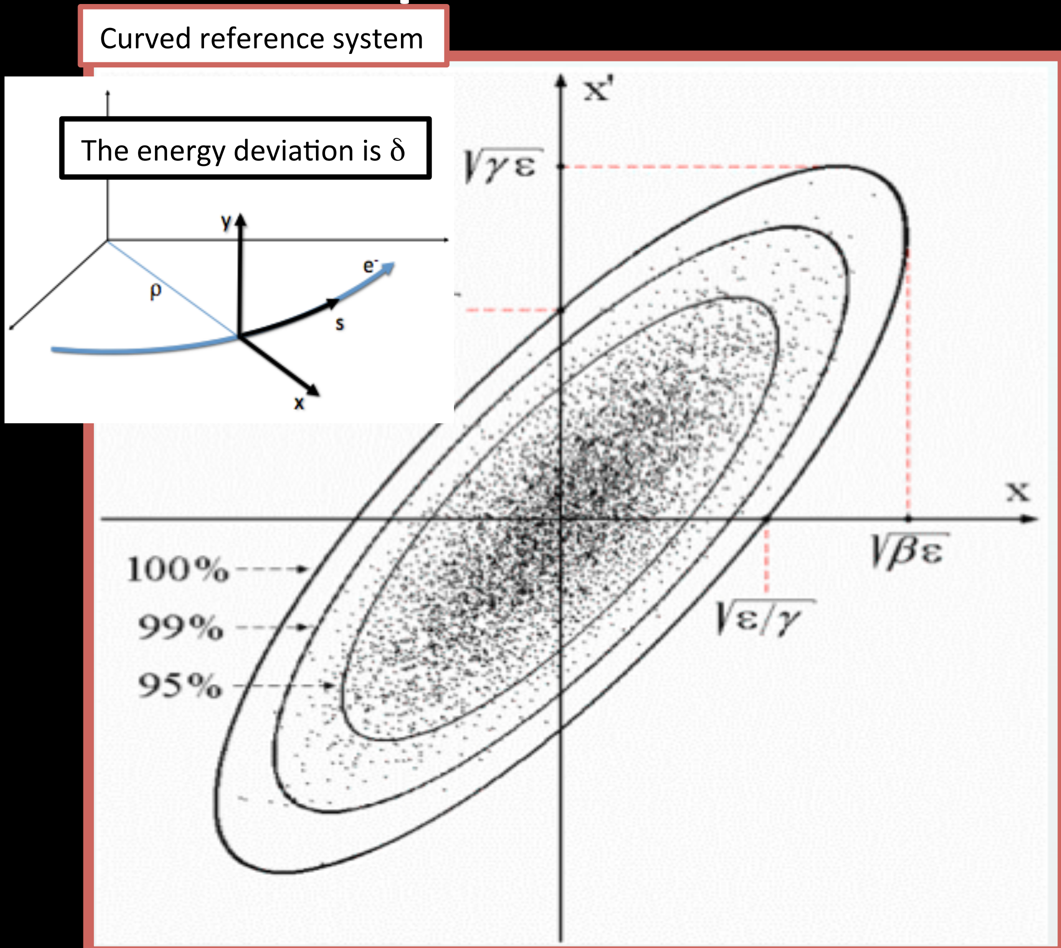
Low horizontal and vertical emittance

Limited by accelerator magnetic lattice and errors

Limited by errors

Phase space: emittance

*Liuville Theorme for protons, equilibrium emittance for electrons.



Phase space plots: at a given location in the ring, particles are distributed in a certain region of phase space. Particle trajectories in the absence of non-linearities are ellipses. The oscillation frequency of all particles within the ellipse is the tune.

The area of phase space at one sigma of the 2D distribution is the emittance. The emittance is invariant along the ring*.

$$\sigma_{eff} = \sigma_{x'}\sigma_x$$

$$\sigma_x = \sqrt{\epsilon_x\beta_x + (\eta_x\delta)^2}$$

$$\sigma_{x'} = \sqrt{\gamma_x\epsilon_x + (\eta'_x\delta)^2}$$

From Twiss parameters: electron beam size and divergence at a given location.

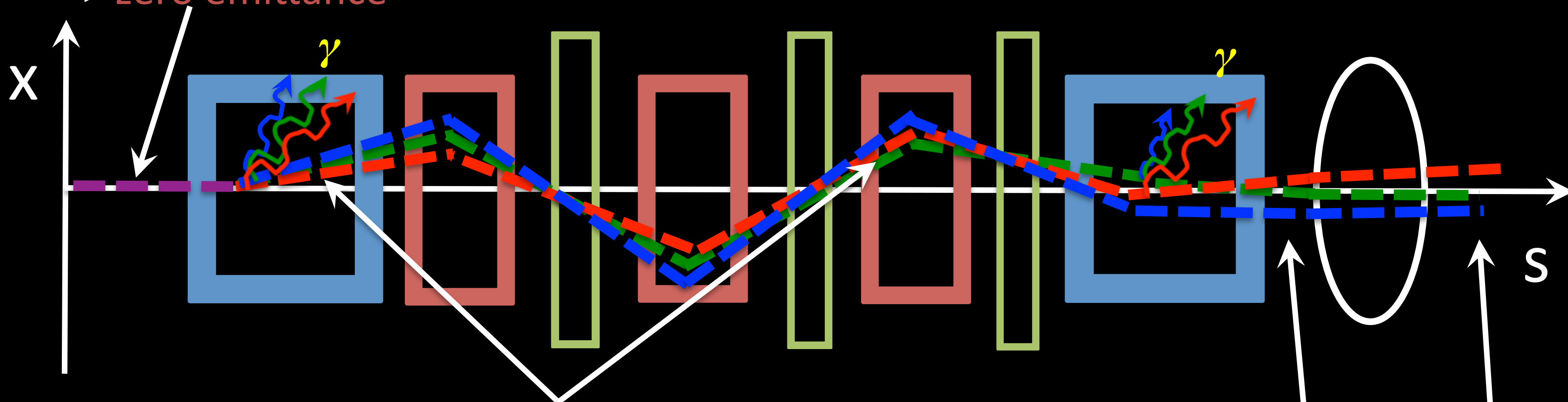
η is the dispersion
η' and its derivative

The same holds in the vertical plane

HOW TO REDUCE THE EMITTANCE?

The magnetic lattice is source of emittance

1) 3 incoming electrons with neither hor. velocity nor energy deviation
=> zero emittance

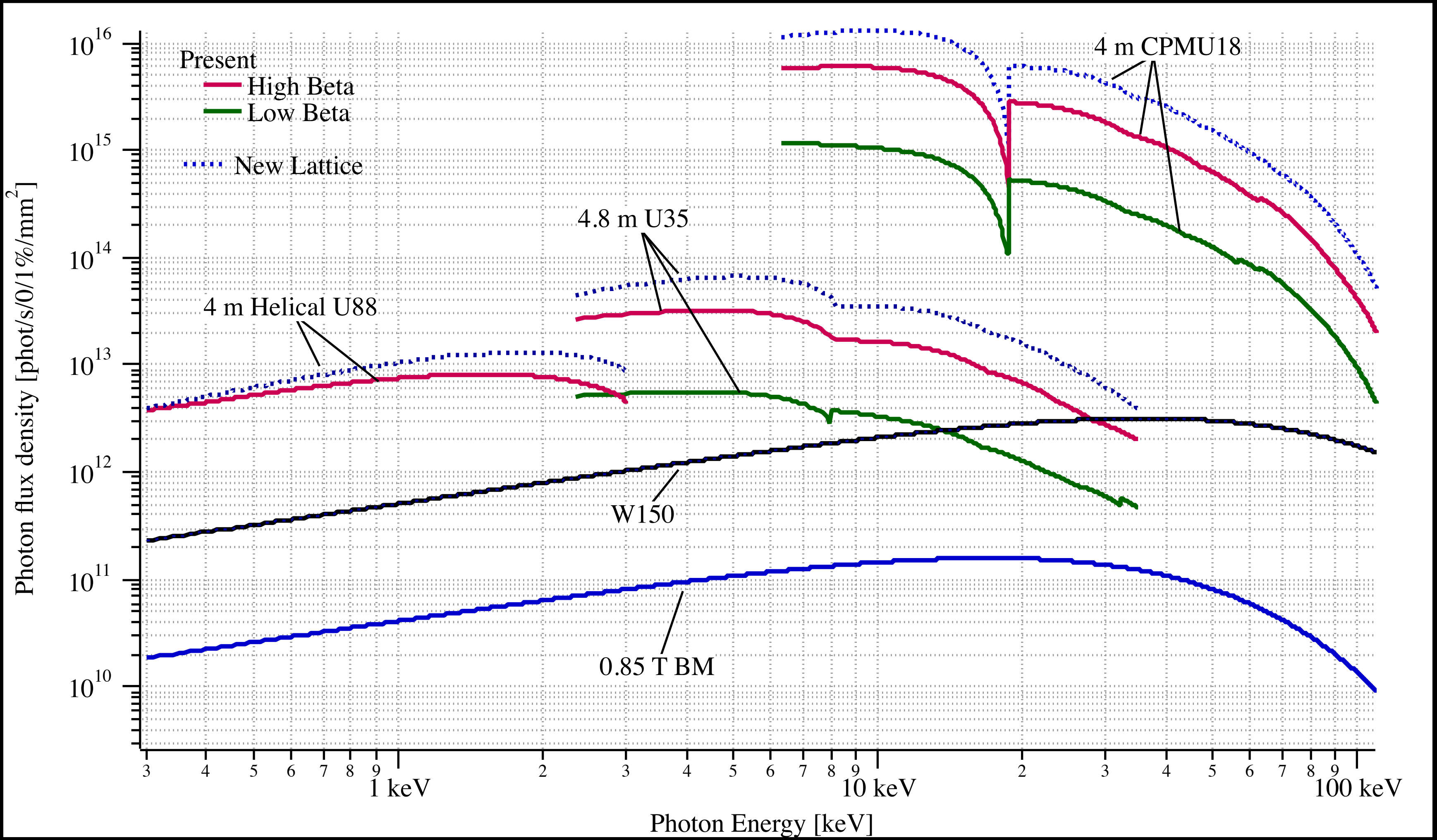


2) each electron emits photons and looses different amount of energies
=> the 3 electrons are bent and focused differently

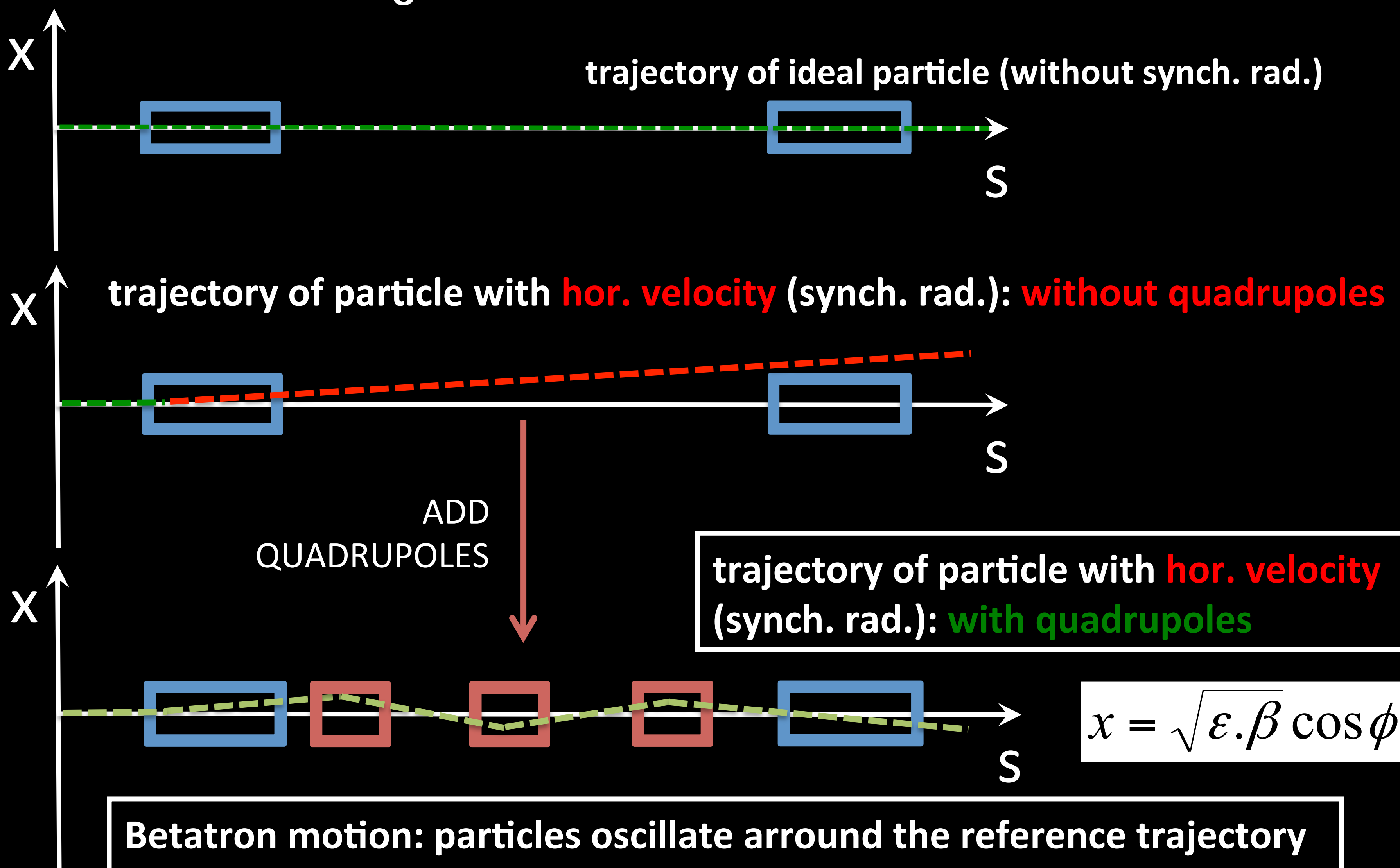
3) @ end of the cell, the 3 electrons have nonzero horizontal velocities
=> nonzero emittance (& energy spread)

4) RF cavity gives back longitudinal radiated energy: 3 electrons have reduced horizontal velocities DAMPING=> nonzero equilibrium emittance

Photon flux density

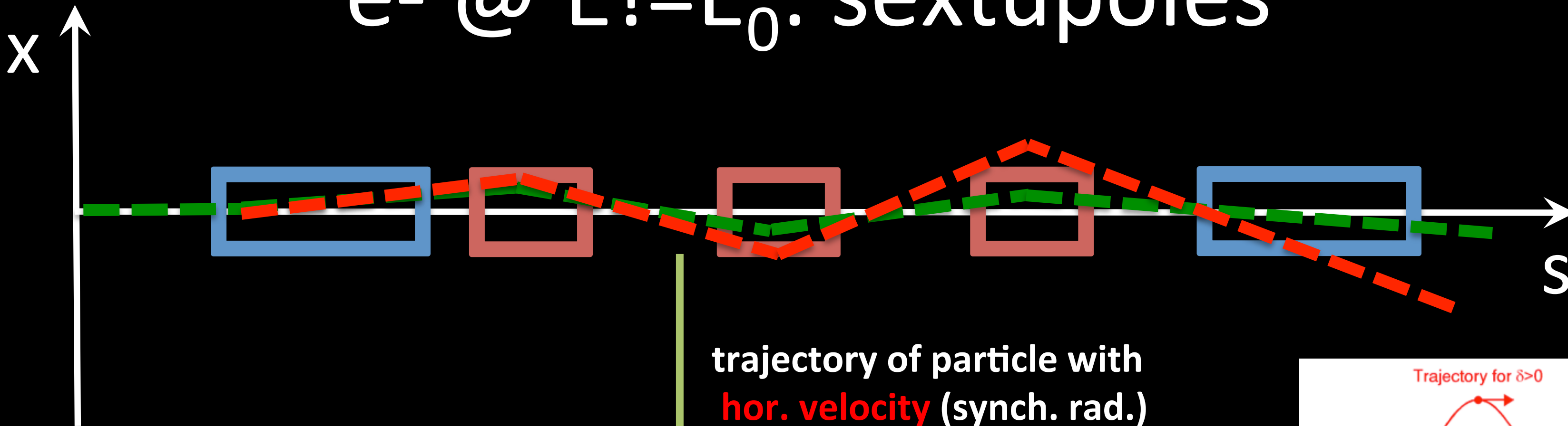


e- @ E=E$_0$: dipoles and quadrupoles

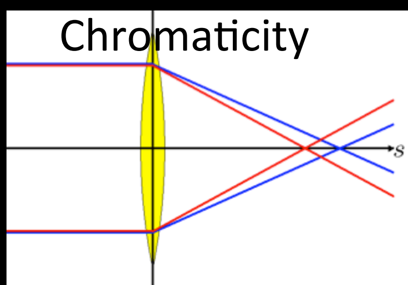


Betatron motion: particles oscillate arround the reference trajectory defined by dipoles: beta functions define the amplitude of the oscillation and the tune the number of oscillation per turn

e- @ E!=E$_0$: sextupoles

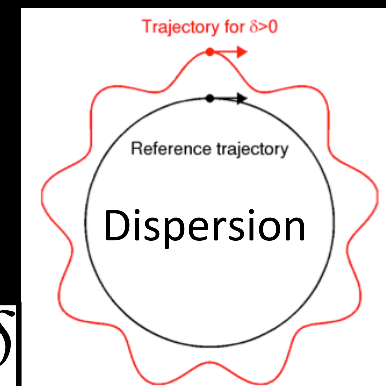


trajectory of particle with
hor. velocity (synch. rad.)
- - - with nominal energy
- - - with energy deviation (synch. rad.)

