Design of a Multipole Kicker Injection Scheme for MAX IV

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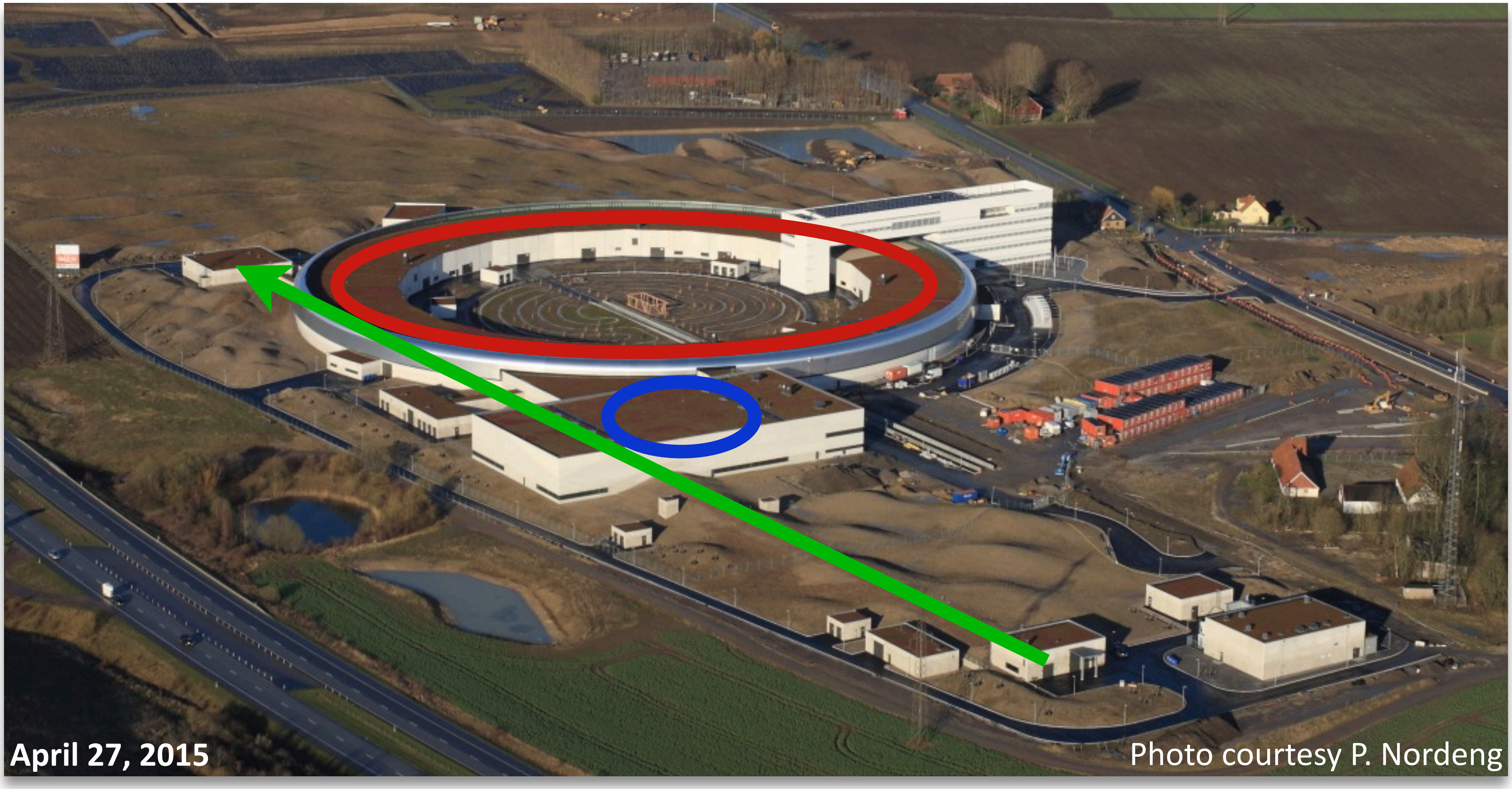
ALS ADVANCED LIGHT SOURCE

Original MAX IV Injection Requirements

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



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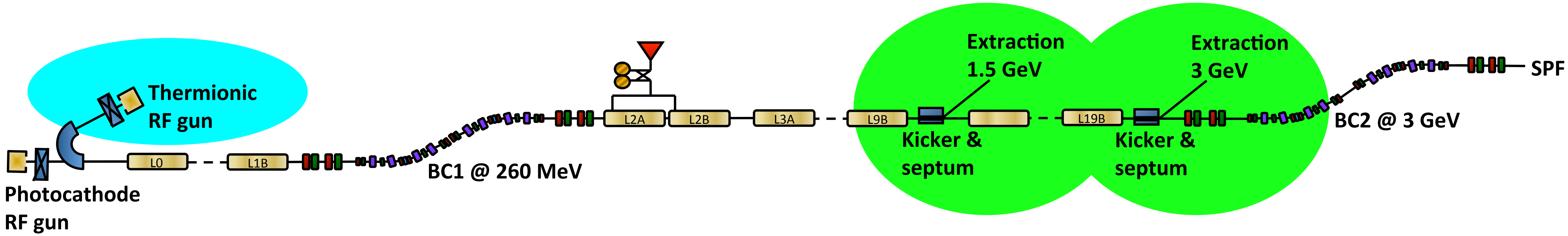
- One dedicated vertical transfer line (achromatic) to each ring, both equipped with DC Lambertson septum (V bend, H separation)



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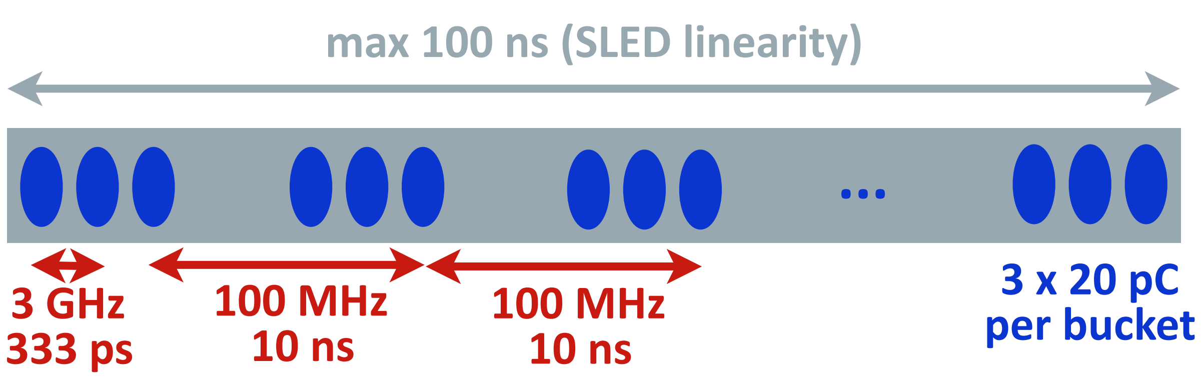

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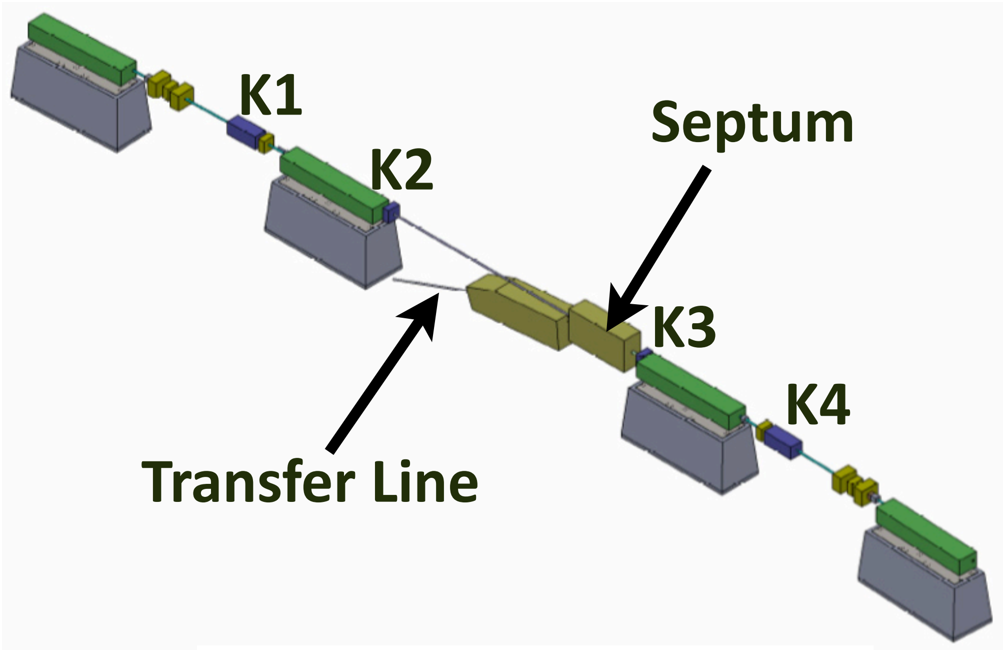
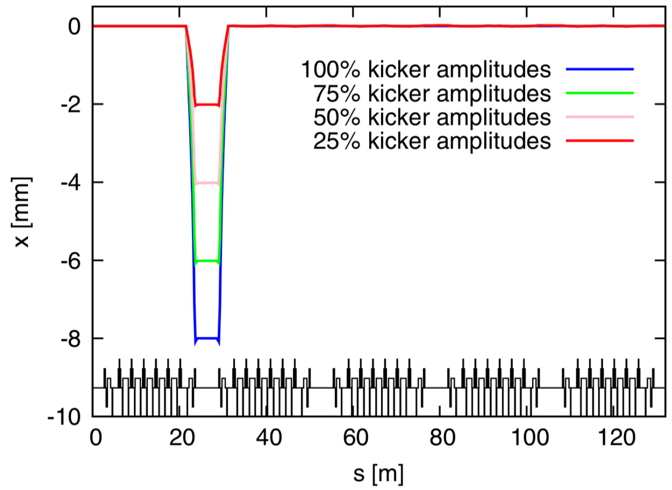
- Overall ring lifetime ≈10 hrs → considered two top-off scenarios:
  - 1% deadband (5 mA) calls for 8.8 nC (15 shots, 1.5 sec) every 6 min
  - Inject every 30 min → 43 nC (72 shots, 7.2 sec) → 5% deadband

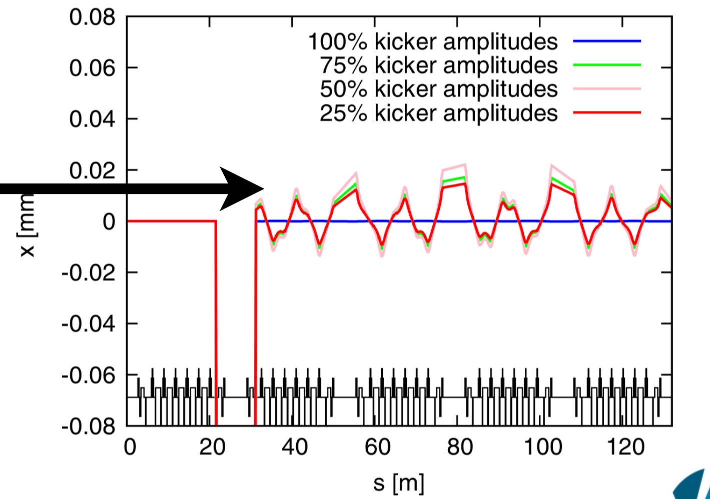
56 h inelastic, 25 h elastic → 17 h gas
>24 h Touschek (depending on IDs, coupling, RF)

Original MAX IV Injection Scheme



- CDR had assumed conventional 4-kicker bump injection
- Growing concern about stored beam stability during top off ➔ 200 nm vertical stability requirement in 3 GeV ring
- But complexity & beam dynamics implications
  - matching, synchronizing and aligning 4 kickers/pulsers to properly close bump
  - strong sextupoles and octupoles in bump ➔ closes at only one energy & *amplitude*
  - 4 kickers and septum require lots of space



