The MAX IV 3 GeV Storage Ring

From Design to Commissioning

Simon C. Leemann
ALS/LBNL, September 29, 2016

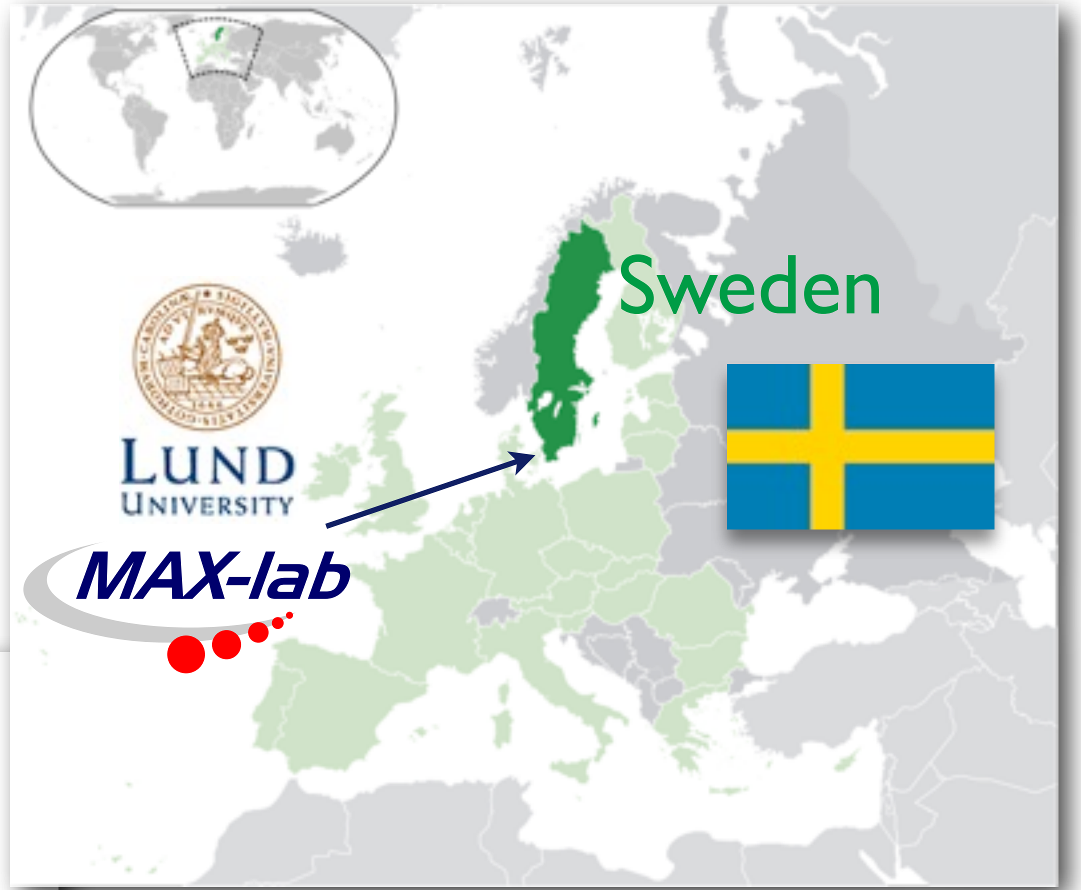
MAX IV

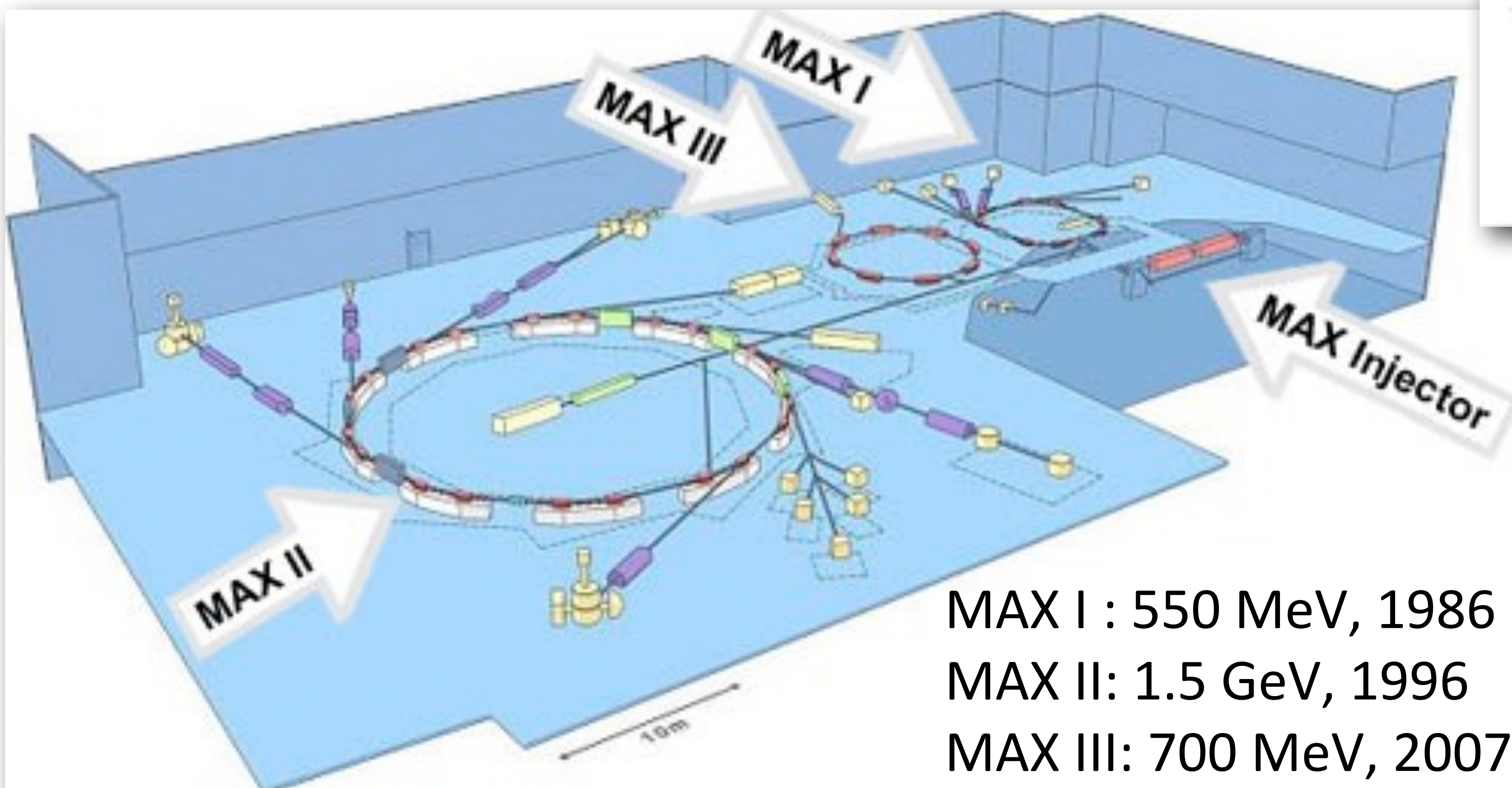
Outline

- Introduction
  - MAX IV Facility Overview
  - Origins of the MAX IV 3 GeV Ring Lattice
- The MAX IV 3 GeV Storage Ring
  - Linear & Nonlinear Optics
  - Performance
- Linac & Injection
- Commissioning Experience
  - Brief Linac Commissioning Summary
  - 3 GeV Storage Ring Commissioning
- Outlook & Upgrade Ideas

Once upon a time in a very cold & distant land...

- Around 2007: MAX-lab operating three storage rings for users
- But wants to expand towards high-brightness x-rays

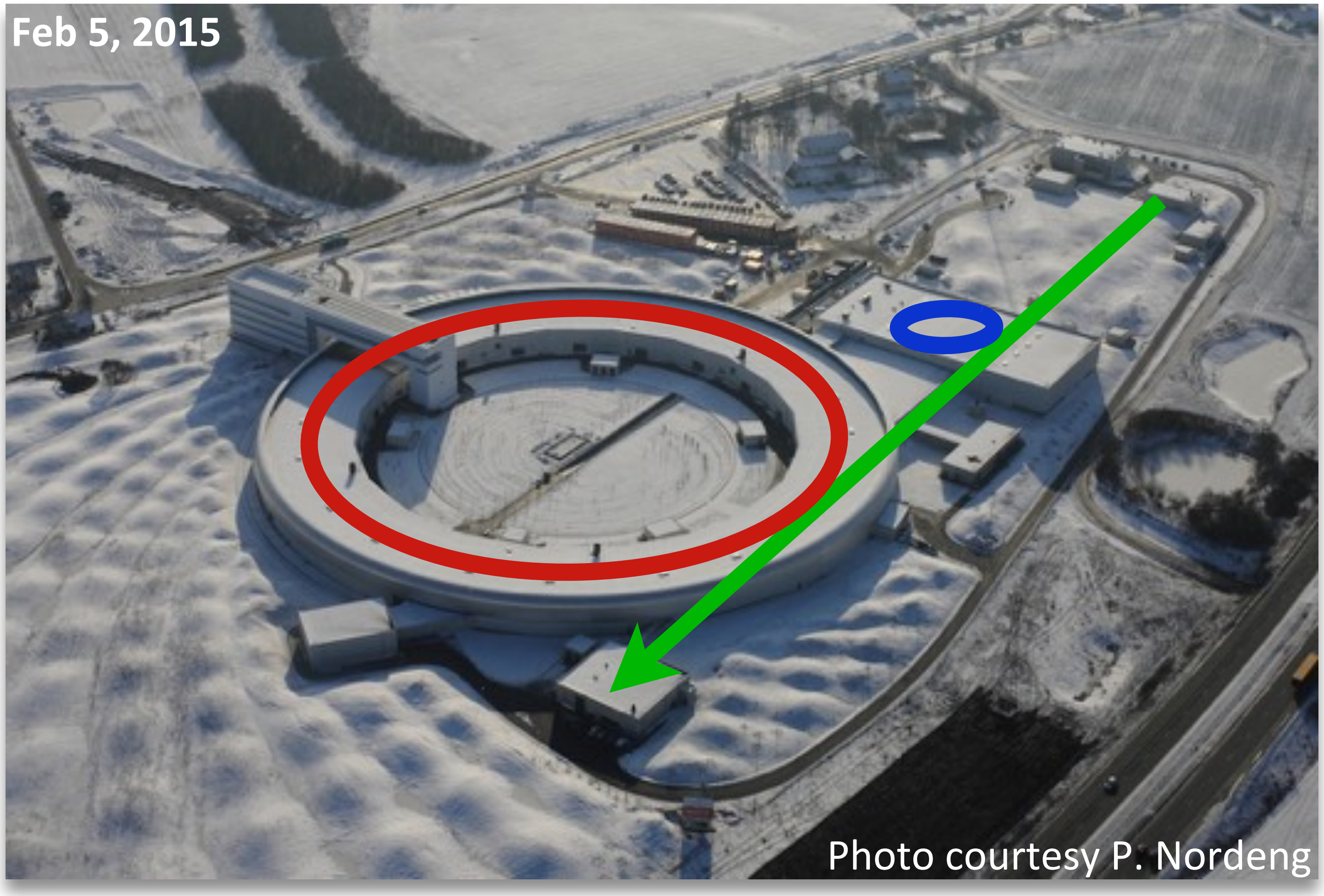




MAX I : 550 MeV, 1986
MAX II: 1.5 GeV, 1996
MAX III: 700 MeV, 2007

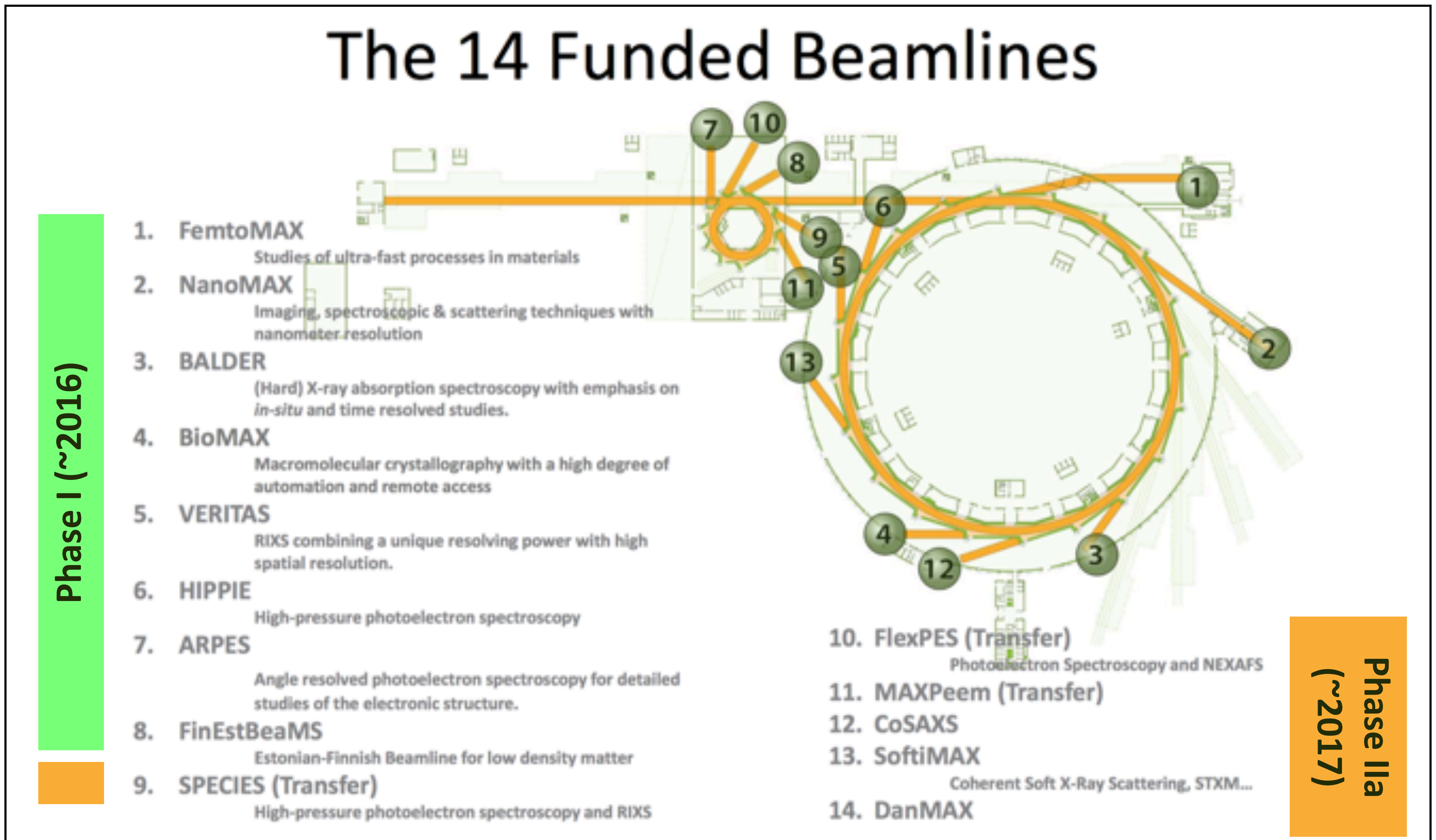
MAX IV Facility Overview

- These plans call for a new facility
- Quickly realize a single accelerator cannot cover the entire required spectral and temporal range
- After a facility-wide optimization, decide instead to build 3 new accelerators:
  - one ≈3.5 GeV linac as SPF/FEL driver & ring injector (separate guns)
  - two separate storage rings at 1.5 GeV (UV) and 3 GeV (x-rays)



MAX IV Facility Overview (cont.)

- Facility can accommodate up to 32 user beamlines:
  3 @ SPF, 10 @ 1.5 GeV SR, 19 @ 3 GeV SR
- 14 have been funded in our first two beamline phases



MAX IV Origins

- 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

MAX IV Origins (cont.)

- 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 ($\varepsilon_x \sim 1/N_b^3$)

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

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

TME

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

TME: brute-force approach $I_5/I_2 \rightarrow 0$ easily leads to overstrained optics, chromaticity wall

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TME MBA

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

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

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TME

MBA

$$=$$

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

TME: brute-fo

MBA: many w

Gradient dipo

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.

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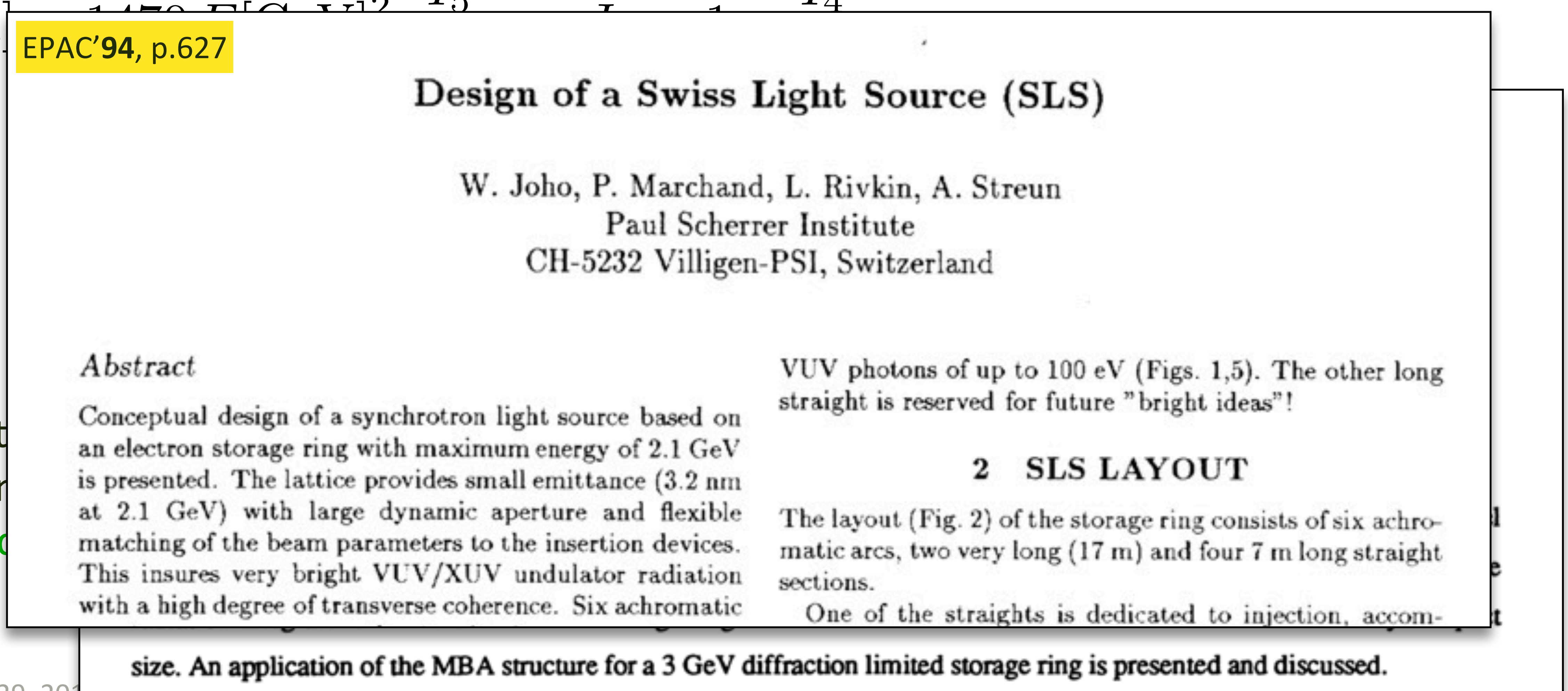
$\varepsilon_0[\mathrm{nm\,rad}]$ … I_5 … I_4

$I_2 =$

TME: brut

MBA: mar

Gradient c



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.

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ε_0[nm

TME:
MBA:
Gradi

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

Design of a Diffraction Limited Light Source (DIFL)

D. Einfeld, J. Schaper, Fachhochschule Ostfriesland, Constantiaplatz 4, D-26723 Emden
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.

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ε_0

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

LATTICE STUDIES FOR A HIGH-BRIGHTNESS LIGHT SOURCE

D. Kaltchev*, R.V. Servranckx, M.K. Craddock†
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T2A3
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 ®rst, the phase advance per cell was set solely to obtain low emittance, as in the original SLS design. One

on ... the

coherent radiation. A first disign of a Diffraction Limited

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.

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Gradi...

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TME

MBA

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

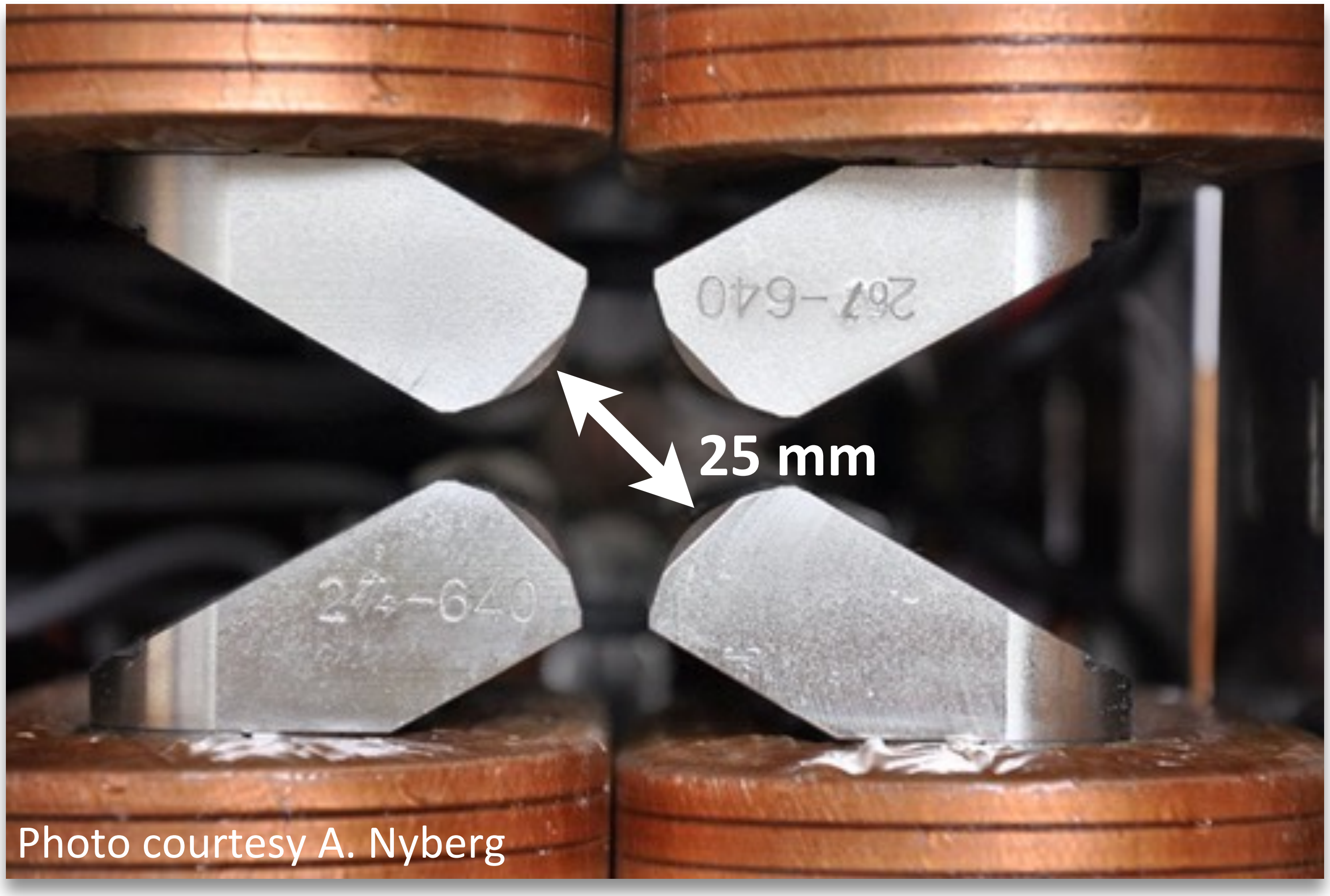
Gradient Dipoles

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

- During 1990s considered “nice idea” but not realizable

MAX IV Origins (cont.)

- During the 2000s MAX-lab becomes convinced it has the technology to realize an MBA lattice
  - compact magnets (narrow gaps → short but strong), magnet integration (common magnet block = “girder”), use of combined-function magnets



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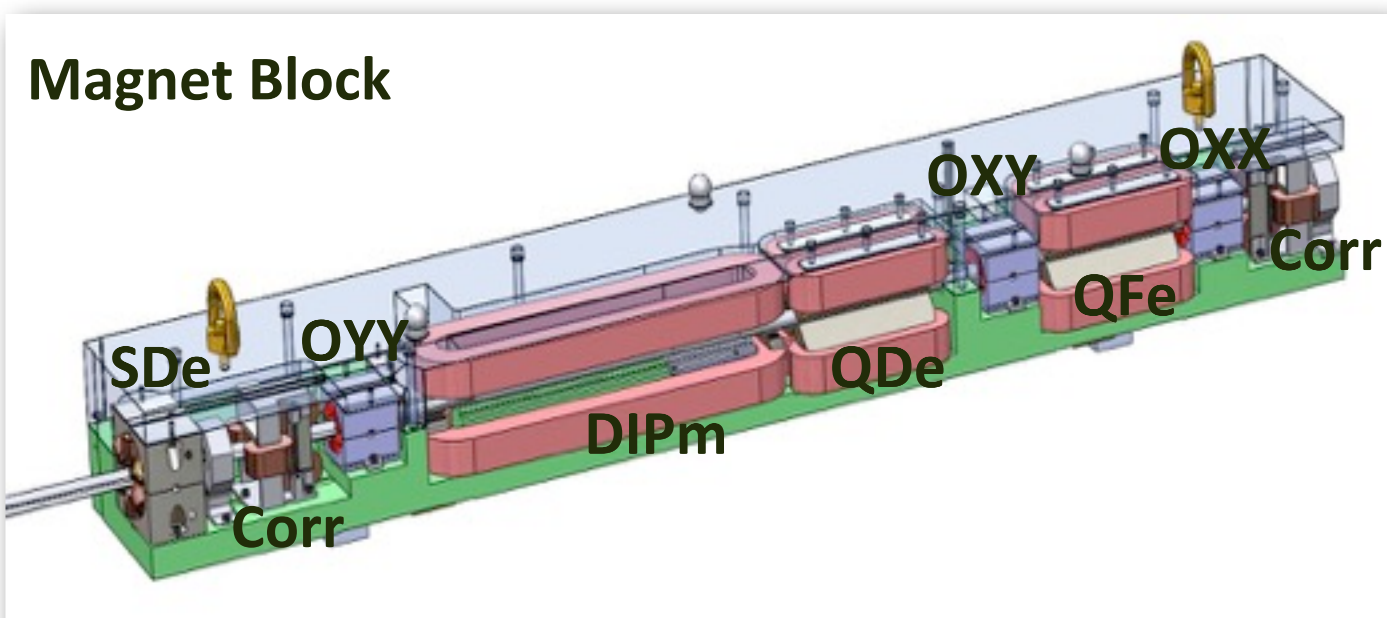

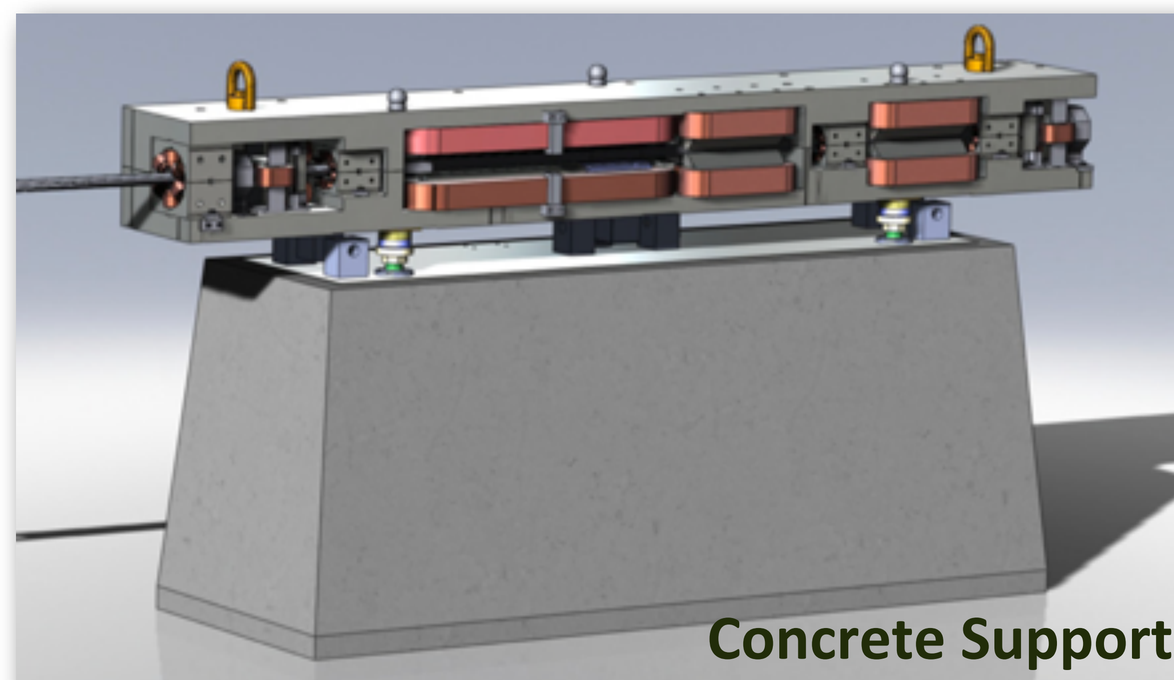

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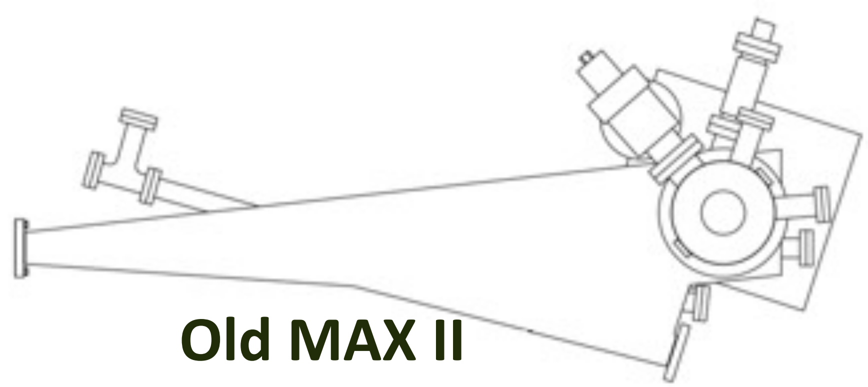
JSR **21**, 884-903 (2014)

Photos courtesy M. Johansson

MAX IV Origins (cont.)

- During the 2000s MAX-lab becomes convinced it has the technology to realize an MBA lattice
  - 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

MAX IV Origins (cont.)

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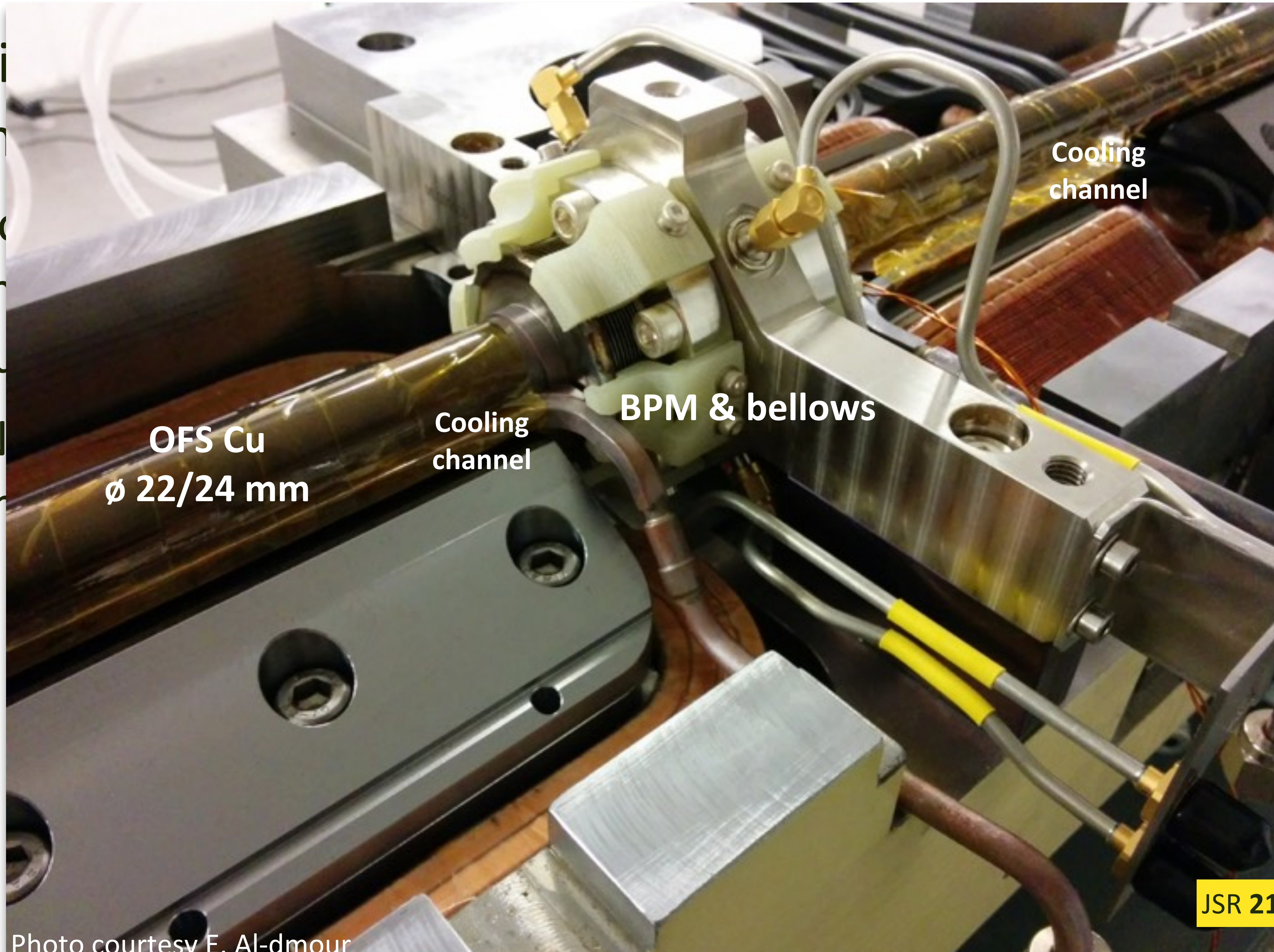
– N… nt
m…
… OFS Cu



JSR **21**, 878-883 (2014)

MAX IV Origins (cont.)

- During the 2000s MAX-lab becomes convinced it has the technology to realize an MBA lattice
  - 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 passive harmonic cavities → ensure stability, good Touschek lifetime & mitigate emittance blowup from IBS

MAX IV Origins (cont.)

- During the 2000s MAX-lab becomes convinced it has the technology to realize an MBA lattice

IPAC’**11**, MOPC051, p.193

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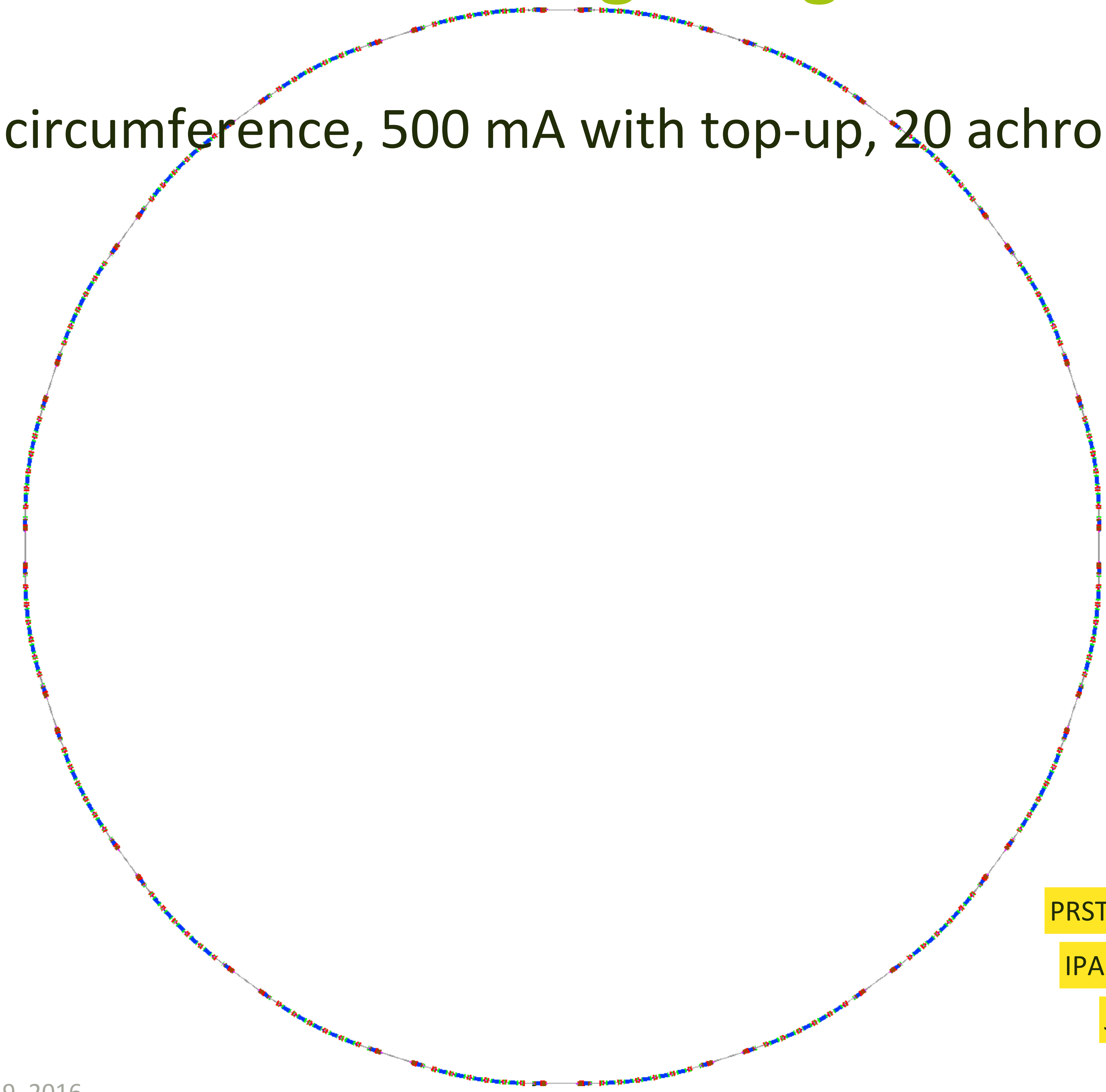
The MAX IV 3 GeV Storage Ring

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



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

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

JSR **21**, 862-877 (2014)

The MAX IV 3 GeV Storage Ring (cont.)

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

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

JSR **21**, 862-877 (2014)

The MAX IV 3 GeV Storage Ring (cont.)

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

701 (2009)

59, p.3029

JSR **21**, 862-877 (2014)

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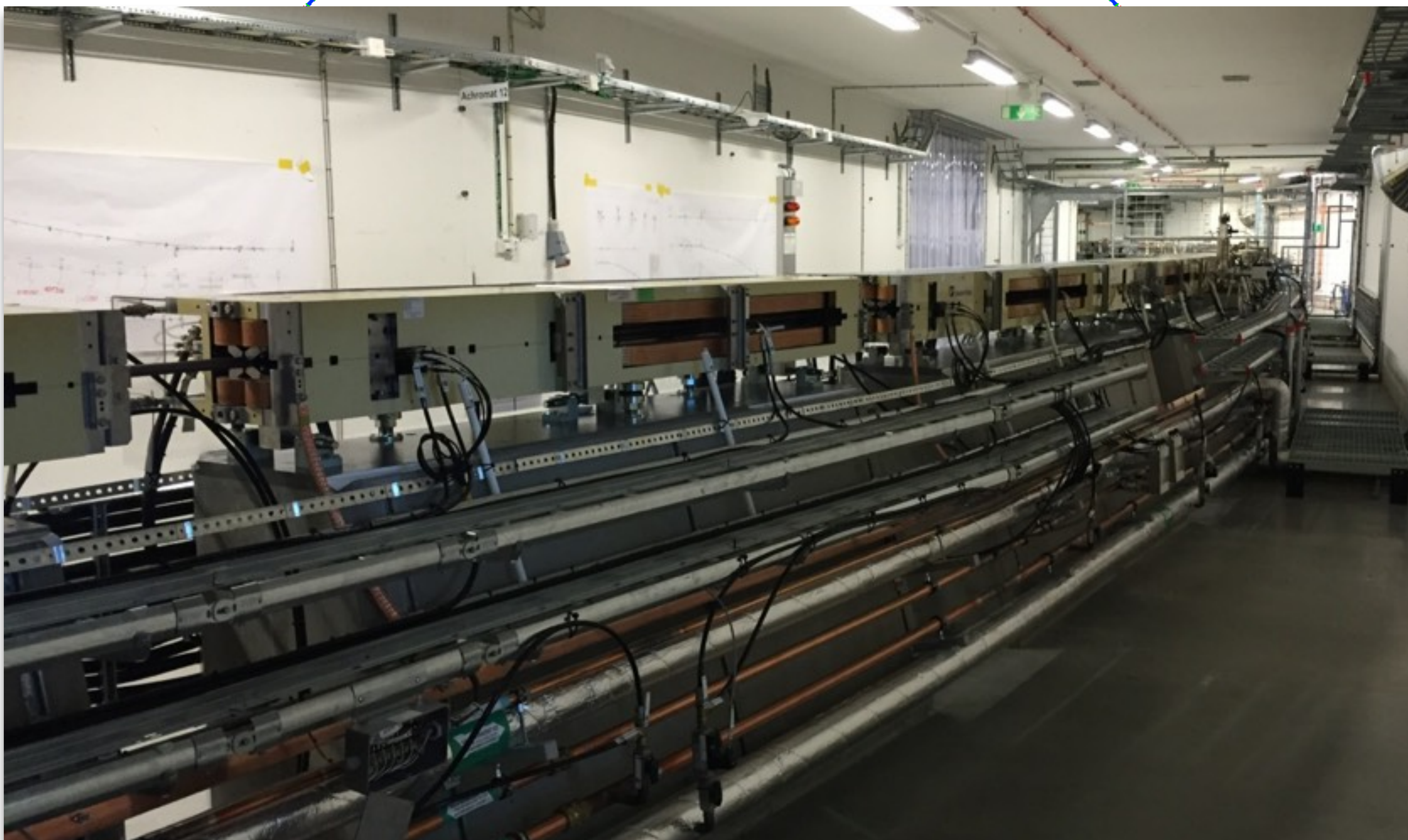


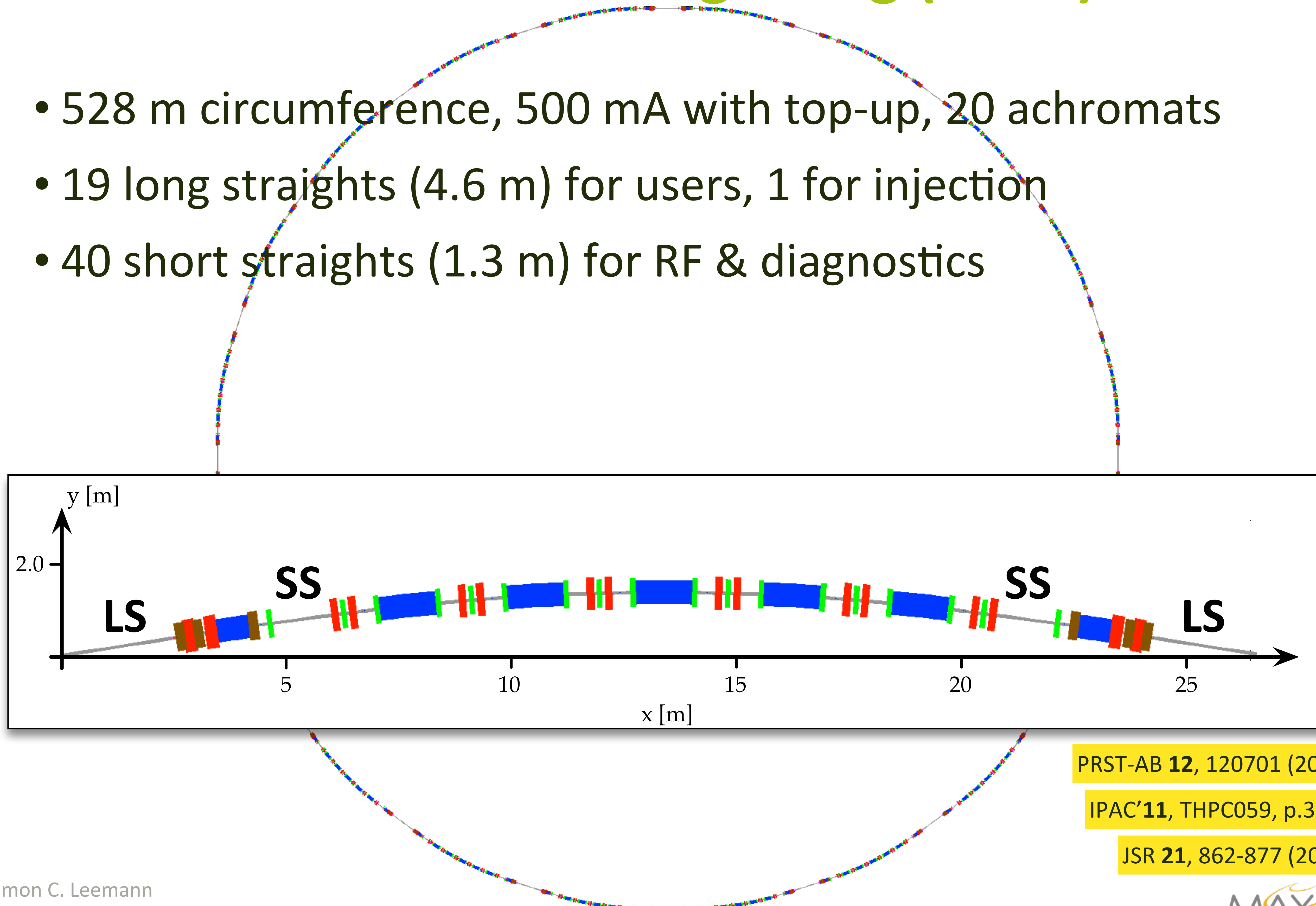
701 (2009)

59, p.3029

JSR **21**, 862-877 (2014)

The MAX IV 3 GeV Storage Ring (cont.)

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



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

IPAC’**11**, THPC059, p.3029

JSR **21**, 862-877 (2014)

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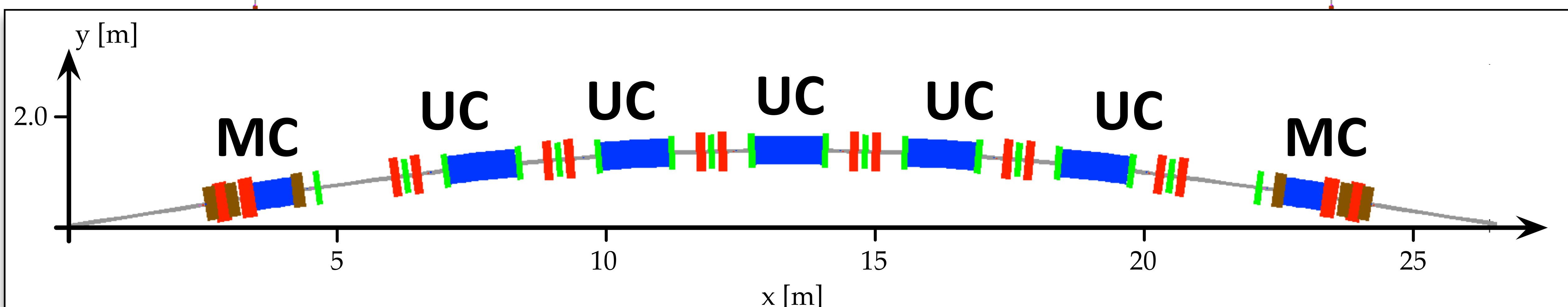
- 40 short straights (1.3 m) for RF & diagnostics
- 7-bend achromat: 5 unit cells (3°) & 2 matching cells (1.5° LGB)



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

IPAC’**11**, THPC059, p.3029

JSR **21**, 862-877 (2014)

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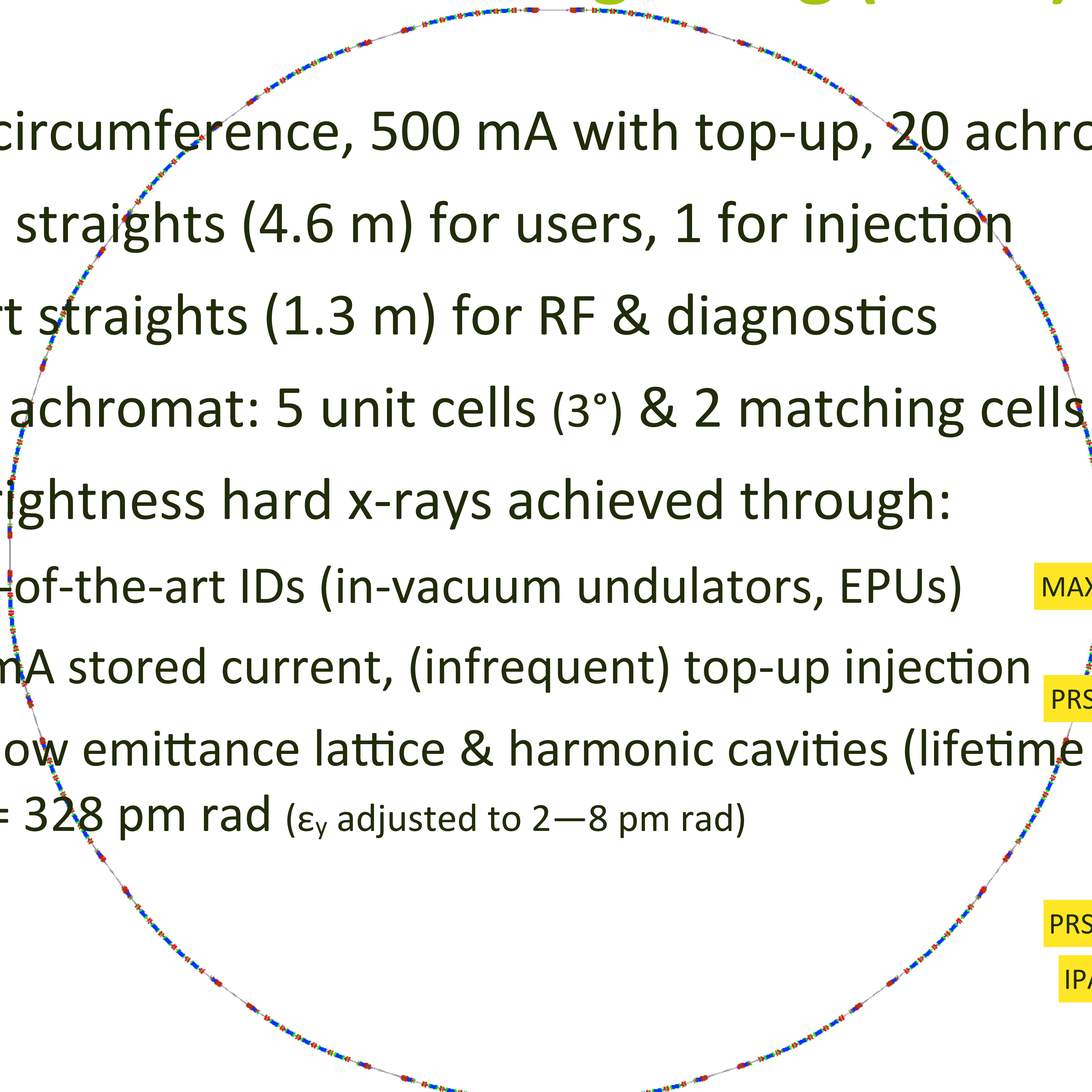


- 528 m circumference, 500 mA with top-up, 20 achromats
- 19 long straights (4.6 m) for users, 1 for injection
- 40 short straights (1.3 m) for RF & diagnostics
- 7-bend achromat: 5 unit cells (3°) & 2 matching cells (1.5° LGB)
- High-brightness hard x-rays achieved through:
  - state-of-the-art IDs (in-vacuum undulators, EPUs)
  - 500 mA stored current, (infrequent) top-up injection
  - ultralow emittance lattice & harmonic cavities (lifetime & IBS)
    - ➔ ε_x = 328 pm rad (ε_y adjusted to 2—8 pm rad)

MAX-lab Int.Note 20100215

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

PAC'**13**, MOPHO05

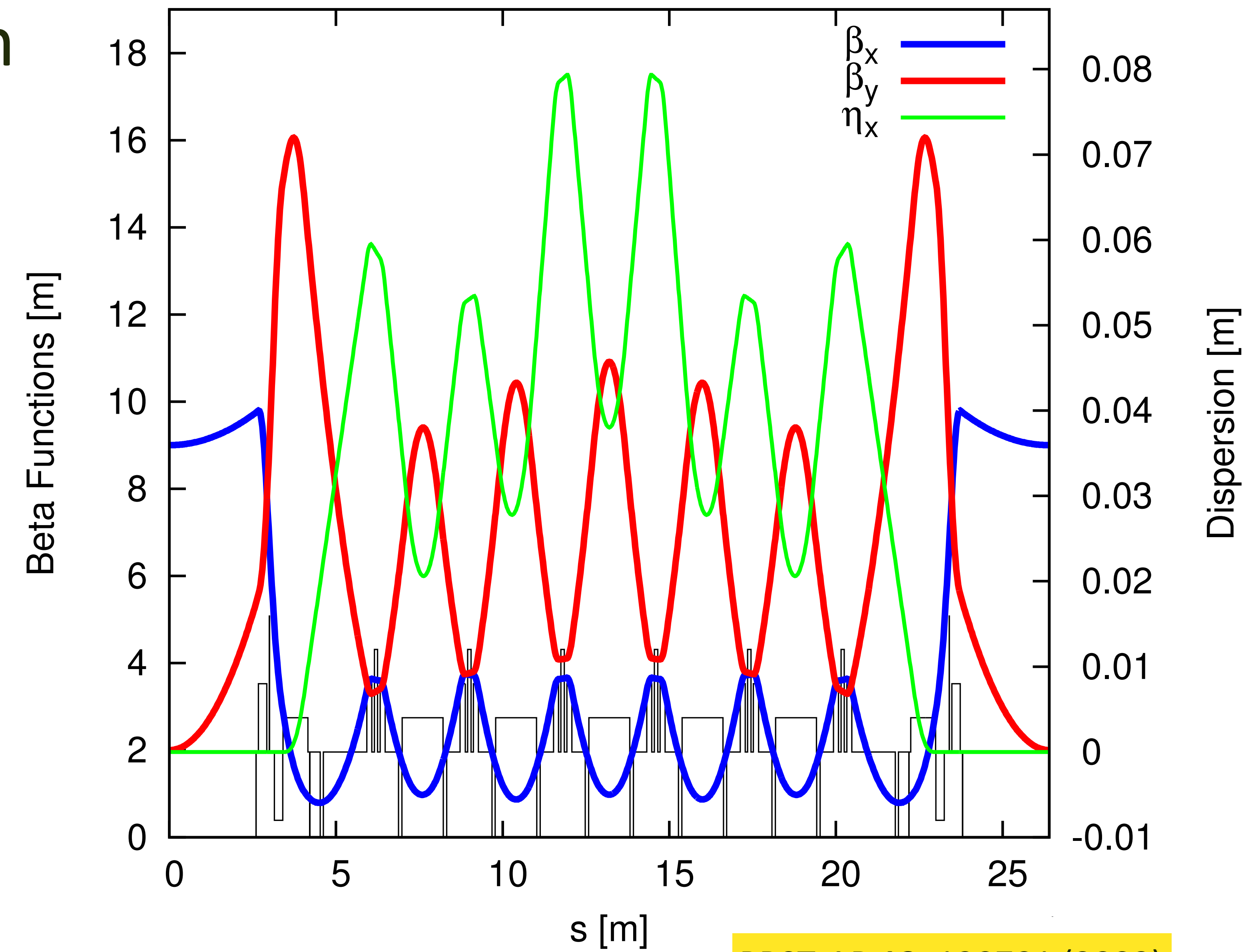
PRST-AB **12**, 120701 (2009)

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

JSR **21**, 862-877 (2014)

Linear Optics

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



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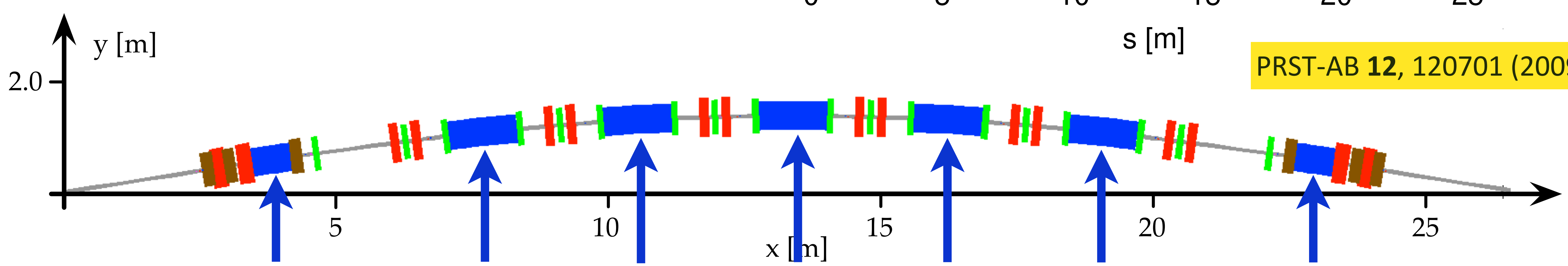
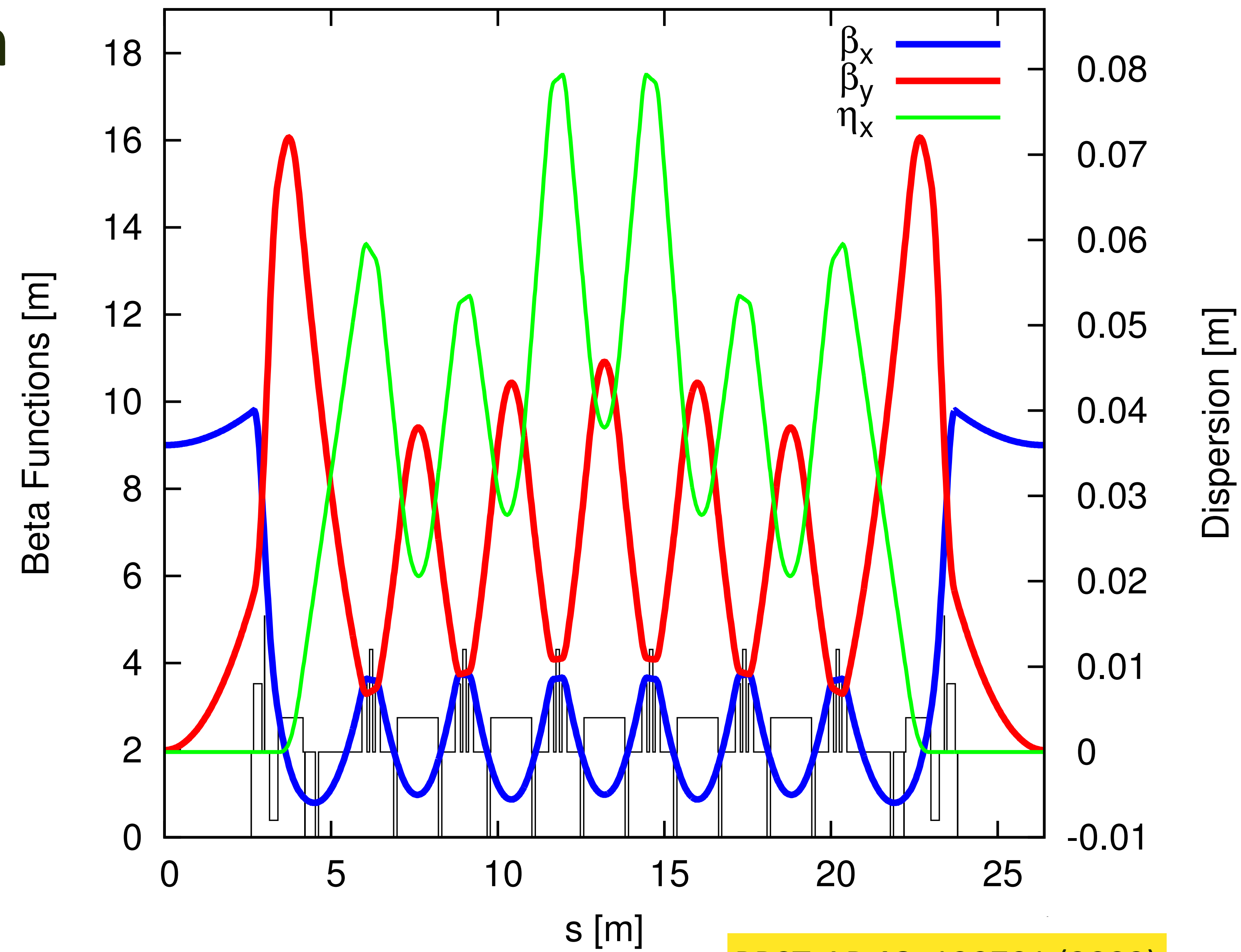


Linear Optics (cont.)

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



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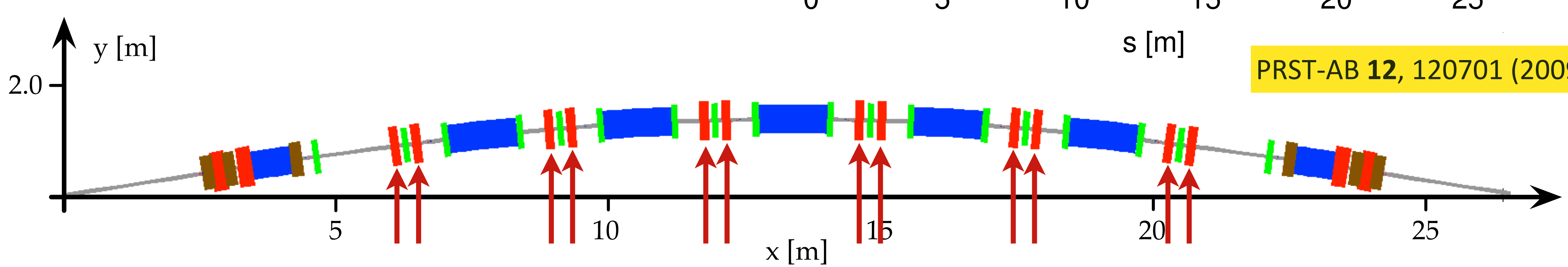
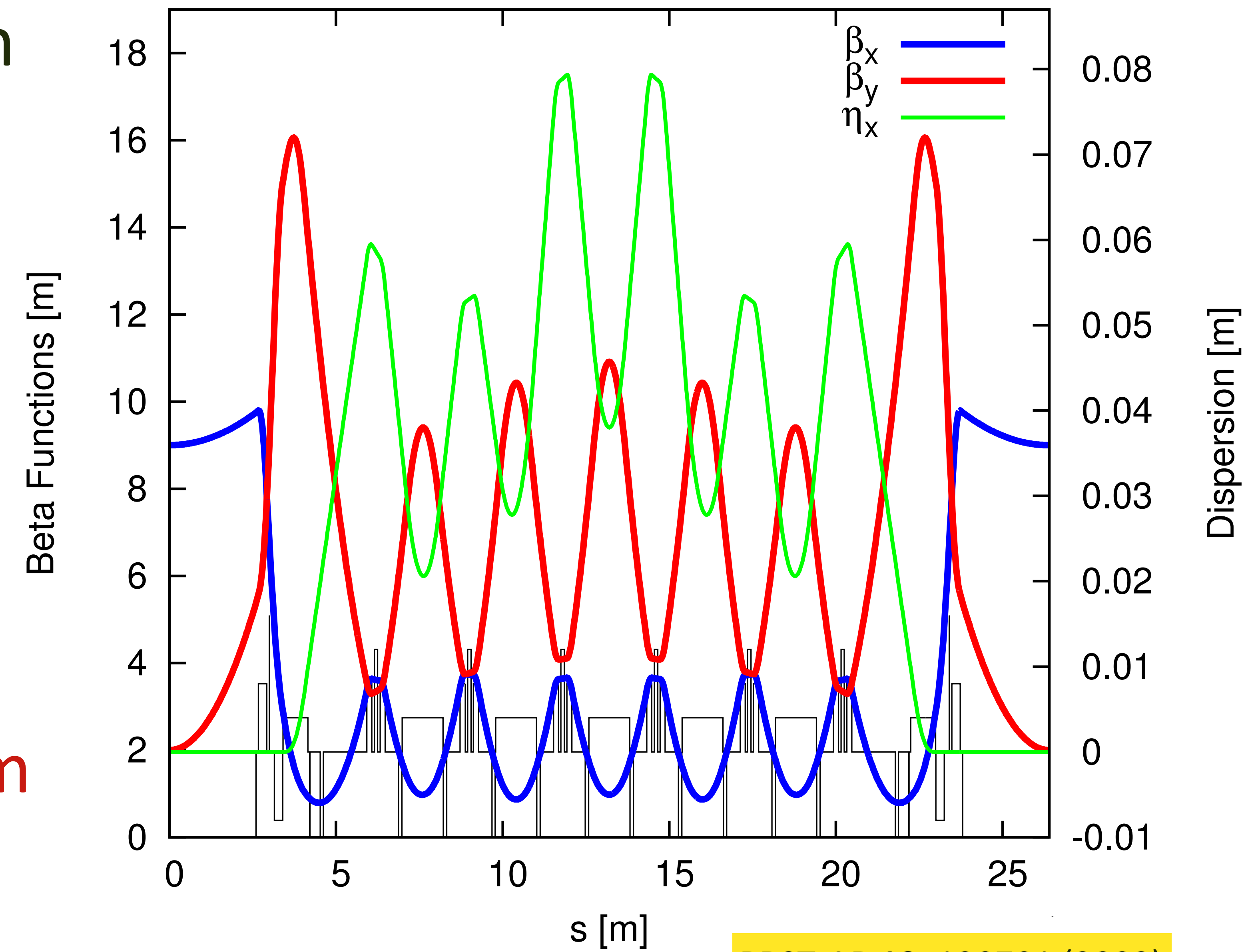


Linear Optics (cont.)

- 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, $\sigma_y^* = 2\text{-}4$ µm



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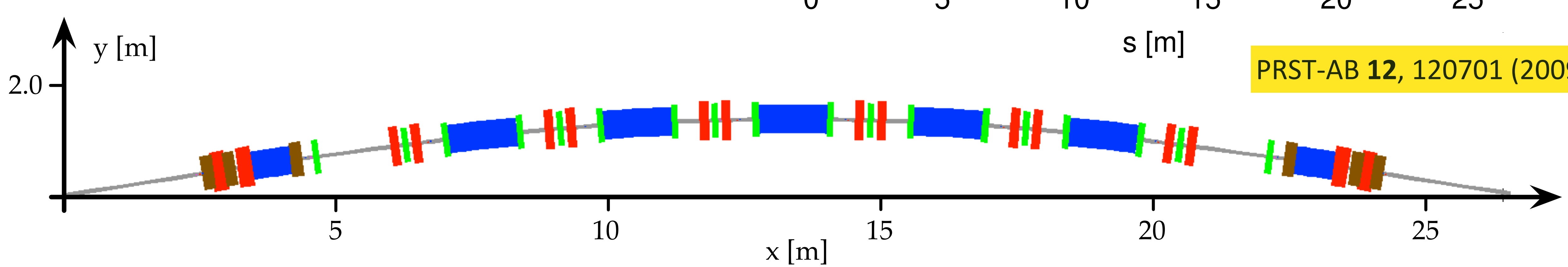
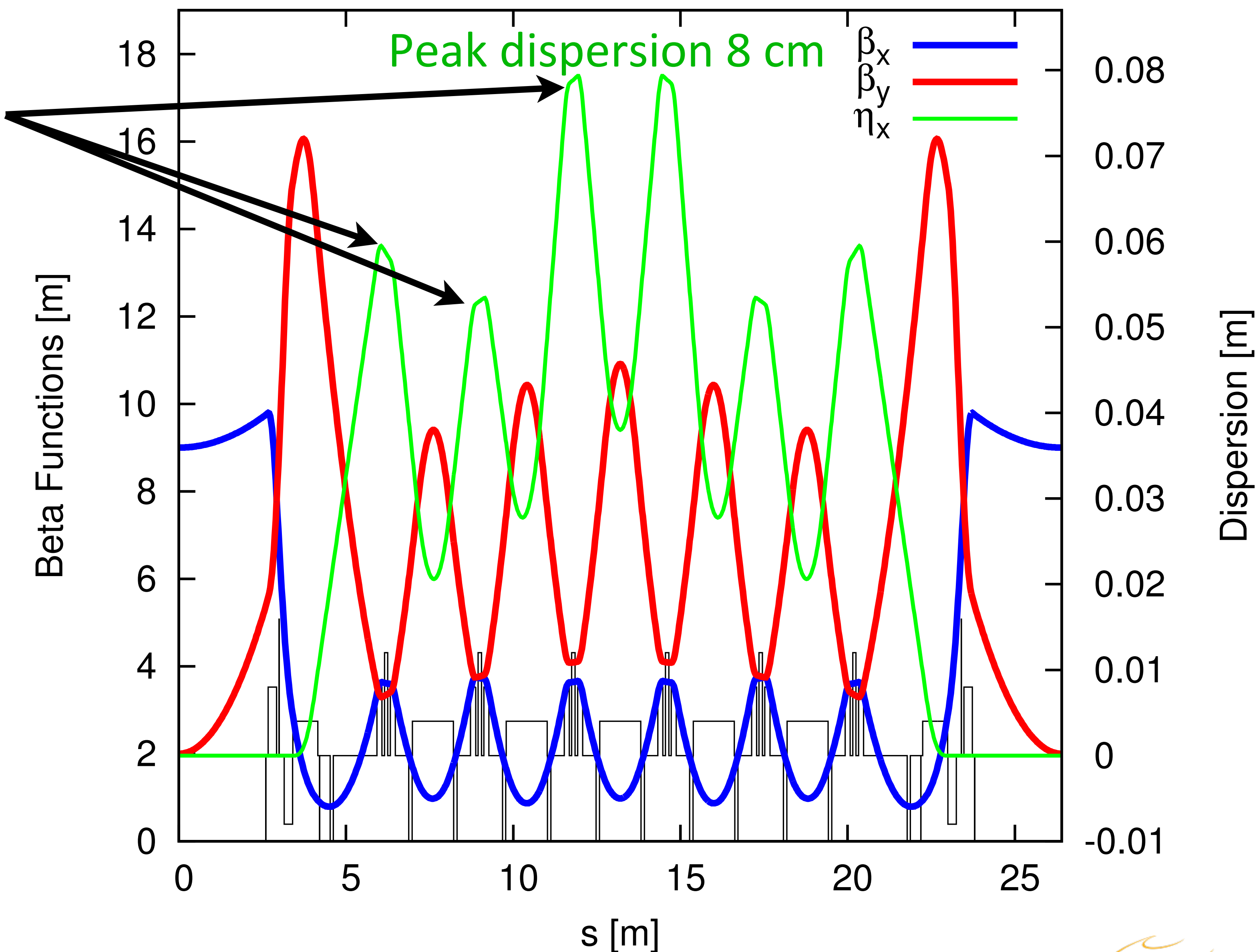


Nonlinear Optics

- 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)

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

Klotz & Mülhaupt, 4GLS WS, SLAC, 1992

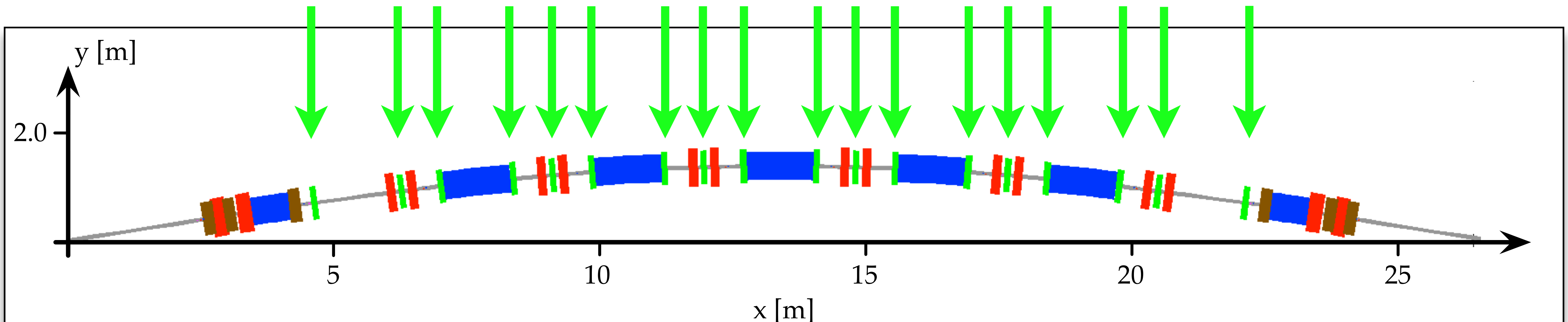


Nonlinear Optics (cont.)

- Natural $\xi_{x,y} \approx -50$ → many 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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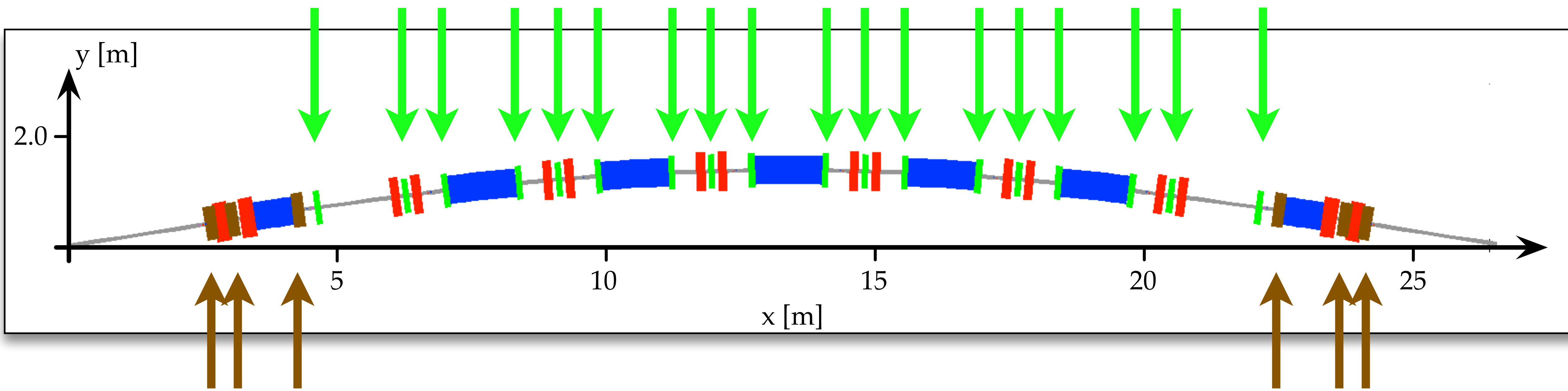
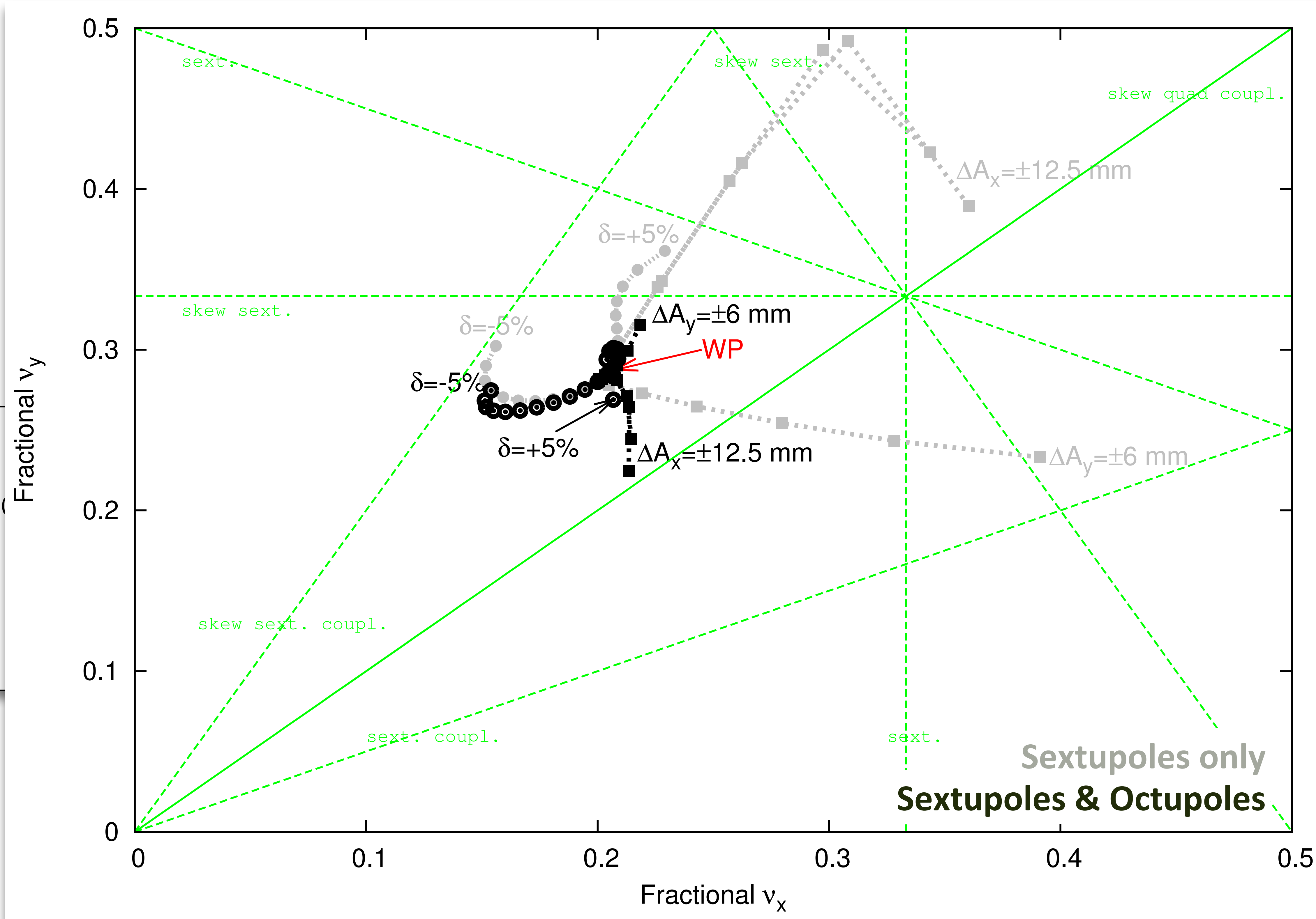


- Strong sextupoles drive large ADTS → achromatic octupoles allow tailoring ADTS to first order → minimize tune footprint

Nonlinear Optics (cont.)



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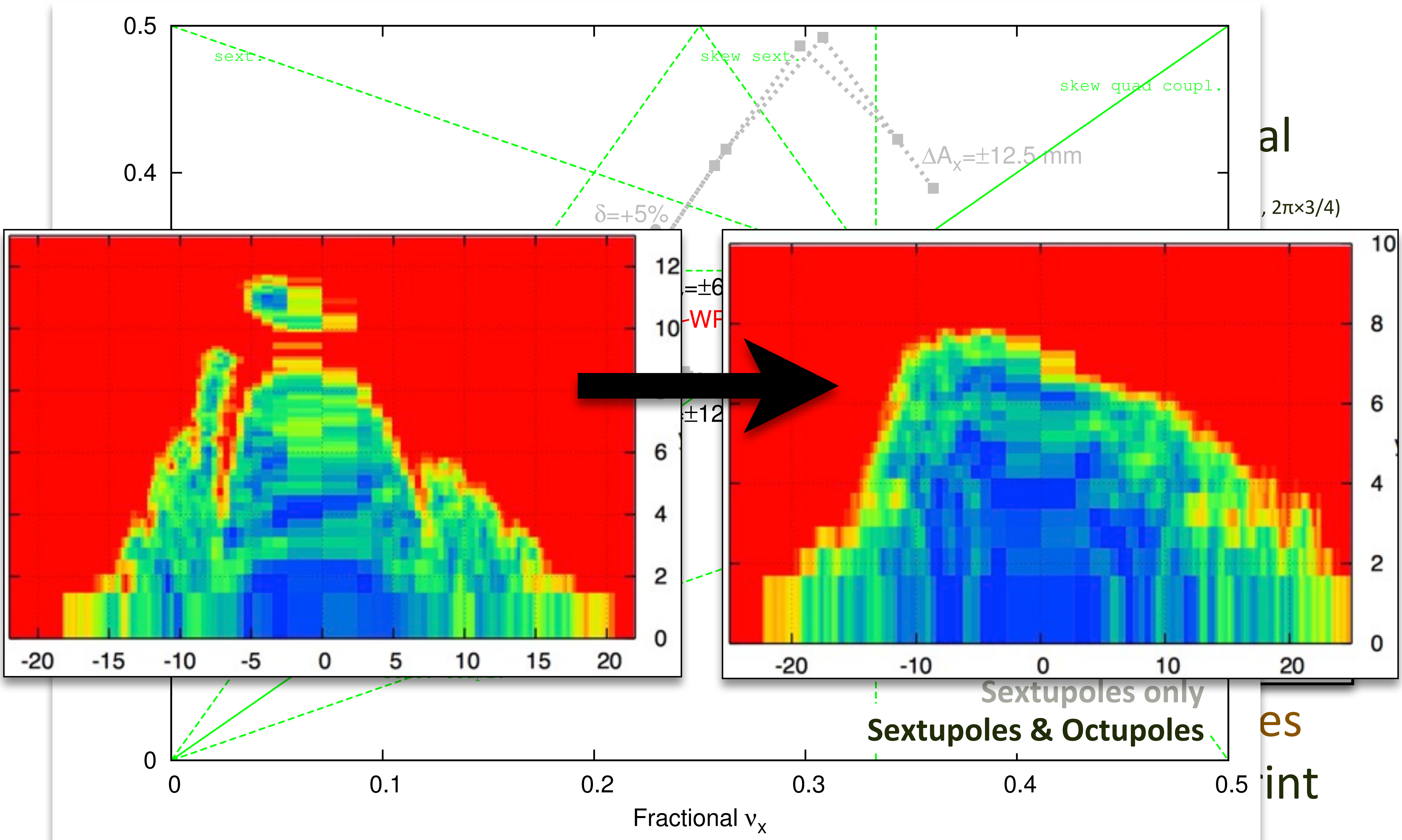
Nonlinear Optics (cont.)



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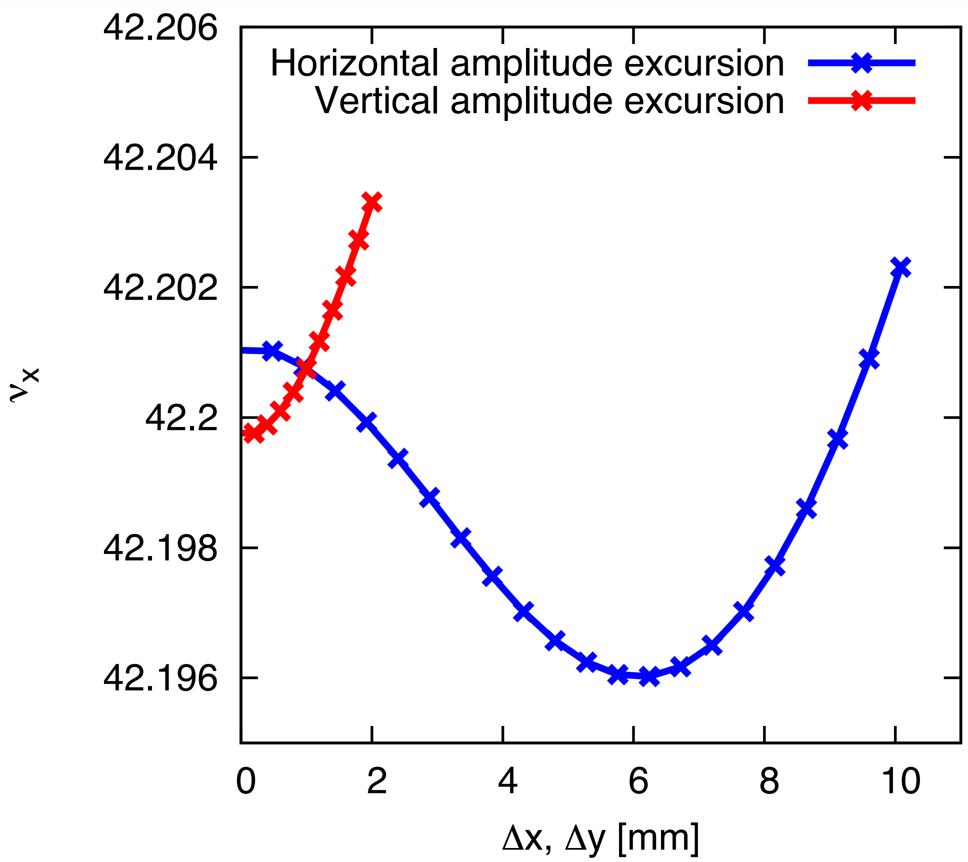
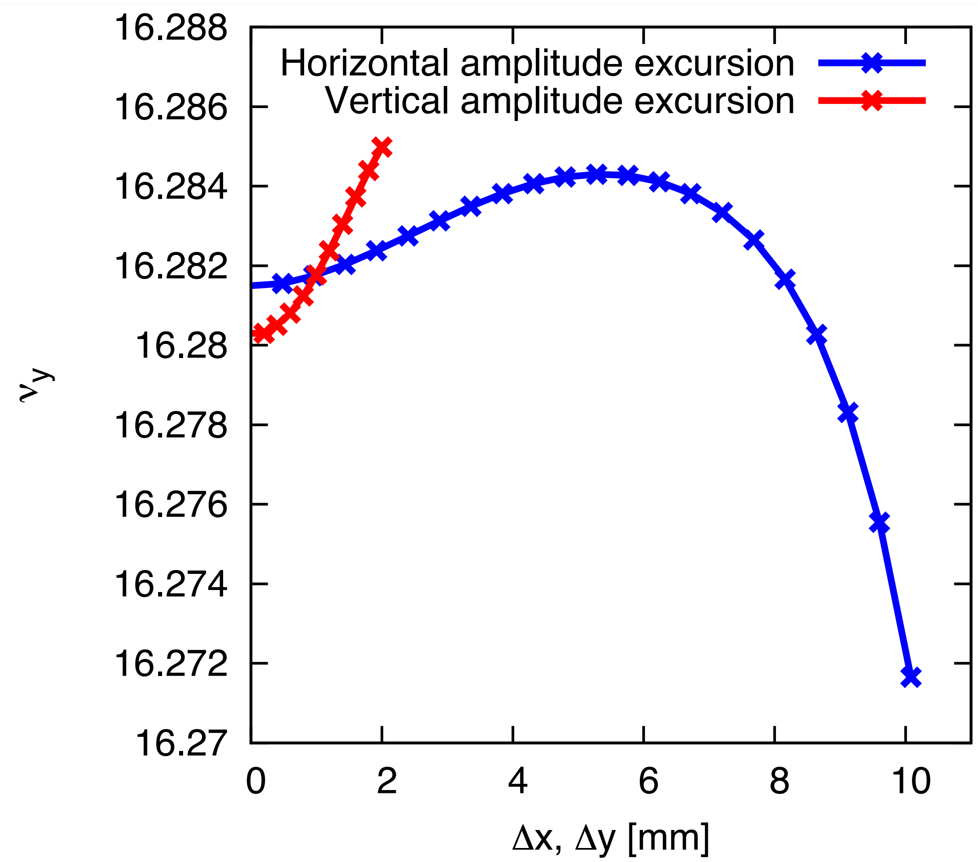
Optics Performance

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

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

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



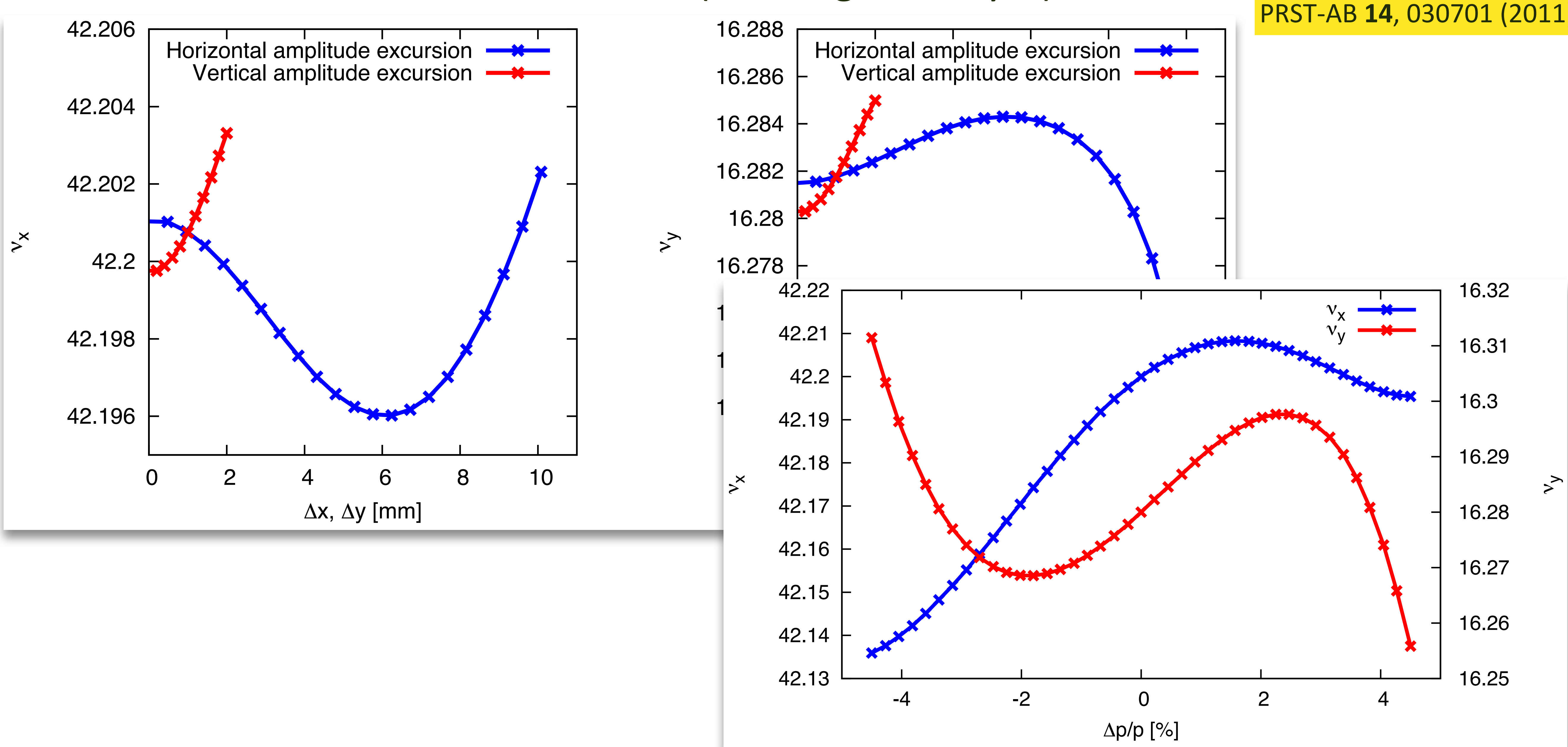


Optics Performance (cont.)

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

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

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



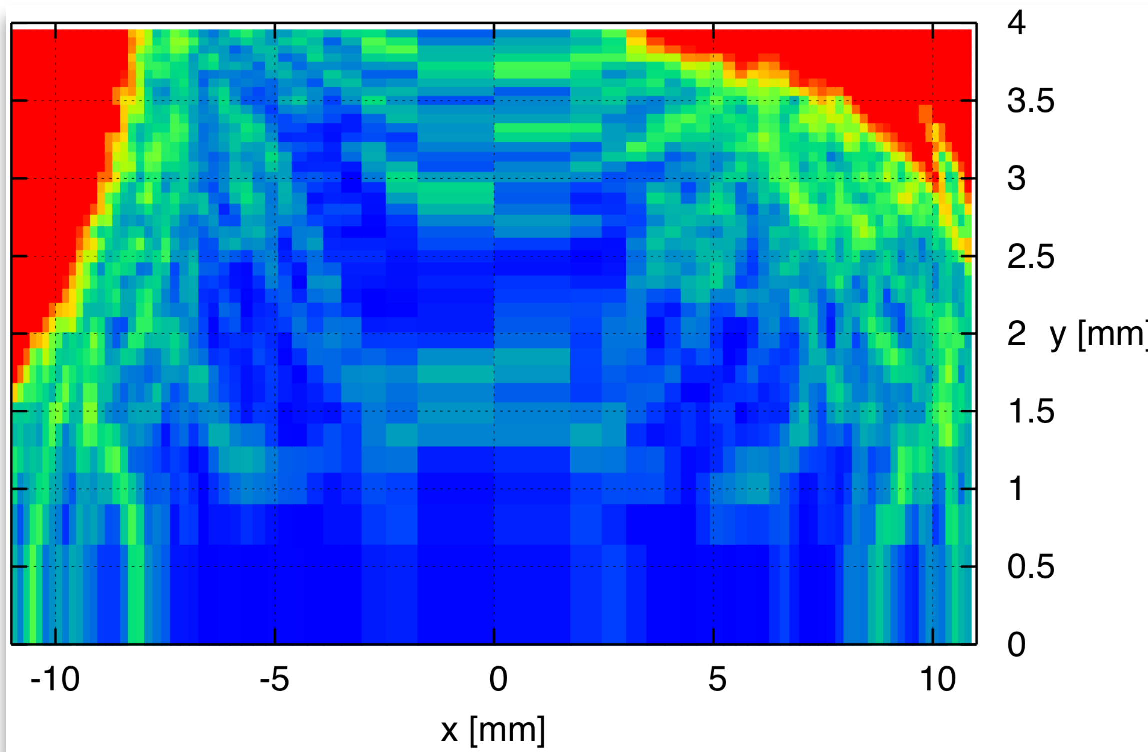
Optics Performance (cont.)

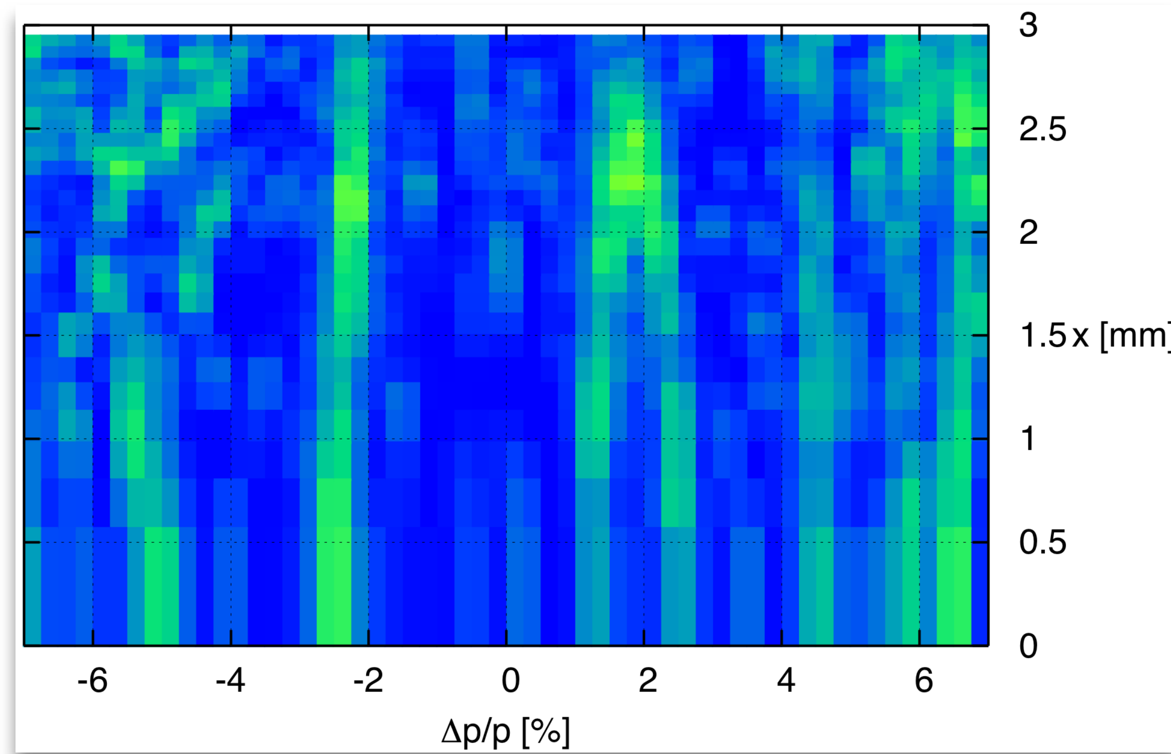
- Nonlinear optimization results in small amplitude-dependent and chromatic tune shifts (tracking in Tracy-3)

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





Optics Performance (cont.)

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

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

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

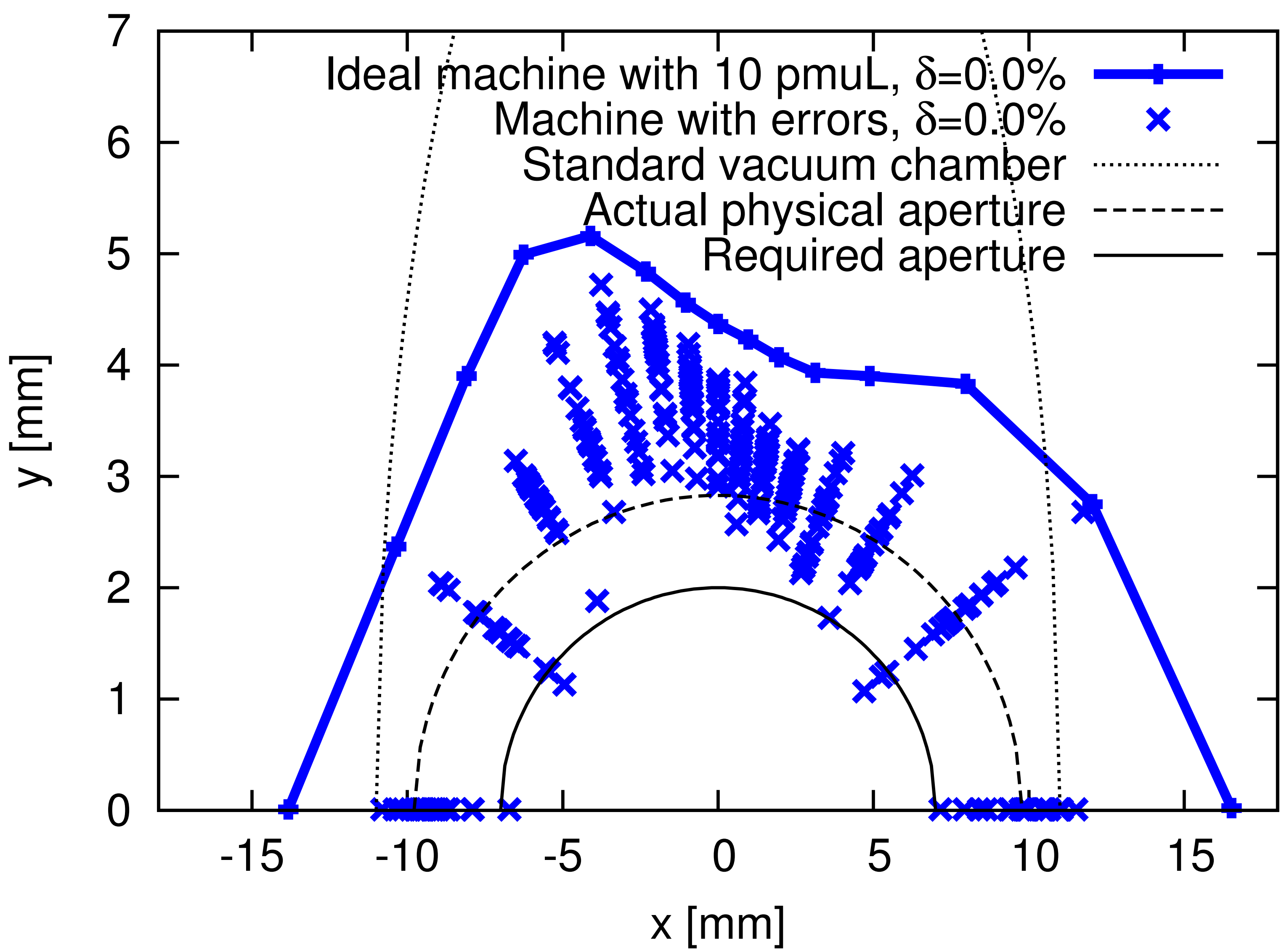
- Overall tune footprint becomes very compact both on and off momentum
  - large on-momentum DA ensures good injection efficiency
  - large off-momentum DA ensures good lattice MA
  - DA stable under influence of IDs, magnet errors & misalignments

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



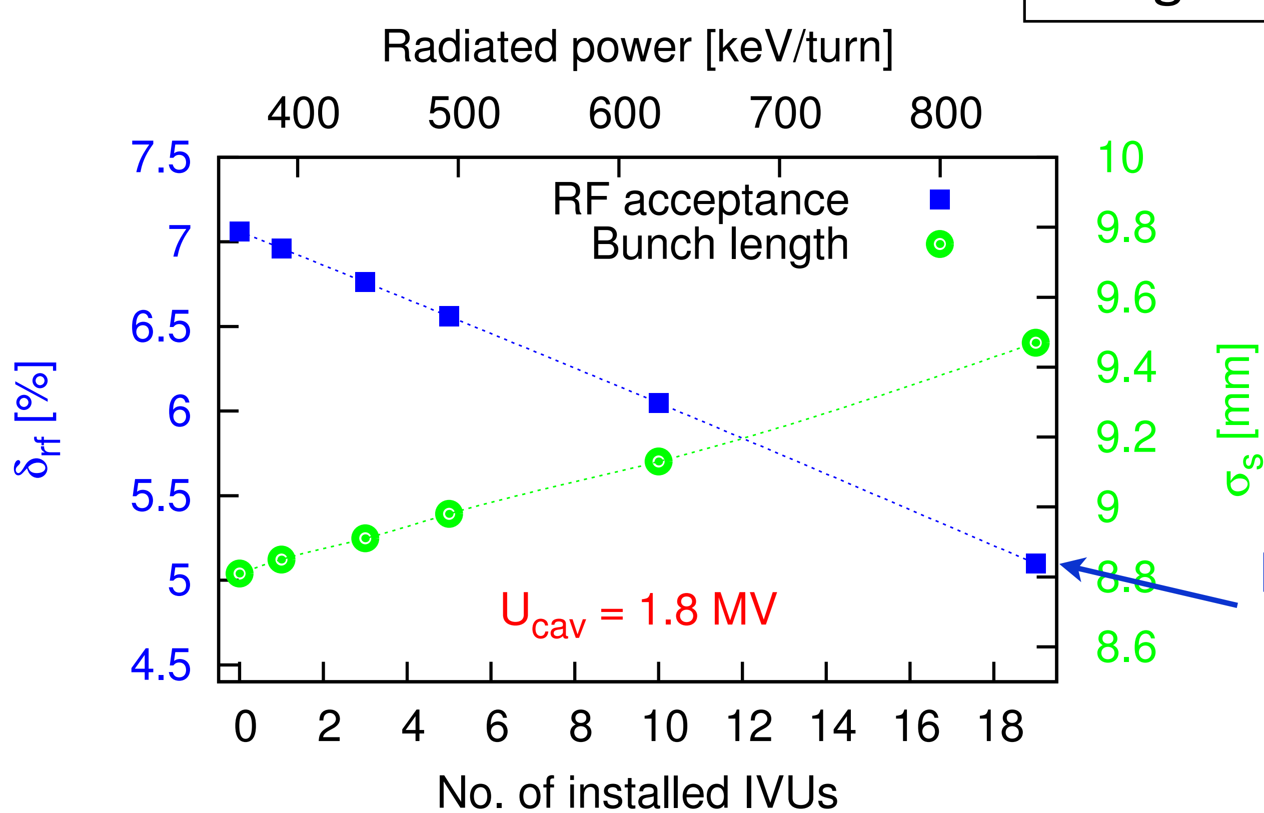
- IVU "pmuL":
  3.7 m long, 1.1 T peak field,
  18.5 mm period, 4.2 mm gap
- Misalignments:
  50 μm rms H/V
  0.2 mrad rms roll } for each magnet block
  25 μm rms H/V
  0.2 mrad rms roll } for all magnets within
- Field Errors:
  0.05% rms within each family
- Multipole Errors:
  Upright and skew multipoles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

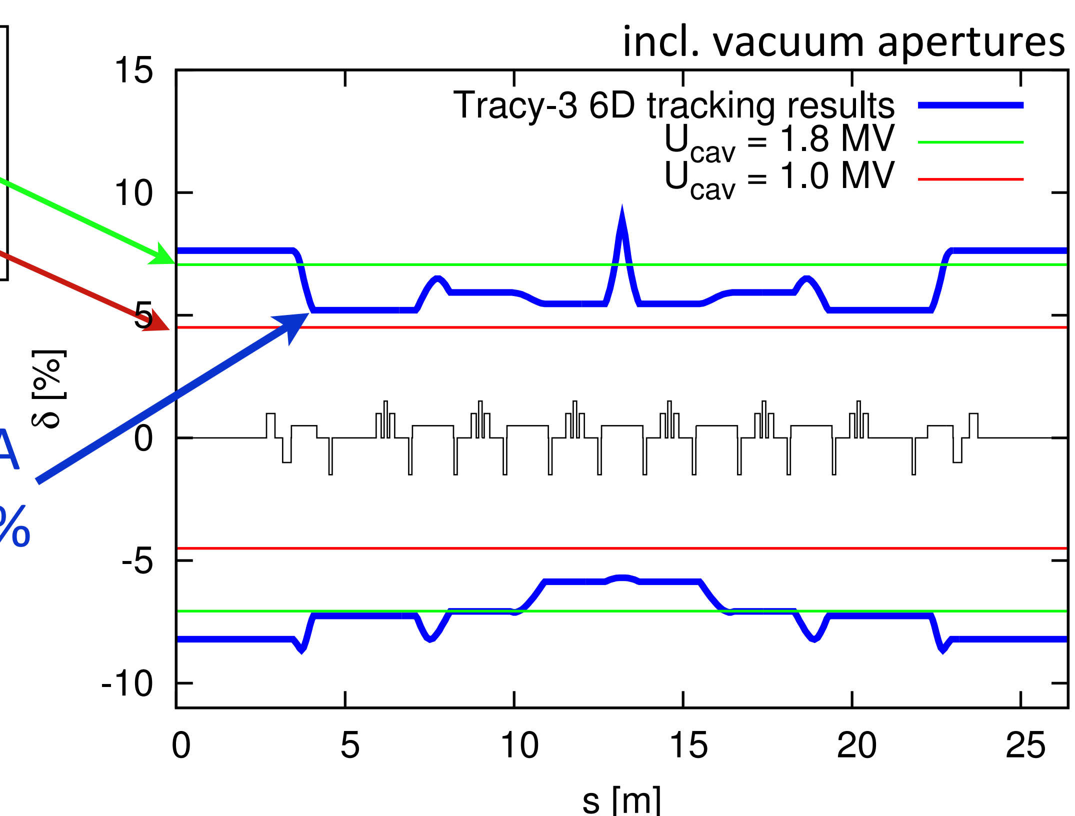
Optics Performance (cont.)

- 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: δ_{acc} > 4.5%





Lattice MA always >5%

RF acceptance always >5%

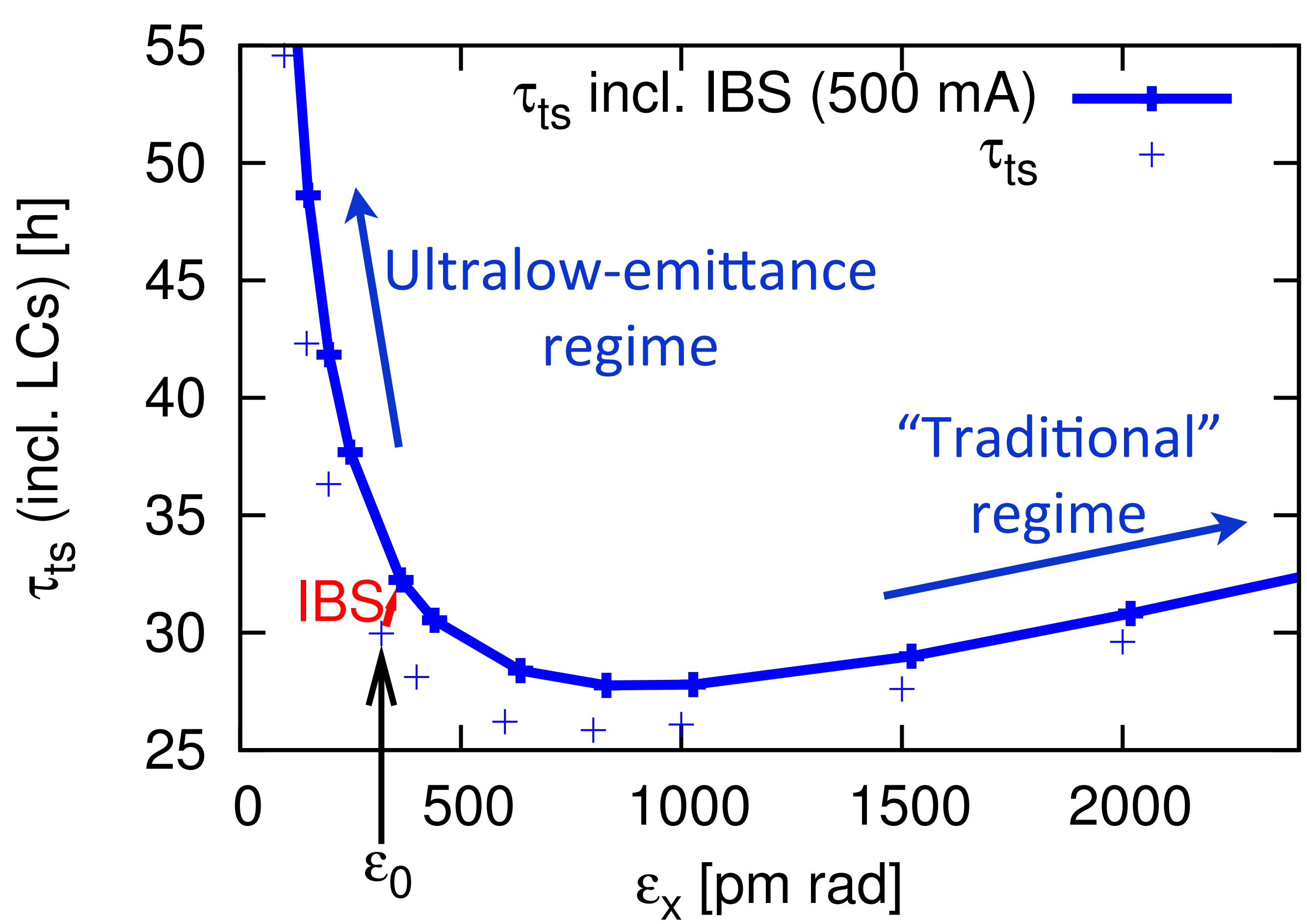
Optics Performance (cont.)

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

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

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

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



MAX IV 3 GeV SR (bare lattice)

I = 500 mA

δ_{acc} = 4.5%

σ_δ = const

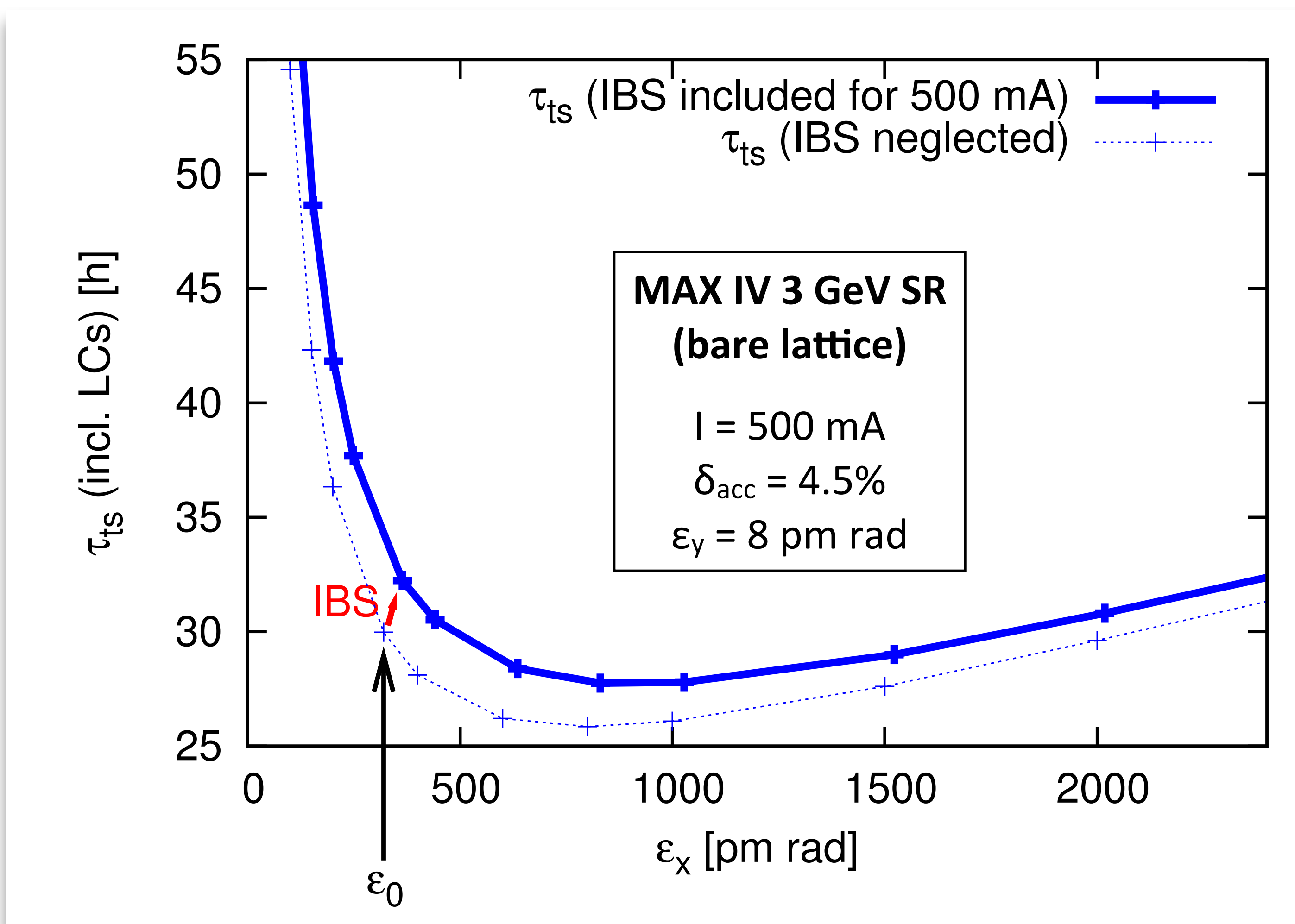
ε_y = 8 pm rad

Optics Performance (cont.)

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

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

- Large overall MA is required if ultralow emittance should render good Touschek lifetime
  (low emittance → small transverse momenta → few scattering events lead to actual Touschek <u>loss</u>)
- Use 300 MHz Landau cavities to stretch bunches ×5 ➔ extend Touschek lifetime beyond gas lifetime



Optics Performance (cont.)

- Large overall MA is required if ultralow emittance should render good Touschek lifetime
  (low emittance ➔ small transverse momenta ➔ few scattering events lead to actual Touschek loss)

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

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

- Use 300 MHz Landau cavities to stretch bunches ×5 ➔ extend Touschek lifetime beyond gas lifetime
- At MAX IV Landau cavities are indispensable to maintain ultralow emittance despite strong IBS at 500 mA stored current (5 nC/bunch)

Optics Performance (cont.)

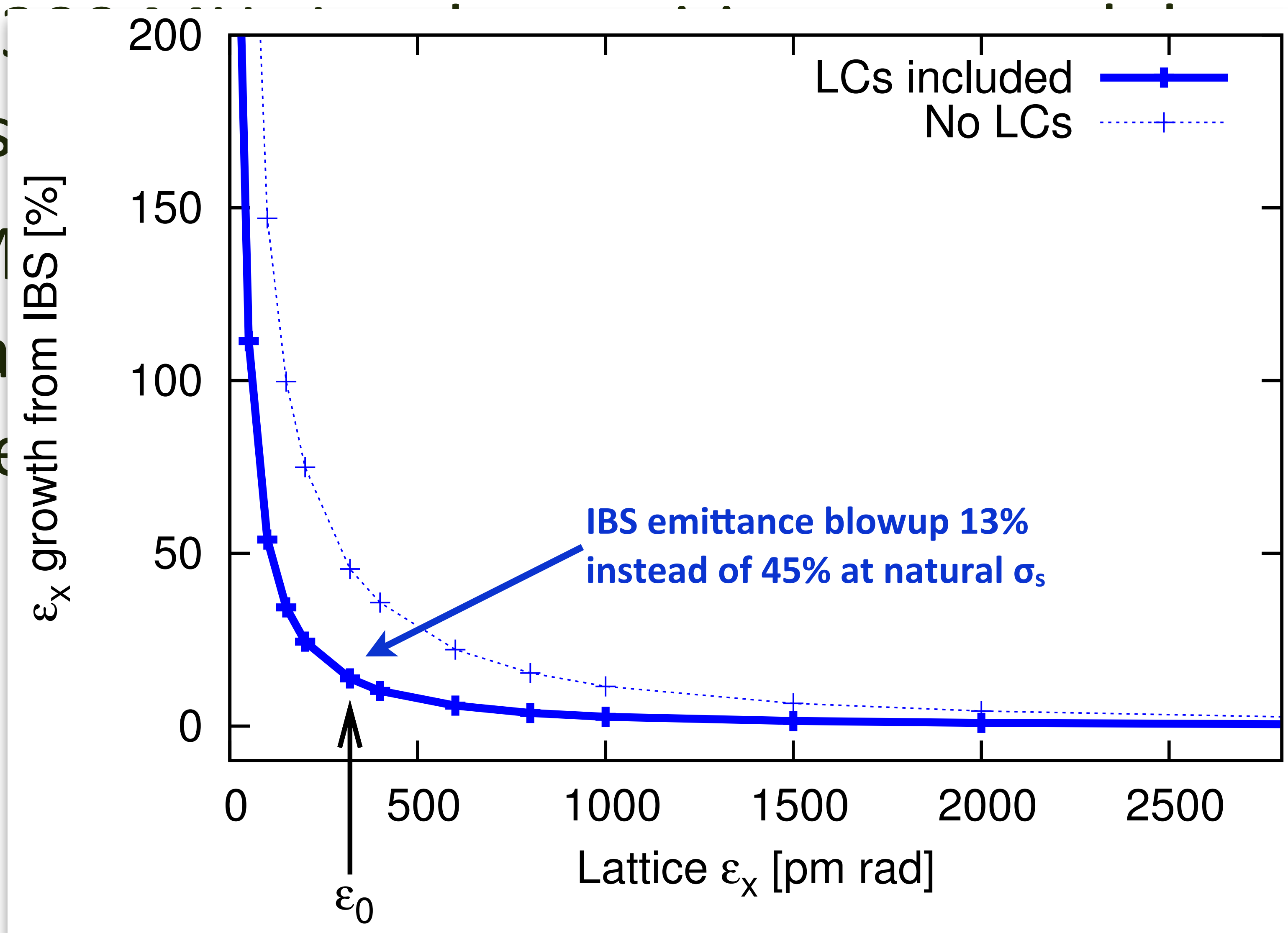
- Large overall MA is required if ultralow emittance should render good Touschek lifetime

  (low emittance → small transverse momenta → few scattering events lead to actual Touschek loss)

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

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

- Use … ches ×5 → extend Tous…
- At M… to maintain ultra… mA stored curre…



MAX IV 3 GeV SR (bare lattice)

$I = 500$ mA

$\delta_{acc} = 4.5\%$

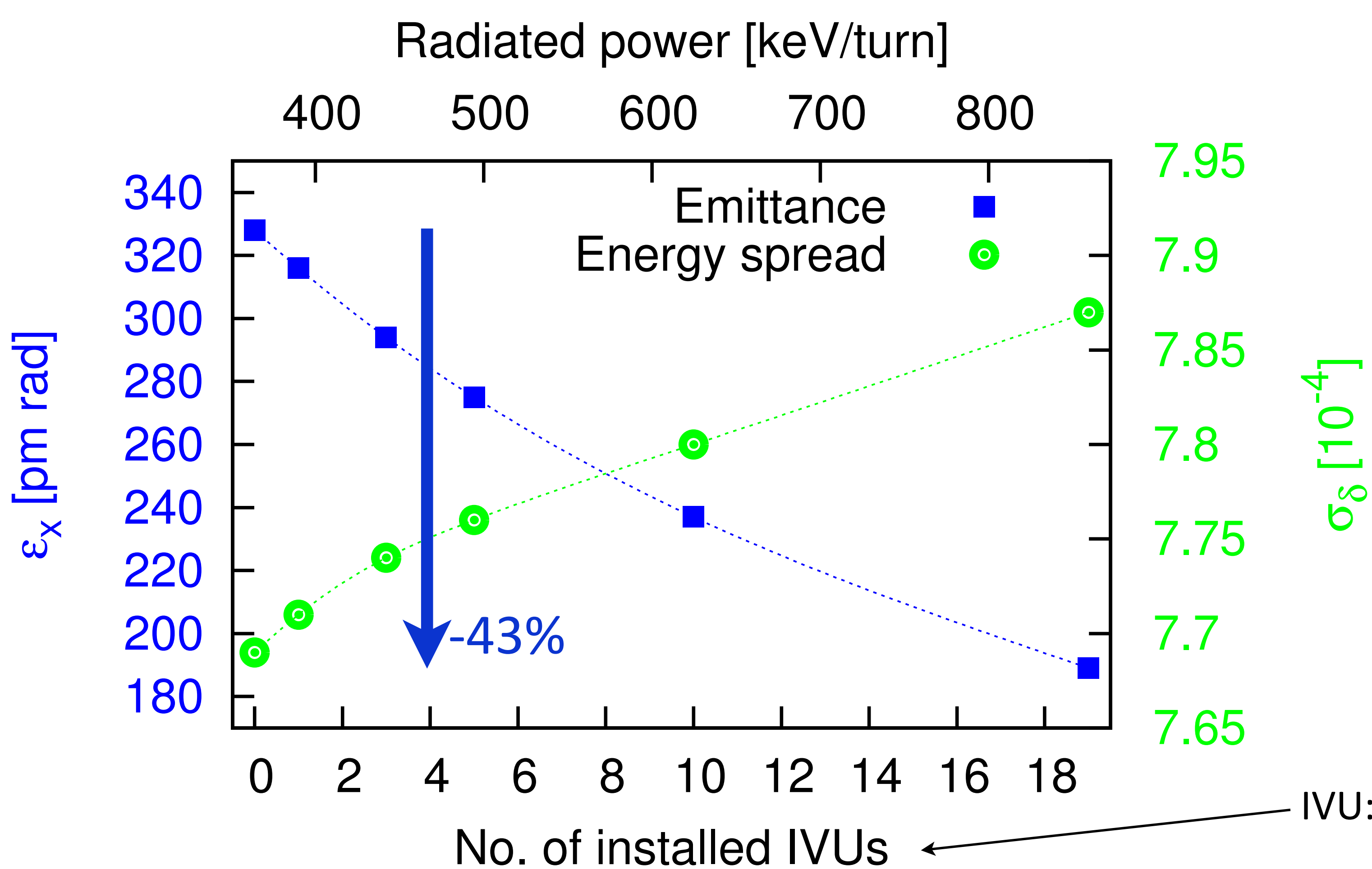
$\sigma_\delta \approx$ const

$\varepsilon_y = 8$ pm rad

Optics Performance (cont.)

- These modern rings are really a different beast
  - MBA lattices employ very weak dipoles
  - installed DWs and/or IDs can have huge impact on rad. power
  - emittance & energy spread determined by IDs & gap settings

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



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

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

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

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

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

Optics Performance (cont.)

- These modern rings are really a different beast PRST-AB **17**, 050705 (2014)
  - MBA lattices employ very weak dipoles
  - installed DWs and/or IDs can have huge impact on rad. power
  - emittance & energy spread determined by IDs & gap settings
  - IBS entangles longitudinal and transverse dynamics (@ low/medium energy)
  - despite top-up, as gaps change during user shifts → varying emittance, bunch length, lifetime, etc. → will need to monitor closely → feedback wiggler?

Linac & Injection

- MAX IV linac: 39 S-band structures & 19 RF stations (SS modulator, klystron, and SLED cavities) → ≈3.5 GeV (on crest)

Linac & Injection (cont.)

- MAX IV linac: 39 S-band structures & 19 RF stations (SS modulator, klystron, and SLED cavities) ➔ ≈3.5 GeV (on crest)

Linac & Injection (cont.)

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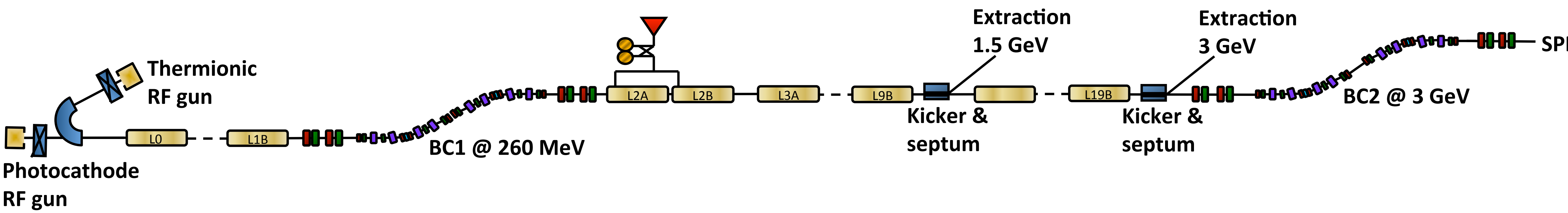
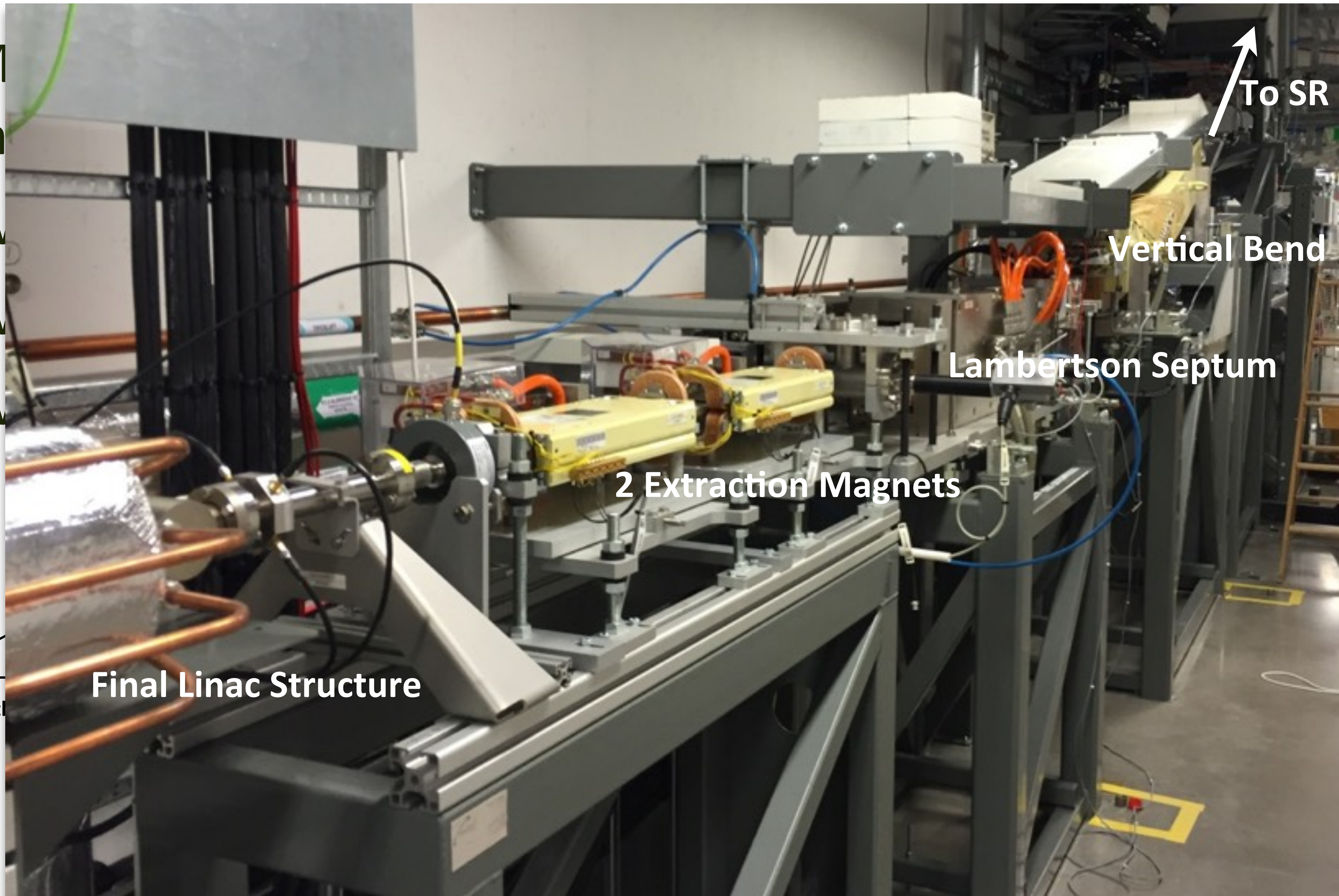
Linac & Injection (cont.)

- MAX IV linac: 39 S-band structures & 19 RF stations (SS modulator, klystron, and SLED cavities) → ≈3.5 GeV (on crest)
- Two guns (SPF/FEL vs. ring injection)
- Two magnetic bunch compressors (SPF/FEL)
- Two extraction points to SR transfer lines



Linac & Injection (cont.)

- M
  m … st)
- Tv
- Tv
- Tv

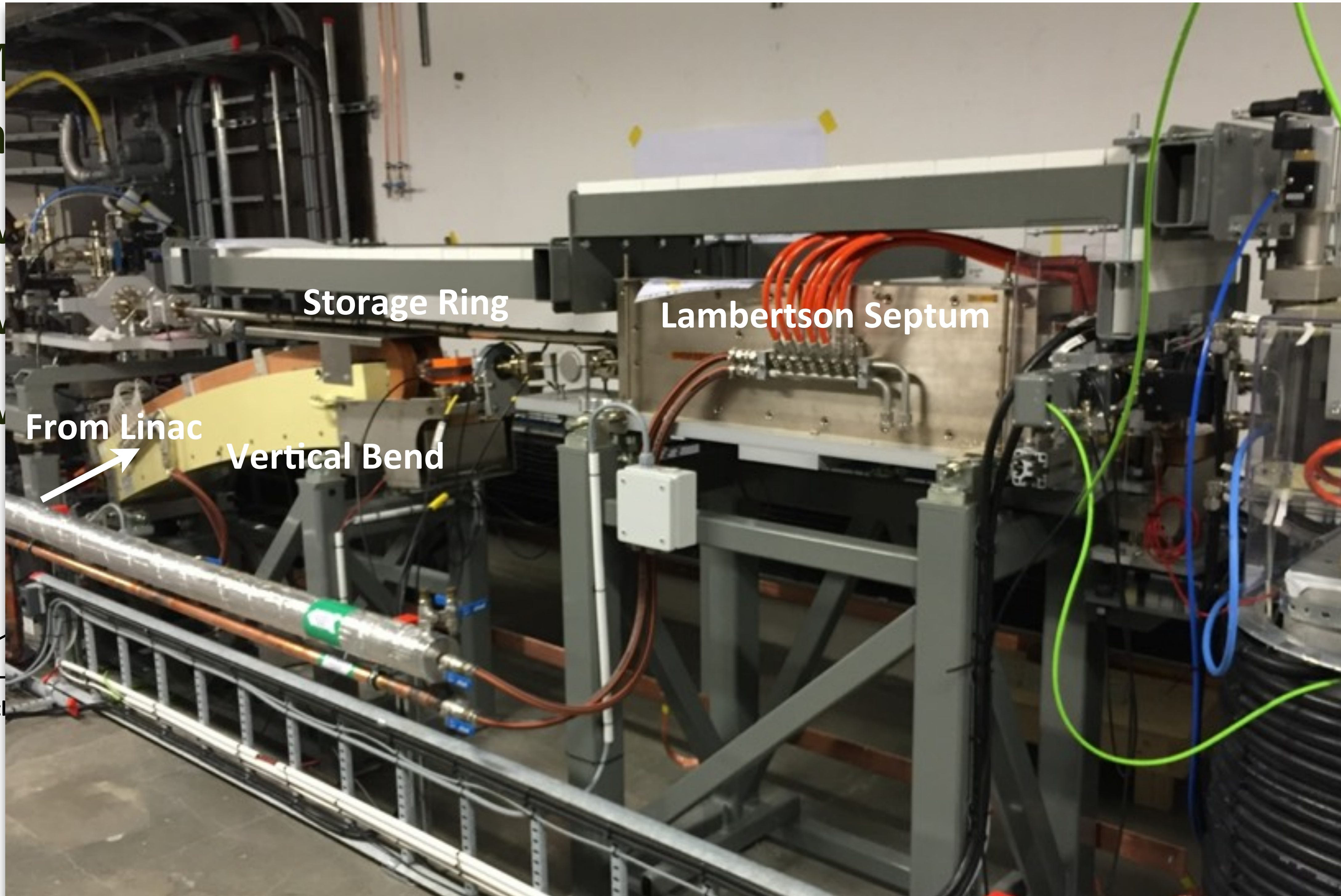


Photocat
RF gun

SPF

Linac & Injection (cont.)

- M
  m st)
- Tv
- Tv
- Tv

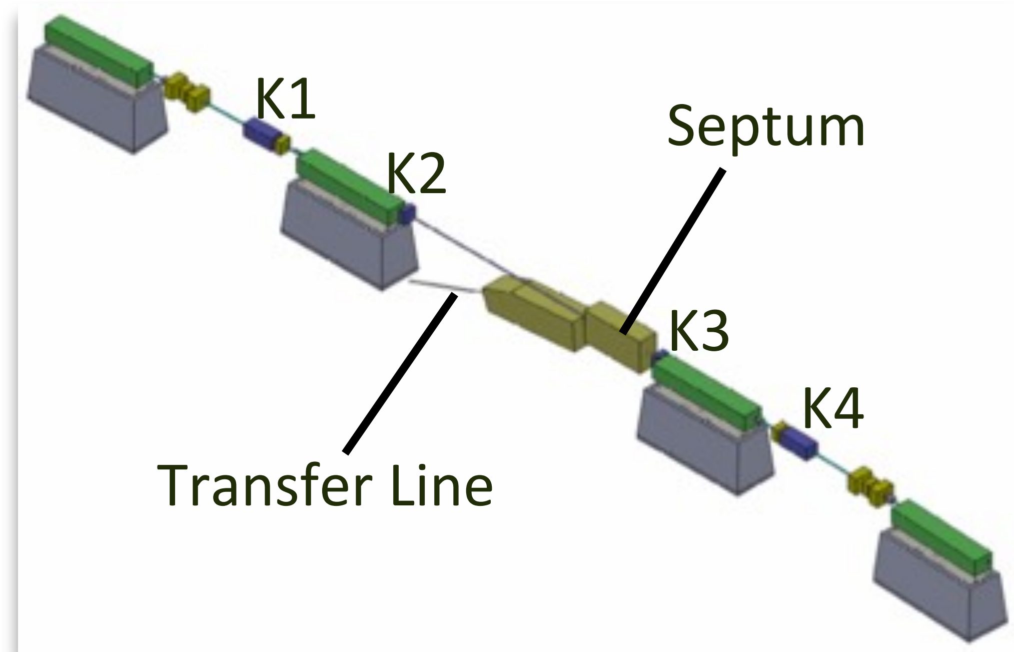


Photocatl
RF gun

SPF

Linac & Injection (cont.)

- The original plan: conventional 4-kicker bump injection
- But worried about stored beam stability during top-up
  - 200 nm vertical stability requirement



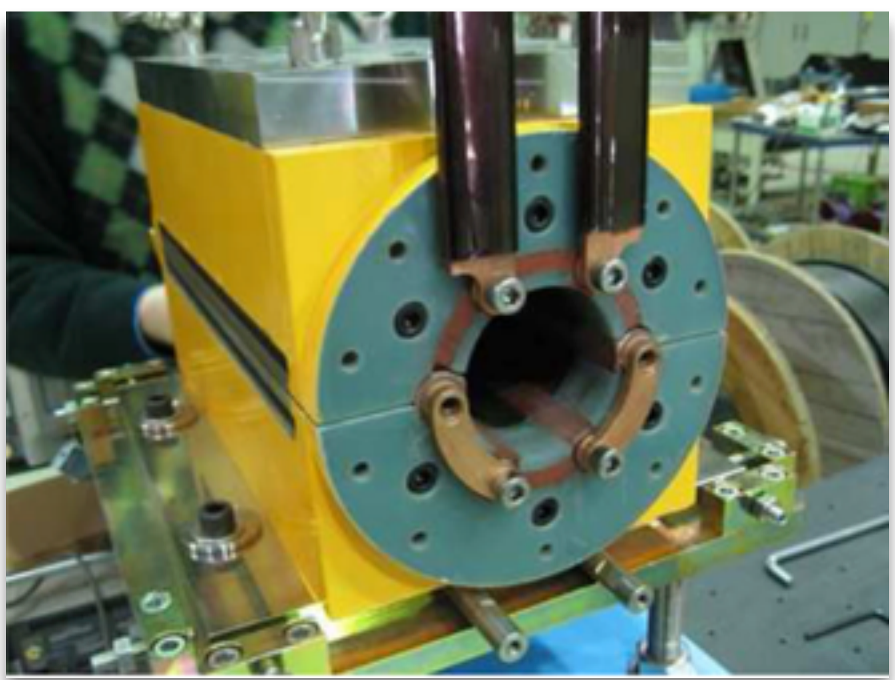
- Also worried about complexity
  - matching, synchronizing and aligning 4 kickers/pulsers to properly close bump
  - strong sextupoles & octupoles within bump: bump can only be properly closed for one energy and amplitude
  - 4 kickers and septum require lots of space

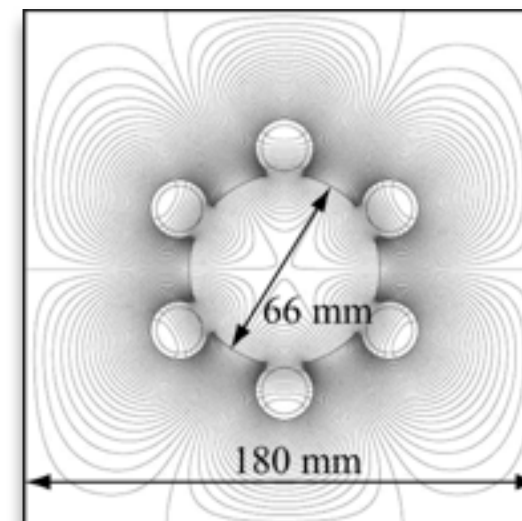
Linac & Injection (cont.)

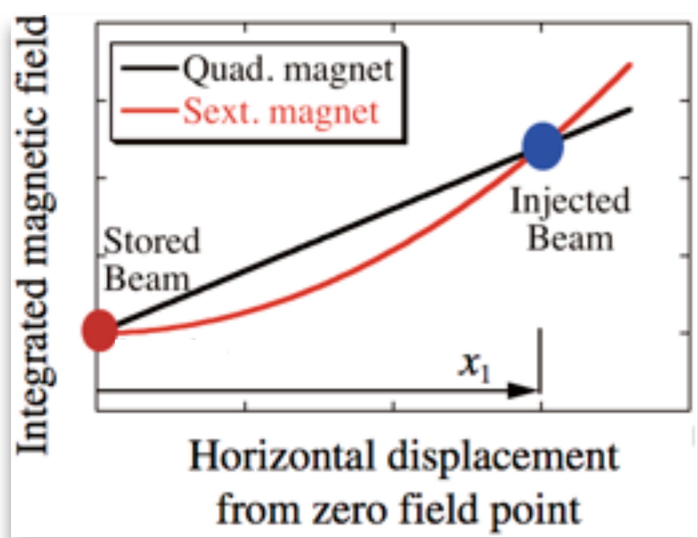
- Intrigued by KEK's pioneering work on PQM and PSM
  - align only a single magnet to stored beam
  - synchronize only one pulser to injection
  - PSM field flat around stored beam
  - ➡ minute perturbation of stored beam by PSM

PRST-AB **10**, 123501 (2007)

PRST-AB **13**, 020705 (2010)







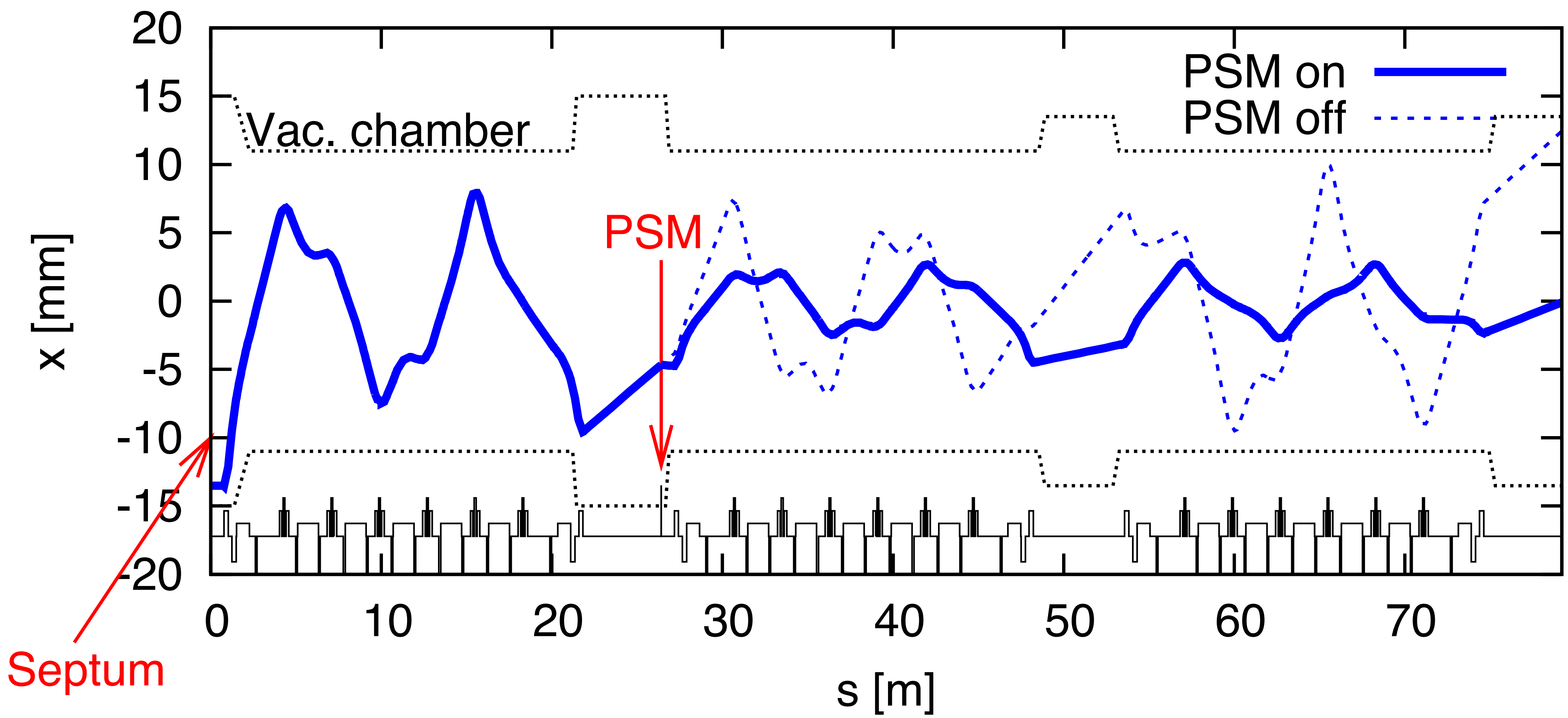
Magnetic field at 15 mm	40 mT
Magnetic length	300 mm
Bore diameter	66 mm
Peak current	3000 A
Pulse length	1.2 / 2.4 μs

Linac & Injection (cont.)

- Decided to use pulsed sextupole magnet injection for top-up injection into both MAX IV storage rings

PRST-AB **15**, 050705 (2012)

- Strong nonlinearities in MAX IV storage rings → tracking (Tracy-3, DIMAD): optimization of beam position/angle in septum & location/strength of PSM



$$\cos \phi_{\text{psm}} = \pm \frac{A_{\text{red}}}{A_{\text{inj}}}$$

$$\frac{|x_{\text{psm}}|}{\sqrt{\beta_{\text{psm}}}} < A_x$$

$$(b_3 L) = \frac{\theta_{\text{psm}}}{{x_{\text{psm}}}^2}$$

Determine location of PSM ϕ_{psm} and kick θ_{psm} required to minimize invariant after capture

Linac & Injection (cont.)

- Decided to use pulsed sextupole magnet injection for top-up injection into both MAX IV storage rings

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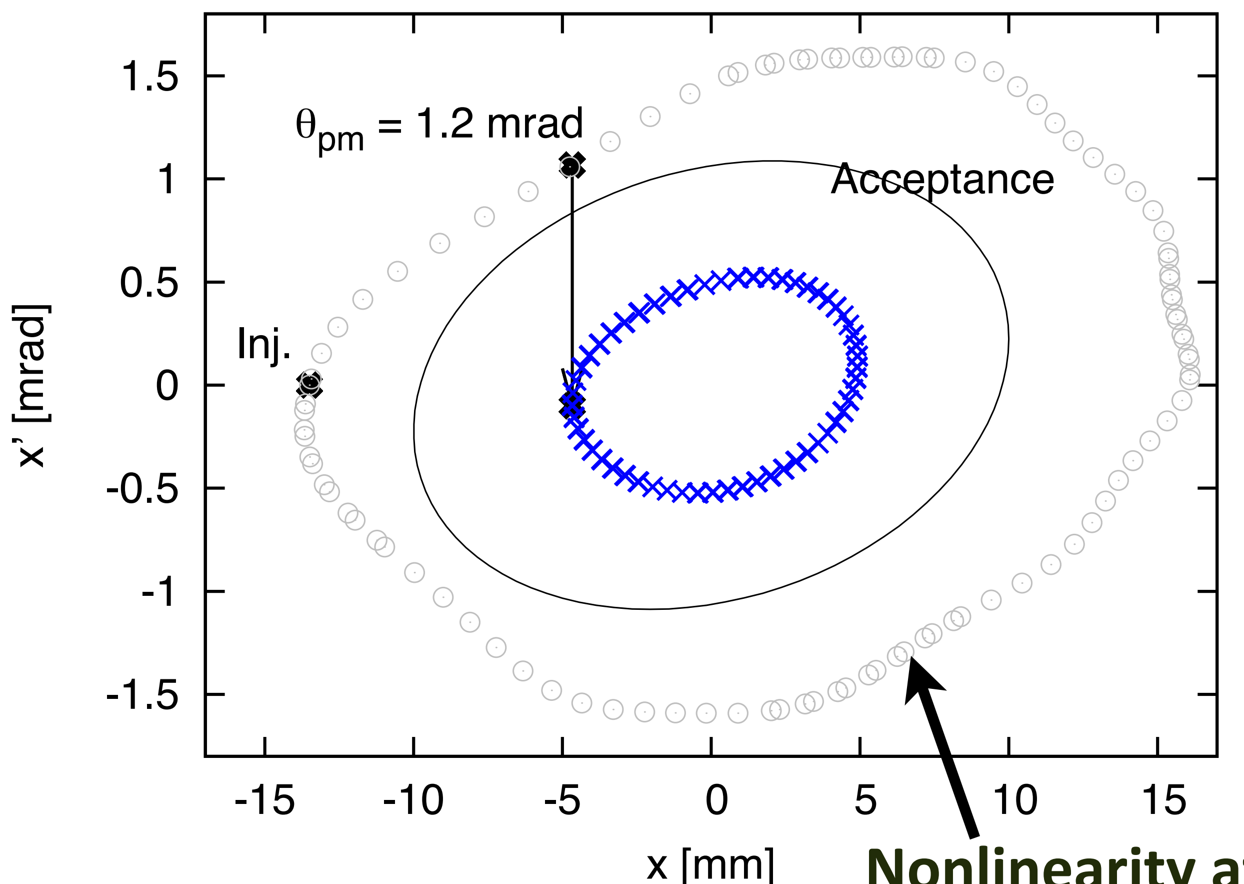

Nonlinearity at large amplitudes

≈1.2 mrad to minimize reduced invariant

≈0.8 mrad sufficient for capture within (design) acceptance

Linac & Injection (cont.)

- Decided to use pulsed sextupole magnet injection for top-up injection into both MAX IV storage rings

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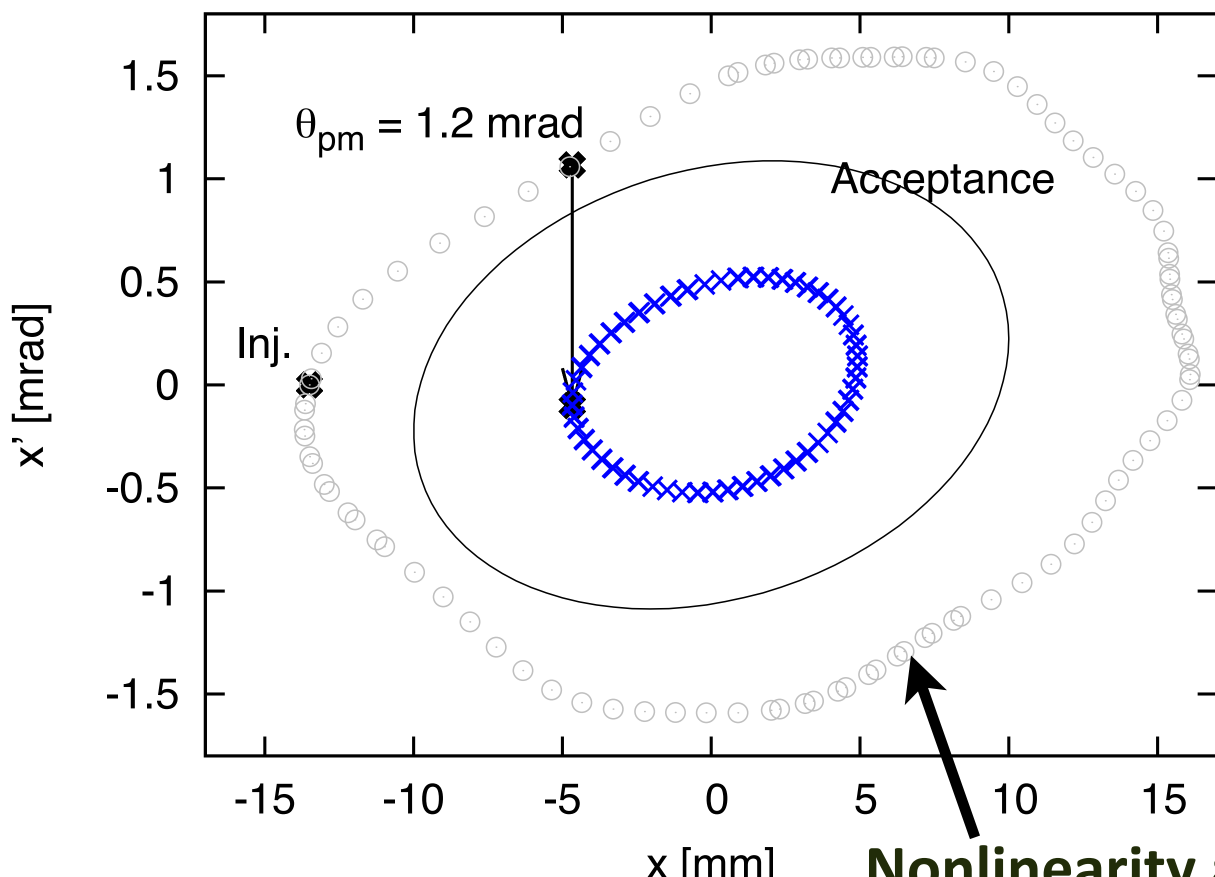
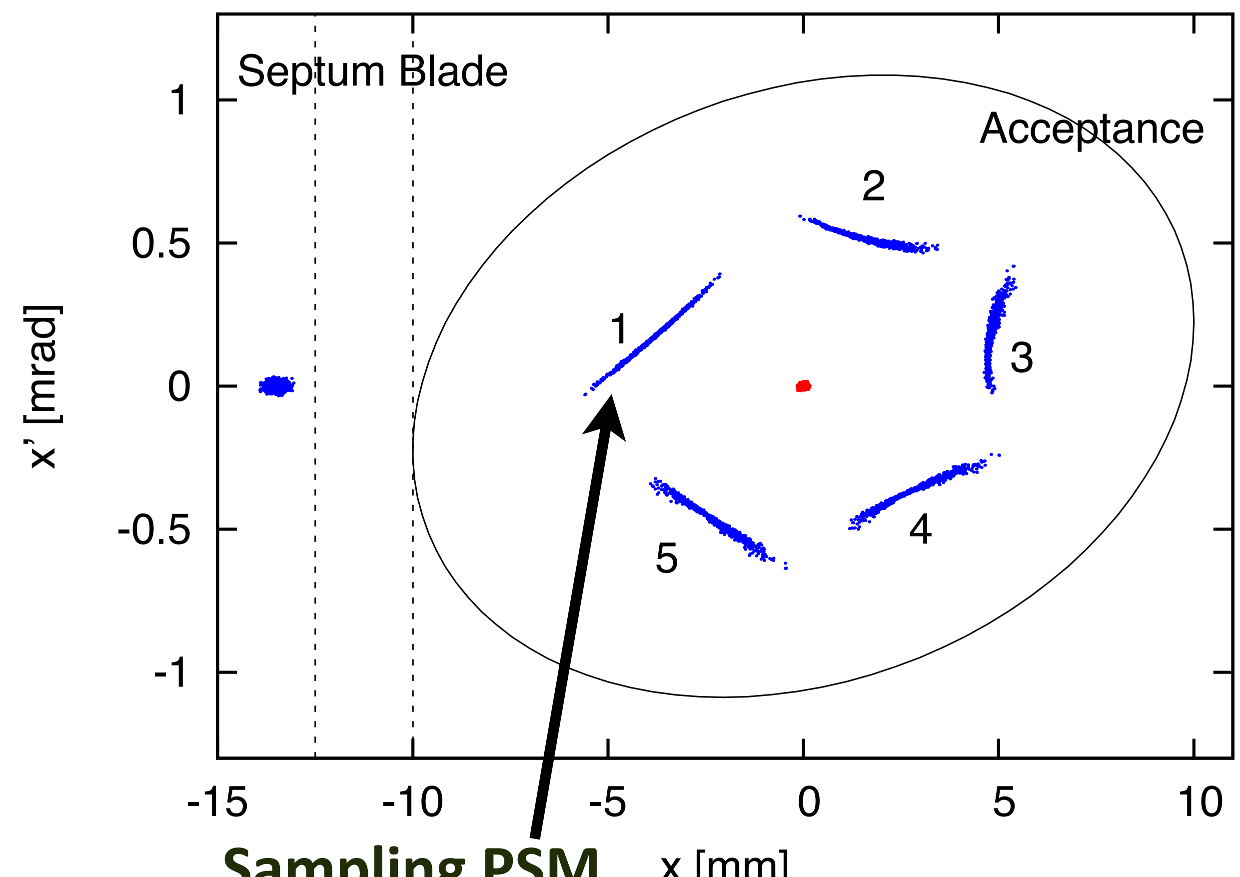


Nonlinearity at large amplitudes



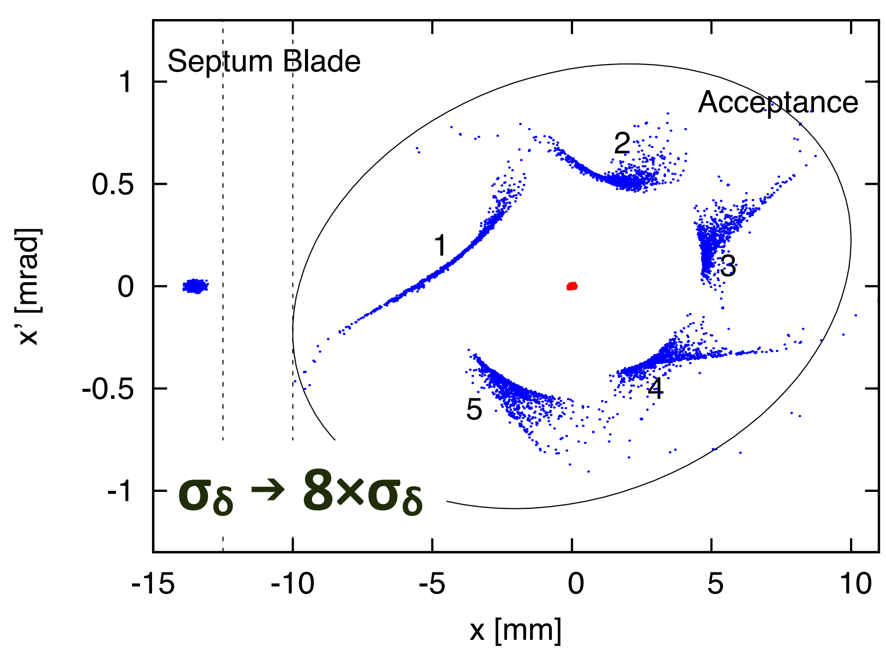
Sampling PSM field gradient

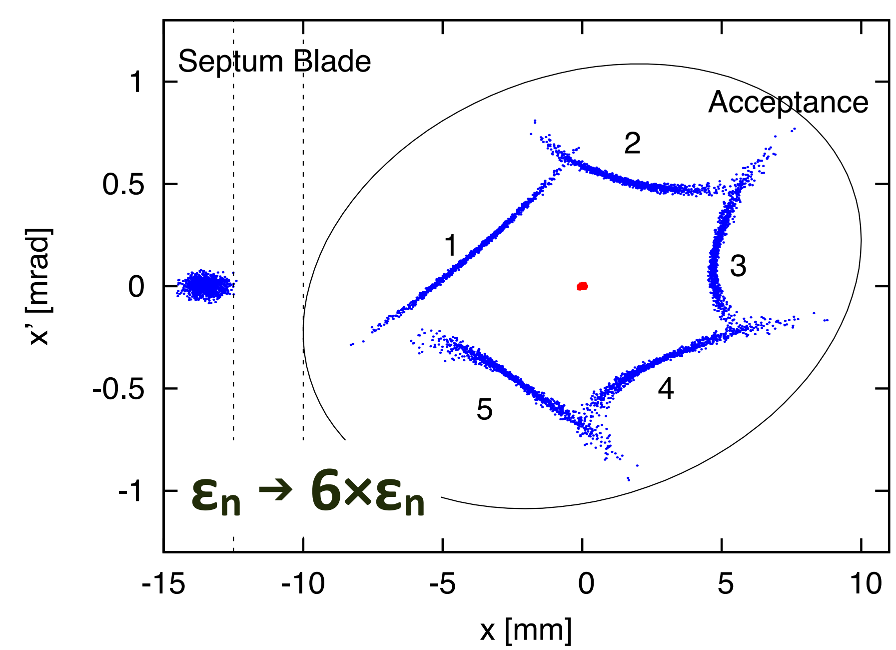
Linac & Injection (cont.)

- Decided to use pulsed sextupole magnet injection for top-up injection into both MAX IV storage rings

PRST-AB **15**, 050705 (2012)

- Strong nonlinearities in MAX IV storage rings → tracking (Tracy-3, DIMAD): optimization of beam position/angle in septum & location/strength of PSM
- PSM gradient not an issue because of low injected emittance (linac: ε_n = 10 mm mrad → ε_x = 1.7 nm rad; SR: ≈0.3 nm rad, ≈11 mm mrad acceptance)
- Capture shows significant tolerance to injection errors (low injected emittance in conjunction with comparably large ring acceptance)

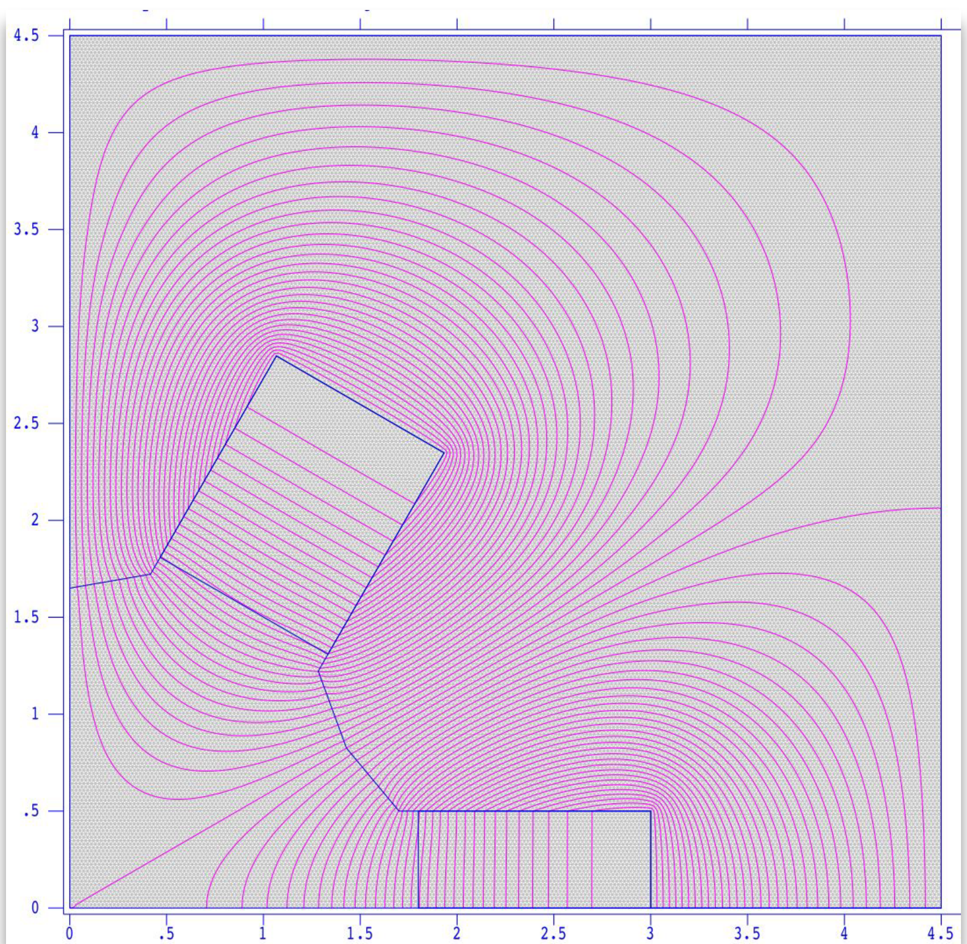




Linac & Injection (cont.)

- After working on a reference design for a MAX IV pulsed sextupole magnet...

PAC'**13**, WEPSM05

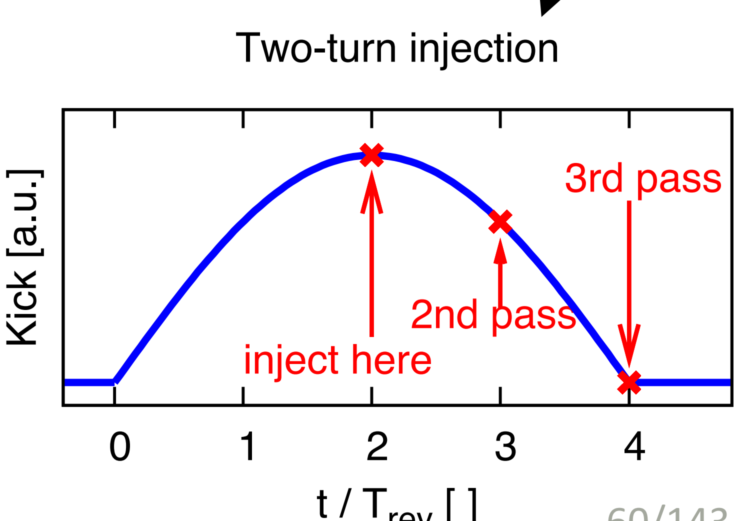


- symmetry required to minimize stored beam perturbation
- cannot accommodate for aspect ratio of BSC
- 20.6 J stored energy @ 300 mm length

Magnetic field at 4.7 mm	39 mT
Magnetic length	300 mm
Bore diameter	32 mm
Peak current	2125 A
Pulse length 3 GeV / 1.5 GeV	3.5 μs / 640 ns

19.3 kV

93 kV @ 400 mm length



PRST-AB **15**, 050705 (2012)

Linac & Injection (cont.)

- After working on a reference design for a MAX IV pulsed sextupole magnet... switched to a better idea

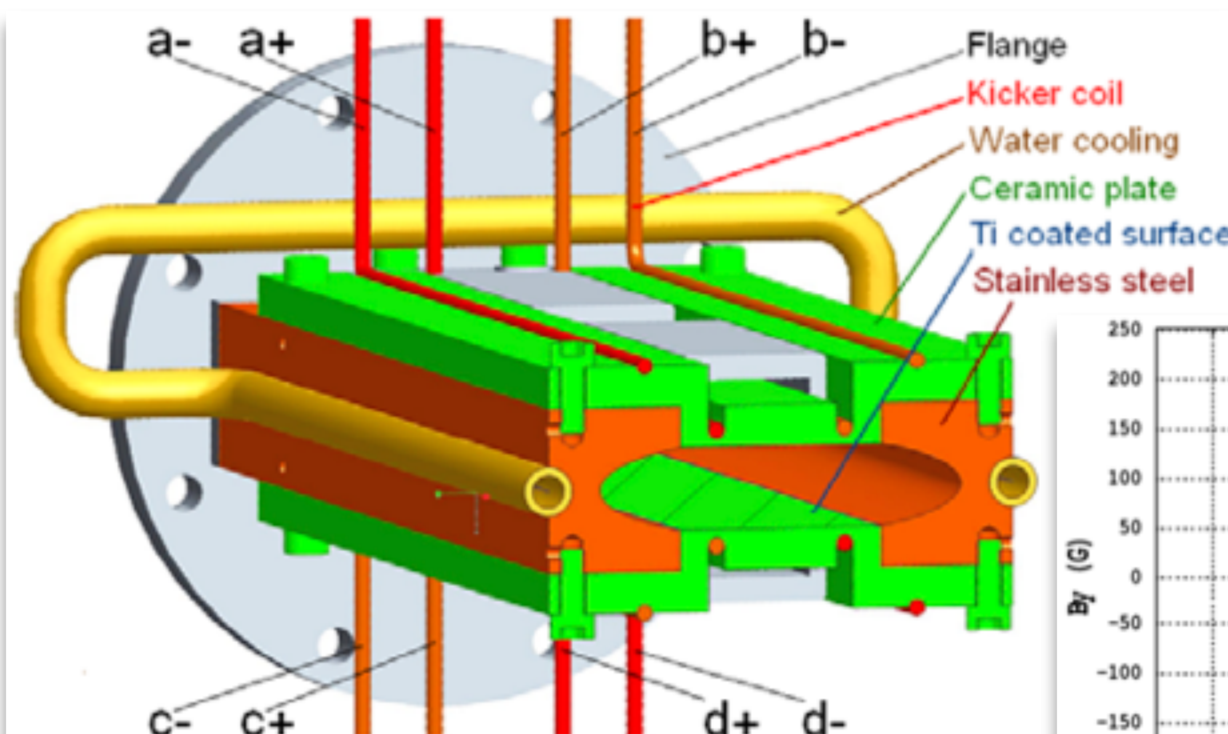
PAC'**13**, WEPSM05

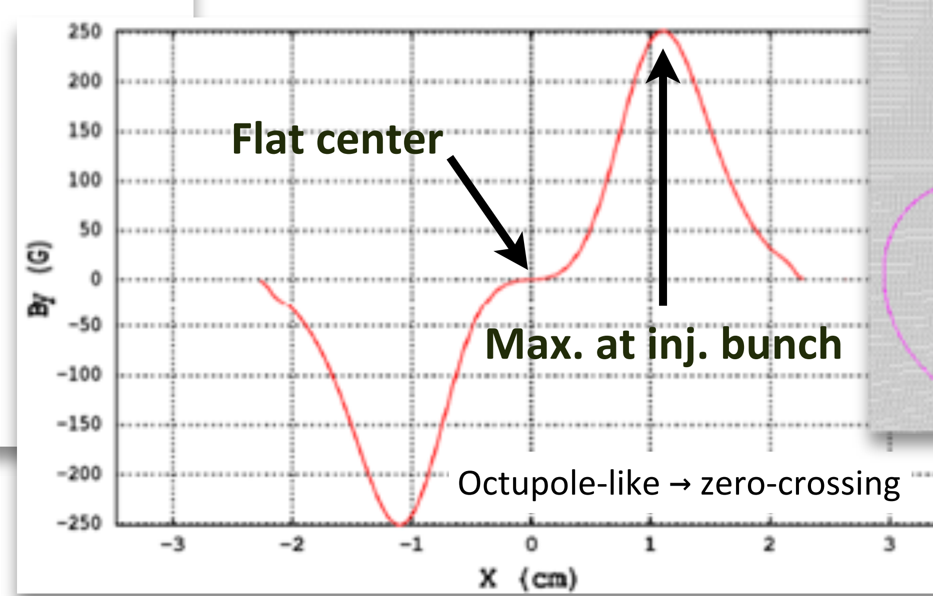
- BESSY nonlinear injection kicker prototype

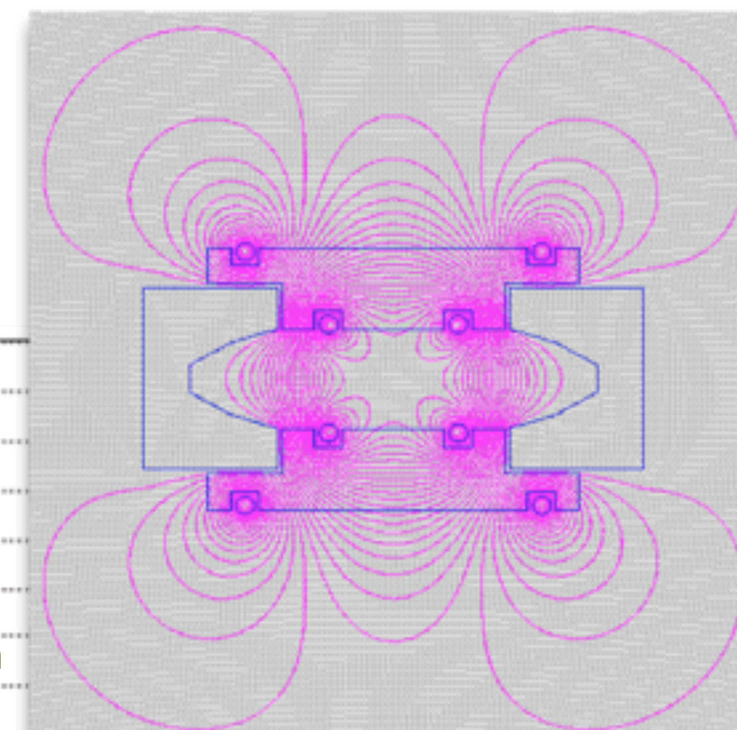
P. Kuske, Top-up WS, Melbourne, 2009

IPAC'**11**, THPO024, p.3394

  - stripline-like design with 4 low-impedance coils
  - minimize stored beam perturbation (octupole-like around center)

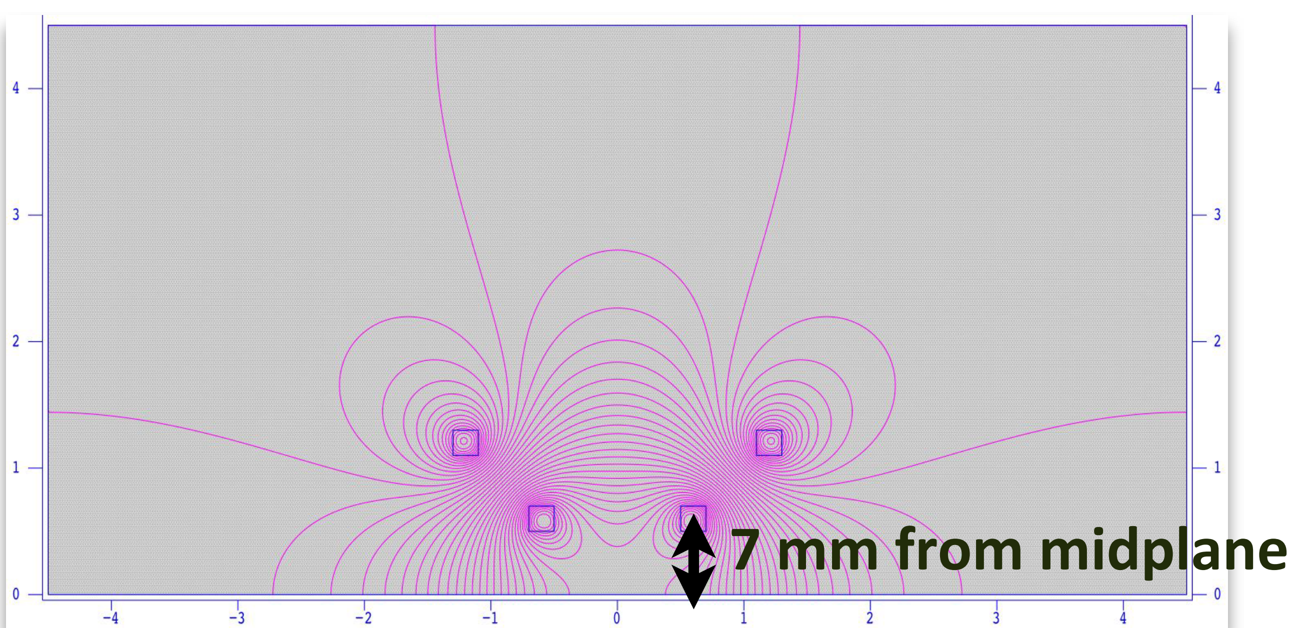


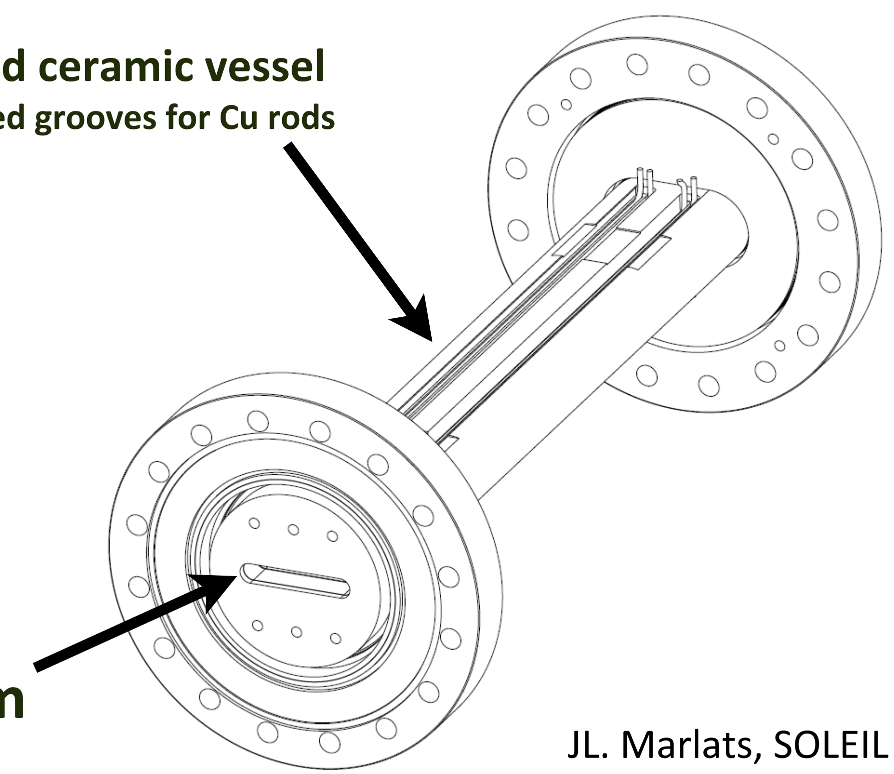




Linac & Injection (cont.)

- In 2011 entered collaboration with SOLEIL in association with HZB to develop a new nonlinear injection kicker for MAX IV based on the original BESSY concept
- Considering MAX IV vertical aperture requirements and chosen vacuum vessel design, will have to inject on slope





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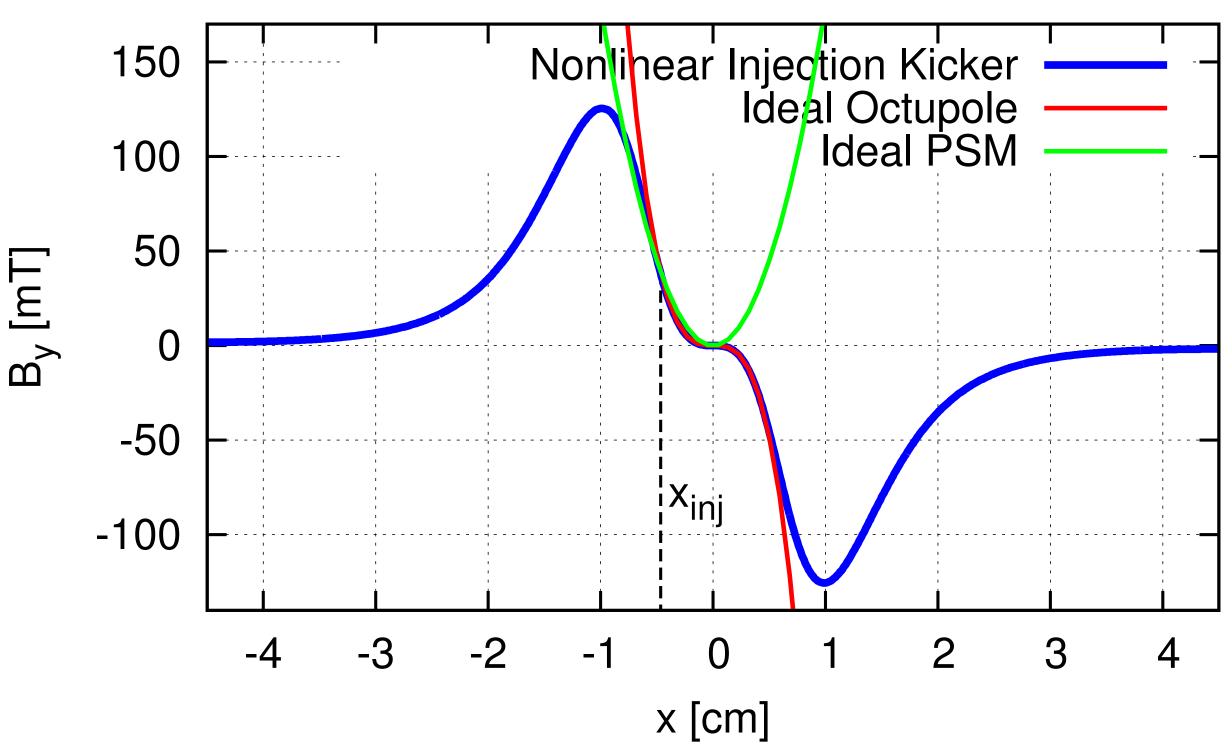
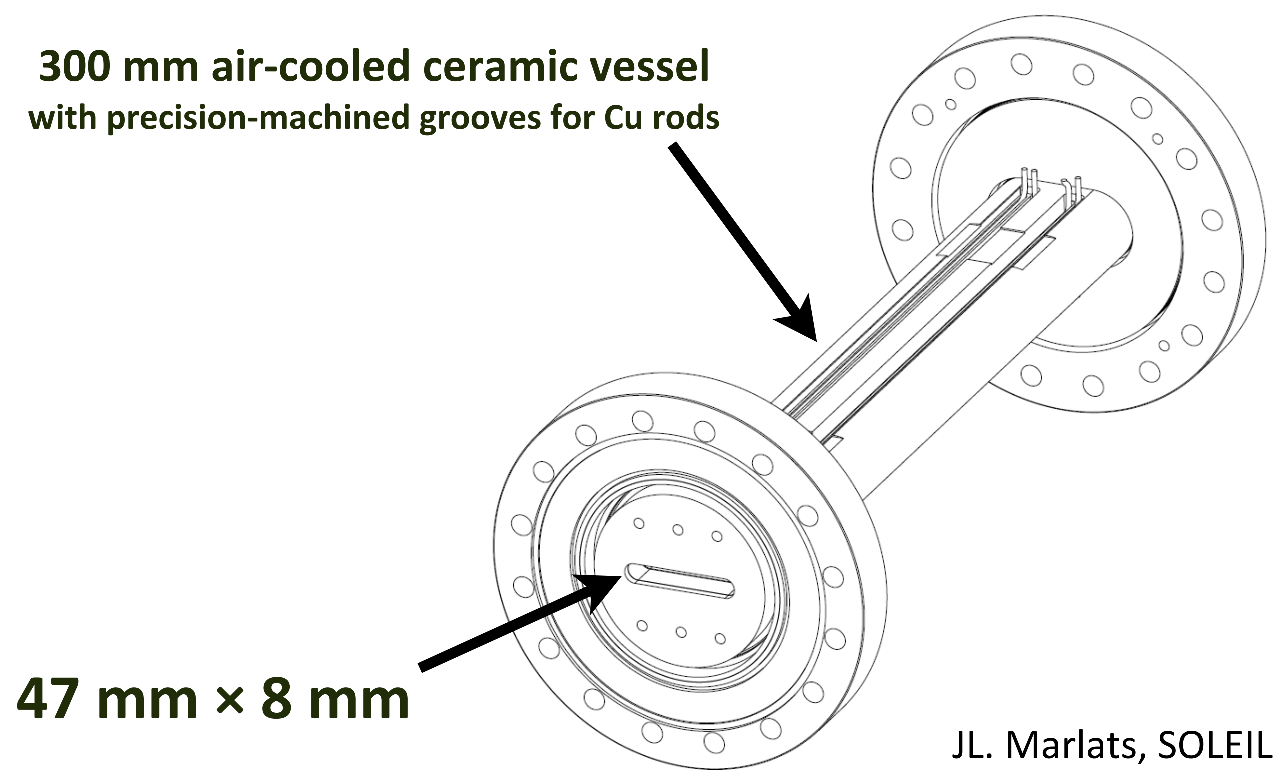
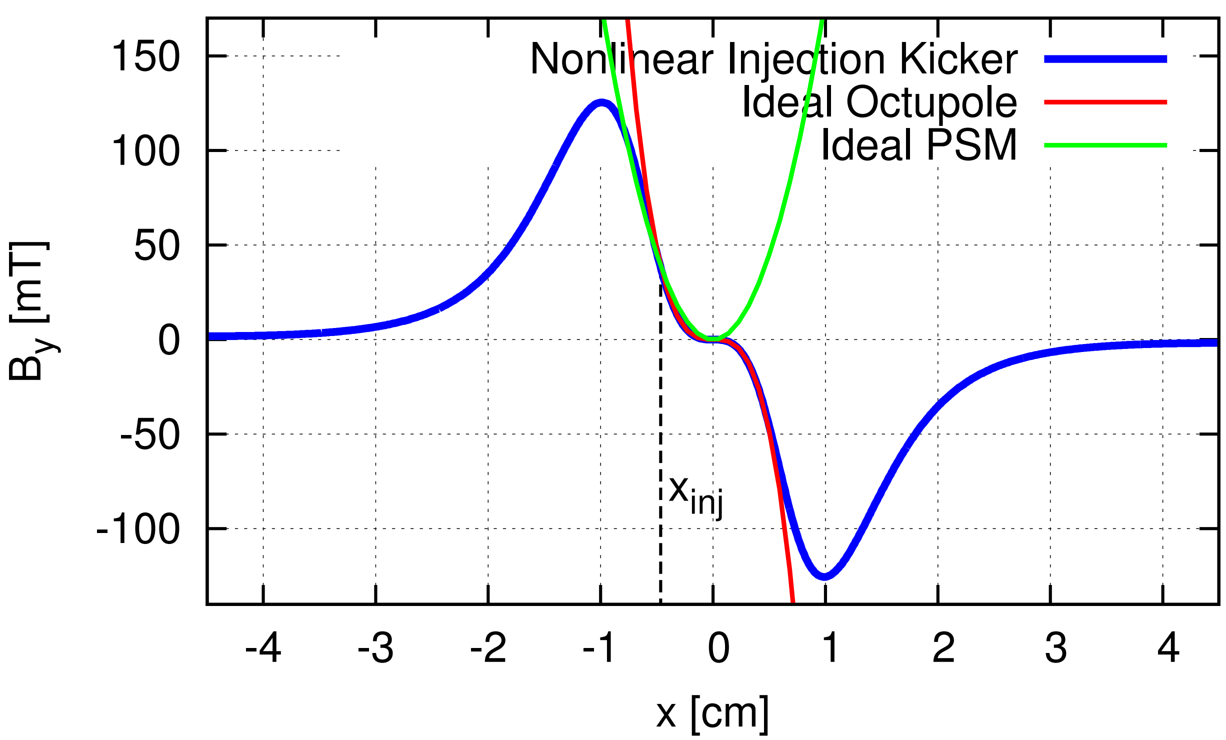


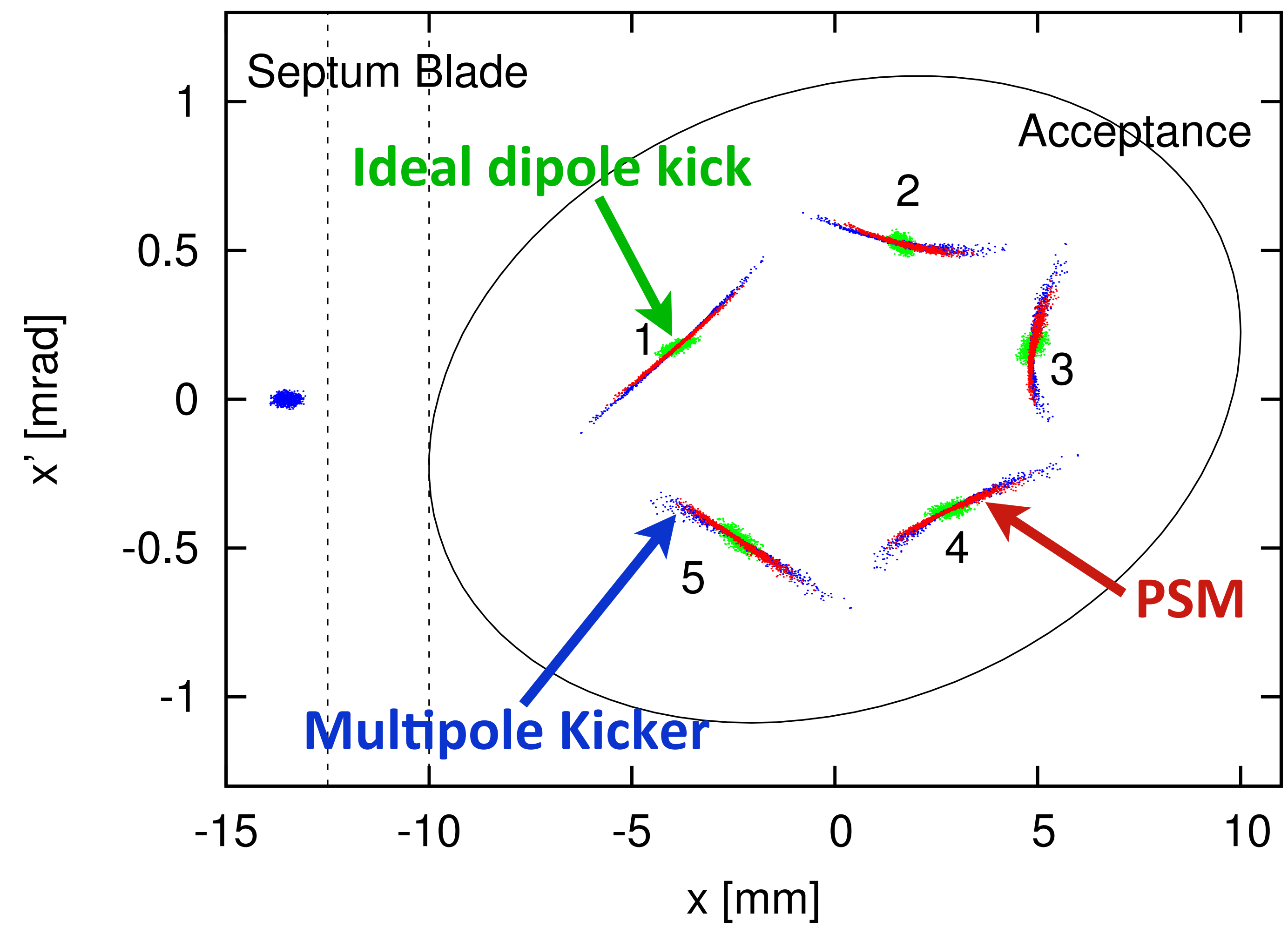


JL. Marlats, SOLEIL

Linac & Injection (cont.)

- But thanks to low-emittance injection from MAX IV linac, can inject on slope without sampling too much gradient for good capture



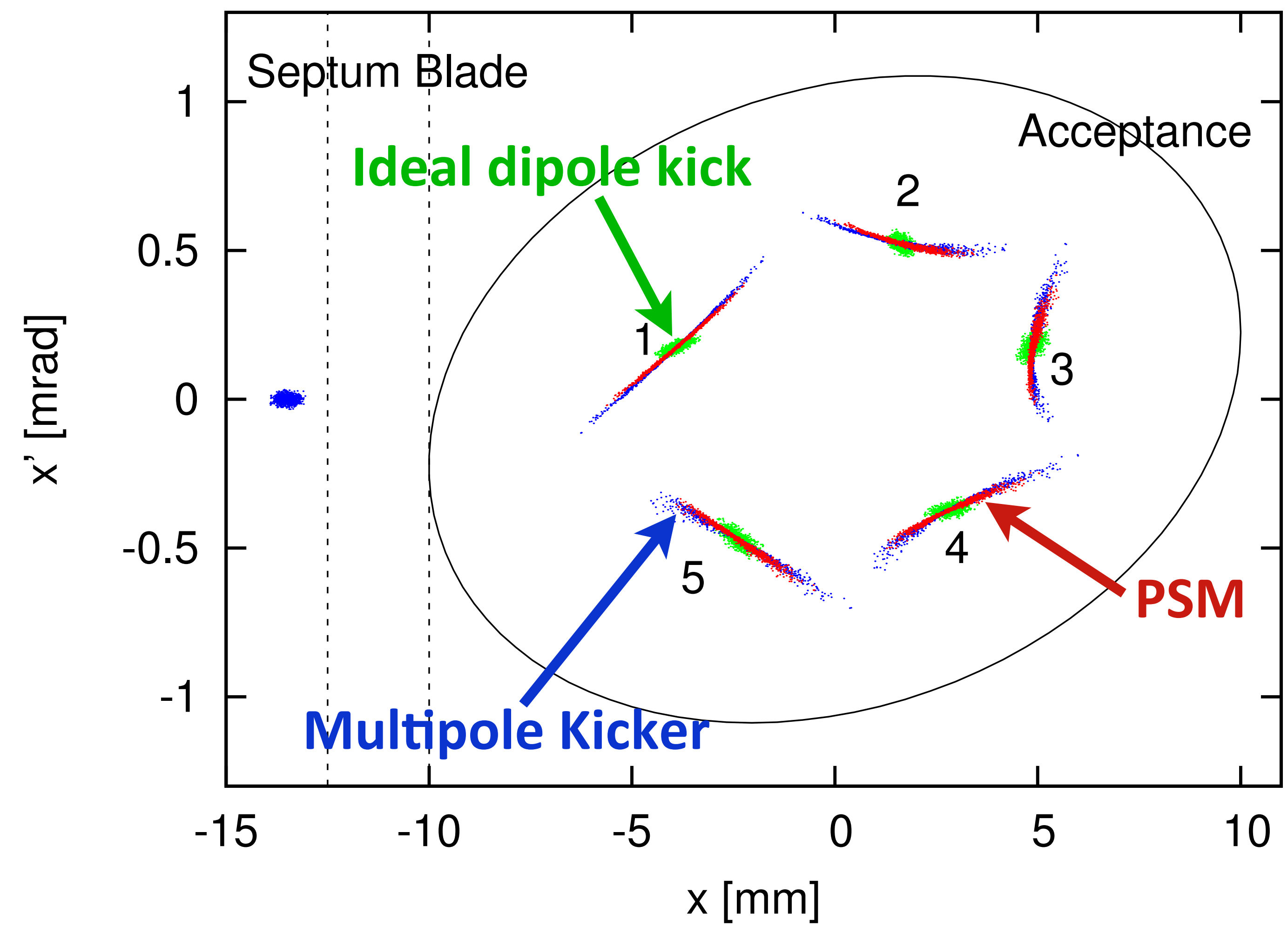


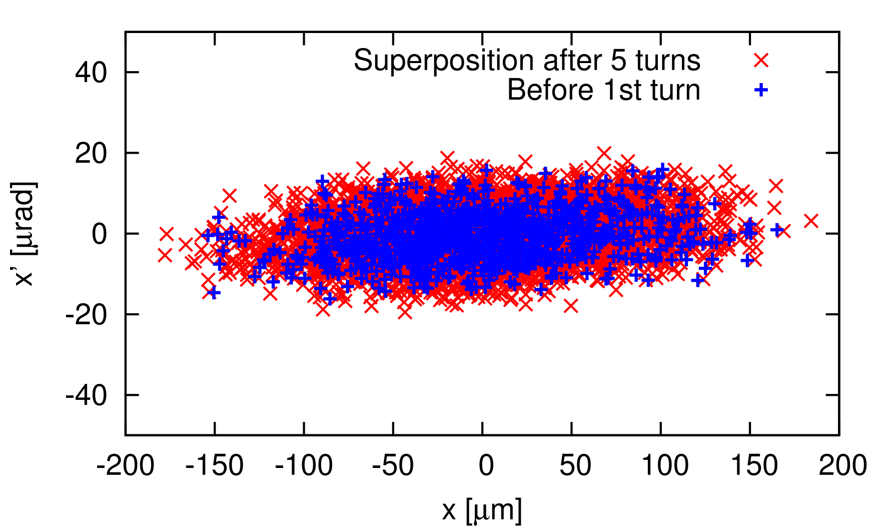
Field data for tracking extracted from OPERA models (static & transient) including 4 μm Ti coating
(OPERA model courtesy P. Lebasque, SOLEIL)

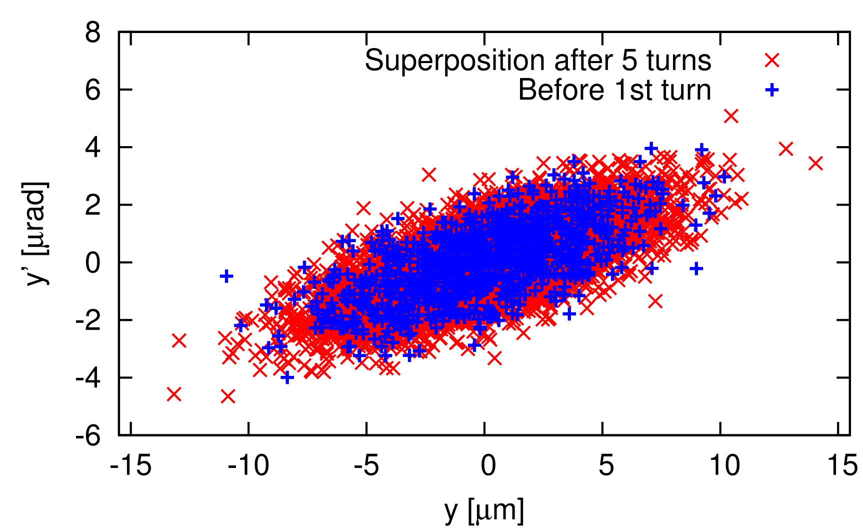
PAC'**13**, WEPSM05

Linac & Injection (cont.)

- Injected beam and stored beam see octupole-like field
- 39 mT delivered to injected beam at 4.7 mm as required
- Stored beam perturbation remains negligible







Field data for tracking extracted from OPERA models (static & transient) including 4 µm Ti coating
(OPERA model courtesy P. Lebasque, SOLEIL)

PAC'**13**, WEPSM05

Linac & Injection (cont.)

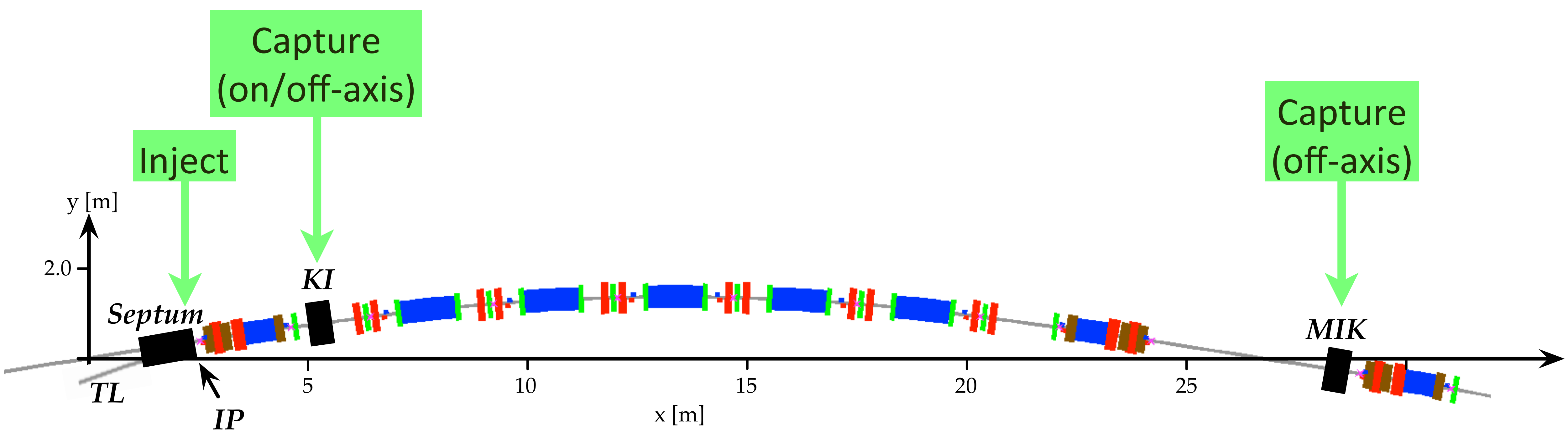
- Nonlinear kicker (MIK) should enable transparent top-up injection during user shifts

PRST-AB **15**, 050705 (2012)

- But tricky to commission (kick scales ≈ x^3)

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

- Instead, for commissioning use single dipole kicker (KI)



Linac & Injection (cont.)

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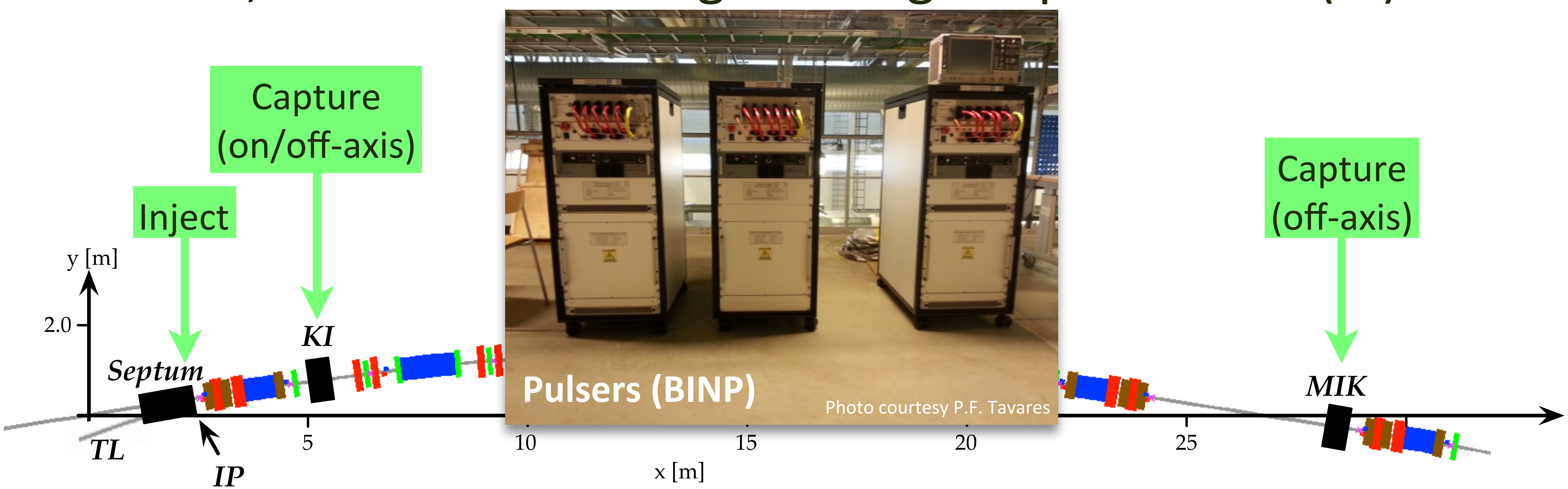

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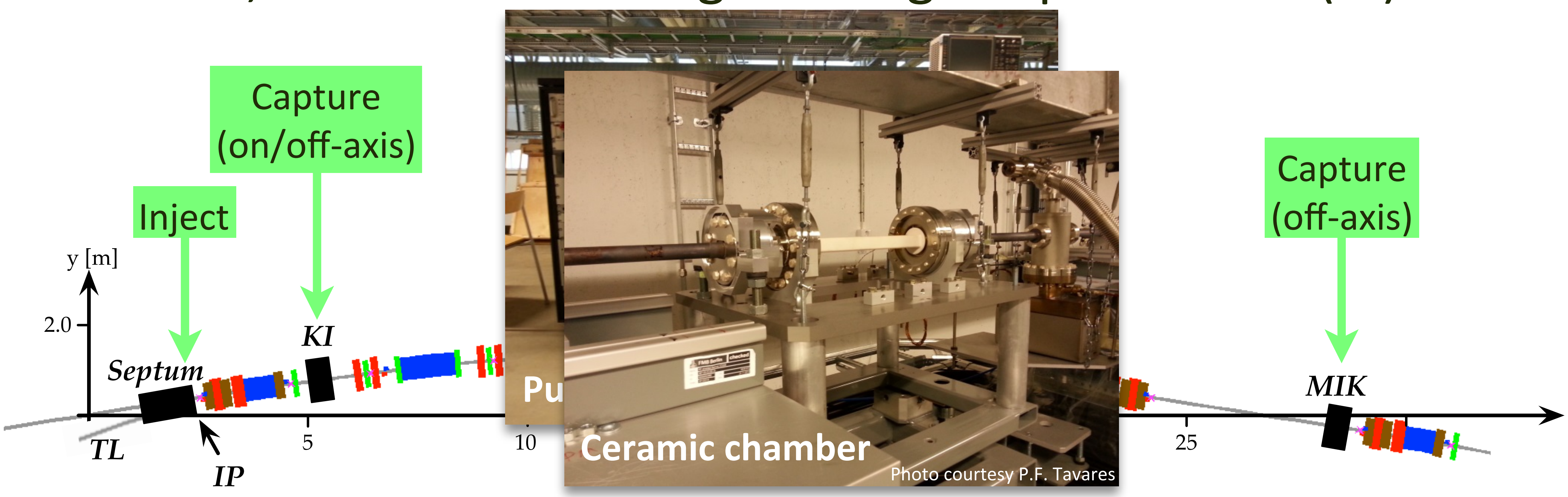

Linac & Injection (cont.)

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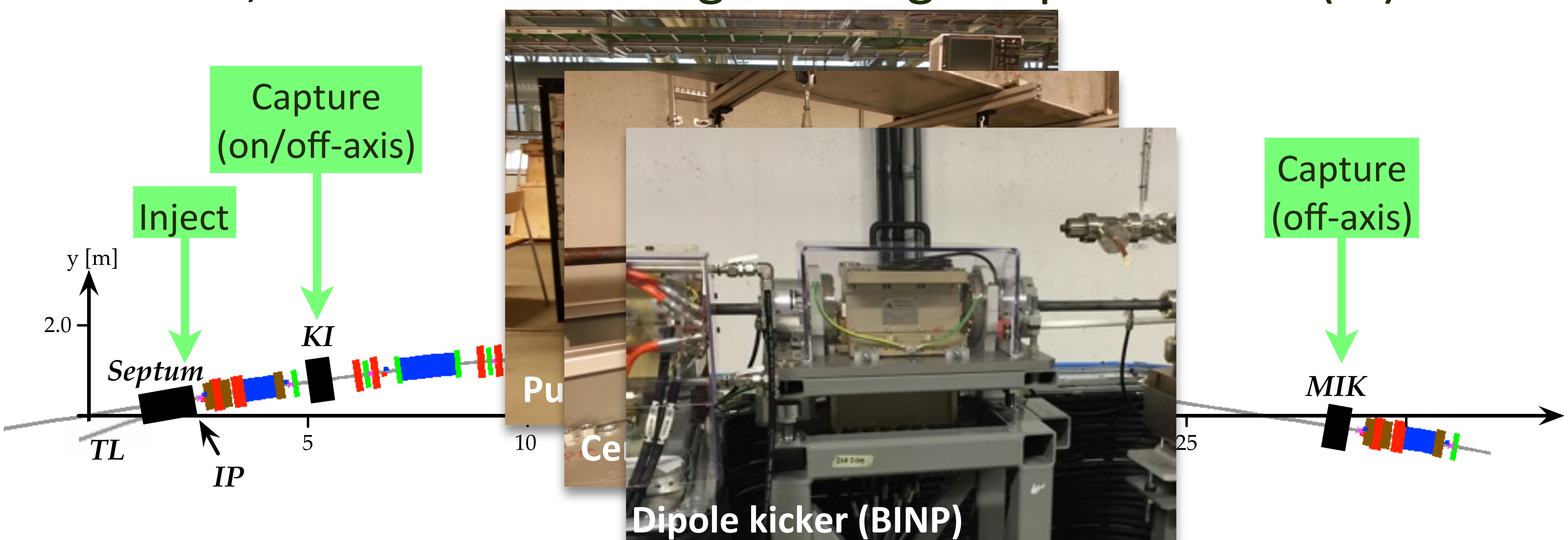
NIM-A **693**, 117, 2012

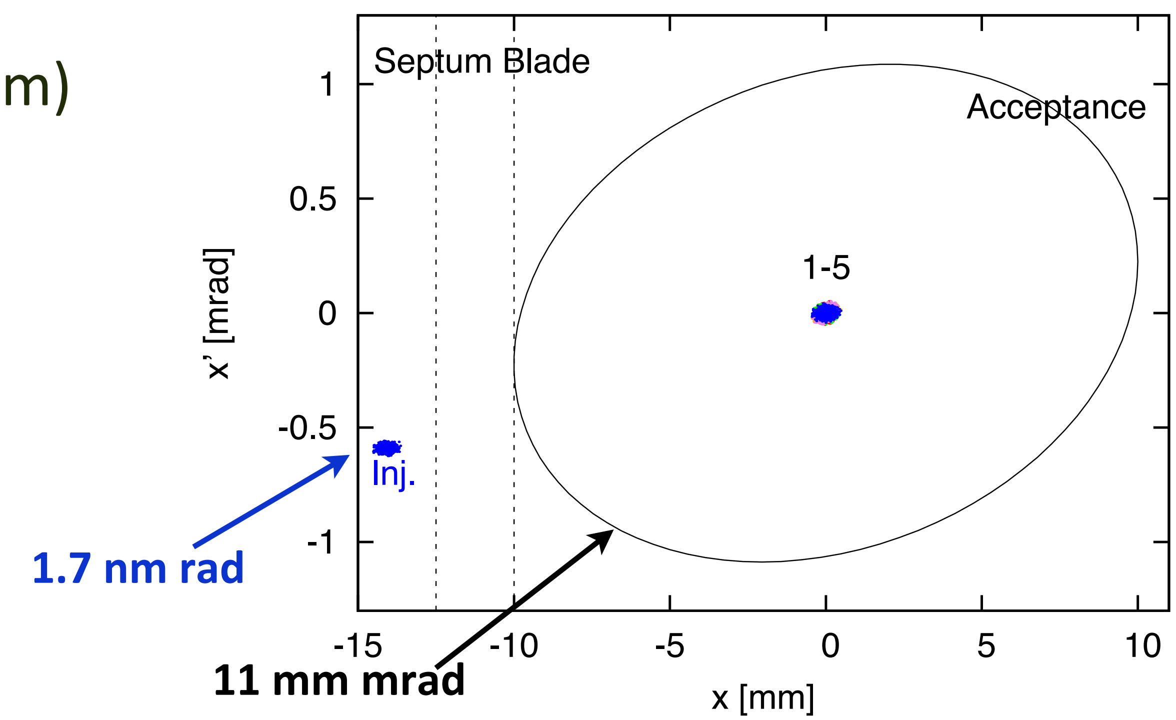
- Instead, for commissioning use single dipole kicker (KI)

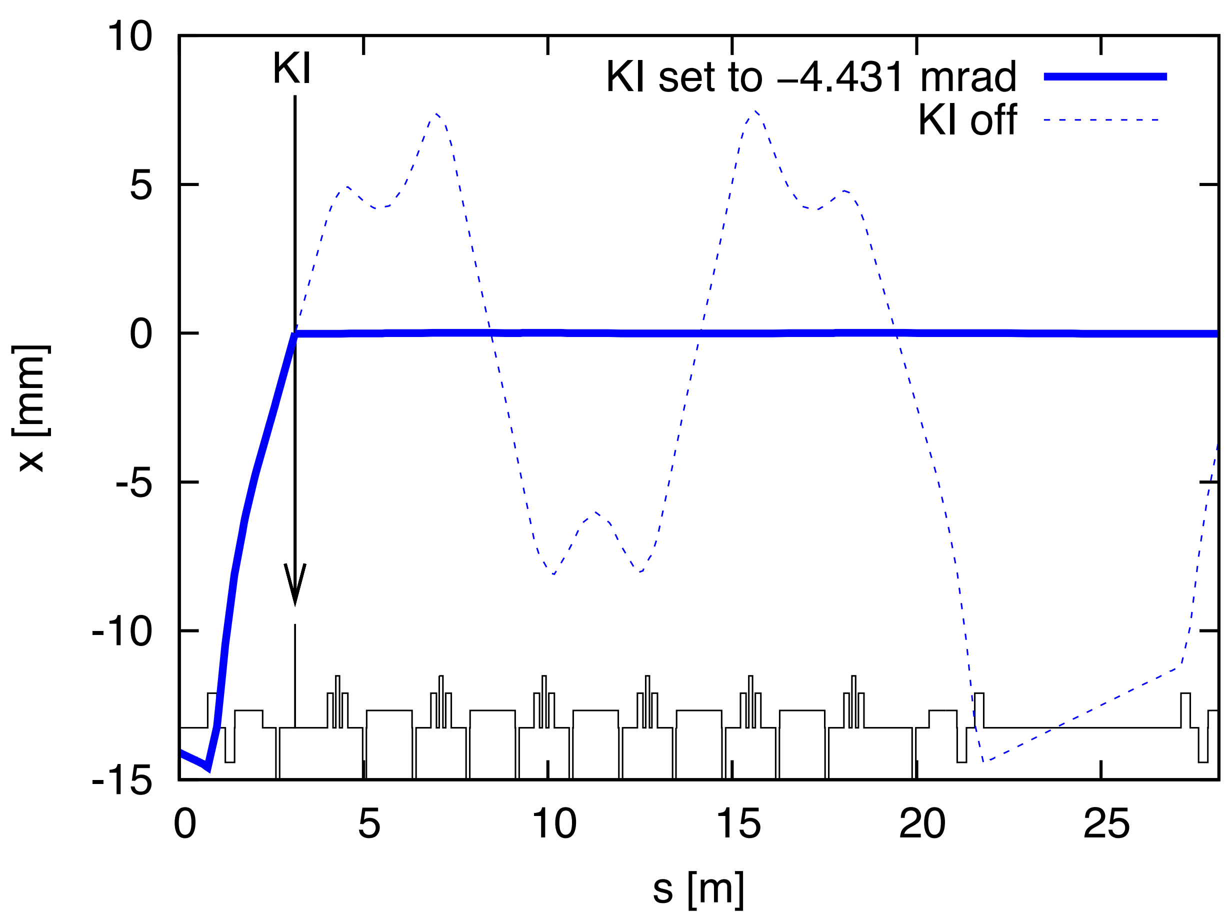


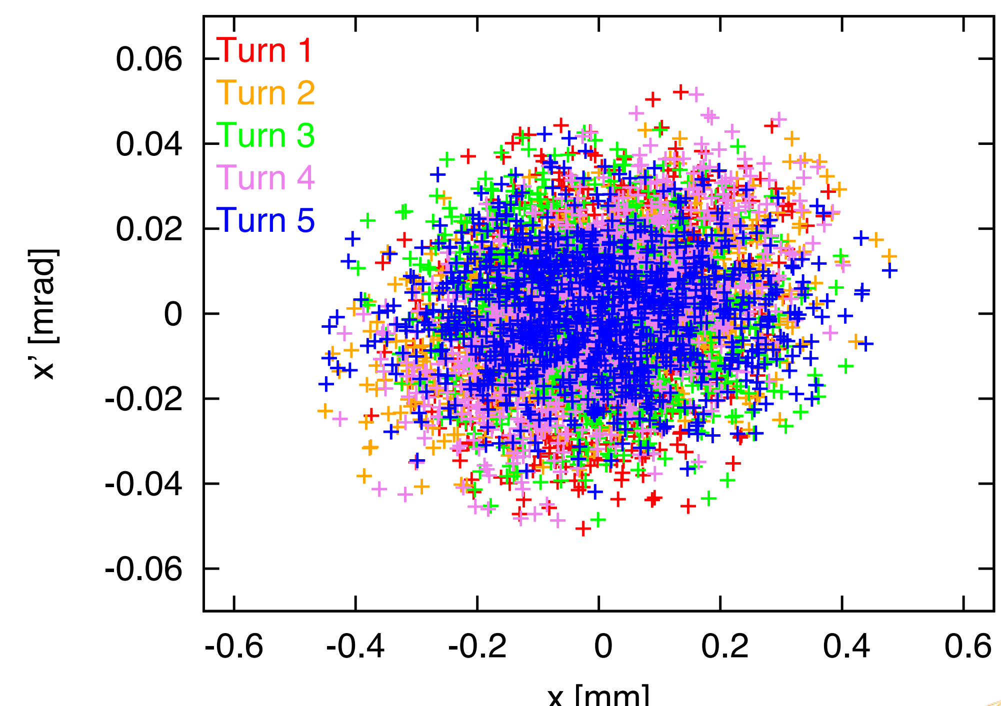
Linac & Injection (cont.)

- Injection with a single dipole kicker:
  - on-axis injection (-0.6 mrad at septum)

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



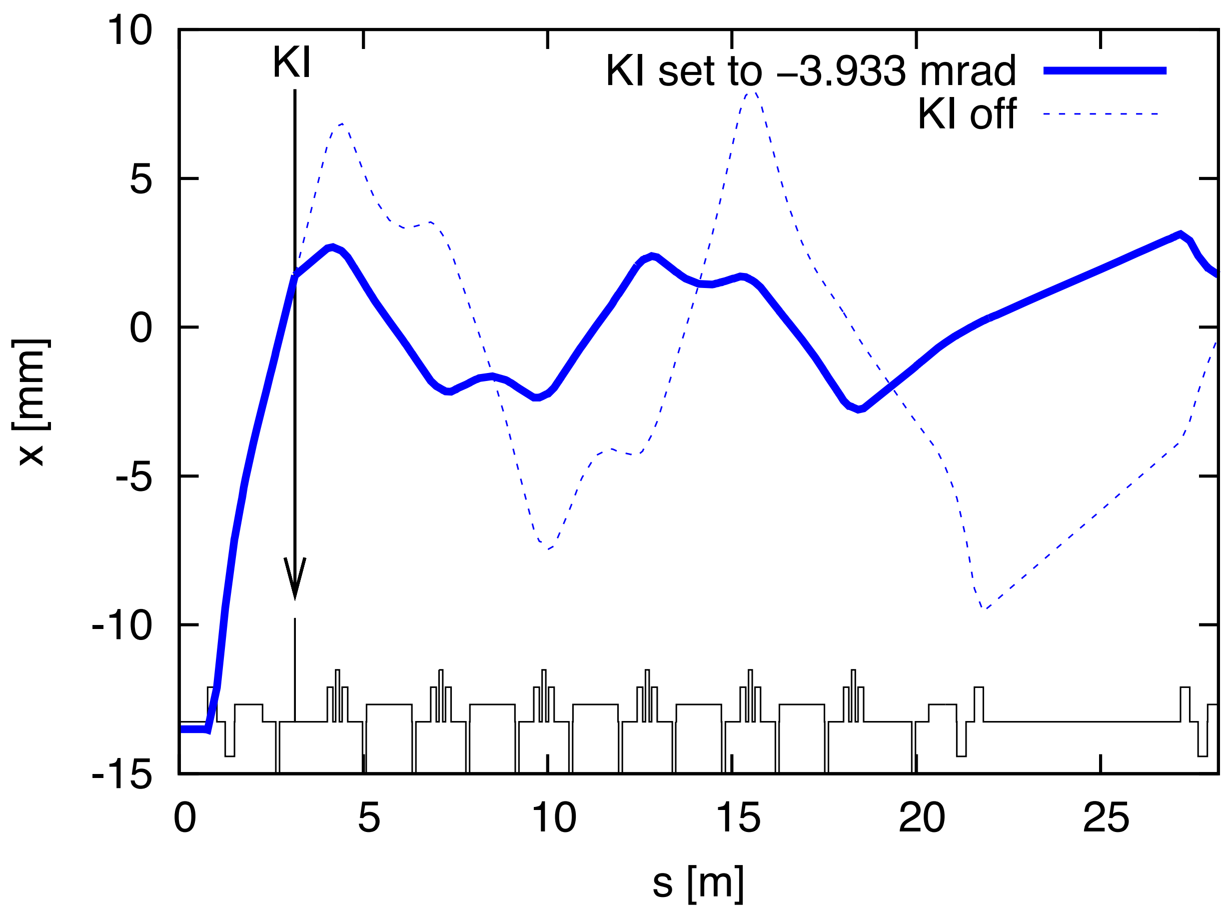


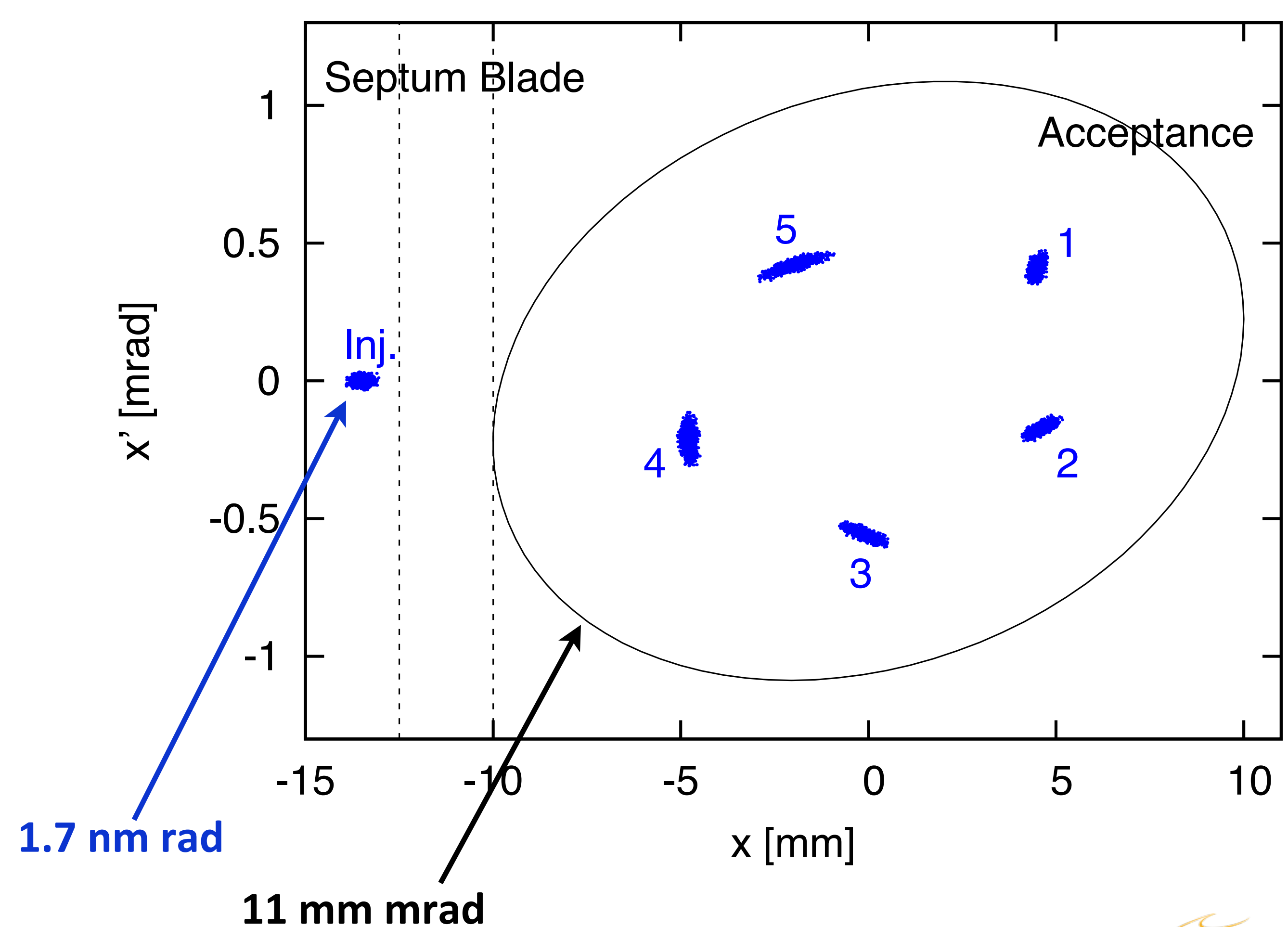


Linac & Injection (cont.)

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

- Injection with a single dipole kicker:
  - on-axis injection (-0.6 mrad at septum)
  - off-axis injection

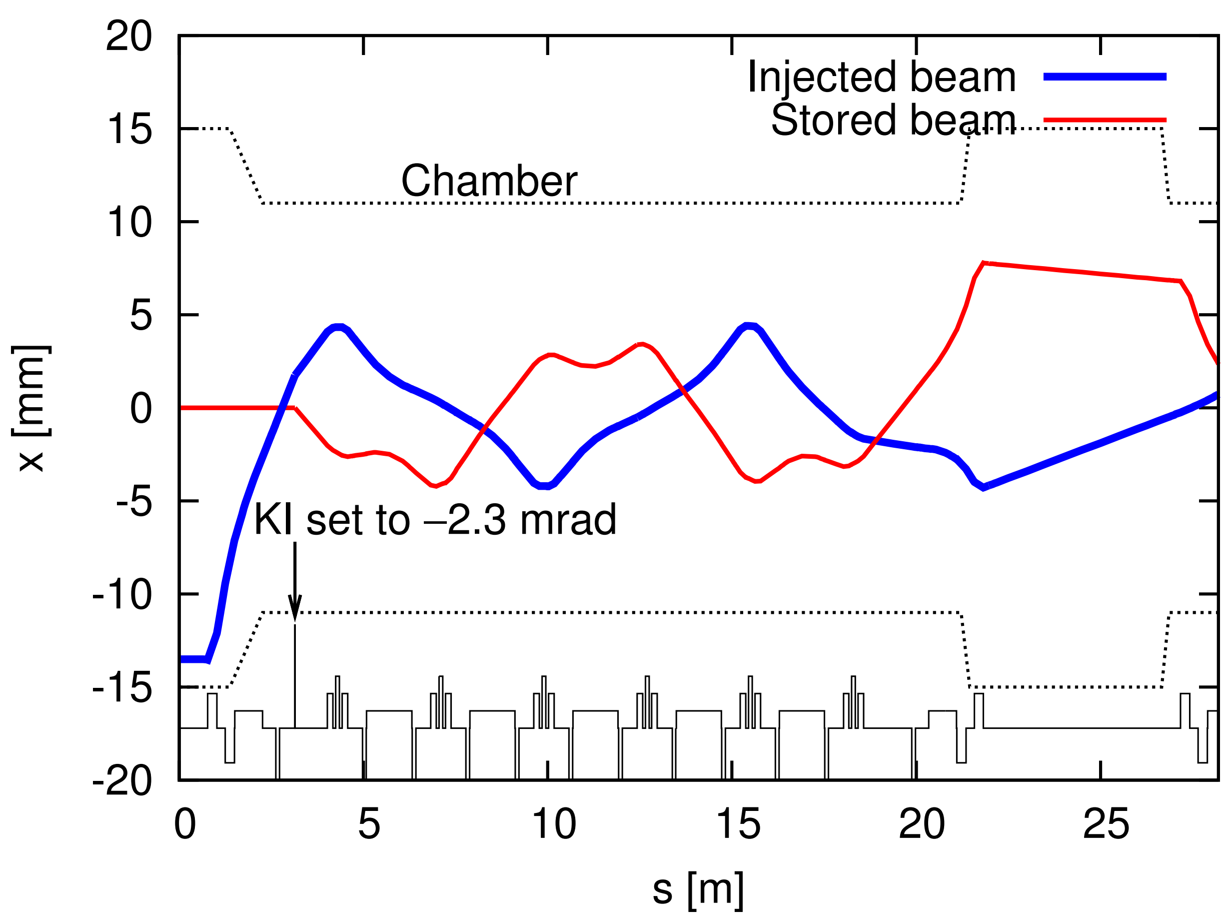


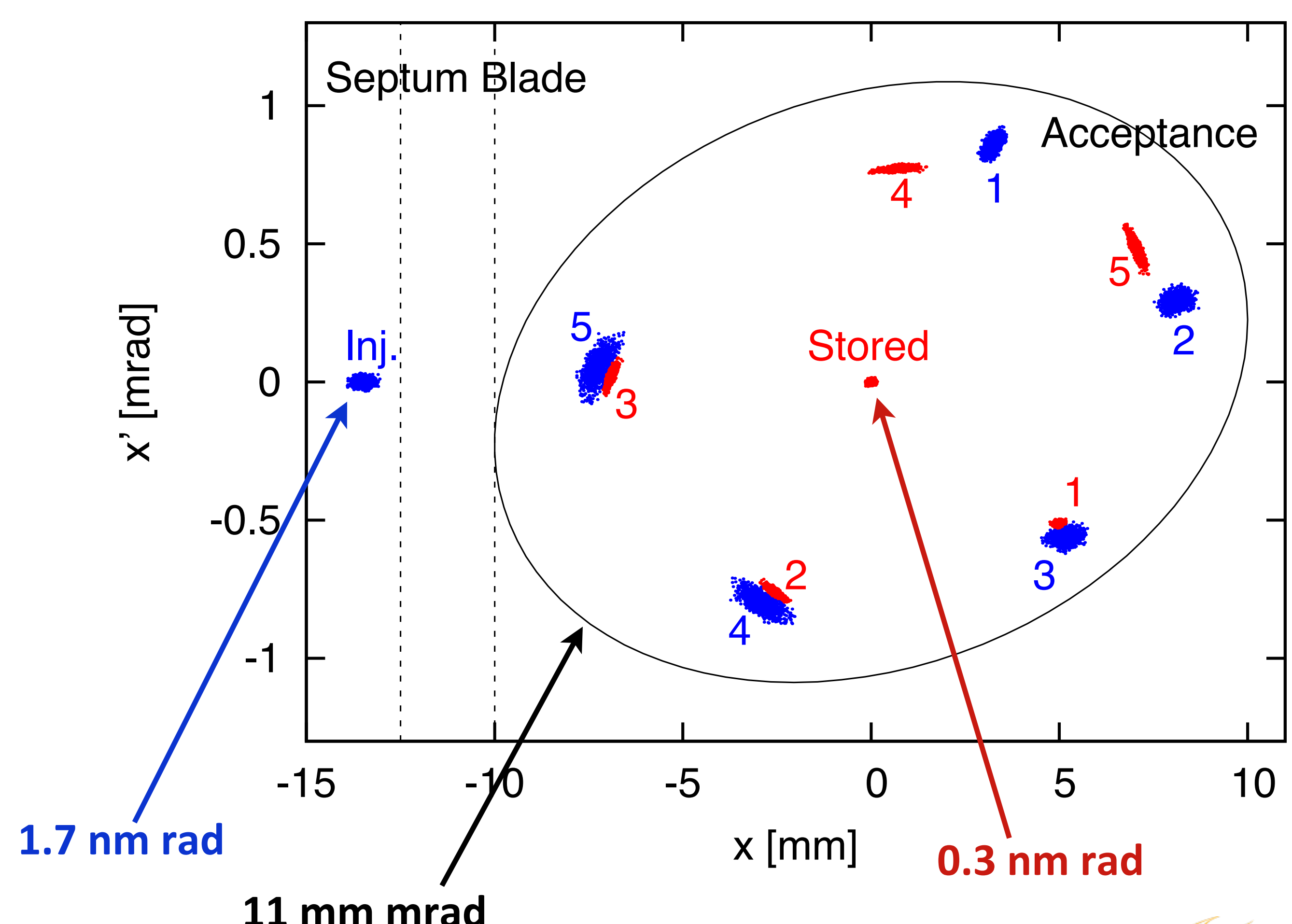


Linac & Injection (cont.)

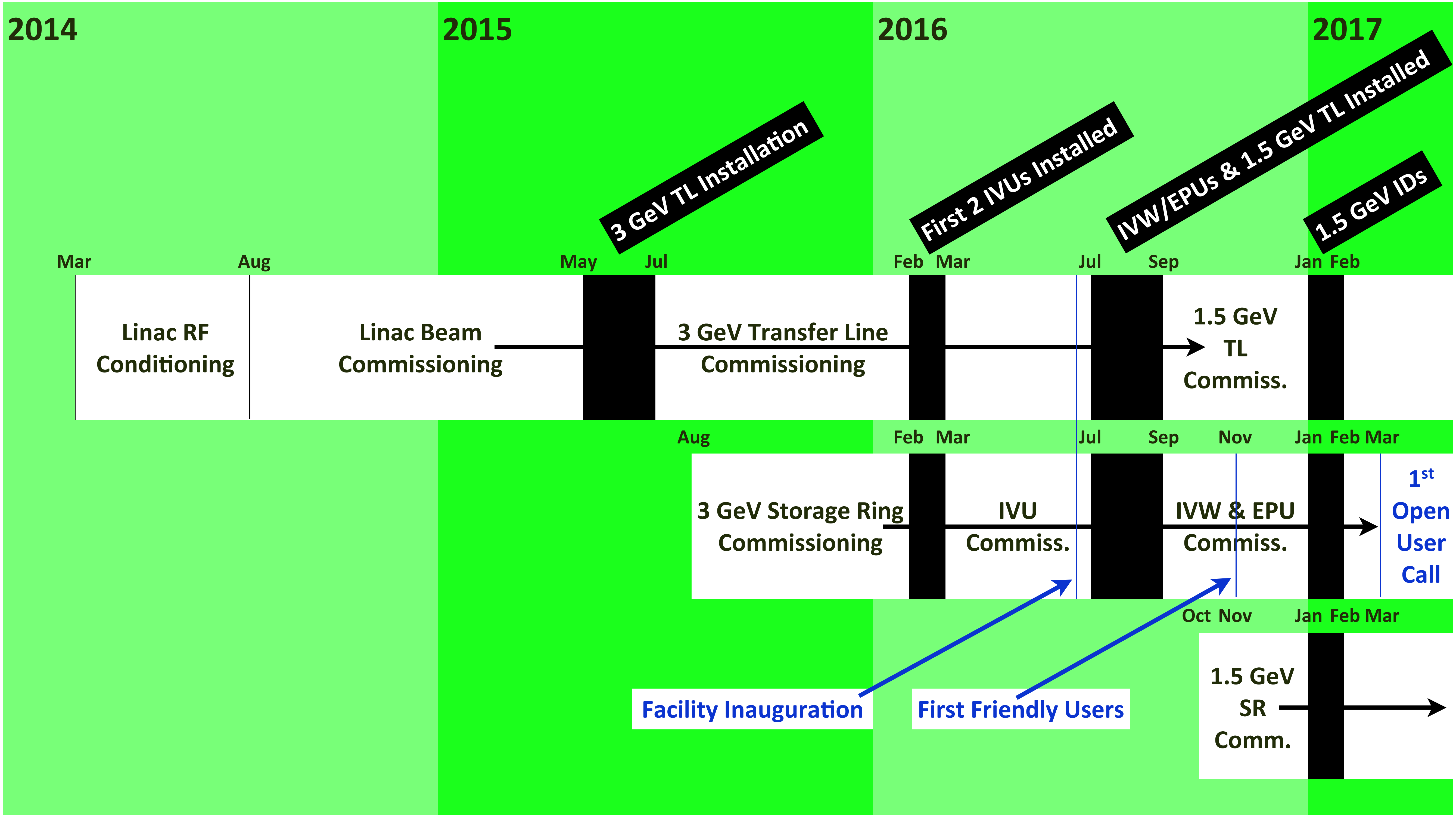
NIM-A **693**, 117, 2012

- Injection with a single dipole kicker:
  - on-axis injection (-0.6 mrad at septum)
  - off-axis injection
  - and allows for accumulation



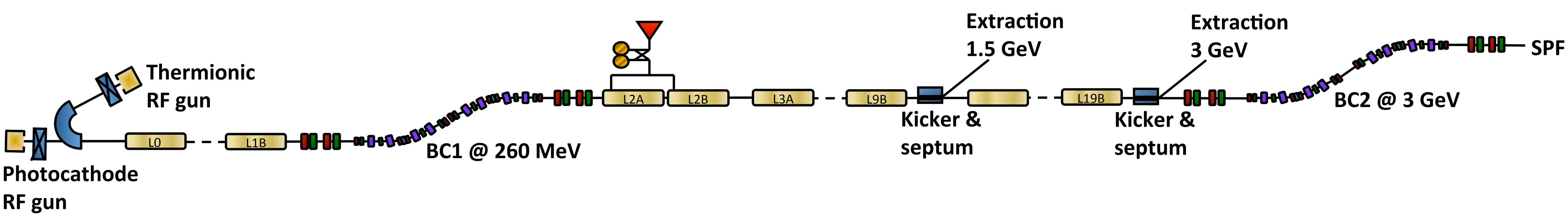


Commissioning Timeline



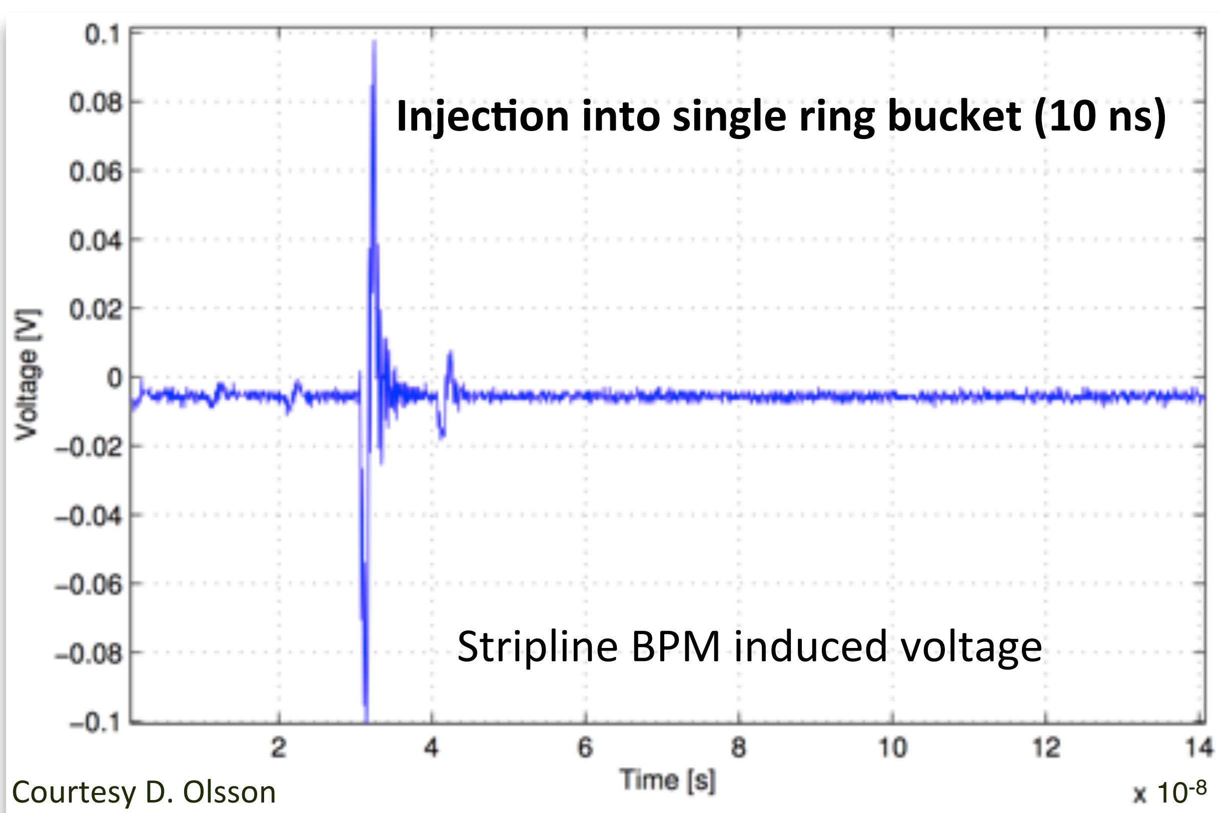
Linac Commissioning Summary

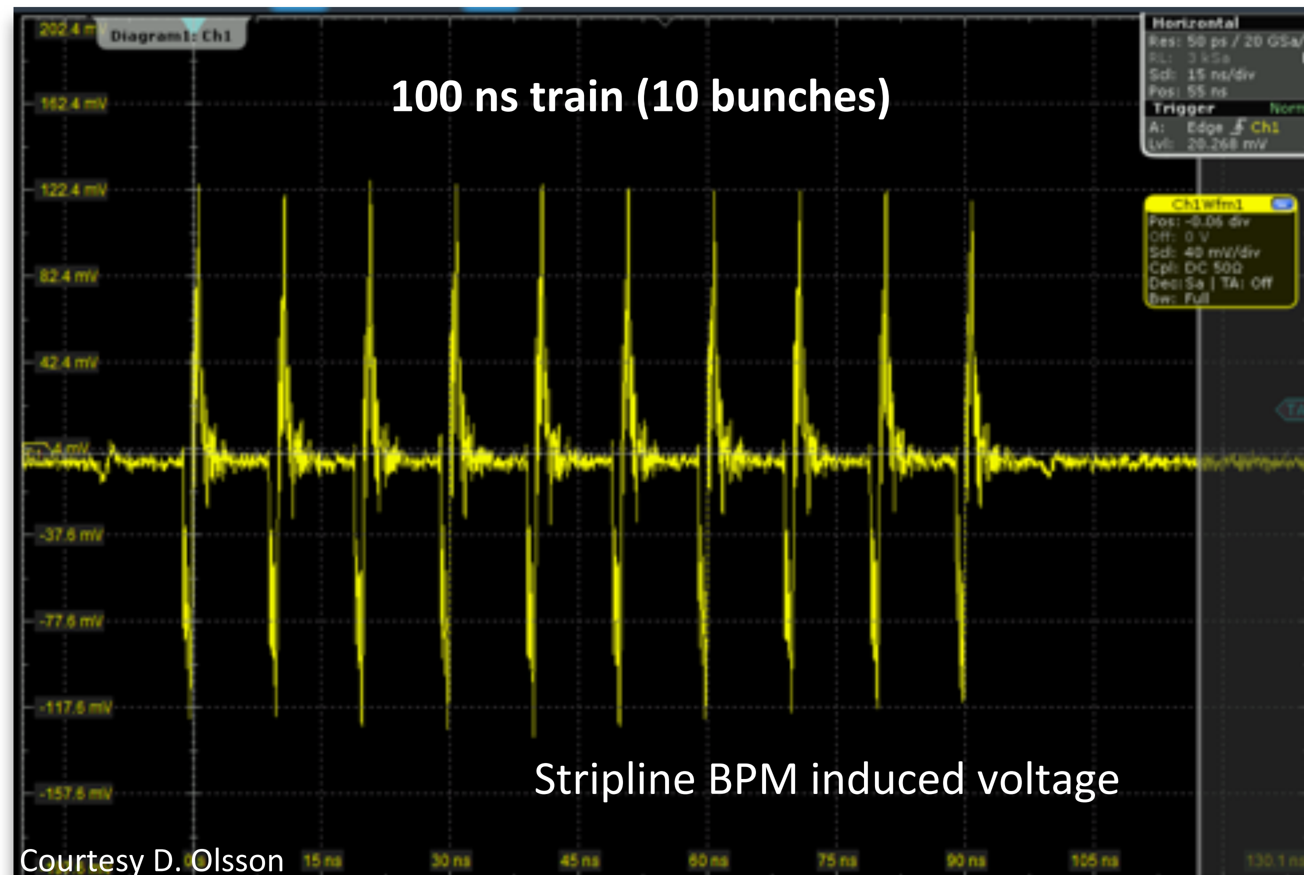
- Linac beam commissioning started August 2014
- Eventually reached 3.2 GeV in BC2
  - ≈0.8 nC in 100 ns train delivered at 1 Hz (corresponds to ≈0.5 mA in SR)
  - ≈7 mm mrad delivered in vertical plane (chopper sweep plane)
  - roughly on-crest phasing of all linacs → ±0.3% energy spread

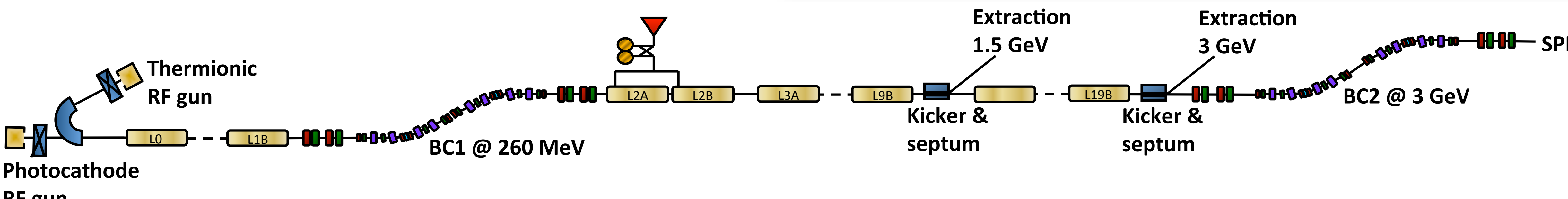


Linac Commissioning Summary (cont.)

- 500 MHz and 100 MHz bunch structures delivered
- Injection demonstrated in trains and single-bunch

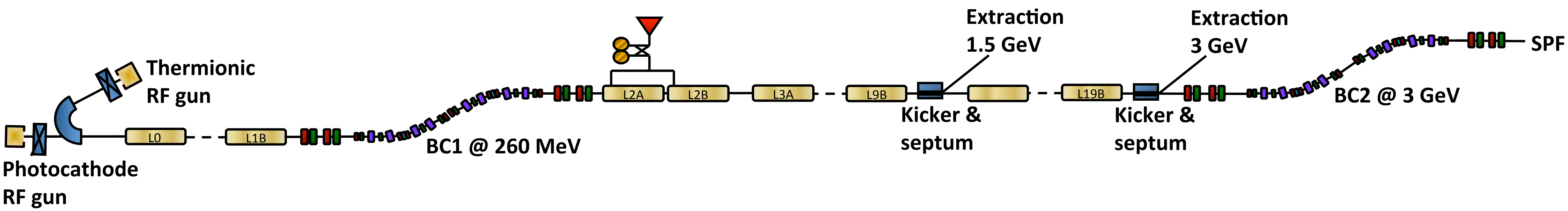






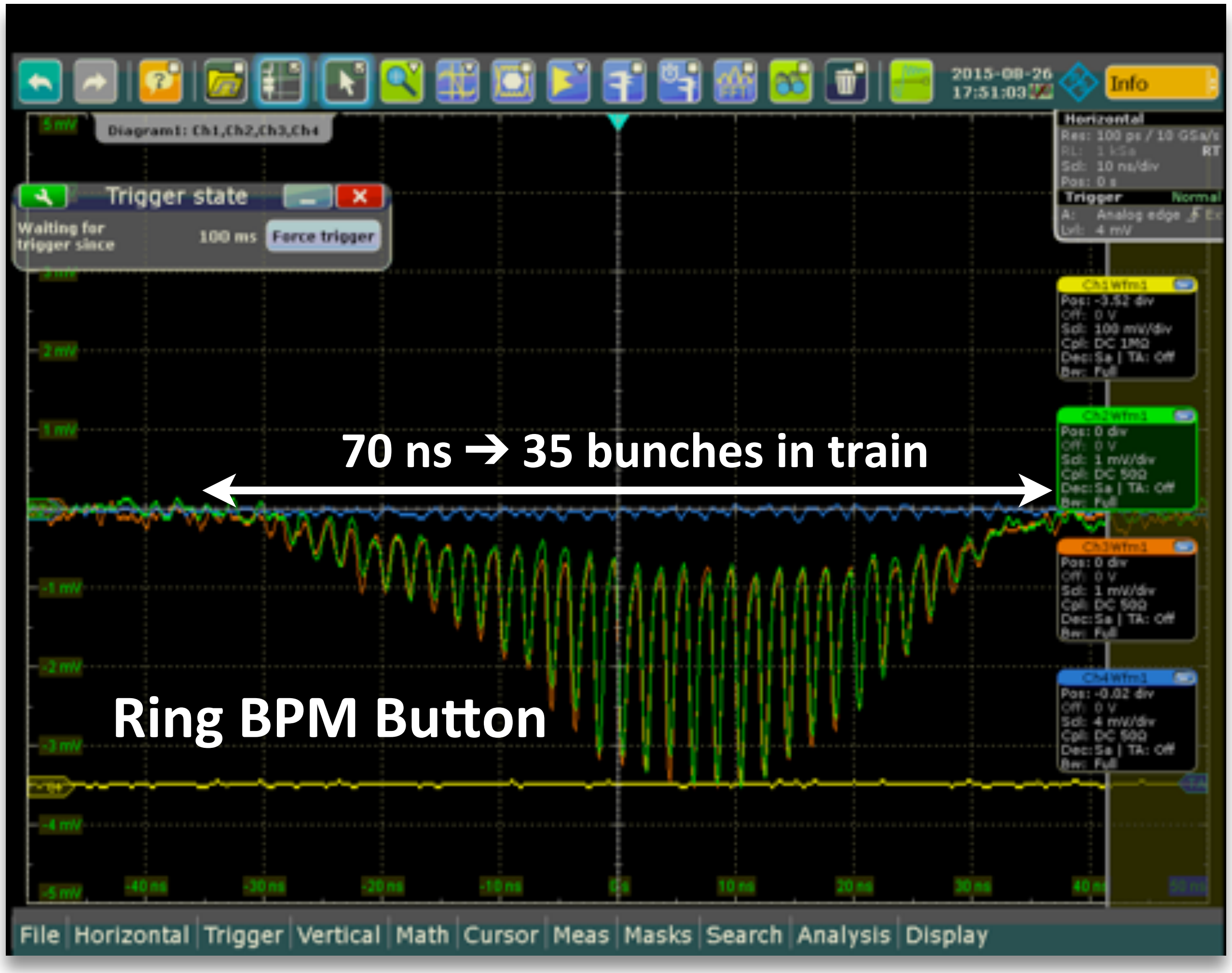
Linac Commissioning Summary (cont.)

- Linac went into shutdown at end of April 2015 for transfer line installations & last phase of exp. hall construction
- Linac restarted Aug 3, 2015



3 GeV Storage Ring Commissioning

- First beam into full 3 GeV transfer line (TL) on Aug 10
- TL optics fixed, successful injection into 3 GeV SR on Aug 19



3 GeV Storage Ring Commissioning (cont.)

- First beam into full 3 GeV transfer line (TL) on Aug 10
- TL optics fixed, successful injection into 3 GeV SR on Aug 19
- With some manual adjustments of angle and position at injection point in SR (using diode rings), immediately detected beam on all BPMs in first achromat (up to first closed valve)

≈950 pC at linac extraction

≈400 pC at storage ring injection

≈ 2 mm × 1 mm

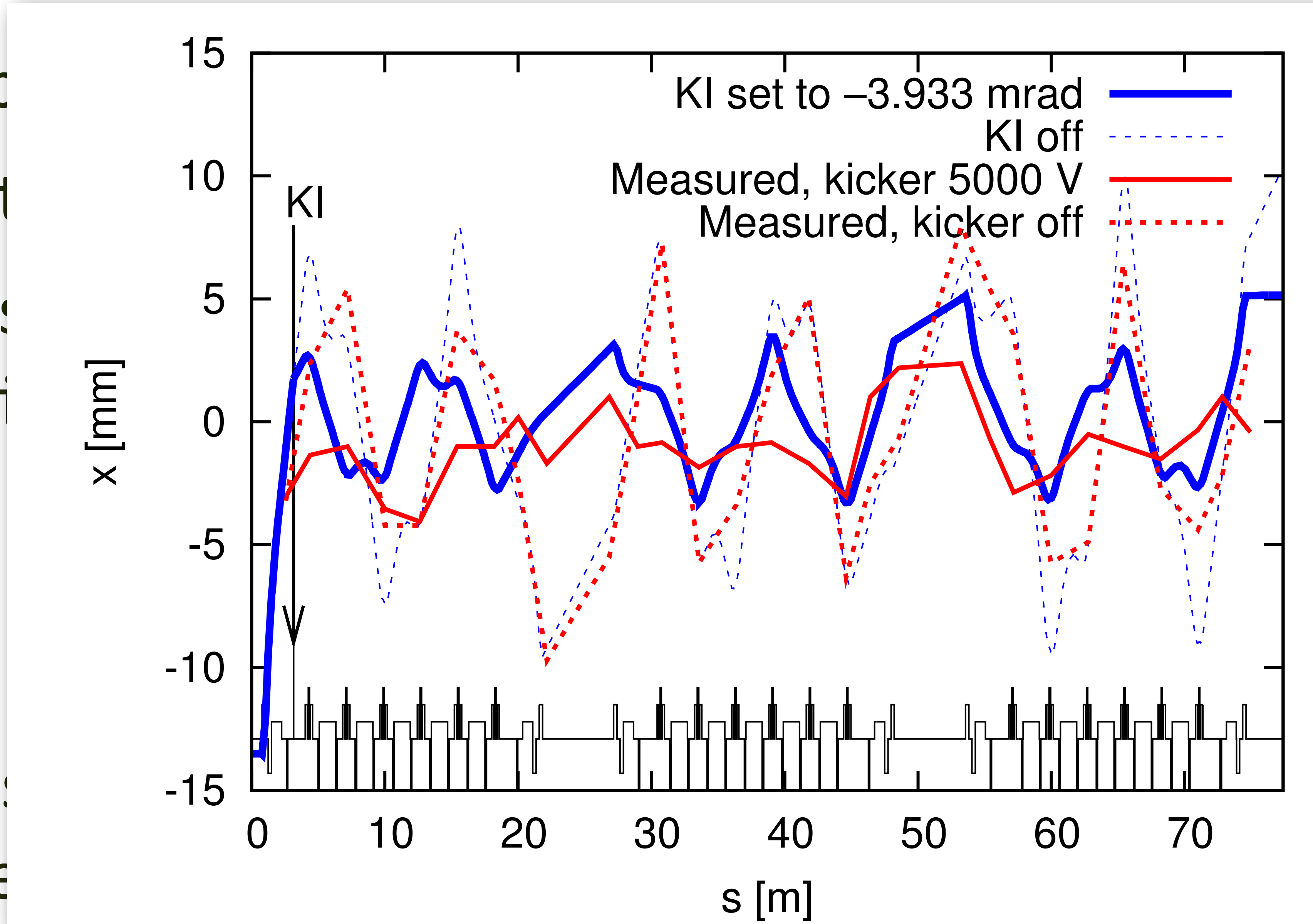
3 GeV Storage Ring Commissioning (cont.)

- First beam into full 3 GeV transfer line (TL) on Aug 10
- TL optics fixed, successful injection into 3 GeV SR on Aug 19
- With some manual adjustments of angle and position at injection point in SR (using diode rings), immediately detected beam on all BPMs in first achromat (up to first closed valve)

- To pass beyond straight 4 (without correctors), required exciting dipole injection kicker (exactly according to design)
- Exited dipole kicker at ≈75% of nominal strength and saw amplitudes reduce roughly 60% (Libera Brilliance+ SP read-out)

3 GeV Storage Ring Commissioning (cont.)

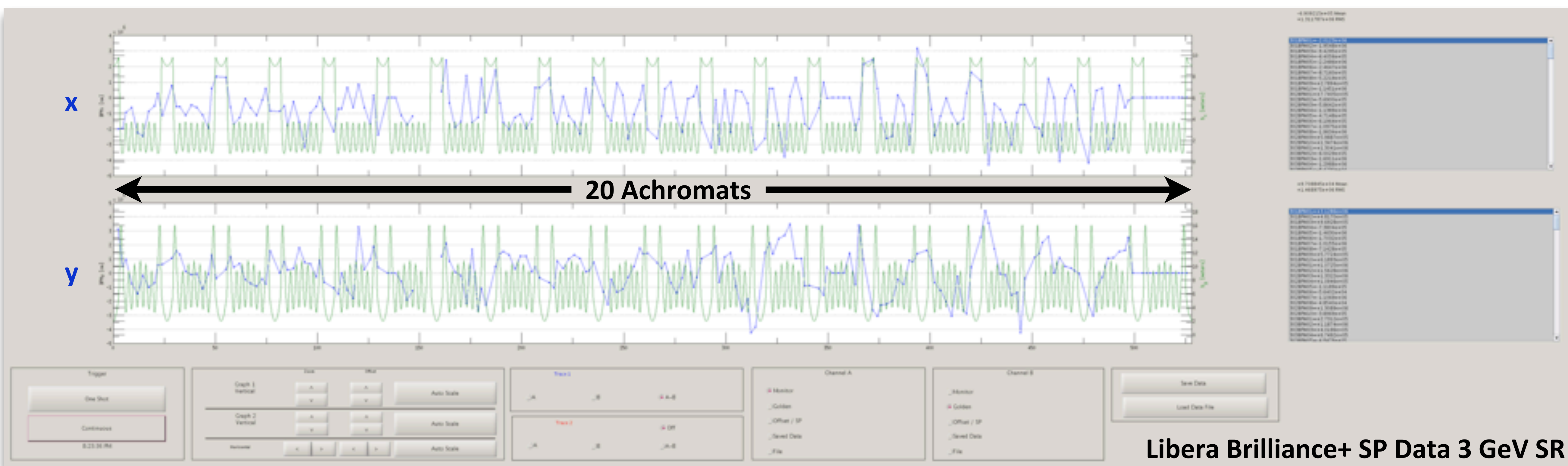
- First b… …10
- TL opt… …on Aug 19
- With … …tion at injecti… …detected beam… …sed valve)



- To pa… …exciting dipole…
- Exited dipole kicker at ≈75% of nominal strength and saw amplitudes reduce roughly 60% (Libera Brilliance+ SP read-out)

3 GeV Storage Ring Commissioning (cont.)

- Aug 25, 10pm: reached first full turn without exciting a single corrector & all magnets at nominal optics for 3.0 GeV
- Without sextupoles & octupoles lost beam in straight 11 (while all correctors set to zero); vertical orbit substantially reduced with focusing from sextupoles & octupoles



3 GeV Storage Ring Commissioning (cont.)

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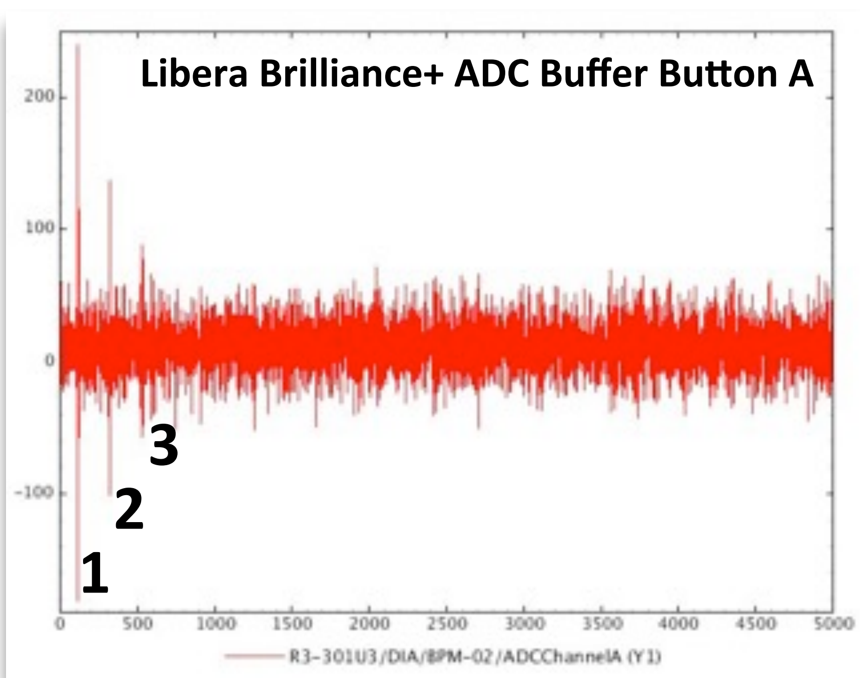
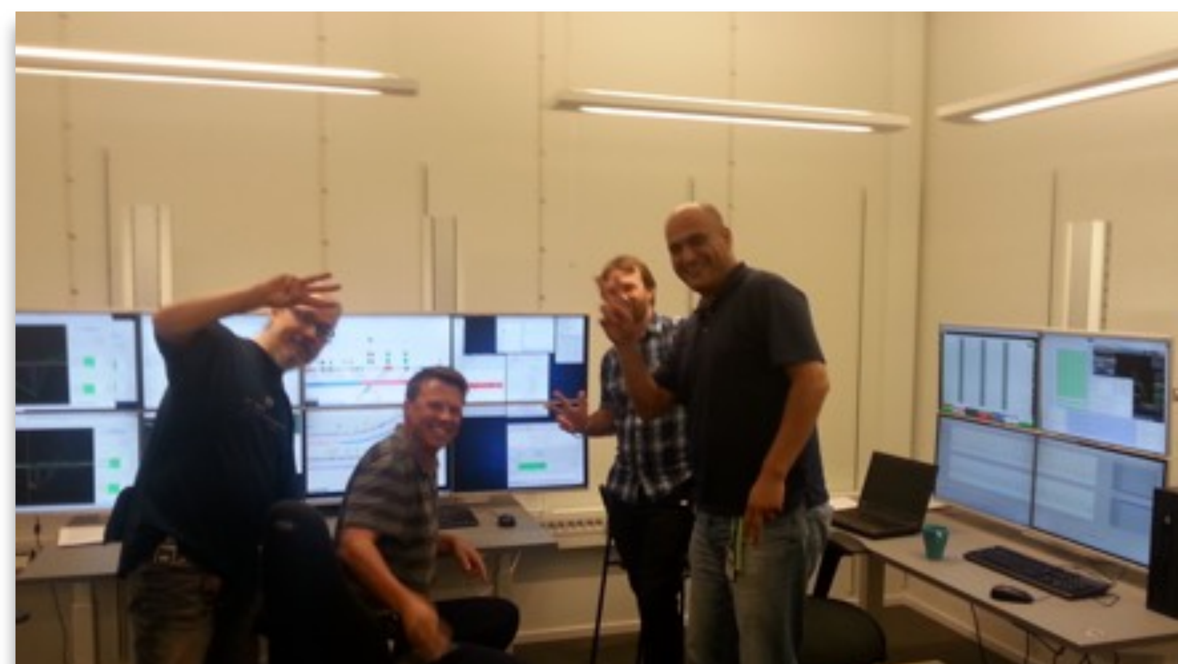
- After a few minutes of manual corrector adjustments and optics tweaking (mainly in TL and end of linac) recorded 3 passages





3 GeV Storage Ring Commissioning (cont.)

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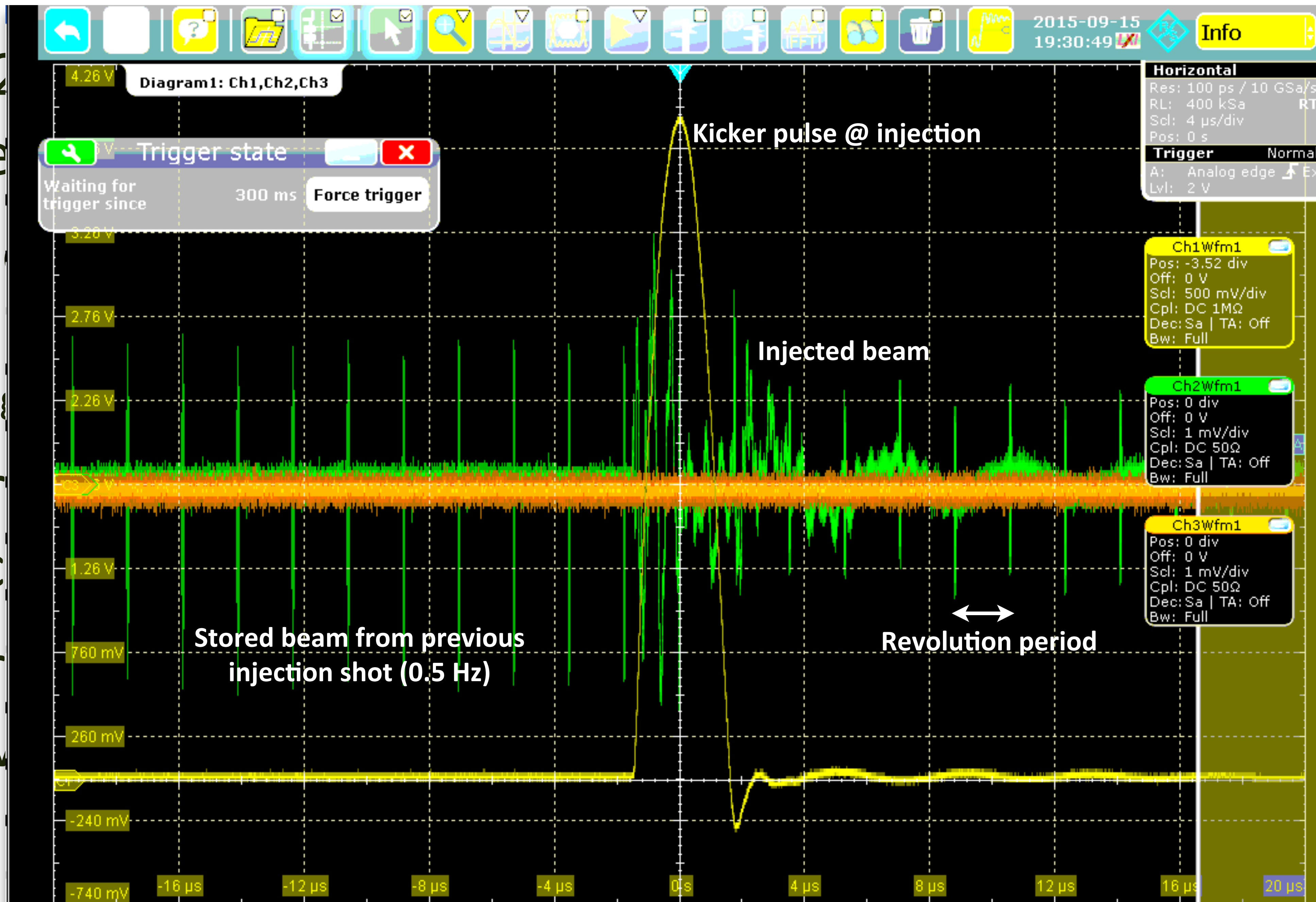
- Without sextupoles & octupoles lost beam in straight 11 (while all correctors set to zero); vertical orbit substantially reduced with focusing from sextupoles & octupoles
- After a few minutes of manual corrector adjustments and optics tweaking (mainly in TL and end of linac) recorded 3 passages
- After RF conditioning (3 cavities ready for beam @ 15-20 kW) and various other fixes...

3 GeV Storage Ring Commissioning (cont.)

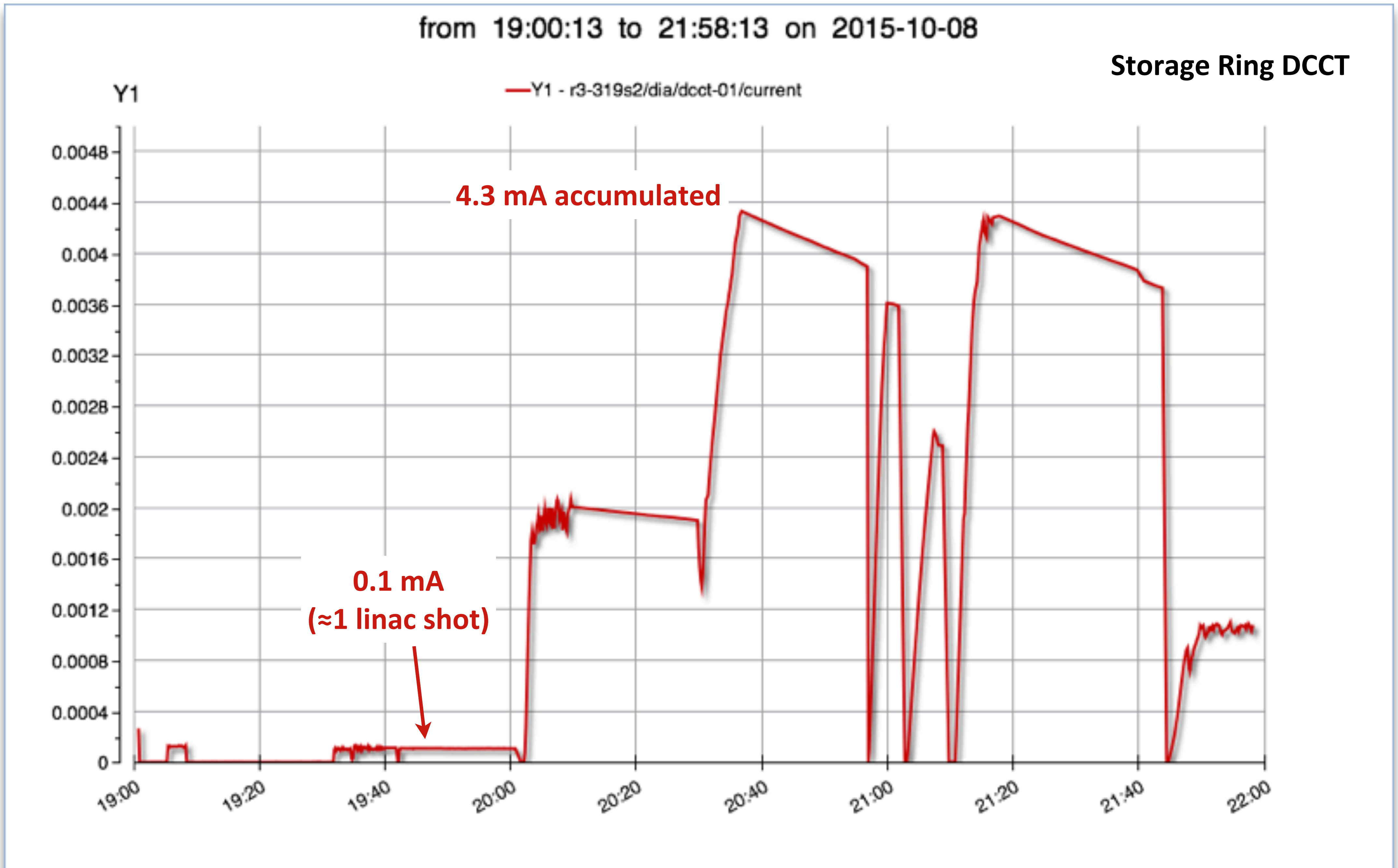
- Aug 2 … single corre…
- With… 1 (whil… ed with focusin…
- After… nd optic… es
- After… 20 kW) and v…



- First stored beam on Sep 15 → ≈0.1 mA (≈170 pC from linac)

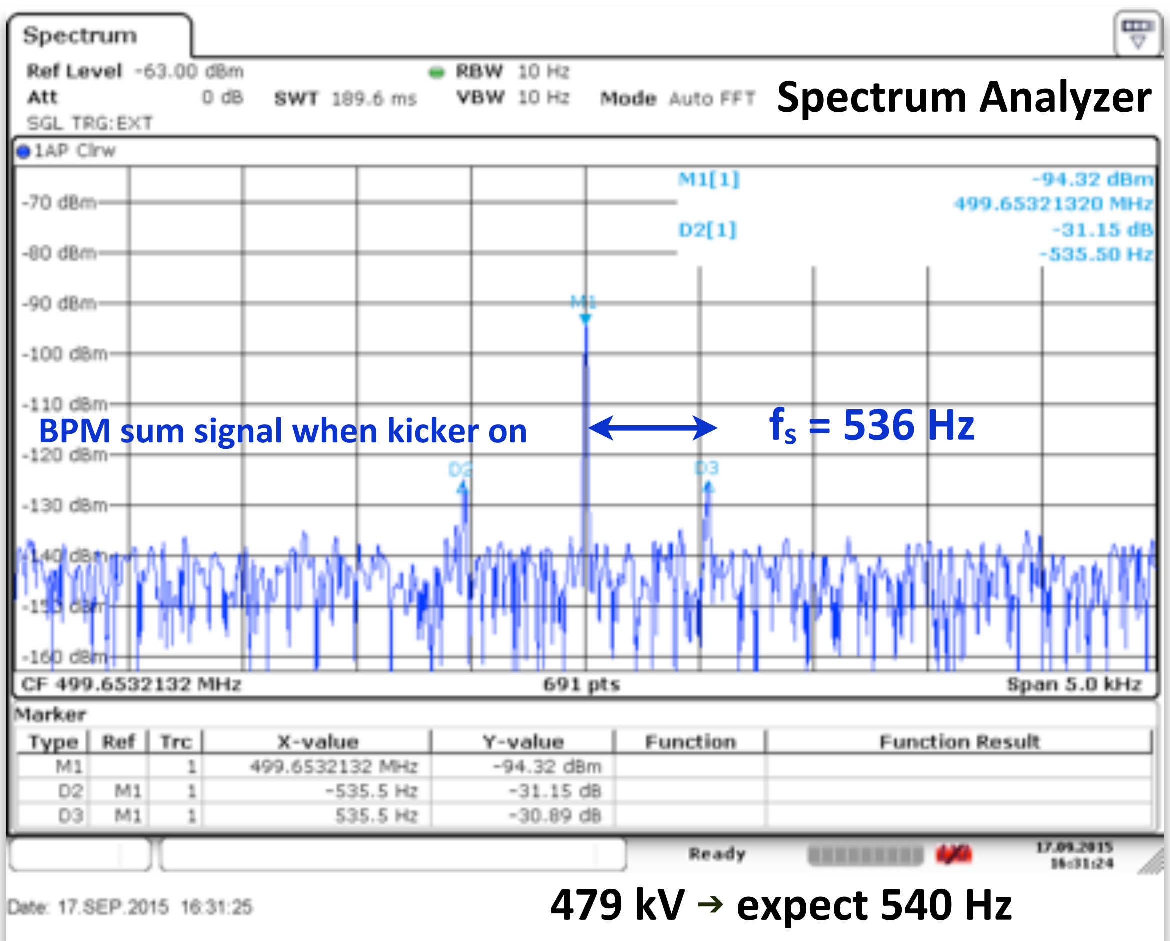
3 GeV Storage Ring Commissioning (cont.)

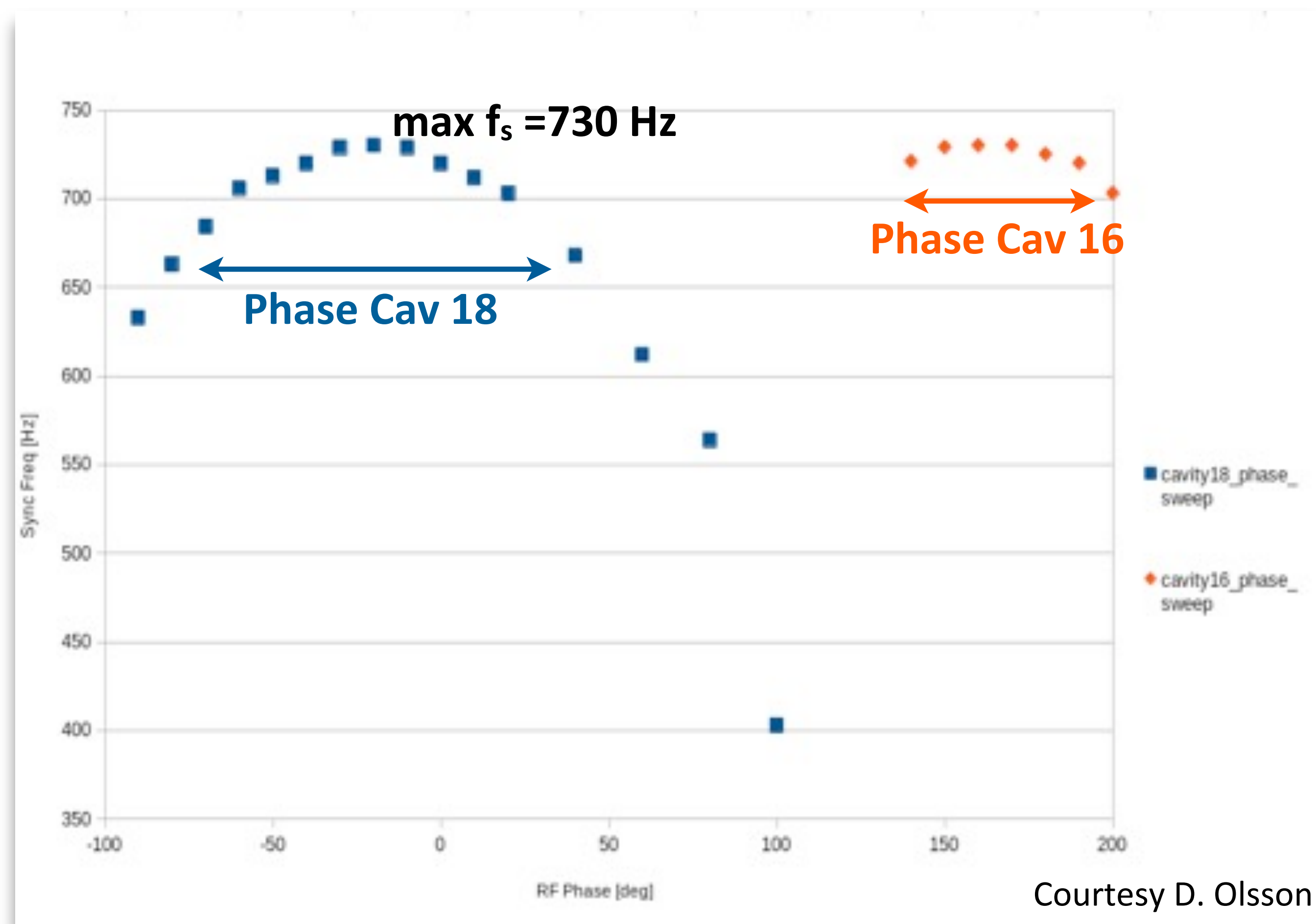
- First stacking observed Oct 8



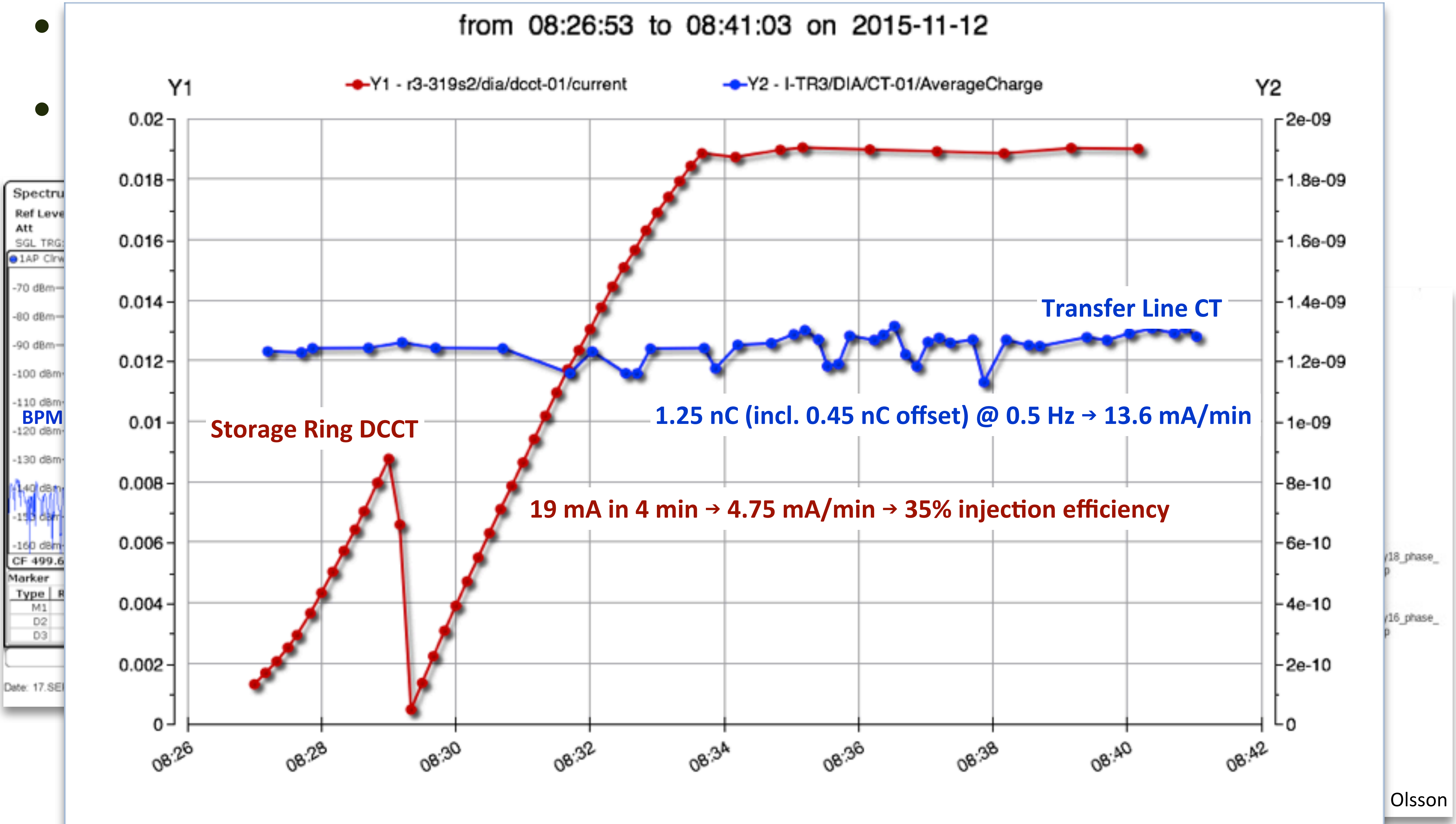
3 GeV Storage Ring Commissioning (cont.)

- First stacking observed Oct 8
- Phasing 2 ring cavities → maximize f_s and improve inj. rate



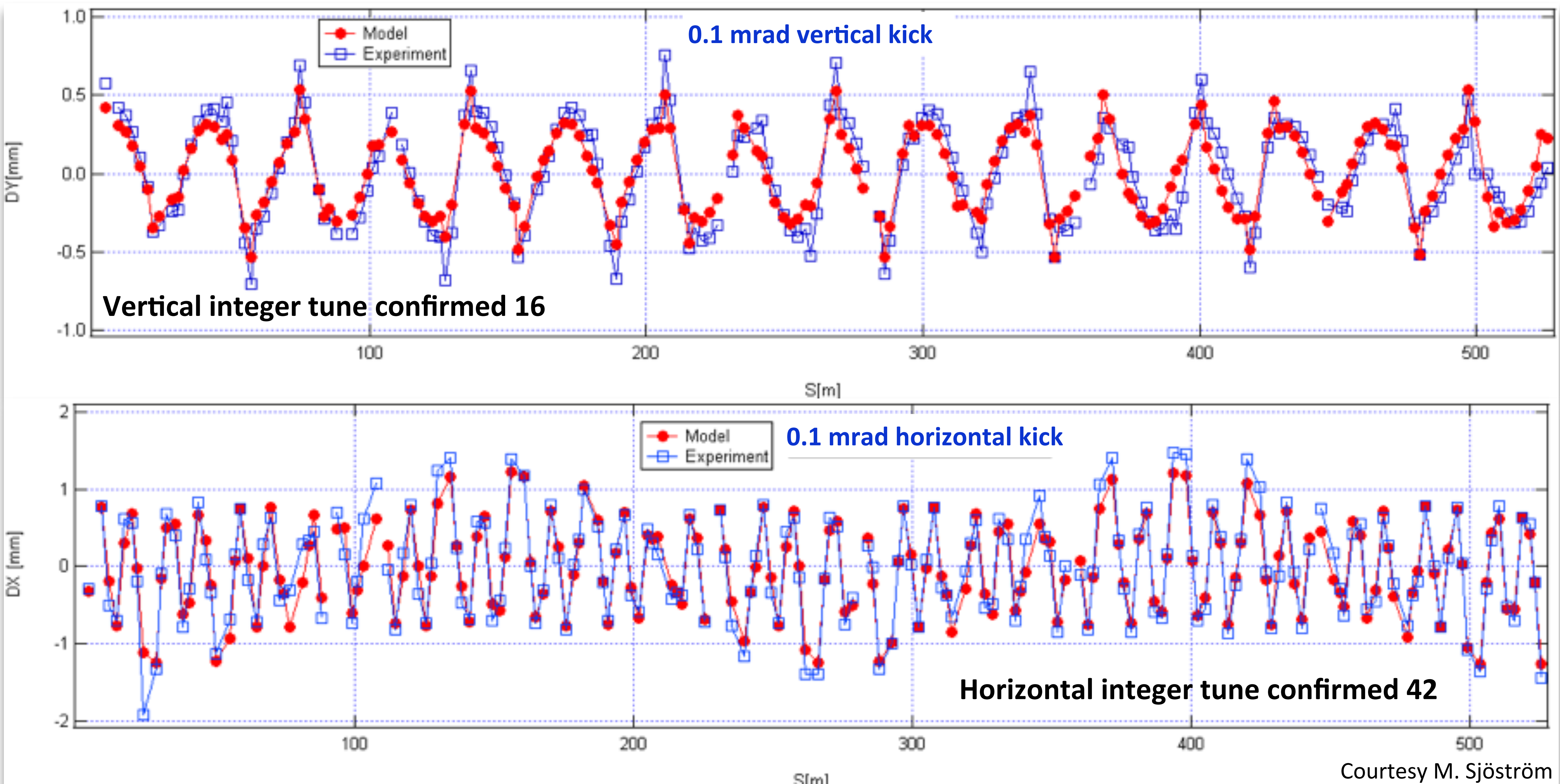


3 GeV Storage Ring Commissioning (cont.)



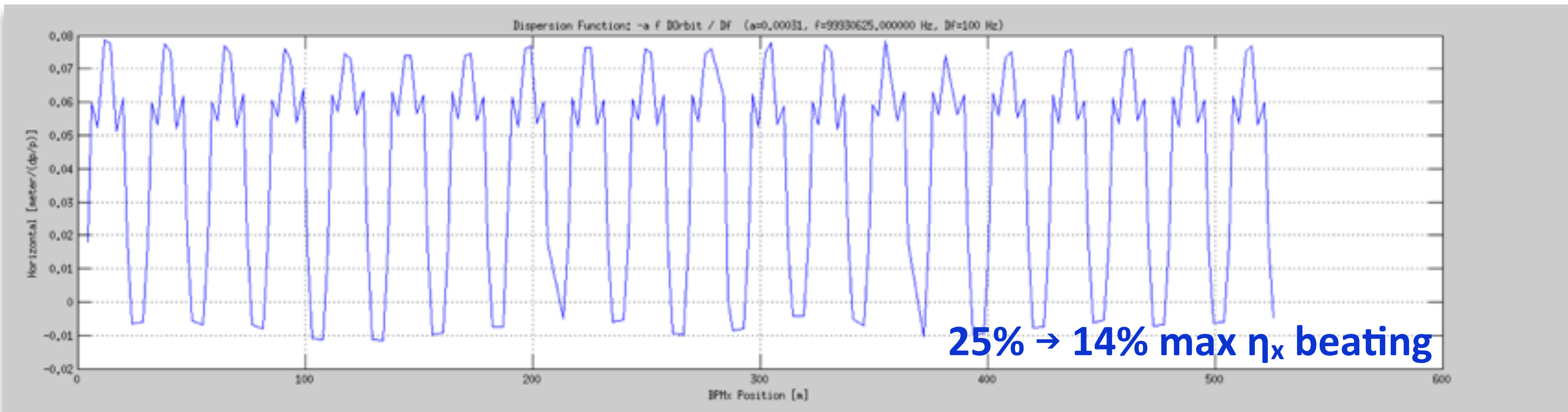
3 GeV Storage Ring Commissioning (cont.)

- First linear optics studies & corrections

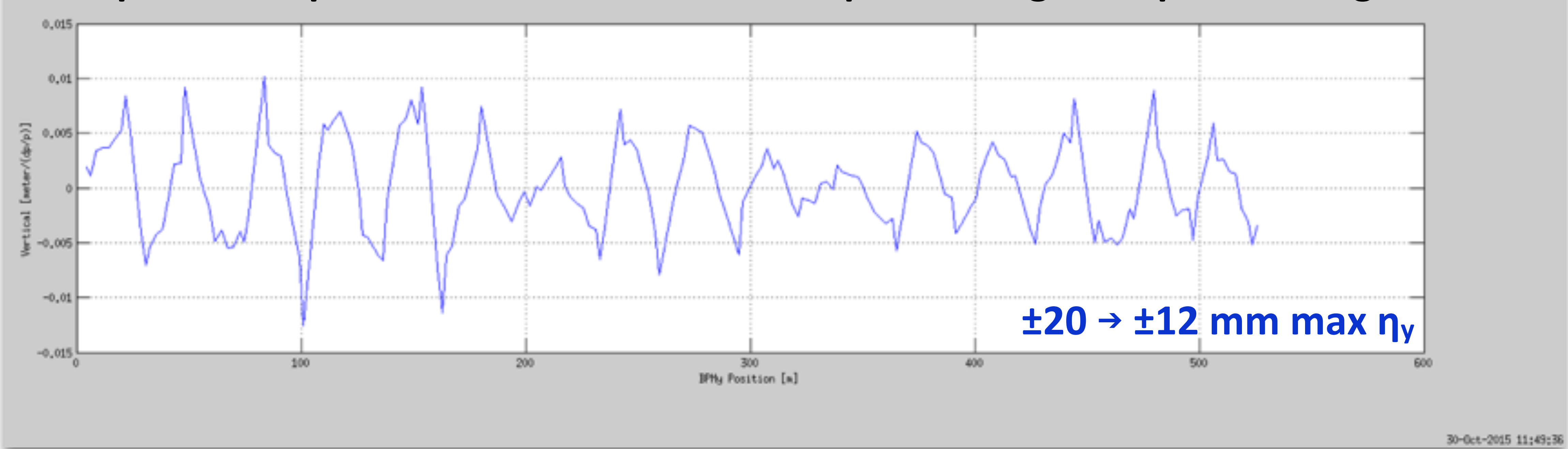


3 GeV Storage Ring Commissioning (cont.)

- First linear optics studies & corrections



Dispersion improved after first LOCO attempts & fixing sextupole misalignment

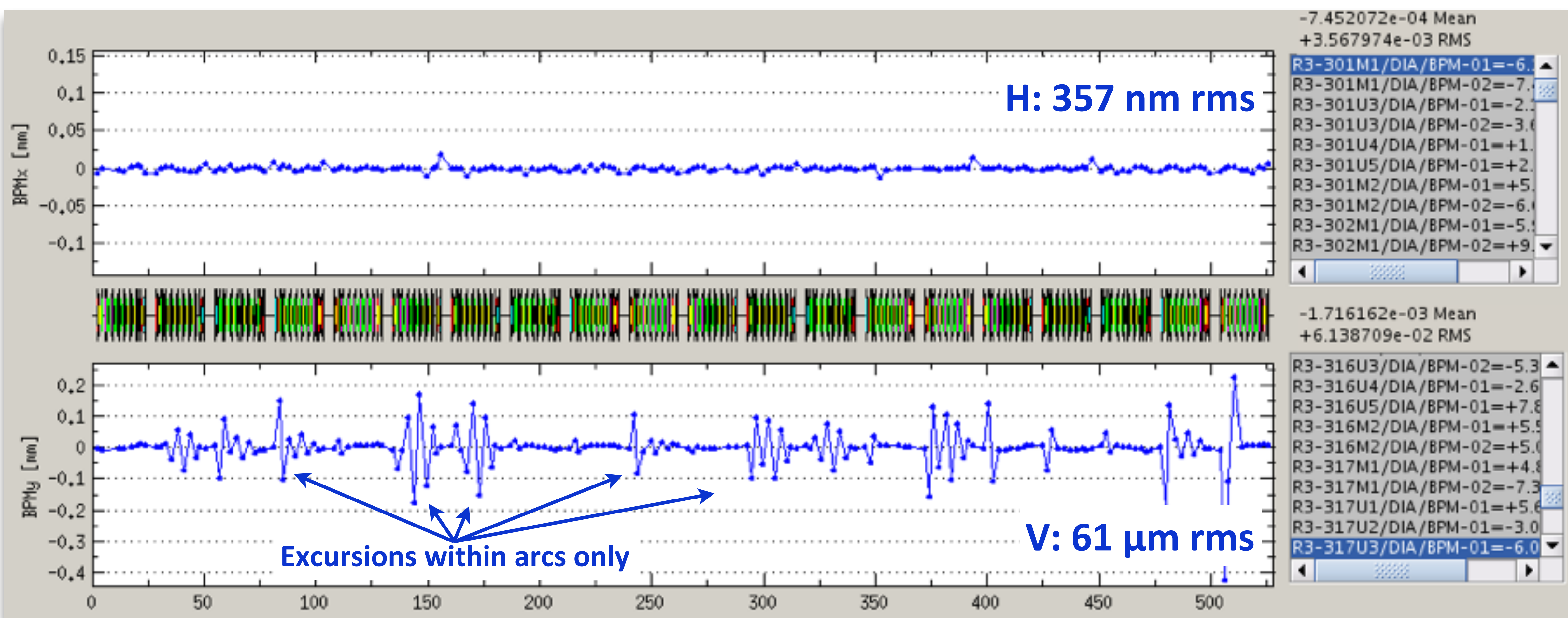


3 GeV Storage Ring Commissioning (cont.)

- First linear optics studies & corrections
- BPM offsets relative to adjacent sextupole/octupole via auxiliary coil powered as upright quad

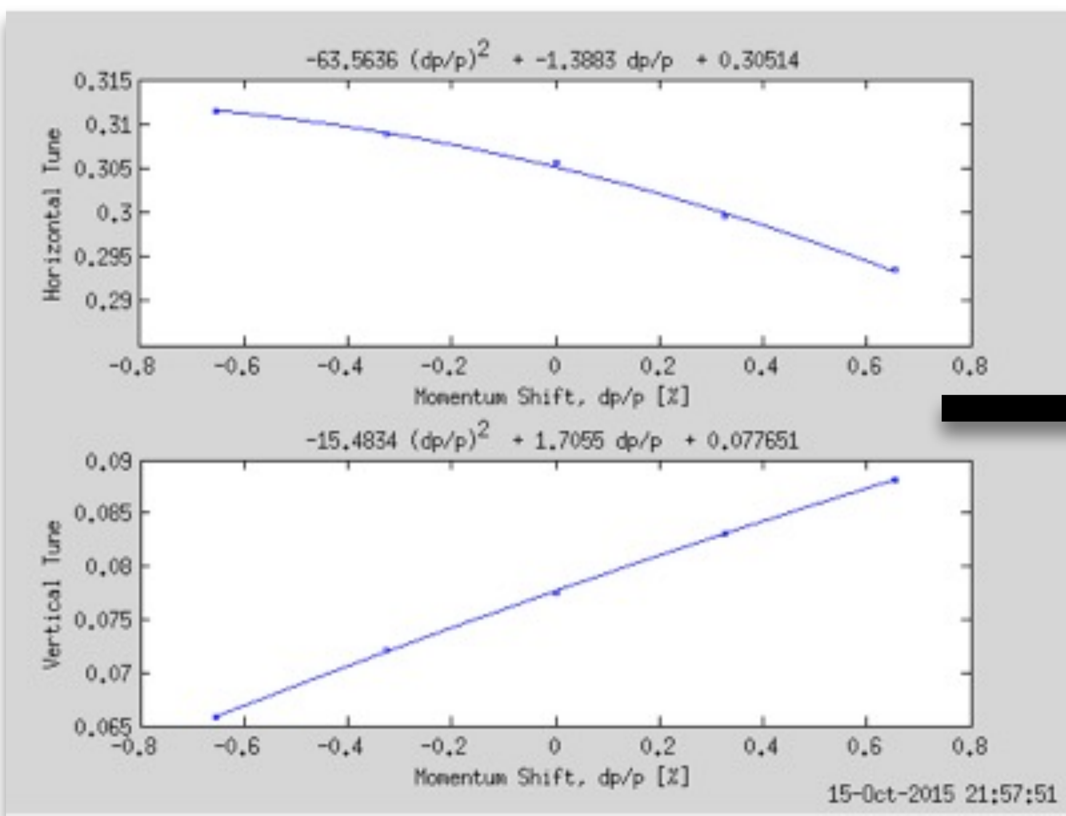
3 GeV Storage Ring Commissioning (cont.)

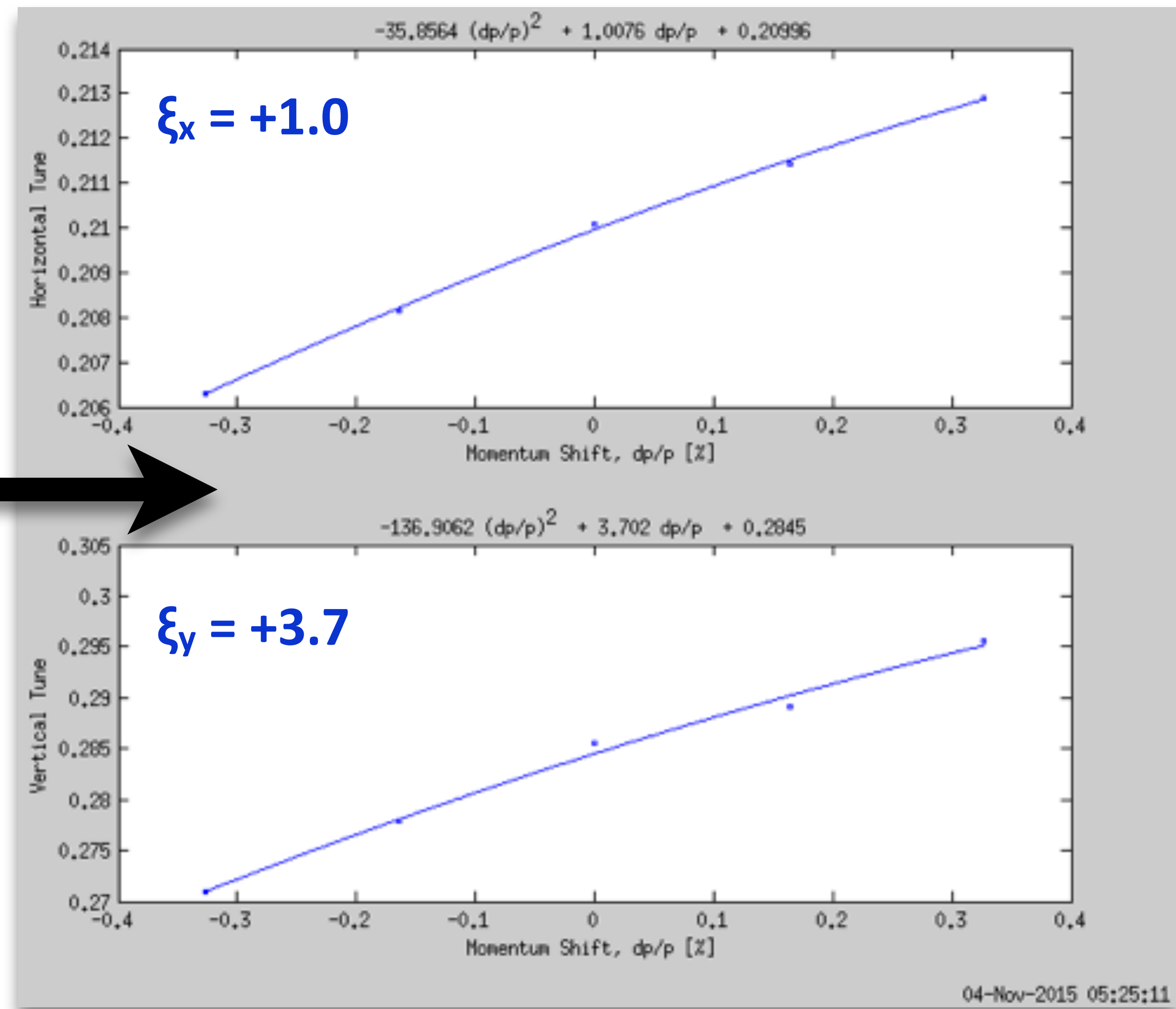
- First linear optics studies & corrections
- BPM offsets relative to adjacent sextupole/octupole via auxiliary coil powered as upright quad
- Orbit correction to <1 µm rms in H; larger in V (since $N_{BPM} > N_{VCM}$)
  → apply weighting so orbit always locked down in ID straights



3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
  - after adjusting towards design tunes (0.20/0.28)
  - using only 2 chromatic sextupole families
  - limited $\Delta p/p$ range → $\xi^{(2)}$?





3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
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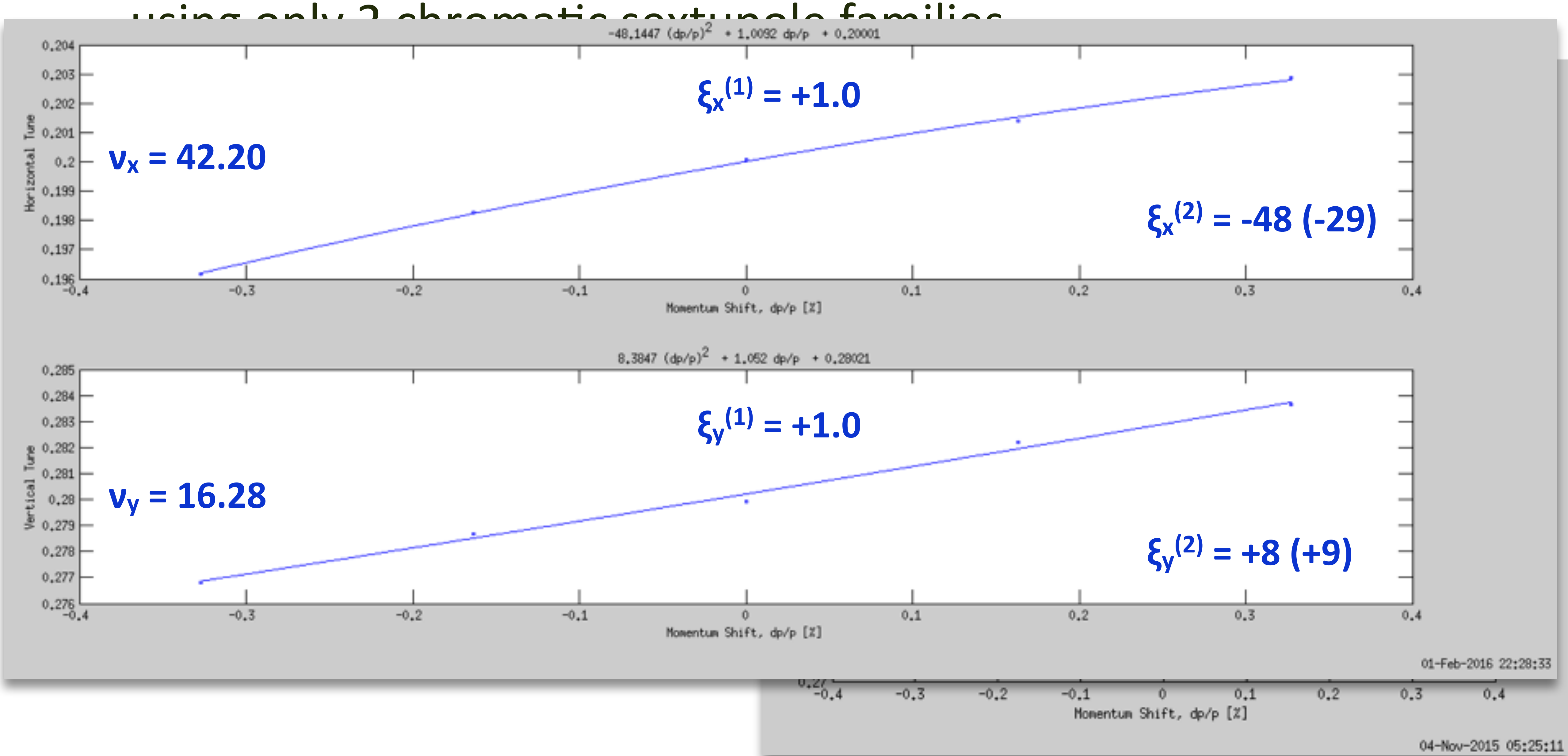


3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

IPAC’**16**, WEPOW034

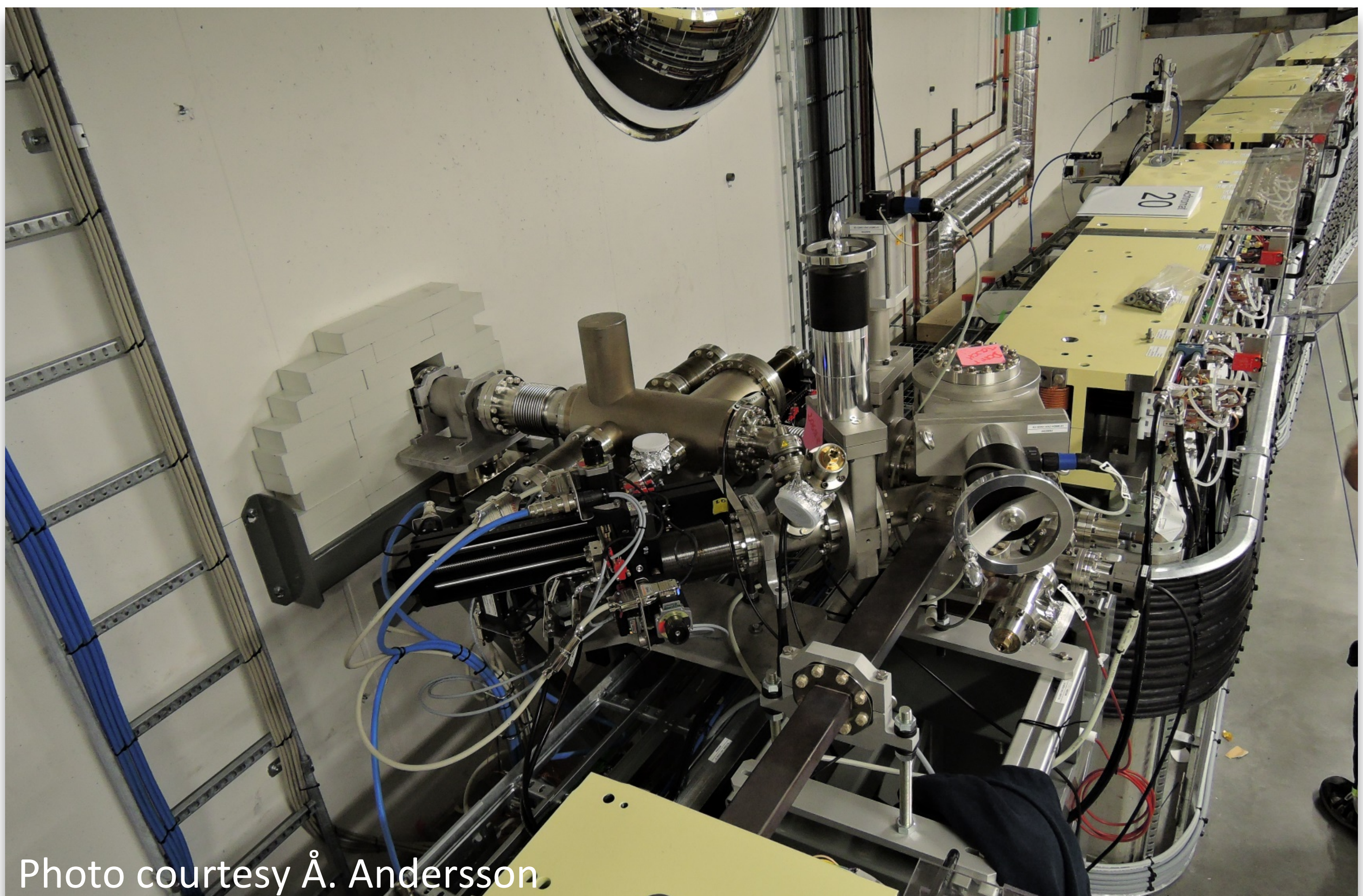
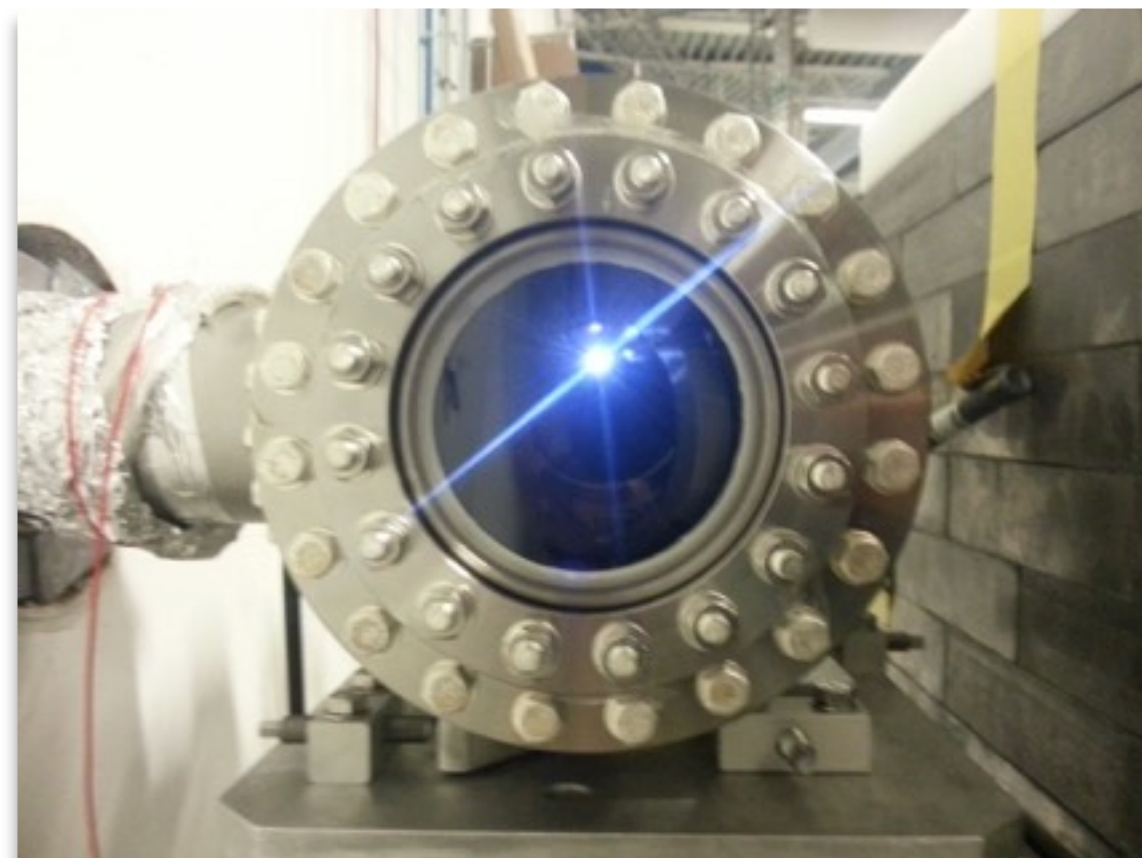


Photo courtesy Å. Andersson



3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

IPAC'**16**, WEPOW034

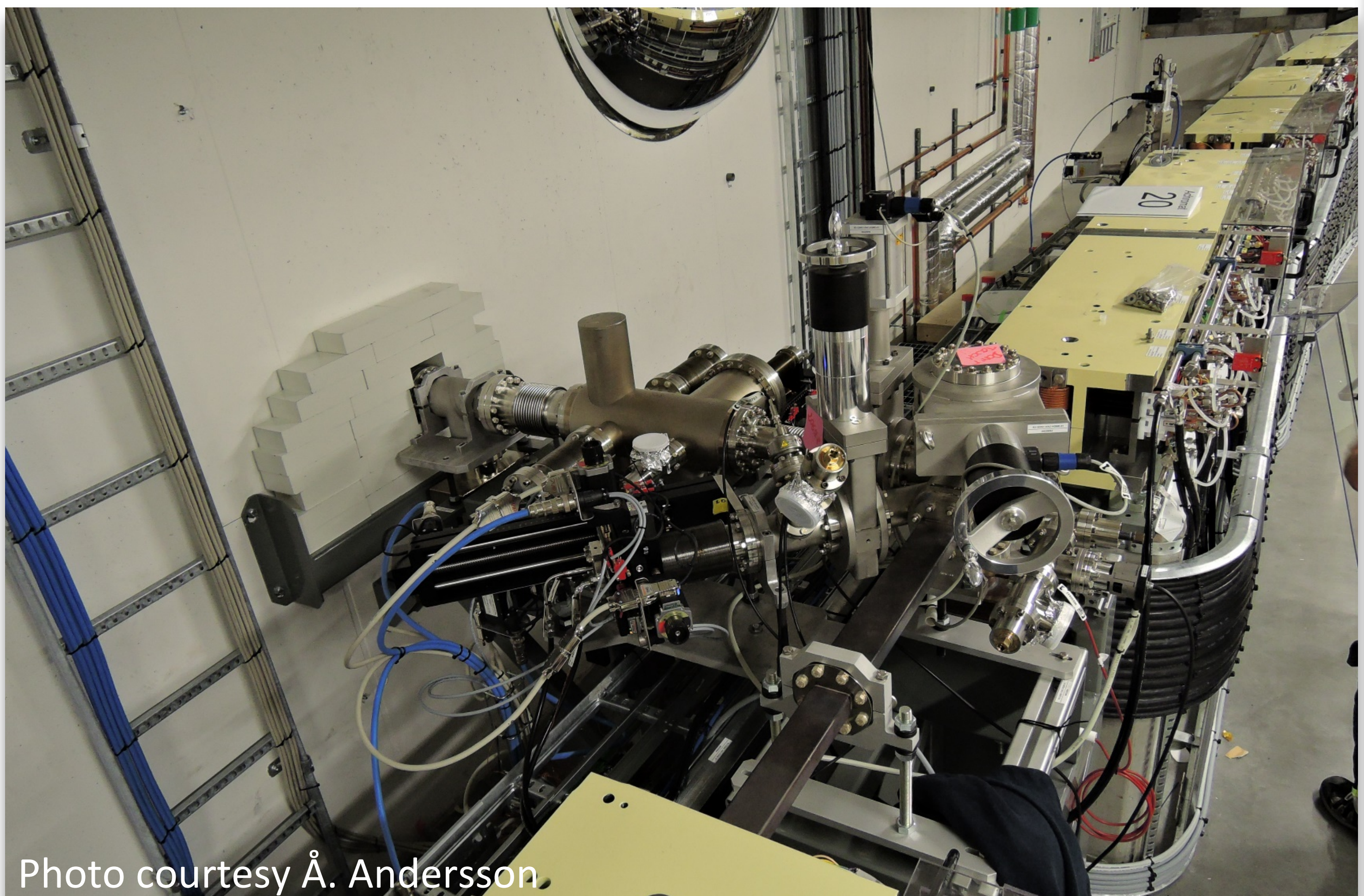
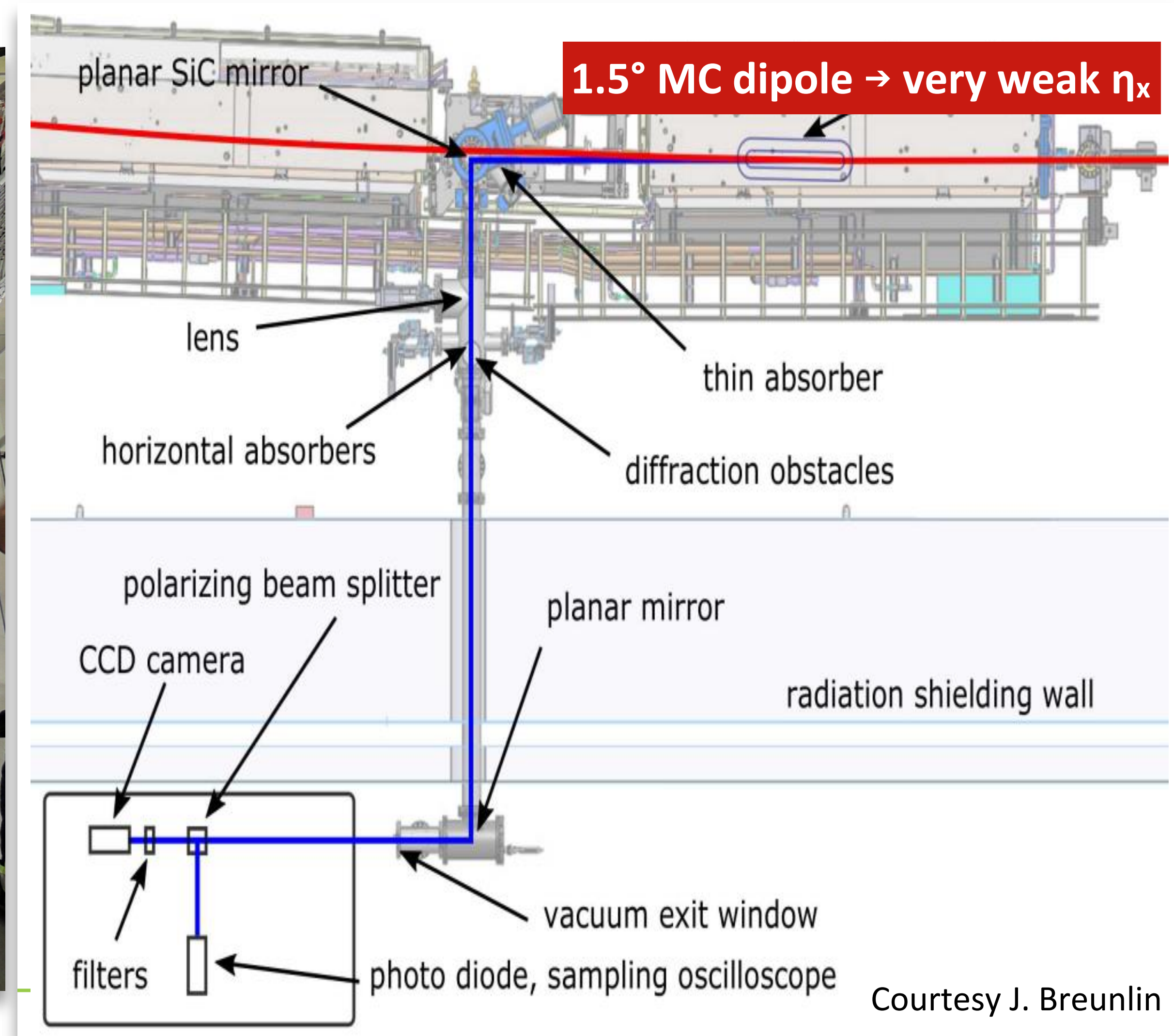


Photo courtesy Å. Andersson

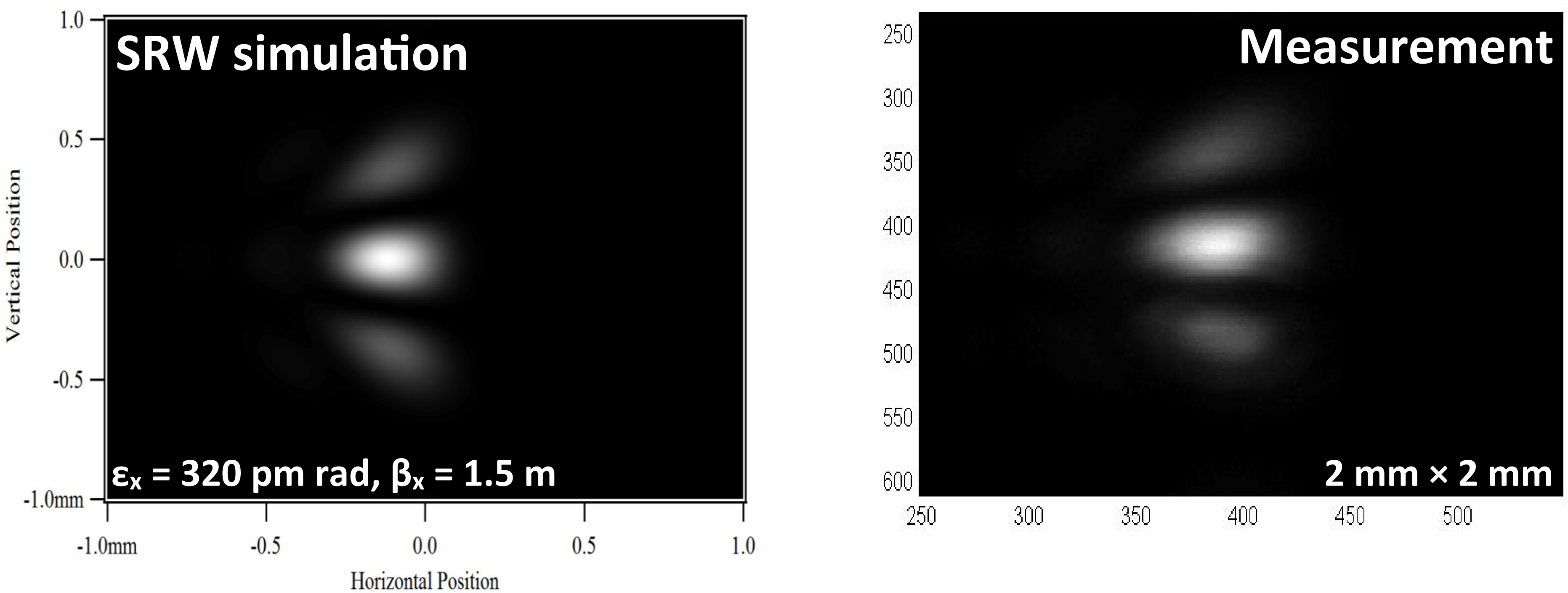


Courtesy J. Breunlin

3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

IPAC'**16**, WEPOW034



Sigma polarized SR, 632.8 nm, SRW calculation (left) and measured image (right). The simulation is done for ε_x = 320 pm rad, β_y = 1.5 m.
Both figures show a 2 x 2 mm^2 area of the image plane.
The fringe pattern is too weak to be visible.

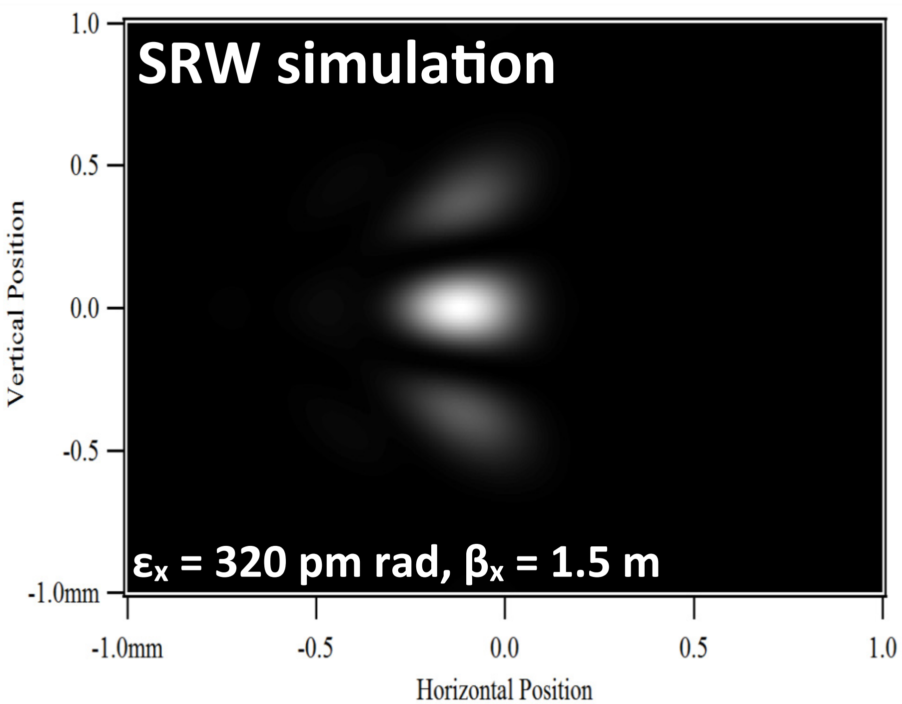
Optical magnification of m=-2.28 is taken into account in the SRW model
Horizontal opening angle: 6 mrad
Vertical opening angle: 8 mrad
Exposure time: 2.9 ms

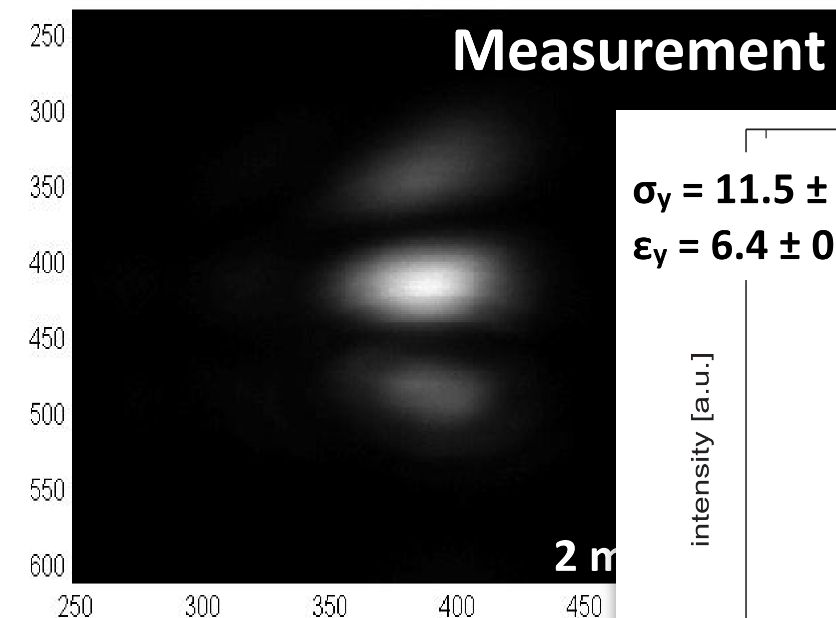
Courtesy J. Breunlin

3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

IPAC'**16**, WEPOW034





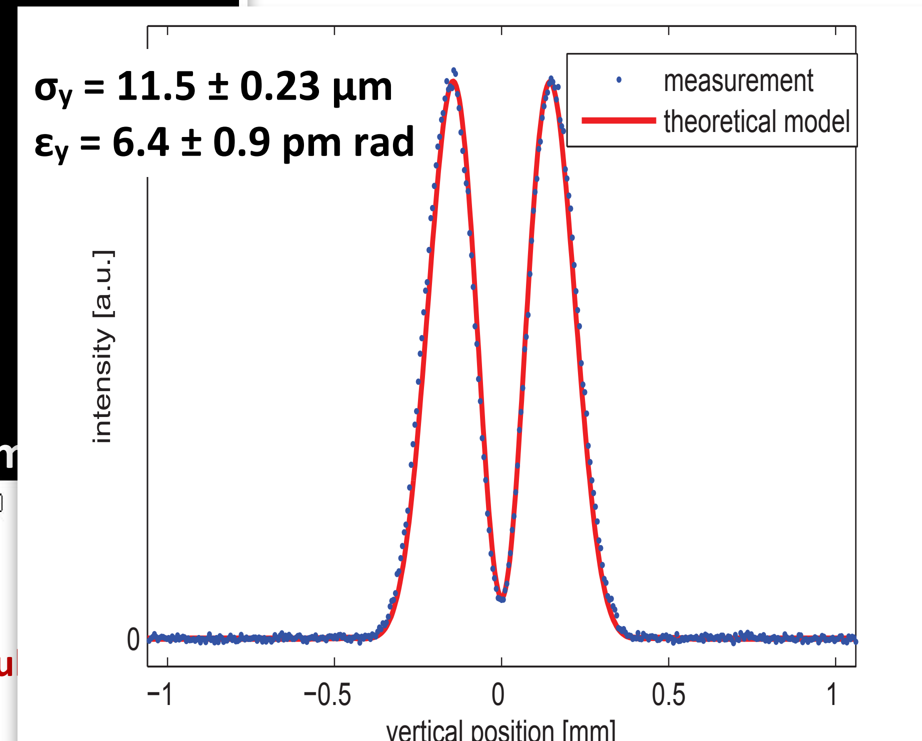


Figure 3: Vertical profile of imaged π-polarized SR at 488 nm wavelength. Measurement (blue dots) and SRW calculation (red lines). The vertical beam size is 11.5 μm.

Sigma polarized SR, 632.8 nm, SRW calculation (left) and measured image (right). The simu
done for ε_x = 320 pm rad, β_y = 1.5 m.
Both figures show a 2 x 2 mm^2 area of the image plane.
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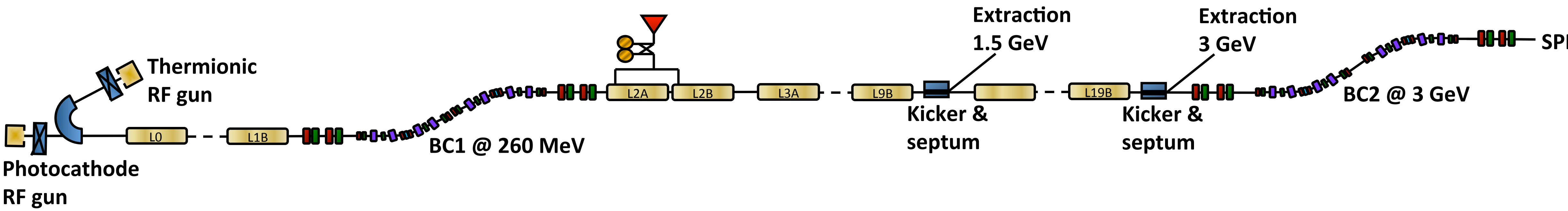
Optical magnification of m=-2.28 is taken into account in the SRW model
Horizontal opening angle: 6 mrad
Vertical opening angle: 8 mrad
Exposure time: 2.9 ms

Courtesy J. Breunlin

3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2
- Top-up running since Nov (closed shutters)
  - injector & linac switch between SPF operation and ring injection (involves on-the-fly switching of guns, linac optics, and linac extraction dipoles)



3 GeV Storage Ring Commissioning (cont.)

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- First light seen on diagnostic beamline Nov 2
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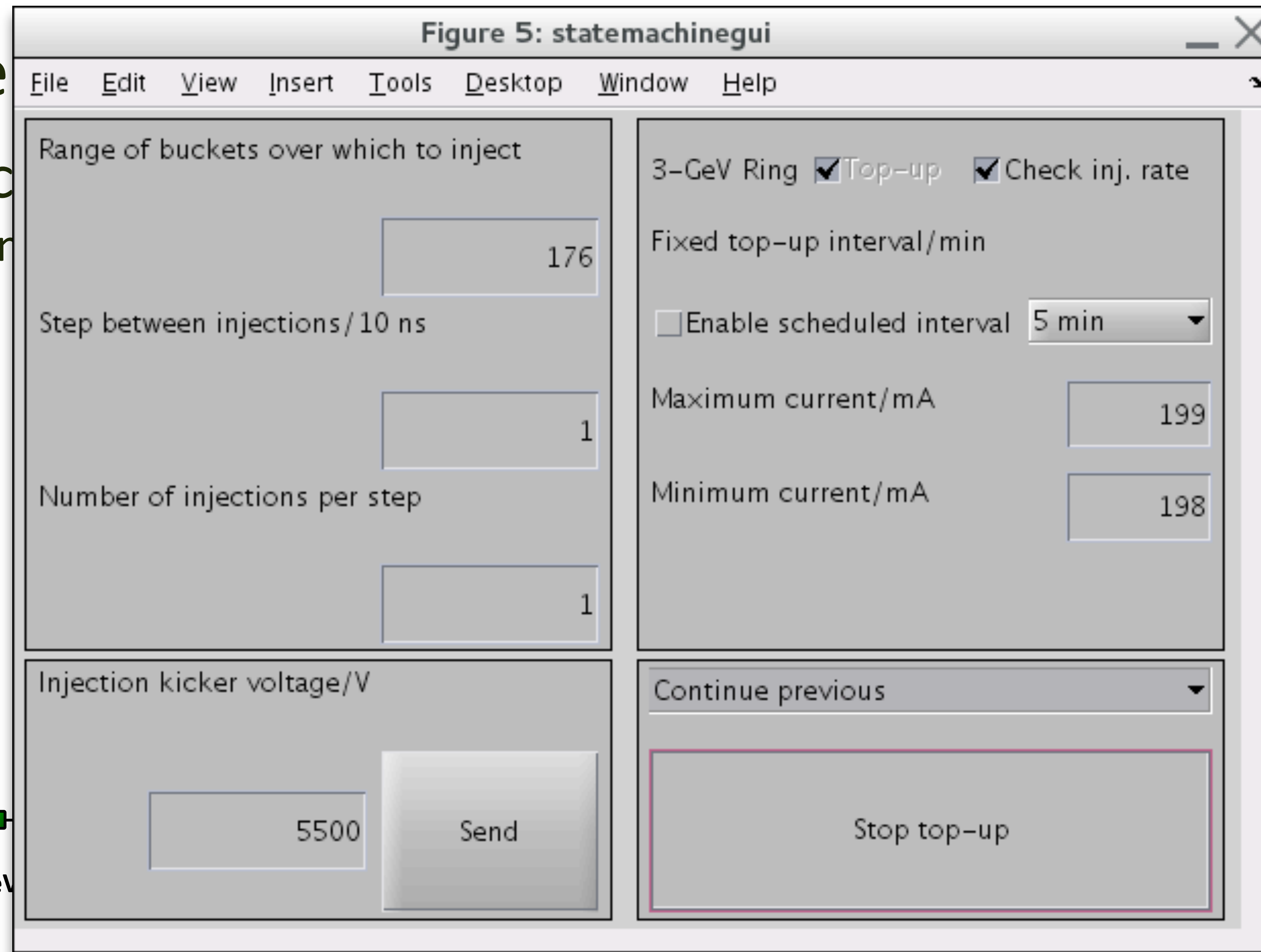
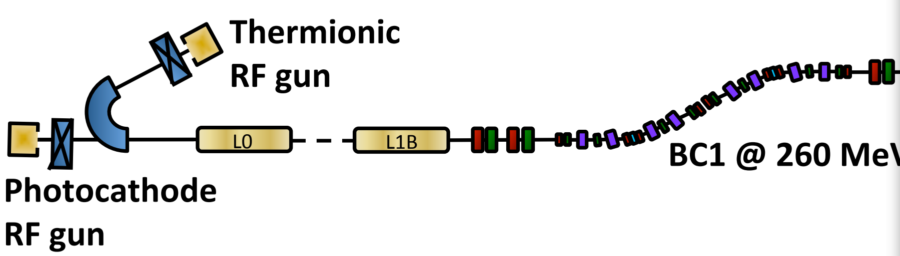
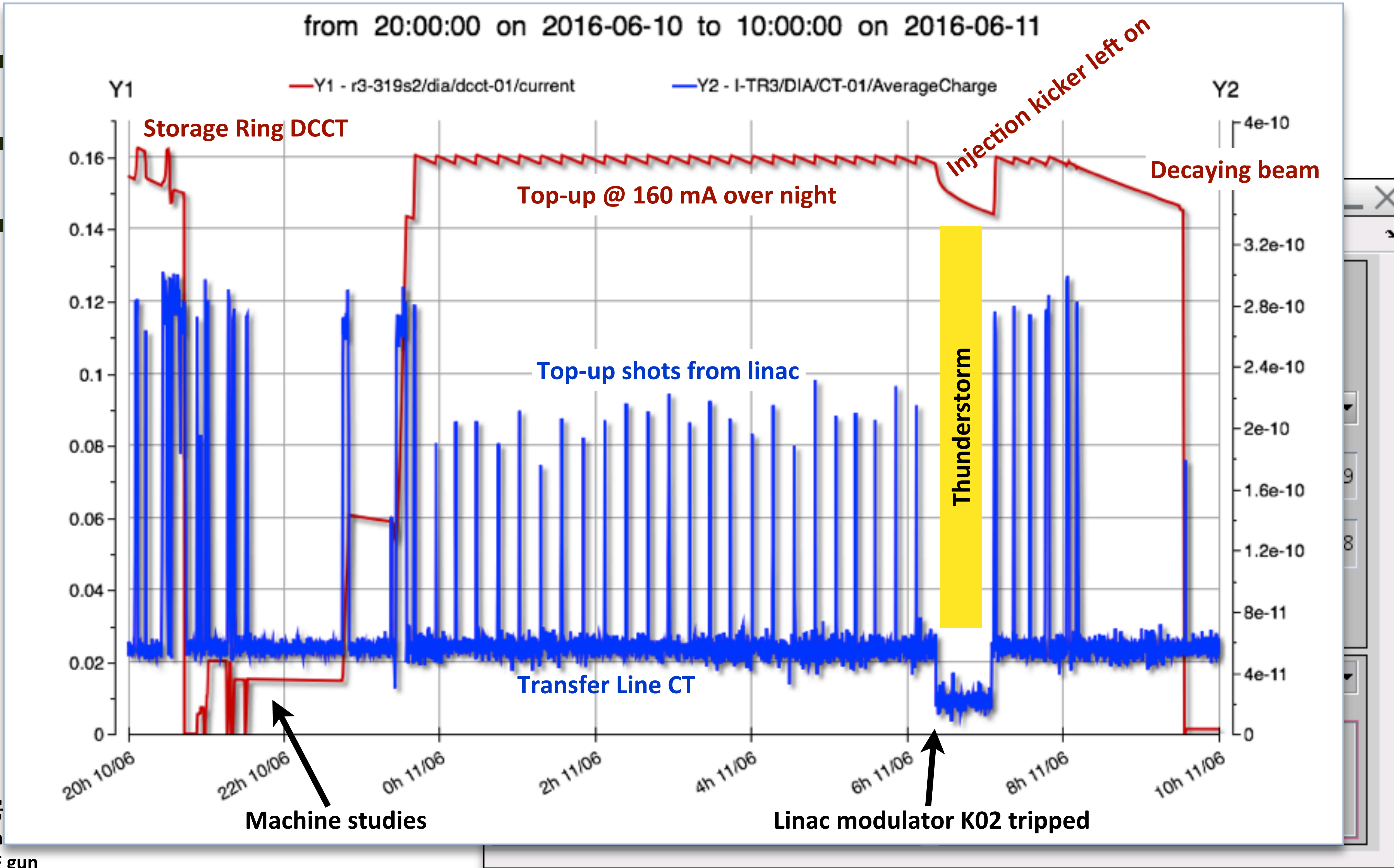
    (involves on-the-fly switchir





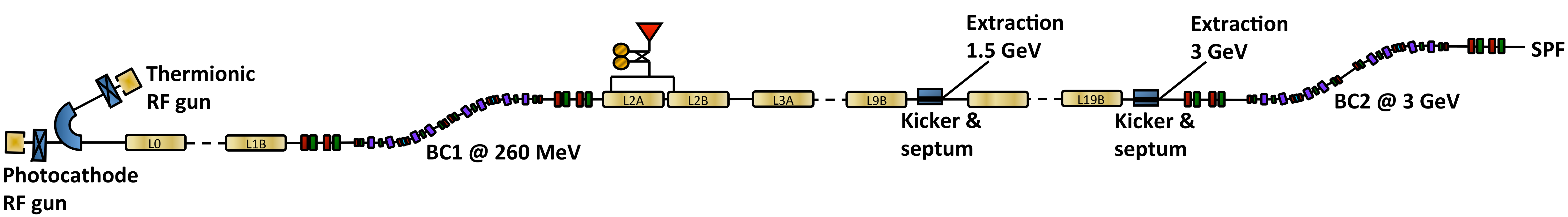
3 GeV Storage Ring Commissioning (cont.)



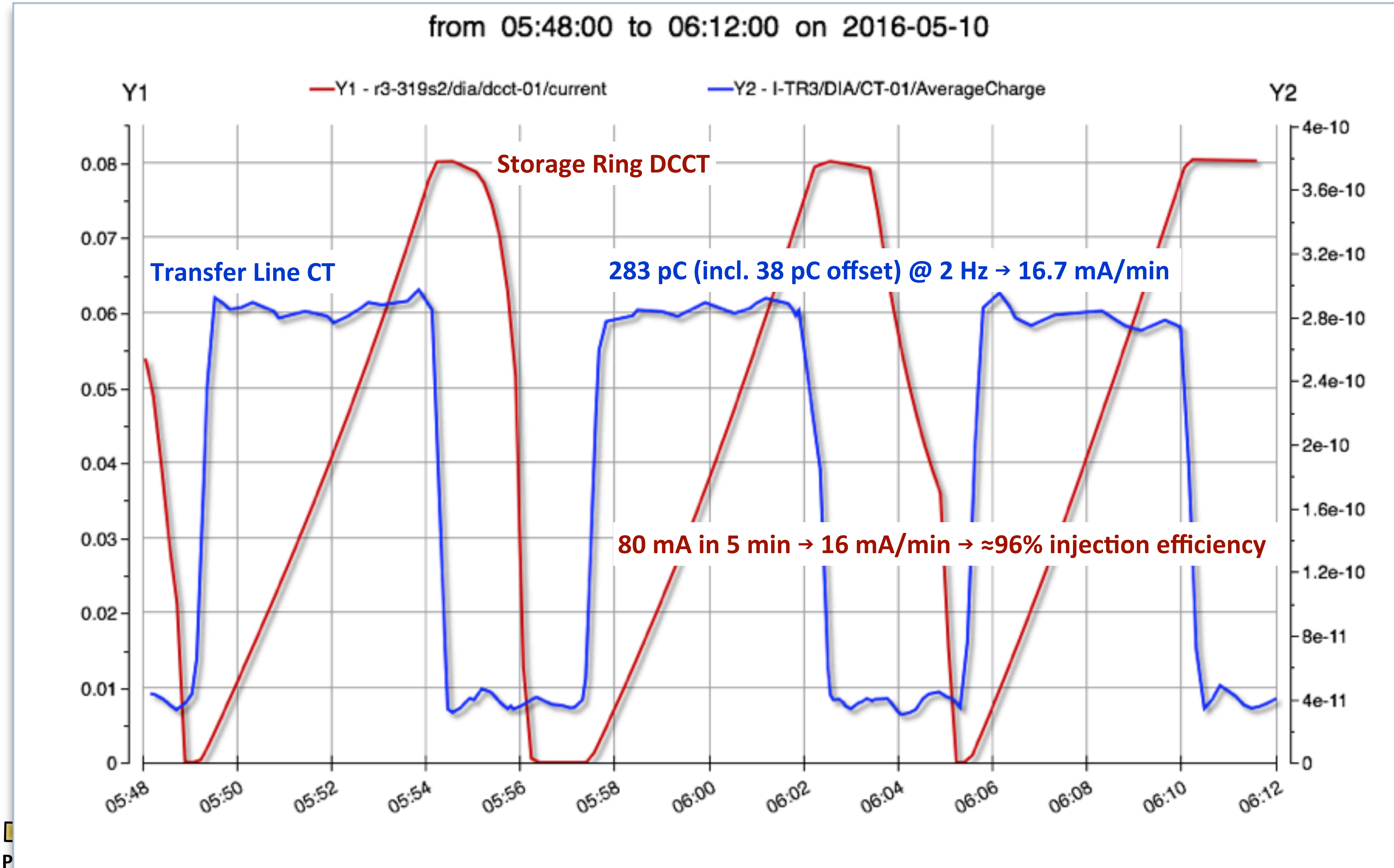
Ph
RF gun

3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2
- Top-up running since Nov (closed shutters)
  - injector & linac switch between SPF operation and ring injection (involves on-the-fly switching of guns, linac optics, and linac extraction dipoles)
  - injector & linac routinely running at 2 Hz since Nov
  - injection efficiency improved (ring phase acceptance!)



3 GeV Storage Ring Commissioning (cont.)

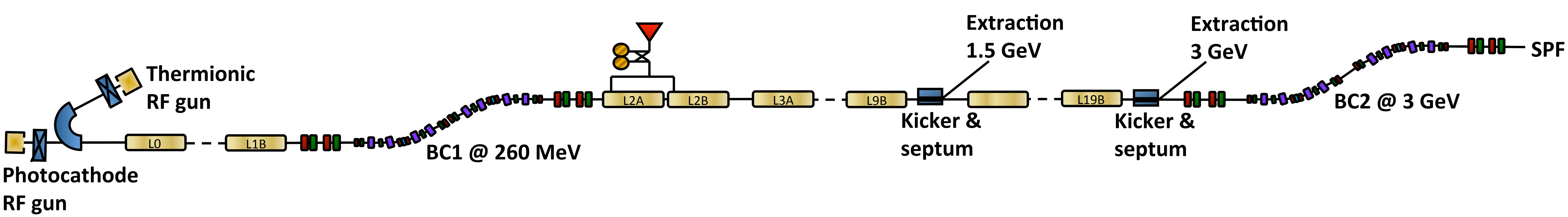


PF

P
RF gun

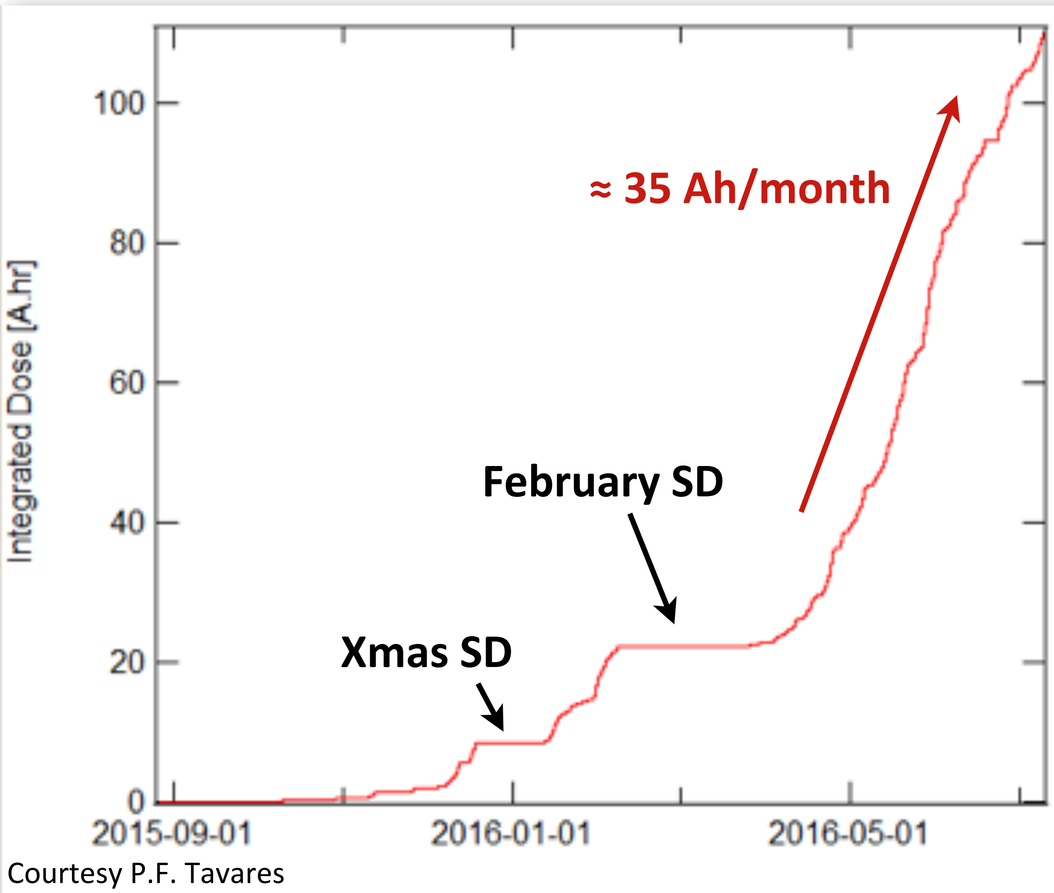
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2
- Top-up running since Nov (closed shutters)
  - injector & linac switch between SPF operation and ring injection (involves on-the-fly switching of guns, linac optics, and linac extraction dipoles)
  - injector & linac routinely running at 2 Hz since Nov
  - injection efficiency improved (ring phase acceptance!)
  - integrated dose increasing → improving ring vacuum

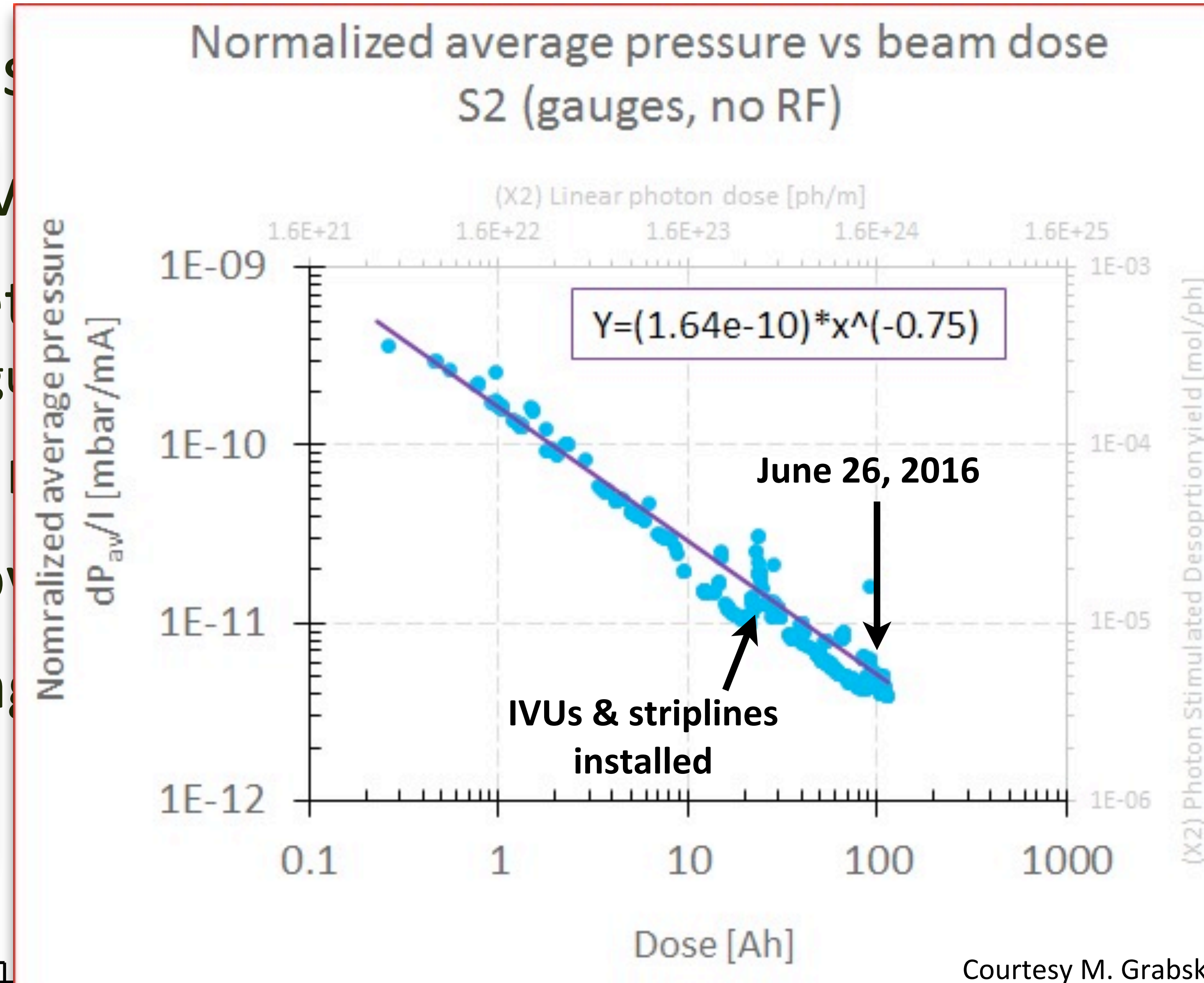


3 GeV Storage Ring Commissioning (cont.)

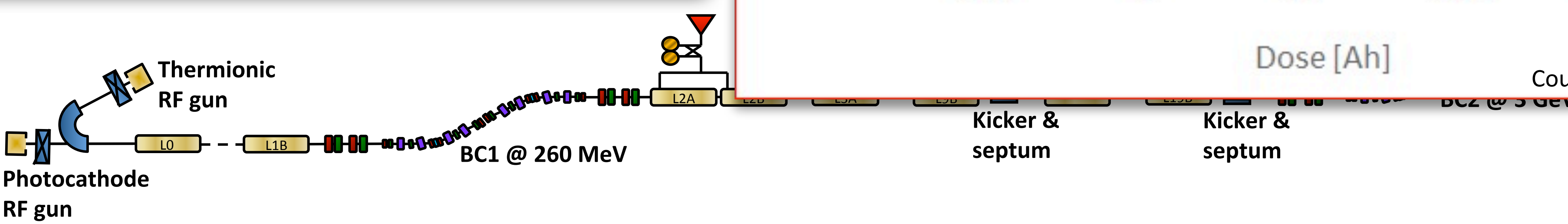
- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnos



Courtesy P.F. Tavares

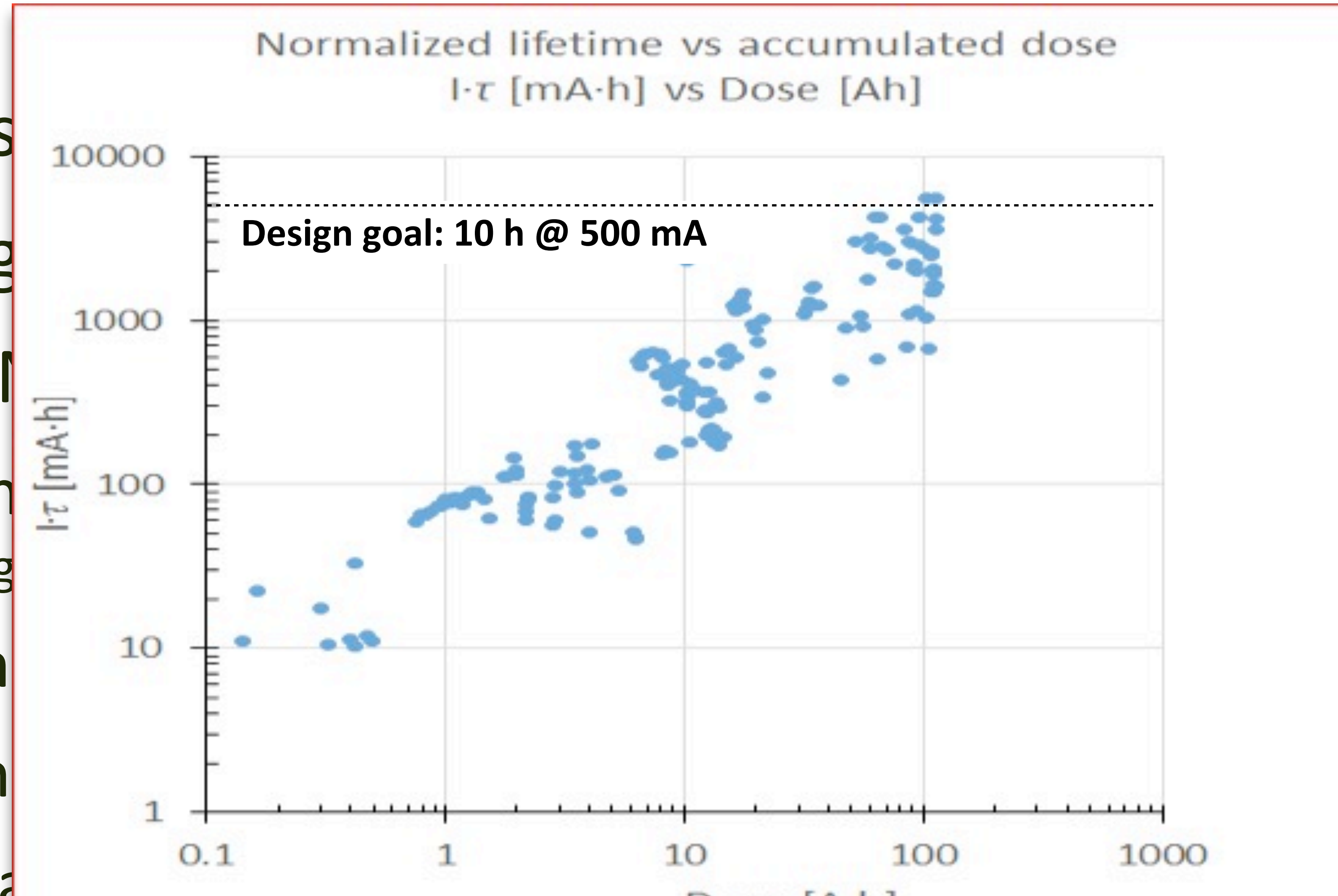


Courtesy M. Grabski

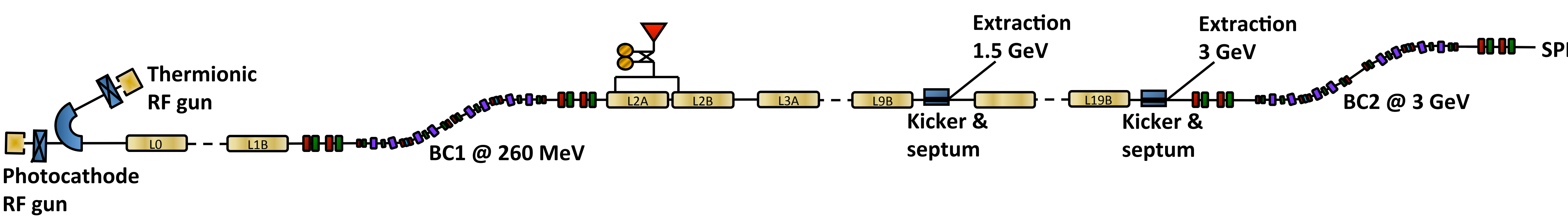


3 GeV Storage Ring Commissioning (cont.)

- First attempts at meas
- First light seen on diag
- Top-up running since I
  - injector & linac switch
    (involves on-the-fly switching
  - injector & linac routin
  - injection efficiency im
  - integrated dose increa
  - ➡ improving beam lifetime (along with effect of bunch lengthening from passive harmonic cavities)

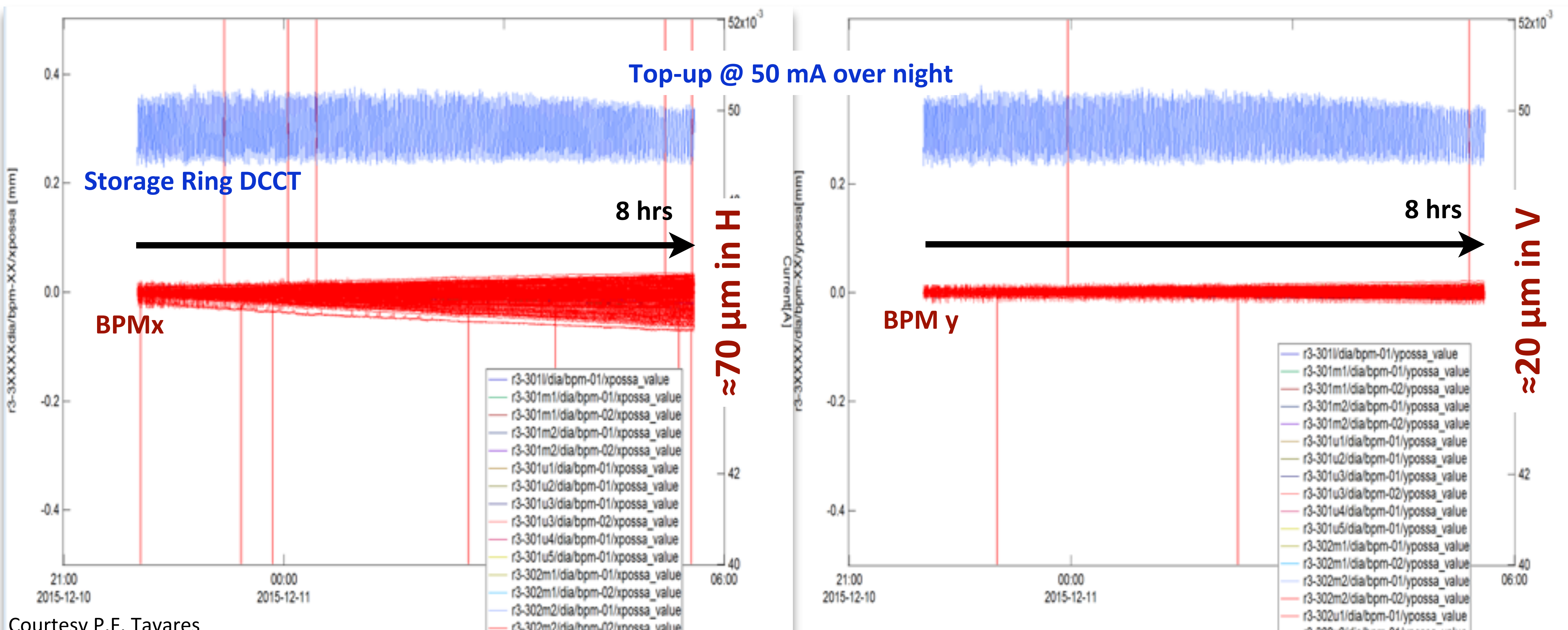


Courtesy M. Grabski



3 GeV Storage Ring Commissioning (cont.)

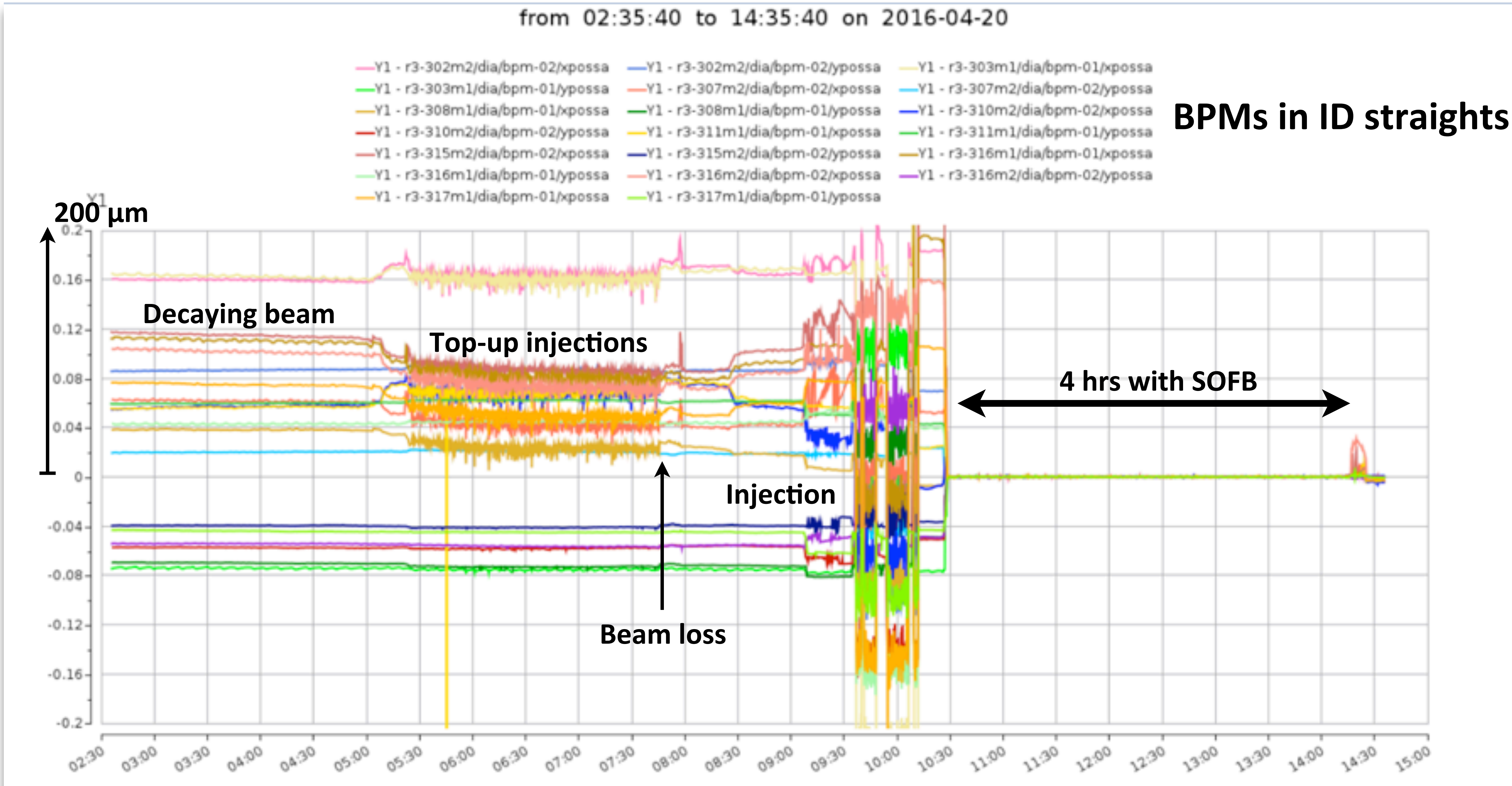
- Orbit drifts observed during top-up operation
  - 70 μm / 20 μm observed over 8 hours
  - unphysical BPM spikes observed → implications for bad orbit trip (MPS)



3 GeV Storage Ring Commissioning (cont.)

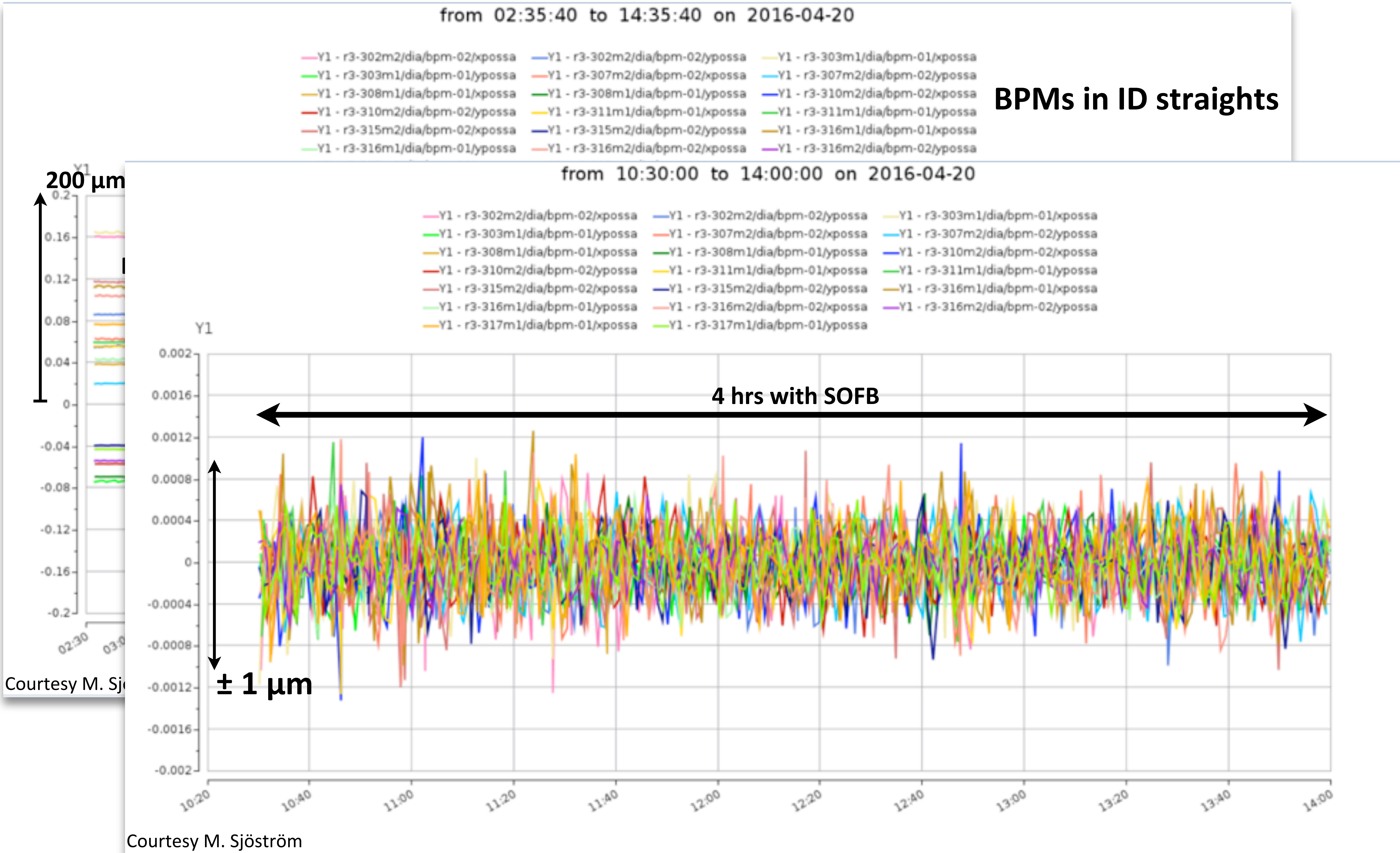
- Orbit drifts observed during top-up operation
  - 70 µm / 20 µm observed over 8 hours
  - unphysical BPM spikes observed → implications for bad orbit trip (MPS)
- SOFB now routinely running at ≈0.5 Hz (target: 10 Hz)
  - sub-micron stability in H, but larger in V ($N_{BPM} > N_{VCM}$)
  - weighting → in ID straights still locked down to 200-400 nm

3 GeV Storage Ring Commissioning (cont.)



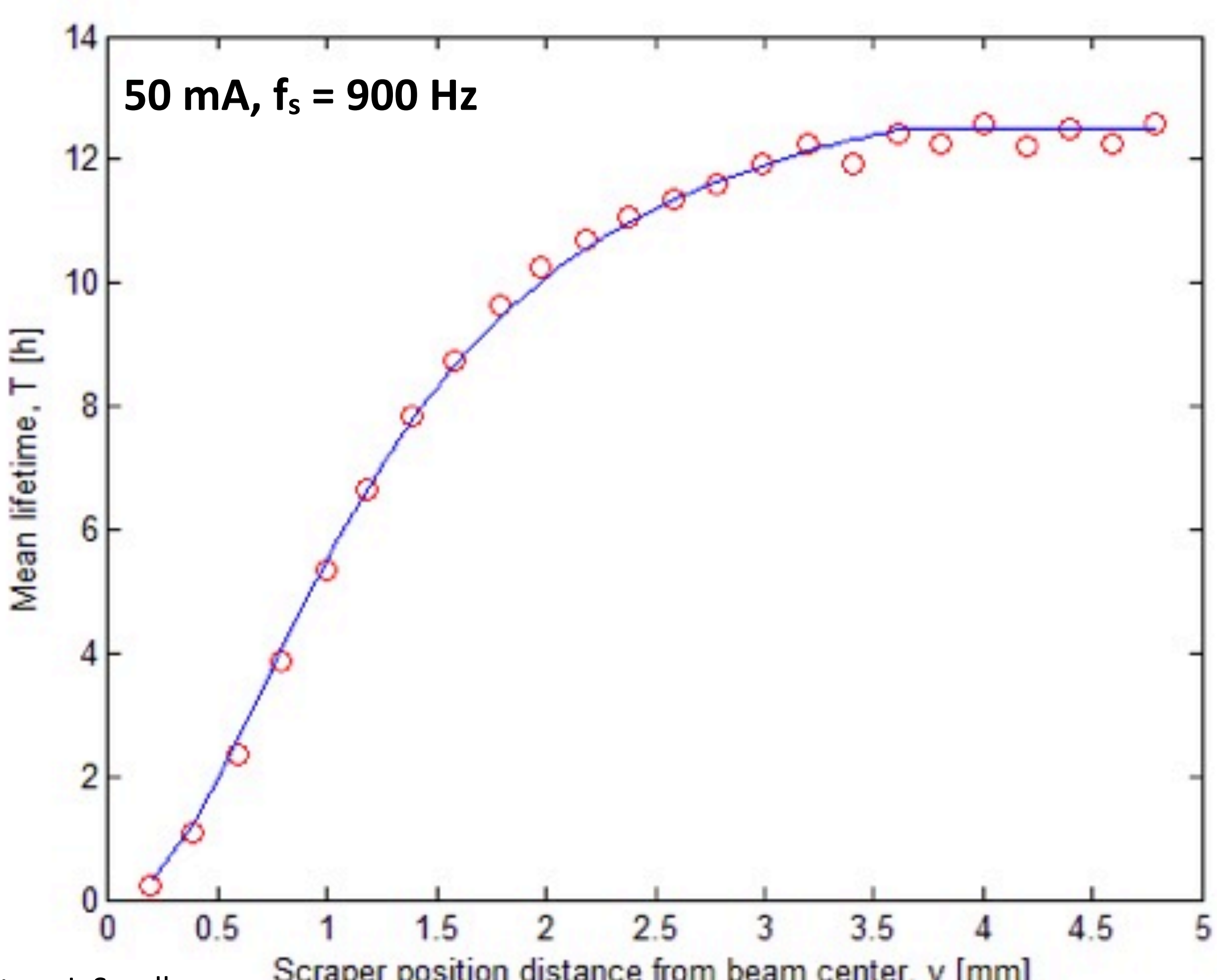
Courtesy M. Sjöström

3 GeV Storage Ring Commissioning (cont.)



3 GeV Storage Ring Commissioning (cont.)

- Attempted first scraper measurements
  - mean pressure seen by beam: $P_{[10^{-9}\ \mathrm{Torr}]} = 0.0178 \times I_{[\mathrm{mA}]} + 0.6088$
  - lifetimes



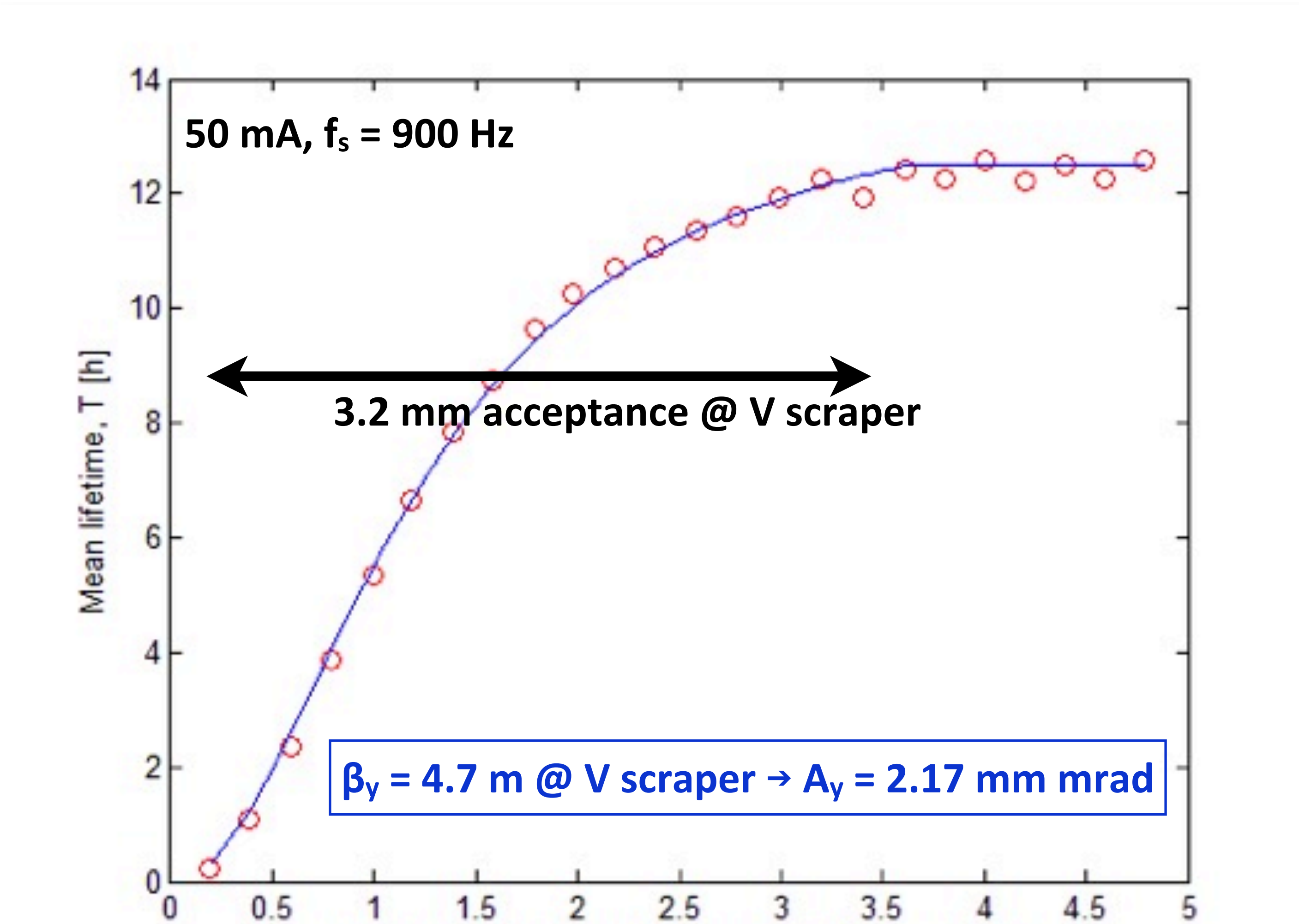
Courtesy J. Sundberg

At 50 mA & f_s = 900 Hz:
- P = 2.1e-9 mbar
- δ_{rf} = 4.2%

→ τ_{el} = 111 h
→ τ_{bs} = 68 h
→ τ_{ts} = 18 h

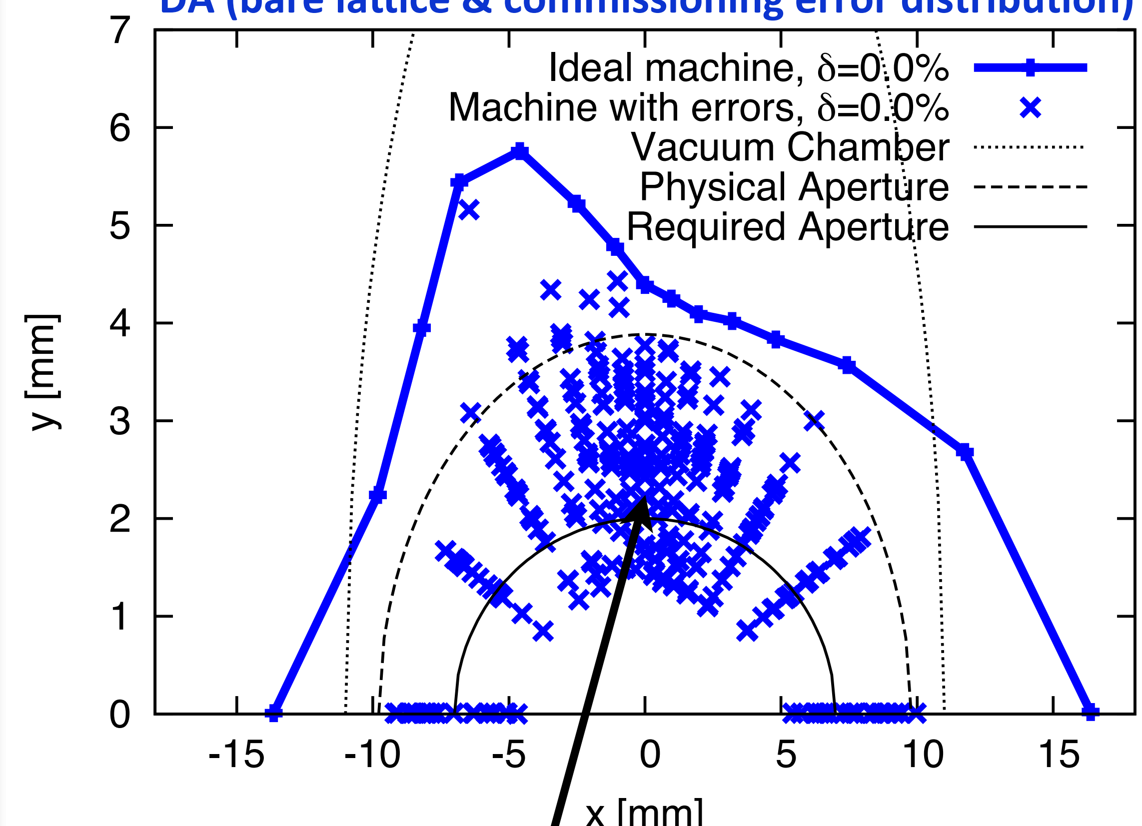
3 GeV Storage Ring Commissioning (cont.)

- Attempted first scraper measurements
  - mean pressure seen by beam: $P_{[10^{-9}\,\mathrm{Torr}]} = 0.0178 \times I_{[\mathrm{mA}]} + 0.6088$
  - lifetimes & ring acceptance (in conjunction with local beta measurements)



Courtesy J. Sundberg

MAX-lab Int.Note 20121107



A_y = 2.17 mm mrad → a_y = 2.1 mm @ ID straight

3 GeV Storage Ring Commissioning (cont.)

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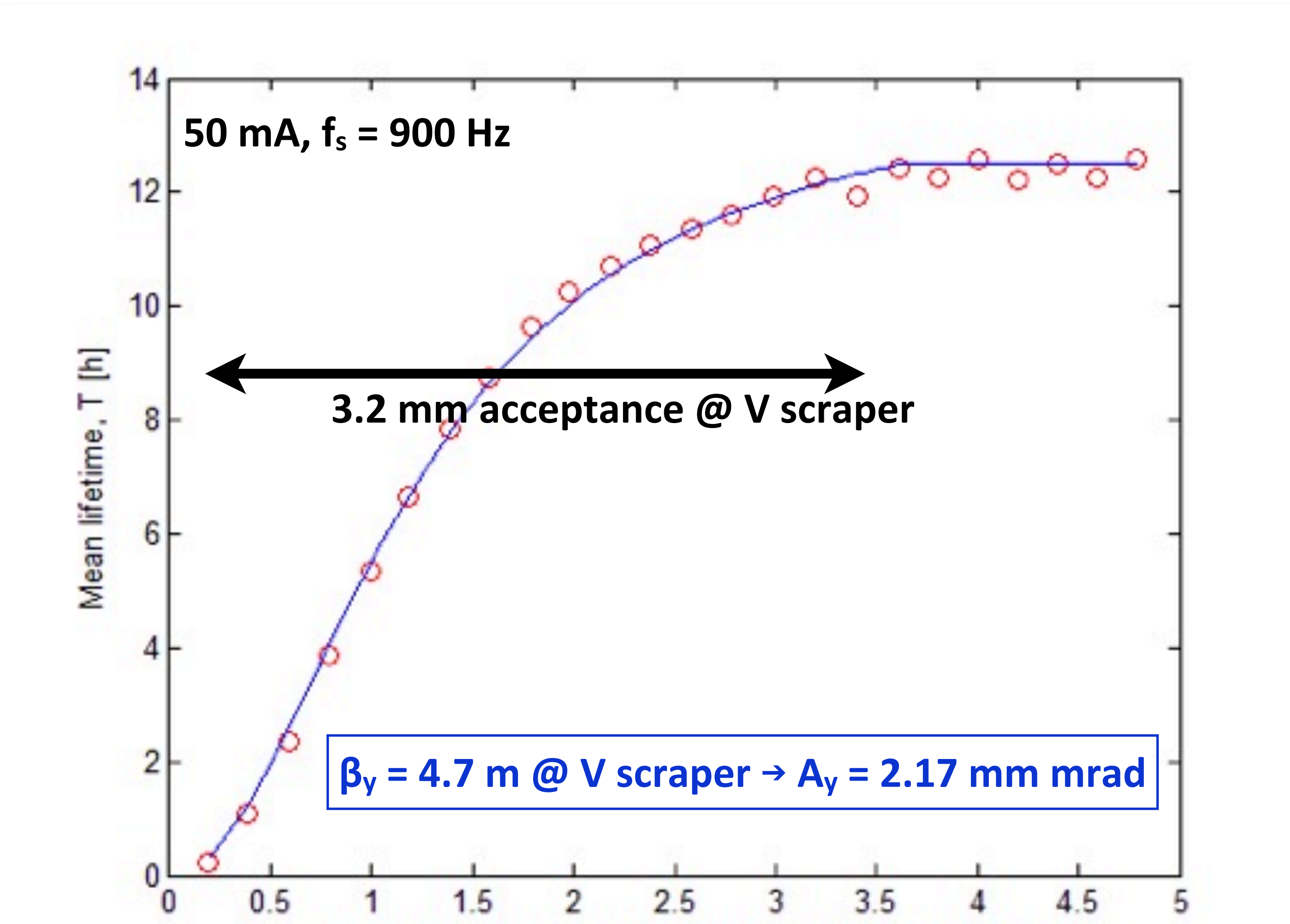
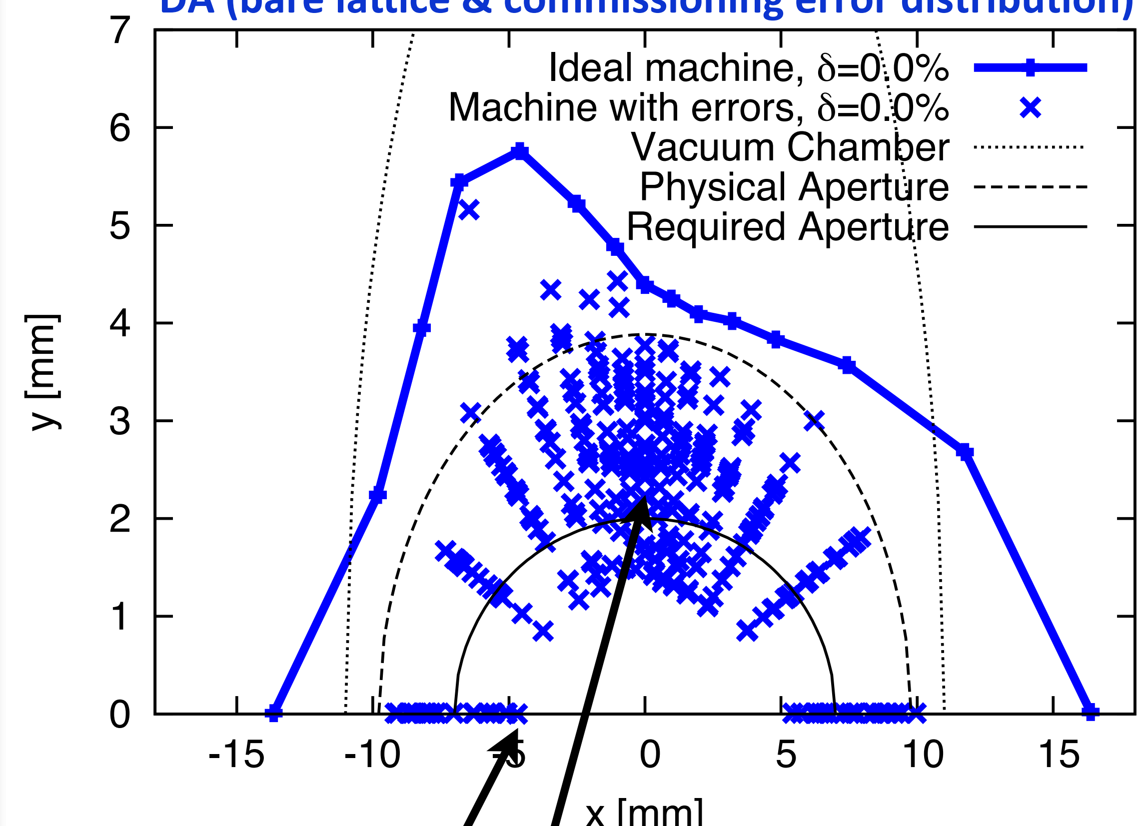


Courtesy J. Sundberg

MAX-lab Int.Note 20121107



A_y = 2.17 mm mrad → a_y = 2.1 mm @ ID straight

4.9 mm @ H scraper → A_x = 2.5 mm mrad → a_x = 4.8 mm @ ID straight

3 GeV Storage Ring Commissioning (cont.)

- First two IVUs installed during Feb 2016 shutdown
  - Hitachi, 18 mm period, 4.2 mm magnetic gap, 2 m length, 1.3 T peak field

3 GeV Storage Ring Commissioning (cont.)

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  - for BioMAX and NanoMAX beamlines

Courtesy U. Johansson


Courtesy U. Johansson

3 GeV Storage Ring Commissioning (cont.)

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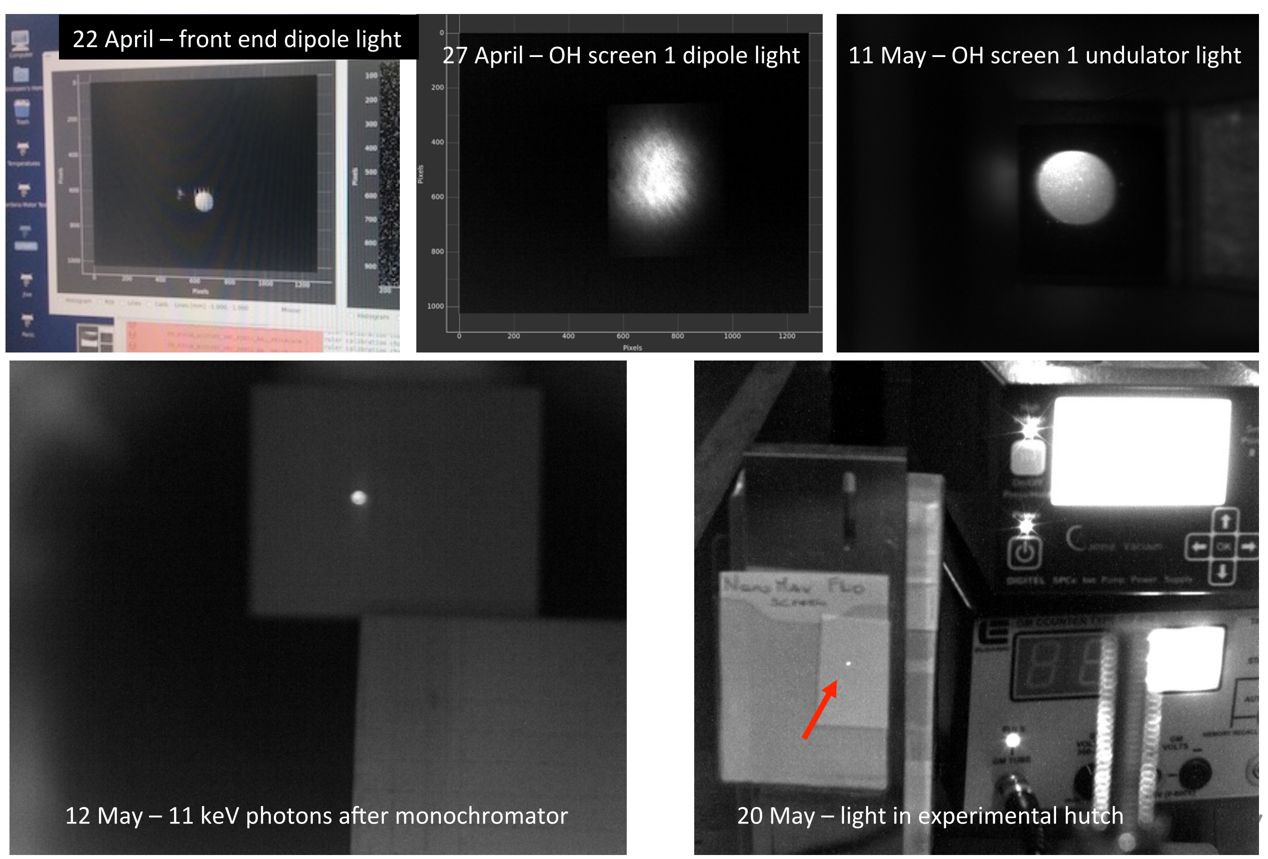
  - for BioMAX and NanoMAX beamlines
- ID, FE & BL commissioning started Apr 2016

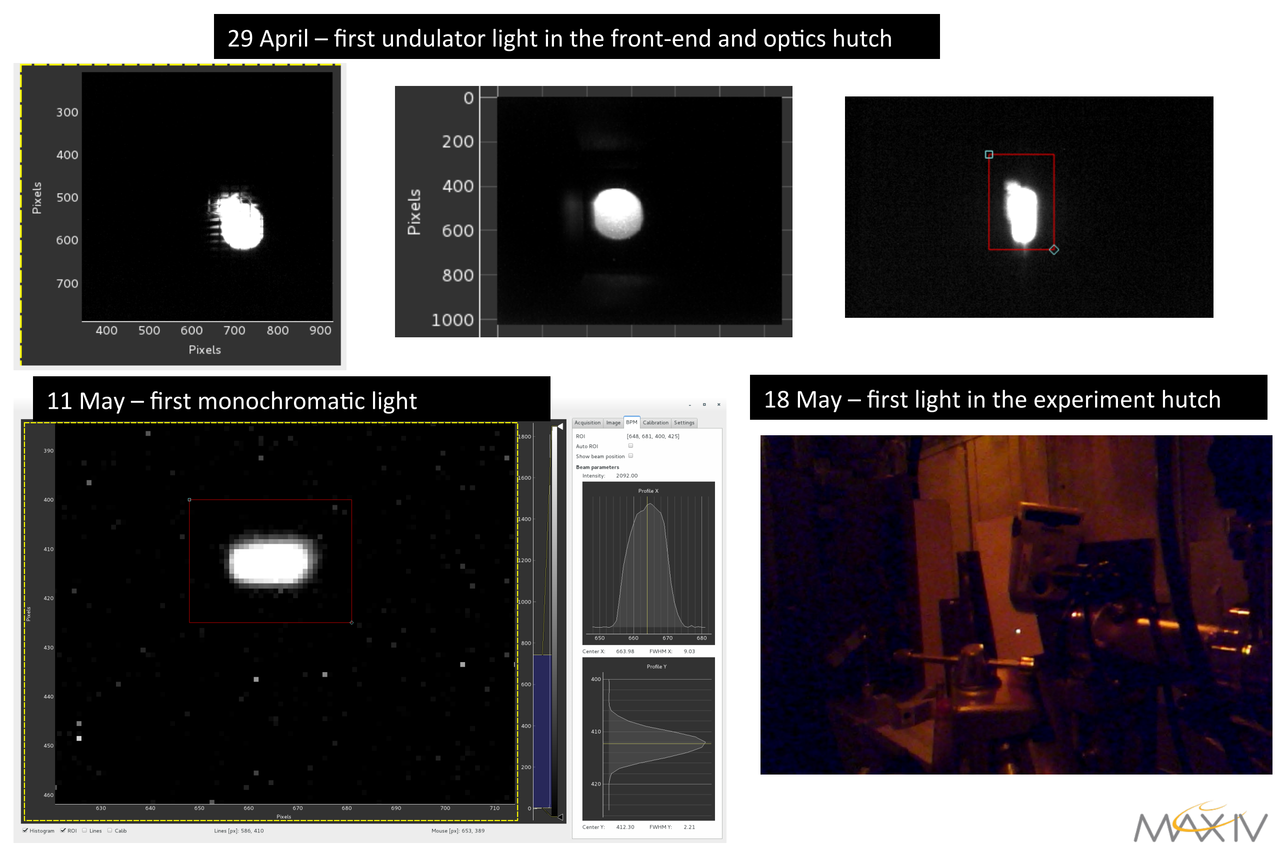
Courtesy U. Johansson

NanoMAX commissioning



Courtesy T. Ursby

BioMAX X-ray commissioning



3 GeV Storage Ring Commissioning (cont.)

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- May 11: 10 mm gaps on both BLs (FB loop for ID correctors closed)
- May 11-19: first monochromatic beams (on detector / 11 keV)

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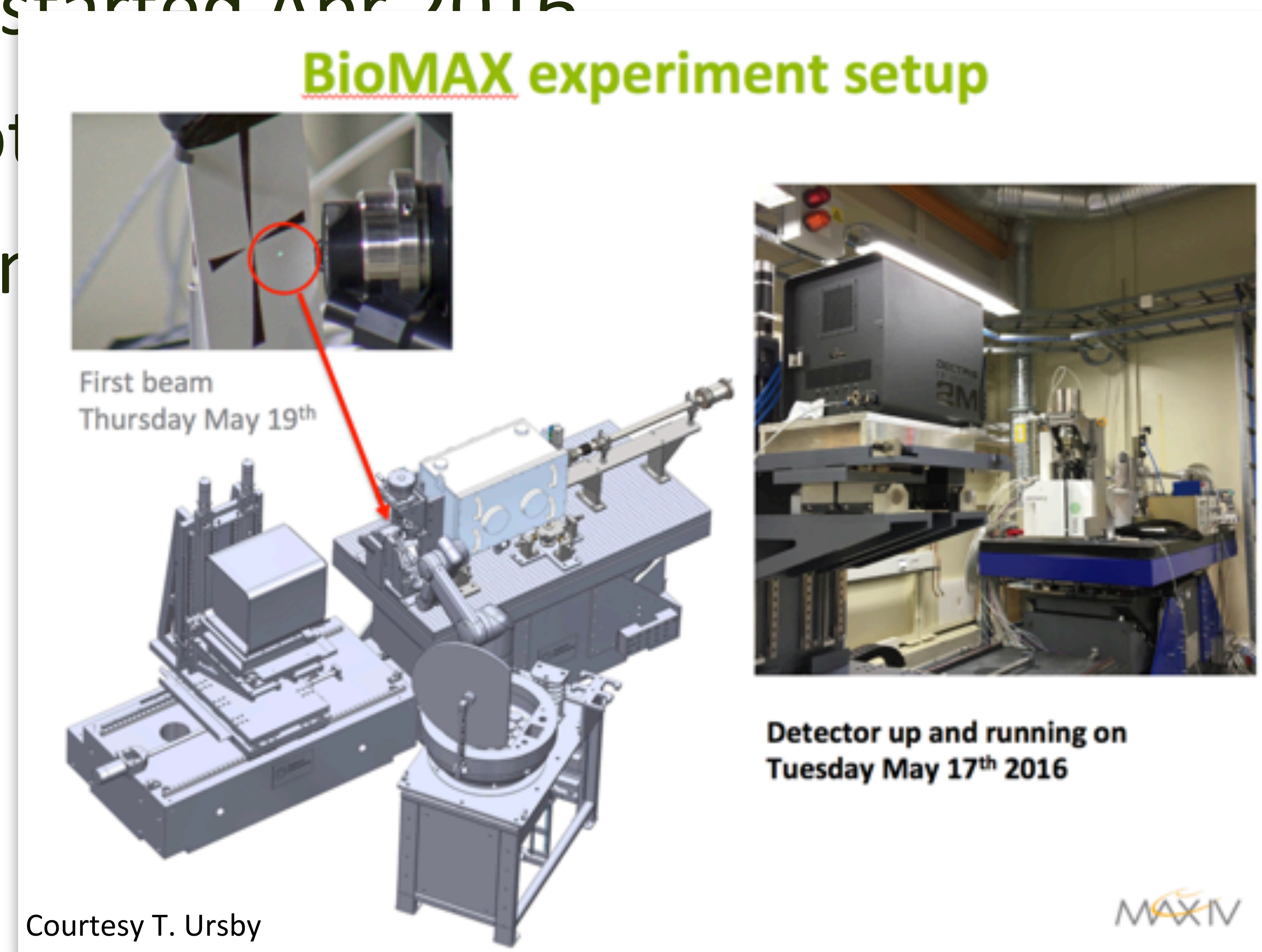

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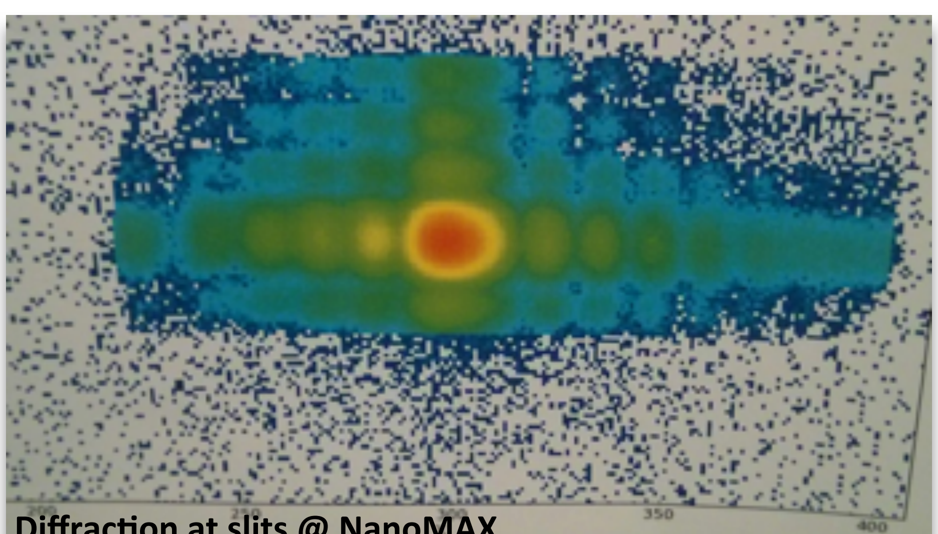

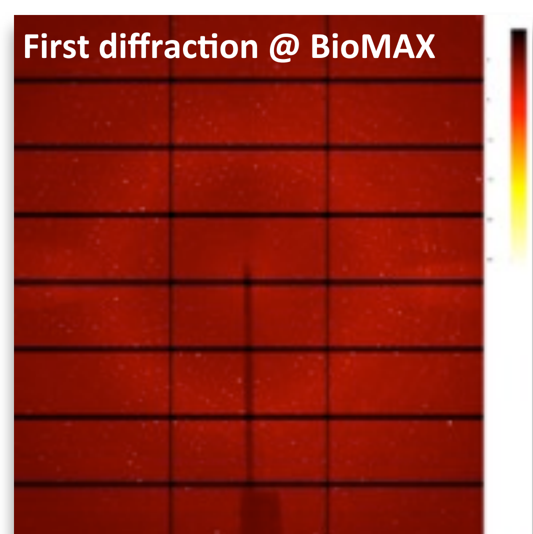

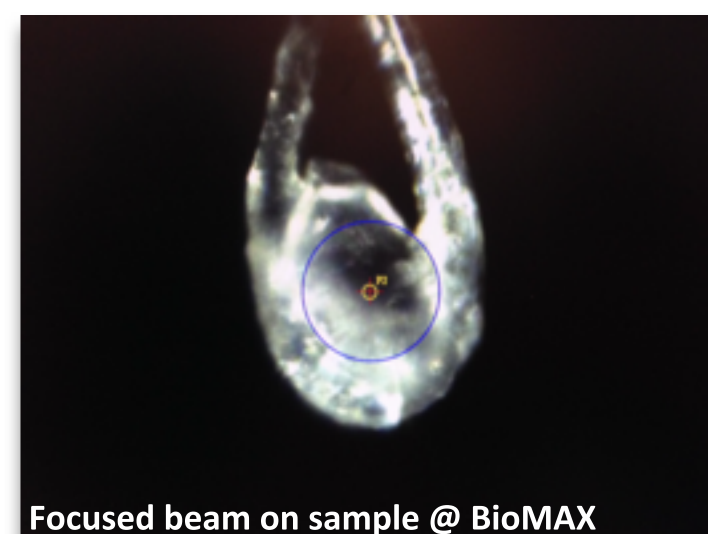

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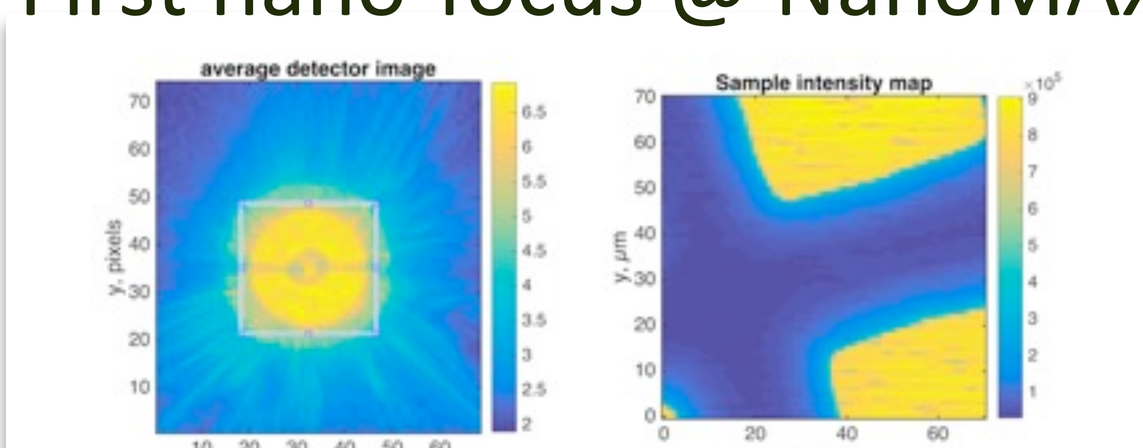
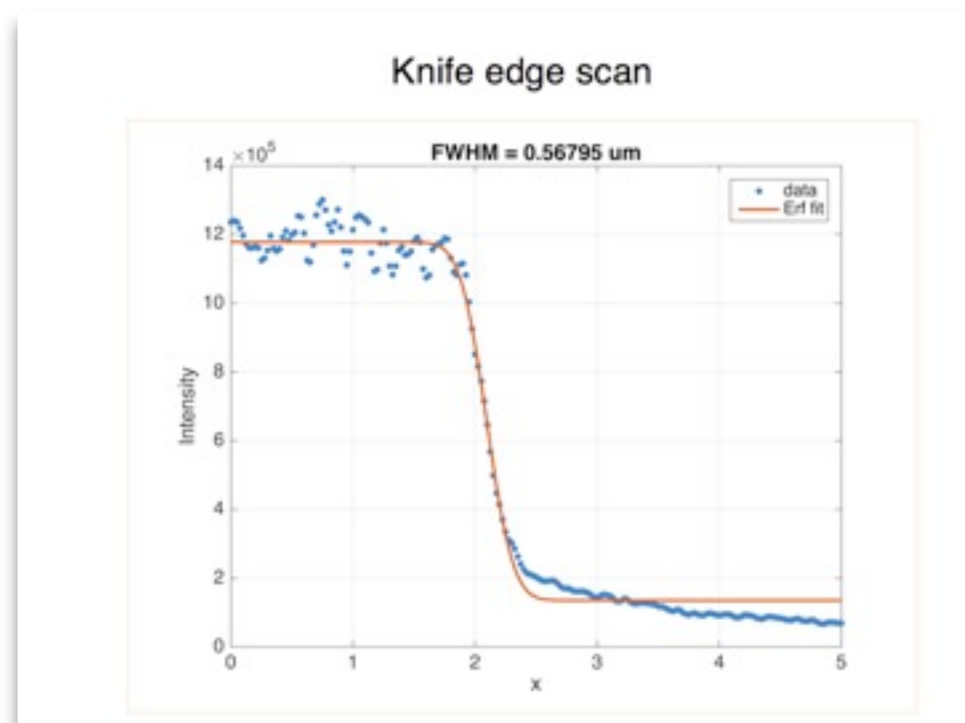
- June 20: First nano-focus @ NanoMAX



Coarse TEM grid



MAX IV Inauguration

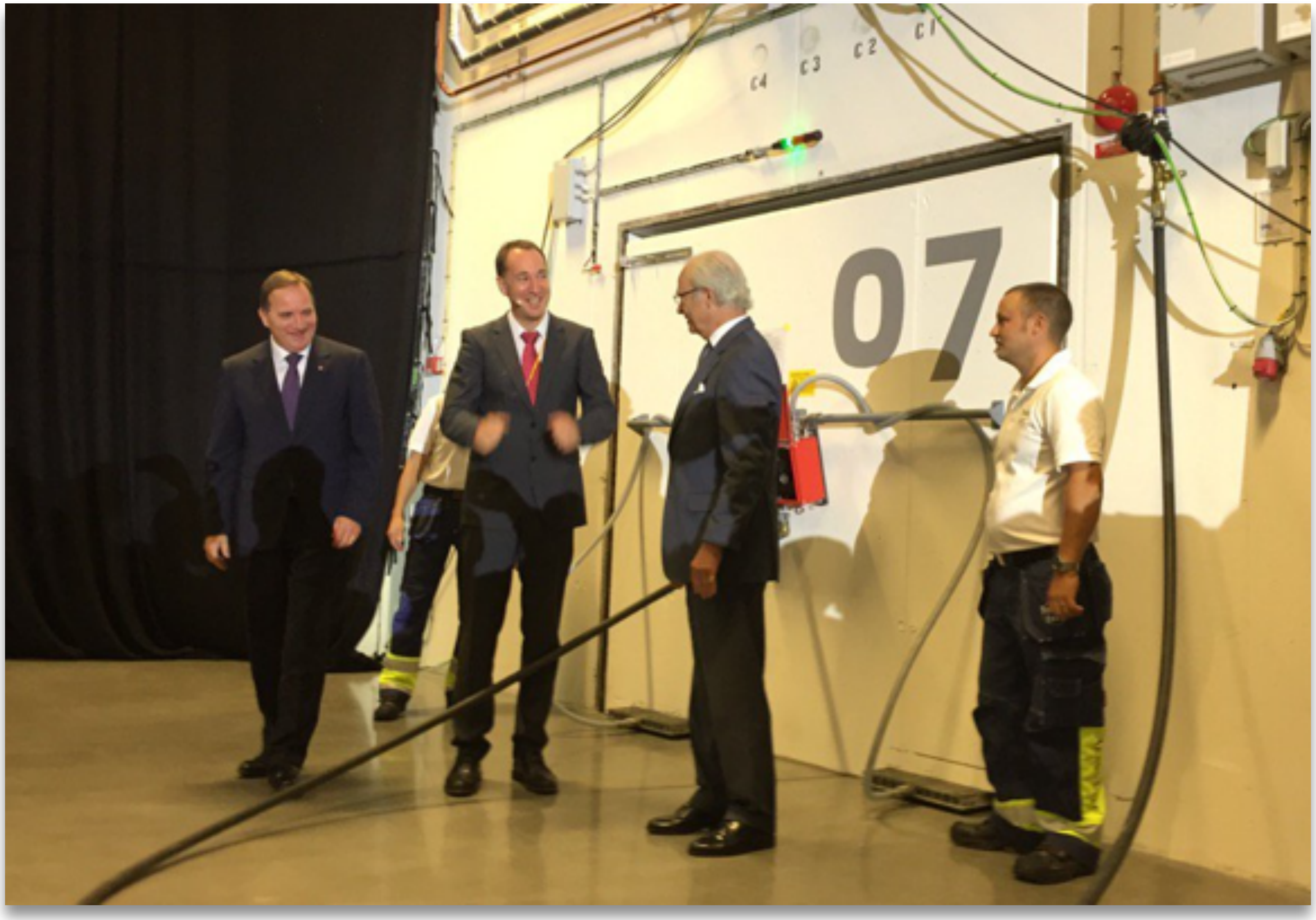
- Brightest time of the year: June 21, 2016 @ 13:08:55 (local noon)

While the rest of Sweden was celebrating Midsummer like this...

MAX IV Inauguration (cont.)

- Brightest time of the year: June 21, 2016 @ 13:08:55 (local noon)

...we inaugurated our new facility.

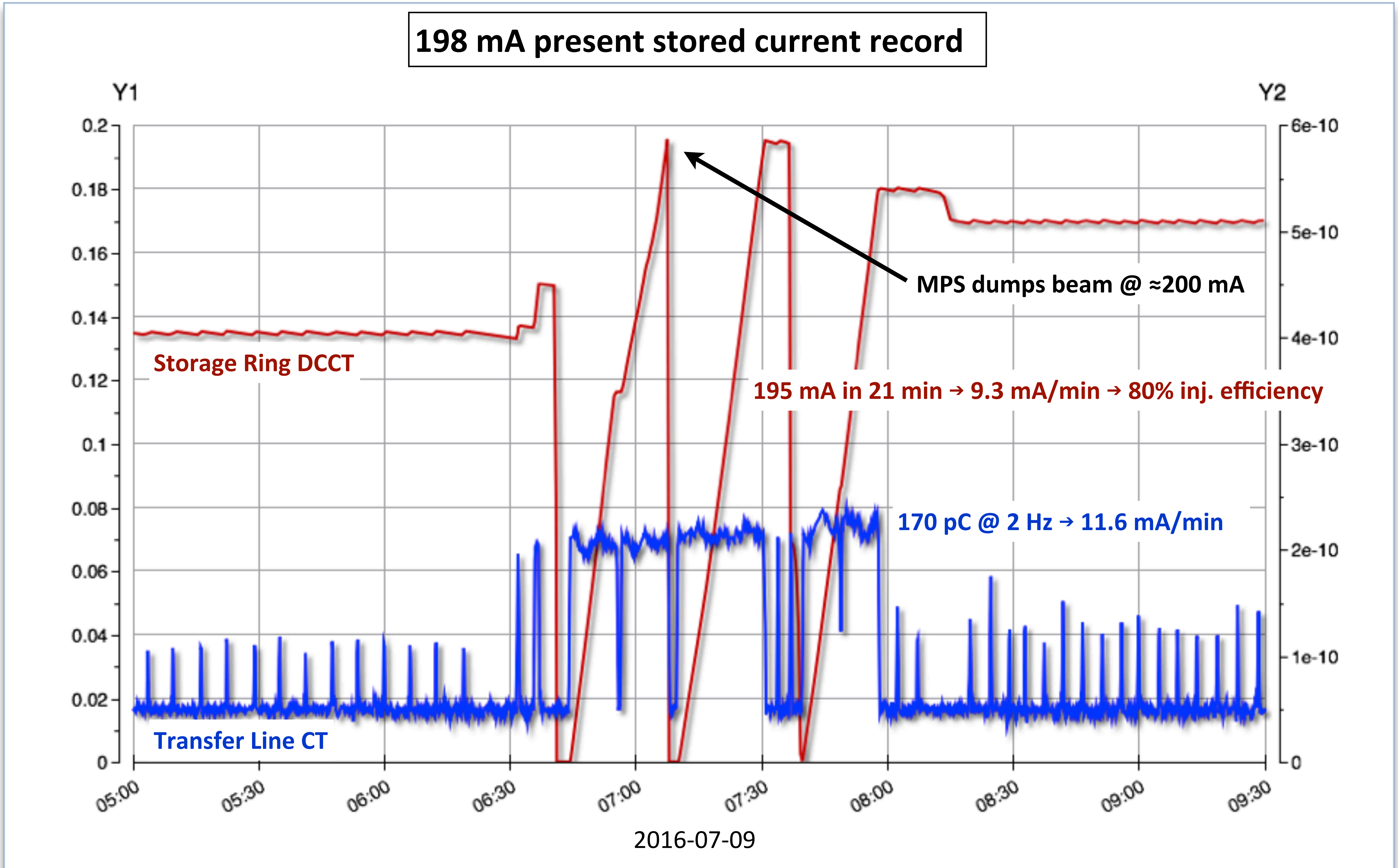


A very proud director after having closed the last port with a little help from two “friends”

MAX IV Inauguration (cont.)

- Brightest time of the year: June 21, 2016 @ 13:08:55 (local noon)

3 GeV Storage Ring Commissioning (cont.)



3 GeV Storage Ring Commissioning (cont.)

- Finally, need to also focus on stability & collective effects
  - 3 passive Landau cavities ($R_s \approx 2.5$ MΩ) allow for tuning to flat-potential conditions already @ 150 mA

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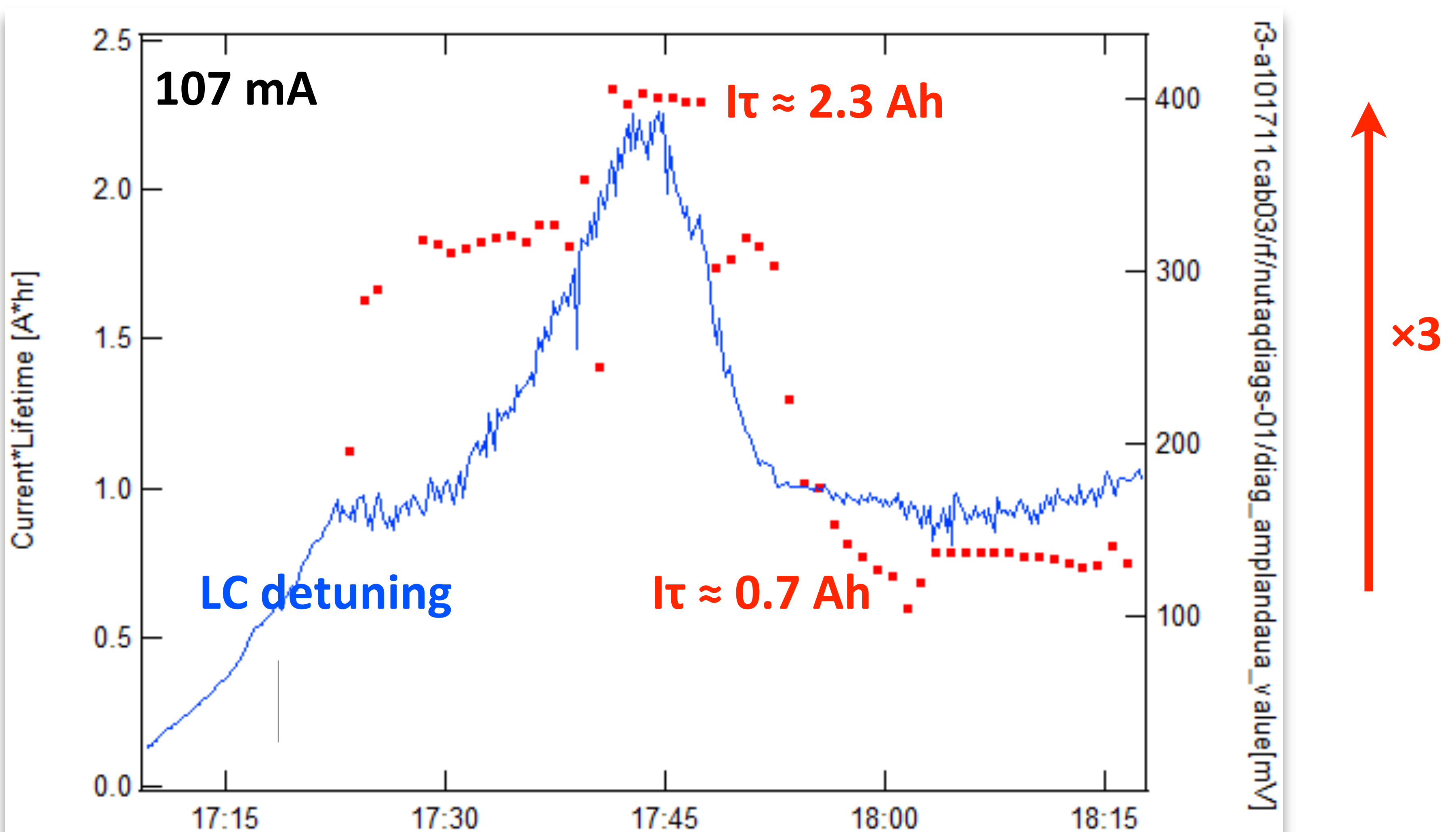

Courtesy P.F. Tavares

3 GeV Storage Ring Commissioning (cont.)

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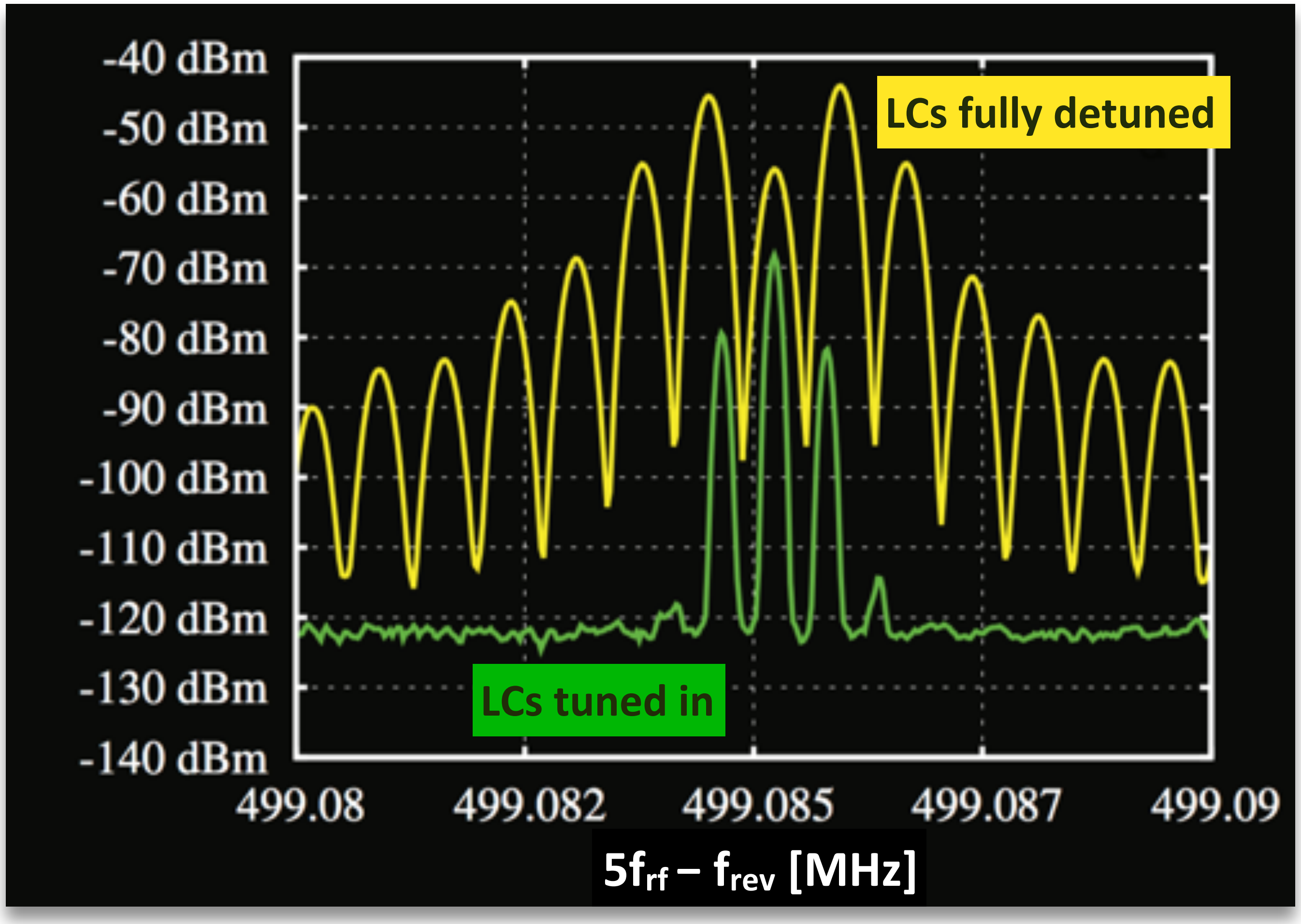
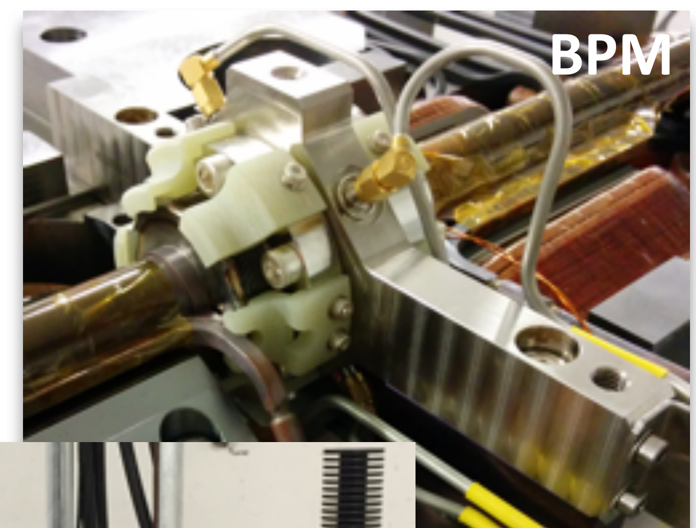


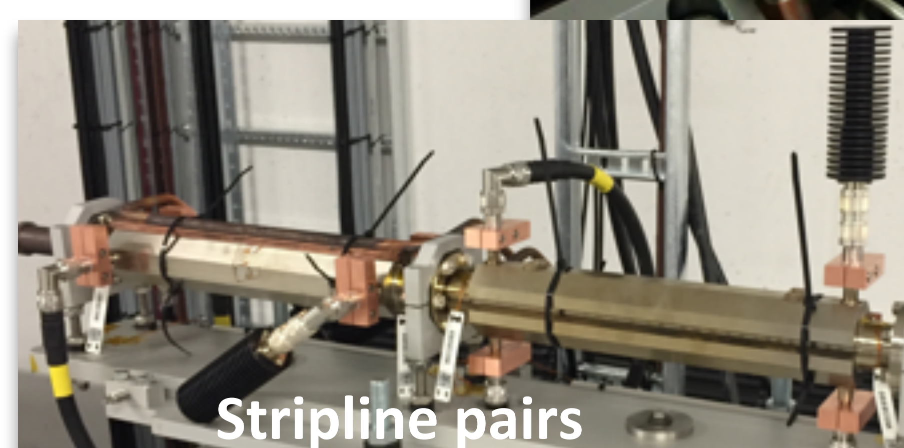
IPAC'**16**, WEPO035, p.2911

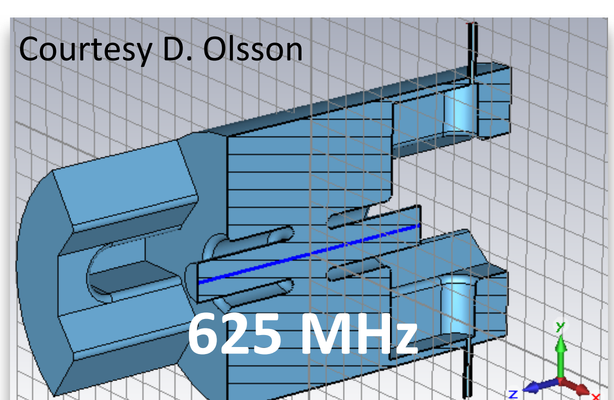
Stabilized CB mode @ 120 mA (–20 dB)

3 GeV Storage Ring Commissioning (cont.)

- Finally, need to also focus on stability & collective effects
  - 3 passive Landau cavities ($R_s \approx 2.5$ MΩ) allow for tuning to flat-potential conditions already @ 150 mA
  - Achieved >2 Ah under stable conditions (top-up running & BbB FB loop closed)
  - Started commissioning of Dimtel BbB FB system
    - extra ring BPM used as sensor
    - Pair of H & V striplines as transverse actuators
    - Presently also using H striplines in common mode as weak longitudinal actuator (until FB cavity ready)







3 GeV Storage Ring Commissioning (cont.)

- Example: observed HOM-driven longitudinal motion at few mA in uniform fill → cavity temp. tuning, LC tuning, BbB FB

Slide by D.Olsson

Longitudinal CBIs

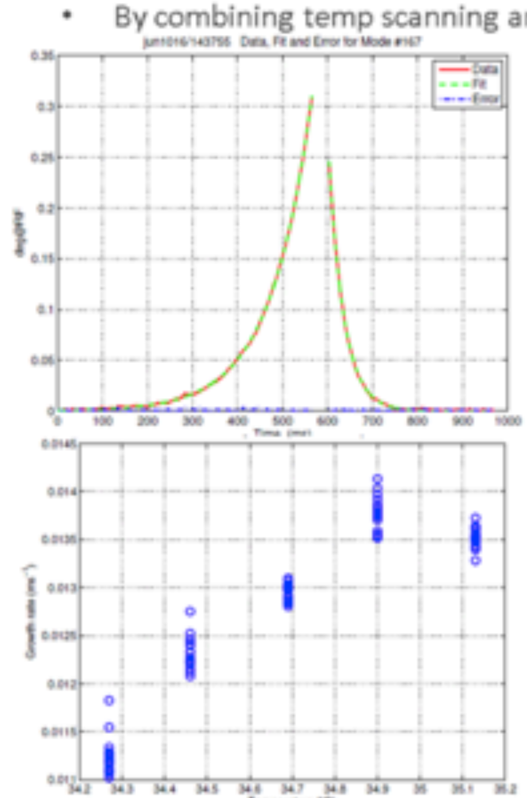
- In an evenly filled storage ring, h CBI modes exist with the bunch phase advance

$$\Delta\phi = m\frac{2\pi}{h}, \qquad m = 0,1,\ldots,h-1, \qquad h \text{ is the harmonic number}$$

- The narrow band HOMs in the cavities can be shifted by tuning the volume and the temperature (see Jonas Björklund-Svensson's master thesis).
- By combining temp scanning and (weak) longitudinal feedback, it was possible to keep a stable beam at 80 mA.

