Error Studies for the v20r Baseline Lattice

Alternate ALS-U Lattice

Simon C. Leemann

ALS-U Beam Physics Technical Review, April 5, 2018

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U.S. DEPARTMENT OF ENERGY | Office of Science

ALS-U ADVANCED LIGHT SOURCE

Part I

Error Studies for the v20r Baseline Lattice

Error Studies – at a "conceptual level"

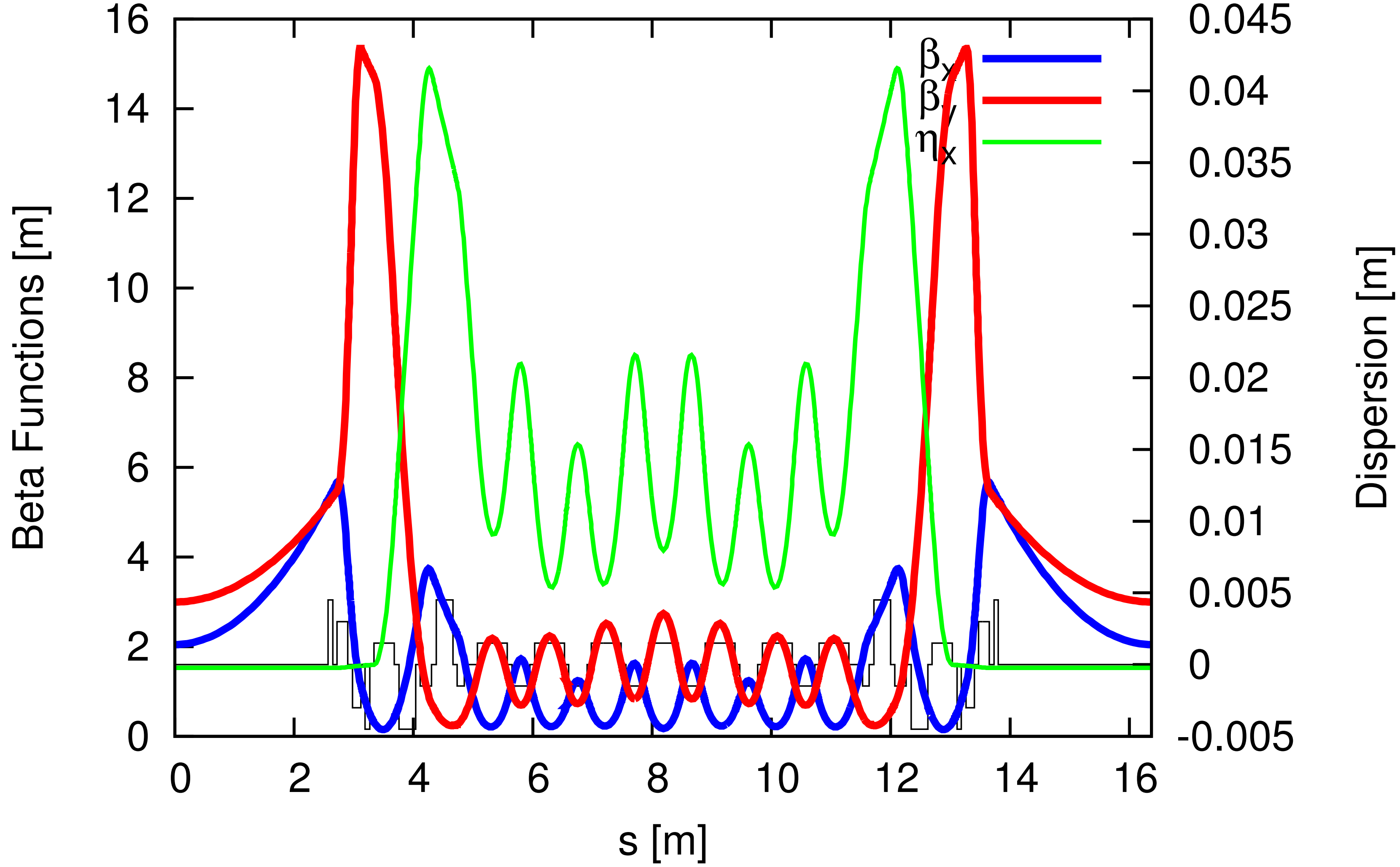
- Identify modeling tools → ideally independent tools to benchmark & cross-check
- Define and distinguish error models
- Prepare workflows → production runs, specification, iteration
- Define data formats, provide post-processing tools, etc.

- In order to verify the above, use "mock cases"

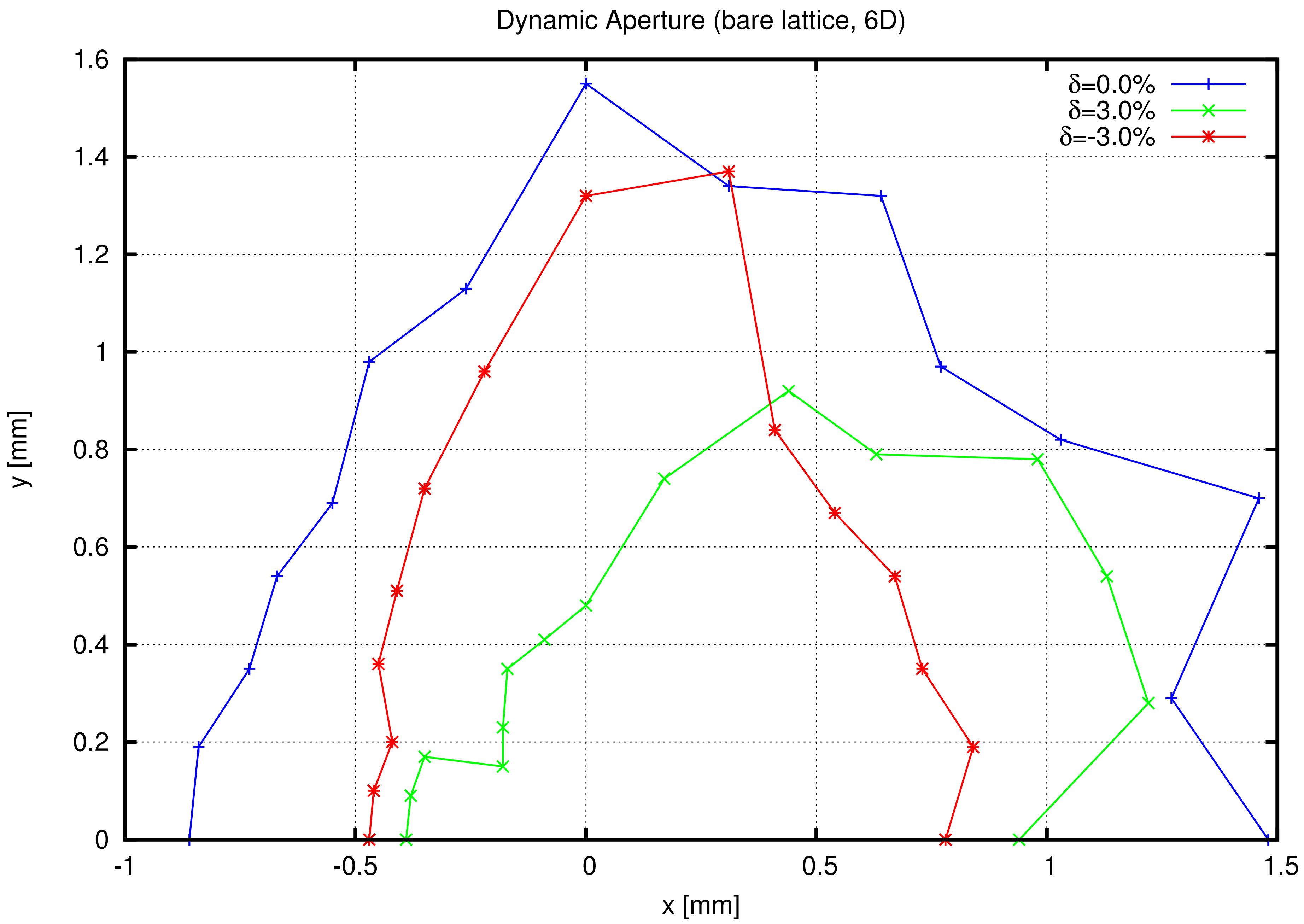
- At this point we *do not* intend to demonstrate we have all the answers, but we *do* want to show
  - we are asking the relevant questions
  - we see the path ahead that will get us from conceptual to detailed design

Tracy-3 lattice & model set up for v20r baseline

- Magnet lattice translated from elegant, linear optics agree well
- 20 BPMs inserted according to current vacuum design
- 18 (thin) CM pairs installed @ all RBs and sextupoles (→ #CM < #BPM)



Tracy-3 lattice & model set up for v20r baseline



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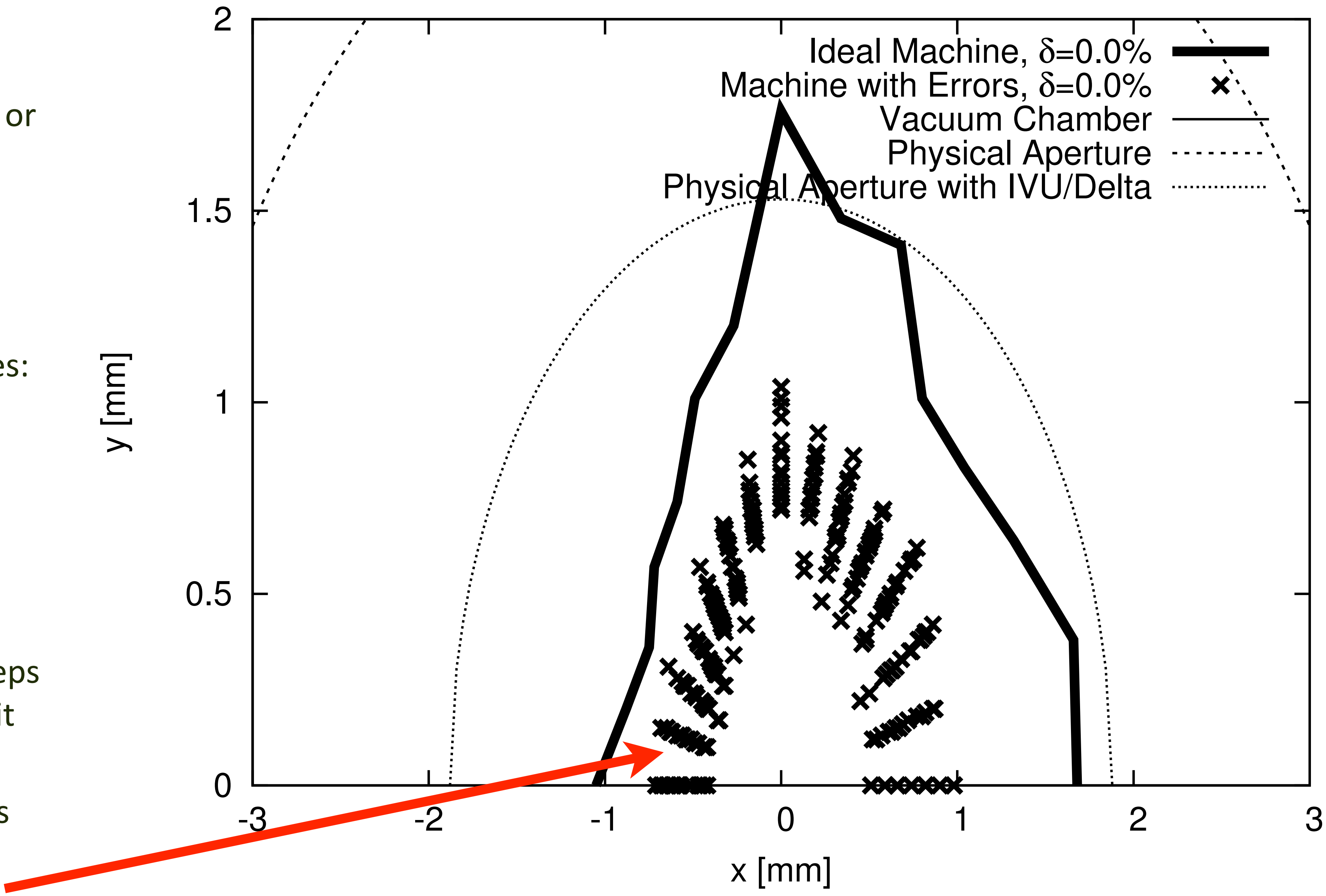
A first simple Tracy-3 error/correction model

- For all pure quads & sextupoles:
  - 25 µm rms in x/y
  - 0.2 mrad rms roll
- No alignment errors on bends or RBs
- BPM errors set to zero
- No girders, no girder misalignments
- For all pure quads & sextupoles:
  - 0.05% rms field error on primary component
- Gaussian with cut at ±2σ (20 seeds)
- So far no multipole errors
- Misalignments scaled up in steps to facilitate finding closed orbit
  - For each step, orbit corr. applied in three iterations
  - No linear optics or skew quadrupole corrections



Linear optics corrections will be required

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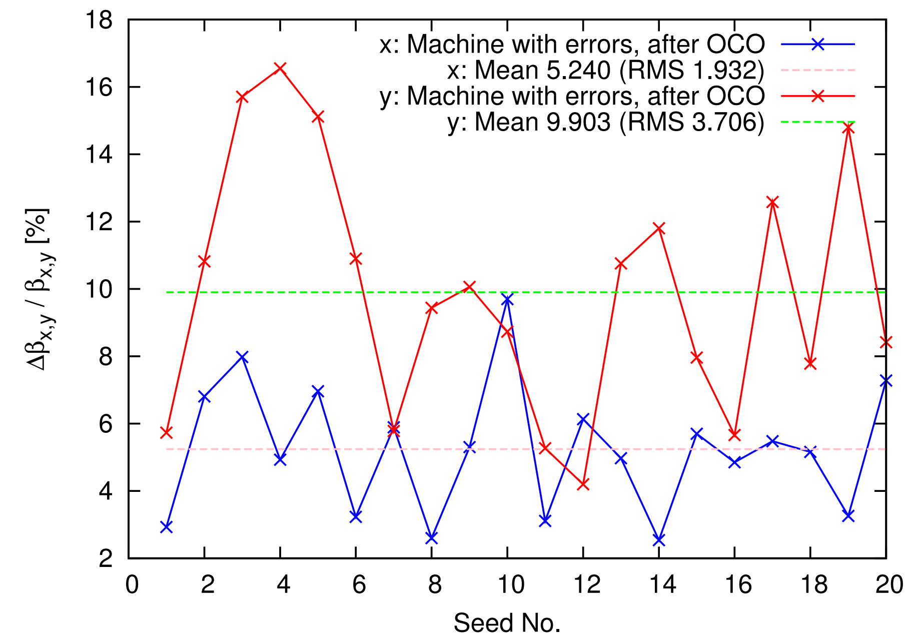
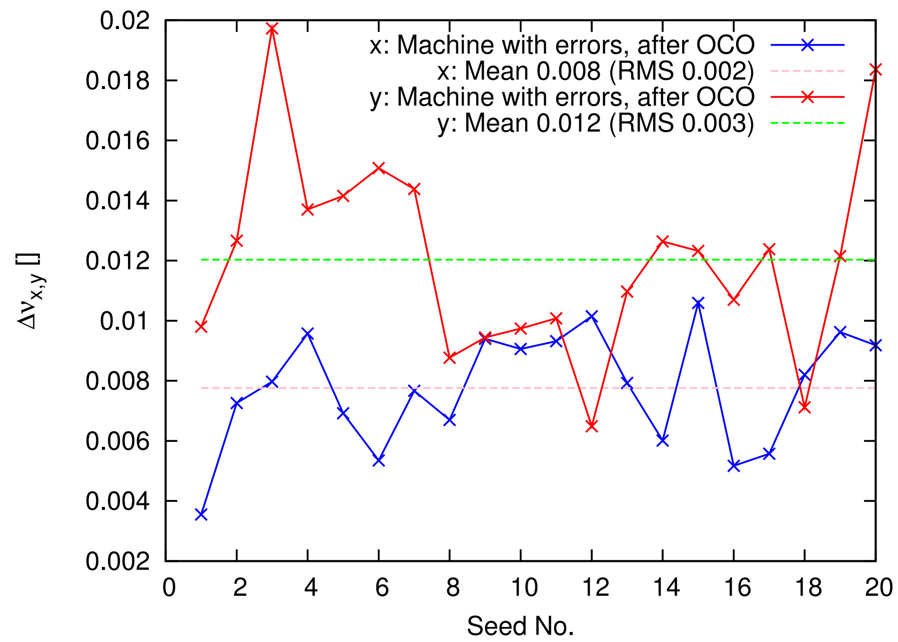
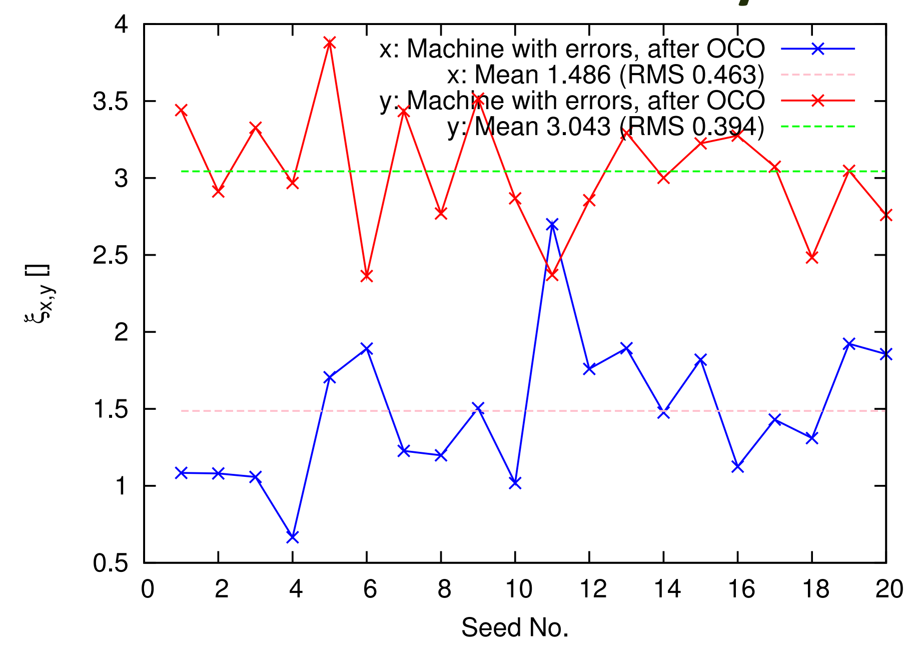
Beta Beat



Tune Error



Linear Chromaticity



Skew quadrupole corrections will be required

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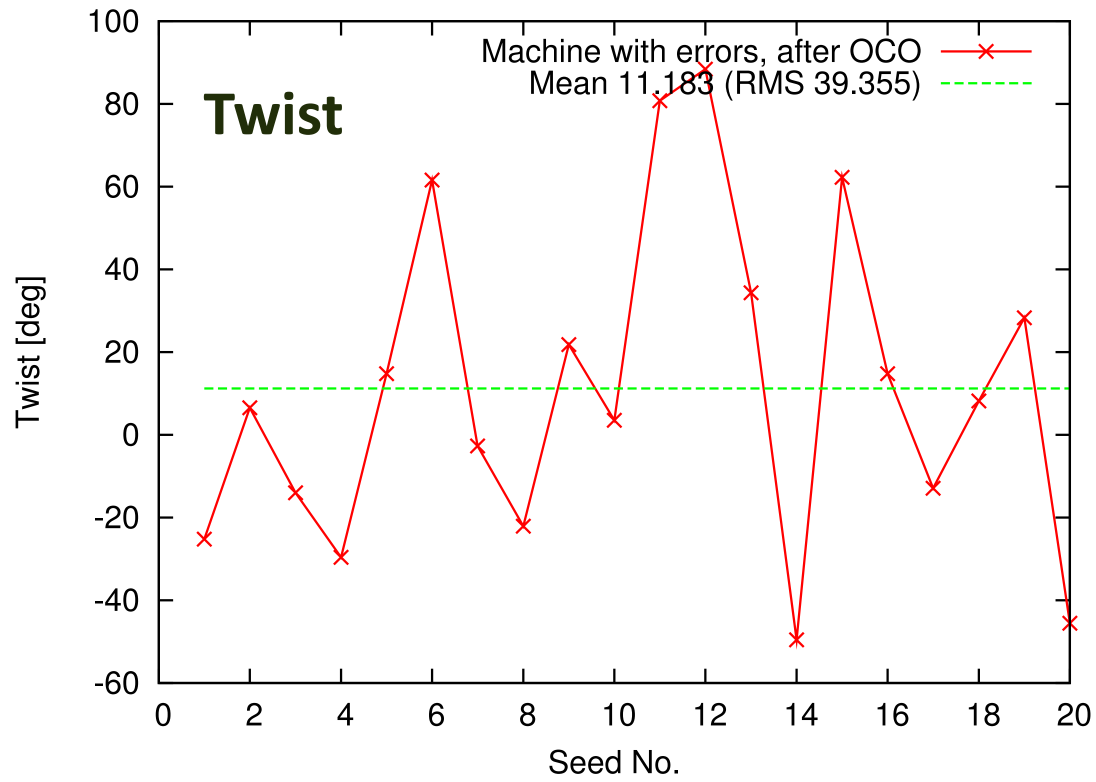

