Survey of Injection Schemes for Next-Generation Light Source Rings

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Outline

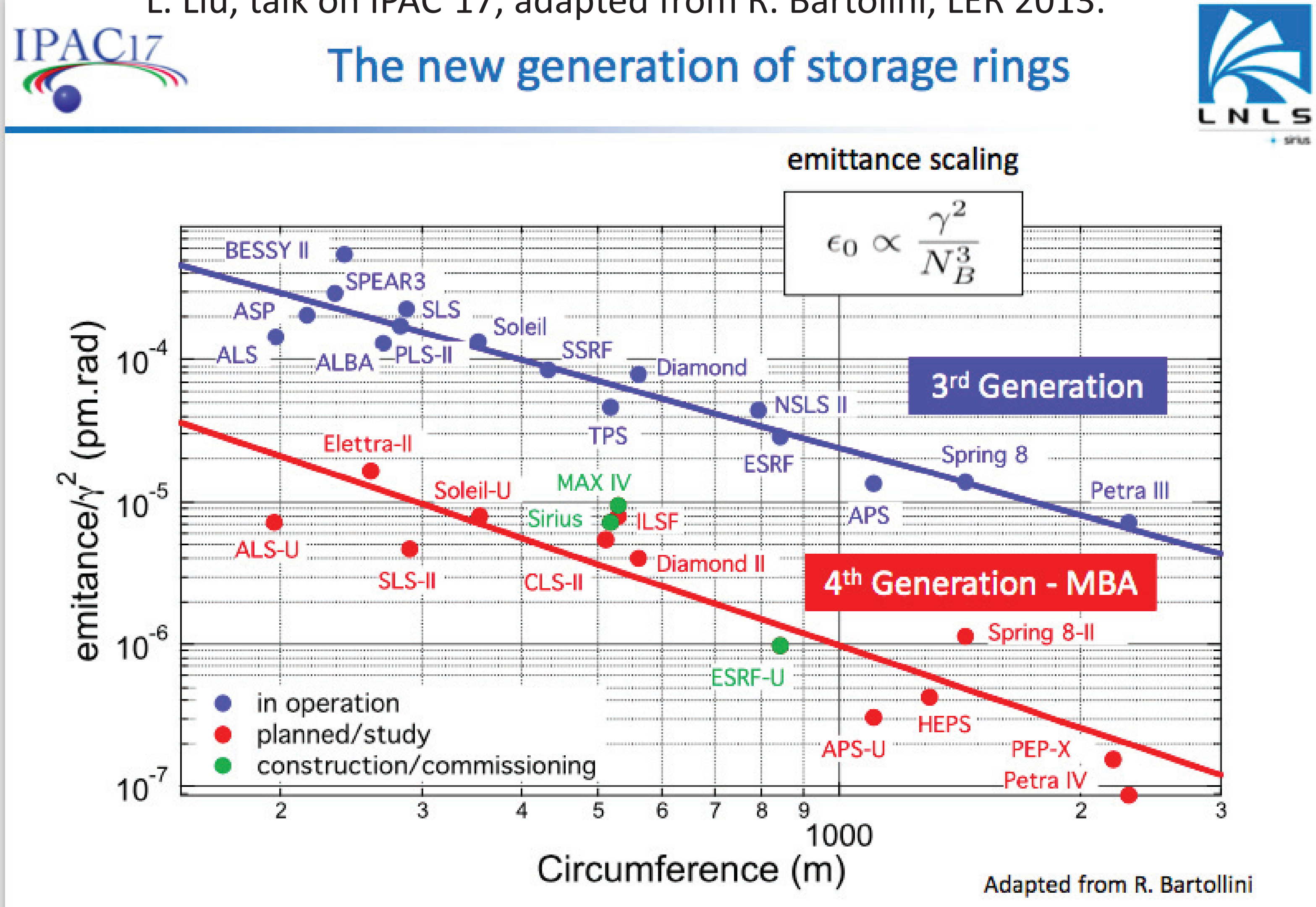
- Motivation
- General introduction of injection schemes
- Injection schemes based on conventional dipole kickers
- Injection schemes based on multipole (nonlinear) kickers
- Injection schemes based on ultra-fast stripline kickers
  - swap-out injection
  - longitudinal injection
- Summary

Motivation

- Why injection is a major design issue for next-generation light source rings?

Next generation light source rings

L. Liu, talk on IPAC'17, adapted from R. Bartolini, LER 2013.

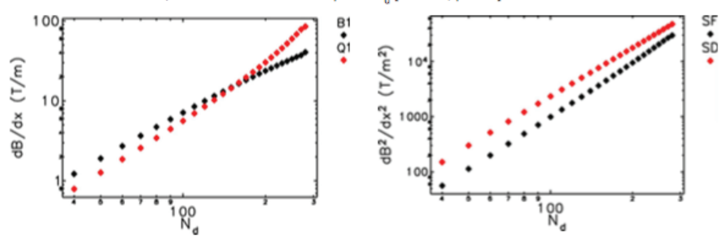


Trend in horizontal acceptance

Nonlinear dynamics M. Borland, talk on NAPAC 2016

- Reduction of the emittance requires stronger, more frequent focusing
  - Quadrupole gradients scale like N_d^2
- This increases the natural chromaticity and reduces dispersion
  - Integrated sextupole strengths scale like N_d^3
- This leads to strong higher-order aberrations
  - Reduced dynamic acceptance, leading to more difficult injection
  - Reduced local momentum acceptance, leading to shorter Touschek lifetime
  - Both lead to shorter gas-scattering lifetime

Scaling of quadrupole (left) and sextupole (right) strength for a model ring composed of TME cells, vs the total number of dipoles N_d [JSR 21, p. 912]



Trend in horizontal acceptance

$$A_x = \frac{DA_x^2}{\beta_x}$$

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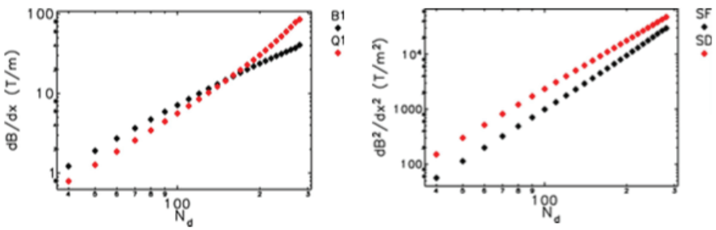

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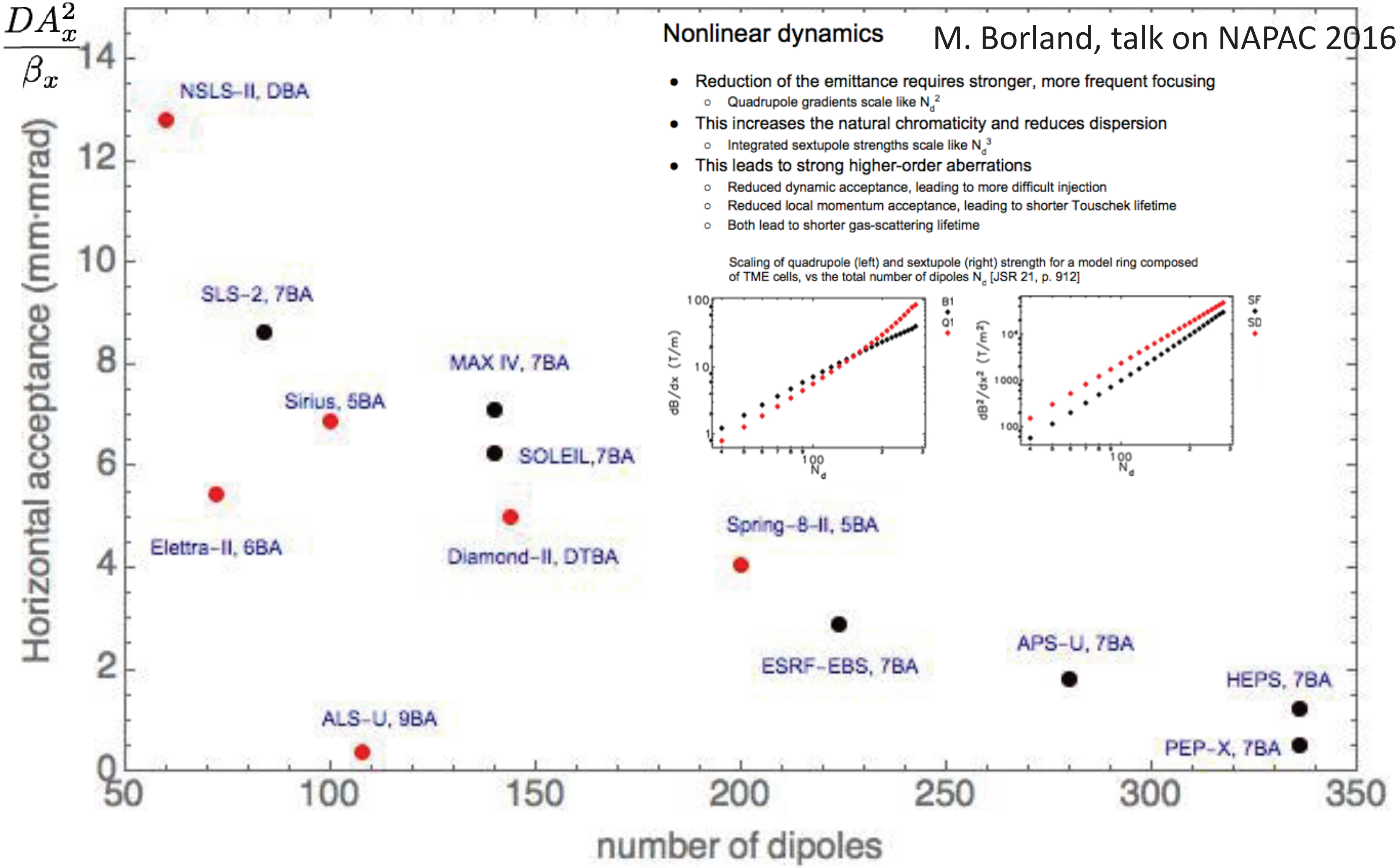

