Pulsed Multipole Injection in the MAX IV Storage Rings

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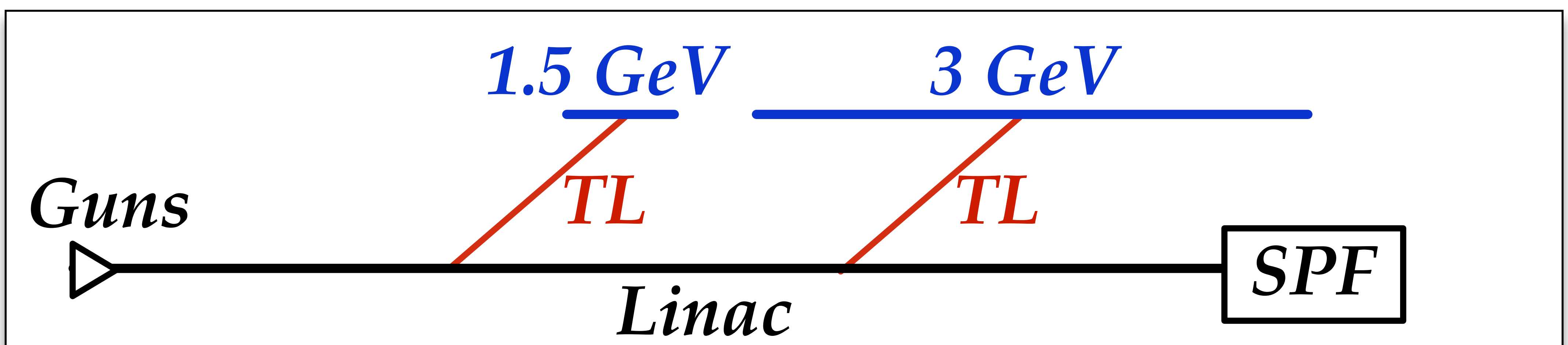
MAX IV Injection Overview

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

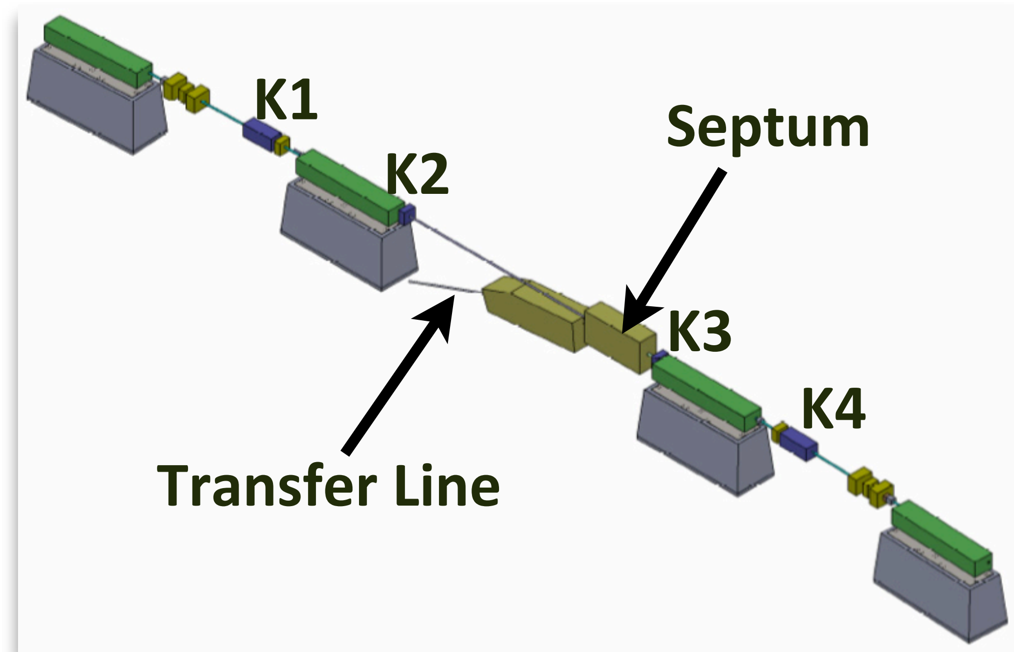
MAX IV Injection Overview (cont.)

- Full energy (underground) linac delivers top-up shots to two storage rings: 3 GeV storage ring and 1.5 GeV storage ring
- Two dedicated vertical (achromatic) transfer lines
- 10 Hz injection rep rate
- Injection into rings via DC Lambertson septum
- Inject bunches with ε_n = 10 mm mrad, σ_δ = 0.1%



MAX IV Injection Requirements

- Original design: conventional 4-kicker bump injection



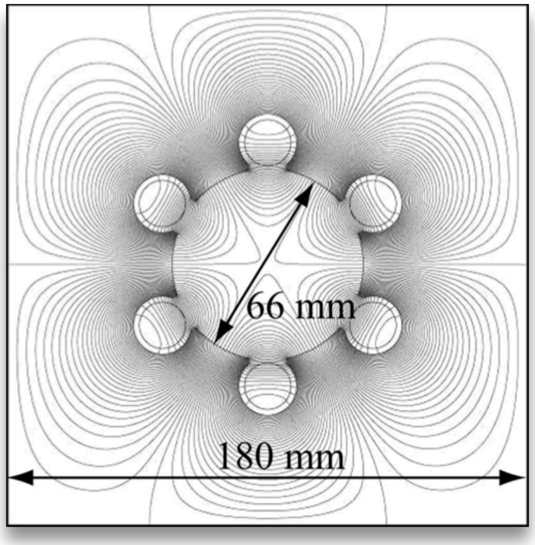
- But worried about stored beam stability during top-up
  - 200 nm vertical stability requirement!
- Also worried about complexity
  - matching, synchronizing and aligning 4 kickers/pulsers to properly close bump
  - strong sextupoles & octupoles within bump: bump can only be properly closed for one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

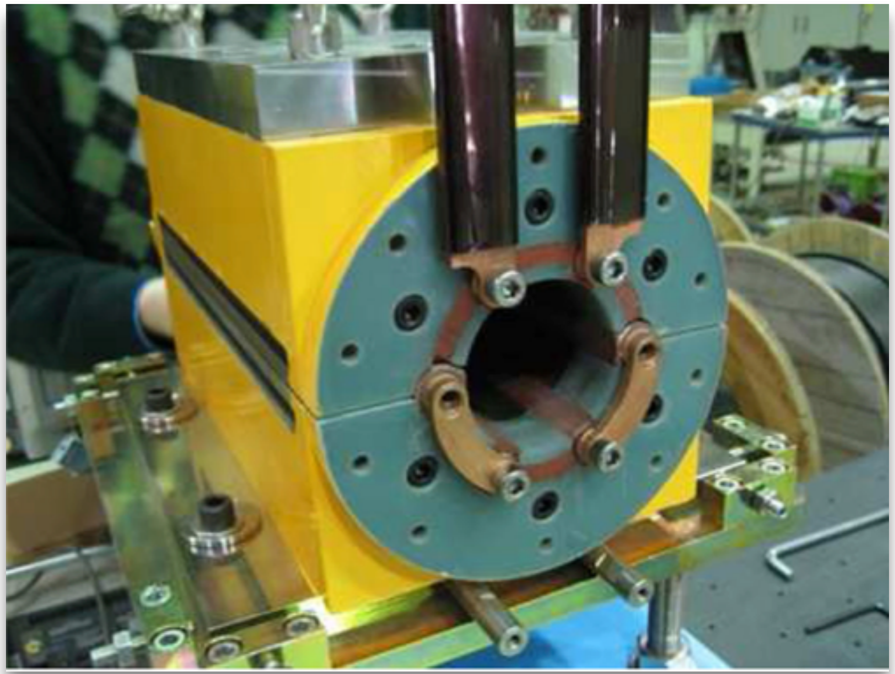
MAX IV Injection Requirements (cont.)

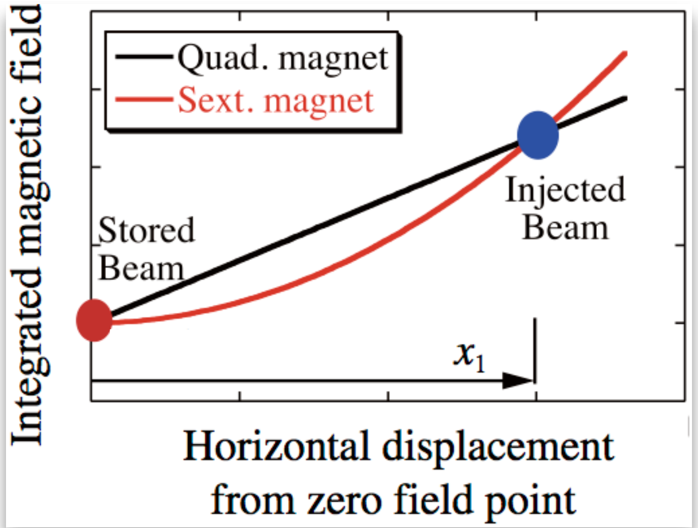
- Intrigued by KEK's pioneering work on PQM and PSM
  - align only a single magnet to stored beam
  - synchronize only one pulser to injection
  - PSM field flat around stored beam
  - ➡ minor perturbation of stored beam by PSM

