Broadband lasercooling of relativistic C^{3+} ions at the ESR

Danyal Winters[1], Colin Clark[1], Christina Dimopoulou[1], Tino Giacomini[1], Christophor Kozhuharov[1], Thomas Kühl[1,2,3], Yuri Litvinov[1], Matthias Lochmann[1,2], Wilfried Nörtershäuser[1,2,4], Fritz Nolden[1], Rodolfo Sanchez[1,2],Shahab Sanjari[1], Markus Steck[1], Thomas Stöhlker[1,3,5], Johannes Ullmann[1],

Tobias Beck[4], Gerhard Birkl[4], Benjamin Rein[4], Sascha Tichelmann[4], Thomas Walther[4],

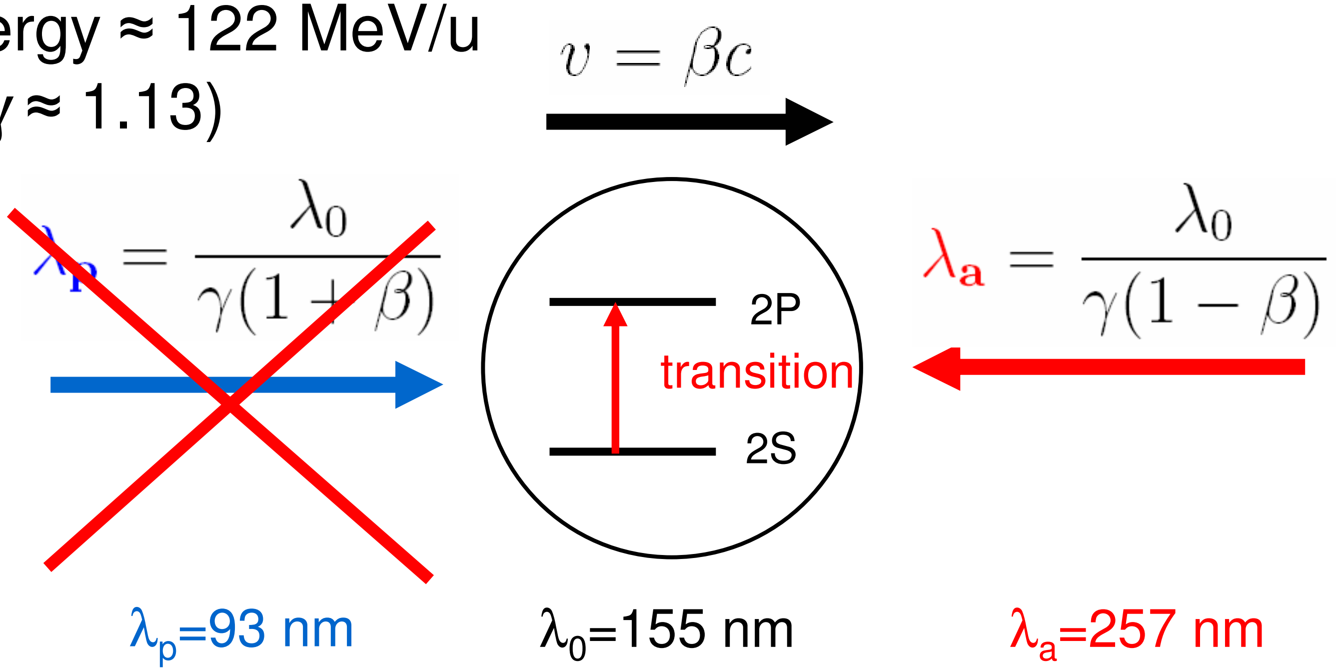
Xinwen Ma[6], Weiqiang Wen[6], Jie Yang[6], Dacheng Zhang[6],

Ulrich Schramm[7], Michael Seltmann[7], Mathias Siebold[7], Michael Bussmann[7]

[1]**GSI Darmstadt**, [2]Uni Mainz, [3]HI Jena, [4]TU Darmstadt, [5]Uni Jena
[6]IMP CAS Lanzhou, China, [7]HZDR Dresden

The principle: laser cooling of stored relativistic ions

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

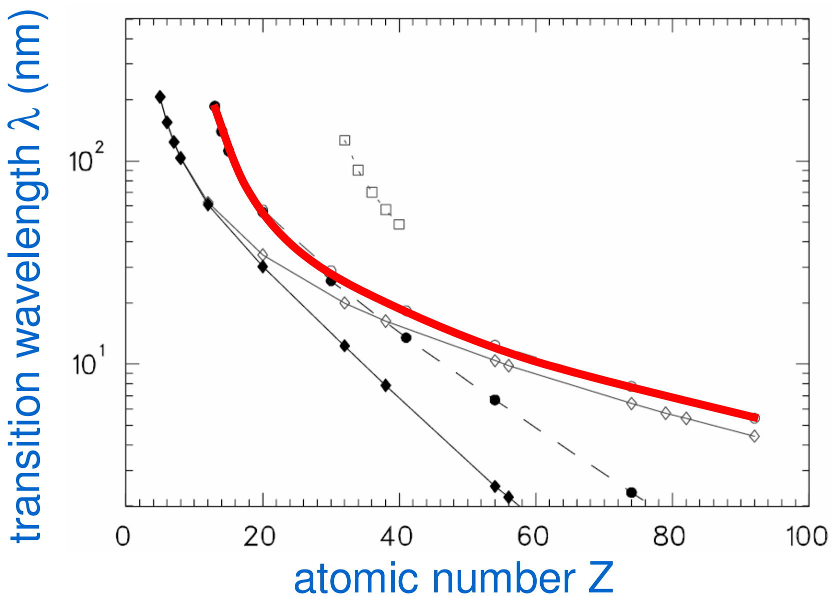


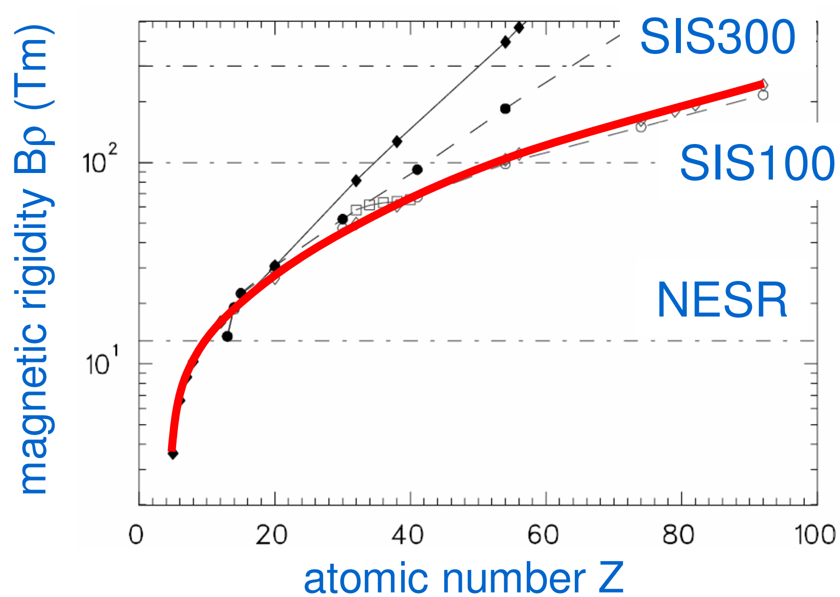
In our case, the cooling laser force is counteracted by the restoring force of the `*bucket*´ when **the ion beam is bunched**.