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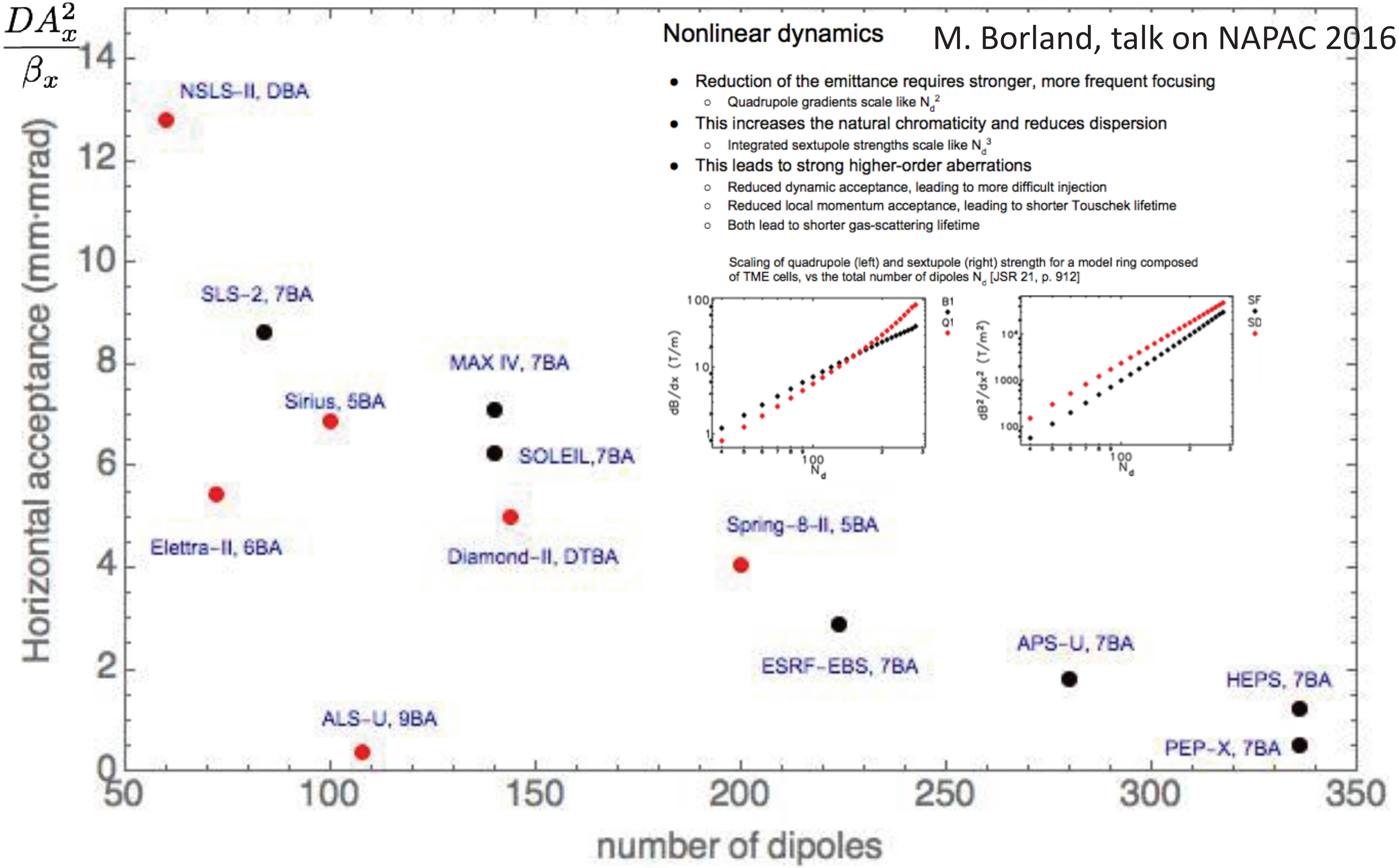
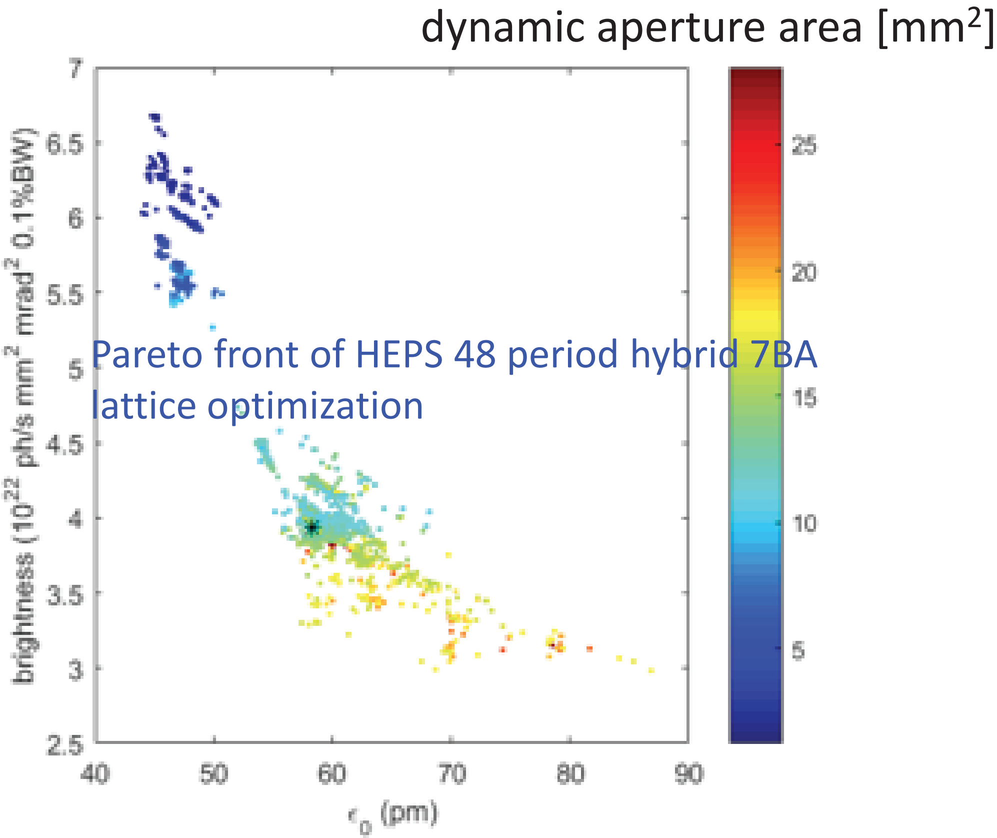
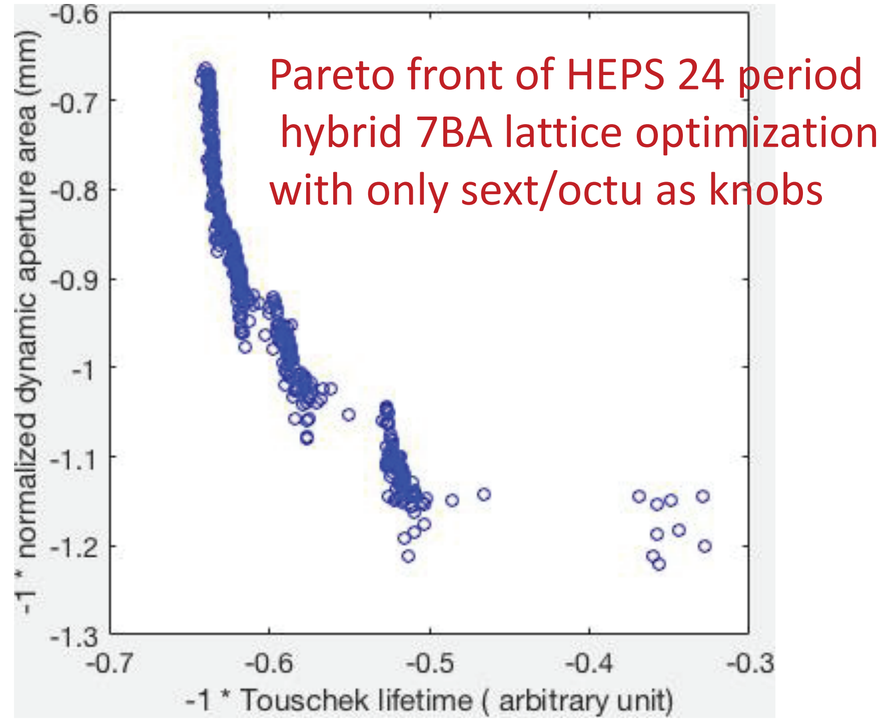


The DA of NSLS-II & MAX IV are measurement results, others are tracking results with errors.

Compromises in lattice optimization

Courtesy of Yi Jiao, IHEP





Generally, there is a compromise between brightness (emittance, matching of electron/photon phase space), dynamic aperture and Touschek lifetime in the lattice optimization.

Why injection is a major design issue?

Why injection is a major design issue?

- Greater challenges in lattice design to obtain a large dynamic aperture to accommodate conventional injection schemes.
- Some new injection schemes have been developed in recent years, in different stages of R&D and/or beam tests.
- As will be shown later, different injection schemes have different requirements on dynamic aperture.
- Choice among conventional schemes and new schemes affects the overall design of the light source.
- Each MBA-based ring design needs to find a balance between a high brightness, large enough DA for the chosen injection scheme, and a reasonable beam lifetime.

