Commissioning Progress at the
MAX IV 3 GeV Storage Ring

Simon C. Leemann
6th Low Emittance Rings Workshop, SOLEIL, October 26–28, 2016

MAX IV

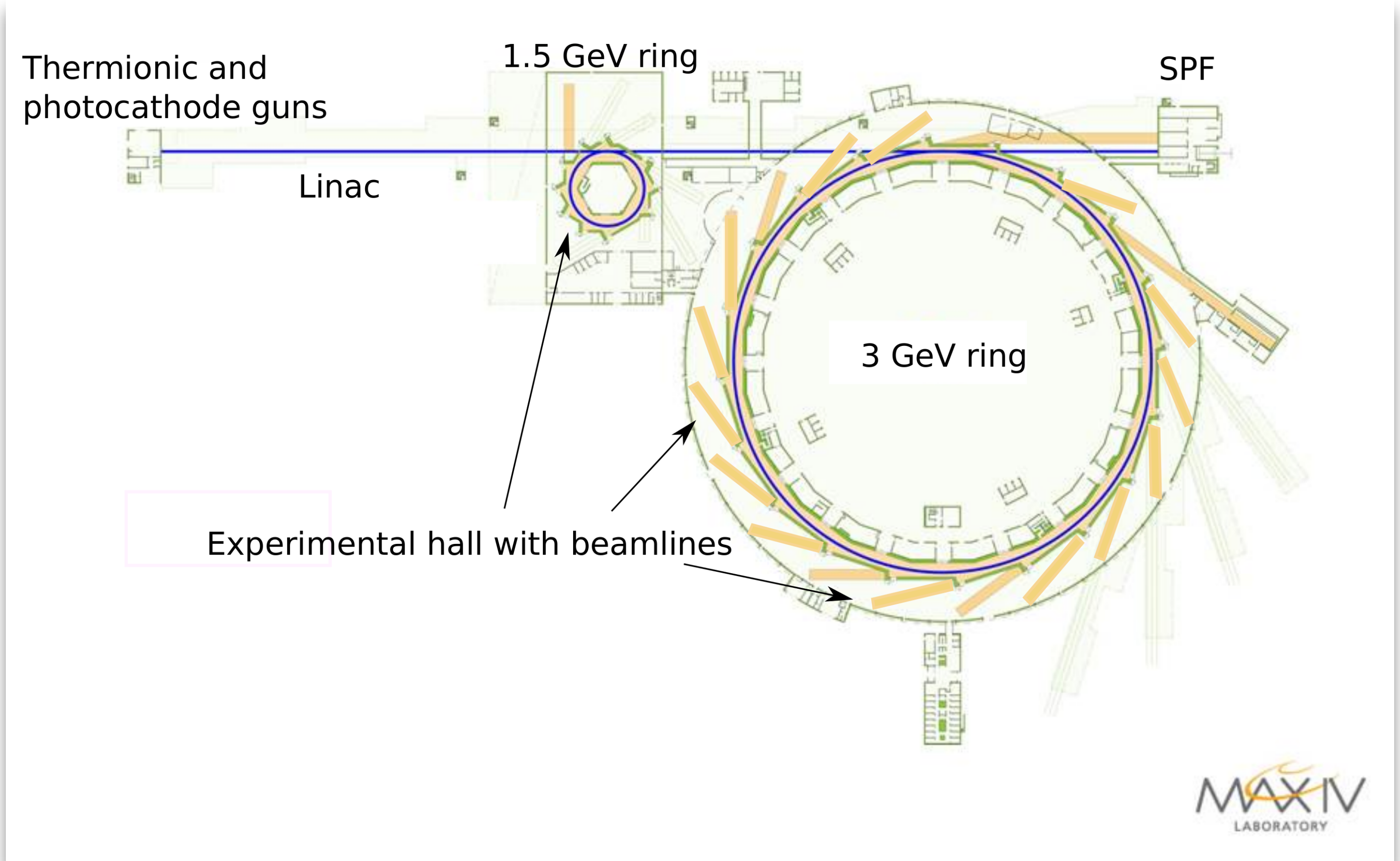
Outline

- Introduction
  - MAX IV Facility Overview
  - 3 GeV Storage Ring Lattice & Technology
- Commissioning of the MAX IV 3 GeV Storage Ring
  - Commissioning Timeline
  - Beam Commissioning of the Bare Machine
  - First Insertion Devices
  - Facility Inauguration
- Outlook

Collective Effects → Galina's talk on Thu
Subsystems Report → Magnus' talk on Fri

MAX IV Facility Overview

- In the early 2000s, MAX-lab wants to build new x-ray source
- Quickly realize a single new 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)



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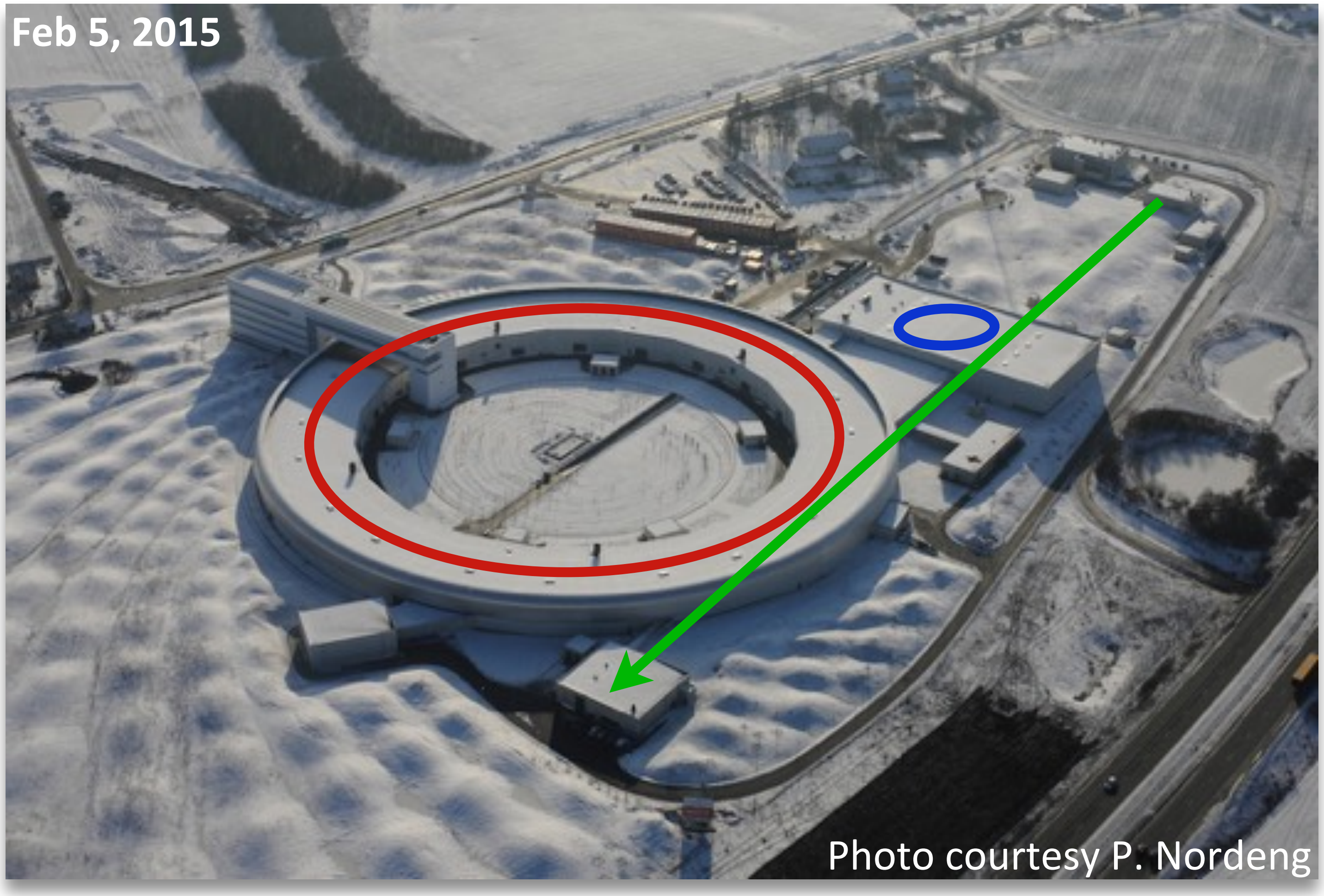
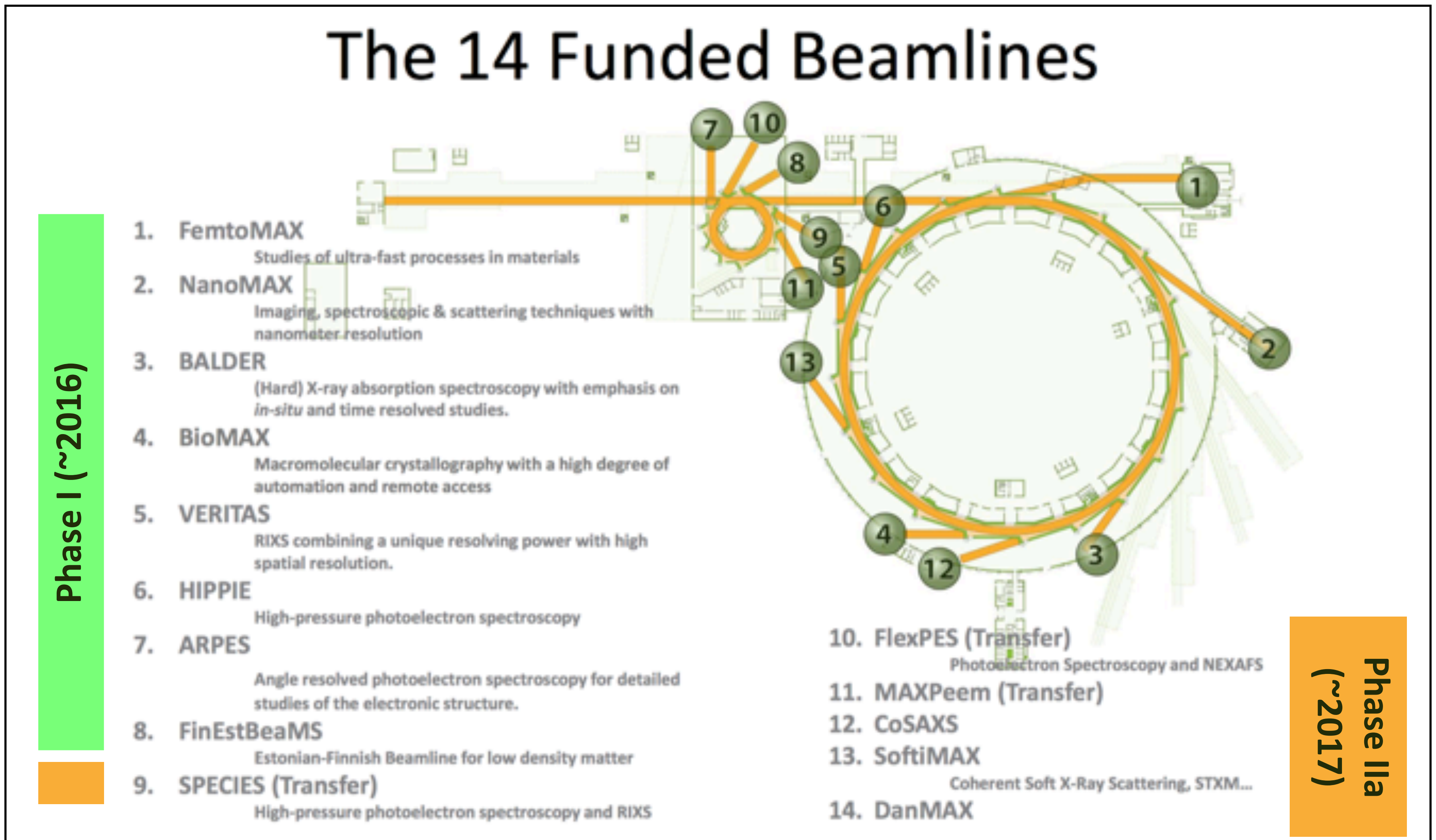


MAX IV Facility Overview (cont.)

- 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 3 GeV Storage Ring

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

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

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

TME

MBA

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

MAX IV 3 GeV Storage Ring (cont.)

- The **multibend achromat** proposed already in the 1990s...

  SPIE Vol. 2013, 1993 EPAC'**94**, p.627 PAC'**95**, TPG08, p.177 PAC'**95**, FAB14, p.2823

- ... became a reality @ MAX IV due to several technological breakthroughs

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  - compact magnets (narrow gaps ➔ short but strong), magnet integration (common magnet block = “girder”), use of combined-function magnets

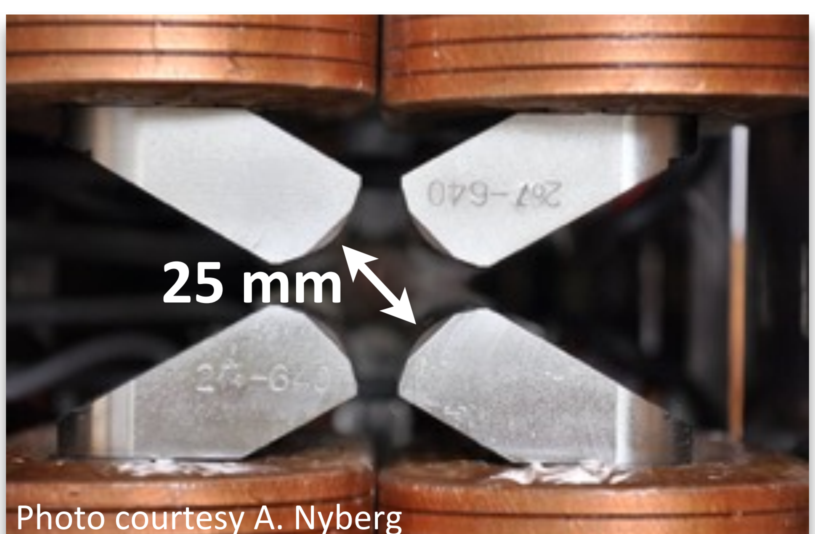

Photo courtesy A. Nyberg


Photo courtesy M. Johansson

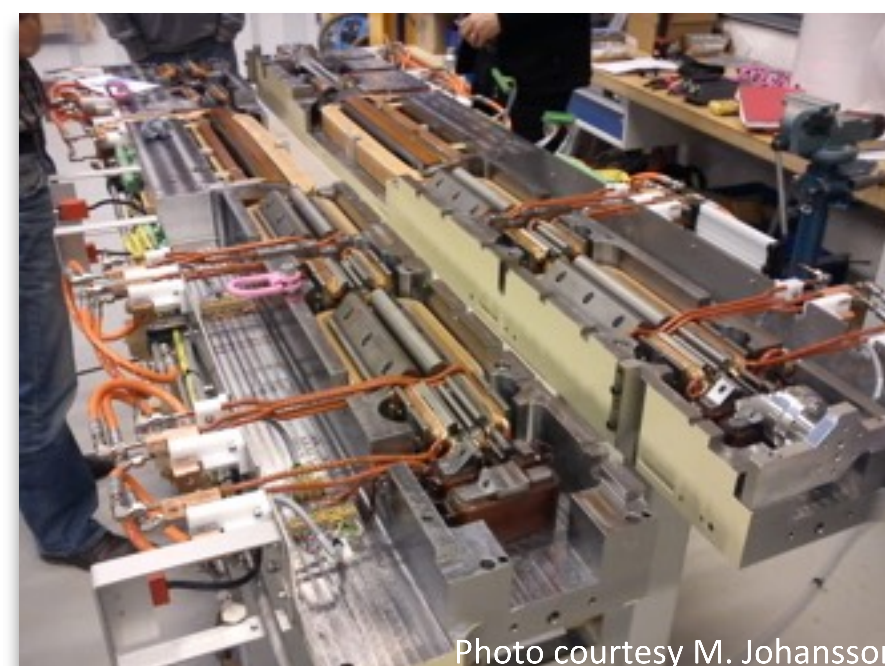
Photo courtesy M. Johansson

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

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  - NEG-coated vacuum chambers → narrow magnet gaps & tight magnet spacing

MAX IV 3 GeV Storage Ring (cont.)

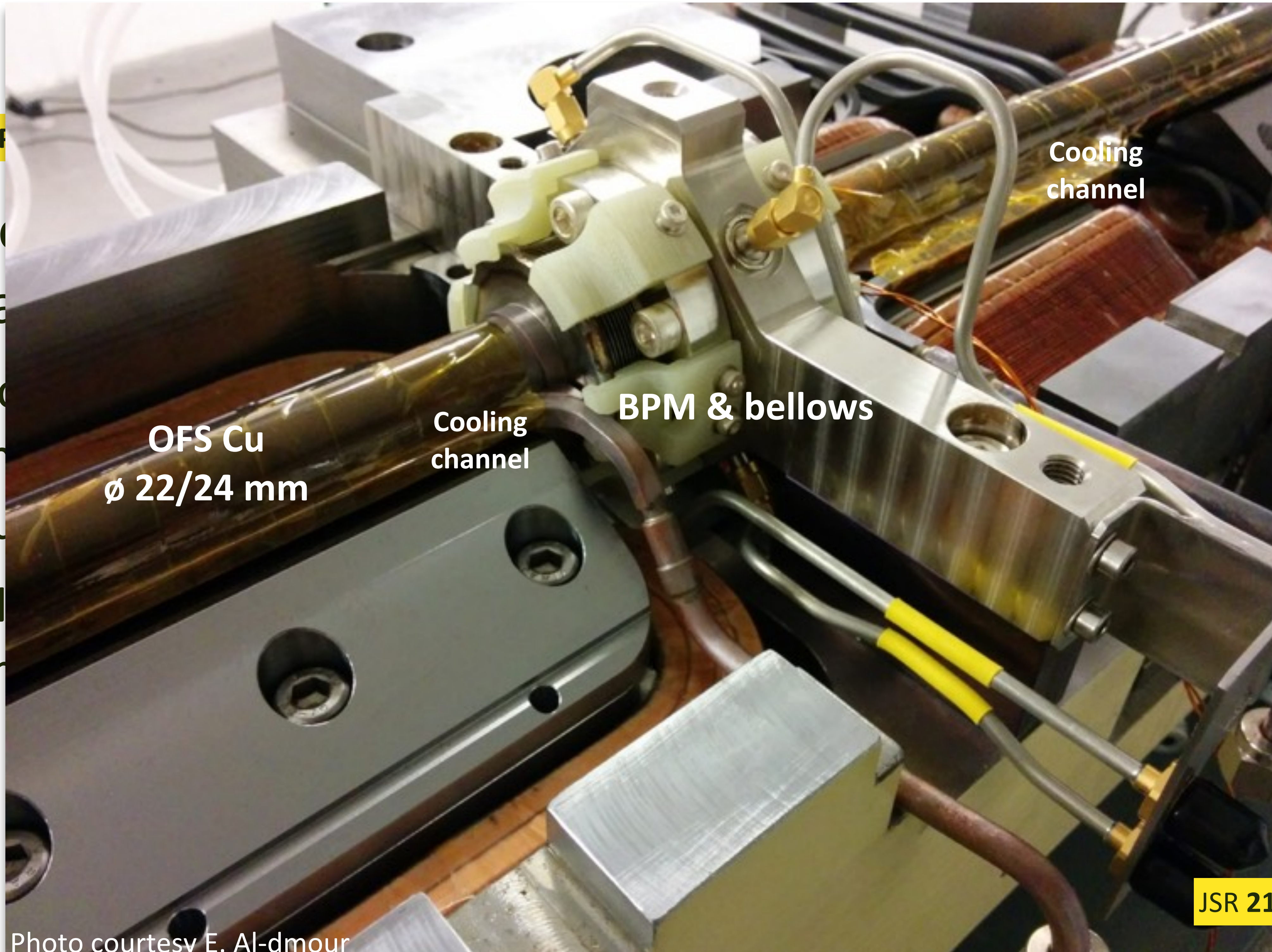
• The … s…

SP

• … b … cal brea…

– c… in … ined- fu…

– N … nt m…



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

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- ... became a reality @ MAX IV due to several technological breakthroughs
  - 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 stability, good Touschek lifetime & mitigate emittance blowup from IBS

MAX IV 3 GeV Storage Ring (cont.)

- The **multibend achromat** proposed already in the 1990s ...

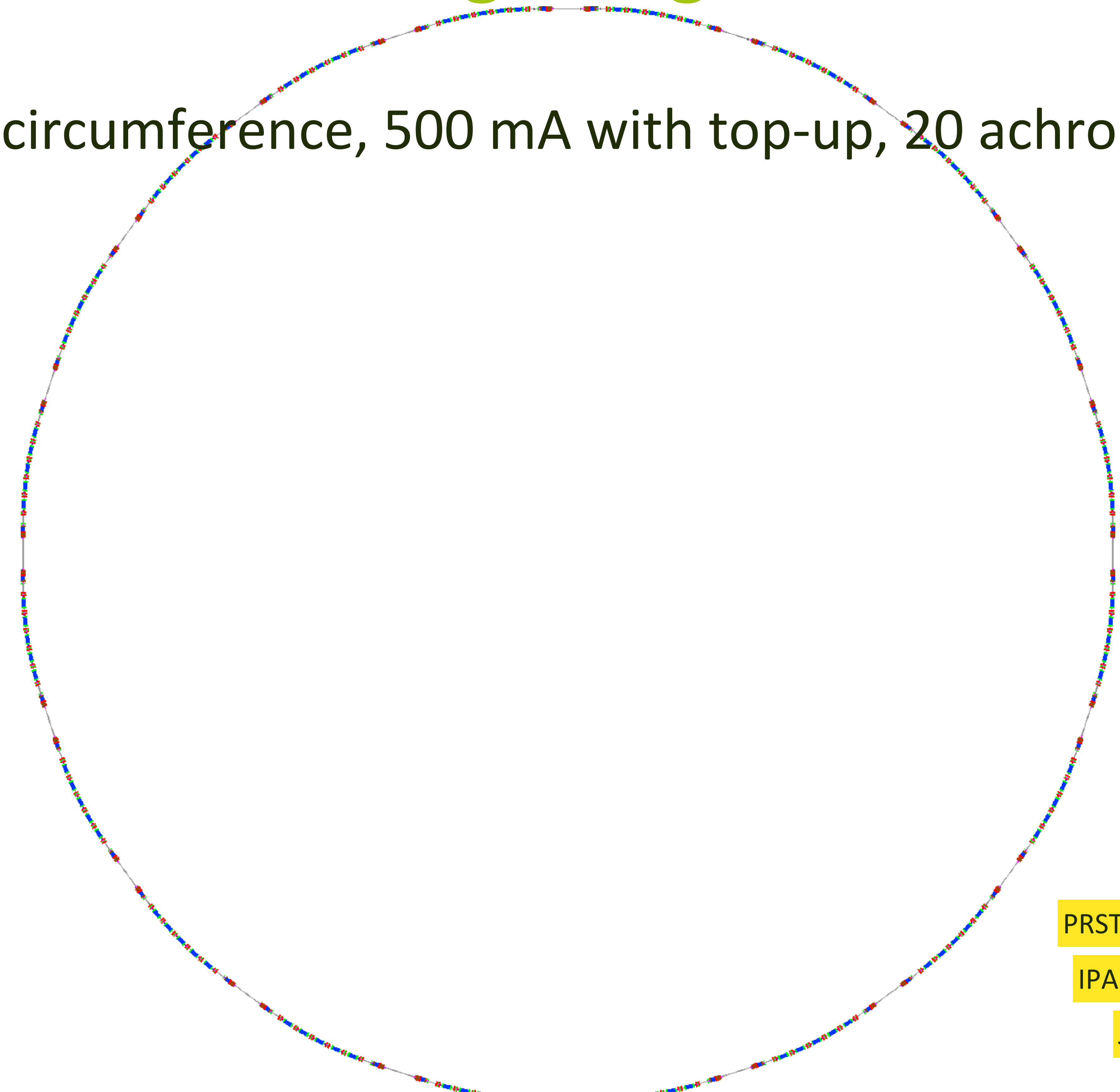
  S... , TPG08

- ... b... V du... al brea...
  - c... ps → ... i... t blo... ned-f...
  - N... rs → ... t m...
  - 1... mon... , g... tigat... S

IPAC’**11**, MOPC051, p.193

MAX IV 3 GeV Storage Ring Lattice

• 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)

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9, p.3029

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

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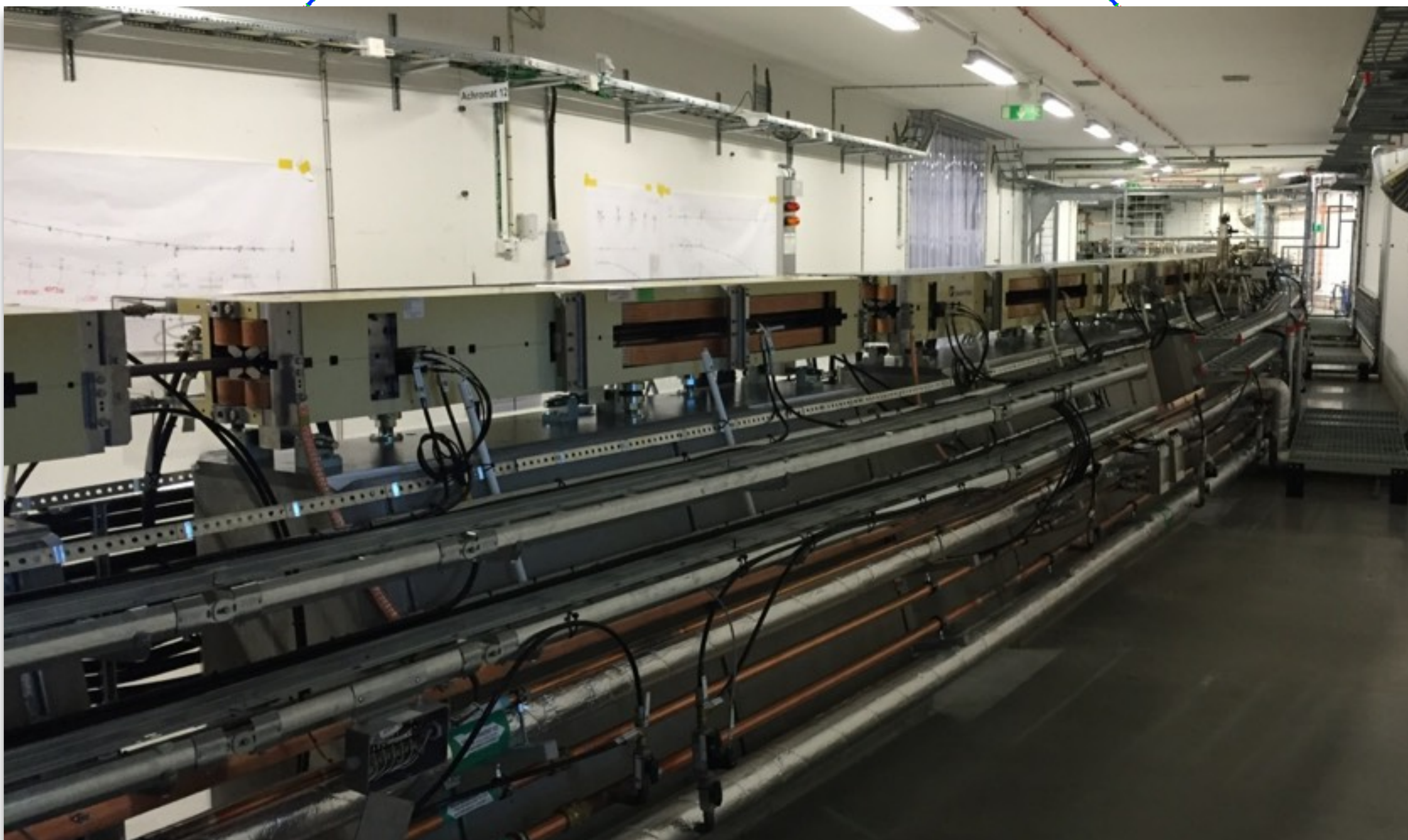


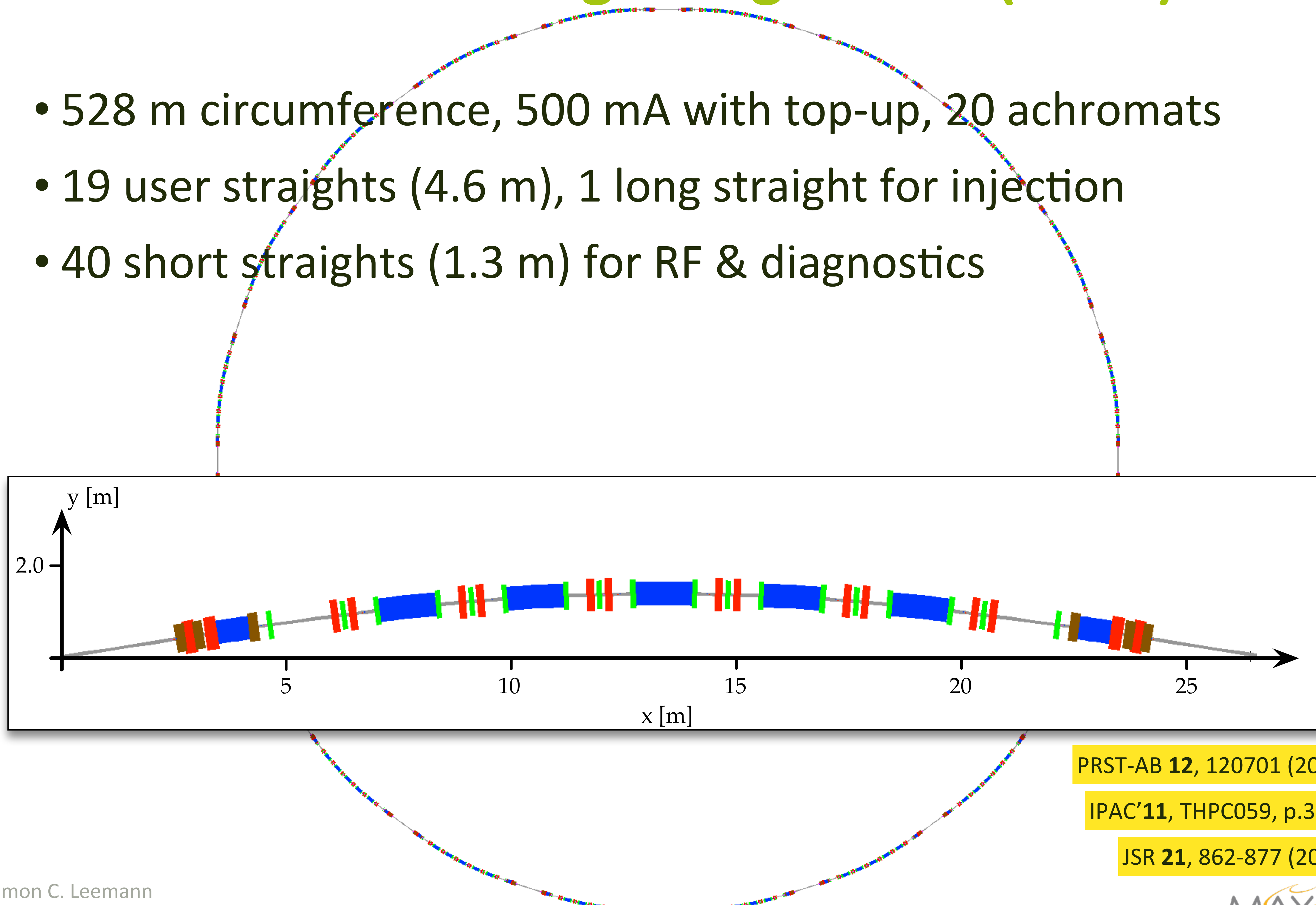
701 (2009)

59, p.3029

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

MAX IV 3 GeV Storage Ring 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



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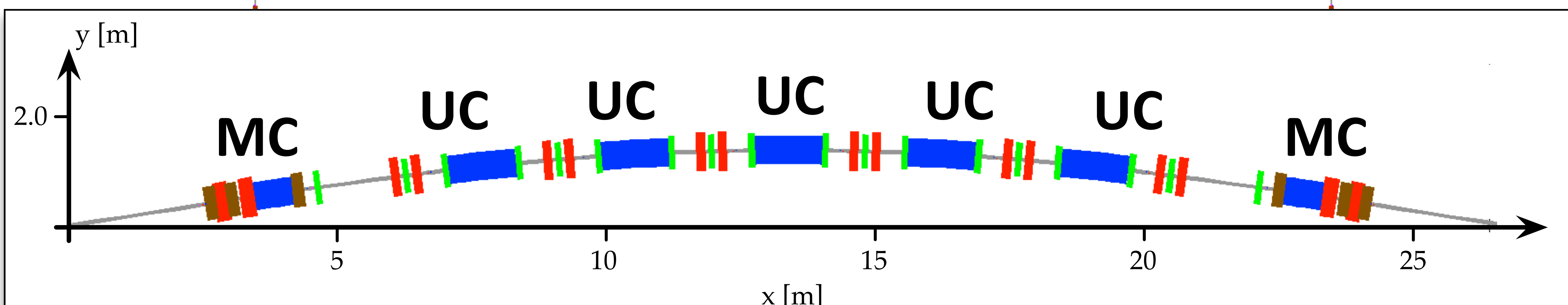