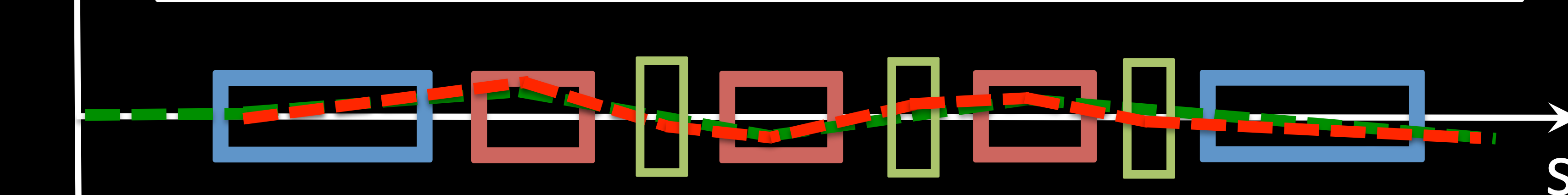


ADD SEXTUPOLES

$$\Delta x(s) = D_x(s)\delta$$

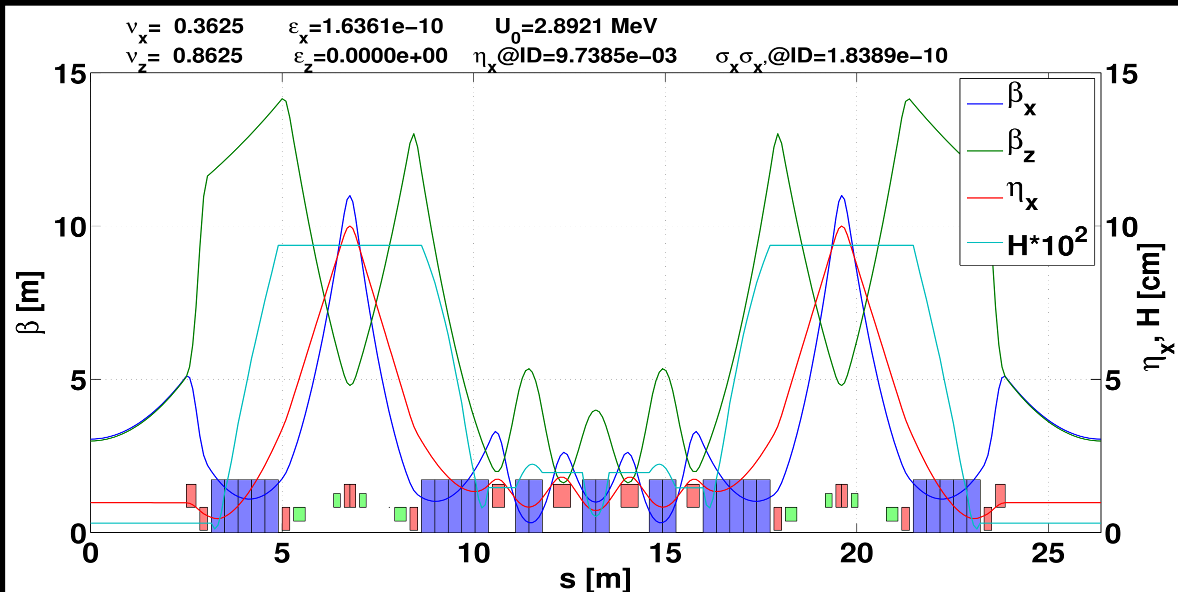


$$Chromaticity\ [>0] \propto -\beta_x K_1\ (@quads)\ + D_x K_2\ (@sext.)$$



PARTICLES NOT ON THE NOMINAL ENERGY ARE FOCUSED using sextupoles.

ESRF lattice cell highlights



$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2}$$

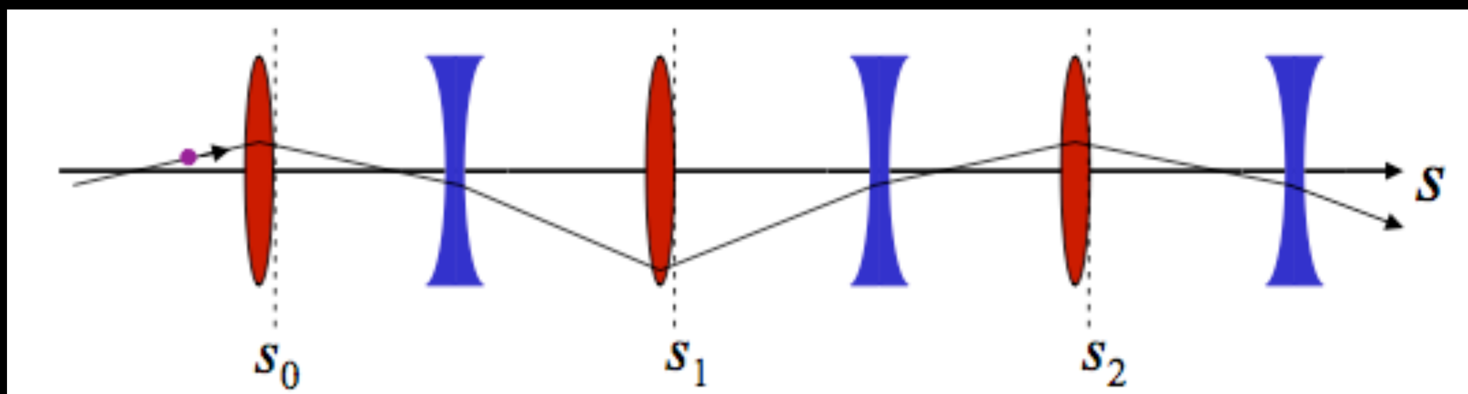
$$\epsilon_x^{DBA}(\mathrm{radm}) = 5.036\,10^{-13}\,E^2(\mathrm{GeV}^2)\,\theta^3(\mathrm{deg}^3)$$

1. Disperson bumps
2. Combined function magnets
3. 7 bend
4. Longitudinal gradient dipole for higher dispersion bump
5. -I transfromation between sextupoles for first order RDT compensation.
6. Octupoles
7. 10 mm Hor. DA
8. 150 pm

Betatron Tune

Beam focused by quadrupoles, oscillation amplitude ($\beta(s)$) and phase ($\phi(s)$) depend on s. The emittance ε is a global parameter, determined by the lattice and by the particle.

$$x = \sqrt{\varepsilon.\beta}\cos\phi$$



The number of oscillations after one turn of the storage ring is called the TUNE. Fractional part is interesting for beam dynamics

The tunes and linear combinations of the tunes must not be integer or fractional, to avoid resonant conditions, that may lead to beam loss. ESRF tunes (34.44, 13.39)

Tune varies with amplitude of oscillation and with change of energy.

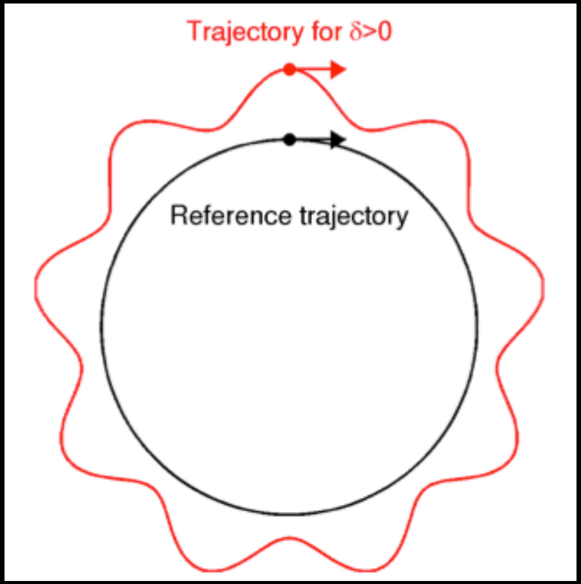
Dispersion and chromaticity

Dispersion describes the change in orbit due to a change of energy

$$\Delta x(s) = \eta_x(s)\delta$$

Local radial displacement due to momentum spread

Dispersion function

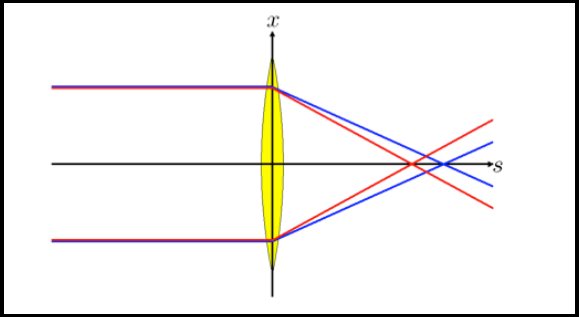


Chromaticity is the variation of focusing strength for particles off momentum. The higher the energy of the particle the longer the focal length

$$\zeta_x = \frac{1}{4\pi}\left[\sum_n^{N_{sext}} (2b_3L)_n \eta_{xn} - \sum_n^{N_{quad}} (b_2L)_n\right]\beta_{xn}$$

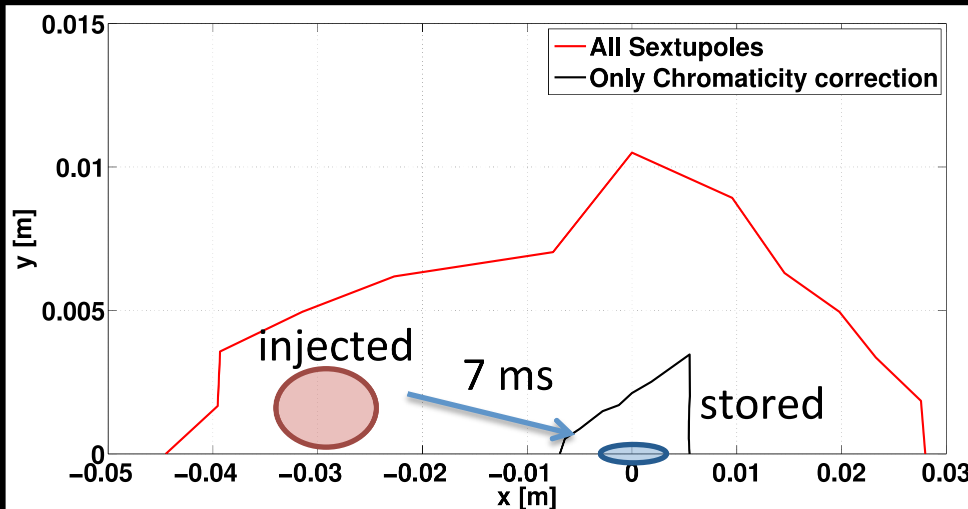
sextupoles

quadrupoles

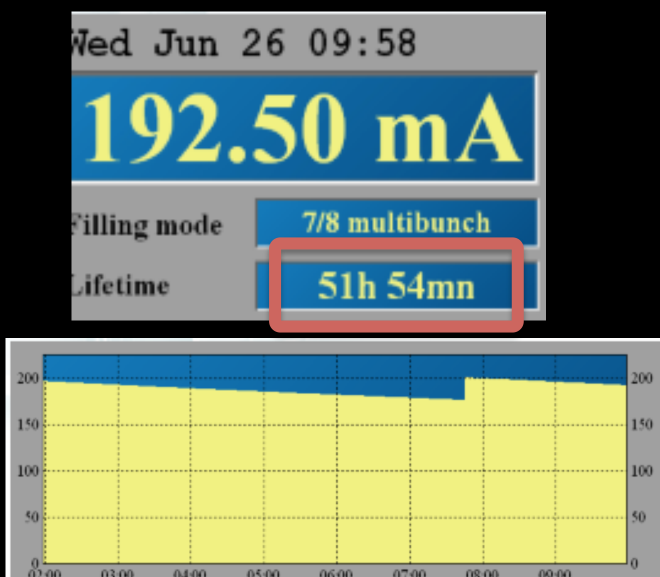


Sextupoles fix the chromaticity

Dynamic aperture and lifetime



Dynamic aperture:
Region of transverse space where tracked particles survive at least a given number of turns (512 here). Need sufficient dynamic aperture to inject the beam off axis in a region where it may survive.



Lifetime:
Time to reduce the number of electrons in the bunch by 1/e. Electrons are lost for interaction with residual gas (vaccum lifetime, ESRF~300h) and for coulomb collisions within the bunch leading to a large energy deviation (Touschek scattering, ESRF~50h).
Small beam volume leads to small lifetime.

