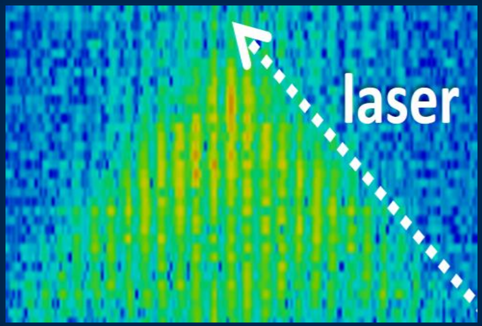
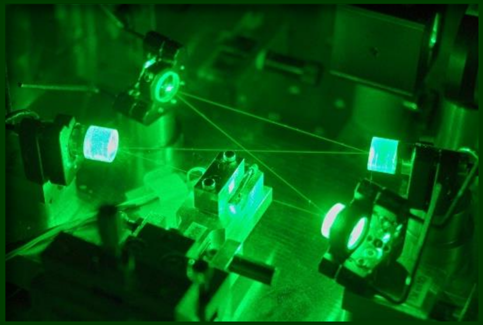
laser cooling of partially stripped relativistic ion beams

bunched ion beams





cw & pulsed laser beams

Danyal Winters
GSI Helmholtzzentrum, Darmstadt

MITP topical workshop “Physics Opportunities with the Gamma Factory” - Dec 2020

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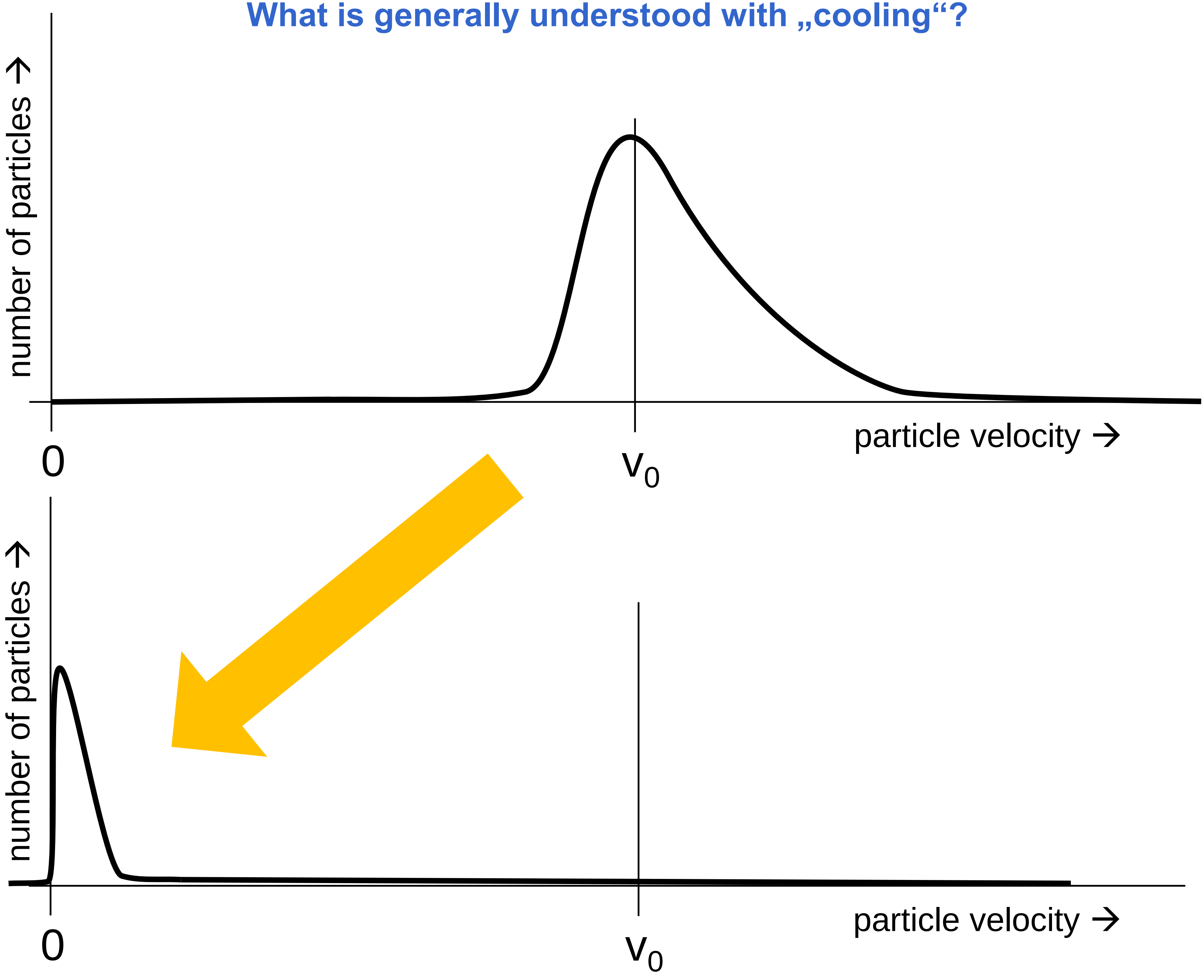
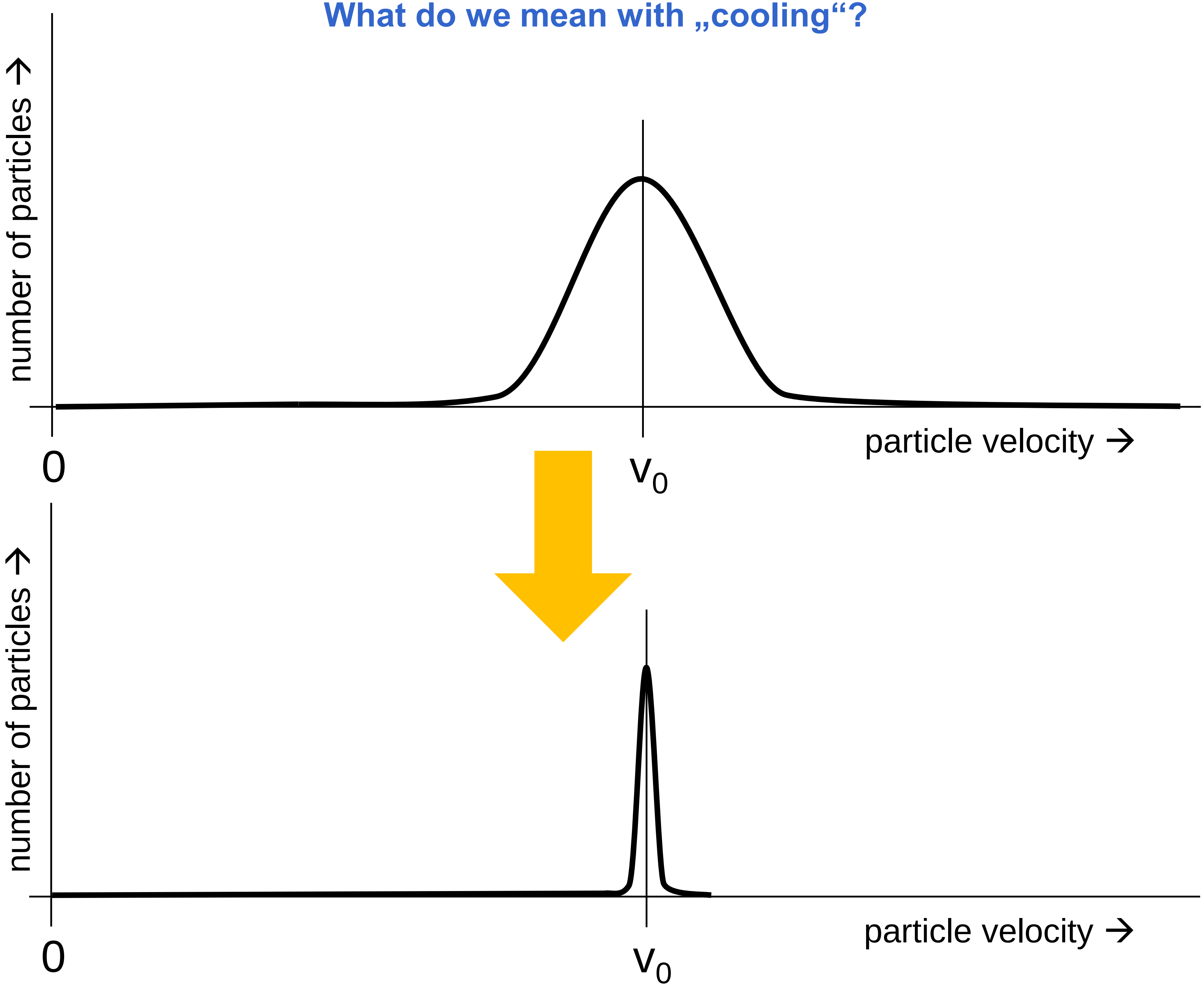
What is generally understood with „cooling“?



What do we mean with „cooling“?



Motivations for laser cooling:

- fundamental aspects of very cold ion beams
  → coupling, ordering → *coherence in fluorescence?*
- advantages of cold ion beams
  → low momentum spread, low emittance → *longer lifetime*
- applicable at almost any circular accelerator
  (laser in/out, bunching, fluorescence detection)

opportunity: laser spectroscopy
→ find transition, measure it precisely

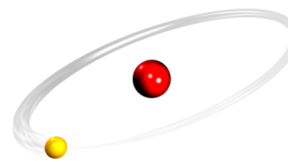
dream: sympathetic cooling
→ laser-cooled ions cool other stored ions

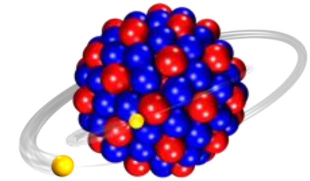
typical

- light ions → heavy ions
- low charge states → high charge states
- low energies → high energies

special

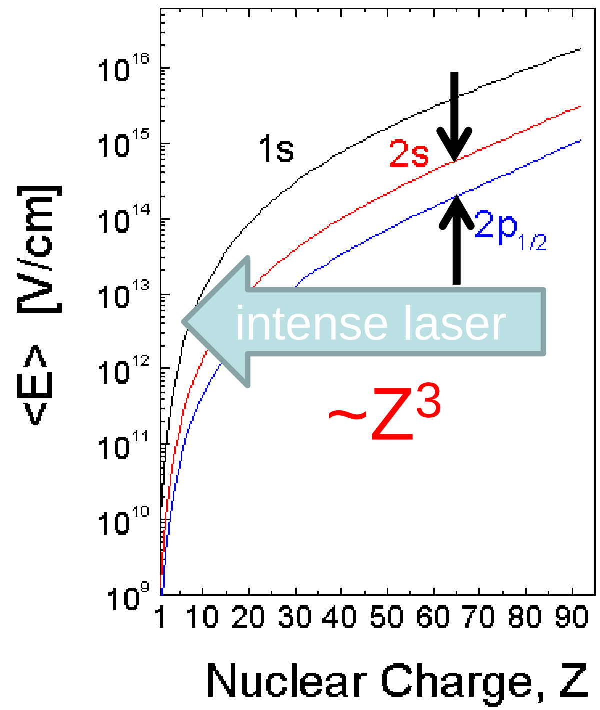
Study simple (few electron) systems to compare theory & experiments.





laser spectroscopy & laser cooling

sparc
Stored Particles Atomic Physics Research Collaboration



Contents

laser cooling people:

ESR

GSI, Darmstadt
Sebastian Klammes[§], Thomas Kühl, Rodolfo Sanchez, Peter Spiller, Markus Steck, Thomas Stöhlker[#], **Danyal Winters**
([§]auch TU-Darmstadt, [#]auch HI Jena & Uni-Jena)

HZDR, TU-Dresden
Michael Bussmann, Markus Löser, Mathias Siebold, Ulrich Schramm

TU-Darmstadt
Tobias Beck, Gerhard Birkl, Oliver Boine-Frankenheim, Lewin Eidam, Daniel Kiefer, Benedikt Langfeld, Wilfried Nörtershäuser, Benjamin Rein, Thomas Walther

IMP-CAS, Lanzhou, China
Dongyang Chen, Zhongkui Huang, Xinwen Ma, Weiqiang Wen, Hanbing Wang, Dacheng Zhang

CSRe

Uni Münster
Axel Buß, Volker Hannen, Johannes Ullmann, Ken Ueberholz, Christian Weinheimer, Daniel Winzen

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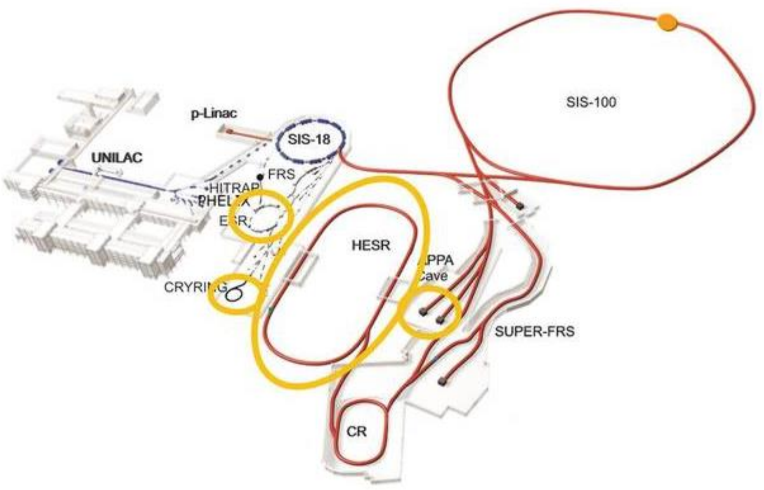
High Energy Single Pass Experiments
HITRAP / Traps
Intense Laser / Ion Interaction
Laser cooling
Laserspektroscopy
Photon and X-ray Spectrometers
Photon Detector Development

SPARC Working Groups: Coordinators

Working Group	Coordinators
Electron / Positron Spectrometers	Xinwen Ma / Siegbert Hagmann
Electron Targets / Cooler	Carsten Brandau / Stefan Schippers
High Energy Single Pass Experiments	Alexandre Gumberidze / Angela Bräuning-Demian
HITRAP / Traps	Frank Herfurth / Wolfgang Quint
Intense Laser / Ion Interaction (intense laser)	Vincent Bagnoud / Thomas Kühl
Laser Cooling	Michael Bussmann / Danyal Winters
Laser Spectroscopy	Wilfried Nörtershäuser / Rodolfo Sanchez
Photon and X-Ray Spectrometers	Martino Trassinelli / Heinrich Beyer
Photon Detector Development	Günter Weber / Andreas Fleischmann
Reaction Microscope	Daniel Fischer / Siegbert Hagmann
Ring Physics and Performance	Michael Lestinsky / Yuri Litvinov
Slow Ion / Surface Experiments	Angela Bräuning-Demian
Target Developments	Robert Grisenti / Alfons Khoukaz
Theory: Atomic Structure / Collision Dynamics	Stephan Fritzsche / Andrey Surzhykov
Technical Support	**Coordinators**
Data Analysis and Simulations	Harald Bräuning
SPARC DAQ / Slow Controls	Harald Bräuning / Uwe Spillmann
SPARC Infrastructure	Angela Bräuning-Demain

sparc
Stored Particles Atomic Physics Research Collaboration

Facilities at FAIR to be used by SPARC



The experimental facilities to be used by SPARC at FAIR-MSV:

- APPA cave (high energy single pass experiments at SIS100)
- HESR (high energy experimental storage ring, maximum magnetic rigidity of 50 Tm)
- ESR (experimental storage ring, maximum magnetic rigidity of 10 Tm)
- CRYRING (experimental storage ring, maximum magnetic rigidity of 1.4 Tm)
- HITRAP (trapping and low energy beam facility for highly charge ions at the ESR)
- SIS100 (synchrotron with a maximum magnetic rigidity of 100 Tm)

Contents

1. motivation
2. laser cooling collaboration
3. principles, techniques, exp. setup
4. ESR & CSRe results
5. 3D laser cooling?
6. outlook

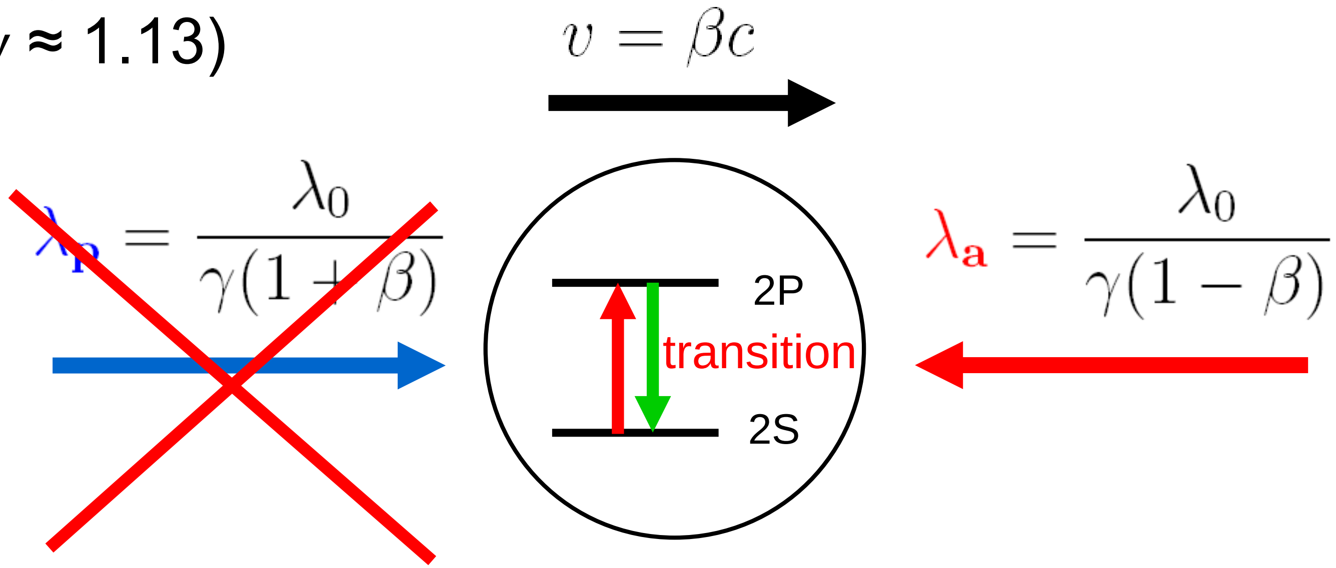
Laser cooling of stored coasting ion beams was first demonstrated at the TSR in Heidelberg (Germany) [5], and at ASTRID in Aarhus (Denmark) [6]. Laser cooling of stored bunched ion beams was demonstrated a few years later at ASTRID [7], followed by studies at the TSR [8, 9]. Experiments on laser-cooled ion crystal structures were performed in circular Paul traps [10] while ion beam crystallization was studied at the table top storage ring PALLAS [11, 12] in Munich (Germany). At the experimental storage ring (ESR) in Darmstadt (Germany), first laser cooling experiments with relativistic ion beams [13] were conducted. Transverse laser cooling has been studied in detail at the S-LSR [14] in Kyoto (Japan). At the CSRe [15] in Lanzhou (China) experiments with relativistic ion beams have been started. $^{16}O^{5+}$
For a good review of the topic, see [16].

References

[5] Schröder S *et al* 1990 *Phys. Rev. Lett.* **64** 2901
[6] Hangst J S *et al* 1991 *Phys. Rev. Lett.* **67** 1238
[7] Hangst J S *et al* 1995 *Phys. Rev. Lett.* **74** 4432
[8] Lauer I *et al* 1998 *Phys. Rev. Lett.* **81** 2052
[9] Eisenbarth U *et al* 2000 *Nucl. Instrum. Meth. Phys. Res.* A **441** 209
[10] Birkl G *et al* 1992 *Nature* **357** 310
[11] Schätz T *et al* 2001 *Nature* **412** 6848
[12] Schramm U *et al* 2001 *Phys. Rev. Lett.* **87** 184801
[13] Schramm U *et al* 2005 *Proc. PAC 2005* (*Knoxville, USA*) p 401 FOAD004
[14] Noda A *et al* 2005 *Proc. COOL 2007* (*Bad Kreuznach, Germany*) p 221 FRM1I01
[15] Wen W *et al* 2013 *Phys. Scr.* **T156** 014090
[16] Schramm U *et al* 2004 *Prog. Part. Nucl. Phys.* **53** 583

The principle: laser cooling of stored bunched relativistic ion beams

ESR example:
C^{3+} ion energy ≈ 122 MeV/u
($\beta \approx 0.47$, $\gamma \approx 1.13$)

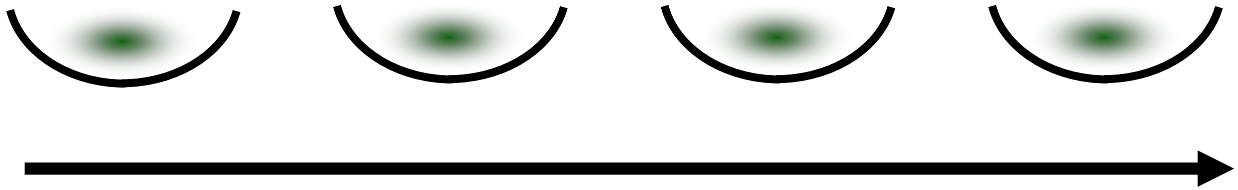


λ_p=93 nm λ_0=155 nm λ_a=257 nm

The ion absorbs many directional momenta from the photons and decays each time with a random recoil, averaging out to zero.

