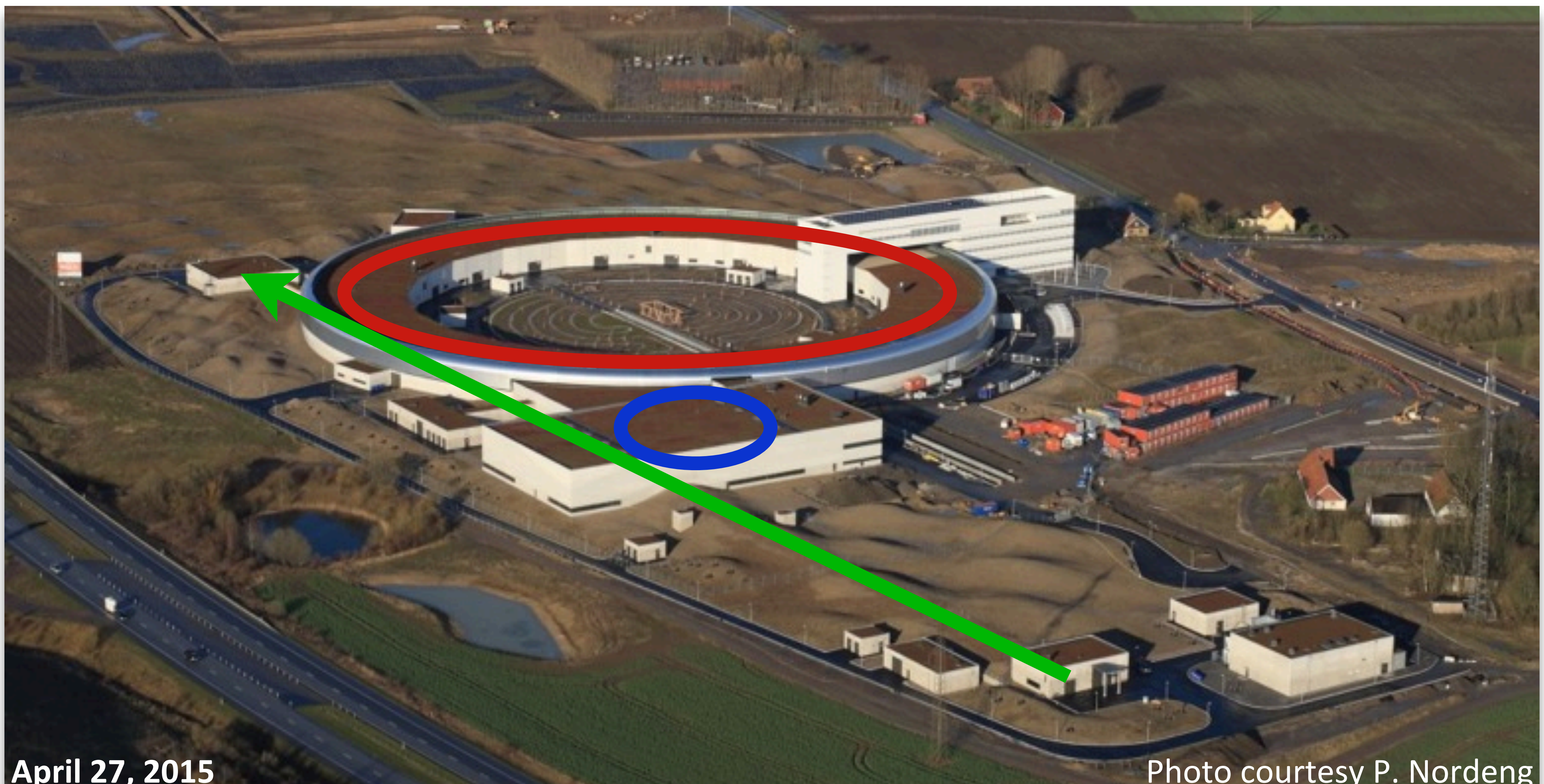
Pulsed Multipole Injection for the MAX IV Storage Rings

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

MAX IV

MAX IV Injection Overview

- Full-energy (underground) linac drives short pulse facility & delivers top-up shots to two storage rings: 3 GeV storage ring and 1.5 GeV storage ring



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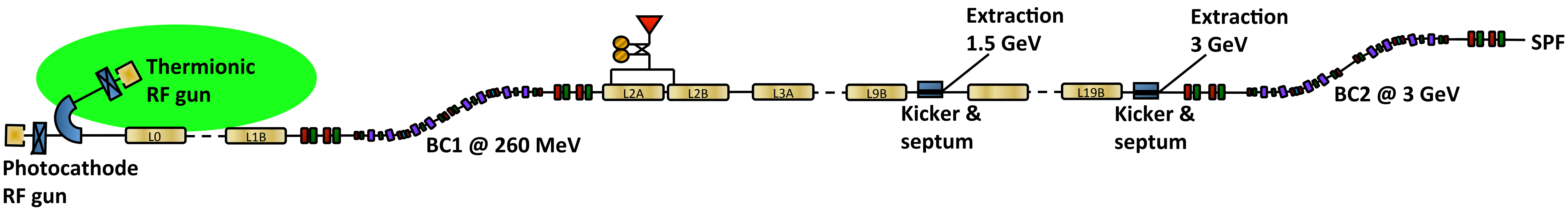
- Thermionic RF gun (S-band) with RF chopper injects at 10 Hz



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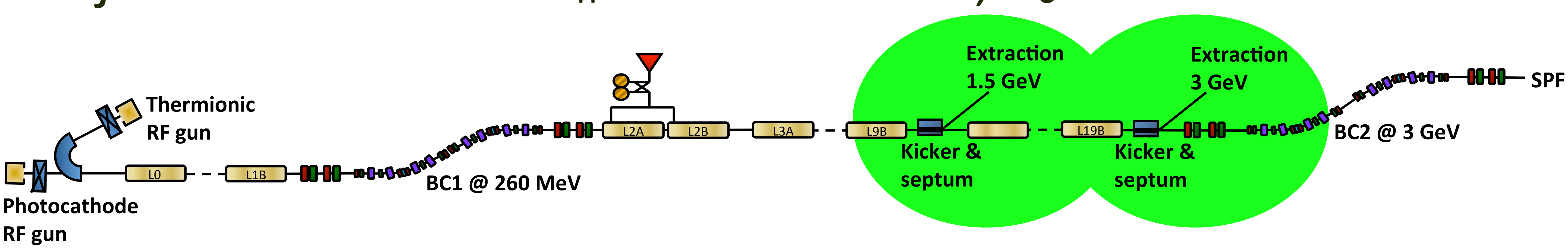
- SR injection interrupts SPF operation (photogun @ 100 Hz)
  ➔ re-phase linacs & ramp extraction magnets
- Two dedicated vertical (achromatic) transfer lines
- Injection into rings (100 MHz) via DC Lambertson septum
- Inject bunches with ε_n = 10 mm mrad, σ_δ = 0.1%



MAX IV Injection Overview (cont.)

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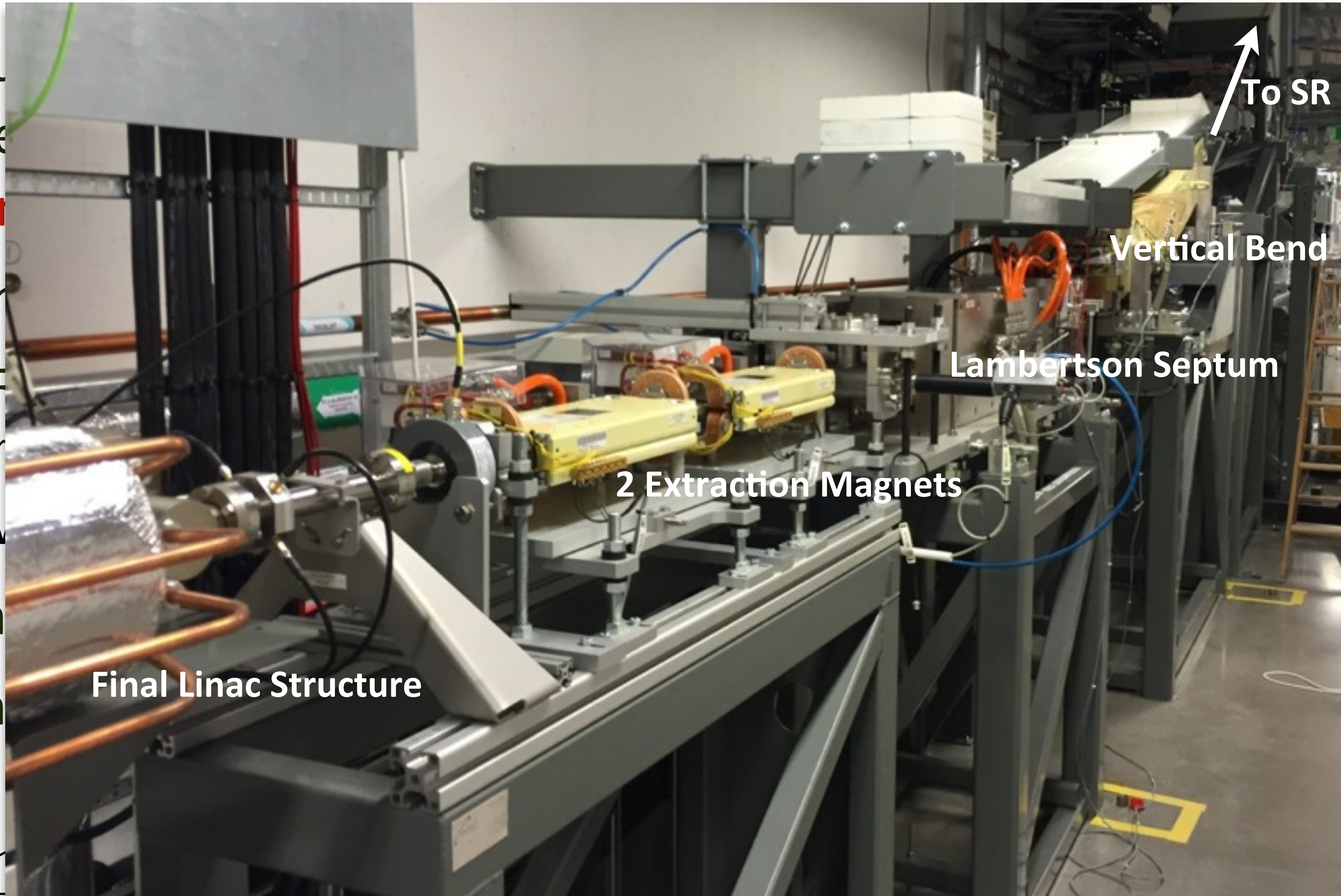

SPF

Photocathode
RF gun

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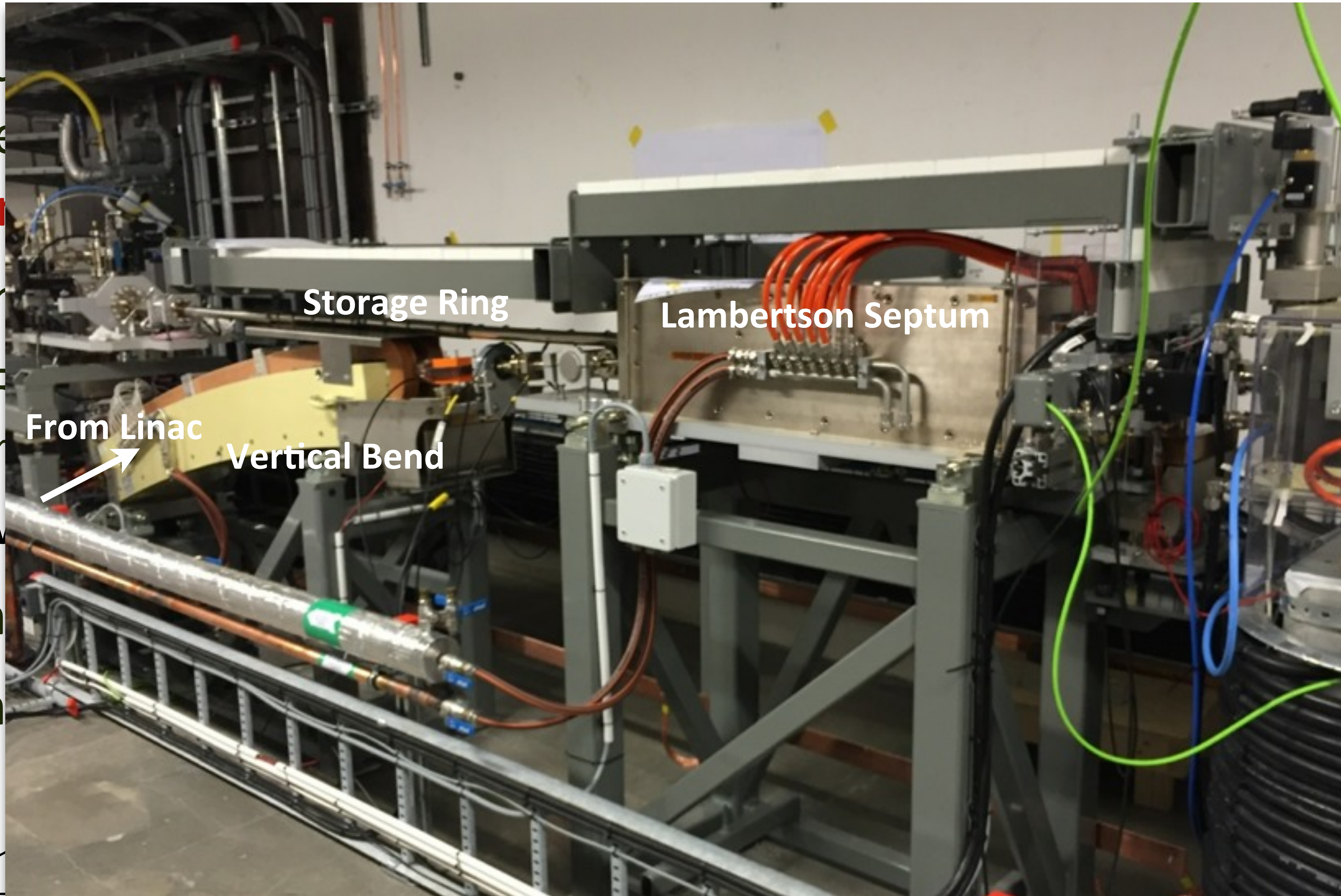
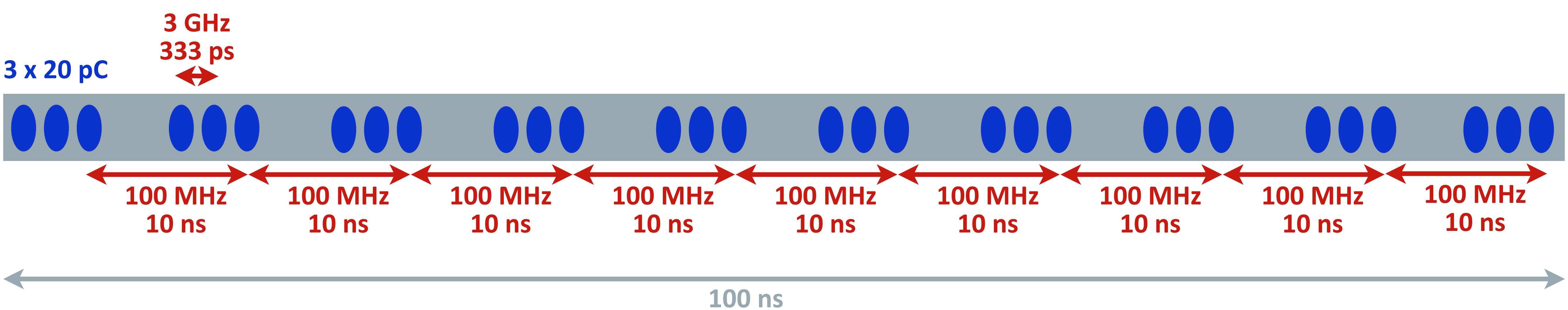