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 SIS300 shifts wavelengths to `normal´ lasers!





needs fast transition: $2S_{1/2} \rightarrow 2P_{1/2}$

$\gamma \rightarrow B\rho$

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

Laser cooling specifications

	PALLAS	TSR	ESR	SIS 300
Ion species	$^{24}Mg^{+}$	$^{9}Be^{+}$	$^{12}C^{3+}$	$^{238}U^{89+}$
Circumference (m)	0.36	55	108	1080
$\eta_{cooling}$ (%)	1	8	8	3
Periodicity	900	2 (4)	2	~60
Tune	~60	2.8	2.3	~15
γ (γ_{max})	1	1.001	1.13	30^{b} (35)
β	$\sim 10^{-5}$	0.041	0.47	0.9994
$\hbar\omega_{in}$ (eV)	4.4	4.0^{a}	4.8	4.8 (4.0)
$\hbar\omega_{0}$ (eV)	4.4	3.8	7.9*	280
$\hbar\omega_{out}(\Theta = 0^{\circ})$ (eV)	4.4		13.3	19 600
Lifetime τ_0 [ns]	3.7	8.3	3.8*	0.06
$I_{sat,0}$ (W/cm^2)	0.76	0.4	1.3	4×10^{6}
S	1–15	1–10	<10	<0.005
Cooling force $F_{max,out}$ (eV/m)	2.0	0.76	15	160^{c}
$\tau'_{cooling,out}$ [s]		0.001	0.002	1
$\tau_{cooling,out}$ [s]		0.01–0.1	0.02–0.2	10–100
Relative width (Γ_0/ω_0) [10^{-8}]	4	2	2	4
$\Delta p/p$ from Γ_0/ω_0 [10^{-7}]		5	0.4	0.4
$T_{Doppler,out} = \hbar\Gamma_{out}/(2k)$ (K)	0.001	0.0005	0.001	1.9
$E_{Coulomb}$ (10 μm) (K)			15	13 000
$\Delta p/p$ ($N = 10^8$, equilibrium)			ecool: $<10^{-5}$ laser: $<10^{-6}$	— $\approx 5 \times 10^{-5}$

Results of previous beamtimes

Laser cooling of C^{3+} at 122 MeV/u in the ESR
in 2004 and 2006

2004: "simple" laser system for first tests
on the 2s → 2p transition @ ~155 nm

2006: scanning laser system to improve the
cooling scheme

measurement of $2S_{1/2} \rightarrow 2P_{1/2\ \&\ 3/2}$

Uncertainty in
absolute ion energy

Schramm, Bussmann et al.	● $(2S_{1/2} \rightarrow 2P_{1/2})$ [nm]	● $(2S_{1/2} \rightarrow 2P_{3/2})$ [nm]
ESR C^{3+} experiment	**155.0705 (39) (3)**	**154.8127 (39) (2)**
Theory (I. Tupitsyn, V. Shabaev)	**155.0739 (26)**	**154.8173 (53)**

Experiment motivation

- Laser cooling is a great cooling method for heavy ions with relativistic velocities
- Precision spectroscopy of Li-like ions (Na-like)
- Laser cooling without pre-electron cooling
- Fluorescence detection with PMT and Channeltron
- All-optical detection of the momentum spread ($\Delta p/p<10^{-7}$) of the ion beam
- Study ordering of the ions in the beam at very low momentum spread

Limitations of previous beamtimes (2004 and 2006)

- initial electron cooling was required
- laser force → small momentum spread
- bucket frequency was scanned, not the laser
- Schottky detection is limited in sensitivity
- fluorescence photons are difficult to detect

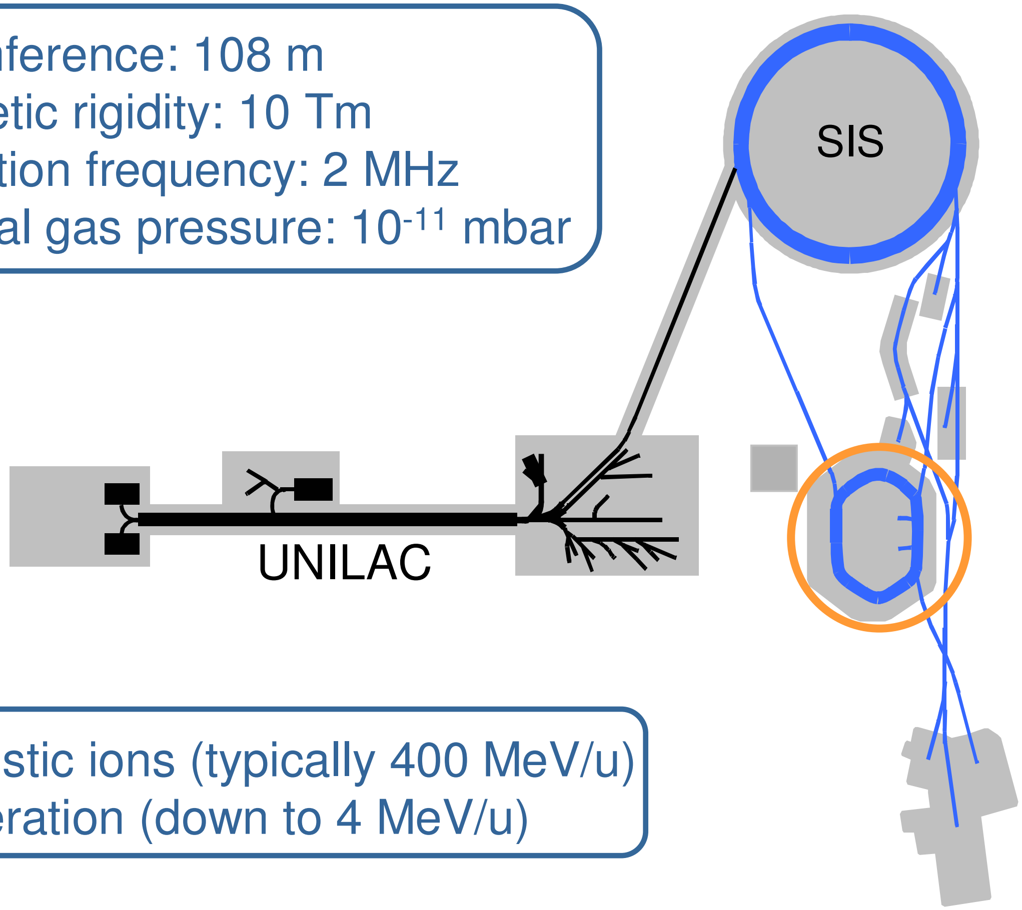
What's new?

- fast scanning CW diode laser (TU Darmstadt)
- Schottky resonator
- ionization profile monitor
- fluorescence detection system with UV PMT and UV channeltron (in vacuo)
- data acquisition and control system

The experimental storage ring at GSI

circumference: 108 m
magnetic rigidity: 10 Tm
revolution frequency: 2 MHz
residual gas pressure: 10^{-11} mbar

ion sources



ESR

relativistic ions (typically 400 MeV/u)
deceleration (down to 4 MeV/u)