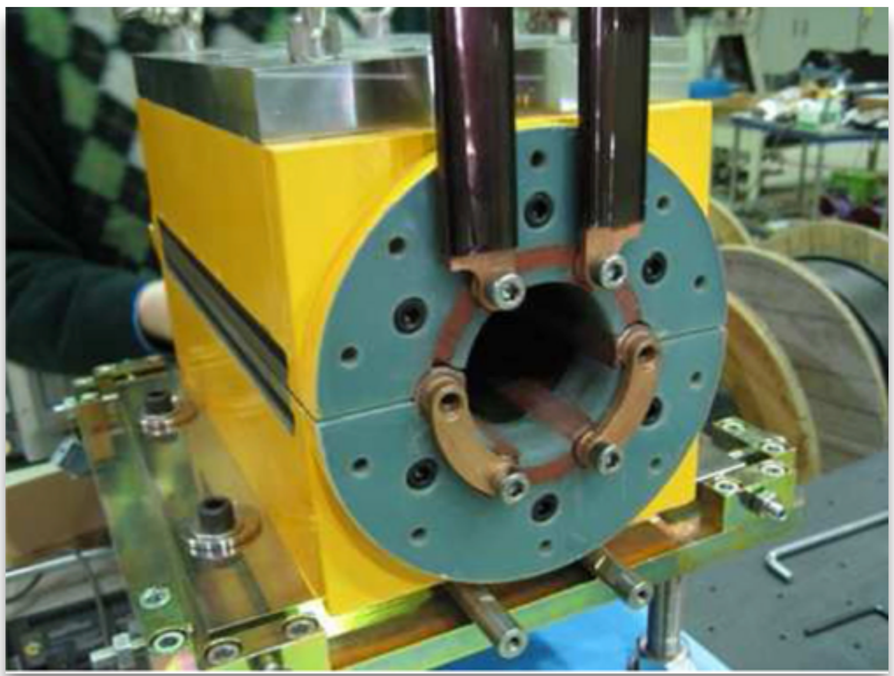


Intrigued by Recent Developments at PF-AR & PF

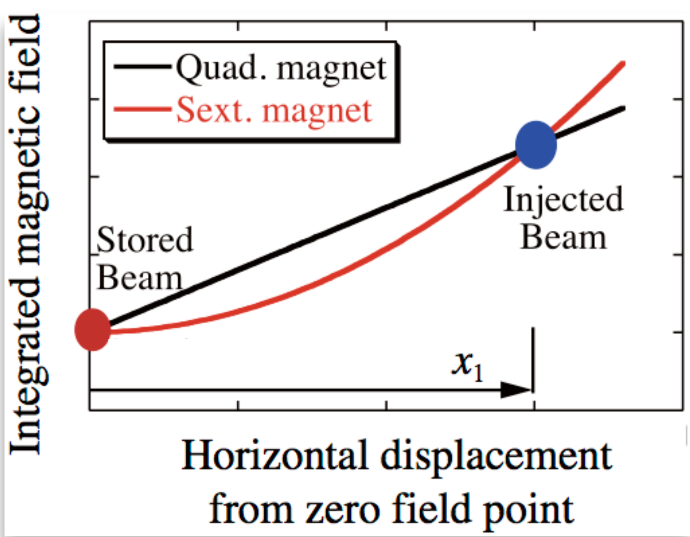
- KEK had recently pioneered pulsed multipole injection: PQM & PSM
- Several key advantages for MAX IV
  - align only a single magnet to stored beam
  - synchronize only one pulser to injection
  - PSM field flat at stored beam → minute perturbation during top off
  - PSM slope at injected beam tolerable
    (linac delivers 1.7 nm rad)

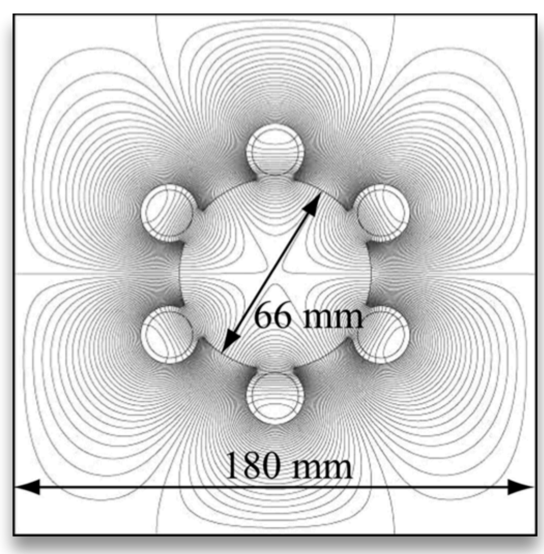
PRST-AB **10**, 123501 (2007)

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

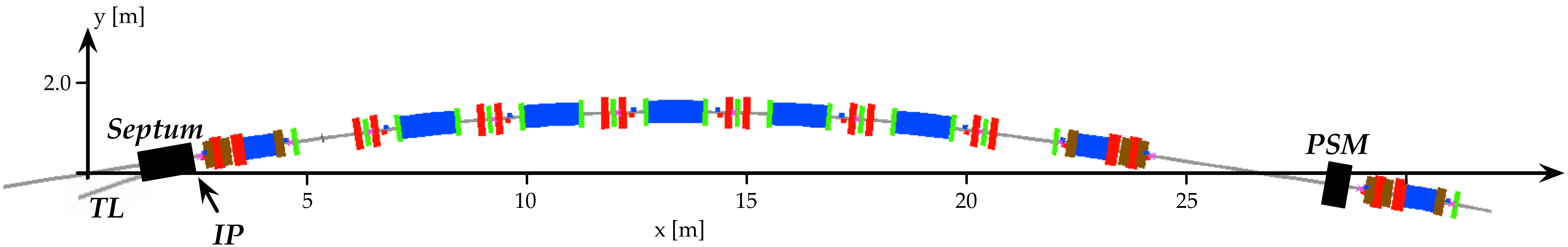


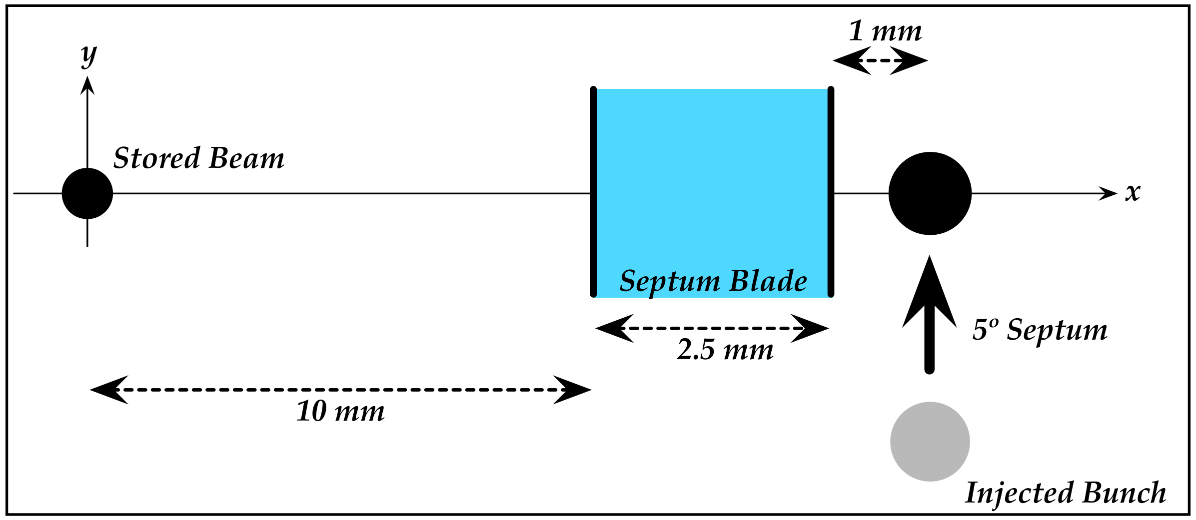


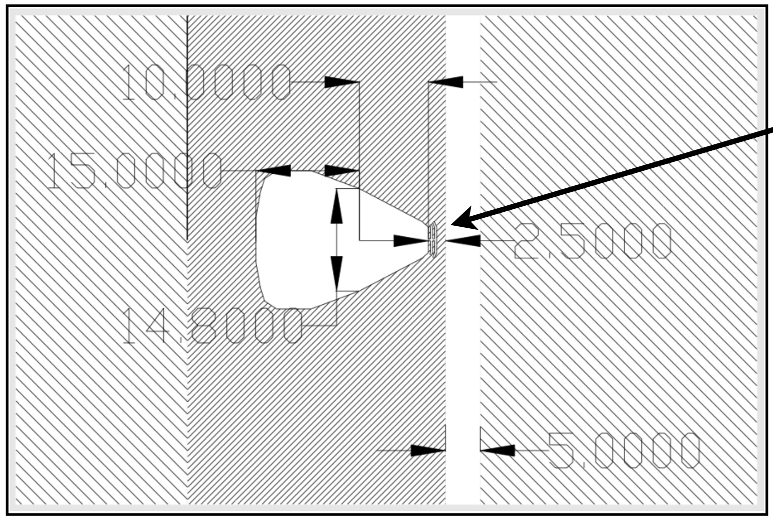
First Attempt: Pulsed Sextupole Injection for MAX IV

- Decided to use PSM injection for top-off into both MAX IV rings
- Strong nonlinearities in MAX IV storage rings ➔ tracking (Tracy-3, DIMAD): optimization of beam position/angle in septum & PSM location/strength

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







Septum nose with filter

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

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

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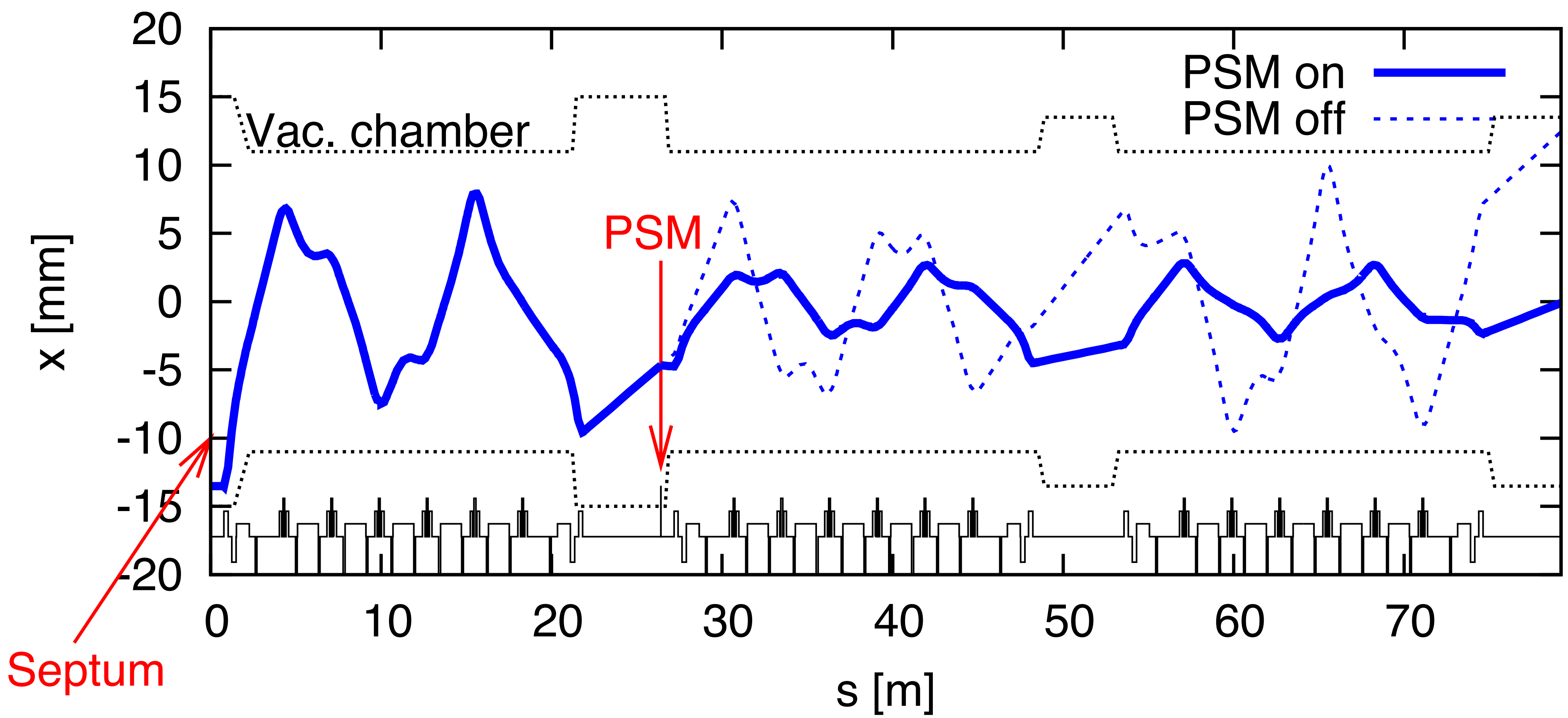

