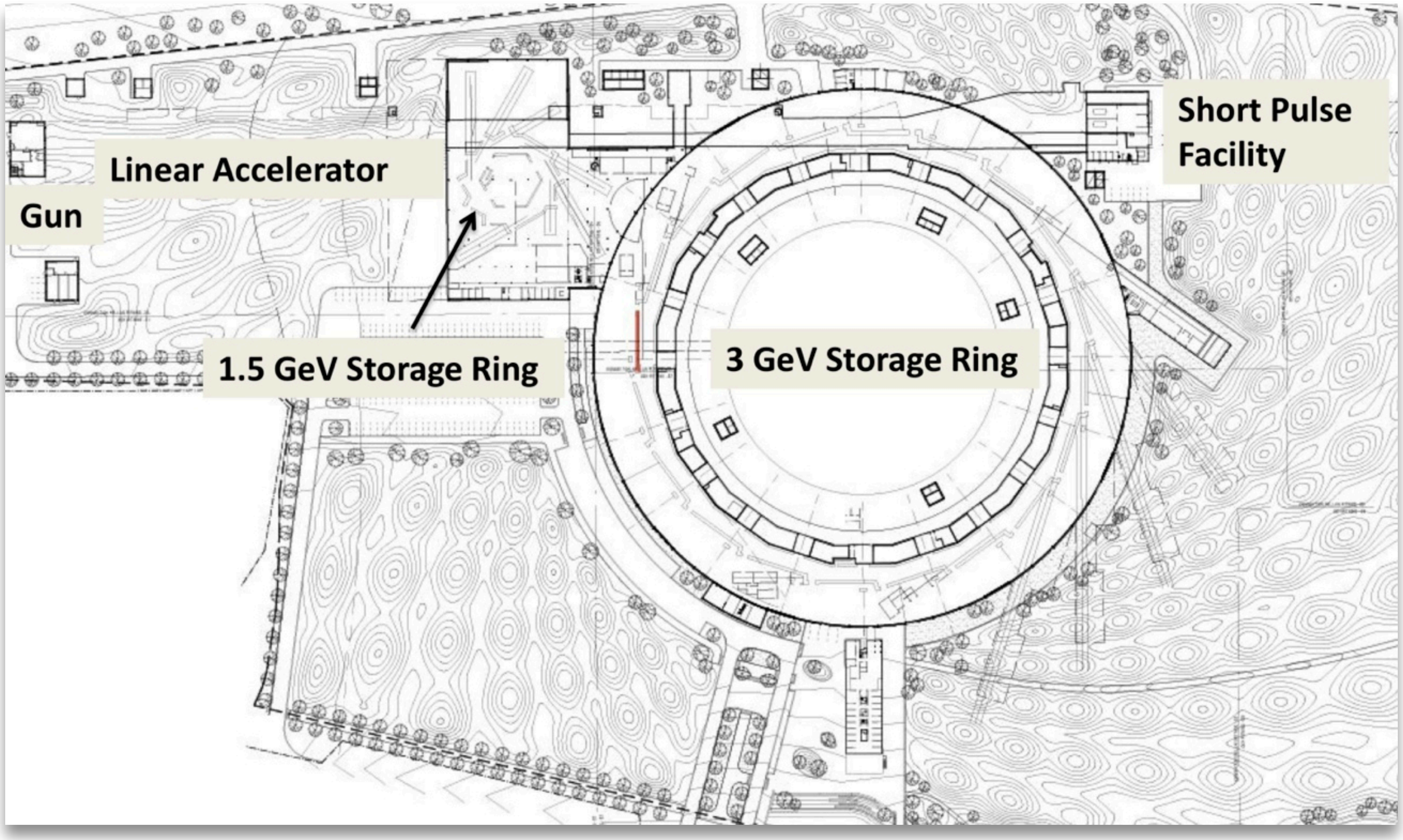
The MAX IV 3 GeV Storage Ring Lattice

Simon C. Leemann
1st Workshop on Low Emittance Lattice Design, April 23-24, 2015

Origins of the MAX IV 3 GeV Ring Lattice

- Realization that a single accelerator cannot cover the entire required spectral and temporal range → decision to build
  - one full-energy linac → SPF/FEL driver & ring injector (separate guns)
  - two separate storage rings at 1.5 GeV and 3 GeV



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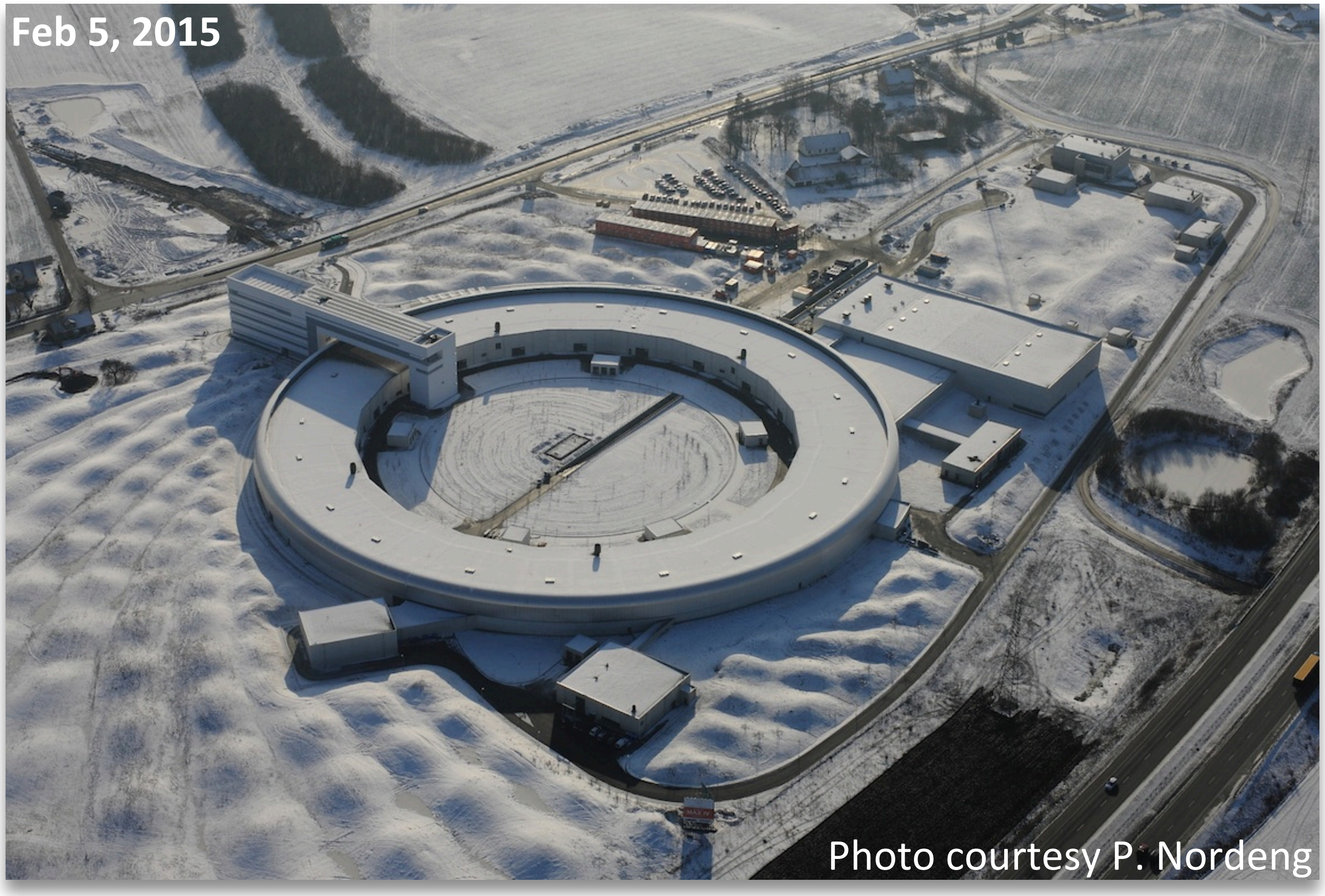

Feb 5, 2015

Photo courtesy P. Nordeng

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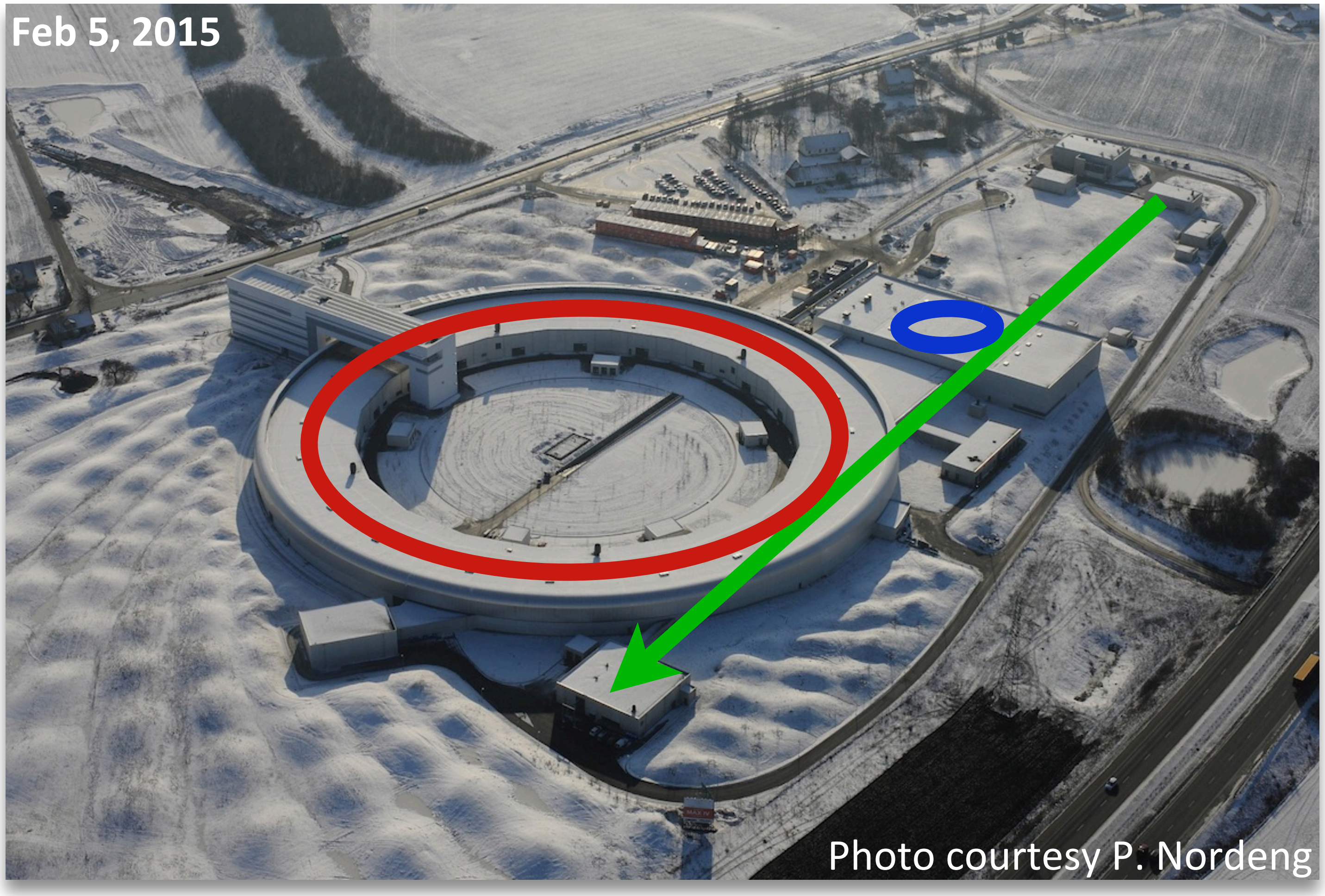

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- 3 GeV storage ring targets x-ray users → high brightness via state-of-the-art IDs, high-current top-up operation & ultralow emittance

Origins of the MAX IV 3 GeV Ring Lattice (cont.)

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

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

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

$$I_2 = \oint \frac{ds}{\rho^2}$$

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

$$I_5 = \oint \frac{\mathcal{H}}{|\rho^3|} ds$$

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

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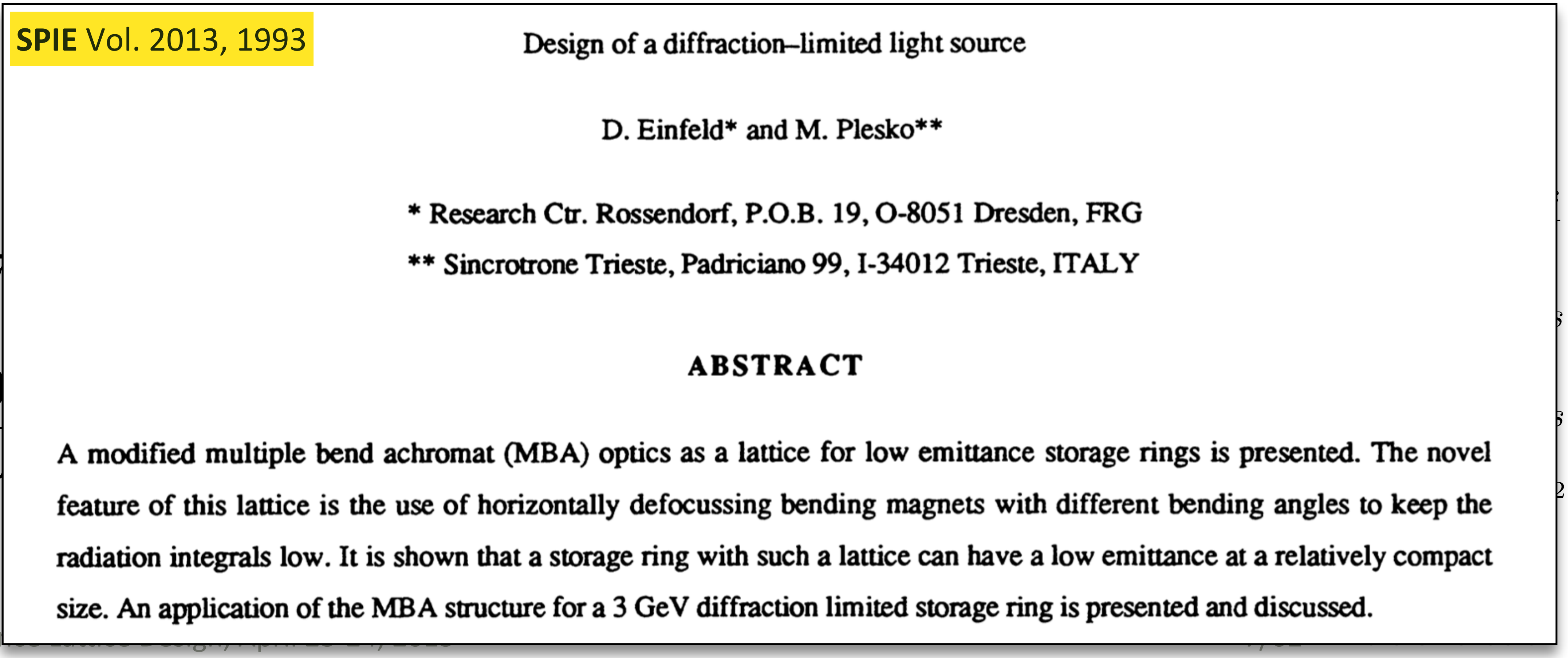
- Ultralow

$$\varepsilon_0[\mathrm{nm\,rad}] = 147$$

$$= \frac{0.0}{J}$$



SPIE Vol. 2013, 1993

Design of a diffraction–limited light source

D. Einfeld* and M. Plesko**

* Research Ctr. Rossendorf, P.O.B. 19, O-8051 Dresden, FRG

** Sincrotrone Trieste, Padriciano 99, I-34012 Trieste, ITALY

ABSTRACT

A modified multiple bend achromat (MBA) optics as a lattice for low emittance storage rings is presented. The novel feature of this lattice is the use of horizontally defocussing bending magnets with different bending angles to keep the radiation integrals low. It is shown that a storage ring with such a lattice can have a low emittance at a relatively compact size. An application of the MBA structure for a 3 GeV diffraction limited storage ring is presented and discussed.

Origins of the MAX IV 3 GeV Ring Lattice (cont.)

- Realization that a single accelerator cannot cover the entire required spectral and temporal range ➞ decision to build
  - one full-energy linac ➞ SPF/FEL driver & ring injector
  - two separate storage rings at 1.5 GeV and 3 GeV
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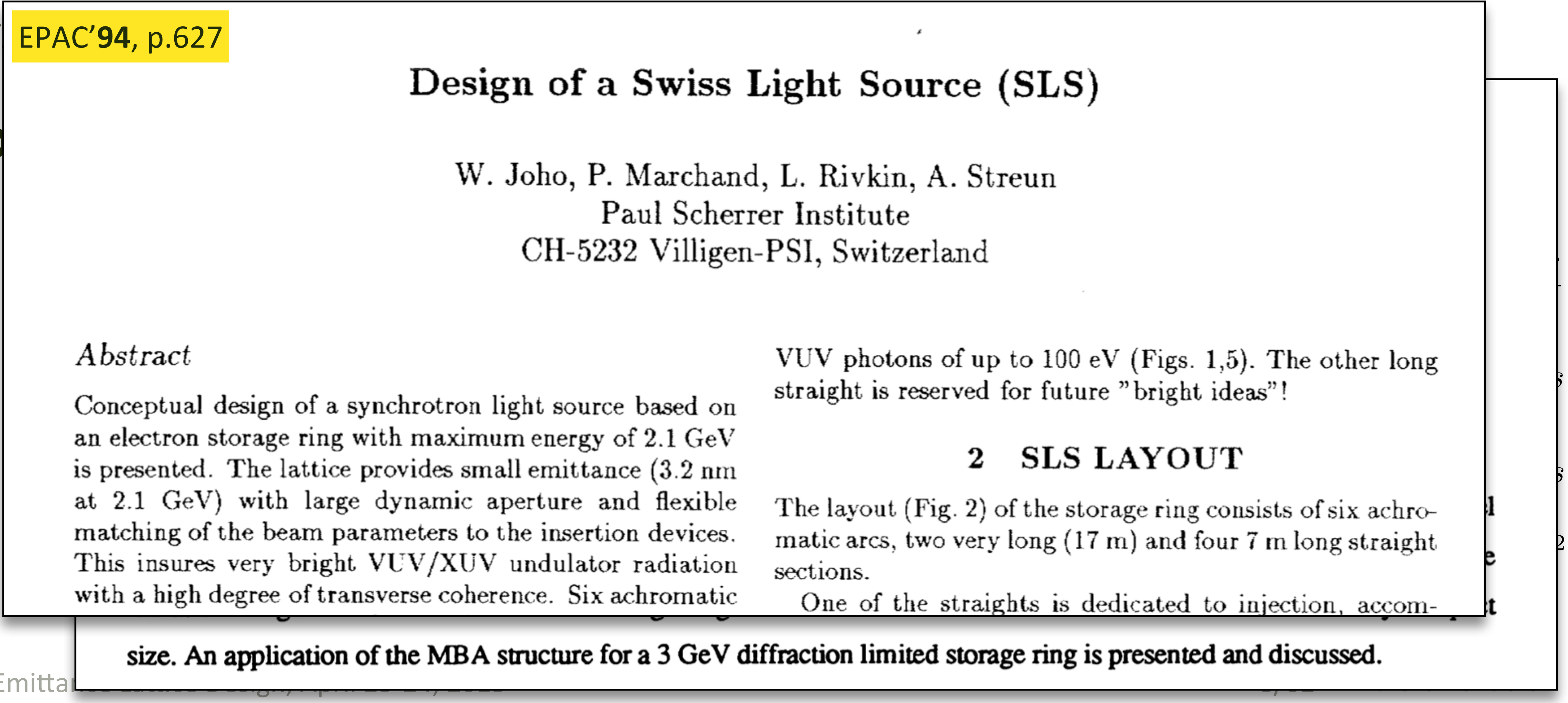
- Ultralo

$$\varepsilon_0[\mathrm{nm\,rad}] =$$

$$=$$



EPAC'**94**, p.627

Design of a Swiss Light Source (SLS)

W. Joho, P. Marchand, L. Rivkin, A. Streun
Paul Scherrer Institute
CH-5232 Villigen-PSI, Switzerland

Abstract

Conceptual design of a synchrotron light source based on an electron storage ring with maximum energy of 2.1 GeV is presented. The lattice provides small emittance (3.2 nm at 2.1 GeV) with large dynamic aperture and flexible matching of the beam parameters to the insertion devices. This insures very bright VUV/XUV undulator radiation with a high degree of transverse coherence. Six achromatic

VUV photons of up to 100 eV (Figs. 1,5). The other long straight is reserved for future "bright ideas"!

2 SLS LAYOUT

The layout (Fig. 2) of the storage ring consists of six achromatic arcs, two very long (17 m) and four 7 m long straight sections.

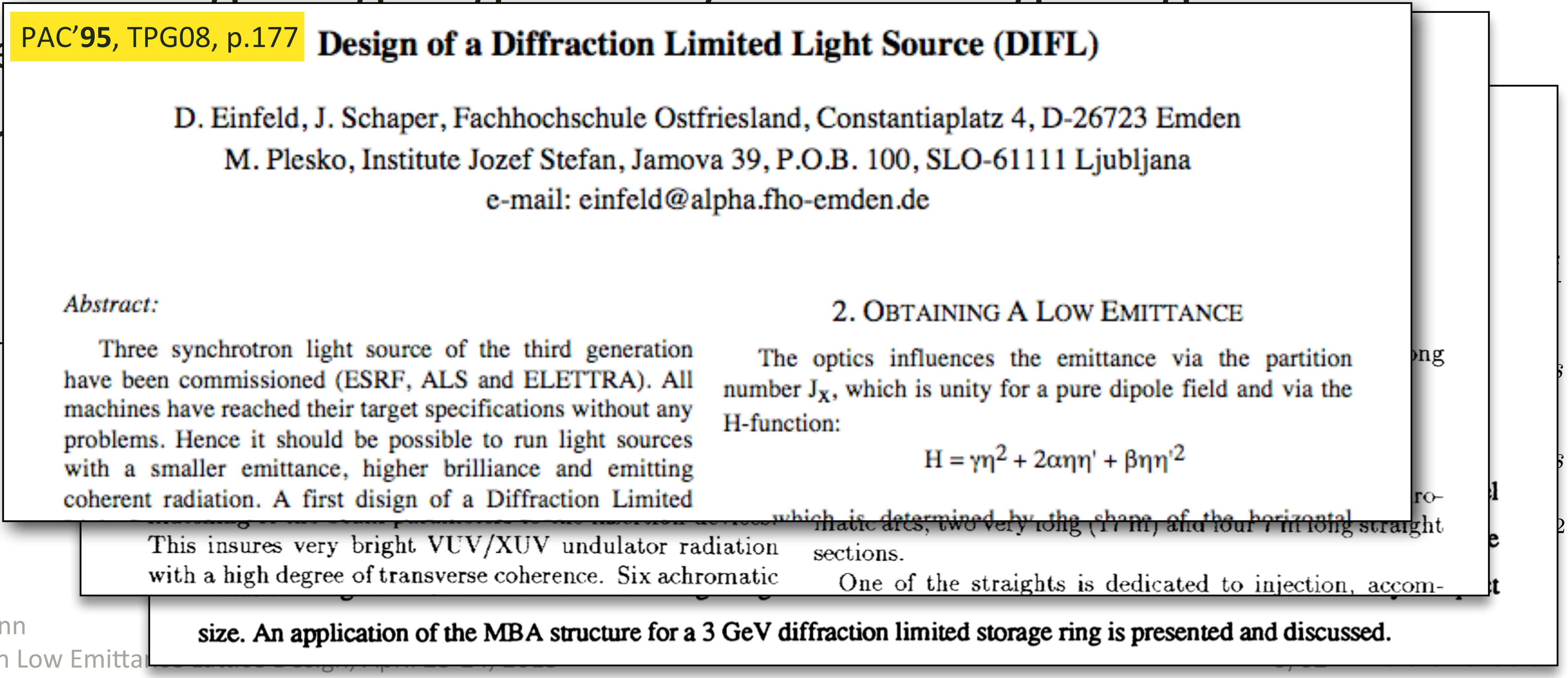
One of the straights is dedicated to injection, accom-

size. An application of the MBA structure for a 3 GeV diffraction limited storage ring is presented and discussed.

Origins of the MAX IV 3 GeV Ring Lattice (cont.)

