Laser cooling of stored relativistic ion beams

full ion beam diagnostics

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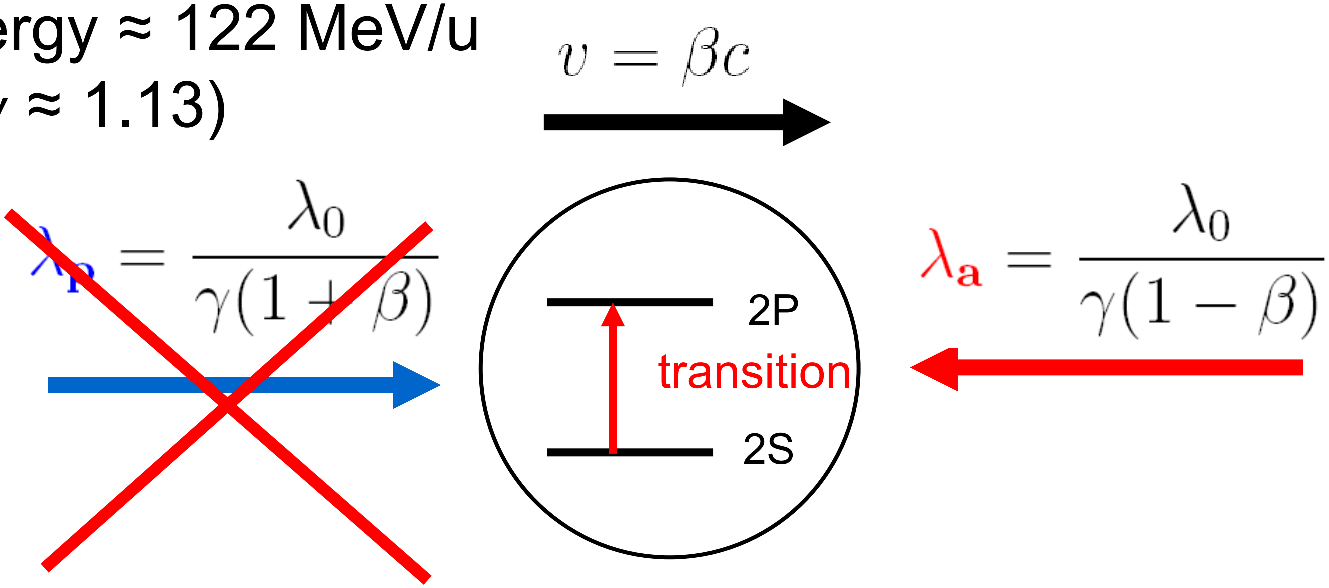
Motivation

- spectroscopy of high-Z Li- and Na-like ions (SIS100/300, NESR)
- only cooling method for SIS300...
- study laser cooling without pre-electron cooling
- set up fluorescence detection to determine the lower limit of the longitudinal momentum ($\Delta p/p<10^{-7}$)
- study ordering of the ions in the beam at very low momentum spread
- use broadband pulsed laser cooling for fast cooling of many ions

The principle: laser cooling of relativistic ions

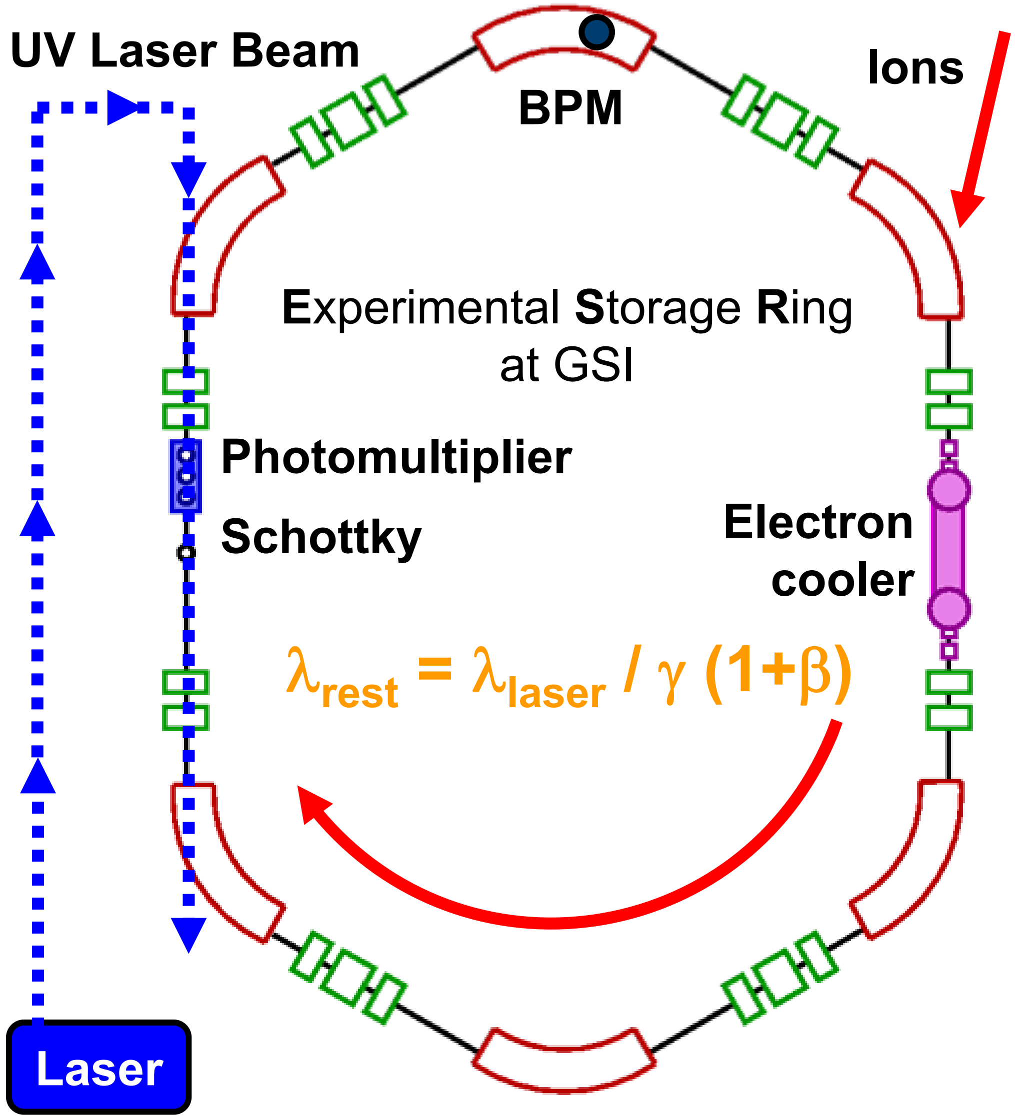
C^{3+} ion energy ≈ 122 MeV/u
($\beta \approx 0.47$, $\gamma \approx 1.13$)



λ_p=93 nm λ_0=155 nm λ_a=257 nm

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

Experimental setup (2004/2006)



Ion Species: C^{3+}

E_{beam} = 122 MeV/u
= 1.47 GeV
(β = 0.47, γ = 1.13)
f_{rev} = 1.295 MHz
τ_{beam} ~ 300 s
(no cooling)

Ar^{+} ion laser (cw)
SHG
λ_{laser} = 257.34 nm

$2S_{1/2} \rightarrow 2P_{1/2}$
λ_{rest} = 155.07 nm
τ_{rest} = 3.8 ns

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

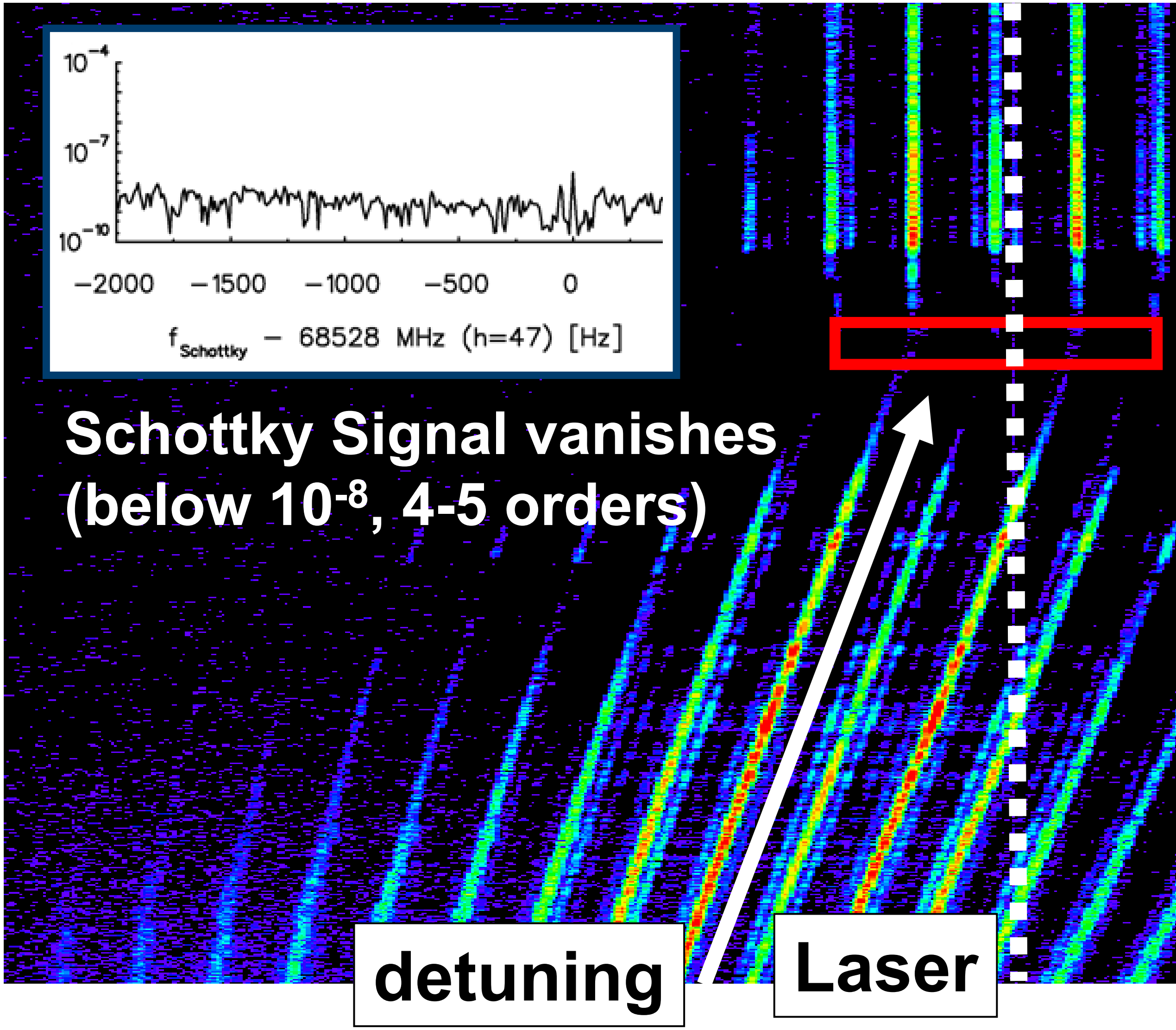
2006: scanning laser system to improve the
cooling scheme

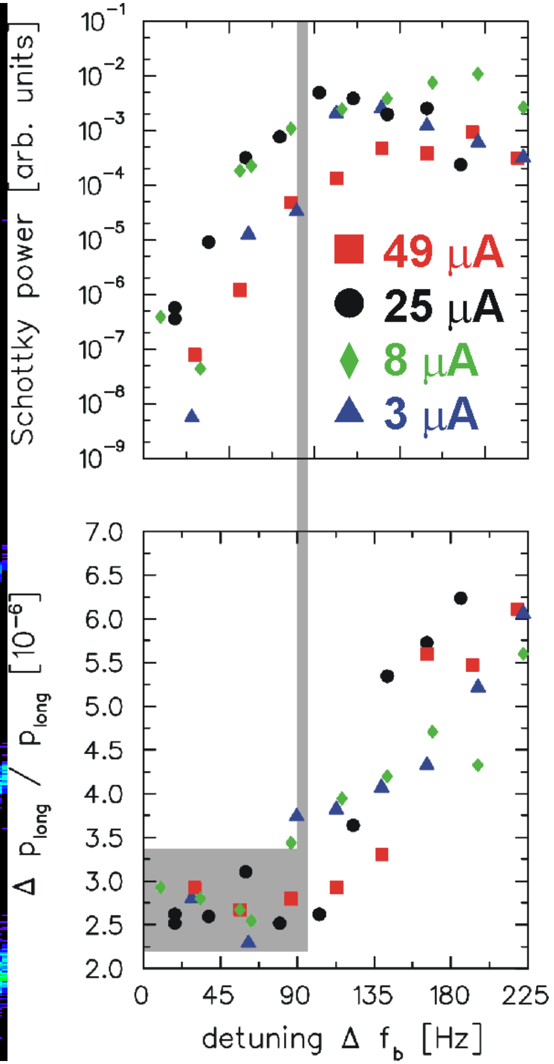
measurement of $2S_{1/2} \rightarrow 2P_{1/2\ \&\ 3/2}$

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)**

What happens at small detuning?





h = 20 I_{ion} = 16 µA   bunch length= 1.01…0.78 m   bunch width = 5.26 mm I_{ecool} = 2 mA

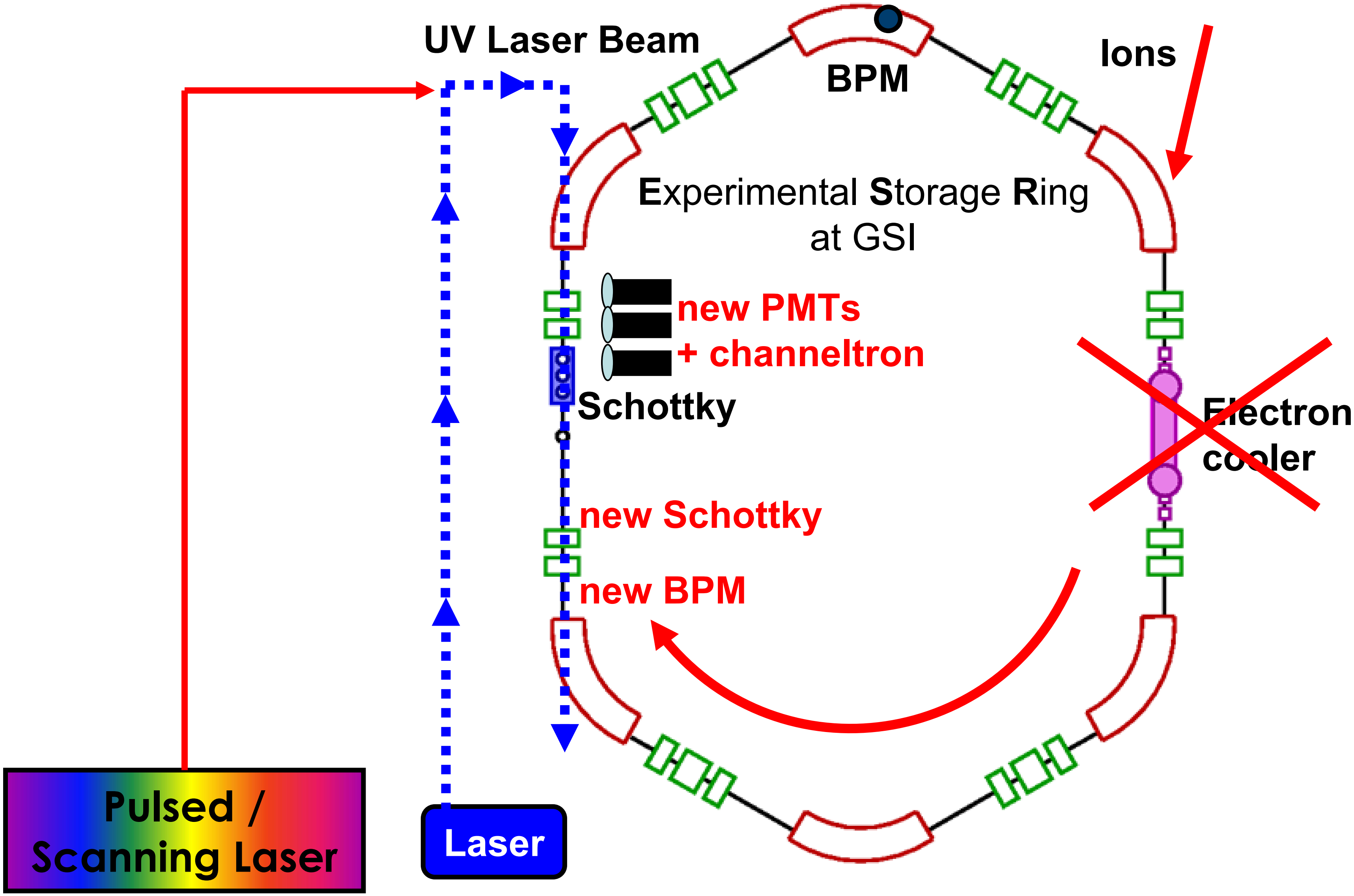
Limitations at previous beamtimes

- pre-electron cooling was required ☹
- laser force → small momentum spread ☹

↕

- bucket frequency was scanned, not the laser
- Schottky detection is limited in sensitivity ☹

