

Scaling laser cooling of ion beams toward high beam energies

Michael Bussmann¹, Markus Löser^{1,6}, Michael Seltmann¹, Matthias Siebold¹,
Ulrich Schramm^{1,6}, Tobias Beck³, Benjamin Rein³, Daniel Kiefer³, Sebastian Klammes³,
Thomas Walther³, Sascha Tichelmann³, Gerhard Birkel³, Rodolfo Sanchez-Alarcon^{2,4},
Johannes Ullmann^{2,4}, Matthias Lochmann^{2,4}, Wilfried Nörtershäuser^{3,4}, Lewin Eidam³, Oliver
Boine-Frankenheim^{2,3}, Danyal Winters², Christophor Kozhuharov², Shahab Sanjari², Yuri
Litvinov², Tino Giacomini², Markus Steck², Christina Dimopoulou², Fritz Nolden², Slava
Shevelko², Thomas Stöhlker², Peter Spiller², Weiqiang Wen⁵, Jie Yang⁵, Dacheng Zhang⁵,
Xinwen Ma⁵, Axel Buß⁷, Christian Egelkamp⁷, Daniel Winzen⁷, Volker Hannen⁷

¹ Helmholtz-Zentrum Dresden-Rossendorf

² GSI Helmholtzzentrum für Schwerionenforschung

³ Technische Universität Darmstadt

⁴ Universität Mainz

⁵ Institute for Modern Physics, Lanzhou

⁶ Technische Universität Dresden

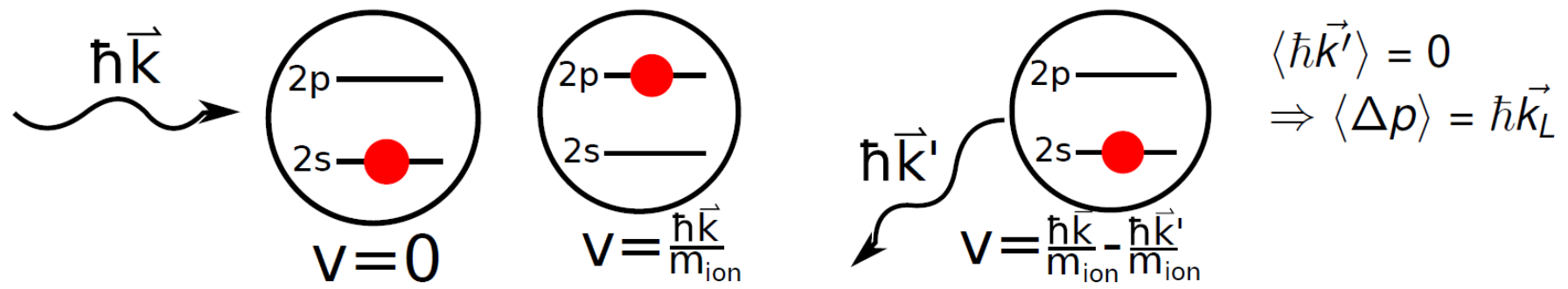
⁷ Universität Münster

HZDR

 **HELMHOLTZ**
ZENTRUM DRESDEN
ROSSENDORF

Laser Cooling in a Nutshell

Using fast atomic transitions in ions for laser cooling



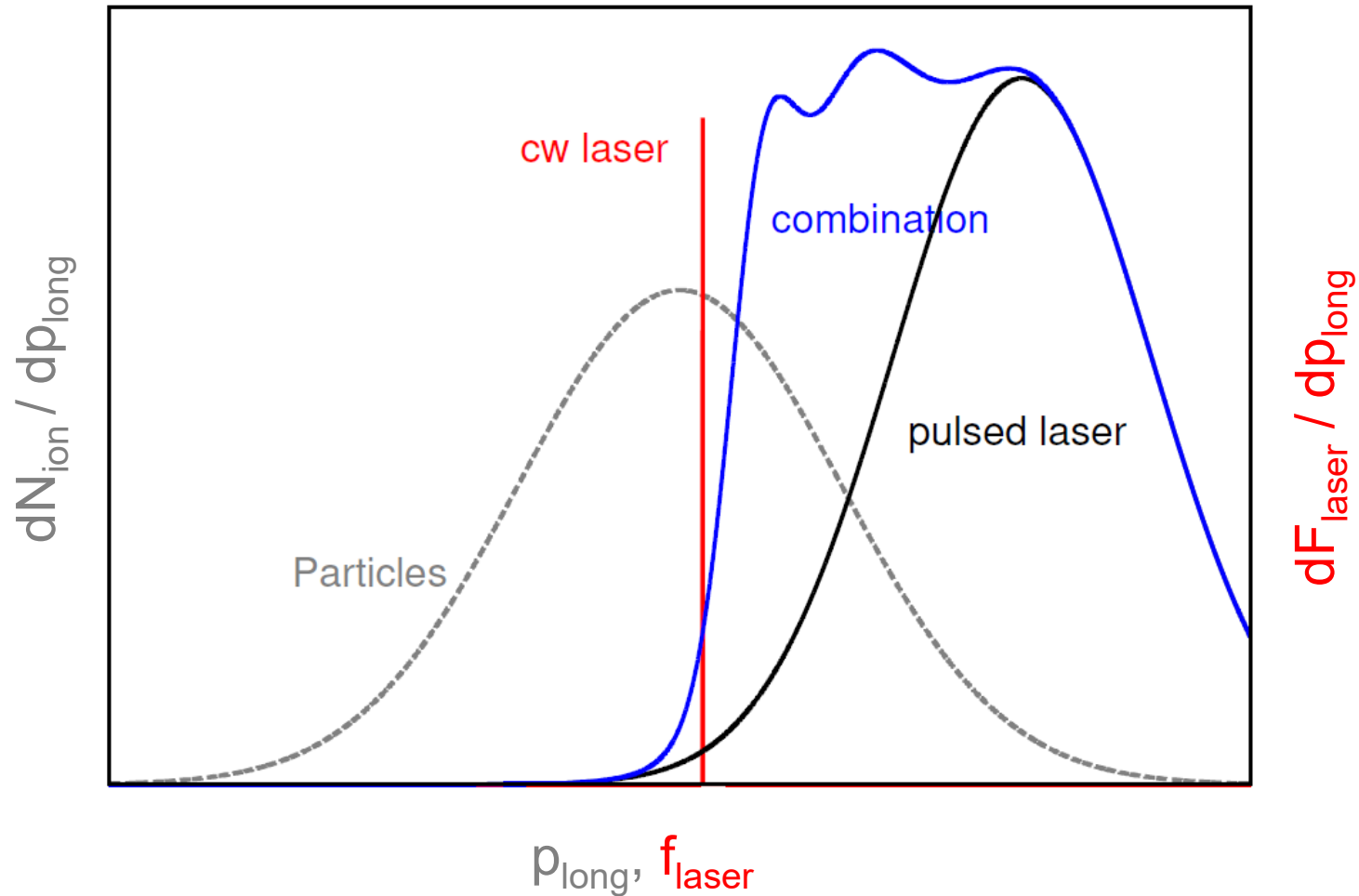
$$\omega_{\text{laser}} - \vec{k}_{\text{laser}} \cdot \vec{v}_{\text{ion}}$$