- Realization that a single accelerator cannot cover the entire required spectral and temporal range → decision to build
  - one full-energy linac → SPF/FEL driver & ring injector
  - two separate storage rings at 1.5 GeV and 3 GeV
- 3 GeV storage ring targets x-ray users → high brightness via state
- Ultr

$\varepsilon_0 [\mathrm{nm\,rad}$



PAC’**95**, TPG08, p.177

Design of a Diffraction Limited Light Source (DIFL)

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M. Plesko, Institute Jozef Stefan, Jamova 39, P.O.B. 100, SLO-61111 Ljubljana
e-mail: einfeld@alpha.fho-emden.de

Abstract:

Three synchrotron light source of the third generation have been commissioned (ESRF, ALS and ELETTRA). All machines have reached their target specifications without any problems. Hence it should be possible to run light sources with a smaller emittance, higher brilliance and emitting coherent radiation. A first disign of a Diffraction Limited

2. OBTAINING A LOW EMITTANCE

The optics influences the emittance via the partition number J_x, which is unity for a pure dipole field and via the H-function:

$$H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$

This insures very bright VUV/XUV undulator radiation with a high degree of transverse coherence. Six achromatic

sections.

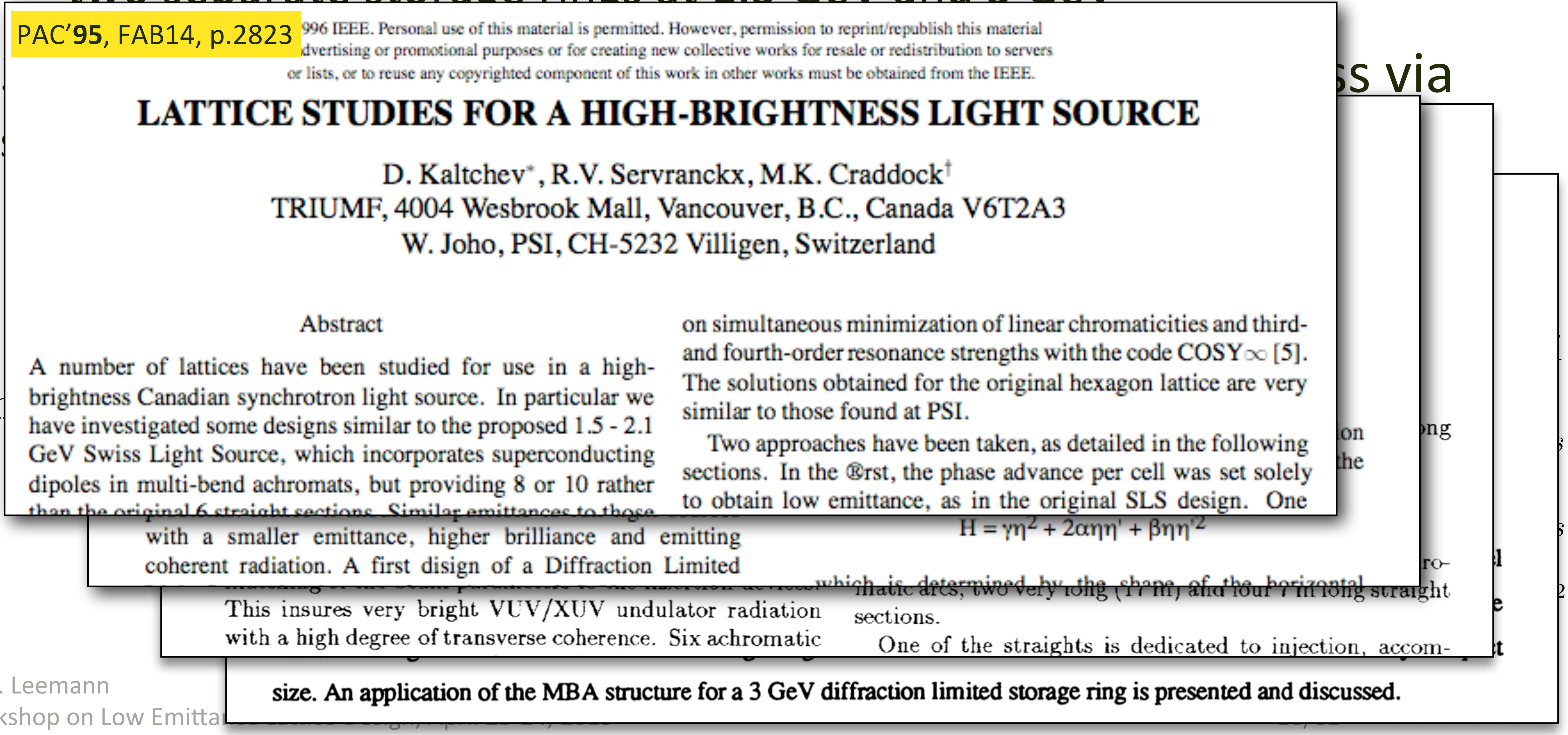
One of the straights is dedicated to injection, accom-

size. An application of the MBA structure for a 3 GeV diffraction limited storage ring is presented and discussed.

Origins of the MAX IV 3 GeV Ring Lattice (cont.)

- Realization that a single accelerator cannot cover the entire required spectral and temporal range → decision to build
  - one full-energy linac → SPF/FEL driver & ring injector
  - two separate storage rings at 1.5 GeV and 3 GeV
- ss via

ε_0[nm



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

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LATTICE STUDIES FOR A HIGH-BRIGHTNESS LIGHT SOURCE

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W. Joho, PSI, CH-5232 Villigen, Switzerland

Abstract

A number of lattices have been studied for use in a high-brightness Canadian synchrotron light source. In particular we have investigated some designs similar to the proposed 1.5 - 2.1 GeV Swiss Light Source, which incorporates superconducting dipoles in multi-bend achromats, but providing 8 or 10 rather than the original 6 straight sections. Similar emittances to those

on simultaneous minimization of linear chromaticities and third- and fourth-order resonance strengths with the code COSY∞ [5]. The solutions obtained for the original hexagon lattice are very similar to those found at PSI.

Two approaches have been taken, as detailed in the following sections. In the first, the phase advance per cell was set solely to obtain low emittance, as in the original SLS design. One

with a smaller emittance, higher brilliance and emitting coherent radiation. A first disign of a Diffraction Limited

$H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$

This insures very bright VUV/XUV undulator radiation with a high degree of transverse coherence. Six achromatic

matic arcs, two very long (17 m) and four 7 m long straight sections.

One of the straights is dedicated to injection, accom-

size. An application of the MBA structure for a 3 GeV diffraction limited storage ring is presented and discussed.

Origins of the MAX IV 3 GeV Ring Lattice (cont.)

- Around 2002, MAX-lab considers MBA lattice can be realized in conjunction with
  - compact magnets (narrow gaps → short but strong), magnet integration (common magnet block = “girder”), use of combined-function magnets

Origins of the MAX IV 3 GeV Ring Lattice (cont.)

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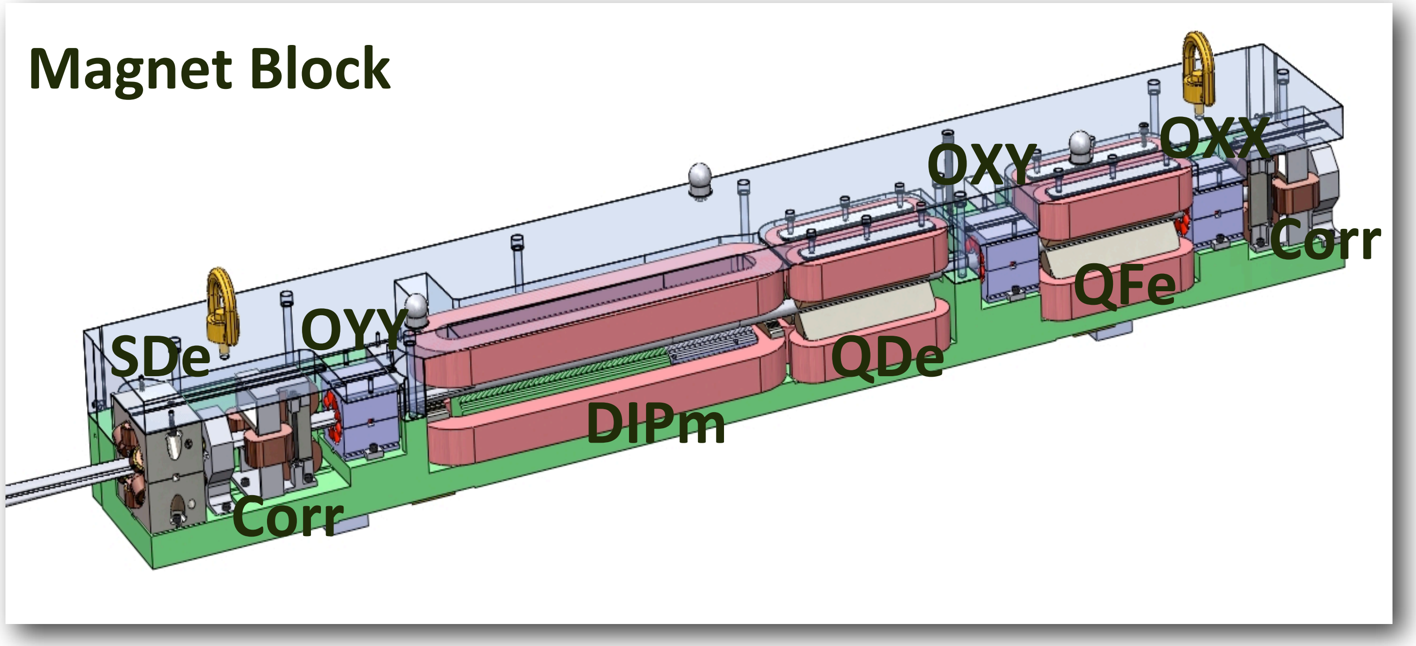

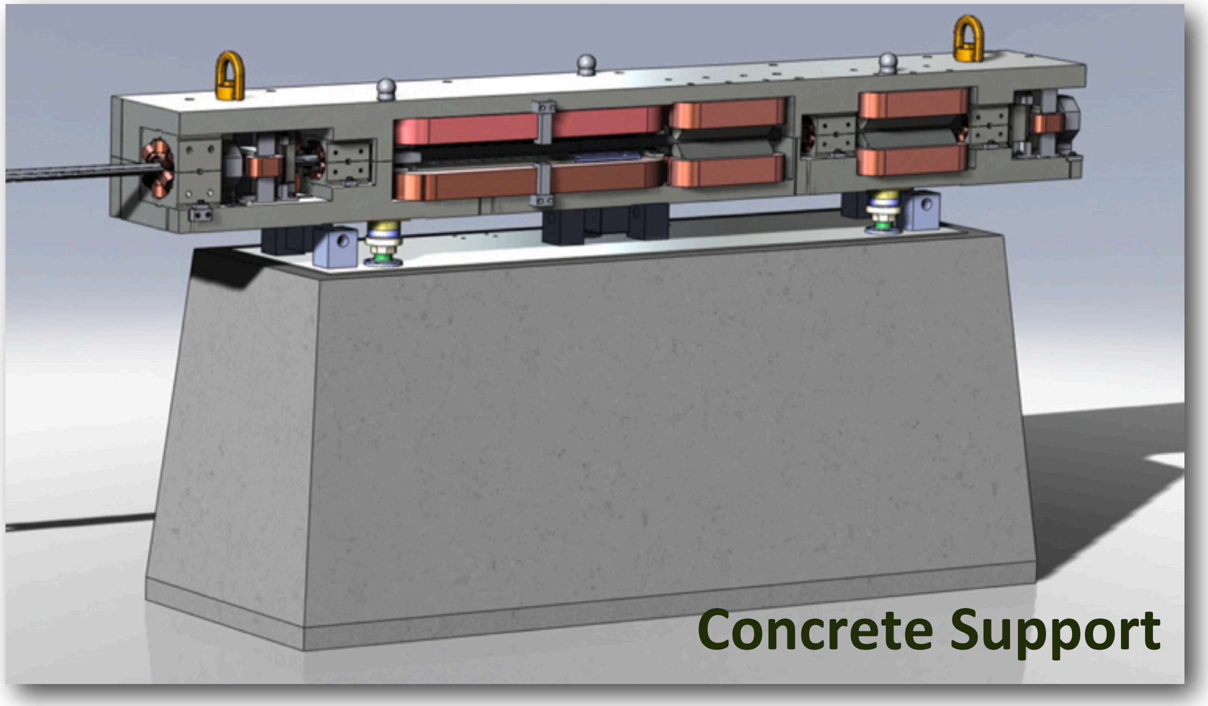

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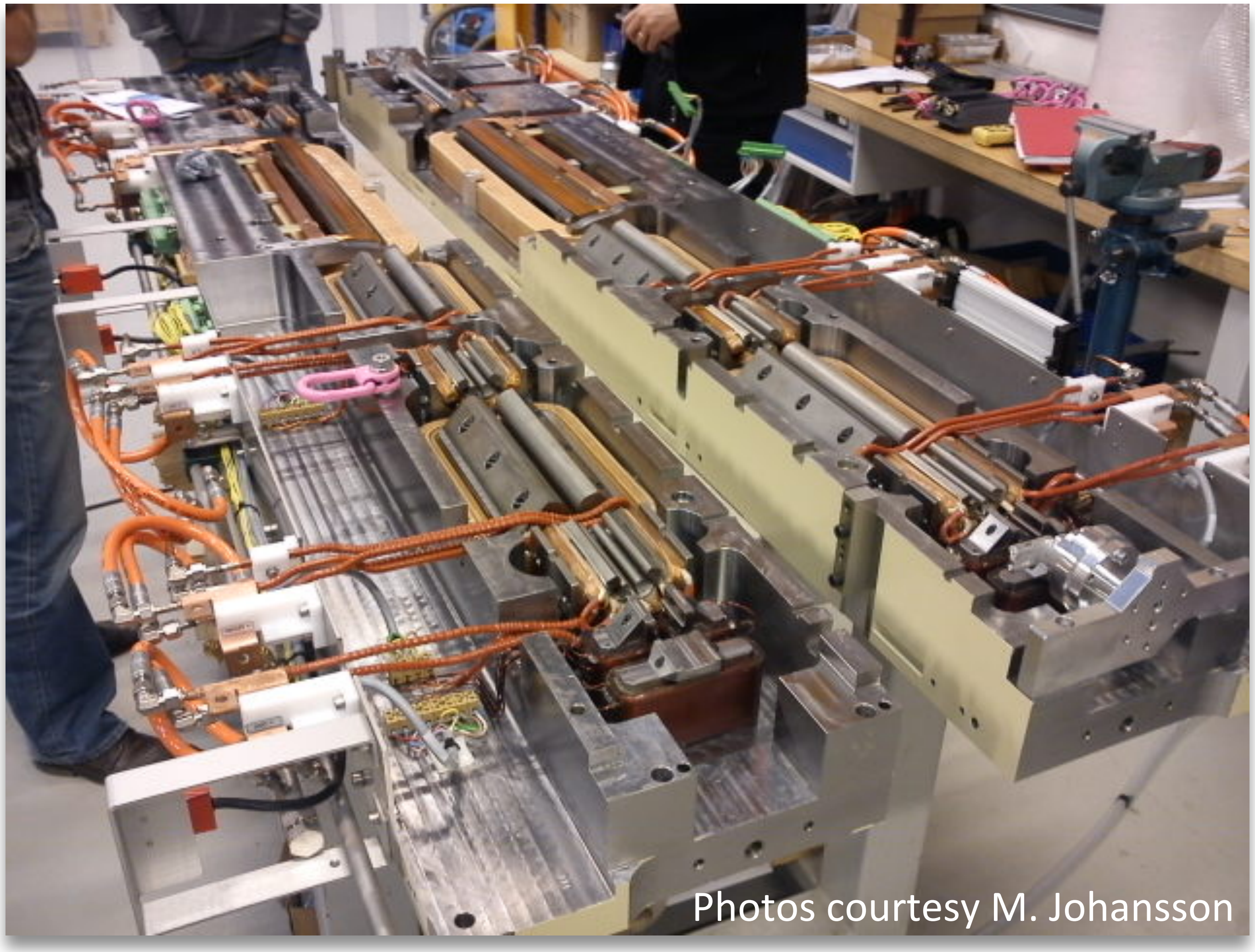

Photos courtesy M. Johansson

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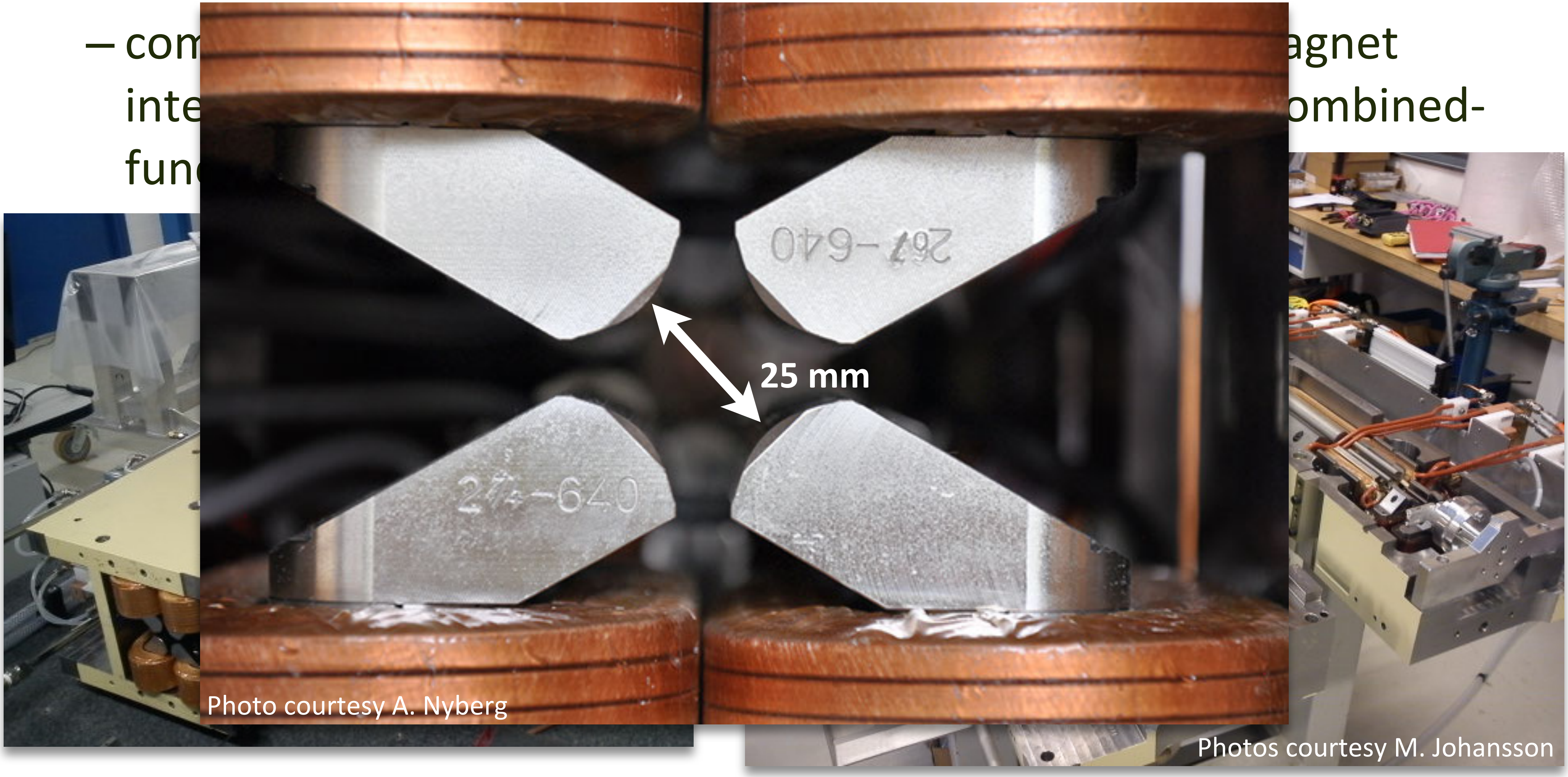
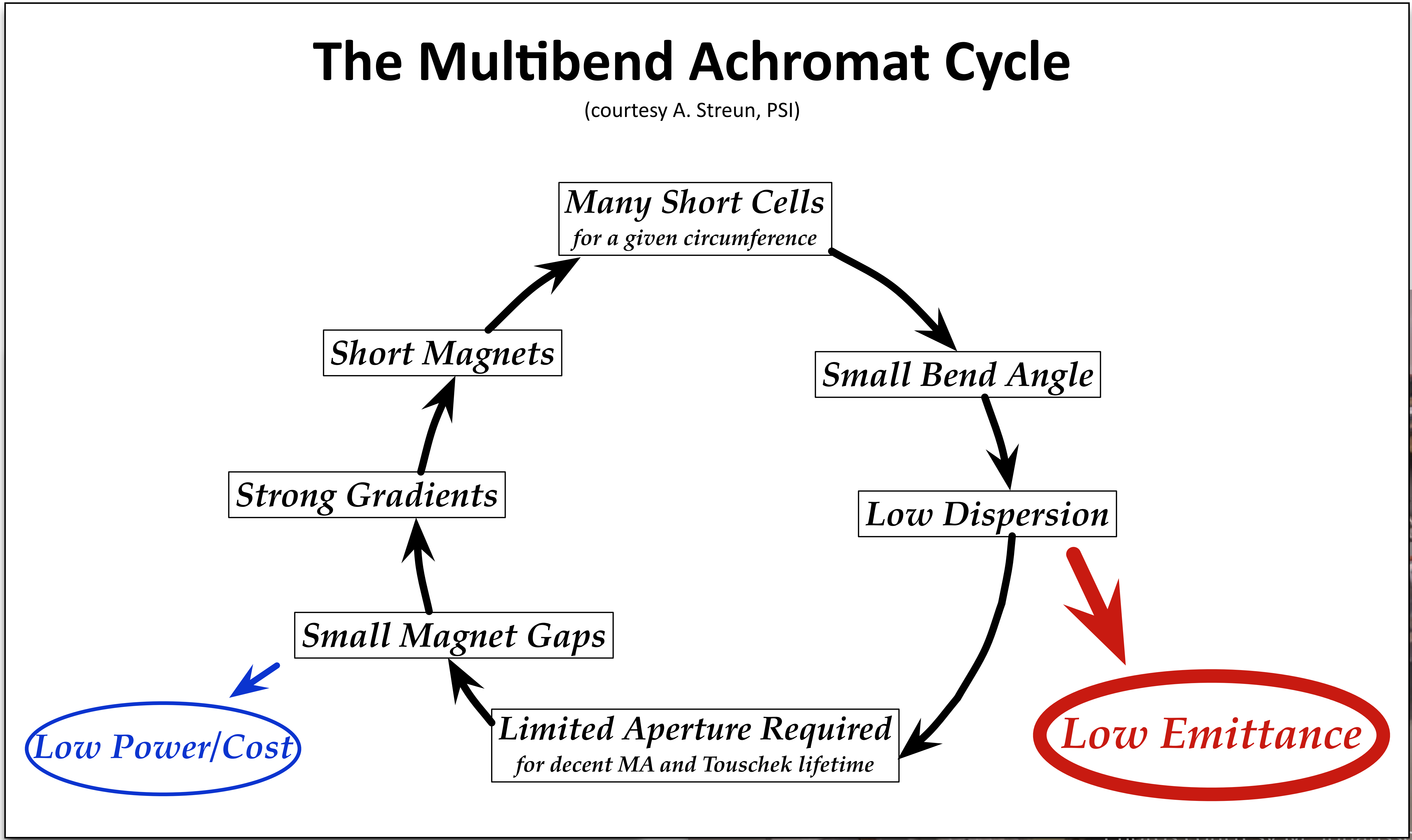


Photo courtesy A. Nyberg

Photos courtesy M. Johansson

Origins of the MAX IV 3 GeV Ring Lattice (cont.)



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

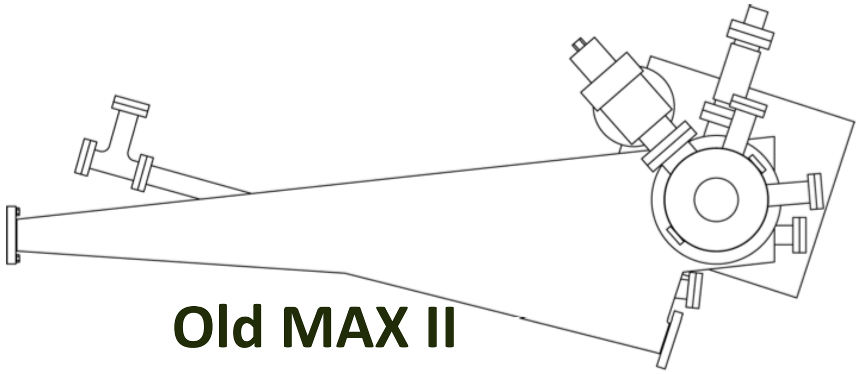
Low Power/Cost

Photos courtesy M. Johansson

Origins of the MAX IV 3 GeV Ring Lattice (cont.)