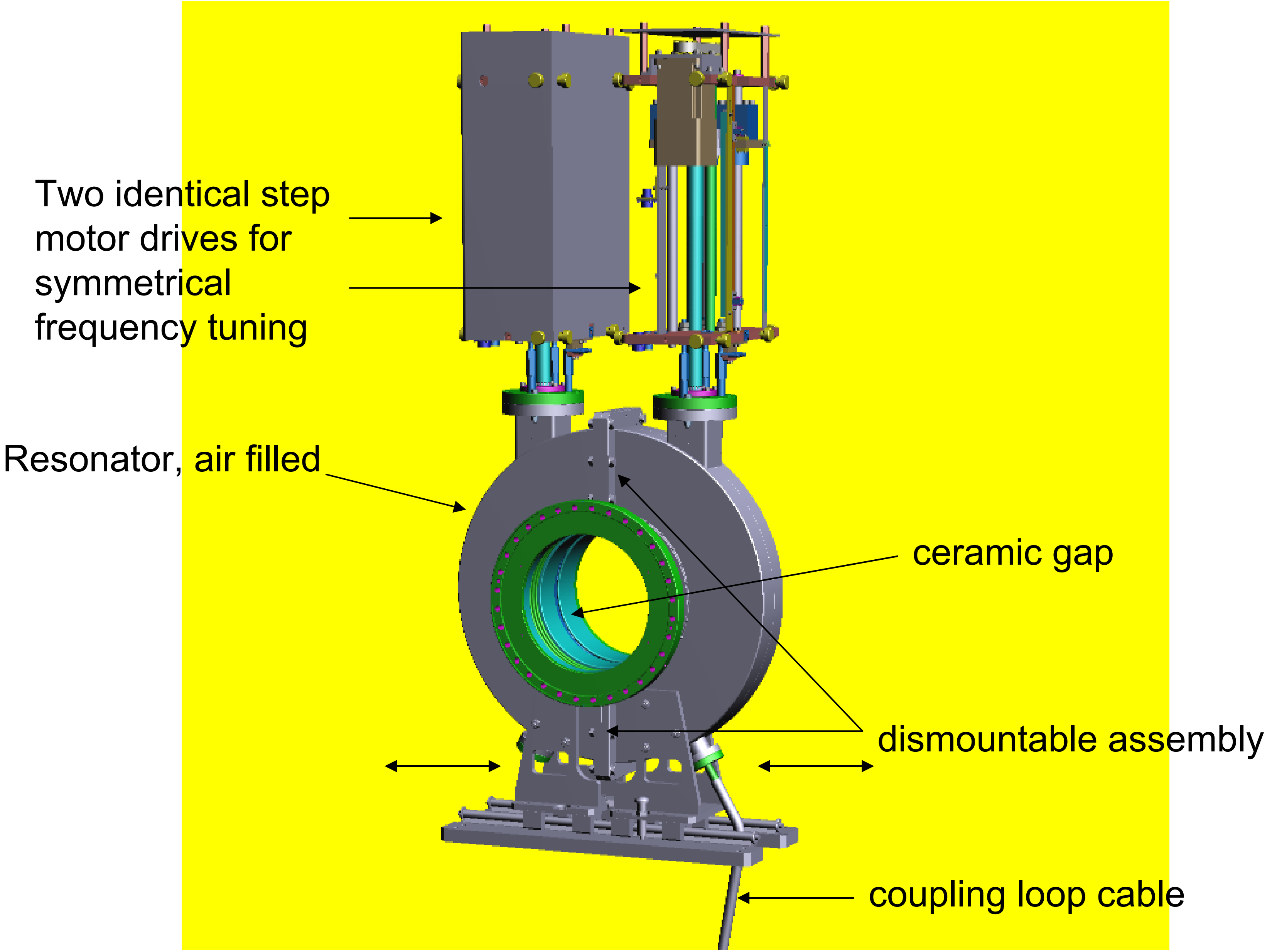
Experiment improvements



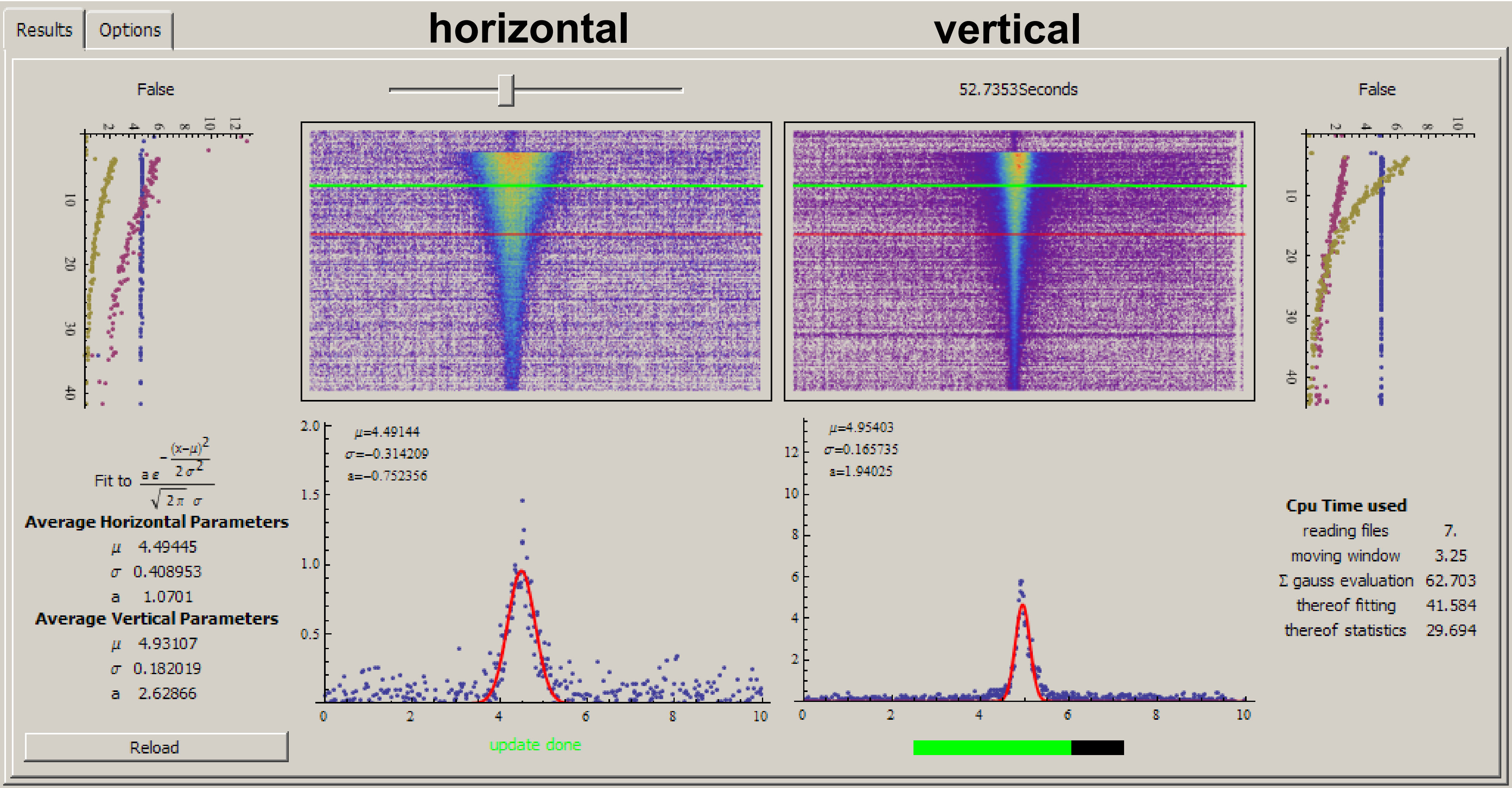
Tools for the next beamtime

- new pulsed laser system (HZDR)
- new "fixed" CW laser (DL, 1024 nm)
- new "scanning" CW laser (ECDL, 30 GHz / ms)
- new Schottky pick-up system (pill-box design)
- new beam profile monitor (MCP - CCD / ms)
- new UV-PMTs and UV-channeltron (in vacuum)
- new data acquisition and control system (NI compact RIO)

New Schottky pick-up system

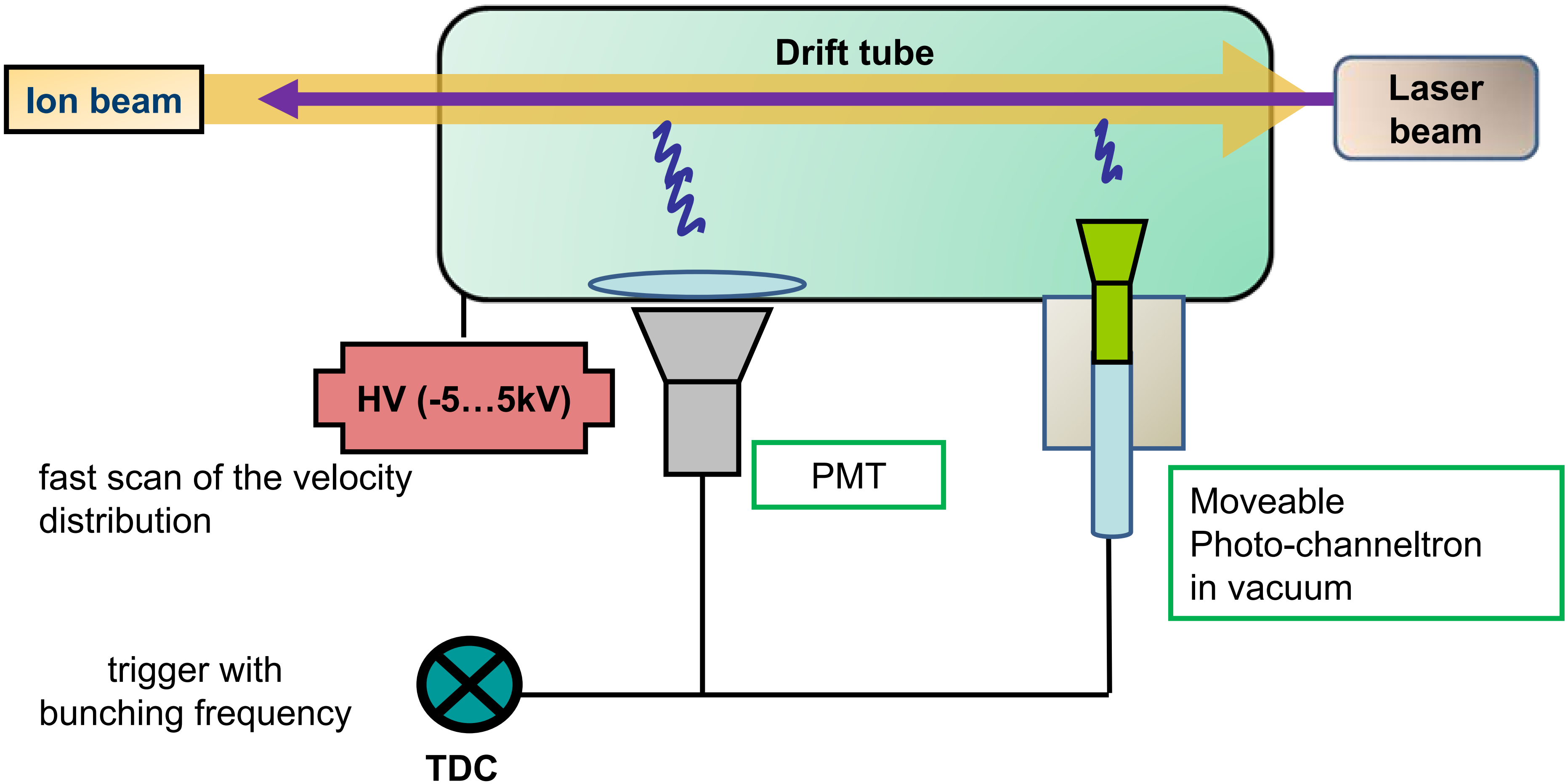


New beam profile monitor (BPM)



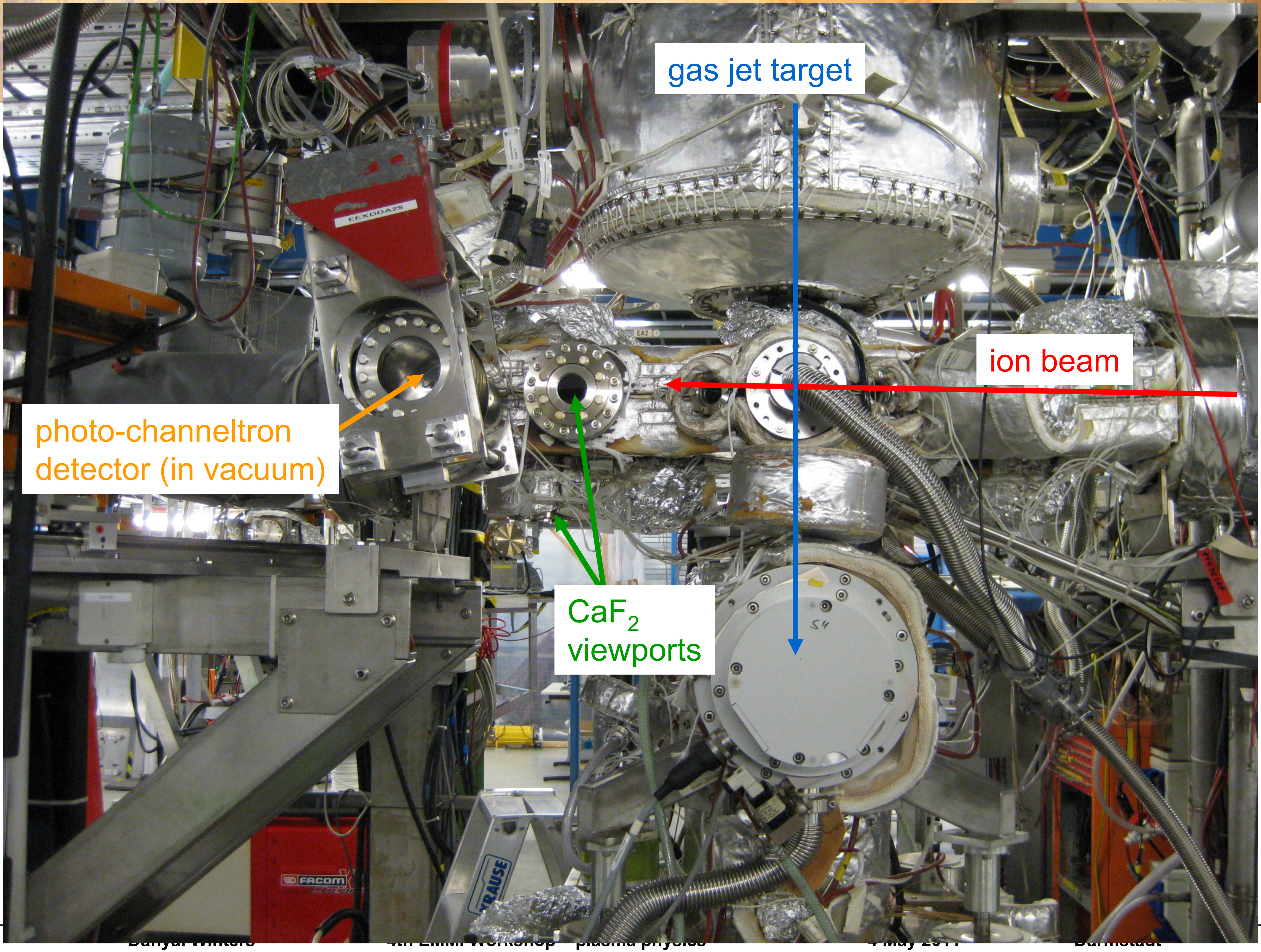
Play with - laser power- laser scanning- bucket frequency detuning- bucket amplitude → Vertical and Horizontal temperature