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

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





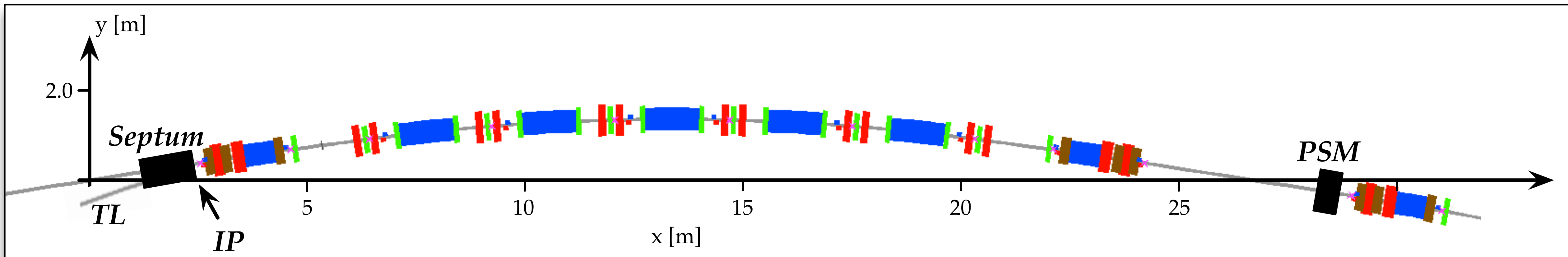


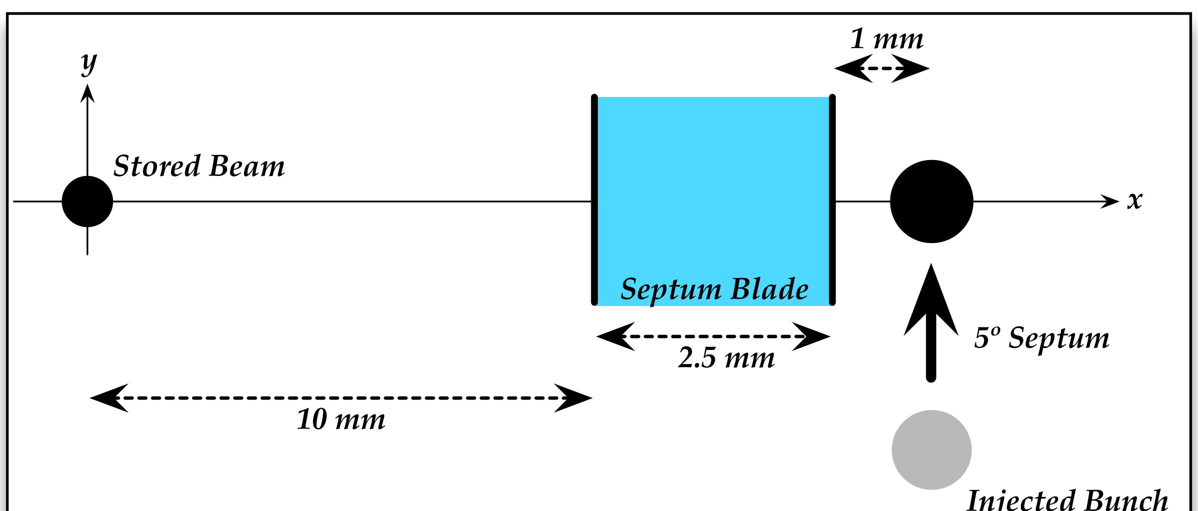
Magnetic field at 15 mm	40 mT
Magnetic length	300 mm
Bore diameter	66 mm
Peak current	3000 A
Pulse length	1.2 / 2.4 μs

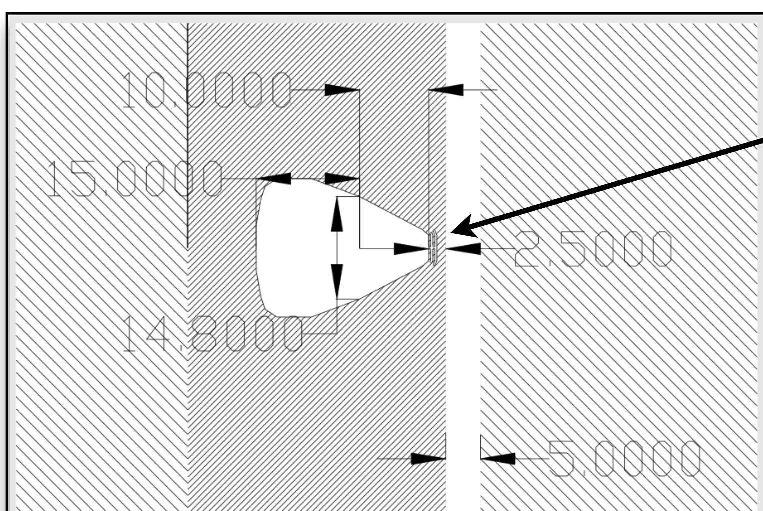
Pulsed Sextupole Injection for MAX IV

- Strong nonlinearities in MAX IV rings ➔ derive injection scheme from tracking
  - optimization of where to put beam in septum and PSM in lattice

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







Septum nose with filter

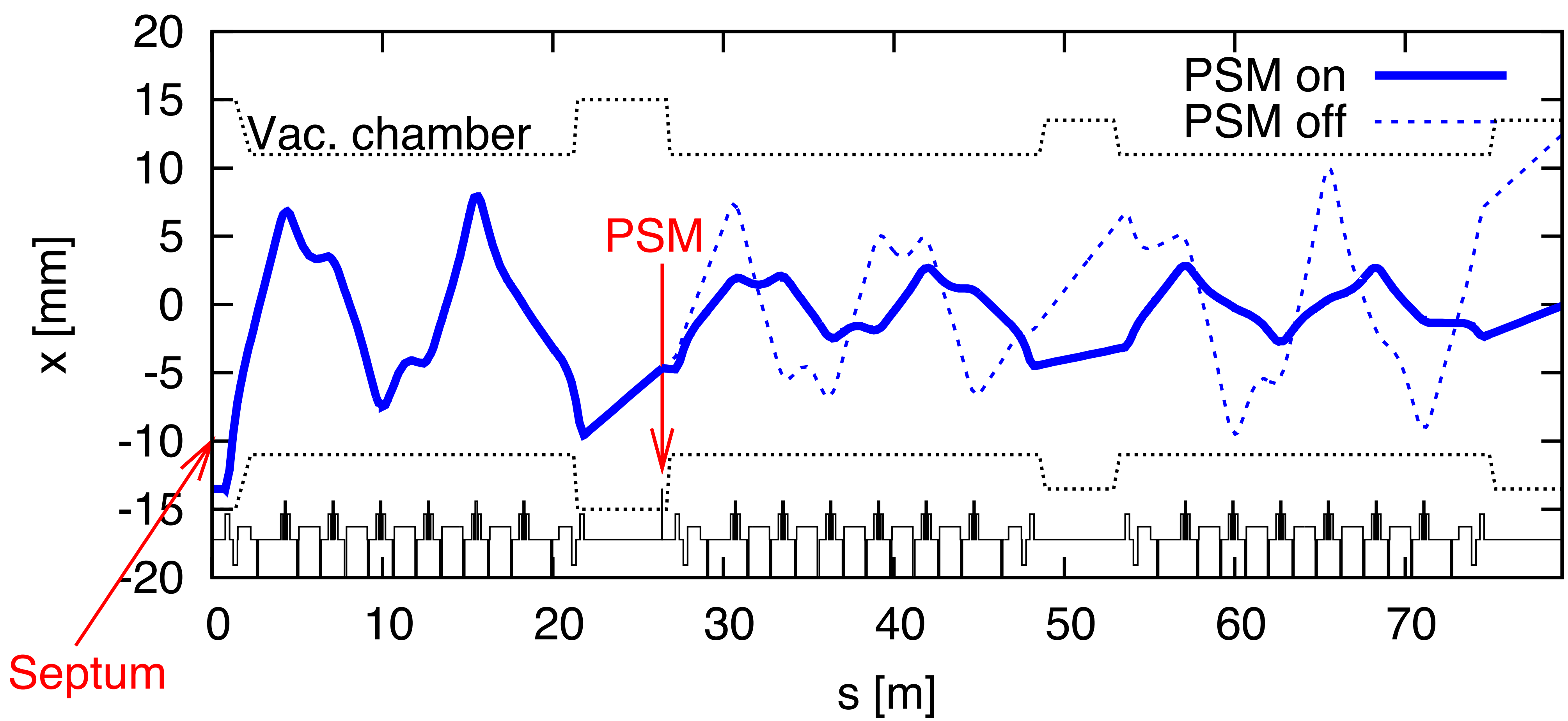
NIM-A **490**, 592, 2002

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

Pulsed Sextupole Injection for MAX IV (cont.)

- Strong nonlinearities in MAX IV rings ➔ derive injection scheme from tracking
  - optimization of where to put beam in septum and PSM in lattice
  - ideal kick strength to minimize injection amplitudes