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

Photon
Momentum

Scattering
Rate

Laser force momentum acceptance range is small for cw-lasers



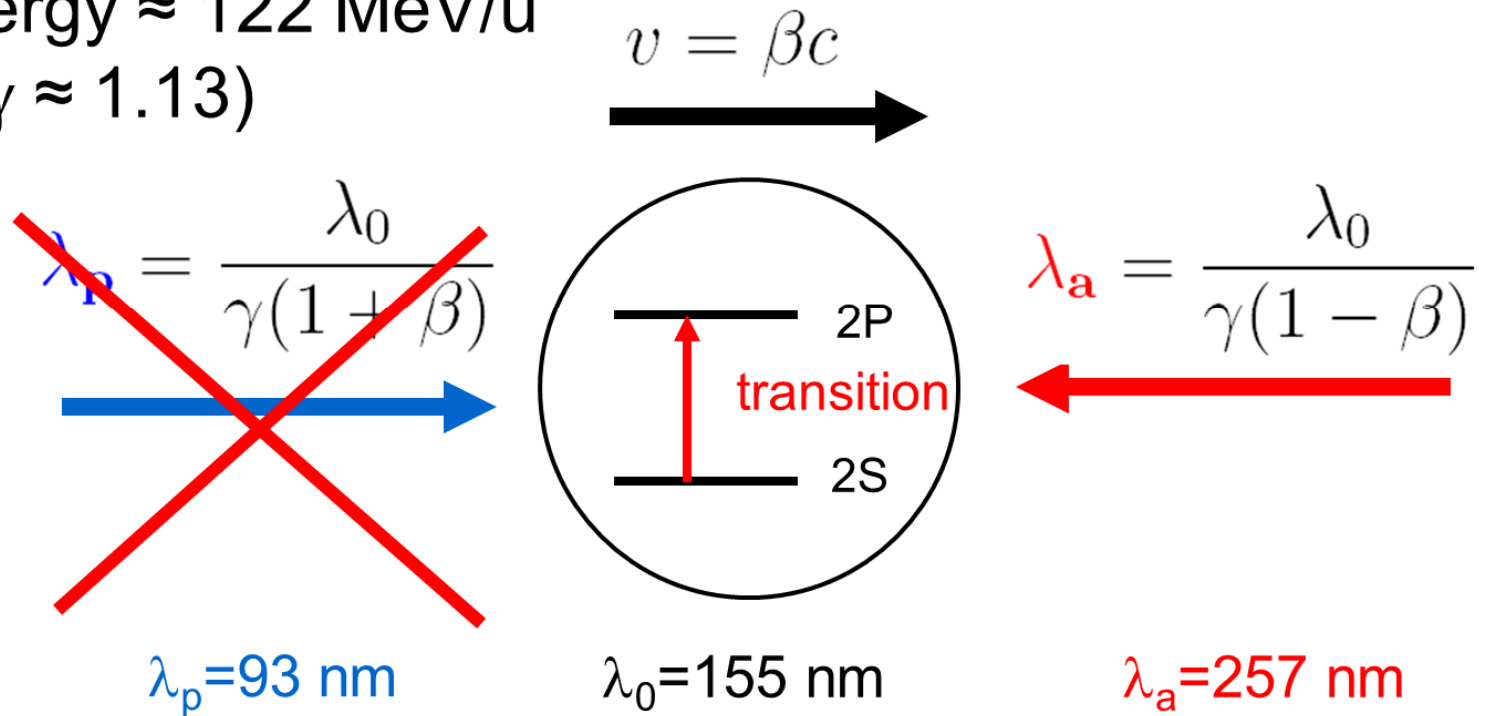
... but can be large for pulsed lasers

© Lewin Eidam

The relativistic Doppler shift of the laser wavelength is HUGE

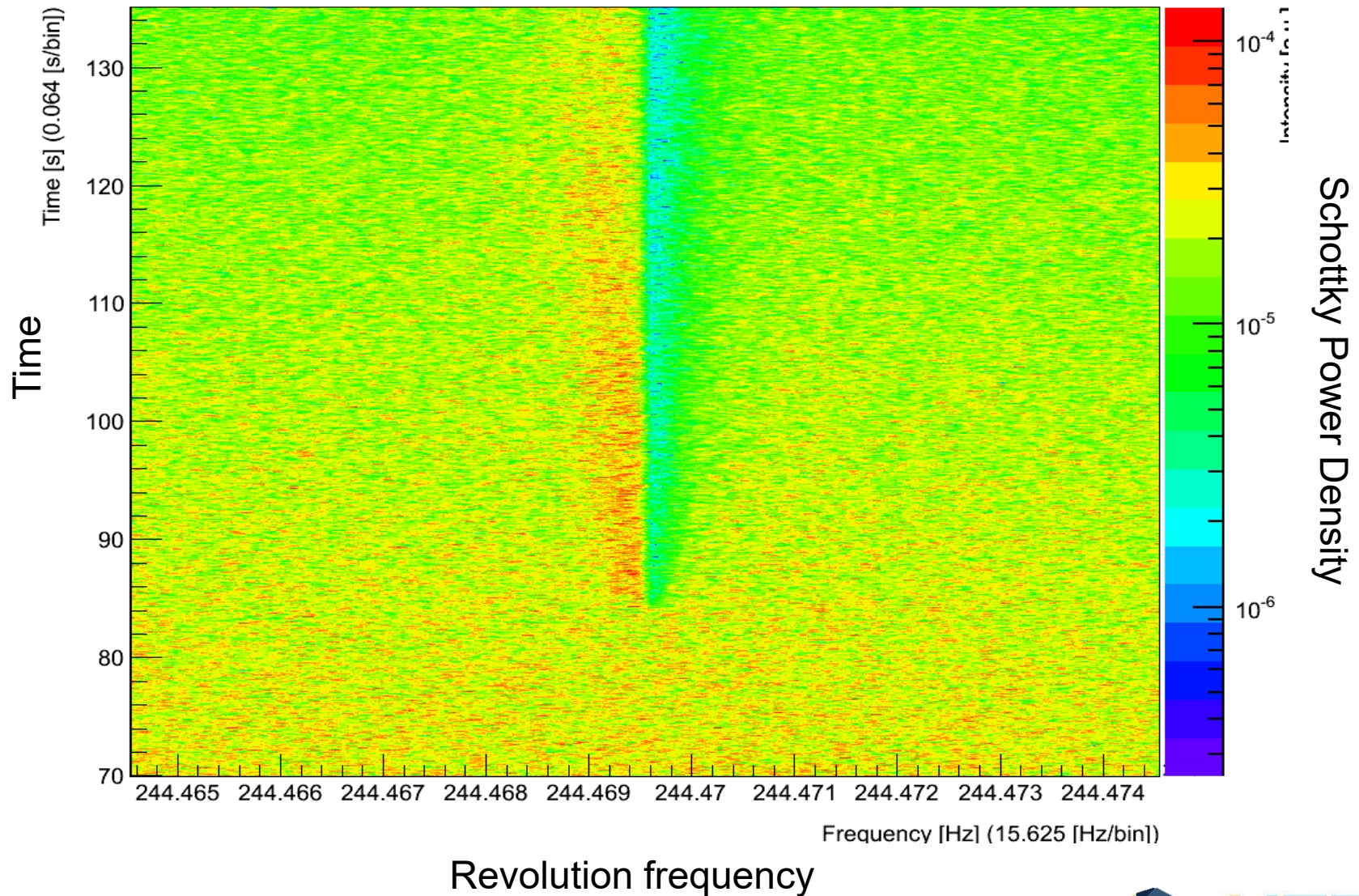
ESR example:

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

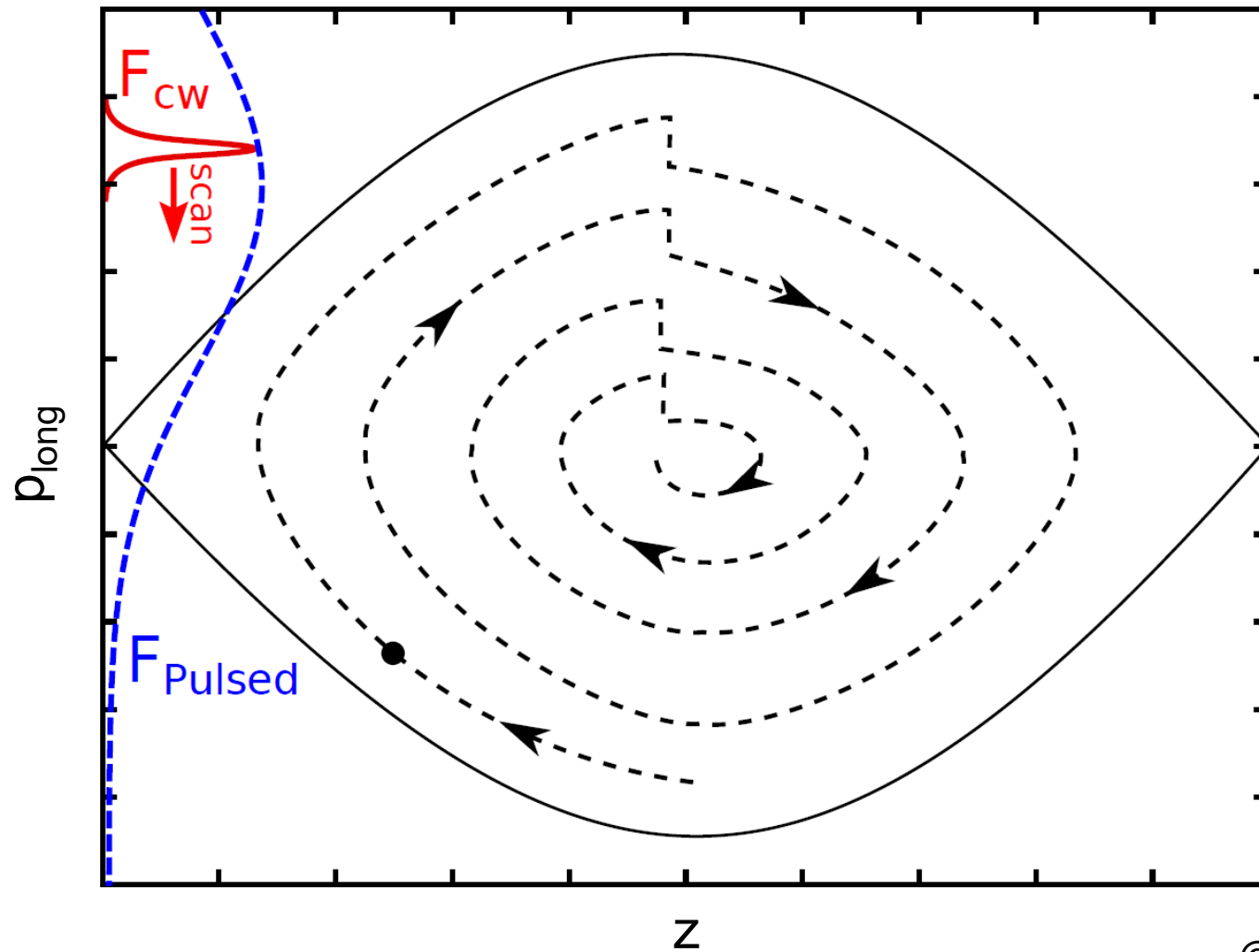


© Danyal Winters

Cooling a coasting beam with a cw laser

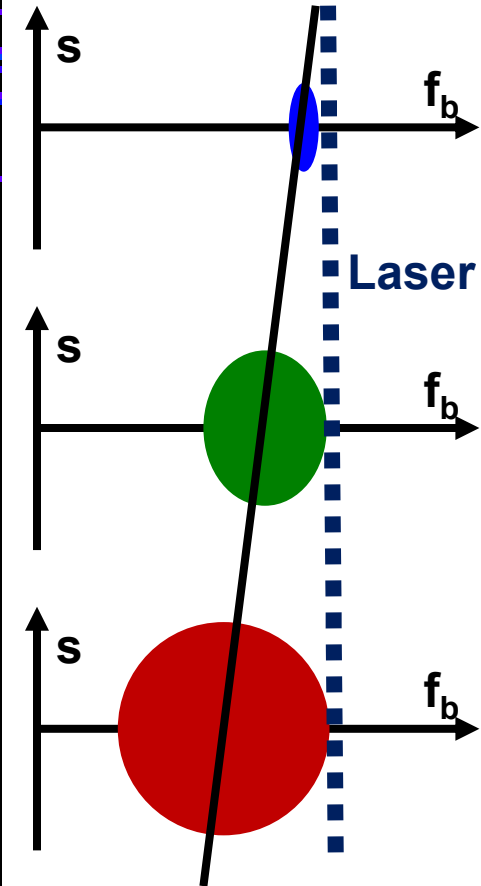
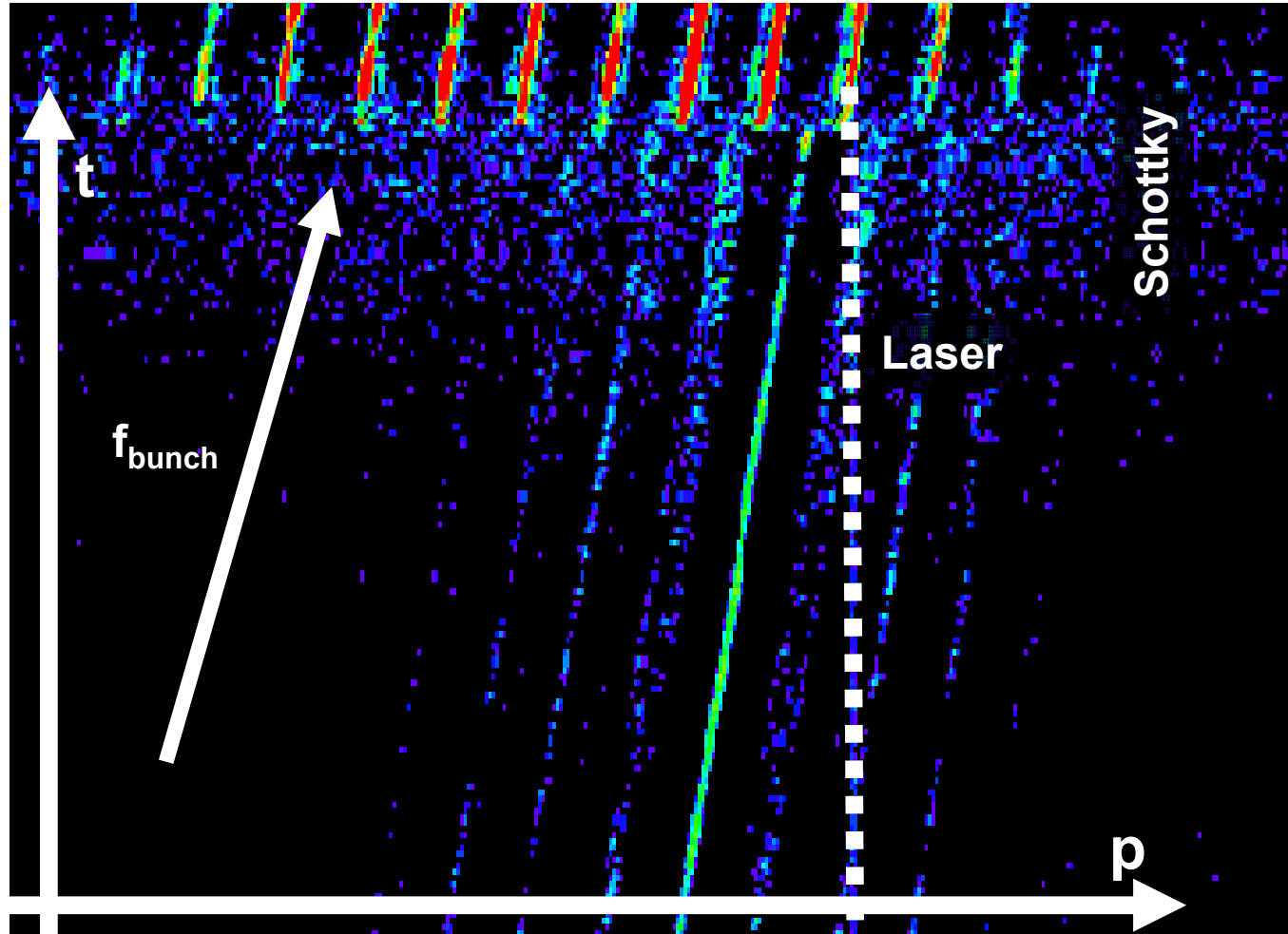


