The Metrology Light Source - Status and Applications

Jörg Feikes Helmholtz-Zentrum Berlin
using material from
Gerhard Ulm, Roman Klein PTB
Markus Ries, Tobias Goetsch, Gode Wüstefeld HZB

Bird eyes View of HZB Adlershof

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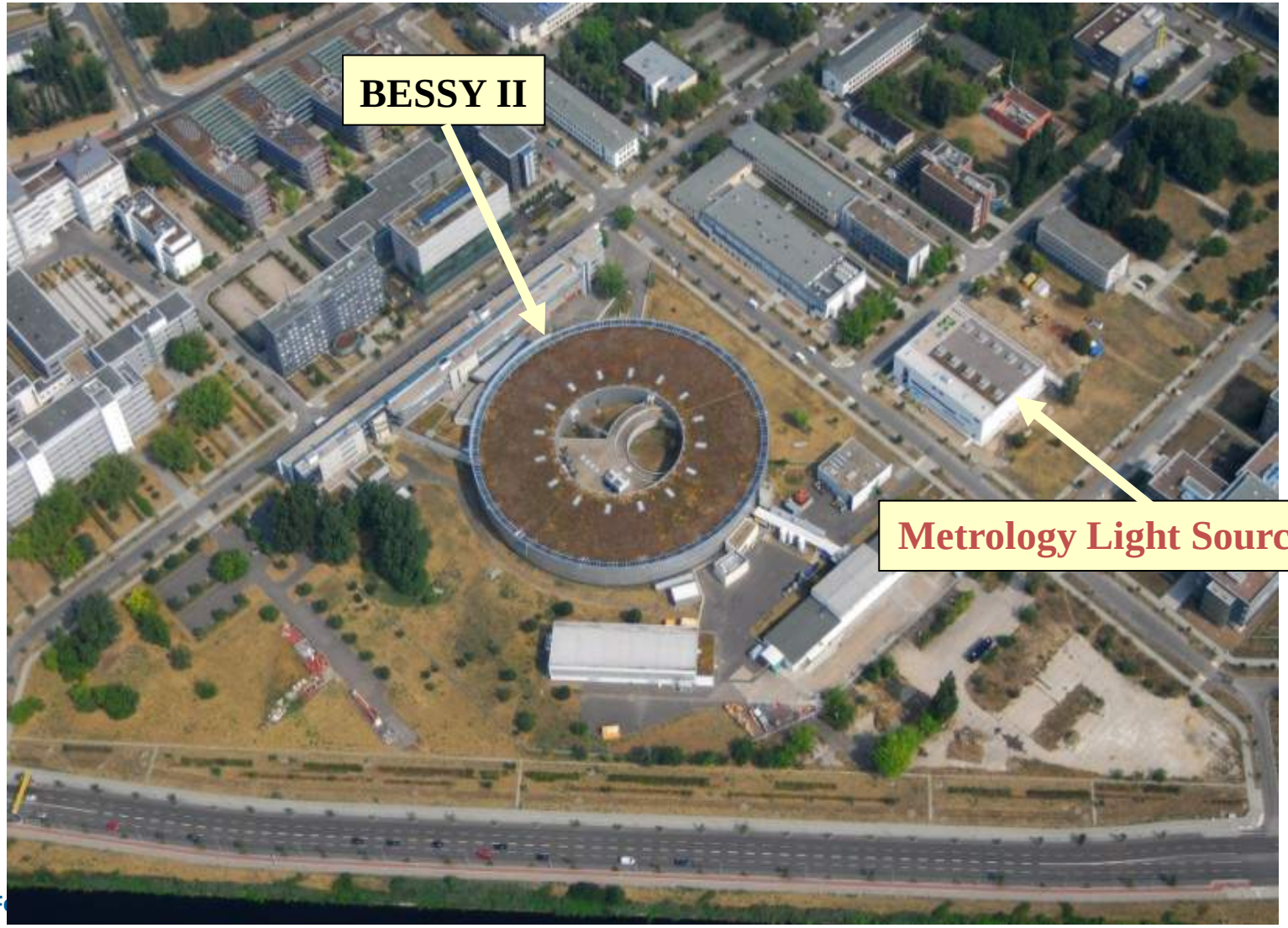

MLS machine

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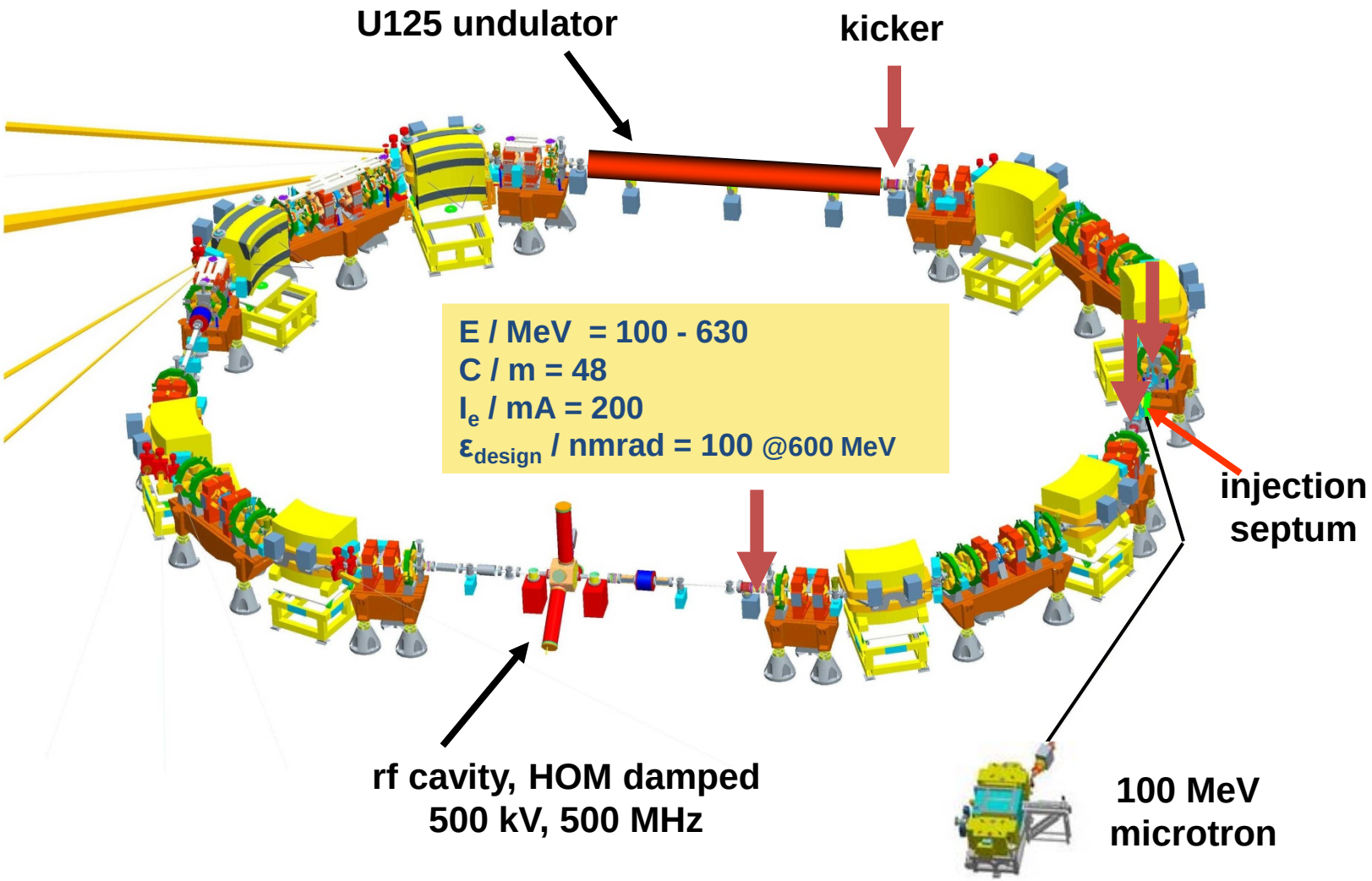

Beamlines and experimental stations at the MLS

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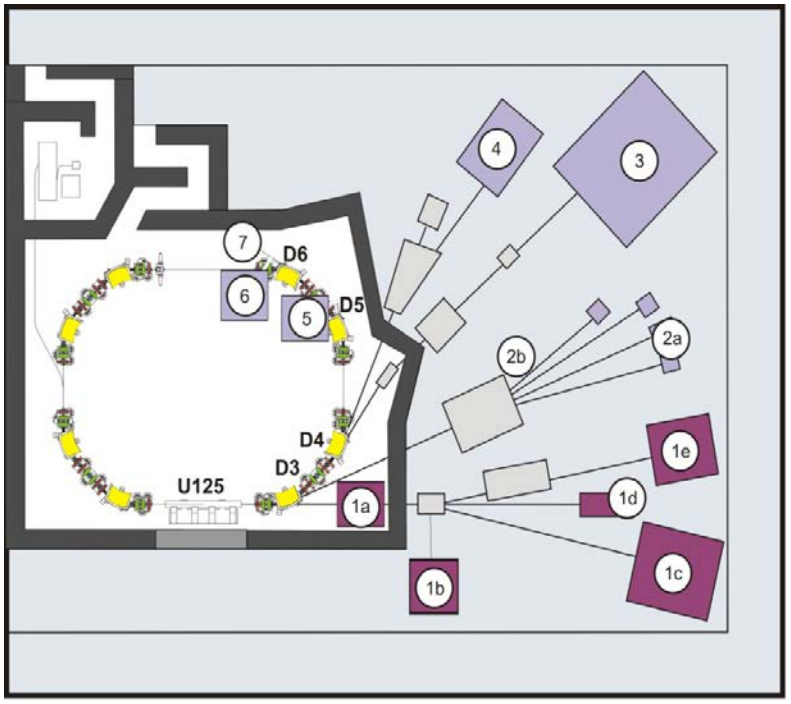
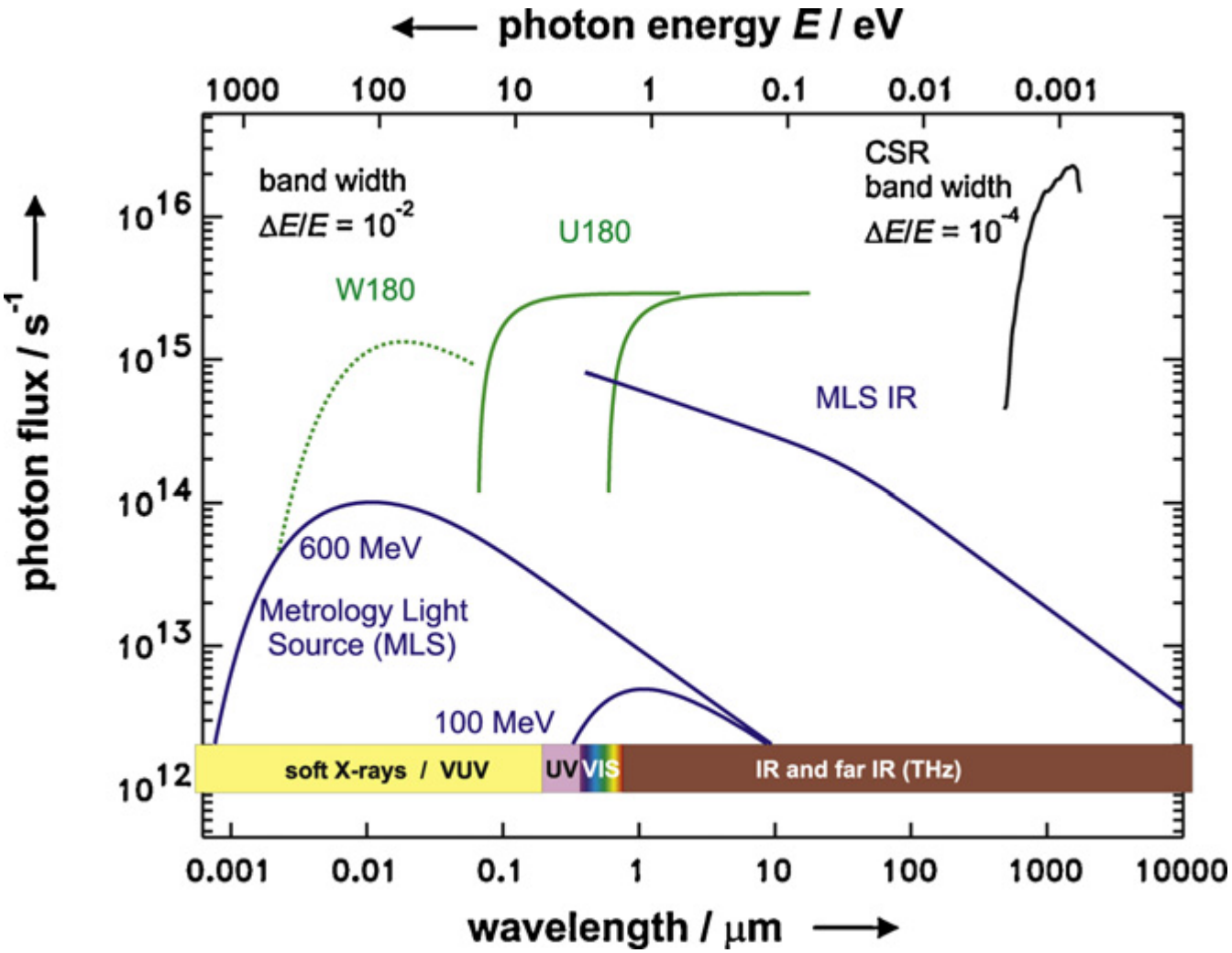