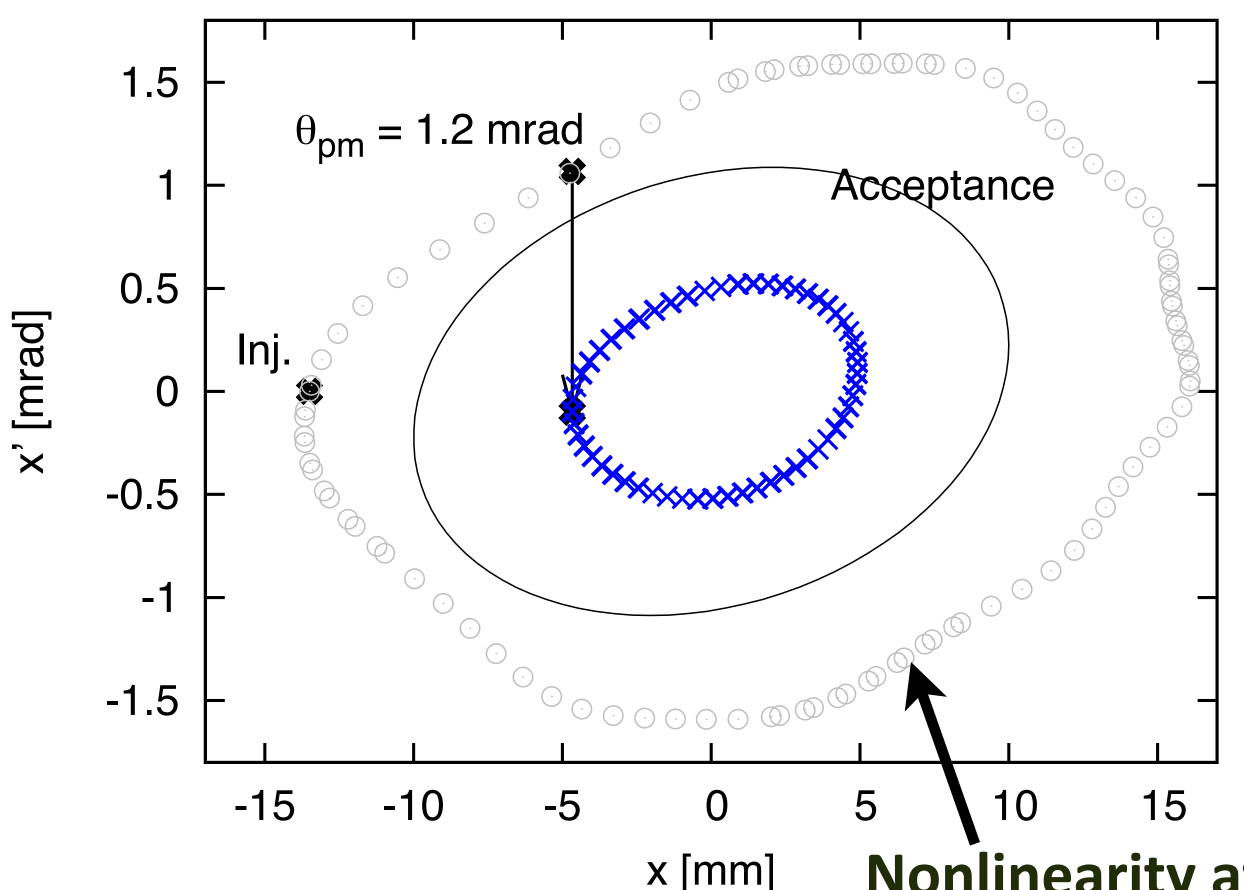
PRST-AB **15**, 050705 (2012)



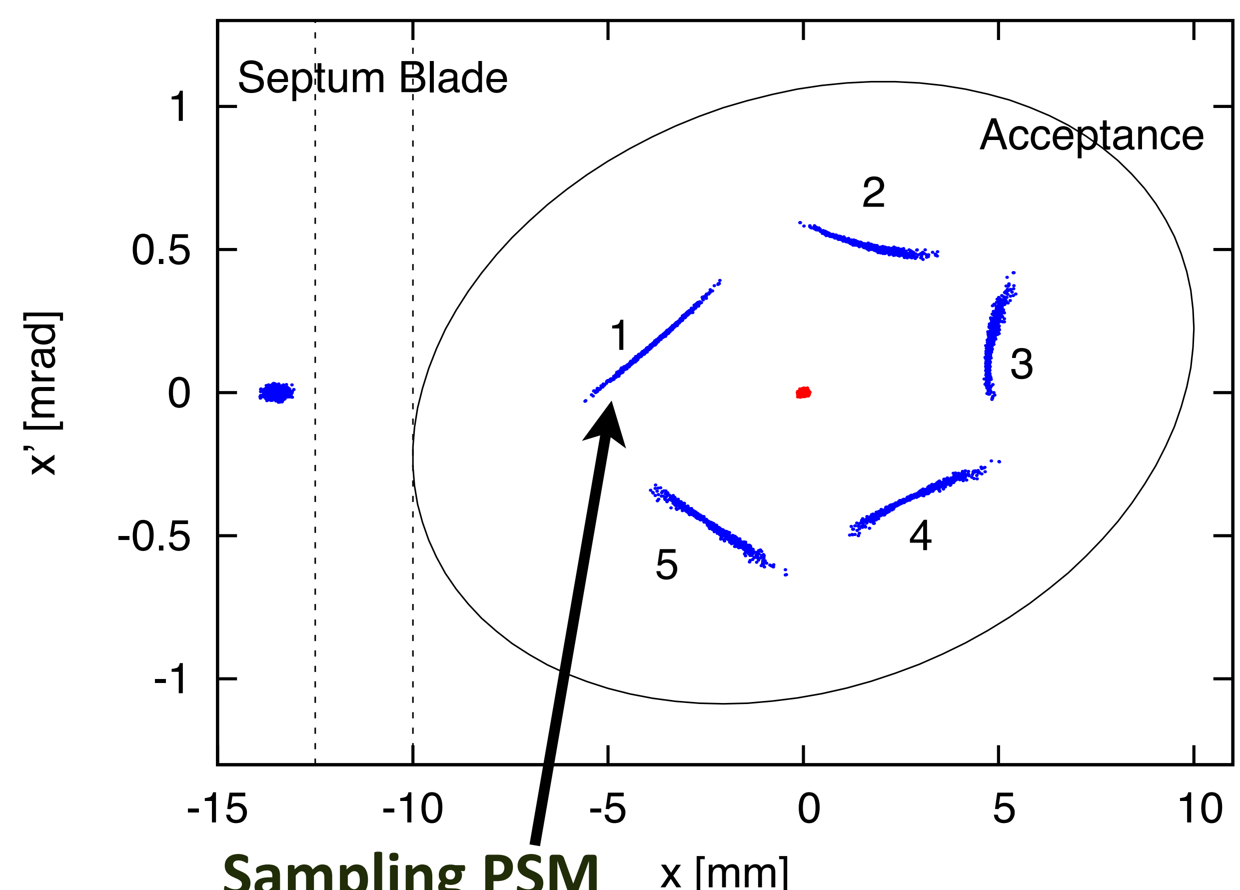
Pulsed Sextupole Injection for MAX IV (cont.)

- Strong nonlinearities in MAX IV rings → derive injection scheme from tracking
  - optimization of where to put beam in septum and PSM in lattice
  - ideal kick strength to minimize injection amplitudes

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



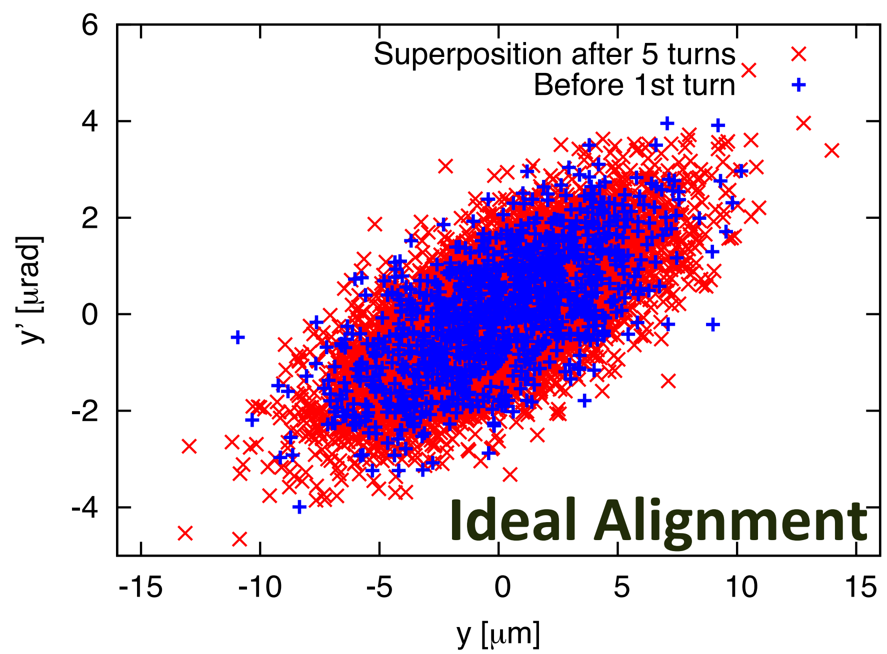
Nonlinearity at large amplitudes

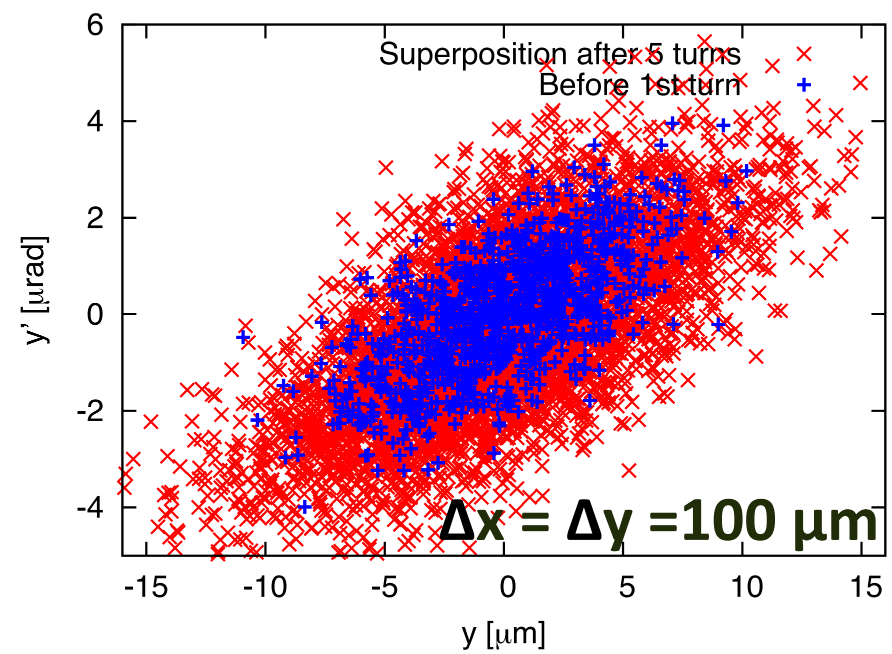


Sampling PSM field gradient

Pulsed Sextupole Injection for MAX IV (cont.)