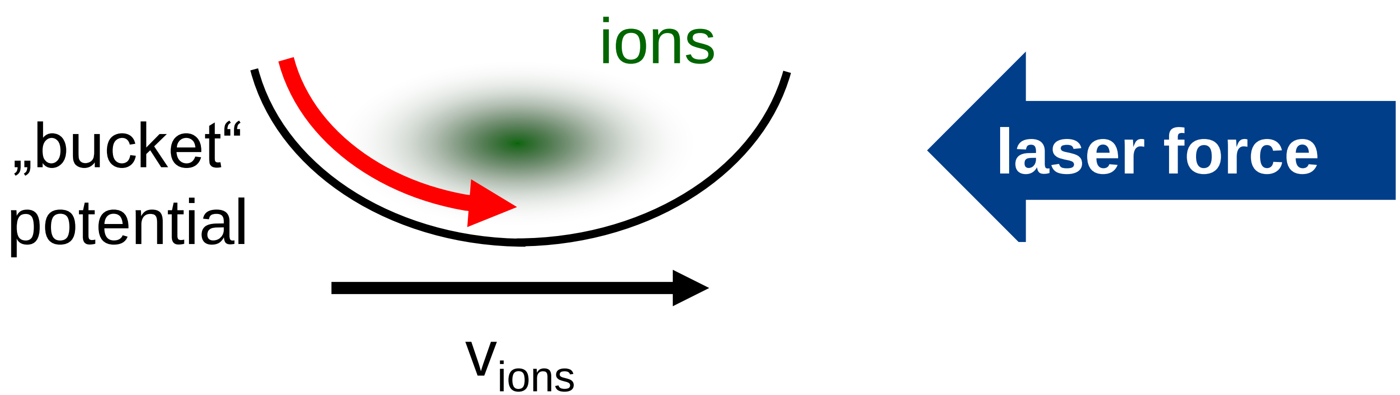
In our case, the cooling laser force is counteracted by the restoring force of the *`bucket´* when **the ion beam is bunched**.

bunching the ion beam counteracts the laser force



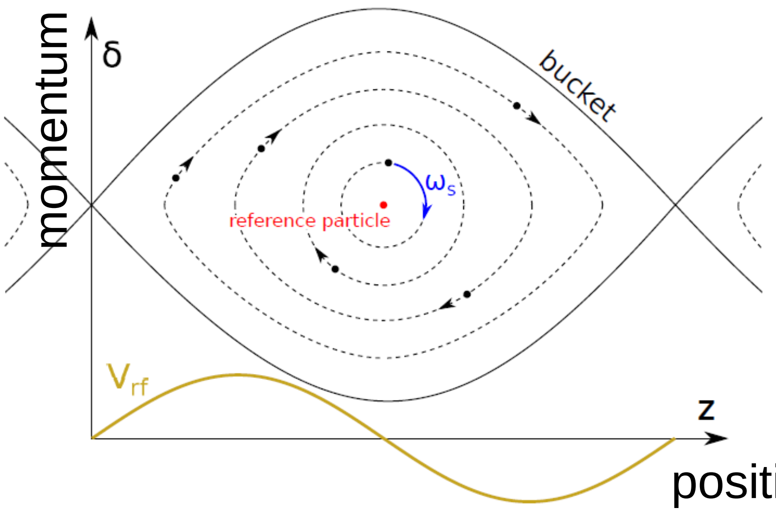
$f_{bunch} = h \times f_{rev} \rightarrow h$ bunches

The ions (repeatedly) pass through a cavity to which an rf-signal is applied, which frequency is a multiple of the ion revolution frequency (~MHz).
The bunching amplitude is typically low, but all ions need to be in a bucket.

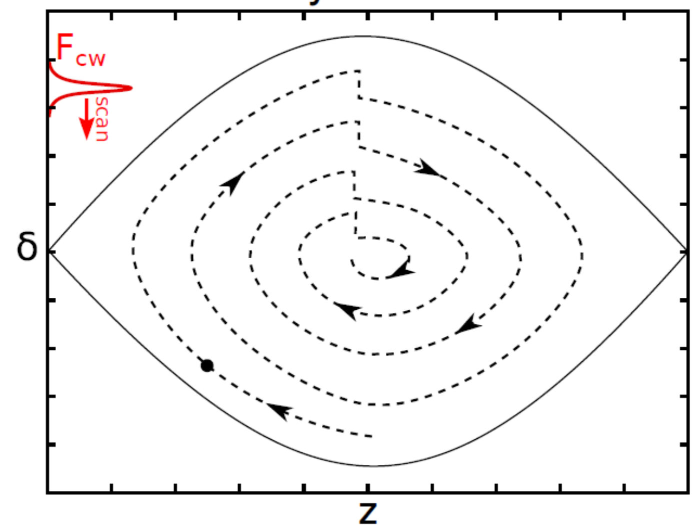


challenges laser cooling in accelerator:

- single laser beam:
  ⇒ no stable point & only deceleration possible
- very hot initial ion ensemble:
  ⇒ laser does not interact with all ions simultaneously



`phase space´



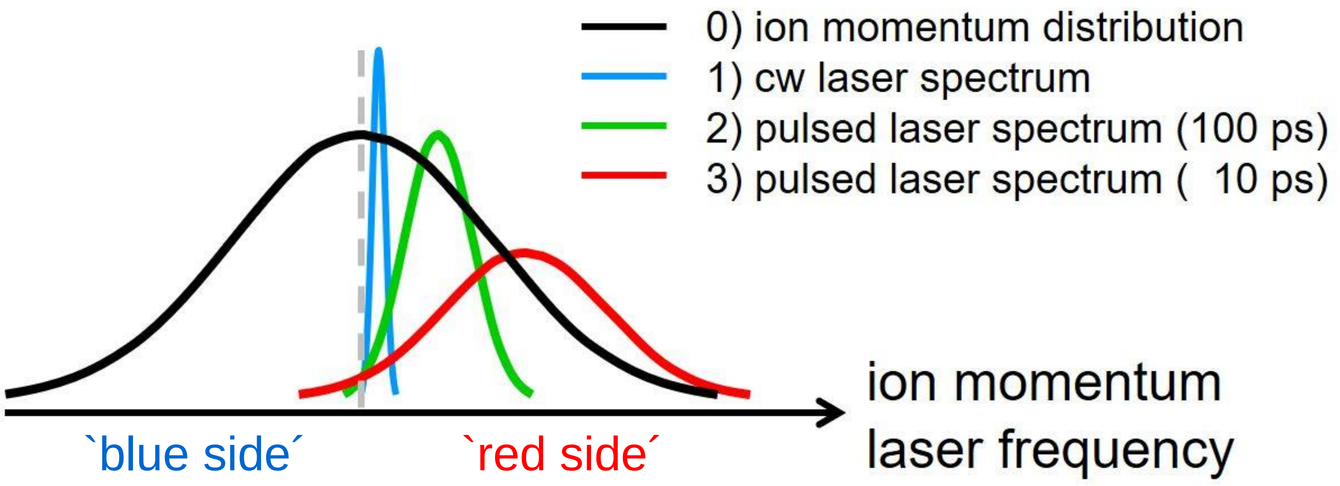
The ions perform synchrotron oscillations inside the bucket potential.

Lewin Eidam

Laser cooling can, in principle, be done at many circular accelerators!

Difficulties are:

- spatial and temporal (pulsed laser) overlap of laser beam & ion beam
- linewidth (MHz) and scan range (GHz) of laser (rep. rate)
- initial velocity spread of ion beam ($\Delta p/p$)
- detection of fluorescence from ions



→ laser systems which have enough power, stability, reliability, rep. rate, and `tuning´ to allow for proper and fast ion beam cooling.

$$\lambda_{laser} = f(B\rho, \underbrace{Q, M, \lambda}_{\text{ion}})$$ for a fixed accelerator

length	108,36	m		length	1083,6	m	10xESR
Bρ	**6,6**	Tm		Bρ	**94**	Tm	
Q	3		C3+	Q	28		Ga28+
e	1,60E-19	C		e	1,60E-19	C	
M	12		C3+	M	69		Ga28+
u	1,66E-27	kg		u	1,66E-27	kg	
c	3,00E+08	m/s		c	3,00E+08	m/s	
γ	1,13			γ	12,30		
ß	0,47			ß	1,00		
Ek	123,09	MeV/u		Ek	10547,76	MeV/u	
f	1,30	MHz		f	0,28	MHz	
ion	**155,00**	nm	C3+	ion	**20,79**	nm	Ga28+
laser	257,60	nm		laser	510,31	nm	
	ESR				**SIS100**		

UV laser

visible laser

Ions for laser cooling @ FAIR

Calculations by Shevelko: (accuracy $\Delta\lambda/\lambda = 10^{-2}$)
transition energies and rates – many elements!

Calculations by Borschevsky / Yerokhin: (accuracy $\Delta\lambda/\lambda = 10^{-4}$)
transition energies and rates – selected species!

All transitions are between a ground state and the nearest upper state, mostly $s_{1/2} \rightarrow p_{1/2\ \&\ 3/2}$. These are $\Delta n=0$ transitions.
($\Delta n=1$ transitions are possible, but have not been calculated yet.)

The range of transition energies has been selected as follows:
step 1: fix laser wavelength (λ), fix magnetic rigidity ($B\rho$)
step 2: calculate Q/A (charge-to-mass ratio) for Z=1 to 92 → range Q/A
step 3: calculate γ and λ_0 as a function of Q/A → range λ_0
step 4: within range λ_0, look for the possible Z-range
For those ions, also transition rates (Hz) have been calculated.

Weiqiang Wen / Michael Bussmann
laser saturation intensities
fluorescence yields

This table gives an overview of all types of ions which satisfy the requirements (λ_{laser} & $B\rho$).

by Slava Shevelko

2. Regime: $B\rho$ = 100 Tm, λ(laser) = 257 nm (4.824 eV)

approx.

El. sequence	Q/M range	Transition	j-j transition	ΔE laser, nm	Nucl. charge Z_n range
Li-like	0.25 – 0.43	2s – 2p	1/2 – 1/2	9 – 16	38 – 60
			1/2 – 3/2		28 - 36
Be-like	0.17 – 0.40	$2s^2$ – 2s2p	1/2 – 1/2	10 - 23	30 - 56
			1/2 – 3/2		25 - 36
B-like	0.08 – 0.40	$2s^22p$ – $2s2p^2$	1/2 – 1/2	10 - 48	17 - 56
			1/2 – 3/2		13 - 33
Na-like	0.04 – 0.34	3s – 3p	1/2 – 1/2	12 - 90	16 – 49
			1/2 – 3/2		16 - 40
K-like	0.025 – 0.30	4s – 4p	1/2 – 1/2	13 - 130	24 - 80
			1/2 – 3/2		24 - 58

These are lithium-like ions, beryllium-like ions, etc.
Ergo: At the SIS100, Z = 60 is the maximum (theoretically, for Li-like ions)
However, Li-like xenon (Z=54) seems to be more realistic.

There is (still) an interest in Li-like ions ☺

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covering atomic, molecular, and optical physics and quantum information

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QED calculation of the $2p$ fine structure in Li-like ions

Vladimir A. Yerokhin, Mariusz Puchalski, and Krzysztof Pachucki
Phys. Rev. A **102**, 042816 – Published 20 October 2020

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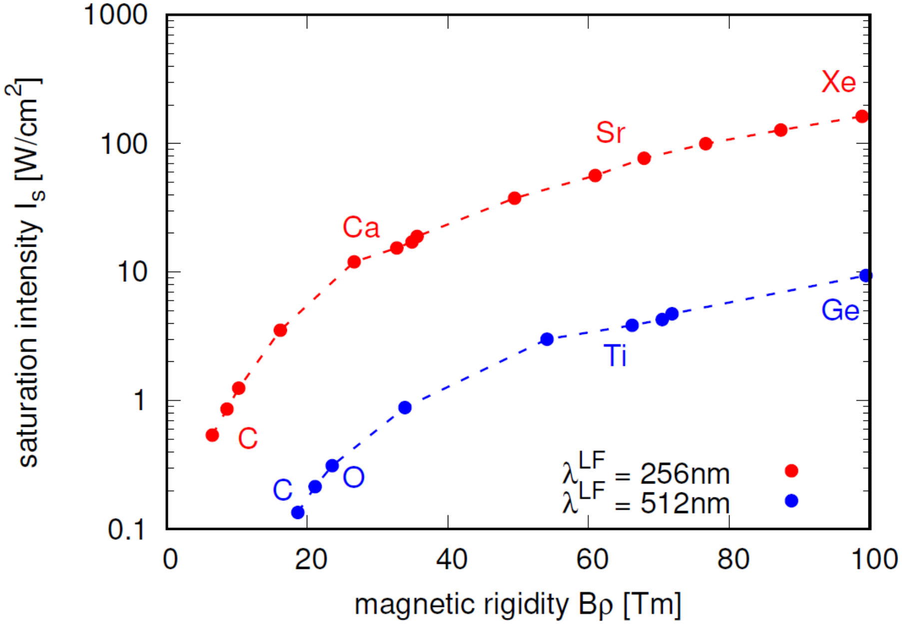
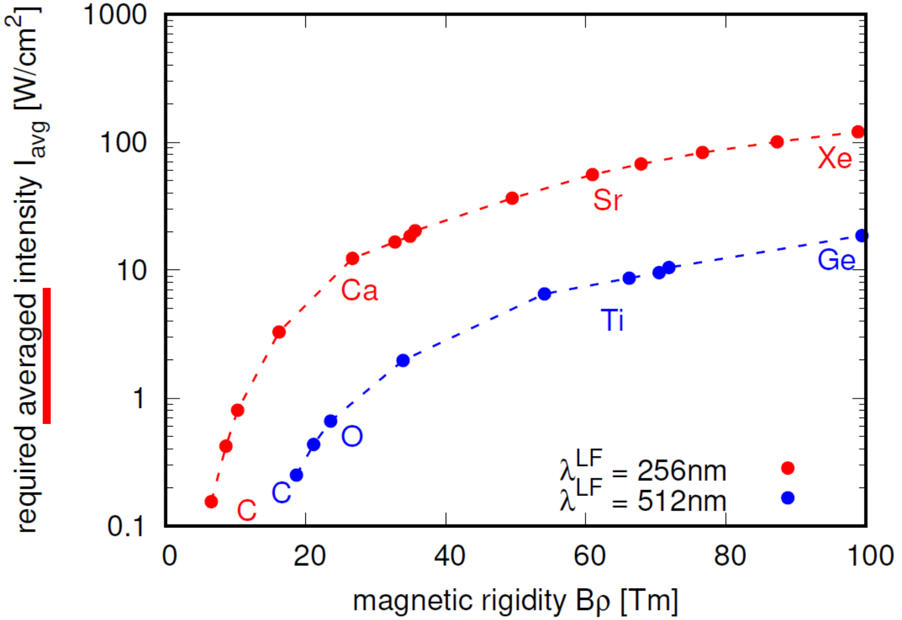
Relativistic configuration-interaction calculations of the energy levels of the $1s^2 2l$ and $1s2l2l'$ states in lithiumlike ions: Carbon through chlorine

V. A. Yerokhin, A. Surzhykov, and A. Müller
Phys. Rev. A **96**, 042505 – Published 26 October 2017; Erratum Phys. Rev. A **96**, 069901 (2017)

in order to saturate the transitions in PSI, high laser intensities are required



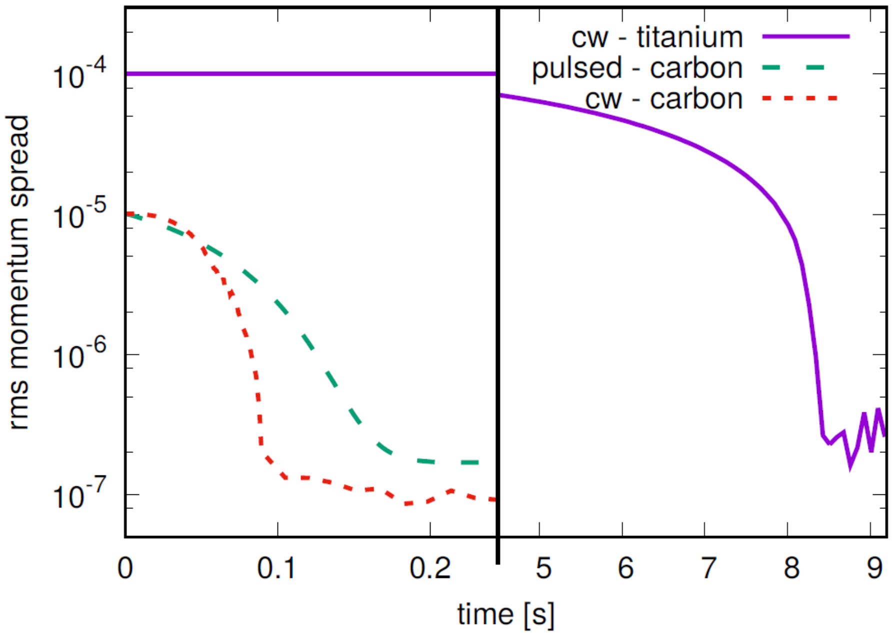
for cw laser

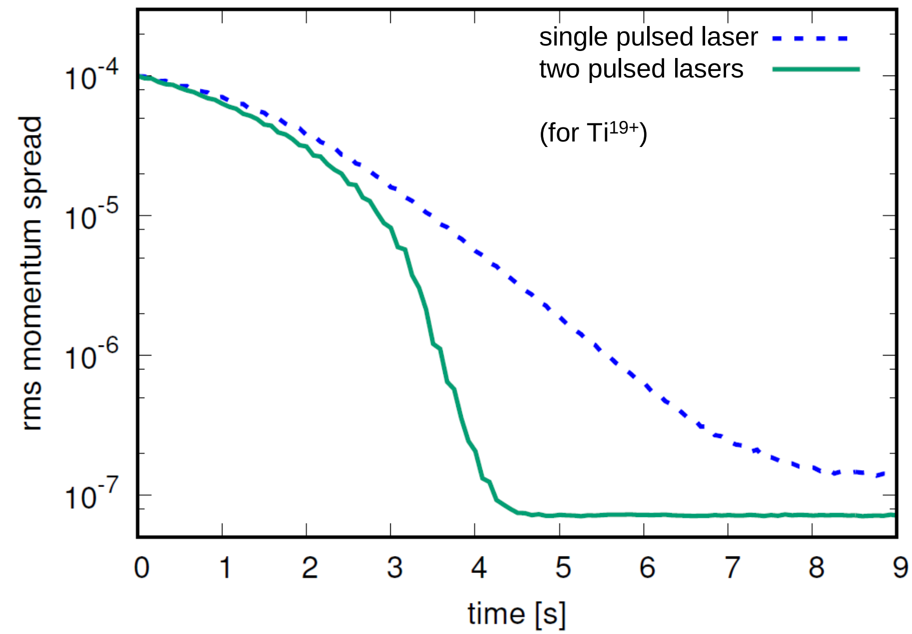


for pulsed laser

Lewin Eidam

cooling times of only a few seconds are expected, and so are very low momentum spreads