Wavelength range at MLS

Extreme UV to far-IR (**4 nm to 7 mm**) at **6** user beamlines

1a	(undulator) IR radiation / laser for Compton-	2	UV/VUV monochromator (source
1	backscattering	b	calibration)
b	deflected undulator radiation (IR/VIS)	3	EUV plane-grating monochromator
1c	deflected undulator radiation (high-flux experiments)	4	UV/VUV monochromator (detector
1	direct undulator radiation / Compton–backscattering	5	calibration)
d	UV/VUV monochromator for undulator radiation	6	THz beamline
1e	direct calculable bending magnet radiation	7	IR beamline
2a			diagnostics frontend

Spectrum of emitted SY-Light



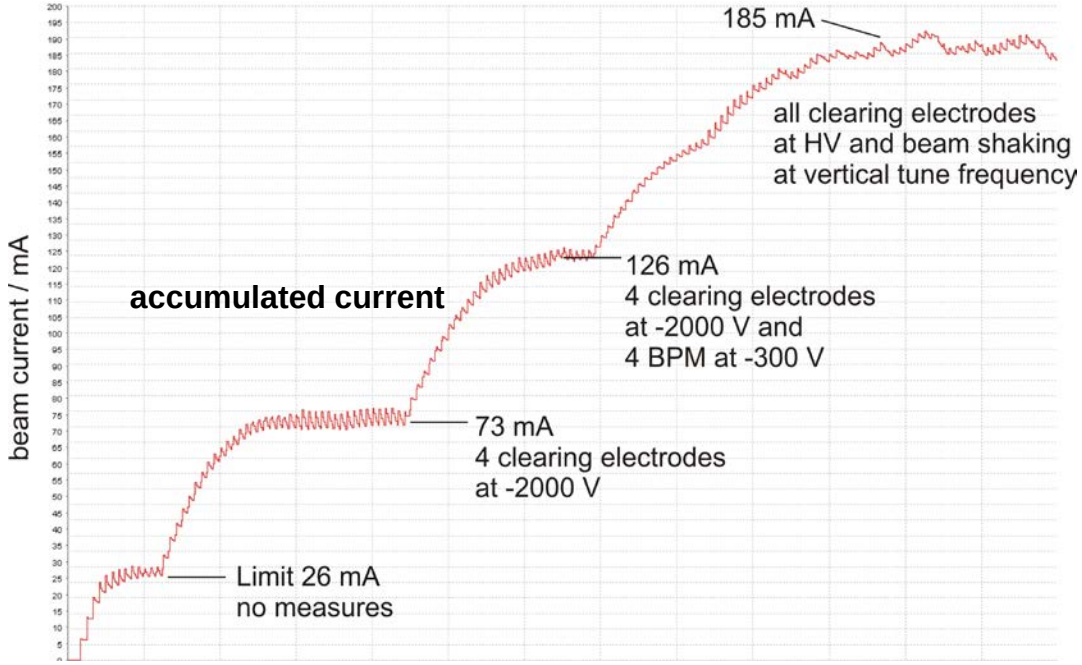
History

MLS is **owned** by PTB – designed, constructed and **operated** by HZB
(PTB pays HZB 1.6 M€/y for service and hardware development)

- **Sep 24 2004 – Jan 1 2007** construction period, MLS budget **10.02 Million Euro**
- **July 13, 2007** first accumulated beam **1mA**
- **Aug 14, 2007** first beam ramped to **630 MeV**
- **Aug 25, 2007** accumulation up to **10 mA** by slow injection (every 6 s)
- **Sep/Oct 2007** current limit around **12 mA --> Ions**
- **April 1, 2008** start of regular **user operation**
- **May 5, 2008** design current of **200 mA** reached

Ion effects during accumulation

at MLS the beam dynamics is strongly dominated by ions (-> Beam blow up with current)



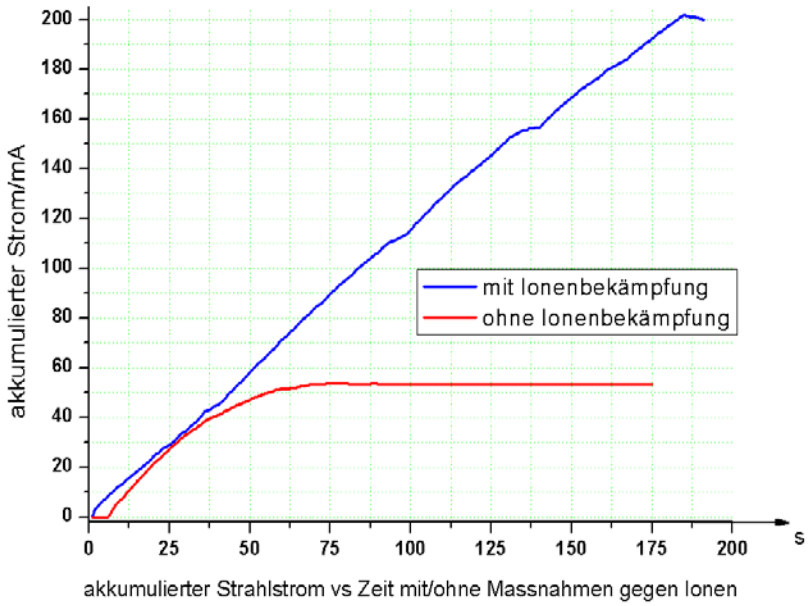
Experiment from Jan 2009 (accumulation@0.2Hz)

Countermeasures against Ions

- **installation of clearing electrodes**
- **beam shaking**
- **improving vacuum conditions by permanent beam scrubbing**

Combating Ion effects

Ions prevent accumulation above 50 mA

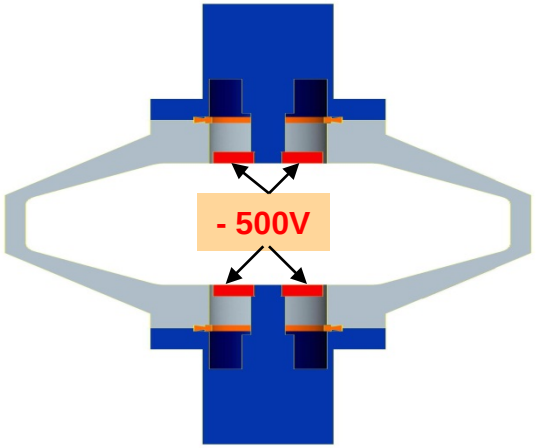


akkumulierter Strahlstrom vs Zeit mit/ohne Massnahmen gegen Ionen

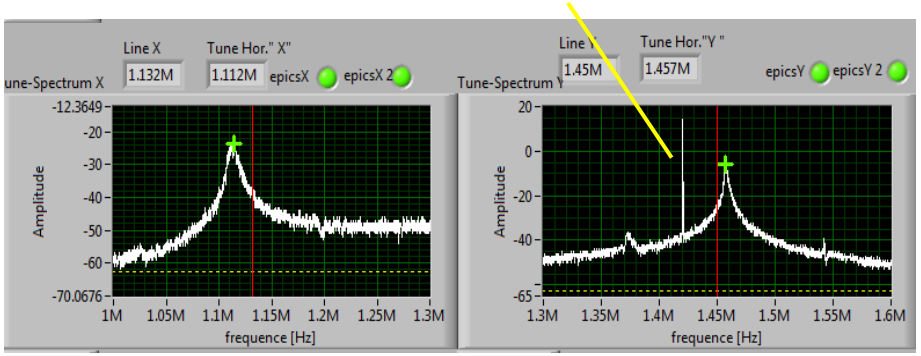
2013: Current still limited by ion induced beam blow up

*since 2010 accumulation is at **2 Hz***
*(design was **10 Hz**)*

-500V at Clearing electrodes (BPM type) x8



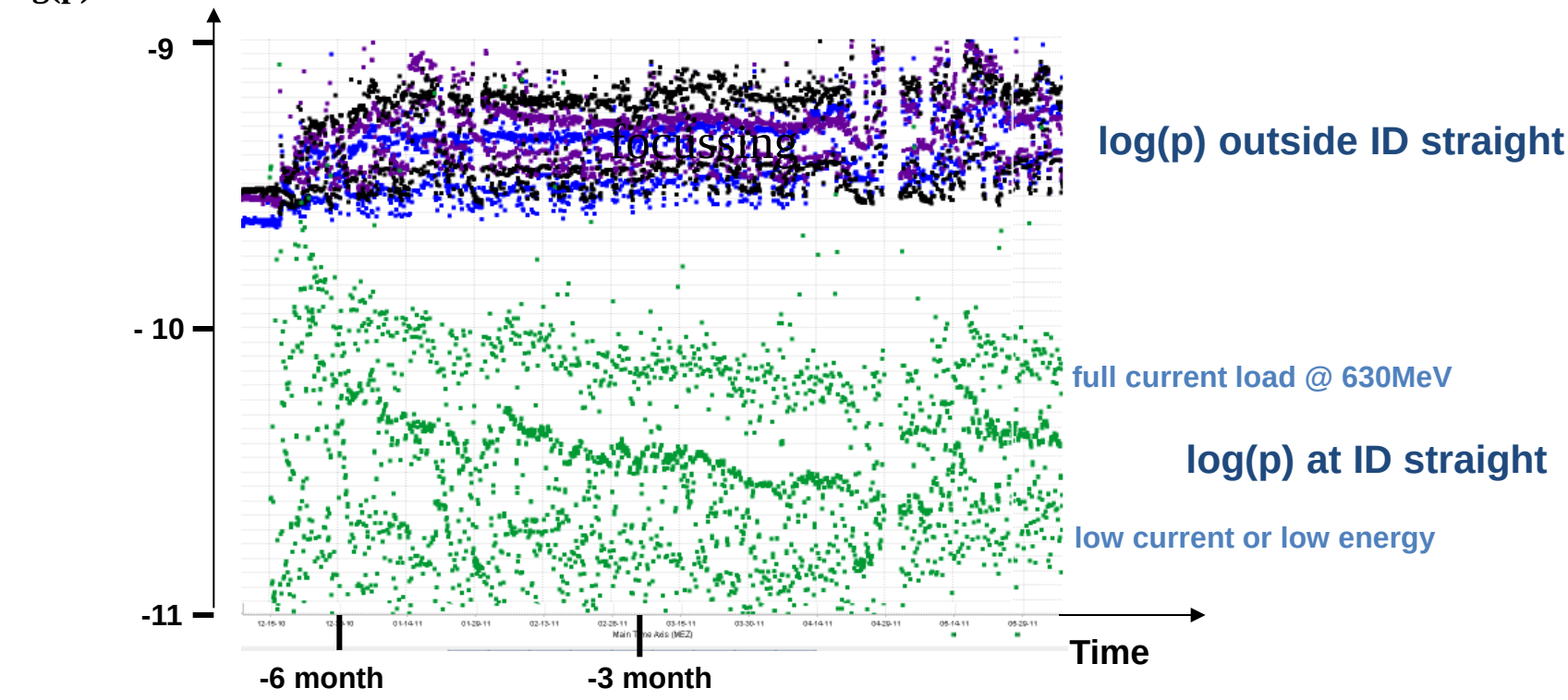
Ion-Shaking below vert. Tune



Improving vacuum conditions

December 2010 installation of ID **NEG chamber**
first experience with NEG coating at BESSY-site