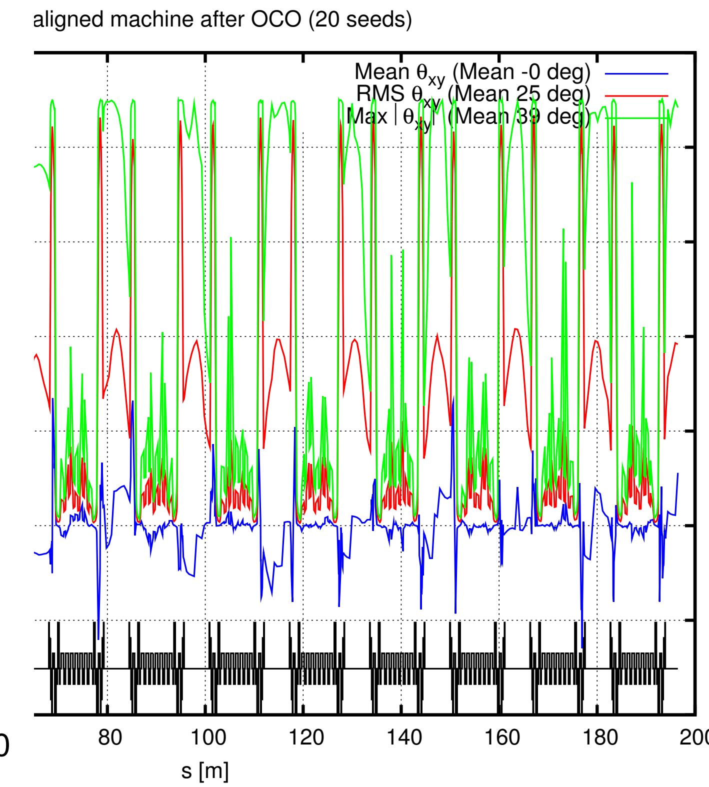

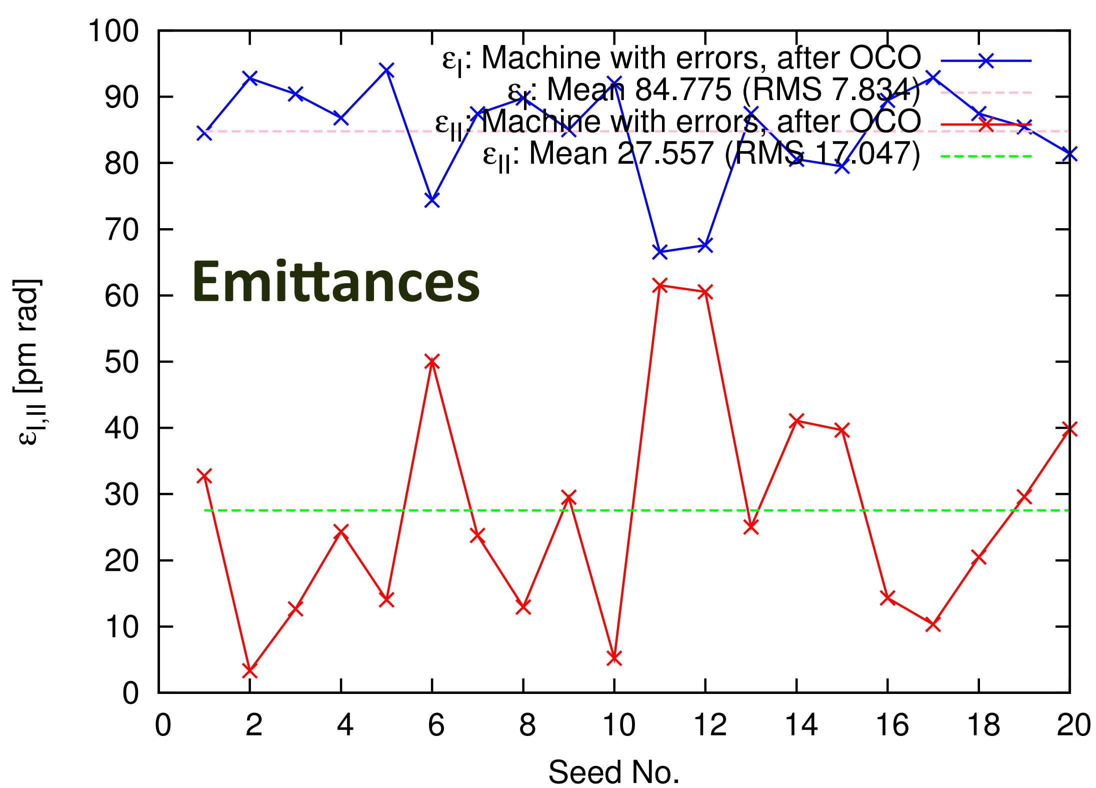

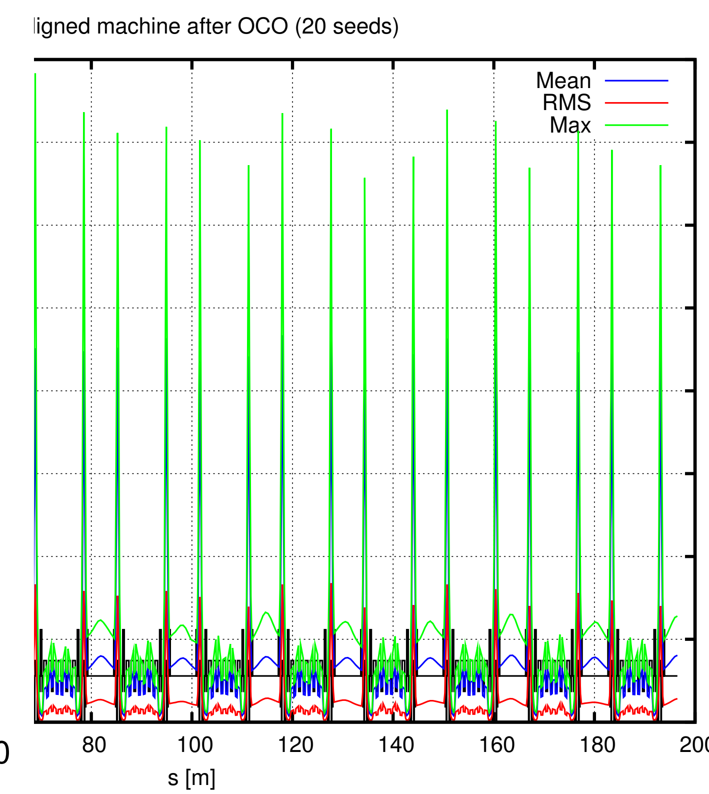

Verify BPM/CM layout allows for successful OC

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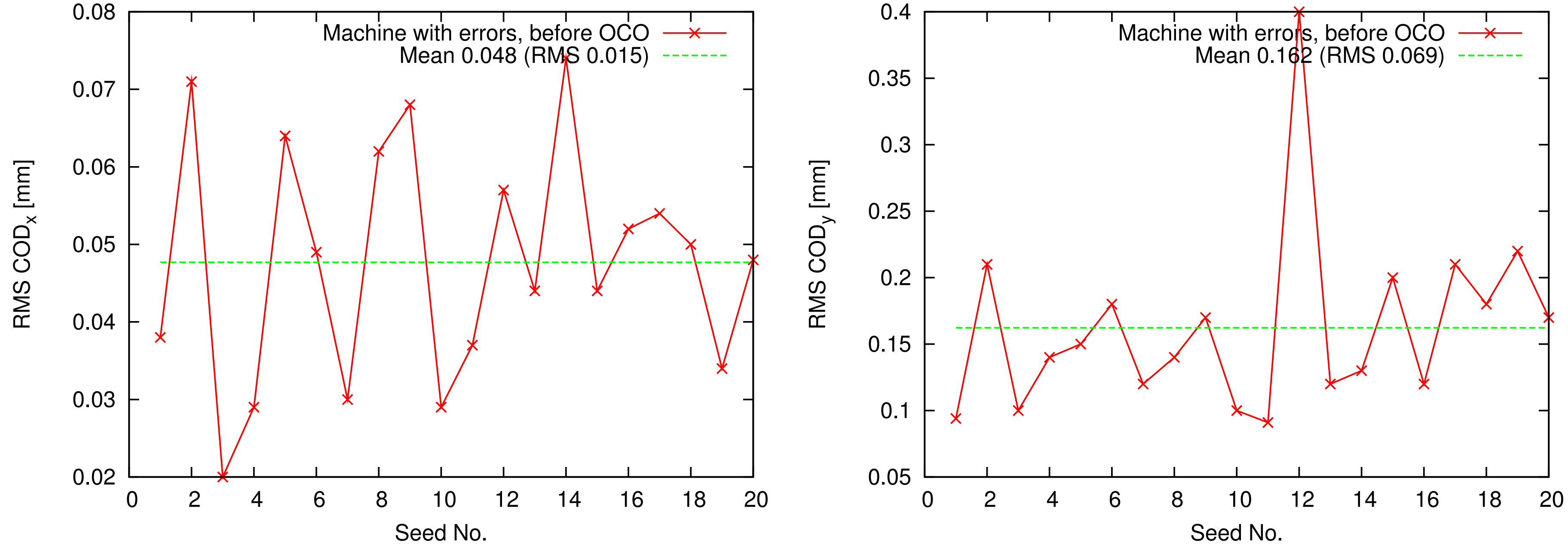
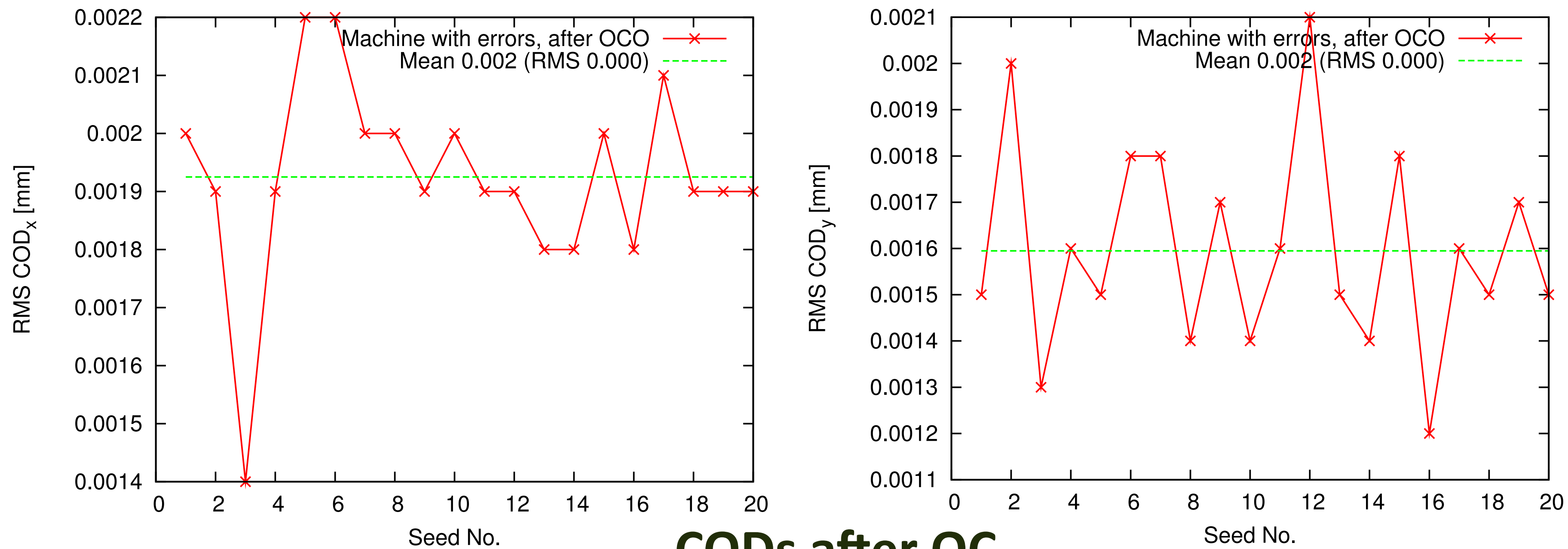
CODs before OC





CODs after OC

And what are the associated CM requirements?

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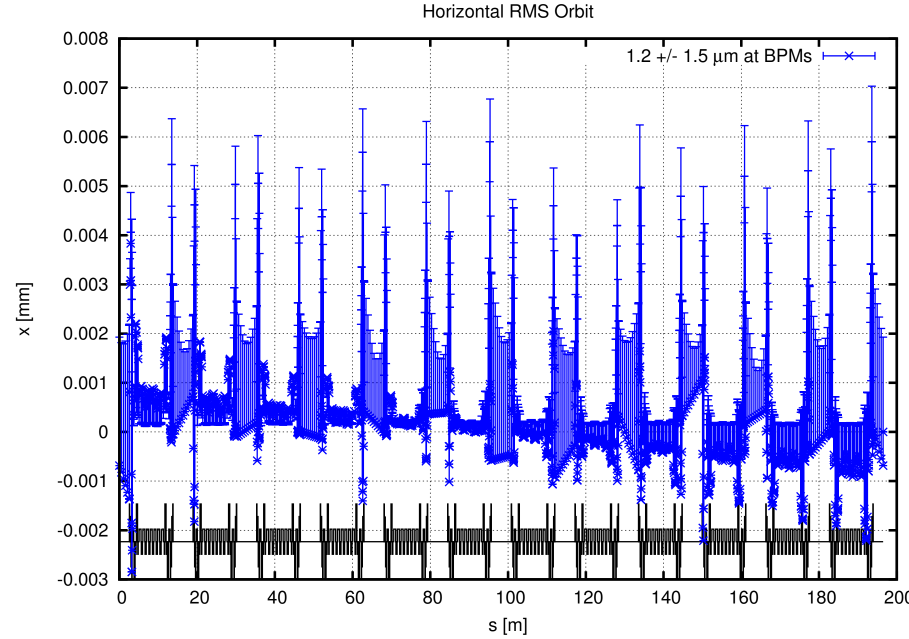

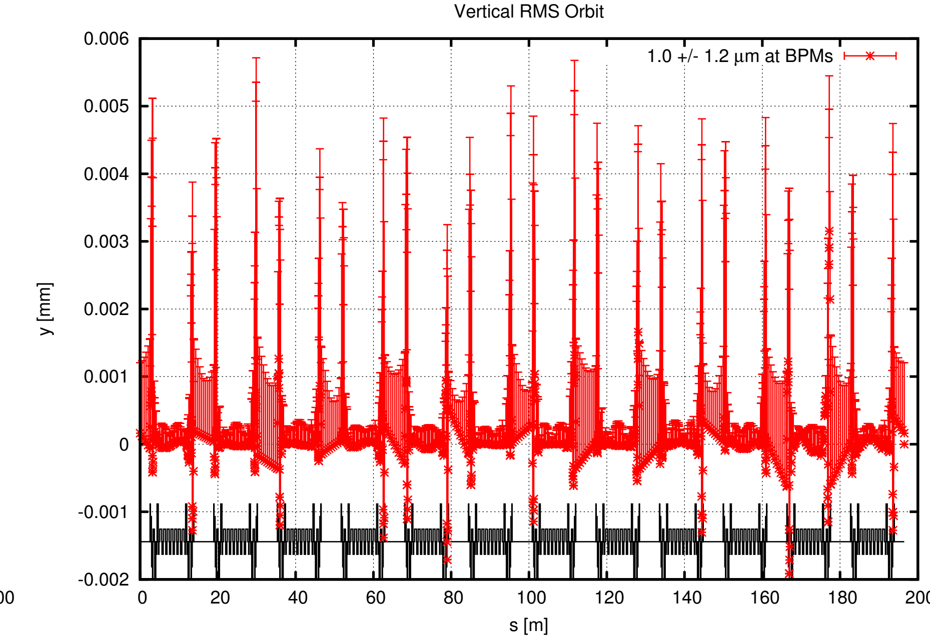

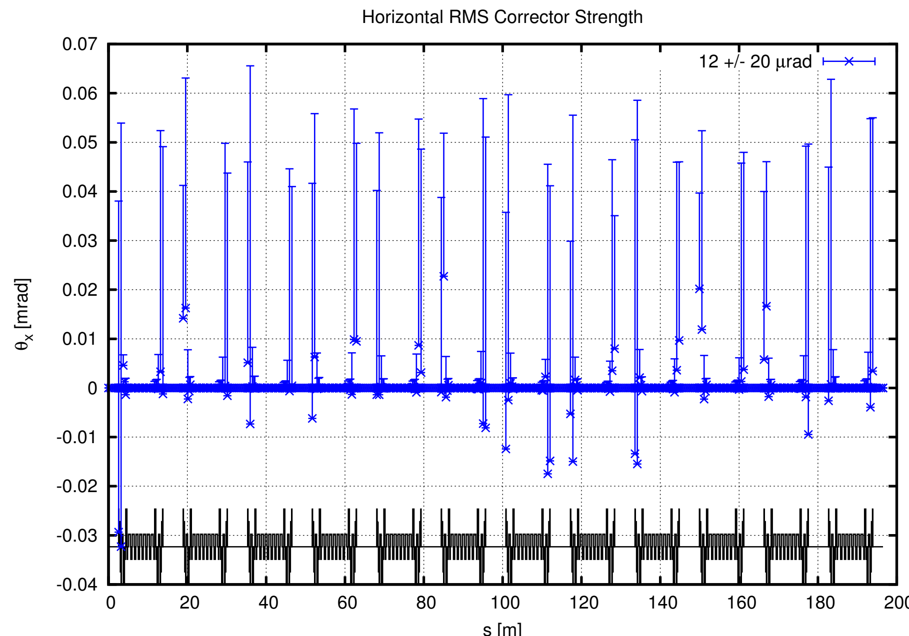

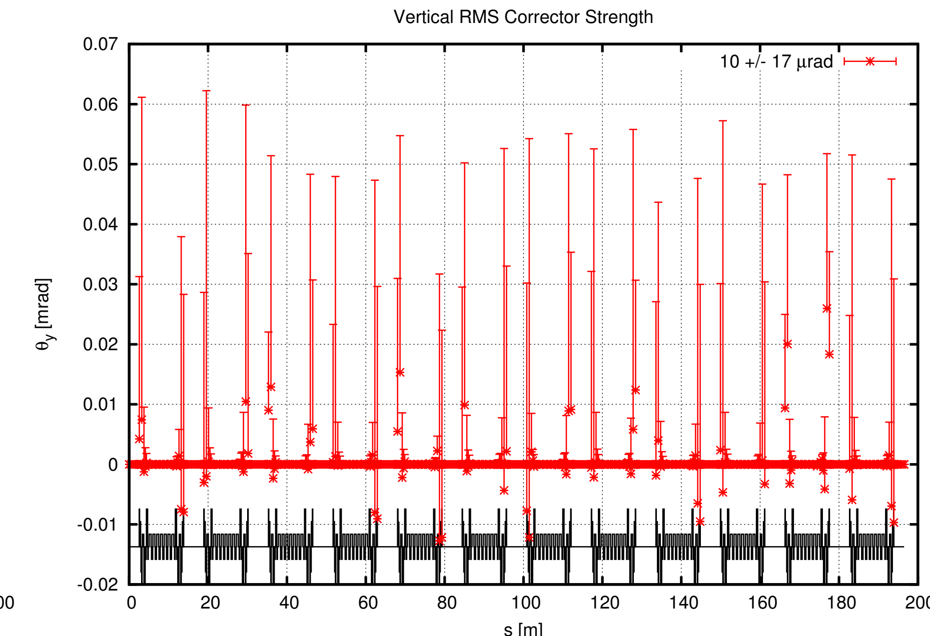

Required CM Strength

Sensitivity – which specs do we focus on?