Achieving ultra low emittance lattice

$$\epsilon_x = C_q \frac{\gamma^2}{\boxed{J_x}} \boxed{\frac{I_5}{I_2}}$$

$$\epsilon_x^{DBA}(\mathrm{rad\,m}) = 5.036\,10^{-13} \boxed{E^2(\mathrm{GeV}^2)} \boxed{\theta^3(\mathrm{deg}^3)}$$

$$I_5 = \int \frac{\mathcal{H}_u}{\rho^3} ds$$

Curly-H

$$I_2 = \int \left(\frac{1}{\rho_x^2} + \frac{1}{\rho_y^2} \right) ds$$

$$\mathcal{H}_u = \beta_u D_u'^2 + 2\alpha D_u D_u' + \gamma_u D_u^2$$

Small bending angles

Small beam Energy

Optics: Twiss and dispersion

Combined function magnets

Available space, €

X-ray energy

Strong focusing

Ultimate Storage Ring lattices

Strong chromaticity

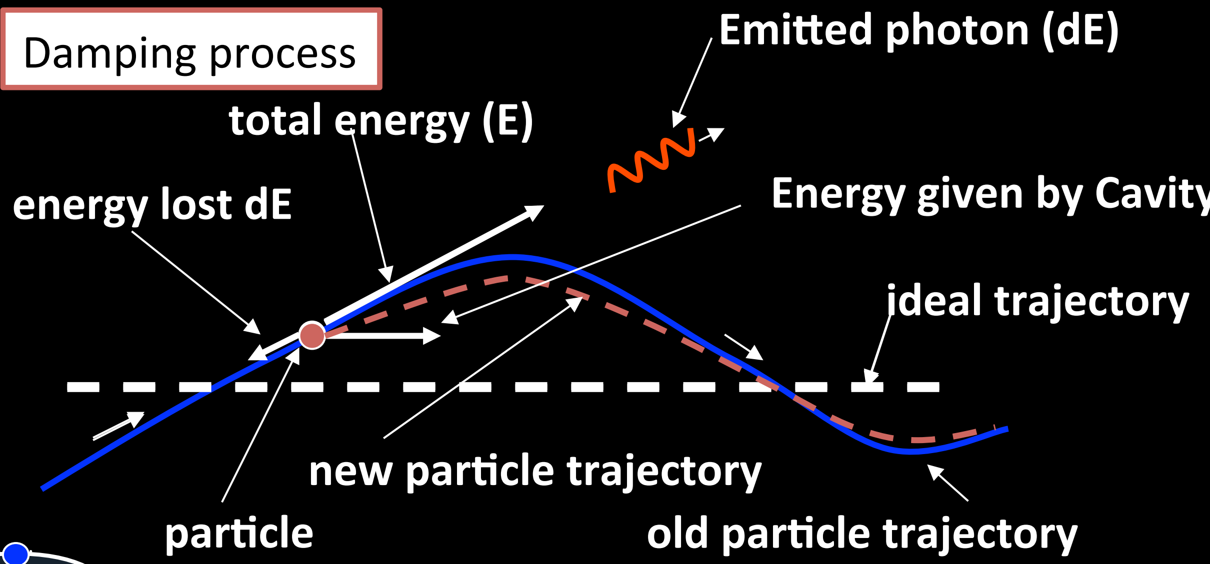
Injection

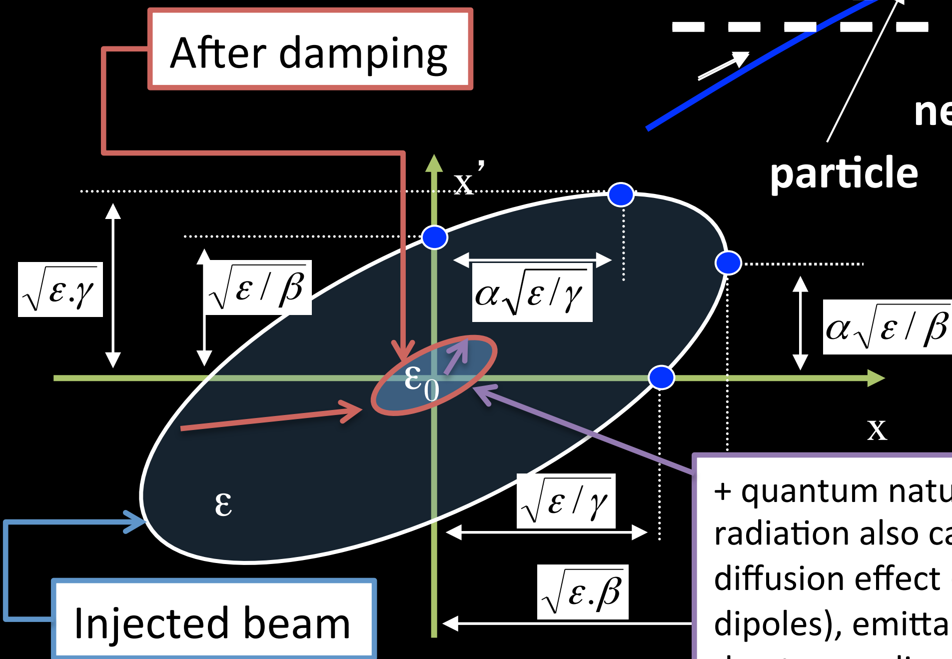
Beam lifetime

Non linearity

Aperture

Equilibrium Emittance





+ quantum nature of radiation also causes a diffusion effect (mainly dipoles), emittance growth due to coupling with transverse, (dispersion)

Equilibrium horizontal emittance is not zero. Defined by the Twiss parameters (α,β,γ) and by the bending magnets

$$I_5 = \int \frac{\mathcal{H}_u}{\rho^3} ds$$

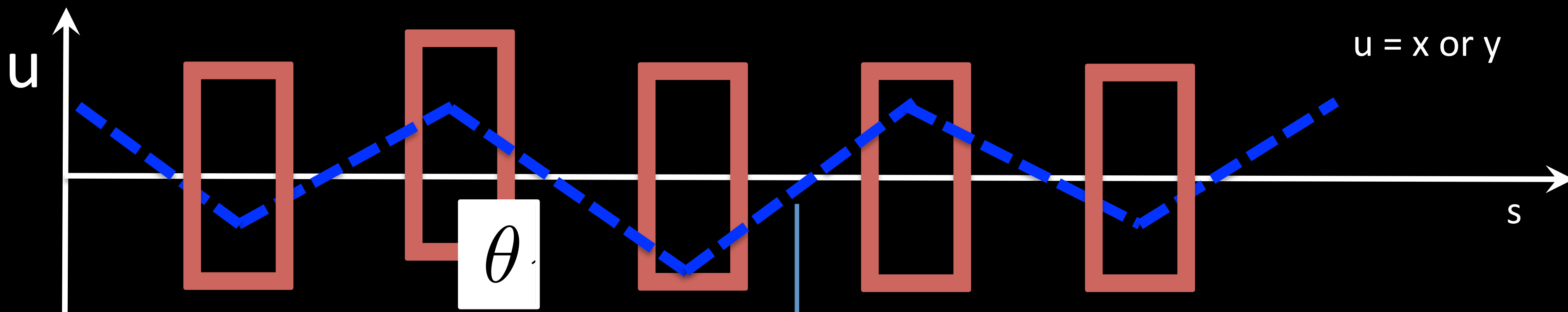
$$I_2 = \int \left(\frac{1}{\rho_x^2} + \frac{1}{\rho_y^2}\right) ds$$

$$\mathcal{H}_u = \beta_u D_u'^2 + 2\alpha D_u D_u' + \gamma_u D_u^2$$

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2}$$

$$\epsilon_x^{DBA}(\mathrm{radm}) = 5.036\, 10^{-13}\, E^2(\mathrm{GeV}^2)\theta^3(\mathrm{deg}^3)$$

Example: Orbit correction

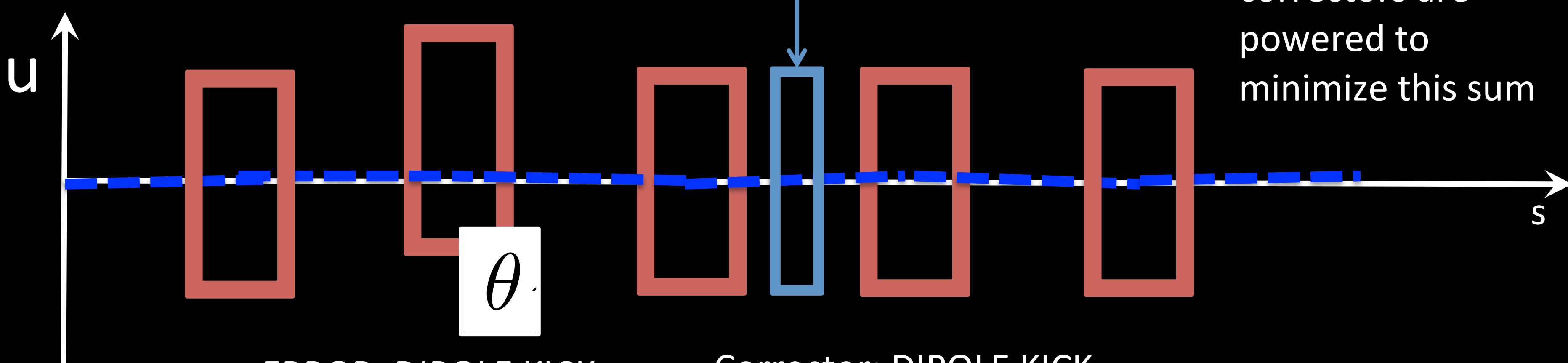


ERROR: DIPOLE KICK

Add a corrector dipole

$$\Delta u(s) = \frac{\sqrt{\beta(s)}}{2\sin \pi Q} \sum_{i=1}^{N} \theta_i \sqrt{\beta_i(s)} \cos\left(|\phi(s) - \phi_i(s)| - \pi Q\right)$$

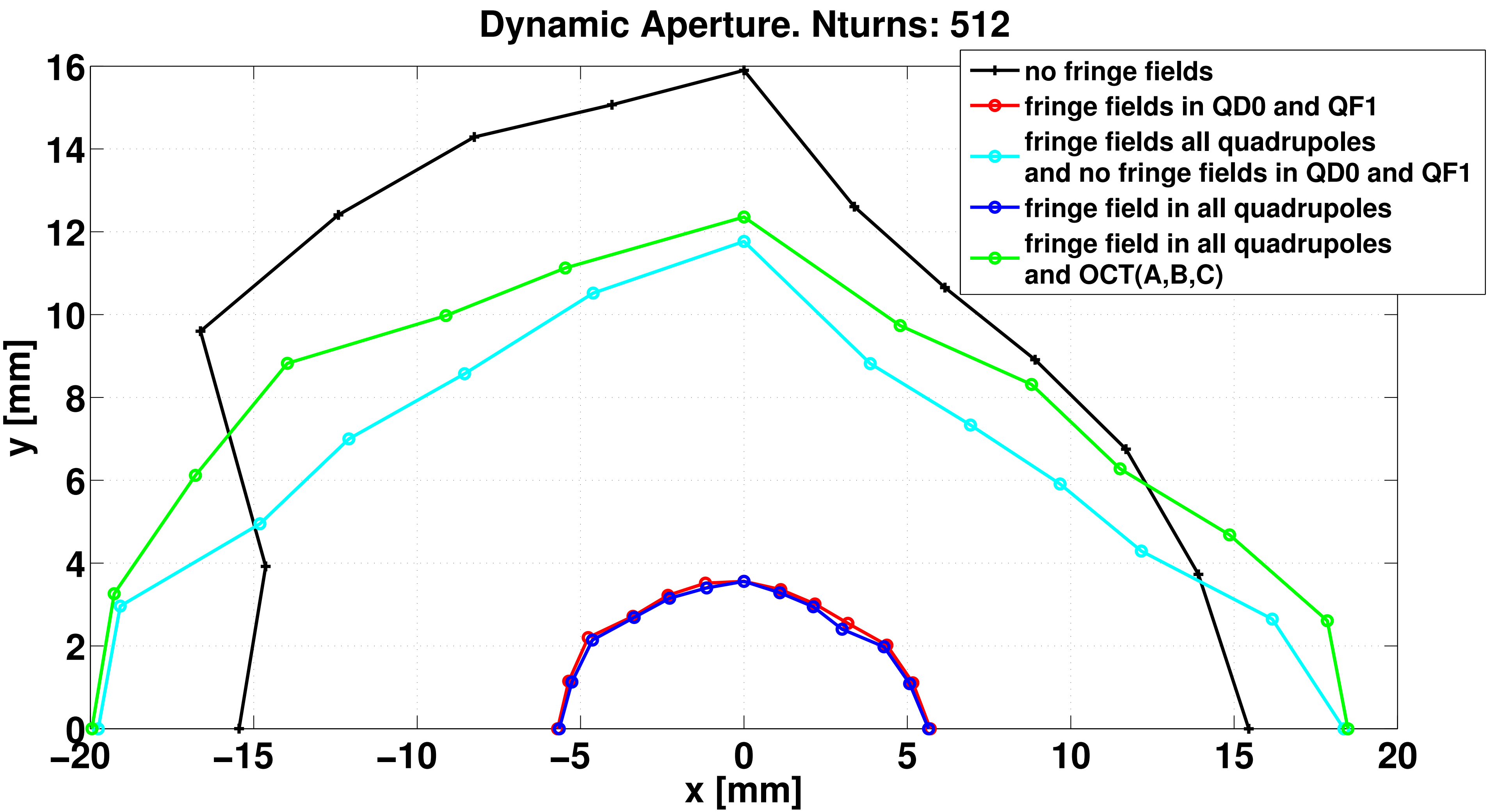
θ may be originated from an error or a dipole or a corrector. To reduce Δu to zero correctors are powered to minimize this sum