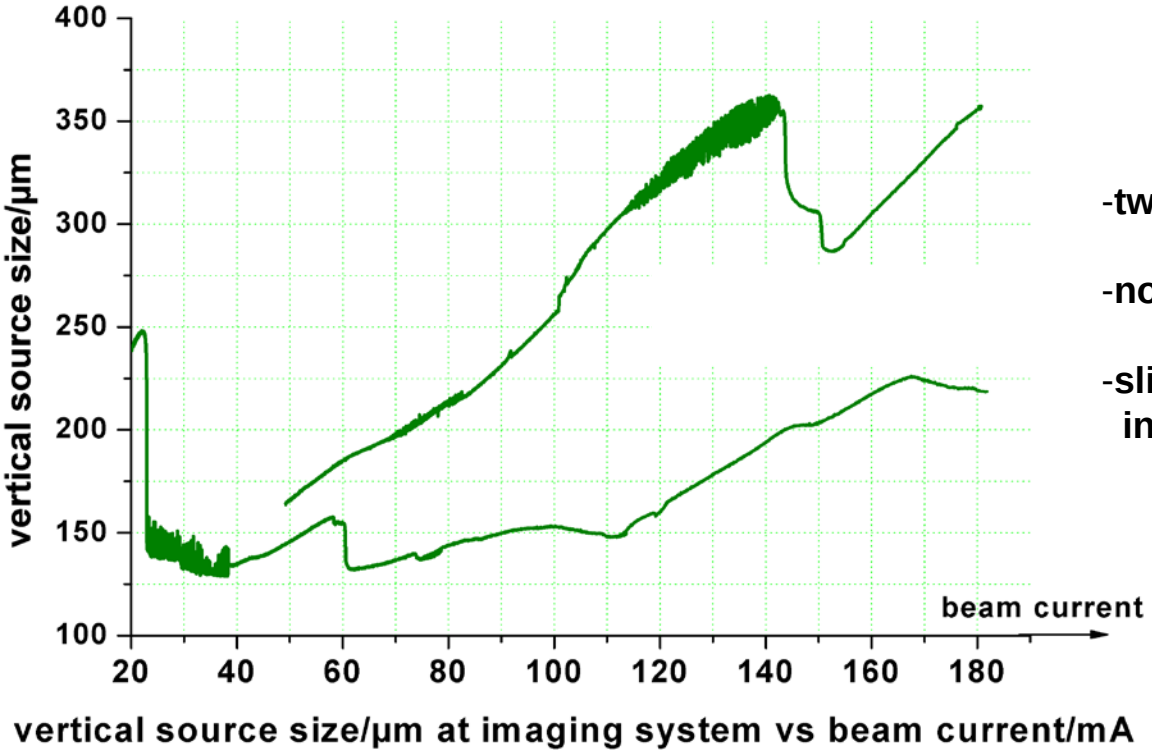
Pressure values measured after NEG installation **12/15/10- 6/1/11**



Ions: missing Stability of vertical Source Size

Beam Blow Up in MB mode due to Beam-Ion interact. –> varying σ_z with current
-> considerable fluctuations of σ_z over one run
-> not reproducable – different behaviour from run to run

-> <u>Not acceptable for users !</u>



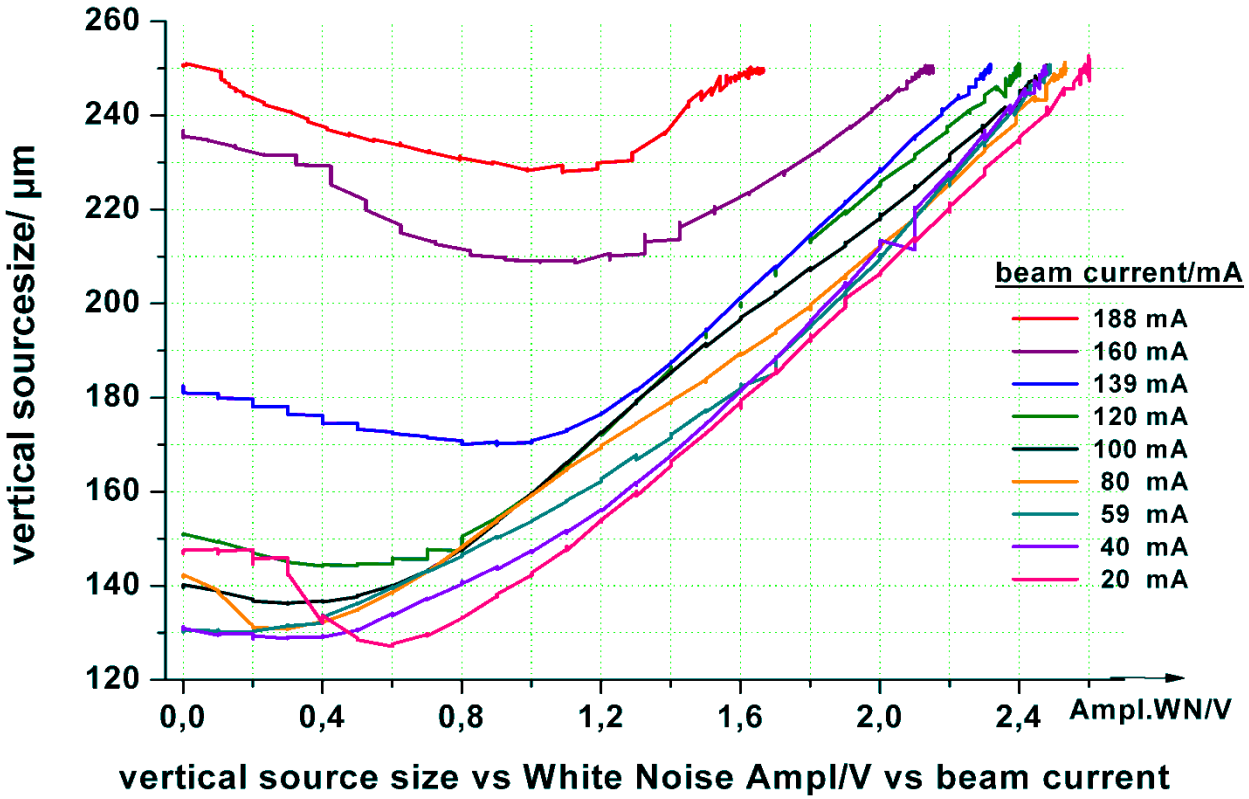
-two consecutive user-runs

-no change of machine settings

-slightly different homogenity in bunch filling

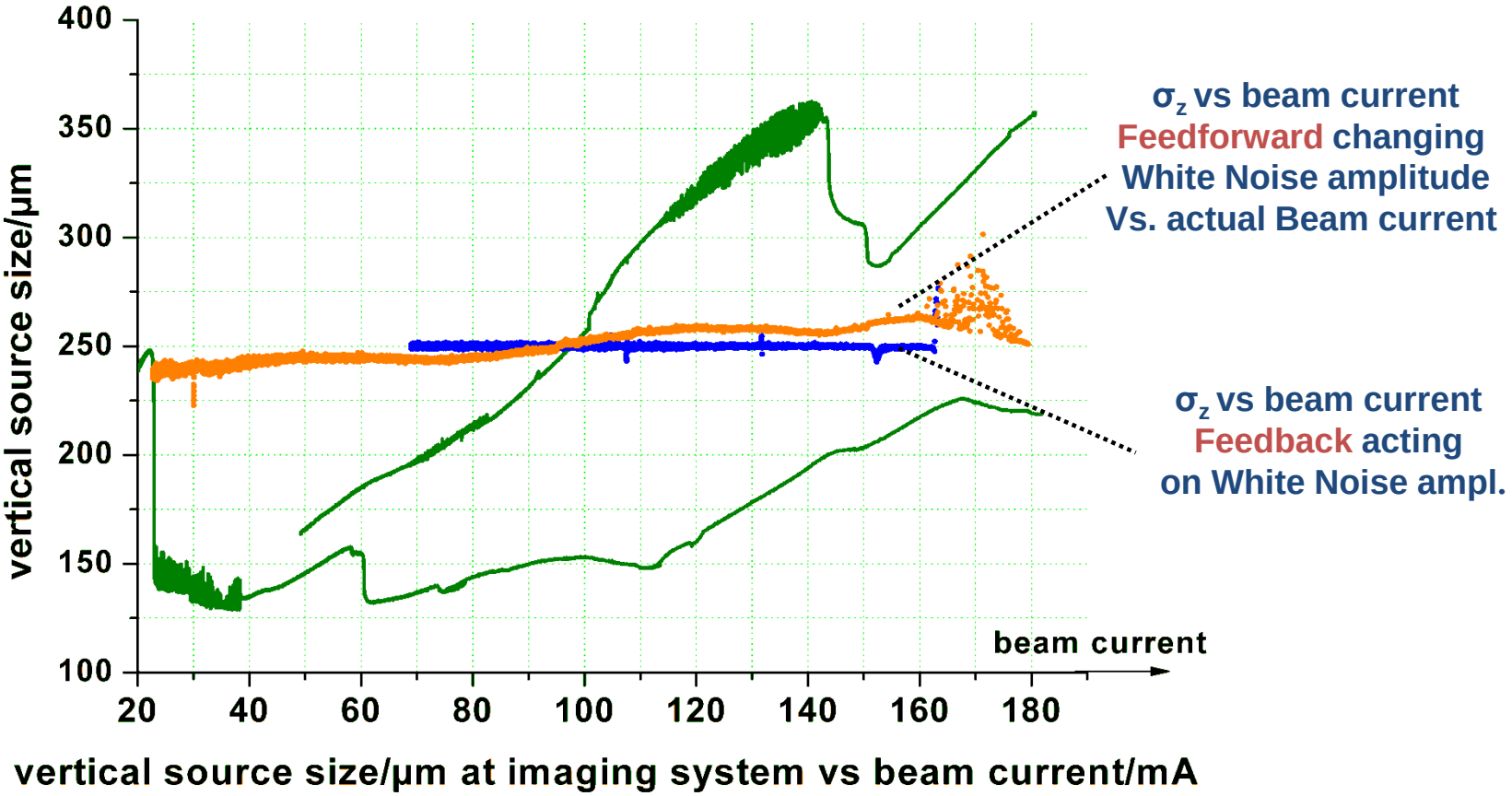
Stable Beam Size with White Noise Excitation

Source size effect of „white noise“ exc. depends on beam current
by adjusting **noise amplitude vs. beam current** -> **stable source size**