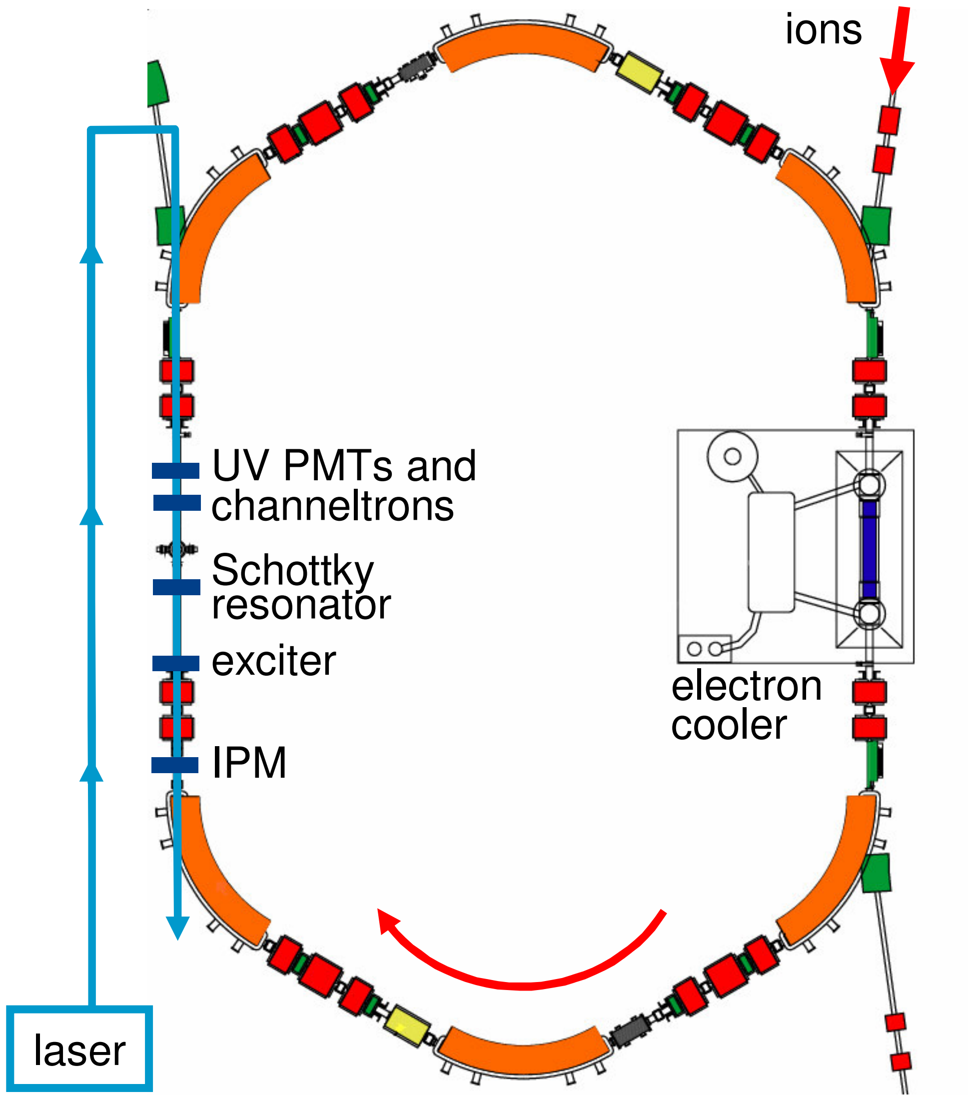
Experiment improvements

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

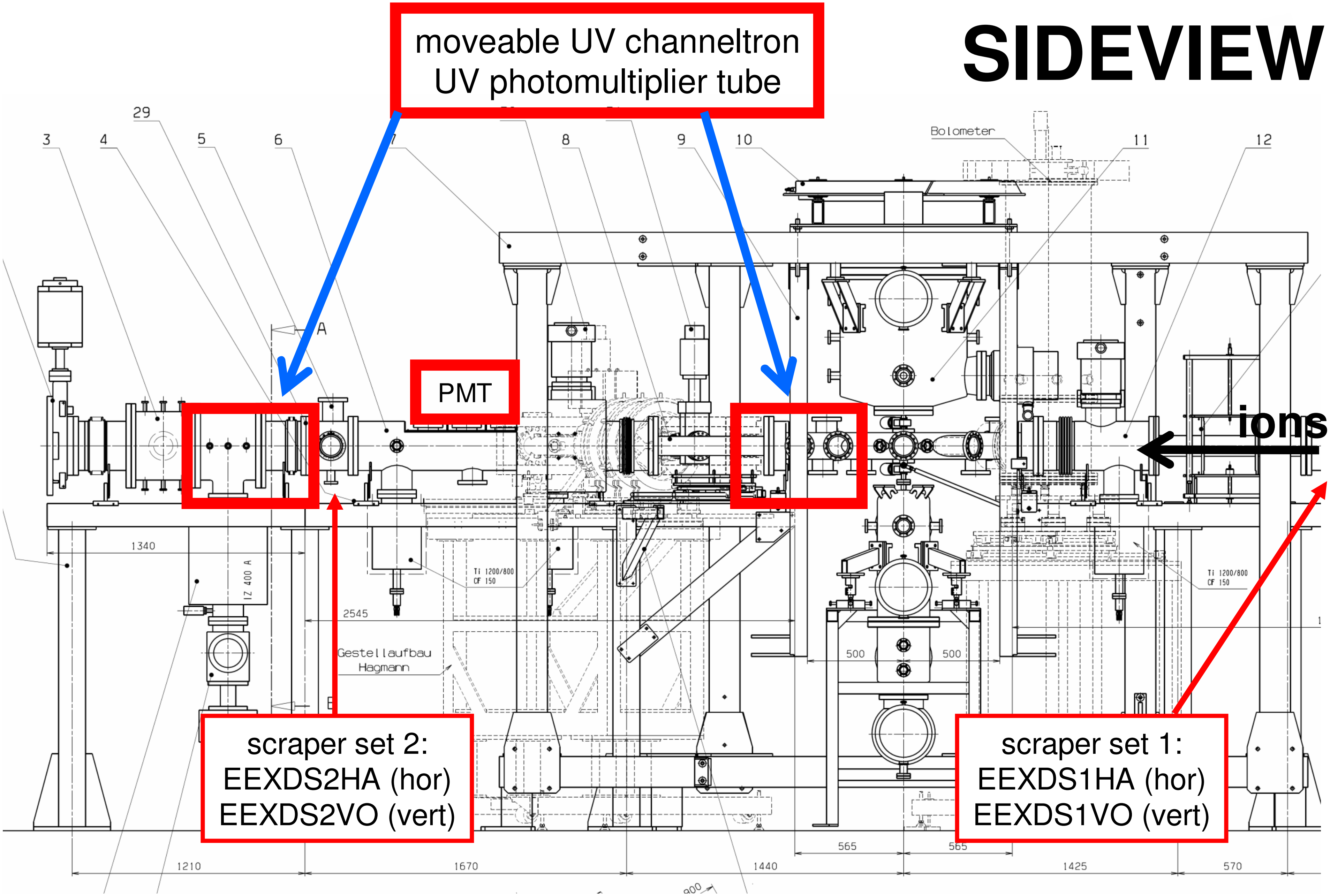
E_{kin} = 122 MeV/u
= 1.47 GeV
(β = 0.47, γ = 1.13)
f_{rev} = 1.295 MHz
τ_{beam} ~ 400 s

λ_{laser} = 257 nm

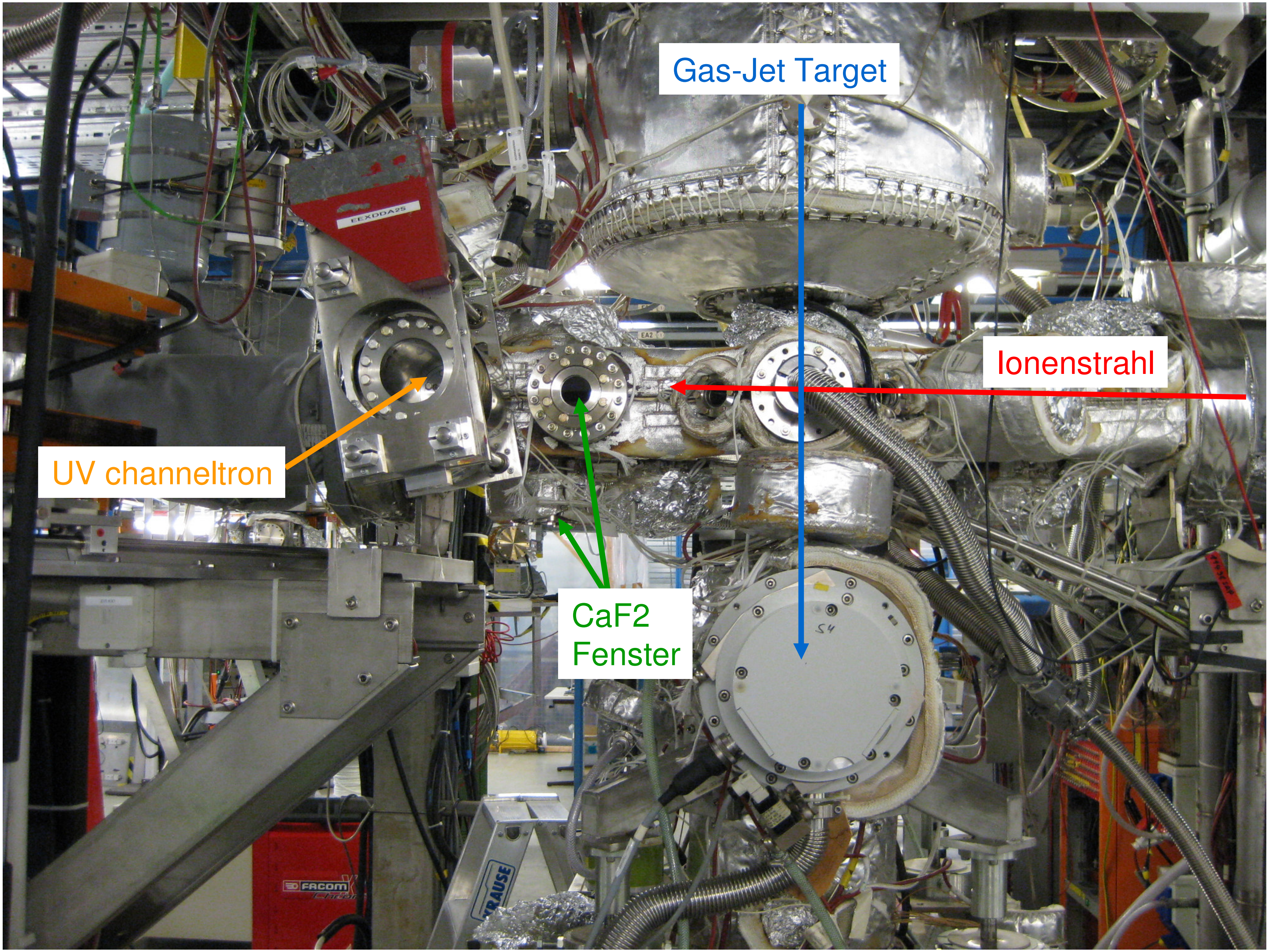
$2S_{1/2} \rightarrow 2P_{1/2}$
λ_{rest} = 155 nm
τ_{rest} = 3.8 ns