- Good tolerance to errors because of large ring acceptance
- PSM gradient not an issue because of low injected emittance
- But tolerances are tight
  - Requirement for low perturbation: excellent alignment
  - Alignment adjustment can be beam-based via orbit bump
  - Girder design to facilitate beam-based re-alignment of the PSM





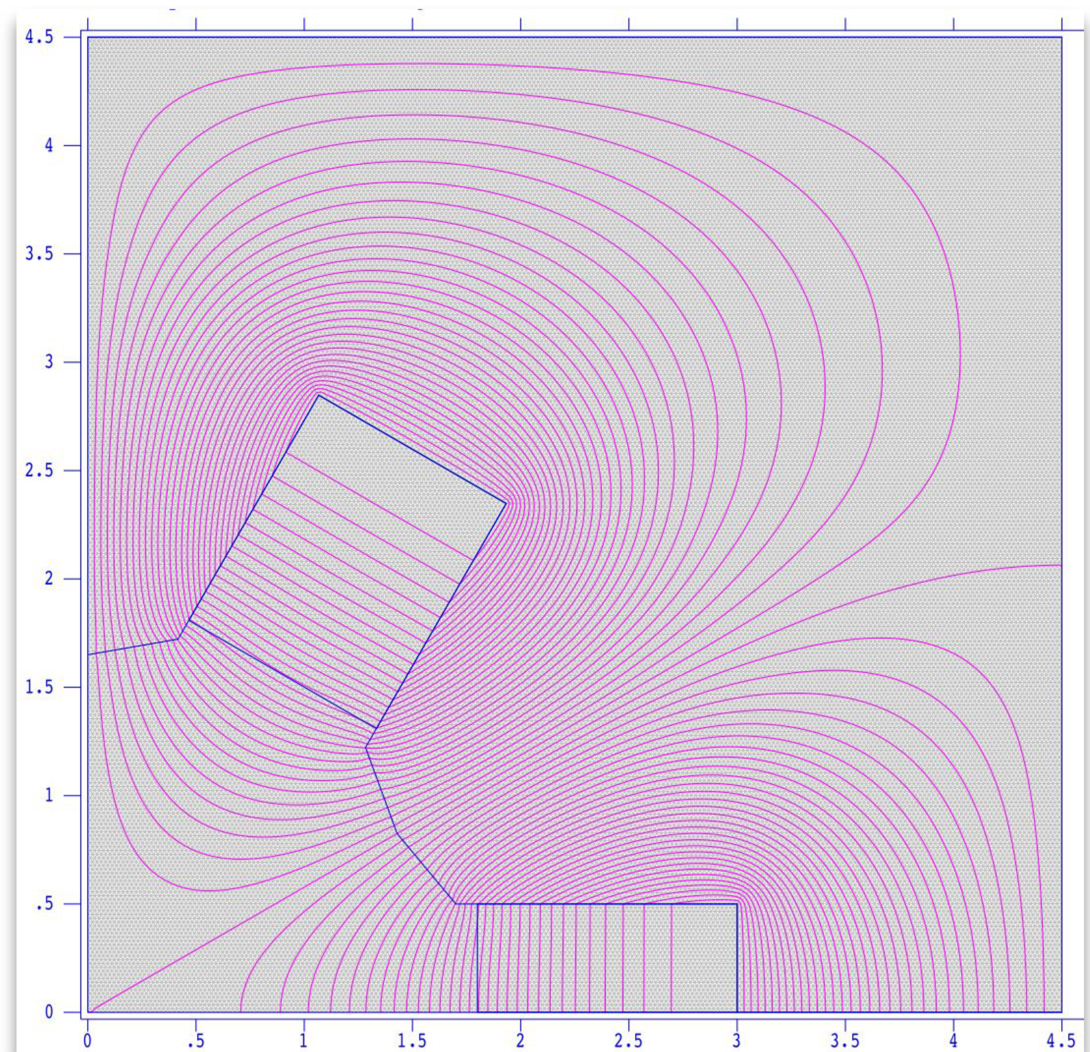
PRST-AB **15**, 050705 (2012)

Reference Design for a MAX IV PSM

- Initially, attempted a solid iron PSM following KEK design
  - symmetry required to minimize stored beam perturbation
  - ➡ cannot accommodate for aspect ratio of BSC
  - 21 J stored energy
  - in 3 GeV ring: 3.5 us pulse
  - but in 1.5 GeV ring: 640 ns pulse
  - ➡ requires 93 kV pulser voltage!

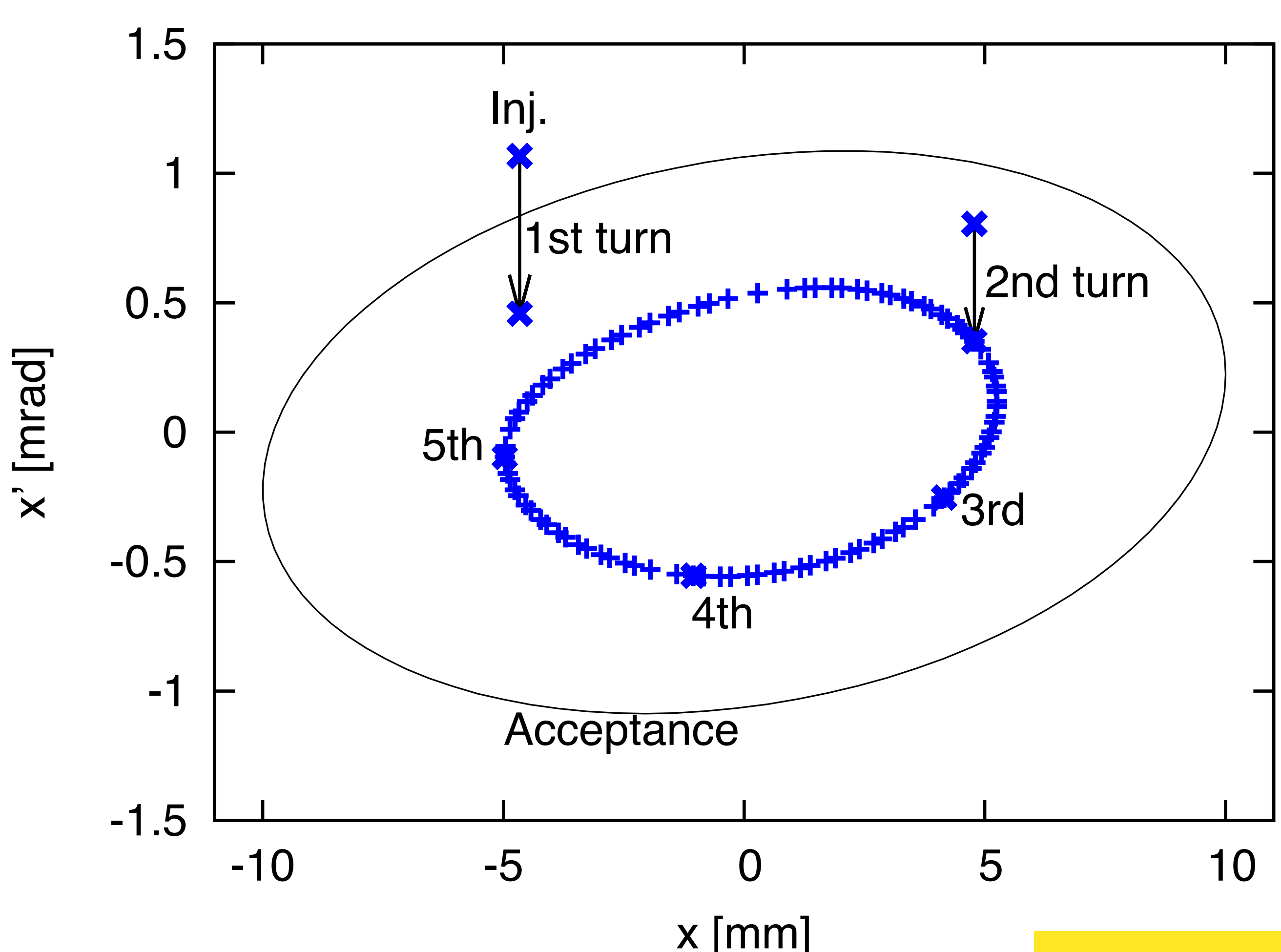
PAC'**13**, WEPSM05

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

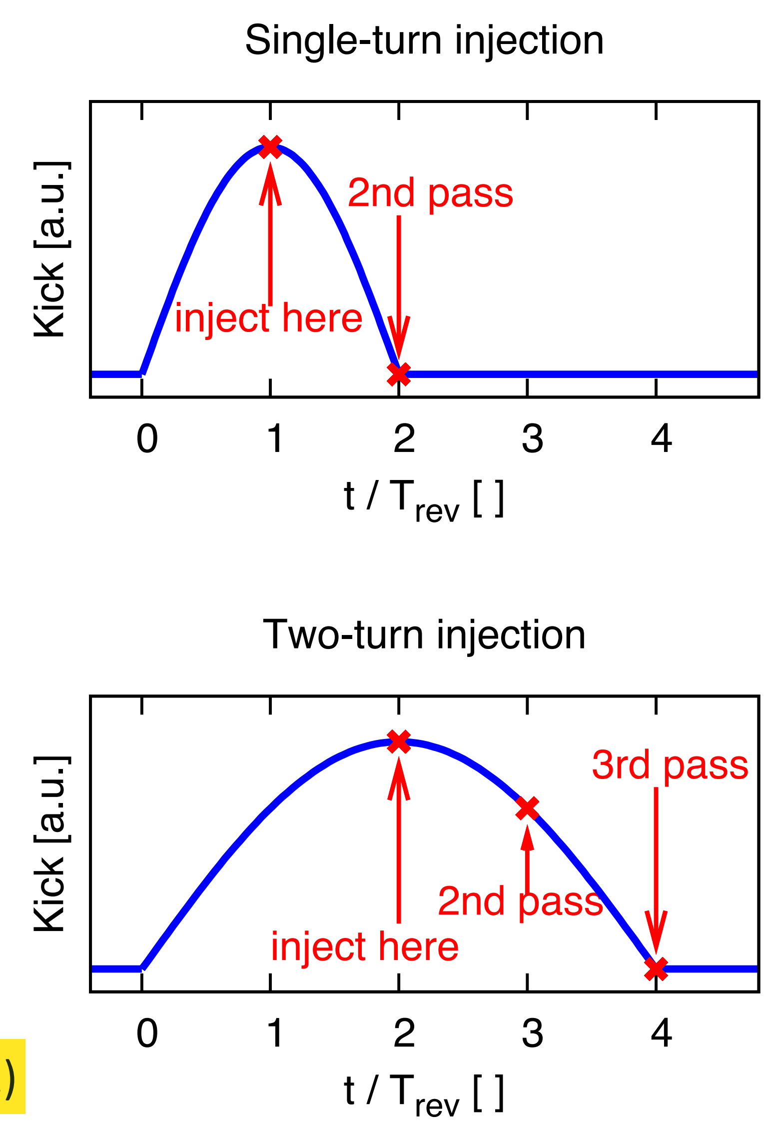


Reference Design for a MAX IV PSM (cont.)

- 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



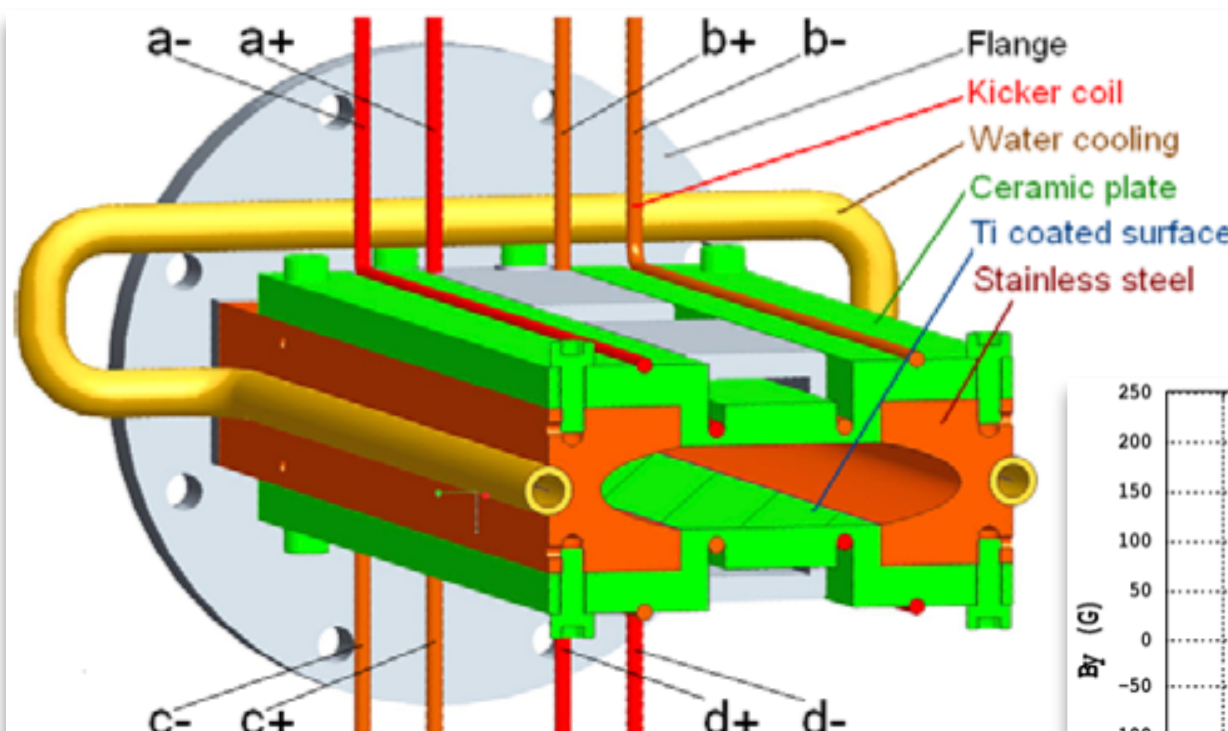
PRST-AB **15**, 050705 (2012)

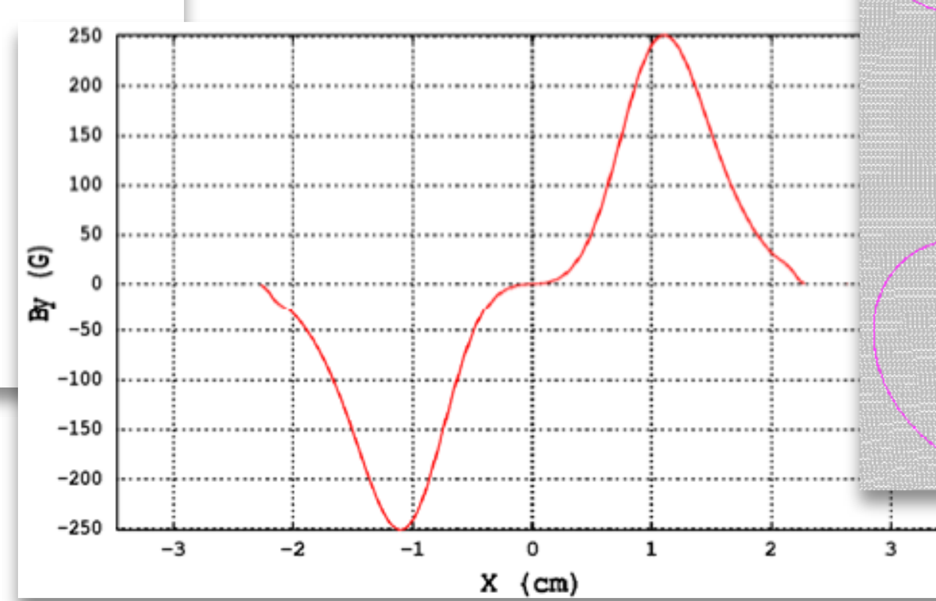


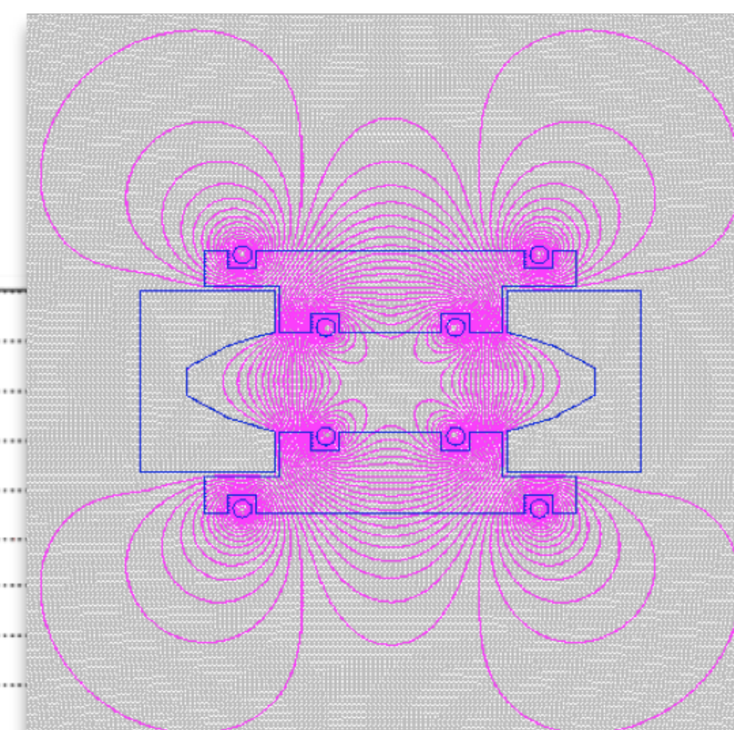
A Better Idea: Nonlinear Injection Kicker

- Need to further reduce stored energy to get voltage down
- BESSY nonlinear injection kicker prototype
  - stripline design with low inductance
  - minimize stored beam perturbation (octupole-like around center)

IPAC'11, THPO024, p.3394

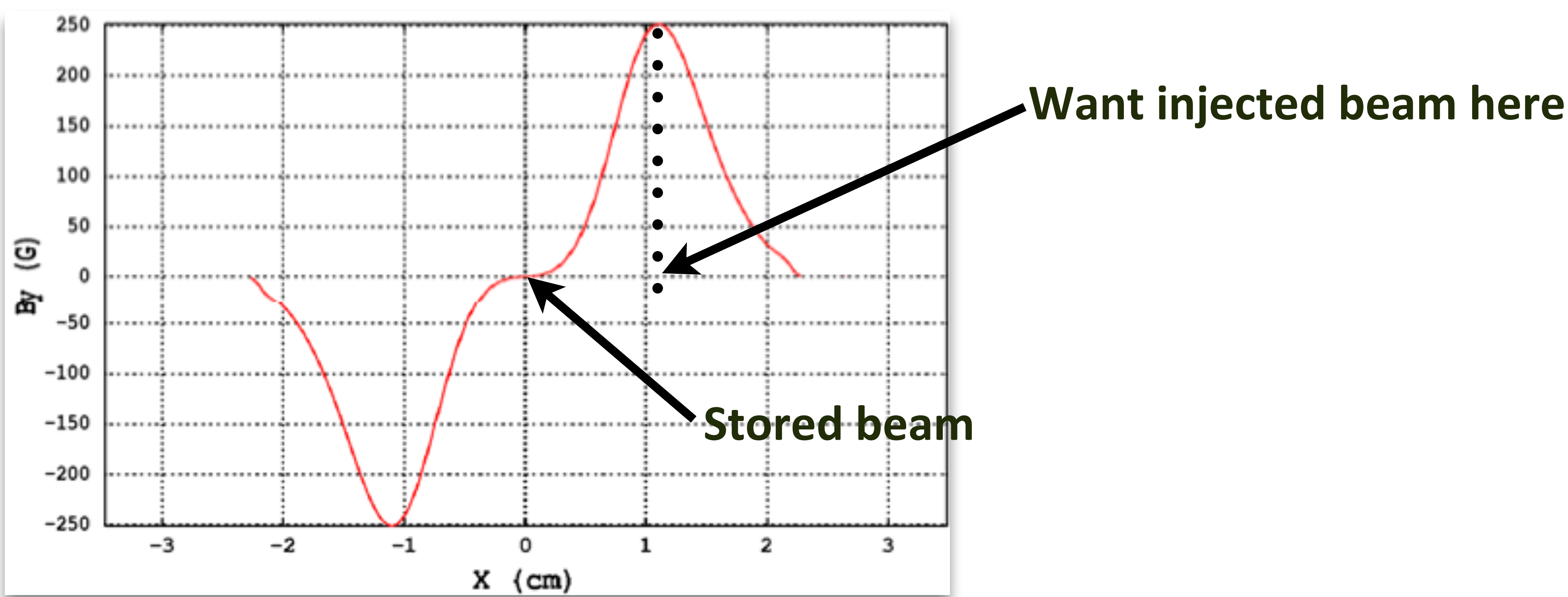






Adapting the BESSY Kicker to MAX IV

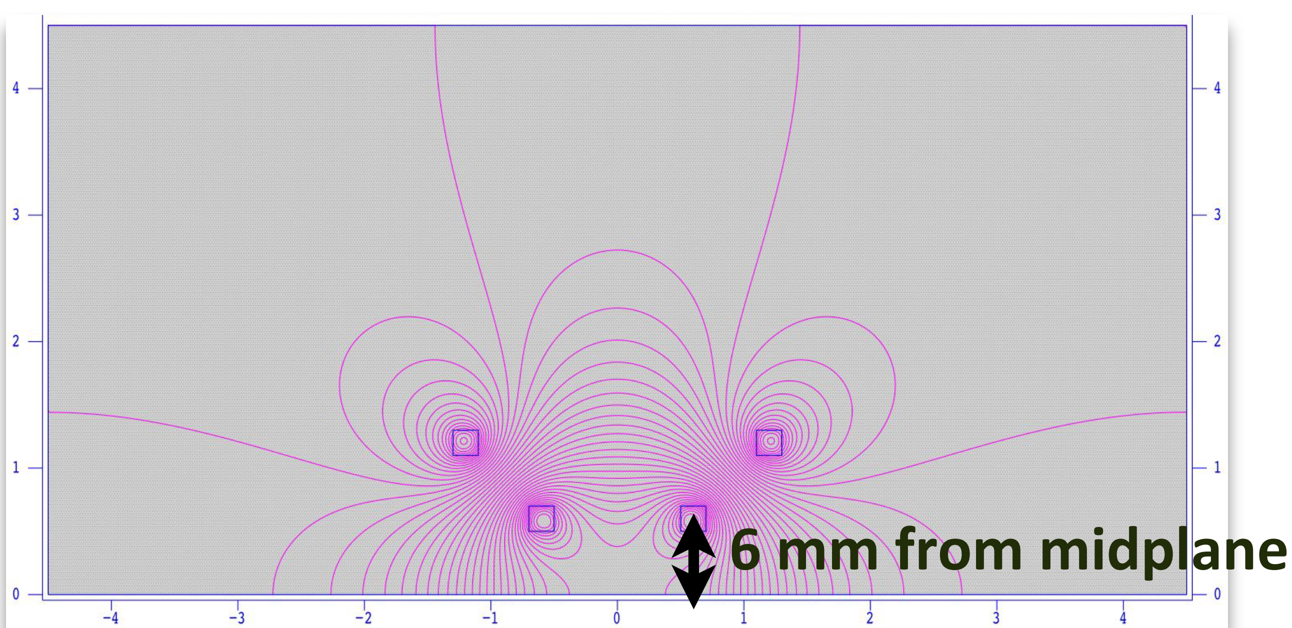
- BESSY kicker most efficient if maximum kick delivered at location of injected beam
  - In BESSY II this is at ≈11 mm, but in MAX IV this is at ≈5 mm
  - Maximum can be moved closer to stored beam if vertical separation between inner rods is reduced

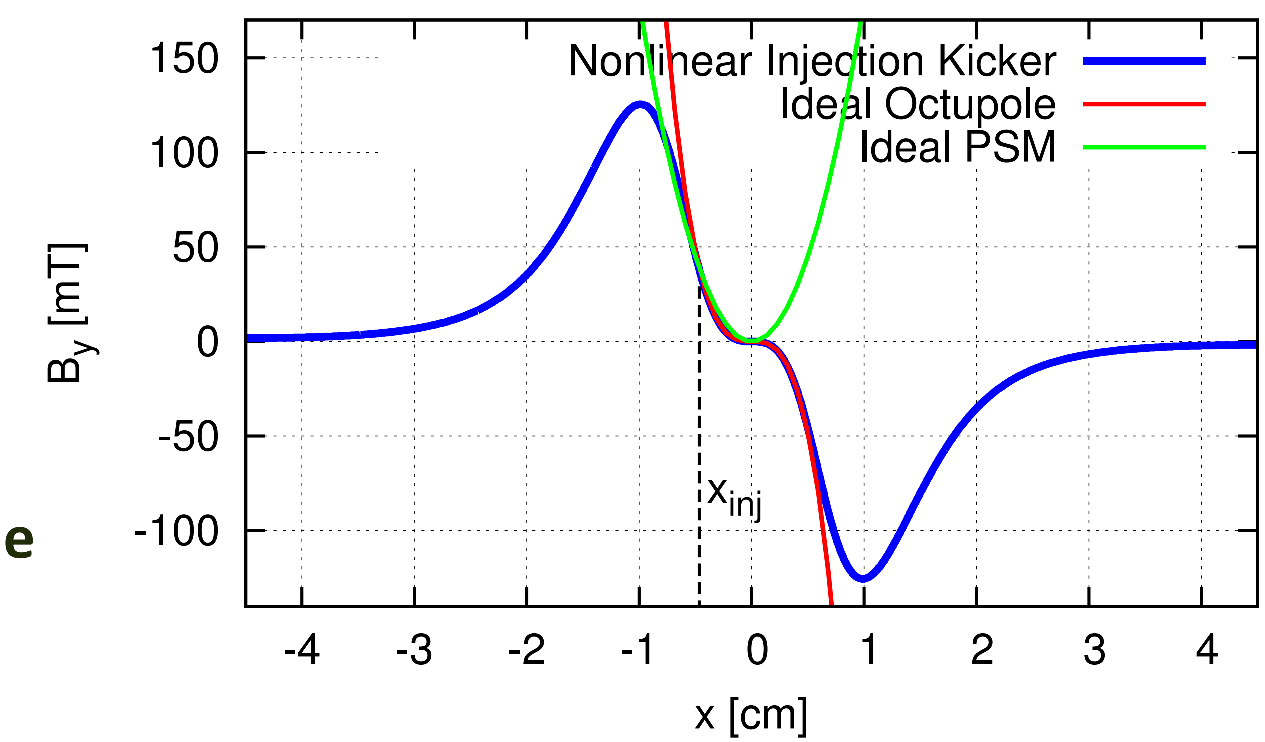


Adapting the BESSY Kicker to MAX IV (cont.)

- BESSY kicker most efficient if maximum kick delivered at location of injected beam
  - In BESSY II this is at ≈11 mm, but in MAX IV this is at ≈5 mm
  - Maximum can be moved closer to stored beam if vertical separation between inner rods is reduced
  - In MAX IV cannot reduce vertical aperture that much