$$\cos\phi_{\mathrm{psm}} = \pm\frac{A_{\mathrm{red}}}{A_{\mathrm{inj}}}$$

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

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

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

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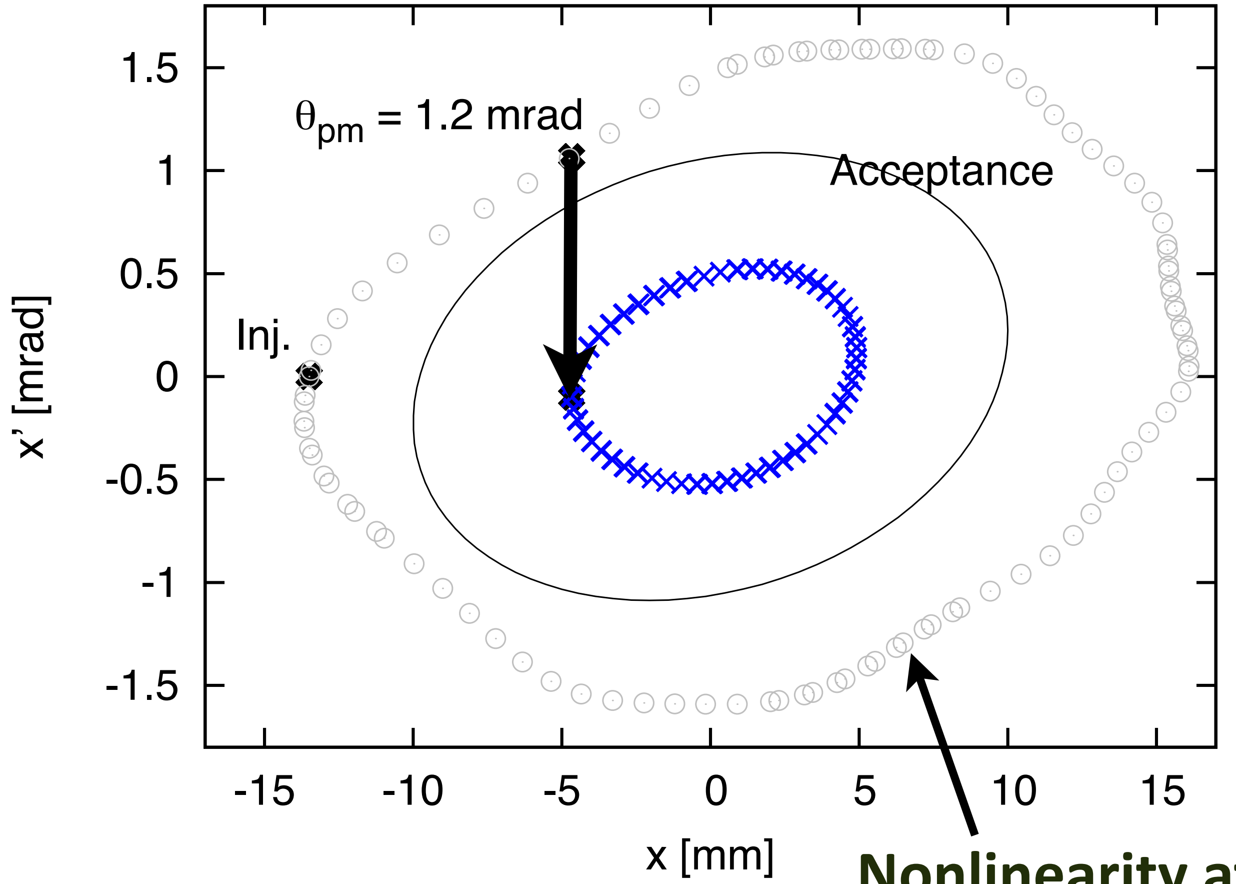

Nonlinearity at large injection amplitudes

≈1.2 mrad to minimize reduced invariant

≈0.8 mrad sufficient for capture within (design) acceptance

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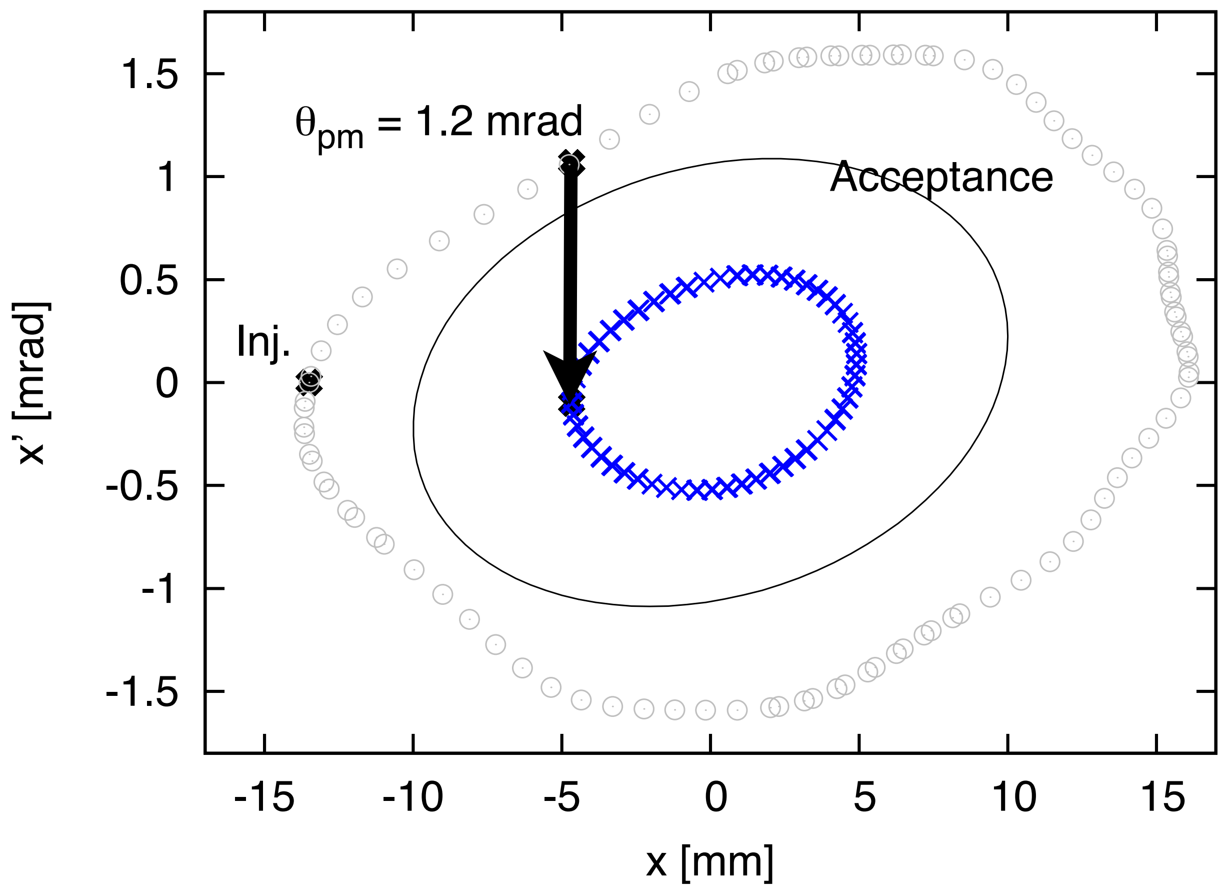

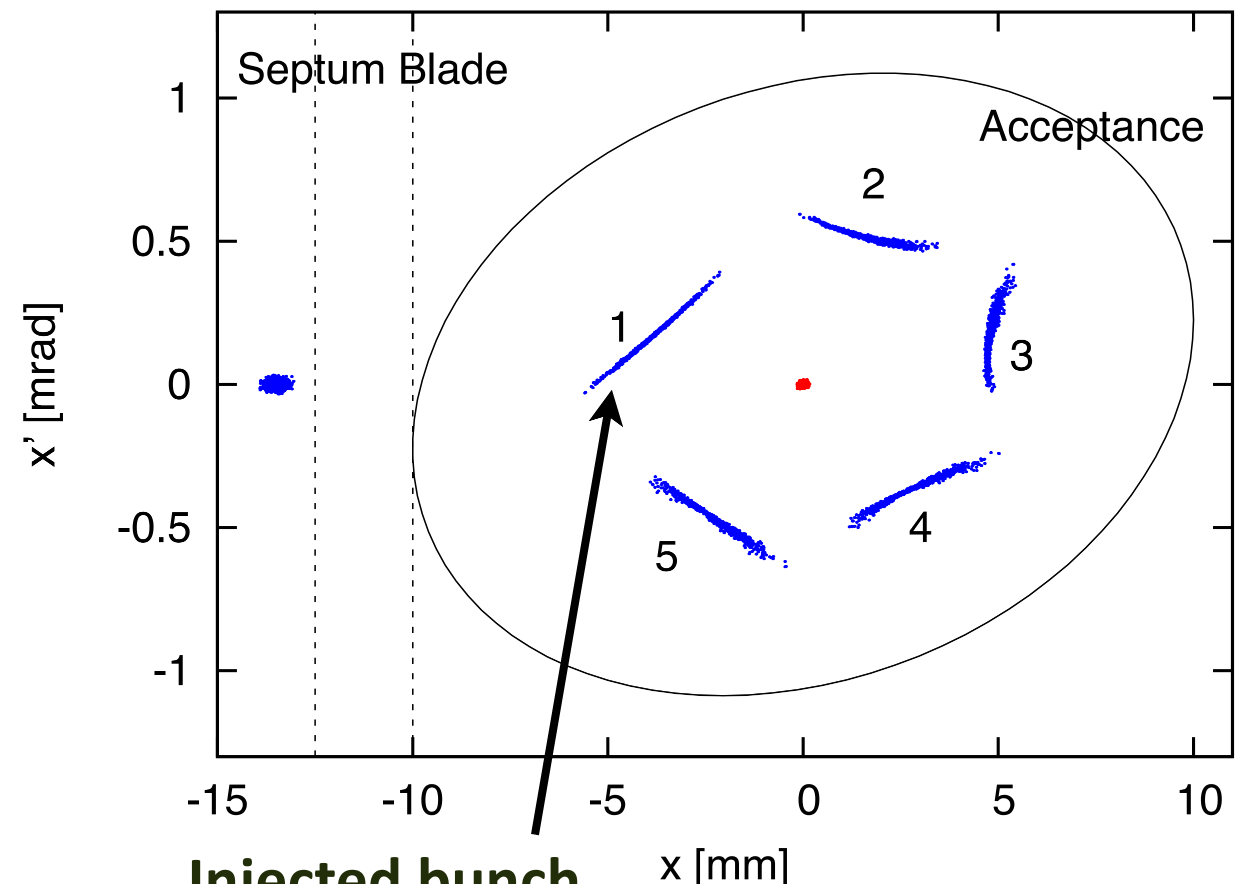

Injected bunch sampling PSM slope

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- Capture shows significant tolerance to injection errors (1.7 nm rad injected emittance vs. ≈11 mm mrad ring acceptance)

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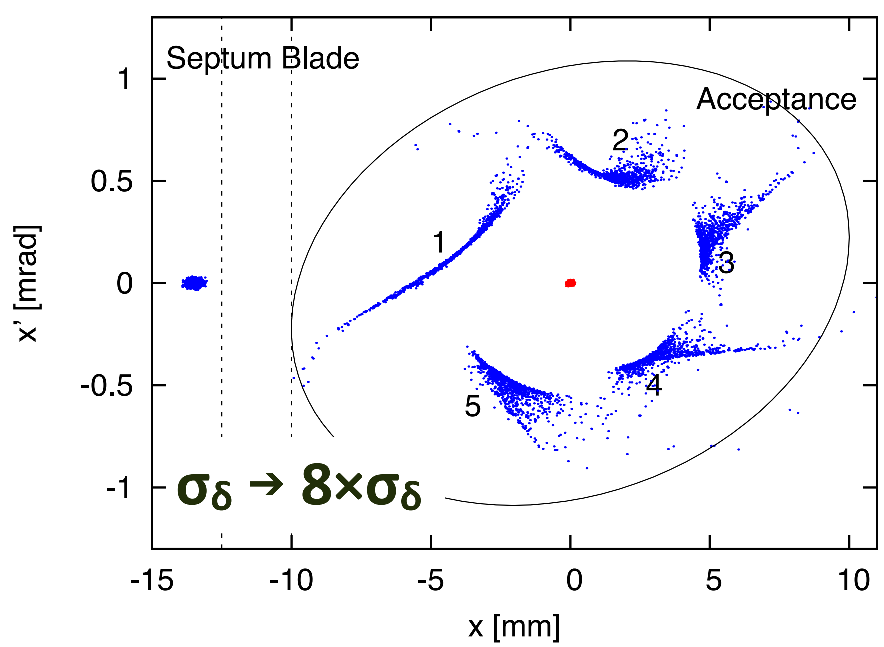

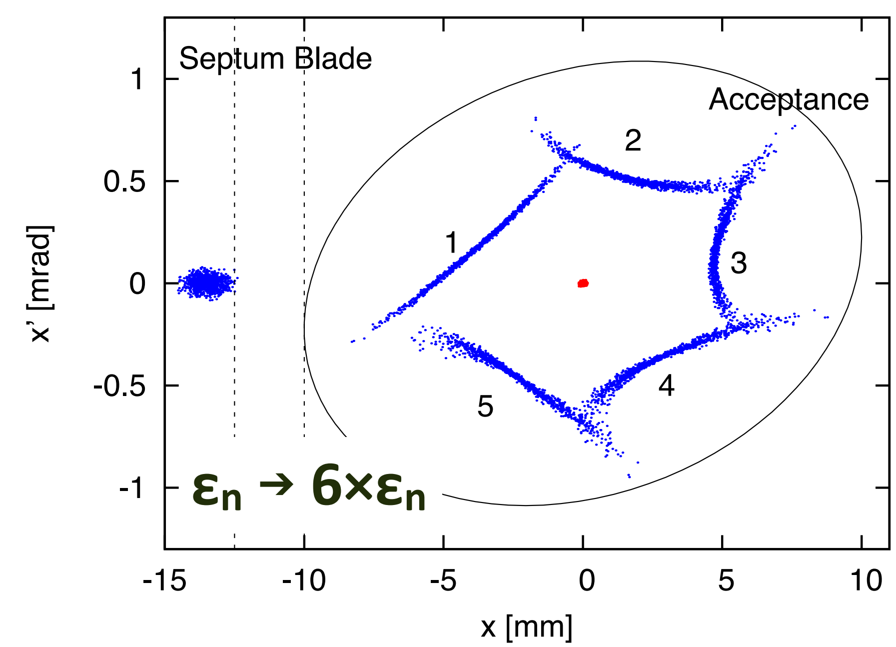

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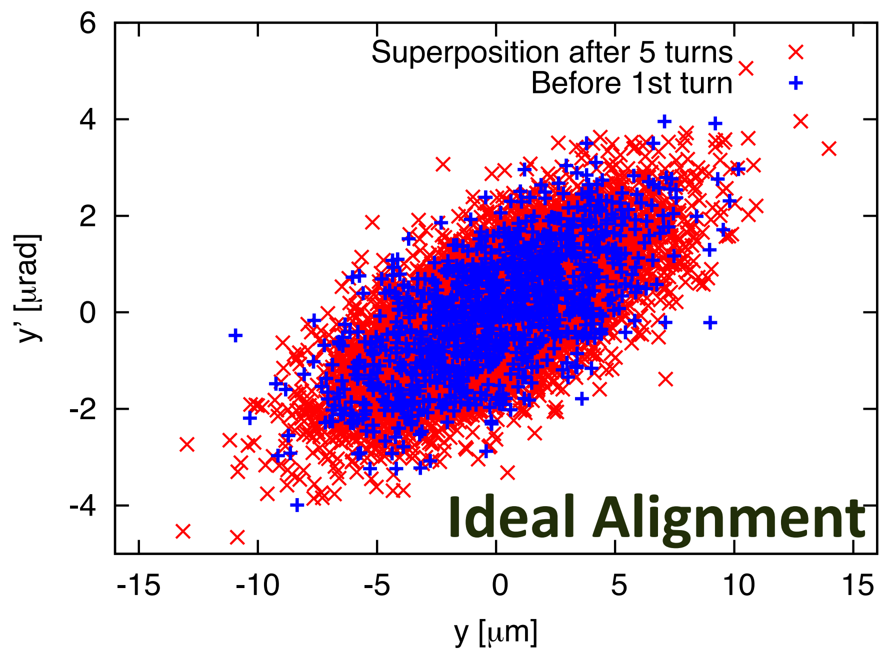
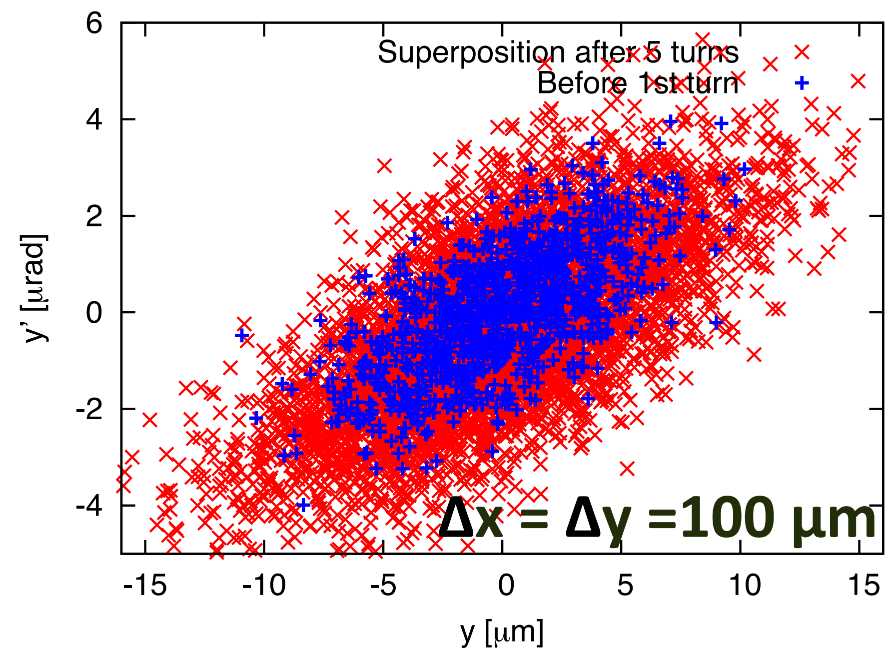
- But tolerances for fully transparent top off are tight (negligible residual fields/gradients at stored beam & girder design to facilitate beam-based PSM re-alignment)





Our Reference Design for a MAX IV PSM

- Attempted a solid iron PSM following KEK PF design

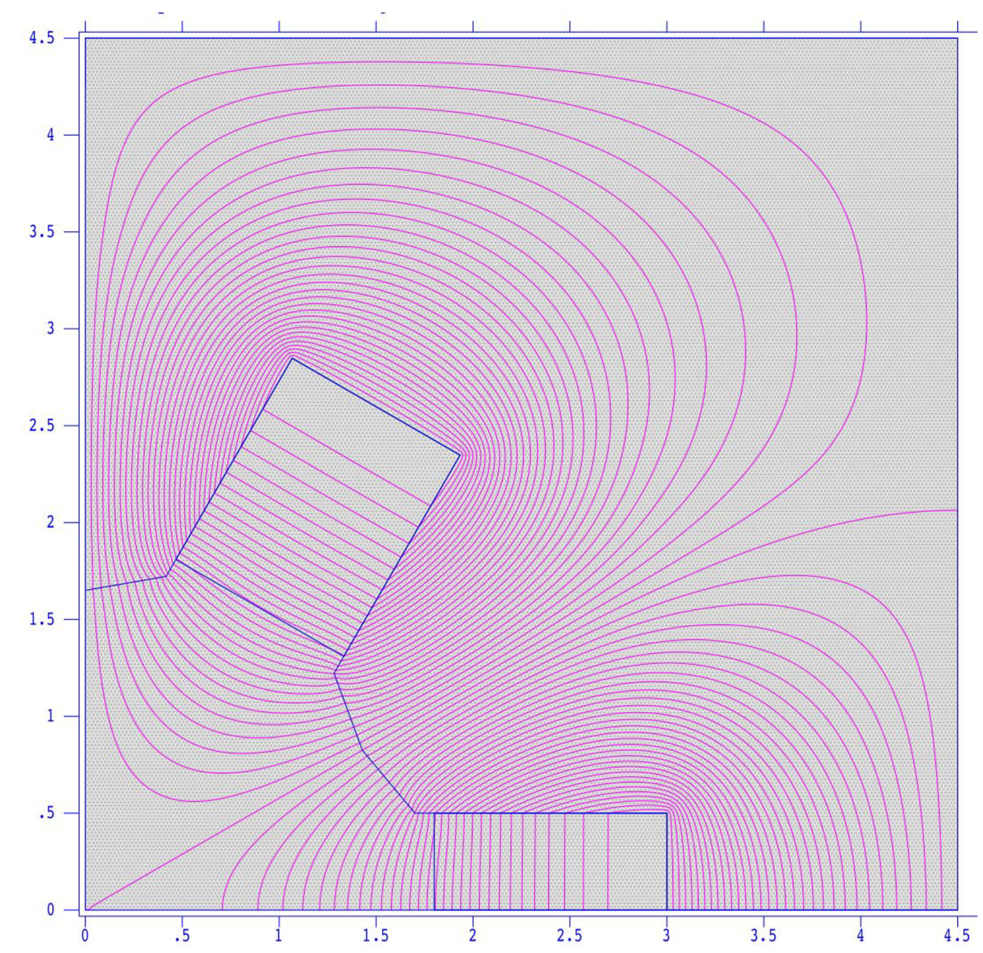
PAC'**13**, WEPSM05

  - take advantage of reduced gap required by MAX IV rings
  - but cannot exploit aspect ratio of beam-stay-clear requirements (symmetry required to minimize stored beam perturbation)

- 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

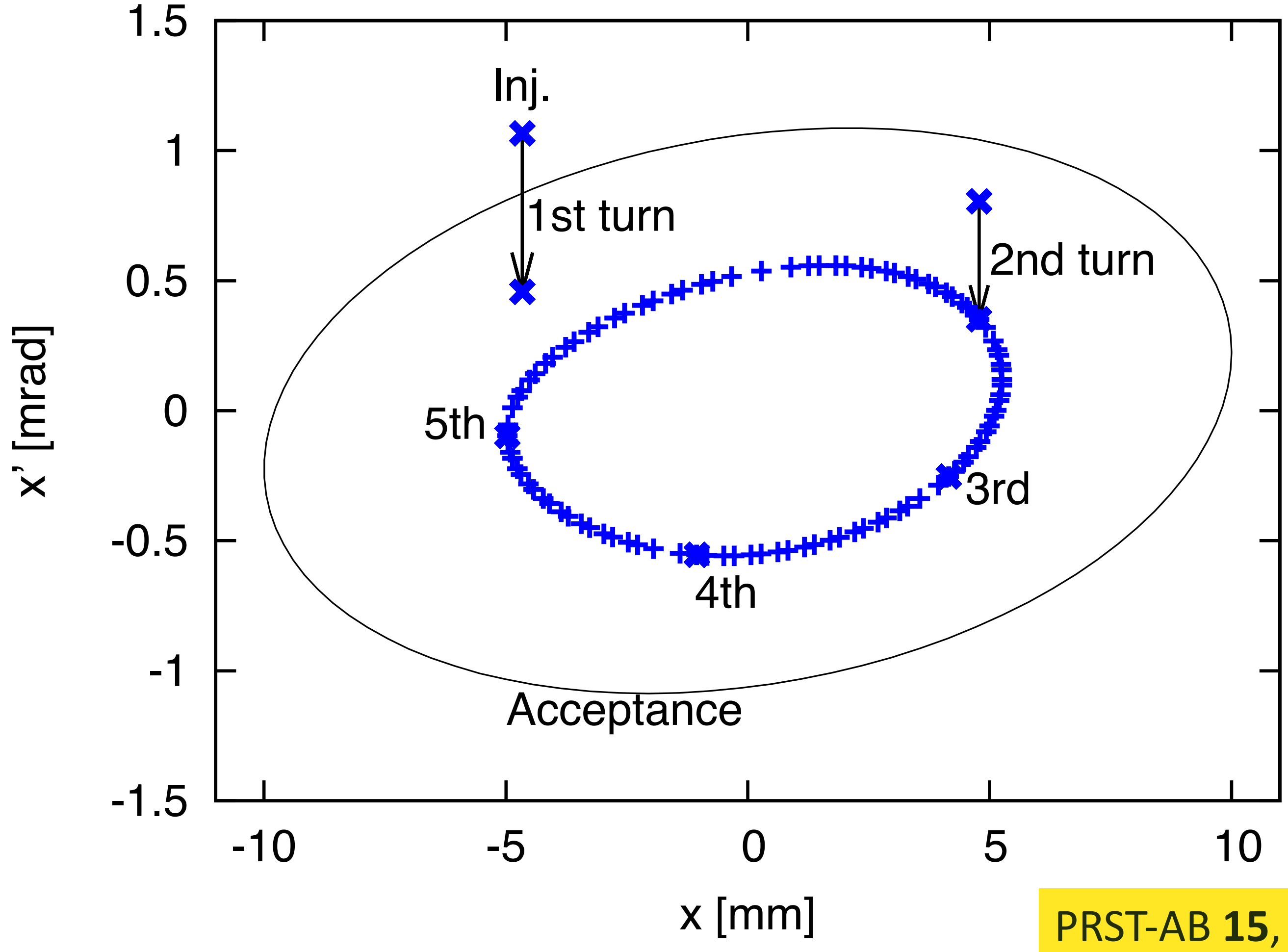
  - but in 1.5 GeV ring: 640 ns pulse length calls for 93 kV (despite 400 mm length)



Our Reference Design for a MAX IV PSM (cont.)

PAC’**13**, WEPSM05

- 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 much more rigid (lattice tunability)



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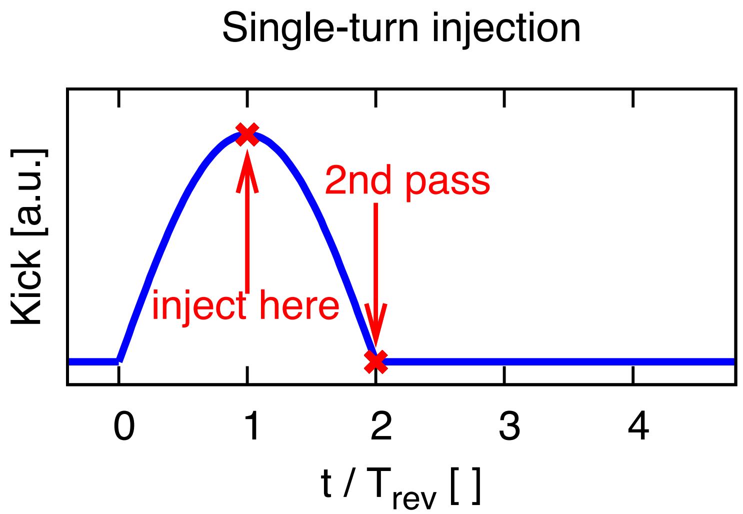
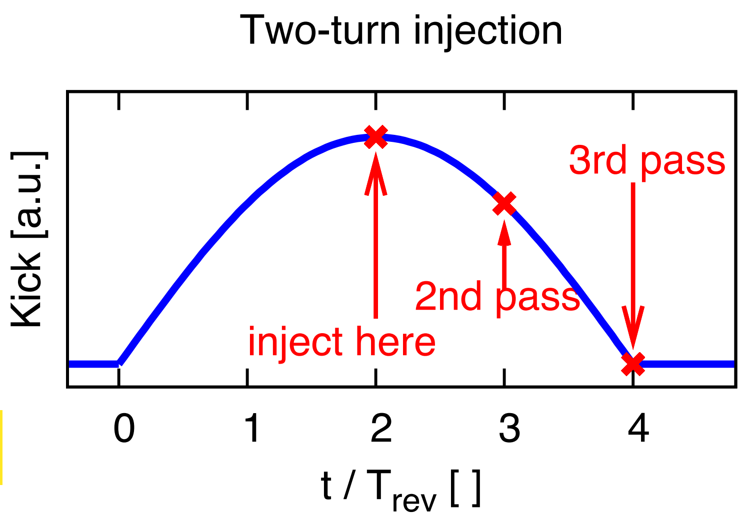


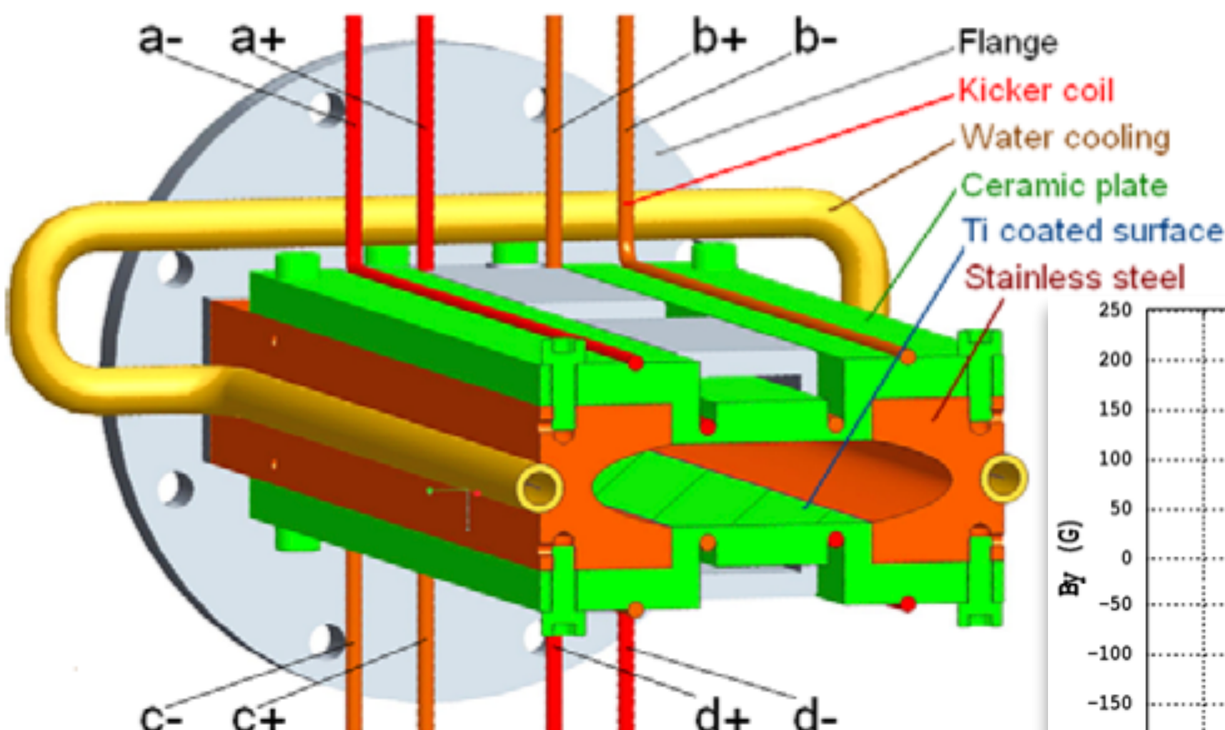


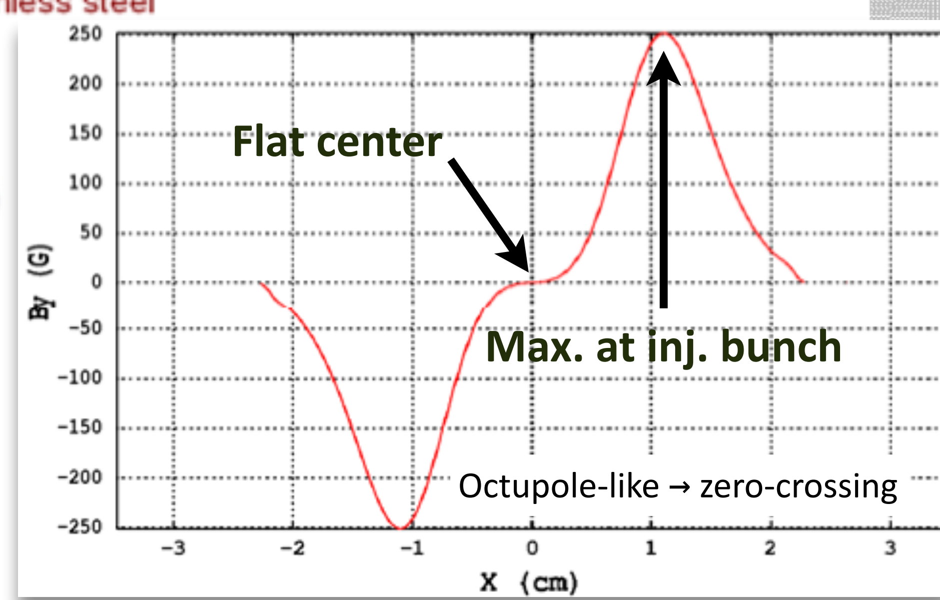
A Much Better Idea: BESSY Nonlinear Kicker

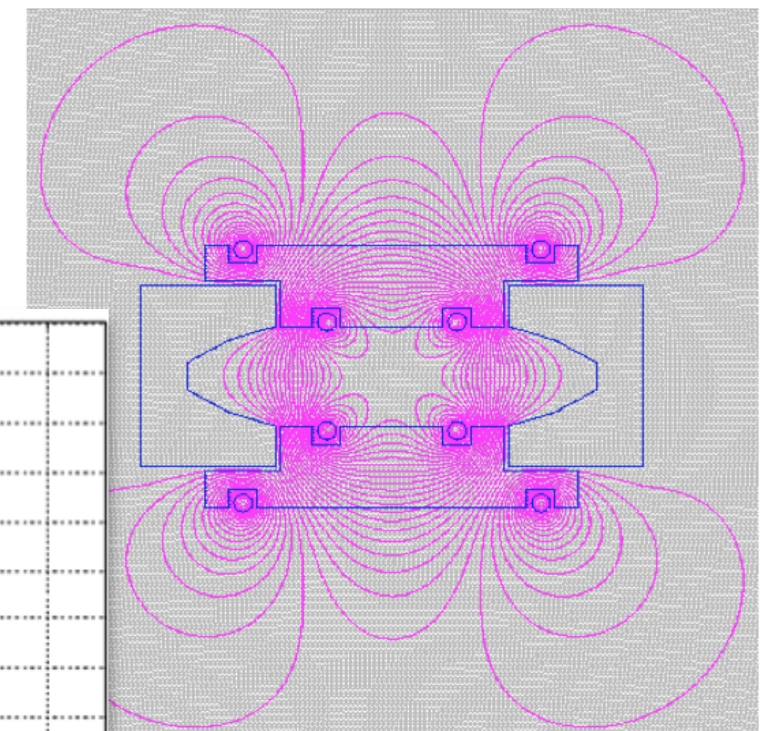
- Pulser voltage requirements can be lowered if stored energy in kicker magnet is reduced → abandon solid iron magnet
- BESSY nonlinear injection kicker prototype
  - stripline-like design with 4 low-impedance conductors
  - minimize stored beam perturbation & maximize kick at injection

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

IPAC’**11**, THPO024, p.3394



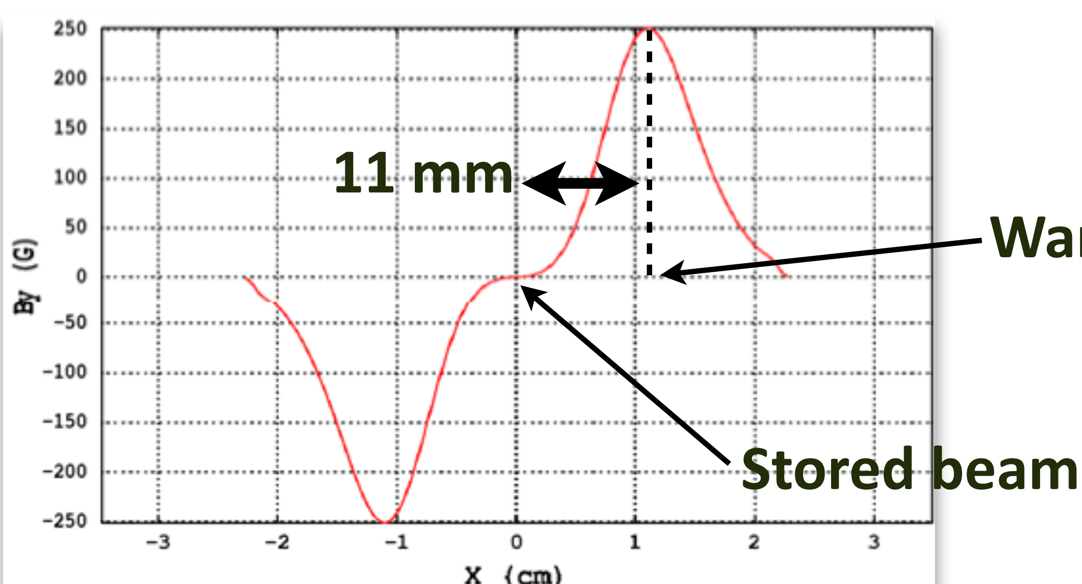


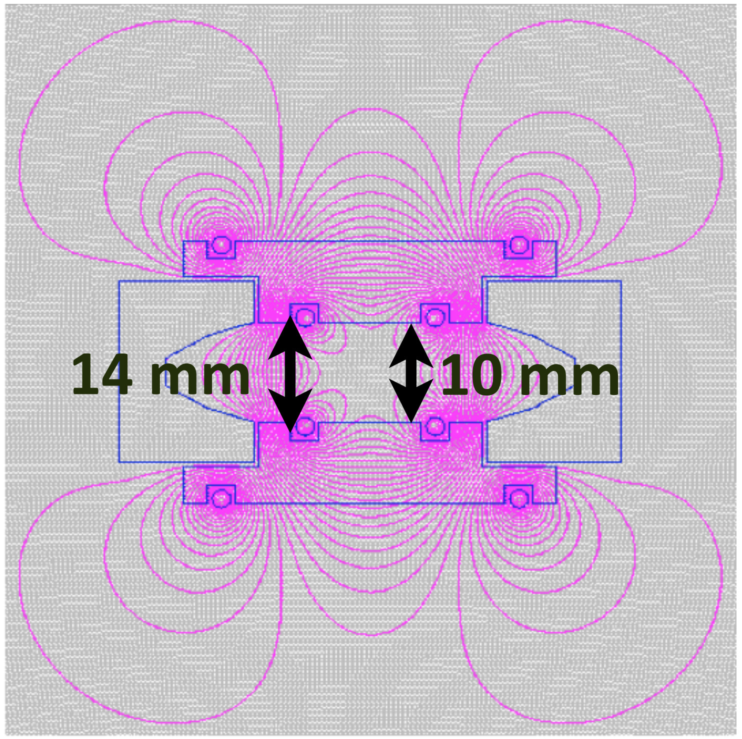


Second Attempt: MAX IV Multipole Injection Kicker

PAC'**13**, WEPSM05

- In 2011 started collaboration with SOLEIL & HZB to develop new nonlinear injection kicker for MAX IV based on 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 (note: ±4 mm BSC in EPU chambers)





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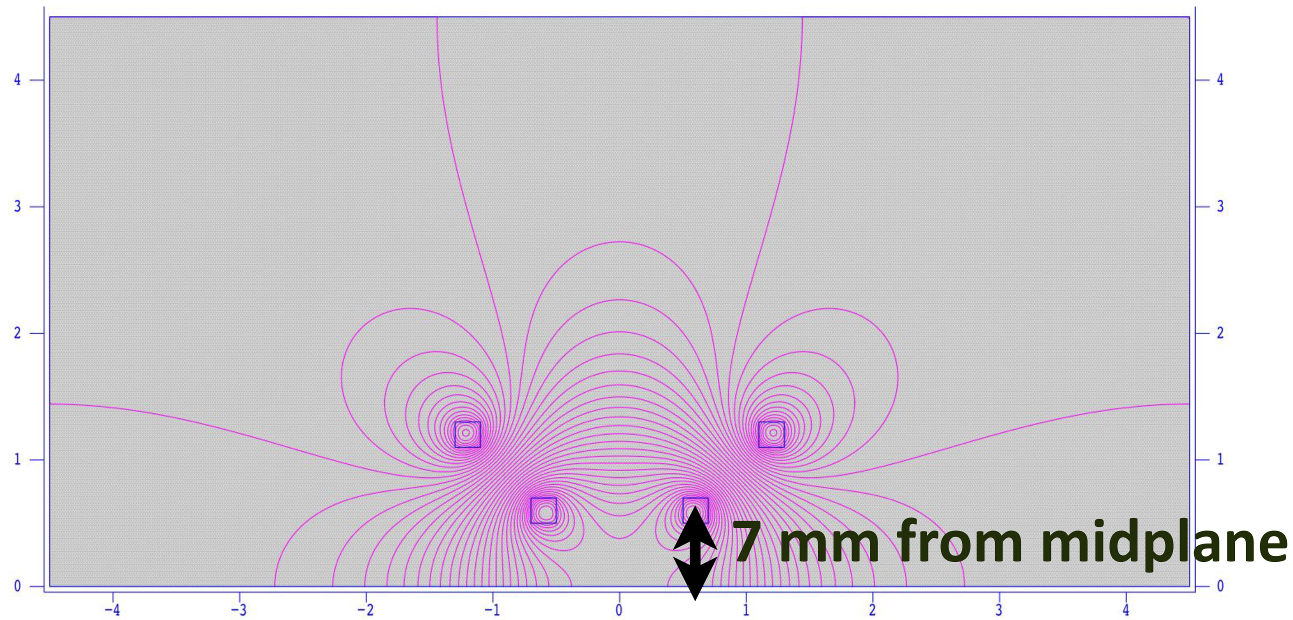
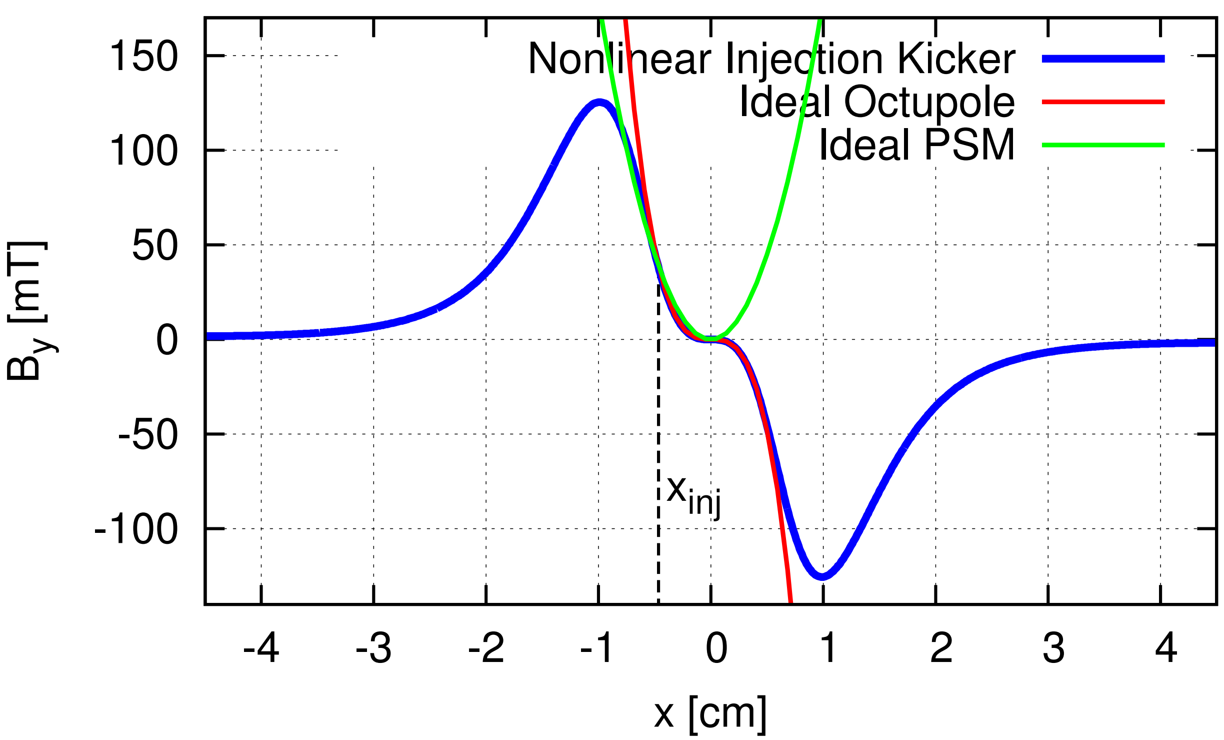
- Assumptions for ceramic chamber & conductor cross-section requirements → inner rods at ±7 mm → max kick at ≈10 mm





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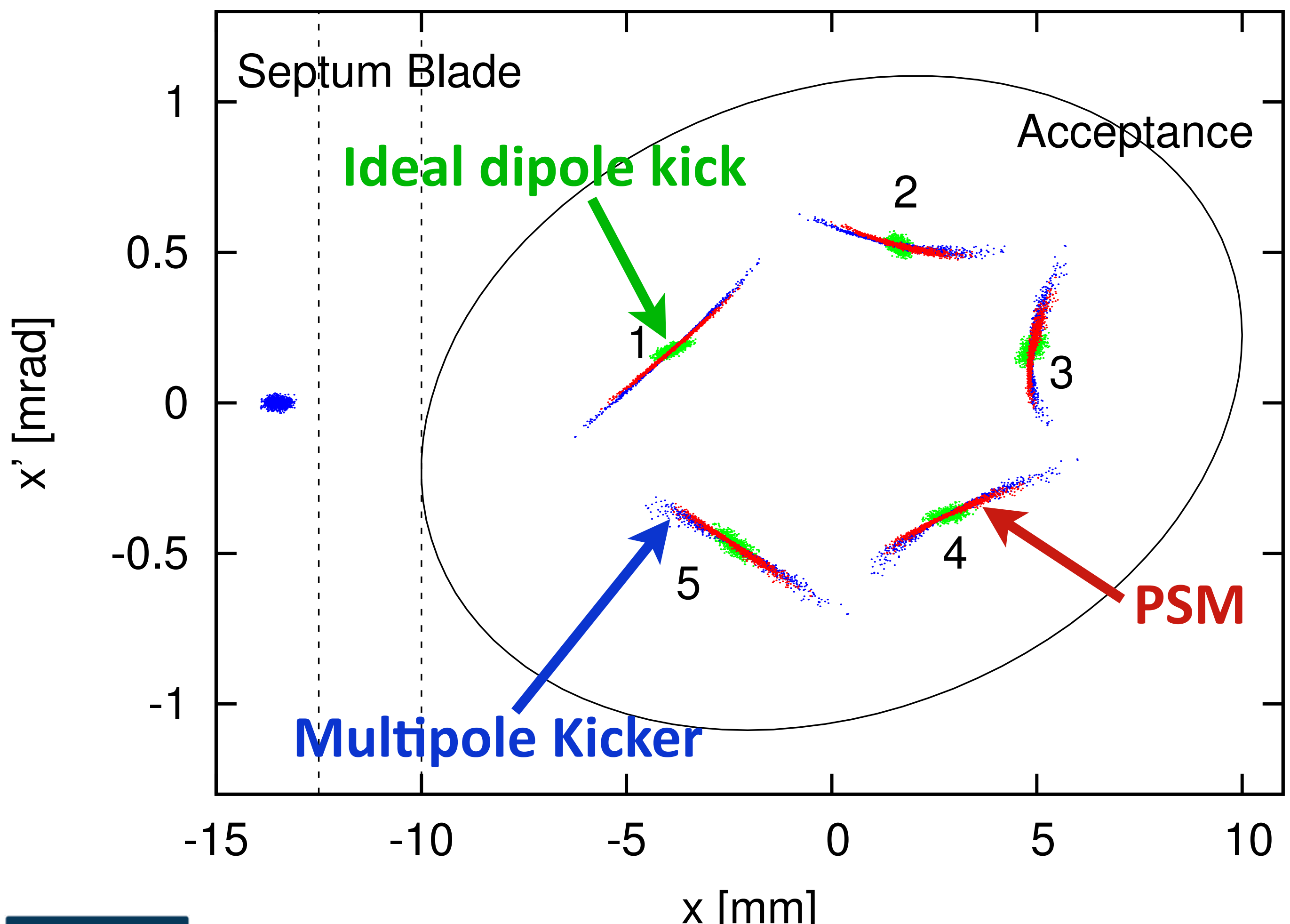

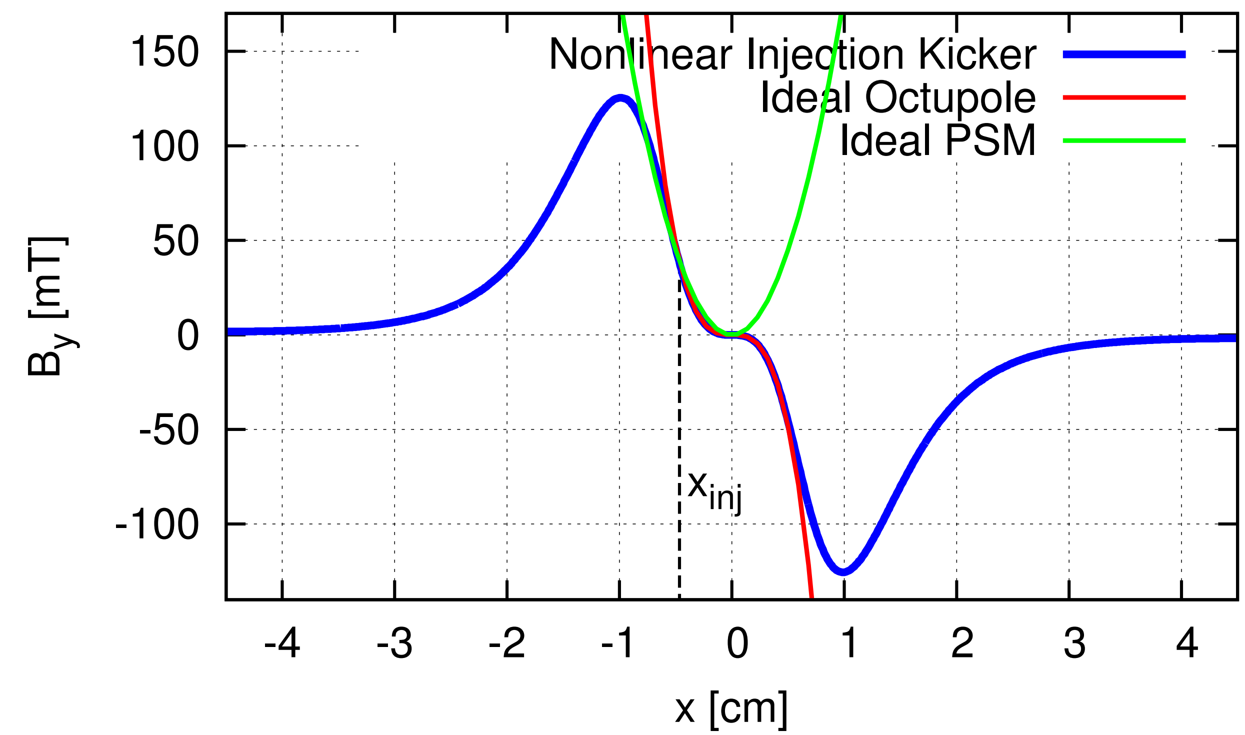

Field data for tracking extracted from OPERA models (static & transient) including 4 µm Ti coating
(OPERA model courtesy P. Lebasque, SOLEIL)

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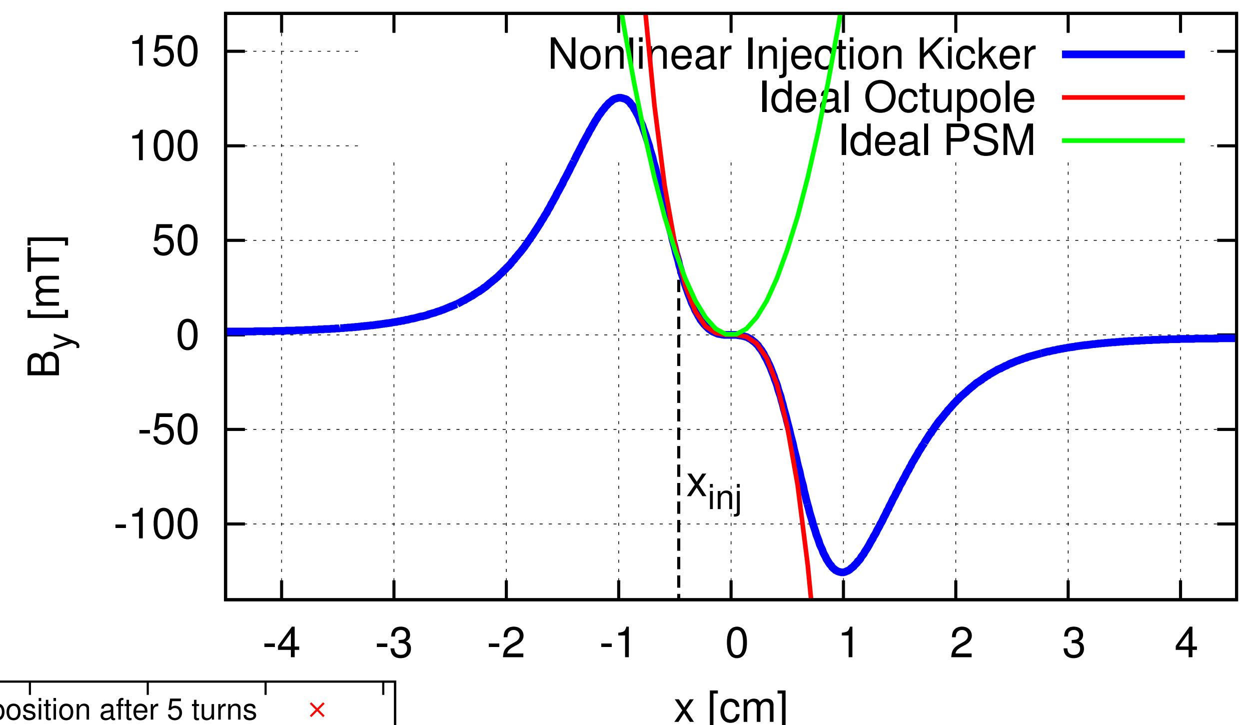
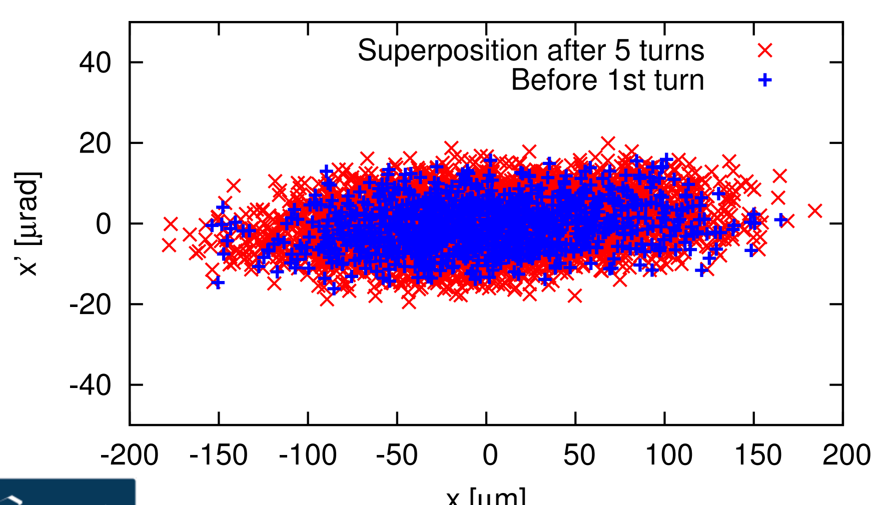
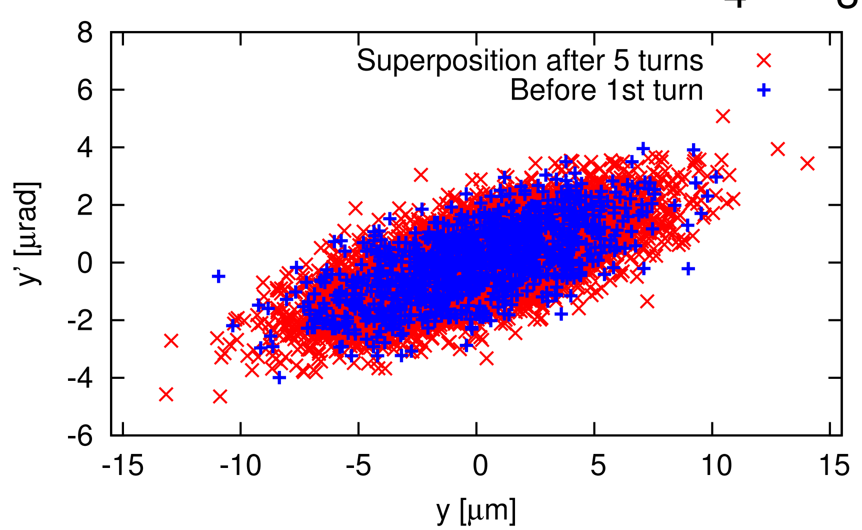
- Low-emittance injection from MAX IV linac ➔ inject on slope without sampling too much gradient
- Injected beam and stored beam see octupole-like field
- 39 mT at injected beam (x = –4.7 mm)
- Negligible stored beam perturbation







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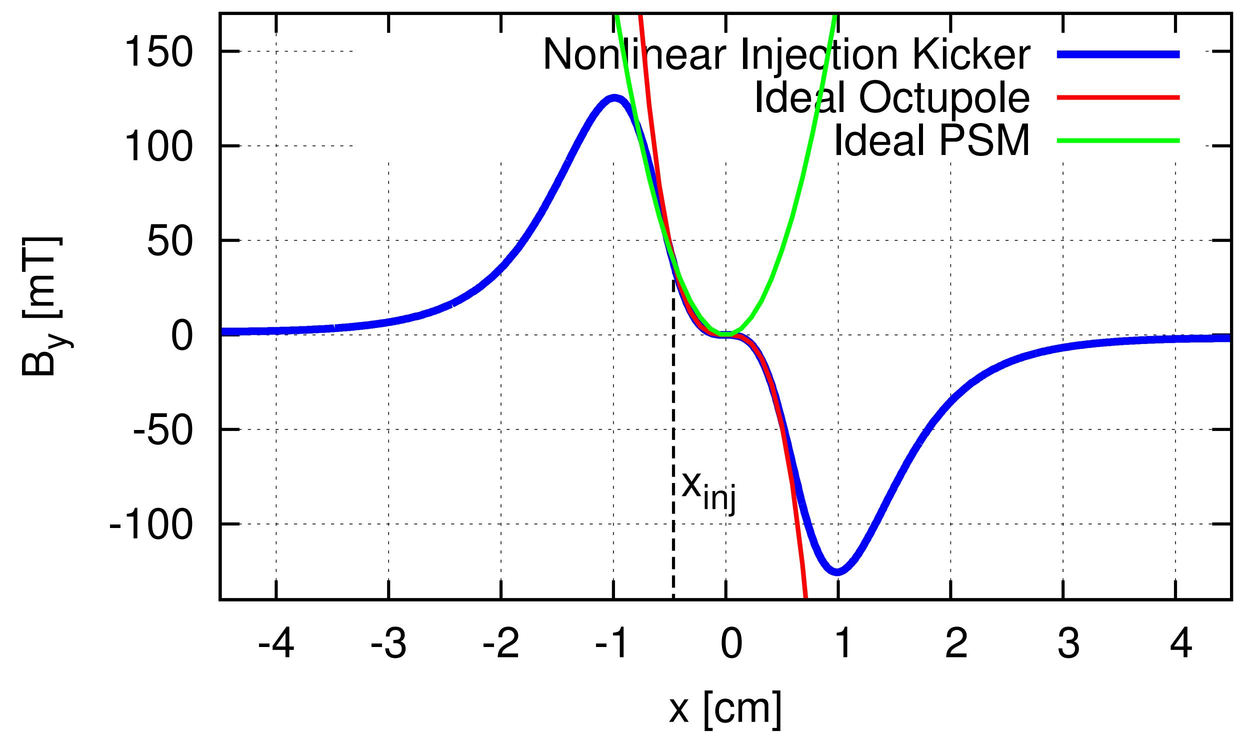
- 39 mT at injected beam (x = –4.7 mm)
- Negligible stored beam perturbation
- Note: acceptable residual gradient at stored beam is independent of emittance (≈0.3 T/m at MAX IV)

$$\left.\frac{\partial B_y}{\partial x}\right|_{\rm res} < 10\% \times \frac{B\rho}{\beta_x L}$$



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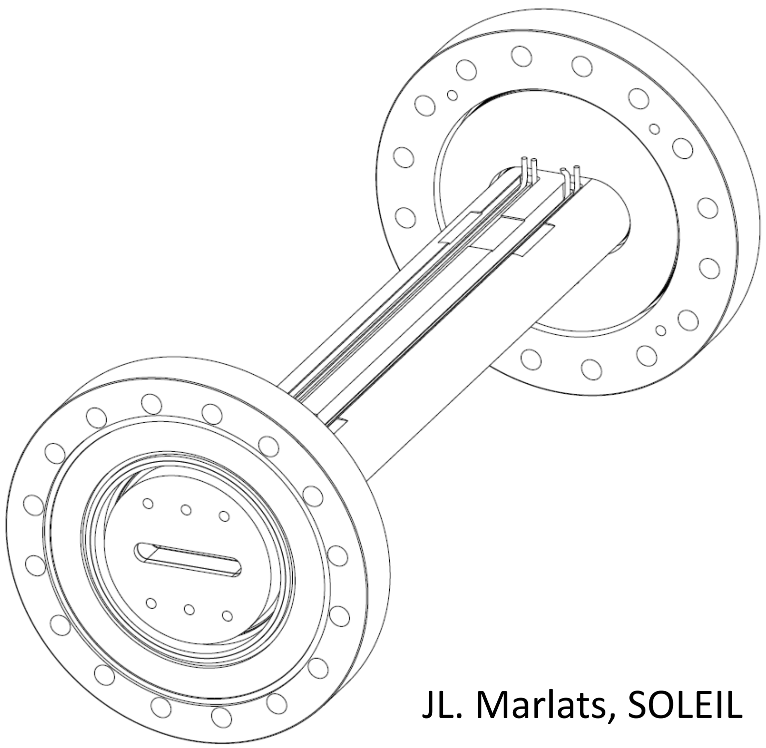
PAC'**13**, WEPSM05

- Other changes to satisfy MAX IV constraints & benefit from prototyping efforts at HZB
  - ±10 micron machining tolerance for grooves in chamber ➔ field quality at stored beam (simulations showed geometry of terminals not equally critical for field quality)
  - all four coils powered in series ➔ minimize field imbalance at stored beam
  - complete ceramic vacuum vessel without metallic wall parts ➔ minimize field distortions
  - increased horizontal aperture of the chamber (47 mm x 8 mm BSC) ➔ no synchrotron radiation on chamber ➔ allows for air cooling



JL. Marlats, SOLEIL

Second Attempt: MAX IV Multipole Injection Kicker

TABLE I. Pulsed sextupole magnet parameters for injection into the MAX IV storage rings.

	B'' [T/m^2]	L [m]	τ [μs]
3 GeV PSM, nominal	3575	0.3	3.5
Reduced kick	2420	0.3	3.5
Two-turn injection	1867	0.3	7.0
1.5 GeV PSM, nominal	1847	0.4	0.64
Reduced kick	665	0.4	0.64
Two-turn injection	1847	0.4	1.28
Two-turn reduced-kick injection	1475	0.4	1.28

TABLE II. Pulser requirements for PSM injection into the MAX IV 3 GeV [1.5 GeV] storage ring.

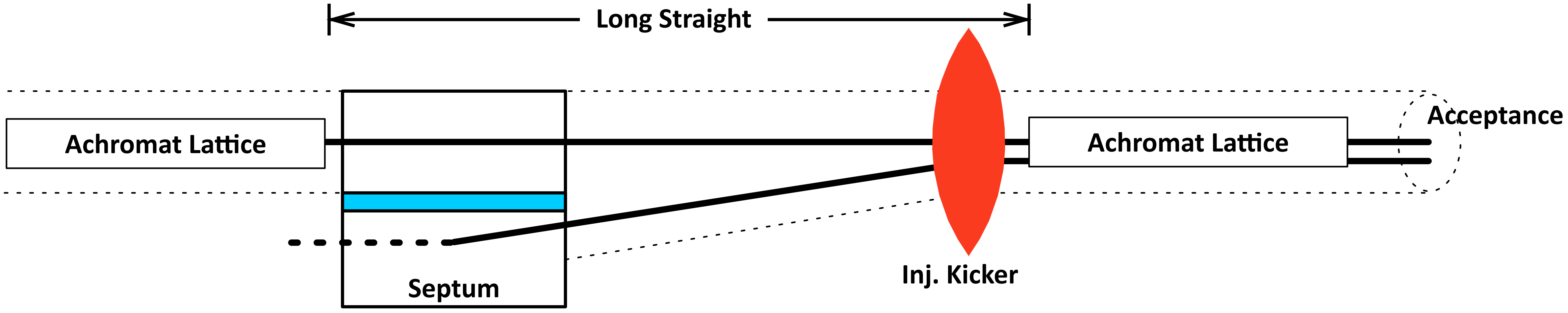
Pulse length	<3.5 μs [640 ns]
Pulse length (two-turn injection)	<7.0 μs [1.28 μs]
Fall time	<1.8 μs [320 ns]
Amplitude jitter within	$\pm 0.1\%$
Long-term amplitude drift	$<1\%$
Timing jitter within	± 5 ns
Maximum repetition rate	10 Hz

TABLE III. Tolerances for misalignments and residual dipole fields on axis in the PSMs for the MAX IV storage rings.

3 GeV PSM horizontal misalignment	<96 μm
3 GeV PSM vertical misalignment	<10 μm
3 GeV PSM integrated residual dipole field (H)	<1 μT m
3 GeV PSM integrated residual dipole field (V)	<5 μT m
3 GeV horizontal angular acceptance at IP	± 0.1 mrad
1.5 GeV PSM horizontal misalignment	<202 μm
1.5 GeV PSM vertical misalignment	<10 μm
1.5 GeV PSM integrated residual dipole field (H)	<1.5 μT m
1.5 GeV PSM integrated residual dipole field (V)	<15 μT m
1.5 GeV horizontal angular acceptance at IP	± 0.2 mrad

Final Thoughts — If we did it all over again

- MAX IV multipole injection scheme had to be shoehorned into layout designed for conventional injection ➔ septum close to downstream end of injection straight
- Much nicer would be to have it all in injection straight ➔ no optics between septum and MIK ➔ inject at slight angle



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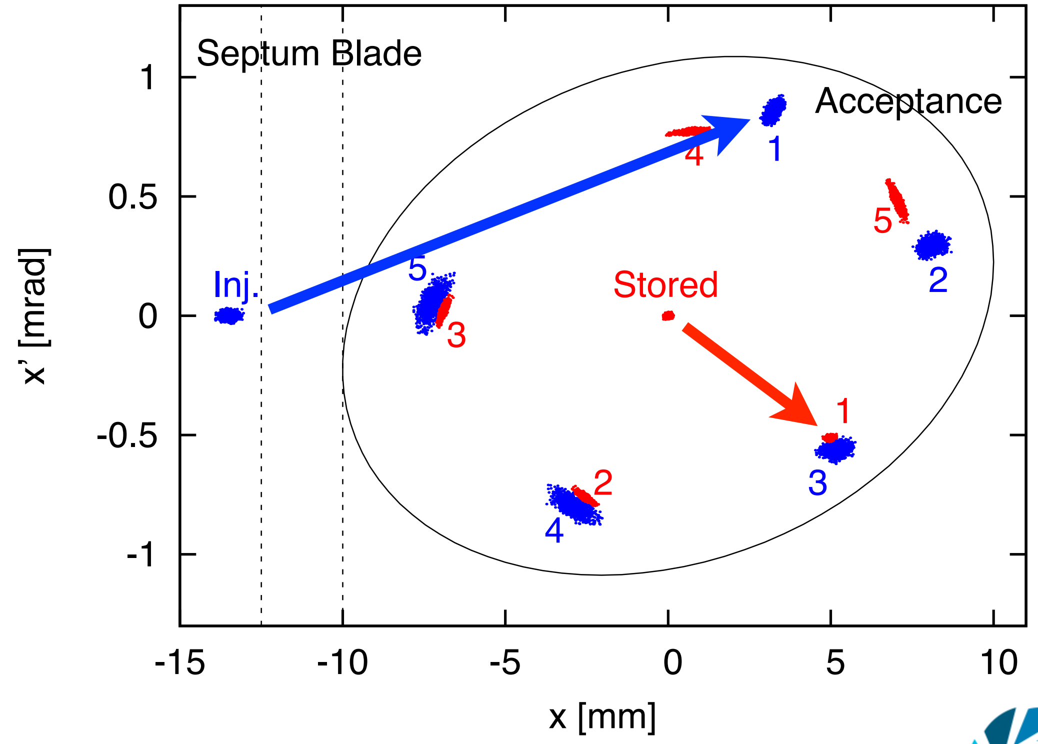
- Exploit 100 MHz RF ➔ top-off with only a single 20-ns dipole kicker
  - **no swap-out** (MAX IV commissioned and operated for users with single dipole kicker)
  - **top off:** sharing dipole kick between injected bunch and one stored bunch renders <0.6% perturbation of stored beam emittance

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



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- Much nicer would be to have it all in one straight → no optics between septum and MIK → inject at slight angle
- Exploit 100 MHz RF → top-off with only a single 20-ns dipole kicker
- Low-emittance injection into large acceptance → very high capture efficiency even when nonlinear kicker cannot be perfectly matched
  - full-energy linac (MAX IV), but expensive if not required for FEL
  - in-tunnel booster (SLS, ALBA) is inexpensive & robust alternative
  - for ALS-U AR we're considering offsetting stored beam through NLK to accommodate for reverse situation (200 nm booster beam into 2 nm AR)

Final Thoughts — If we did it all over again (cont.)

- Would on-axis injection (swap-out) have been a better choice?
  - DA requirements can be substantially relaxed by on-axis injection
  - But recall: low/medium energy rings need large MA to get good Touschek lifetime

$$\tau_{\mathrm{ts}} \sim \gamma^3 \qquad \delta_{\mathrm{rf}} \sim \sqrt{\frac{V_{\mathrm{rf}}}{\gamma}}$$

assuming $V_{\mathrm{rf}} \gg U_{\mathrm{loss}}$

On-axis injection is very intriguing

- relieves storage ring of large DA requirements ➔ push optics to the limit
- storage ring can be tailored exclusively to high-brightness photon production

But requires either

- **strong injector** to enable *extract & dump* (APS-U)
- **accumulator ring** (ALS-U) ➔ can be tailored to injection/accumulation without concern for users (e.g. top off doesn't have to be transparent)

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- MAX IV example (3 GeV ring)
  - 8 cm peak dispersion in achromat → need roughly ±4 mm horizontal DA in injection straight to ensure 4.5% MA
  - Off-axis injection required about ±5 mm horizontal DA → gain only 1 mm

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- Rings with large MA present opportunity for on-axis/off-energy injection ➔ Masamitsu's talk

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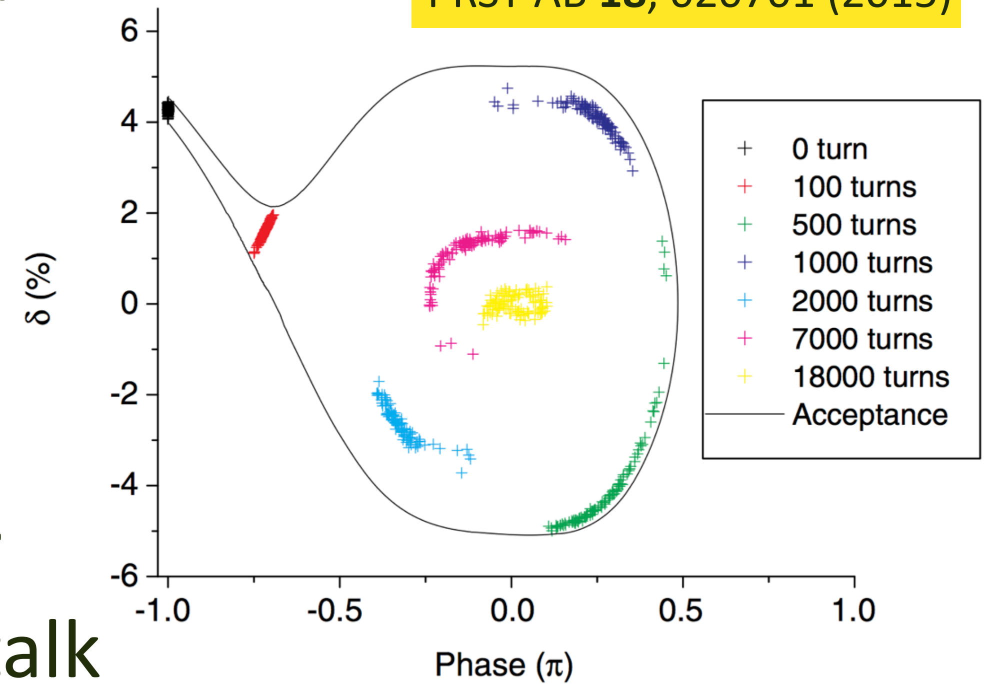

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Thank You!

Questions?

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