- Around 2002, MAX-lab considers MBA lattice can be realized in conjunction with
  - compact magnets (narrow gaps → short but strong), magnet integration (common magnet block = “girder”), use of combined-function magnets
  - NEG-coated vacuum chambers → narrow magnet gaps & tight magnet spacing

J. Vac. Sci. Technol. A **28**(2), Mar/Apr 2010



Old MAX II
dipole chamber (SS)

→

MAX II test
cooled & NEG-coated Cu

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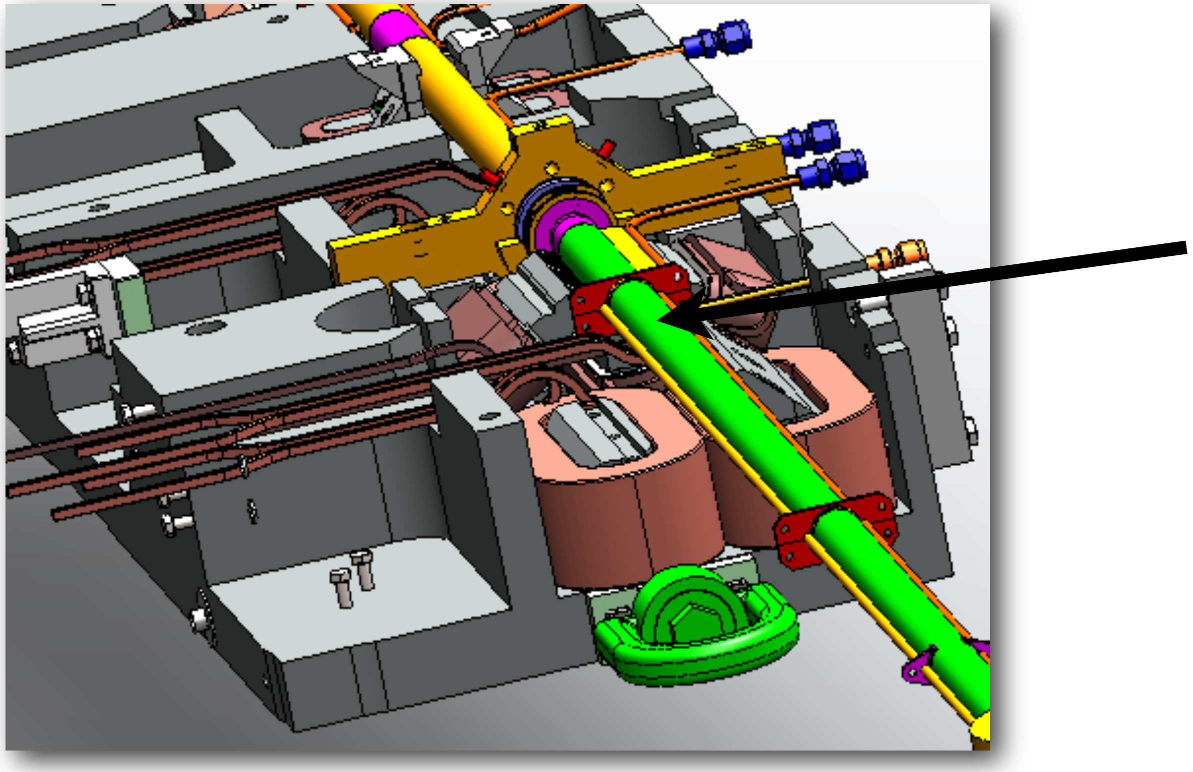

NEG-coated OFS Cu
24 mm OD

Origins of the MAX IV 3 GeV Ring Lattice (cont.)

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  - N ght
    m

)

OFS Cu

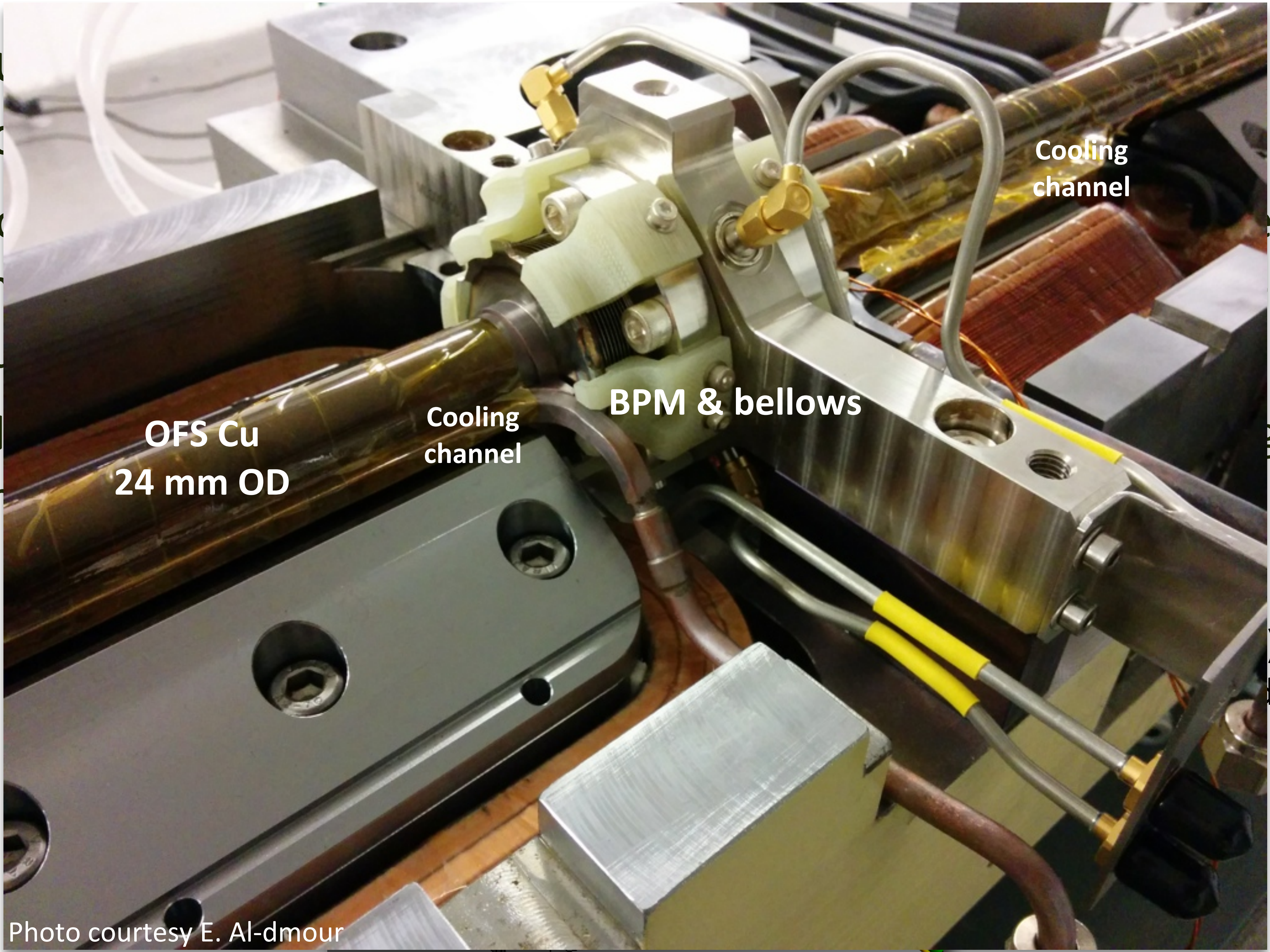

Photo courtesy E. Al-dmour

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  - compact magnets (narrow gaps → short but strong), magnet integration (common magnet block = "girder"), use of combined-function magnets
  - NEG-coated vacuum chambers → narrow magnet gaps & tight magnet spacing
  - 100 MHz RF system with harmonic cavities → ensure good Touschek lifetime & mitigate emittance blowup from IBS

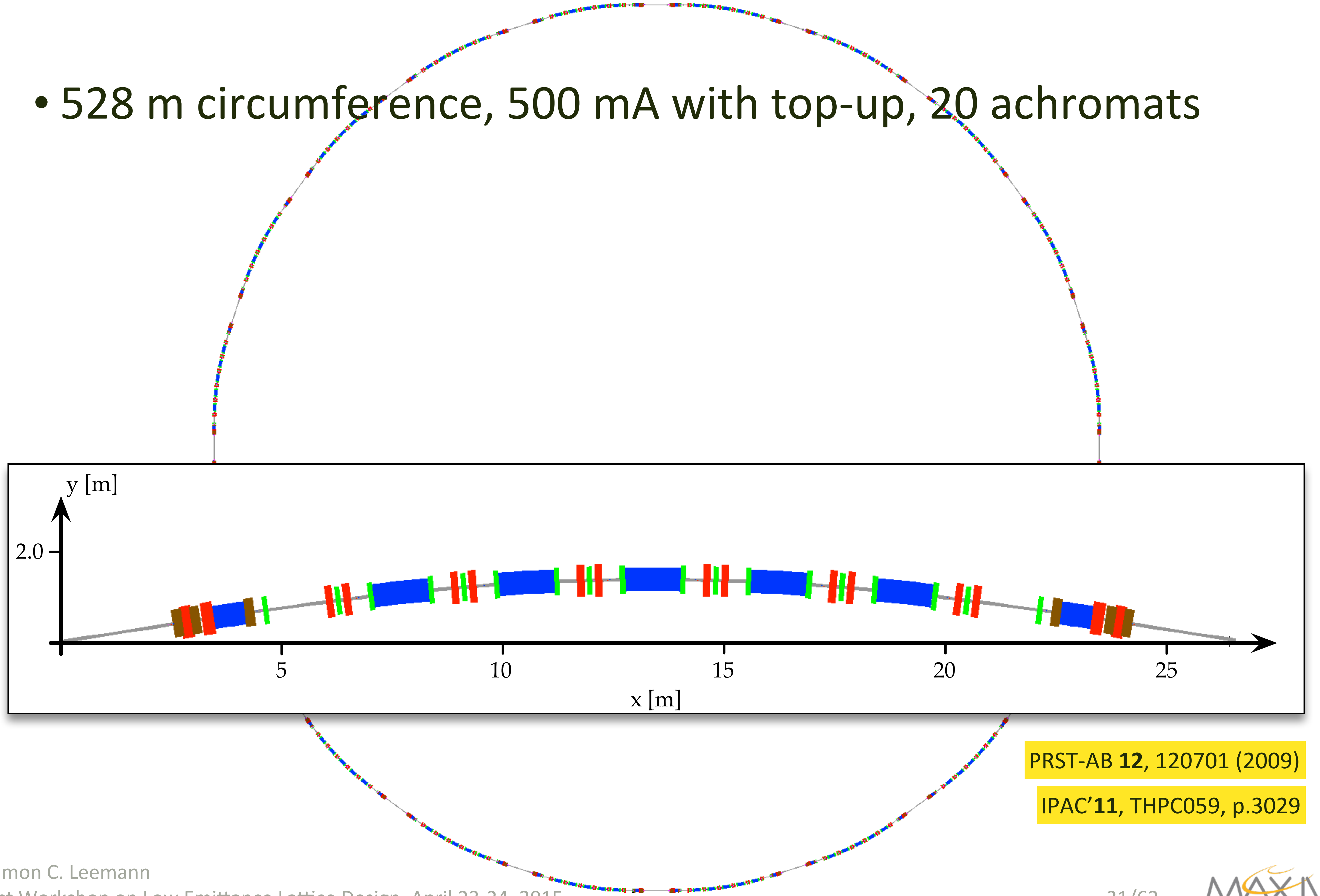
Origins of the MAX IV 3 GeV Ring Lattice (cont.)

- Around 2002, MAX-lab considers MBA lattice can be realized

Photos courtesy P. F. Tavares

The MAX IV 3 GeV MBA Lattice

- 528 m circumference, 500 mA with top-up, 20 achromats

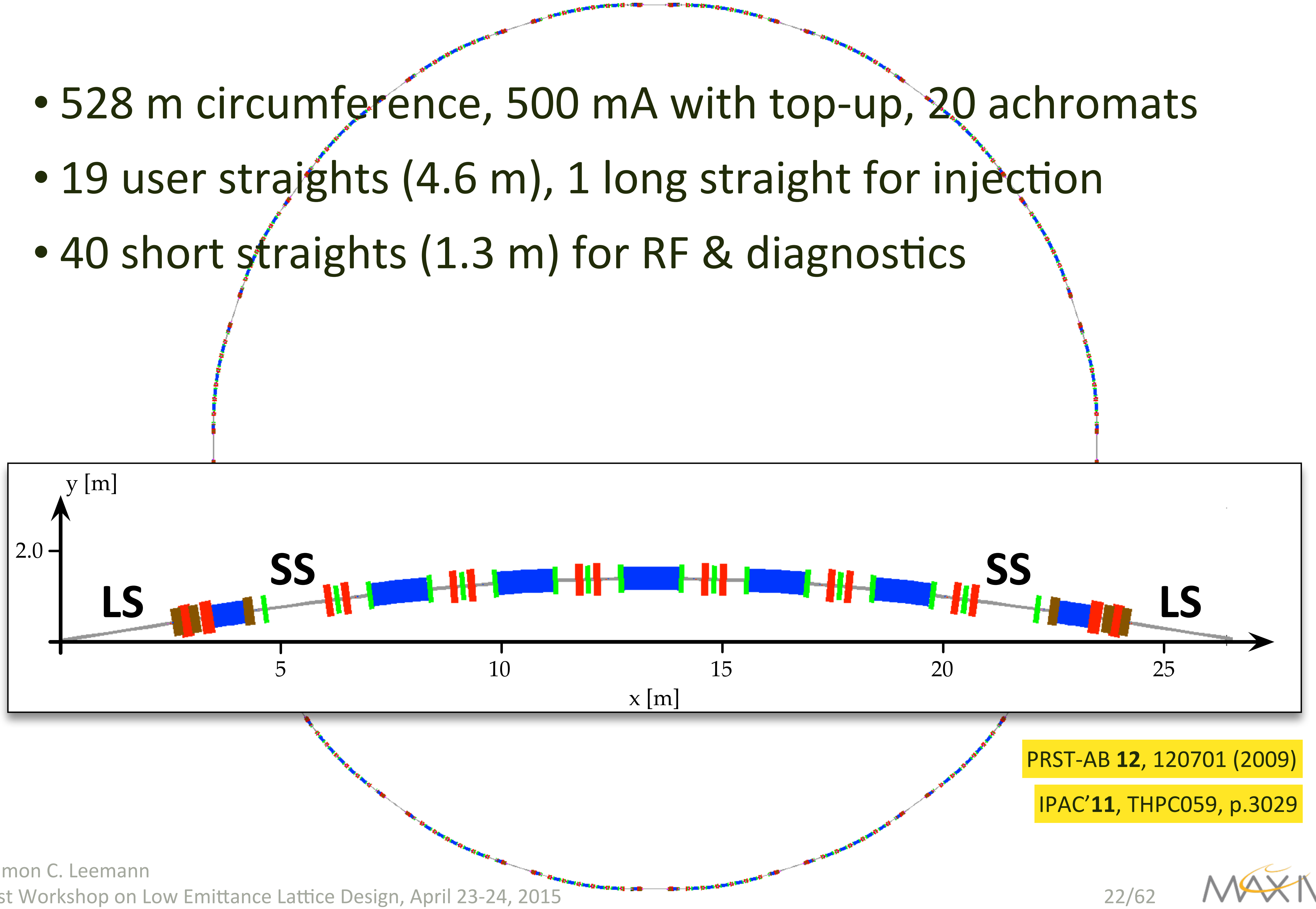


PRST-AB **12**, 120701 (2009)

IPAC’**11**, THPC059, p.3029

The MAX IV 3 GeV MBA Lattice (cont.)

- 528 m circumference, 500 mA with top-up, 20 achromats
- 19 user straights (4.6 m), 1 long straight for injection
- 40 short straights (1.3 m) for RF & diagnostics

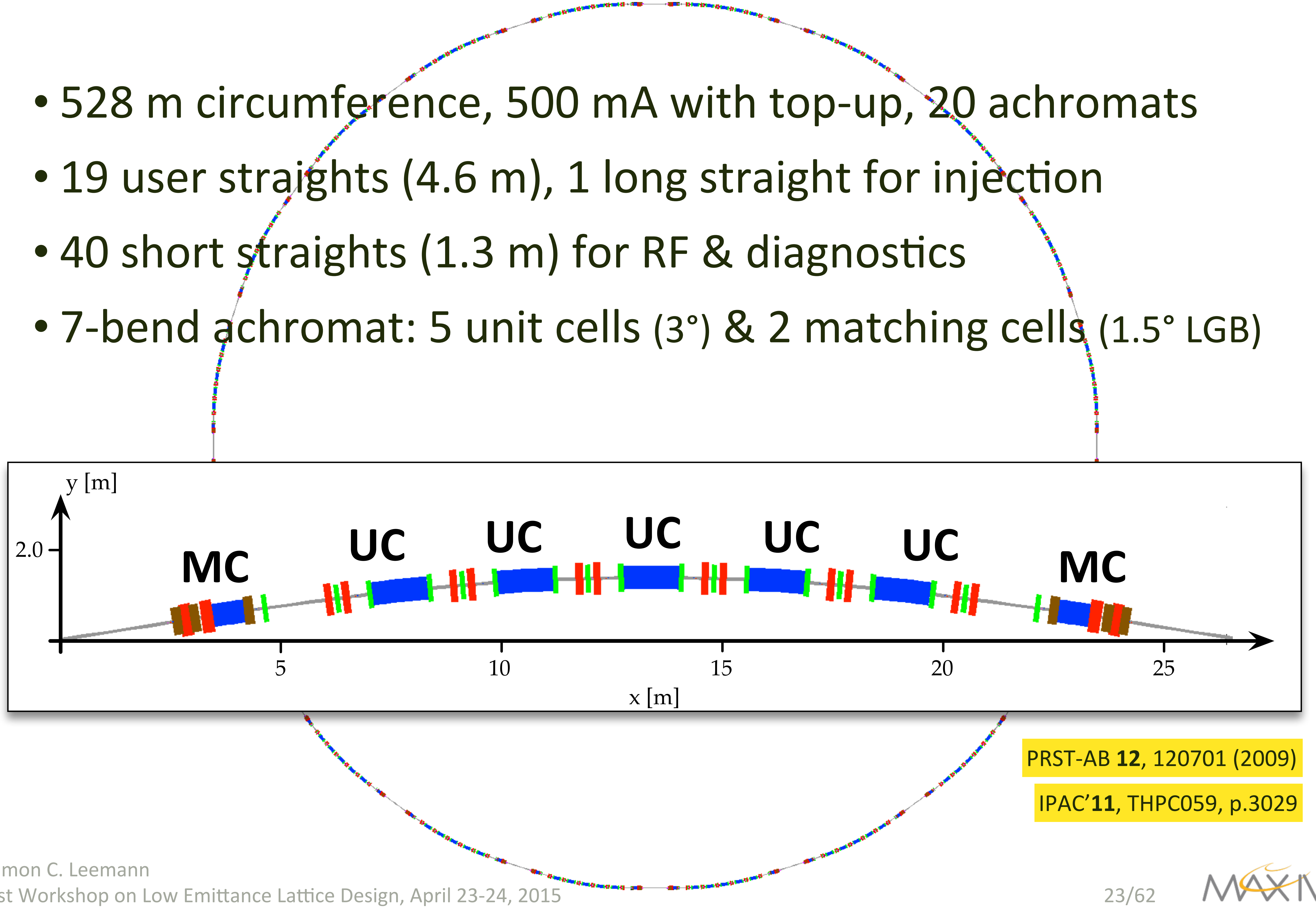


PRST-AB **12**, 120701 (2009)

IPAC’**11**, THPC059, p.3029

The MAX IV 3 GeV MBA Lattice (cont.)

- 528 m circumference, 500 mA with top-up, 20 achromats
- 19 user straights (4.6 m), 1 long straight for injection
- 40 short straights (1.3 m) for RF & diagnostics
- 7-bend achromat: 5 unit cells (3°) & 2 matching cells (1.5° LGB)



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The MAX IV 3 GeV MBA Lattice (cont.)

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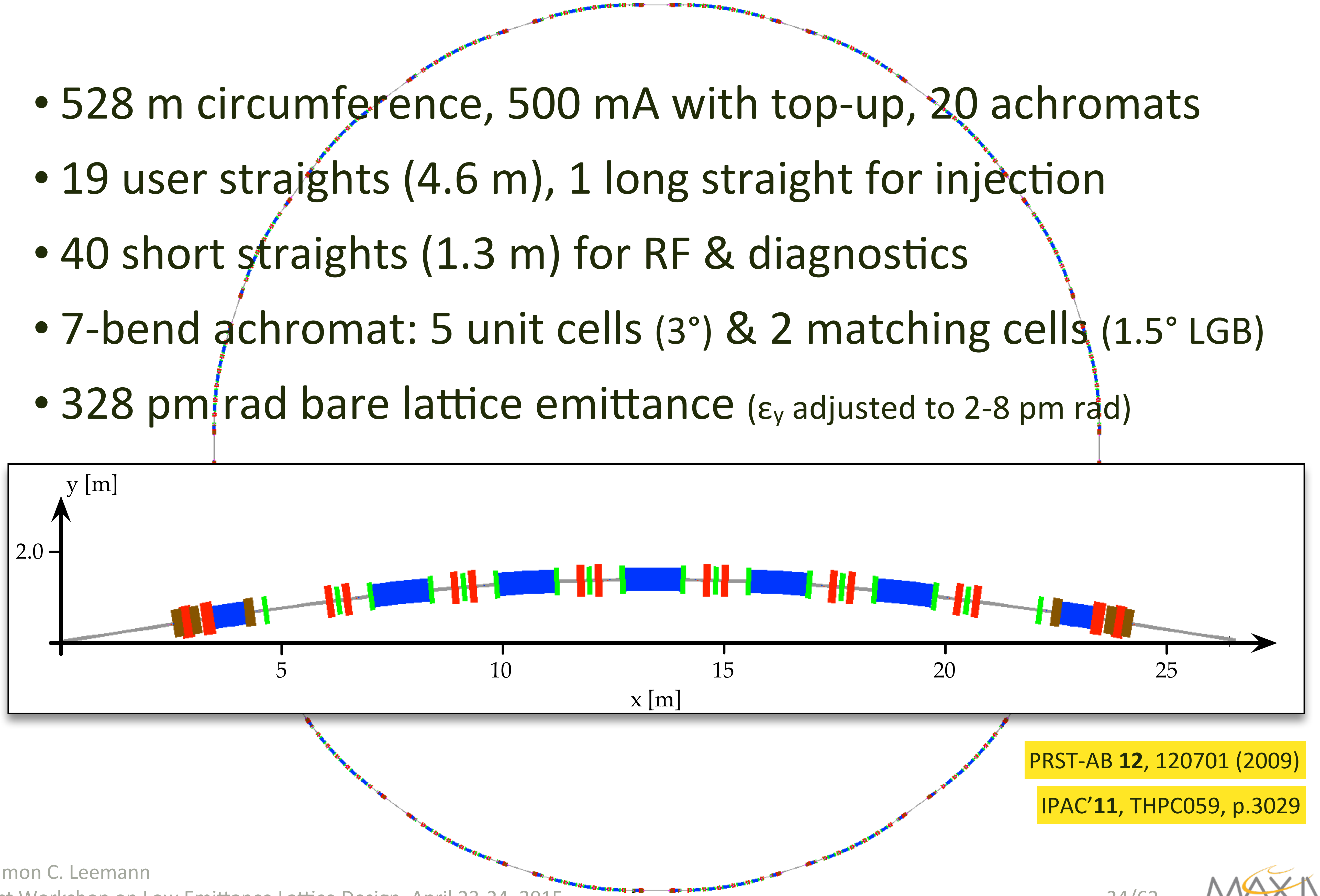
- 7-bend achromat: 5 unit cells (3°) & 2 matching cells (1.5° LGB)
- 328 pm rad bare lattice emittance (ε_y adjusted to 2-8 pm rad)