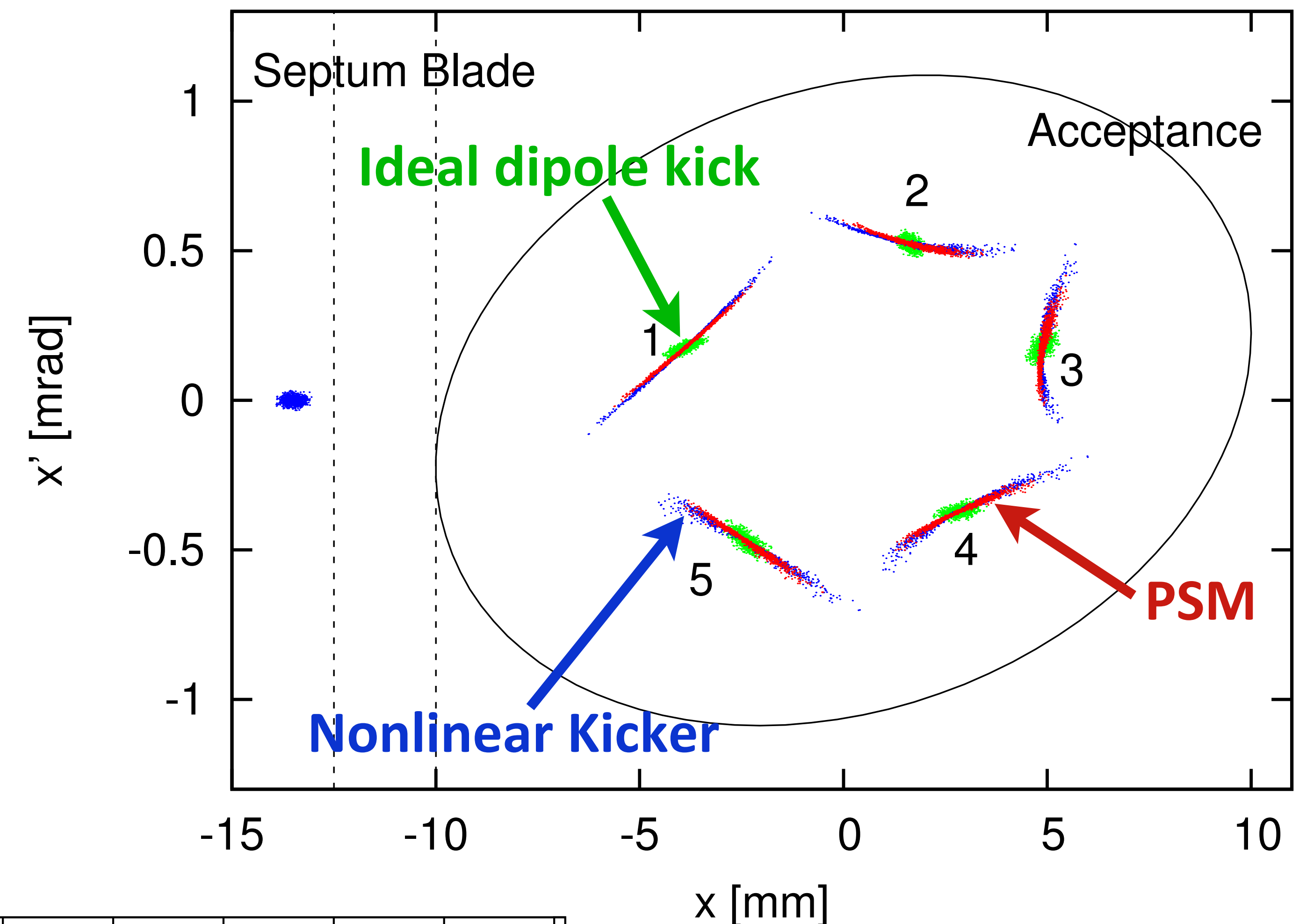
PAC'**13**, WEPSM05



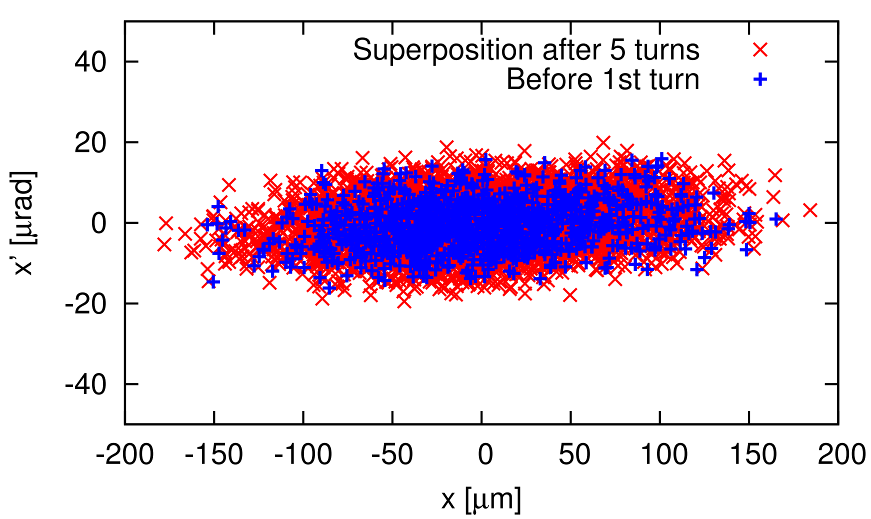


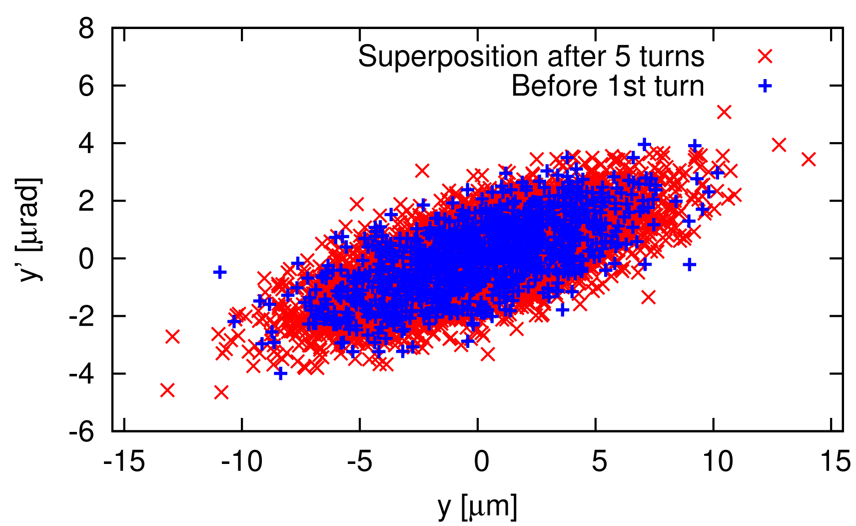
Adapting the BESSY Kicker to MAX IV (cont.)

- But can inject on slope
  - ➡ Sampling gradient is not a problem because of low emittance of injected beam from MAX IV linac



- Stored beam perturbation remains negligible
  (even with 5 µm Ti coating)





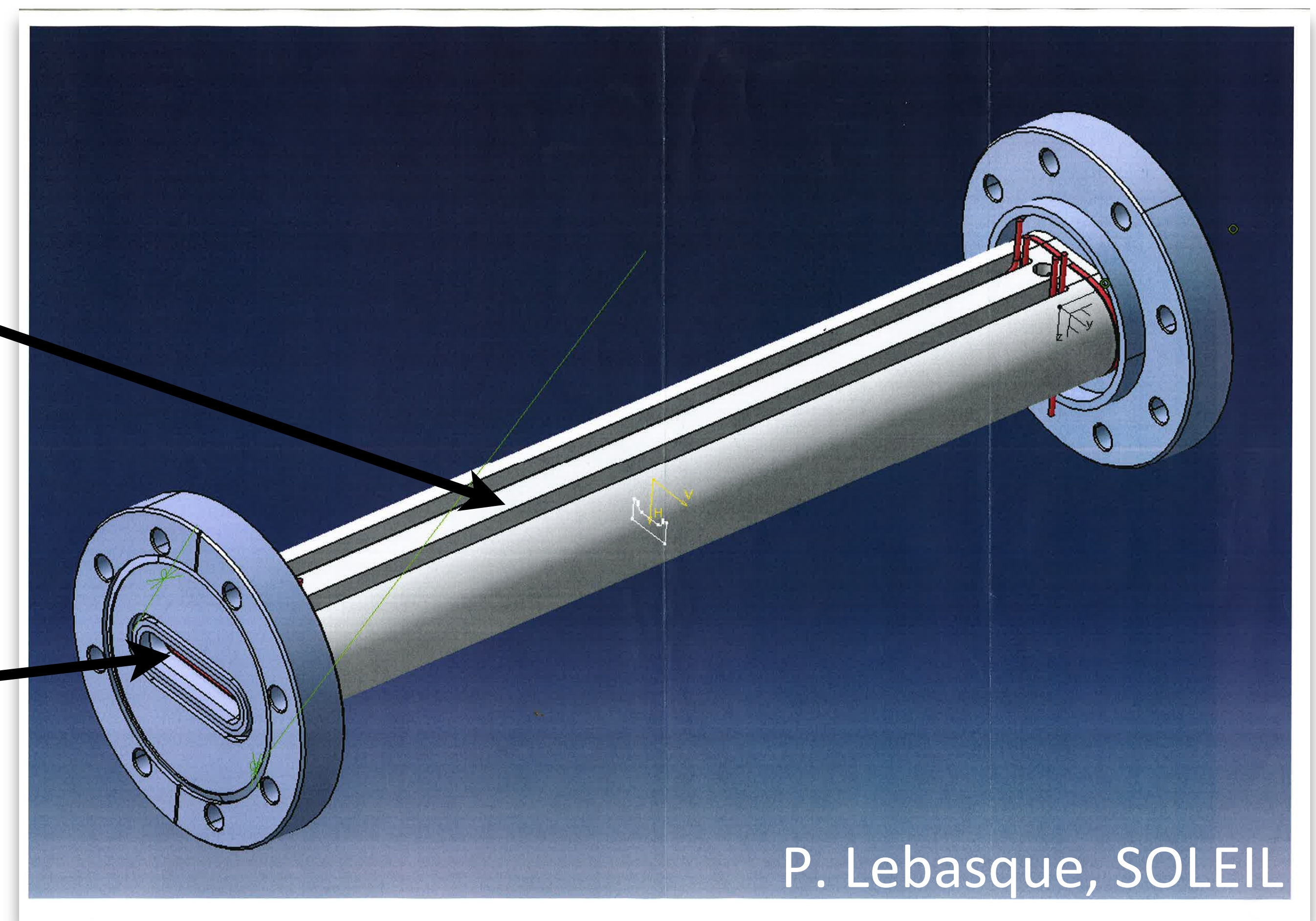
PAC'**13**, WEPSM05

Adapting the BESSY Kicker to MAX IV (cont.)

➡ Initiated collaboration with SOLEIL and BESSY to build nonlinear injection kicker for both MAX IV storage rings as well as SOLEIL

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

42 mm x 8 mm
(no synchrotron radiation on chamber)

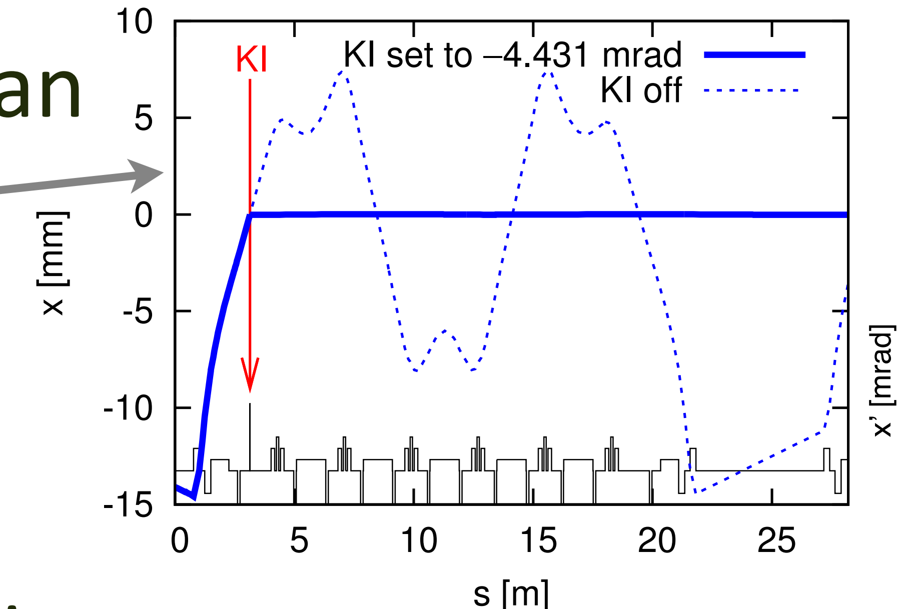


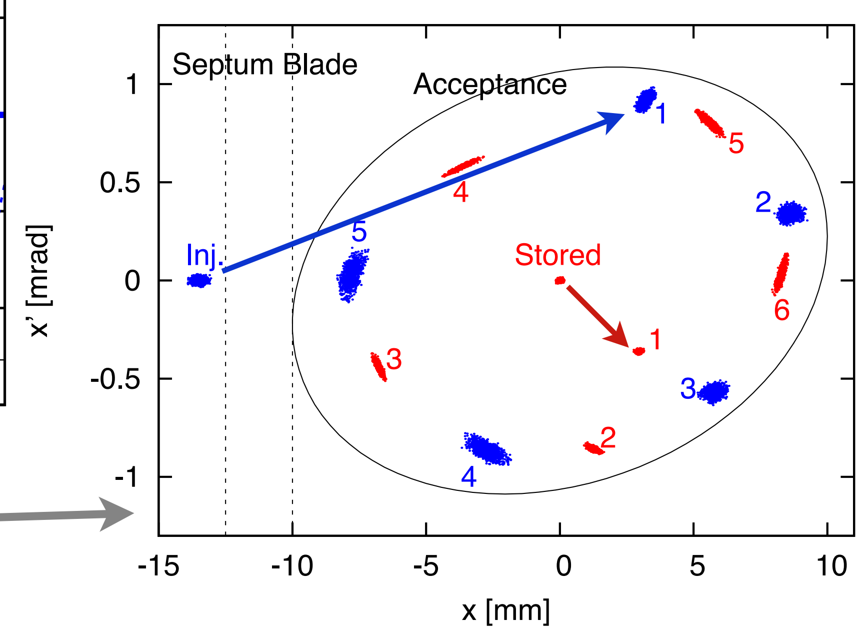
Commissioning

- Pulsed multipole injection depends strongly on position & angle of injected beam in nonlinear kicker (kick scales ≈x^3)
- Commissioning new ring with a nonlinear kicker *is not trivial*
  - ➡ use single dipole kicker close to septum for simple & robust injection during early commissioning

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

- Single dipole kicker can
  - – inject on-axis
  - – inject off-axis
  - – allows for accumulation

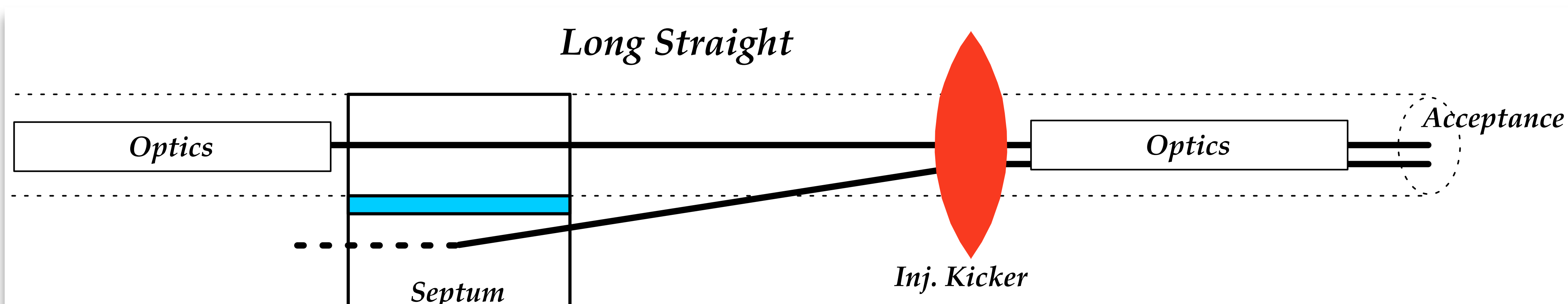




- After commissioning will become our horizontal pinger

Injection — Lessons to be learned

- Our solution shoehorned into a previously designed conventional injection scheme with 4 dipole kickers
  - Septum installed at downstream end of injection straight
  - Our nonlinear 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 angle if necessary)



Injection — Lessons to be learned (cont.)

- Name of the game is low-emittance injection into large acceptance rings
  - Large acceptance ring means a ring with good DA
  - Low-emittance injection can be realized via
    - linac (costly if not otherwise required)
    - large circumference in-tunnel booster e.g. SLS (cheap and simple, yet reliable)

Injection — Lessons to be learned (cont.)

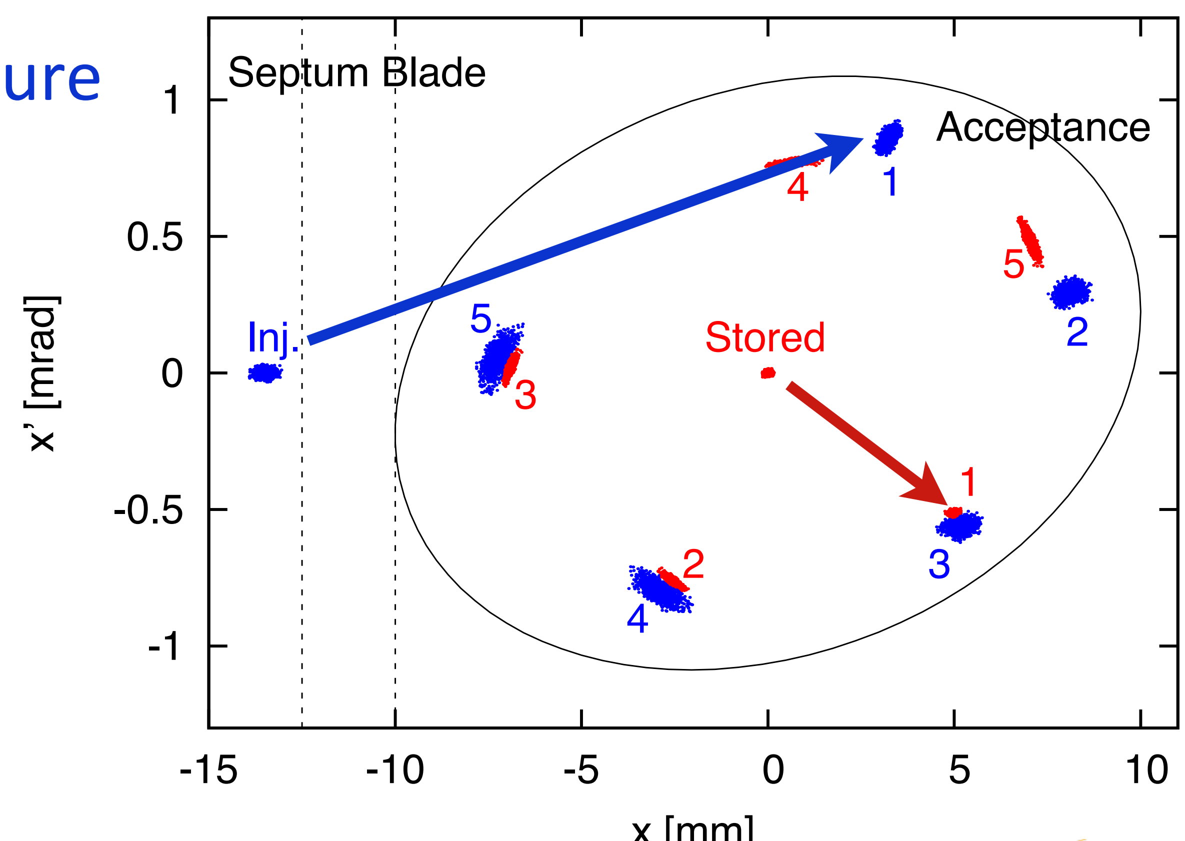
- For BESSY-type approach: need aggressive engineering!
  - ➡ i.e. bring rods close to stored beam
    - need good coupling control
    - could be easier in cases where this is a retrofit (vertical acceptance well understood and prior operational experience with in-vacuum ID's exists)

- 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!

Injection — Dreaming...

- For top-up what we really want is a fast dipole kicker
  - roughly 1–2 mrad kick
  - "fast" = 3 ns rise, 3 ns flat top, 3 ns fall
    - bunch by bunch injection, i.e. for each injection shot filling pattern monitor determines most depleted bucket → inject into that bucket
  - this does not have to be swap-out injection!
    - we already showed that we can capture **without kicking out** stored beam
    - level of disturbance to users on the order of 1/h since only a single bunch is excited
      (e.g. 0.6% perturbation for MAX IV users)
  - this injection can be on or off axis

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



Injection — Dreaming... (cont.)

- But in fact, the kickers wouldn't have to be that fast...
  - MAX IV linac can inject in trains of ten consecutive 100 MHz bunches @ 10 Hz
  - If we have a "slower" kicker with
    - ≈50 ns rise time & ≈50 ns fall time
    - ≈100 ns flat-top (doesn't have to be very "flat")

➡ We can still apply "train-by-train" injection for 2/3 our buckets
(i.e. 333 mA stored current without change to nominal single-bunch charge)

- top-up disturbance to users on ≈9% level