Review of multiple injection kicker designs

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Overview

Motivations to use nonlinear kicker for Top-Up injection.

Concepts of nonlinear kicker **across space & time.**

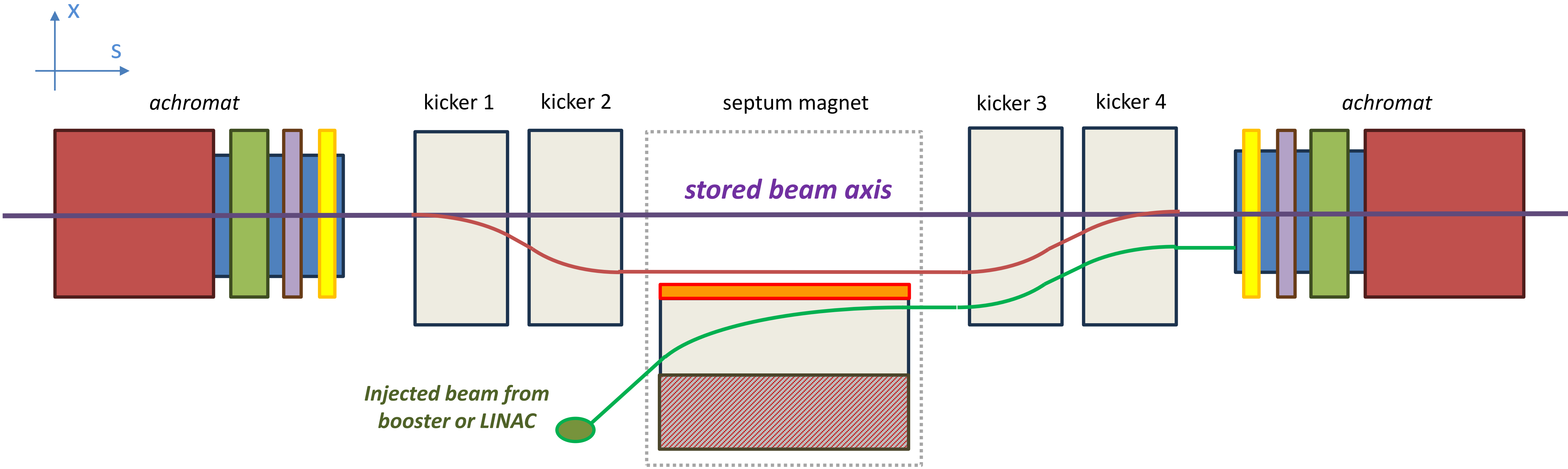
Define what a nonlinear kicker is.

Achieved performances on current storage rings.

Perspectives for nonlinear kickers for 4th generation light sources.

Note: nonlinear kicker will be used, as it is more general/common than multipole injection kicker.

Brief recap of the 4-kicker bump Top-Up injection scheme.



kicker : *pulsed dipole magnet*

septum magnet *: dipole magnet with magnetic field separation with blade (orange)*

Perfect injection

- **Stored beam perfectly on axis after bump (*position & angle*).**
- **Injected beam oscillates and damps into stored beam (betatron oscillation).**

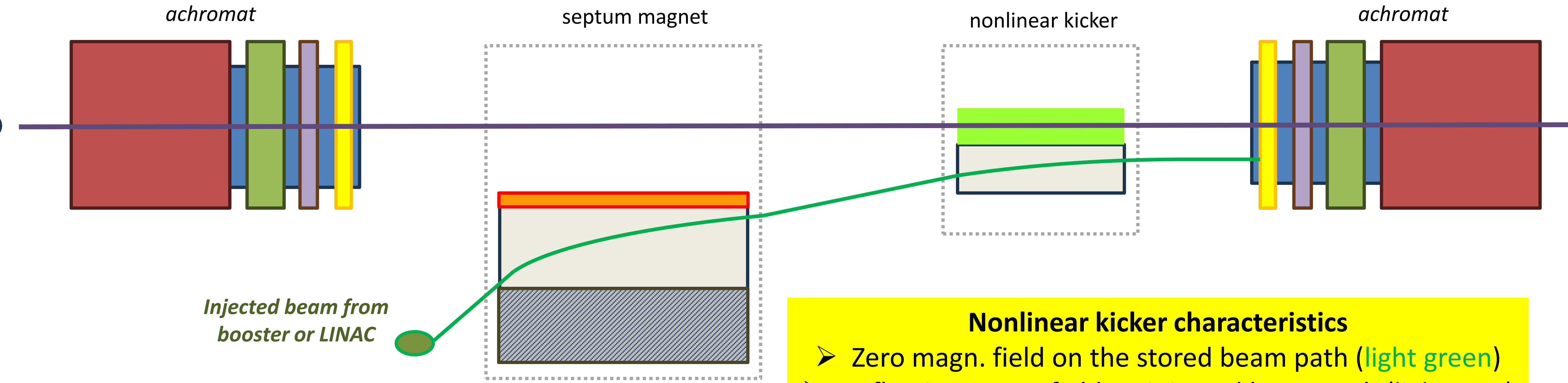
Limitations of the 4-kicker bump Top-Up injection scheme

- **Non identical kickers = non prefect closure of the bump**
  - *Magnet mechanical tolerances & alignment errors.*
  - *Pulser jitter & mismatch of pulsed current waveforms.*
  - *Eddy currents due to ceramic chamber coating & nearby parts altering the magnetic field response on beams.*
- *Other factors : leakage field of septum magnets, booster ramped magnets, etc.*
- **Injection transparency criteria are commonly defined :**

Residual stored beam position oscillation : < 10 % of beam size.
Residual stored beam size oscillation : < 10 % of beam size.

- **Aims at limiting the oscillation of the stored beam and thus the photons beams on the experiments during the Top-Up injection process.**
- **Extremely challenging to achieve excellent dipole kicker systems to meet these criteria.**

Using a nonlinear kicker…



Nonlinear kicker characteristics

- Zero magn. field on the stored beam path (light green)
- Deflection magn. field on injected beam path (light grey)
- Pulsed magnet

Perfect injection

- **Stored beam perfectly on axis since it is not kicked (*position & angle*).**
- **Injected beam kicked in the storage ring and performs betatron oscillation.**

Injection with a nonlinear kicker

- **Transparent** since no magnetic field perturbs the stored beam.
- **Allows Top-Up injection.**
- Uses less space than 4 kickers.