We need to bunch relativistic beams to have a stable cooling point



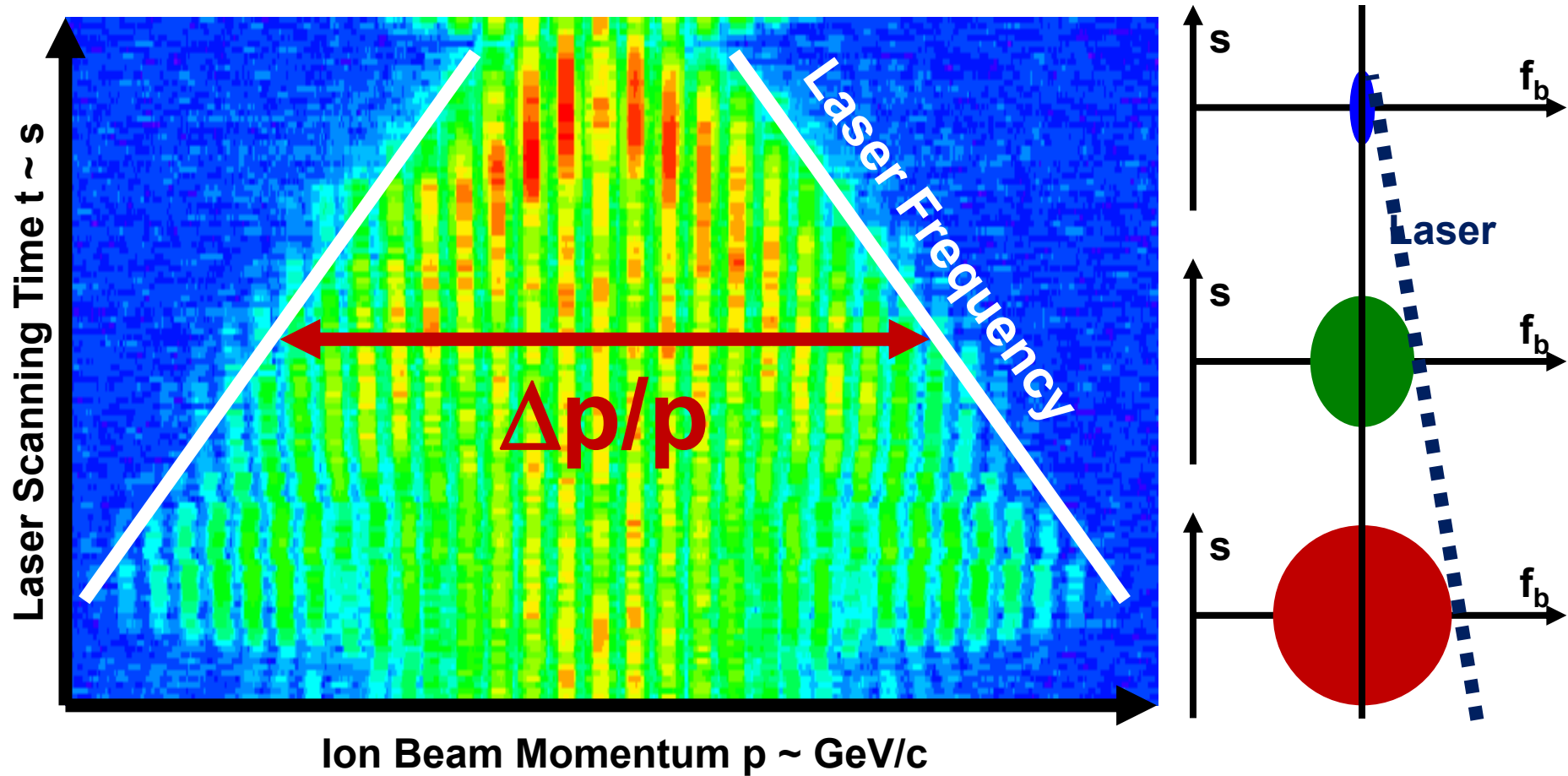
© Lewin Eidam

Technique 1: Scanning the bunching frequency

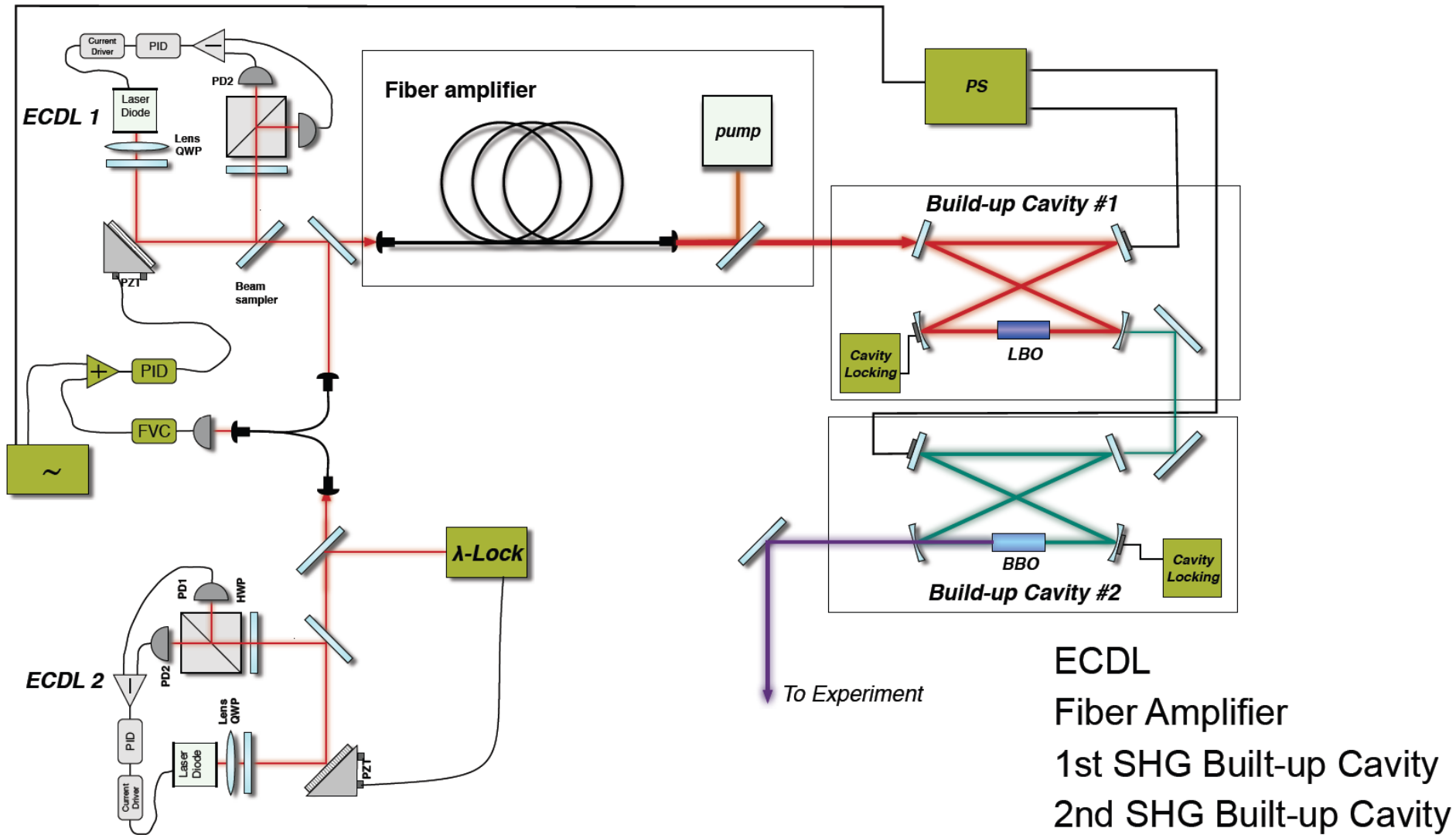


$$f_{\text{bunch}} = 20 \times 1.295 \text{ MHz} \quad \Delta f_{\text{bunch}} / \Delta t = 20 \text{ Hz} / 5 \text{ s} \quad f_{\text{sync}} \sim 170 \text{ Hz} \quad \Delta p / p_{\text{accept}} \approx 10^{-5}$$

