Pulsed Multipole Injection in the MAX IV Storage Rings
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 $\varepsilon_n = 10 \text{ mm mrad}$, $\sigma_\delta = 0.1\%$
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)

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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

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PRST-AB 15, 050705 (2012)
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NIM-A 490, 592, 2002
NIM-A 547, 686, 2005
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• 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
Pulsed Sextupole Injection for MAX IV (cont.)

• Strong nonlinearities in MAX IV rings → derive injection scheme from tracking
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PRST-AB 15, 050705 (2012)
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

\[ \Delta x = \Delta y = 100 \, \mu m \]
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!

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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
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)

Simon C. Leemann
Workshop on Diffraction Limited Storage Rings, SLAC, December 9-11, 2013
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 $\approx 11$ mm, but in MAX IV this is at $\approx 5$ 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 $\approx 11$ mm, but in MAX IV this is at $\approx 5$ 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

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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)
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 $\approx x^3$)

• Commissioning new ring with a nonlinear kicker is not trivial
  ➞ use single dipole kicker close to septum for simple & robust injection during early commissioning

• Single dipole kicker can
  – inject on-axis
  – inject off-axis

  – allows for accumulation

• After commissioning will become our horizontal pinger

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NIM-A 693, 117, 2012
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
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
  - $\approx 50$ ns rise time & $\approx 50$ ns fall time
  - $\approx 100$ ns flat-top (doesn’t have to be very “flat”)

$\Rightarrow$ 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 $\approx 9\%$ level