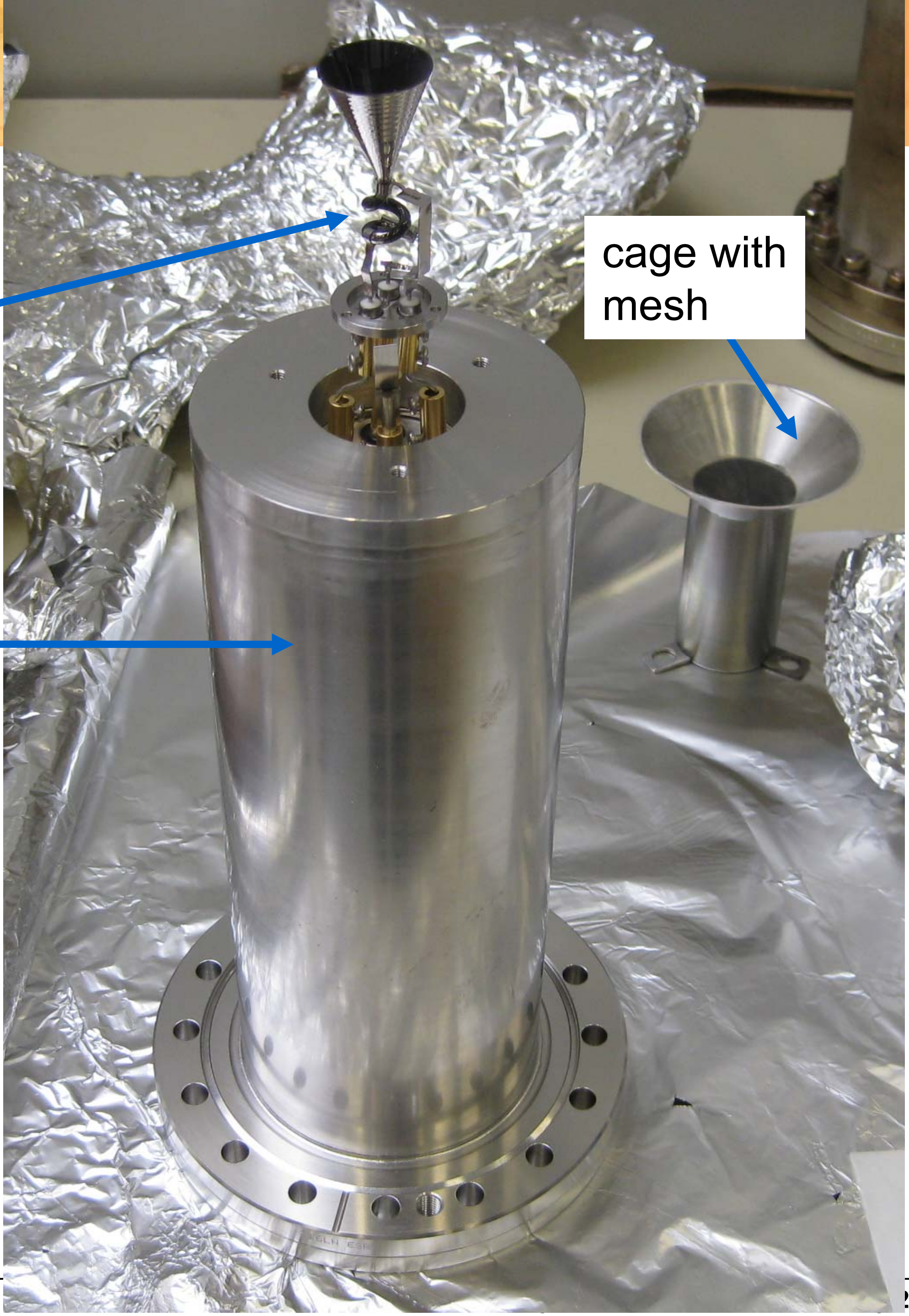
New optical diagnostics



fast scan of the velocity distribution

trigger with bunching frequency


gas jet target
ion beam
photo-channeltron
detector (in vacuum)
CaF2
viewports


channeltron
"hat"
cage with mesh

New data acquisition and control system

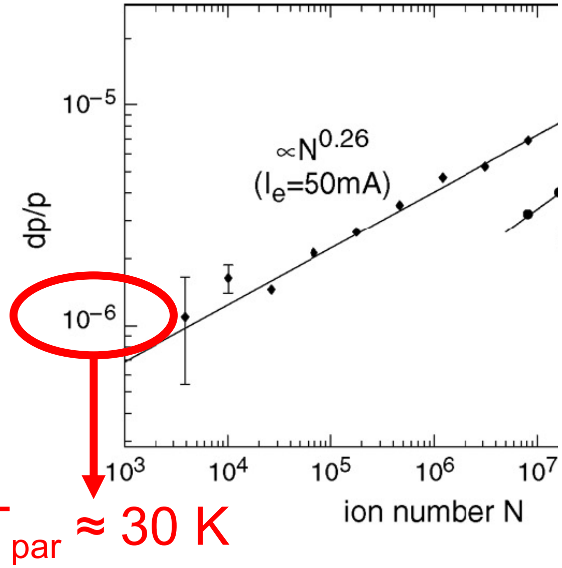
HOST PC

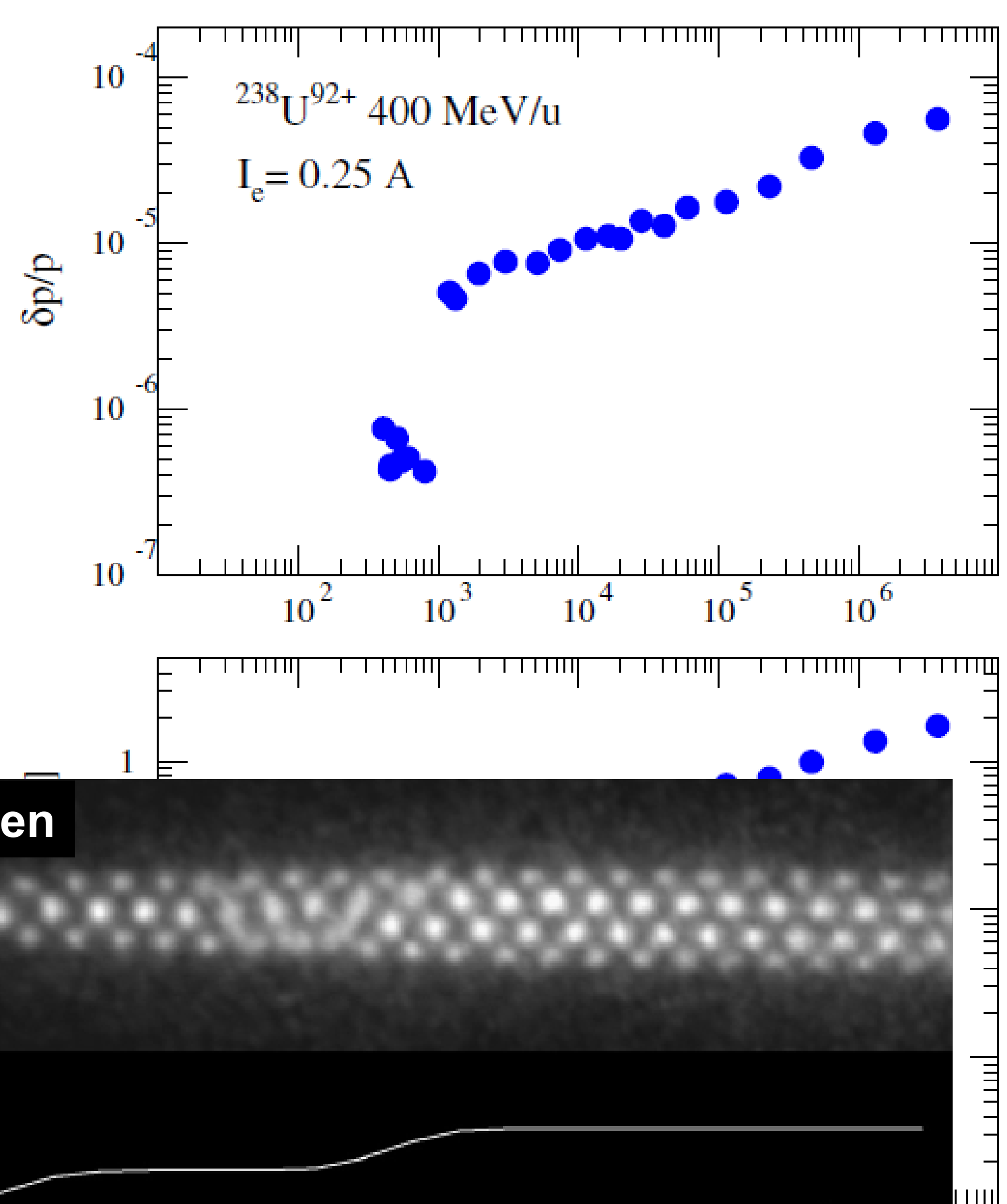
- compact
- modular
- flexible (FPGA)
- stable & robust
- easy to use

- Use LabView with network to control the system
- data transfer between the controller and the chassis, and between the controller and the host PC
- Save the data in controller or host -PC

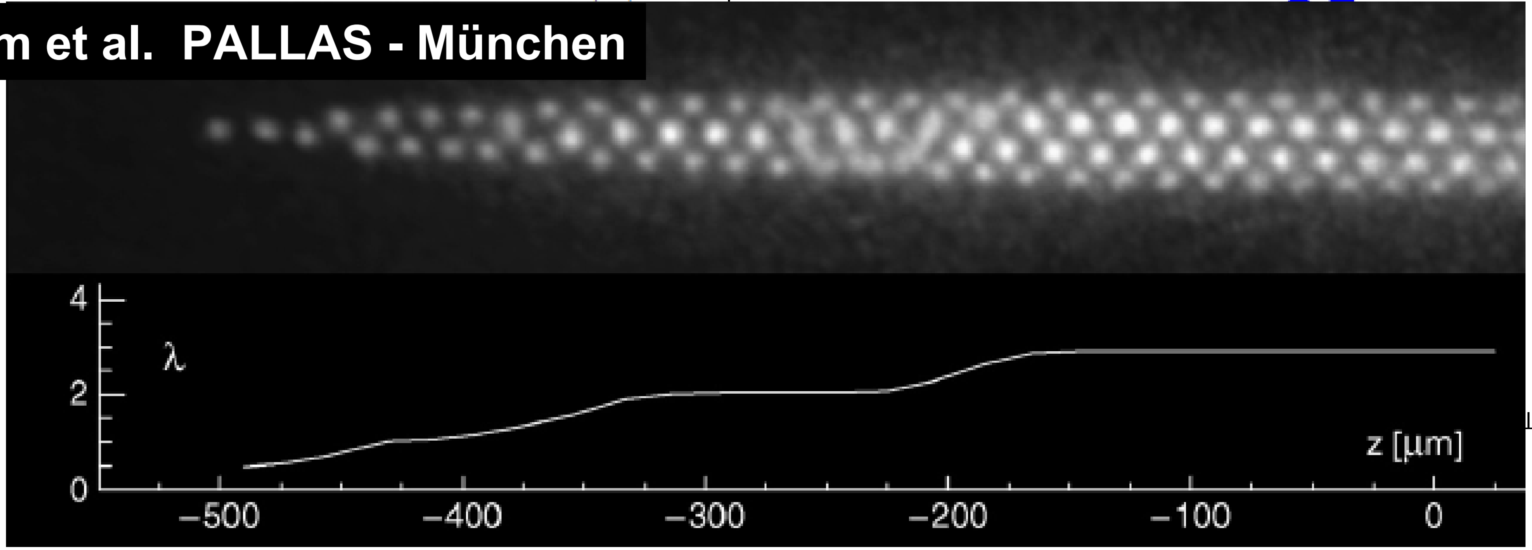
Nice results

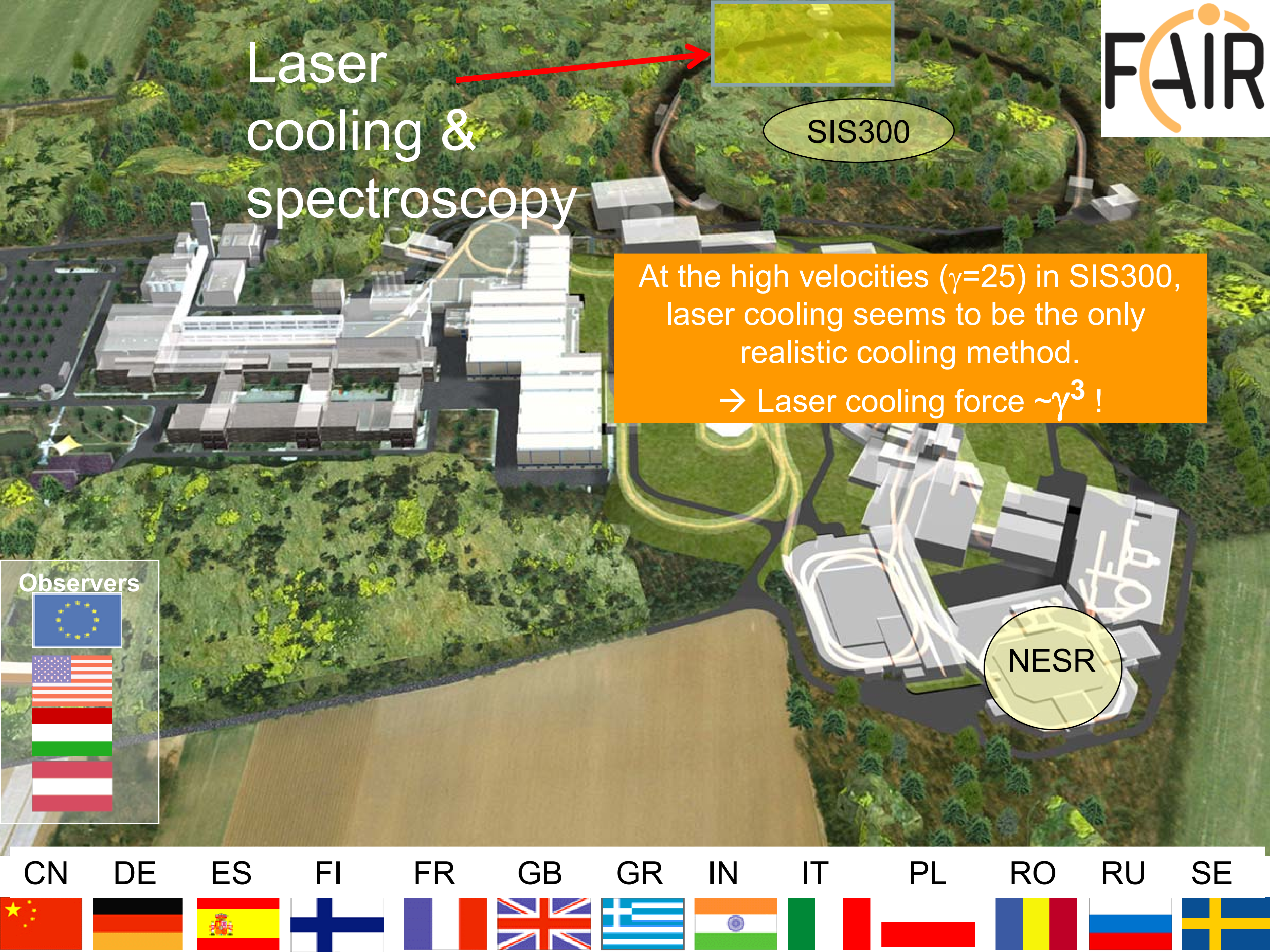
Steck et al. ESR - Darmstadt





Schramm et al. PALLAS - München

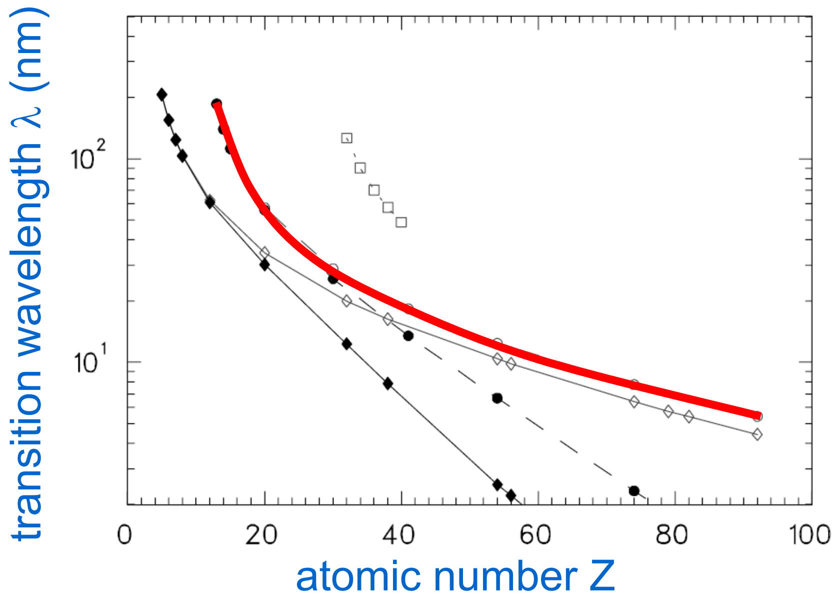


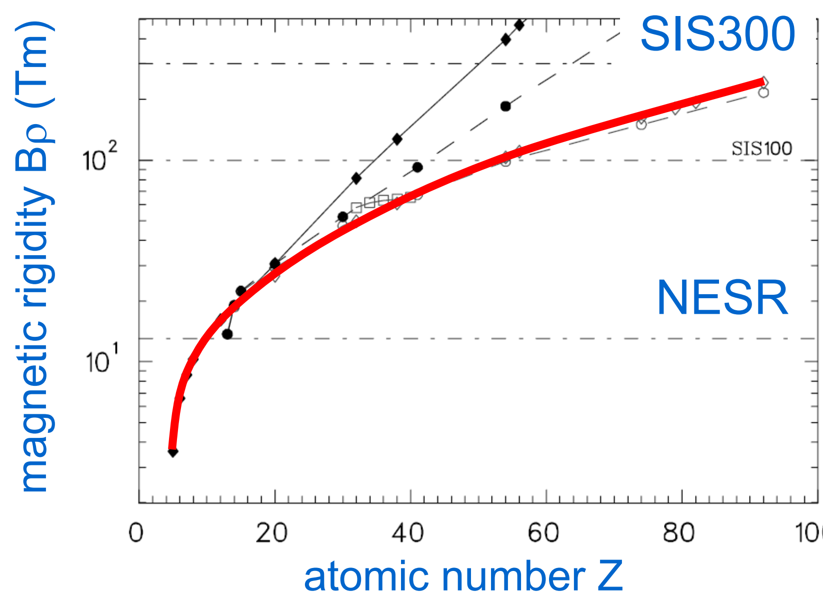

Laser cooling & spectroscopy
SIS300
At the high velocities (γ=25) in SIS300, laser cooling seems to be the only realistic cooling method.
→ Laser cooling force ~γ^3 !
NESR
Observers
CN DE ES FI FR GB GR IN IT PL RO RU SE

Laser cooling of Li-like ions at the SIS300

The transition wavelengths strongly depend on the atomic number Z!

The Doppler boost of the SIS300 shifts wavelengths to `normal´ lasers!