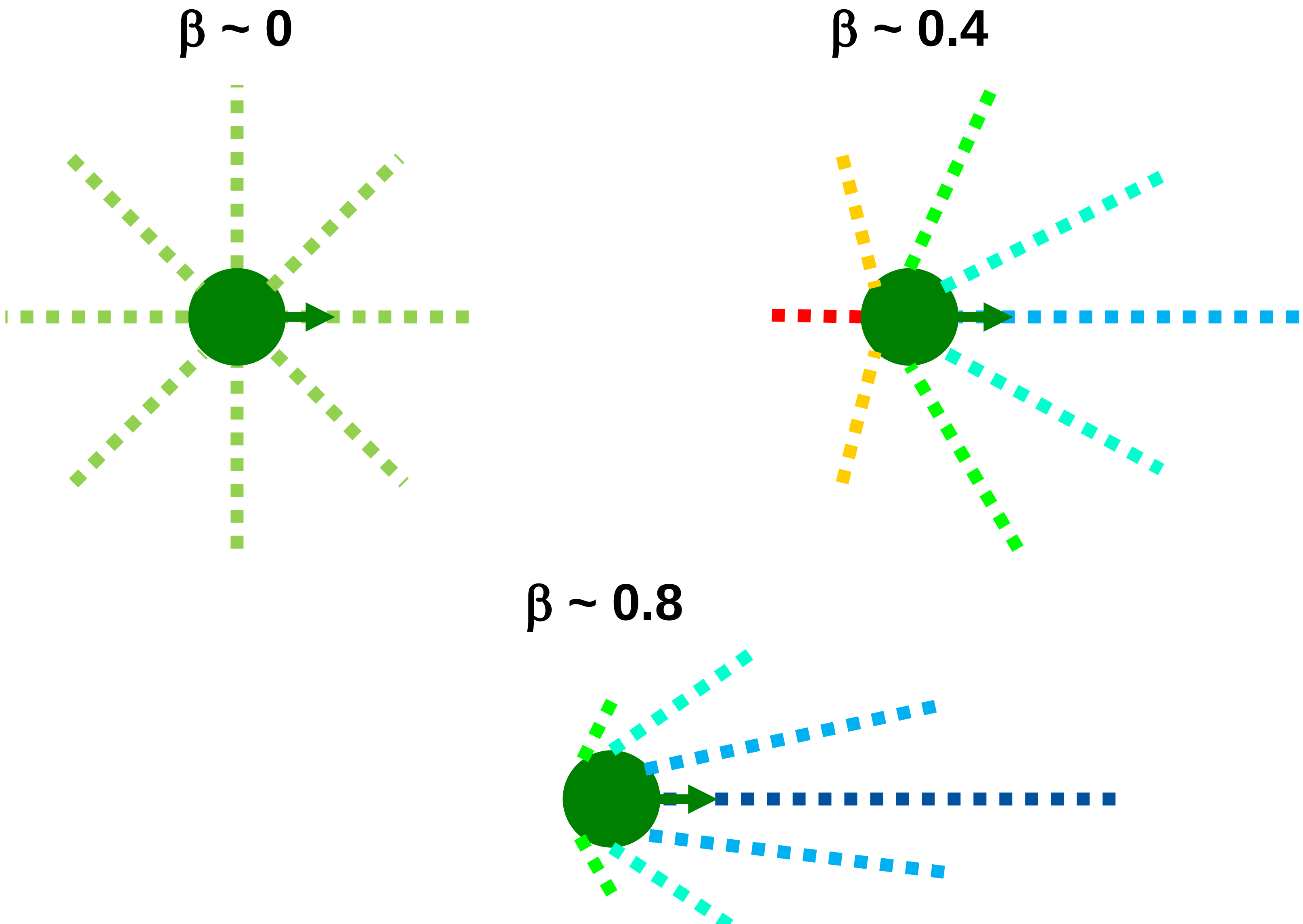
@ESR @SIS100 @SIS100

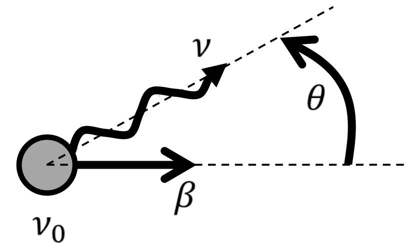
	ESR	SIS100
ion	$^{12}C^{3+}$	$^{48}Ti^{19+}$
L_{acc}	$108\,m$	$1083\,m$
T_{rev}	$0.8\,\mu s$	$3.6\,\mu s$
$L_{interact}$	$25\,m$	$26\,m$
$\sigma_{\delta 0}$	10^{-5}	10^{-4}
d_{beam}	$3\,mm$	$10\,mm$
γ	1.13	8.50
γ_t	2.4	15
h	20	8

Lewin Eidam

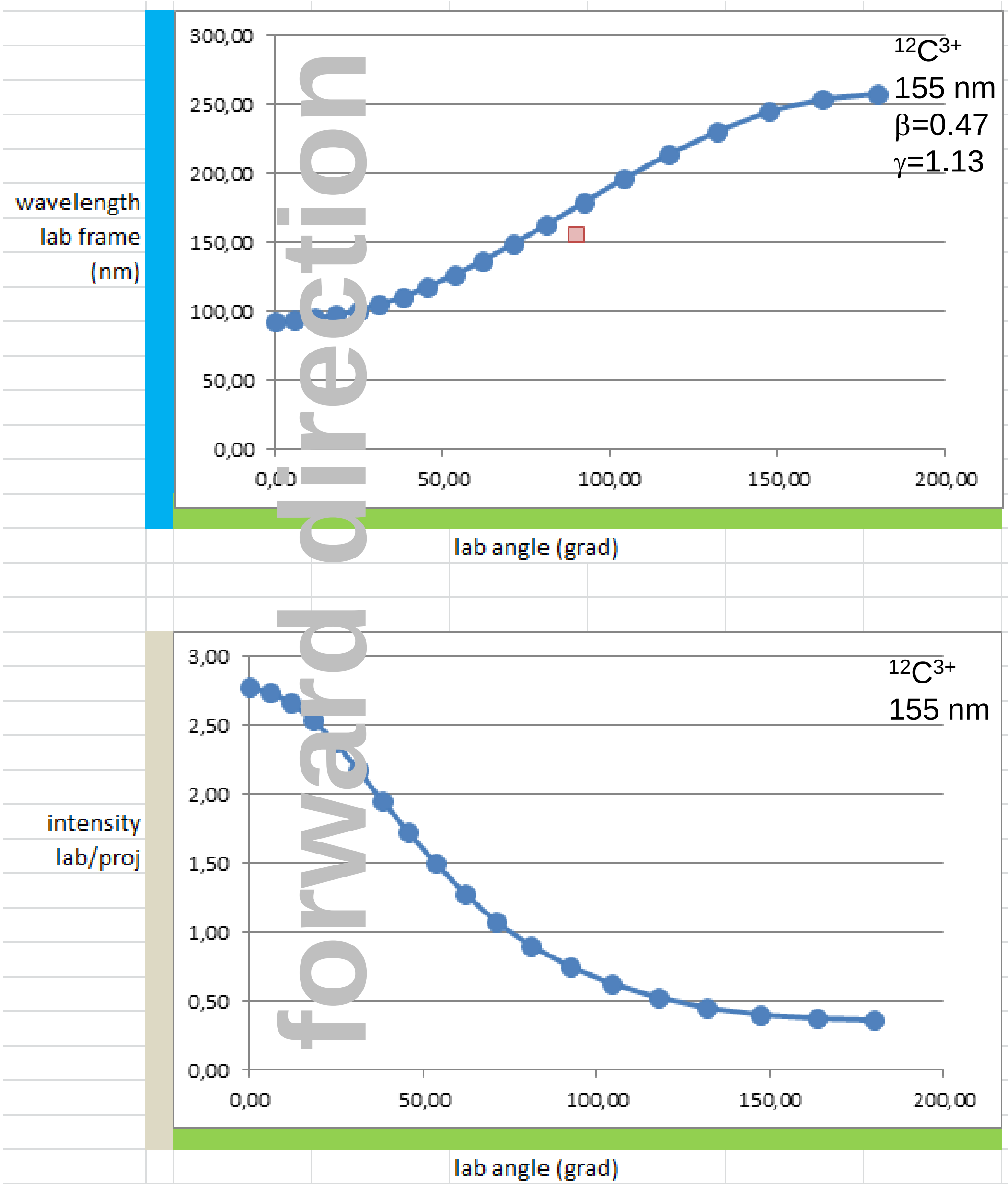
Show the two movies
by Lewin Eidam.

Doppler-boosted wavelength and fluorescence direction





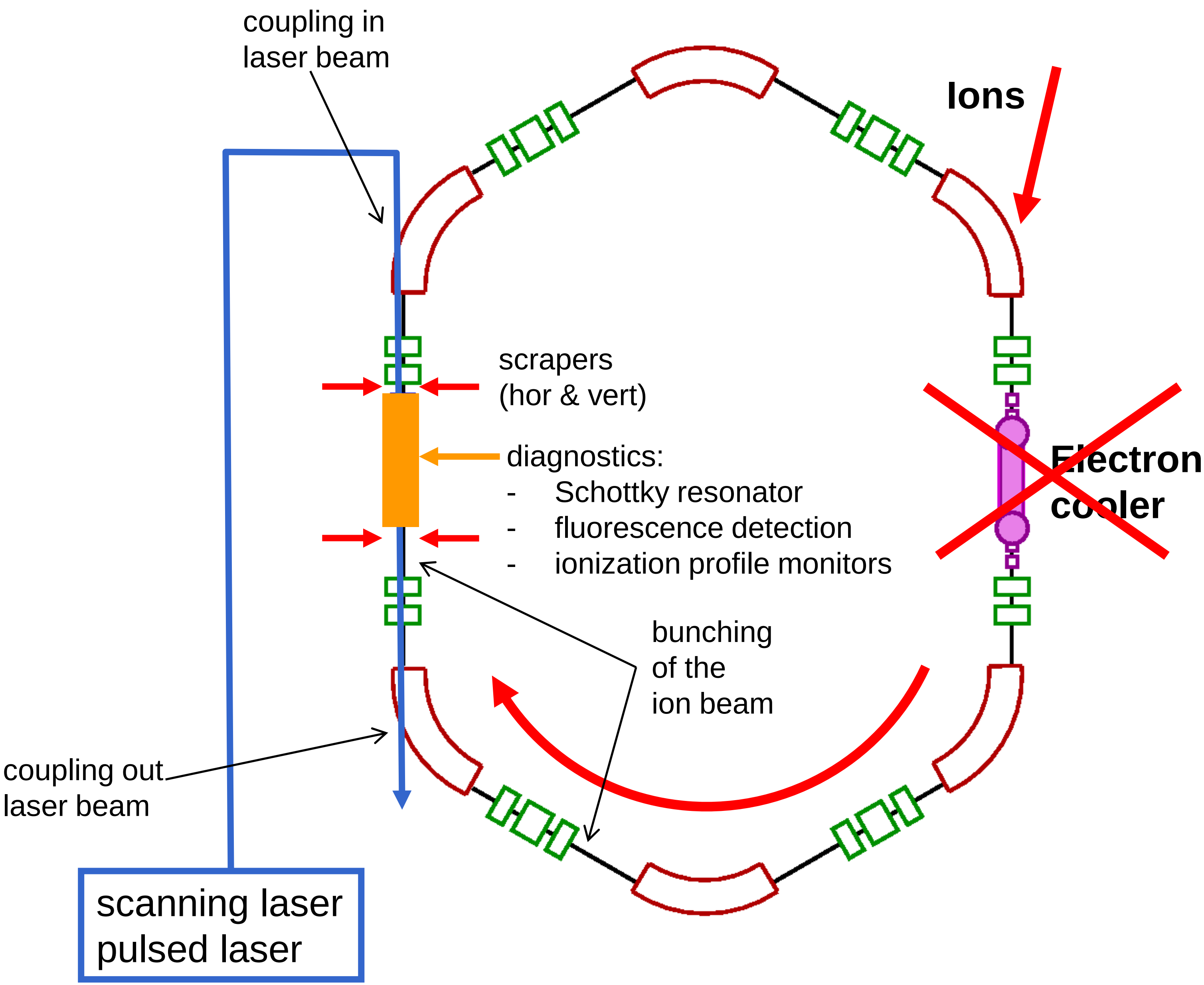
Doppler „boost“ of the transition wavelength



Doppler „boost“ of the emission direction

At high γ, the ion beam emits like a `searchlight´ → Gamma Factory

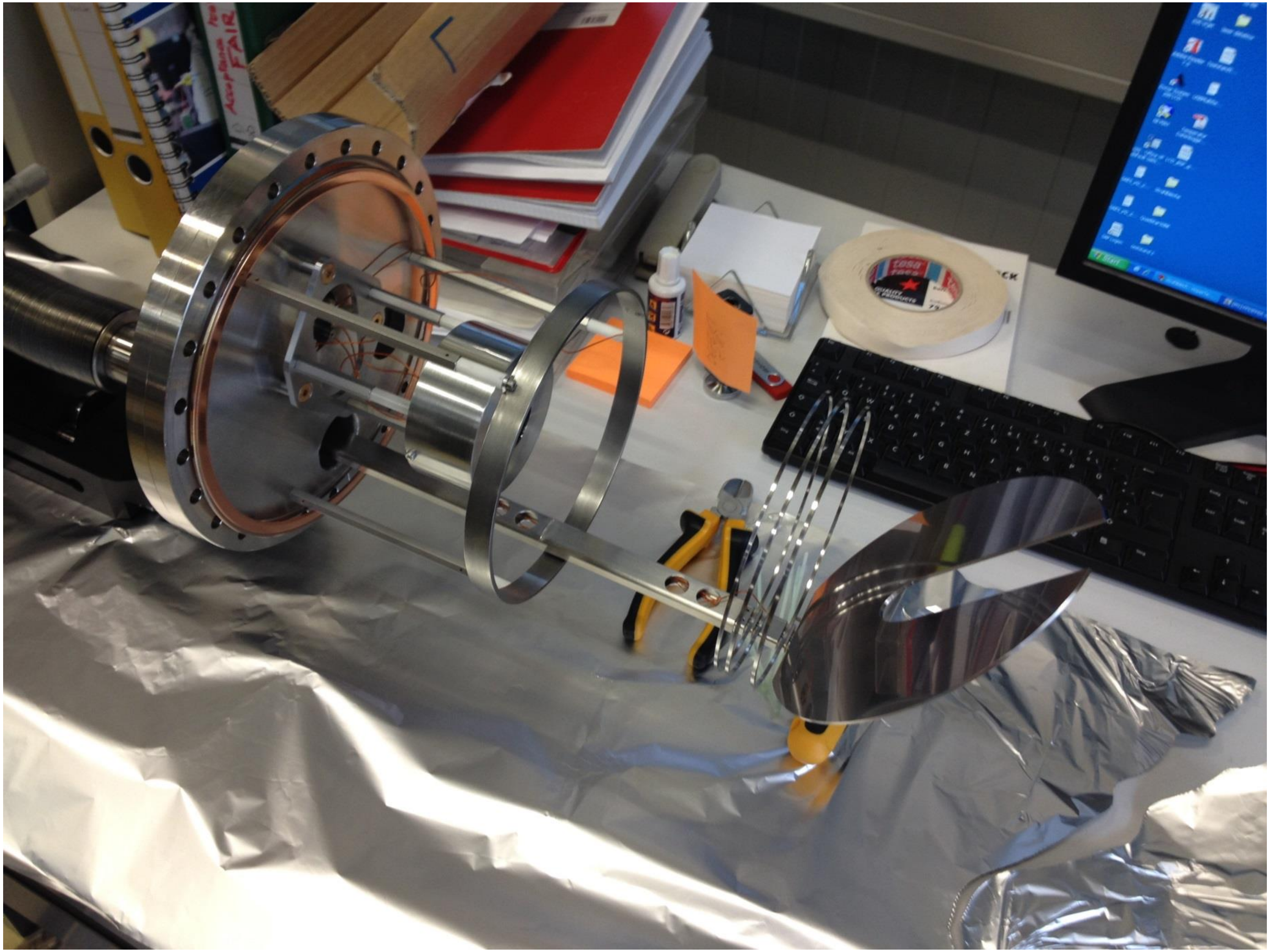
Experimental setup @ ESR



moveable CsI-cathode for XUV fluorescence detection

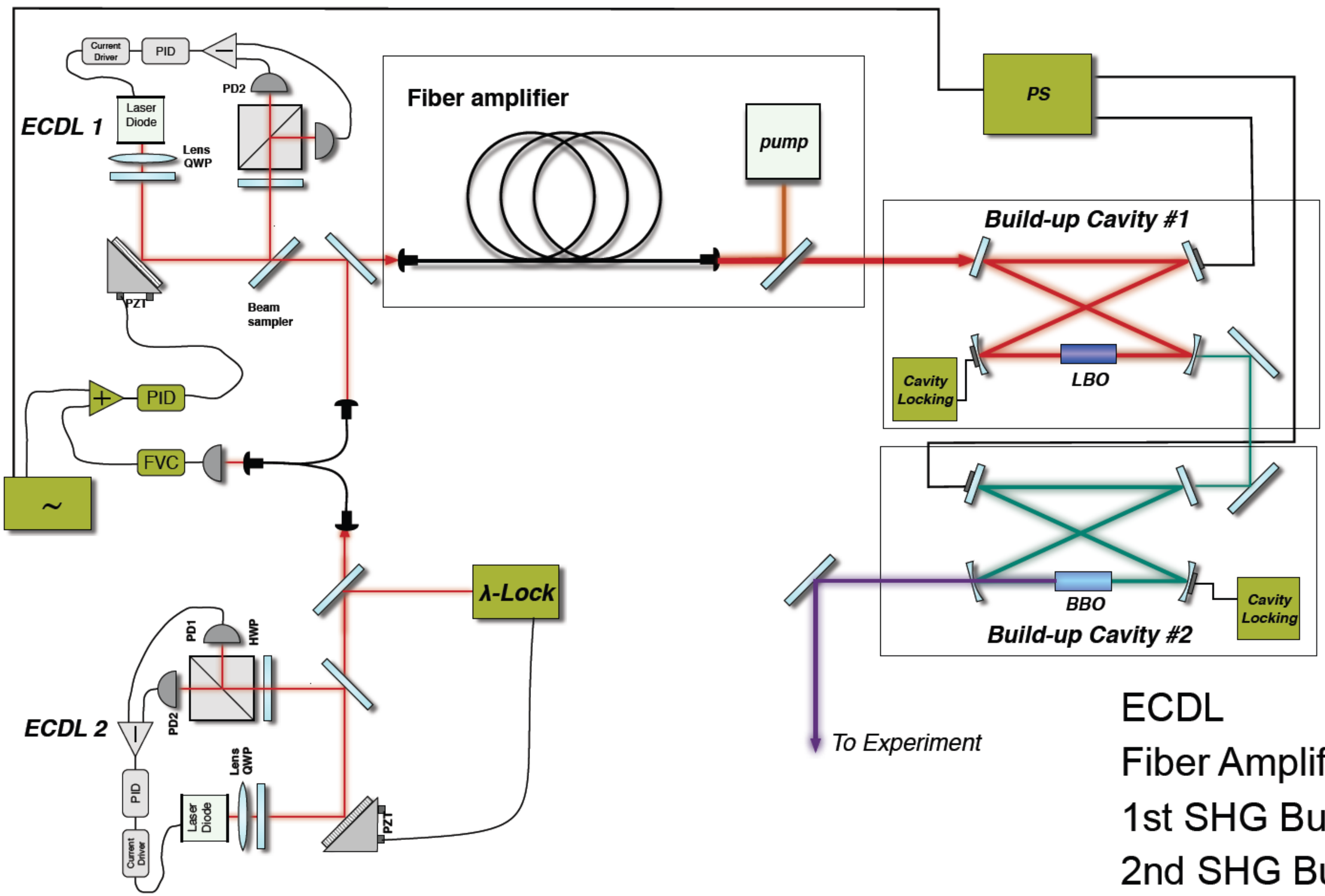
→ BMBF funding: group of Prof. Christian Weinheimer (Uni Münster)

moveable CsI-cathode for XUV fluorescence detection



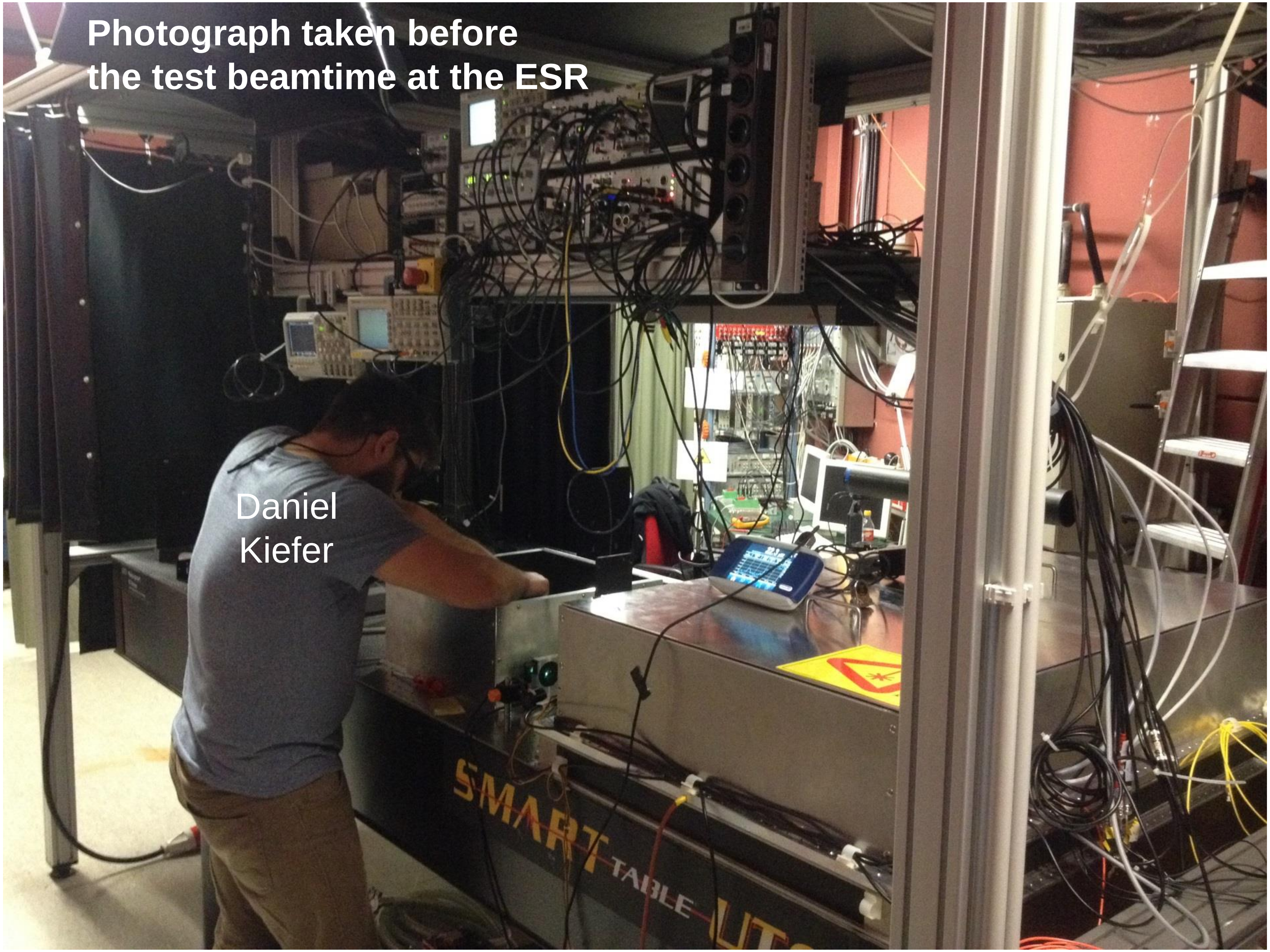
→ BMBF funding: group of Prof. Christian Weinheimer (Uni Münster)