SPF

Photocathode
RF gun

MAX IV Injection Requirements

- Ring injection occurs at 10 Hz (governed by SR damping time)
  - Each 100 ns linac shot consists of up to 10 bunch trains (10 × 10 ns, governed by linac field uniformity [SLEDs])
  - Each bunch train can contain up to 60-100 pC (3-5×20 pC @ 3 GHz) depending on ring RF settings (injection phase acceptance)



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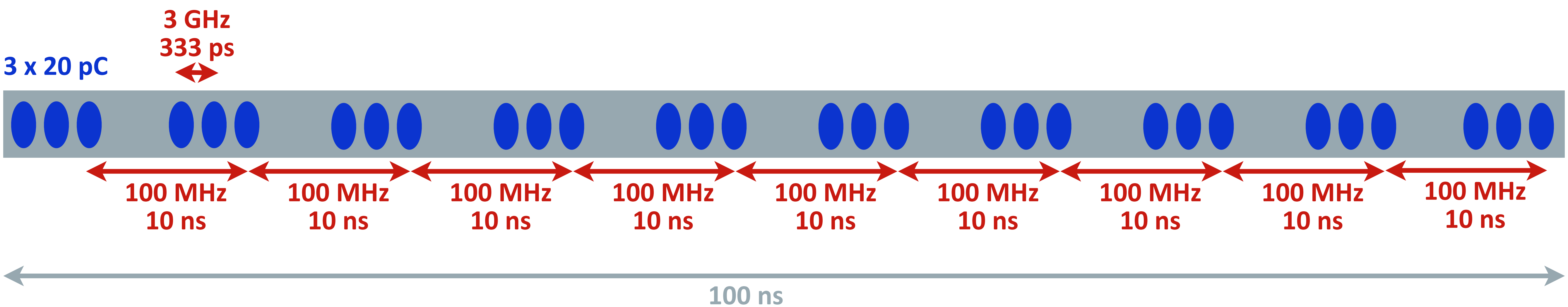


➡ This results in 0.6-1 nC (0.3-0.6 mA in 3 GeV ring) per linac shot or injection at 6-10 nC/s (3.4-5.7 mA/s in 3 GeV ring) at 100% efficiency

MAX IV Injection Requirements (cont.)

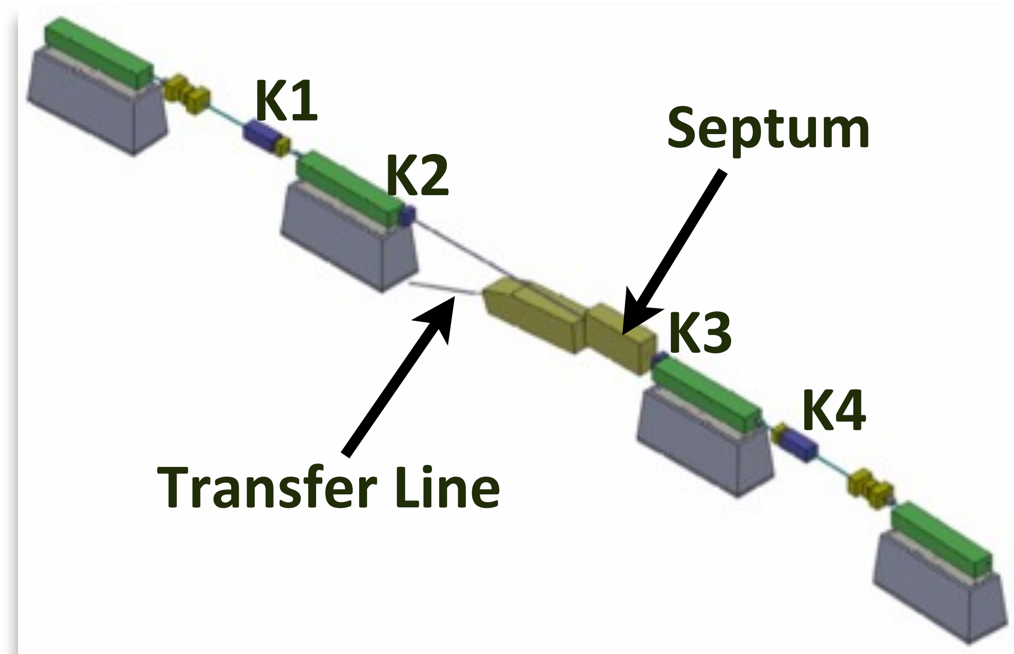
56 h inelastic
25 h elastic
>24 h Touschek (depending on IDs, coupling, RF)

- Total lifetime in rings is ≈10 h @ 500 mA
- 176 bunches → 5 nC/bunch for 500 mA (1.5 GeV ring: 32 bunches)
- Assuming ≈100% injection efficiency, two scenarios define limits for 3 GeV top-up injection:
  - 60-100 pC (1 bucket) every ≈2.5 sec → 0.007% deadband (0.034 mA)
  - 1% deadband (5 mA) → 8.81 nC (15 shots) every 6 min
  - Since extraction magnet ramping takes ≈2 sec, the latter has been the preferred option → top-up injections take ≈2% of overall linac time from SPF

➡ In general, need to consider implications for filling pattern homogeneity vs. "quiet time", requirements on gun/injector reliability, user preferences, etc.

Injection & Capture

- Original design: conventional 4-kicker bump injection



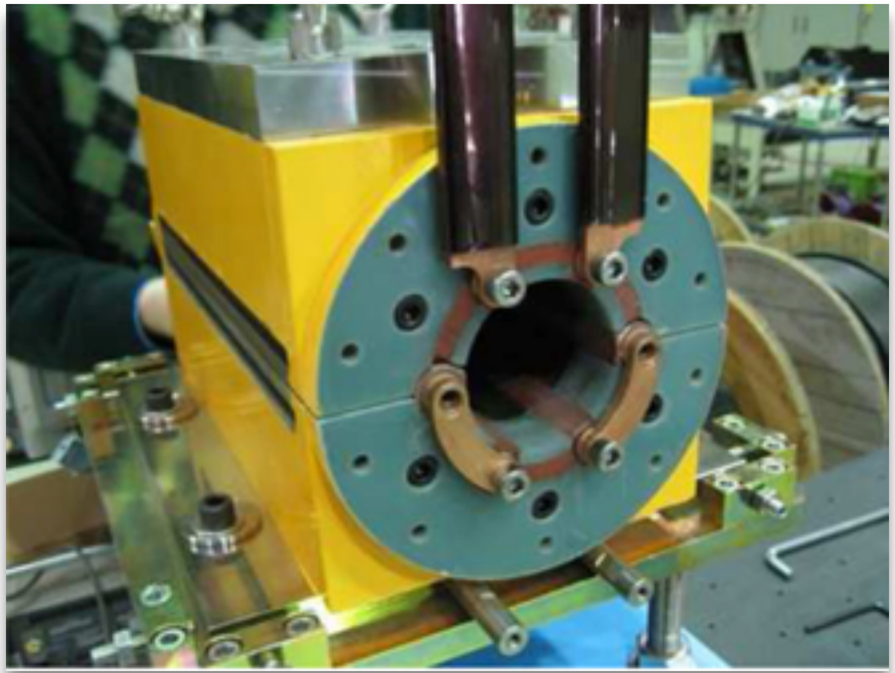
- But worried about stored beam stability during top-up
  - 200 nm vertical stability requirement
- Also worried about complexity
  - matching, synchronizing and aligning 4 kickers/pulsers to properly close bump
  - strong sextupoles & octupoles within bump: bump can only be properly closed for one energy and amplitude
  - 4 kickers and septum require lots of space

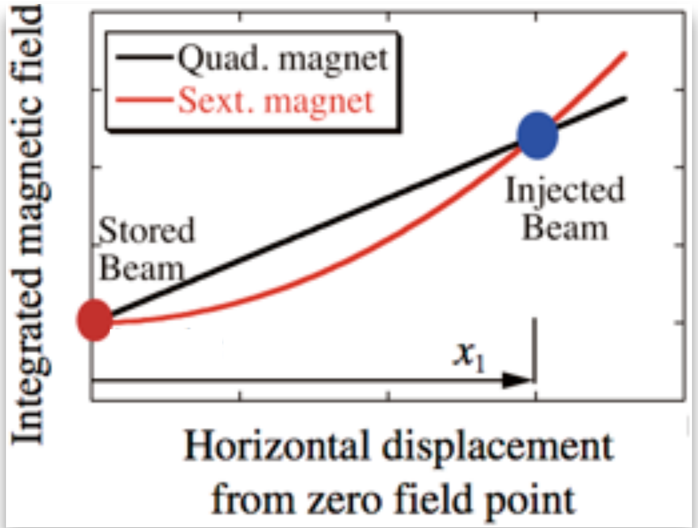
Injection & Capture (cont.)

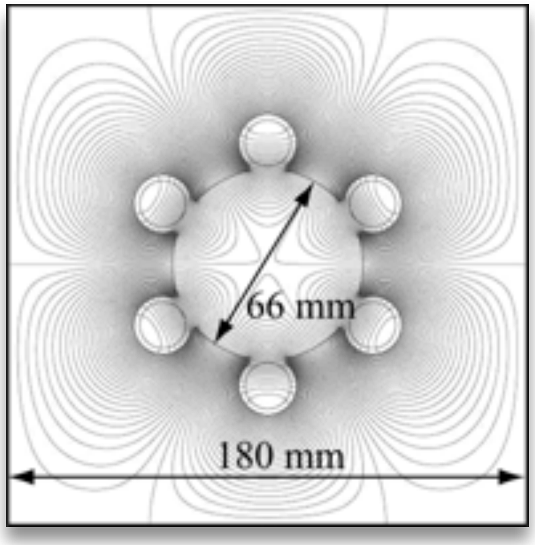
- Intrigued by KEK's pioneering work on PQM and PSM
  - align only a single magnet to stored beam
  - synchronize only one pulser to injection
  - PSM field flat around stored beam
  - ➡ minute perturbation of stored beam by PSM

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

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







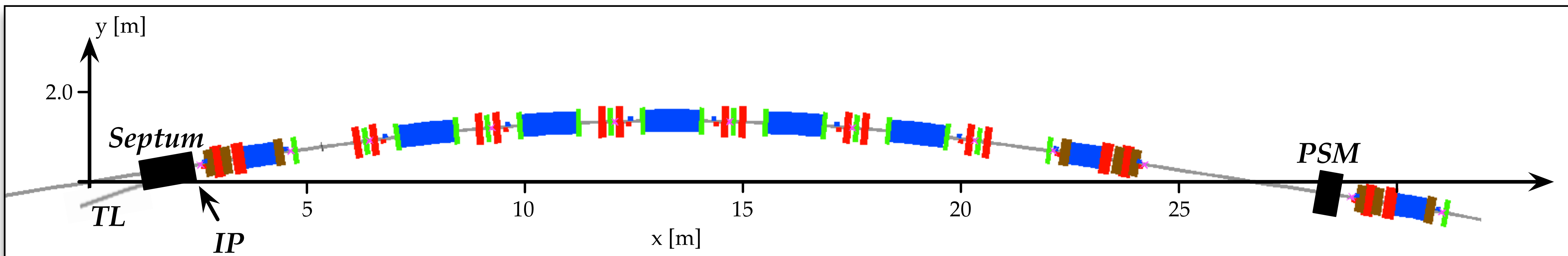
Magnetic field at 15 mm	40 mT
Magnetic length	300 mm
Bore diameter	66 mm
Peak current	3000 A
Pulse length	1.2 / 2.4 μs

