Status of the MAX IV Accelerators
IPAC 2019

Pedro F. Tavares

on behalf of the MAX IV team

MAX IV

Outline

- MAX IV Laboratory Overview
- The MAX IV Accelerators
- MAX IV Injector LINAC Highlights
- MAX IV 1.5 GeV Ring Highlights
- The MAX IV 3 GeV ring
  - Conceptual Design
  - Commissioning Timeline & Achieved Performance
  - Highlights
- Future Perspectives
- Conclusions

MAX IV: The Swedish National Synchrotron Radiation Facility

Conceptual Basis of the MAX IV Design

- Scientific Case calls for high brightness radiation over **a wide spectral and time structure range**: IR to Hard R-rays, Short X-Ray Pulses.

- Need for high brightness: low emittance and optimized insertion devices.

- This is hard to achieve in a single machine
  - higher electron beam energy favours harder photons
  - lower electron beam energy favours softer photons
  - Hard to produce short pulses in storage rings

One size does not fit all !

The MAX IV Approach

- **Different machines for different uses:**
  - A **high energy ring** with ultralow emittance for hard X-ray users.
  - A low emittance **low energy ring** for soft radiation users
  - A LINAC based source for generating **short pulses** and allowing for future development of an FEL source.

All sharing common infrastructure and technical solutions

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The MAX IV Accelerators

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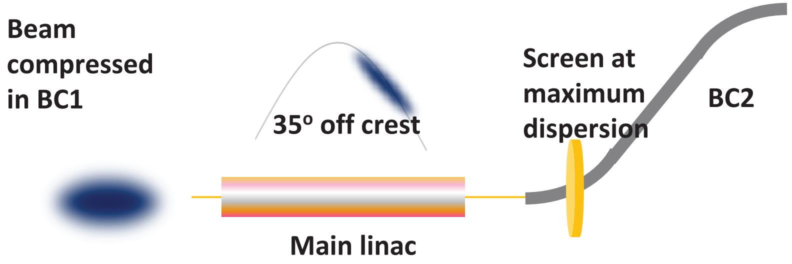
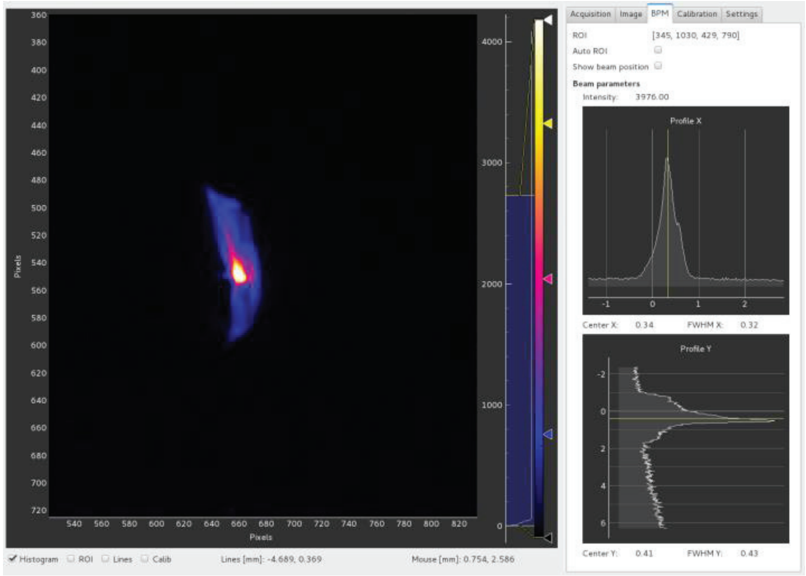
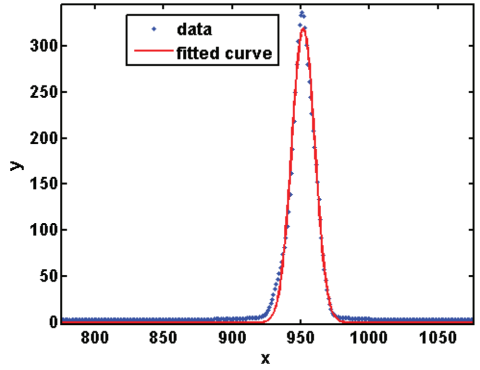
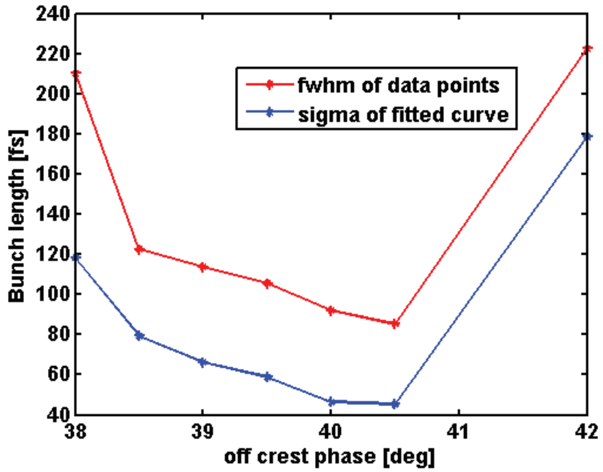
LINAC Highlights: Short bunches





On May 23rd 2018 we measured below 100 fs fwhm for the first time. Lowest measurement was 45 fs FWHM, and 28 fs RMS.





We could compress more, but didn't have resolution to measure anything shorter.

Slide by Sara Thorin

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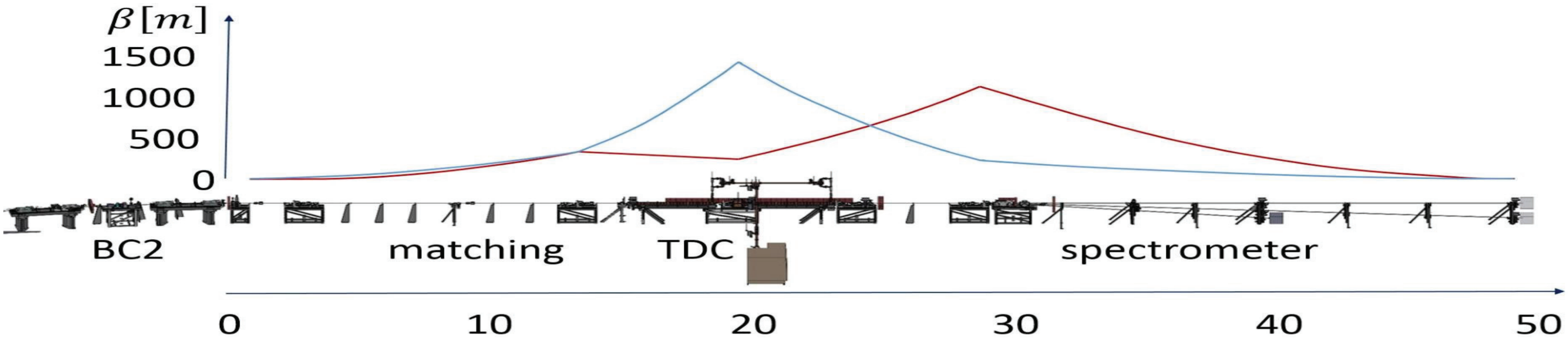
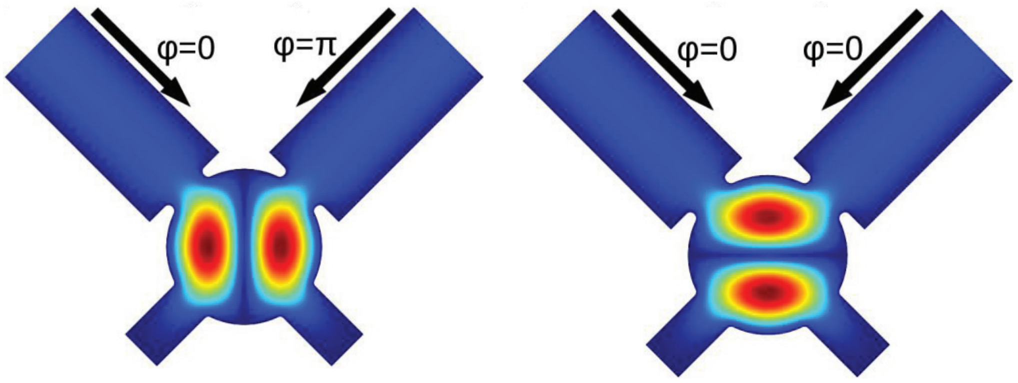
Transverse Deflecting Cavity Setup



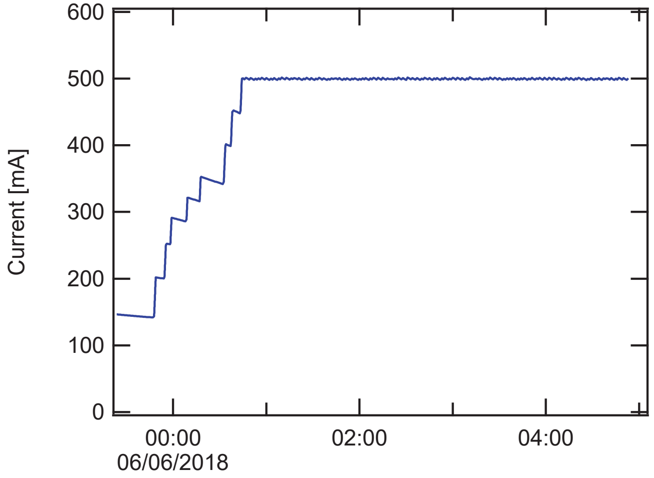
- S-band
- Solid State Moduator and SLED
- >100 MV integrated field
- 1 fs resolution ➡ long setup, large beta
- Switchable polarization (phase II)

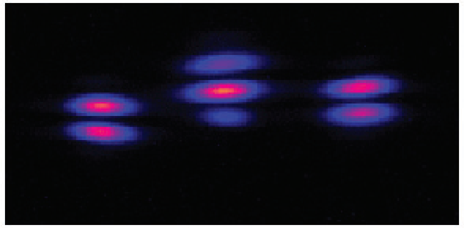


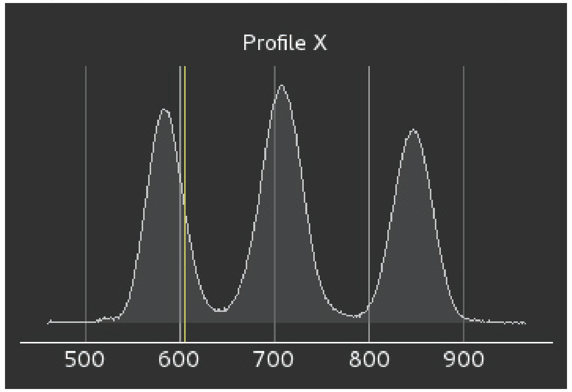
Electric field in the TM_{110} mode

Highlights 1.5 GeV Ring

Design Current - 500 mA





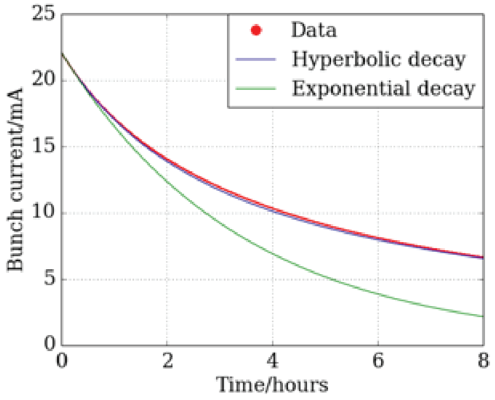


TRIBS

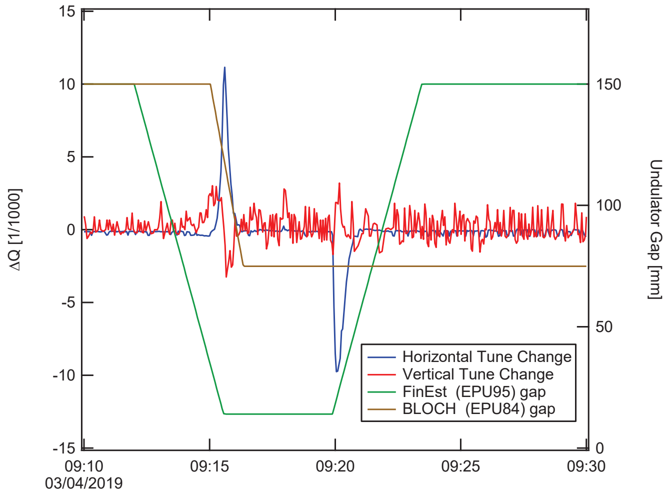
Thanks to Paul Goslawksi and the BESSY team