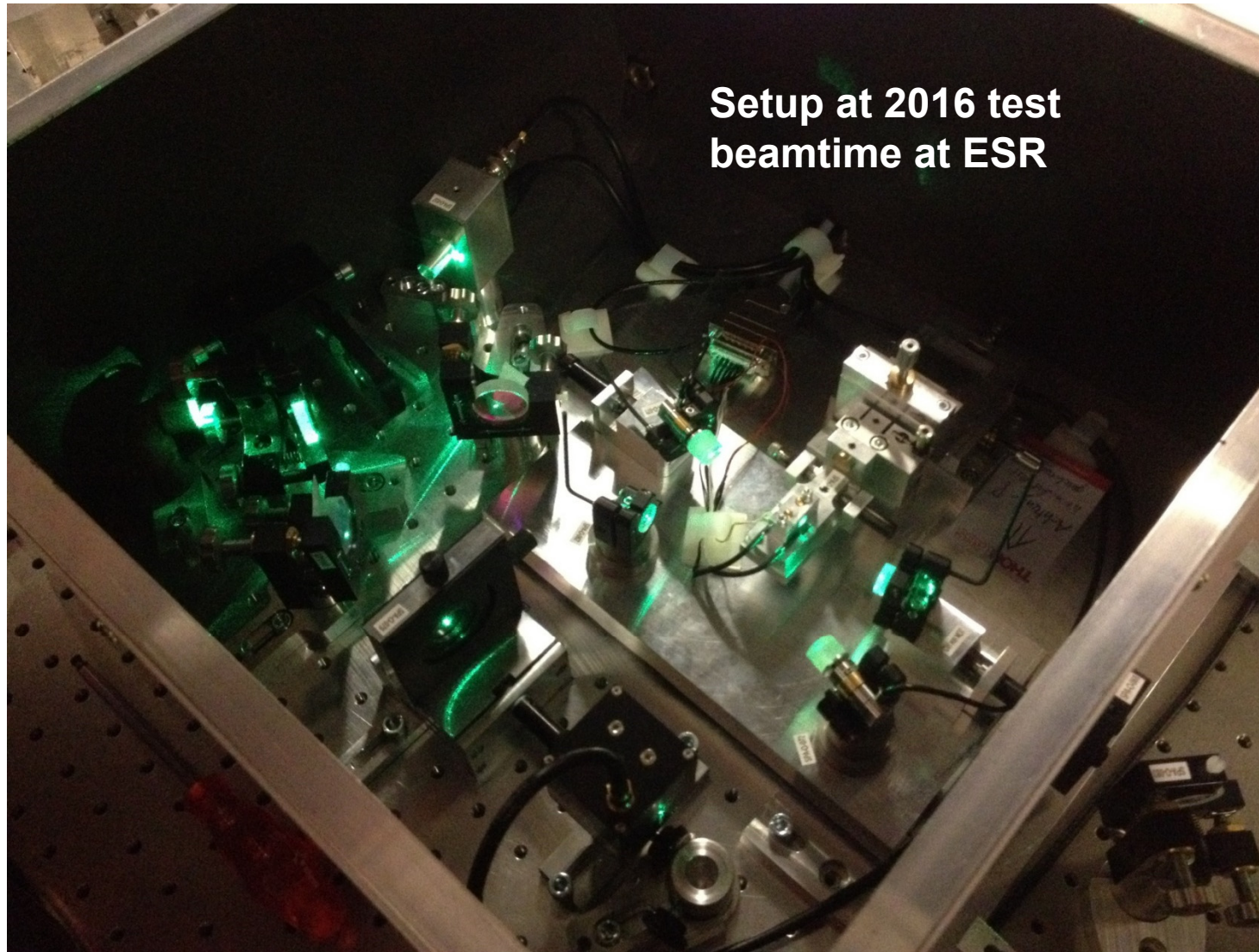
Technique 2: Scanning the laser frequency



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



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



Laser cooling in a nutshell

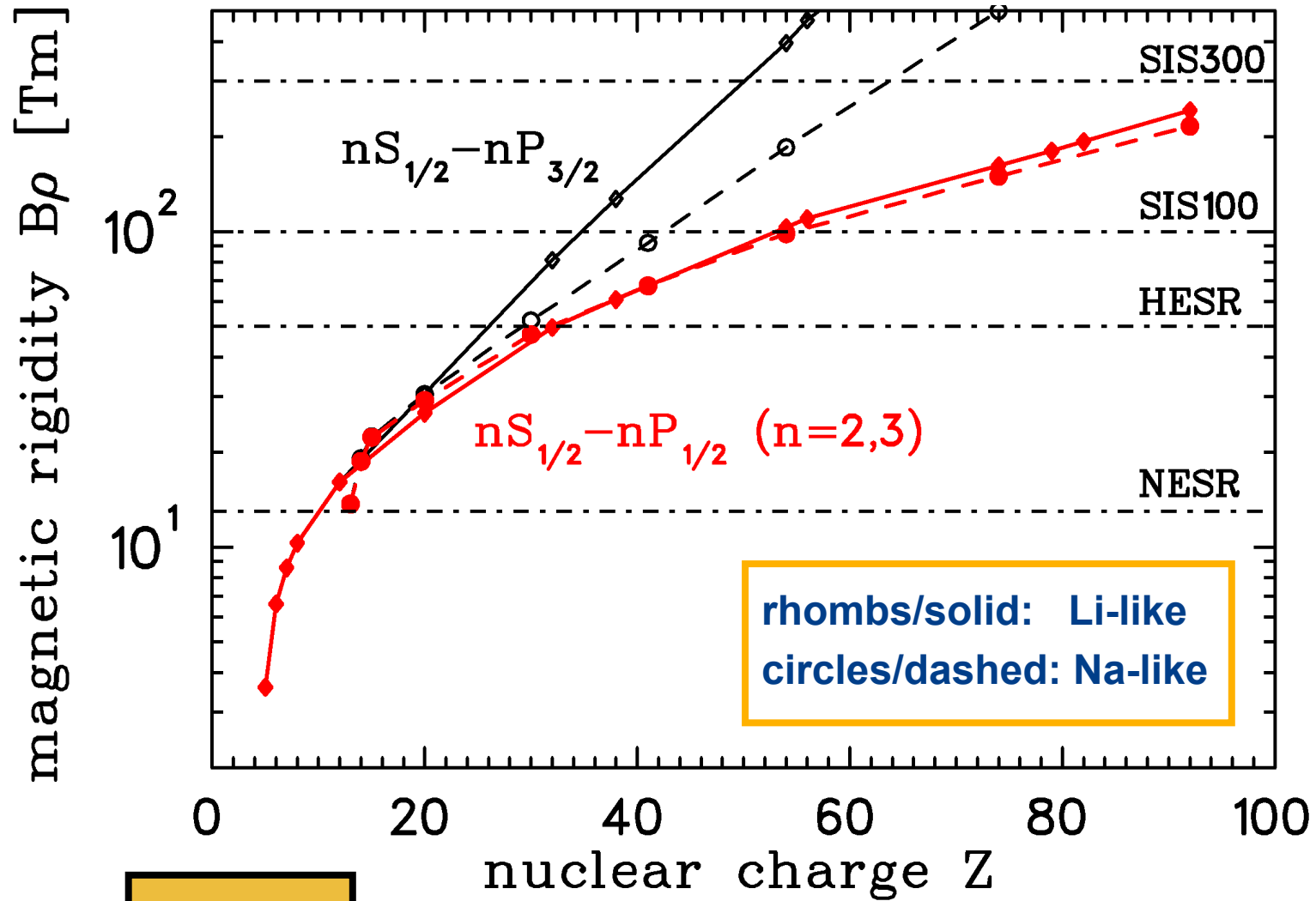
- A cw laser has small momentum acceptance ($<10^{-7}$ dp/p)
- Scanning laser or bunching frequency can cool a large dp/p
- Pulsed lasers can cool large dp/p beams „in parallel“
- The relativistic Doppler shift affect transition wavelengths ...
- ... and lifetimes
- Typically, one needs bunching to have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