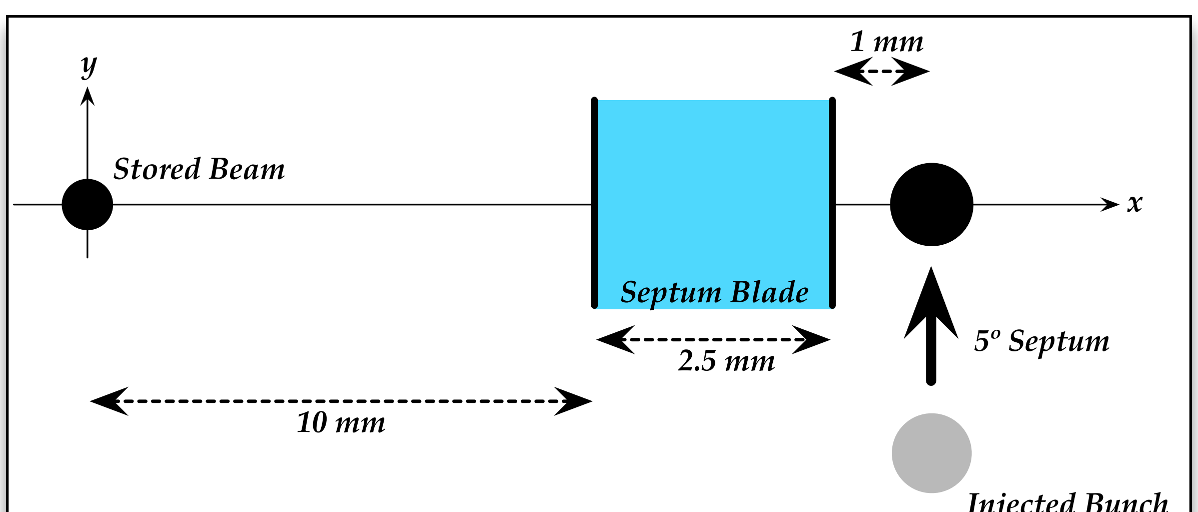
Injection & Capture (cont.)

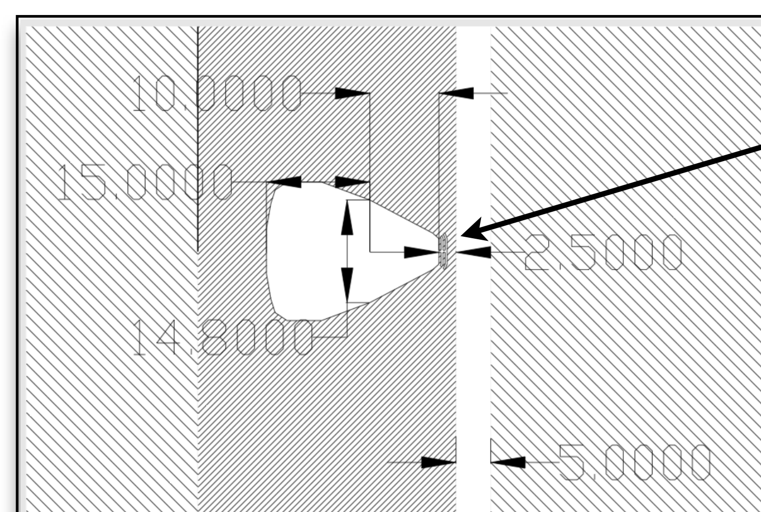
- Decided to use pulsed sextupole magnet injection for top-up injection into both MAX IV storage rings

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







NIM-A **490**, 592, 2002

NIM-A **547**, 686, 2005

Injection & Capture (cont.)

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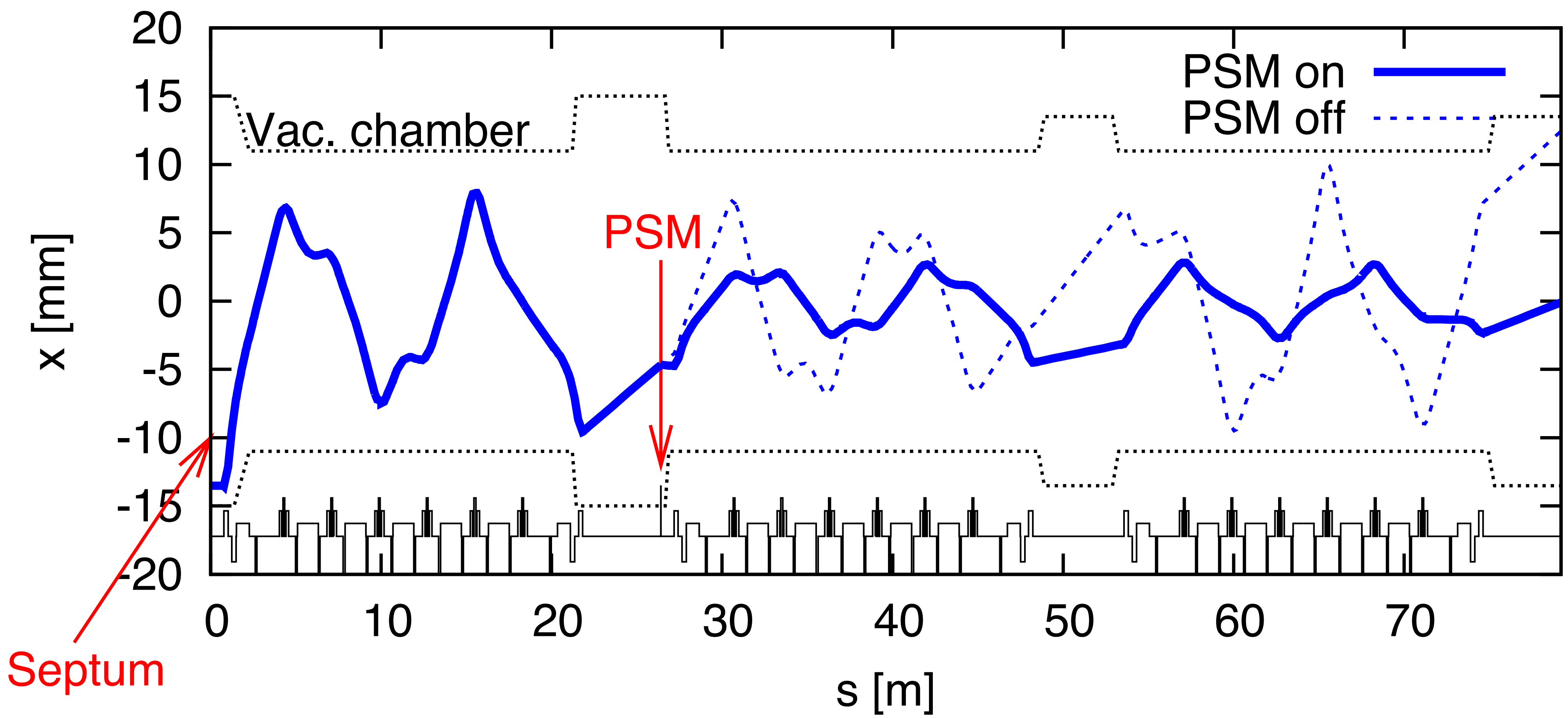

$$\cos\phi_{\text{psm}} = \pm\frac{A_{\text{red}}}{A_{\text{inj}}}$$

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

$$(b_3L) = \frac{\theta_{\text{psm}}}{x_{\text{psm}}^{\;2}}$$

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

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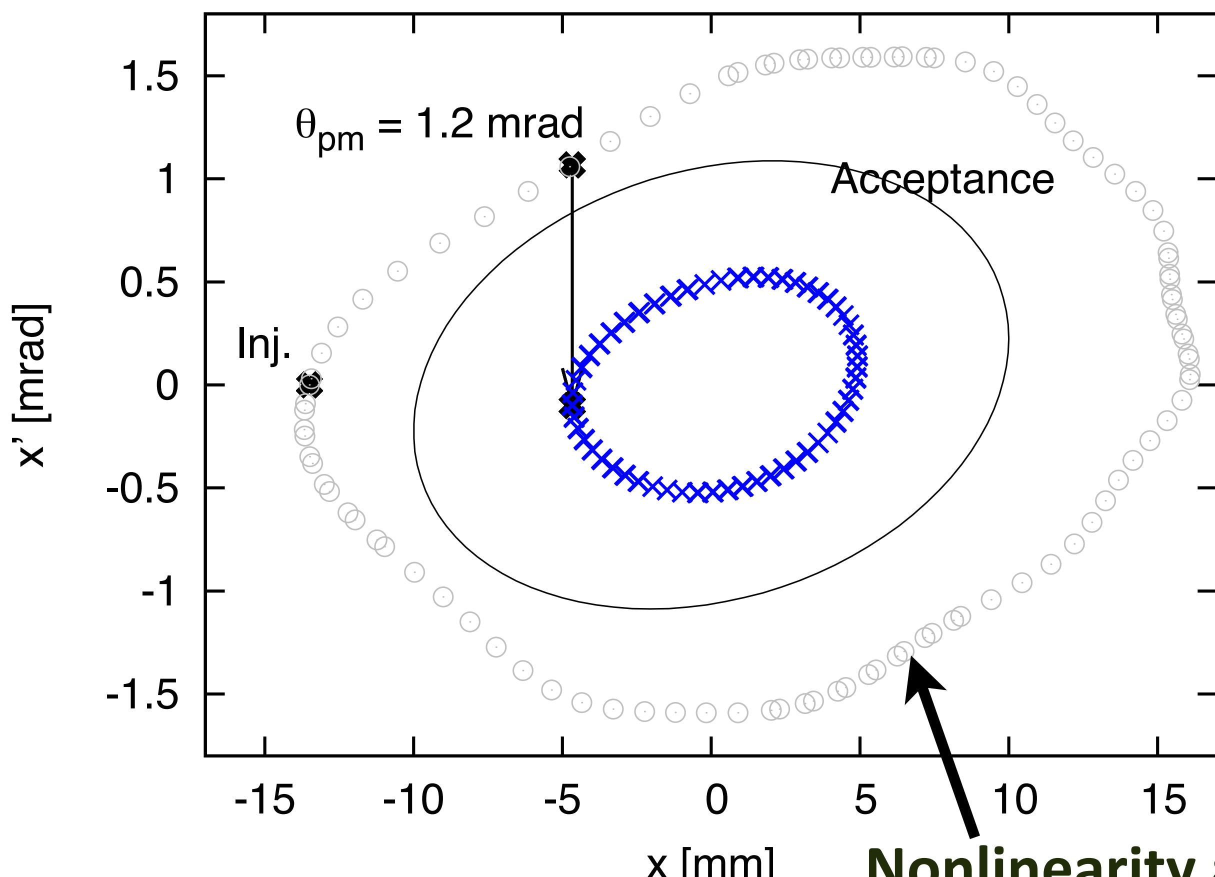

Nonlinearity at large amplitudes

≈1.2 mrad to minimize reduced invariant

≈0.8 mrad sufficient for capture within (design) acceptance

Injection & Capture (cont.)

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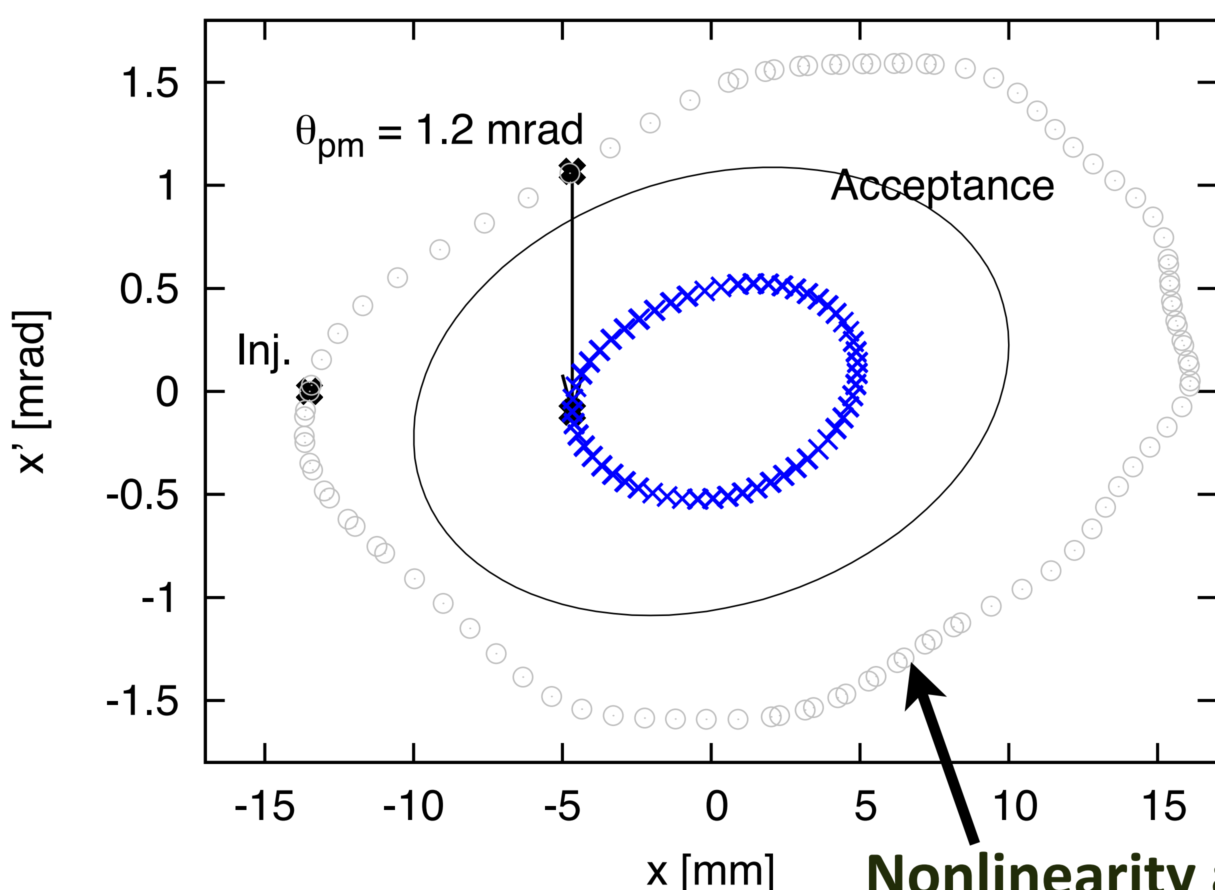

