Lattice Design for the MAX IV 3 GeV Storage Ring

A Multibend Achromat with Higher-order Multipoles

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Workshop on Accelerator R&D for Ultimate Storage Rings, Huairou, Beijing, China, Oct 30 - Nov 1, 2012

MAX IV LABORATORY

MAX IV Facility at a Glance

- MAX IV design premise: one size *does not* fit all

Short pulses:

- 3.5 GeV linac & SPF (~30 fs, 100 Hz), FEL upgrade option

High average brightness:

- 1.5 GeV storage ring DBA lattice, 6 nm rad, IR & UV users
- 3 GeV storage ring MBA lattice, ~300 pm rad, x-ray users

Multibend Achromats

- Equilibrium emittance in a flat ring

$$\varepsilon_0[\mathrm{nm\,rad}] = 1470\,E[\mathrm{GeV}]^2\,\frac{I_5}{J_x I_2}, \quad J_x = 1 - \frac{I_4}{I_2}$$

$$I_2 = \oint \frac{ds}{\rho^2}, \quad I_4 = \oint \frac{\eta}{\rho}(\frac{1}{\rho^2} + 2b_2)ds, \quad I_5 = \oint \frac{\mathcal{H}}{\rho^3}ds$$

$$\mathcal{H} = \gamma_x\eta^2 + 2\alpha_x\eta\eta' + \beta_x\eta'^2$$

- TME: minimize I_5/I_2 → overstrained optics?
- MBA: many weak dipoles → relax optics!

$$\varepsilon_0[\mathrm{nm\,rad}] = \frac{7.8}{J_x}\,E[\mathrm{GeV}]^2\,\Phi[^\circ]^3\,\frac{F(\beta_x,\eta)_\rho}{12\sqrt{15}}, \quad \Phi[^\circ]^3 \propto \frac{1}{N_{\mathrm{bend}}^3}$$

Multibend Achromats

- Concept already published in the 1990s
  - NIM-A 335 1993, Einfeld et al.: *A modified QBA optics for low emittance rings* — QBA
  - EPAC'94 , Joho et al.: *Design of a Swiss Light Source* — 6x7BA
  - PAC'95, Einfeld et al.: *Design of a Diffraction Limited Light Source* — 12x7BA
  - PAC'95: Kaltchev et al.: *Lattice Studies for a High-brightness Light Source* — QBA, 5BA, 6BA

Multibend Achromats

- Issues: space requirements, no. of user straights
  - weak bends → large circumference → cost!
    - ➡need very compact optics
  - strong focusing & weak bends → low dispersion → strong chromatic sextupoles
    - ➡need to carefully optimize nonlinear optics

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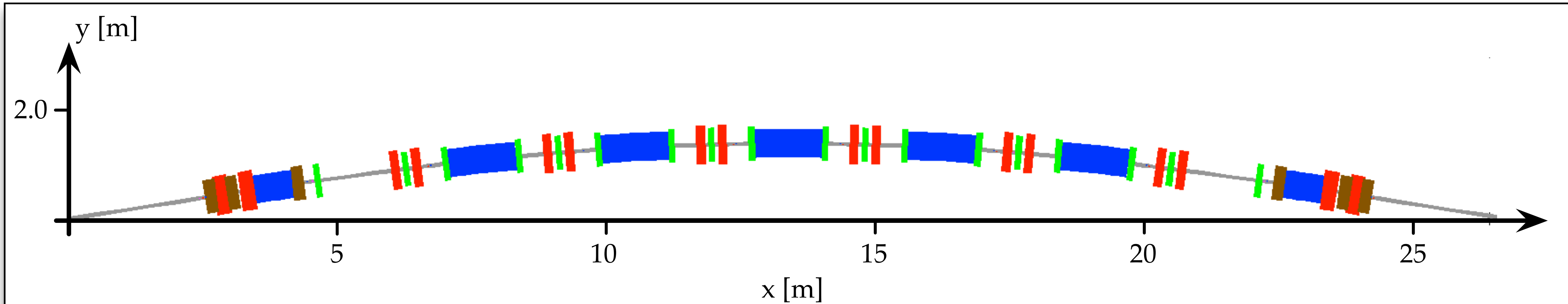
    - ➡need to carefully optimize nonlinear optics
- Early 2000s: MAX-lab convinced
  - innovative technology allows for very compact optics

  ➡MBA is robust & inexpensive path to very low emittance

MAX IV Multibend Achromat Lattice



- After several iterations (~2003-2011) arrived at
  - –20-fold 7BA @ 3 GeV, 528 m circumference
  - –19 user straights (4.6 m)
  - –40 short straights (1.3 m, RF & diagnostics)
  - –326 pm rad bare lattice emittance
  - –vertical emittance adjusted to diffraction limit (~1 Å)

NIM-A **508**, 480 (2003)

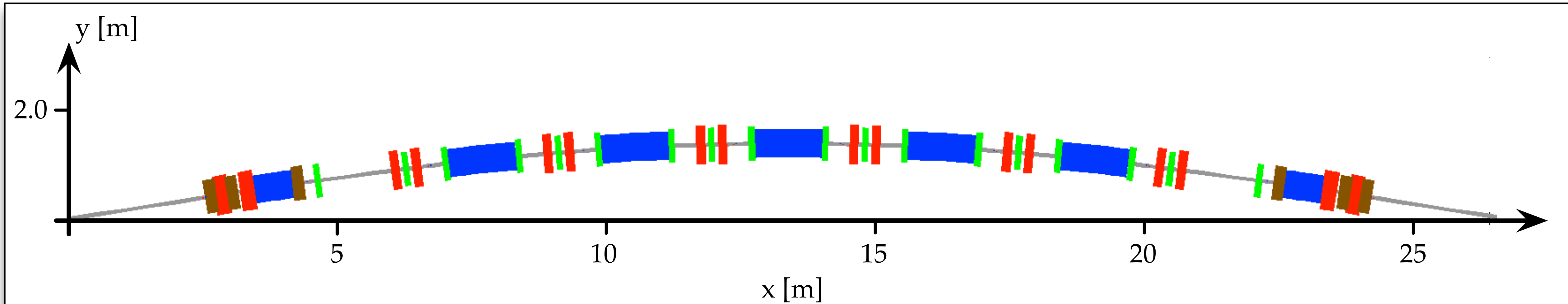
PAC'**07**, MOZAAB02, p.74

NIM-A **587**, 221 (2008)

PRST-AB **12**, 120701 (2009)

IPAC'**11**, THPC059, p.3029

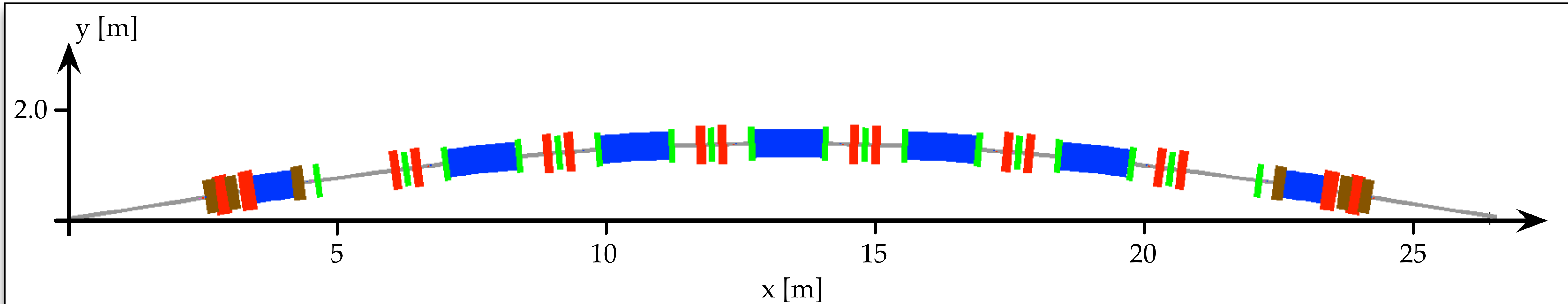
MAX IV Multibend Achromat Lattice



- 7BA: 5 unit cells (3°), 2 matching cells (1.5°)
- Compact optics → combined-function magnets
  - –gradient dipoles (increases J_x → reduces ε_0)
  - –quadrupole-sextupole sandwich
  - –sextupole-dipole sandwich

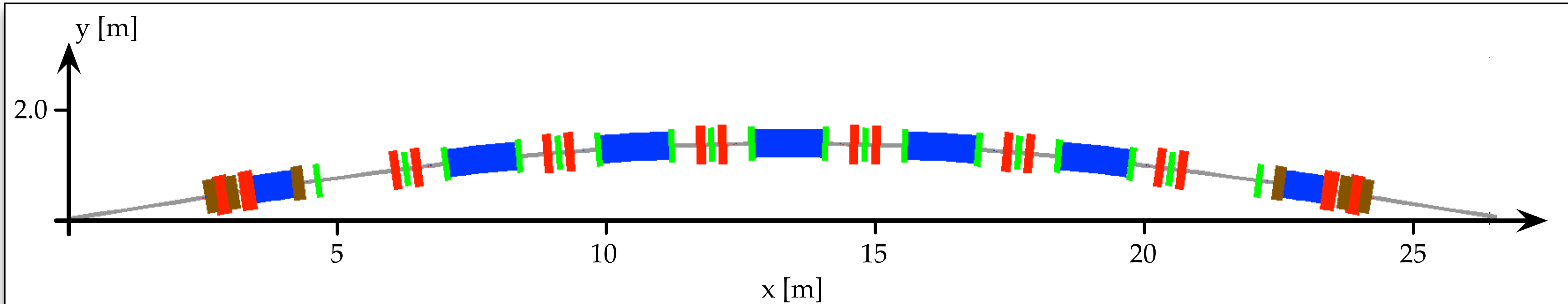
} instead of originally foreseen combined-function magnets
→ tuning flexibility, better DA

MAX IV Multibend Achromat Lattice



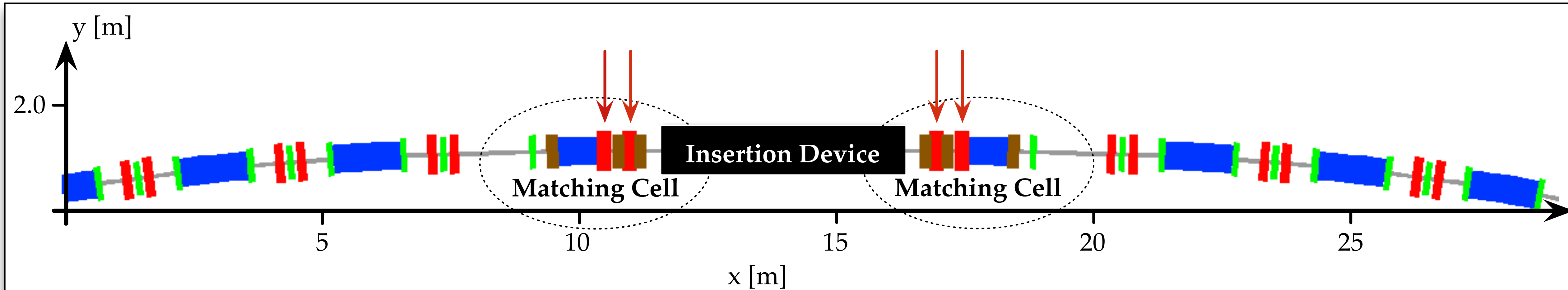
- Many distributed sextupoles → correct chromaticity where it's created (limits chromatic beta beating)
- Dedicated octupoles → nonlinear optimization

MAX IV Multibend Achromat Lattice



- Extra windings on all sextupoles and octupoles
  - skew quads → betatron coupling, vertical dispersion
    - adjust vertical beam size in IDs to diffraction limit
  - auxiliary sextupoles (outside of families!)
    - nonlinear optics corrections

MAX IV Multibend Achromat Lattice

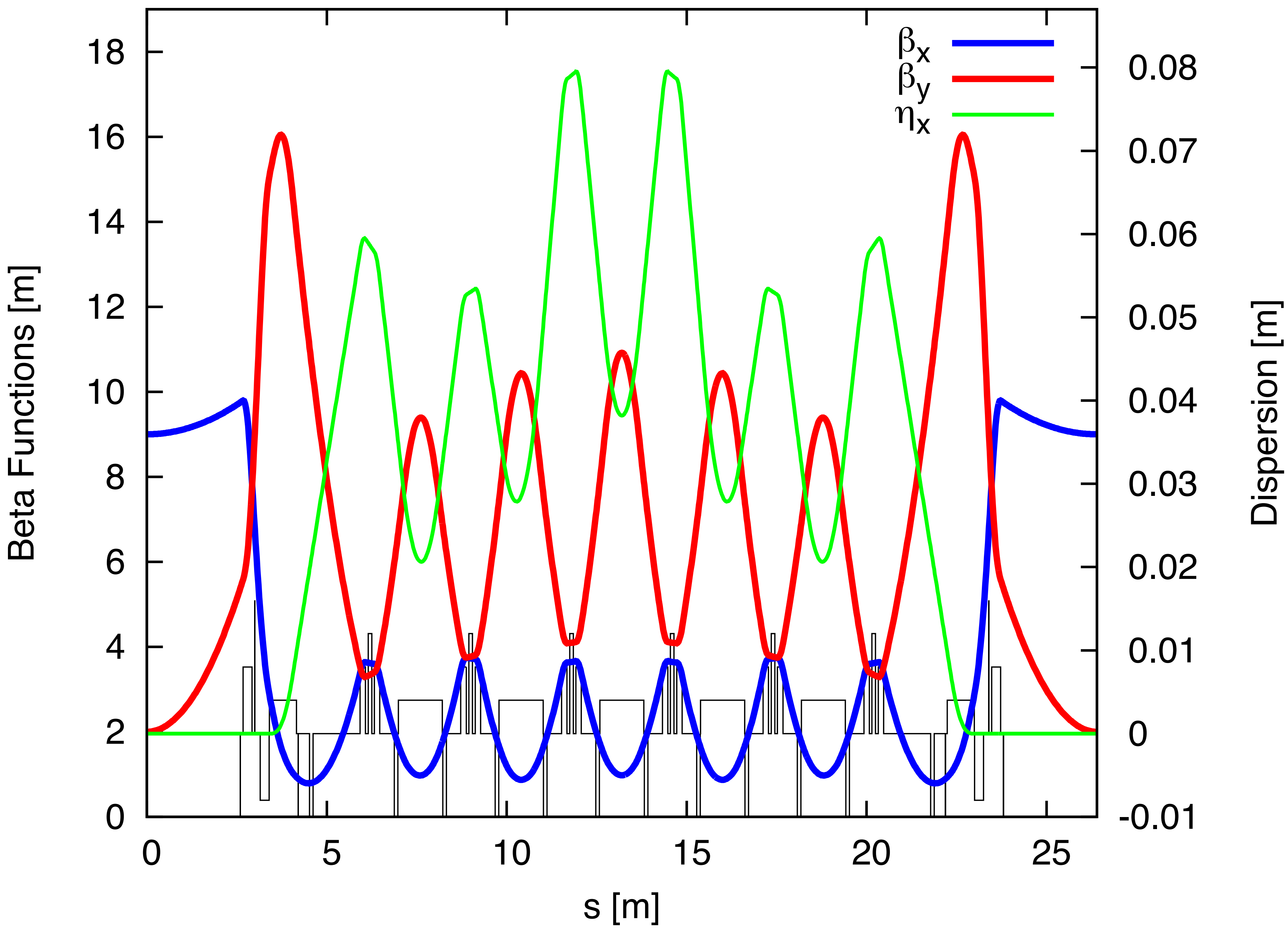


- Tuning & ID matching:
  - –quadrupole doublets in each matching cell
  - –pole-face strips in dipoles

➡ideally ID gap movement should be transparent to rest of machine (linear and nonlinear optics!)

PAC'**11**, TUP235, p.1262

MAX IV MBA Optics



$\nu_x = 42.20$

$\nu_y = 16.28$

$\beta_x^* = 9$ m

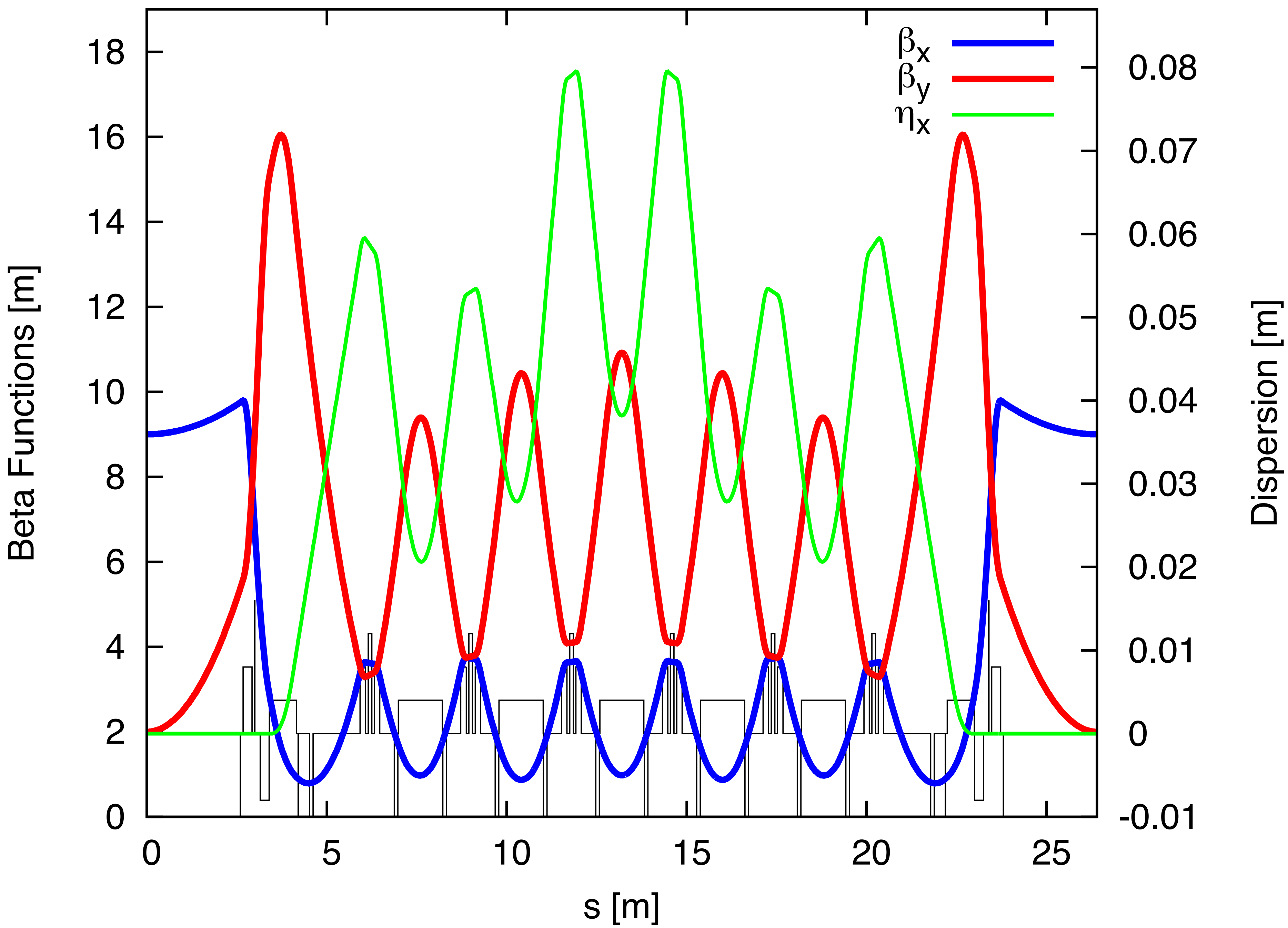
$\beta_y^* = 2$ m

$\eta_x^* = 8$ cm

$\sigma_x^* = 42\text{-}60$ μm

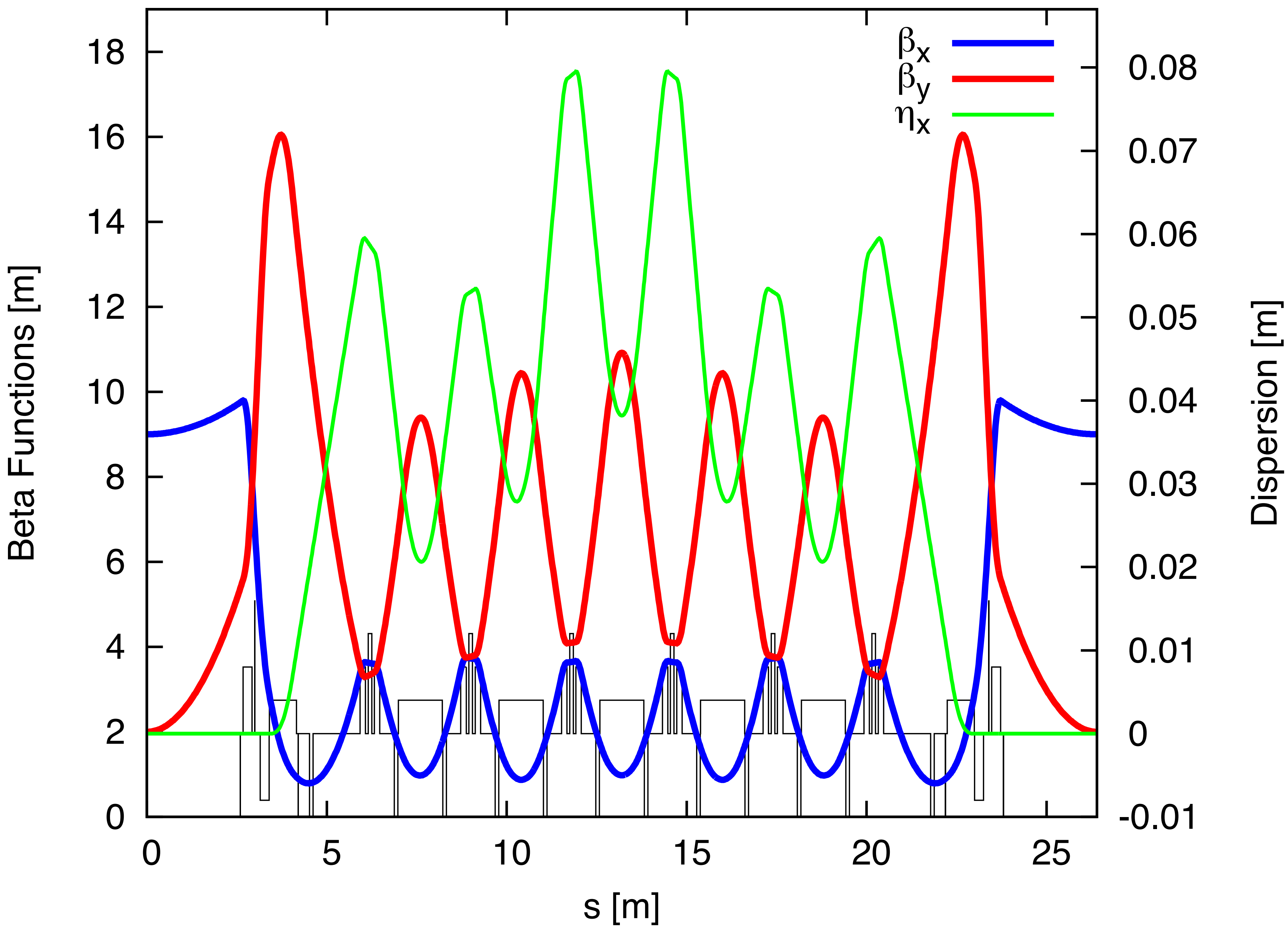
$\sigma_y^* = 2\text{-}5$ μm

MAX IV MBA Optics



- Dipoles
  ~0.5 T
  ~9 T/m
- Quadrupoles
  ~40 T/m
- Sextupoles
  ~2000 T/m^2
- Octupoles
  ~30000 T/m^3

Nonlinear Optics



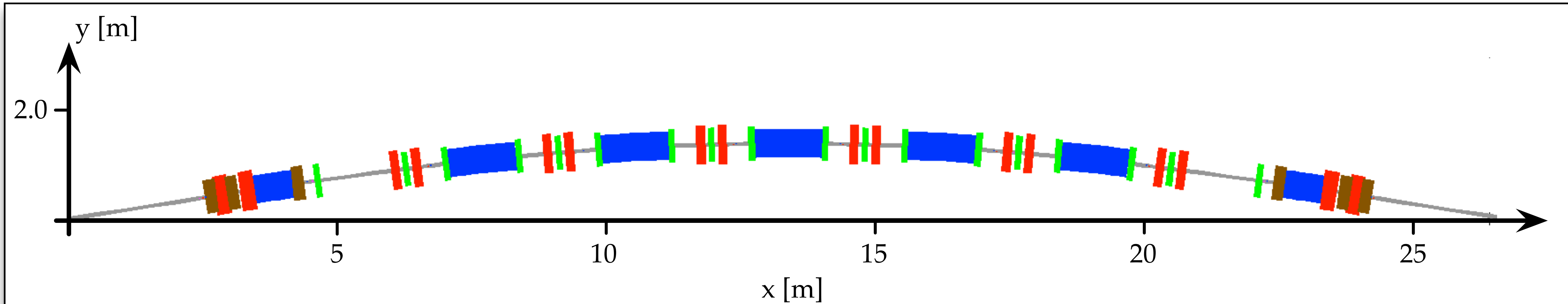
$\xi_x = -50.0$

$\xi_y = -50.2$

Cell phase advance:

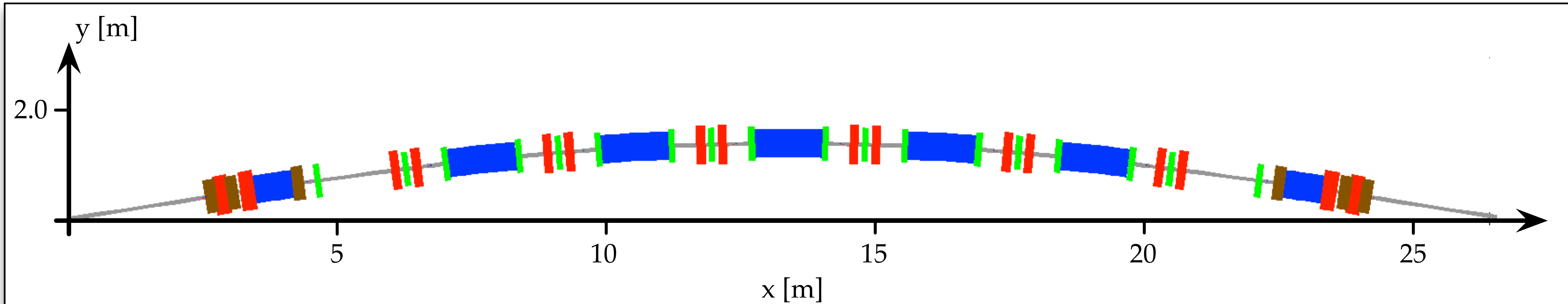
$\approx 2\pi\times(2;3/4)$

Nonlinear Optics



- Large natural chromaticity
- Correct with strong chromatic sextupoles (low dispersion)
- Adjust sextupoles correction (5 families) to minimize RDTs (SVD & weighting, OPA, Tracy-3)
- But... strong sextupoles give rise to large ADTS

Nonlinear Optics

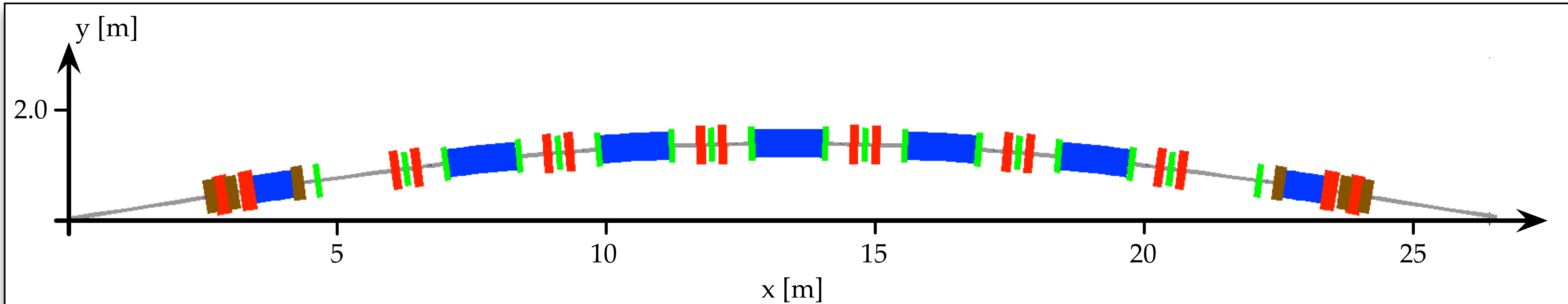


- Dispersion-free octupoles
  - correct ADTS to first order (instead of 2nd-order correction with sextupoles and possible run-away issues)

PRST-AB **14**, 030701 (2011)

- Efficient use of octupoles for ADTS correction frees up sextupoles for chromatic corrections while minimizing 1st-order RDTs

Nonlinear Optics



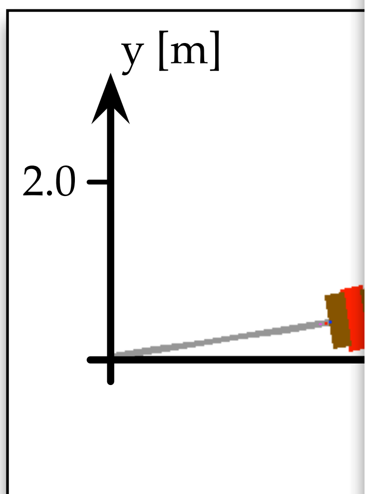
- Optimization objectives:

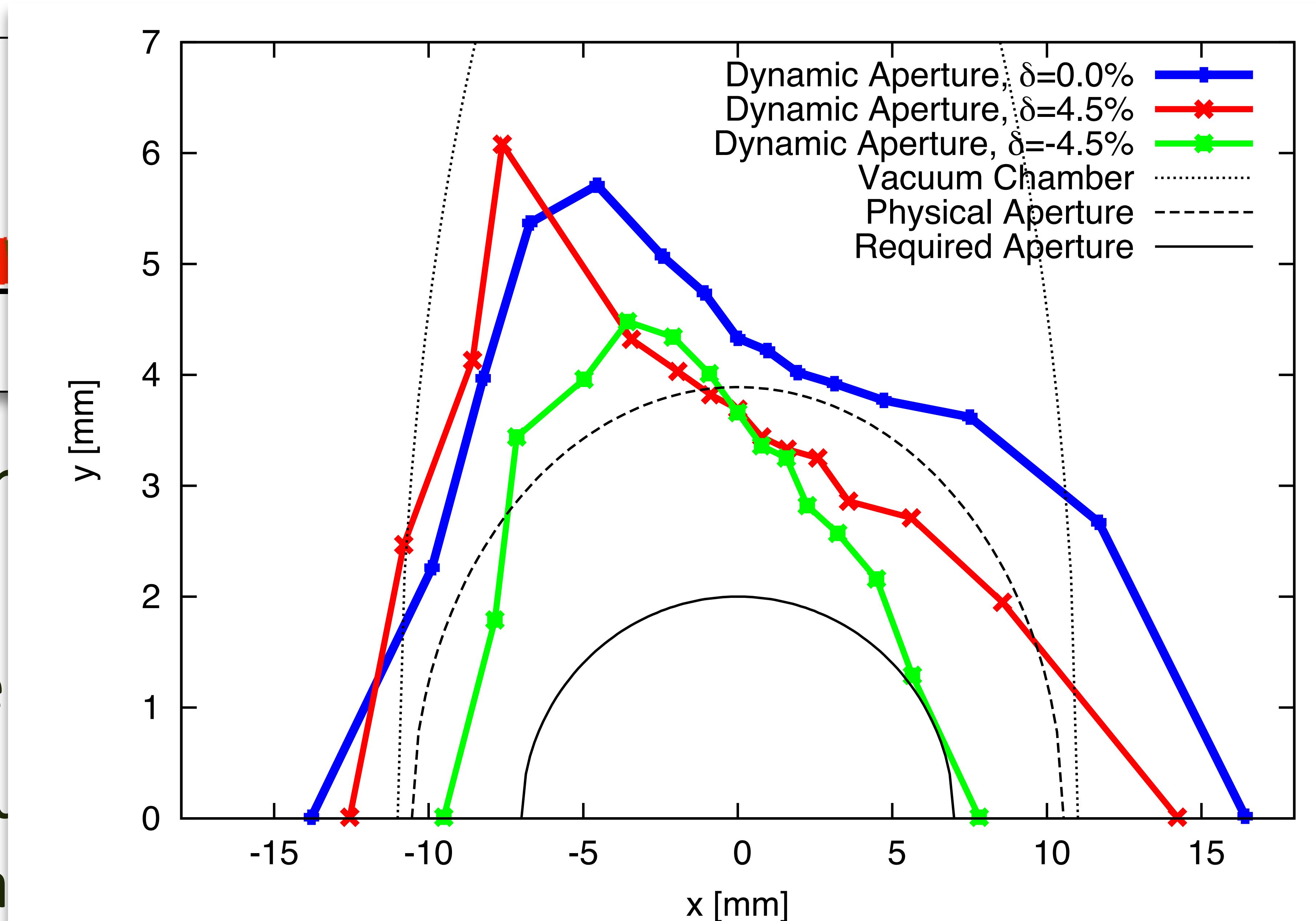
PRST-AB **14**, 030701 (2011)

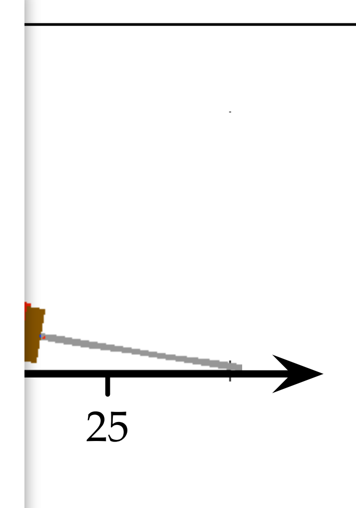
  – set 1st-order ADTS terms to minimize overall ADTS over as much of physical acceptance as possible
  – adjust higher-order chromaticities (→ decapoles?) to wrap up chromatic tune shift around WP

➡ minimize tune footprint → large DA on&off mom.

Nonlinear Optics







B **14**, 030701 (2011)

- Opti
  - –set … TS
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  - –adju … ?) to
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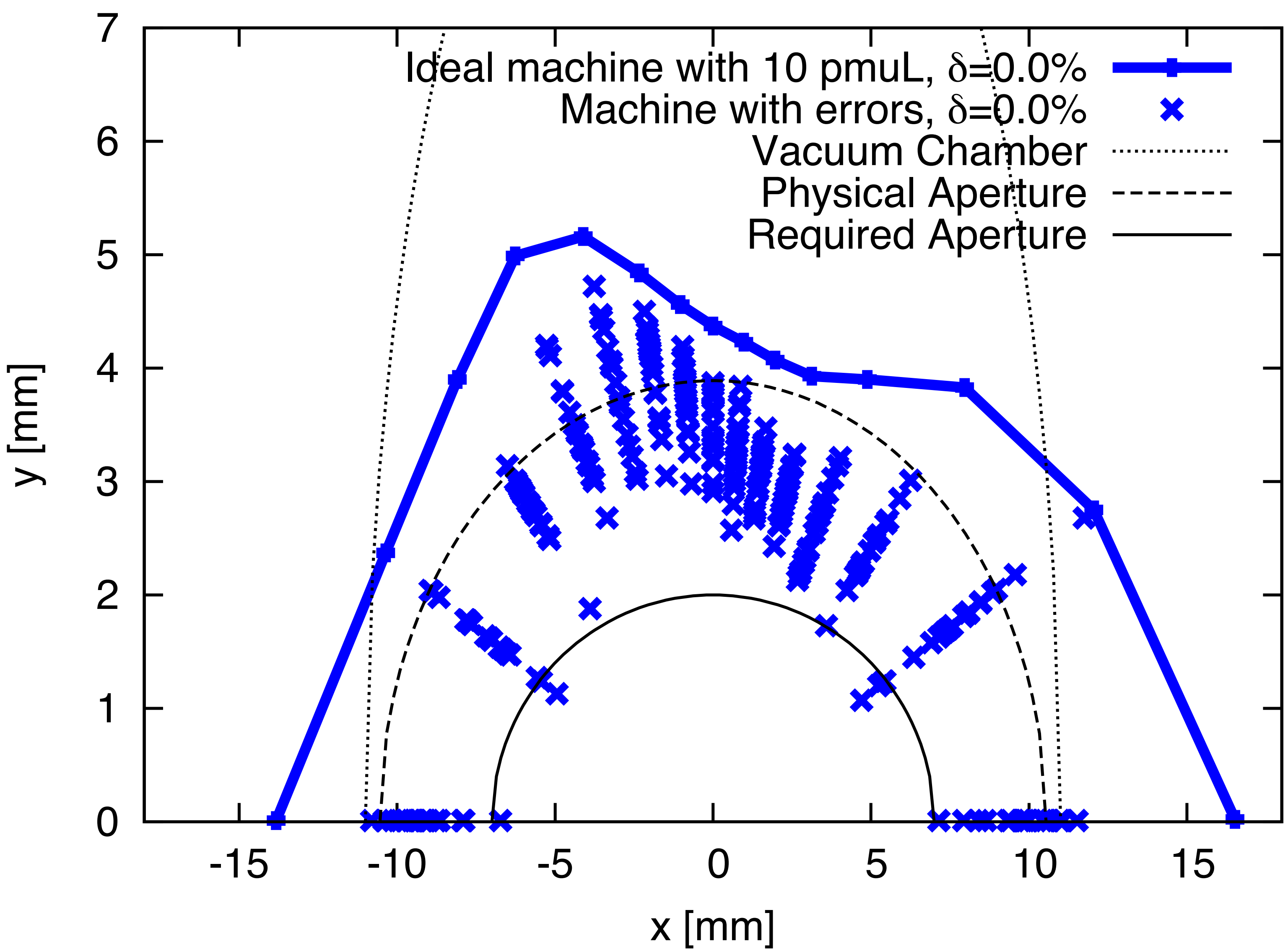
➡minimize tune footprint → large DA on&off mom.

Nonlinear Optics

- DA is stable under influence of IDs & errors

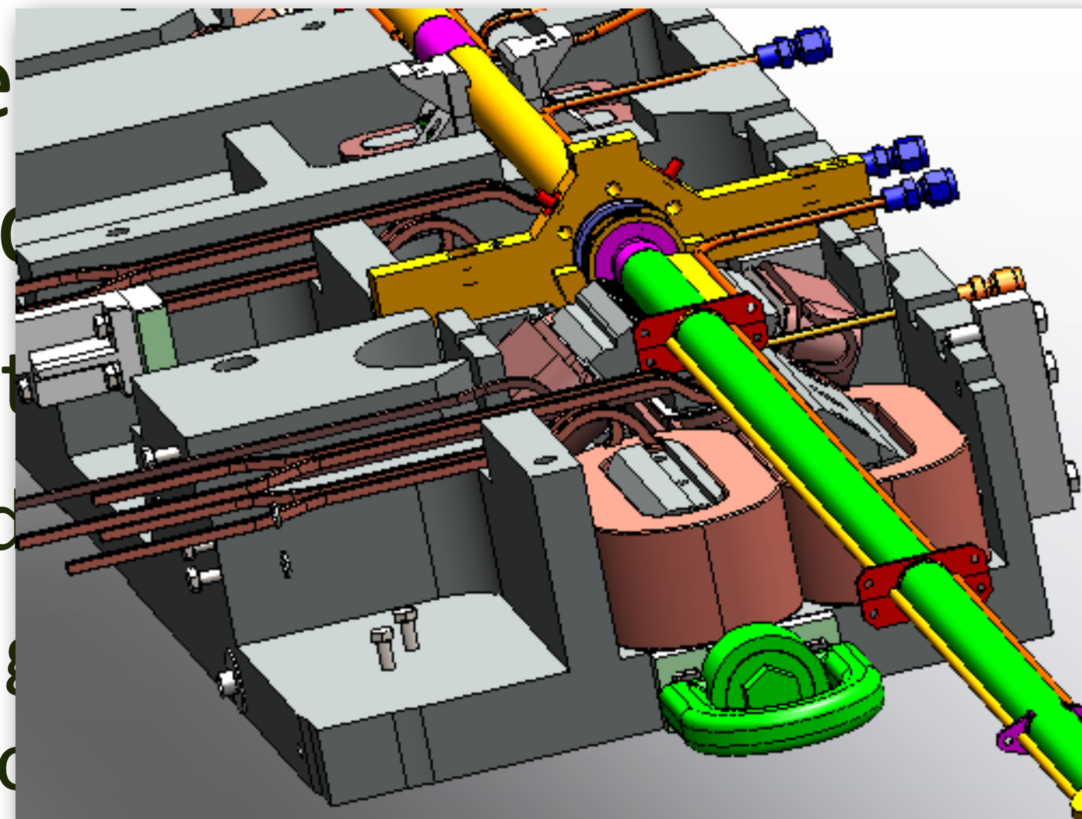


- IVU "pmuL":
  3.7 m long, 1.1 T peak field,
  18.5 mm period, 4.2 mm gap
- Misalignments:
  50 μm rms H/V
  0.2 mrad rms roll } for each magnet block
  25 μm rms H/V
  0.2 mrad rms roll } for all magnets within
- Field Errors:
  0.05% rms within each family
- Multipole Errors:
  Upright and skew multipoles added

Extra Ingredients: Making the MBA Lattice Work

- Small magnet bores (~25 mm) in order to achieve required gradients → compact optics
  - but this limits vacuum aperture
    - doesn't lead to MA problems because of low dispersion
    - but pumping cross-section limited & insufficient space for pumps, absorbers, antechambers, etc.

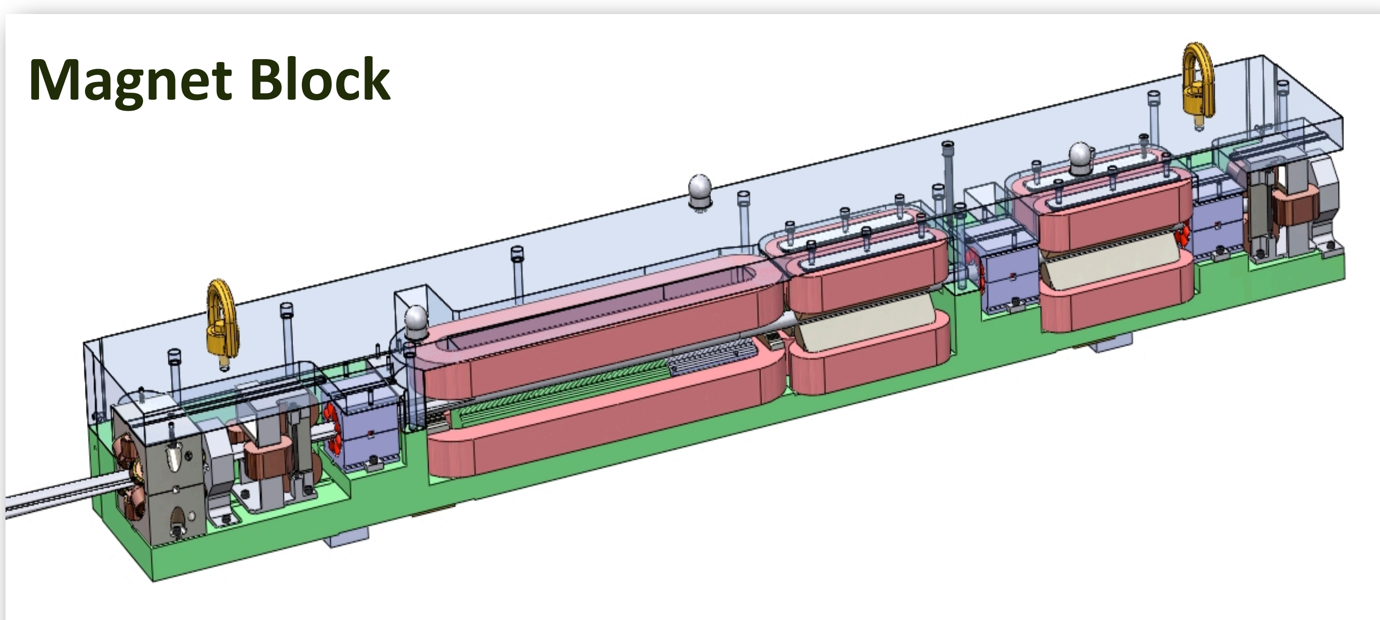
Extra Ingredients: Making the MBA Lattice Work

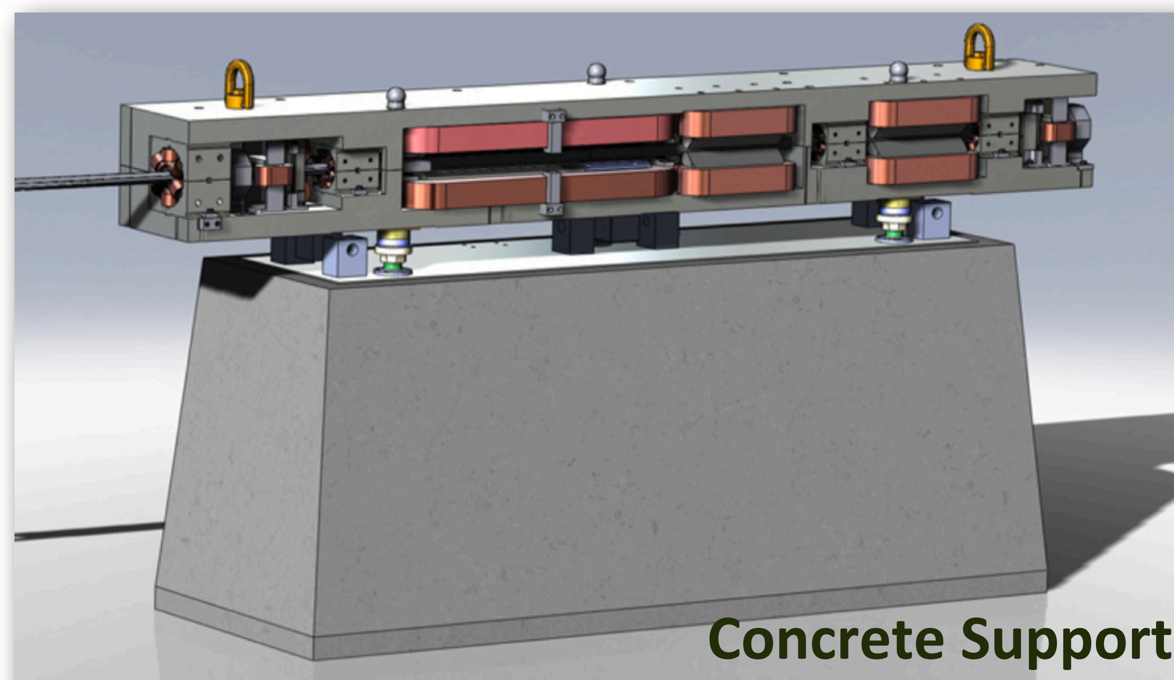
- Small magne der to achieve
  required grac s
  
  - but this limit
    - doesn't leac low dispersion
    - but pumpin fficient space for
      pumps, absc
- Instead, linear pumping through slim NEG-coated Cu chamber with external cooling channel
  - ➡Eshraq Al-Dmour's presentation

Extra Ingredients: Making the MBA Lattice Work

- Many small magnets machined from a common solid iron block installed on massive concrete supports → alignment & stability

➡Martin Johansson's presentation





Extra Ingredients: Making the MBA Lattice Work

- 500 mA in 176 bunches @ ~300 pm rad, narrow Cu chamber → worry about Touschek lifetime, instabilities, collective effects, IBS, ...
  - very long bunches thanks to
    - 100 MHz main RF system → Mikael Eriksson's presentation
    - Landau cavities at the third harmonic stretch bunches by up to a factor 5 → increases Touschek lifetime

Extra Ingredients: Making the MBA Lattice Work

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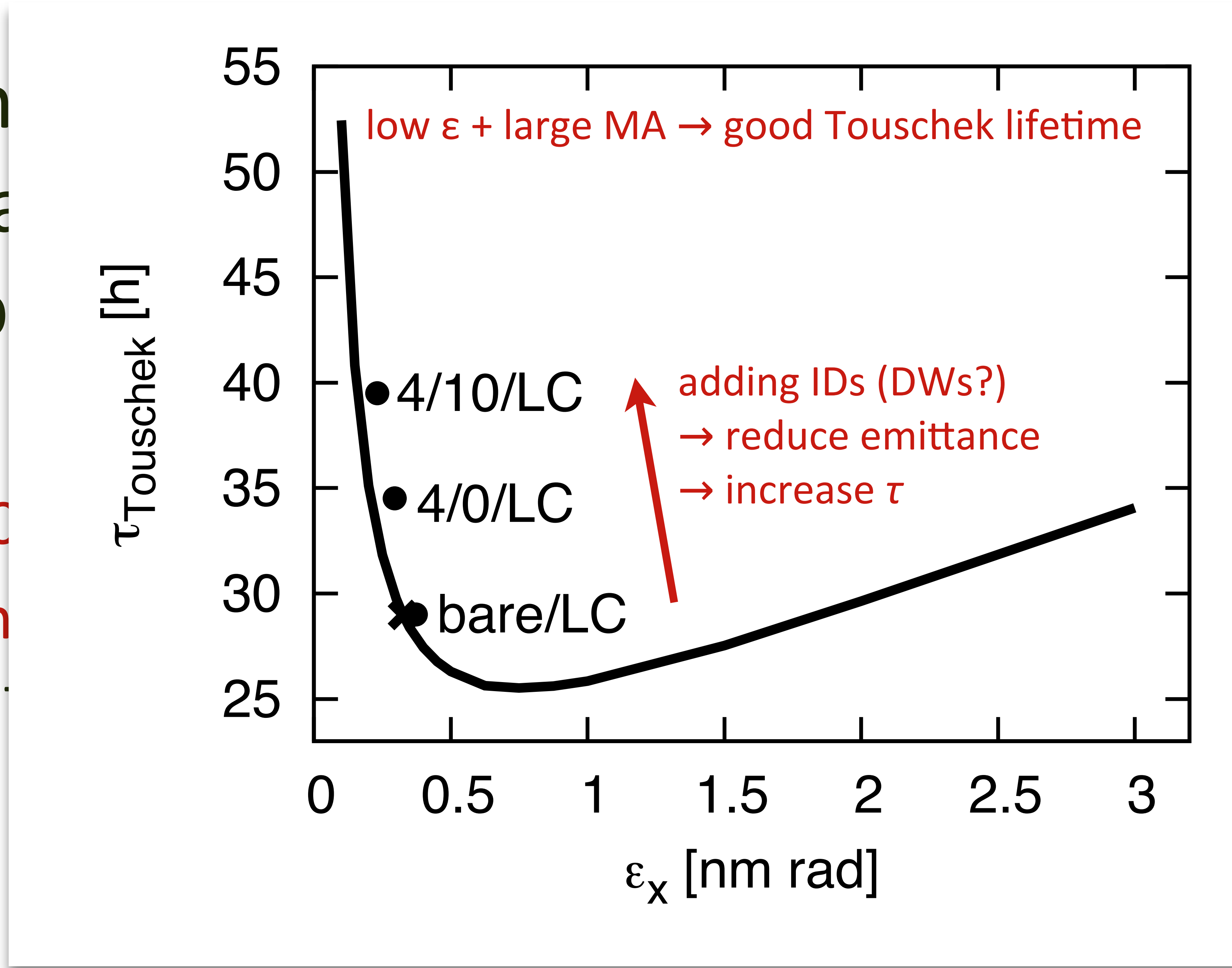
  - –very
    - 100 … sentation
    - Lan … ches by up



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    - Landau cavities at the third harmonic stretch bunches by up to a factor 5 → increases Touschek lifetime
  - bunch lengthening also enables us to cope with strong IBS: emittance blowup due to IBS @ 500 mA reduced from ~42% to ~11% with Landau cavities

PRST-AB **12**, 120701 (2009)