Picture by D.K.Olsson

Single Bunch

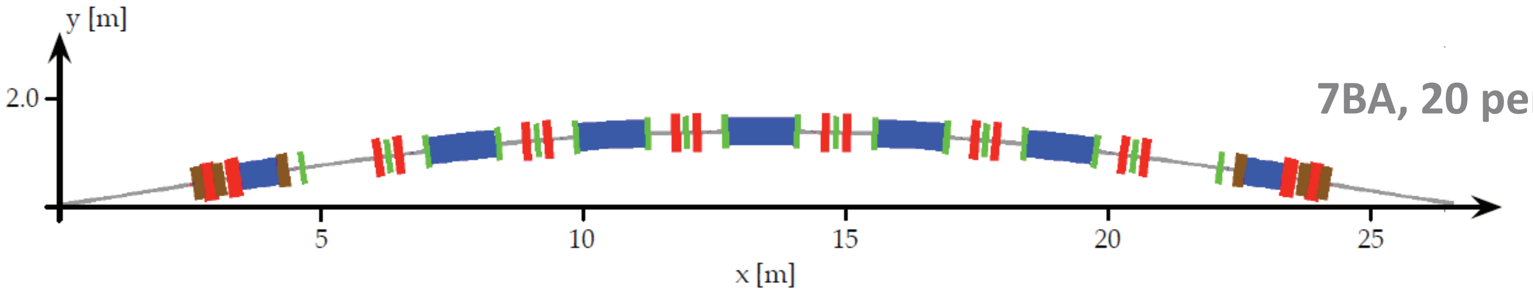


Plot by Francis Cullinan



Global Tune Feedback

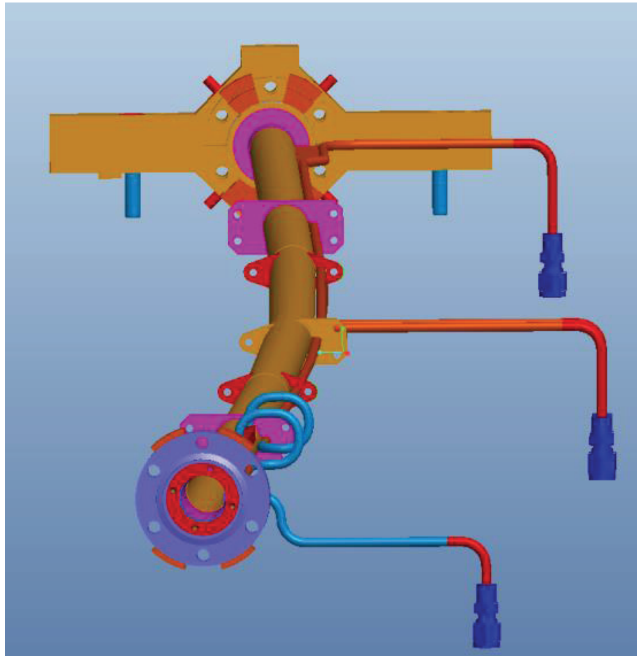
MAX IV 3 GeV ring: 528 m, 330 pmrad



7BA, 20 periods

100 MHz RF
Passive HC

Circular, copper NEG-coated chambers



Compact Magnets

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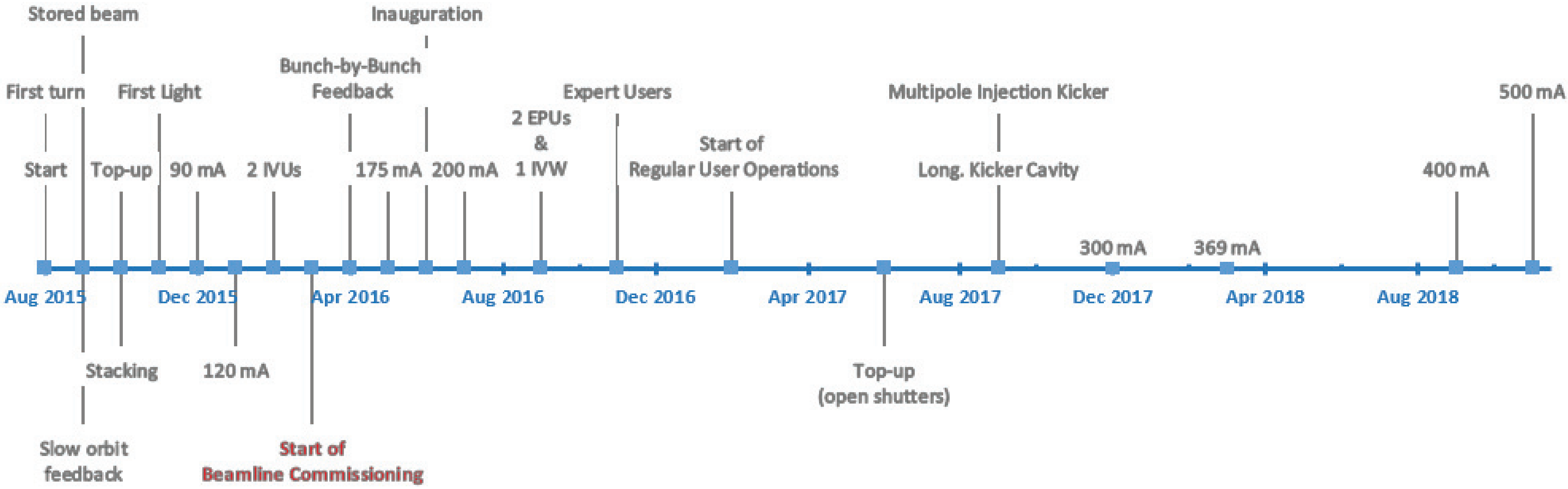
3 GeV Ring – achieved performance

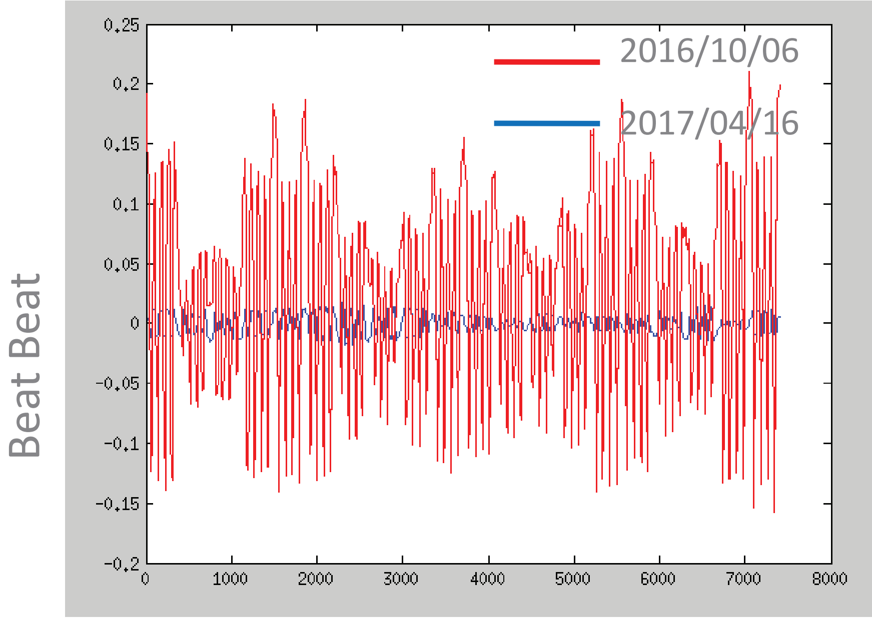
- 500 mA stored current in multibunch mode demonstrated during accelerator studies
  - Regular delivery to beamlines at ~ 250 mA (RF power limitations)
- ~ 9 mA stored current in single-bunch mode.
- ~ 20 A.h lifetime.current product from gas scattering
- $\gtrsim$ 90% injection efficiency
- Emittances: ε_x=320 ± 18 pm rad; ε_y =6.5 ± 1 pm rad
- RMS orbit stability (up to 5 kHz) better than 2.0/5.0 % of beam size (H/V).
- Beta beats < ± 2 %, Residual Vertical Dispersion < 0. 6 mm RMS

3 GeV Ring Commissioning & Operations Timeline

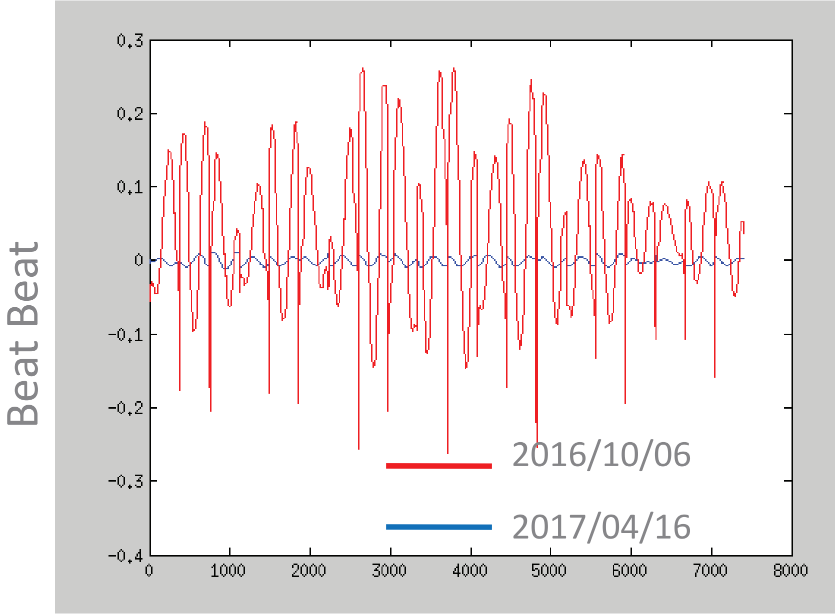


Beta-beat correction

Horizontal

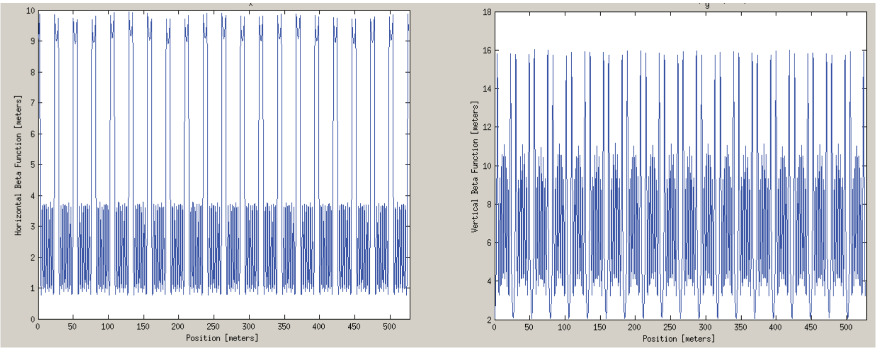


Vertical

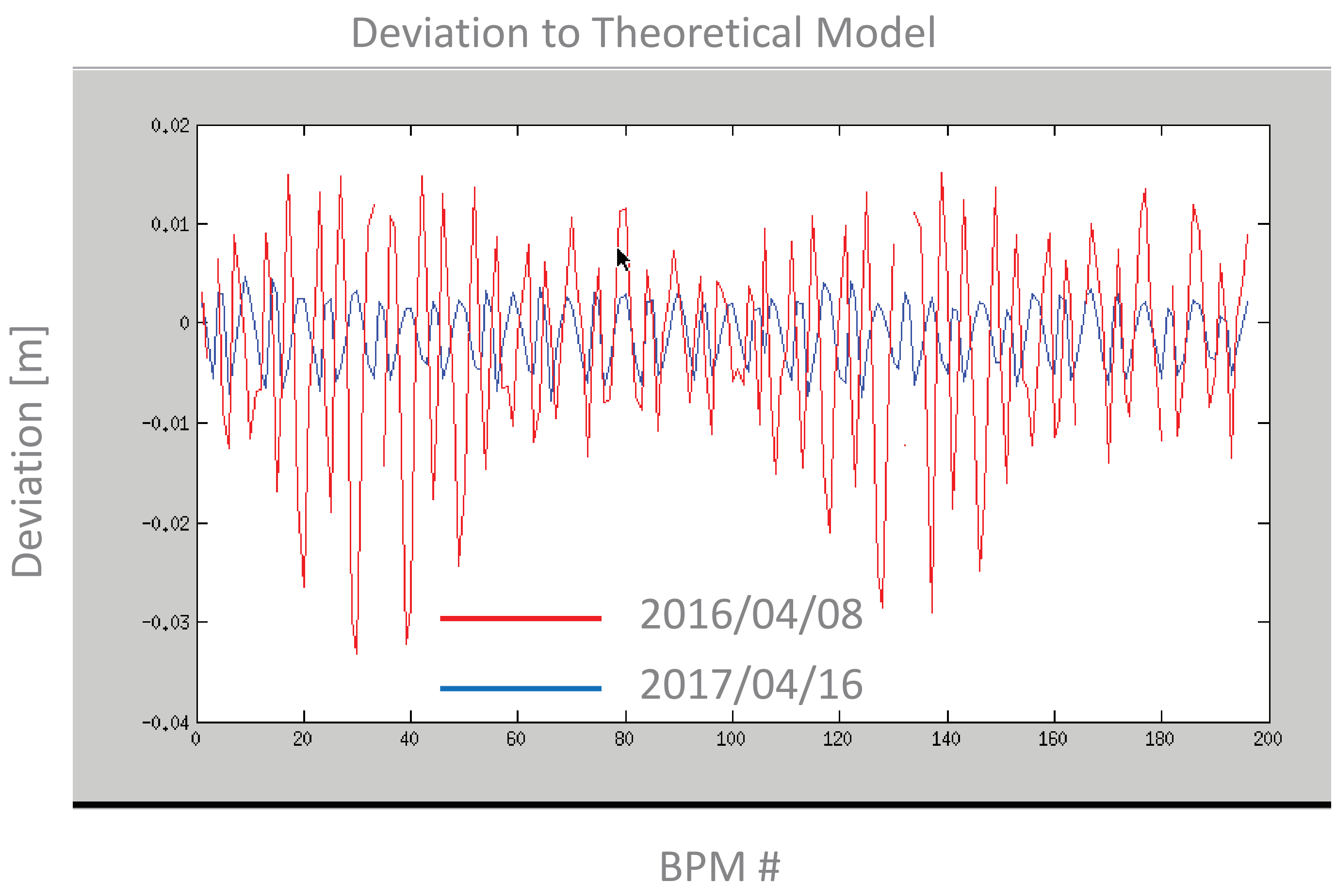


Beat beats reduced from ± 20/25 % to less than ± 2/1.5 %.

Betatron Functions from LOCO fits

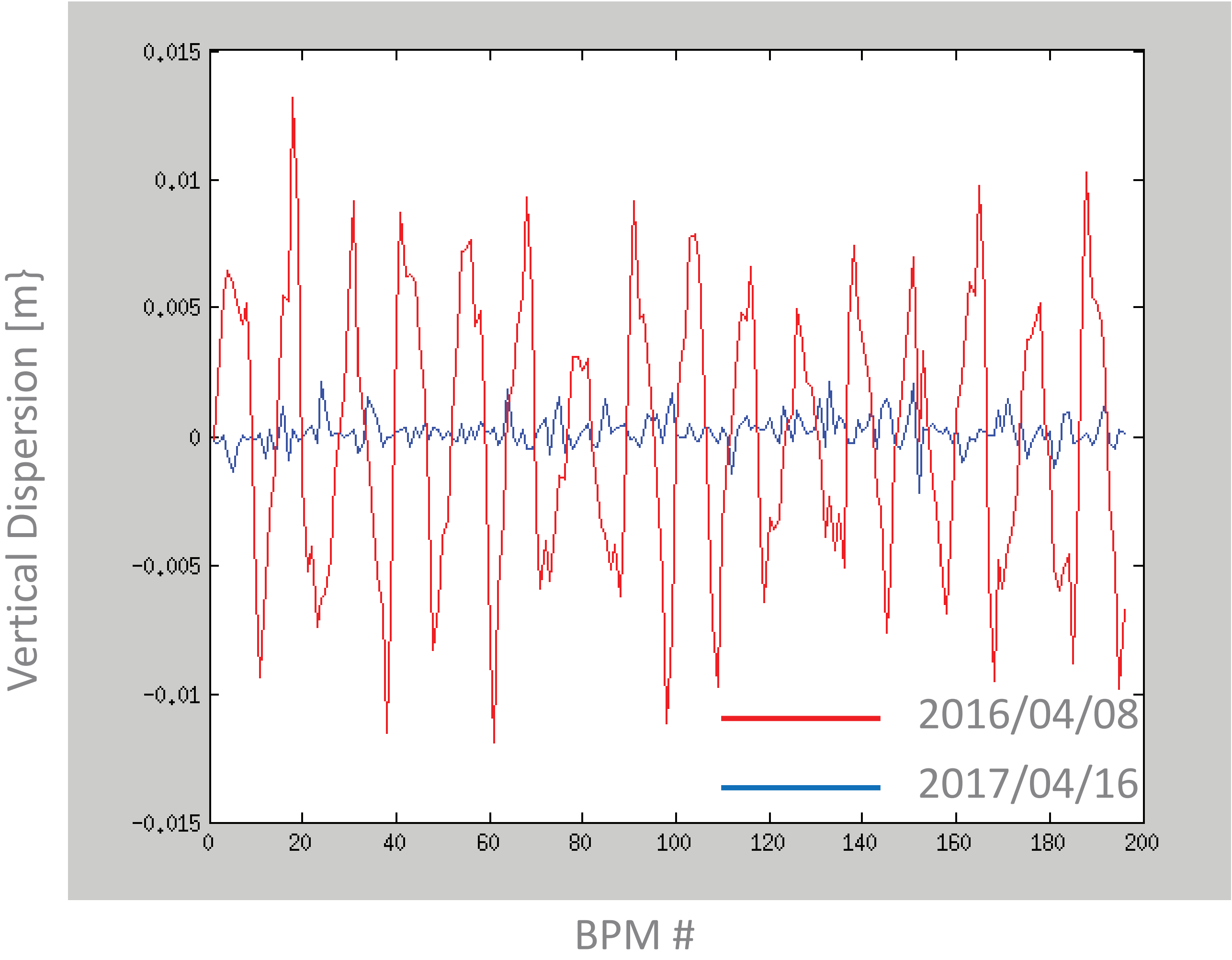


Correction of horizontal dispersion beating



RMs deviation to model reduced from 15 mm to 3.5 mm

Correction of residual vertical dispersion

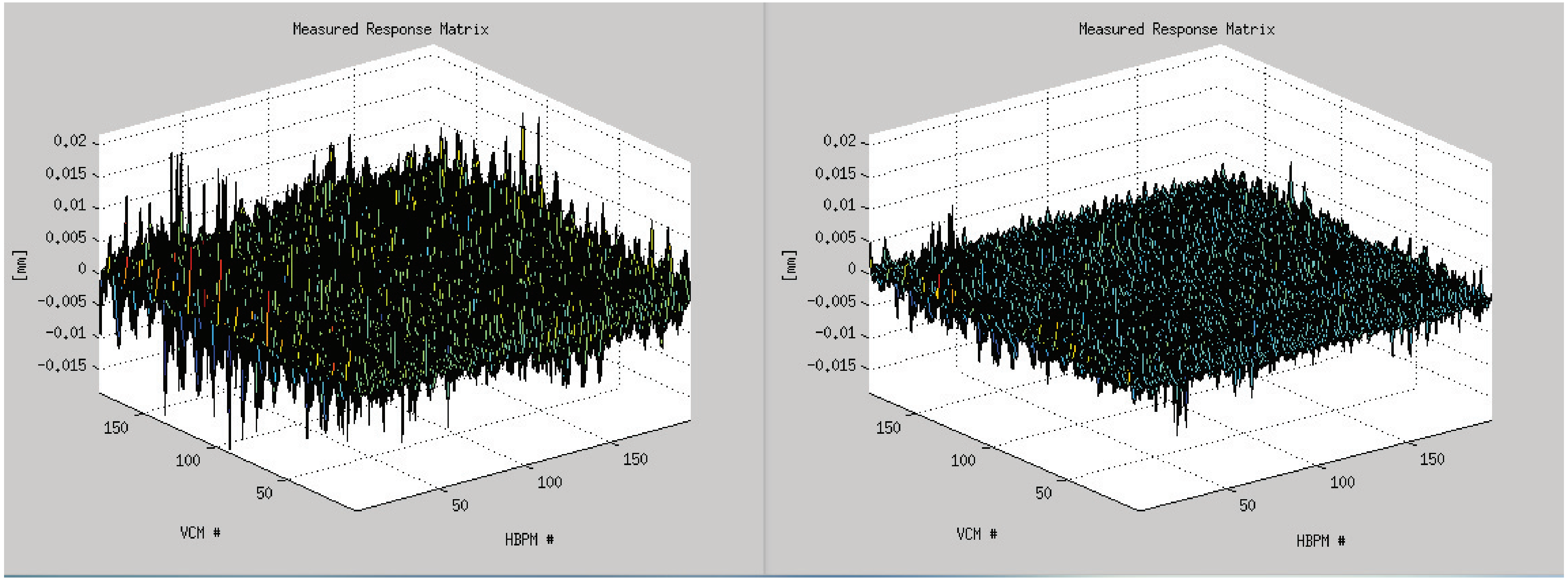


40 dispersive skews reducing the vertical dispersion. Maximum strength is roughly half of the available.

RMS reduced from 5 mm to 0.6 mm

Correction of betatron coupling

40 non-dispersive skews reducing the coupling.
Maximum strength is roughly half of the available.

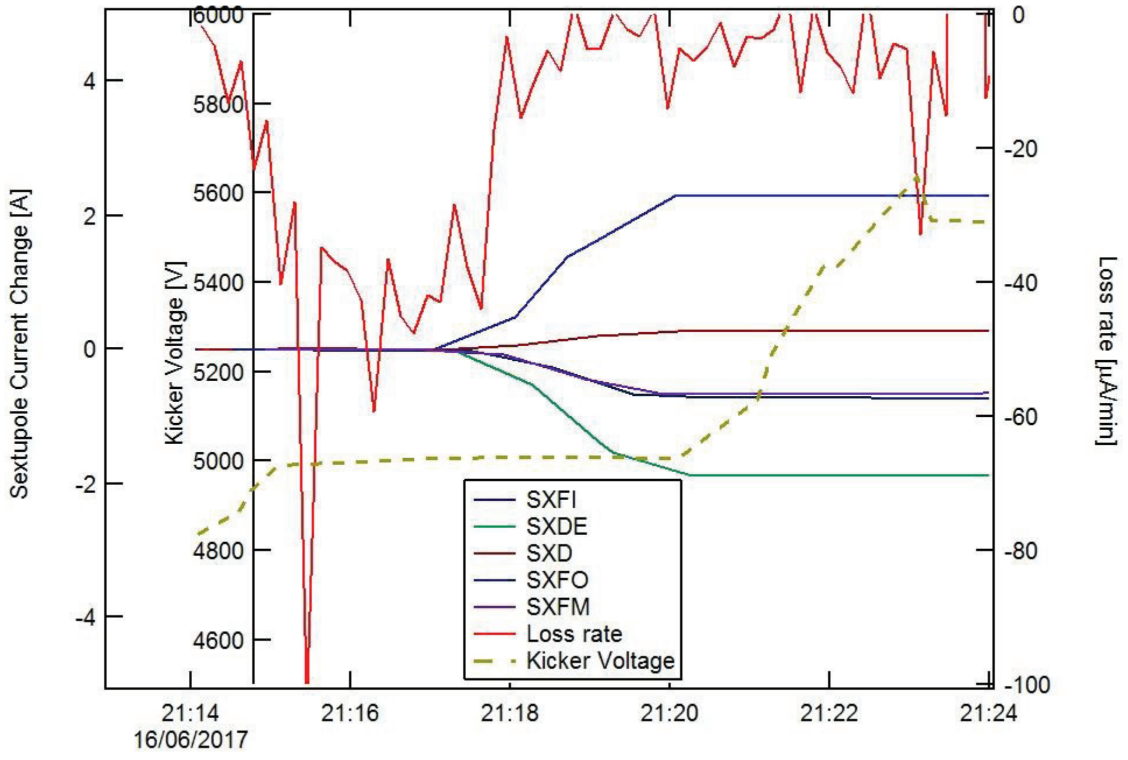


Slide by Å.Andersson

Non-linear Lattice Optimization

Thanks to Xiaobiao Huang for providing the RCDS code

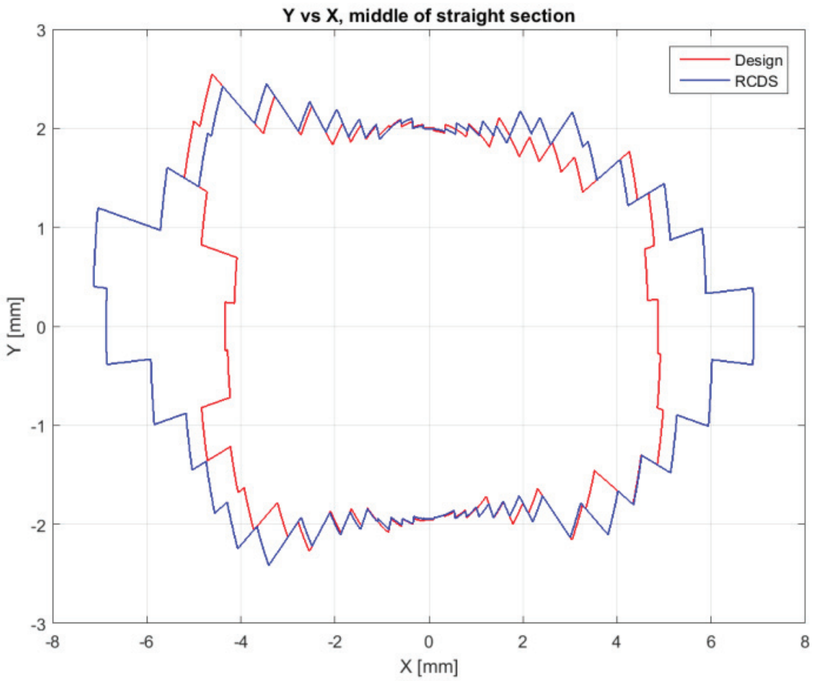
RCDS (**Robust Conjugate Direction Search**) applied using all sextupole (5) and octpole families (3) as knobs and beam loss rate while kicking the beam as a proxy for dynamic aperture.



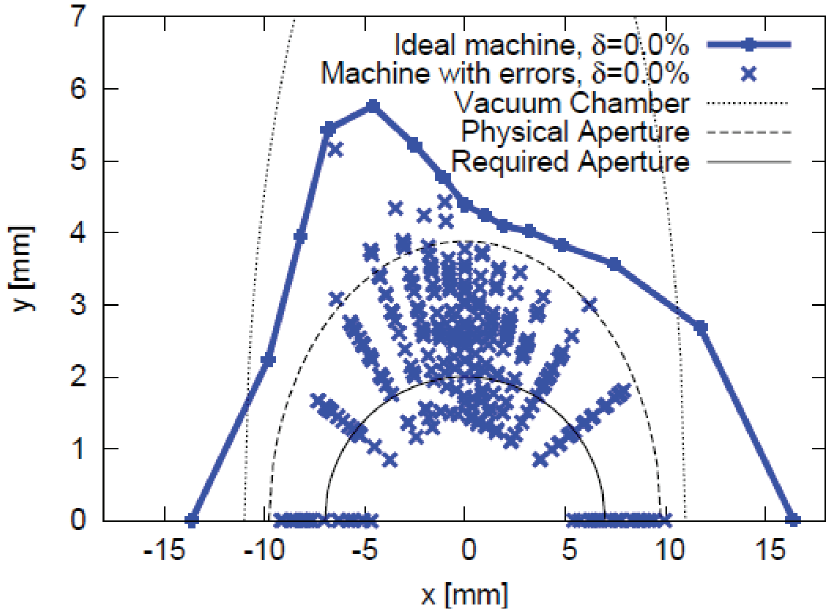
Data by M.Sjöström and D.K.Olsson

Dynamic Aperture Measurements

- Excite oscillations with pulsed magnets and look for amplitudes that lead to beam loss.
- Turn-By-Turn BPM data



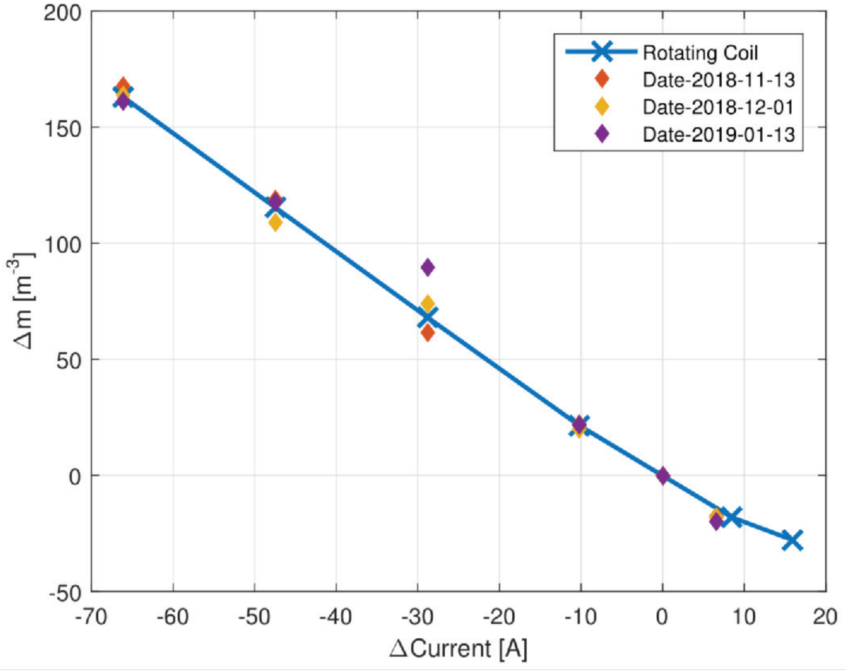
Measurements by D.K.Olsson



MAX-lab internal note 20121107
S.C.Leemann

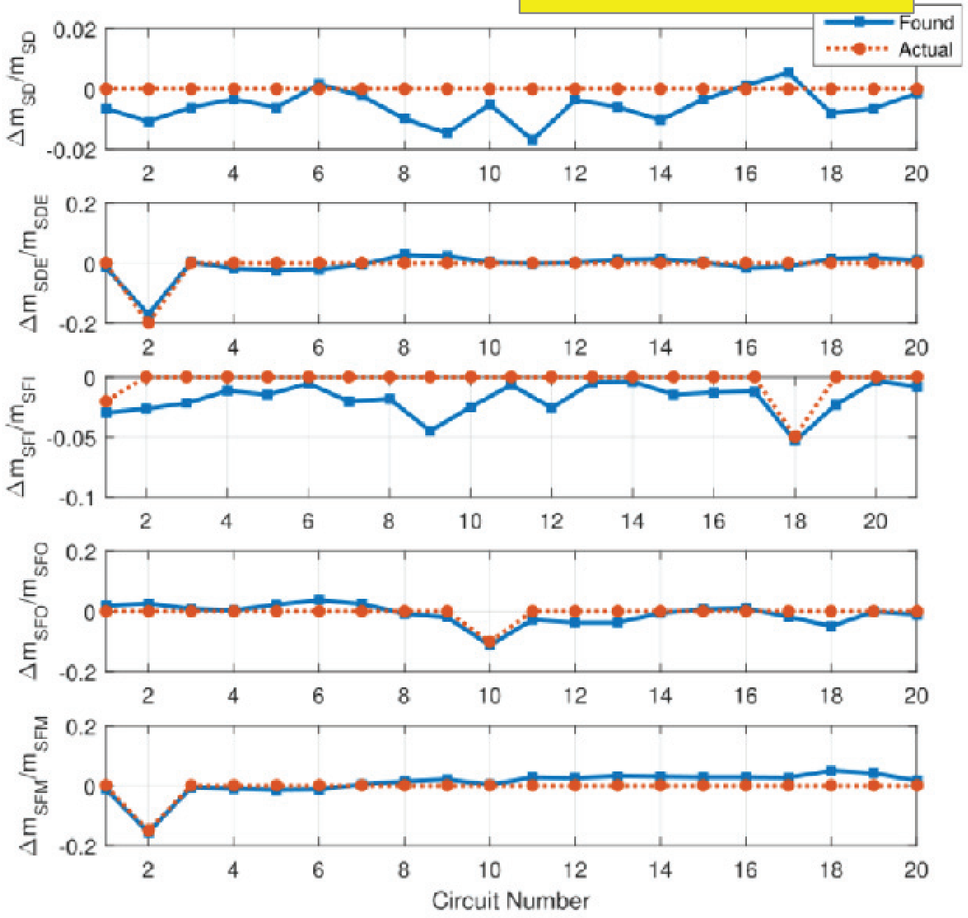
Non-Linear Lattice Studies

Poster:TUPGW064



Sextupole Calibration from second-order dispersion beating

Poster:MOPTS004



Sextupole Strength determination from off-energy orbit response matrix fits

Data and plots by D.K.Olsson

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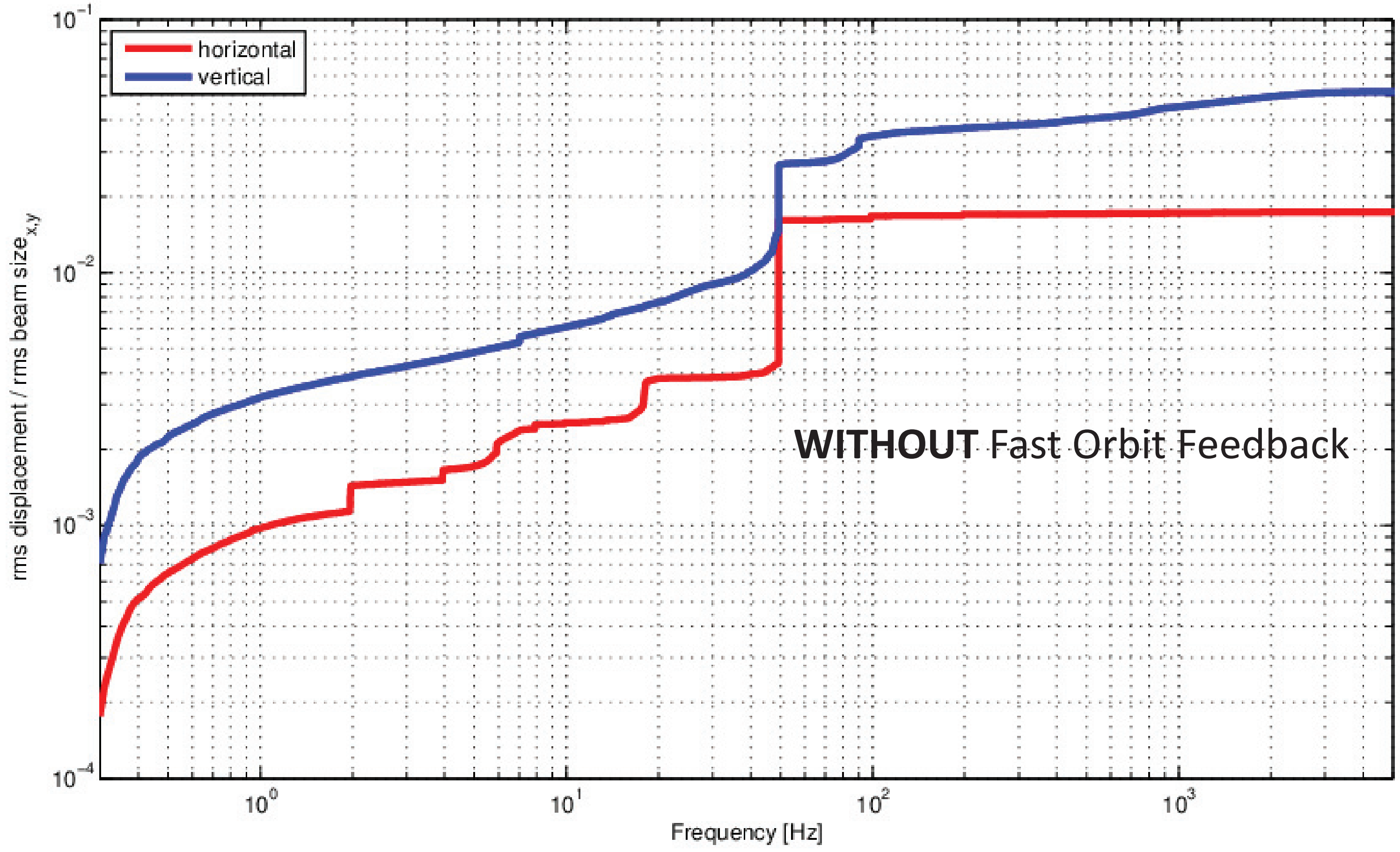
Orbit Stability – Short Term

Average of 13 long straight flanking BPMs
April 2019, 250 mA beam current

Plot By Jonas Breunlin

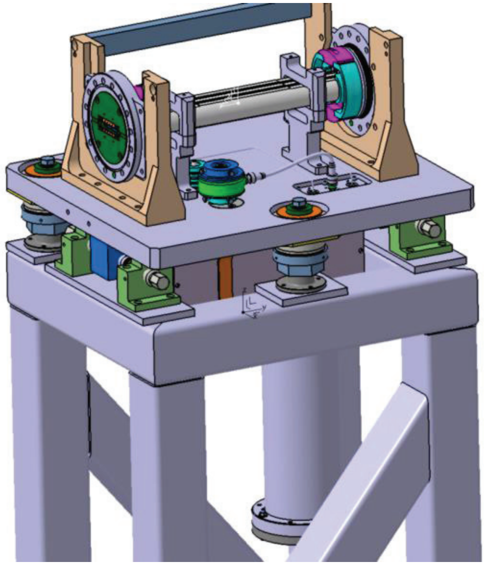


Integrated up to 5 kHz

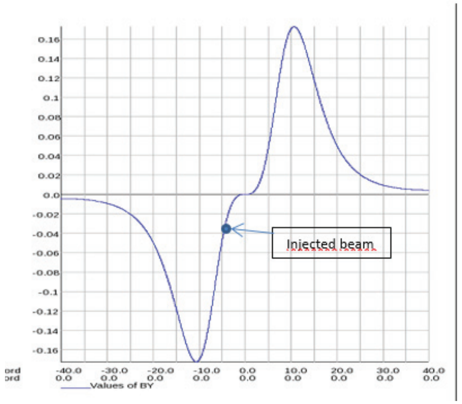
- ❑ Horizontal RMS < 2.0 % of RMS beam size
- ❑ Vertical RMS < 5.0 % of RMS beam size

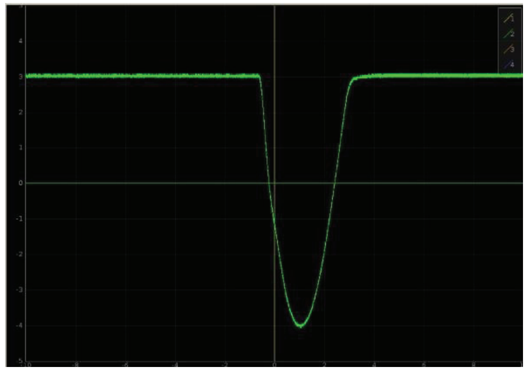
3 GeV Ring Highlights: Multipole Injection Kicker (MIK)

- Objective: achieve near transparent top-up injection.
- Joint project with **SOLEIL** based on original concept from **BESSY**.
- **First prototype** installed in the 2017 shutdown.
- Injection with MIK (up to 500 mA) demonstrated.
- Perturbation to the stored beam reduced by a factor ~60.

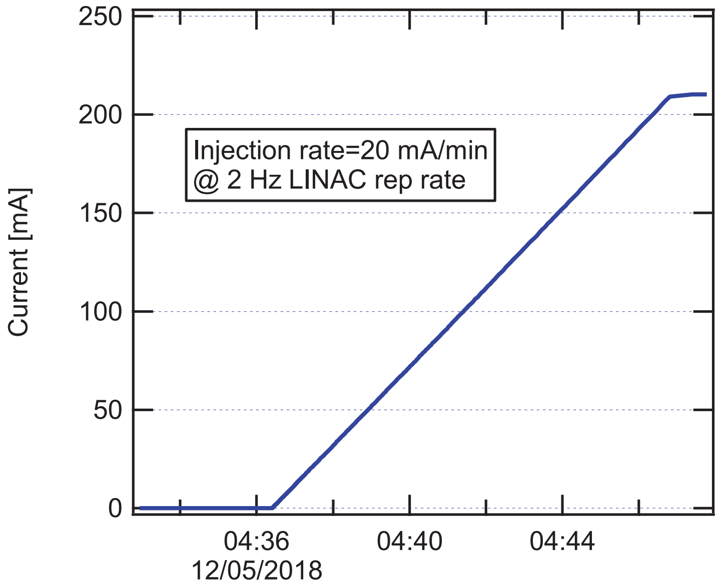


Drawings by SOLEIL
P.Lebasque
P.Alexandre



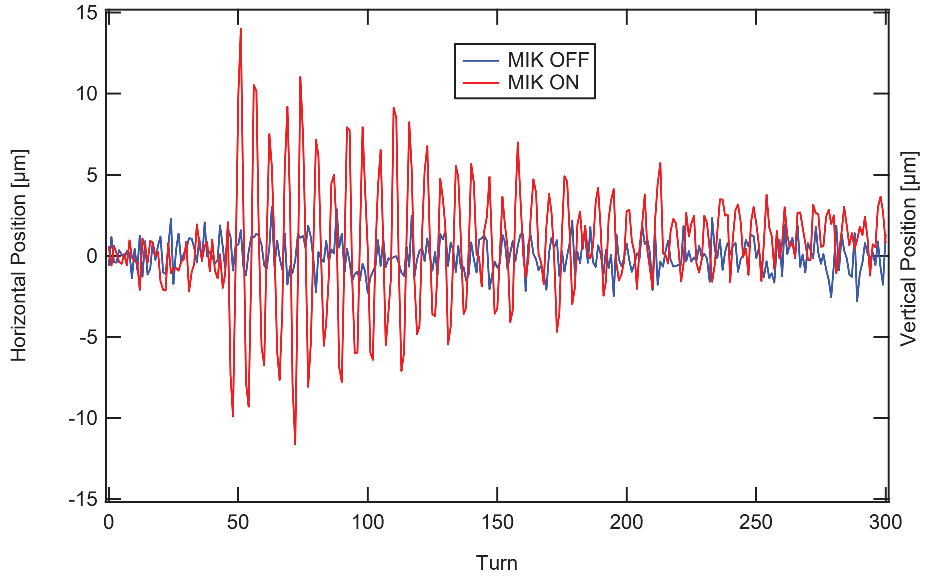


Injection with the MIK

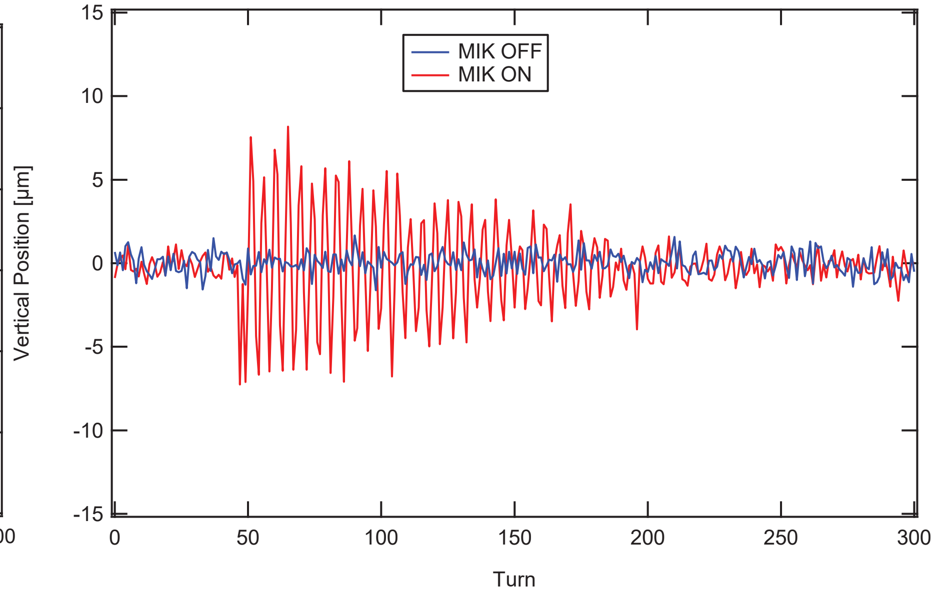


Residual Orbit Perturbations

- 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 $\beta_x = 9.0\ m\ \beta_y = 2.0\ m$



Horizontal = $\pm 13\ \mu m$



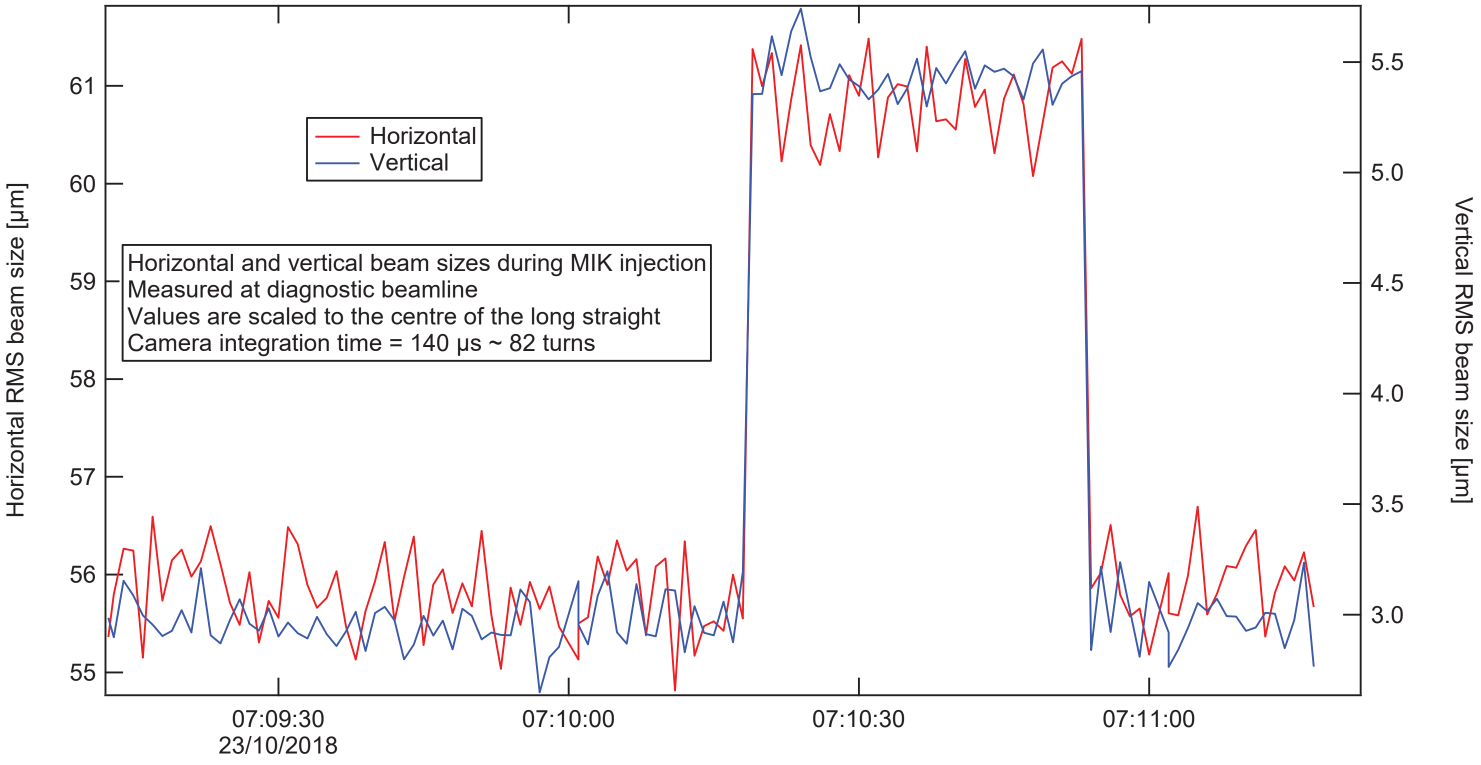
Vertical = $\pm 8\ \mu m$

Residual Beam Size Perturbation

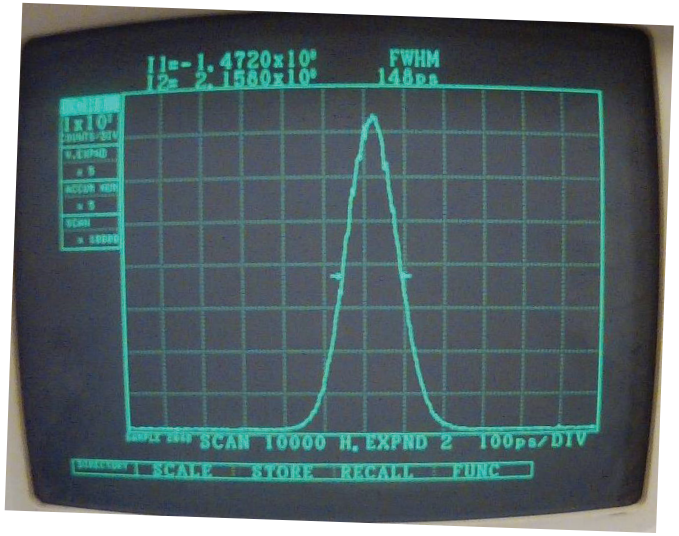
Transverse beam profile in a diagnostic beamline during MIK injection

- Multi bunch fill at 150 mA
- Camera Integration time: ~82 turns
- Camera acquisition synchronized with kicks

Poster:TUPGW063



Effective Impedance Measurements



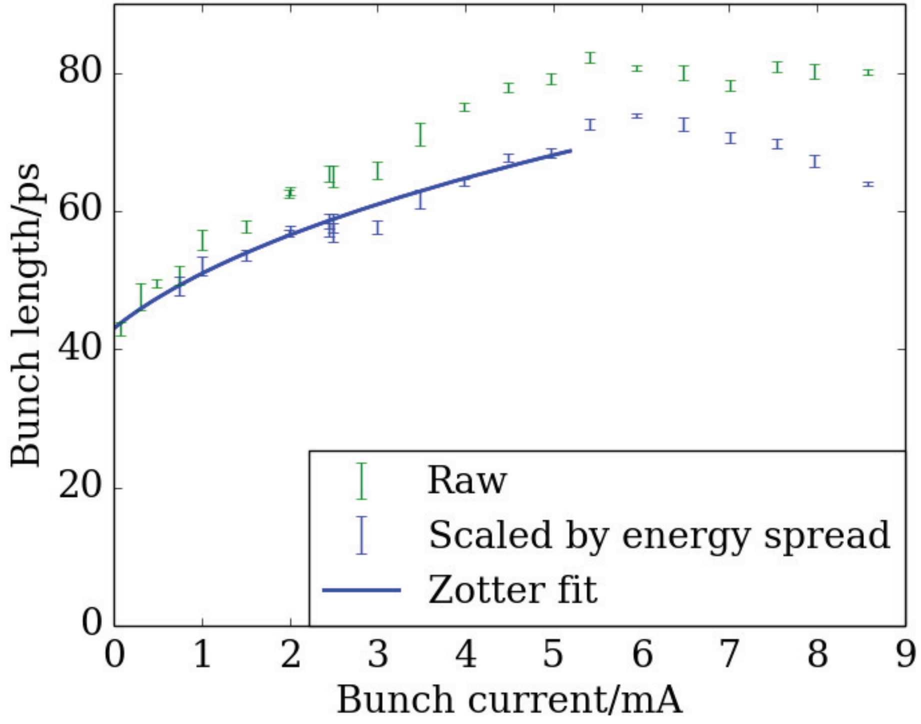
Progress on measurements of longitudinal effective impedance $(Z/n)_{eff}$

- Last component to be precisely measured

New energy-spread measurement to remove effect of IBS

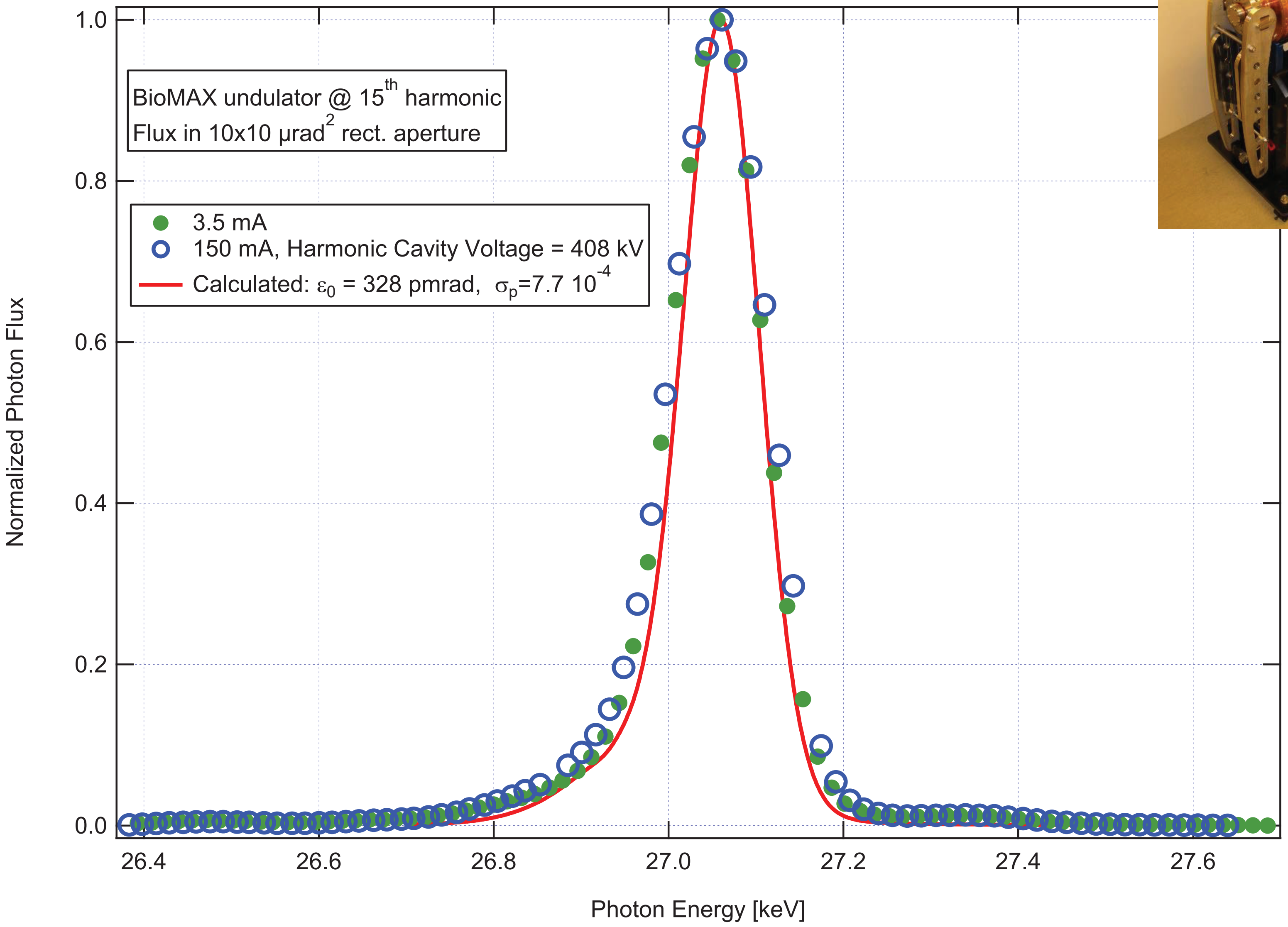
- Especially significant due to low horizontal emittance
- Increase in of around 20 % at 4 mA, agrees with IBS prediction

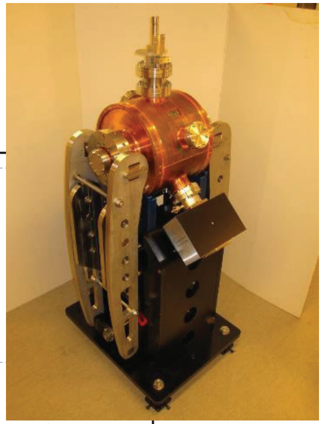
Systematic uncertainties still large



Slide by Francis Cullinan

Long Bunches and ID spectra

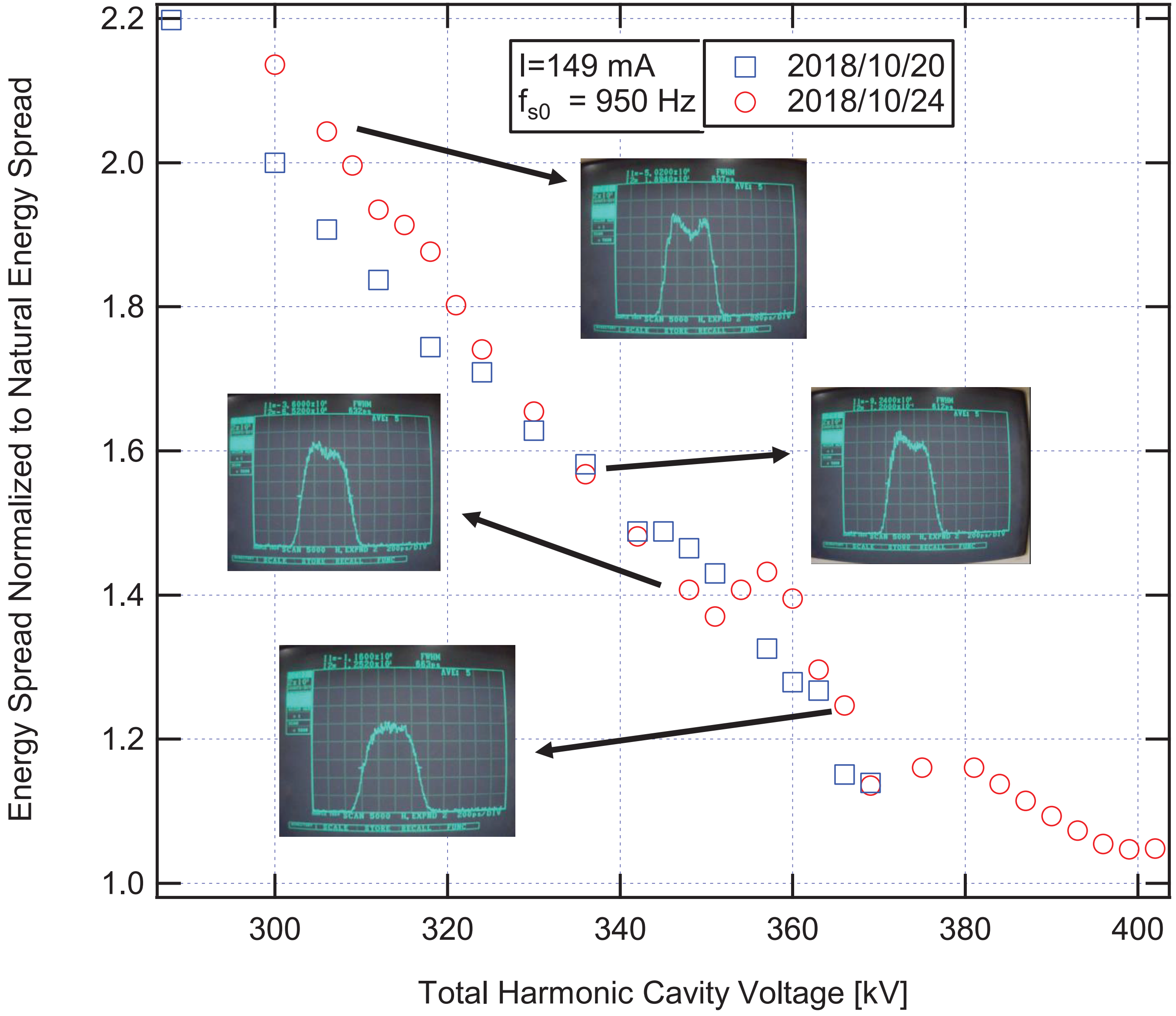




Experimental data courtesy Thomas Ursby and Ana Gonzalez

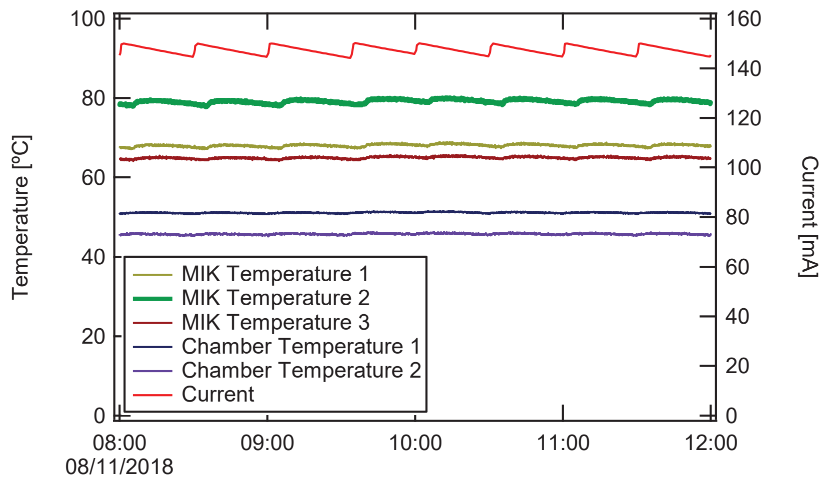
Harmonic Cavities

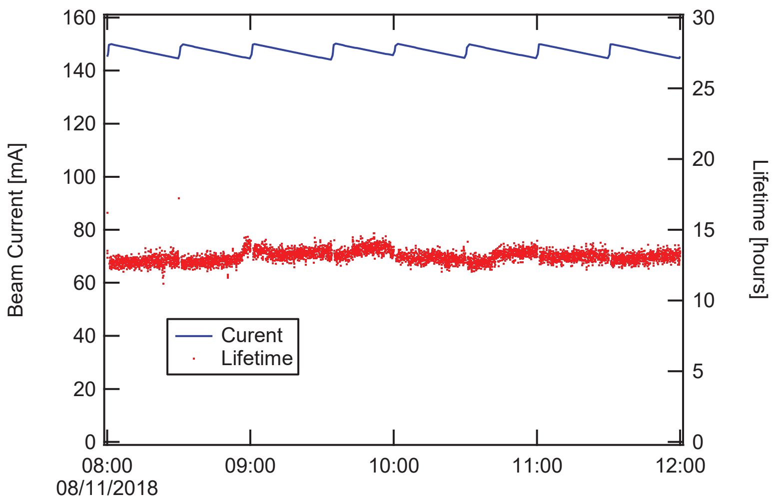
Suppression of Coupled Bunch Instabilities and Bunch Lengthening



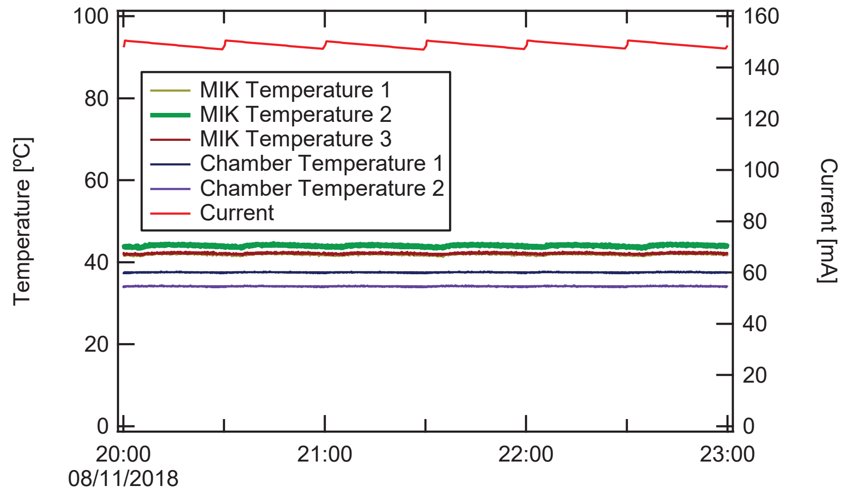
Harmonic Cavities: Lifetime and Chamber Heating

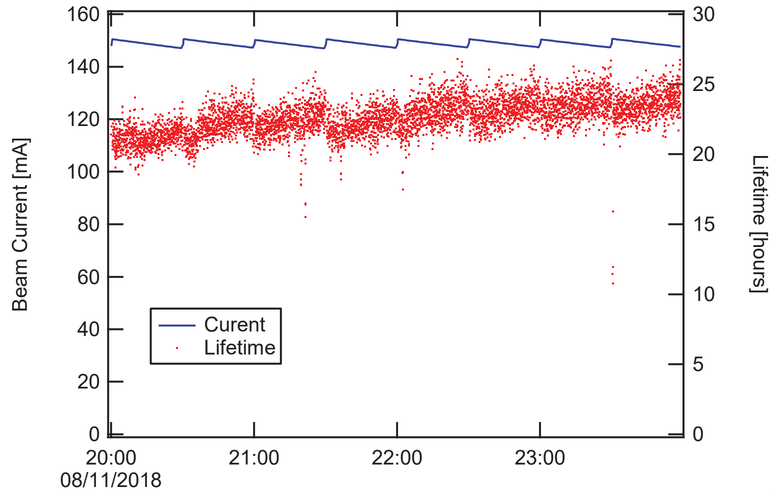
Harmonic cavities **OUT**, BbB **ON**





Harmonic cavities **IN**, BbB **OFF**

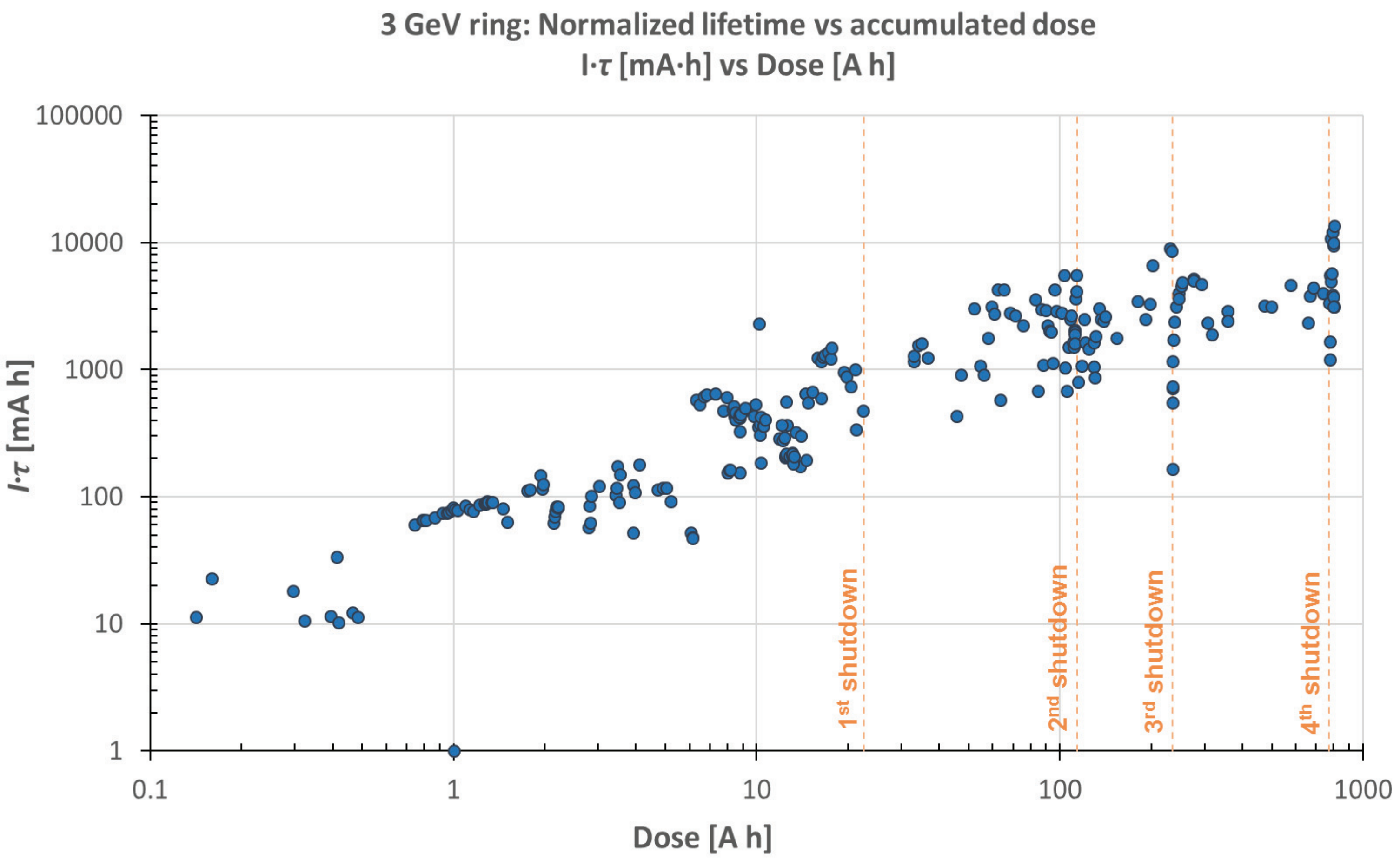




Vacuum performance

Slide by E.Al-Dmour

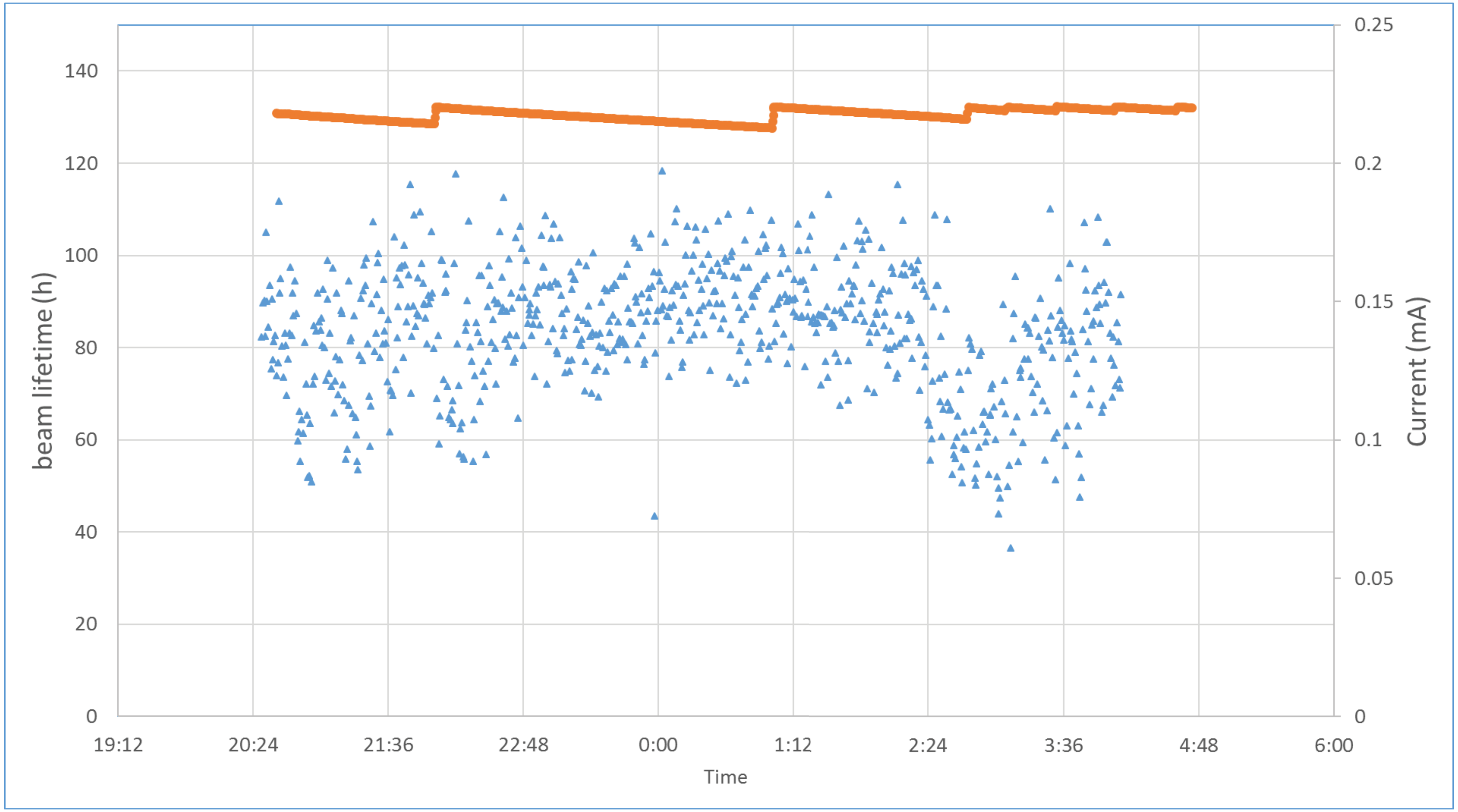
Beam lifetime: the normalized beam lifetime I.τ [mAh] vs. accumulated beam dose [Ah]



After each shutdown there is increase in the average pressure and reduction in the lifetime, but recovery is relatively fast (18-30 Ah), depends on the shutdown scope.

Vacuum lifetime

Test was done where the effective bunch length was very large (beam longitudinally unstable), the total lifetime is mainly gas lifetime, total lifetime was around 90h (I.tau $_{gas} \approx 20\text{Ah}$).



Slide by E.Al-Dmour

Neon Venting in the 3 GeV Ring

- A conventional vacuum intervention in R3 takes 2-3 weeks due to the need to reactivate the NEG coating.
- In the 2018 summer shutdown, we tested a new procedure (developed originally at CERN) in which
  - the chambers are vented with ultra-pure neon gas (instead of nitrogen).
  - The time the chamber remains open is minimized by careful planning of the intervention.
  - The chamber is pumped down **WITHOUT** reactivation (i.e., no baking at ~200 °C)
- This reduces the intervention time to just a few days.
- The big question was: **how does the vacuum pressure and beam lifetime recover after such an intervention ?**

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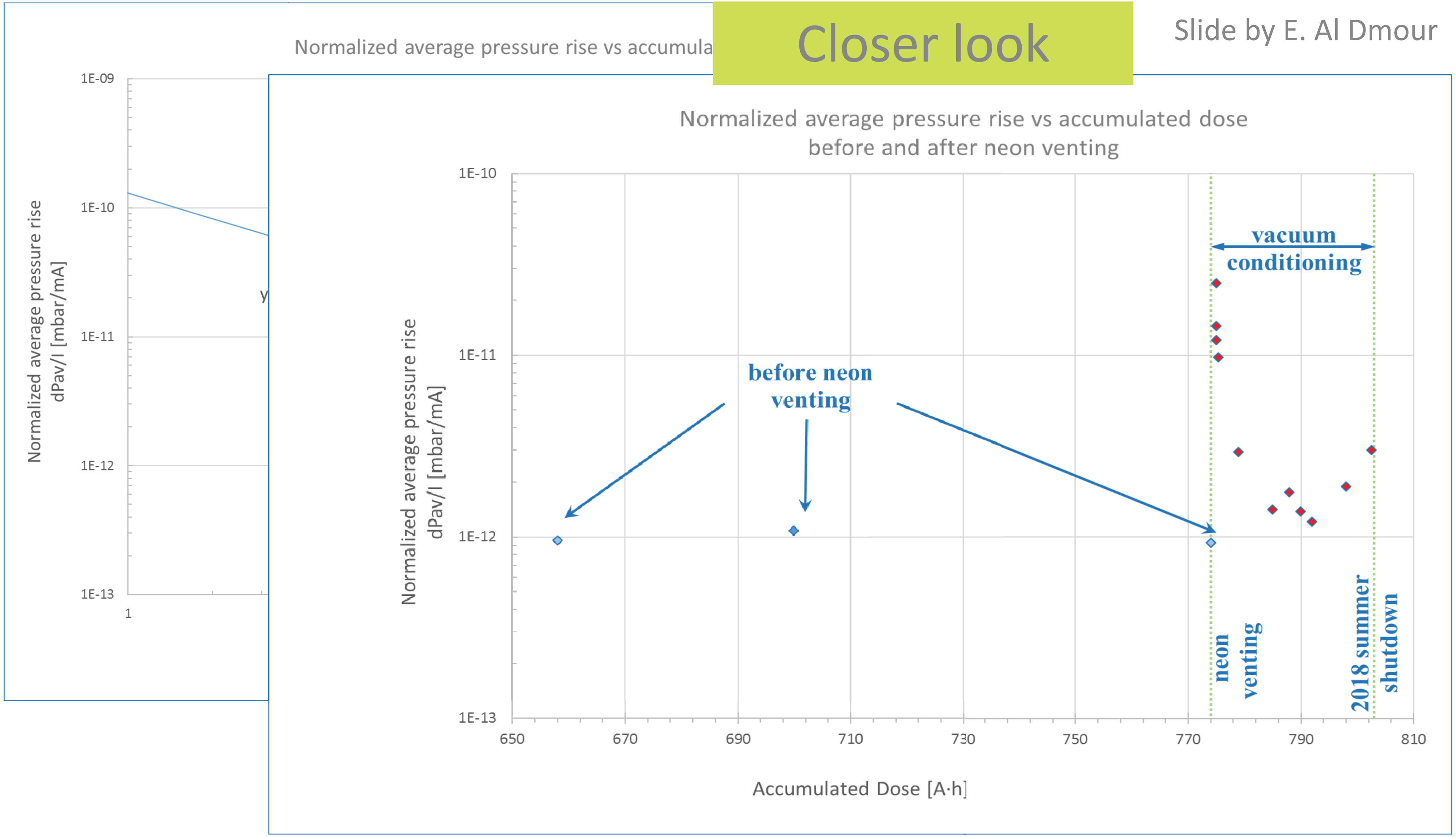
Vacuum conditioning after neon venting intervention.

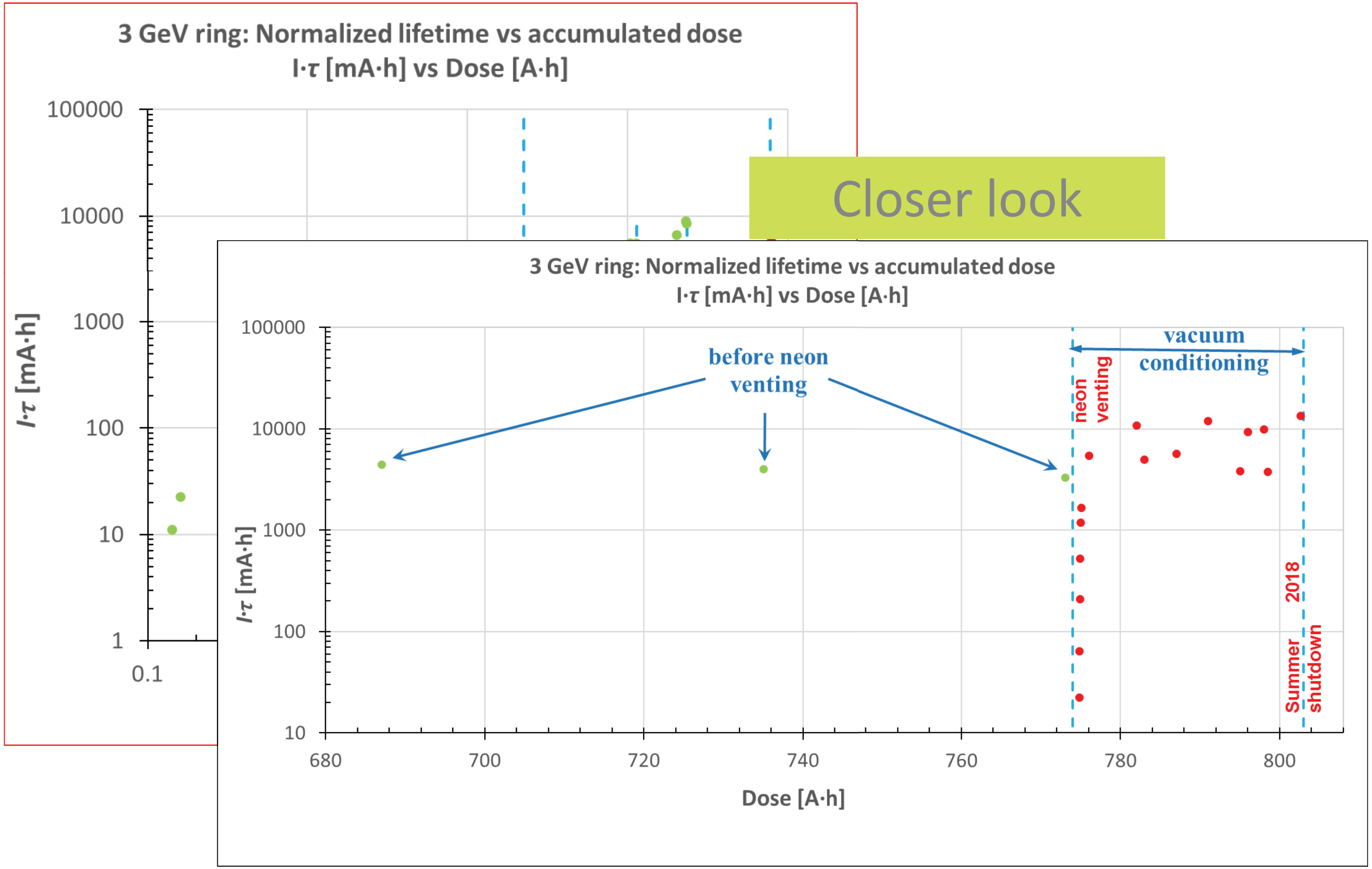
Slide by E. Al Dmour



The average pressure recovered after around 18Ah, highest pressure readings were close to the areas were we have exchanged the vacuum chambers.

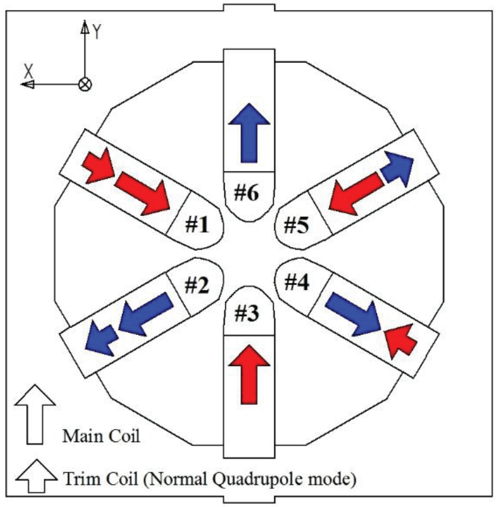
Slide by E. Al Dmour

Life time after neon venting

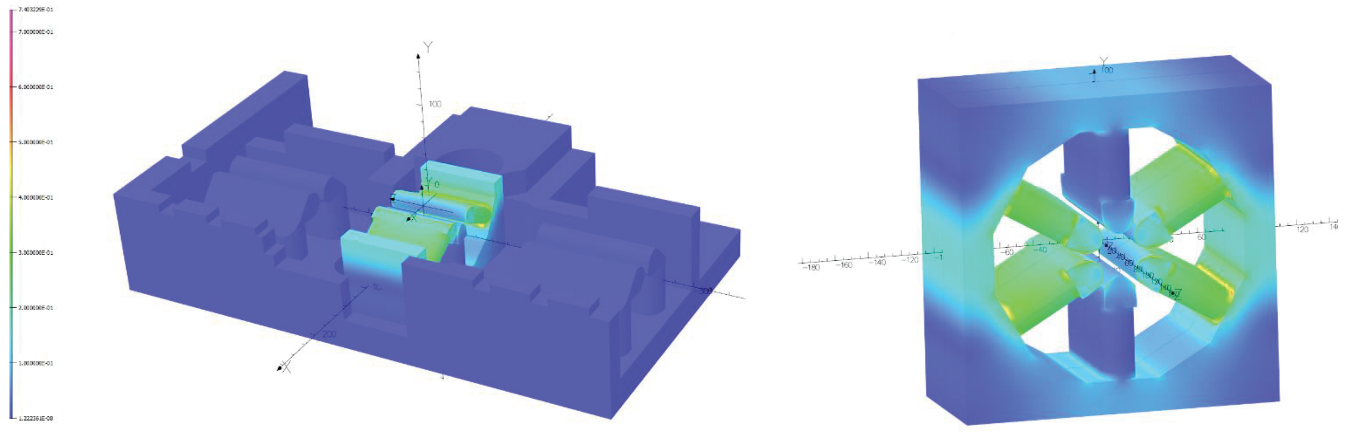


Beam-based BPM calibration and magnet saturation

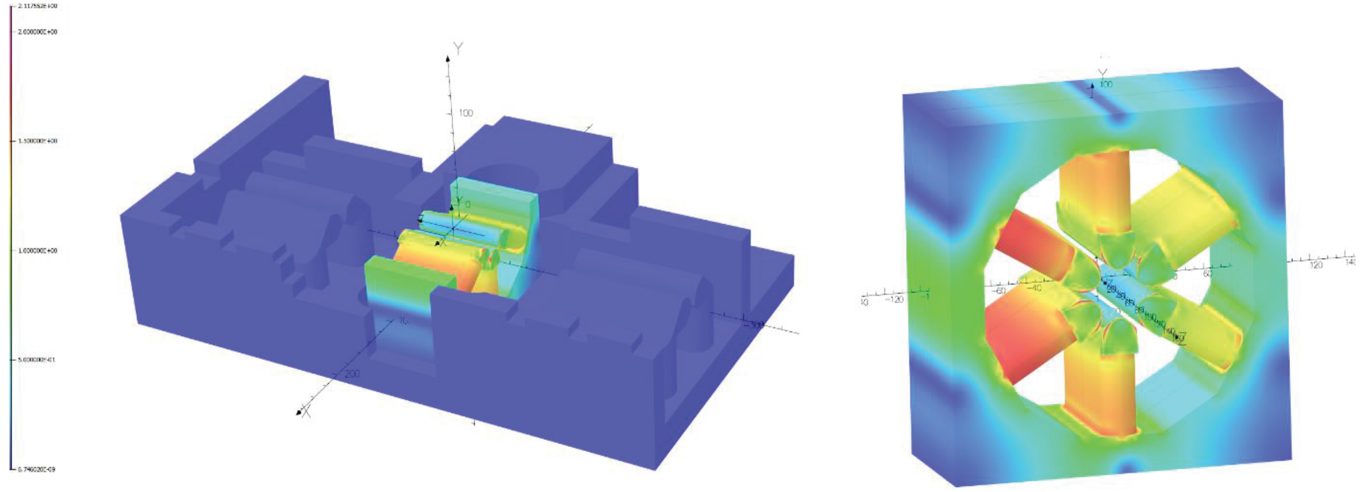
- At MAX IV, BPM based callibration is done with respect to nearby *sextupoles.*
- Trim coils are used to generate a quadrupole field on a sextupole yoke
- Early during commissioning a dependence of the measured offsets on the excitation of the sextupole main coils
- Magnet saturation was suspected early on, but 2D simulations could not explain the magnitude of the effect



Only Trim Coils ON

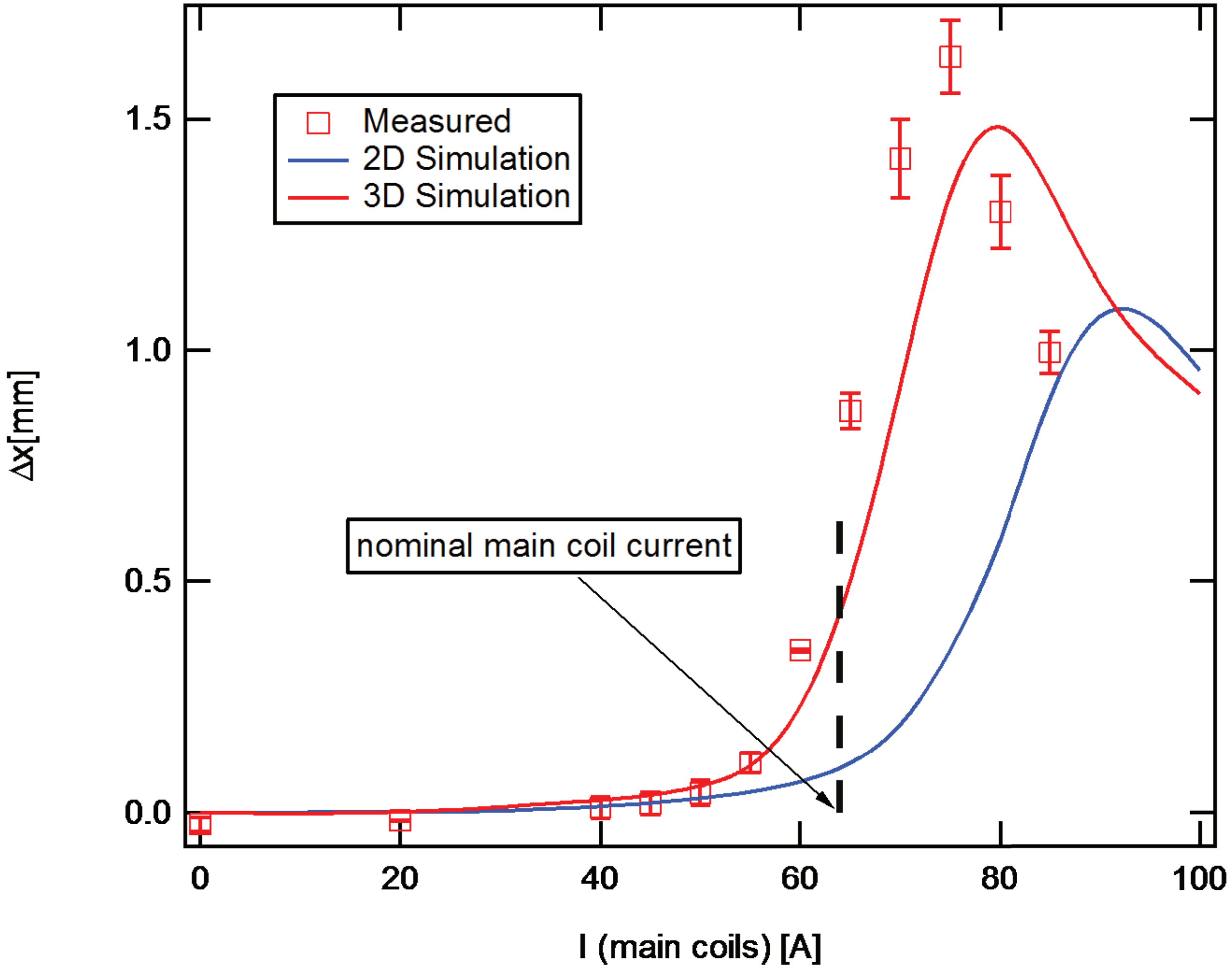


Trim Coils + Main Coils ON



Calculations and pictures by Alexey Vorozhtsov

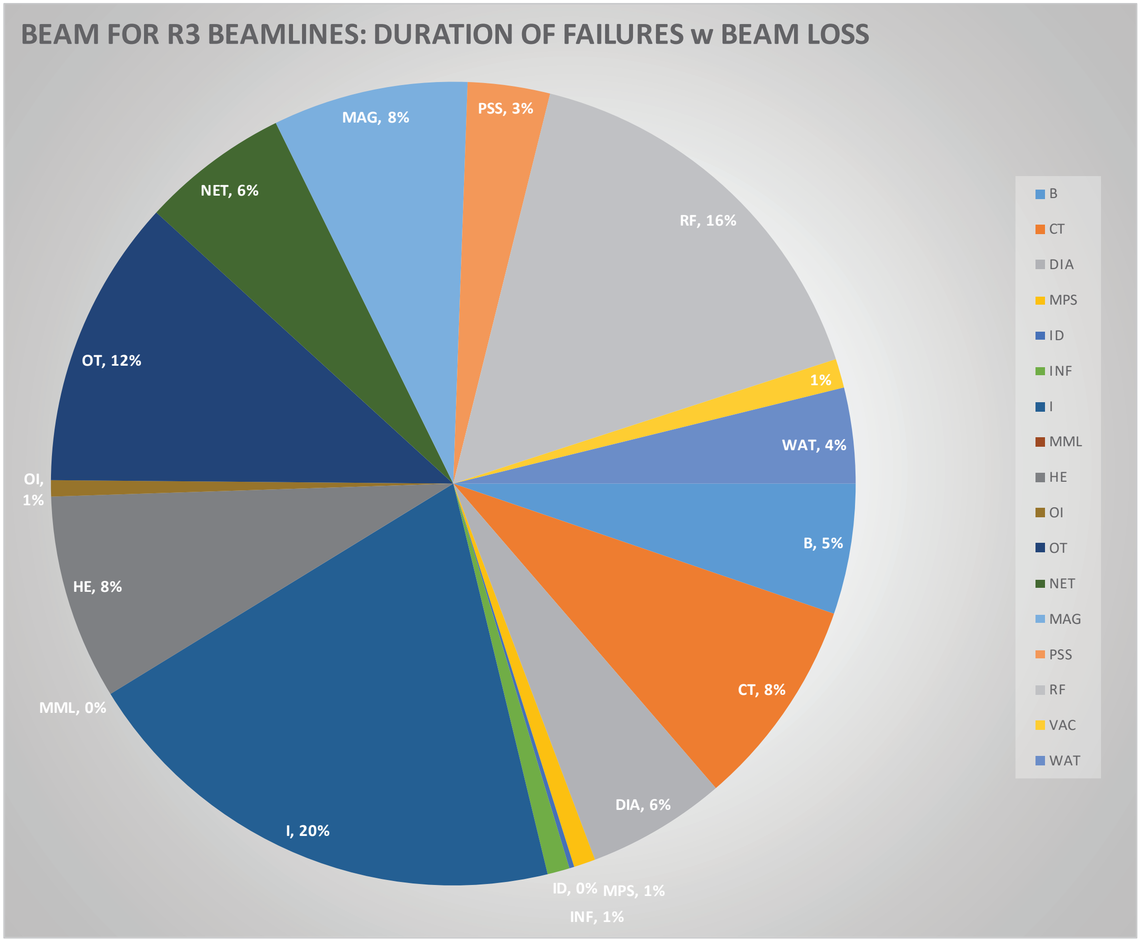
Simulation vs Experiments



simulated data by Alexey Vorozhtsov
experimental data by Robin Svärd

2018 3 GeV Ring Operations Summary

- 24/7 Accelerator operations since January 2018.



- 4068 scheduled delivery hours
- 96.2 % availability
- 34.5 h MTBF
- 1.3 h MTTR

Plots and data by Stephen Molloy

Future Perspectives: A soft X-ray free-electron laser @ MAX IV

A working group co-chaired by Anders Nilsson and Stefano Bonetti at Stockholm University.

- A workshop at Stockholm University March 21-23, 2016
- 120+ participants

- Uses the existing 3 GeV MAX IV injector LINAC
- 1-5 nm wavelength range

Funding (~30 MSEK) for a CDR from Stockholm Universty, Upsalla University, KTH, Lund University, MAX IV and the Wallenberg Foundation (KAW).

CDR to be delivered in Q1 2021

MAX IV LABORATORY

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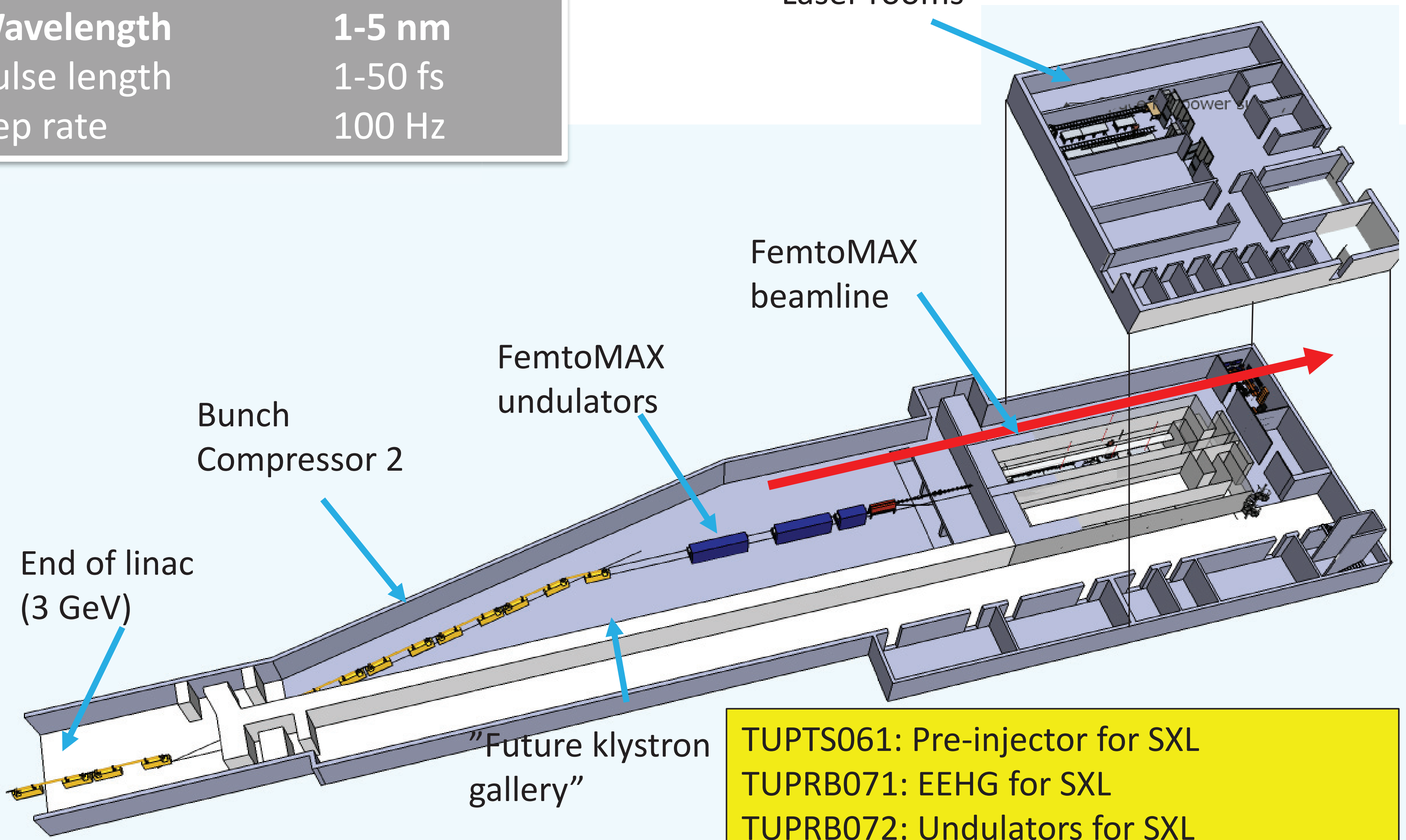
Future Perspectives: A soft X-ray free-electron laser @ MAX IV

Wavelength	**1-5 nm**
Pulse length	1-50 fs
Rep rate	100 Hz



TUPTS061: Pre-injector for SXL
TUPRB071: EEHG for SXL
TUPRB072: Undulators for SXL
THPGW052: Photocathode laser diffuser

MAX IV

Conclusions

- MAX IV has sucessfully demonstrated the first fourth generation storage-ring based ultra-low emittance source that used the Multi-Bend Achromat.
- Next immediate plans at MAX IV: a soft X Ray FEL
- Further brightness improvements are on the way.

Poster: TUPGW075

Thank you for your attention

MAX IV