First Commissioning Experience at the MAX IV 3 GeV Storage Ring

Simon C. Leemann
Low Emittance Rings 2015 Workshop, September 15–17, 2015

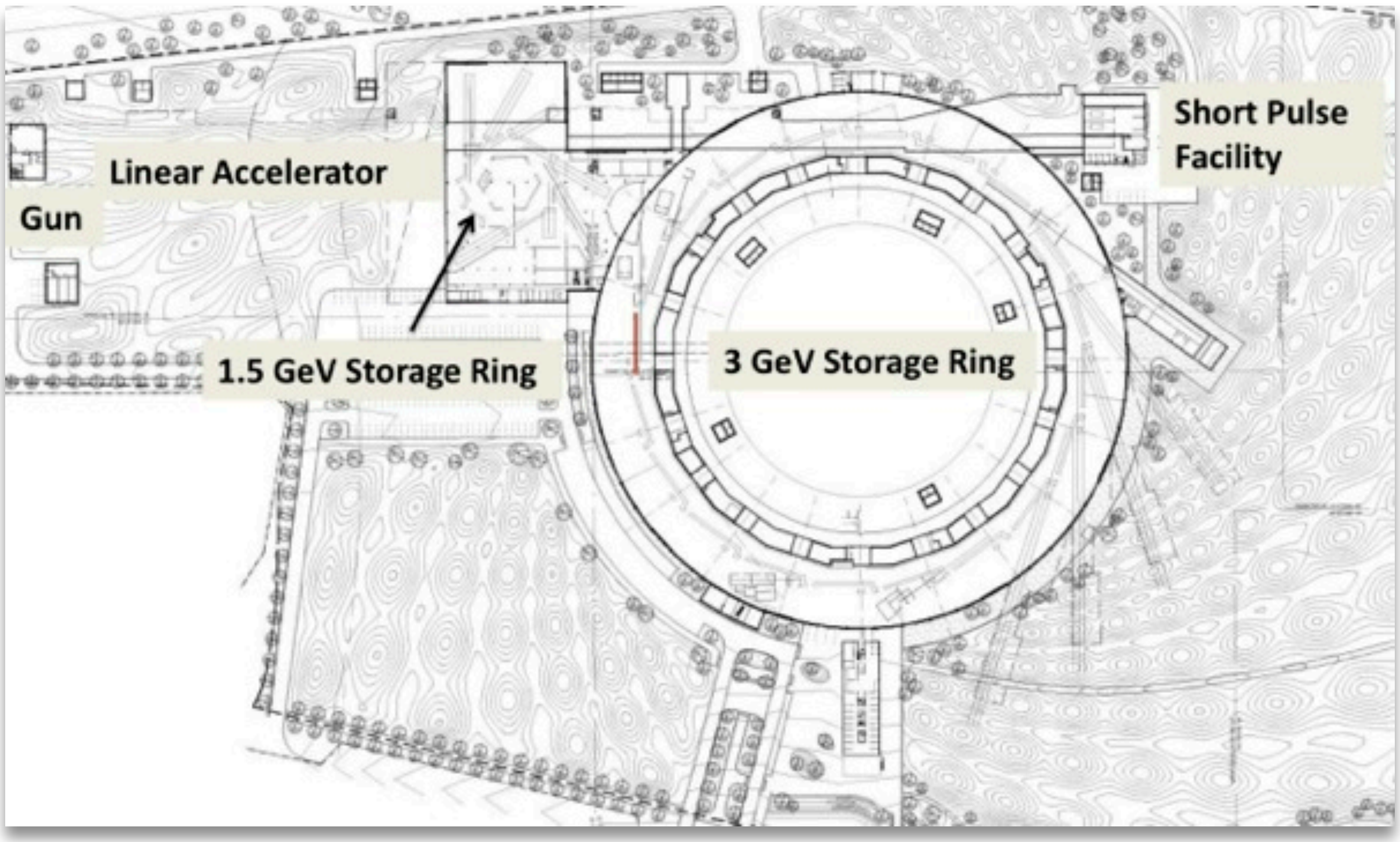
Outline

- MAX IV Facility Overview
- The MAX IV 3 GeV Storage Ring
    - Optics & Performance
    - Technology
- Linac & Injection
    - Injection into Storage Rings
    - Linac Commissioning Summary
- 3 GeV Storage Ring Commissioning
    - First Results
    - Outlook

started Aug 10

Facility Overview

- MAX IV consists of two storage rings and a full-energy injector linac for top-up
- SRs @ 1.5 GeV and 3 GeV, ≈3.5 GeV linac also drives SPF/FEL



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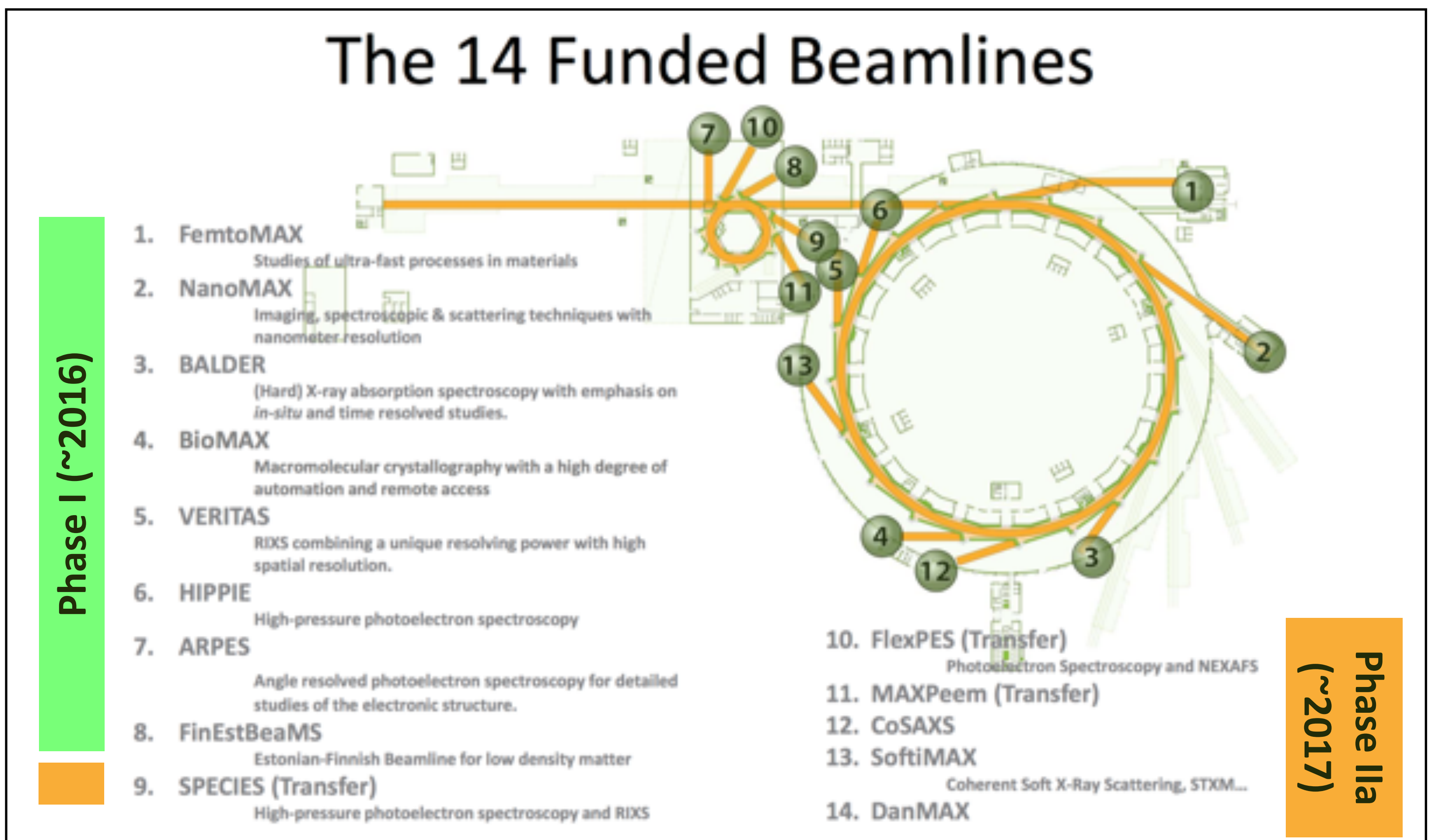
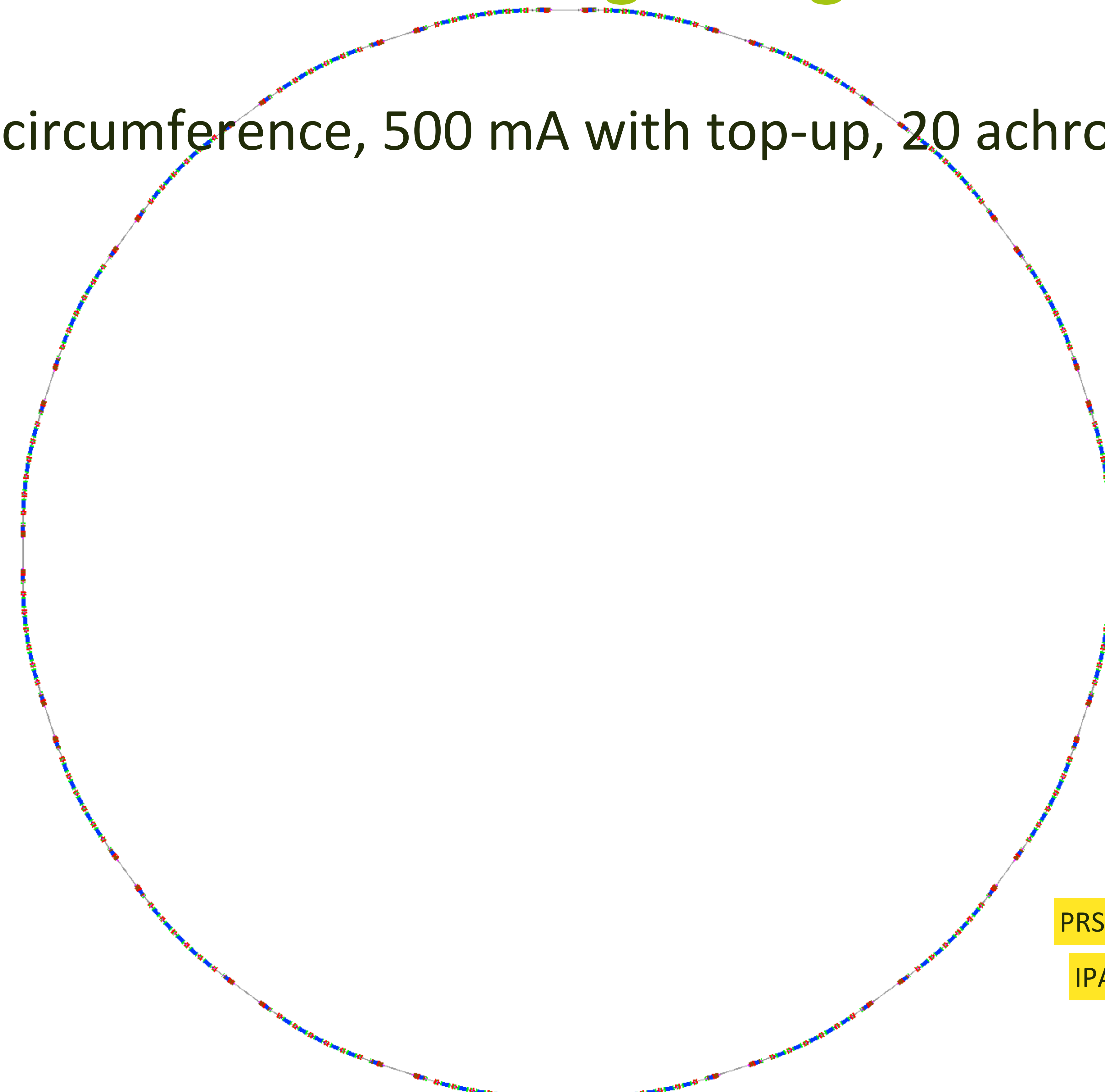
- SRs @ 1.5 GeV and 3 GeV, ≈3.5 GeV linac also drives SPF/FEL
- User beamlines: 3 @ SPF, 10 @ 1.5 GeV SR, 19 @ 3 GeV SR



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)

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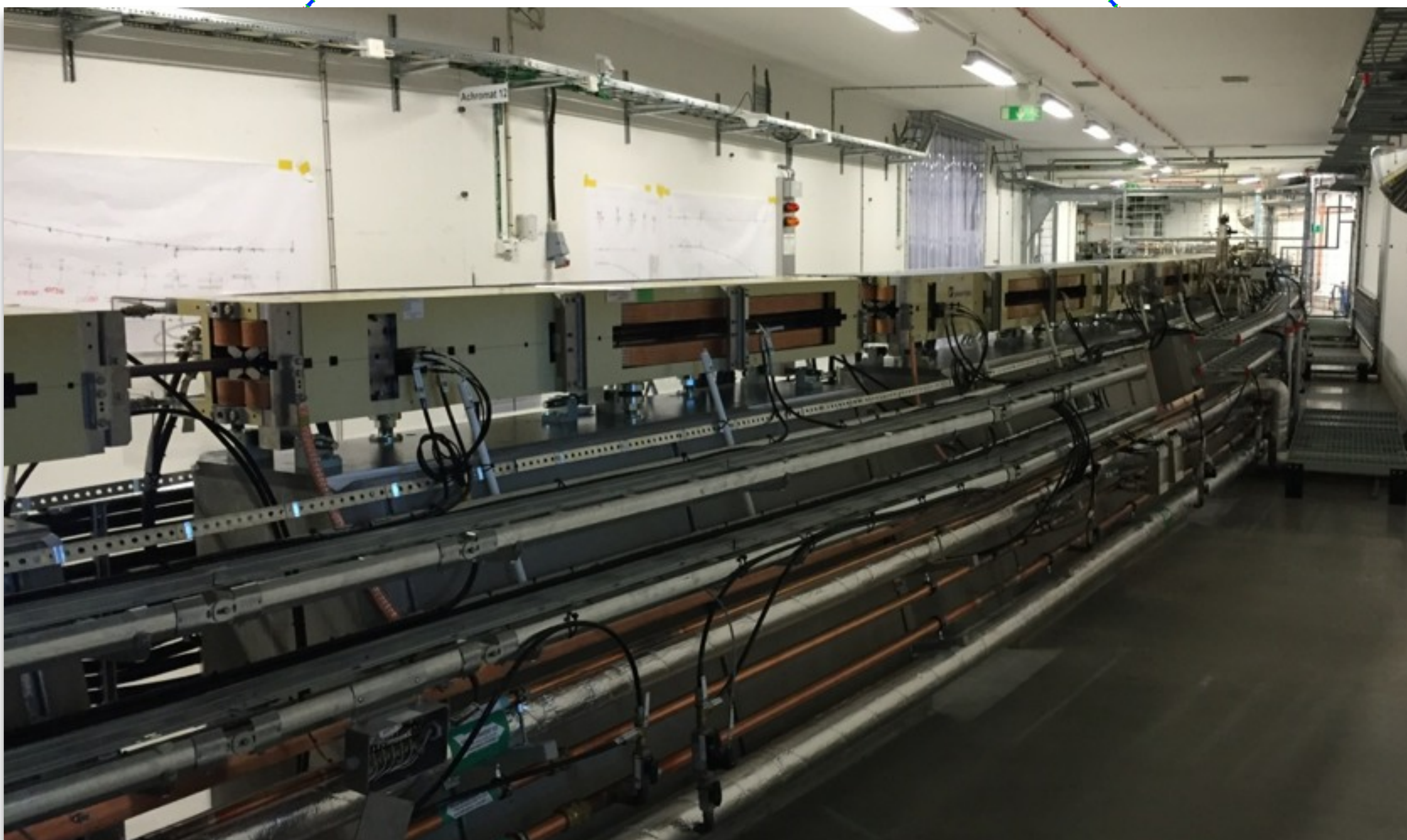


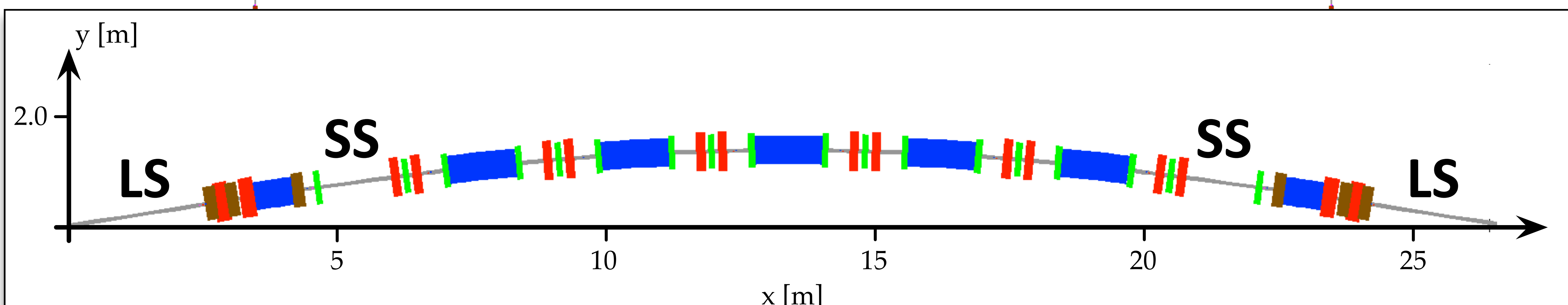
701 (2009)

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

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- 19 long straights (4.6 m) for users, 1 for injection
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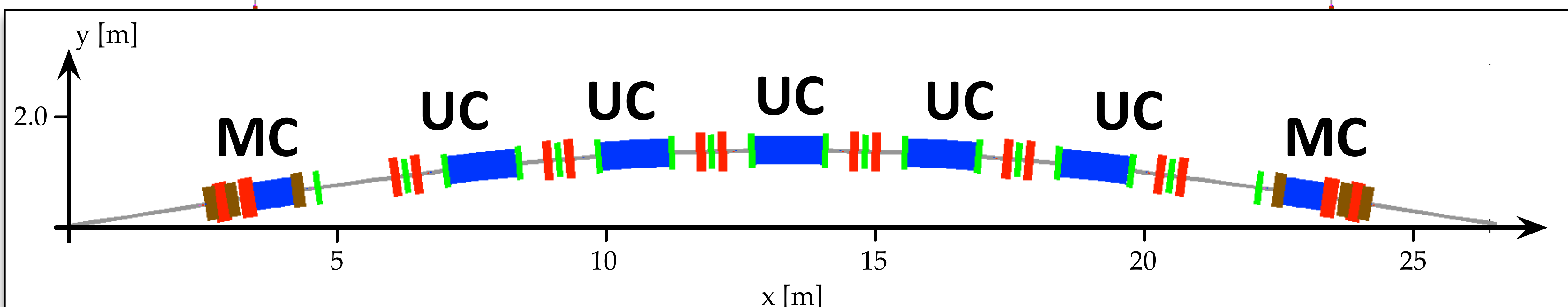
- 7-bend achromat: 5 unit cells (3°) & 2 matching cells (1.5° LGB)



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

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

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

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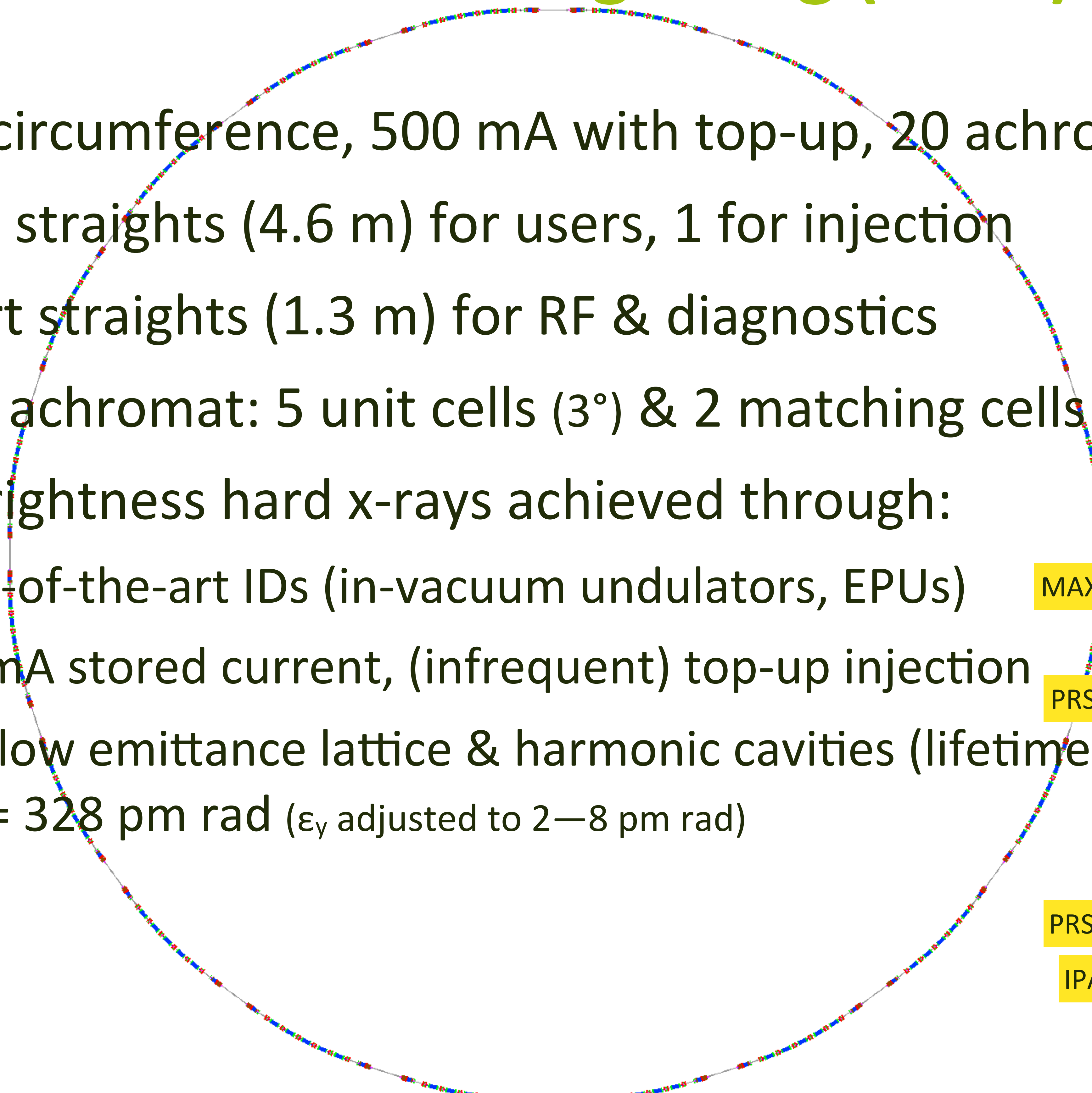

- 528 m circumference, 500 mA with top-up, 20 achromats
- 19 long straights (4.6 m) for users, 1 for injection
- 40 short straights (1.3 m) for RF & diagnostics
- 7-bend achromat: 5 unit cells (3°) & 2 matching cells (1.5° LGB)
- High-brightness hard x-rays achieved through:
  - State-of-the-art IDs (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)

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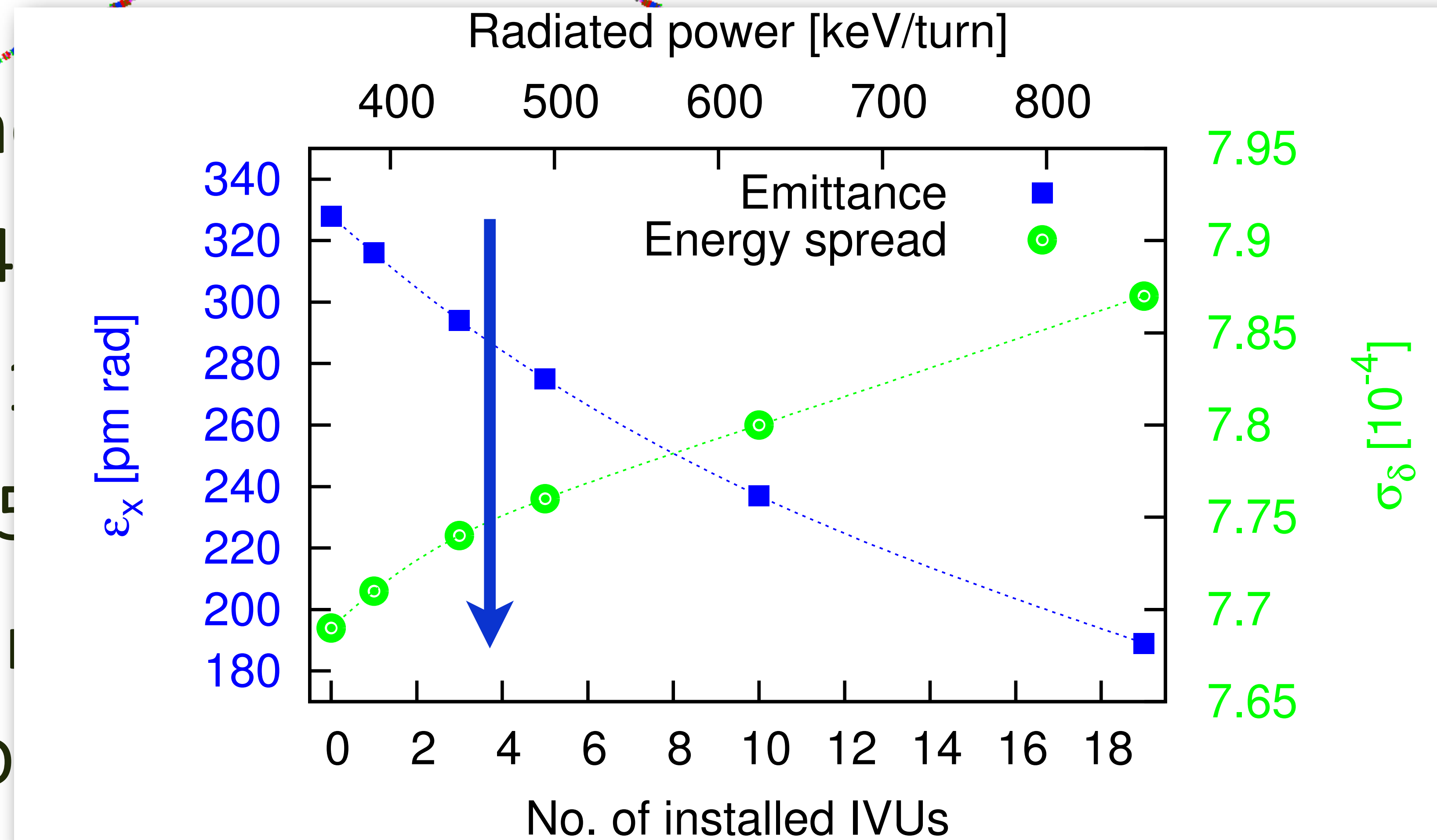
  - State-of-the-art ID
  - 500 mA stored current, (infrequent) top-up injection
  - Ultralow emittance lattice & harmonic cavities (lifetime & IBS)
    - ➔ ε_x = 328 pm rad (ε_y adjusted to 2—8 pm rad)
    - … ≈ 200 pm rad (with IDs, incl. IBS @ 500 mA)



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

PAC’**13**, MOPHO05

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

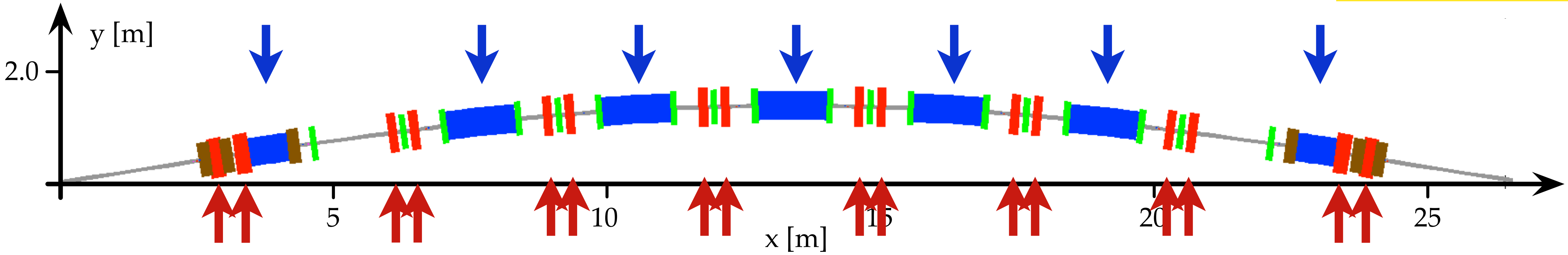
IPAC’**11**, THPC059, p.3029

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

Optics and Performance

- Compact, fully-integrated magnet design concept → strong focusing from gradient dipoles and interleaved quadrupoles

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



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- Compact, fully-integrated magnet design concept
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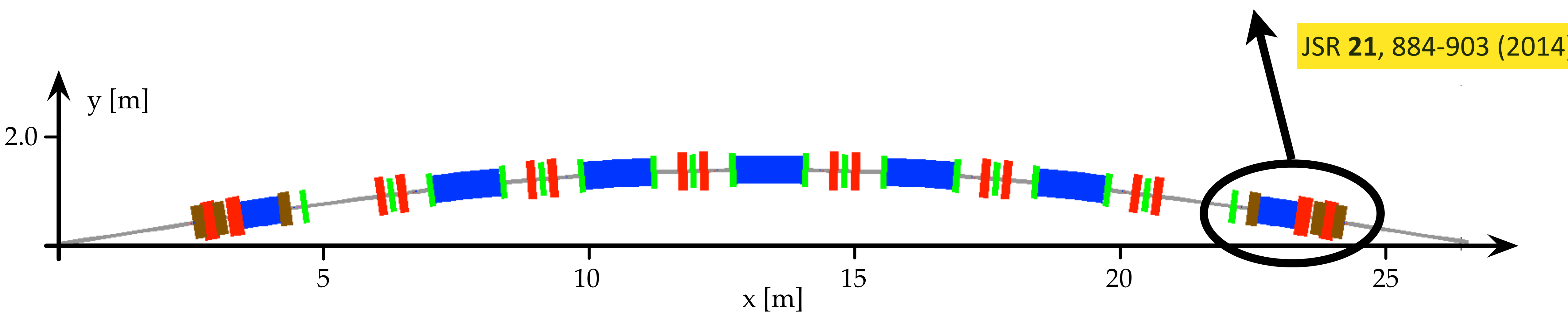
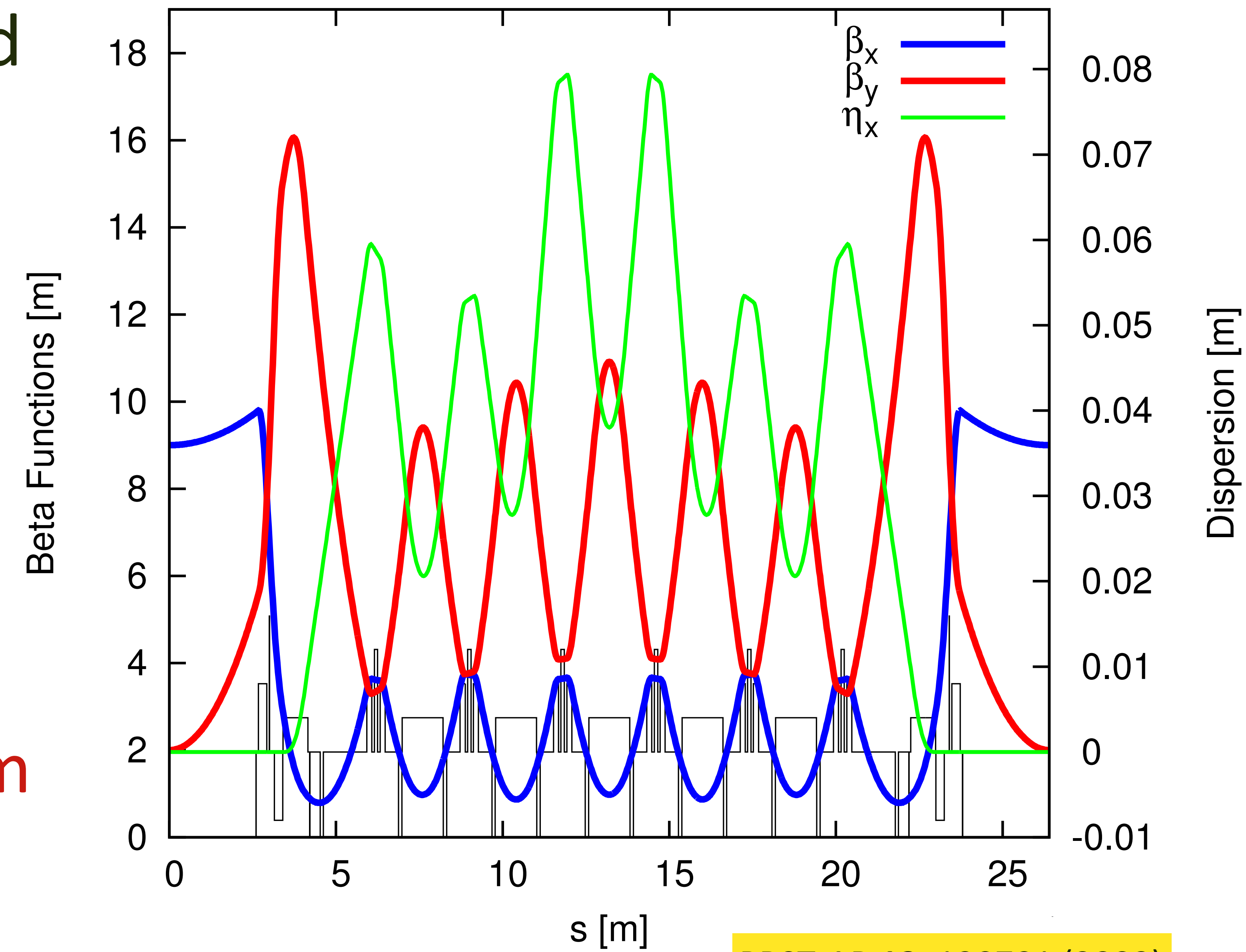


Optics and Performance (cont.)