SIDEVIEW

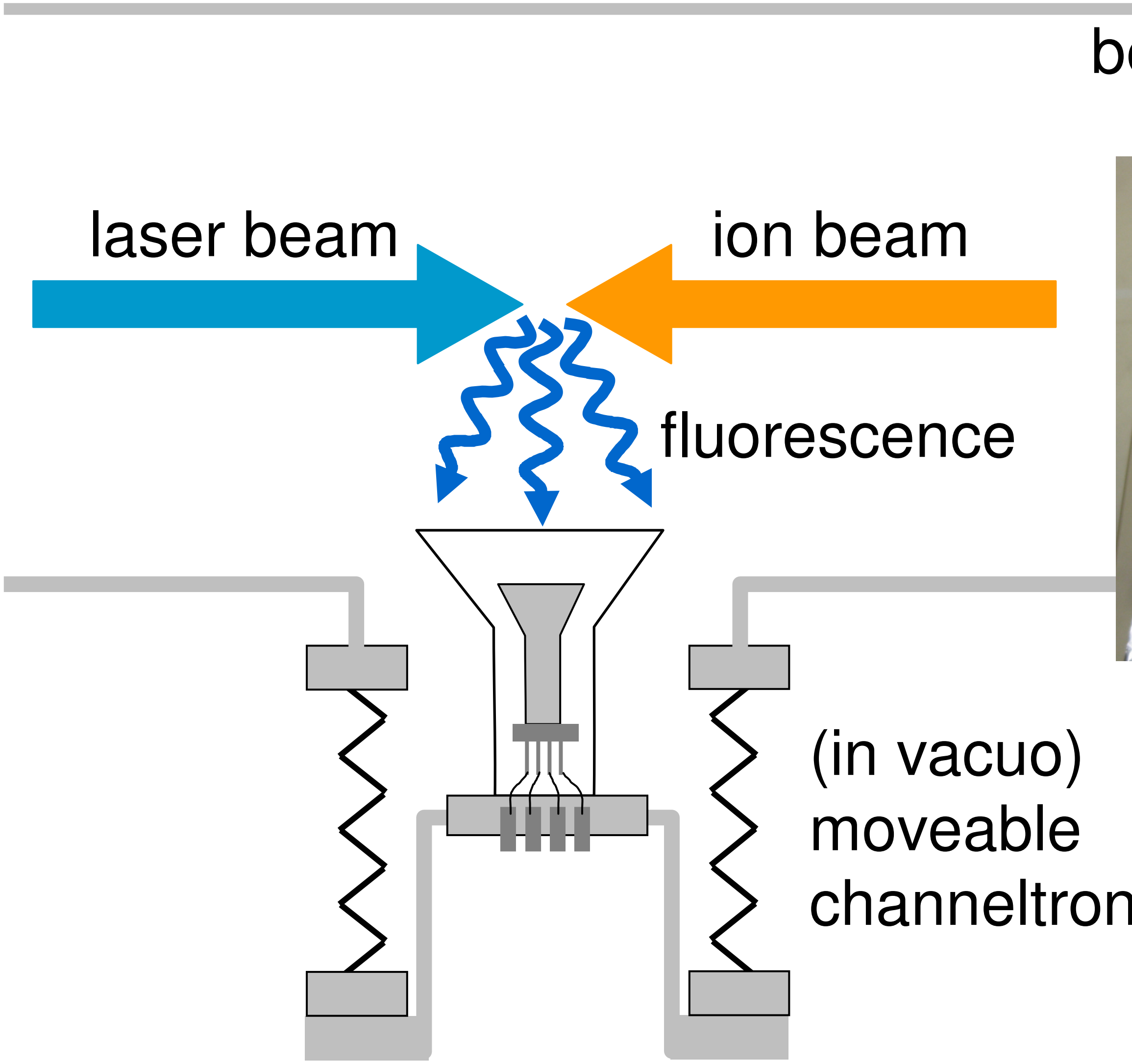


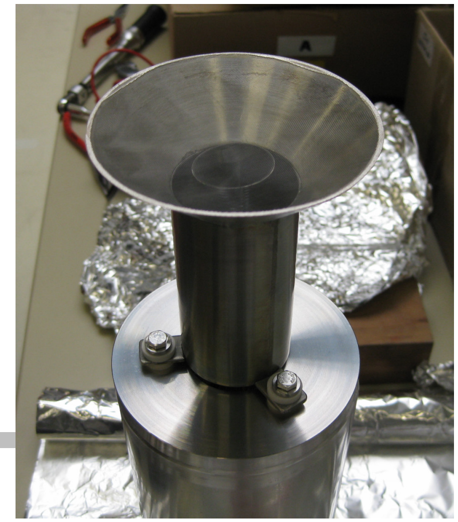
moveable UV channeltron
UV photomultiplier tube
PMT
ions
scraper set 2:
EEXDS2HA (hor)
EEXDS2VO (vert)
scraper set 1:
EEXDS1HA (hor)
EEXDS1VO (vert)
Bolometer
Gestellaufbau
Hagmann
3
4
29
5
6
7
8
9
10
11
12
1340
2545
500
500
565
565
1210
1670
1440
1425
570