General introduction

Aspects of an injected scheme for an electron storage ring

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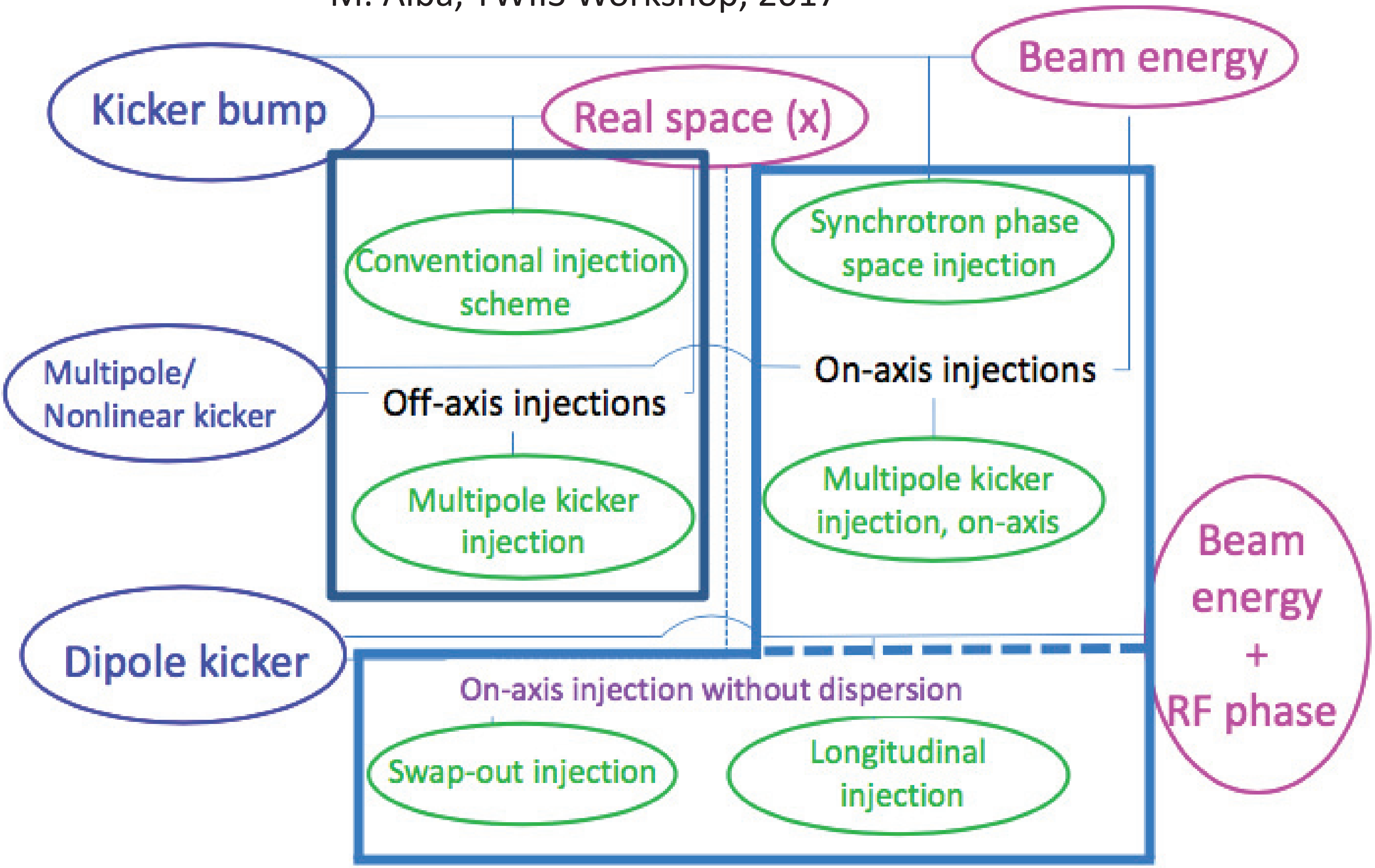
- Separation in 6D phase space between injected & stored bunch?
  - Phase space separation enables "accumulation" with the help of radiation damping, both injected and stored bunches must be contained in the ring acceptance.
  - No phase space separation leads to "swap-out" of stored bunch by fresh injected bunch, only injected bunch needs to be contained in the ring acceptance, relaxed requirement on DA.
  - "Off-axis" vs "On-axis"
    - "On-axis" means there is no transverse separation, leading to relaxed requirement on on-momentum DA.

Aspects of an injected scheme for an electron storage ring

- Pulsed kicker (low field, fast rise/fall time)
  - Bring injected beam into the ring acceptance and within septum blade in following turns by either or both
    - moving the local orbit bump towards the injected beam
    - deflecting injected beam towards stored beam
- Septum
  - Bring injected beam as close as possible to reference orbit
  - Trick: separate vacuum chamber with field region and field free region, **septum thickness**

Zoo of injection schemes

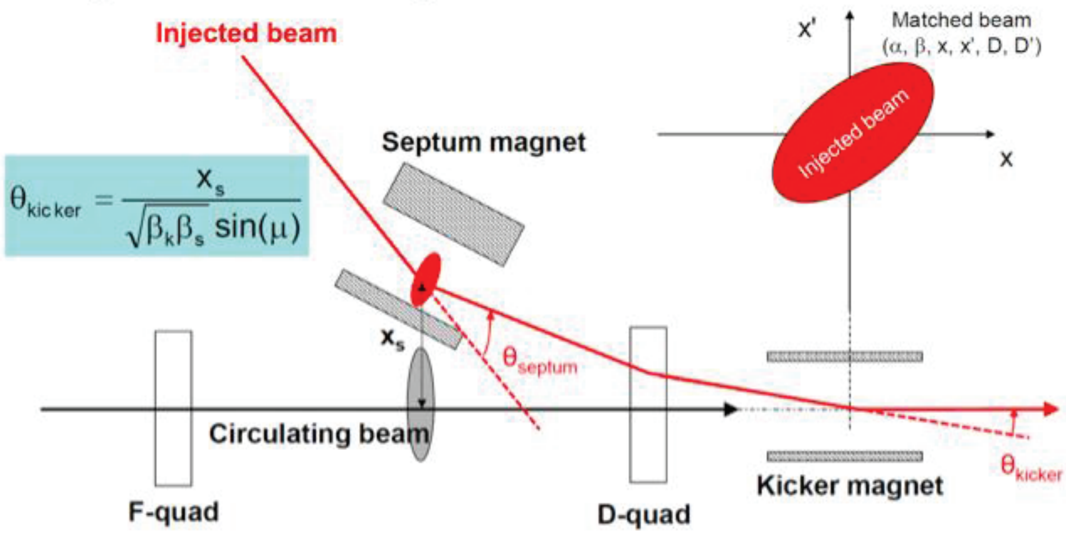
M. Aiba, TWIIS Workshop, 2017



Injection schemes based on conventional dipole kickers

a stored bunch train or all stored bunches are perturbed during injection.

Injection with a single dipole kicker



S. C. Leemann, NIM A 693 (2012) 117.

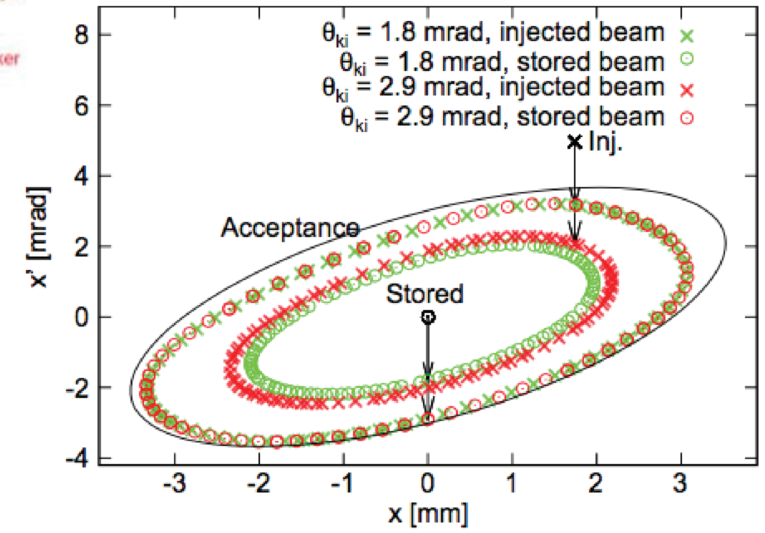
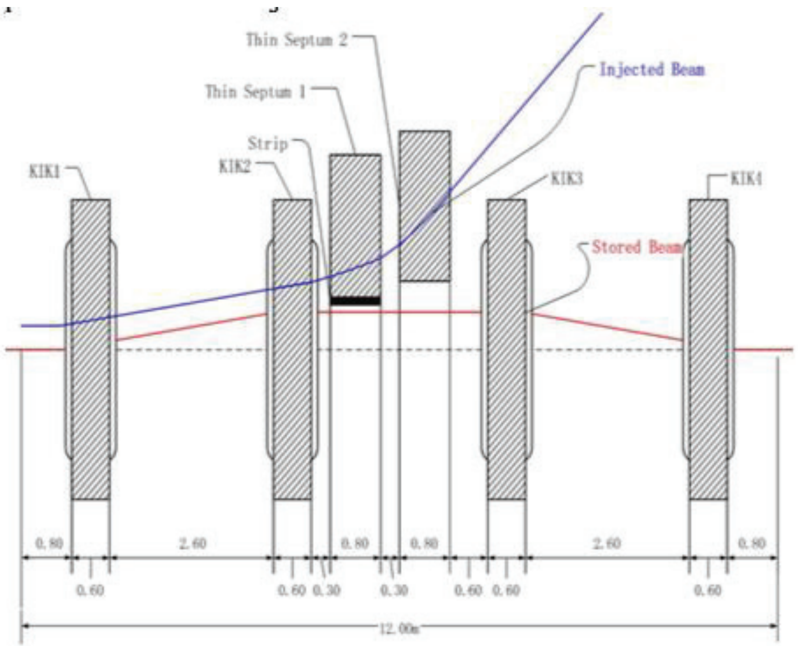


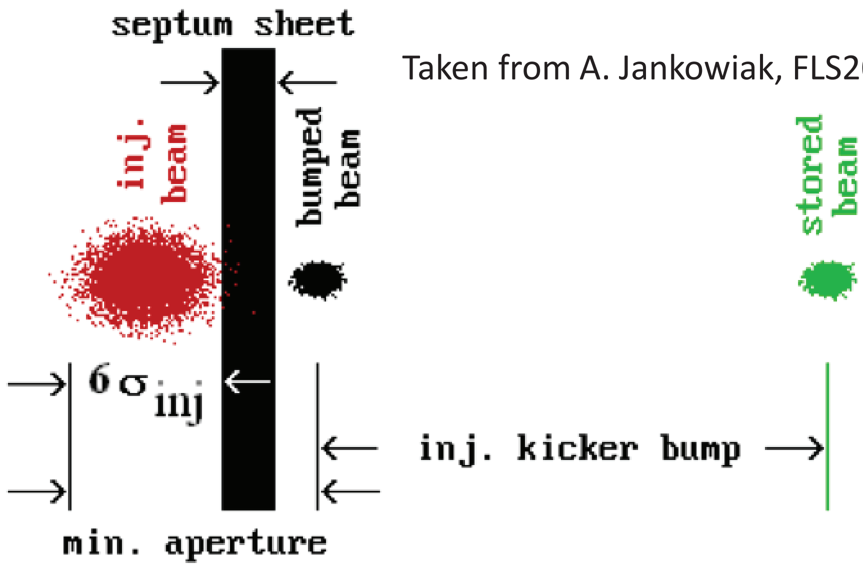
Fig. 6. Injection with the dipole kicker into the MAX IV 3 GeV storage ring. The plot shows the minimum kick required to inject into the acceptance as well as the maximum kick that can be applied without ejecting stored beam particles out of the acceptance.