- Compact, fully-integrated magnet design concept
  ➔ strong focusing from gradient dipoles and interleaved 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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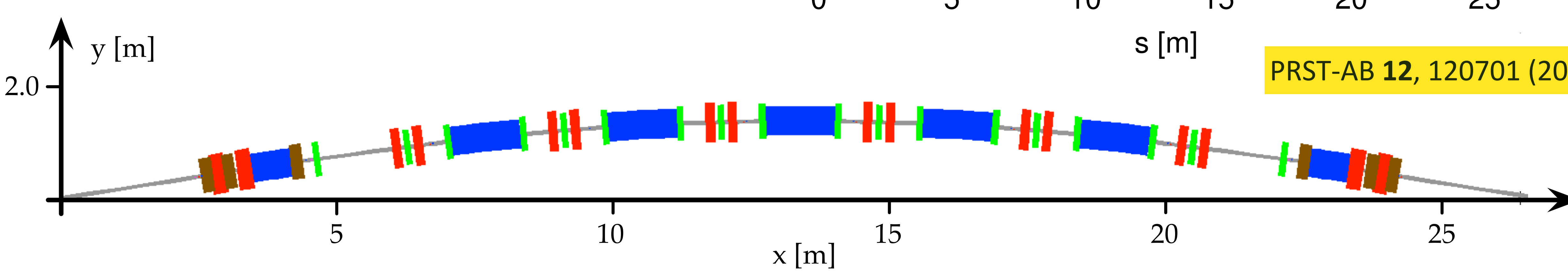
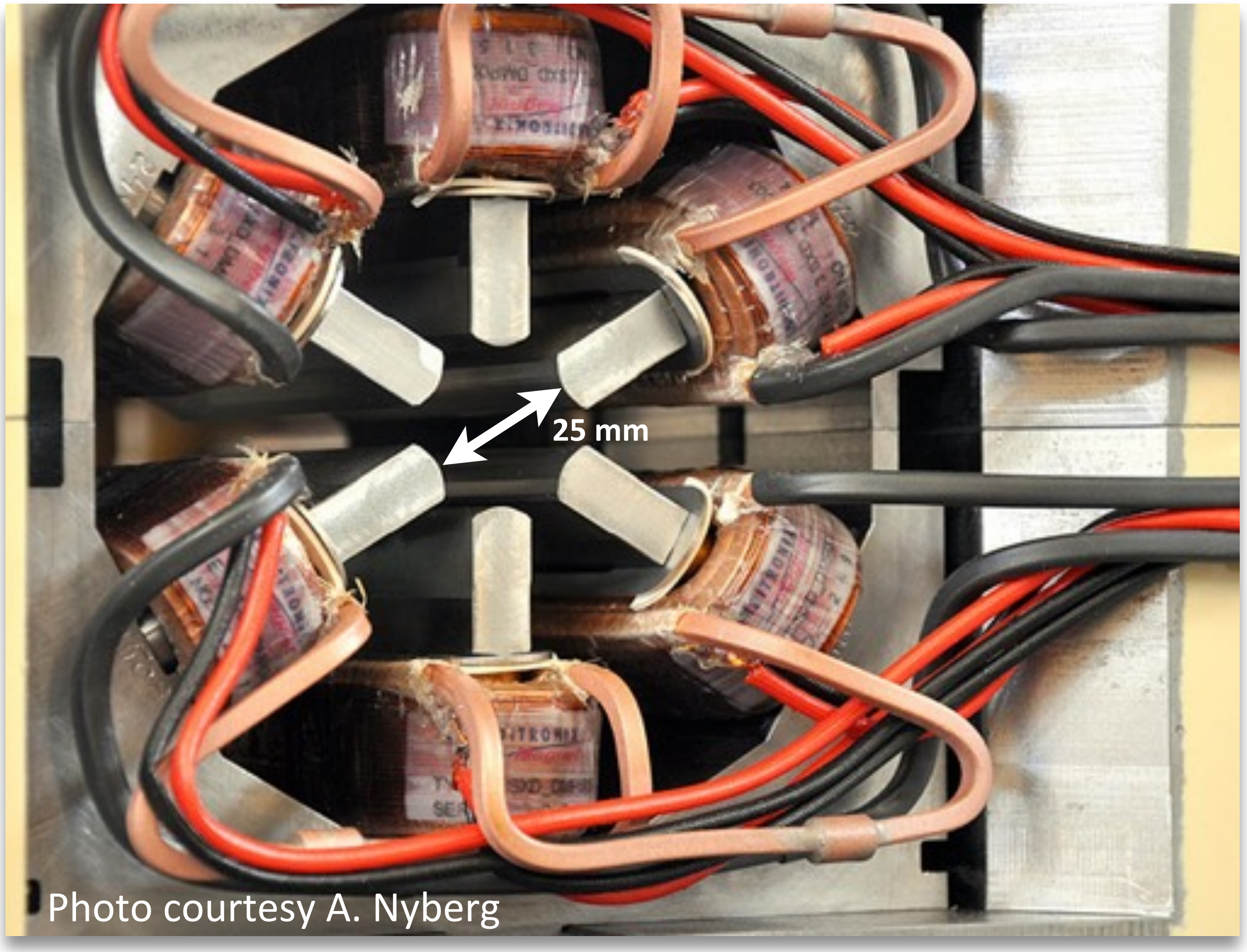
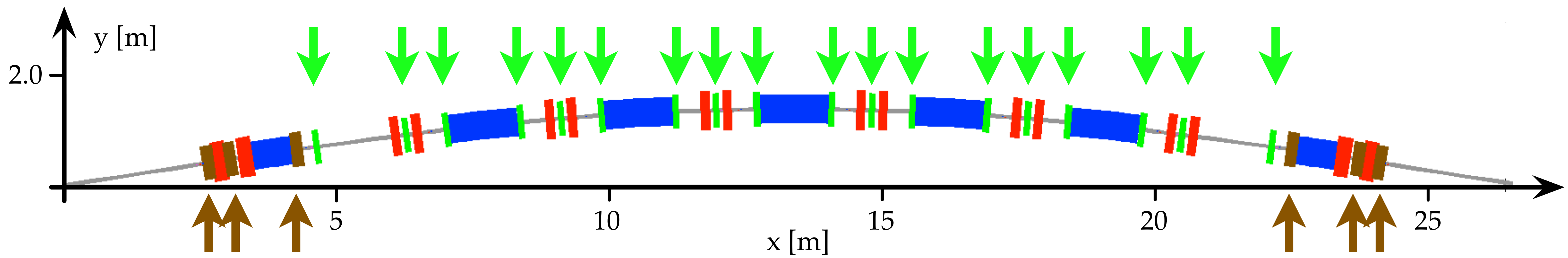


Optics and Performance (cont.)

- Many strong, distributed sextupoles & achromatic octupoles





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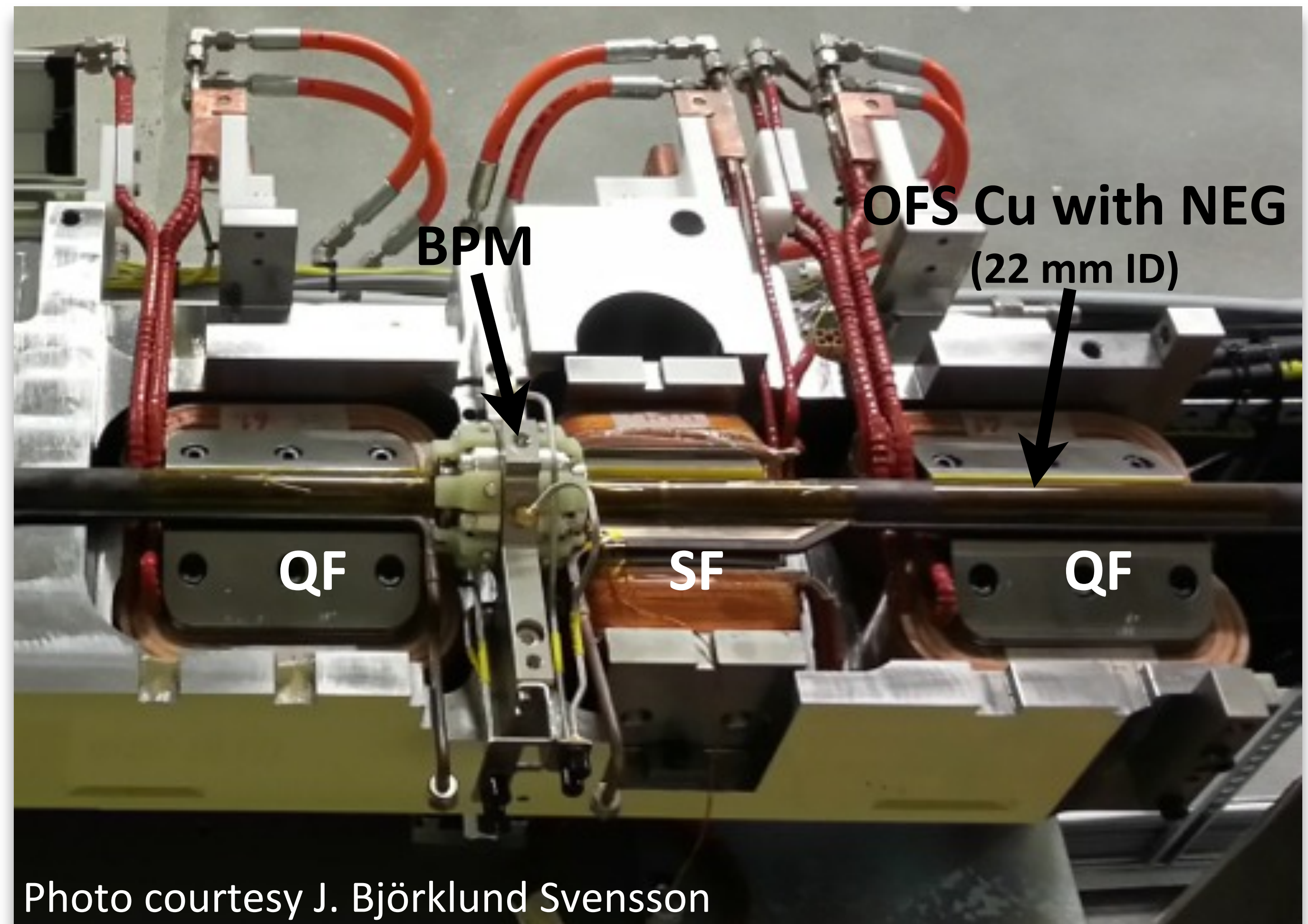
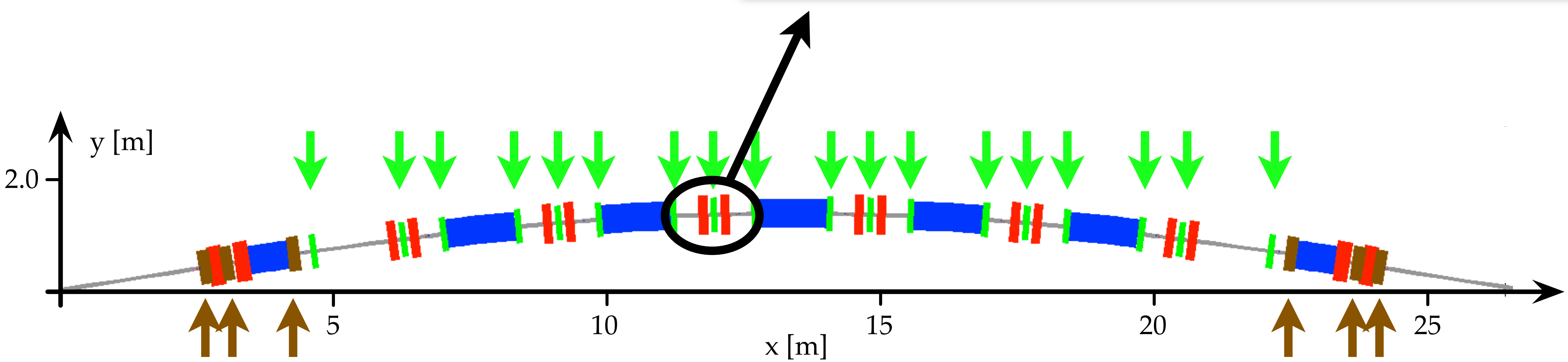


Photo courtesy J. Björklund Svensson



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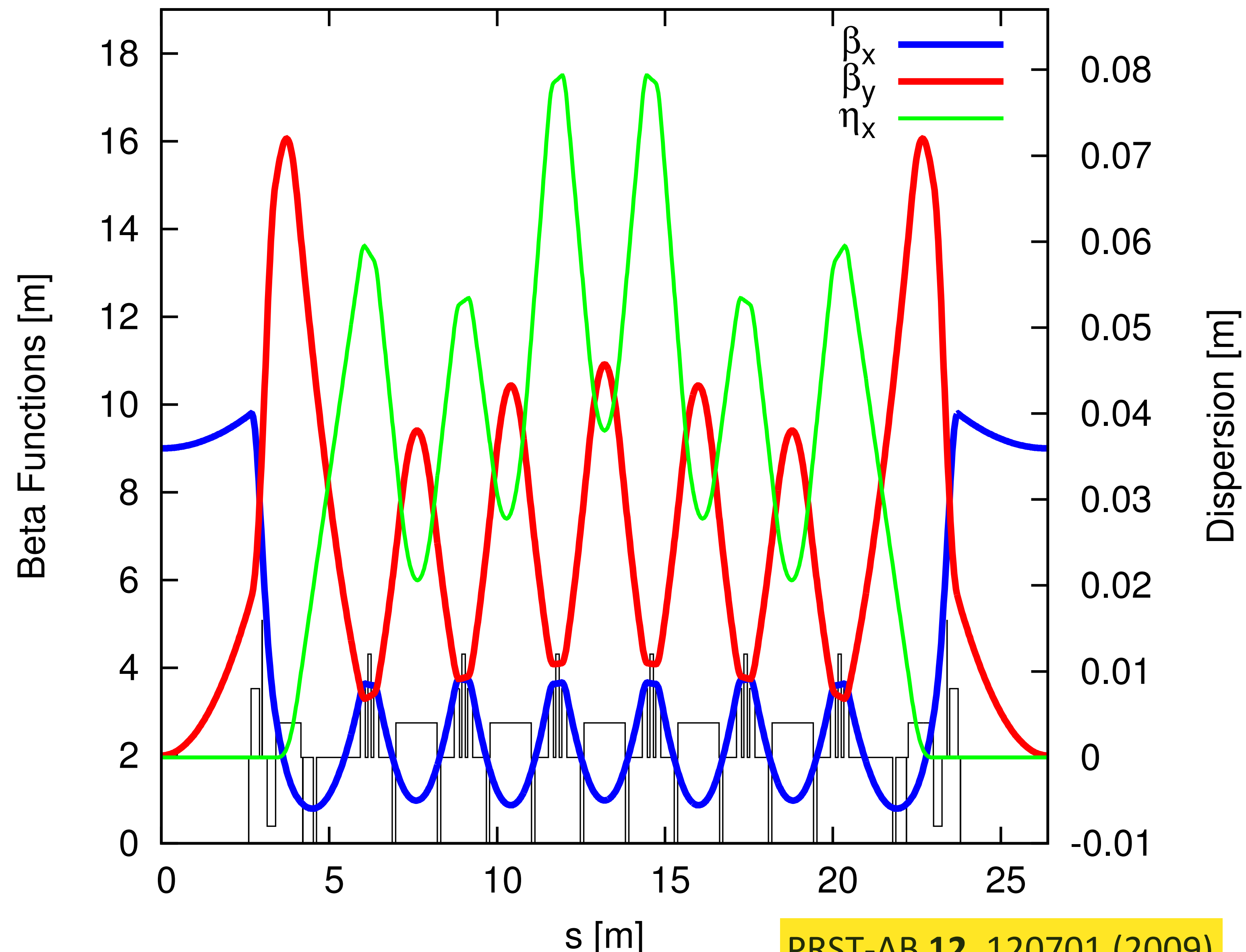
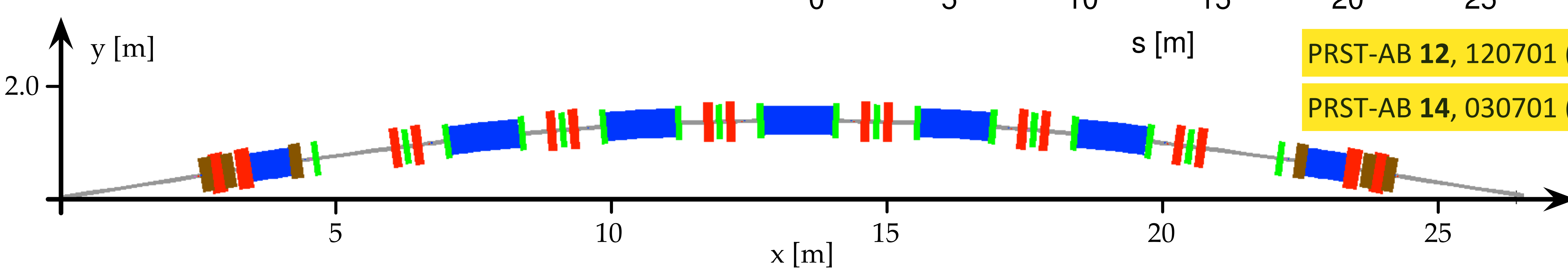


PRST-AB **12**, 120701 (2009)

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



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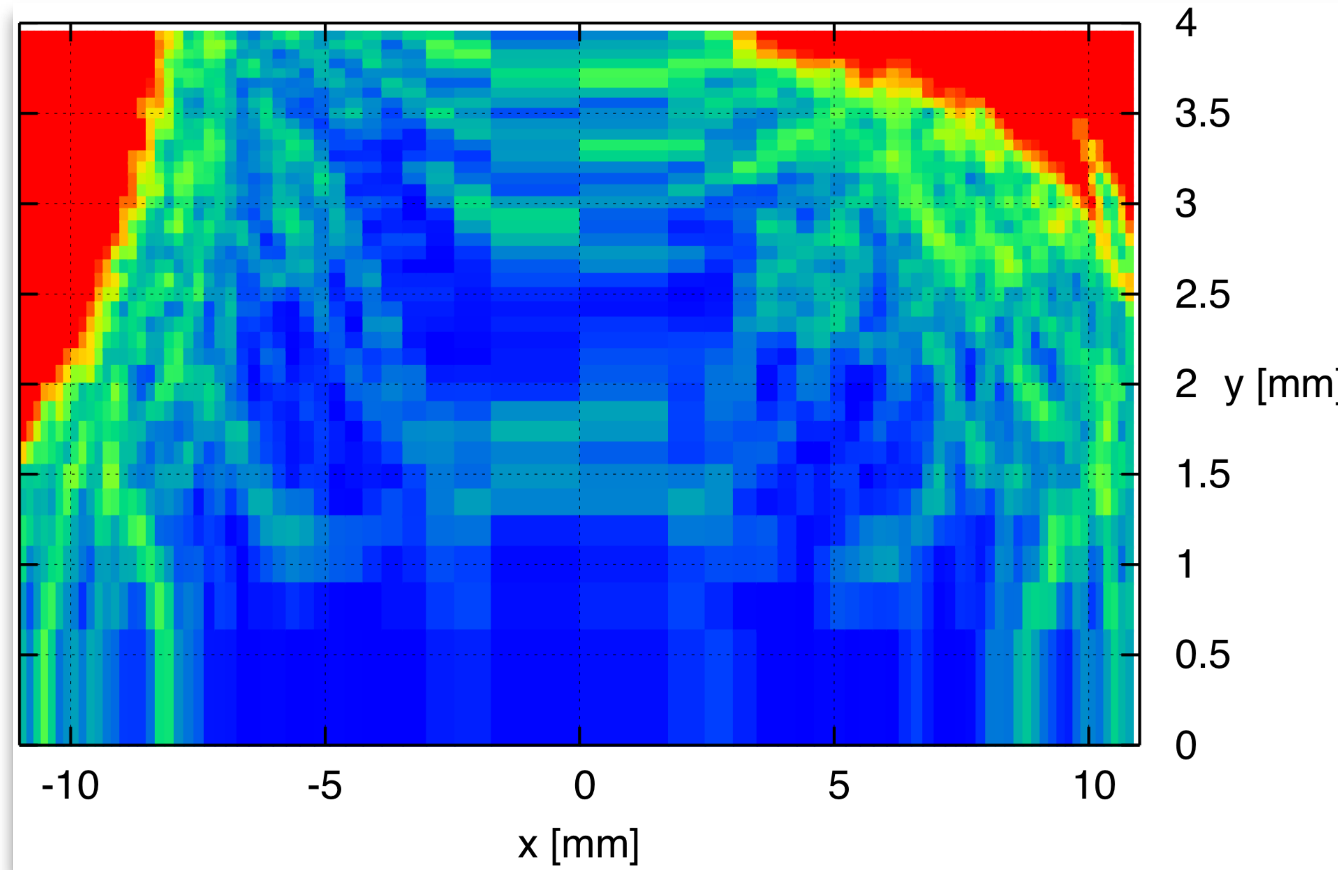

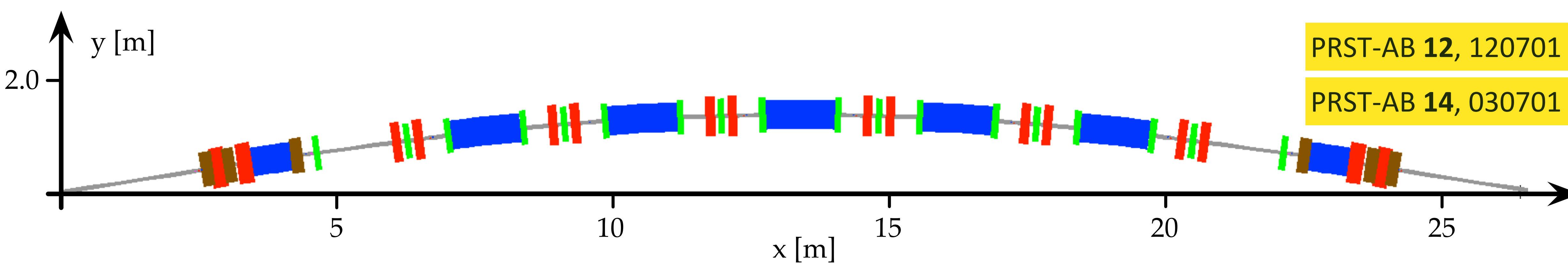

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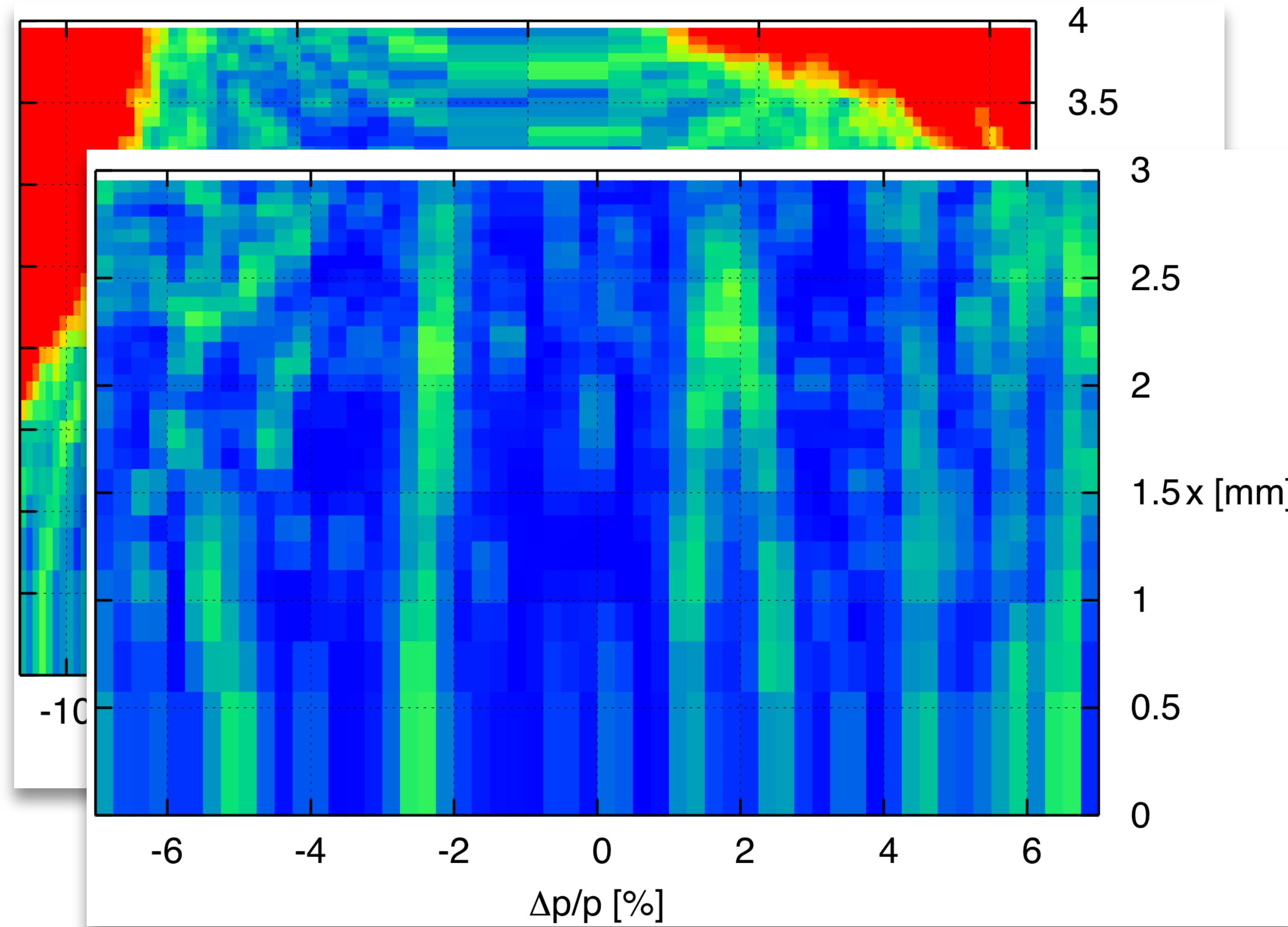

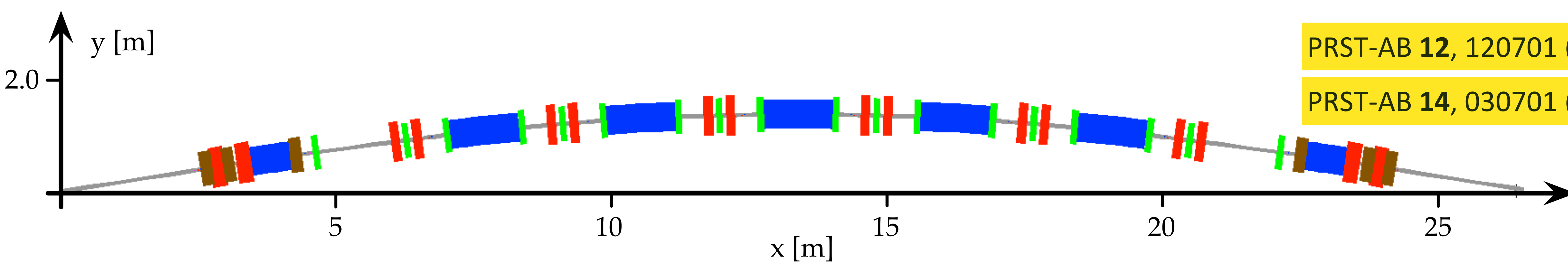

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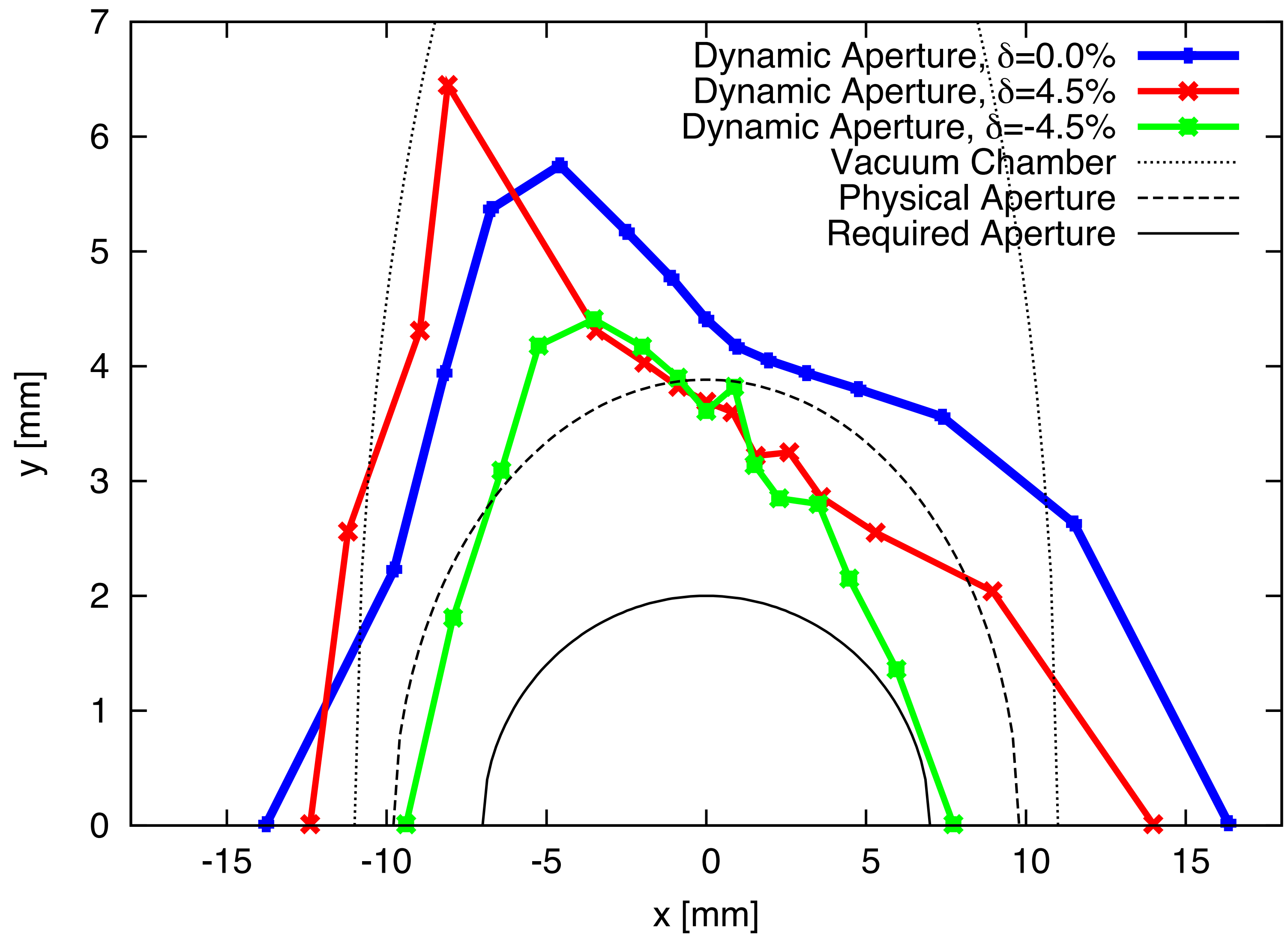

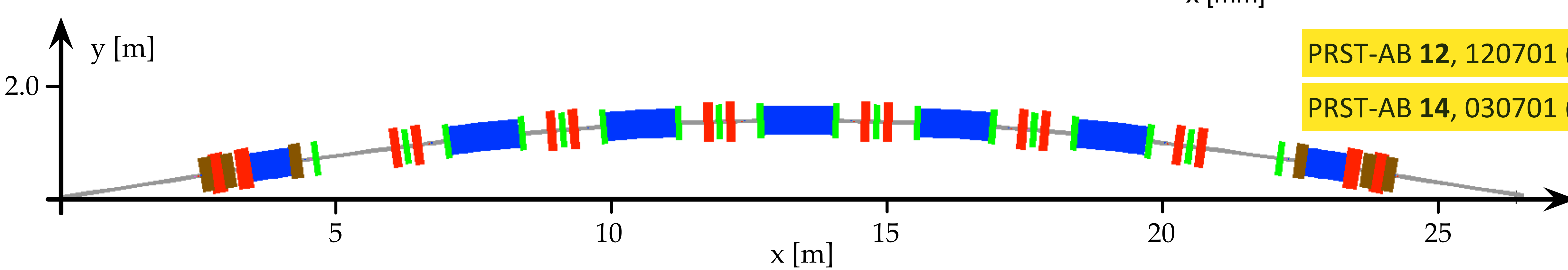

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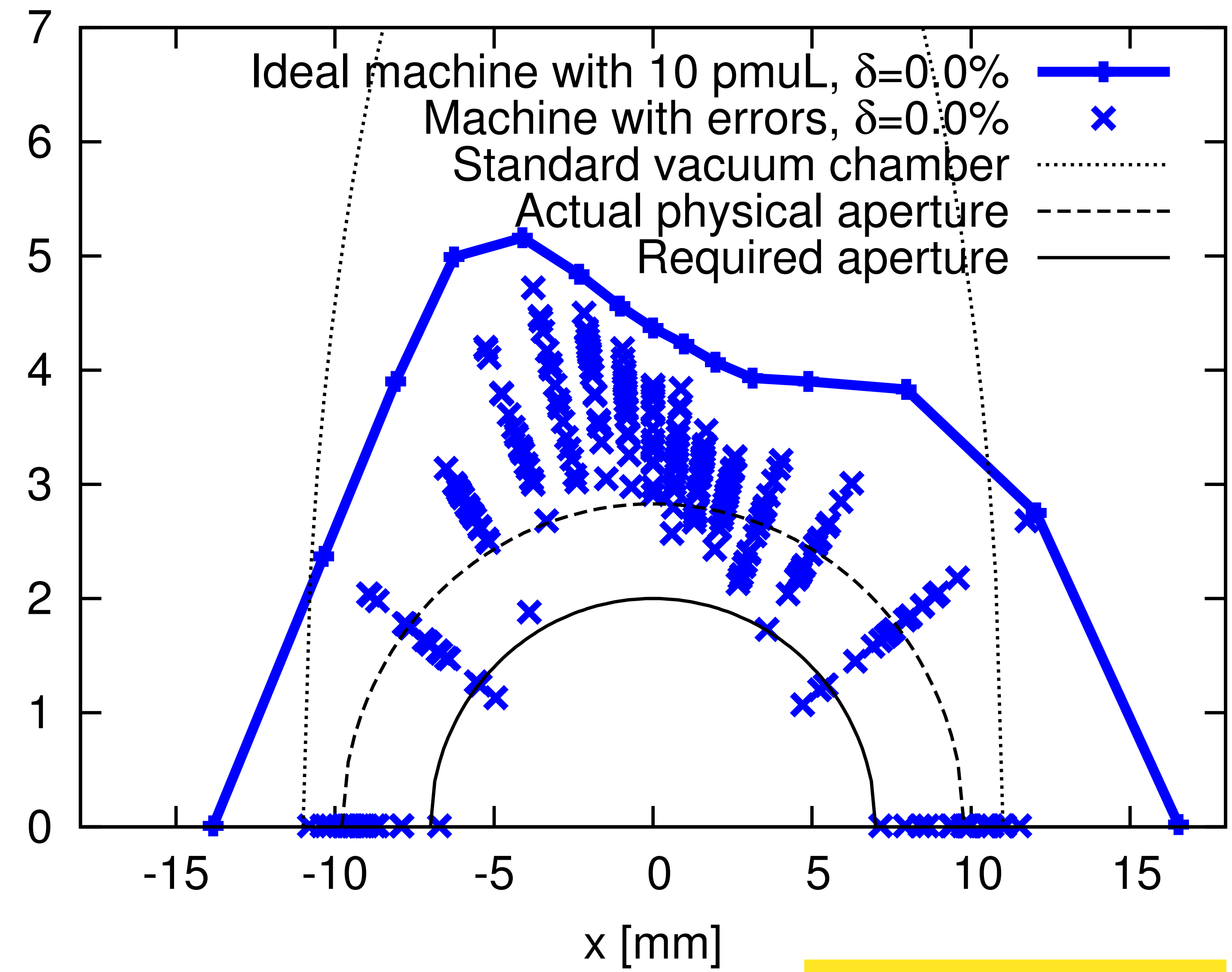
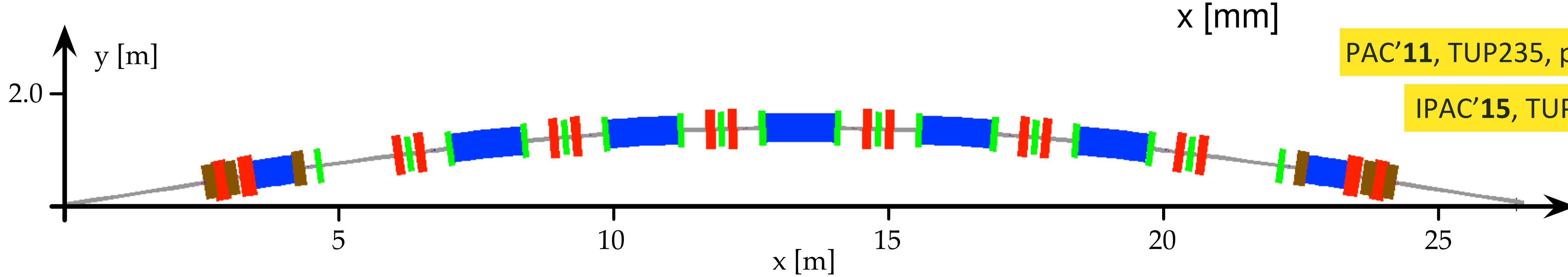


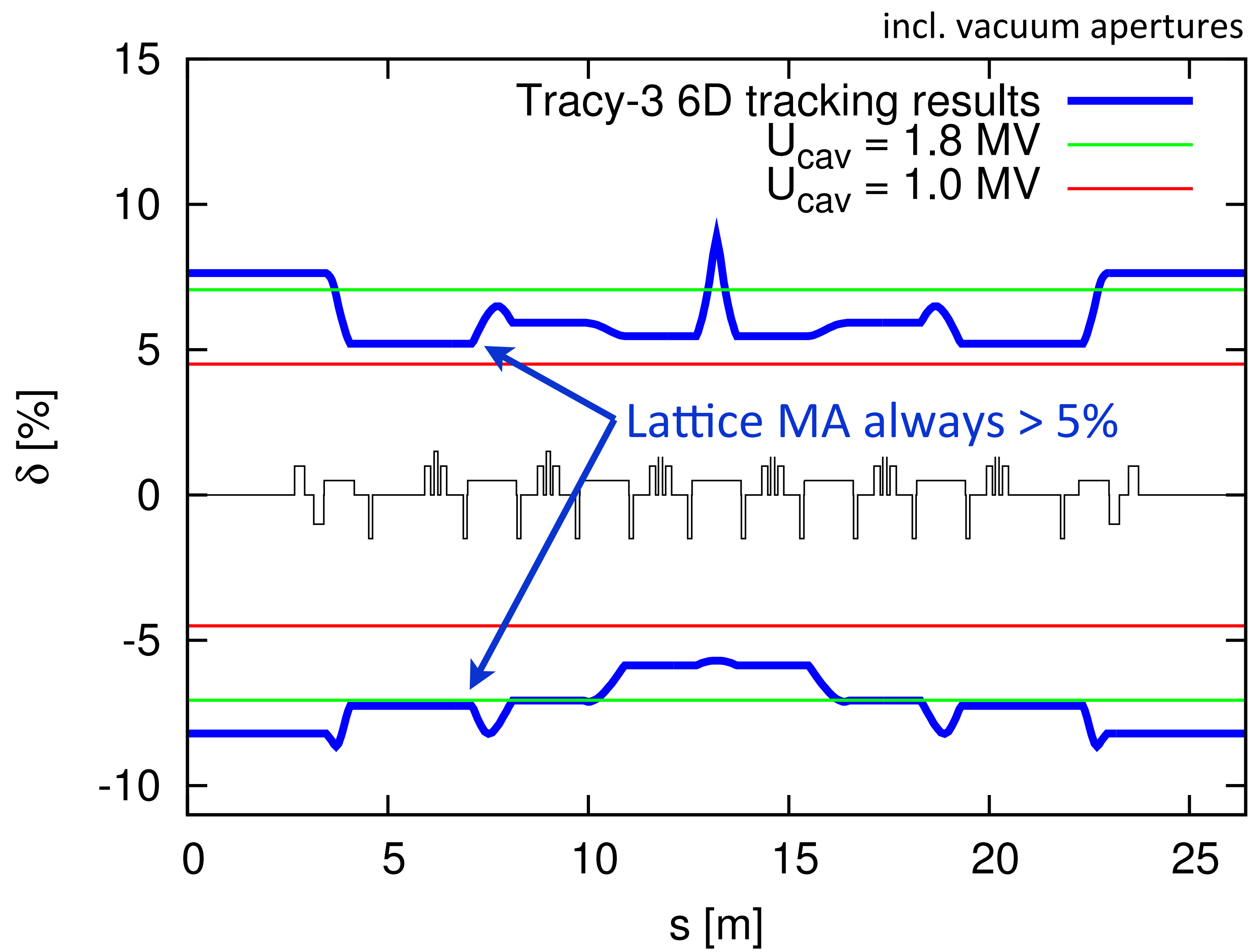
PAC'**11**, TUP235, p.1262

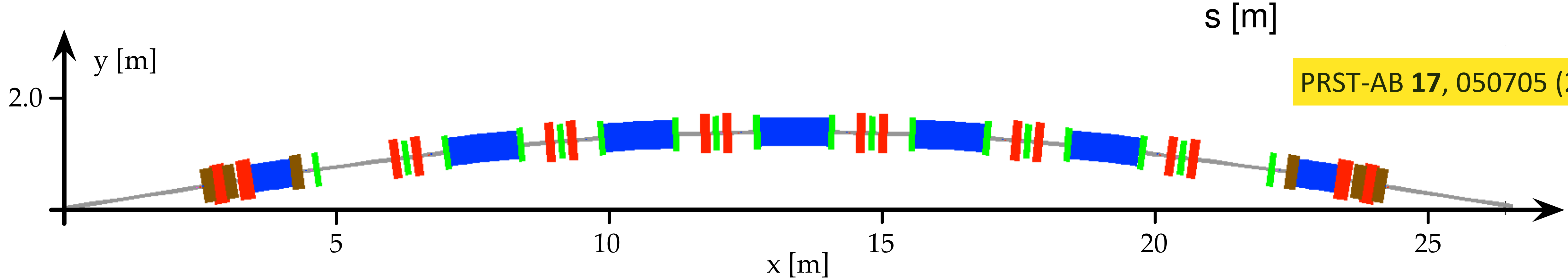
IPAC'**15**, TUPJE038



Optics and Performance (cont.)