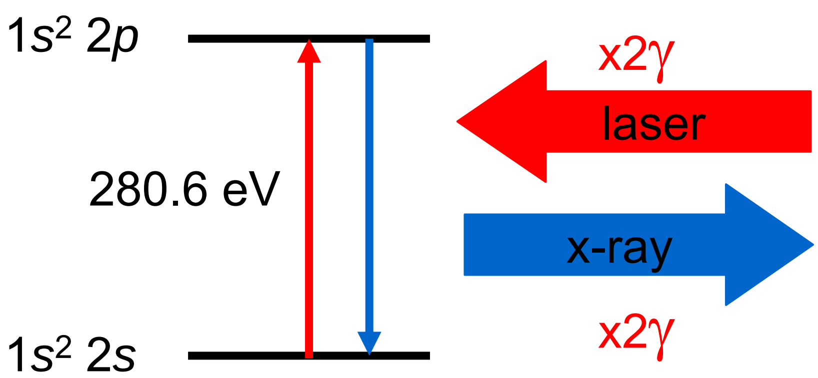
needs fast transition: $2S_{1/2} \rightarrow 2P_{1/2}$

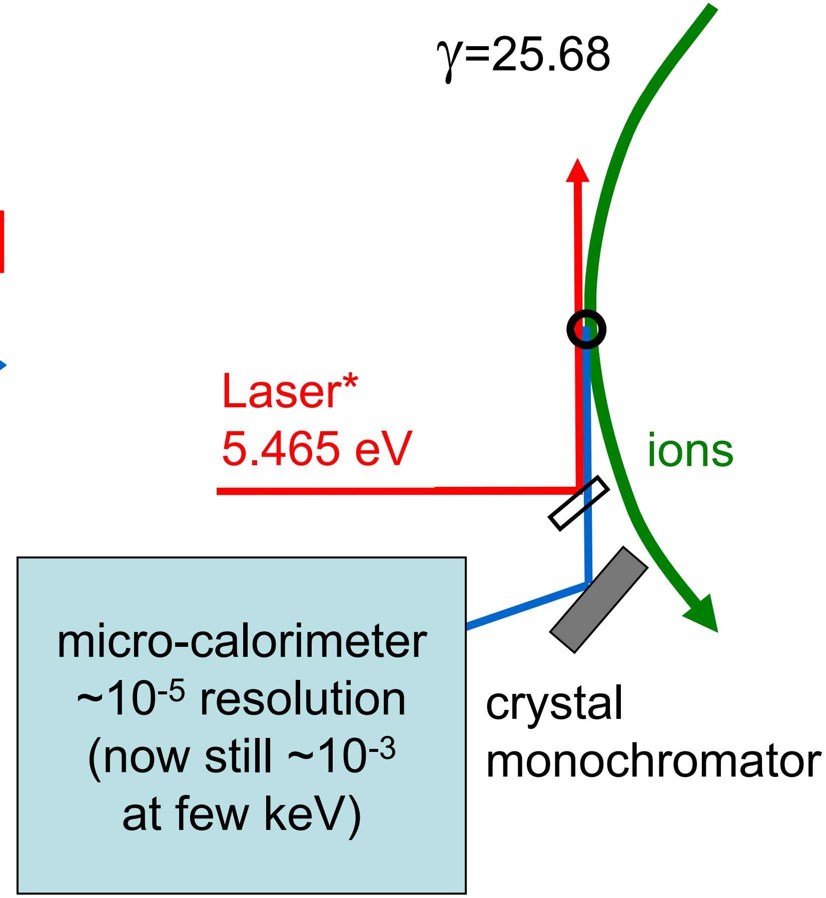
$\gamma \rightarrow B\rho$

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

Laser spectroscopy at the SIS300

QED in lithium-like systems



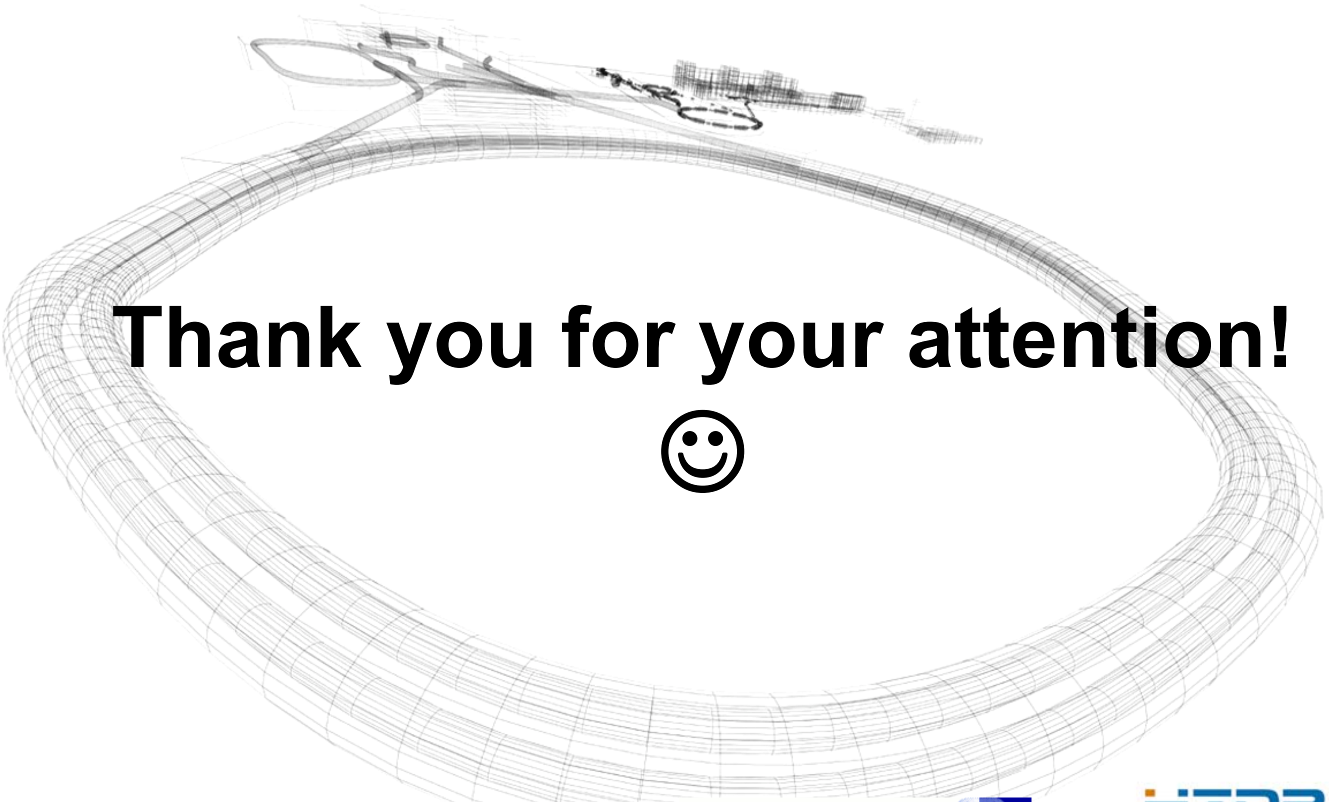


Up to a factor 4 better resolution!

(ΔE/E of the transition)

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

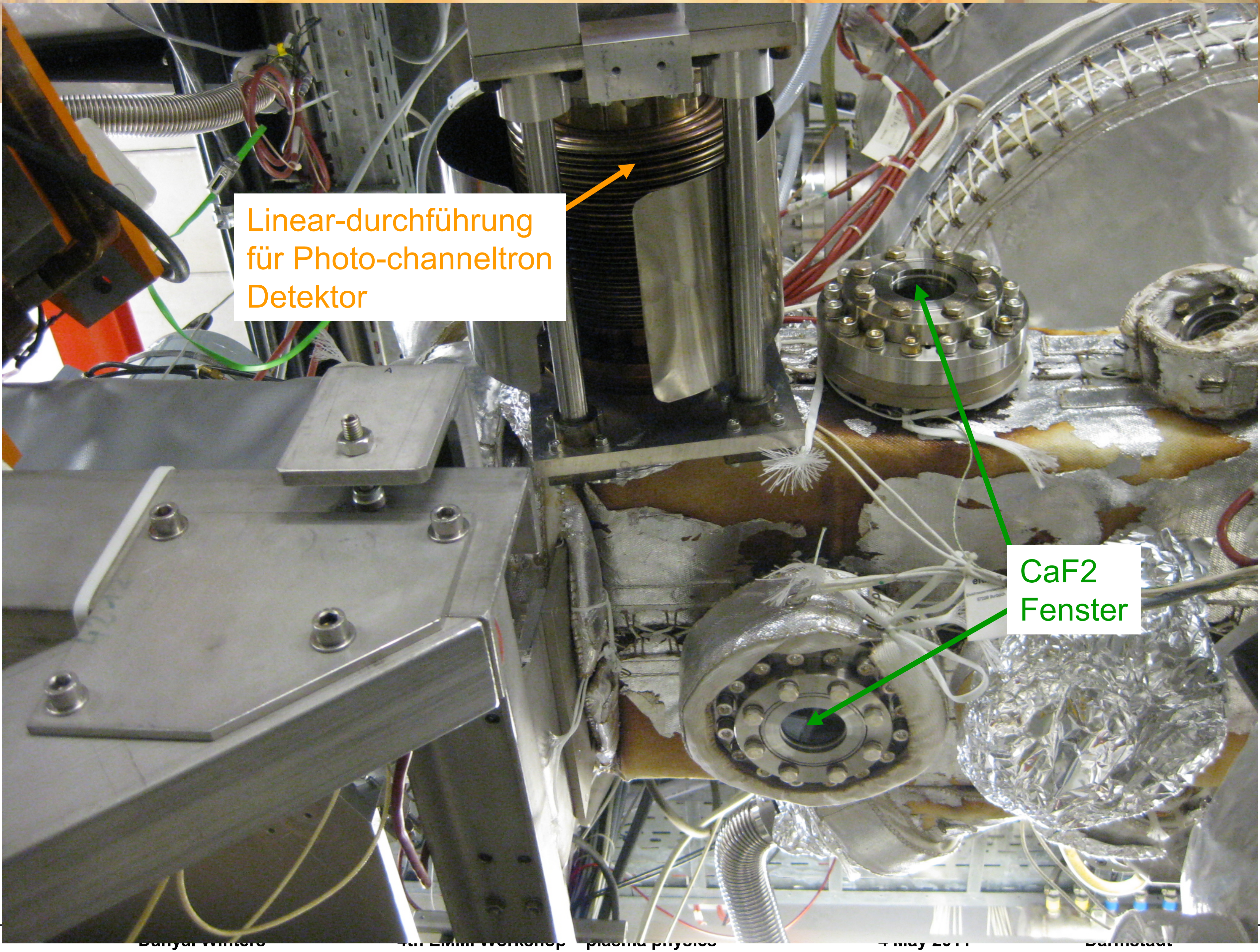
* 454 nm frequency doubled



Thank you for your attention!

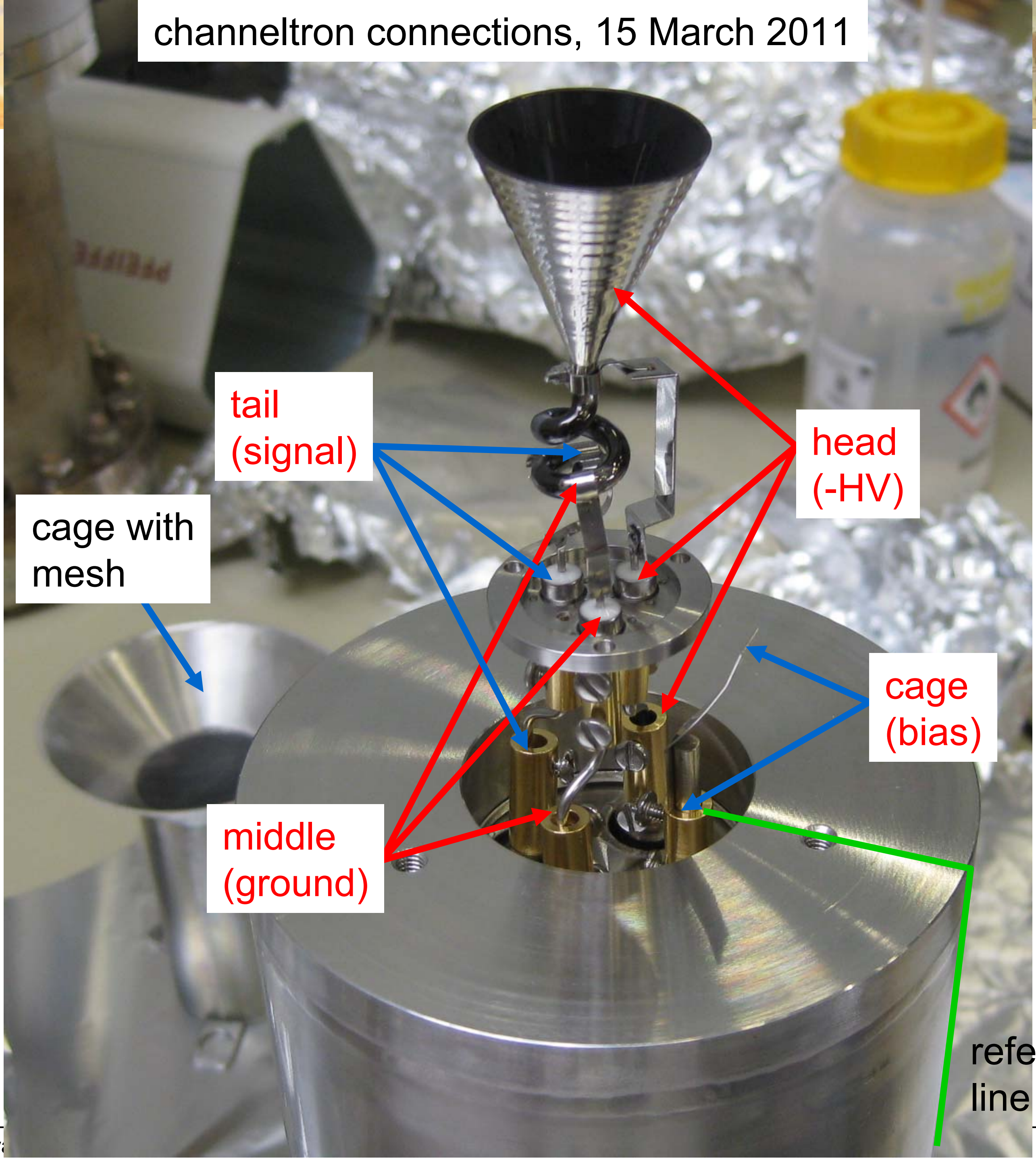
☺

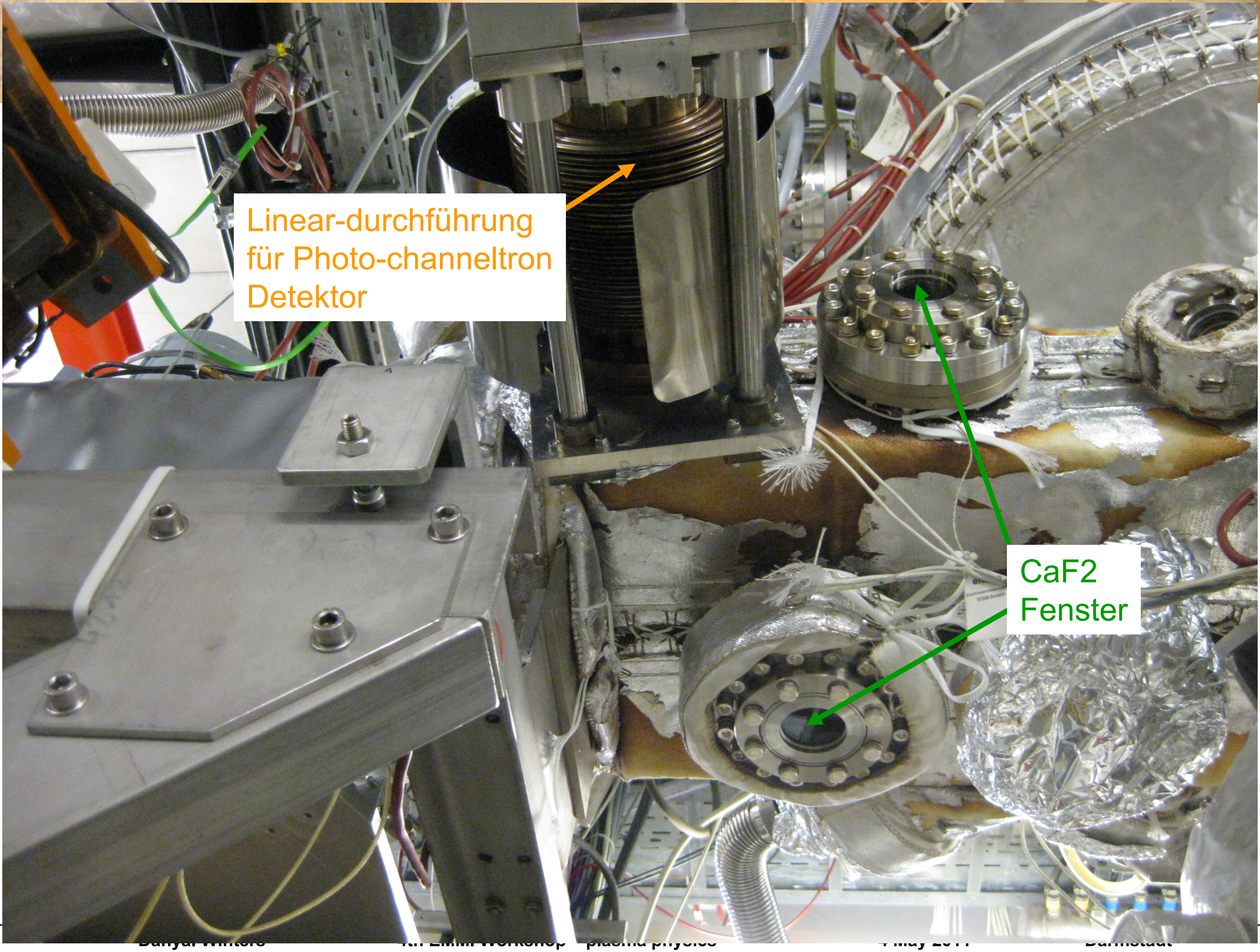
EXTRA SLIDES


Linear-durchführung
für Photo-channeltron
Detektor
CaF2
Fenster

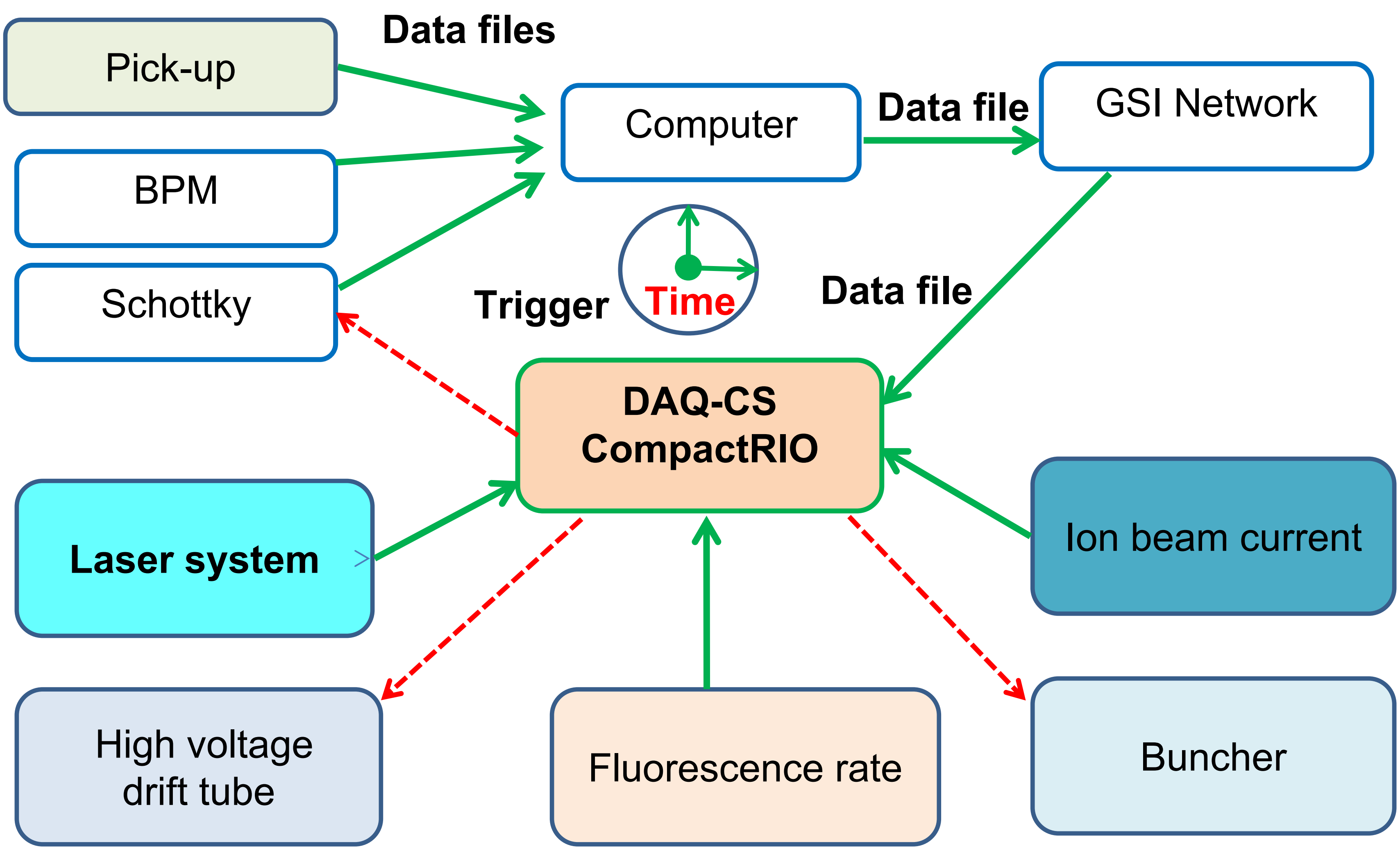

cage with mesh
reference line

channeltron connections, 15 March 2011

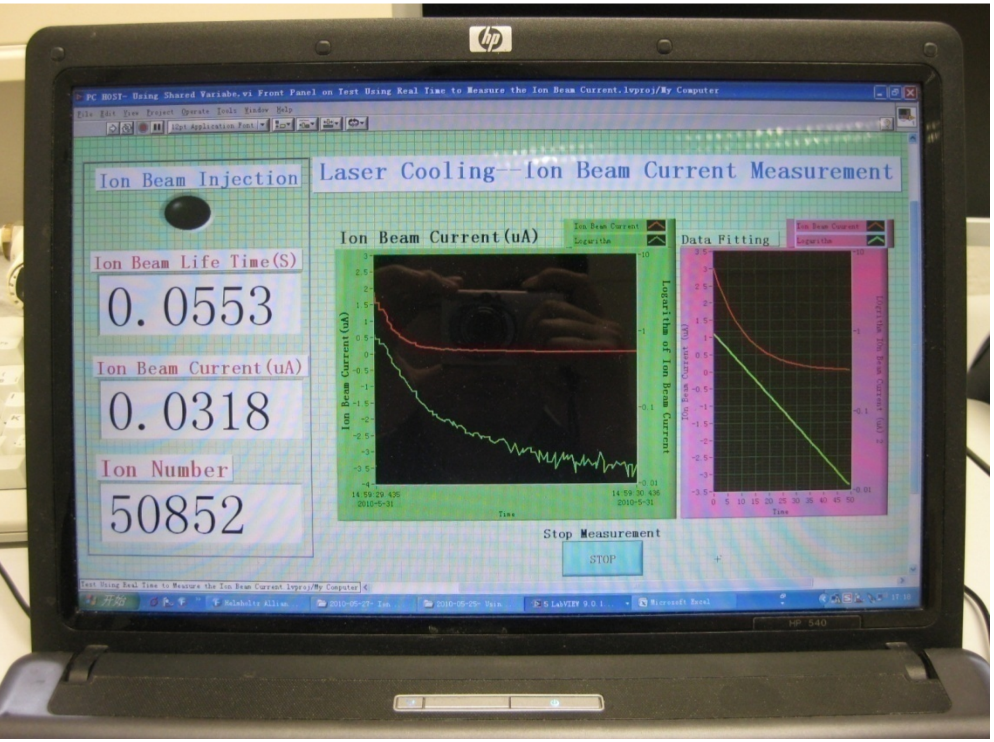



Linear-durchführung
für Photo-channeltron
Detektor
CaF2
Fenster

New data acquisition and control system



Labview interface: ion beam current readout



a. Ion beam injection will be the trigger signal

b. Display Ion beam current

c. Online data fitting

d. Display ion beam life-time

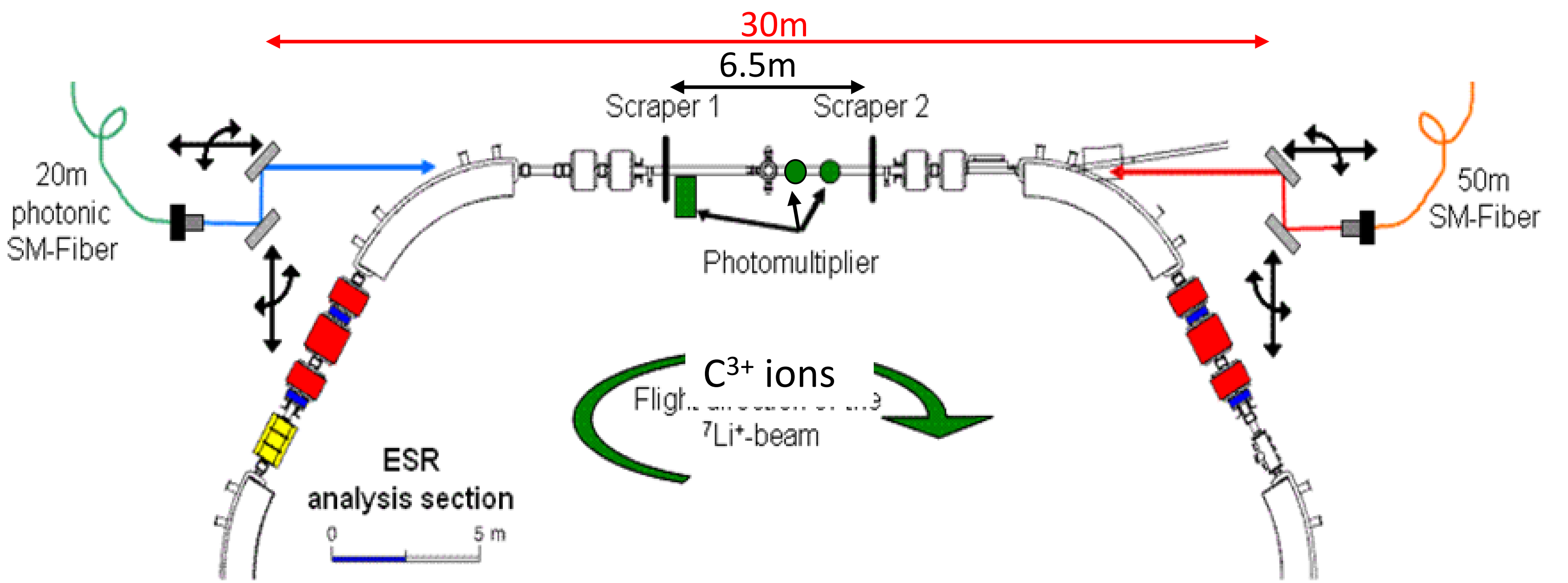
e. Display ion number

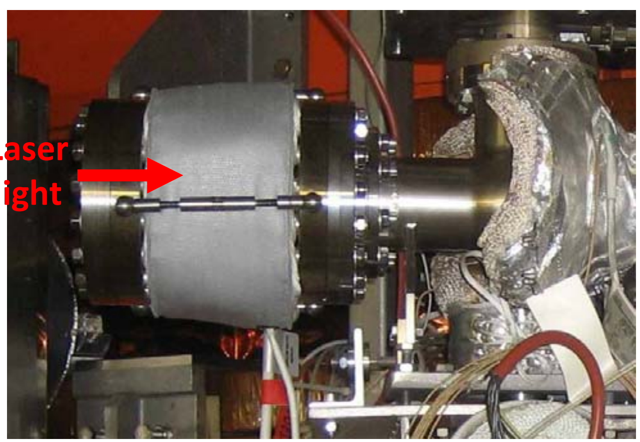
f. Save the data sheet for offline analysis

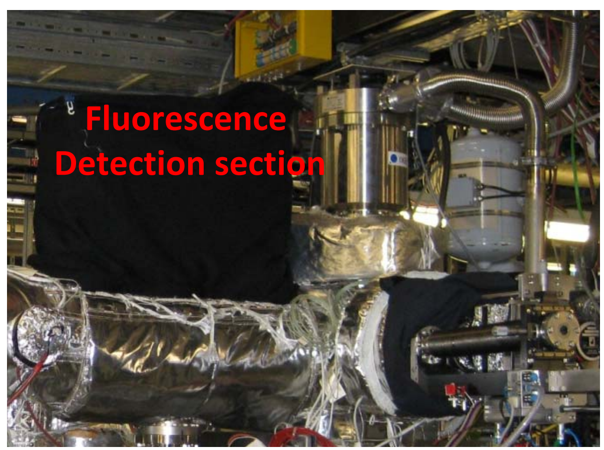
$$I(t) = I(0) \cdot \exp(-\frac{t}{\tau})$$

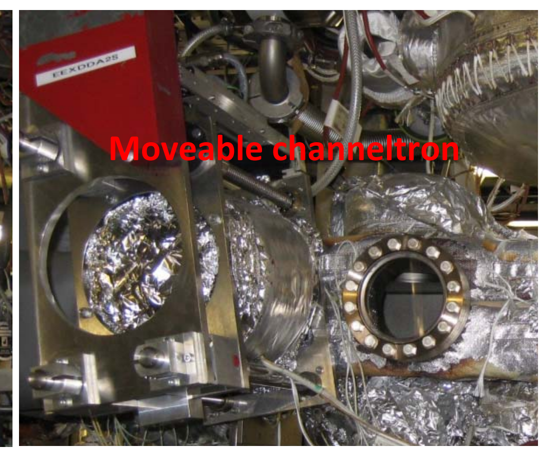
$$N_{ion} = \frac{I_{ion}}{f_{rev} \cdot q \cdot e}$$

Laser access and fluorescence detection









Fluorescence detection:

MPF Products, Inc.
Your Connection for Knowledge, Inventory, and Service in Hermetic Electrical and Optical Components

CaF2 viewports
UHV CF63, 1.9" view
Excimer 157 nm
Transmission at 157 nm > 85%
Max Bakeout 200 ºC

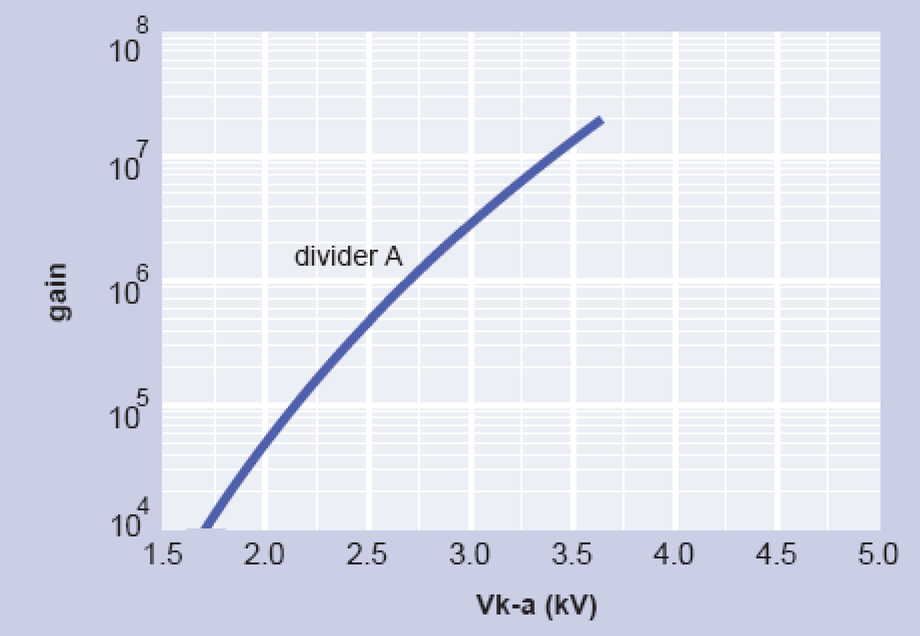
ET Enterprises electron tubes

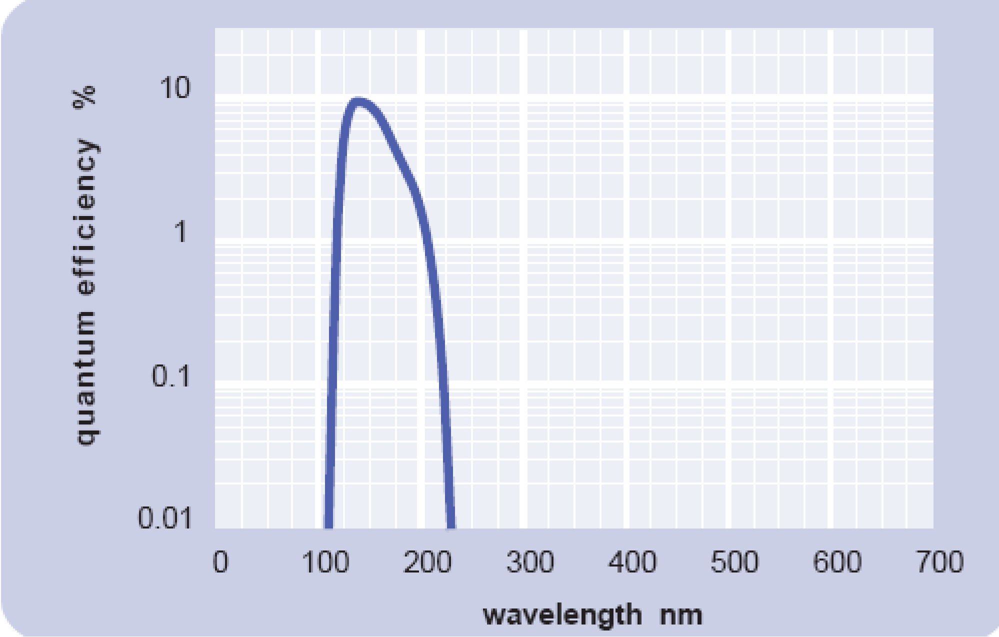
Photomultiplier tube
9423B (51 mm diameter) - CsI coated, MgF2 window
spectral range: 110-230 nm
QE @ 157 nm: several percent
dark count rate: 20 Hz

PHOTONIS

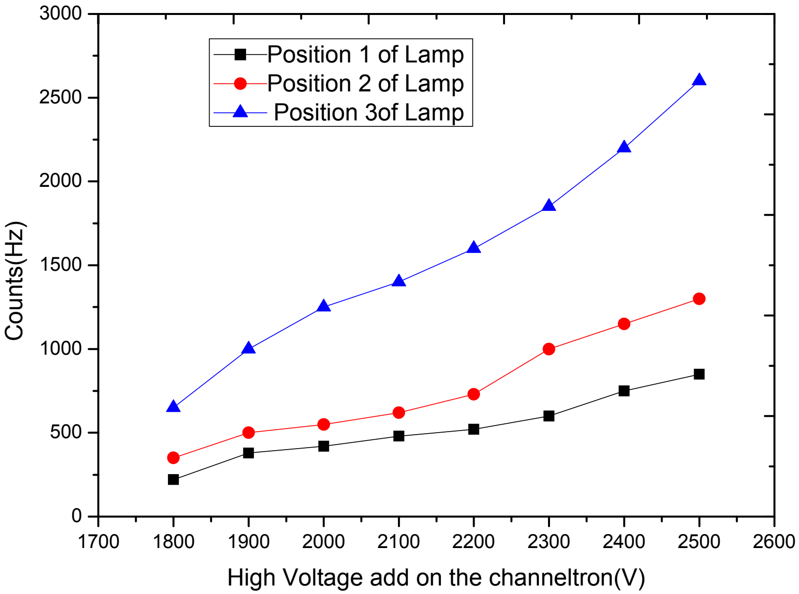
Photo-channeltron
Mass Analyzer Products
MAP 215-50, CEM 4869 cone CsI
26mm diameter

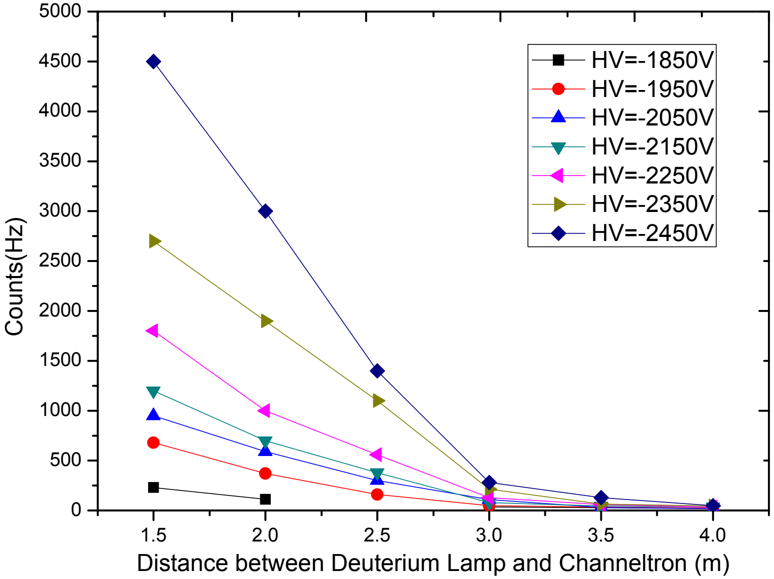
Photomultiplier tube for detecting UV light



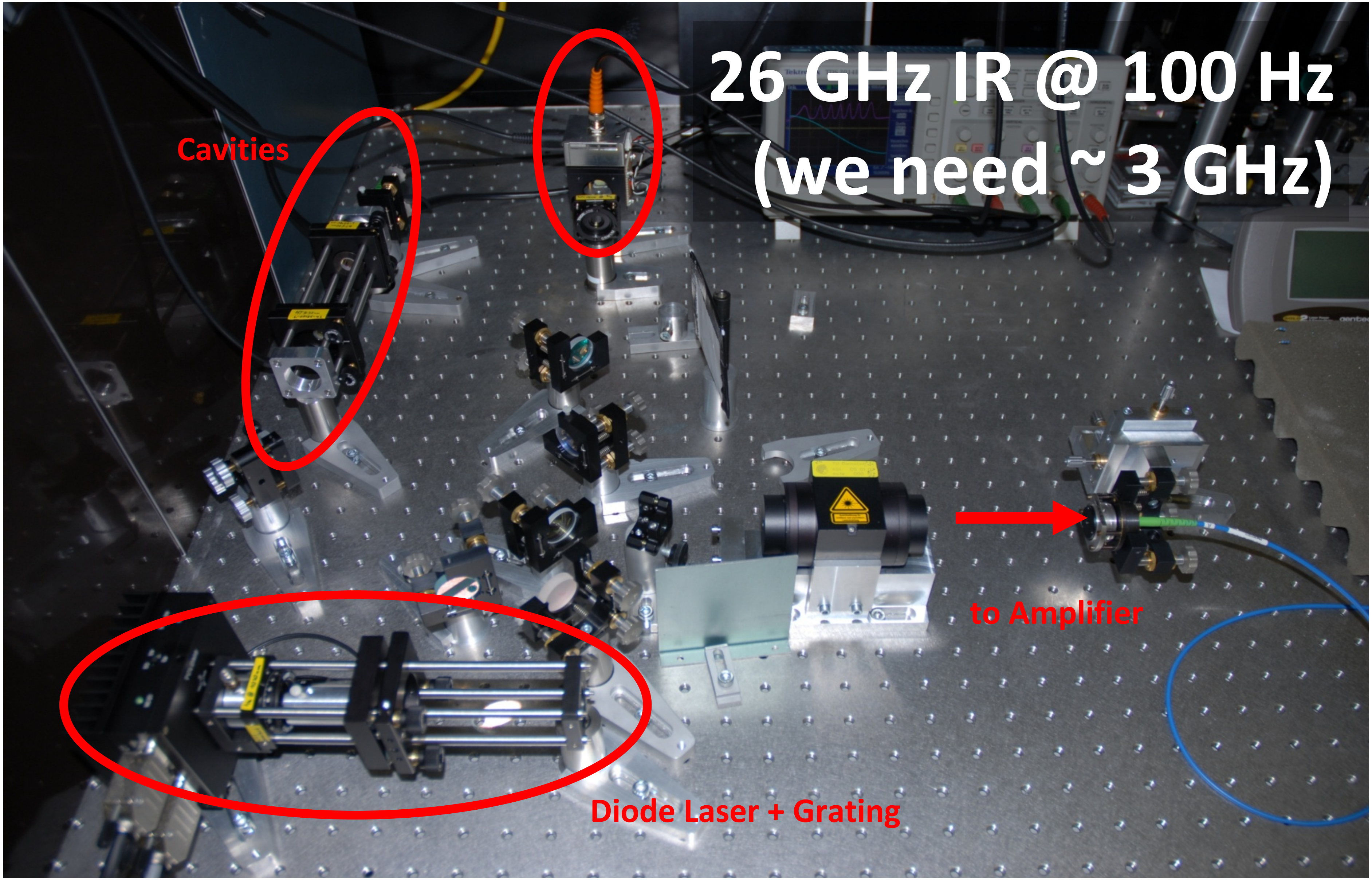


Testing channneltron with deuterium lamp

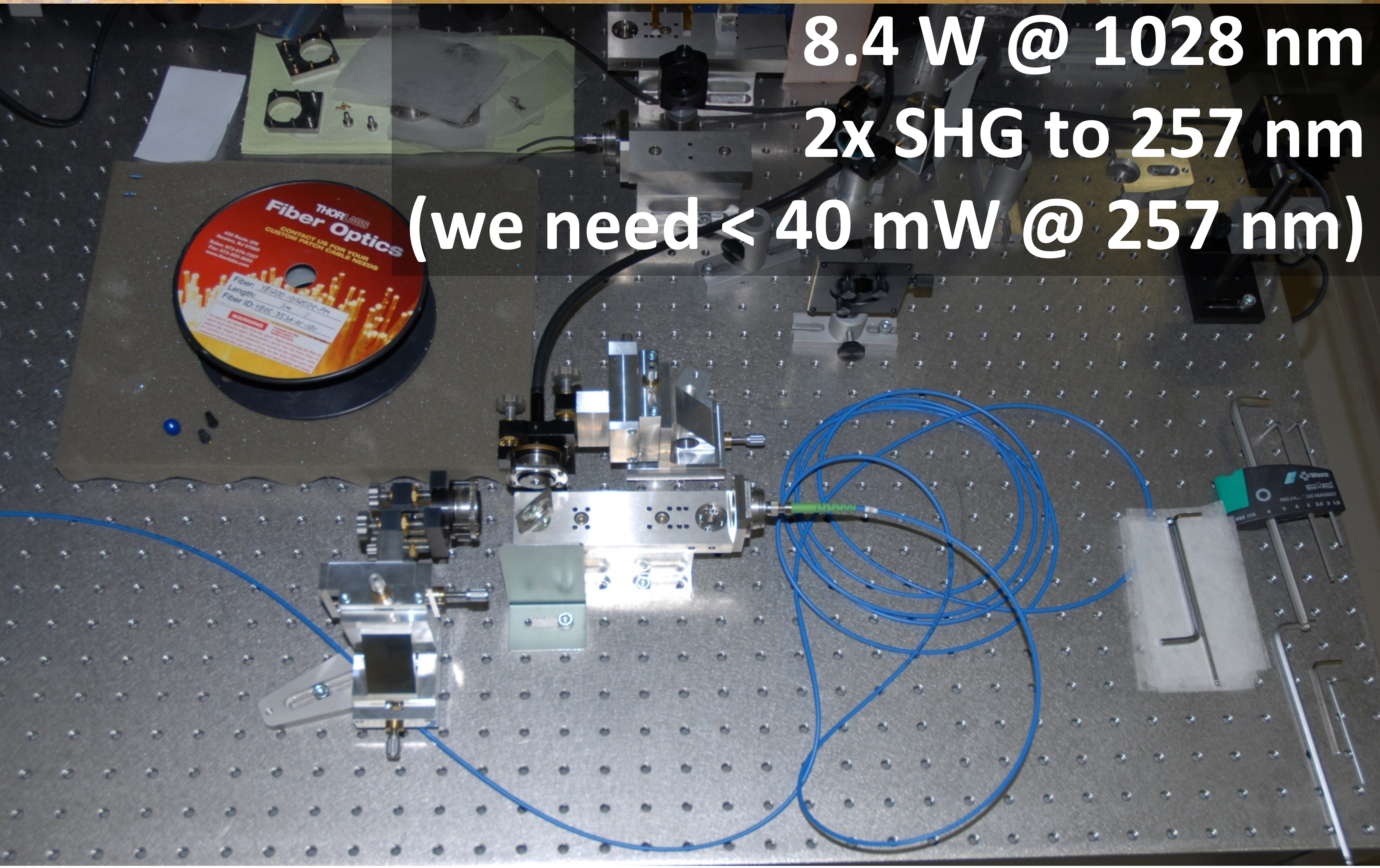




External Cavity Diode Laser



Fibre Amplifier



8.4 W @ 1028 nm

2x SHG to 257 nm

(we need < 40 mW @ 257 nm)

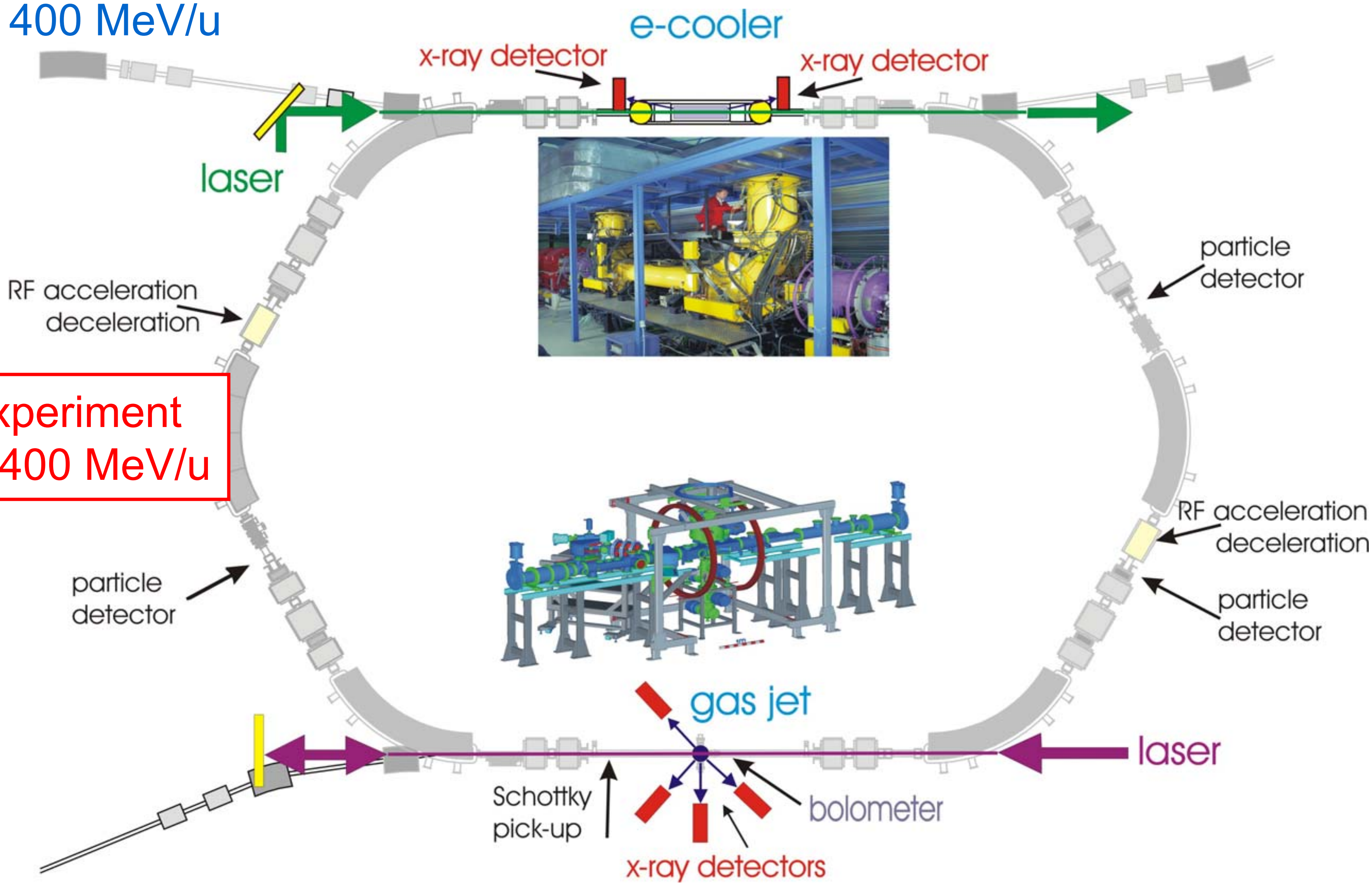
Advantages of compactRIO

- Reconfigurable input and output modules (hardware) for different signals
- Small and stable embedded real time processor
- Rapidly design custom hardware reconfigurable FPGA chips provide the flexibility, performance, and reliability of custom hardware
- LabView graphical development tools for rapid development
- Control and communication via ethernet, complete system can be controlled by LabView (via network)

Spectroscopy at the ESR

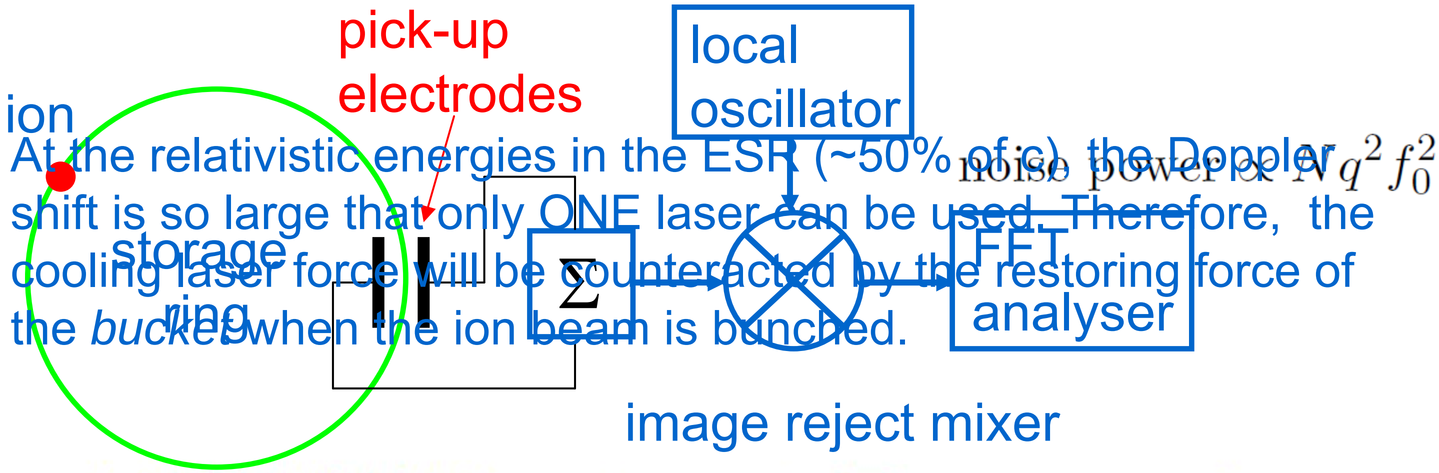
Injection Energy
400 MeV/u

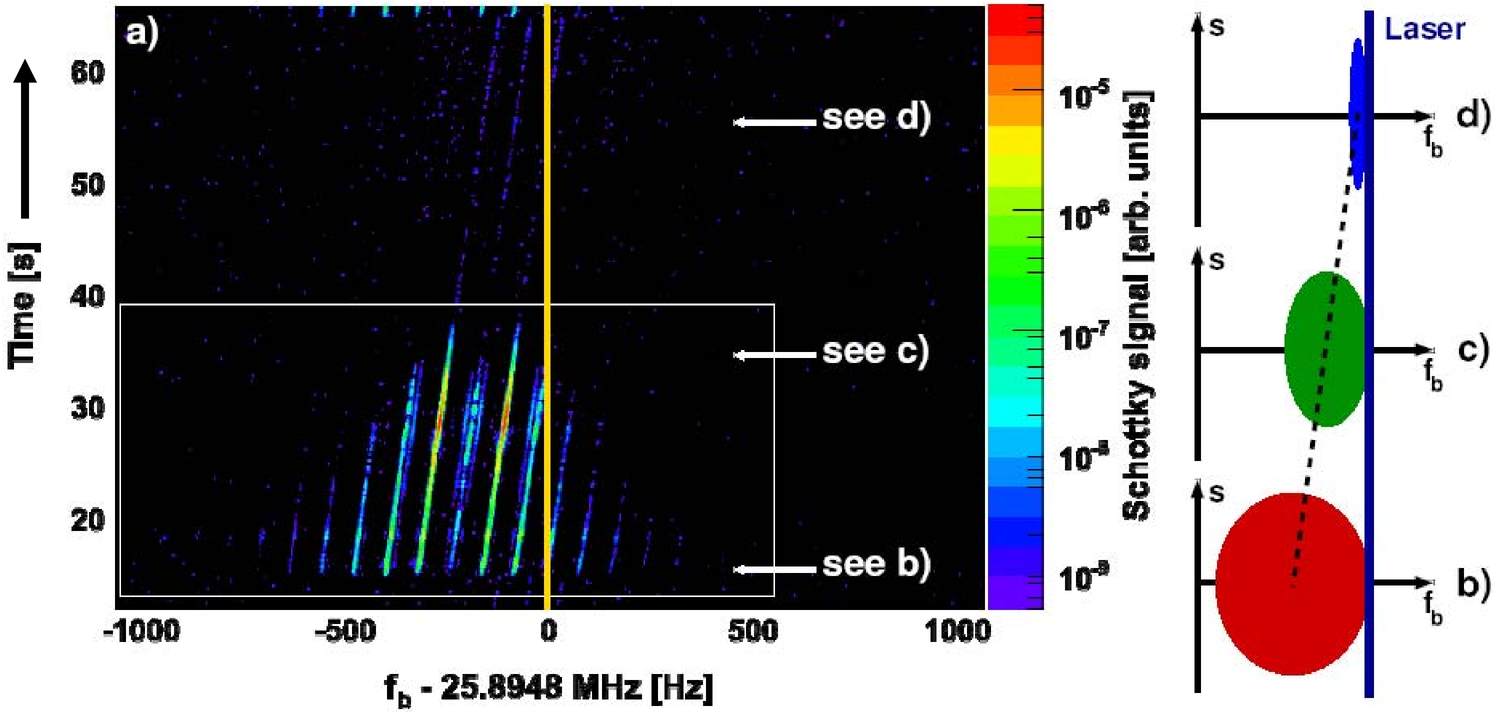
Experiment
4-400 MeV/u



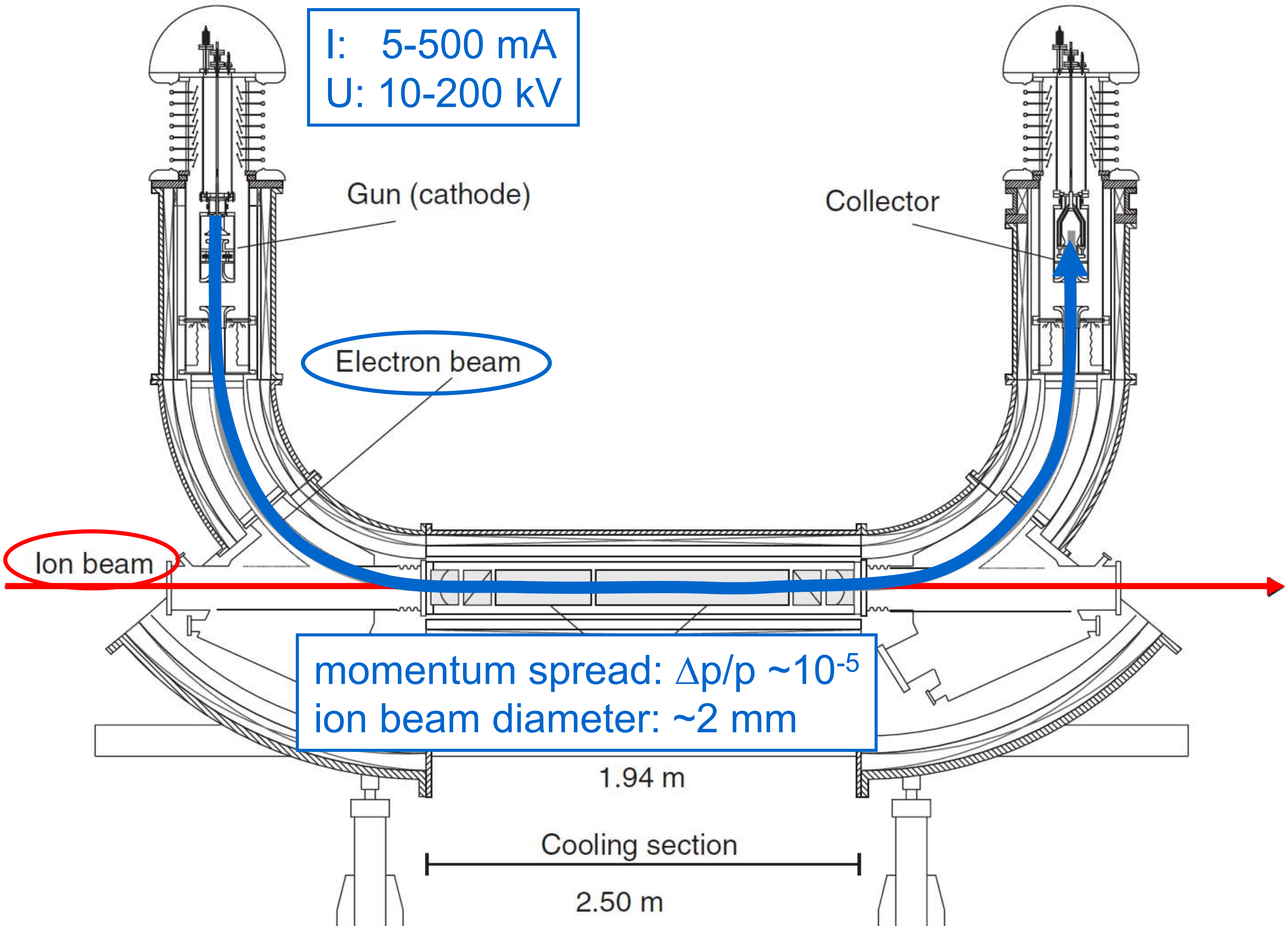
Schottky diagnostics at the ESR

At the relativistic energies in the ESR (~50% of c), the Doppler shift is so large that only ONE laser can be used. Therefore, the cooling laser force will be counteracted by the restoring force of the *bucket* when the ion beam is bunched.



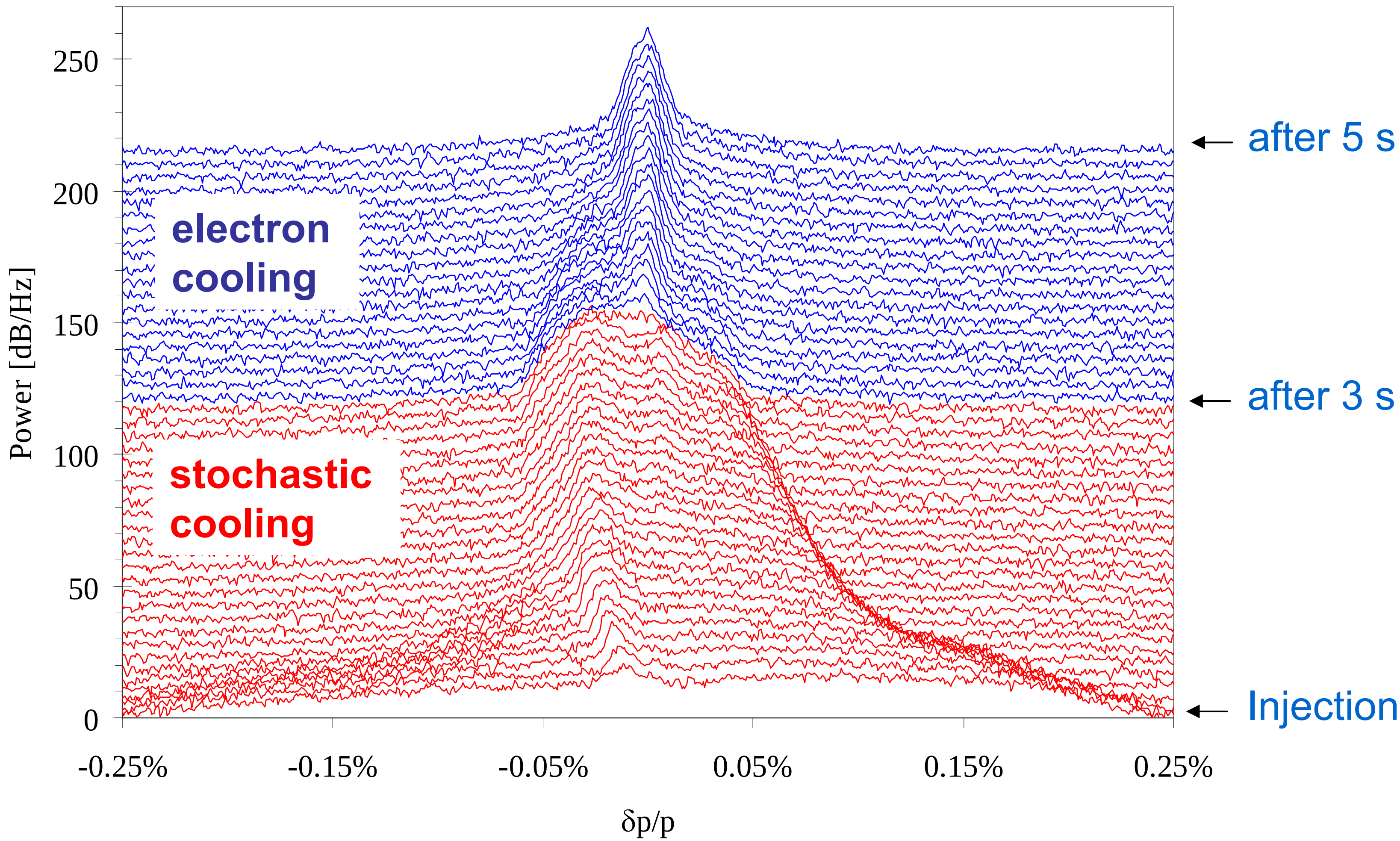


Electron cooler at the ESR



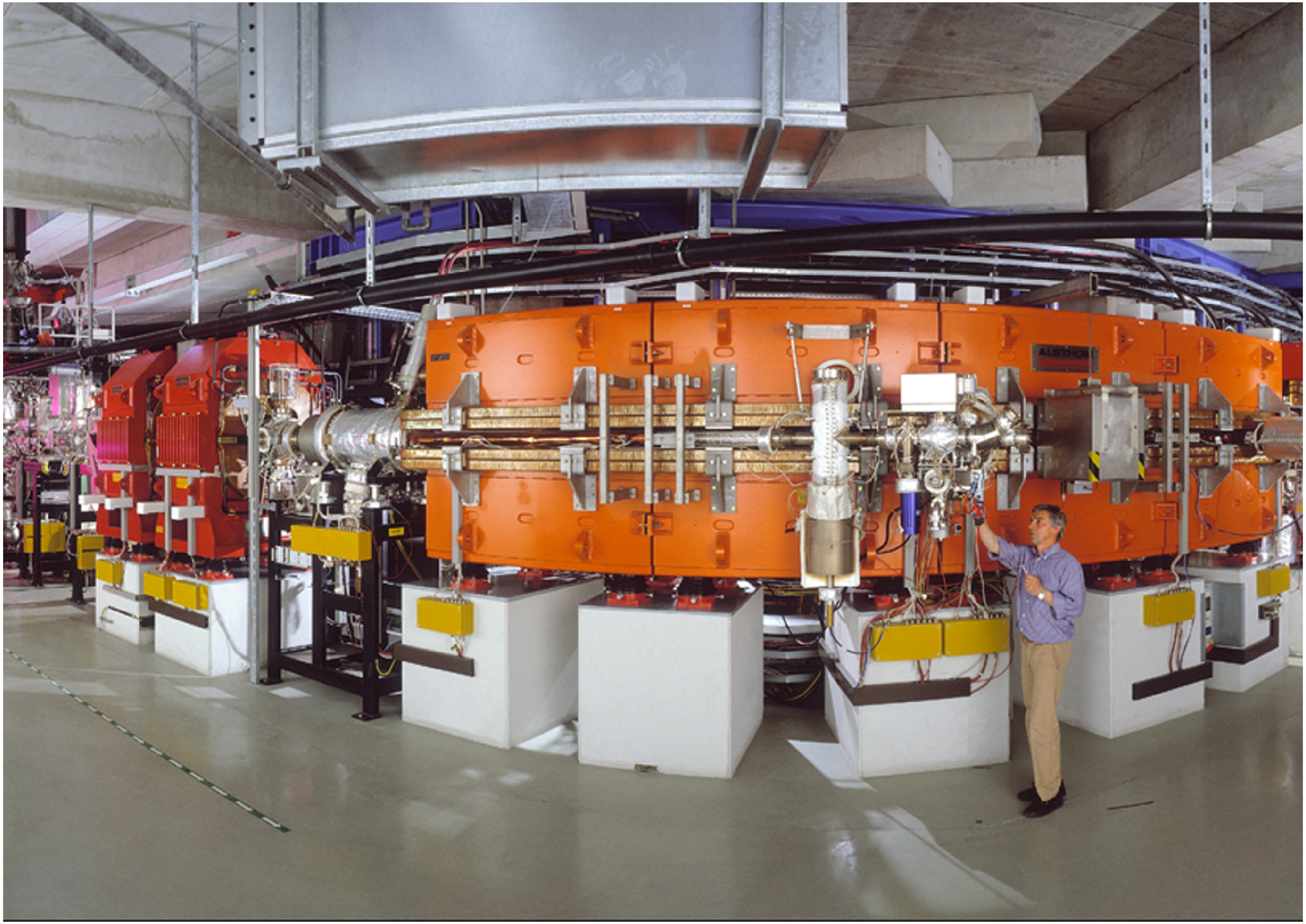
Cooling: narrowing velocity, size and divergence

uranium ions stored in the ESR

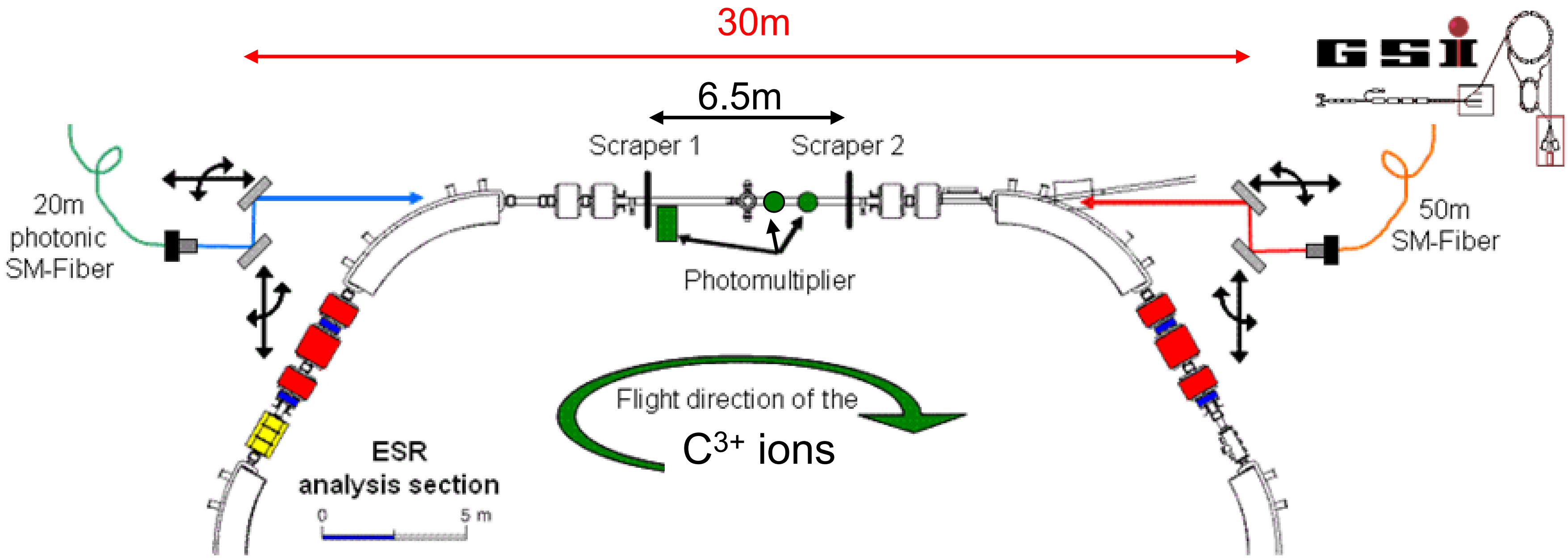


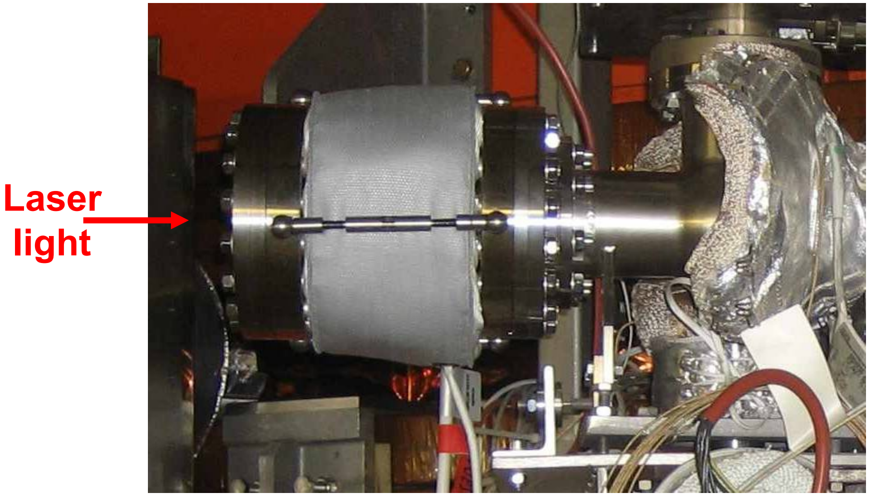
momentum distribution

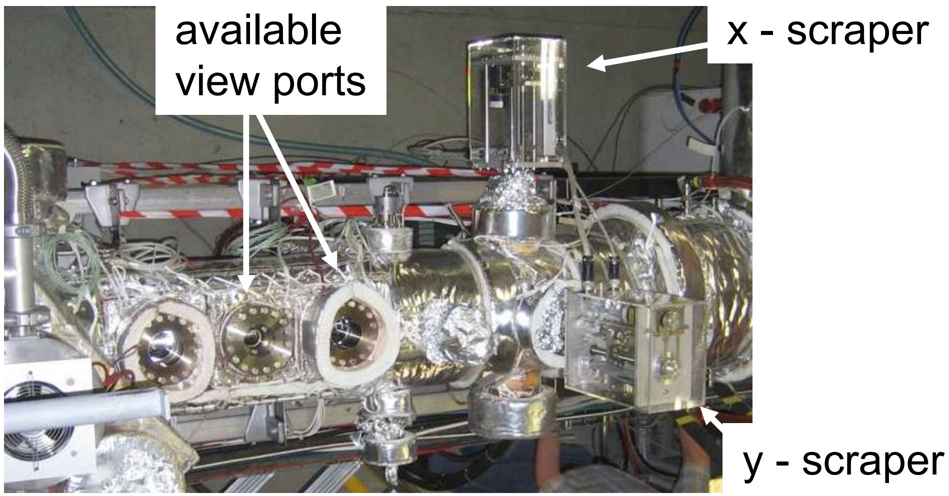
Photograph of the ESR



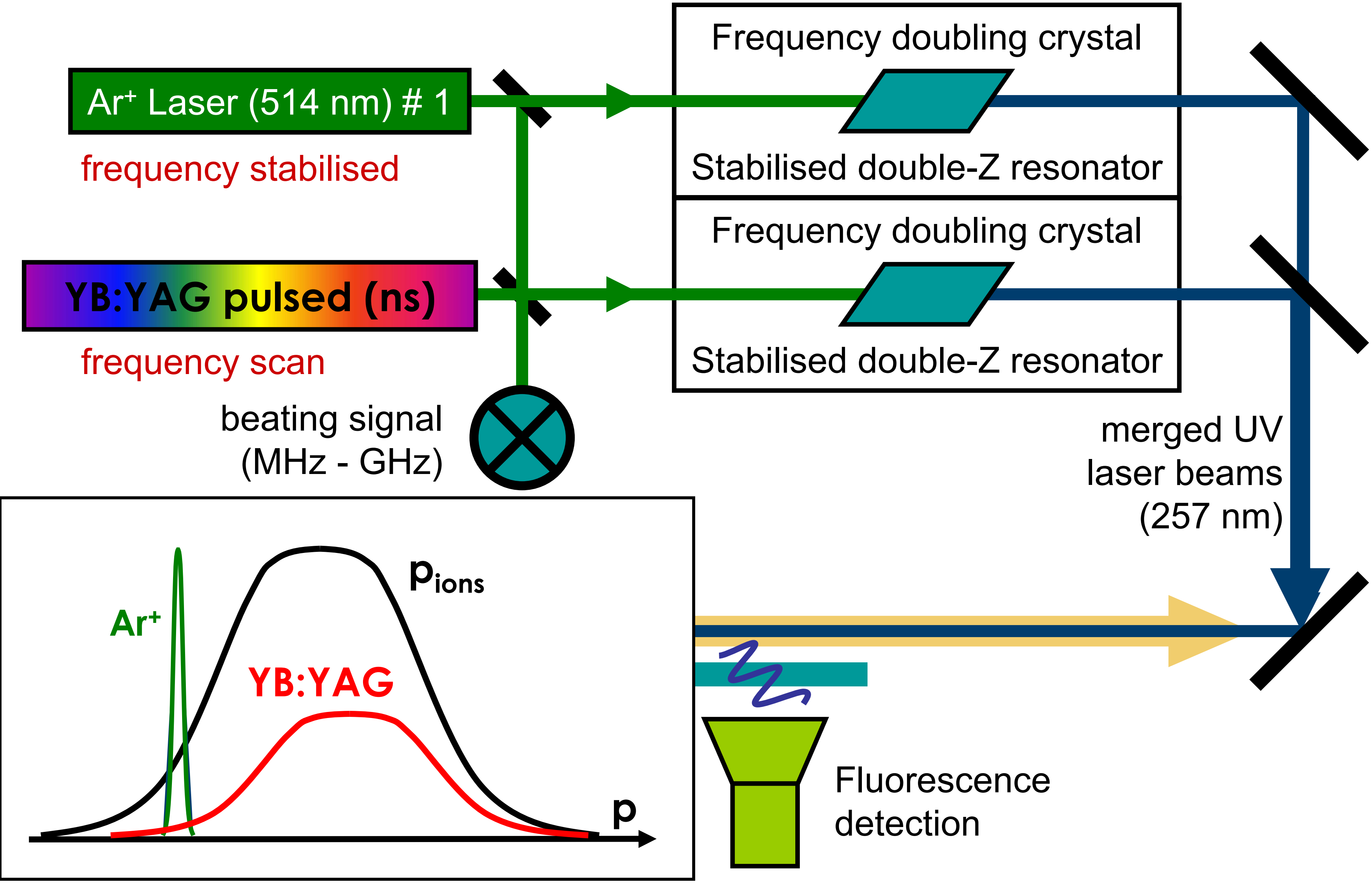
How to access the ESR?



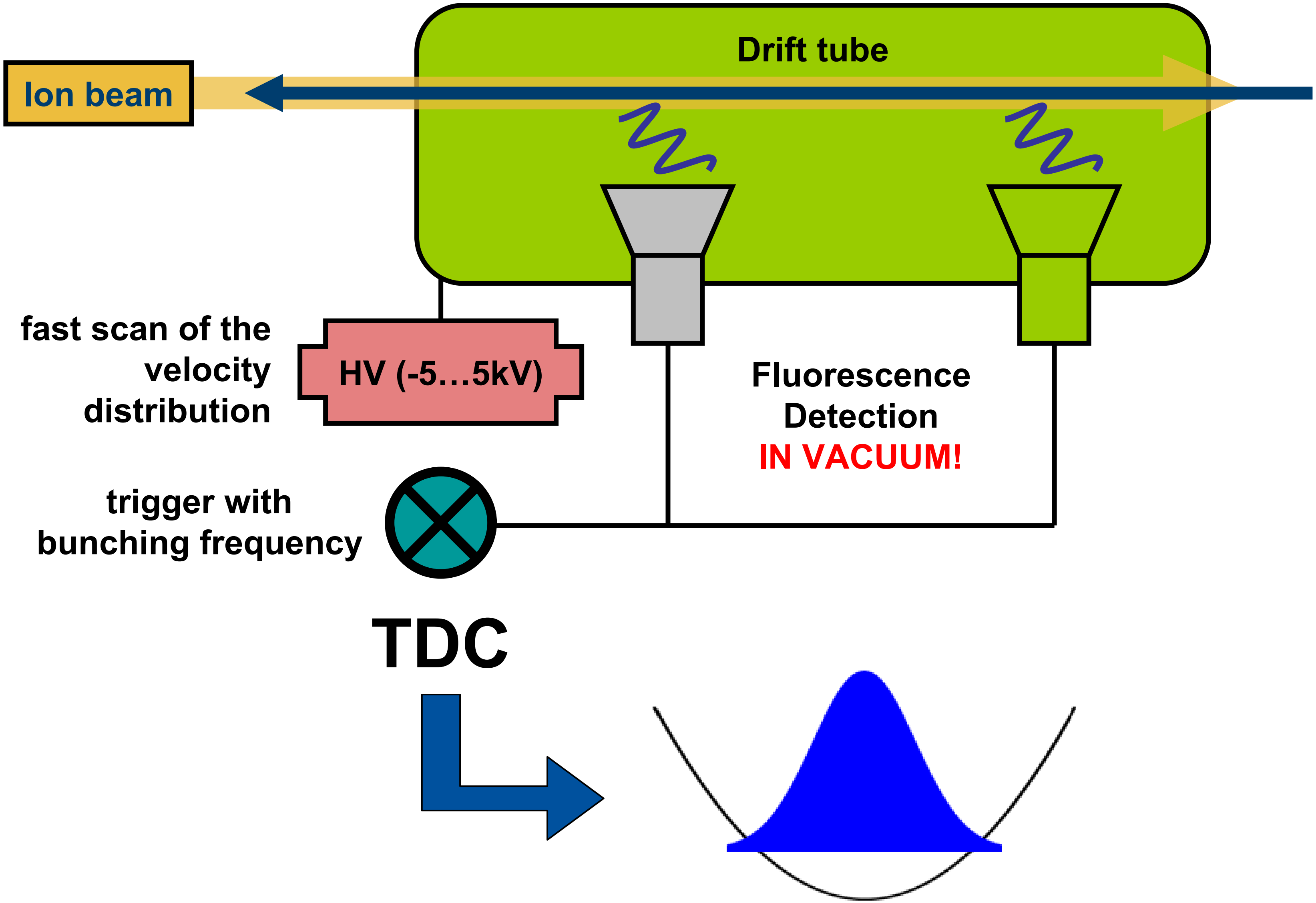




Laser systems for laser cooling



Optical Schottky Diagnosis



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	$\sim$60
Tune	$\sim$60	2.8	2.3	$\sim$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
$\hbar\omega_{out}(\Theta = 0°)$ (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: $<10^{-6}$	— $\approx 5 \times 10^{-5}$

Ultralow Momentum Spread & Strong Coupling

- ♦ pure electron cooling
- ◊ pure laser cooling
- ★ laser cooling + electron cooling (1 mA)

Dashed lines:

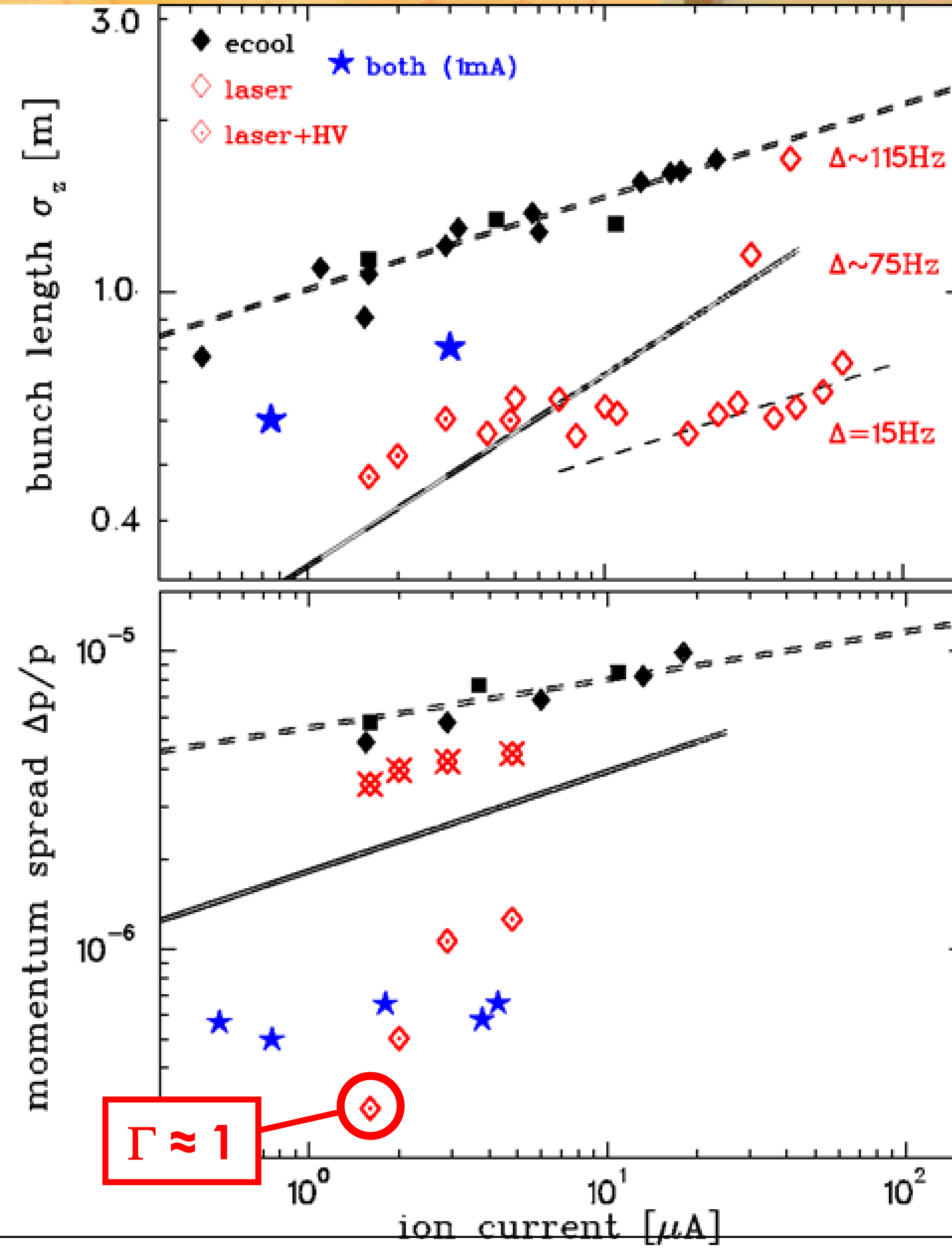
~ $N^{1/6}$ (IBS)

Solid lines:

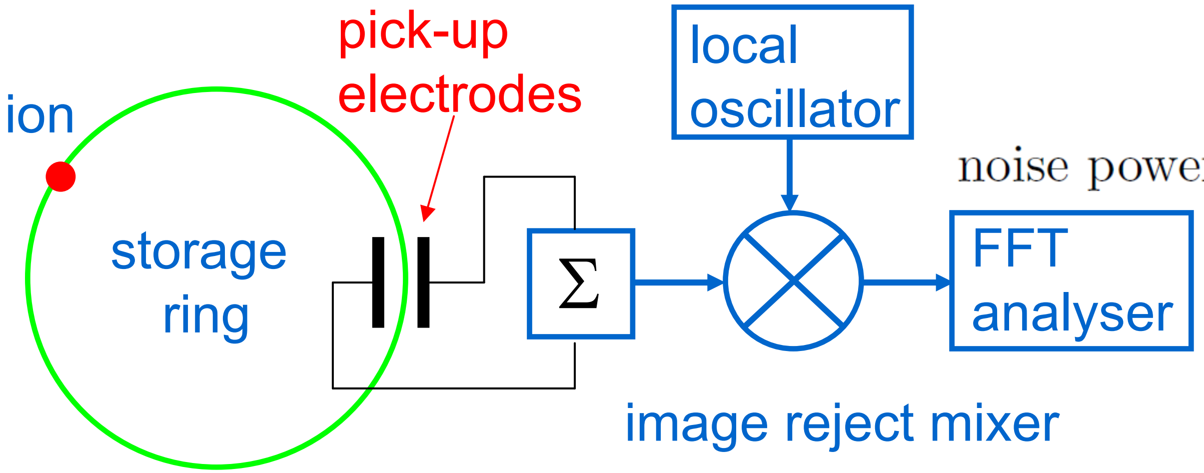
~ $N^{1/3}$ (space charge)

10 x smaller Momentum Spread

Strong Coupling observed (Needed for Crystallization)



Schottky mass spectrometry (ESR)



$$\text{noise power} \propto N q^2 f_0^2$$

$$\frac{\delta f}{f} = \eta \frac{\delta p}{p} = \left(\frac{1}{\gamma^2} - \alpha_p\right) \frac{\delta p}{p}$$

$$\gamma^2 = \frac{1}{1-\beta^2} \qquad \beta = v/c$$

$$f = n f_0$$

$$f_0 = (\beta c)/C$$

(velocity / circumference)

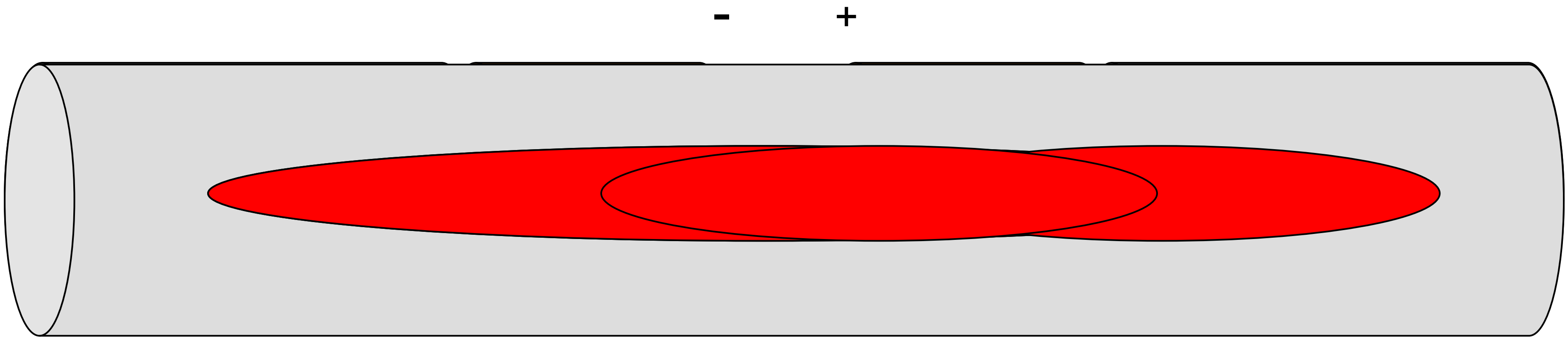
$$\alpha_p = \frac{dC/C}{d(B\rho)/(B\rho)}$$

$$B\rho = \frac{m}{qe}\gamma(\beta c)$$

(magnetic rigidity)

$$\frac{\delta f}{f} = -\alpha_p \frac{\Delta(m/q)}{(m/q)}$$

mass / charge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RF field ~