Laser cooling at the SIS100

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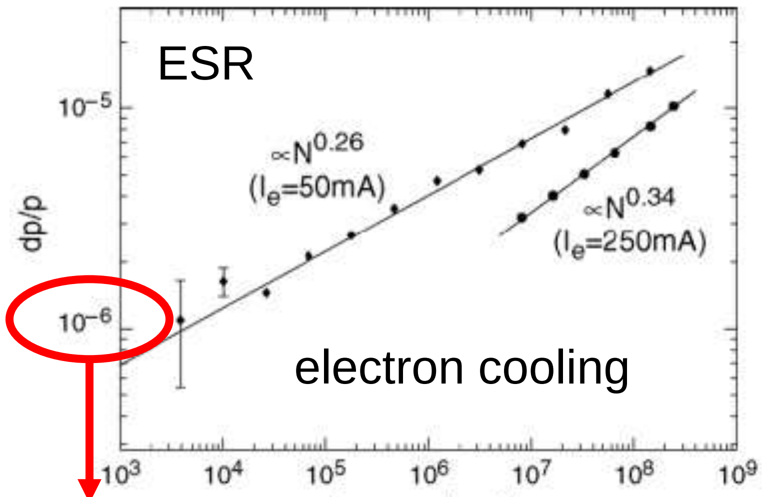
ICST for FAIR in Europe,
Worms, Germany
Wednesday 15 October 2014

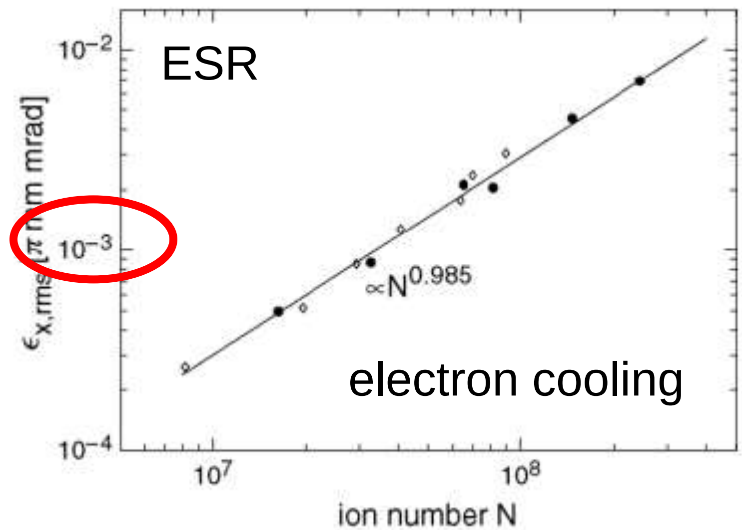
Reasons for performing laser cooling at the SIS100 (300):

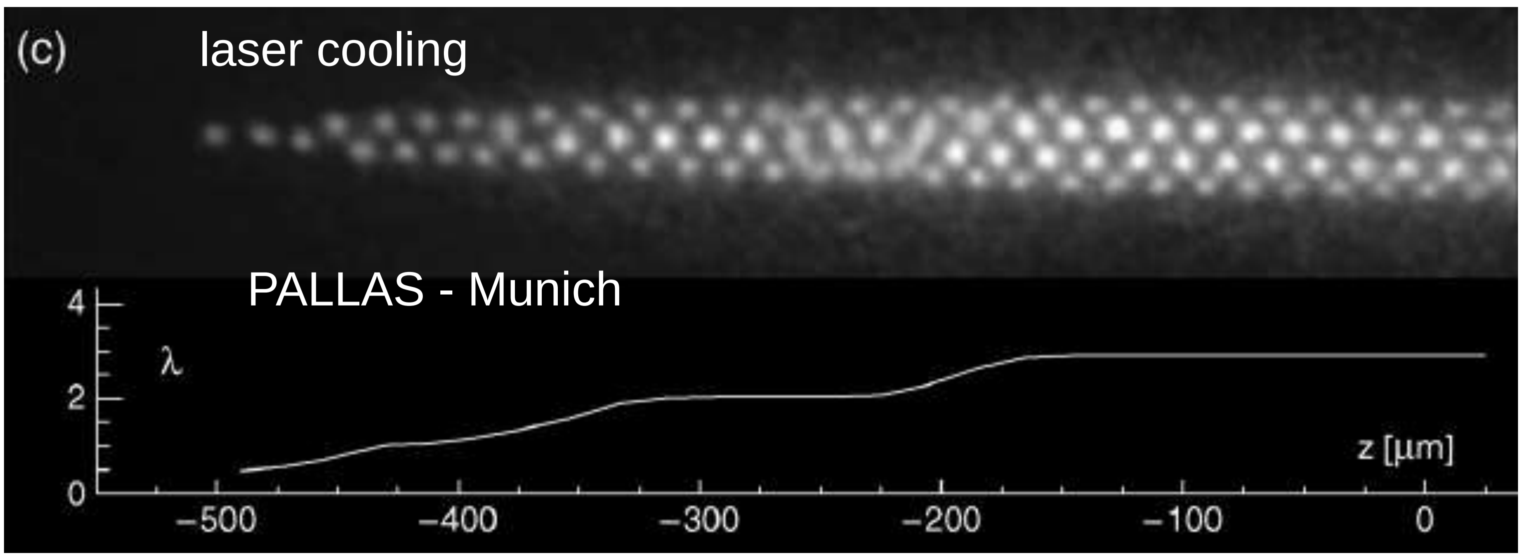
- no other cooling technique available
- possible other methods become technically very complicated and expensive (e.g. electron cooling, stochastic cooling)
- the laser cooling forces strongly improves with increasing γ, whereas electron cooling becomes less effective (slow), and stochastic cooling works best for a fixed energy and a few ions
- by exploiting the huge relativistic Doppler shift, the recipe can be rather flexible (different ions, different energies)
- extraction of very cold, very short, ultra-relativistic bunches of ions towards experiments could be possible

Nice results of strongly cooled ion beams



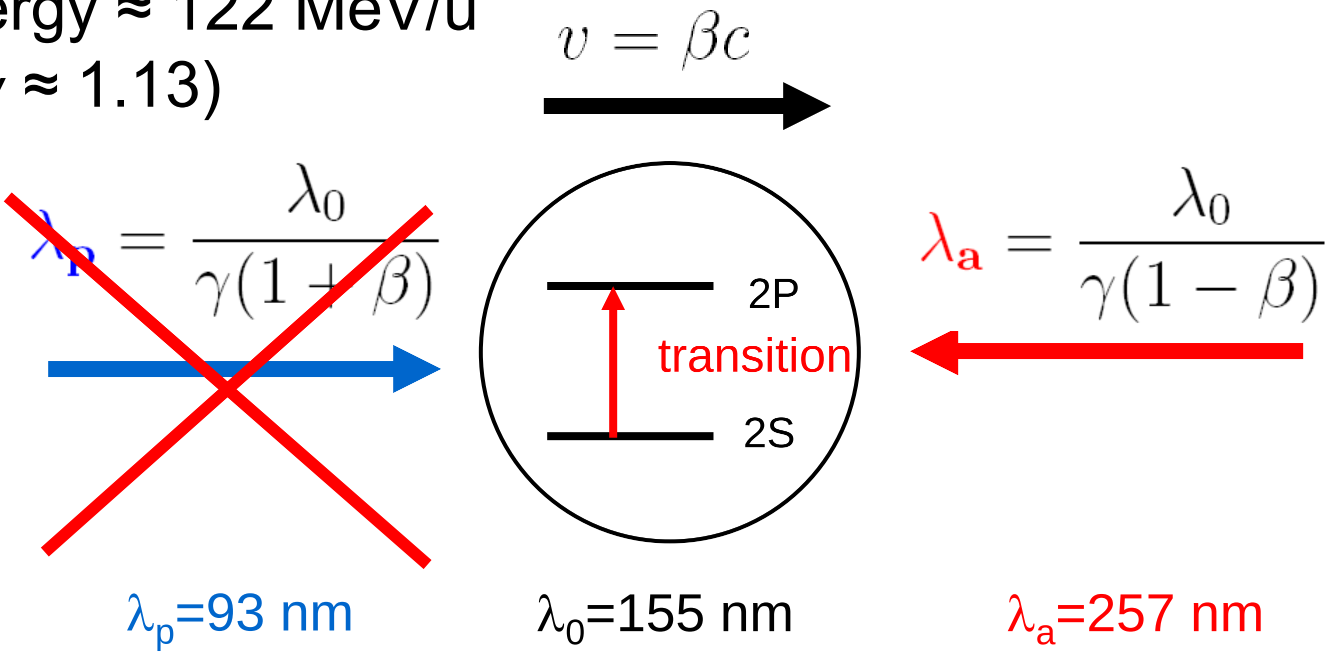
$T_{par} \approx 30$ K





The principle: laser cooling of stored relativistic ions

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



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

ion

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

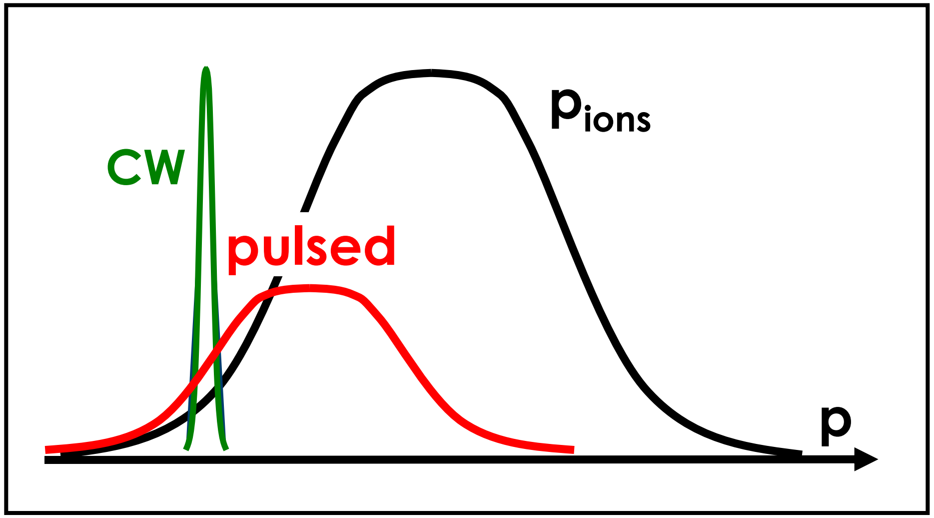
length	108,36	m	
Bp	**6,6**	Tm	
Q	3		C3+
e	1,60E-19	C	
M	12		C3+
u	1,66E-27	kg	
c	3,00E+08	m/s	
γ	1,13		
ß	0,47		
Ek	123,09	MeV/u	
f	1,30	MHz	
ion	**155,00**	nm	C3+
laser	257,60	nm	
	ESR		

normal laser

Laser cooling can, in principle, be done at many circular accelerators!
At FAIR at the storage rings (ESR, CRYRING, HESR),
but also at the synchrotrons (SIS100/300).

Difficulties are:

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



Experimental setup at the ESR

ion species: $^{12}C^{3+}$

bunched beam!

E_{beam} = 122 MeV/u

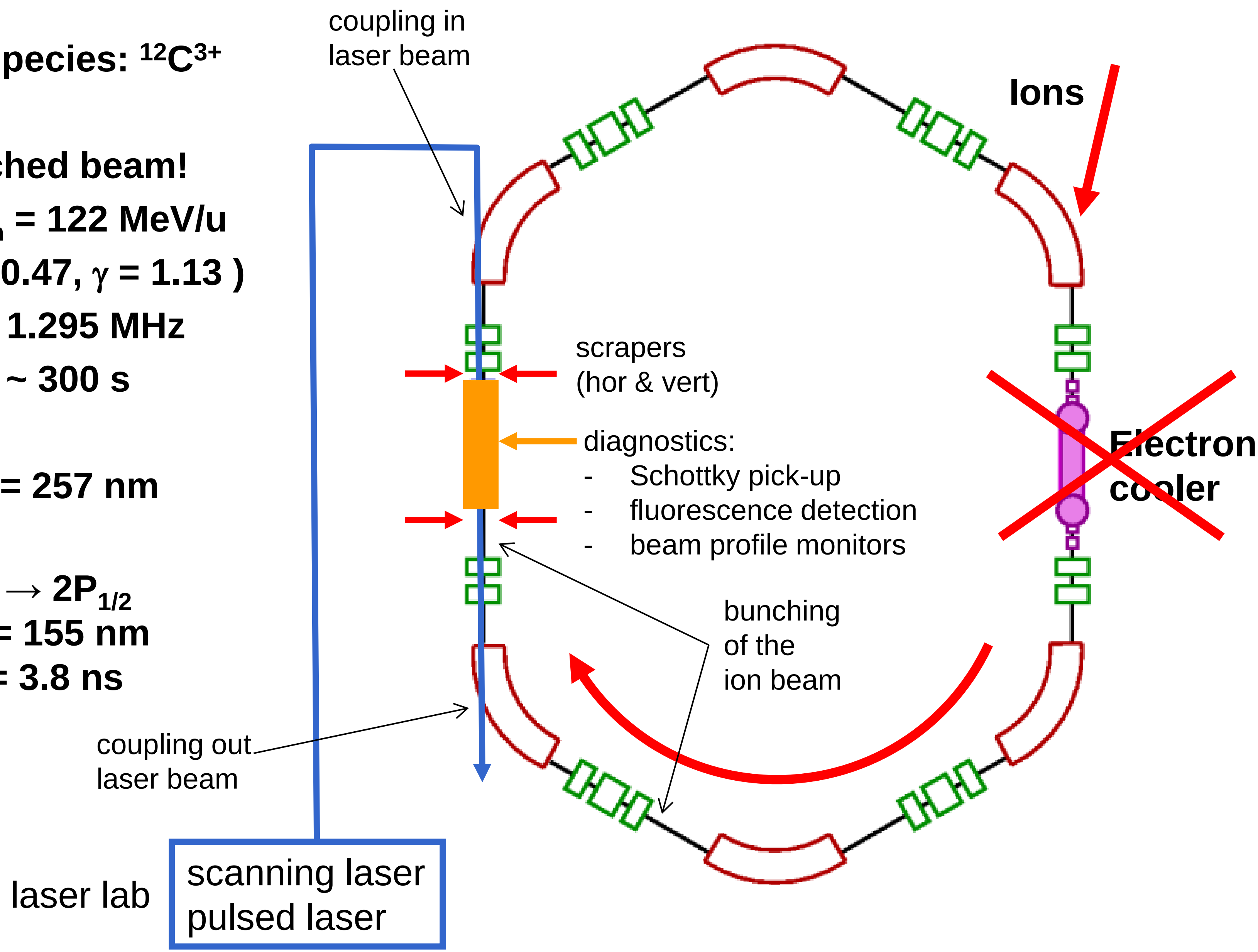
(β = 0.47, γ = 1.13)

f_{rev} = 1.295 MHz

τ_{beam} ~ 300 s

λ_{laser} = 257 nm

$2S_{1/2} \rightarrow 2P_{1/2}$
λ_{rest} = 155 nm
τ_{rest} = 3.8 ns



used laser systems:

cw Ar^+ laser (514 nm) +
1 frequency doubling stage (257 nm)

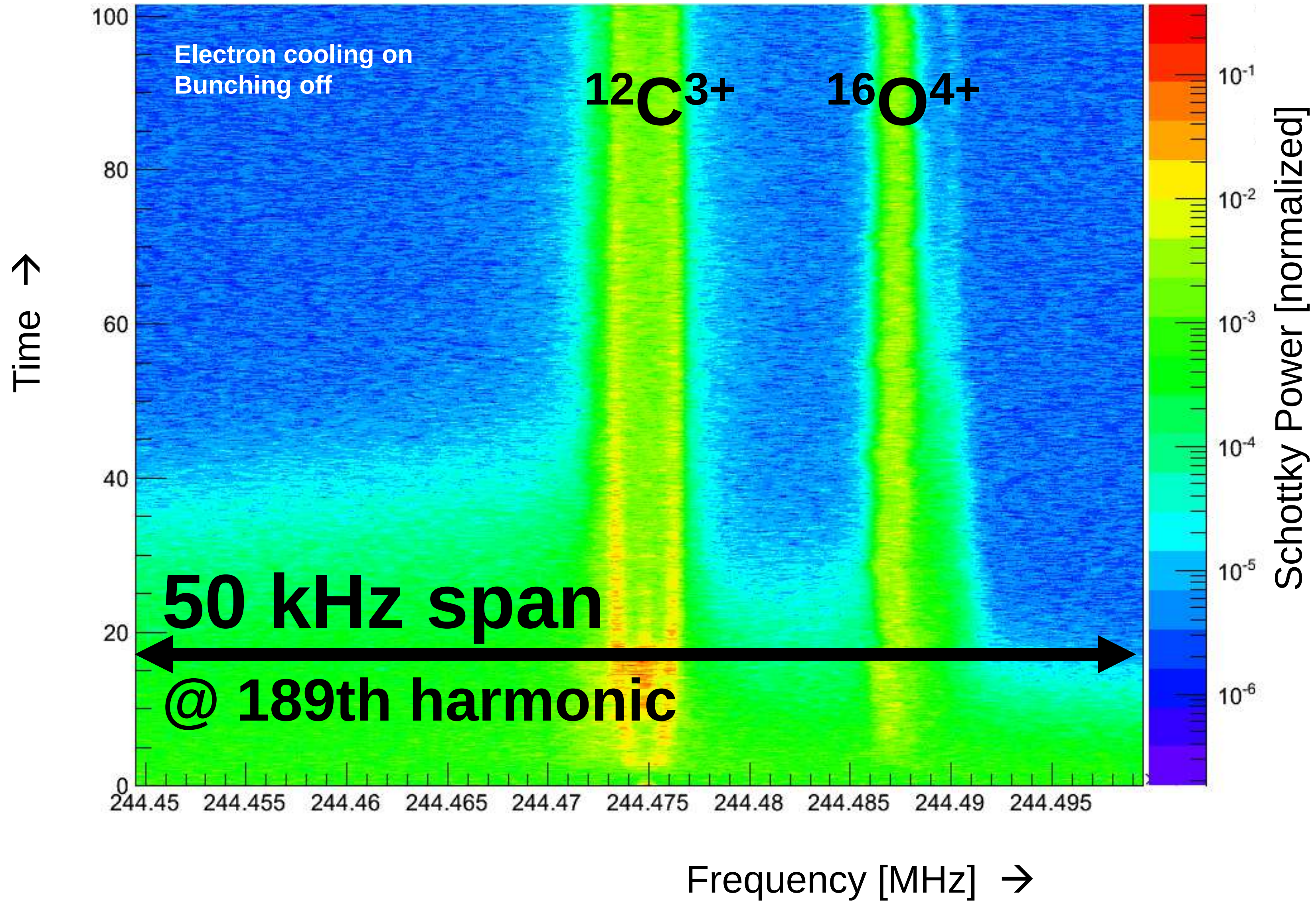
tuneable cw ECDL (diode, 1028 nm) +
fiber amplifier +
2 frequency doubling stages (514 and 257 nm)

pulsed laser system (1028 nm) +
2 frequency doubling stages (514 and 257 nm)

laser beam stabilization system (50 – 100 m length)

Preliminary results from the ESR

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



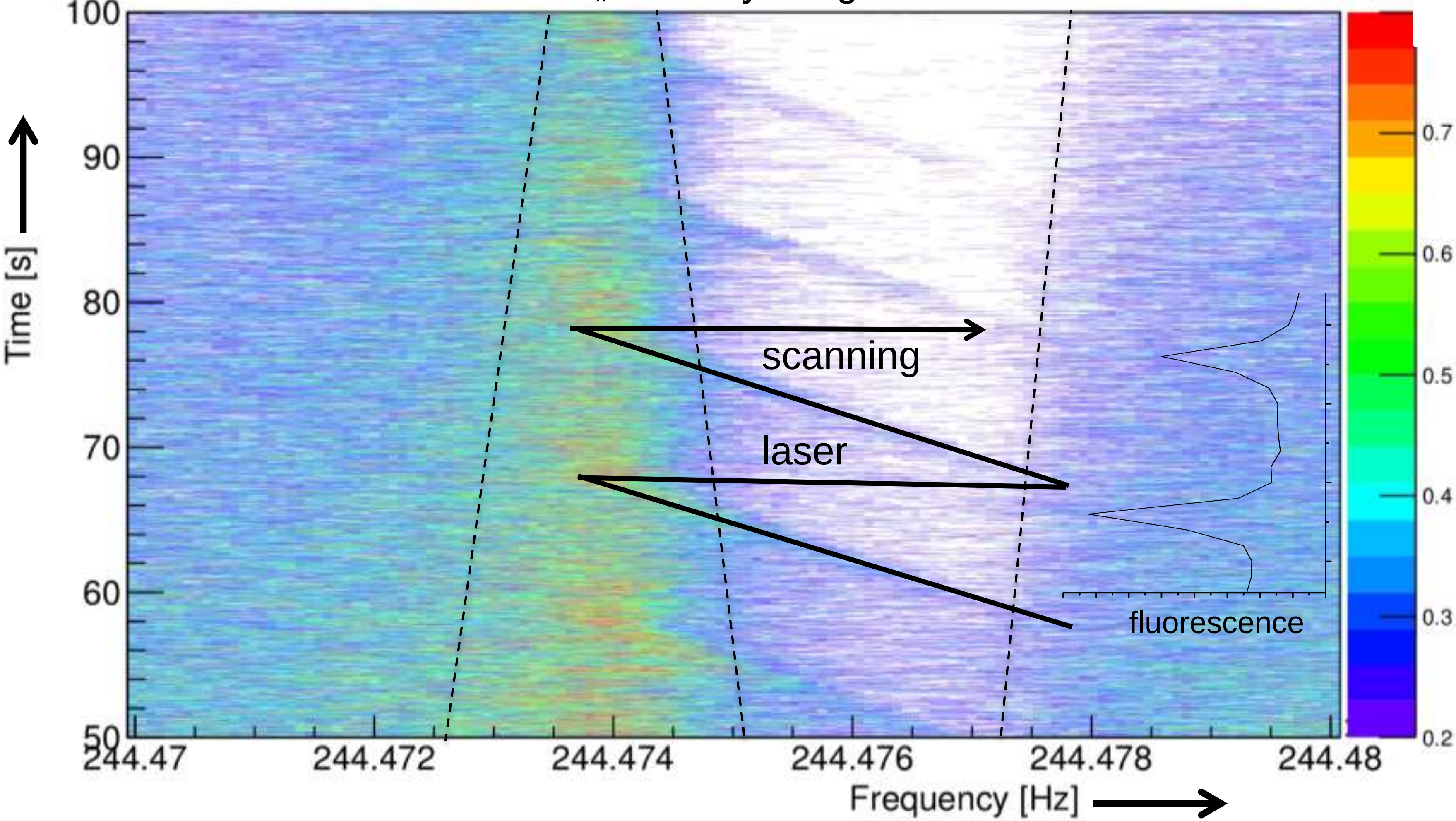
Laser cooling of C^{3+} ions in the ESR

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

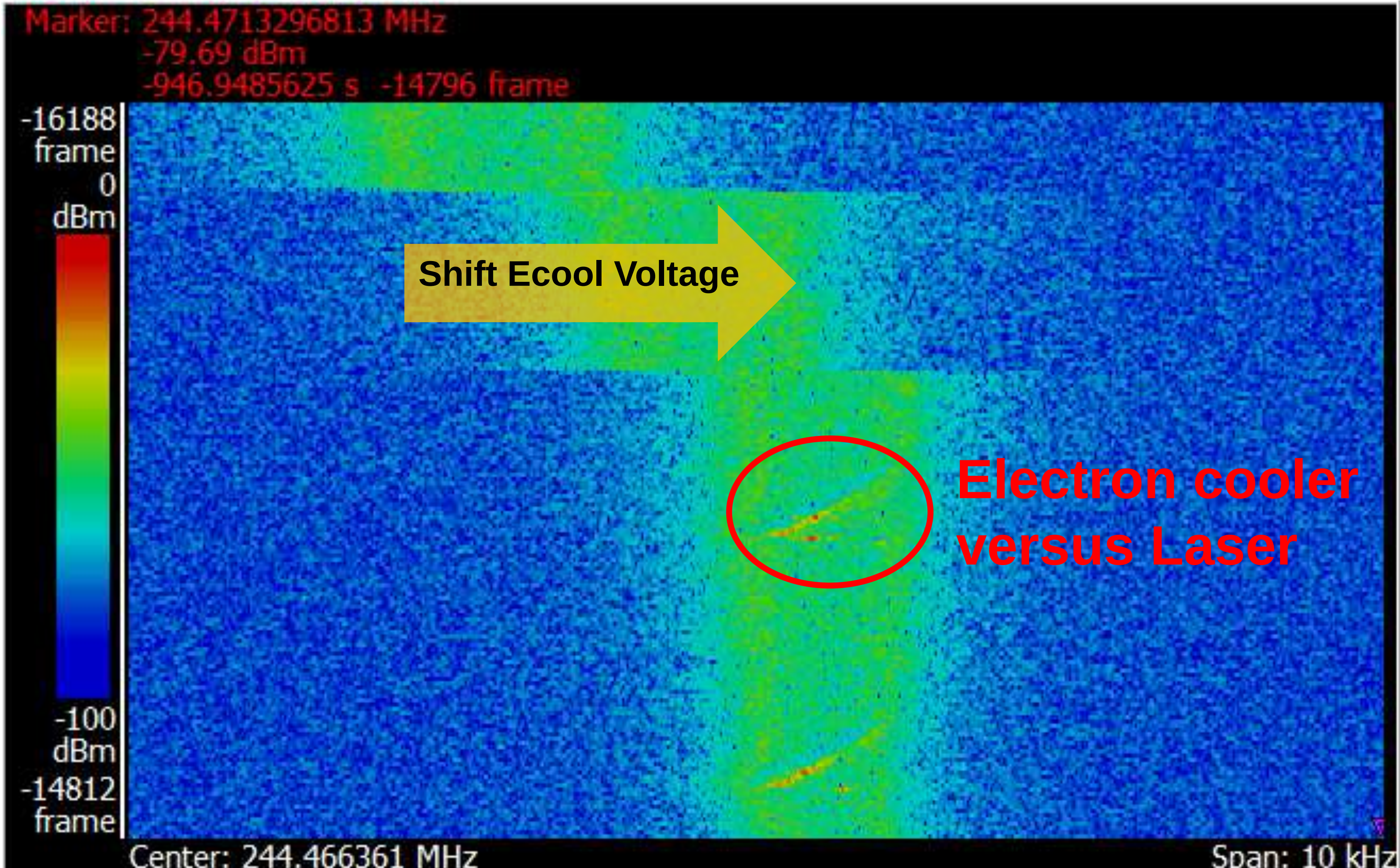
→ the UV-fluorescence from the ions is detected in vacuo, and peaks when the laser is resonant

„Schottky image“

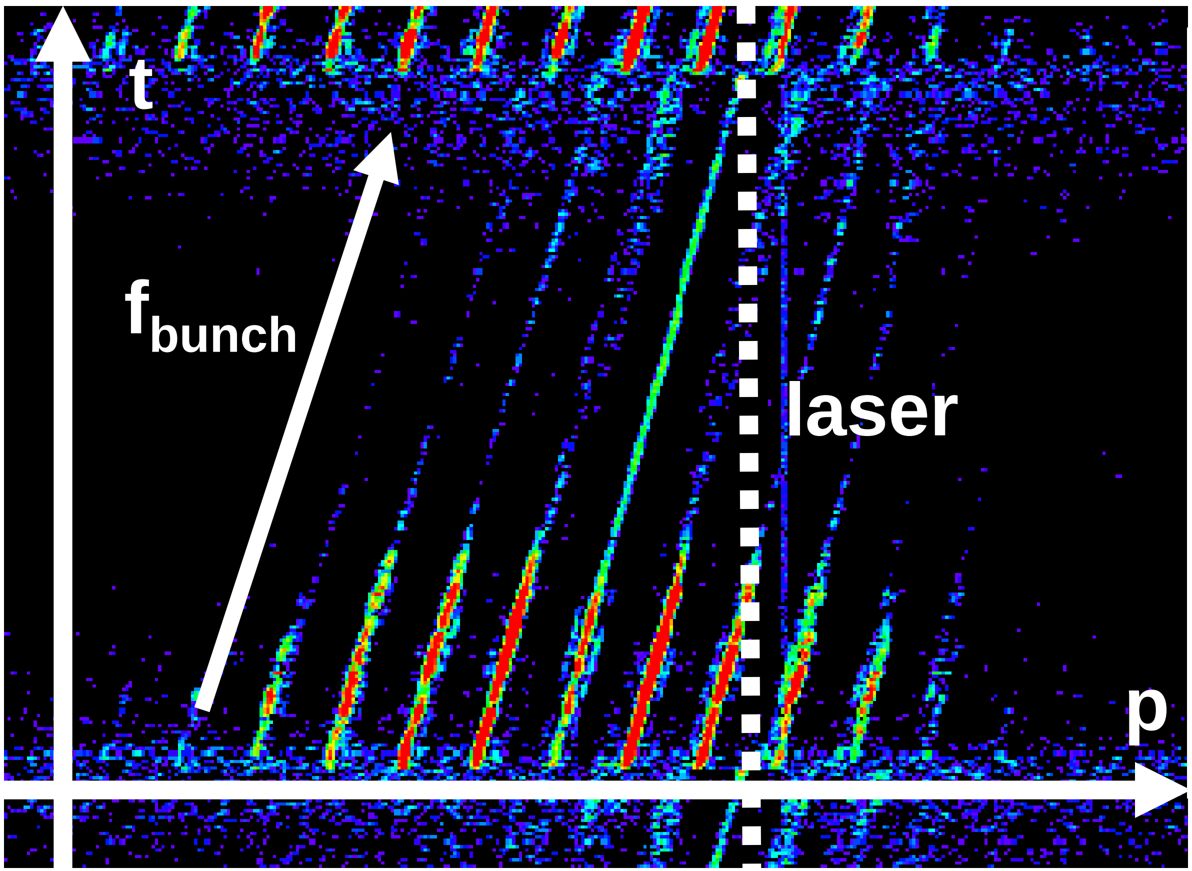


(189th harmonic)

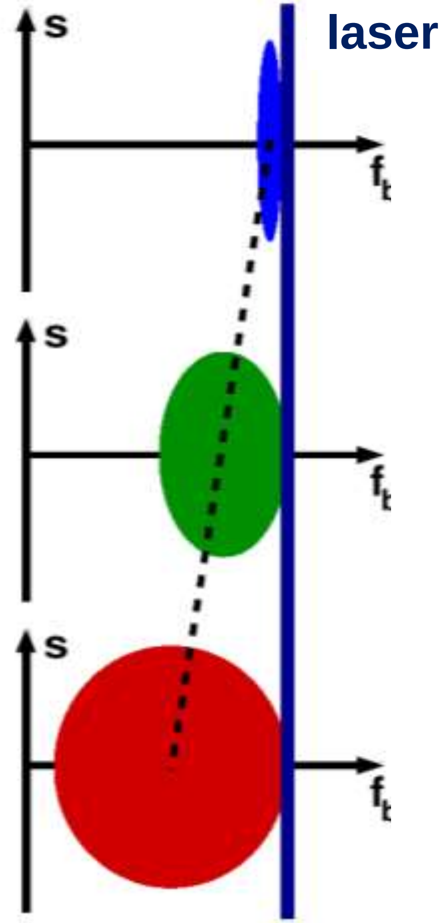
Electron cooling vs. laser cooling of C^{3+} at ESR



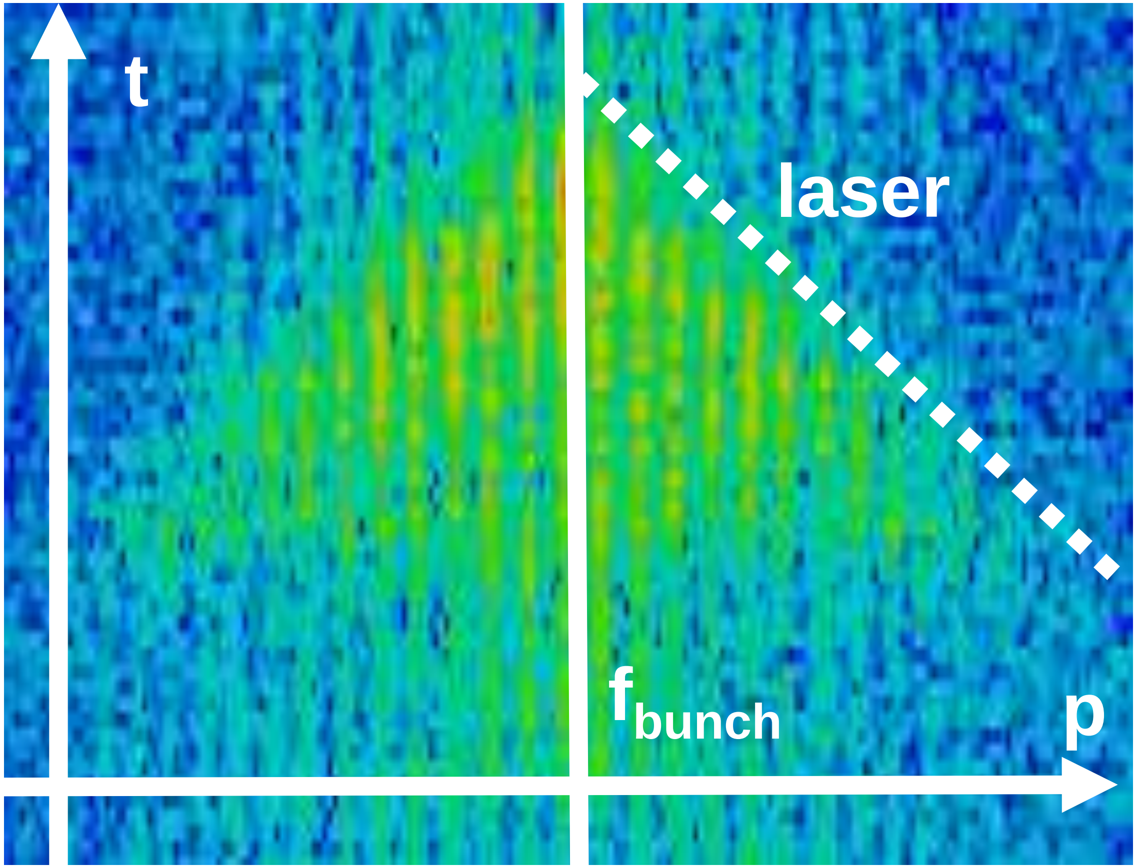
Experimental demonstration at the ESR of two possibilities:
1) scanning the bunching frequency at a fixed laser frequency



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



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



„Schottky image“
hor: frequency
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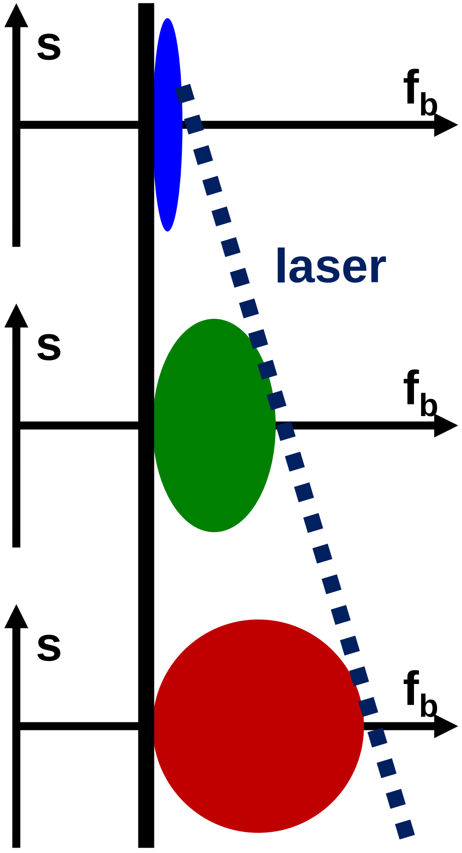
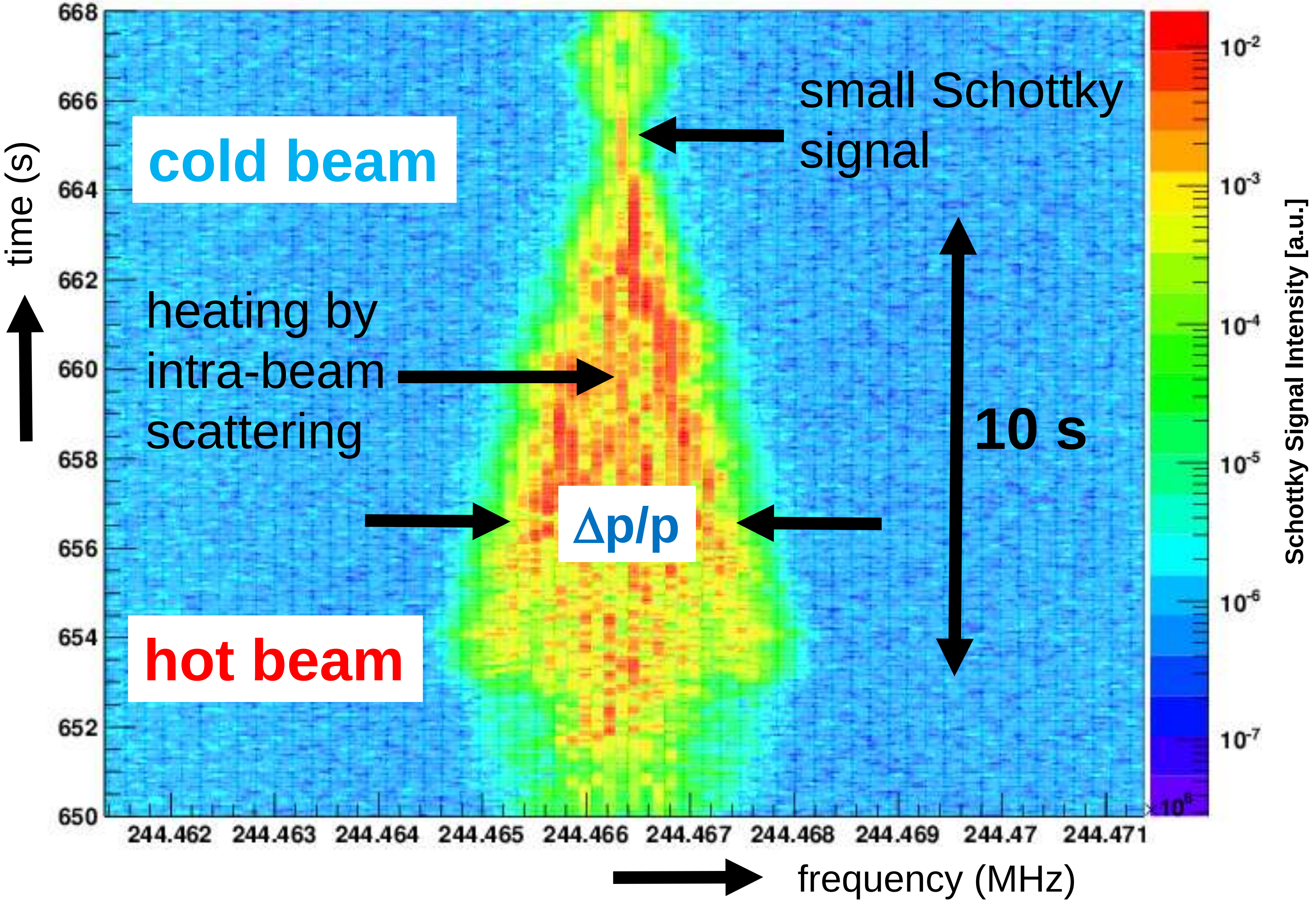
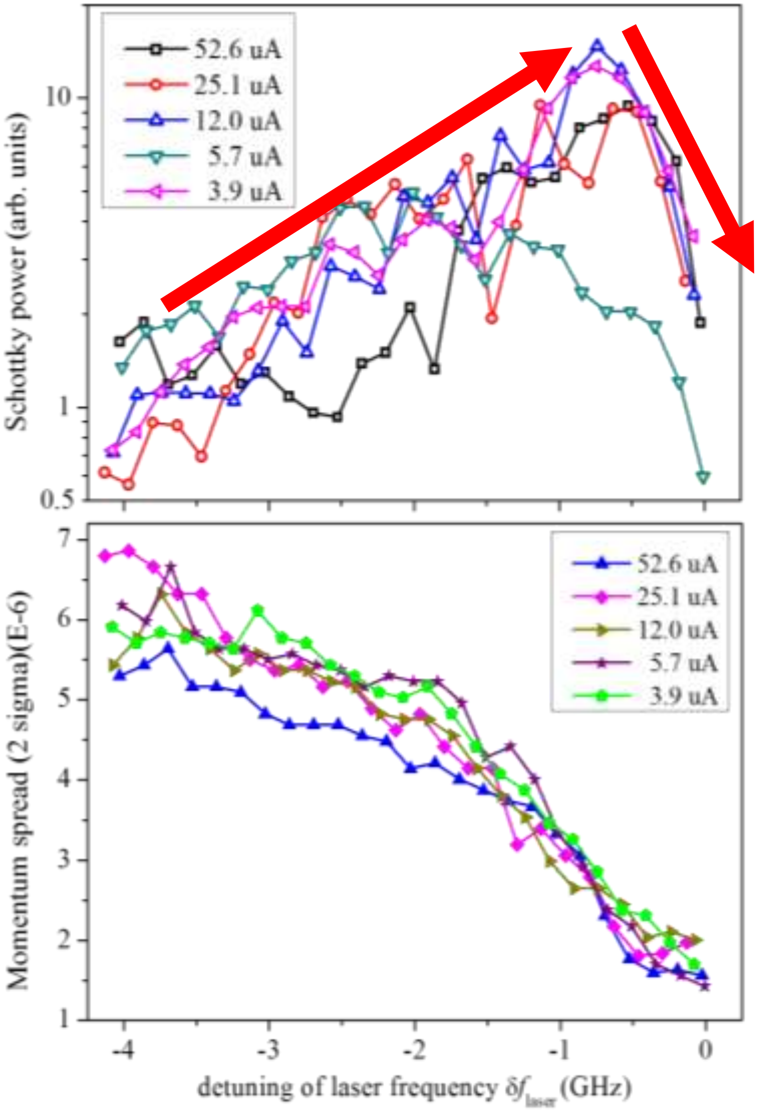


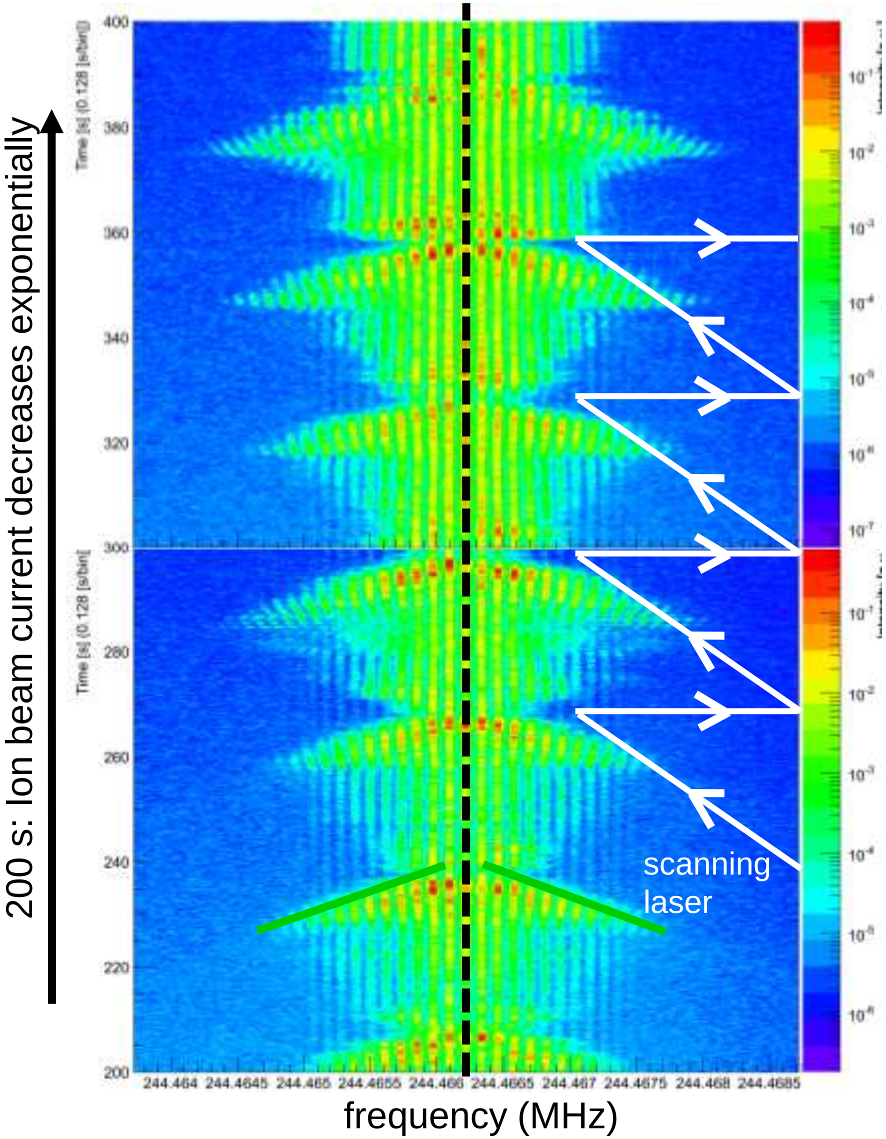
C^{3+} ions stored in the ESR, 122 MeV/u, scanning the laser frequency



In general, within a few seconds, the scanning laser can effectively cool all the ions in the bunch. If the laser scans faster, or if a pulsed laser is used, this greatly improves!

Latest results: laser cooling almost independent of ion beam current

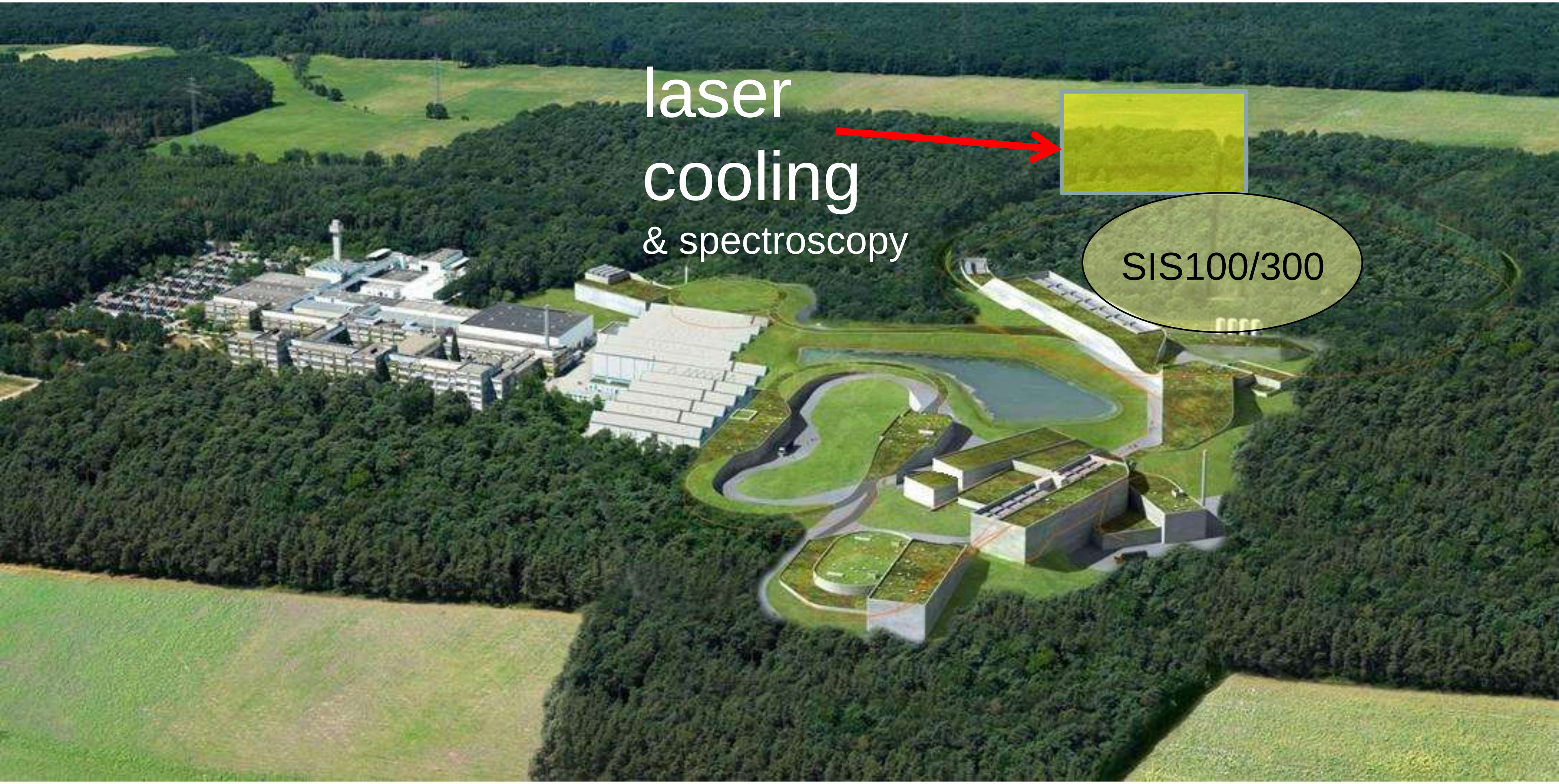




Darmstadt

Lanzhou, China

für



At the high velocities (high γ) in SIS100/300, laser cooling seems to be the only realistic cooling method.

→ Laser cooling force scales strongly with γ !

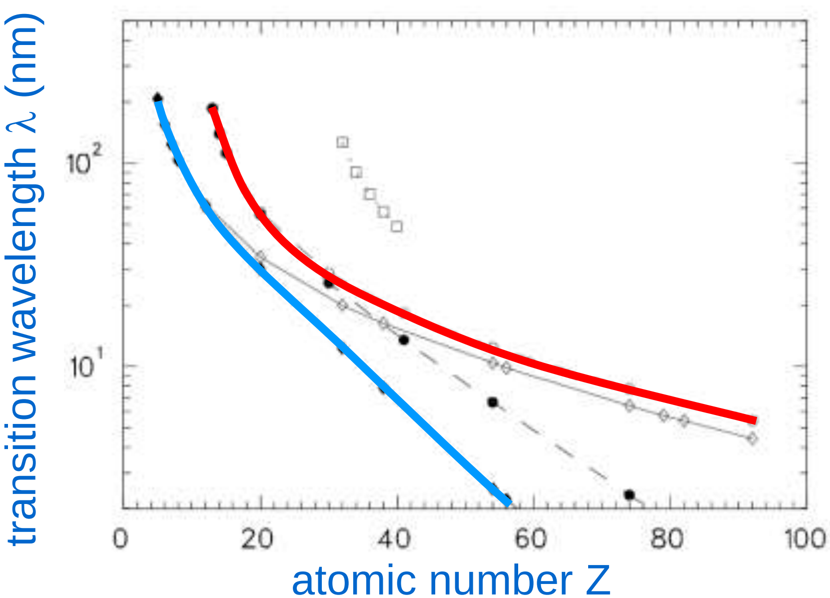
FAIR construction site

Luftbild des Baufeldes vom 05.05.2013 (Foto: Jan Schäfer für FAIR)

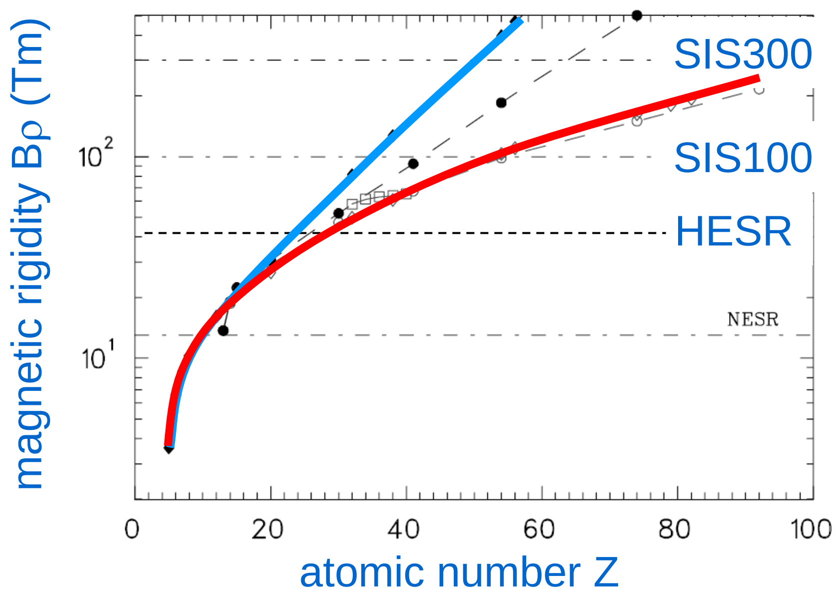
Laser cooling of Li-like ions at the SIS100/300

The transition wavelengths strongly depend on the atomic number Z!

The Doppler boost of the SIS100/300 shifts wavelengths to `normal´ lasers!
(Laser cooling is also planned for the HESR.)



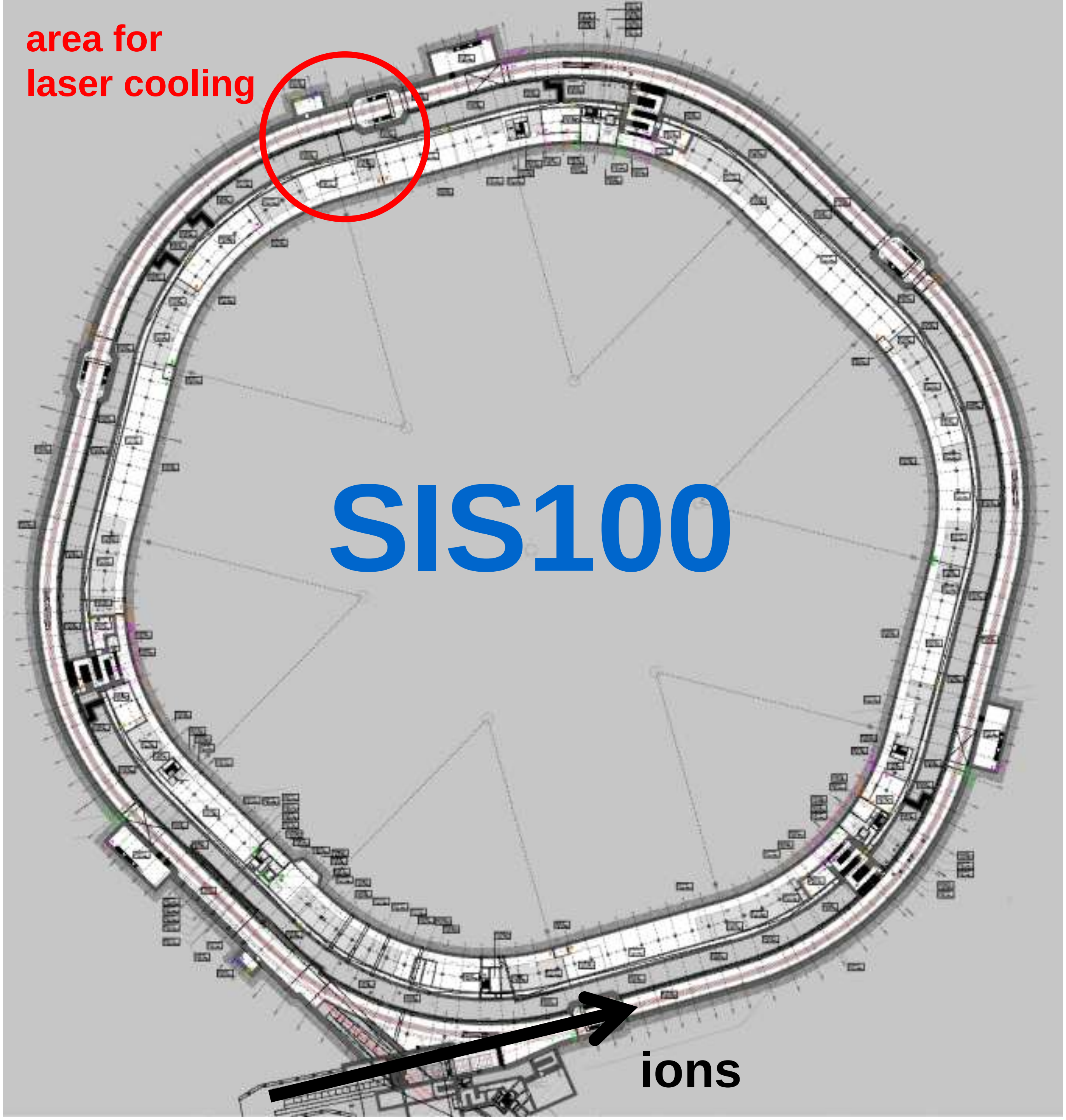
needs fast transitions!

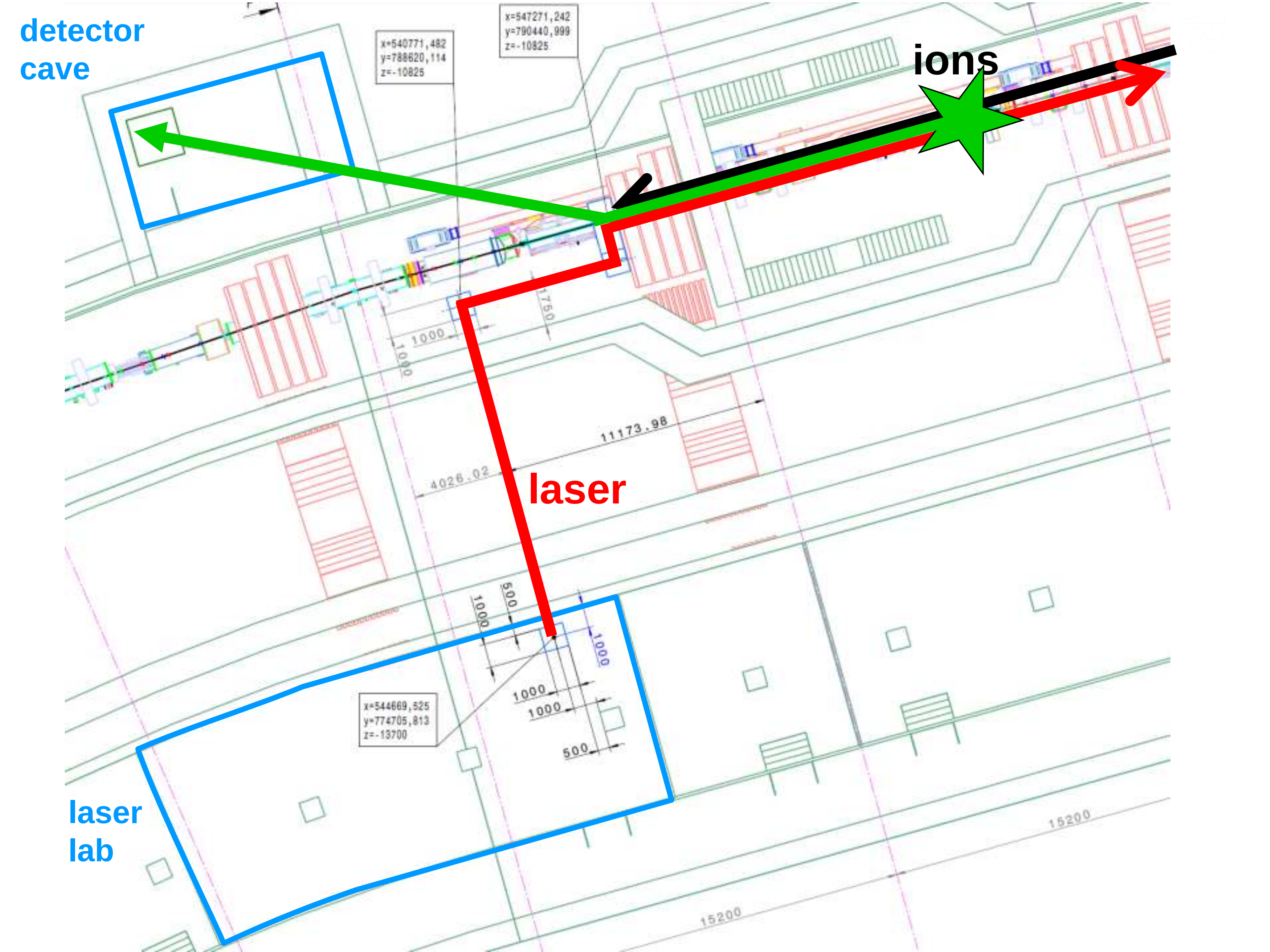


$\gamma \rightarrow B\rho$

Li-like ions (3 e^-)
Na-like ions (4 e^-)

U. Schramm, M. Bussmann *et al*.


area for
laser cooling
SIS100
ions

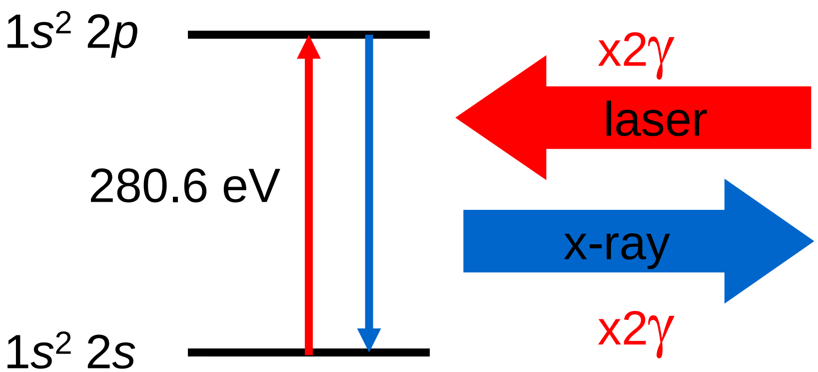


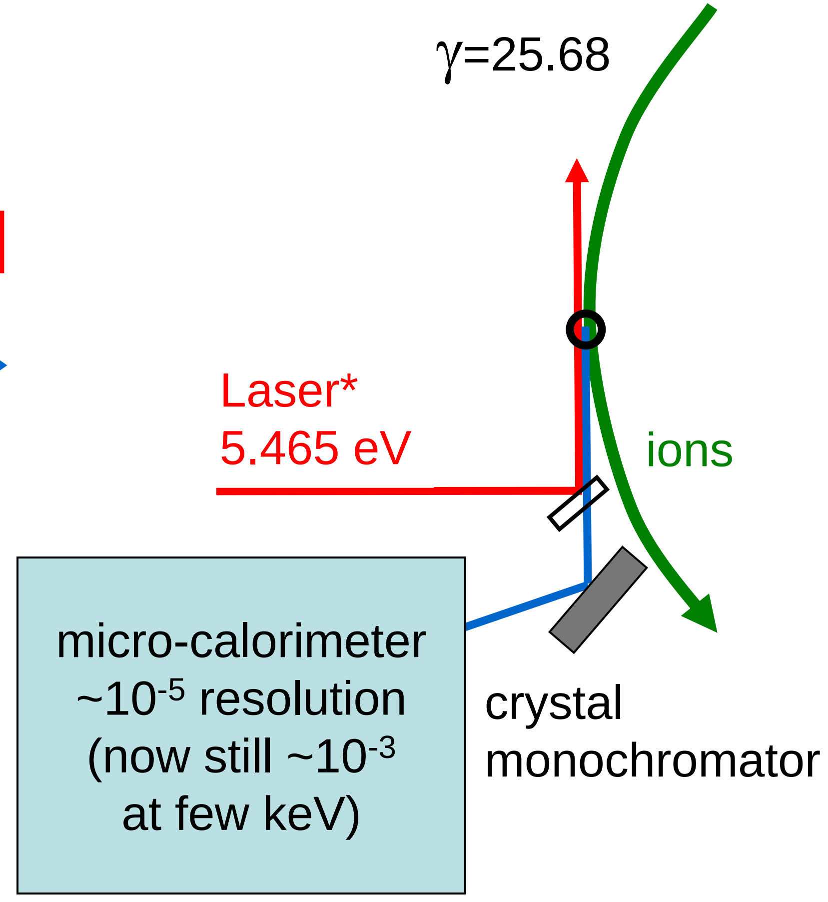
detector
cave
ions
laser
laser
lab
x=540771,482
y=788620,114
z=-10825
x=547271,242
y=790440,999
z=-10825
x=544669,525
y=774705,813
z=-13700
11173.98
4026.02
15200

Laser spectroscopy at the SIS300

(also possible at SIS100 and HESR, but with lower γ)

QED in lithium-like uranium





Up to a factor 4 better resolution!

(ΔE/E of the transition)

H. Backe, Hyp. Int. **171,** 93 (2007).

* 454 nm frequency doubled

SPARC Laser Cooling, people:

GSI

Christina Dimopoulou, Tino Giacomini, Christophor Kozhuharov, Thomas Kühl[a,c], Yuri Litvinov, Matthias Lochmann[a], Wilfried Nörtershäuser[a,b], Fritz Nolden, Rodolfo Sanchez, Shahab Sanjari, Markus Steck, Thomas Stöhlker[c], Johannes Ullmann[b], Carsten Omet, Peter Spiller, **Danyal Winters**

([a]auch Uni Mainz, [b]auch TU-Darmstadt, [c] auch HI Jena)

HZDR, TU-Dresden

Ulrich Schramm, Michael Seltmann, Mathias Siebold, **Michael Bussmann**

TU-Darmstadt

Tobias Beck, Gerhard Birkl, Benjamin Rein, Sascha Tichelmann, Thomas Walther

IMP-CAS, Lanzhou, China

Xinwen Ma, Weiqiang Wen, Jie Yang, Dacheng Zhang

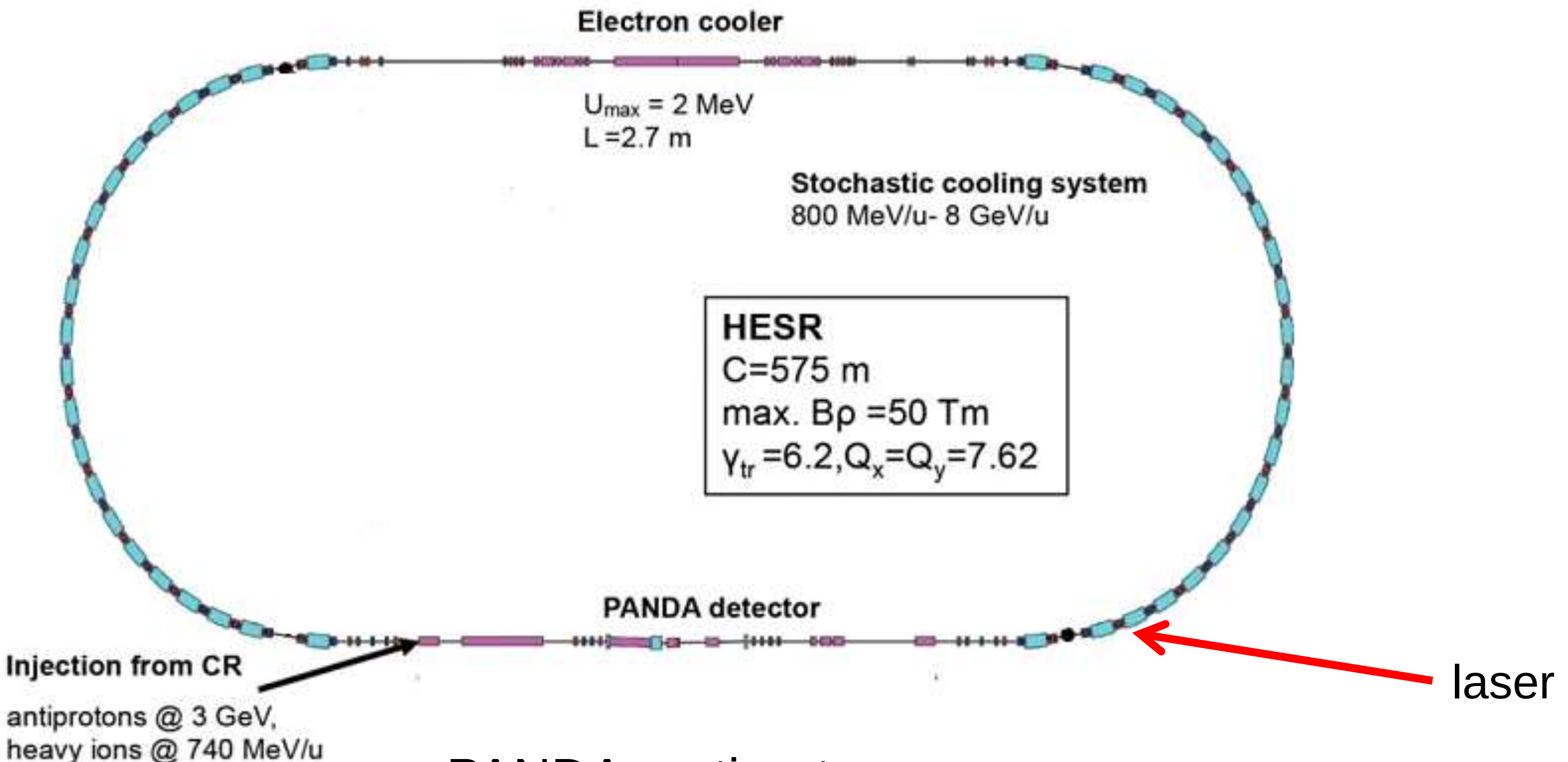
Uni-Münster

Volker Hannen, Jonas Vollbrecht, Christian Weinheimer

Thank you for your attention ☺

The end.

Properties of the High Energy Storage Ring (HESR)

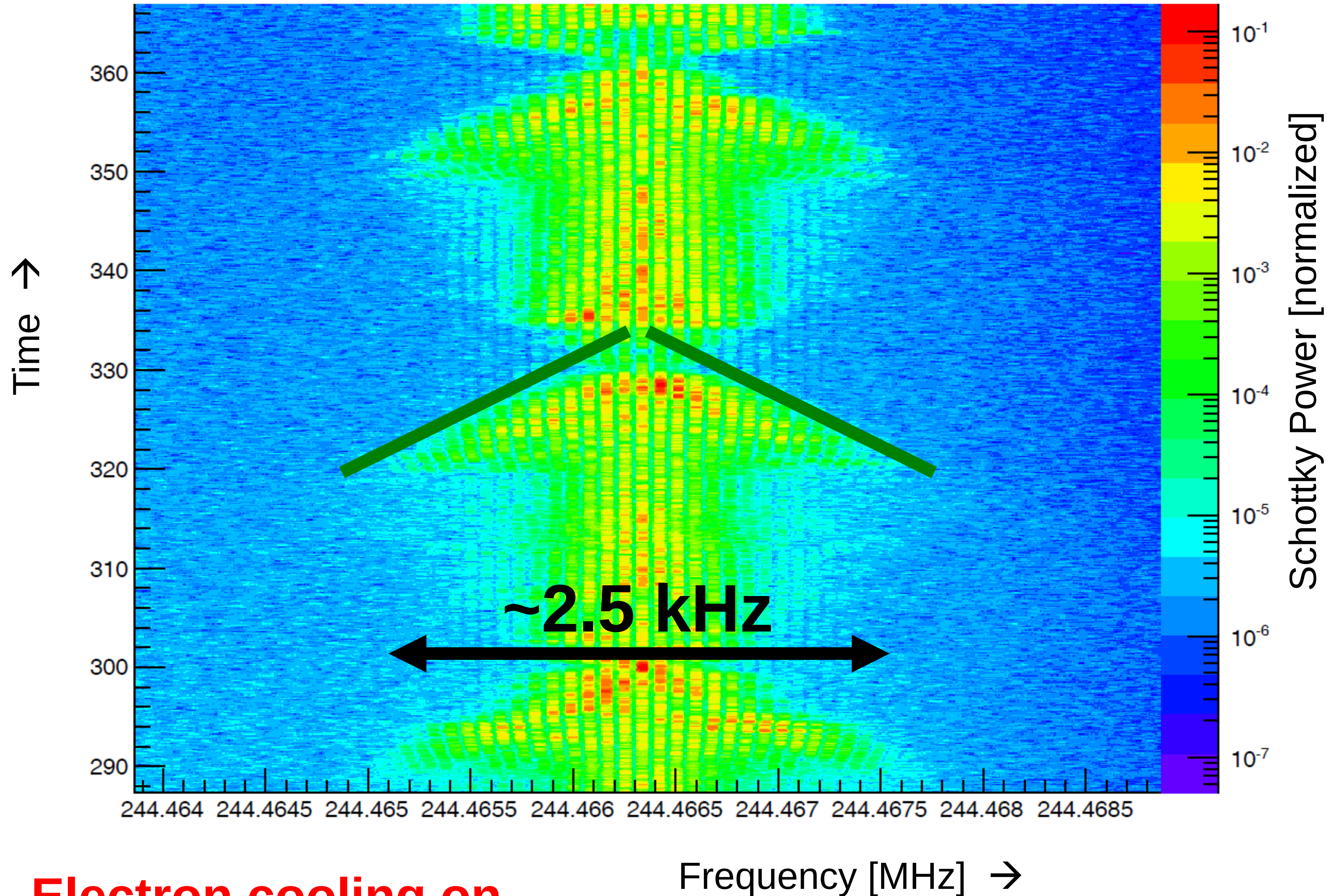


PANDA: antiprotons
SPARC: heavy HCI

x-ray laser spectroscopy (HESR up to γ=6): $2s_{1/2}$ → $2p_{3/2}$

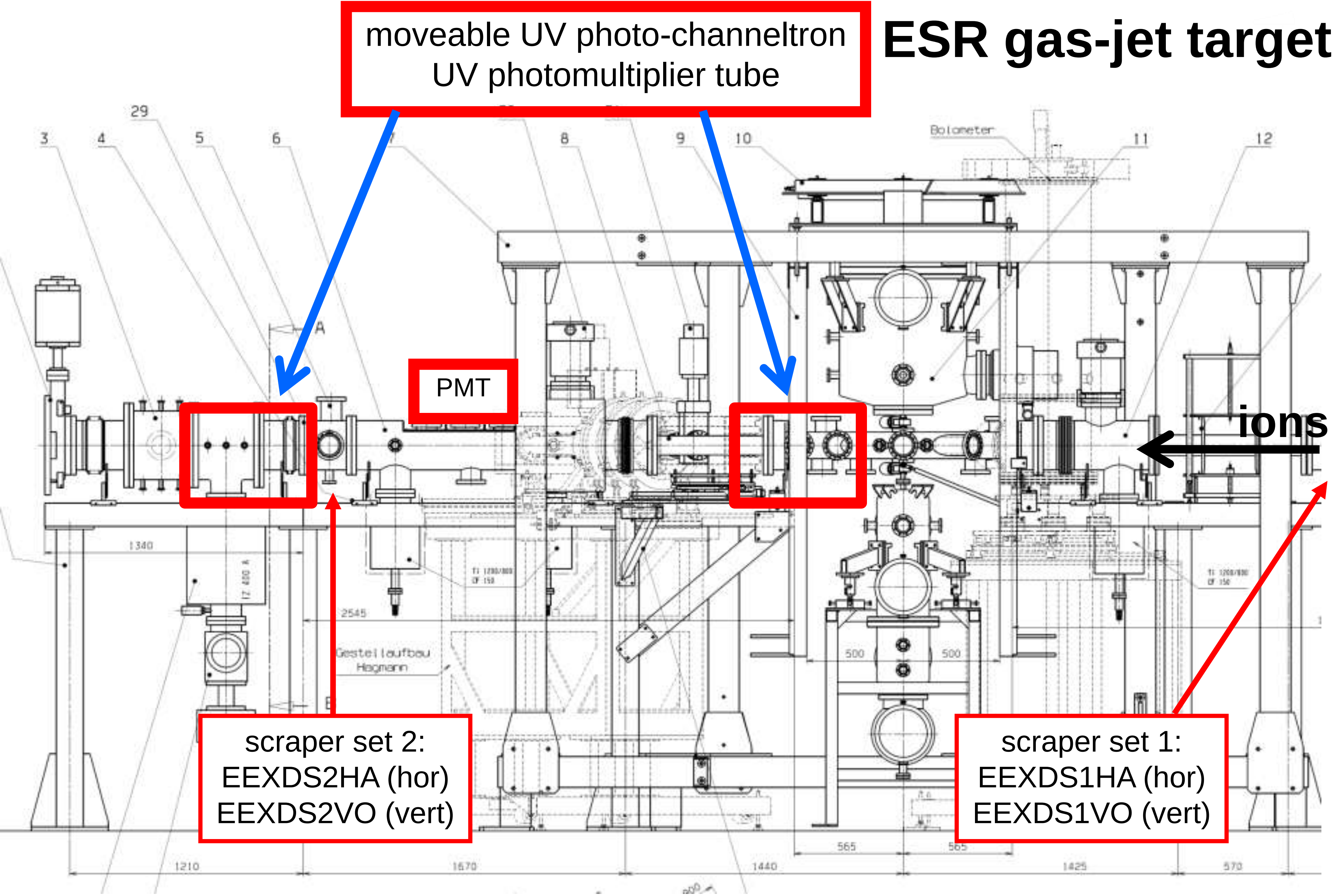
"OPERATION OF THE HESR STORAGE RING OF THE FAIR PROJECT WITH IONS AND RARE ISOTOPES", M. Steck et al. Proceedings of IPAC2012, New Orleans, Louisiana, USA

preliminary experimental results:



Electron cooling on
Bunching on

ESR gas-jet target

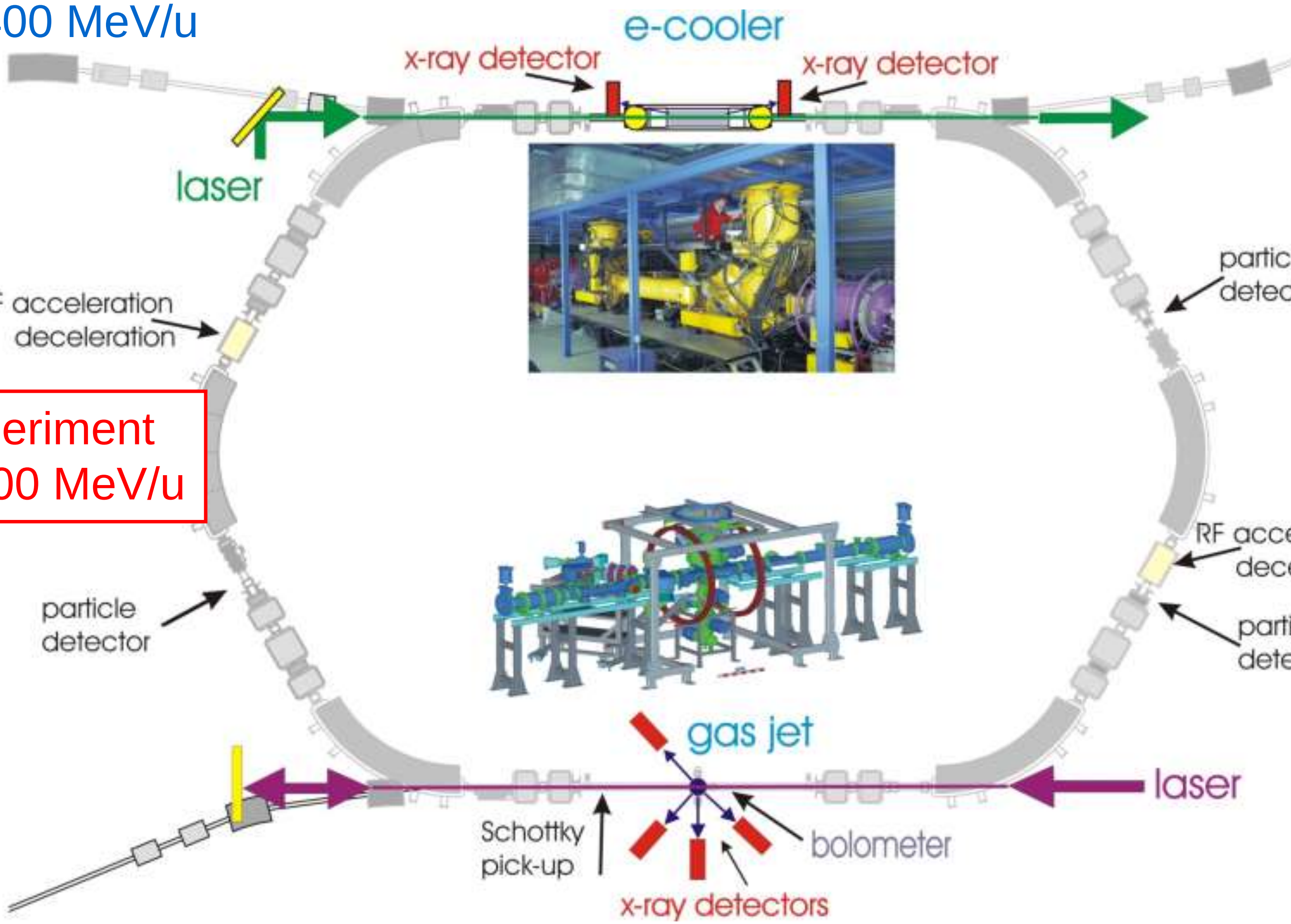


Spectroscopy at the ESR

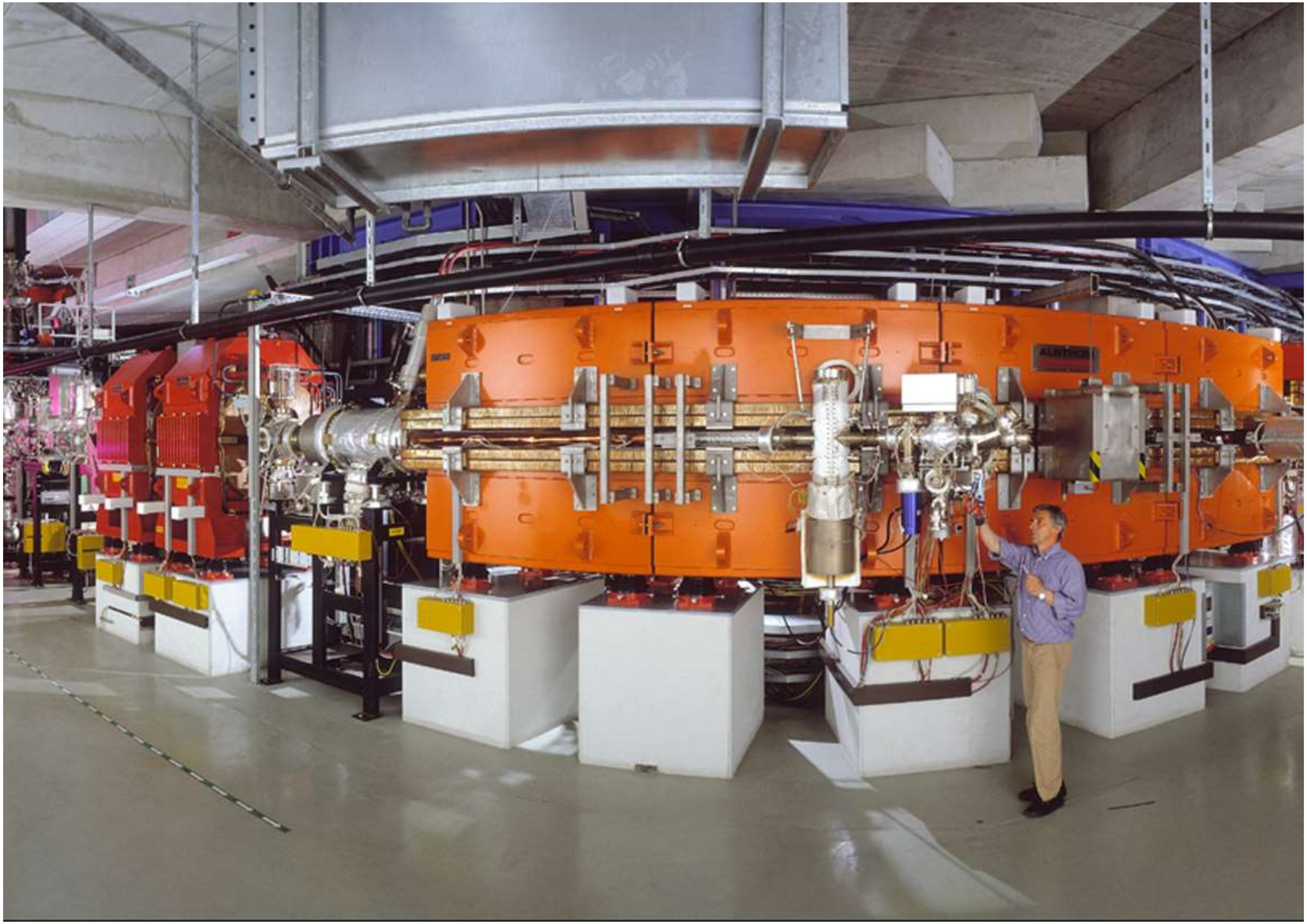
ca. 108 m

Injection Energy
400 MeV/u

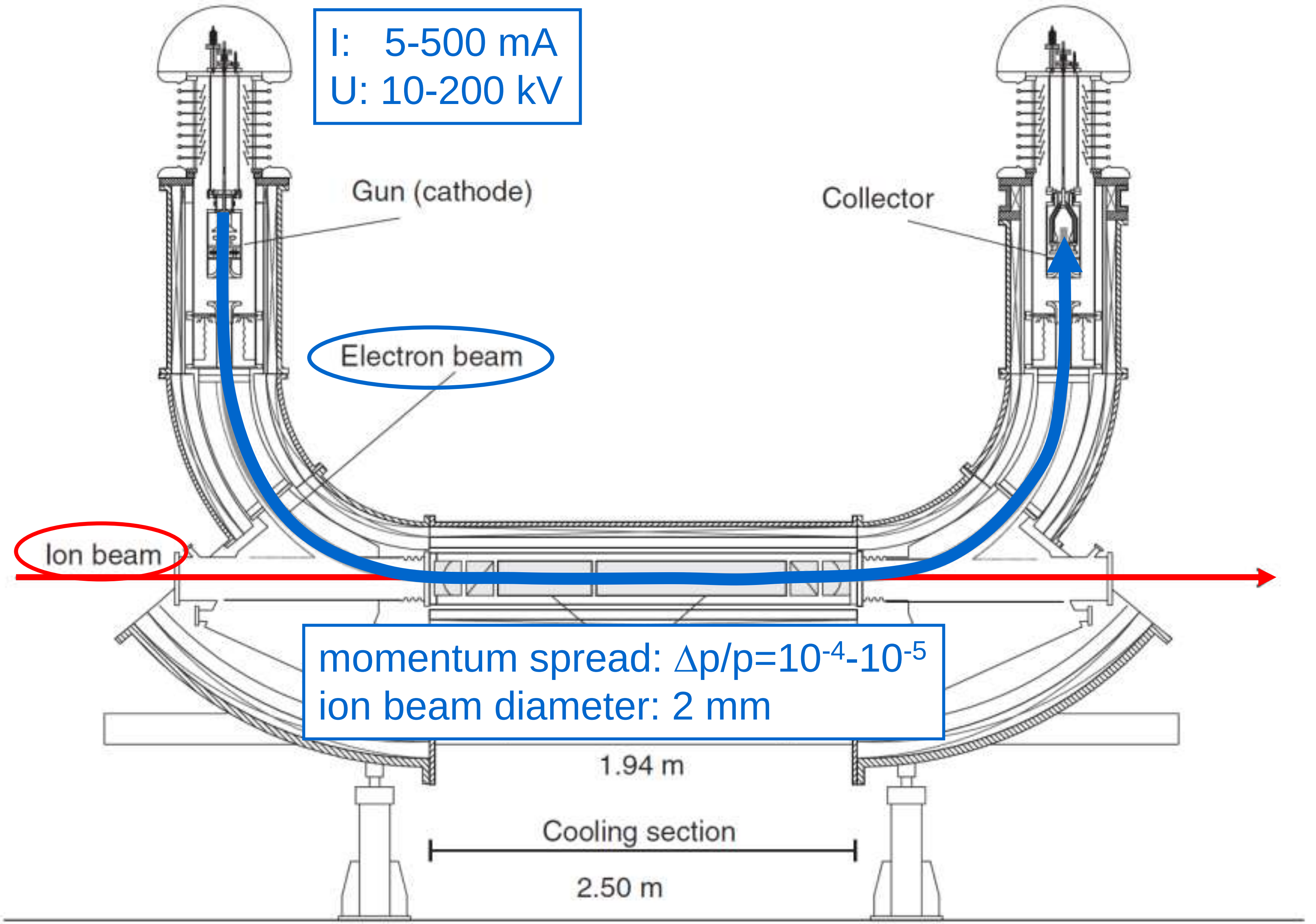
Experiment
4-400 MeV/u



Photograph of the ESR

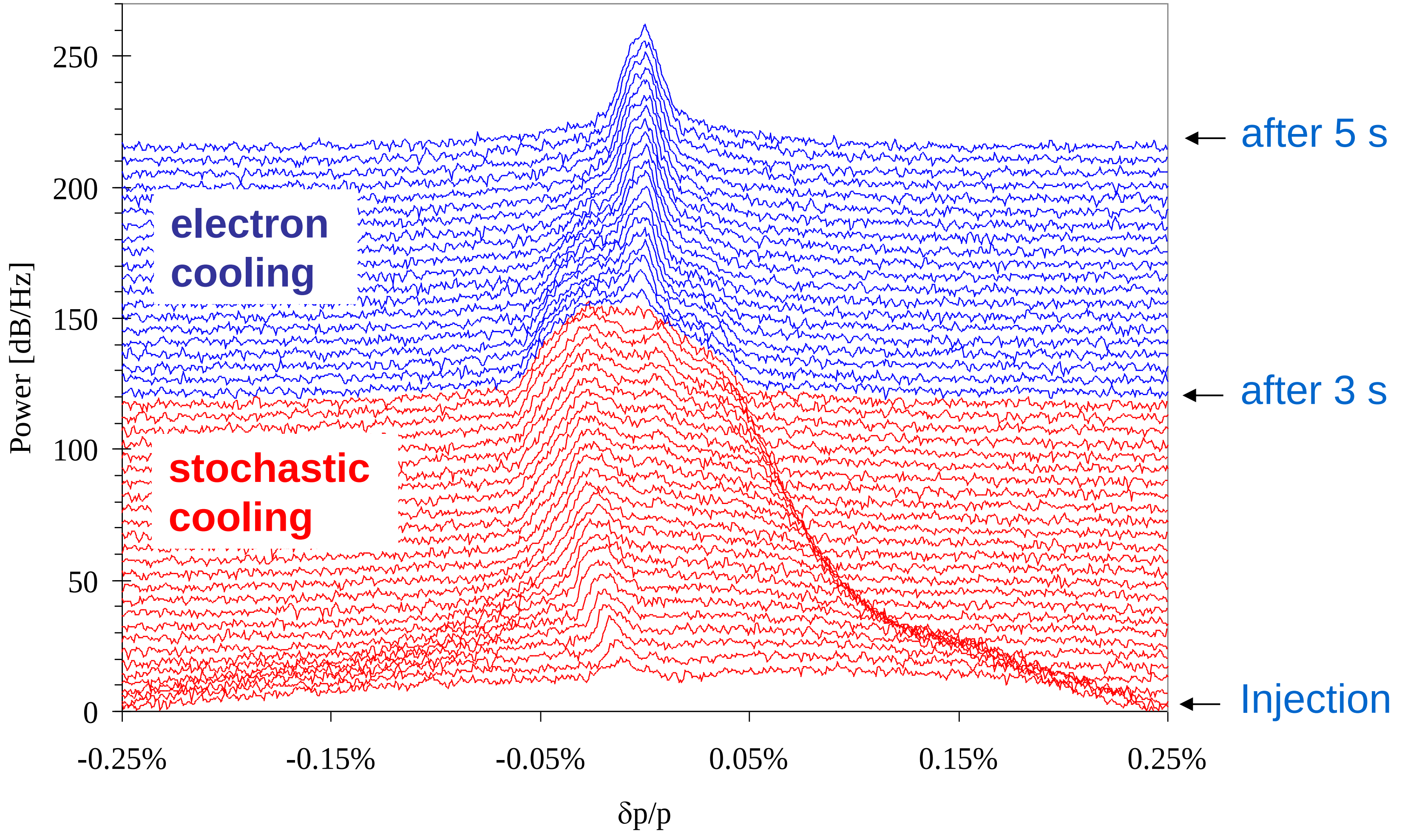


Electron cooler at the ESR



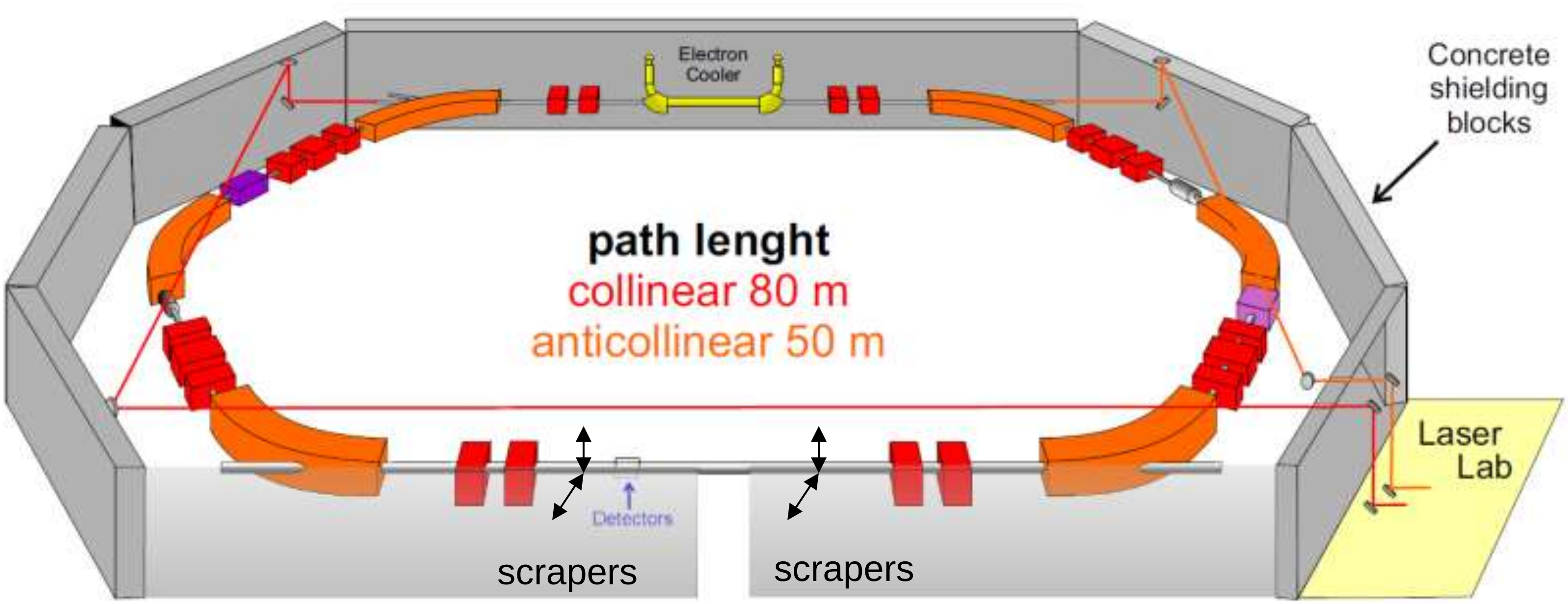
Cooling: narrowing velocity, size and divergence

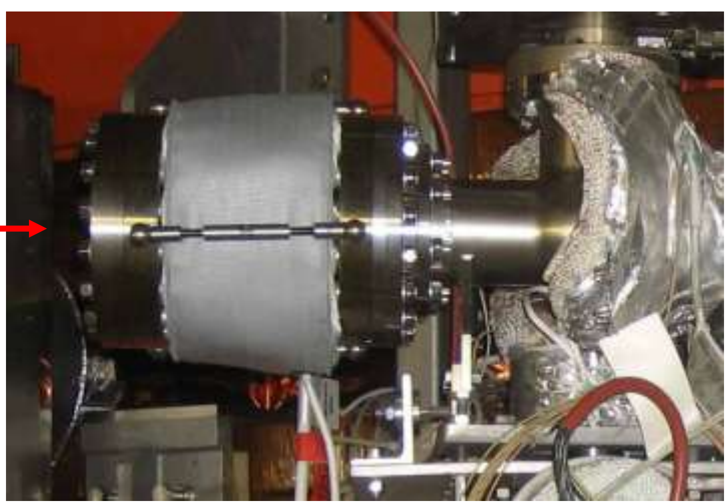
uranium ions stored in the ESR

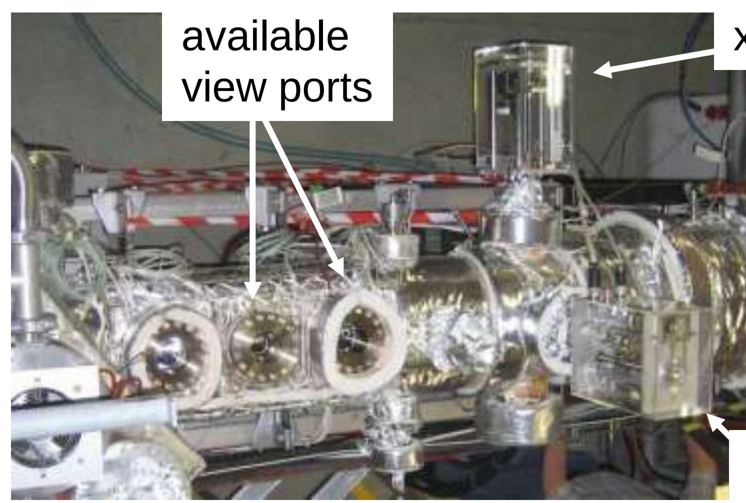


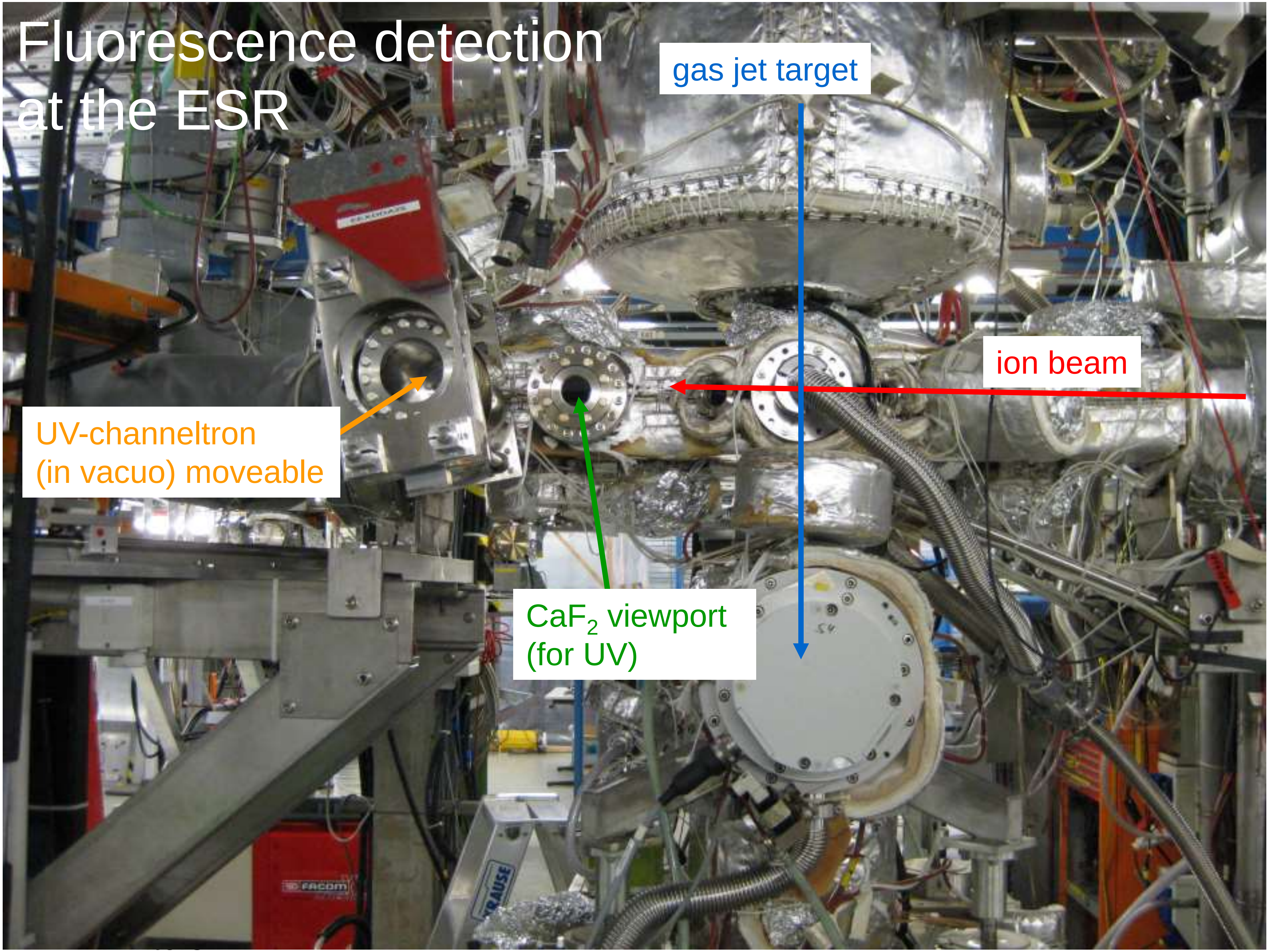
momentum distribution

Lasers at the ESR

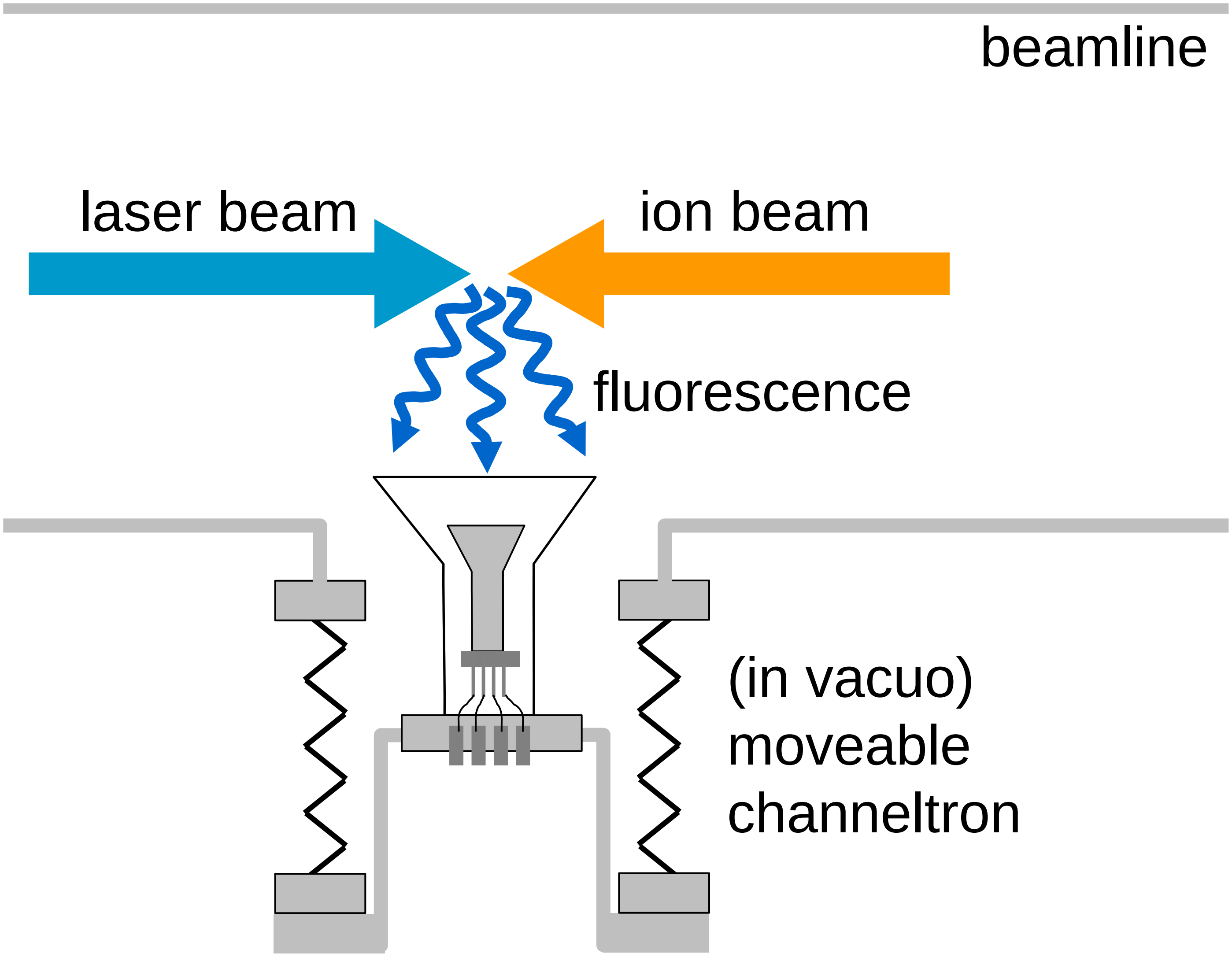






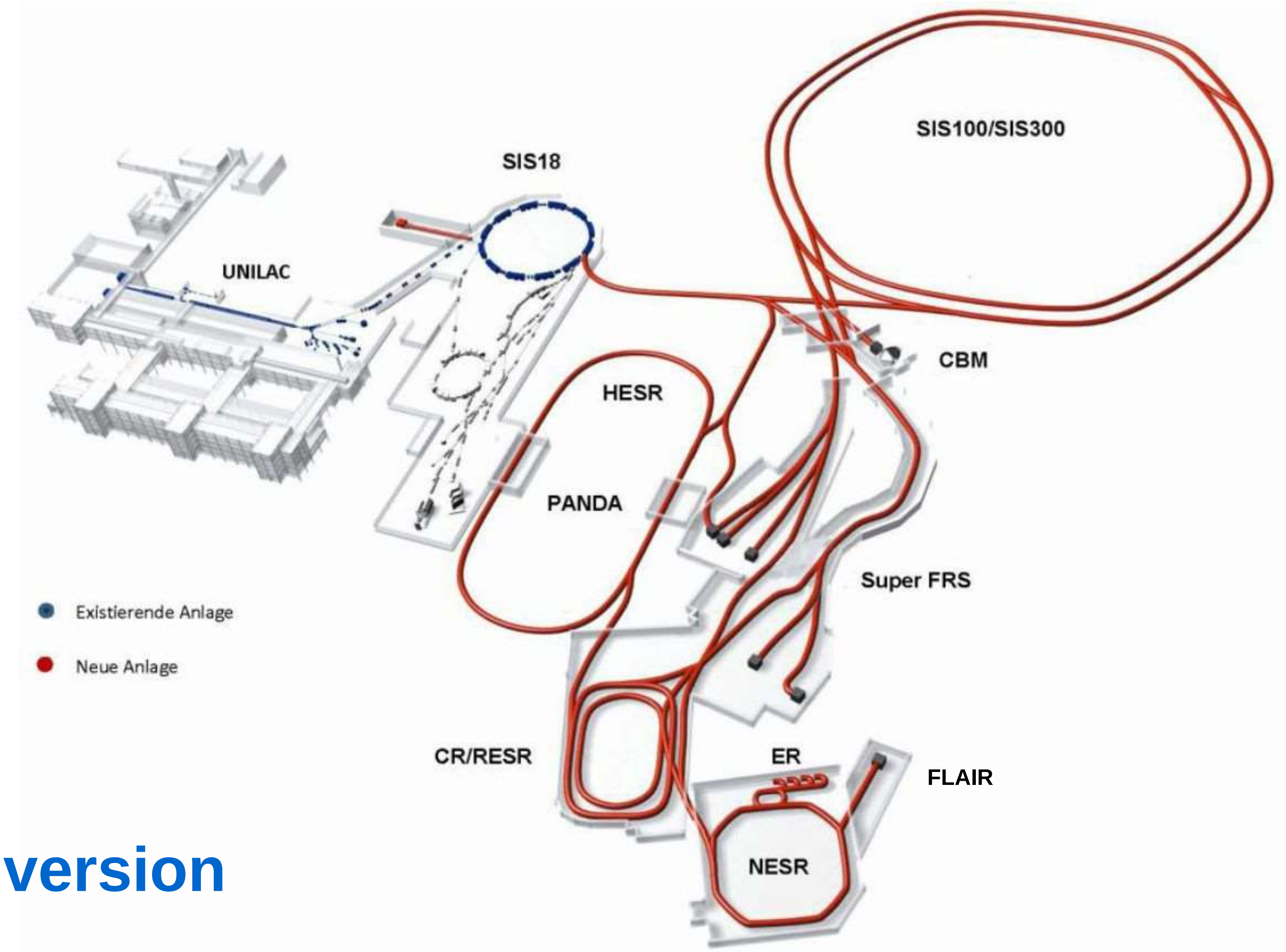

Fluorescence detection
at the ESR
gas jet target
ion beam
UV-channeltron
(in vacuo) moveable
CaF2 viewport
(for UV)

In-vacuo UV-sensitive (CsI coated) photo-channeltron



group of Prof. Gerhard Birkl (TU-Darmstadt)

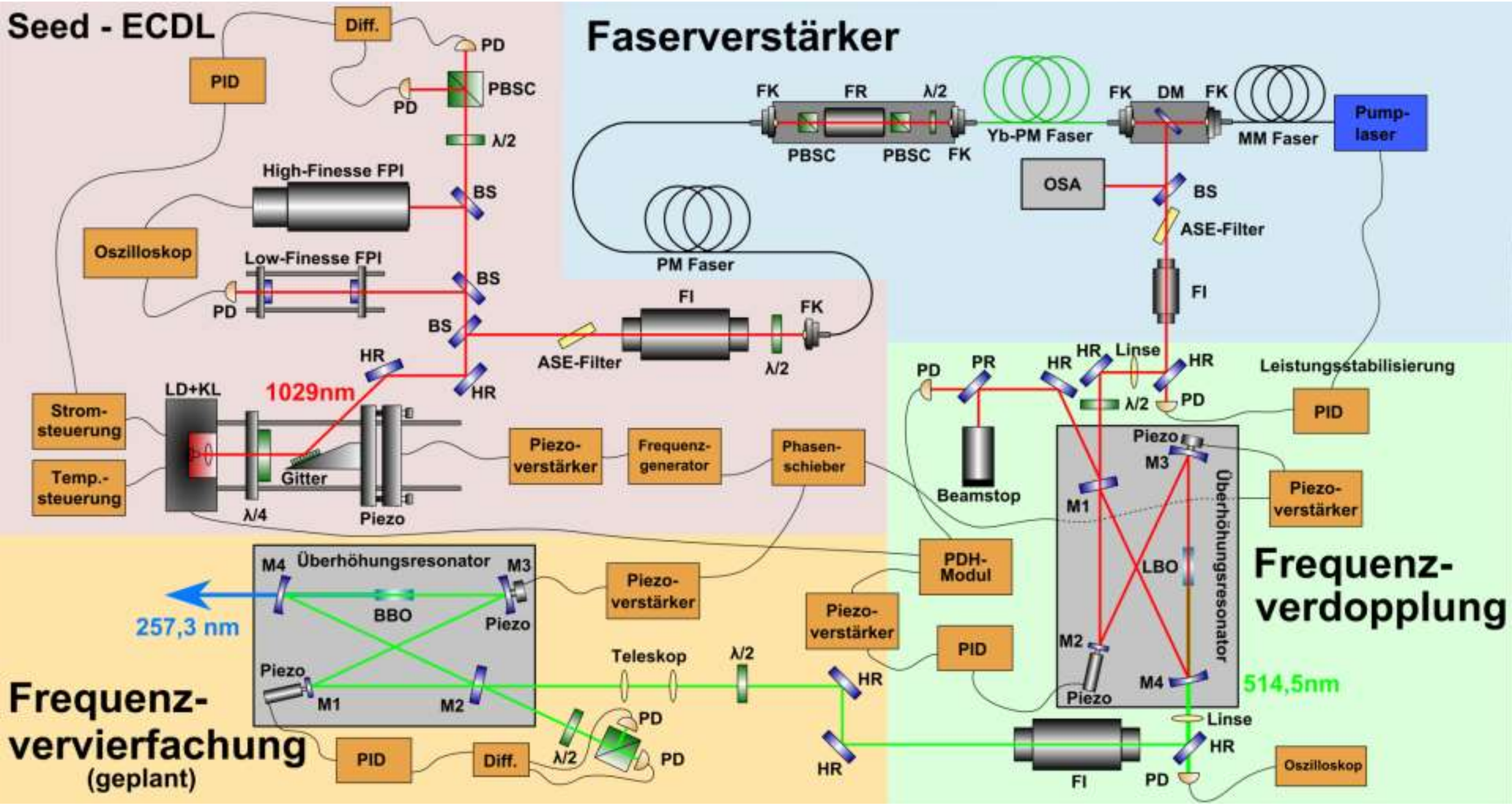
Facility for Antiproton and Ion Research (FAIR)



full version

ECDL scanning cw laser system

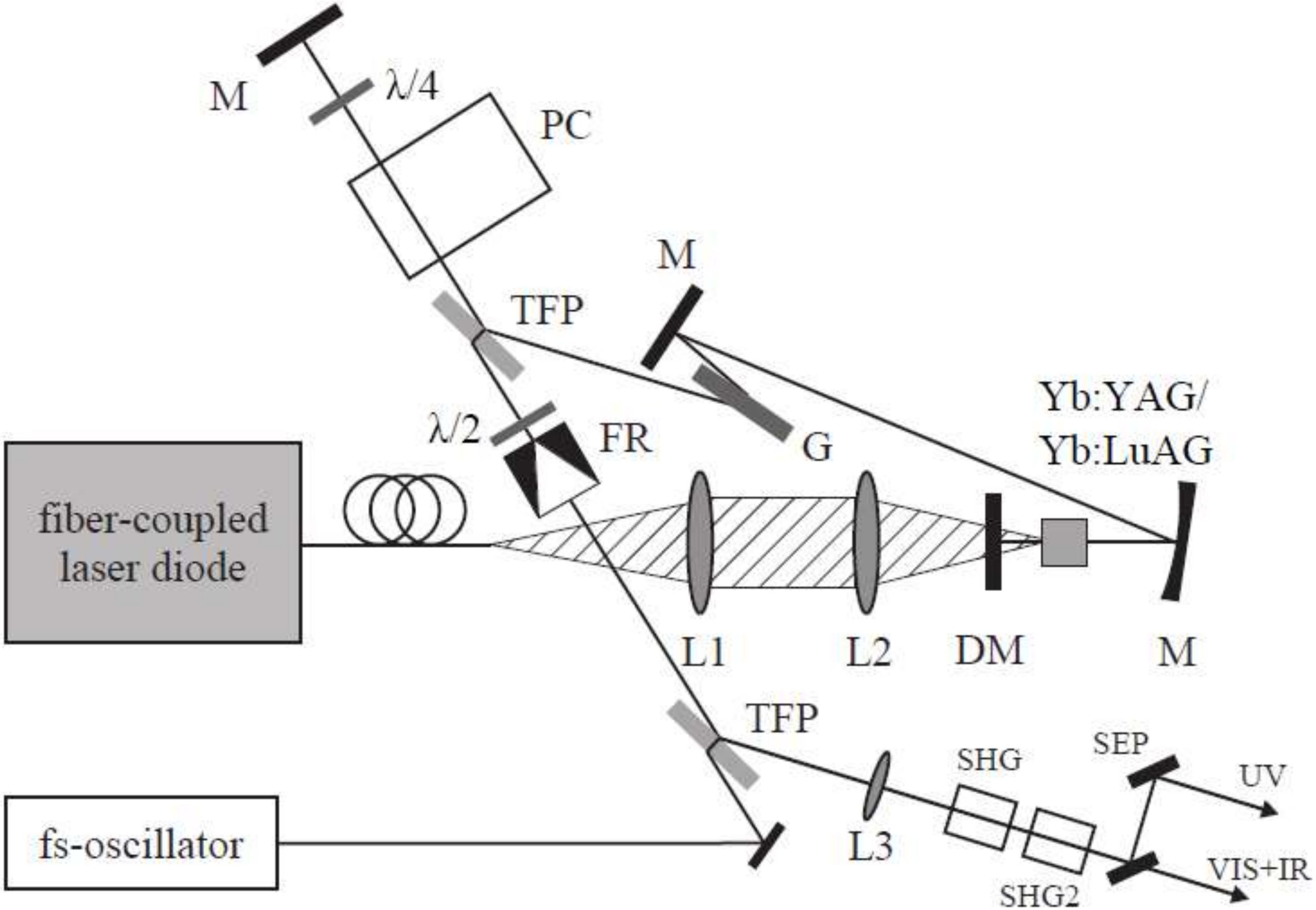
(20 GHz IR, 3 GHz needed)



Group of Prof. Thomas Walther (TU-Darmstadt)

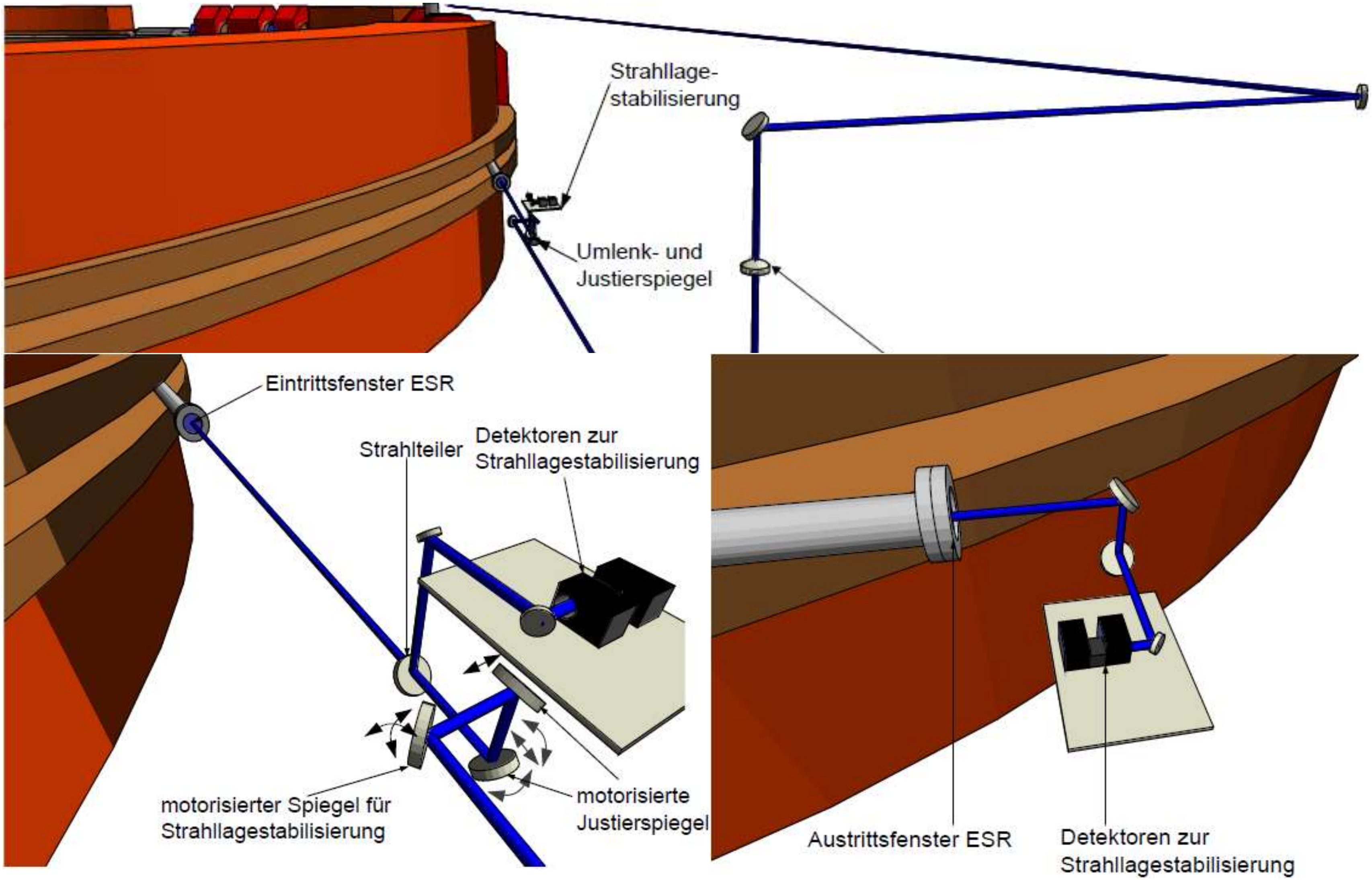
Pulsed laser system

frequency-selective intra-cavity grating

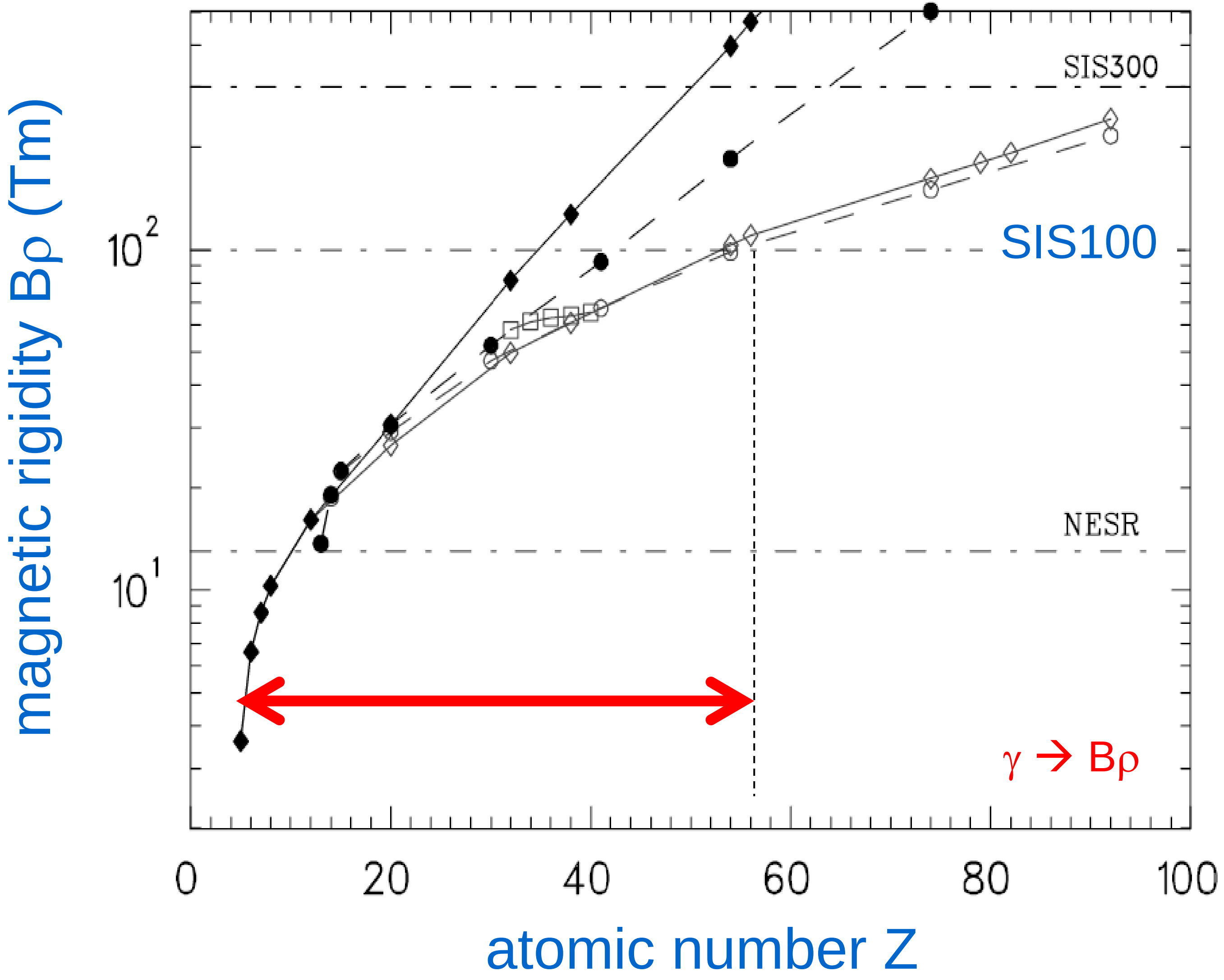


Group of Prof. Ulrich Schramm (HZDR, TU-Dresden)

Laser beam transport and stabilization



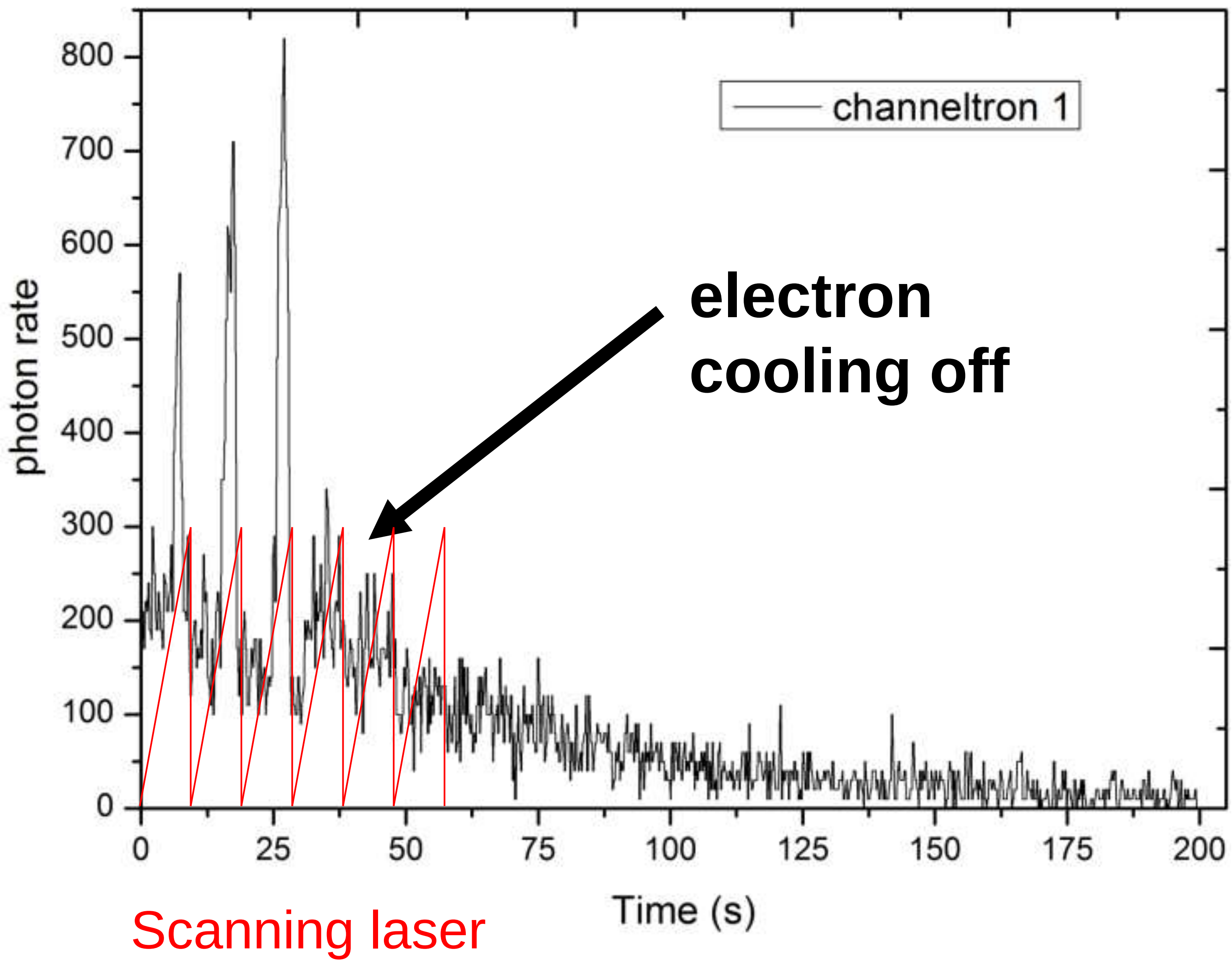
Group of Prof. Wilfried Nörtershäuser (TU-Darmstadt)



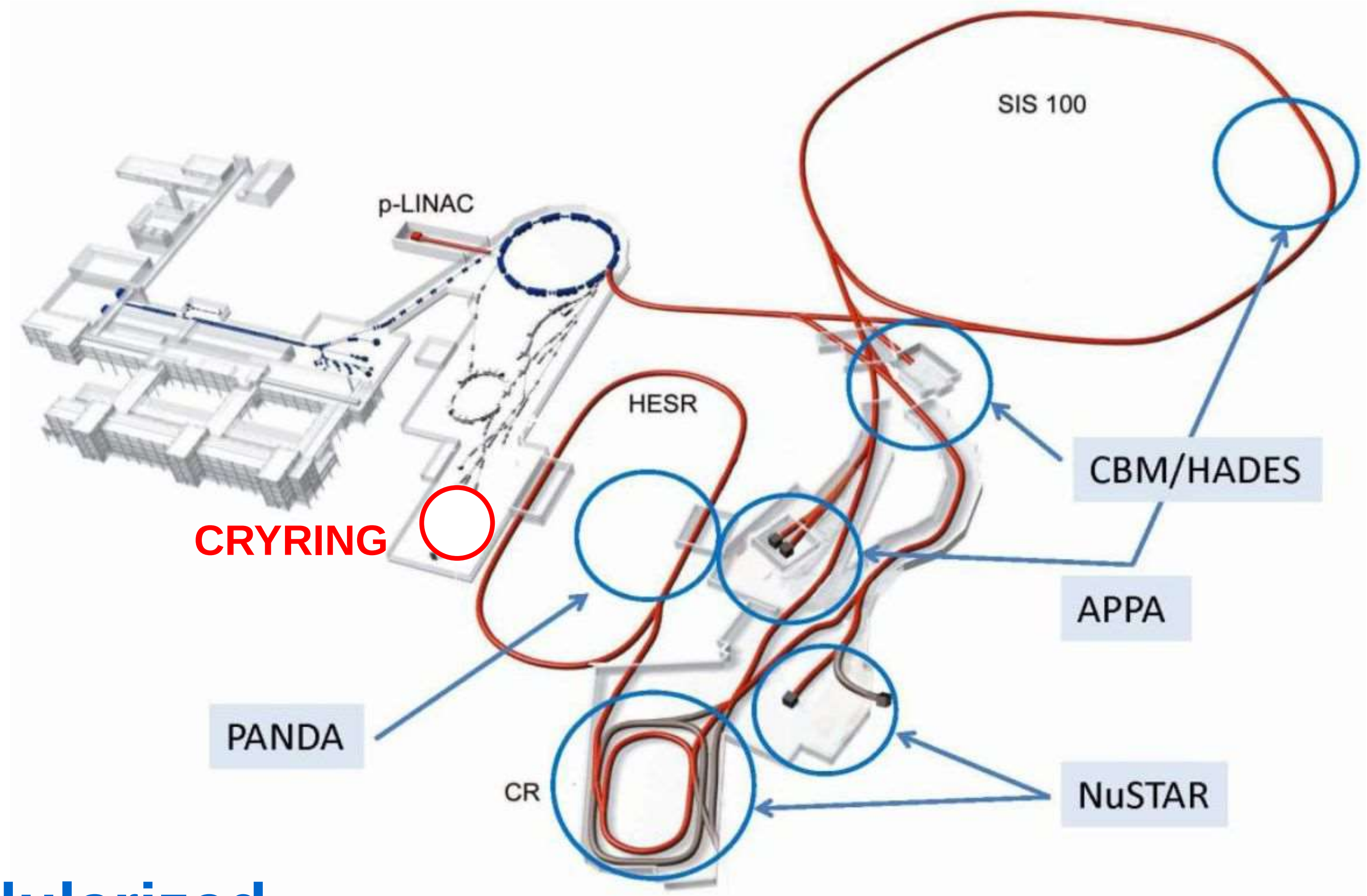
requirement: laser cooling needs fast transitions!

Li-like ions (3 e^-)
Na-like ions (4 e^-)

Fluorescence from the ions detected by the channeltron



Facility for Antiproton and Ion Research (FAIR)



modularized
start version