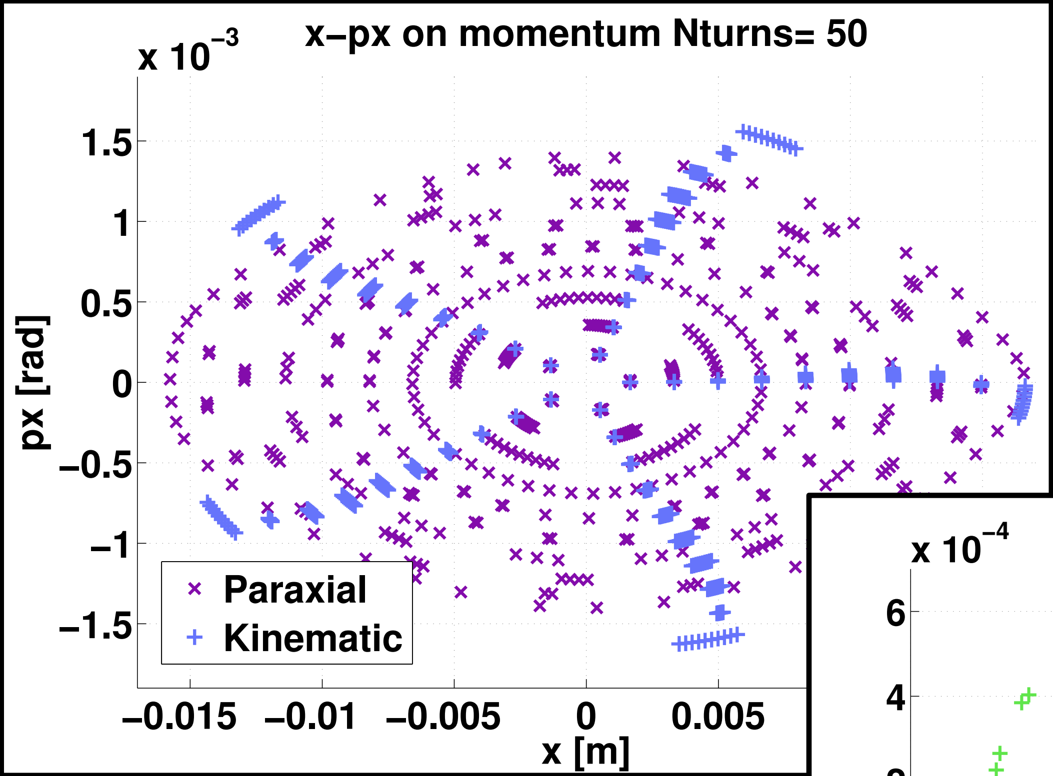
ERROR: DIPOLE KICK

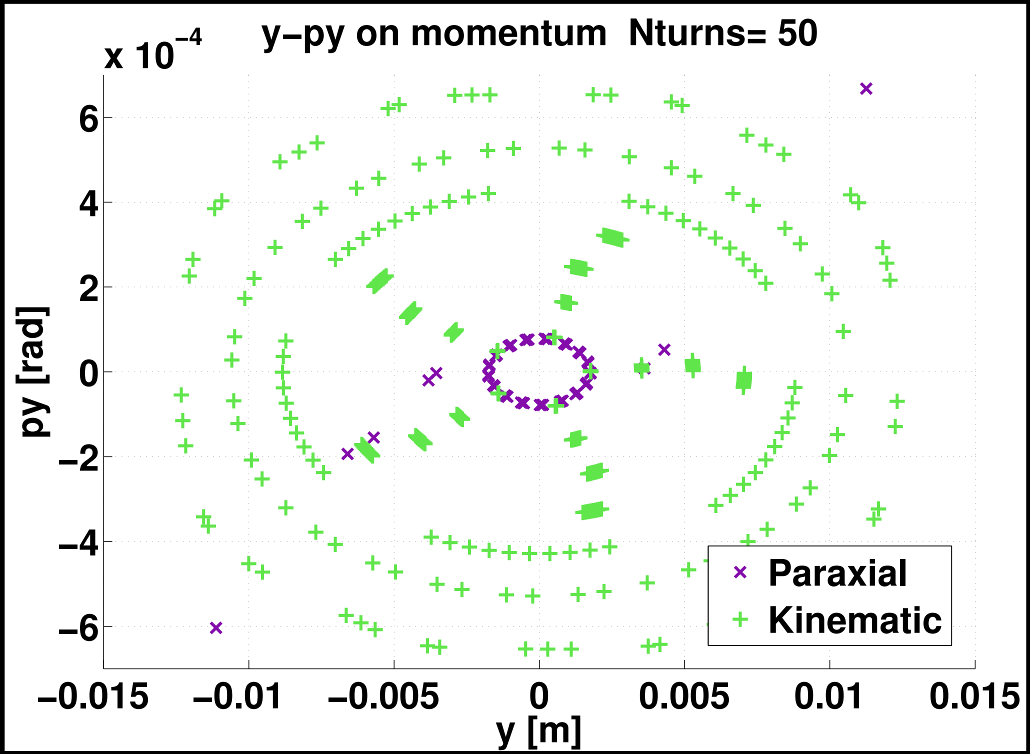
Corrector: DIPOLE KICK

Kinematic term for the Tau-charm collider



Fringe fields for the Tau-charm collider





Additional slides on:

ATMATCH

ATMATCH: matching and optimizations

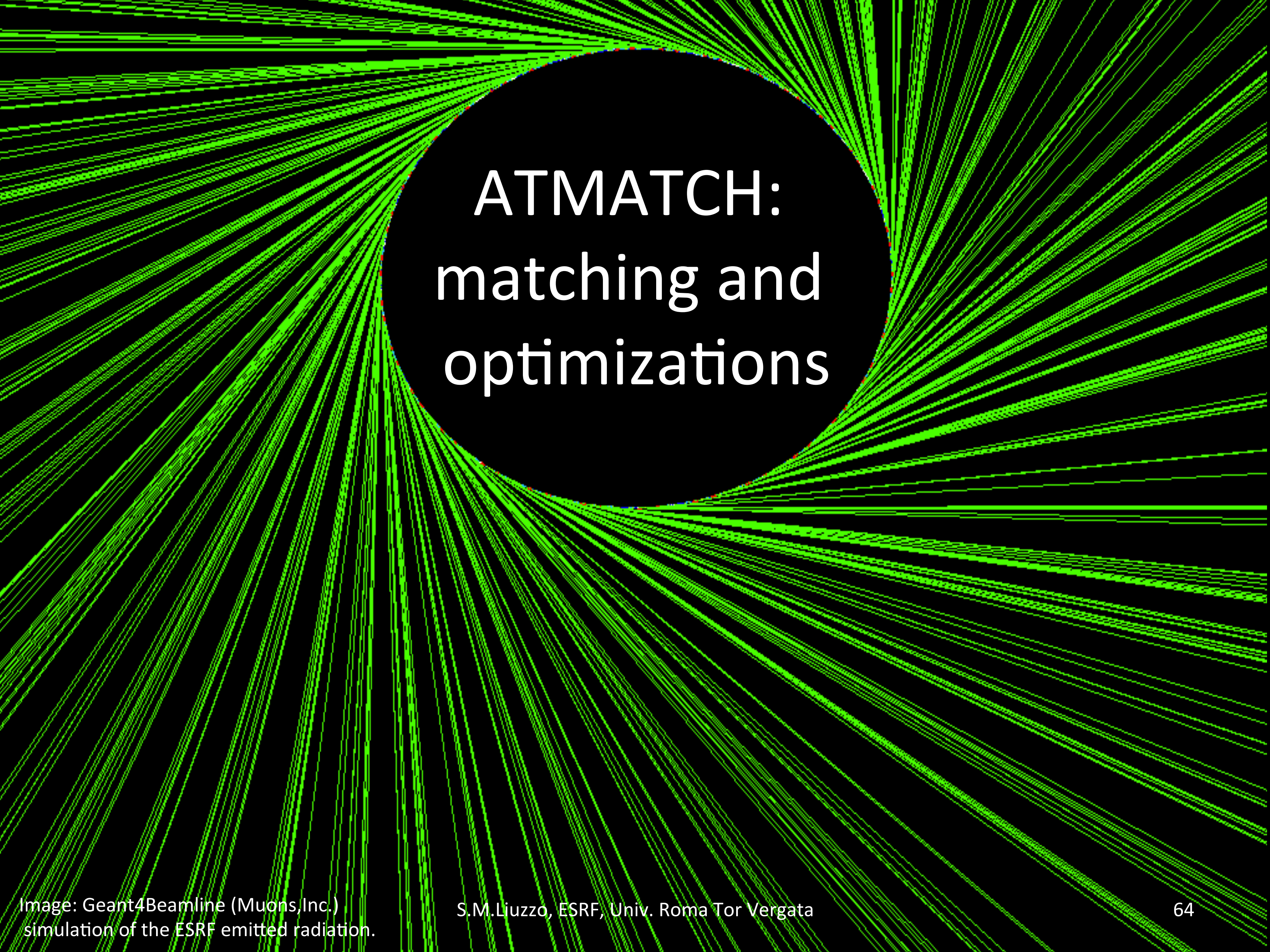


Image: Geant4Beamline (Muons,Inc.) simulation of the ESRF emitted radiation.

ATMATCH: AT general purpose fitting routine.

AT Lattice
(cell array of structures)

- Element name
- Quadrupole, Sextupole
- Integration method
- Length
- Position
- Errors
- Multipole expansion
- …

Variables
(array of structures)

- Field to change in AT
- Limits

or

- Function (conditions!)
- Limits

Constraints
(array of structures)

- function of the AT lattice
- Wished value limits
- Weight

ATMATCH

LOOP

change Variables ⇨ new AT Lattice ⇨ compute Constraints

AT Lattice

(cell array of structures)

FamName: 'BPI4U' Magnet name

Length: 0.3606 Magnet Length

PolynomA: [0 0 0] Skew multipole components

PolynomB: [3.7048e-06 0 0 0 0 0 0 0 0 0] Normal multipole components

NumIntSteps: 10 slices: in each slice integration is performed with a symplectic integrator

BendingAngle: 0.0126

EntranceAngle: 0.0161

ExitAngle: 0

PassMethod: 'BndMPoleSymplectic4Pass' Integration method, the Hamiltonian (compiled C code (mex), may prototype in matlab).

Class: 'Bend' Magnet type

R1: [6x6 double]

R2: [6x6 double]

T1: [-4.0359e-16 0 8.3758e-16 0 0 0]

T2: [4.0359e-16 0 -8.3758e-16 0 0 0]

Alignment and rotation errors

Other...

Many multipoles on the same magnets. No need for slicing to model a complex-real magnet

Other parameters according to magnet type, or other elements like beam position monitors, scrapers, elements to simulate collisions or collective effects

ATMATCH: AT general purpose fitting routine.

Variables
(array of structures)

```
Variab1=....
atVariableBuilder(...
RING,{'QD',’SF'},...
{{'PolynomB',{1,2}},...
{'PolynomB',{1,3}}});
```

```
Variab2=...
atVariableBuilder(atlattice,...
 {@(atlattice)fun(atlattice,arg,...)},
{0.01});
```

```
Variab1=struct('Indx’, QDindx,...
    'LowLim',{[],[]}, 'HighLim',{[],[]},...
    'Parameter’,{'PolynomB',{1,2}});
```

Variables may modify lattice parameters described in the AT structure

Variables may be defined as functions

Conditioned variables!
Ex: change the length of 10 dipoles, keeping the total bending angle constant

matlab

ATMATCH

```
newatlattice=atmatch(atlattice,Variab,Constr,tol,niter,verbosity,@lsqnonlin);
```

ATMATCH: AT general purpose fitting routine.

The computations of optics and beam parameters (β, α, η, tunes, chromaticity) are performed in a single call. No loss of CPU time

Any function may be used as a constraint:
Emittance
Combinations of beam parameters
Output of other programs
Online data from control system
Dynamic aperture, lifetime,...

Constraints
(array of structures)

```
c1=...
atlinconstraint(qfmindx(2),...
{{'beta',{1}},{'beta',{2}}},...
[17.3,0.58], [17.3,0.58], [1 1]);
```

```
Constr=struct(..
'Fun',@(arg)fun(atlattice,arg,...),...
   'Min',d,    'Max',d,...
   'RefPoints',[],...
   'Weight',1); %
```

matlab

ATMATCH

```
newatlattice=atmatch(atlattice,Variab,Constr,tol,niter,verbosity,@lsqnonlin);
```

ATMATCH: AT general purpose fitting routine.

Variables
(array of structures)

```
Variab1=....
atVariableBuilder(...
RING,{'QD',’SF'},...
{{'PolynomB',{1,2}},...
{'PolynomB',{1,3}}});
```

```
Variab2=...
atVariableBuilder(atlattice,...
 {@(arg)fun(arg,...)},{0.01});
```

Constraints and variables may be user defined functions.

Constraints
(array of structures)

```
c1=...
atlinconstraint(qfmindx(2),...
{{'beta',{1}},{'beta',{2}}},...
[17.3,0.58], [17.3,0.58], [1 1]);
```

```
Constr=struct(..
'Fun',@(arg)fun(arg,...),...
   'Min',d,    'Max',d,...
   'RefPoints',[],...
   'Weight',1); %
```

The computations of optics and beam parameters (beta, alpha, dispersion, tunes, chromaticity) are performed in a single call.

matlab

ATMATCH

```
newatlattice=atmatch(atlattice,Variab,Constr,tol,niter,verbosity,@lsqnonlin);
```

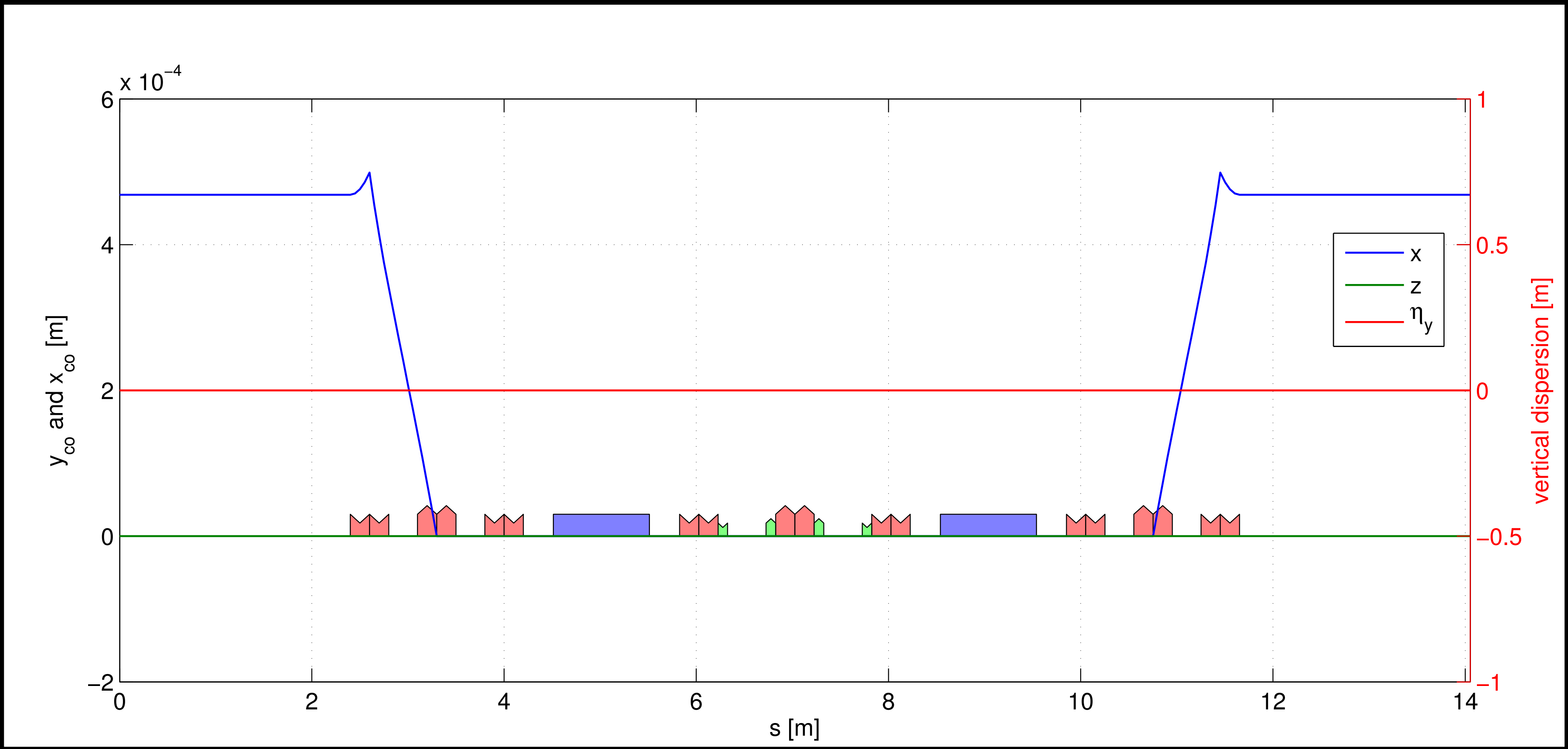
Examples

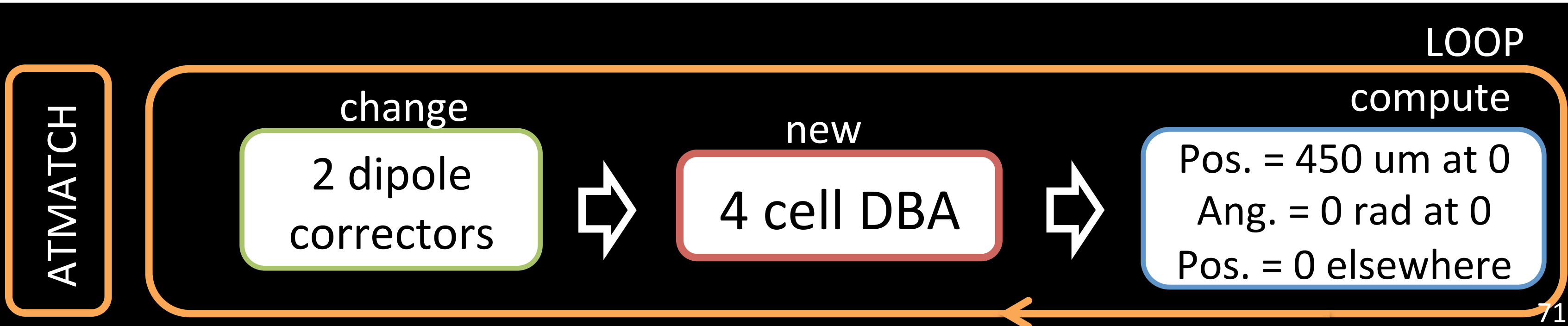
- Orbit bump: injection, X-ray beam pointing
- Beta functions : local beam size