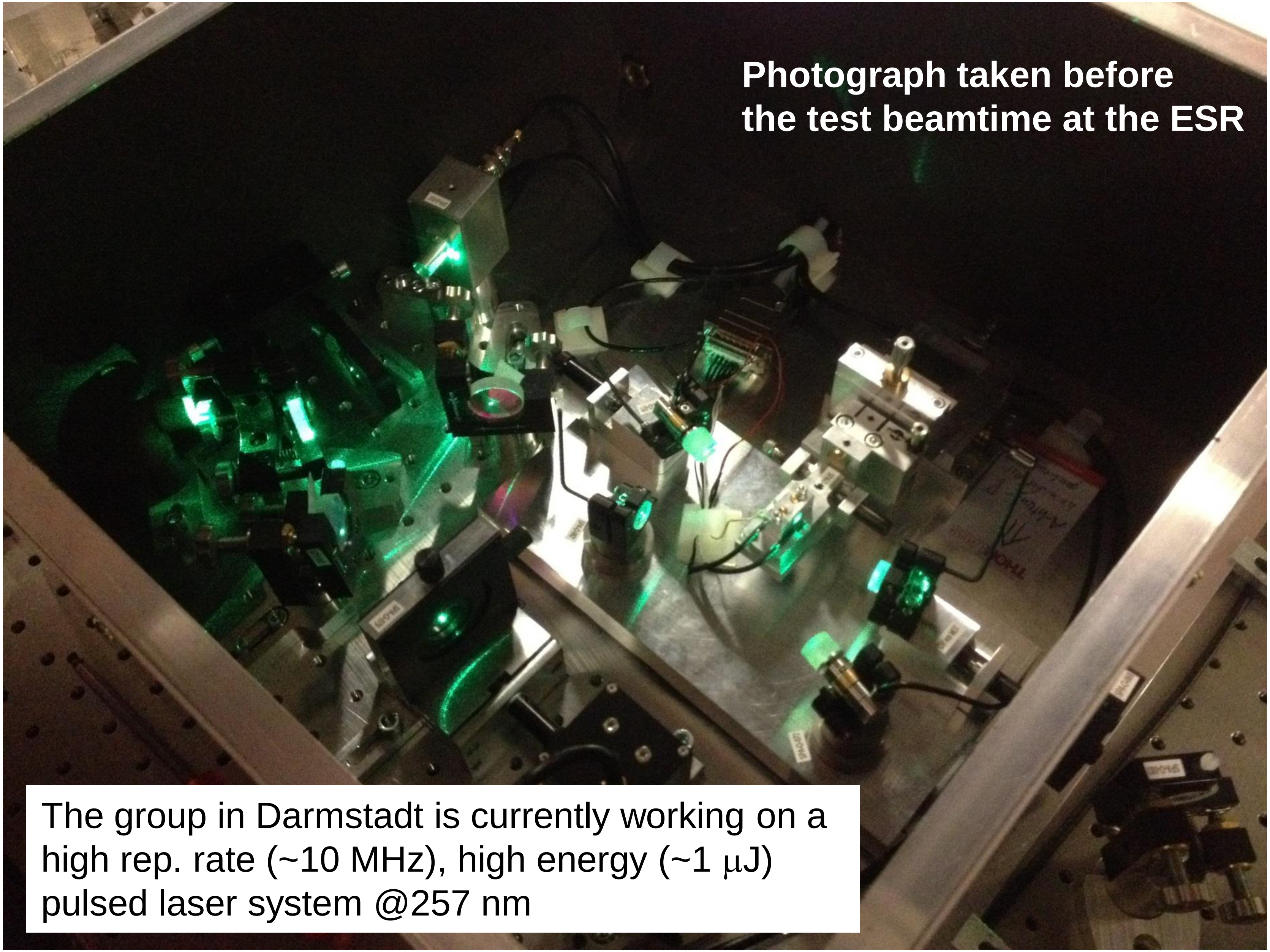
ECDL scanning cw laser system
(20 GHz IR, 3 GHz needed)



ECDL
Fiber Amplifier
1st SHG Built-up Cavity
2nd SHG Built-up Cavity

→BMBF funding: group of Prof. Thomas Walther (TU-Darmstadt)


Photograph taken before
the test beamtime at the ESR
Daniel
Kiefer
SMART TABLE

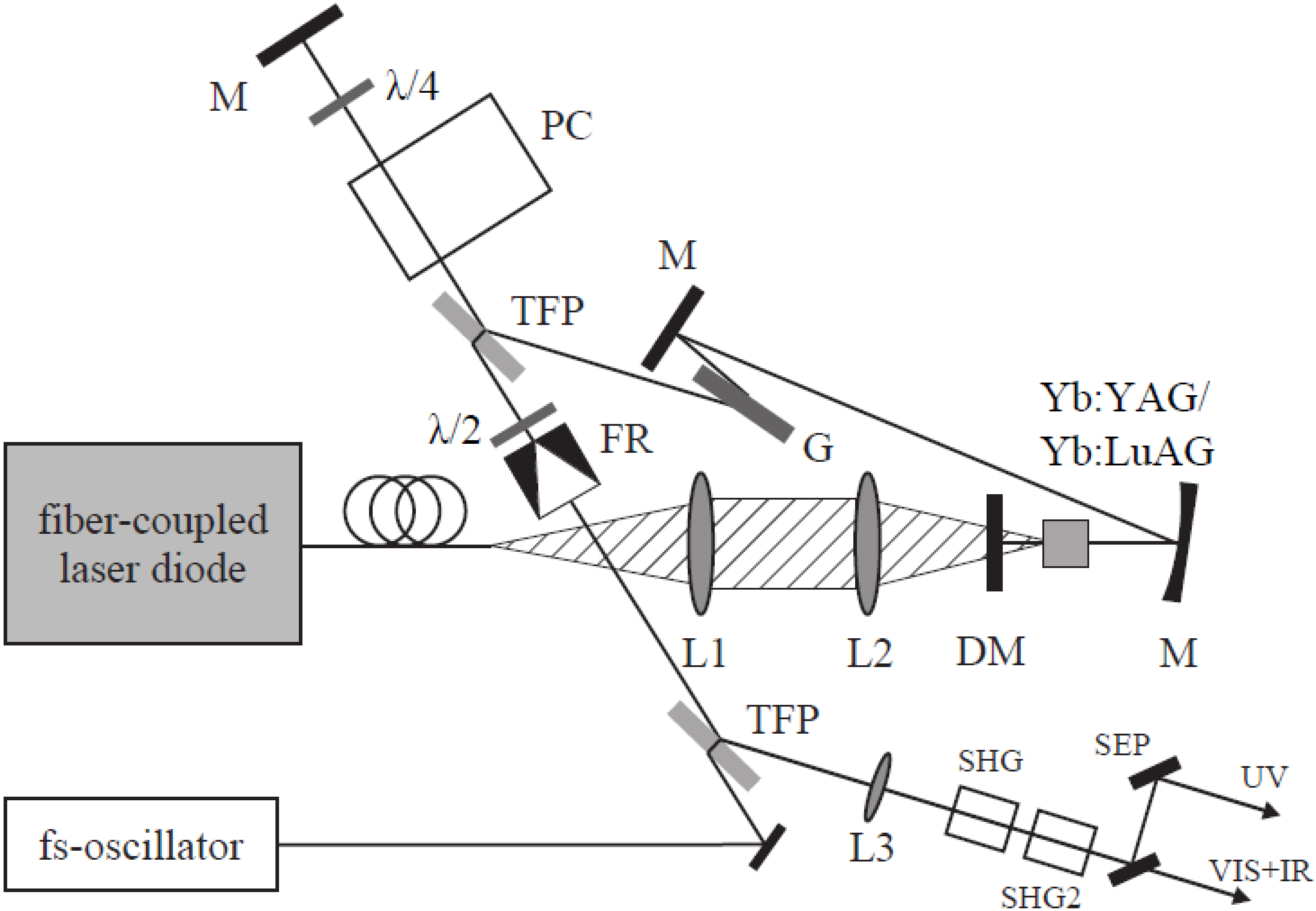


Photograph taken before the test beamtime at the ESR

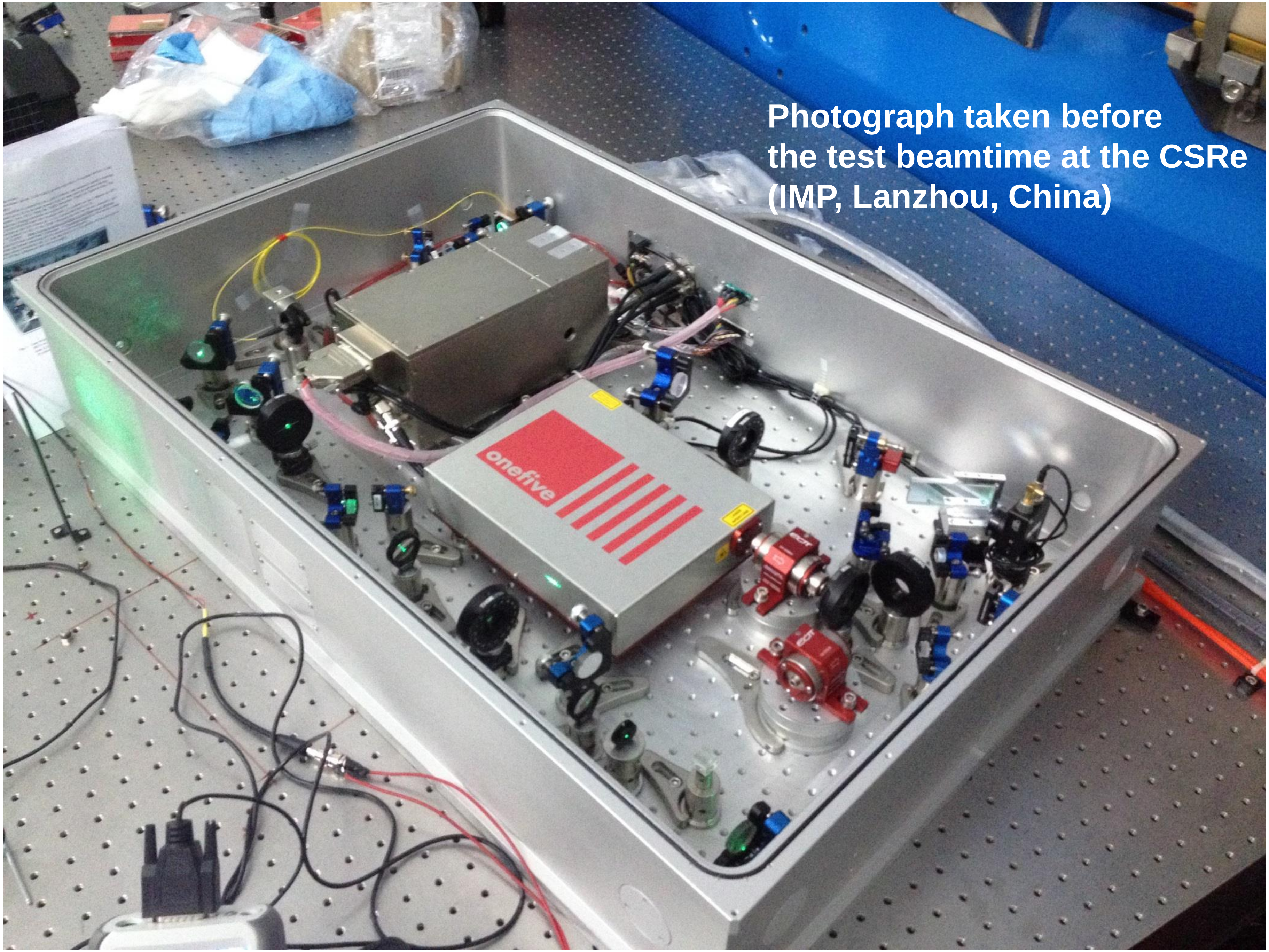
The group in Darmstadt is currently working on a high rep. rate (~10 MHz), high energy (~1 μJ) pulsed laser system @257 nm

Pulsed laser system

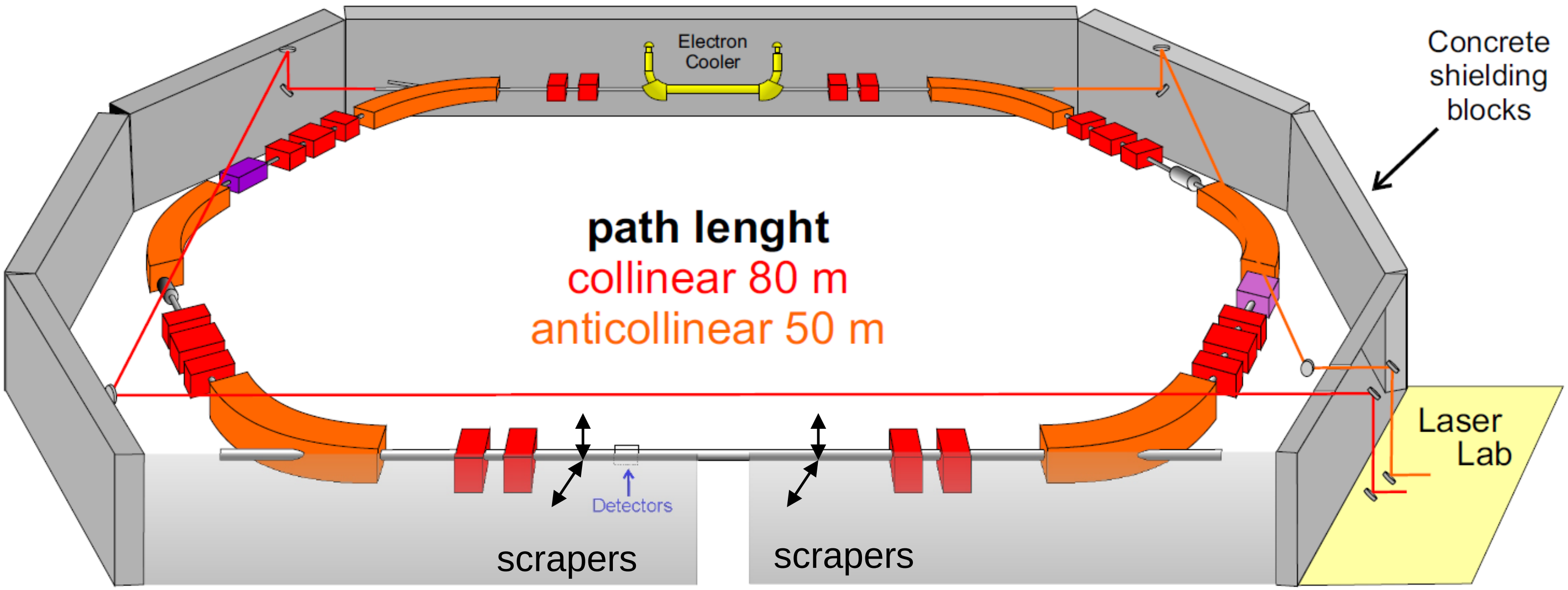
frequency-selective intra-cavity grating

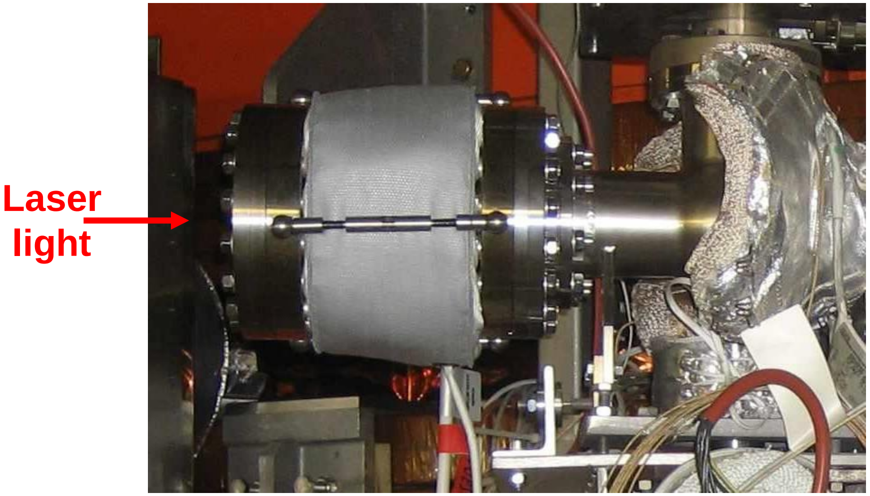


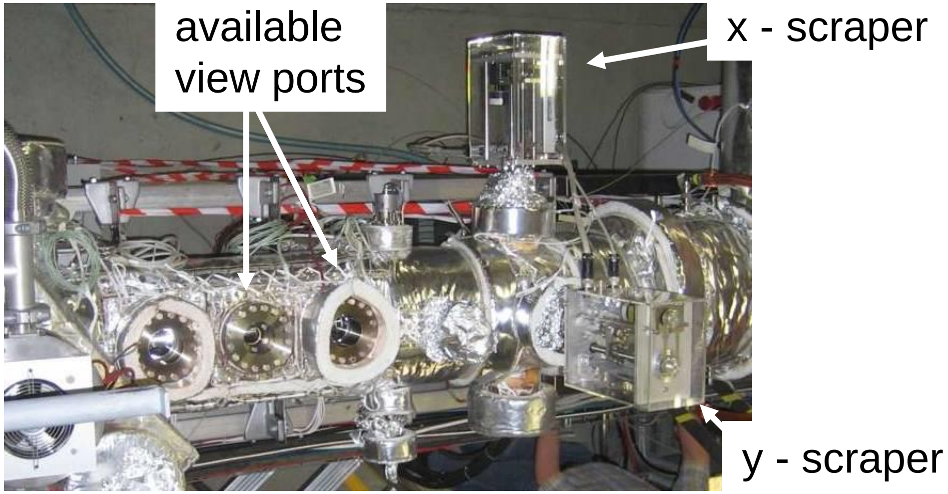
→ BMBF Funding: group of Prof. Ulrich Schramm (HZDR, TU-Dresden)


Photograph taken before
the test beamtime at the CSRe
(IMP, Lanzhou, China)
onefive

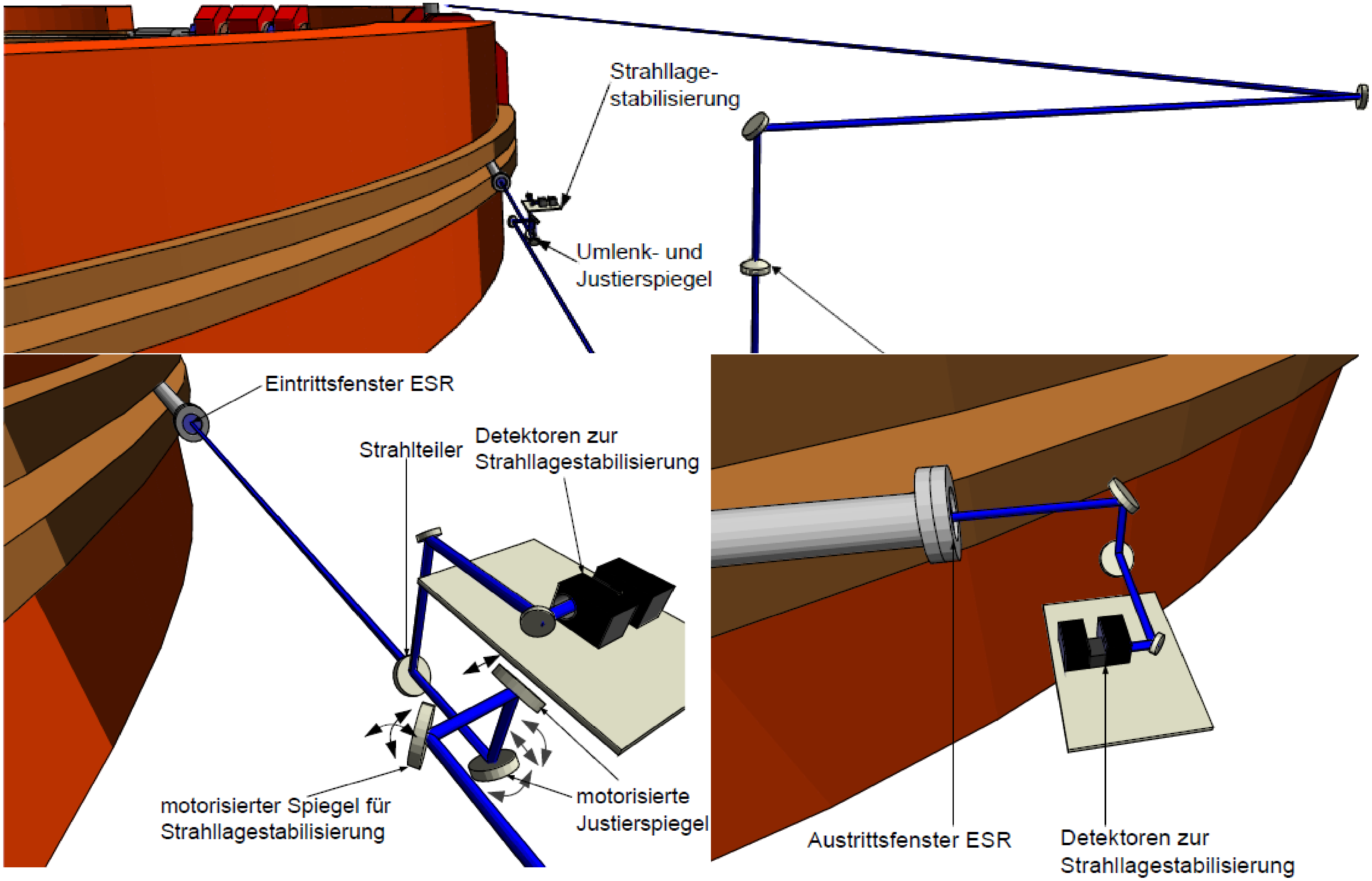
Lasers at the ESR







Laser beam transport and stabilization



→ BMBF Funding: group of Prof. Wilfried Nörtershäuser (TU-Darmstadt)

