First Upgrade Ideas for the MAX IV 3 GeV Storage Ring

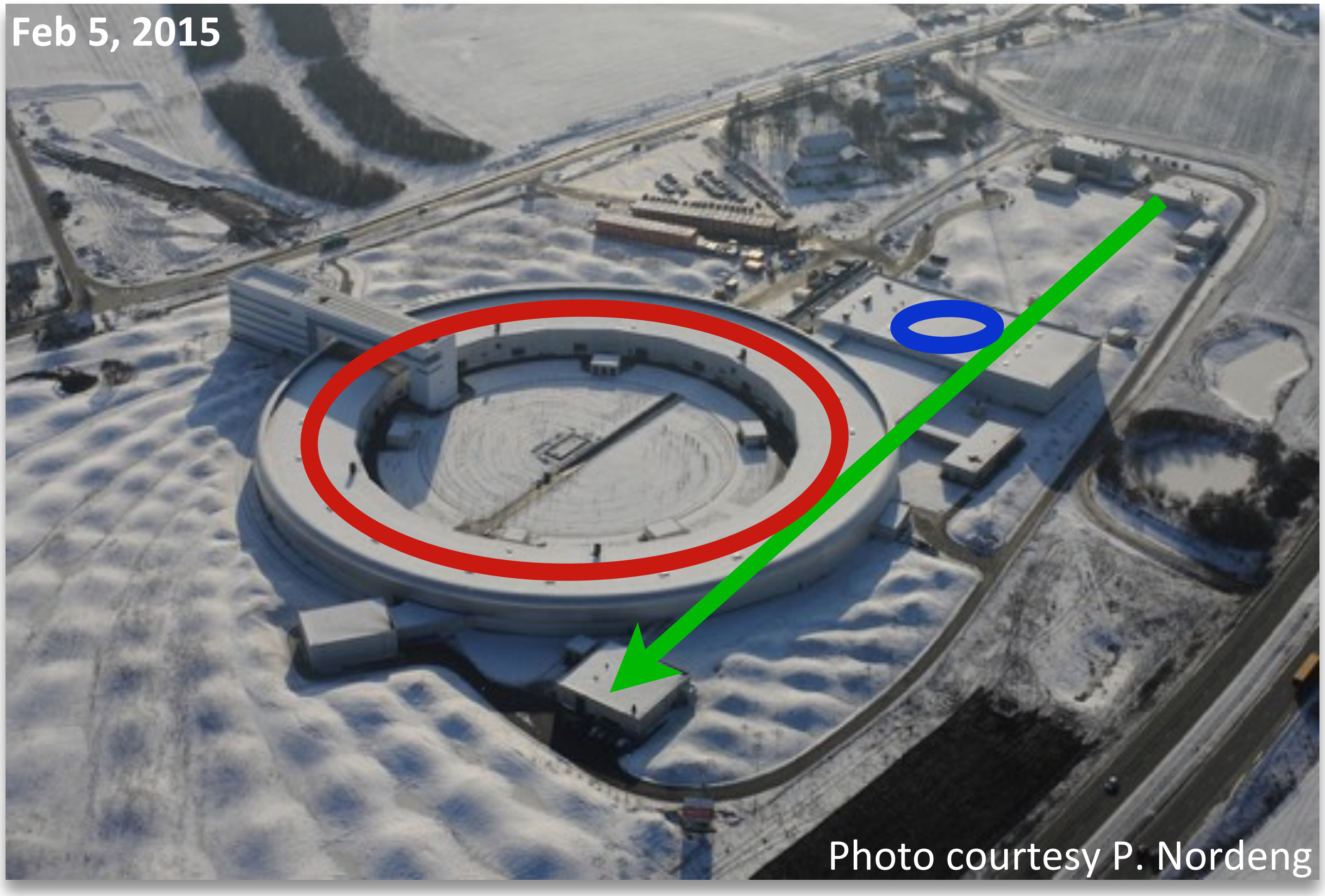
Simon C. Leemann
2nd Workshop on Low Emittance Ring Lattice Design, Dec 1-2, 2016

Outline

- Introduction
  - MAX IV Facility Overview
  - MAX IV 3 GeV Storage Ring Lattice & Optics
  - Brief Commissioning Timeline
- Upgrade Strategy & Upgrade Ideas
  - Coupling Reduction
  - Lifetime Improvements from Dispersion Bumps
  - Improved Optics Matching & Emittance Reduction
  - Effects of Insertion Devices
  - More Radical Improvements from GLASS & MOGA
  - New Injection & More

The MAX IV Facility

- ***One size does <u>not</u> fit all!*** MAX IV Facility employs 3 separate accelerators to cover required spectral and temporal range
  - one **≈3.5 GeV linac** → SPF/FEL driver & ring injector (separate guns)
  - two separate storage rings at **1.5 GeV (UV)** and **3 GeV (x-rays)**



Feb 5, 2015

Photo courtesy P. Nordeng

The MAX IV 3 GeV Storage Ring

- MAX IV 3 GeV storage ring designed for x-ray users ➔ high brightness via state-of-the-art IDs, high-current top-up operation & **ultralow emittance**
- Ultralow emittance achieved through **MBA lattice** ($\varepsilon_x \sim 1/N_b^3$)

SPIE Vol. 2013, 1993

EPAC'**94**, p.627

PAC'**95**, TPG08, p.177

PAC'**95**, FAB14, p.2823

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

TME

MBA

$$= \frac{0.0078}{J_x}\,E[\mathrm{GeV}]^2\,\Phi[^\circ]^3\,\frac{F\left(\beta_x,\eta\right)_\rho}{12\sqrt{15}}, \qquad \Phi[^\circ]^3 \propto \frac{1}{N_b^3}$$

Gradient Dipoles

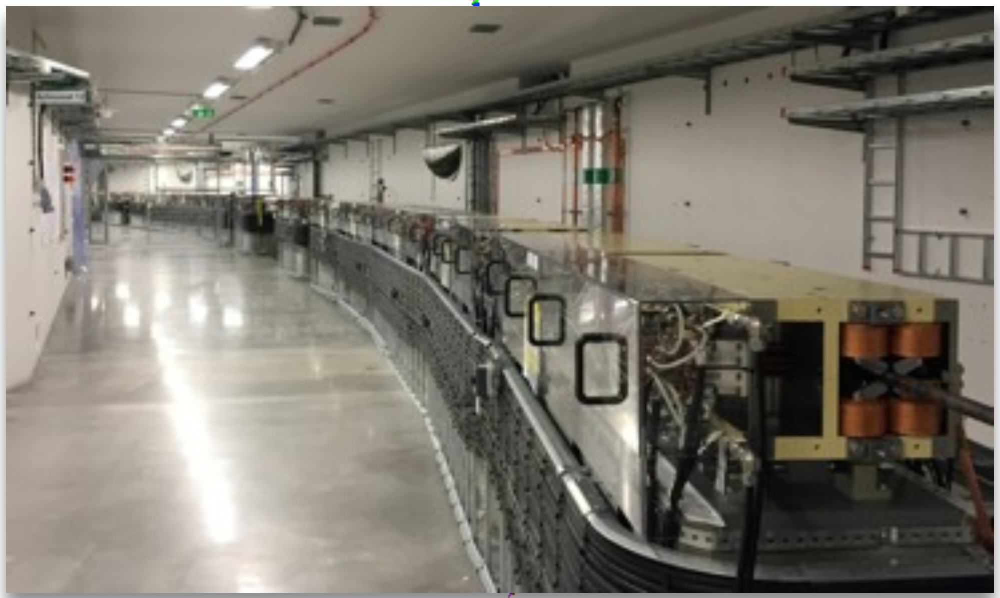
$$I_2 = \oint \frac{ds}{\rho^2} \qquad I_4 = \oint \frac{\eta}{\rho}\left(\frac{1}{\rho^2}+2b_2\right)ds \qquad I_5 = \oint \frac{\mathcal{H}}{|\rho^3|}ds \qquad \mathcal{H} = \gamma_x\eta^2 + 2\alpha_x\eta\eta' + \beta_x\eta^2$$

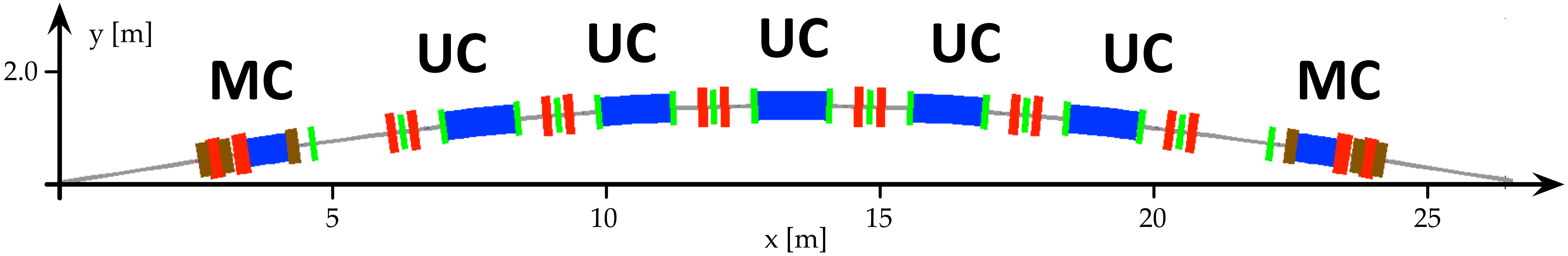
TME: brute-force approach I_5/I_2 ➔ 0 easily leads to overstrained optics, chromaticity wall
MBA: many weak dipoles, distributed chromaticity correction ➔ allows relaxing optics
Gradient dipoles: reduce emittance, allow for more compact optics ➔ improves MBA

The MAX IV 3 GeV Storage Ring (cont.)

PRST-AB **12**, 120701 (2009)
PRST-AB **14**, 030701 (2011)
IPAC’**11**, THPC059, p.3029
JSR **21**, 862-877 (2014)

- MAX IV 3 GeV storage ring according to design:
  - 20-fold MBA lattice, 528 m, 500 mA with top-up
  - 7-bend achromat: 5 **unit cells** (3°) & 2 **matching cells** (1.5° LGB)
  - ε_x = 328 pm rad, ε_y = 8 pm rad





The MAX IV 3 GeV Storage Ring (cont.)

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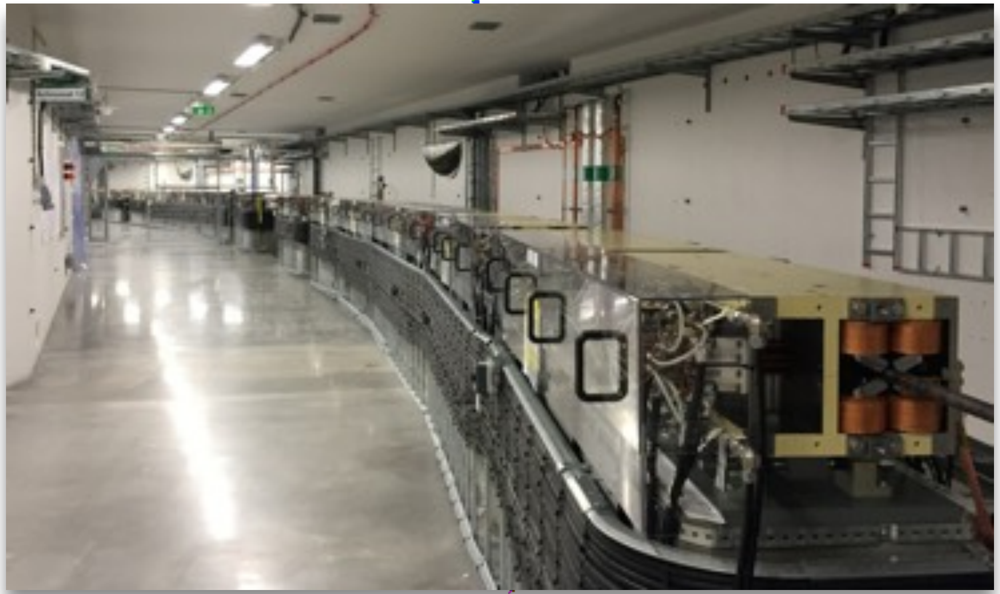
  - – 7-bend achromat: 5 **unit cells** (3°) & 2 **matching cells** (1.5° LGB)
  - – ε_x = 328 pm rad, ε_y = 8 pm rad
  - – Each MBA cell realized as one solid magnet block (compactness, alignment, stability)



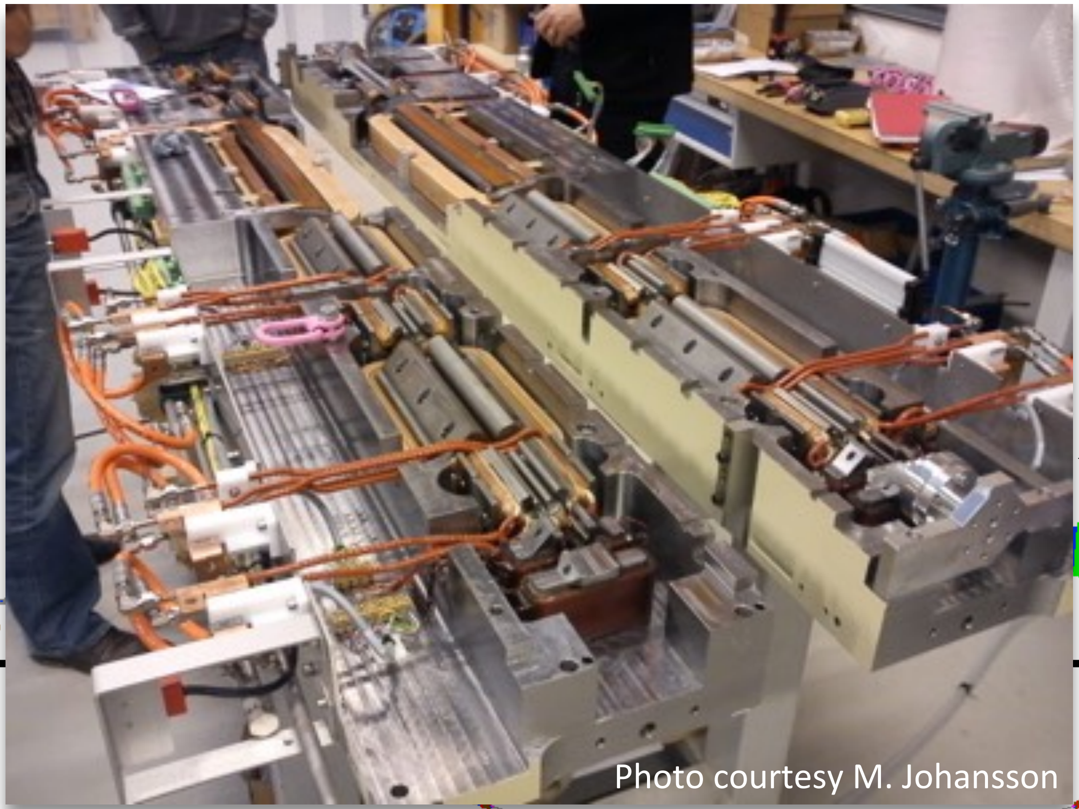
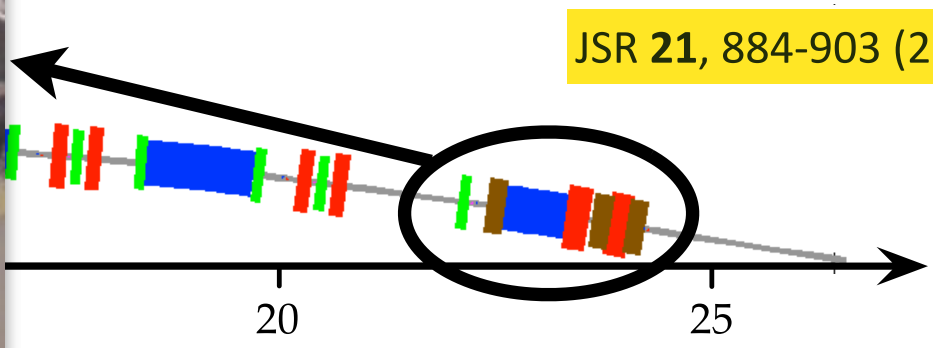


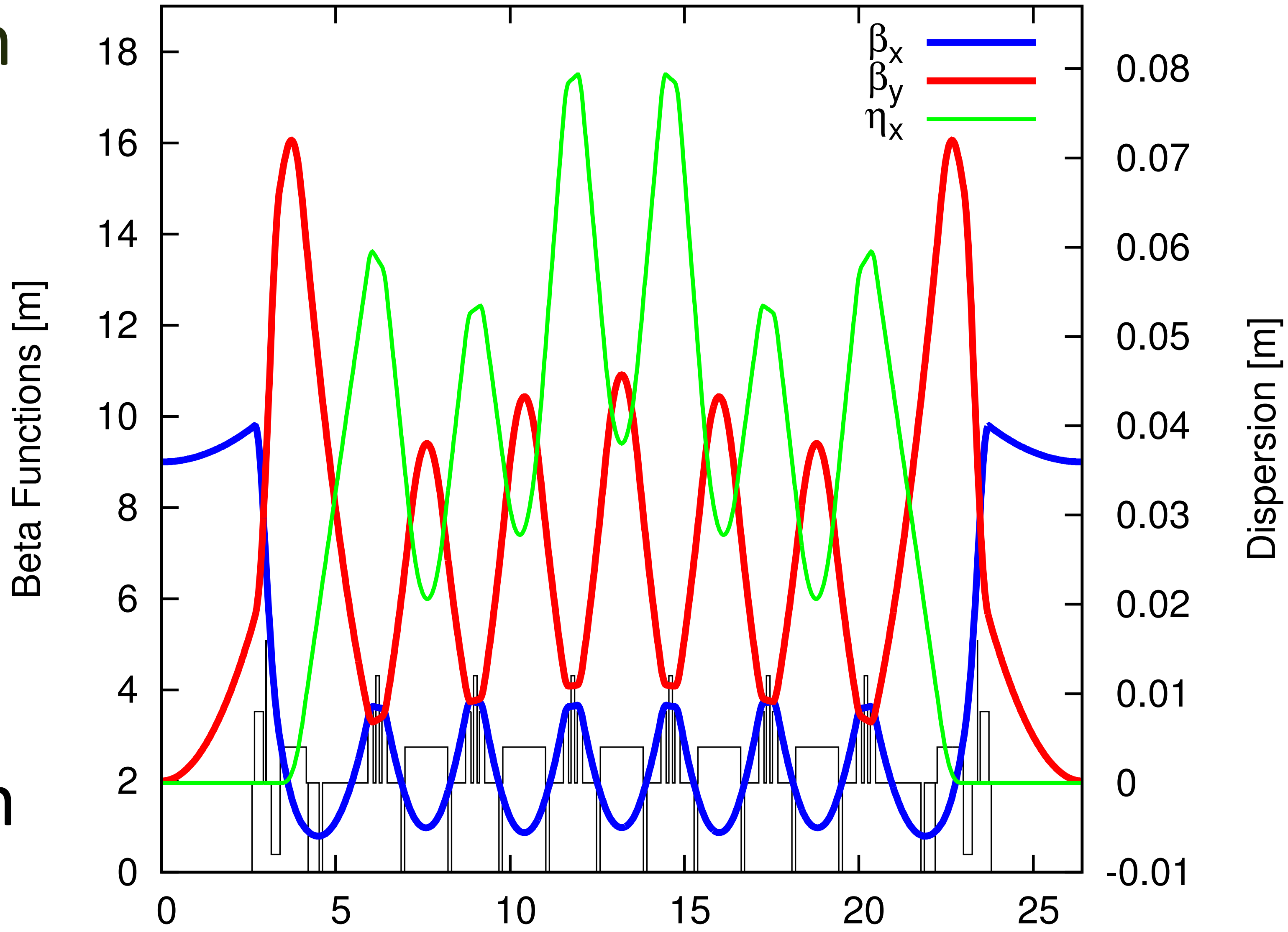
Photo courtesy M. Johansson



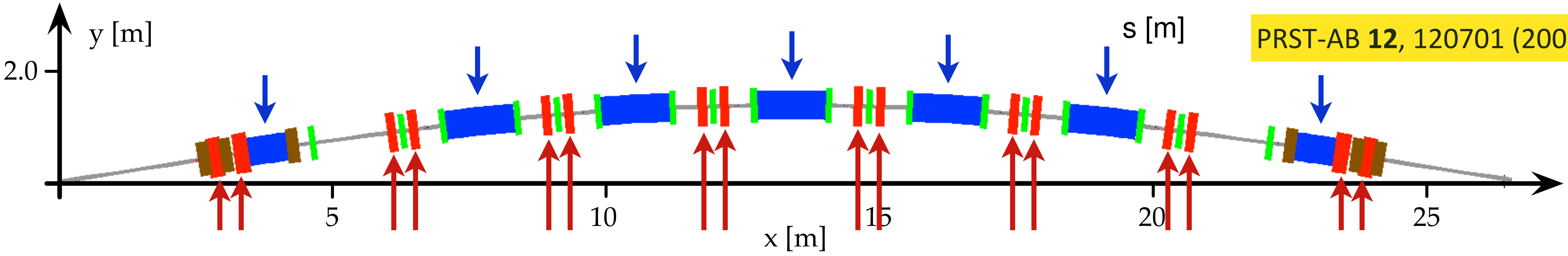
JSR **21**, 884-903 (2014)

The MAX IV 3 GeV Storage Ring Lattice

- **Gradient dipoles** perform vertical focusing ($\varepsilon_x \sim 1/J_x$)
- Gradient dipoles inter-leaved with **horizontally focusing quadrupoles**
- $\nu_x = 42.20$, $\nu_y = 16.28$
  $\beta_x^* = 9$ m, $\beta_y^* = 2$ m
- $\sigma_x^* = 54$ µm, $\sigma_y^* = 2$-4 µm

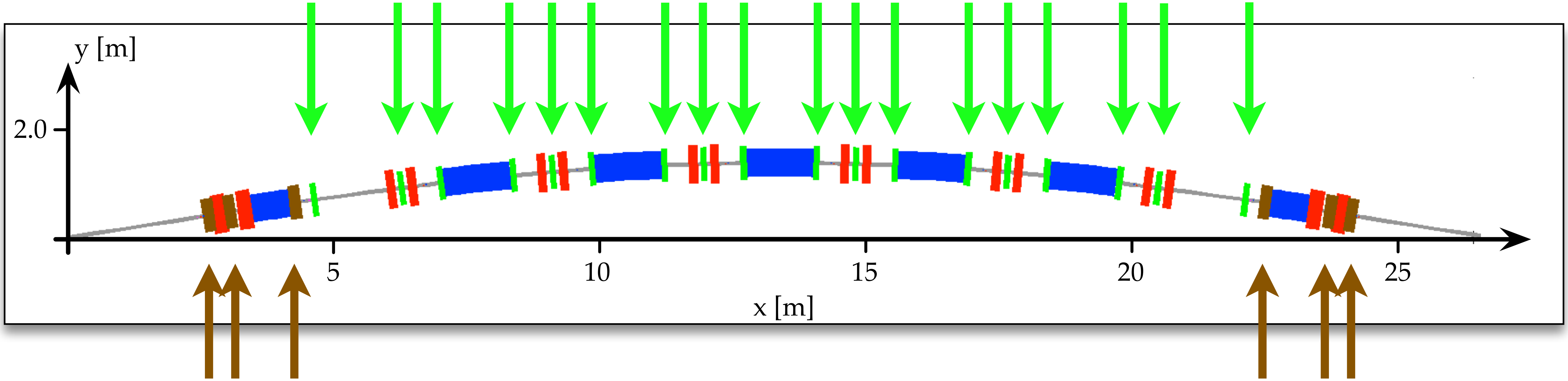


PRST-AB **12**, 120701 (2009)



The MAX IV 3 GeV Storage Ring Lattice (cont.)