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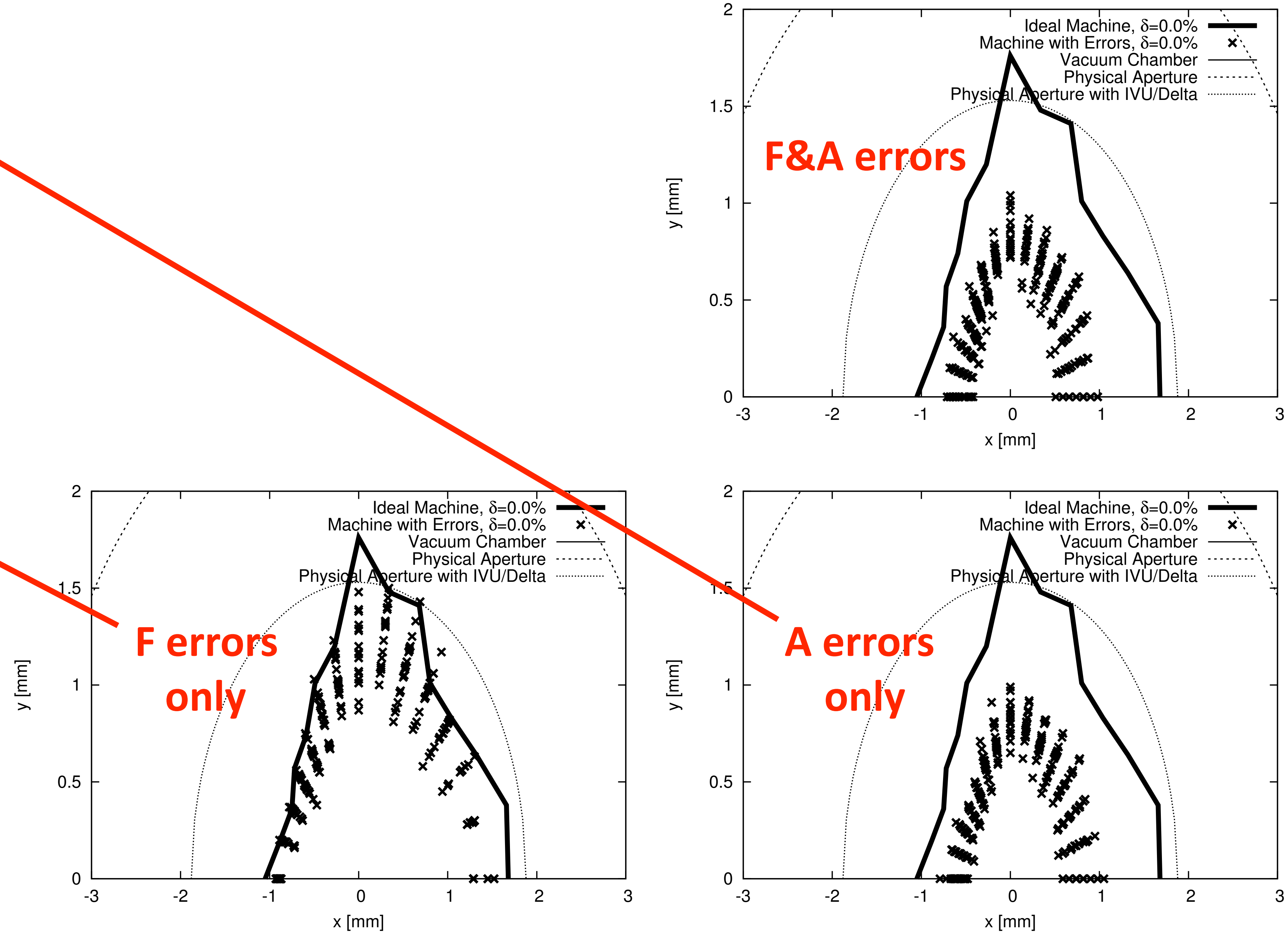

Derive beam physics-motivated specifications

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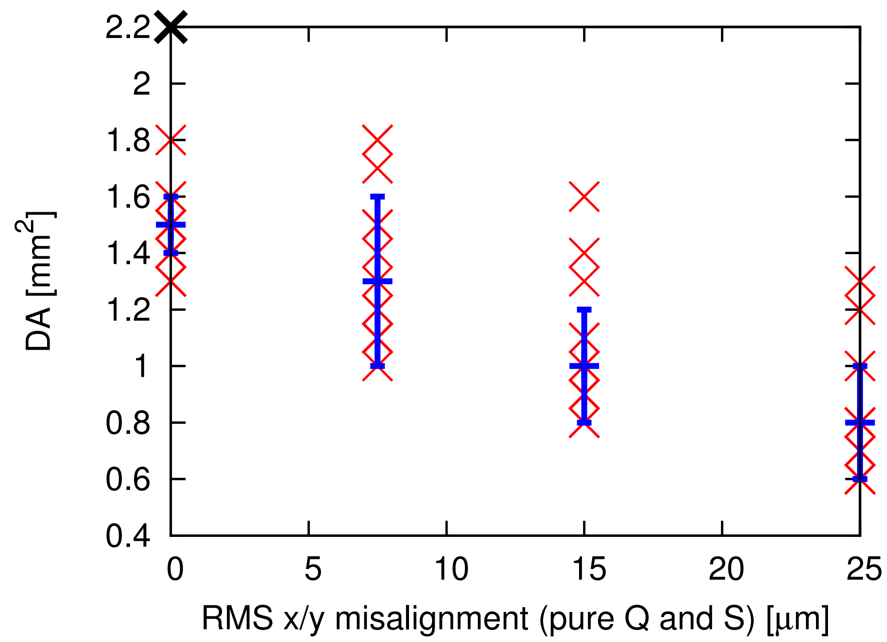
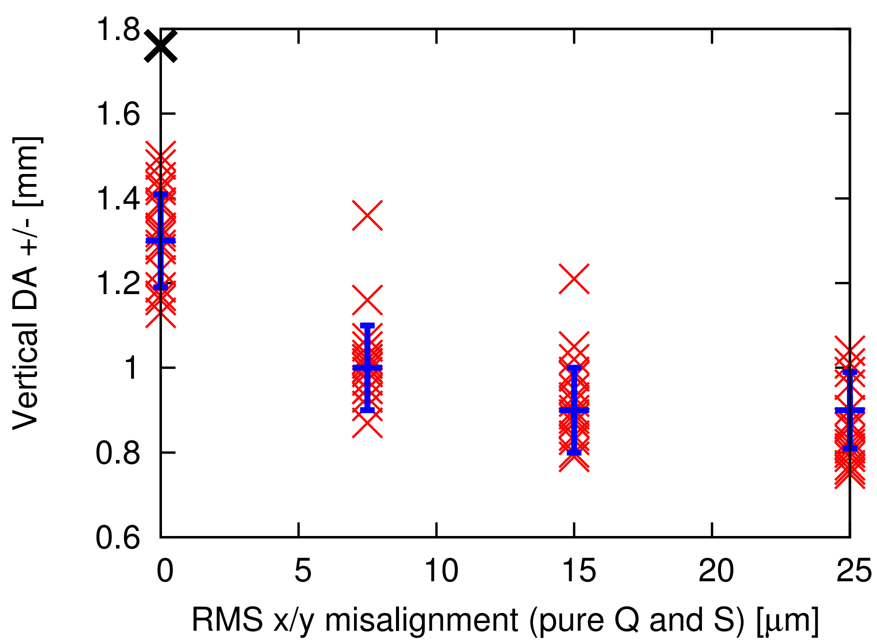
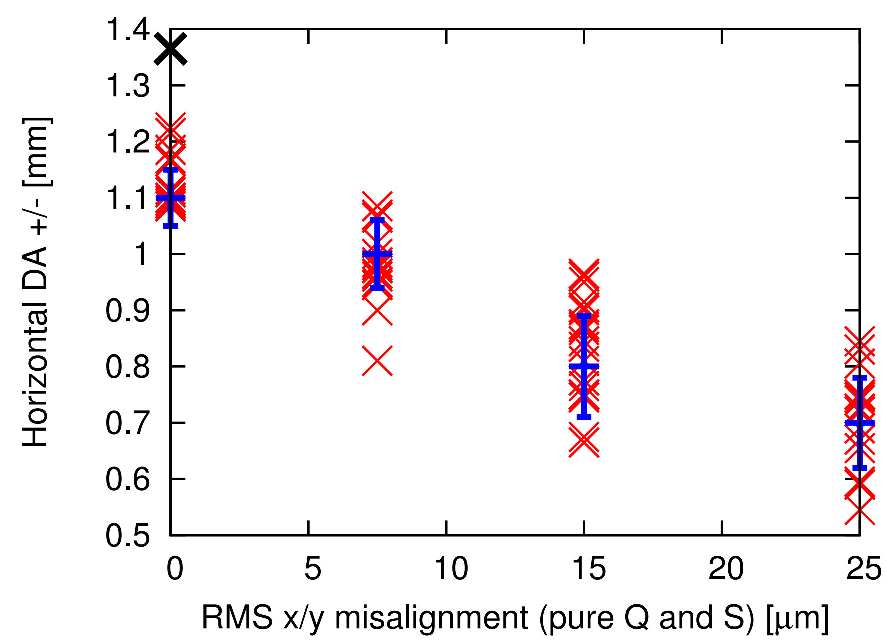






Not mentioned, but not forgotten

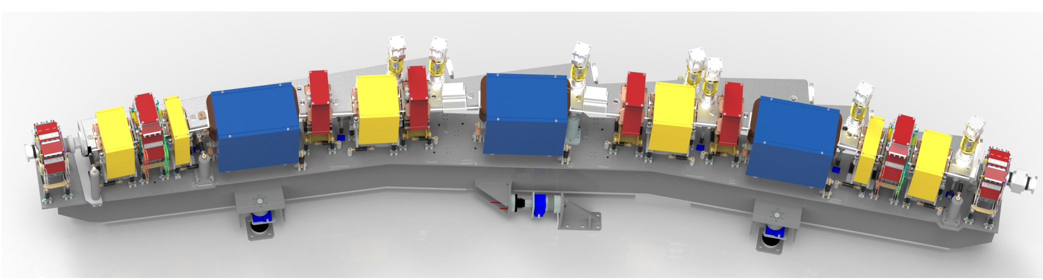
- Girders
- Insertion devices (lattice tunability, stability)
- FOFB
- Power supply topology and stability

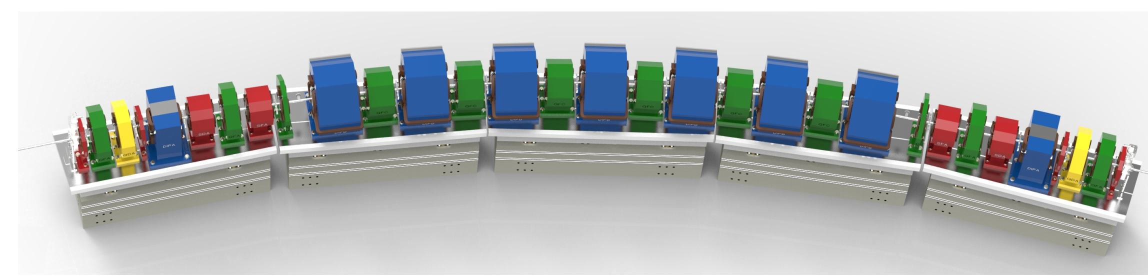
- Most important next steps:
  - Linear optics corrections
  - Commissioning simulations → Thorsten's presentation

Part II | Alternate ALS-U Lattice

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)
- Baseline relies on "pseudo-hybrid MBA" lattice with 9 bends (→ 110 pm rad) & offset focusing quadrupoles (reverse bending) → 92 pm rad





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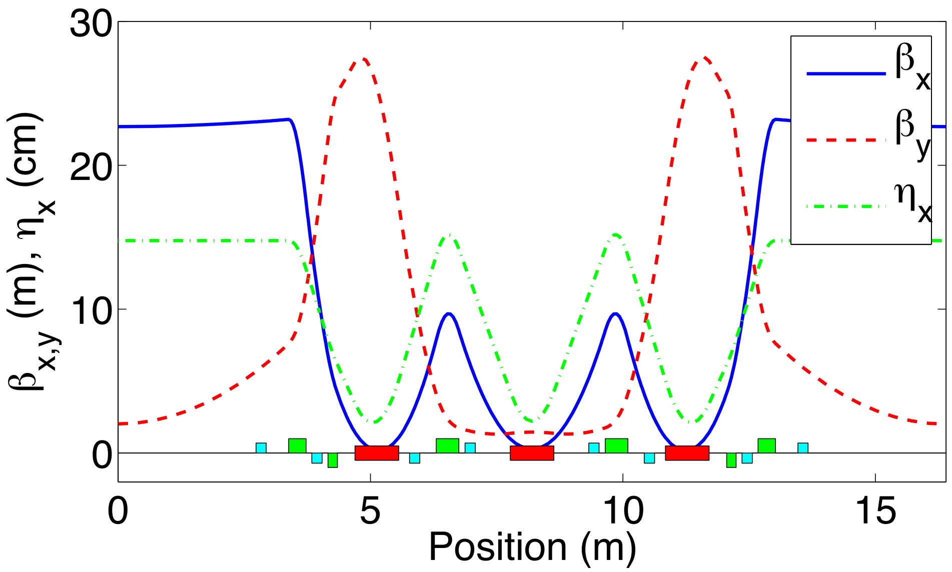

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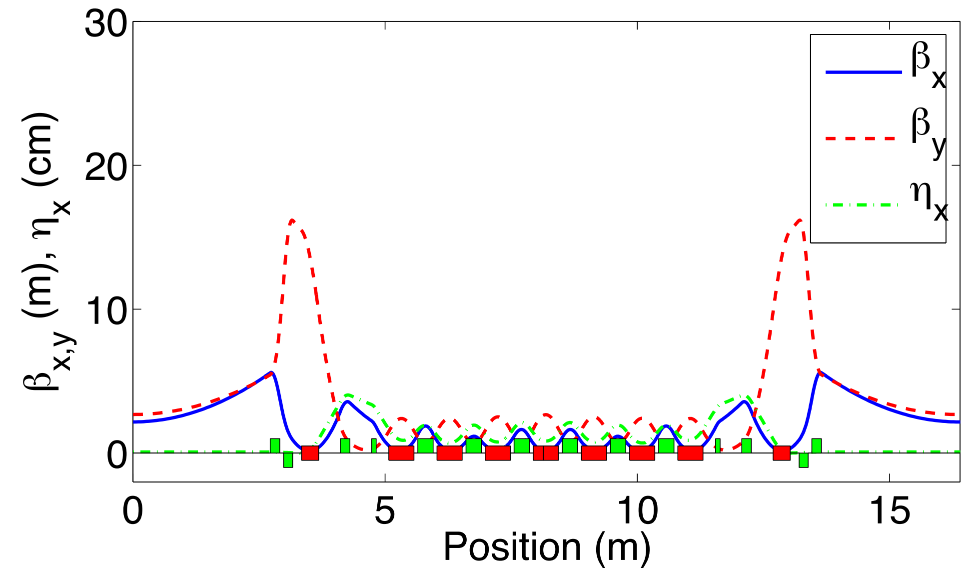
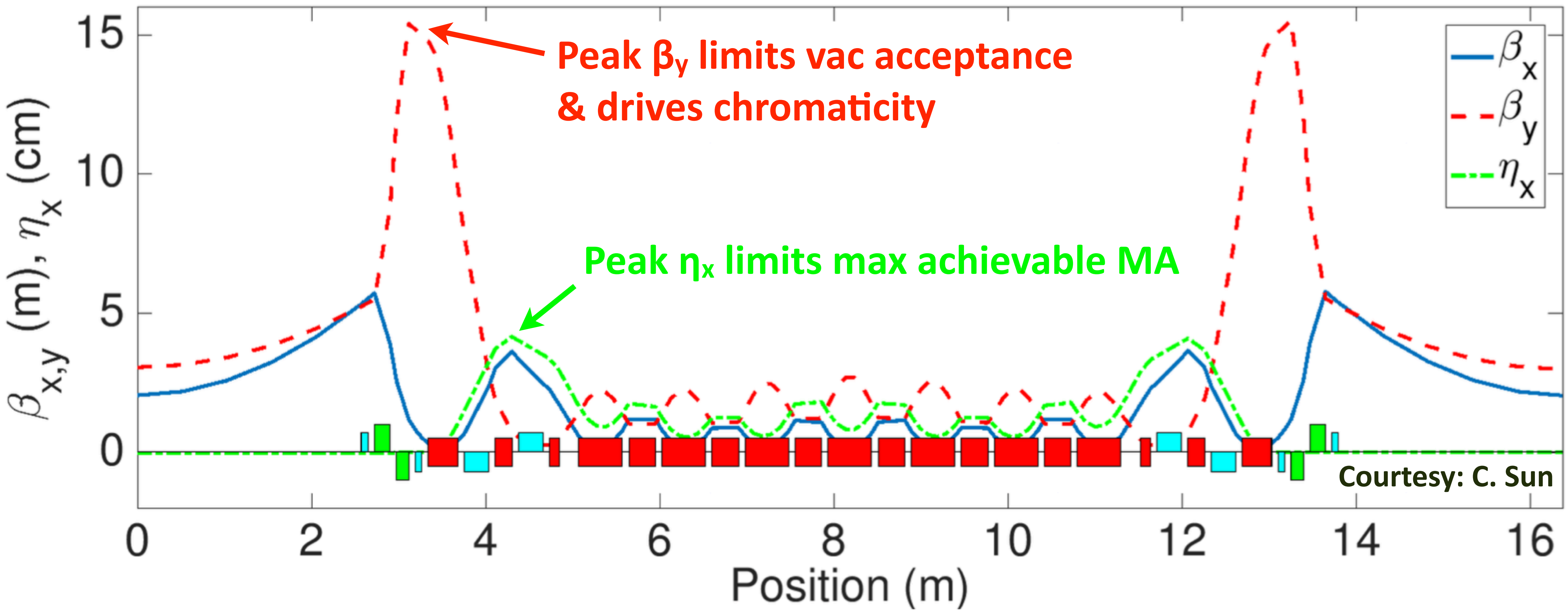


Setting the Scene: Baseline Lattice v20r (cont.)

- But this kind of ultra-high brightness approach comes at a price:
  - **Strained linear optics** → larger peak β/η functions drive natural chromaticity and aperture requirements → increases magnet gaps → weakens focusing → breaks MBA feedback cycle



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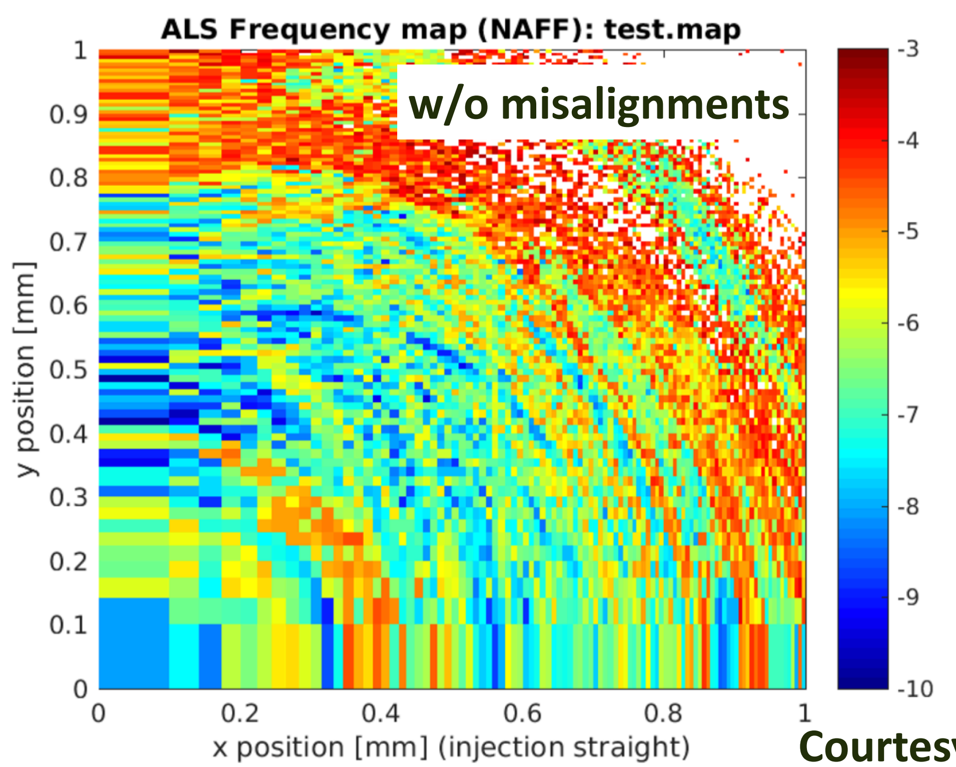
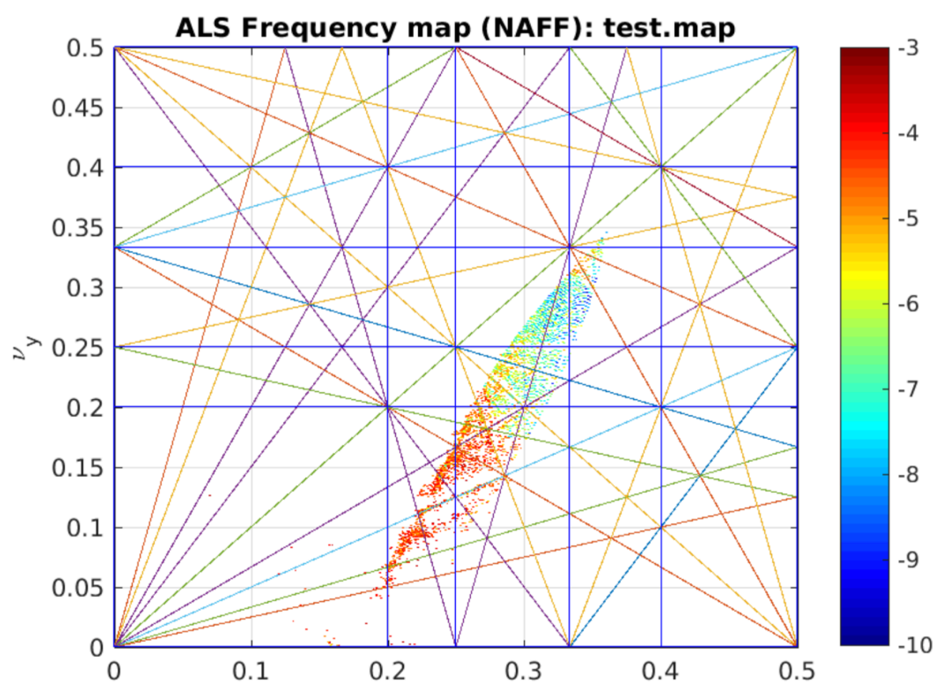
  - **Small DA**: believe can be tolerated by virtue of on-axis injection from low-emittance accumulator ring (swap-out)

~1 mm DA required for injected beam with ε ≈ 2 nm rad, β ≈ 20 m

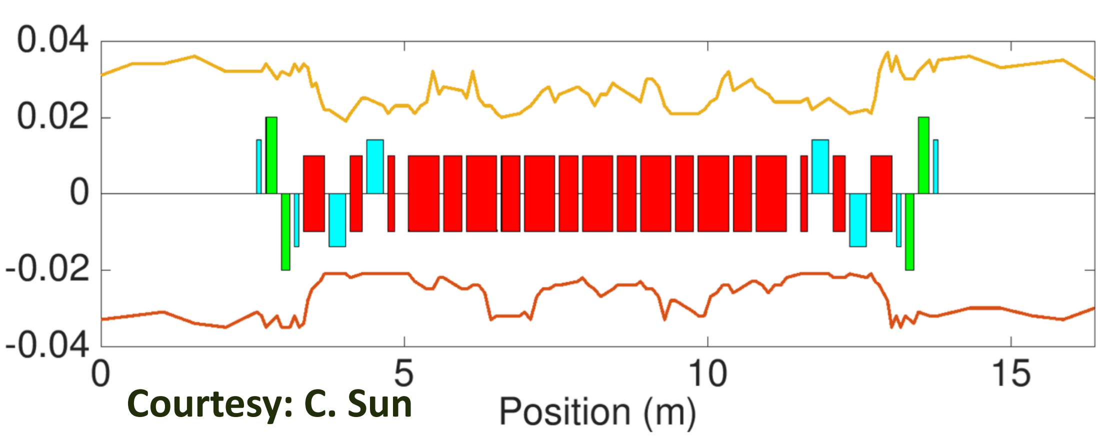




Courtesy: C. Sun

Setting the Scene: Baseline Lattice v20r (cont.)

- But this kind of ultra-high brightness approach comes at a price:
  - **Strained linear optics** → larger peak β/η functions drive natural 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: >4 hrs lifetime at 30 s injection interval allows for 1 mA deadband)



Courtesy: C. Sun

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

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

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)

Setting the Scene: Baseline Lattice v20r (cont.)

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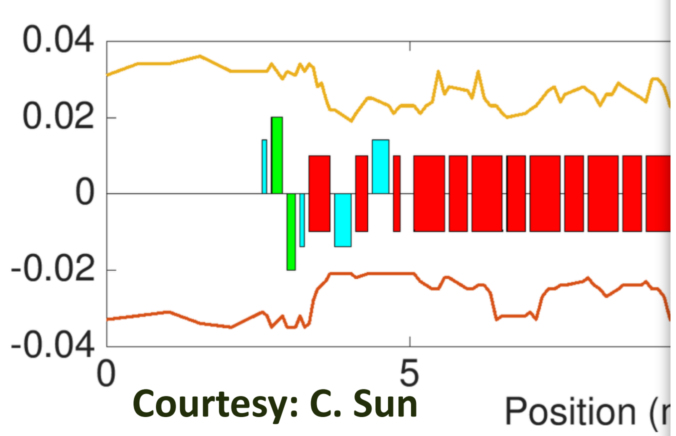

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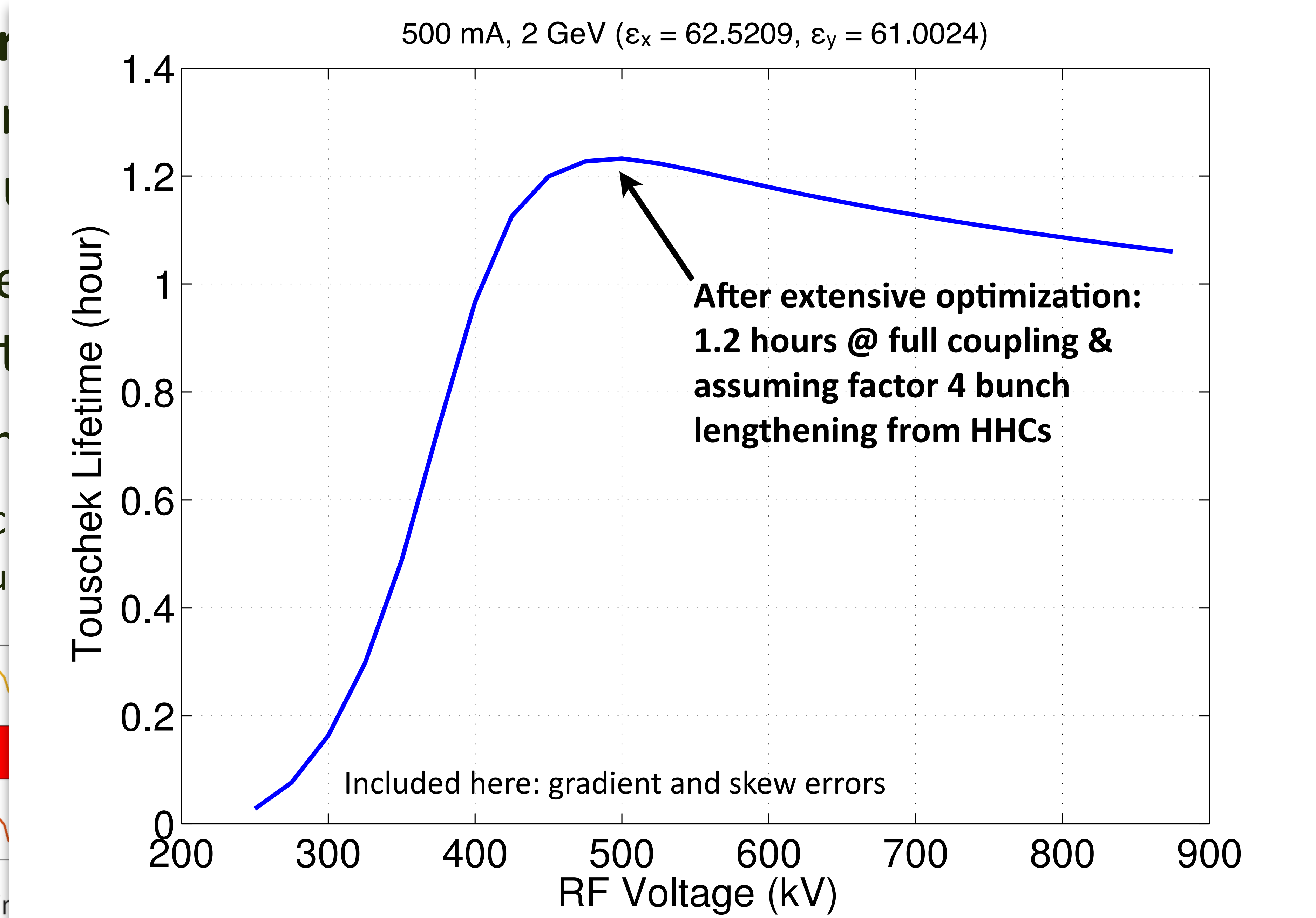


Outline for an Alternate Design

- 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

    NIM-A **737**, 148-154 (2014)
    NIM-A **770**, 98-112 (2015)

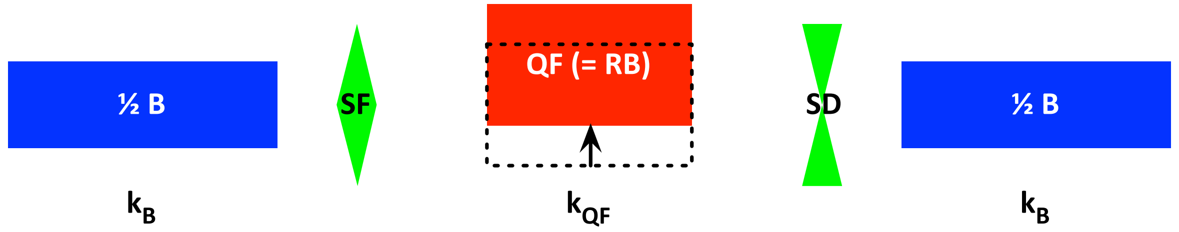
  – leveraging reverse bending to minimize emittance
    (within limits set by momentum compaction deemed acceptable)

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

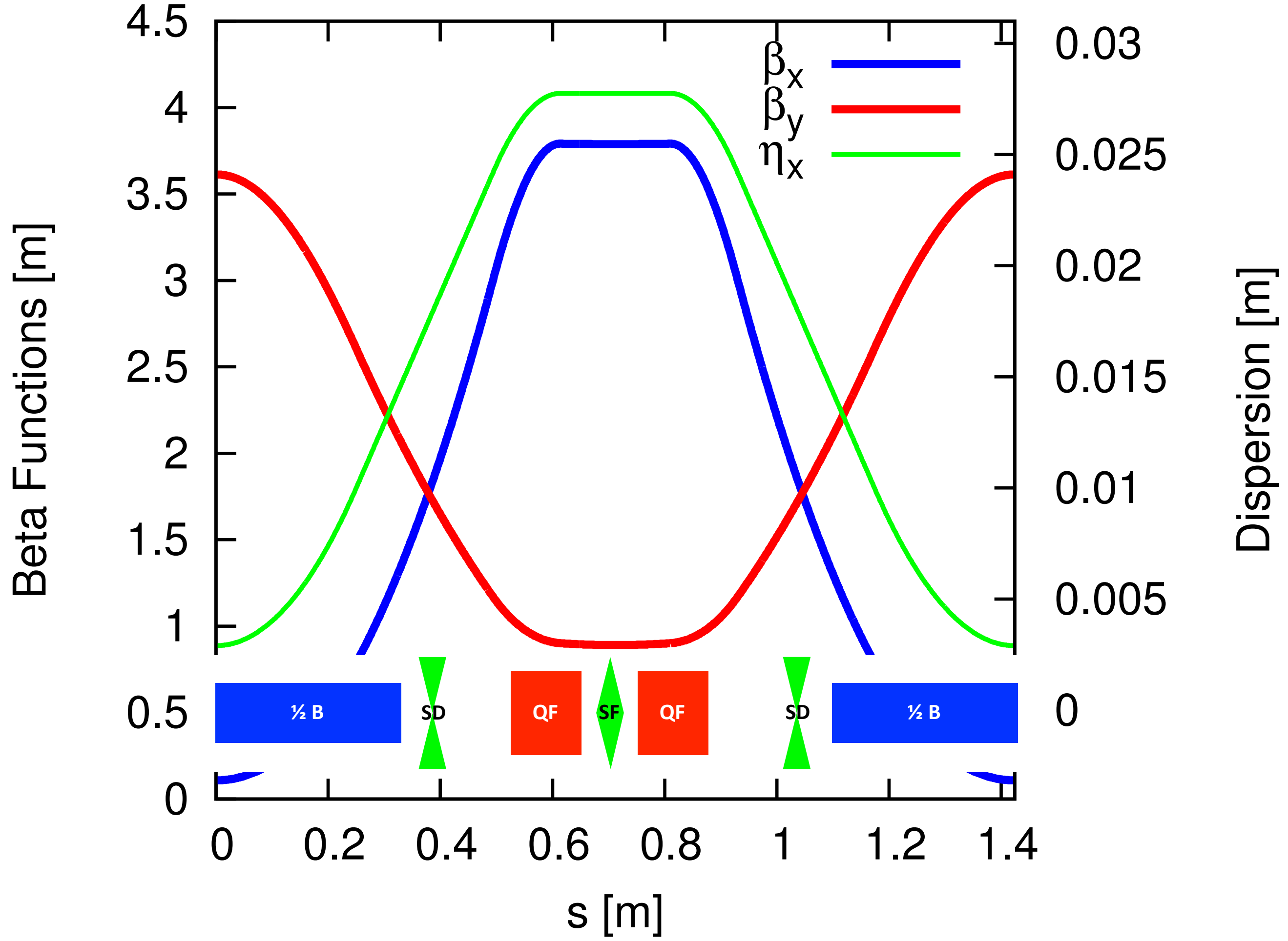
  – tuning linear optics of the unit cell so that overall MBA sector becomes higher-order achromat (geom. aberrations / RDTs minimized within)

Lattice & Optics

- Distributed chromatic correction → 7BA implemented as
  - 5 unit cells (UC)



Usual spacing between magnets: >100 mm
Min. separation: 48 mm (>2.5× min. magnet bore)



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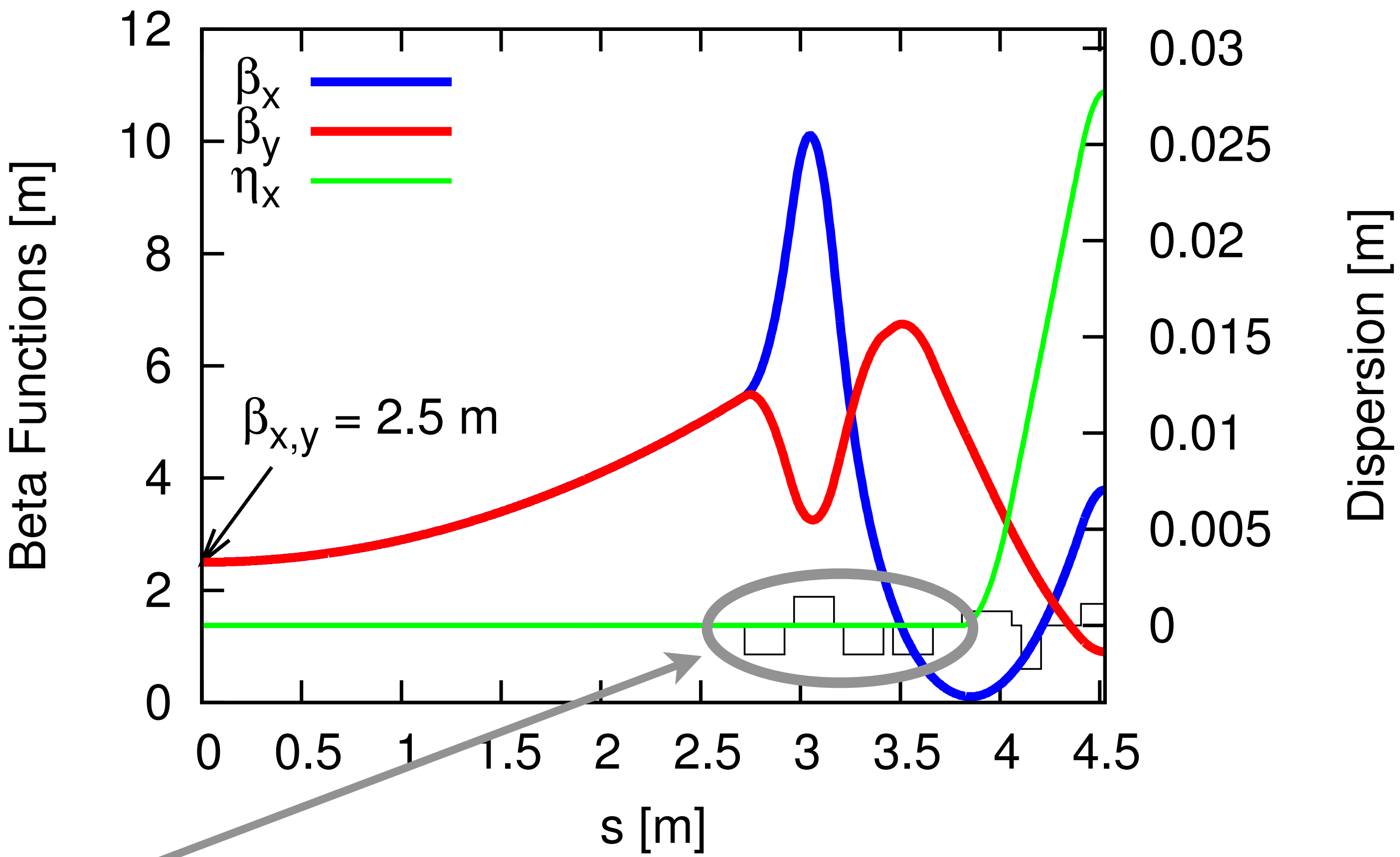
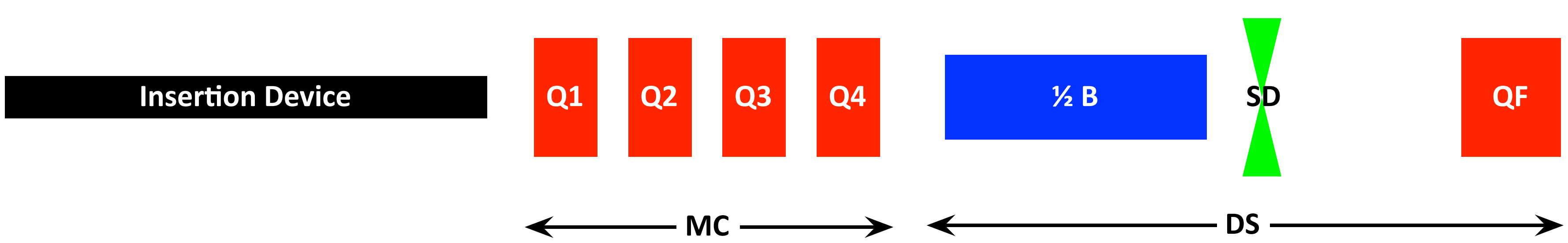
Lattice & Optics (cont.)

- Distributed chromatic correction → 7BA implemented as
  - 5 unit cells (UC)
  - 2 pairs of dispersion suppressors (DS) & matching cells (MC)

Usual spacing between magnets: >100 mm
Min. separation: 48 mm (>2.5× min. magnet bore)

SS length: 5.5 m (+350 mm compared to v20r)





Lattice & Optics (cont.)

- Distributed chromatic correction → 7BA implemented as
  - 5 unit cells (UC)
  - 2 pairs of dispersion suppressors (DS) & matching cells (MC)
- Longitudinal gradient bends (LGB) and reverse bends (RB) minimize emittance while also preventing lattice from becoming isochronous

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

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

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

Lattice & Optics (cont.)

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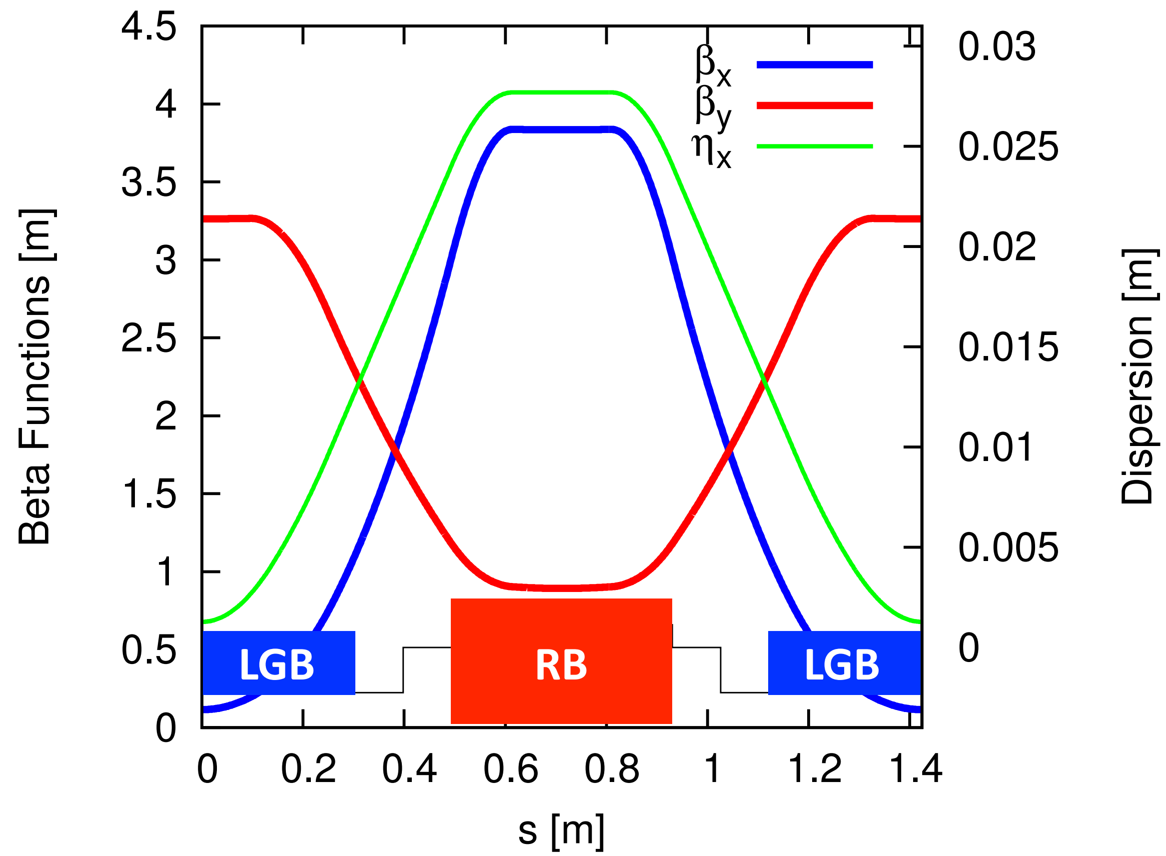

$$\alpha_c = \frac{1}{C}\left(\int_{LGB}\frac{\eta_x}{\rho}ds + \int_{RB}\frac{\eta_x}{\rho}ds\right) < 0$$

Small Negative Large

Yes we can!

Lattice & Optics (cont.)

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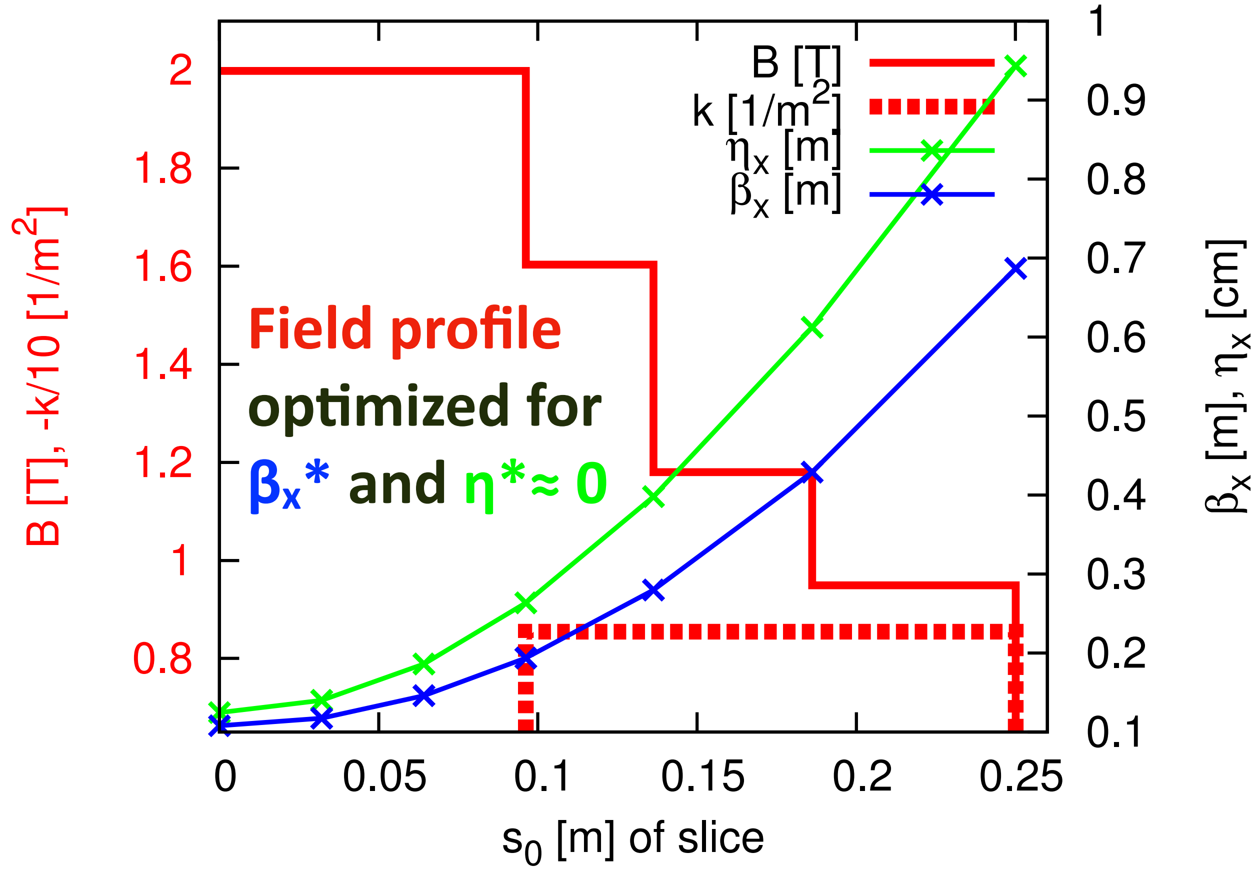
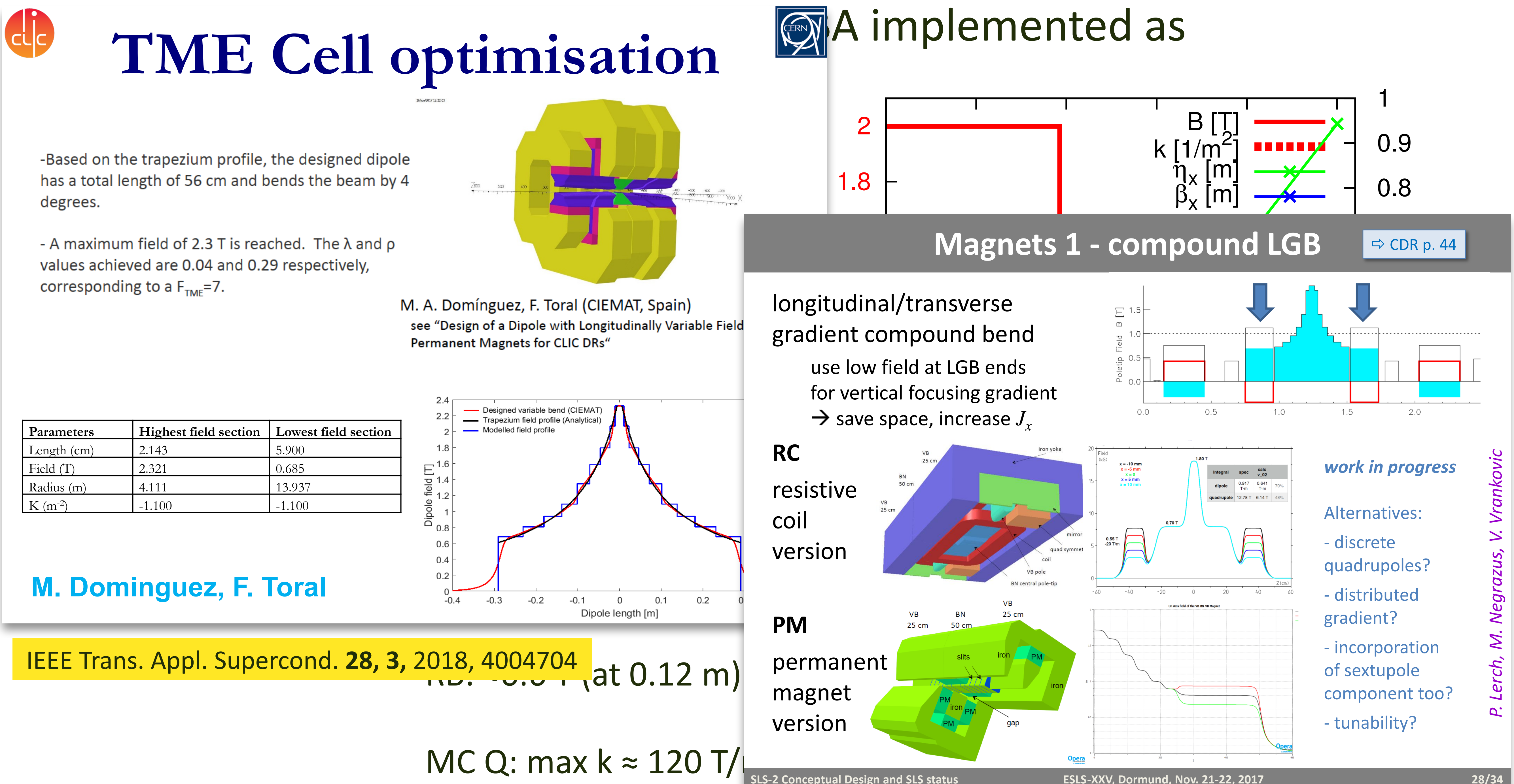


RB: ≈0.6 T (at 0.12 m) & max k ≈ 108 T/m (→ 5.7 mm offset)

MC Q: max k ≈ 120 T/m (at uniform 0.2 m length)

Lattice & Optics (cont.)



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

SLS-2 CDR, Dec 2017

Lattice & Optics (cont.)

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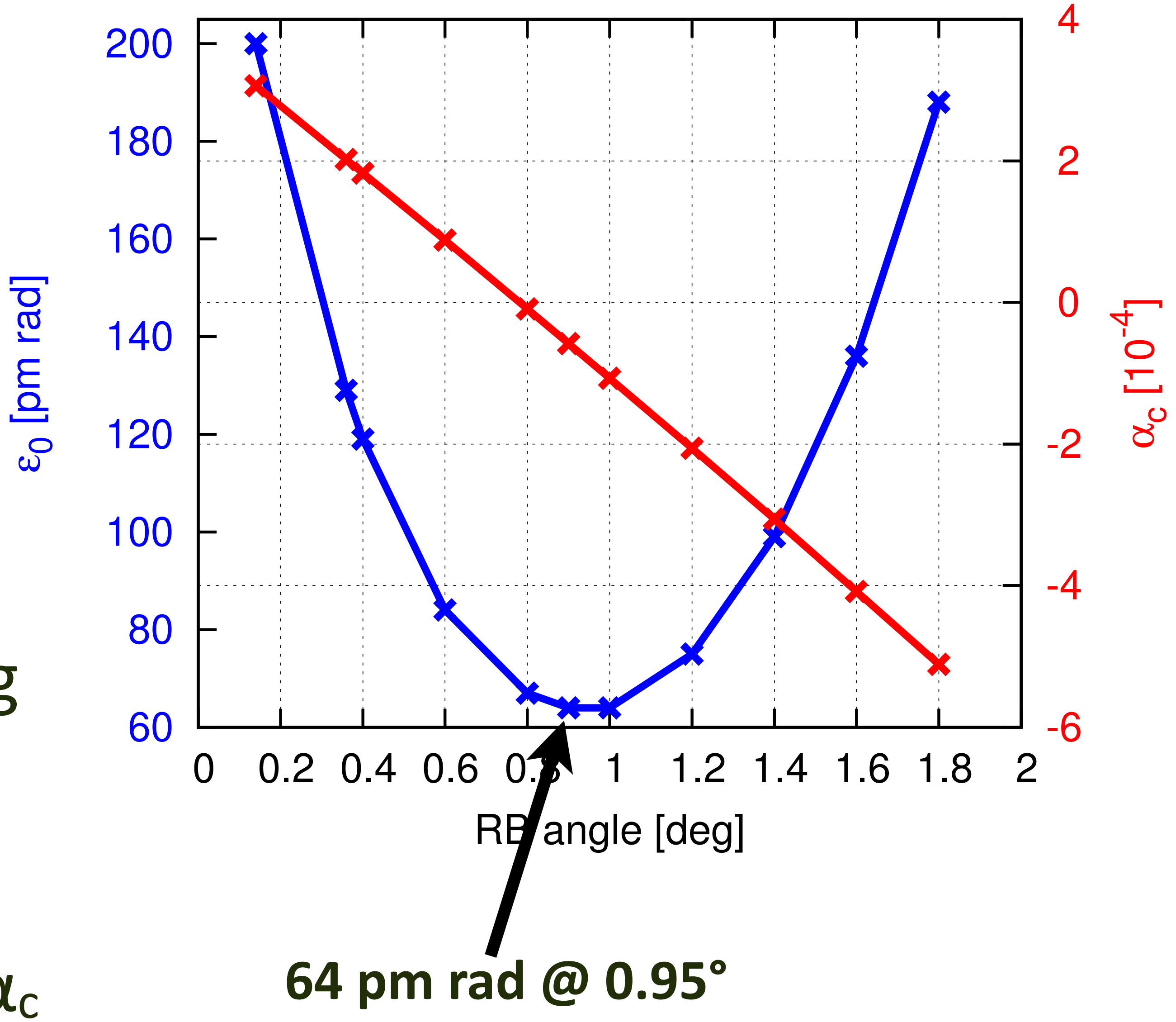
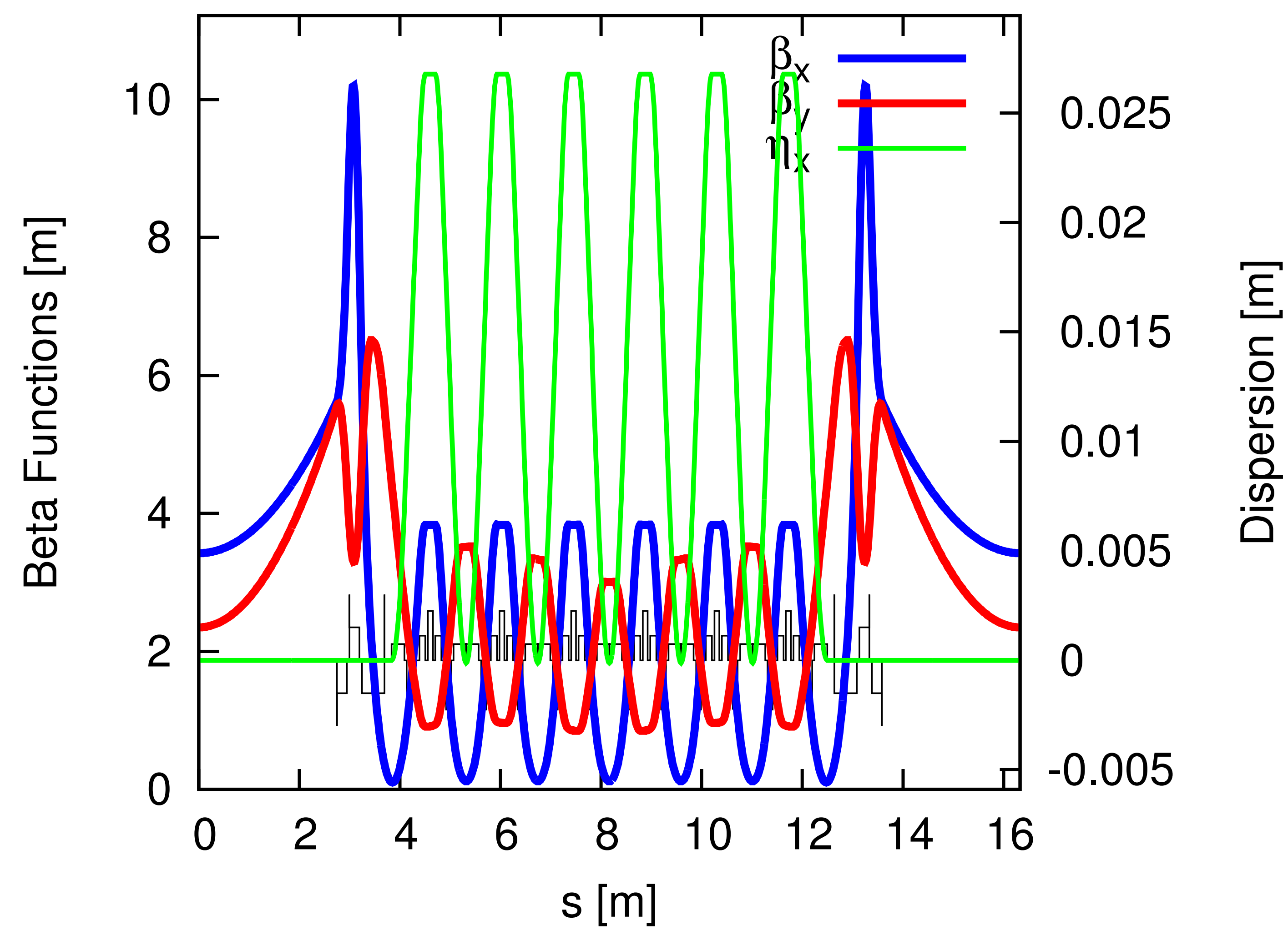
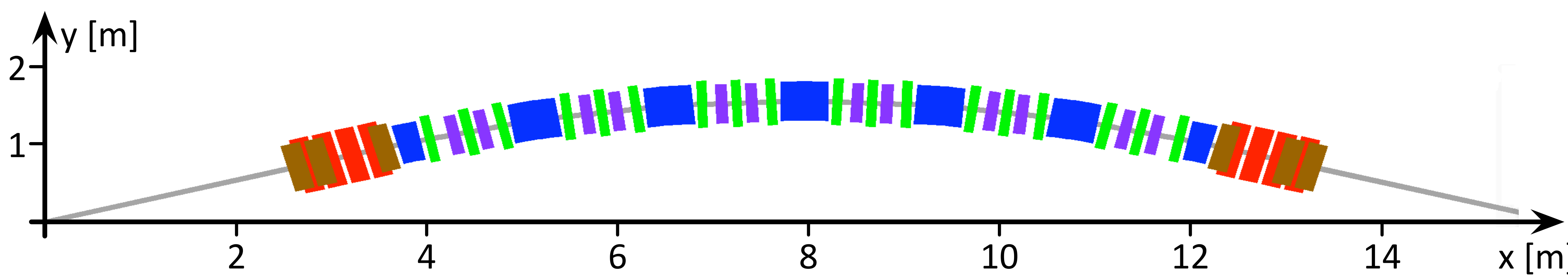
  - 5 unit cells (UC)
  - 2 pairs of dispersion suppressors (DS) & matching cells (MC)
- Longitudinal gradient bends (LGB) and reverse bends (RB) minimize emittance while also preventing lattice from becoming isochronous
- Set UC tunes $2\pi \times ({}^{3}/_{7}, {}^{1}/_{7})$ & detune RB angle for acceptable α_c (1.27° → ε_0 = 89 pm, $\alpha_c = -1.25\times10^{-4}$)



Linear Optics Summary

- ε_0 = 89 pm, $\alpha_c = -1.25\times10^{-4}$
- J_x = 1.74, U_0 = 457.7 keV
- **$\varepsilon_{x,y}$ = 57 pm rad** (fully coupled)
- $\sigma_{x,y}$ = 14/12 µm @ ID
- ν_x = 39.36, ν_y = 14.38
  (chosen with consideration to NL dynamics)
- $\xi_x = -106.0$, $\xi_y = -35.9$
- Peak $\beta \approx 10$ m, $\eta < 27$ mm





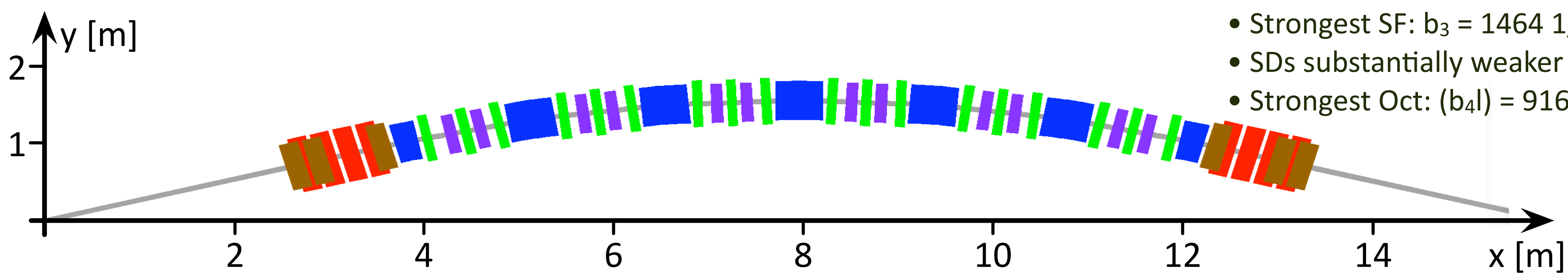
Nonlinear Optics

- Large no. of sextupoles at various phase advances → cancel residual RDTs entirely **within** achromat: 3 SF & 4 SD in UCs (SH & O in MCs)
- 7 chromatic sextupole knobs, 5 can be chosen freely
- Tune sextupoles for:
  - linear chromatic correction: –106/–36 → –1/–1
  - 1st/2nd-order RDTs (weighted SVD to cancel)
  - 2nd/3rd-order chromaticity (weighted SVD to achieve target values)
- Adjust octupoles to tailor ADTS (matrix inversion → achieve target values)

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

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

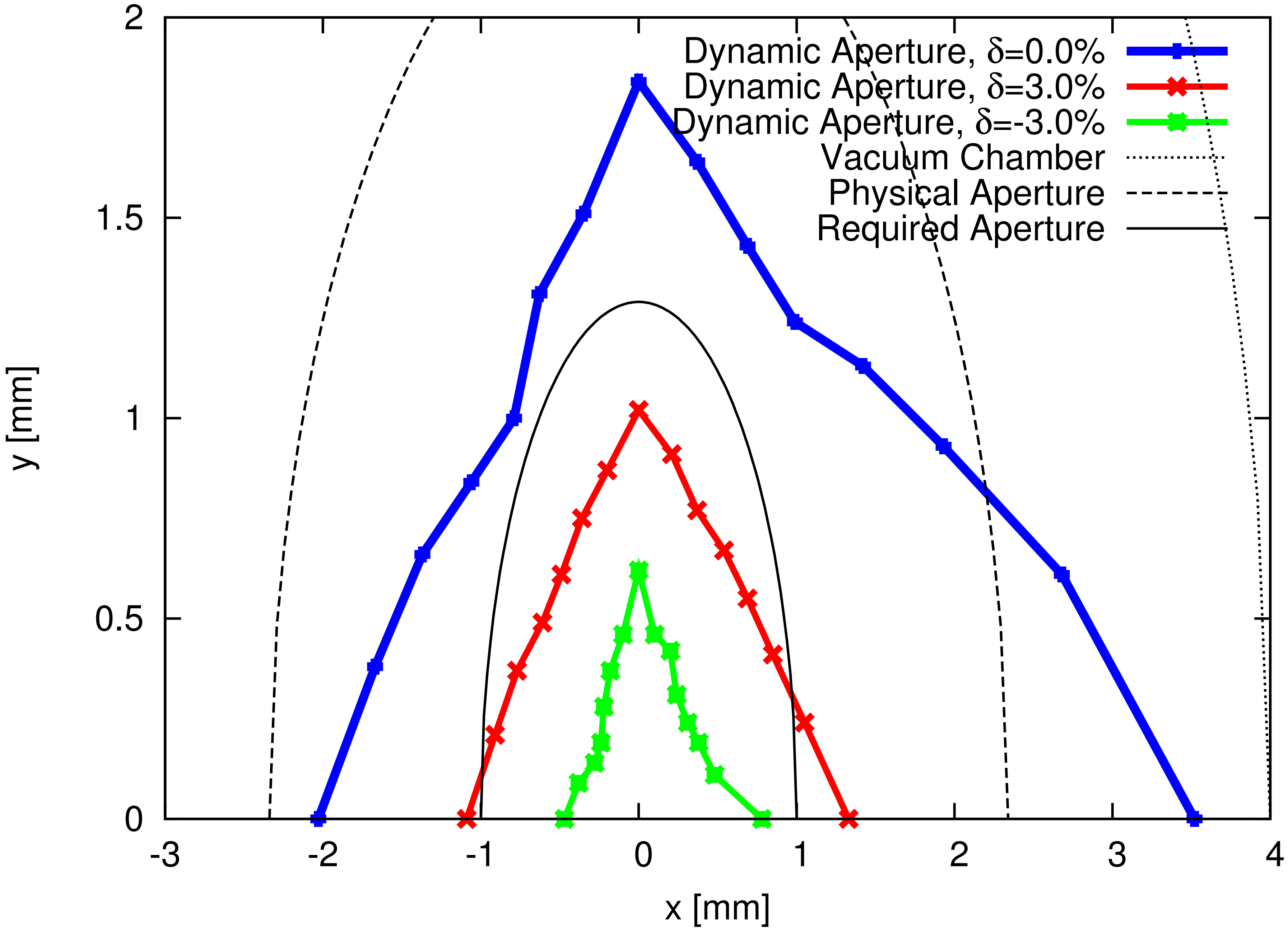
From iterations with tracking studies



- Strongest SF: b_3 = 1464 1/m³
- SDs substantially weaker
- Strongest Oct: $(b_4 l)$ = 9168 1/m³

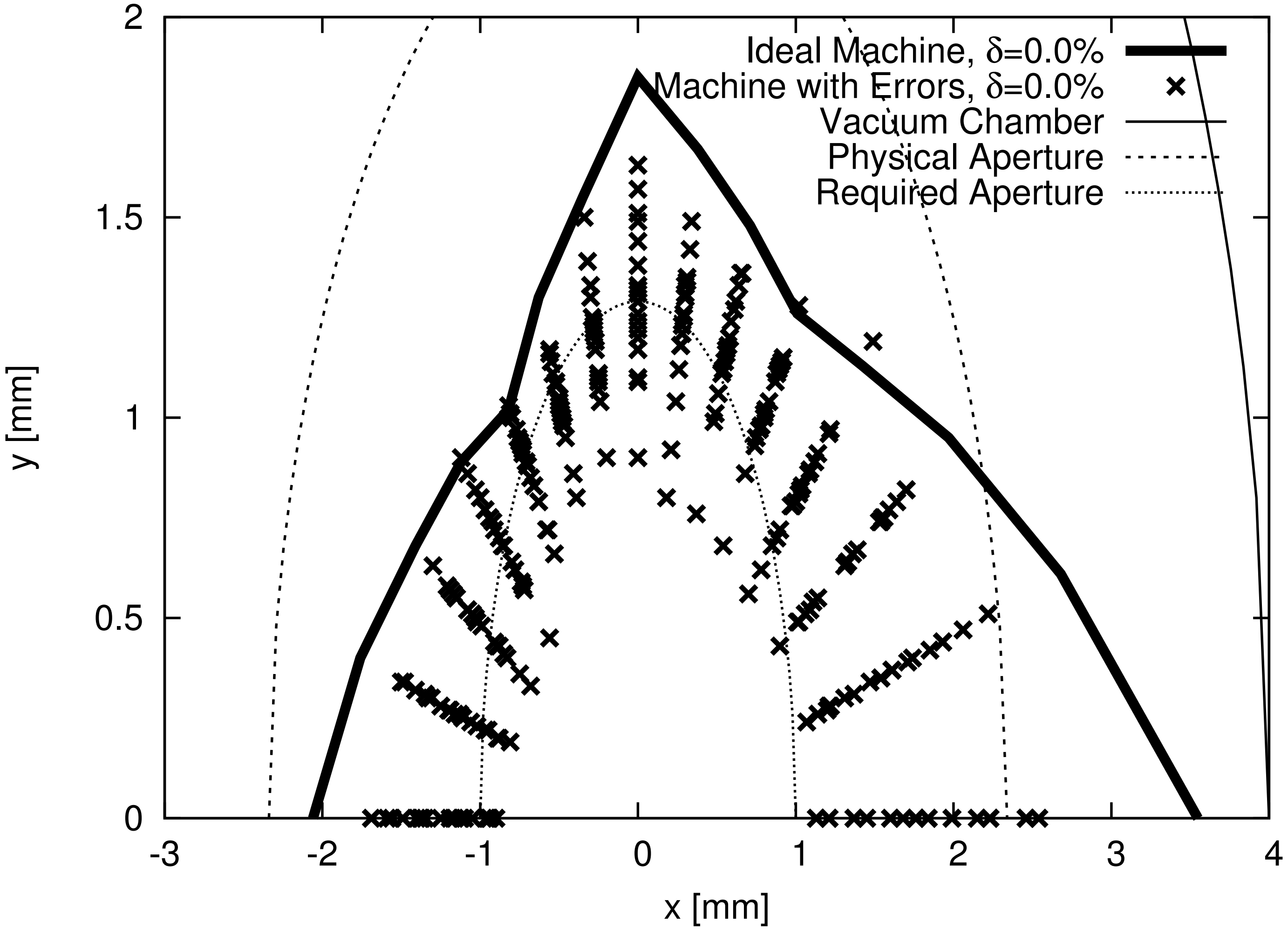
Expected Performance: DA

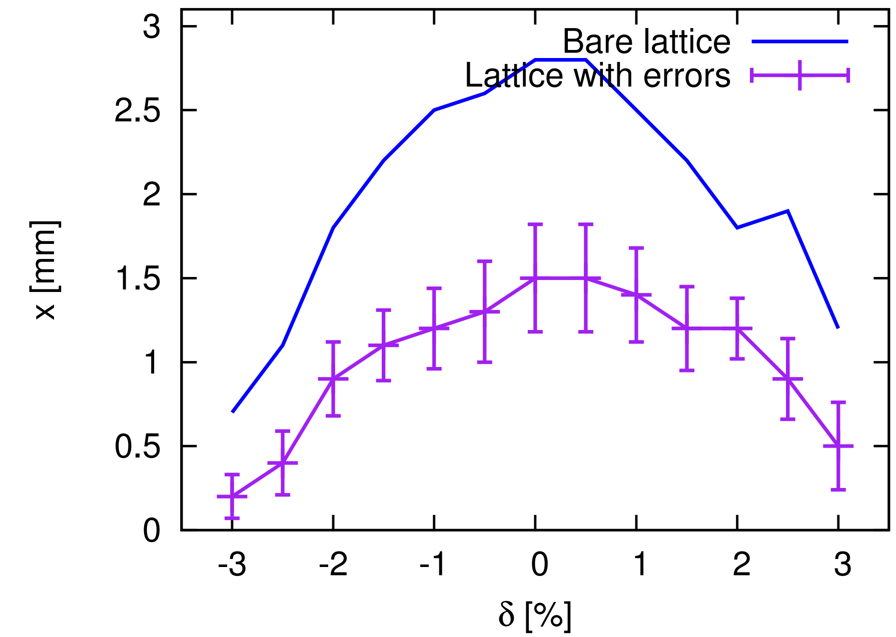
- Verify in 6D tracking that DA large on & off momentum

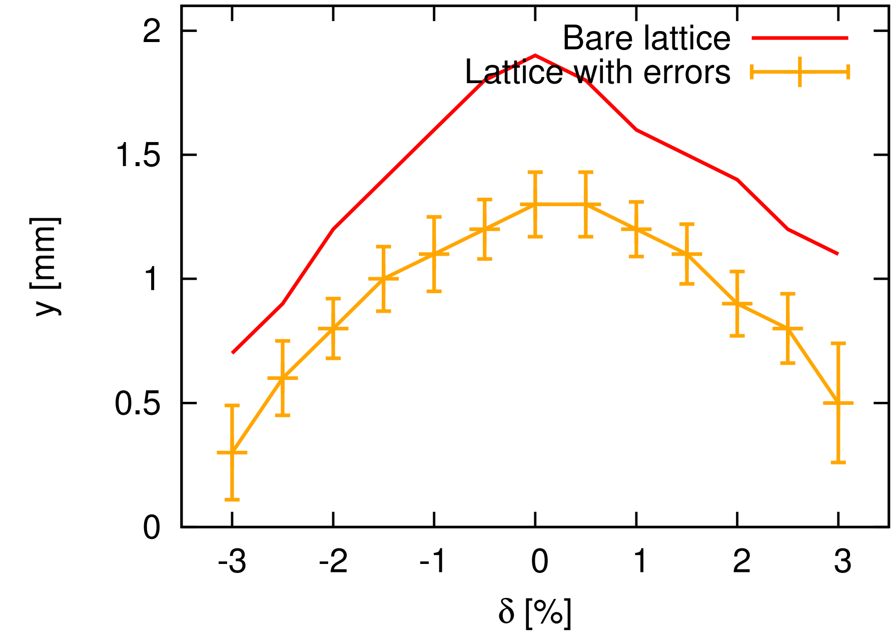


Expected Performance: DA with Errors

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







Quads & sextupoles:
- **25 µm rms in x/y**
- **0.2 mrad rms roll**

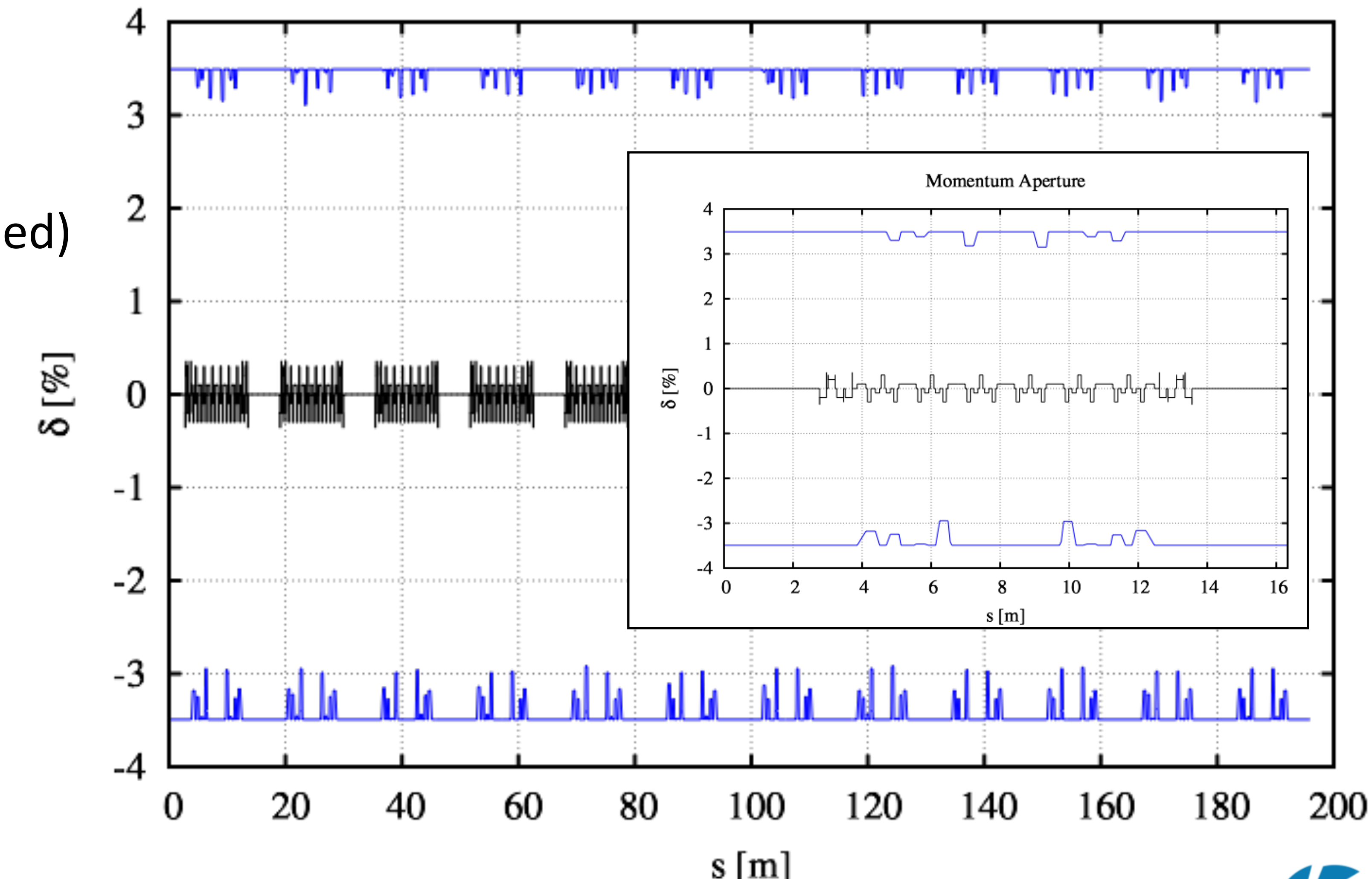
Quads:
- **0.05% rms gradient variation**

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

→ Orbit corrected
→ No skew correction
→ No beta beat correction

Expected Performance: LMA & Touschek

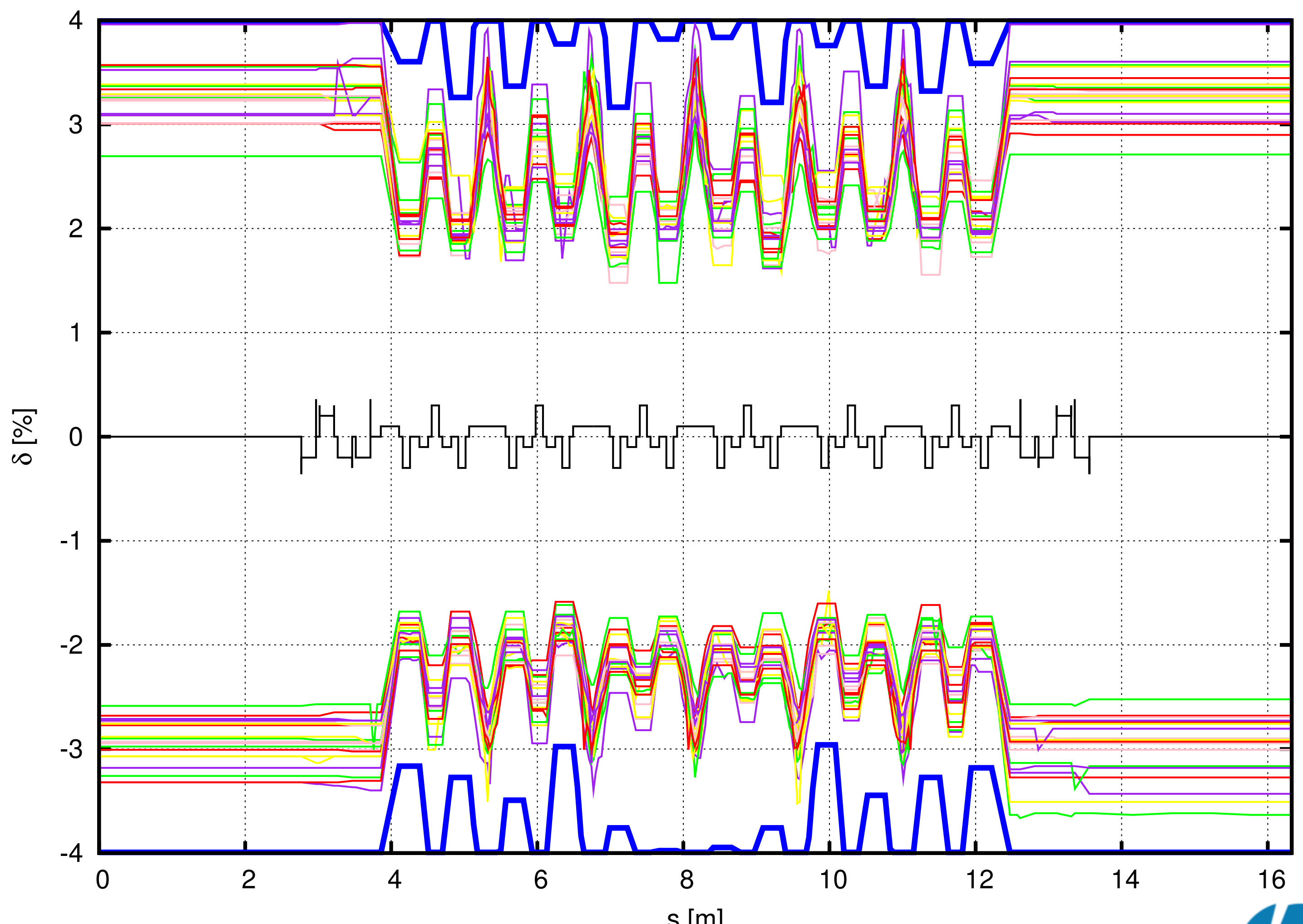
- LMA from 6D tracking with errors → large overall MA possible provided sufficient RF acceptance available
  - LMA somewhat asymmetric due to better DA for $\delta>0$
  - Overall MA calculated assuming 0.83 MV → δ_{rf} = 3.5%
  - 6D Touschek tracking
    → **5.2 hrs incl. HHCs**
    (5.8 hrs if IBS @ 500 mA included)



Expected Performance: LMA & Touschek (cont.)

- LMA from 6D tracking with errors ➔ large overall MA possible provided sufficient RF acceptance available
  - LMA somewhat asymmetric due to better DA for δ>0
  - Overall MA calculated assuming 0.83 MV ➔ δ_{rf} = 3.5%
  - 6D Touschek tracking ➔ **5.2 hrs incl. HHCs** (5.8 hrs if IBS @ 500 mA included)
  - First error runs indicate ➔ **2.5+ hrs** incl. HHCs
  - And ALS RF still provides headroom to exploit

$\tau_{ts} \propto \delta_{acc}^3$



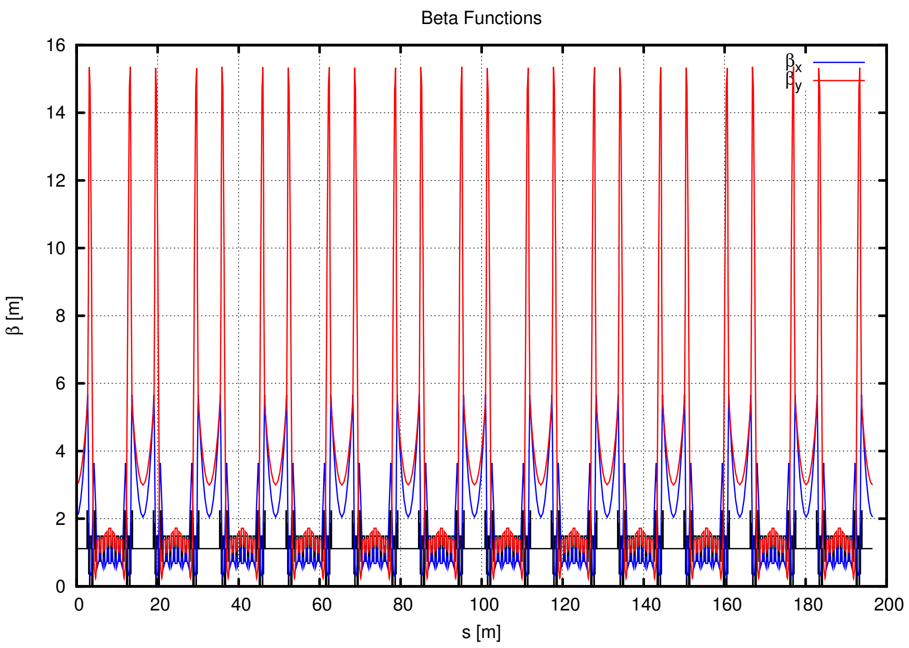
What does this leave us with?

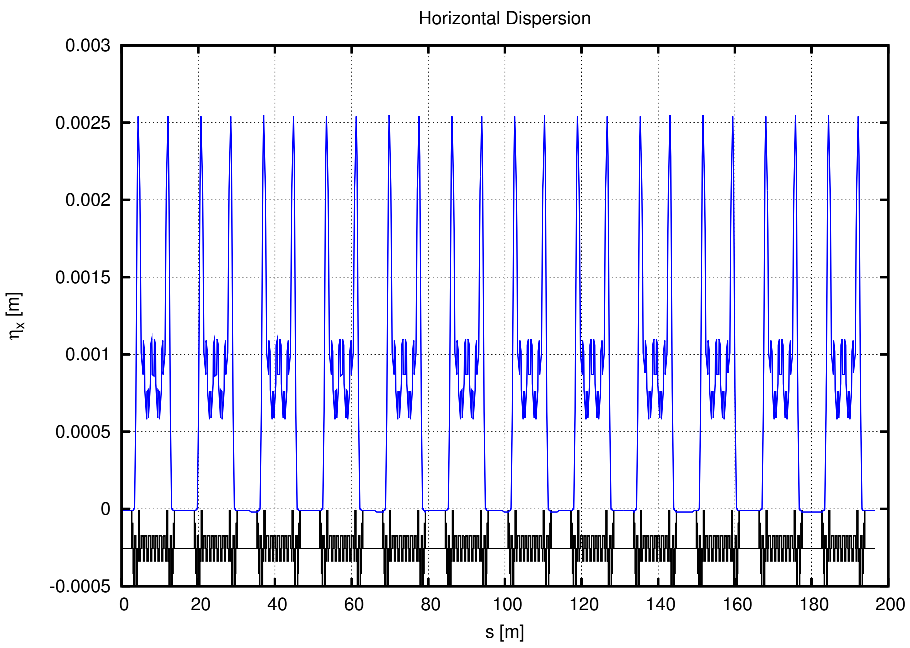
- The ALS-U 7BA is only a preliminary physics design
  - Would need to be thoroughly optimized for brightness & lifetime
- Baseline v20r has seen substantially more optimization and is more mature
- However, this alternate design shows a lot of potential
  - Large DA, better lifetime, and potentially very high brightness
  - Associated engineering challenges: LGBs, strong sextupoles, vacuum chamber design
- Does the 7BA show enough potential to warrant further study effort during the upcoming PDR phase?

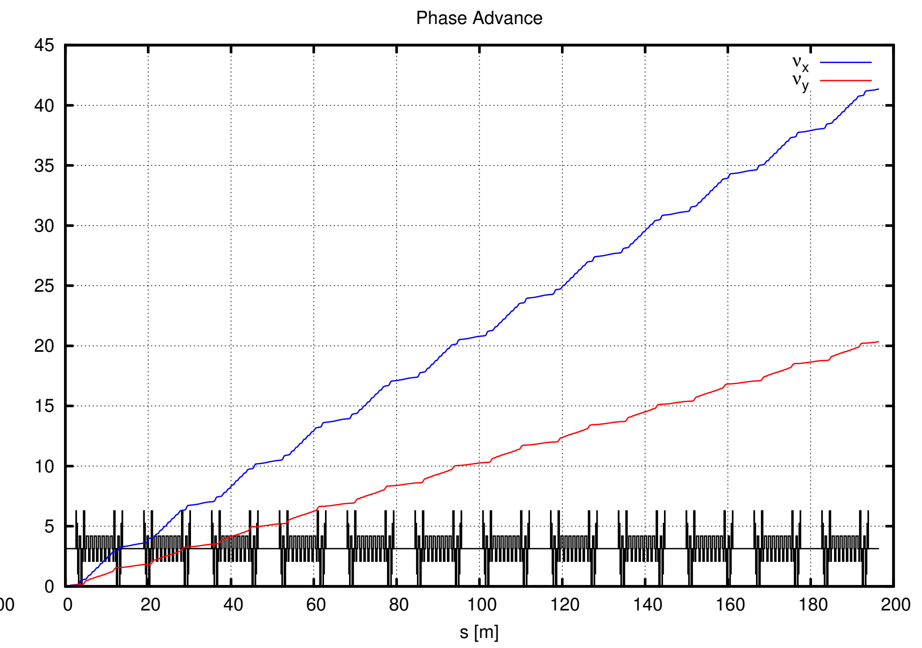
Backup (Part I)

Tracy-3 lattice & model set up for v20r baseline

- Magnet lattice translated from elegant, linear optics agree well
- 20 BPMs inserted according to current vacuum design
- 18 (thin) CM pairs installed @ all RBs and sextupoles (→ #CM < #BPM)







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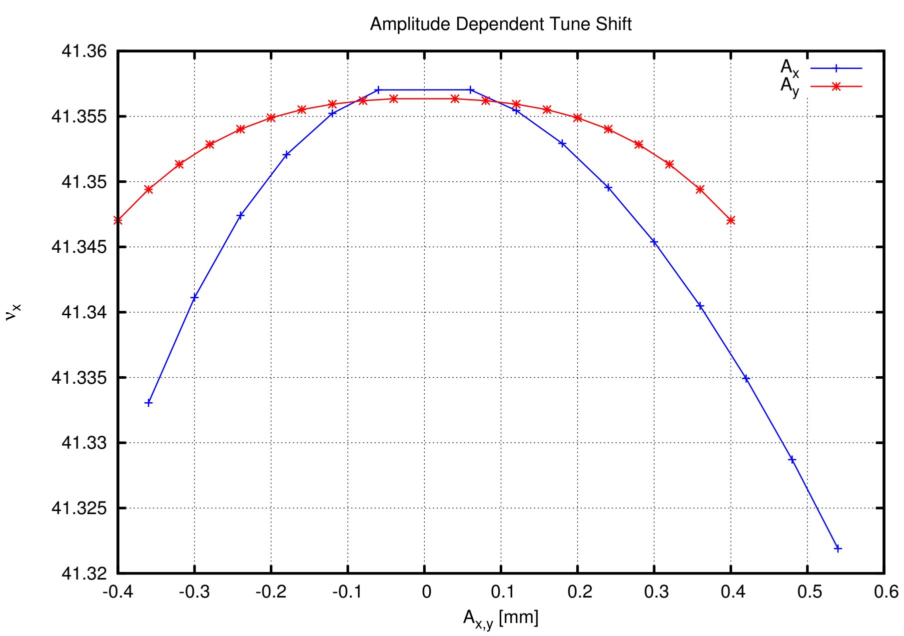

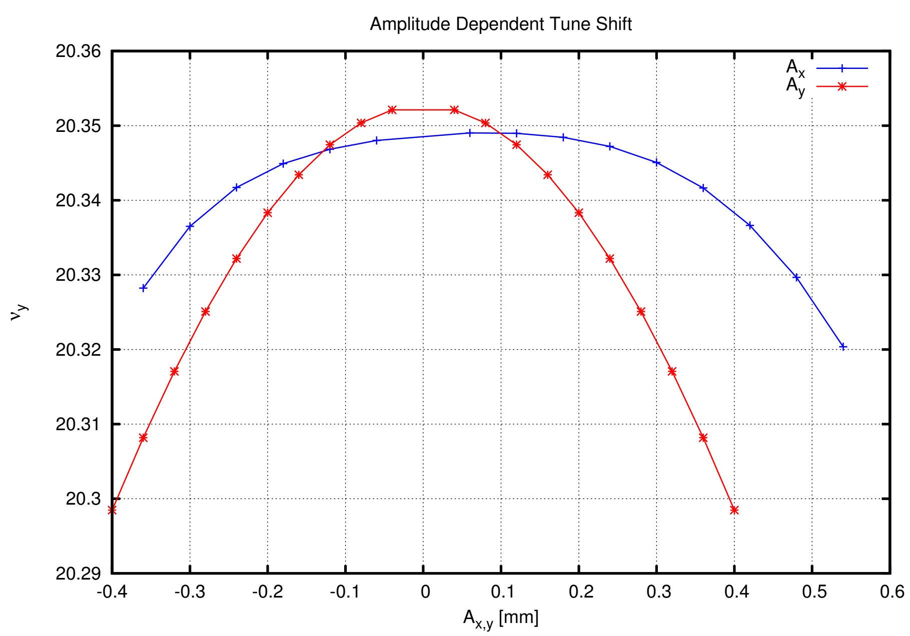

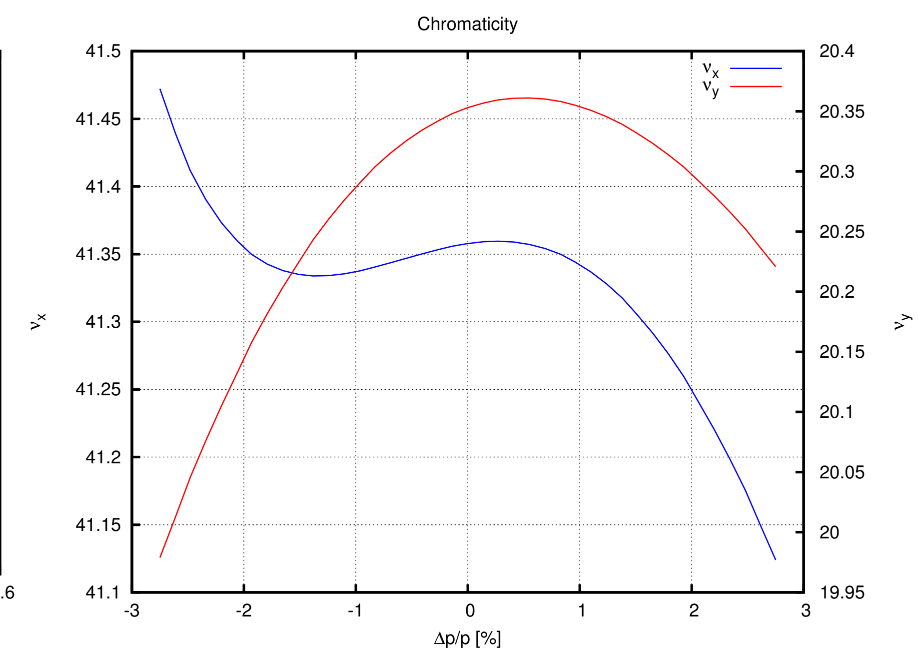

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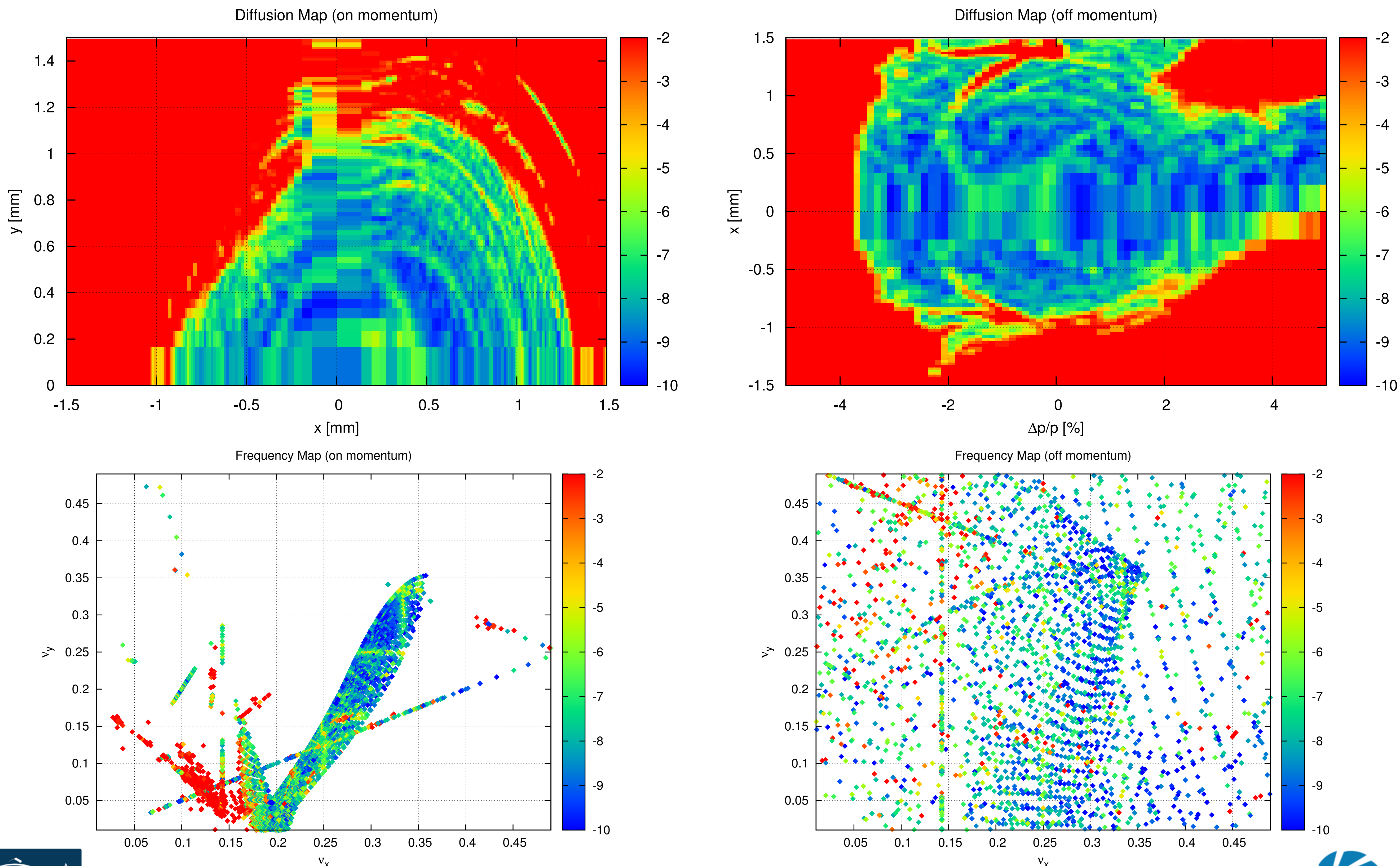
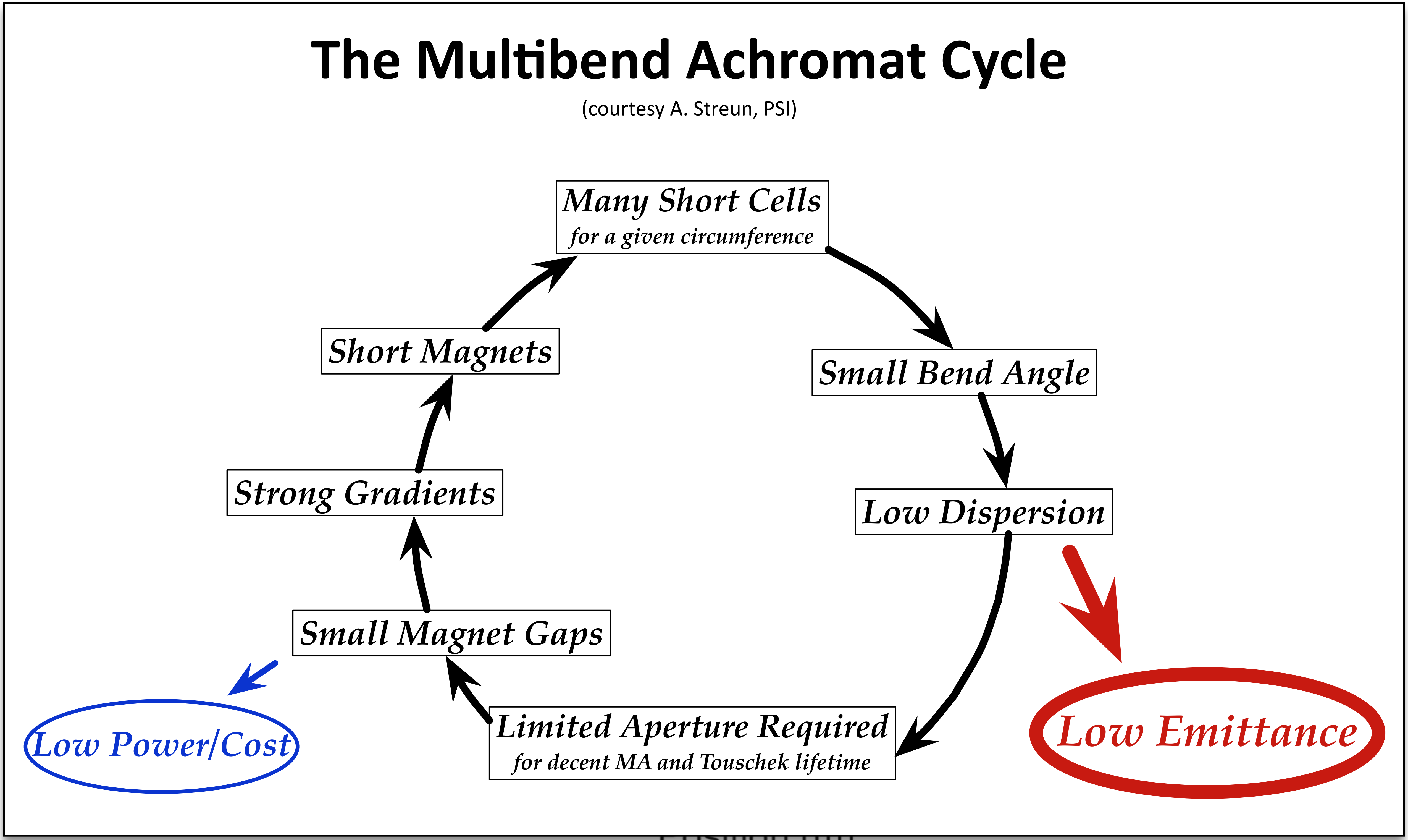


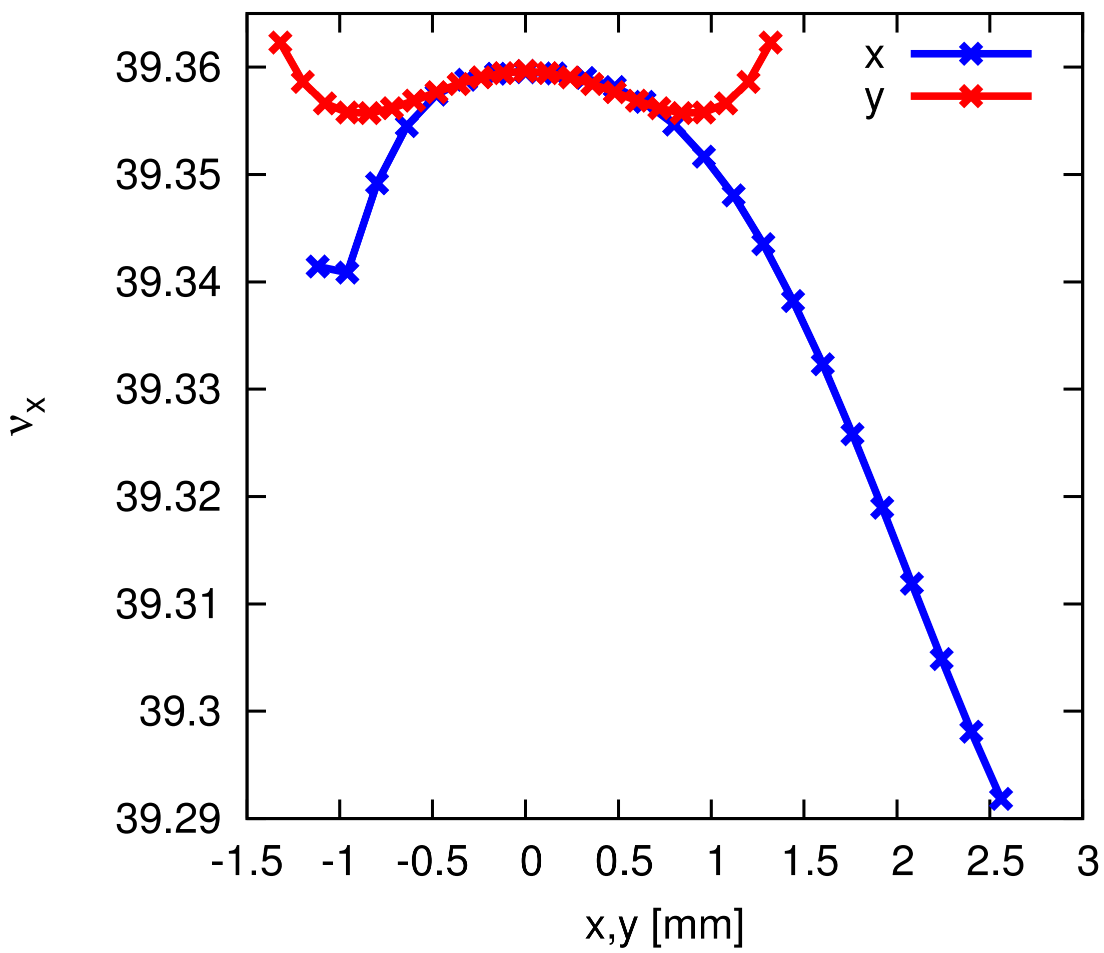
Backup (Part II)

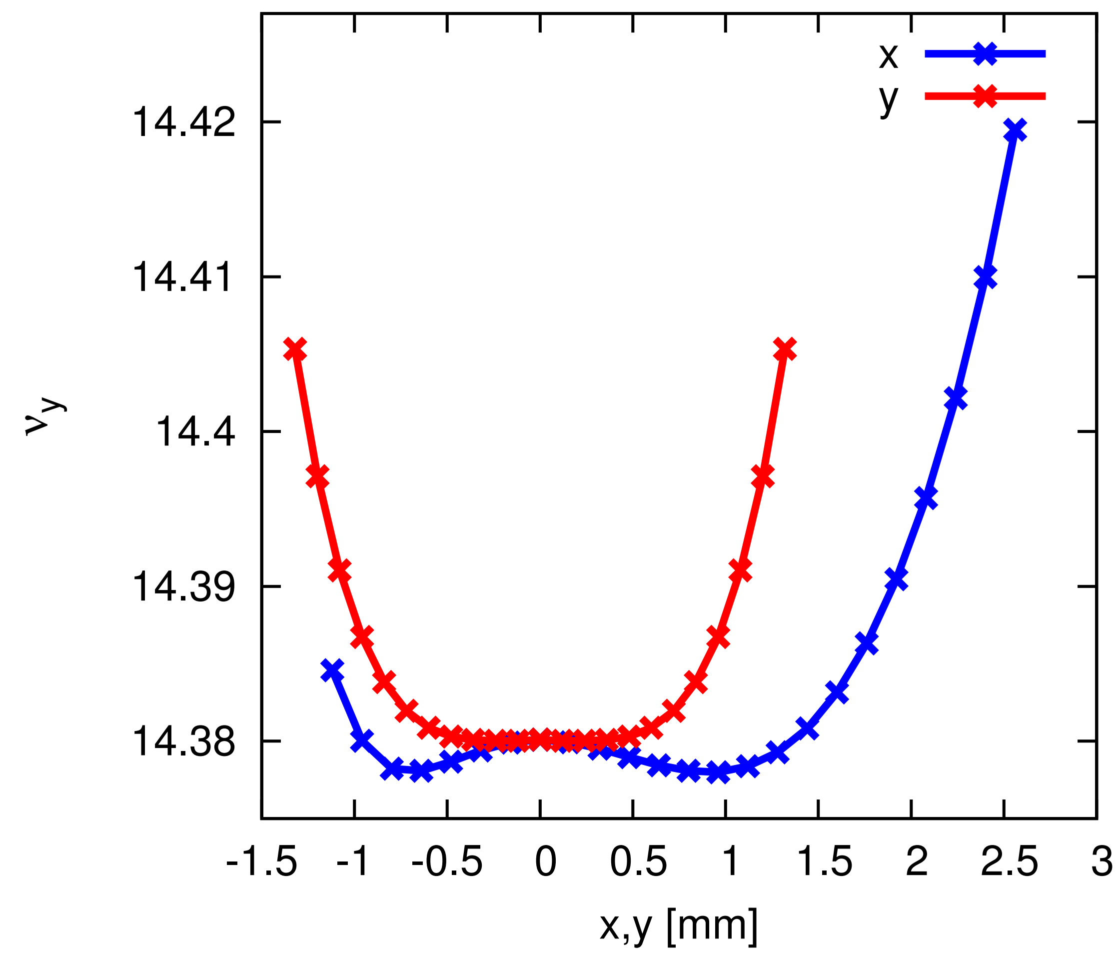
Setting the Scene: Baseline Lattice v20r (cont.)



Expected Performance: Tune Shifts

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





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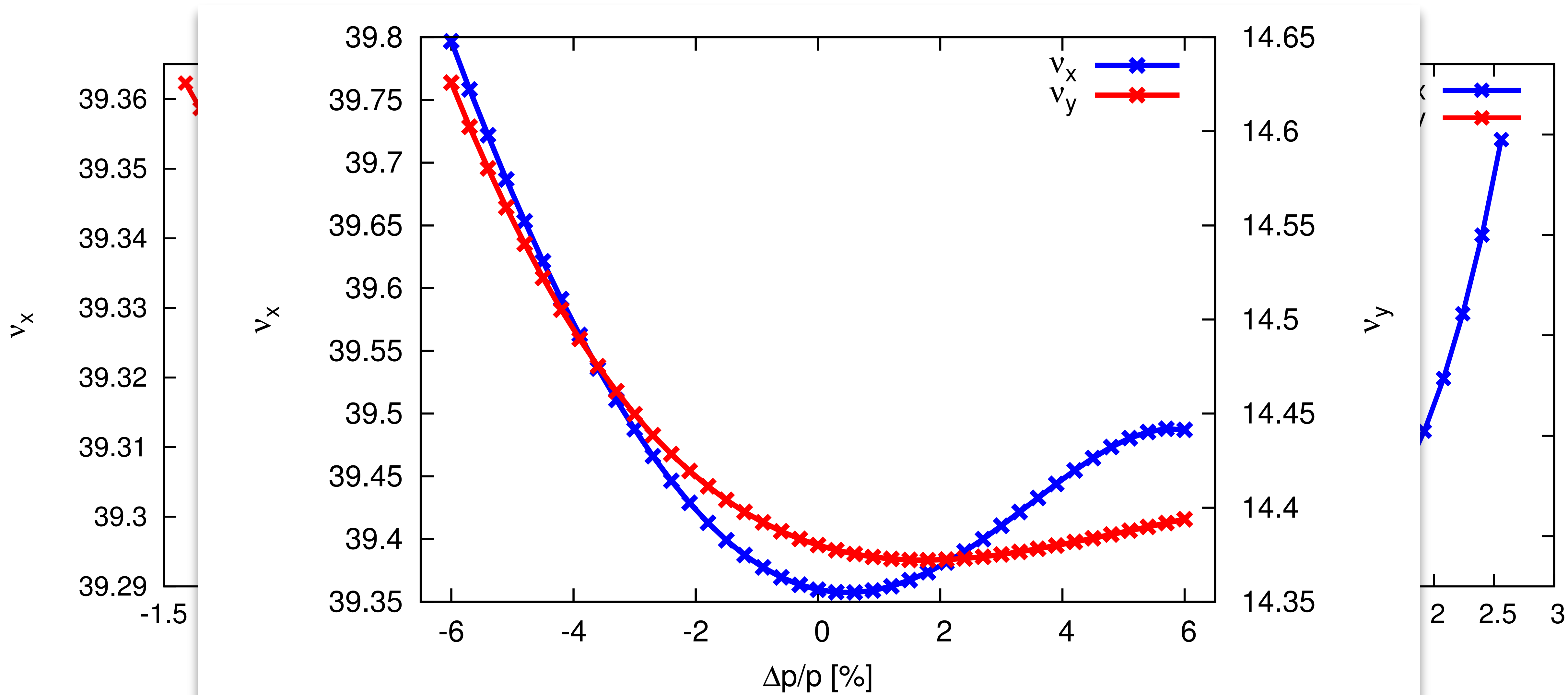
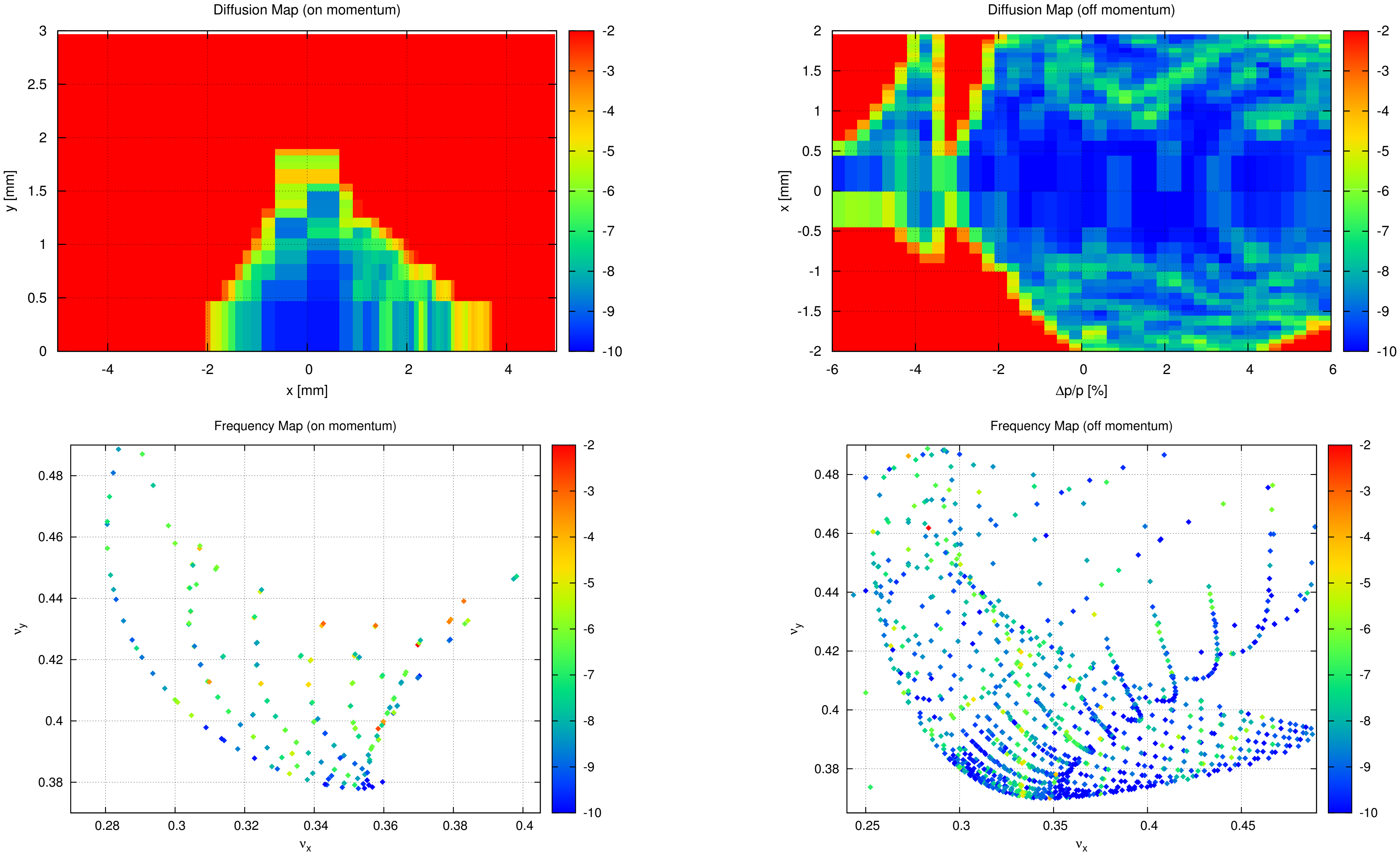


Expected Performance: FMA

- Compact tune footprint results in homogeneous low diffusion rates



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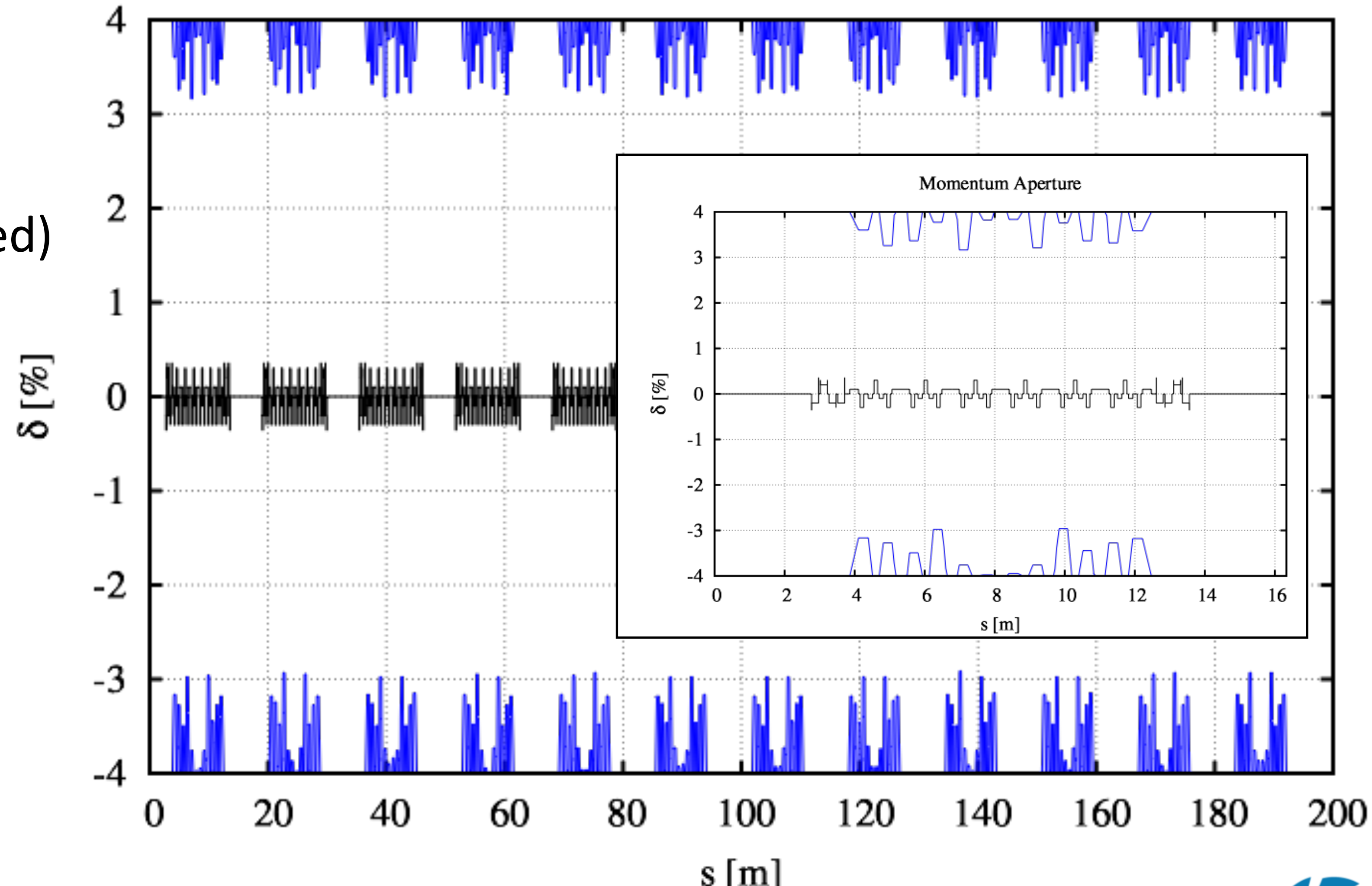
  - 6D Touschek tracking
    → **5.2 hrs incl. HHCs**
    (5.8 hrs if IBS @ 500 mA included)
  - Overall MA dominated by RF acceptance
    → δ_{rf} = 4.0% (0.91 MV) renders **8.0 hrs**

$$\tau_{ts} \propto \delta_{acc}^3$$



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ALS-U

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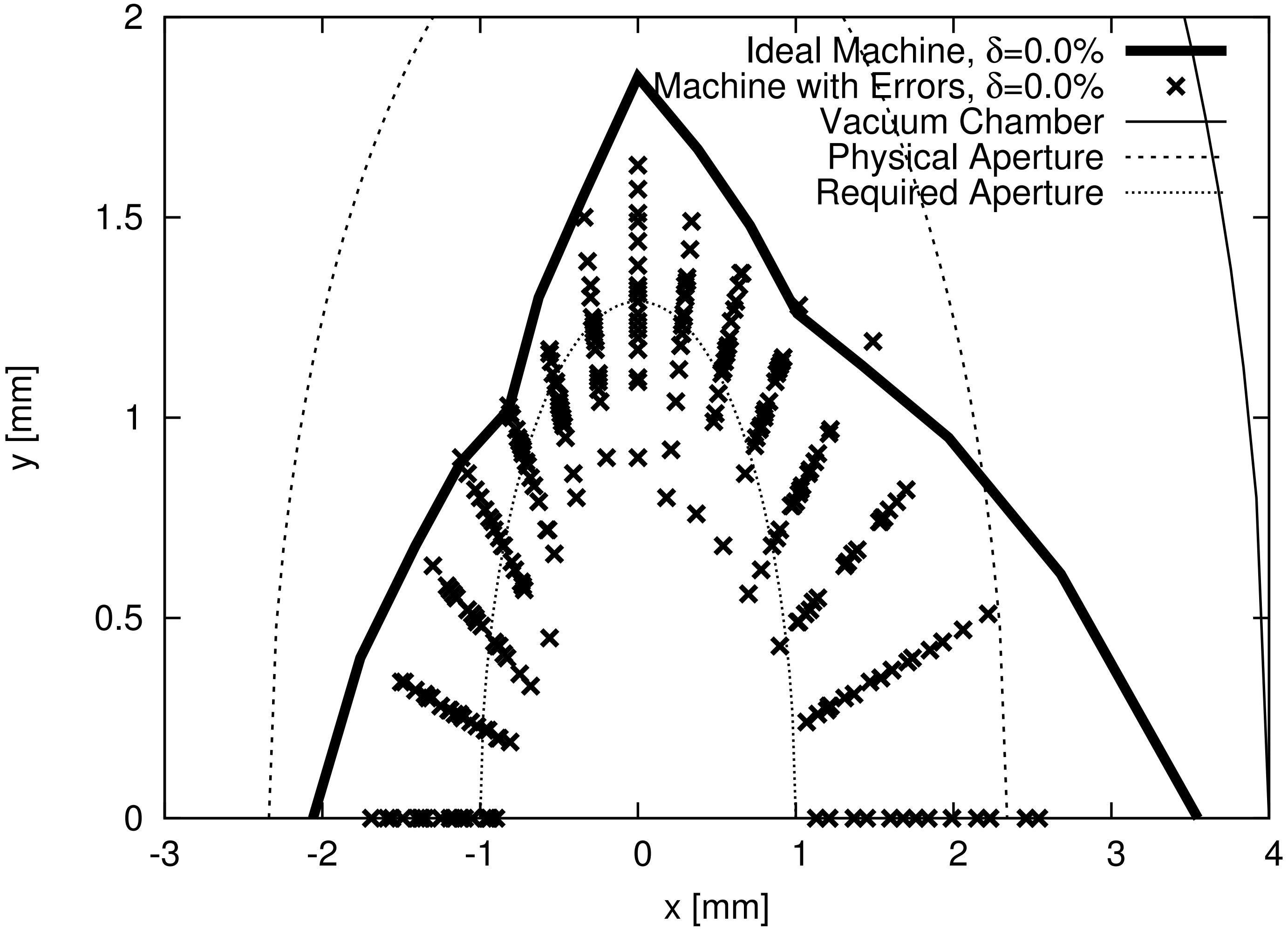

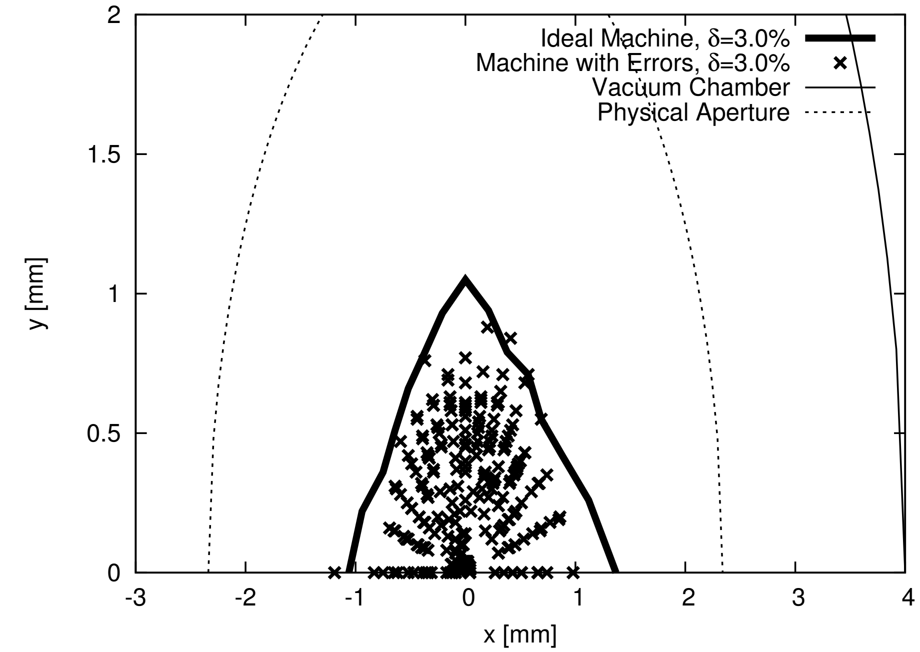

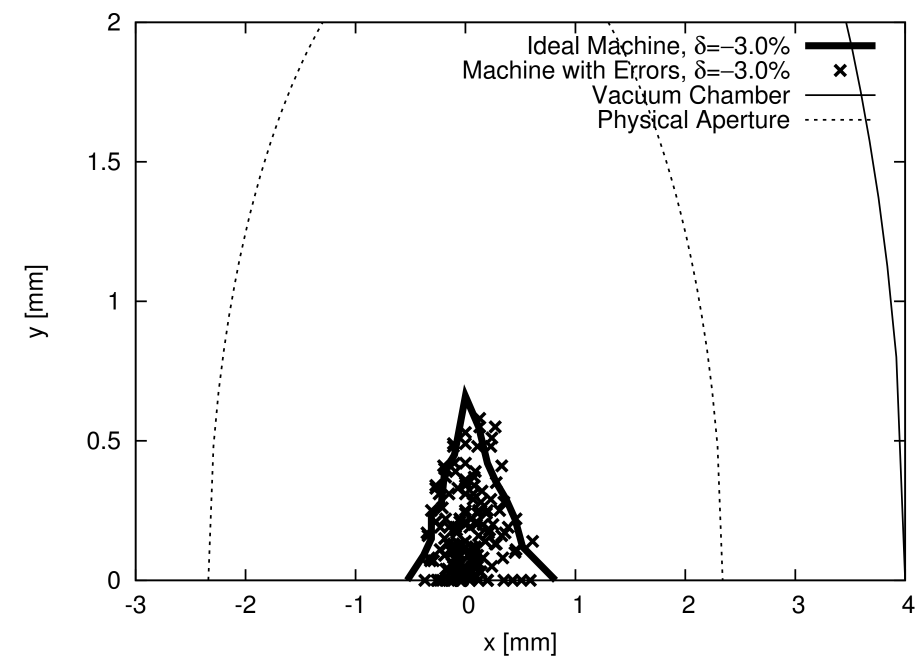

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