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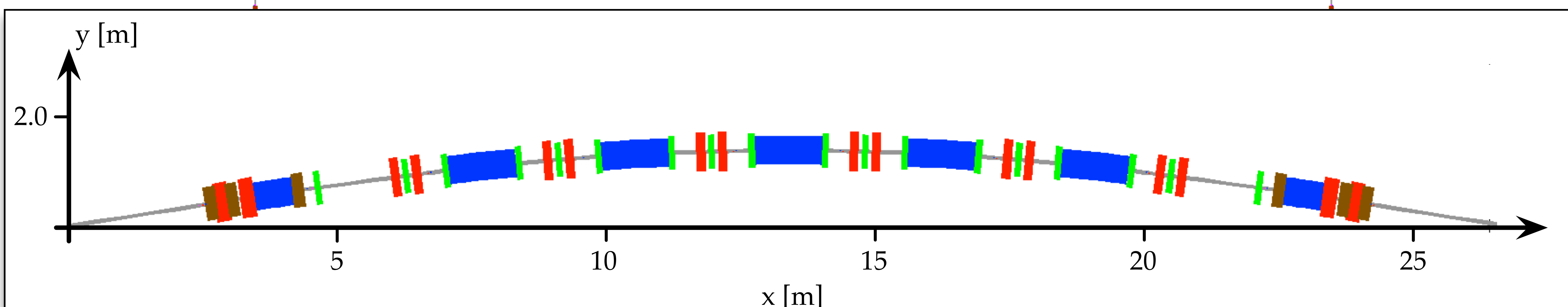
- 328 pm rad bare lattice emittance (ε_y adjusted to 2-8 pm rad)



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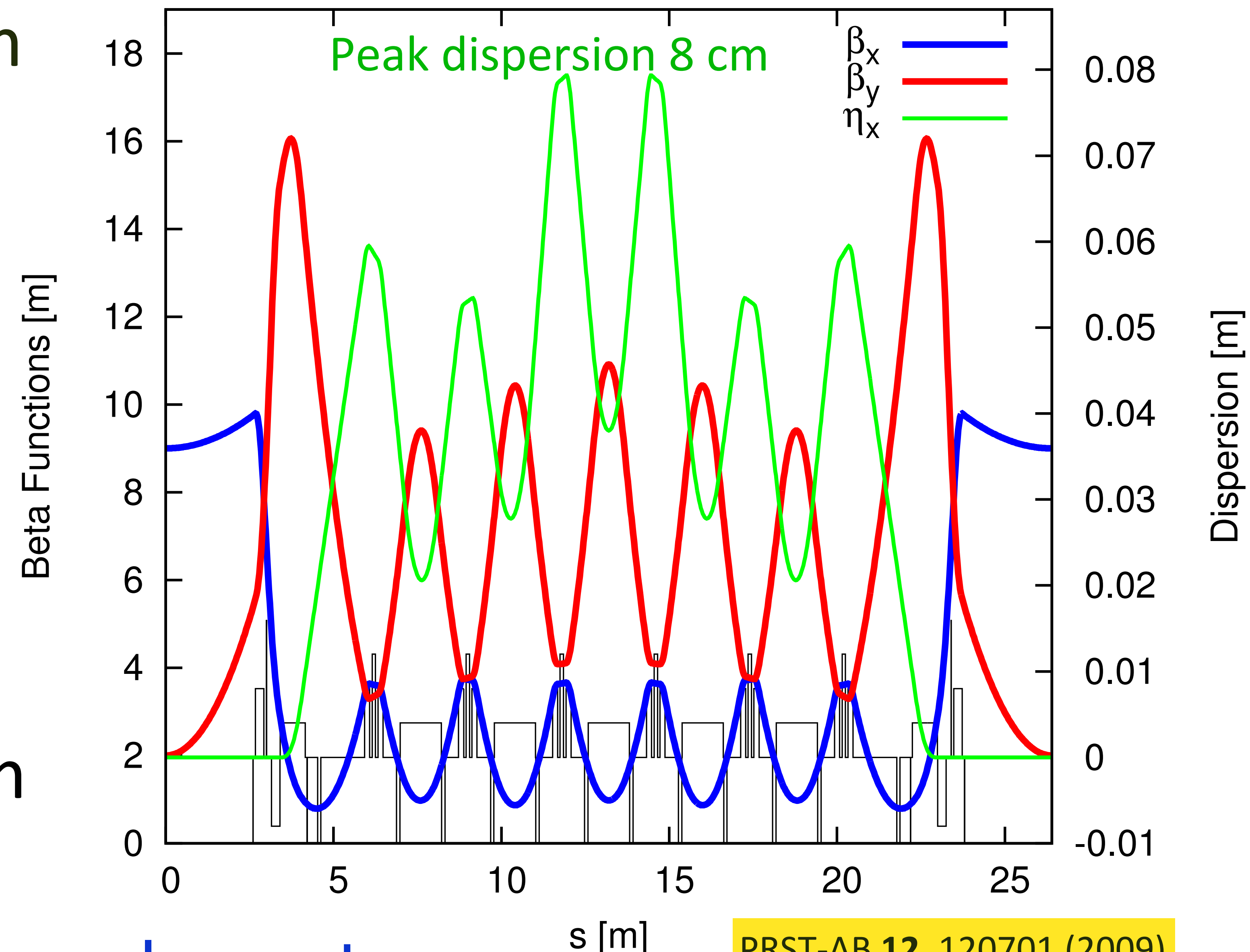
JSR **21**, 862-877 (2014)

Linear & Nonlinear Optics

- **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
- $\sigma_x^* = 54\ \mu$m, $\sigma_y^* = 2\text{-}4\ \mu$m



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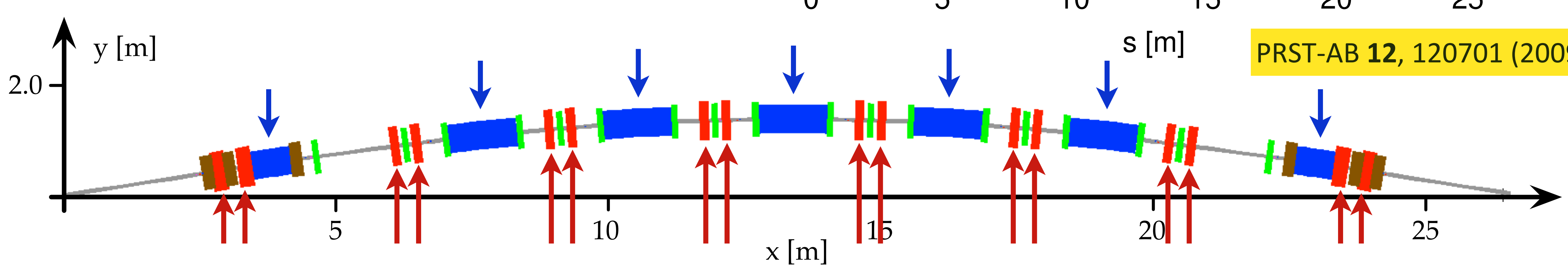
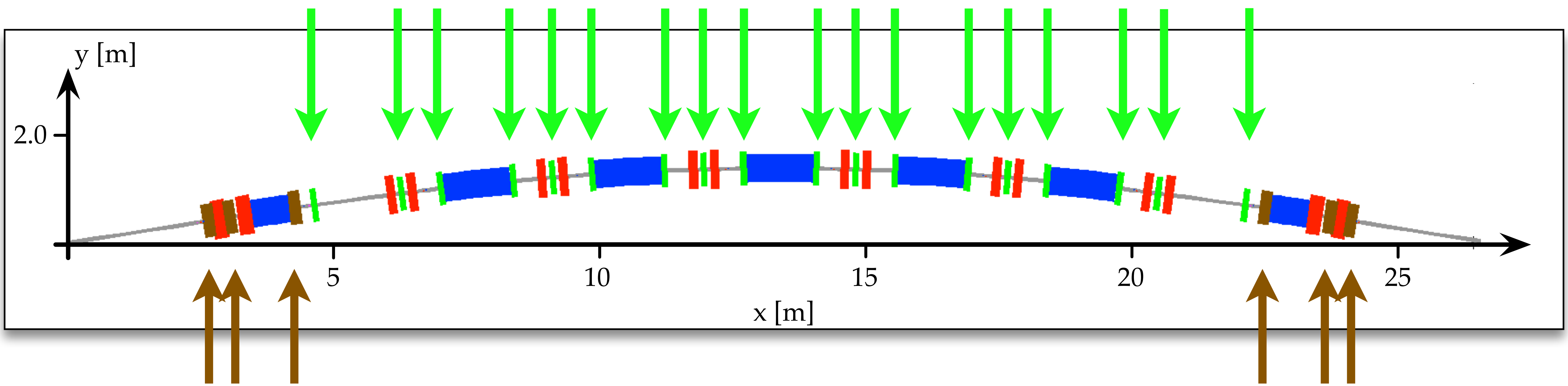


Linear & Nonlinear Optics (cont.)

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



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

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

Expected Performance (cont.)

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

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

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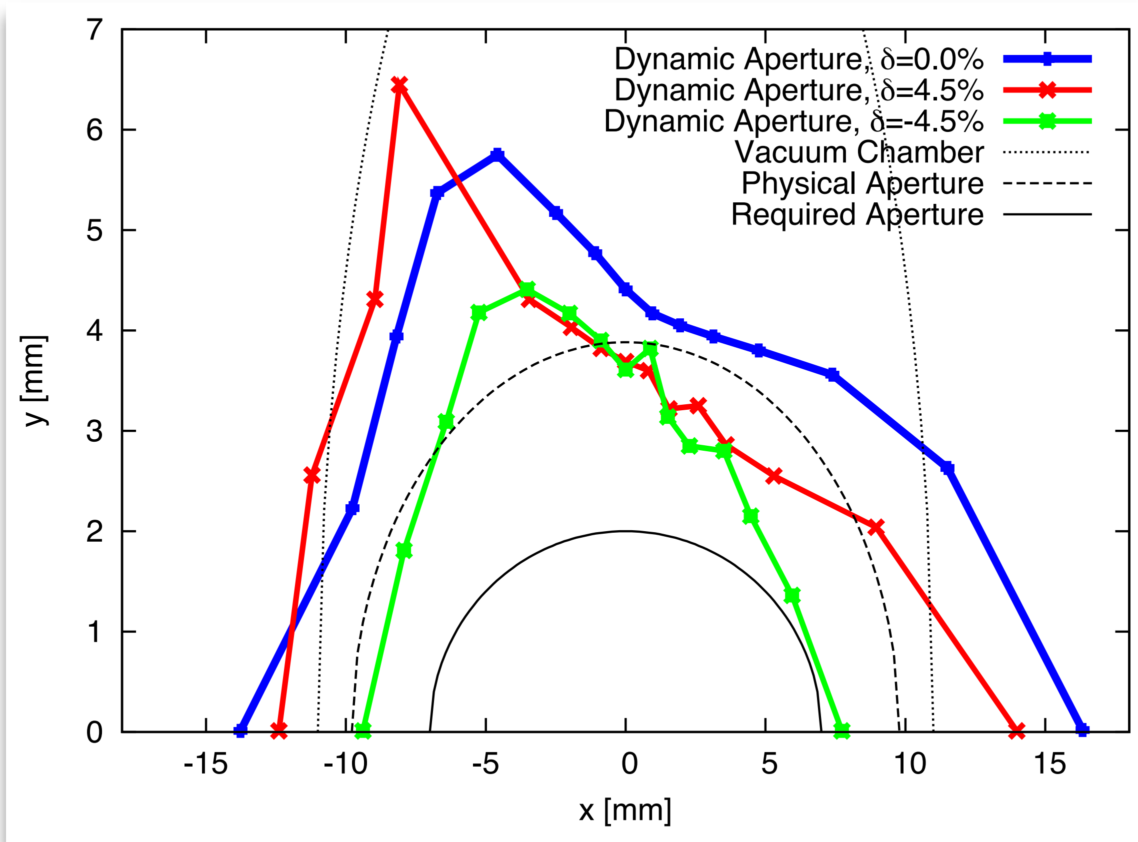
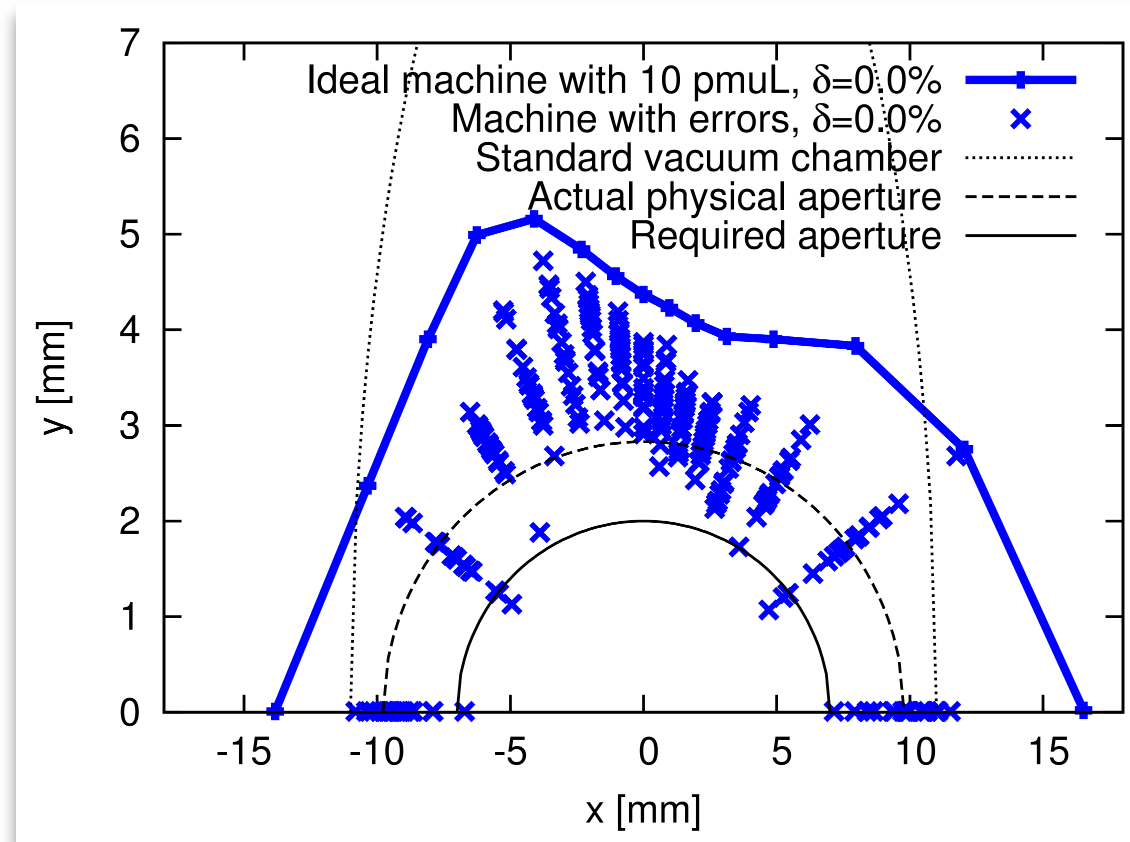
- Overall tune footprint becomes very compact both on and off momentum → large on/off-momentum DA

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

IPAC'**15**, TUPJE038





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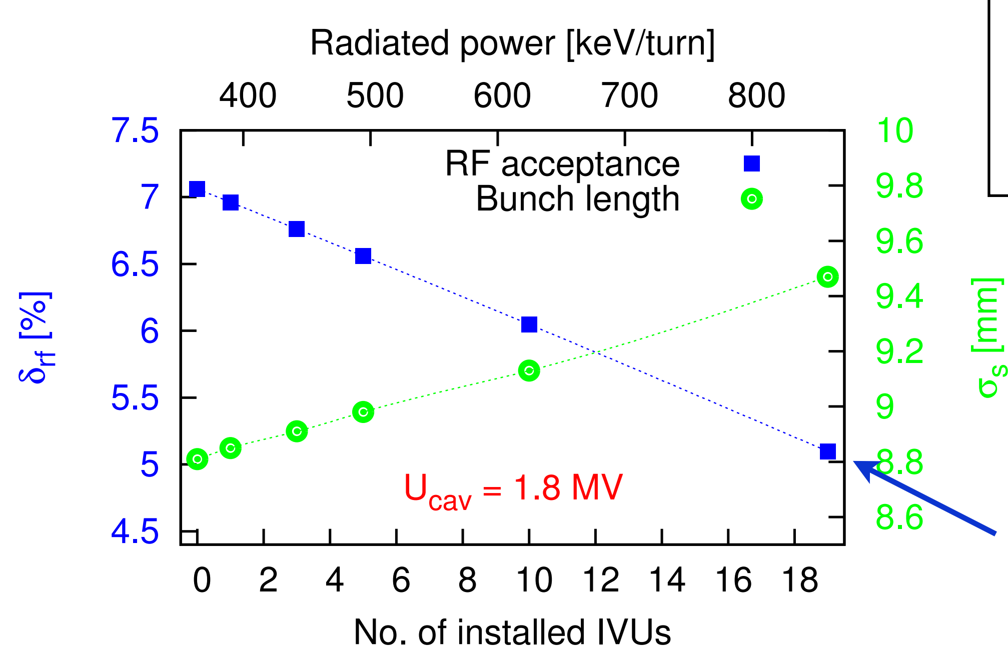
- Large lattice MA in conjunction with appropriately dimensioned RF system ➔ large overall MA

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



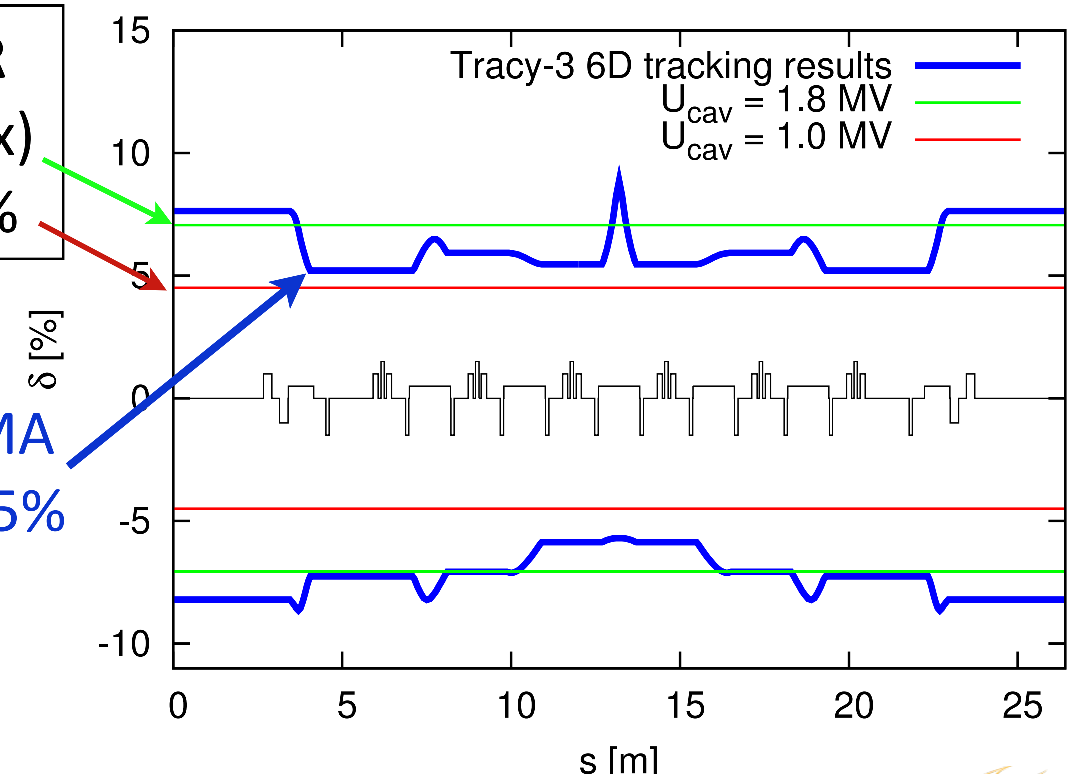
MAX IV 3 GeV SR

U_{cav} = 1.8 MV (max)

Target: δ_{acc} > 4.5%

Lattice MA always >5%

RF acceptance always >5%



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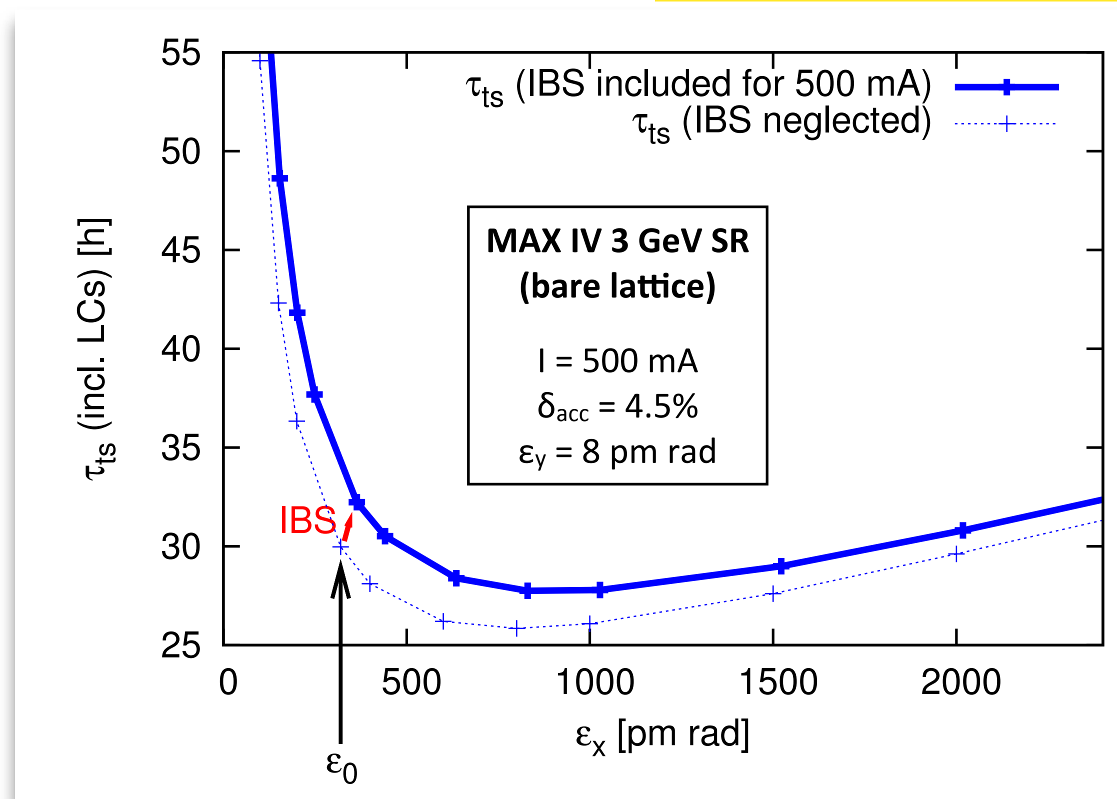
PRST-AB **17**, 050705 (2014)

- Large overall MA is required for good Touschek lifetime despite ultralow emittance



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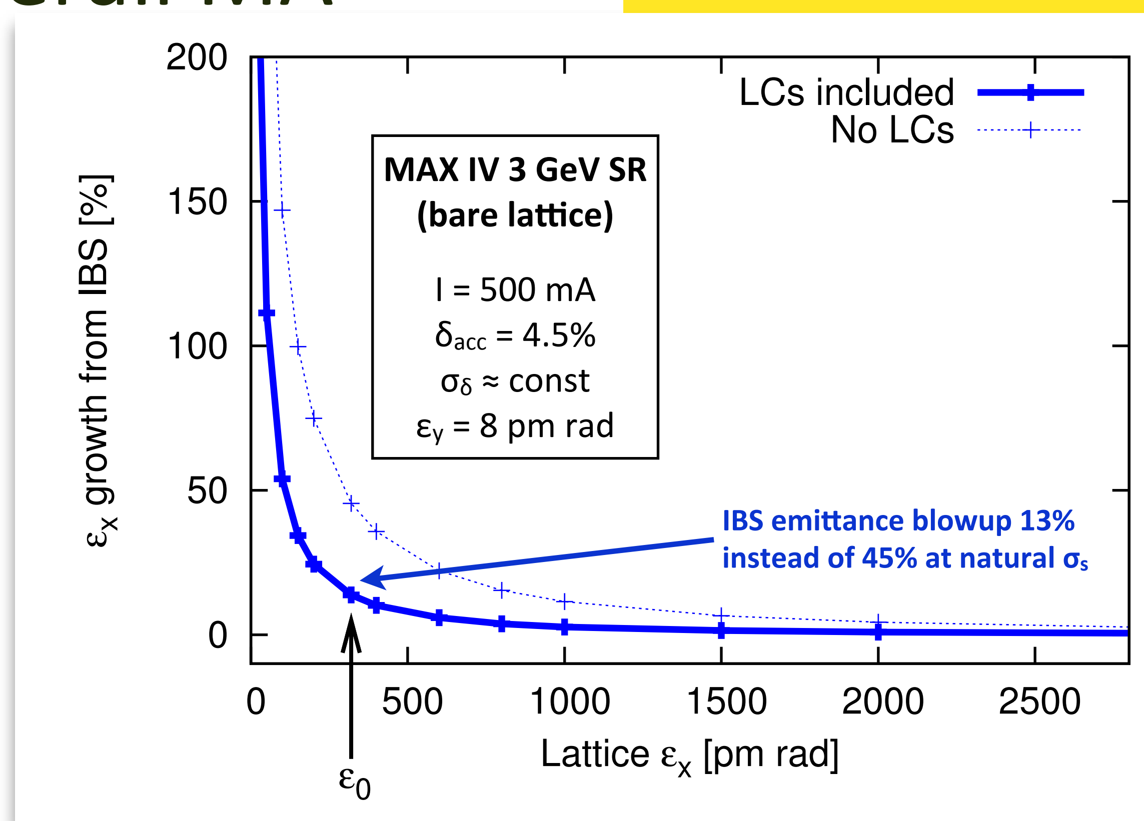
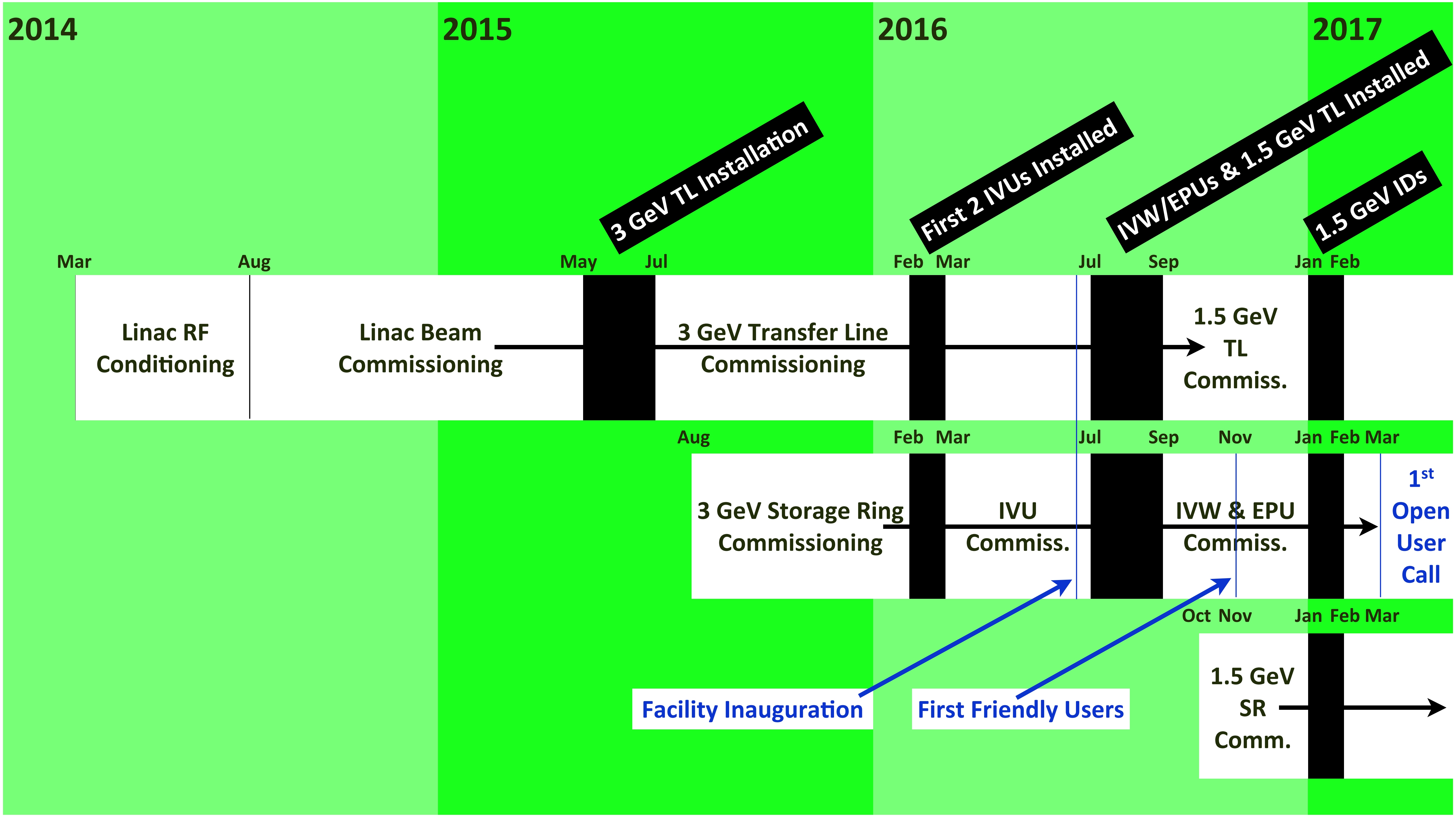
PRST-AB **17**, 050705 (2014)

- Large overall MA is required for good Touschek lifetime despite ultralow emittance
- Landau cavities stretch bunches ×5 ➔ extend Touschek lifetime & reduce emittance blowup by IBS



Commissioning Timeline



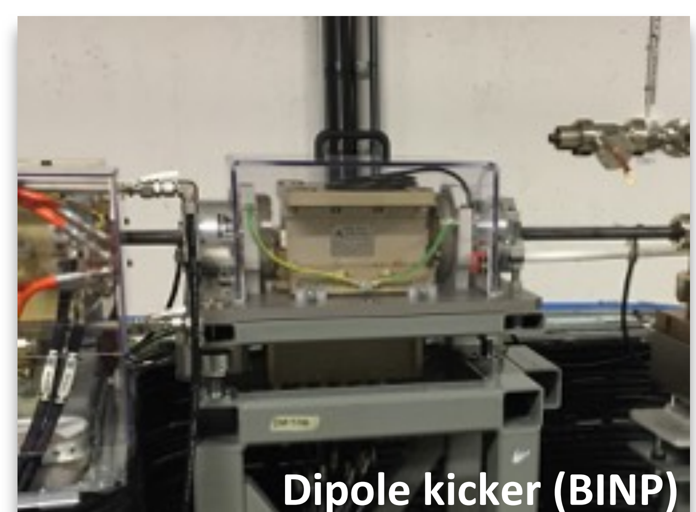
3 GeV Storage Ring Commissioning

- At LER 2015 in Grenoble had just reported first turns...