- For on-axis injection, commonly used in boosters and can be used in initial commissioning of storage rings.
- In off-axis injection, the ring acceptance is shared by injected & stored bunch to allow accumulation. Top-up operation at MAX IV, though quite large perturbation to user experiments. Being replaced by MKI.

Pulsed-bump injection



SSRF injection region, H. H. Li, et al. EPAC'08, wepc041



Taken from A. Jankowiak, FLS2012

- Widely used in existing electron storage rings
- 4, 3 or 2 kickers to set up a pulsed local bump lasting ~ revolution period
- most MBA designs still keeps this as baseline/optional injection scheme

✓ Dynamic aperture must accommodate:

- injected beam size (~ $6\sigma_{inj}$)
- stored beam size (~$5\sigma_{sto}$)
- Distance between the two beams for septum blade and margin (typically larger than 2 ~ 3 mm)

Application in MBA-based rings

Application in MBA-based rings

- Dedicated high-beta straight section for improved DA and acceptance.
  - Concern: symmetry breaking & smaller LMA and lifetime, ESRF-EBS, PEP-X (5 m -> 200 m)
  - Tradeoff: keeping lattice symmetry with interleaved high-beta & low beta straight sections sacrificing brightness in a fraction of IDs, Sirius.
- Lower injected beam emittance
  - linac injector promises ~ 1 nm rms injected beam emittance, MAX IV, Spring-8 II
  - extraction at off-energy from existing booster: ESRF-EBS (95->60 nm), APS-U
  - emittance exchange in booster/transport line, *P. Kuske, IPAC'16*
- Better phase space matching within ring acceptance
  - Unequal beta-functions of transport line & ring at IP (A. Streun, SLS-TME-TA-2002-0193).
  - Phase space shaping with sextupole in transport line (S. White, IPAC 16, THPMR016)
- Reduction of septum blade
  - the "anti-septum" scheme

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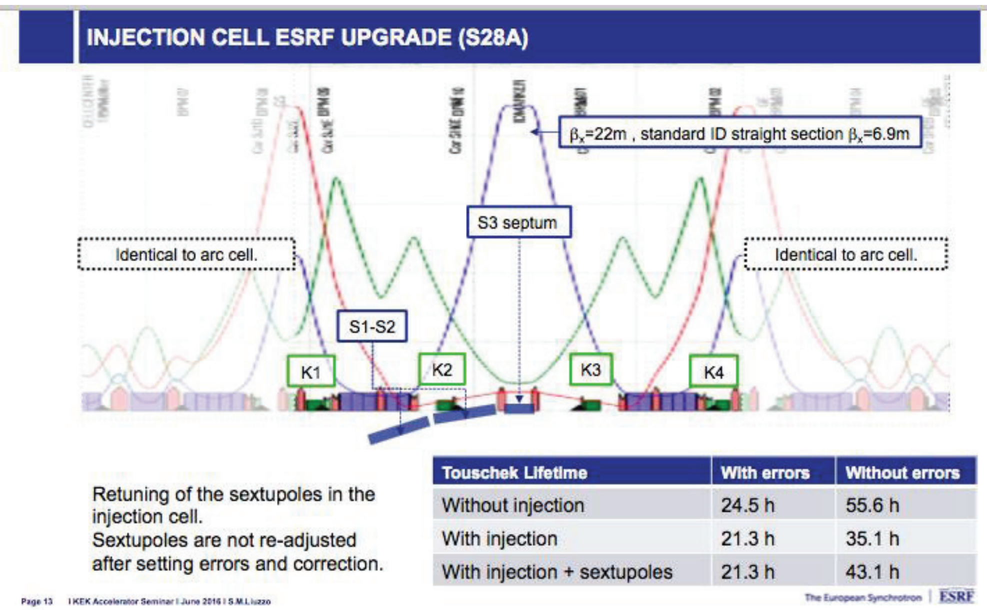

Touschek Lifetime	With errors	Without errors
Without injection	24.5 h	55.6 h
With injection	21.3 h	35.1 h
With injection + sextupoles	21.3 h	43.1 h

nterleaved high-beta & low beta straight sections
Sirius.

ed beam emittance, MAX IV, Spring-8 II

oster: ESRF-EBS (95->60 nm), APS-U

: line, *P. Kuske, IPAC'16*

ring acceptance

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  - the "anti-septum" scheme

The "anti-septum" scheme

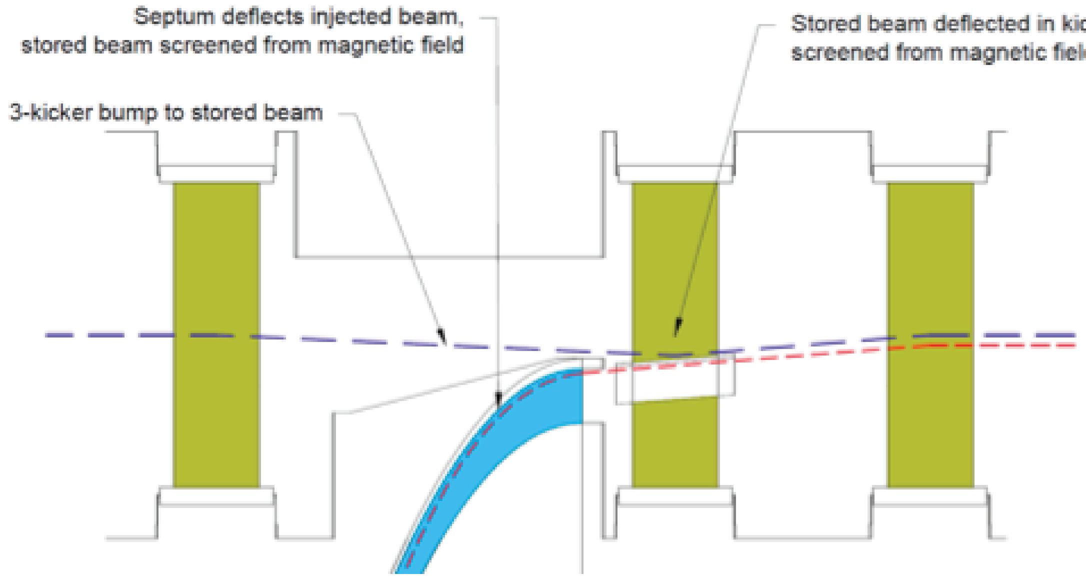
C. Gough, TWIIS Workshop, 2017

Description of Antiseptum Scheme

A conventional injection scheme is based on a septum to deflect the injected bunch with a fast pulsed bump using kickers to bring the stored beam close to the septum wall.

With the novel "antiseptum" improvement, the bump kickers are fitted with a metal eddy current conductor which screens the injected bunch from deflection without changing the stored beam bump behaviour. This metal screen then forms the final septum, but inverted in function of the conventional approach, hence the name "anti-septum". The approach does not remove the need for the main septum magnet, but for modest cost it permits the injected bunch to be brought closer to the stored beam.

1 mm anti-septum !!



Variants of kicker-bump scheme

P. Collier, PAC95, 551

M. Borland, APSU Forum, 2015.03

Variants of kicker-bump scheme

- synchrotron injection
  - large dispersion (~ 17 cm) required, not compatible with ultra-low emittance MBA lattice design

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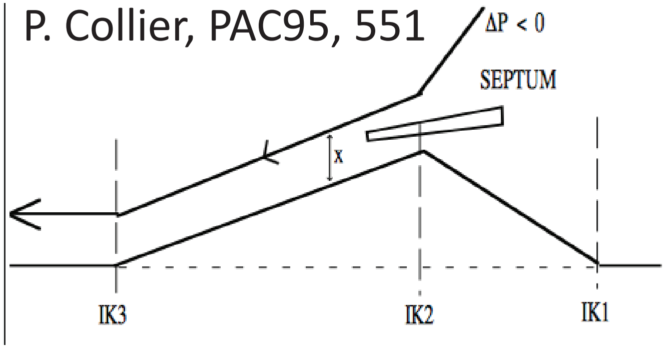

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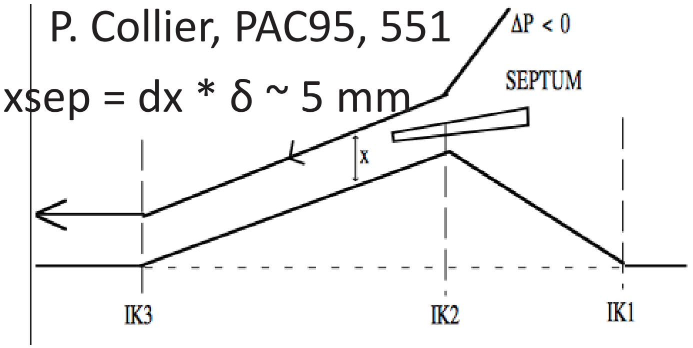

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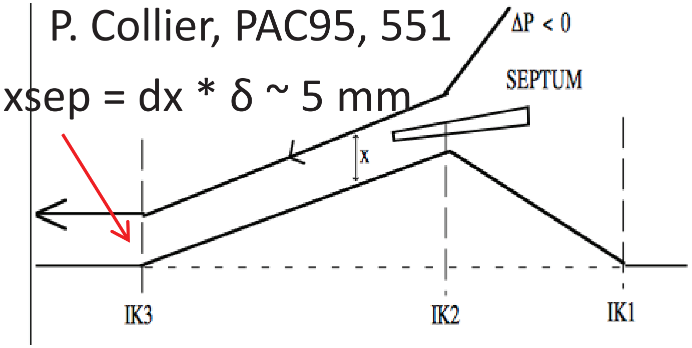
xsep = dx * δ ~ 5 mm



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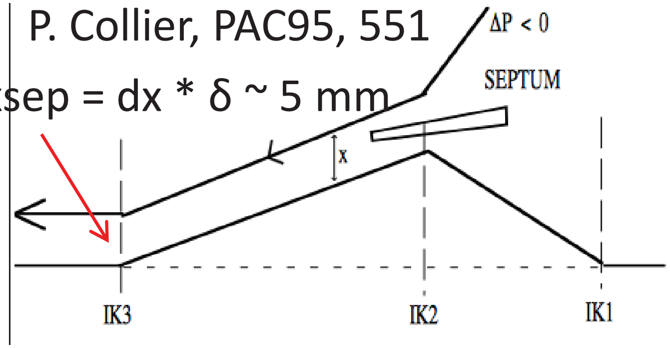