Multiple variants of injection schemes

Vertical/horizontal betatron oscillation, longitudinal plane, combination of multiple planes, multi-turn injection, *etc.*

depending on your dynamic aperture and what is acceptable for the storage ring lattice…

See reference [1]

Nonlinear kicker related work across the world

- **America**
  - Advanced Light Source (USA)
  - Advanced Photon Source (USA)
  - Canadian Light Source (Canada)
  - **SIRIUS (Brazil)**
- **Asia & Oceania**
  - **Photon Factory KEK (Japan)**
  - HEFEI (China)
  - Taiwan Photon Source (Taiwan)
  - Pohang Light Source (S. Korea)
  - Australian Light Source (Australia)
- **Europe**
  - **BESSY II (Germany)**
  - **MAX-IV (Sweden)**
  - Swiss Light Source (Switzerland)
  - **SOLEIL (France)**
  - ESRF (France)
  - Diamond (United Kingdom)
  - DESY PETRA IV (Germany)
  - ALBA (Spain)

Studied injection with an NLK

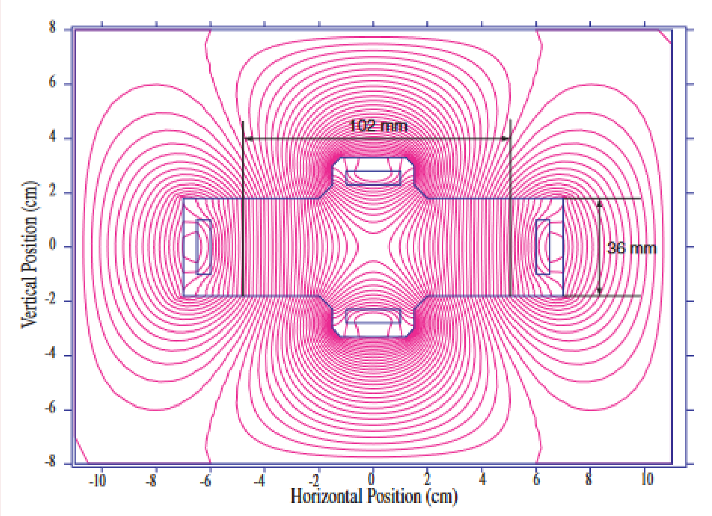
Studied NLK topologies

Prototyped an NLK (for lab or use on beam)

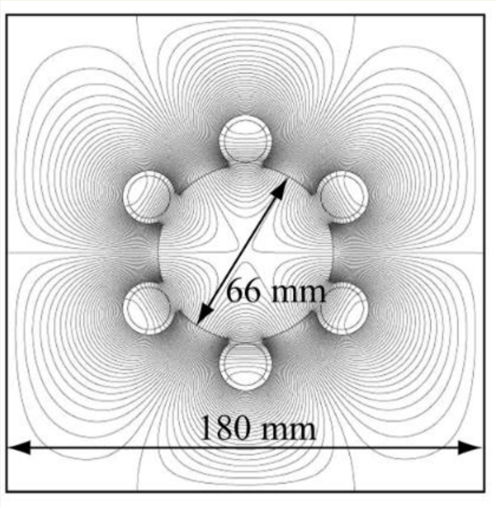
Developed and use daily an NLK for storage ring injection

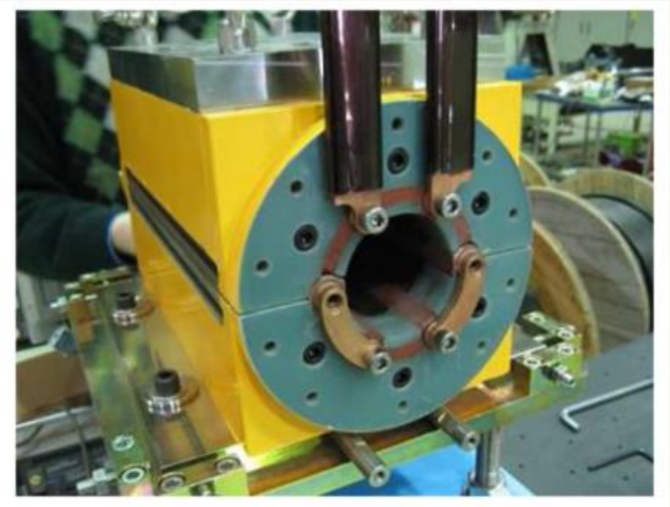
Many thanks to the colleagues of various facilities for sharing information !

2007 – 2010 : KEK Photon Factory in Japan

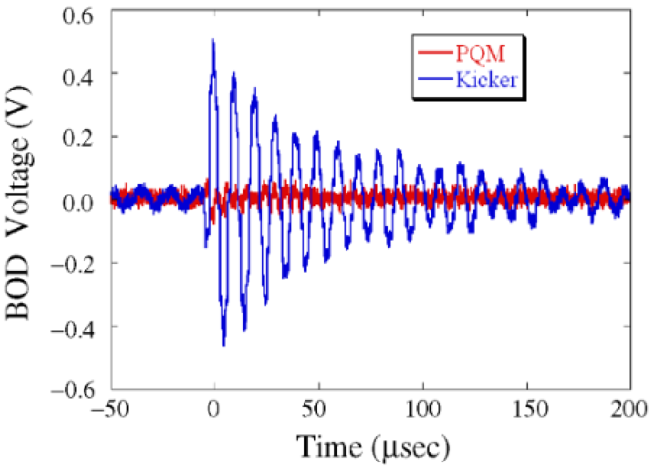


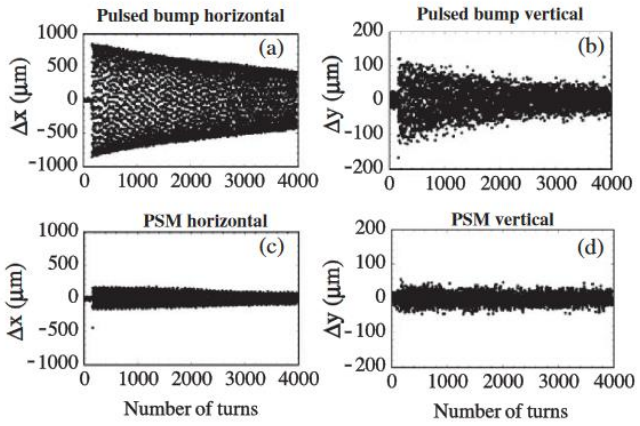
Pulsed Quadrupole Magnet (PQM) [2]





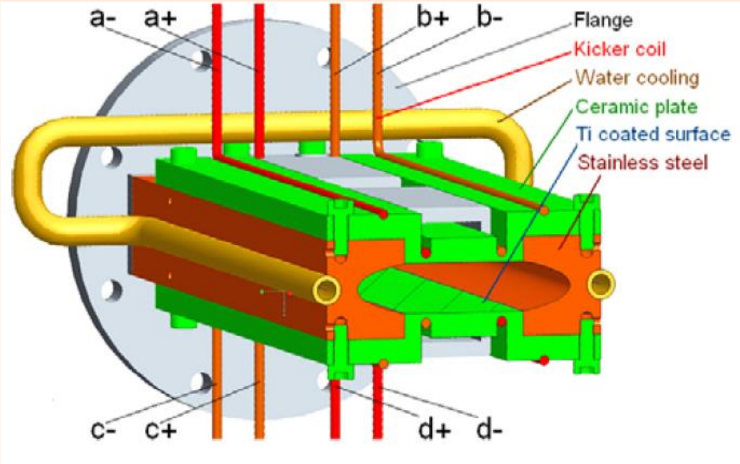
Pulsed Sextupole Magnet (PSM) [3]





Comparison in residual kick on stored beam
Kickers & PQM (left)
Kickers & PSM (right)

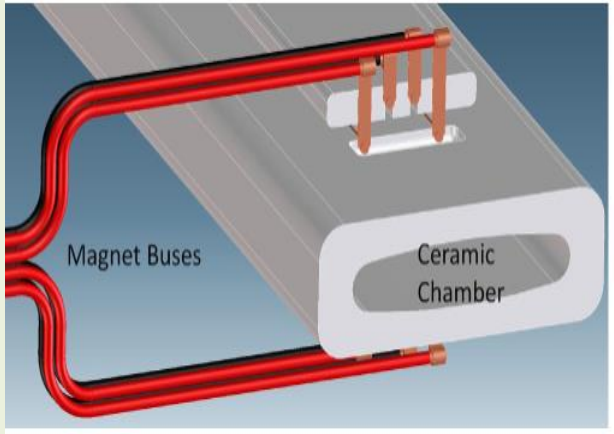
2009 – 2017 : nonlinear kickers (NLK) first generation



NLK at BESSY II [4]

Novel 8 conductor design.
In-vacuum configuration with ceramic plates and stainless-steel cooling parts.