- Many strong, distributed sextupoles & achromatic octupoles
  - ➡ minimize RDTs & tune footprint (chr.TS & ADTS)
  - ➡ large DA (on and off-energy, incl. IDs & errors)
  - ➡ good injection efficiency & large lattice MA





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

Technology

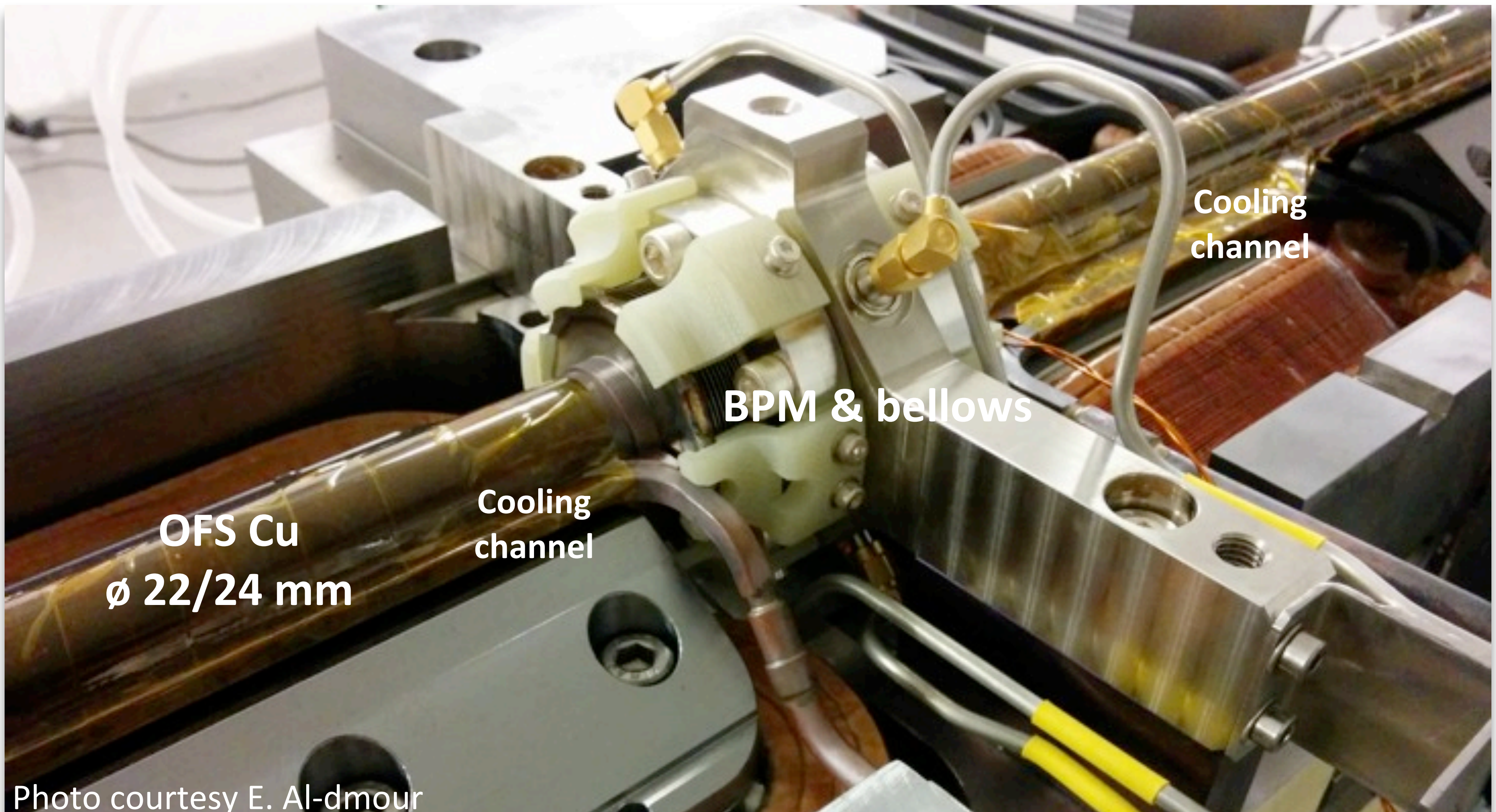
- 100 MHz main RF system with passive 3rd harmonic cavities

IPAC’**11**, MOPC051, p.193

Technology (cont.)

- 100 MHz main RF system with passive 3rd harmonic cavities
- Copper vacuum system with NEG coating

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



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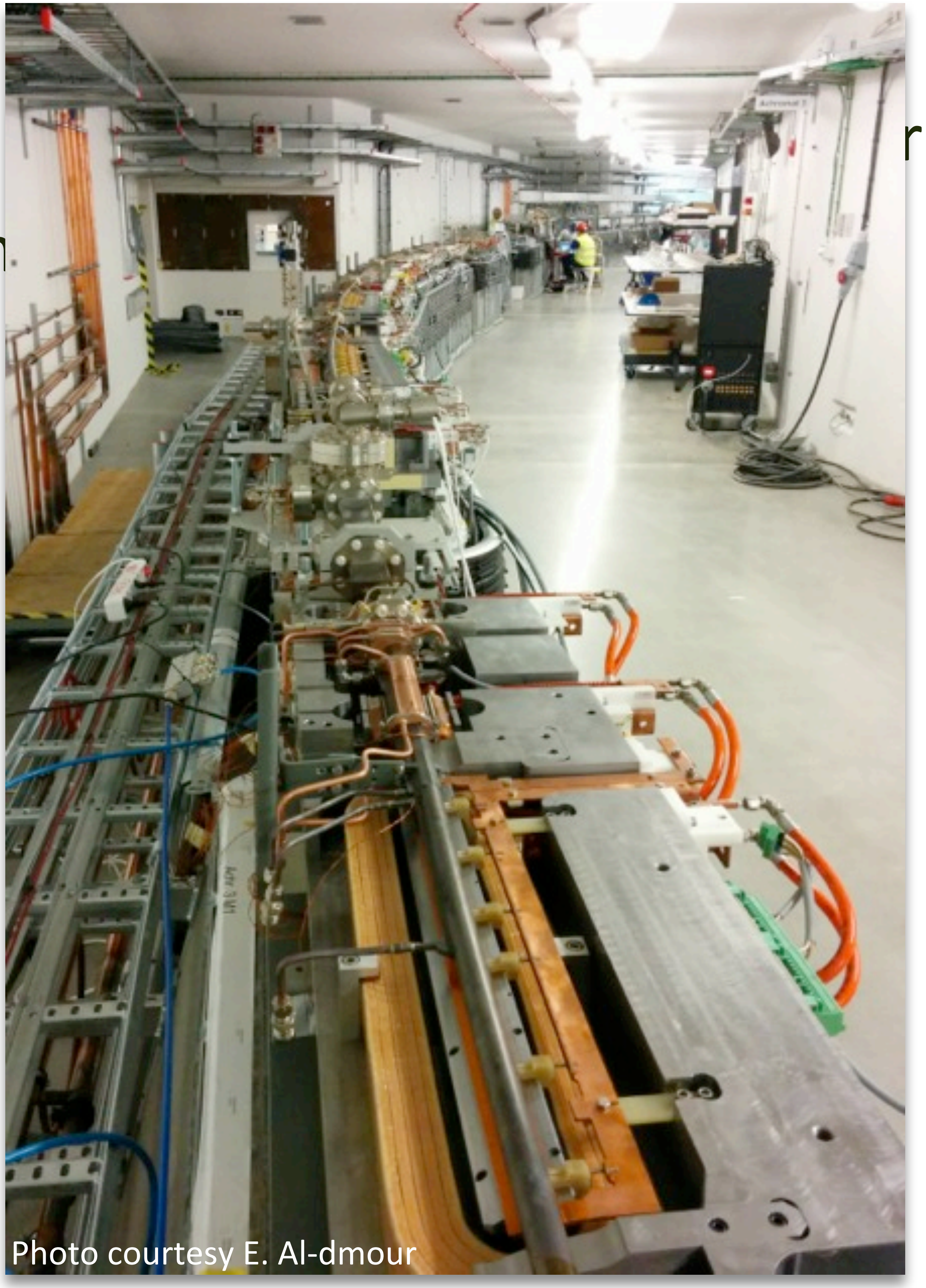
JSR **21**, 878-883 (2014)



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- 100 MHz main RF system with passive 3rd harmonic cavities
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  - Gradient dipoles equipped with pole-face strips → adjust vertical focusing within roughly ±4% (requires dipole feedback)

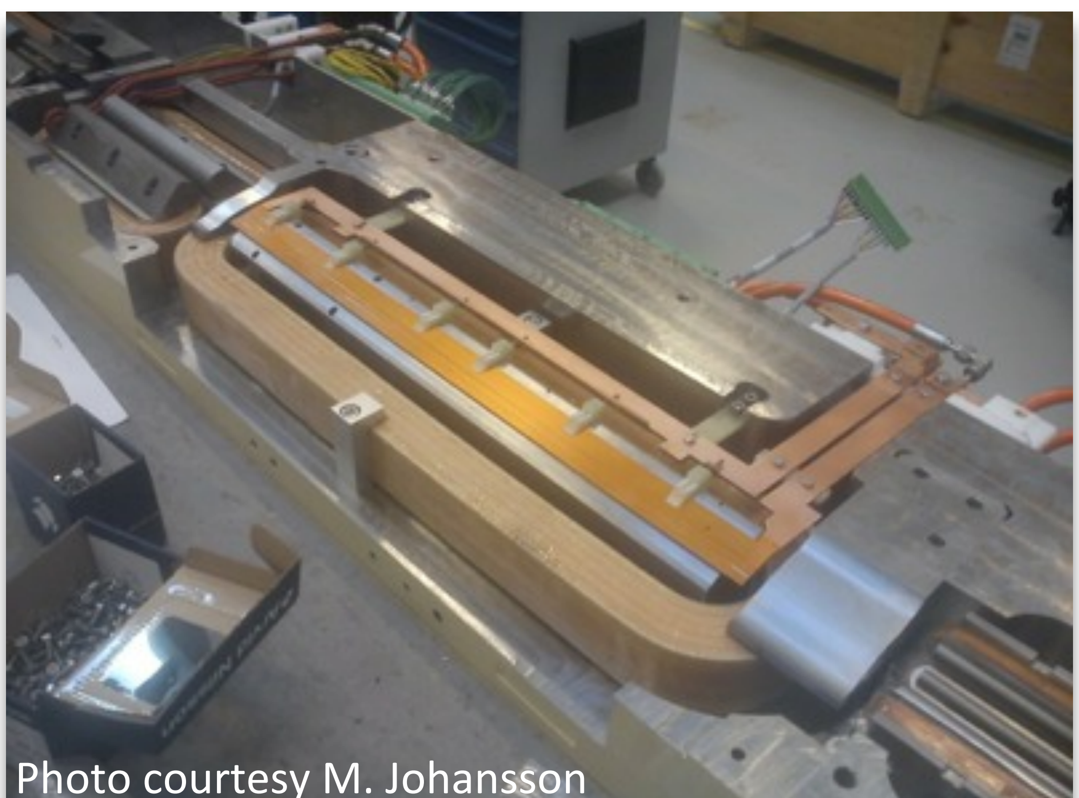
Photo courtesy M. Johansson


Photo courtesy A. Nyberg

Technology (cont.)

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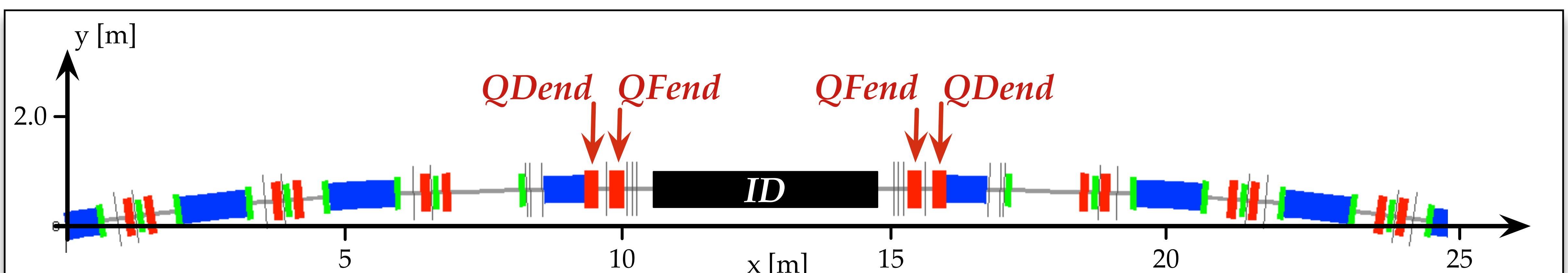
  - Quadrupole doublets in long straights → match optics to IDs and restore tunes (ideally makes IDs transparent to arc optics)

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

IPAC'**15**, TUPJE038



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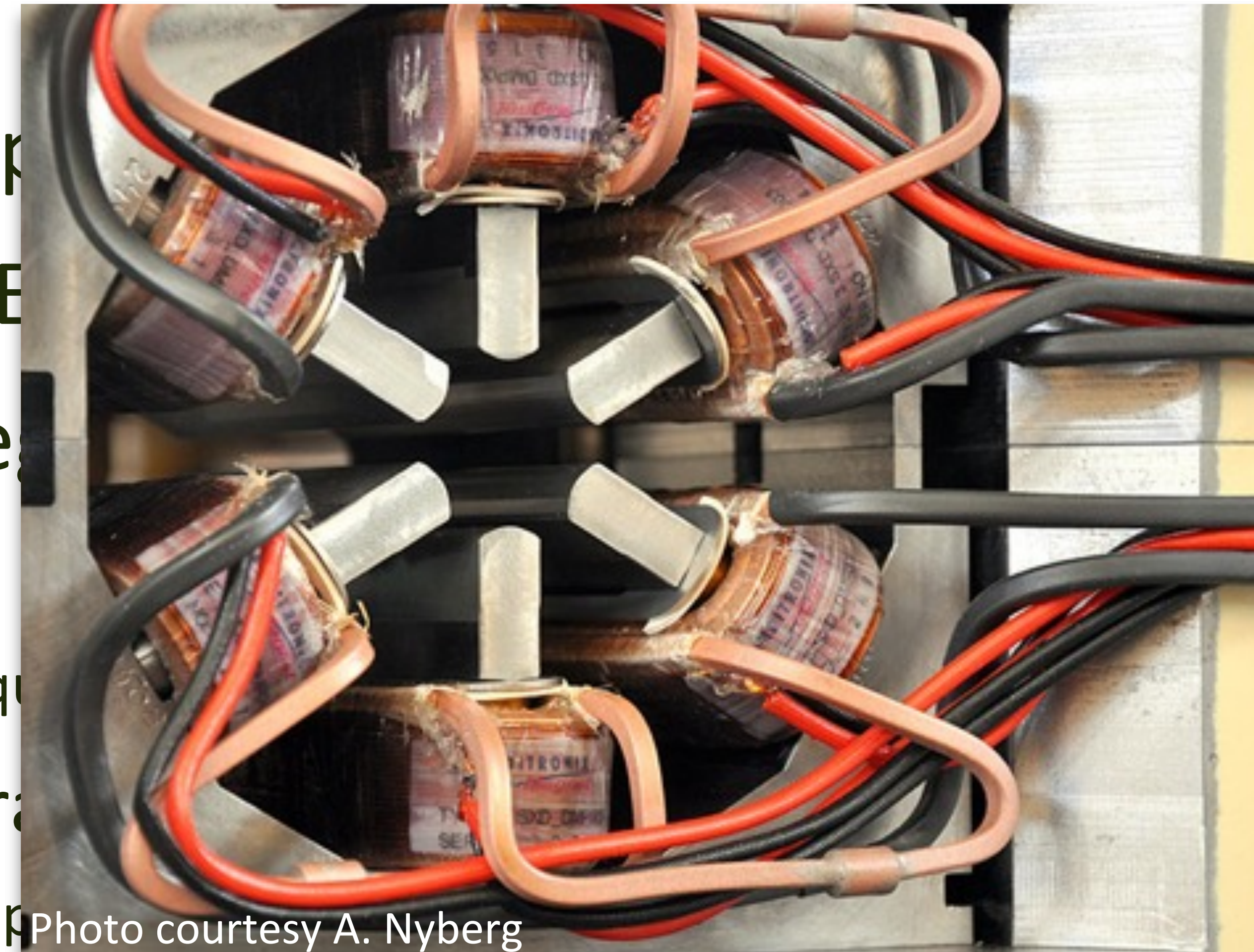
Photo courtesy A. Nyberg

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- Various optics corrections (inte
  - Gradient dipoles equipped with focusing within roughly ±4% (requ
  - Quadrupole doublets in long stra restore tunes (ideally makes IDs transp
  - All sextupoles and octupoles carry auxiliary windings; can be remotely switched between:
    - H/V dipole corrector (in addition to dedicated SOFB & FOFB correctors)
    - Auxiliary sextupole → nonlinear corrections
    - Skew quadrupole → ***coupling & dispersion control***
    - Upright quadrupole → ***calibrate BPMs to adjacent sextupole/octupole***

Linac & Injection

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

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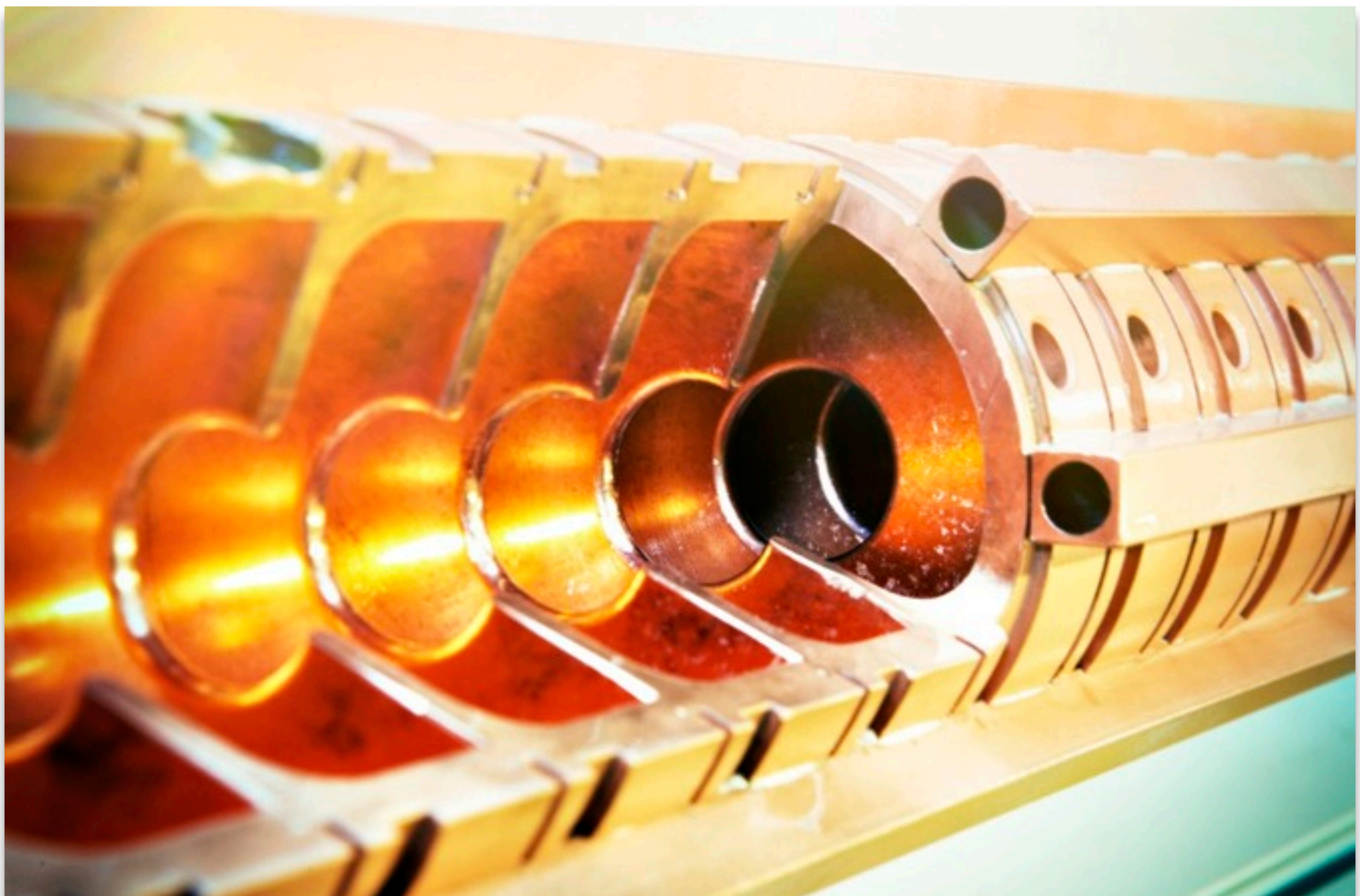

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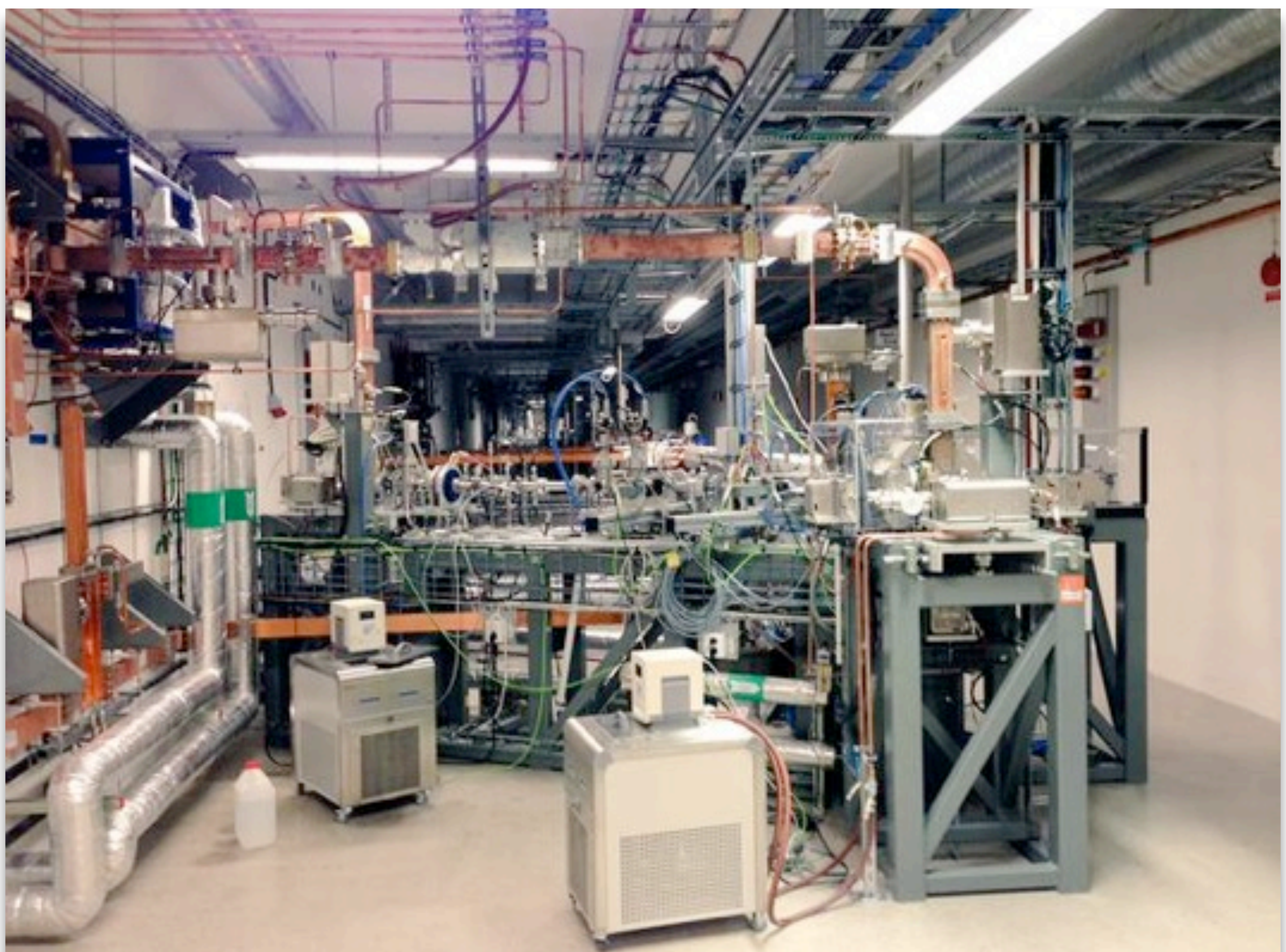

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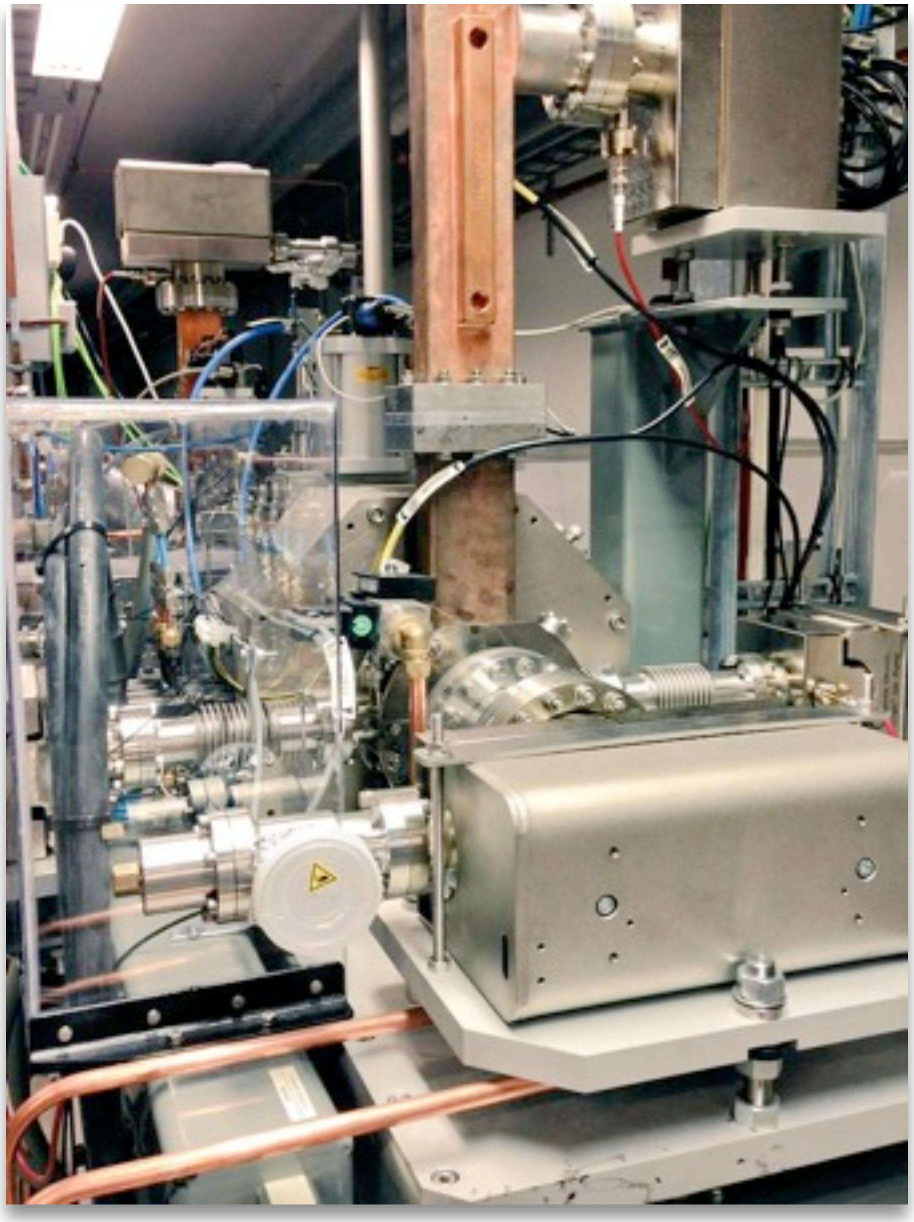
- Two injector systems:
  - Photocathode RF gun → SPF and FEL
    (100 pC at 100 Hz, 1 mm mrad, ≈10 ps → 100 fs FWHM)



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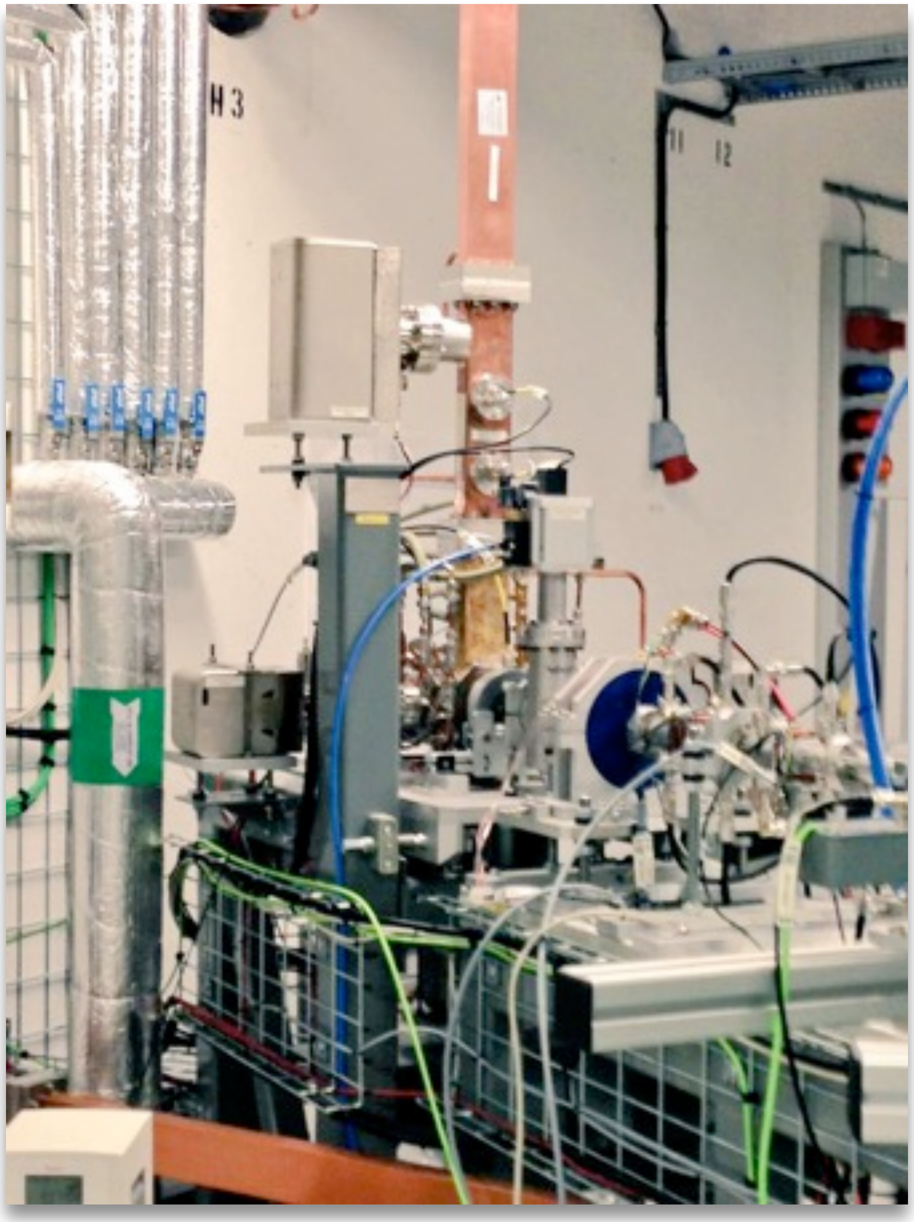
- Two injector systems:
  - Photocathode RF gun ➔ SPF and FEL (100 pC at 100 Hz, 1 mm mrad, ≈10 ps ➔ 100 fs FWHM)
  - Thermionic RF gun (with RF chopper and energy filter) ➔ high-charge injection into SRs (1 nC in 100 ns train at 10 Hz, ≈10 mm mrad)



Linac & Injection (cont.)