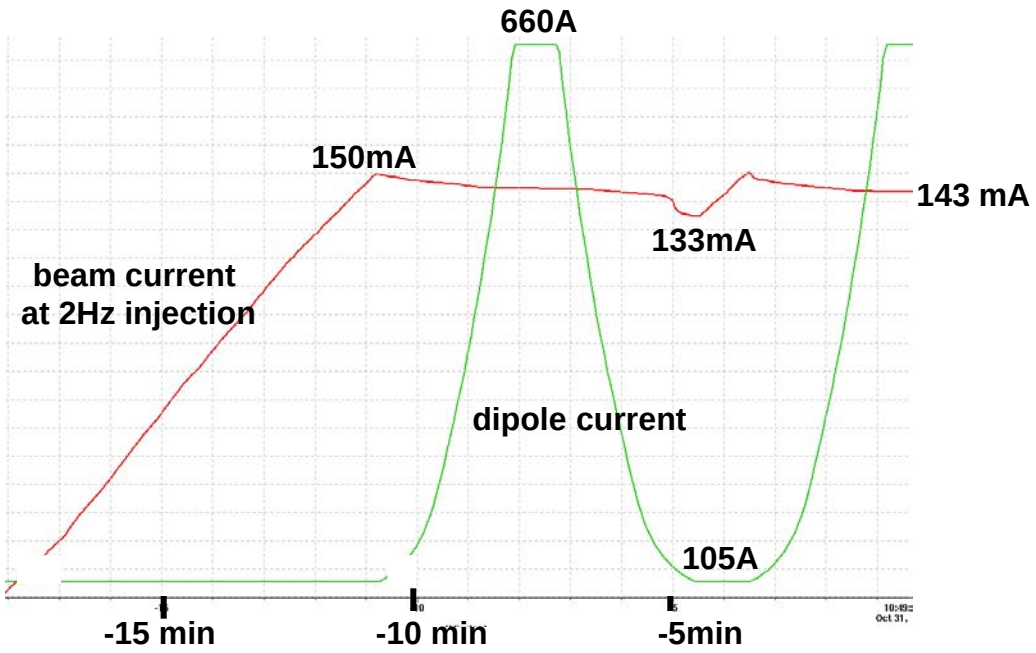


Constant Source size by White Noise exitation

Ion induced beam blow up during user operation combated by white noise excitation – noise amplit. controlled with Feedback or Feedforward



Current conserving refill cycle



beam current remains stored during complete ramp cycle ->

- advantage: reduced activation

- **draw back: magnets are not degaussed -> strong hysteresis -> errors in handling of magnets = serious impact !**

MLS Operation

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User operation: Mo-Fr 7h-23h + "dawn special" (= no operator)

typical for MLS operation are varying user conditions

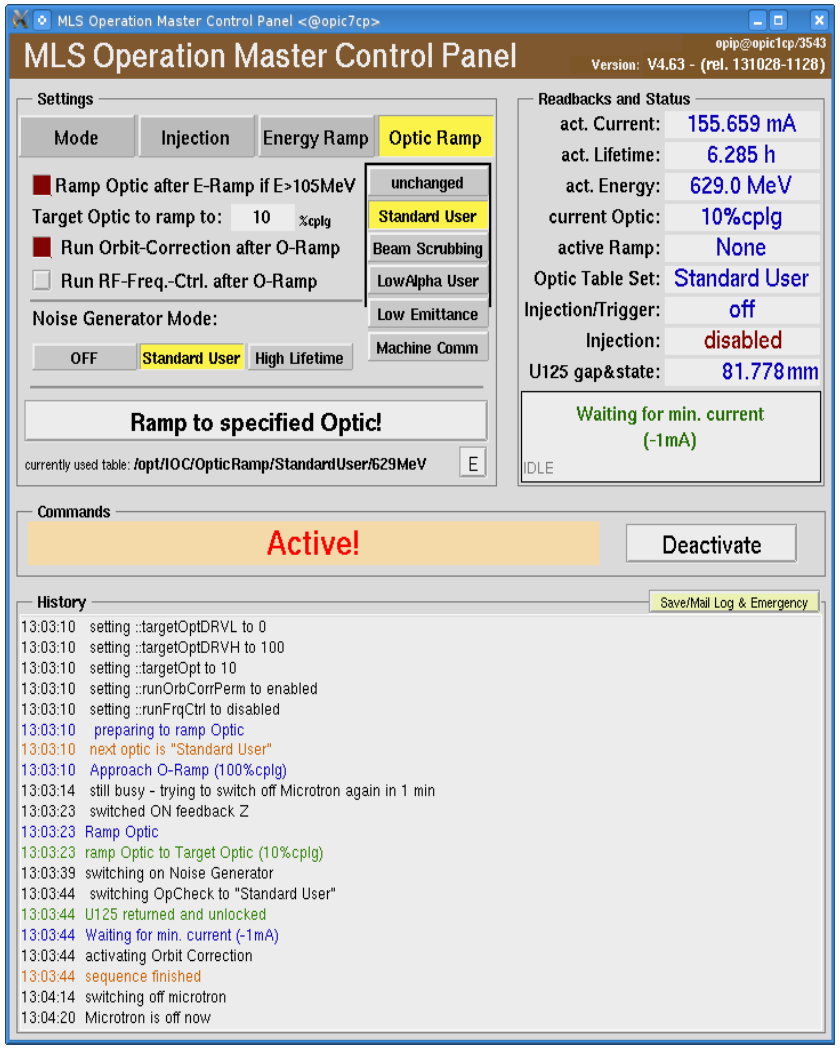
- **beam current :** 1e (1pA) – 200 mA
- **beam energy :** 105 MeV – 630 MeV
- **momentum compaction factor:** 0.033 - 0.00005
- **different emittances/beam sizes:** 40 – 500 nmrad/ σ_z = 100µm…2000µm

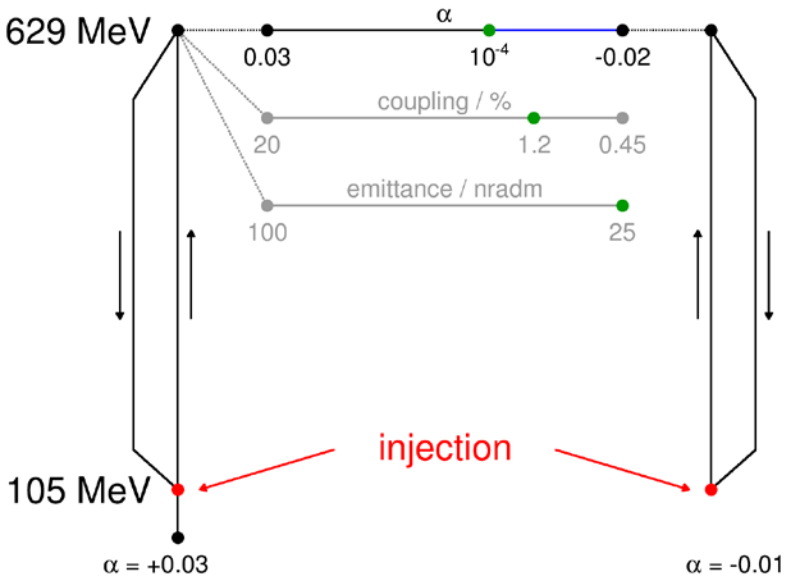
state changes are complex. Errors are likely and potentially serious

-> operation is done by an

automated state machine = „Operation Master"

The Operation Master – a State Machine





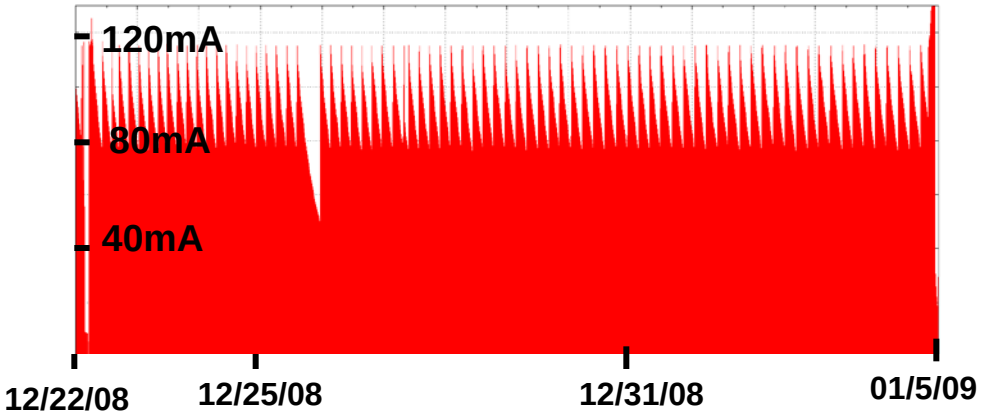
Operation Master performs transition

- analyzes actual machine state
- checks that all subsystems are ready
- transition to ramp state
- ramps down to injection energy
- switch on systems for injection
- injects to desired current and ramps up to desired energy
- switches off sub-systems not needed
- performs transition to desired machine state
- configures and starts sub-systems for user run

The Operation Master – a State Machine II

concept of “state machine“ stretches far beyond concept of „automated operation“ -> enables secure state control

automated operation Dez08-Jan09:

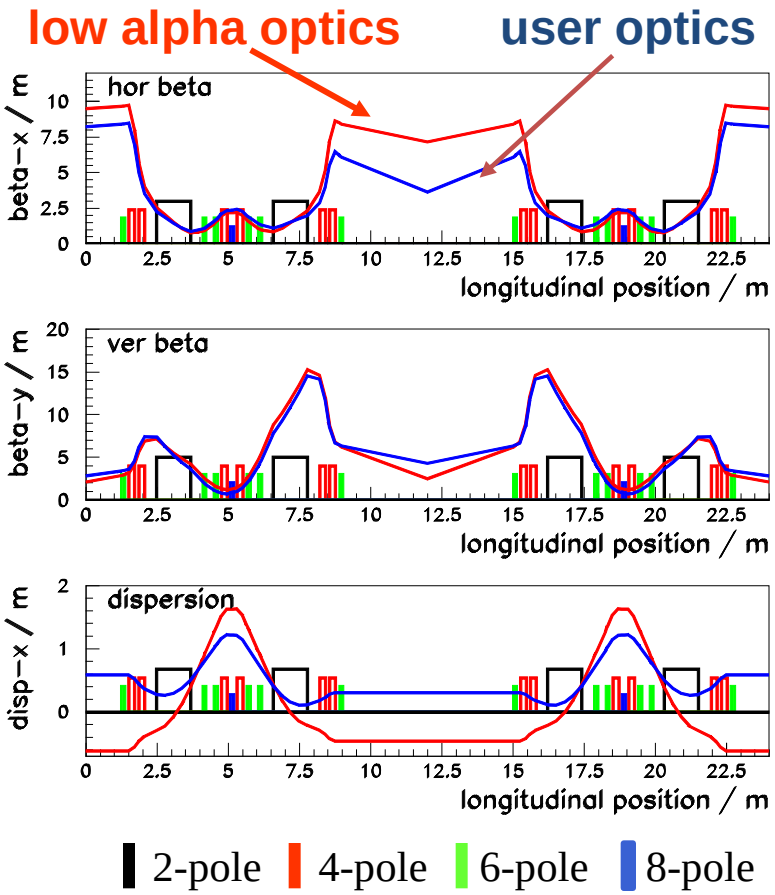


2 weeks of unmaned operation

early application of the state machine concept

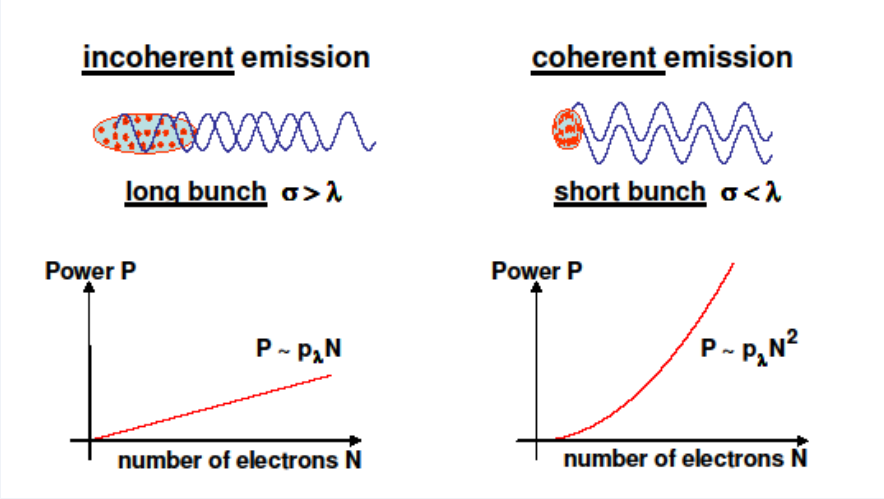
MLS optic functions

MLS is first ring optimized for low alpha operation by use of octupoles



THz radiation in Short Bunch mode

„Low-α“



nonlinear momentum compaction factor α

- $\alpha \rightarrow$ change of orbit length with respect to the momentum deviation $\delta = \frac{\Delta p}{p_0}, \frac{\Delta L}{L_0} \approx \alpha \delta$
- α is one of the parameters that determine the bunch length

$$\sigma \propto \sqrt{\alpha}$$

- α itself can be momentum dependent

$$\alpha(\delta) = \underbrace{\alpha_0}_{\text{quadrupole}} + \underbrace{\alpha_1}_{\text{sextupole}} \delta + \underbrace{\alpha_2}_{\text{octupole}} \delta^2 \ldots$$

magnet:

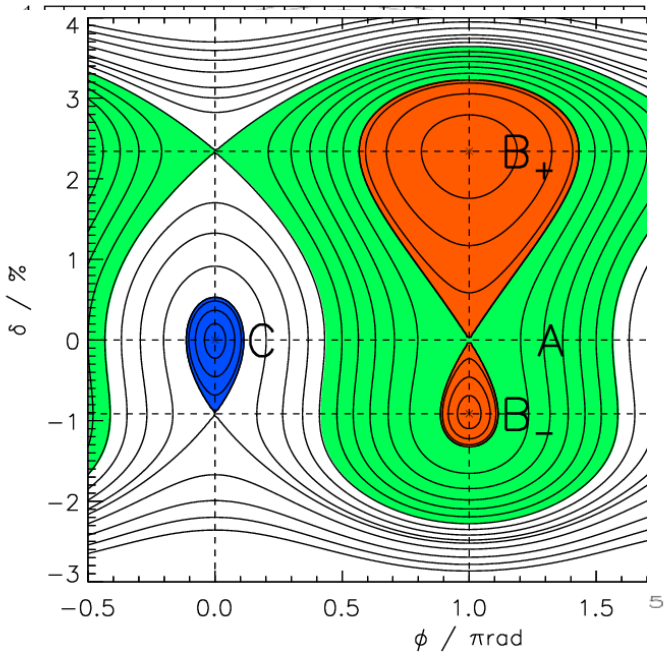
- higher orders are important for quasi-isochronous optics

Low Alpha Operation - Nonlinear Buckets

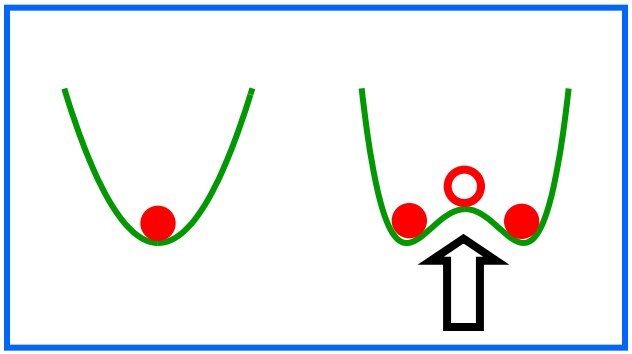
(M. Ries, IPAC 2011, San Sebastian)

adjusted with octupole

$$\mathscr{H}(\phi,\delta) = 2\pi q f_{\mathrm{rev}} \left(\frac{\alpha_0}{2} + \frac{\alpha_1}{3}\,\delta + \frac{\alpha_2}{4}\,\delta^2 \ldots \right) \delta^2 + \frac{eU_0 f_{\mathrm{rev}}}{\beta^2 E_0} \cos(\phi)$$



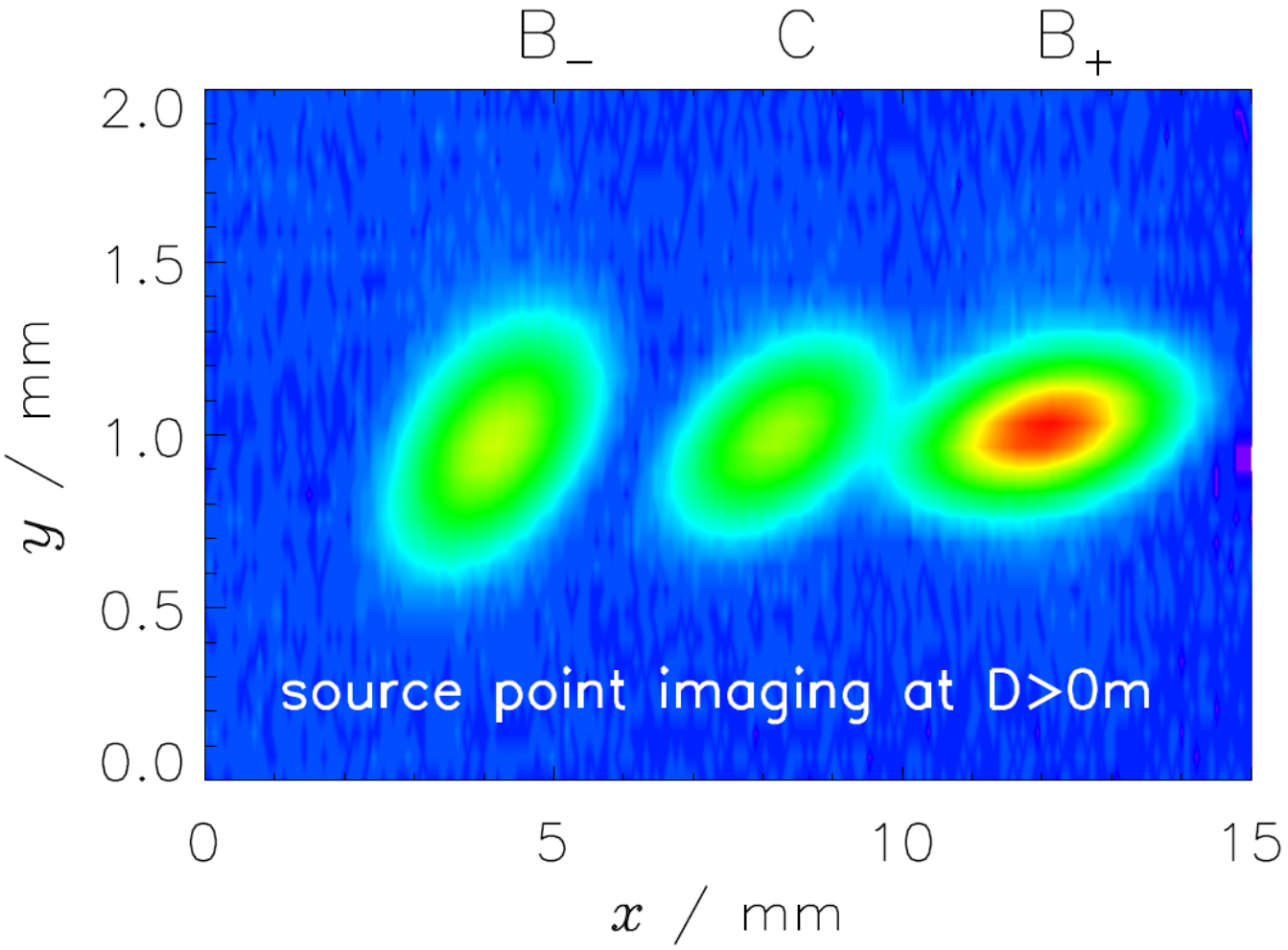
fixed points



fixed points :