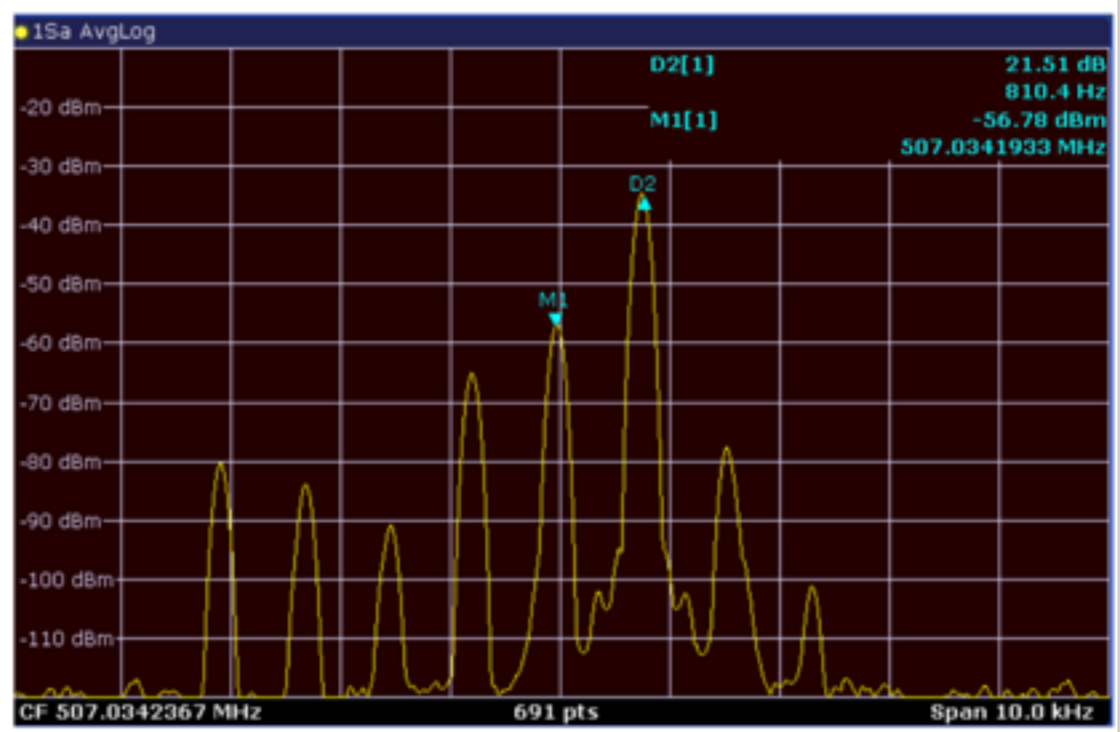
Grow/damp study on HOM #167

Growth rate vs. cavity temp. for HOM #167



Grow/damp measurement on mode #167 vs temperature in Cavity 17

HOM #13 excited @ 80 mA



The spectrum of the sum signal when mode #13 is excited (marker D2) . Marker M1 is the 13:th rev harmonic

3 GeV Storage Ring Commissioning (cont.)

- Example: no clear evidence of RW instability
  - could store >120 mA without LCs or feedback
  - predicted RW threshold was only 40 mA

SOLEIL SYNCHROTRON — MAX IV LABORATORY

Instability thresholds overview

	Chroma	geom. Impedance HC off	geom. Impedance HC on	RW longrange, bare HC off	RW longrange, bare HC on	RW 5 IDs HC on
LON	-	620	970	-	-	-
VER	0.0	920	710	40	40	-
	1.0	2200	10400	-	900	380
	1.2	3170	15100	50	1250	540
HOR	0.0	2010	2020	120	140	-
	1.0	>2050	17100	150	3500	> 3500
	1.2	5040	21900	-	-	-

Threshold currents in mA

Slide by M.Klein & G. Skripka

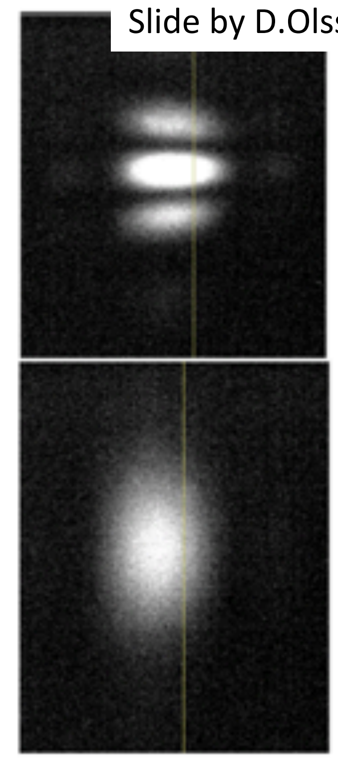
3 GeV Storage Ring Commissioning (cont.)

- Example: no clear evidence of RW instability but ion-driven instabilities apparent in both transverse planes

Transverse CBIs

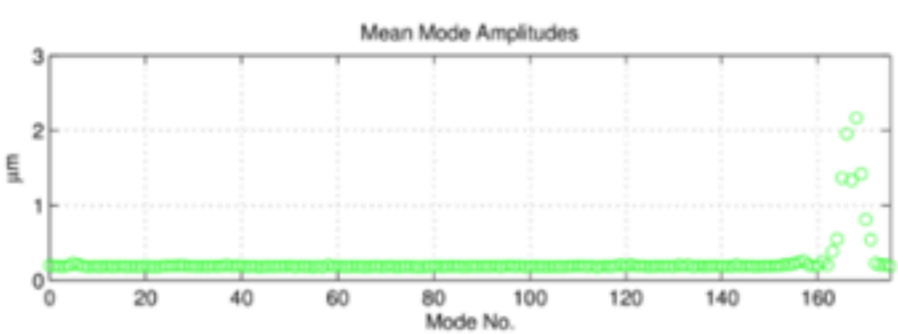
Slide by D.Olsson

- No clear evidences of resistive wall instabilities
- However, we detect ion-driven instabilities in both transverse planes, and their effect on the effective emittance can clearly be seen at the diagnostic beam line.
- Typical features of such ion-driven instabilities are
  - Wide band (they excite several CBI modes)
  - Low amplitude saturation
  - Excitation of high-index modes
- One cure can be to introduce ion clearing gaps (to be investigated...).

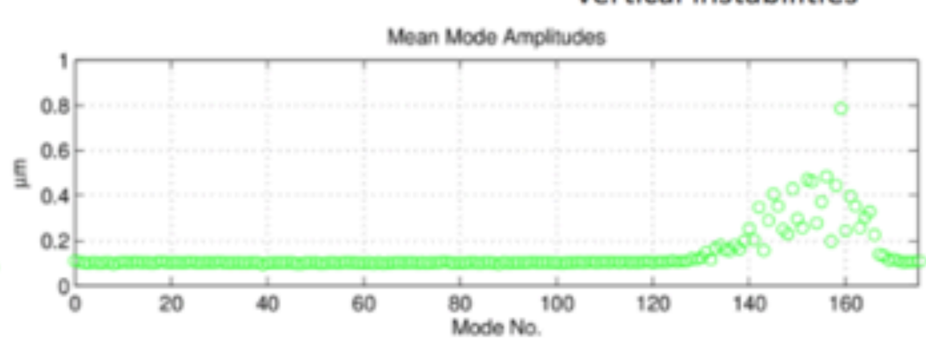


The effects of vertical instabilities

Instability observed @ diagnostic BL (σ polarization)



The oscillation amplitudes of the horizontal modes

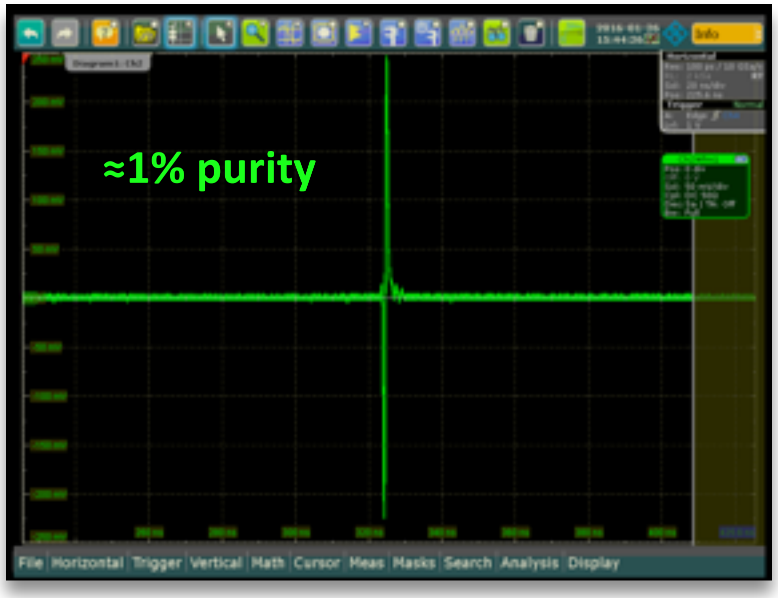


The oscillation amplitudes of the vertical modes

Many high-index modes excited in both planes

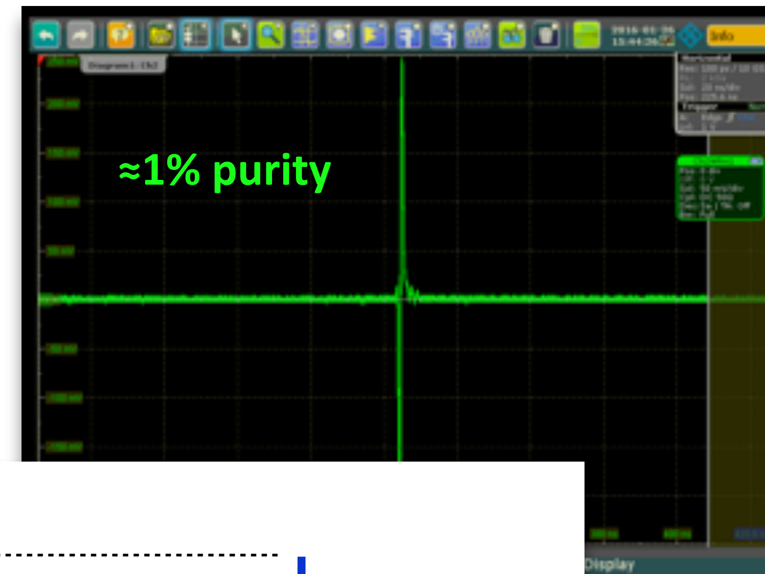
3 GeV Storage Ring Commissioning (cont.)

- Example: single-bunch (SB) collective effects → TMCI & PWD
  - either SB injection or clearing with BbB FB
  - adjusted $\xi_{x,y}$ towards zero

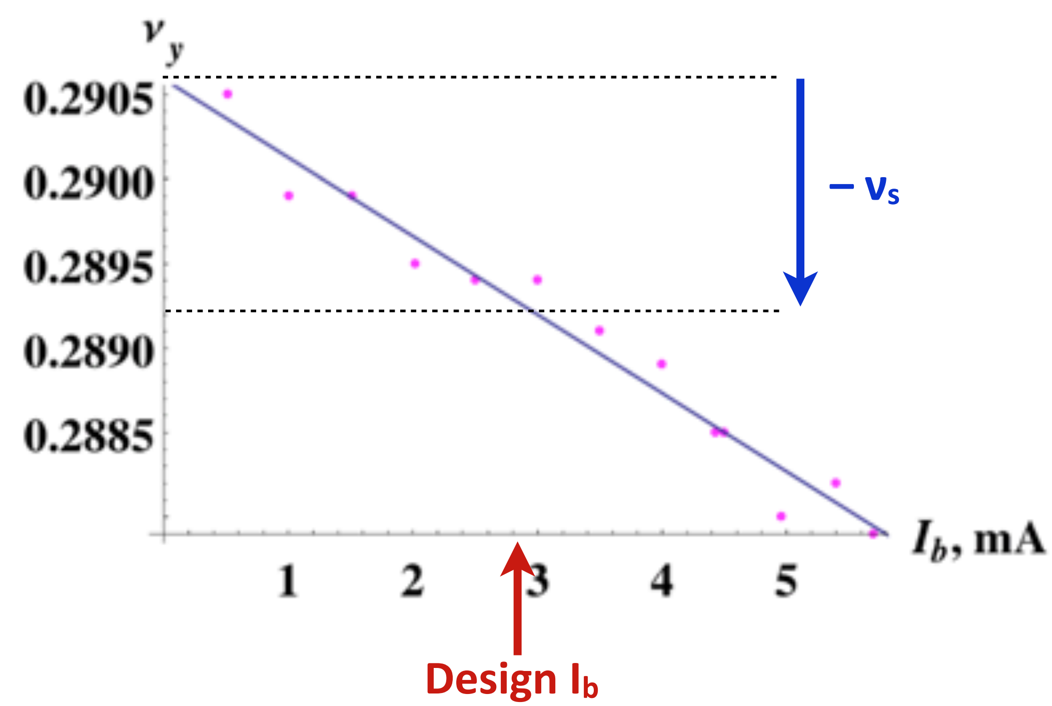


3 GeV Storage Ring Commissioning (cont.)

- Example: single-bunch (SB) collective effects → TMCI & PWD
  - – either SB injection or clearing with BbB FB
  - – adjusted $\xi_{x,y}$ towards zero
  - – no sign of TMCI up to 8.5 mA SB current (500 mA even fill → 2.85 mA/bunch)



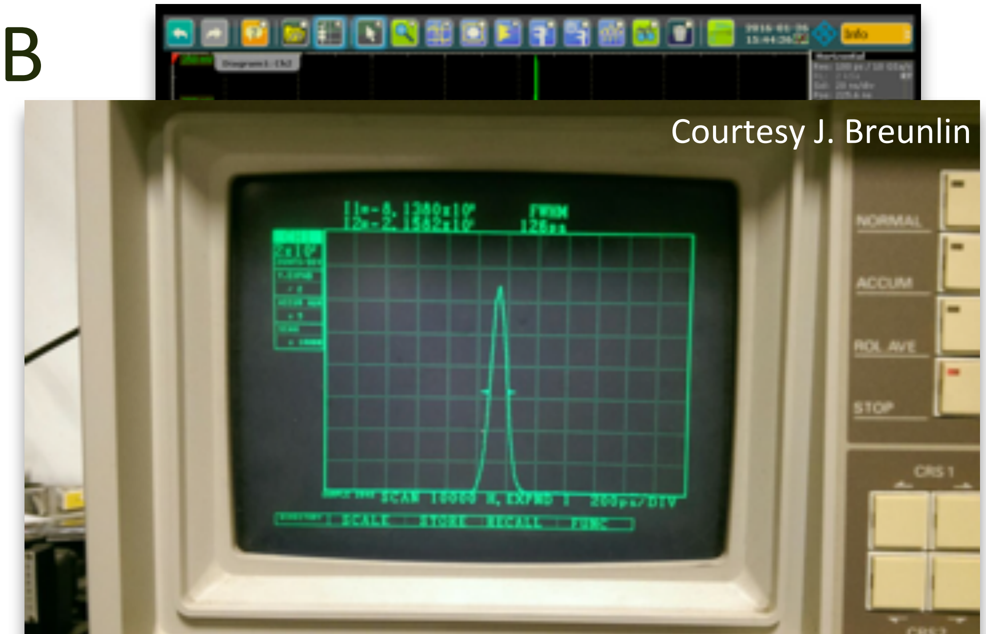
- $\xi_x = 0.4$ and $\xi_y = 0.03$
- Synchrotron tune $\nu_s = 0.00134$
- Vertical tune shift by more than ν_s
- MOSES shows modes 0 and -1 detuning in the same direction

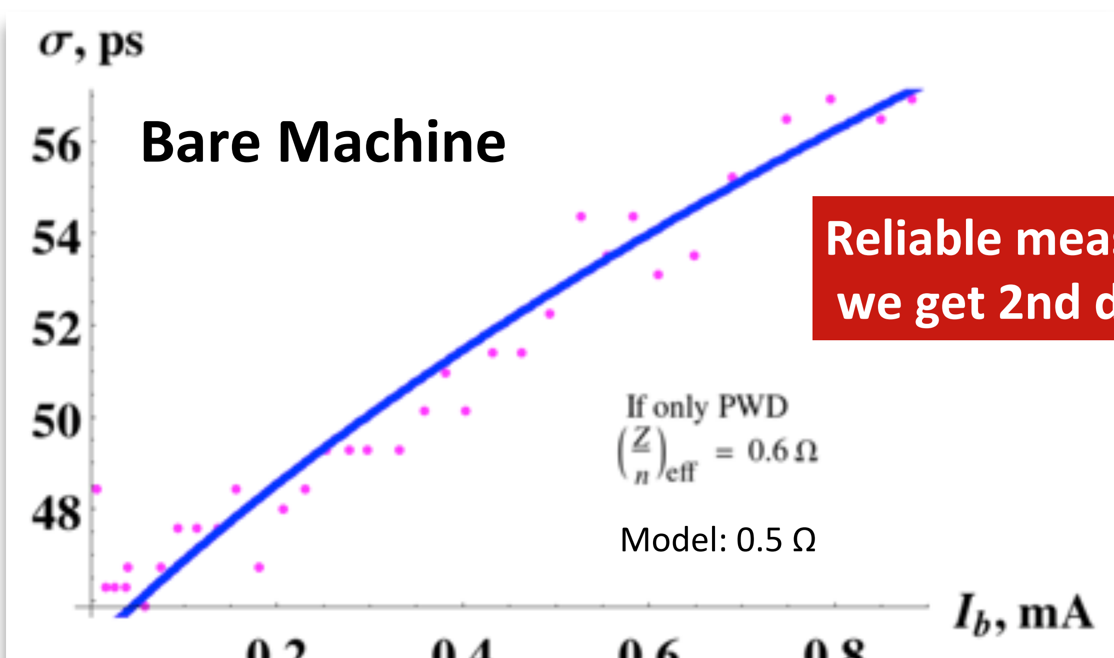


Slide by G. Skripka

3 GeV Storage Ring Commissioning (cont.)

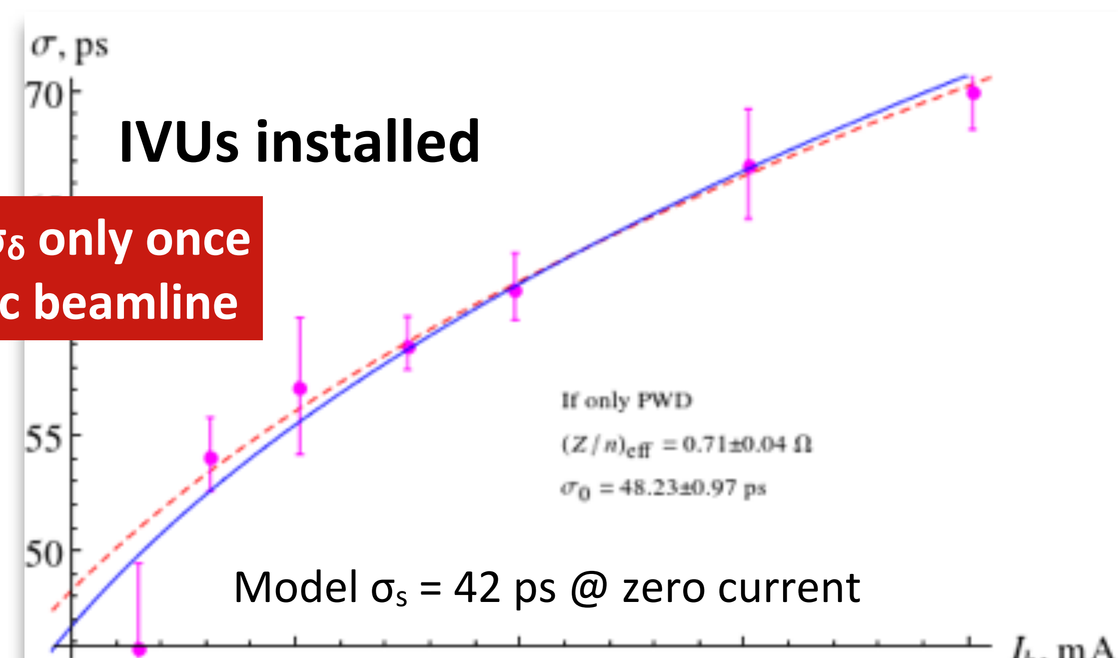
- Example: single-bunch (SB) collective effects ➔ TMCI & PWD
  - either SB injection or clearing with BbB FB
  - adjusted $\xi_{x,y}$ towards zero
  - no sign of TMCI up to 8.5 mA SB current
    (500 mA even fill ➔ 2.85 mA/bunch)
  - Bunch length measured with sampling oscilloscope @ diagnostic BL


Courtesy J. Breunlin



Courtesy G. Skripka

Reliable measure of σ_δ only once we get 2nd diagnostic beamline



Courtesy G. Skripka

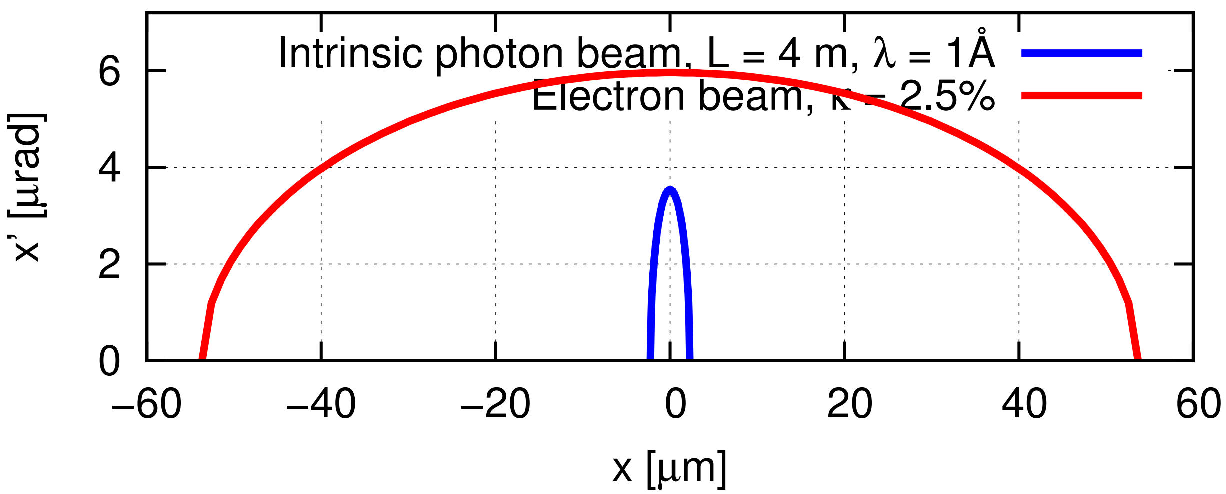
Outlook

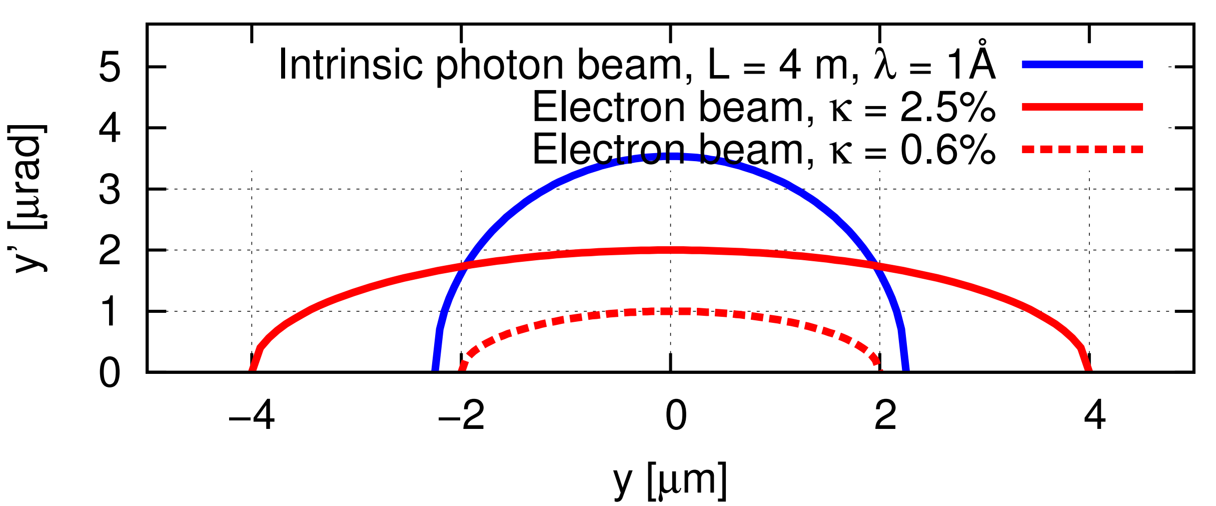
- Continue commissioning of 3 GeV storage ring
  - optics & IDs
  - 2nd diagnostic beamline, longitudinal bunch profile
  - RF conditioning main cavities and LCs (high current)
  - collective effects & BbB feedback commissioning
  - integrate fast corrector PSs & LB+ units → commission FOFB
- Just started commissioning of 1.5 GeV storage ring
  - first IDs to be installed in 1.5 GeV SR during early 2017
- "Friendly users" arrive Nov 2016
- First open user call for Mar 2017

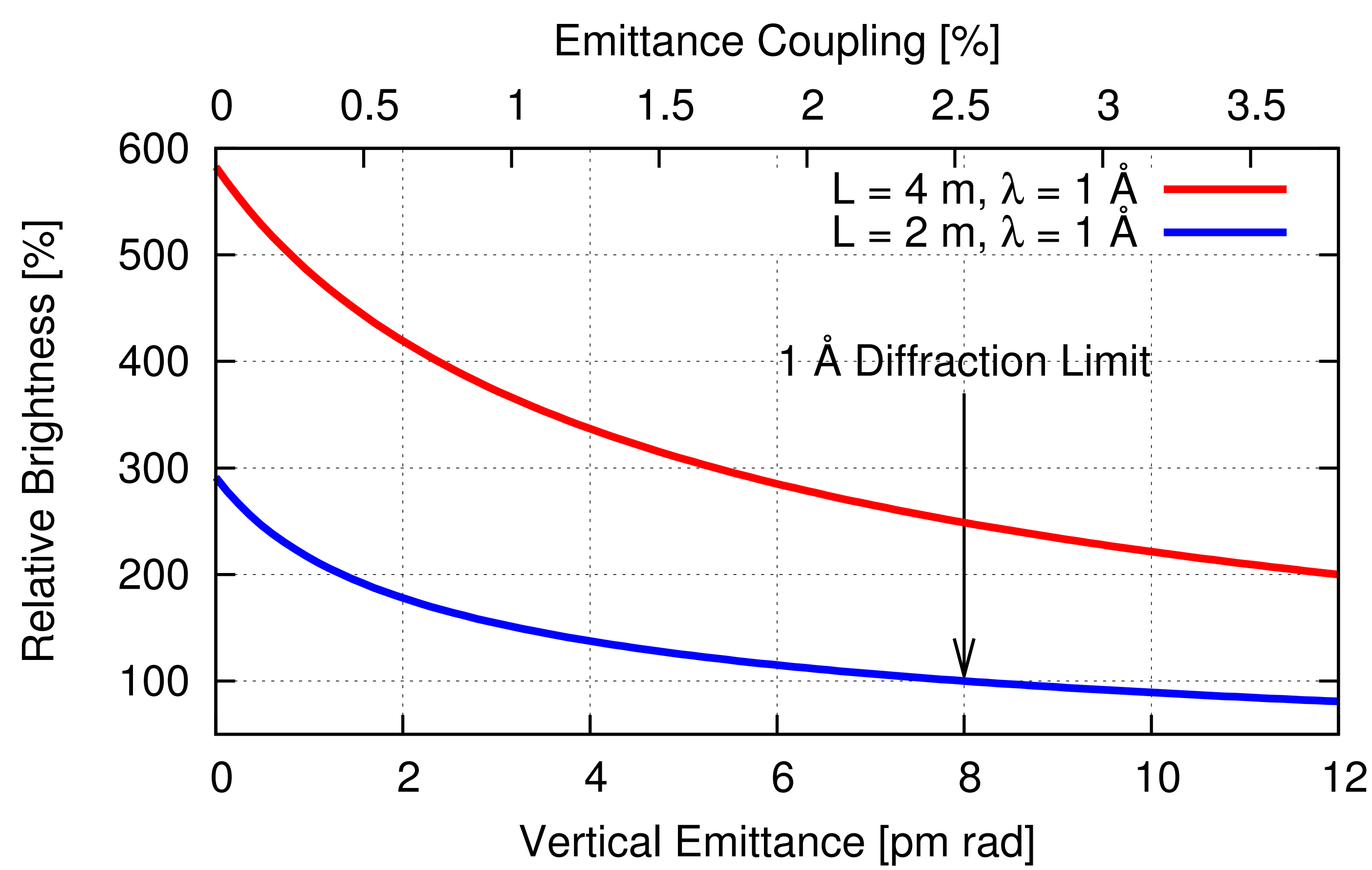
Upgrade Ideas

- Improved matching to IDs (coupling, optics in straights)
  - Transverse coherence and brightness at 1 Å almost doubled by setting ε_y = 8 → 2 pm rad

PAC’**13**, MOPHO05, p.243





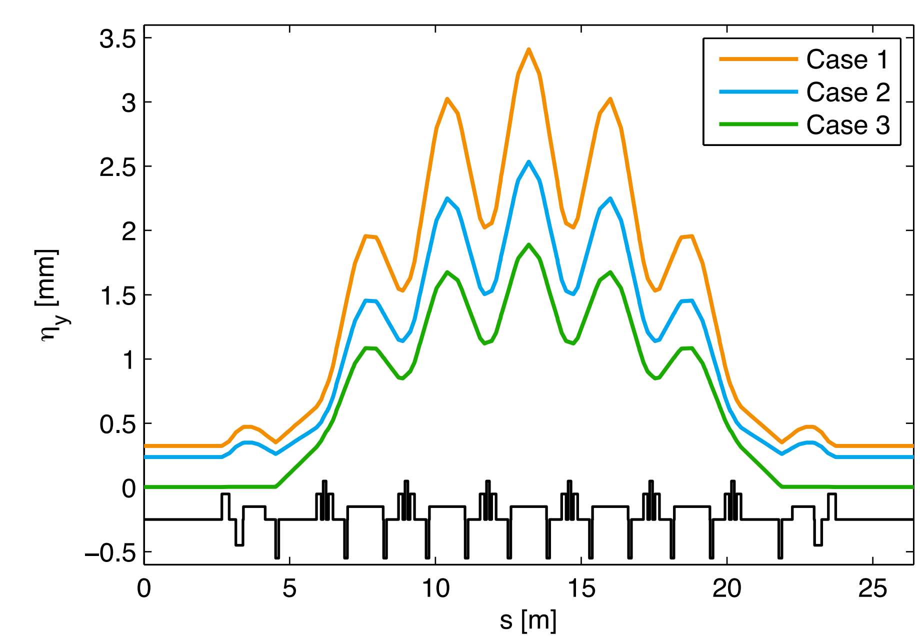


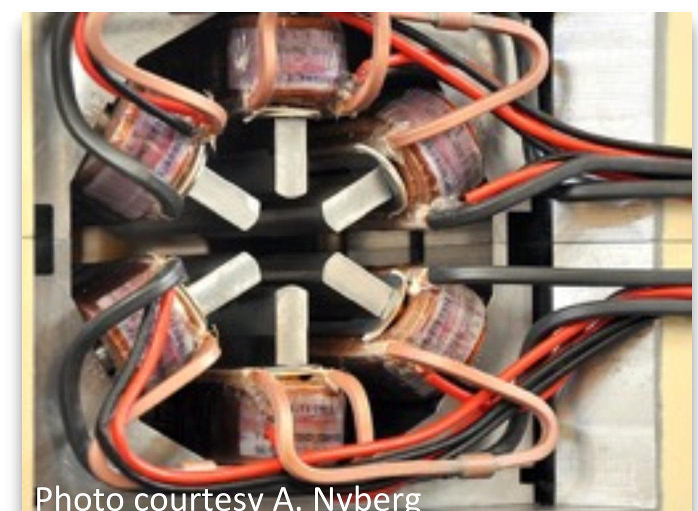
Upgrade Ideas (cont.)

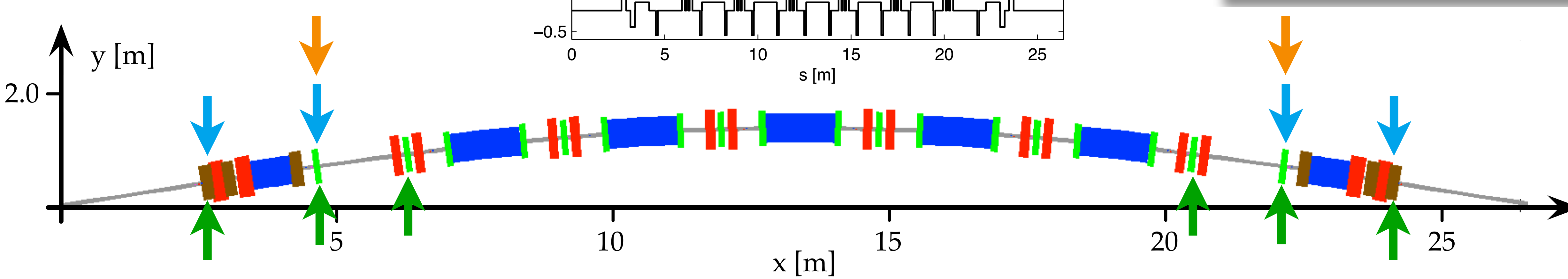
- Improved matching to IDs (coupling, optics in straights)
  - Transverse coherence and brightness at 1 Å almost doubled by setting ε_y = 8 → 2 pm rad $\quad \tau_{ts} \propto \sqrt{\varepsilon_y} \propto \sqrt{\kappa}$

    PAC'**13**, MOPHO05, p.243
  - Good Touschek lifetime maintained by exciting vertical dispersion bumps in all arcs (transparent in ID straights)

    PRAB **19**, 060701 (2016)







Upgrade Ideas (cont.)

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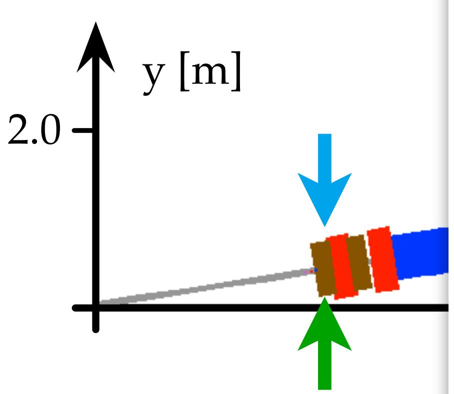

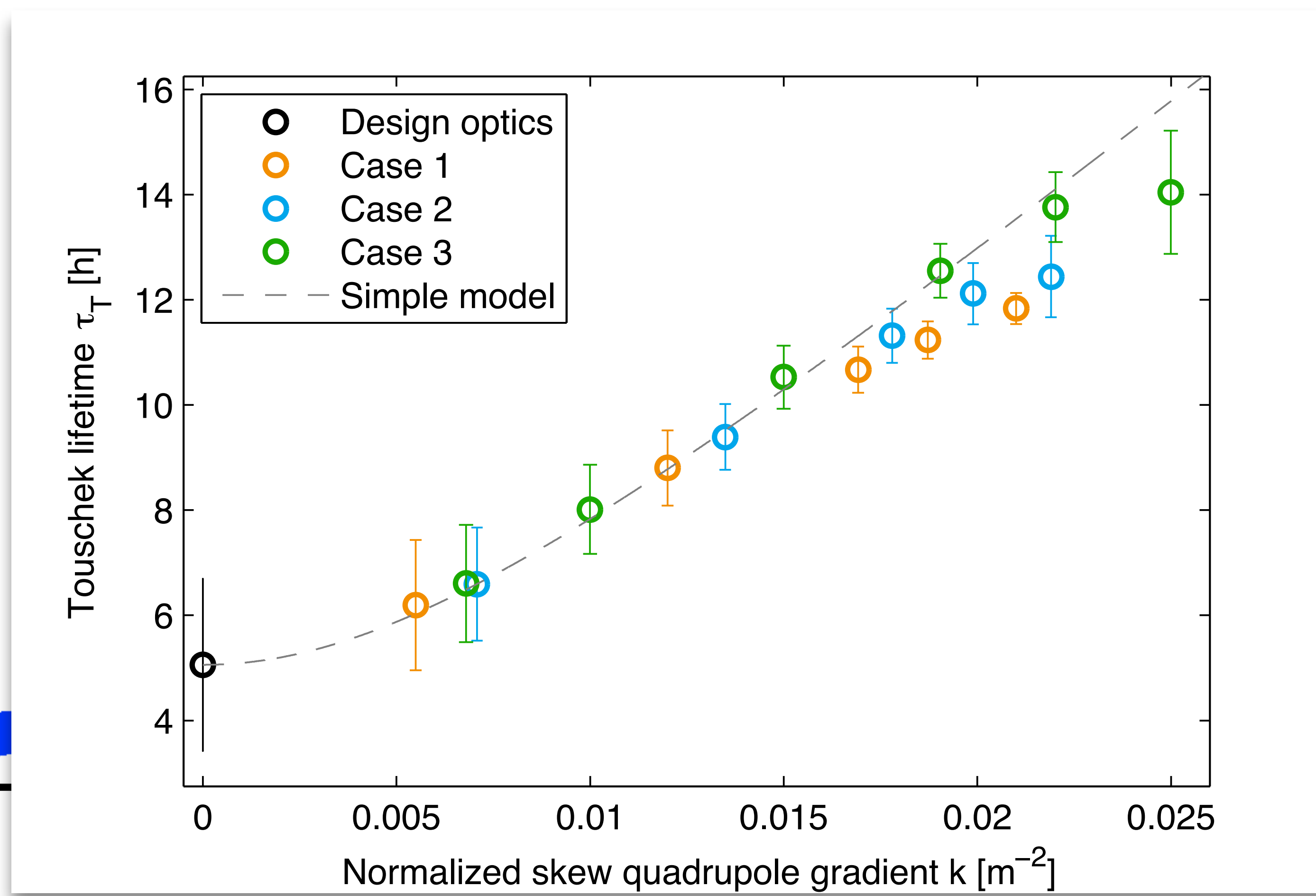

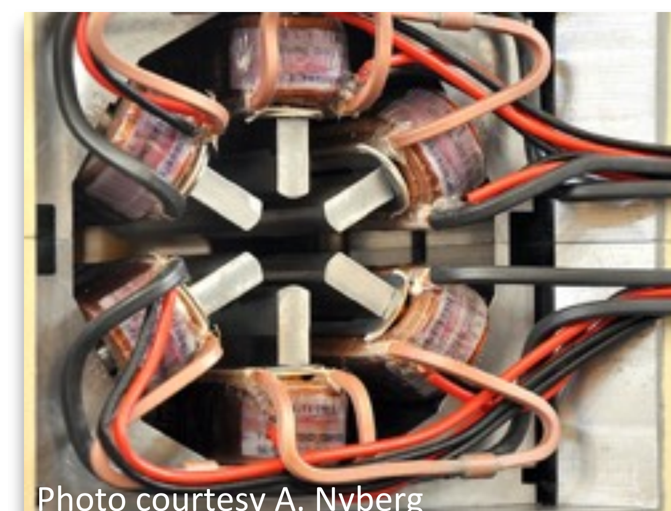

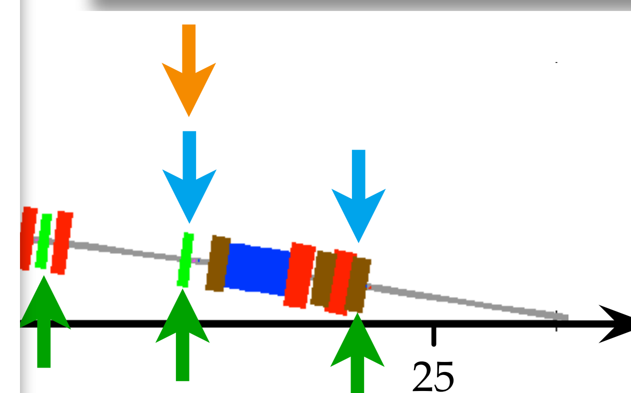

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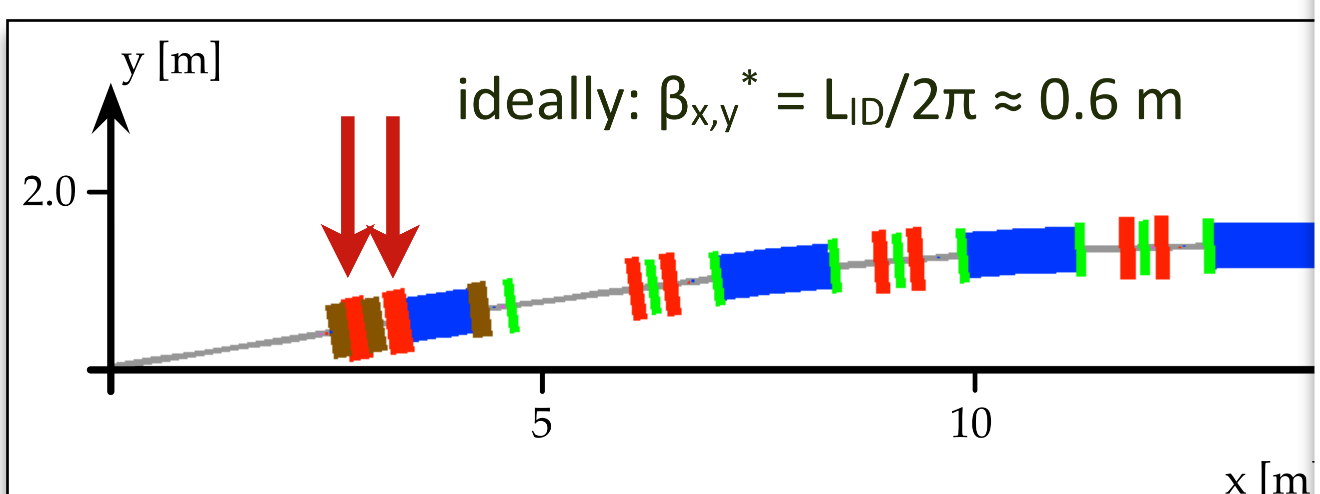
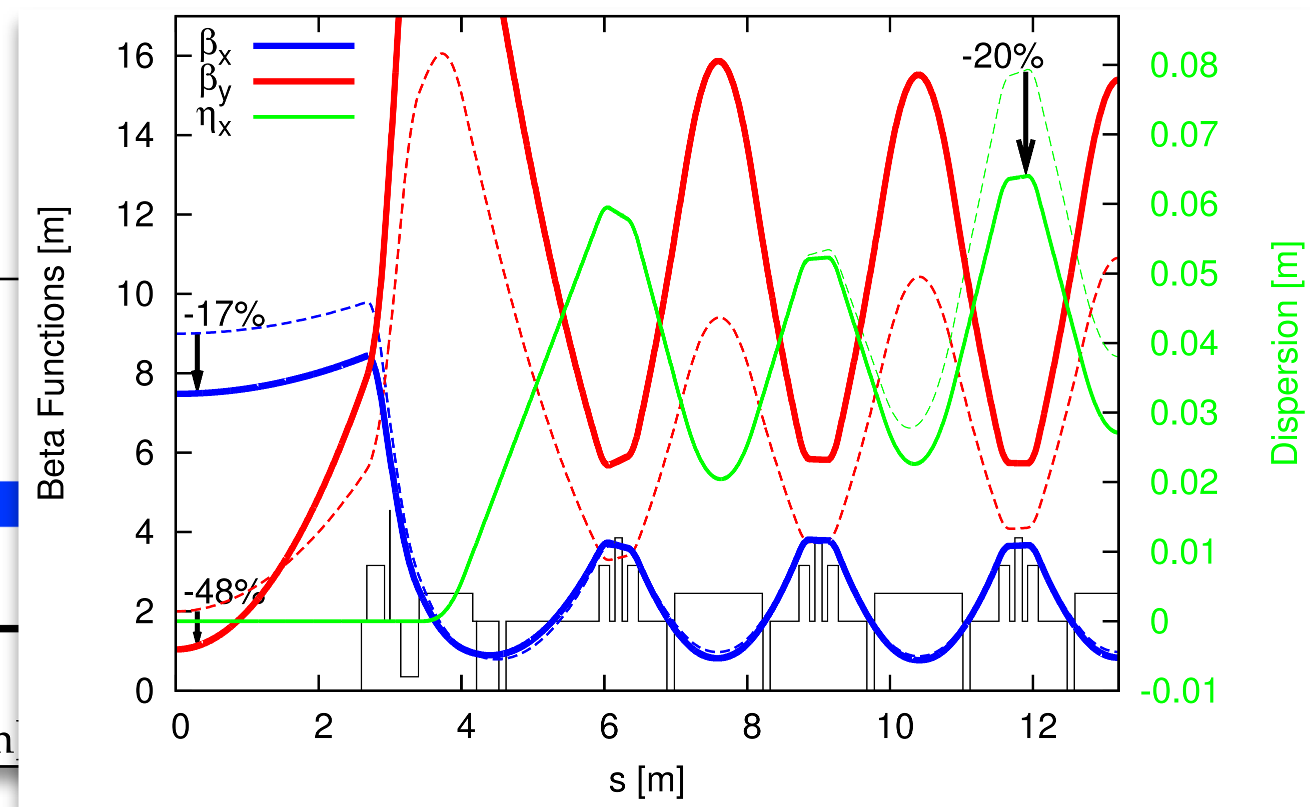
- Increase focusing in arc → ε_x reduced to 269 pm rad (-18%) while retaining satisfactory DA & lifetime IPAC'**14**, TUPRI026, p.1615





Upgrade Ideas (cont.)

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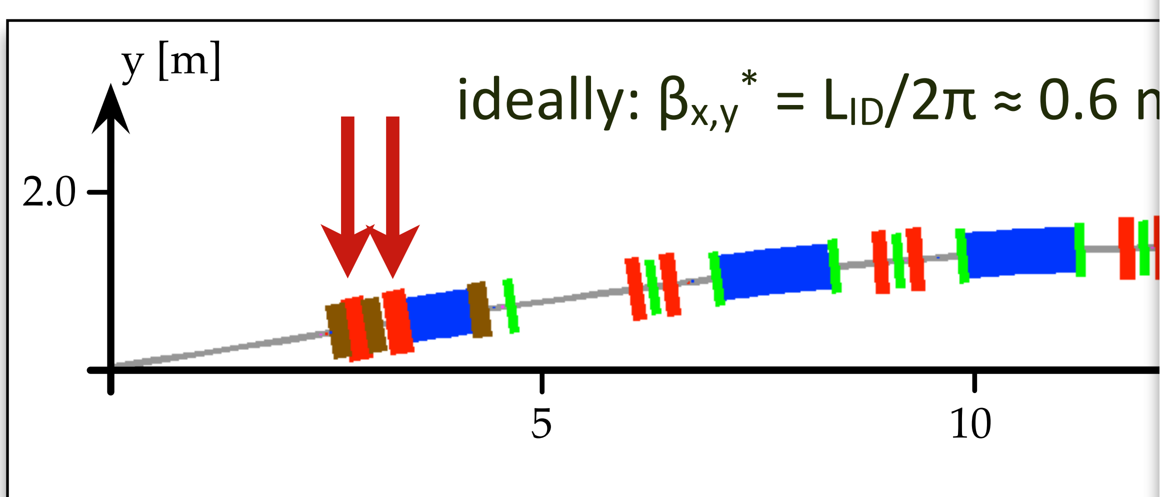

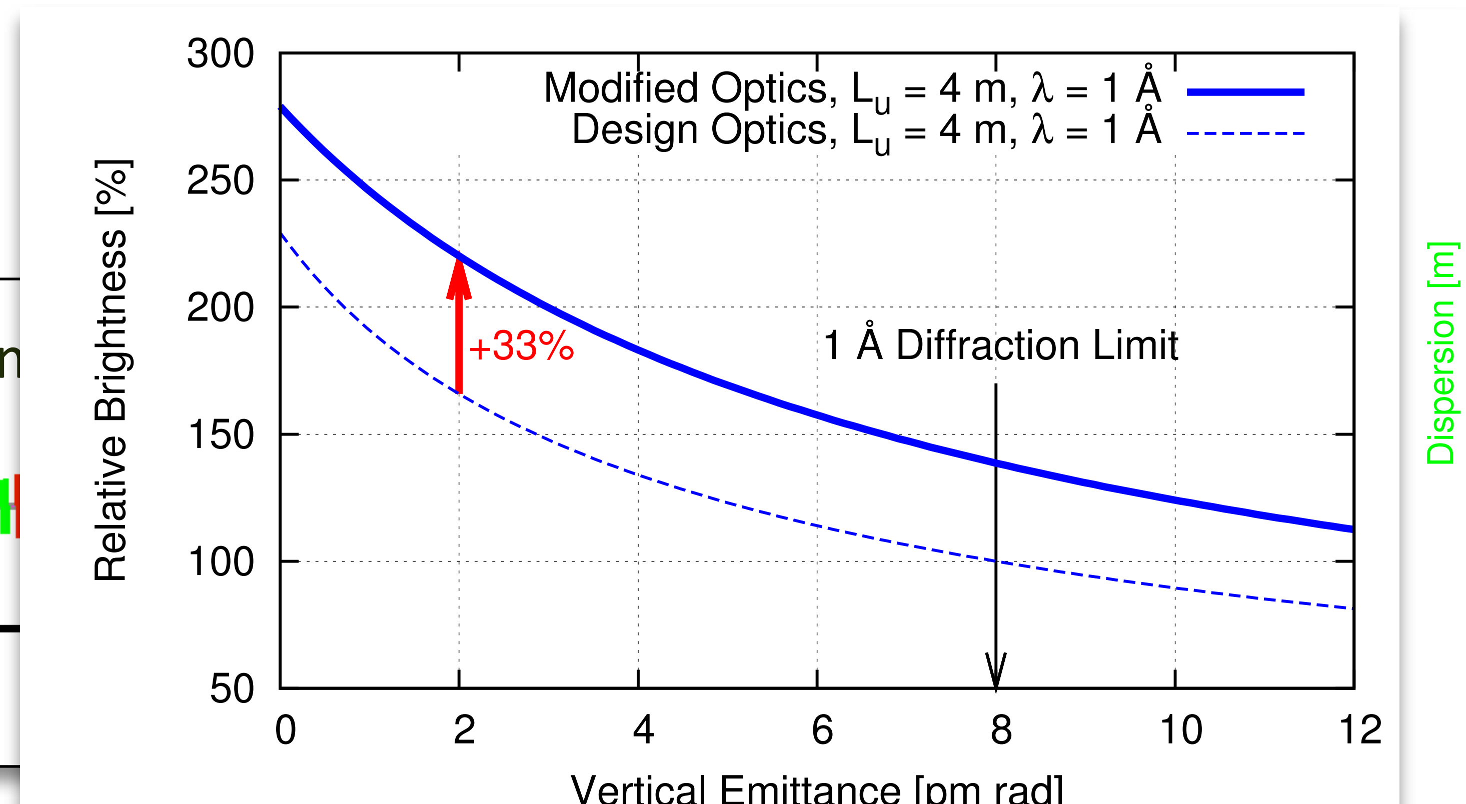

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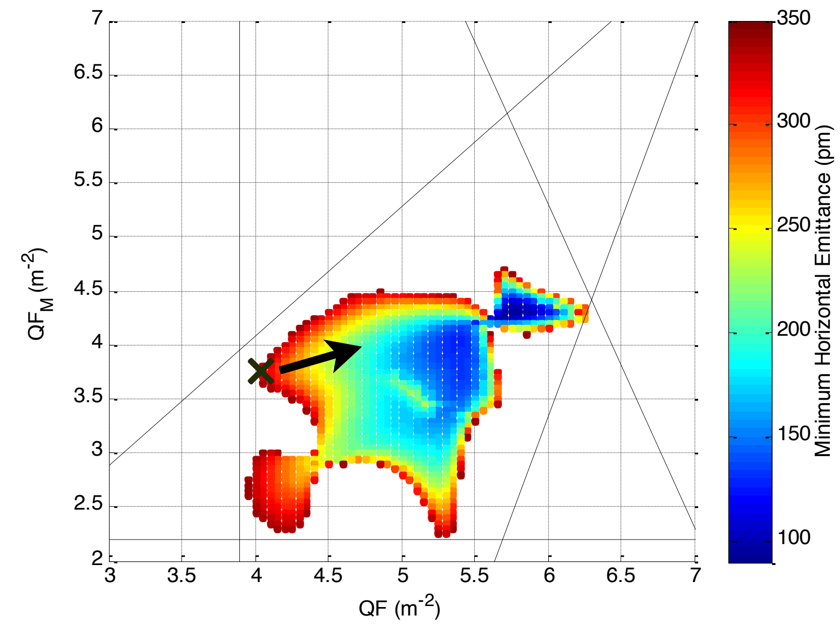
- First GLASS/MOGA studies assuming PSs can be exchanged → 221 pm rad



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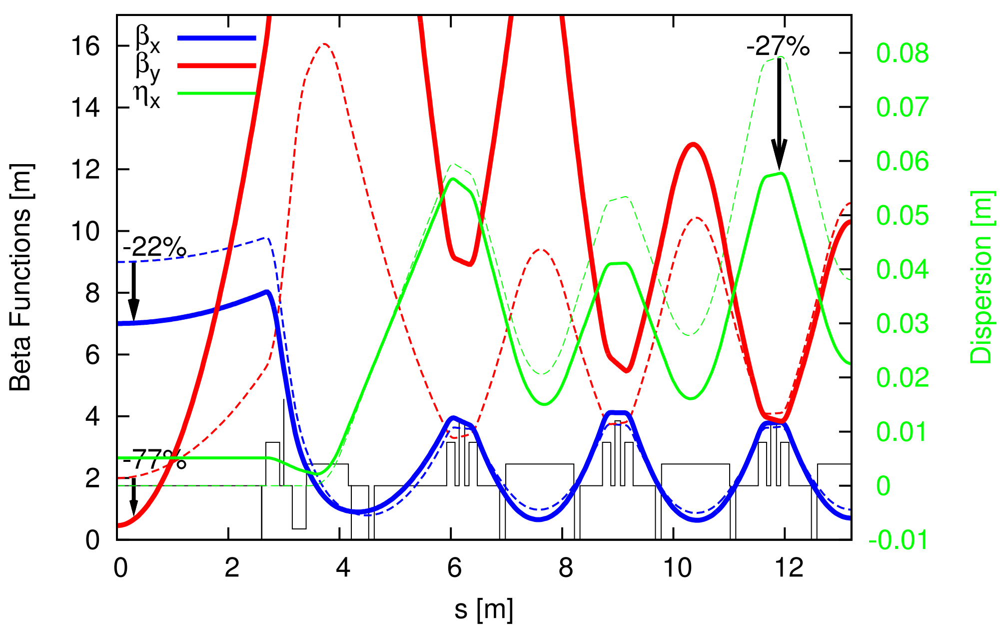

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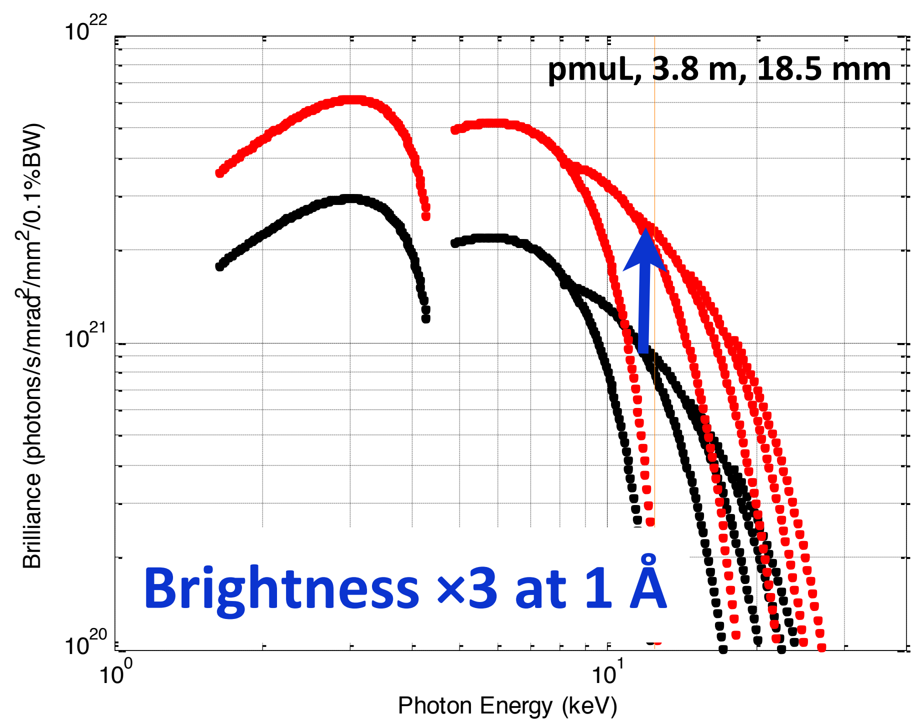

- First GLASS/MOGA studies assuming PSs can be exchanged ➔ 221 pm rad
- Assuming on-axis inj. ➔ ≈170 pm rad or ≈150 pm rad (w/ IDs and IBS @ 500 mA)

Thanks for your attention!

Photo courtesy L. Jansson, August 24, 2015