Gas-Jet Target
Ionenstrahl
UV channeltron
CaF2
Fenster

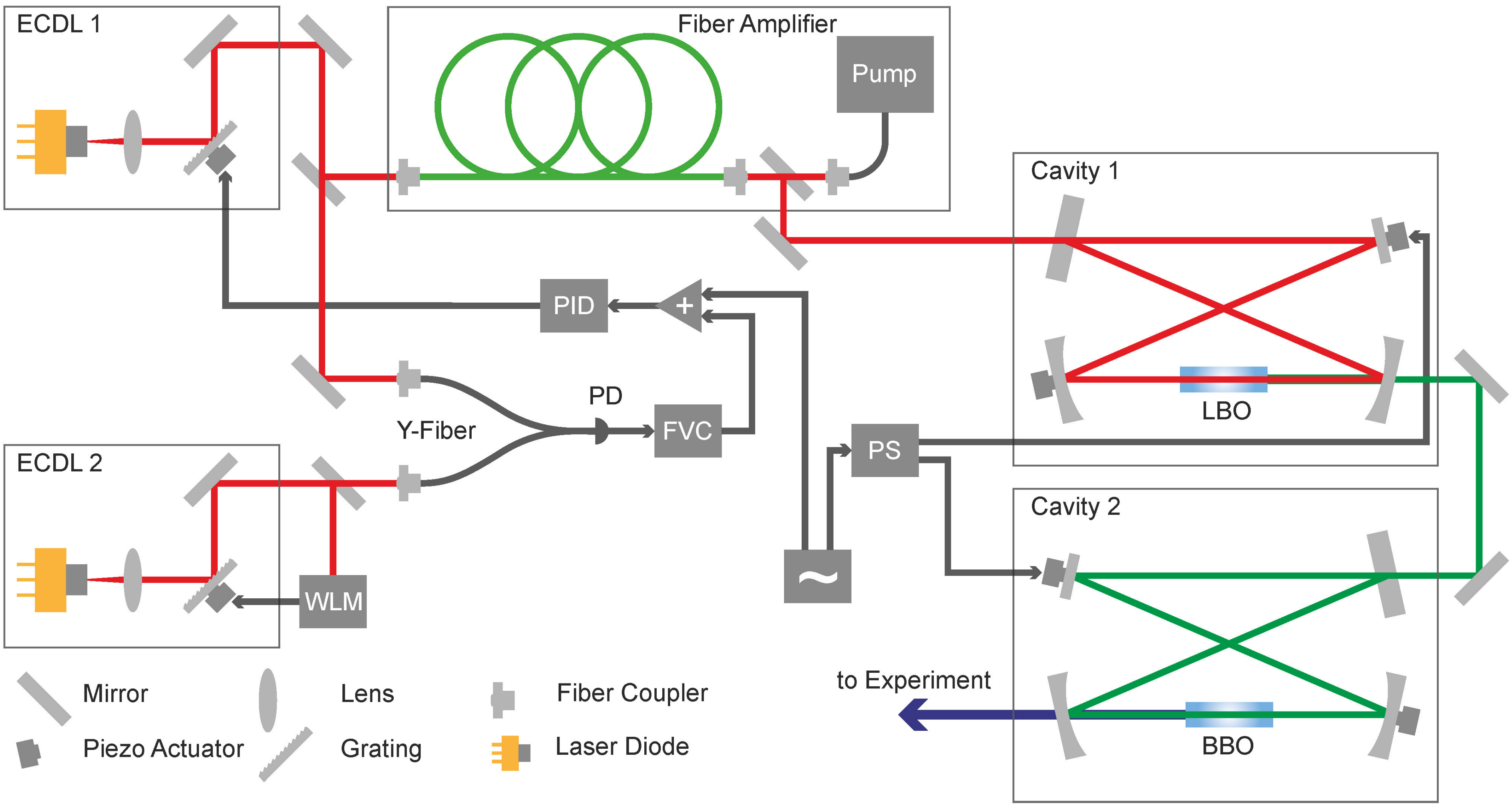
In-vacuo UV-sensitive (CsI coated) channeltron





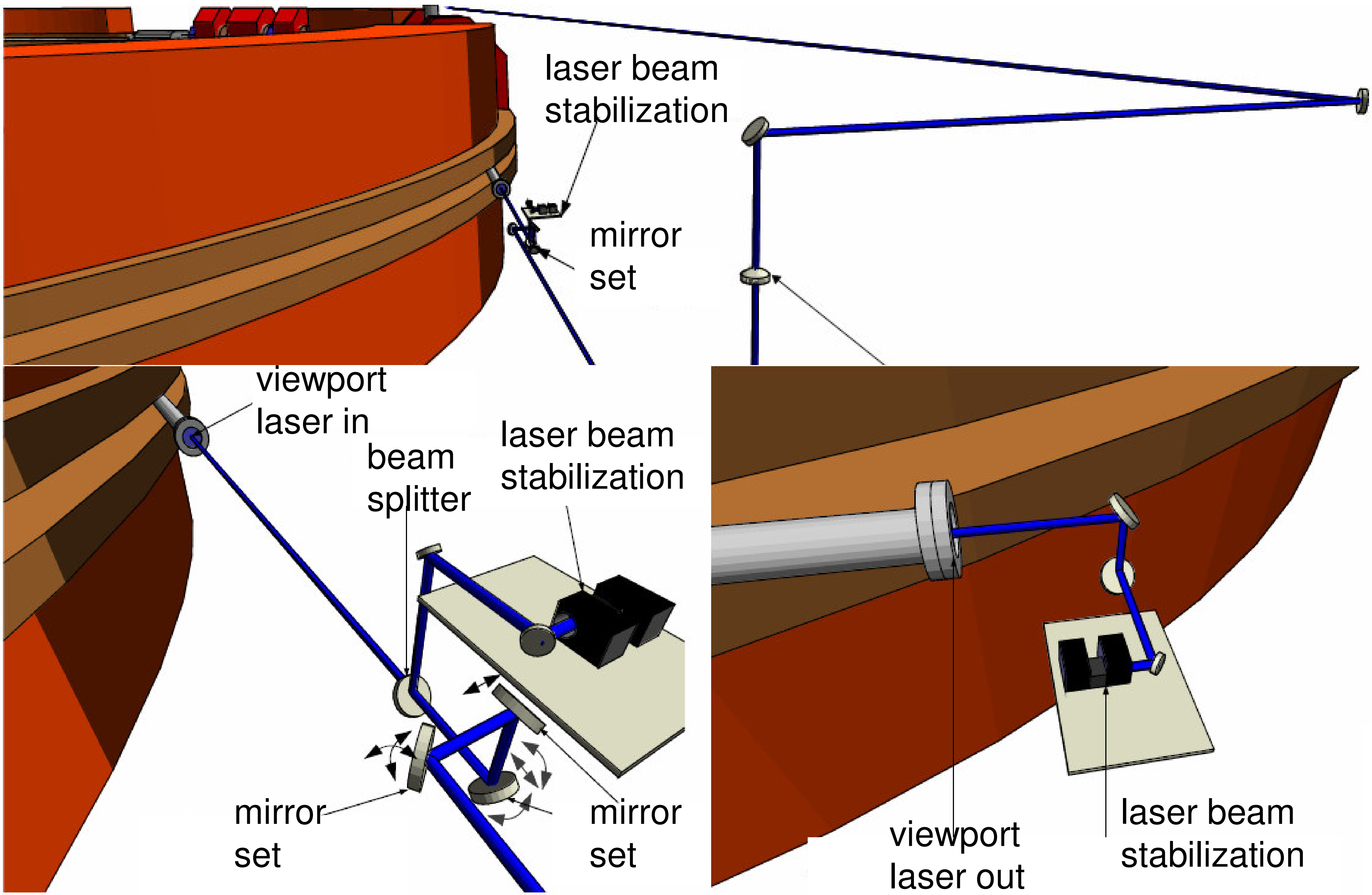
→ BMBF Funding: Gerhard Birkl (TU Darmstadt)

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



→BMBF funding: Thomas Walther, Tobias Beck (TU Darmstadt)