Applications in the new lattice

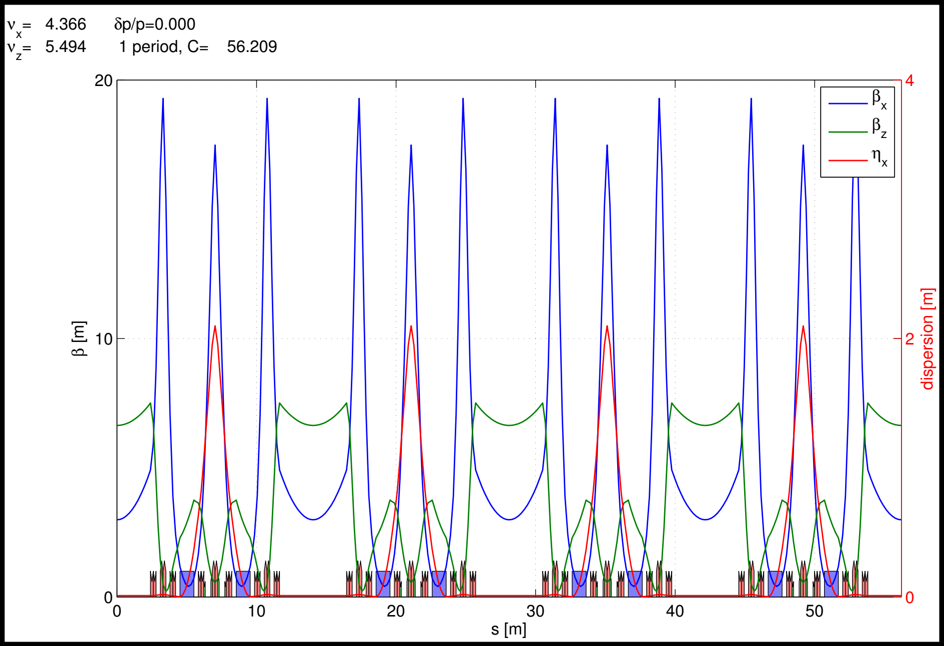
- Emittance: global beam size
- Dispersion bump setting for lower sextupoles
- Tune variation at large amplitudes: lifetime, injection

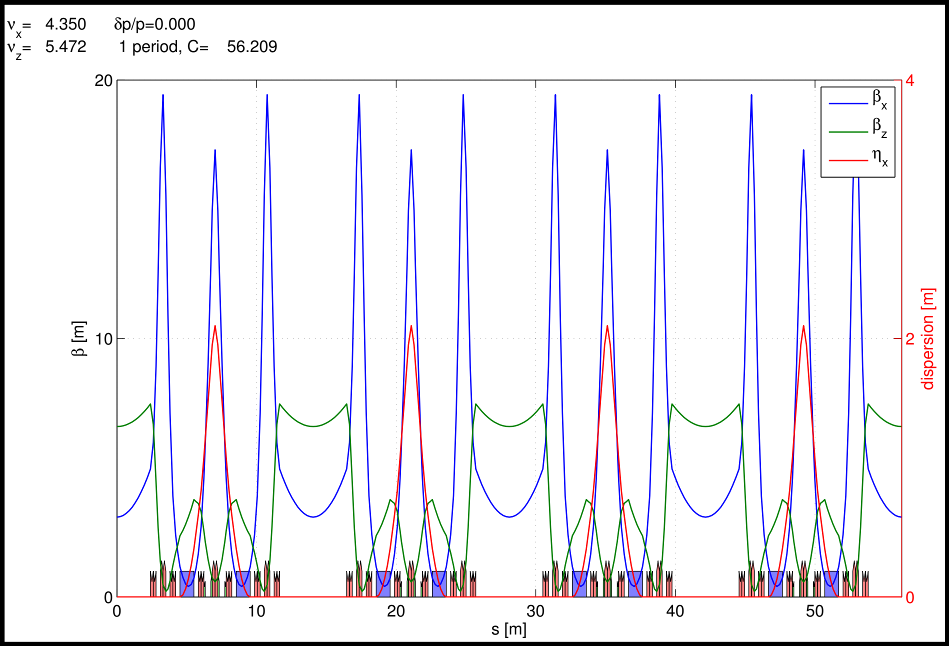
ATMATCH Example: fit of an orbit bump

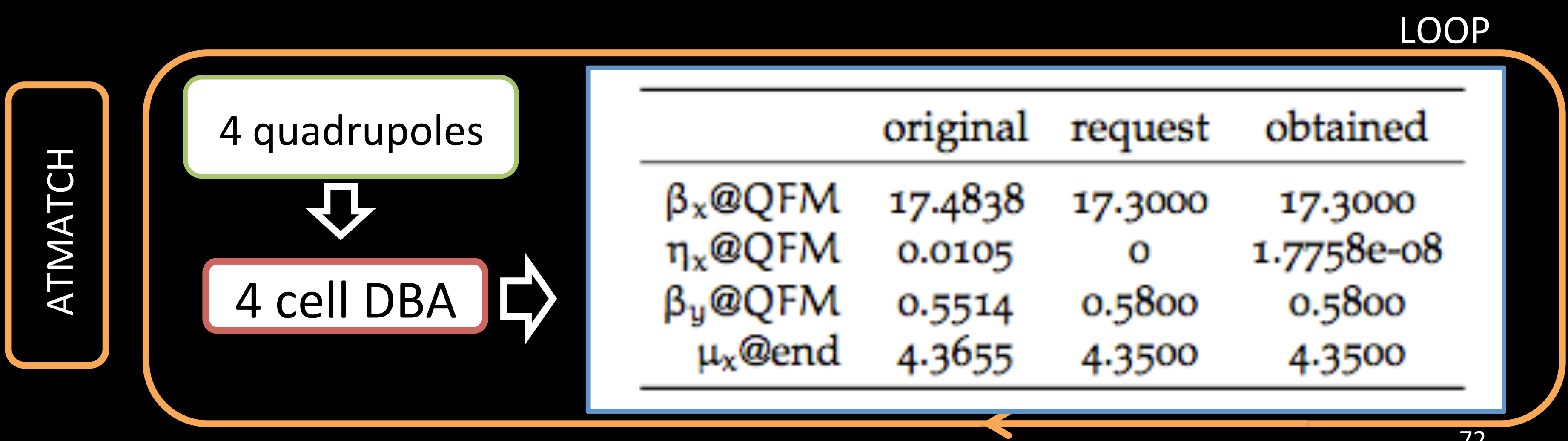




ATMATCH Example: fit of optical functions (Twiss)

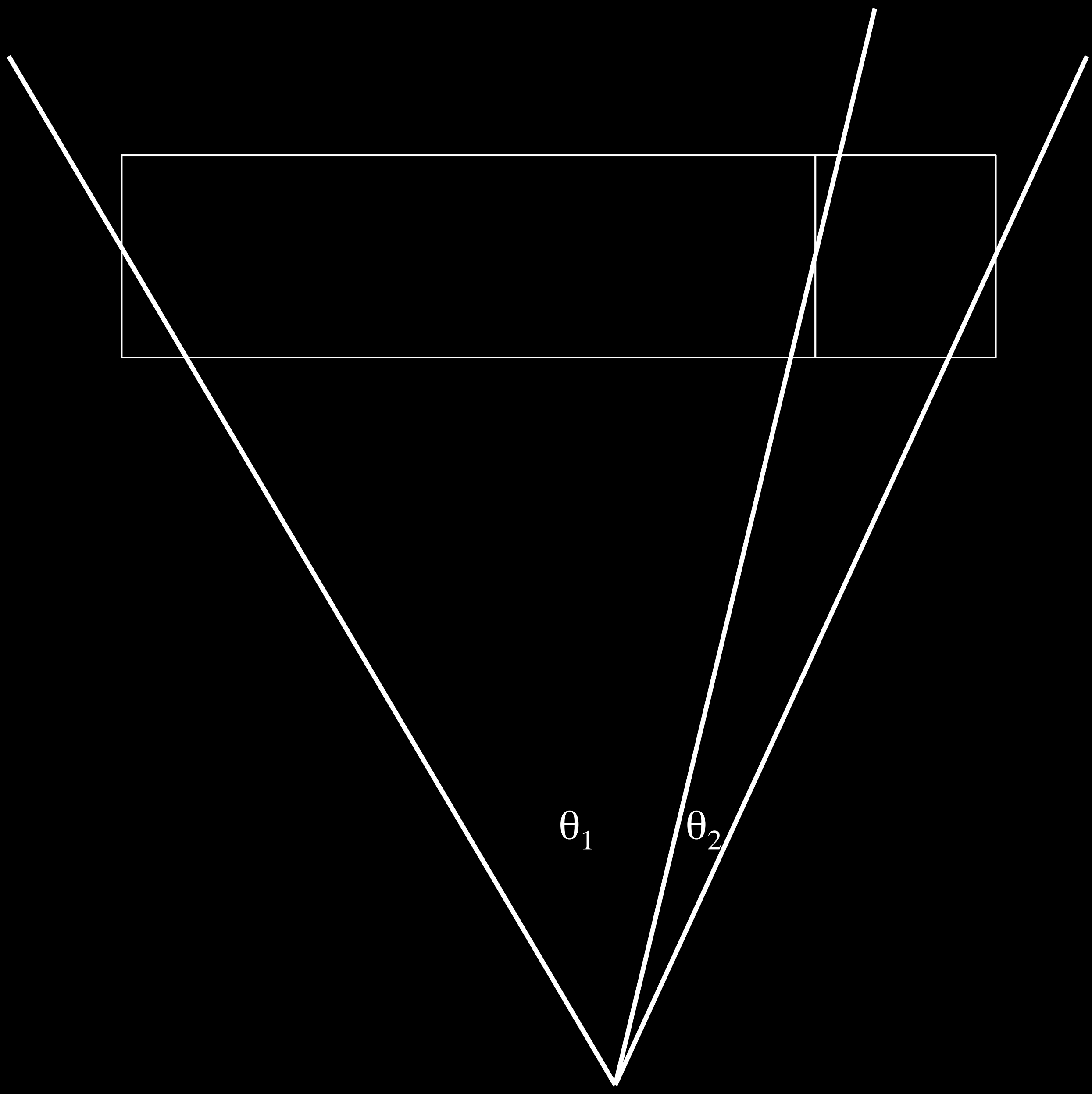






	original	request	obtained
β_x@QFM	17.4838	17.3000	17.3000
η_x@QFM	0.0105	0	1.7758e-08
β_y@QFM	0.5514	0.5800	0.5800
μ_x@end	4.3655	4.3500	4.3500