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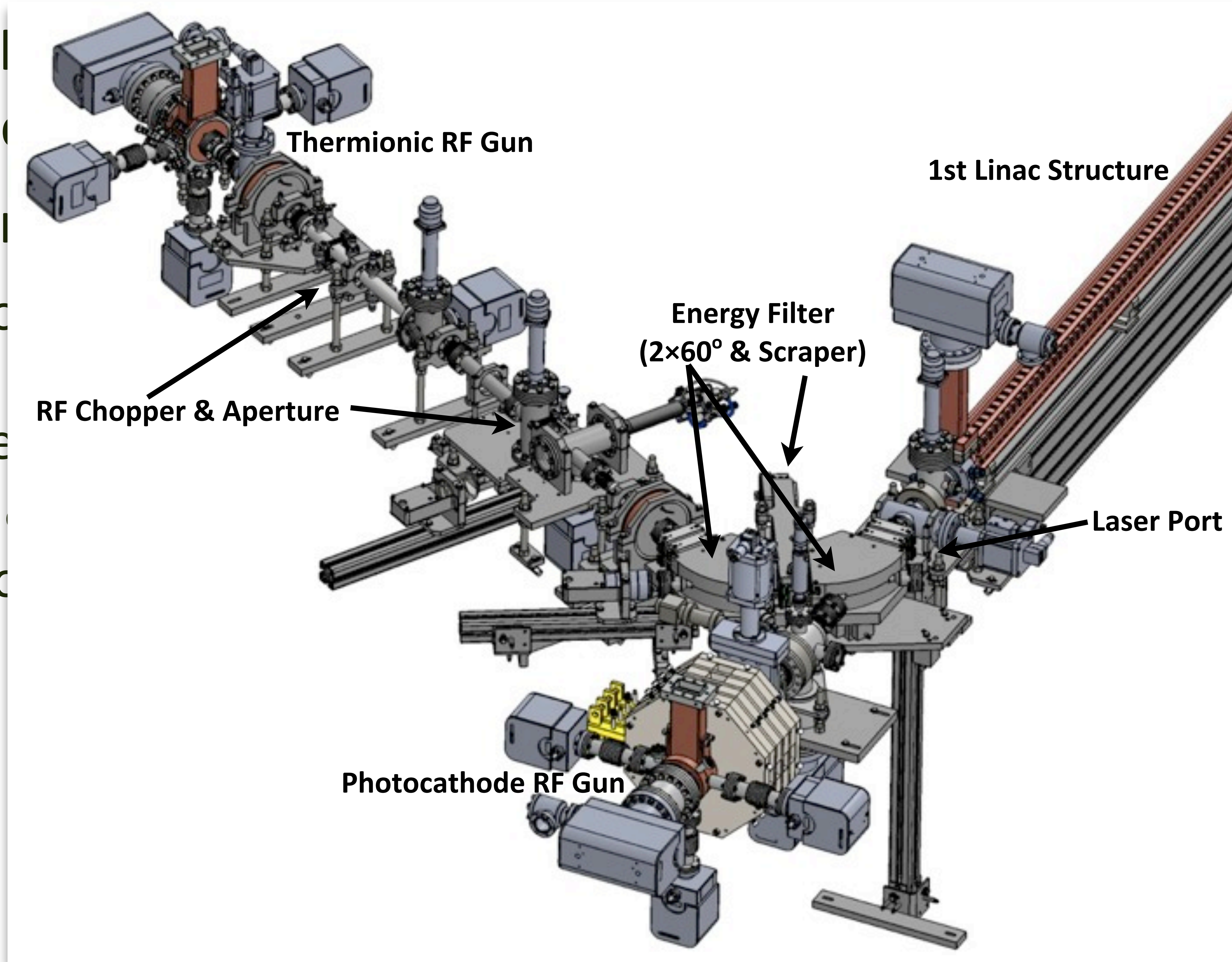

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  - Thermionic RF gun (with RF chopper and energy filter) → high-charge injection into SRs (1 nC in 100 ns train at 10 Hz, ≈10 mm mrad)
- For SPF/FEL: linac contains two magnetic bunch compressors
- For top-up injection into SRs → on-the-fly switching:
  - Linac re-phased to on-crest acceleration → no compression
  - Ramp extraction magnets to either vertical transfer line (1.5 & 3 GeV)

Linac & Injection (cont.)

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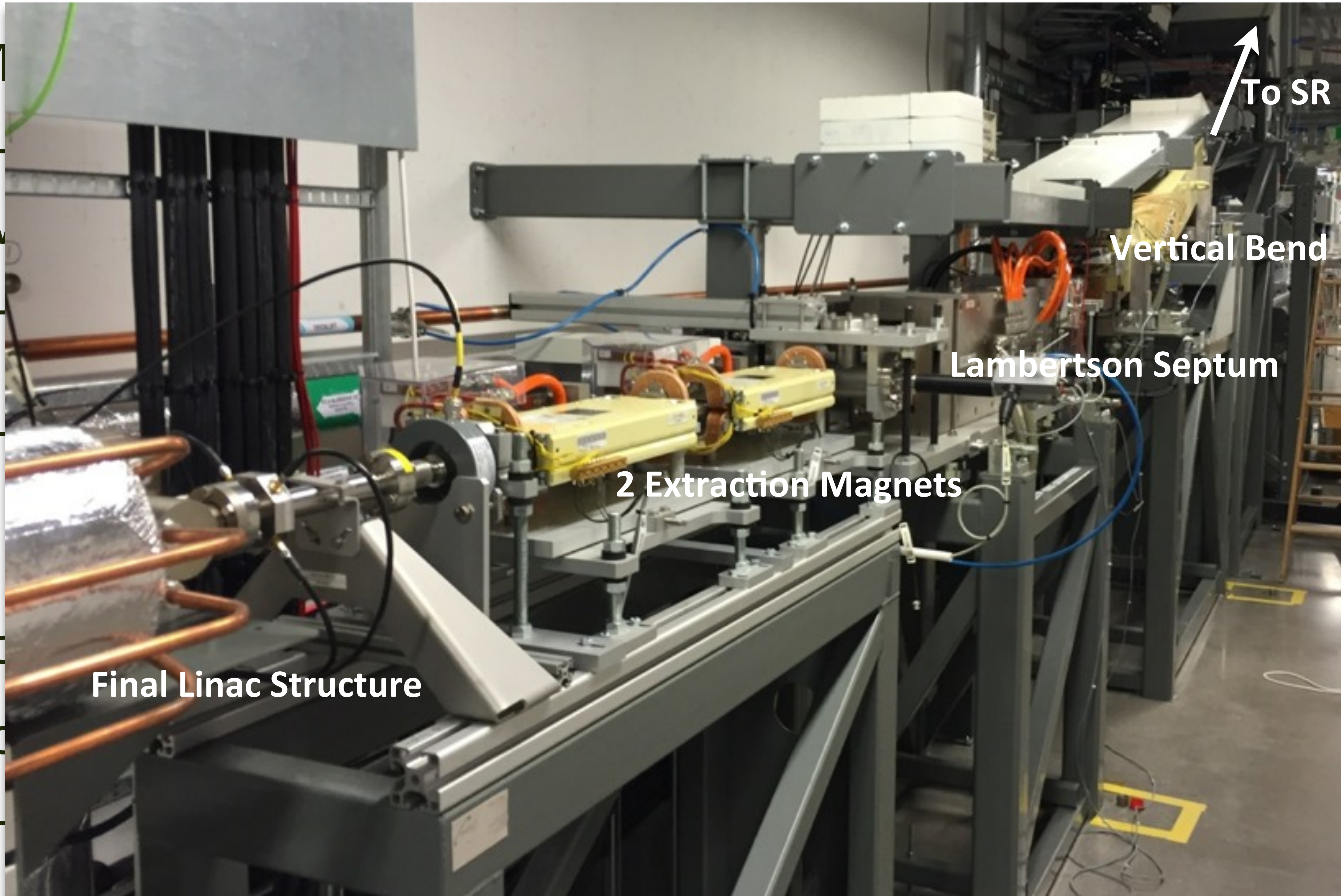

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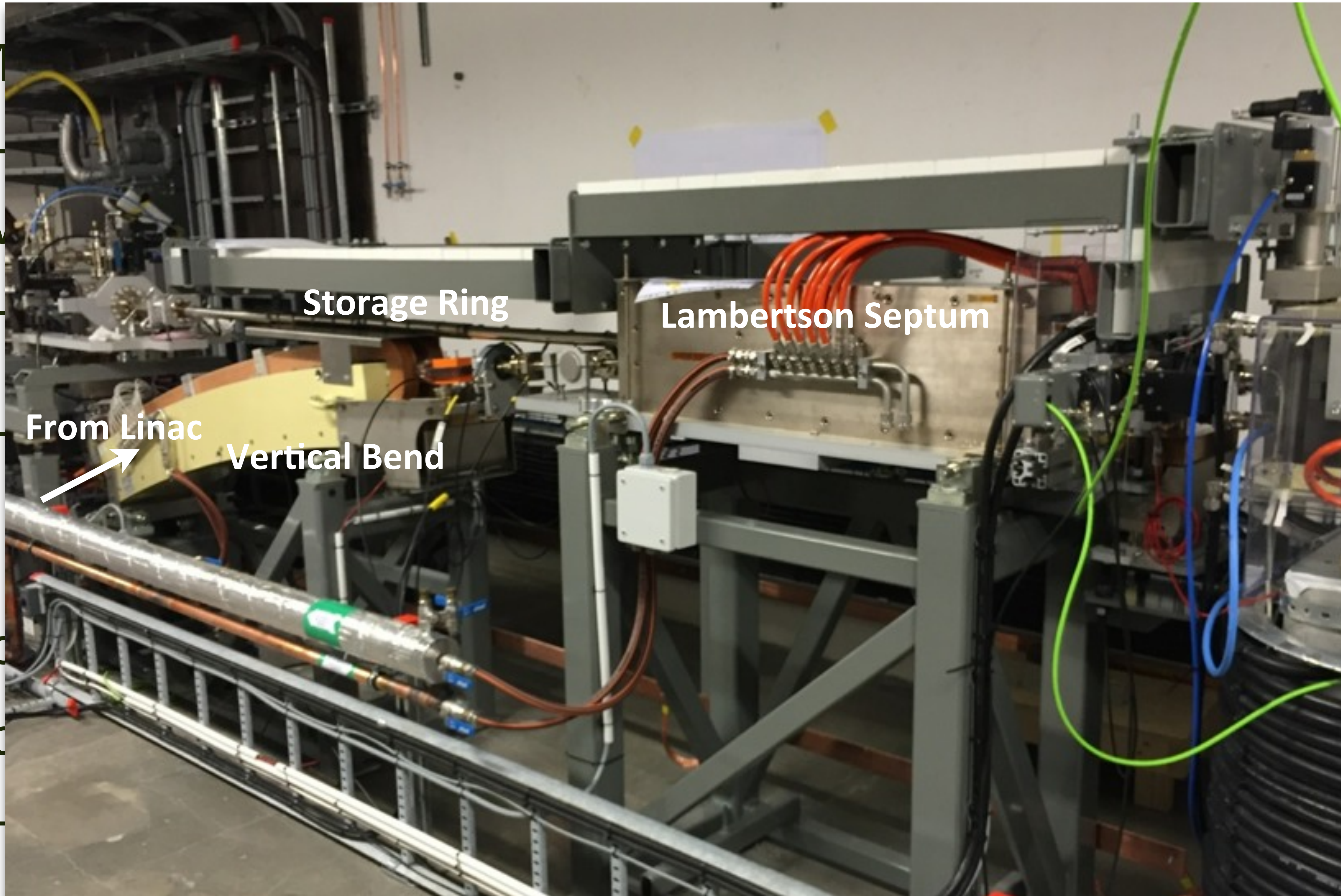
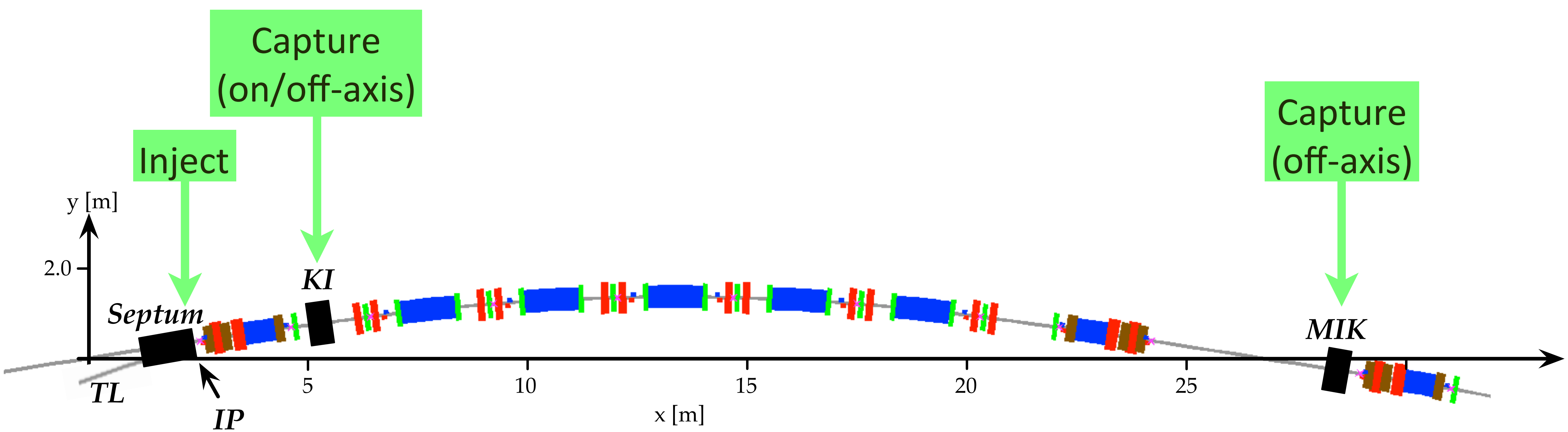


Linac & Injection (cont.)

- Injection
  - Nonlinear kicker (MIK) → transparent top-up injection, but tricky to commission (kick scales ≈ x^3)
  - Single dipole kicker (KI) → use during early commissioning

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

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



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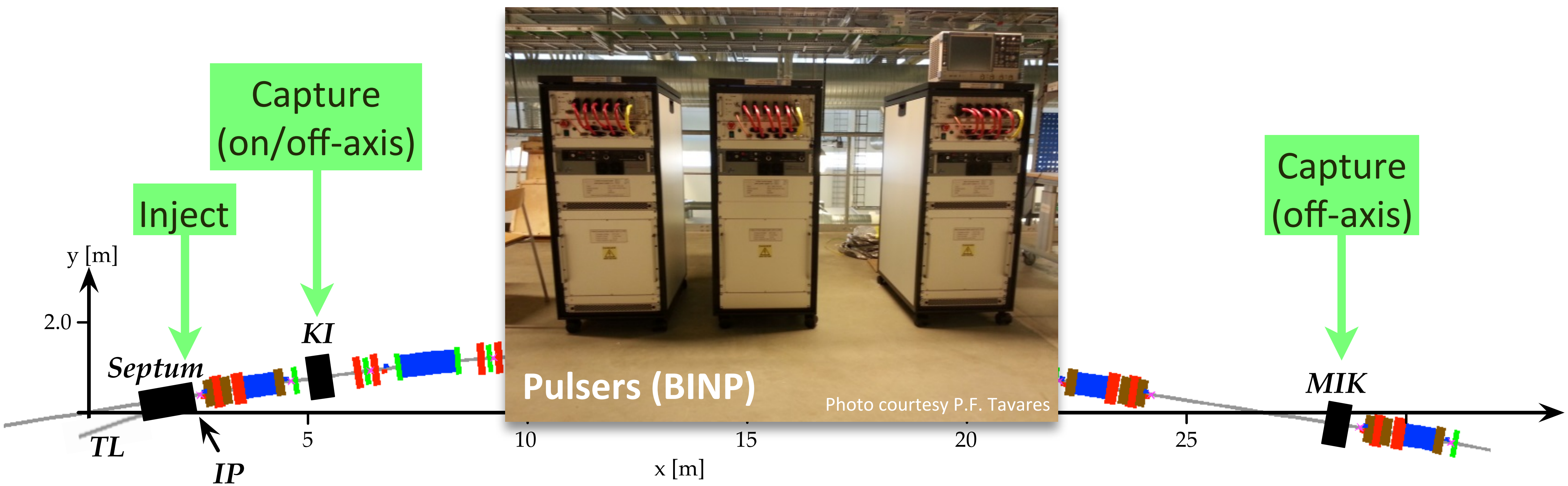


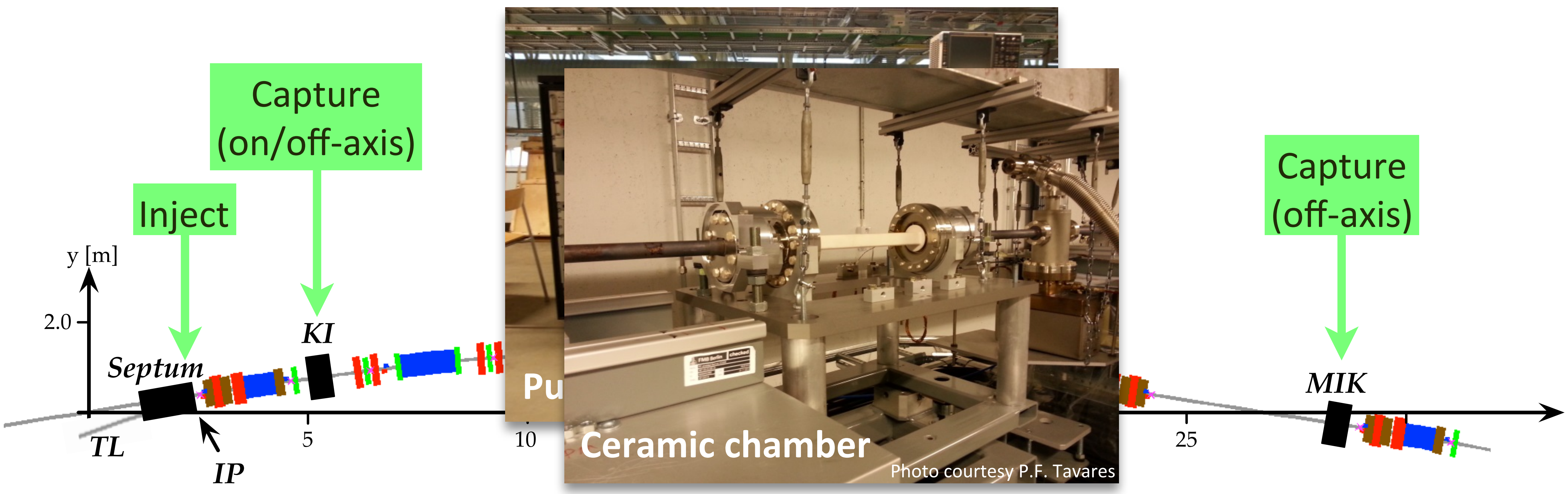
IPAC'**14**, MOPME072

Linac & Injection (cont.)

- Injection
  - Nonlinear kicker (MIK) → transparent top-up injection, but tricky to commission (kick scales ≈ x^3)
  - Single dipole kicker (KI) → use during early commissioning

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

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



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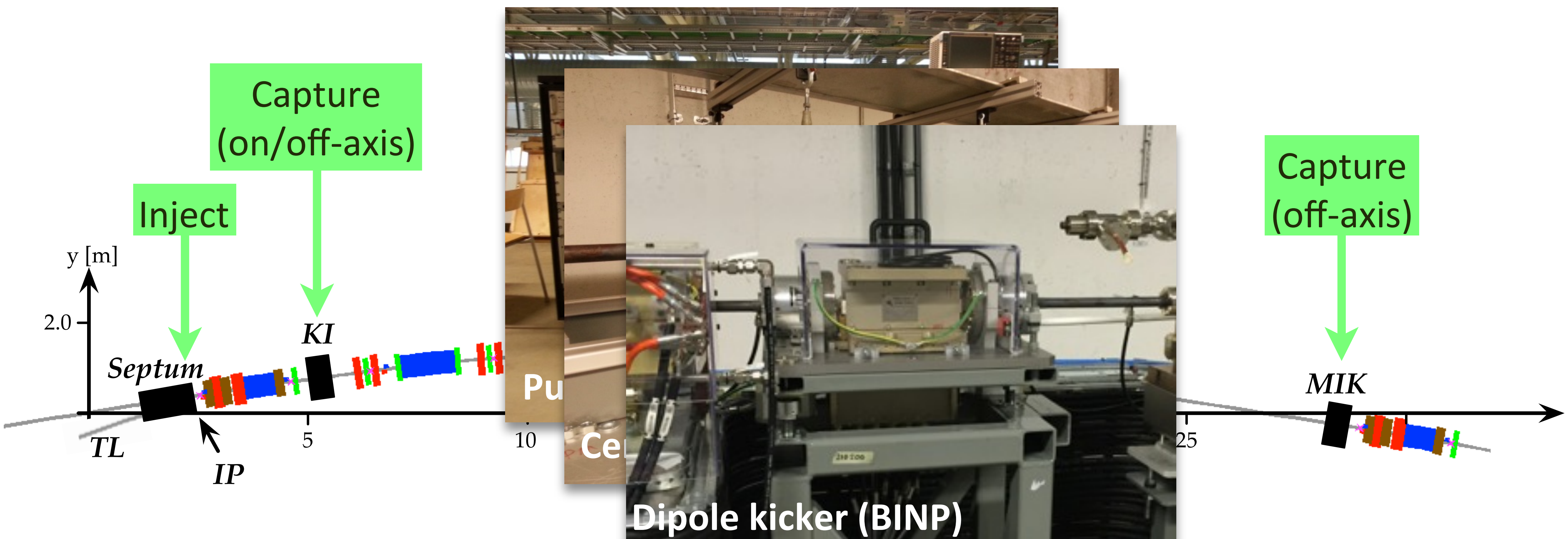
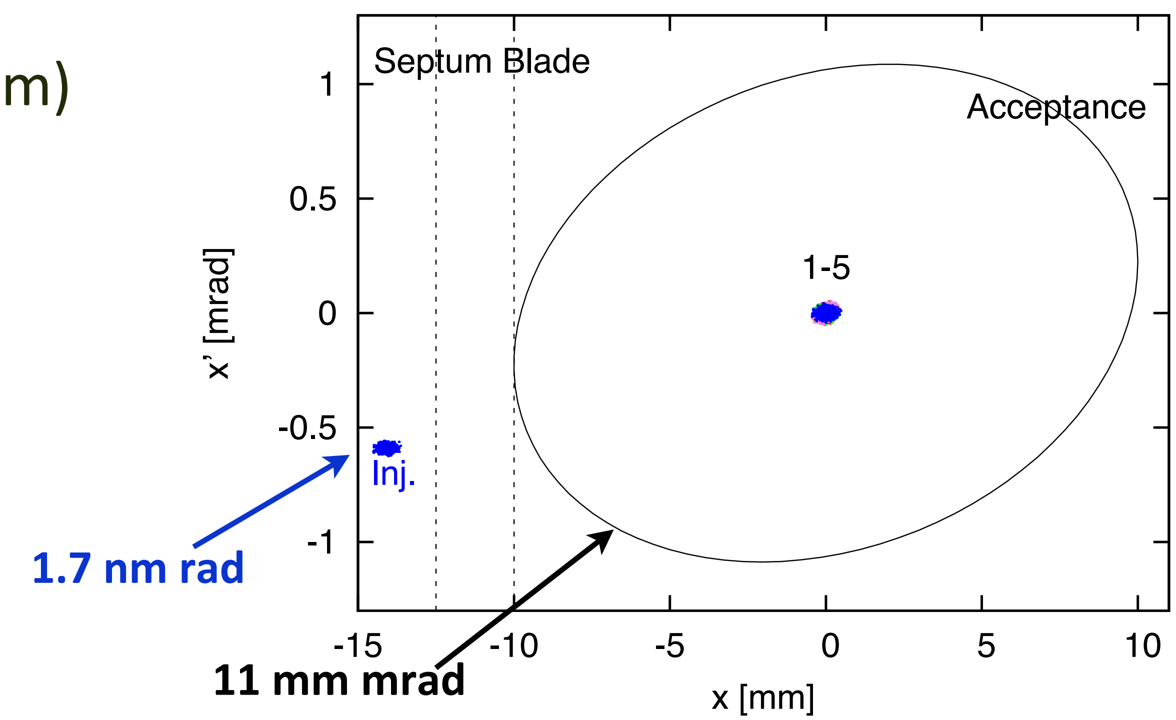
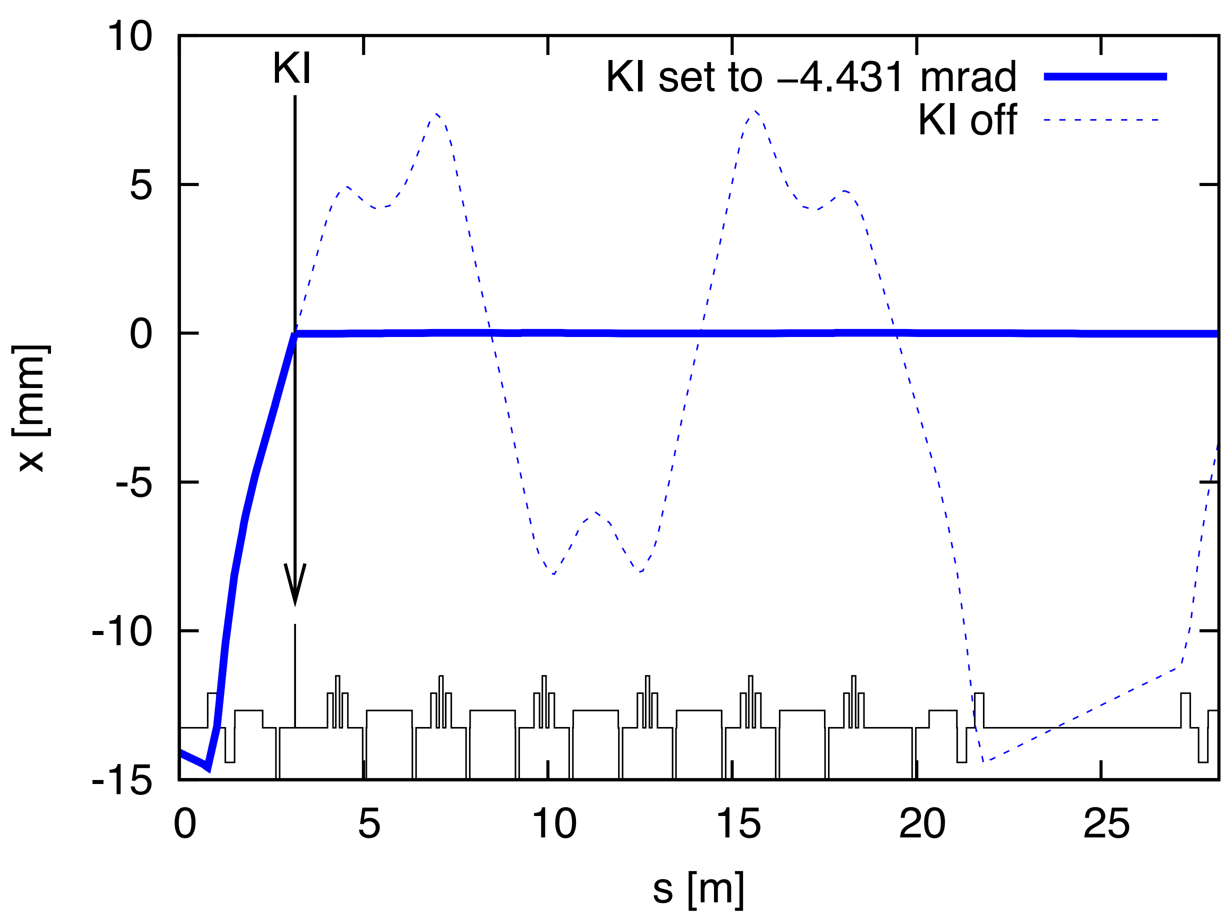


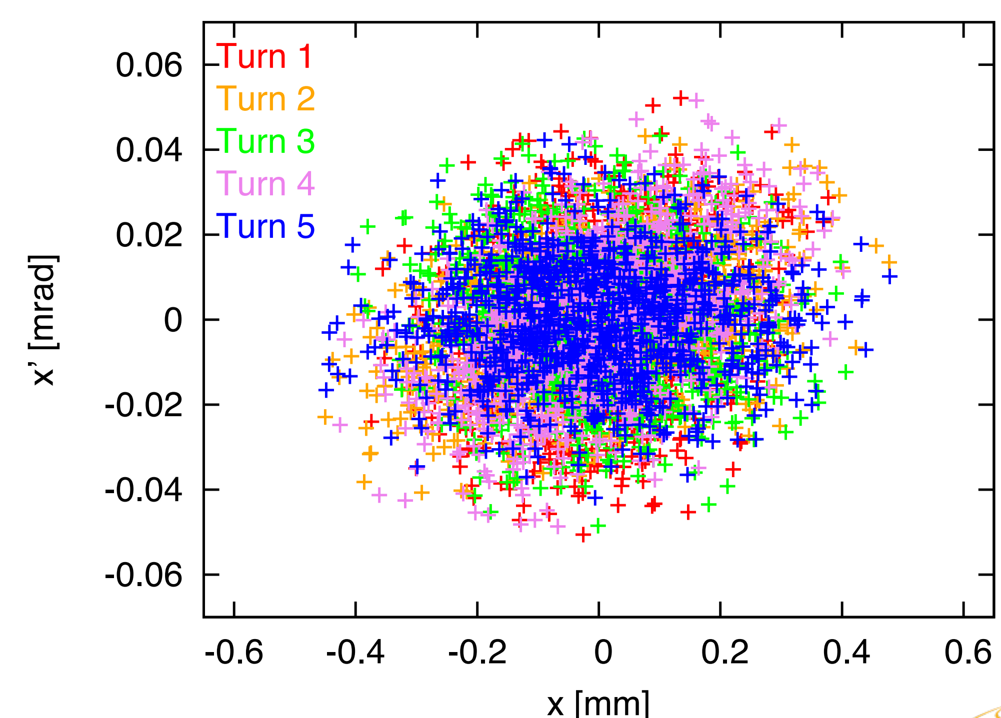
Linac & Injection (cont.)

- 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

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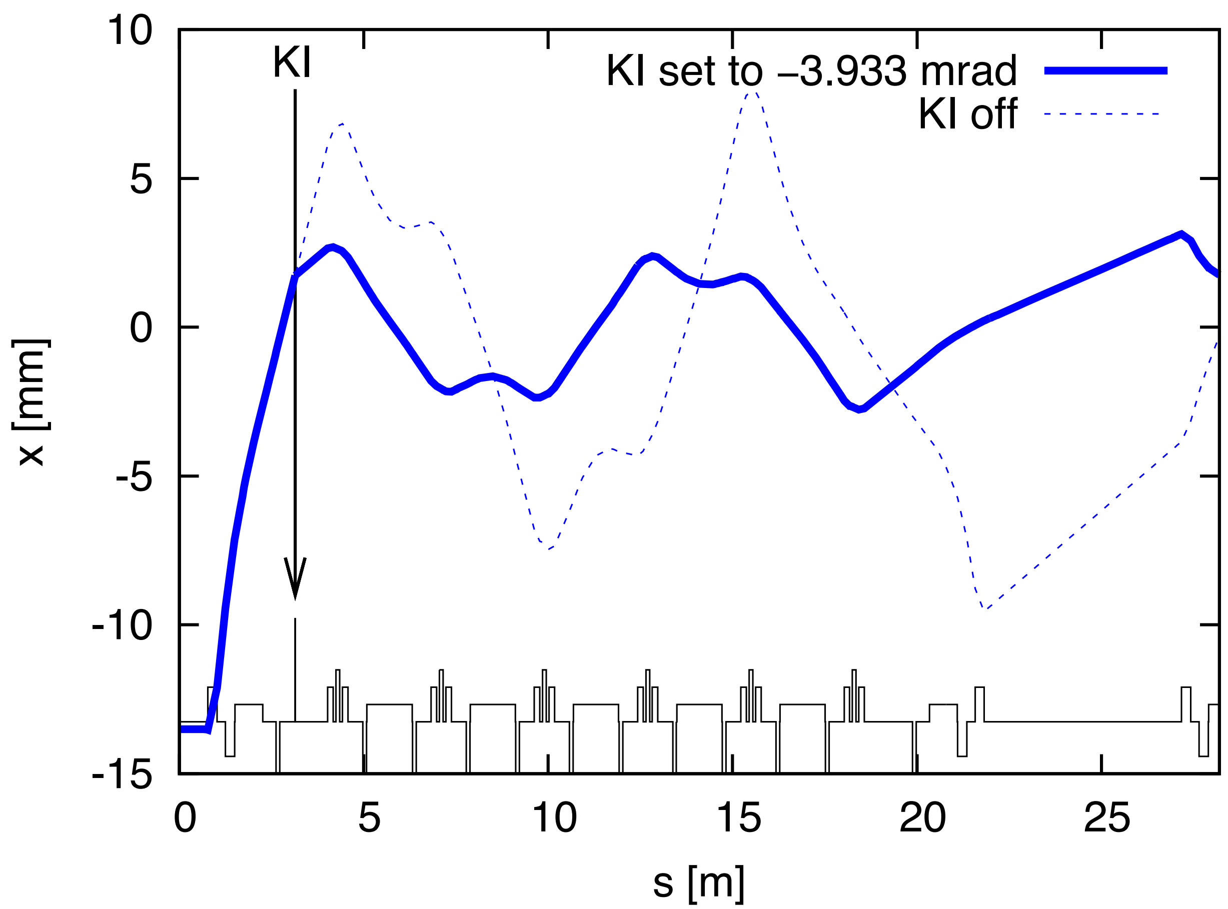
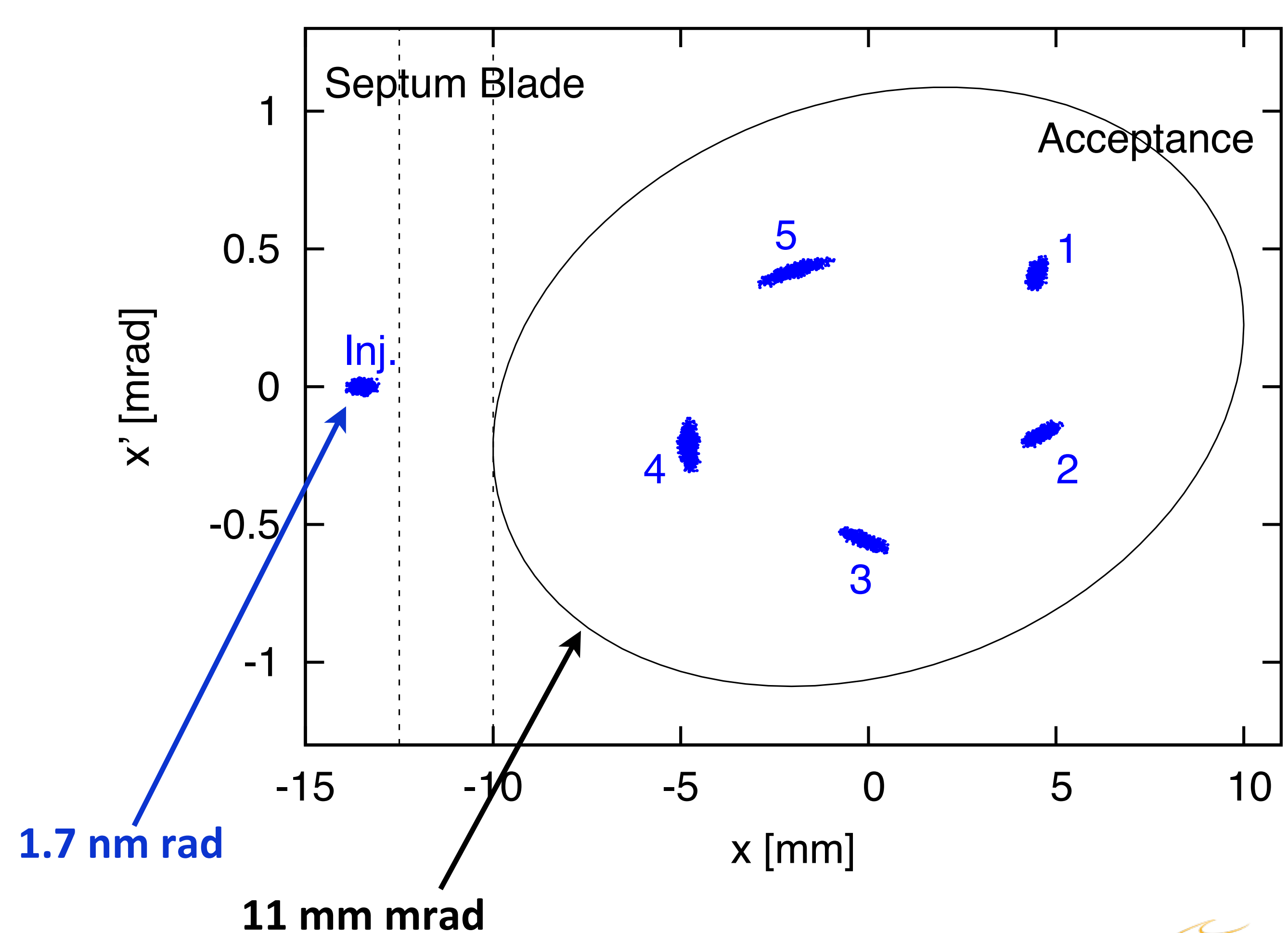
  - off-axis injection





Linac & Injection (cont.)