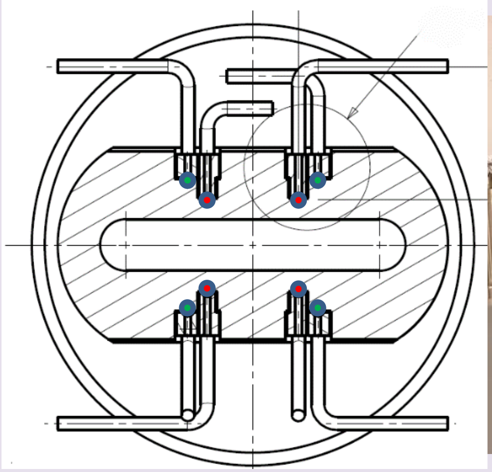
Used for beam dynamics study at BESSY II.



NLK at ALS [5]

Development up to prototype based on 8 conductor topology.

Alumina chamber.



NLK at MAX IV & SOLEIL [6]

2012-2017 Collaboration.
Nicknamed **MIK (Multipole Injection Kicker).**
8 conductor design based on BESSY II NLK.
Sapphire vacuum chamber.
In daily operation at MAX IV on 1.5 & 3 GeV rings.
Used for beam dynamics study at SOLEIL.

Dimensioning elements of an NLK

1. Conductors parallel to the longitudinal axis

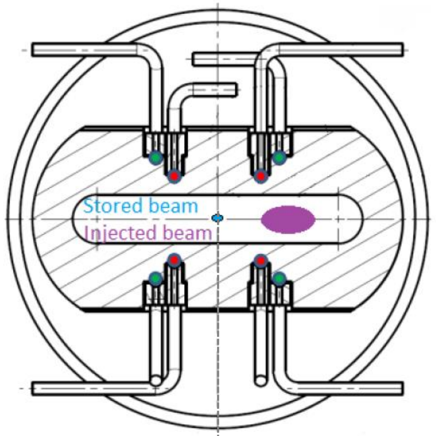
- **Minimum of 8 conductors (*à la BESSY II*) or more.**
  - *Limited by inductance, due to pulsed operation.*
  - *As close as possible to beams.*

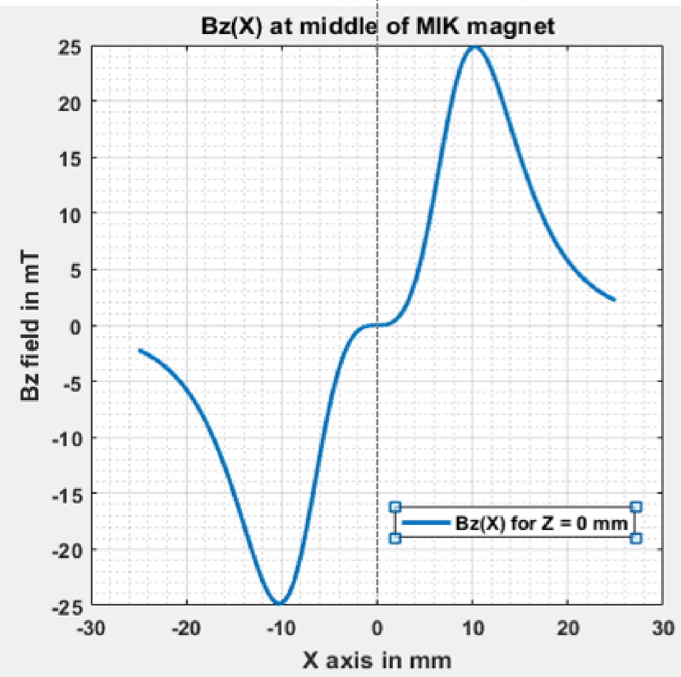
- **The location of conductors dictates the magnetic field distribution:**
  - *Octupolar zero field at center for stored beam.*
  - *Field off axis for injected beam.*
  - *Location of peak magnetic field from ~7 to ~11 mm.*

- **Accuracy of position of conductors determines at first order the quality of the zero-field region.**
  - *No yoke seen so far used in NLK.*
  - *The zero-field region at center degrades significantly with errors.*

- **Conductors powered in series and/or parallel by one or more pulsed power supplies.**

- **High voltage (up to 20 kV) encountered around compact conductor structures.**
- **Pulses up to 10 kA and few μs of duration.**





2. A ceramic chamber

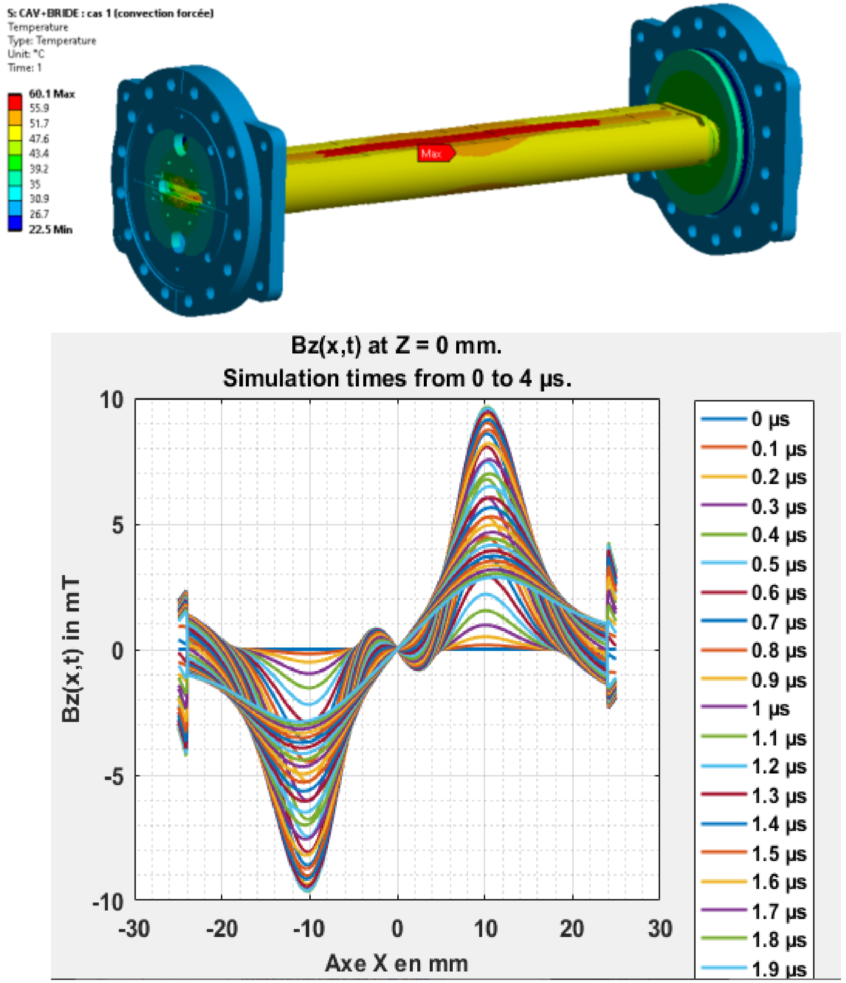
- **Provides vacuum tightness for the beam.**
  - *Choice materials: alumina, sapphire, other.*

- **Can receive accurate machining to house the conductors.**
  - **Machining tolerances in the range of few dozen micrometers.**
  - *Conductor are held in place by brazing or gluing.*

- **Internal aperture receives a metallic coating.**
  - *Usually titanium.*

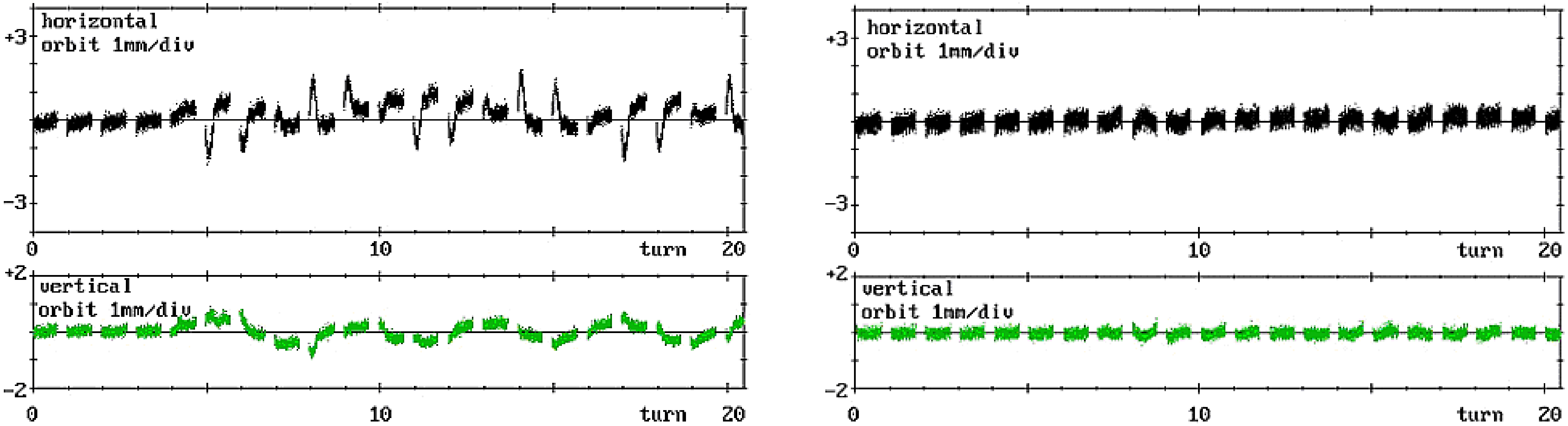
- **Thickness coating to allow:**
  - Acceptable pulsed magnetic field distortion.
    - Amplitude, phase, harmonics…
  - Acceptable levels of beam induced heat load.

3. As well as mechanics for precision magnet alignment and reliable & precision high voltage pulsed power supply.

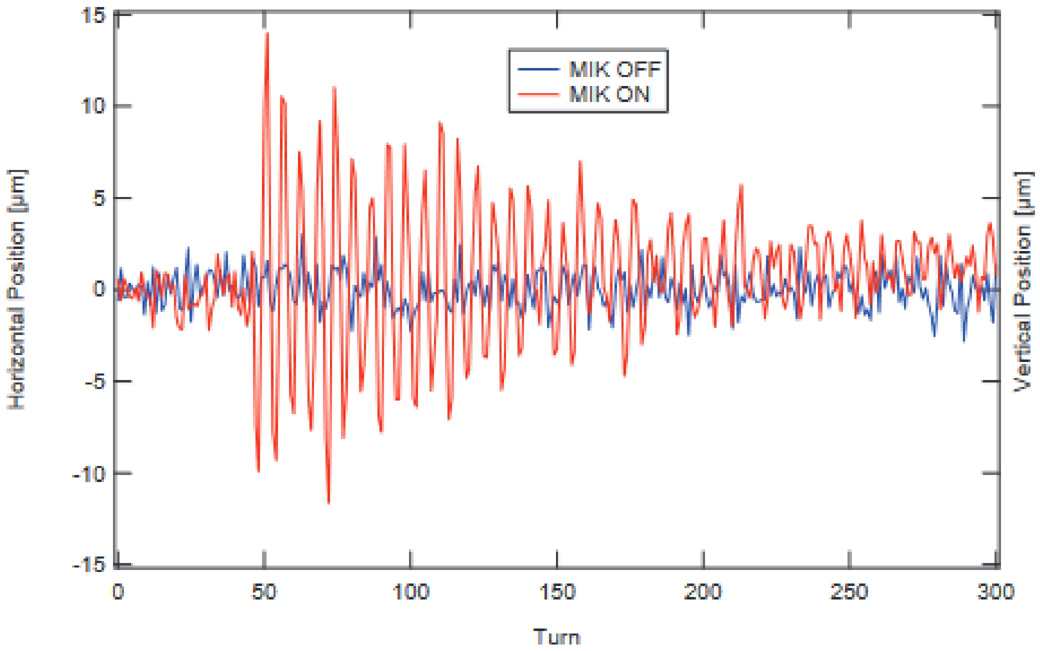


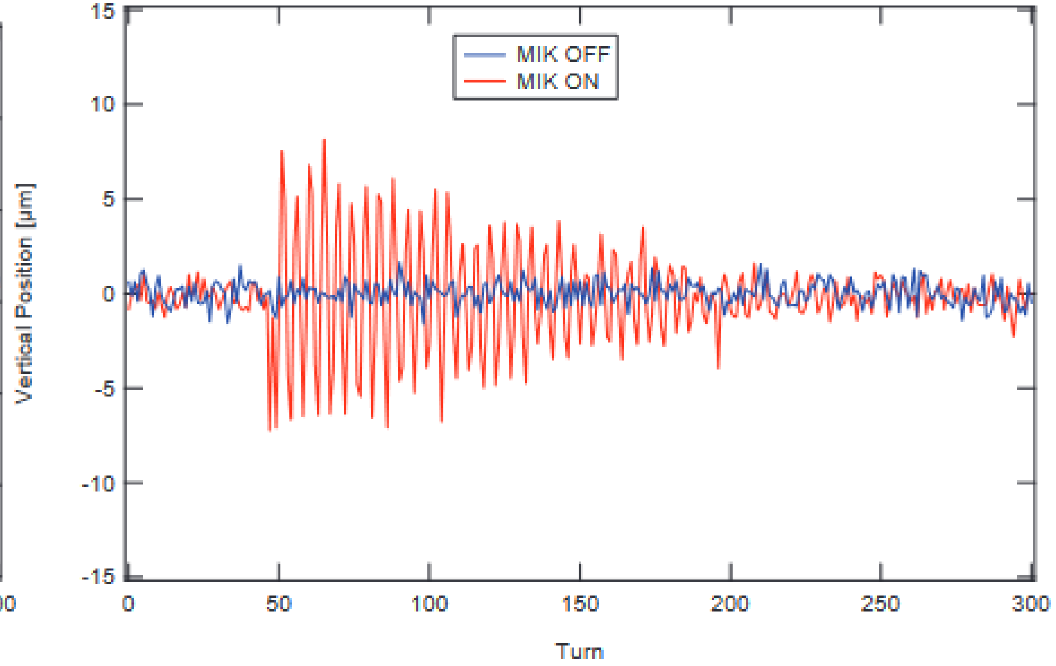
Top : FEA Thermal simulation (MIK @ SOLEIL) [7]
Bottom : simulated magnetic distortion with a hypothetical copper coating of MIK chamber

Achieved performances on storage rings : **BESSY II.**



Orbit distortion	4 kickers	NLK
Horizontal plane	~ 1000 µm	~ 50 µm
Vertical plane	~ 300 µm	~ 50 µm



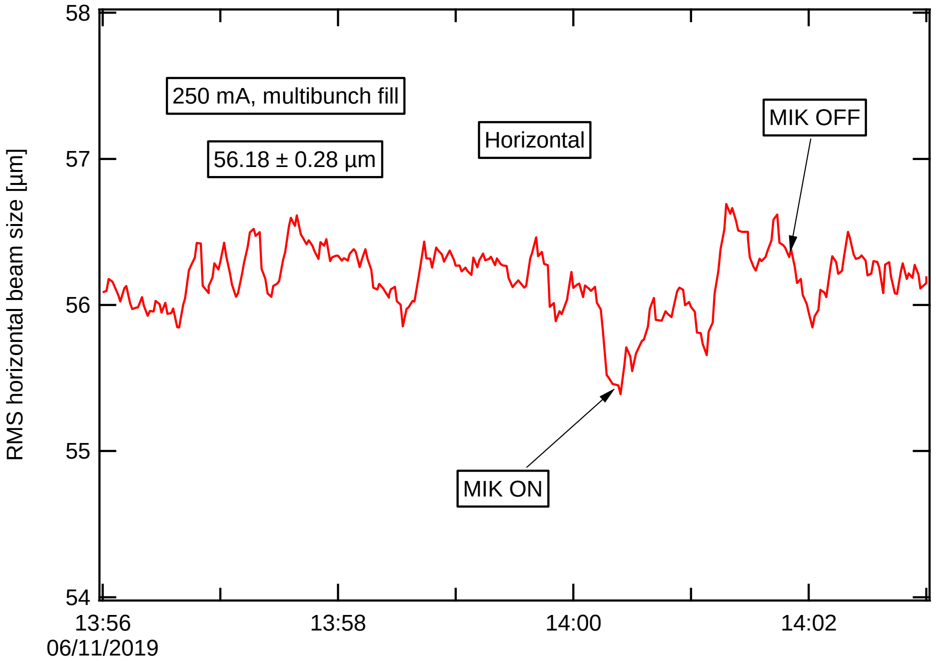


Horizontal = $\pm 13\ \mu m$

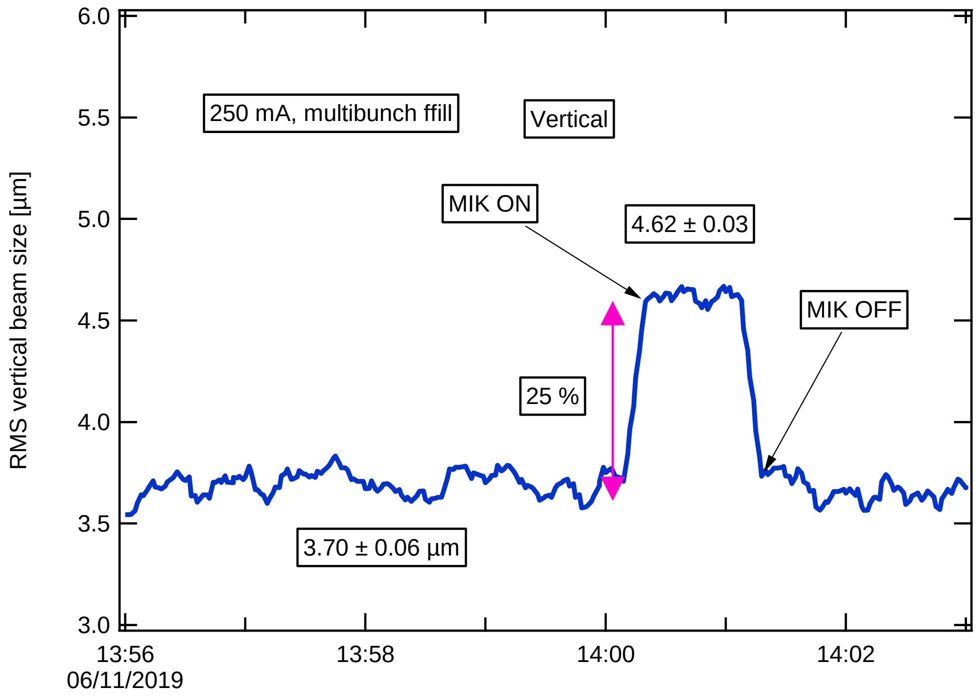
Vertical = $\pm 8\ \mu m$

- Store 10 consecutive bunches
- Scan of stored beam position at the MIK
- Amplitudes measured from Turn-By-Turn libera data stream
- One BPM at $\beta_x = 9.6\ m\ \beta_y = 4.80\ m$
- Amplitudes scaled to centre of long straigt where $\beta_x = 9.0\ m\ \beta_y = 2.0\ m$
- Beam size : 56 µm H x 3.5 µm V.

Achieved performances on storage rings: **MAX IV 3 GeV ring .**

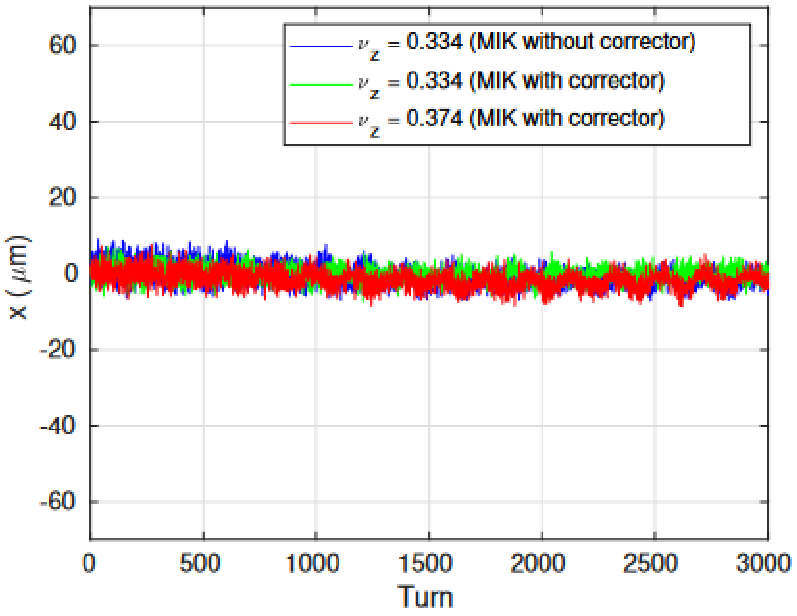


Horizontal transparency ≲ { 0.3 µm, 0.5 % σ }

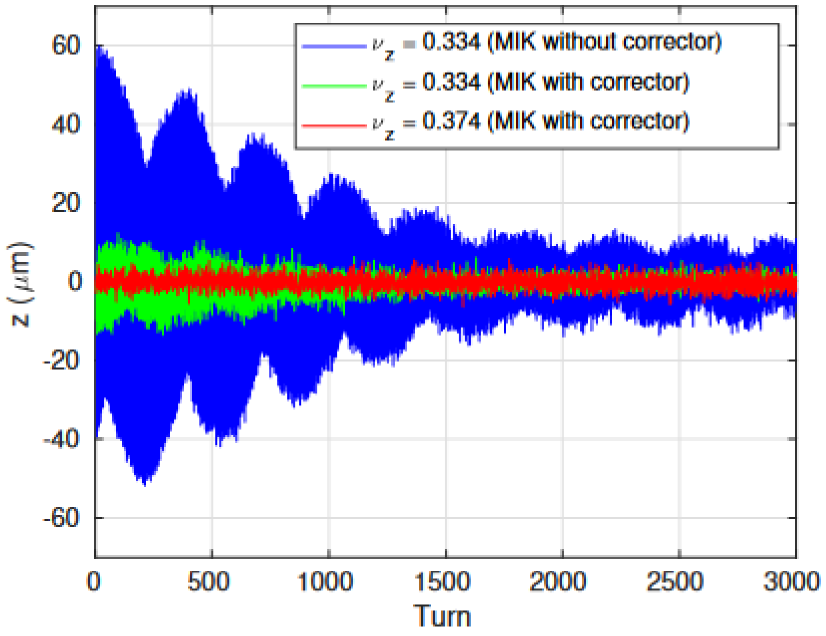


Vertical transparency ≲ { 0.9 µm, 25 % σ }

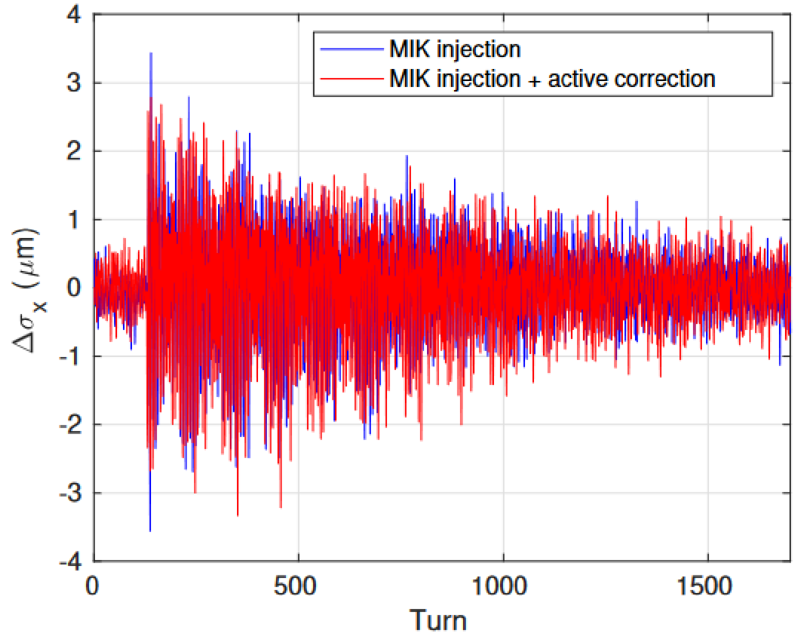
Transverse beam profile measured at diagnostic beamline while pulsing the MIK.
Values scaled to the centre of the long straight.



Horizontal beam position with MIK injection



Vertical beam position with MIK injection



Horizontal beam size with MIK injection

Use of a spare vertical pinger used to compensate vertical dipole defect field of MIK on SOLEIL storage ring

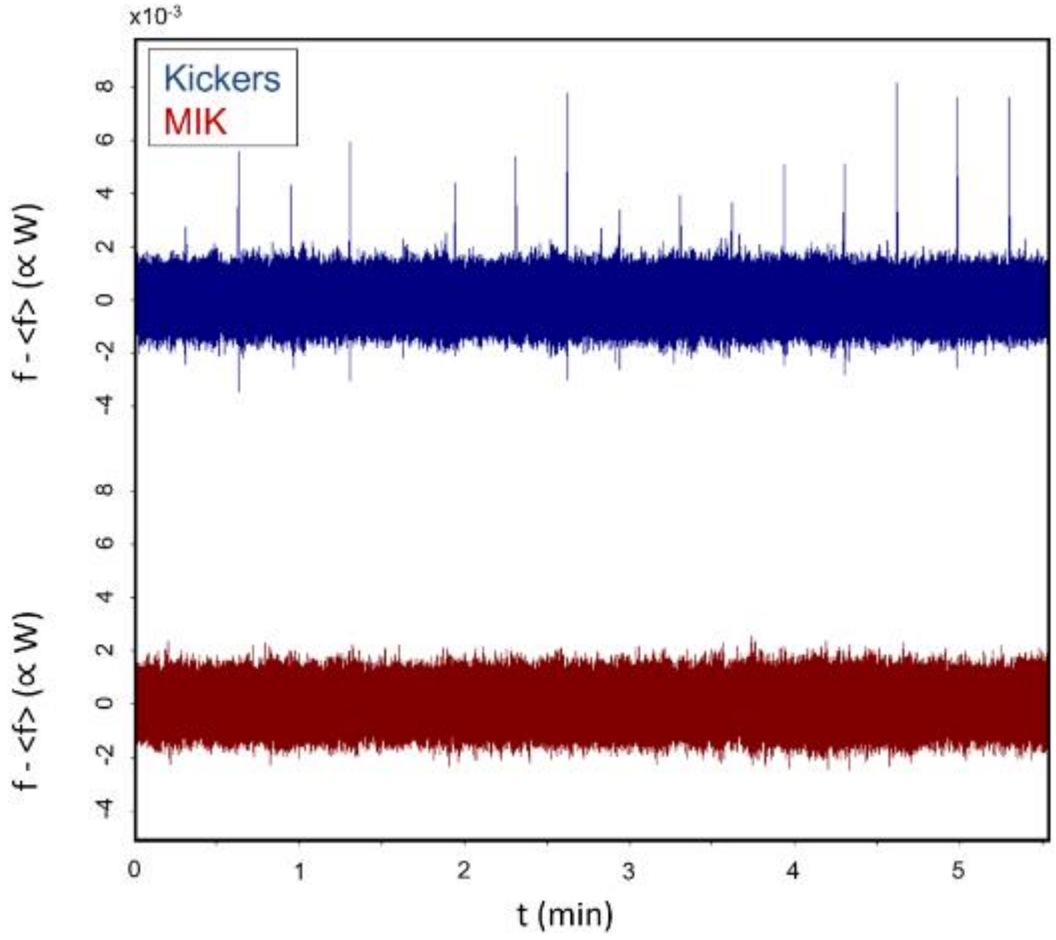


Figure 5.87: Two interferograms recorded with the infrared beamline AILES in the case of the kickers (blue) and MIK (dark red) triggering. The storage ring is operated in uniform filling pattern (500 mA). The triggering of the kickers can be identified by the resulting perturbations which have characteristic peaks contrary to the MIK.

Comparison between 4-kicker and MIK Top-Up injection on IR beamline during interferogram measurements.

[8]

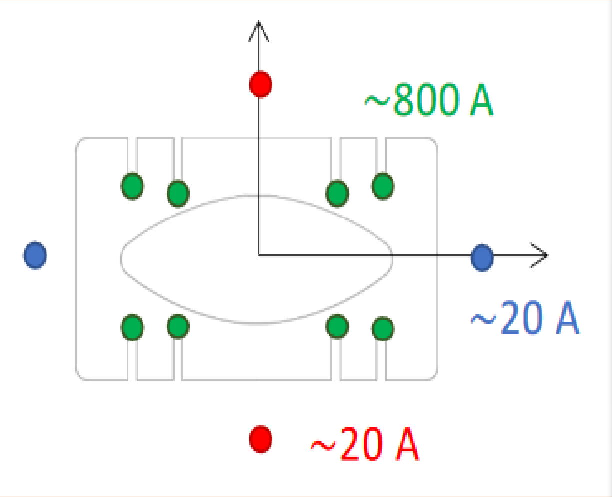
- First generation of NLK: based on 8-conductor design of BESSY II.
  - Static conductors around ceramic & metallic parts.
  - Accurate positioning of the conductors through precise machining of ceramics.

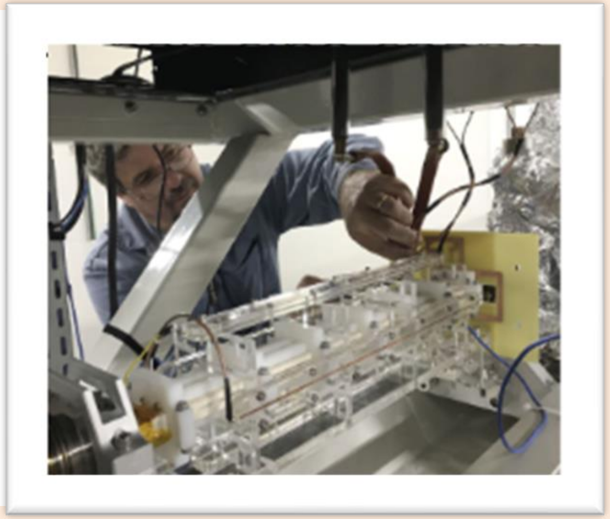
- **Significant gain in Top-Up injection transparency !**
  - Stored beam residual oscillation (position & size) are within the dozen µm range.

- **Still no ideal ?**
  - **4th generation light sources have considerably lower emittances & smaller DA.**
  - **Same transparency requirements lead to extremely low defect fields at center !**

➢ **Second generation of NLK : incorporates correction schemes**
  - ➢ **Additional pulsed corrector, field correction conductors, movable conductors, etc..**

Nonlinear kicker : next generation



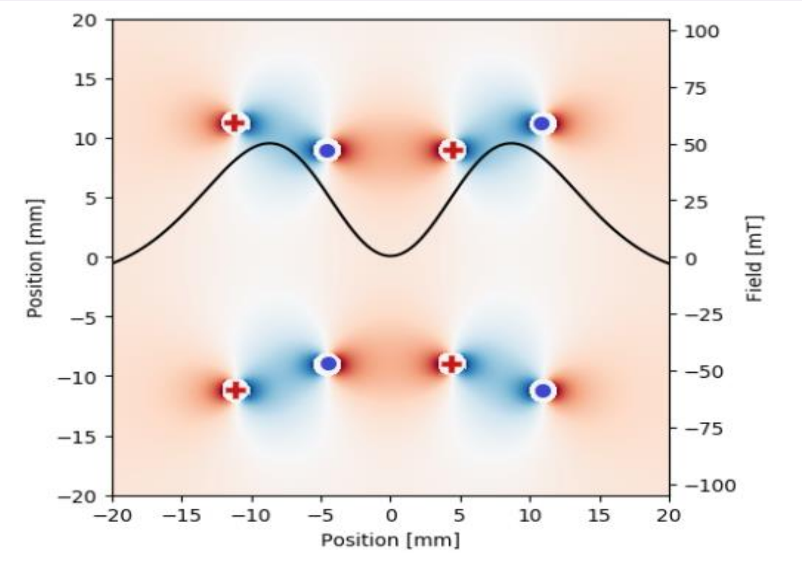


NLK at SIRIUS [9]

8 main conductor design (*green conductors*).

Additional pairs of conductors for compensating eddy currents and mechanical errors (*red & blue conductors*).

Alumina ceramic chamber – 9 mm vertical aperture.
1 mm ceramic thickness (atm to vacuum)
In operation at present on Sirius.

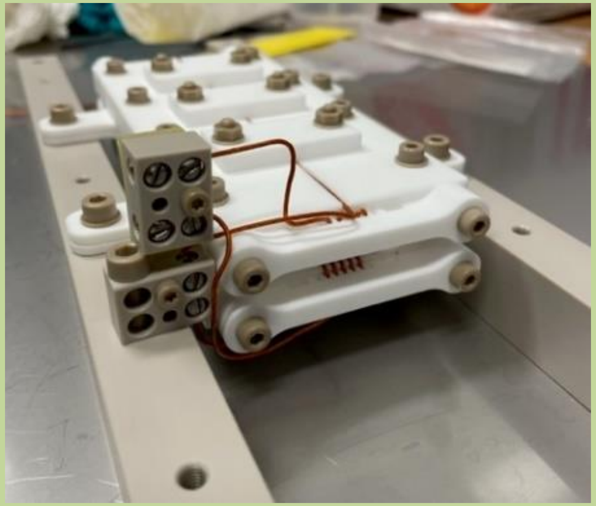


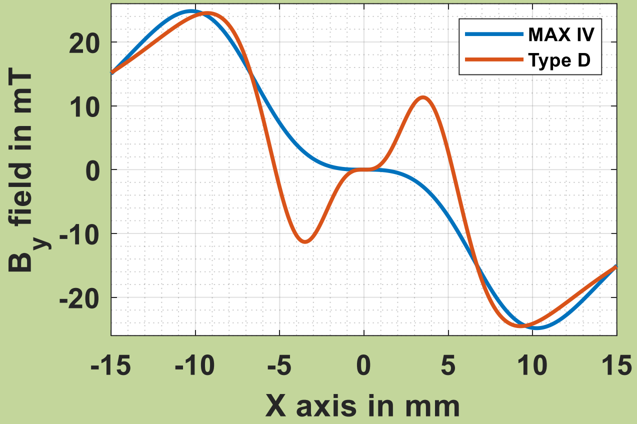
NLK at ALBA [10]

Nicknamed **DDK (Double Dipole Kicker).**
2 electrically independent sets of 4 conductors

- **Perform a dipole kick or a nonlinear kick depending on which combination of conductors are powered.**
- **Proposed coating structure to cancel eddy current contribution.**

To be prototyped and tested on current ALBA storage ring.