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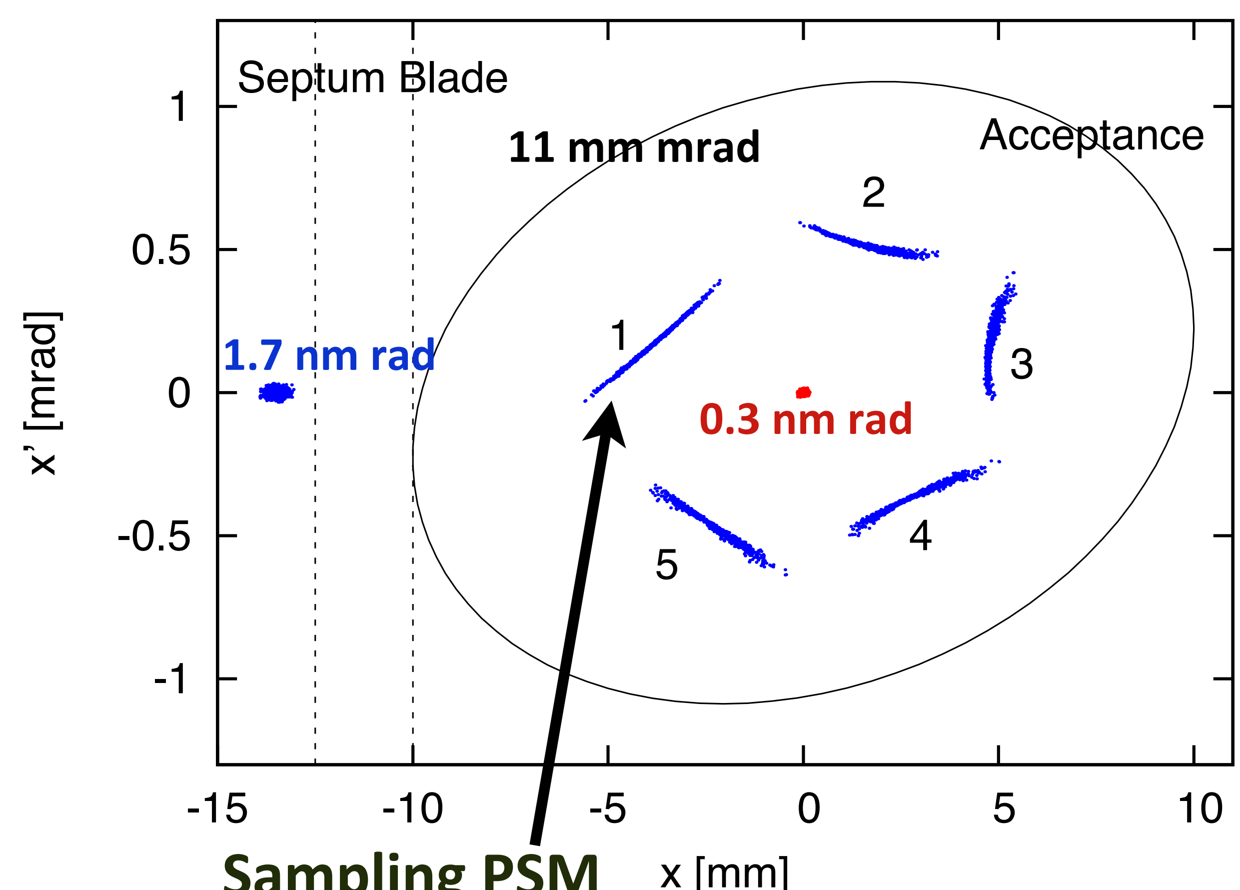


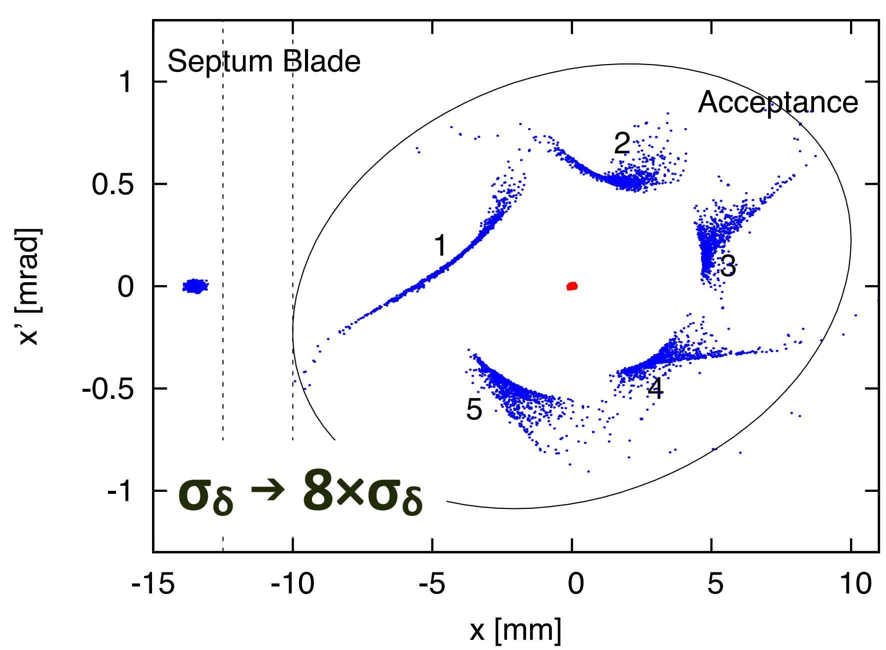
Sampling PSM field gradient

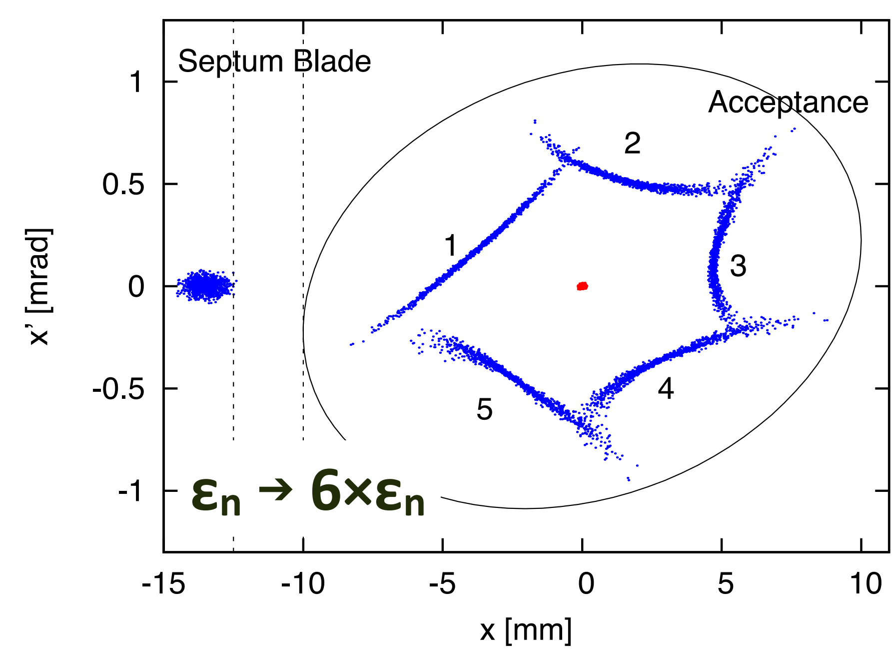
Injection & Capture (cont.)

- 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)





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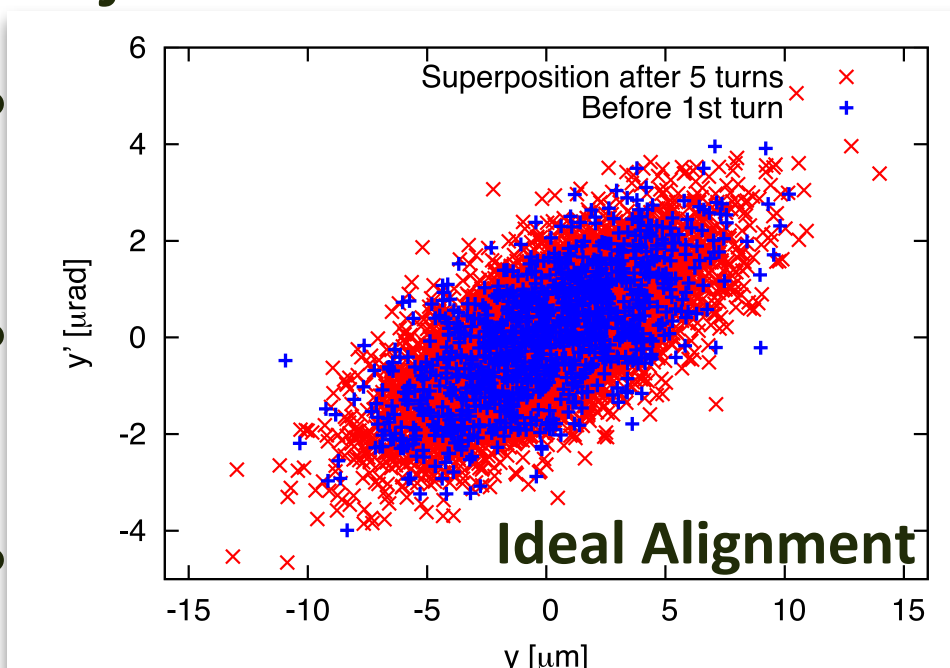
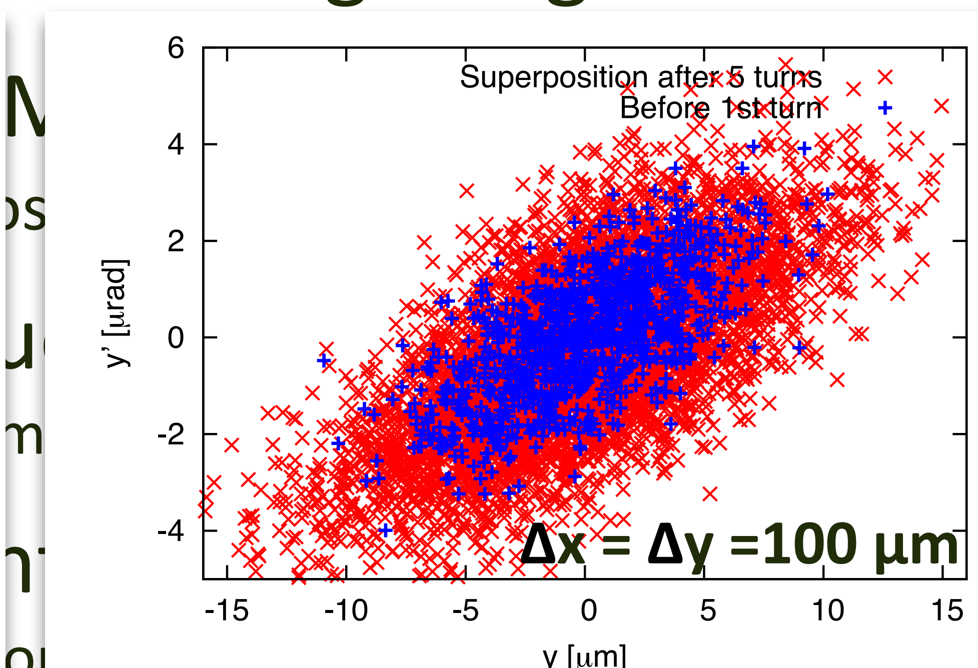




- M … king (Tracy-3, … strength of PSM
- … d emittance … acceptance)
- … rrors … nce)

- But tolerances are tight for fully transparent top-up injection
  - Requirement for low perturbation: excellent alignment & negligible residual fields/gradients
  - Alignment adjustment can be beam-based via orbit bump
  - ➡ Girder design to facilitate beam-based re-alignment of the PSM

Reference Design for a MAX IV PSM

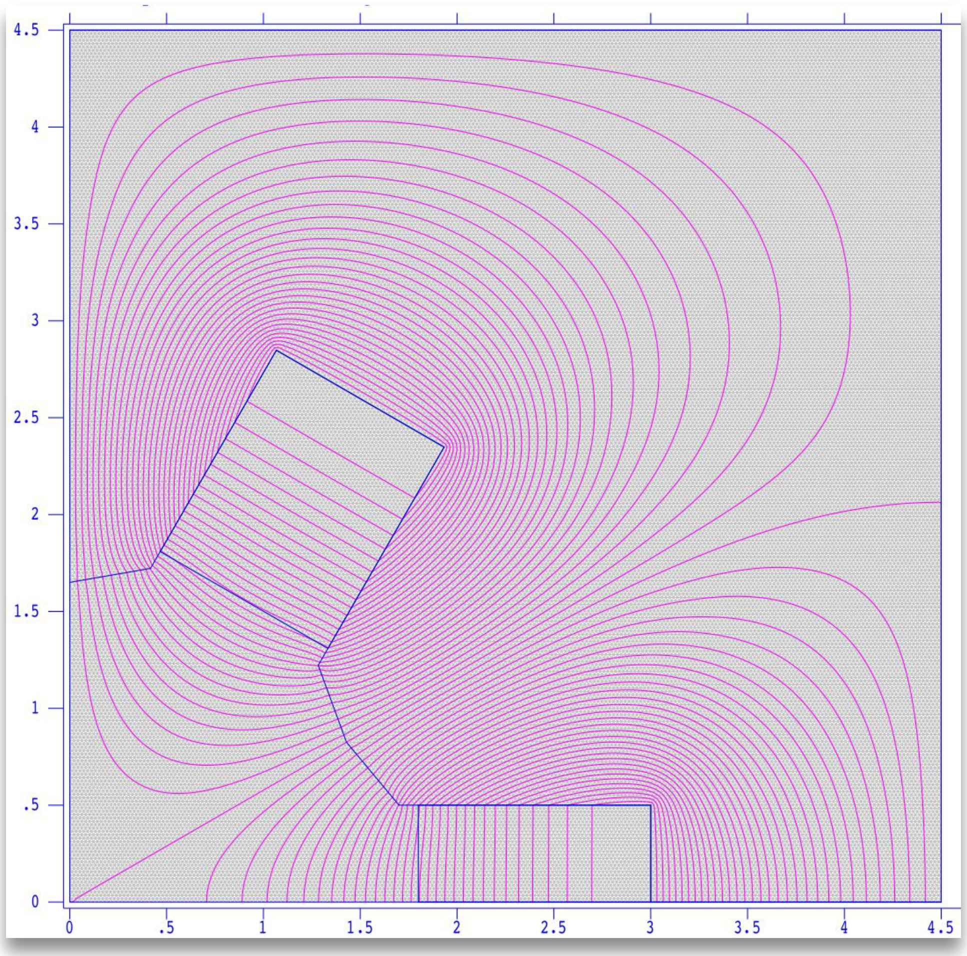
- Initially, attempted a solid iron PSM following KEK design
  - make use of reduced gap required in MAX IV
  - symmetry required to minimize stored beam perturbation
  - ➡ cannot accommodate for aspect ratio of BSC

PAC'**13**, WEPSM05

- 300 mm length ➔ 20.6 J stored energy
  - 3.5 μs pulse in 3 GeV ring ➔ 19.3 kV

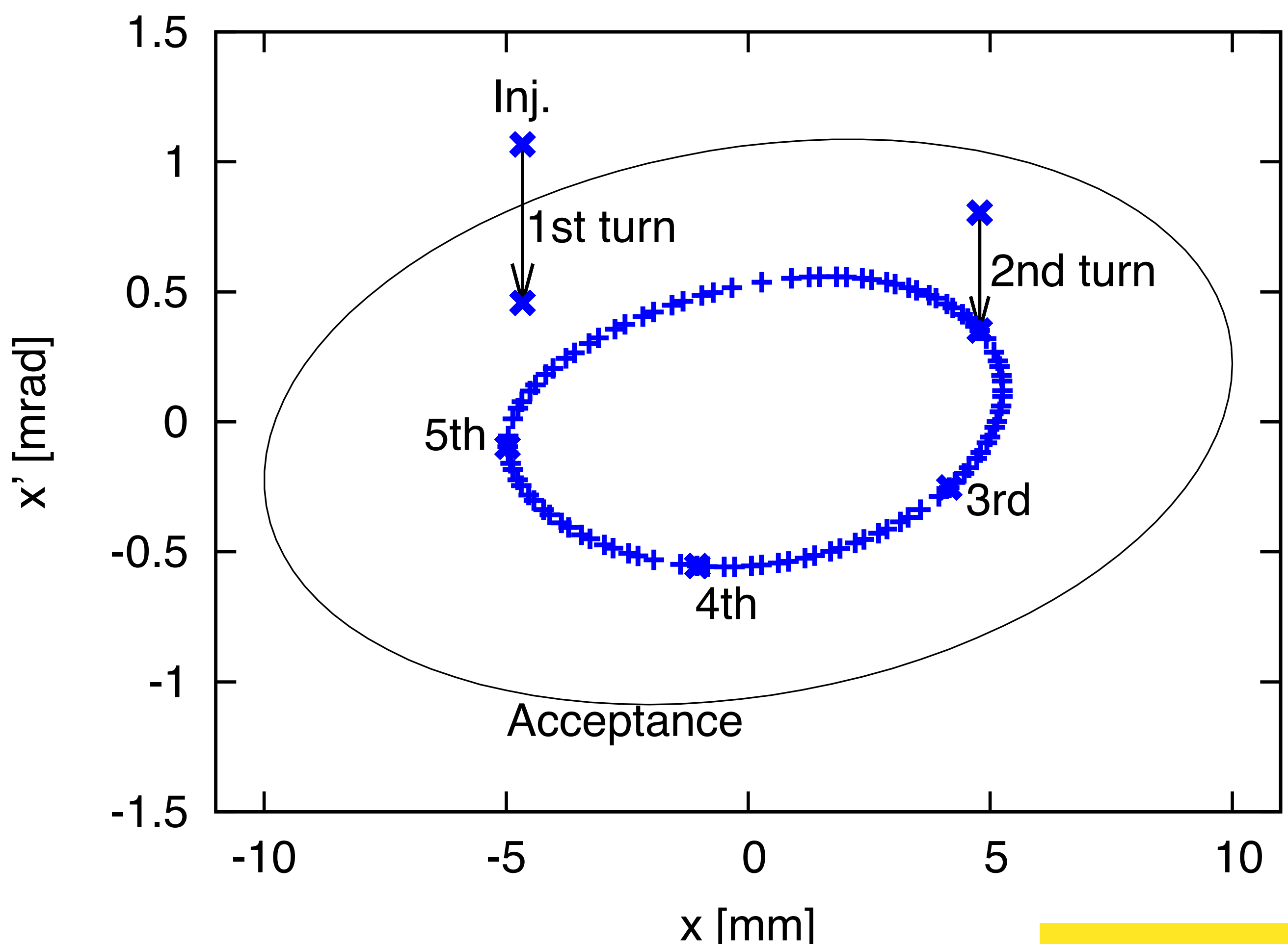
Magnetic field at 4.7 mm	39 mT
Magnetic length	300 mm
Bore diameter	32 mm
Peak current	2125 A
Pulse length	3.5 μs

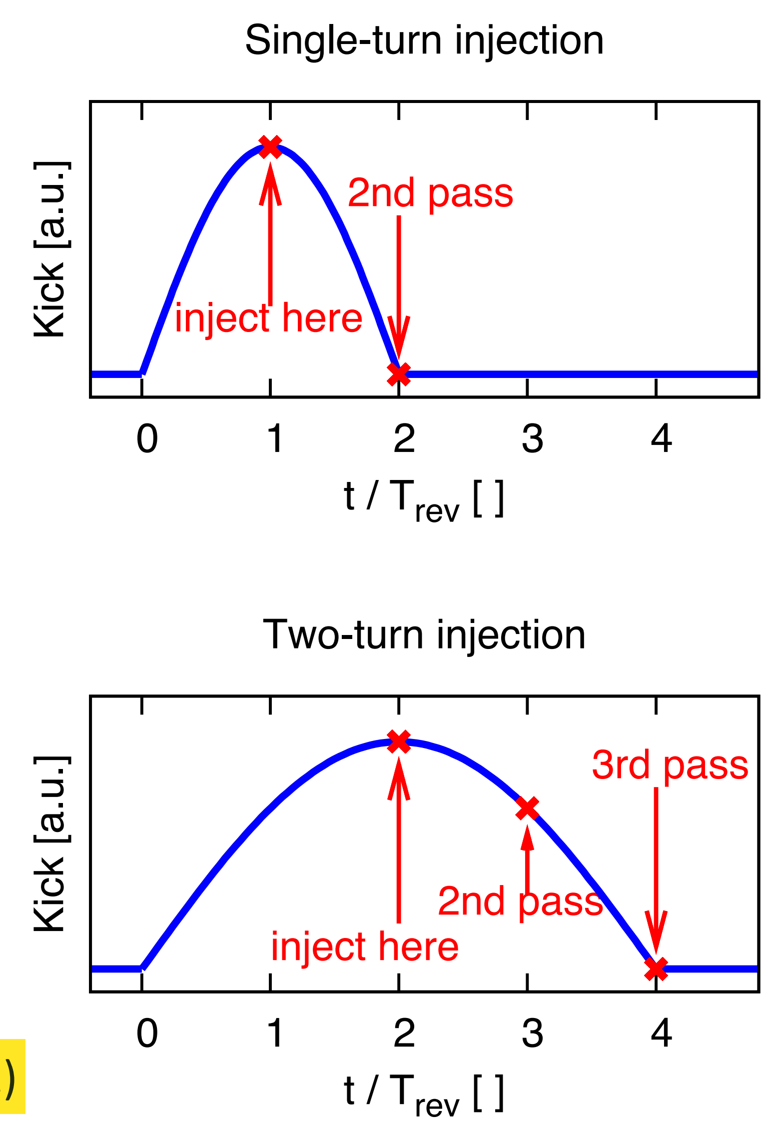
  - but in 1.5 GeV ring: 640 ns pulse length calls for 93 kV (even at 400 mm length)



Reference Design for a MAX IV PSM (cont.)

- Short pulse duration leads to very large pulser voltage
  (320 ns revolution period in 1.5 GeV storage ring → 640 ns pulse duration)
- Two-turn injection relaxes requirements, but makes injection even more optics-dependent





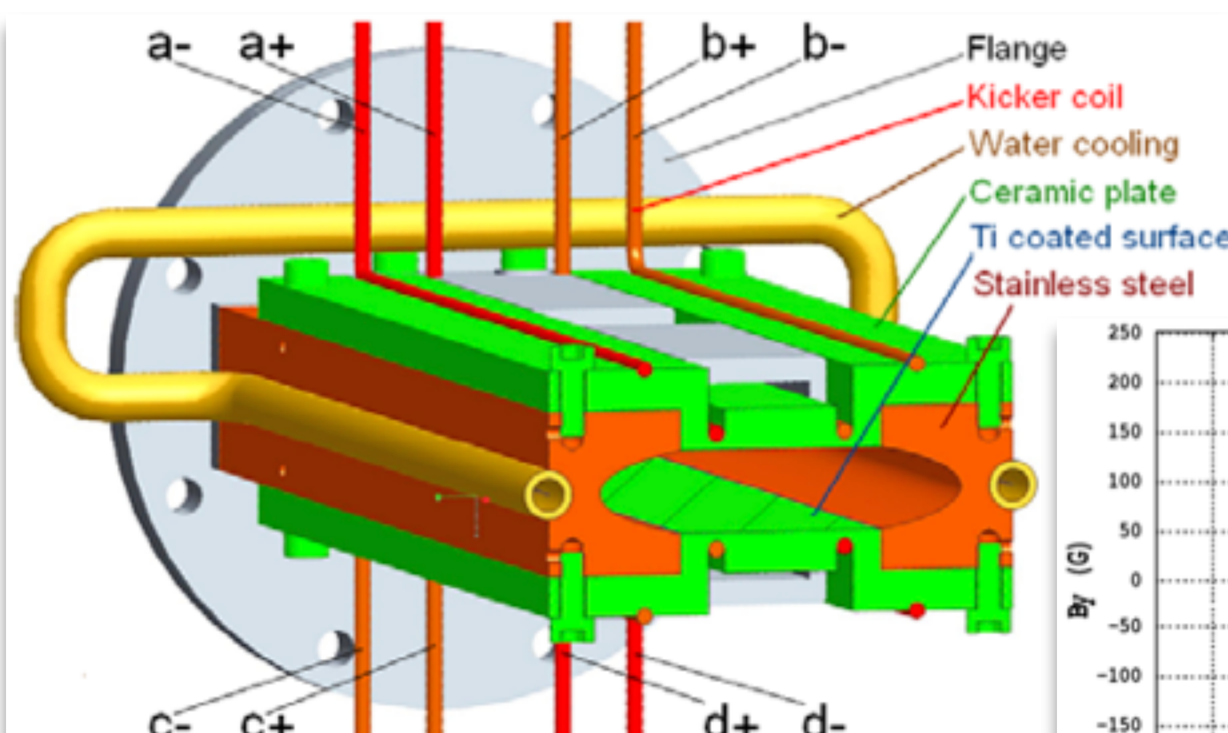
PRST-AB **15**, 050705 (2012)

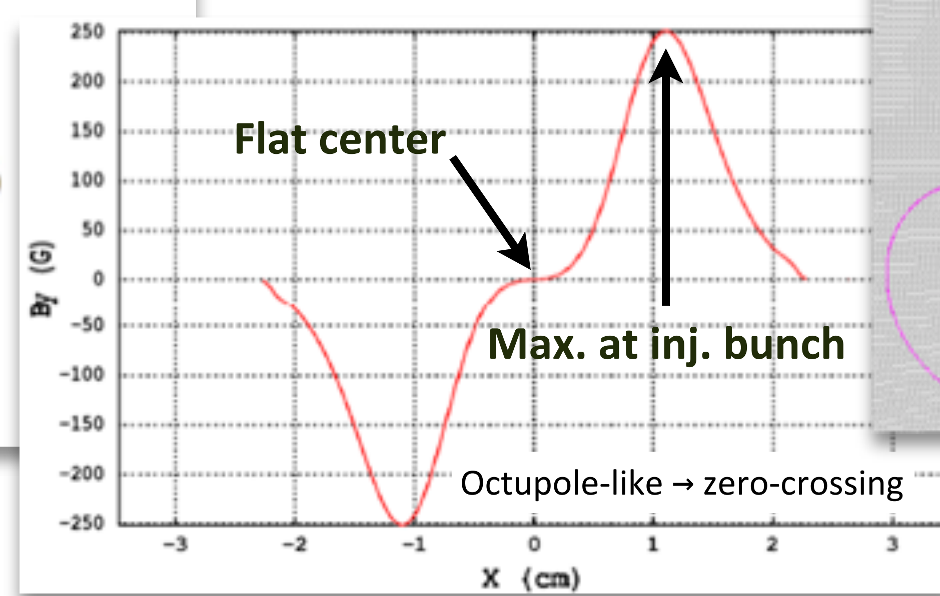
A Better Idea: BESSY Nonlinear Kicker

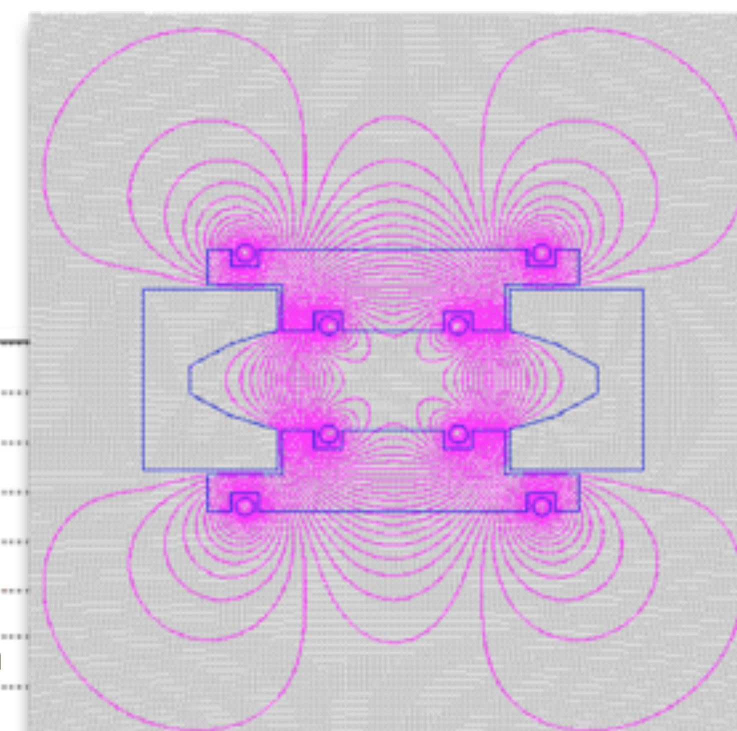
- Pulser voltage requirements can be lowered if stored energy in kicker magnet is reduced ➔ give up solid iron magnet
- BESSY nonlinear injection kicker prototype
  - stripline-like design with 4 low-impedance coils
  - minimize stored beam perturbation (octupole-like around center)

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

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

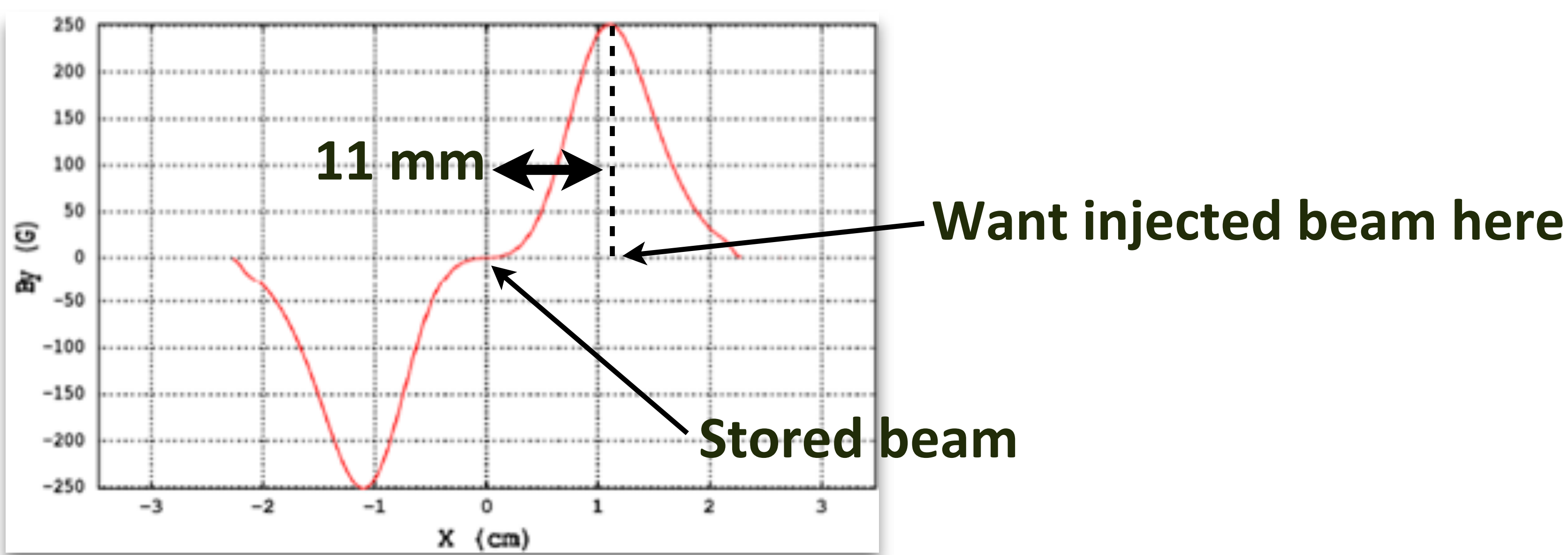


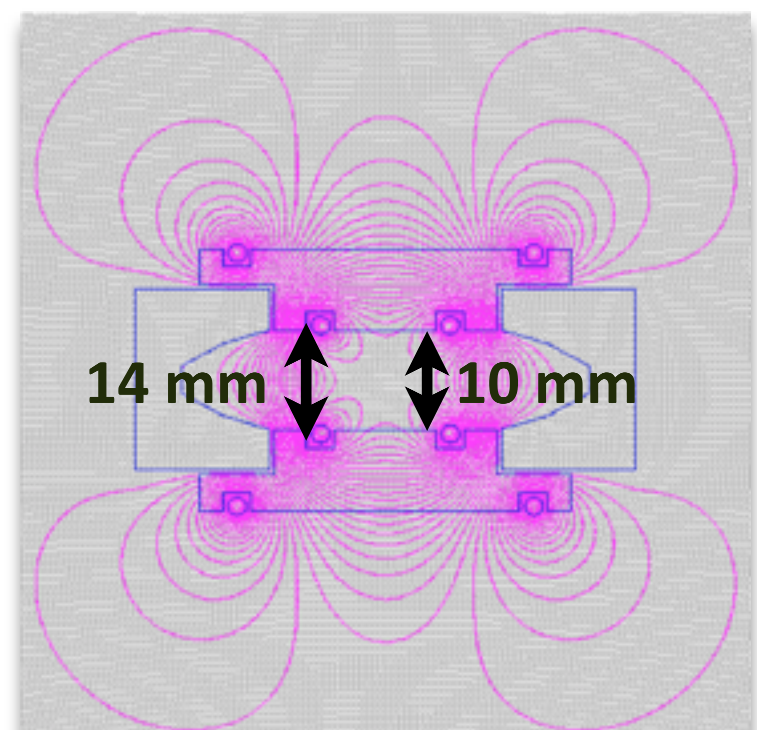




The MAX IV Multipole Injection Kicker

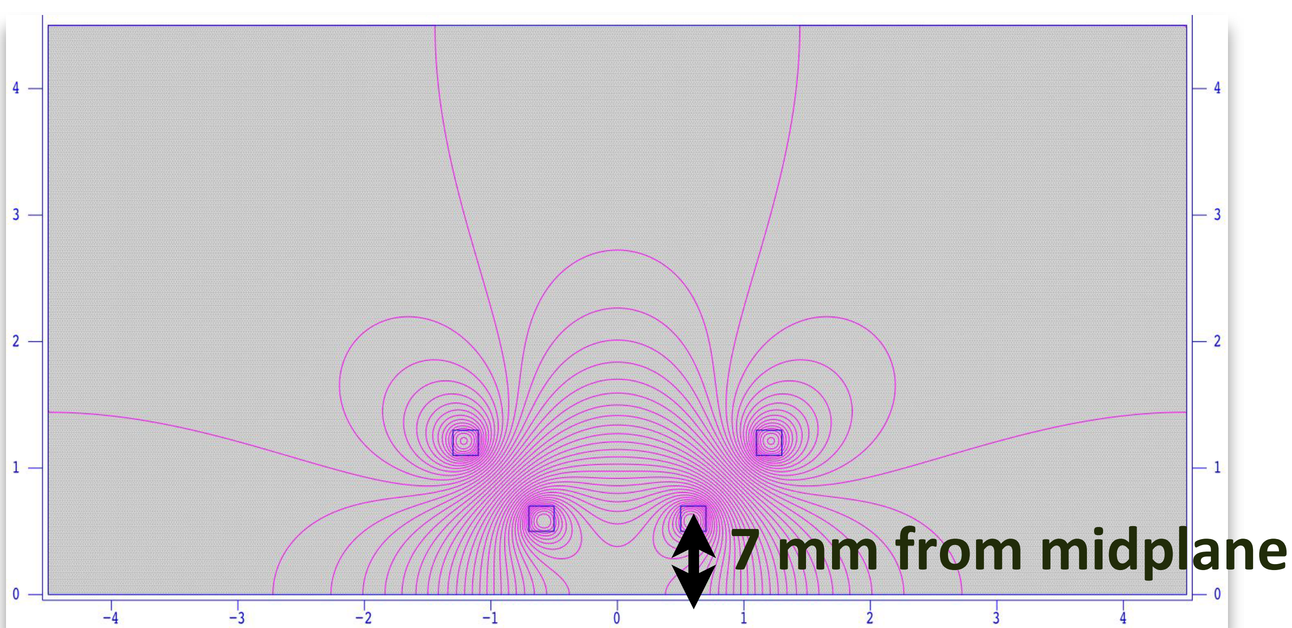
- In 2011 entered collaboration with SOLEIL in association with HZB to develop a new nonlinear injection kicker for MAX IV based on the original BESSY concept
  - BESSY kicker most efficient if injected beam placed at location of maximum kick (≈11 mm at BESSY II, but only ≈5 mm in MAX IV)
  - Maximum kick can be moved closer to stored beam if vertical separation between inner rods is reduced

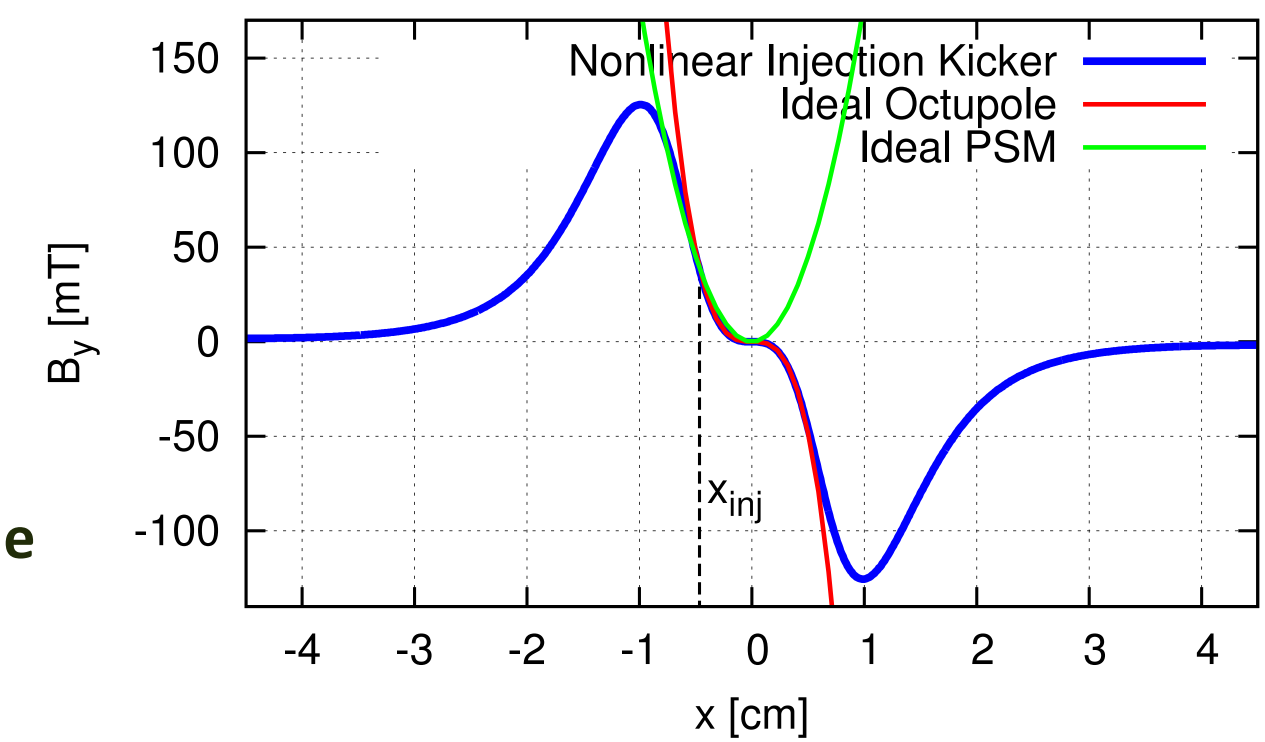




The MAX IV Multipole Injection Kicker (cont.)

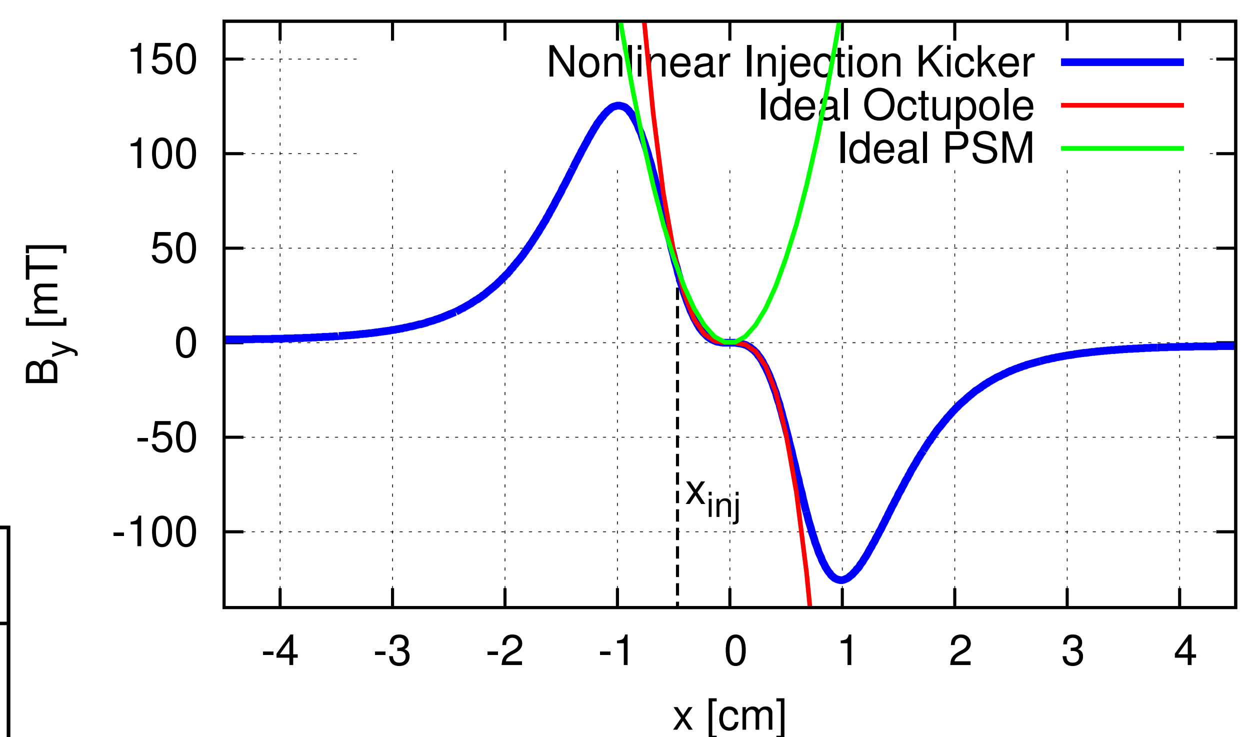
- In MAX IV did however not want to introduce such a vertical acceptance limitation ➔ injection kicker vertical aperture specified like narrow-gap chambers for EPUs (±4 mm)
- In conjunction with design of ceramic chamber (insulator) and conductor cross-section requirements, this puts inner conductors separation at ±7 mm ➔ max kick at ≈10 mm

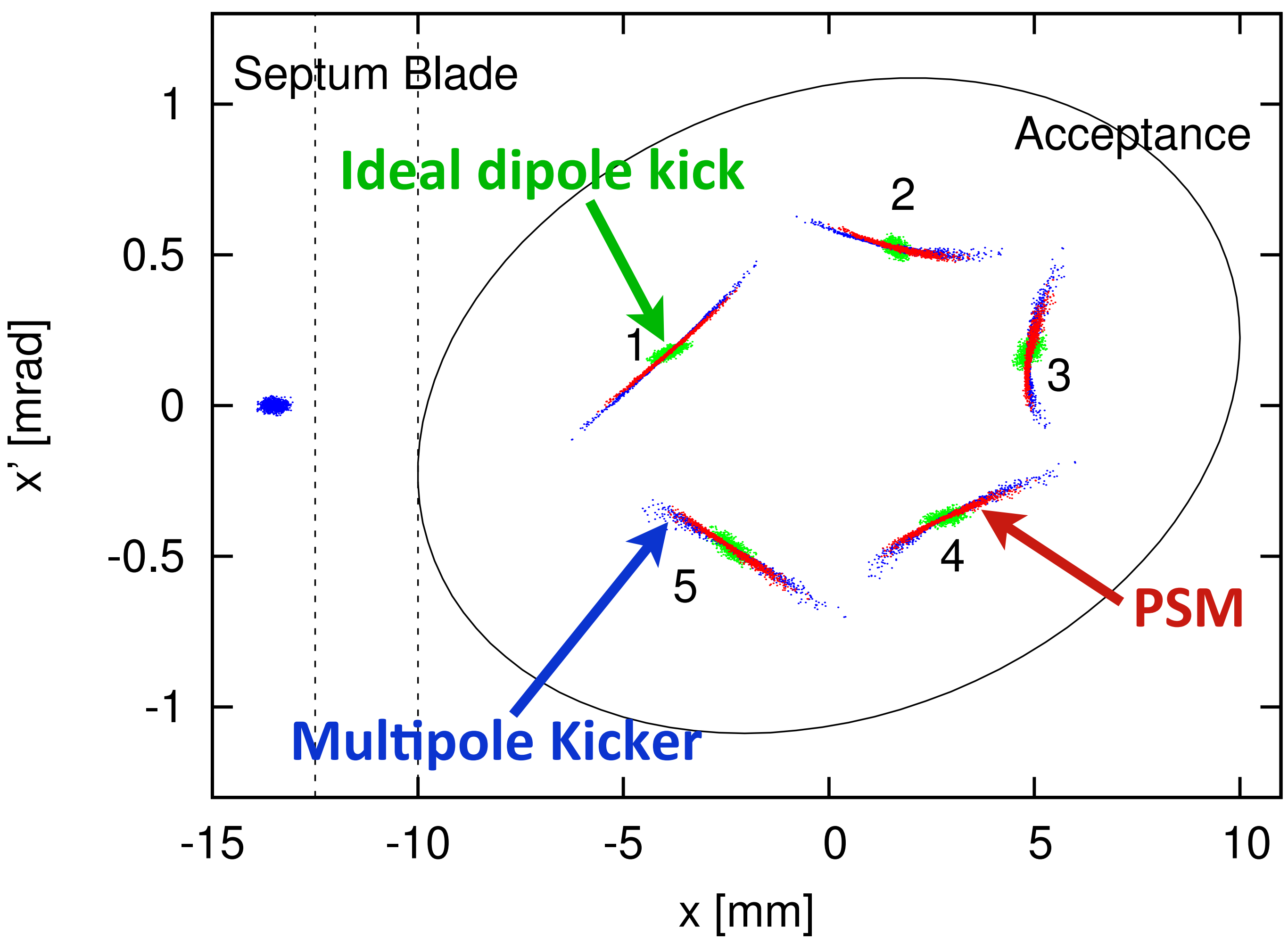




The MAX IV Multipole Injection Kicker (cont.)

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





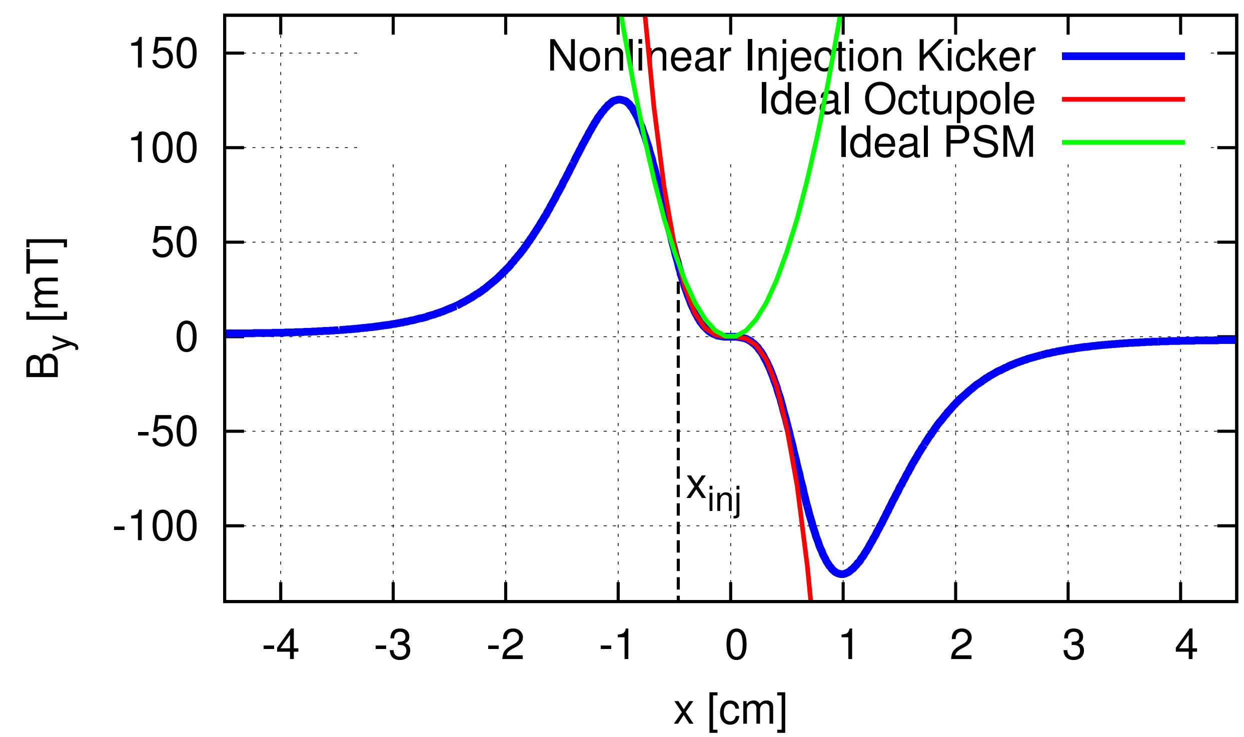
Field data for tracking extracted from OPERA models (static & transient) including 4 µm Ti coating

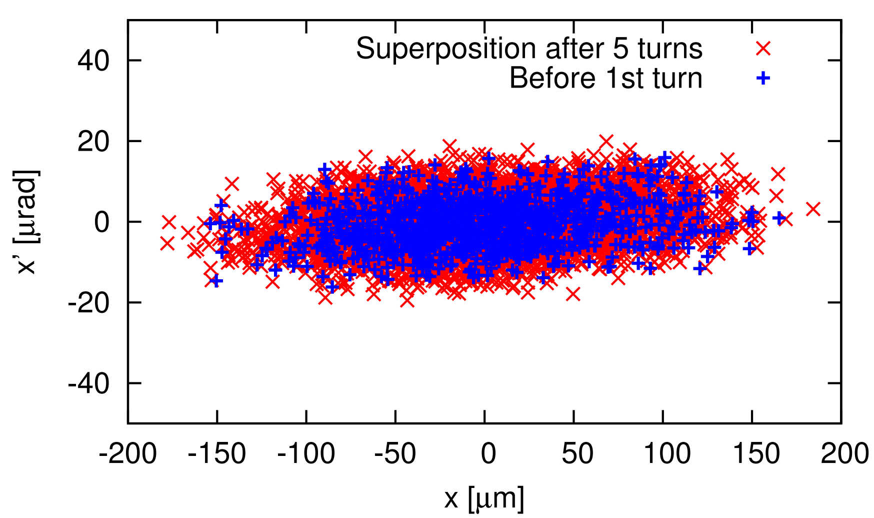
(OPERA model courtesy P. Lebasque, SOLEIL)

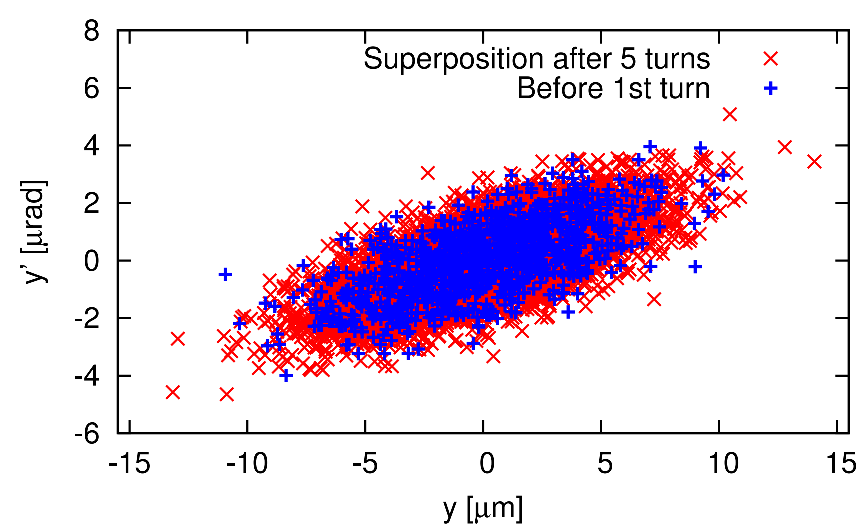
PAC'**13**, WEPSM05

The MAX IV Multipole Injection Kicker (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

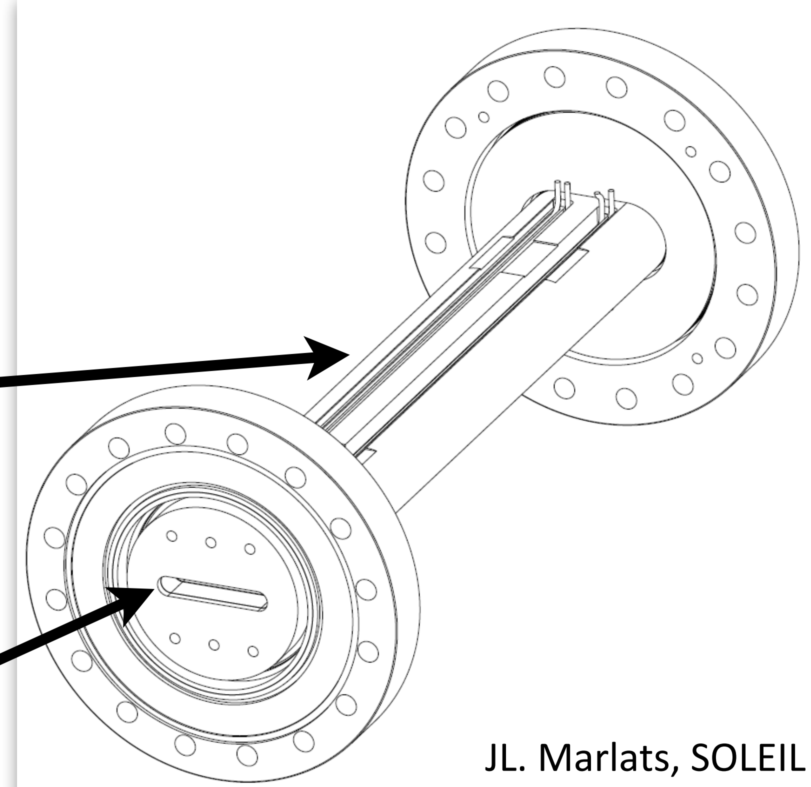
- Note: acceptable residual gradient at stored beam is independent of emittance (≈0.3 T/m at MAX IV) $\left.\frac{\partial B_y}{\partial x}\right|_{\mathrm{res}} < 10\% \times \frac{B\rho}{\beta_x L}$

Technology: Vacuum Chamber

- Mechanical & vacuum design delivered by SOLEIL
- Unlike BESSY prototype, the SOLEIL design for the MAX IV multipole kicker has a complete ceramic vacuum vessel without metallic walls (→ minimize field distortions)
- Horizontal aperture of the chamber increased → no synchr. radiation on chamber → air cooling
- Extensive chamber prototyping

300 mm air-cooled ceramic vessel
with precision-machined grooves for Cu rods

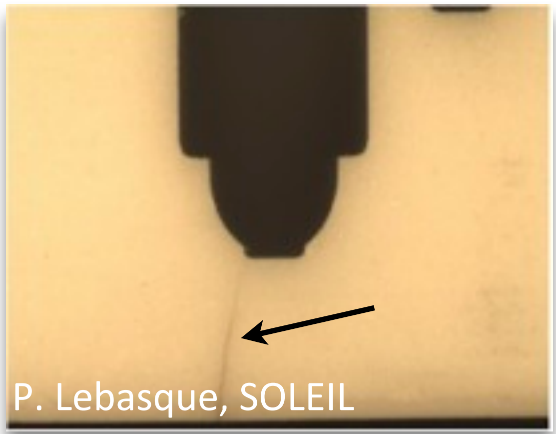
47 mm × 8 mm

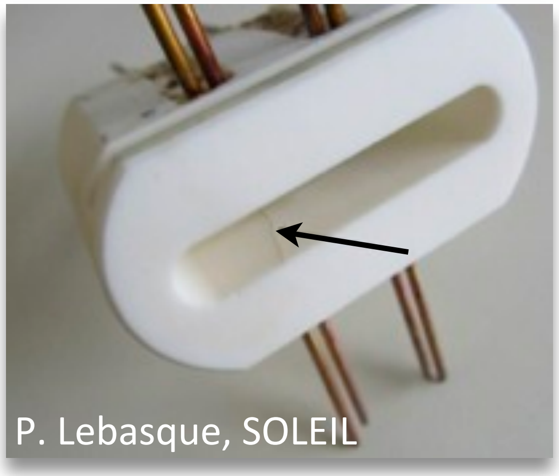


JL. Marlats, SOLEIL

Technology: Vacuum Chamber (cont.)

- Main difficulties with mockup have been
  - precision-machining of ceramics with grooves for Cu rods (±10 µm position accuracy required for Cu rods)
  - dielectric rigidity & mechanical strength (increased vessel thickness compared to BESSY prototype, 1 → 2 mm at thinnest location)
  - groove profile & groove milling
  - cracks as a result of thermal shocks and/or mechan. stress in connection with the polymerization process (gluing ceramic strips to fix Cu rods in grooves)





- Leading to an improved design for the final specification
  - direct-bonding of two chamber halves (single-crystal sapphire)
  - CFT in Feb 2015, supplier selection June 2015, chamber delivery expected by end of 2015, Ti coating @ ESRF

Technology: Coils & Pulser

- EM modeling & power electronics simulations by SOLEIL
- Unlike BESSY prototype, the SOLEIL design for the MAX IV multipole kicker has all 4 coils connected in series (field imbalance)
- HV switches (IGBT, 4×2400 A) and diode modules (10×1500 A) received; HV capacitor (2×1100 nF) charging PSs ordered
- Mechanical and electrical assembly design complete
- Controls hardware installed in cabinets & PLC circuits tested
- Controls software (Tango) under development

Magnetic field at 4.7 mm	39 mT
Magnetic length	300 mm
Full apertures	47 × 8 mm
Peak current	≈7.7 kA
Pulse length	3.5 μs
Required charging voltage	≈15 kV

Electrical diagram removed at request of SOLEIL (intellectual property concern)

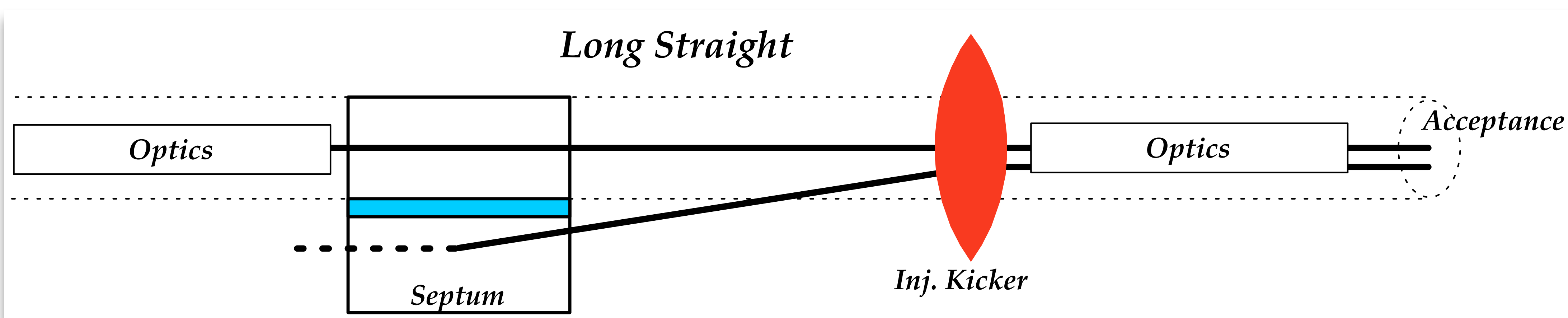
P. Alexandre, SOLEIL

Outlook

- Expect arrival of multipole injection kicker in early 2016
- Installation in MAX IV 3 GeV storage ring shortly thereafter
- Initial storage ring commissioning can be carried out with single dipole kicker (cf. Tuesday presentation)
- Multipole kicker for 1.5 GeV ring has been temporarily delayed because of additional challenges:
  - 640 ns pulse → very high voltage required → revisit pulser design?
  - reconsider original goal to use same chamber in both rings?
  - reducing vertical acceptance allows substantial reduction of required current (due to nonlinear nature of kicker) → relax voltage

Final Thoughts

- Our solution shoehorned into a previously designed conventional injection scheme with 4 dipole kickers
  - Septum installed at downstream end of injection straight
  - Our multipole kicker is in 2nd straight, after one full achromat
  - ➡ limits optics tuning and makes commissioning more difficult
- If we could do it from scratch: put it all into injection straight
  - septum at upstream end
  - injection kicker at downstream end (can inject at slight angle)



Final Thoughts (cont.)

- Nonlinear injection requires aggressive engineering
- Ideally should bring rods even closer to stored beam (≈2 mm)
  - needs excellent coupling control
  - possibly less demanding in cases where this is a retrofit (vertical acceptance well understood and prior operational experience with in-vacuum IDs)

Final Thoughts (cont.)

- Key to nonlinear injection: low-emittance injection into comparably large ring acceptance
  - Low-emittance injection can be realized via
    - linac (costly if not otherwise required... FEL)
    - large circumference in-tunnel booster e.g. SLS (cheap and simple, yet reliable)
  - Large acceptance requires ring with decent DA
- Note: on-axis vs. off-axis injection ➔ either way cannot relax DA requirements substantially
  - In MAX IV want ≈5% MA, but have ≈8 cm max dispersion ➔ need ±4 mm horizontal acceptance to ensure sufficient MA
  - Horizontal DA required for off-axis injection is ≈5 mm

  ➡ only ≈1 mm to be gained

Final Thoughts (cont.)

- However, on-axis injection with fast dipole kickers is nevertheless very appealing in 100 MHz rings because of naturally large bunch separation
- Off-energy on-axis injection in MAX IV studied by M. Aiba and colleagues at SLS
  - robust against machine errors
  - single-bunch injection at minimal DA requirements
  - no swap-out, no dumping, and no accumulator required
  - can top up fractional bunch charge

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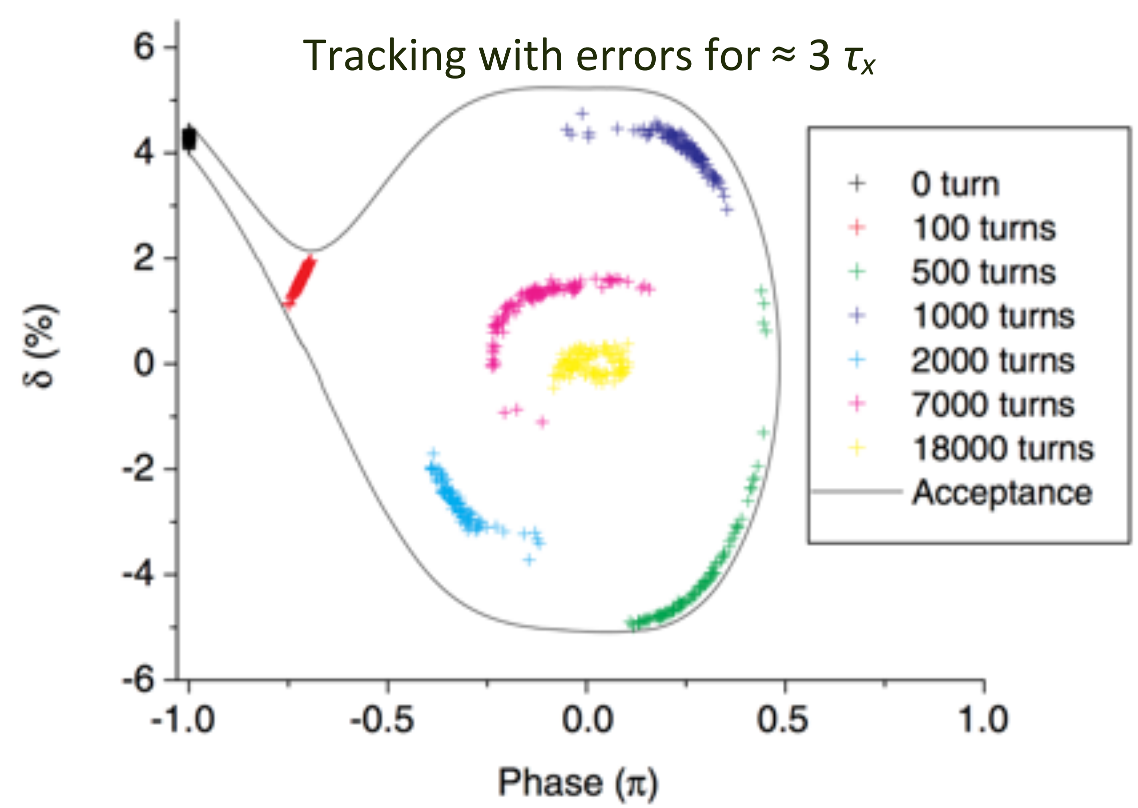

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Photo courtesy L. Jansson, August 24, 2015

Thanks for your attention!

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