- **Chromatic sextupoles** correct linear chromaticity ($\xi_{x,y} \approx -50 \rightarrow +1$) & tailor its higher orders → additional sextupoles used to minimize first-order RDTs (low since phase advance ≈ 2π×2, 2π×3/4)
- Strong sextupoles drive large ADTS → **achromatic octupoles** allow tailoring ADTS to first order → minimize tune footprint

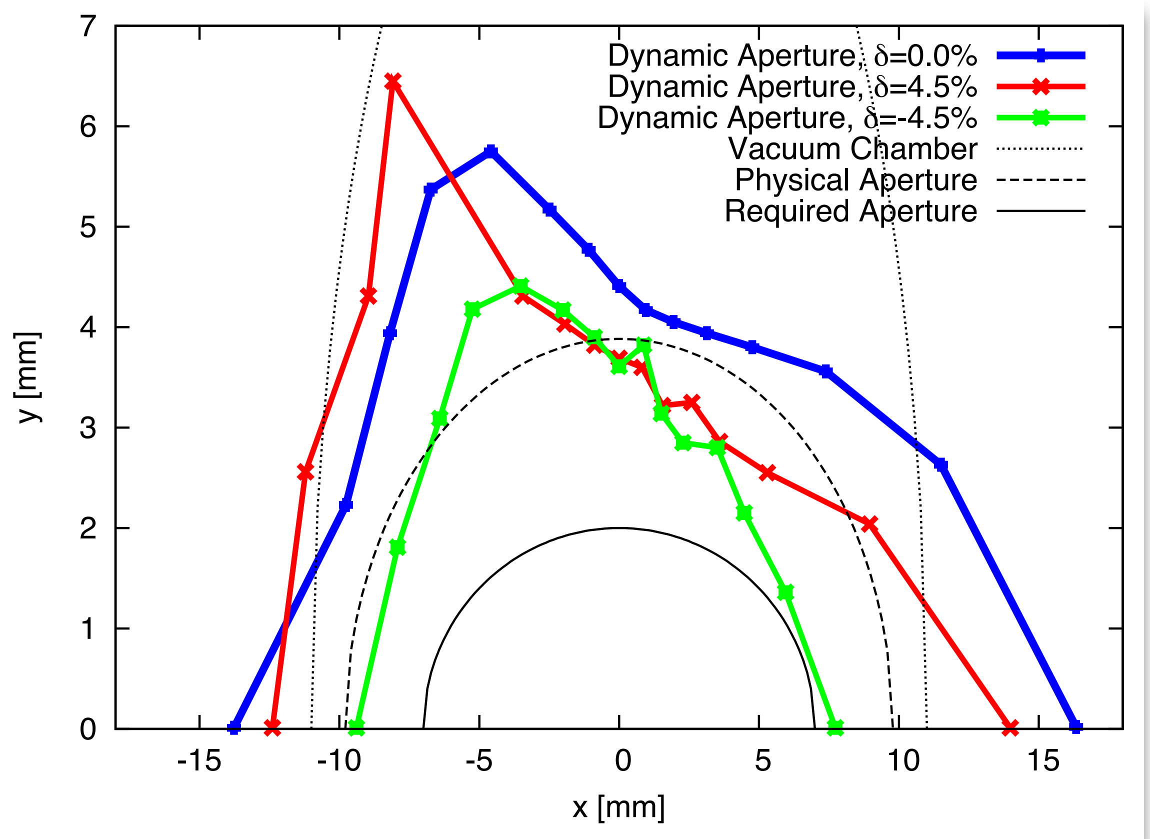


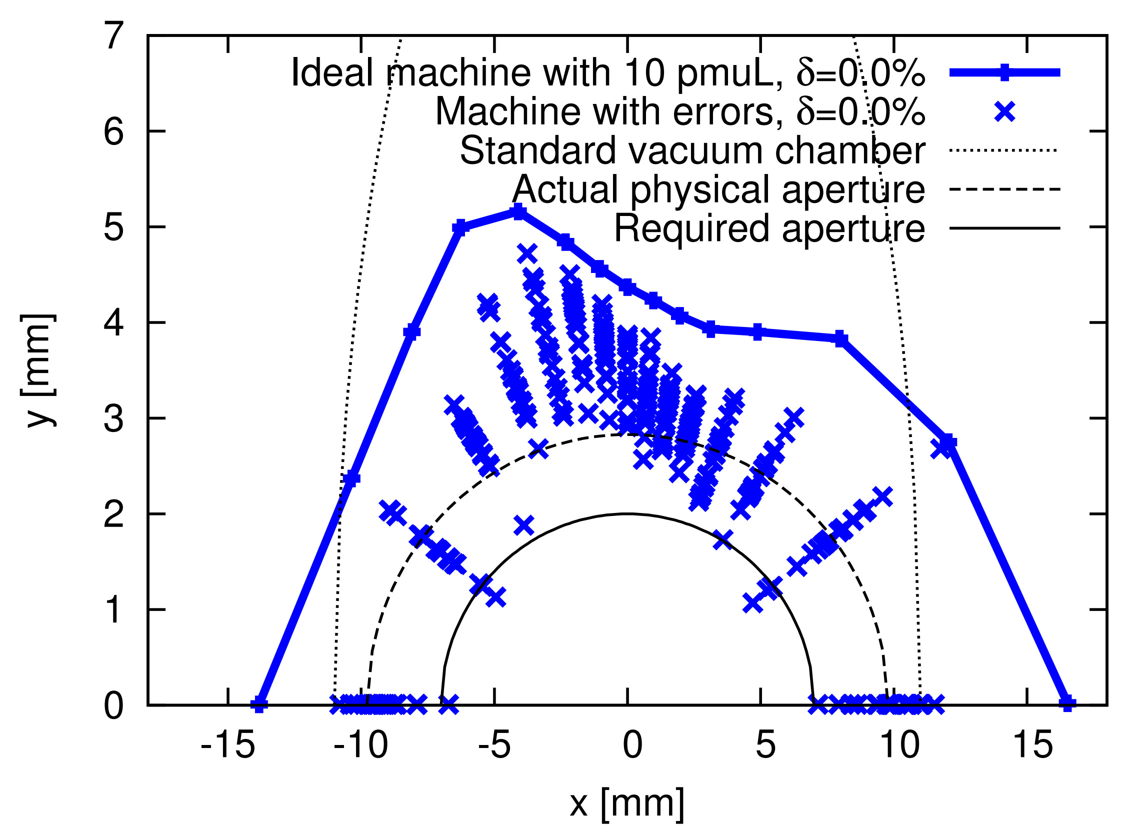
PRST-AB **12**, 120701 (2009)

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

The MAX IV 3 GeV Storage Ring Lattice (cont.)

- Resulting in:
  - very compact tune footprint ➔ good DA on and off energy...
  - ...that remains stable under influence of IDs and imperfections





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

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

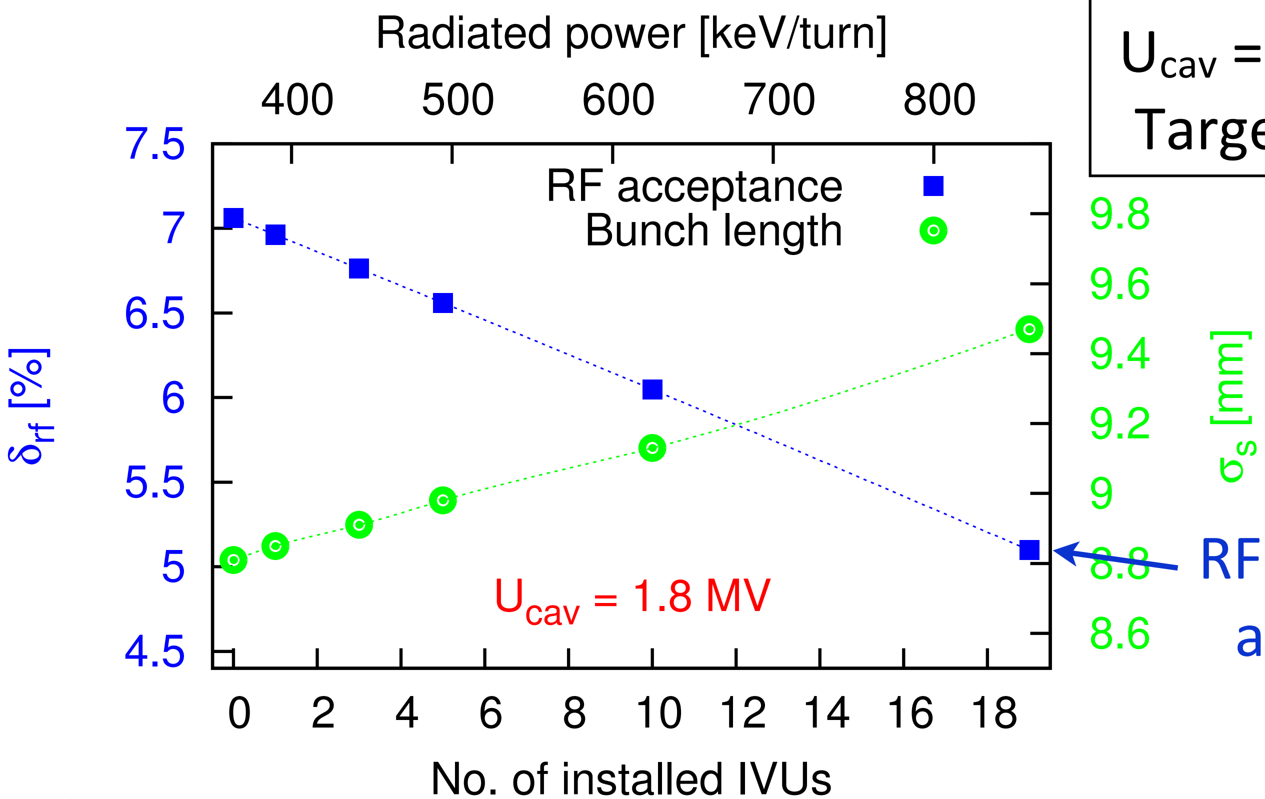
PAC’**11**, TUP235, p.1262

IPAC’**15**, TUPJE038

The MAX IV 3 GeV Storage Ring Lattice (cont.)

- Resulting in:
  - very compact tune footprint → good DA on and off energy...
  - ...that remains stable under influence of IDs and imperfections
  - Thus enabling large lattice MA...
  - ...and with appropriately dimensioned RF → large overall MA

PRST-AB **17**, 050705 (2014)



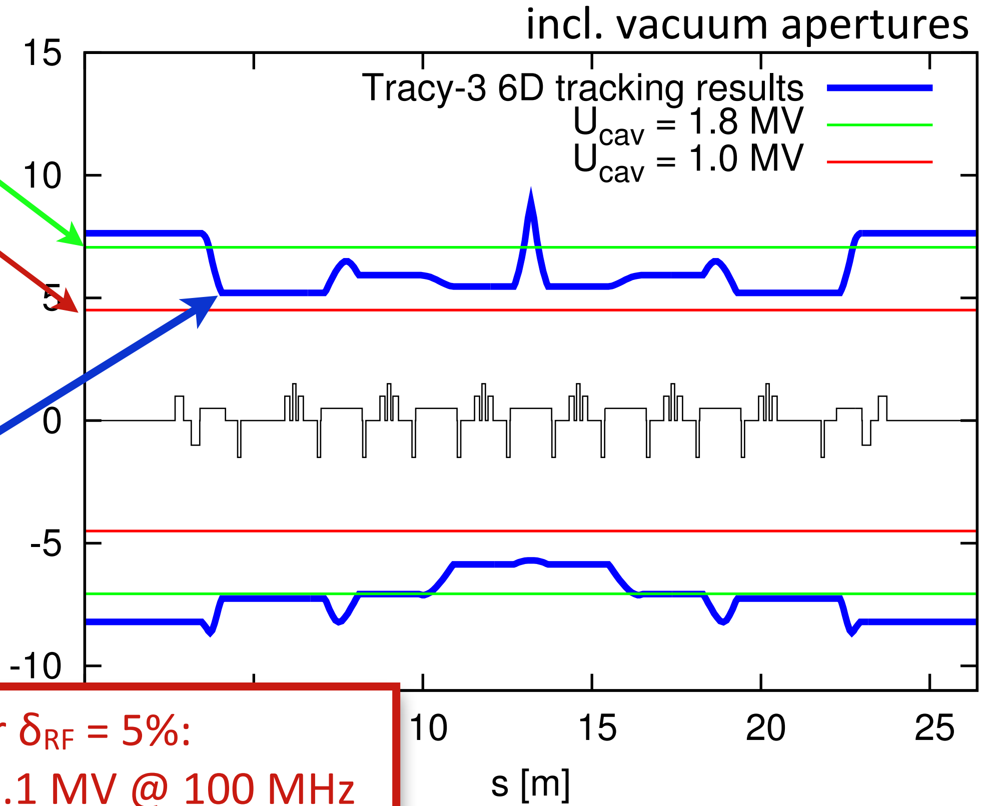
MAX IV 3 GeV SR

U_{cav} = 1.8 MV (max)

Target: $\delta_{acc} > 4.5\%$

Lattice MA always >5%

RF acceptance always >5%



For δ_{RF} = 5%:

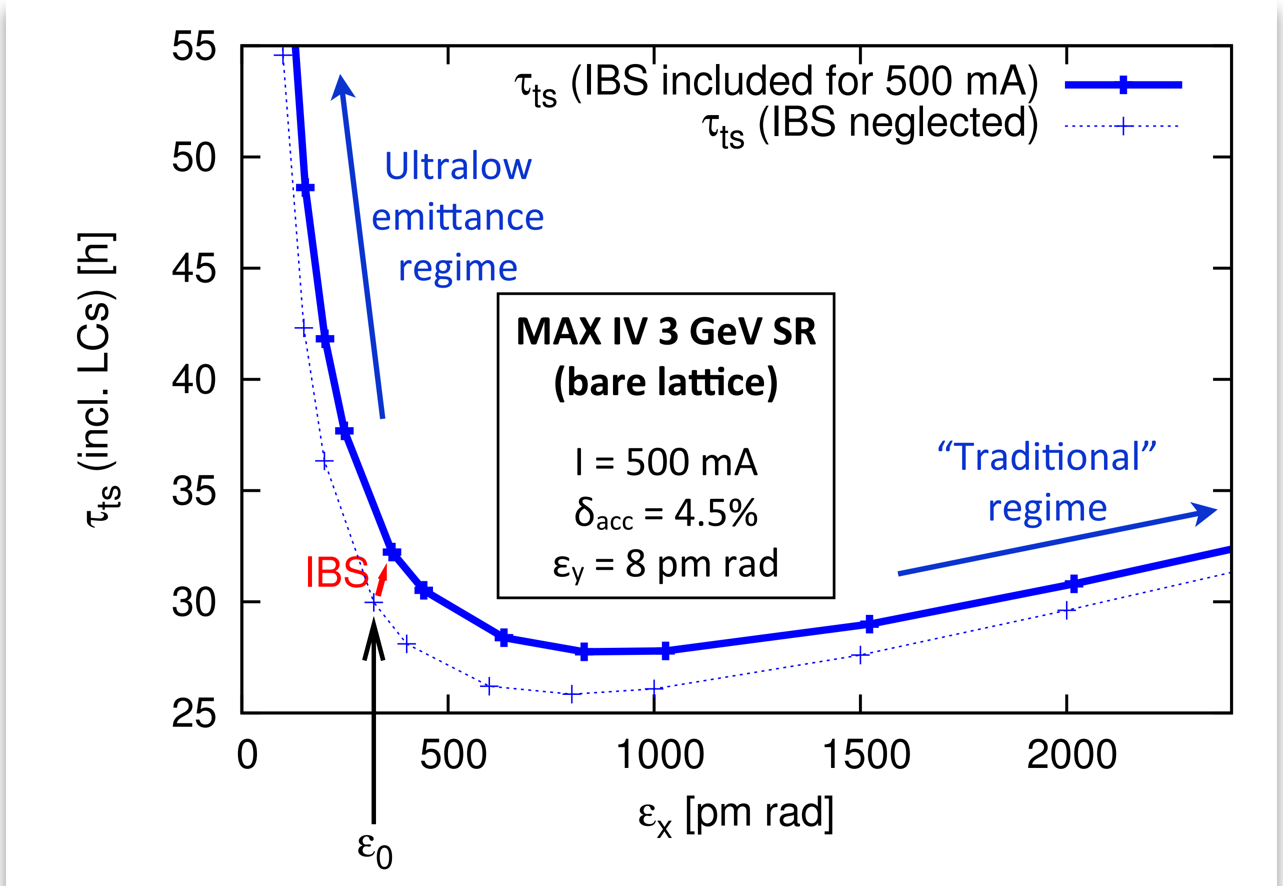
- 1.1 MV @ 100 MHz
- 3.7 MV @ 500 MHz

→ Cu losses, power bill

The MAX IV 3 GeV Storage Ring Lattice (cont.)

- Resulting in:
  - very compact tune footprint ➔ good DA on and off energy...
  - ...that remains stable under influence of IDs and imperfections
  - Thus enabling large lattice MA...
  - ...and with appropriately dimensioned RF ➔ large overall MA
  - Large overall MA ➔ good Touschek lifetime
    (in spite of ultralow emittance)
  - Harmonic LCs limit very strong IBS at medium energy...
  - ...while further improving Touschek lifetime

PRST-AB **17**, 050705 (2014)



From Design to Operation — Commissioning Timeline

- 3 GeV storage ring commissioning started in Aug 2015
- First turn Aug 25, first stored beam Sep 15, first stacking Oct 8
- **First light** from diagnostics beamline Nov 2015
- Start running top-up & SOFB
- First two **IVUs** installed Feb 2016, first monochromatic beams on detector May 2015

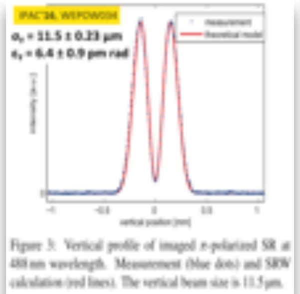
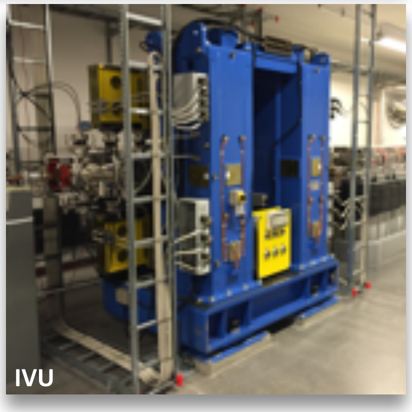
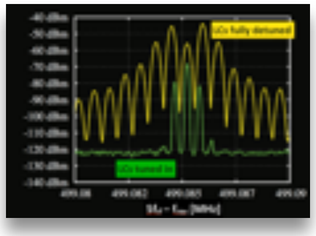
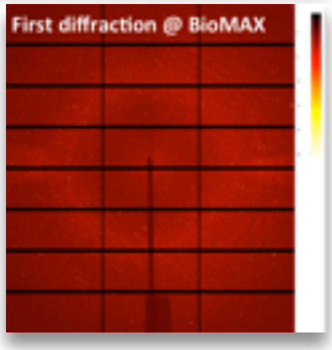


Figure 3: Vertical profile of imaged π-polarized SR at 488 nm wavelength. Measurement (blue dots) and SRW calculation (red lines). The vertical beam size is 11.5 μm.

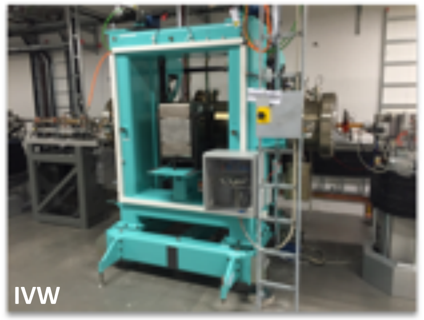


- **Landau cavities** tuned in April 2016, started **BxB FB** & collective effects studies
- **Facility inauguration** June 21, 2016 @ 13:08:55 (local noon)
- **198 mA stored** July 2016





- First **in-vac wiggler** & first two **EPUs** installed in Aug 2016
- First "friendly users" Dec 2016
- First open user call expected for Mar 2017
- Meanwhile considering first upgrade ideas...



Upgrade Ideas

- Strategy Plan MAX IV Laboratory 2013-2026

  http://www.maxlab.lu.se/strategy_report

Strategy Plan MAX IV Laboratory 2013-2026

- Storage ring upgrades call for
  - electron beam stability improvements
  - brightness & coherence improvements (3 GeV)
  - fill pattern development → timing experiments

  https://www.maxiv.lu.se/science/accelerator-physics/current-projects/timing-modes-in-the-max-iv-storage-rings/

- Focus here will be on brightness & coherence improvements in the MAX IV 3 GeV storage ring

Strategy for Improved Brightness in 3 GeV SR

- Improve brightness **within limits of current design**
  - via improved matching to IDs (better choice of coupling & straight section optics) → also improves coherence (important at e.g. NanoMAX BL)
  - via lower lattice emittance (within existing hardware limits)
- In a later phase, procure **new magnet power supplies** and/or split up magnet families → more substantial emittance reduction & brightness improvement
- However, could require **mitigation measures**:
  - if new optics/coupling setting lead to unacceptably low Touschek lifetime → dispersion bumps in arcs
  - new on-axis injection → allows for harder optics and opens up potential for round beams (enabling new IDs)

Coupling Reduction

Opt. Eng. Vol. **32**, No. 2, p. 342 (1995)

PAC'**13**, MOPHO05, p.243

- **Spectral brightness** is determined by spectral flux & effective transverse emittances

$$\mathcal{B}(\lambda) = \frac{\mathcal{F}(\lambda)}{(2\pi)^2 \mathcal{E}_x \mathcal{E}_y},$$

- **Effective emittance** is convolution of electron beam emittance and emittance of intrinsic photon beam

$$\mathcal{E}_{x,y} = \Sigma_{x,y} \Sigma_{x',y'}$$

$$\Sigma_{x,y} = \sqrt{\sigma_r^2 + \sigma_{x,y}^2} \qquad \Sigma_{x',y'} = \sqrt{\sigma_{r'}^2 + \sigma_{x',y'}^2}$$

- The **coherent fraction** for a given radiated wavelength is also determined by the effective emittance

$$f_c(\lambda) = \frac{\mathcal{F}_c(\lambda)}{\mathcal{F}(\lambda)} = \frac{\mathcal{B}(\lambda)\,(\lambda/2)^2}{\mathcal{F}(\lambda)} = \frac{(\lambda/4\pi)^2}{\mathcal{E}_x \mathcal{E}_y}$$

Coupling Reduction (cont.)