- Injection with a single dipole kicker:
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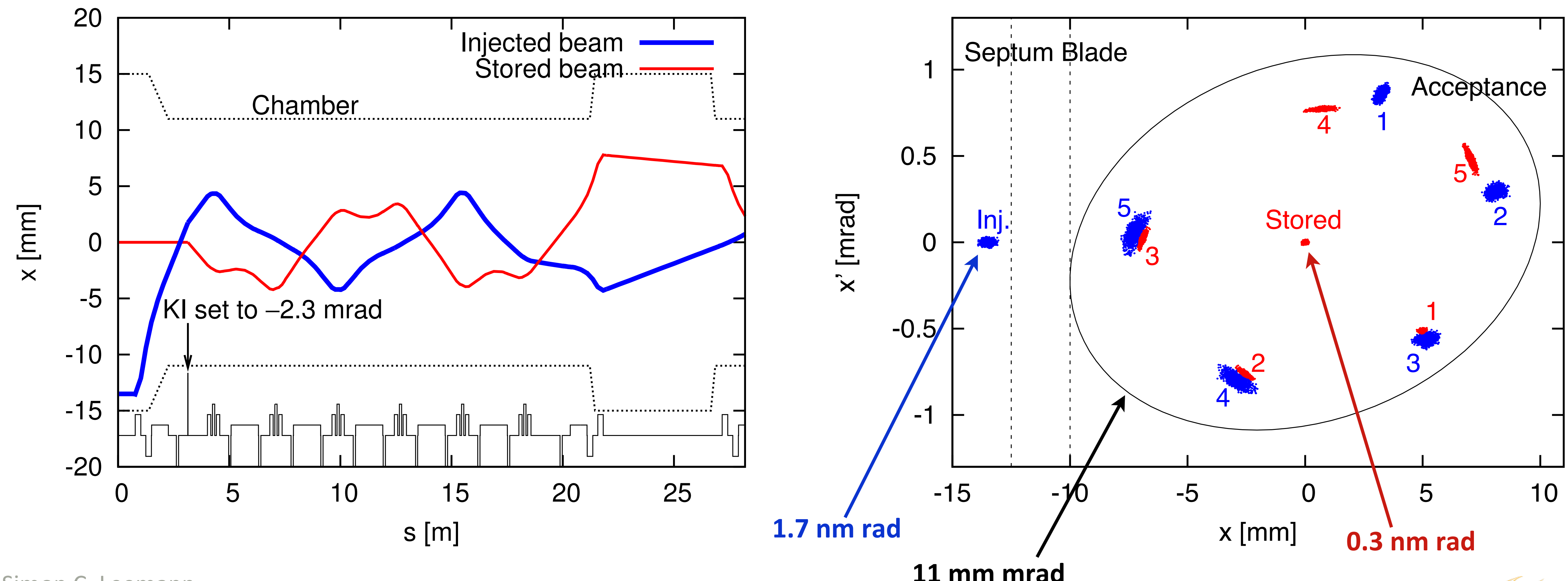
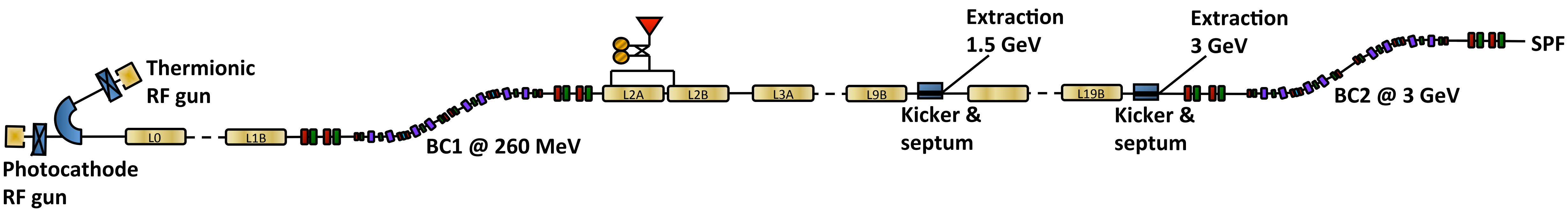
  - and allows for accumulation

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



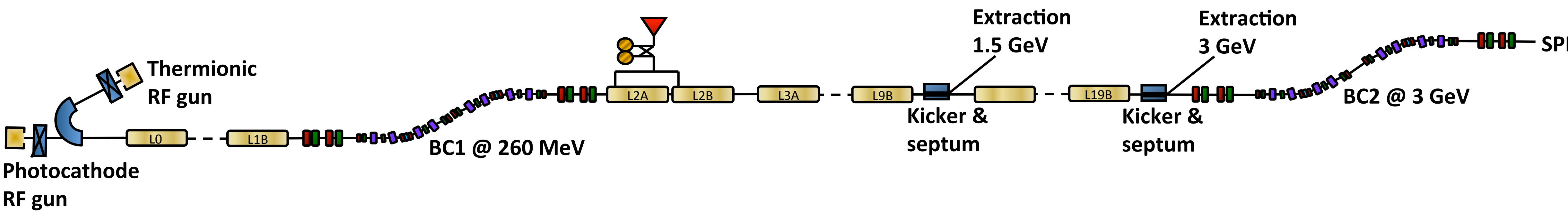
Linac Commissioning Summary

- Linac commissioning started March 2014 with conditioning of RF structures; after vacuum intervention (waveguides & SLEDs)
  - 13 of 19 stations running at full power (e.g. 100 MeV from L0)
  - all other structures reached 95% power → 3.2 GeV in BC2

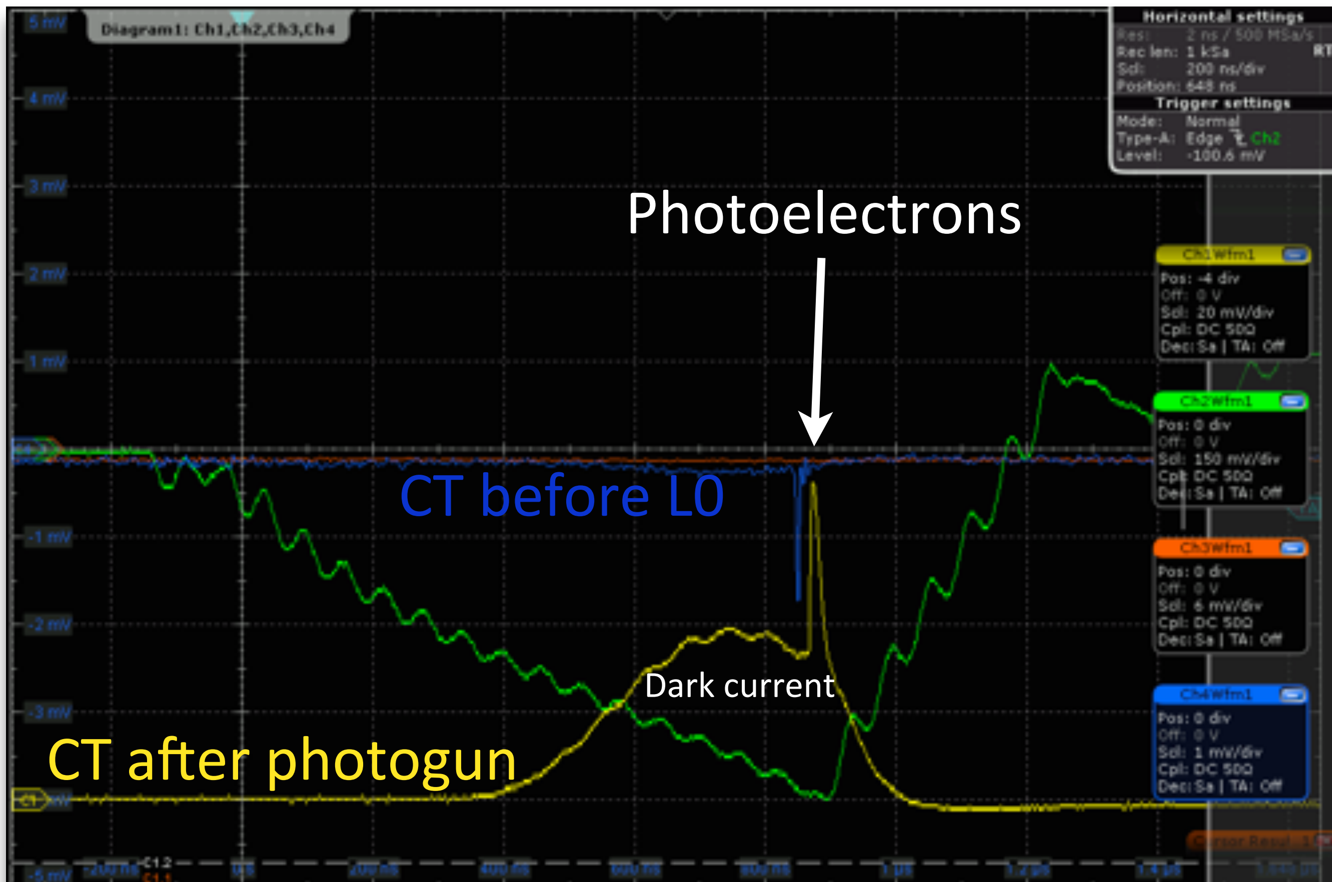


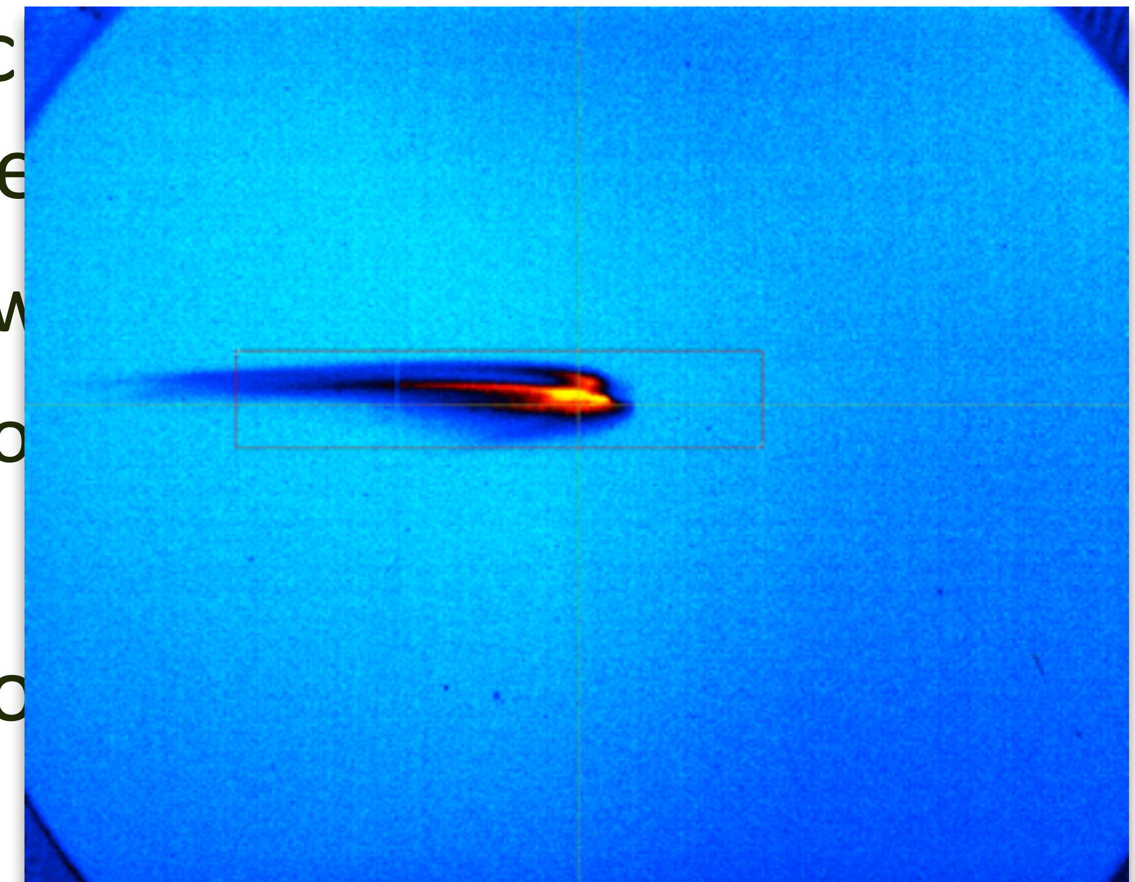
Linac Commissioning Summary (cont.)

- Linac commissioning started March 2014 with conditioning of RF structures; after vacuum intervention (waveguides & SLEDs)
  - 13 of 19 stations running at full power (e.g. 100 MeV from L0)
  - all other structures reached 95% power → 3.2 GeV in BC2
- Klystron for thermionic gun failed in Feb 2015 (vac. interlock & grounding issues → severe arcing) → started photocathode commissioning
  - ≈150 pC delivered to SPF
  - ≈2.2 mm mrad at BC2 (laser pulse too short (< 3 ps) & photo gun energy low)



Linac Commissioning Summary (cont.)





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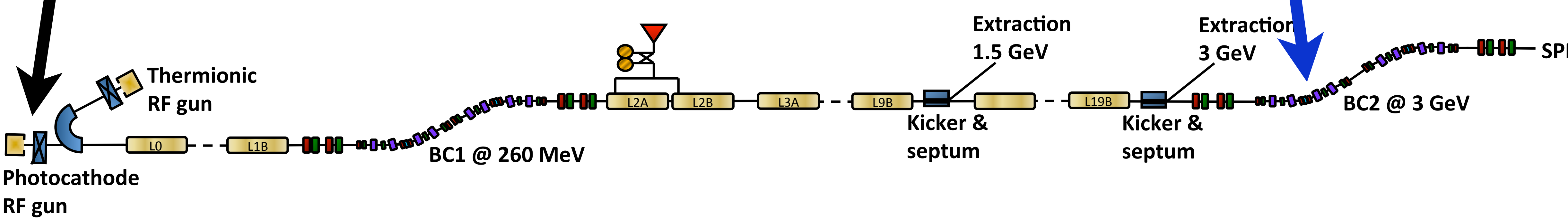


Linac Commissioning Summary (cont.)

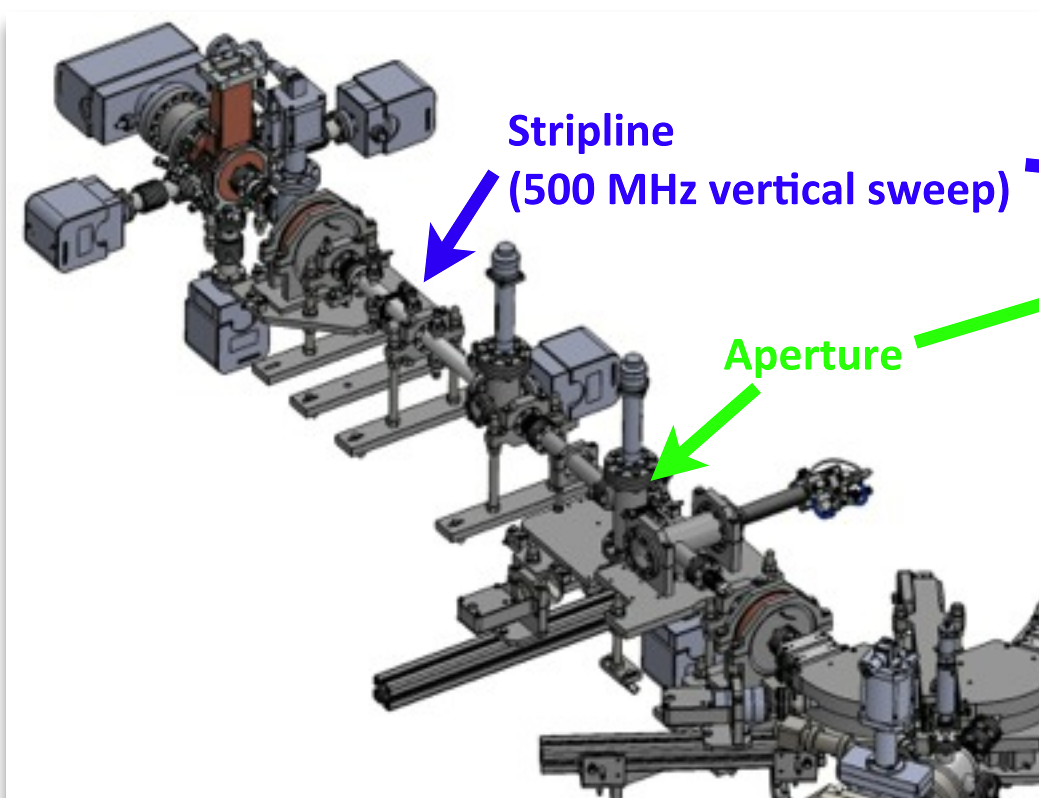
- In April 2015 commissioned new thermionic gun klystron
- In conjunction with RF chopper system, delivered 500 MHz structure required for initial ring commissioning (BPM response)

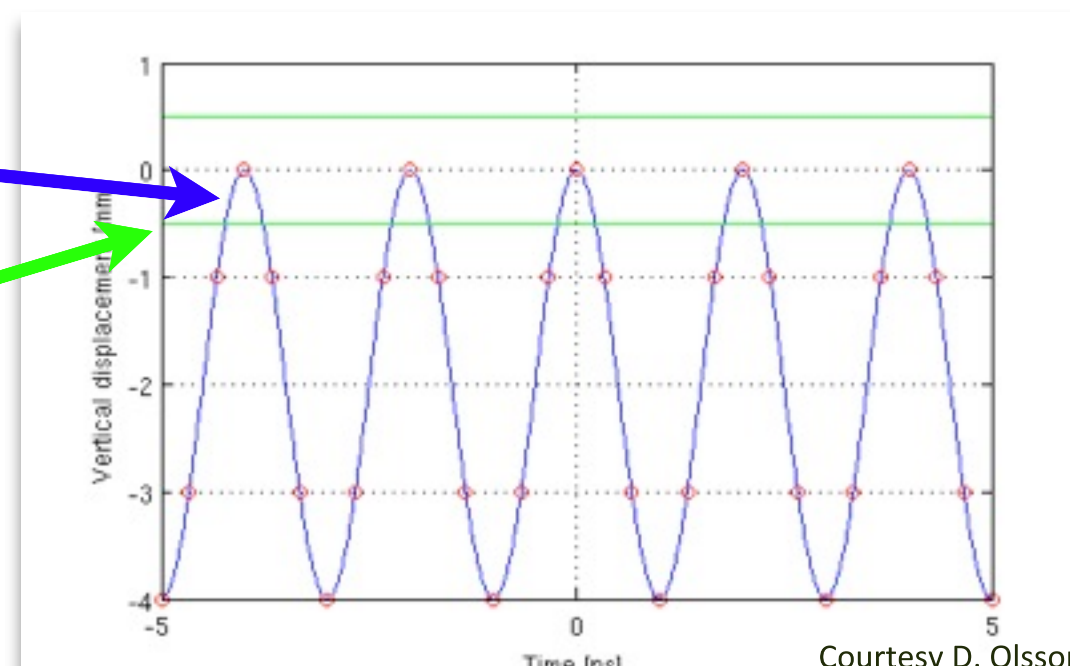
500 MHz structure imprinted on top of S-band structure

5× ~20 pC

10 ns (1 ring bucket)

Repeat ten times → inject 100 ns train (10 ring buckets) with ≈1 nC





Courtesy D. Olsson

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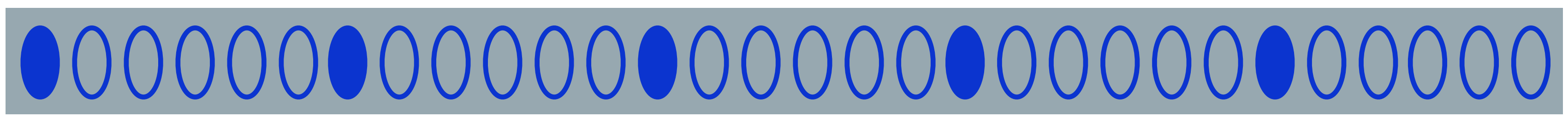
5× ~20 pC  10 ns (1 ring bucket)

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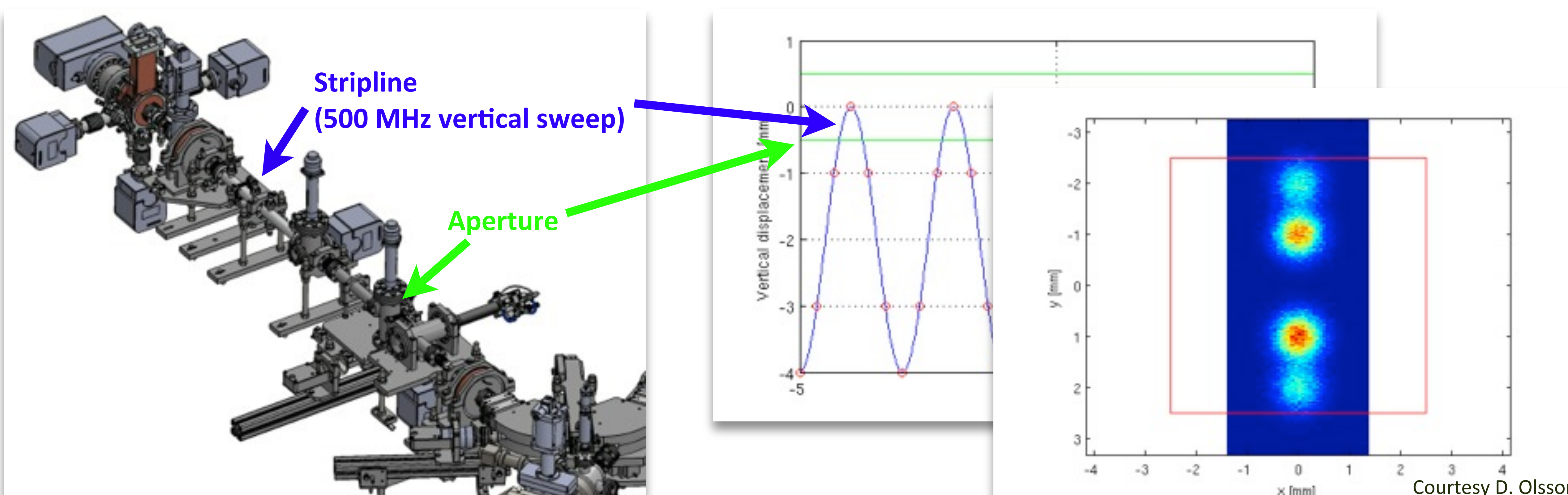

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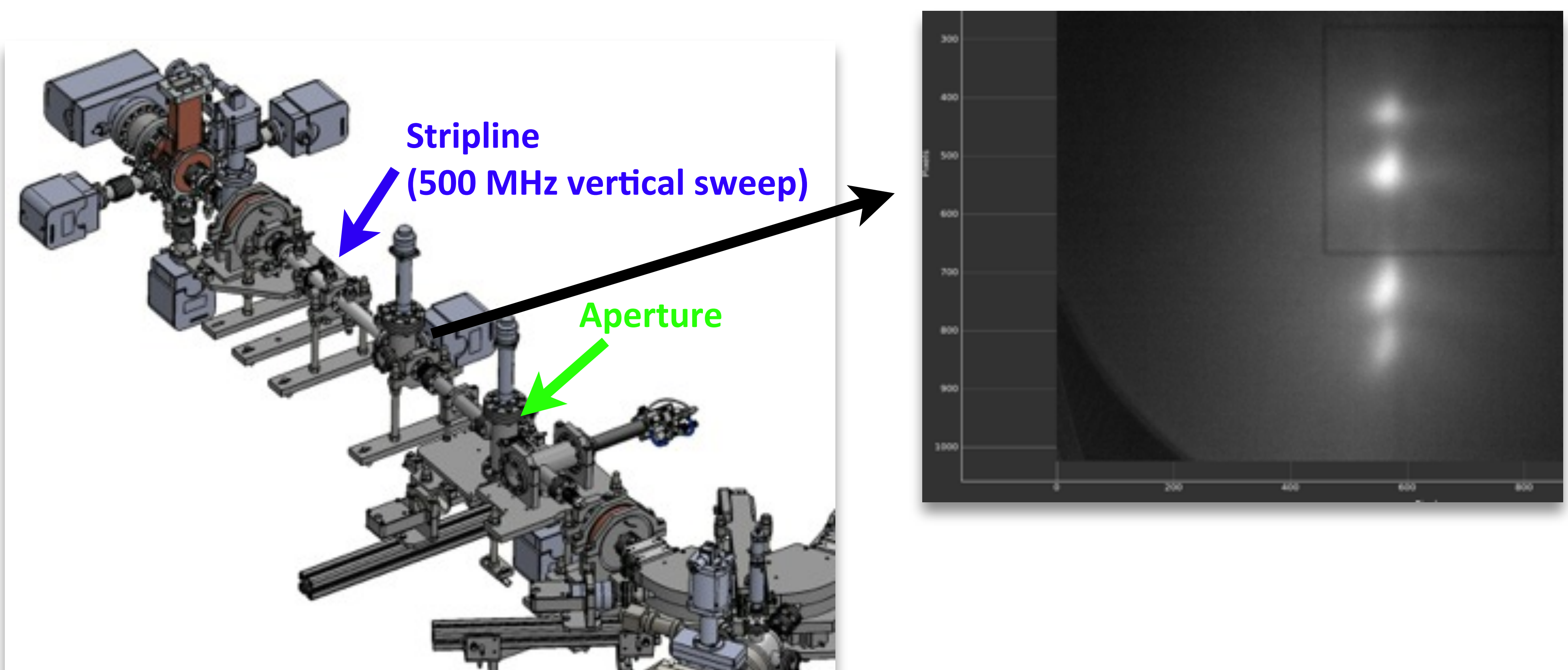

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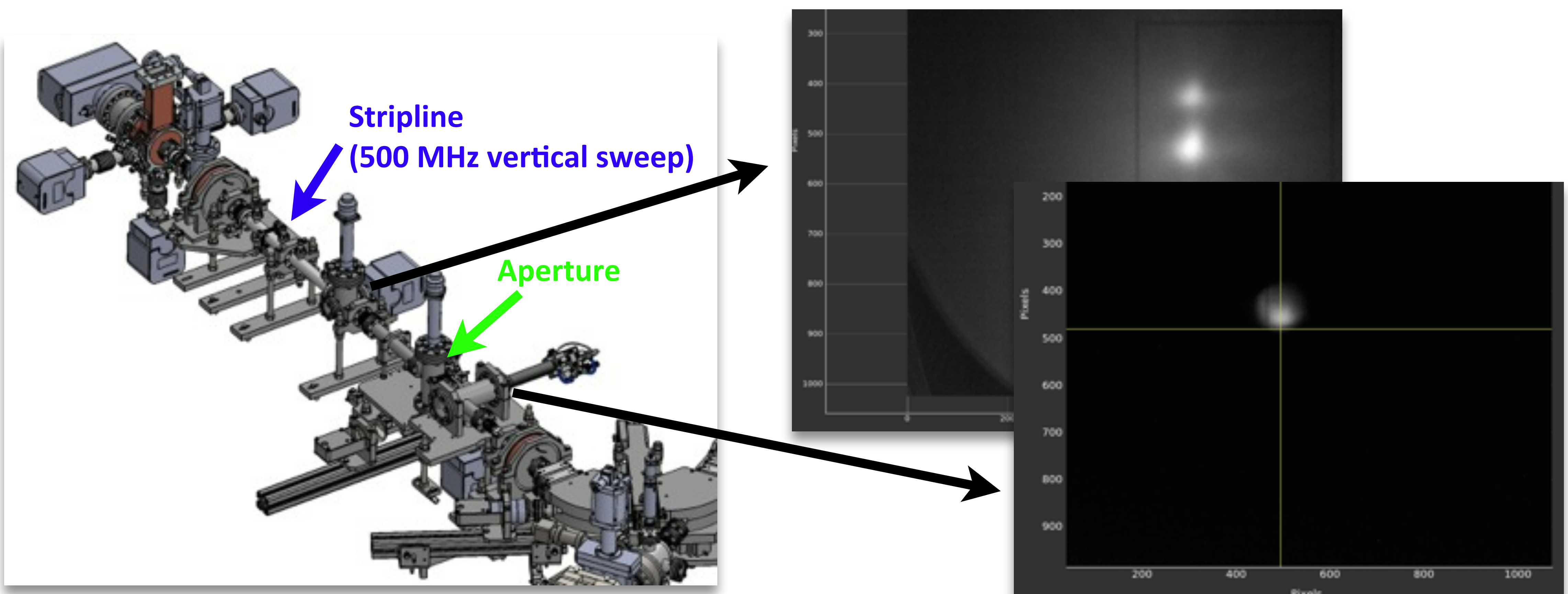

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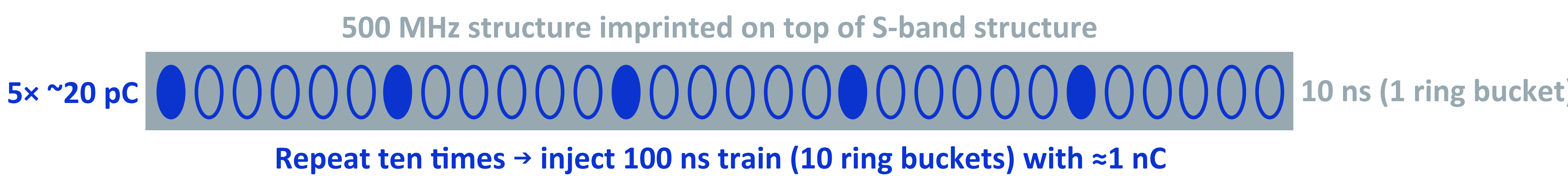

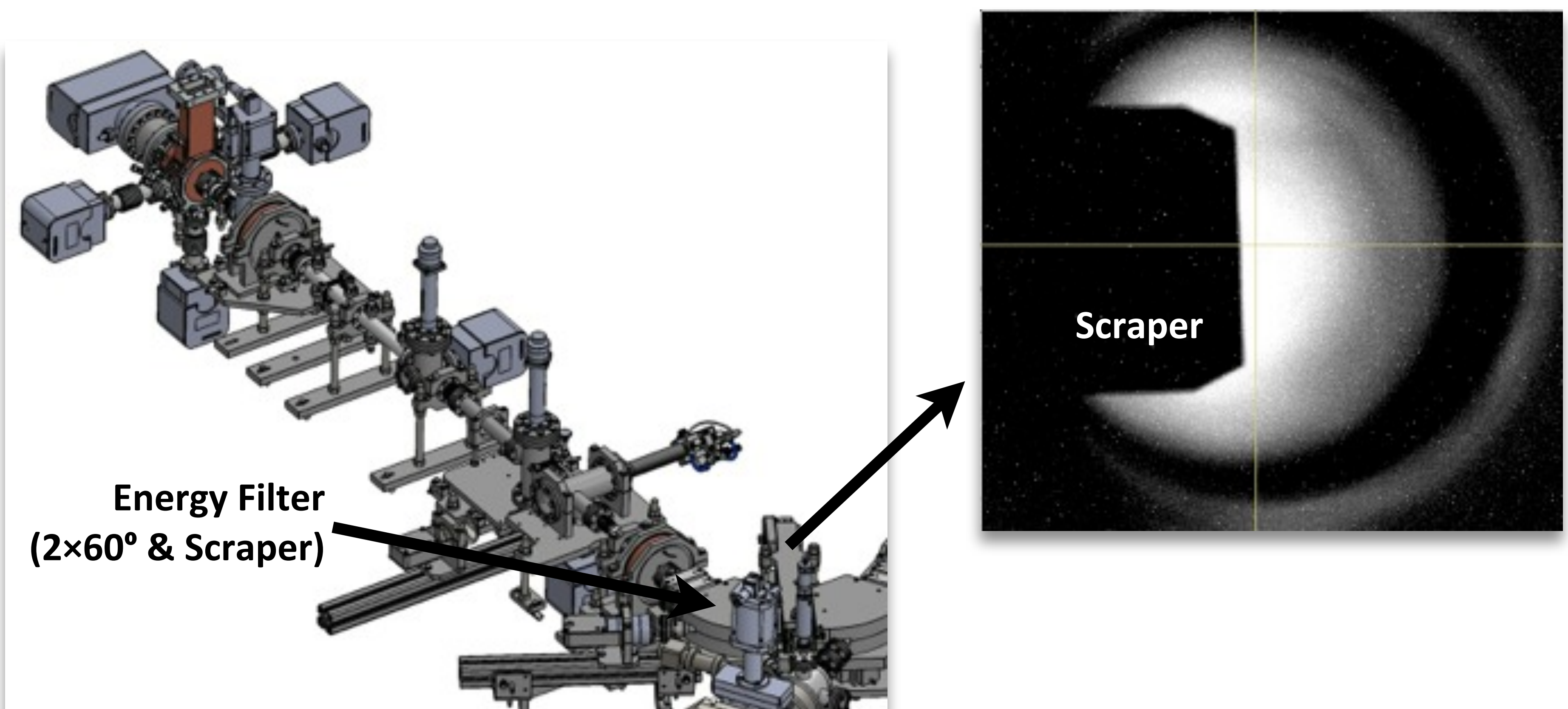

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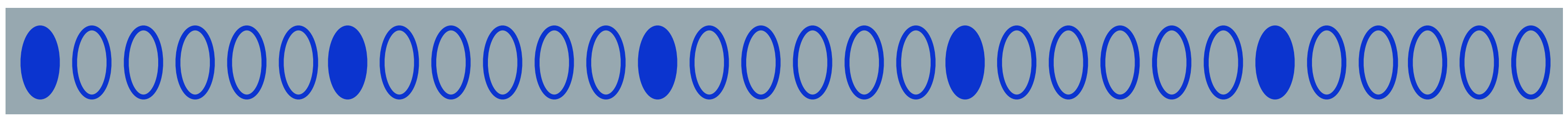

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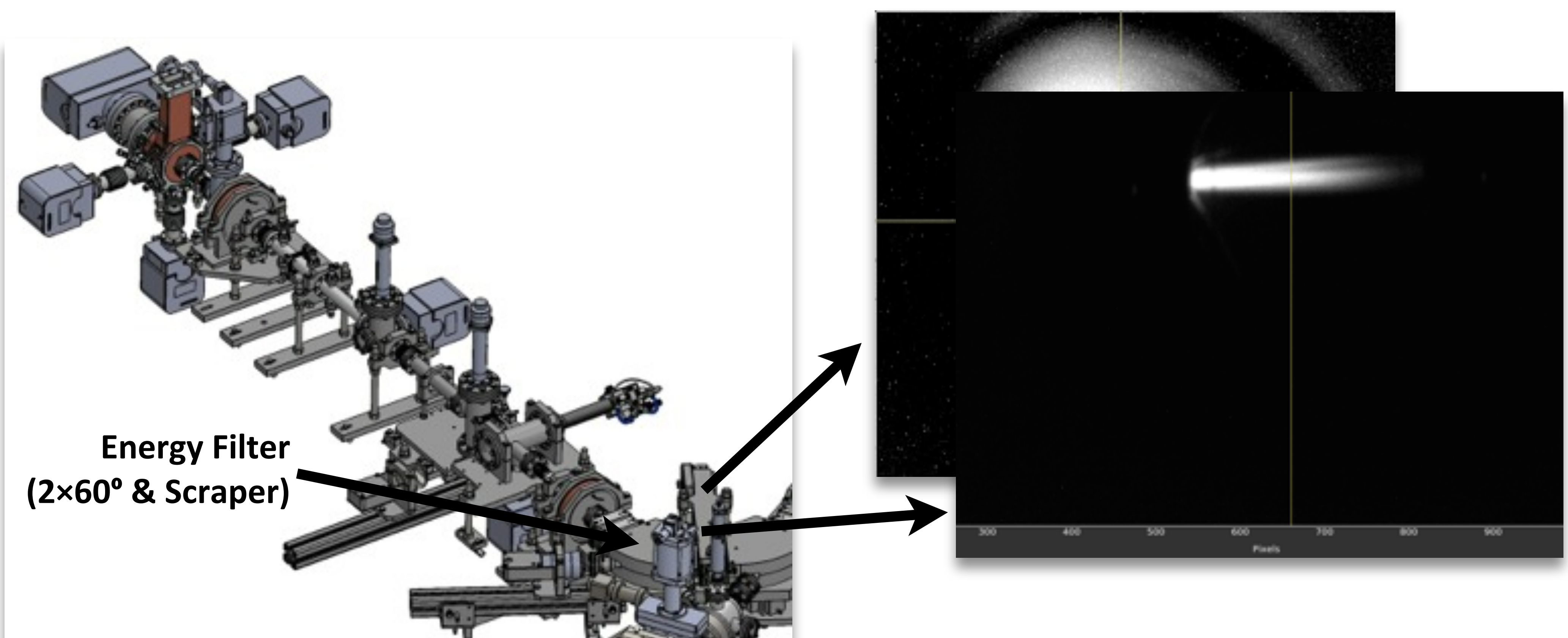

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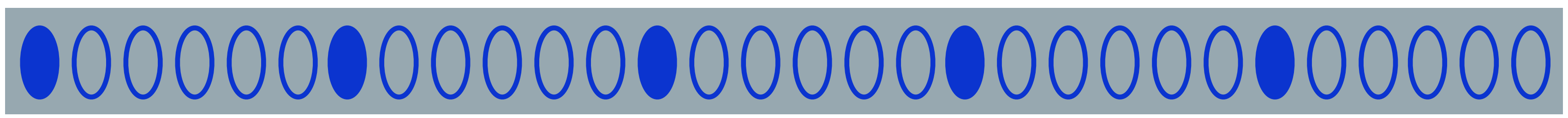

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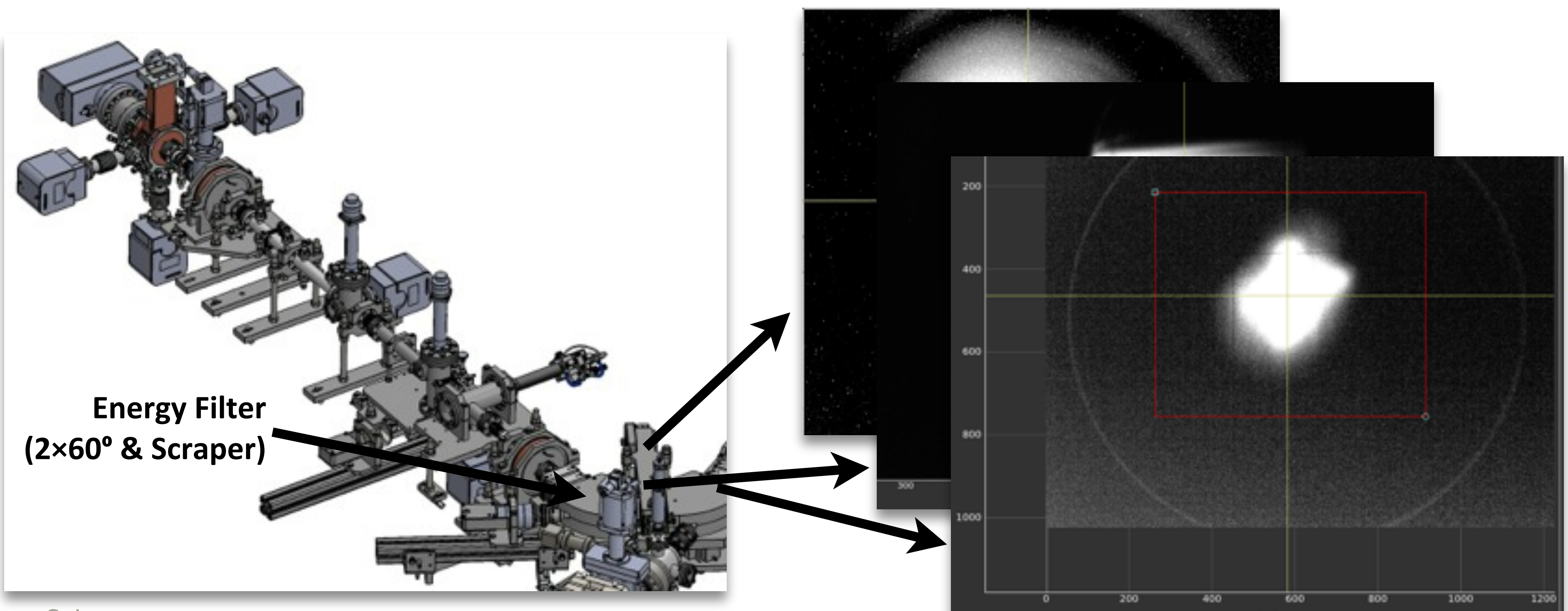

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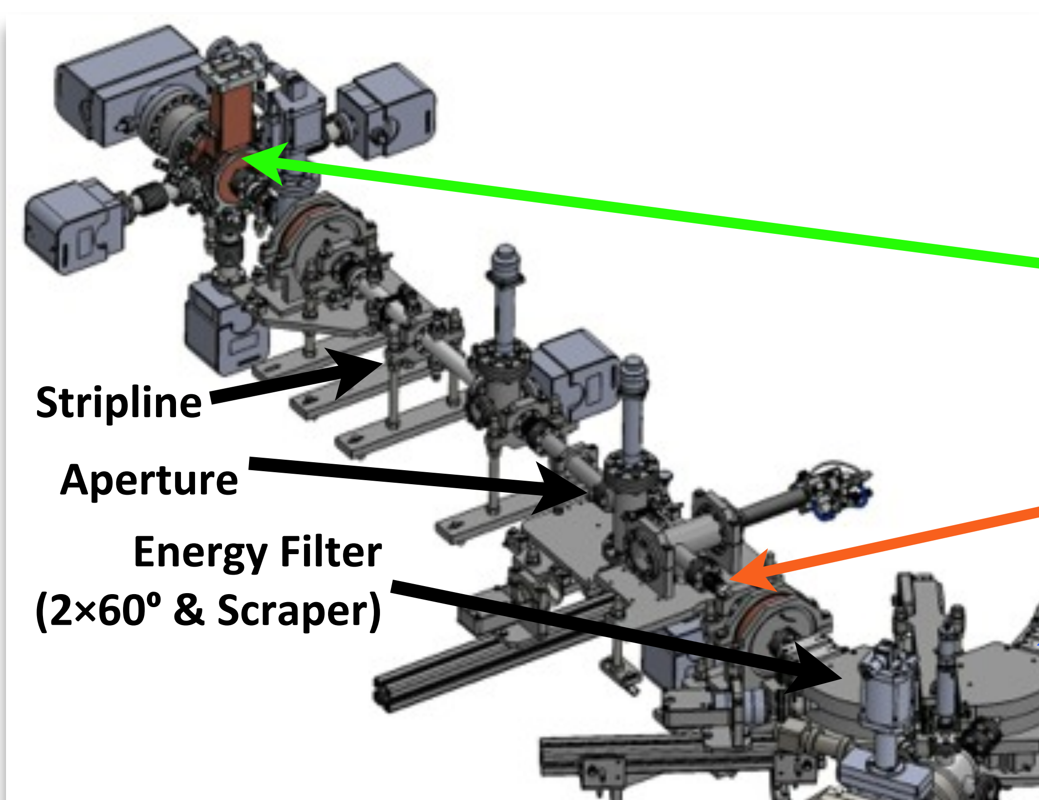
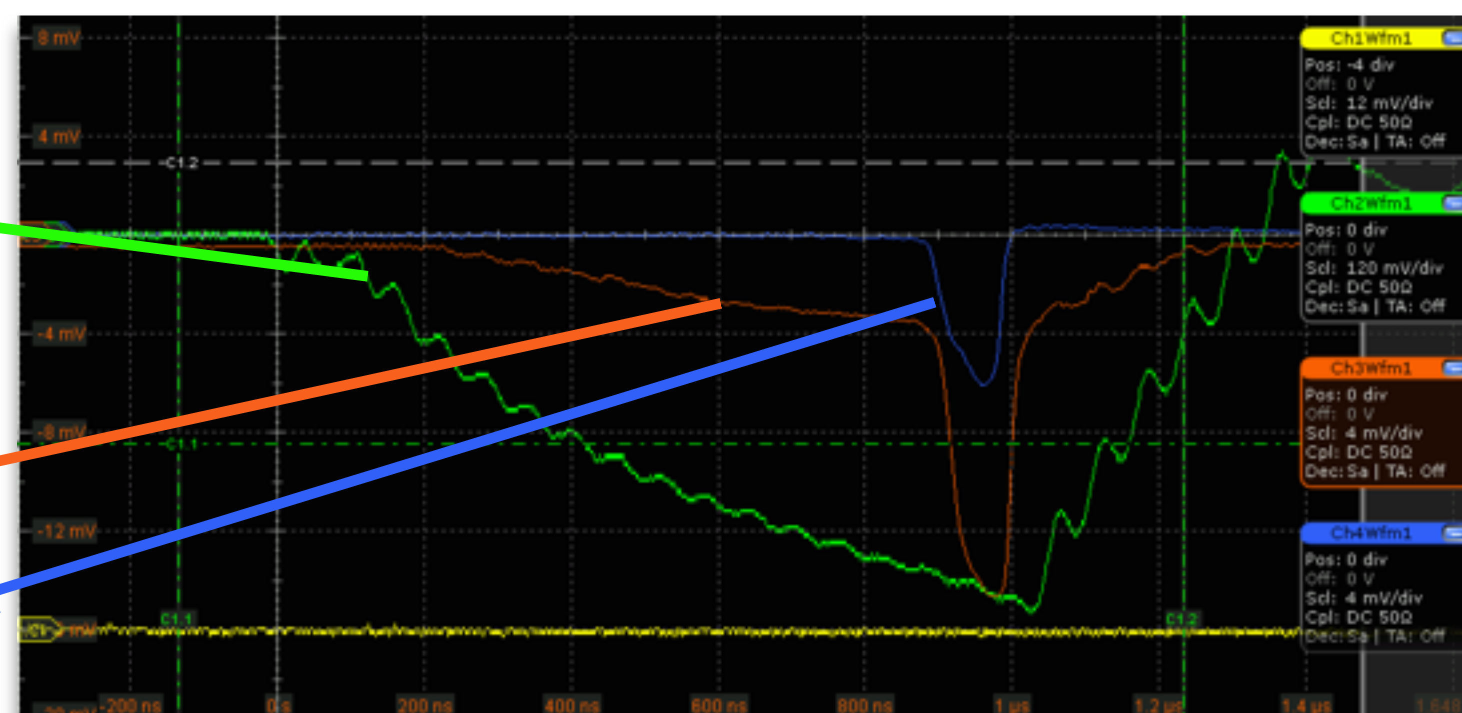
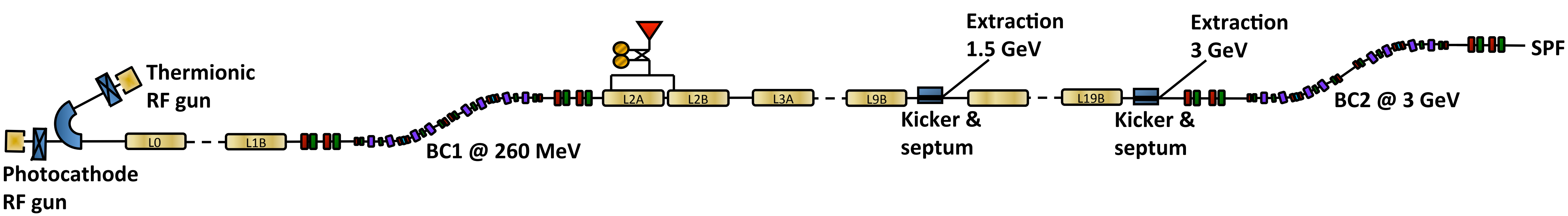




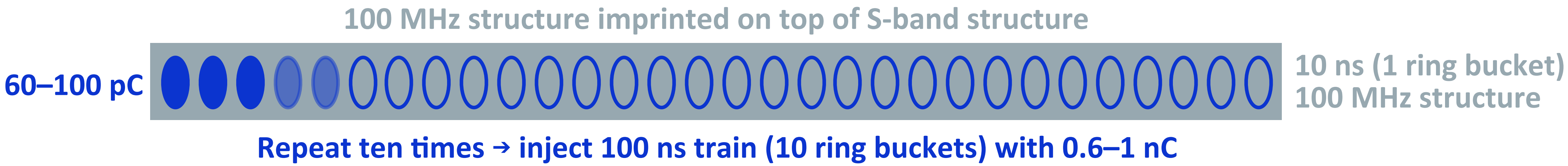
Linac Commissioning Summary (cont.)

- In April 2015 commissioned new thermionic gun klystron
- In conjunction with RF chopper system, delivered 500 MHz structure required for initial ring commissioning (BPM response)
  - ≈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
  - good position/angle stability at 3 GeV extraction (Libera Single Pass E)



Linac Commissioning Summary (cont.)

- With frequency combiner (100 & 300 MHz) RF chopper demonstrated 100 MHz structure required for ring injection once ring RF switched on (injection phase acceptance)

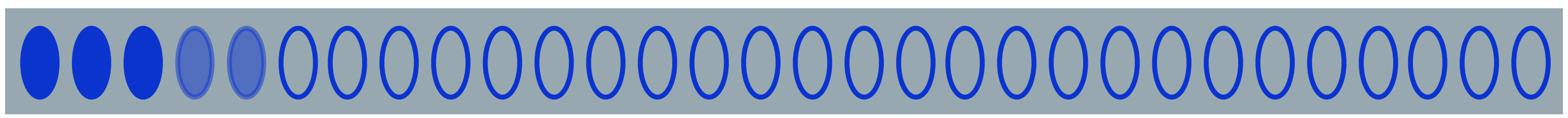


Linac Commissioning Summary (cont.)

- With frequency combiner (100 & 300 MHz) RF chopper demonstrated 100 MHz structure required for ring injection once ring RF switched on (injection phase acceptance)

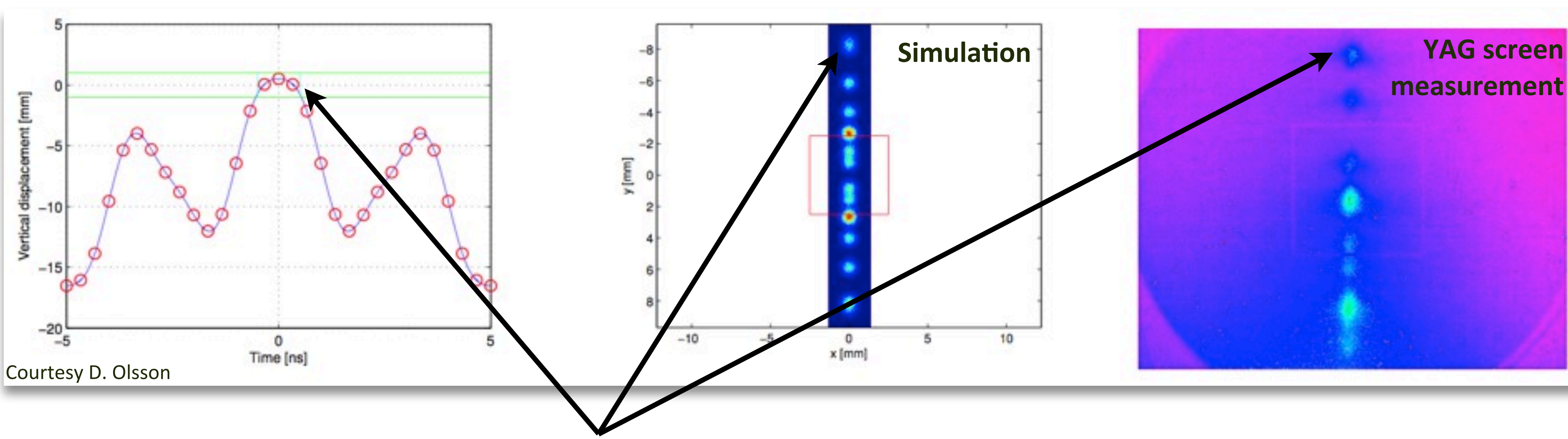
100 MHz structure imprinted on top of S-band structure

60–100 pC



10 ns (1 ring bucket)
100 MHz structure

Repeat ten times → inject 100 ns train (10 ring buckets) with 0.6–1 nC

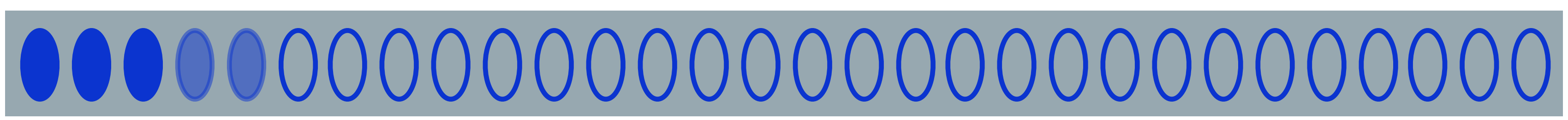


~3×20 pC per ring bucket (10 ns)

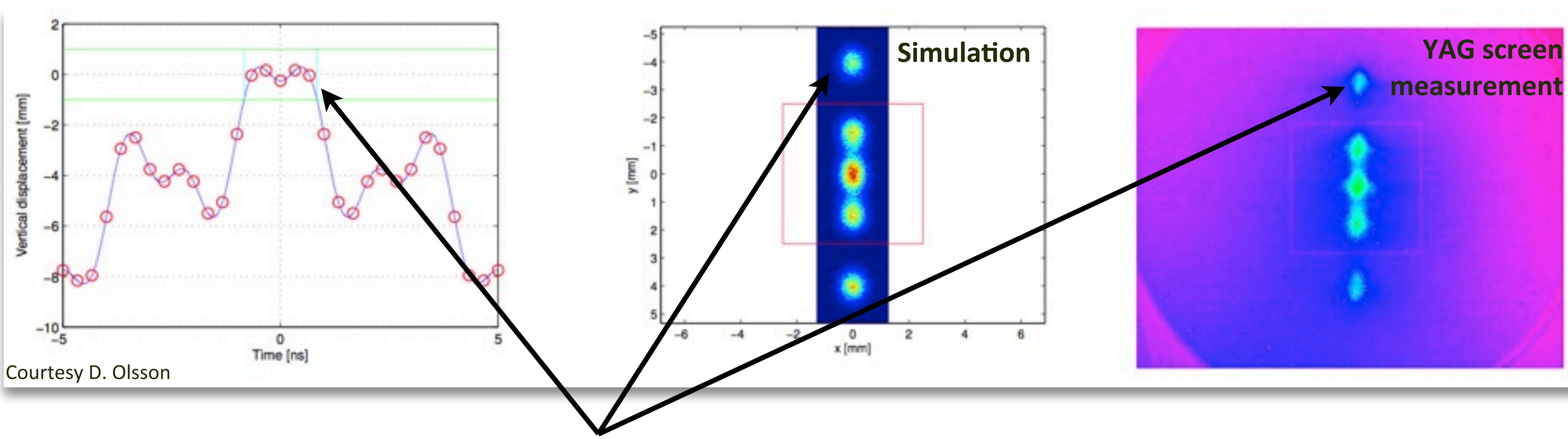
Linac Commissioning Summary (cont.)

- With frequency combiner (100 & 300 MHz) RF chopper demonstrated 100 MHz structure required for ring injection once ring RF switched on (injection phase acceptance)

100 MHz structure imprinted on top of S-band structure



Repeat ten times → inject 100 ns train (10 ring buckets) with 0.6–1 nC



Courtesy D. Olsson

~5×20 pC per ring bucket (10 ns)

Linac Commissioning Summary (cont.)

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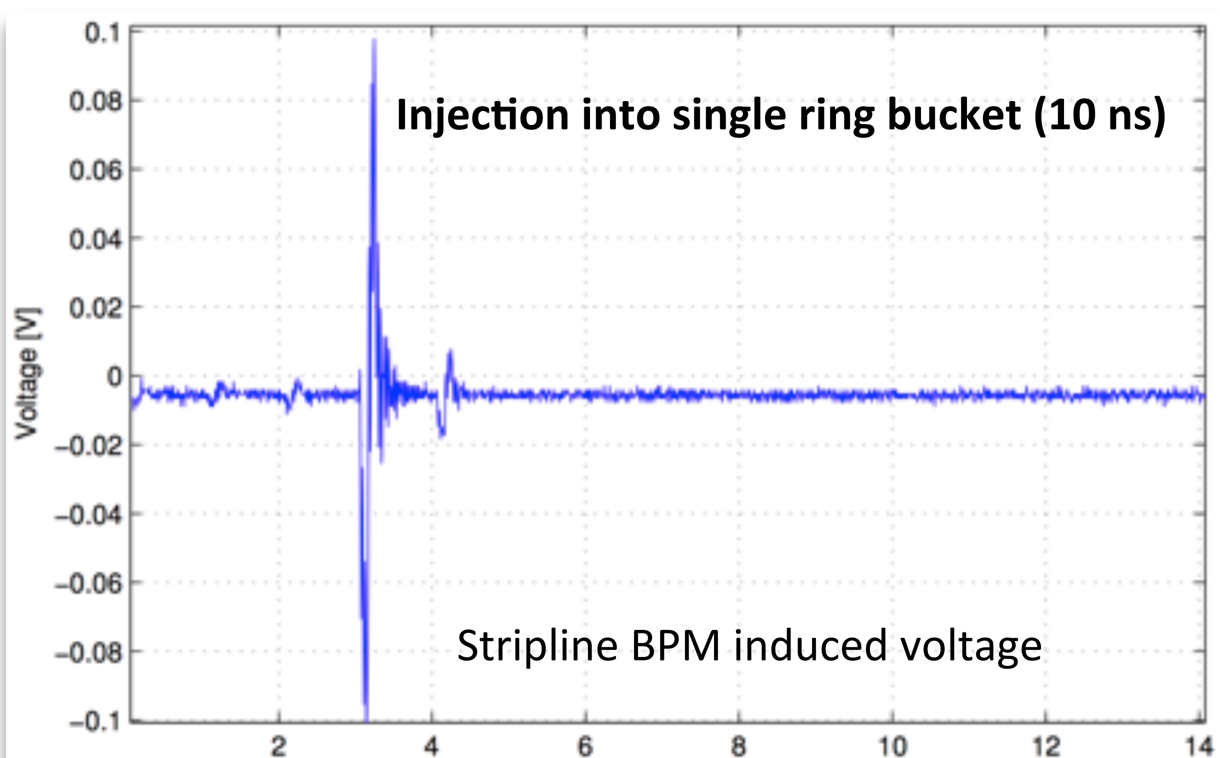


Courtesy D. Olsson

Linac Commissioning Summary (cont.)

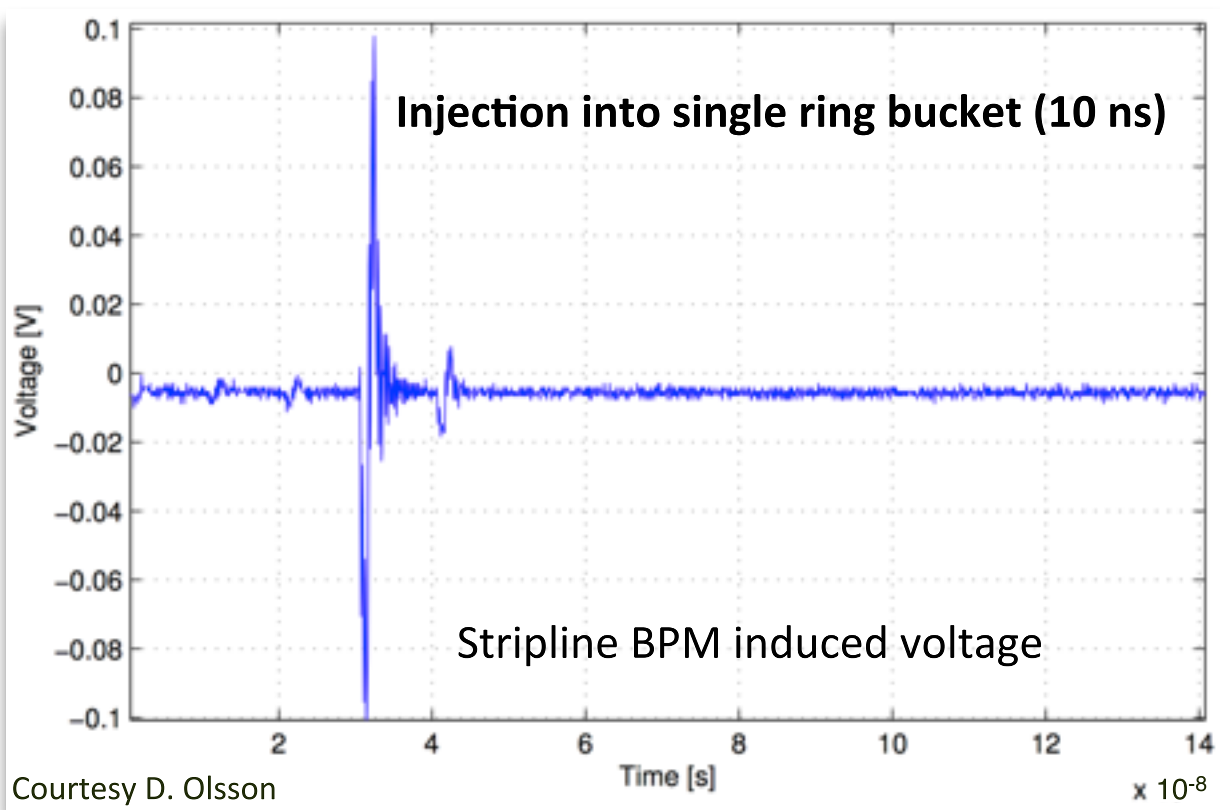
- With frequency combiner (100 & 300 MHz) RF chopper demonstrated 100 MHz structure required for ring injection once ring RF switched on (injection phase acceptance)

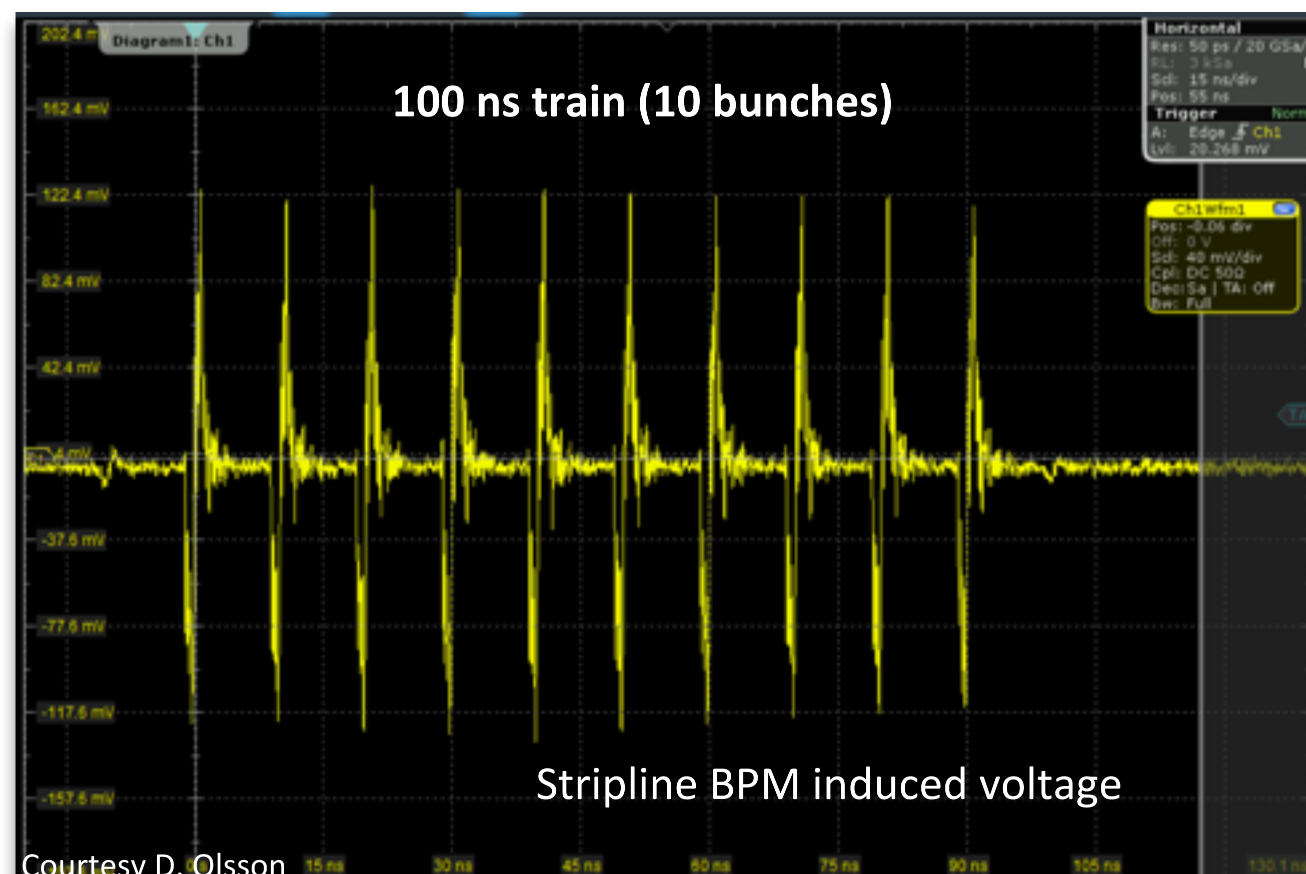
100 MHz structure imprinted on top of S-band structure

60–100 pC

10 ns (1 ring bucket)
100 MHz structure

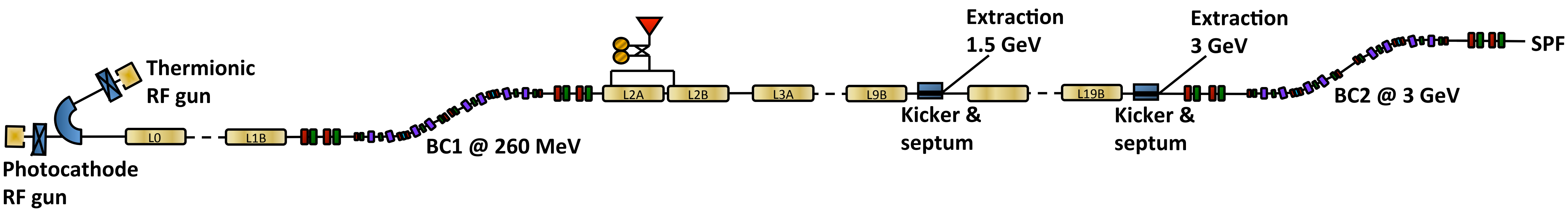
Repeat ten times → inject 100 ns train (10 ring buckets) with 0.6–1 nC





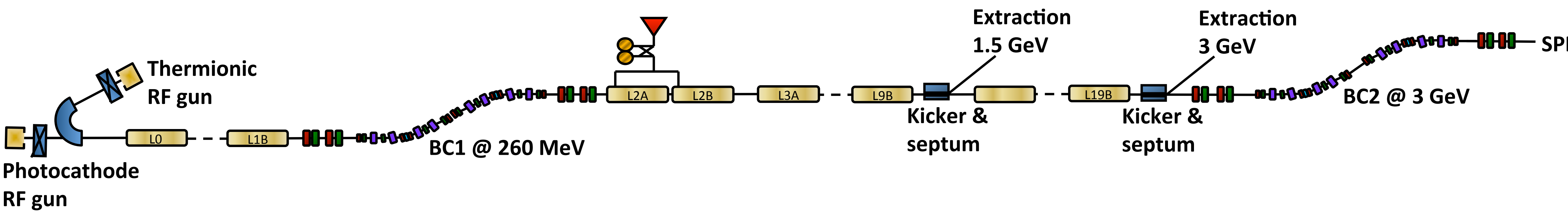
Linac Commissioning Summary (cont.)

- With frequency combiner (100 & 300 MHz) RF chopper demonstrated 100 MHz structure required for ring injection once ring RF switched on (injection phase acceptance)
- Linac went into shutdown at end of April 2015 for transfer line installations & last phase of exp. hall construction
- Linac RF stations started re-conditioning July 2015
- Linac restarted Aug 3, 2015



Linac Commissioning Summary (cont.)