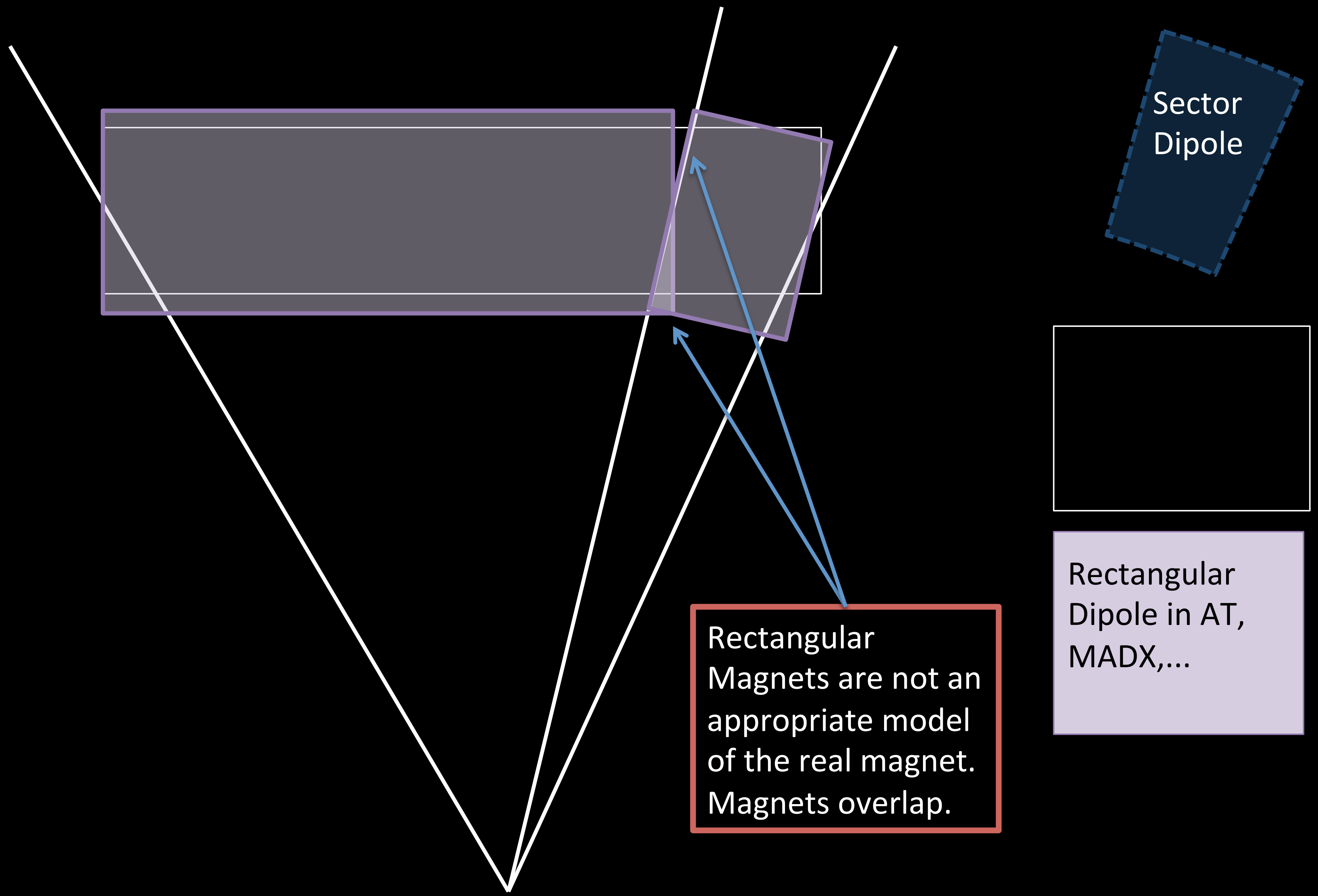
Additional slides on:
dipole models

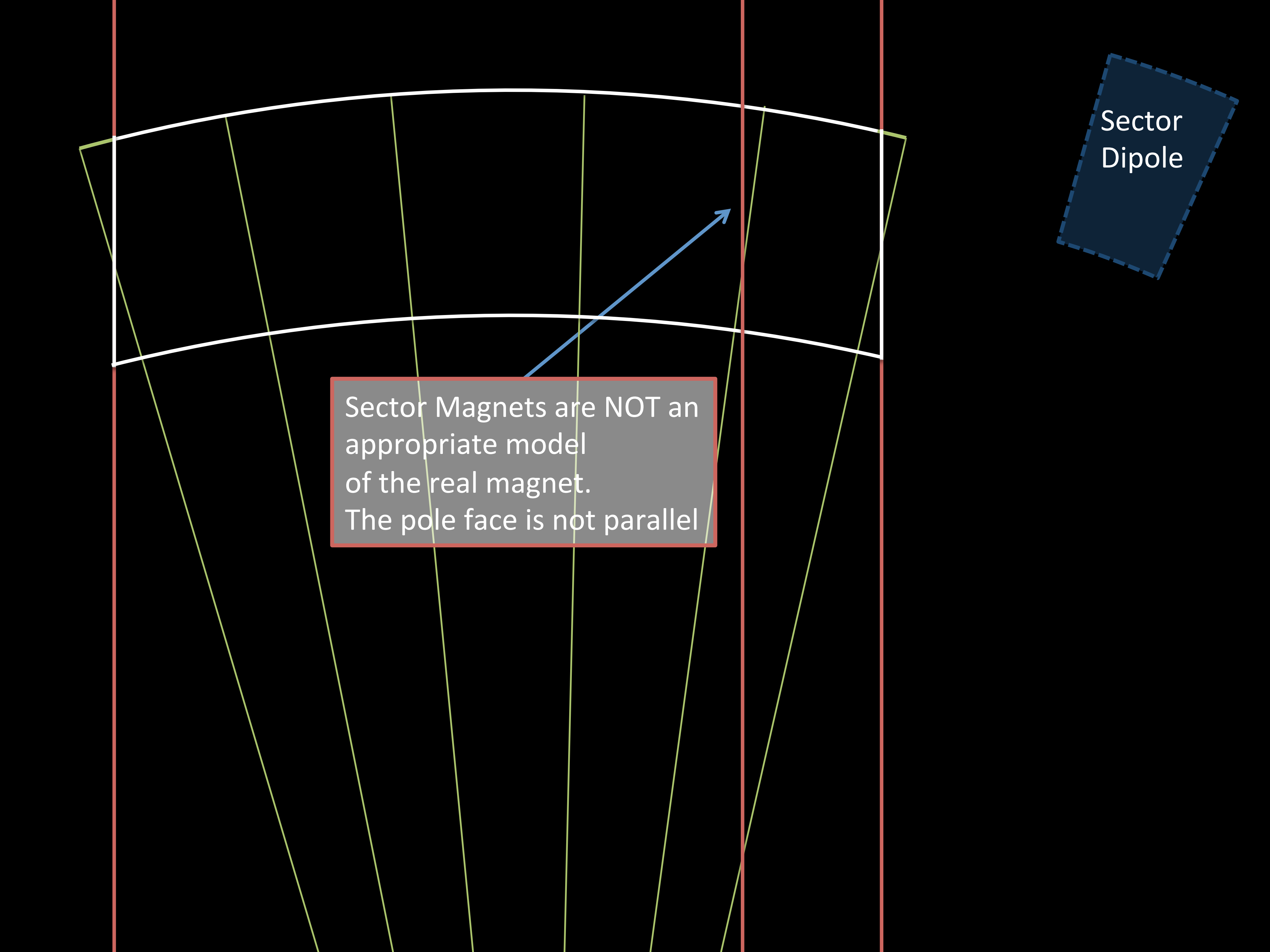


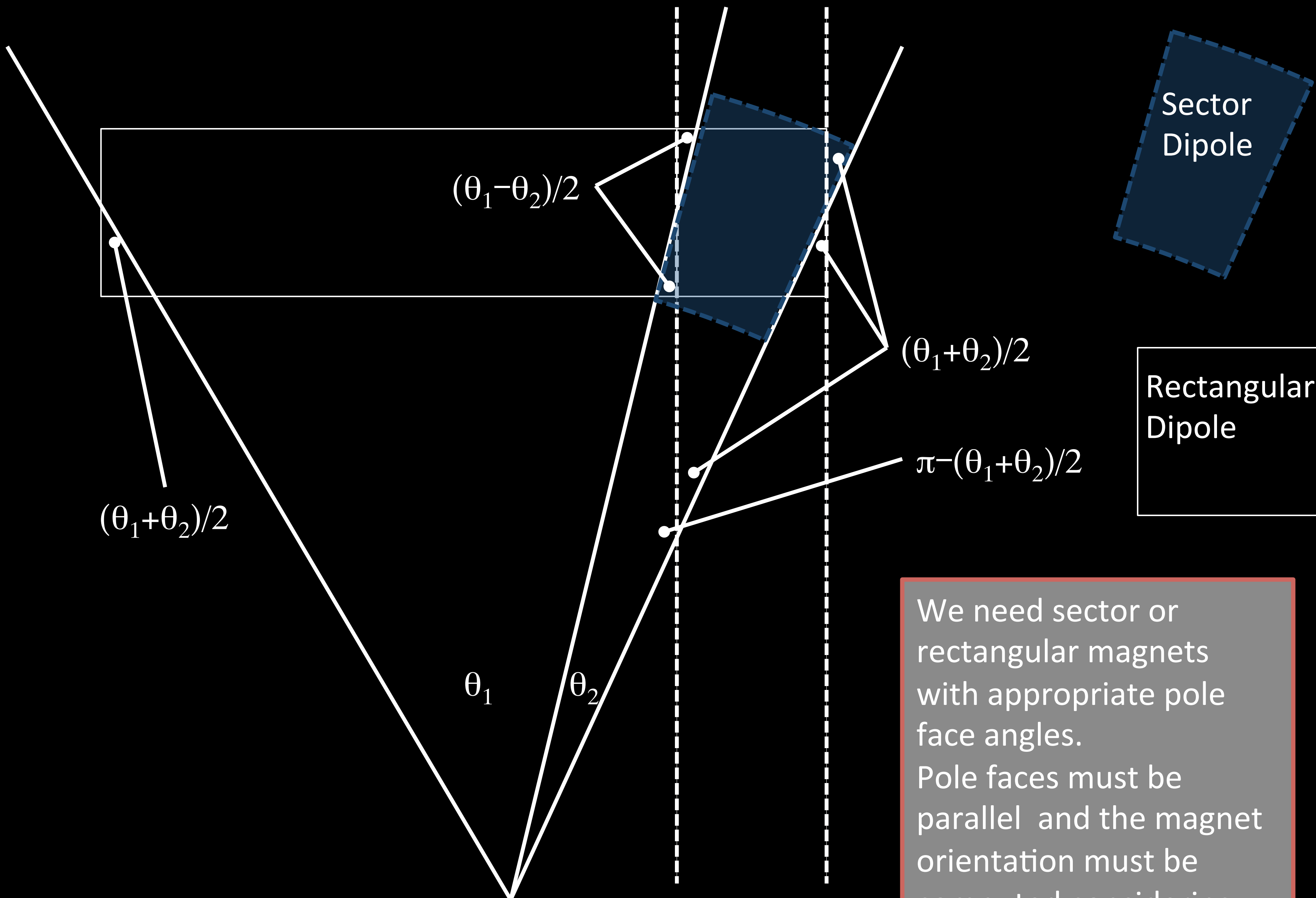
A Dipole magnet with different bending angles has to be built.

HOW TO MODEL IT IN OUR CODES?

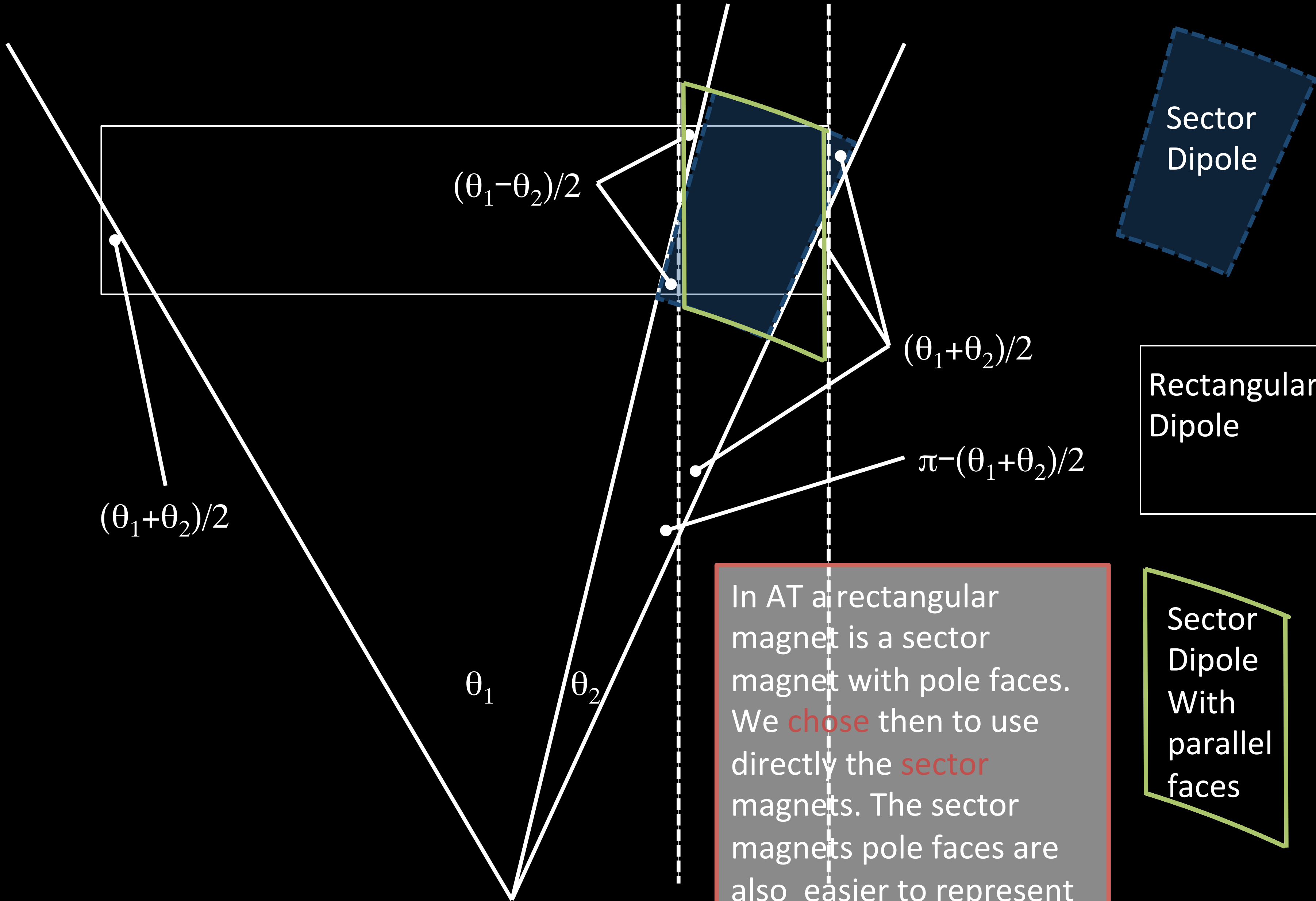
Realizable Rectangular Dipole


Sector Dipole
Rectangular Dipole in AT, MADX,...
Rectangular Magnets are not an appropriate model of the real magnet. Magnets overlap.

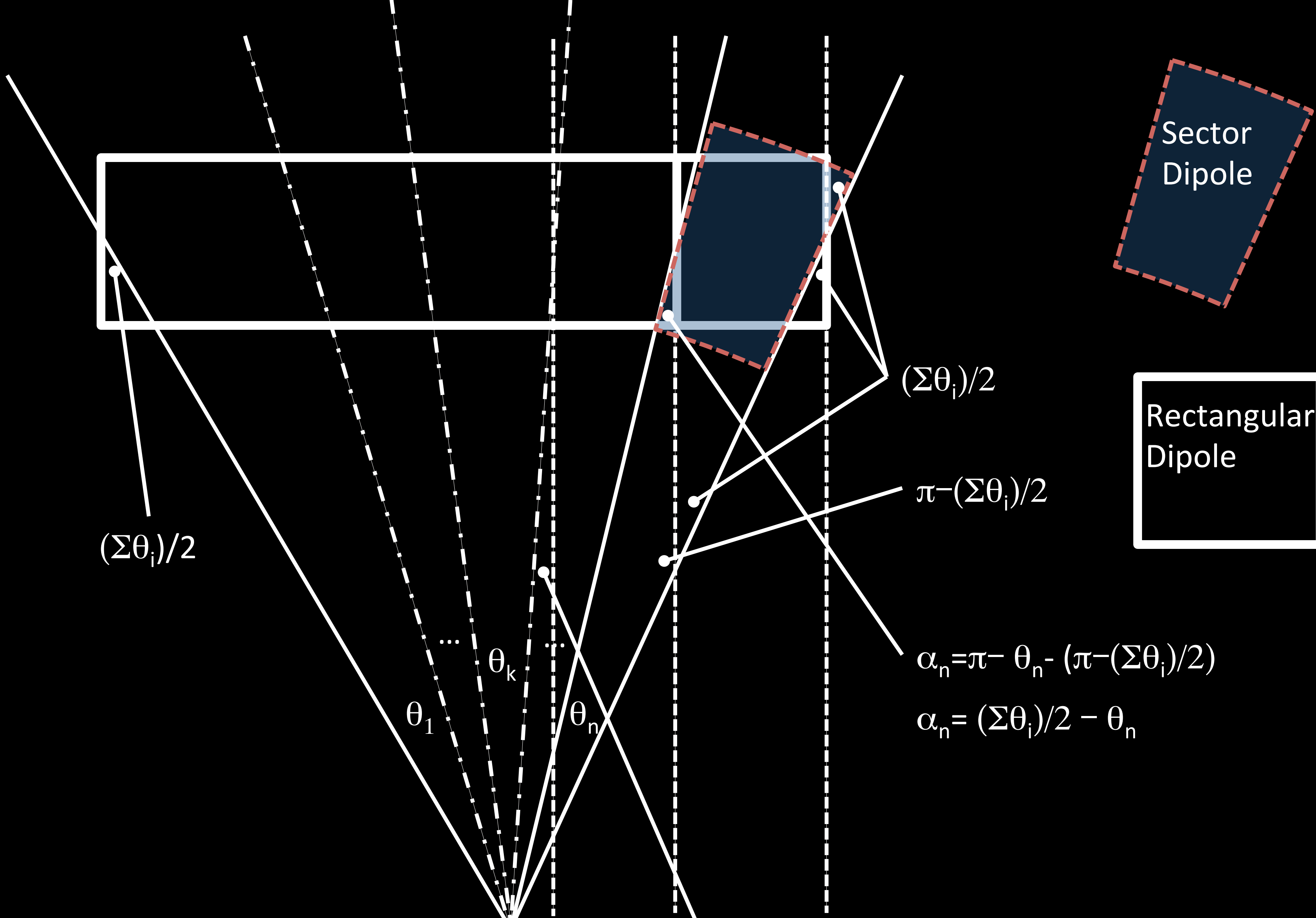

Sector Dipole
Sector Magnets are NOT an appropriate model
of the real magnet.
The pole face is not parallel



We need sector or rectangular magnets with appropriate pole face angles.
Pole faces must be parallel and the magnet orientation must be computed considering the total bending angle.