© Lewin Eidam



Towards high Energies

Addressing many ion species with a single laser system



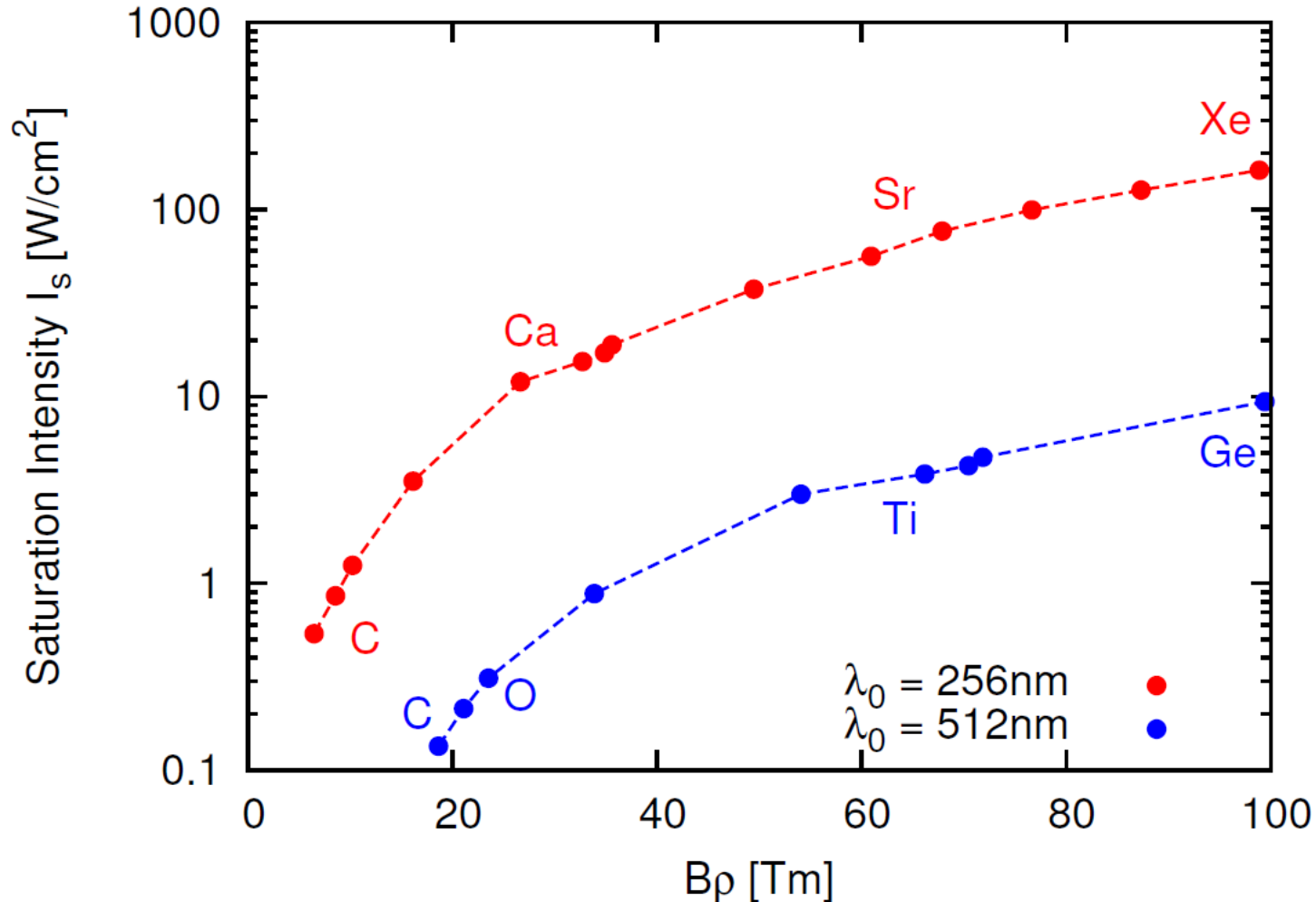
$$\gamma \rightarrow B\rho$$

Example: CSRe at IMP, Lanzhou

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

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

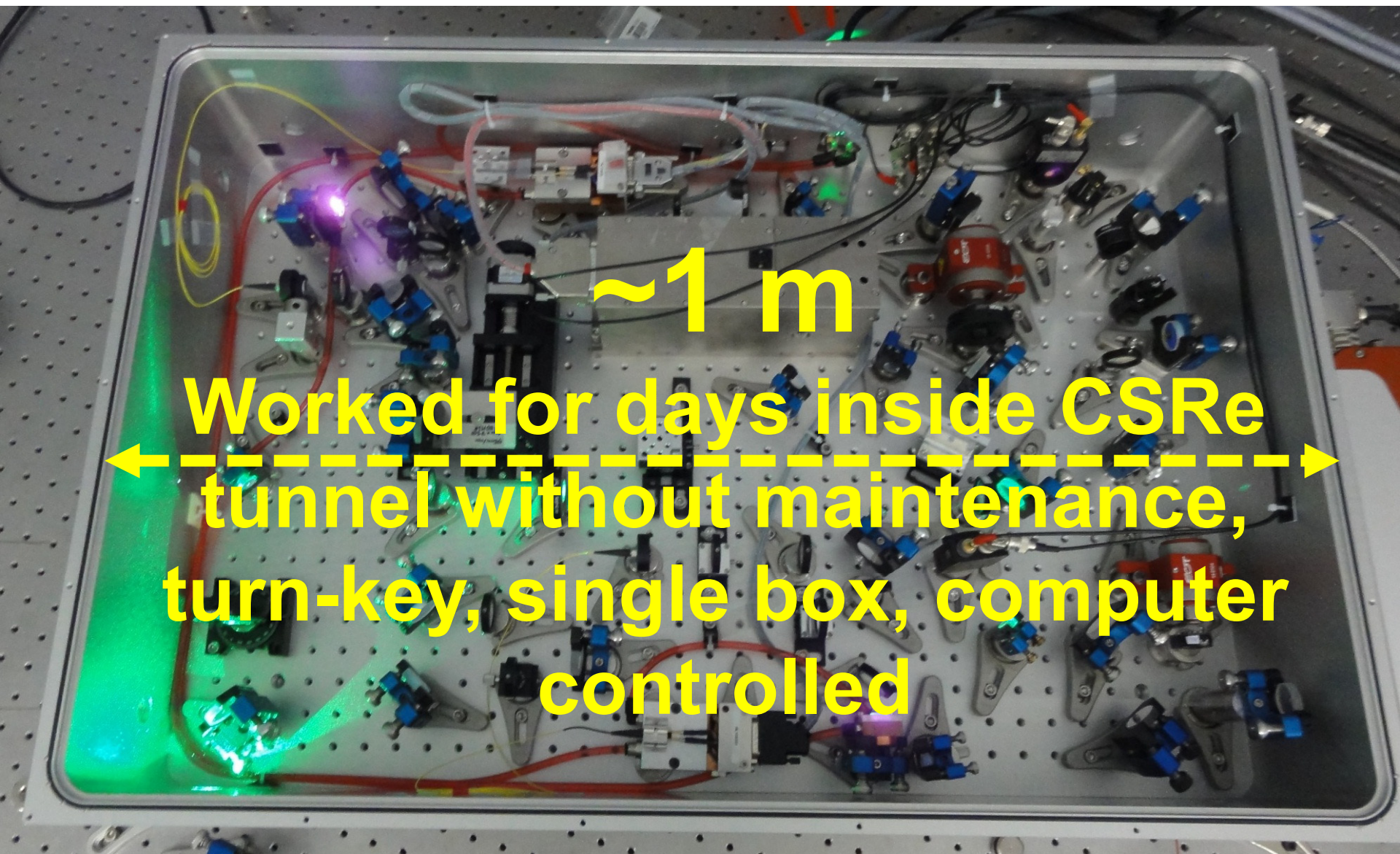
We need LOTS of laser power to saturate cooling transitions



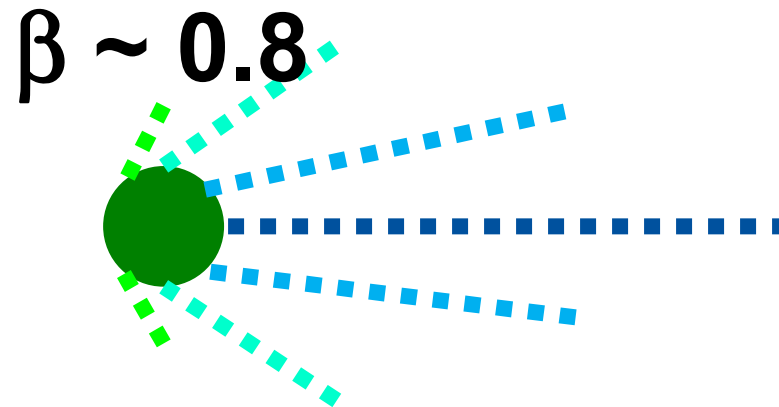
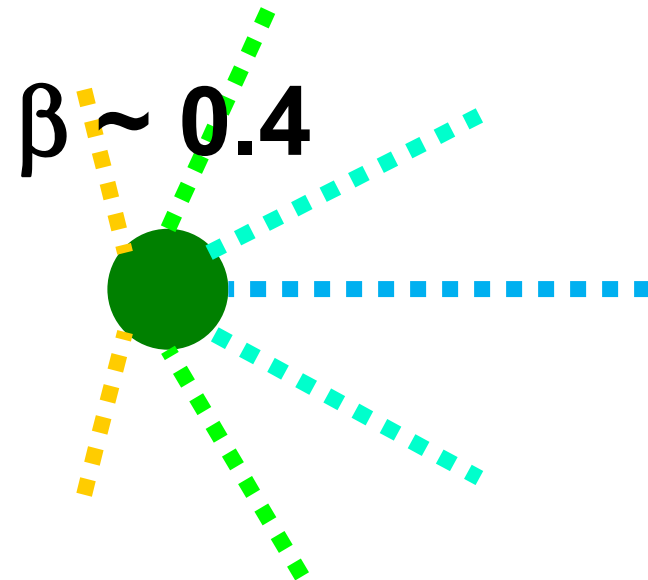
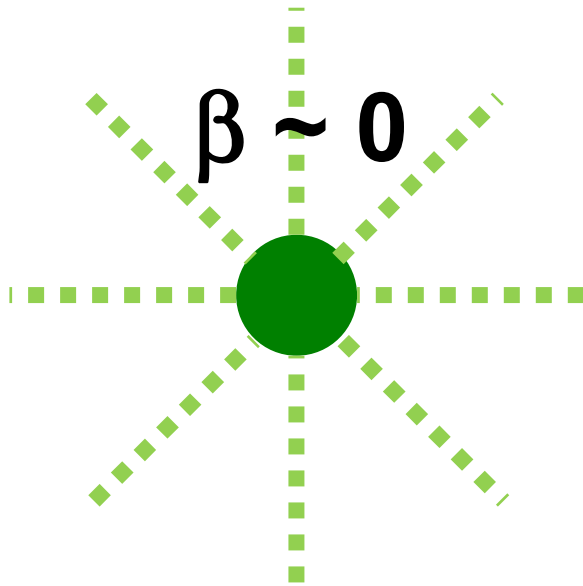
e.g. $\varnothing 10\text{ mm}$ @ SIS 100 relates to 100 W @ 257 nm

© Lewin Eidam

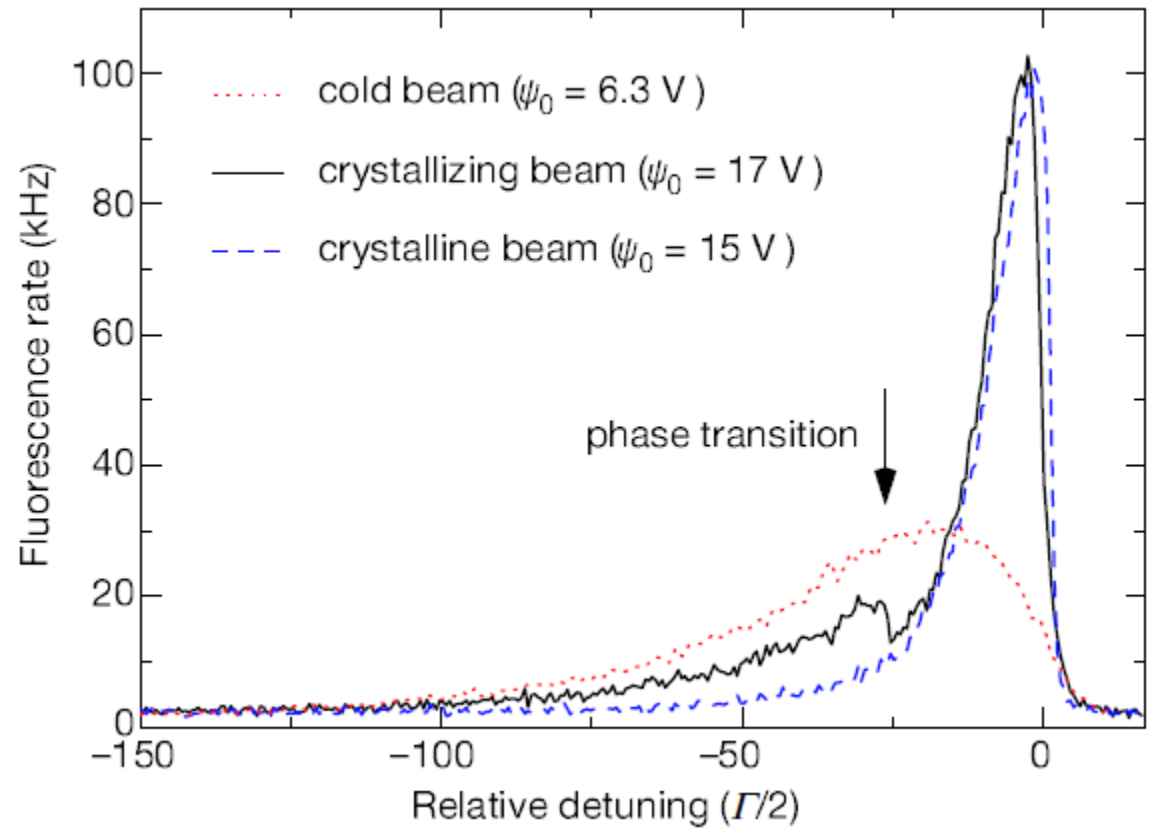
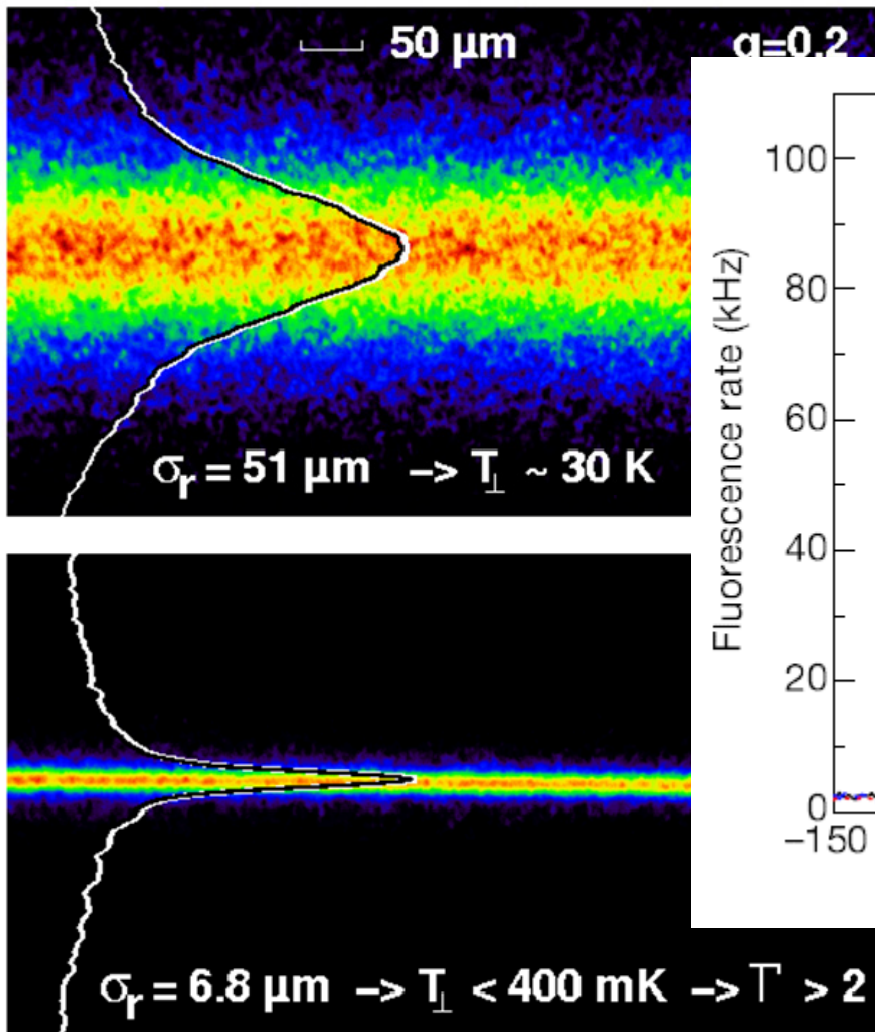
Turn-key pulsed laser system ($\Delta p/p$ acc. $\sim 10^{-4}$, MHz repetition rate)