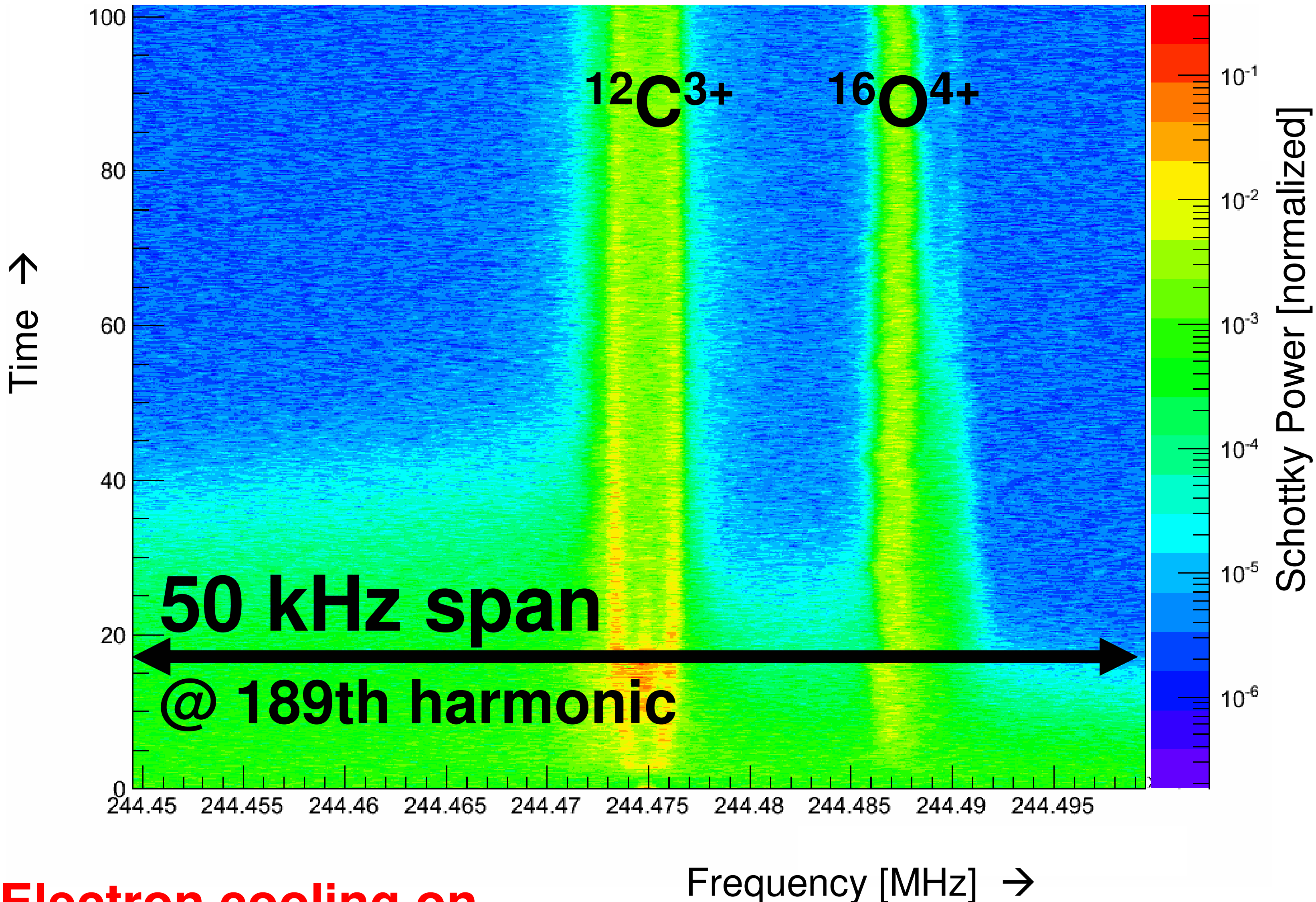
Laser beam transport and stabilization



Wilfried Nörtershäuser, Johannes Ullmann (TU Darmstadt)