In AT a rectangular magnet is a sector magnet with pole faces. We chose then to use directly the sector magnets. The sector magnets pole faces are also easier to represent in figure.



$$\alpha_{k,entrance} = -(\Sigma\theta_{i(1:k-1)} - \Sigma\theta_{i(k:n)})/2$$

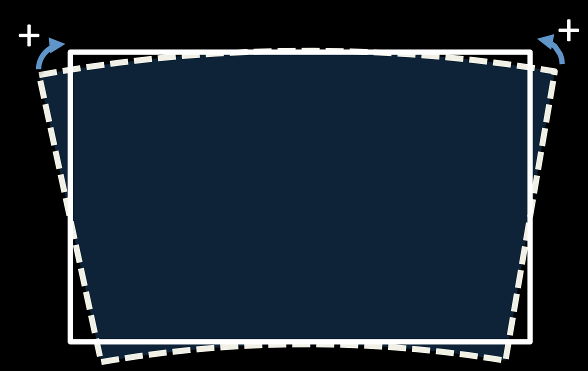
$$\alpha_{k,exit} = (\Sigma\theta_{i(1:k)} - \Sigma\theta_{i(k+1:n)})/2$$

- Dipoles in mad8 model are rectangular with length of magnet as length.
- In AT magnet length is the arc length.
- All dipole sliced in AT have different lengths

since the bending angle of each slice is different

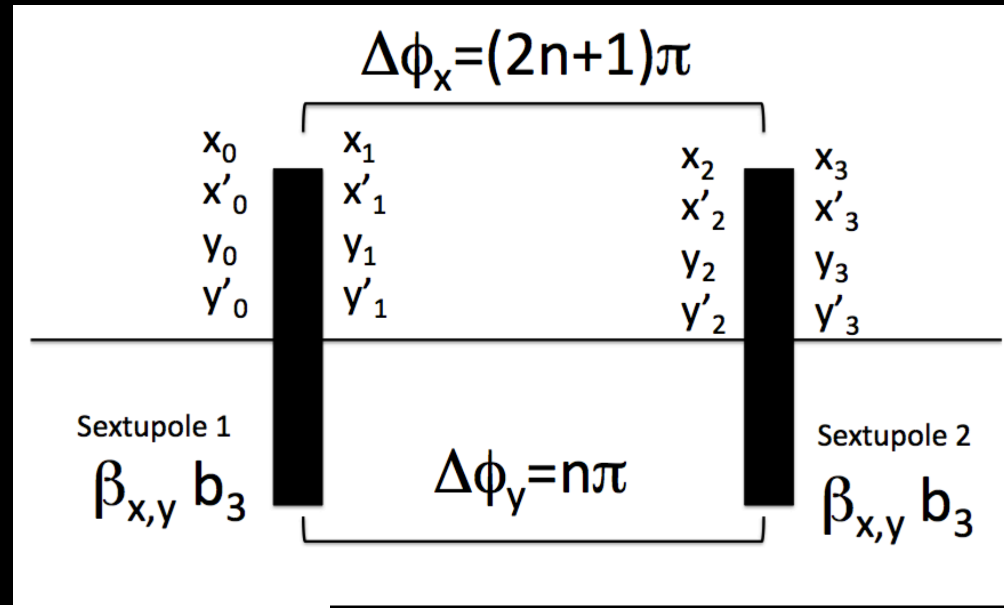
- The distance pole to pole of the magnets slices in the model are all equal.

- Entrance and exit pole face angle direction convention.
  To transform a sector magnet in a rectangular one
  positive entrance and exit angles apply.



Compensation of non-linearity

The ESRF lattice design features an intrinsic compensation of first order sextupolar resonances. With a correct phase advance choice.



$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} x_0 \\ x_0' + b_3 x_0^2 \end{pmatrix} \quad ,$$

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = R(\Delta\phi_x) \begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} x_0 \cos\Delta\phi_x - \left(x_0' + b_3 x_0^2\right) \sin\Delta\phi_x \\ x_0 \sin\Delta\phi_x + \left(x_0' + b_3 x_0^2\right) \cos\Delta\phi_x \end{pmatrix} \quad ,$$

$$\begin{pmatrix} x_3 \\ x_3' \end{pmatrix} = \begin{pmatrix} x_2 \\ x_2' + b_3 x_2^2 \end{pmatrix} \quad ,$$

If the correct phase advance is chosen

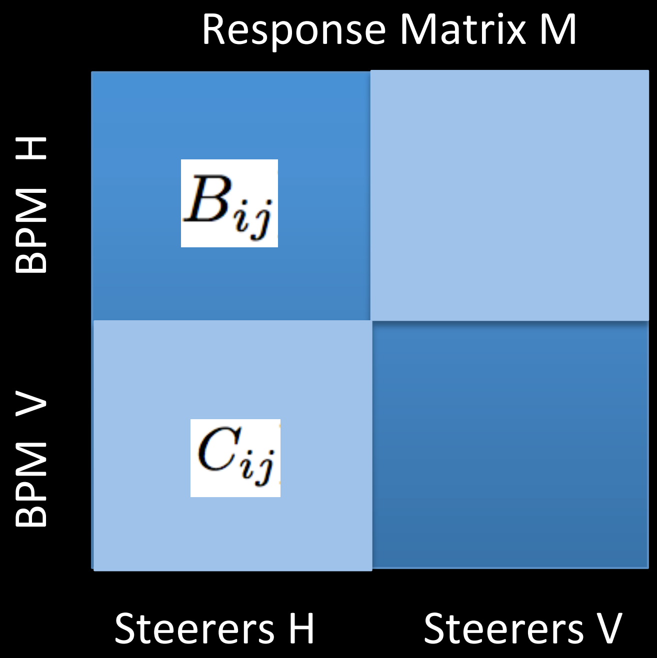
$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} -x_0 \\ -x_0' - b_3 x_0^2 \end{pmatrix} \quad ,$$

$$\begin{pmatrix} x_3 \\ x_3' \end{pmatrix} = \begin{pmatrix} -x_0 \\ -x_0' - b_3 x_0^2 + b_3 \left(-x_0\right)^2 \end{pmatrix} = \begin{pmatrix} -x_0 \\ -x_0' \end{pmatrix} \quad .$$

Additional effects due to thick magnets and fringe fields need to be corrected

Additional Slides on:
LET and Emittance tuning

LOW VERTICAL EMITTANCE TUNING: LET



Orbit correction

$$\vec{x} = M\vec{\theta}$$

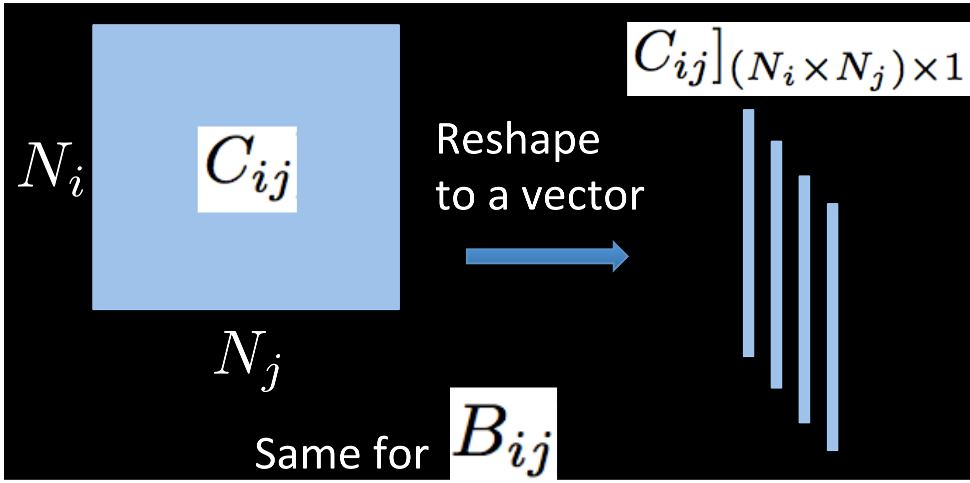
$$M_{ij} = \frac{\partial x_i}{\partial \theta_j}$$

Dispersion response matrix (deviation from reference)

$$\vec{\eta} = M^{disp}\vec{\theta}$$

$$M^{disp}_{ij} = \frac{\partial \eta_i}{\partial \theta_j}$$

SVD (pseudo inverse) of M to calculate Correction $\vec{\theta}$



$$M^{C_{ij}}_{ik} = \frac{\partial}{\partial \theta_k}\frac{\partial x_i}{\partial \theta_j}$$

Mainly determined by sextupoles

Using the sextupoles off axis effects

N_i C_{ij} N_j

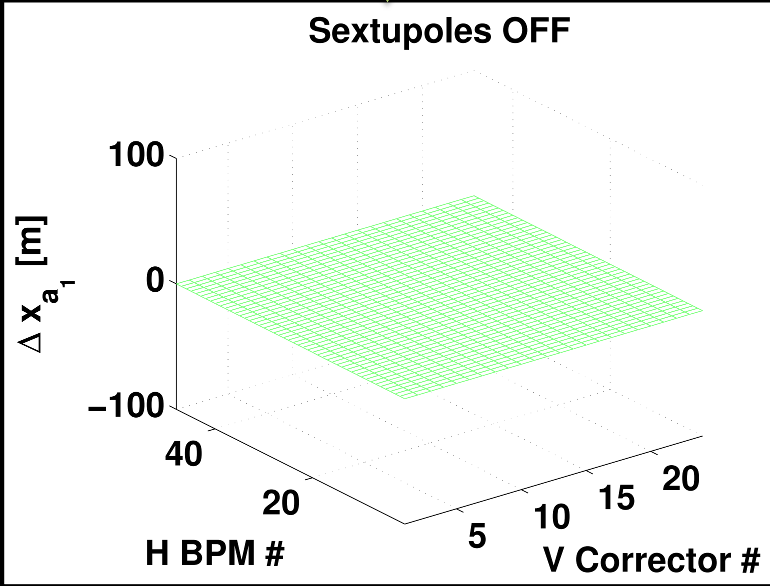
Reshape to a vector

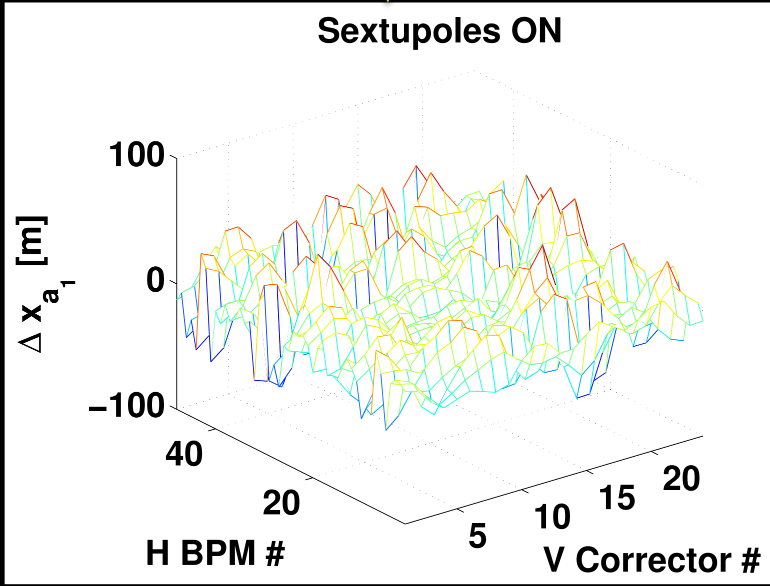
$C_{ij}]_{(N_i \times N_j)\times 1}$

Same for B_{ij}

$$M_{ik}^{C_{ij}} = \frac{\partial}{\partial\theta_k}\frac{\partial x_i}{\partial\theta_j}$$

determined by sextupoles

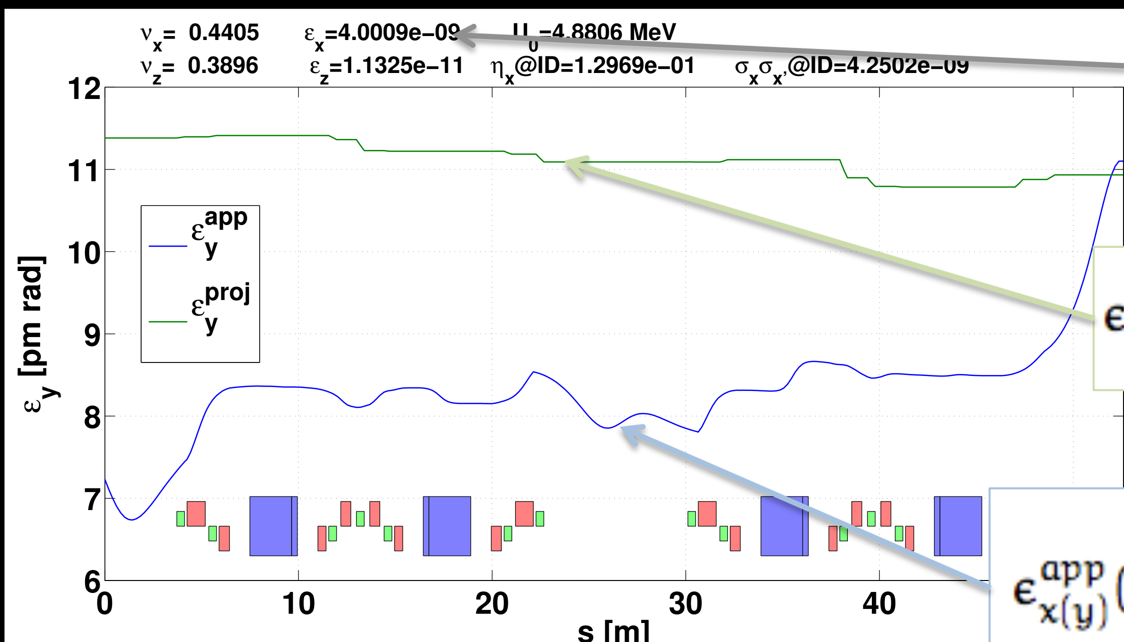




Emittance measurements

In presence of coupling emittance is not constant along the ring!

(see: A. Franchi et al. *Phys. Rev. ST Accel. Beams*, 14:034002, Mar 2011.)