First full turn

- without exciting a single corrector
- all magnets at nominal optics for 3.0 GeV
  (excitations according to magnetic measurement data)
- using a single dipole kicker for injection

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



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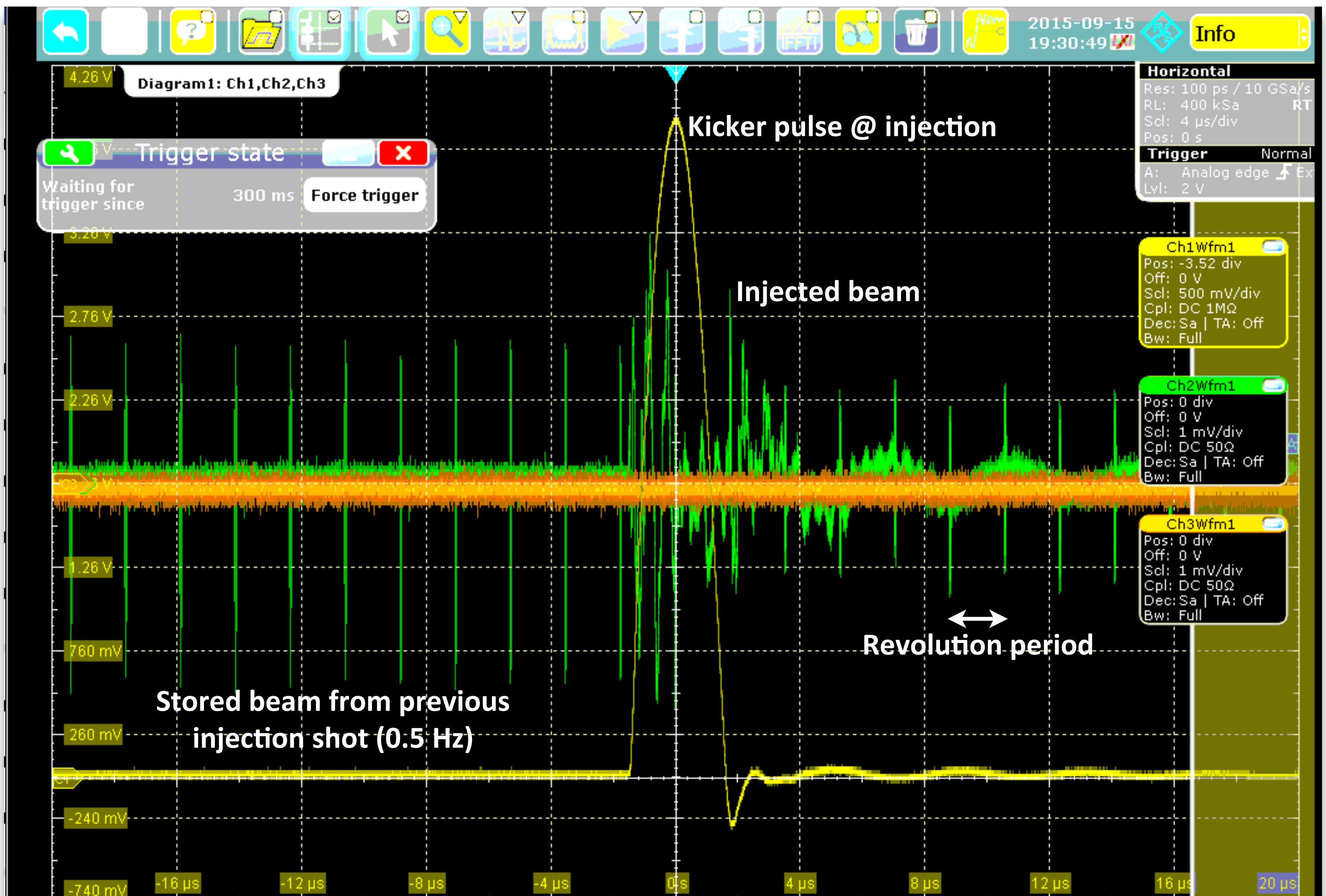
- First stored beam on Sep 15 → ≈0.1 mA (≈170 pC from linac)



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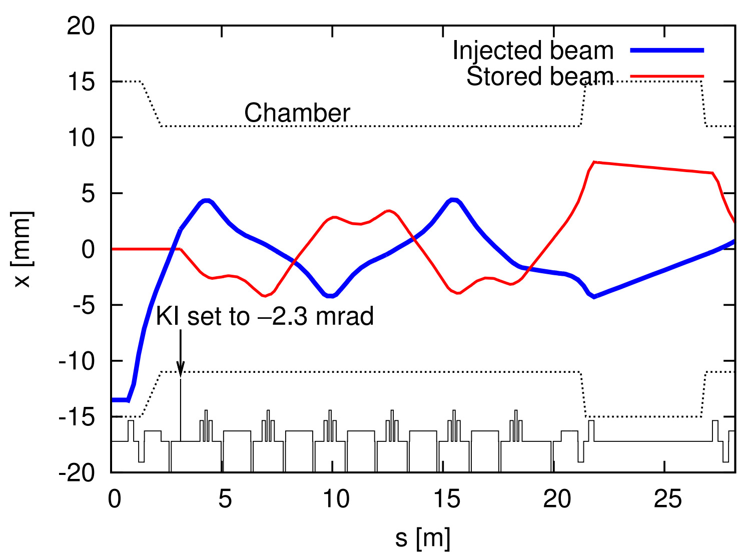
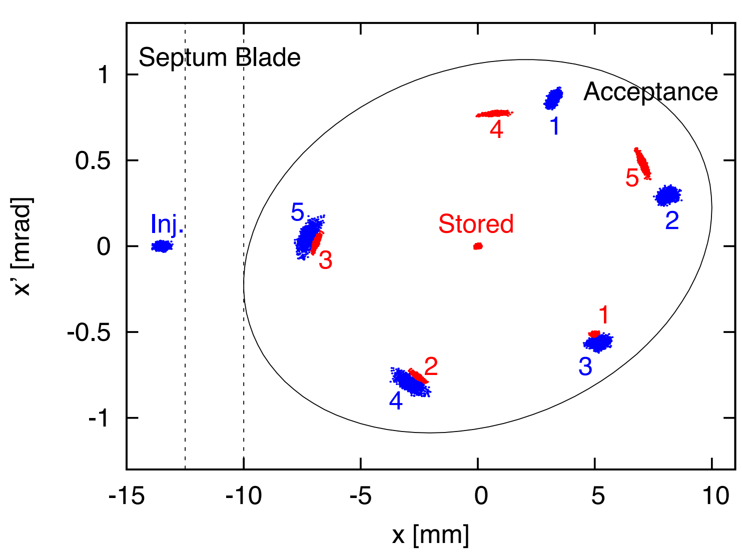
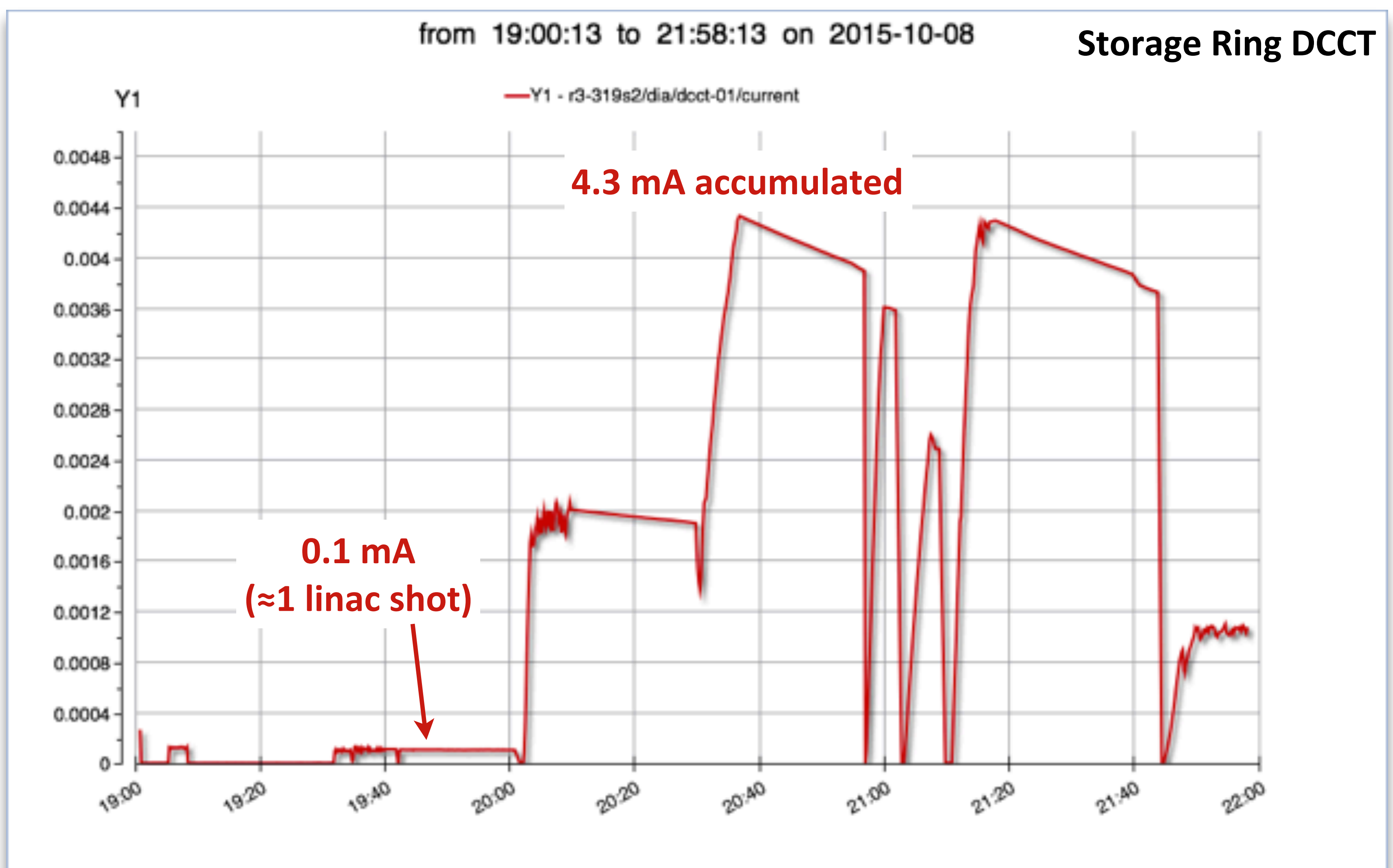
- First stacking observed Oct 8 (@ reduced dipole kicker strength) NIM-A **693**, 117, 2012







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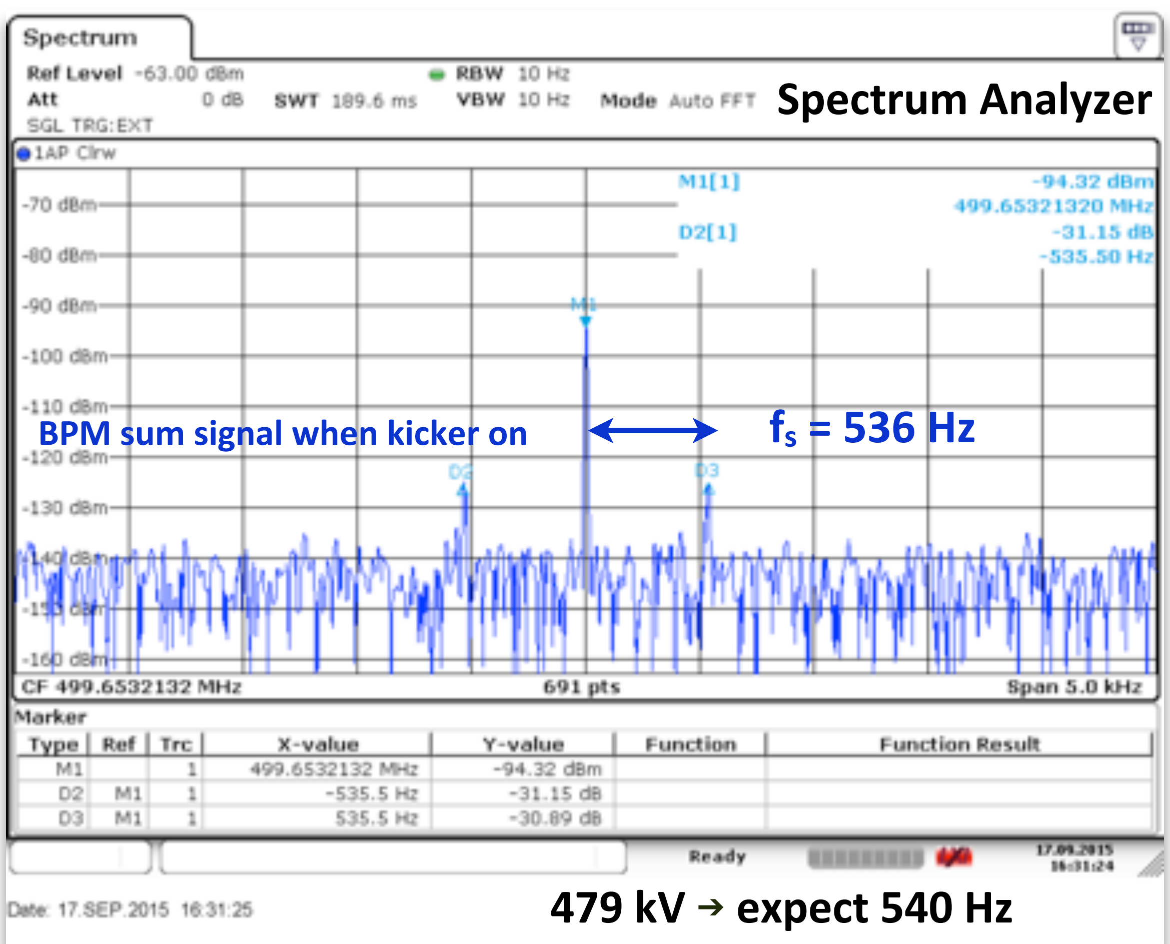
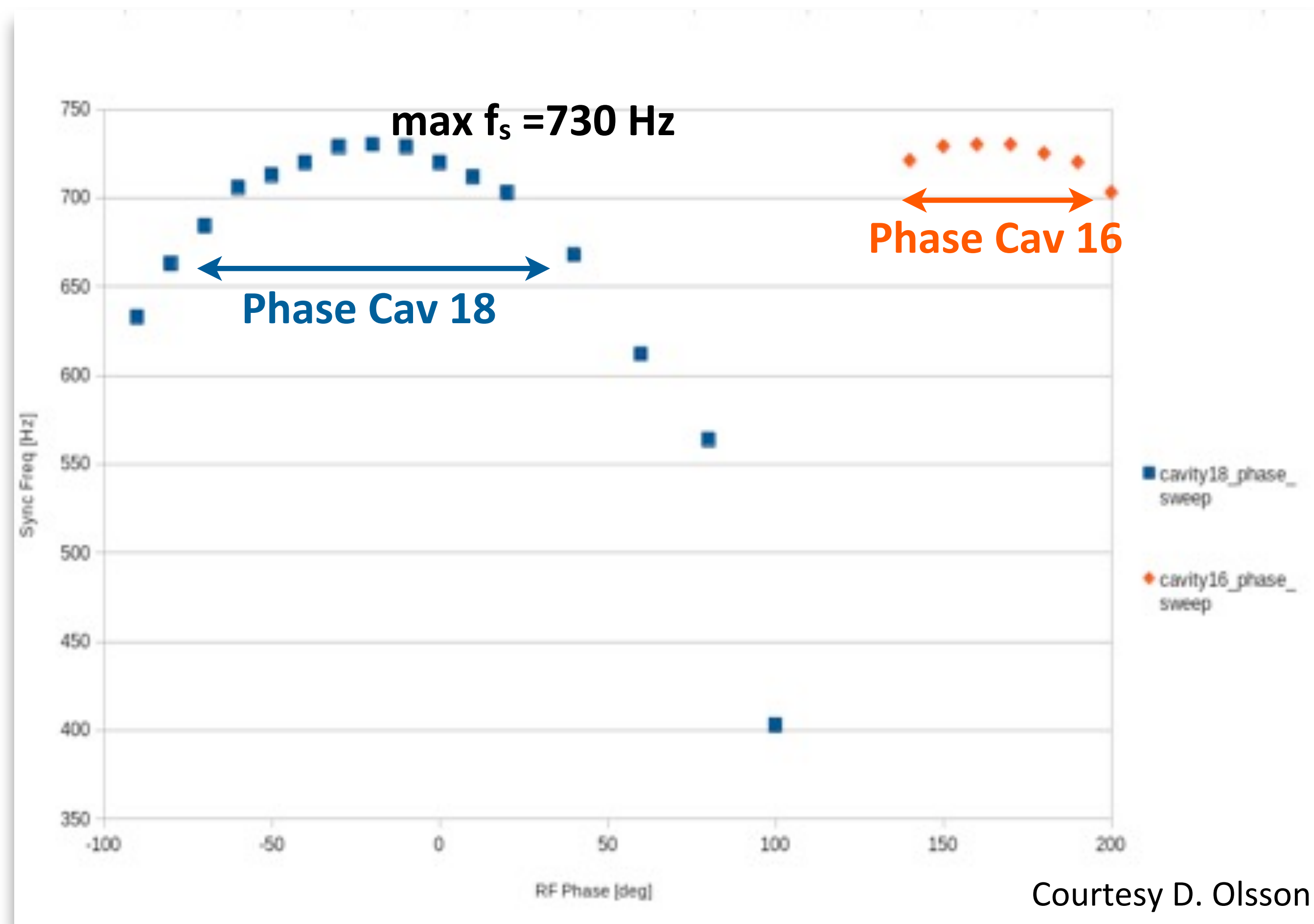
- Phasing 2 ring cavities → maximize f_s and improve inj. rate





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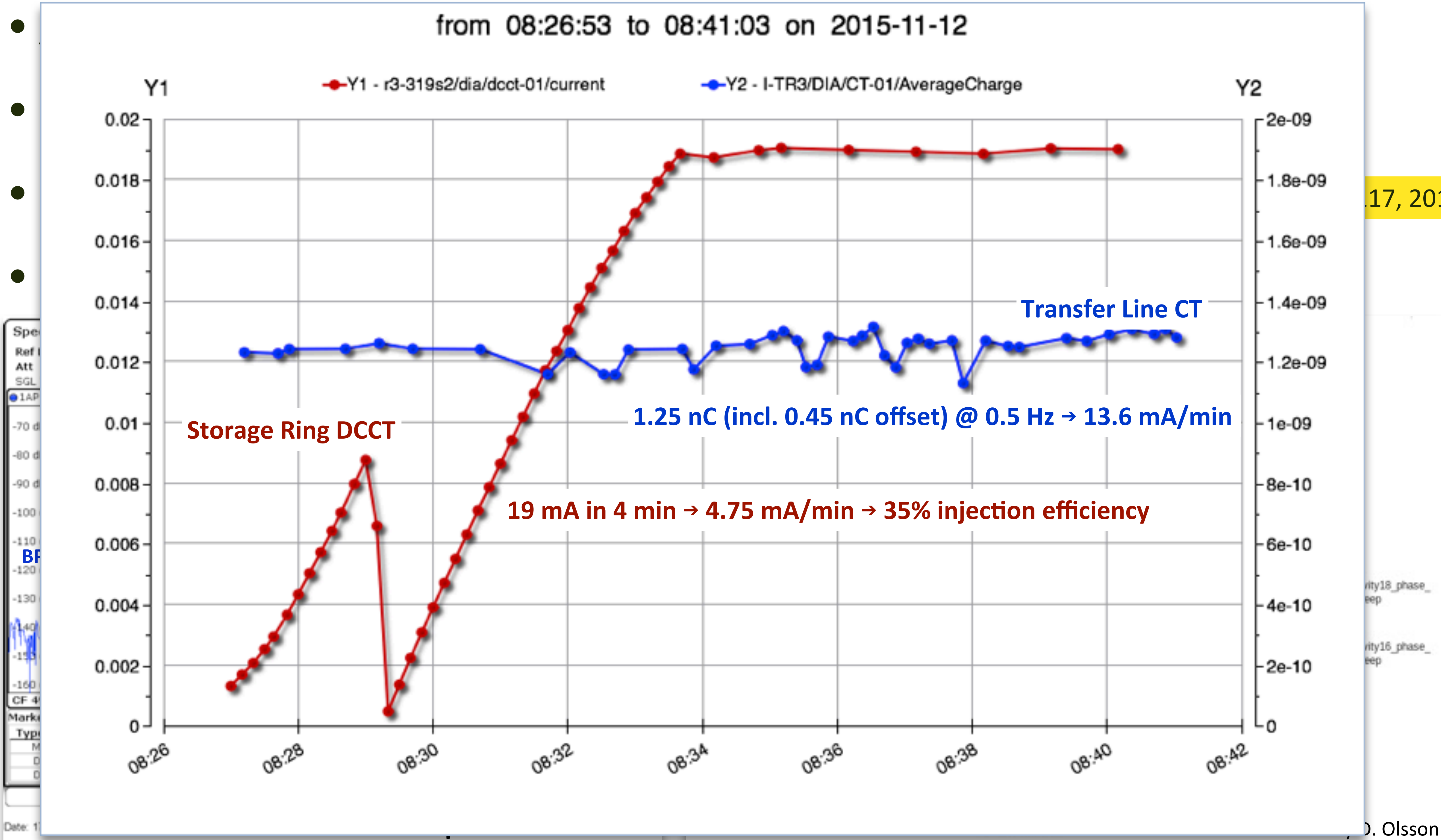
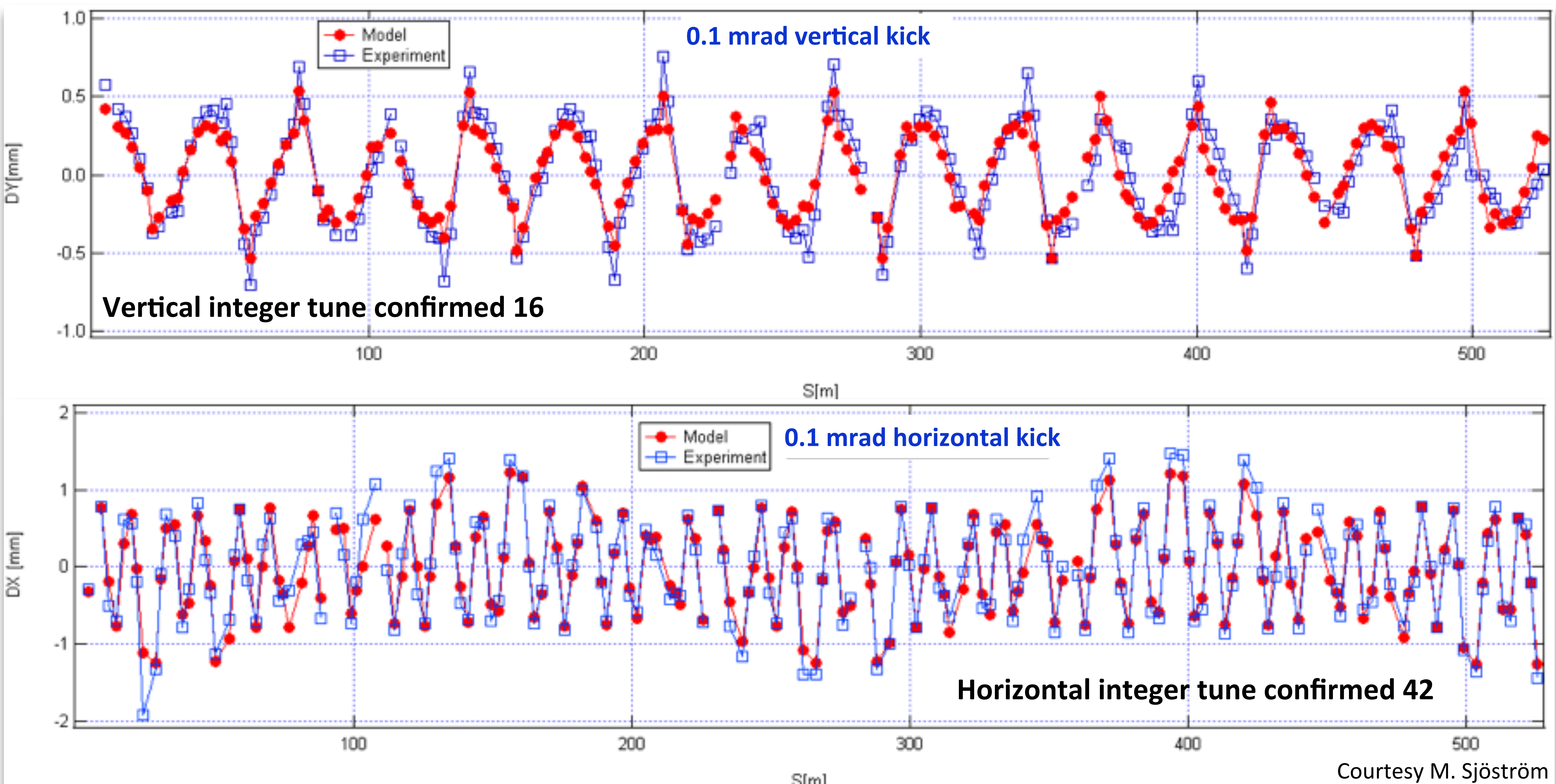


17, 2012

D. Olsson

3 GeV Storage Ring Commissioning (cont.)

- First linear optics studies & corrections



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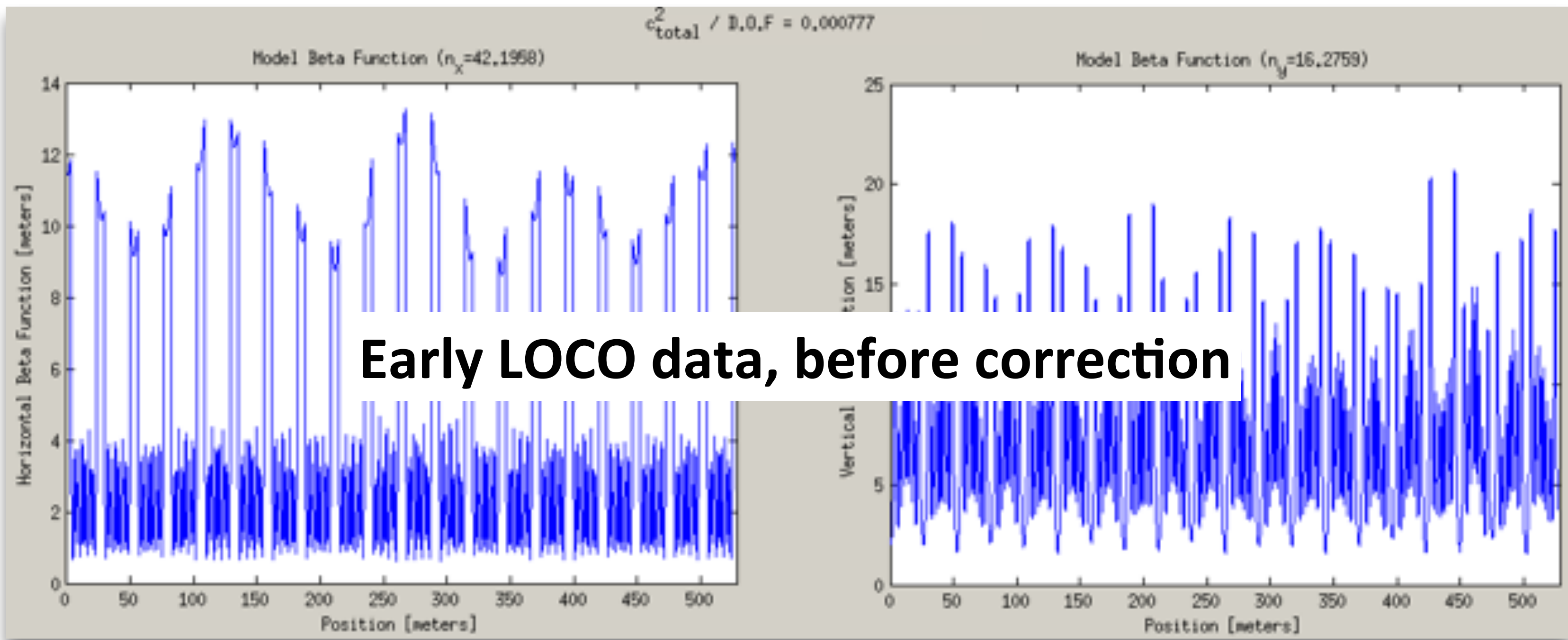

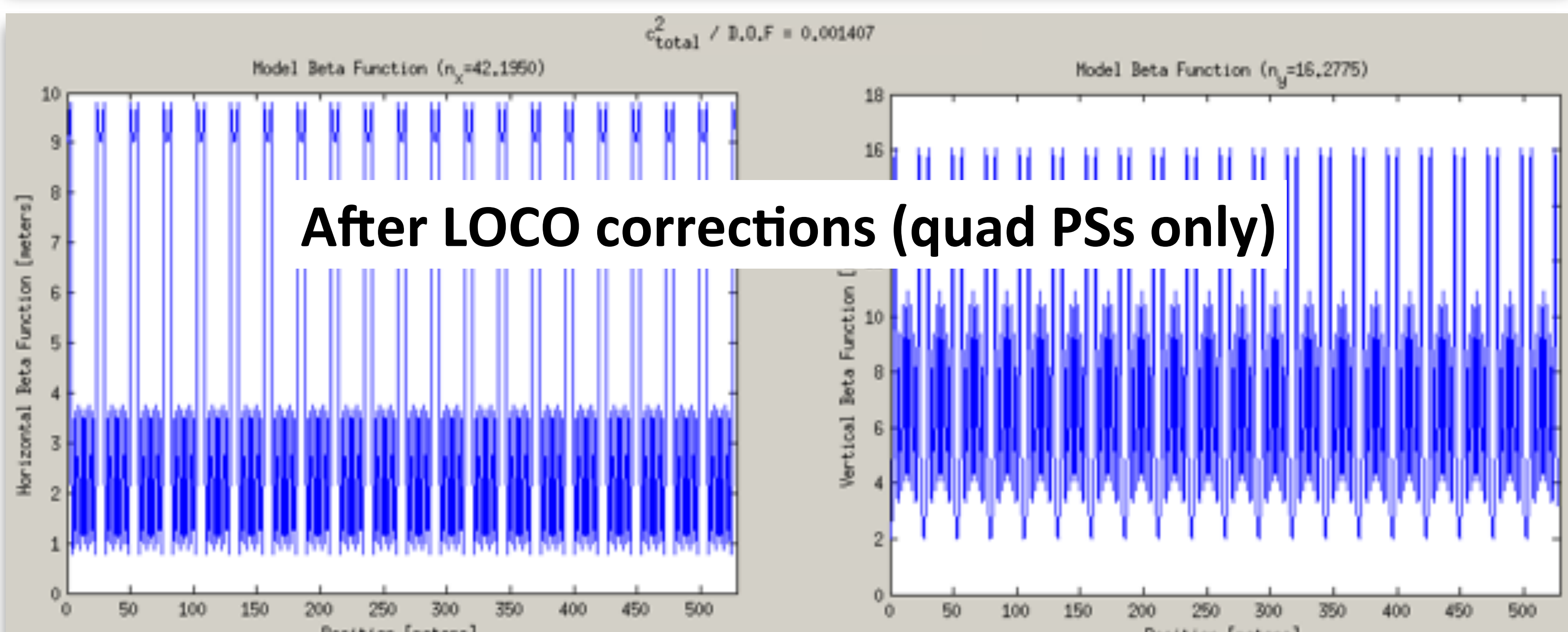

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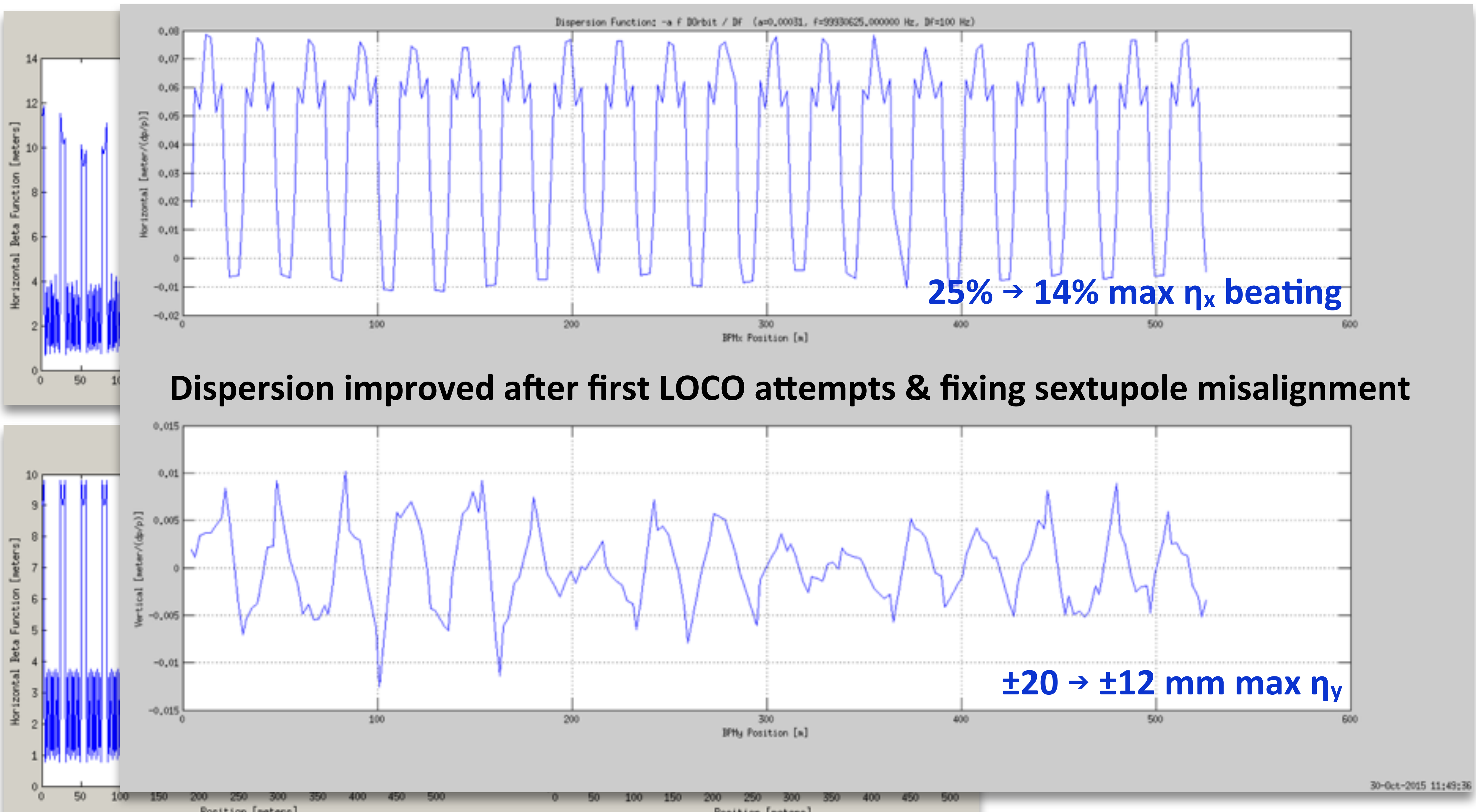