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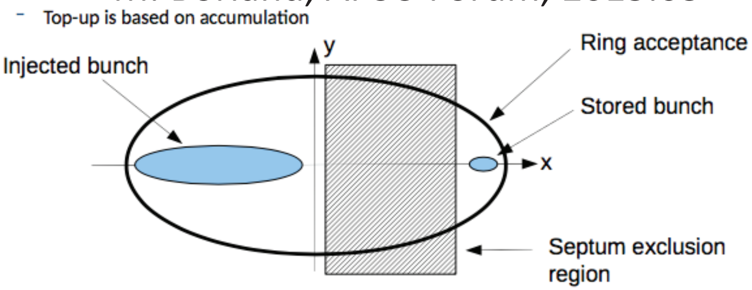

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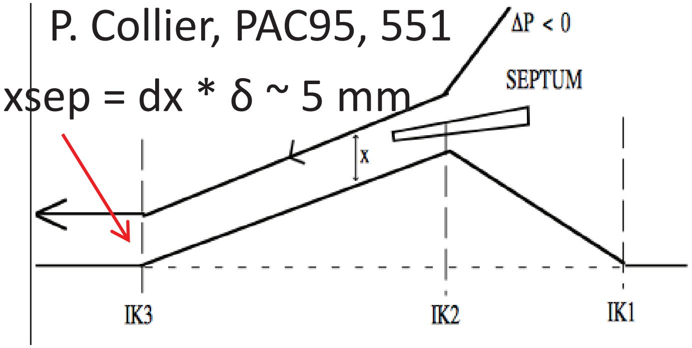

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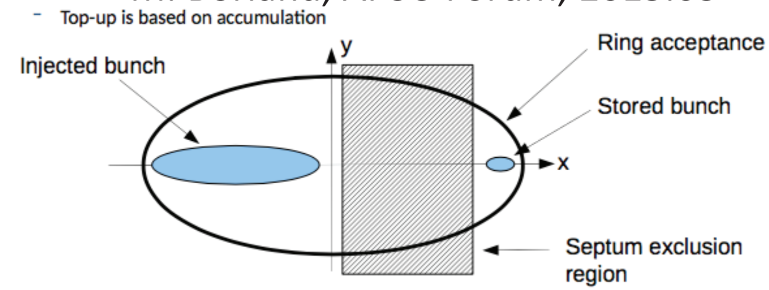

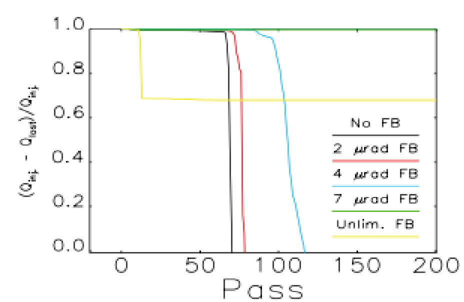

Figure 2: Injection losses as a function of pass for various maximum feedback strength limits during accumulation.

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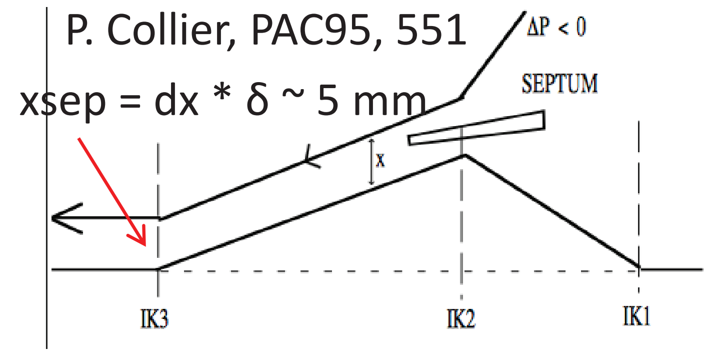
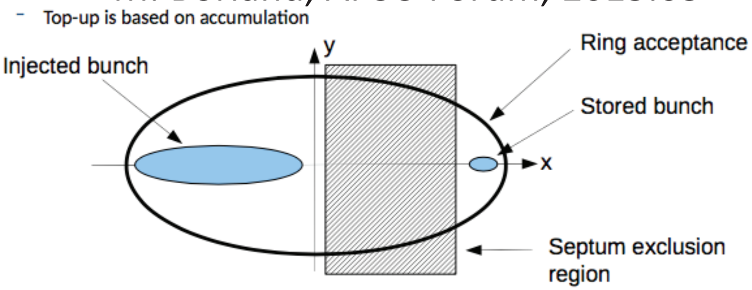


- Non-closure kicker bump injection -> DA shared between injected and stored bunches
  - APS-U alternative lattice design for off-axis injection scheme: Y. Sun et al, IPAC15, TUPJE071
  - concern: beam instability at injection for high bunch charge in the presence of small horizontal physical aperture: R.Lindberg, NAPAC2016, WEPOB08

M. Borland, APSU Forum, 2015.03



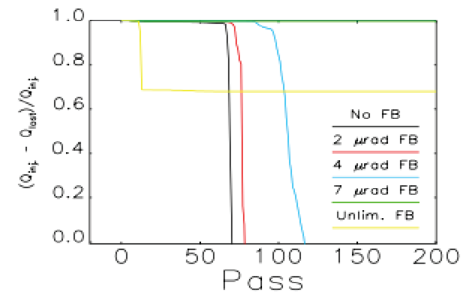


Figure 2: Injection losses as a function of pass for various maximum feedback strength limits during accumulation.

Common issue: injection transients

- Causes:
  - non-linearity of sextupoles between bump magnets
  - non-similarity of 4-kicker shape
  - leakage field of septum
  - bump magnet tilt
  - etc
- Many years of efforts in different facilities, perturbation on stored bunch centroid is still way above 10% beam size. Though users don't necessarily complain and use gating signal.
- In MBA-based light sources, the horizontal beam size becomes much smaller, though vertical beam size is of similar order. Users might be more sensitive to the injection transients.

Injection schemes based on multipole/nonlinear kickers

Pulsed multipole(nonlinear) kicker injection

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 123501 (2007)

New injection scheme using a pulsed quadrupole magnet in electron storage rings

Kentaro Harada,* Yukinori Kobayashi, Tsukasa Miyajima, and Shinya Nagahashi
Photon Factory, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
(Received 30 July 2007; published 21 December 2007)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 020705 (2010)

Beam injection with a pulsed sextupole magnet in an electron storage ring

Hiroyuki Takaki and Norio Nakamura
Institute for Solid State Physics, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581. Japan
Yukinori Kobayashi, Kentaro Harada, Tsukasa Miyajima, Akira Ueda, Shinya Nagahashi, Miho
Takashi Obina, and Tohru Honda
Photon Factory, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801
(Received 8 February 2009; published 24 February 2010)

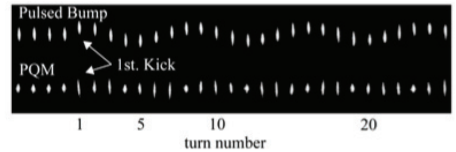
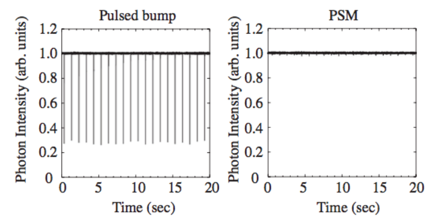


FIG. 4. Turn-by-turn stored beam profiles in pulsed bump injection (upper figure) and PQM injection (lower figure) monitored by a fast gated camera at the PF-AR. The horizontal axis represents a turn number and the vertical axis represents a horizontal direction.



. Stability of photon intensity at BL-14A in the pulsed bump injection (left graph) and the PSM injection (right graph). The
in appeared at exactly 1 Hz in both graphs, synchronized with the beam injection. The sampling rate of the signals was 10 kHz.

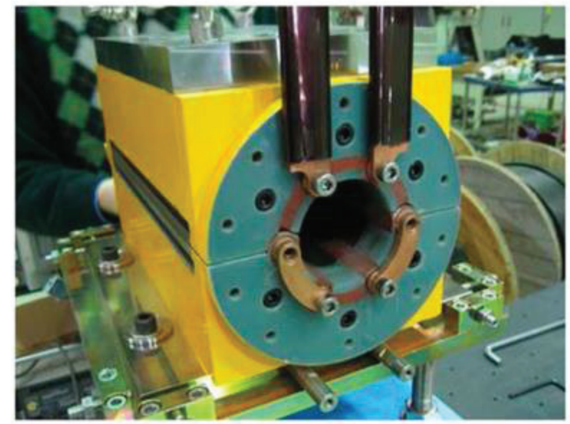
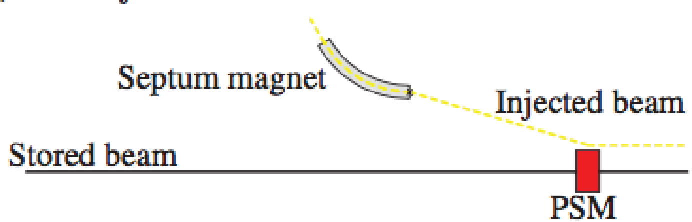


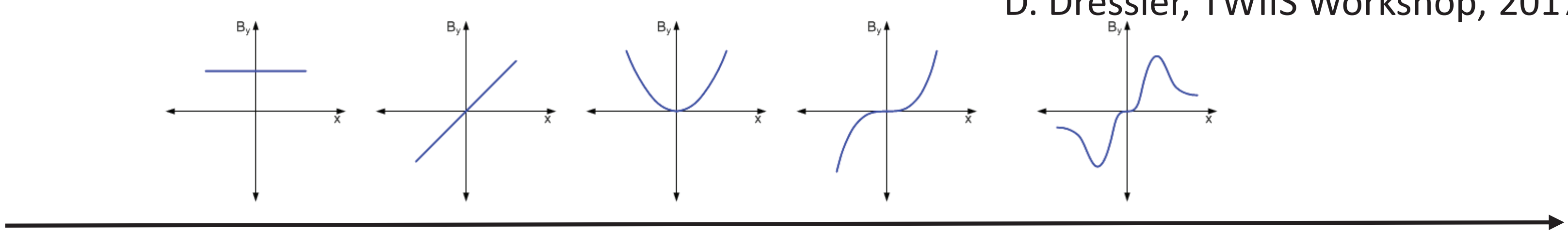
FIG. 13. (Color) Front view of the PSM. The glass epoxy board (green) and the epoxy resin (brown) are used for insulation.