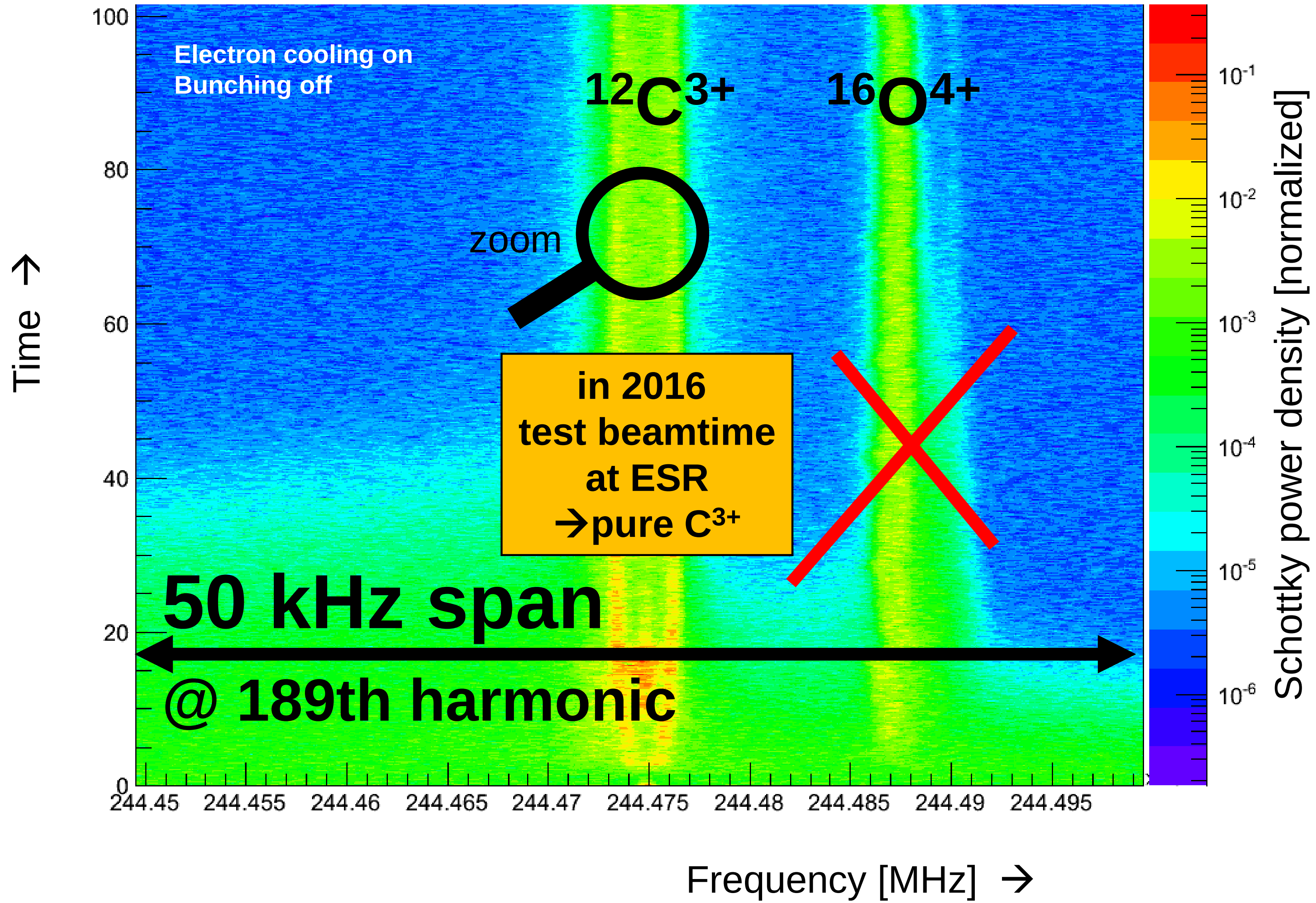
→ ARD M&T – SIS100 (GSI)

Contents

ESR results Darmstadt

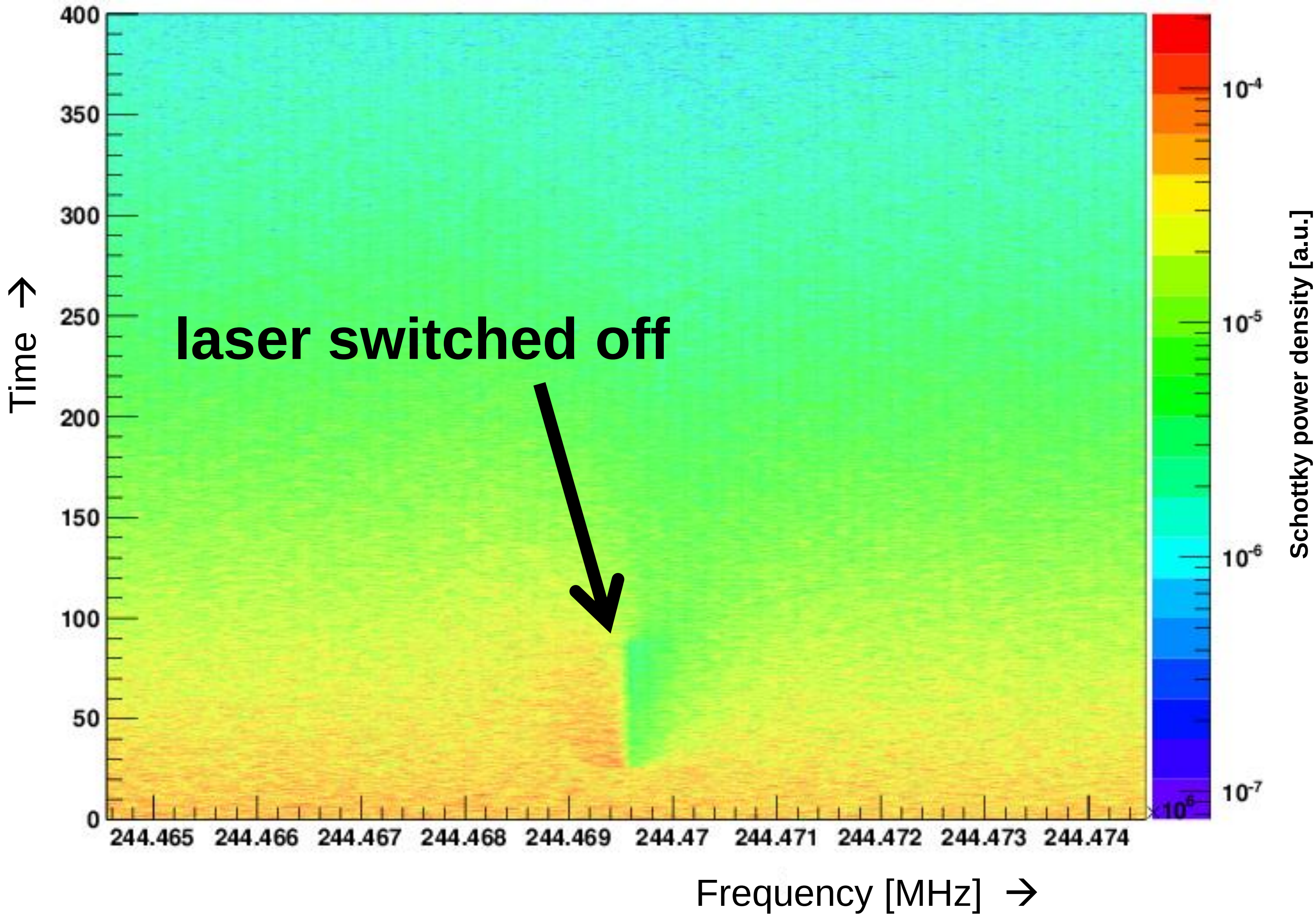
coasting beams

Two ion species stored: $^{12}C^{3+}$ (88%) & $^{16}O^{4+}$ (12%)



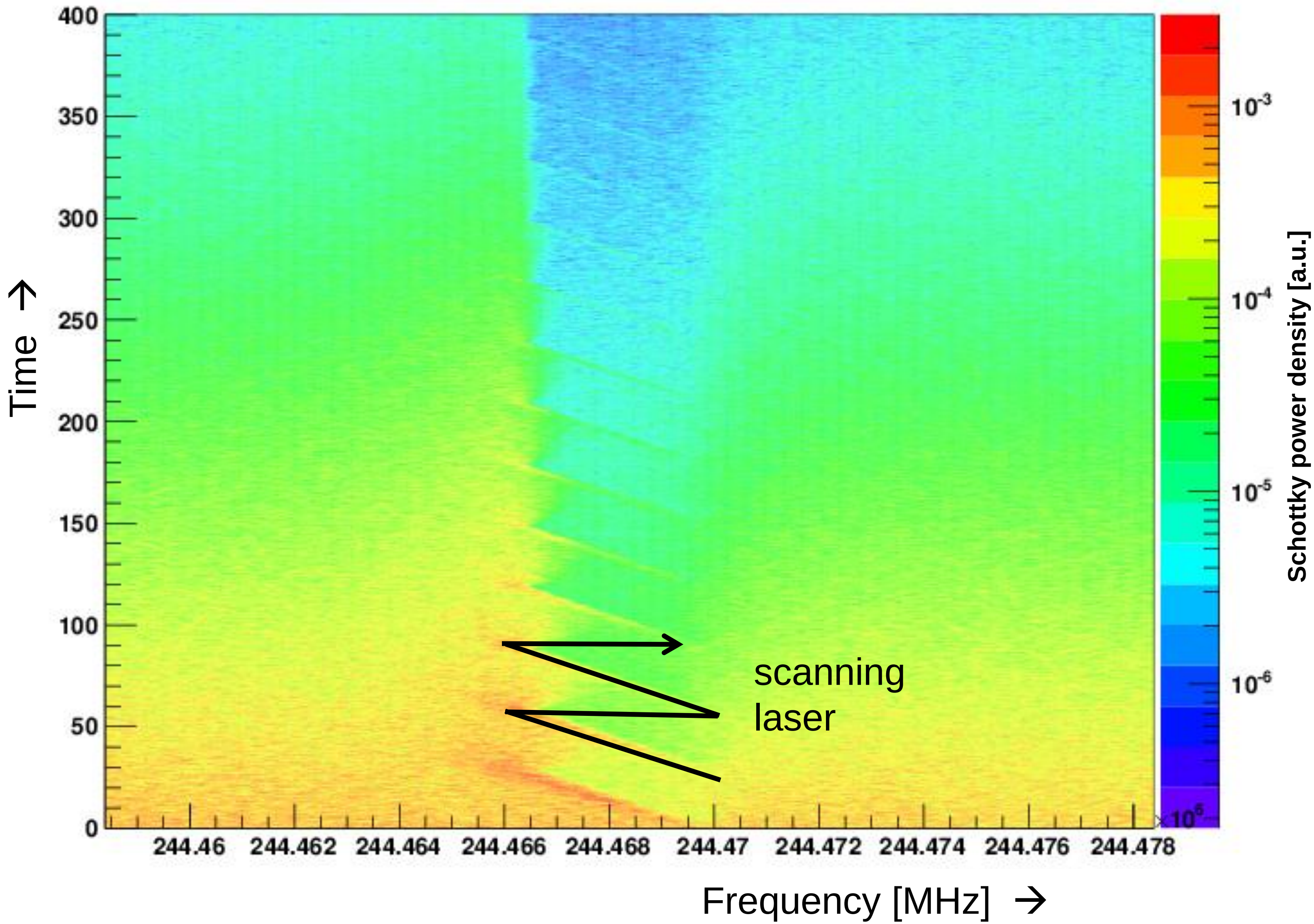
2012 ESR data

coasting beams cannot be laser-cooled to a stable fix point



2012 ESR data

burning a hole in a coasting beam (C^{3+})



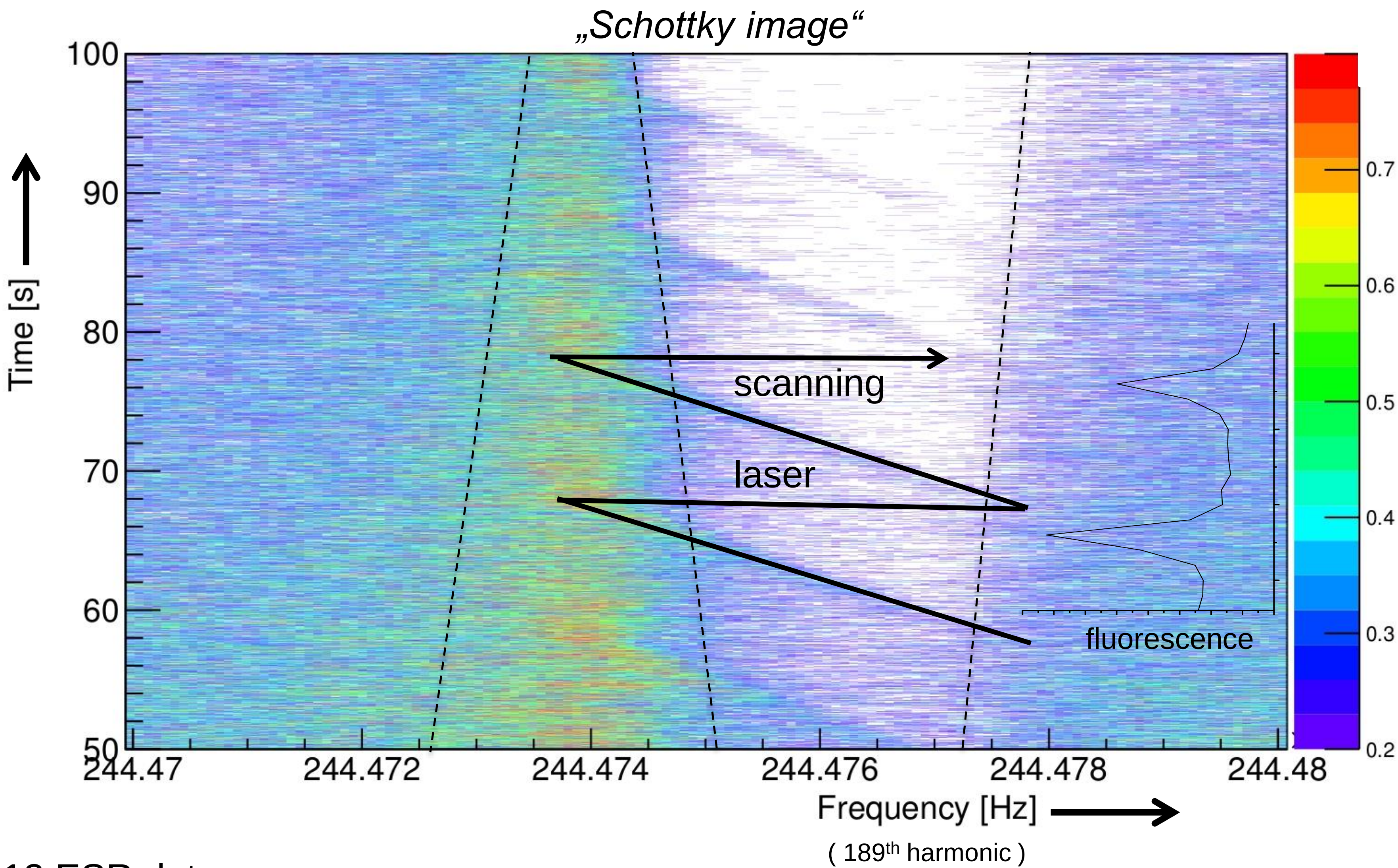
2012 ESR data

coasting ion beam (no bunching), no electron cooling, scanning CW diode laser (~12 GHz, ~10 s)

→ the laser pushes ions from a large momentum range into a narrow band

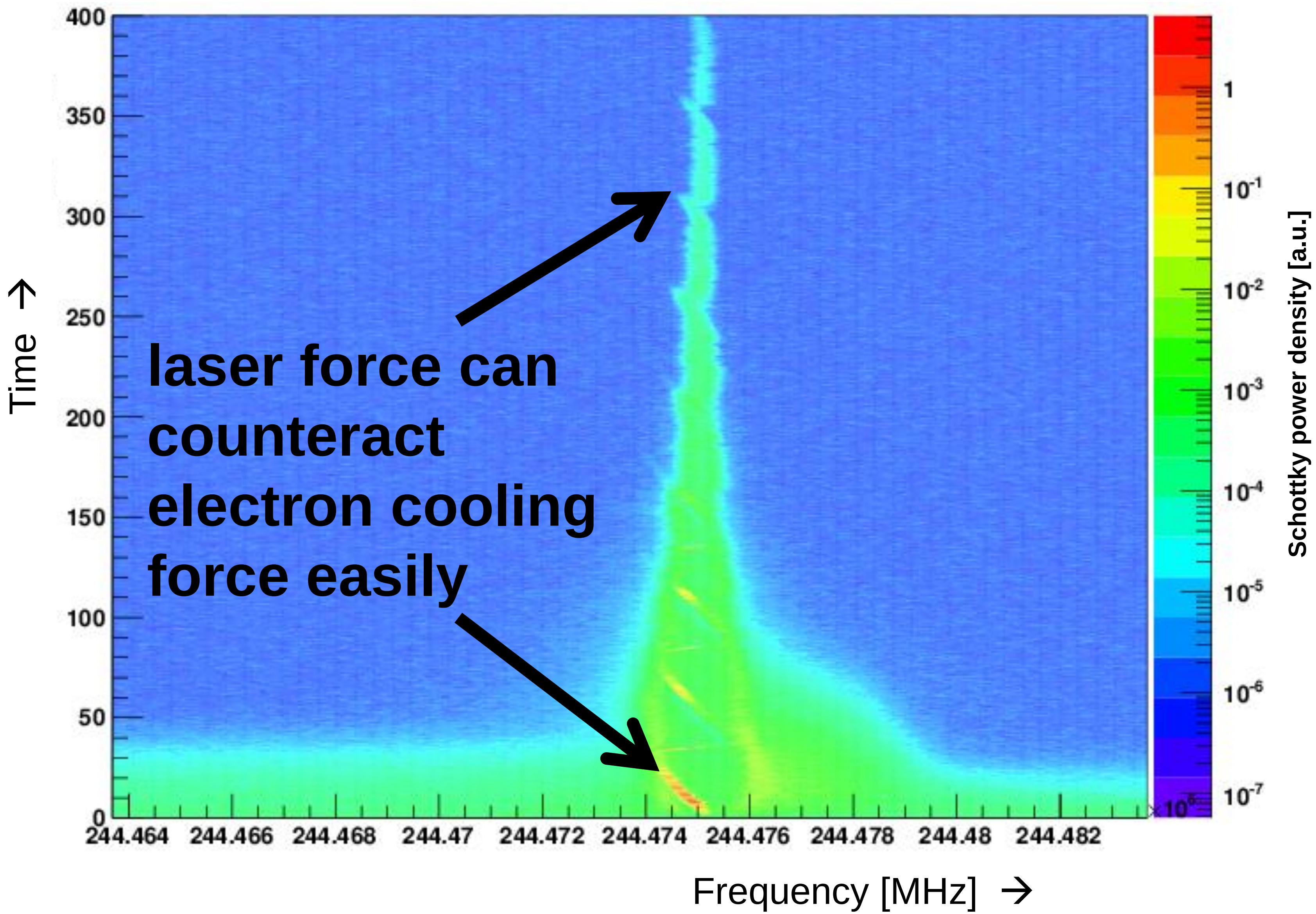
→ scanning over the whole bucket acceptance → $\Delta f/f \sim 10^{-5}$

→ the UV-fluorescence from the ions is detected in vacuo, and peaks when the laser is resonant