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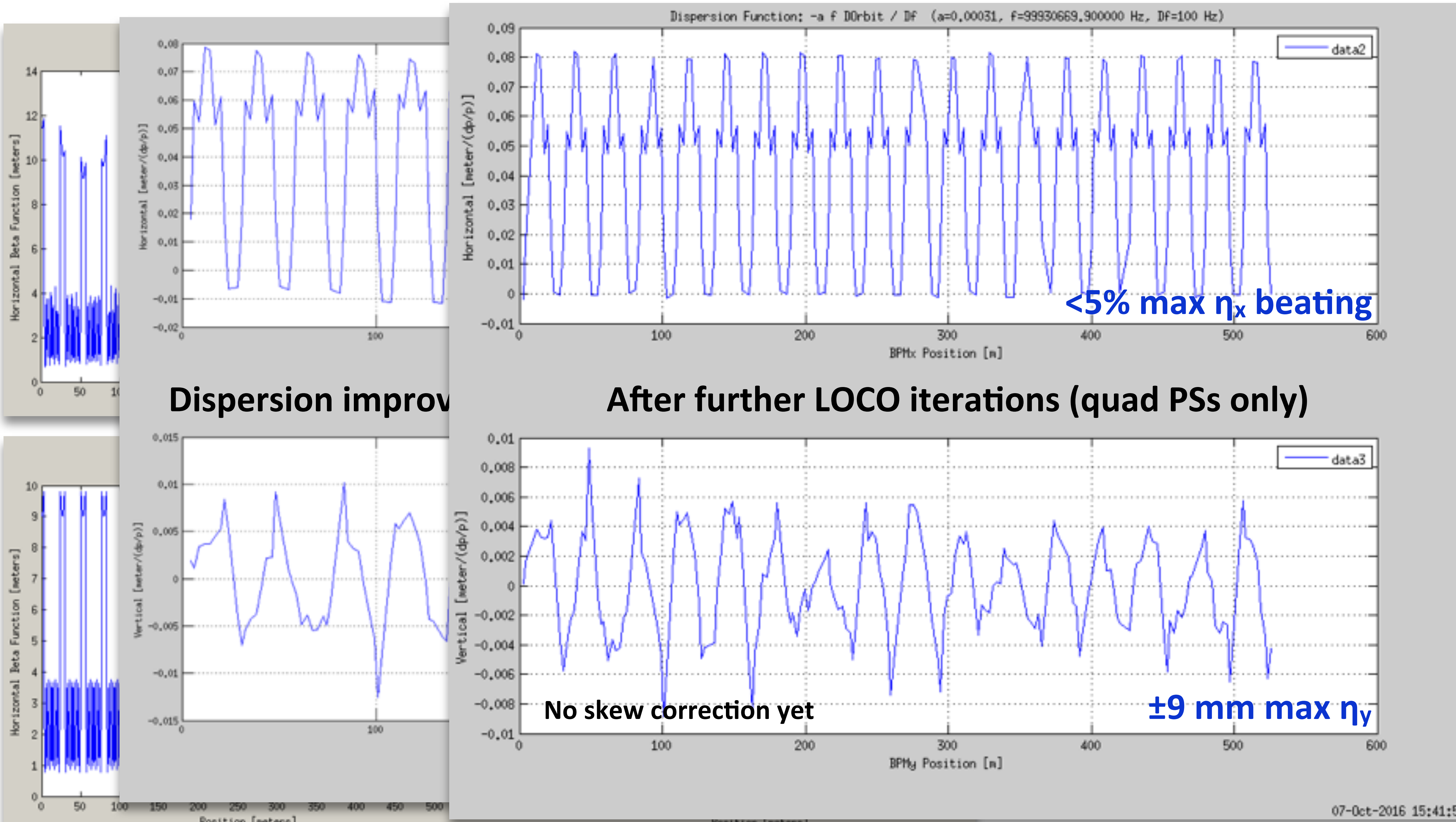
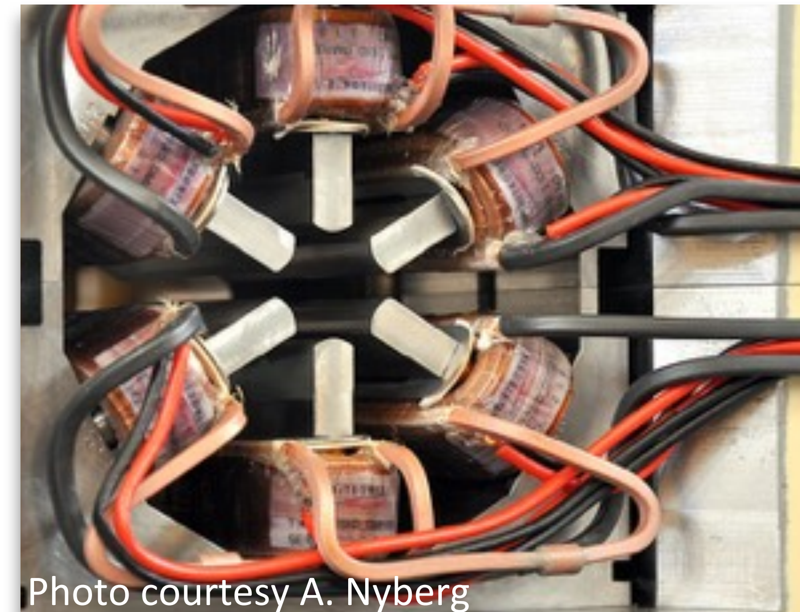
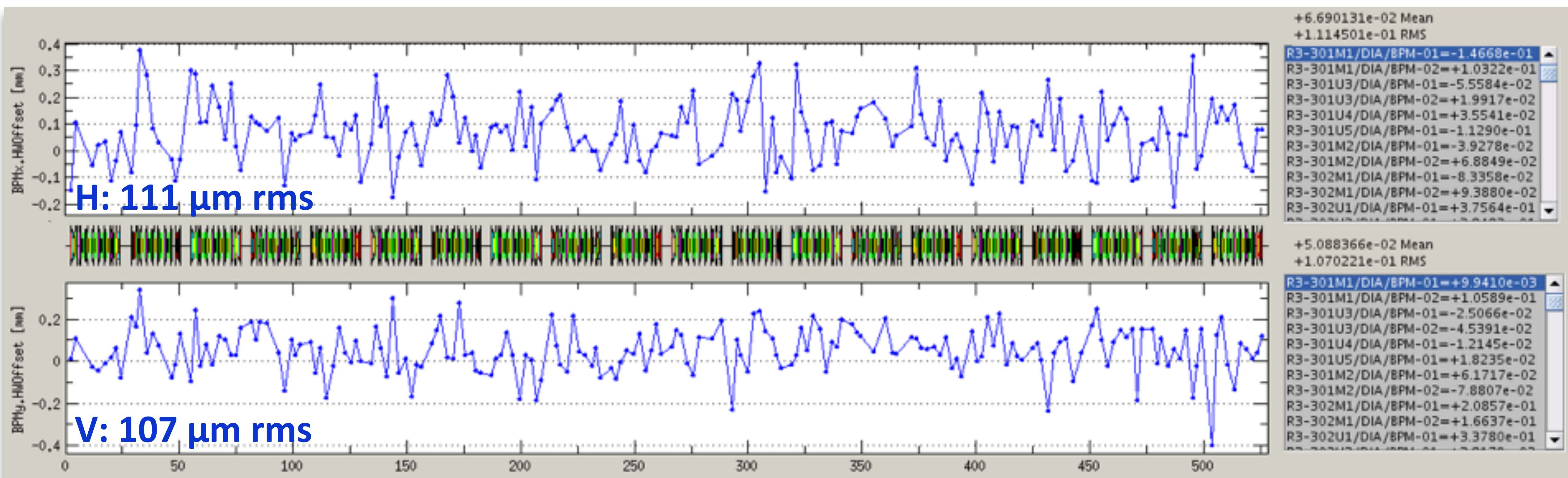


3 GeV Storage Ring Commissioning (cont.)

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

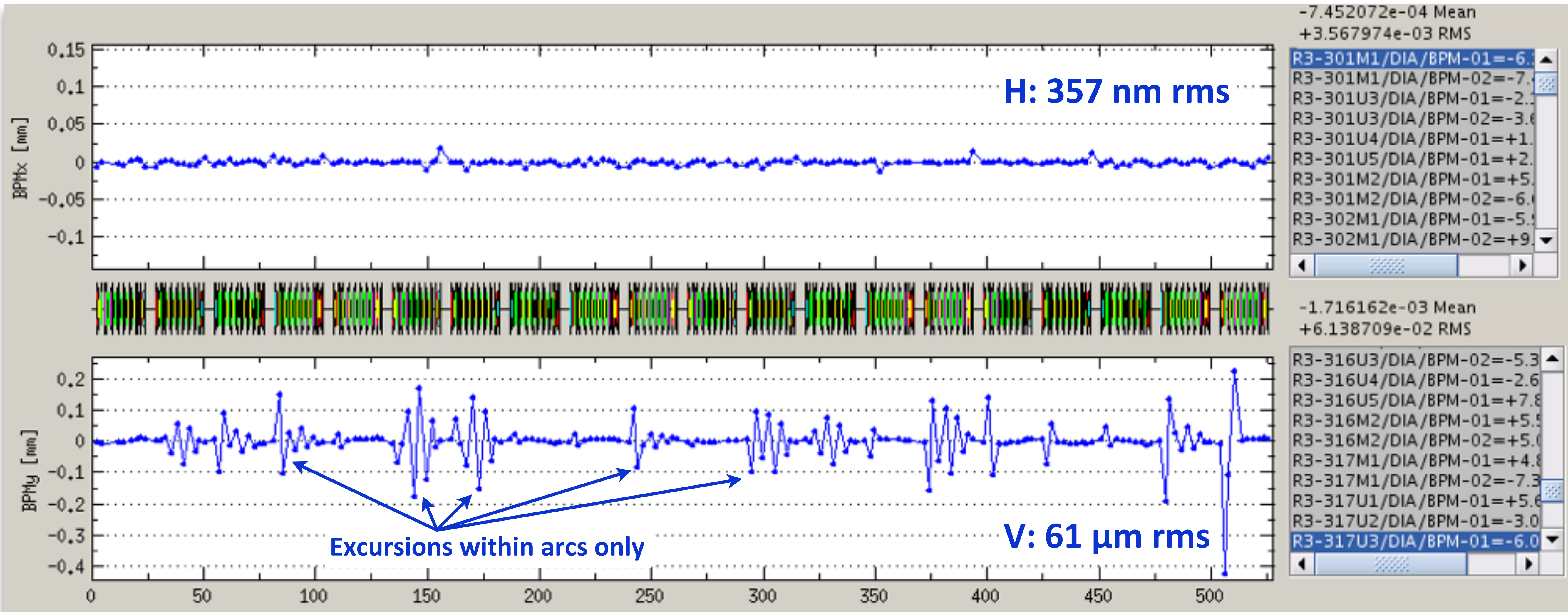




3 GeV Storage Ring Commissioning (cont.)

- First linear optics studies & corrections
- BPM offsets relative to adjacent sextupole/octupole via auxiliary coil powered as upright quadrupole
  - downloaded to our 200 Libera Brilliance+ units
  - above 3 mA orbit must be within ±1 mm in both planes
  - if 5 BPMs show bad orbit (or any BPM in an ID straight) MPS dumps beam

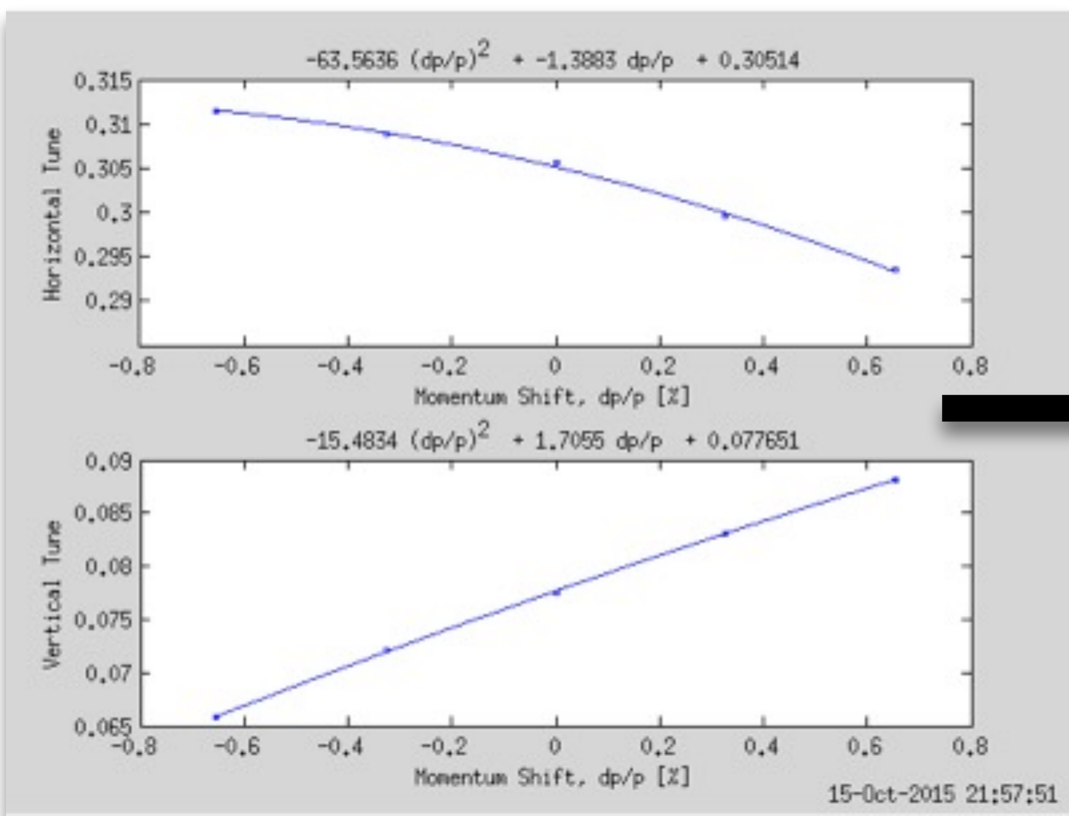
3 GeV Storage Ring Commissioning (cont.)

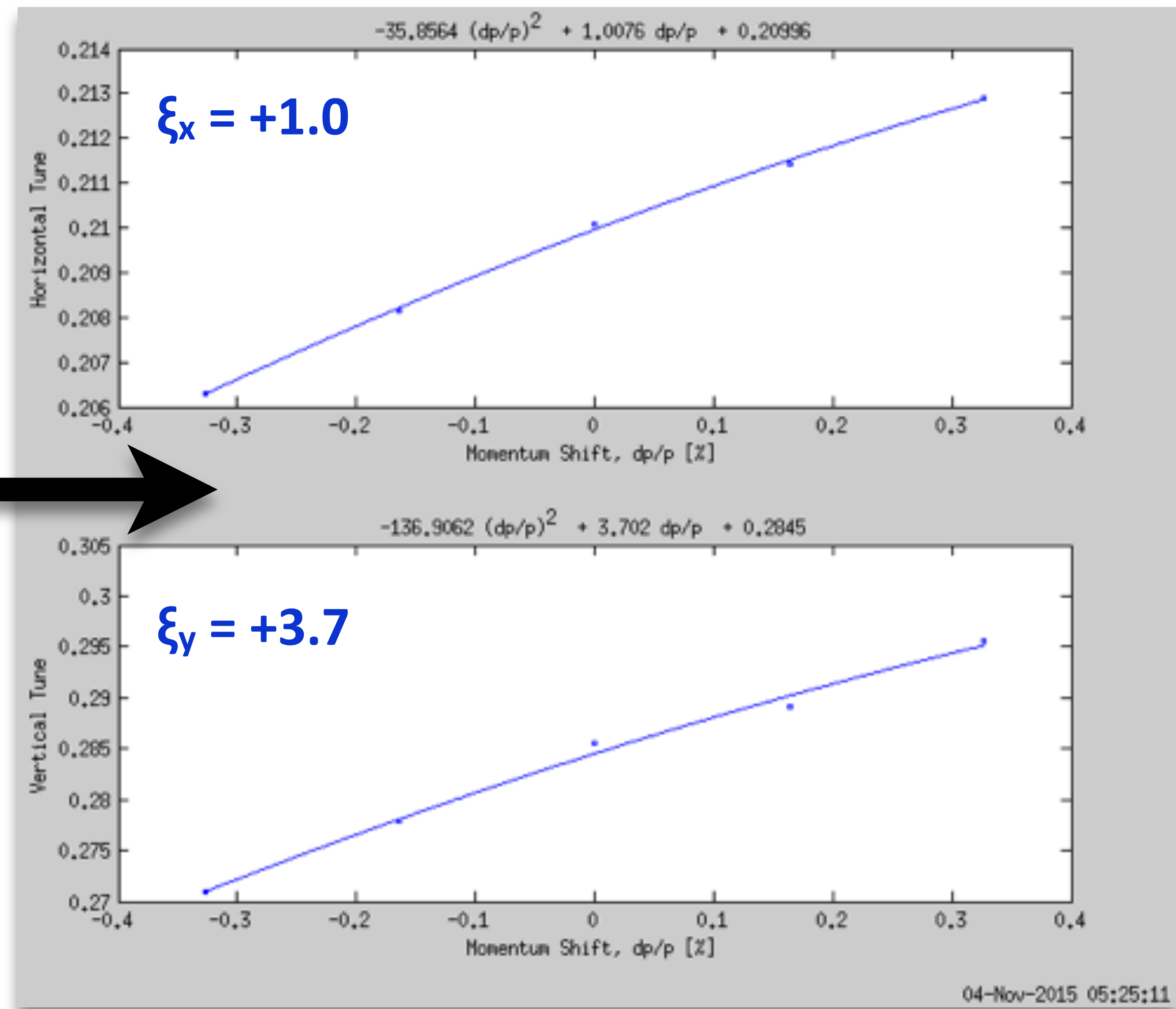


- Orbit correction to <1 µm rms in H; larger in V (since $N_{BPM} > N_{VCM}$)
  → apply weighting so orbit always locked down in ID straights

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 → $\xi^{(2)}$?





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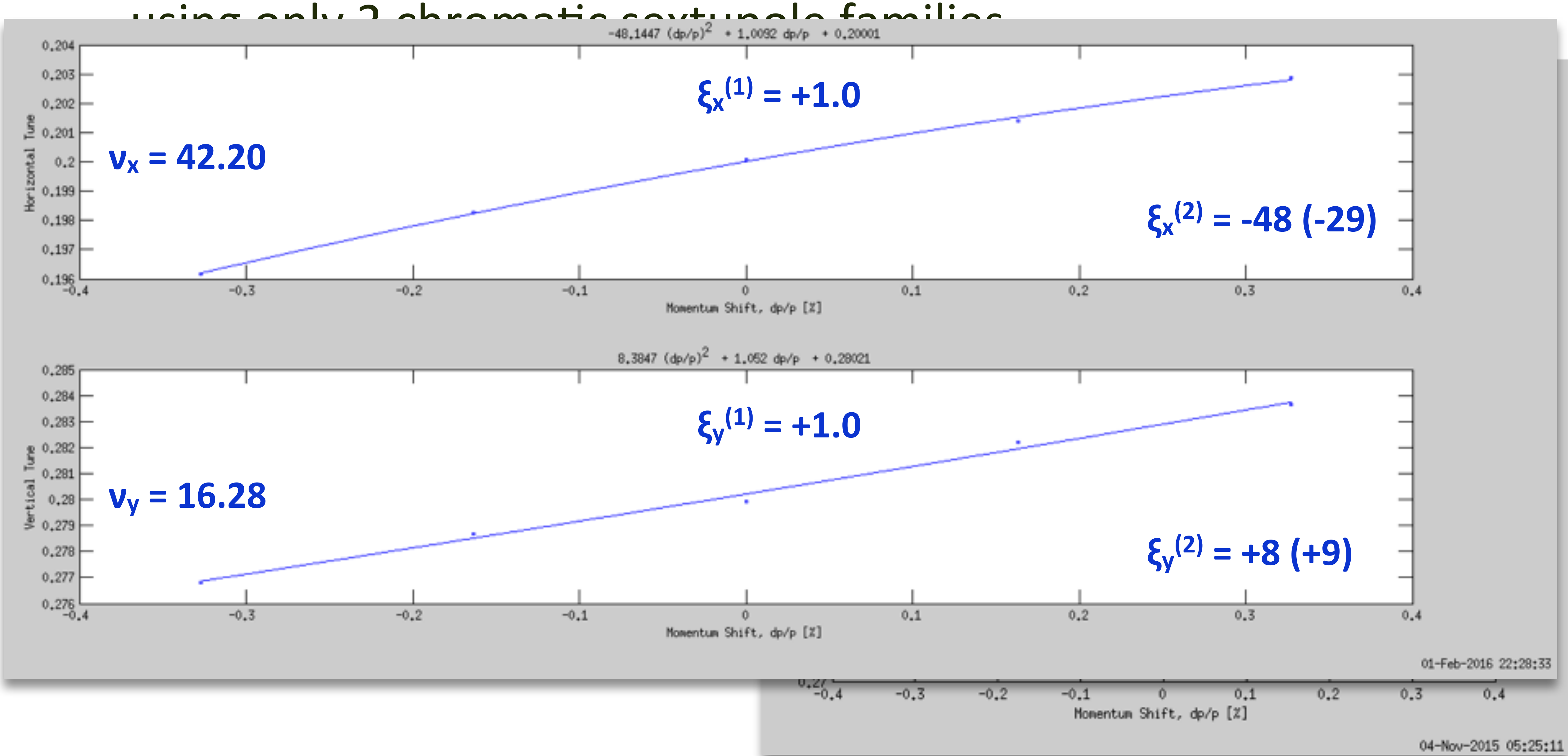
  - using only 2 chromatic sextupole families



3 GeV Storage Ring Commissioning (cont.)

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

IPAC'**16**, WEPOW034

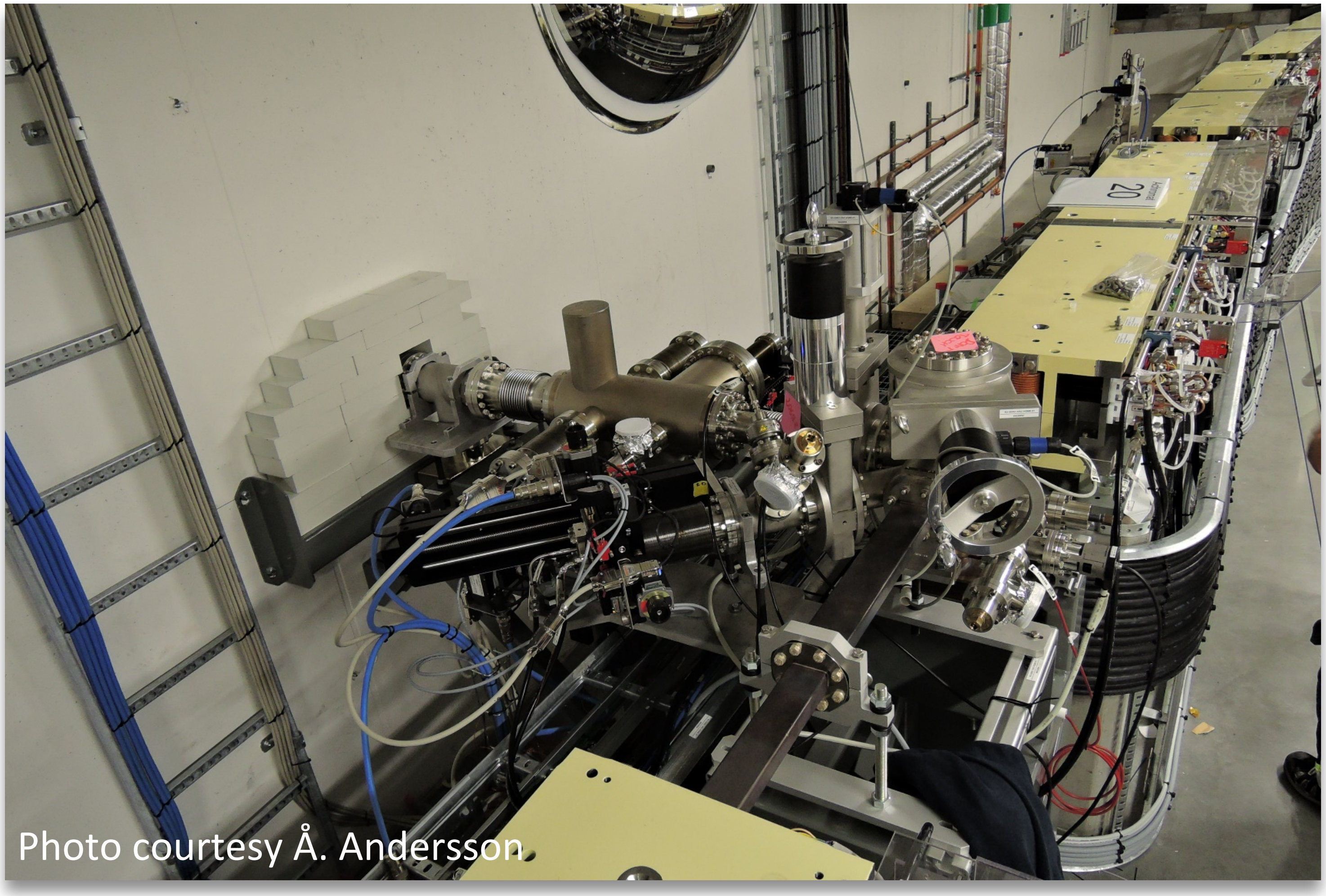
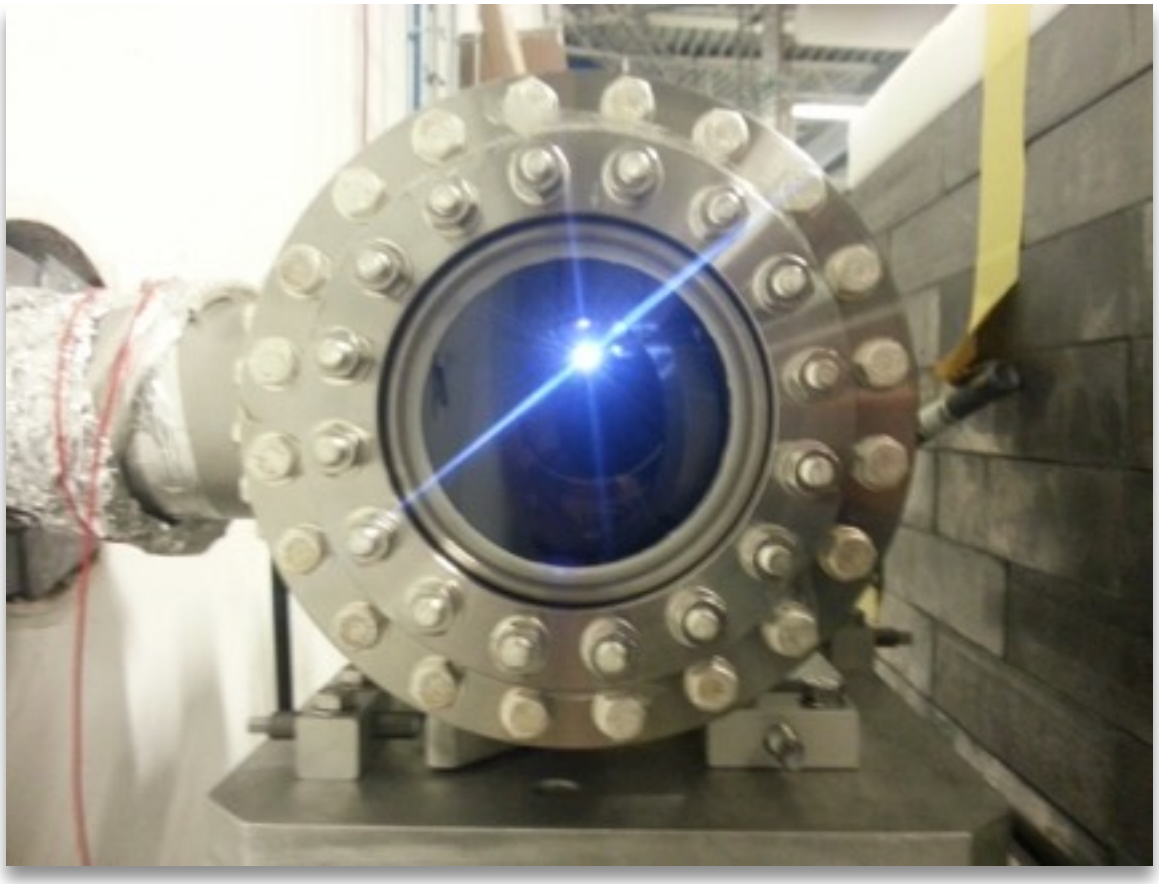


Photo courtesy Å. Andersson



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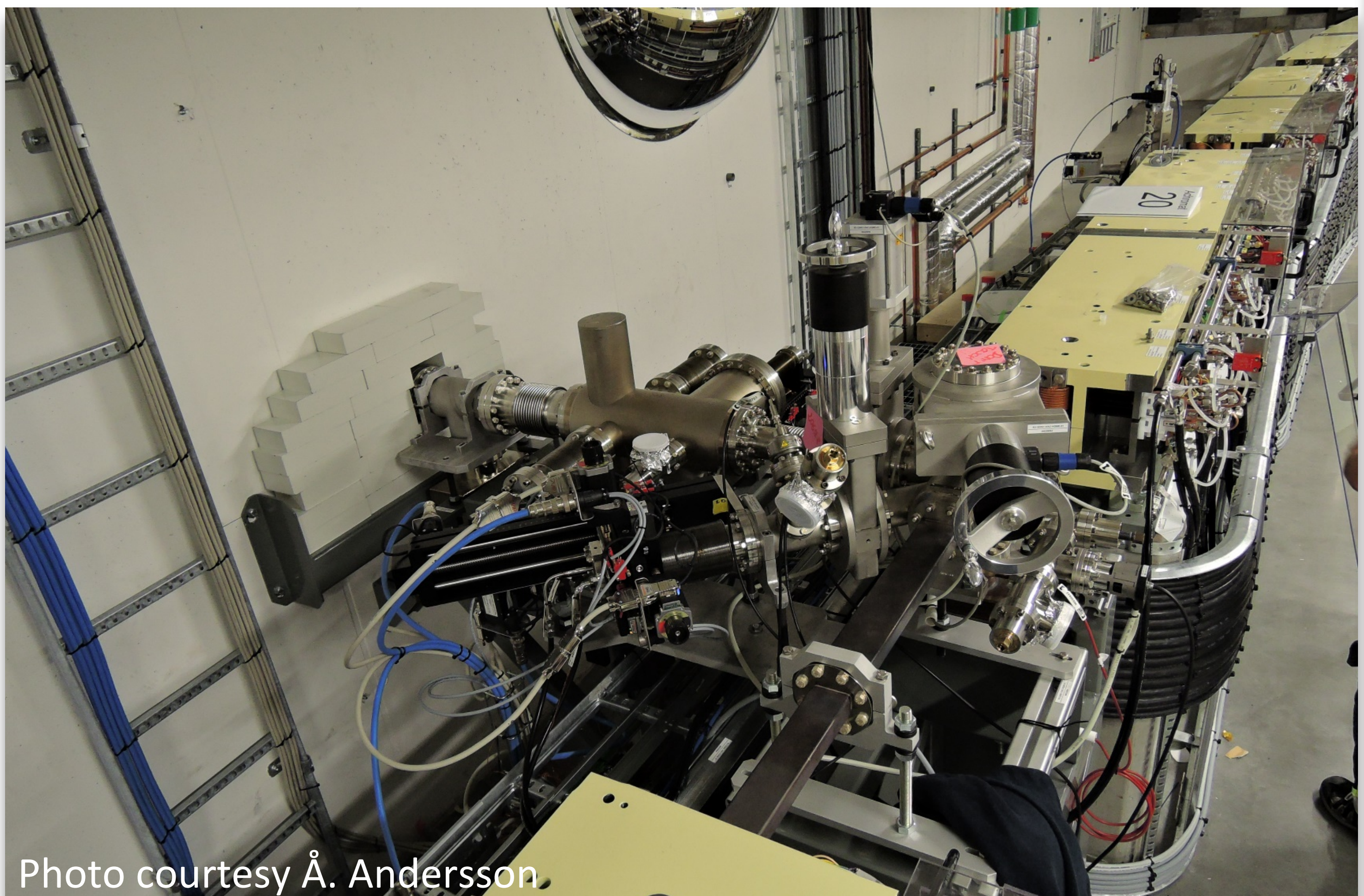
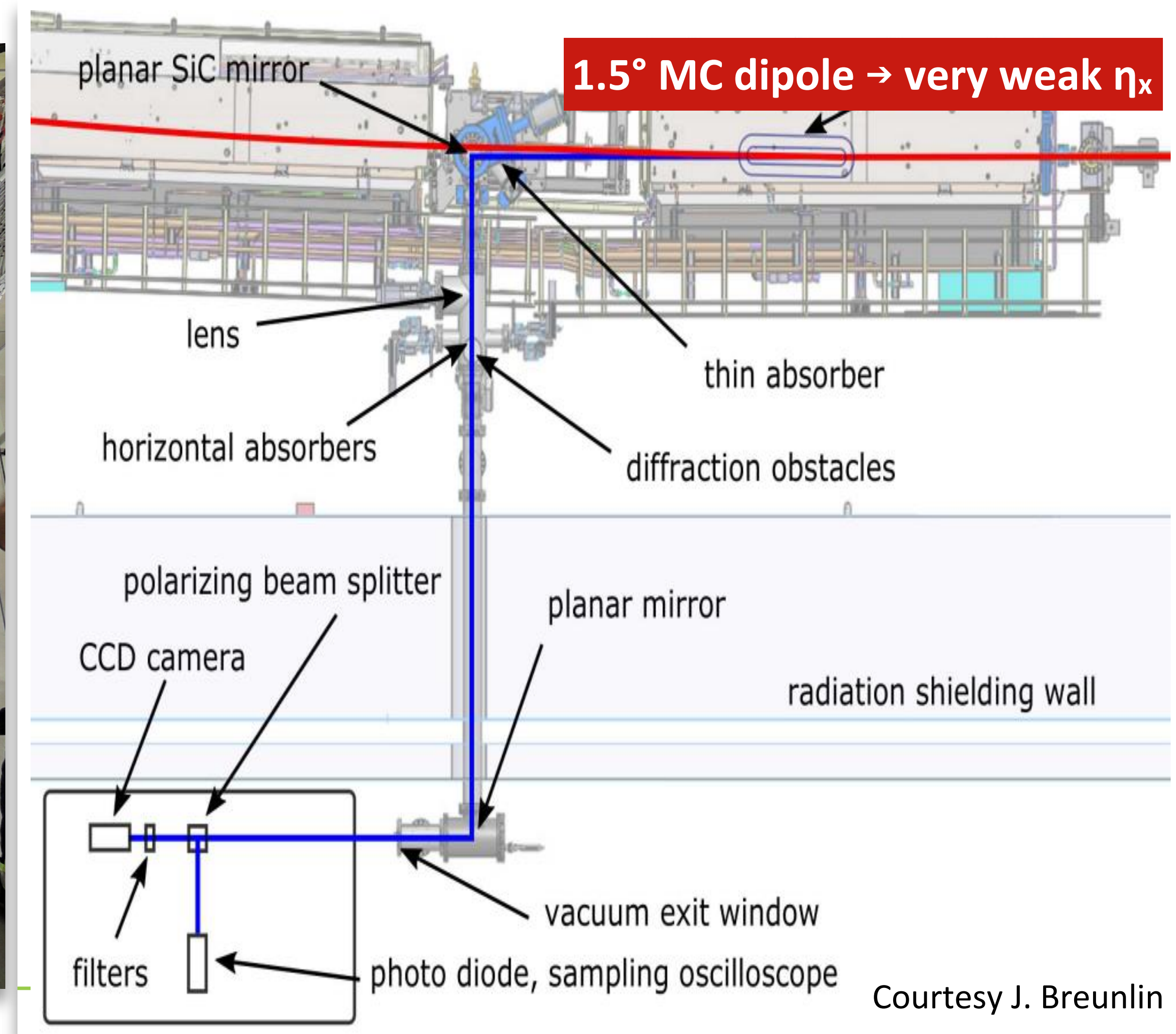


Photo courtesy Å. Andersson



Courtesy J. Breunlin

3 GeV Storage Ring Commissioning (cont.)

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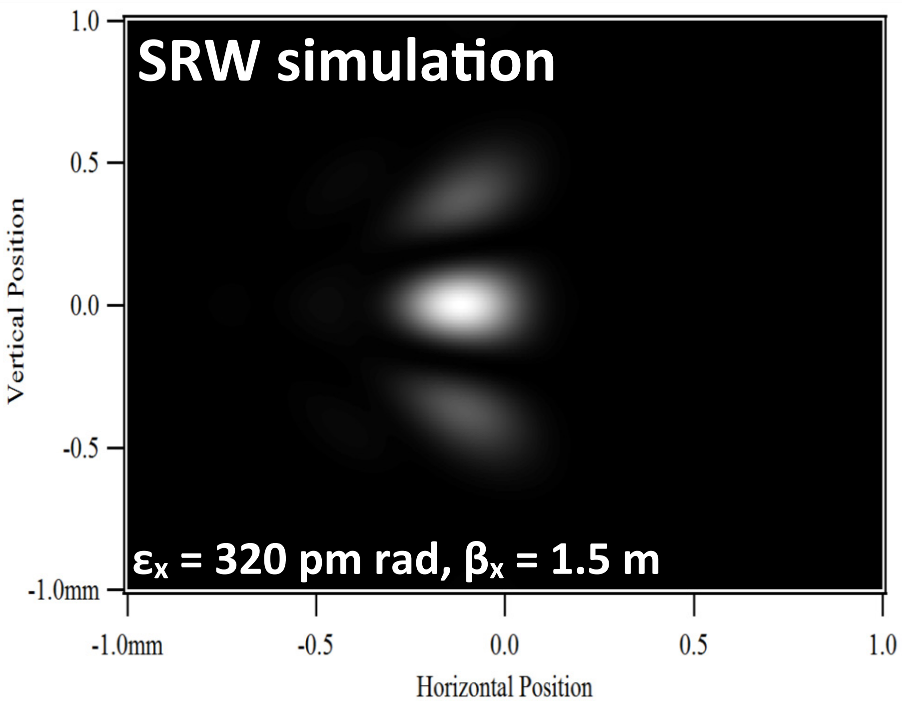
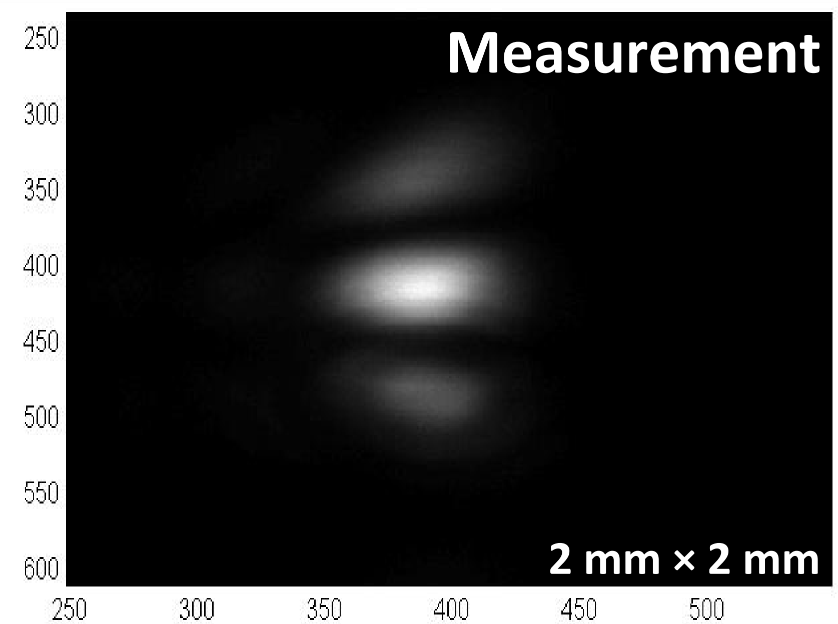
IPAC'**16**, WEPOW034





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.

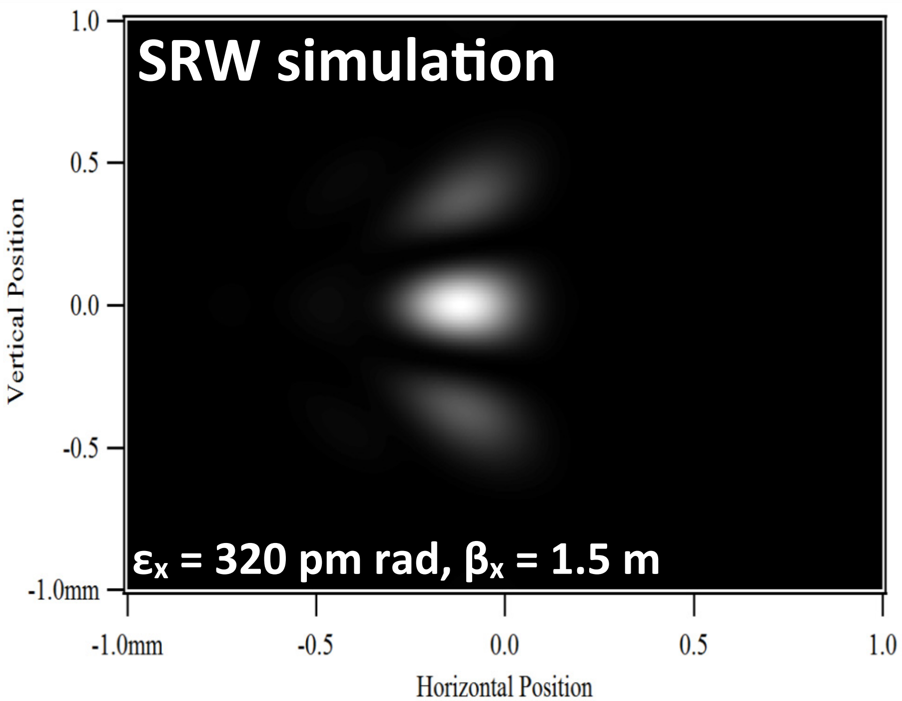
Optical magnification of m=-2.28 is taken into account in the SRW model
Horizontal opening angle: 6 mrad
Vertical opening angle: 8 mrad
Exposure time: 2.9 ms

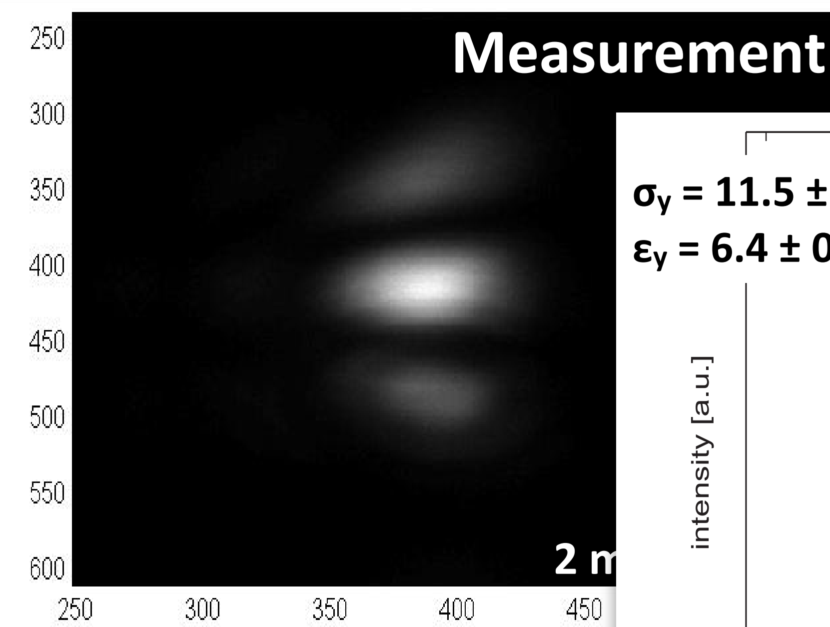
Courtesy J. Breunlin

3 GeV Storage Ring Commissioning (cont.)

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

IPAC'**16**, WEPOW034





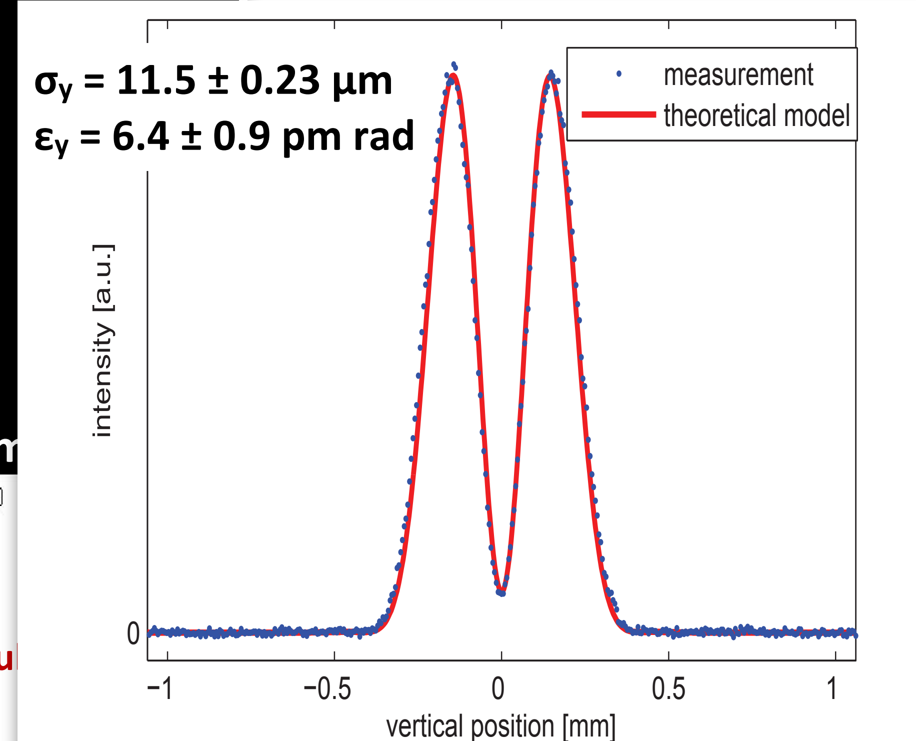


Figure 3: Vertical profile of imaged π-polarized SR at 488 nm wavelength. Measurement (blue dots) and SRW calculation (red lines). The vertical beam size is 11.5 µm.

Sigma polarized SR, 632.8 nm, SRW calculation (left) and measured image (right). The simu
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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

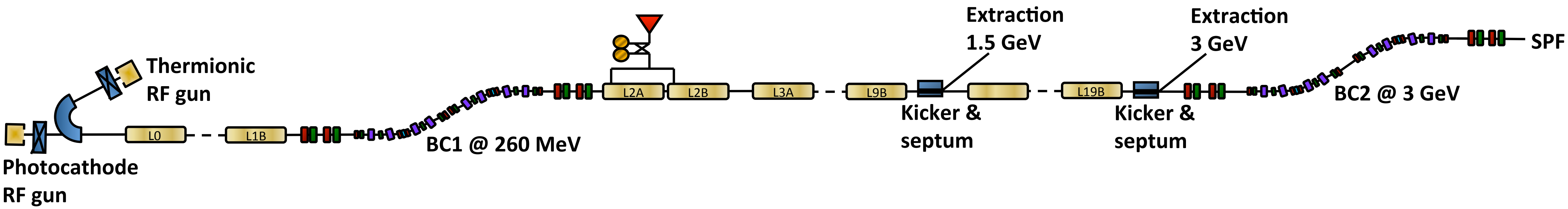
Courtesy J. Breunlin

3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2
  - installing 2nd diagnostic BL in 2017 (on 3° dipole) → σ_δ

3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2
  - installing 2nd diagnostic BL in 2017 (on 3° dipole) ➔ σ_δ
- Top-up running since Nov (closed shutters)
  - injector & linac switch between SPF operation and ring injection
    - 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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- Top-up running since
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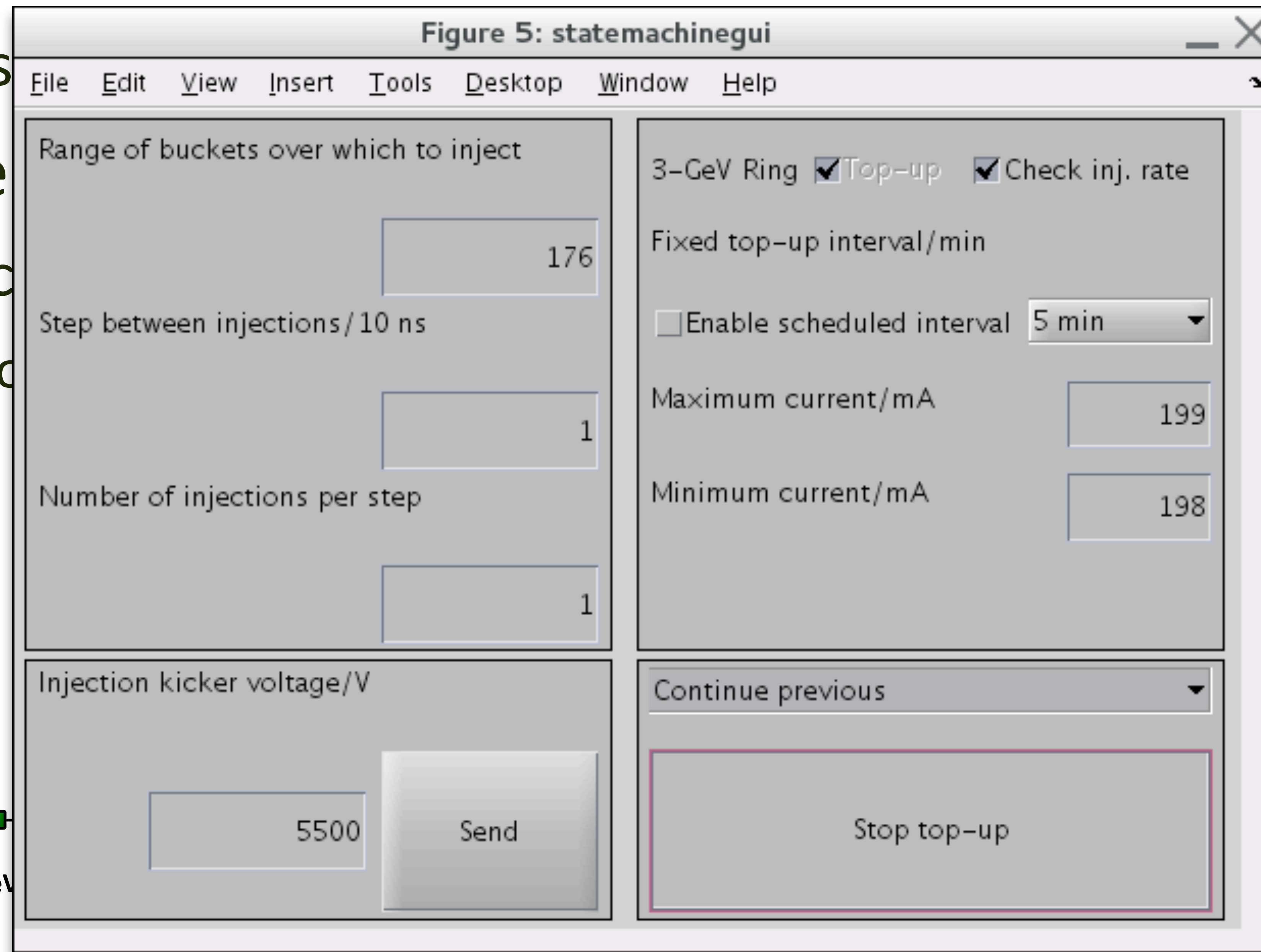
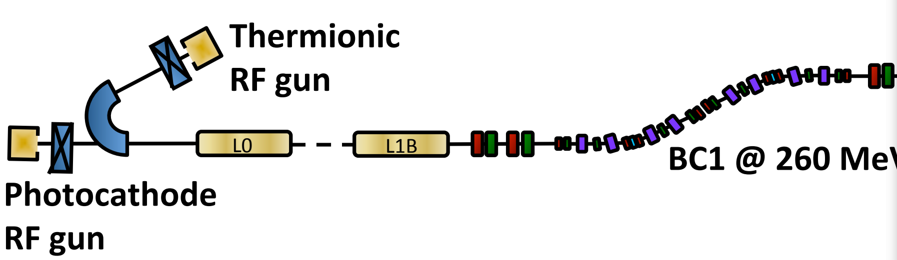
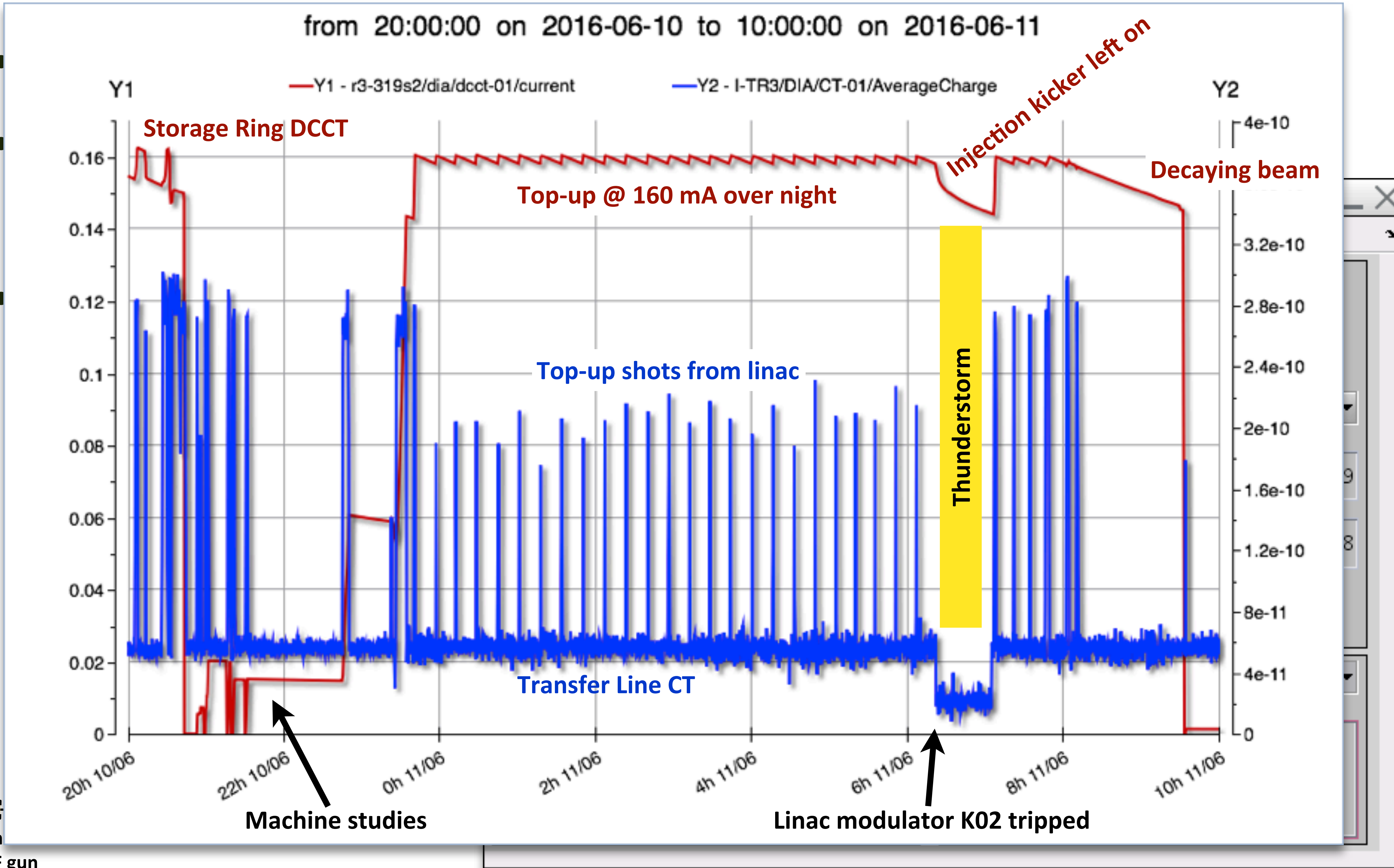
    - on-the-fly switching c





3 GeV Storage Ring Commissioning (cont.)



Ph
RF gun

3 GeV Storage Ring Commissioning (cont.)

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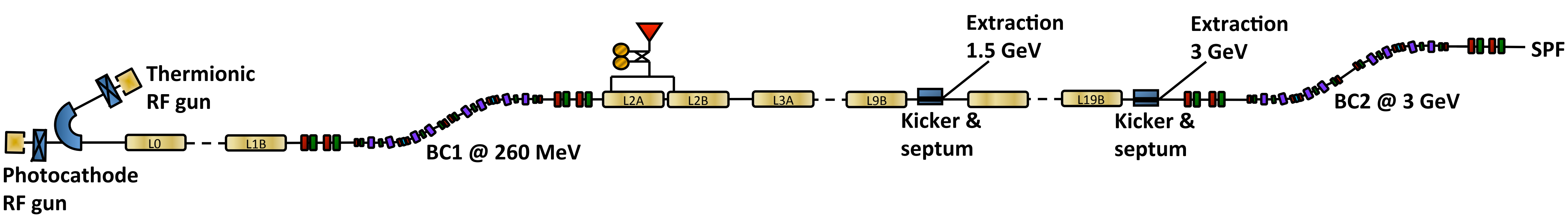
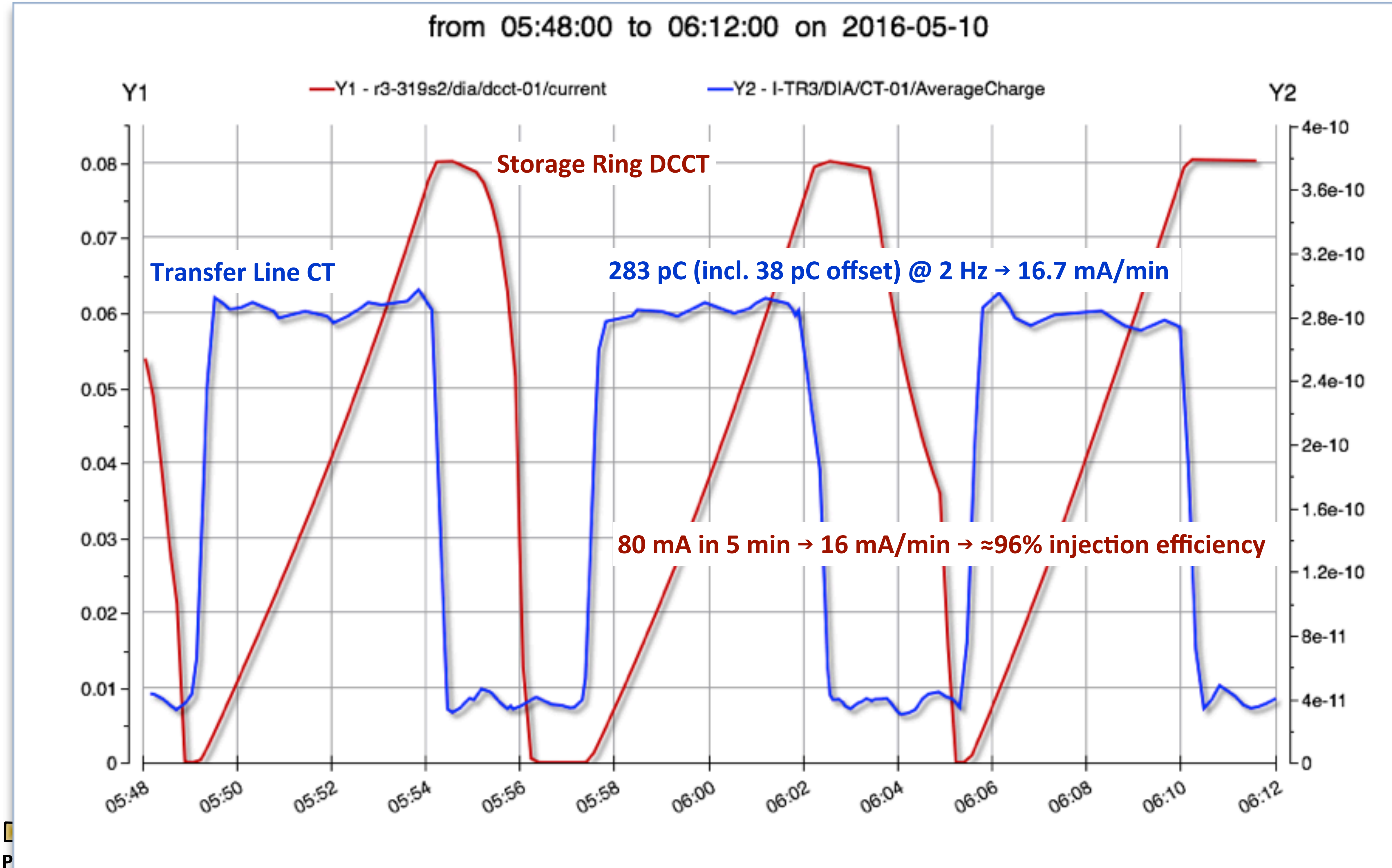
    - on-the-fly switching of guns, linac optics, and linac extraction dipoles
  - injector & linac routinely running at 2 Hz since Nov
  - injection efficiency improved (ring phase acceptance!)



3 GeV Storage Ring Commissioning (cont.)



PF

P
RF gun

3 GeV Storage Ring Commissioning (cont.)

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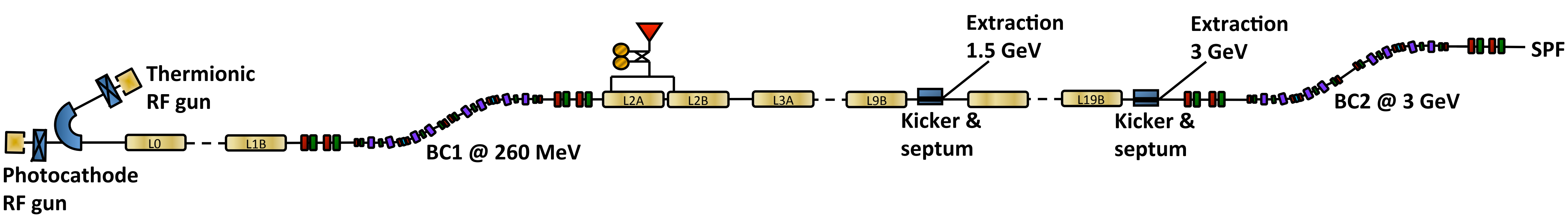
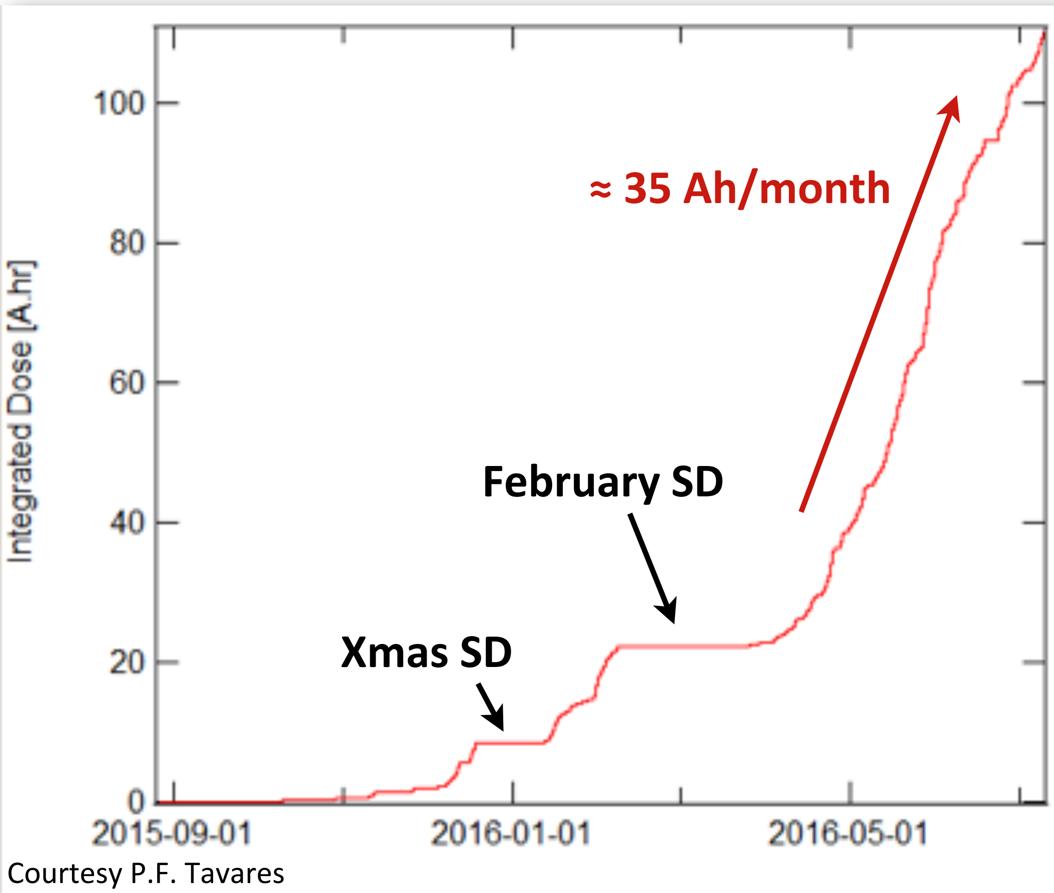
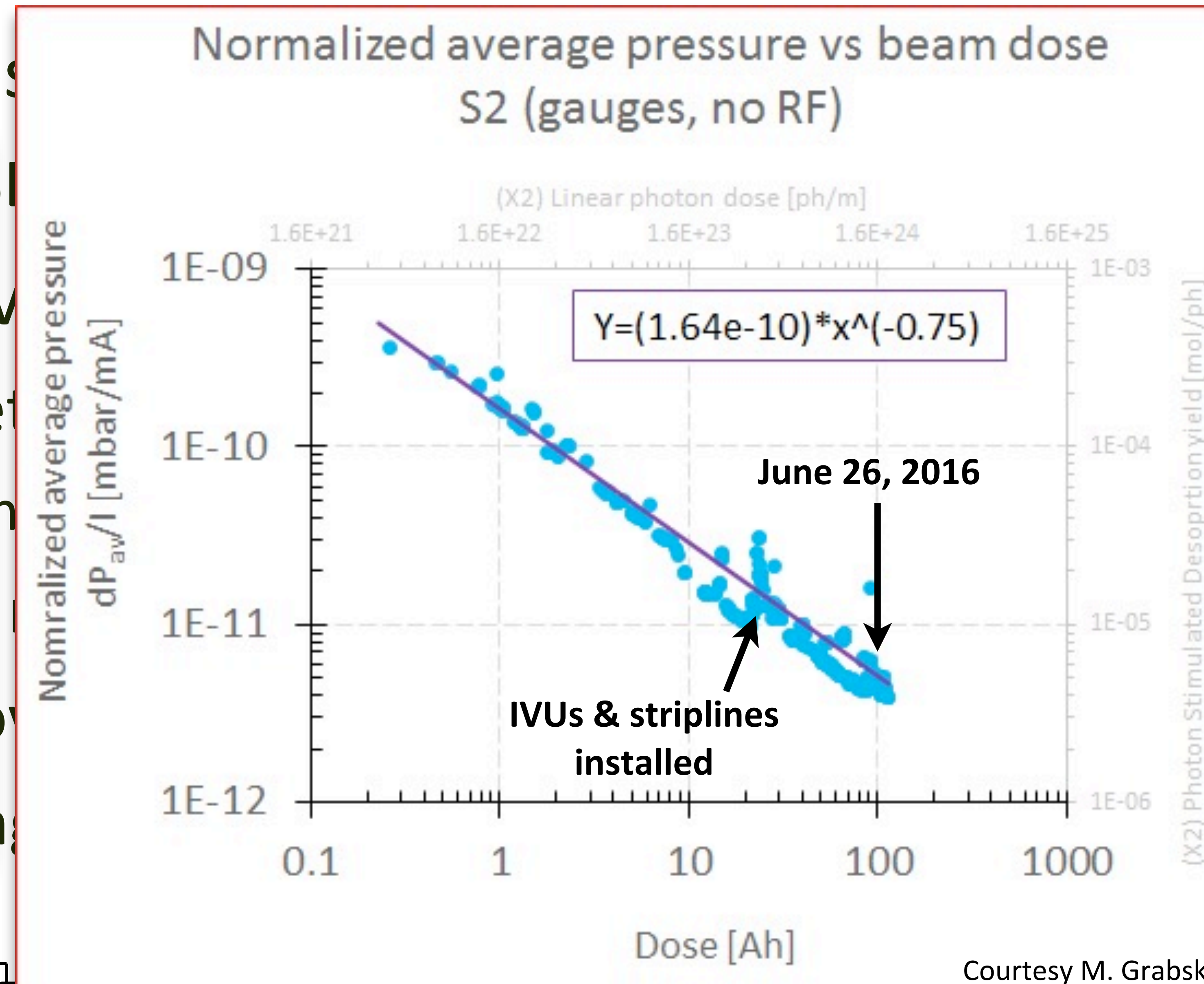
  - integrated dose increasing → improving ring vacuum

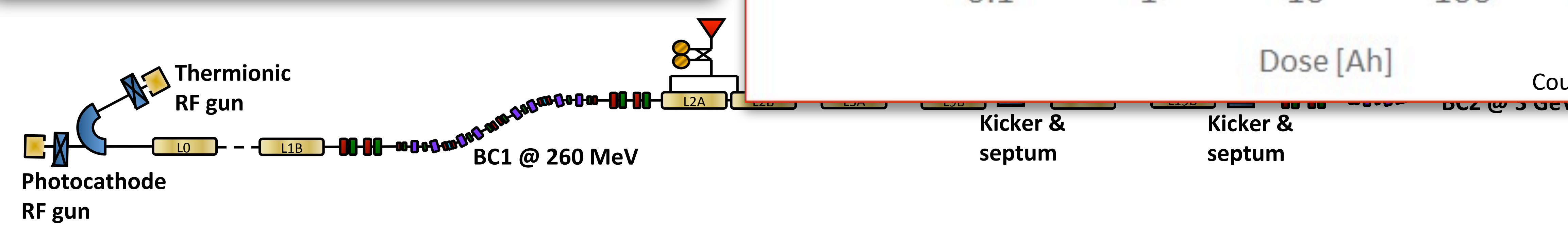


3 GeV Storage Ring Commissioning (cont.)

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

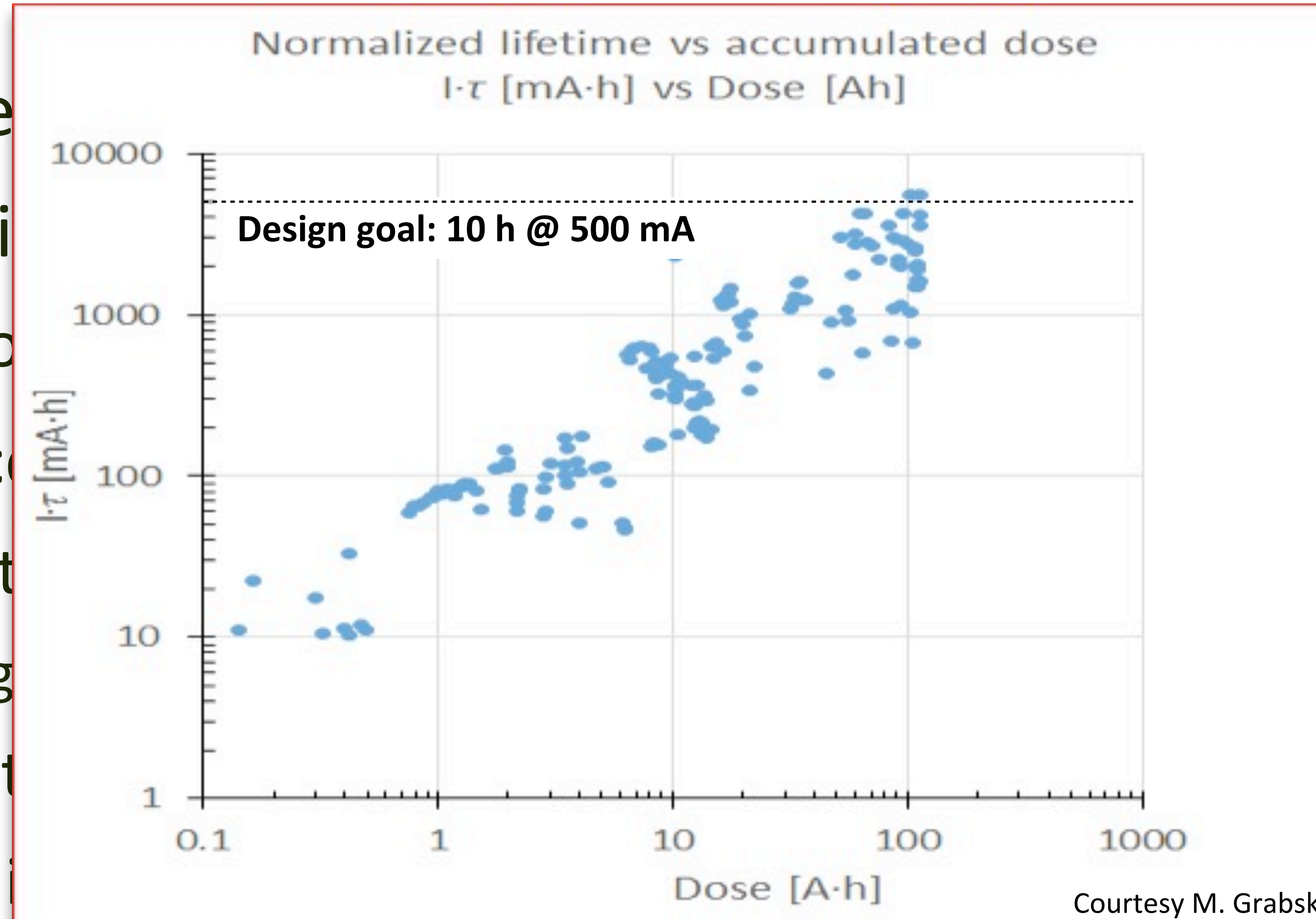




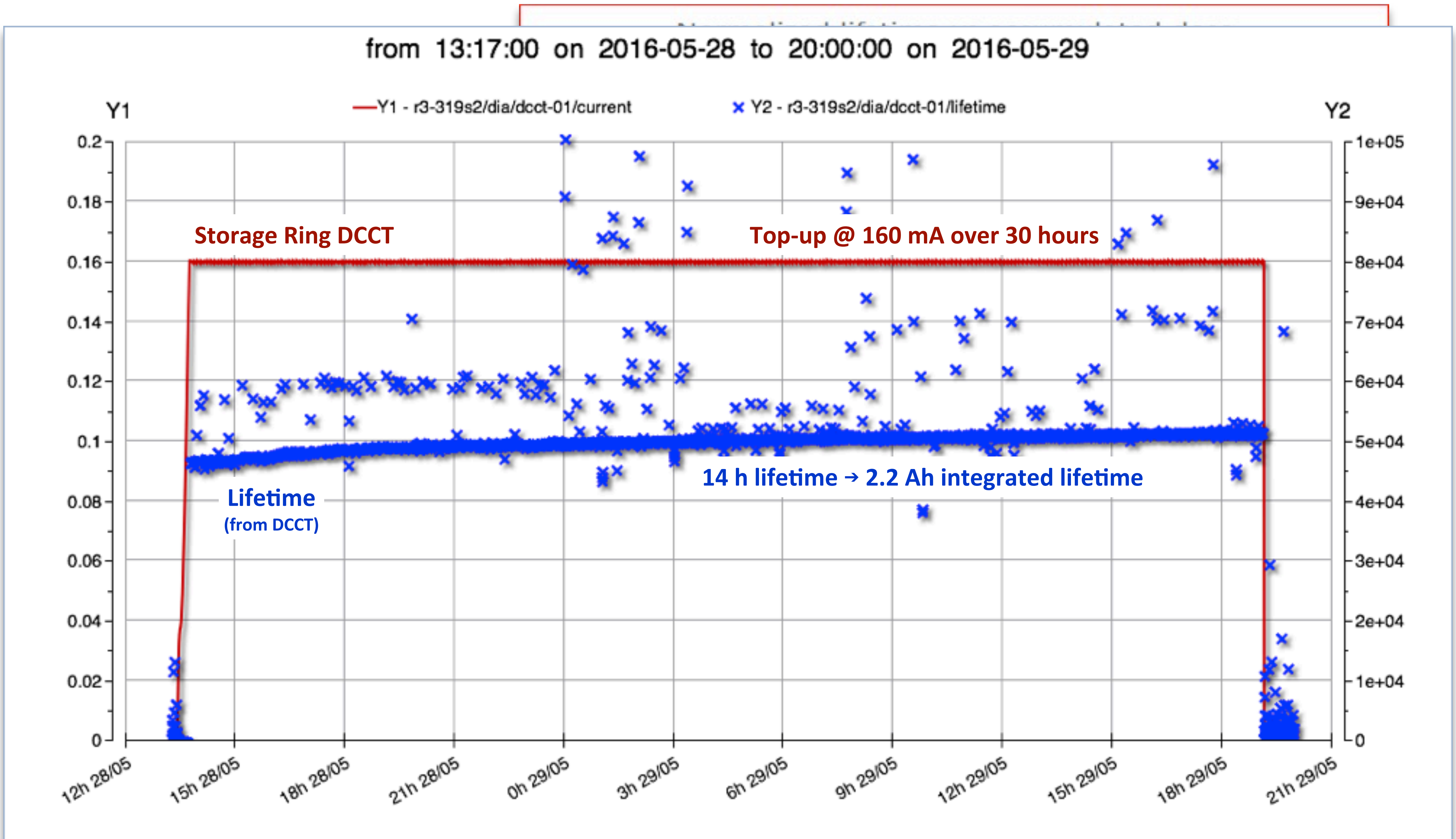


3 GeV Storage Ring Commissioning (cont.)

- First attempts at me
- First light seen on di
  - installing 2nd diagno
- Top-up running sinc
  - injector & linac swit
    - on-the-fly switching
  - injector & linac rout
  - injection efficiency i
  - integrated dose increasing → improving ring vacuum
  - ➡ improving beam lifetime (along with effect of bunch lengthening from passive harmonic cavities)

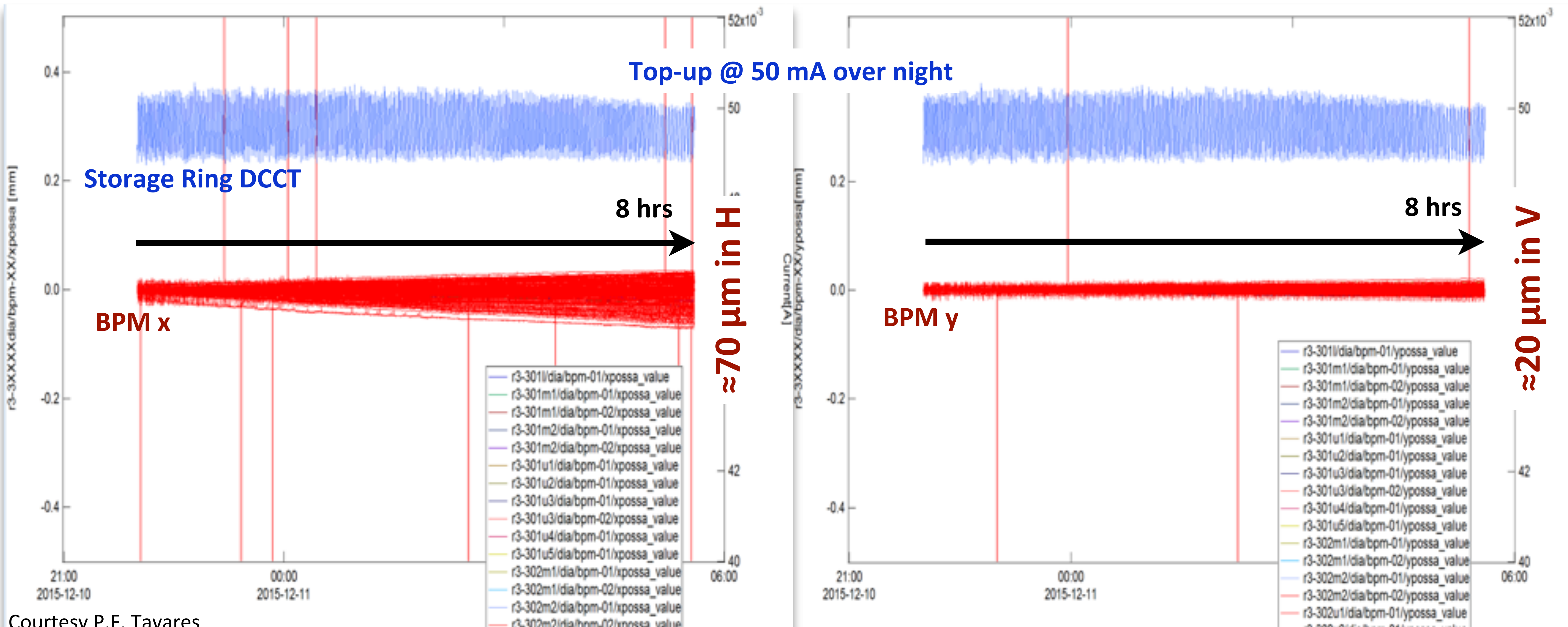


3 GeV Storage Ring Commissioning (cont.)



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)

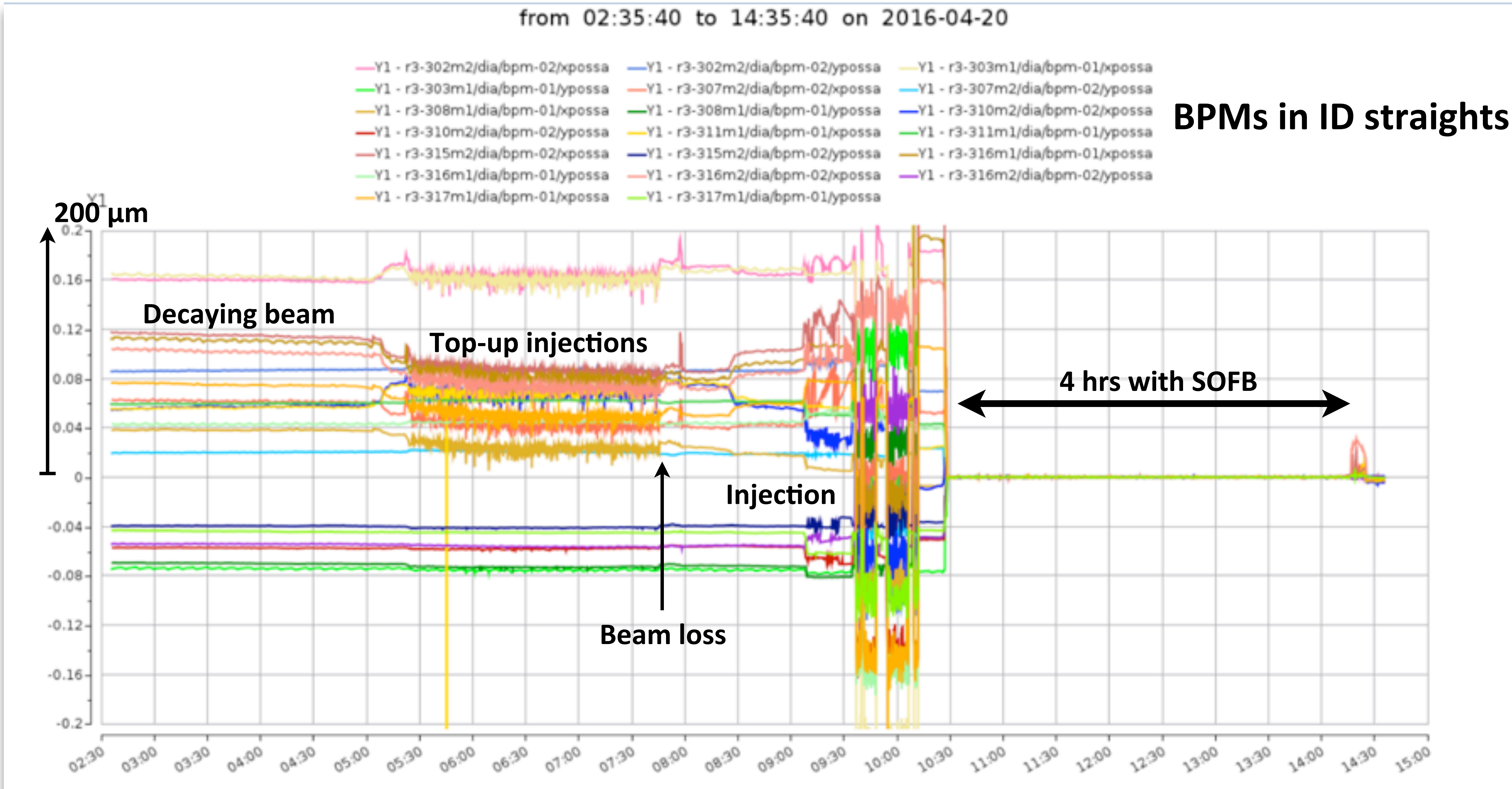


Courtesy P.F. Tavares

3 GeV Storage Ring Commissioning (cont.)

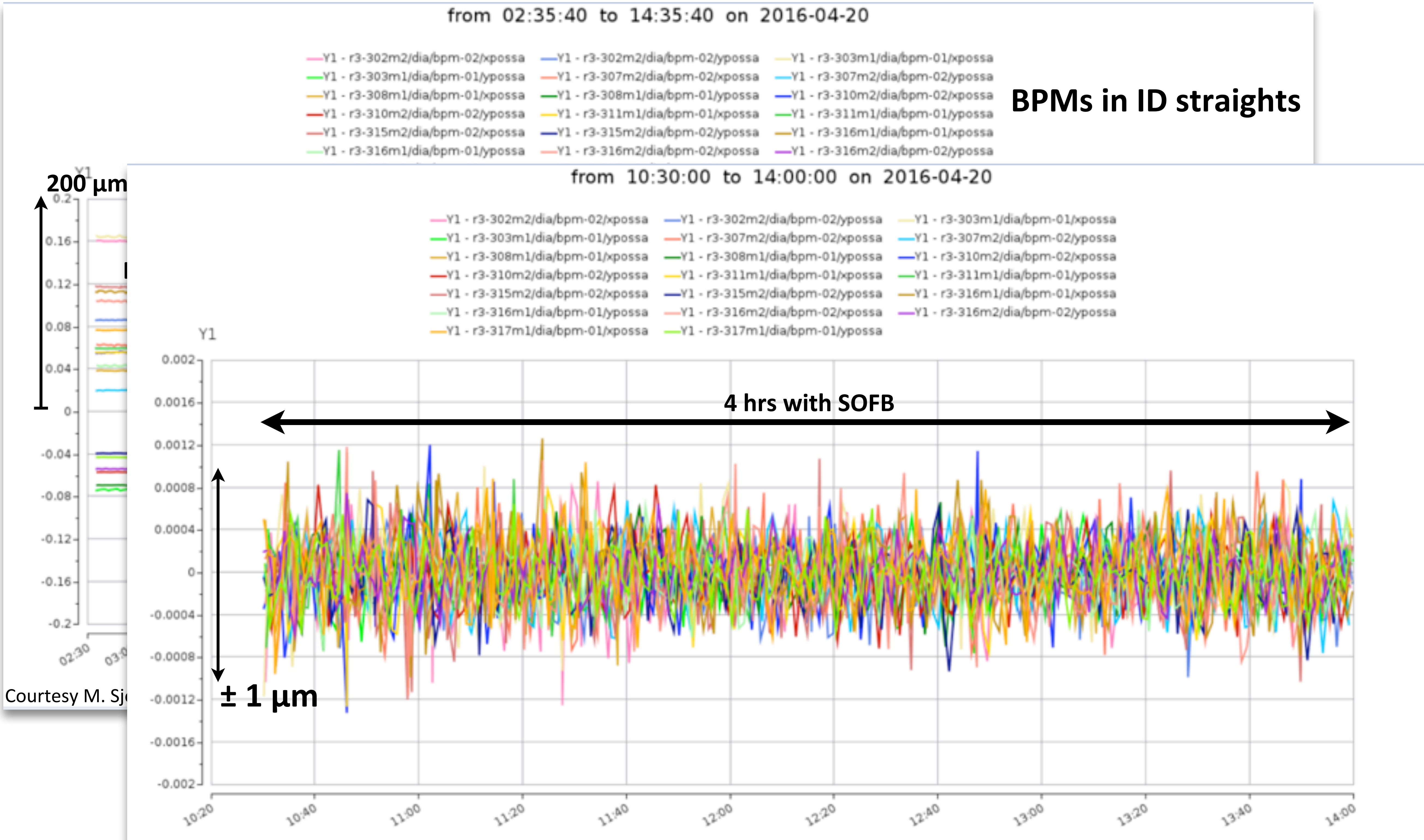
- Orbit drifts observed during top-up operation
  - 70 µm / 20 µm observed over 8 hours
  - unphysical BPM spikes observed → implications for bad orbit trip (MPS)
- SOFB now routinely running at ≈0.5 Hz (target: 10 Hz)
  - sub-micron stability in H, but larger in V ($N_{BPM} > N_{VCM}$)
  - weighting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

3 GeV Storage Ring Commissioning (cont.)



Courtesy M. Sjöström

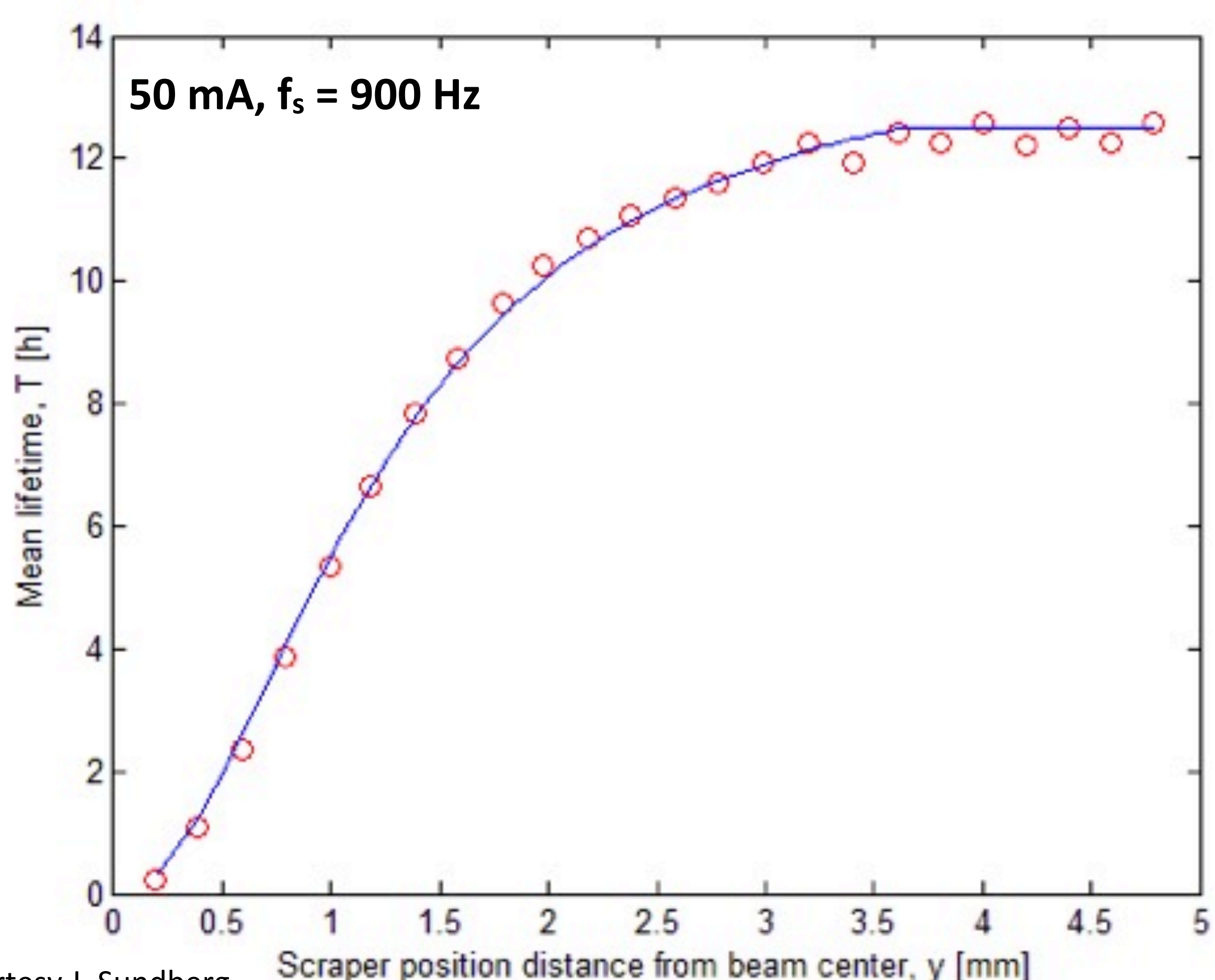
3 GeV Storage Ring Commissioning (cont.)



Courtesy M. Sjöström

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



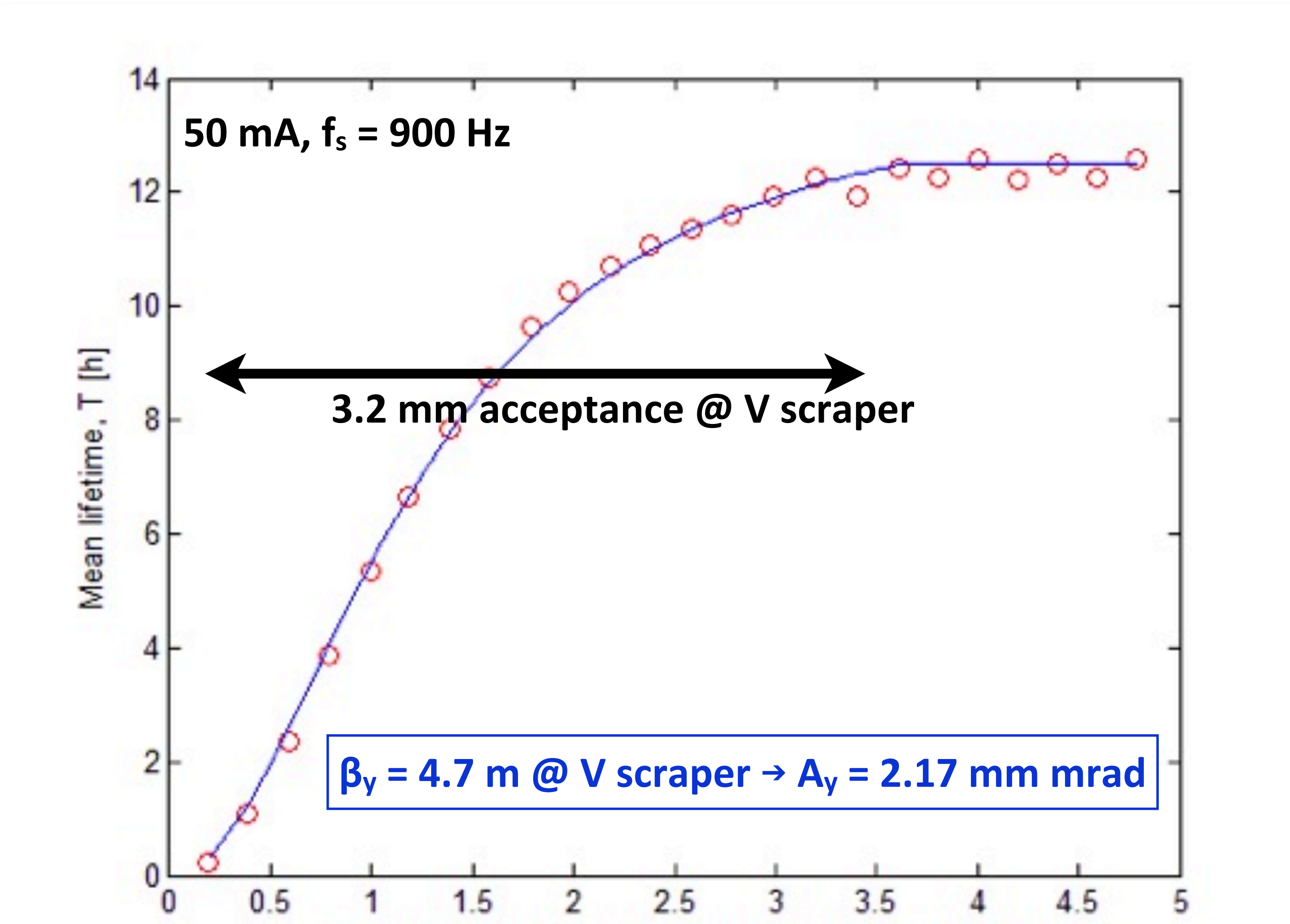
Courtesy J. Sundberg

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

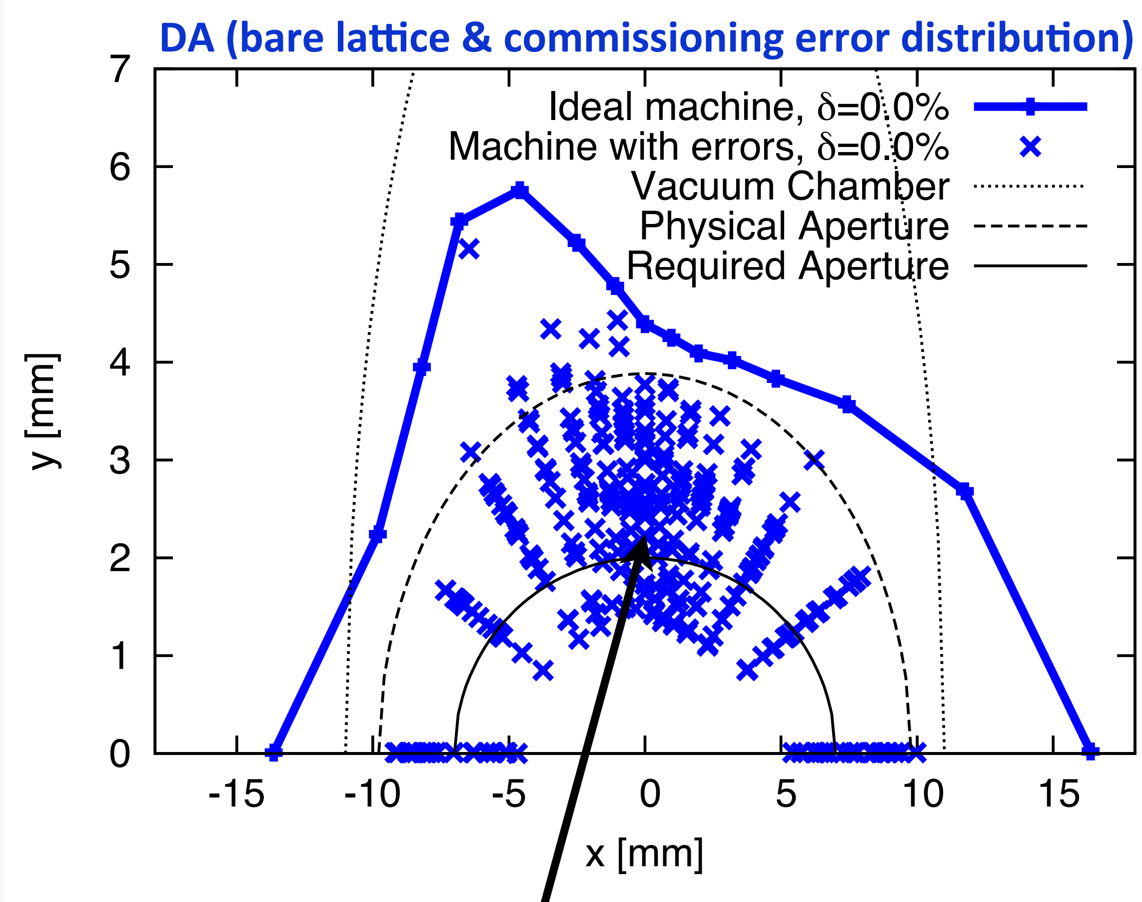
3 GeV Storage Ring Commissioning (cont.)

- 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

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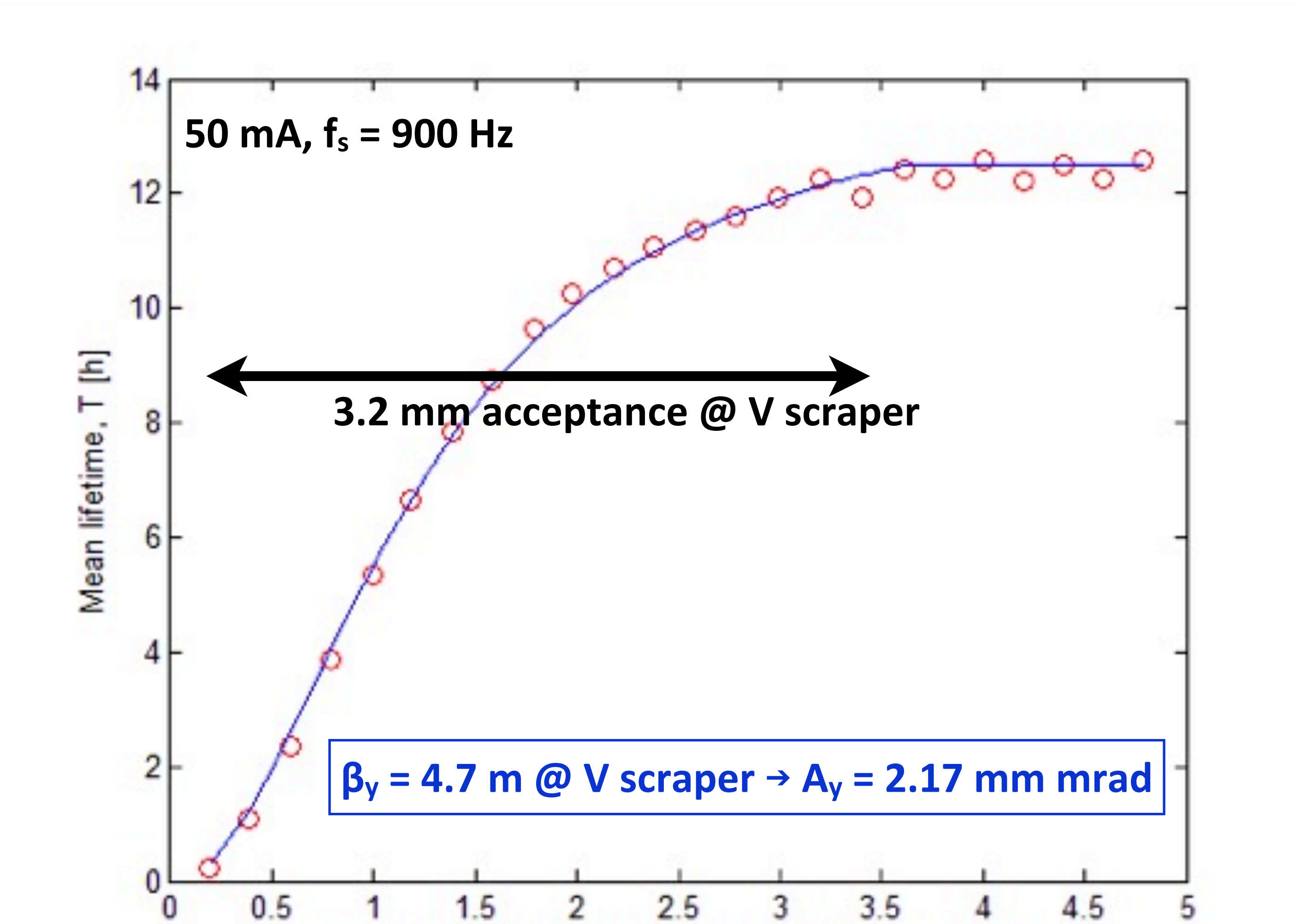
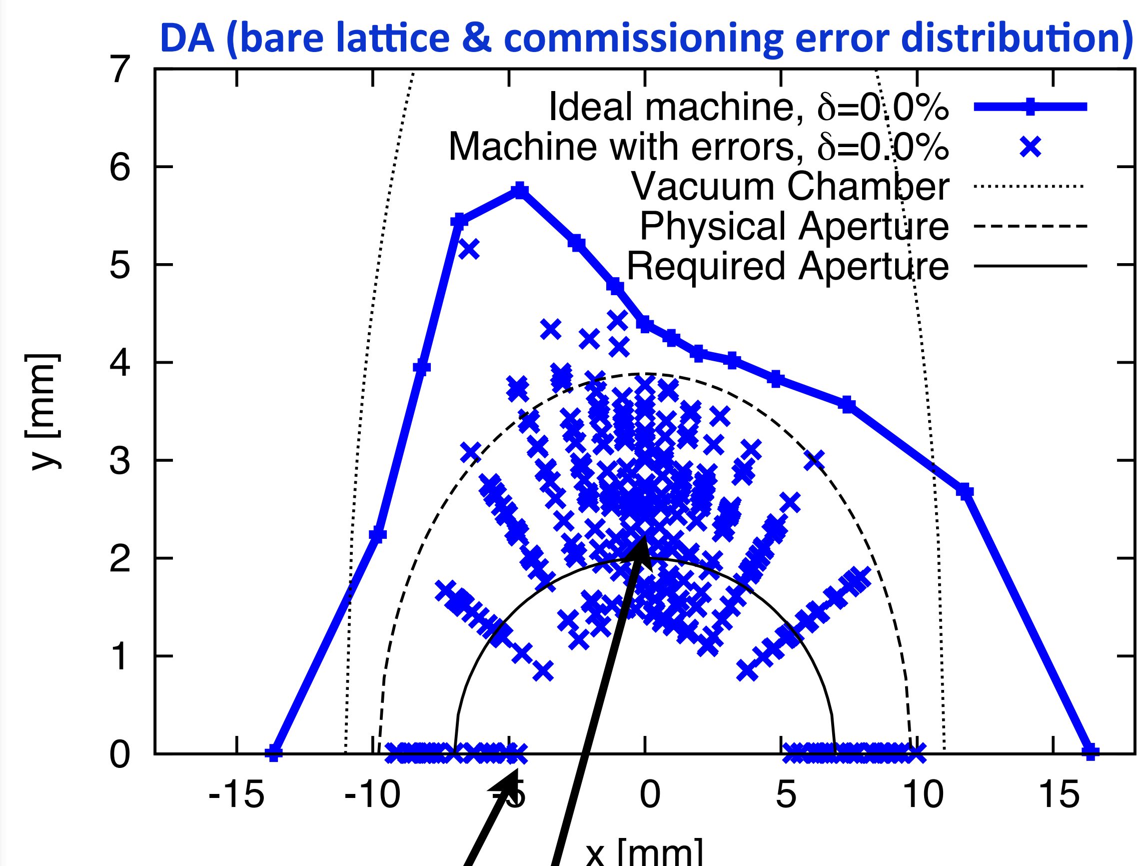


Courtesy J. Sundberg

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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Courtesy U. Johansson

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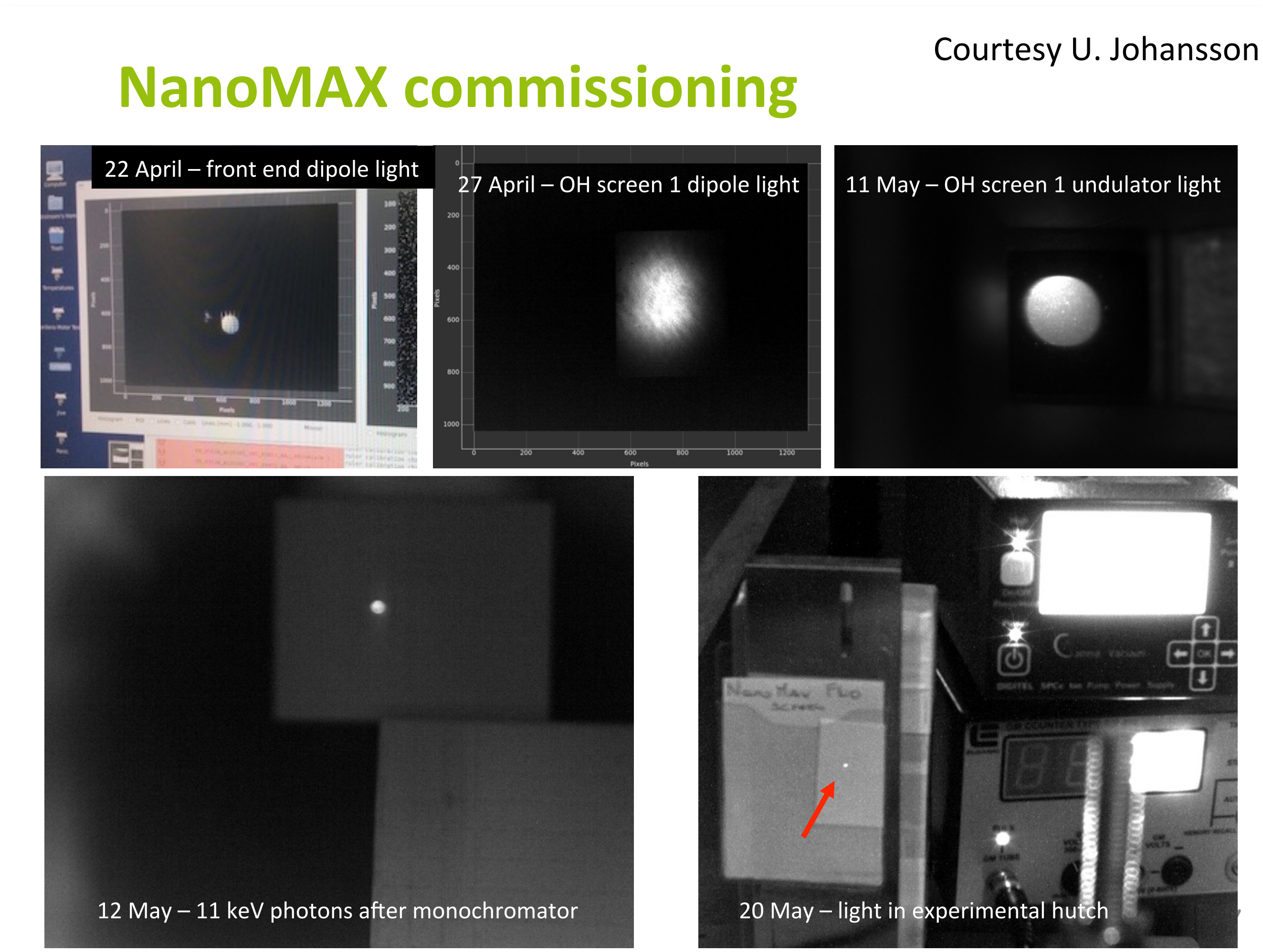

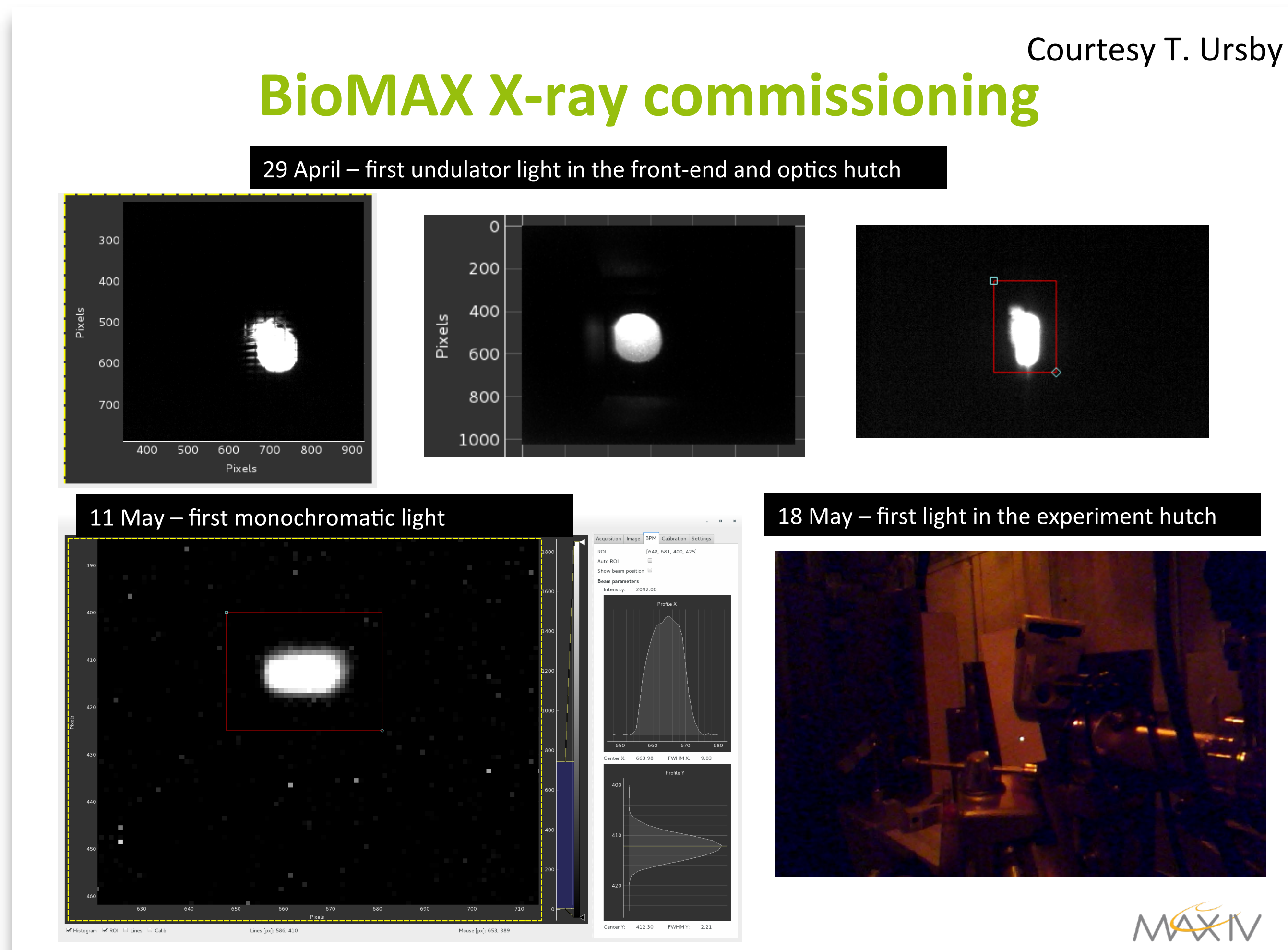

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- May 11: 10 mm gaps on both BLs (FB loop for ID correctors closed)
- May 11-19: first monochromatic beams (on detector / 11 keV)

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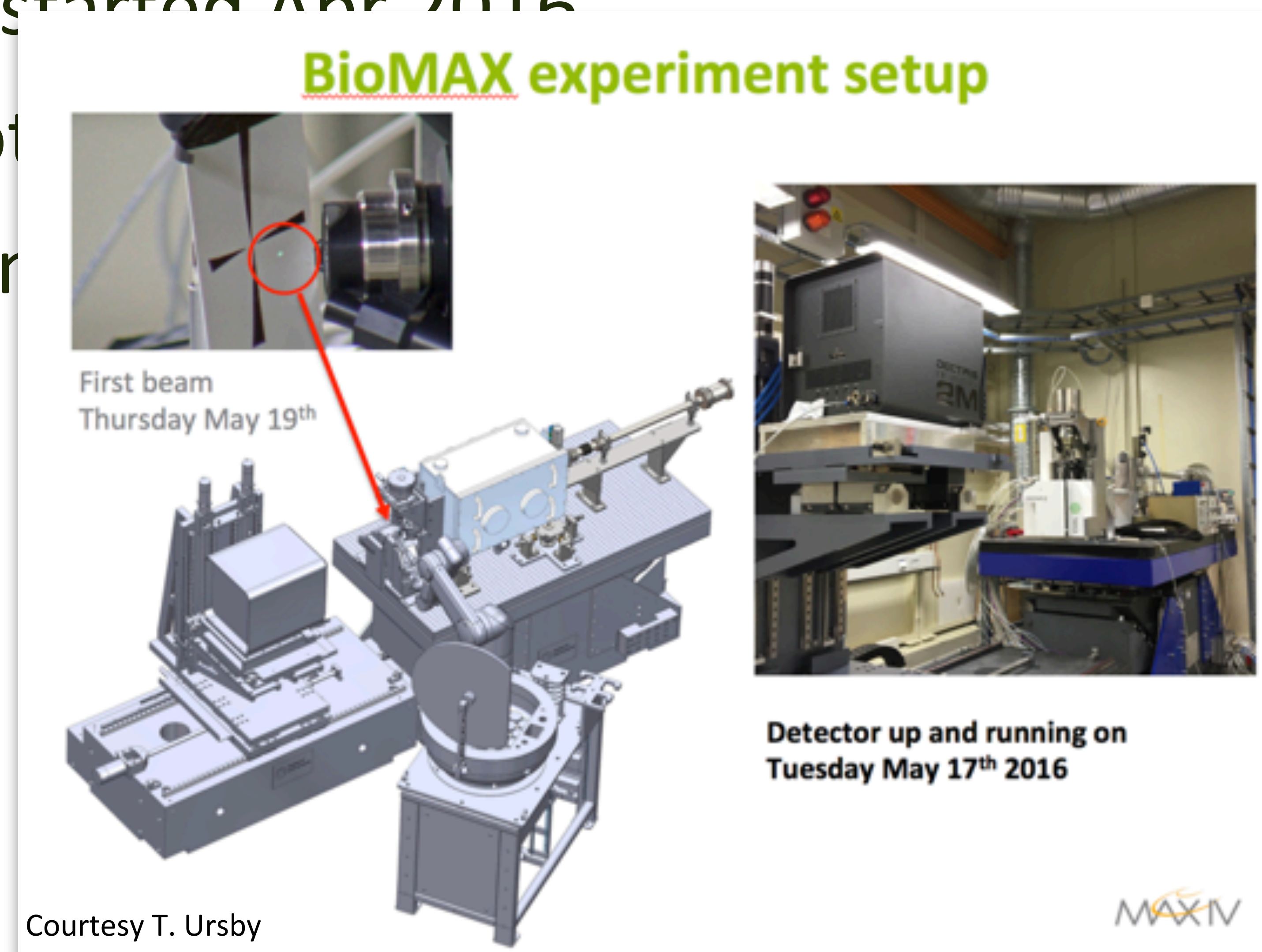

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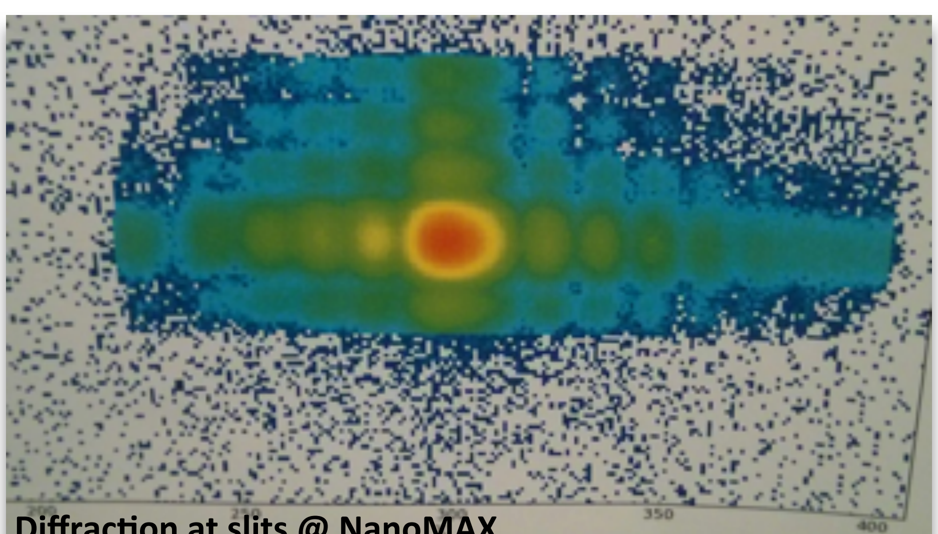
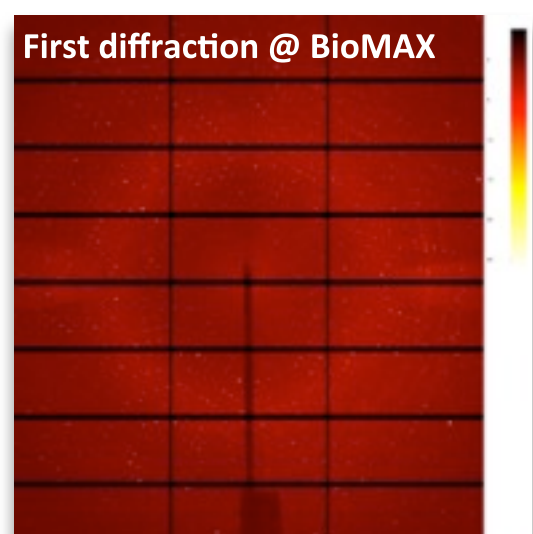
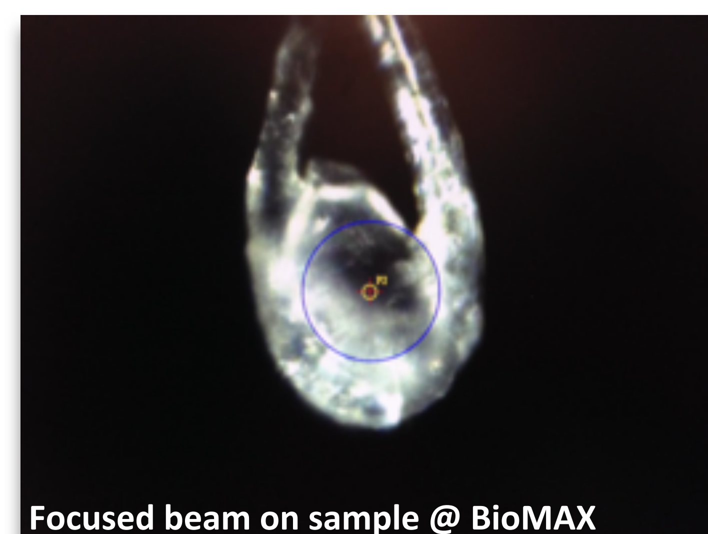
- June 8/9: First diffraction patterns


Diffraction at slits @ NanoMAX


First diffraction @ BioMAX


Focused beam on sample @ BioMAX

3 GeV Storage Ring Commissioning (cont.)

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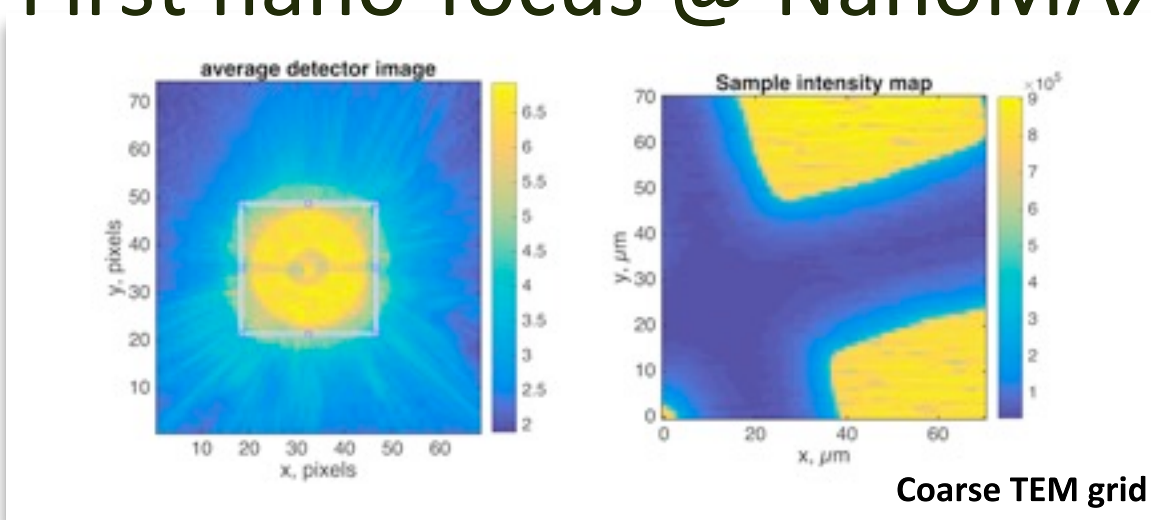
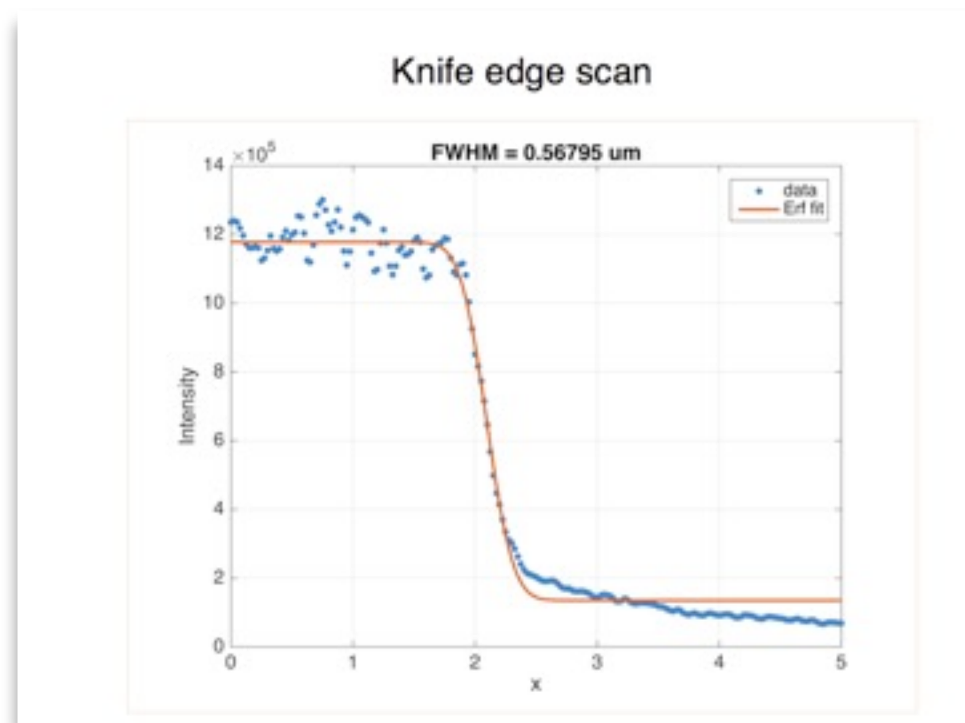
- June 20: First nano-focus @ NanoMAX



Coarse TEM grid



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- May 11-19: first monochromatic beams (on detector / 11 keV)
- June 8/9: First diffraction patterns
- June 20: First nano-focus @ NanoMAX
  → just in time for inauguration on June 21
- June 30: closed to 4.5 mm gap

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...

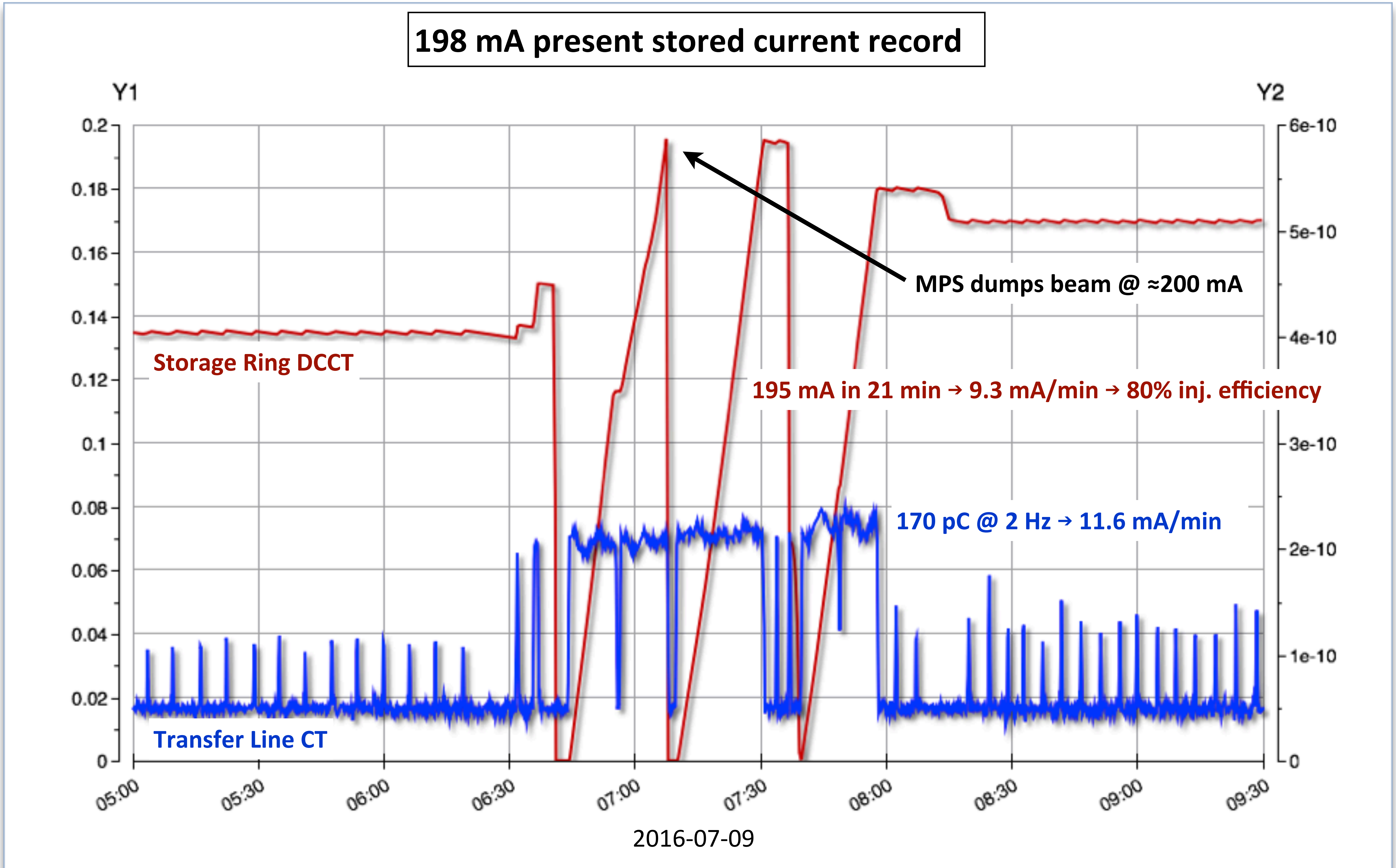
MAX IV Inauguration (cont.)

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

...we inaugurated our new facility.

- After inauguration, 3 weeks left until summer shutdown

3 GeV Storage Ring Commissioning (cont.)

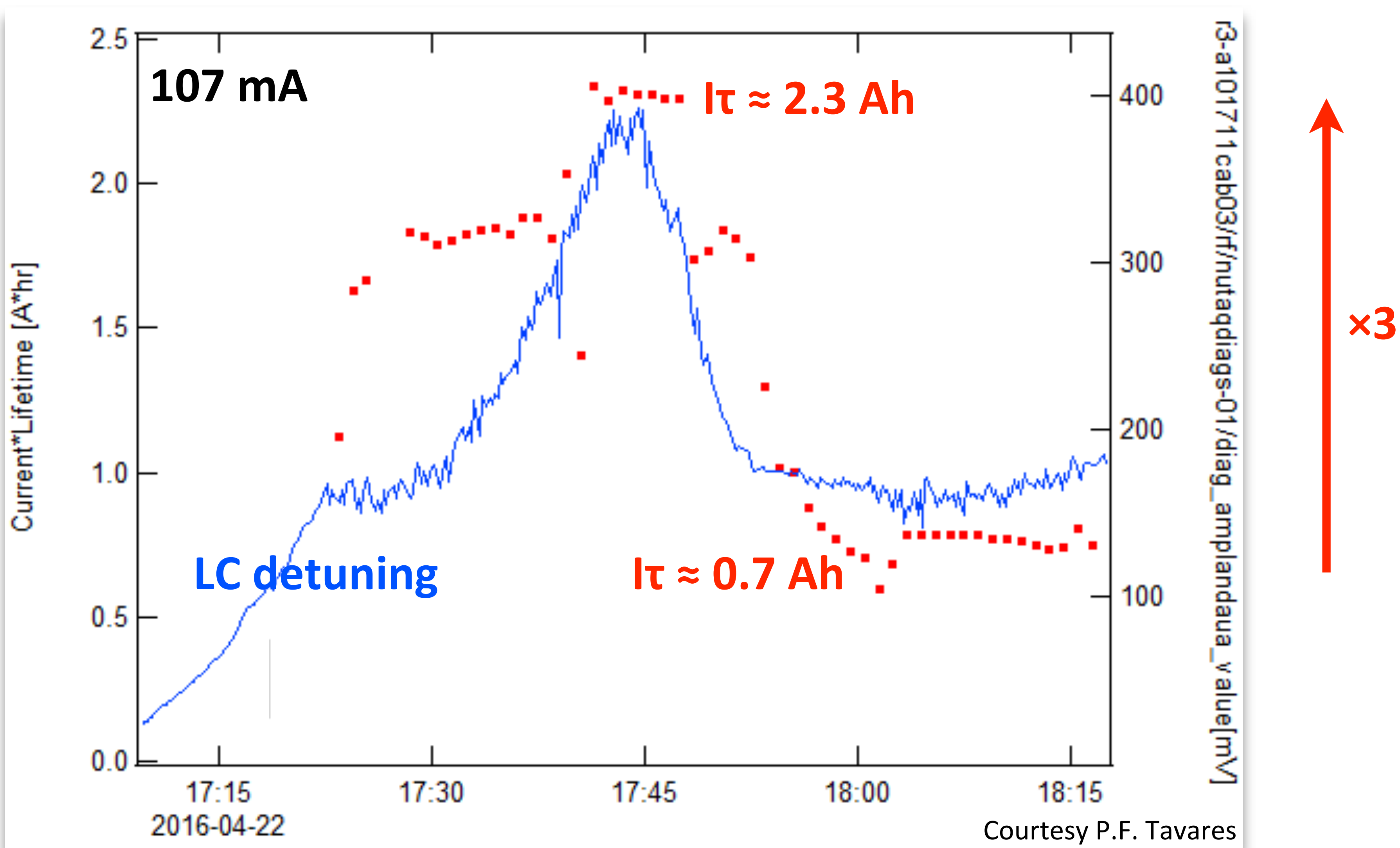


3 GeV Storage Ring Commissioning (cont.)

- 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

3 GeV Storage Ring Commissioning (cont.)

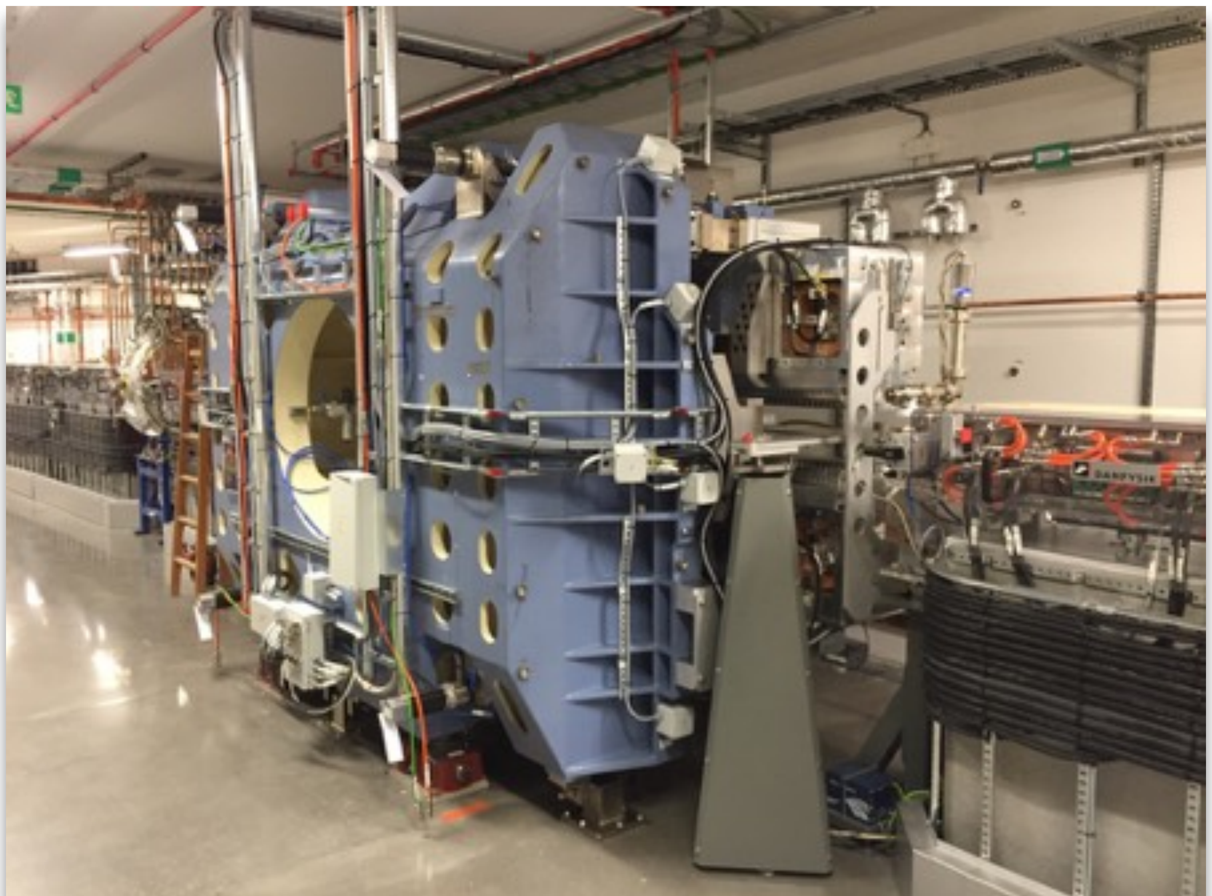
- Finally, need to also focus on stability & collective effects
  - 3 passive Landau cavities ($R_s \approx 2.5$ MΩ) allow for tuning to flat-potential conditions already @ 150 mA
  - Achieved >2 Ah under stable conditions (top-up running & BbB FB loop closed)



Courtesy P.F. Tavares

3 GeV Storage Ring Commissioning (cont.)

- During recent summer shutdown installed three new IDs



EPU48 → VERITAS (RIXS)
EPU53 → HIPPIE (AP-XPS, AP-XAS)

3.9 m magnetic length, 69/77 periods,
11 mm min. magnetic gap, ≈1.1 T peak field

Manufactured at MAX IV

In-vac Wiggler → BALDER (XAS, XES)

2.0 m magnetic length, 50 mm period,
4.2 mm min. magnetic gap, ≈2.4 T peak field

Manufactured by SOLEIL

Outlook

- Continue commissioning of 3 GeV storage ring
  - optics & IDs
  - 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
- What remains to be installed during 2017
  - 2nd diagnostic BL on 3 GeV SR
  - 2 additional linac stations (2 stations with 4 structures each → 4 stations with 2 structures each)
  - 3 IDs in 3 GeV SR (2 IVUs, 1 EPU) & 3 IDs in 1.5 GeV SR (2 new EPUs, 1 EPU from MAX II)

Acknowledgements

- Thanks to all who contributed to MAX IV commissioning:
  - MAX IV Operators
  - Technical support at MAX IV
  - Machine Division staff, graduate students, and guests:

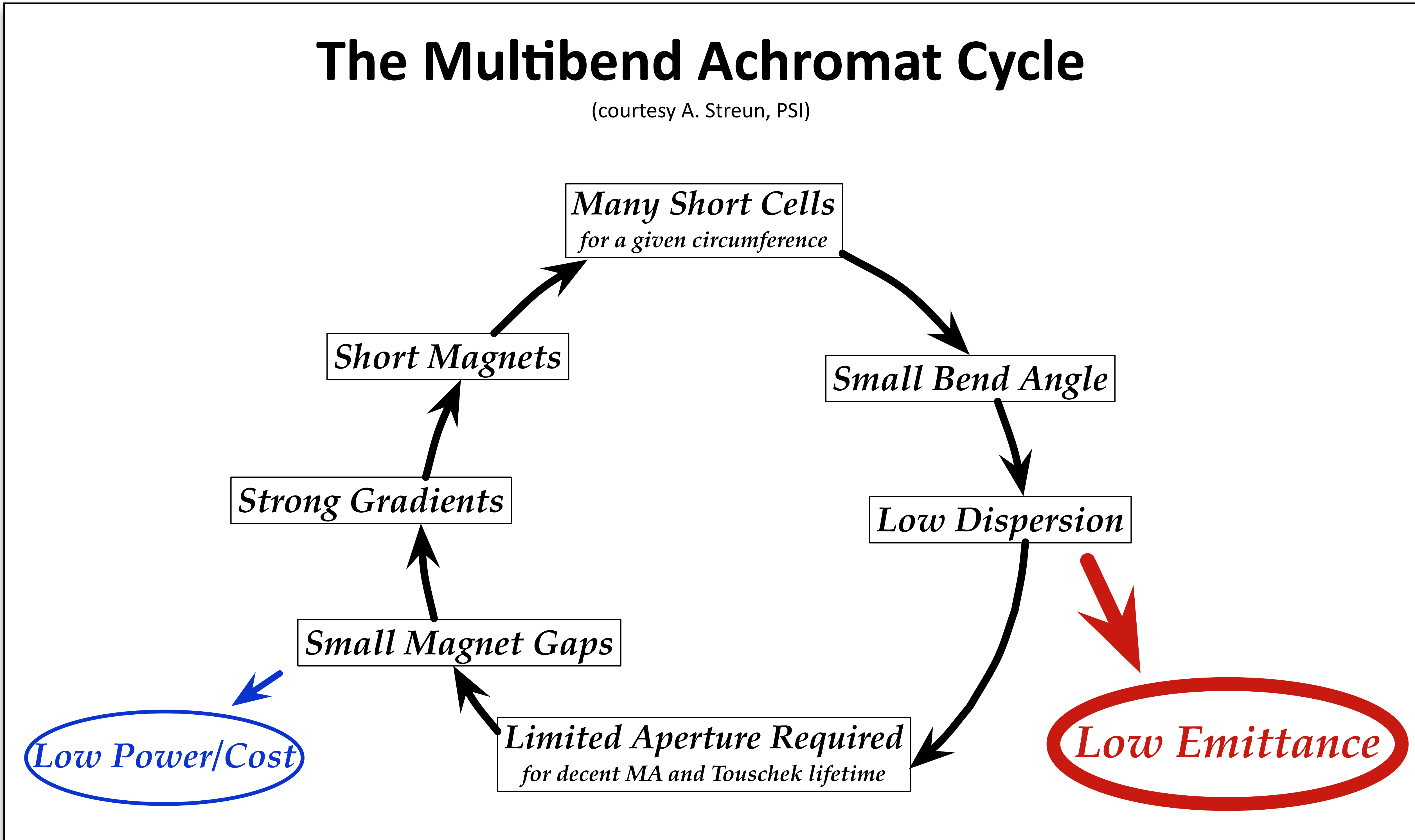
    Mikael Eriksson, Sara Thorin, Erik Mansten, Dionis Kumbaro, David Olsson, Sverker Werin, Francesca Curbis, Olivia Karlberg, Joel Andersson, Filip Lindau, Robert Lindvall, Lennart Isaksson, Pedro F. Tavares, Magnus Sjöström, Galina Skripka, Martin Johansson, Eshraq Al-dmour, Åke Andersson, Dieter Einfeld, Les Dallin, Francis Cullinan, Ryutaro Nagaoka, Oleg Chubar
  - Our colleagues at SOLARIS and many other labs

Photo courtesy L. Jansson, August 24, 2015

Thanks for your attention!

Photo courtesy L. Jansson, August 24, 2015

Backup: The MBA – A Virtuous Circle



Backup: Optics Tuning & Corrections

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

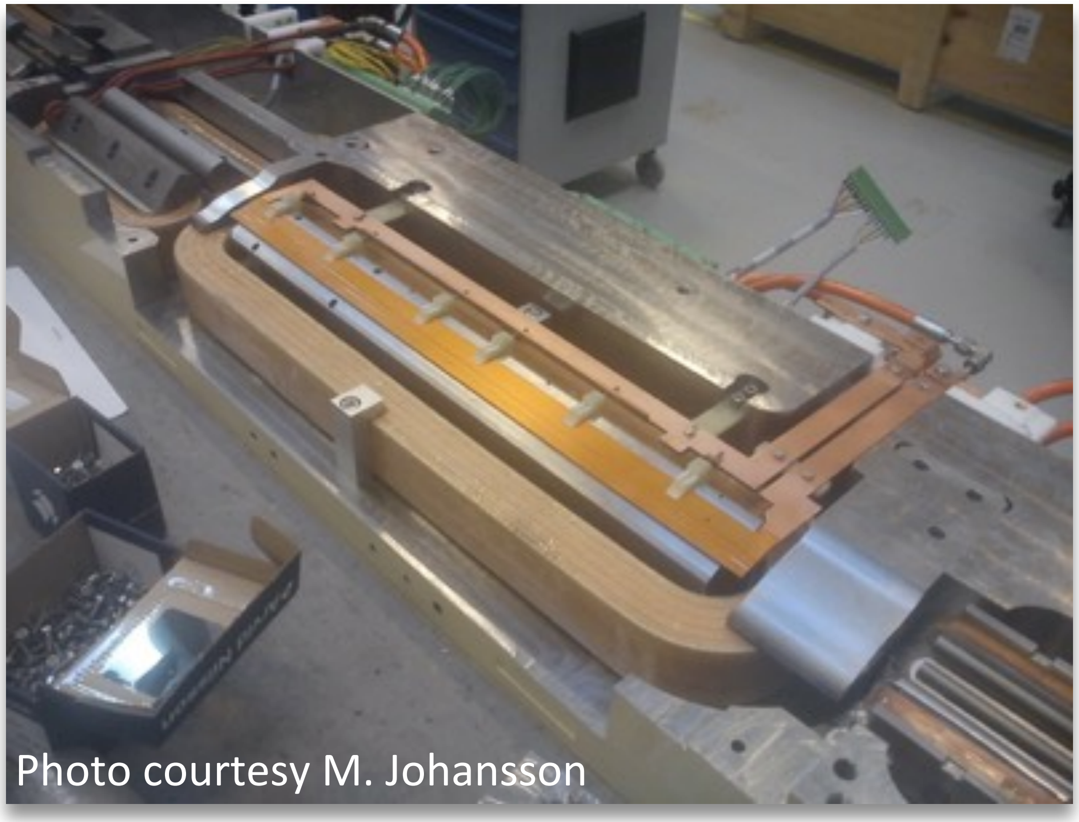
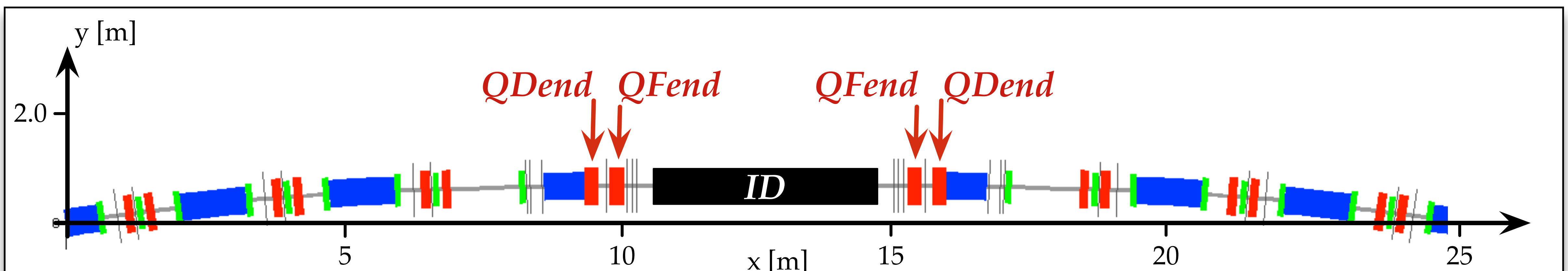


Photo courtesy M. Johansson


Photo courtesy A. Nyberg

Backup: Optics Tuning & Corrections (cont.)

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

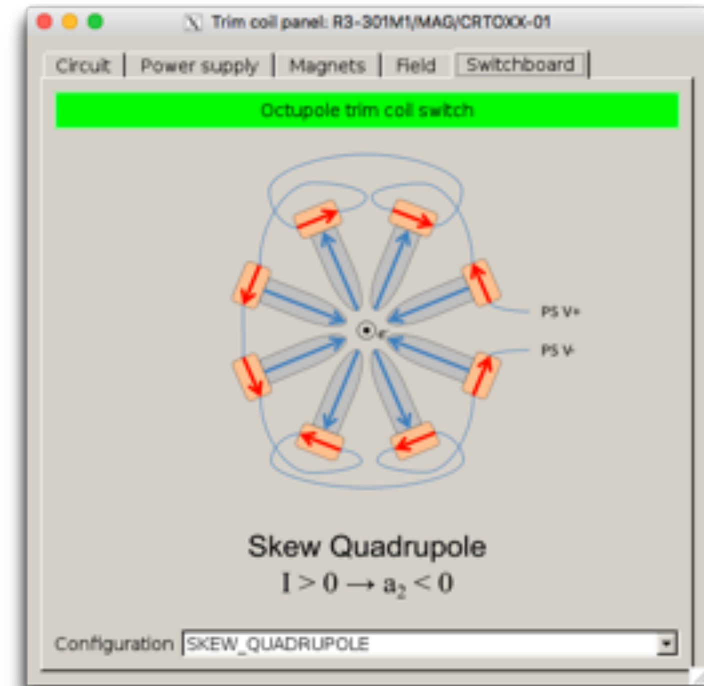


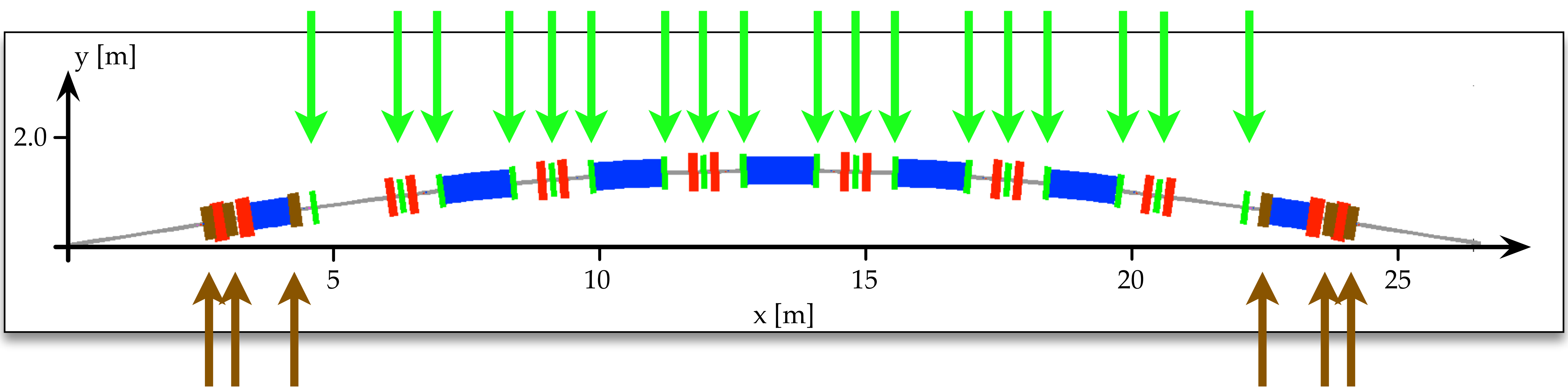
PAC'**11**, TUP235, p.1262

IPAC'**15**, TUPJE038

Backup: Optics Tuning & Corrections (cont.)

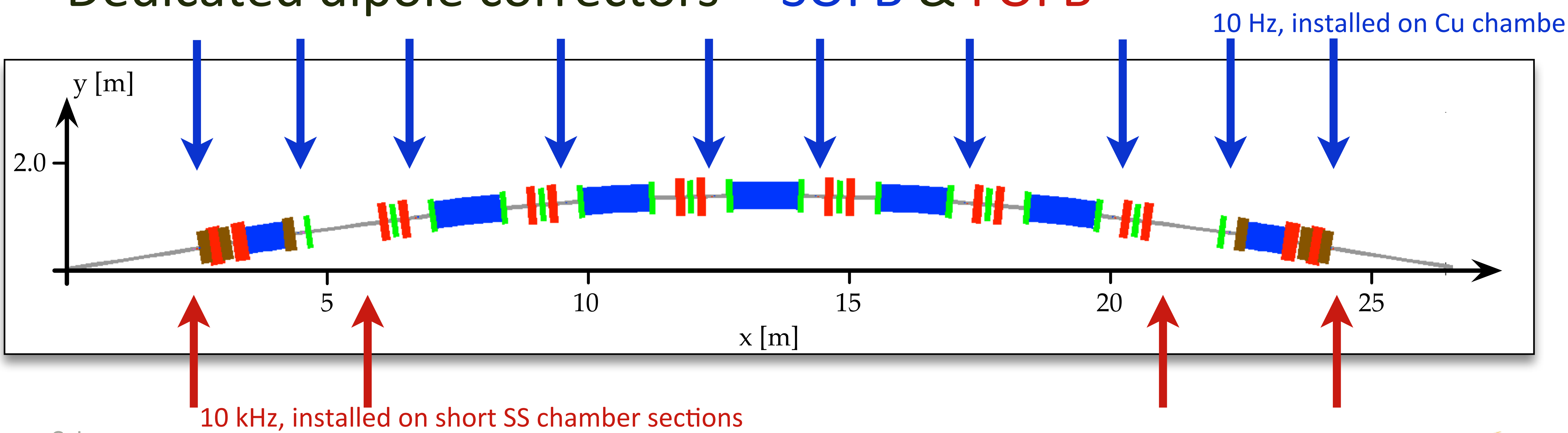
- All sextupoles and octupoles carry auxiliary winding
- Can be powered as: (remotely switchable)
  - auxiliary sextupole → nonlinear corrections
  - skew quadrupole → coupling & dispersion control
  - upright quad → calibrate BPMs to adjacent sext/oct
  - dipole correctors, in addition to...





Backup: Optics Tuning & Corrections (cont.)

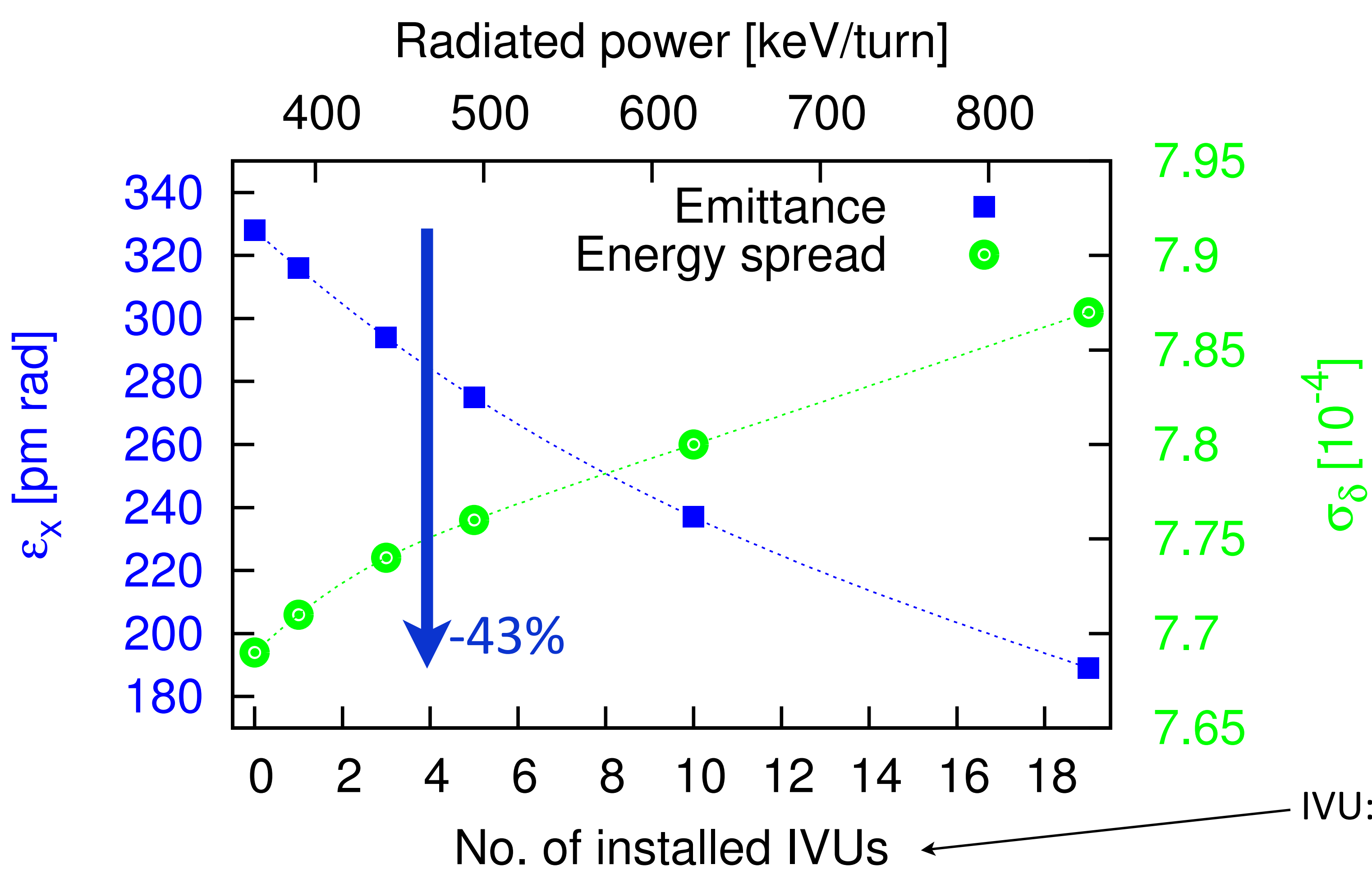
- All sextupoles and octupoles carry auxiliary winding
- Can be powered as: (remotely switchable)
  - auxiliary sextupole → nonlinear corrections
  - skew quadrupole → coupling & dispersion control
  - upright quad → calibrate BPMs to adjacent sext/oct
  - dipole correctors, in addition to...
- Dedicated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



Backup: MBA Rings – a Different Beast

- 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

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

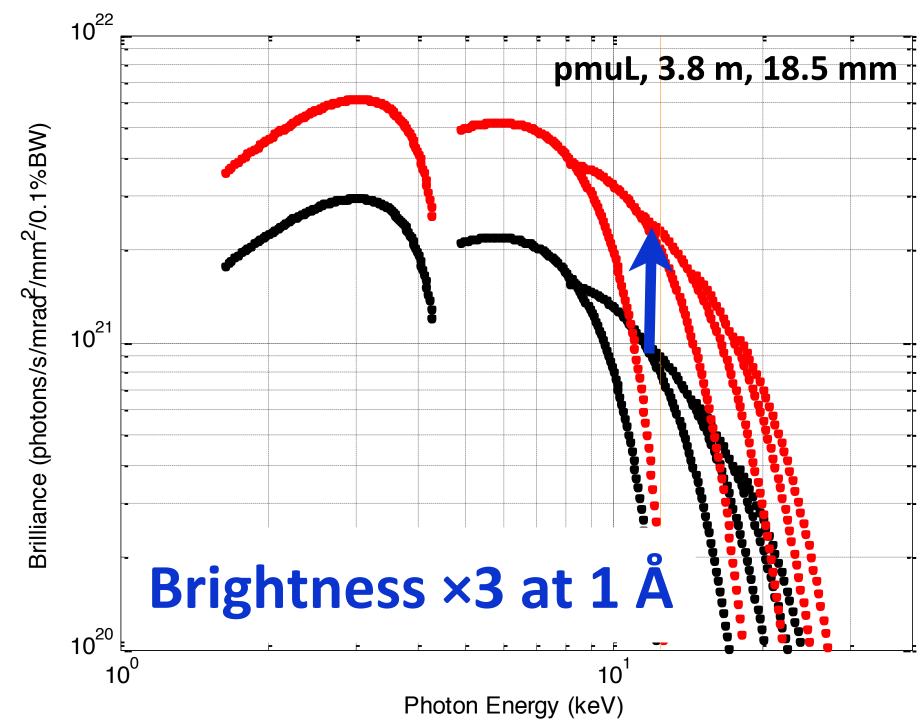
$$\varepsilon_0 \propto \gamma^2 \frac{I_5}{I_2 - I_4} \qquad I_5 = \int \frac{\mathcal{H}}{|\rho^3|} ds$$

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

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

Backup: First 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 $\quad \tau_{ts} \propto \sqrt{\varepsilon_y} \propto \sqrt{\kappa}$ 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)
- Increase focusing in arc → ε_x reduced to 269 pm rad (-18%) while retaining satisfactory DA & lifetime IPAC'**14**, TUPRI026, p.1615



- 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)