ALS-U: Ideas for a Novel 7BA Lattice Using Longitudinal Gradient Bends & Reverse Bends

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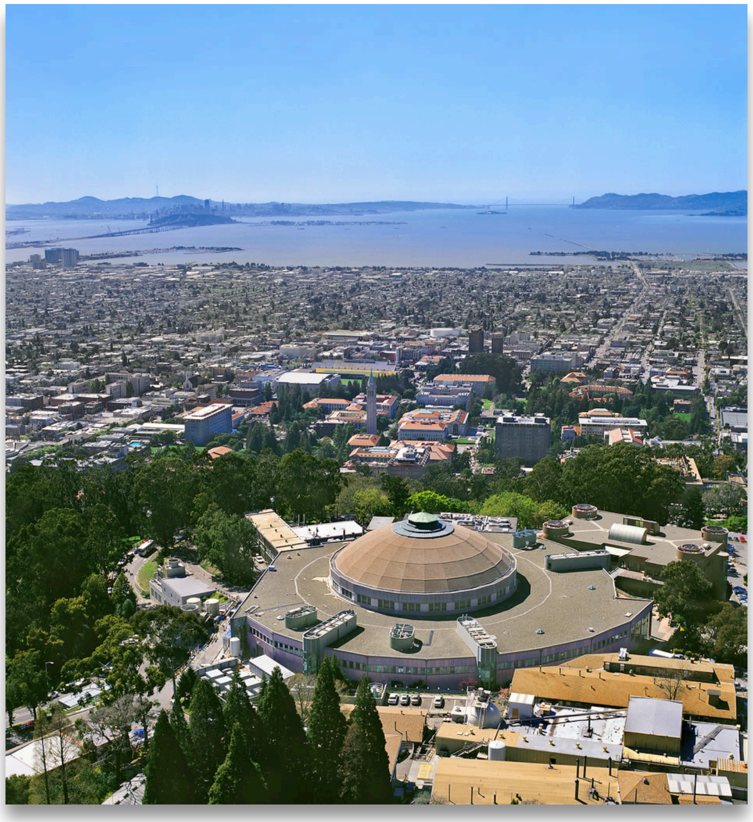
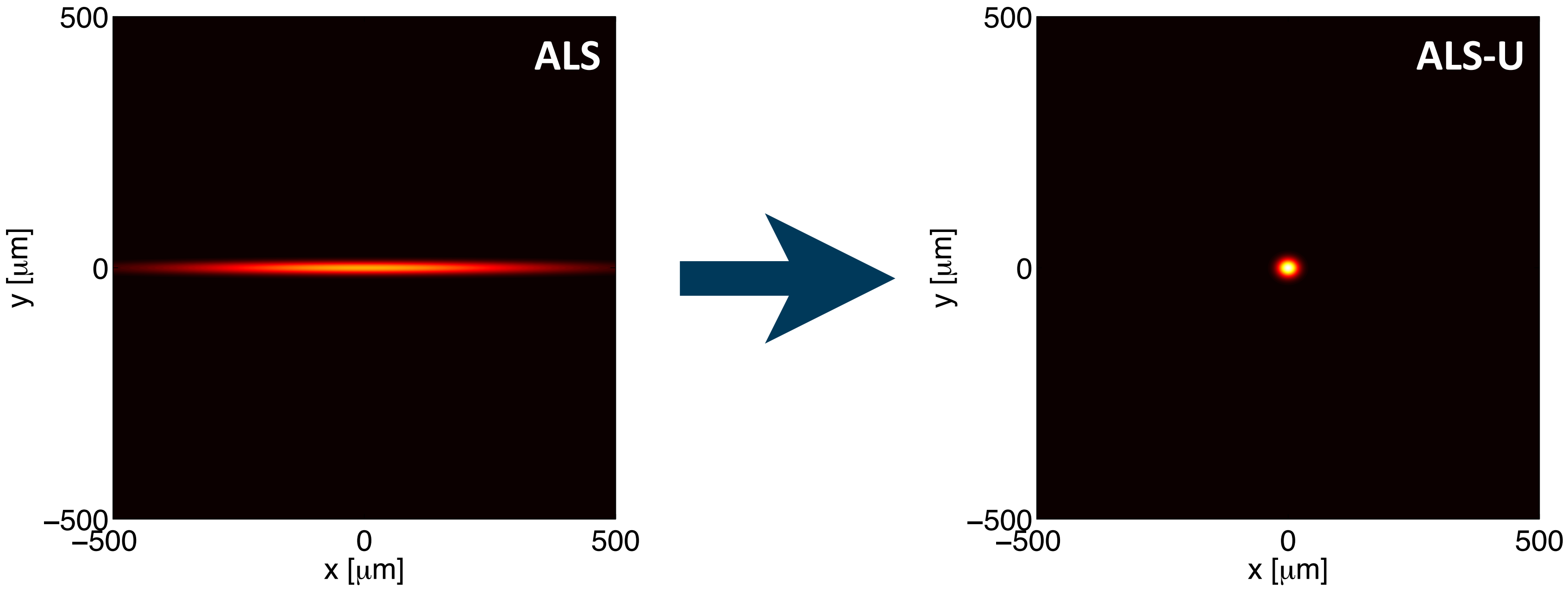
ALS-U ADVANCED LIGHT SOURCE

Setting the Scene: ALS-U Goals

- ALS-U is a MBA-based upgrade of the 25 year old ALS
- ALS until most recently the world's brightest SXR source at 2 keV
- ALS-U is a diffraction-limited SXR source delivering ultra-bright, coherent, and round photon beams within the existing ALS hall





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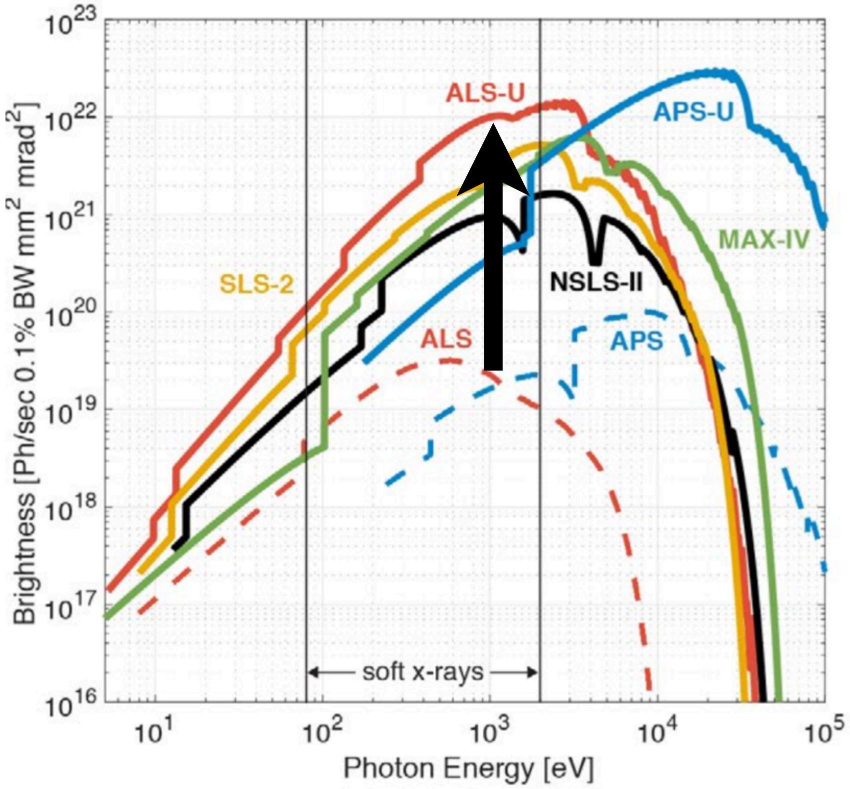
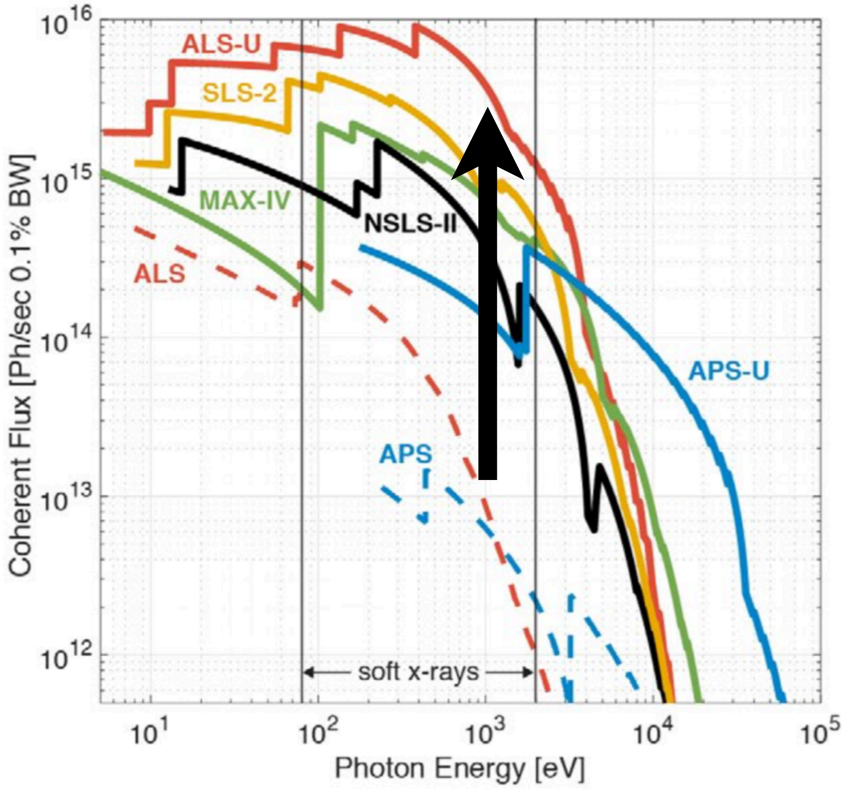
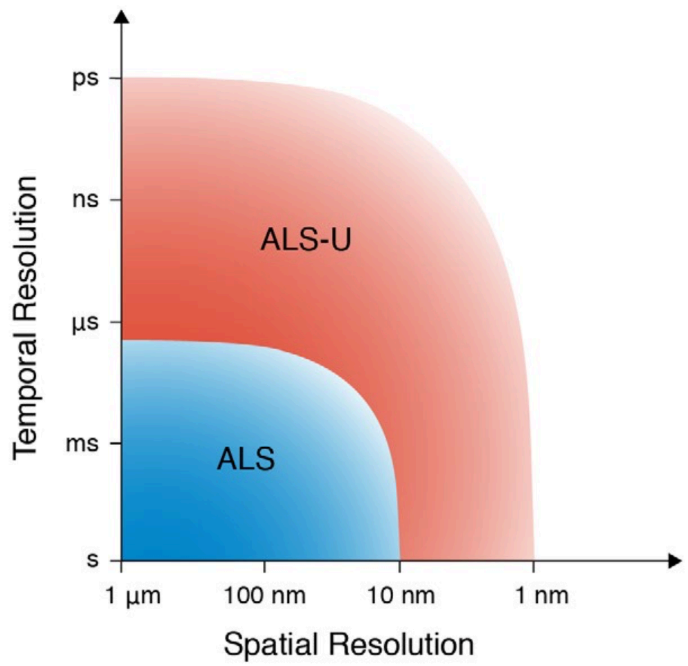




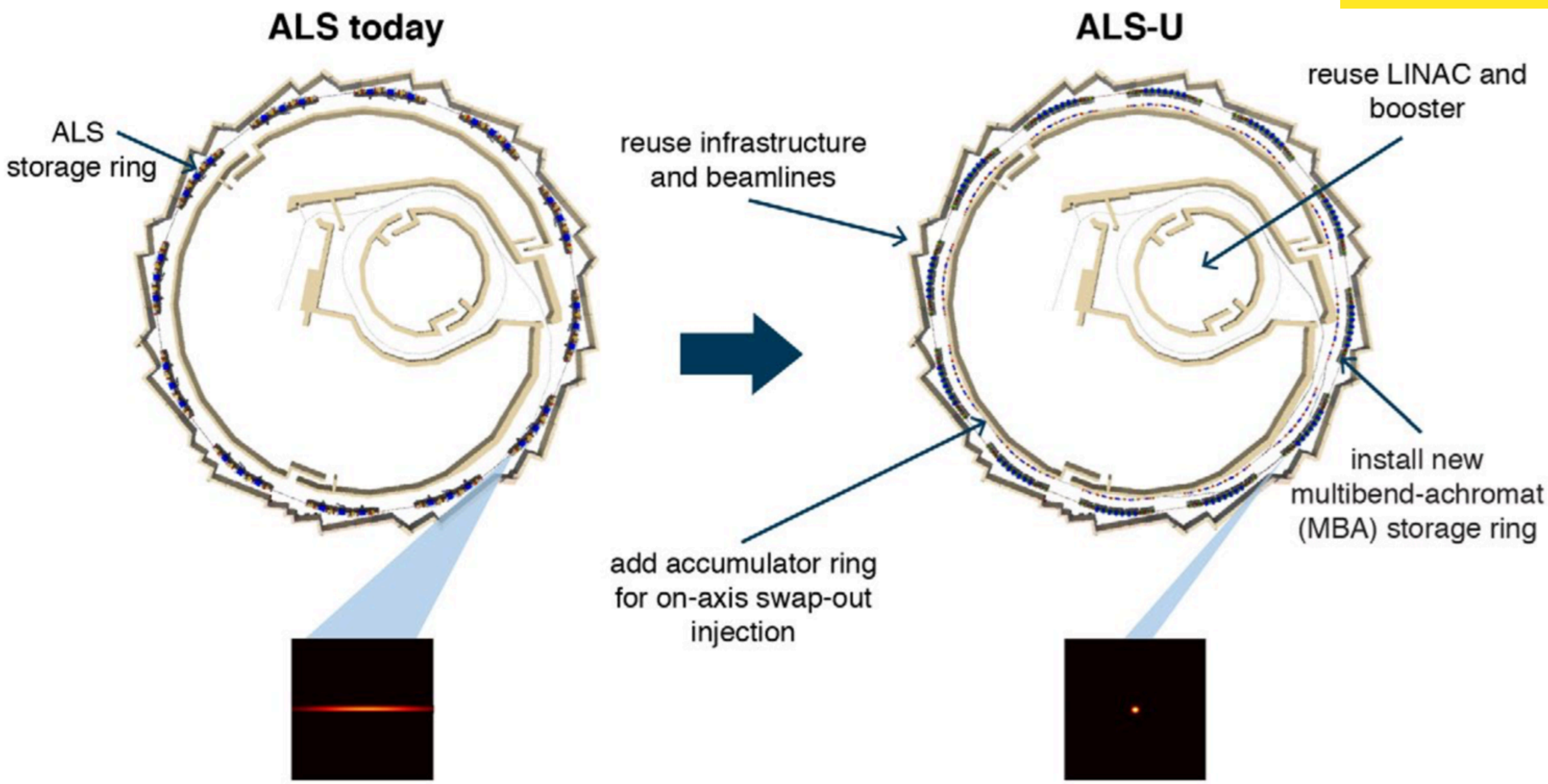


Over ×100 in brightness *and* coherent flux @ 1 keV

Setting the Scene: Baseline Lattice v20r

- ALS-U baseline calls for 2 GeV, 500 mA, and <75 pm rad (in both planes @ full coupling) inside the existing ALS tunnel (<200 m circumference)

IPAC'17, WEPAB104, p.2824



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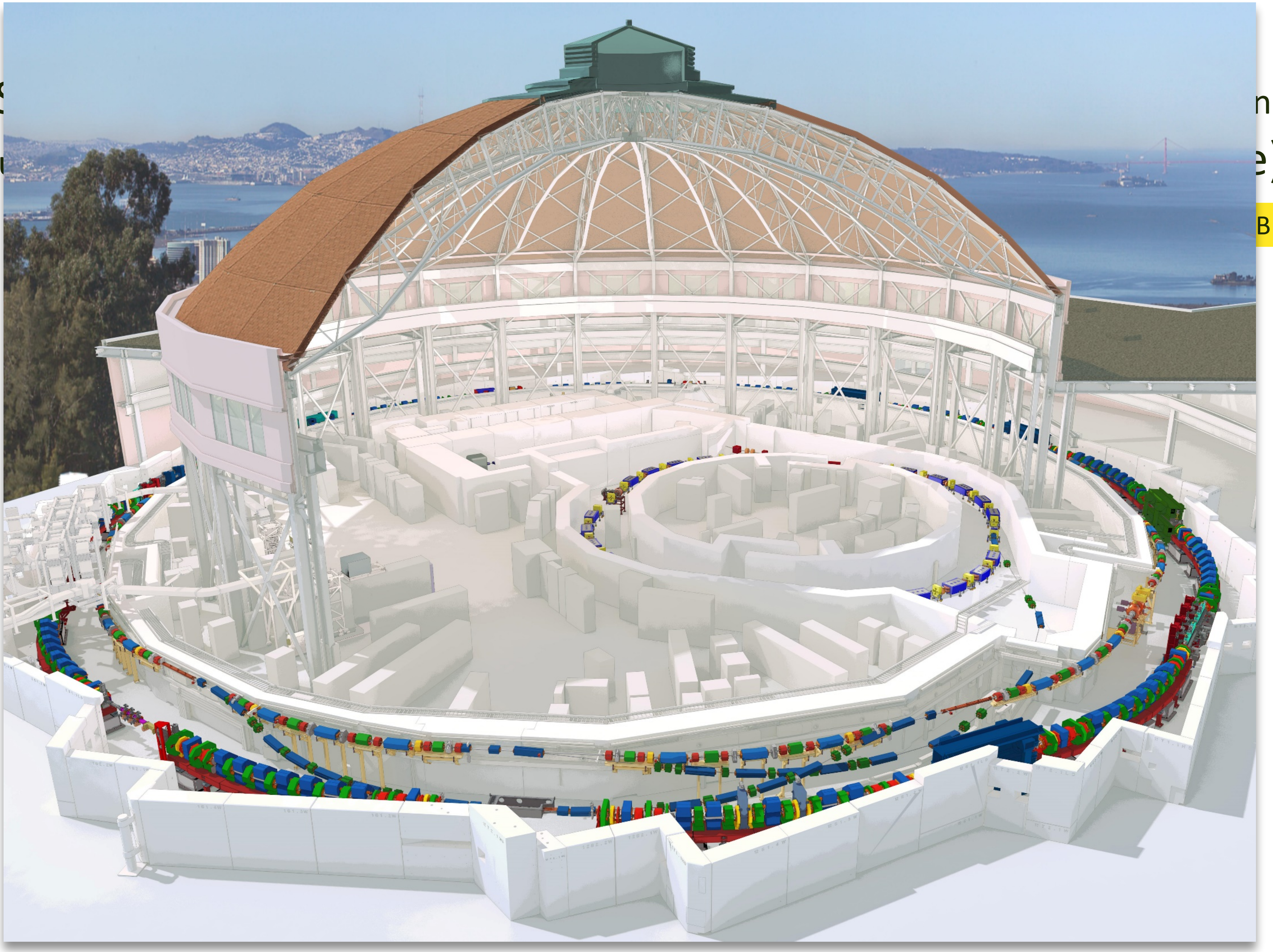
B104, p.2824



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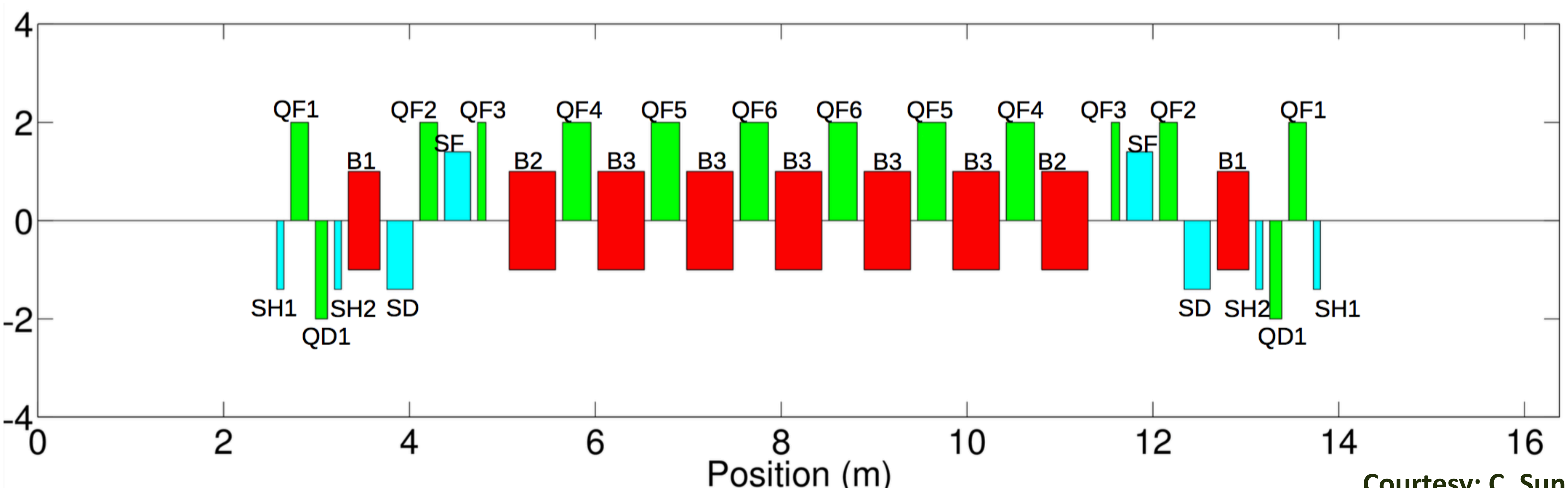
IPAC'13, MOPEA008, p.79



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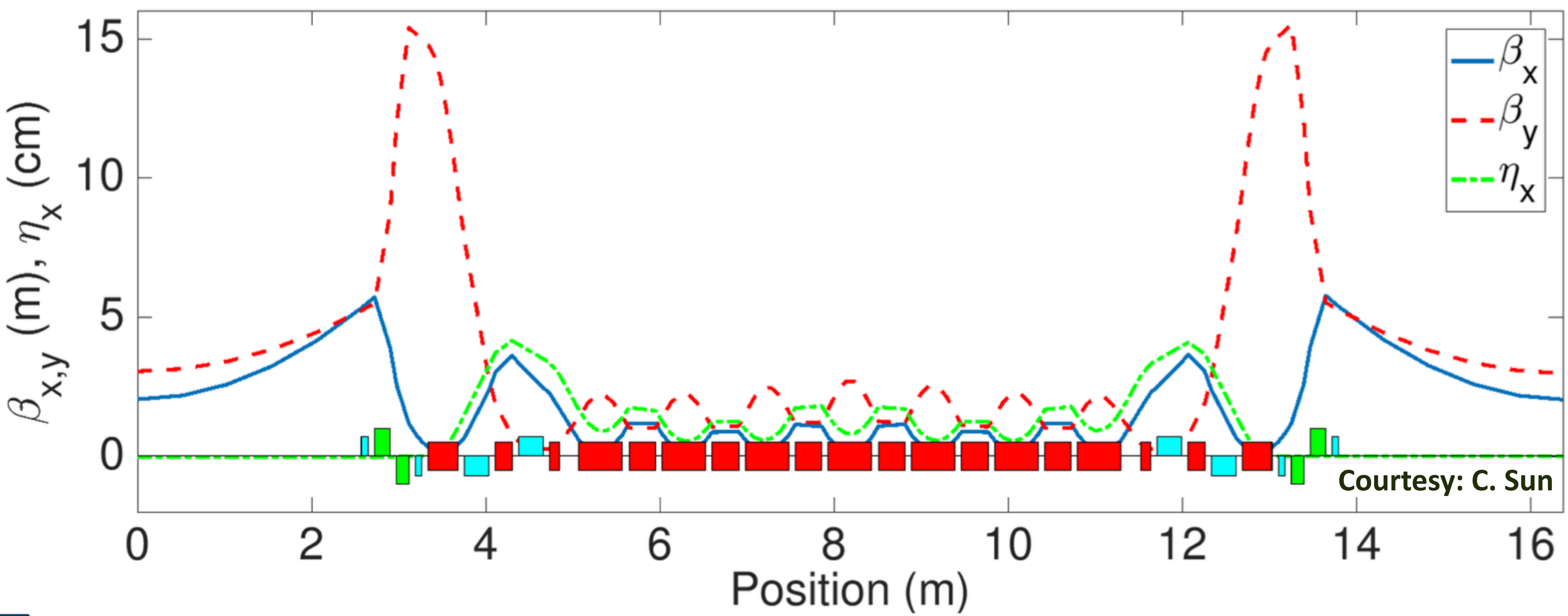
IPAC'17, WEPAB105, p.2827 **IPAC'13**, MOPEA008, p.79



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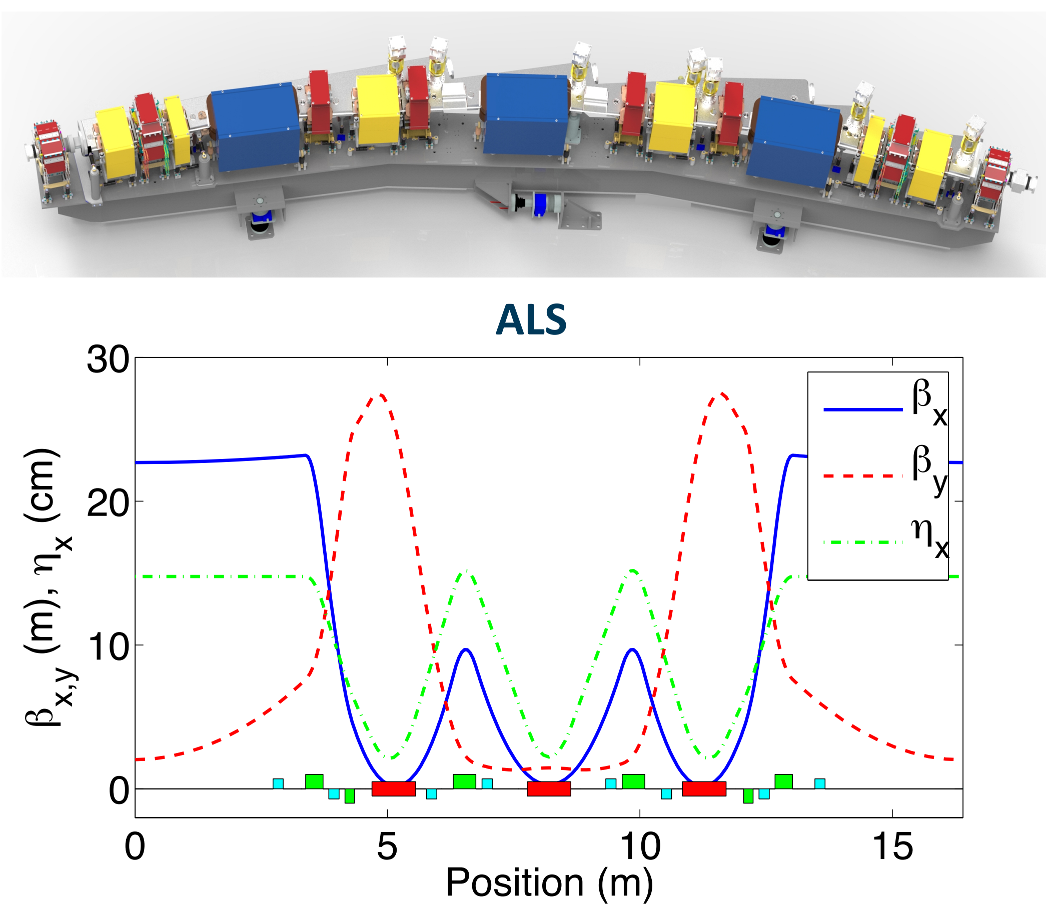
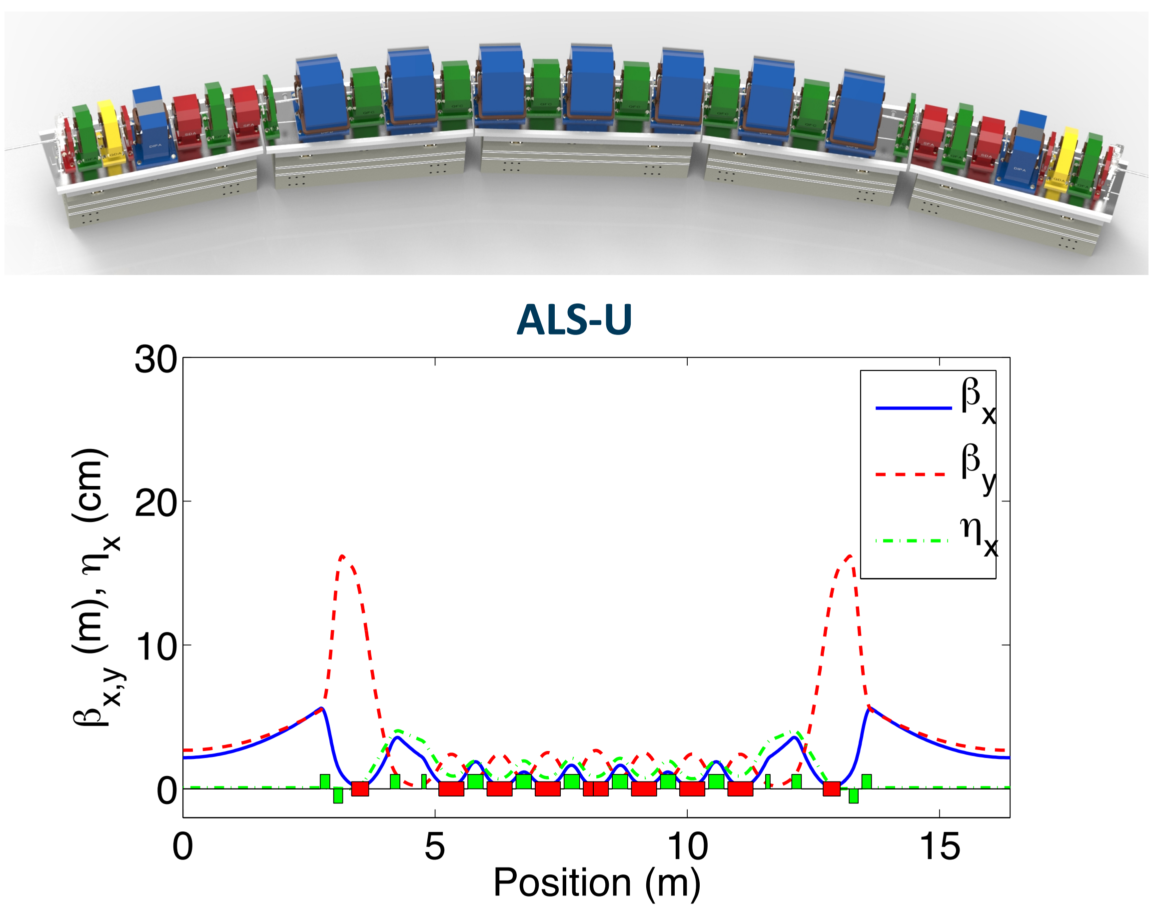
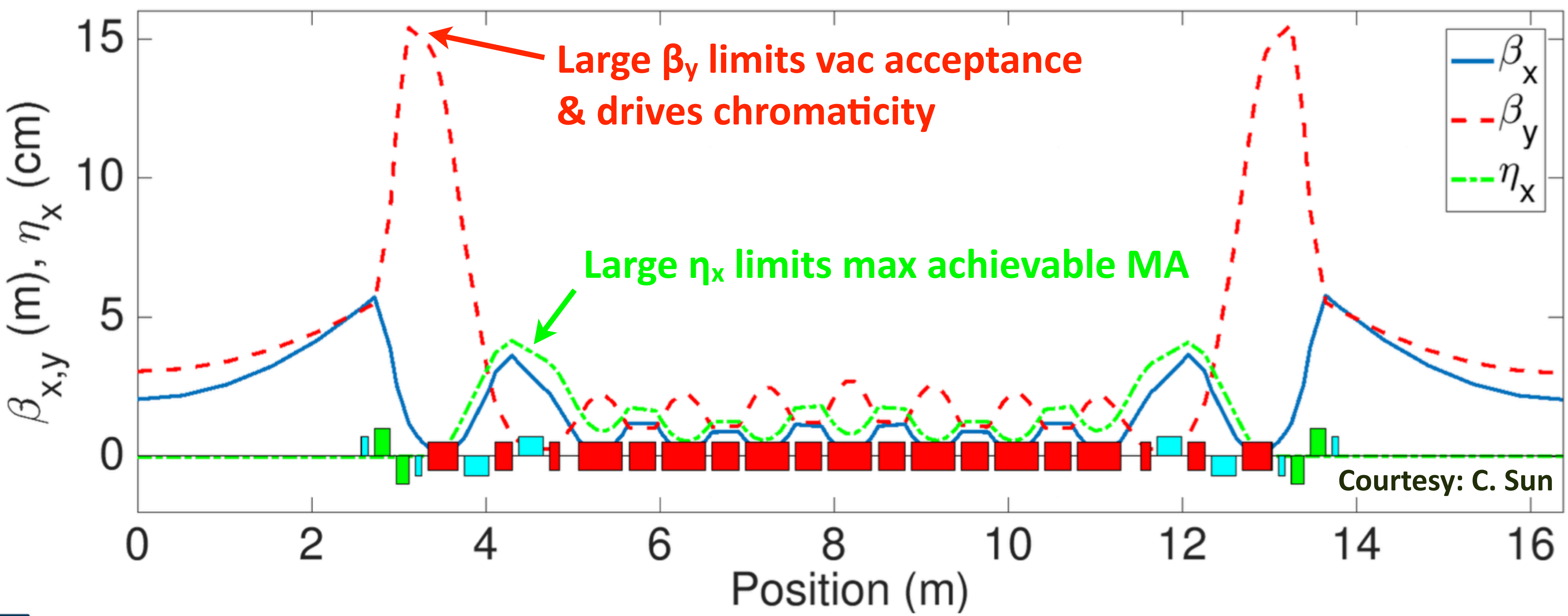




Setting the Scene: Baseline Lattice v20r (cont.)

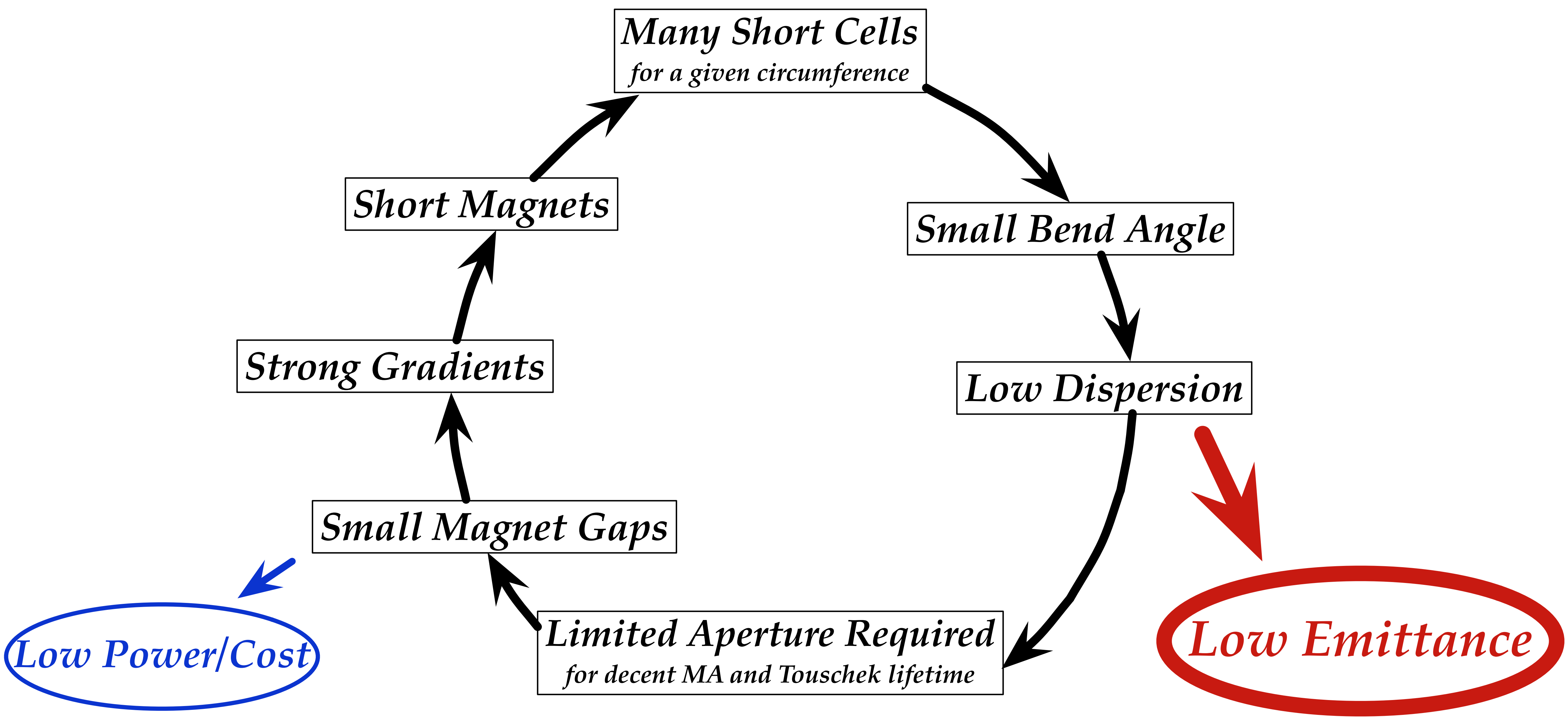
- But this kind of ultra-high brightness approach comes at a price:
  - **Strained linear optics** ➔ large peak β/η functions ➔ drives up nat. chromaticity and aperture requirements ➔ increases magnet gaps ➔ weakens focusing ➔ breaks MBA feedback cycle



Setting the Scene: Baseline Lattice v20r (cont.)

The Multibend Achromat Cycle

(courtesy A. Streun, PSI)



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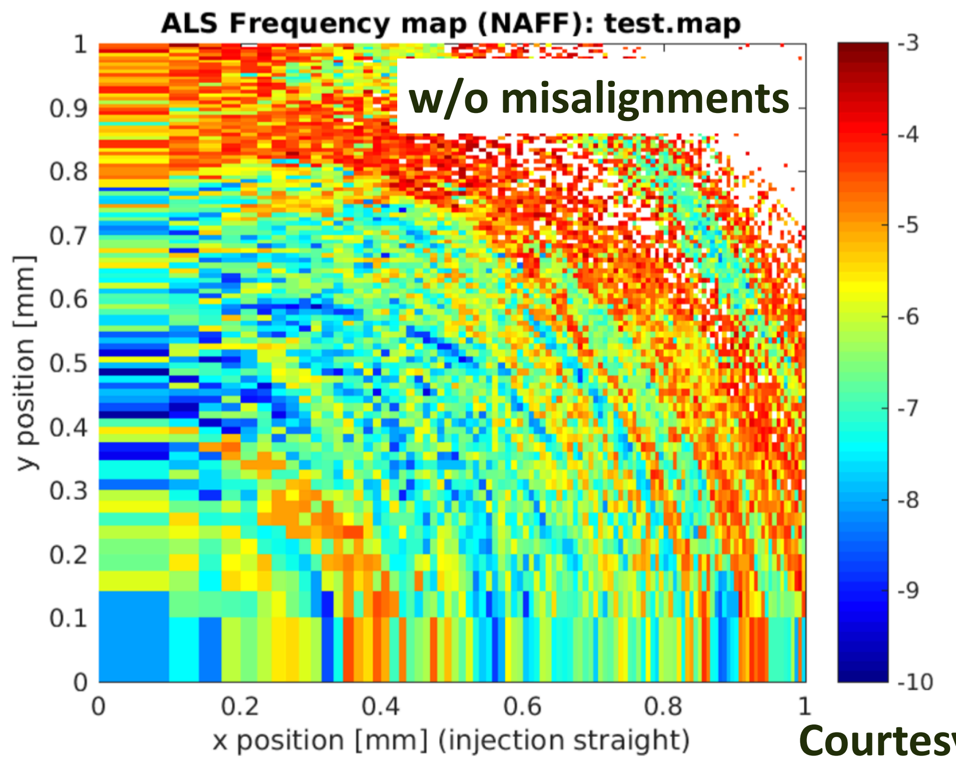
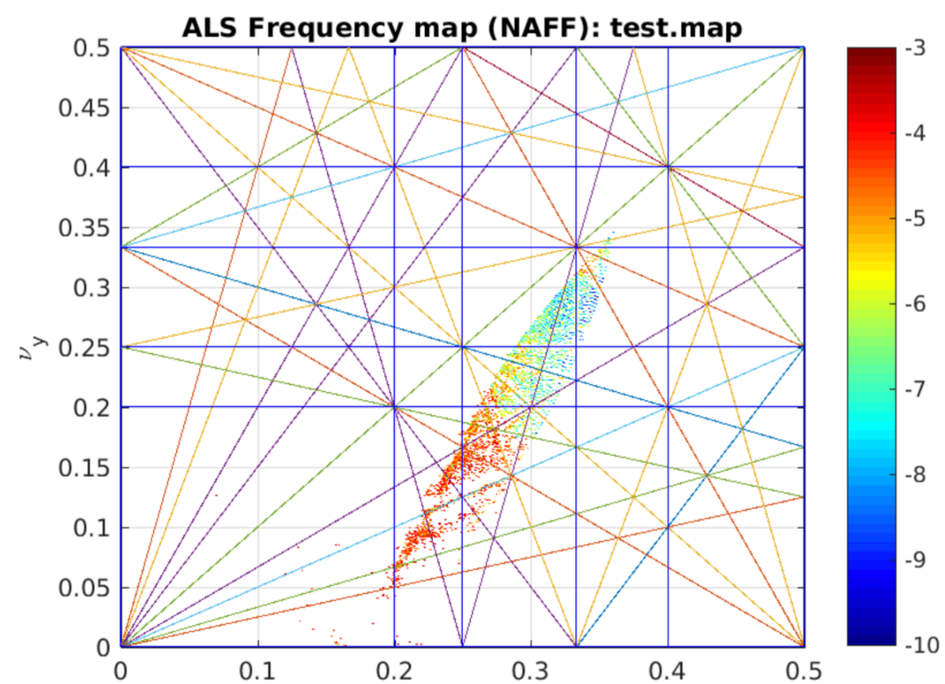
  - **Small DA**: believe can be tolerated by virtue of on-axis injection from low-emittance accumulator ring (swap-out)

~1 mm DA required for injected beam with $\varepsilon \approx 2$ nm rad, $\beta \approx 20$ m





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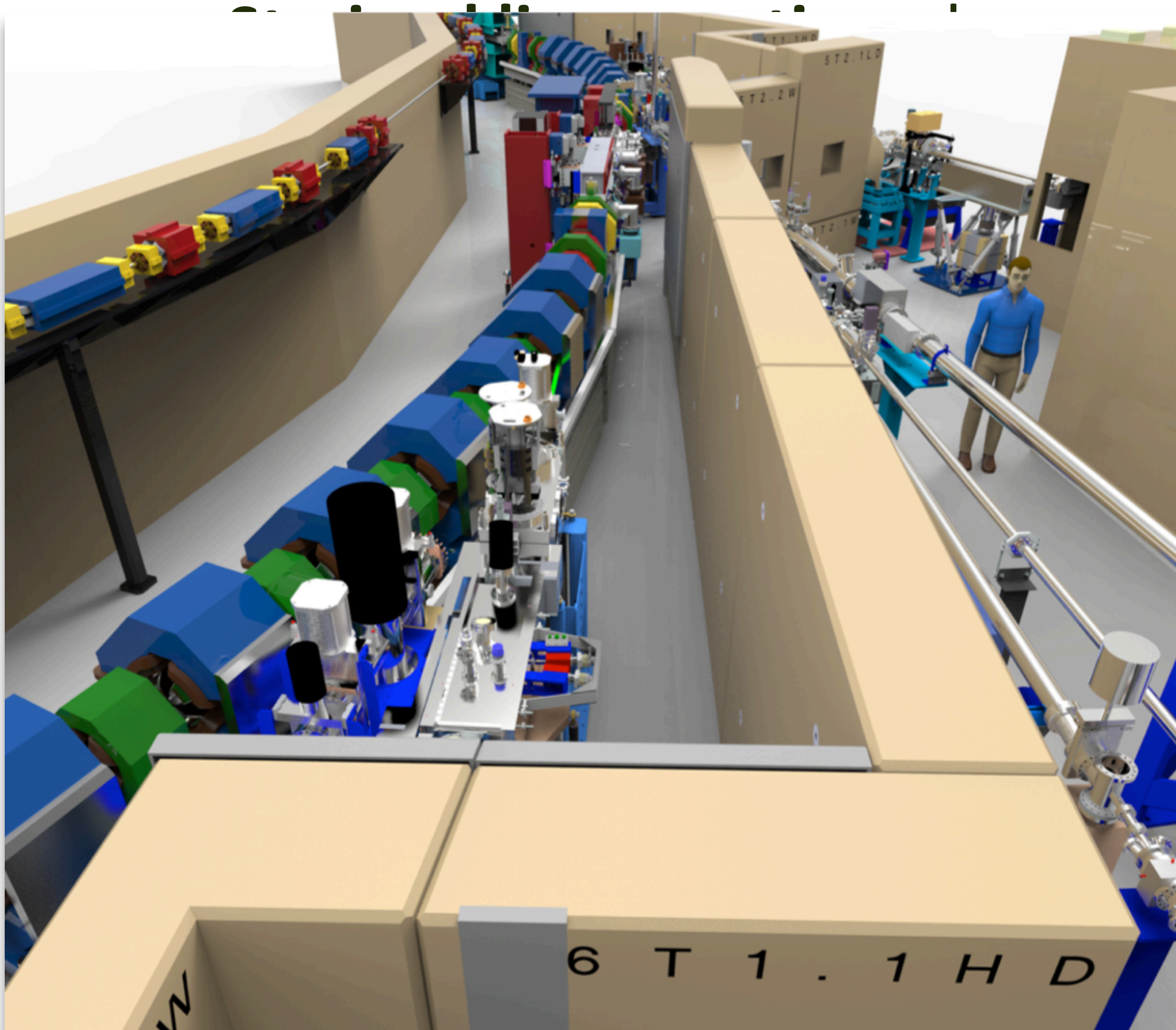

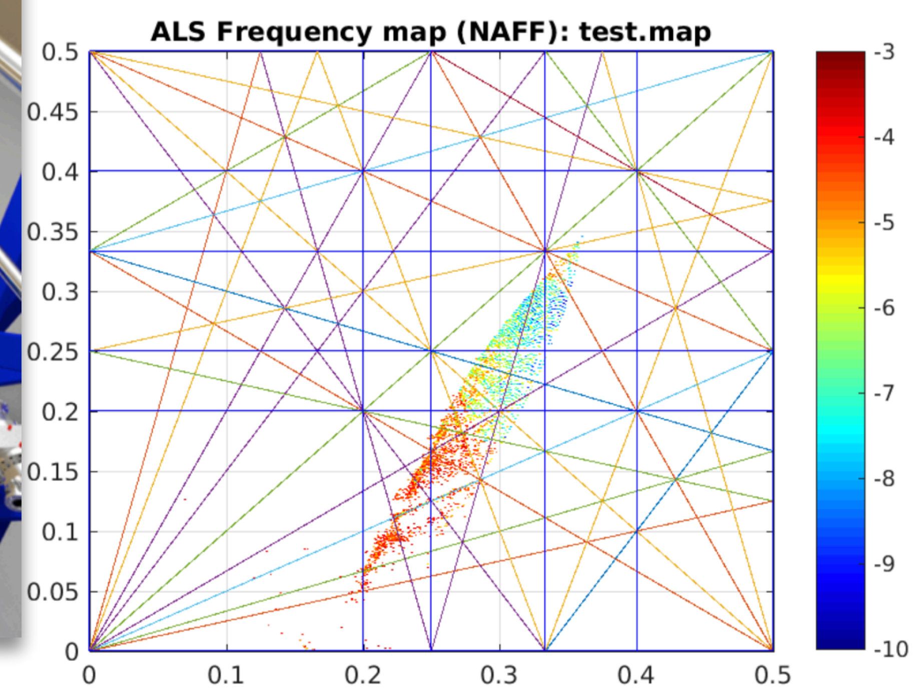

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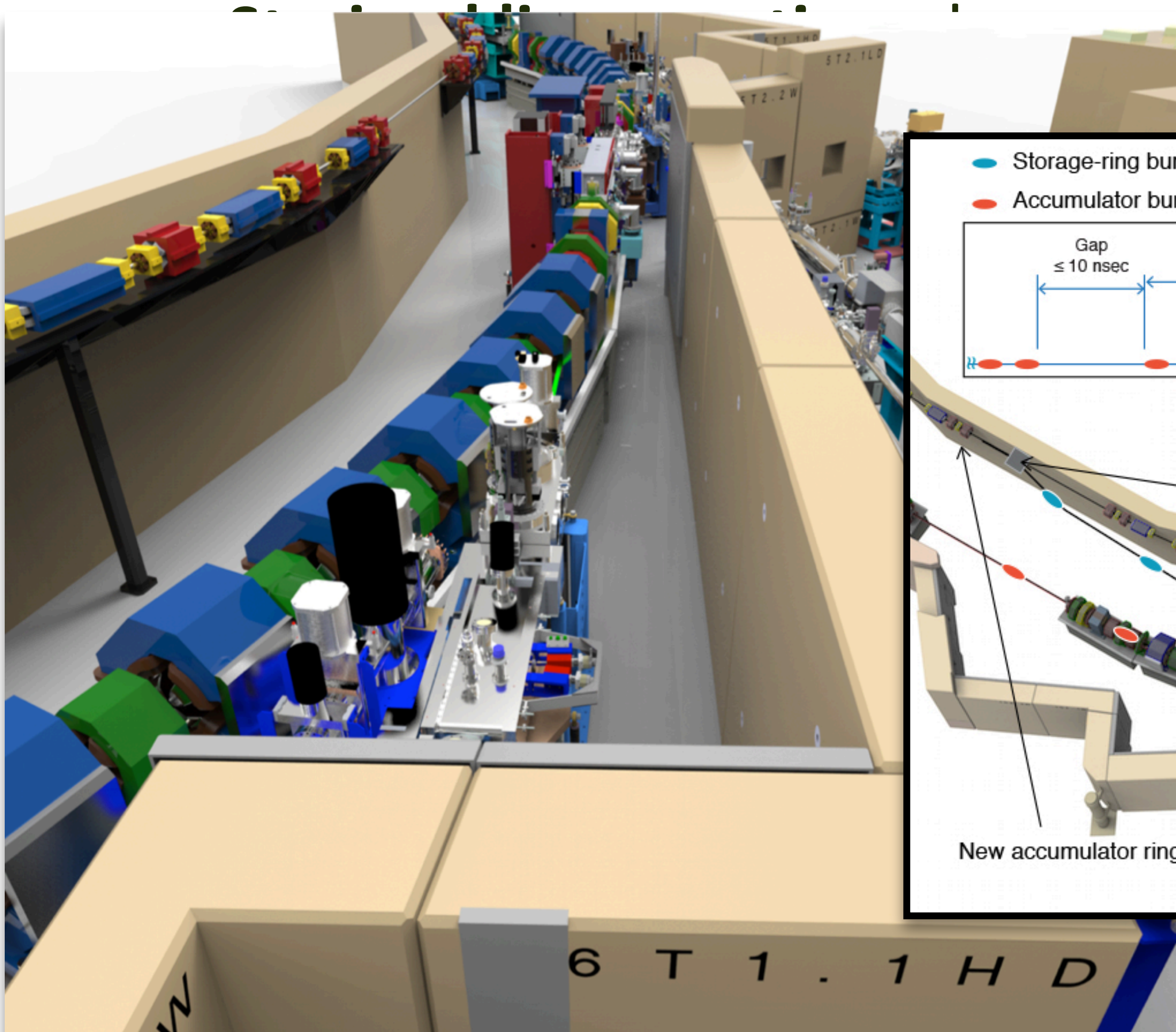

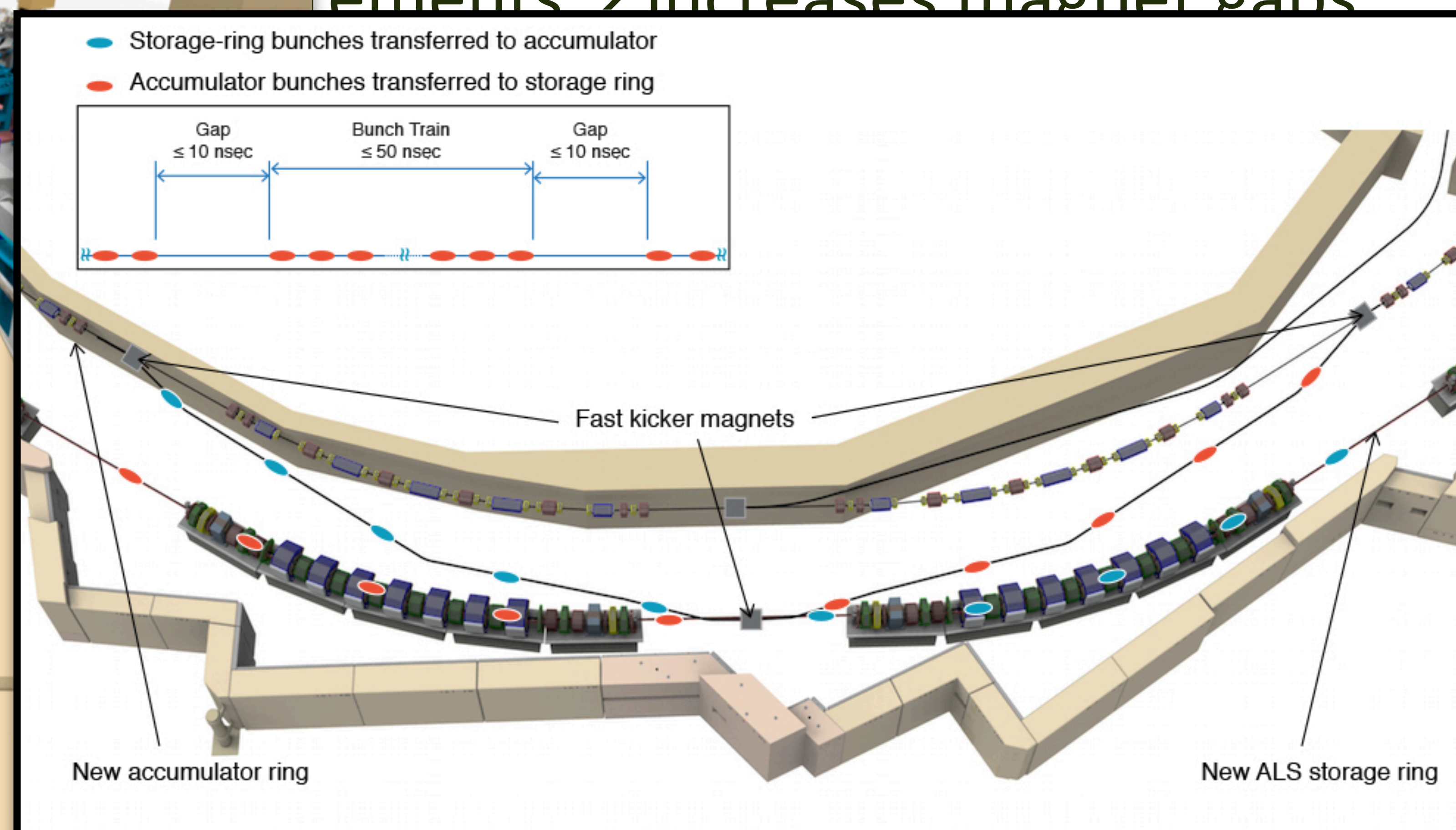

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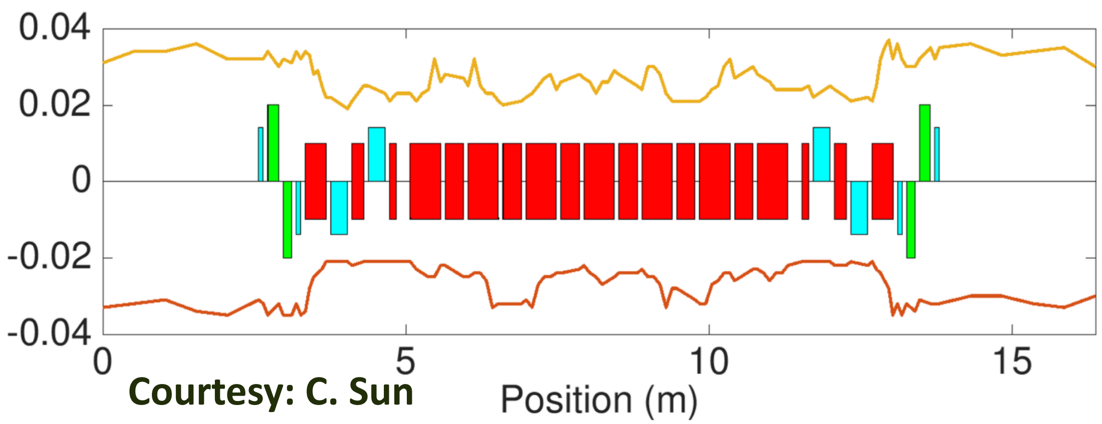
Setting the Scene: Baseline Lattice v20r (cont.)

- But this kind of ultra-high brightness approach comes at a price:
  - **Strained linear optics** → large peak β/η functions → drives up nat. chromaticity and aperture requirements → increases magnet gaps → weakens focusing → breaks MBA feedback cycle
  - **Small DA**: believe can be tolerated by virtue of on-axis injection from low-emittance accumulator ring (swap-out)
  - **Limited MA**: major problem in low-E rings where (despite potentially large RF acceptance) Touschek scattering severely limits lifetime **ALARA**
  (top off isn't silver bullet: 1 mA deadband & ≥30 s injection interval → >4 hrs lifetime required)



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$$\tau_{\mathrm{ts}} \sim \gamma^3$$

$$\delta_{\mathrm{rf}} \sim \sqrt{\frac{V_{\mathrm{rf}}}{\gamma}}$$

assuming $V_{\mathrm{rf}} \gg U_{\mathrm{loss}}$

- High-E rings get decent Touschek despite low LMA (RF acc limited so large LMA serves no purpose)
- Low-E rings need large MA to get decent Touschek (LMA needs to exceed naturally larger RF acc)

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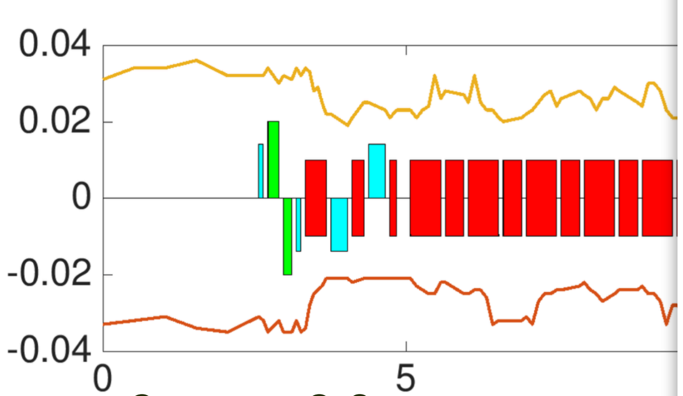

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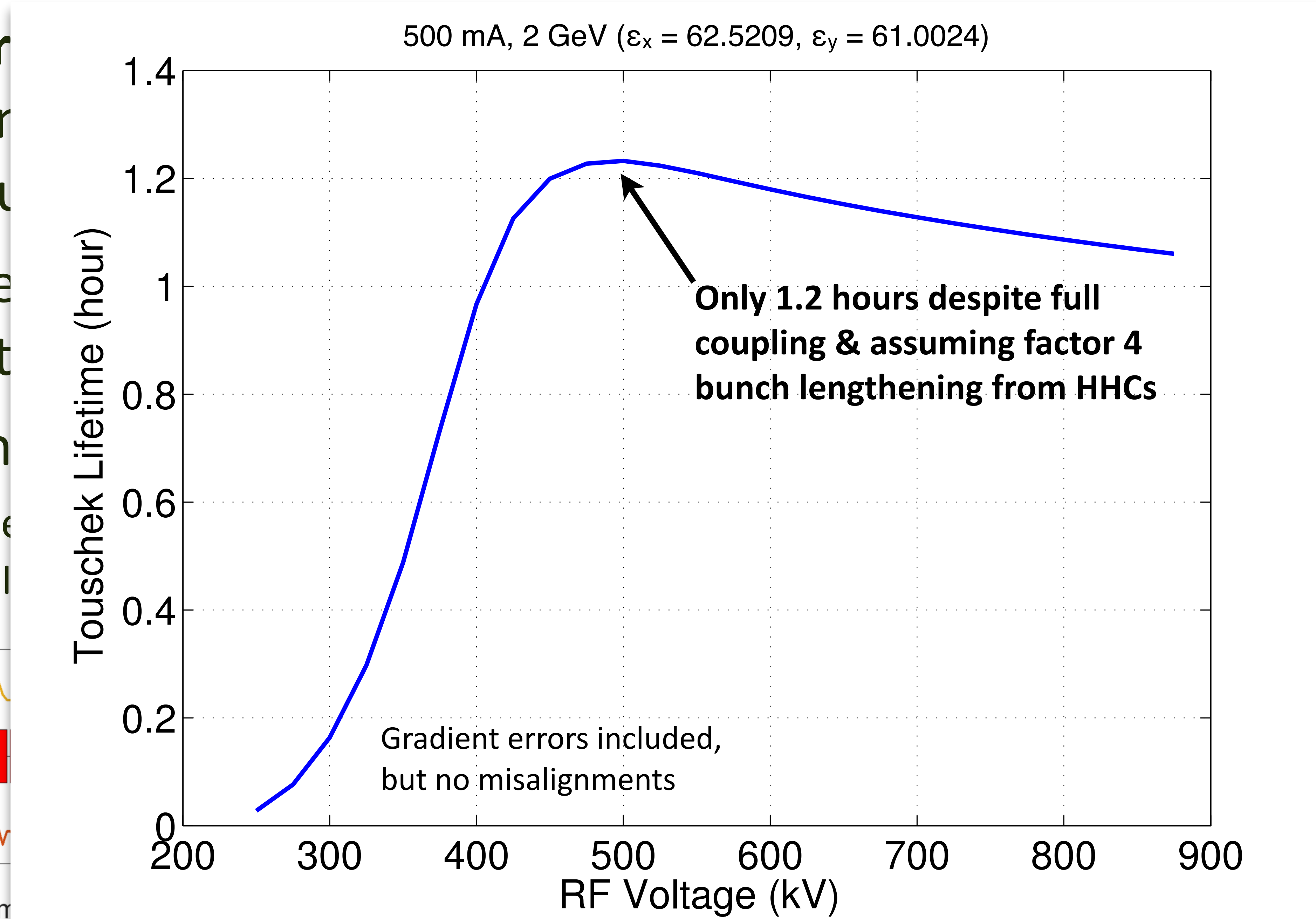



So what can we do about this?

Outline for an Alternate Design

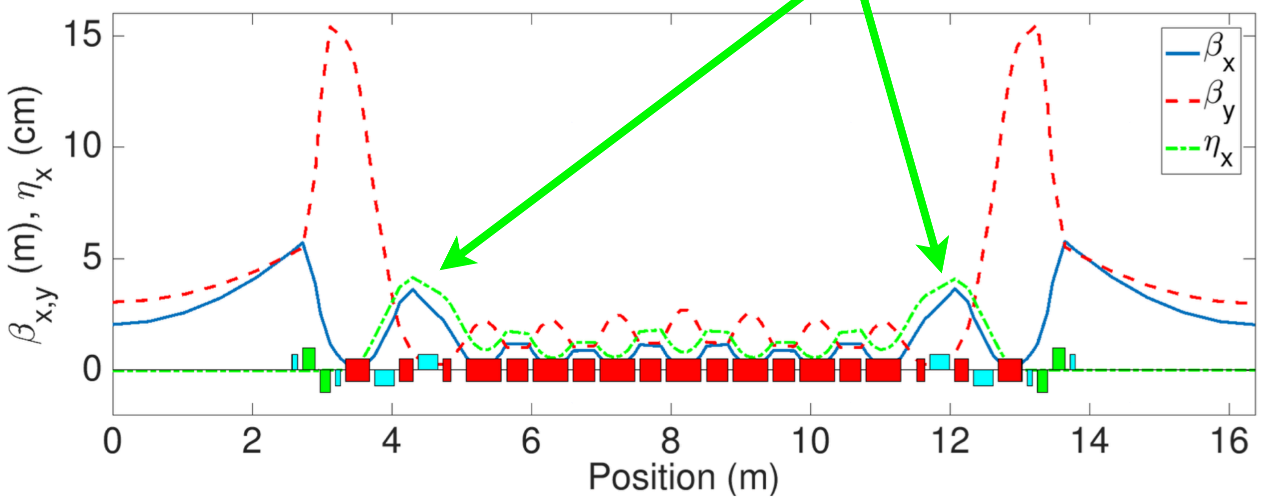
- Main problem of ALS-U baseline lattice is poor off-momentum performance resulting from excessive chromatic beating
  (even in perfect HMBA phase advance between sextupoles required for -*I* transformation breaks down off energy)
- MAX IV-style MBA

  PRST-AB **12**, 120701 (2009) PRST-AB **14**, 030701 (2011)

  – leverages distributed chromatic correction to ensure large MA
  – employs octupoles to limit tune footprint and hence maximize DA
- However, MAX IV lattice is too relaxed to meet ALS-U target emittance
  (scaled to energy & circumference: 2850 pm rad) ➔ push to its limits by
  – adding longitudinal gradients to the dipoles
  – leveraging reverse bending to minimize emittance (within limits set by momentum compaction deemed acceptable)
  – tuning linear optics of the unit cell so that overall MBA sector becomes higher-order achromat (geom. aberrations / RDTs minimized within)

Unit Cell Design – Baseline vs. New

- ALS-U Baseline 9BA: 2× dispersion bumps + 7× TME-like bend cells



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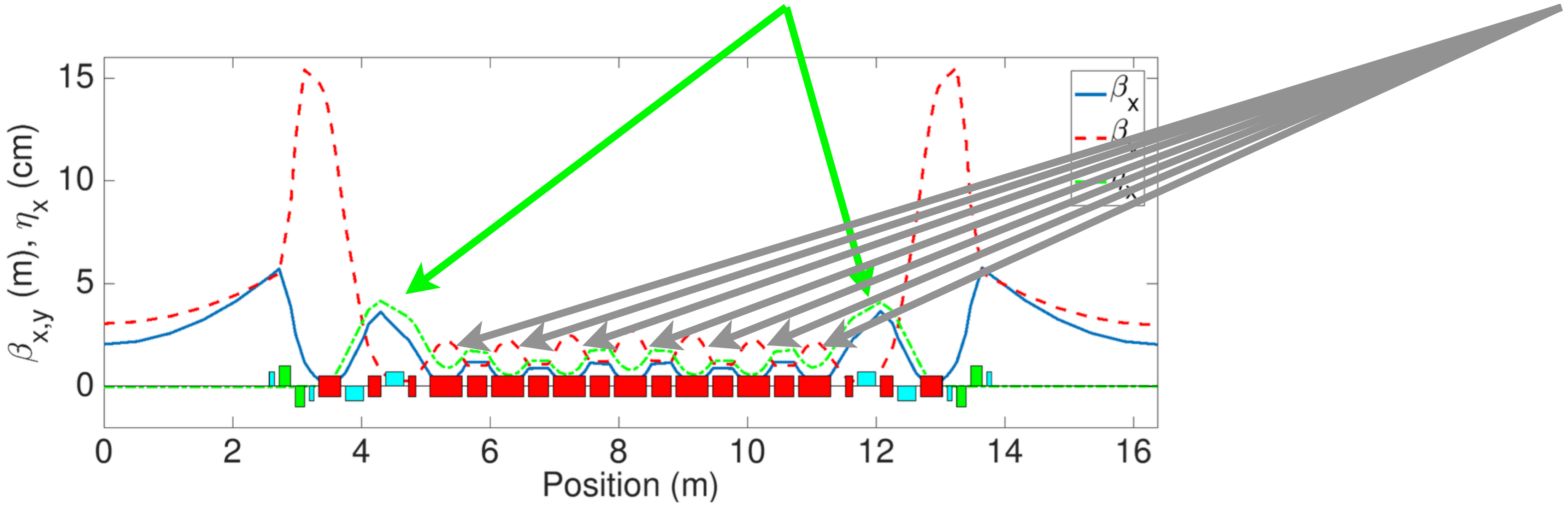

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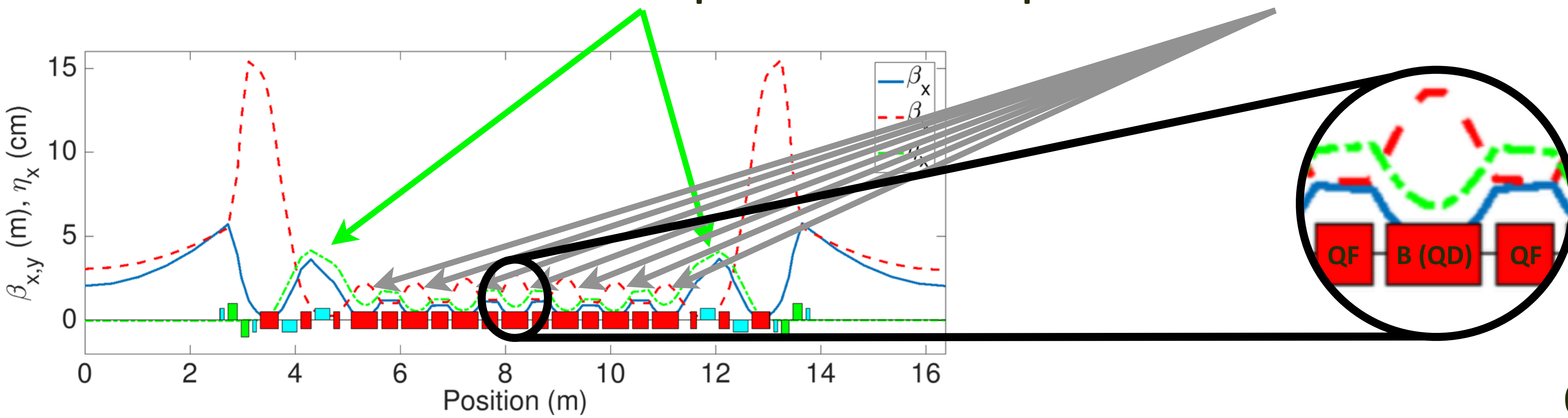

9 bends

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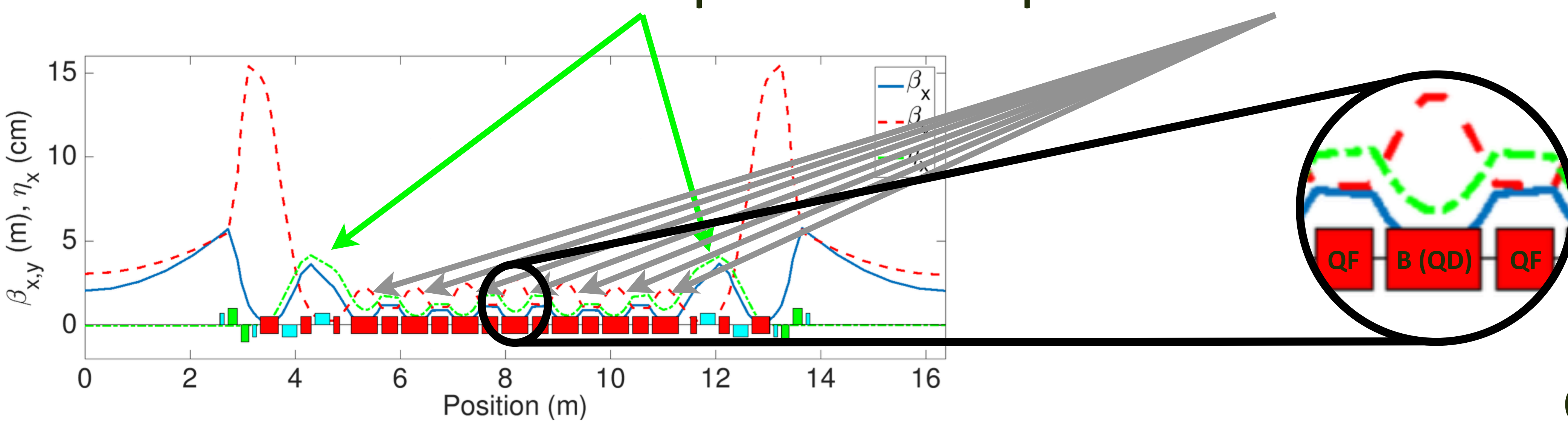

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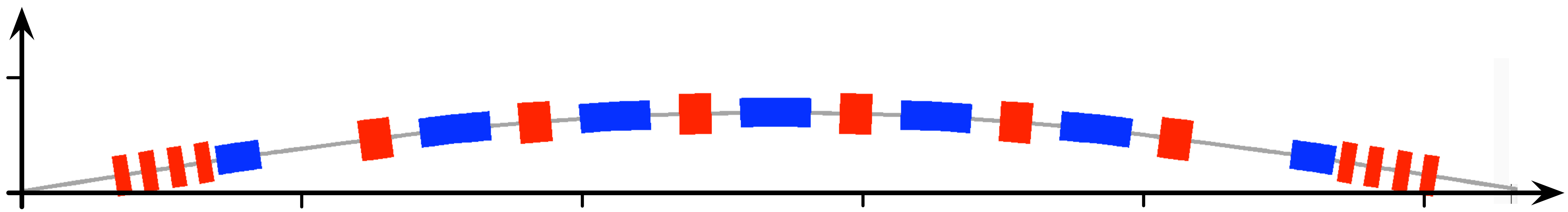
- New MBA based on: 2× matching cells (MC) + 2× dispersion suppressors (DS) + ***n***× unit cells (UC)



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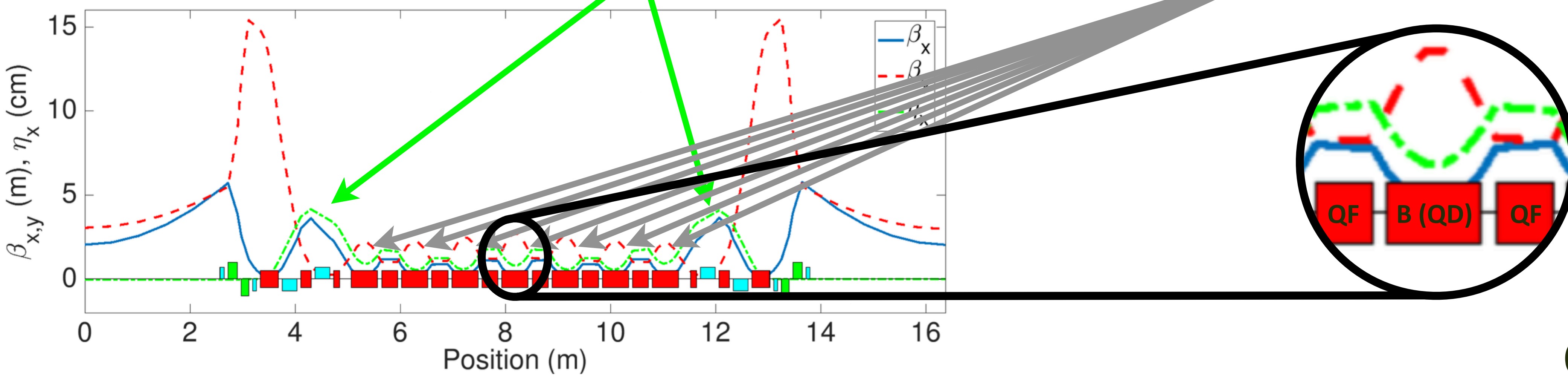

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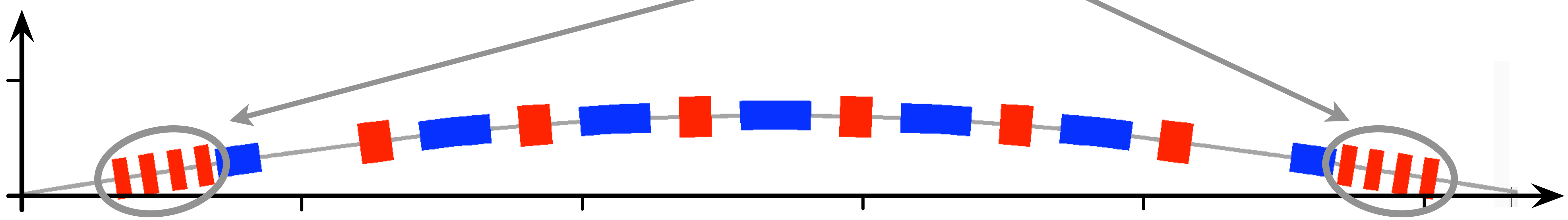

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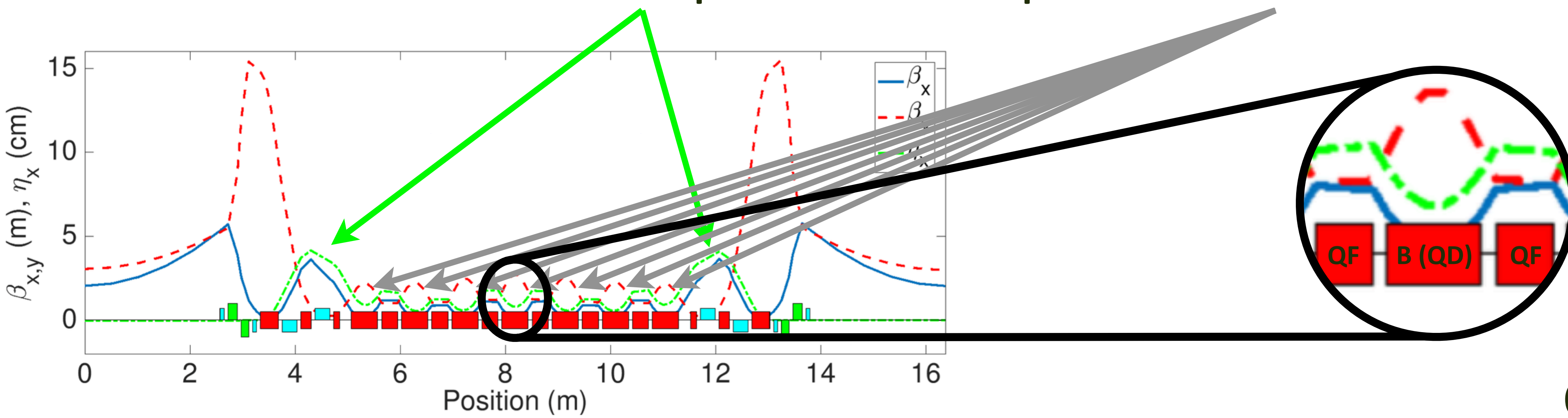

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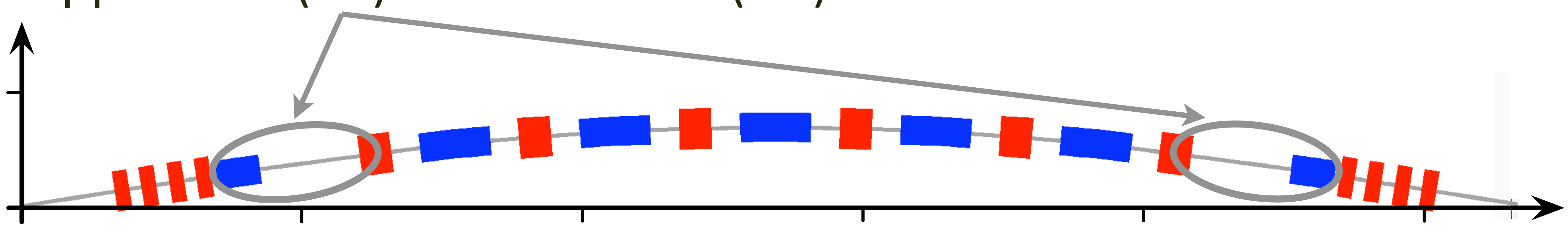

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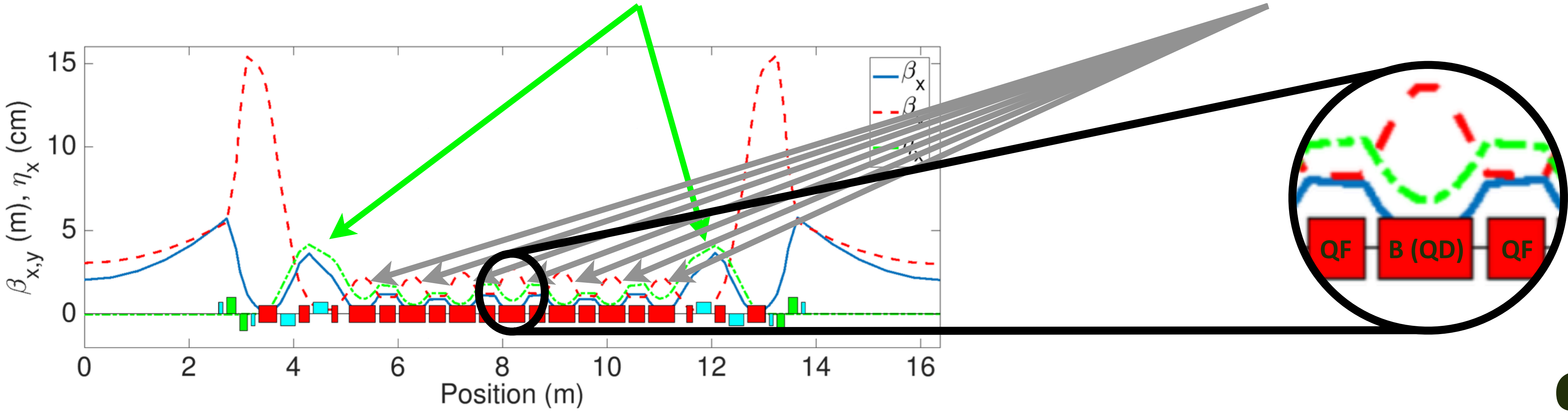

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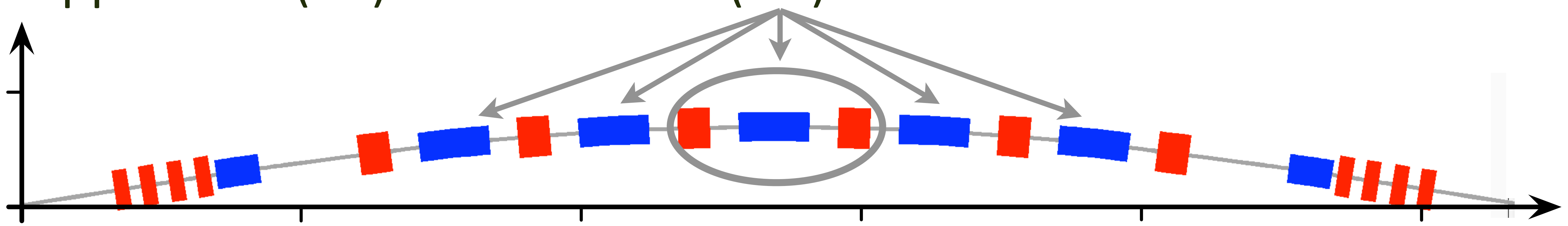

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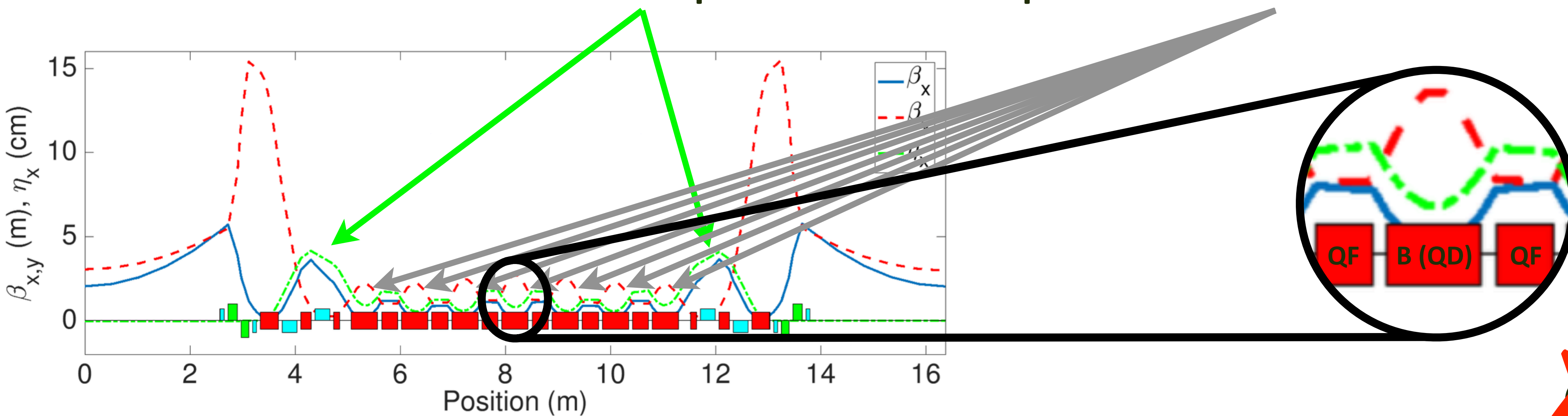

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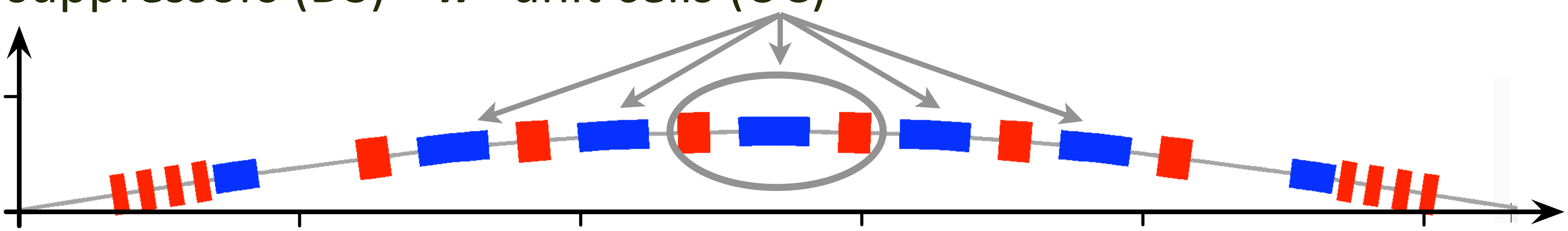

- However, new UC must also provide space for SF/SD → ***n***<7

Unit Cell Design – Baseline vs. New (cont.)

- What is maximum ***n*** we can fit? And with fewer bends, can we still achieve sufficiently low emittance?

$$\varepsilon_0 \propto \frac{\gamma^2}{N_B^3}$$

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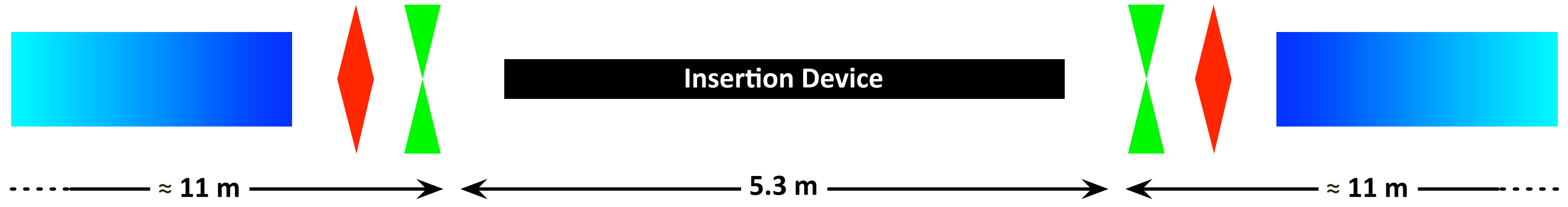
- 196 m circumference & 12× 5.3 m SS → ≈ 11 m per achromat



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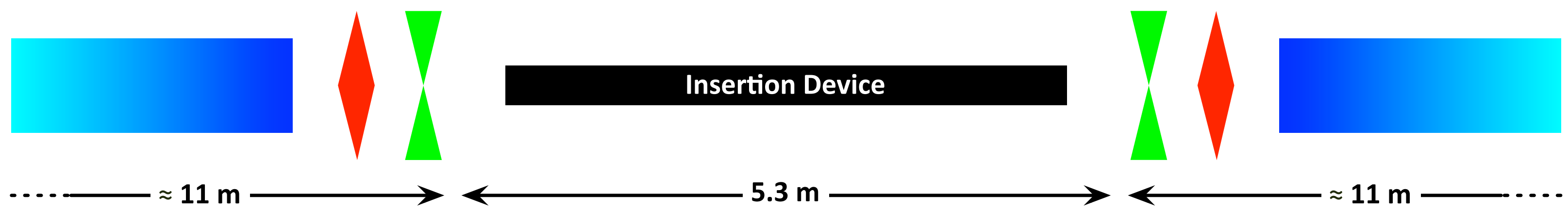
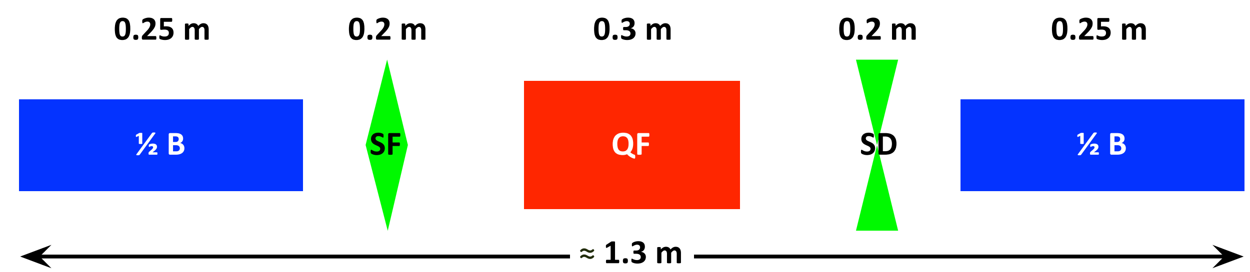


- Assuming roughly 0.5 m bend, 0.3 m quadrupole, 2× 0.2 m for SF/SD ➔ basic cell length ≈ 1.3 m



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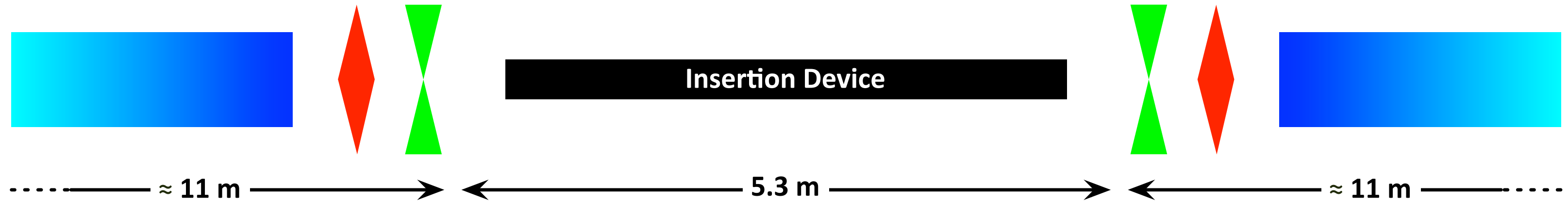

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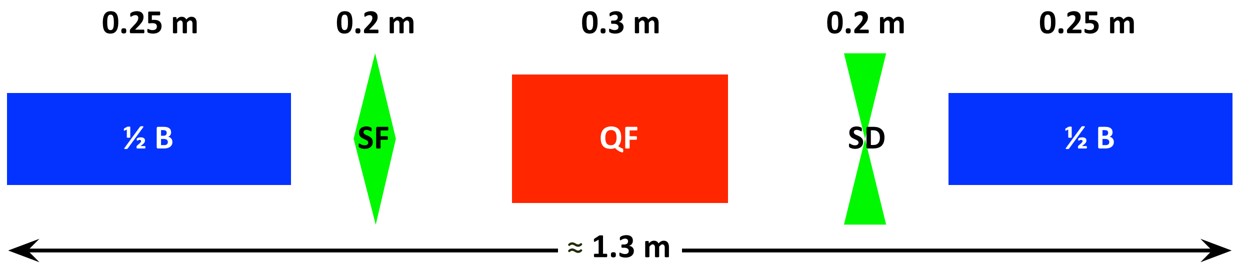
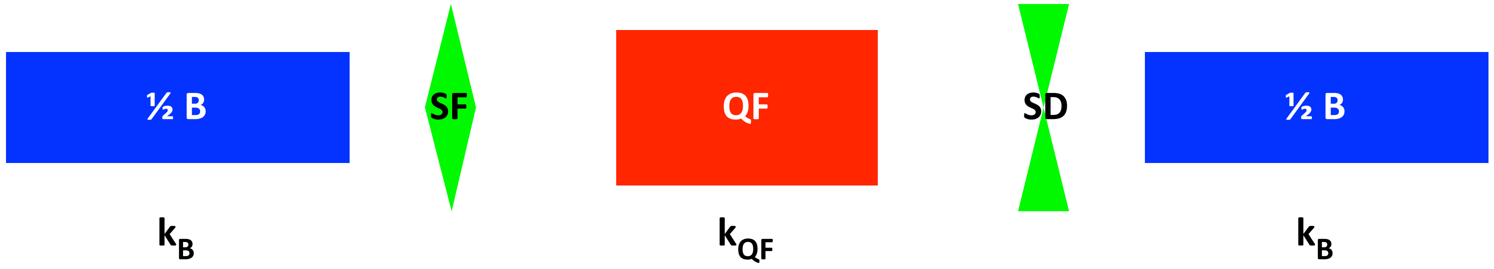


- Assuming 2× 1.6 m reserved for MCs ➔ leaves 6× 1.3 m which can be implemented as 5× UCs + 2× DSs (since DS ≈ ½ UC) ➔ new lattice is a **7BA**

Unit Cell Design – Baseline vs. New (cont.)

- For this UC length & bend angle, a first study using the simplest UC structure…



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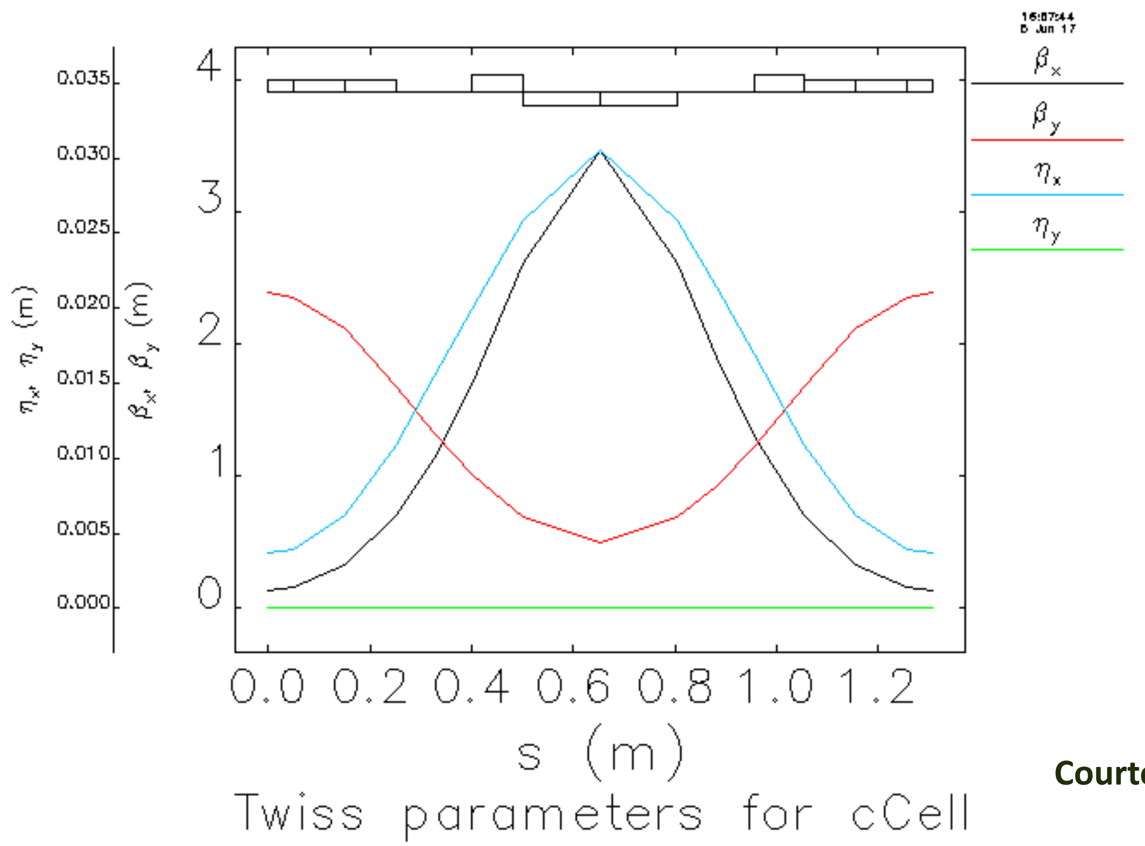

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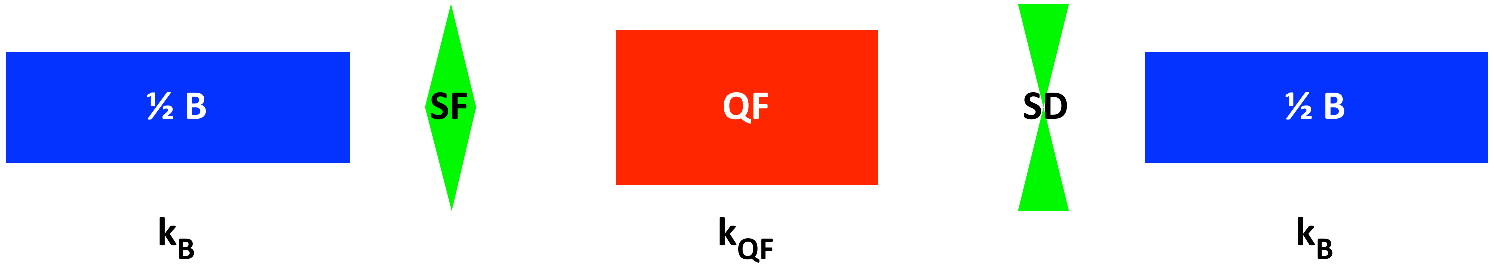

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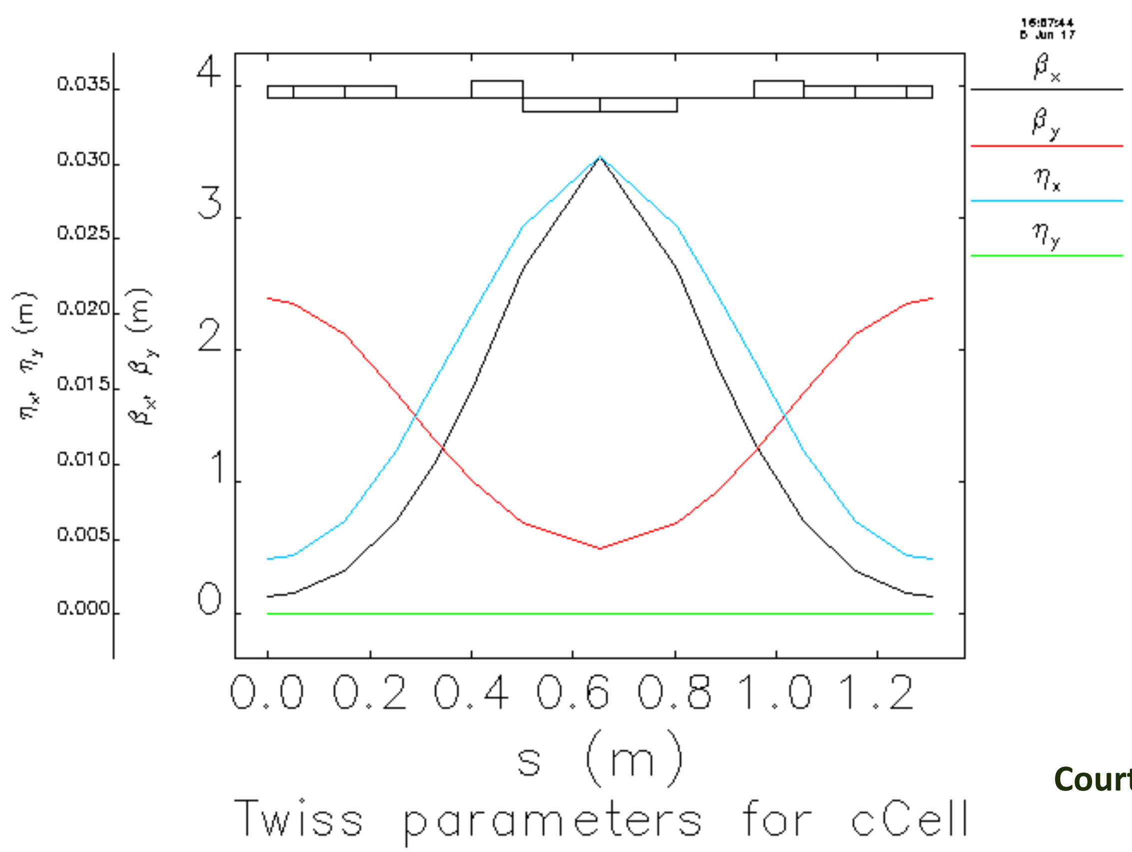

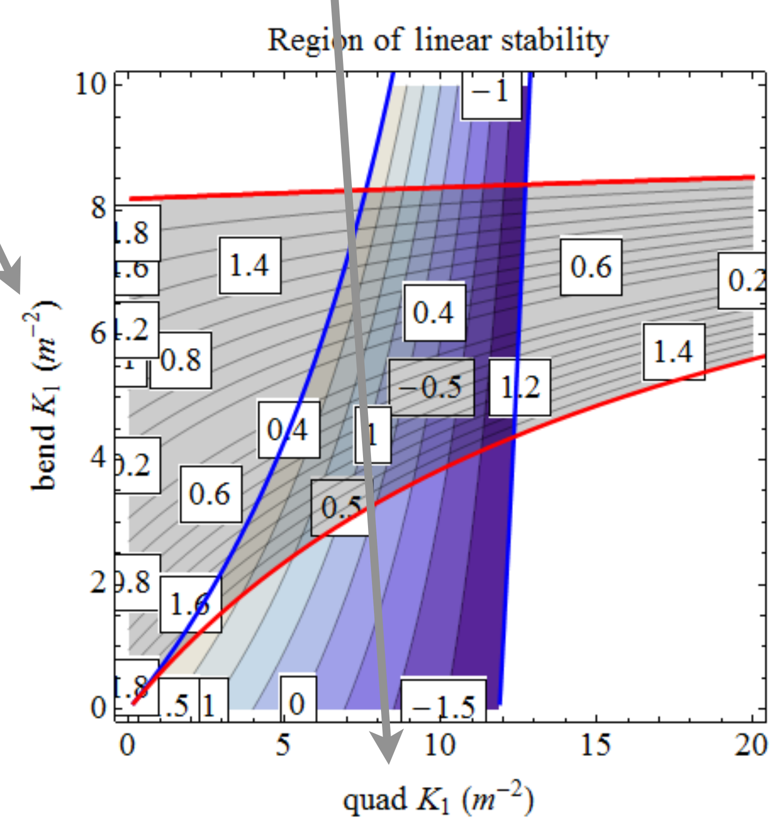

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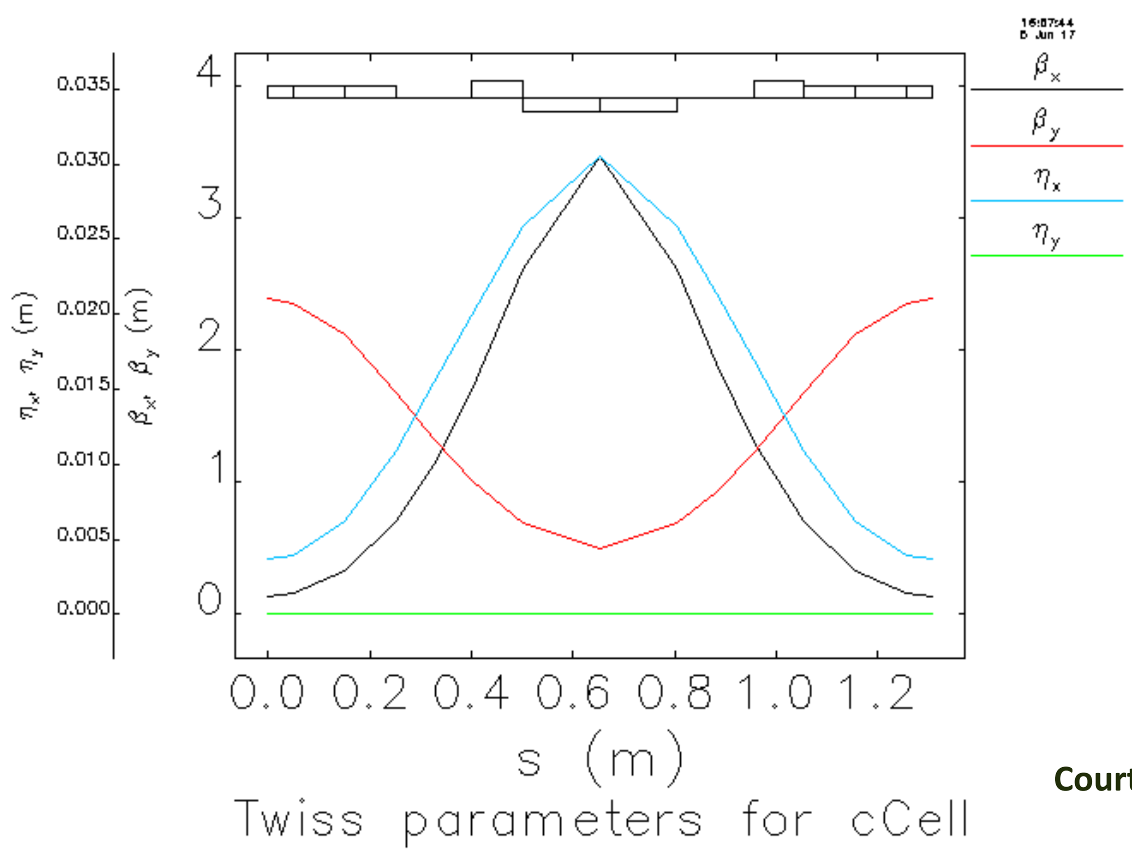
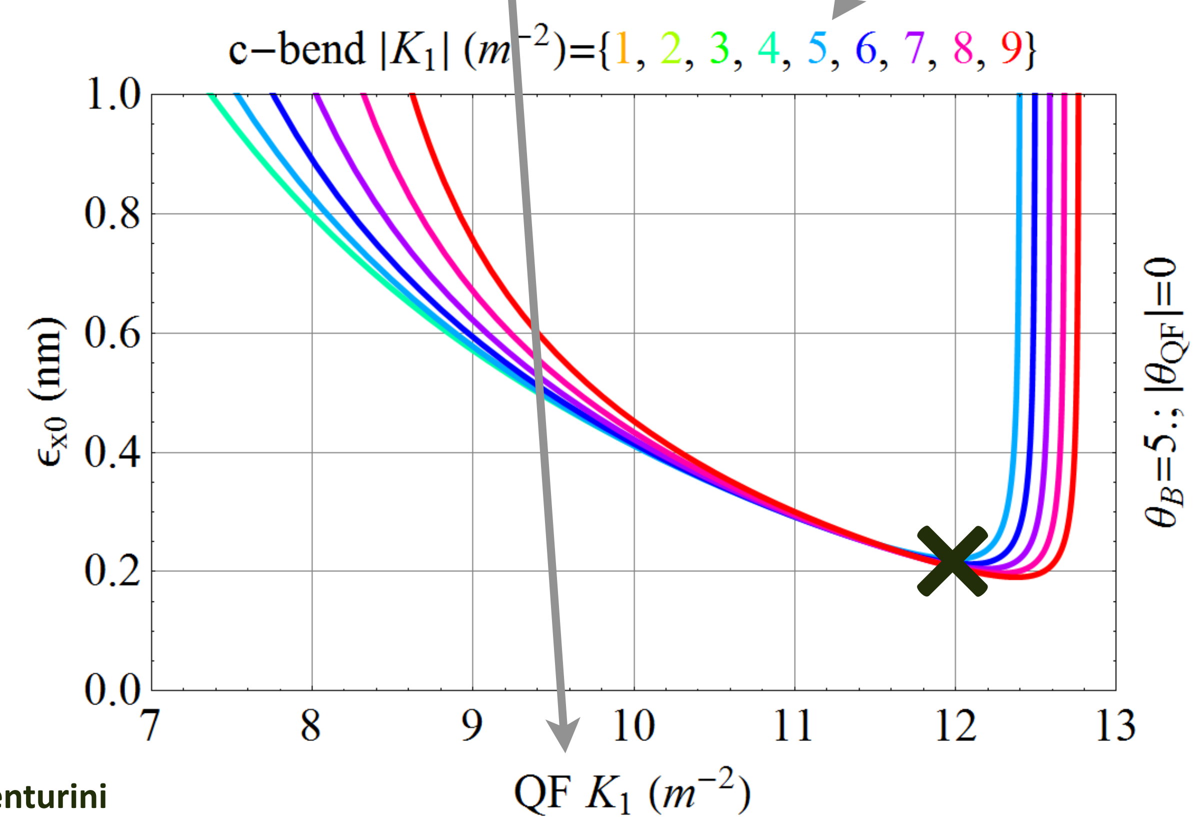
- For this UC length & bend angle, a first study using the simplest UC structure…

- … allows parametric studies for achievable ε vs. UC gradients → stable solutions exist, but render at best ε ≈ 200 pm (for k_{QF} ≈ 12)





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NIM-A **737**, 148-154 (2014)

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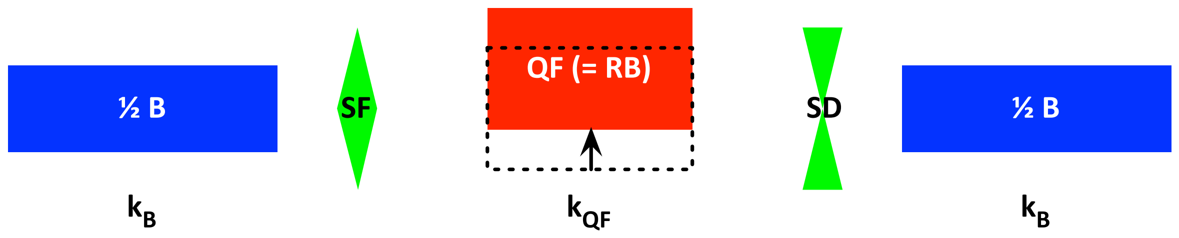
- Assume QF implemented as offset quadrupole → generates both horizontal focusing & reverse bending (need to compensate for in B)



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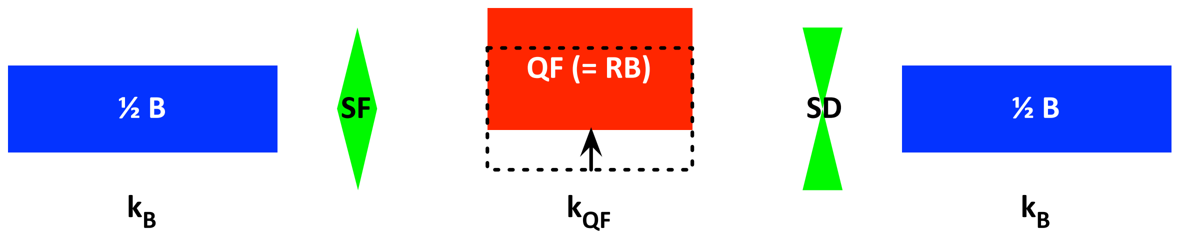
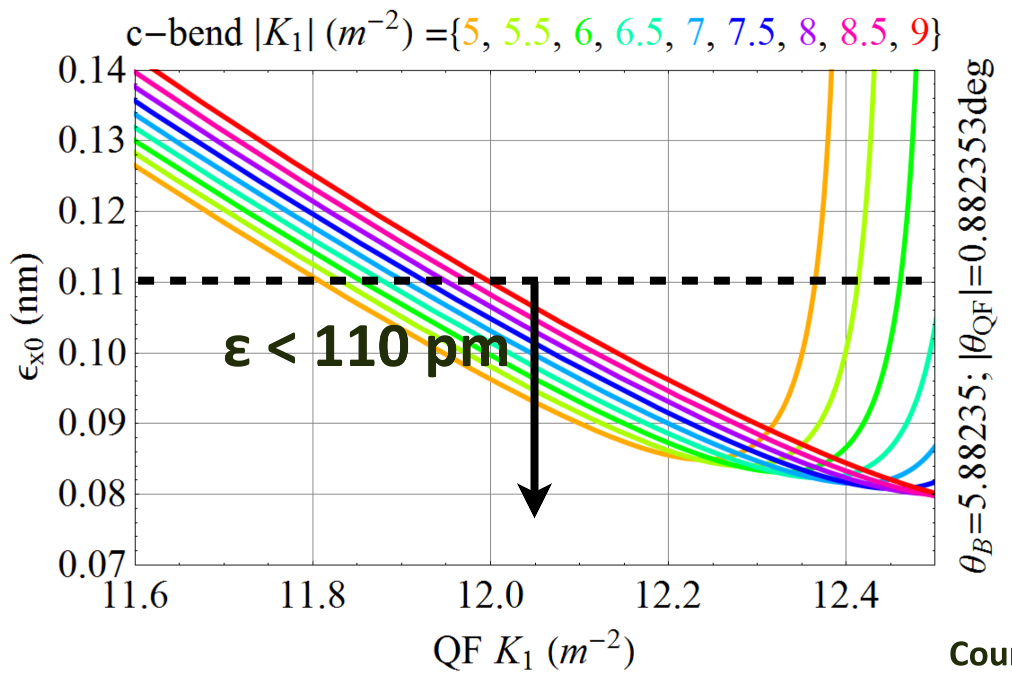
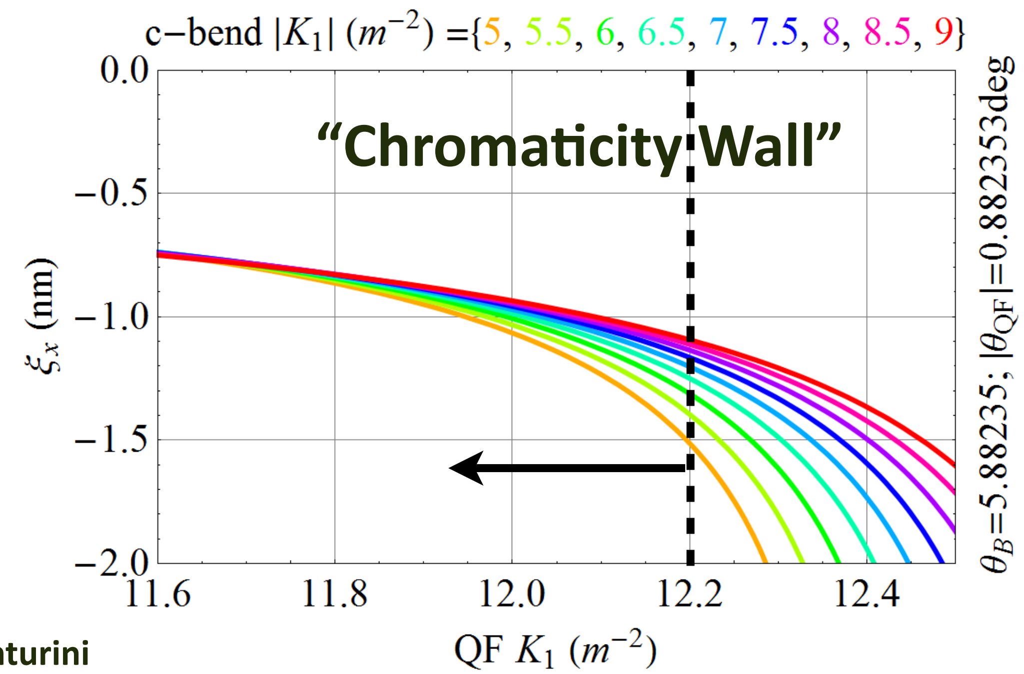


- Stability diagram indicates there are solutions ε < 110 pm for $k_{QF} \geq 11.8$ and $k_B \geq 5$ (assuming RB with 15% of dipole bend angle)



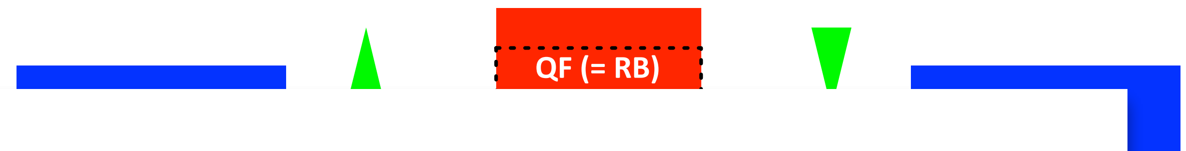
Courtesy: M. Venturini

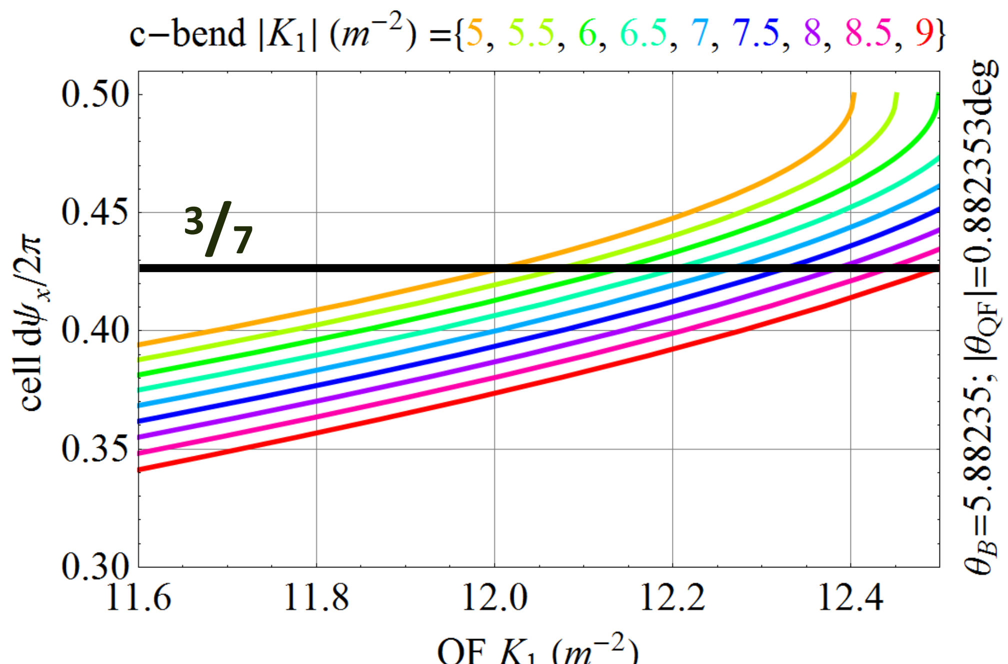


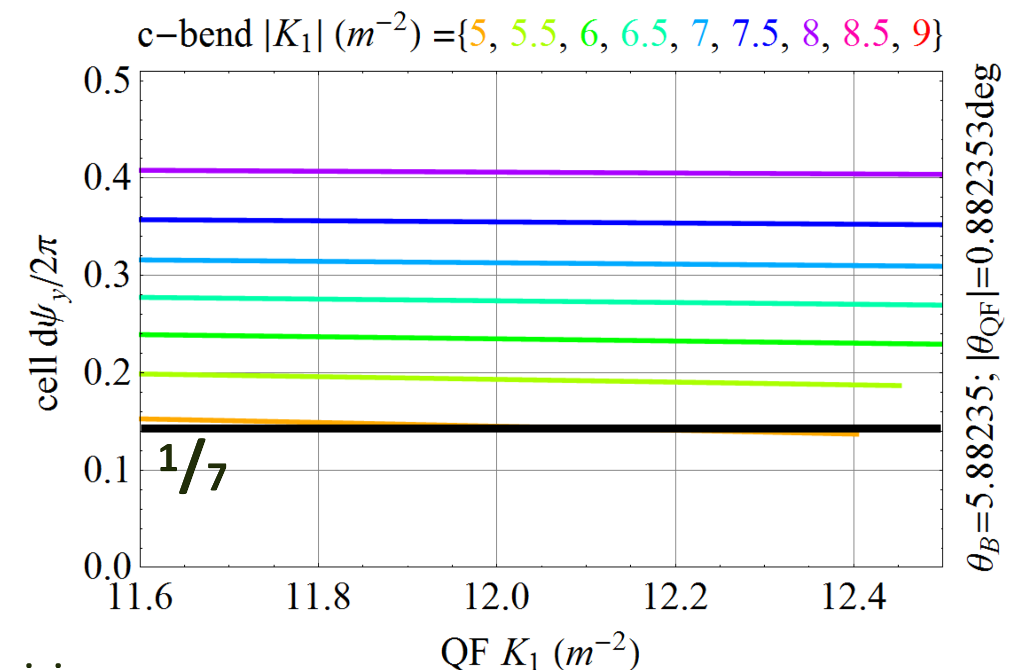
Unit Cell Design – Baseline vs. New (cont.)

NIM-A **737**, 148-154 (2014)

- However, **reverse bend (RB)** can substantially suppress emittance
- Assume QF implemented as offset







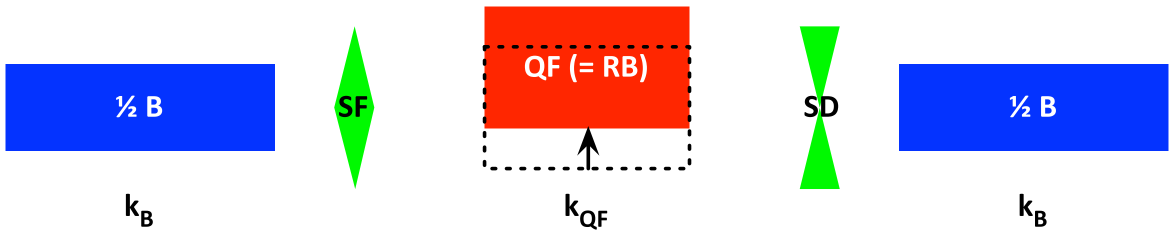
Courtesy: M. Venturini

- Solutions allow for suitable phase advances: within each UC want tunes $2\pi \times (3/7, 1/7)$ → entire 7BA becomes higher-order achromat (canceling geometrical aberrations from sextupoles → cancels RDTs within achromat)

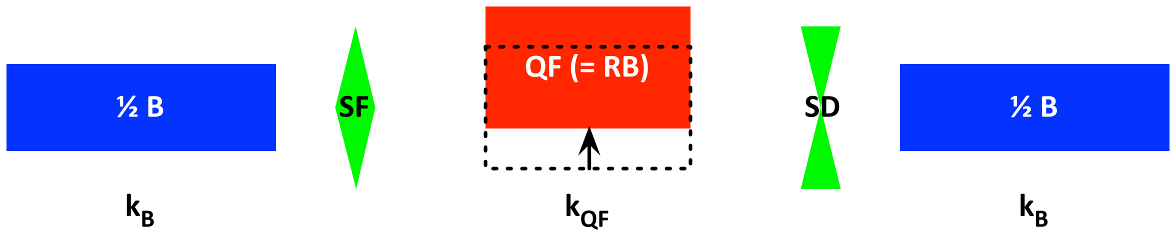
NIM-A **645**, 168-174 (2011) PRST-AB **15**, 054002 (2012)

A More Realistic Unit Cell

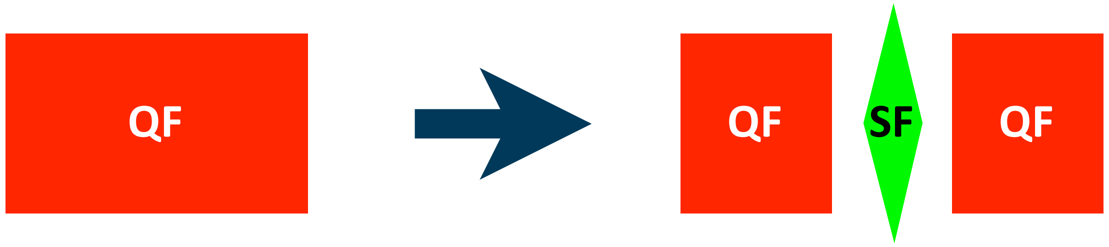
- Improve the toy model UC...



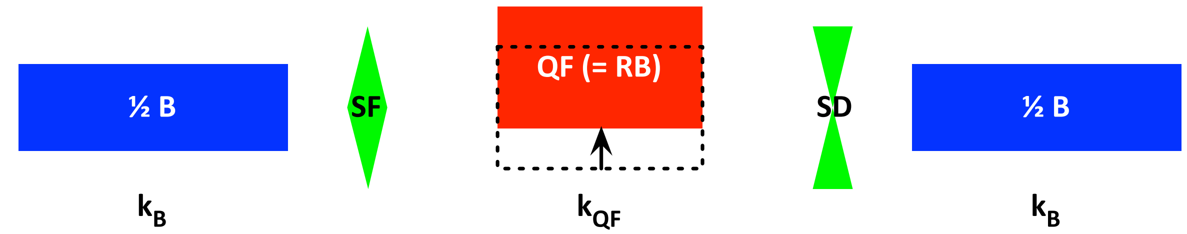
A More Realistic Unit Cell (cont.)



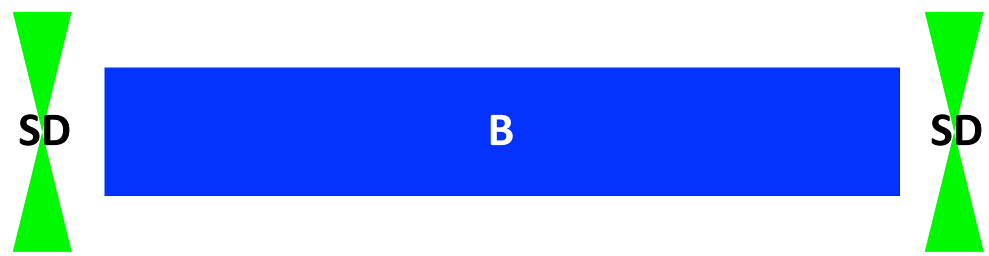
- Improve the toy model UC...
  - Want SF at max β_x → split QF (RB) & insert SF at center



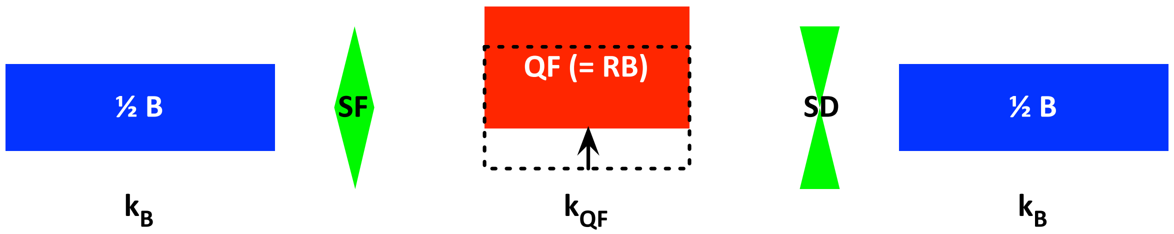
A More Realistic Unit Cell (cont.)



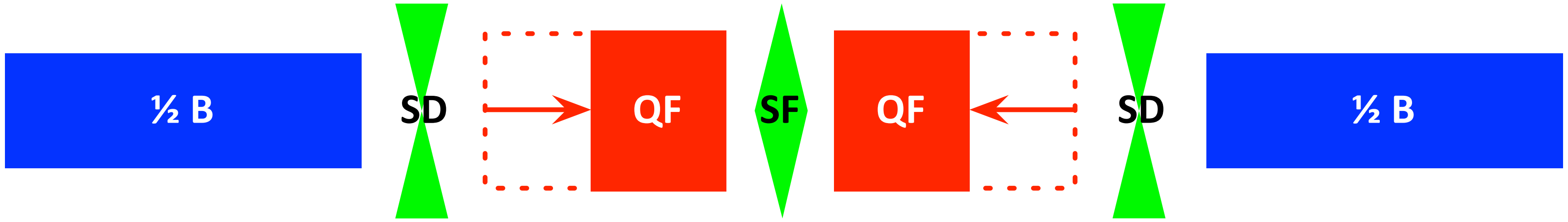
- Improve the toy model UC…
  - Want SF at max β_x → split QF (RB) & insert SF at center
  - Want SD close to max β_y → install SD in pairs flanking UC bends



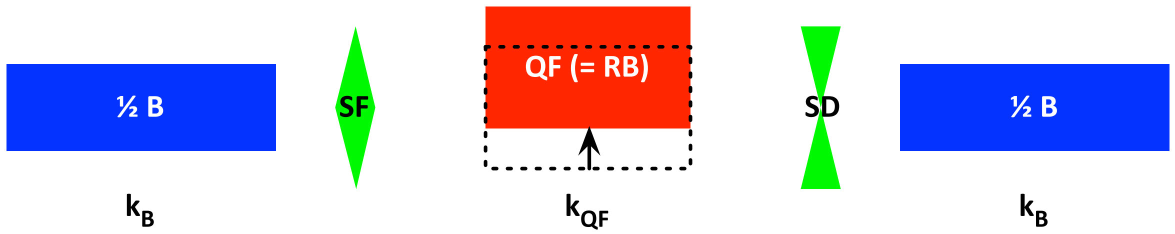
A More Realistic Unit Cell (cont.)



- Improve the toy model UC...
  - Want SF at max β_x → split QF (RB) & insert SF at center
  - Want SD close to max β_y → install SD in pairs flanking UC bends
  - Shorten QF (RB) to make space for SF & SD



A More Realistic Unit Cell (cont.)



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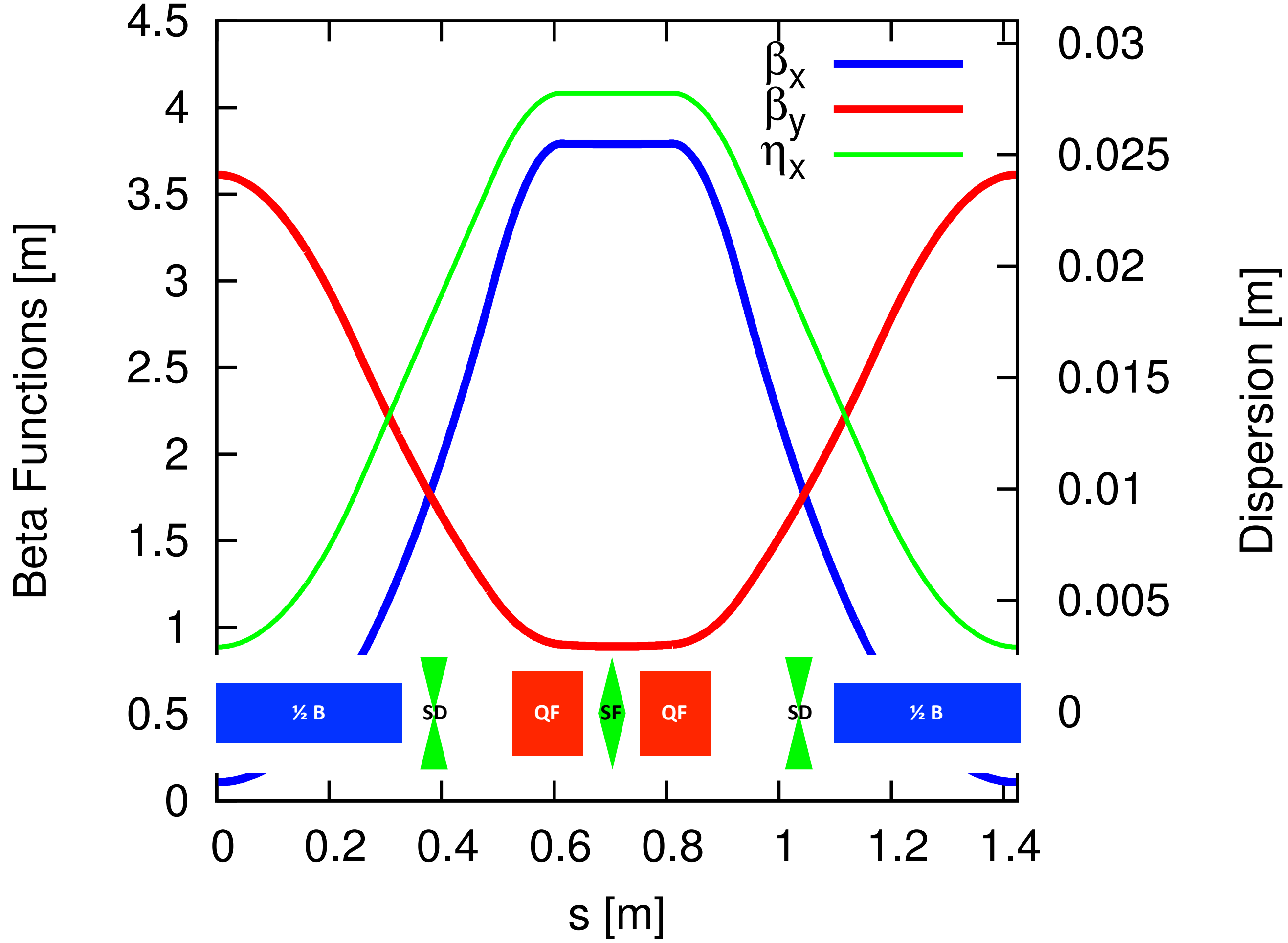
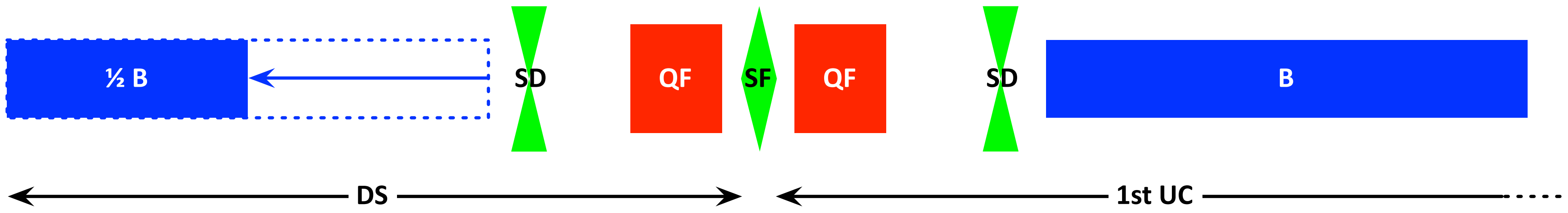


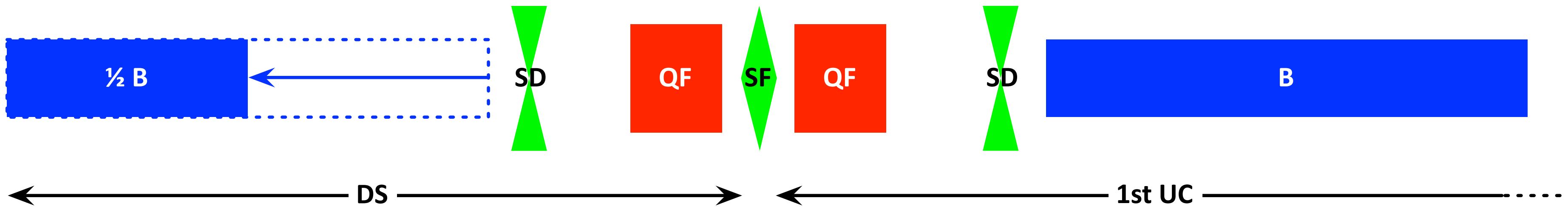
From Unit Cell to Dispersion Suppressor

- “Missing bend scheme”: DS dipole has half bend angle of UC dipole

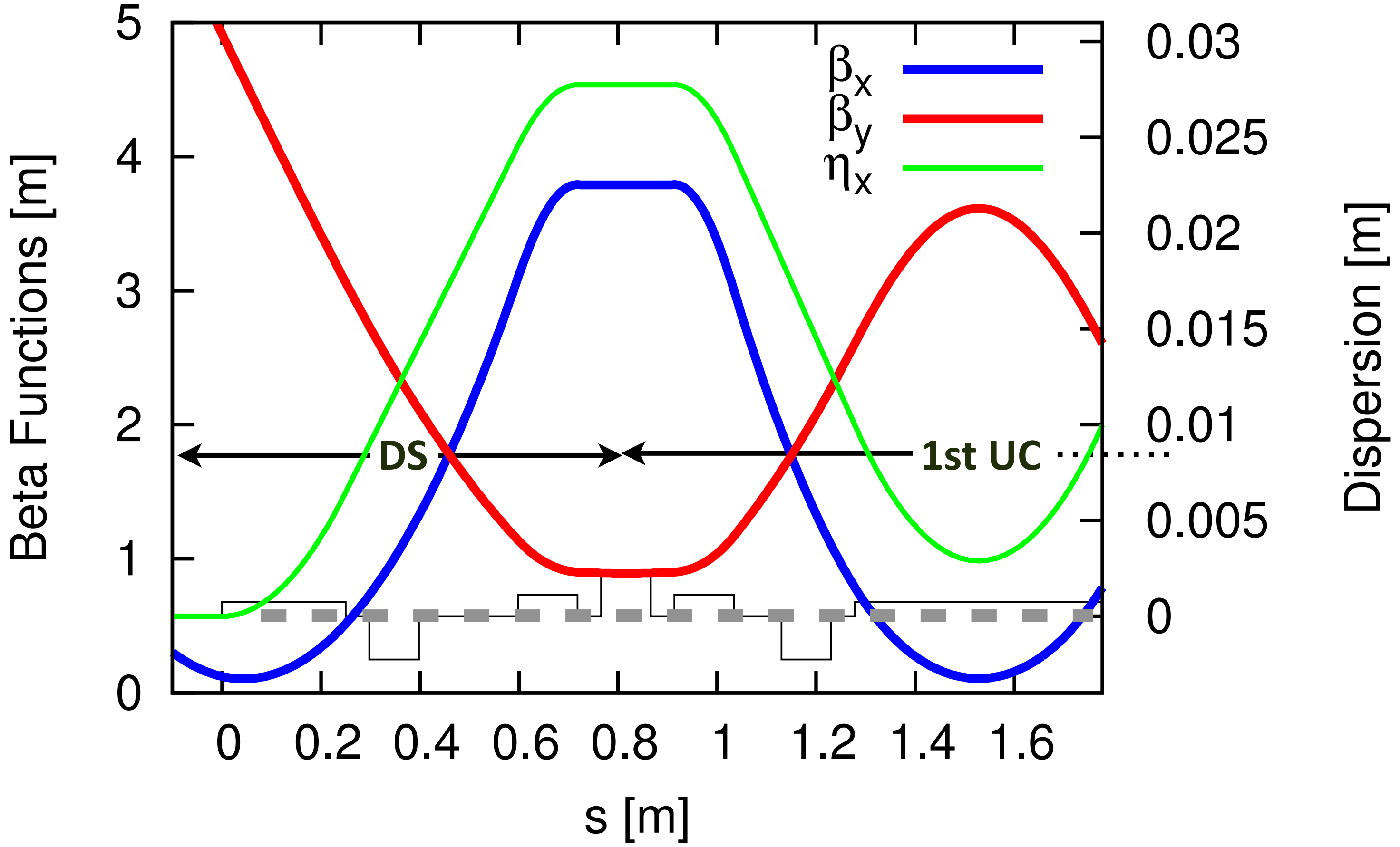


From Unit Cell to Dispersion Suppressor (cont.)

- “Missing bend scheme”: DS dipole has half bend angle of UC dipole

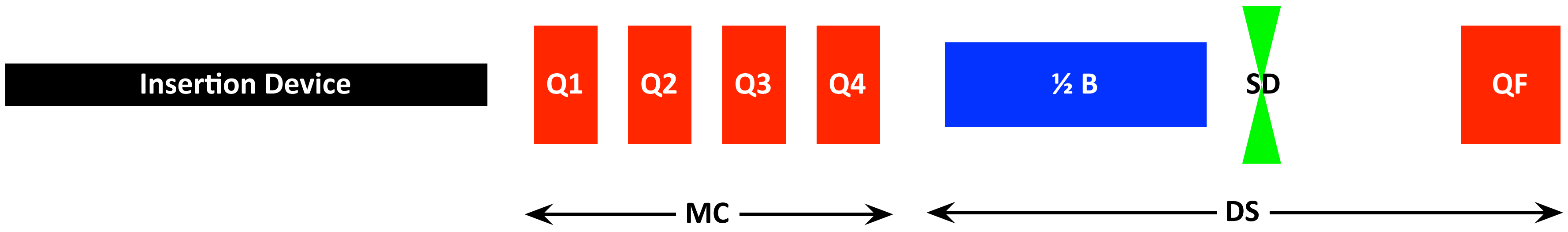


- Use approximately same QF gradient as in UC, but adjust QF–B separation to ensure dispersion fully suppressed at dipole end
  (UC by itself does not close dispersion)



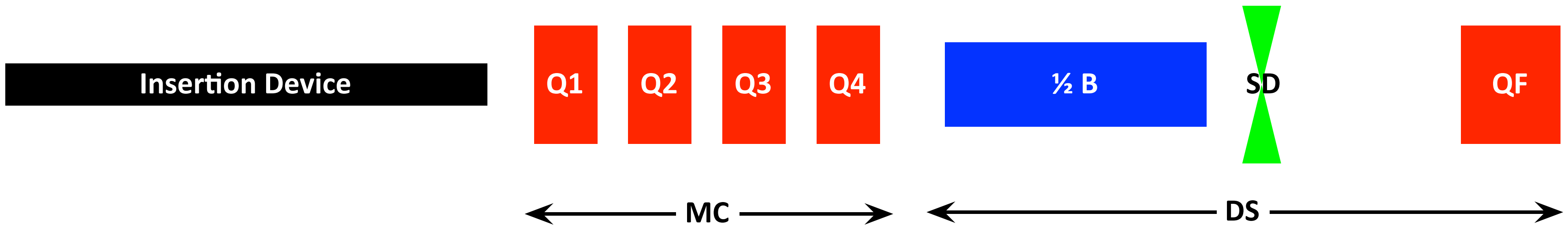
Optics Matching to IDs: Matching Cell

- 4 quadrupoles allows adjusting $\beta_{x,y}$ in IDs & setting working point

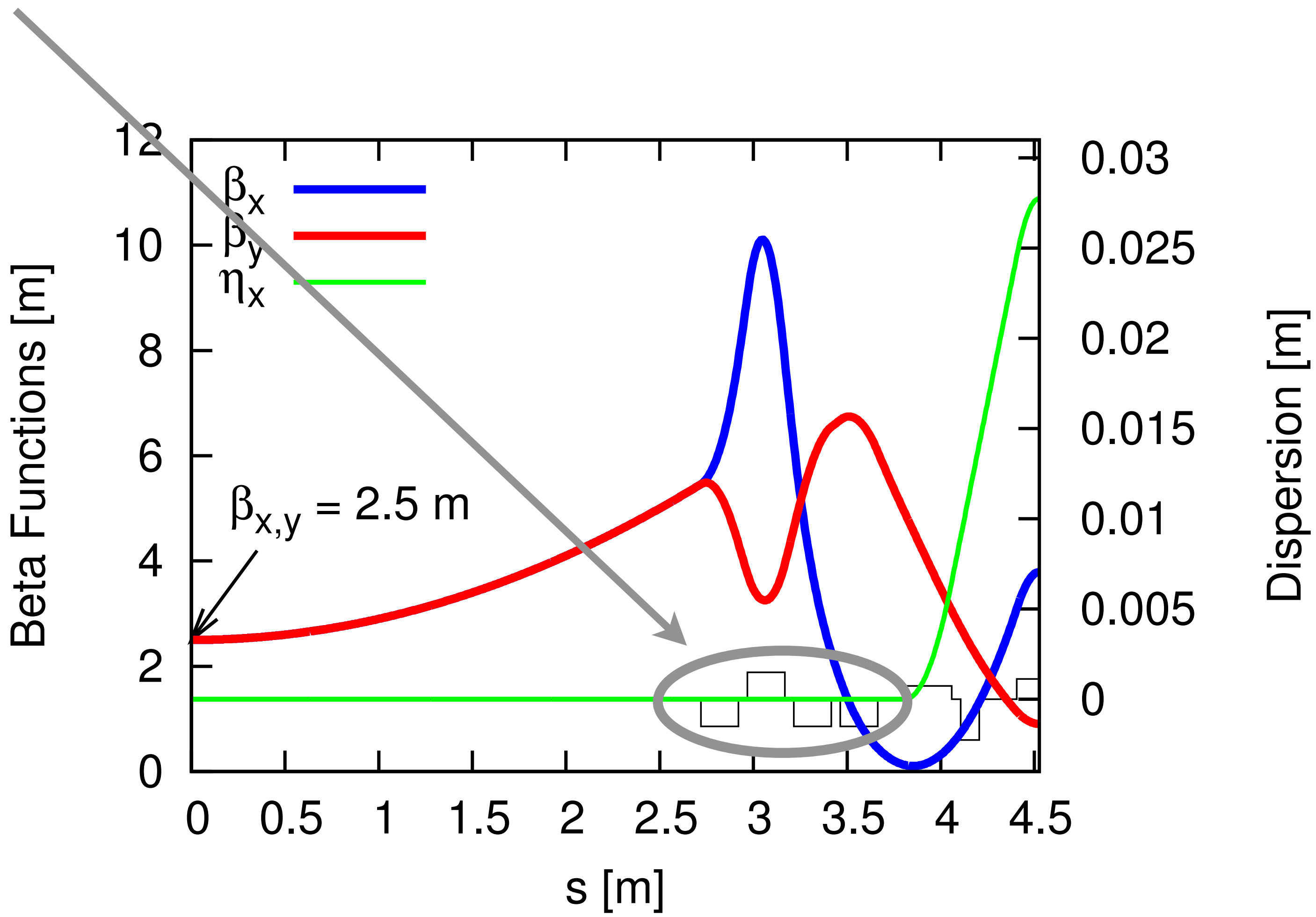


Optics Matching to IDs: Matching Cell (cont.)

- 4 quadrupoles allows adjusting $\beta_{x,y}$ in IDs & setting working point



- Fewer quadrupoles can be used but usually results in larger peak $\beta_{x,y}$



Optics Matching to IDs: Matching Cell (cont.)

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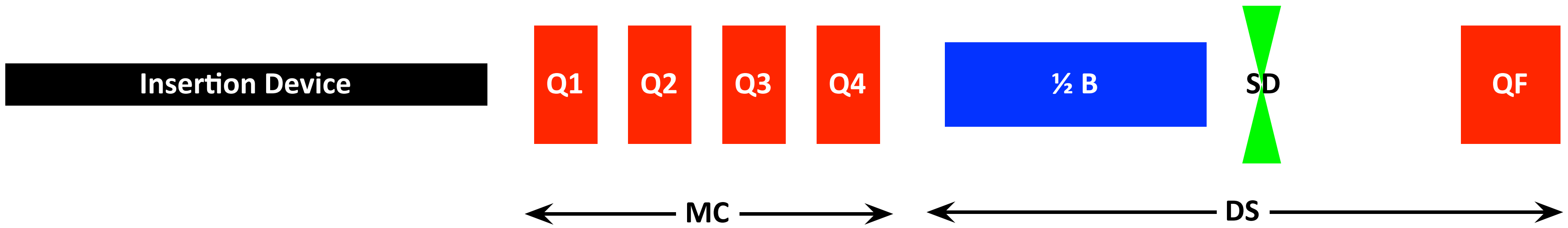
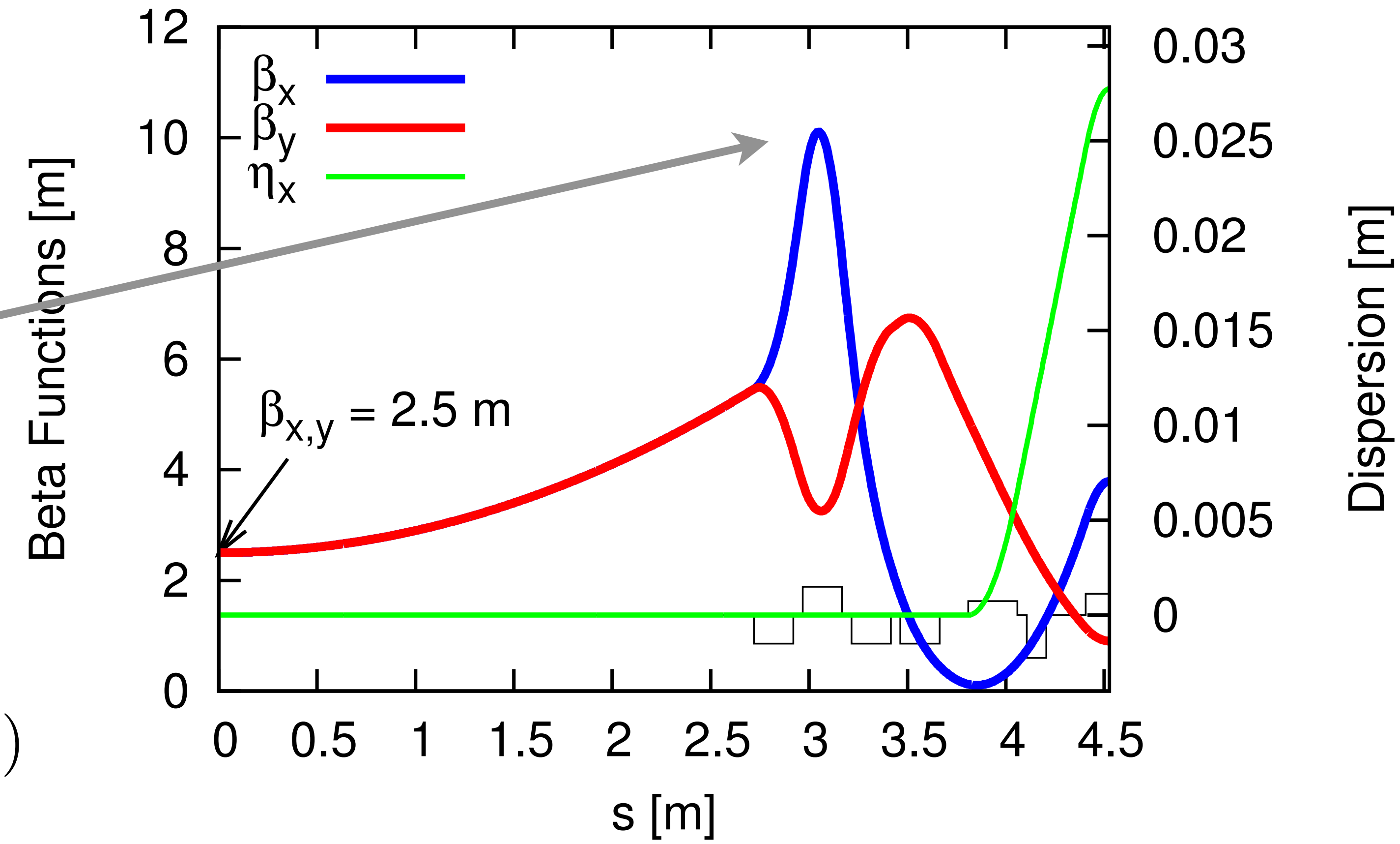


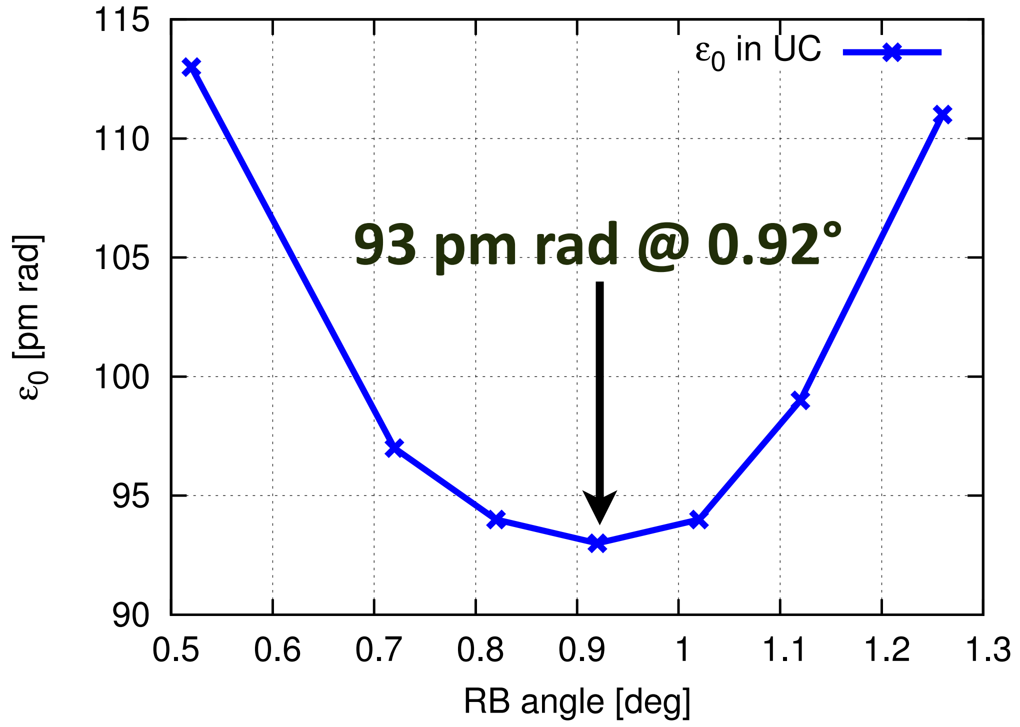
- Fewer quadrupoles can be used but usually results in larger peak $\beta_{x,y}$
- Ensure $\beta_{x,y}$ limited in order to minimize natural $\xi_{x,y}$
  (MCs increase overall $\xi_{x,y}$ by +40%)

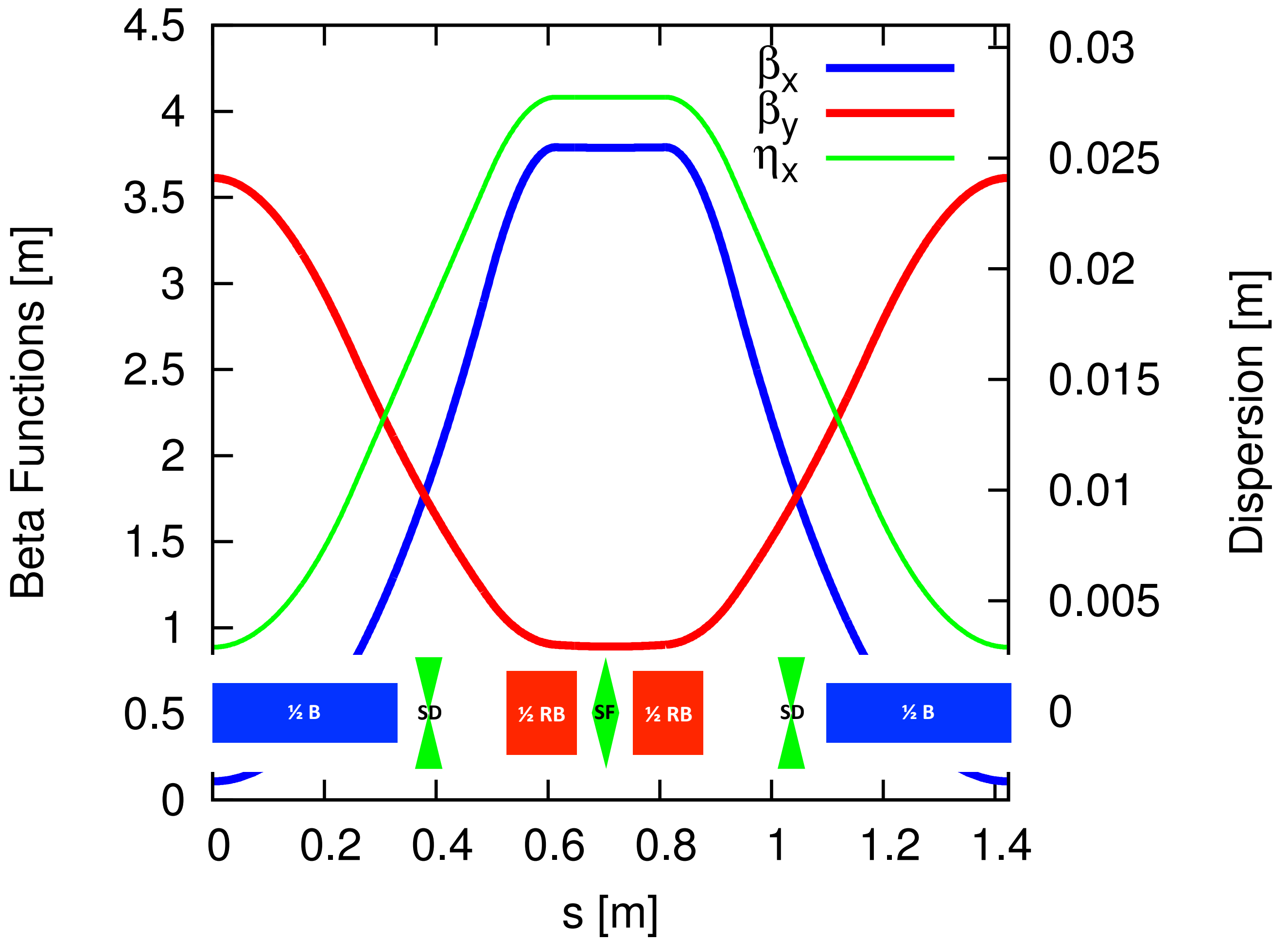


$$\xi_{x/y} = \mp \frac{1}{4\pi} \sum_{i=1}^{N} \beta_{x/y,i} \left((b_2 L)_i - 2(b_3 L)_i \eta_{x,i} \right)$$

The Resulting 7BA

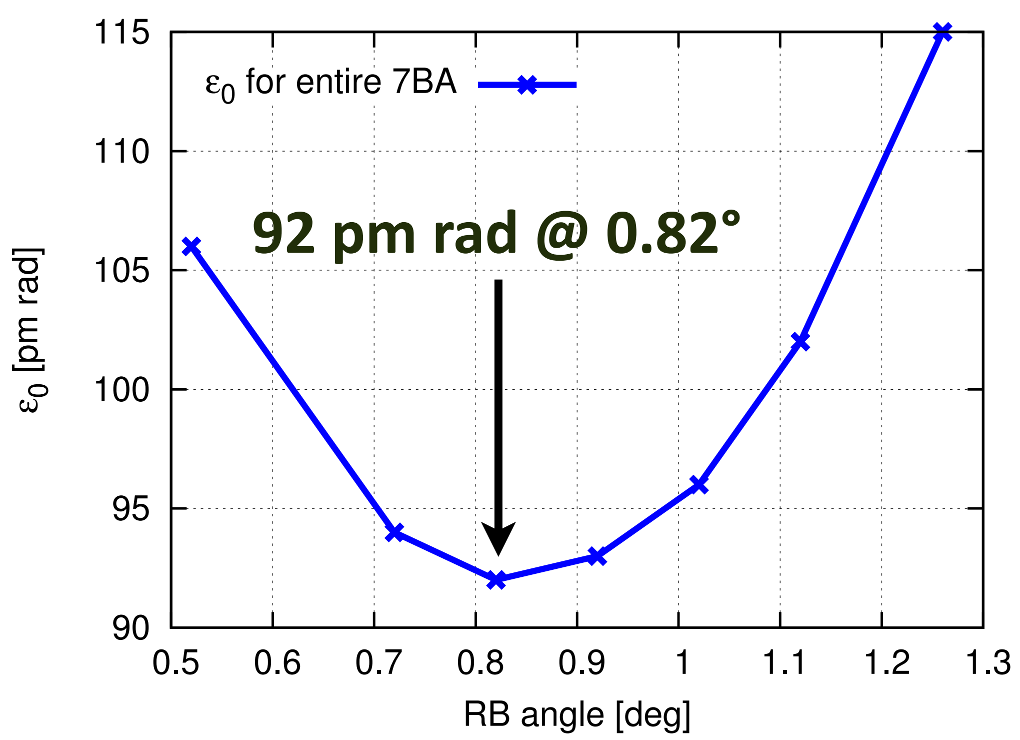
- Exploit last free knob → set RB angle to minimize emittance

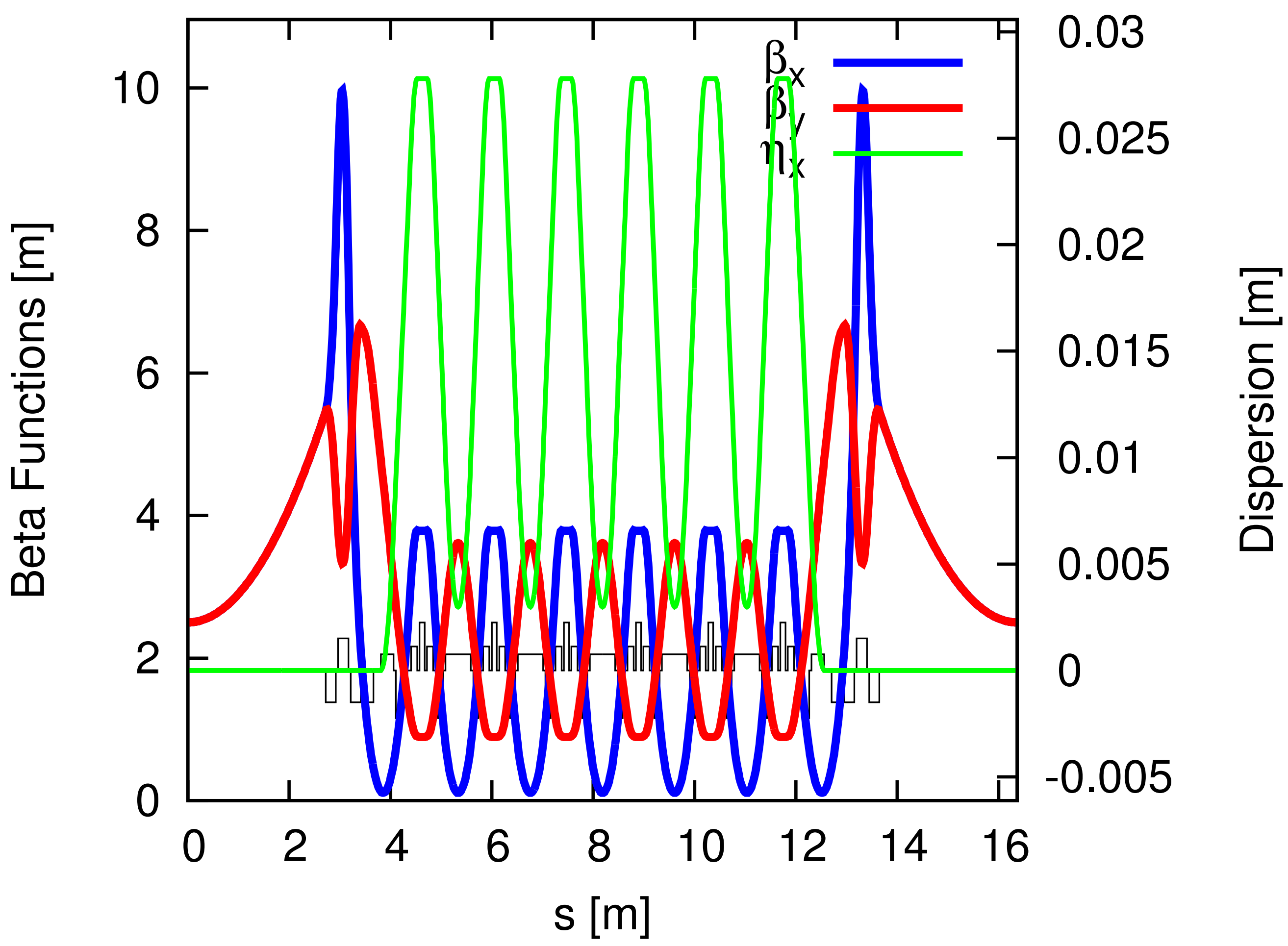




The Resulting 7BA (cont.)

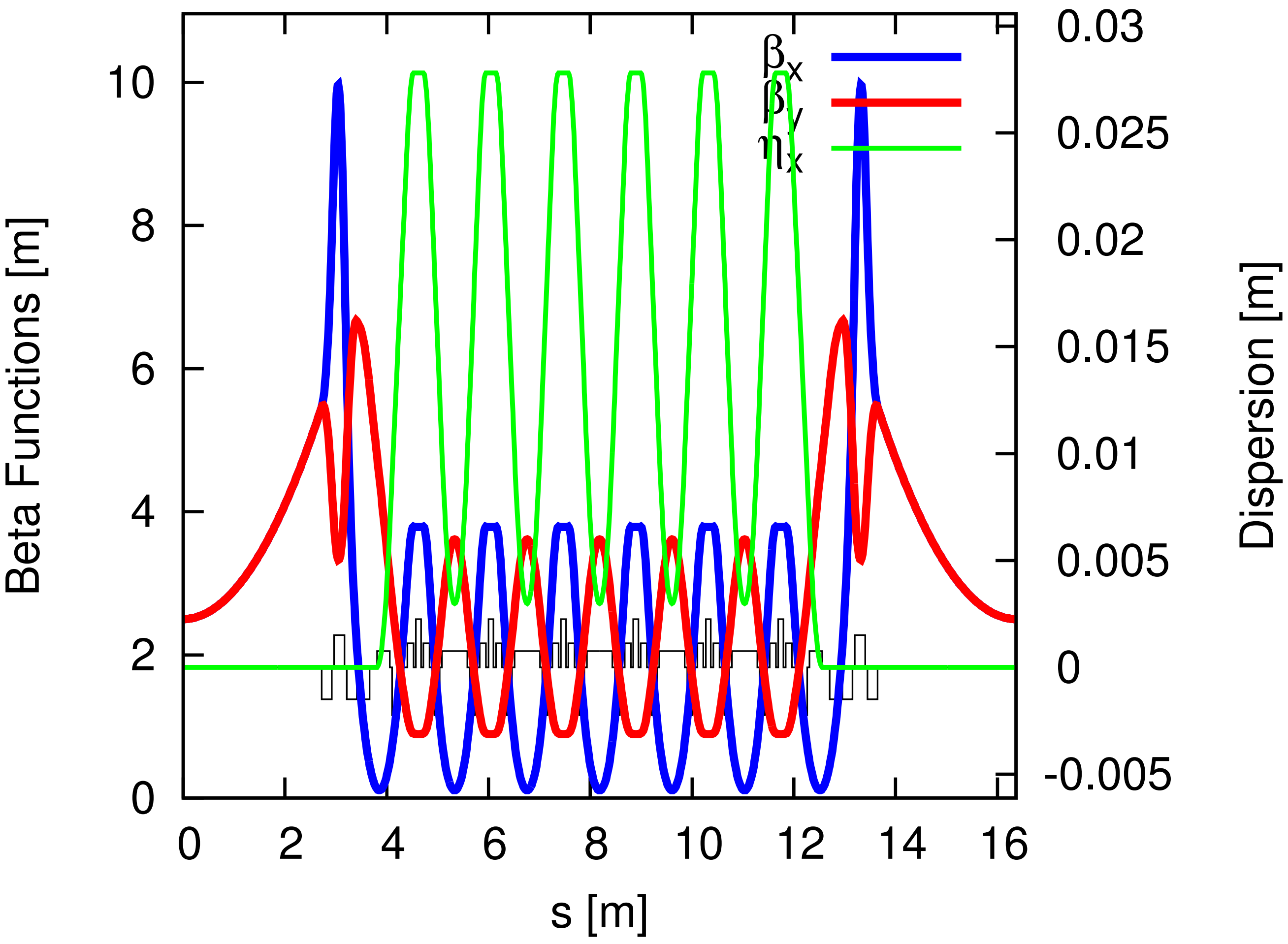
- Exploit last free knob ➔ set RB angle to minimize emittance
- Assemble these UCs together with DSs & MCs, tune β* ➔ new 7BA





The Resulting 7BA (cont.)

- Exploit last free knob ➔ set RB angle to minimize emittance
- Assemble these UCs together with DSs & MCs, tune β^* ➔ new 7BA
- Very attractive parameters for 196.4 m ring:
  - ε_0 = 92 pm, β^* = 2.5 m @ ID
  - **$\varepsilon_{x,y}$ = 59 pm rad** (fully coupled)
  - U_0 = 360.6 keV, J_x = 1.790
  - ν_x = 39.84, ν_y = 14.41
  - ξ_x = –103.6, ξ_y = –36.28
  - peak $\beta_{x,y}$ & η very low



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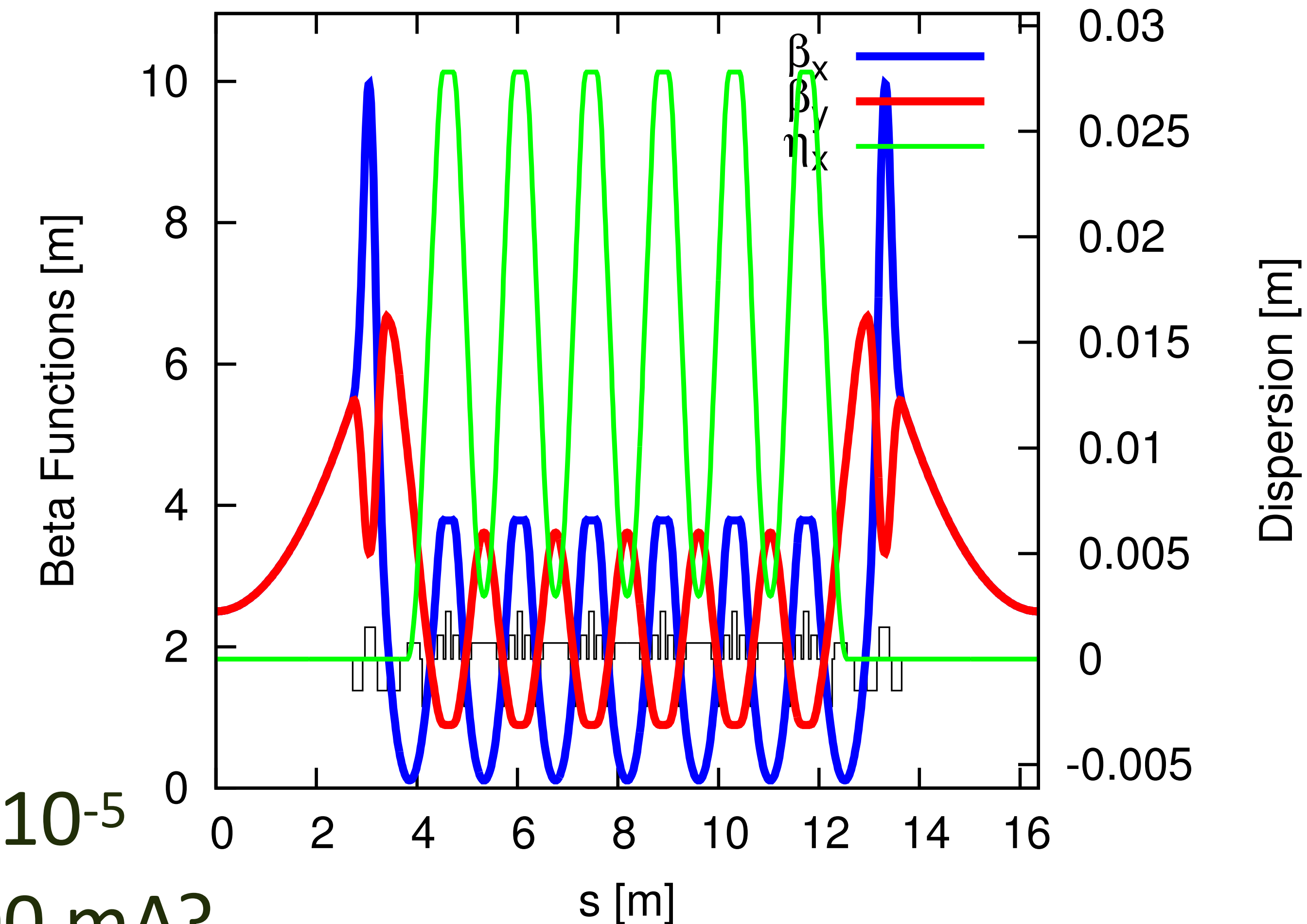
  - $\xi_x = -103.6$, $\xi_y = -36.28$
  - peak $\beta_{x,y}$ & η very low

... but quasi-isochronous: $\alpha_c = 2.8\times10^{-5}$

➔ will we be able to stably store 500 mA?



The Dispersion Conundrum

- Low emittance requires low dispersion

Suppress dispersion in bends!

$$\varepsilon_0 \propto \gamma \frac{I_5}{I_2 - I_4} \propto \frac{I_5}{J_x U_0}$$

$$I_5 = \oint \frac{\mathcal{H}}{|\rho^3|} ds, \quad \mathcal{H} = \gamma \eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$

$$I_2 = \oint \frac{ds}{\rho^2}, \quad I_4 = \oint \frac{\eta}{\rho}\left(\frac{1}{\rho^2} + 2b_2\right) ds$$

The Dispersion Conundrum (cont.)

- Low emittance requires low dispersion

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- But low dispersion is what minimizes momentum compaction

$$\alpha_c = \frac{1}{C} \oint \frac{\eta}{\rho} ds$$

... so it would appear ultralow emittance has to result in isochronous lattices

The Dispersion Conundrum (cont.)

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- But low dispersion is what minimizes momentum compaction

$$\alpha_c = \frac{1}{C}\oint \frac{\eta}{\rho} ds$$

... so it would ^ appear ultralow emittance has to result in isochronous lattices

almost

- However, these two conditions do not have to be satisfied equally in all parts of the cell!

Longitudinal Gradient Bends

- The trick we can therefore play is to $\alpha_c = \frac{1}{C}\left(\int_{LGB} \frac{\eta_x}{\rho} ds + \int_{RB} \frac{\eta_x}{\rho} ds\right) < 0$

  Small Negative Large Yes we can!

  - increase dispersion in QF/RB to increase momentum compaction (where contribution to emittance is small)
  - decrease dispersion in bend to suppress emittance (which also helps shift momentum compaction)

Longitudinal Gradient Bends (cont.)

$$\alpha_c = \frac{1}{C}\left(\int_{LGB}\frac{\eta_x}{\rho}ds + \int_{RB}\frac{\eta_x}{\rho}ds\right) < 0$$

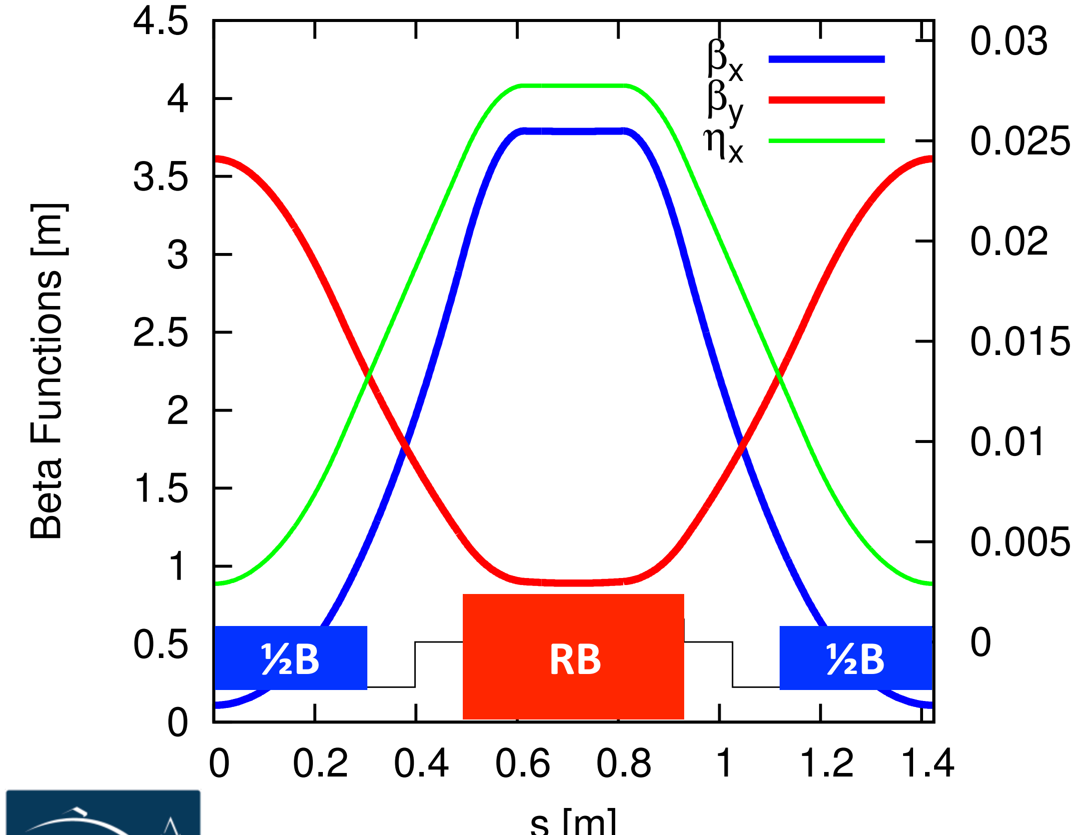
Small Negative Large

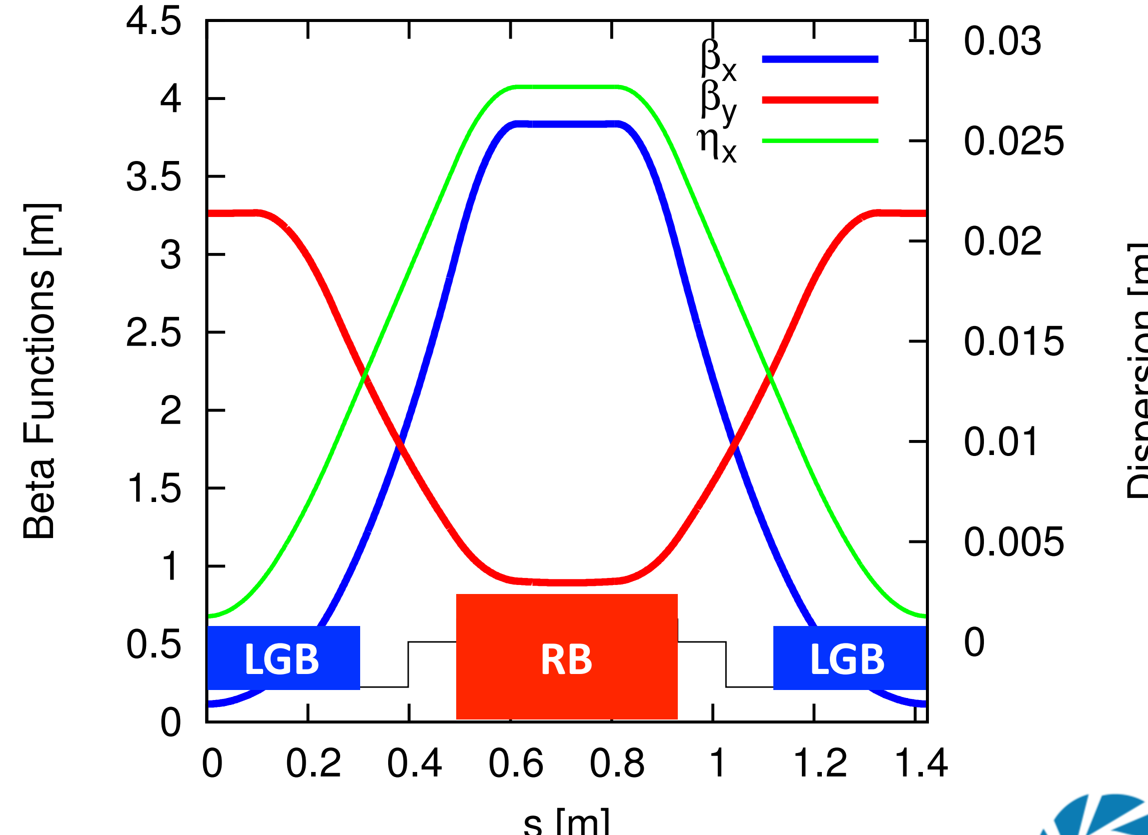
Yes we can!

- The trick we can therefore play is to
  - increase dispersion in QF/RB to increase momentum compaction (where contribution to emittance is small)
  - decrease dispersion in bend to suppress emittance (which also helps shift momentum compaction)

NIM-A **770**, 98-112 (2015)

- The silver bullet that enables this is the **longitudinal gradient bend**



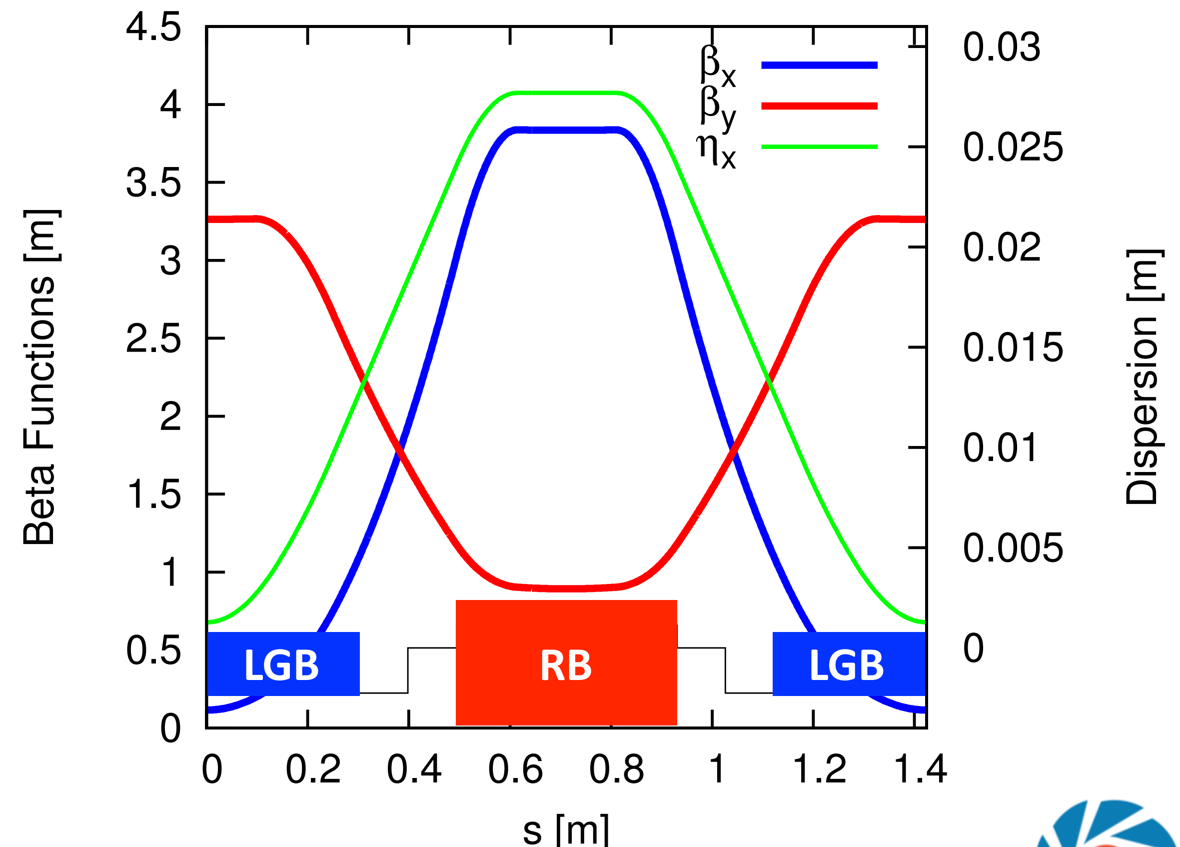


Longitudinal Gradient Bends (cont.)

$$\alpha_c = \frac{1}{C}\left(\int_{LGB} \frac{\eta_x}{\rho} ds + \int_{RB} \frac{\eta_x}{\rho} ds\right) < 0$$

Small Negative Large Yes we can!

- Microwave instability triggered by low ***absolute*** α_c
- Head-tail stability does ***not*** require positive α_c
- If α_c negative, correct to negative $\xi_{x,y}$ → lower sextupole gradients
- Two stages:
  - Exploit RB to fully suppress η_x in bend & then leverage LGB to suppress emittance
  - Detune from minimum ε in order to ensure larger negative α_c



LGB Cell for Lowest Emittance

- Instead of RB angle for minimum ε_0 in UC → minimize η^* in bend

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$$I_5 = \oint \frac{\mathcal{H}}{|\rho^3|} ds, \quad \mathcal{H} = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$

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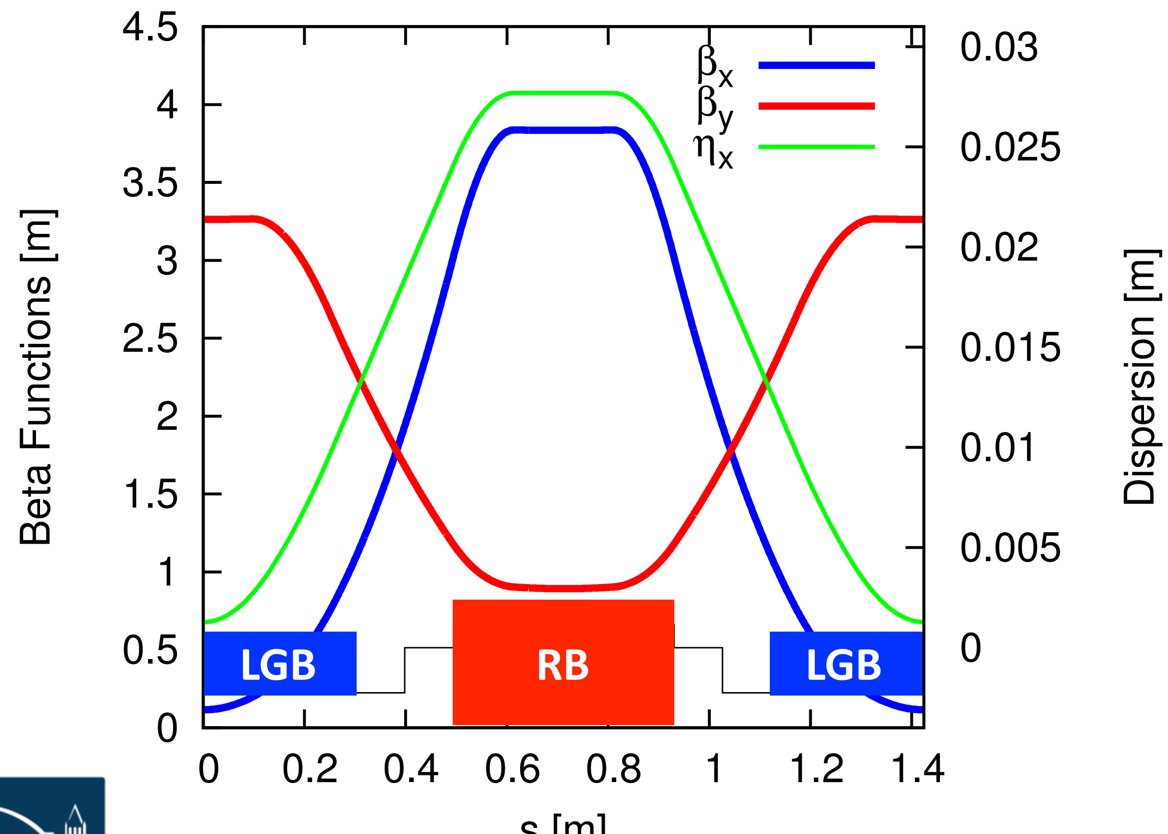
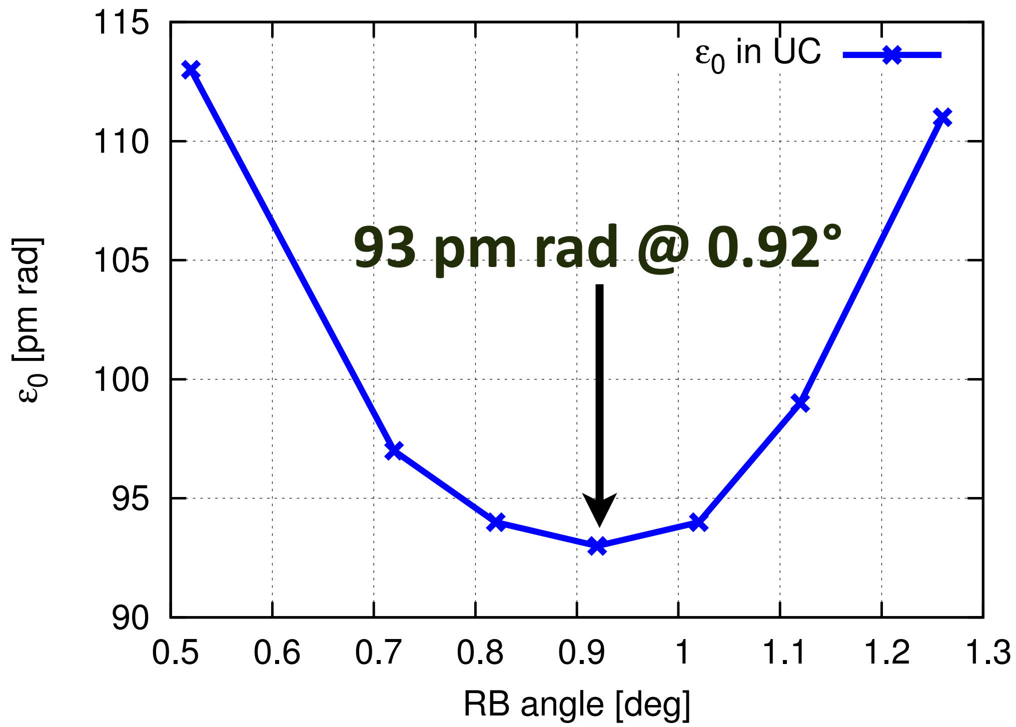
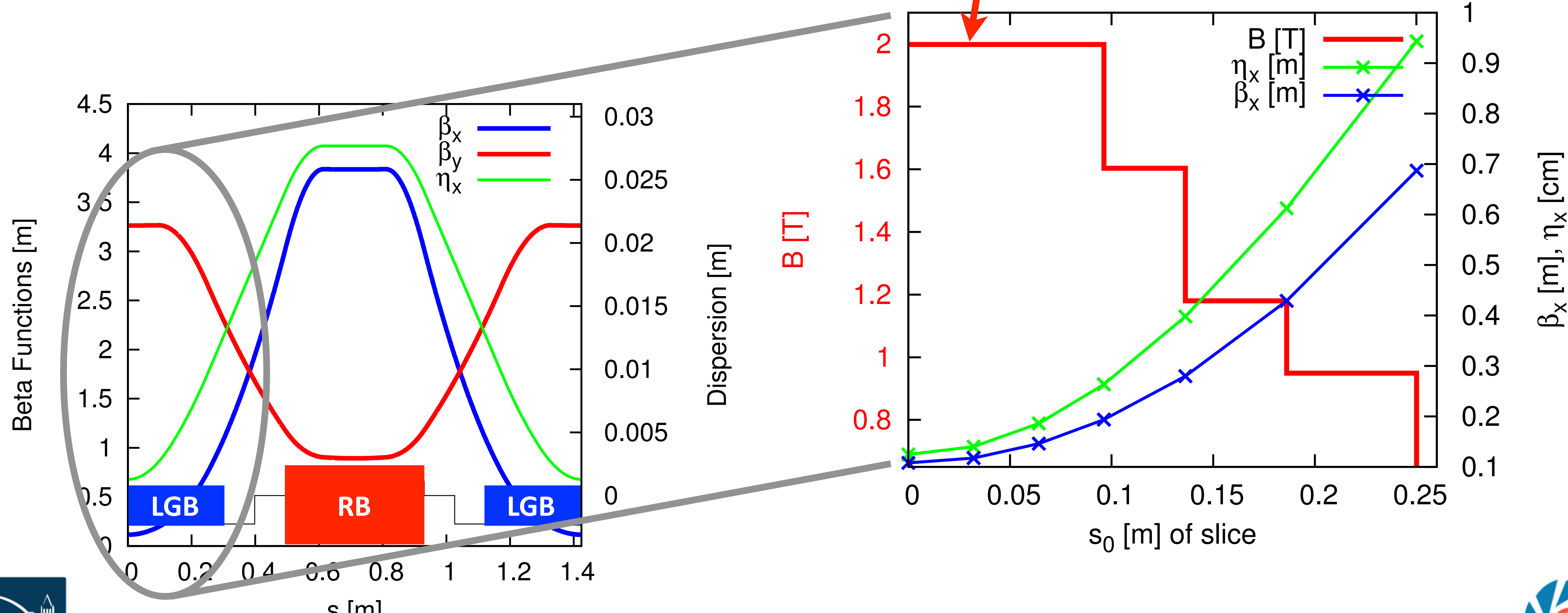




LGB Cell for Lowest Emittance (cont.)

- Instead of RB angle for minimum ε_0 in UC → minimize η^* in bend
- Calculate LGB profile to optimally suppresses ε_0 at this RB angle → in other words, for given bend angle, B^* (assume 2 T possible), β_x^*, and $\eta^* \approx 0$ → what is ideal longitudinal profile $B(s)$?



LGB Cell for Lowest Emittance (cont.)

- Instead of RB angle for minimum ε_0 in UC → minimize η^* in bend
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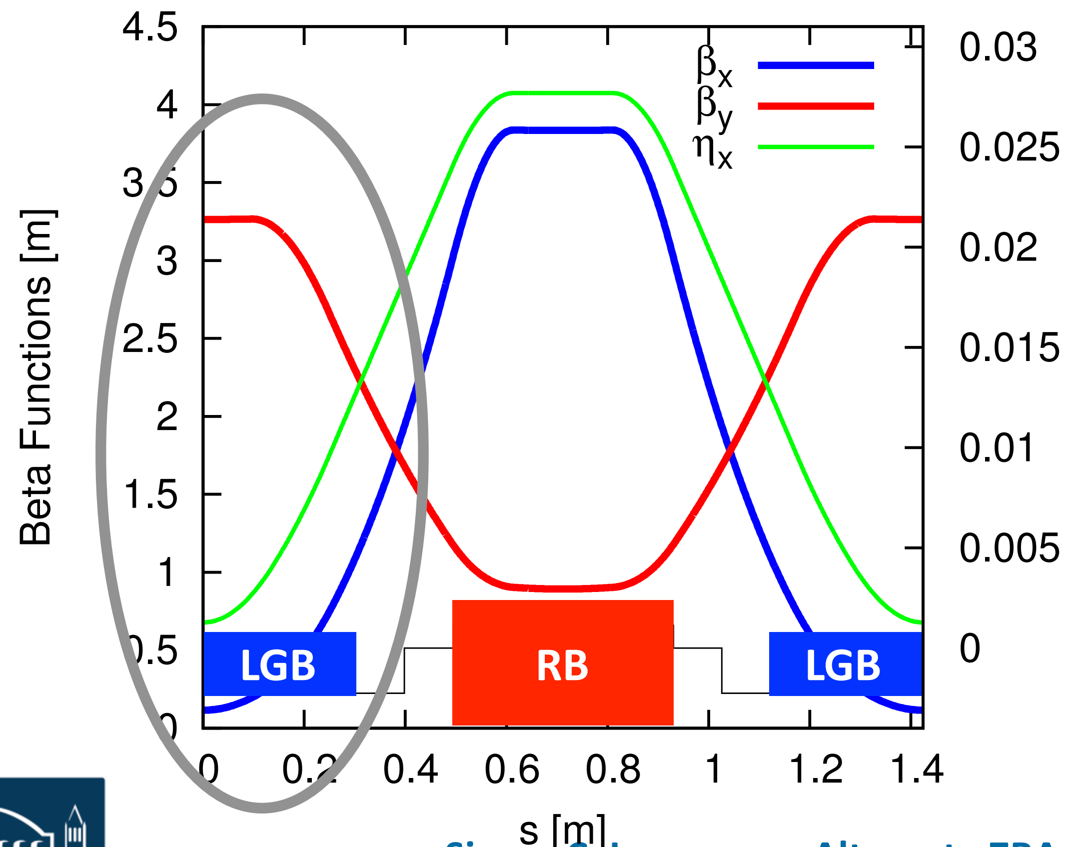
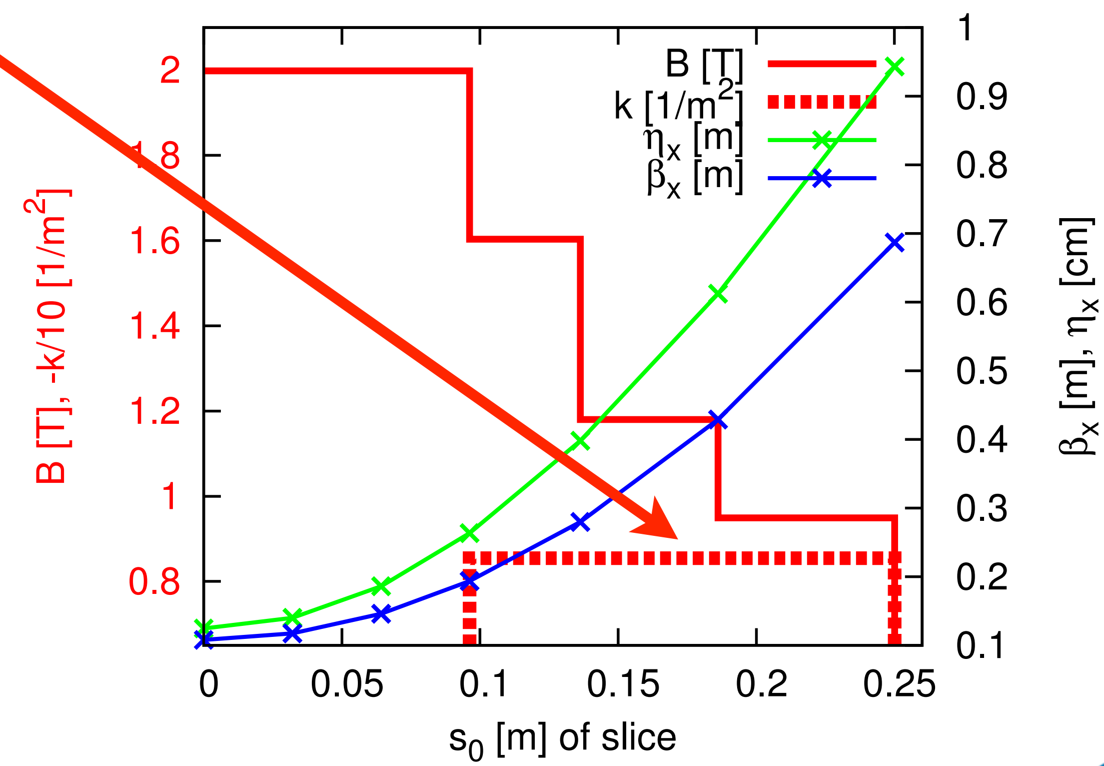
- Finally, add vertical focusing to weaker outer sections of LGB and adjust (together with RB gradient) for $2\pi \times (3/7, 1/7)$ cell tune





LGB Cell for Lowest Emittance (cont.)

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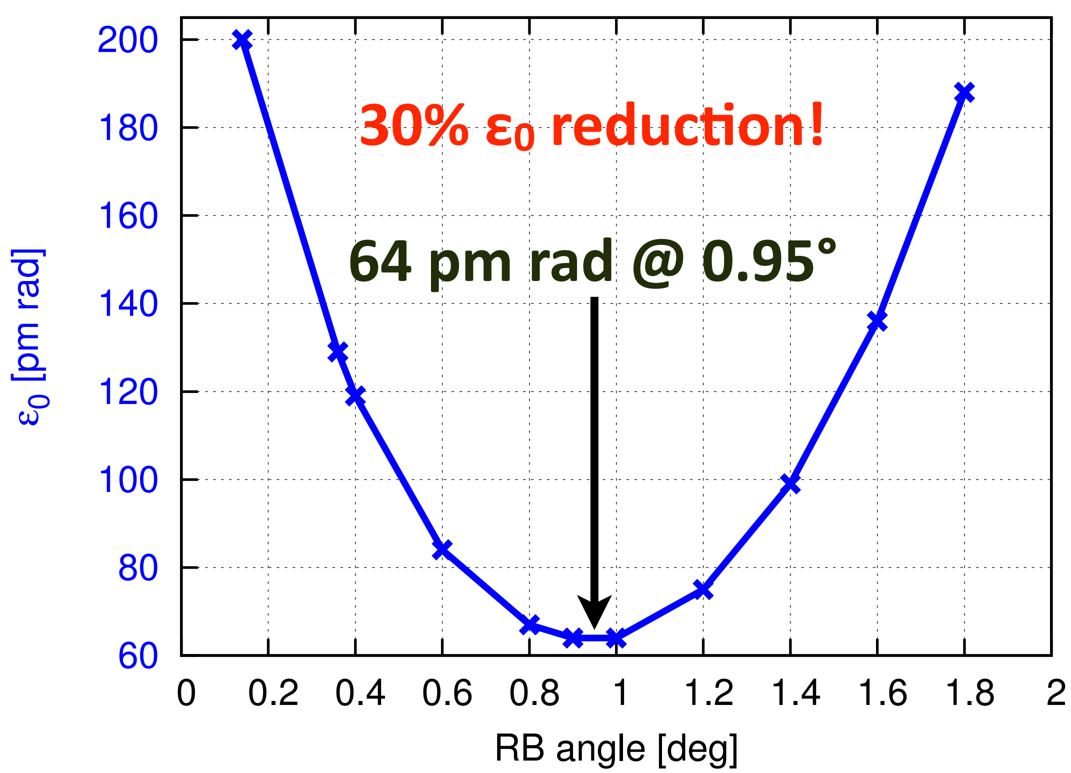
- Then re-tune RB angle for min. ε_0 in UC & final cell tune adjust



LGB Cell for Lowest Emittance (cont.)

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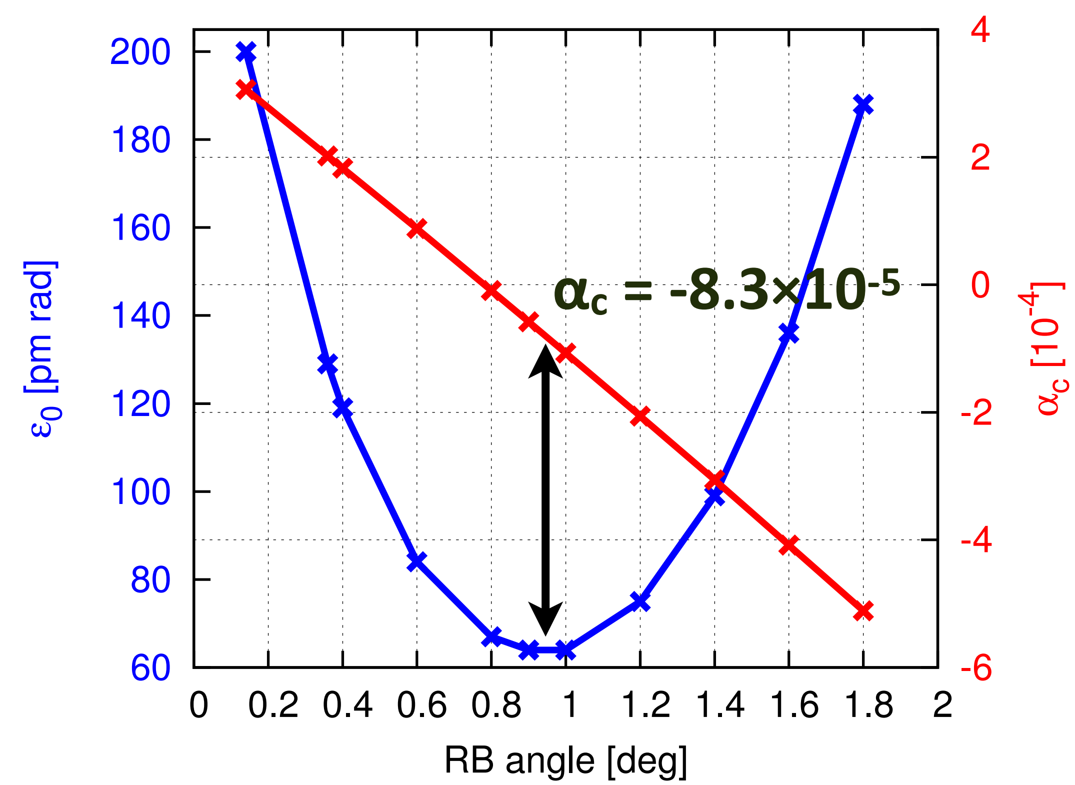
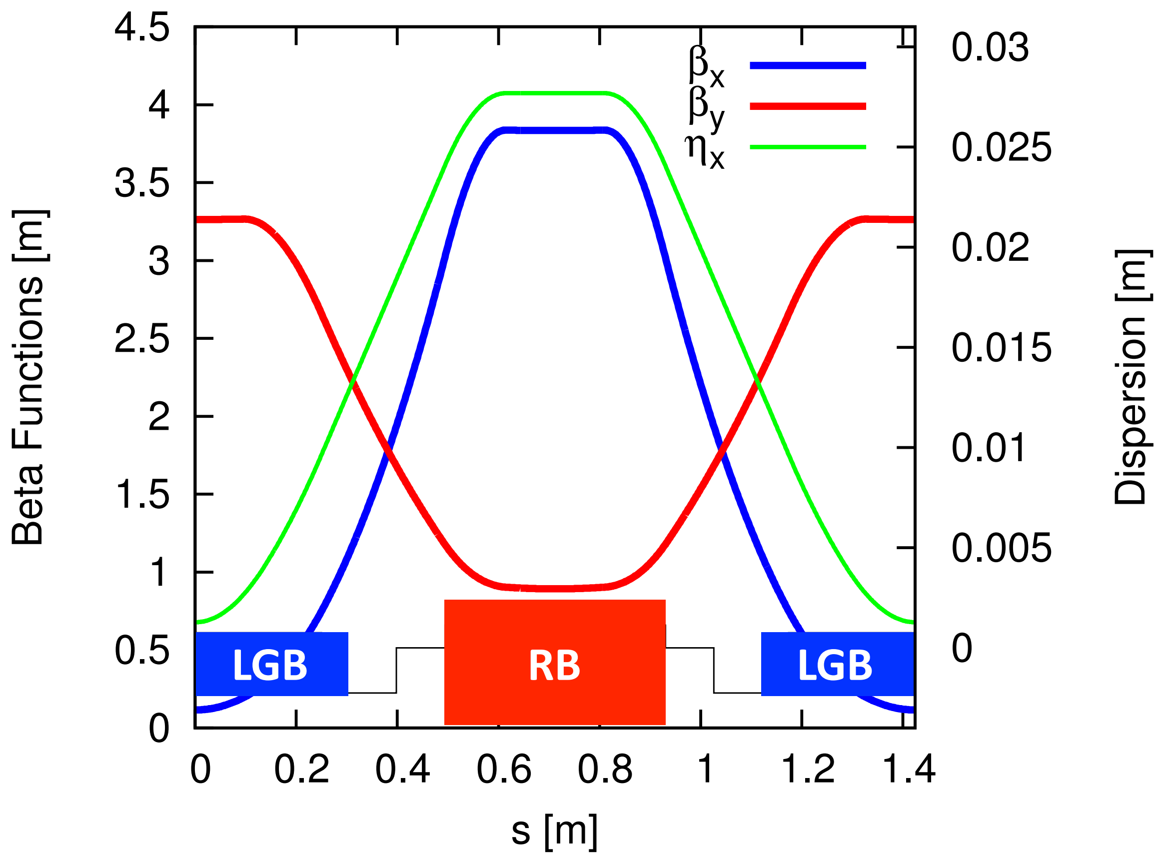
- Calculate LGB profile to optimally suppresses ε_0 at this RB angle ➔ in other words, for given bend angle, B^* (assume 2 T possible), β_x^*, and $\eta^* \approx 0$ ➔ what is ideal longitudinal profile $B(s)$?
- Finally, add vertical focusing to weaker outer sections of LGB and adjust (together with RB gradient) for $2\pi \times (^3/_7, ^1/_7)$ cell tune
- Then re-tune RB angle for min. ε_0 in UC & final cell tune adjust

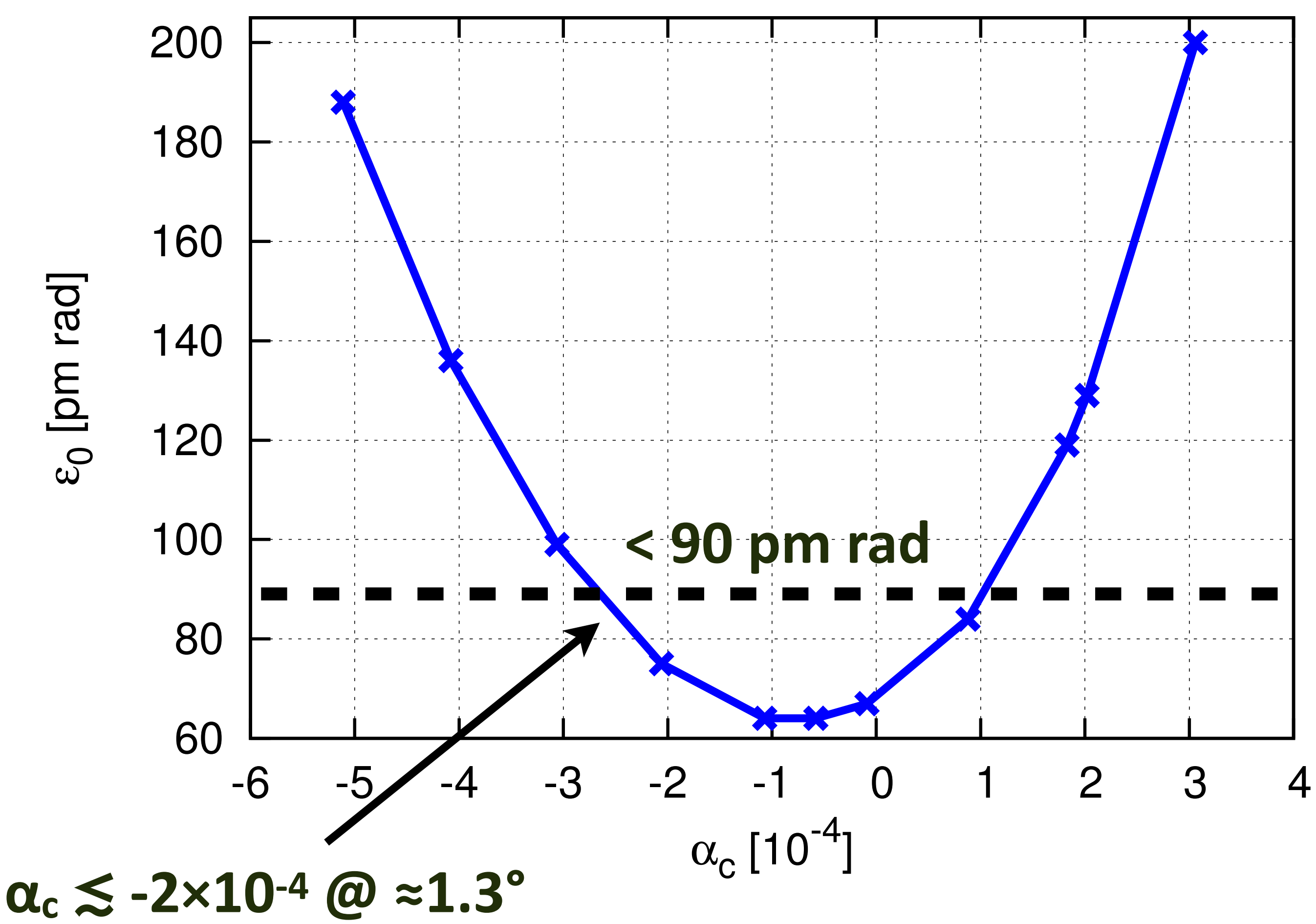
  ➔ as expected, emittance can be much lower, but still, lattice eventually becomes isochronous



Detuned LGB Cell for Increased Mom. Compaction

- Adjust RB angle to provide sufficient momentum compaction
- Re-adjust LGB and RB gradients for $2\pi \times (^3/_7, ^1/_7)$ cell tune

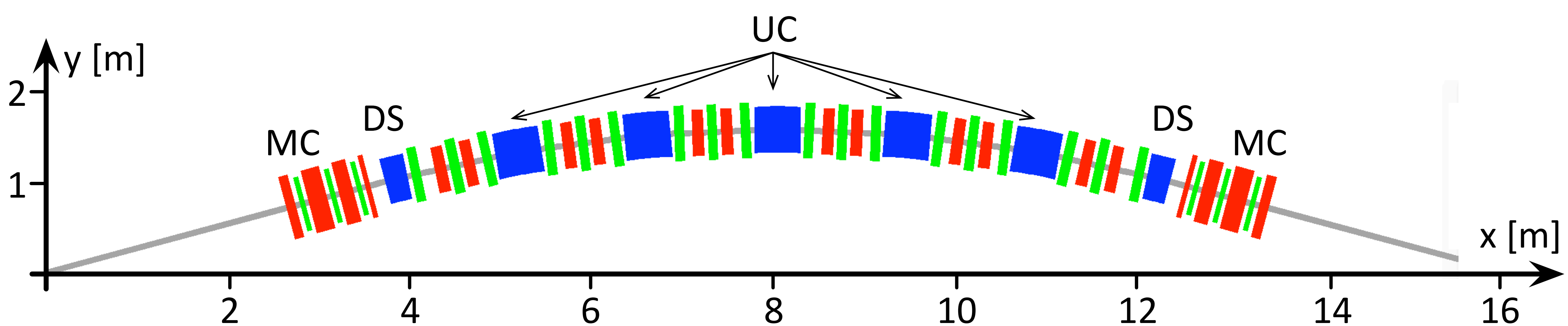




Linear Optics Summary

IPAC'18, THPMF077, p.4252

- Use this detuned UC for new near-min-ε 7BA
- Add appropriately tuned DS and MC (MC quads tuned to desired WP and for $\beta^* \approx 2.2$ m)
- In DS use regular TGB instead of LGB → no HXR shining into SS



Linear Optics Summary (cont.)

IPAC'18, THPMF077, p.4252

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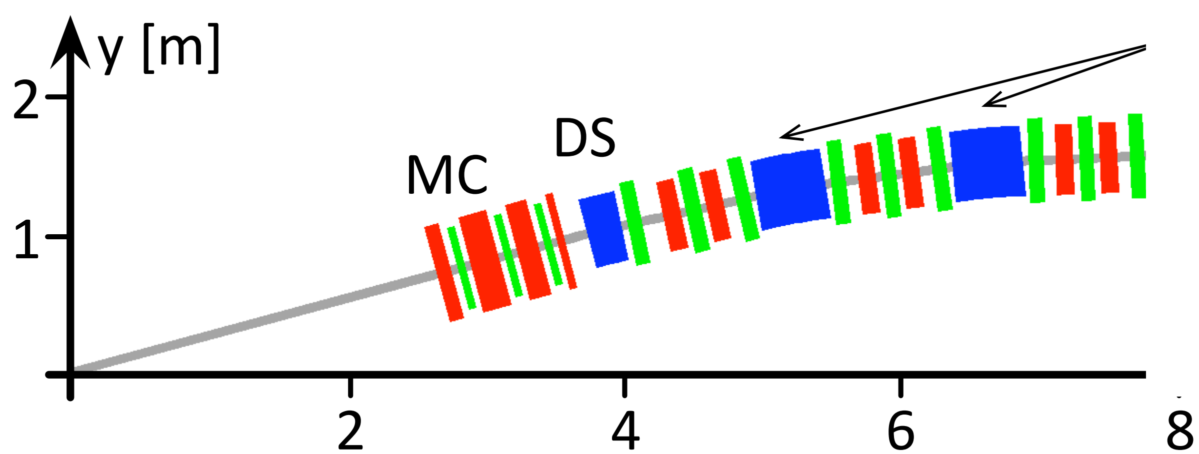

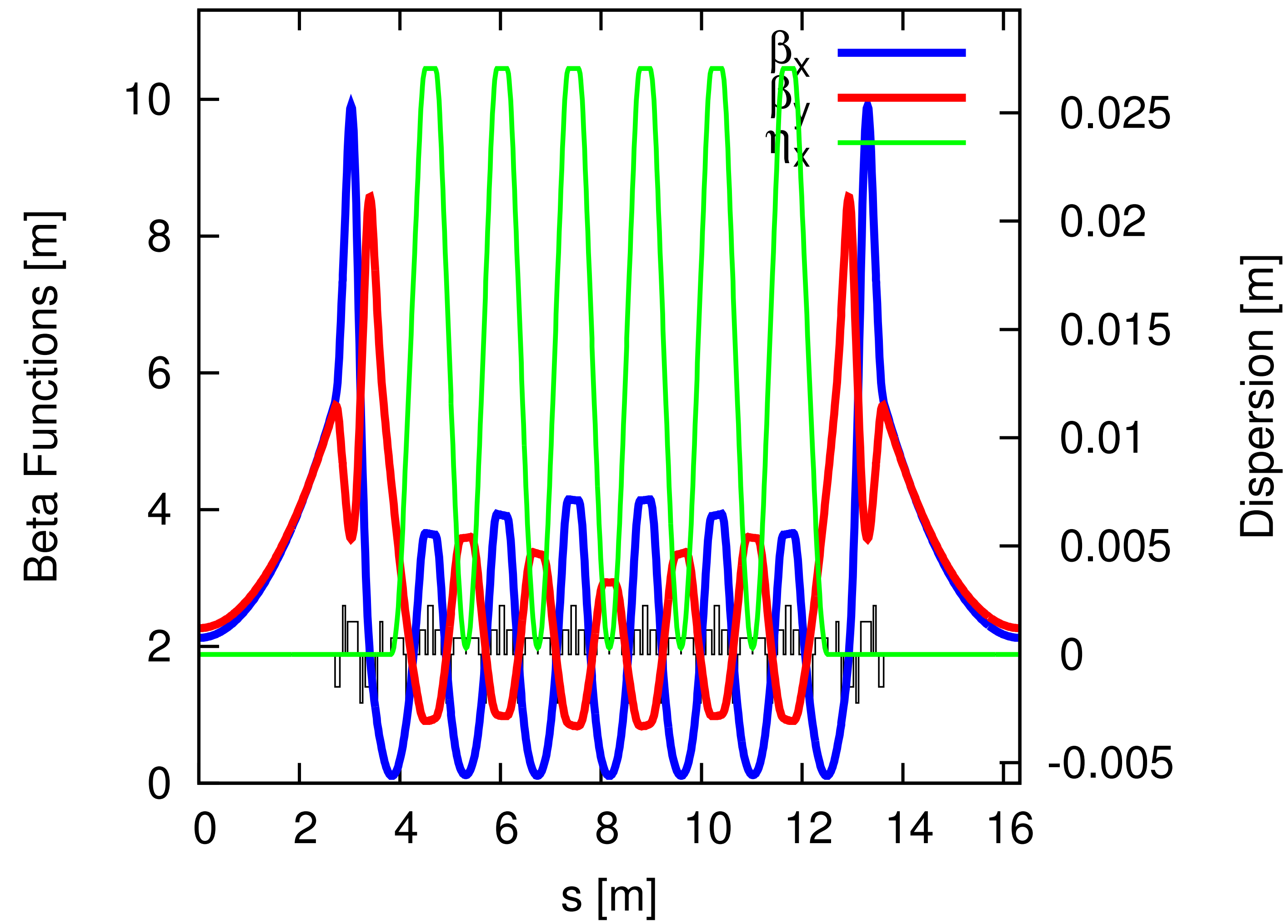

Linear Optics Summary (cont.)

IPAC'18, THPMF077, p.4252

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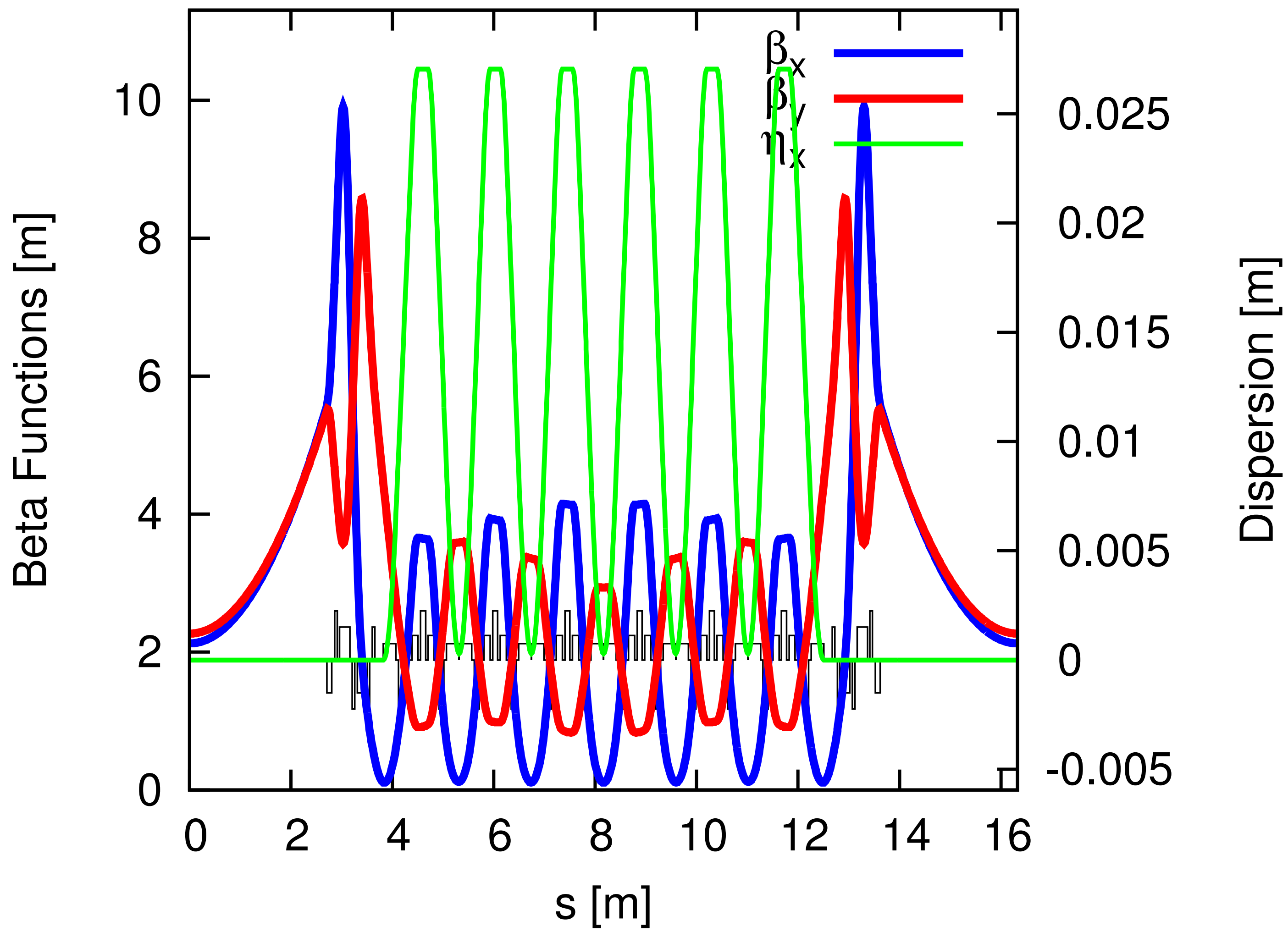
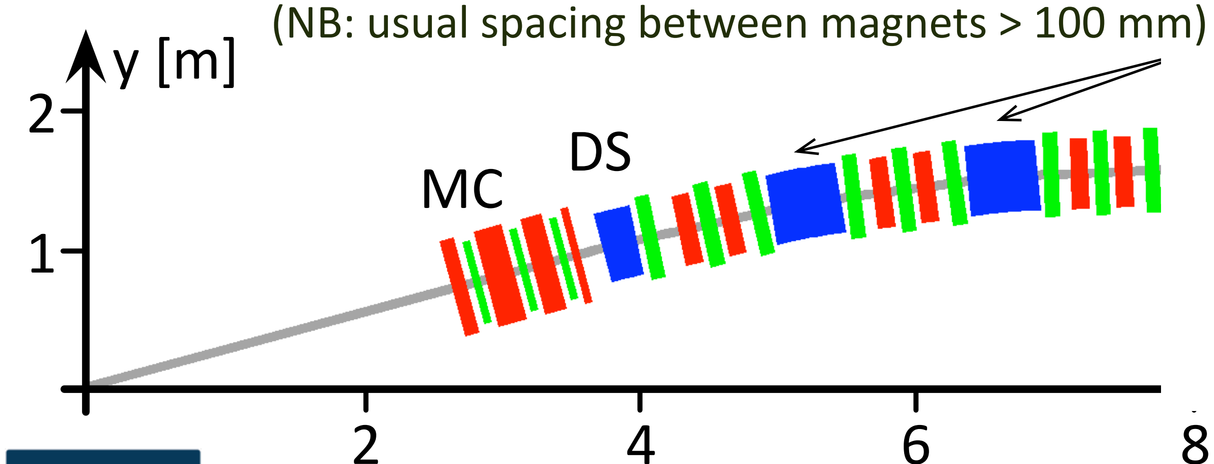
- Add appropriately tuned DS and MC (MC quads tuned to desired WP and for $\beta^* \approx 2.2$ m)
- In DS use regular TGB instead of LGB → no HXR shining into SS
- $\varepsilon_0 = 78$ pm, $\alpha_c = -1\times10^{-4}$
- $J_x = 1.72$, $U_0 = 442.6$ keV
- **$\varepsilon_{x,y} = 49$ pm rad** (fully coupled)
- $\sigma_{x,y} \approx 10$ µm @ ID ($\beta_{x,y} \approx 2.2$ m)
- $\nu_x = 40.38$, $\nu_y = 14.36$
  (chosen with consideration to NL dynamics)
- $\xi_x = -106.4$, $\xi_y = -40.1$
- Peak $\beta \approx 10$ m, $\eta < 27$ mm

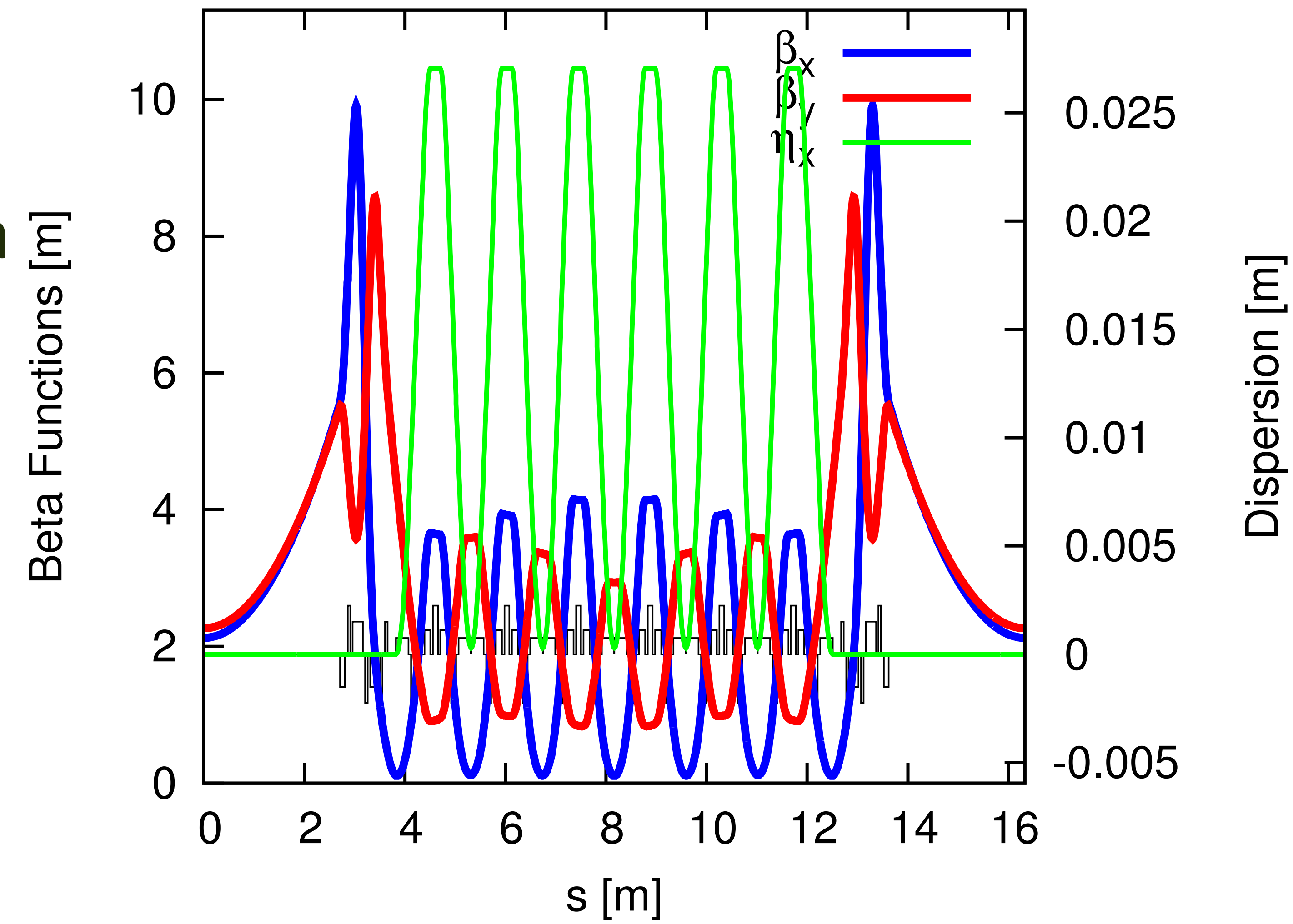


Linear Optics Summary (cont.)

IPAC'18, THPMF077, p.4252

- Magnet requirements:
  - Bends 6.2°, RBs 1.2°
  - RB: ≈0.56 T (0.12 m) & max k ≈ 108 T/m → 5.2 mm offset
  - k @ LGB ends: ≈ –57 T/m
  - MC quads max k: ≈ 102 T/m
  - min. separation between magnets: 48 mm
    (>2.5× min. magnet bore)
    (NB: usual spacing between magnets > 100 mm)



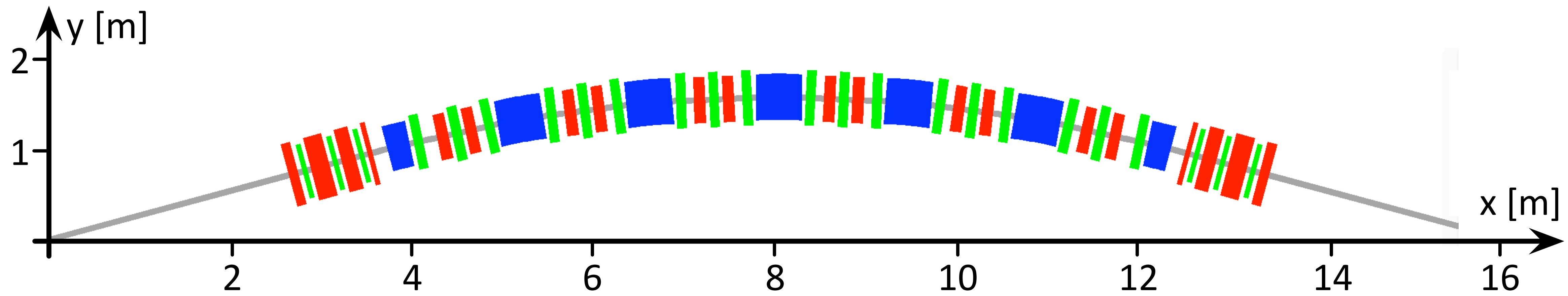


Nonlinear Optics

- HMBAs have large dispersion bumps which relaxes (few) sextupoles
- But our 7BA offers large number of sextupoles at various phase advances ➔ cancel RDTs entirely **within** achromat

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

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



Nonlinear Optics (cont.)

- HMBAs have large dispersion bumps which relaxes (few) sextupoles
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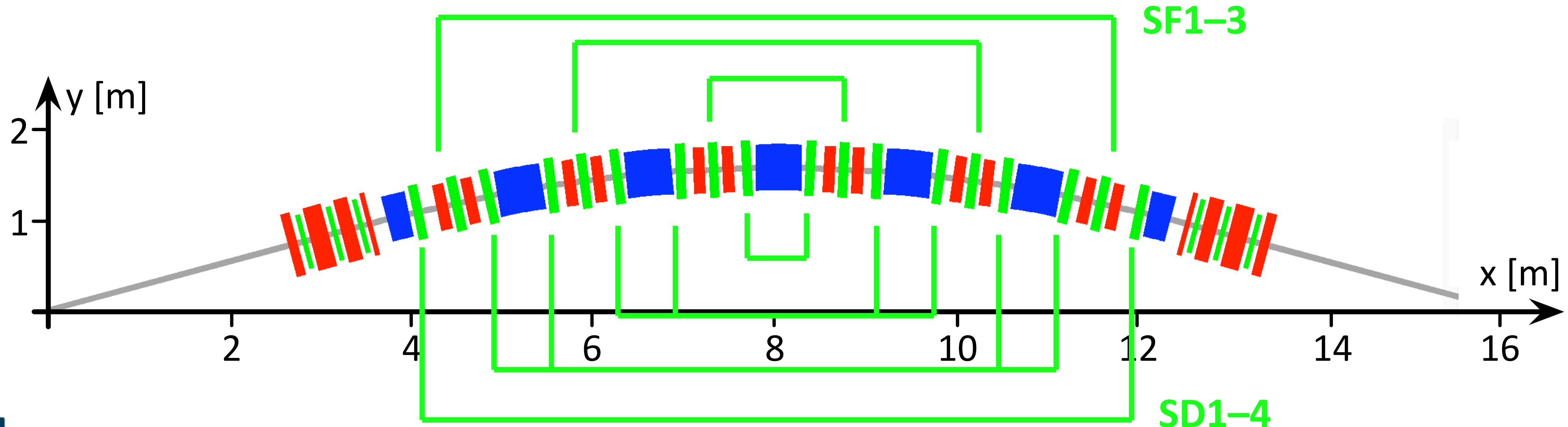
PRST-AB **12**, 120701 (2009)

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

- Introduce 7 chromatic sextupole families: 3 SF & 4 SD
  – SD families in UC come in pairs flanking main bends



Nonlinear Optics (cont.)

- HMBAs have large dispersion bumps which relaxes (few) sextupoles
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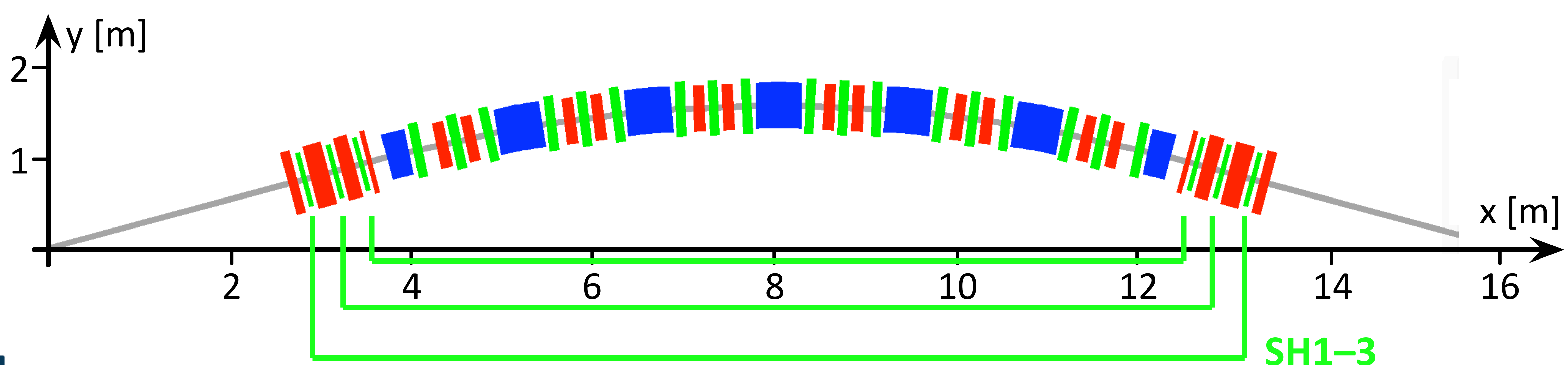
- Add 3 harmonic sextupole families to MC (completing higher-order achromat)



Nonlinear Optics (cont.)

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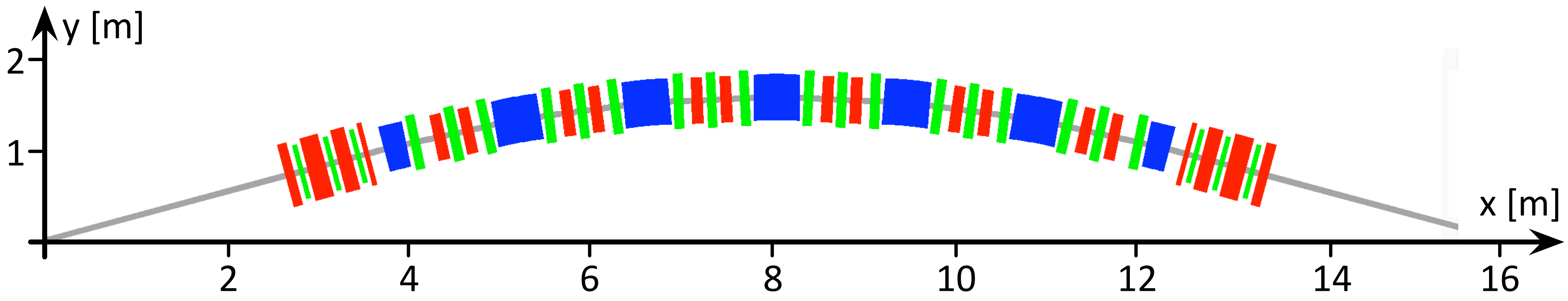
- But our 7BA offers large number of sextupoles at various phase advances ➔ cancel RDTs entirely **within** achromat

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

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

- Introduce 7 chromatic sextupole families: 3 SF & 4 SD
  – SD families in UC come in pairs flanking main bends
- Add 3 harmonic sextupole families to MC (completing higher-order achromat)
- Investigated achromatic octupoles in MC ➔ no substantial benefit considering space requirements (NB: do not expect amplitudes >1 mm @ octupoles)

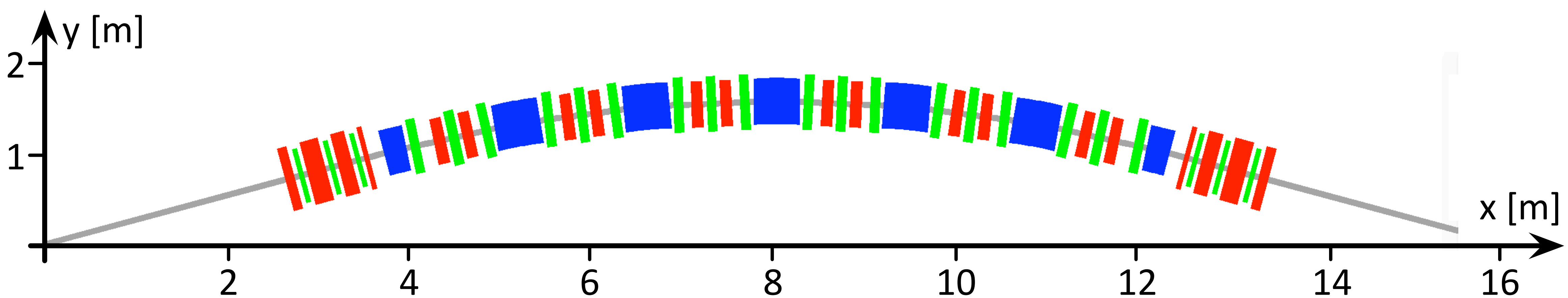


Nonlinear Optics (cont.)

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

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

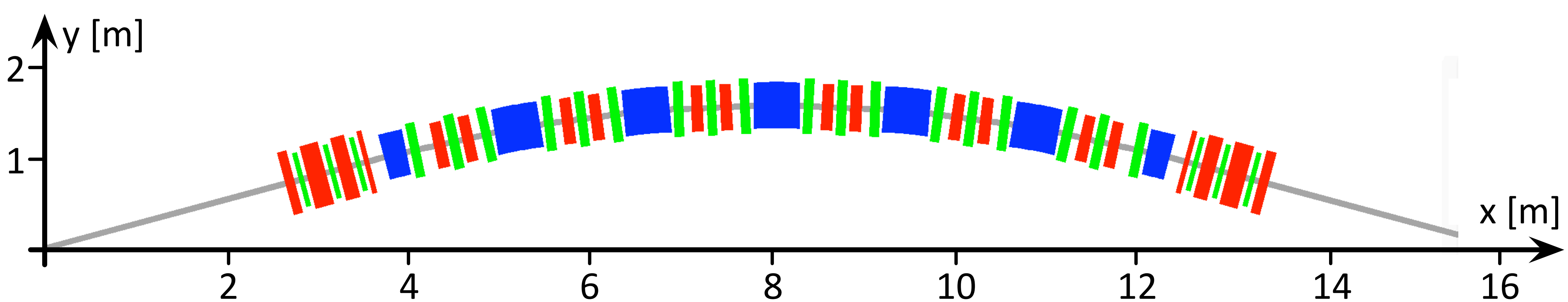
- In total 10 nonlinear knobs
- 7 chromatic sextupole knobs, 5 can be chosen freely
- Tune sextupoles for:
  - linear chromatic correction: –106/–40 ➔ –1/–1
  - 1st/2nd-order RDTs (weighted SVD to cancel)
  - 2nd/3rd-order chromaticities (weighted SVD to achieve specific target values)
  - 1st-order ADTS terms (weighted SVD to achieve specific target values)



Nonlinear Optics (cont.)

NIM-A **645**, 168-174 (2011) PRST-AB **15**, 054002 (2012)

- Because of higher-order achromat tuning we suppress RDTs
  - Note, this is just an approximation:
    - finite sextupole lengths
    - MC+DS ≠ UC in terms of phase advance
    - detuning of achromat to achieve desired overall WP
    - degeneracy of RDTs



Nonlinear Optics (cont.)

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PRST-AB **12**, 120701 (2009) PRST-AB **14**, 030701 (2011)

- Only linear ADTS can be set, but higher orders present & strong
  - cancelation of linear ADTS is therefore insufficient
  - instead, adjust linear terms to compensate for higher-order contributions over relevant amplitudes (acceptance)

Nonlinear Optics (cont.)

NIM-A **645**, 168-174 (2011) PRST-AB **15**, 054002 (2012)

- Because
  - Note,
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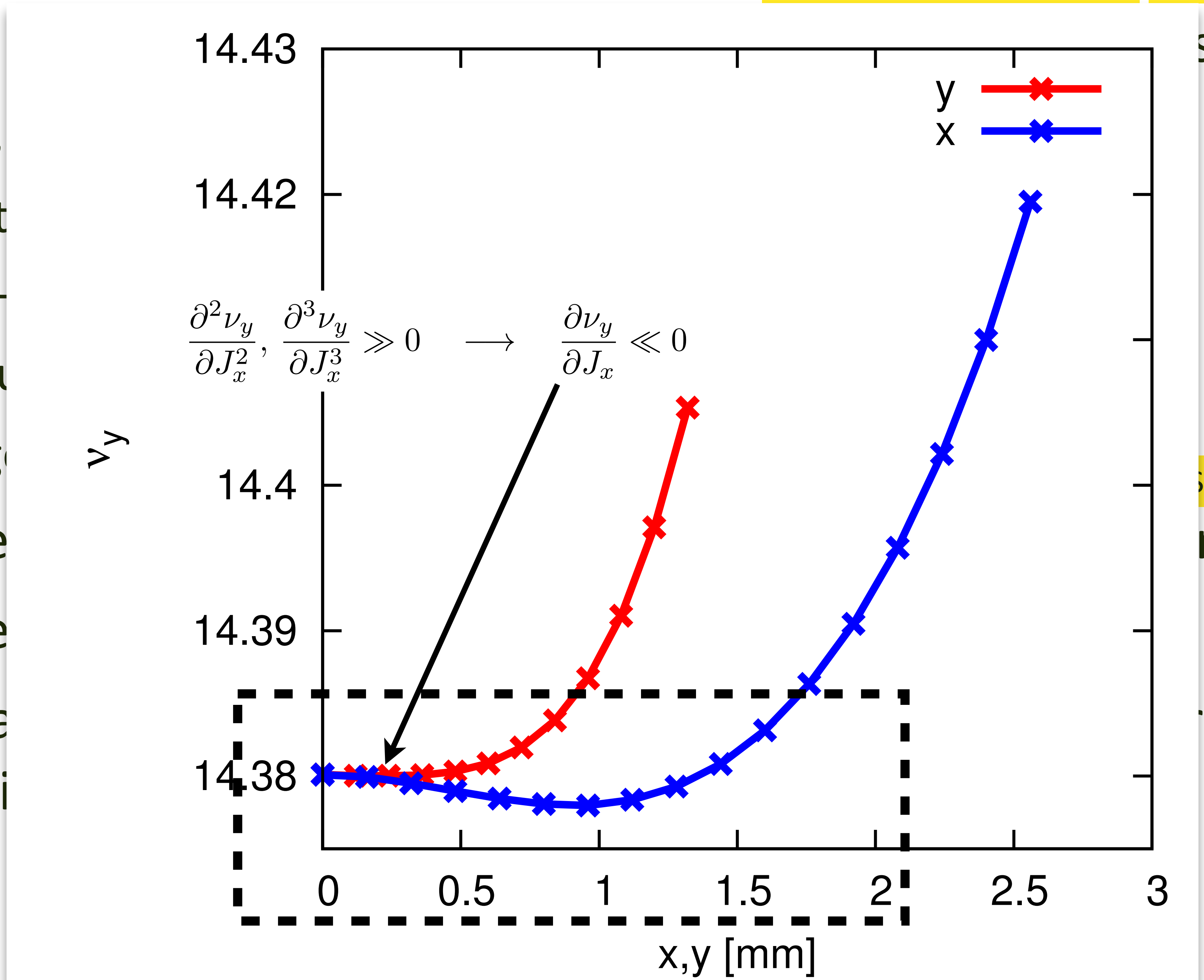
…T-AB **14**, 030701 (2011)



Nonlinear Optics (cont.)

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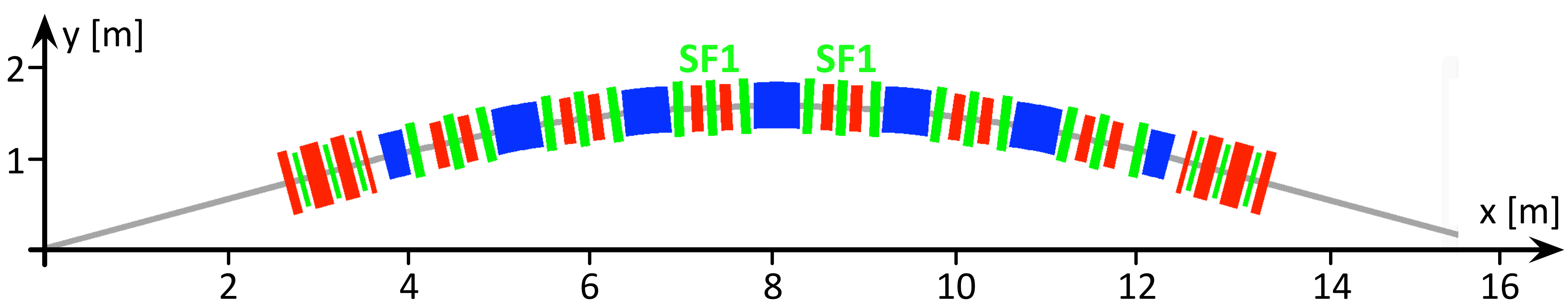
- Only linear ADTS can be set, but higher orders present & strong
  - cancelation of linear ADTS is therefore insufficient
  - instead, adjust linear terms to compensate for higher-order contributions over relevant amplitudes (acceptance)
- Process requires many iterations with 6D tracking to determine and confirm (errors) optimum tuning

Nonlinear Optics (cont.)

IPAC'18, THPMF077, p.4252

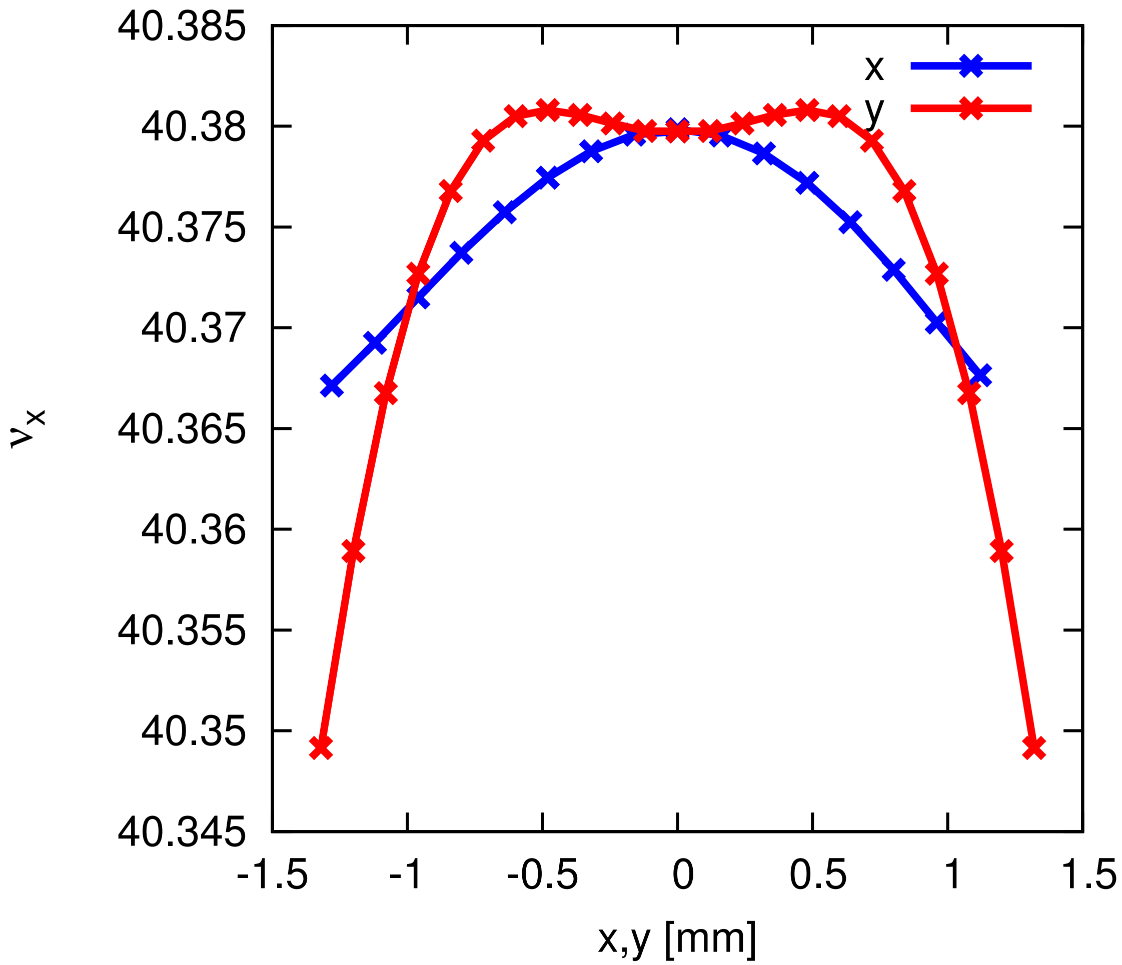
- Sextupole requirements:
  - $b_3 \leq 1667\ 1/m^3$ (assume 18 mm magnet bore, limit PTF to <0.9 T)
  - 18 mm bore → uniform 15 mm arc chamber → exceeds ±4.5 mm acceptance (in both planes) across entire ID straight
  - strongest family SF1: $b_3 = 1645\ 1/m^3$
  - SH and SD families (all but one) substantially weaker

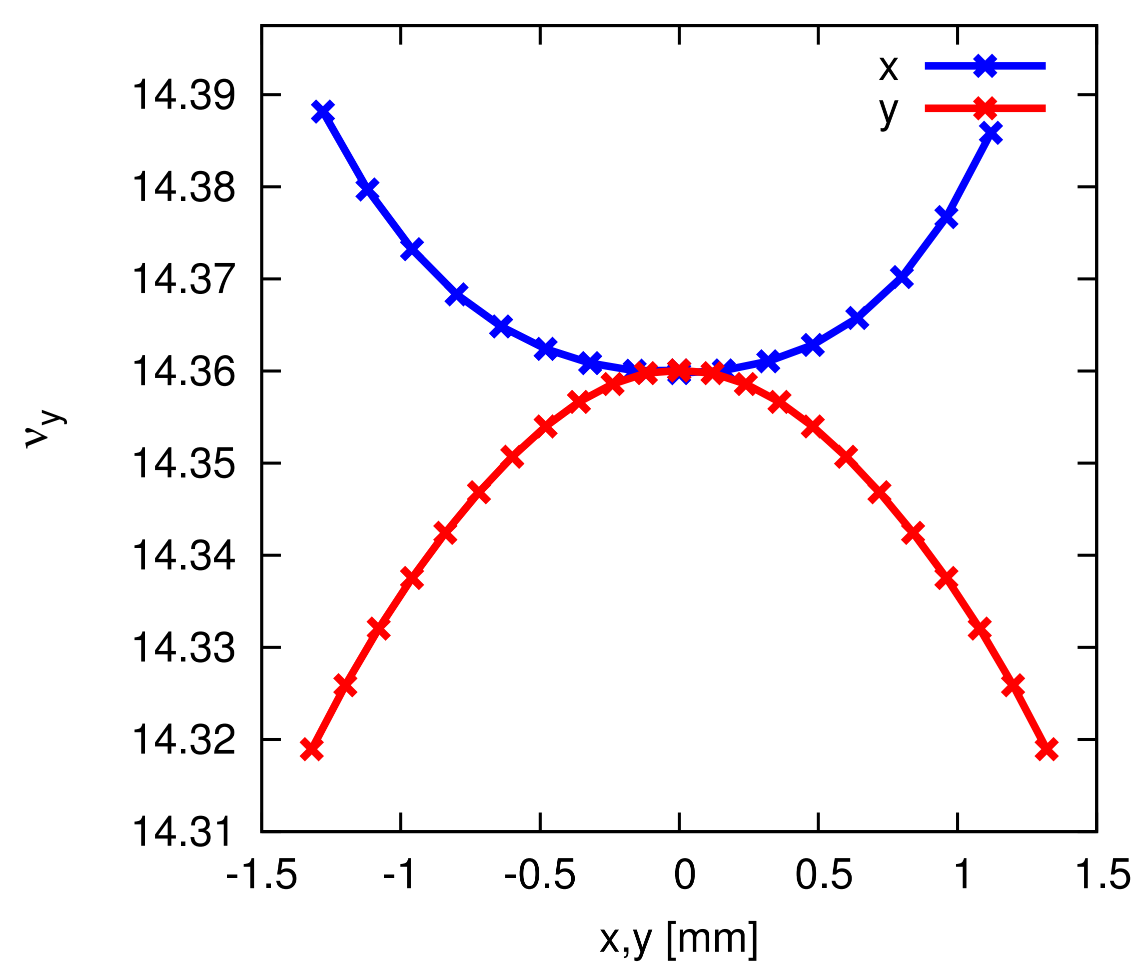


Expected Performance: Tune Shifts

IPAC'18, THPMF077, p.4252

- Resulting tune shifts small across relevant range (acceptance) ➔ small tune footprint, clear of harmful resonances (proximity to coupling res. for round beam)





Expected Performance: Tune Shifts (cont.)

IPAC'18, THPMF077, p.4252

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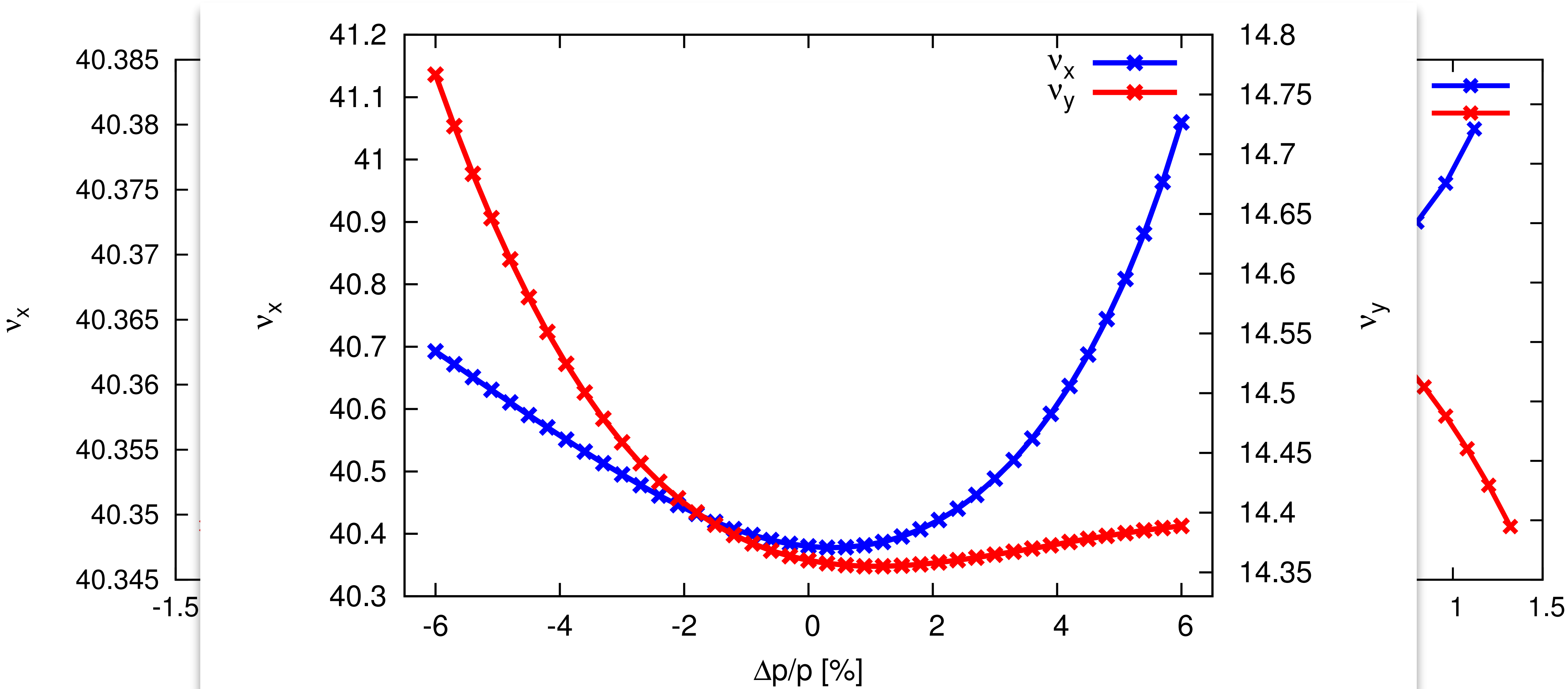

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Expected Performance: Tune Shifts (cont.)

IPAC'18, THPMF077, p.4252

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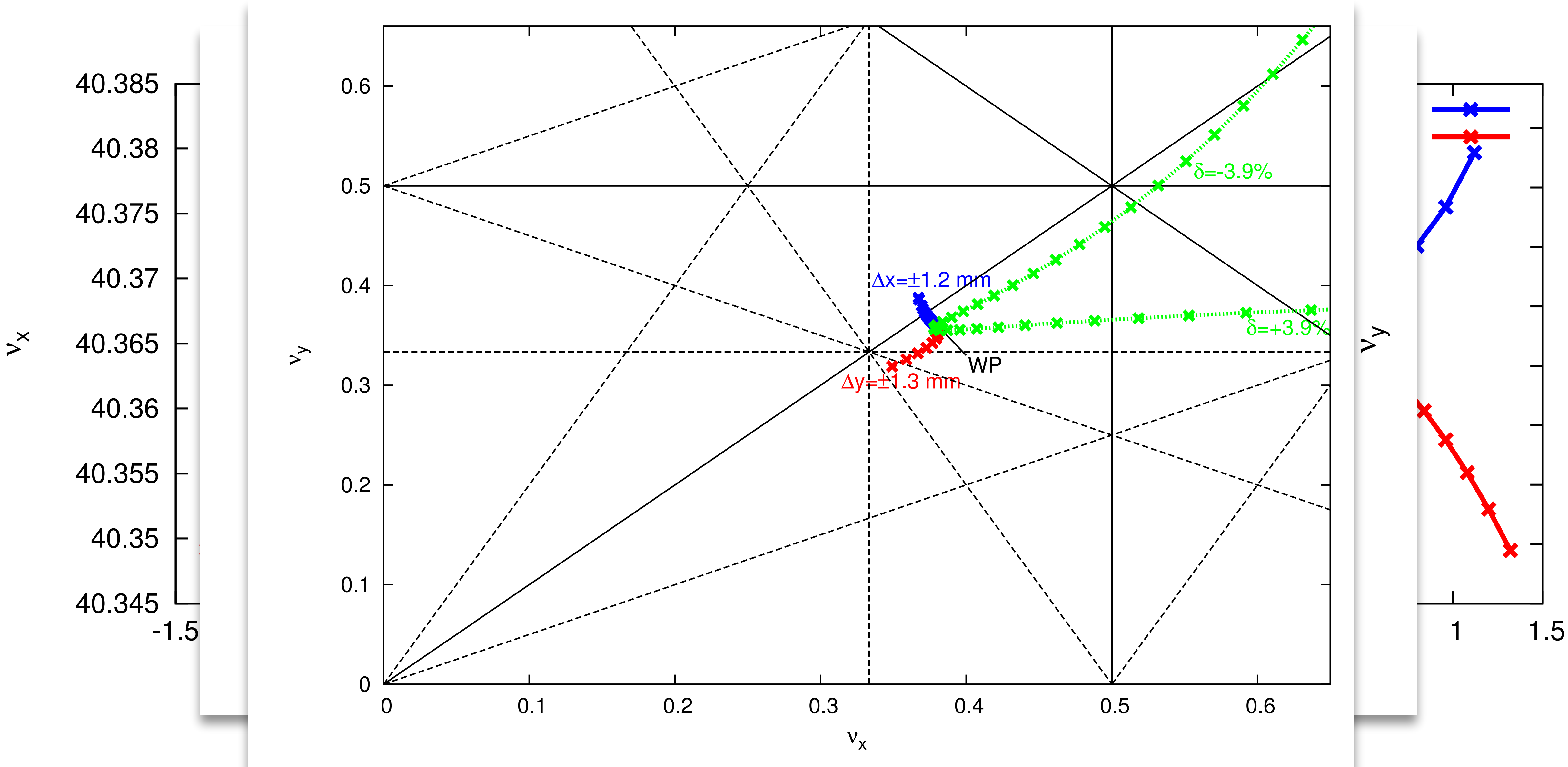
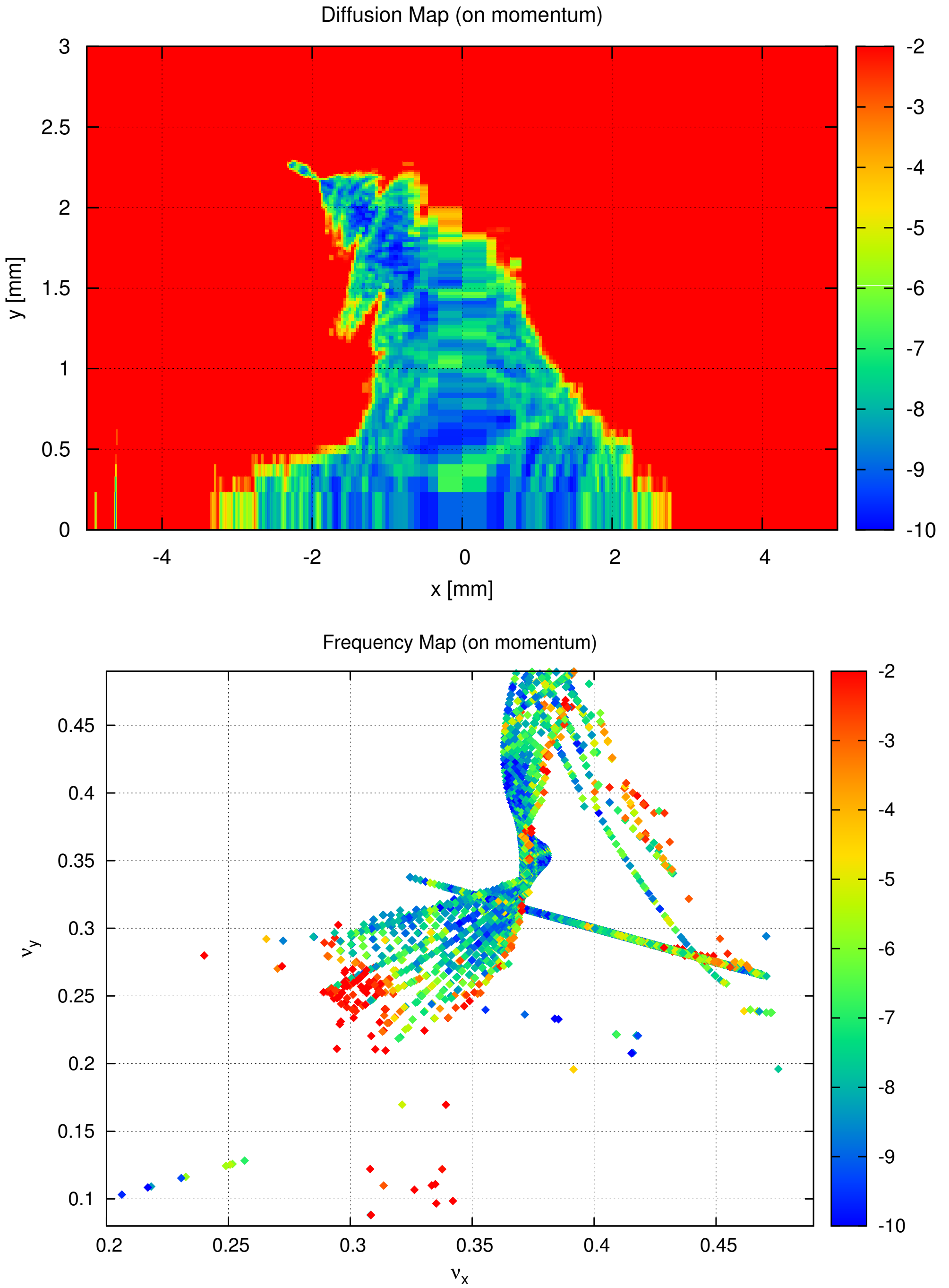


Expected Performance: FMA

IPAC'18, THPMF077, p.4252

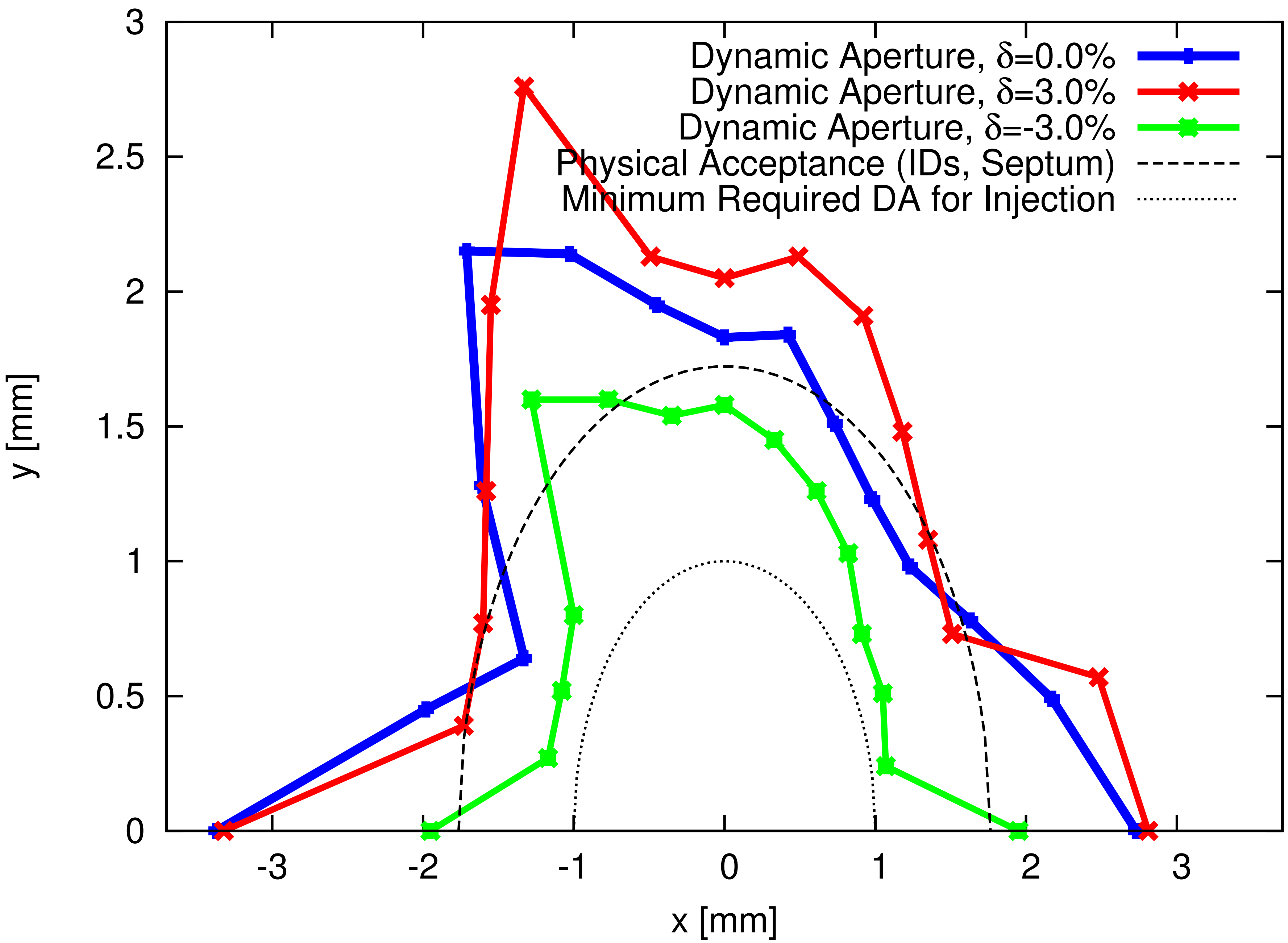
- Compact tune footprint results in homogeneous low diffusion rates



Expected Performance: DA

IPAC'18, THPMF077, p.4252

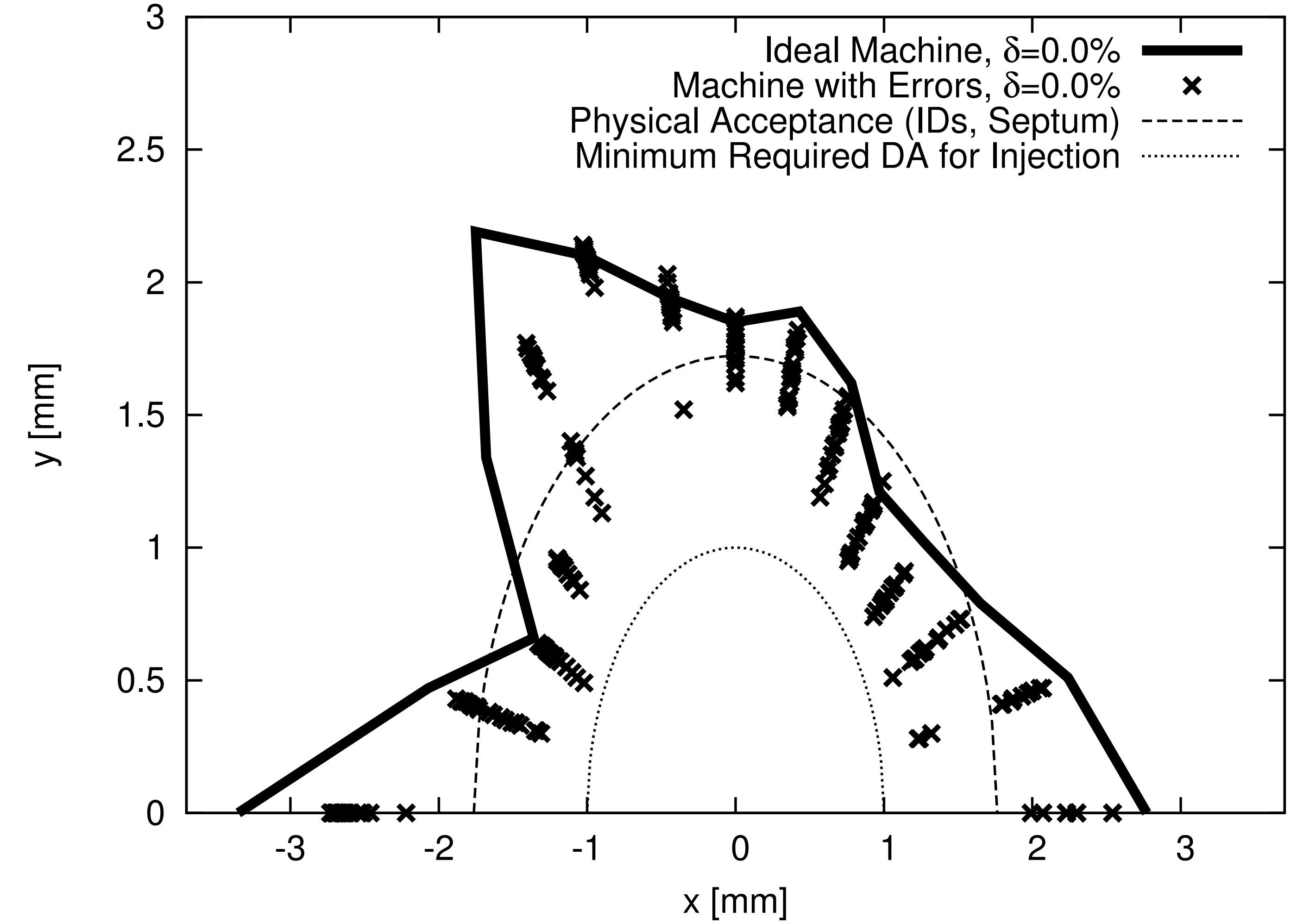
- FMA is 4D ➔ verify in 6D tracking that DA large on & off momentum

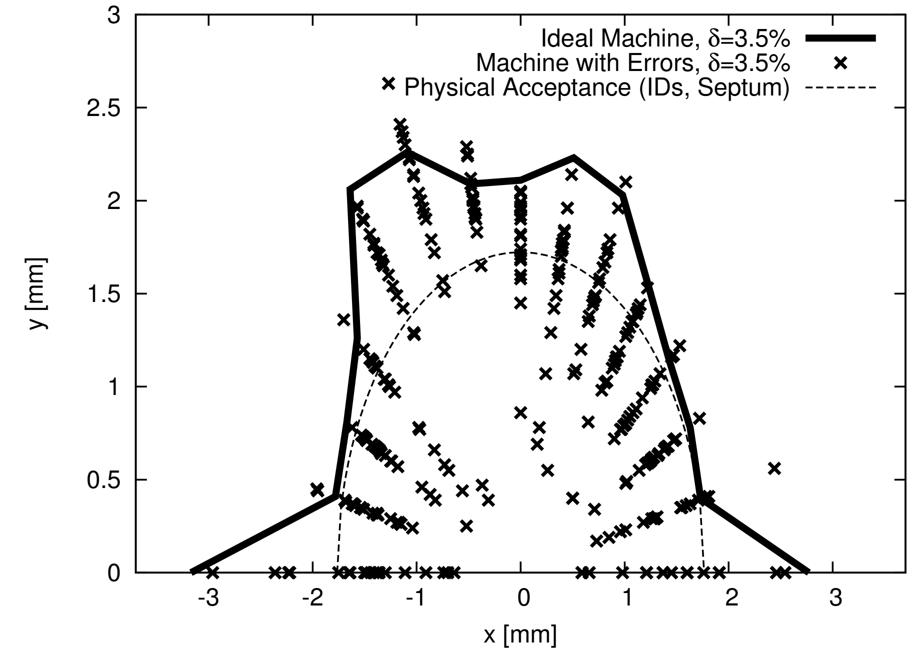


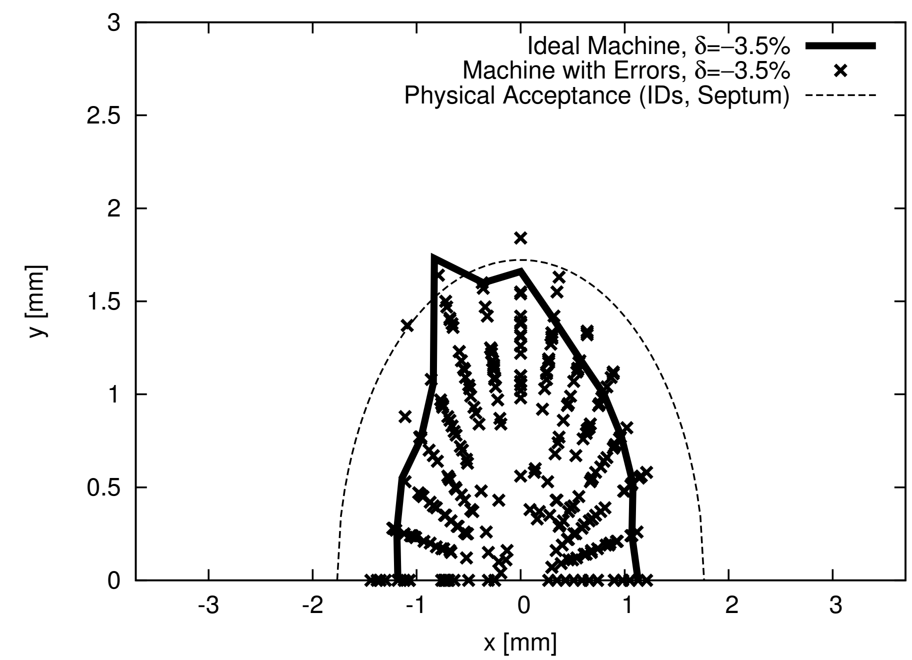
Expected Performance: DA with Errors

IPAC'18, THPMF077, p.4252

- Verify DA preserved in real machine, i.e. when incl. imperfections







Dipoles & BPMs:
- **misaligned & rolled**

Quadrupoles & Sextupoles:
- **misaligned & rolled**
- **field errors & skew errors**

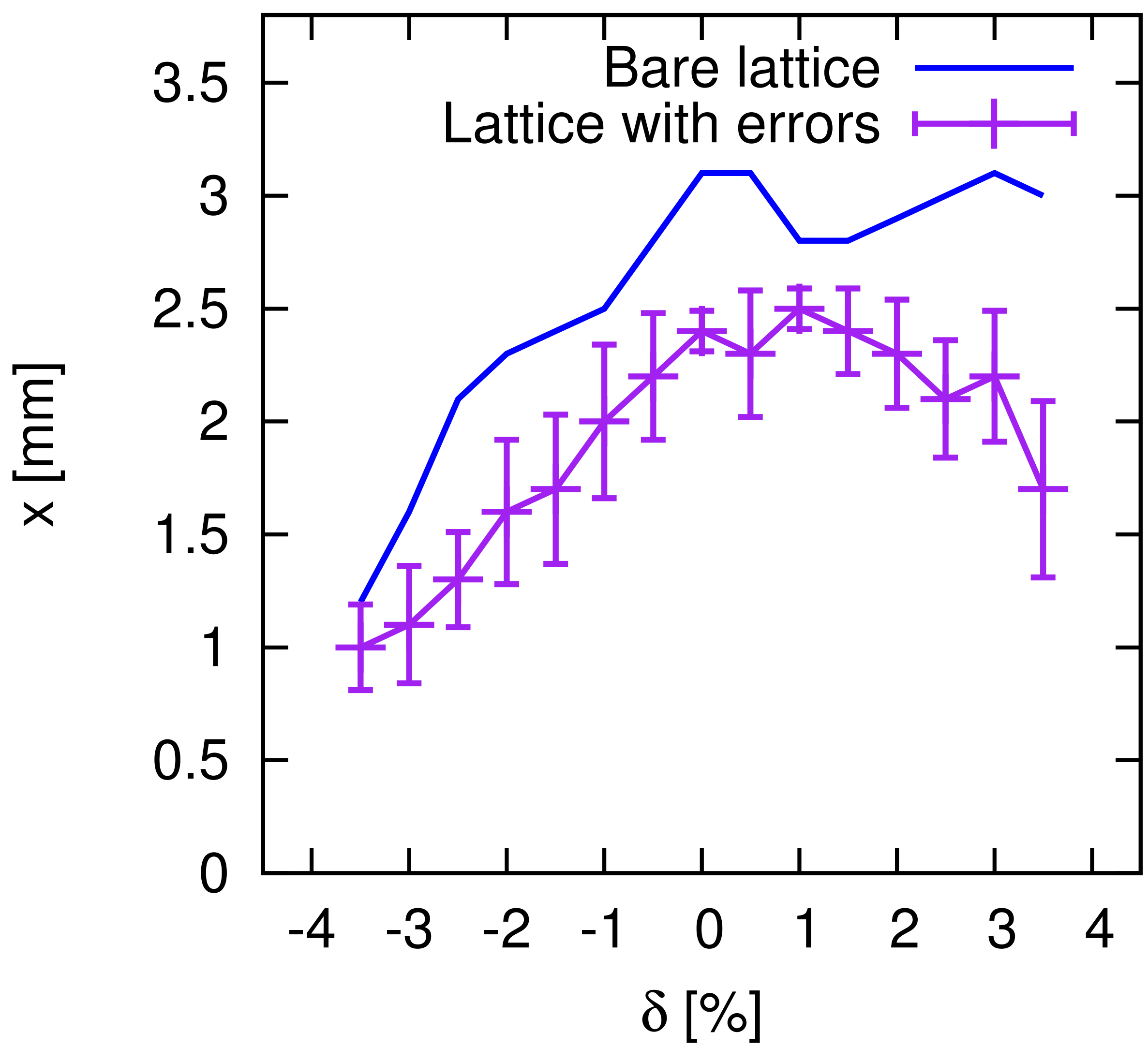
- **Gaussian, ±2σ cut**
- **20 random seeds**

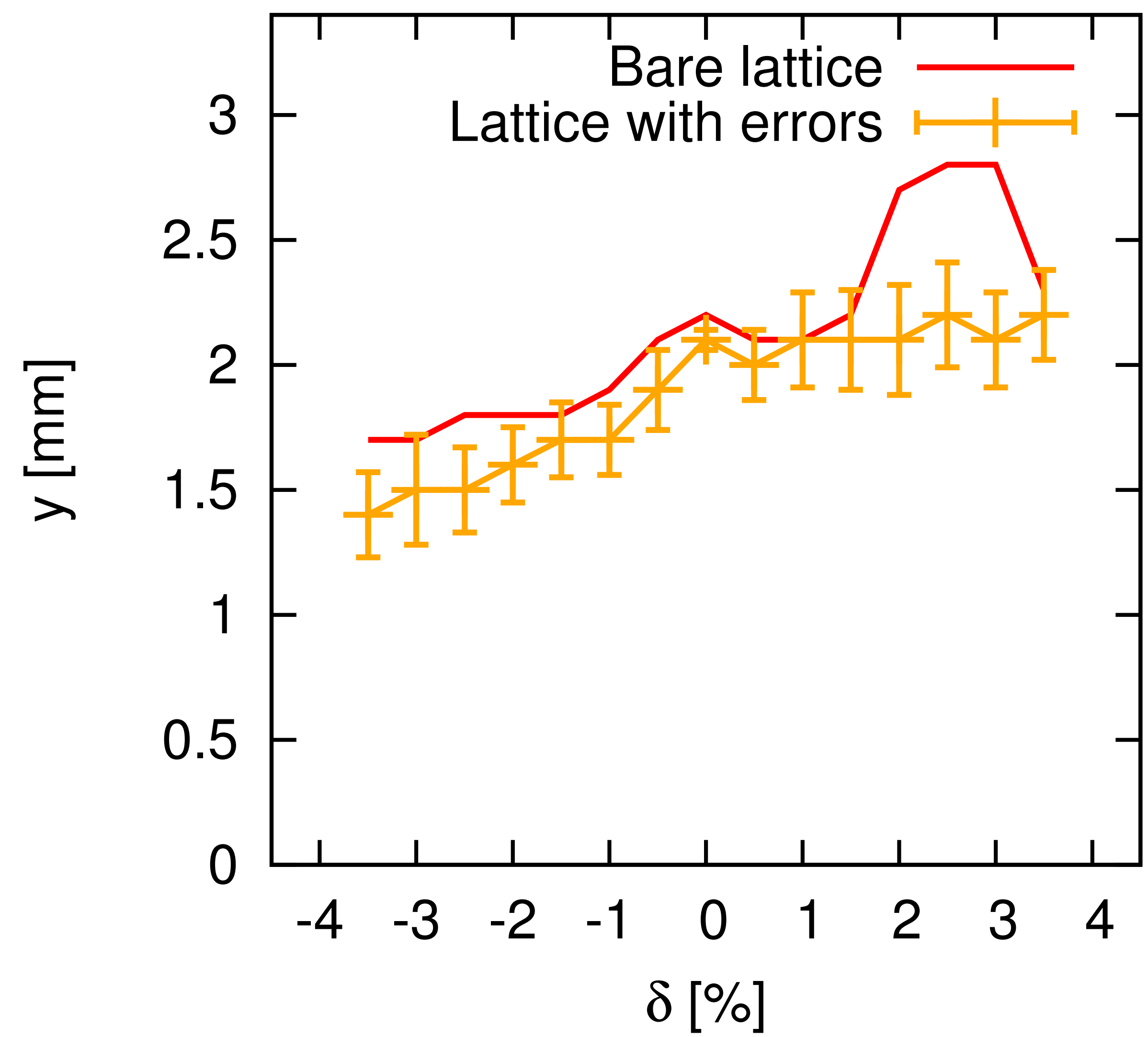
→ Orbit corrected
→ No skew correction
→ Errors scaled until ≈3 μm rms CODs and ≈2% beta beat

Expected Performance: DA with Errors (cont.)

IPAC'18, THPMF077, p.4252

- Sufficient off-mom. DA (incl. errors) required to ensure large LMA

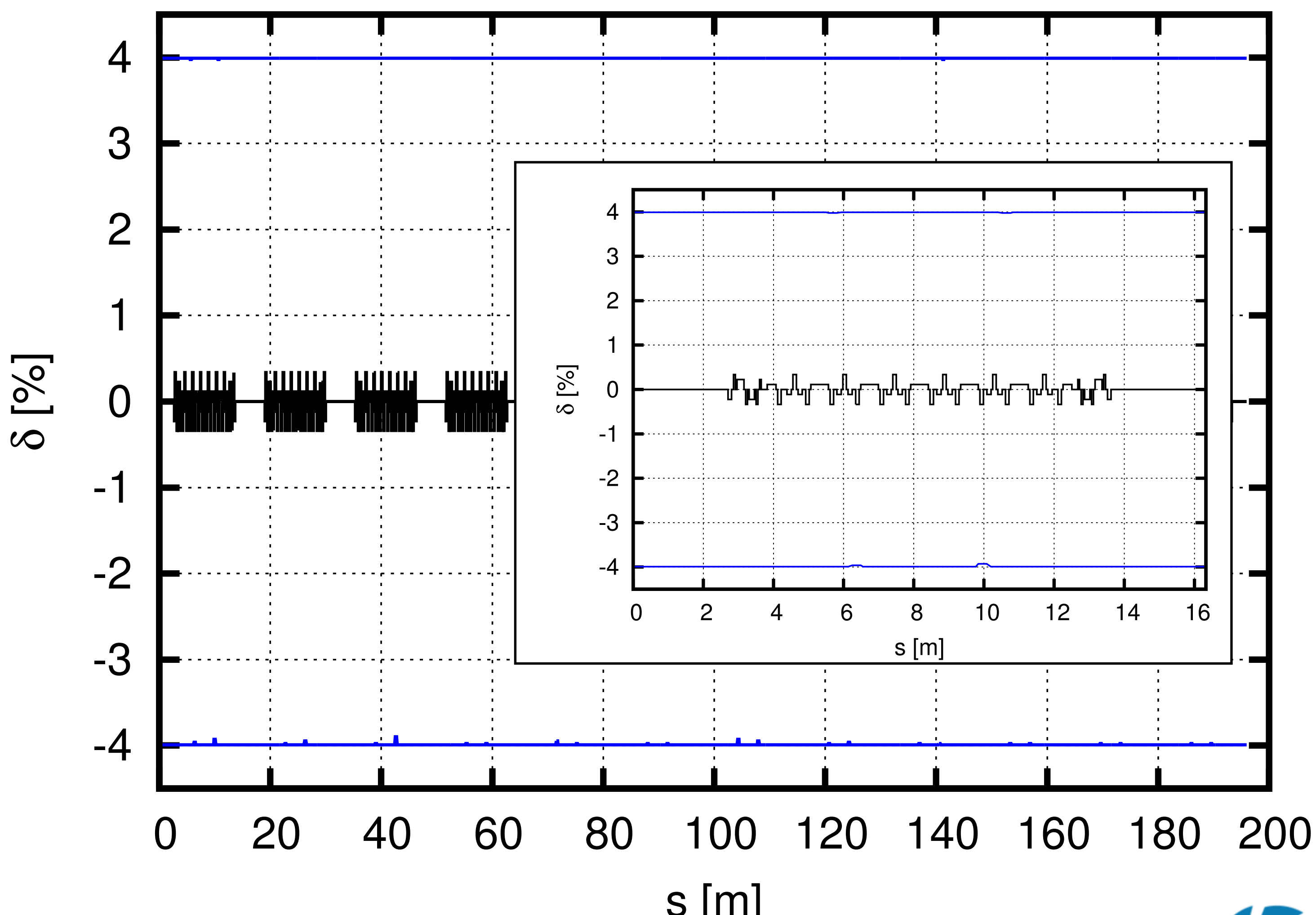




Expected Performance: LMA & Touschek

IPAC'18, THPMF077, p.4252

- LMA from 6D tracking with errors → large overall MA possible by virtue of LMA matching/exceeding RF acceptance (bucket height)
  - LMA somewhat asymmetric due to better DA for δ>0
  - Overall MA calculated assuming 0.715 MV → δ_{rf} = 4%
  - 6D Touschek tracking
    → **7.1 hrs incl. HHCs**
    (≈7.9 hrs if IBS @ 500 mA included)



Expected Performance: LMA & Touschek (cont.)

IPAC'18, THPMF077, p.4252

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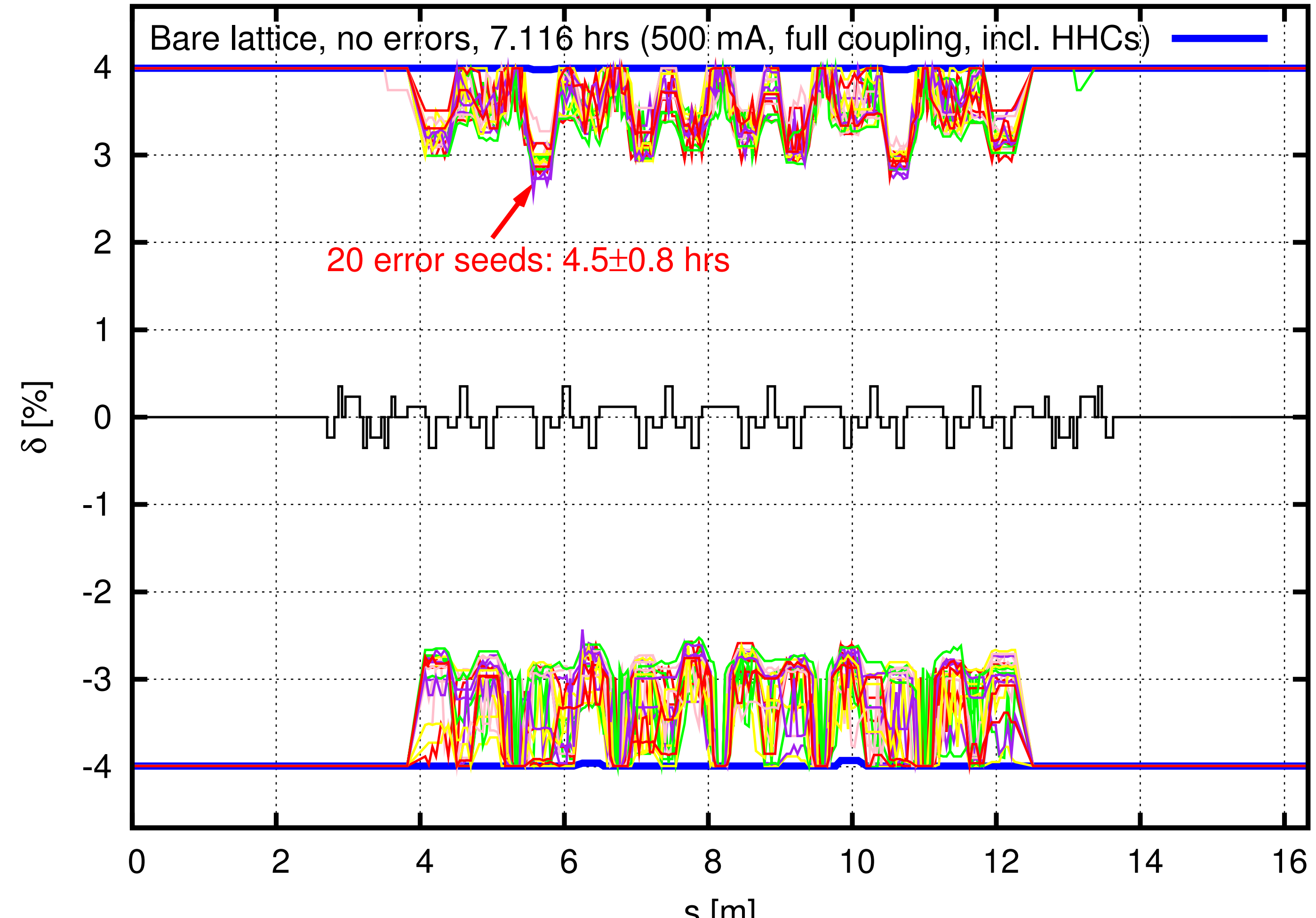
    ➔ **7.1 hrs incl. HHCs**
    (≈7.9 hrs if IBS @ 500 mA included)
  - Using 20 error seeds
    ➔ **4.5 ± 0.8 hrs** incl. HHCs



Expected Performance: LMA & Touschek (cont.)

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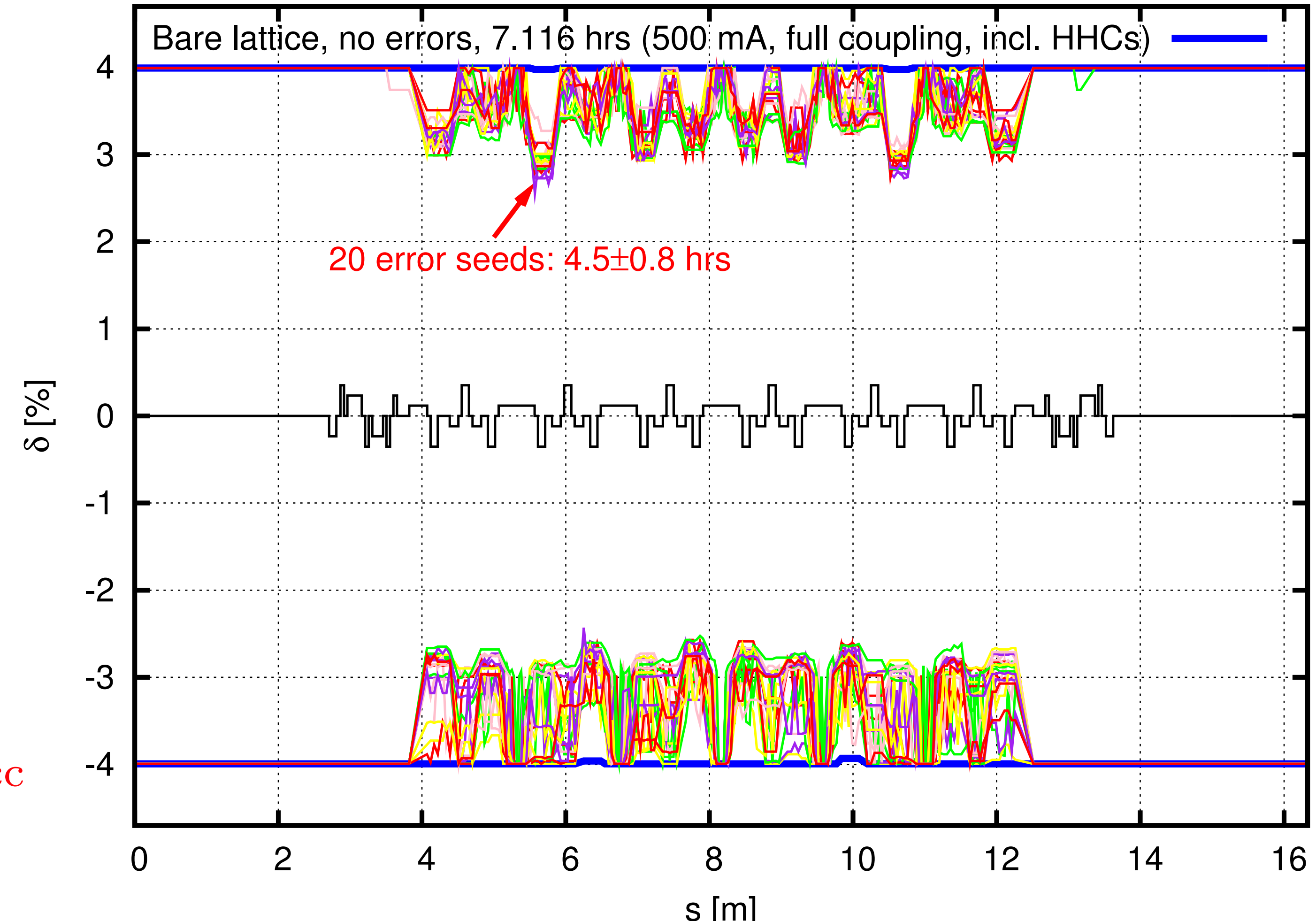
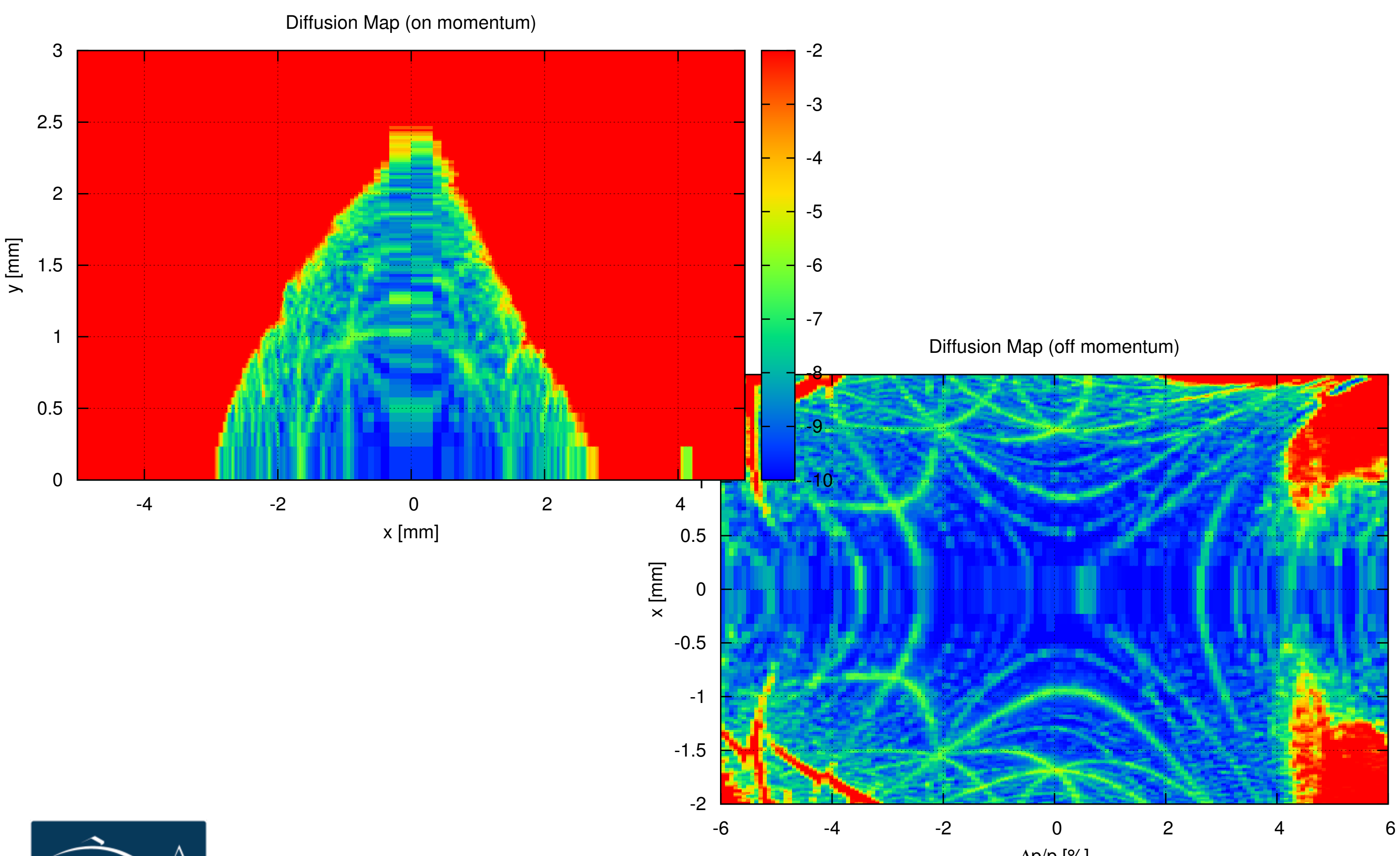
  - 6D Touschek tracking ➔ **7.1 hrs incl. HHCs** (≈7.9 hrs if IBS @ 500 mA included)
  - Using 20 error seeds ➔ **4.5 ± 0.8 hrs** incl. HHCs
  - Overall MA determined to large extent by assumed RF acceptance ➔ exploit $\tau_{\text{ts}} \propto \delta_{\text{acc}}^3$

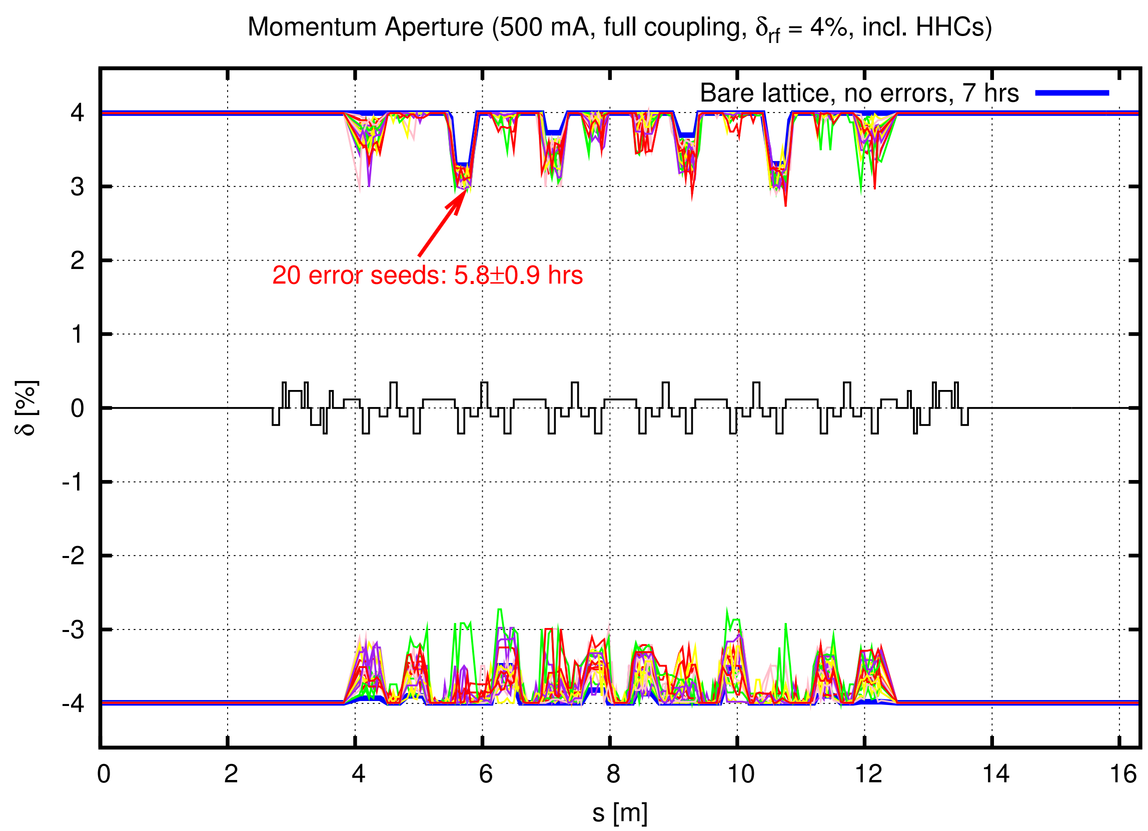


Expected Performance after MOGA Optimization

to be published at **IPAC'19**

- MOGA optimization using 10 sextupole families (8 DOF) carried out in collaboration with Masamitsu Aiba (SLS)
  - Sextupole gradients reduced while **DA** becomes larger and more uniform both on & off energy → **±2.5 mm** (with errors)
  - **Touschek lifetime** around **6 h** (with errors) @ 500 mA, incl. HHCs



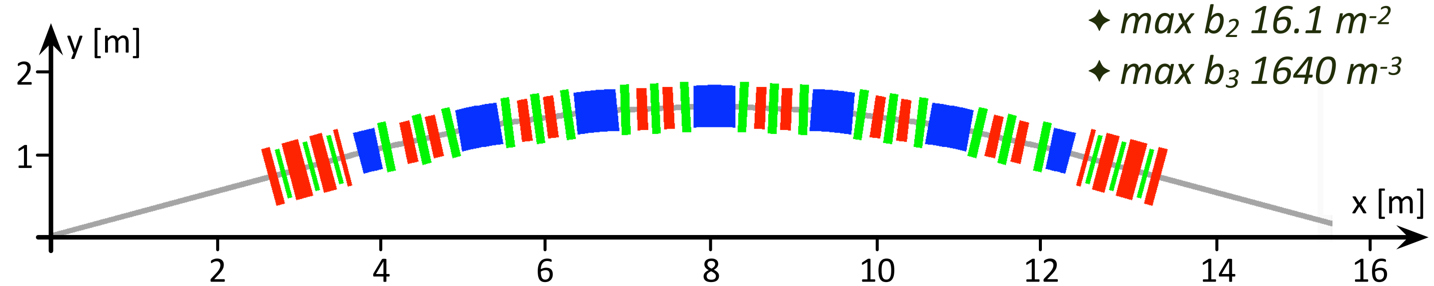


Summary: A 7BA with LGBs & RBs for ALS-U

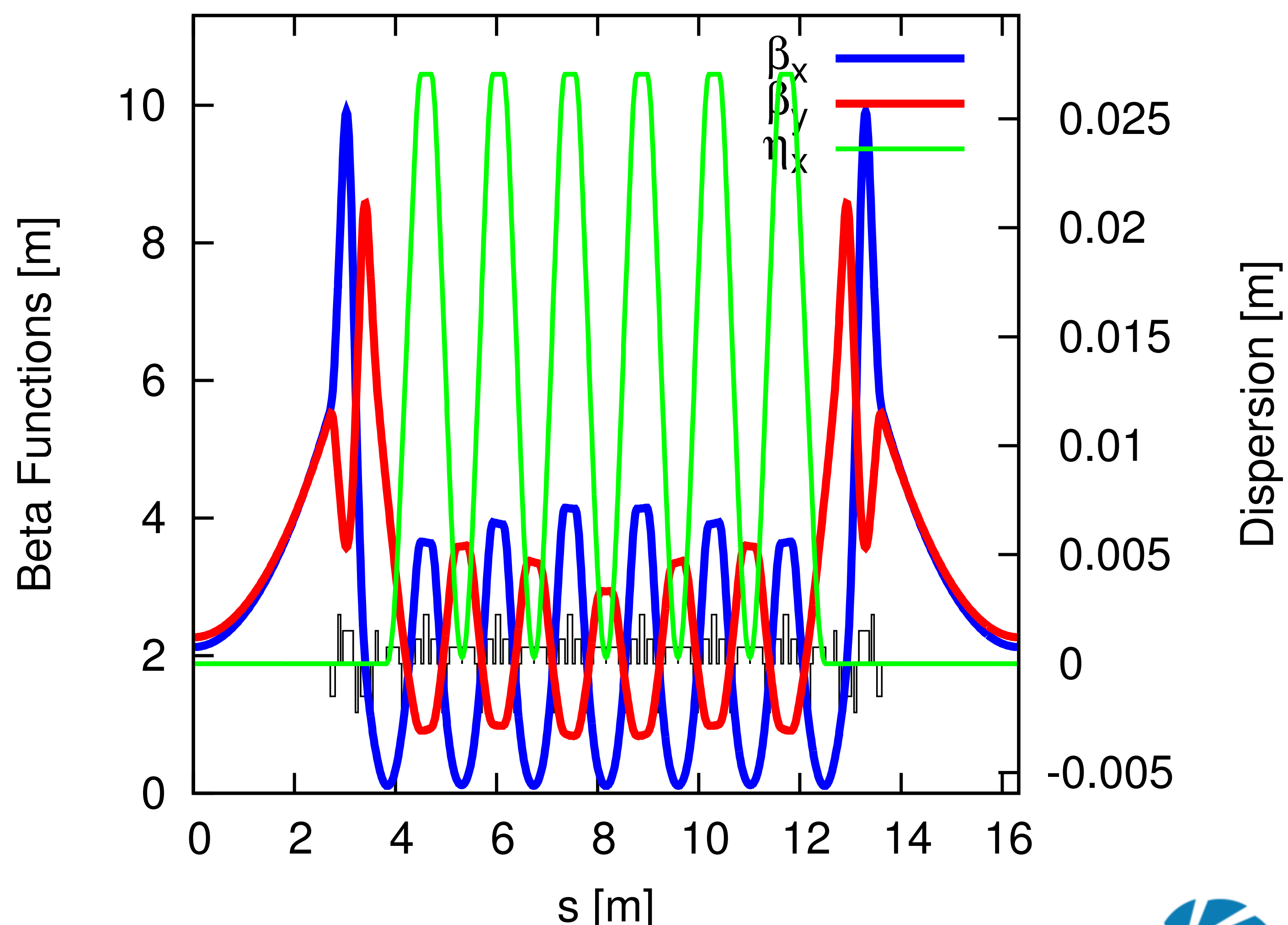
to be published at **IPAC'19**

- LGBs & RBs allow suppressing emittance → reduce N_b to provide space for distributed chromatic correction → superior DA & LMA

✦ 6.2°/1.2° bend/reverse
✦ max b_2 16.1 m^{-2}
✦ max b_3 1640 m^{-3}



- **$\varepsilon_{x,y}$ = 49 pm rad** (fully coupled)
- **≈3×10^{21} ph/s/m²/mrad²/0.1%BW** (@ 1 keV from 4-m 28-mm Delta)
- ε_0 = 78 pm, $\alpha_c = -1\times10^{-4}$
- J_x = 1.72, U_0 = 442.6 keV
- @ IDs: $\sigma_{x,y} \approx 10\ \mu$m ($\beta_{x,y} \approx 2.2$ m)
- ν_x = 40.38, ν_y = 14.36
- $\xi_x = -106.4$, $\xi_y = -40.1$
- DA approx. ±2.5 mm (incl. errors)
- **6 ± 1 hrs Touschek lifetime** @ 500 mA (incl. errors and HHCs)



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Thank You

Acknowledgments

S. De Santis, T. Hellert, A. MacDowell, H. Nishimura, C. Pappas, D. Robin, F. Sannibale, C. Steier, C. Sun, C. Swenson, M. Venturini, E. Wallén, W. Wan (LBNL)

A. Streun, M. Aiba (PSI)

J. Bengtsson (Diamond)

M. Johansson (SLAC)

H. Tarawneh (MAX IV)

L. Dallin (CLS)

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ALS ADVANCED LIGHT SOURCE

Backup Slides

A few Comments on Negative α_c & α_2

- Microwave instability triggered by low ***absolute*** α_c
- Head-tail stability does ***not*** require positive α_c
- If α_c negative, correct to negative $\xi_{x,y}$ → reduces sextupole gradients
- Negative but sizable α_c is advantageous compared to almost isochronous ring
- Experience with negative α_c @ other machines:
  - SuperACO, BESSY, ANKA, MLS, DIAMOND **PhD Thesis M. Ries 2014**
  - SLS-2 designed to operate @ 400 mA with negative α_c **SLS-2 CDR**, Dec 2017
- Potential well distortion @ negative α_c
  - bunch shortens with rising Q_b at first (slightly lower threshold for turbulent bunch lengthening)
  - even w/o HHCs SLS-2 anticipates I_b = 2 mA due to $\alpha_c = -1.3\times10^{-4}$

A few Comments on Negative α_c & α_2 (cont.)

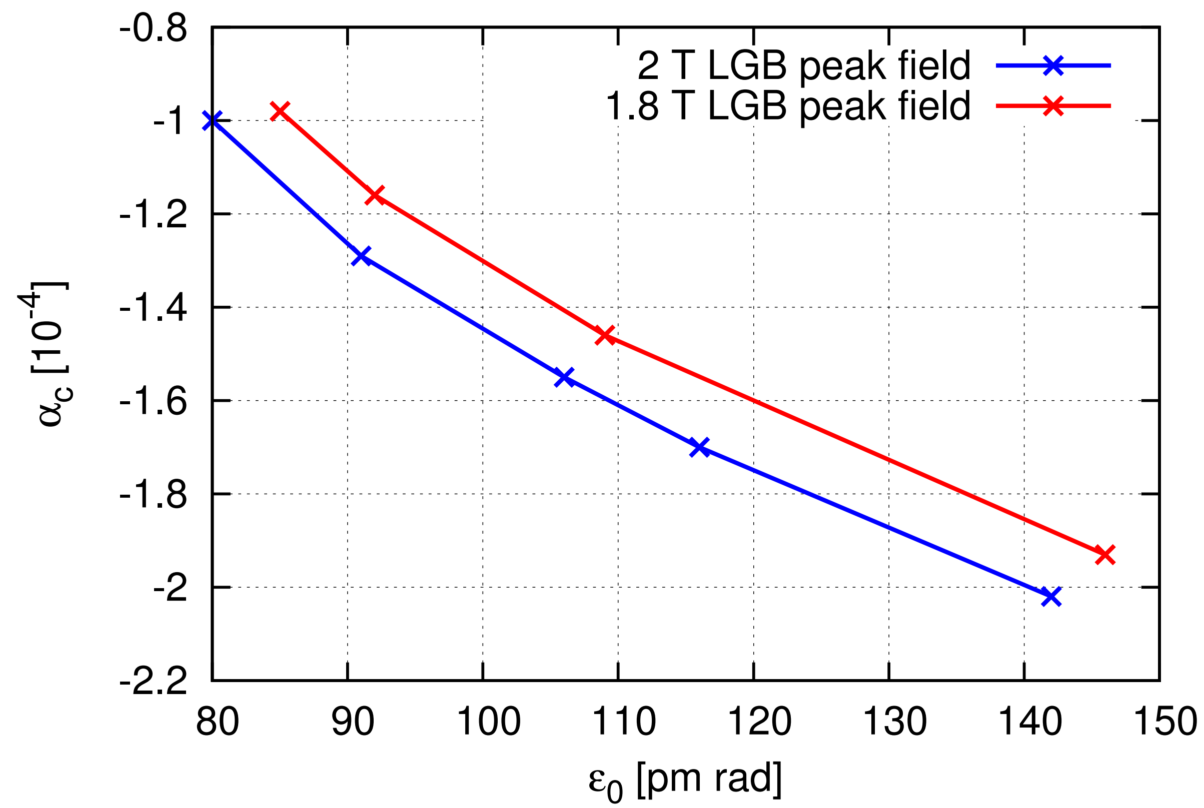
- Bucket distortion from large α_2 → problematic alpha bucket
  - RF acceptance $\delta_{rf} \sim (V_{rf}/\alpha_c)^{1/2}$ → $|\alpha_c/\alpha_2|$ — PRL **84**, 5516-5519 (2000)
  - phase acceptance $\Delta\phi \sim |\alpha_c/\alpha_2|\ (V_{rf}/\alpha_c)^{-1/2}$
- So why not modify α_2 with sextupoles? $\alpha_2 \propto \oint \frac{\partial\eta/\partial\delta}{\rho} ds, \quad \frac{\partial\eta}{\partial\delta} \propto (b_3 l)\,\eta^2$
  - Would require chromatic sextupoles with $\eta \gg \beta_{x,y}$ ← **Doesn't exist in MBA!**
  - Instead increase $|\alpha_c|$ to required level determined by "stiff" α_2
  - SOLEIL ran experiments with α_c/α_2 = 10% → three simultaneously stored beams — PRST-AB **16**, 054001 (2013)
  - SLS-2 designed to operate at $\alpha_c/\alpha_2 \approx 9\%$ — **SLS-2 CDR**, Dec 2017
- Use tracking (ideally self-consistent including HHC, impedance → PWD, etc.) to verify stable longitudinal behavior in presence of negative α_c, small α_c/α_2, gaps in fill pattern, transients, etc. → works for this lattice by virtue of α_3 compensation

Considerations for the LGB

- How important is the LGB? Could it be replaced with a regular TGB?
  - Used same version of previous lattice for comparison study
  - Instead of LGB use TGB (6.7° → 1.56 T, –33.5 T/m)
  - Tuned to exact same $\alpha_c = -1.7\times10^{-4}$ → requires more RB
    - Increases radiated power, σ_δ, and J_x (slightly)
    - Results in 116 → 189 pm (+63%)

Considerations for the LGB (cont.)

- How important is the LGB? Could it be replaced with a regular TGB?
  - Used same version of previous lattice for comparison study
  - Instead of LGB use TGB (6.7° → 1.56 T, –33.5 T/m)
  - Tuned to exact same $\alpha_c = -1.7\times10^{-4}$ → requires more RB
    - Increases radiated power, σ_δ, and J_x (slightly)
    - Results in 116 → 189 pm (+63%)
- Does the LGB really have to be so aggressive, i.e. are 2 T necessary?
  - Significant emittance penalty from relaxing LGB peak field
  - Without sacrificing α_c expect >10 pm rad



Considerations for the LGB (cont.)

- How shall the LGB be implemented?
- Possible collaboration with SLS-2 which will require such a magnet?

IPAC **2015**, TUPJE047, 1724

IPAC **2016**, WEPOW038, 2922

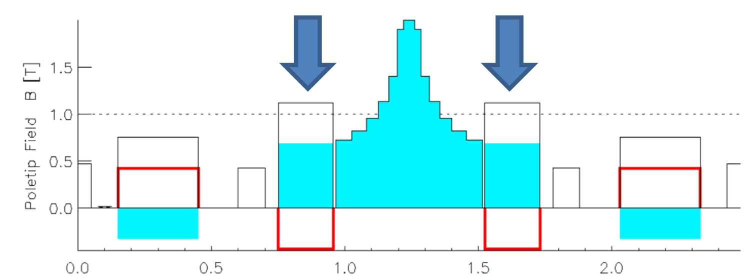
SLS-2 CDR, Dec 2017

Magnets 1 - compound LGB

⇨ CDR p. 44

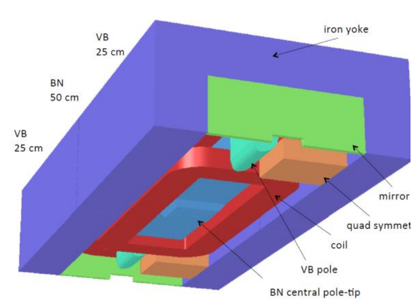
longitudinal/transverse gradient compound bend

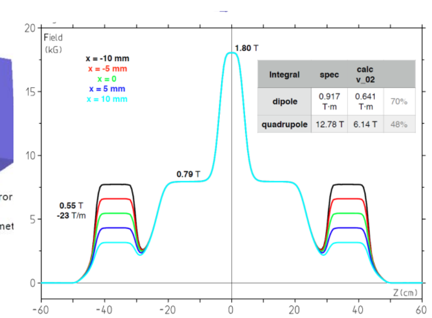
use low field at LGB ends for vertical focusing gradient
→ save space, increase J_x



RC

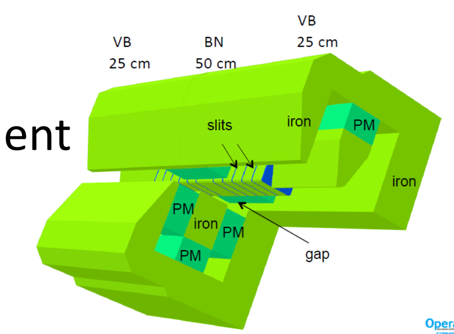
resistive coil version





PM

permanent magnet version



work in progress

Alternatives:
- discrete quadrupoles?
- distributed gradient?
- incorporation of sextupole component too?
- tunability?

P. Lerch, M. Negrazus, V. Vrankovic

SLS-2 Conceptual Design and SLS status ESLS-XXV, Dormund, Nov. 21-22, 2017 28/34

Considerations for the LGB (cont.)

- How shall the LGB be implemented?
- Possible collaboration with SLS-2 which will require such a magnet? Or with CLIC?

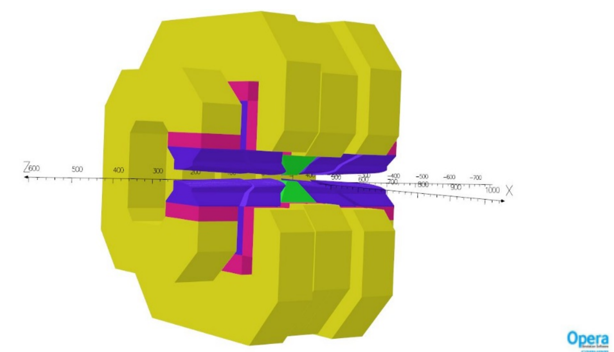
IPAC **2015**, TUPJE047, 1724

IPAC **2016**, WEPOW038, 2922

TME Cell optimisation

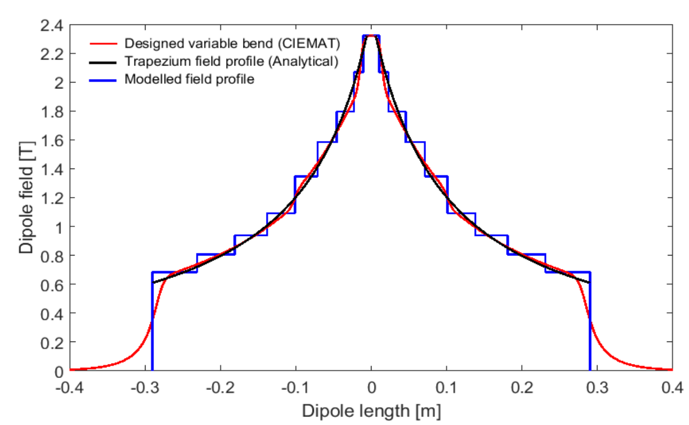
-Based on the trapezium profile, the designed dipole has a total length of 56 cm and bends the beam by 4 degrees.

- A maximum field of 2.3 T is reached. The λ and ρ values achieved are 0.04 and 0.29 respectively, corresponding to a F_{TME}=7.



M. A. Domínguez, F. Toral (CIEMAT, Spain)
see "Design of a Dipole with Longitudinally Variable Field using Permanent Magnets for CLIC DRs"

Parameters	Highest field section	Lowest field section
Length (cm)	2.143	5.900
Field (T)	2.321	0.685
Radius (m)	4.111	13.937
K (m^{-2})	-1.100	-1.100



M. Dominguez, F. Toral

IEEE Trans. Appl. Supercond. **28, 3,** 2018, 4004704

Considerations for the LGB (cont.)

IPAC **2015**, TUPJE047, 1724

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- How shall the LGB be implemented?
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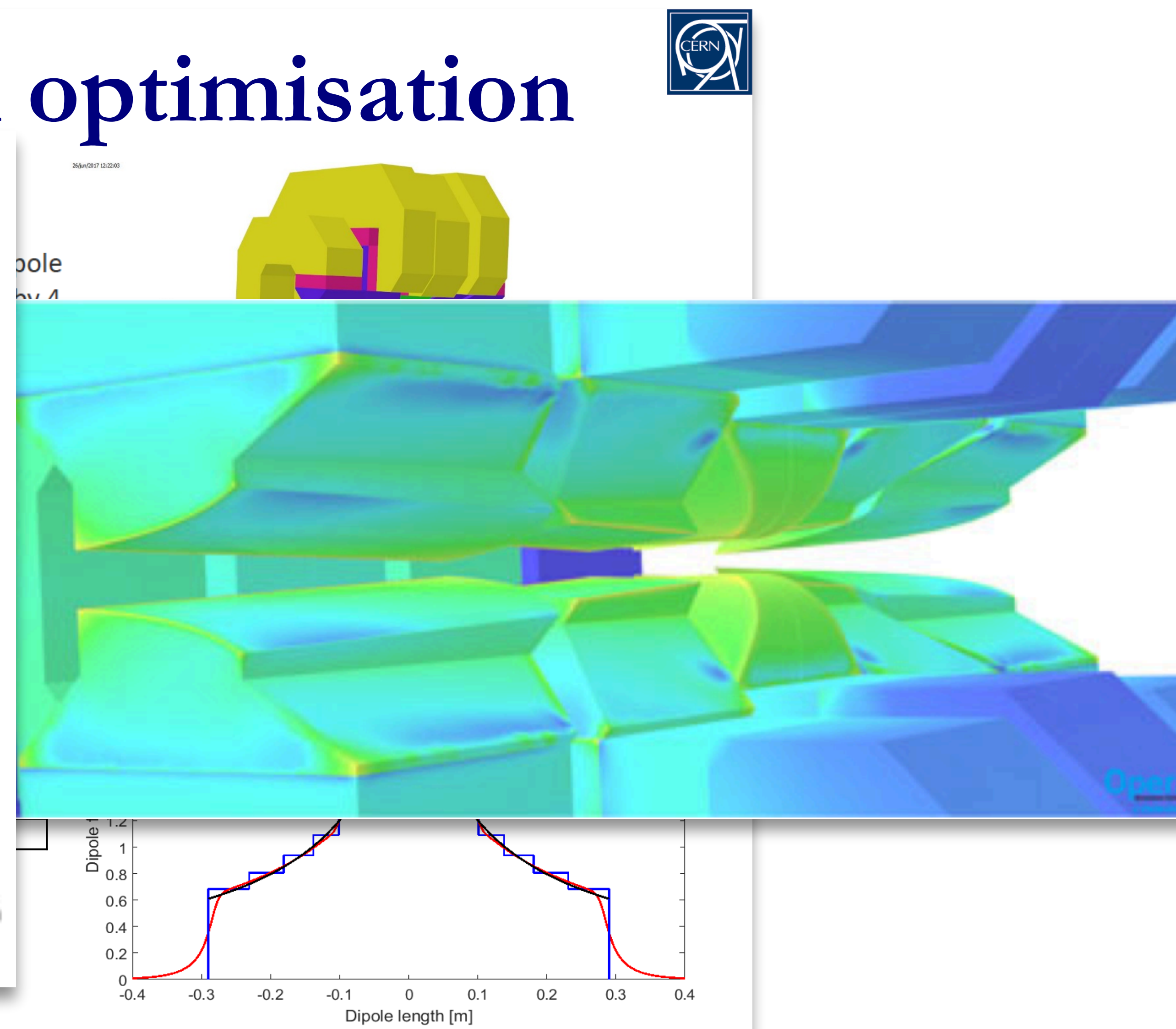

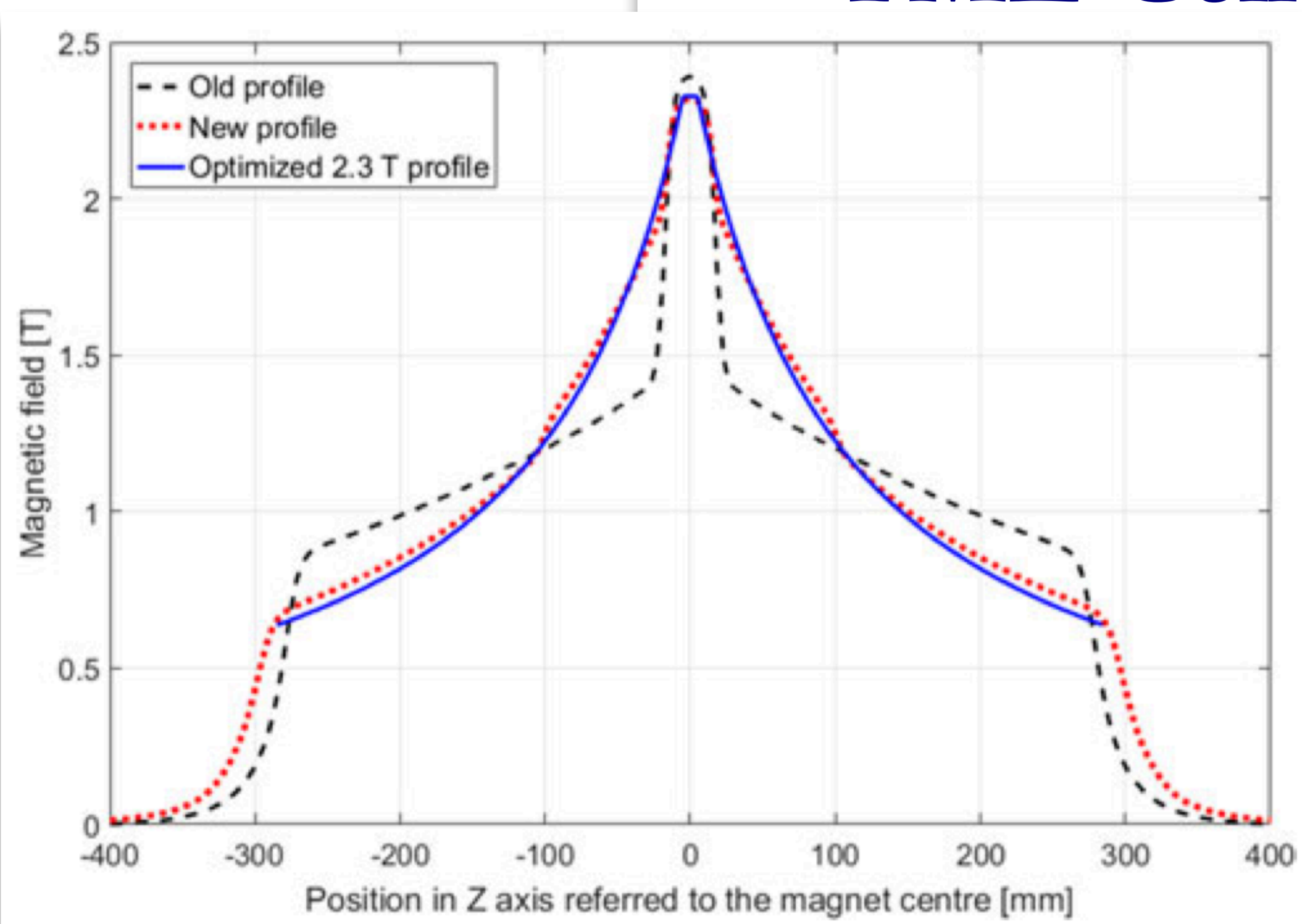

IEEE Trans. Appl. Supercond. **28, 3,** 2018, 4004704

Considerations for the LGB (cont.)

IPAC **2015**, TUPJE047, 1724

IPAC **2016**, WEPOW038, 2922

- How shall the LGB be implemented?
- Possible collaboration with SLS-2 which will require such a magnet? Or with CLIC?

- Could LGB be replaced with more relaxed TGB-SB-TGB sandwich?
- Will likely want permanent magnets for LGB (and possibly also RB)
  - only limited tuning capability required
  - do not want to reserve space for coils
    - hard focusing of longitudinally dense UC required for ultra-low emittance
    - in case of TGB-SB-TGB sandwich, dip in field has to be avoided at all cost
  - reduction of power consumption and dissipated heat

Other Technical Considerations

- Magnet strengths are tough → small magnets are strong magnets → ultimately, impedance/resistive wall budget should determine the minimum acceptable magnet bore
- Vacuum design still has to ensure UHV conditions (→ NEG) but also remove entire synchrotron radiation heat load & get light out to users → feeds back to magnet design

Other Technical Considerations (cont.)

- Magnet strengths are tough → small magnets are strong magnets → ultimately, impedance/resistive wall budget should determine the min
- Vac … so rem … use

- **Synchrotron radiation heat load** $P \sim I\gamma^4/\rho$
- More interesting: $P/L \sim I\gamma^4/\rho^2$
  - MAX IV 3 GeV storage ring (500 mA): ≈1.5 W/mm
  - ALS-U v20 @ 500 mA → ≈2.2 W/mm (1.5× higher than MAX IV)
- But also need to take into account beam height on chamber
  - $h = 2l/\gamma$, with distance from source $l = (2r_c\rho)^{0.5}$, chamber radius r_c
- Therefore, better measure is power per area: $P/(Lh) \sim I\gamma^5/(r_c^{0.5}\rho^{2.5})$
  - MAX IV 3 GeV storage ring (500 mA): ≈6.9 W/mm²
  - ALS-U v20 with 13/20 mm chamber → ≈12.2 W/mm² (1.8× higher than MAX IV)

✳ *Increased RB of 7BA & its smaller chamber will further increase power density*

✳ *However, APS-U also faces a heat load 2–3× higher than MAX IV*

Other Technical Considerations (cont.)

- Magnet strengths are tough ➔ small magnets are strong magnets ➔ ultimately, impedance/resistive wall budget should determine the minimum acceptable magnet bore
- Vacuum design still has to ensure UHV conditions (➔ NEG) but also remove entire synchrotron radiation heat load & get light out to users ➔ feeds back to magnet design
- A successful design will require several iterations between magnet, vacuum, and lattice design
- This was successfully done at MAX IV ➔ resulted in a design where push was made on all fronts resulting in a balanced ***and*** robust design (for its time)
  ➔ ***now is the time to define the <u>new</u> "state-of-the-art" ring design***