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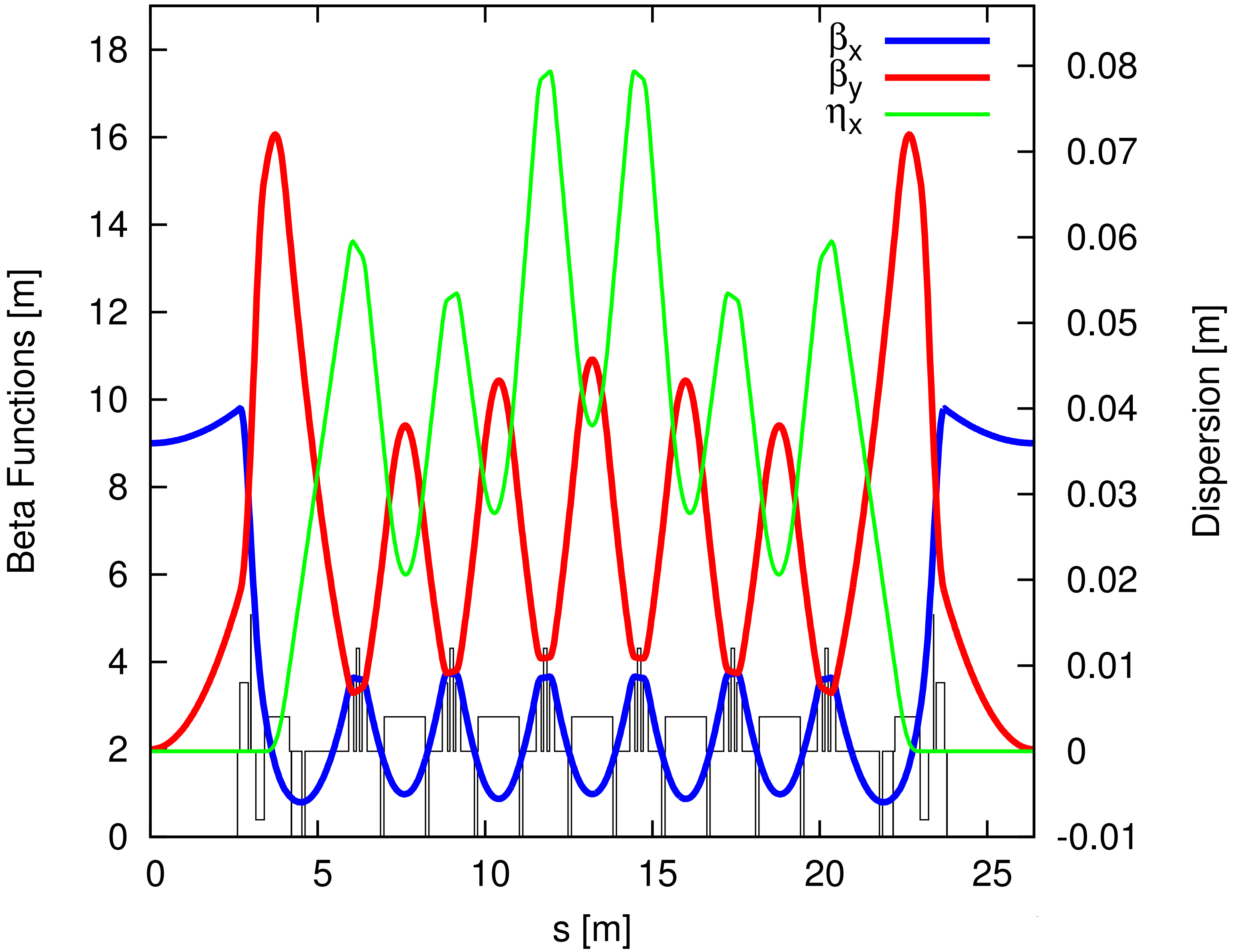
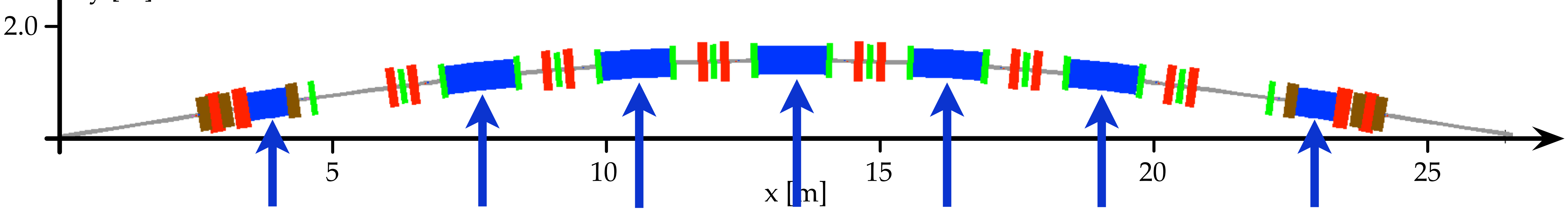
Linear Optics

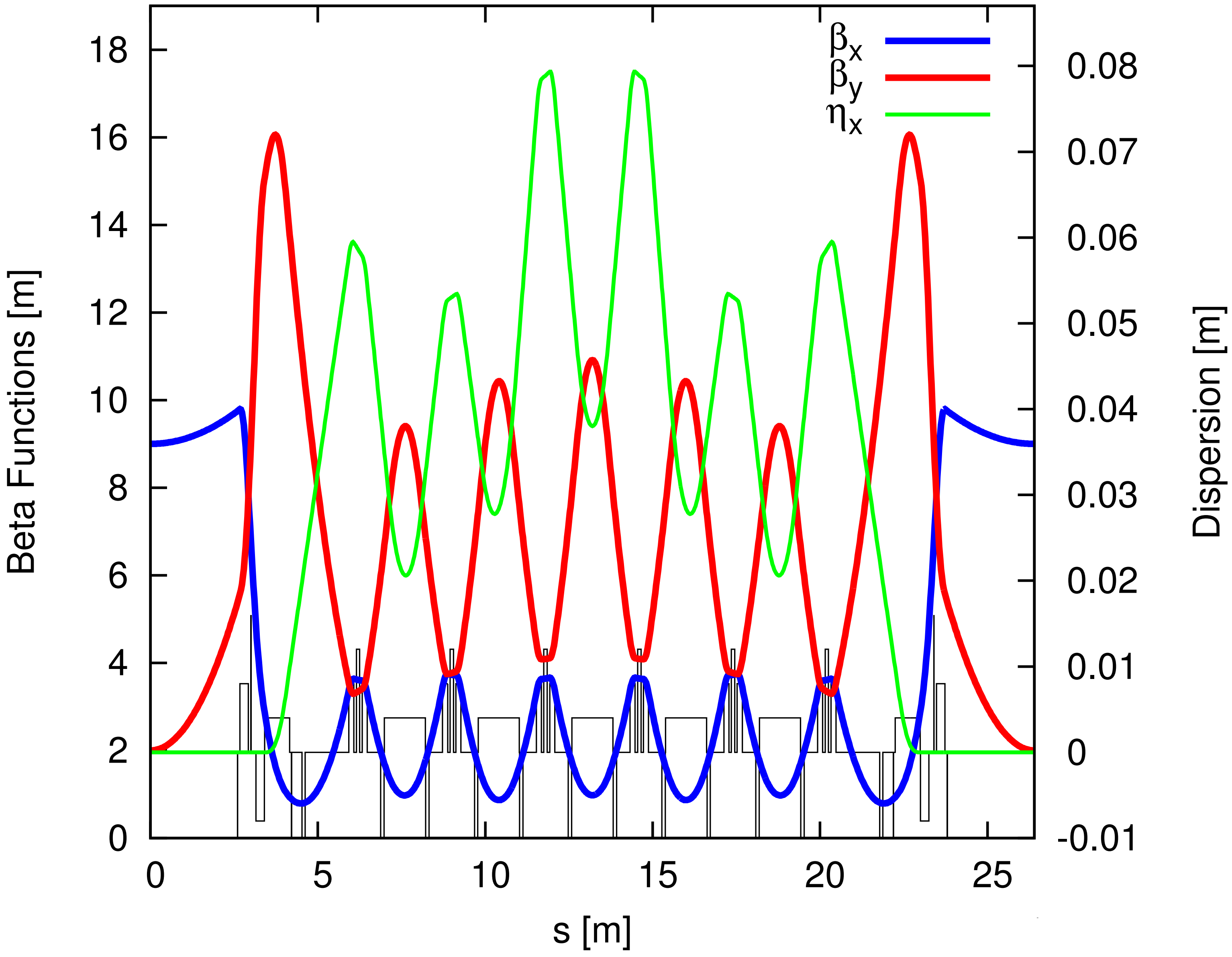
- **Gradient dipoles** perform vertical focusing ($\varepsilon_x \sim 1/J_x$)

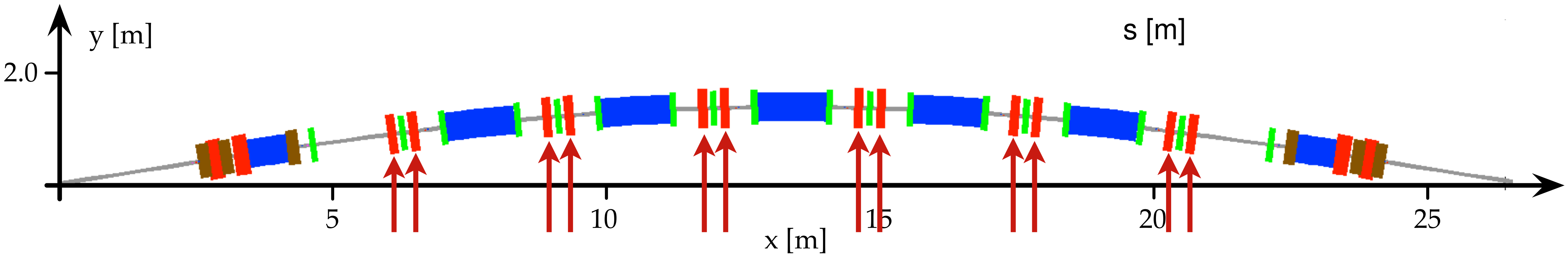




Linear Optics (cont.)

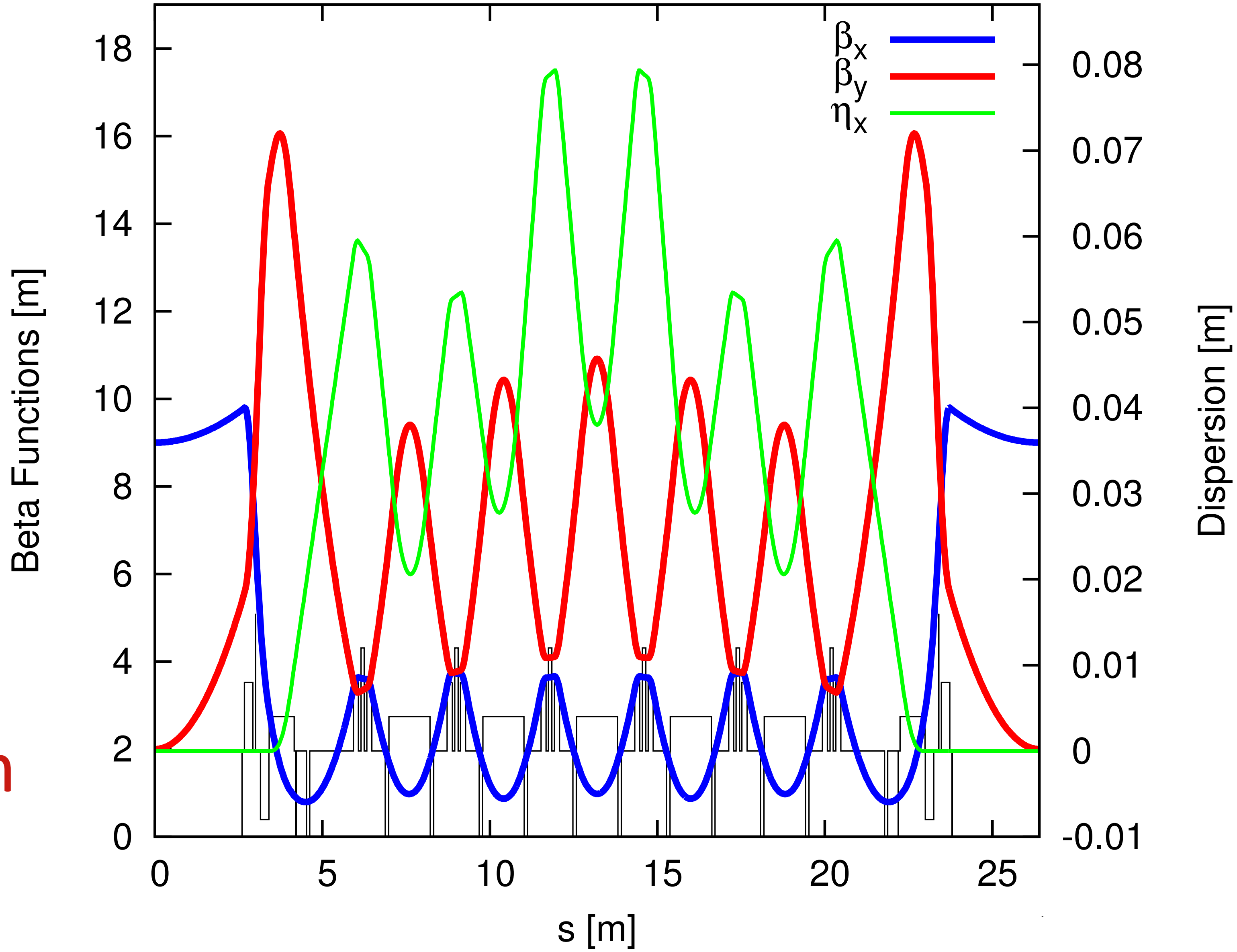
- Gradient dipoles perform vertical focusing $(\varepsilon_x \sim 1/J_x)$
- Gradient dipoles interleaved with horizontally focusing quadrupoles

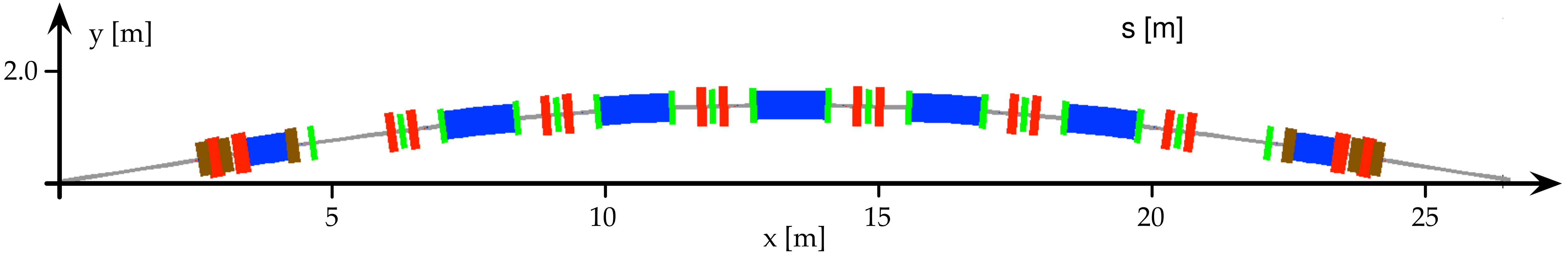




Linear Optics (cont.)

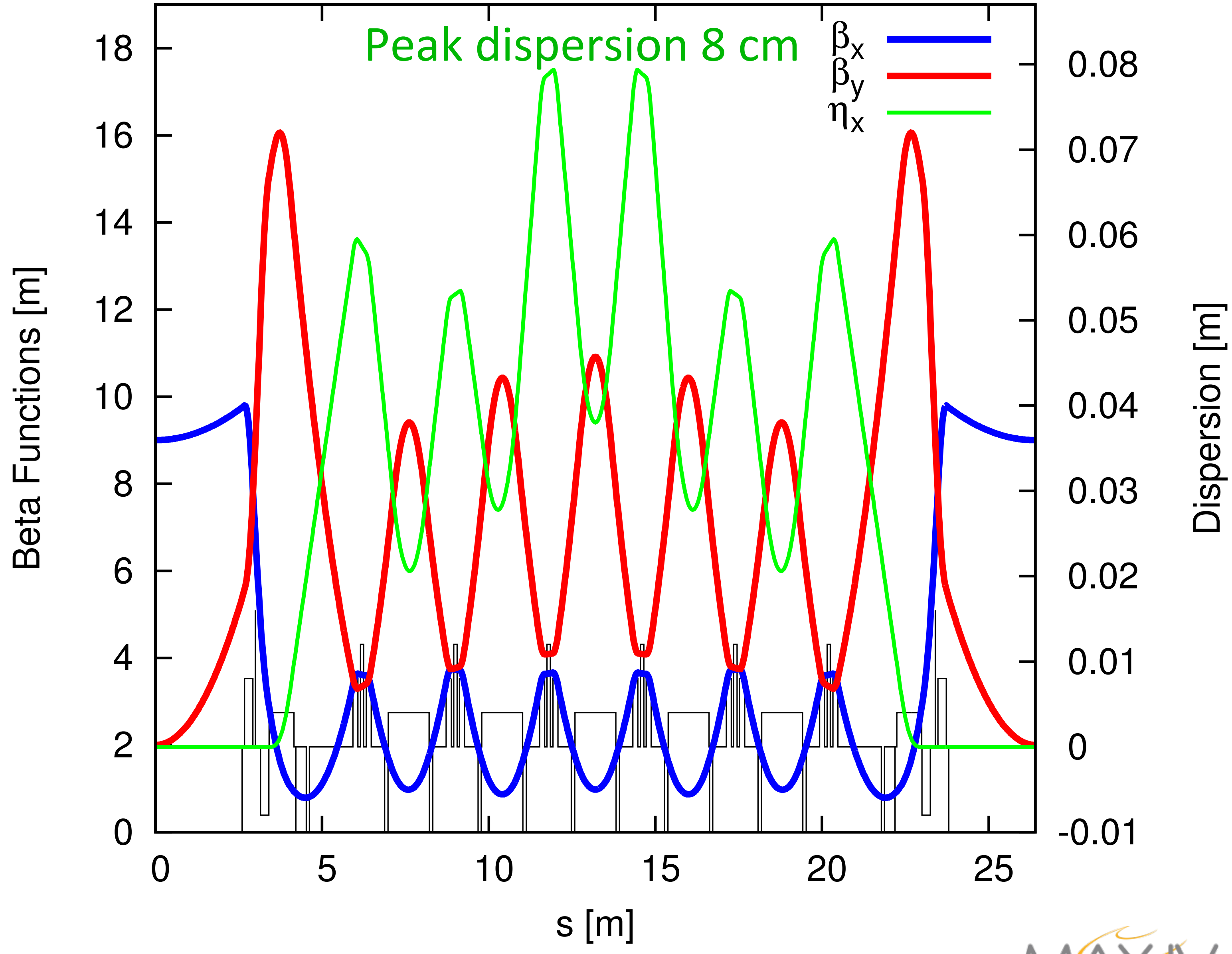
- Gradient dipoles perform vertical focusing ($\varepsilon_x \sim 1/J_x$)
- Gradient dipoles interleaved with horizontally focusing quadrupoles
- $\nu_x = 42.20$, $\nu_y = 16.28$
  $\beta_x^* = 9$ m, $\beta_y^* = 2$ m
- $\sigma_x^* = 54$ µm, $\sigma_y^* = 2$-4 µm





Nonlinear Optics

- Strong focusing & weak bends ➙ low dispersion ➙ strong chromatic sextupoles ➙ intricate nonlinear optics required to achieve large DA & MA (needs to remain stable under influence of IDs and errors!)



Nonlinear Optics (cont.)

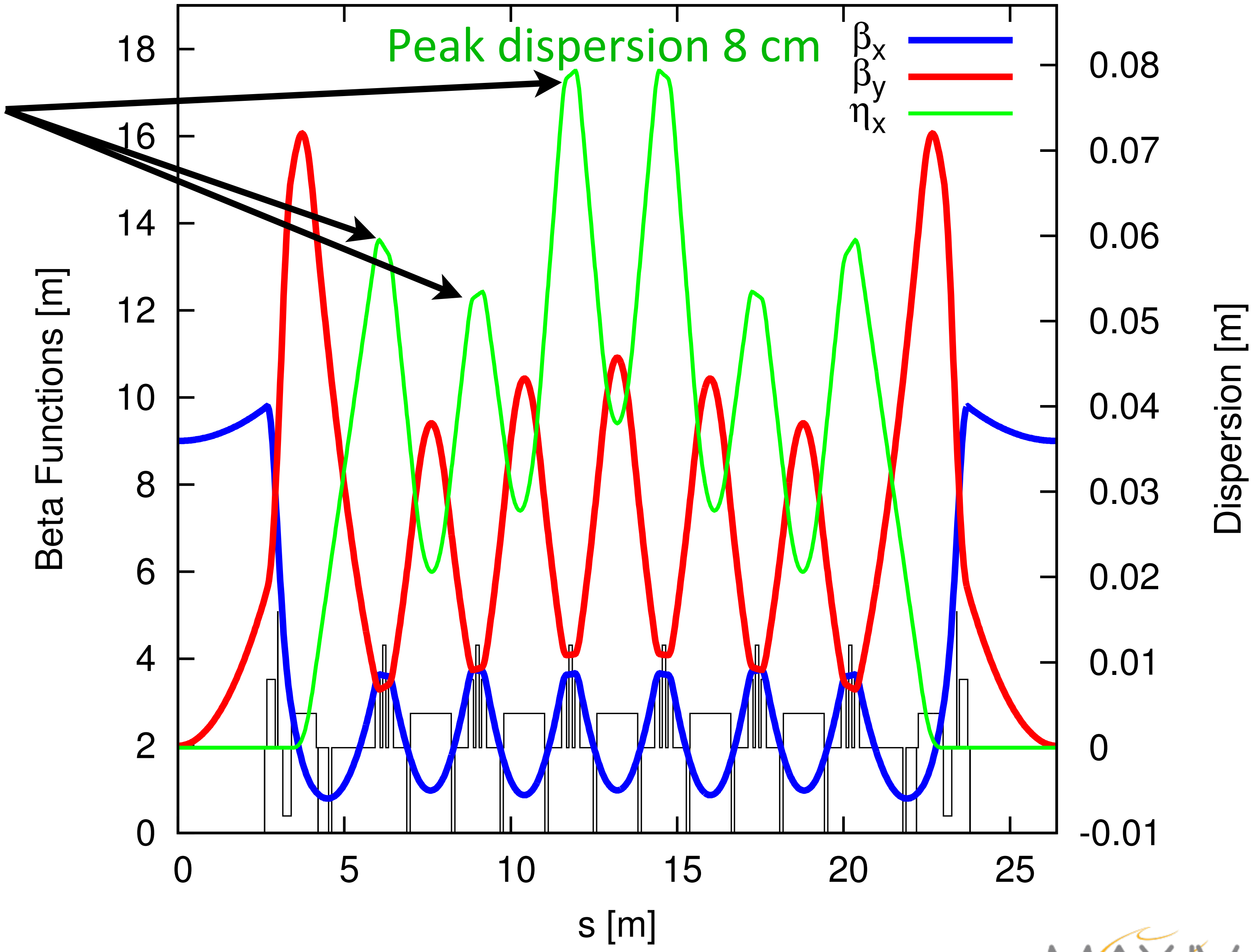
- Strong focusing & weak bends ➝ low dispersion ➝ strong chromatic sextupoles ➝ intricate nonlinear optics required to achieve large DA & MA (needs to remain stable under influence of IDs and errors!)

