FRXAA1 – Laser Cooling of Relativistic Heavy Ion Beams

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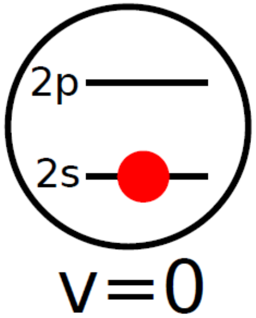
Laser Cooling in a Nustshell

Using fast atomic transitions in ions for laser cooling



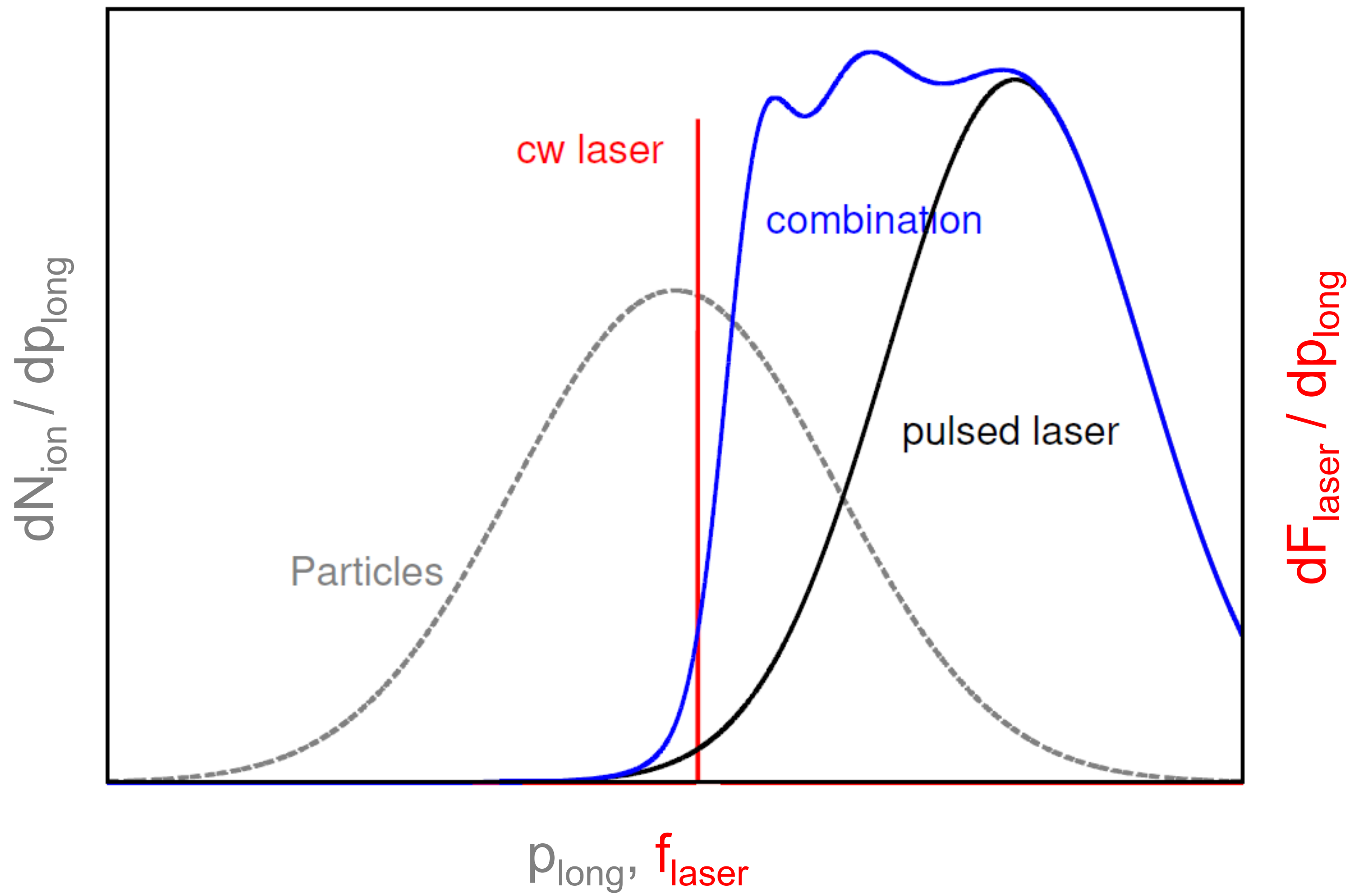
$$\omega_{laser} - \vec{k}_{laser} \cdot \vec{v}_{ion}$$

$$\vec{F}(\vec{v}_{ion}) = \pi\hbar\vec{k}_{laser} \times L(\omega) / \tau_{trans}$$

Photon Momentum

Scattering Rate

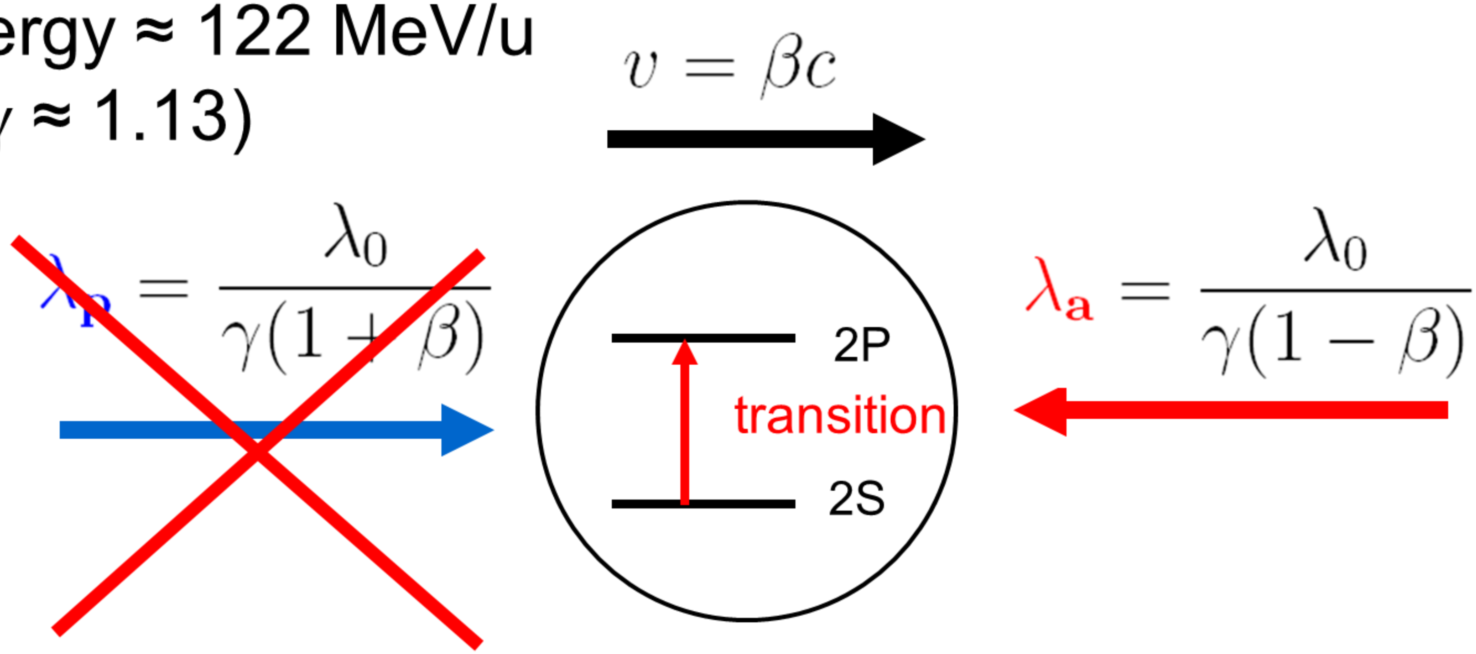
Laser force momentum acceptance range is small for cw-lasers



… but can be large for pulsed lasers

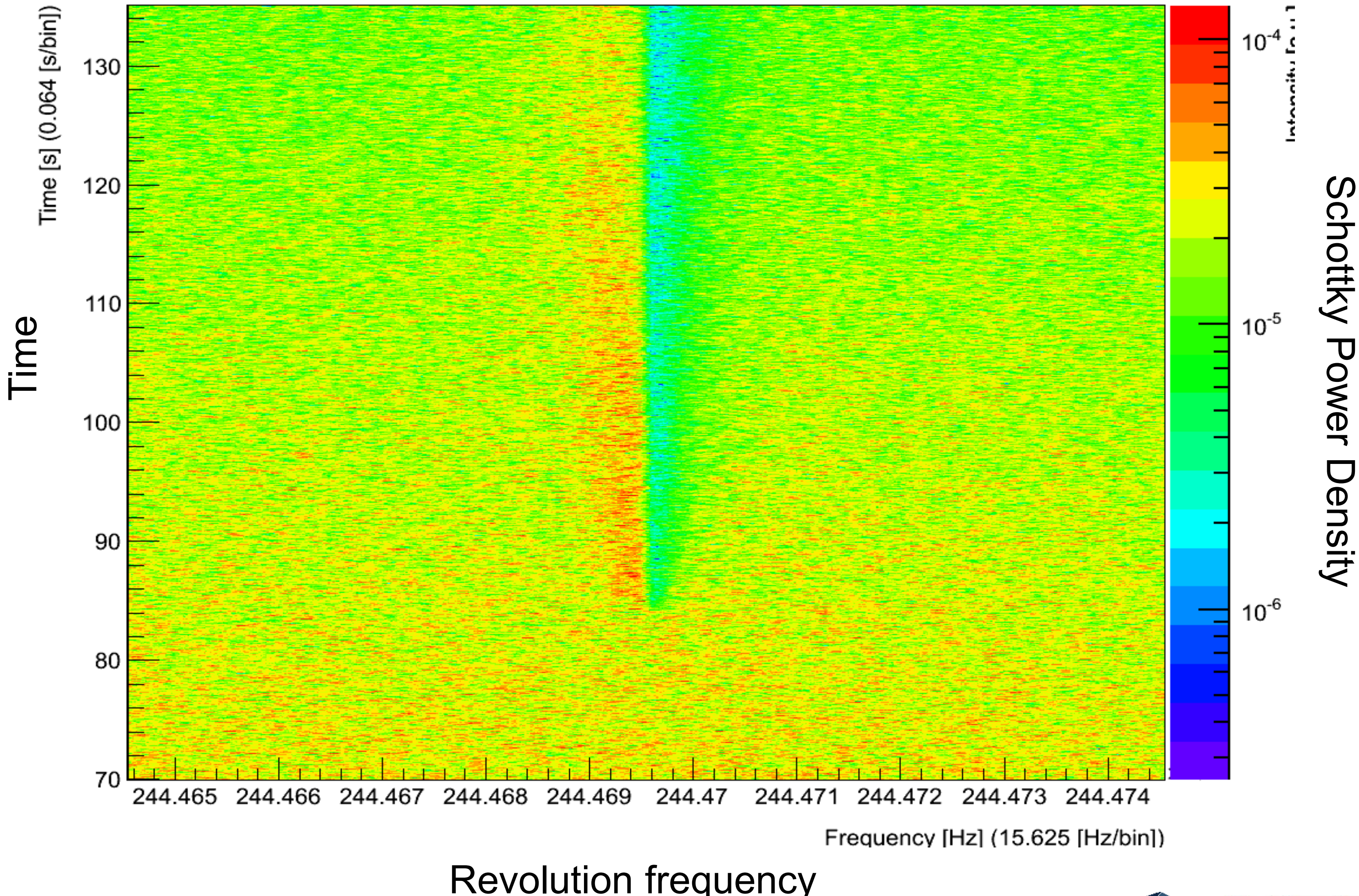
The relativistic Doppler shift of the laser wavelenghth is HUGE

ESR example:
C^{3+} ion energy ≈ 122 MeV/u
(β ≈ 0.47, γ ≈ 1.13)

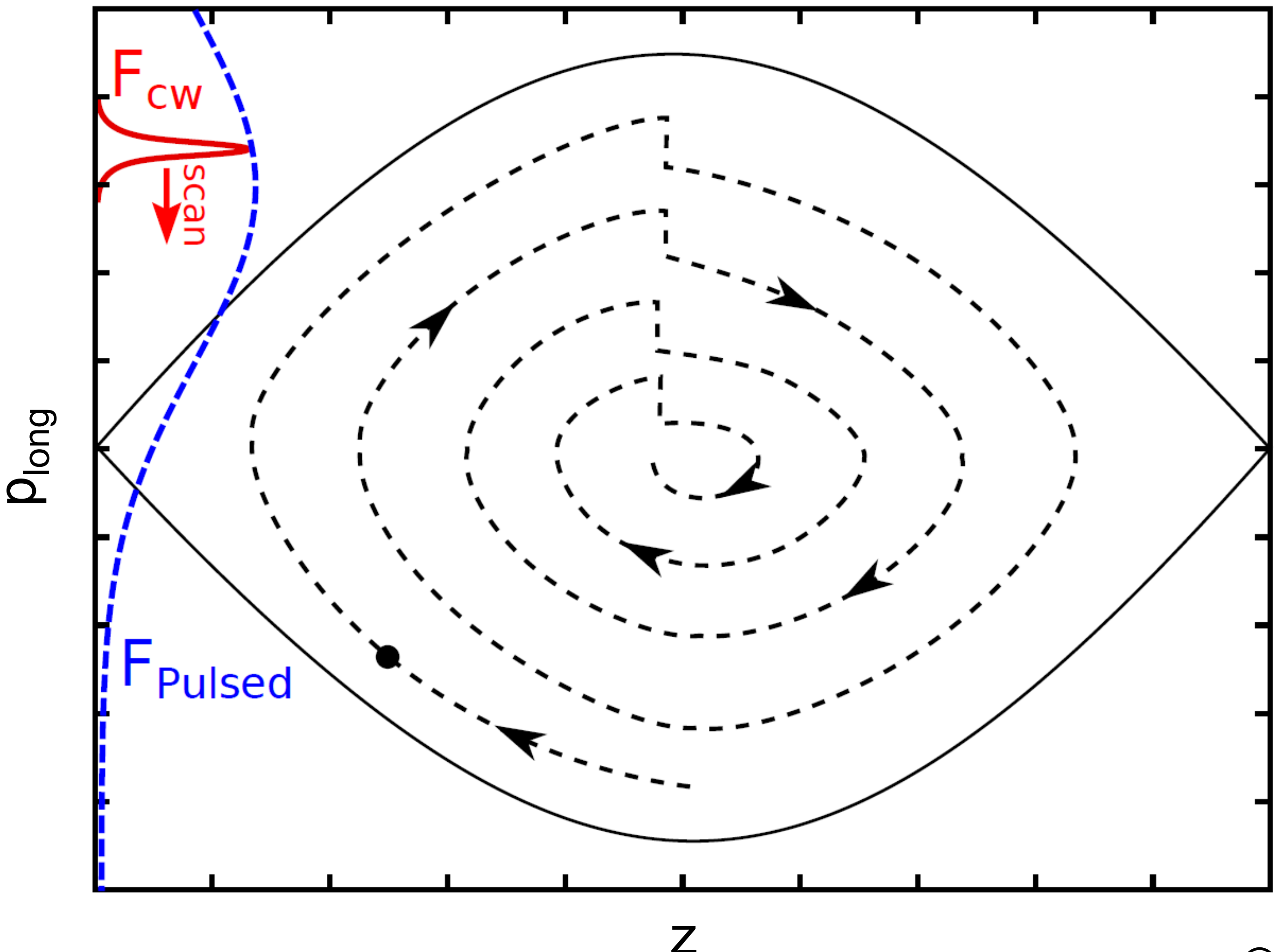


λ_p=93 nm λ_0=155 nm λ_a=257 nm

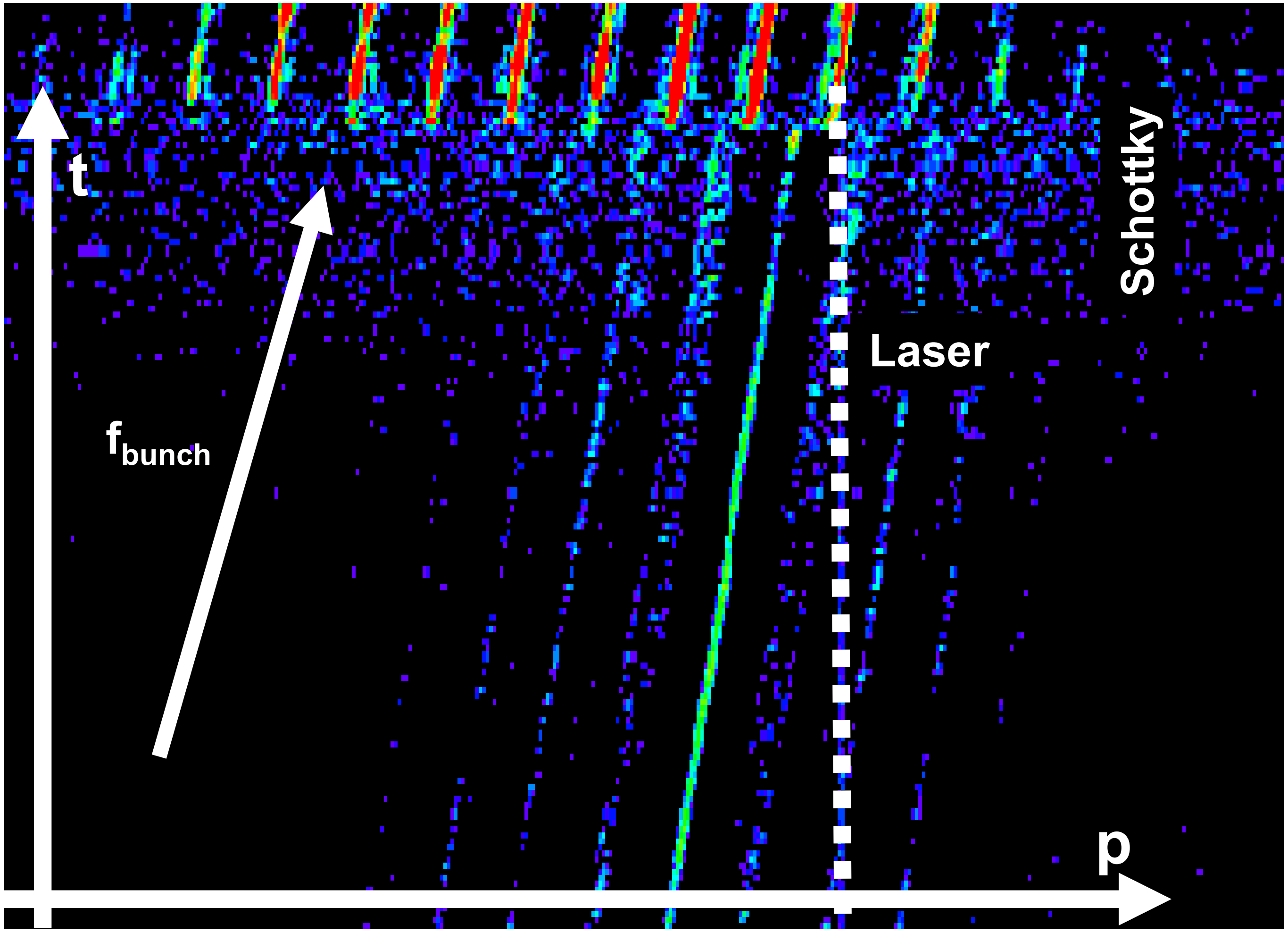
Cooling a coasting beam with a cw laser

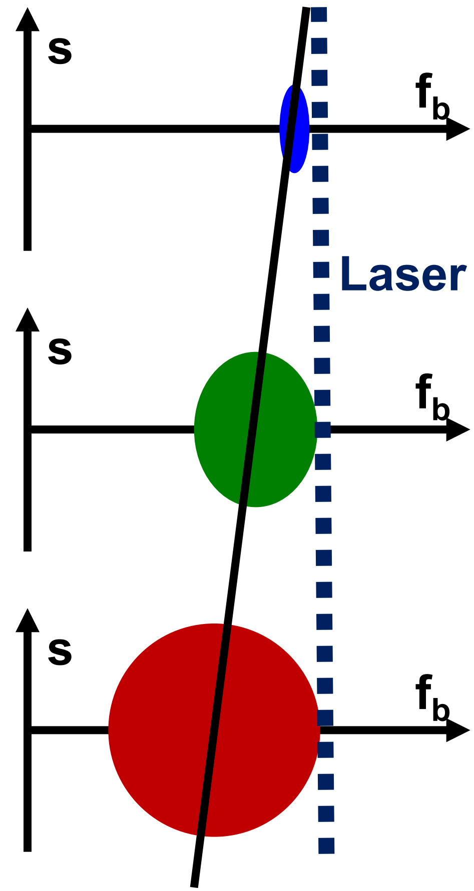


We need to bunch relativistic beams to have a stable cooling point



Technique 1: Scanning the bunching frequency





f_{bunch} = 20 x 1.295 MHz — $\Delta f_{bunch}/\Delta t$ = 20 Hz / 5 s — f_{sync} ~ 170 Hz — $\Delta p/p_{accept} \approx 10^{-5}$

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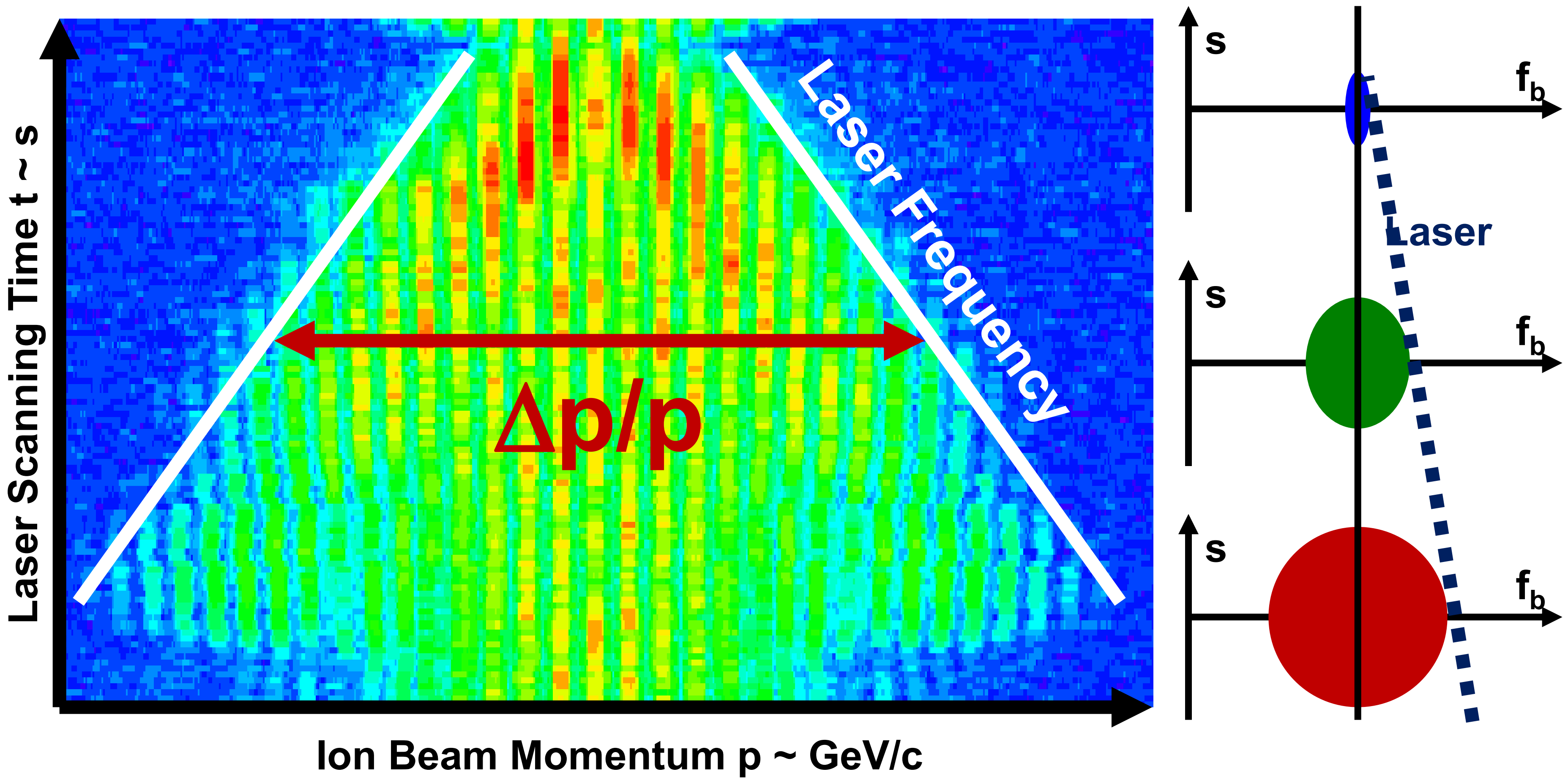
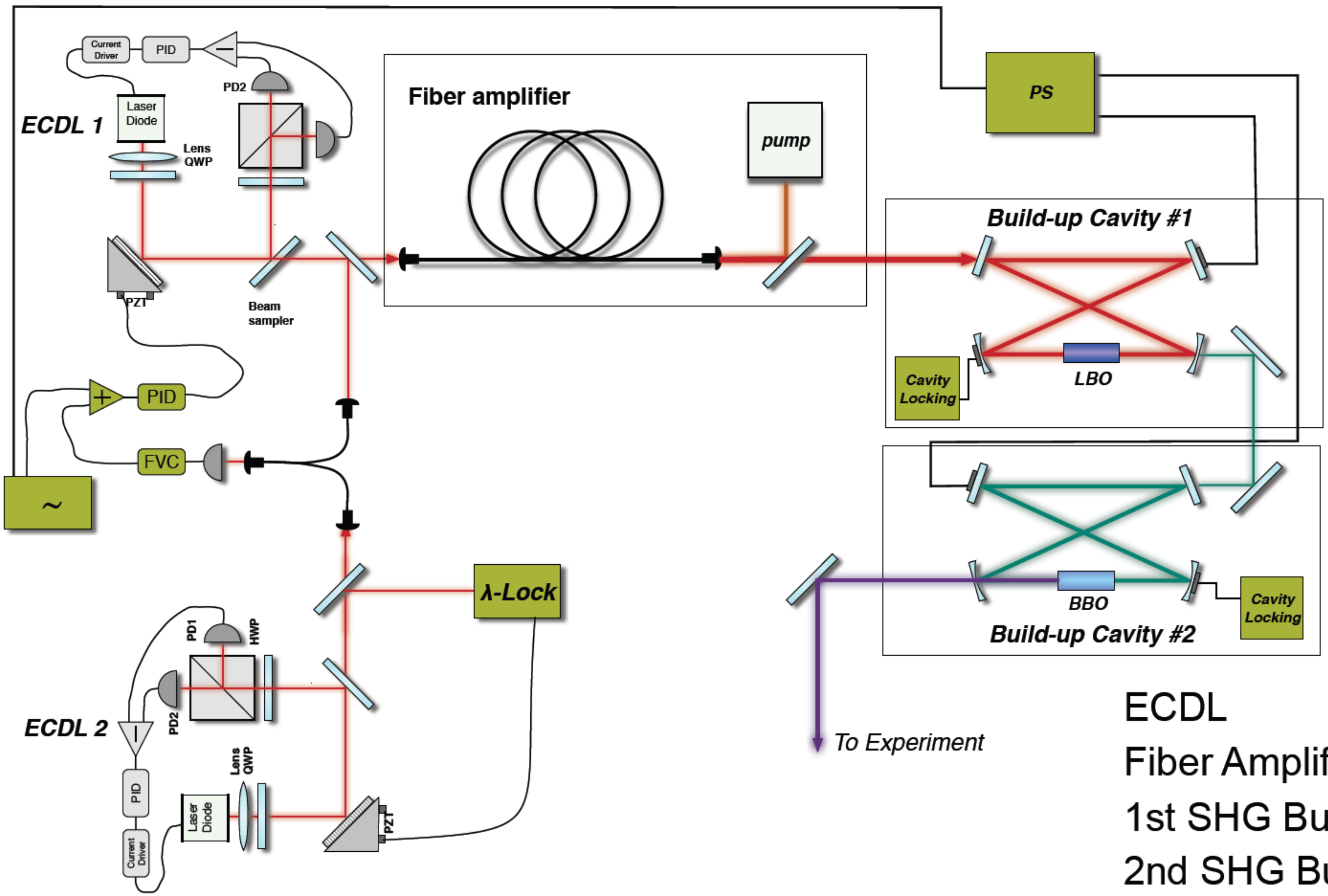
Technique 2: Scanning the laser frequency



Broad-scanning cw laser system (T. Walther, TU Darmstadt)



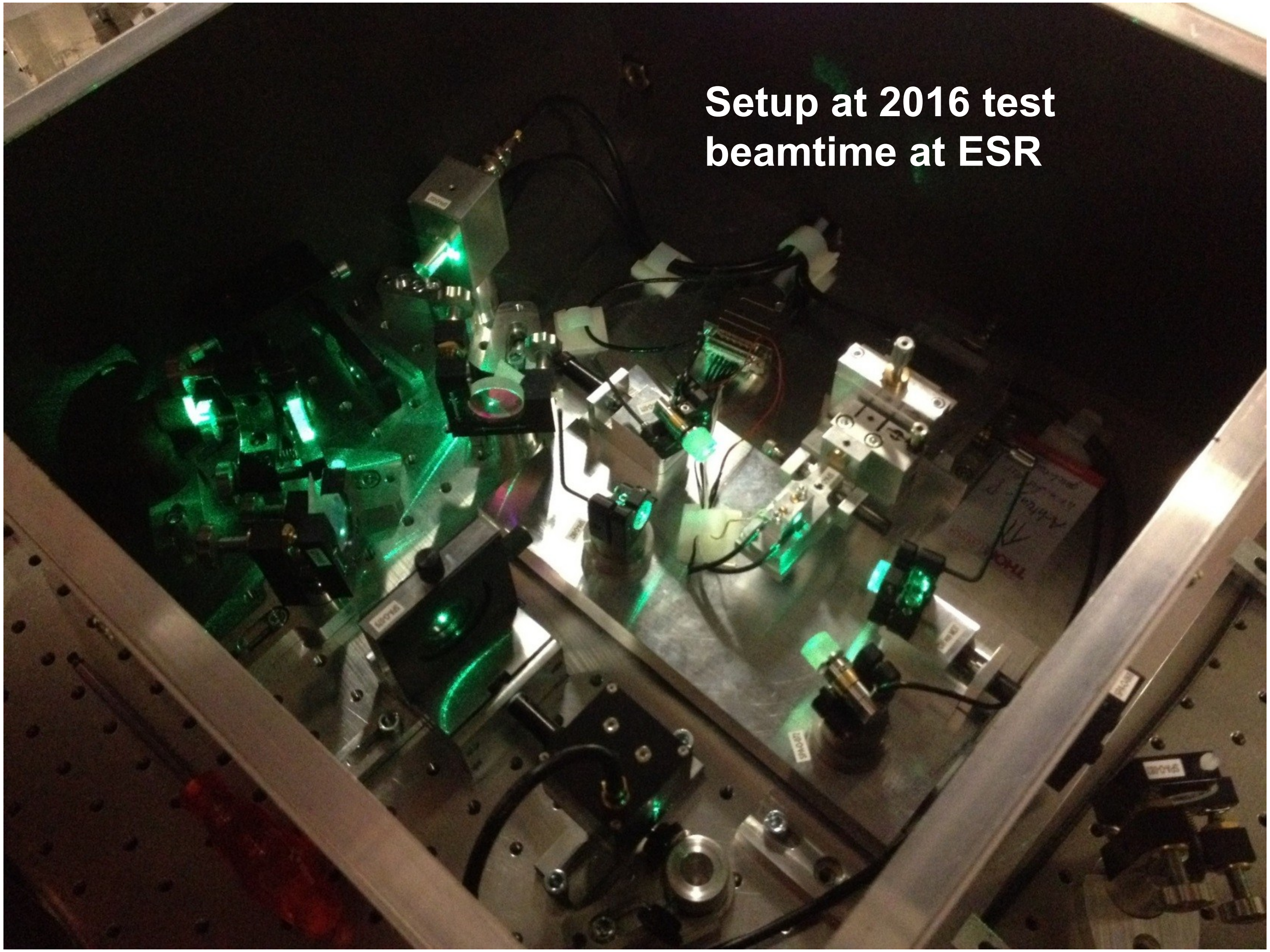
ECDL

Fiber Amplifier

1st SHG Built-up Cavity

2nd SHG Built-up Cavity

Broad-scanning cw laser system @ ESR, GSI, Darmstadt

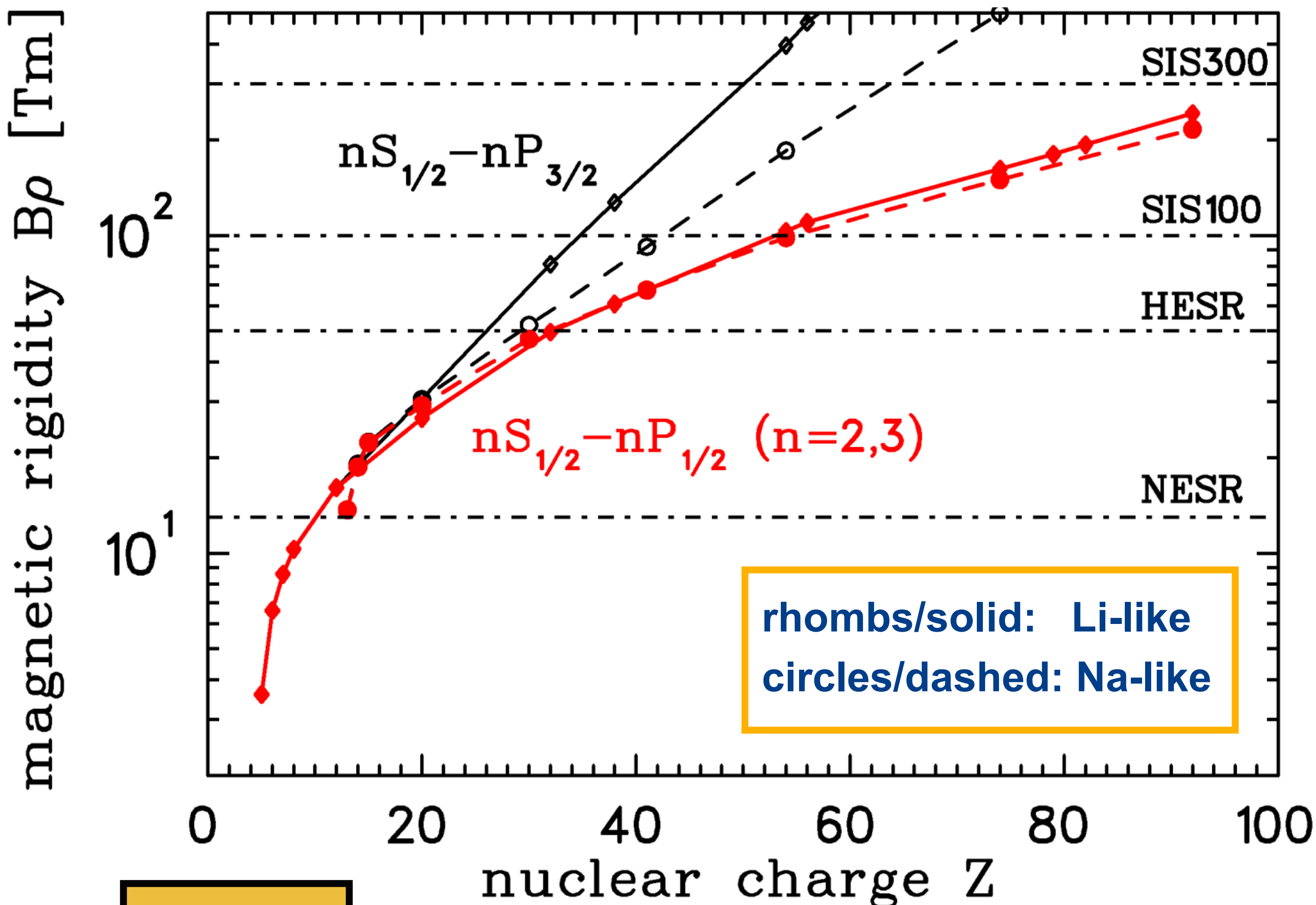


Laser cooling in a nutshell

- A cw laser has small momentum acceptance ($<10^{-7}$ dp/p)
- Scanning laser or bunching frequency can cool a large dp/p
- Pulsed lasers can cool large dp/p beams „in parallel“
- The relativistic Doppler shift affect transition wavelengths …
- … and lifetimes
- Typically, one needs bunching to have stable cooling

Towards high Energies

Addressing many ion species with a single laser system



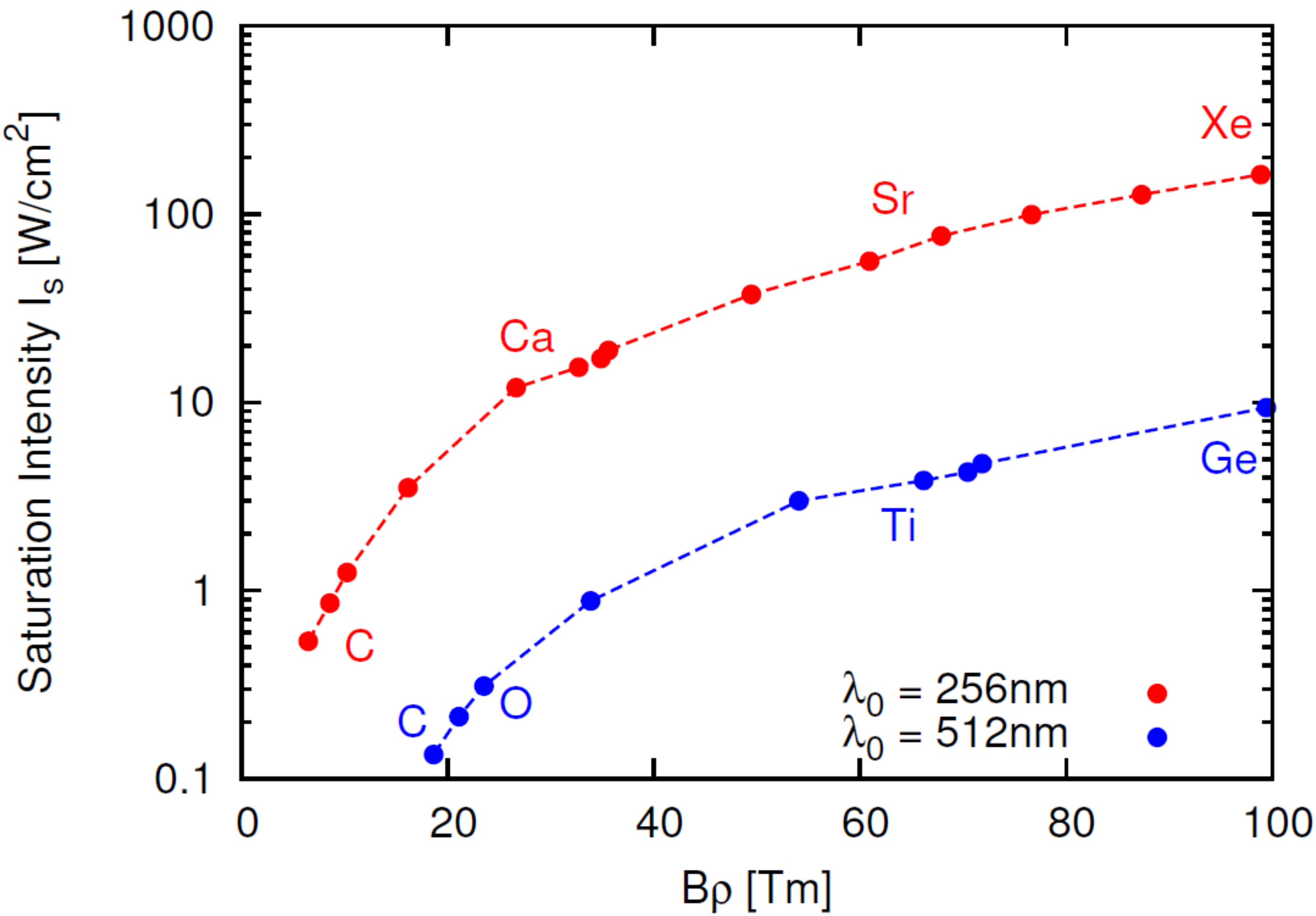
$\gamma \rightarrow B\rho$

Example: CSRe at IMP, Lanzhou

$$\gamma = \sqrt{((B\rho\, Qe)/(m_0 c)) + 1}$$

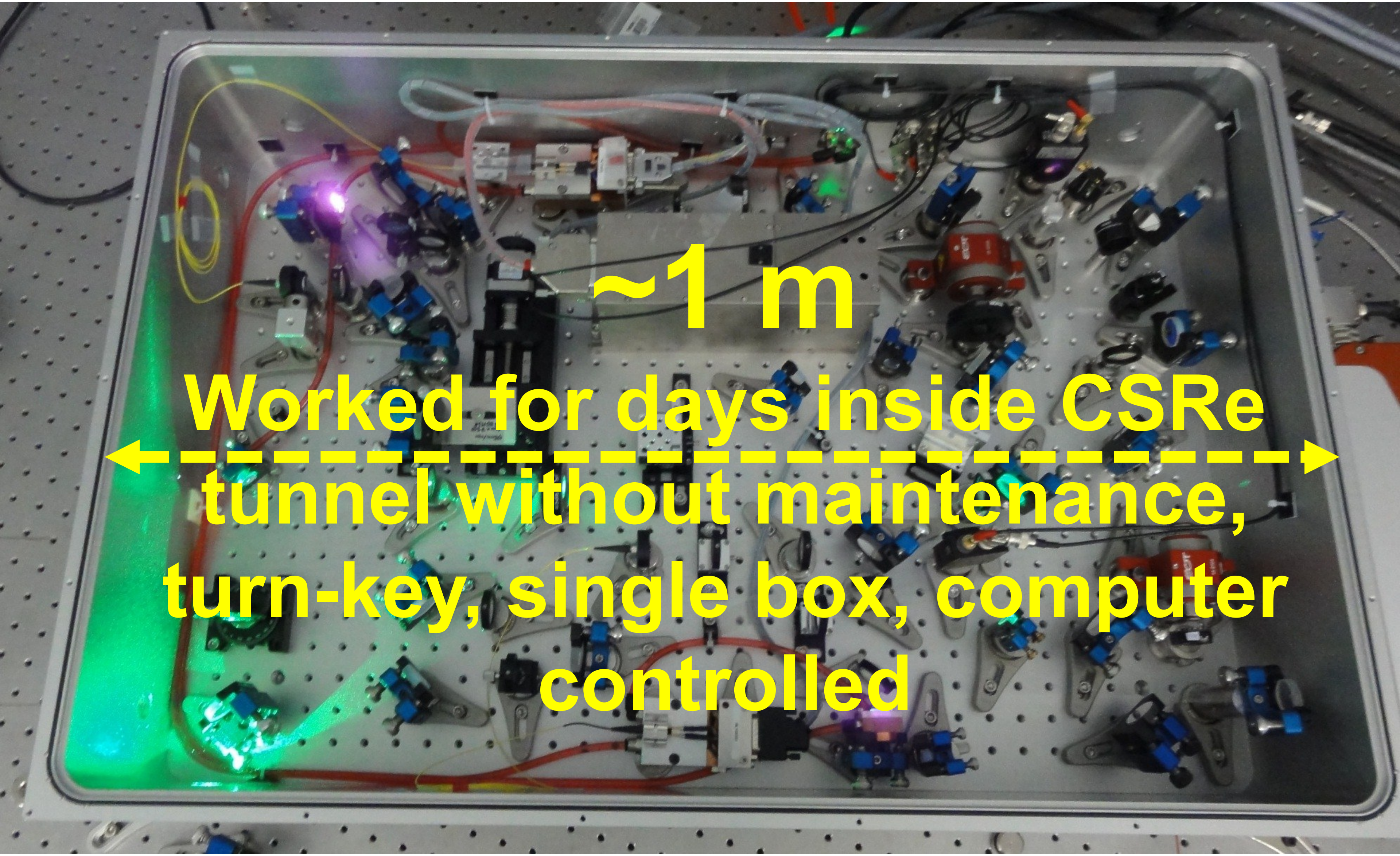
A	Q	$2P_{1/2}$ $2S_{1/2}$ rest	$2P_{1/2}$ $2S_{1/2}$ rest	γ	β	$2P_{1/2}$ $2S_{1/2}$ lab	$2P_{1/2}$ $2S_{1/2}$ lab
9	1	313.2	315.2	1.06	0.32	**435.7**	**438.5**
11	2	206.8	206.6	1.14	0.48	**349.8**	**349.5**
12	3	155.1	154.8	1.25	0.60	**311.7**	**311.2**
14	4	124.3	123.9	1.32	0.65	**271.7**	**270.8**
16	5	103.8	103.2	1.38	0.69	**240.9**	**239.6**

We need LOTS of laser power to saturate cooling transitions

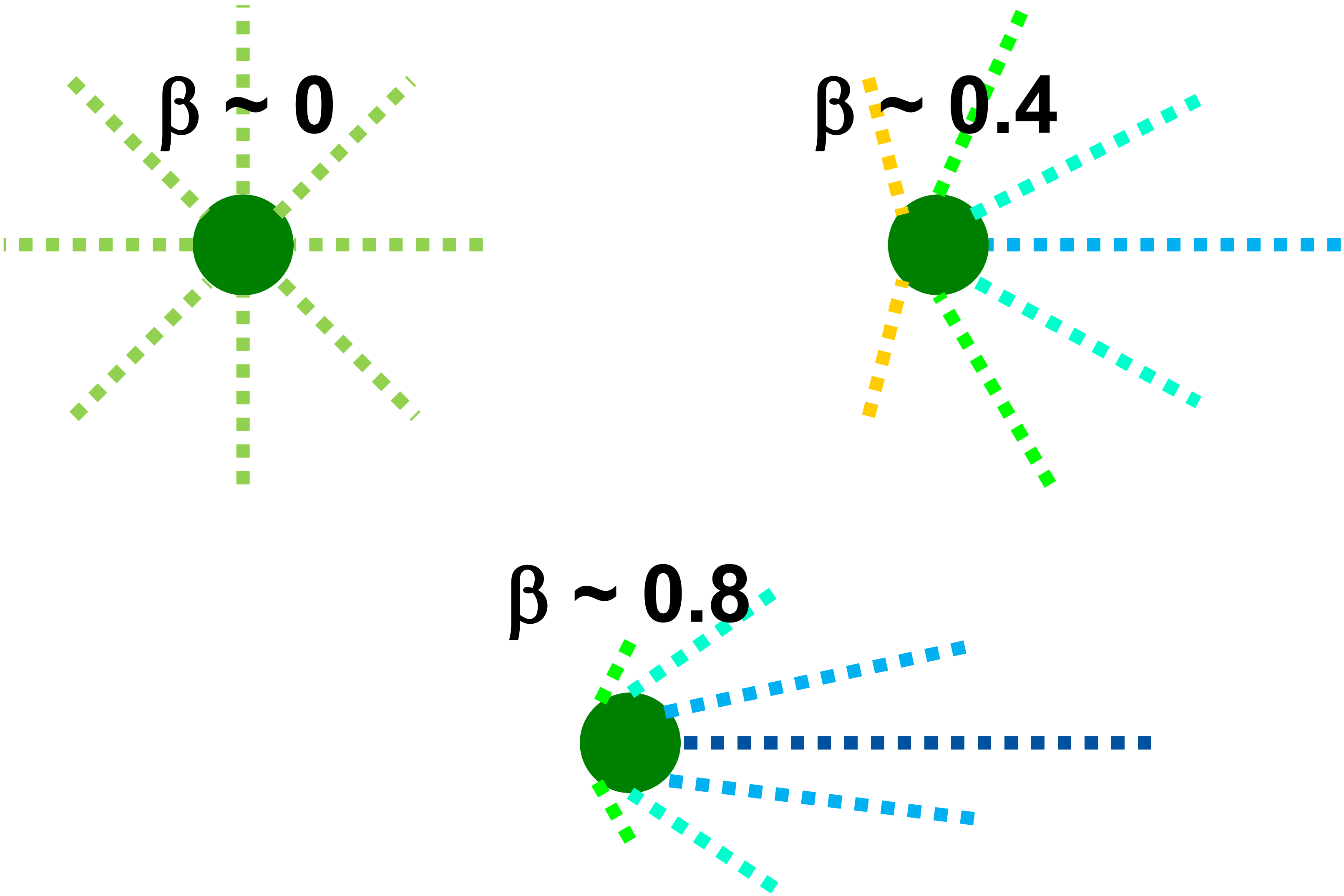


e.g. Ø10 mm @ SIS 100 relates to 100 W @ 257 nm

Turn-key pulsed laser system (Δp/p acc. ~ 10^{-4}, MHz repetition rate)



Lorentz-boosted fluorescence as diagnostic



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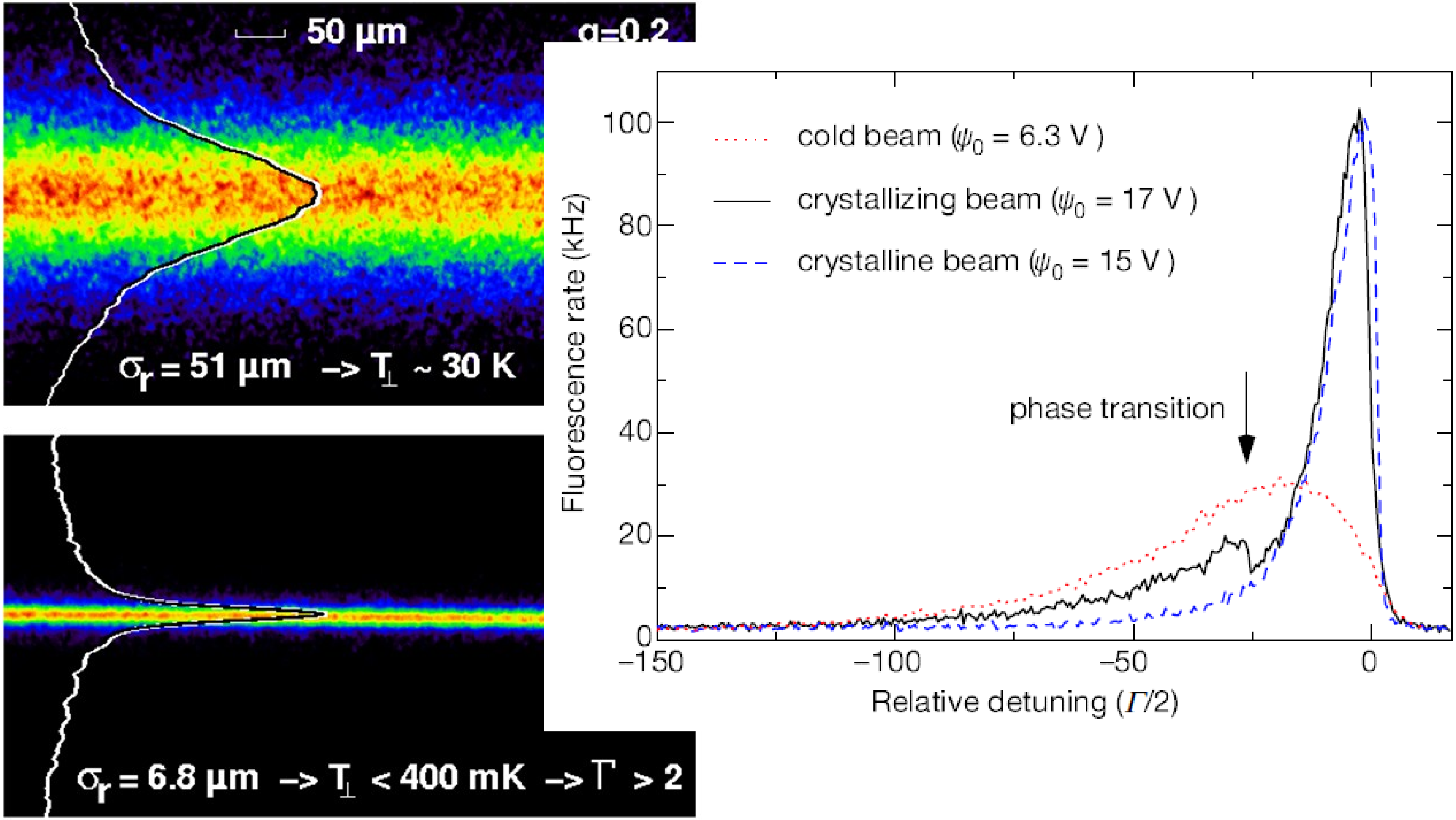
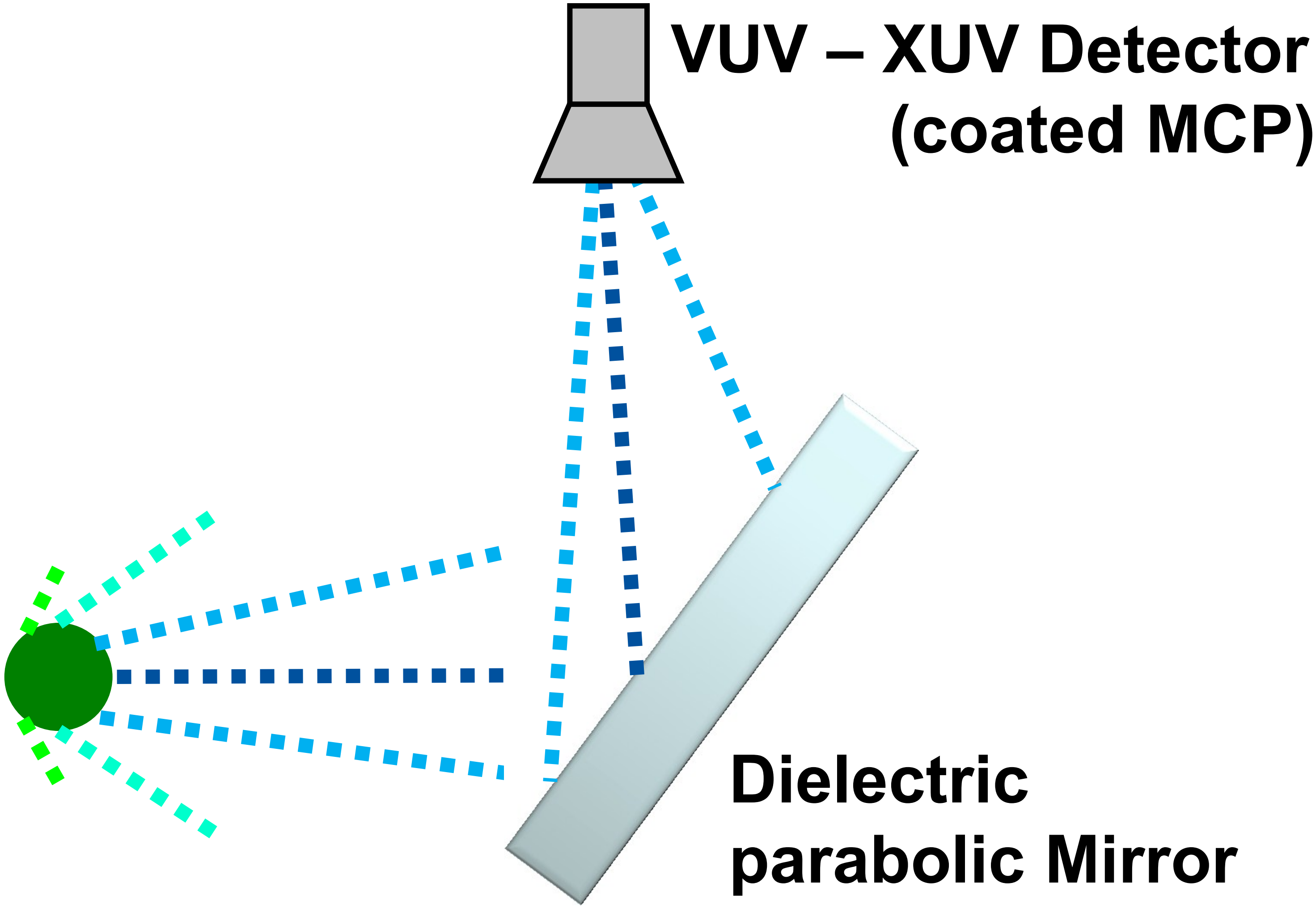
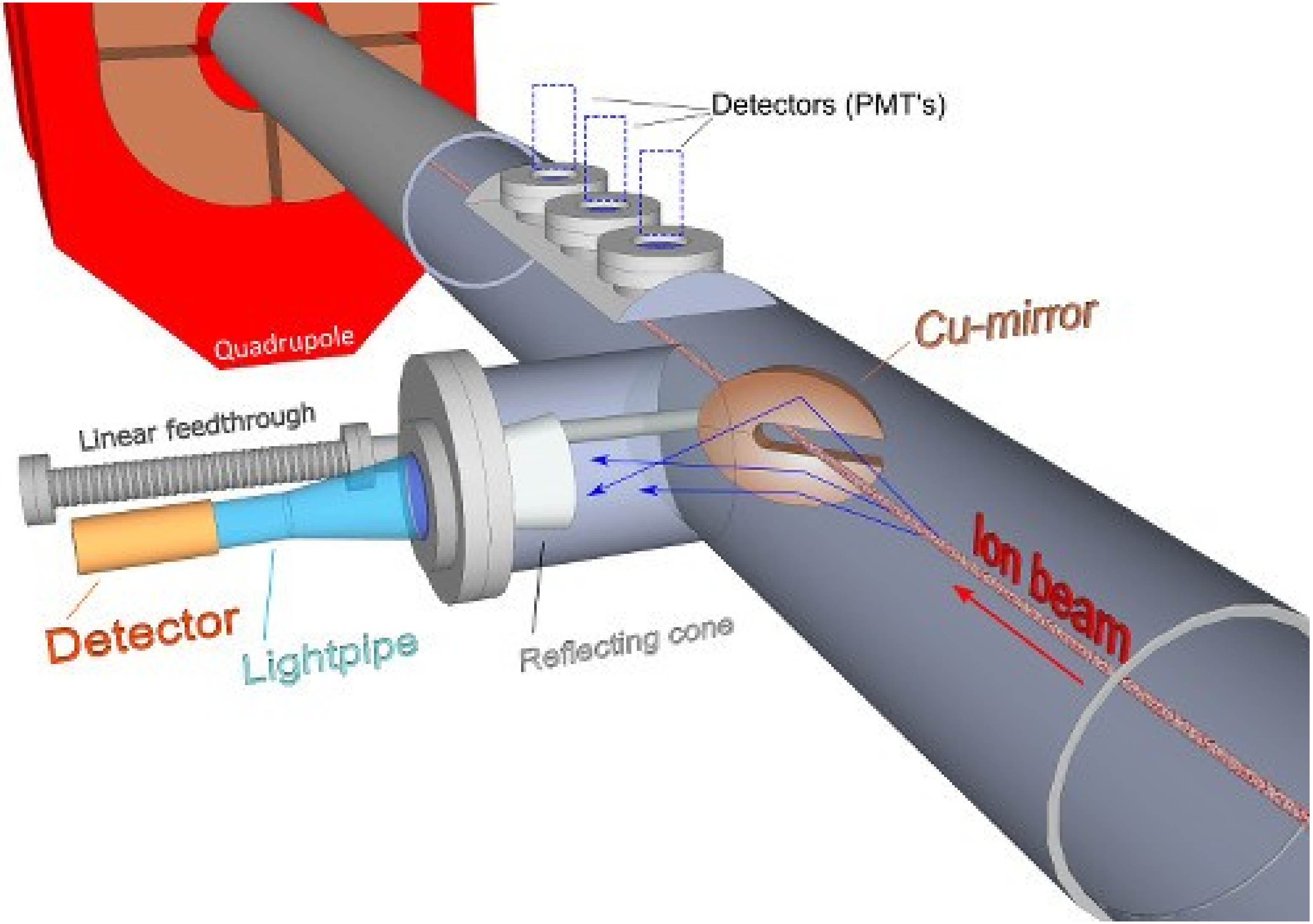
Using fluorescence intensity as a diagnostic (@ PALLAS)



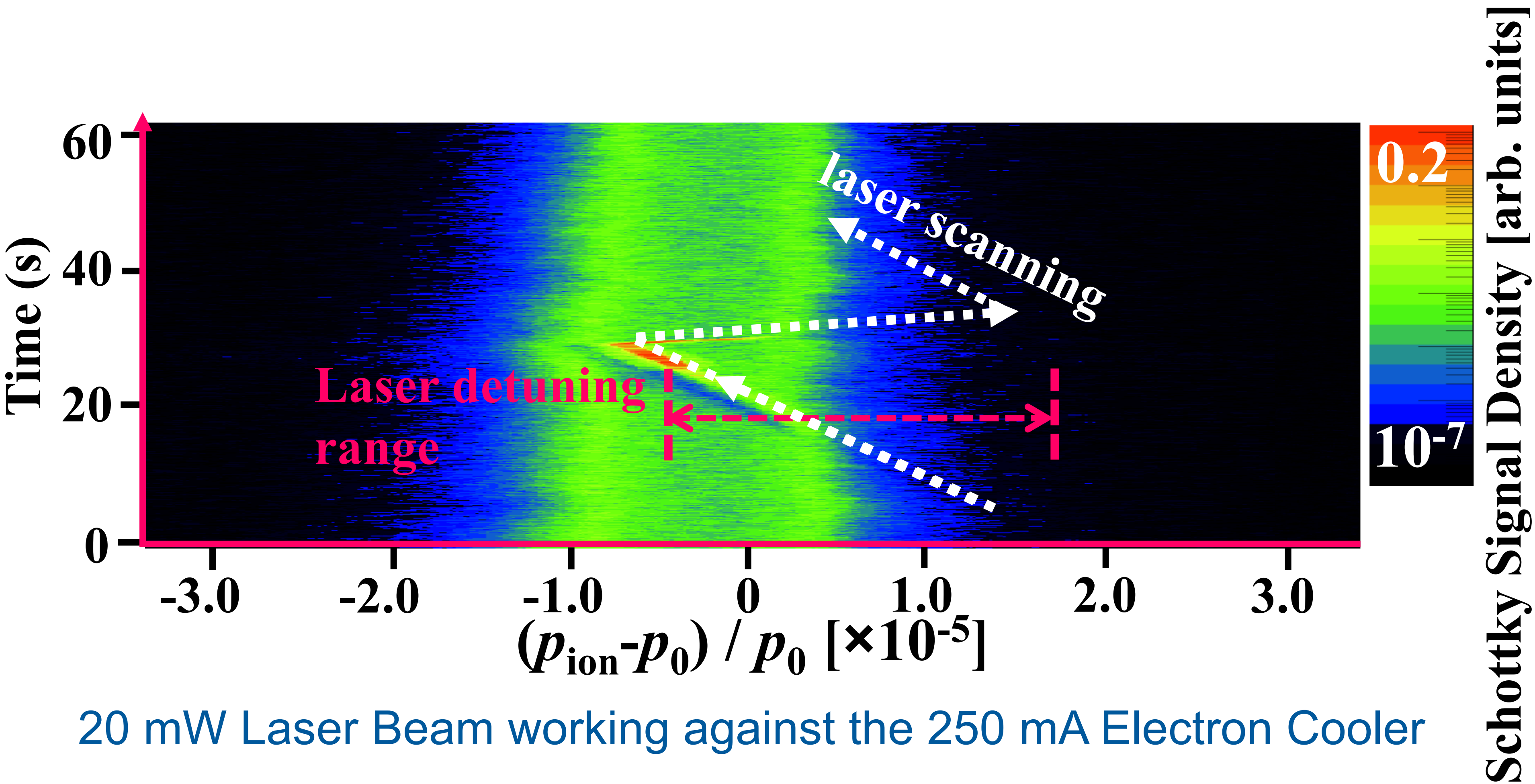
The in-beam mirror concept



In-beam mirror design (updated in 2016, M. Lochmann, V. Hannen)



Laser cooling force increases with beam energy



20 mW Laser Beam working against the 250 mA Electron Cooler

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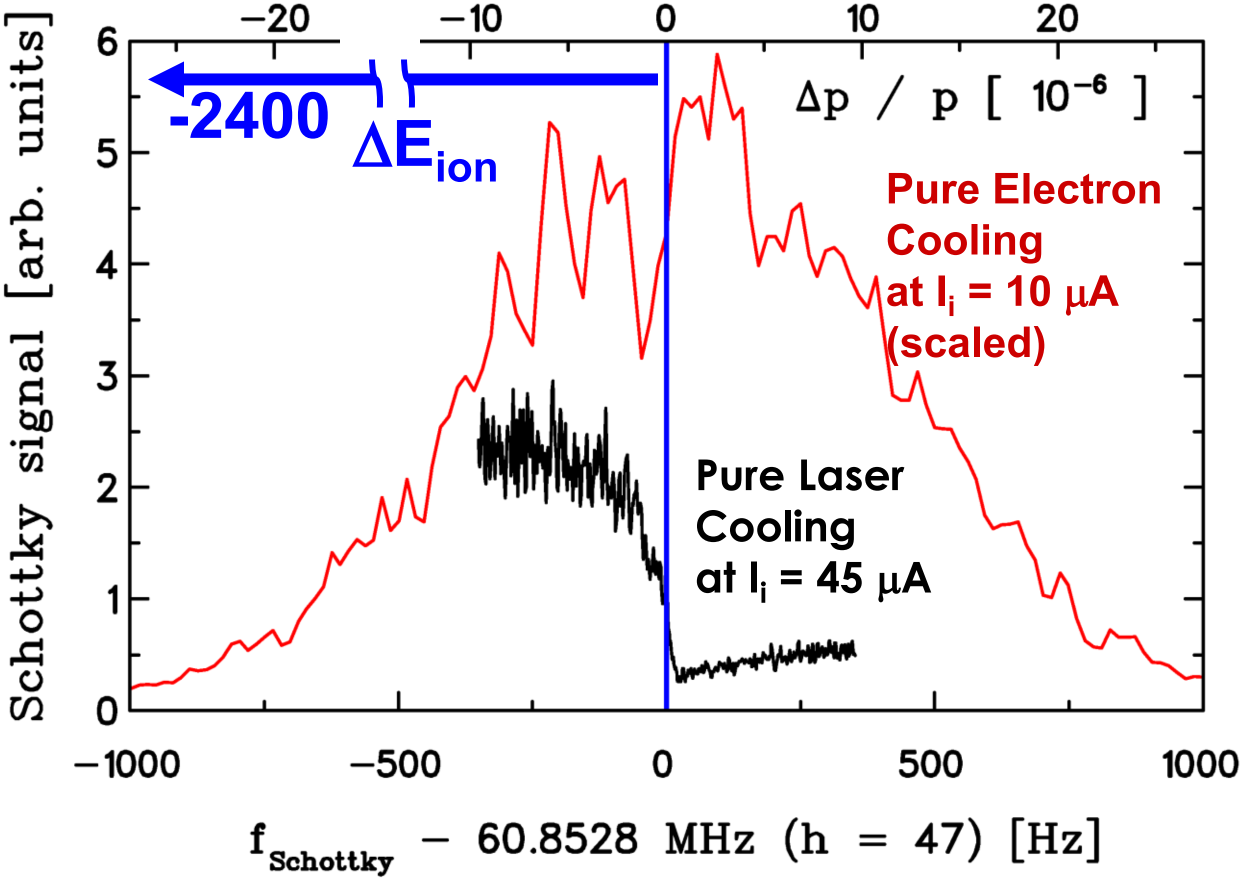
Towards high energies

- The relativistic Doppler effect „shifts“ the transition wavelength
- We use this to cool many ion species with a single laser system
- With increasing energies the laser force becomes stronger
- With increasing energies and ion charge we need more power
- Pulsed lasers can deliver enough power in a compact form
- Fluorescence detection is complimentary to standard techniques

Spectroscopy

C^{3+} spectroscopy in the old days



- Mark Doppler-shifted transition in Schottky spectrum (coasting)
- Adjust electron cooled distribution to the same revolution frequency
- Extrapolate to zero ion current to eliminate space charge effects

Uncertainty in absolute ion energy

	λ ($2S_{1/2} \rightarrow 2P_{1/2}$) [nm]	λ ($2S_{1/2} \rightarrow 2P_{3/2}$) [nm]
ESR C3+ experiment	155.0705 (39) (3)	154.8127 (39) (2)
Theory (I. Tupitsyn, V. Shabaev)	155.0739 (26)	154.8173 (53)

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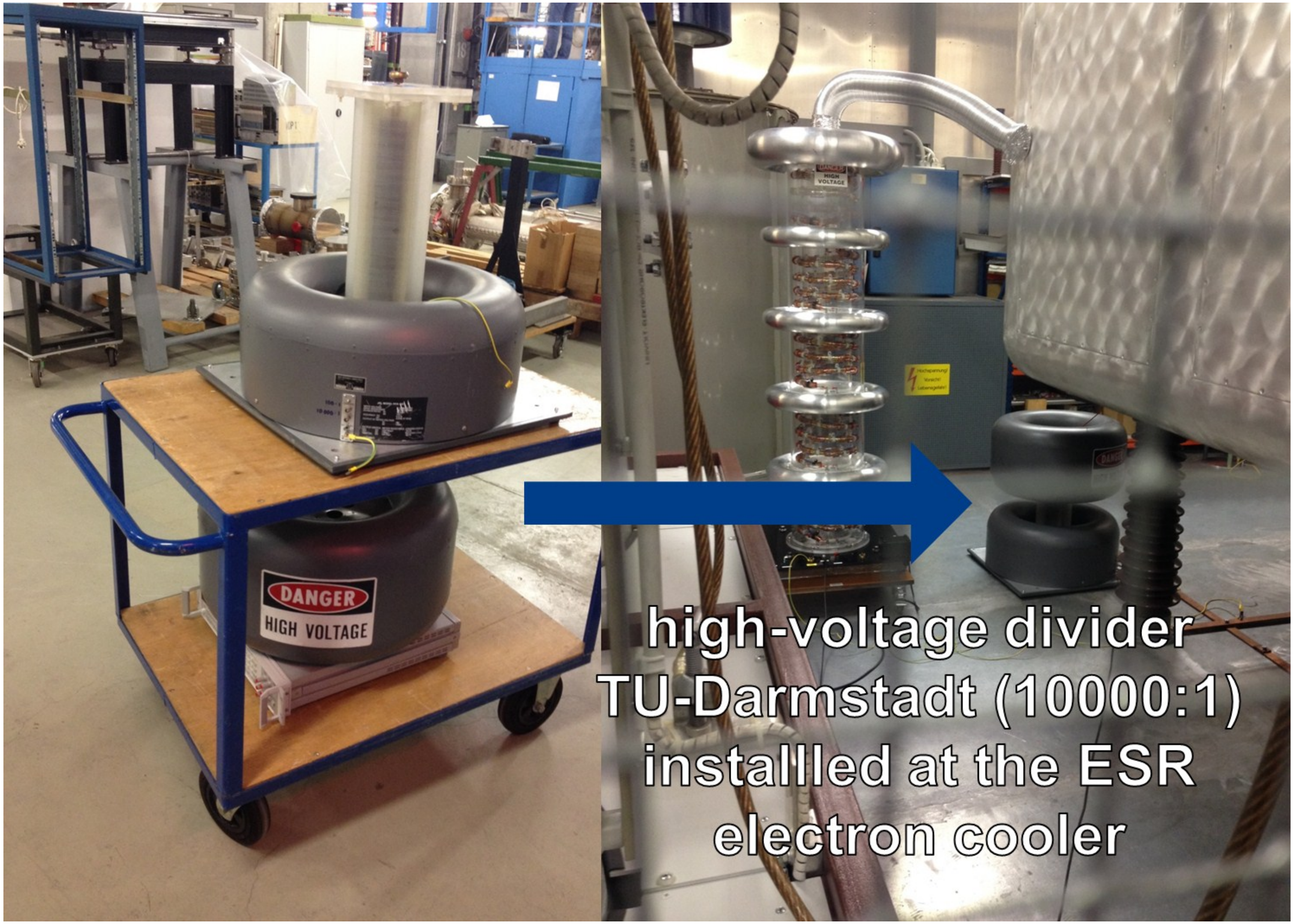
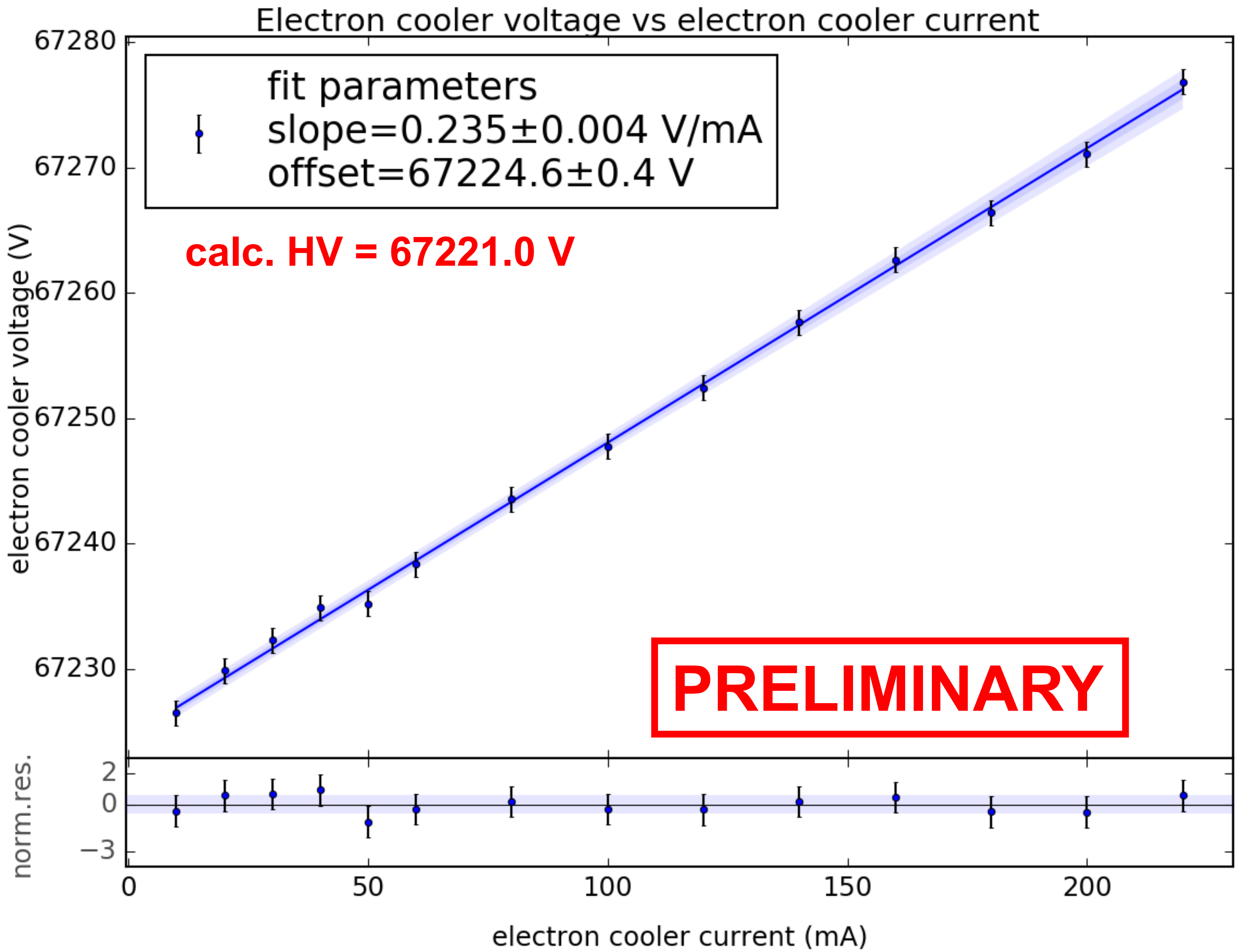
Nörtershäuser group effort for increasing voltage accuracy



Preliminary results with PTB-calibrated electron cooler voltage

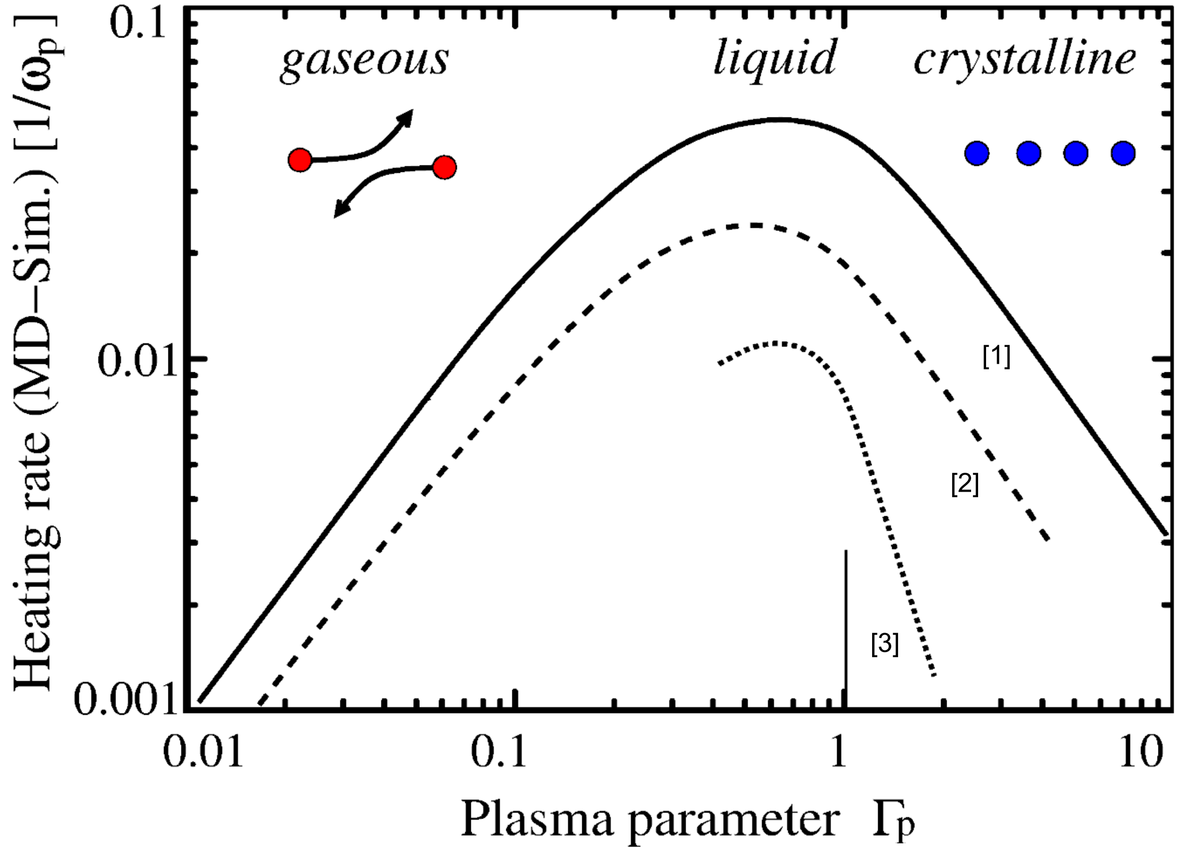


Spectroscopy

- Precision spectroscopy „for free“
- QED effects at higher energies and ion charge
- Fluorescence detection mandatory
- At ultra-relativistic energies precise beam energy measurement

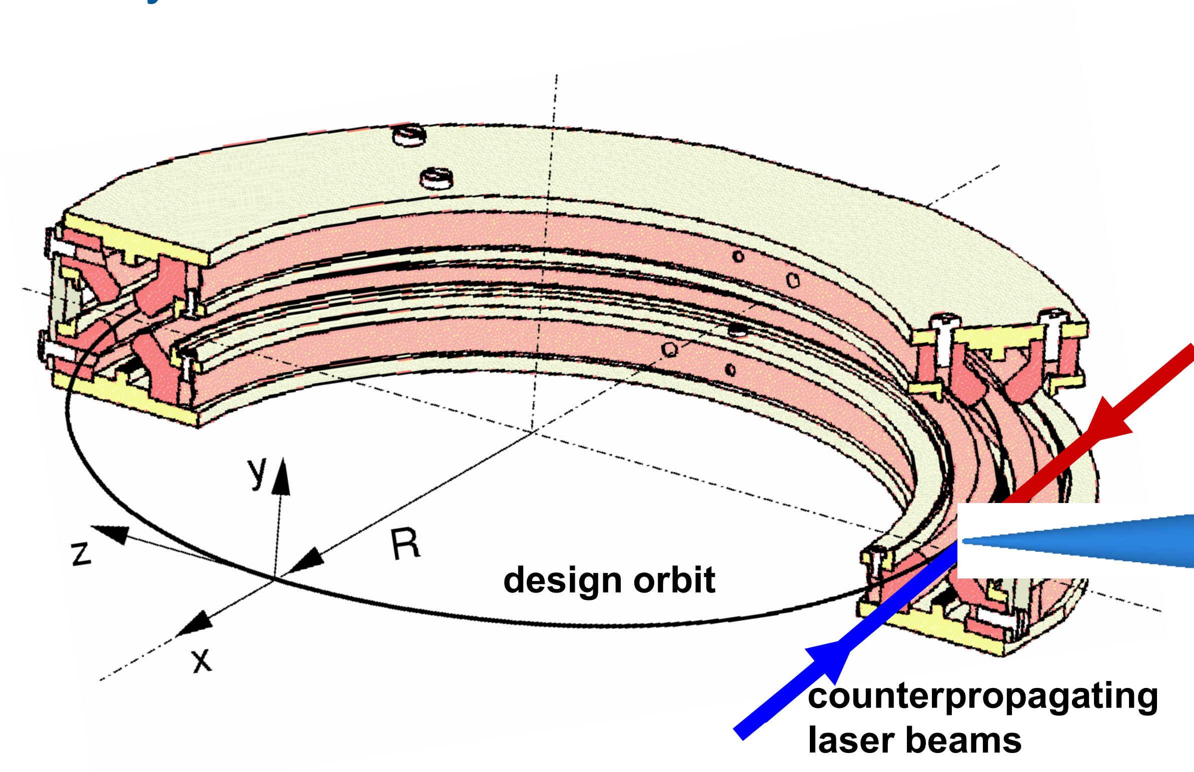
Ultracold Ion Beams

With increasing coupling, IBS increases (but not forever!)



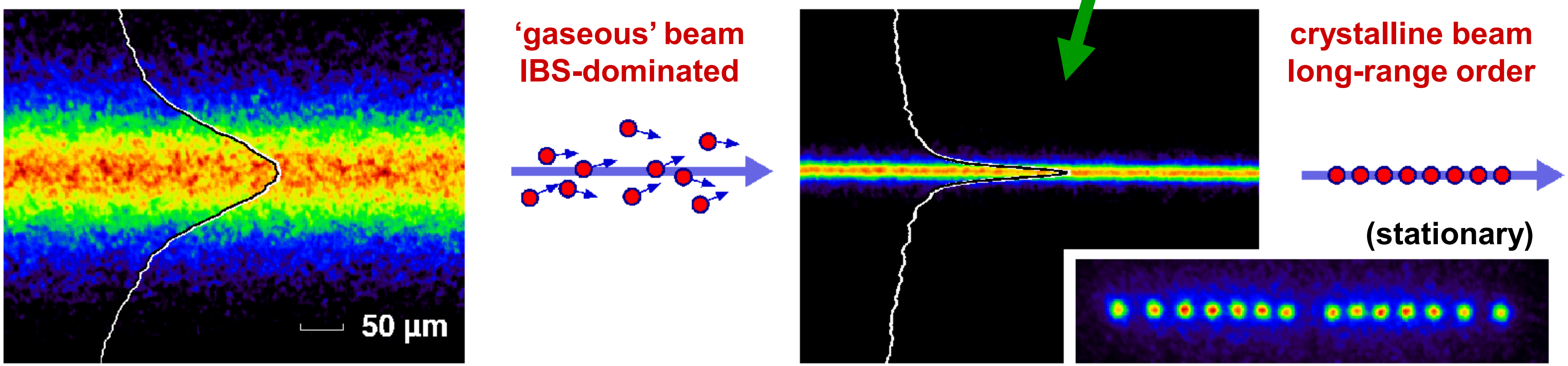
$$\Gamma_P = \frac{E_{\text{Coulomb}}}{E_{\text{thermal}}} = \frac{Z_{ion}^2 e^2}{4\pi\varepsilon_0 a_{\text{WS}} \cdot k_{\text{B}} T_{\text{ion}}}, \quad a_{WS} = \left(\frac{4}{3}\pi\, n_{ion}\right)^{-\frac{1}{3}}$$

„Crystalline" ion beams at the eV RFQ storage ring PALLAS

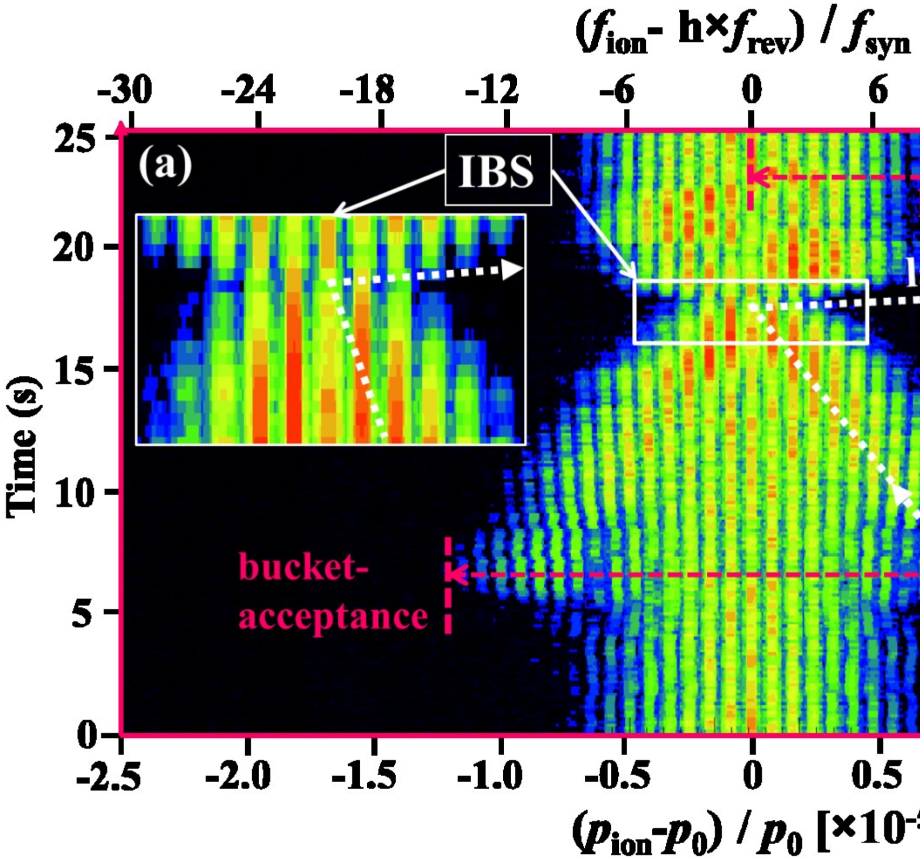


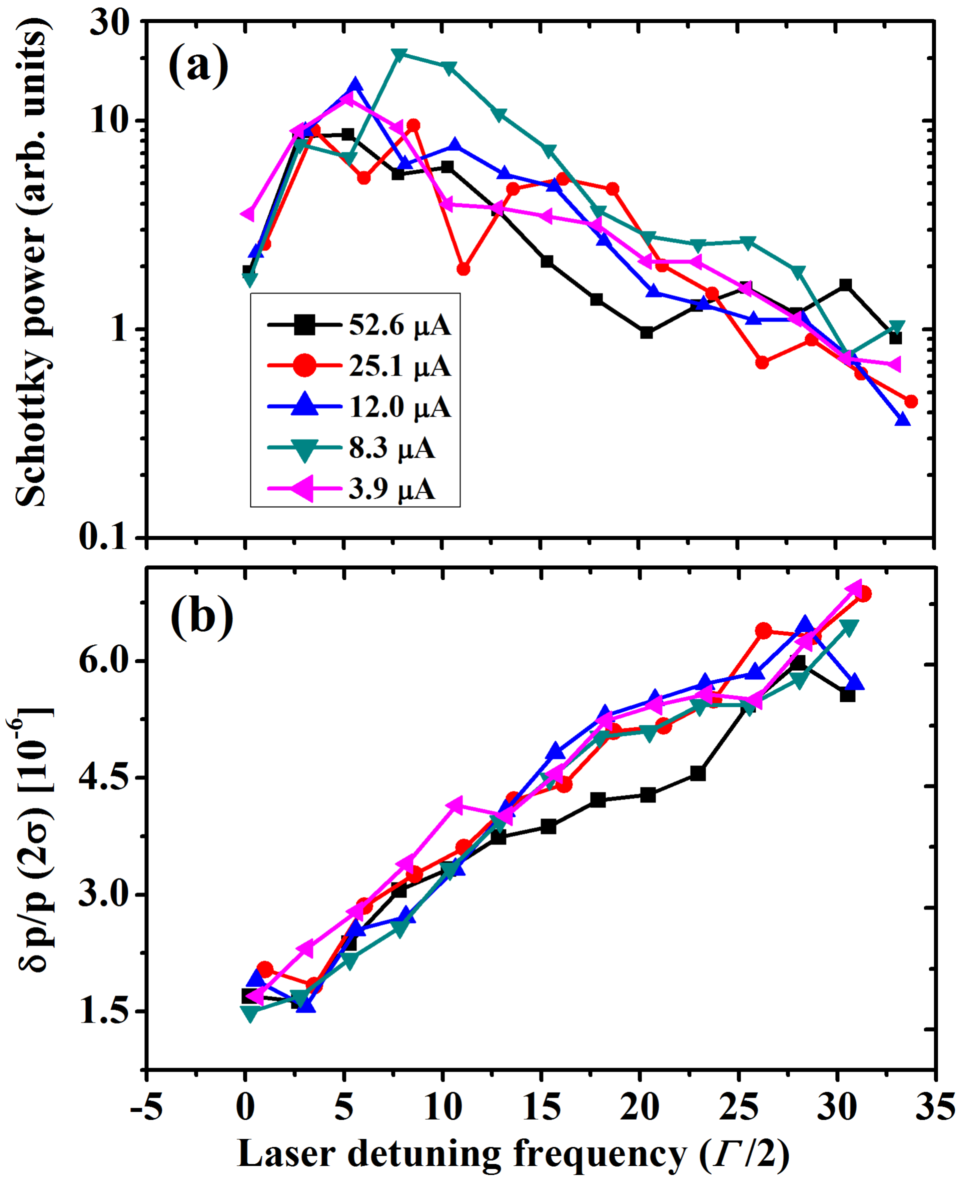
PALLAS

- Beam energy ~eV
- Radius 57 mm
- Tune 50
- Periodicity 800



Schottky measurements of bunched laser cooled C^{3+} beams





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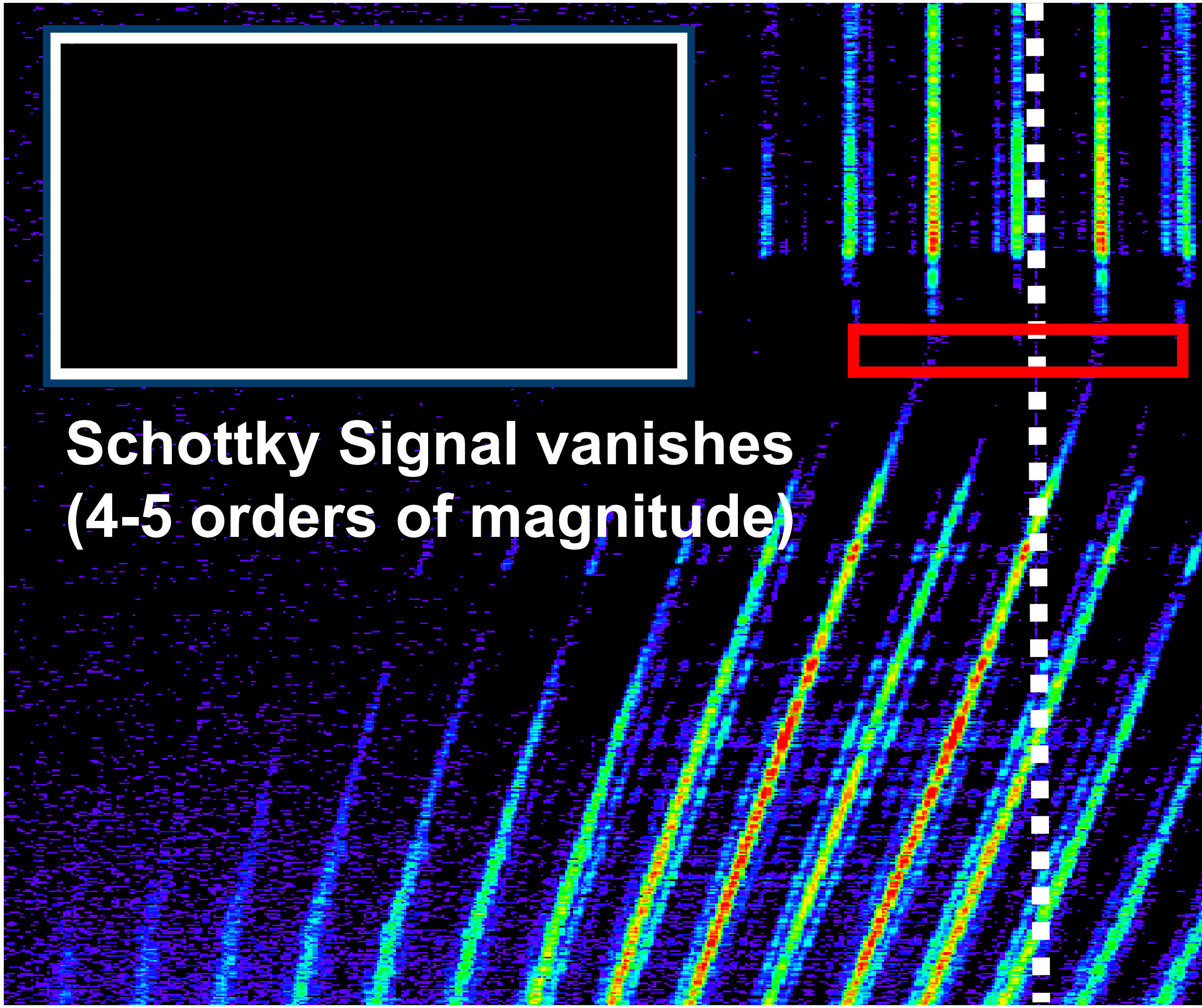
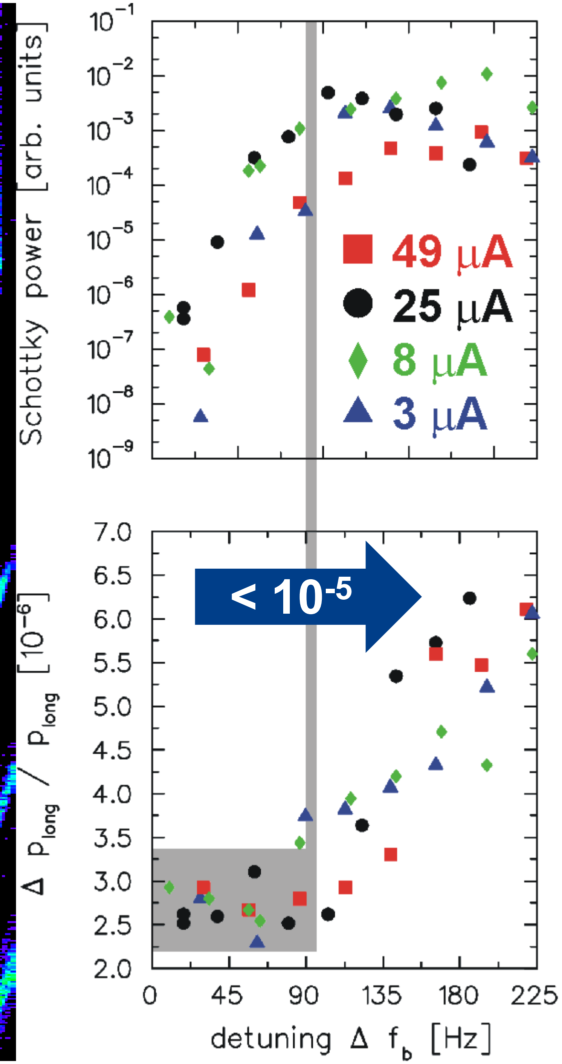
Zero Schottky signal @ 16 μA (much better vacuum in 2006)





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

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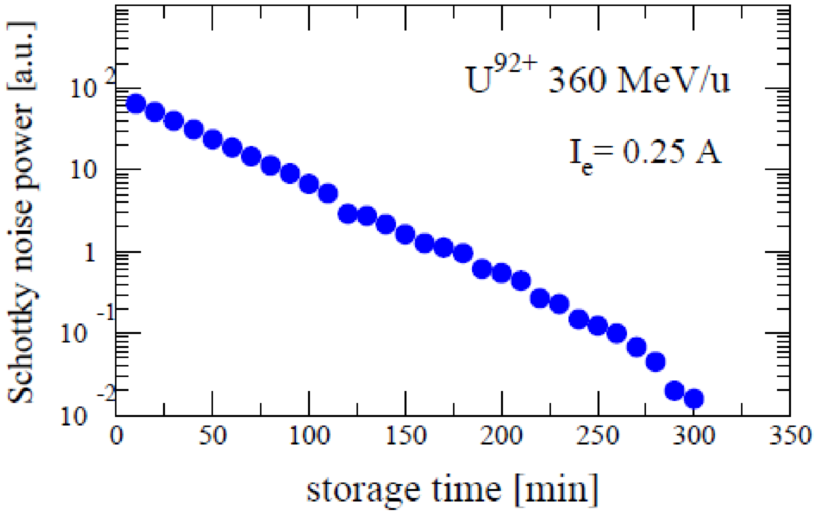
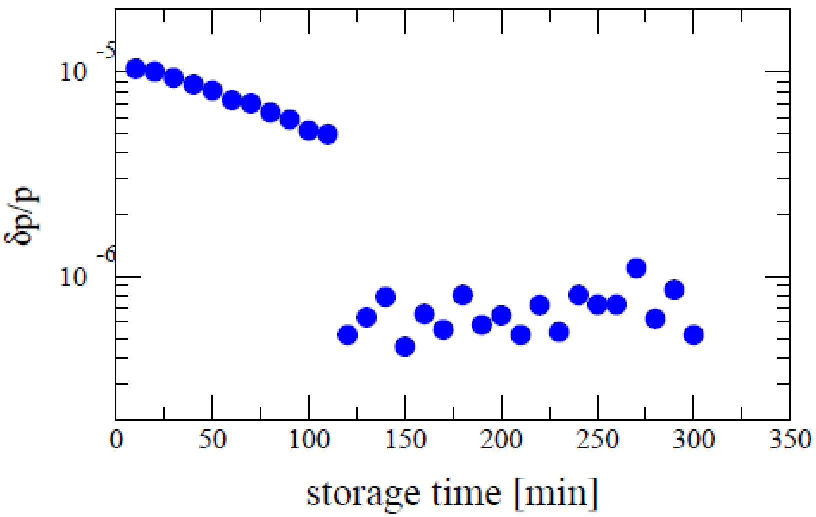
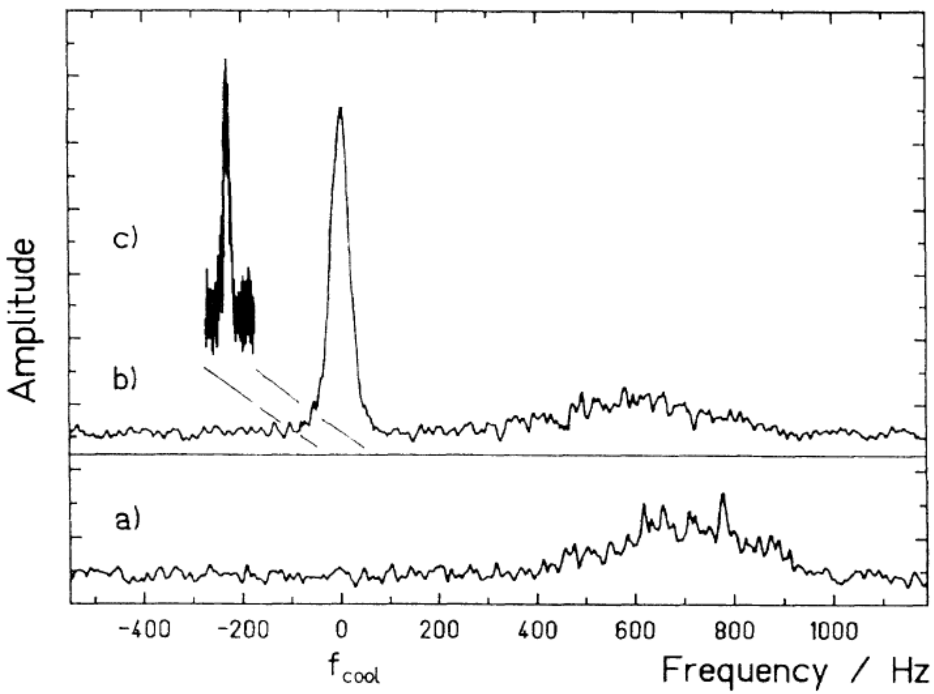
What does zero Schottky signal even mean?

ESR, electron cooled, coasting beam (2001)





TSR, laser cooled, coasting beam (1990)



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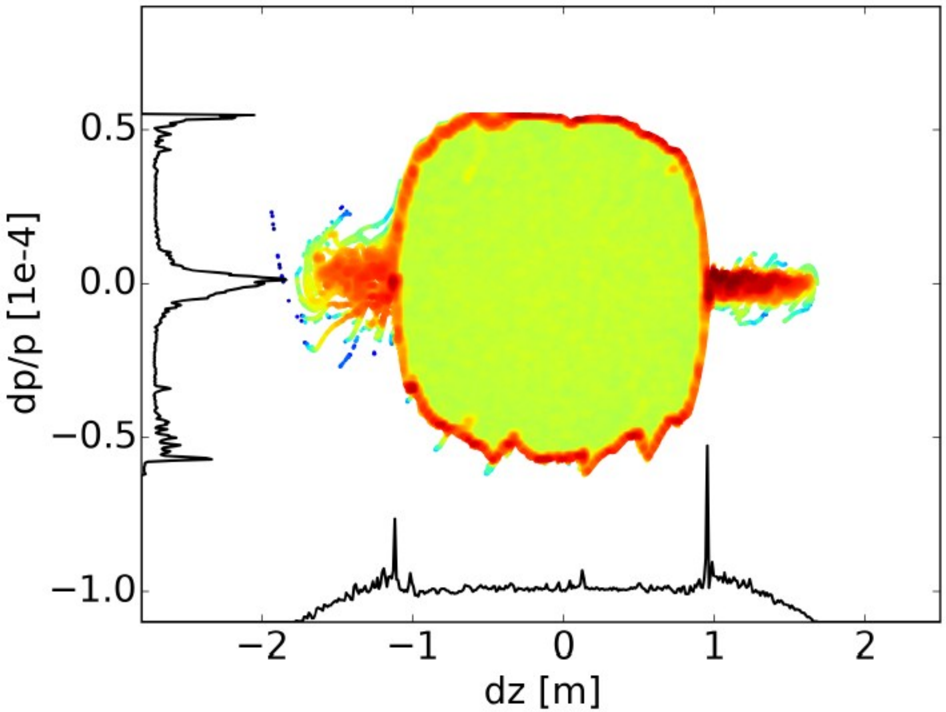
Ultracold ion beams

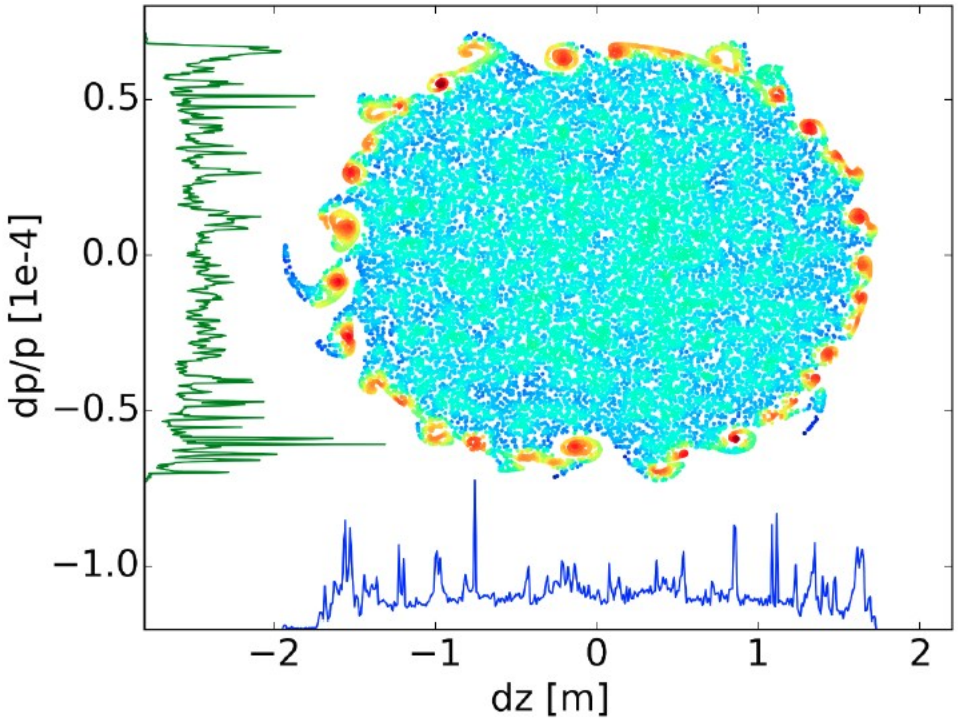
- Unlikely to see crystallization…
- … but who knows?
- Coupling to transverse degree of freedom needed
- Zero Schottky signal for bunched beams not understood
- Fluorescence detection might give clues

Intense
Ion Beams

Space charge effects when using a scanning cw laser (Simulation!)



Space charge „flattens out“ bucket, ions do no longer perform synchrotron oscillations



Strong instabilities (~ negative mass) due to high density at the border of the phase space to where the cw laser pushes ions with higher momenta

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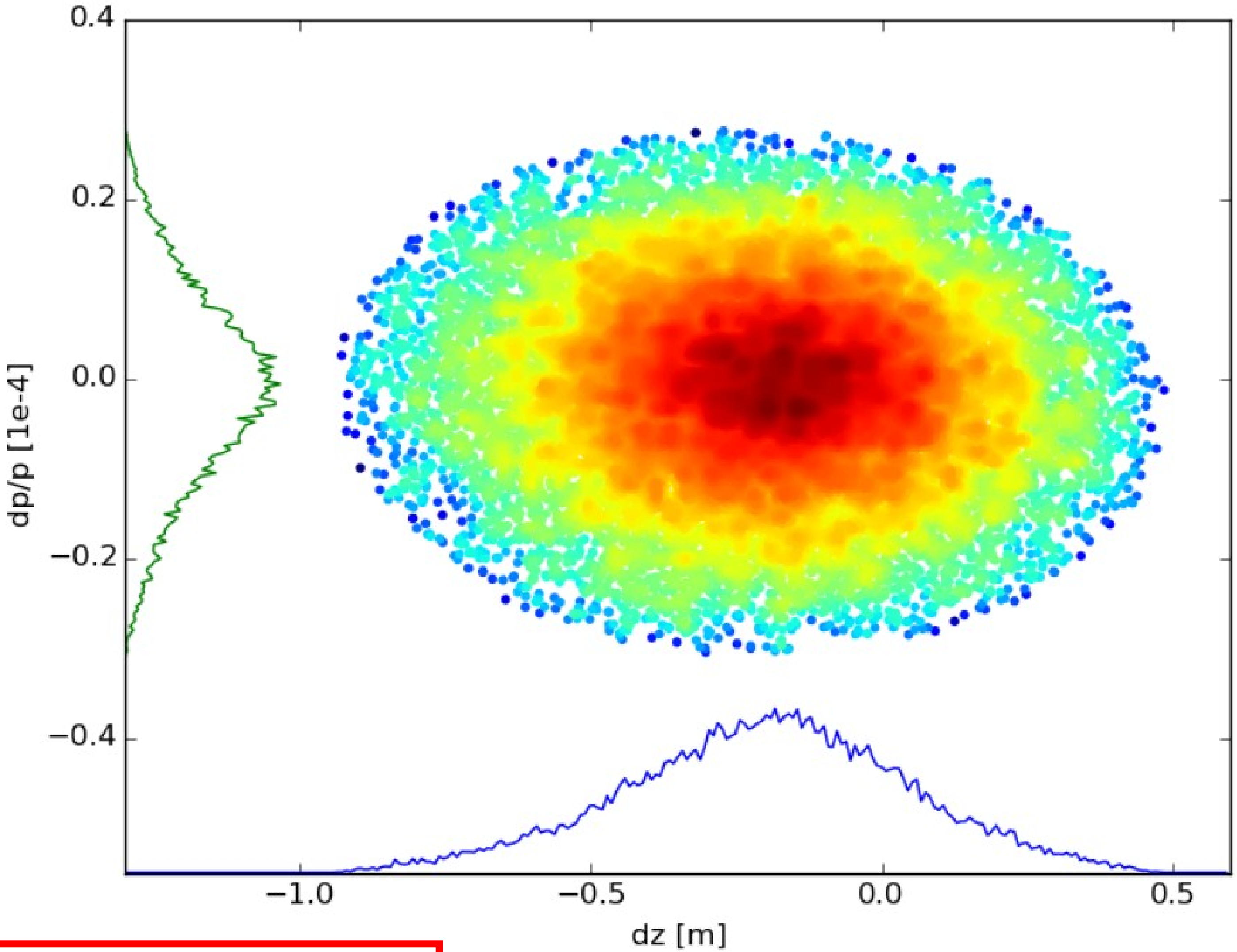
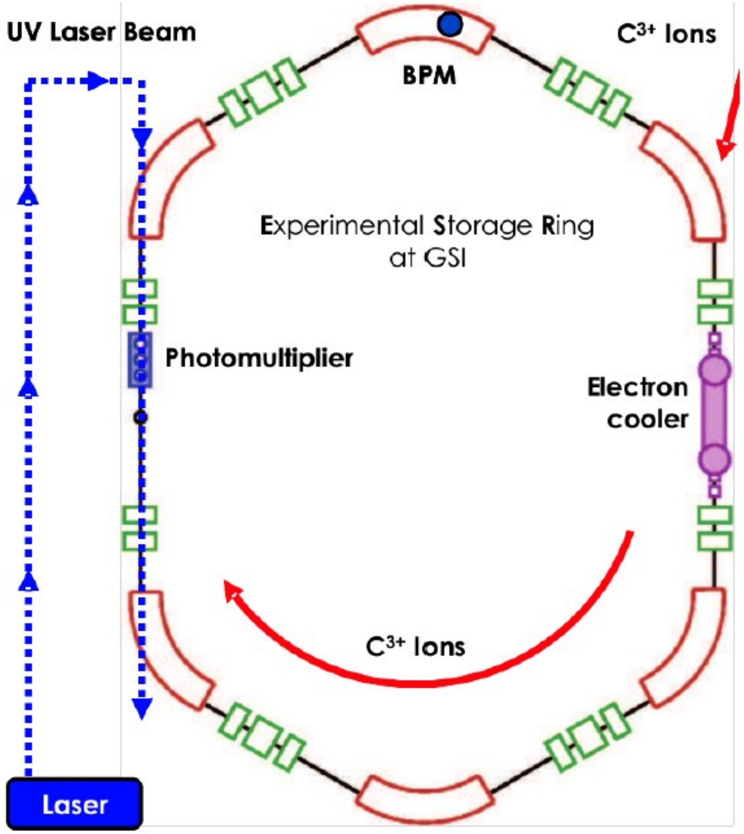
Both effects suppressed when using pulsed lasers (Simulation!)

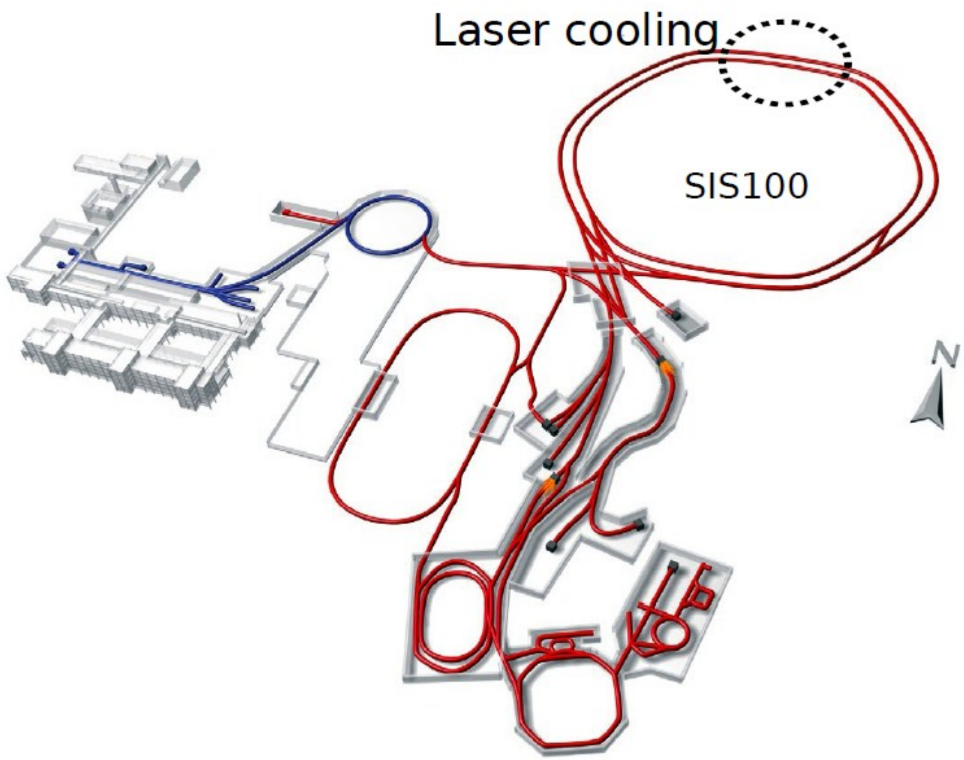


PRELIMINARY

Preliminary cooling times estimates comparing ESR to SIS100

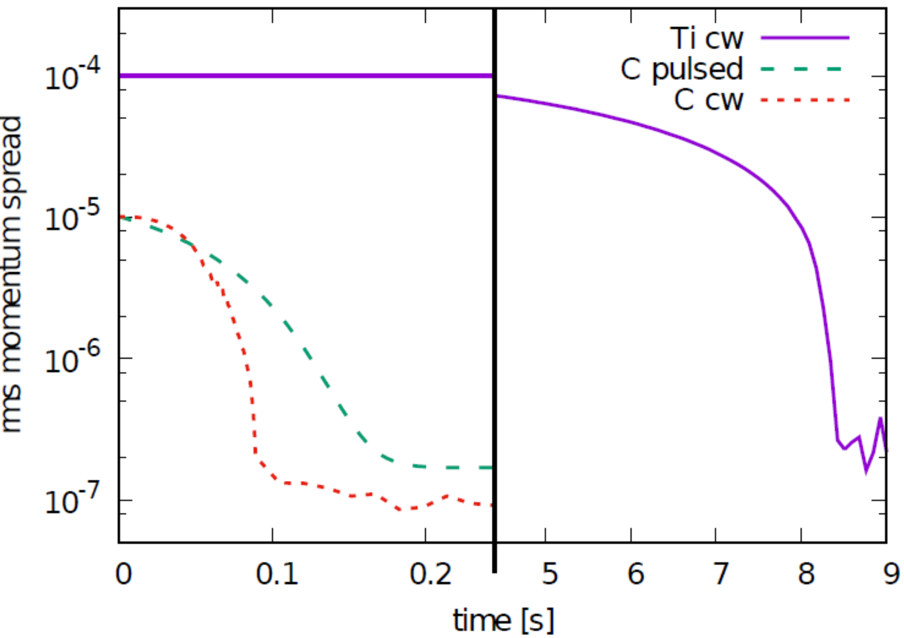
	Ion	T_{rev}	$L_{interact}$	$\delta_{rms\,0}$	d_{beam}	γ	L_{bunch}
ESR	$^{12}C^{3+}$	$0.8\,ms$	$25\,m$	10^{-5}	$3\,mm$	1.13	$4\,m$
SIS100	$^{48}Ti^{19+}$	$3.6\,ms$	$26\,m$	10^{-4}	$10\,mm$	8.50	$100\,m$





Preliminary cooling times estimates comparing ESR to SIS100

	λ_L	P_L	n_{scat}	$\Delta\delta^{LF}$	Δ_{fwhm}	ρ_{excit}^{pulsed}
$^{12}C^{3+}$	$256\,nm$	$20\,mW$	7.5	$1.5 \cdot 10^{-9}$	$5.8 \cdot 10^{-8}$	0.278
$^{48}Ti^{19+}$	$512\,nm$	$5\,W$	4.7	$9.3 \cdot 10^{-10}$	$3.9 \cdot 10^{-8}$	$8 \cdot 10^{-5}$



	$^{12}C^{3+}$	$^{48}Ti^{19+}$
d_{scan}^{max} analytic	$2 \cdot 10^{-10}$	$2 \cdot 10^{-11}$
d_{scan} sim	$2 \cdot 10^{-10}$	$1 \cdot 10^{-10}$
N_p^{max} analytic	$6.7 \cdot 10^{6}$	$6.8 \cdot 10^{7}$
N_p sim	$1.5 \cdot 10^{6}$	10^{7}
L_{equ} sim	1.4 m	3.6 m

PRELIMINARY

Thank you!