2012 ESR data

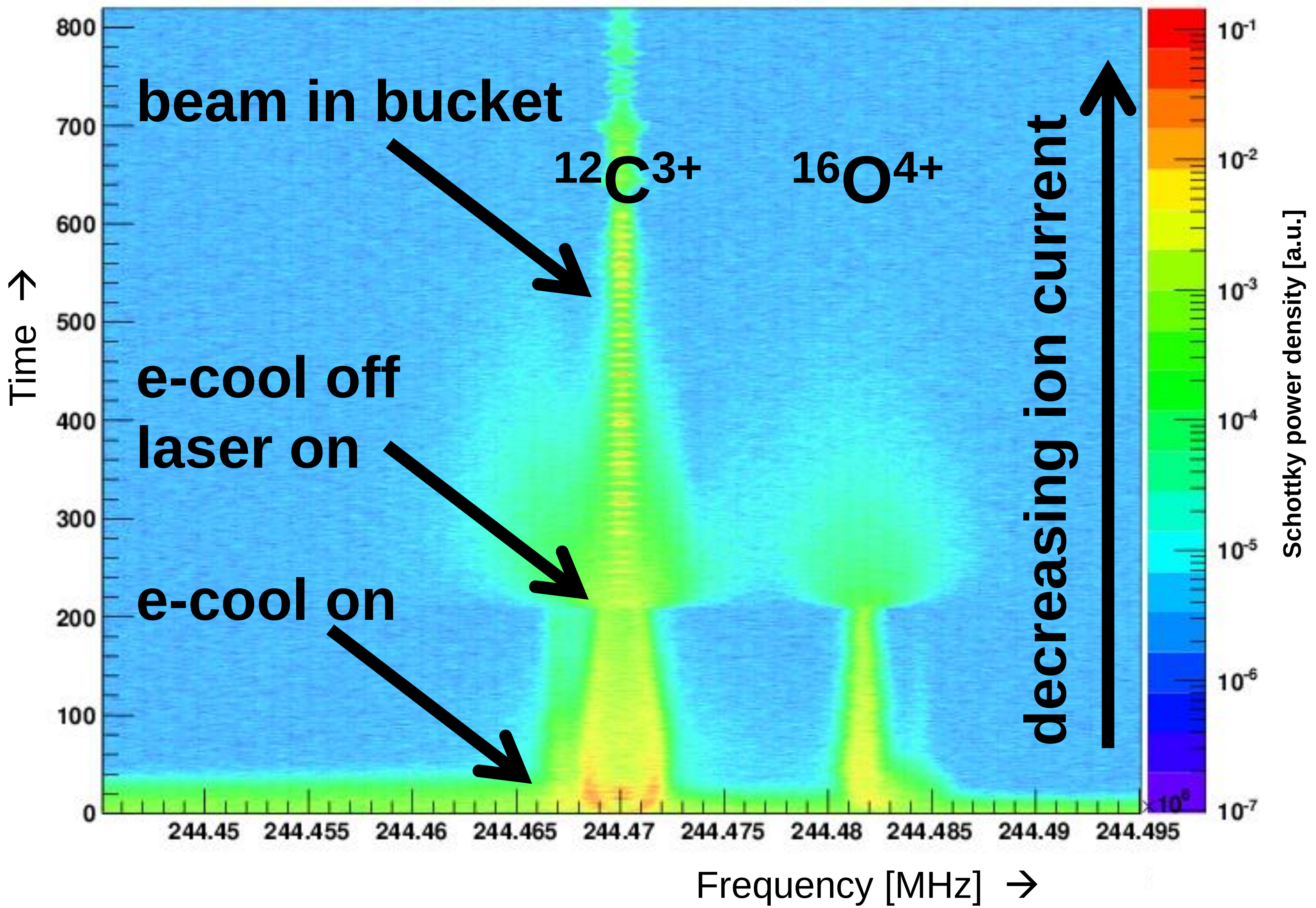
laser cooling vs. electron cooling → no bunching!



2012 ESR data

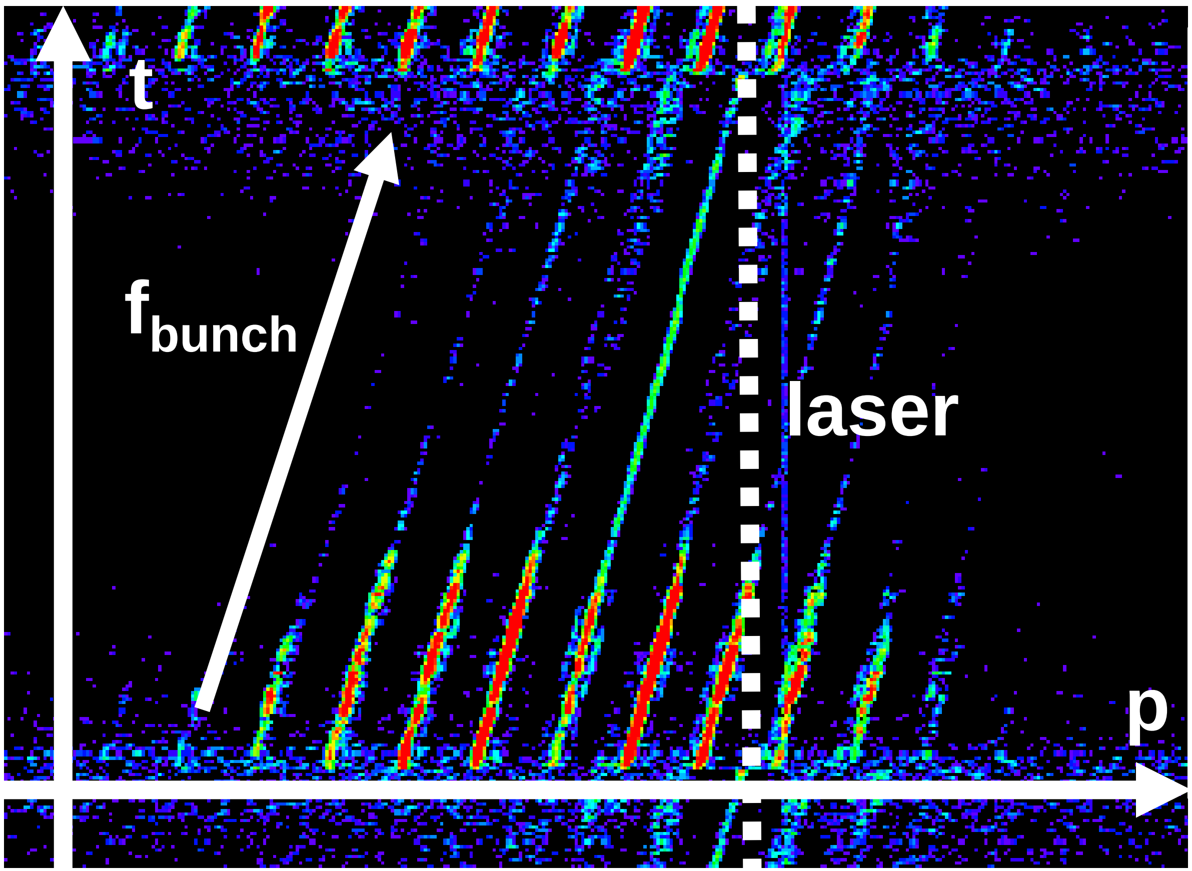
bunched beams

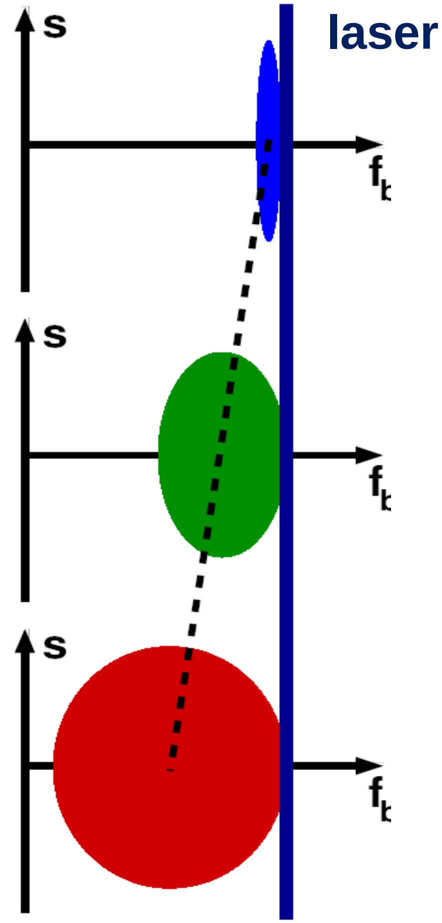
laser frequency scan < initial momentum spread @ high currents



2012 ESR data

Experimental demonstration at the ESR of two possibilities:
1) scanning the bunching frequency at a fixed laser frequency (2006)

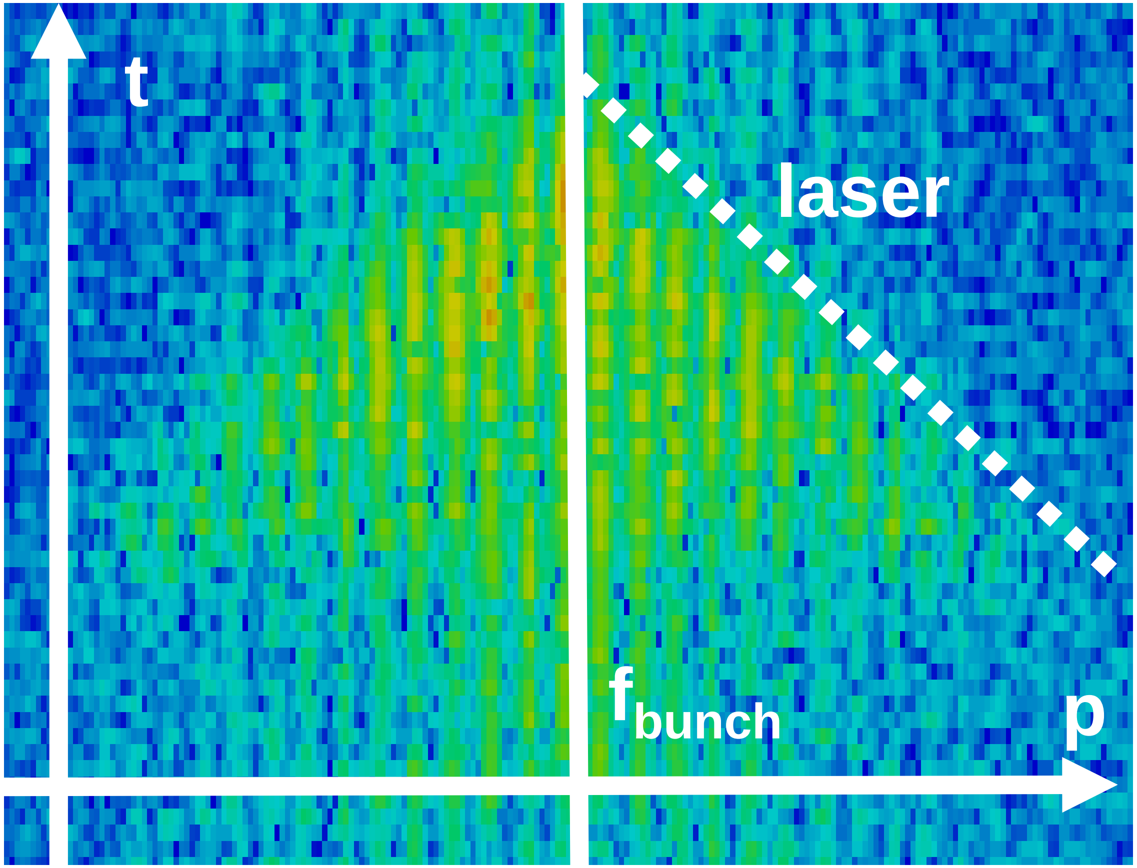




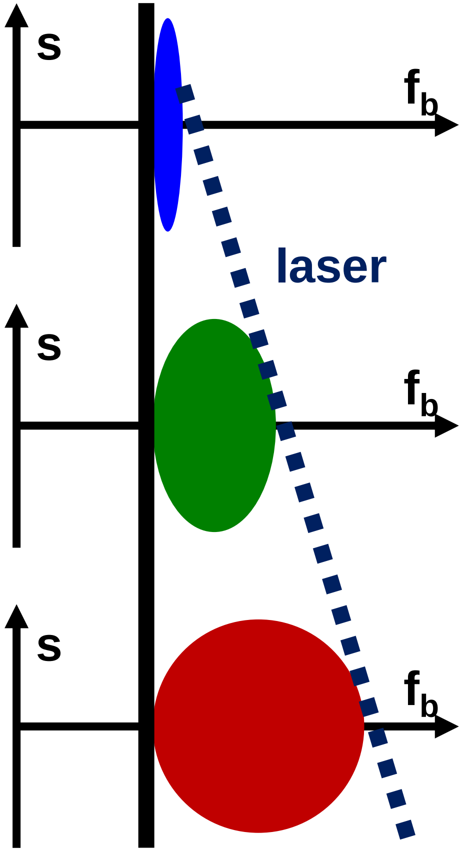
„Schottky image“
hor: frequency
vert: time
color: Intensity

2004/2006 ESR data

Experimental demonstration at the ESR of two possibilities:
2) scanning the laser frequency at a fixed bunching frequency (2012)

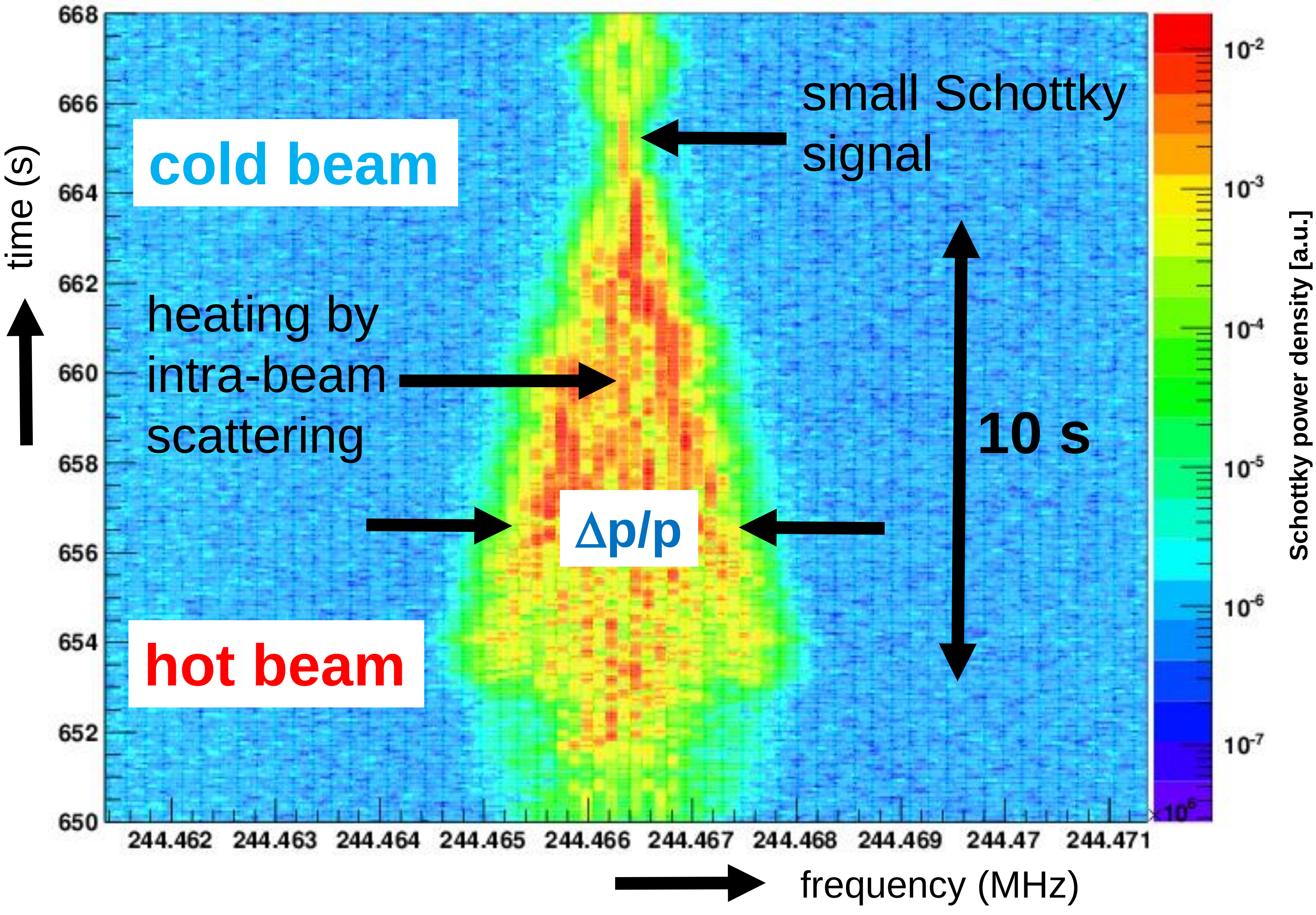


„Schottky image“
hor: frequency
vert: time
color: Intensity



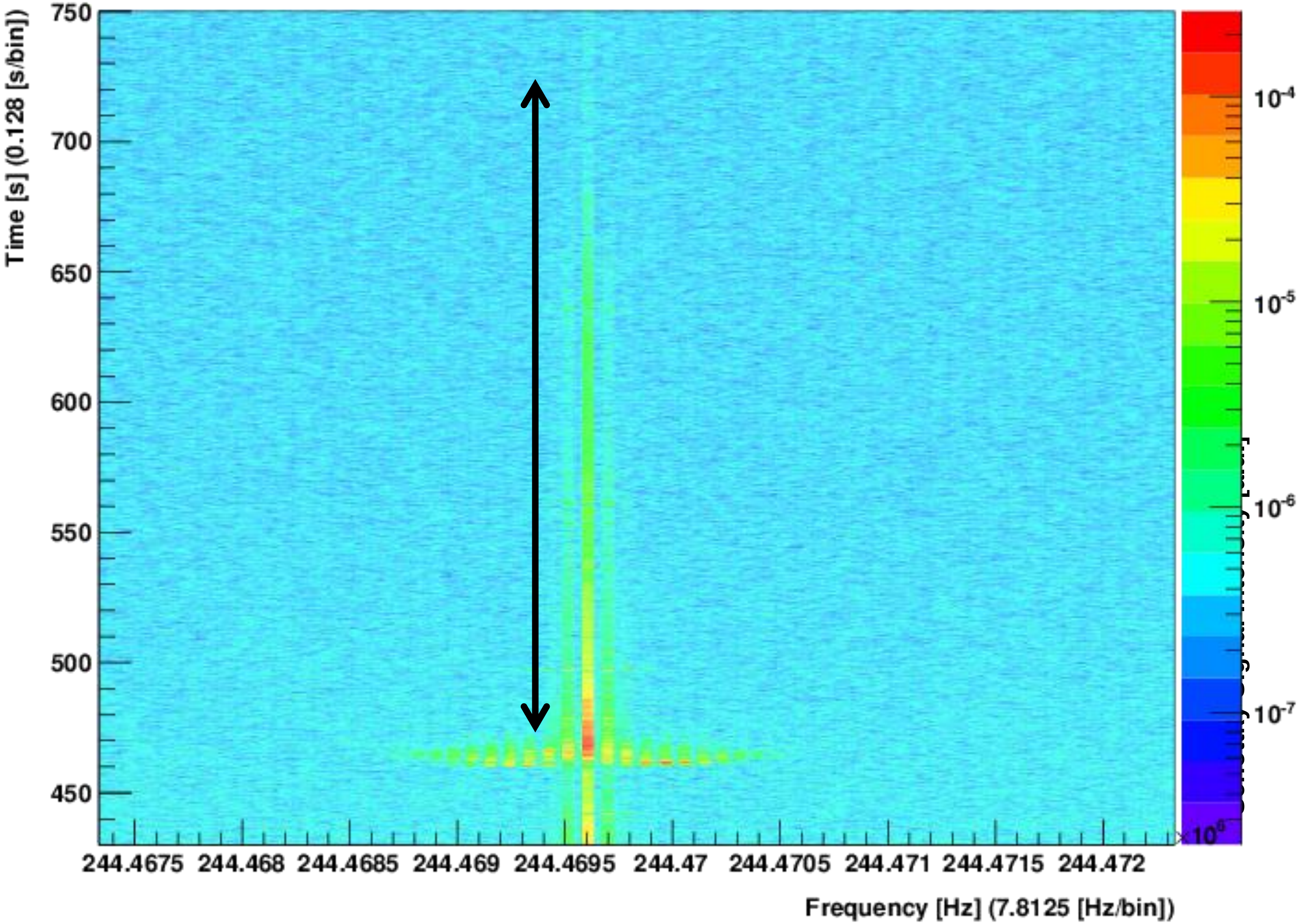
2012 ESR data

C^{3+} ions stored in the ESR, 122 MeV/u, scanning the laser frequency



2012 ESR data

laser-cooled ion beam → 250 s



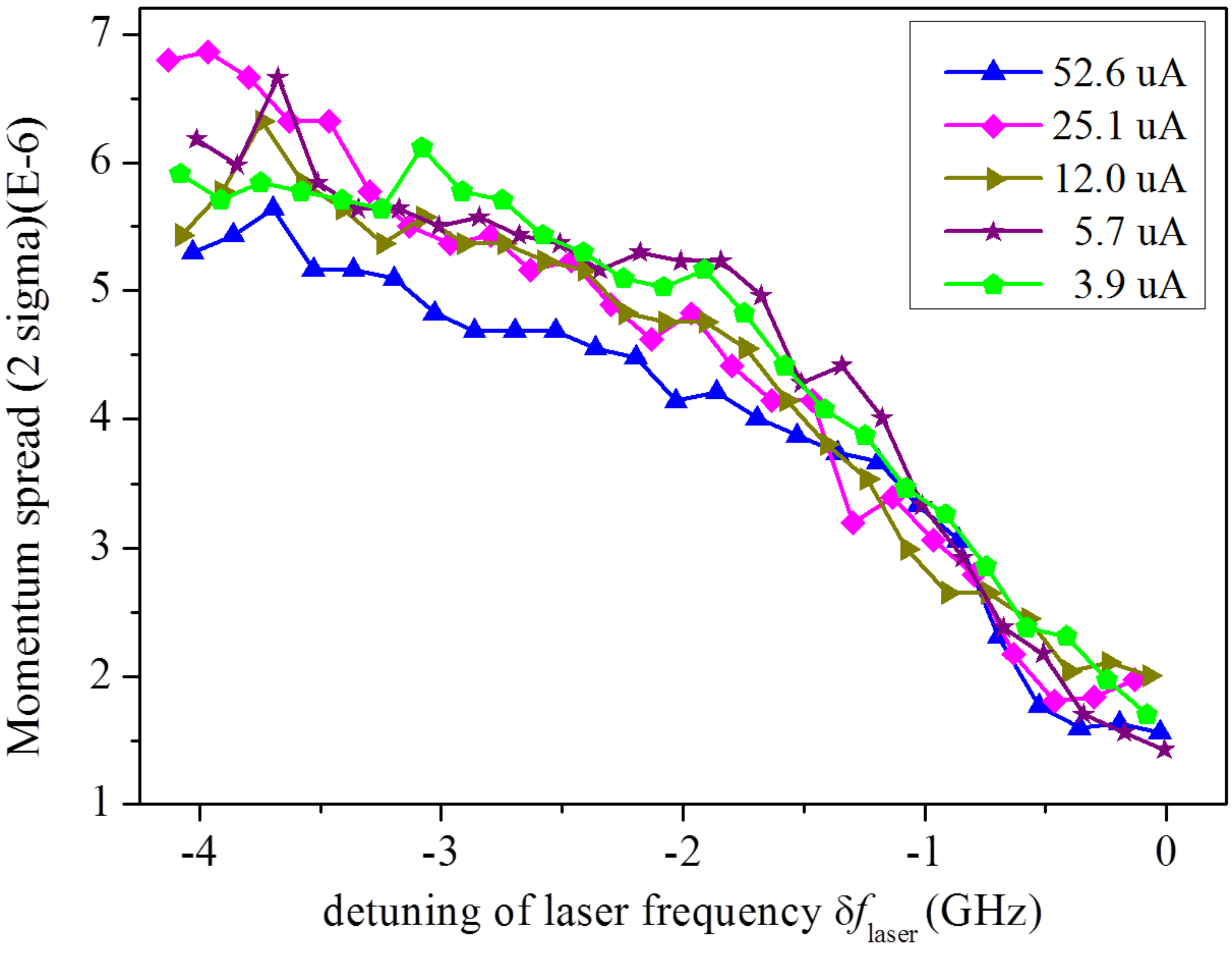
2012 ESR data

time

&

intensity

momentum spread reduction independent from ion beam current

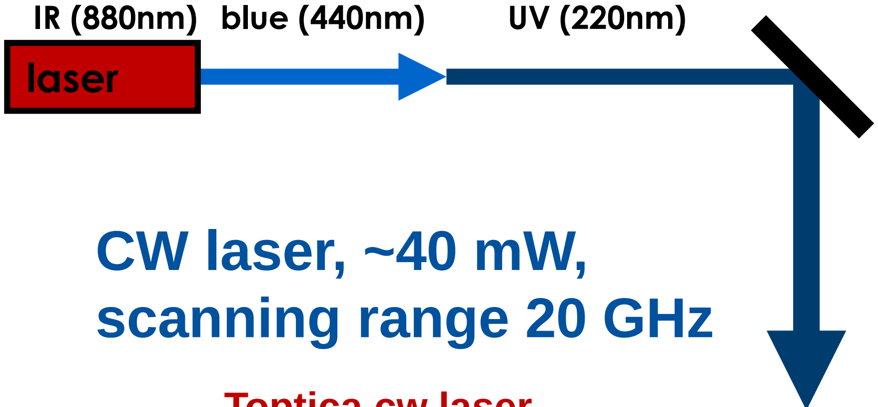


because it is a scan, this is also a time axis

2012 ESR data

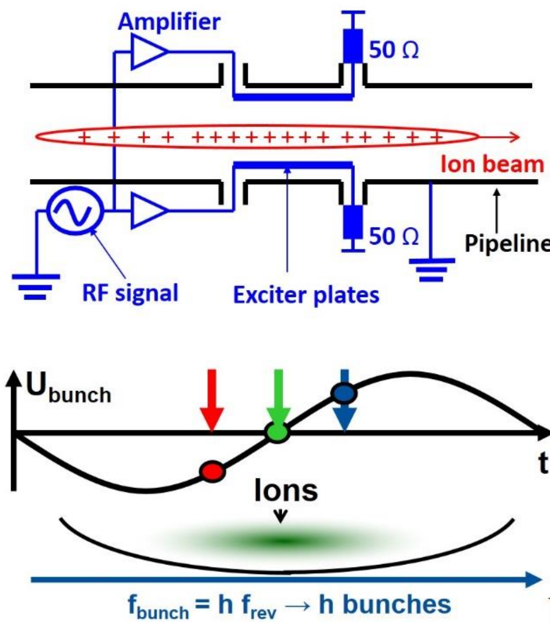
CSRe results
Lanzhou

Laser system, RF-buncher and Schottky pick-up at the CSRe in Lanzhou, China

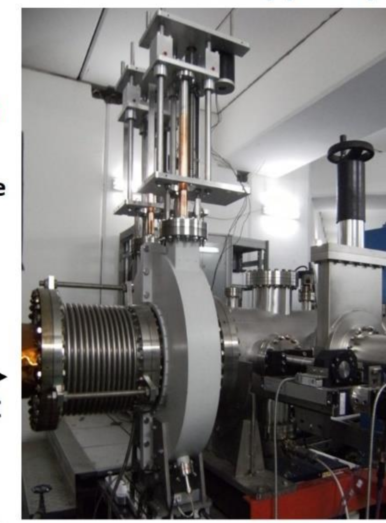


CW laser, ~40 mW, scanning range 20 GHz

Toptica cw laser

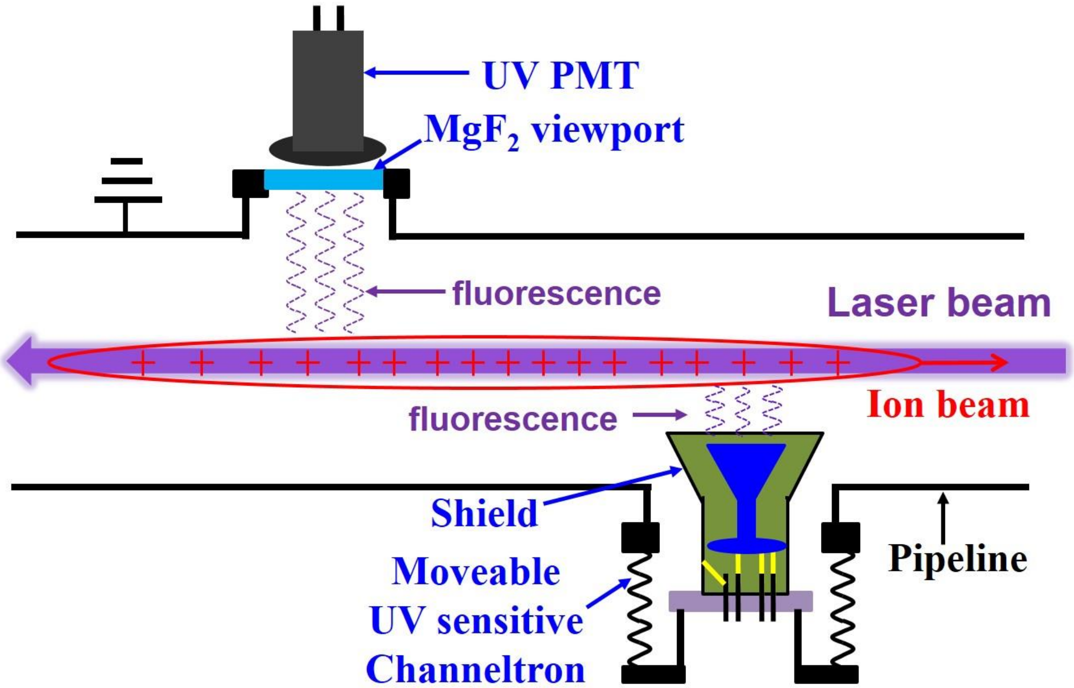


Resonant Schottky pick-up

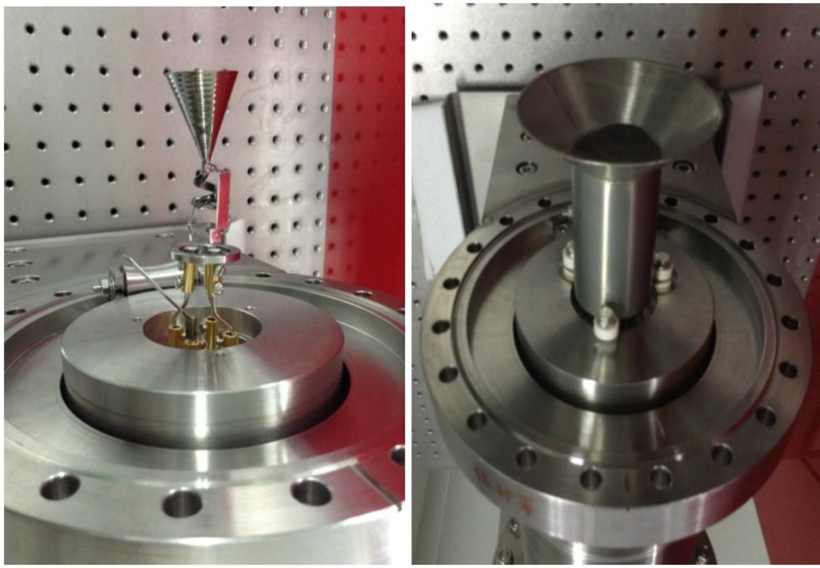


W.Q. Wen, et al., NIMA 736(2014)75

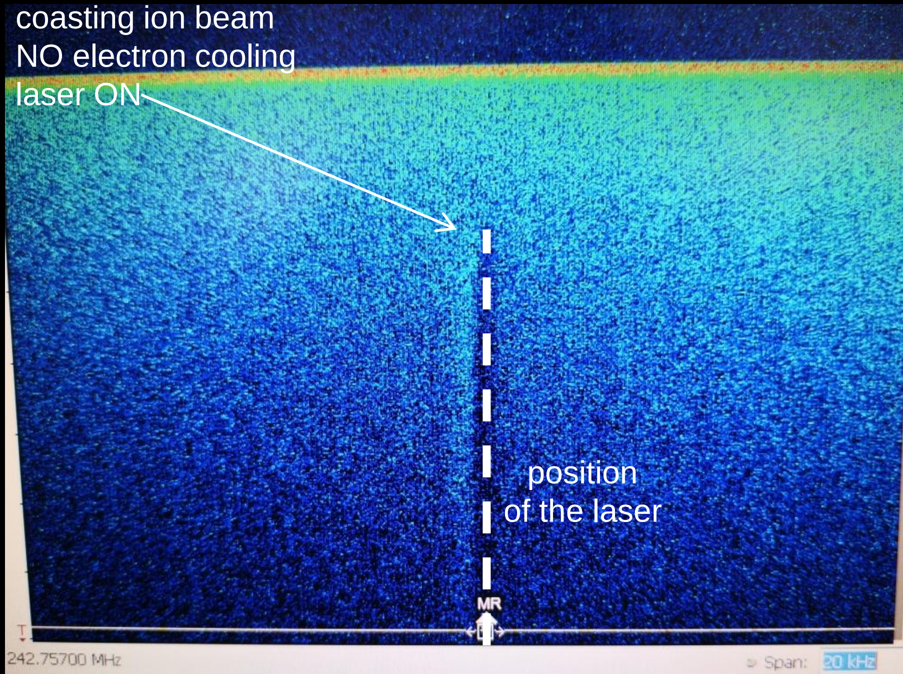
Optical diagnostic system at the CSRe



UV-sensitive Channeltron

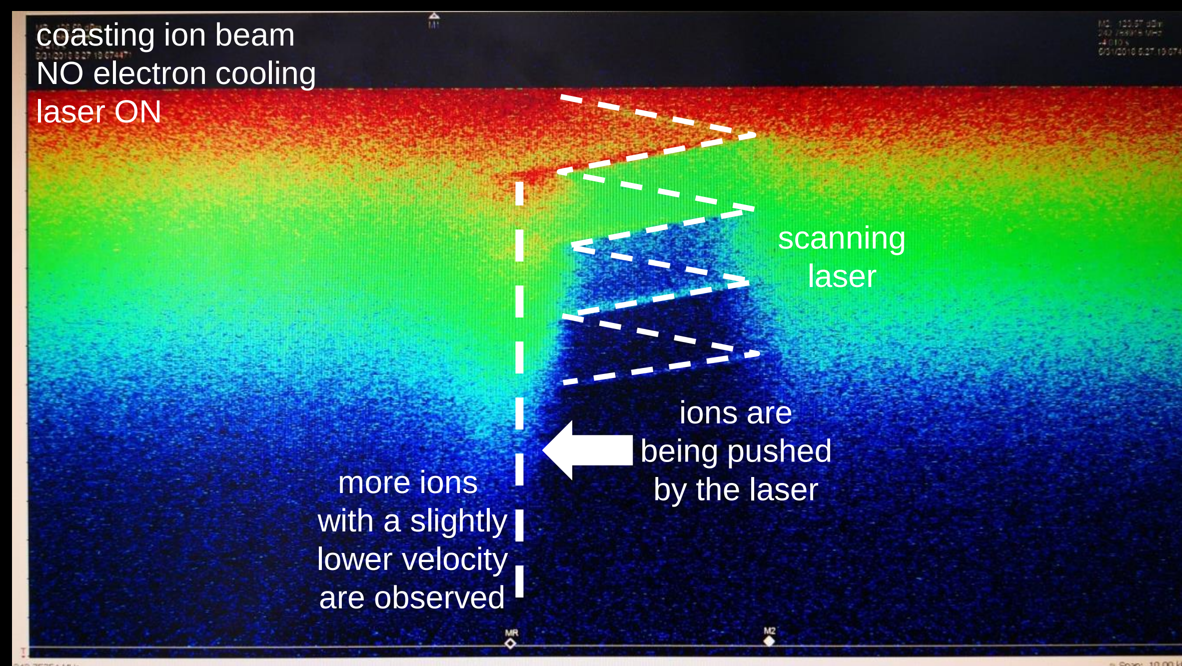


CSRe @IMP (CAS)
Lanzhou, China
$^{16}O^{5+}$ (Li-like)
$2s_{1/2} \rightarrow 2p_{1/2}$ (103 nm)
276 MeV/u (β=0.64)
220 nm cw laser



fixed
wavelength
cw laser

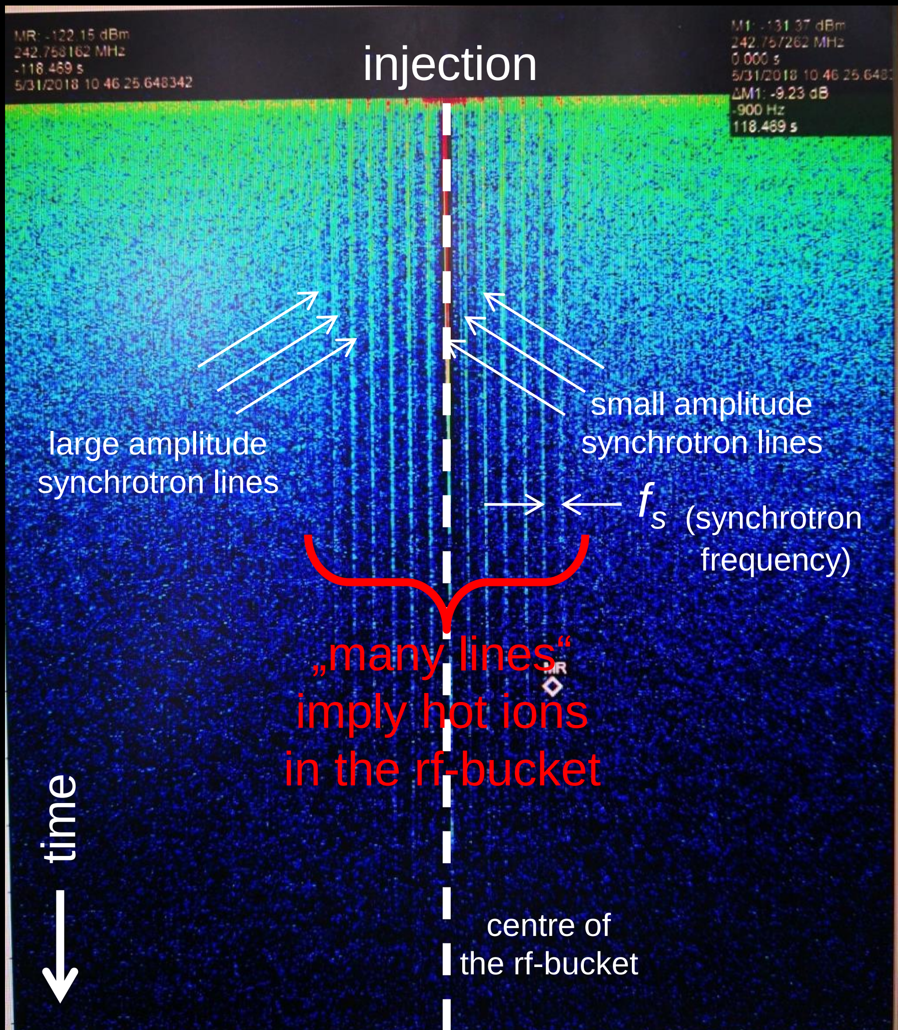
scanning
wavelength
cw laser

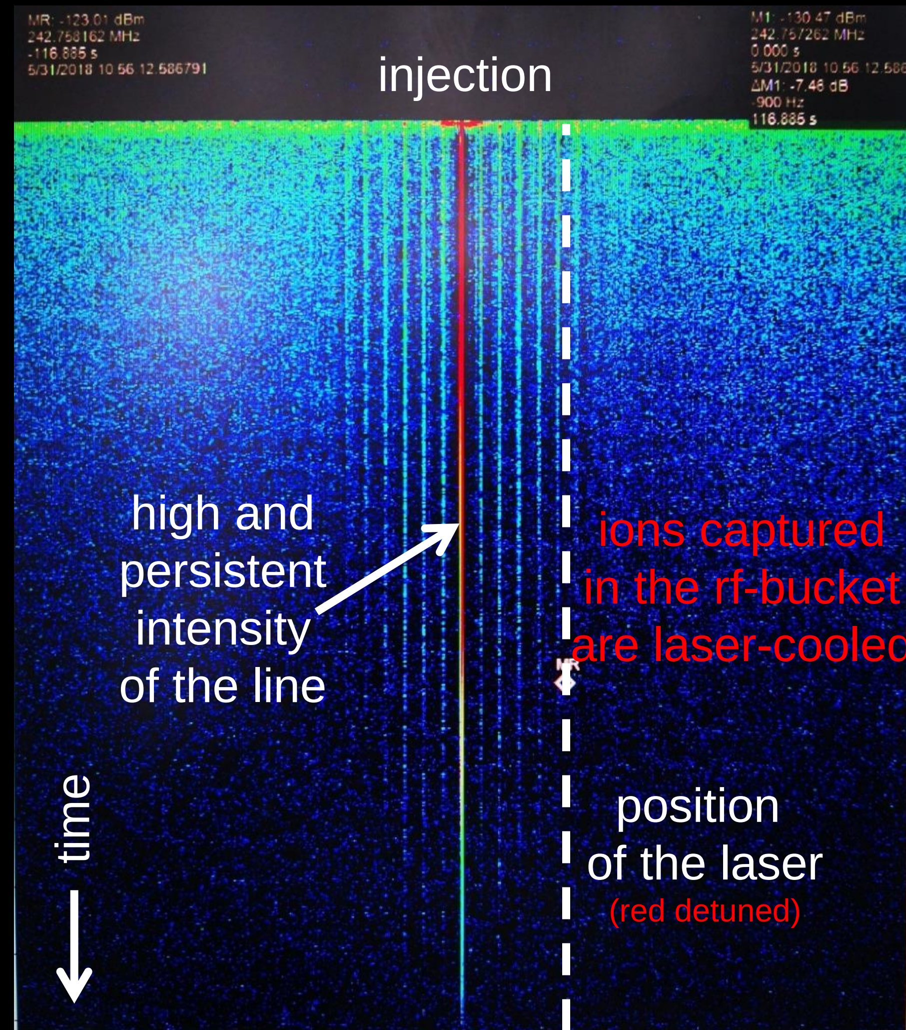


CSRe @IMP (CAS)
Lanzhou, China
$^{16}O^{5+}$ (Li-like)
$2s_{1/2} \rightarrow 2p_{1/2}$ (103 nm)
276 MeV/u (β=0.64)
220 nm cw laser

- **bunched ion beam** (h=33)
- **NO electron cooling**
- **laser OFF**

- **bunched ion beam** (h=33)
- **NO electron cooling**
- **laser ON**





frequency (MHz) ⟶
(164th harmonic of the ion revolution frequency)

frequency (MHz) ⟶
(164th harmonic of the ion revolution frequency)

Contents

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 532, Issues 1–2, 11 October 2004, Pages 150-156

Ion beam cooling at S-LSR project

Akira Noda

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Available online 26 June 2004.

Proceedings of COOL 2007, Bad Kreuznach, Germany THM1I02

ELECTRON COOLING EXPERIMENTS AT S-LSR

T. Shirai[#], S. Fujimoto, M. Ikegami, H. Tongu, M. Tanabe, H. Souda, A. Noda
ICR, Kyoto-U, Uji, Kyoto, Japan,
K. Noda, NIRS, Anagawa, Inage, Chiba, Japan,
T. Fujimoto, S. Iwata, S. Shibuya, AEC, Anagawa, Inage, Chiba, Japan,
E. Syresin, A. Smirnov, I. Meshkov, JINR, Dubna, Moscow Region, Russia
H. Fadil, M. Grieser, MPI Kernphysik, Saupfercheckweg, Heidelberg, Germany

Transverse cooling happens naturally because all components of the ion momentum are lost due to the emission of radiation but only the longitudinal component is restored in the RF-resonator of the storage ring. Therefore, the typical time required for the transverse cooling is the time it takes to radiate the full ion energy.

The equilibrium ion bunch parameters are determined by the balance between the laser cooling and different sources of beam heating (stochastic heating due to the randomness of emitted photon energy, heating due to the intra-beam scattering and collective instabilities).

In the case of broad-band laser cooling [8] (with the uniform frequency spectrum of the laser light), if the photon emission happens in dispersion-free region, and neglecting collective effects, the equilibrium energy spread can be found as

$$\frac{\sigma_E}{E} = \sqrt{\frac{1.4(1+D)\hbar\omega_1^{\max}}{mc^2}}, \tag{1}$$

where D is the saturation parameter which is normally below one (see [8] for details), $\hbar\omega_1^{\max}$ the maximum energy of the emitted photon, and m the ion mass. The equilibrium emittance reads

$$\epsilon_{x,y} = \frac{3}{20}\frac{\hbar\omega_1^{\max}}{mc^2\gamma^2}\beta_{x,y}, \tag{2}$$

where $\beta_{x,y}$ is the beta-function in the interaction region.

[8] E. G. Bessonov and K. J. Kim, "Radiative cooling of ion beams in storage rings by broadband lasers", *Phys. Rev. Lett.* **76** (1996) 431–434.

In the case of non-zero dispersion function in the interaction region it is possible to use dispersive coupling between longitudinal and transverse motion in order to achieve faster transverse cooling [12]. The mechanism of the longitudinal–horizontal coupling through dispersion is illustrated in Fig. 2.

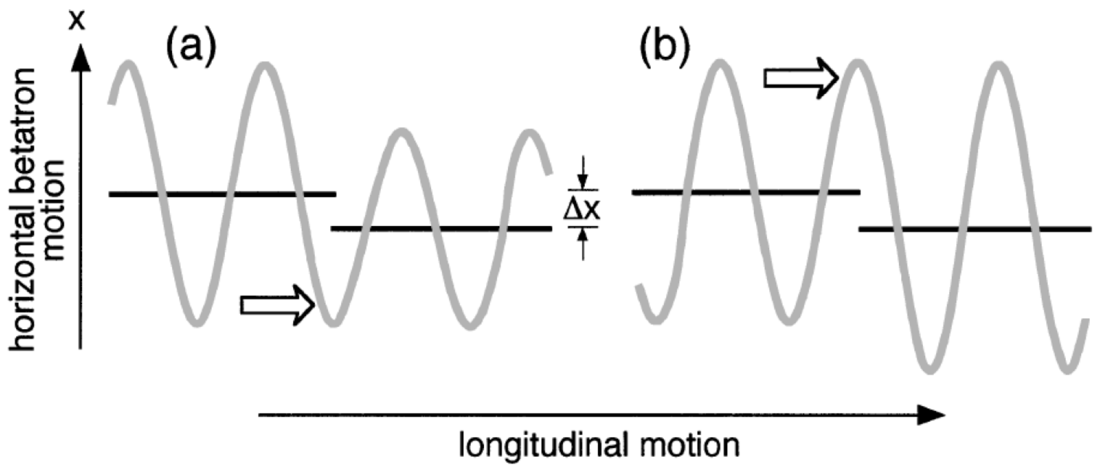


Fig. 2: Horizontal betatron oscillations of a stored ion around the central orbit in a region with positive dispersion. The moment of photon emission and the corresponding change of the central orbit is indicated by the arrow. A reduction (increase) of the amplitude of the oscillation which occurs when the ion radiates a photon in a negative $x < 0$ (positive $x > 0$) phase of the betatron oscillation is depicted on the left (a) (right (b)). The transverse cooling will occur in the case depicted on this figure if more photons are emitted at $x < 0$ rather than at $x > 0$. (Adapted from [12].)

[12] I. Lauer *et al.*, "Transverse Laser Cooling of a Fast Stored Ion Beam through Dispersive Coupling", *Phys. Rev. Lett.* **81** (1998) 2052–2055.

correspondence with Witek:

Well, as you know (and have cited in your paper), the method of „dispersive cooling“ and “betatron coupling” has been demonstrated by Lauer et al. at the TSR in Heidelberg. Indeed, this method is 3D. The results are good, although the transverse laser cooling effect is by far not as strong as the longitudinal one.

It think it is important to realize that, at the TSR, they always had the possibility to start with a pre-cooled ion beam, using the electron cooler.
The electron cooler was also used to achieve “betatron coupling”:
“... by coupling both degrees of freedom by a 40 mT longitudinal field of the electron cooler solenoid …”

I do not know if such pleasant initial conditions will exist at the LHC and at the SPS.
Using a calibrated electron cooler, a known ion orbit, and Schottky diagnostics (measuring the ion revolution frequency), one obtains:
1) a good value for the absolute ion energy and
2) a low initial longitudinal (and transversal) ion momentum spread

If one would need to start (first at the SPS and later at the LHC) with a “large absolute uncertainty” in the ion velocity (in the LHC and SPS) and a “large longitudinal ion momentum distribution” (Dp/p), it may be difficult to
1) find the transition in the first place and
2) achieve cooling over the complete ion beam velocity distribution

In your paper, you wrote:
“This scheme requires two different lasers and two different photon–PSI interaction points. The focal point of the first-laser beam is shifted towards the negative horizontal position with respect to the ion beam centre (for a positive value of the dispersion function) by a value of Δx. This laser has a broad frequency spectrum allowing to excite the ions over the full spread of their energies. The focal point of the second-laser beam is centred on the ion beam axis. Its frequency band is tuned to excite only those of the ions which carry the energy above its central value. In order to suppress the vertical betatron oscillations, one needs to couple them to the horizontal ones using the transverse betatron coupling resonance. To achieve an efficient coupling, the frequency of the vertical betatron oscillations should be close enough to the frequency of the horizontal betatron oscillations.”

A few questions:

- What will be used (at SPS and LHC) for the “betatron coupling”?

- Will it indeed be possible - for a certain (large) range of ions – to operate the rings at almost equal hor. and vert. betatron frequencies?

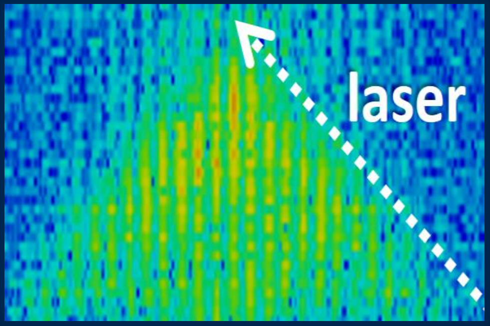
- It is yet another criteria on the experiment, besides laser wavelength (and width), transition wavelength in the ion, ion velocity (and width), ion-bunch & laser-pulse timing.

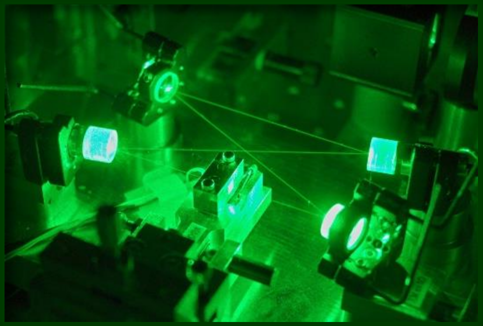
- Will there be two interaction points available/possible at the SPS and LHC? Or does this require a few changes in the rings?

Contents

Heavy-ion laser cooling pilot facility

bunched ion beams





cw & pulsed laser beams

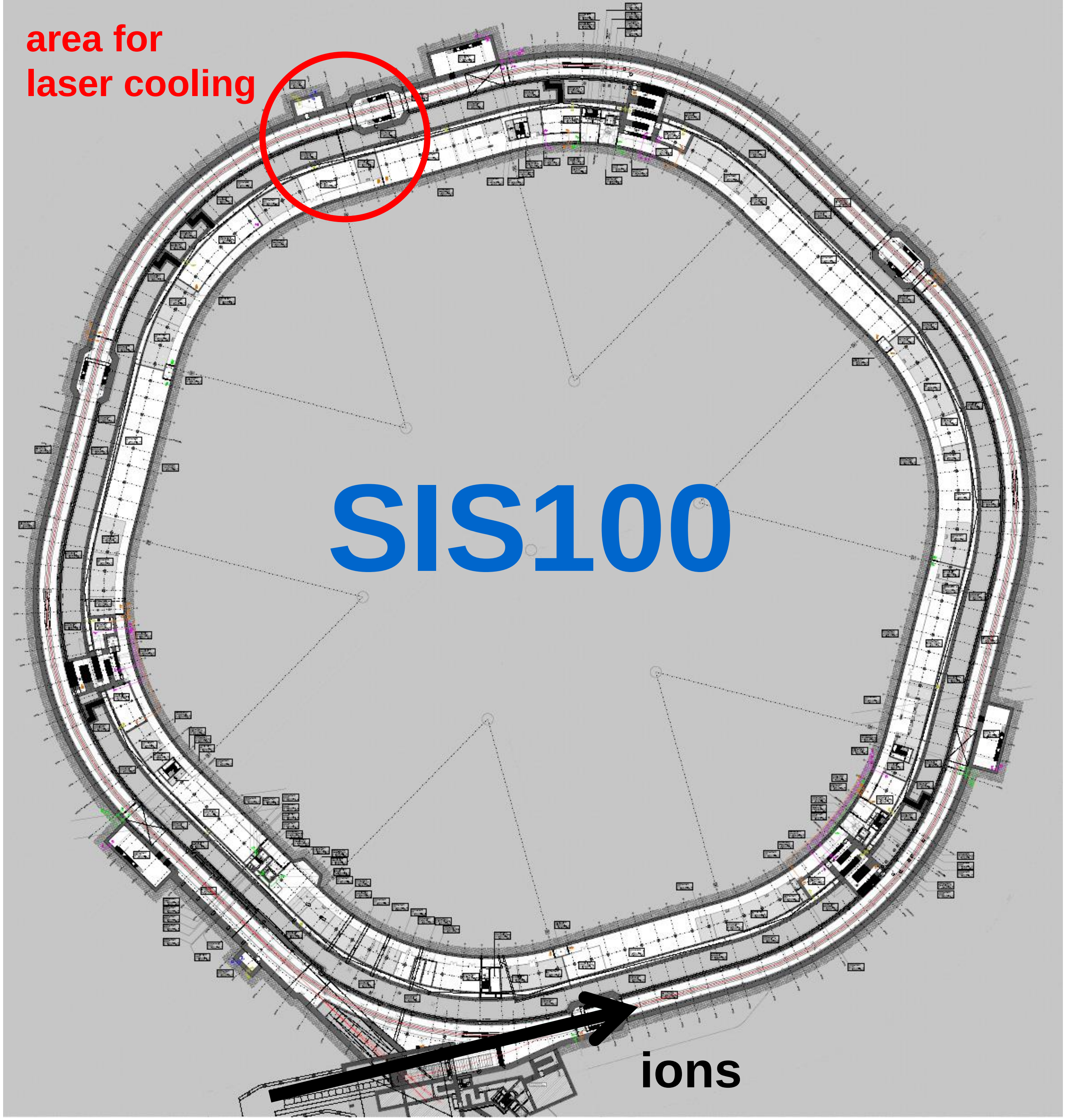
- Laser-cooled relativistic heavy-ion beams (γ up to 13 , Z = 10 - 60)
- Only cooling method at SIS100 energies ($\Delta p/p$ down to 10^{-7})
- Extraction of very cold and very short ultra-relativistic ion bunches

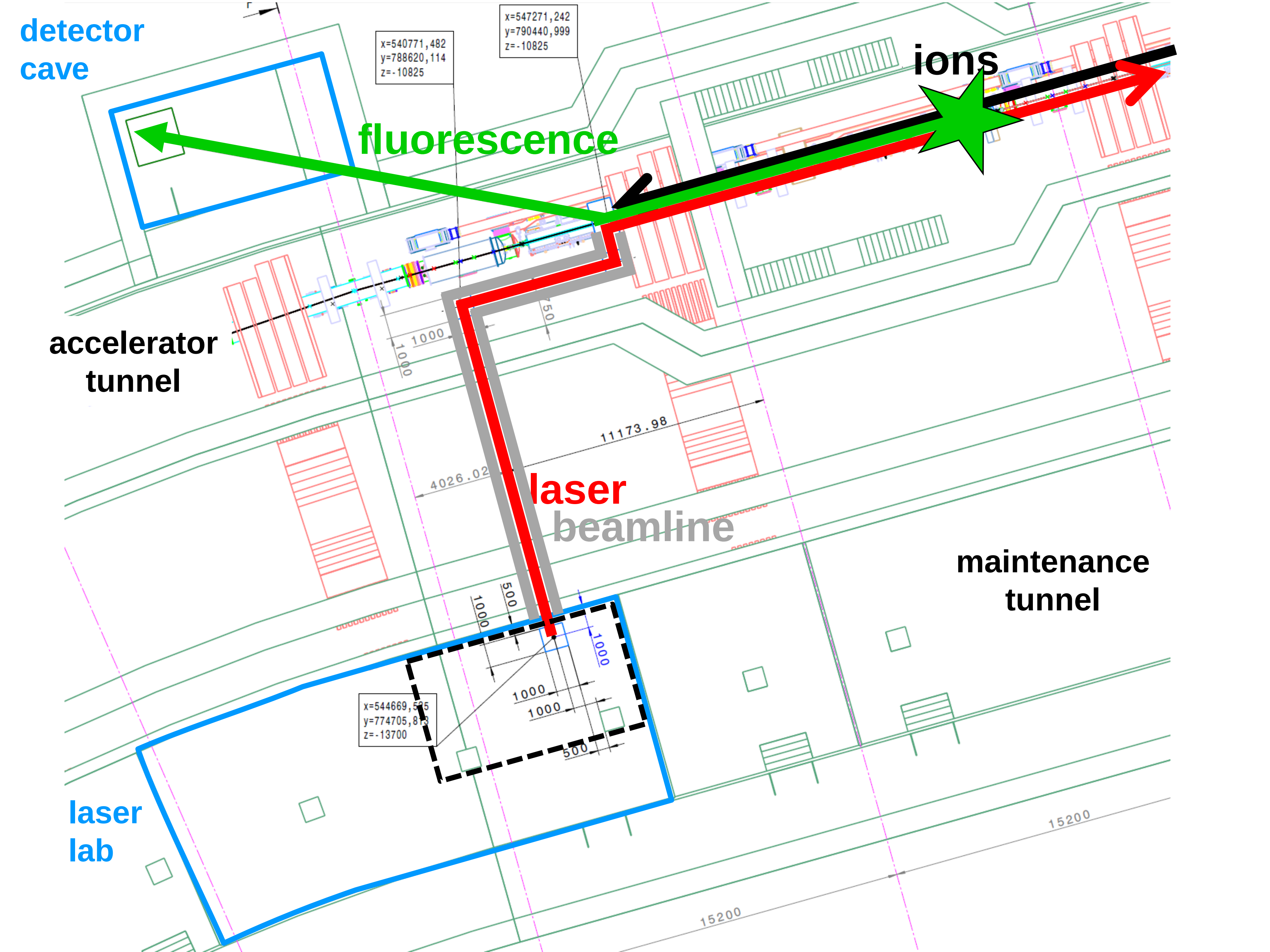
April 2018
SIS100 tunnel

July 2018
SIS100 tunnel

September 2018
SIS100 tunnel

September 2020


area for
laser cooling
SIS100
ions


detector cave
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ions
fluorescence
accelerator tunnel
1000
1000
11173.98
4026.02
laser
beamline
maintenance tunnel
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1000
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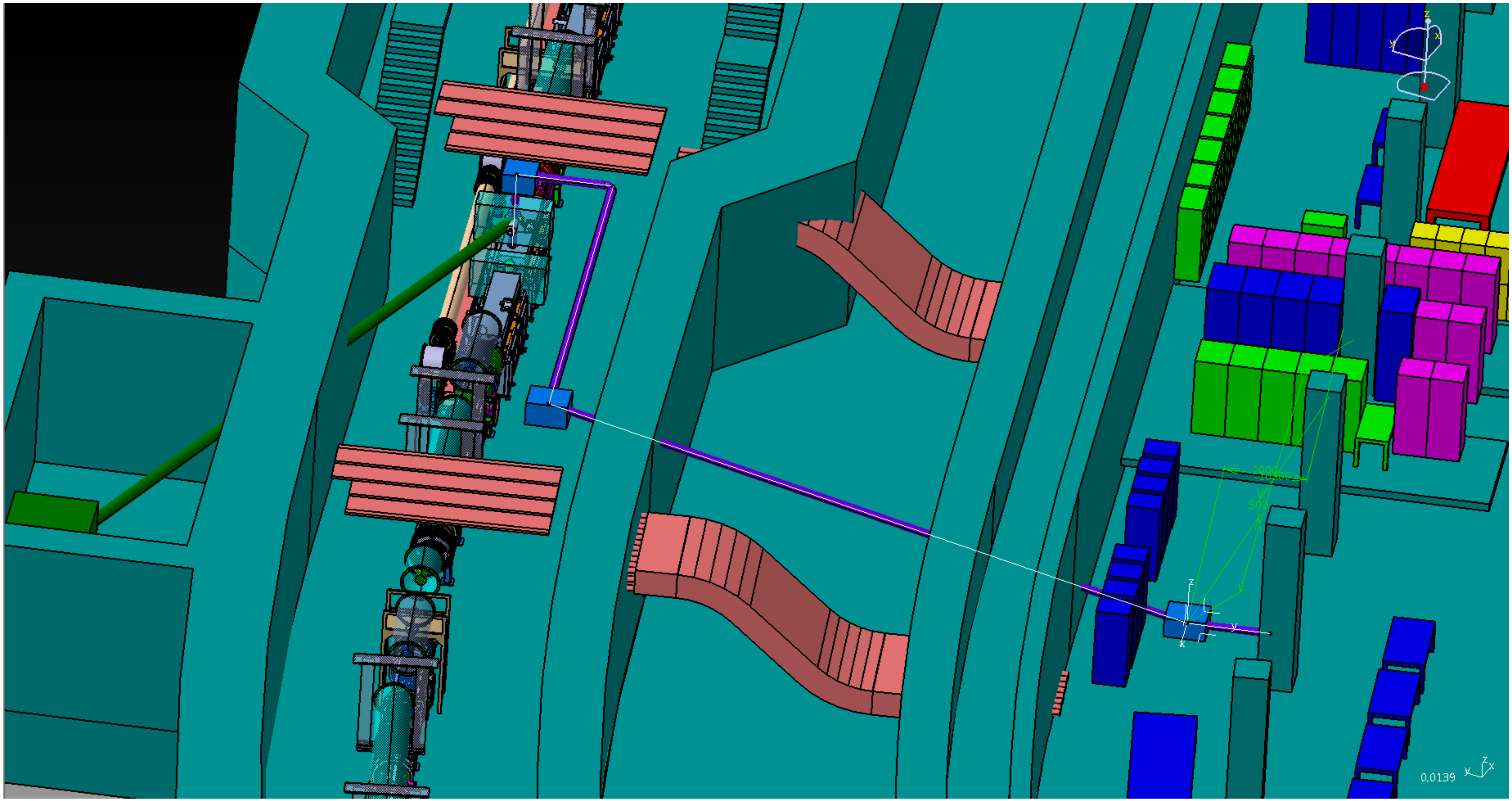
laser lab
15200
15200



accelerator tunnel

maintenance tunnel

The end.

Thank you for your attention!