NLK for SOLEIL II [11]

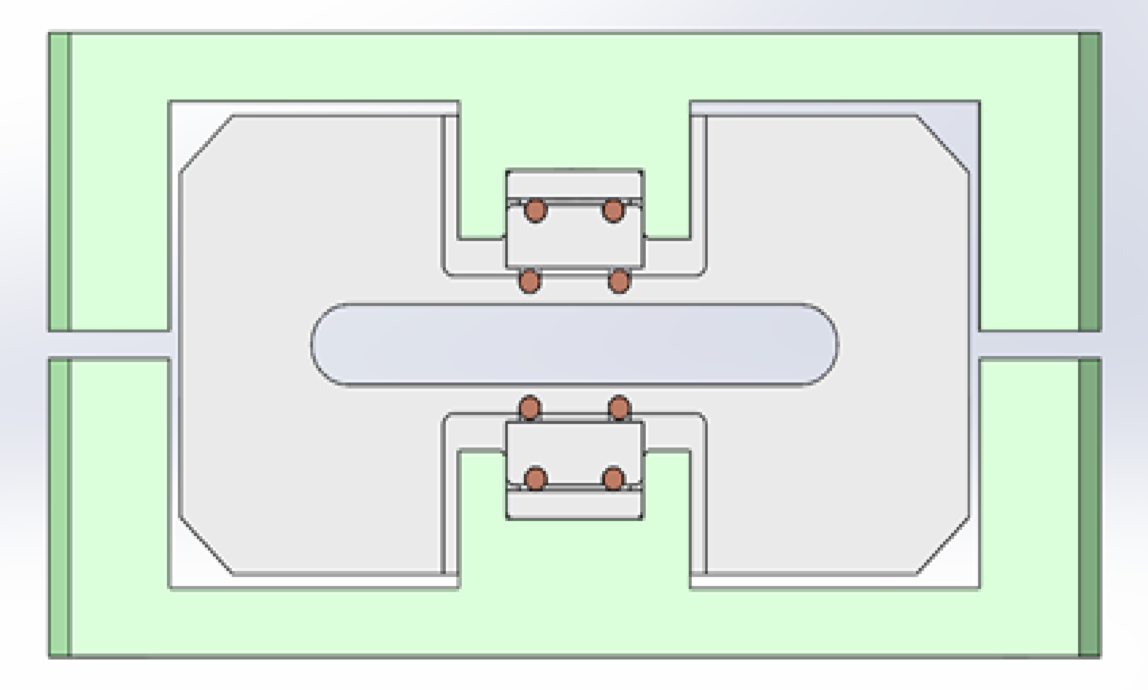
12 main conductor design (type D).

2 conductors movable in vertical and horizontal direction to adjust zero magnetic field on stored beam.

7 mm aperture / 150 mm long (mag. length) / Type D.

- **Magnetic peak located at 3.5 mm from stored beam.**

Advanced prototyping & final design in progress.



NLK at ESRF-EBS

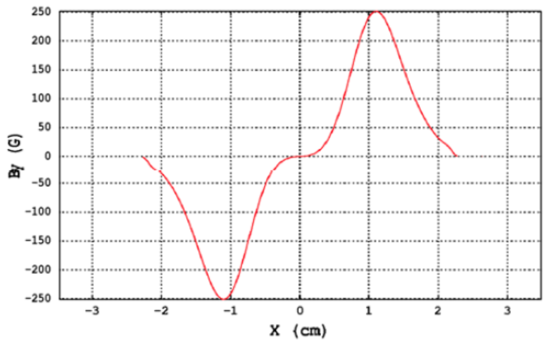
8 main conductor design.

- **Zero field region to be adjusted by moving 4-conductor assemblies.**

Prototyping & feasibility phases.

To conclude

- **Nonlinear kickers:**
  - **Since the 1st generation**: ensemble of conductors to produce a nonlinear magnetic field.
    - *Nice zero field region at center (low dipole & quadrupole) and a large peak field off axis.*
    - ➢ **Impressive gain in transparency of Top-Up injection in operation.**
  - **Extensive engineering :**
    - Ceramic mechanical design & conductor position accuracy.
    - Titanium coating: eddy currents vs. beam induced thermal loads.
    - Miniature systems with challenging high-voltage & pulsed current problematics.
  - **2nd generation of NLK**: correction schemes to reach ultra-low defect fields on stored beam.



- **For future machines (4th gen. and +):**
  - Will the dynamic aperture & ring designs still allow using NLK ?
  - Will the peak magnetic location field be required closer to stored beam ?
  - Redefine transparency criteria ?
  - Investigation of non-linear stripline kickers ! Proposed design at HEPS [12].

Readings

[1] : M. Aiba, “Review of Top-up Injection Schemes for Electron Storage Rings”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1745-1750.

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[5] : G. C. Pappas et al., “Development of Nonlinear Injection Kicker Magnet for ALS Accelerator”, in Proc. 6th Int. Particle Accelerator Conf. (IPAC’15), Richmond, VA, USA, May 2015, pp. 1837–1839

[6] : P. Alexandre, R. Ben El Fekih, A. Letresor, S. Thoraud, J. da Silva Castro, F. Bouvet, J. Breunlin, Å. Andersson, and P. Tavares, Transparent top-up injection into a fourth-generation storage ring, Nucl. Instrum. Methods Phys. Res., Sect. A 986, 164739 (2021).

[7] : A. Gamelin *et al.*, “Investigation of RF Heating for the Multipole Injection Kicker Installed at SOLEIL”, in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2233-2236.

[8] : Thesis R. Ollier, “Multipole Injection Kicker studies and commissioning for a transparent injection in the SOLEIL synchrotron” 2022 - 2022UPASP165 - https://www.theses.fr/2022UPASP165

[9] : L. Lin, “SIRIUS, a 4th Generation Synchrotron Light Source in Brazil”, ICABU 2023,

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[11] : P. Alexandre, R. Ben El Fekih, F. Bouvet, and M.-A. Tordeux, “Pulsed Magnets and Power Supplies for Injection & Extraction in the SOLEIL II Project”, presented at the IPAC'23, Venice, Italy, May 2023, paper THPA175

[12] : J. Chen *et al.*, “A Novel Non-Linear Strip-Line Kicker Driven by Fast Pulser in Common Mode”, in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2345-2348

Readings

Extras

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