(b) PSM injeciton



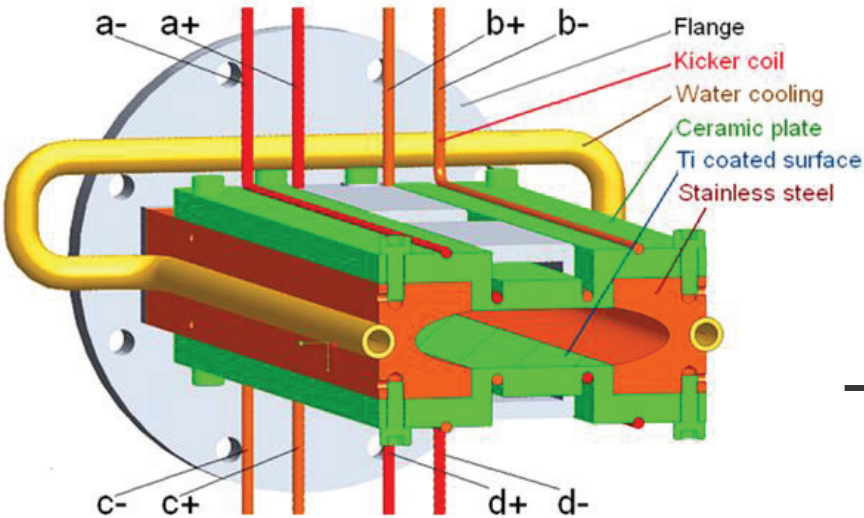
magnetic field distribution of injection kickers:

D. Dressler, TWIIS Workshop, 2017

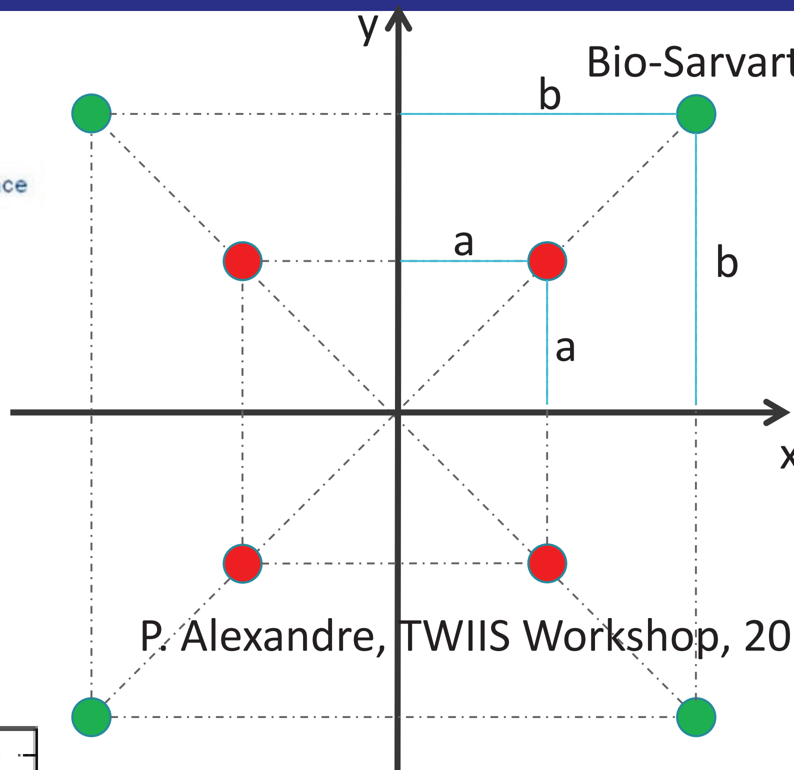


- reduced kick on stored beam, more transparent injection

BESSY-II design and variant for MAX IV & SOLEIL

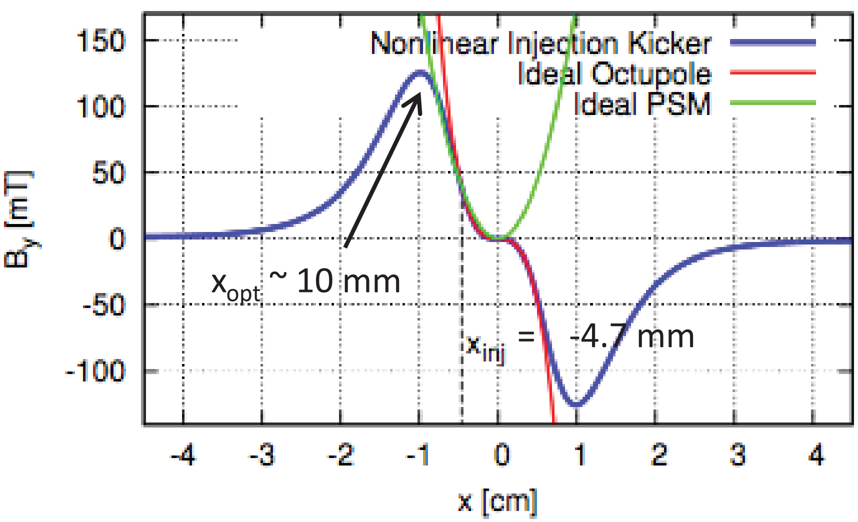


T. Atkinson et al., IPAC 2011, THPO024.



P. Alexandre, TWIIS Workshop, 2017

S. Leemann, PAC2013, WEPSM05



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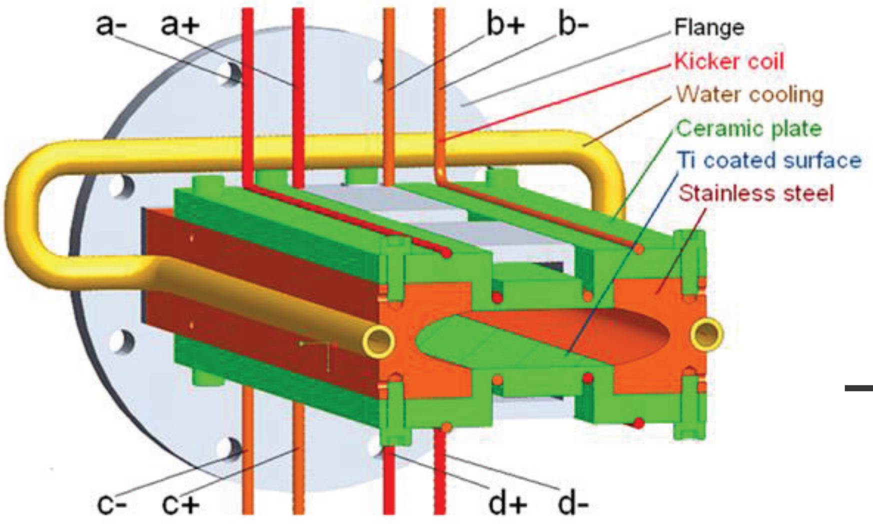

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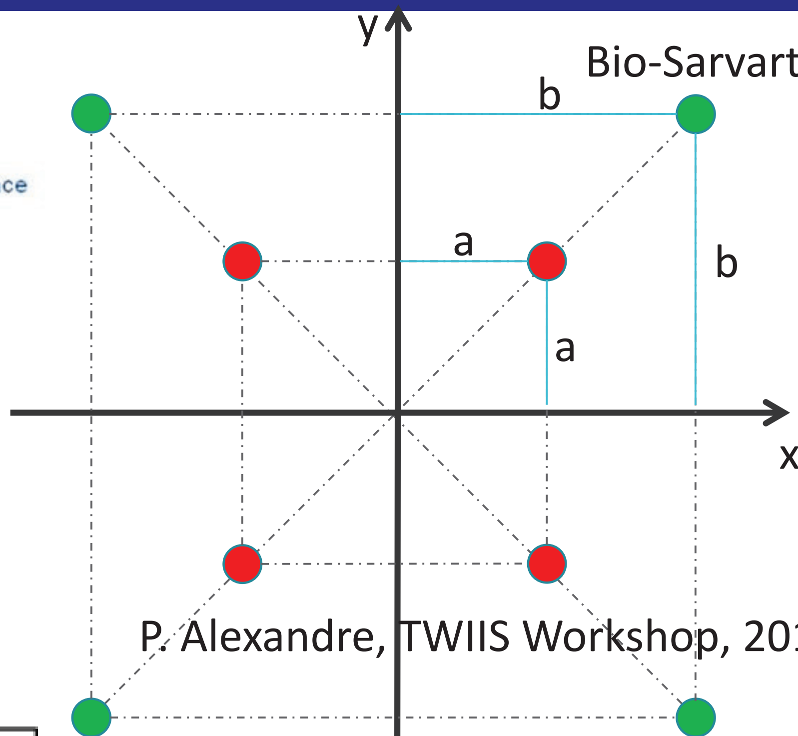
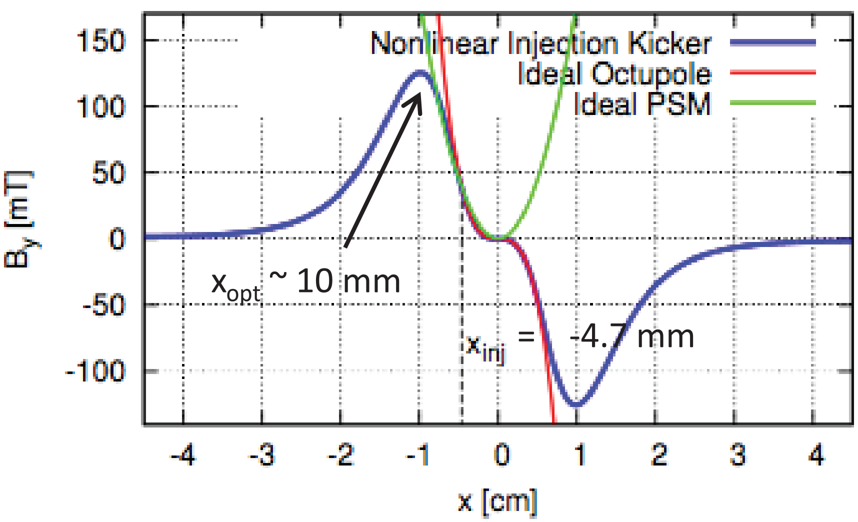