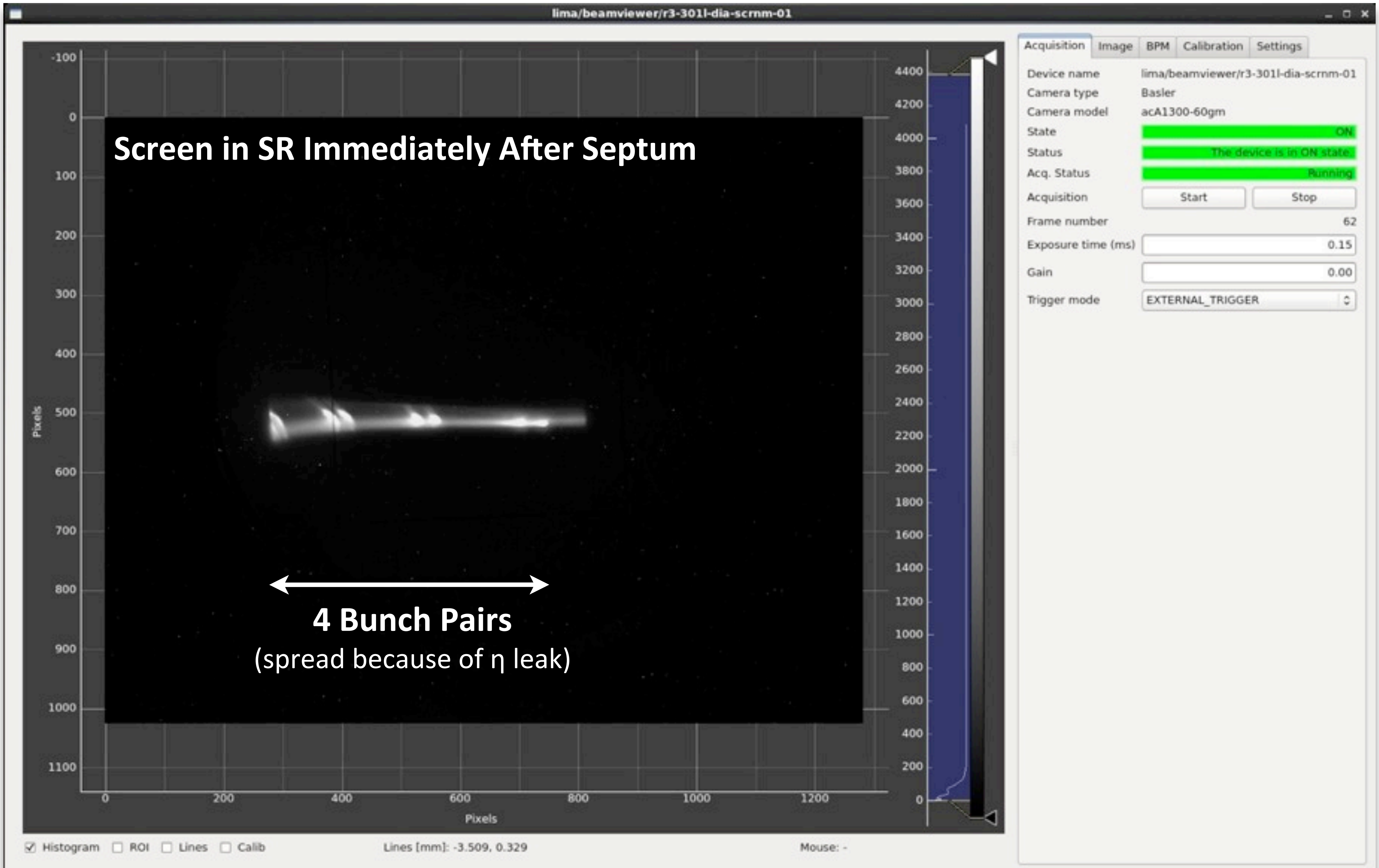
- After restart, quickly reached pre-shutdown performance:
  - 3.17 GeV (limited power from one RF station after vacuum intervention)
  - ≈1 nC (limited at EF, radiation protection concern) in ≈100 ns train with 500 MHz structure at 1 Hz (currently limited by commissioning license)
  - Potential for charge increase:
    - filament current (6.5 → 6.8 A)
    - gun cavity power (2.7 → 3 MeV seen at test stand)
    - +50% by relaxing EF settings (max. 200 keV spread)
  - Losses along linac eventually limited to few % (several CTs along linac)



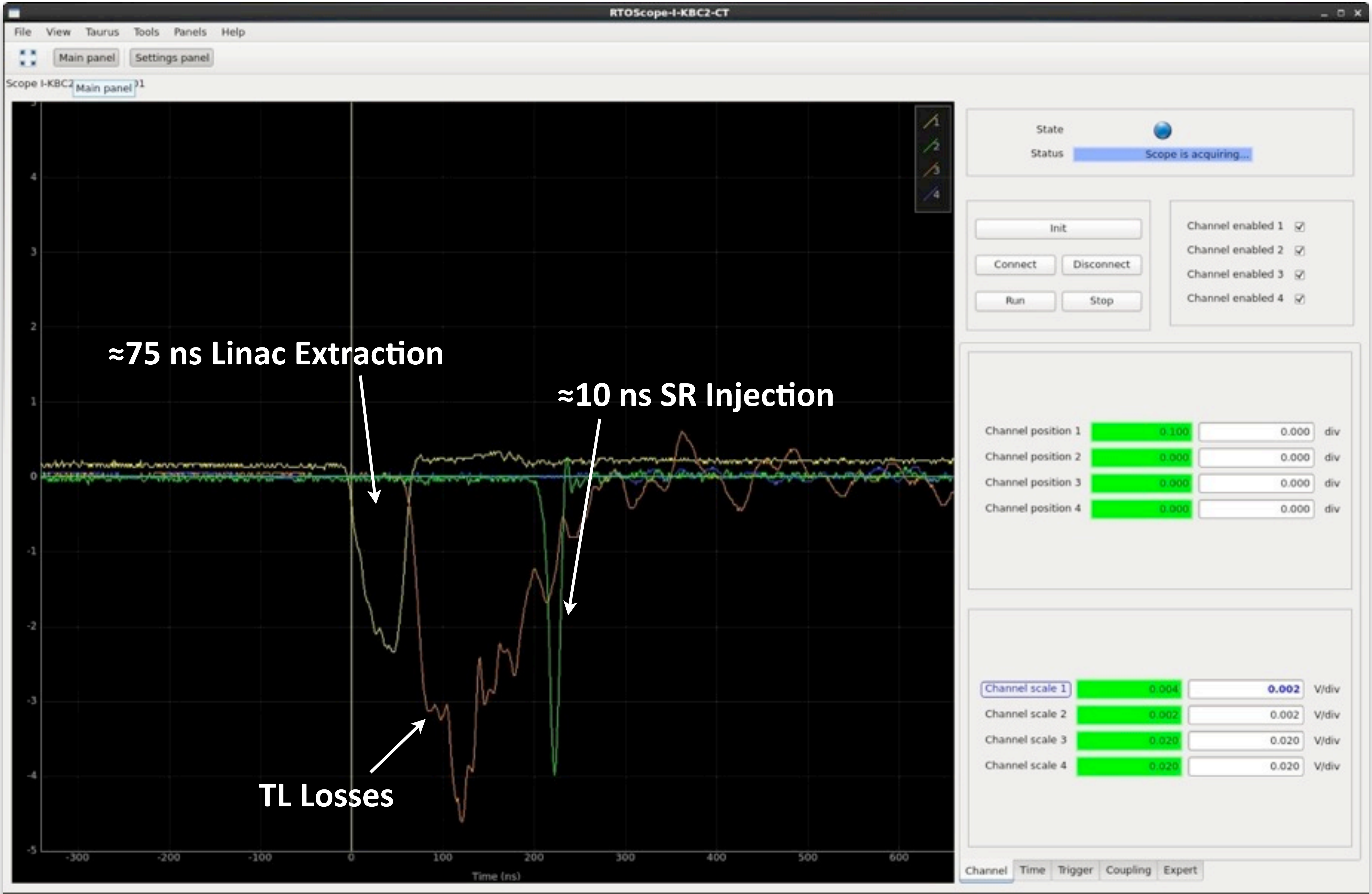
3 GeV Storage Ring Commissioning

- First beam into full 3 GeV transfer line (TL) on Aug 10
- Energy lowered to ≈3 GeV (according to TL dipoles) via modulator power
- First attempt at injection into 3 GeV ring on Aug 11
  - TL optics set to design, only rough manual trajectory correction
  - Dispersion leak from TL leads to dispersed beam and substantial charge reduction at ring entrance

3 GeV Storage Ring Commissioning (cont.)



3 GeV Storage Ring Commissioning (cont.)

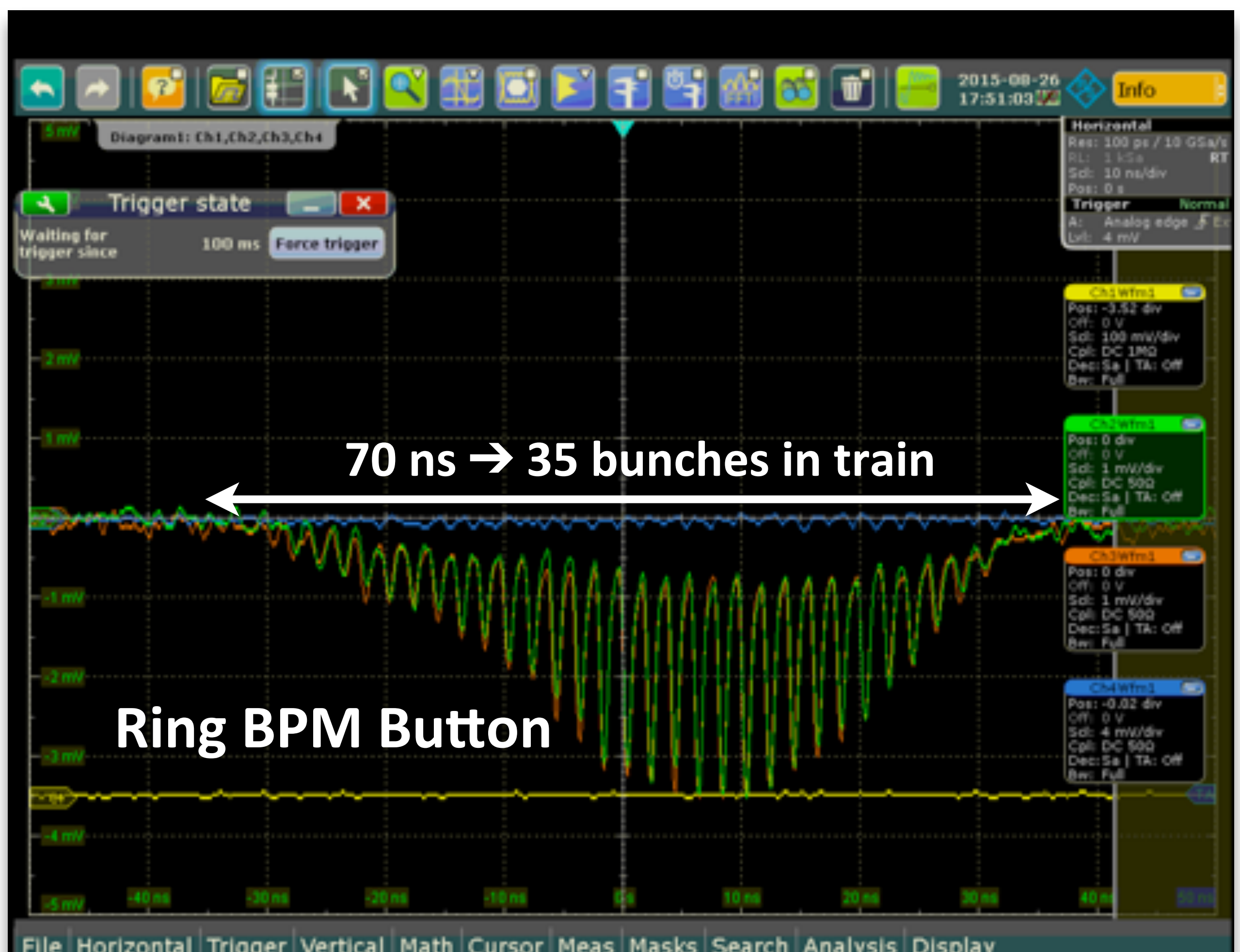


3 GeV Storage Ring Commissioning (cont.)

- Spent roughly one week on various improvements/fixes
  - Optimization of the TL optics & trajectory
  - Ongoing controls work (vacuum, BPMs)
- Proceeded with injection into 3 GeV SR on Aug 19

3 GeV Storage Ring Commissioning (cont.)

- Spent roughly one week on various improvements/fixes
  - Optimization of the TL optics & trajectory
  - Ongoing controls work (vacuum, BPMs)
- Proceeded with injection into 3 GeV SR on Aug 19



3 GeV Storage Ring Commissioning (cont.)

- Spent roughly one week on various improvements/fixes
  - Optimization of the TL optics & trajectory
  - Ongoing controls work (vacuum, BPMs)
- Proceeded with 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

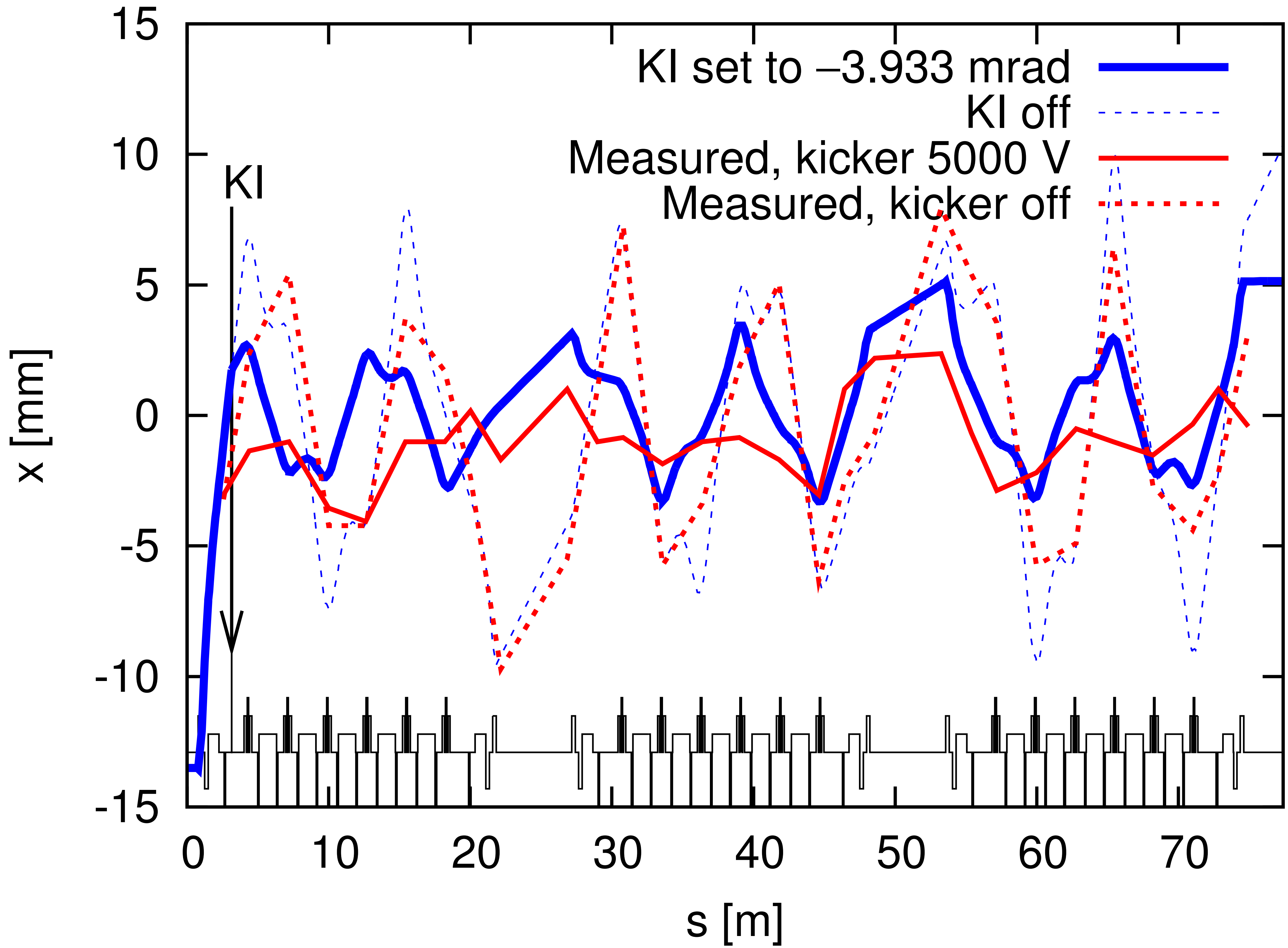
≈400 pC at storage ring injection

≈ 2 mm × 1 mm

3 GeV Storage Ring Commissioning (cont.)

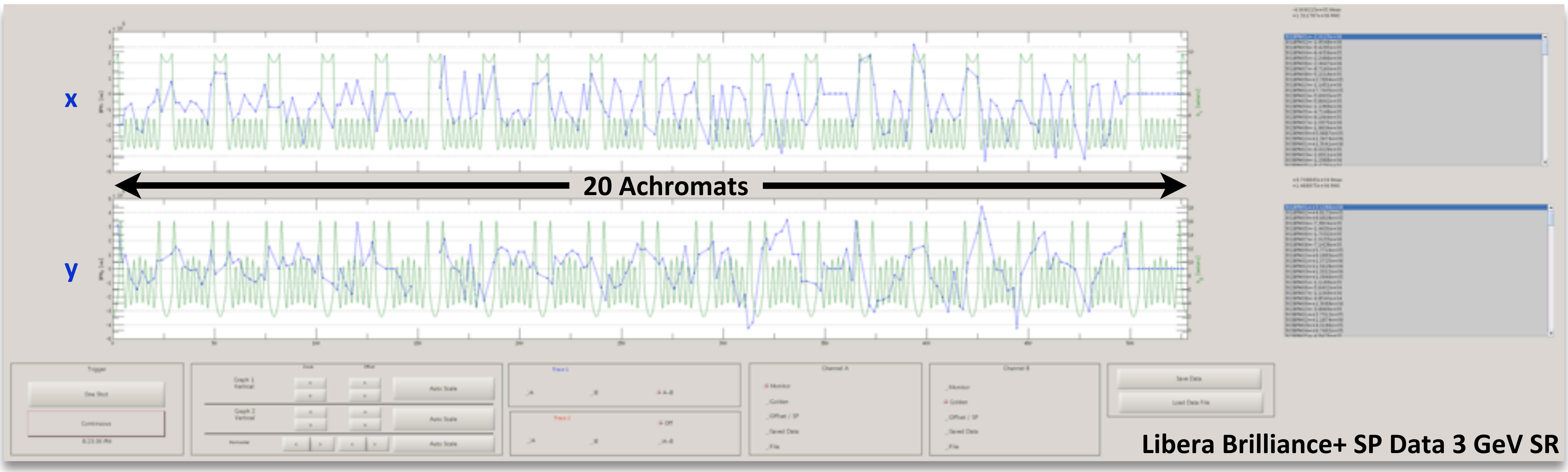
- Spent roughly one week on various improvements/fixes
  - Optimization of the TL optics & trajectory
  - Ongoing controls work (vacuum, BPMs)
- Proceeded with injection into 3 GeV SR on Aug 19
- With some manual adjustments of angle and position at injection point in SR (using diode rings), immediately 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.)



3 GeV Storage Ring Commissioning (cont.)

- Commissioning license required radiation survey to be performed valve by valve (≈60 valves total) ➔ roughly one week spent to reach first full turn
- Aug 25, 10pm: reached first full turn **without exciting a single corrector & all magnets at nominal optics** for 3.0 GeV

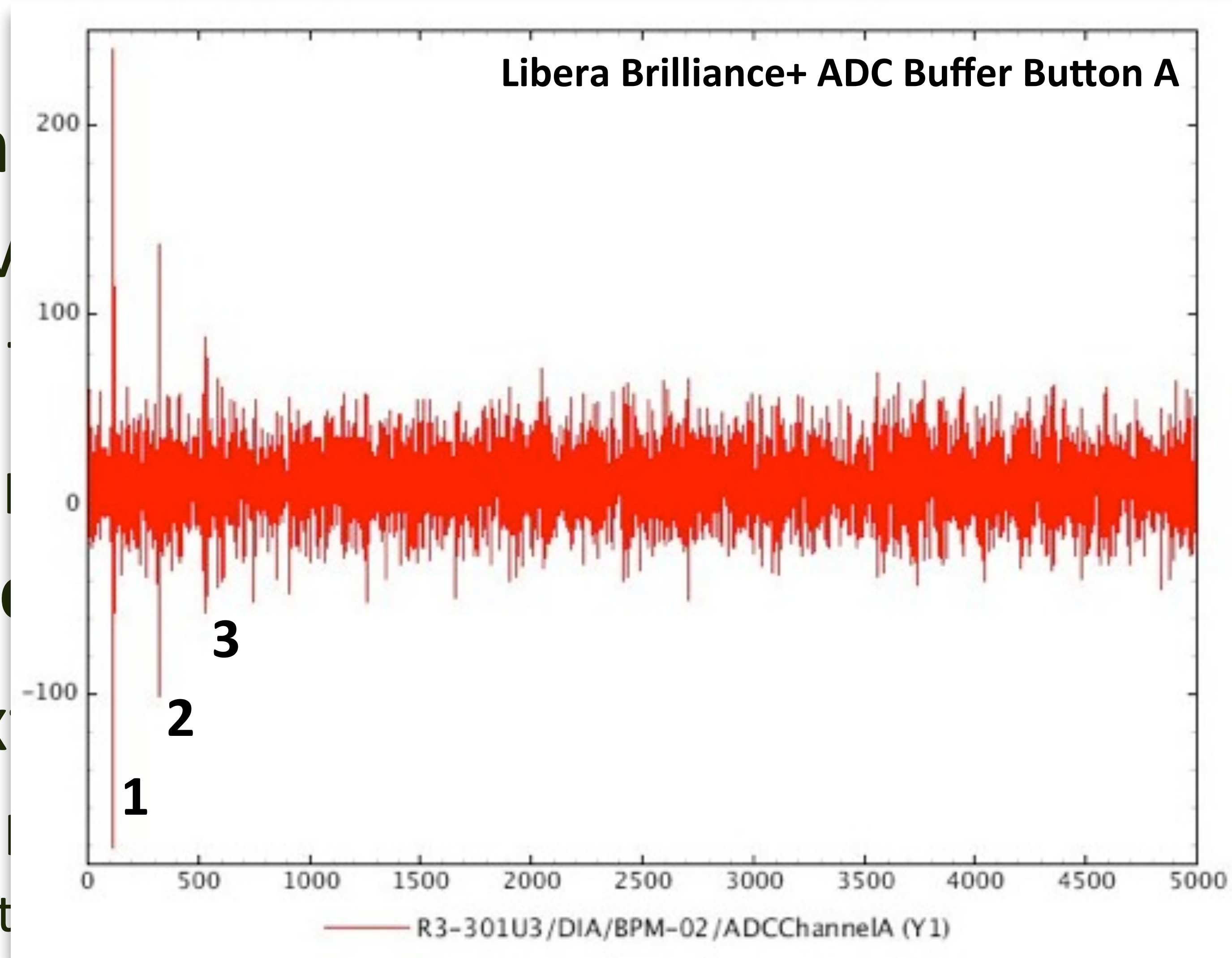


3 GeV Storage Ring Commissioning (cont.)

- Commissioning license required radiation survey to be performed valve by valve (≈60 valves total) → roughly one week spent to reach first full turn
- 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 offsets substantially reduced with focusing from sextupoles & octupoles

3 GeV Storage Ring Commissioning (cont.)

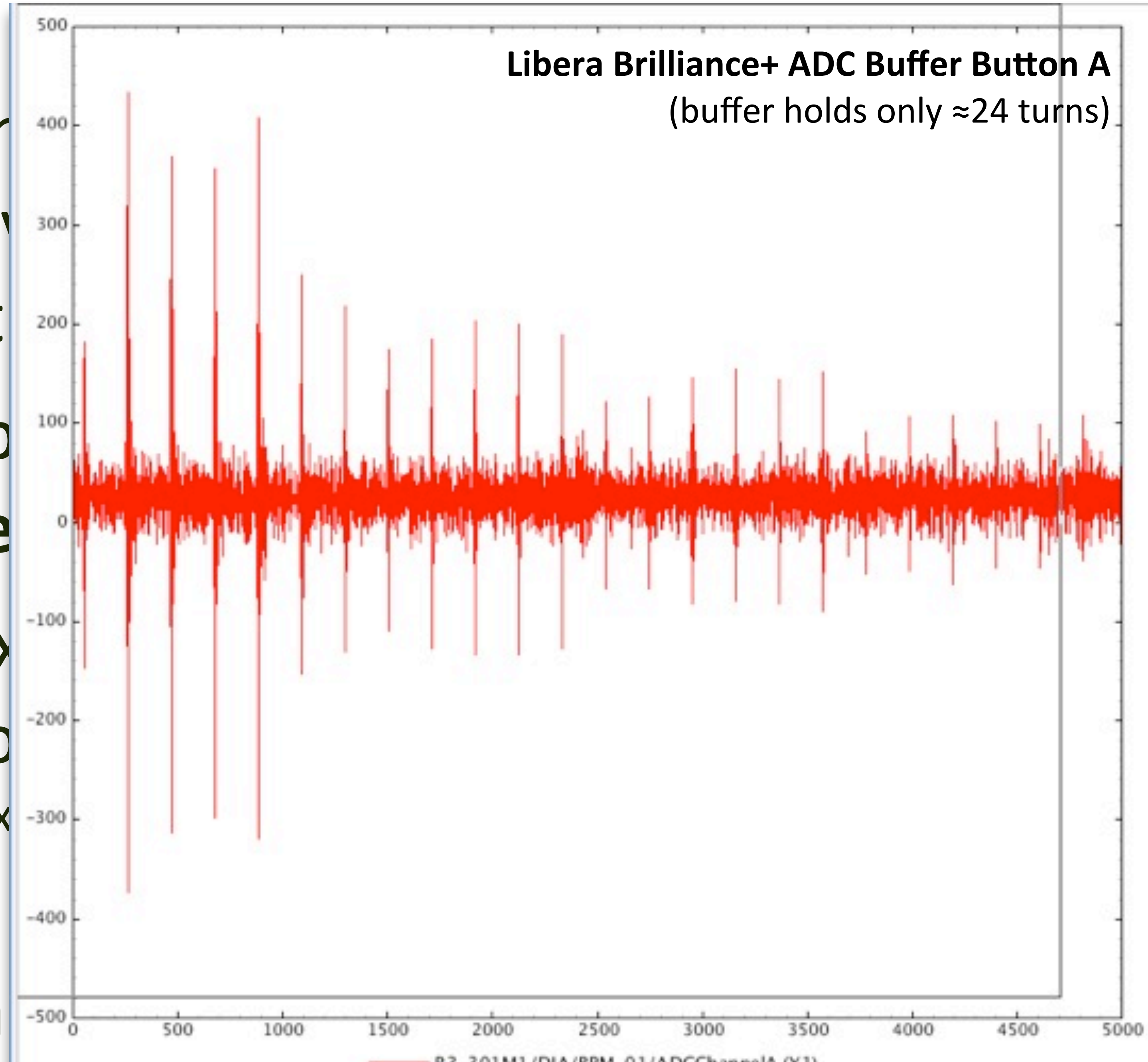
- Commission ... y to be performed v ... ughly one week spent ...
- Aug 25, 10p ... **citing a single corre** ... **s** for 3.0 GeV
- Without sex ... raight 11 (while all co ... ntially reduced with focusing from sext ...



- 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.)

3 GeV Storage Ring Commissioning (cont.)



- Commissior … to be performed … ughly one week spent …
- Aug 25, 10p … **citing a single corre** … s for 3.0 GeV
- Without sex … aight 11 (while all co … tially reduced with focusing from sex …
- After a few … ments and optics twea … passages
- After some more corrector adjustments → 36 passages detected

3 GeV Storage Ring Commissioning (cont.)

- Aug 27-28: cavity troubles (vacuum intervention required)
- Aug 31: dipole kicker breaks down (cabling issue, short to ground → destroyed IGBTs; replaced with spares, together with BINP expert found & replaced faulty resistor in capacitor bank)
- Discovered & fixed inverted quadrupole polarity in TL

3 GeV Storage Ring Commissioning (cont.)

- Aug 27-28: cavity troubles (vacuum intervention required)
- Aug 31: dipole kicker breaks down (cabling issue, short to ground → destroyed IGBTs; replaced with spares, together with BINP expert found & replaced faulty resistor in capacitor bank)
- Discovered & fixed inverted quadrupole polarity in TL
- After tuning relative timing of RF stations could eventually reduce overall energy spread of bunch train to ≈1% and <0.1% within S-band bunches (using dispersive screen in 3 GeV TL)

3 GeV Storage Ring Commissioning (cont.)

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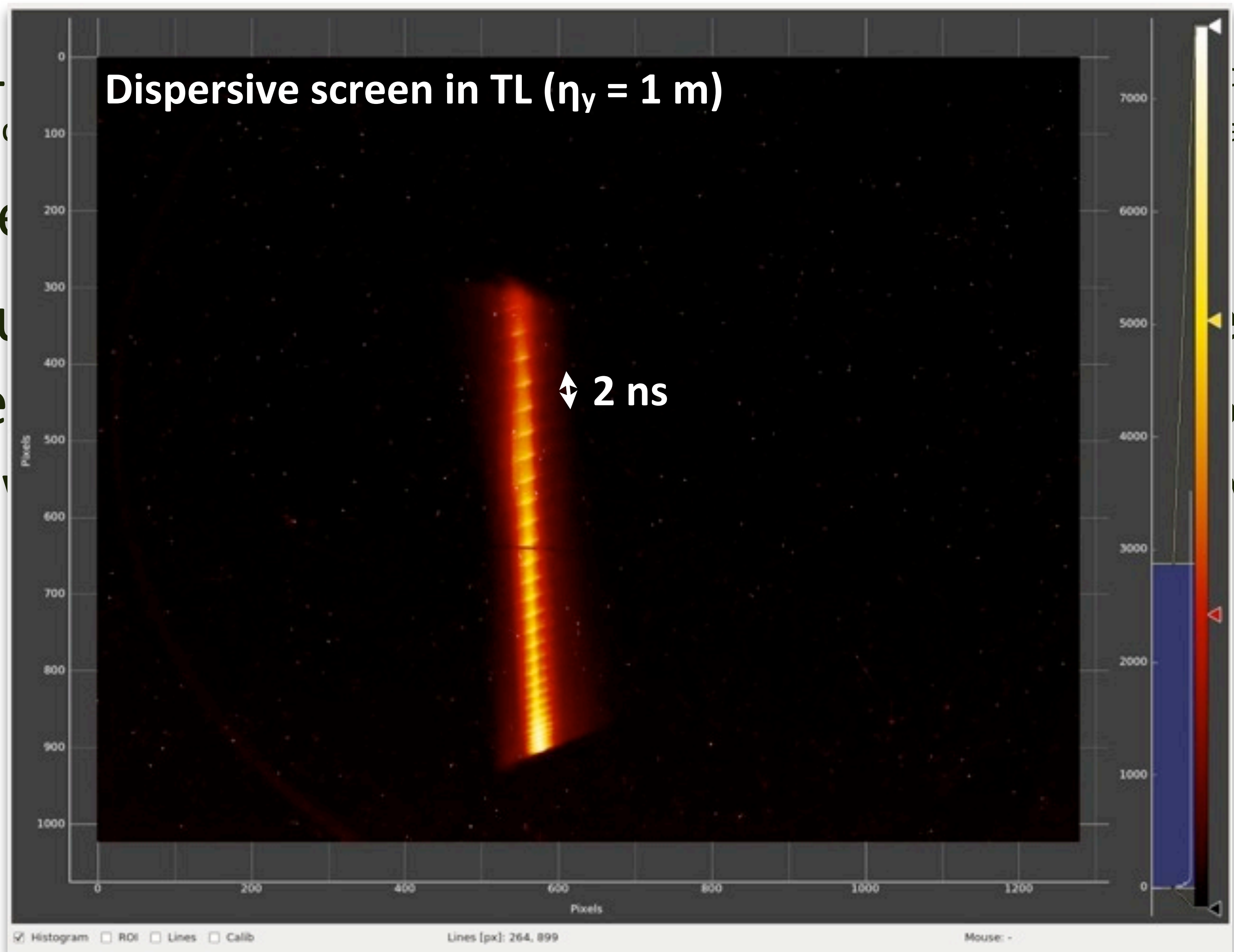

3 GeV Storage Ring Commissioning (cont.)

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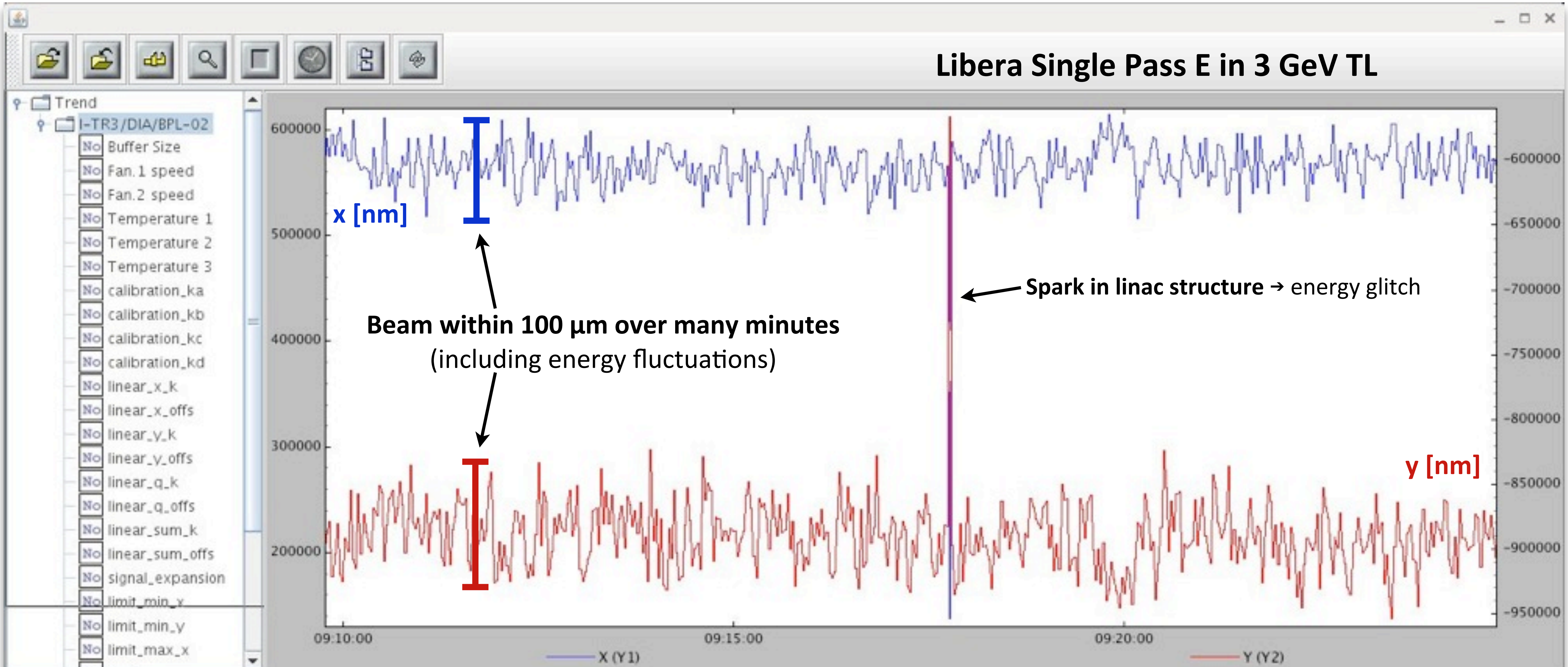
- Discovered & fixed inverted quadrupole polarity in TL
- After tuning relative timing of RF stations could eventually reduce overall energy spread of bunch train to ≈1% and <0.1% within S-band bunches (using dispersive screen in 3 GeV TL)
  - This allowed for much better transmission through TL (max aperture 15 mm, η_y = 1 m) → ≈900 pC in ≈80 ns train into SR
  - Good position/angle stability (<100 µm incl. energy fluctuations @ η_y = 1 m) over time scales of many minutes (Libera Single Pass E)

3 GeV Storage Ring Commissioning (cont.)



– Good position/angle stability (<100 µm incl. energy fluctuations @ η_y = 1 m) over time scales of many minutes (Libera Single Pass E)

3 GeV Storage Ring Commissioning (cont.)

- Some trouble with cooling of dipole PS (low flow, Cu collected on filters)
- Ongoing vacuum issues while conditioning some RF cavities
- Rep. rate lowered to 0.5 Hz & adjusted chopper → ≈1.6 nC at 3 GeV extraction point (radiation protection limitation) → ≈1 nC into SR
- On Sep 11, three cavities ready for beam (≈15-20 kW)
  - 15 kW allows for >200 kV gap voltage (max. gap voltage 300 kV)
  - bare lattice losses 364 keV/turn → minimum 2 cavities required
- Despite attempts at cavity phasing, could not detect any effect on beam so far
- But also only 30+ turns in ring → trying to tweak optics & orbit to increase signal and number of turns

Outlook

- 3 GeV SR commissioning is organized in phases:
  - ***SR Commissioning Phase I:***
    - inject, first turn, many turns, RF, store, OCO, accumulate → reach ≈3 mA
  - ***SR Commissioning Phase II:***
    - reach bare lattice design parameters (apart from current) → vacuum conditioning, improve OCO, LOCO (shunting), diagnostic BLs, NL optimization?, current increase

ID Installation, 1-2/2016

  - ***SR Commissioning Phase III:***
    - accumulate sufficient beam for full BL commissioning → stacking, LCs, impedance characterization, transverse MBFB?, ID commissioning

Inauguration June 21, 2016

  - ***SR Commissioning Phase IV:***
    - high-current stacking, MIK, high-power RF commissioning, FOFB
  - "Post-commissioning activities": user top-up, more IDs, higher-power RF, etc.

8/2015 – 6/2016

6/2016 – ~2017

Outlook (cont.)

- Plans for remainder of 2015: complete commissioning phases I & II → optics, orbit, vacuum, current, diagnostic BLs
- Shutdown in Jan/Feb 2016 → ID installation (along with 2nd diagnostic BL)
- BL commissioning starts Mar 2016 → will influence ring commissioning priorities (ID commissioning time vs. current vs. stability vs. ...)
- Phase III completed by June 21, 2016 → **facility inauguration**
- Inauguration goals:
  - ***Linac*** is reliable injector to 3 GeV SR, ***3 GeV SR*** has stable 10+ mA at several hours lifetime with 2 IDs commissioned, ***first 3 GeV SR BL*** ready for first users, ***FemtoMAX BL*** (SPF) ready to receive light
- Note: 1.5 GeV SR commissioning begins < June 2016

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, Martin Johansson, Eshraq Al-dmour, Åke Andersson, Dieter Einfeld, Les Dallin
  - Our colleagues at SOLARIS and many other labs

Photo courtesy L. Jansson, August 24, 2015

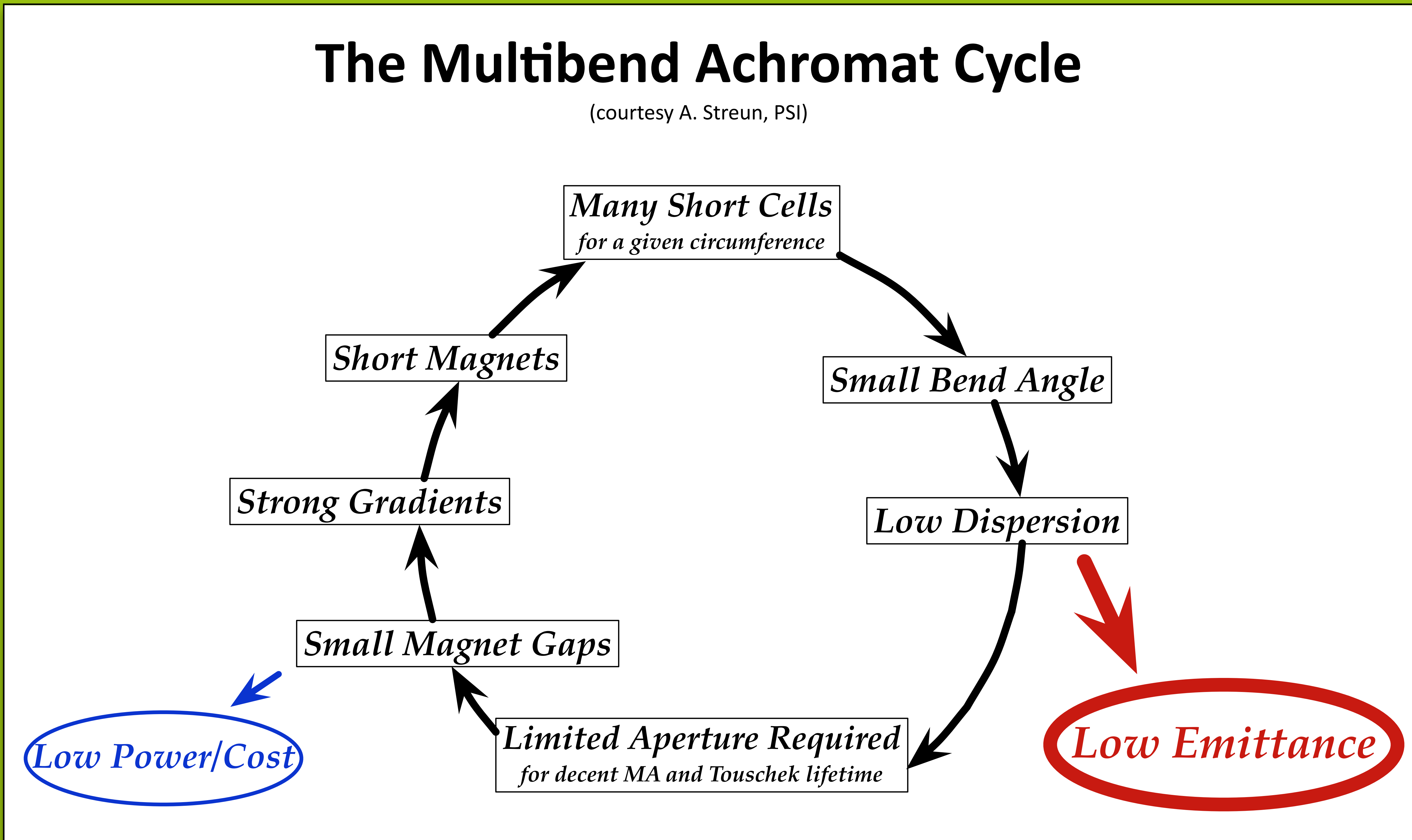
Thanks for your attention!

Photo courtesy L. Jansson, August 24, 2015

Backup Slides

Photo courtesy P. Nordeng, April 27, 2015

Backup: MBA Cycle → Positive Feedback

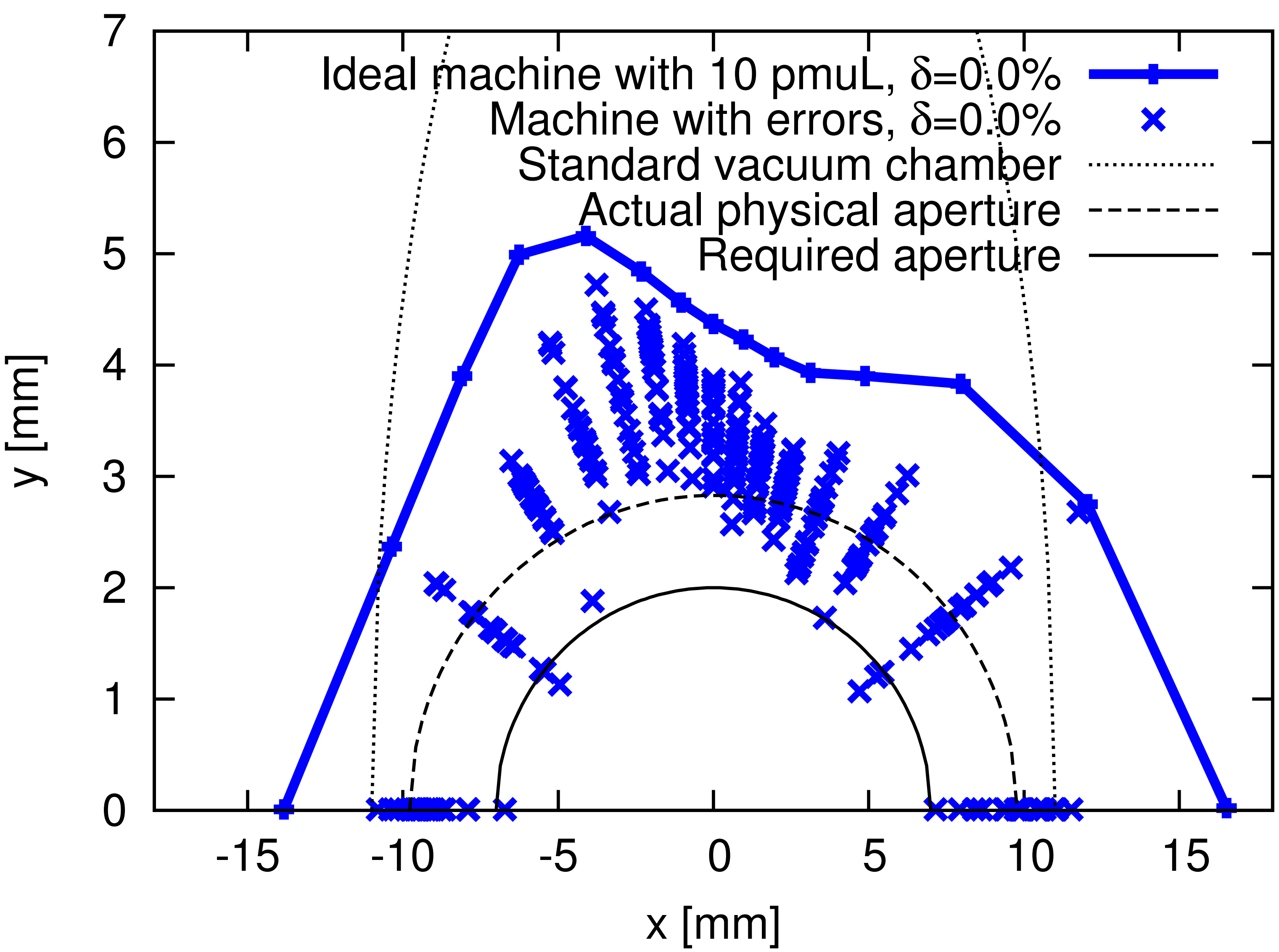


Backup: Imperfection Details & ID Parameters

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

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

IPAC'**15**, TUPJE038



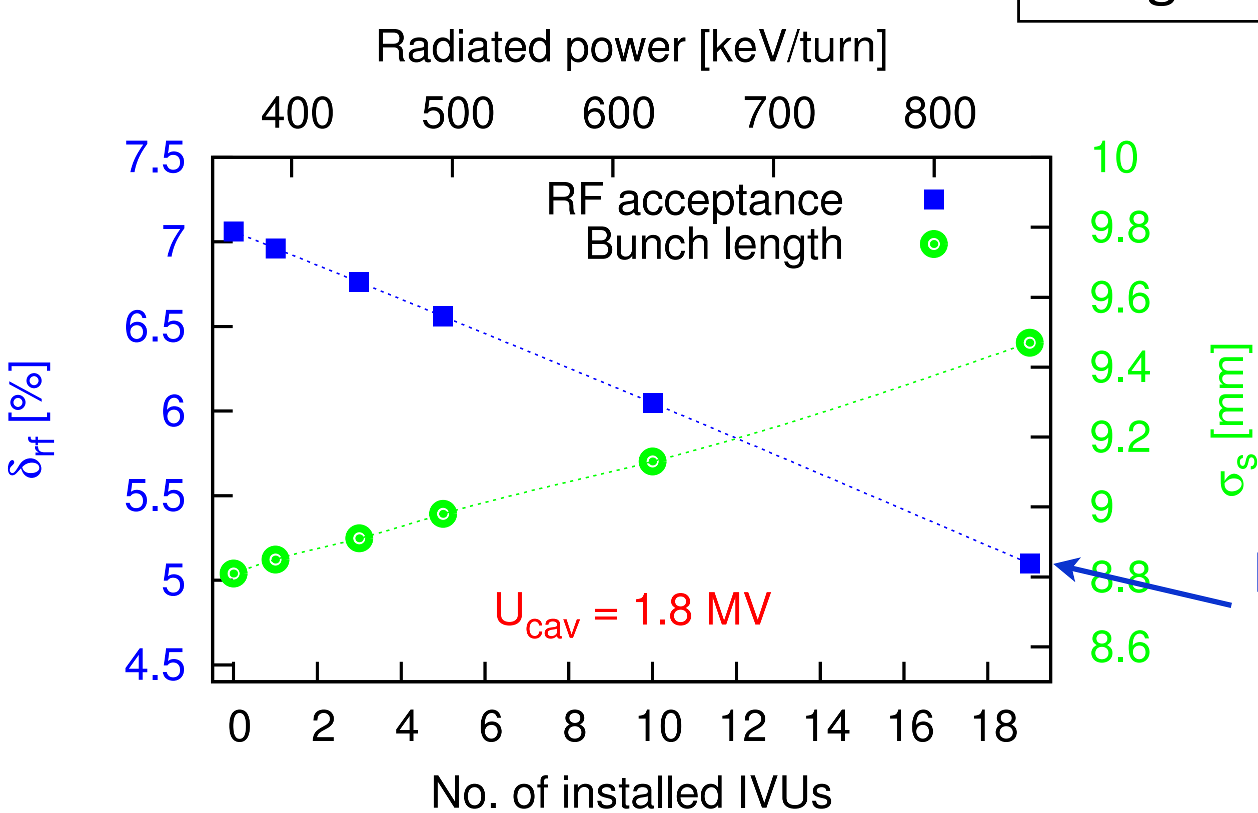
- IVU "pmuL":
  3.7 m long, 1.1 T peak field,
  18.5 mm period, 4.2 mm gap
- Misalignments:
  50 μm rms H/V
  0.2 mrad rms roll } for each magnet block
  25 μm rms H/V
  0.2 mrad rms roll } for all magnets within
- Field Errors:
  0.05% rms within each family
- Multipole Errors:
  Upright and skew multipoles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

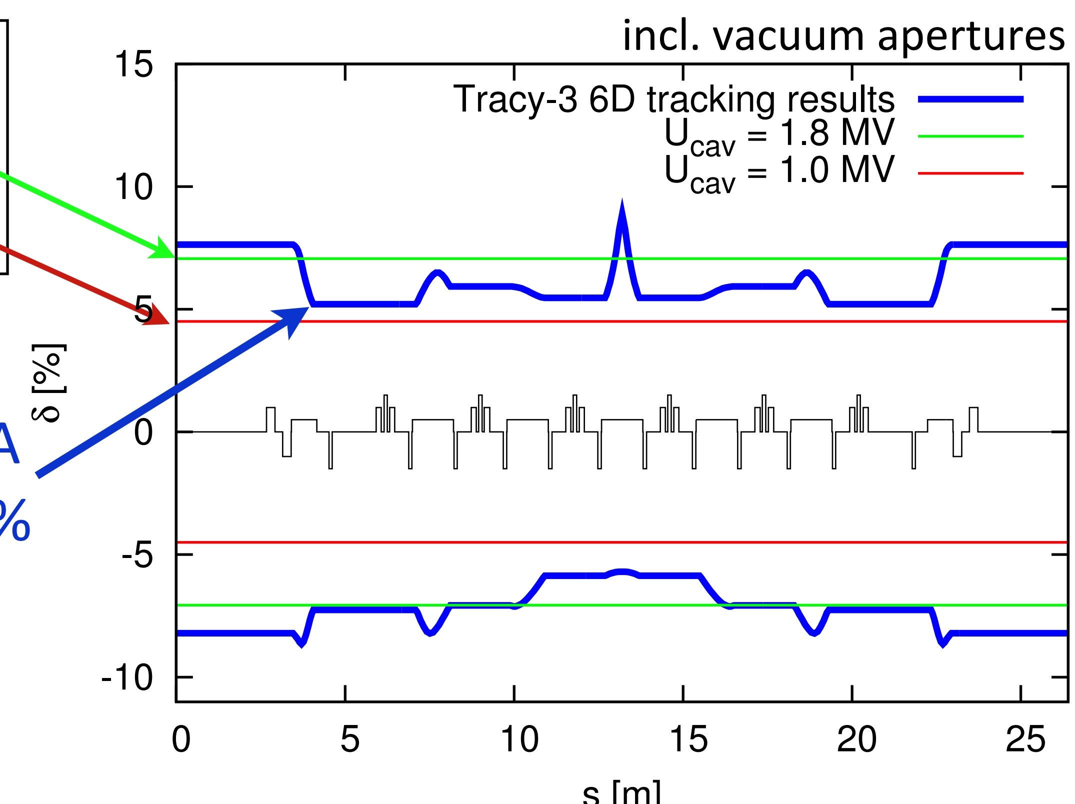
Backup: Large Overall MA with 100 MHz RF

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

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

MAX IV 3 GeV SR
U_{cav} = 1.8 MV (max)
Target: $\delta_{acc} > 4.5\%$





Lattice MA always >5%

RF acceptance always >5%

Backup: Large Overall MA with 100 MHz RF (cont.)

- Large off-momentum DA enables generous lattice MA
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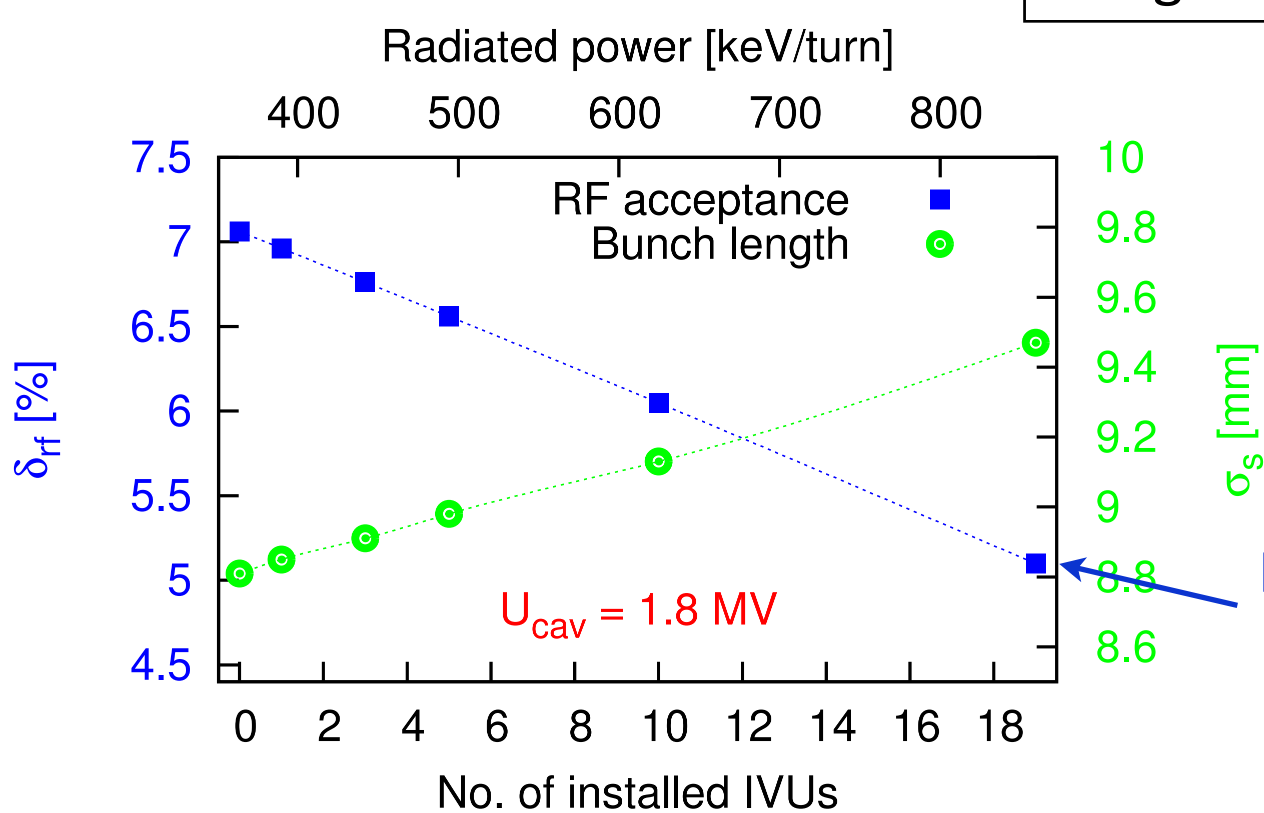
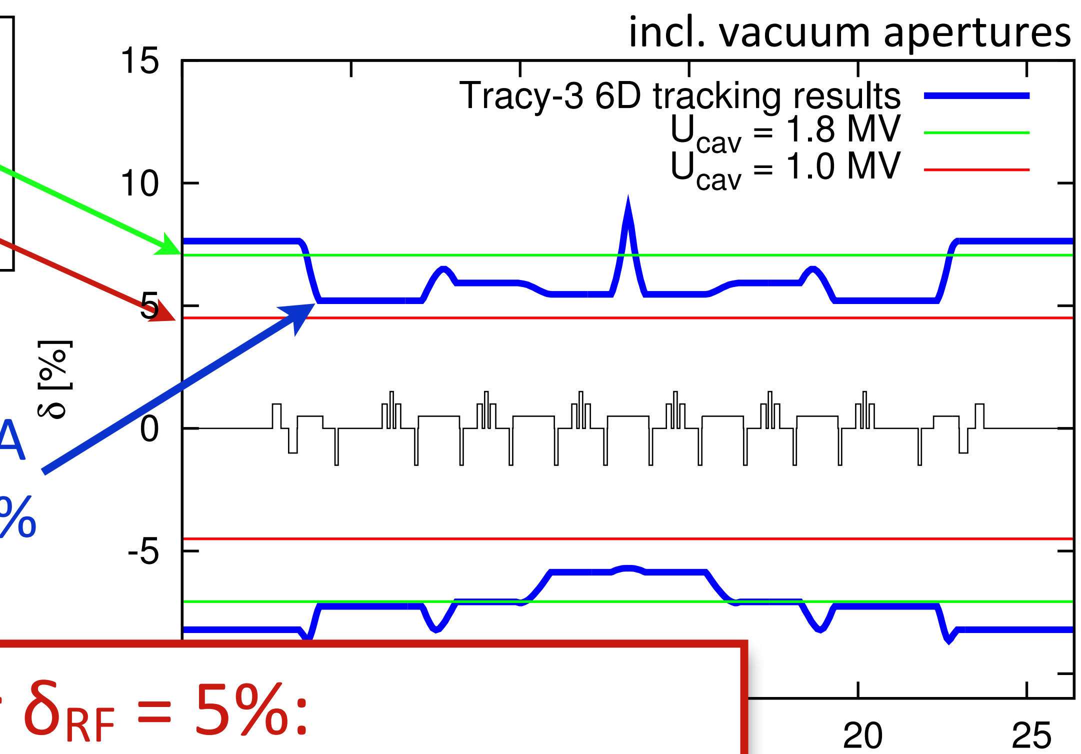


RF acce… always…

Lattice MA always >5%



For δ_{RF} = 5%:
- 1.1 MV @ 100 MHz
- 3.7 MV @ 500 MHz

→ Cu losses, power bill

Backup: Touschek @ Ultralow Emittance

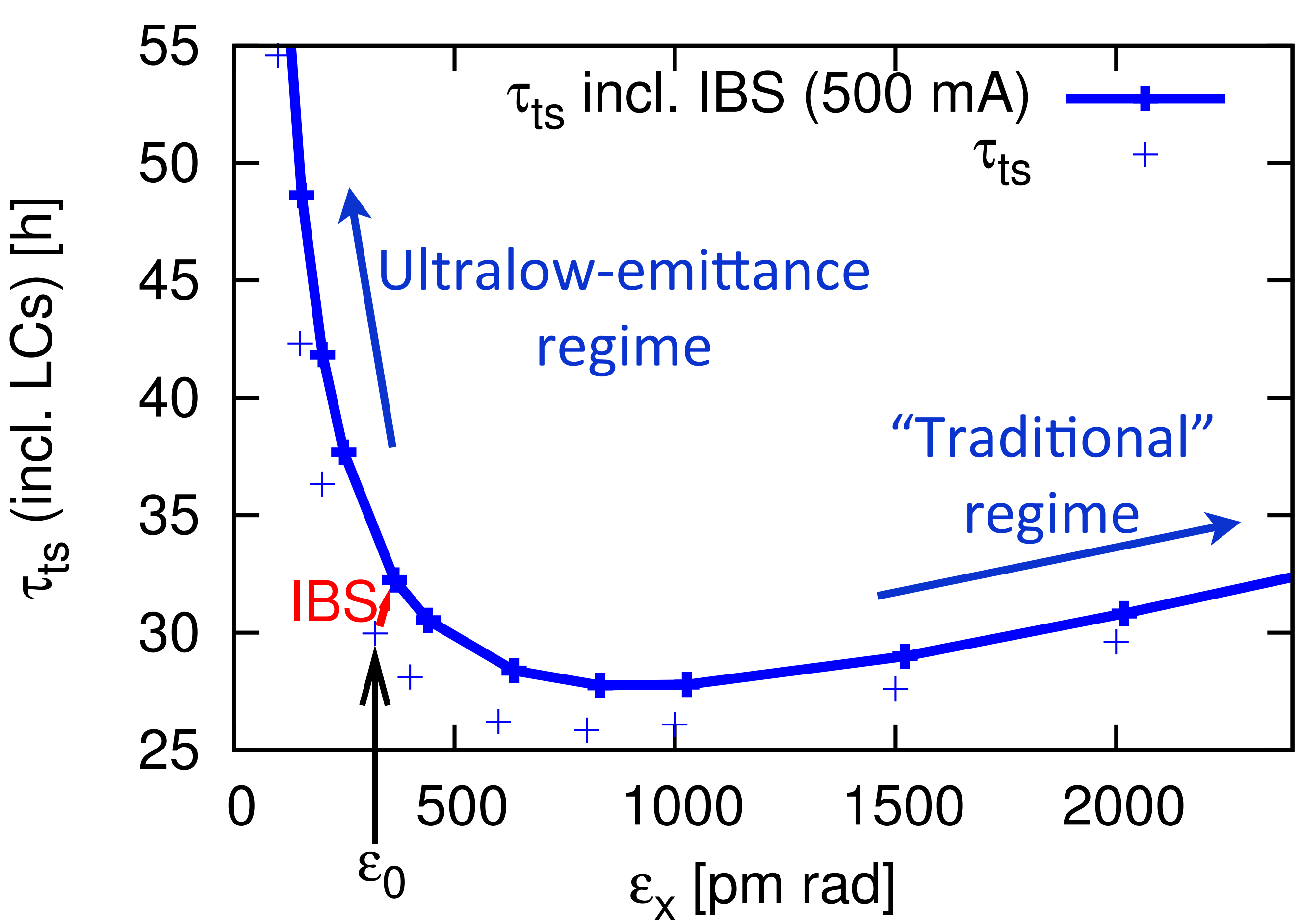
- Large overall MA is required if ultralow emittance should render good Touschek lifetime

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

PRL **10**, 407 (1963)

J. Le Duff, CERN Yellow Report 1989-01

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



MAX IV 3 GeV SR (bare lattice)

I = 500 mA

δ_{acc} = 4.5%

σ_δ = const

ε_y = 8 pm rad

Backup: Touschek @ Ultralow Emittance (cont.)

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  PRL **10**, 407 (1963)

  J. Le Duff, CERN Yellow Report 1989-01

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

- Use 300 MHz Landau cavities to stretch bunches ×5
  ➔ extend Touschek lifetime beyond gas lifetime

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

Backup: Touschek @ Ultralow Emittance (cont.)

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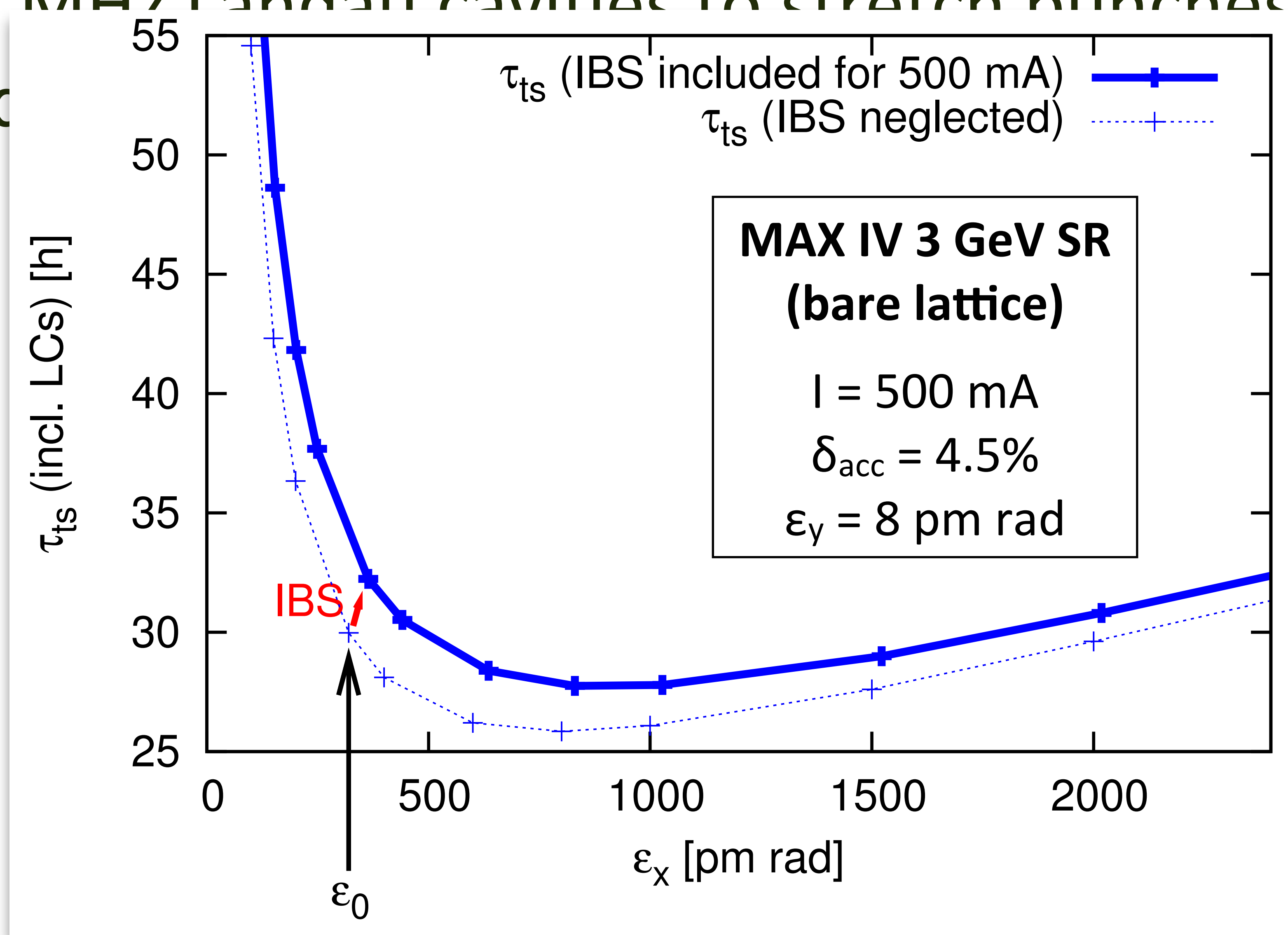

Backup: Touschek @ Ultralow Emittance (cont.)

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  (low emittance → small transverse momenta → few scattering events lead to actual Touschek loss)
- Use 300 MHz Landau cavities to stretch bunches ×5
  → extend Touschek lifetime beyond gas lifetime
- At MAX IV LCs are indispensable to maintain ultralow emittance despite strong IBS at 500 mA stored current (5 nC/bunch)

PRL **10**, 407 (1963)

J. Le Duff, CERN Yellow Report 1989-01

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

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

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

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

CERN-AB-2006-002

Backup: Touschek @ Ultralow Emittance (cont.)

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J. Le Duff, CERN Yellow Report 1989-01

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  ➔ ext... me

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

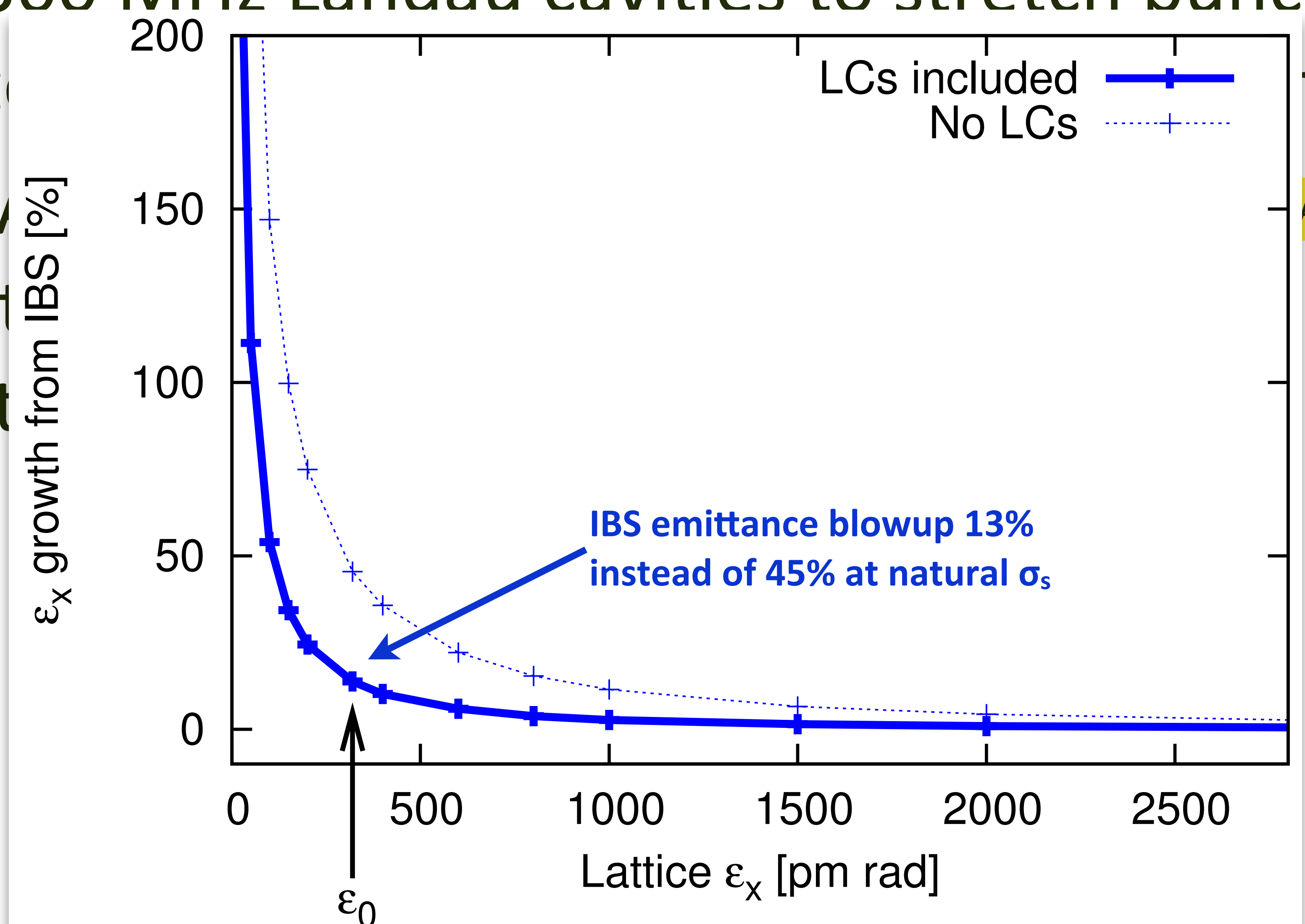
- At MA... maint... IBS at...

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

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

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

CERN-AB-2006-002



MAX IV 3 GeV SR (bare lattice)

$I = 500$ mA

$\delta_{acc} = 4.5\%$

$\sigma_\delta \approx$ const

$\varepsilon_y = 8$ pm rad