Compensate chromaticity where it's created ➝ limit chromatic beta beating

Klotz & Mülhaupt, 4GLS WS, SLAC, 1992

↓

Original idea: dipoles & quads contain sextupole component ➝ limited tunability & poor DA



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↓

Original idea: dipoles & quads
contain sextupole component
→ limited tunability & poor DA

↓

Sextupole insertions in focusing
quadrupoles & sextupole pairs
flanking dipoles

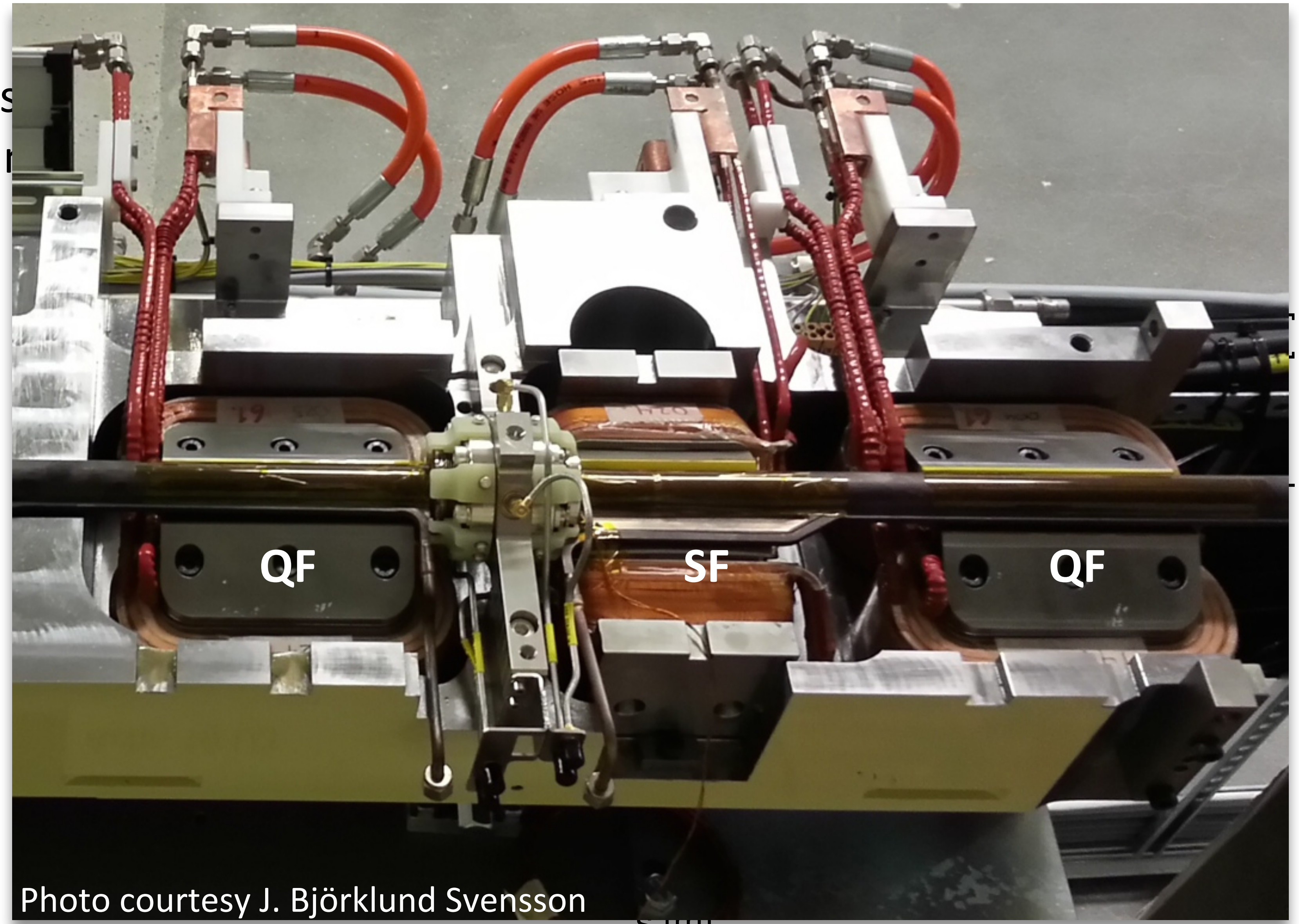


Photo courtesy J. Björklund Svensson

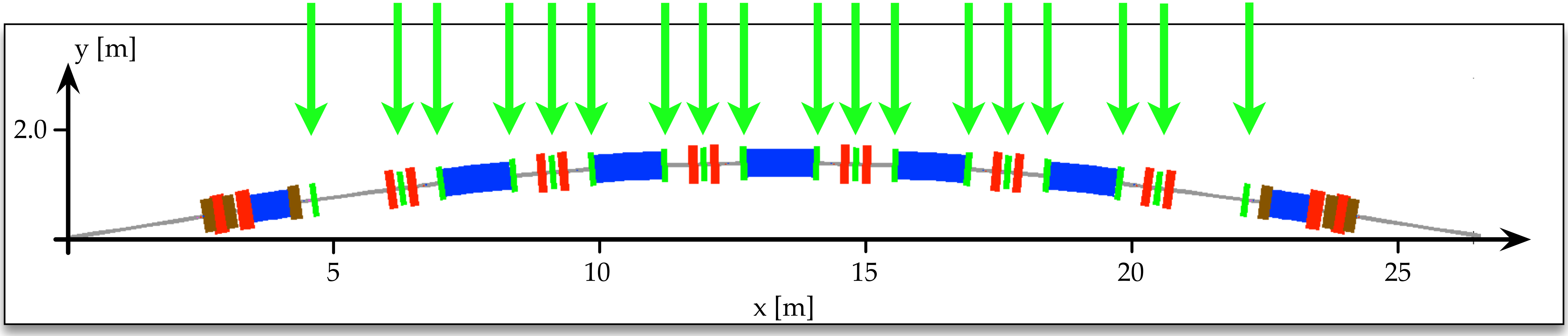
s [m]

Nonlinear Optics (cont.)

- Natural $\xi_{x,y} \approx -50$ → strong chromatic sextupoles → correct linear chromaticity and tailor its higher orders → additional sextupoles used to minimize first-order RDTs (low since phase adv. ≈ 2π×2, 2π×3/4)

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

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



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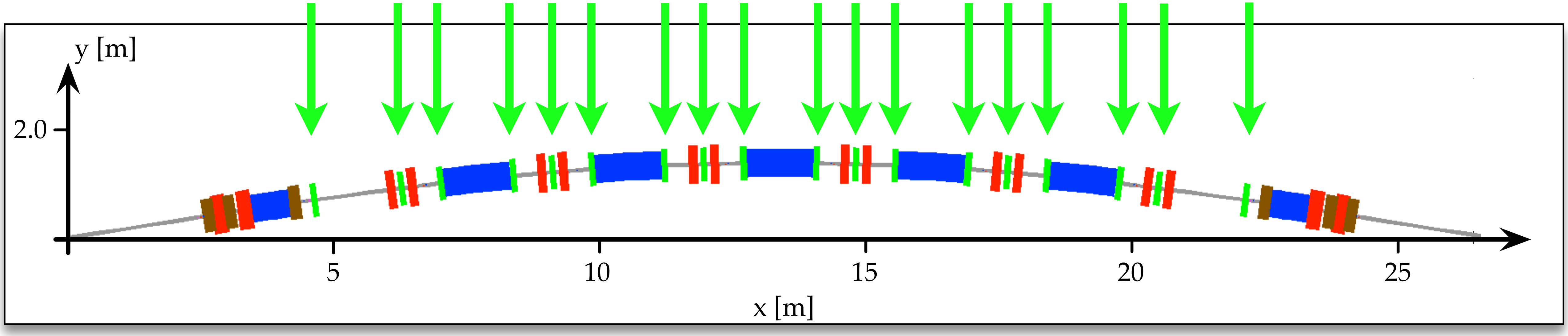

- Note: many short sextupoles allows retaining narrow apertures → positive MBA feedback cycle. On the other hand, blowing up dispersion locally to reduce sextupole gradients → increases aperture requirements (Touschek lifetime) → negative FB

Nonlinear Optics (cont.)

- Na … ct
  lin … nal
  sex

2π×3/4)

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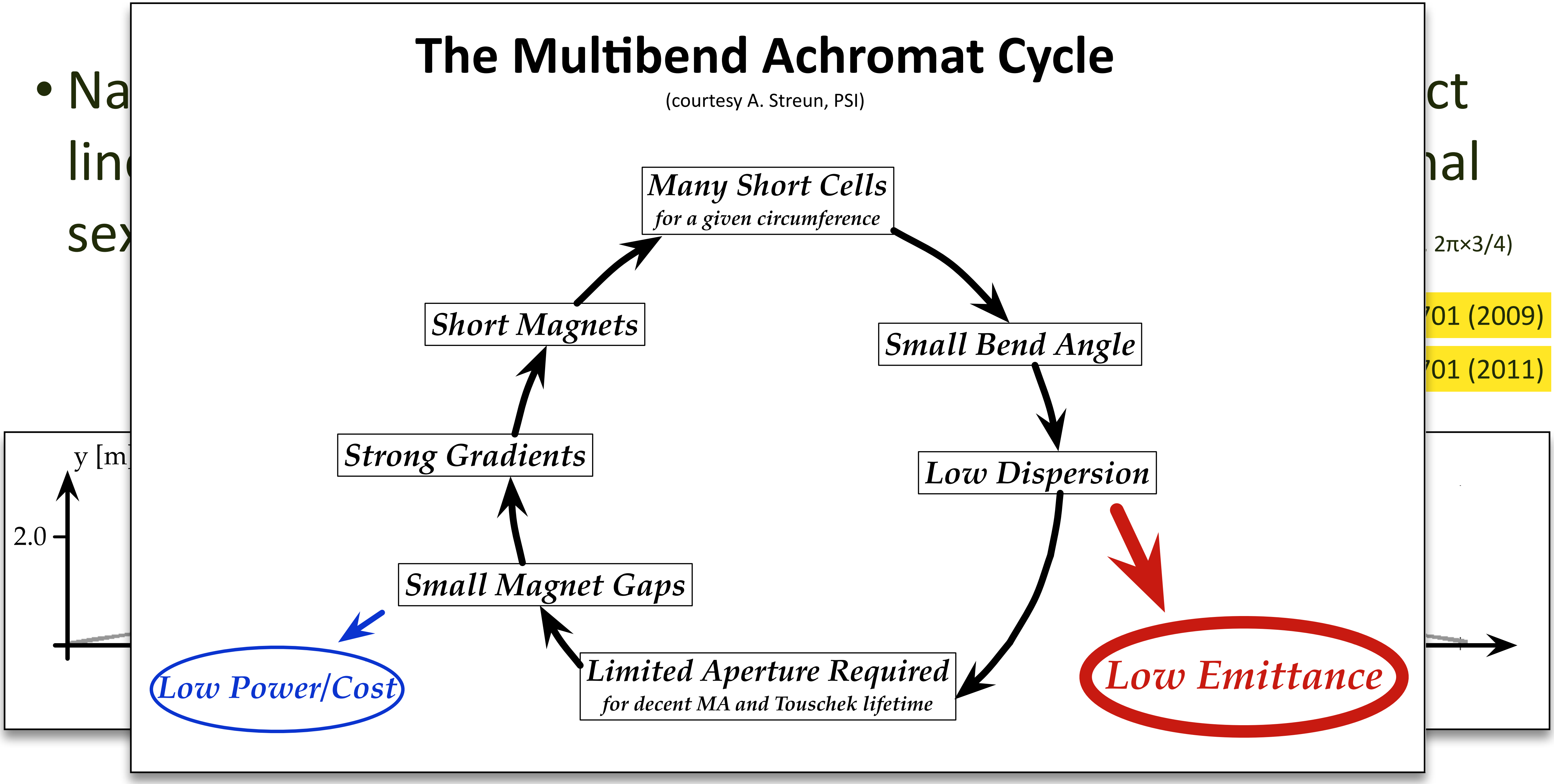


The Multibend Achromat Cycle

(courtesy A. Streun, PSI)

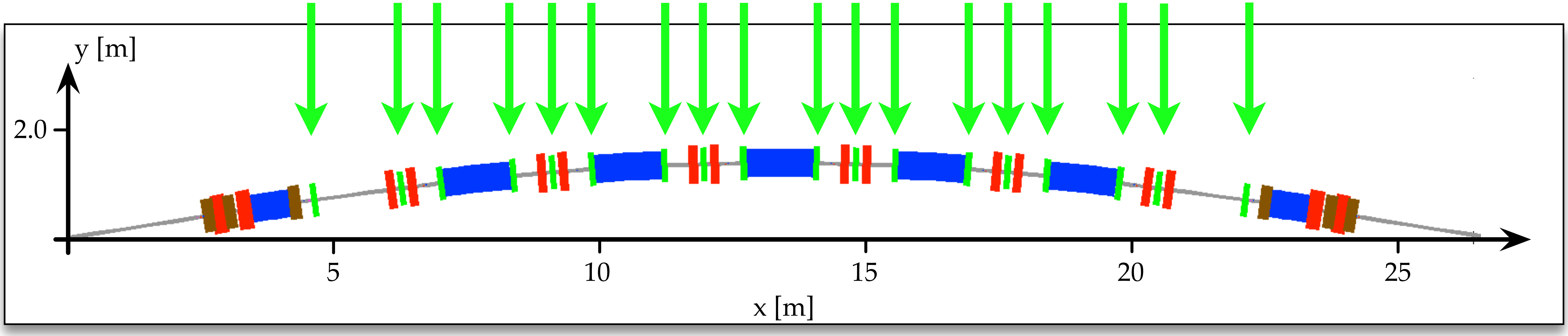
- Note: many short sextupoles allows retaining narrow apertures ➞ positive MBA feedback cycle. On the other hand, blowing up dispersion locally to reduce sextupole gradients ➞ increases aperture requirements (Touschek lifetime) ➞ negative FB

Nonlinear Optics (cont.)

- Natural $\xi_{x,y} \approx -50$ → strong chromatic sextupoles → correct linear chromaticity and tailor its higher orders → additional sextupoles used to minimize first-order RDTs (low since phase adv. ≈ 2π×2, 2π×3/4)

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

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



- Note: interleaving schemes where RDTs are canceled across several achromats can be dangerous since they're easily perturbed by IDs (in ultralow-emittance rings $\varepsilon_0 \approx \varepsilon_{ID}$) → minimize RDTs within achromat instead

Nonlinear Optics (cont.)

- Natural $\xi_{x,y} \approx -50$ ➞ strong chromatic sextupoles ➞ correct linear chromaticity and tailor its higher orders ➞ additional sextupoles used to minimize first-order RDTs (low since phase adv. ≈ 2π×2, 2π×3/4)

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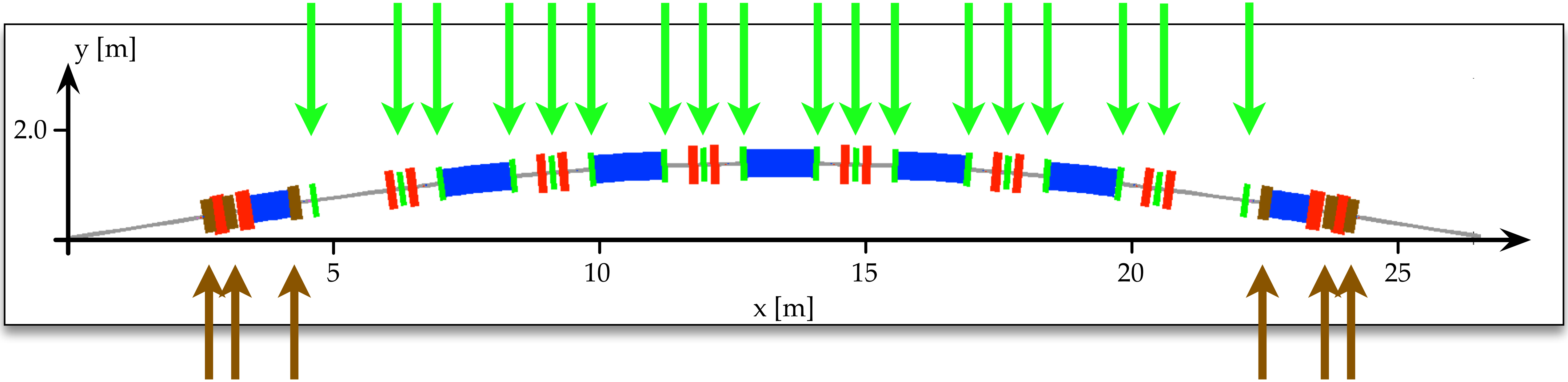
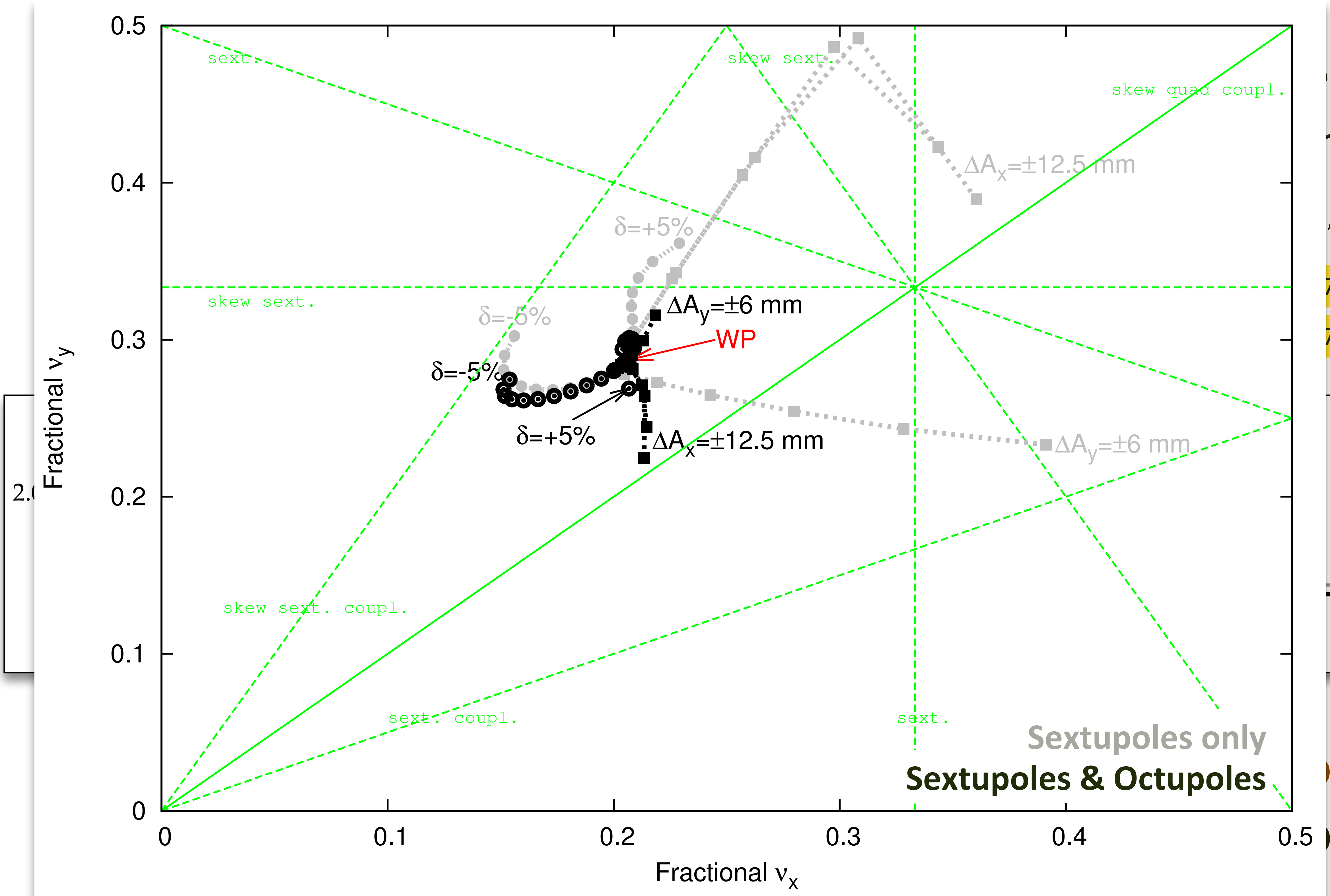


- Strong sextupoles drive large ADTS ➞ achromatic octupoles allow tailoring ADTS to first order ➞ minimize tune footprint

Nonlinear Optics (cont.)



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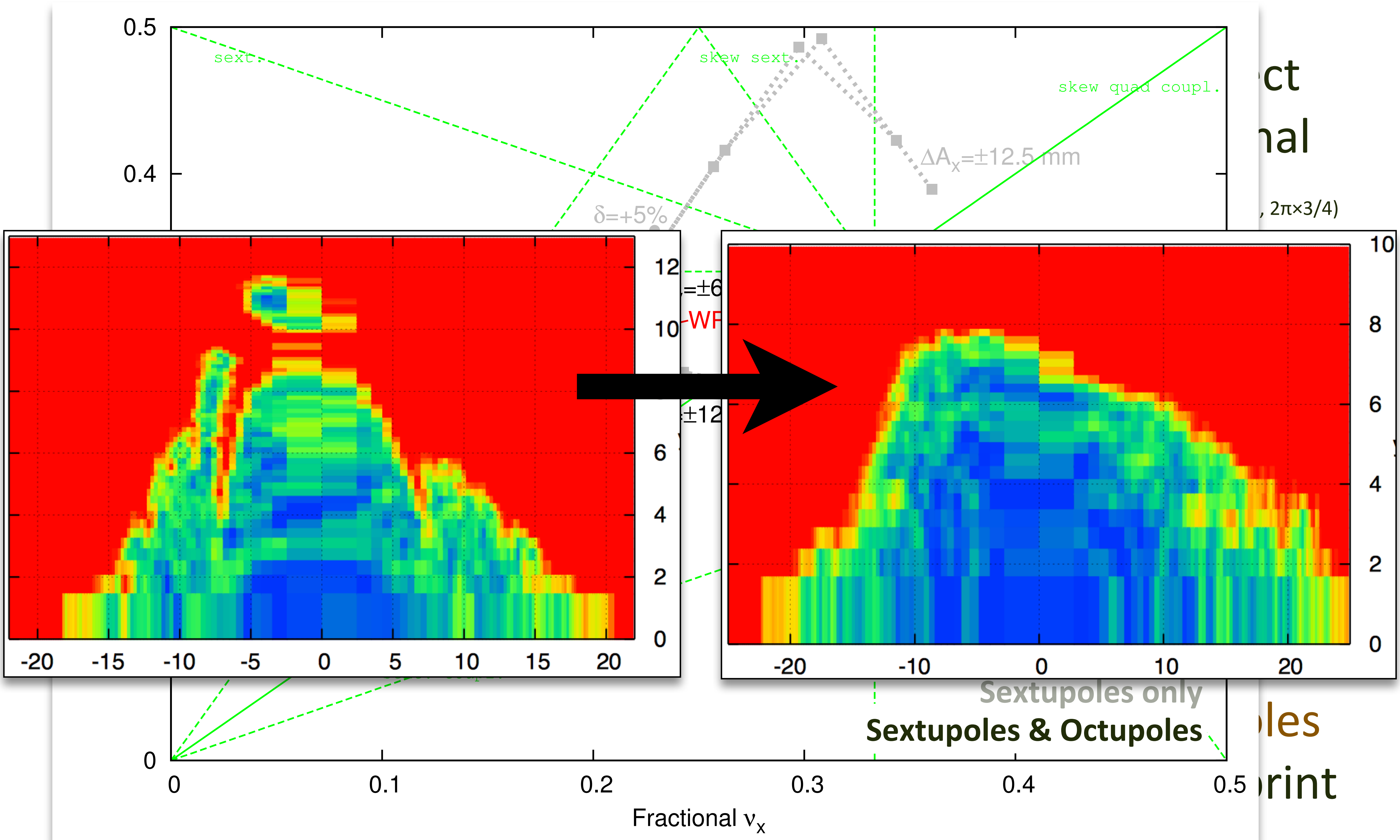
Nonlinear Optics (cont.)



Optics Corrections

- Gradient dipoles equipped with pole-face strips ➞ adjust vertical focusing within roughly ±4%

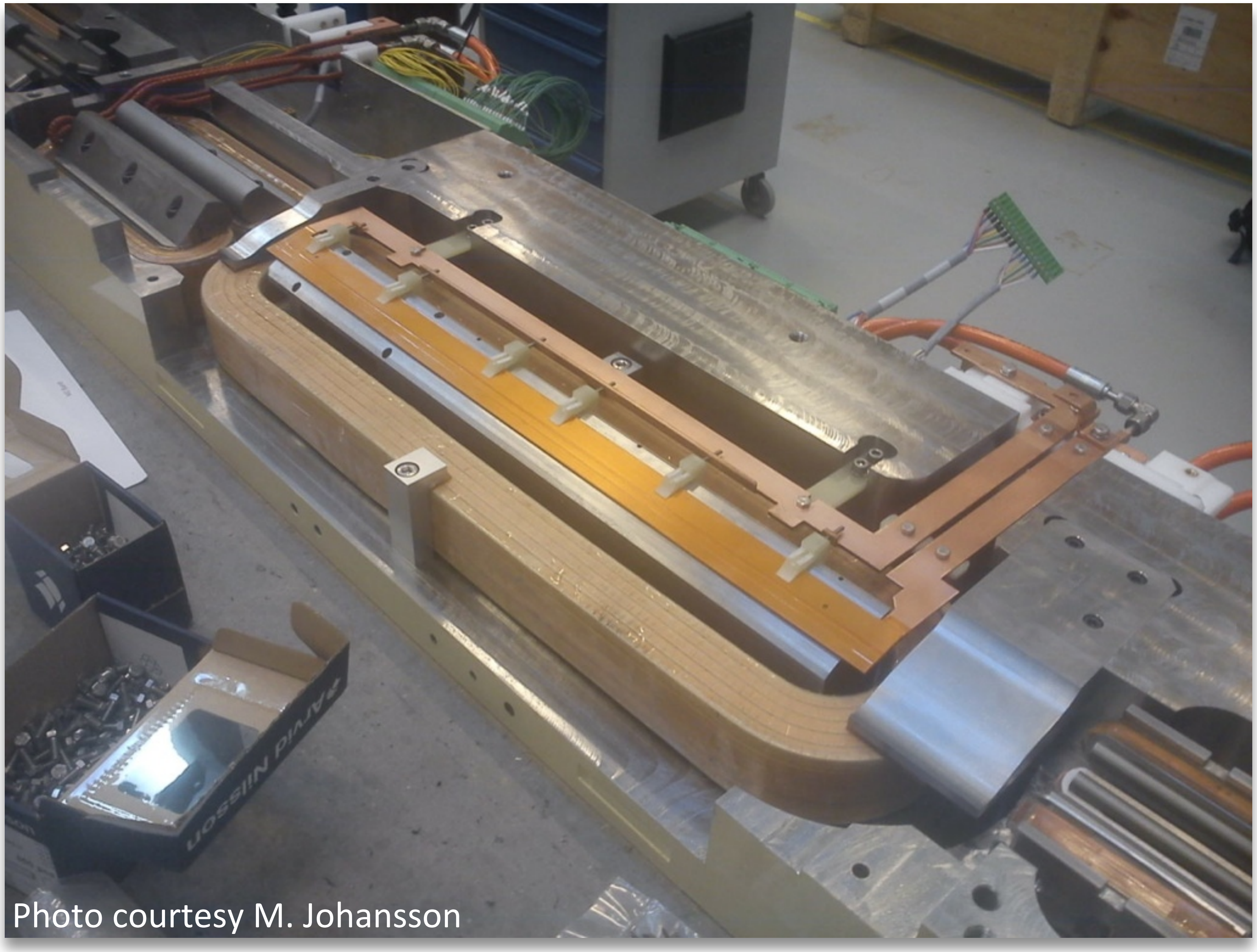


Photo courtesy M. Johansson

Optics Corrections (cont.)

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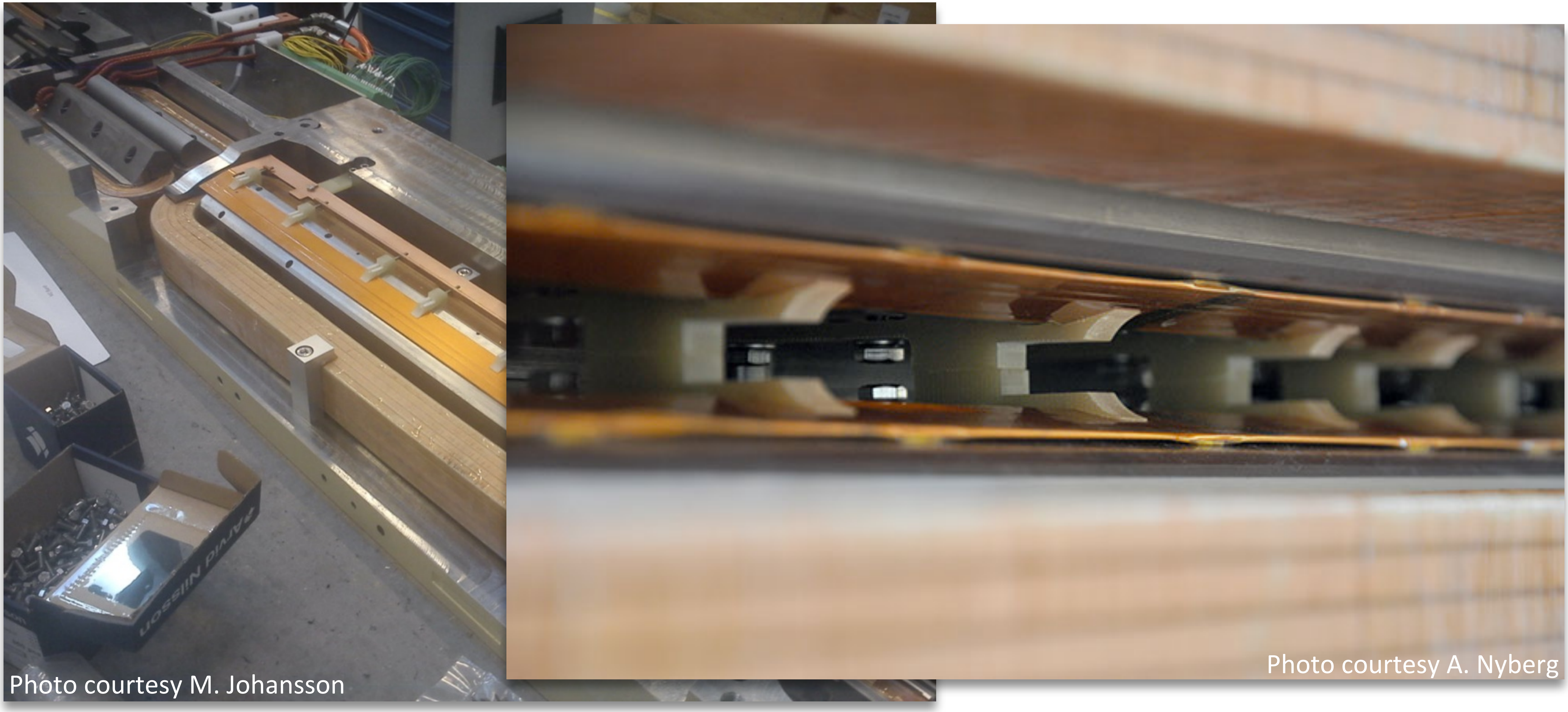
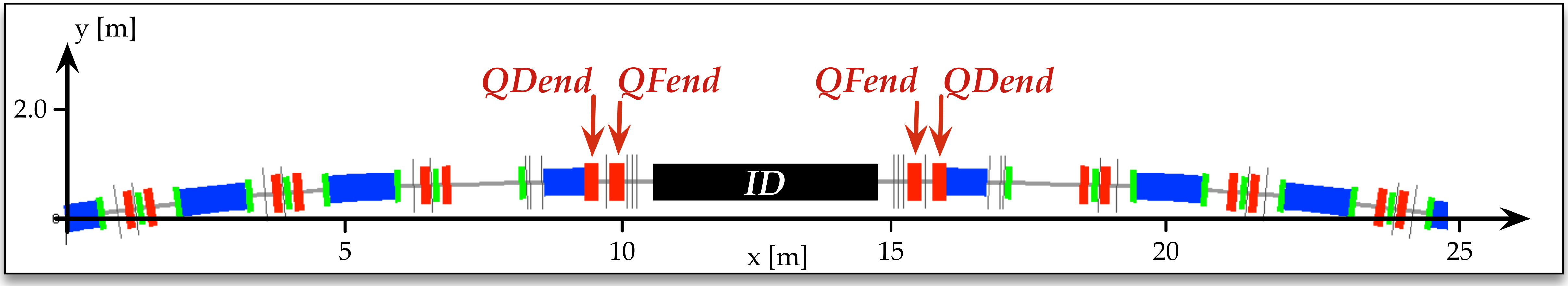


Photo courtesy M. Johansson

Photo courtesy A. Nyberg

Optics Corrections (cont.)

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

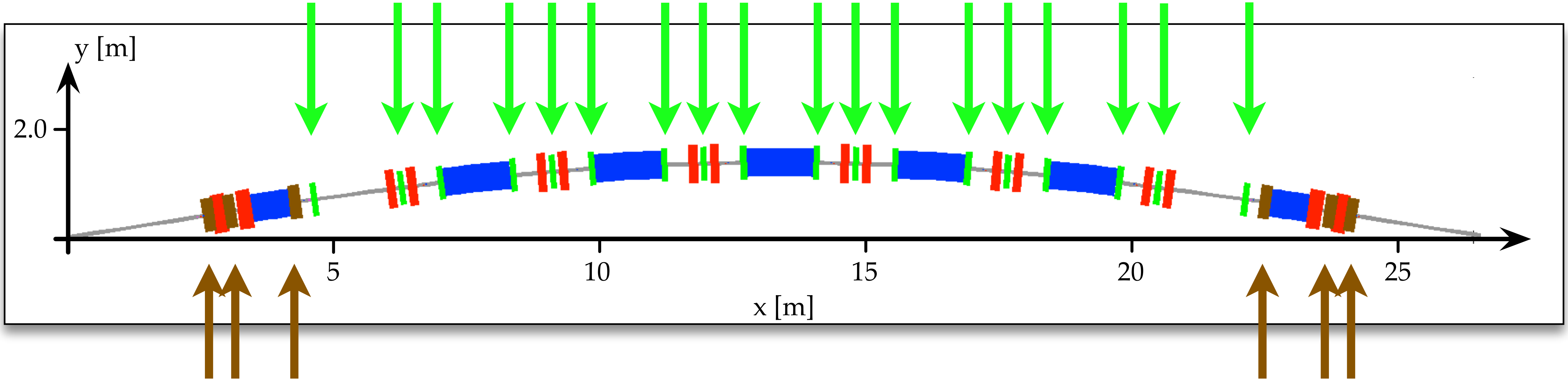


PAC'**11**, TUP235, p.1262

IPAC'**15**, TUPJE038

Optics Corrections (cont.)

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



Optics Corrections (cont.)

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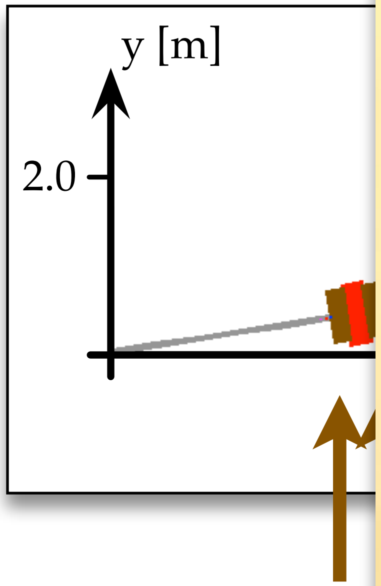


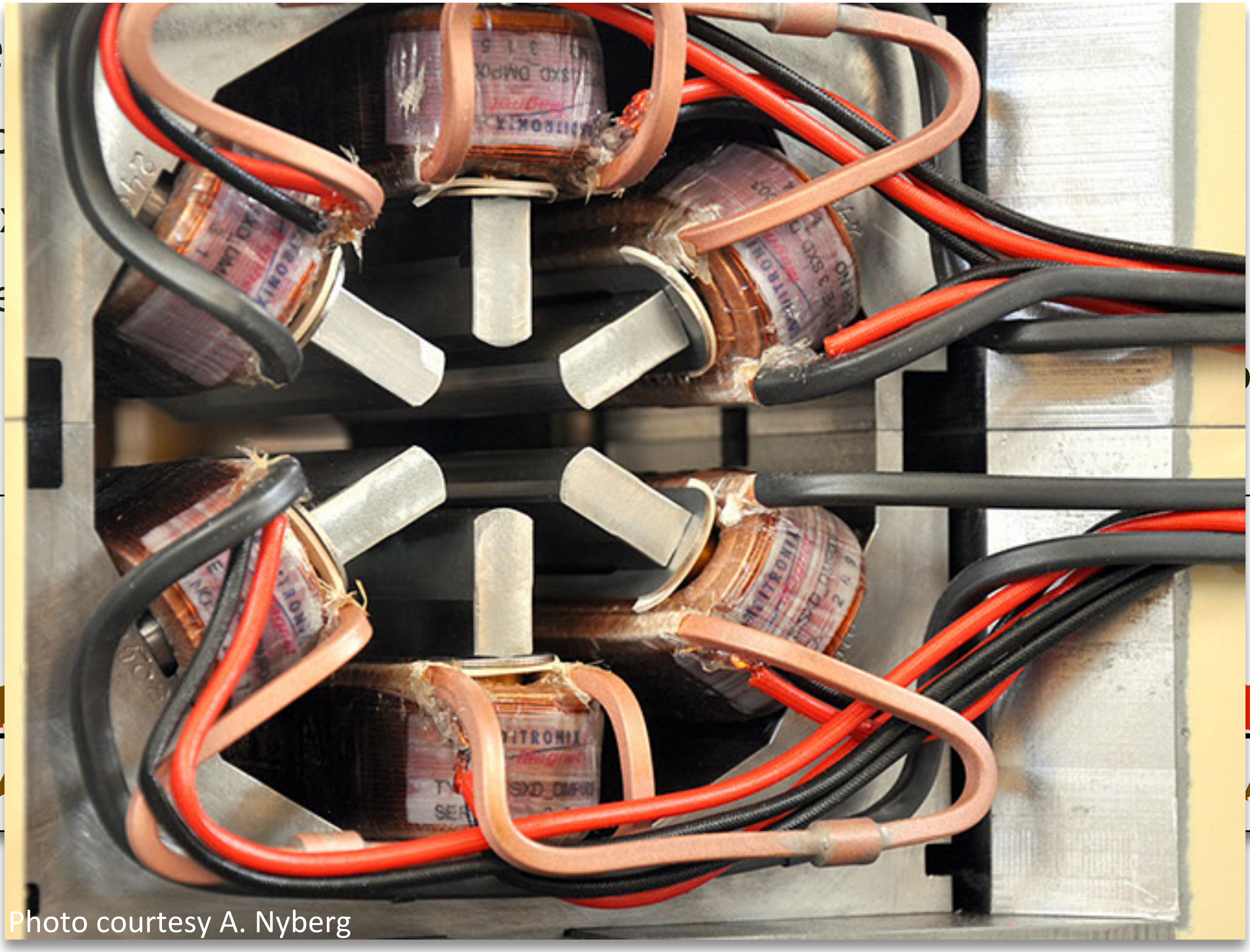


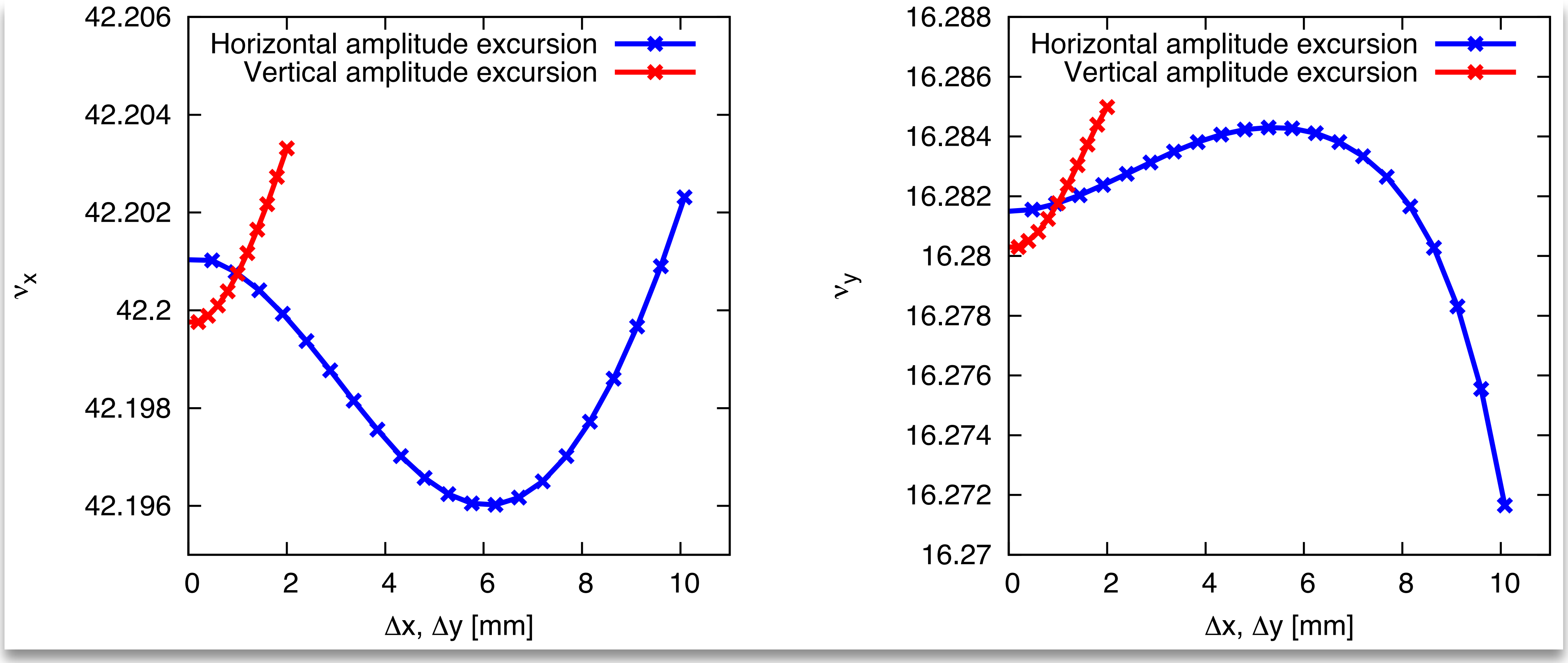
Photo courtesy A. Nyberg

Lattice & Optics Performance

- Nonlinear tuning results in small amplitude-dependent and chromatic tune shifts (tracking performed with Tracy-3)

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

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



Lattice & Optics Performance (cont.)

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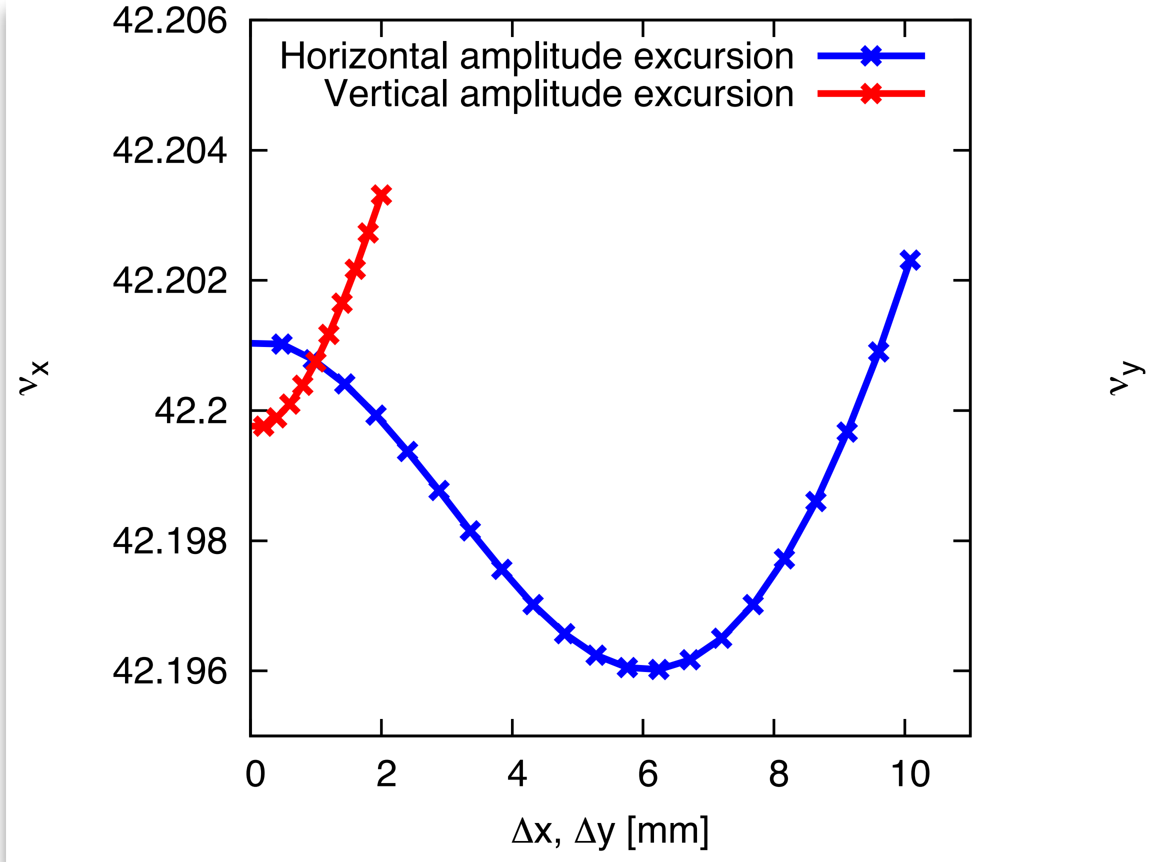

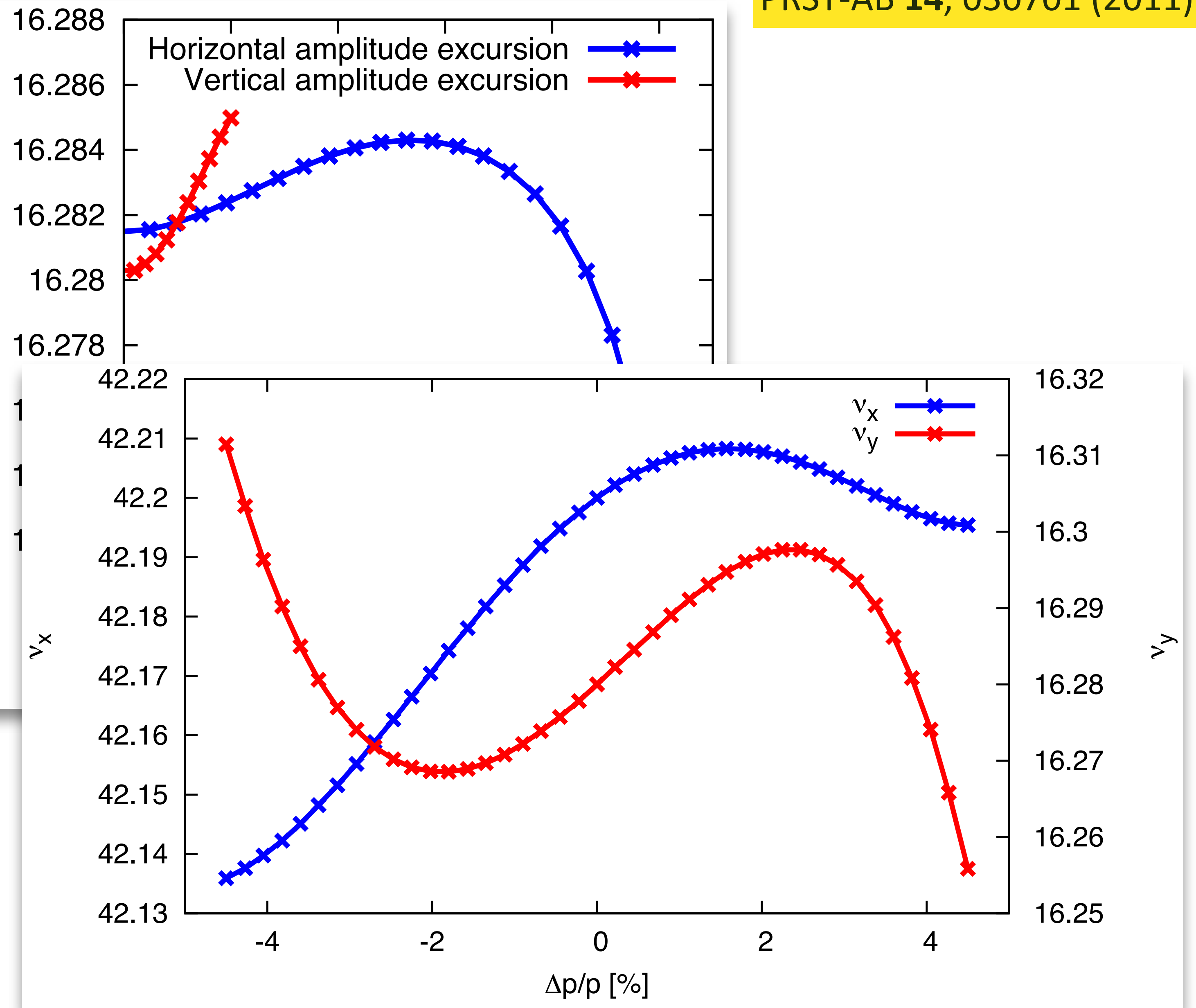

Lattice & Optics Performance (cont.)

- Nonlinear tuning results in small amplitude-dependent and chromatic tune shifts (tracking performed with Tracy-3)

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

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

- Overall tune footprint becomes very compact both on and off momentum
  - Large on-momentum DA ensures good injection efficiency
  - Large off-momentum DA ensures good lattice MA

Lattice & Optics Performance (cont.)

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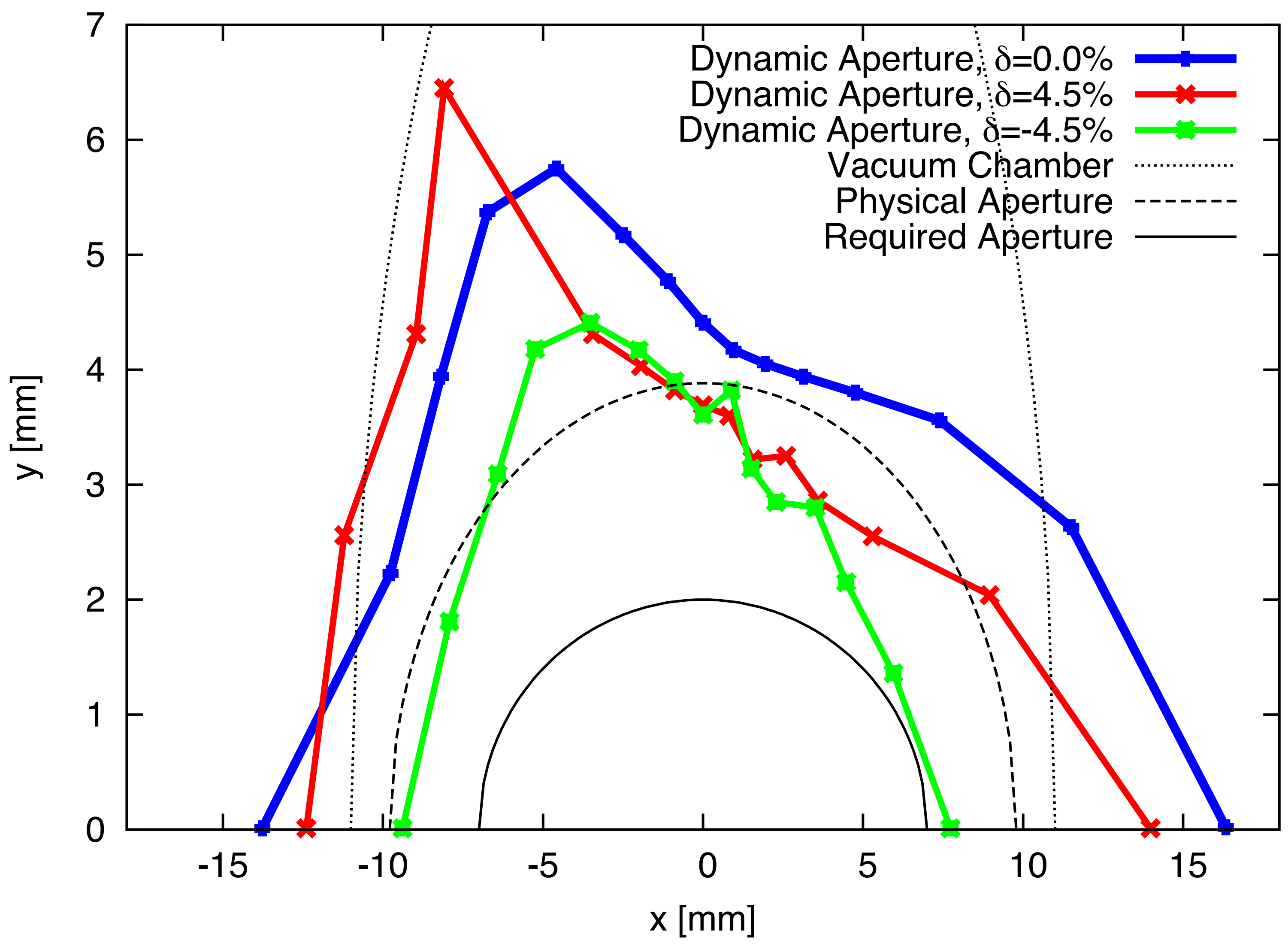


Lattice & Optics Performance (cont.)

- Nonlinear tuning results in small amplitude-dependent and chromatic tune shifts (tracking performed with Tracy-3)

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

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

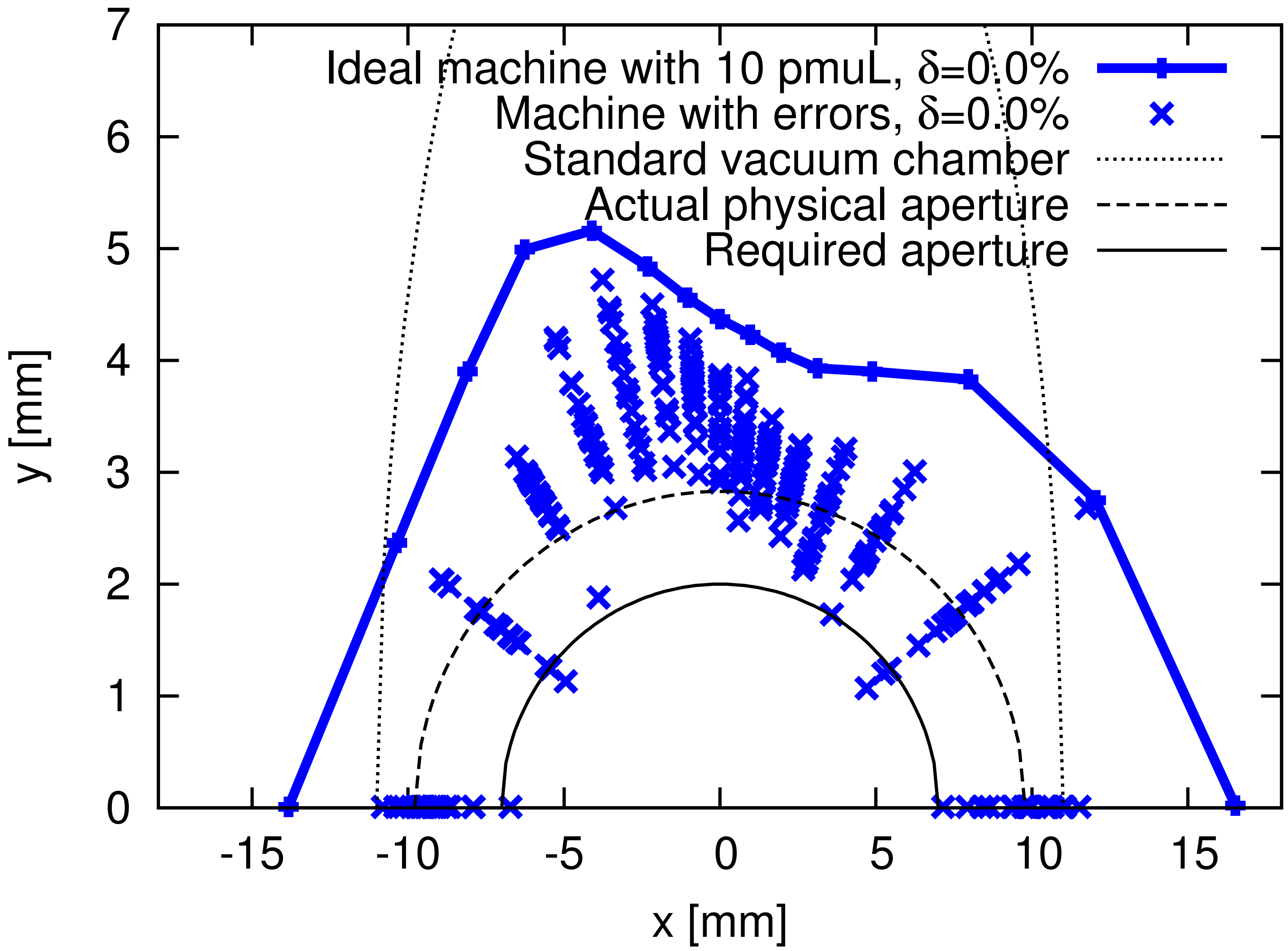
- Overall tune footprint becomes very compact both on and off momentum
  - Large on-momentum DA ensures good injection efficiency
  - Large off-momentum DA ensures good lattice MA
  - DA stable under influence of IDs, magnet errors & misalignments

Lattice & Optics Performance (cont.)

- Example: 10 IVUs, gaps fully closed, ring optics matched, magnet and alignment errors included (20 seeds)

PAC’**11**, TUP235, p.1262

IPAC’**15**, TUPJE038

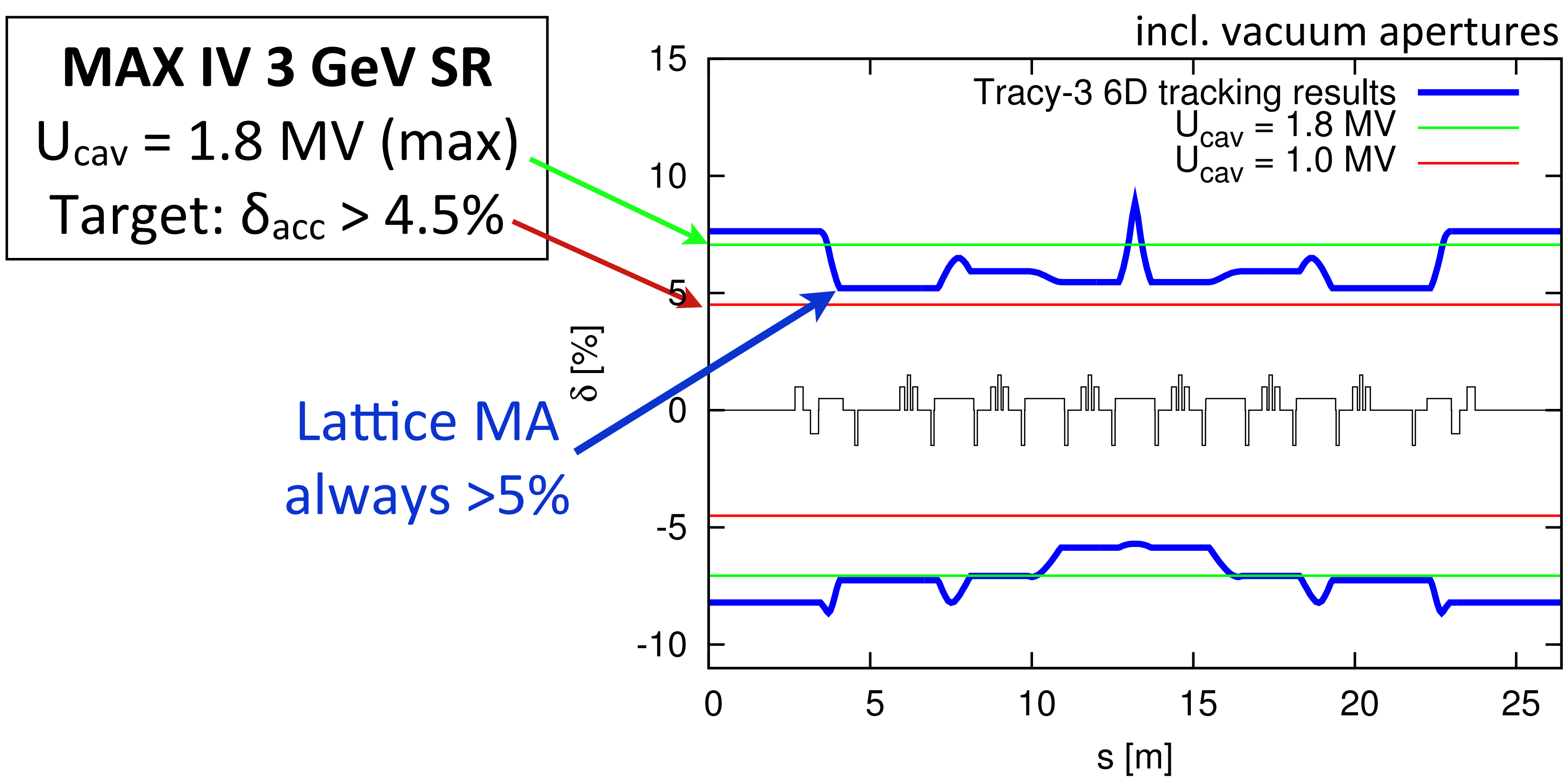


- IVU “pmuL”:
  3.7 m long, 1.1 T peak field,
  18.5 mm period, 4.2 mm gap
- Misalignments:
  50 µm rms H/V
  0.2 mrad rms roll } for each magnet block
  25 µm rms H/V
  0.2 mrad rms roll } for all magnets within
- Field Errors:
  0.05% rms within each family
- Multipole Errors:
  Upright and skew multipoles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

Lattice & Optics Performance (cont.)

- Large off-momentum DA enables generous lattice MA
- In conjunction with appropriately dimensioned RF system can lead to 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%

incl. vacuum apertures

Lattice & Optics Performance (cont.)

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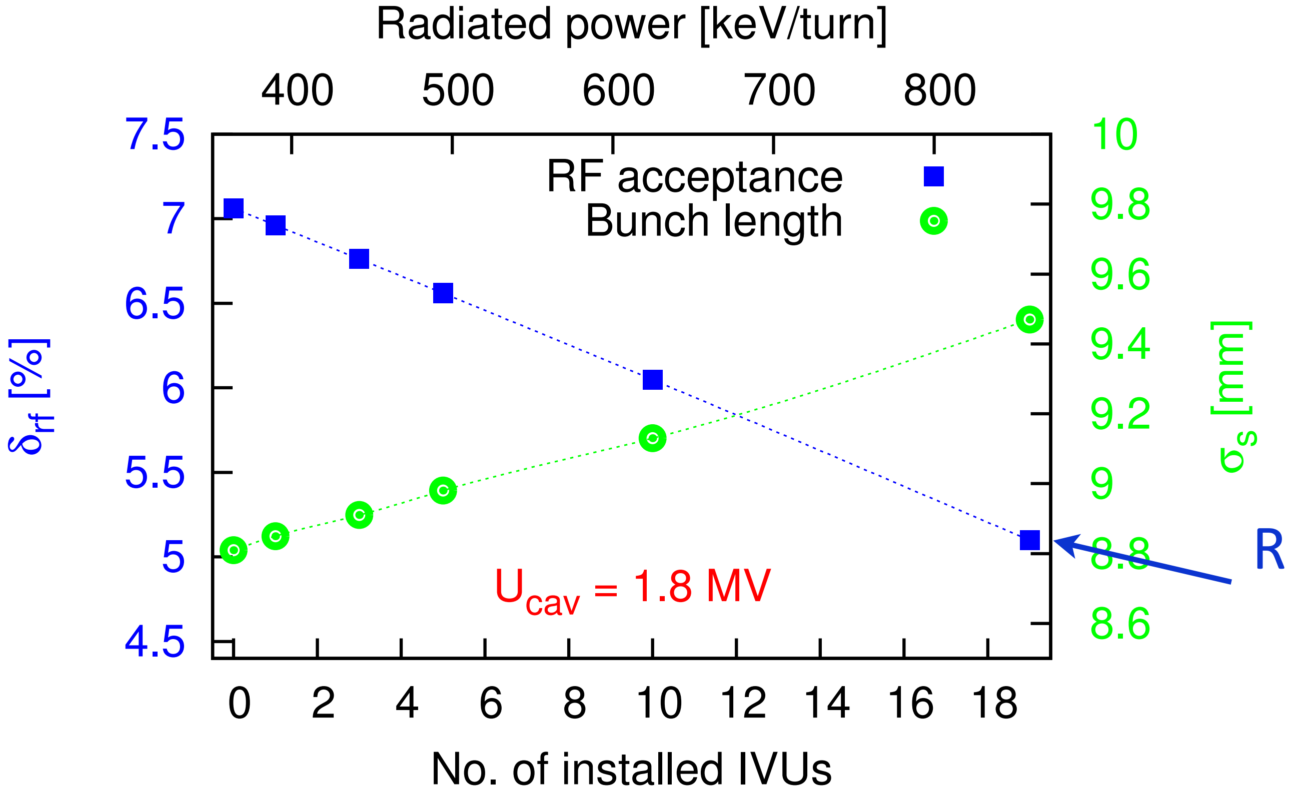

RF acceptance always >5%

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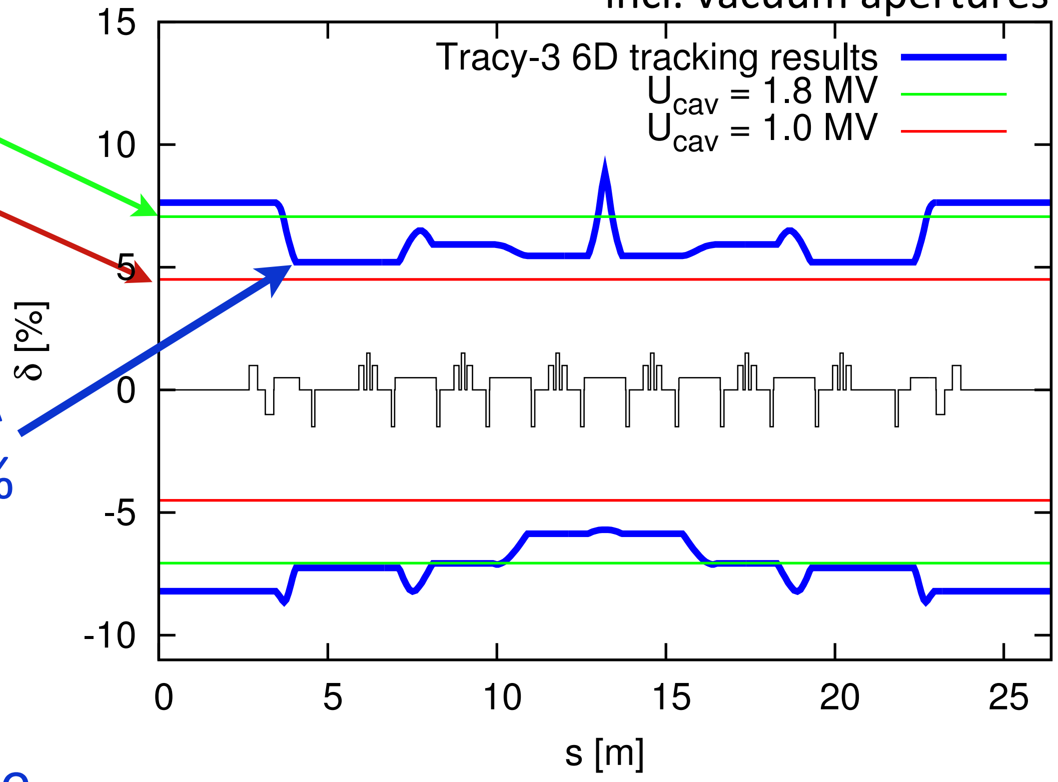

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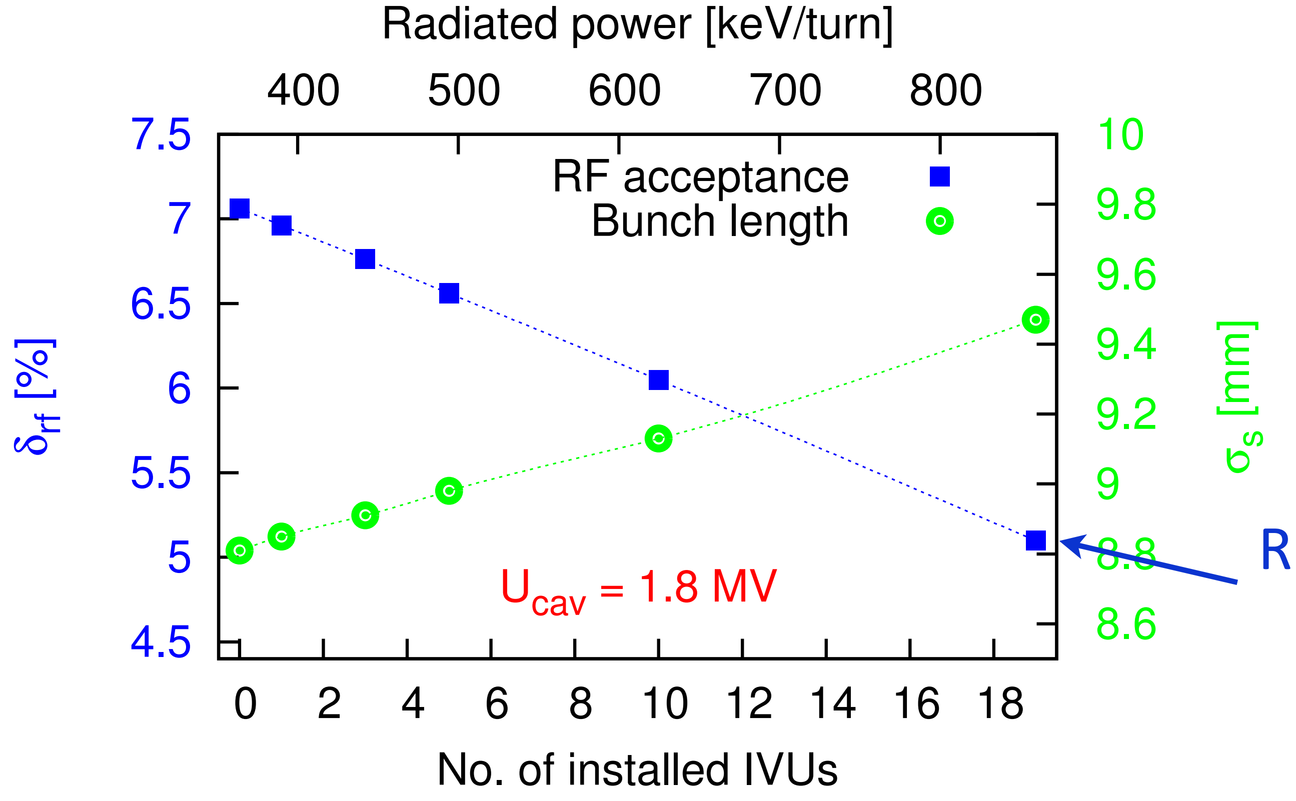
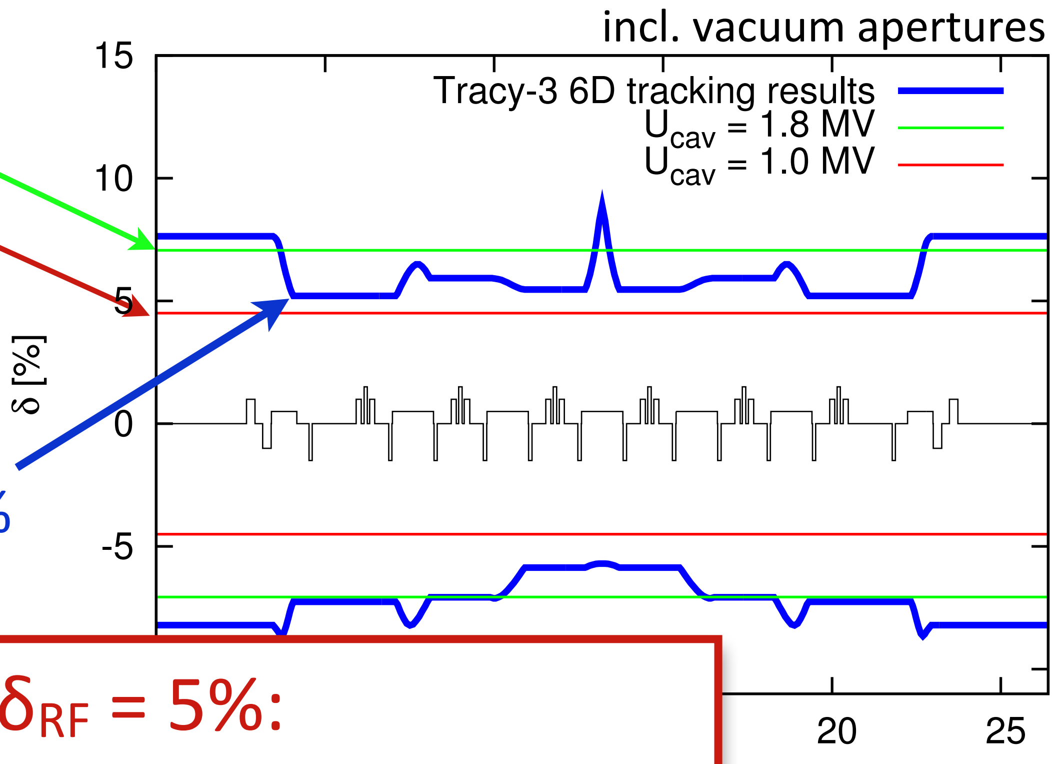




Lattice MA
always >5%

RF acce
always

For δ_{RF} = 5%:

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

➔ Cu losses, power bill

Lattice & Optics Performance (cont.)

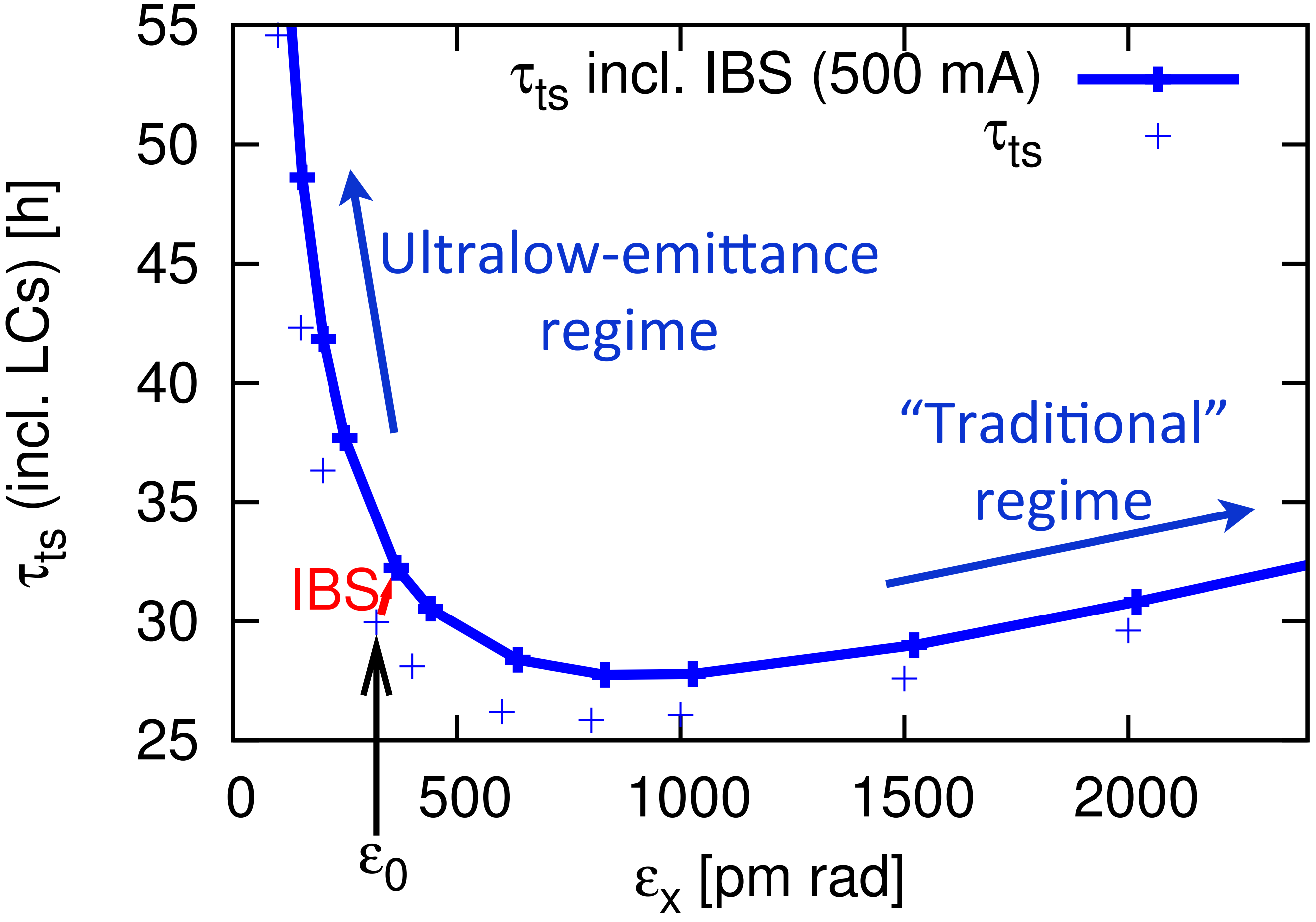
- Large overall MA is required if ultralow emittance should render good Touschek lifetime

PRL **10**, 407 (1963)

J. Le Duff, CERN Yellow Report 1989-01

(low emittance ➞ small transverse momenta ➞ few scattering events lead to actual Touschek <u>loss</u>)

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



MAX IV 3 GeV SR
(bare lattice)

$I = 500$ mA
$\delta_{acc} = 4.5\%$
$\sigma_\delta = \text{const}$
$\varepsilon_y = 8$ pm rad

Lattice & Optics Performance (cont.)

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PRL **10**, 407 (1963)

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- Use 300 MHz Landau cavities to stretch bunches ×5

  ➙ extend Touschek lifetime beyond gas lifetime

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

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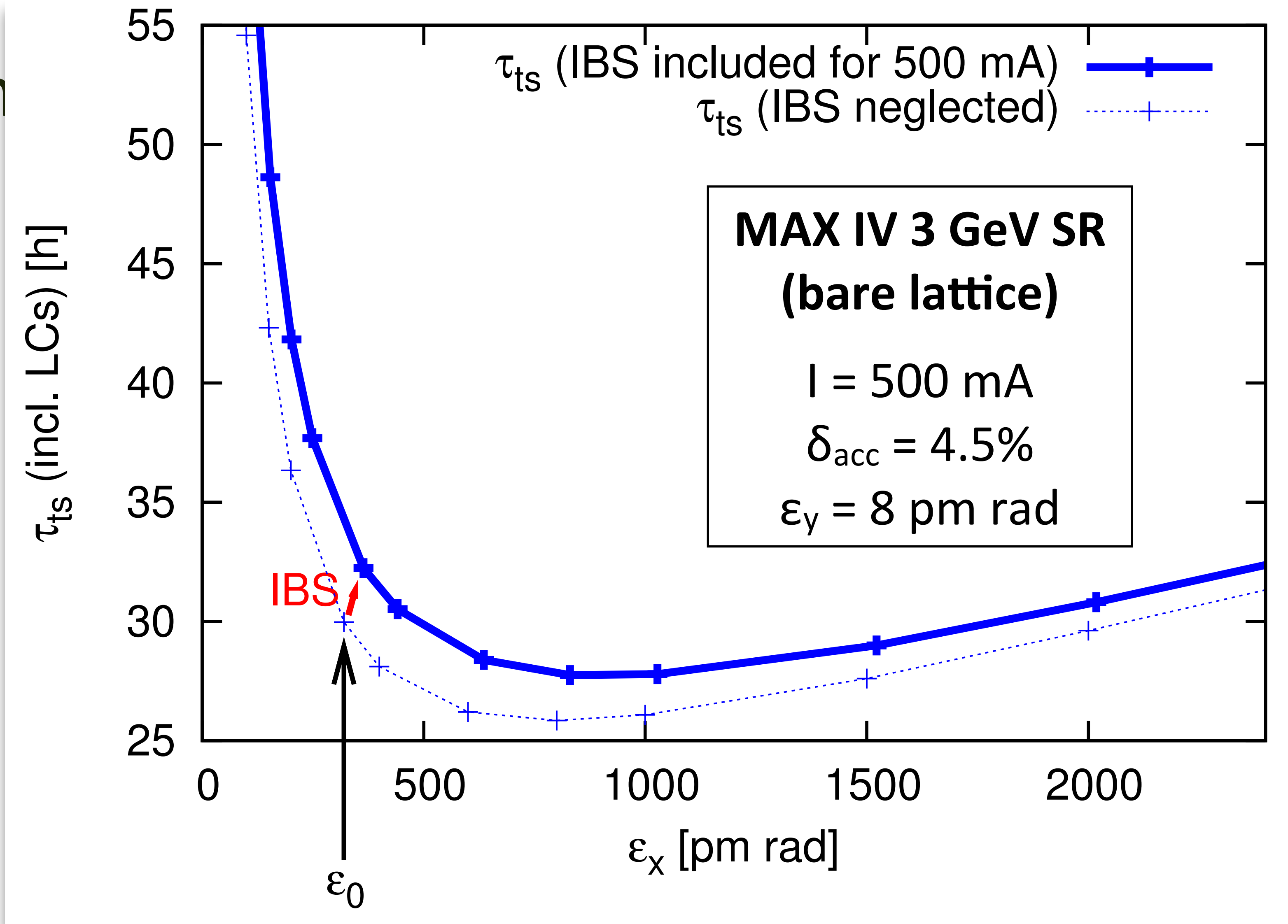

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PRST-AB **17**, 050705 (2014)

- At MAX IV LCs are indispensable to maintain ultralow emittance despite strong IBS at 500 mA stored current (5 nC/bunch)

A. Piwinski, Proc. 9th HEAC, SLAC, 1974

Part. Accel. **13**, 115 (1983)

Part. Accel. **17**, 1 (1985)

CERN-AB-2006-002

Lattice & Optics Performance (cont.)

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

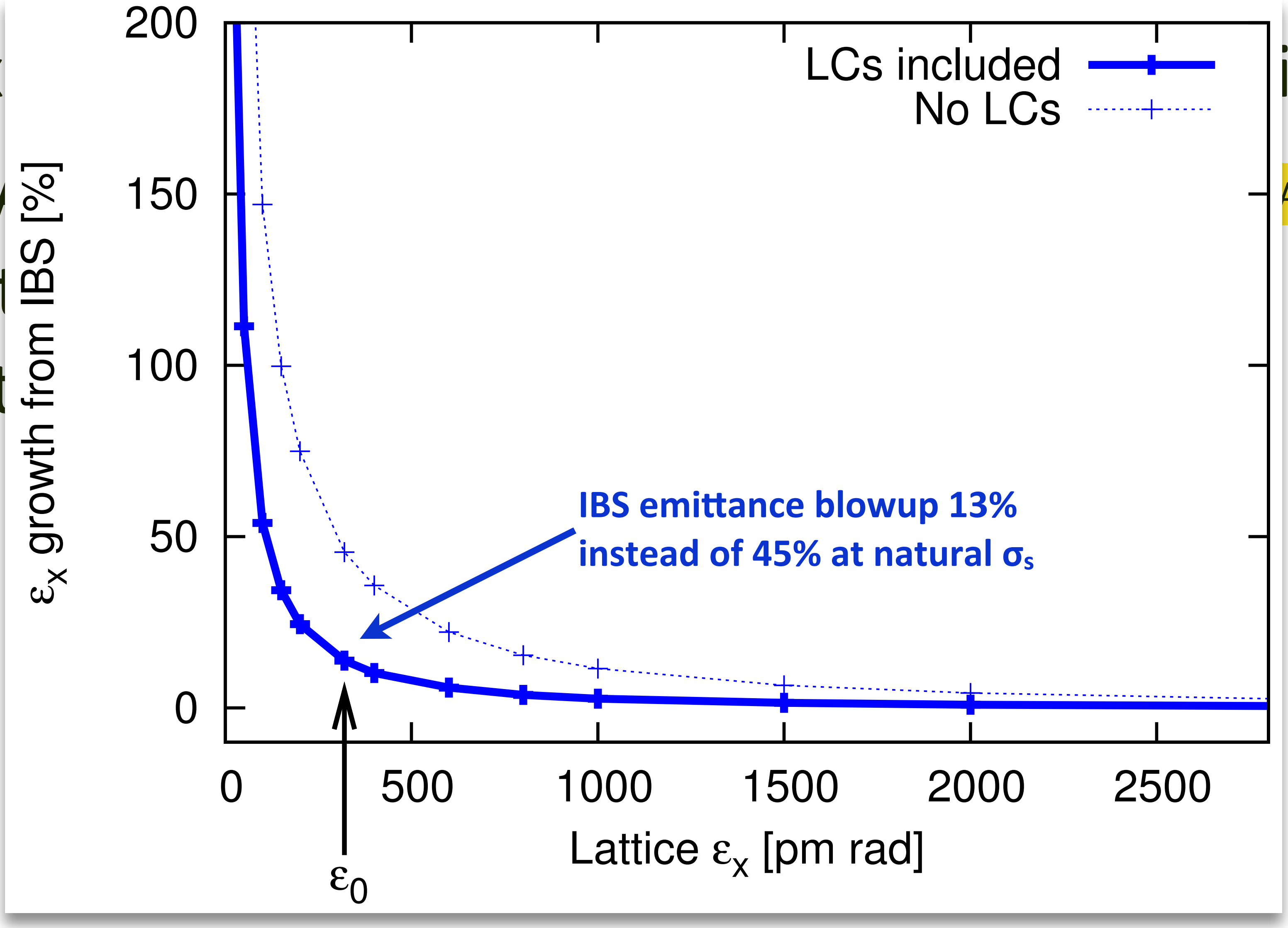
- At MA
  maint
  IBS at

A. Piwinski, Proc. 9th HEAC, SLAC, 1974

Part. Accel. **13**, 115 (1983)

Part. Accel. **17**, 1 (1985)

CERN-AB-2006-002



IBS emittance blowup 13% instead of 45% at natural σ_s

MAX IV 3 GeV SR
(bare lattice)

I = 500 mA
δ_{acc} = 4.5%
$\sigma_\delta \approx$ const
ε_y = 8 pm rad

Recent Developments

- Attempts to find alternate nonlinear optics with MOGA → so far nothing substantially superior

Recent Developments (cont.)

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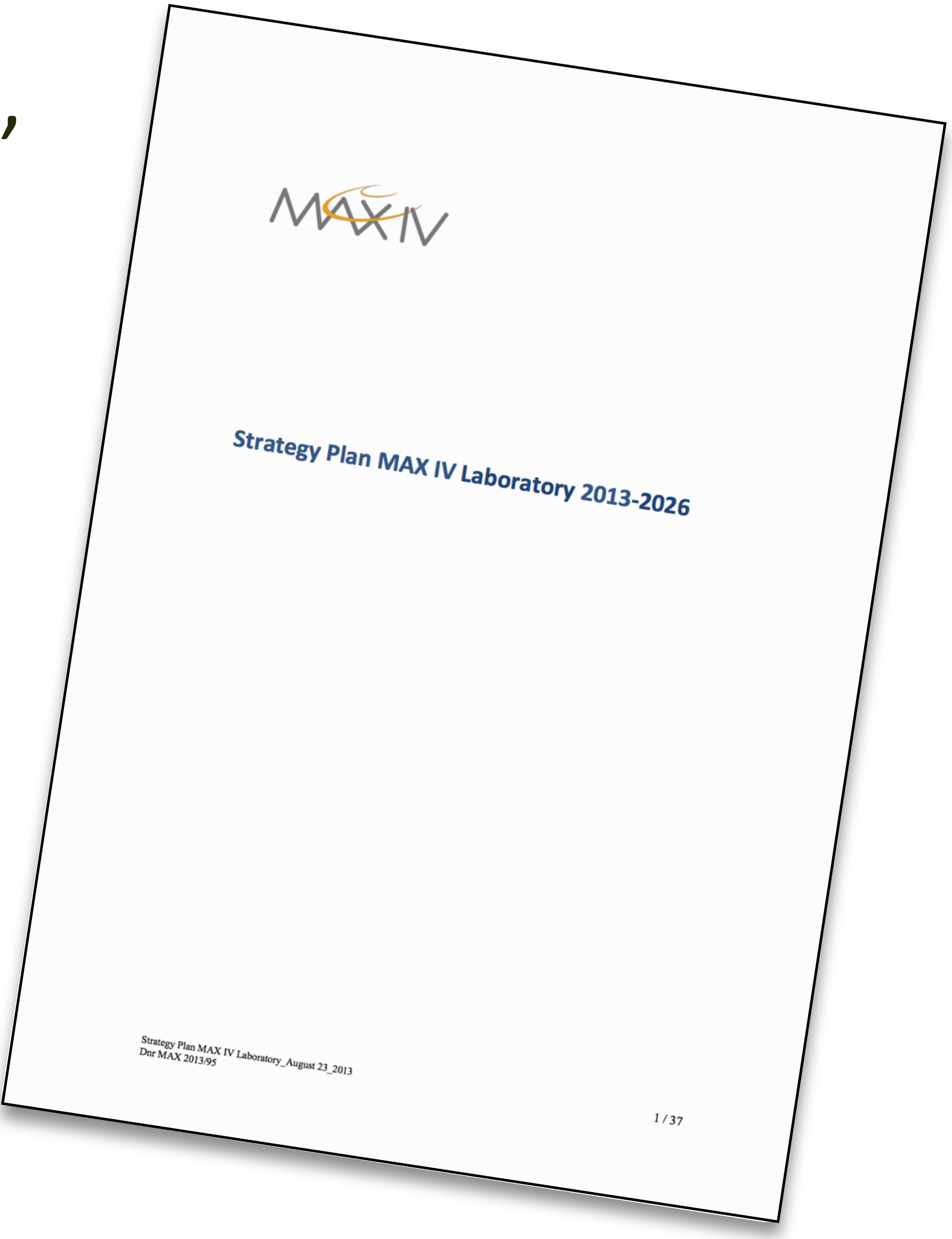
- Started thinking about first “upgrades”



Strategy Plan MAX IV Laboratory 2013-2026

Strategy Plan MAX IV Laboratory_August 23_2013
Dnr MAX 2013/95

1 / 37

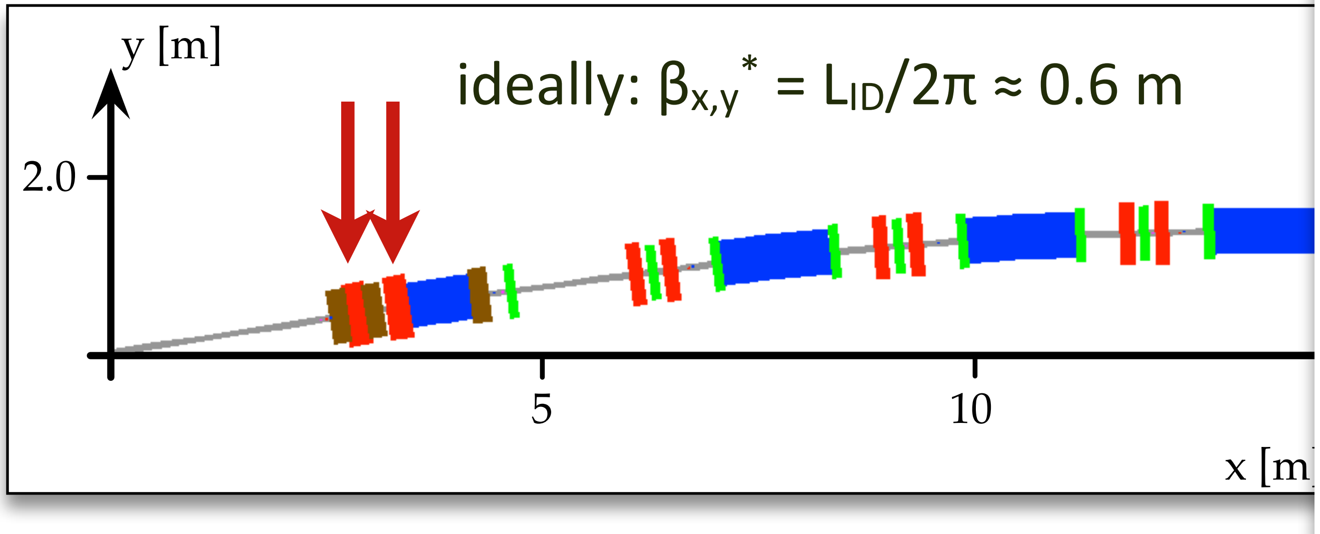
http://www.maxlab.lu.se/strategy_report

Recent Developments (cont.)

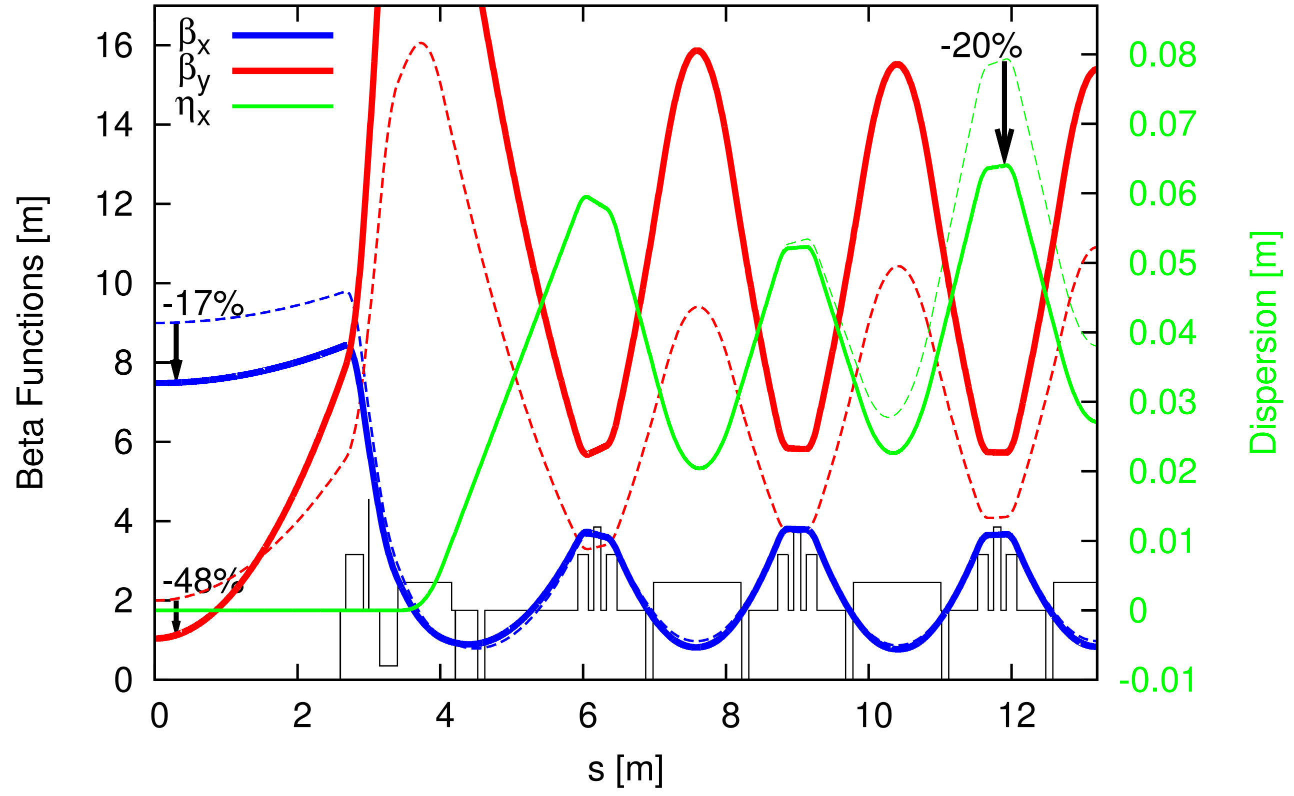
- Attempts to find alternate nonlinear optics with MOGA ➙ so far nothing substantially superior
- Started thinking about first "upgrades"
  - Improved matching to IDs (coupling, optics in straights)
  - Increase focusing in arc ➙ ε_x reduced to 269 pm rad (-18%) while retaining satisfactory DA & lifetime ➙ +40% brightness

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

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



ideally: $\beta_{x,y}^* = L_{ID}/2\pi \approx 0.6$ m



Recent Developments (cont.)

- Attempts to find alternate nonlinear optics with MOGA → so far nothing substantially superior
- Started thinking about first "upgrades"
  - Improved matching to IDs (coupling, optics in straights)
  - Increase focusing in arc → ε_x reduced to 269 pm rad (-18%) while retaining satisfactory DA & lifetime → +40% brightness
  - Further optics tuning ongoing → should allow pushing towards $\varepsilon_x \approx 200$ pm rad, but nonlinear optics become challenging → plan to further investigate using MOGA
  - Lower $\beta_{x,y}$ in straights and $\varepsilon_x \approx 150$ pm rad → will require on-axis injection → started thinking about dipole kicker for single-bunch on-axis injection → potential for entirely new IDs

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

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

Recent Developments (cont.)

- Attempts to fir ith MOGA → so far nothing sub
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PAC'**13**, MOPHO05, p.243

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

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Closing last achromats, getting ready to start ring commissioning Aug 2015

Photo courtesy E. Al-dmour

Thank you for your attention!

Photo courtesy P. Nordeng, Feb 5, 2015