P. Alexandre, TWIIS Workshop, 2017

S. Leemann, PAC2013, WEPSM05

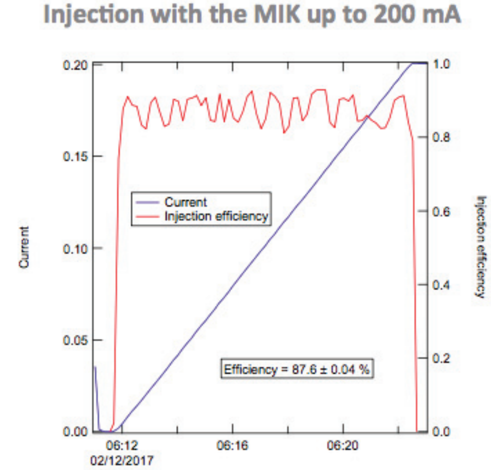


a (mm)	b (mm)	Peak current	Issue
7	10	6.8 kA	Acceptable
8	10	14 kA	Conductors to close to each other
10	13	30.1 kA	Current too high (τ_{pulse} = 3.5 μs)
7	13	5.3 kA	Inductance too high (τ_{pulse} = 3.5 μs)

Recent progress and some comments

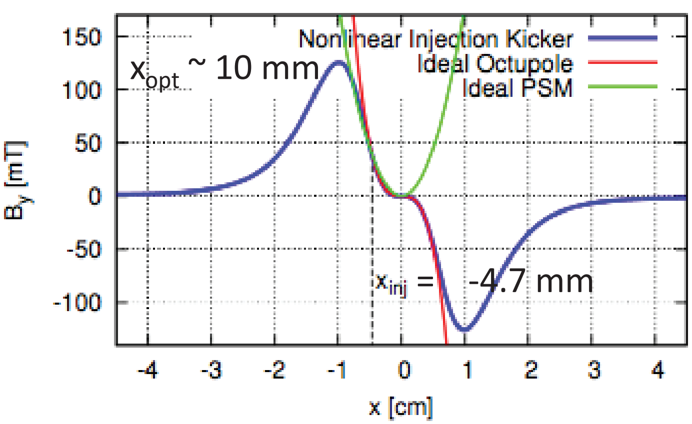
- Recent results from MIK commissioning at MAX IV:
  - Successfully demonstrated high efficiency injection up to 200 mA.
  - Perturbation to the stored beam reduced by a factor~60.
    - H: 27 μm, V: 16 μm, half of peak-to-peak amplitude.

P. F. Tavares, Phangs Workshop, 2017. 12.



S. Leemann, PAC2013, WEPSM05

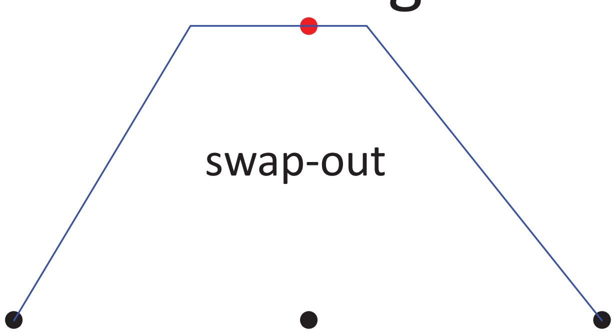
- Comments:
  - With the cumulated experiences of successful operation of MIK, more MBA rings are likely to consider this scheme as a replace of kicker-bump scheme to pursue more transparent injection.
  - Numerical optimization is essential to evaluate the design performance in terms of injection efficiency. P. Kuske LER'18.
  - Concern for a smaller DA & larger injected beam emittance:
    - to reduce x_{opt} from ~ 10 mm to ~ 5 mm , requires more aggressive design: smaller vertical physical aperture ~ 2 mm for stored beam, thinner rods and smaller separation between conductors.
    - otherwise, the injected beam samples the nonlinear kick, and the strong lattice nonlinearity would make it challenging to achieve a high injection efficiency.

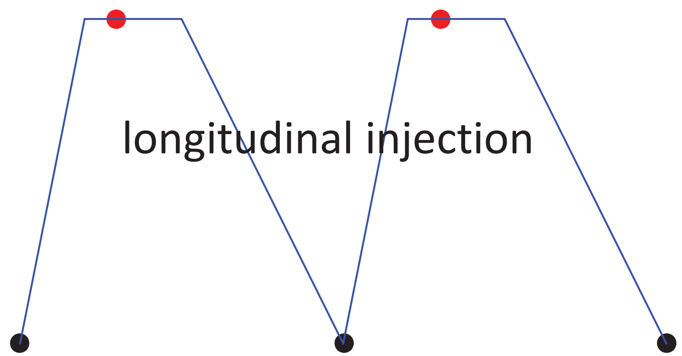


Injection schemes based on ultra-fast stripline kickers

Only 1~3 stored bunch is perturbed.

- Swap-out
- Longitudinal accumulation





Swap-out injection (ALS-U, APS-U, HEPS)

ALS-U bunch train swap-out

C. Steier, IPAC 2017, WEPAB103

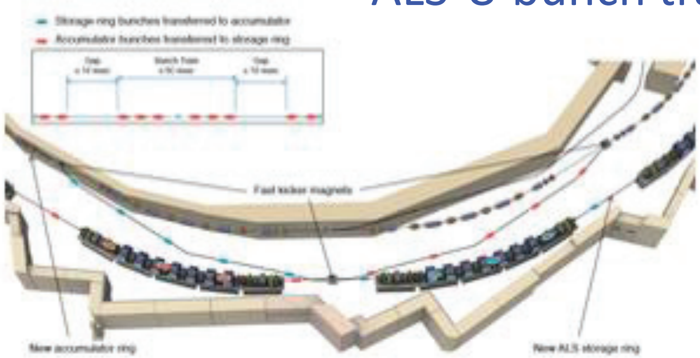


Figure 2: Illustration of the planned swap-out process between the full energy accumulator and the storage ring of ALS-U.

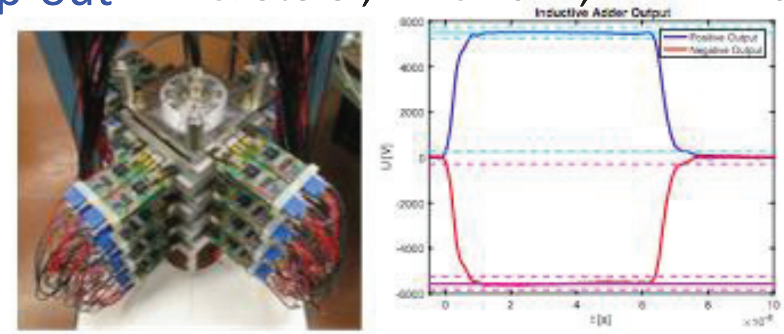
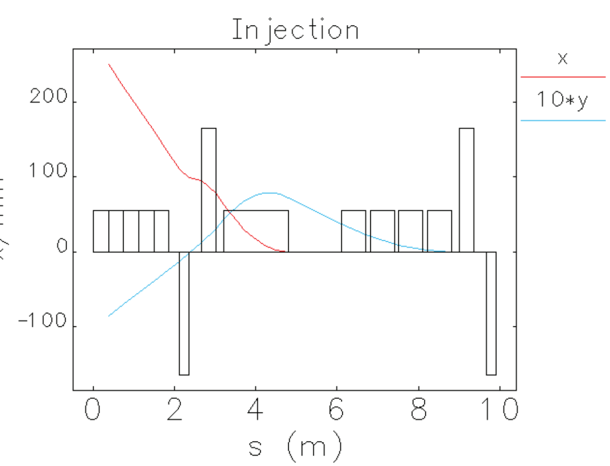
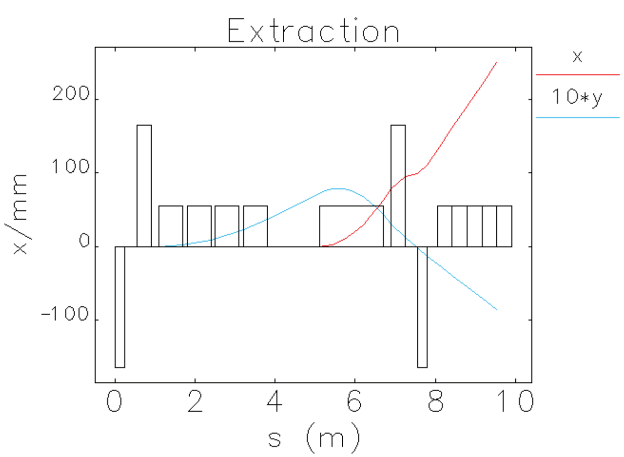
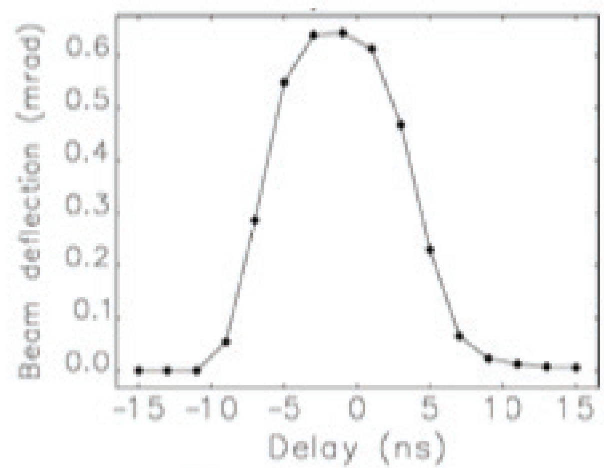


Figure 3: (Left) Full assembly (8 stages) of inductive adder. (Right) Voltage output of inductive adder at 105% of nominal setpoint.

APS-U / HEPS single bunch swap-out







M. Borland et al., NAPAC16

Pros of swap-out schemes

- Allow a much smaller dynamic aperture compared to off-axis injection
- Promise a better photon brightness and transverse coherence.
- Compatible with round beam enabled by sitting near linear coupling resonance
- Compatible with horizontal-gap IDs.

Challenges in swap-out scheme

- ultra-fast injection kicker being test at ALS-U & APS-U, to be tested at BEPCII for HEPS
- Full charge injector
  - a full energy accumulator ring ??
    - affordable for ALS-U
    - might be expensive for APS-U/HEPS
  - APS-U: PAR + acceleration in booster + beam dump in SR
  - HEPS: booster also as an accumulator ring at 6 GeV, extra transport line from ring to the booster.

Still a lot of work to do for both APS-U / HEPS to meet the challenges of ~ 15 nC single bunch in timing mode.

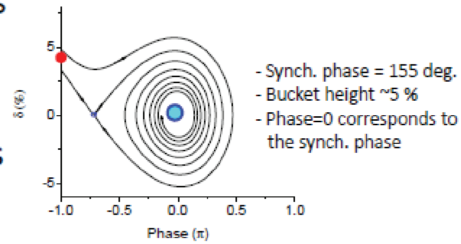
Longitudinal injection into the "golf club"

PAUL SCHERRER INSTITUT PSI

Longitudinal Acceptance (2)

- "Golf-club" acceptance
  - Well known for the cases with acceleration*
  - Because of energy dependent radiation loss in electron storage rings

Long. acceptance plot with synchrotron radiation loss



It allows an injection between two circulating bunches at the expense of slightly higher injection energy!
(Need to match the injection orbit to the off-momentum closed-orbit)

* e.g., P. M. Lapostolle, Los Alamos National Laboratory, LA-11601-MS (1989)

IPAC'14, Dresden, Germany, 18.06.2014 Masamitsu Aiba, PSI

When applied to the case of HEPS

- Much smaller αc leads to more stringent requirements on MA.
- Or more stringent requirements on kicker pulse fall time

Challenging!

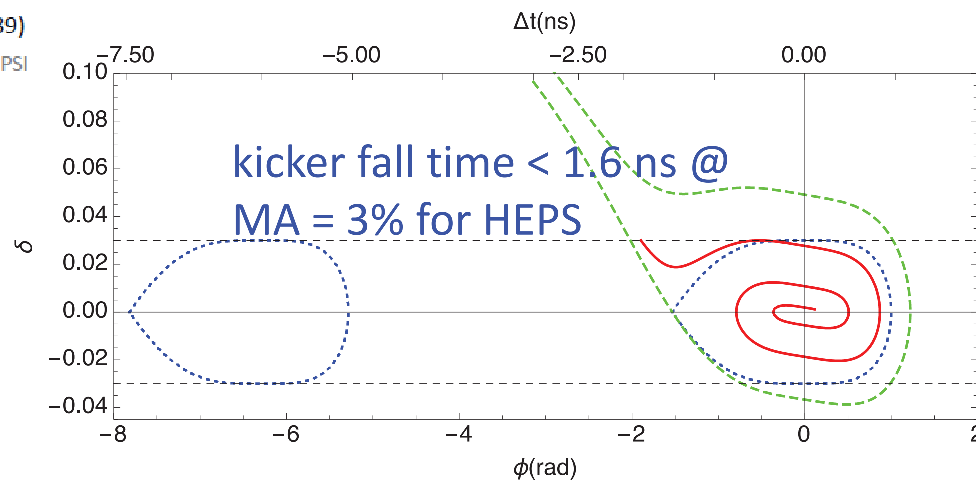
Aiba,et al, PRSTAB, 18, 020701, 2015.

Pros:

✓ No extra hardware complexities.

Cons:

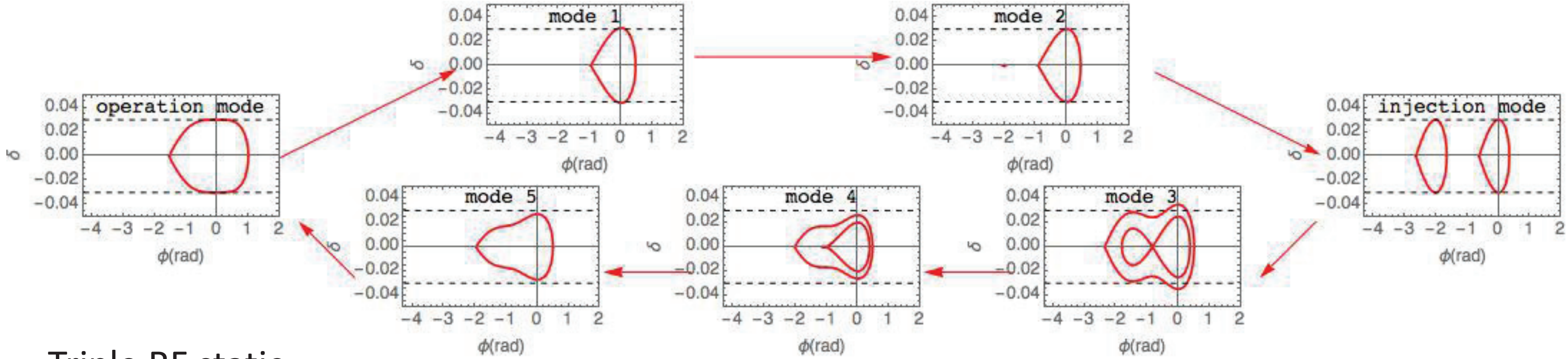
✓ Stringent energy/phase tolerance



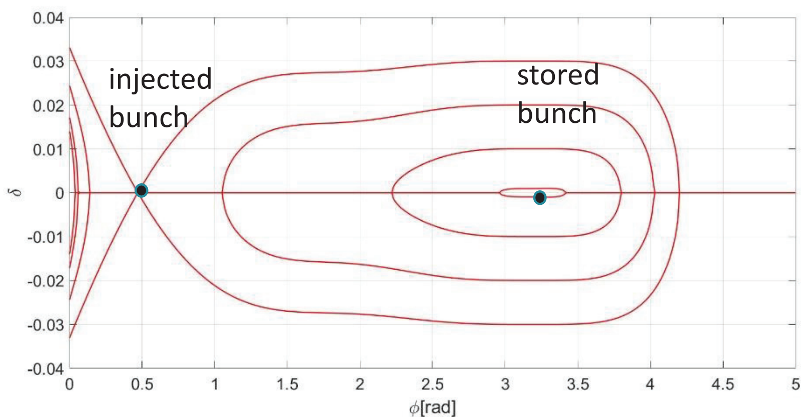
Alternative longitudinal injection schemes

Double-RF gymnastics

Z. Duan, TWIIS Workshop



Triple RF static

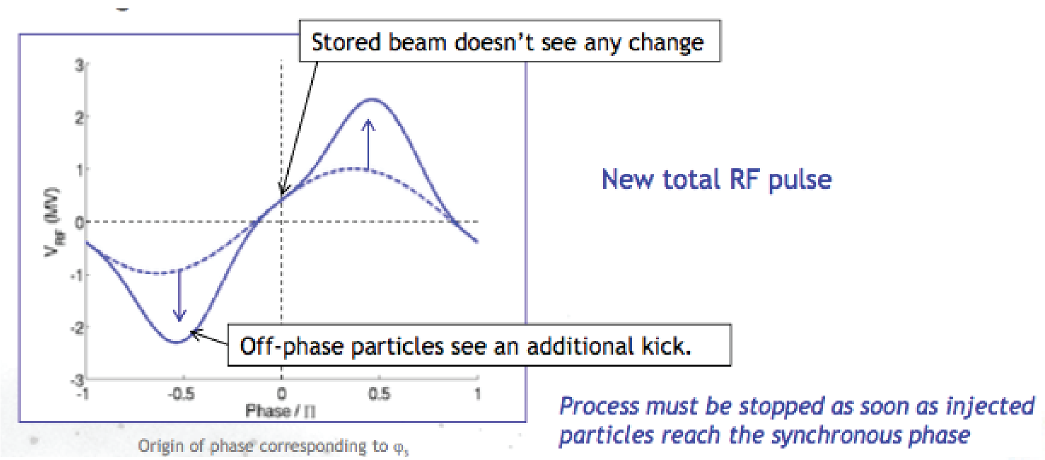


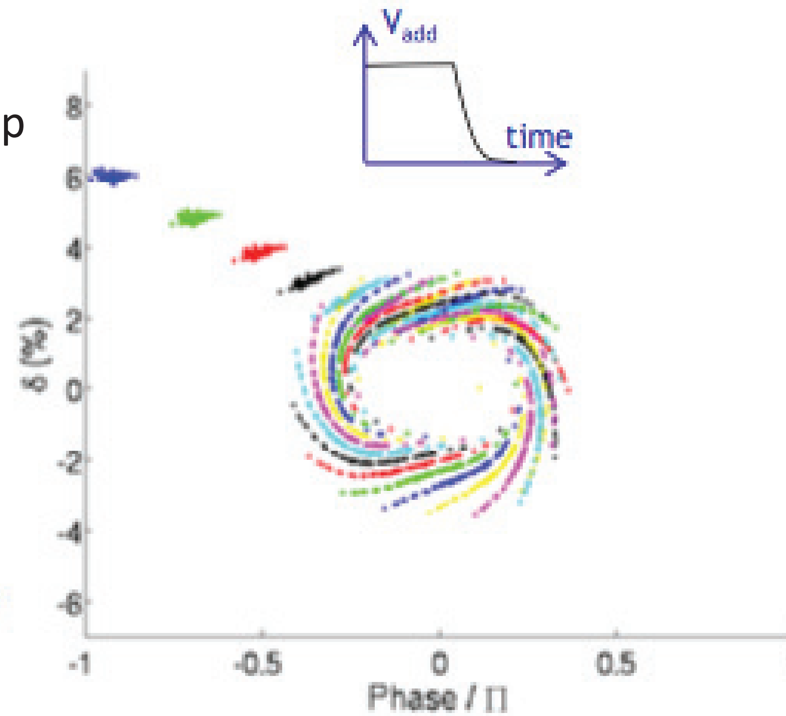
G. Xu, TWIIS Workshop

NLKs as a replacement for ultra-fast stripline kicker

- longitudinal injections favor a lower frequency RF system, which is not always available, resulting very challenging fast stripline kicker specifications
- A very interesting idea is to use a transverse NLK + fast ramping RF pulse (as a "longitudinal NLK") to replace the fast stripline kicker, as proposed by experts in SOLEIL.

M-A. Tordeux, TWIIS Workshop





Comments on longitudinal injection schemes

- Fresh and exciting ideas, some based on ultra-fast kicker, even more challenging than swap-out.
- Requires enough off-momentum DA, and small longitudinal injected beam size is favored.
- Some schemes involves complicated RF manipulation and requires more serious R&D efforts.

Summary

Top-up injection for next-generation rings

- High injection efficiency
  - Large ring acceptance, small injection beam emittance and thin septum blade are favored.
  - Good control and knobs versus injection system errors.
- Transparency
  - Small perturbation on stored beam (MKI), and / or
  - only a small fraction of stored bunches is perturbed (swap-out, longitudinal injection)
- Reliability and robustness
  - Conventional and well-established kicker/septum technology versus new injection hardware designs (MIK, stripline ultra-fast kicker with ns-scale rise/fall time, anti-septum, etc)
  - Extensive R&D and **beam test** is essential for new hardware

Acknowledgement

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- I'd like to thank P. Kuske, M. Borland, Y. Jiao and G. Xu for helpful discussions.
- I'd like to thank the strong support from colleagues of the HEPS team.

Thank you for your attention!