$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2}$$

Invariant

$$\epsilon^{proj}_{x(y)}(s) = \sqrt{\sigma_x(s)\sigma_{p_x}(s) - \sigma^2_{xp_x}(s)}$$

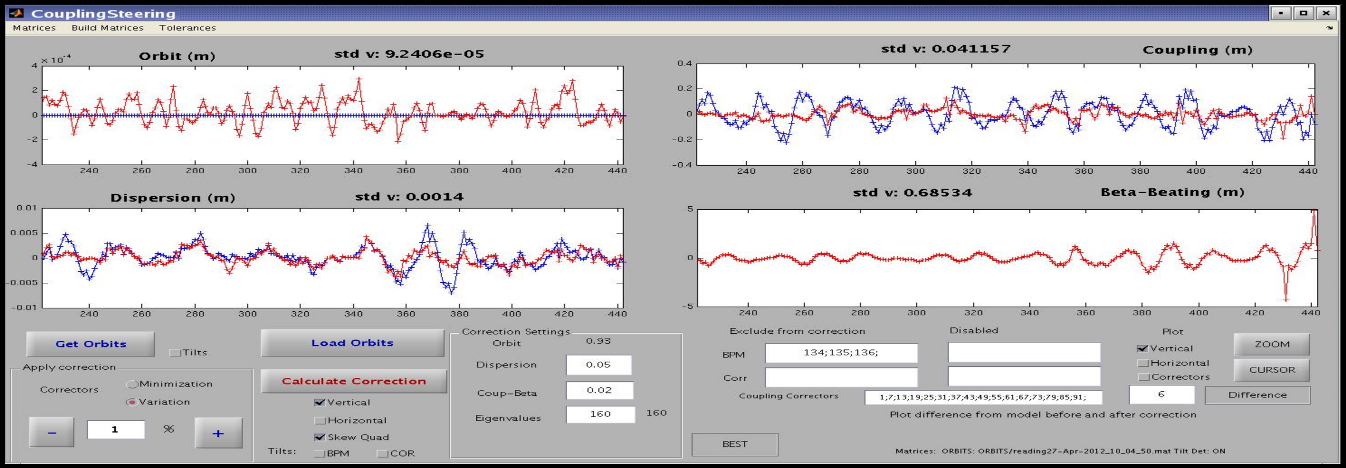
Statistical: Changes at sextupoles

$$\epsilon^{app}_{x(y)}(s) = \frac{\sigma^2_x(s)}{\beta_x(s)} = \frac{\langle x^2(s)\rangle - (\delta\eta_x(s))^2}{\beta_x(s)}$$

Measurable: varies along the ring, oscillatory

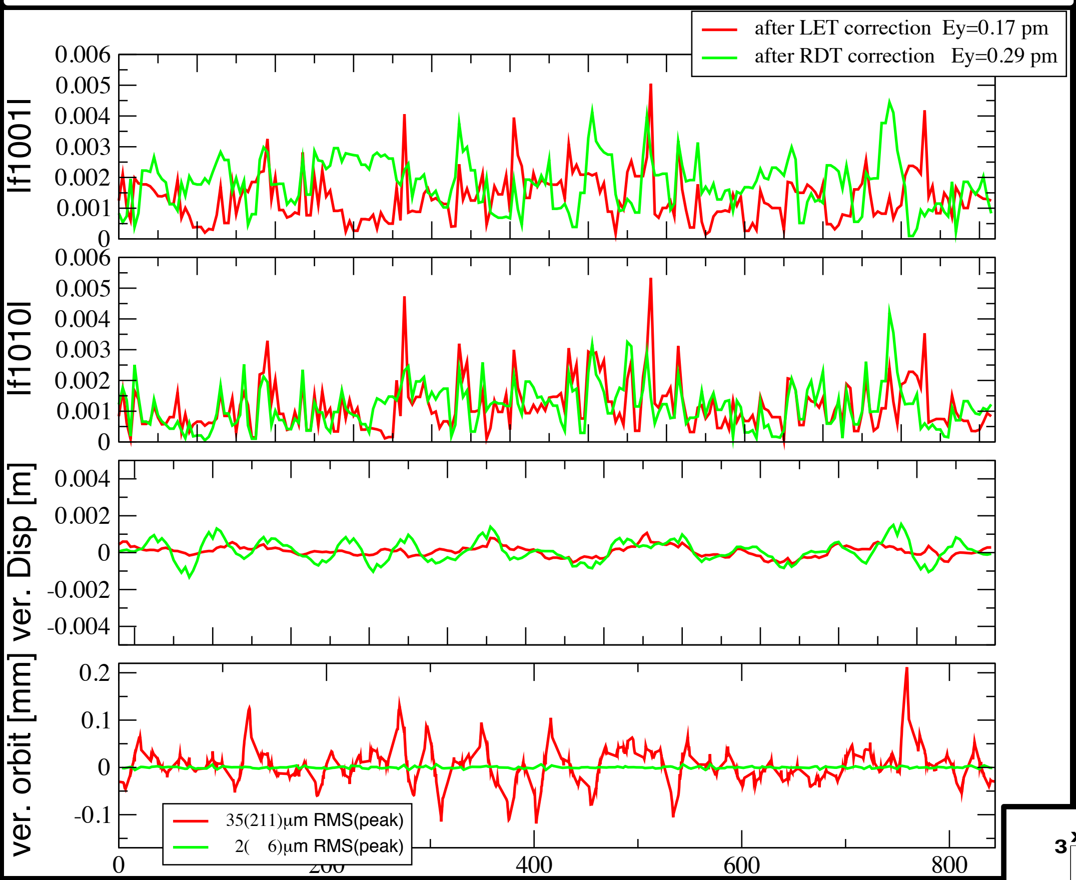
Need to average over many measurements along the ring or rely on global measurements as lifetime.

Tool for LET



- data acquisition (specific for each accelerator control system)
- corrector set application (specific for each accelerator control system). The correctors set is applied simultaneously to all correctors, and may be sent or removed at intermediate steps.
- display of the acquired data
- display of forecasted correction before application and possible recomputation
- computation of correction with settings for the parameters alpha and omega in LET correction and number of eigenvectors for SVD.
- selection of the wished correctors: vertical steerers, horizontal steerers, skew quadrupoles, tilt and gains of Beam Position Monitors.
- Beam position montiors selection and exclusion
- data storage
- offline data analysis
- response matrix computation (from model in MADX)

Comparison of LET to RDT correction technique at ESRF



RDT correction:

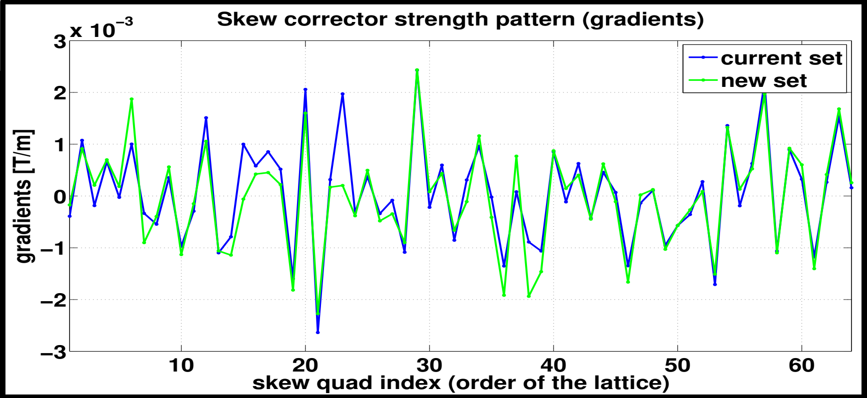
1) Fit lattice model with errors from RM measurements.
2) Compute skew quadrupole resonant driving terms
3) Determine correction.

Comparison to LET

LET with V-steerers only vs RDT with skew-quadrupoles:

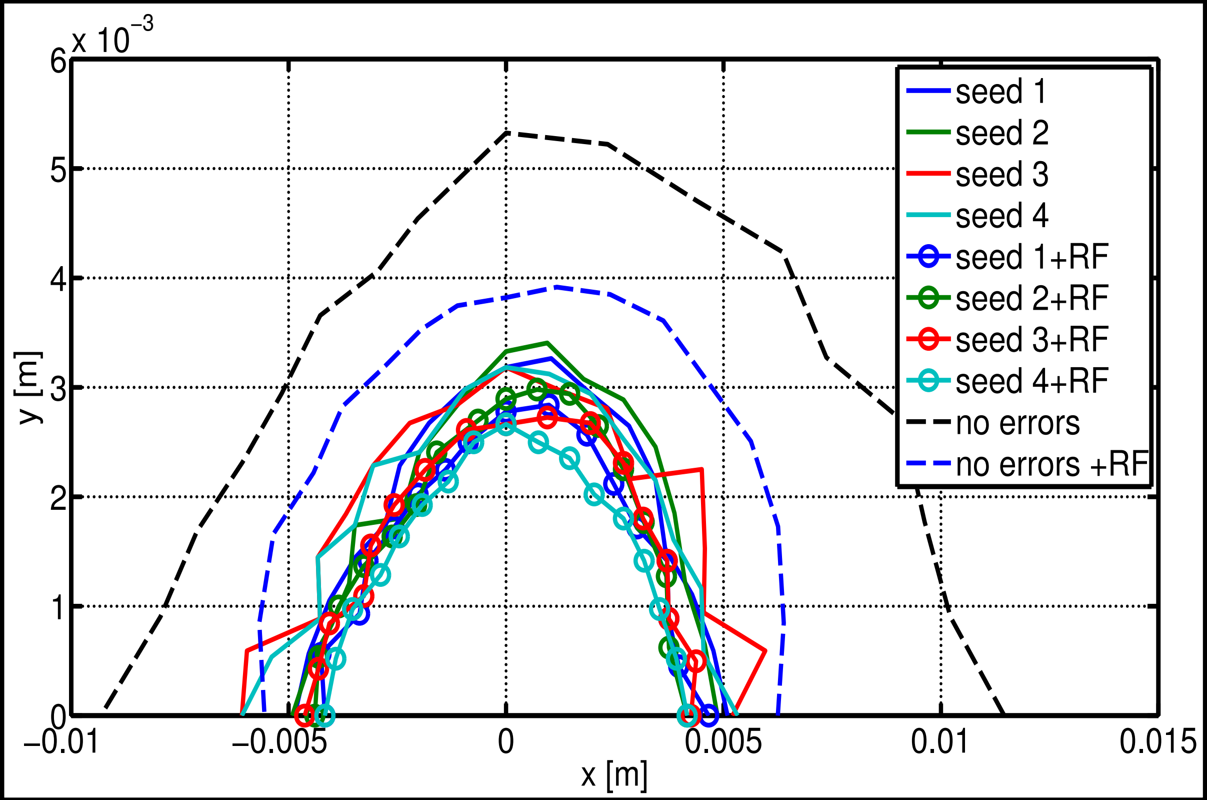
1) Same final skew qaudrupole RDT.
2) Residual vertical dispersion smaller in LET
3) Residual orbit smaller in RDT. (unchanged, correction with skew quad)

Powering skew quadrupoles in LET for correction: almost equal skew quadrupole set.



Additional slides on:
influence of imperfections

DA with: Alignment errors, Multipole errors and RF



Quadrupole DX =50; % mum
Quadrupole DY =40; % mum
Quadrupole Tilt =350; % murad
Sextupole DX=30;% mum
Sextupole DY=30;   % mum

Dipole field error=5*1e-2;
Qaudrupole Field error=1*1e-1;
Sextupole Field error=3*e-1;

Multipole errors as given by
The magnet design

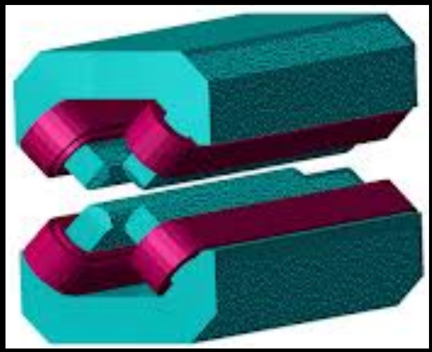
Correction of orbit, coupling and beta beating with all available knobs

-5.1 mm horizontal DA necessary for 100% injection efficiency

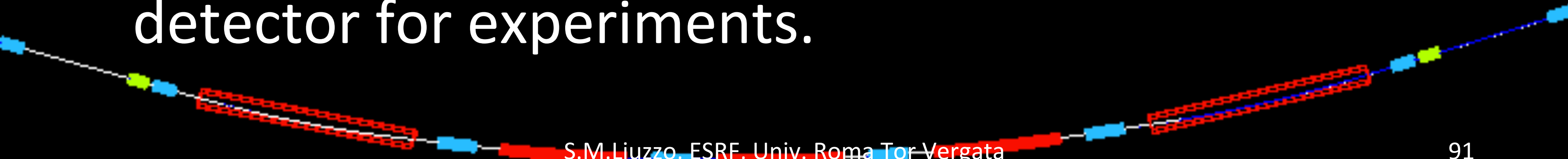
Glossary slides

Magnetic Lattice

Series of magnets to transport or store a bunch of charged particles:

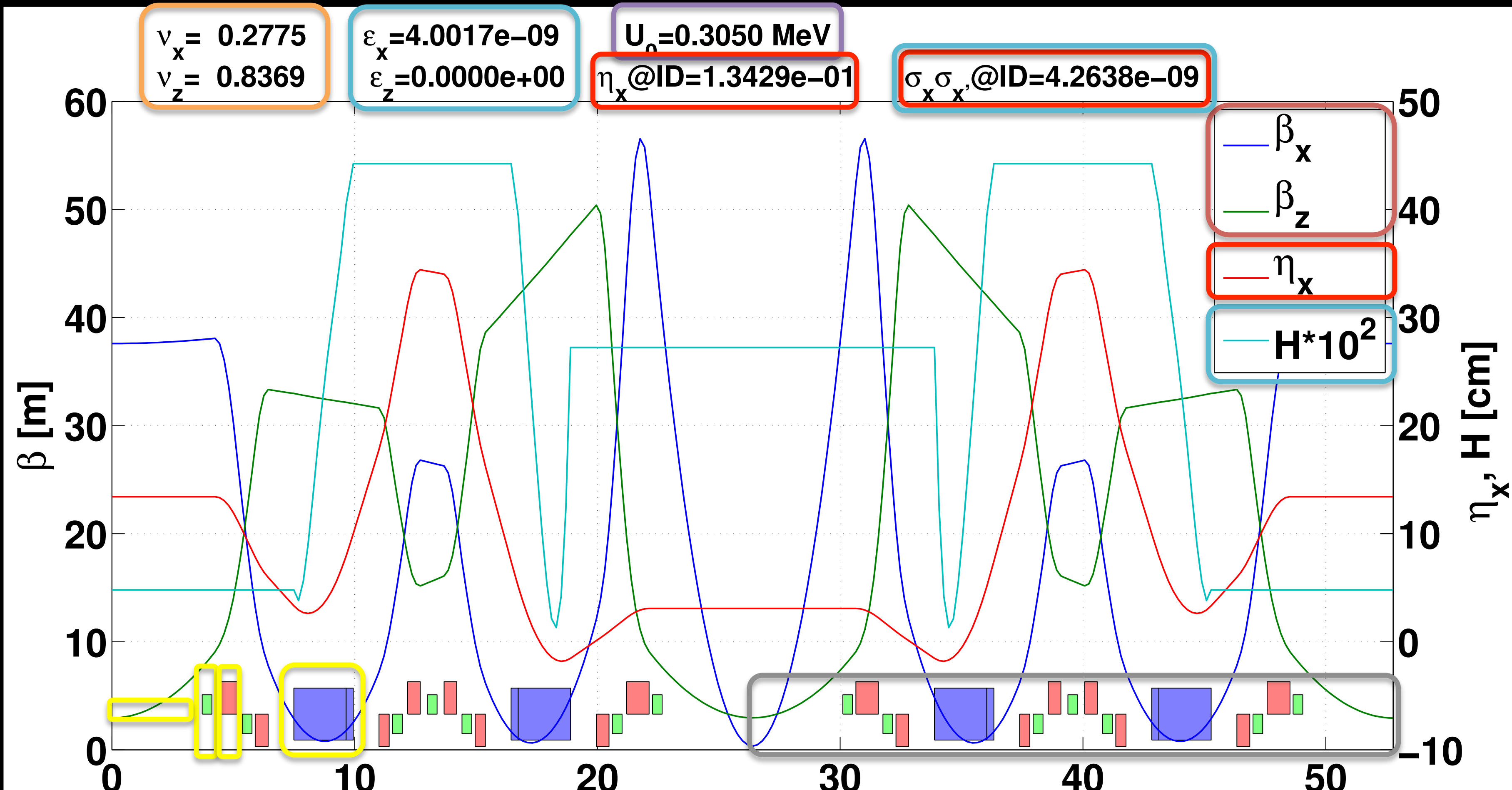


- Dipoles for the reference orbit
- Quadrupole for beam focusing
- Sextupoles for off energy abberations
- RF cavity for acceleration
- Insertion devices and detector for experiments.



Glossary: Optics orbit tune emittance,...

Optics (Twiss parameters): describe the focusing of the beam
Tune: number of oscillations in one turn
Closed Orbit: position of the beam
Emittance: equilibrium with radiation
Energy loss per turn
Dispersion trajectory off energy
magnets: dipole , quadrupoles, sextupoles,...
lattice: the sequence of magnets , 32 Cells



ESRF storage ring lattice