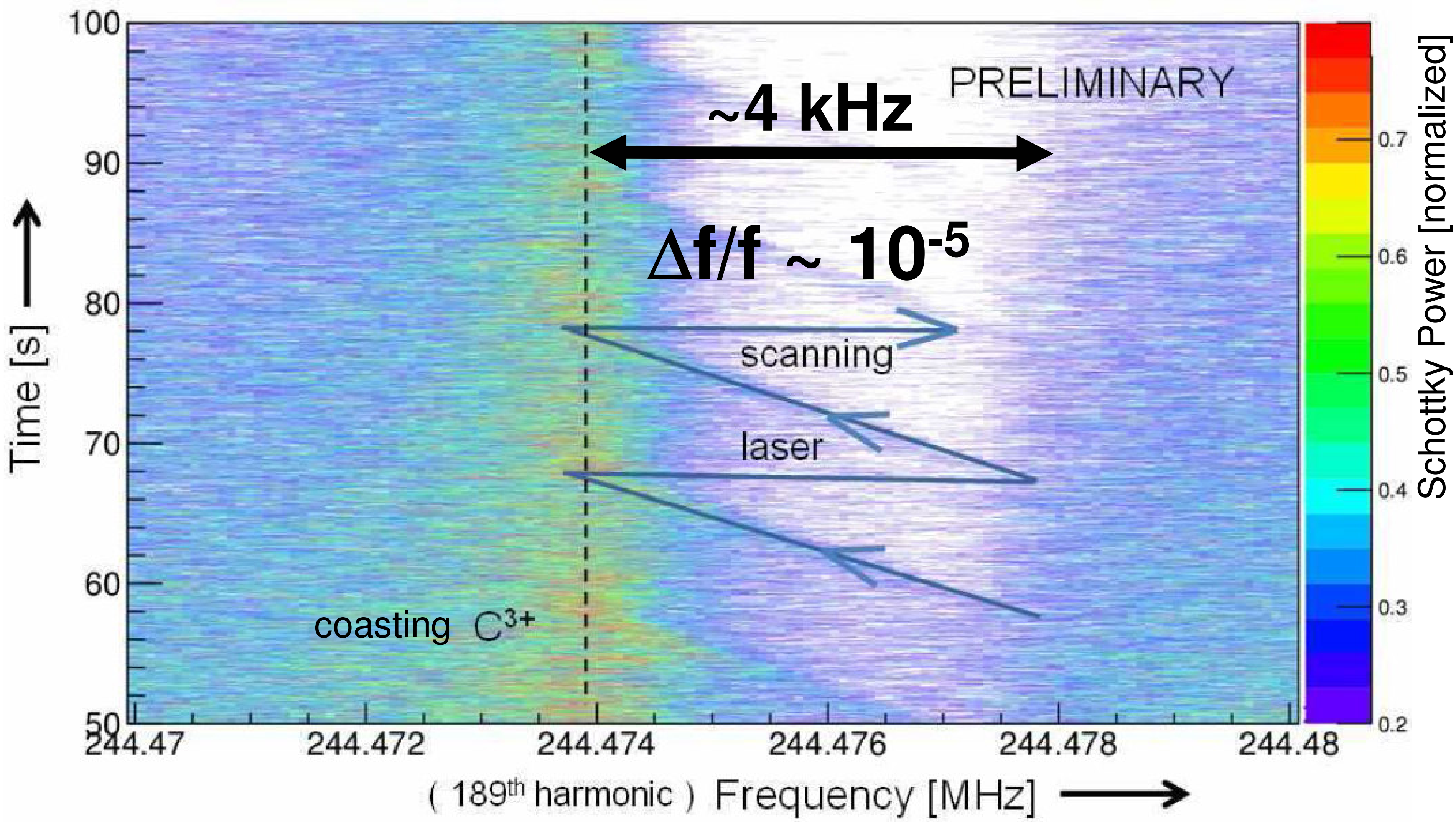
Preliminary Results

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



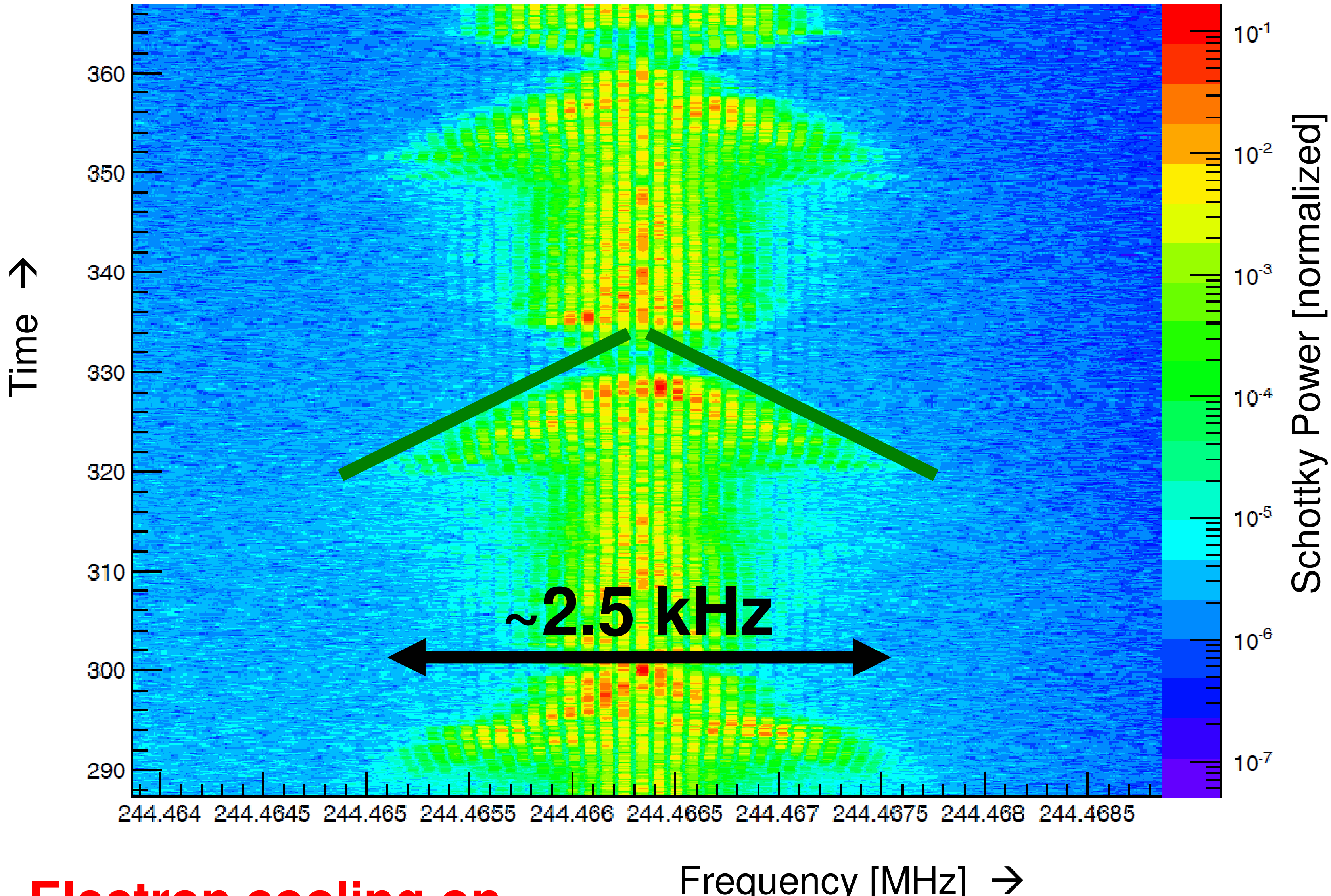
Electron cooling on
Bunching off

The laser scans over the whole bucket acceptance



Electron cooling off
Bunching off

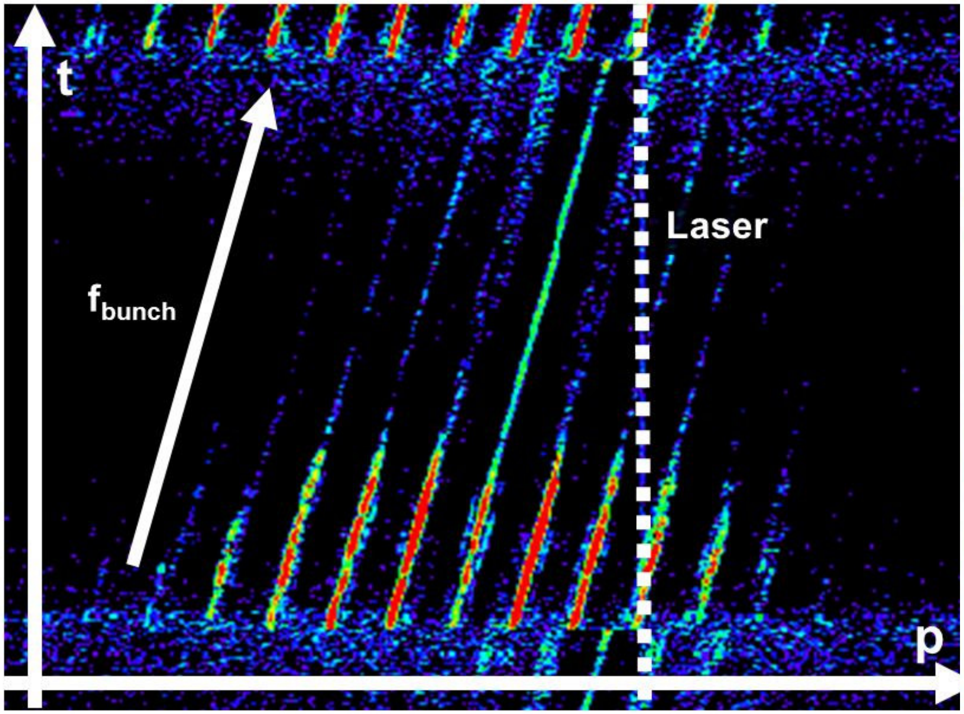
Very preliminary experimental results:



Electron cooling on
Bunching on

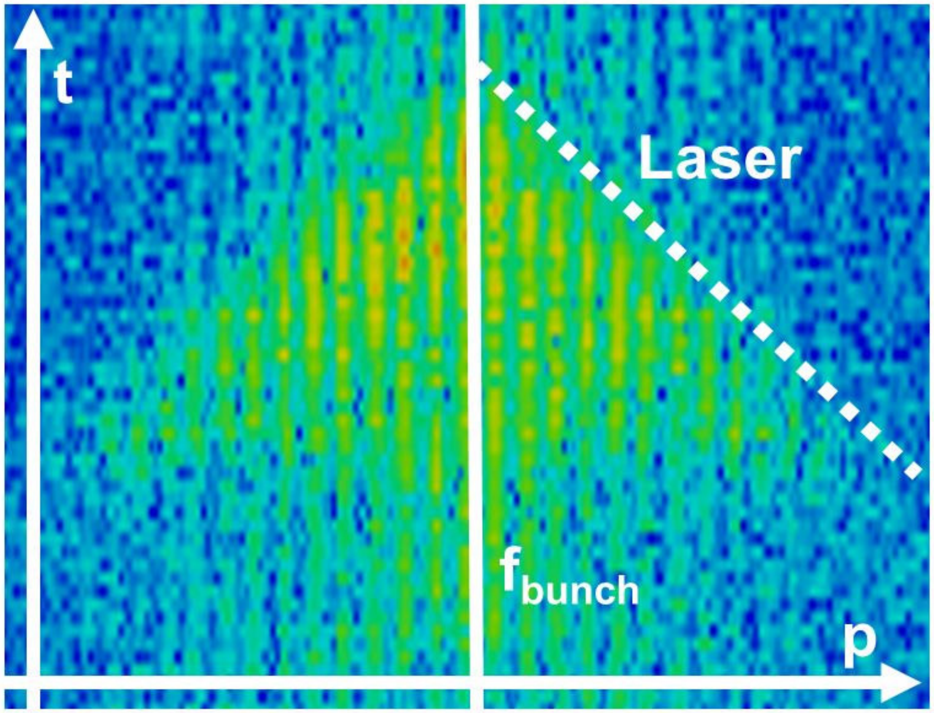
Two laser cooling scenarios

fix laser frequency
scan bunching frequency



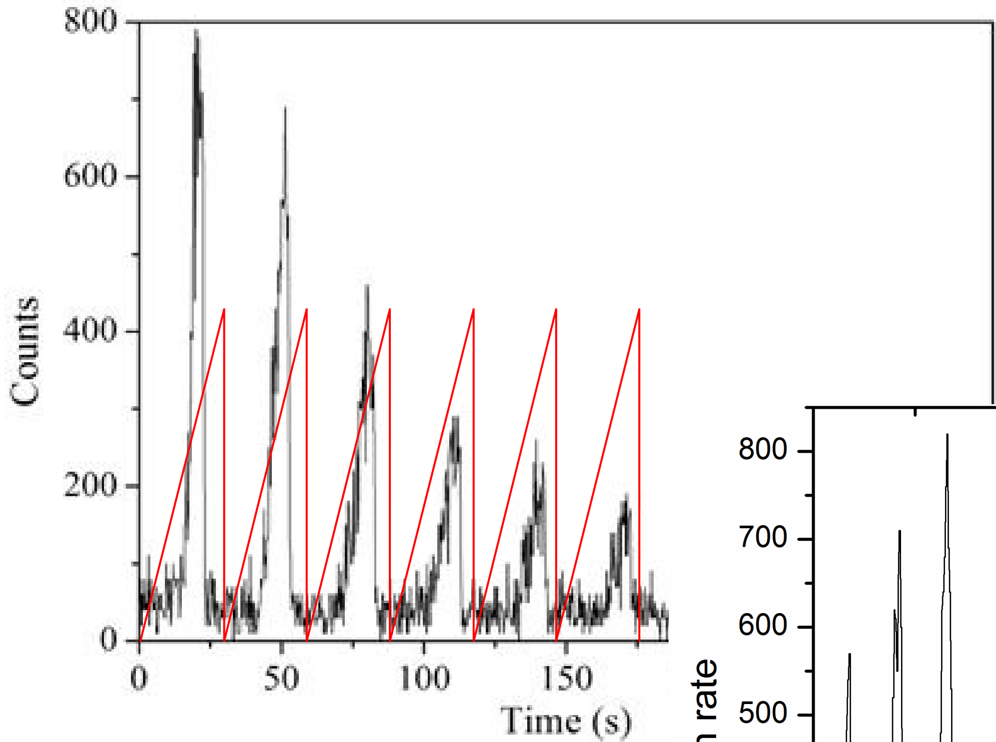
2004 / 2006
ESR beamtime

scan laser frequency
fix bunching frequency

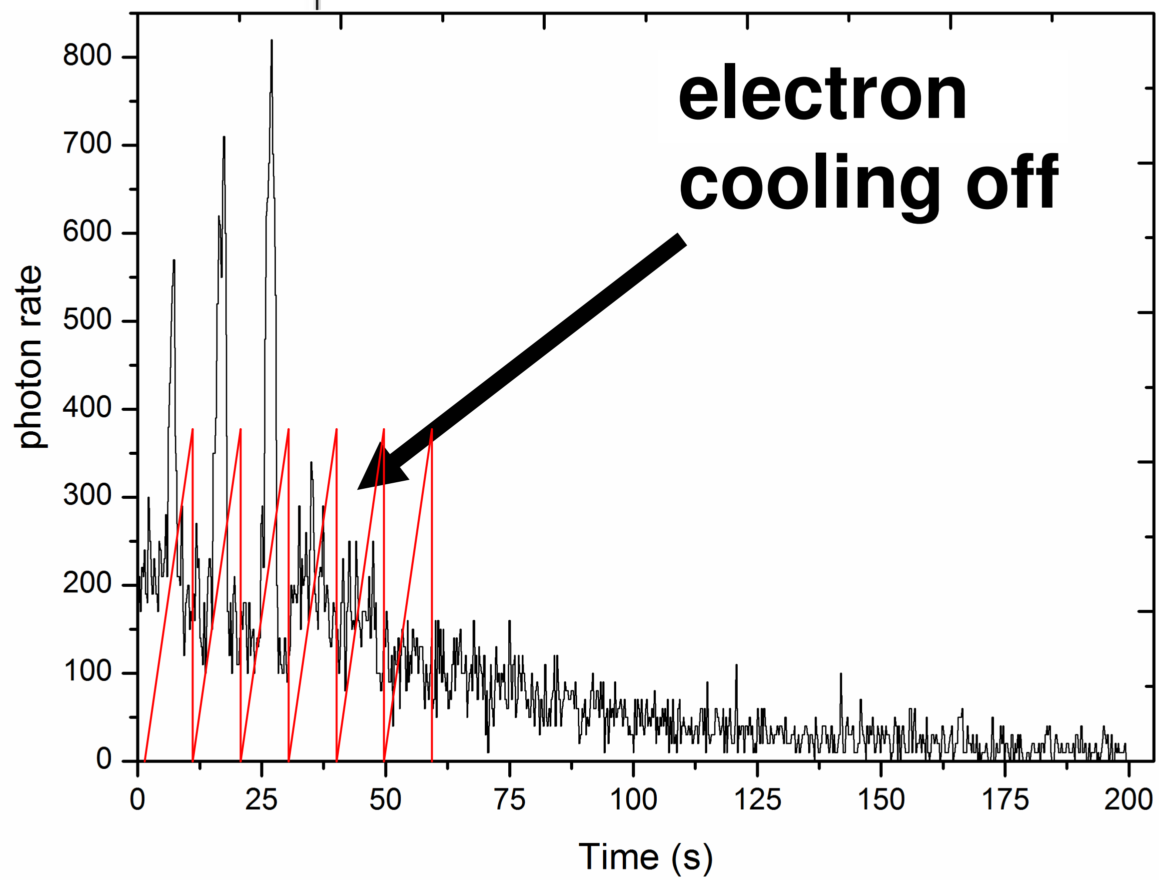


2012
ESR beamtime

Fluorescence from the ions detected by the channeltron



Scanning laser



Conclusions and outlook

At the ESR laser cooling using two scenarios was demonstrated

1) fixed laser freq. & scanning bunching freq.
2) scanning laser freq. & fixed bunching freq.
3) **fixed cw laser + pulsed laser (broadband) & fixed bunching freq.**

Fluorescence was measured by (in vacuo) channeltron

we are looking into other promising systems for the future

We have demonstrated laser cooling with just the scanning laser, also without initial electron cooling

new pulsed laser system is being designed (TUDa / HZDR)

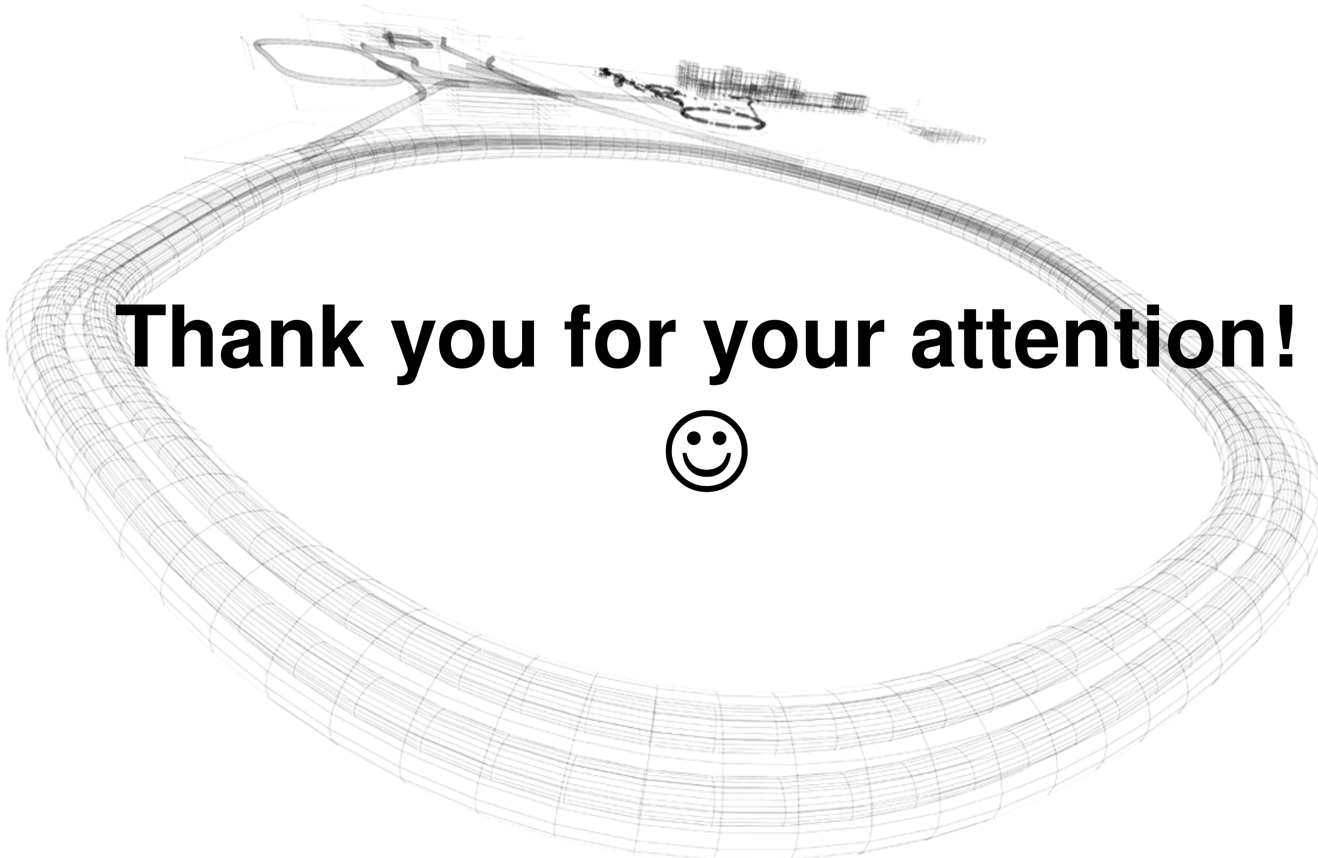
Experiments at the CSRe in Lanzhou are being prepared

Test beamtime in 2013 seems feasible, experiment in 2014?

Preparations for laser cooling at FAIR (HESR, SIS100/300)

First beam from SIS100 might be in 2019.

In 2012 we took a lot of data which is currently being analyzed.



Thank you for your attention!

☺

TECHNISCHE UNIVERSITÄT DARMSTADT

HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF