A non-linear bunch compression scheme for SwissFEL

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SwissFEL seminar

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A non-linear bunch compression scheme for SwissFEL

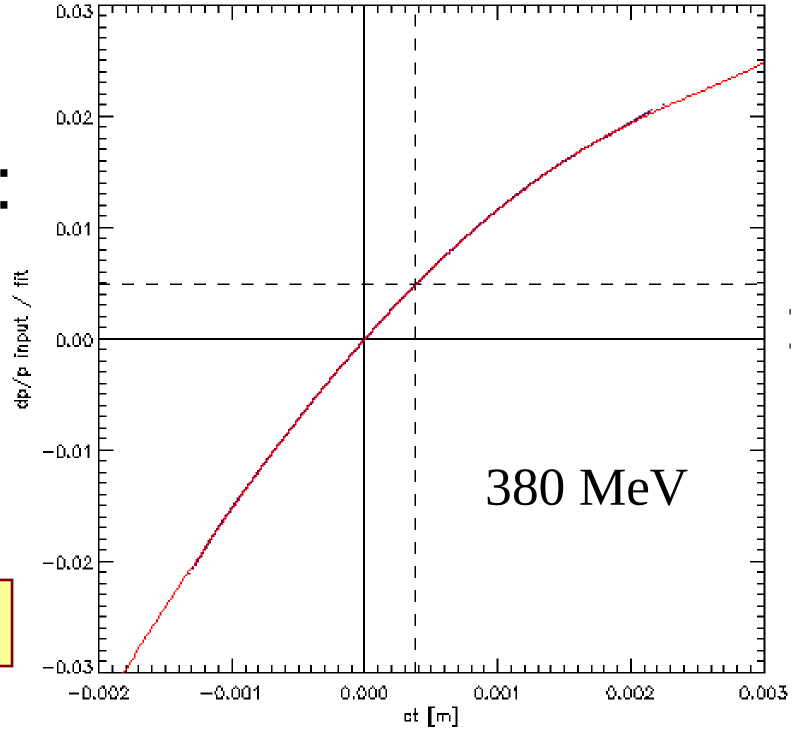
- The problem: longitudinal phase space distortion
- The solution: X-band linac
- The alternative: non-linear bunch compressor (NLBC)
- A basic NLBC feature: particle redistribution
- NLBC design specifications
- Design
  - Theory • 5 design steps • Tool development
- A possible solution and its performance
  - Linearization & compression • Emittance preservation • CSR effects • Misalignment effects • Tuning range
- Diagnostics
- Multipole magnet design
- Conclusions and outlook

The problem

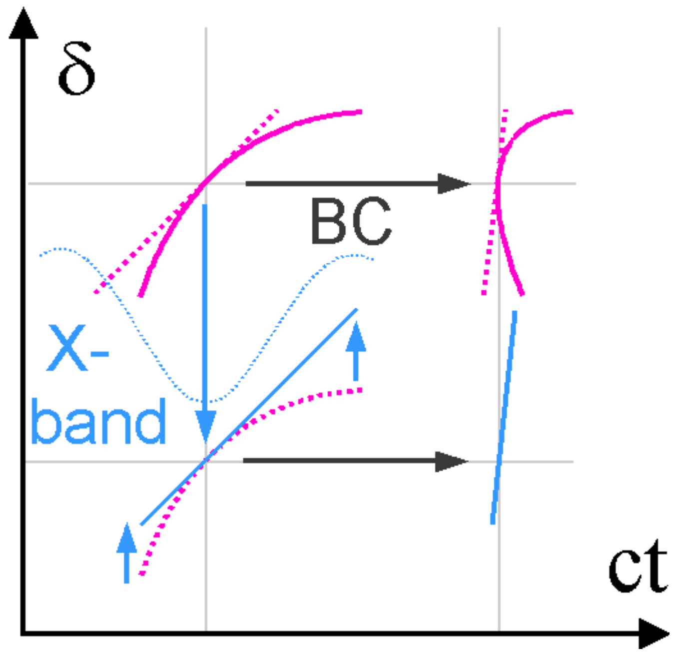
Near-crest S-band acceleration:

- ➔ sinusoidal distortion of longitudinal phase space
- ➔ linear compression fails:
  - ambiguous $\delta(ct)$
  - bad current profile
  - long bunch

$\boldsymbol{\delta := \Delta p / p}$

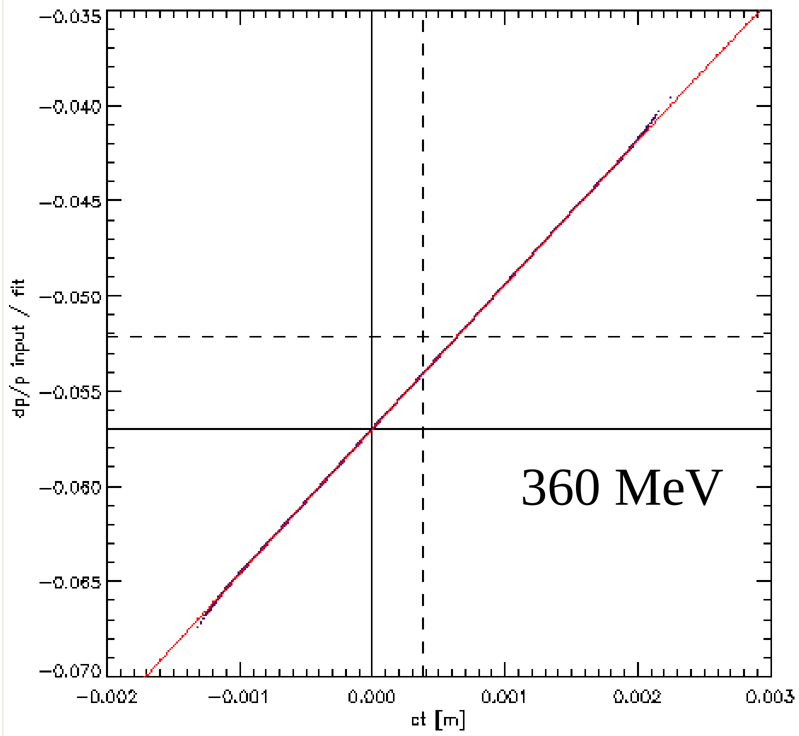


- ➔ Linearization of phase space *before* compression:
- ➔ Higher harmonic linac/cavity (X-band, 12 GHz)

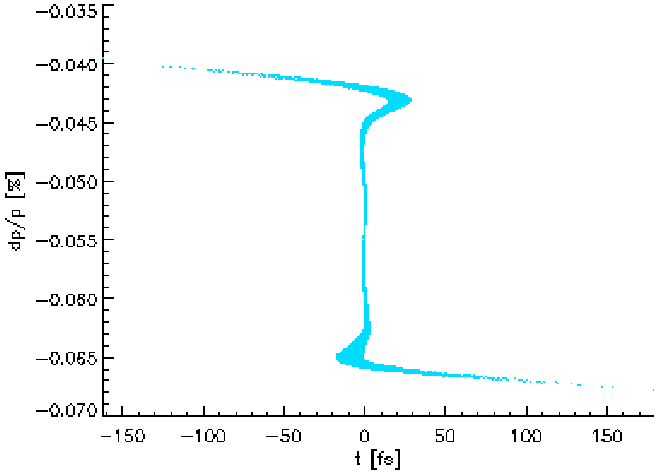


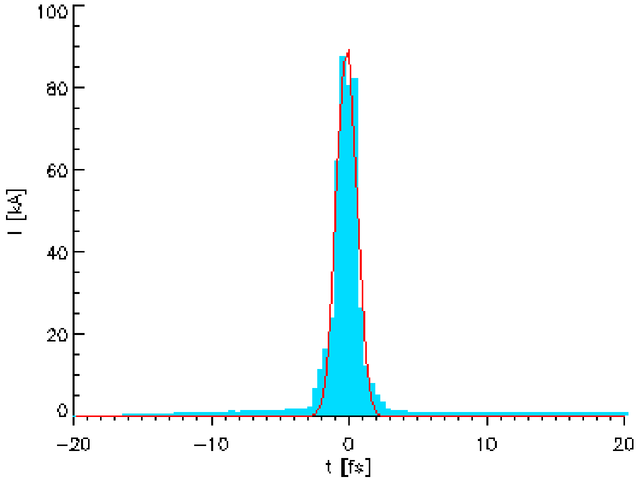
X-band linac

- set amplitude and phase for optimum linearization
- side effect: ~20 MeV (~5%) deceleration.
- test: append *ideal* & *complete* bunch compression (360 MeV):



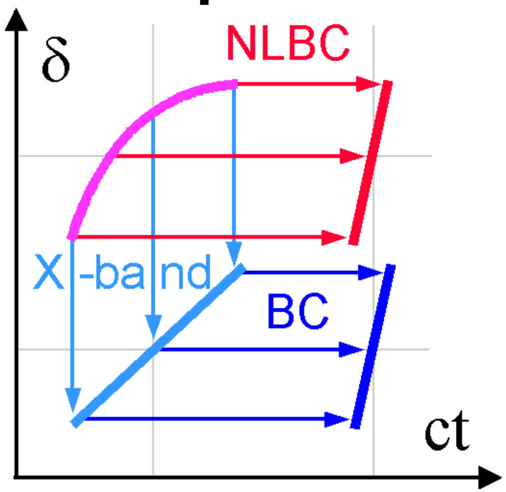
- ✓ peak current > 50 kA
- ✓ bunch length 2..3 fs FWHM
- ✓ efficiency 80..90 % of the particles





(200000 particles with homogenous momentum distribution of 0.01% full width)

Alternative: non-linear bunch compressor



X-band linac disadvantages

- ✘ availability of components
- ✘ tight tolerances
- ✘ costs (installation and operation)

Alternative: NLBC

- orthogonal to XBL: works on $c\Delta t(\delta)$, not on $\Delta\delta(ct)$
- adjust non-linear δ-dependent path length

NLBC requirements, challenges and features

- req's *strictly monotonic* function $\delta(ct) \rightarrow$ off-crest
- linearization performance
- operation and tuning
- feasibility of magnets

$\Big\}$ *design issues...*

- temporal redistribution of particles *feature!*

Particle redistribution

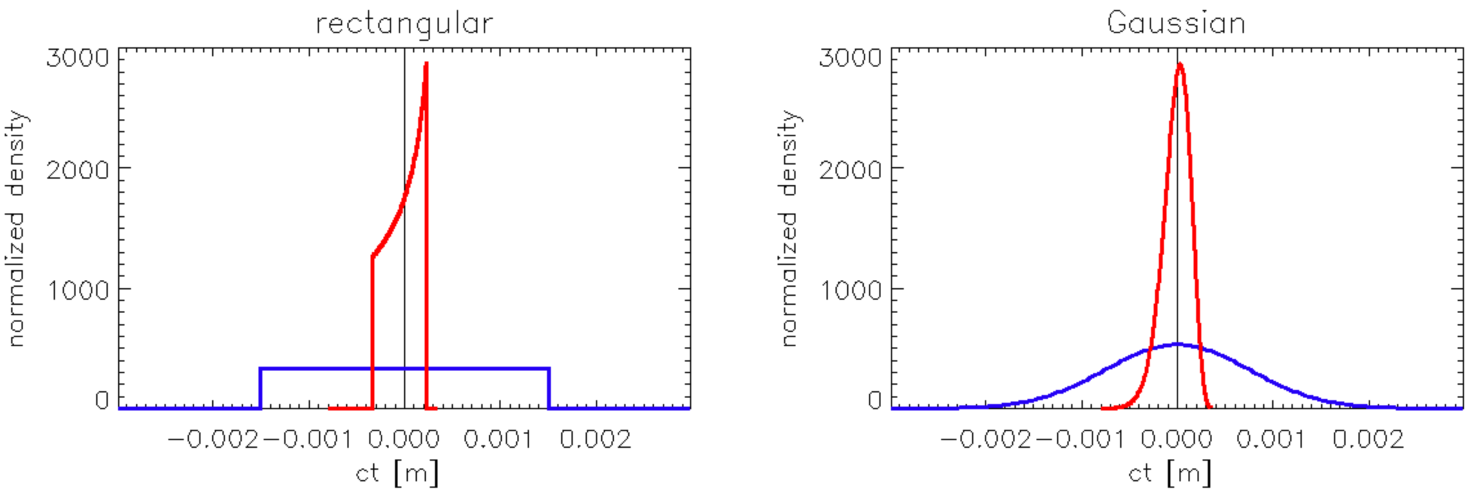
Before NLBC

- time t and momentum $\delta = f(t)$ (for each particle)
- temporal distribution $\lambda(t) = \mathrm{d}N / \mathrm{d}t$

After NLBC (L = path length)

- time $t^* = t + L(\delta)/c = t + L(f(t))/c := g(t) \quad \leftrightarrow \quad t = g^*(t^*)$
  (g^* = inverse function to g)
- new particle distribution:

$$\lambda^*(t^*) = \mathrm{d}N / \mathrm{d}t^* = \mathrm{d}N / \mathrm{d}t \times \mathrm{d}t / \mathrm{d}t^* = \lambda(g^*(t^*)) \times \mathrm{d}g^*(t^*) / \mathrm{d}t^*$$



NLBC
1^{st} & 2^{nd} order
for R_{56} = –60 mm
(factor ≈5
compression)
& T_{566} = –0.73 m

NLBC specifications

([!] = challenge)

- Linearization performance as good as XBL
  - Linear compression $R_{56} = \mathrm{d}L/\mathrm{d}\delta|_o = -60$ mm
  - Quadratic compression $T_{566} = ½\, \mathrm{d}^2L/\mathrm{d}\delta^2|_o = -0.73$ m
  - ...and higher orders [!]
- SwissFEL complication: negative energy chirp (i.e $\delta > 0$ particles come last) $\rightarrow R_{56} < 0$ [✓] , $T_{566} < 0$ [!]
- Lattice layout
  - Total length < **30** m.
  - No deflection, no translation $\rightarrow$ straight lattice.
- Momentum acceptance ±2%
- No (< 5%) increase of slice emittance, due to...
  - multipole magnet nonlinearities,
  - slice centroid offsets $x(\delta)$, $x'(\delta)$ [!],
  - CSR effects for bunch charge of 200 pC.
- Little (<10% [?]) increase of projected emittance.
- Tuneability: R_{56} ±30% [?], T_{566} ±50% [?].
- Operability: diagnostics and tuning procedures.
- Feasibility of magnets [!].

Theory

(*Wiedemann, Particle Accelerator Physics II*)

- Path length

η_0, η_1 first and second order dispersion, $\kappa = 1/\rho$ curvature

$$\Delta L \approx \frac{1}{2}\oint \left(x'^2_\beta + y'^2_\beta + x'^2_o + y'^2_o + \kappa^2 x^2_\beta + \kappa^2 x^2_o\right) ds$$
$$+\delta \underbrace{\boxed{\oint \kappa\eta_o \, ds}}_{R_{56}} + \delta^2 \underbrace{\boxed{\oint \left(\kappa\eta_1 + \underbrace{\tfrac{1}{2}\kappa^2\eta_o^2}_{>0} + \underbrace{\tfrac{1}{2}\eta_o'^2}_{>0}\right) ds}}_{T_{566}} . \tag{6.180}$$

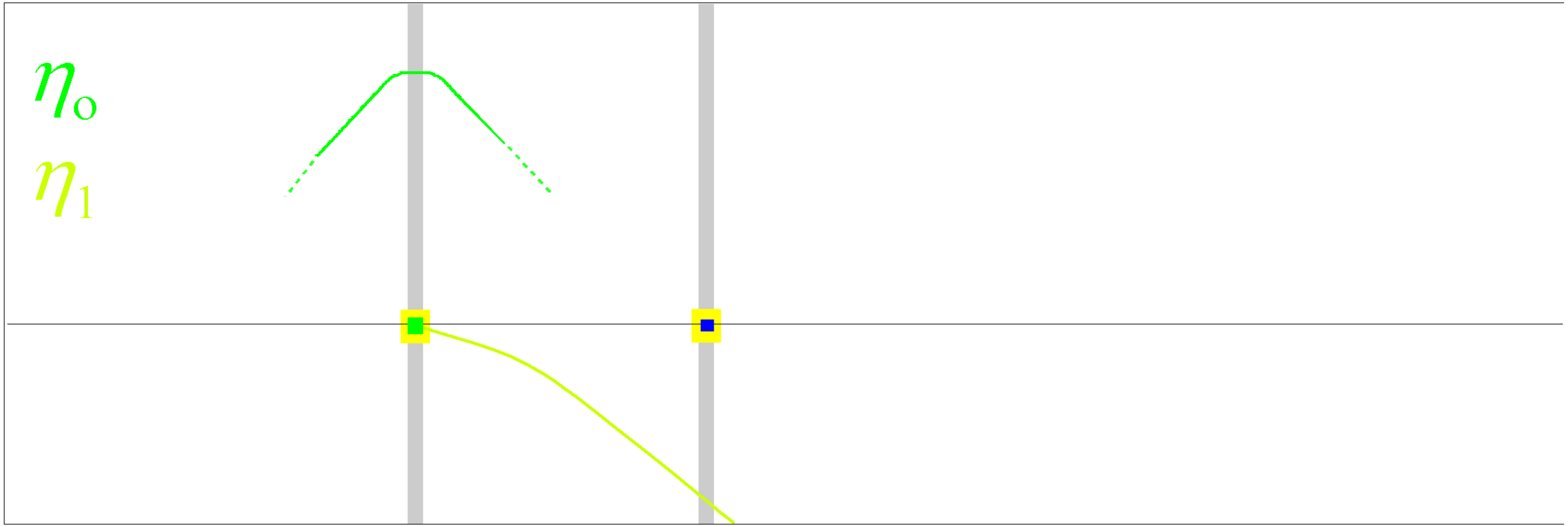
- Second order dispersion $x(\delta) = \eta_0\delta + \eta_1\delta^2 + \ \ldots.$

$k = b_2$ quadrupole strength, $m = 2b_3$ sextupole strength

$$\eta_1'' + K(s)\,\eta_1 = -\kappa - \boxed{\tfrac{1}{2} m\eta_o^2} + (\kappa^3 + 2\kappa k)\,\eta_o^2 + \tfrac{1}{2}\kappa\,\eta_o'^2$$
$$+\kappa'\eta_o\eta_o' + (2\kappa^2 + k)\,\eta_o \tag{4.42}$$

Design 1

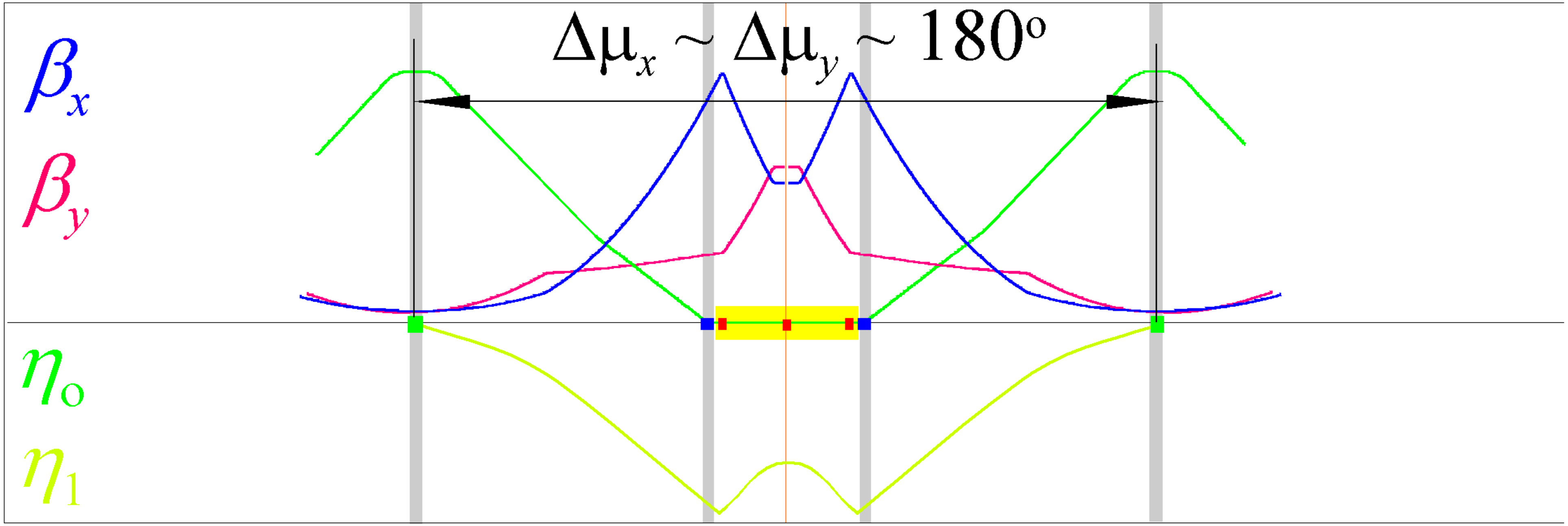
Negative T_{566}



- **Sextupole** ($b_3 > 0$) at location of high dispersion η_o
  $\Rightarrow$ create first order dispersion $\Delta\eta_1' = -(b_3 l)\eta_o^2$
- **Dipole** (angle Φ) at $\eta_1 < 0$
  $\Rightarrow$ get contribution $T_{566} \approx \eta_1 \Phi < 0$

Design 2

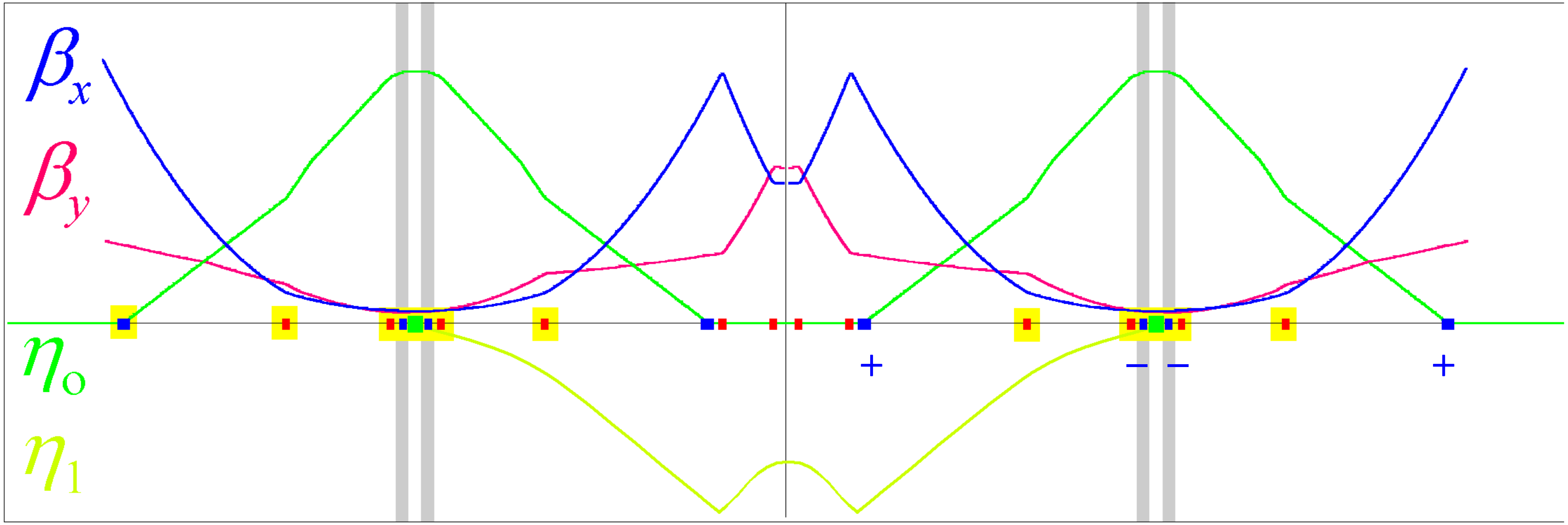
(–I)-transformer



- Append mirror structure and insert quadrupoles to close the η_1-bump.
- Minimize non-linear perturbation: 180^o phase advance between sextupoles to cancel transverse kicks ("(–I)-transformer").
- Minimize chromatic effects: low β_x, β_y in sextupoles.

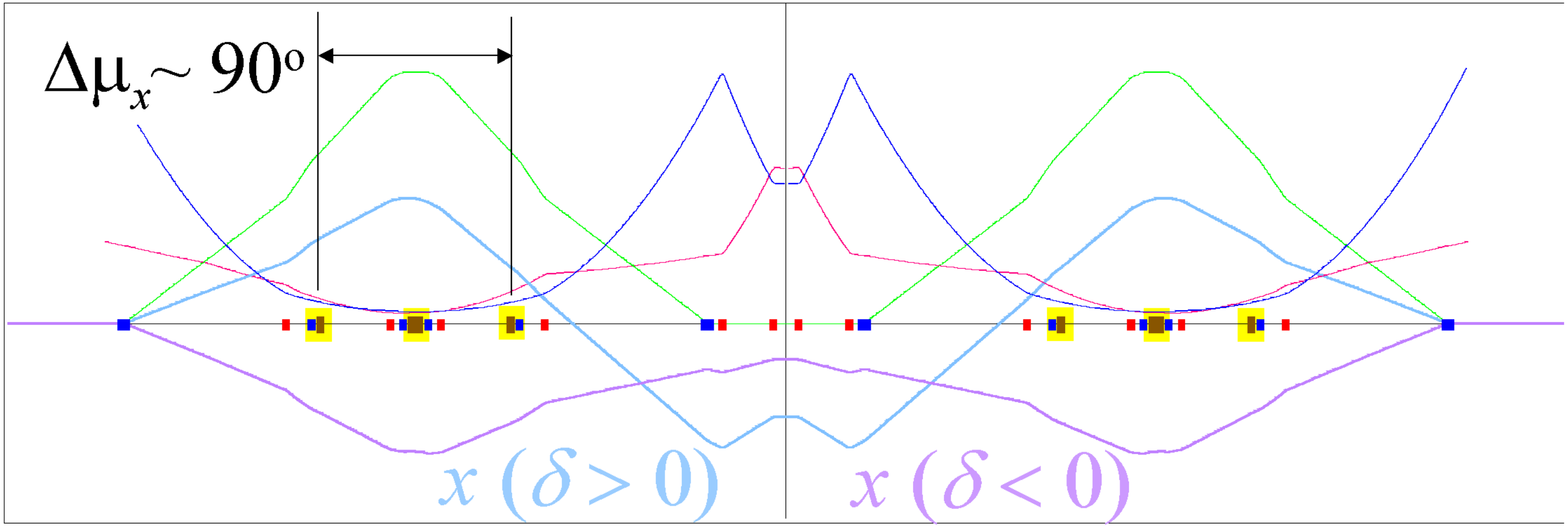
Design 3

Linear lattice



- add dipoles
  - to create the η_o bump,
  - to get required linear compression $\boldsymbol{R_{56}}$ and
  - to obtain a straight lattice (no net deflection $\Sigma\Phi=0$).
- add quadrupoles
  - to get higher η_o , resp. a shorter lattice, and
  - to be able to vary $\boldsymbol{R_{56}}$.

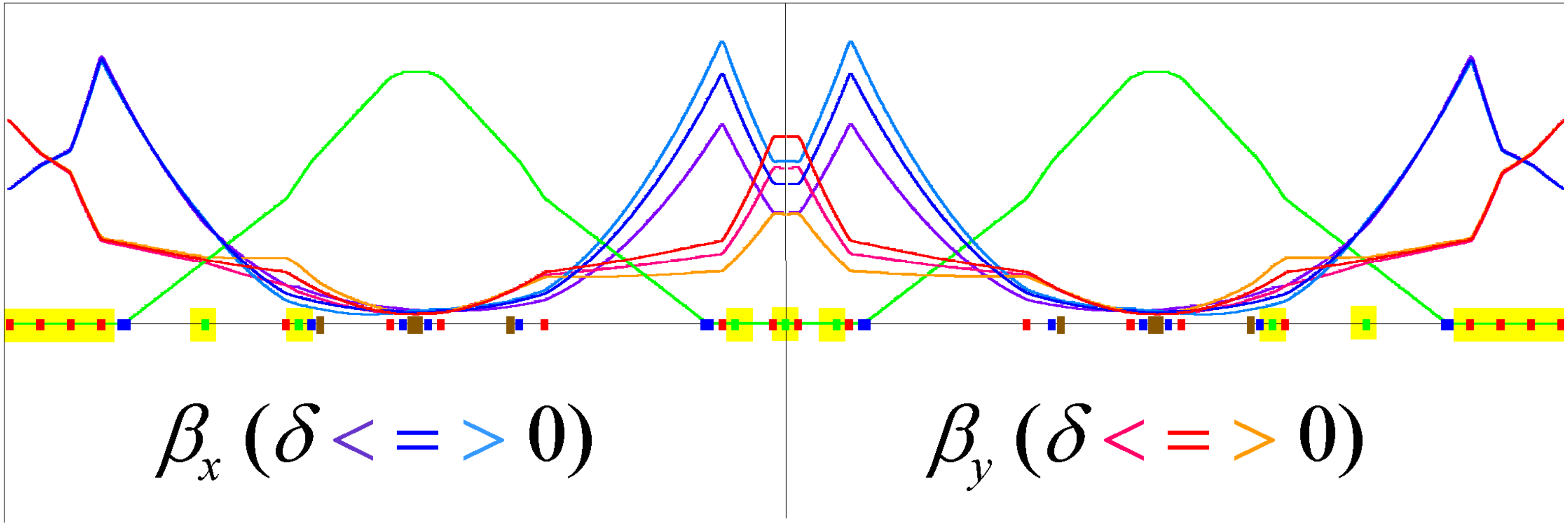
Design 4 # High-order achromat



- Path linearization up to 6^{th} order in δ:
  insert higher order multipoles (up to 16-pole)
- Suppression of slice emittance growth :
  - get $x'(\delta) = 0\ \forall \delta$ at mid plane,
  - while keeping $x(\delta)$ in center dipoles.

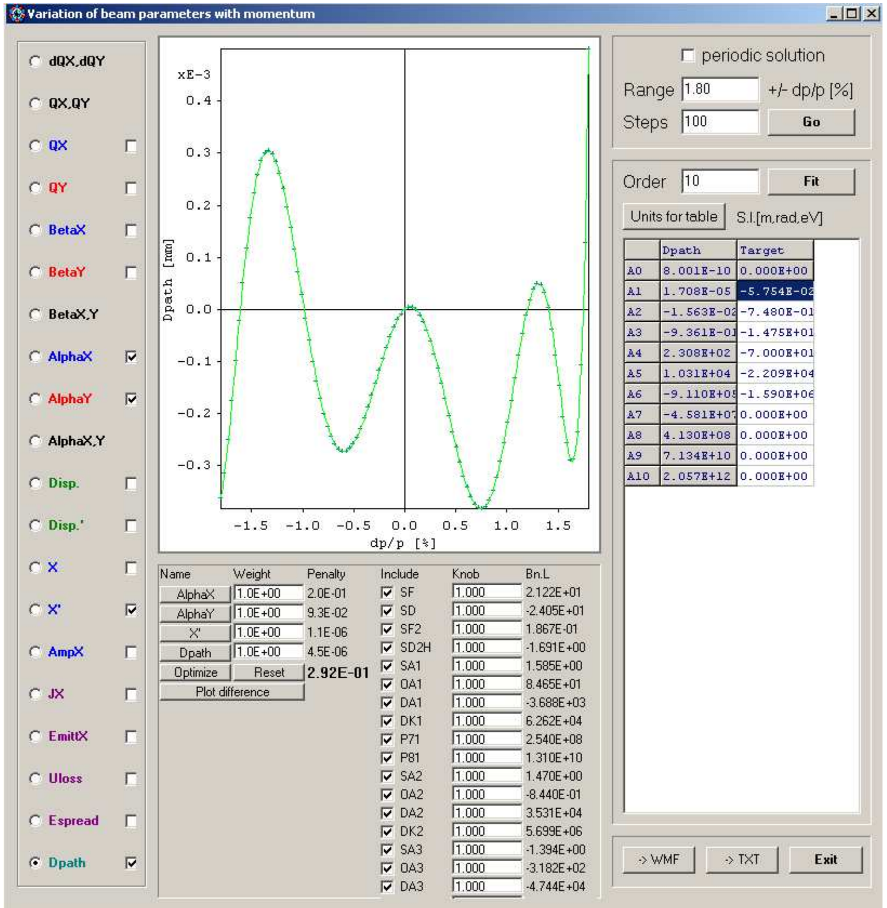
$\Rightarrow$ insert multipole pairs at 90º hor. phase advance.

Design 5 Chromaticity and matching



- Chromaticity correction: insert sextupoles to get $\alpha_x(\delta) = \alpha_y(\delta) = \mathbf{0}\ \forall\delta$ at mid plane.
- Append quadrupole-quadruplets for matching (β_x, α_x, β_y, α_y) to adjacent sections.

Optimization tool development



Penalty function

$$P = \sum_f \sum_\delta w_f \left(f(\delta) - f_T(\delta) \right)^2$$

δ *array* of δ-values

$f(\delta)$ a function (e.g. path length)

$f_T(\delta)$ target function (polynomial)

w_f weight factor

Variables

all non-linear multipoles

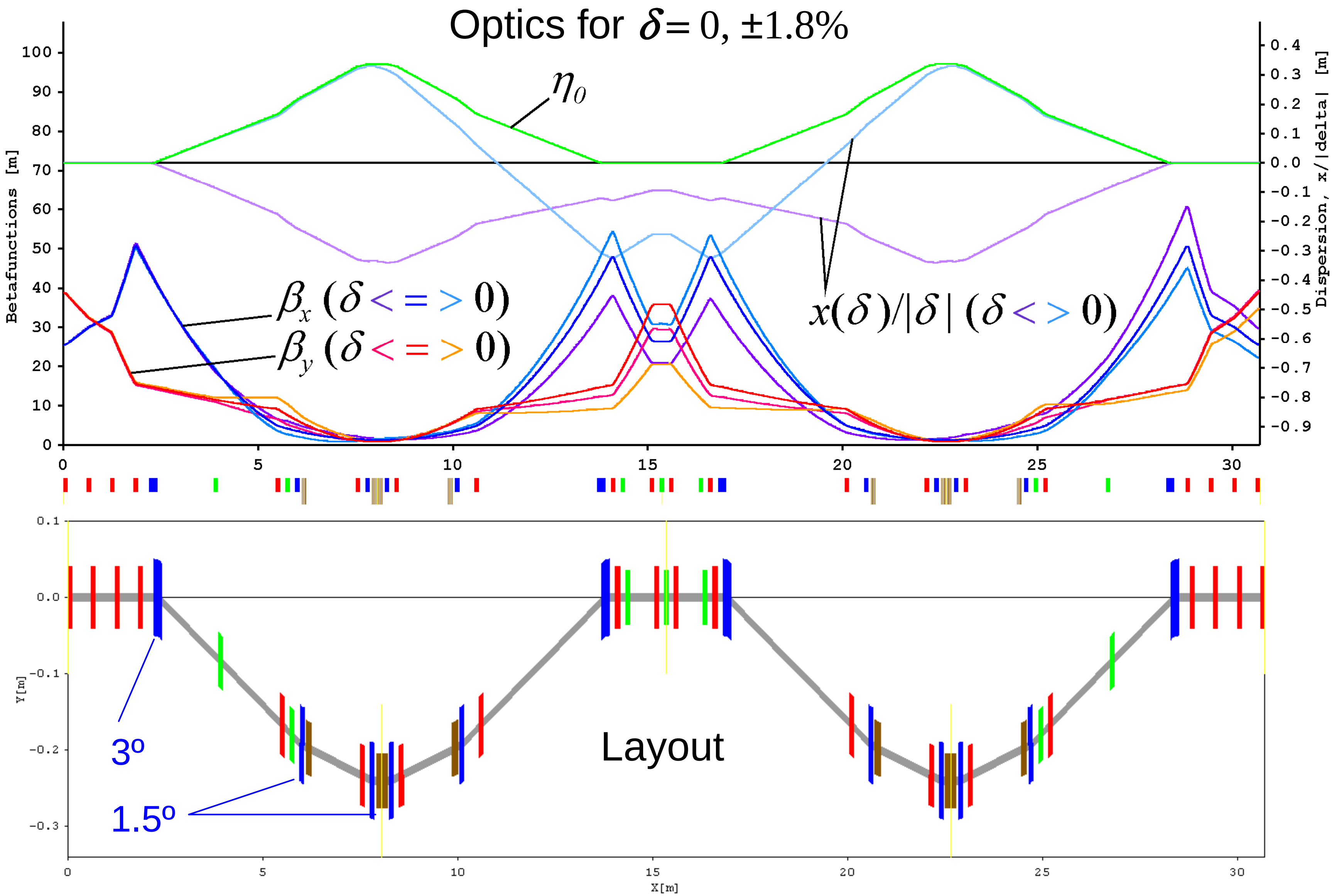
Typical choice of functions

- path length $L(\delta)$
- $x'(\delta)$ at midplane
- $\alpha_x(\delta)$, $\alpha_y(\delta)$ at midplane

OPA upgrade

Further development: target function could be based on CSR simulation data or even on measurements
$\Rightarrow$ iterative optimization and CSR compensation.

A possible solution (Lattice **H6C**)



Performance 1

Linearization

and compression of
longitudinal phase space

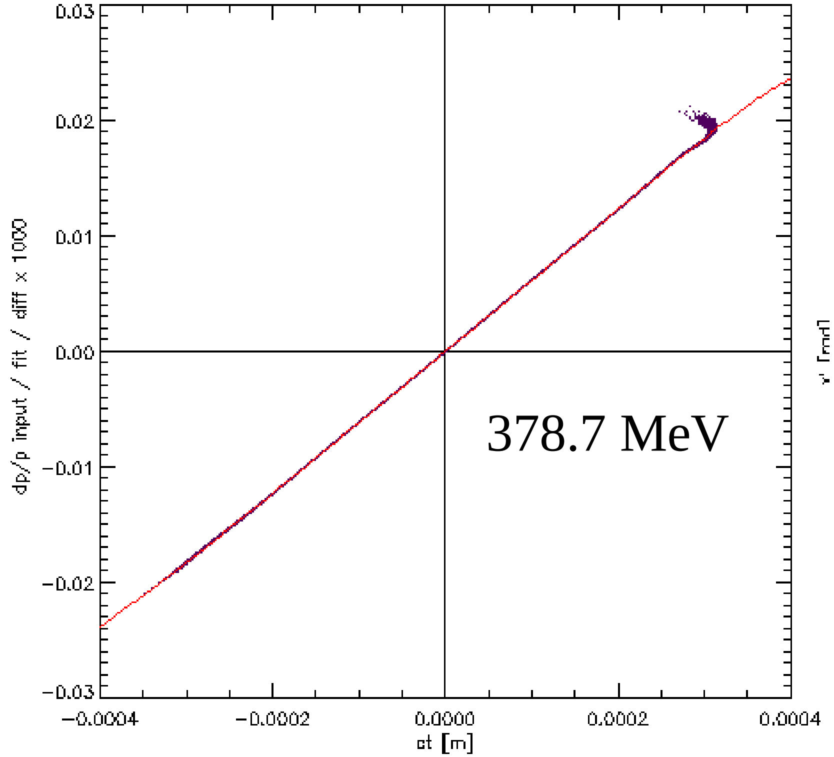
Pathlength

L [m] = 30.7

$-\ \mathbf{0.0575}\ \delta\quad (\mathbf{R_{56}})$

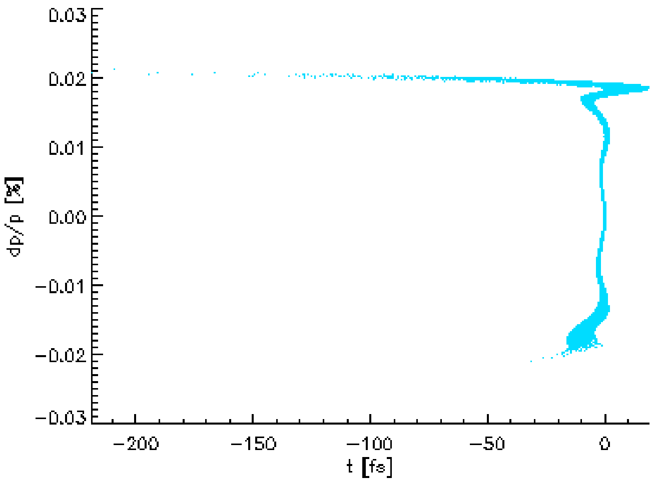
$-\ \mathbf{0.763}\ \ \delta^2\quad (\mathbf{T_{566}})$

$-\ 15.4\ \delta^3 - 140\ \delta^4 - 2{\cdot}10^4\ \delta^5 \ldots$

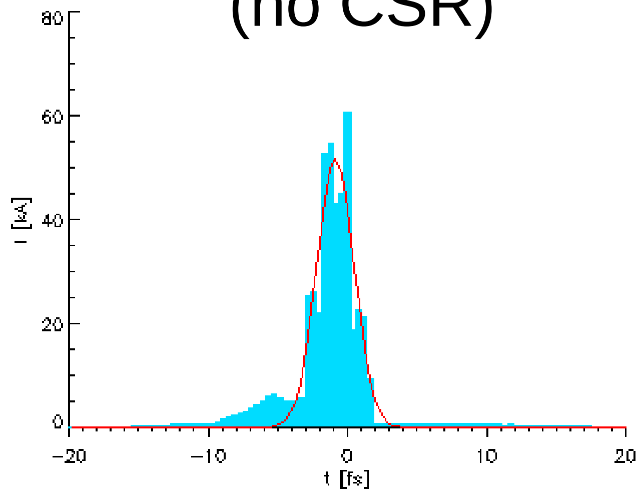


Pulse after complete (ideal) compression:

- ✓ peak current
  50 kA
- ✓ bunch length
  3.1 fs FWHM
- ✓ efficiency
  86 %



(no CSR)



Performance 2

Emittance preservation (no CSR)

Mean slice emittance growth

- 50 slices, time-sorted
- 4000 particles per slice
- each 3 slices at head and tail omitted

- slice centroid ($\bar{x}, \bar{x}'$) subtraction

  ➔ non-linear distortion

  horiz. **+0.8%** vert. **+0.3%**

- including slice centroids

  ➔ dispersive paths non-closure

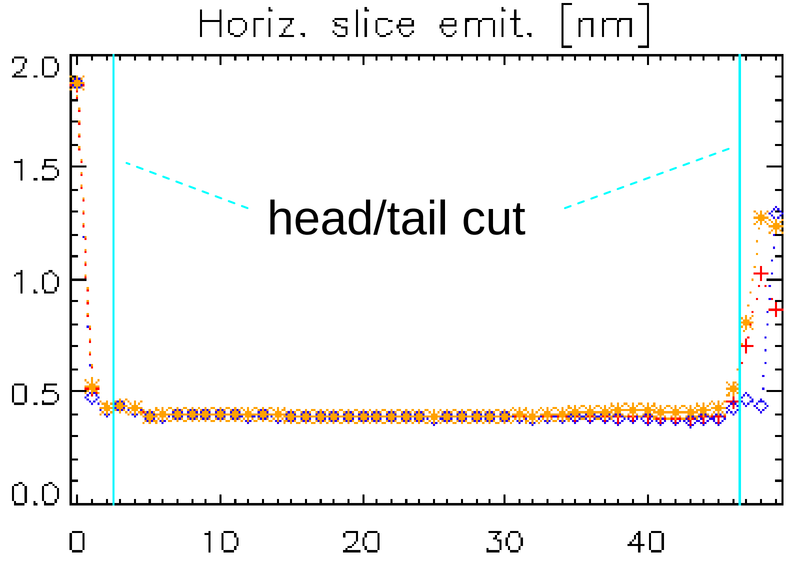
  horiz. **+3.1%** vert. **+0.3%**

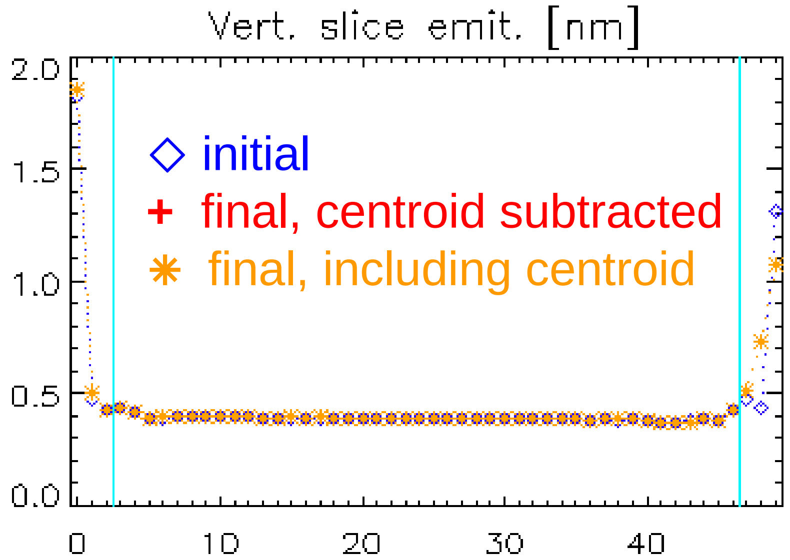
Projected emittance growth

- *all* slices included

➔ chromaticity

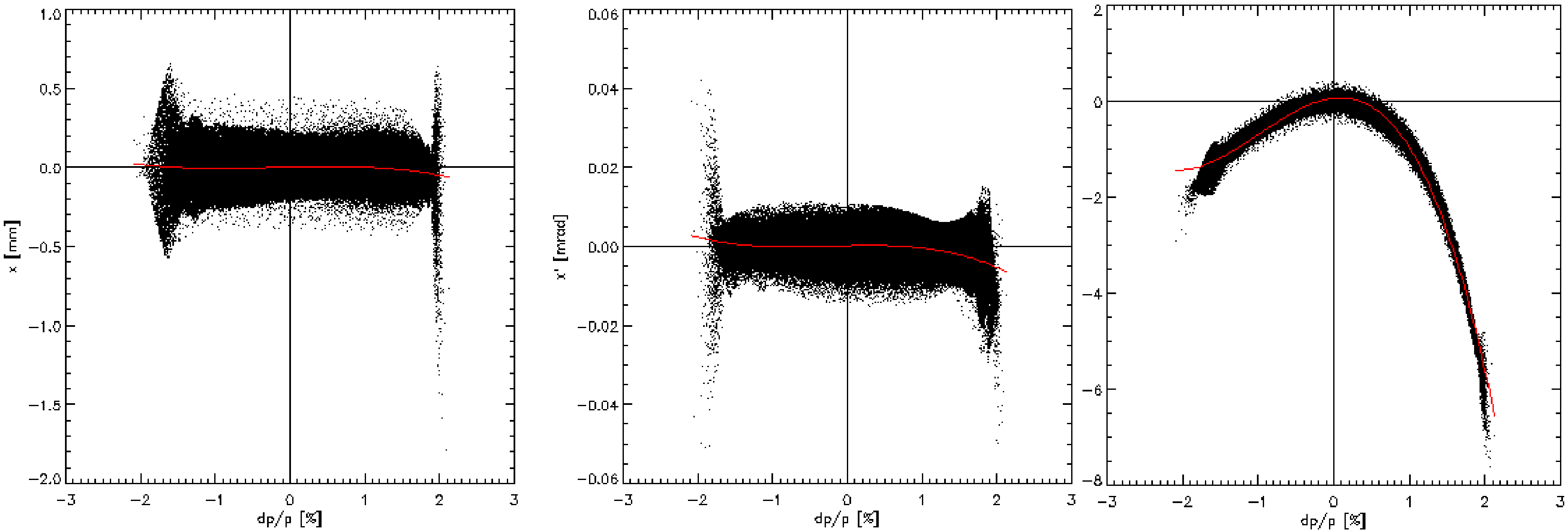
horiz. **+9.1%** vert. **–0.6%`**





Performance 3

Transverse dynamics (no CSR)



$x\,(\delta)$ at exit

centroid < 30 μm

$x'\,(\delta)$ at exit

centroid < 5 μrad

$x\,(\delta)$ at mid plane

$x < 0$ for $\delta \neq 0$

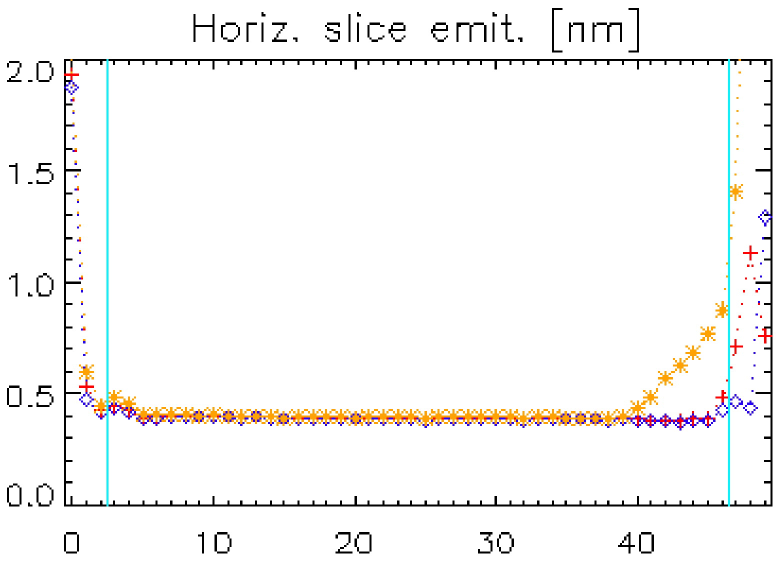
➔ Parabolic $x\,(\delta)$ at mid plane provides the path modulation

➔ Criterion for < 5% slice emittance growth:

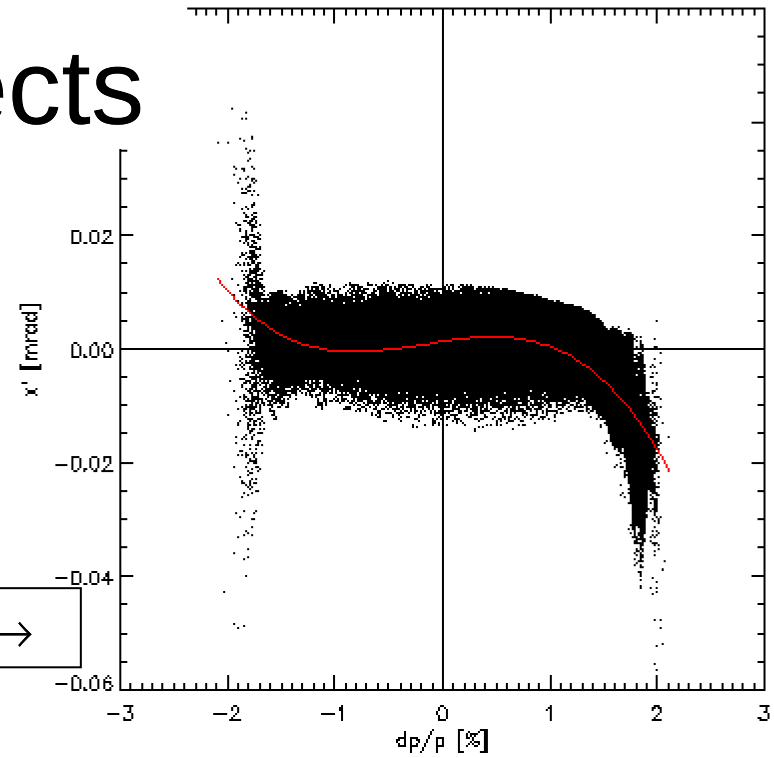
$$x'(\delta)\text{ at midplane} < \tfrac{1}{2}\sqrt{2 \cdot 5\% \cdot 0.4\,\text{nm} / (\beta_{\text{x,midplane}} = 26.5\,\text{m})} \sim 0.7\,\mu\text{rad}$$

Performance 4

Transverse CSR effects



← 1 nC →



Bunch Charge	**0**	**0.2 pC**	**1.0 nC**
Horizontal slice emittance growth	**3.1%**	**4.0%**	**12%**

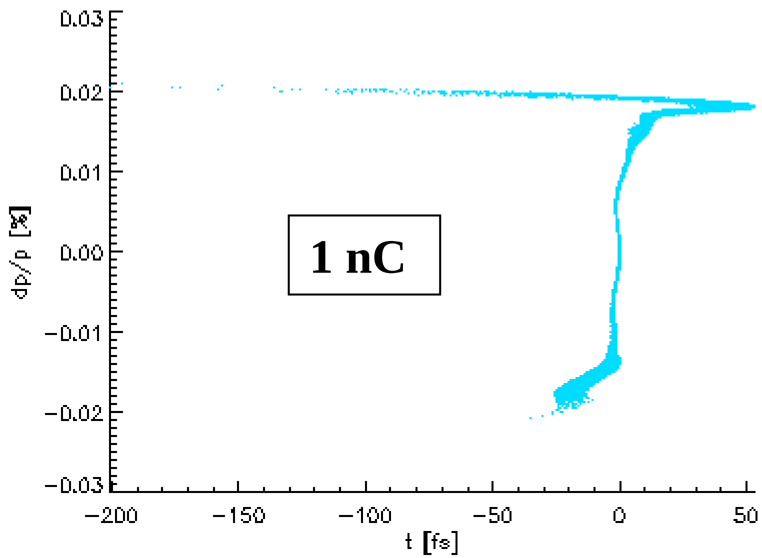
- including centroids (head/tail 3-slice cut)
- almost no effect on slice emittance with centroid subtraction
- source: dispersive path non-closure due to CSR momentum change

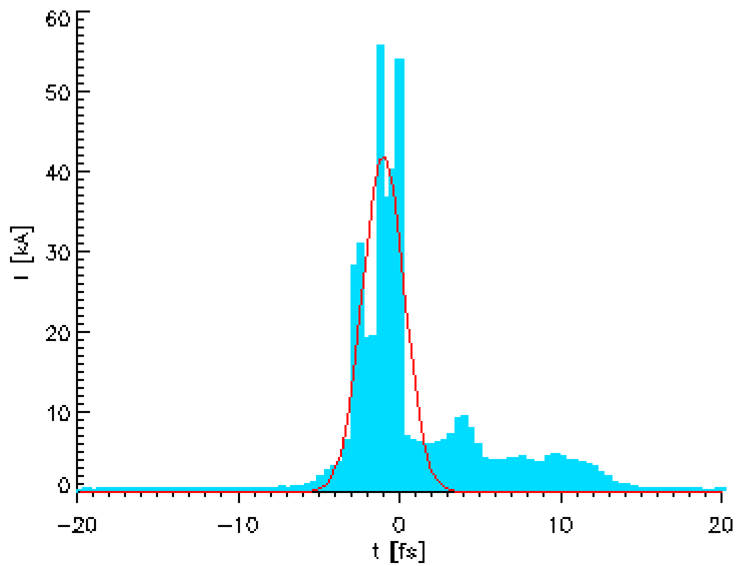
Horizontal projected emittance growth	**9.1%**	**14%**	**48%**

- no effect on vertical emittance

Performance 5

Longitudinal CSR effects





Bunch Charge	**0**	**0.2 nC**	**1.0 nC**
Pulse length FWHM after ideal & complete compression	**3.1 fs**	**3.3 fs**	**3.0 fs**
Efficiency	**86%**	**90%**	**67%**
Peak current	**50 kA**	**50 kA**	**40 kA**

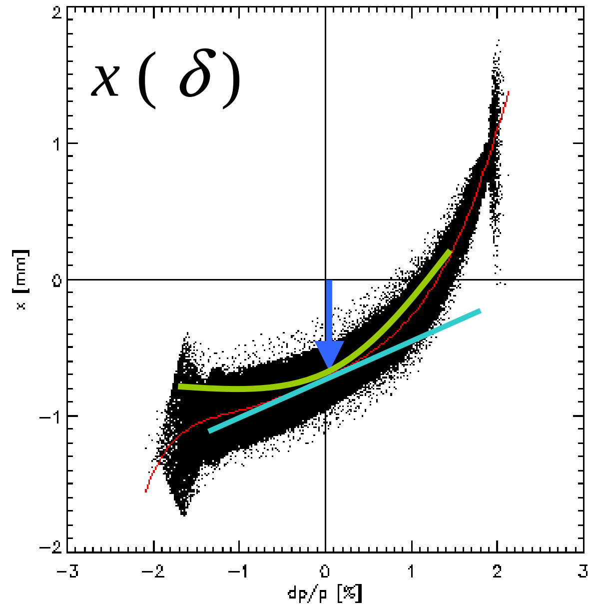
Performance 6

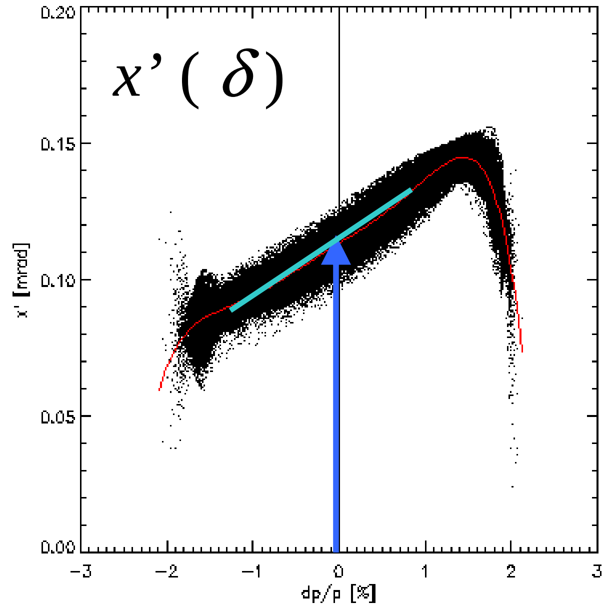
Error studies [preliminary]

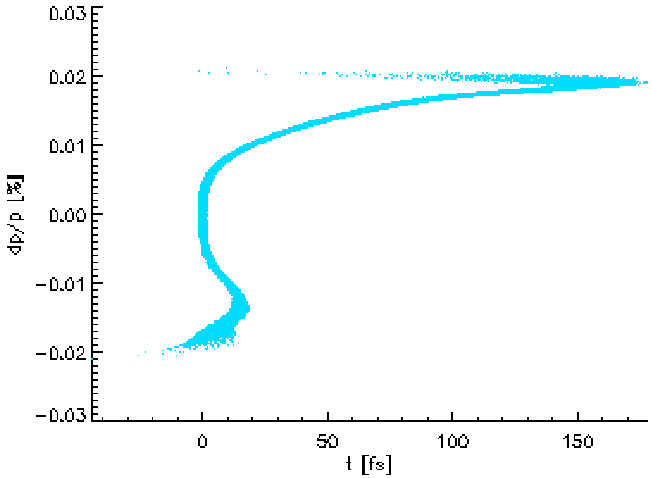
Alignment errors

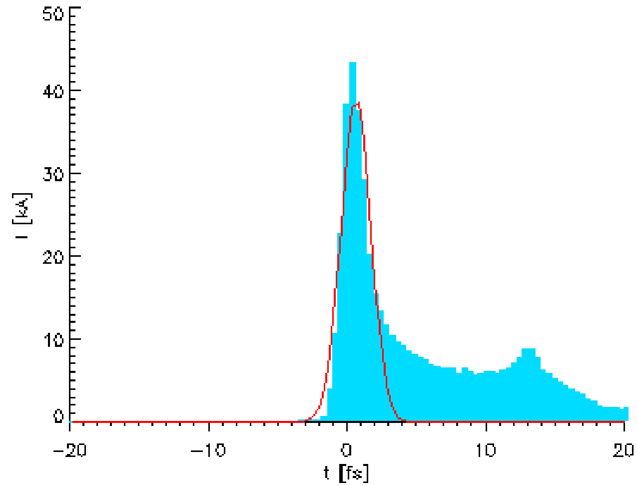
⇒ distortions of

- orbit
- dispersion
- non-linear dispersion
- path length





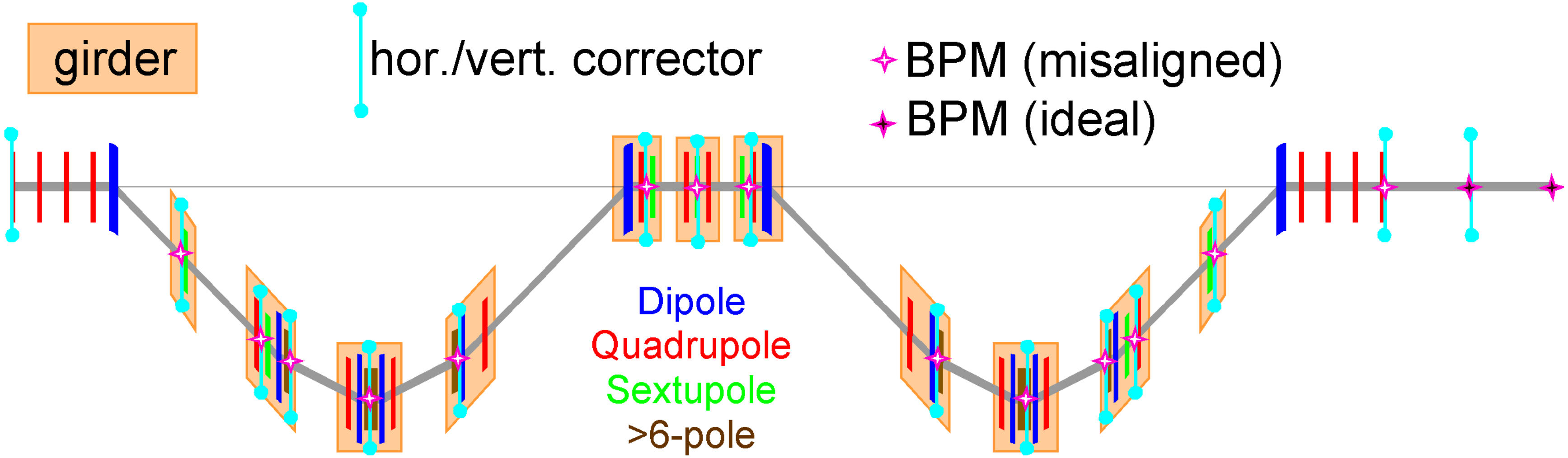




Error settings

x/y misalignments
50 μm rms (cut 2σ)
no roll errors
seed #1
no correction

Error model and trajectory correction



- Corrector/monitor at *every* non-linear element
- Correlated errors (Gaussian, cut 2σ)
  - girder misalignments (x, y) $\sigma = 50\ \mu m$
  - elements on girders (also BPMs) $\sigma = 10\ \mu m$
  - roll errors not yet included
- Correction *not* on beam centroid!

Slice emittance calculation

$$\epsilon = \sqrt{\langle (x-\bar{x})^2 \rangle \langle (x'-\bar{x'})^2 \rangle - \langle (x-\bar{x})(x'-\bar{x'}) \rangle^2}$$

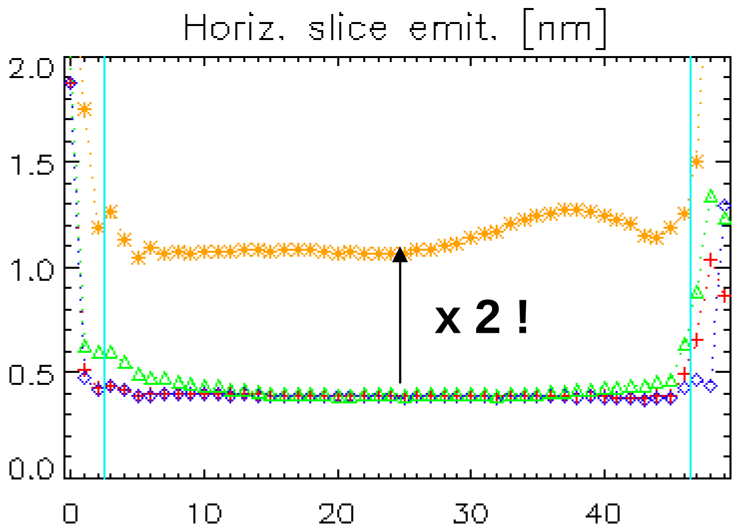
◇ initial

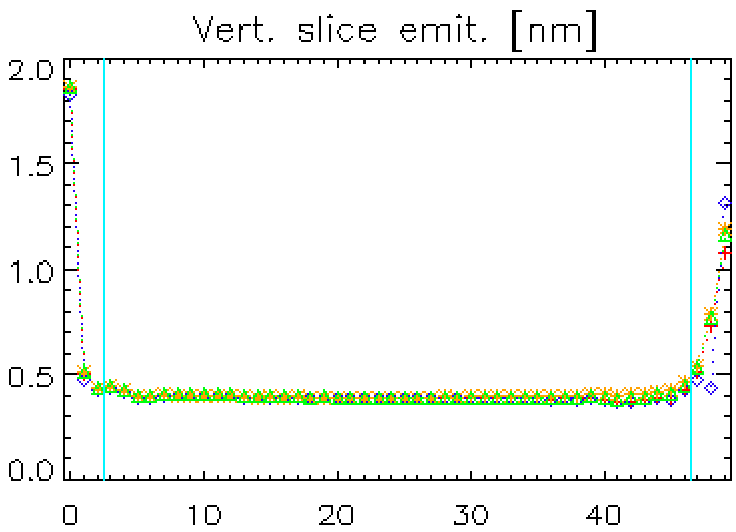
\+ slice centroid subtraction — $\bar{x} = \text{slice center}$

Δ beam centroid subtraction — $\bar{x} = \text{beam center}$

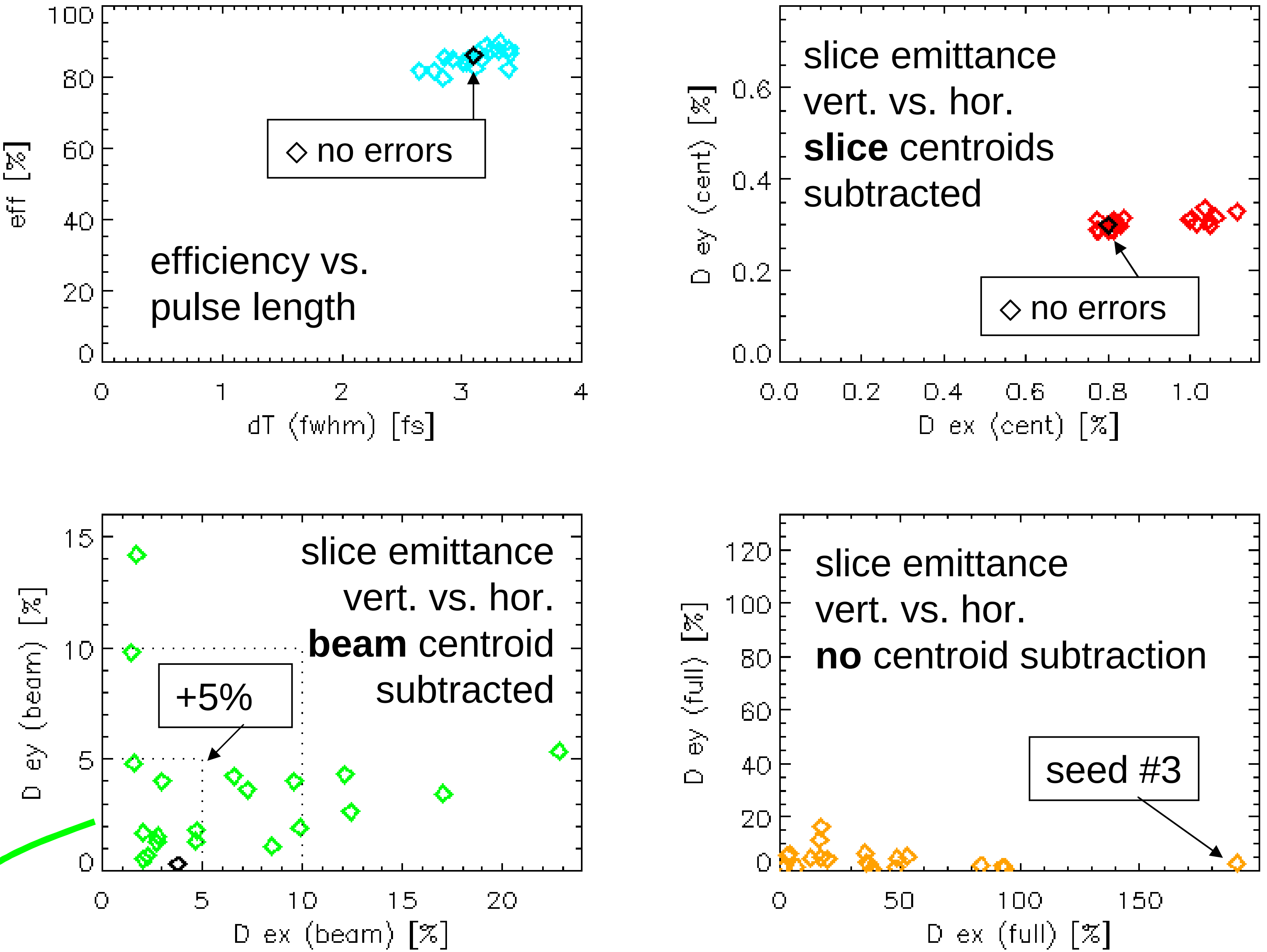
✱ no centroid subtraction — $\bar{x} = 0$

Example: seed # 3   horizontally bad, vertically good





Pulse length and slice emittance (20 seeds)

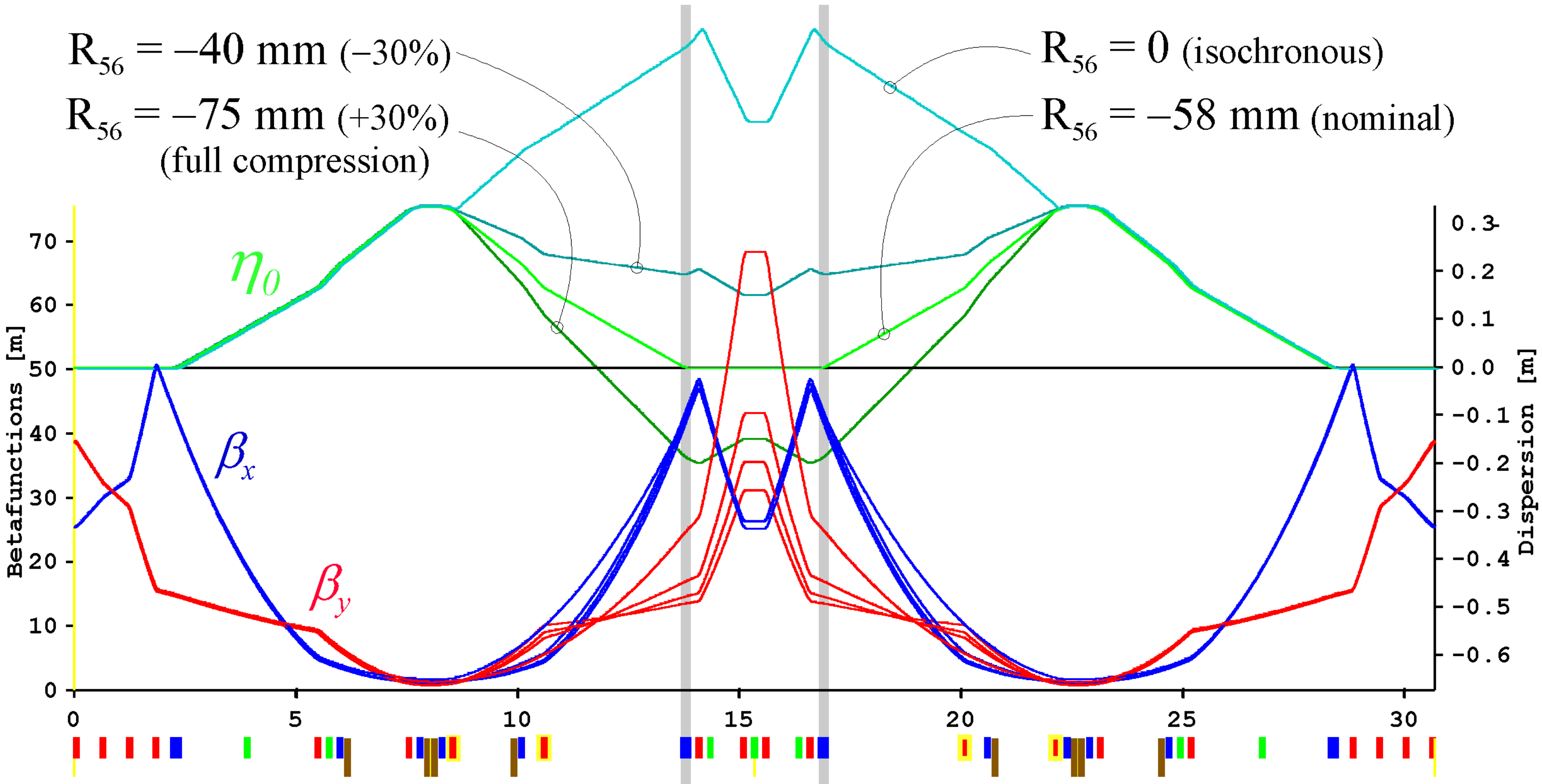


ELEGANT trajectory correction problem?

Mean (max) slice emittance growth hor. 6.8(23)%, vert. 3.6(14)%

Tuning range

Variation of linear compression (R_{56}) while keeping all non-linear terms constant



Preliminary results for slice emittance increase [%]

Variation of R_{56},resp. T_{566} while keeping *all* other orders constant. ELEGANT tracking, no CSR.

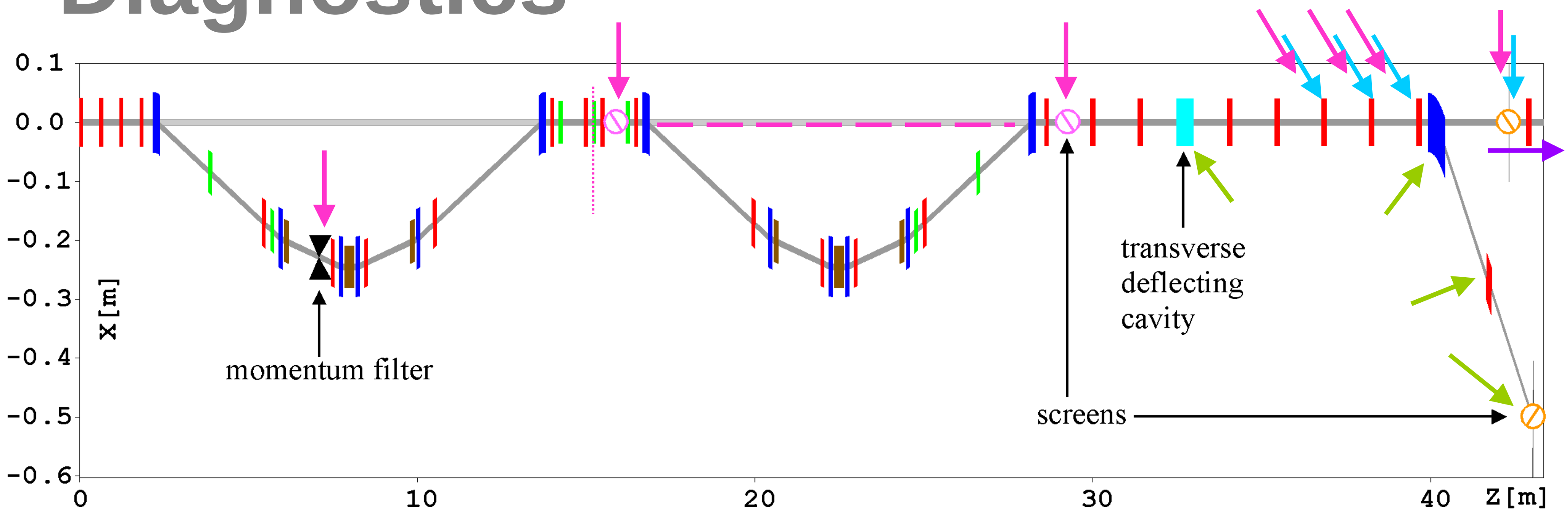
% increase	$\Delta\varepsilon_x$	$\Delta\varepsilon_y$	$\Delta\varepsilon_x$	$\Delta\varepsilon_y$
centroids...	subtracted		included	
nominal	*0.8*	*0.3*	*3.1*	*0.3*
–30% R_{56}[a]	**0.3**	**0.1**	**5.2**	**0.1**
+30% R_{56}[a]	**–0.1**	**0.0**	**6.7**	**0.0**
isochronous[a]	**0.1**	**0.1**	**19**	**0.1**
–50% T_{566}	**0.4**	**0.2**	**2.8**	**0.2**
+50% T_{566}[b]	**14**	**14**	**19**	**13**

Comments:

a linearization insufficient $\Rightarrow$ optimize further (iterate)

b multipoles too strong? (non-linear distortion)

Diagnostics



NLBC (H6C) followed by new diagnostics section
(→ *Eduard Prat, SwissFEL seminar July 20, 2011*)

- projected emittance measurement (quad scan)
- longitudinal phase space imaging (TDC & bend)
- slice emittance measurement (after C-band)

Additional measurements required for tuning:

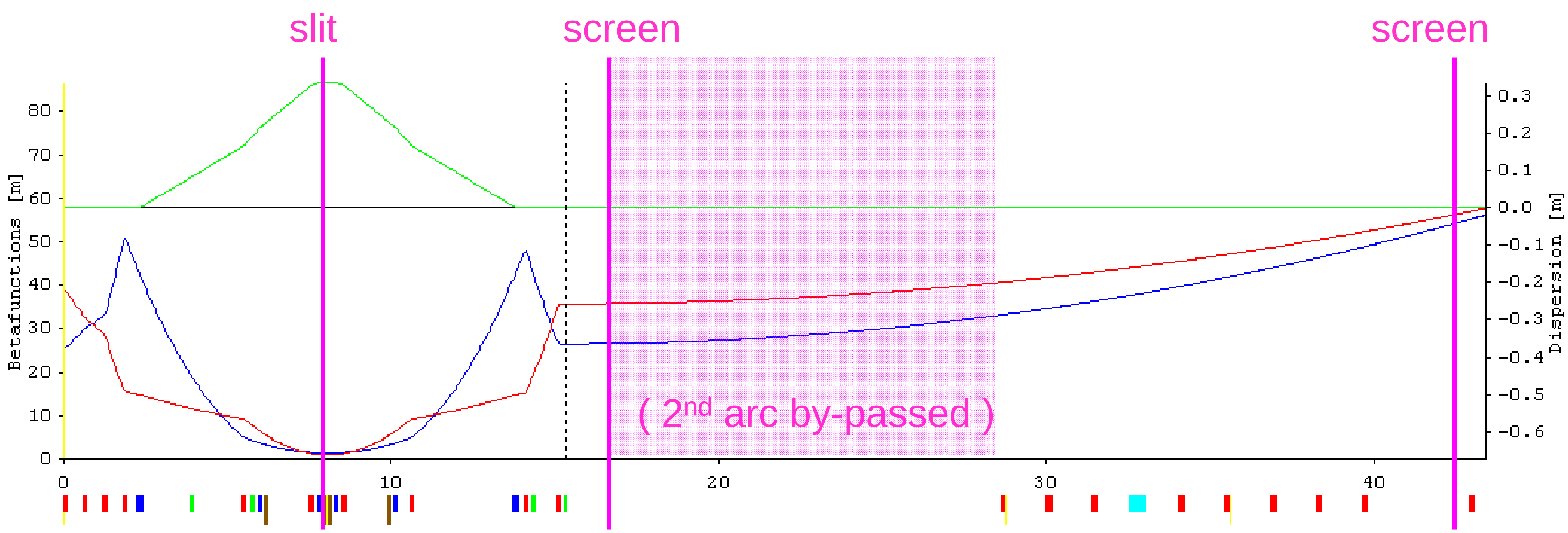
- $x'(\delta)$, $\beta_{x,y}(\delta)$, $\alpha_{x,y}(\delta)$ at midpoint (2nd arc bypass)

Measurement of divergence $x'(\delta)$ at midpoint

- YAG screen resolution $\Delta x \approx 8\ \mu m$
- BPM resolution $\Delta x \approx 5\ \mu m$
- Required accuracy $x' < 0.7\ \mu rad$

$\Rightarrow$ Screen distance > 16 m ✓

- 2nd arc switched off
- Momentum selection by slit at high dispersion



Imaging of longitudinal phase space

- Vertically deflecting cavity
  $f = 3$ GHz, $V = 4.5$ MV, $\beta_{yc} = 40$ m
  $\Delta\mu_y = 90^o$ TDC $\rightarrow$ screen

$$t_{\mathrm{res}} = \sqrt{\frac{\epsilon_y}{\beta_{yc}}} \frac{1}{2\pi f (eV/p_o c)}$$

$\Rightarrow$ Temporal resolution **15 fs (5 µm)**

= 1/20 bunch length for nominal compression

= **5** $\times$ bunch length for full compression

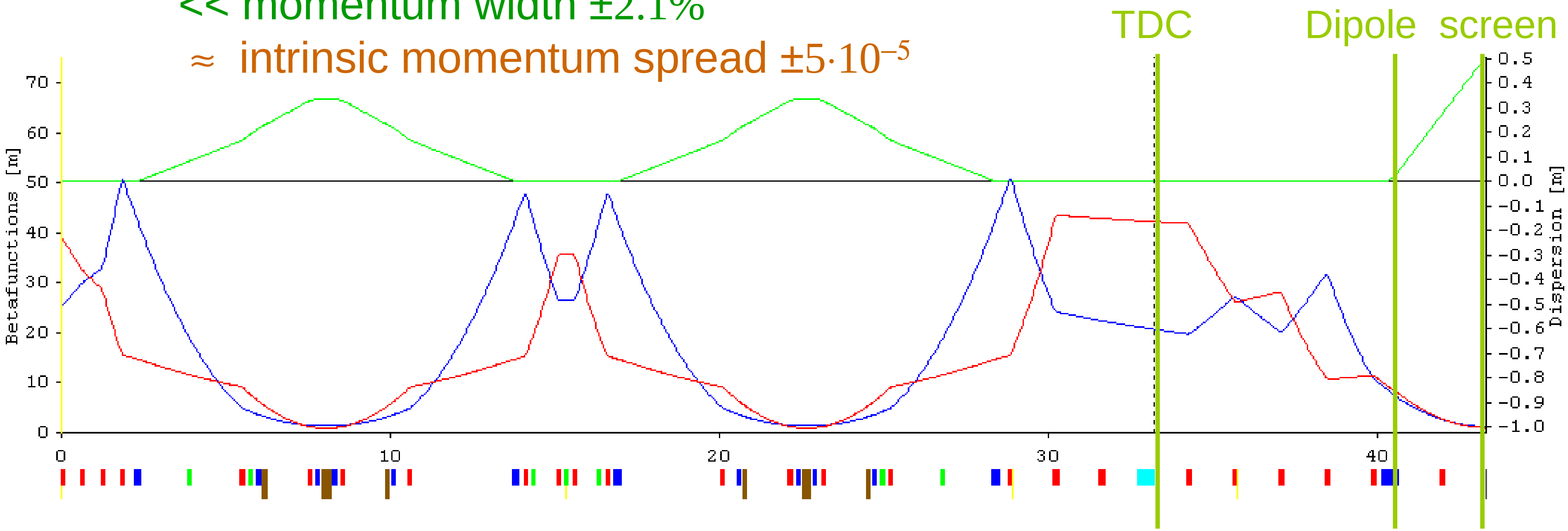
- Horizontally deflecting dipole
  $\Phi = 10^o$ $\rightarrow$ at screen: $\eta_s = 0.5$ m, $\beta_{xs} = 1$m

$$\delta_{\mathrm{res}} = \frac{\sigma_x}{\eta_s} = \frac{\sqrt{\epsilon_x \beta_{xs}}}{\eta_s}$$

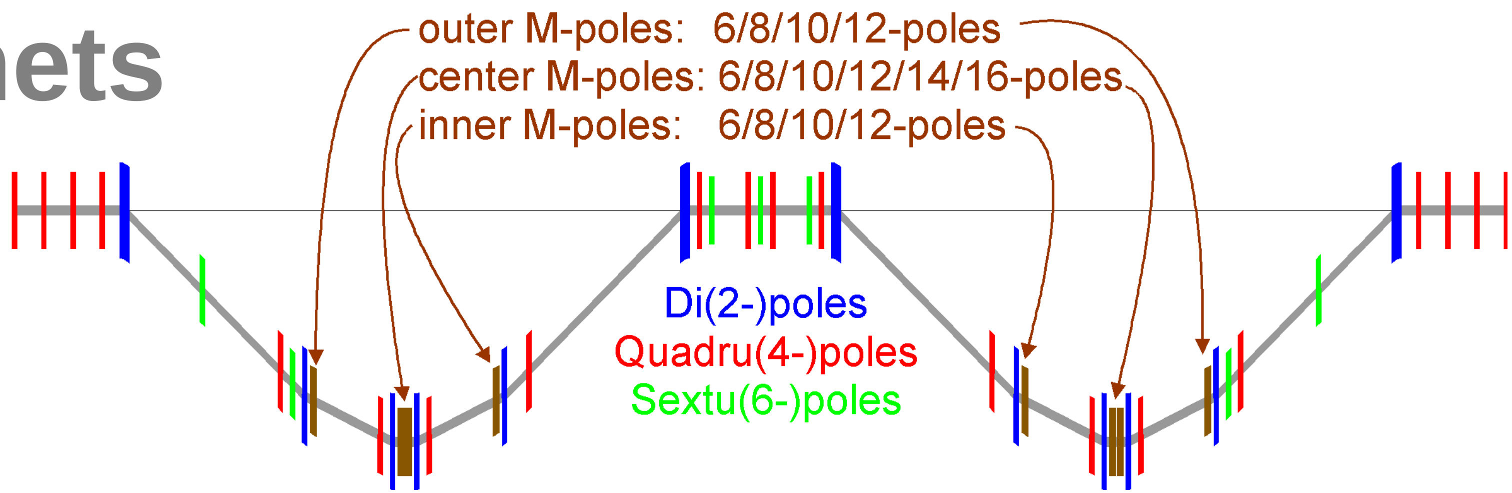
$\Rightarrow$ Momentum resolution **$4 \cdot 10^{-5}$ (15 keV/c)**

<< momentum width ±2.1%

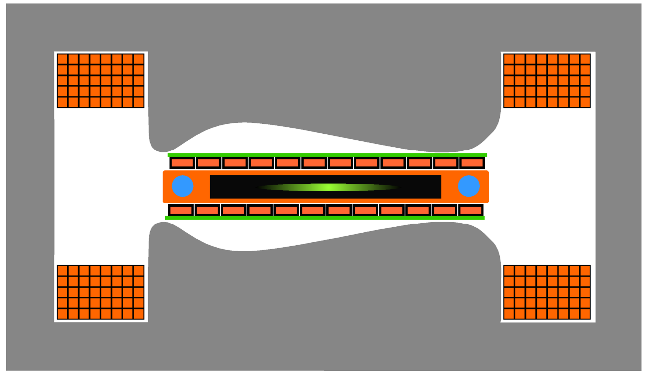
≈ intrinsic momentum spread $\pm 5 \cdot 10^{-5}$



Multipole magnets



First concept: integration in dipoles



- pole contour for nominal mid plane field $B_y(x,0)$
- pole face wires for tuning

Magnet experts (*M. Negrazus, S. Sanfilippo, V. Vrankovic*):

✘ pole face wires too strong

➔ separate dipoles

➔ combine related poles (i.e. 6 and 10)

THE OPERATION OF MULTIPOLE MAGNETS IN THE SRS

by

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- SRS combined $2/4/4^{skew}/6/8/10$-pole (*R. P. Walker*, PAC 1981)

$\Rightarrow$ strength ?

- NLBC beam stay clear:
  - $\eta_{o,max} < 0.35$ m
  - $|\delta|_{max} = 2.1$ %

  $\rightarrow$ $|x| < 7.5$ mm
  - $\varepsilon_{x,y} \approx 0.4$ nm, $\beta_{x,y} < 20$ m

  $\rightarrow$ $10\ \sigma_{x,y} \approx 1$ mm

➔ $\pm 10 \times \pm 3$ mm^2 beam stay clear

➔ pole inscribed radius $R = 10$ mm

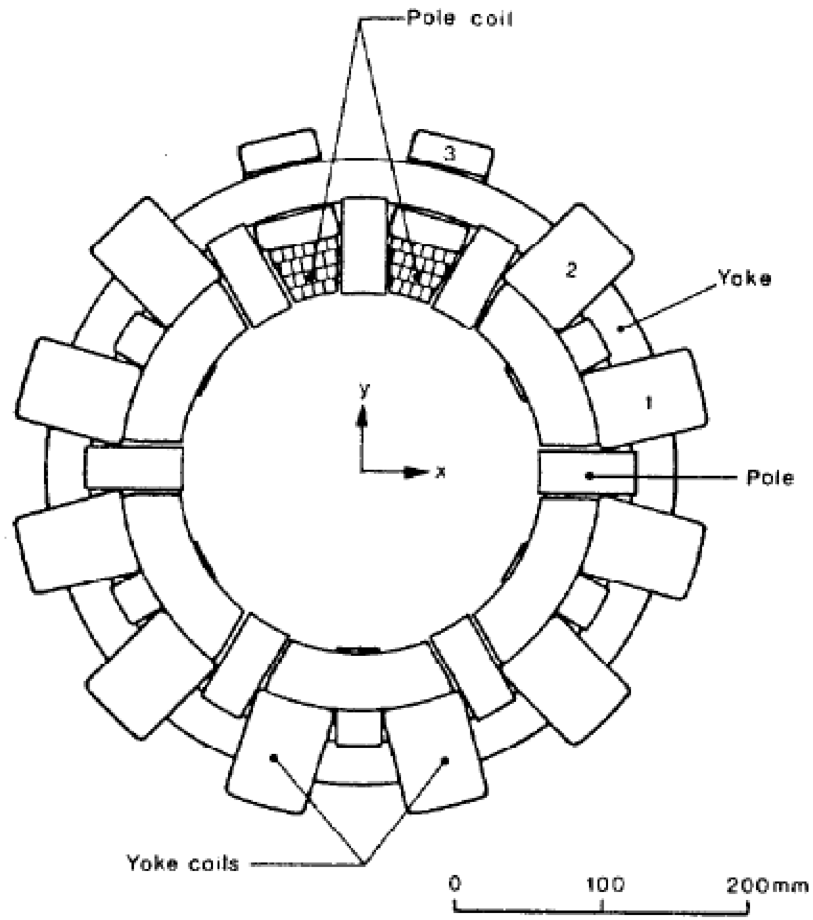
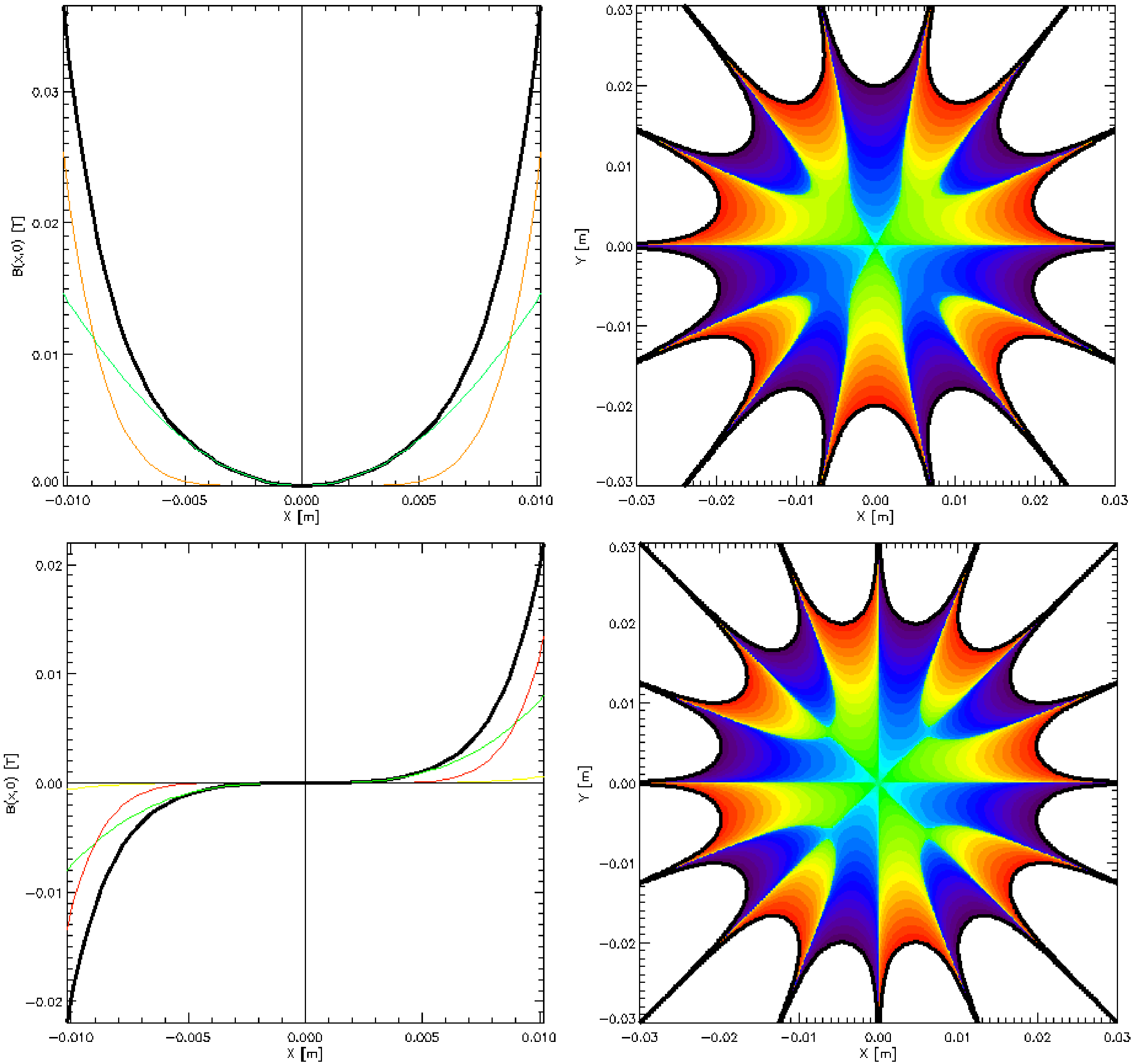


Fig.1 Cross-section of the multipole magnet

e.g. 16-pole:
pole tip field ~R^7
10% $\rightarrow$ factor 2 !



Mid plane field and magnetic potential for

⇖

centre sym. 6/10/14-pole

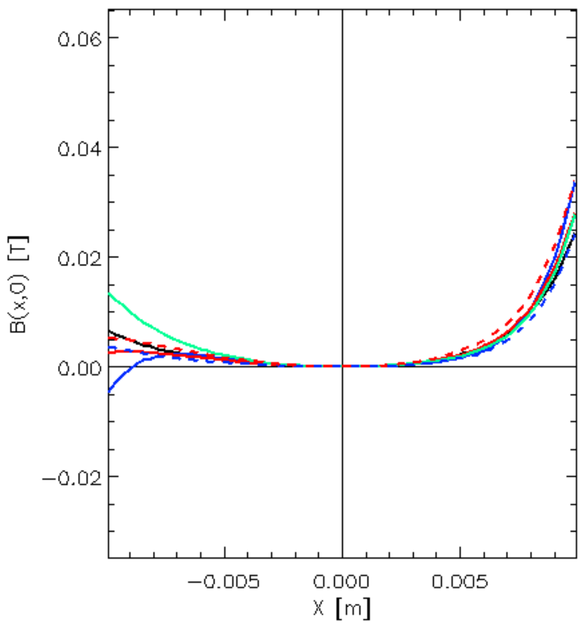
centre asym. 8/12/16-pole

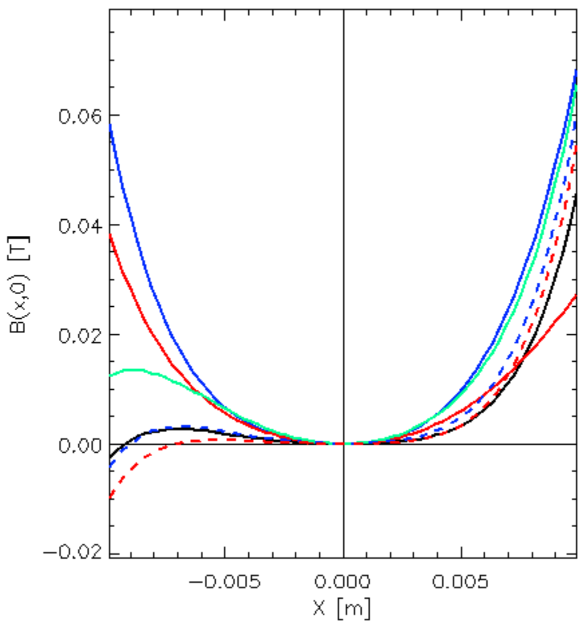
⇙

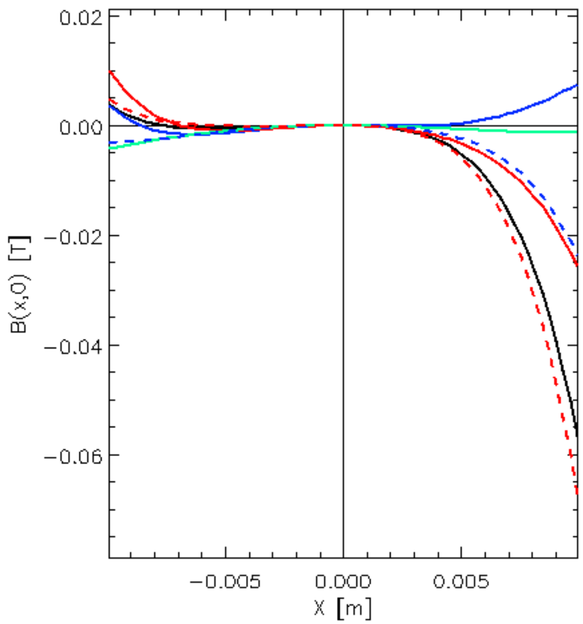
max. pole tip field for all multipoles $B_{PT} < 70$ mT ($R = 10$ mm)

Multipoles tuning range

Midplane field $B_y(x,0)$
for **nominal**, +/–30%, **zero** $\boldsymbol{R_{56}}$ (———)
and for +/– 50% $\boldsymbol{T_{566}}$ (- - - -)



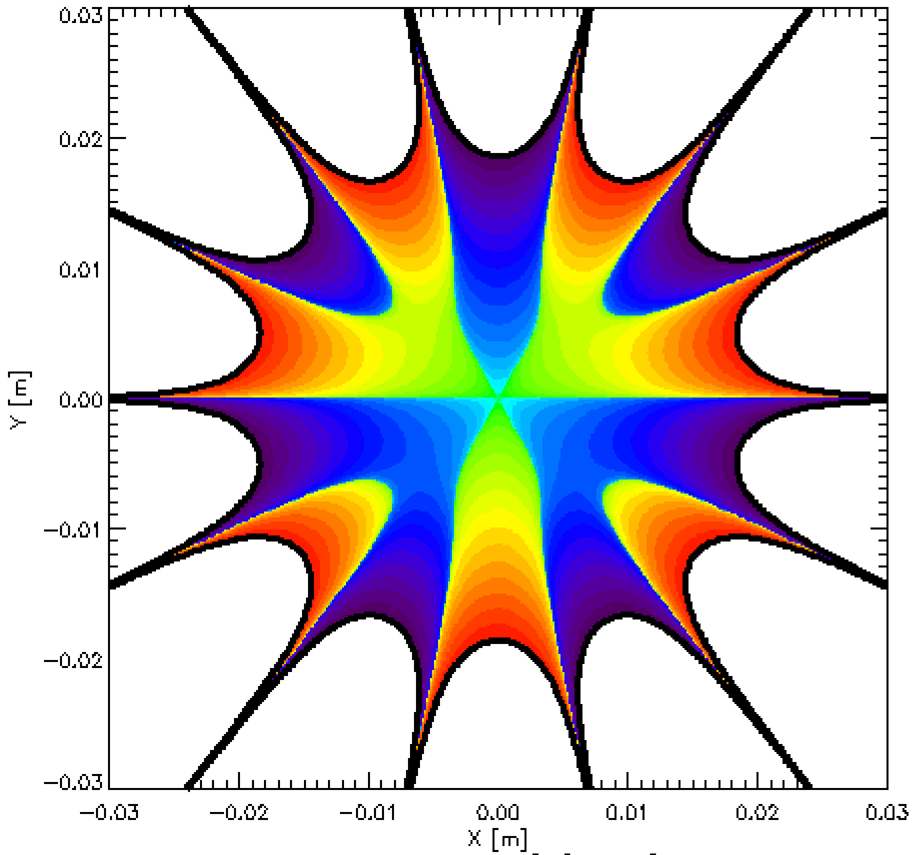




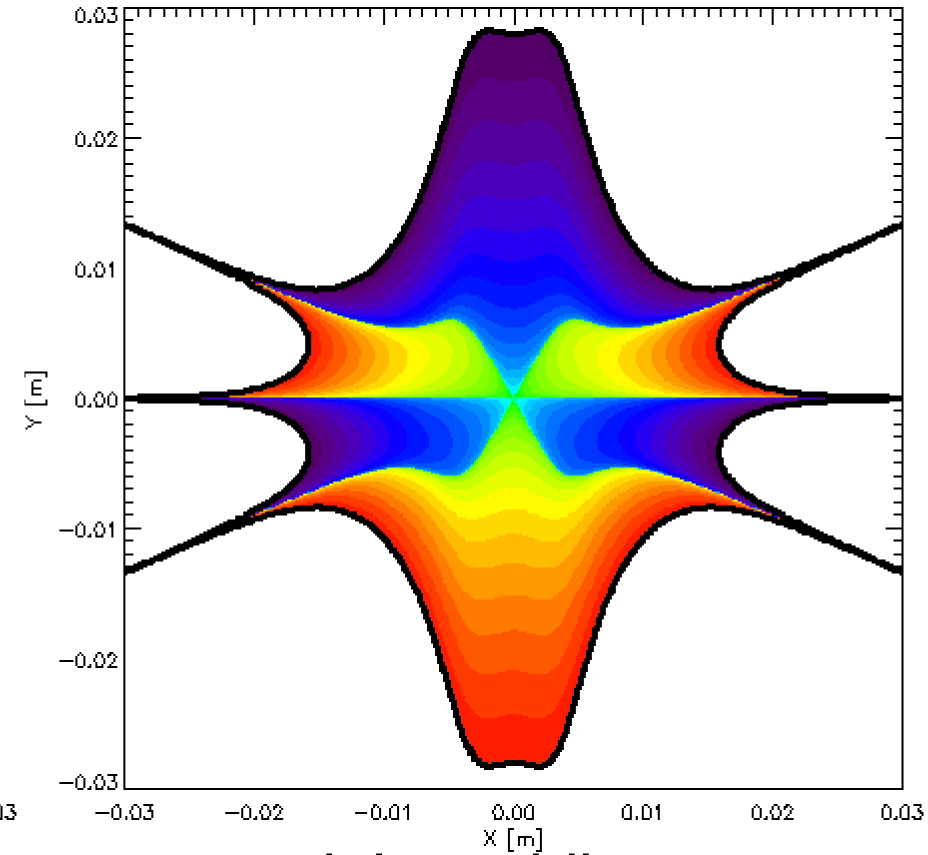
center *outer* *inner*

⇒ independent tunability of multipole components !

Symplified geometry? (e.g. centre 6/10/14-pole)



exact multipole potential



potential providing same midplane field $B_y(x,0)$

- ➔ small vertical beam size: $B_y(x, y \approx 0)$ sufficient?
- ➔ independent tunability of multipole components?

Conclusion

The solution fulfills* the design specs

- in terms of
  • linearization • compression • emittance preservation
- including CSR effects and (small) misalignments,
- for the full R_{56} tuning range
  (isochronous to full compression).

(* some settings need further optimization...)

Critical issues:

- Multipole magnet design:
  • tininess • complexity • precision • tunability.
- Alignment precision: $10\ \mu m$ BPM vs. multipole.
- Complicated set-up procedure:
  model based numerical iterative optimization.

$\Rightarrow$ ***A non-linear bunch compression scheme for SwissFEL may be quite feasible.***

Outlook

Evaluation:

– NLBC vs. X-band linac:
  • feasibility • risk • costs • manpower • etc.

$\Rightarrow$ ***endorse or reject concept***

Next tasks:

– Lattice simplification and consolidation.
– Cover all modes of operation: matching & tuning.
– Refined simulation: complete CSR and error models.
– Refined optimization: iteration and CSR-compensation.
– Magnet design and specification. [**!**]
– Diagnostics specification: devices and performance.
– Procedures for set-up and operation: "super-knobs".

THE END