sin φ =0, α Δp/p =0

Low Alpha Operation - Nonlinear Buckets

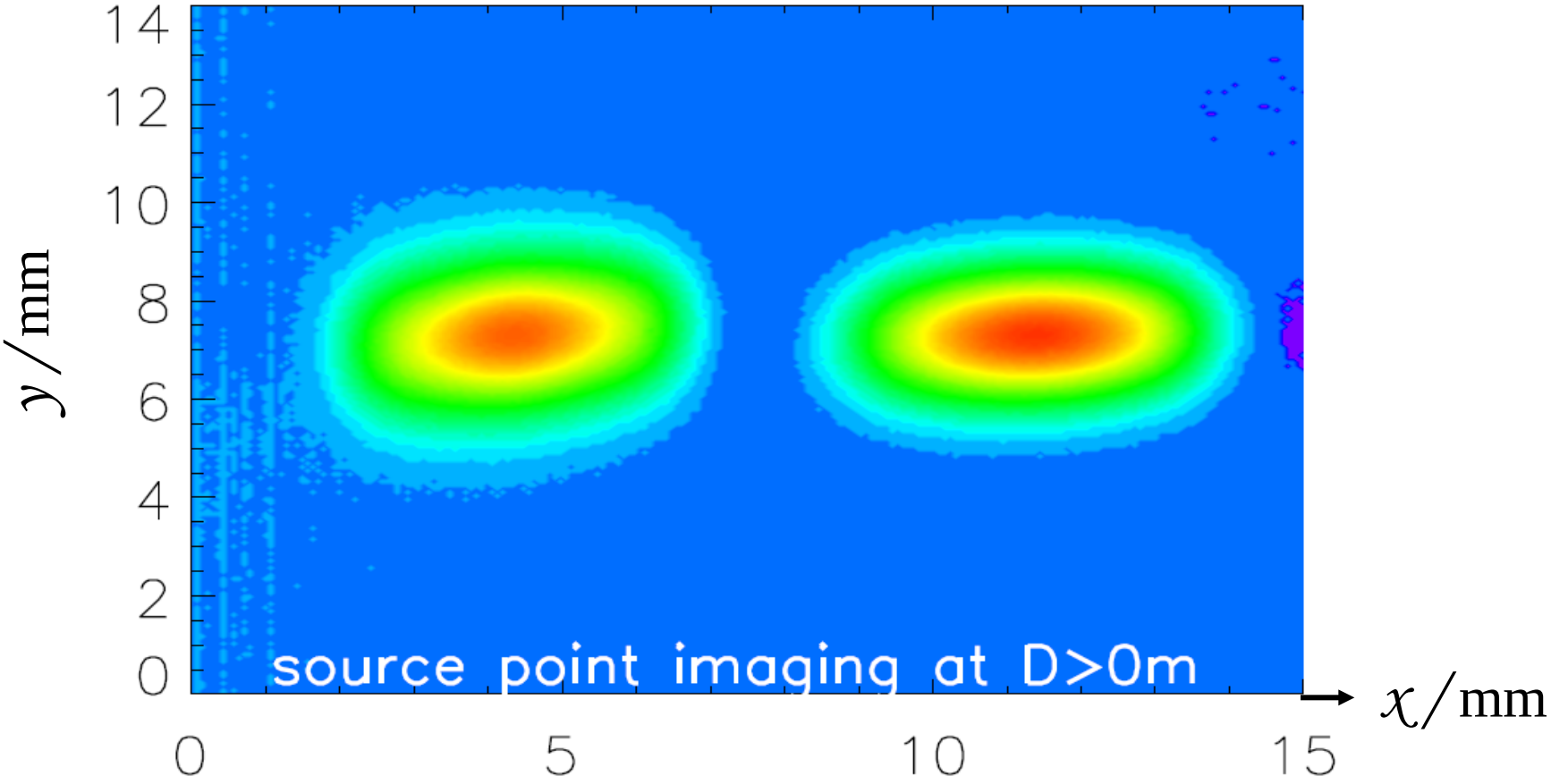


M. Ries *et al.*, Low-ε-Rings 2011, Heraklion, Greece

Low Alpha Operation - Nonlinear Buckets

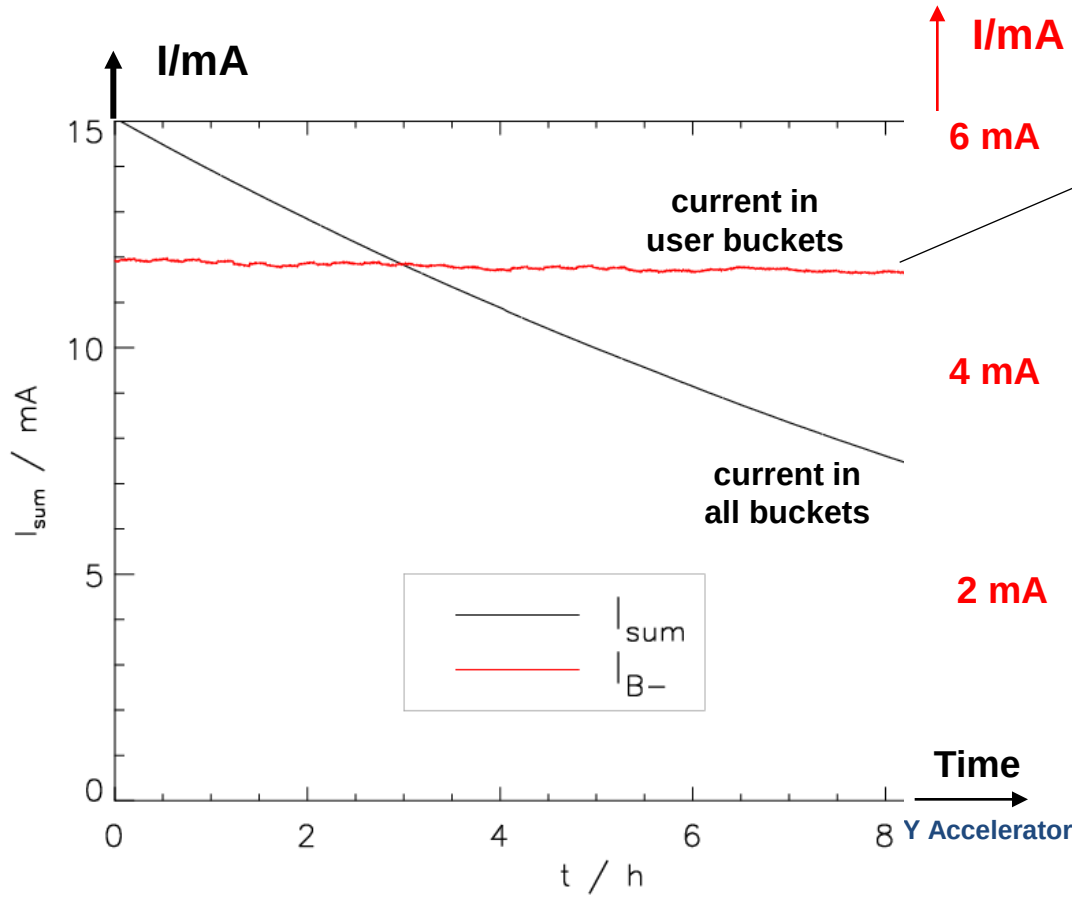
$$E = 629\ \mathrm{MeV},\ I = 170\ \mathrm{mA},\ \tau = 10\ \mathrm{h}$$

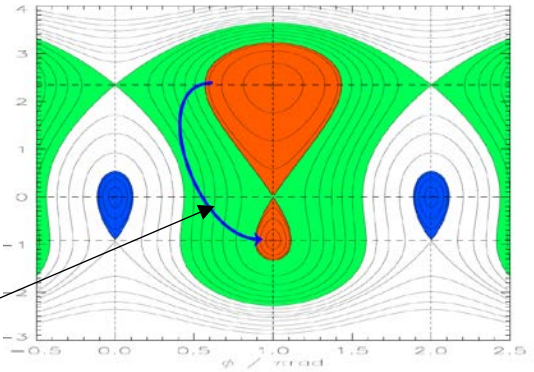
Double beam operation –> well seperated source points at experiment(s)



Top-up Mode using „lifetime feedback“ on double beam

Markus Ries





I/mA

6 mA

4 mA

2 mA

by adjusting the diffusion rate from reservoir to user buckets

beam lifetime ≈ ∞ (nearly)

was achieved for over 10h

Data Base of optional MLS Optics

HZB Helmholtz Zentrum Berlin

Markus Ries

MLS lattice contains **24 indepently powered Quadrupols** grouped in **5 families**

brute force tracking determines optics resulting from all **combined settings of Quad-families** (f.ex. D.Robin + V.Suller et. al. PRST Acc. and Beams 11, 2008)

strength of every Quad-family varied independently in **251 steps ->**

scanning a total number of **800 000 000 000 different optic settings**

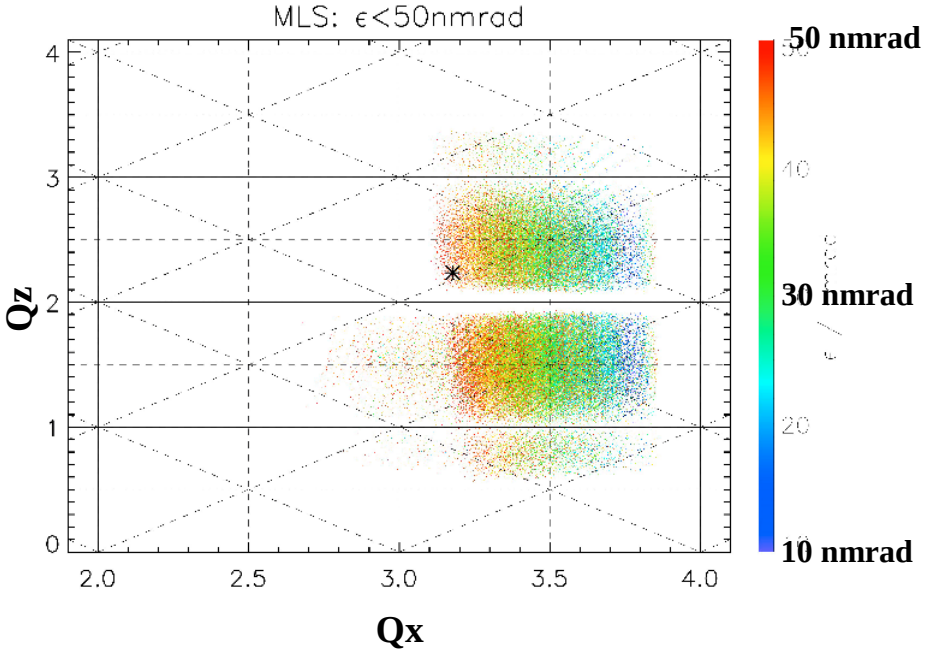
Filtering according reasonable values for beta functions and dispersion result in

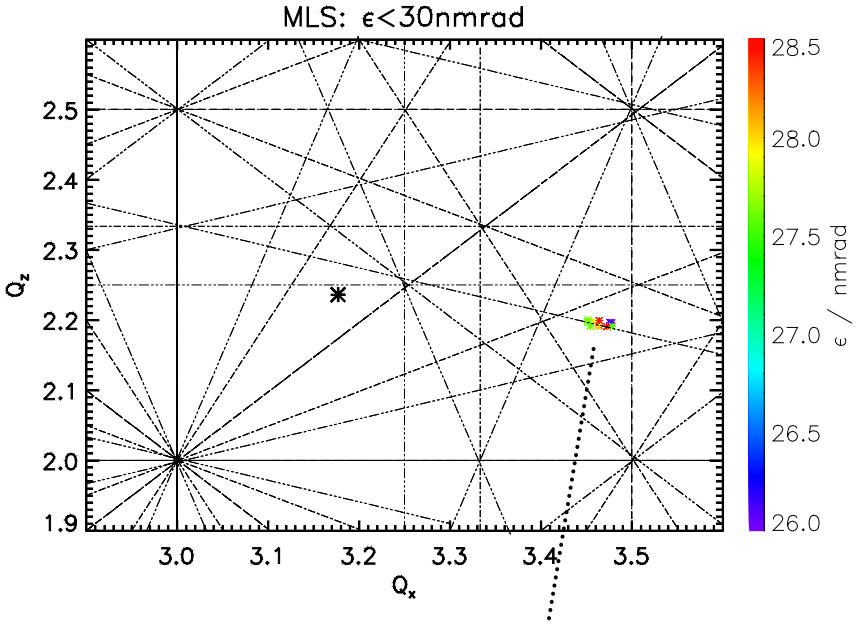
17 000 000 optional alternate optics (4GB) -> MLS optics Data Base

we tried some of them

Example: low emittance optic

DB filtered for settings with **small emittance** ⟶ filter for **accessibility from standard user optic** (no resonance crossing)





low emittance optic was implemented by an optic change from standard optic and shows a promising performance on beamlines tests

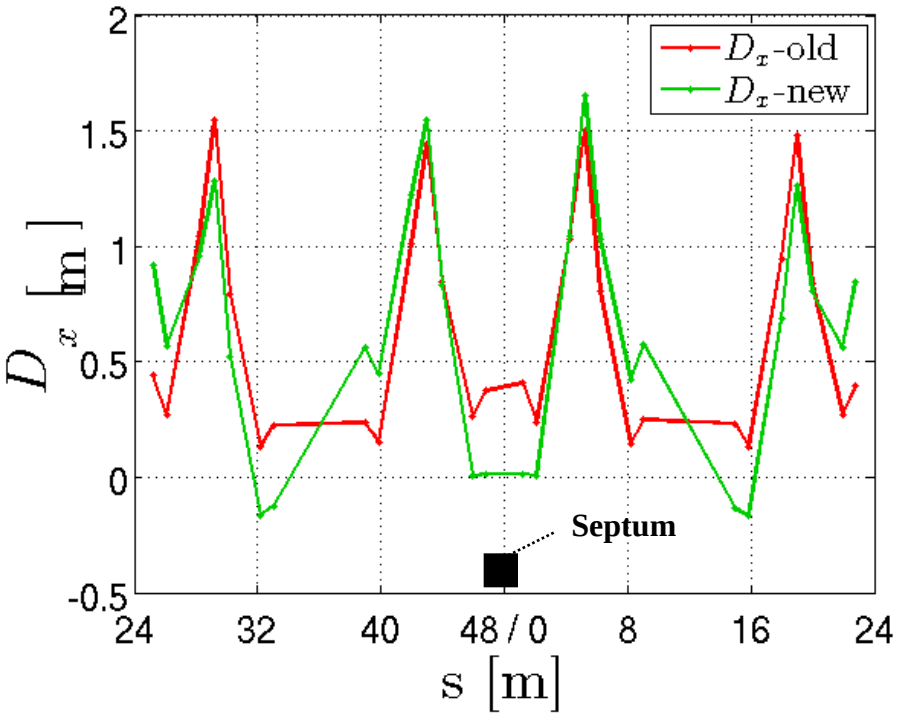
since 28.10.2013 established as „one-button“ option in operation master

Optimizing Optic according Aperture

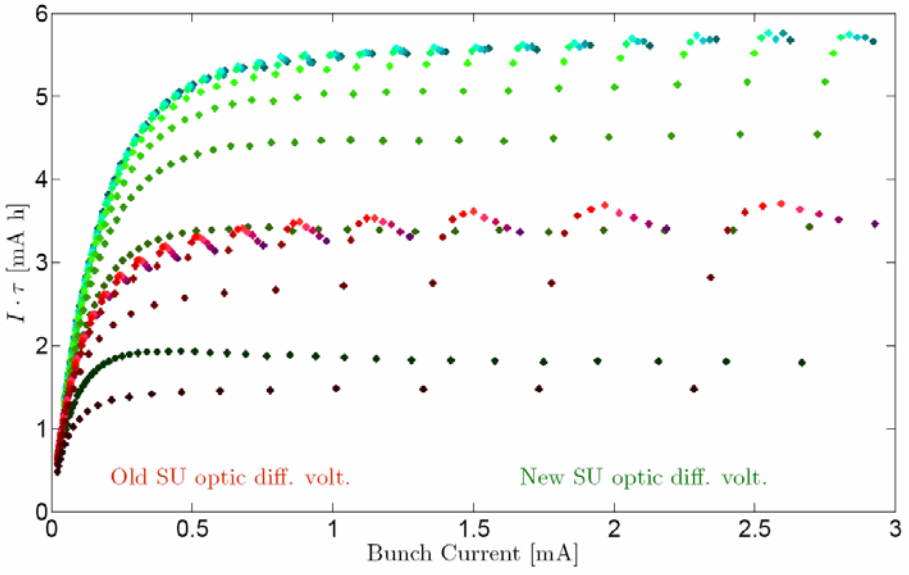
At MLS **Aperture = physical Aperture** (not dynamic)

Smallest value for **horiz. Aperture** is at the **Septum** (**70 mm -> 40 mm**)

Optics with **horiz. Dispersion = 0 at Septum** recently **improved Lifetime by 40 % !**



I*τ [mA*h] vs SB-current vs U_{RF}
red = old, green=new optic



Thesis T. Goetsch, Idea Markus Ries

Use of Robinson Wiggler for Bunch lengthening

increase energy spread + smaller ε_x -> increase bunch length at constant source size

$$\sigma^2 \approx \epsilon\beta + \delta^2 D^2$$

source size in **Standard User Mode (SU)** : **emittance contr. >> dispersive contr.**

$$\epsilon_{SU}\beta_{SU} \approx 1.3 \cdot 10^{-7} m^2 >> 7.7 \cdot 10^{-9} \approx \delta_{SU}^2 D_{SU}^2$$

if **energy spread** is **increased** so far that at source p. $\epsilon\beta = \delta^2 D^2$

and the **emittance is reduced by a factor 2** $\epsilon\beta = \epsilon_{SU}\beta_{SU} / 2$

energy spread and **bunchlength are increased** by factor of **L ~ 4 /V 2 ~ 2.8**

with the **source size unchanged**

Robinson Wiggler

Used 1983 at CERN PS to counteract anti-damping
Recently suggested by A. Nadji to achive low emittances in SR-sources

Increase Energy spread with Robinson Wiggler

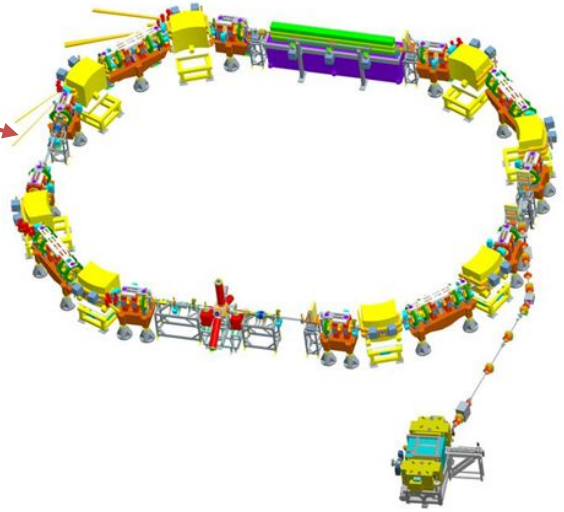
By reducing the long. damping partition number **Js: 2.2 -> 0.2**

energy spread could be increased by a factor of **4**.

Necessary gradients would be low enough for normal conducting Quadrupol

$$\frac{dB_y}{dx} = -17\frac{T}{m}$$

optional position for Robinson Wiggler



SR applications in metrology at MLS

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Radiometry (from the THz to the X-ray range)

- Characterization and calibration of radiation sources and detectors
- Characterization of optical components, in particular for EUV lithography

Nanometrology

- EUV scatterometry

Spectrometry, microscopy and surface characterisation

- IR microspectroscopy and near-field microscopy (nanospectroscopy)
- UV/VUV ellipsometry and electron spectroscopy

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What is Radiometry?

Measuring radiation units

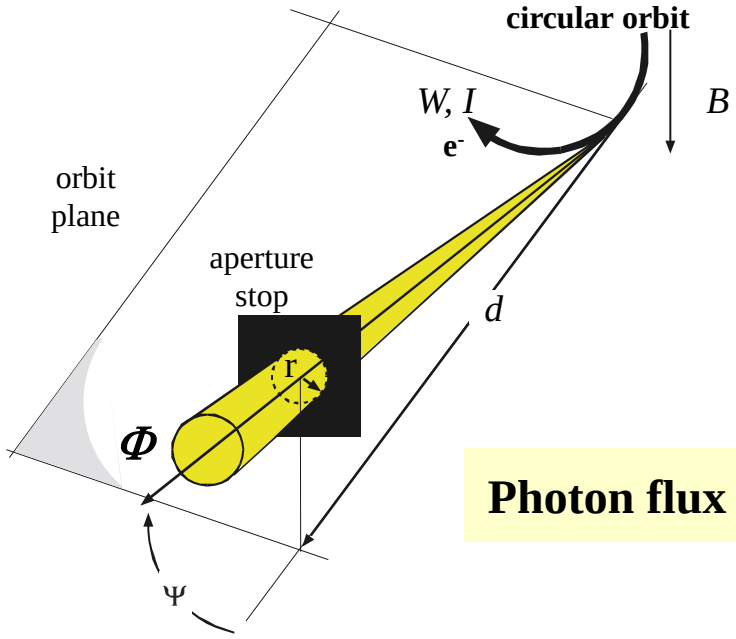
radiometric units

Radiant intensity	/	$W \cdot sr^{-1}$
radiation density	/	$W \cdot m^{-2} \cdot sr^{-1}$
exposure rate	/	$W \cdot m^{-2}$
spectral sensitivity	/	$A \cdot W^{-1}$

…..

Measuring Radiation Power -> reduction to a measurement standard

Calculable Synchrotron Radiation from Bending Magnets



Photon flux $\Phi = \Phi(W, I, B, \sum_y, d, r, \psi)$

• electron beam and storage ring parameters		• geometrical quantities	
W	electron beam energy	d	distance
I	electron current	r	radius of aperture
B	magnetic induction	ψ	emission angle
$\sum_y$	vertical extension and divergence of the beam		

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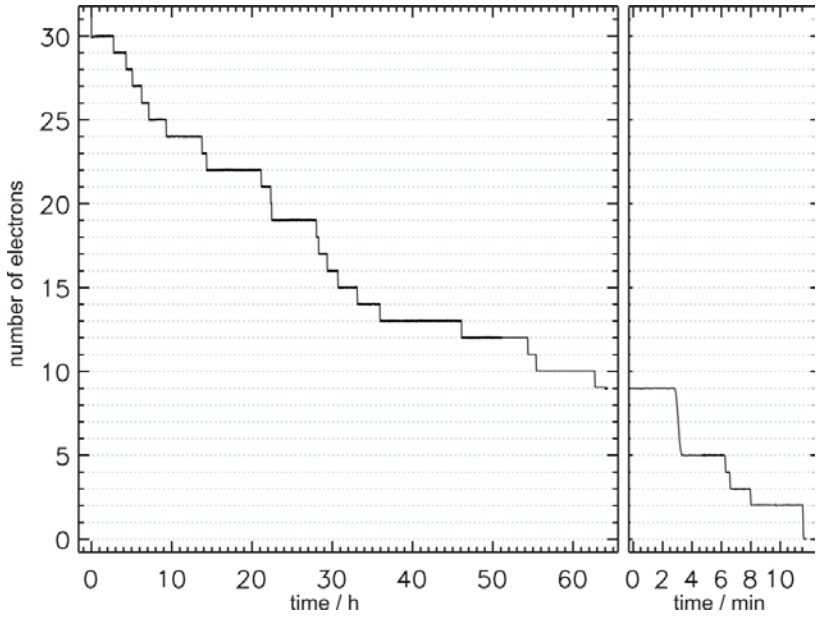
electron energy: **Compton backscattering**

elektron current: **PCT, photodiode**

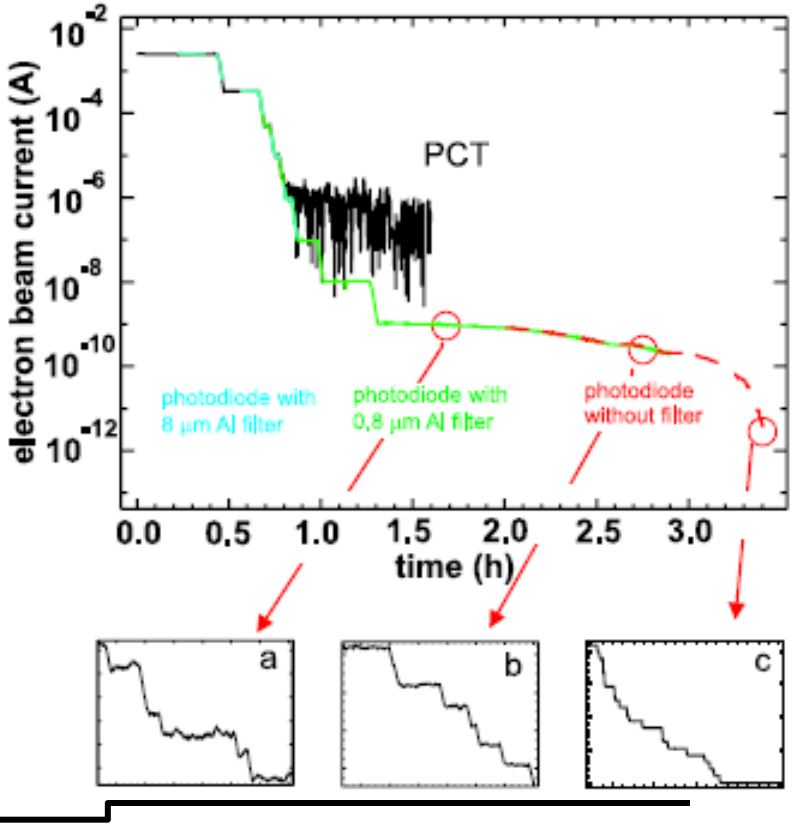
magnetic field: **NMR probe**

source size: **imaging system**



example: beam current measurement

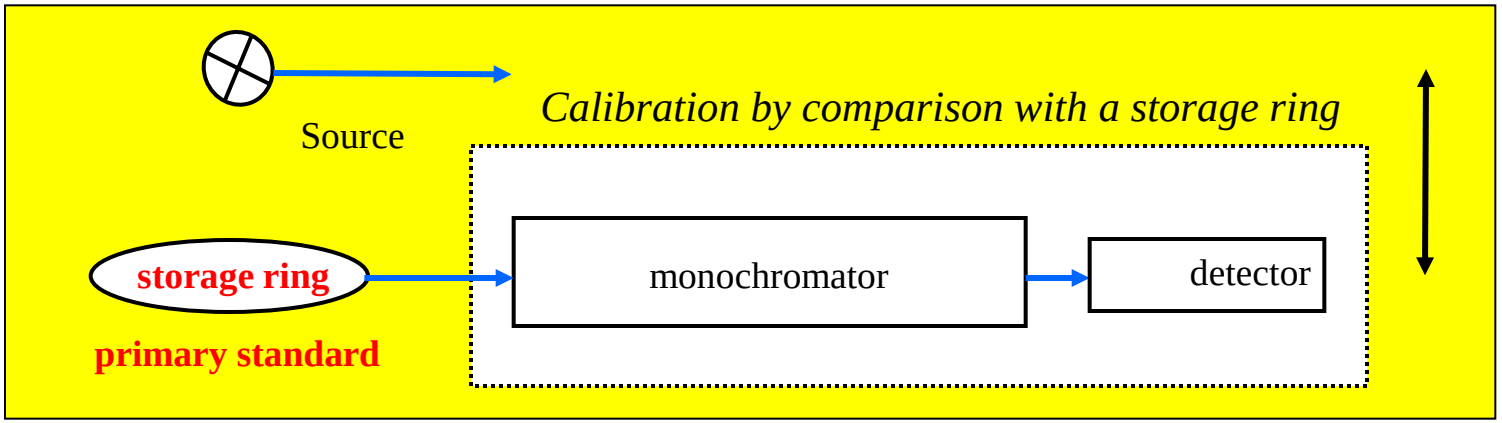
Evaluate numbers of e- covering 12 orders



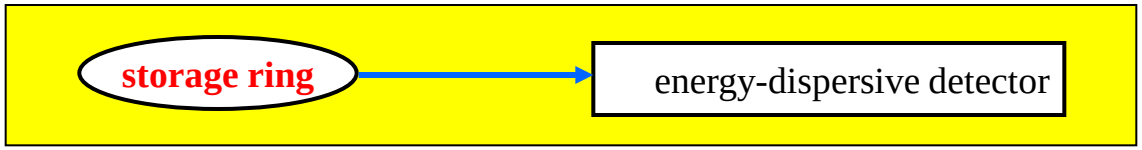
Source-based radiometry

Basis: Primary source standard electron storage ring MLS

- Task 1: Calibration of sources



- Task 2: Calibration of energy-dispersive detectors (e. g. Si(Li), SDD, HPGe)



Important: Storage rings have a dynamic range of up to 12 orders of magnitude in photon flux!

Requirement for calibration: Special operation parameters of the storage ring

Example: calibration of space instrument

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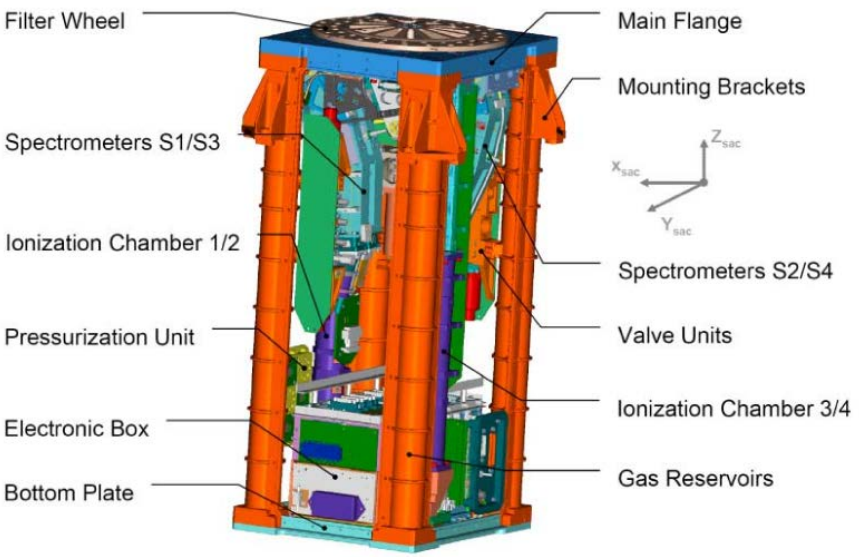
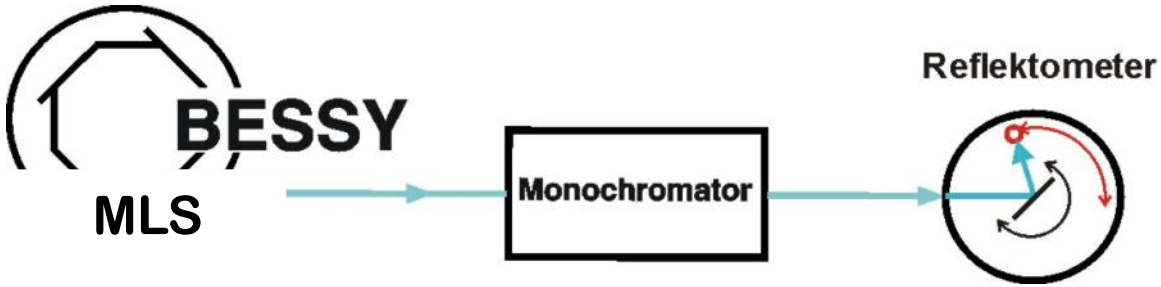
SOL-ACES Modul

Solar Autocalibrating Extreme Ultraviolet Spectrometer



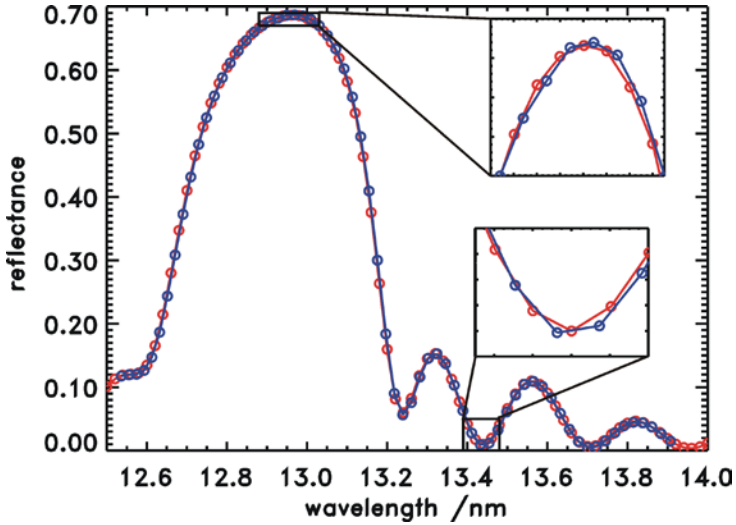
Reflectometry



Huge demand from industry (Zeiss, ASML)
characterizing Multilayer sandwich focussing mirrors used for

13-nm-Lithography (**EUVL**) imaging optics

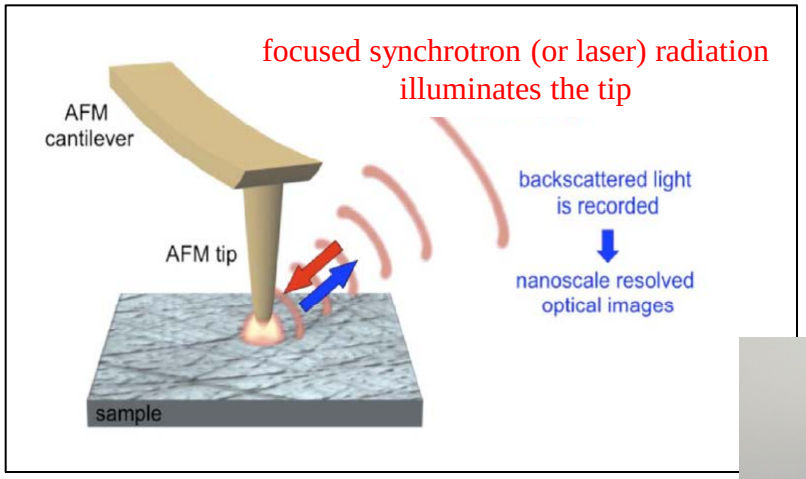
approved surface flatness of **14 pm** (1/7 Angstroem) over a **0.6m** (40kg) **mirror**

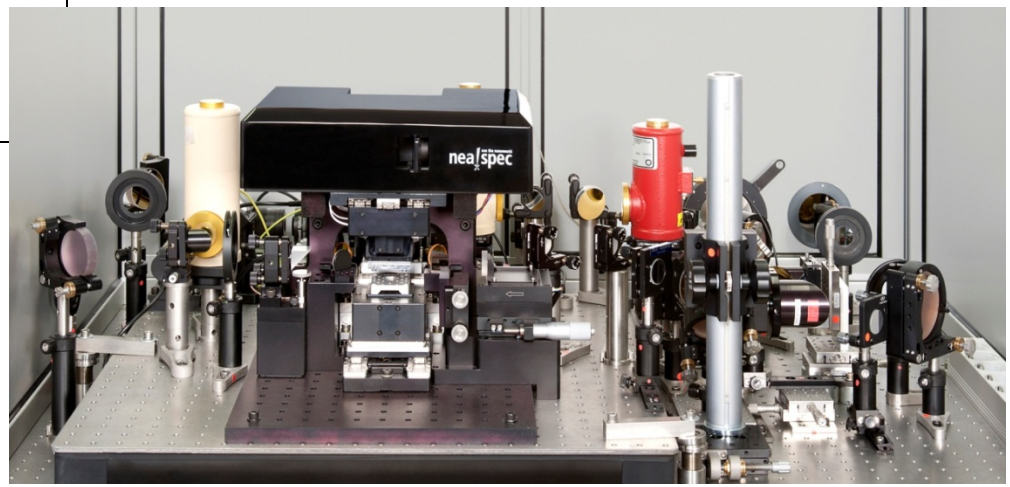


MLS is part of a production chain for innovative wafer factories using 13 nm EUV technology to produce much higher integrated circuits

scanning near-field optical microscopy (s-SNOM)

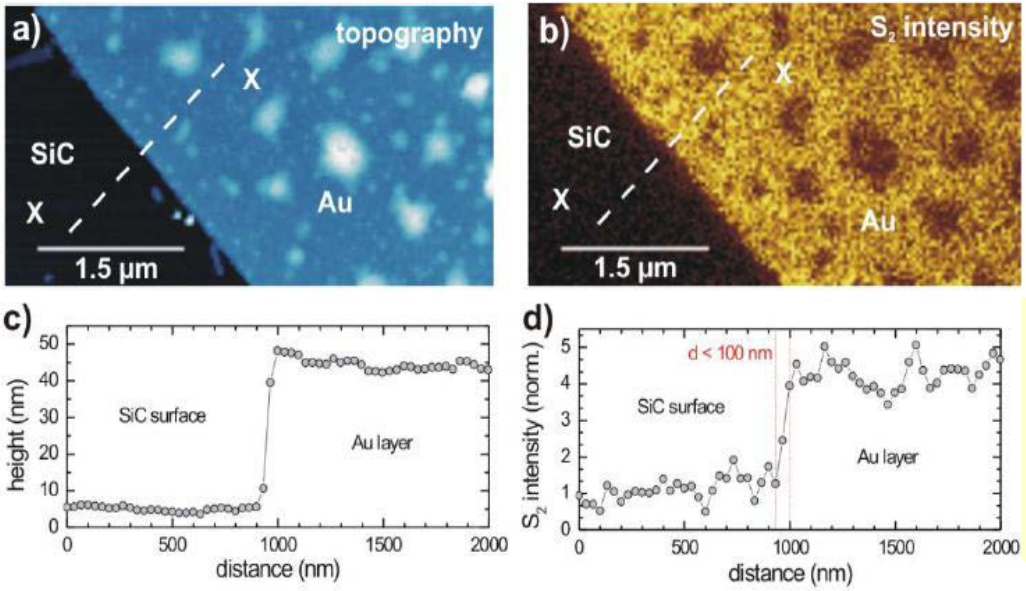
Combination of scanning probe and spectroscopic techniques for chemical imaging and spectroscopy at the nanoscale



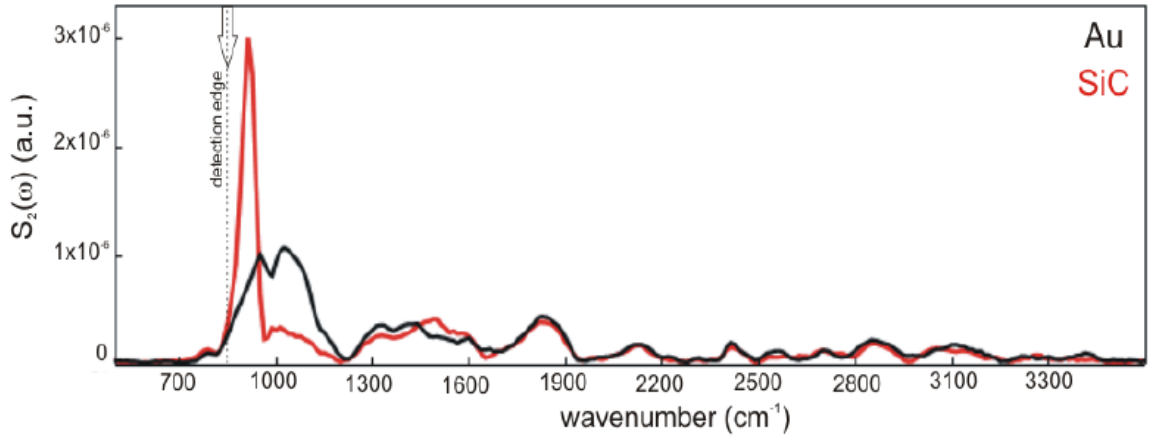


s-SNOM at the MLS IR beamline

Spatial resolution and nano-FTIR spectroscopy with IR-SR



- **spatial resolution < 100 nm**
- **broadband SR enables acquisition of nano-FTIR spectra over a wide spectral range**



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Thank for your interest !