Harmonic Cavities at MAX IV

Å. Andersson, J. Breunlin, F. Cullinan, E. Elafifi, S.-O. Heed, R. Lindvall, L. Malmgren, D. McGinnis, A. Mitrovic, D. Olsson, T. Olsson, M. Sjöström, P. F. Tavares

& the Operations Group

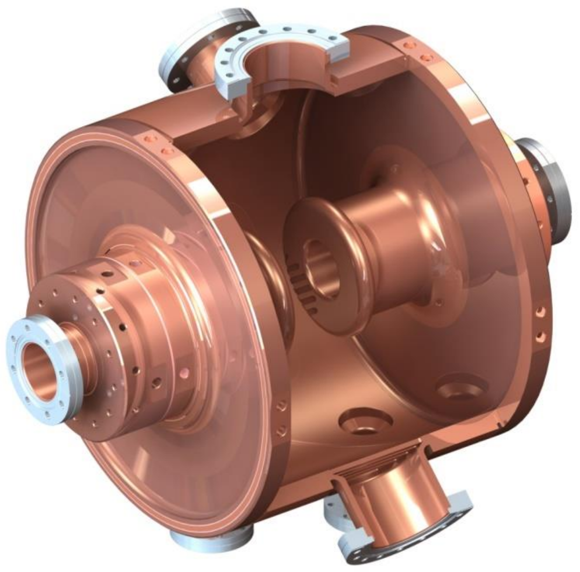
XXVI ESLS Meeting at SOLARIS, Krakow 2018

Outlook

- Design and Philosophy
- 1.5 GeV Ring Status and Outlook
- 3 GeV Ring Status and Outlook

Our 300 MHz 3rd Harmonic Cavities

Mechanical design, Elsayed Elafifi, MAX-lab



Inner length/diameter: 312mm/400mm

Theory R_{sh}/Q: 5.7MΩ/21600
(Definiton: $R_{sh} = V^2/P$)
Measured Q: Around 20900 ➔
R_{sh} = 5.5 MΩ

MAX IV

HC Implementation Philosophy

- Cost-effective with the same system in several machines ➔ MAX IV 3 GeV ring & 1.5 GeV ring ; SOLARIS 1.5 GeV ring ; ASTRID2 0.6 GeV ring.
- All are passive systems, but the cavities could be turned into active ones.
- In both MAX IV rings and in SOLARIS, an **excessive amount of shunt impedance** is installed (*2-4), compared to what's needed at 500 mA (design).
- Allows to run with **lenthened bunches also at lower currents.**
- Should provide a safer **margin towards the Robinson (zero-mode) instability.**

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 064401 (2014)

Equilibrium bunch density distribution with passive harmonic cavities in a storage ring

Pedro F. Tavares, Åke Andersson, Anders Hansson, and Jonas Breunlin

MAX IV Laboratory, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden

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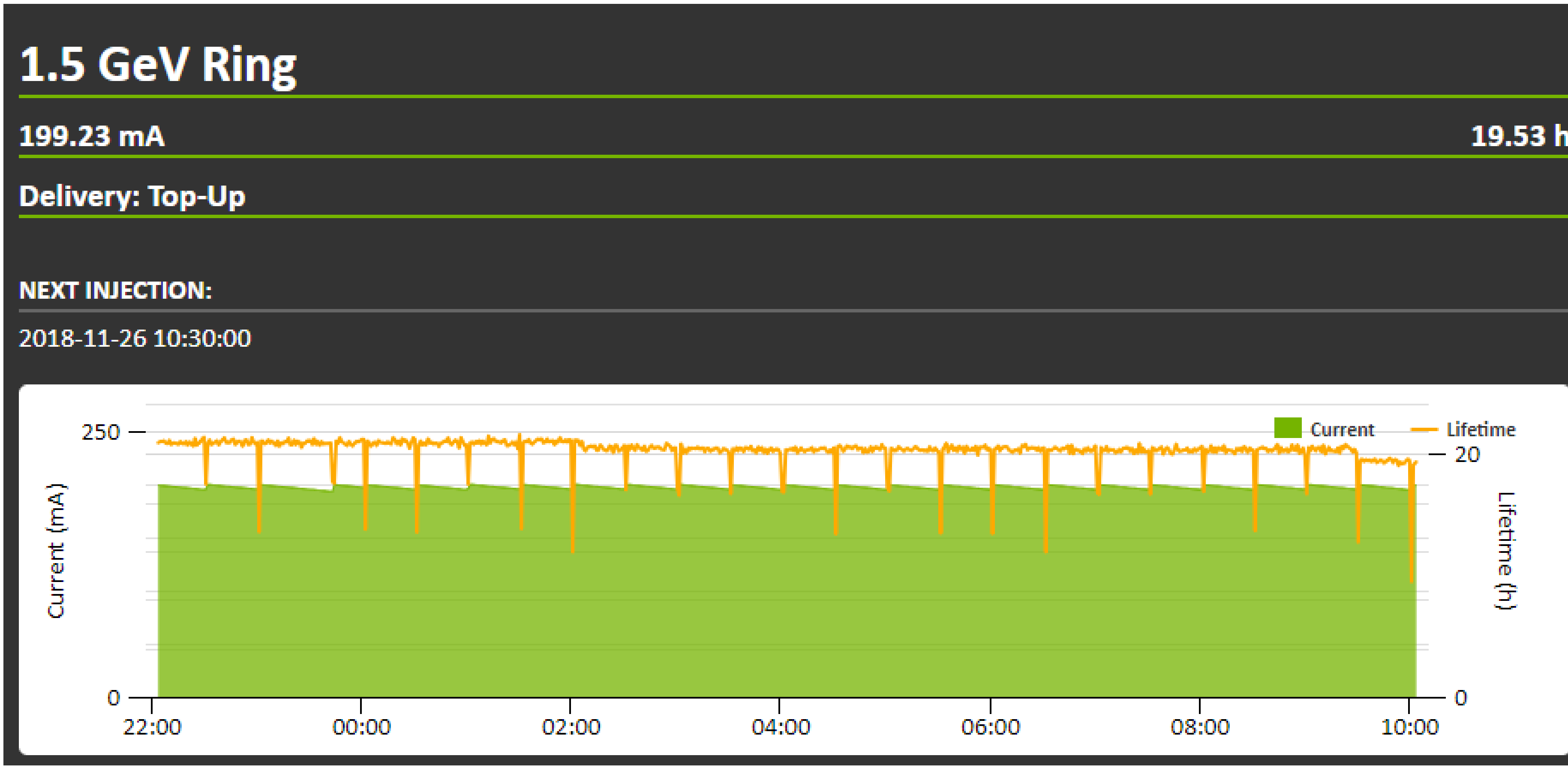
MAX IV

1.5 GeV Ring Delivery



1.5 GeV: RF Straight Section

240 kV 240 kV ~80 kV ~80 kV

A_ε = 3.7 %
f_s = 6.8 kHz

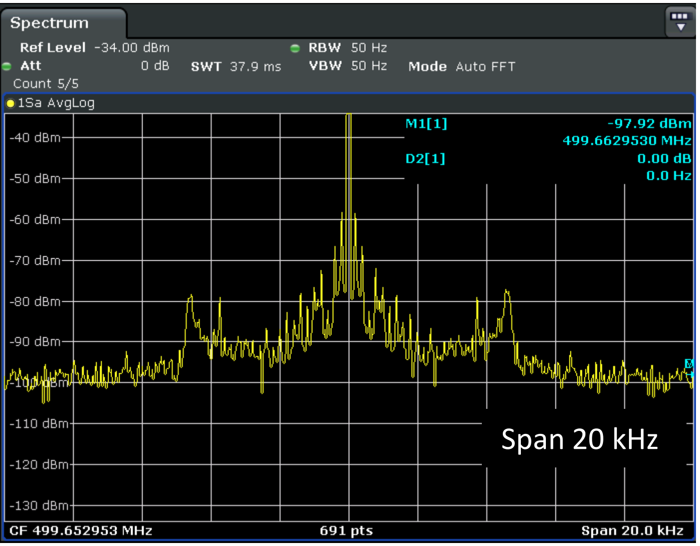
MAX IV

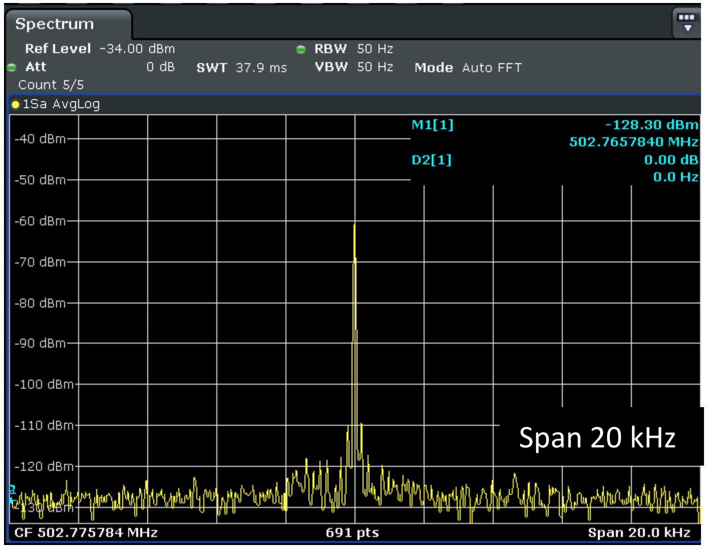
1.5 GeV Ring: HC Impact

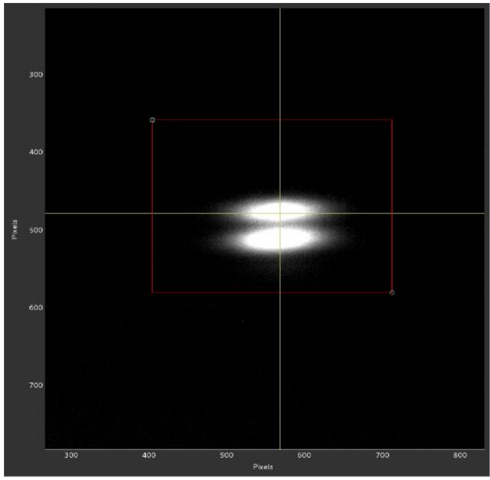
- **With HCs,** an evenly filled bunch train stays stable in all three planes, **without the use of the BbB feedback system**, from around 130mA and upwards.
- **”Auto-tuning”** is applied to the HCs, for maintaining the ~80 kV, when stacking to higher currents.

Longitudinally stable

Transversly stable







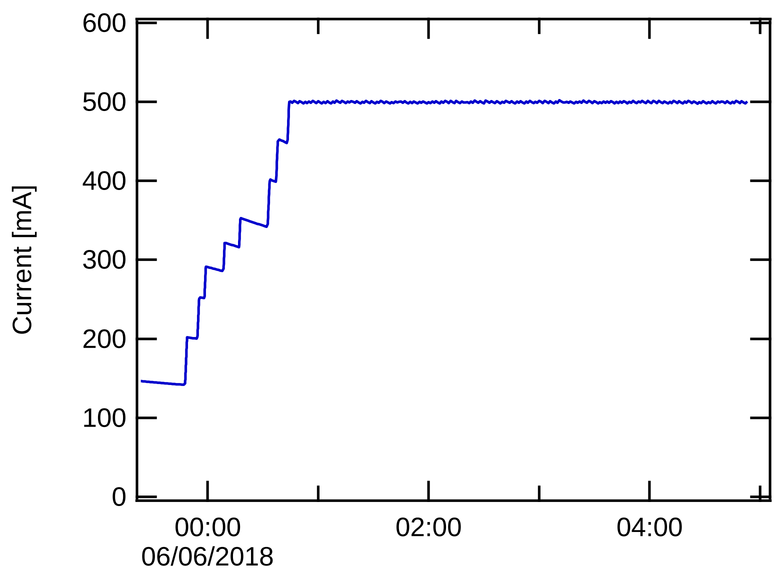
Mode 0

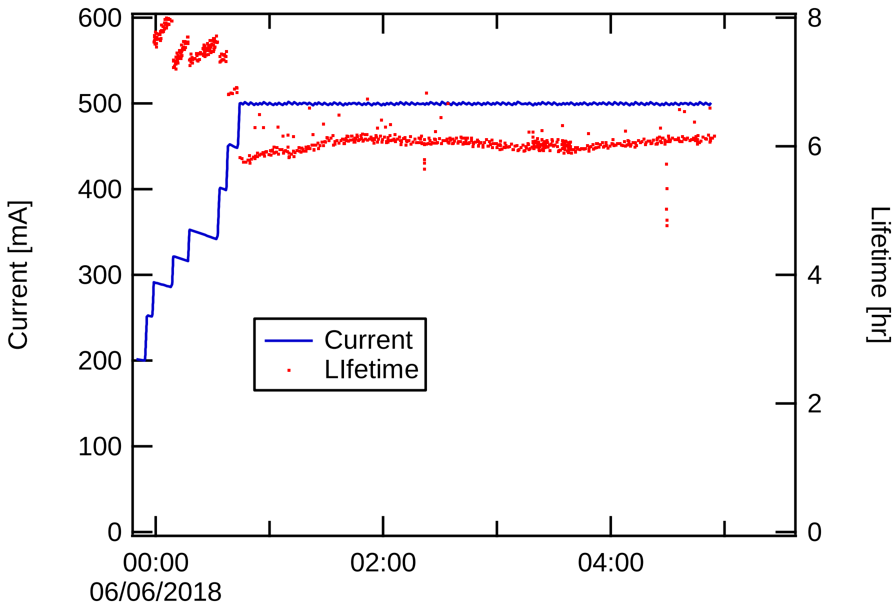
Mode 1 ……. Mode n

Courtesy Robin Svärd & Mathias Brandin

1.5 GeV Ring: Off Delivery time

500 mA in top-up mode during acc. dev. shift.





Night Tuesday 5th to Wednesday 6th of June 2018.

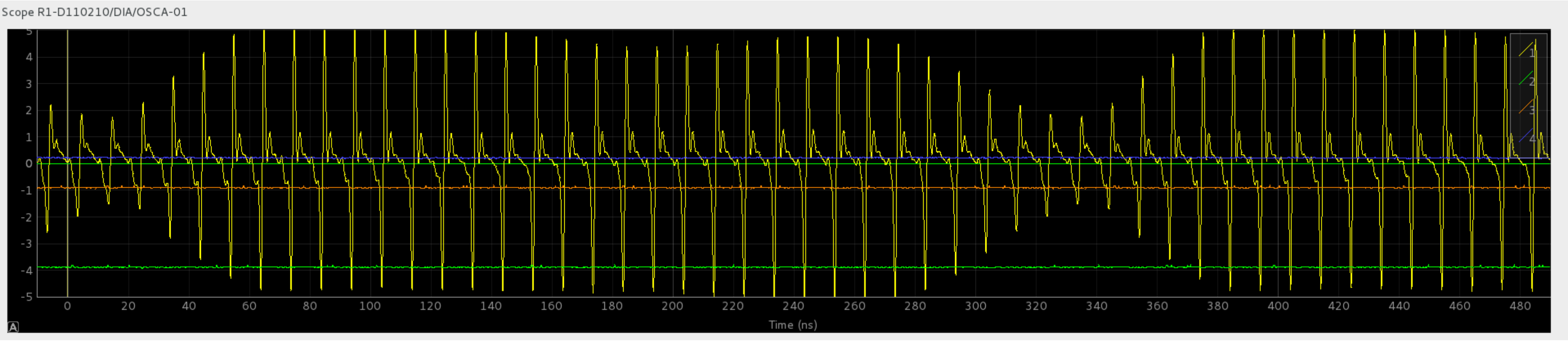
I*Tau = 3 Ah @ 500 mA, but beam was enlarged vertically.

(Design is 5 Ah @ 500 mA)

MAX IV

1.5 GeV Ring Fill Pattern @ 500 mA

- Above a certain current, the beam may go unstable vertically, due to an ion instability. Now at **~450 mA** (earlier at lower currents).
- We counteract by an uneven filling pattern. This, together with the Landau cavities, keep the beam **stable in all three planes up to 500 mA.**



One turn (32 buckets)

- I*Tau = 6 Ah with a vertical emittance of around 50 pmrad

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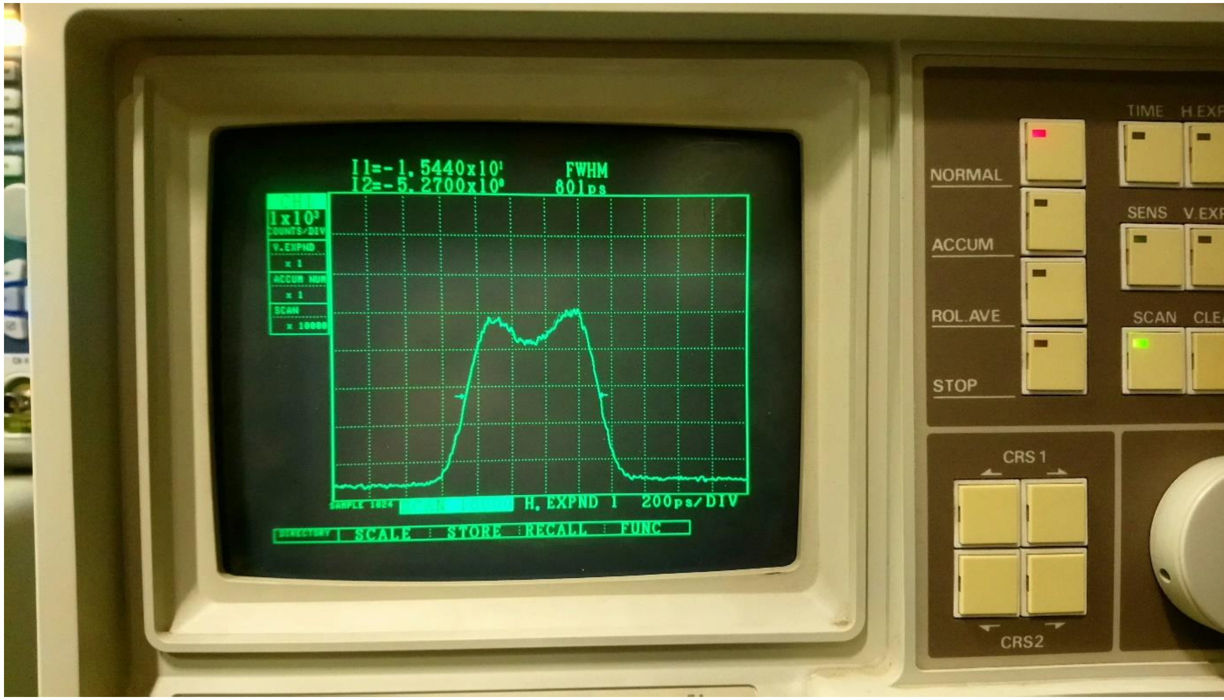
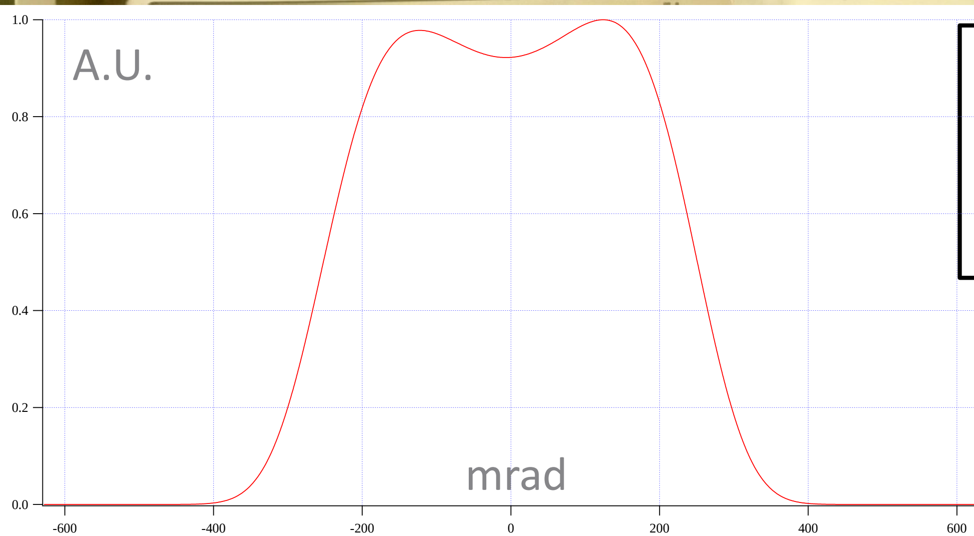
1.5 GeV 180 mA uniform fill



From our Optical Sampling Oscilloscope (OSO): $FWHM_t$ = 800 ps

Natural $FWHM_t$ = 125 ps
➔ Lengthening 6.4
(but rms lengthening is ~5)

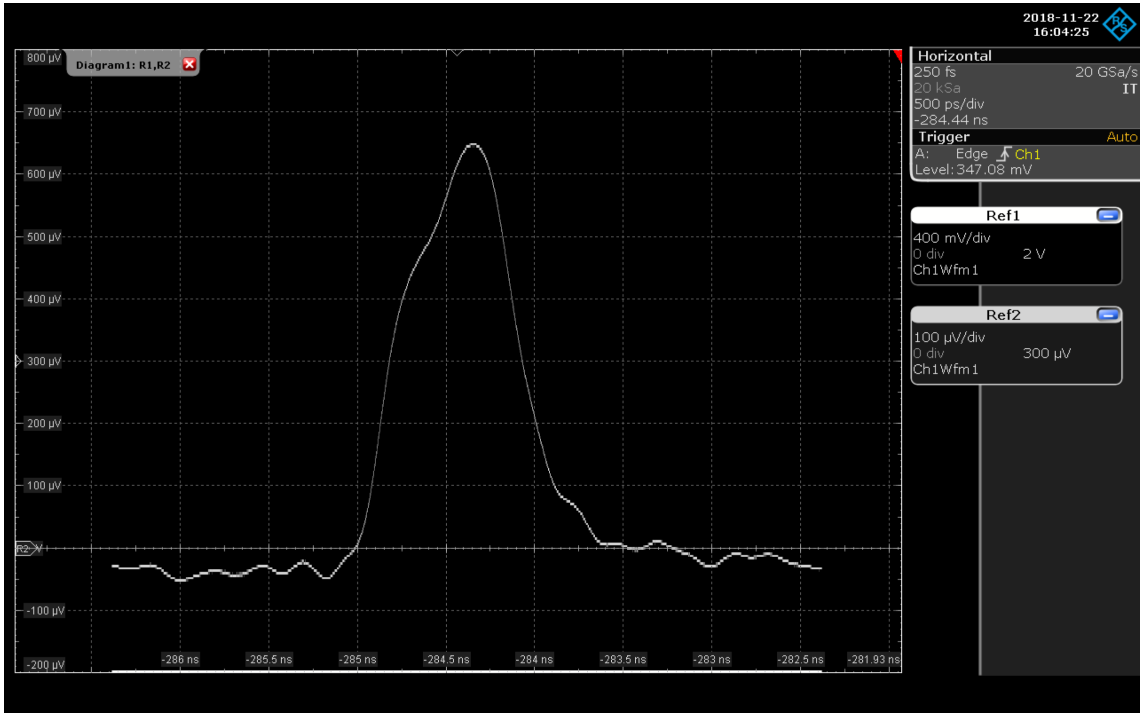


From self-consistent calculation including complex formfactor: $FWHM_t$ = 801 ps

However, we need to assume 79 kV HC-field, but our calibration says 89 kV!!

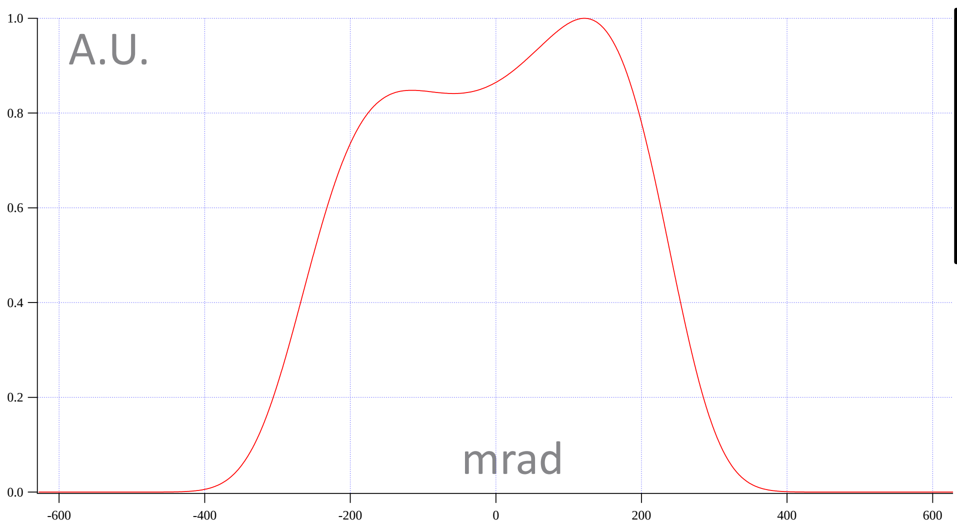
MAX IV

1.5 GeV 360 mA uniform fill



From a Fast FD (30ps rise time) & 6 GHz scope:
FWHM_t = 740 ps

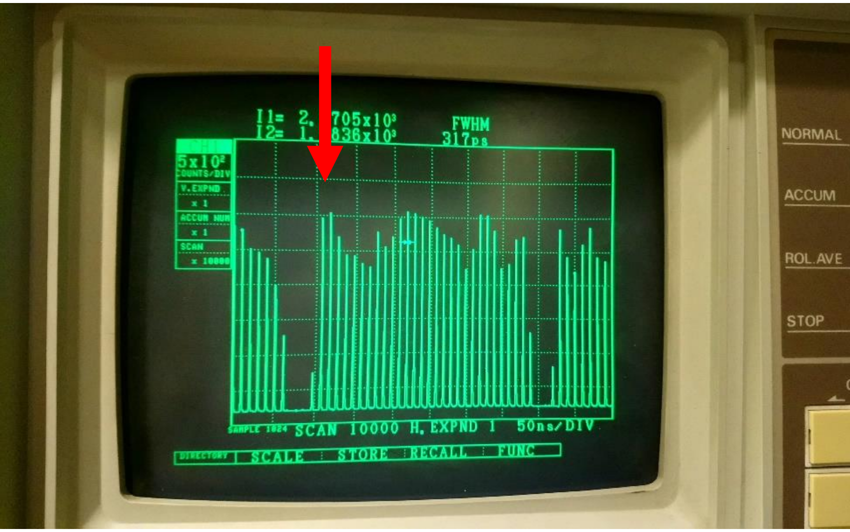
Natural FWHM_t = 125 ps
➔ Lengthening 5.9
(but rms lengthening is ~5)

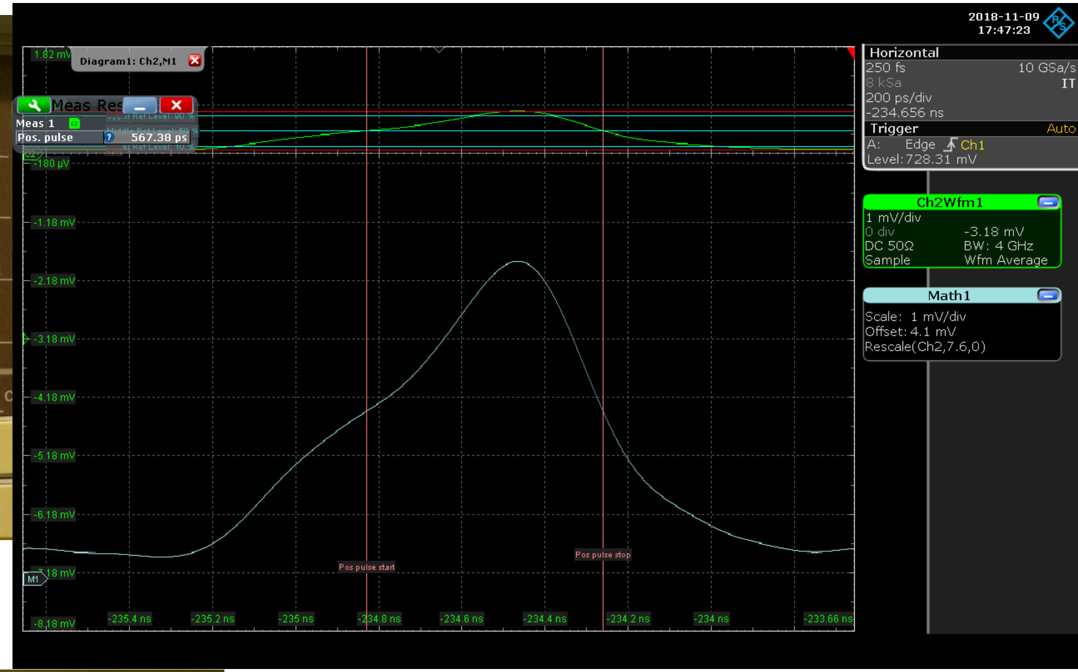


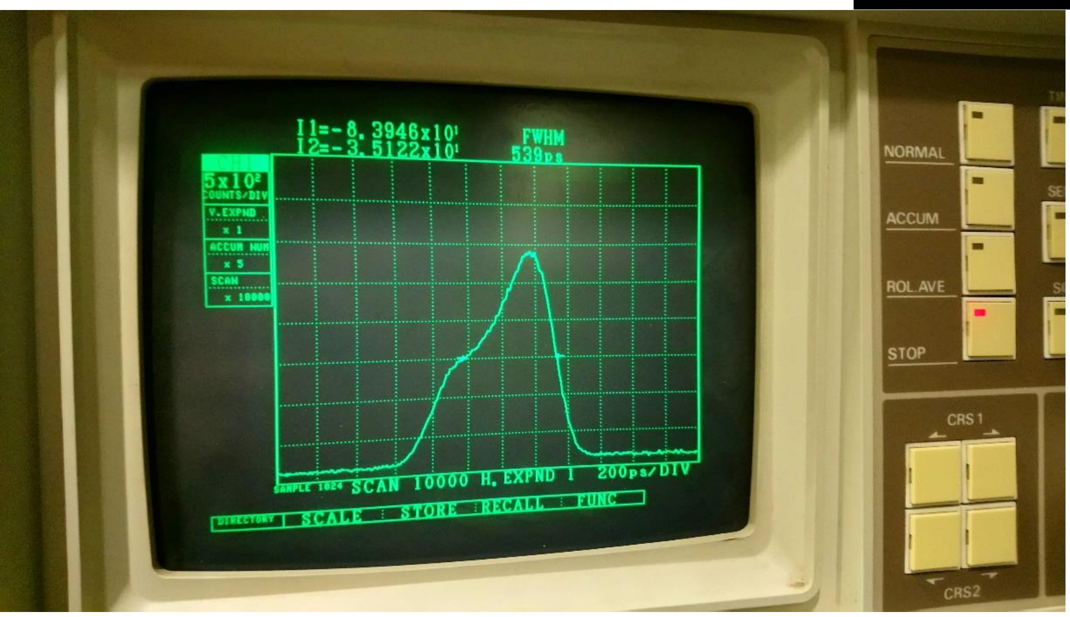
From self-consistent calculation including complex formfactor:
FWHM_t = 781 ps

However, we need to assume 79 kV HC-field, but our calibration says 89 kV!!

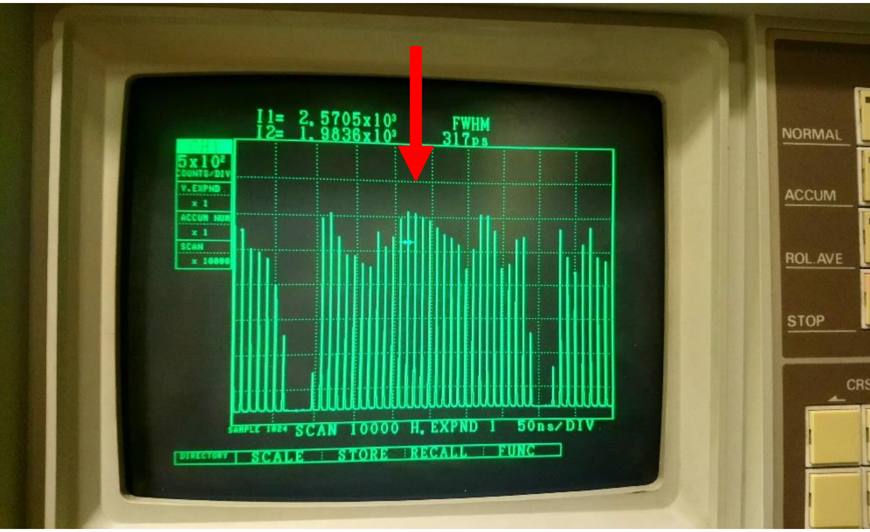
1.5 GeV sharp gap @ 180 mA

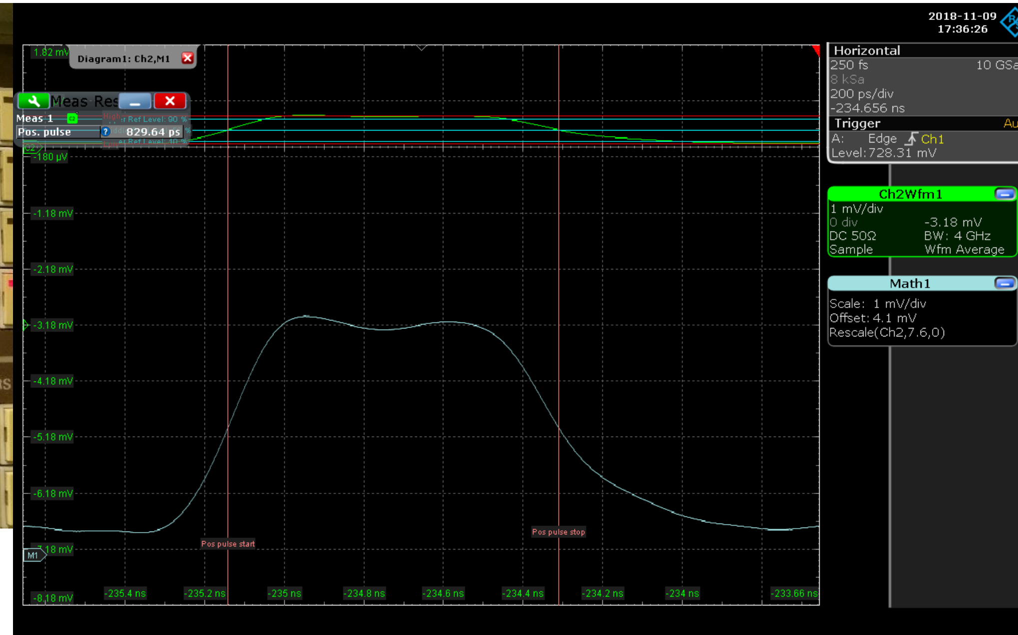




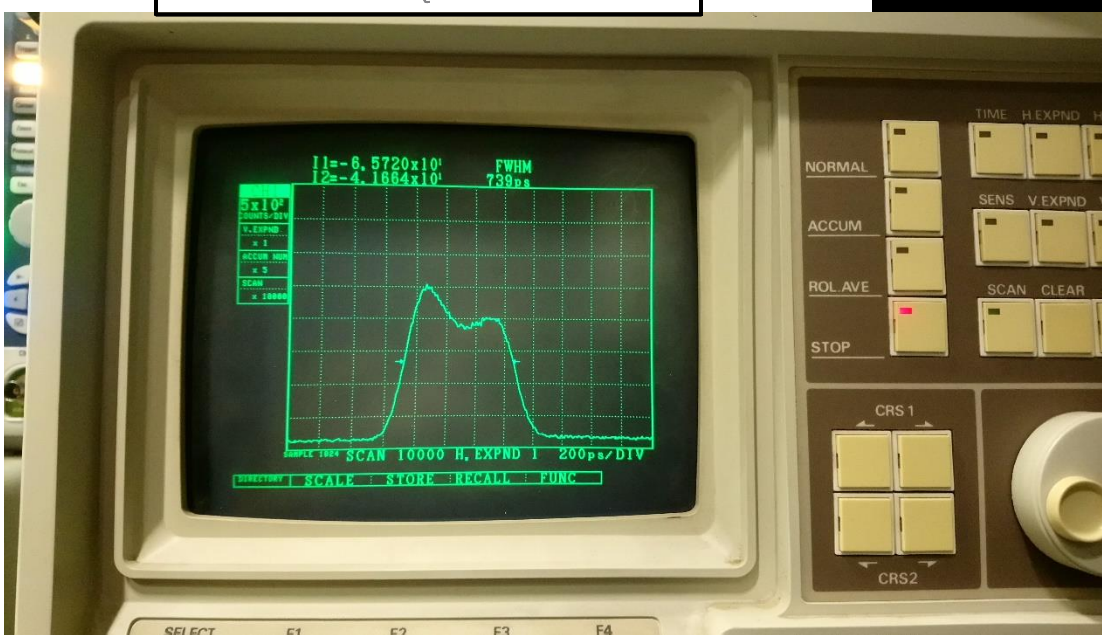


1.5 GeV sharp gap @ 180 mA



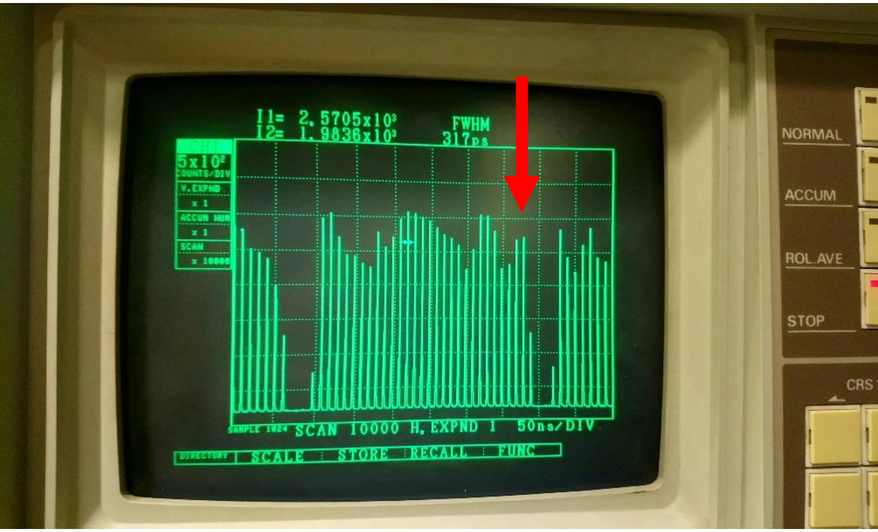


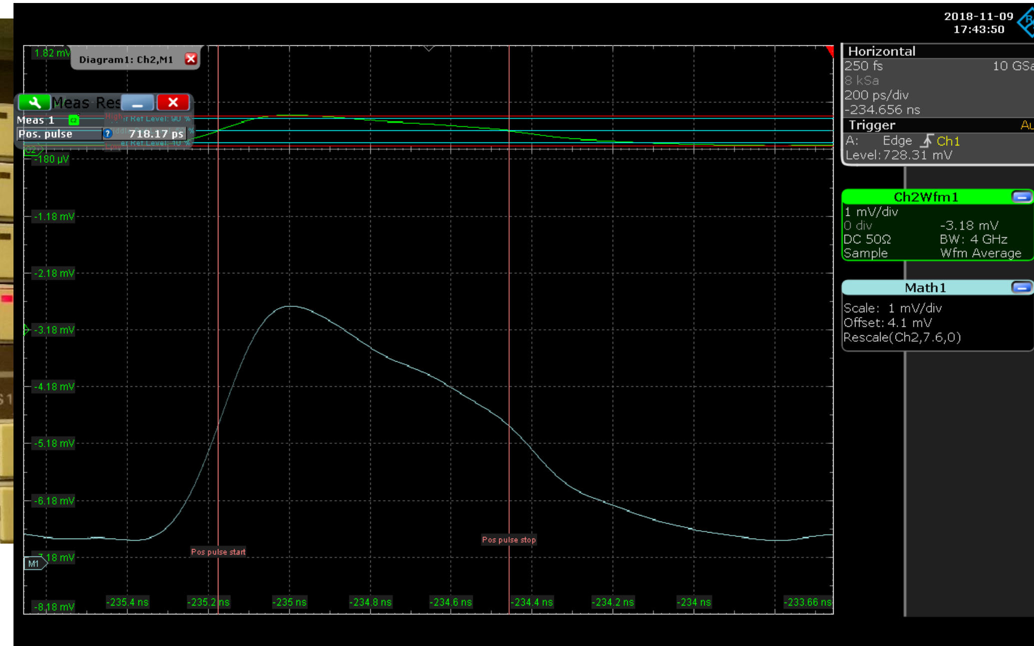
OSO: FWHM$_t$ = 740 ps

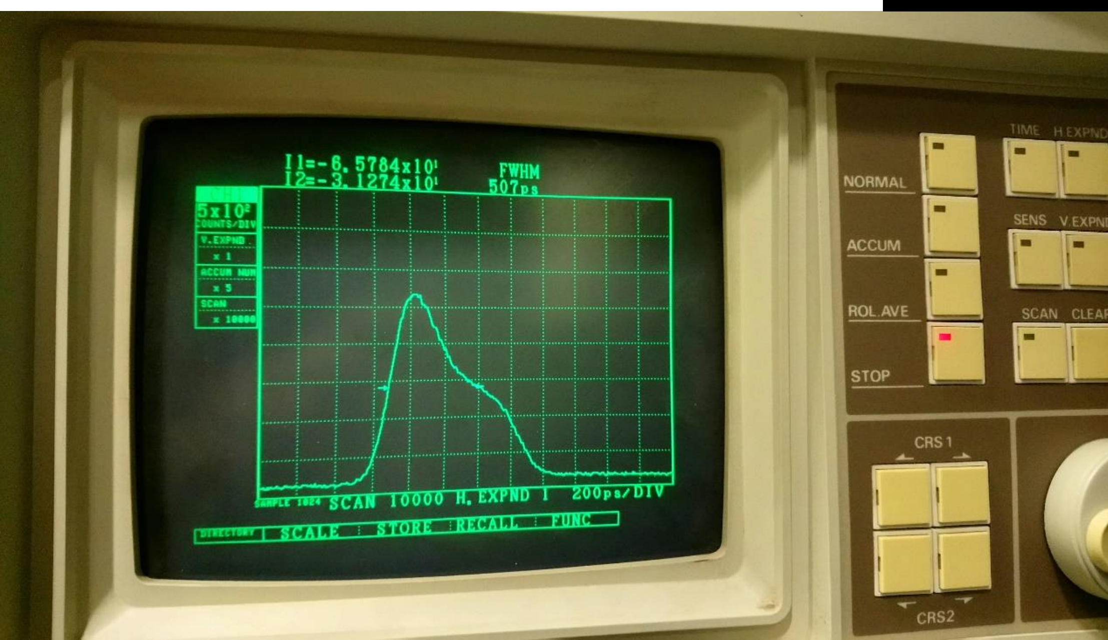


Fast FD: FWHM$_t$ = 830 ps

1.5 GeV sharp gap @ 180 mA







With a short gap, the effective lengthening is less, but not severely bad.

Will be studied, see:

”PRAB, Teresia Olsson, Francis Cullinan et.al. ”Self-consistent calculation of transient beam loading in electron storage rings with passive harmonic cavities”, Accepted for publ.

1.5 GeV Ring Outlook

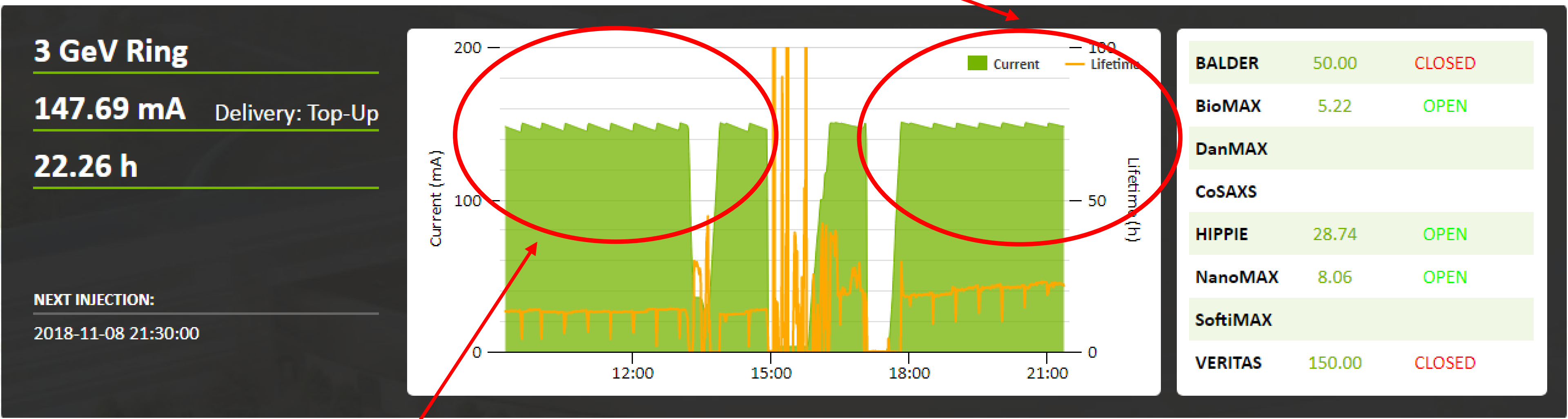
We are delivering at 200 mA. When the beam lines ask for more we plan to:

- Start retracting one HC so that the effective R_{sh} better suits a flat potential.
- SR losses will increase with more IDs. Small adjustments on Main and HC field levels will be required.
- Hope that vacuum conditioning eventually will allow an even fill pattern at 500 mA.

MAX IV

3 GeV Ring Delivery with HC, starting 8th Nov 2018

- Delivery shift: **150 mA** top-up every half hour, **I*Tau ~ 3 Ah with Harmonic Cavities**



- Earlier, we delivered with help of a BbB feedback system acting **longitudinally** against HOM driven Coupled Bunch Instabilities, **I*Tau ~ 2 Ah**
- Around 18:00 we started delivery without help of a BbB feedback, but with **a separate zero-mode feedback (David McGinnis) and the Harmonic Cavities.**

MAX IV

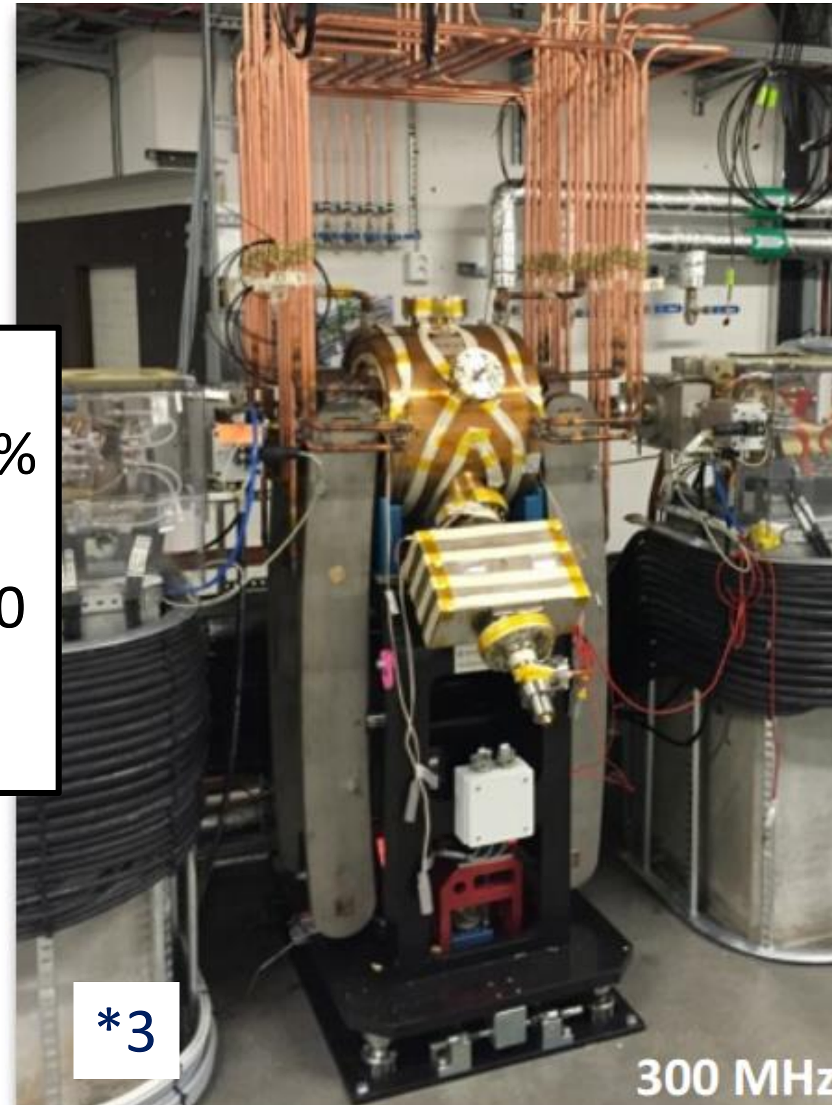
3 GeV Ring, former RF parameters

5*250 kV

A_ε = 5.4 %

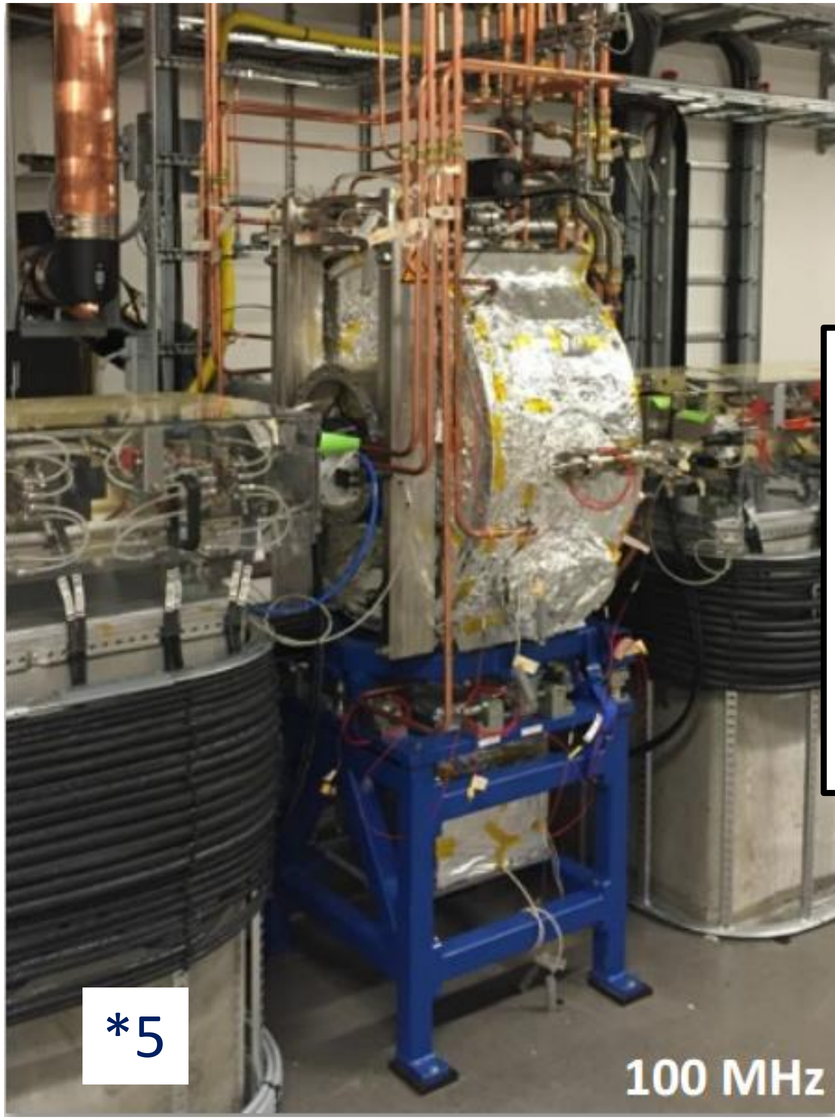
f_s = 1050 Hz

detuned



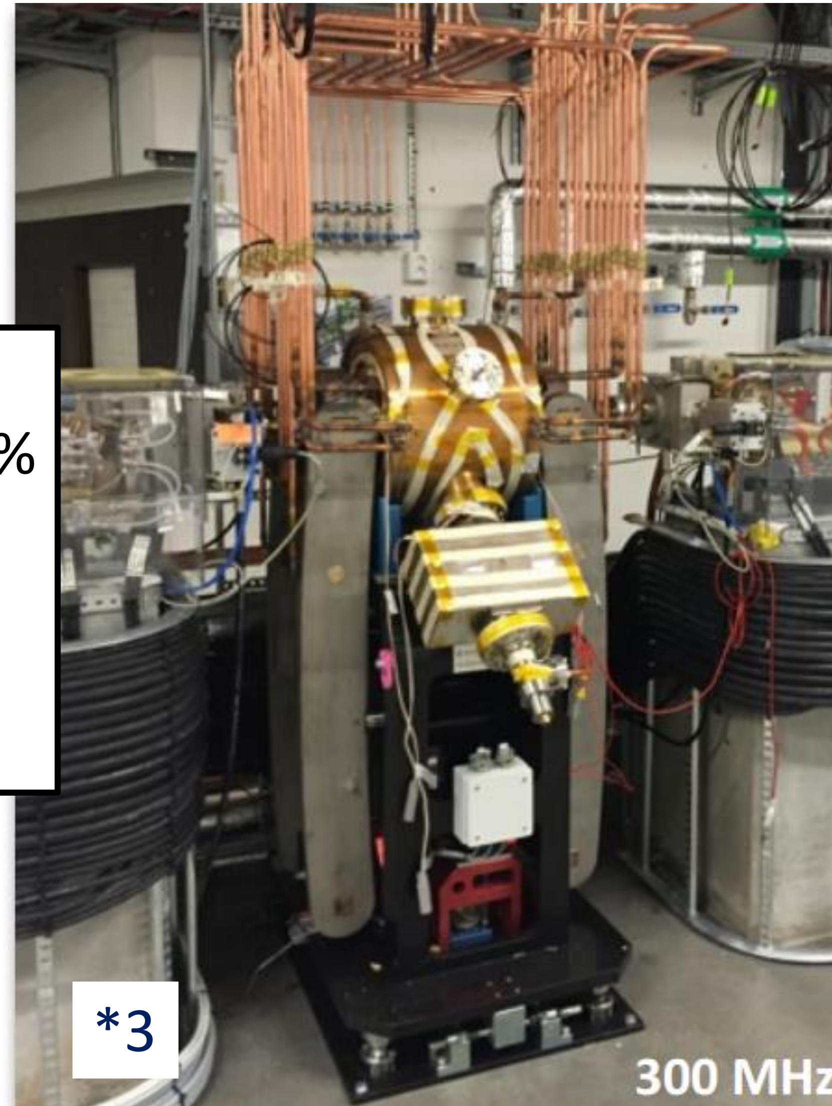
3 GeV Ring, present RF parameters

5*210 kV



A_ε = 4.6 %
f_s = 950 Hz

~3*120 kV



3 GeV Ring, HC Scheme Difficulties

Realizing long bunches with harmonic cavities proved a considerably more difficult challenge for the 3 GeV ring than for the 1.5 GeV ring.

- Attempts to run Landau cavities together with the BbB system were only partly successful (we reached a factor 2 lengthening at 115 mA). Difficulty due to the low synchrotron tune and increasing synchrotron frequency spread as current increases.
- We abandoned (temporarily)* the use of the BbB system!
- Tuning in of **harmonic cavities** was **successful to remove all modes except the mode zero** (predicted not to cause troubles).

David McGinnis came and looked at the beam and said: It's dancing too much! Let me build a **narrow band Mode Zero Damper (MZD)**!

*) BbB feedback work continues; plans for lowering the front-end frequency.

MAX IV

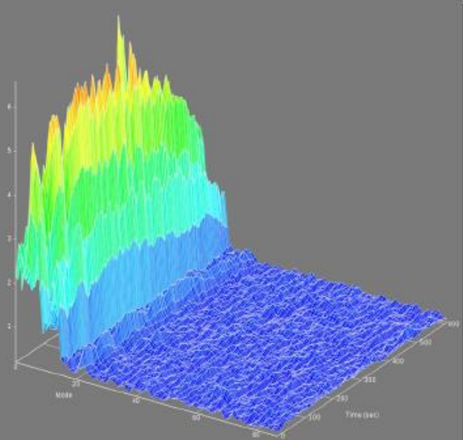
Mode 0 Damper

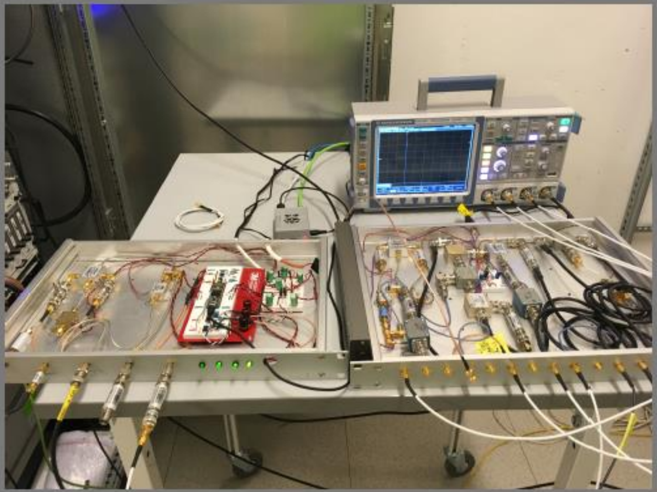
3 GeV Ring

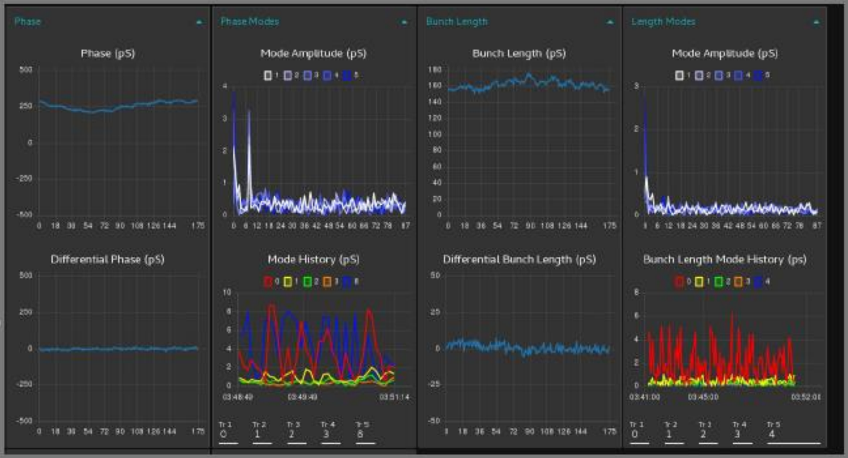
Max IV RF Group

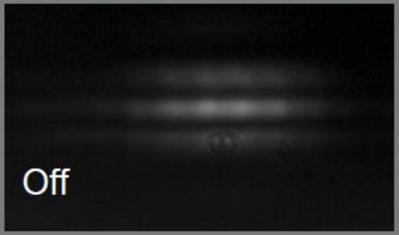
Courtesy D. McGinnis

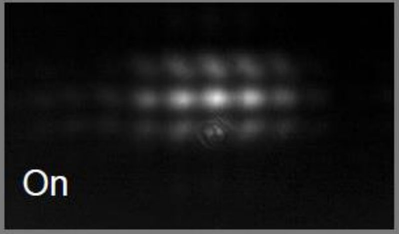
- The Oscillation Overthruster
  - is an instrumentation system that displays the azimuthal Fourier analysis of the longitudinal dipole mode of the bunch pattern in R3
  - It is used for diagnosing longitudinal coupled bunch mode instabilities in R3The Mode 0 Damper
- The Mode 0 damper uses the Oscillation Overthruster front-end to detect the Mode 0 pattern and remove ("damp") the pattern from the beam by modulating the RF phase in Cavity 18 at the synchrotron frequency (~1 kHz)





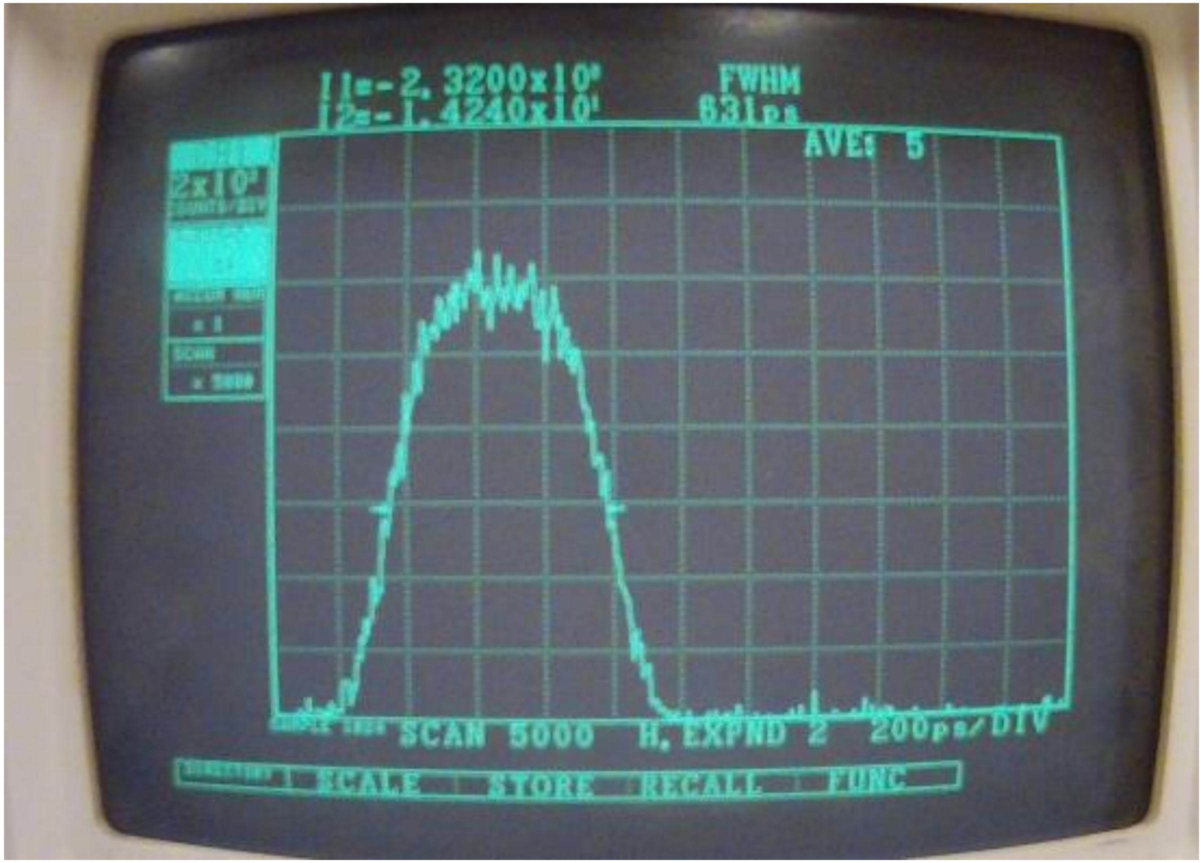






3 GeV Ring: Flat potential case at 75 mA, MZD on

- At this relatively low current and at lower main cavity field (5*157kV == > f_{s0} = 800 Hz), we can demonstrate **the theoretical lengthening of 4.5 along a uniform filling pattern.**

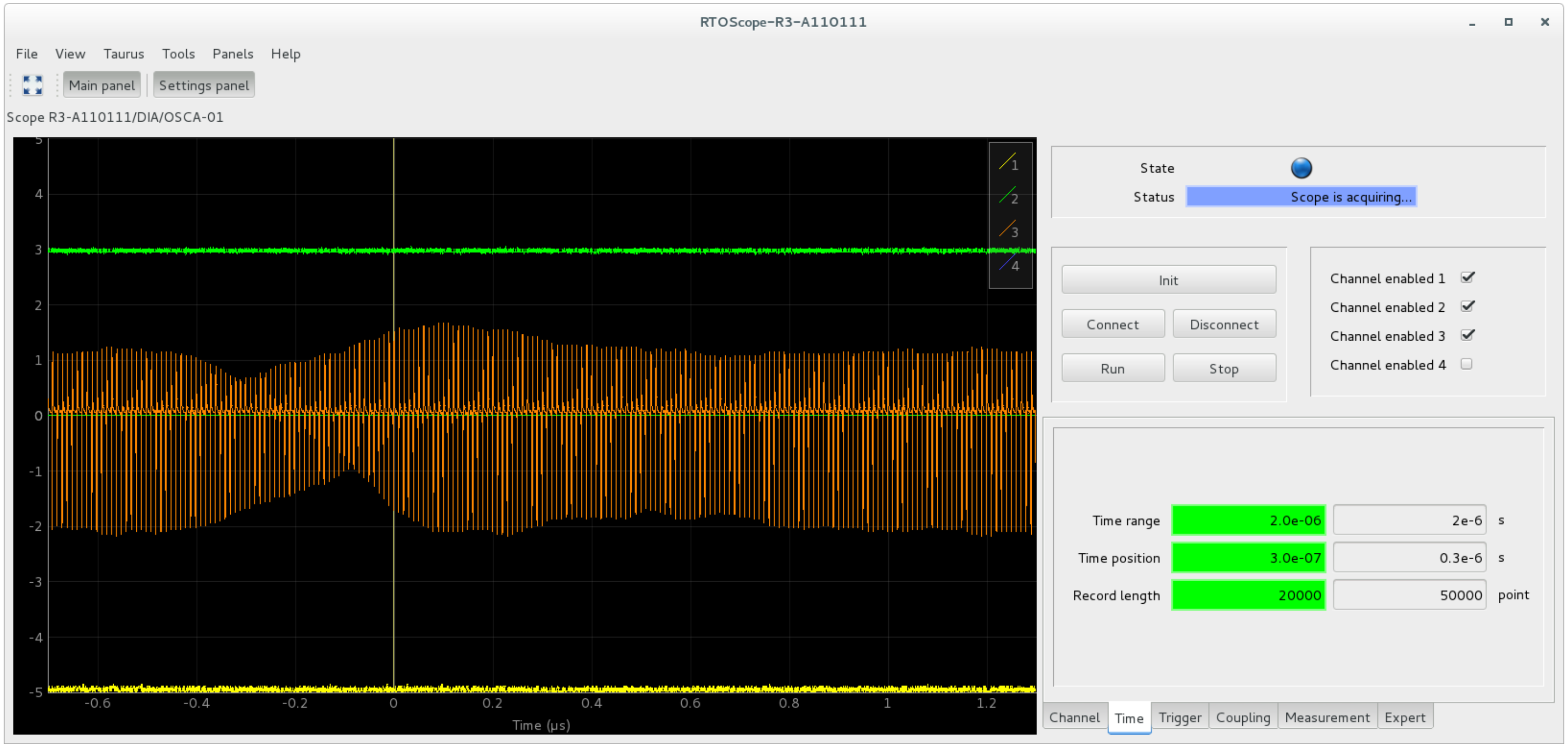


HC fields: ~3*76 kV

However, again our calibration of the HC fields indicates roughly 10 % too high fields.

3 GeV Ring: Bunch lengthening at 150 mA, MZD on

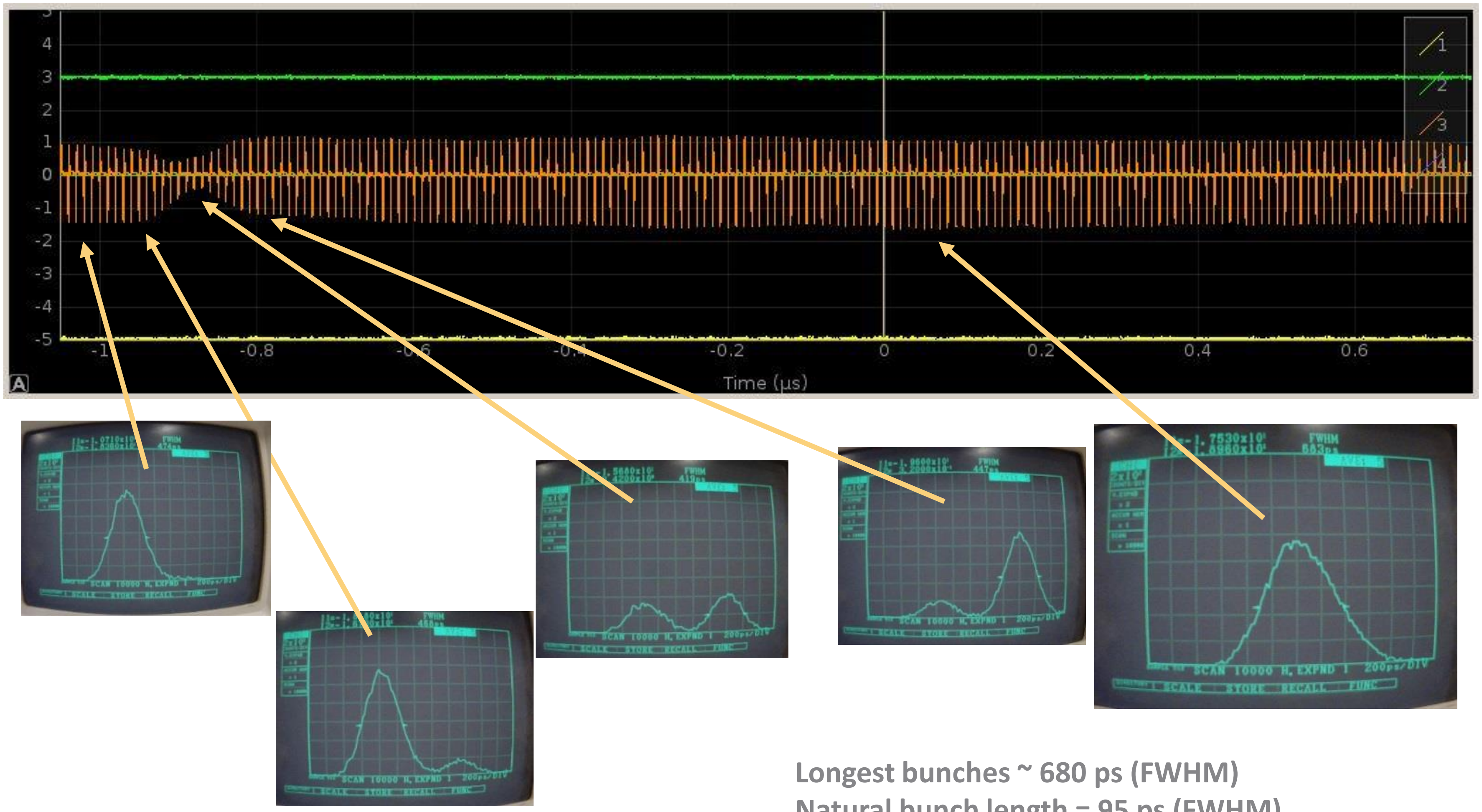
- At higher currents a static phase transient is established along the bunch train.



- The bunch profiles differ along the train, even though the bunch charges are quite similar. Thus, the effective lengthening is slightly less than nominal.

3 GeV Ring: Bunch lengthening at 150 mA, MZD on

Bunch fill-pattern seen on BPM sum signal

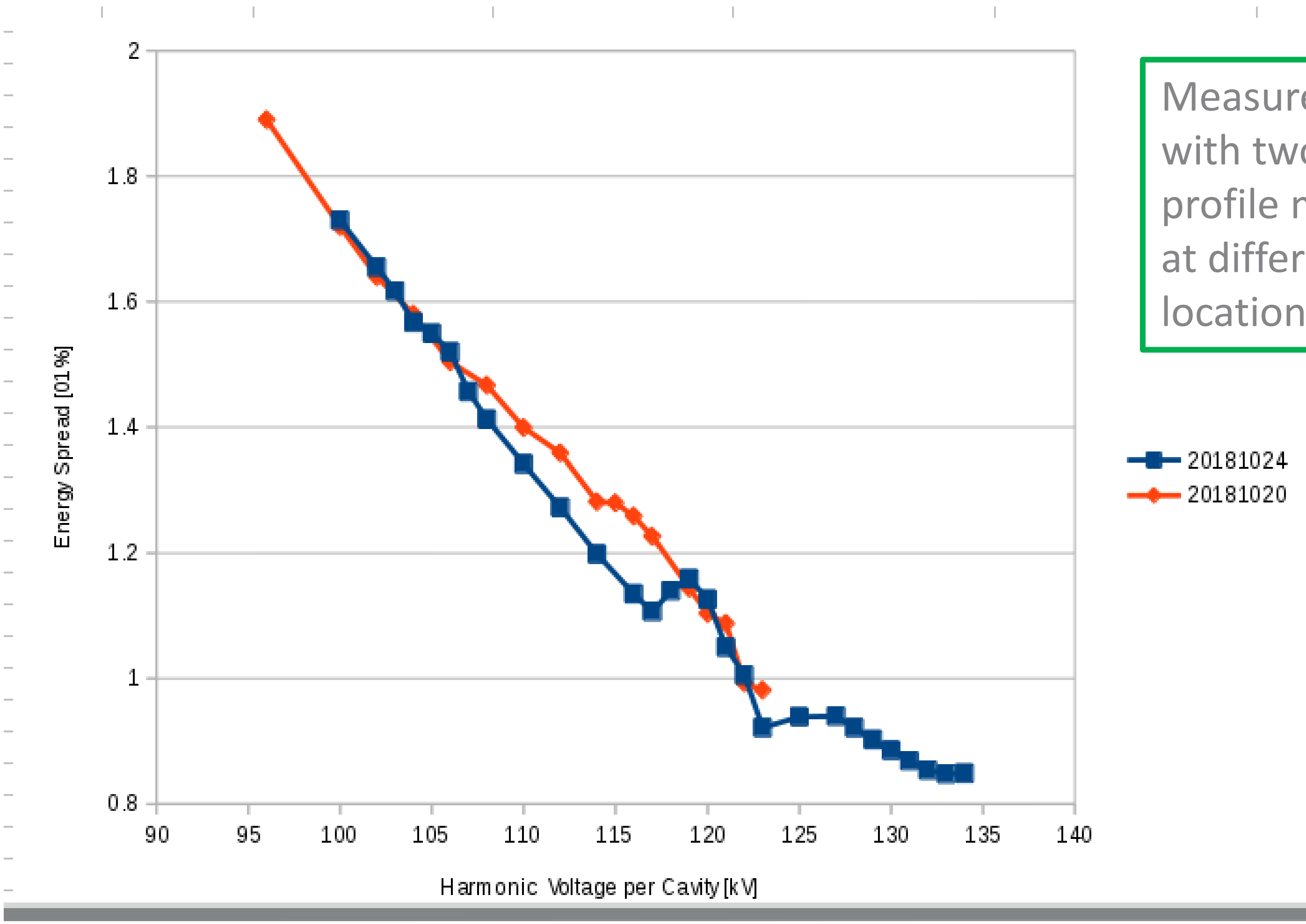


Longest bunches ~ 680 ps (FWHM)
Natural bunch length = 95 ps (FWHM)

Slide by P. F. Tavares

3 GeV Ring: Bunch lengthening at 150 mA

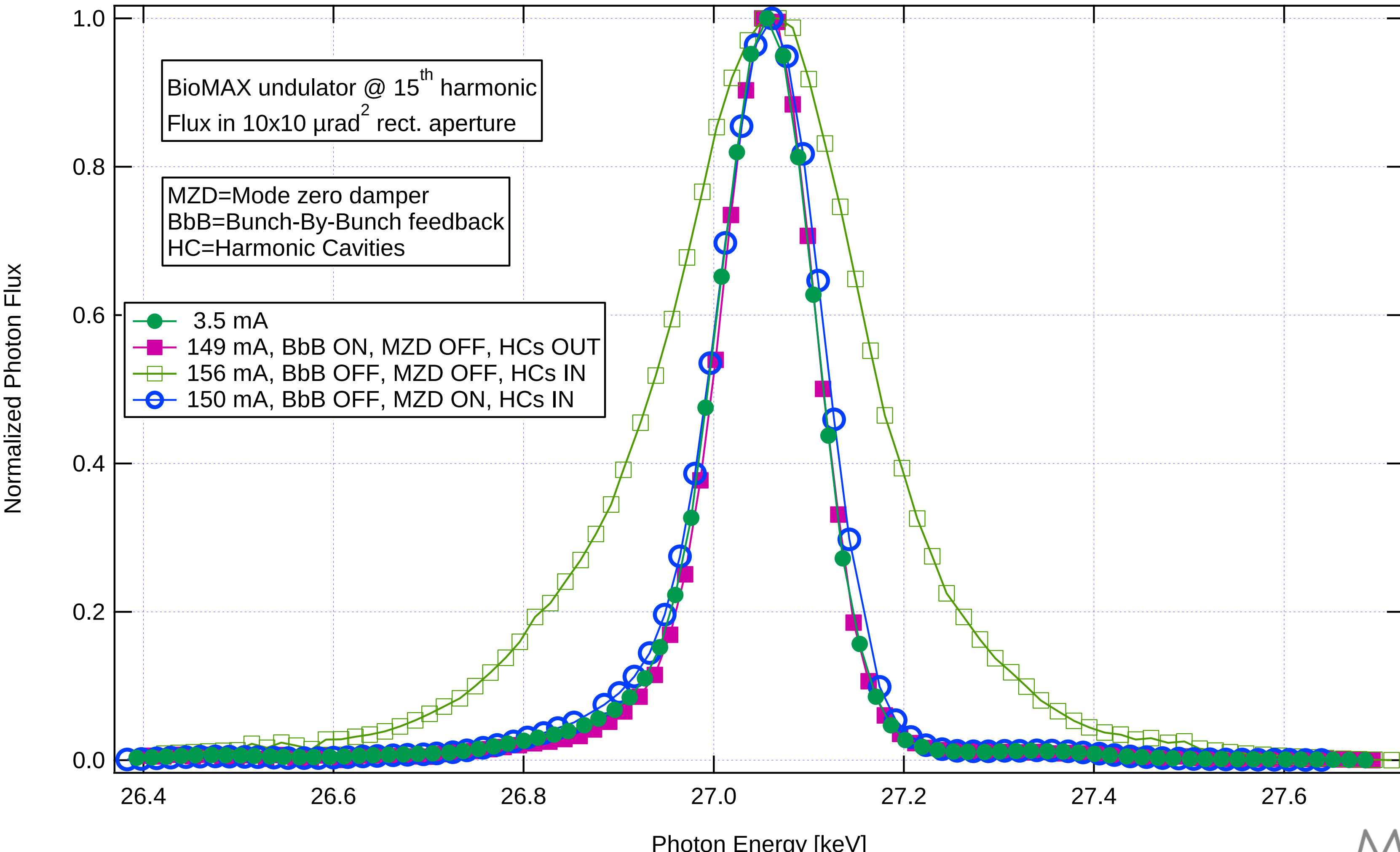
- The energy spread is approaching the natural one (0.8e-3) with increased HHC fields, and the beam is longitudinally stable.



Measurement with two beam profile monitors, at different locations.

3 GeV Ring: Bunch lengthening at 150 mA

- We also verified the low (natural) energy spread at a the BioMAX beam line:



3 GeV Ring Outlook

We are delivering stable beam with elongated bunches at 150 mA. However, we want to understand:

- Why are we Robinson unstable (not using the MZD), even though stability is predicted by theory?
- Why does a static transient establish along the bunch train (I >~ 120 mA)? The effective bunch lenghtening is slightly compromised.

Near future:

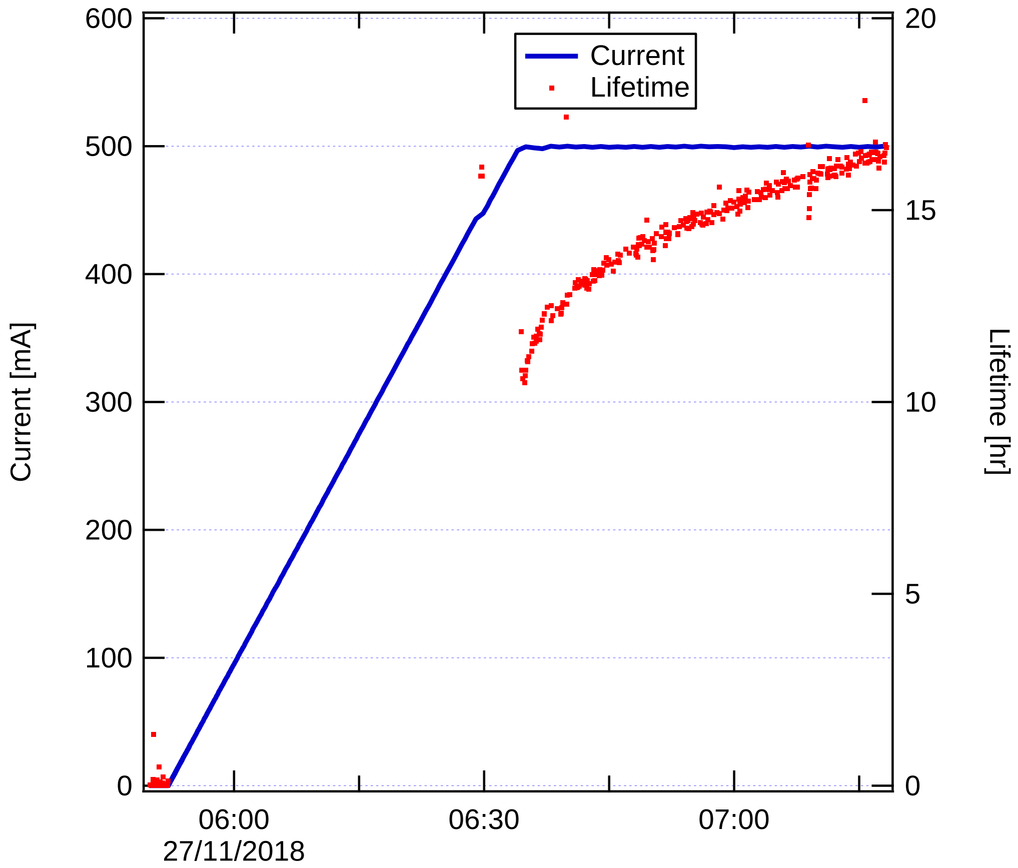
We have verified stable conditions up to 220 mA and will continue exploring **higher currents**, probably with one or two HCs detuned.

”Higher currents”

<==>

(since yesterday)

500 mA (Nominal) in the 3 GeV Ring



Thank you !

Back-up slides

Measured Energy Acceptance

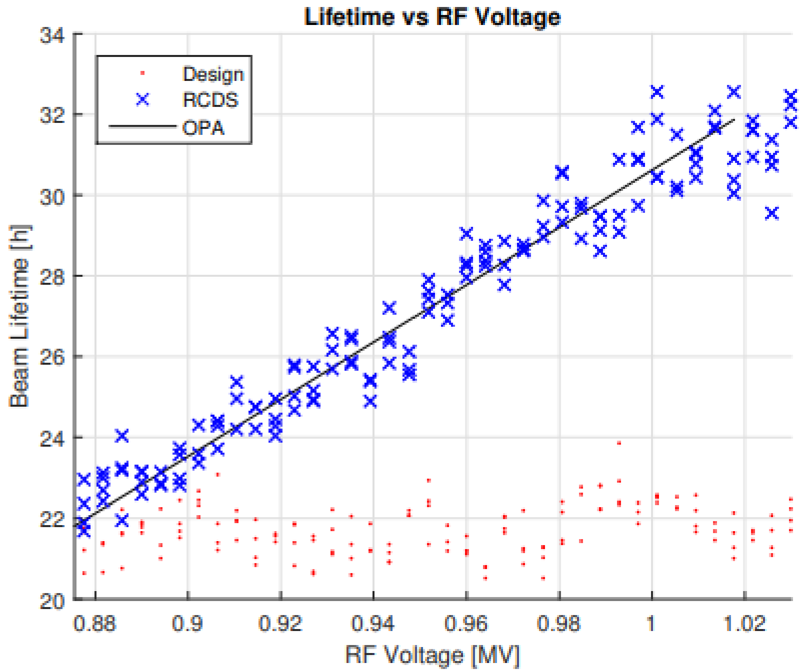
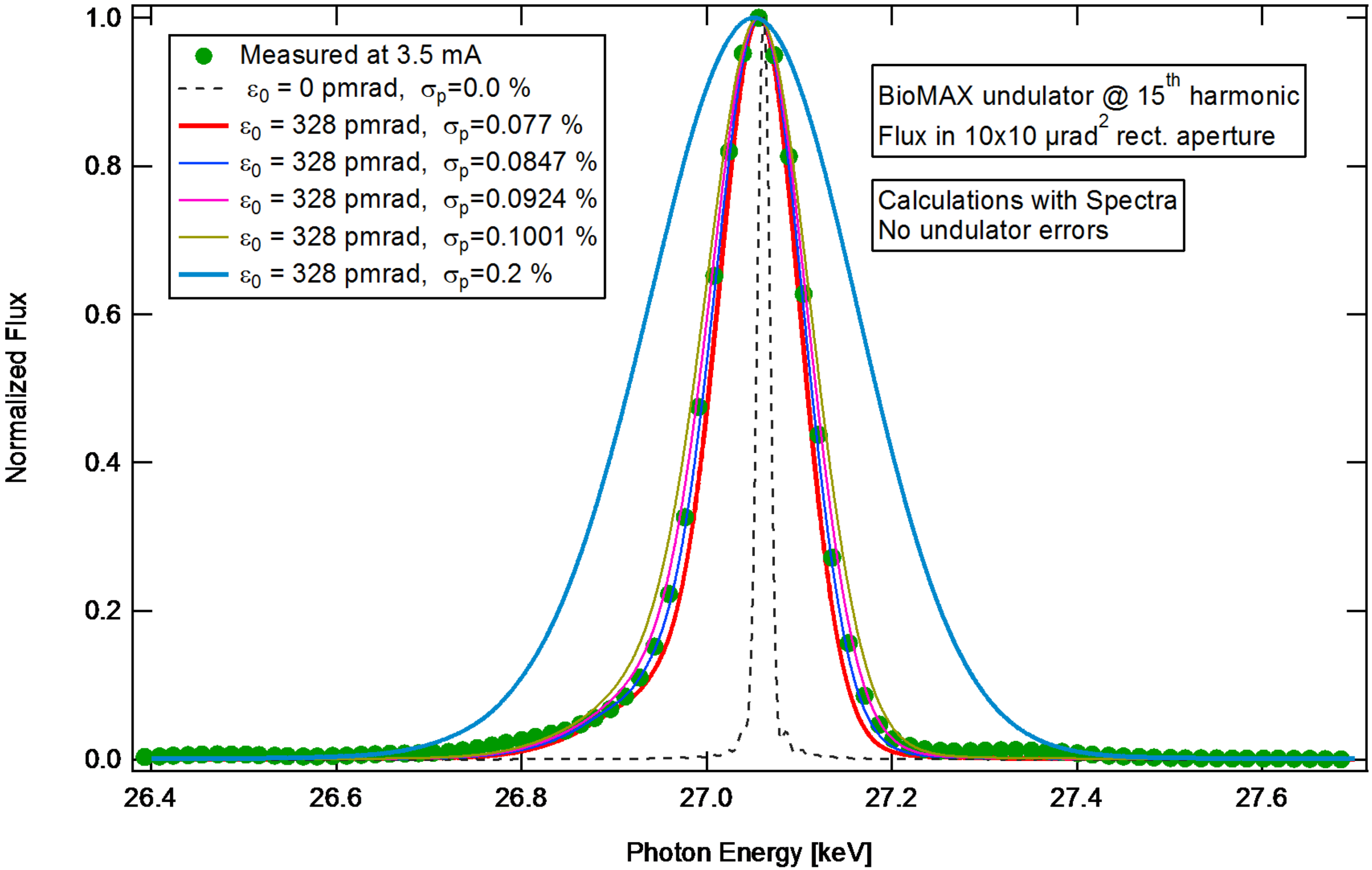


Figure 6: Result of momentum acceptance measurements for the two different non-linear optics. The measurements where taken at a beam current of 75 mA. The black solid line is the fitted results of a simulation in OPA corresponding to a gas lifetime of 95 h.

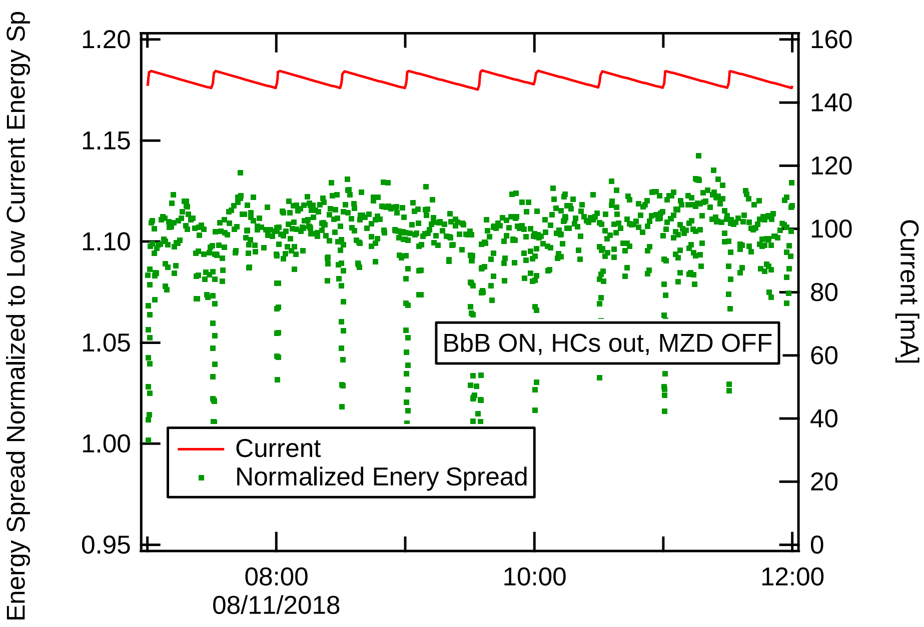
ID spectra and energy spread



MAX IV

Harmonic cavities and Enery Spread

Harmonic cavities OUT



Harmonic cavities IN