Opt. Eng. Vol. **32**, No. 2, p. 342 (1995)

PAC'**13**, MOPHO05, p.243

- Intrinsic photon beam is determined by ID length and wavelength of extracted photons (Gaussian beam approximation)

$$\sigma_r = \frac{\sqrt{2L\lambda}}{4\pi} \qquad \sigma_{r'} = \sqrt{\frac{\lambda}{2L}} \qquad \longrightarrow \qquad \varepsilon_r = \sigma_r \sigma_{r'} = \frac{\lambda}{4\pi}$$

"Diffraction Limit"
(8 pm rad for 1 Å, 12.4 keV)

- For a given electron beam emittance, chose optics to match electron beam to intrinsic photon beam

$$\beta_{x,y} \overset{!}{=} \beta_r = \frac{\sigma_r}{\sigma_{r'}} = \frac{L}{2\pi}$$

≈0.7 m for MAX IV 3 GeV SR

- But in reality:
  - – β_x becomes too small for conventional injection schemes
  - – β_y usually leads to severe acceptance limitation since narrow focus at ID center leads to large beta functions at ID ends

$$\beta_y = \beta_{y,0} + \frac{s^2}{\beta_{y,0}} \qquad \longrightarrow \qquad \beta_{y,0} = L/2$$

To maximize acceptance
(≈2 m for MAX IV 3 GeV SR)

Coupling Reduction (cont.)

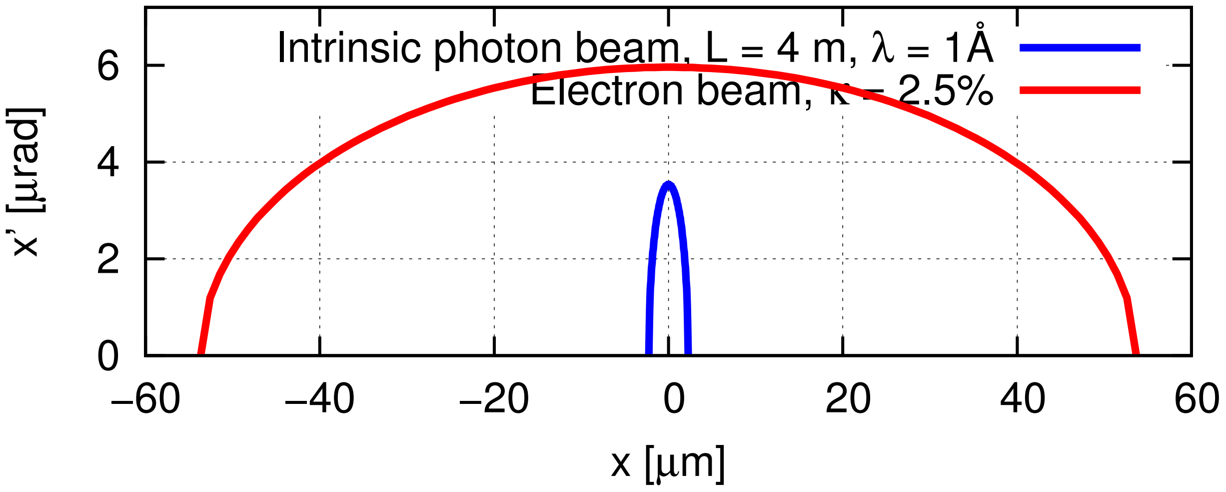
Opt. Eng. Vol. **32**, No. 2, p. 342 (1995)

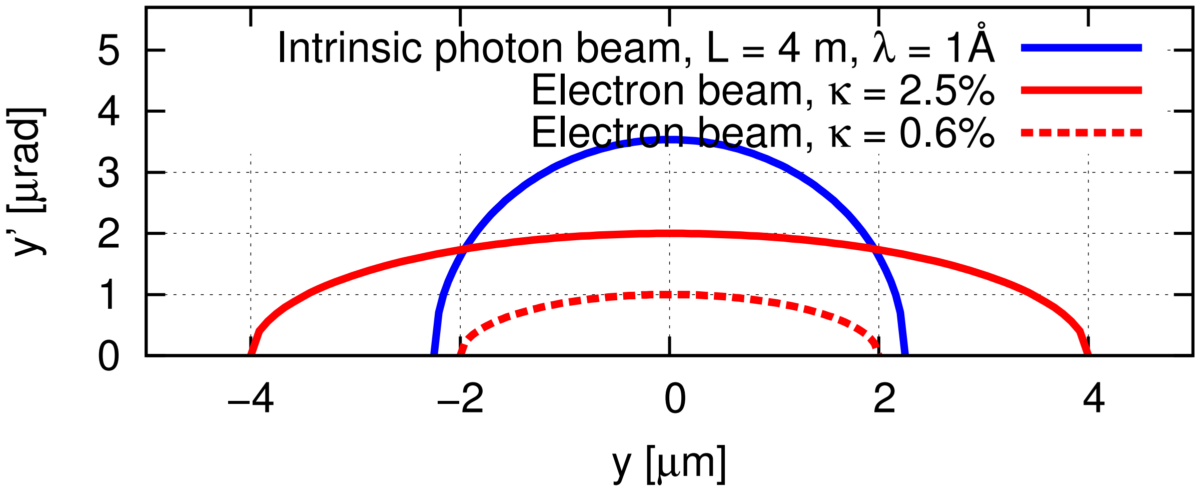
PAC'**13**, MOPHO05, p.243

- So instead of a perfect optics match, reduce emittance coupling ➔ better overlap achieved in vertical plane

$$\varepsilon_0 = \varepsilon_x + \varepsilon_y \qquad \kappa = \frac{\varepsilon_y}{\varepsilon_x} \qquad \varepsilon_x \gg \varepsilon_y \longrightarrow \begin{array}{ccl} \varepsilon_x & = & \dfrac{\varepsilon_0}{1+\kappa} \approx \text{const} \\ \varepsilon_y & \propto & \kappa \end{array} \longrightarrow \mathcal{B}(\lambda) \propto \frac{1}{\mathcal{E}_y}$$

- Despite beta mismatch, this allows decreasing the effective vertical emittance (ε_y = 8 ➔ 2 pm rad corresponds to κ = 2.5% ➔ 0.6%)



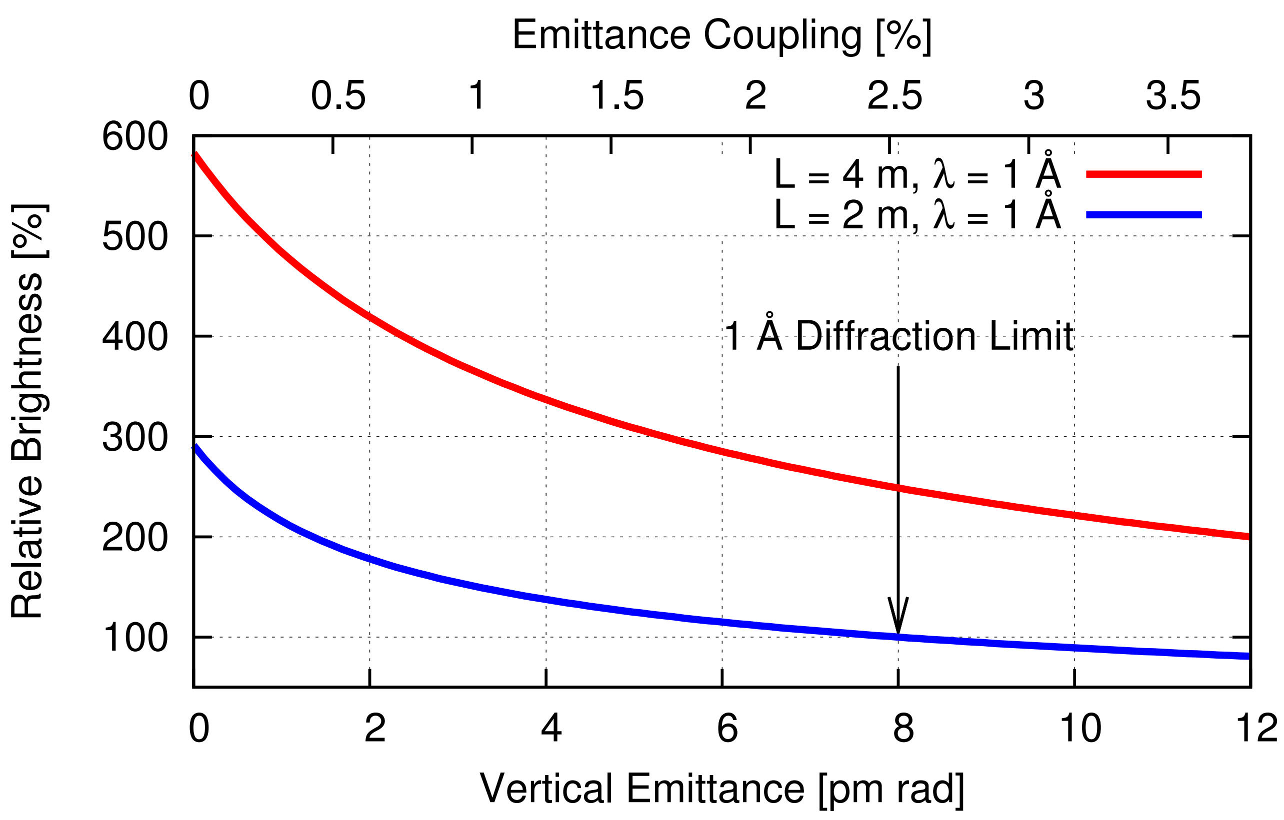


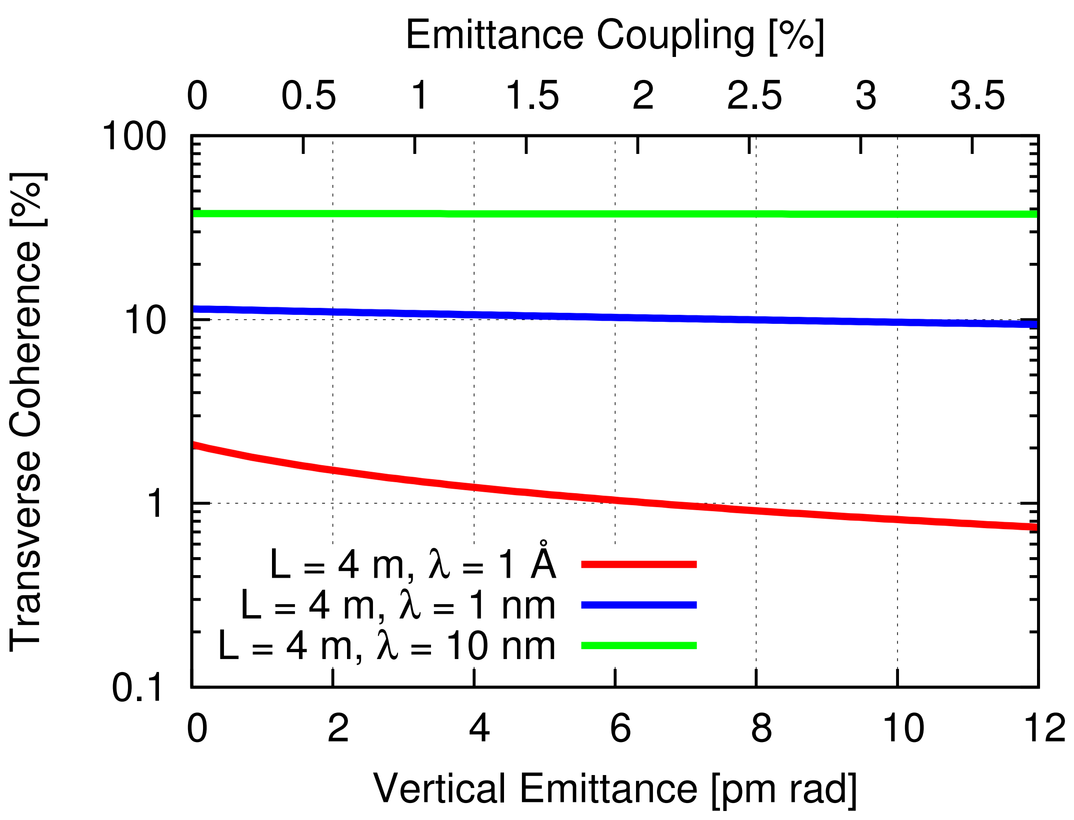
Coupling Reduction (cont.)

Opt. Eng. Vol. **32**, No. 2, p. 342 (1995)

PAC'**13**, MOPHO05, p.243

- Results in significant brightness increase and roughly doubles transverse coherence compared to remaining "at the diffraction limit"





Coupling Reduction (cont.)

Opt. Eng. Vol. **32**, No. 2, p. 342 (1995)

PAC’**13**, MOPHO05, p.243

- But reduced coupling must still render sufficient lifetime

$$\tau_{ts} \propto \sqrt{\varepsilon_y} \propto \sqrt{\kappa}$$

- Tracked various ring configurations including IDs & errors with Tracy-3

PRST-AB **17**, 050705 (2014)

	ε_y [pm rad]	500 mA no LCs	500 mA incl. LCs	Incl. errors & narrow gaps[1]
Bare	8	17.4	87.1	64.3
	2	9.6	45.9	40.7
4 DWs / 10 IVUs	8	20.5	114.3	66.2
	2	10.4	56.1	48.7
Loaded	8	11.7	65.0	37.7
	2	5.8	31.4	27.3

[1] Narrow gaps have not been included in the bare lattice case.

worst-case scenario: τ_{ts} = 27.3 ± 2.1 hrs (20 seeds)

I = 500 mA

U_{cav} = 1.8 MV

IBS included

Two coupling settings:
ε_y = 2 vs. 8 pm rad

τ_{ts} > 27 hrs (requires LCs, dependence on main cavity settings)

τ_{el} = 25 hrs (2 pbar CO, incl. narrow gaps)

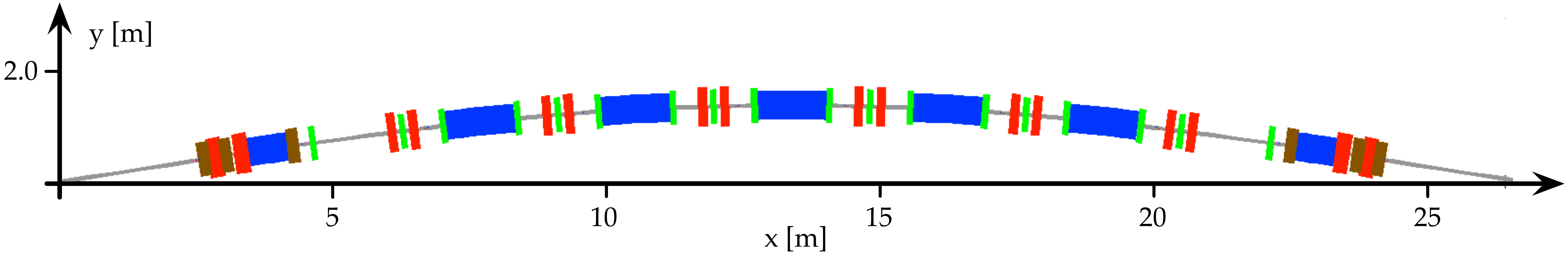
τ_{bs} = 56 hrs (weak dependence on MA, assumed 4.5%)

→ τ > 10 hrs (top-up shot required every 6 minutes @ 1% deadband)

Lifetime Improvements in 3 GeV SR

PRST-AB **19**, 060701 (2016)

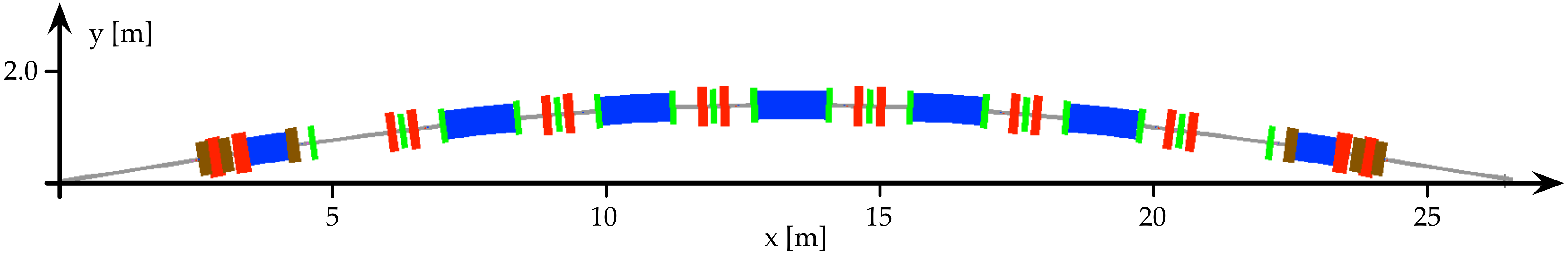
- But what if these lifetime estimates are too optimistic?
  - Could we gain lifetime by blowing up beam size where users won't see it?
- Or what if indeed $\varepsilon_y \approx 1.3$ pm rad after commissioning?
  - Can we set ε_y to a user-defined level in a way that maximizes lifetime?



Lifetime Improvements in 3 GeV SR (cont.)

PRST-AB **19**, 060701 (2016)

- Consider **vertical dispersion bumps in achromat arcs** → set ε_y to user-desired level while increasing Touschek lifetime
  - dispersive blowup away from IDs



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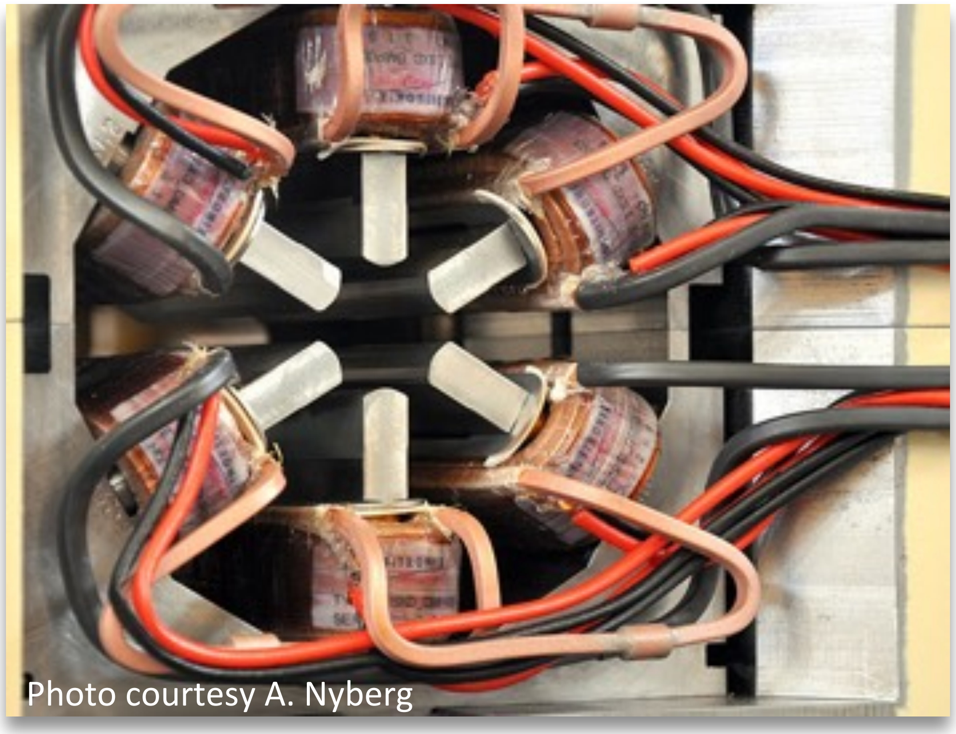
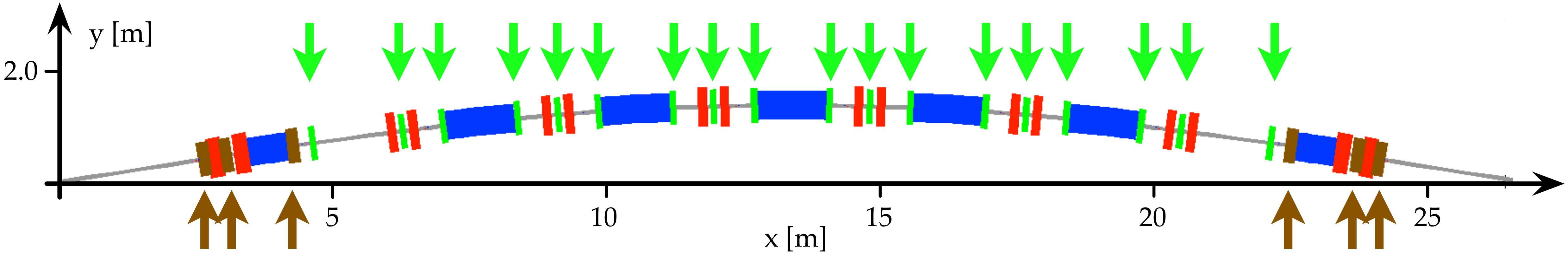


Photo courtesy A. Nyberg



Lifetime Improvements in 3 GeV SR (cont.)

PRST-AB **19**, 060701 (2016)

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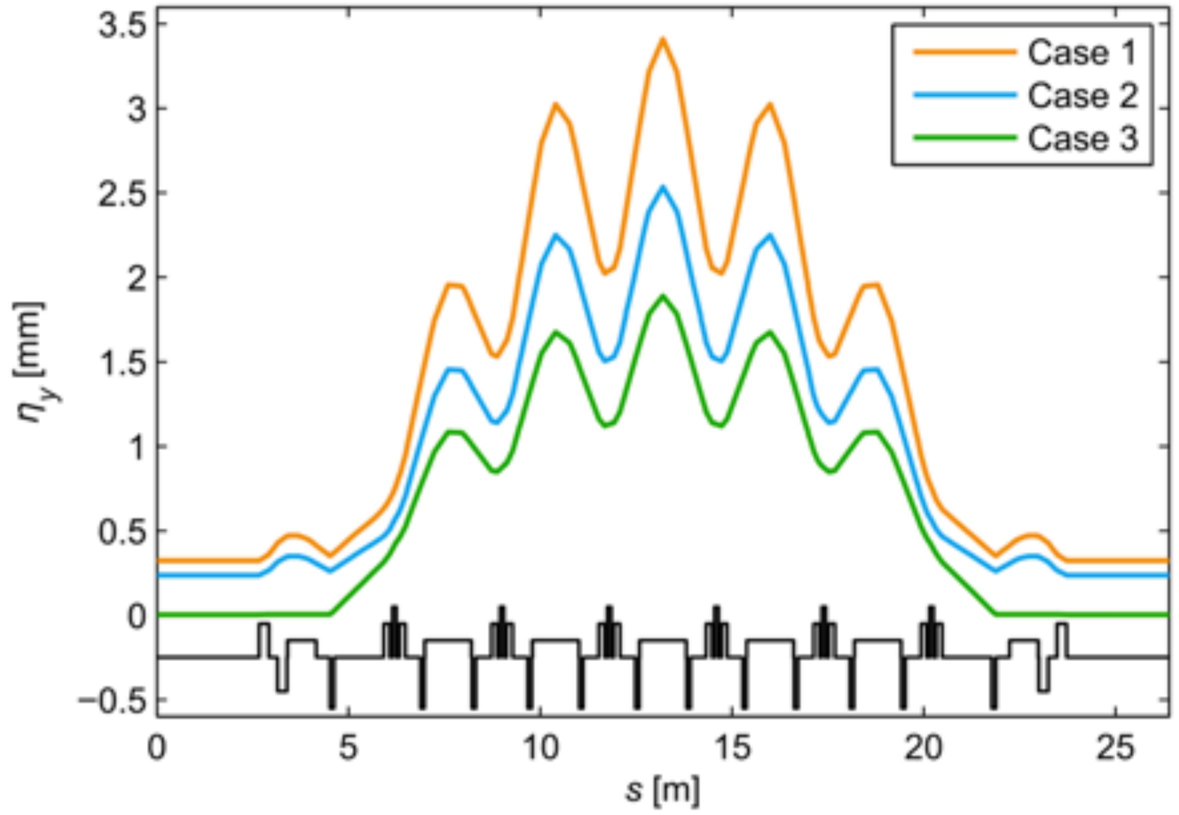
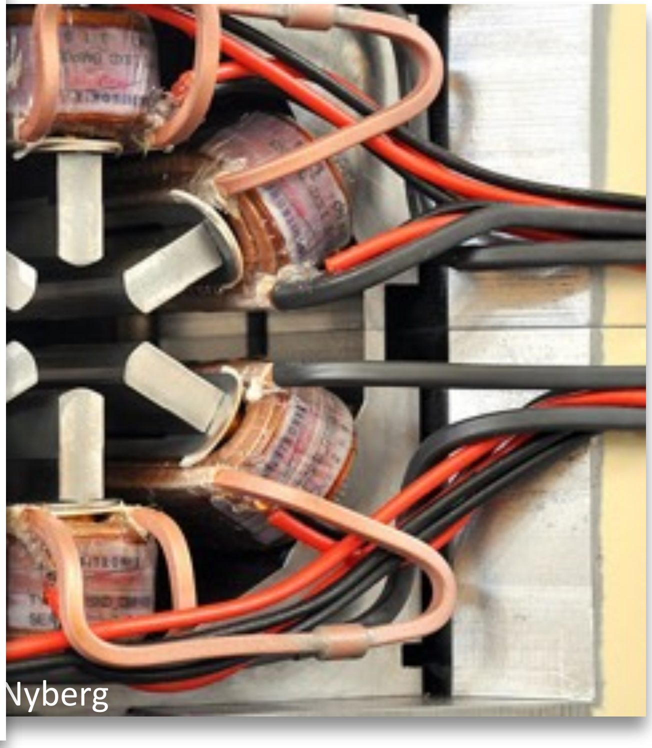
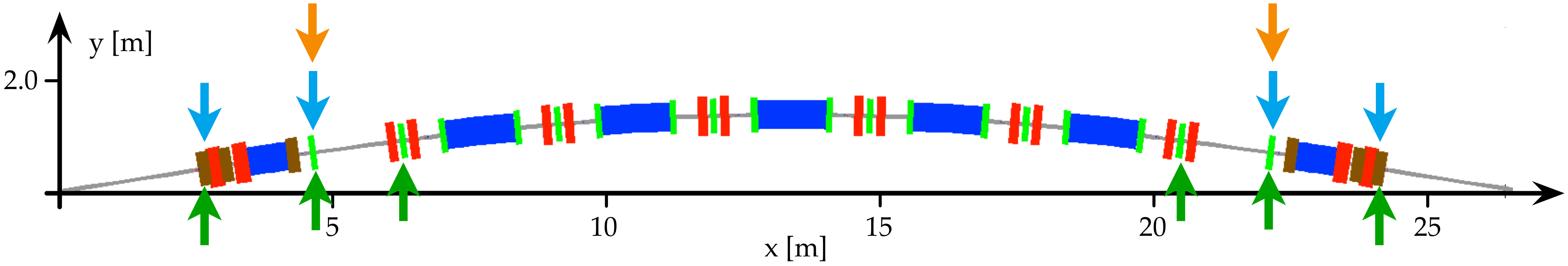


FIG. 2. Ideal vertical dispersion in Cases 1 to 3. Approximately 6.6 pm rad of vertical emittance is created in the ideal lattice which gives on average 7.9 pm rad when including imperfections.



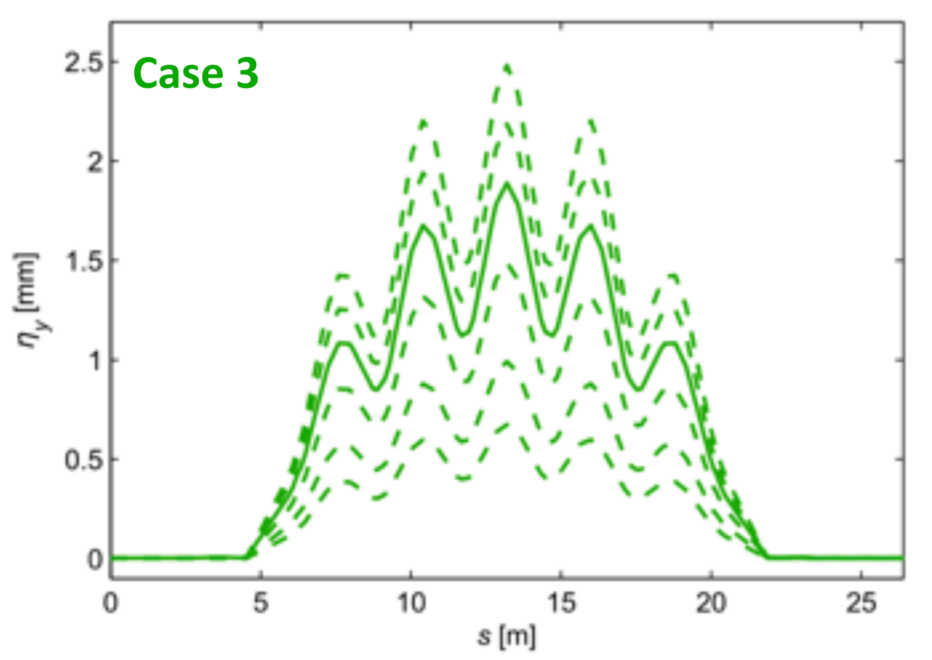
Nyberg



Lifetime Improvements in 3 GeV SR (cont.)

PRST-AB **19**, 060701 (2016)

- Consider **vertical dispersion bumps in achromat arcs** → set ε_y to user-desired level while increasing Touschek lifetime
  - dispersive blowup away from IDs
  - excite 1–3 skew quadrupole pairs (extra windings on sextupoles & octupoles) per achromat to drive closed η_y bump through arc
  - with available skew quad strength can adjust η_y bump amplitude to achieve $\varepsilon_y \approx$ 2–8 pm rad & beyond (typically peak η_y is a few mm, $\lesssim$5% of η_x)



k_s [m^{-2}]	0.007	0.010	0.015	**0.019**	0.022	0.025
ε_{II} [pm rad]	0.9	1.8	4.1	**6.6**	8.9	11.4

Lifetime Improvements in 3 GeV SR (cont.)

PRST-AB **19**, 060701 (2016)

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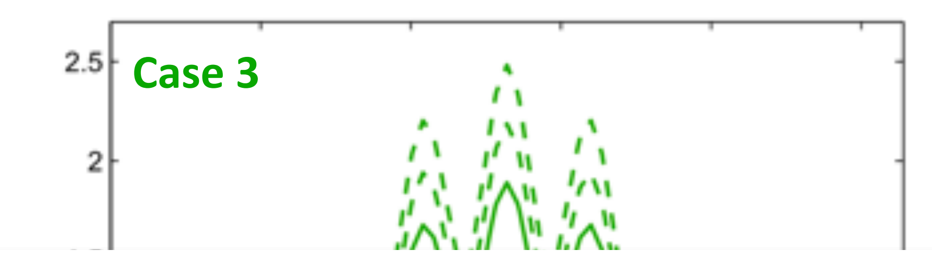


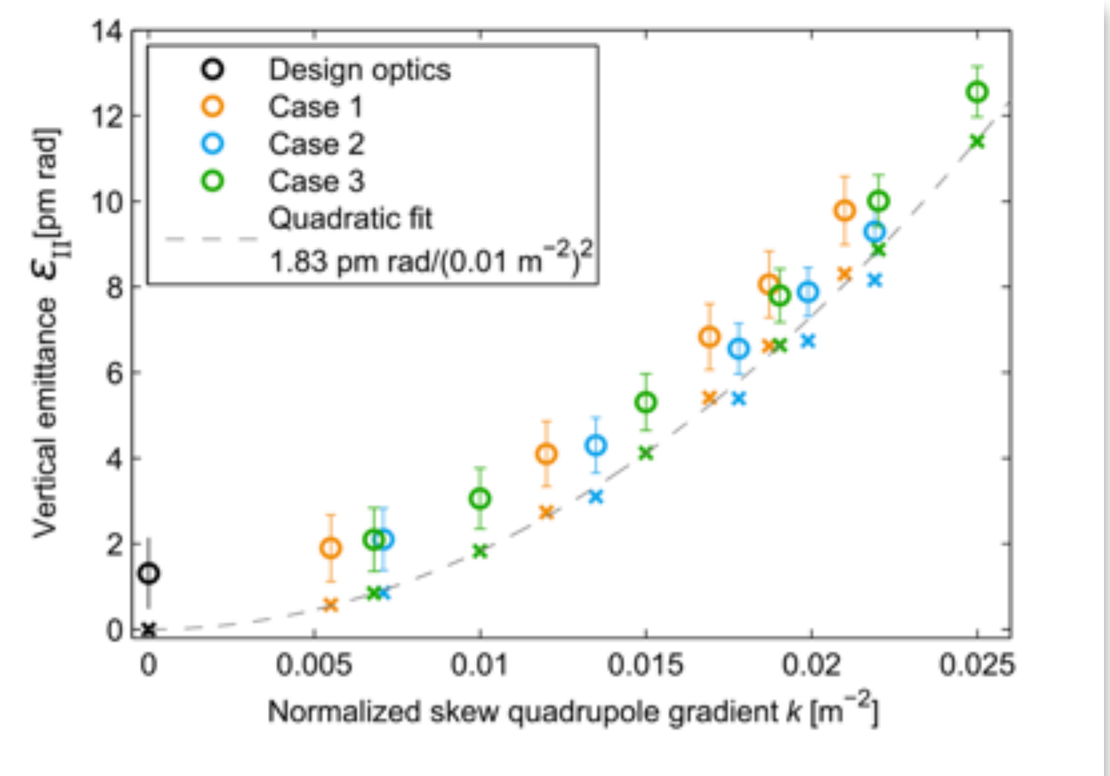
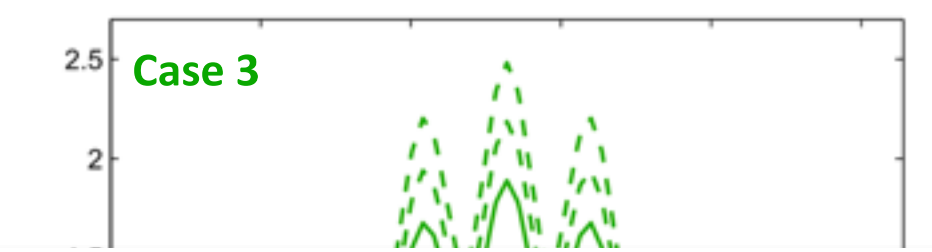


FIG. 5. Vertical emittance scales with skew quadrupole gradient squared. Ideal lattice (x) and error lattice (o) with standard deviations from 10 error seeds. Only the k of the strongest skew quadrupole involved in each case is considered.

Lifetime Improvements in 3 GeV SR (cont.)

PRST-AB **19**, 060701 (2016)

- Consider **vertical dispersion bumps in achromat arcs** → set ε_y to user-desired level while increasing Touschek lifetime
  - dispersive blowup away from IDs
  - excite 1–3 skew quadrupole pairs (extra windings on sextupoles & octupoles) per achromat to drive closed η_y bump through arc
  - with available skew quad strength can adjust η_y bump amplitude to achieve $\varepsilon_y \approx$ 2–8 pm rad & beyond (typically peak η_y is a few mm, ≲5% of η_x)
  - even when including errors, tracking reveals $\varepsilon_y \propto k_s^2 \longrightarrow \tau_{ts} \propto k_s$



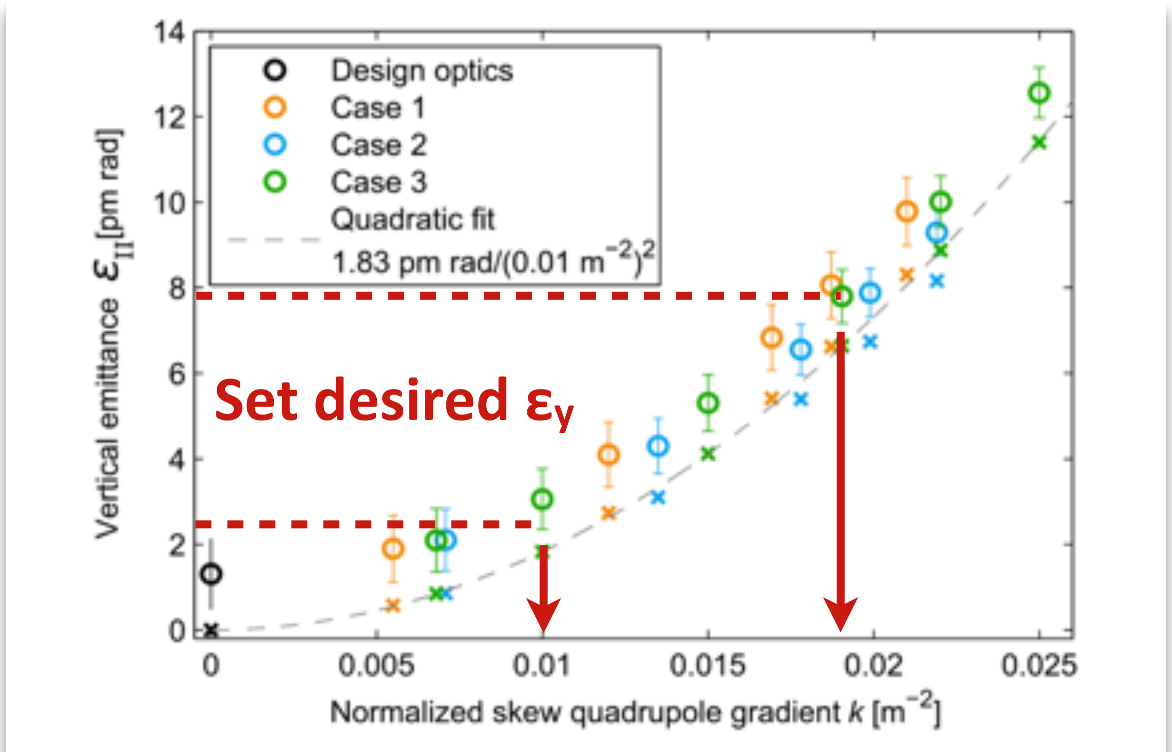
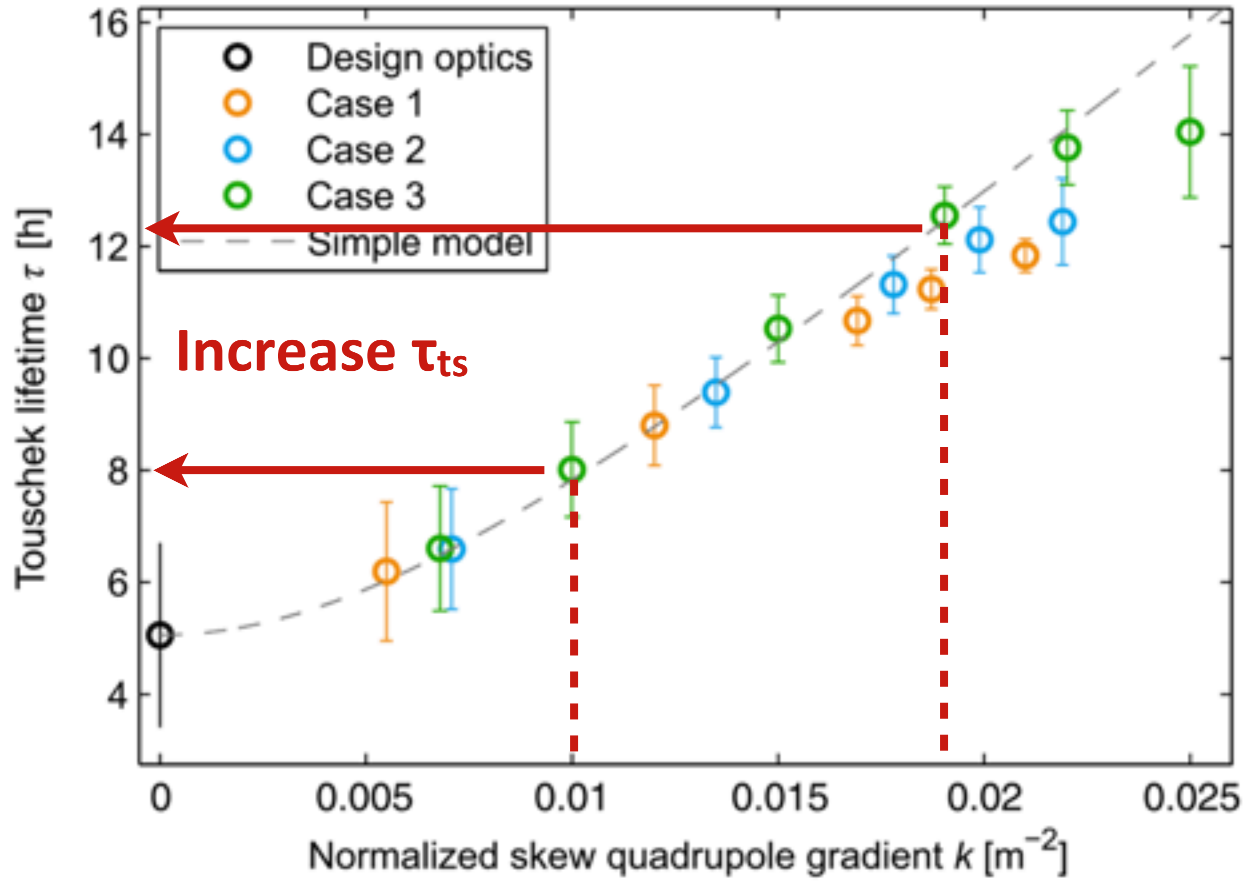


FIG. 5. Vertical emittance scales with skew quadrupole gradient squared. Ideal lattice (x) and error lattice (o) with standard deviations from 10 error seeds. Only the k of the strongest skew quadrupole involved in each case is considered.

Lifetime Improvements in 3 GeV SR (cont.)

PRST-AB **19**, 060701 (2016)

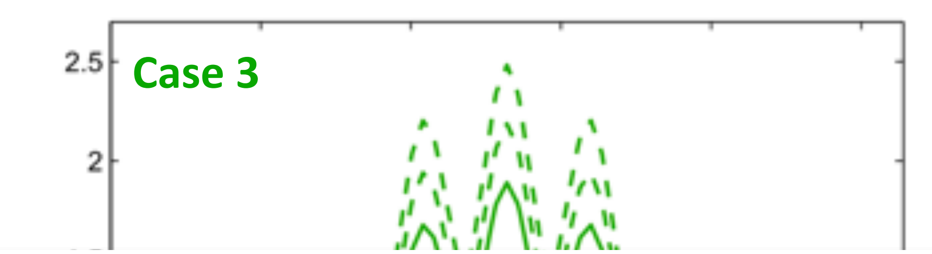


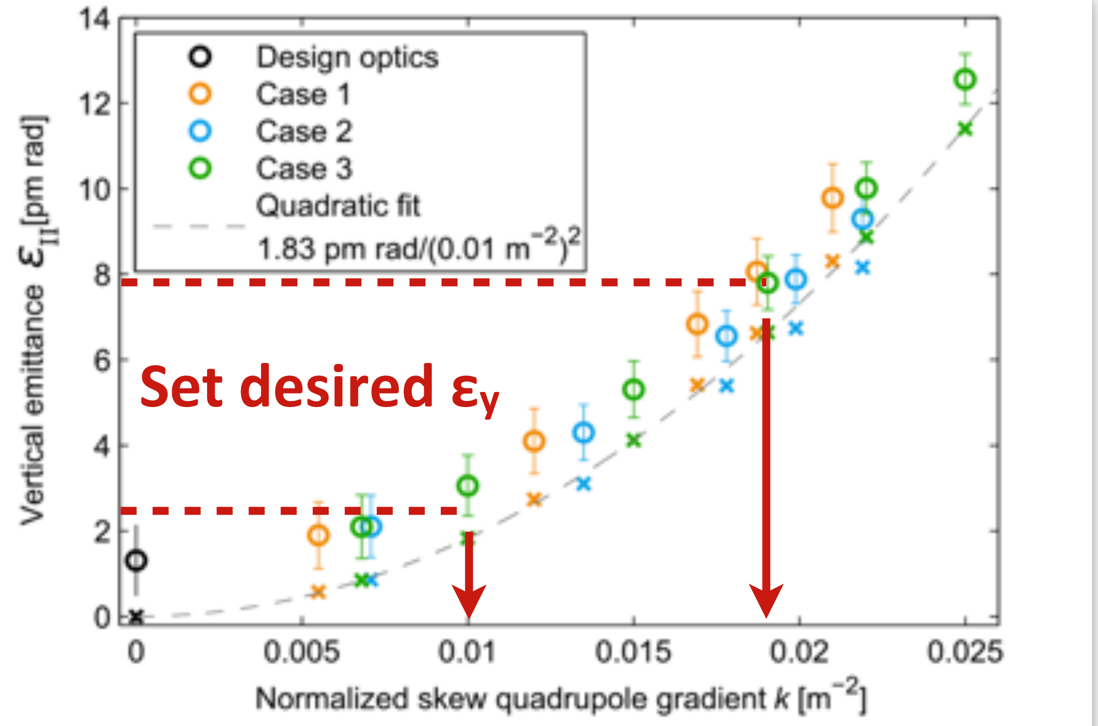
Increase τ_{ts}

FIG. 11. Touschek lifetime as a function of skew quadrupole gradient. Tracking with errors, average and standard deviation for 10 seeds. Only the gradient of the strongest skew quadrupole used in each case is considered in this plot.

ps in achromat arcs → set ε_y

sing Touschek lifetime





Set desired ε_y

FIG. 5. Vertical emittance scales with skew quadrupole gradient squared. Ideal lattice (x) and error lattice (o) with standard deviations from 10 error seeds. Only the k of the strongest skew quadrupole involved in each case is considered.

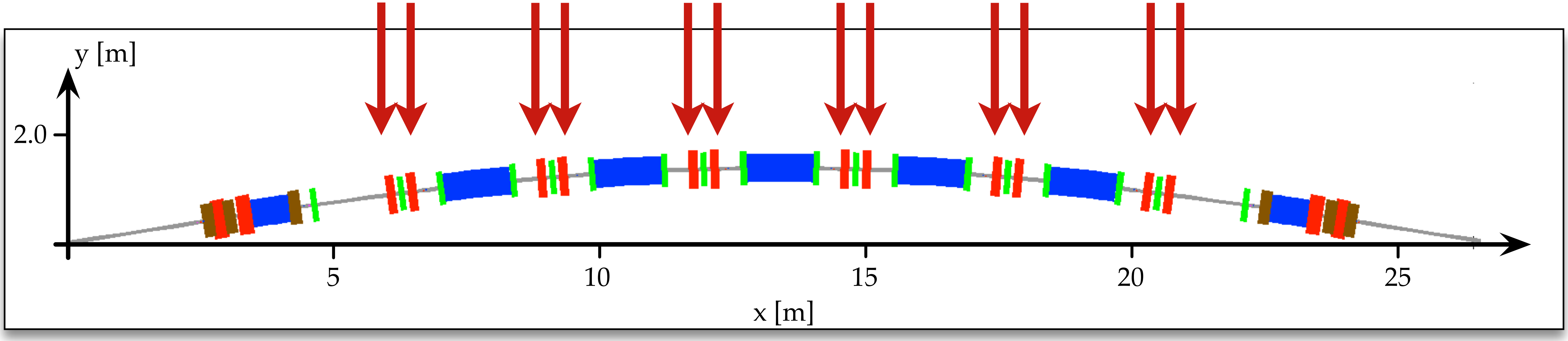
(typically peak η_y is a few mm, ≲5% of η_x)

– even when including errors, tracking reveals $\varepsilon_y \propto k_s^2 \longrightarrow \tau_{ts} \propto k_s$

Better Matching & Emittance Reduction

IPAC’**14**, TUPRI026, p.1615

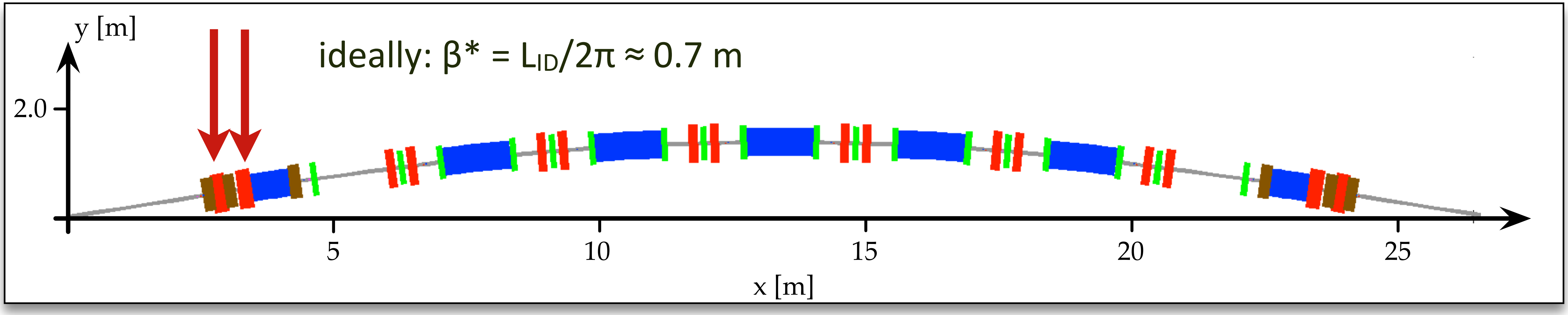
- Improve optics without requiring new magnets or PSs
- Adjust focusing quads in arc & doublets in straights
  - Increase horizontal focusing to lower emittance: 328 → 269 pm rad



Better Matching & Emittance Reduction (cont.)

IPAC’**14**, TUPRI026, p.1615

- Improve optics without requiring new magnets or PSs
- Adjust focusing quads in arc & doublets in straights
  - – Increase horizontal focusing to lower emittance: 328 → 269 pm rad
  - – Decrease $\beta_{x,y}$ in straights to better match intrinsic photon beam
    - $\beta_y^* = 2 \rightarrow 1$ m, $\beta_x^* = 9 \rightarrow 7.5$ m (should still be sufficient for injection)



Better Matching & Emittance Reduction (cont.)

IPAC'**14**, TUPRI026, p.1615

- Improve optics without requiring new magnets or PSs
- Adjust focusing quads in arc & doublets in straights
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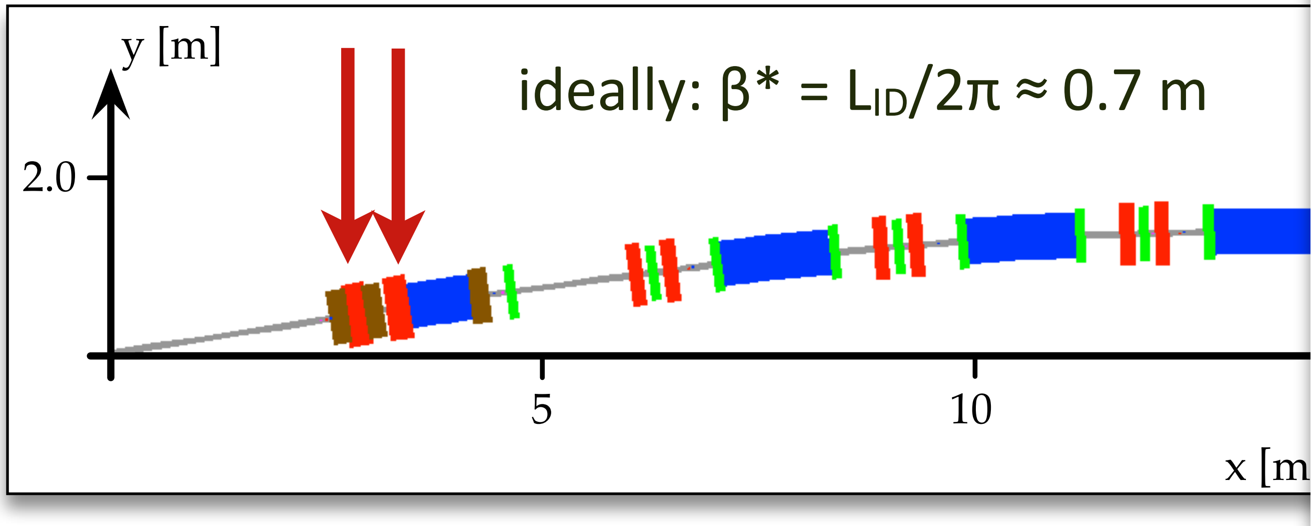
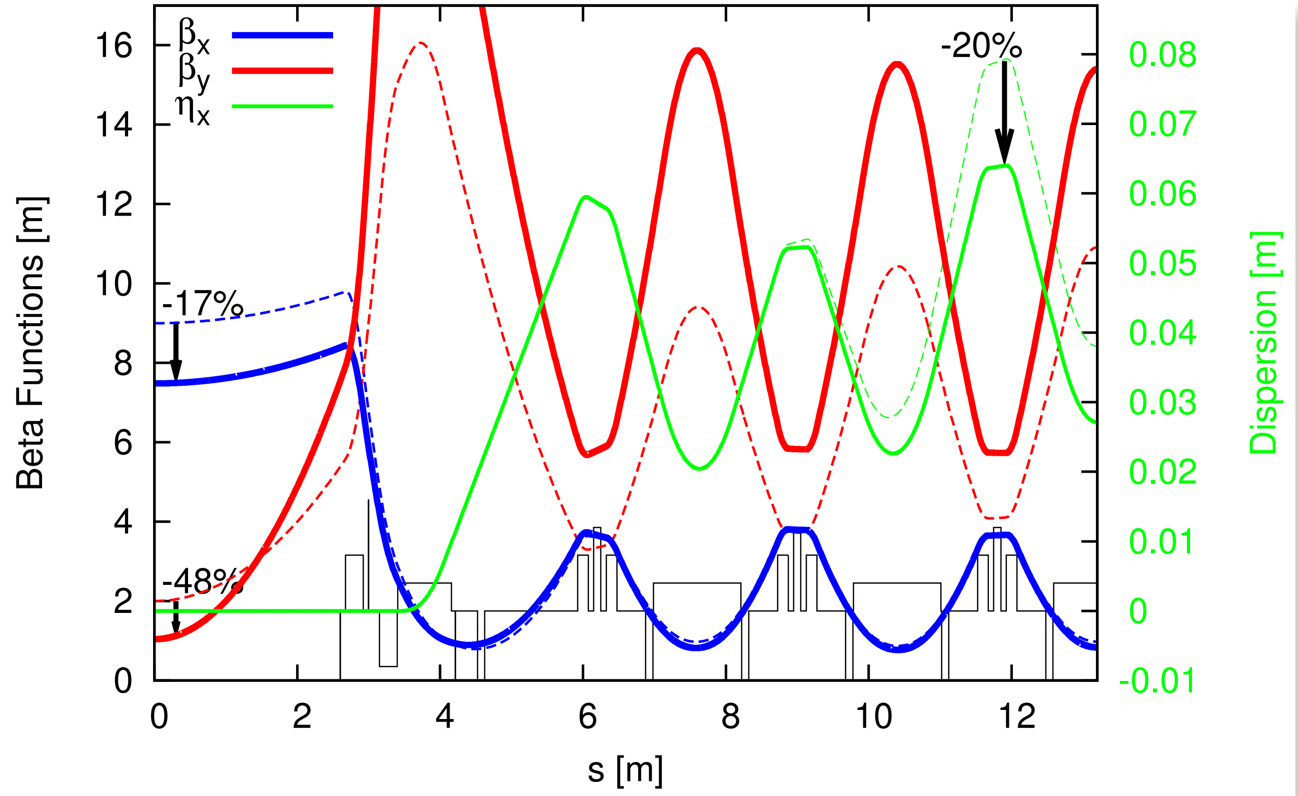
    - $\beta_y^* = 2 \rightarrow 1$ m, $\beta_x^* = 9 \rightarrow 7.5$ m (should still be sufficient for injection)

      $\nu_x = 42.2 \rightarrow 44.2$

      $\nu_y = 16.28 \rightarrow 14.28$



ideally: $\beta^* = L_{ID}/2\pi \approx 0.7$ m



Better Matching & Emittance Reduction (cont.)

IPAC'**14**, TUPRI026, p.1615

- Improve optics without requiring new magnets or PSs
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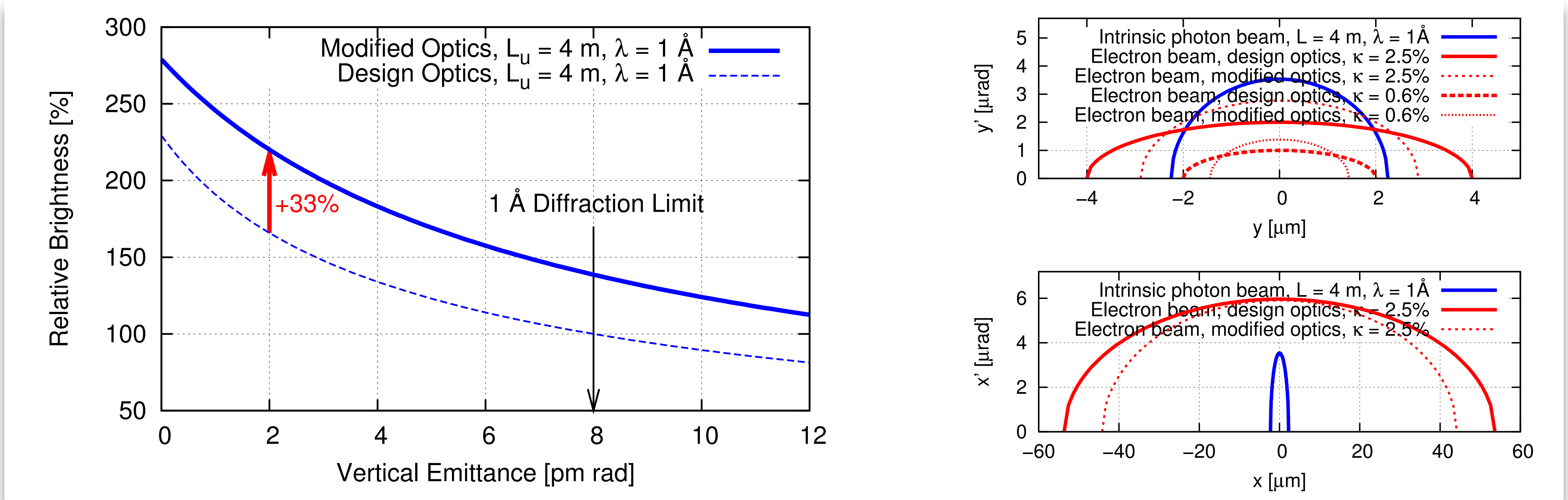
  - Decrease $\beta_{x,y}$ in straights to better match intrinsic photon beam



➡Zero-current emittance reduced by 18% but brightness at 1 Å increases by 30–40% depending on choice of coupling

Better Matching & Emittance Reduction (cont.)

IPAC'**14**, TUPRI026, p.1615

- This is a realistic optics within our current boundary constraints

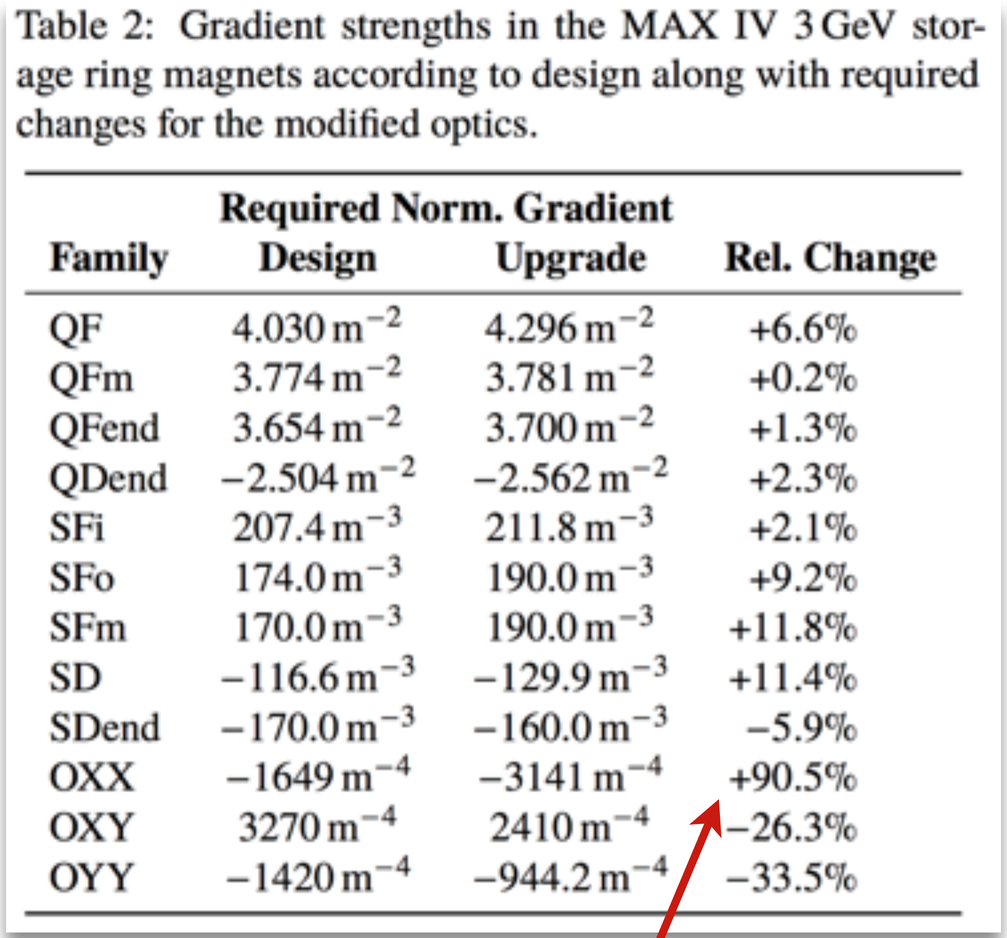
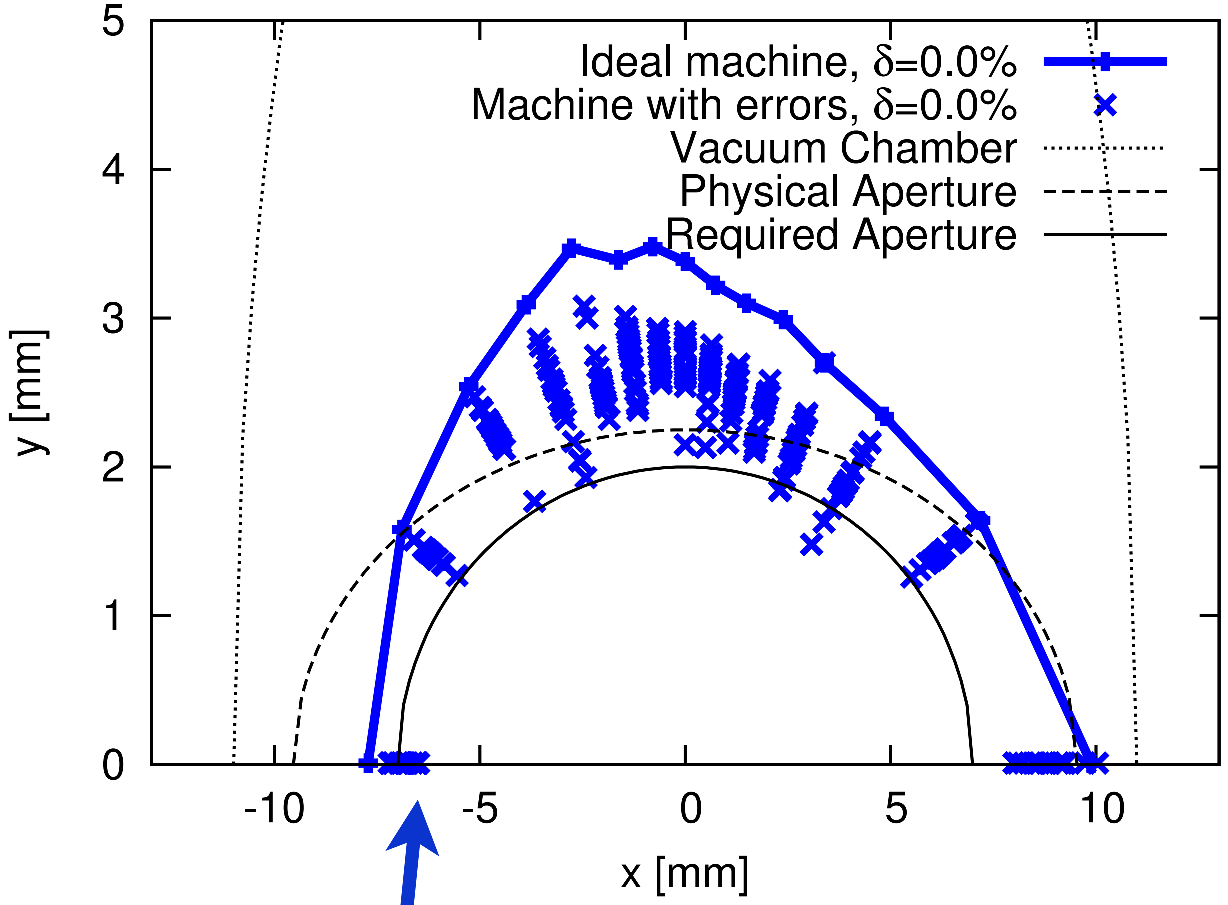


Table 2: Gradient strengths in the MAX IV 3 GeV storage ring magnets according to design along with required changes for the modified optics.

	Required Norm. Gradient		
Family	**Design**	**Upgrade**	**Rel. Change**
QF	$4.030\,\mathrm{m}^{-2}$	$4.296\,\mathrm{m}^{-2}$	+6.6%
QFm	$3.774\,\mathrm{m}^{-2}$	$3.781\,\mathrm{m}^{-2}$	+0.2%
QFend	$3.654\,\mathrm{m}^{-2}$	$3.700\,\mathrm{m}^{-2}$	+1.3%
QDend	$-2.504\,\mathrm{m}^{-2}$	$-2.562\,\mathrm{m}^{-2}$	+2.3%
SFi	$207.4\,\mathrm{m}^{-3}$	$211.8\,\mathrm{m}^{-3}$	+2.1%
SFo	$174.0\,\mathrm{m}^{-3}$	$190.0\,\mathrm{m}^{-3}$	+9.2%
SFm	$170.0\,\mathrm{m}^{-3}$	$190.0\,\mathrm{m}^{-3}$	+11.8%
SD	$-116.6\,\mathrm{m}^{-3}$	$-129.9\,\mathrm{m}^{-3}$	+11.4%
SDend	$-170.0\,\mathrm{m}^{-3}$	$-160.0\,\mathrm{m}^{-3}$	−5.9%
OXX	$-1649\,\mathrm{m}^{-4}$	$-3141\,\mathrm{m}^{-4}$	+90.5%
OXY	$3270\,\mathrm{m}^{-4}$	$2410\,\mathrm{m}^{-4}$	−26.3%
OYY	$-1420\,\mathrm{m}^{-4}$	$-944.2\,\mathrm{m}^{-4}$	−33.5%

Note: PFSs not required; dipole gradients unchanged



Octupoles offer 100% headroom by design

Compatible with present off-axis injection

Better Matching & Emittance Reduction (cont.)

IPAC’**14**, TUPRI026, p.1615

- This is a realistic optics within our current boundary constraints

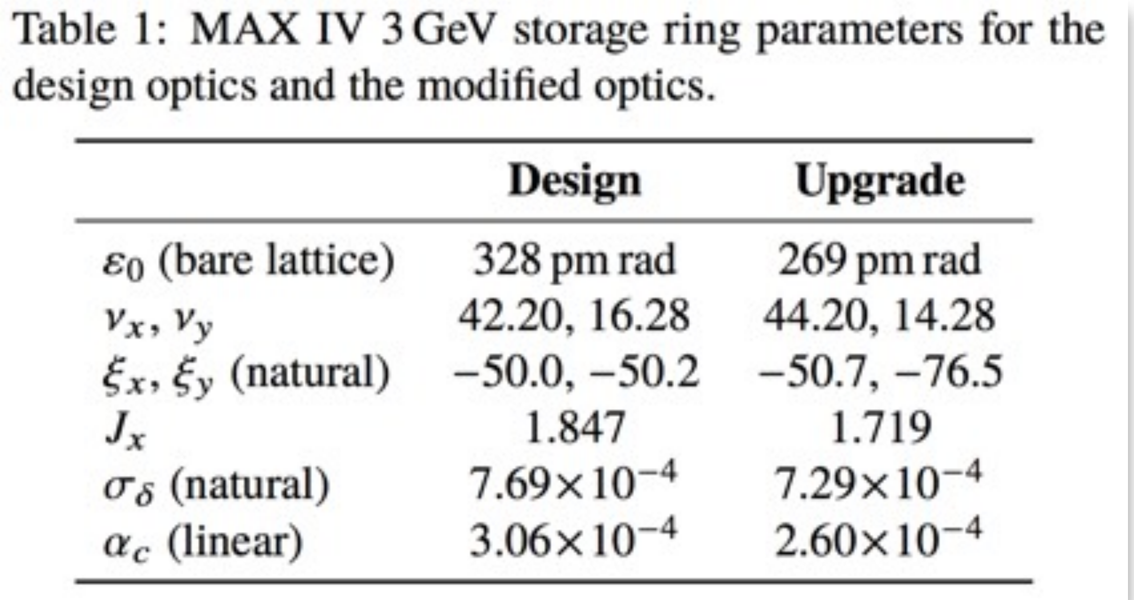
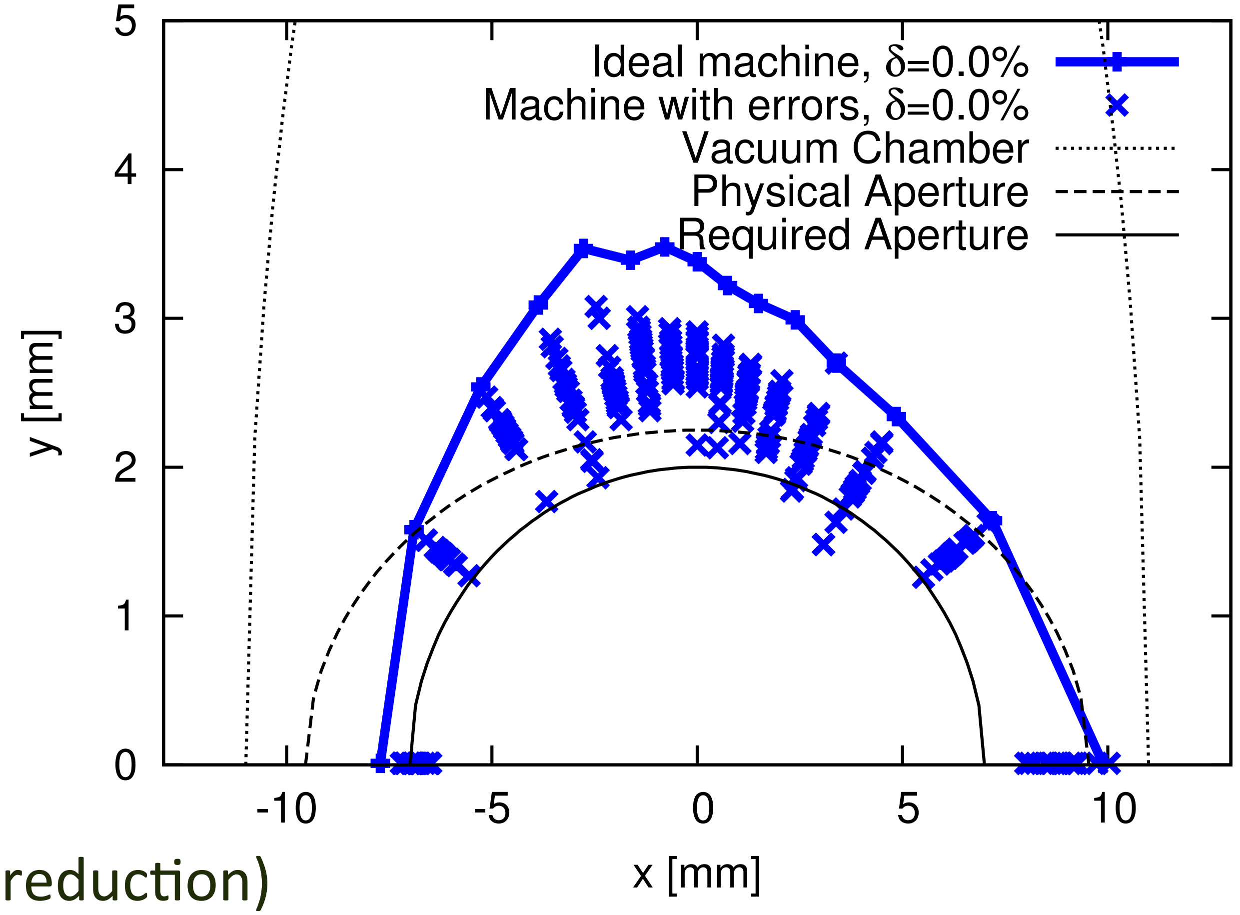


Table 1: MAX IV 3 GeV storage ring parameters for the design optics and the modified optics.

	Design	Upgrade
ε_0 (bare lattice)	328 pm rad	269 pm rad
ν_x, ν_y	42.20, 16.28	44.20, 14.28
ξ_x, ξ_y (natural)	−50.0, −50.2	−50.7, −76.5
J_x	1.847	1.719
σ_δ (natural)	7.69×10^{-4}	7.29×10^{-4}
α_c (linear)	3.06×10^{-4}	2.60×10^{-4}



- Note, α_c even lower (via dispersion reduction)

  ➔ Poor lifetime? Not necessarily since lower ε_x ➔ better τ_{ts}

- Also, lower α_c also gives larger RF acceptance

  (lattice MA exceeds RF acceptance in parts of the lattice)

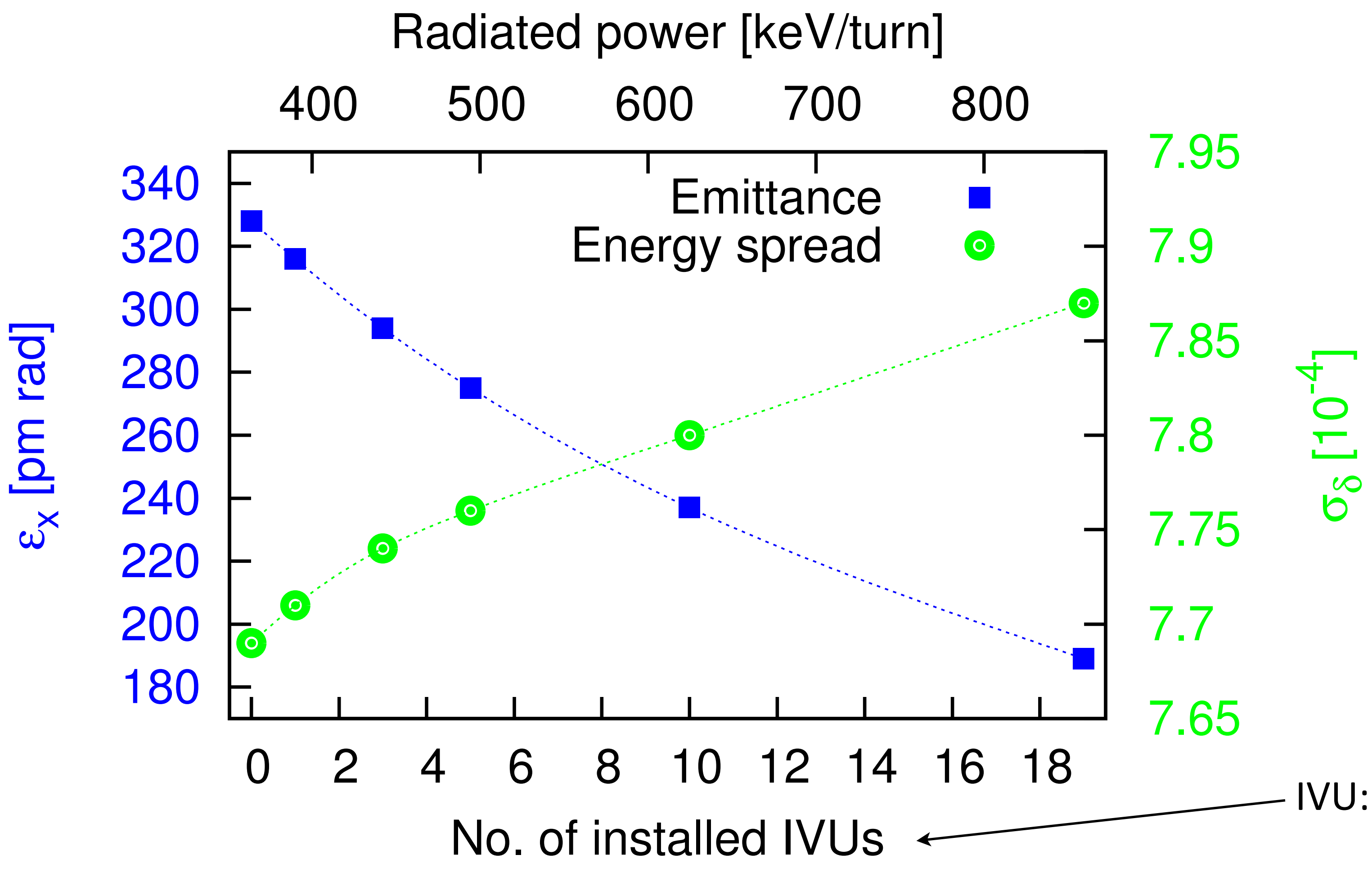
PRST-AB **17**, 050705 (2014)

Better Matching & Emittance Reduction (cont.)

IPAC'**14**, TUPRI026, p.1615

- This is a realistic optics within our current boundary constraints
- Note also, MBA lattice with weak dipoles ➔ very low U_0 ➔ IDs determine ε_x

PRST-AB **17**, 050705 (2014)



MAX IV 3 GeV SR:
Bare: 364 keV/turn
Loaded: ≈1 MeV/turn

IVU: 3.7 m, λ_u = 18.5 mm, B_{eff} = 1.1 T

$$U_0 \propto \gamma^4 I_2 \qquad I_2 = \int \frac{ds}{\rho^2}$$

$$\varepsilon_0 \propto \gamma^2 \frac{I_5}{I_2 - I_4} \qquad I_5 = \int \frac{\mathcal{H}}{|\rho^3|} ds$$

$$I_4 = \int \frac{\eta}{\rho}\left(2k + \frac{1}{\rho^2}\right) ds$$

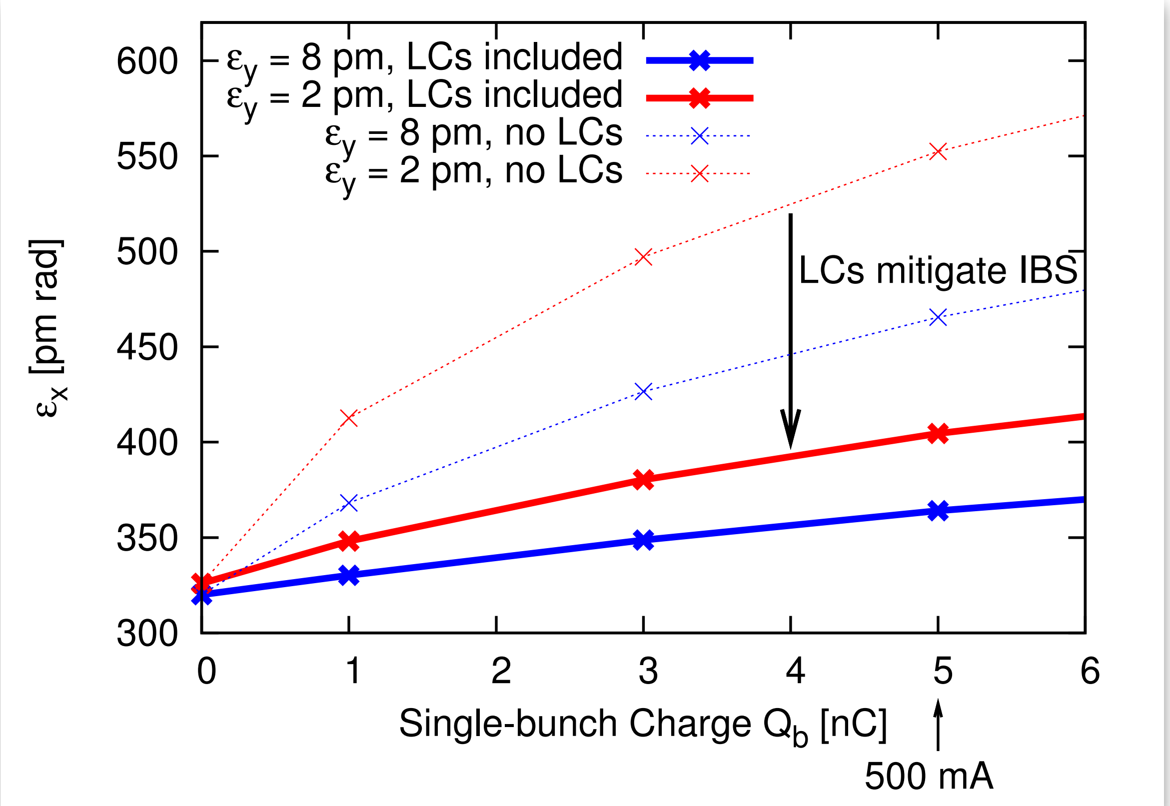
Better Matching & Emittance Reduction (cont.)

IPAC'**14**, TUPRI026, p.1615

- This is a realistic optics within our current boundary constraints
- Note also, MBA lattice with weak dipoles → very low U_0 → IDs determine ε_x → with full ID load ε_x expected to reduce towards
  - ≈180 pm rad at low stored current
  - ≈220 pm rad at 500 mA with LCs (w/o LCs blowup from IBS not manageable)

PRST-AB **17**, 050705 (2014)

MAX-lab Int.Note 20121107



Better Matching & Emittance Reduction (cont.)

IPAC'**14**, TUPRI026, p.1615

- This is a realistic optics within our current boundary constraints
- Note also, MBA lattice with weak dipoles ➔ very low U_0 ➔ IDs determine ε_x ➔ with full ID load ε_0 expected to reduce towards
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  - ≈220 pm rad at 500 mA with LCs
    (w/o LCs blowup from IBS not manageable)

PRST-AB **17**, 050705 (2014)

MAX-lab Int.Note 20121107

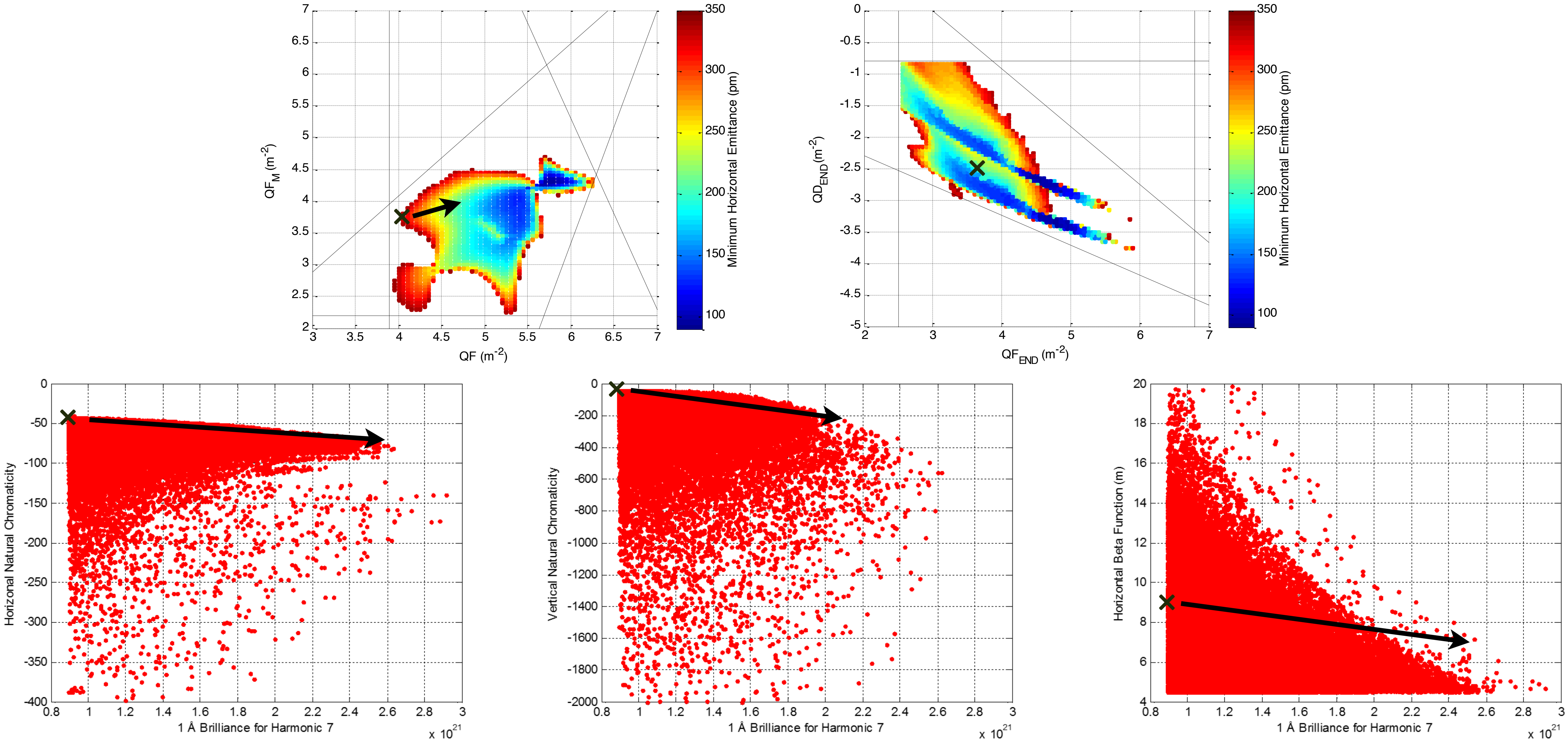
- Nevertheless, can we be more aggressive?
  - increase brightness by factor 2 compared to baseline design?
  - further reduce $\beta_{x,y}$ to improve match to intrinsic photon beam from undulators ➔ is injection still possible?

Further Brightness Improvements

PRST-AB **11**, 024002 (2008)

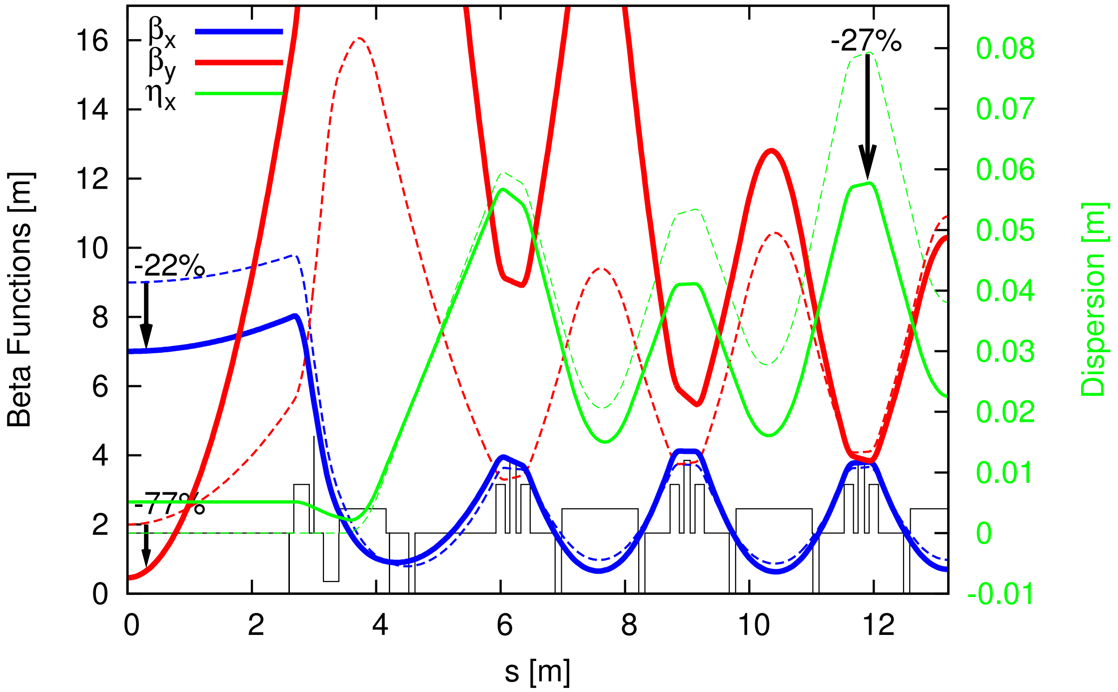
NIM-A **609**, 50, 2009

- Started first GLASS & MOGA studies assuming magnets retained, but PSs can be exchanged (collaboration with Les Dallin & Ward Wurtz, CLS)



Further Brightness Improvements (cont.)

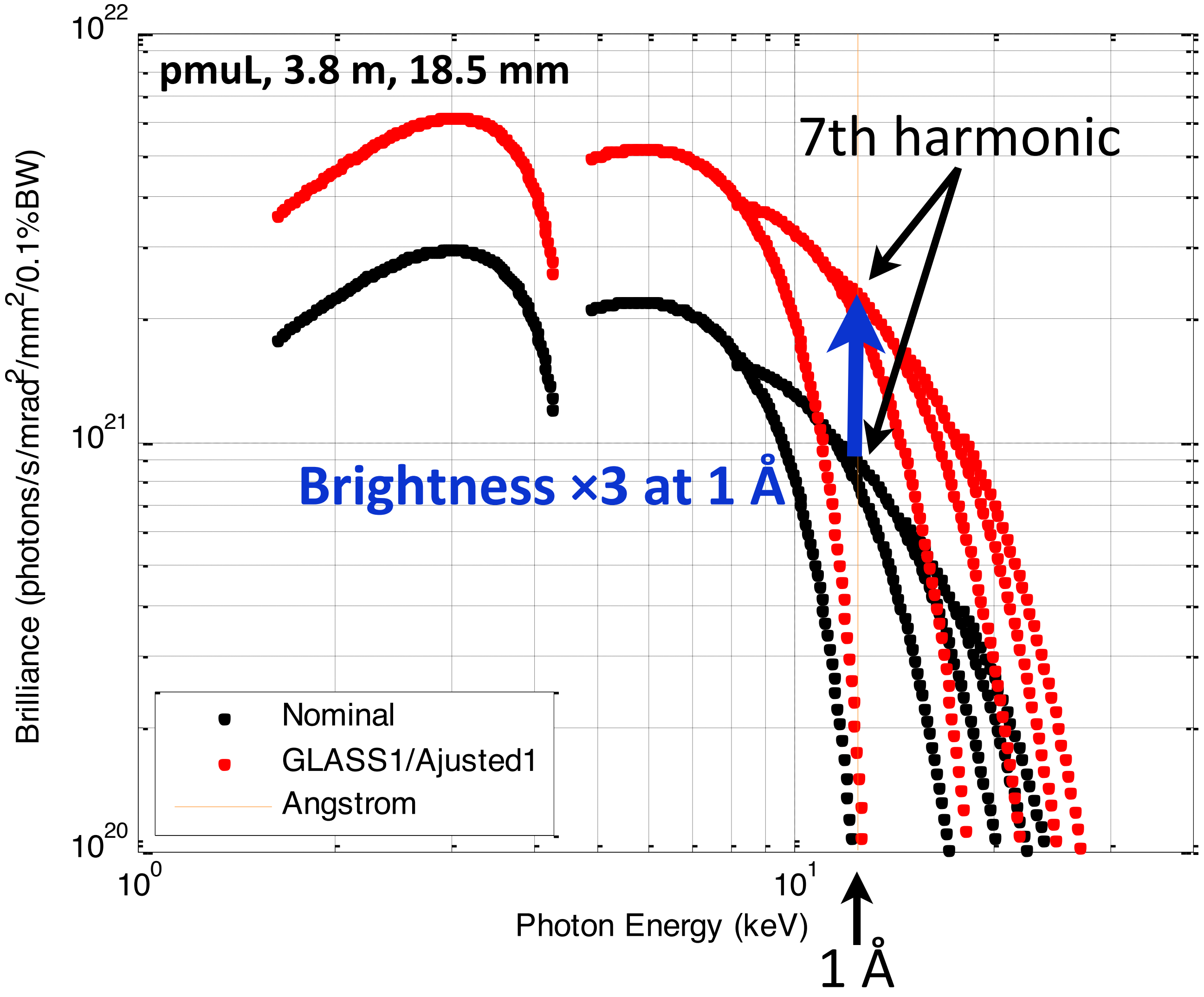
- Started first GLASS & MOGA studies assuming magnets retained, but PSs can be exchanged (collaboration with Les Dallin & Ward Wurtz, CLS)
- Almost a factor 2 can be gained in brightness at 1 Å while retaining $\beta_x = 7$ m for injection
  - $\varepsilon_x = 221$ pm rad (-34%)
  - $\nu_x = 47.20$, $\nu_y = 15.28$
  - $\beta_x^* = 7$ m, $\beta_y^* = 0.46$ m, $\eta_x^* = 5$ mm
  - $\sigma_x^* = 40$ µm, $\sigma_y^* = 1$-2 µm



- QFs need extra 4–15% depending on family (QFs not split up), PFSs require only +2% (of 4% available), sextupoles & octupoles adjusted within original magnet design limits (electrical & thermal, yoke saturation) for $\xi_{x,y} \approx +1$
- But DA challenging (ξ_x=-57, ξ_y=-127) → still needs more nonlinear optimization

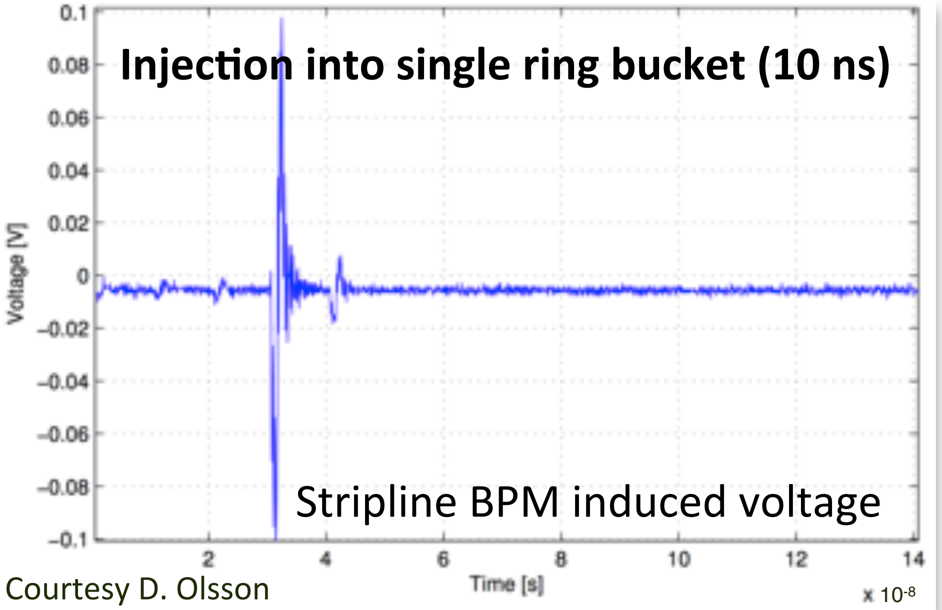
Further Brightness Improvements (cont.)

- Pushing this even farther, we can reach ≈170 pm rad
- With IDs and IBS @ 500 mA this results in **≈150 pm rad** → factor 2 in emittance & factor 3 in brightness compared to baseline design
- But this requires we give up larger $\beta_{x,y}$ in long straights
  - DA/MA appear sufficient in terms of lifetime
  - but will require new injection scheme as we push $\beta_x < 4.5$ m



New Injection into 3 GeV Storage Ring

- **On-axis injection** required for low DA and/or round beam
- Want **fast injection kicker** in order to retain transparent top-up injection → few or single-bunch injection
- Leverage MAX IV advantage: 100 MHz RF → 10 ns bunch spacing
- Our 3 GHz linac is capable of **single-bunch injection**
  - thermionic RF gun equipped with RF chopper to create 100 MHz macro-bunch structure → can be set to single-bucket injection → presently ≈50 pC per bucket at 10 Hz (1% of Q_b)
  - photocathode RF gun (used for SPF) can deliver ≈0.5 nC in a single shot (10% of Q_b)



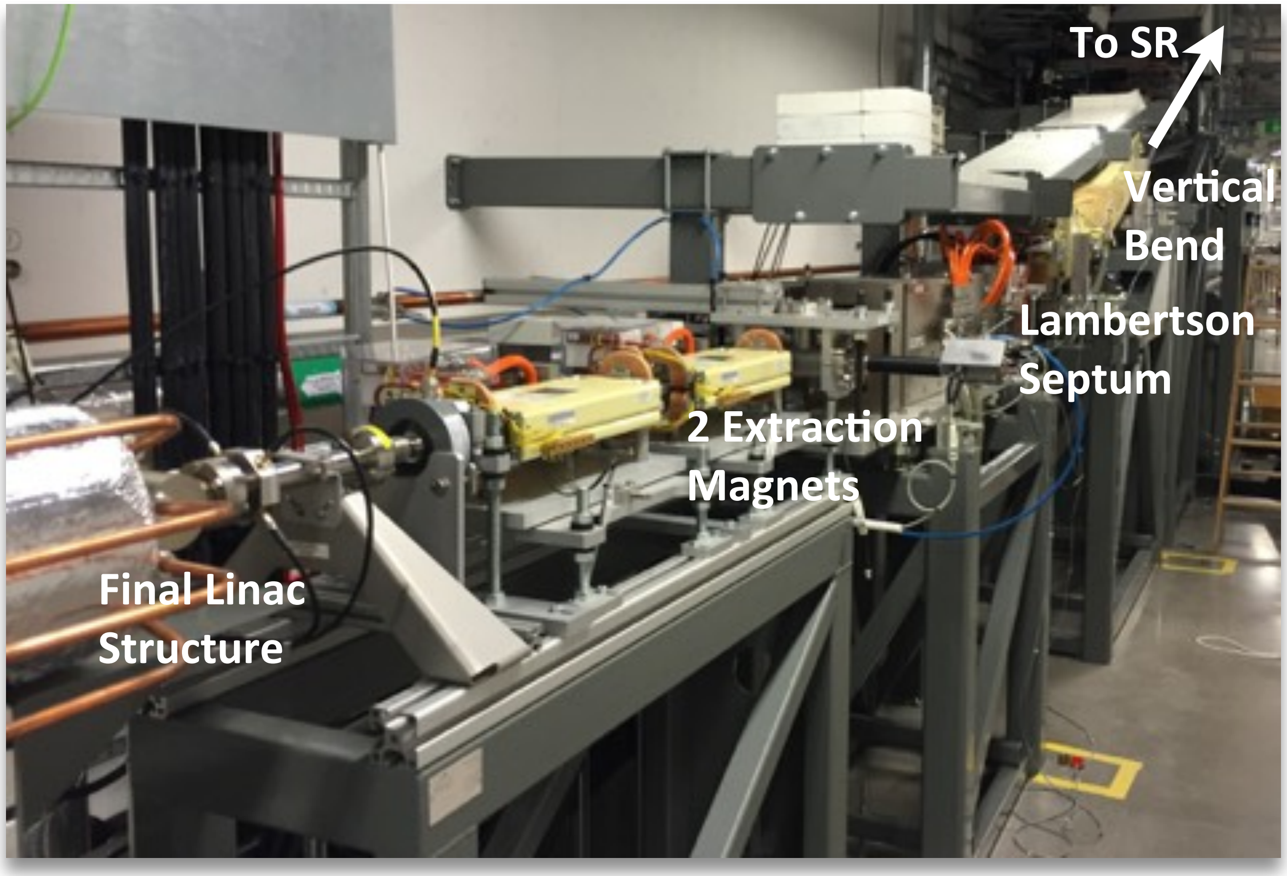
Injection into single ring bucket (10 ns)

Stripline BPM induced voltage

Courtesy D. Olsson

New Injection into 3 GeV Storage Ring (cont.)

- However, present injection switching time dominated by time required to ramp EF dipoles & linac extraction magnets (2× ≈1 sec); linac re-phased quickly

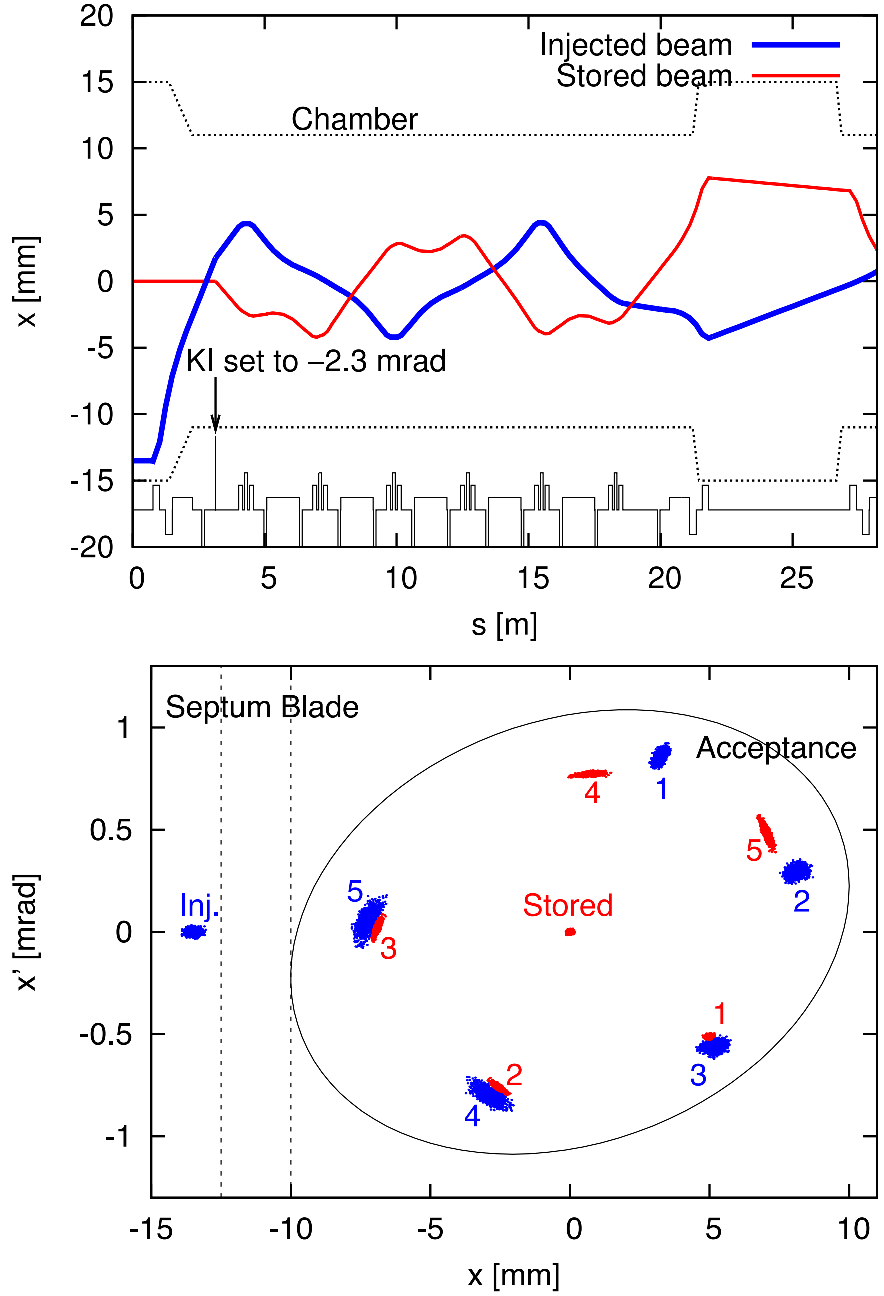


- If switching process accelerated → top-up **bunch-by-bunch** → reduce FP granularity, enable FP feedback & special FPs, etc.

New Injection into 3 GeV Storage Ring (cont.)

- We consider two main options for **bunch-by-bunch injection**:
  - sharing injection kick
    - ⊕ simple (can also inject at angle)
    - ⊖ still requires some DA (“off-axis injection”)
    - ⊖ ideally, should move IP upstream

NIM-A **693**, 117, 2012

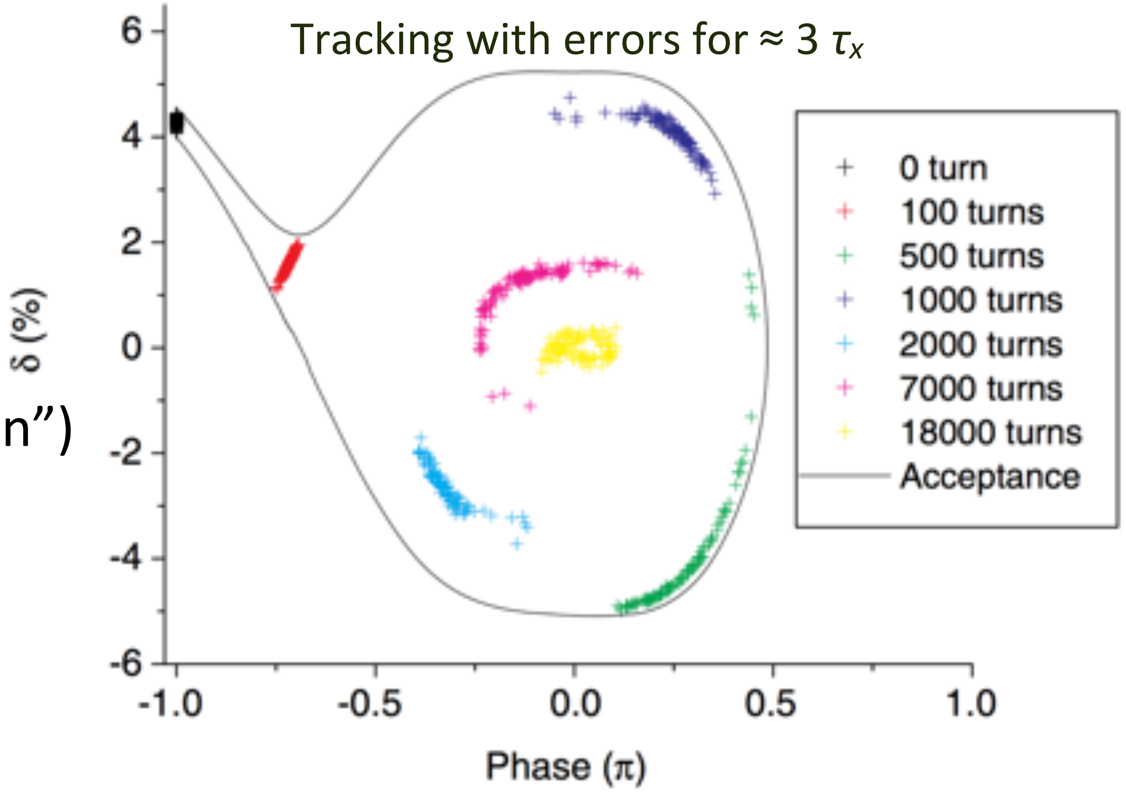


New Injection into 3 GeV Storage Ring (cont.)

- We consider two main options for **bunch-by-bunch injection**:
  - sharing injection kick
    - ⊕ simple (can also inject at angle)
    - ⊖ still requires some DA ("off-axis injection")
    - ⊖ ideally, should move IP upstream
  - off-energy injection (Aiba et al., SLS)
    - ⊕ requires only minimal DA ("on-axis injection")
    - ⊕ robust against machine errors
    - ⊖ requires fast kicker

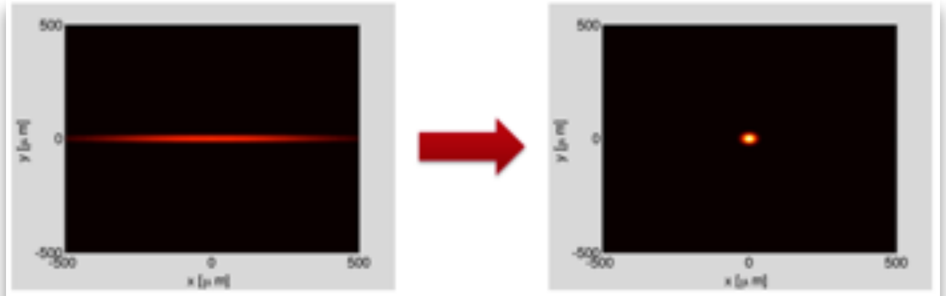
PRST-AB **18**, 020701 (2015)

Tracking with errors for ≈ 3 τ_x

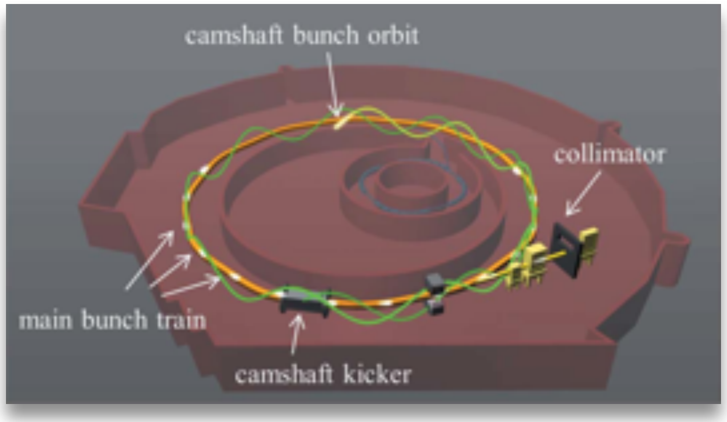


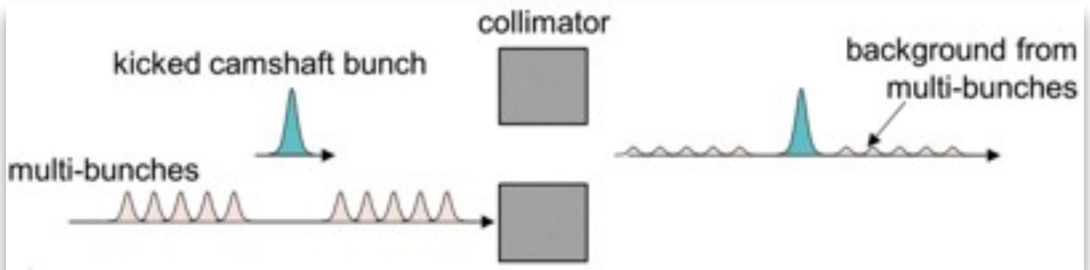
New Injection into 3 GeV Storage Ring (cont.)

- Either way, development of a fast kicker (≈10 ns, ≈2 mrad) presents great potential for MAX IV
  - enables **very hard optics** with low DA
    - highest brightness
    - round beams
    - new IDs (e.g. Delta or SC double-helical)
  - also enables **timing experiments** (e.g. PSB-KAC @ ALS)
    - recently launched @ MAX IV SRI **2015**, THU-P-021 SRN **Vol.28, No.5,** 2015 IPAC'**16**, WEPOW036 IPAC'**16**, WEPOW037
    - without fast kicker would be relegated to 1.5 GeV SR, few days/year



Courtesy C. Steier





PRL **109**, 264801 (2012) JSR **22**, 729-735 (2015)

Summary

- There exist short & medium-term upgrade ideas to **substantially improve brightness & coherence** in 3 GeV SR
  - require varying levels of modification & funding
  - short-term ideas quite advanced
  - medium-term ideas need more work (primarily nonlinear optics & kicker development → feasibility)
- Developed plan how to **further improve lifetime** if required as a consequence of brightness improvements
- Can consider **upgrading injection scheme** if required for more substantial brightness improvements

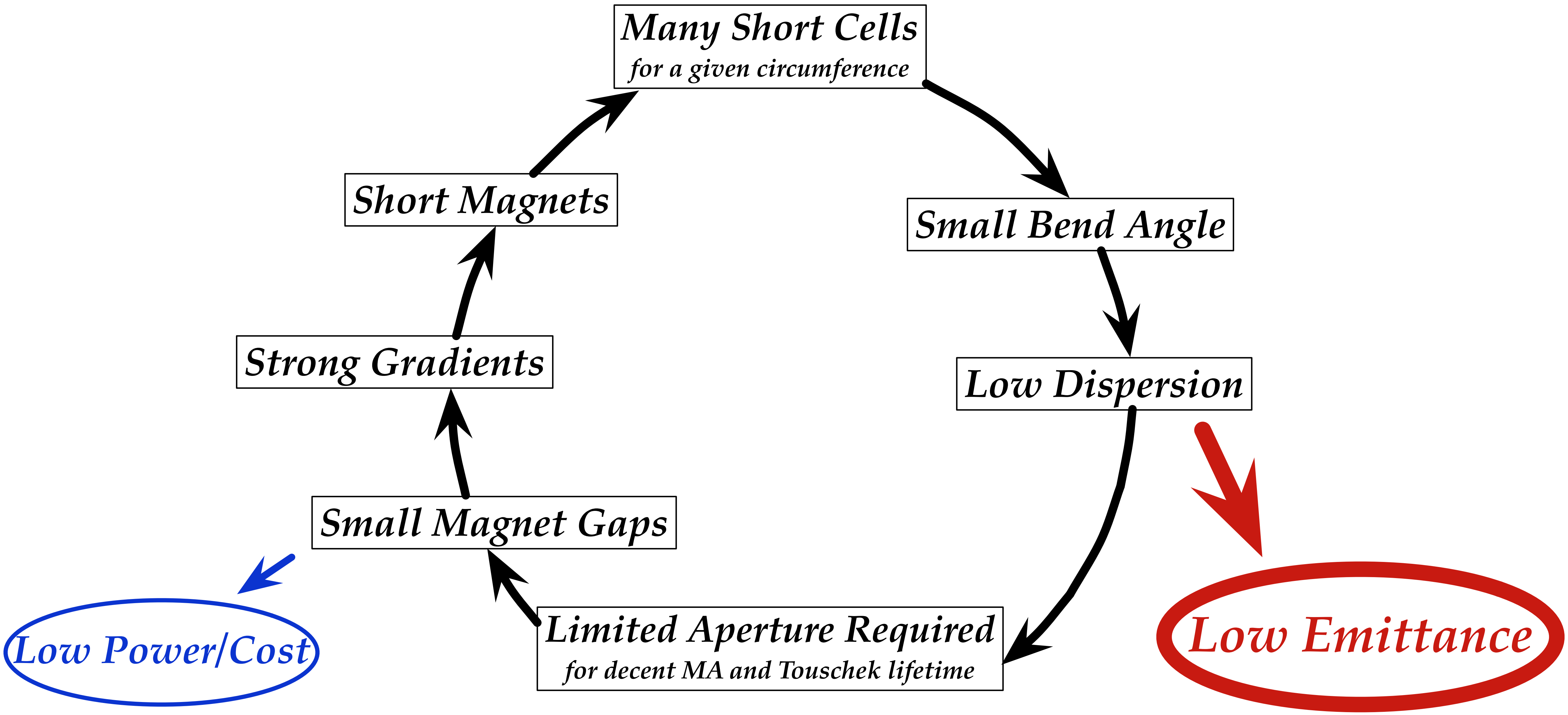
Thanks for your attention!

Photo courtesy P. Nordeng, Feb 5, 2015

Backup: The MBA – A Virtuous Circle

The Multibend Achromat Cycle

(courtesy A. Streun, PSI)



Many Short Cells
for a given circumference

Small Bend Angle

Low Dispersion

Limited Aperture Required
for decent MA and Touschek lifetime

Small Magnet Gaps

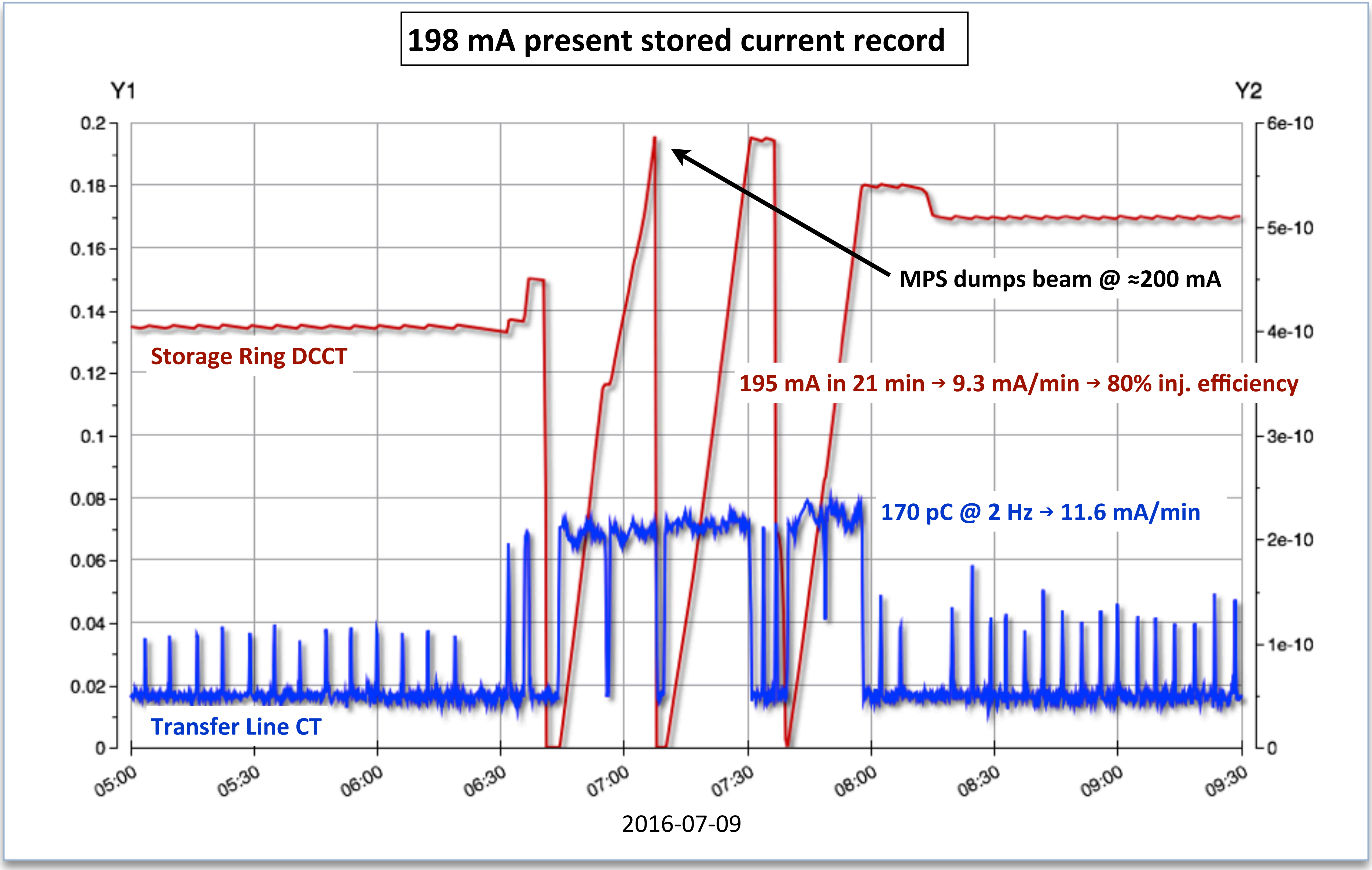
Strong Gradients

Short Magnets

Low Emittance

Low Power/Cost

Backup: 198 mA Stored Current in July 2016



198 mA present stored current record

MPS dumps beam @ ≈200 mA

195 mA in 21 min → 9.3 mA/min → 80% inj. efficiency

170 pC @ 2 Hz → 11.6 mA/min

2016-07-09

Backup: Optics Tuning & Corrections

- **Gradient dipoles** equipped with pole-face strips → adjust vertical focusing within ±4% (requires dipole feedback)

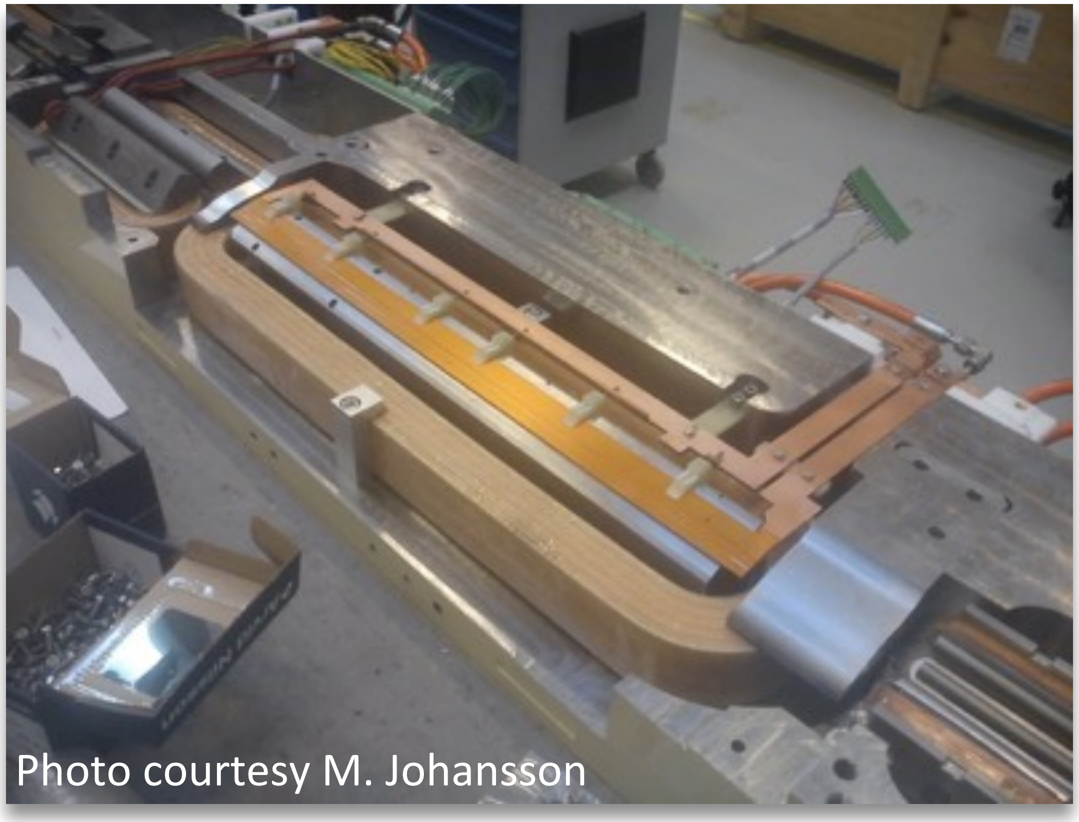
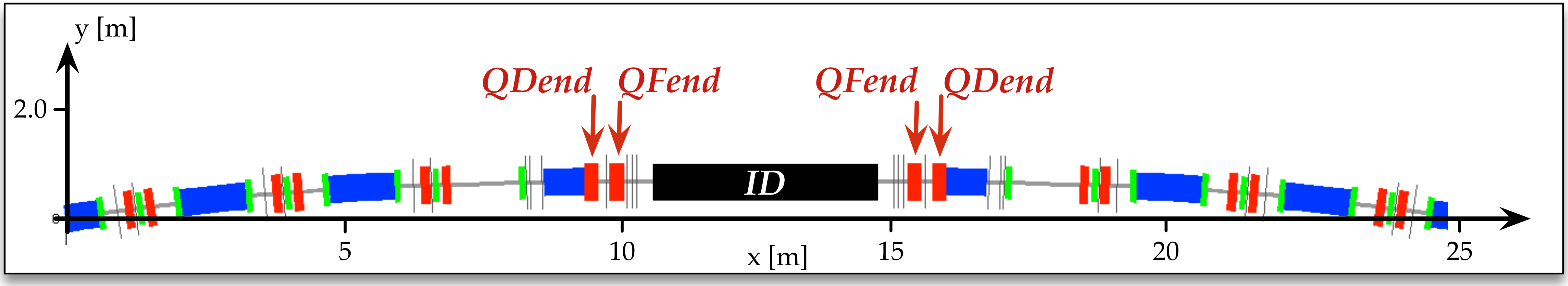


Photo courtesy M. Johansson

Photo courtesy A. Nyberg

Backup: Optics Tuning & Corrections (cont.)

- **Gradient dipoles** equipped with pole-face strips → adjust vertical focusing within ±4% (requires dipole feedback)
- **Quadrupole doublets** in long straights → match optics to IDs and restore tunes (ideally makes IDs transparent to arc optics)

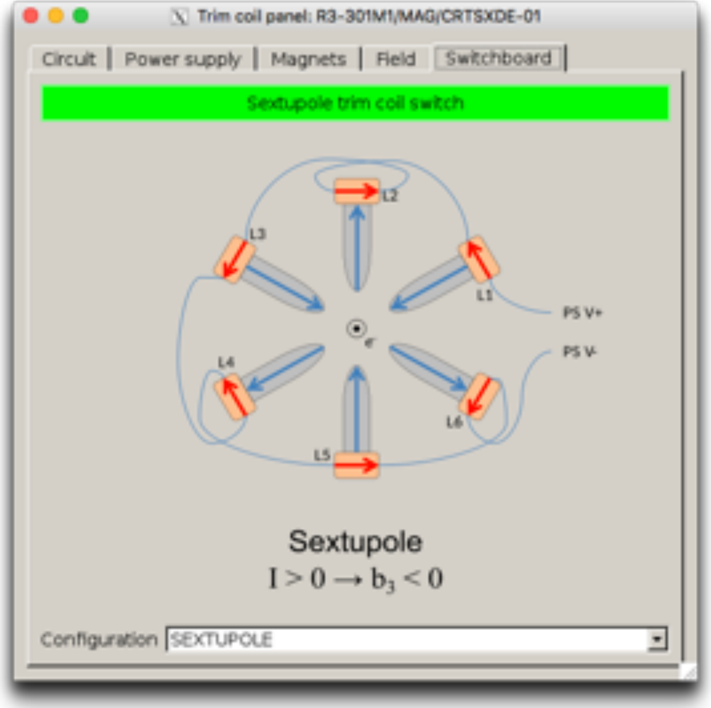


PAC'**11**, TUP235, p.1262

IPAC'**15**, TUPJE038

Backup: Optics Tuning & Corrections (cont.)

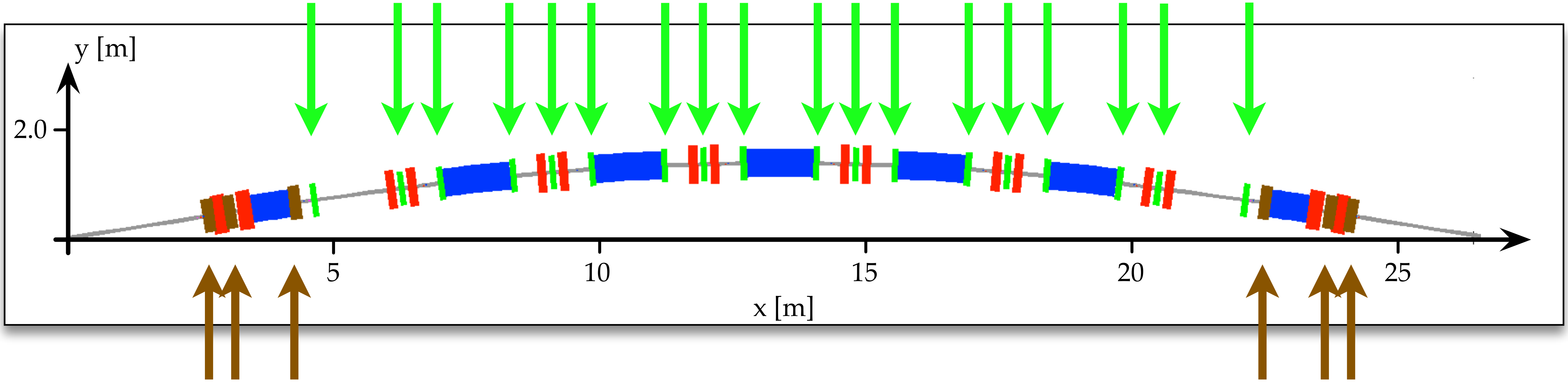
- All **sextupoles** and **octupoles** carry auxiliary winding
- Can be powered as: (remotely switchable)
  - **auxiliary sextupole** → nonlinear corrections
  - skew quadrupole → coupling & dispersion control
  - upright quad → calibrate BPMs to adjacent sext/oct
  - dipole correctors, in addition to...



Sextupole trim coil switch

Sextupole
$I > 0 \rightarrow b_3 < 0$

Configuration: SEXTUPOLE



Backup: Optics Tuning & Corrections (cont.)

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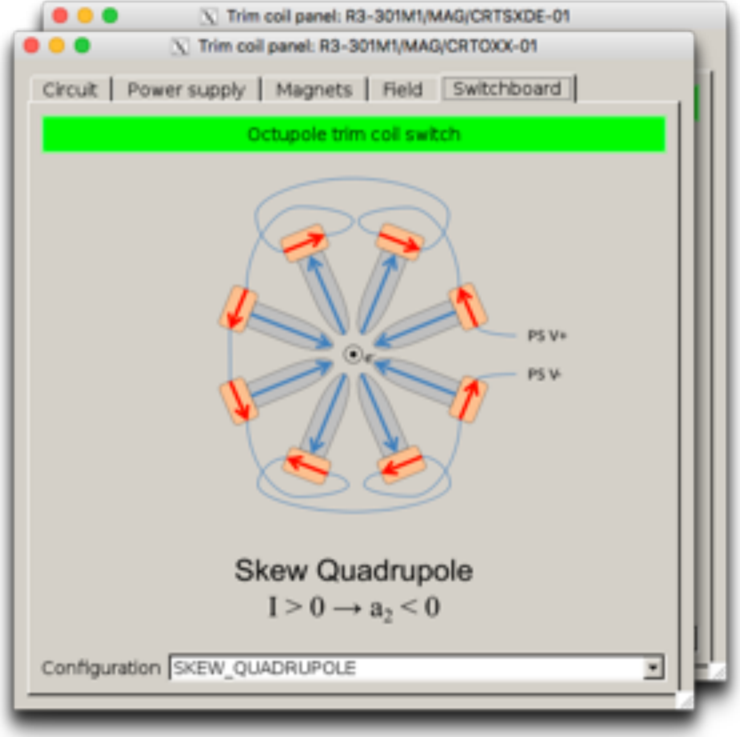
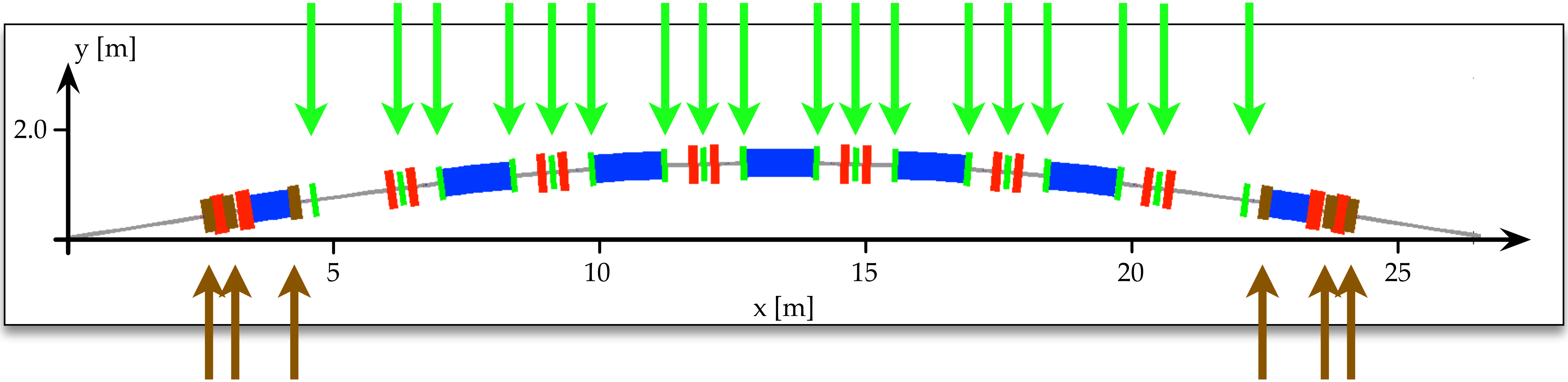


Skew Quadrupole

$I > 0 \rightarrow a_2 < 0$

Configuration SKEW_QUADRUPOLE



Backup: Optics Tuning & Corrections (cont.)

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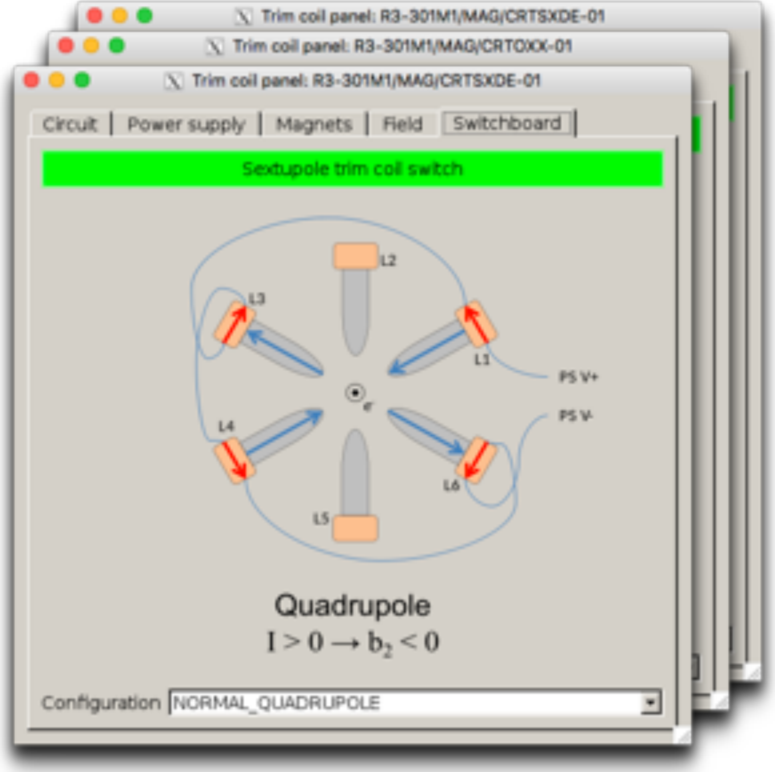
    - skew quadrupole → coupling & dispersion control
    - **upright quad** → calibrate BPMs to adjacent sext/oct
    - dipole correctors, in addition to...

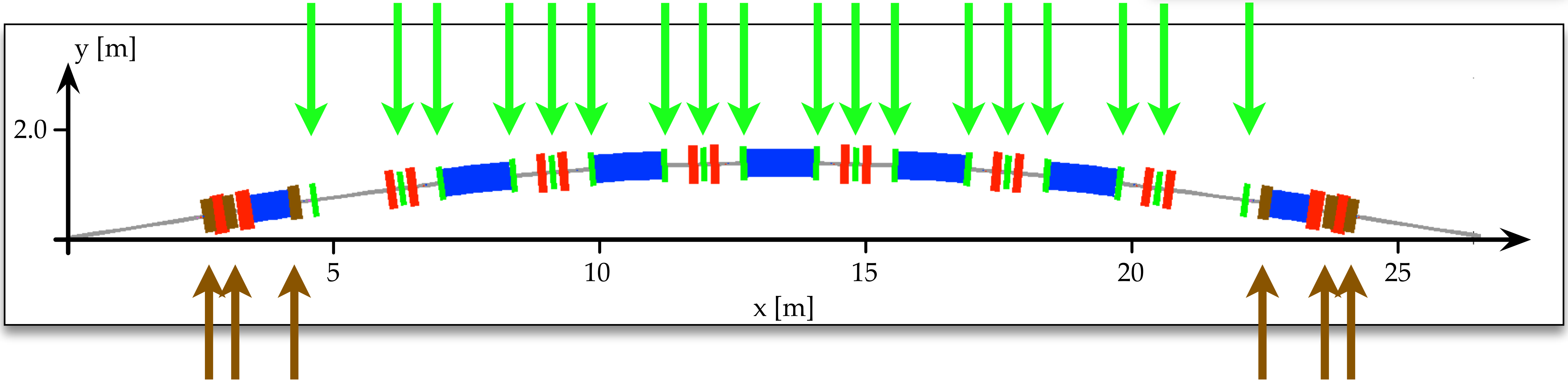


Sextupole trim coil switch

Quadrupole

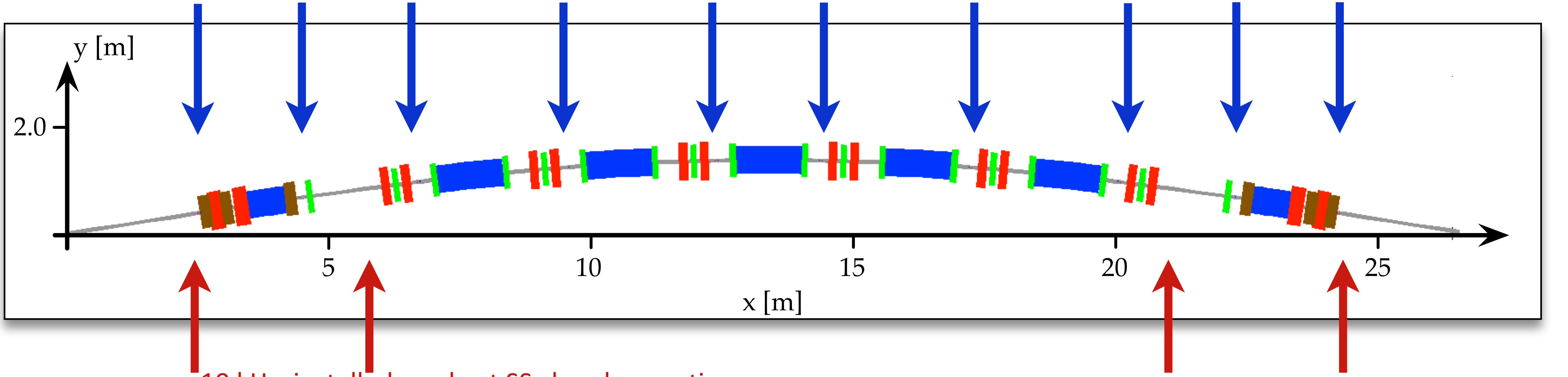
$I > 0 \rightarrow b_2 < 0$

Configuration: NORMAL_QUADRUPOLE



Backup: Optics Tuning & Corrections (cont.)

- All **sextupoles** and **octupoles** carry auxiliary winding
- Can be powered as: (remotely switchable)
    - auxiliary sextupole → nonlinear corrections
    - skew quadrupole → coupling & dispersion control
    - upright quad → calibrate BPMs to adjacent sext/oct
    - dipole correctors, in addition to...
- Dedicated **dipole correctors** → **SOFB** & **FOFB**



Backup: Guns, RF Chopper & Energy Filter