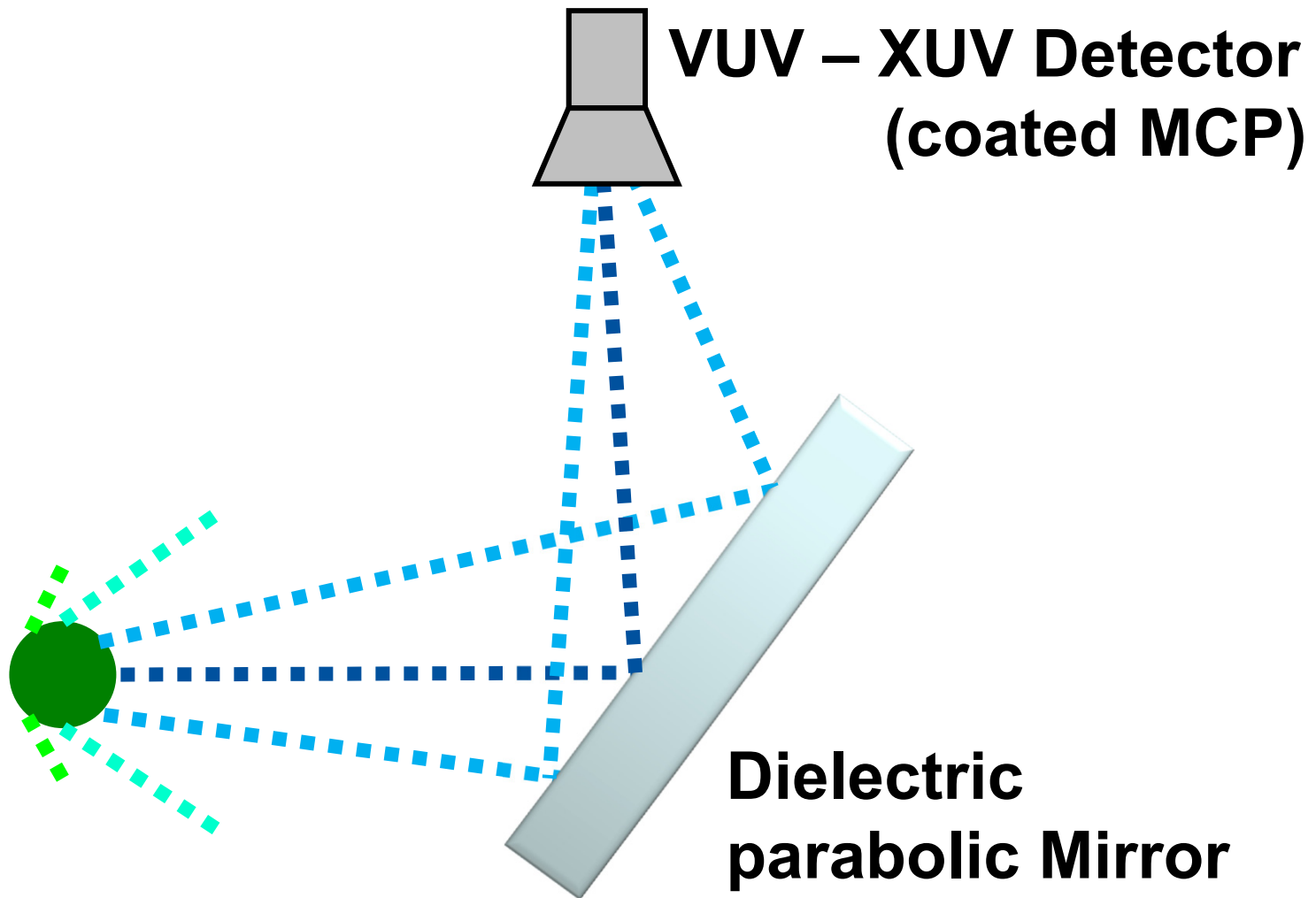
Lorentz-boosted fluorescence as diagnostic



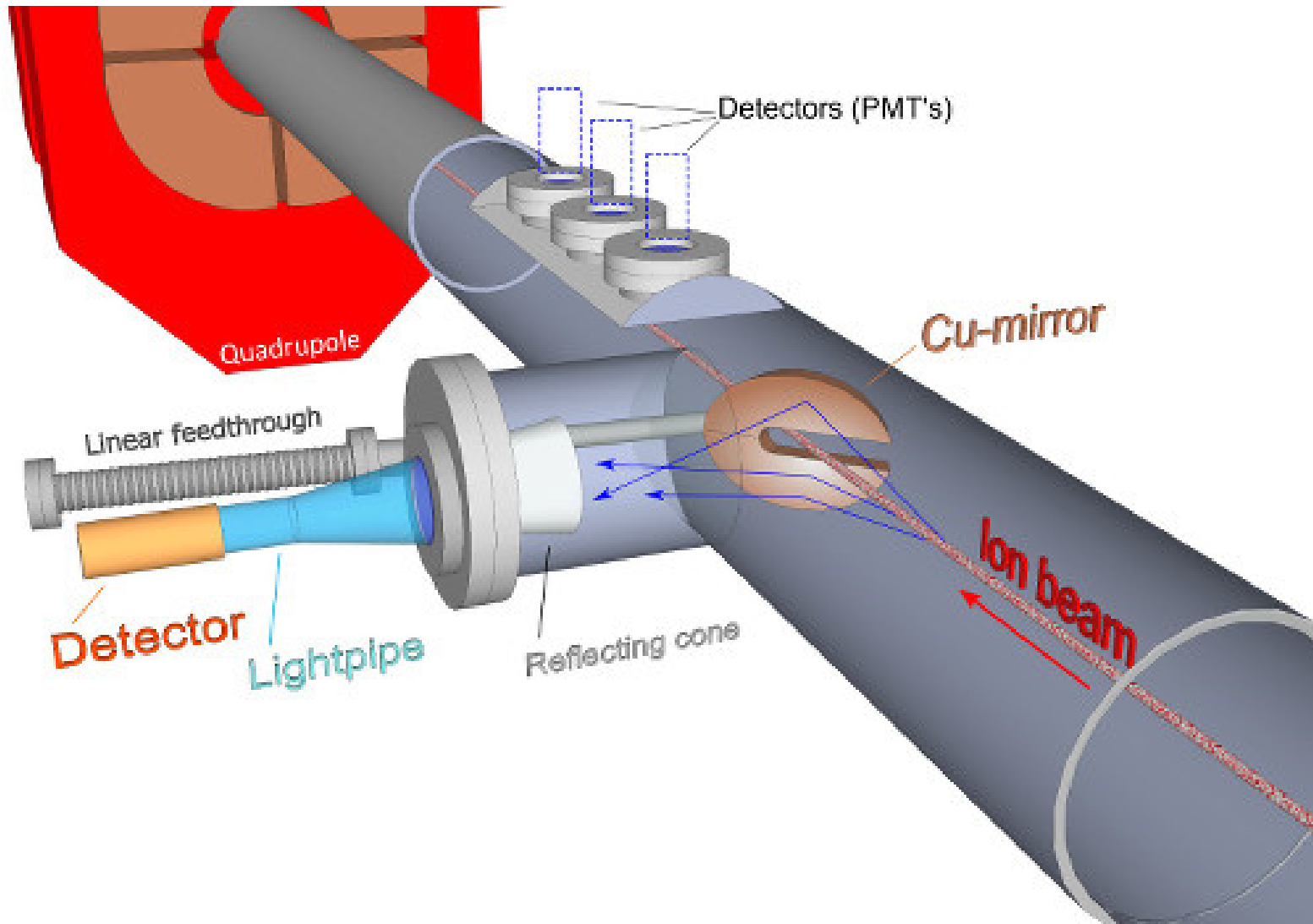
Using fluorescence intensity as a diagnostic (@ PALLAS)



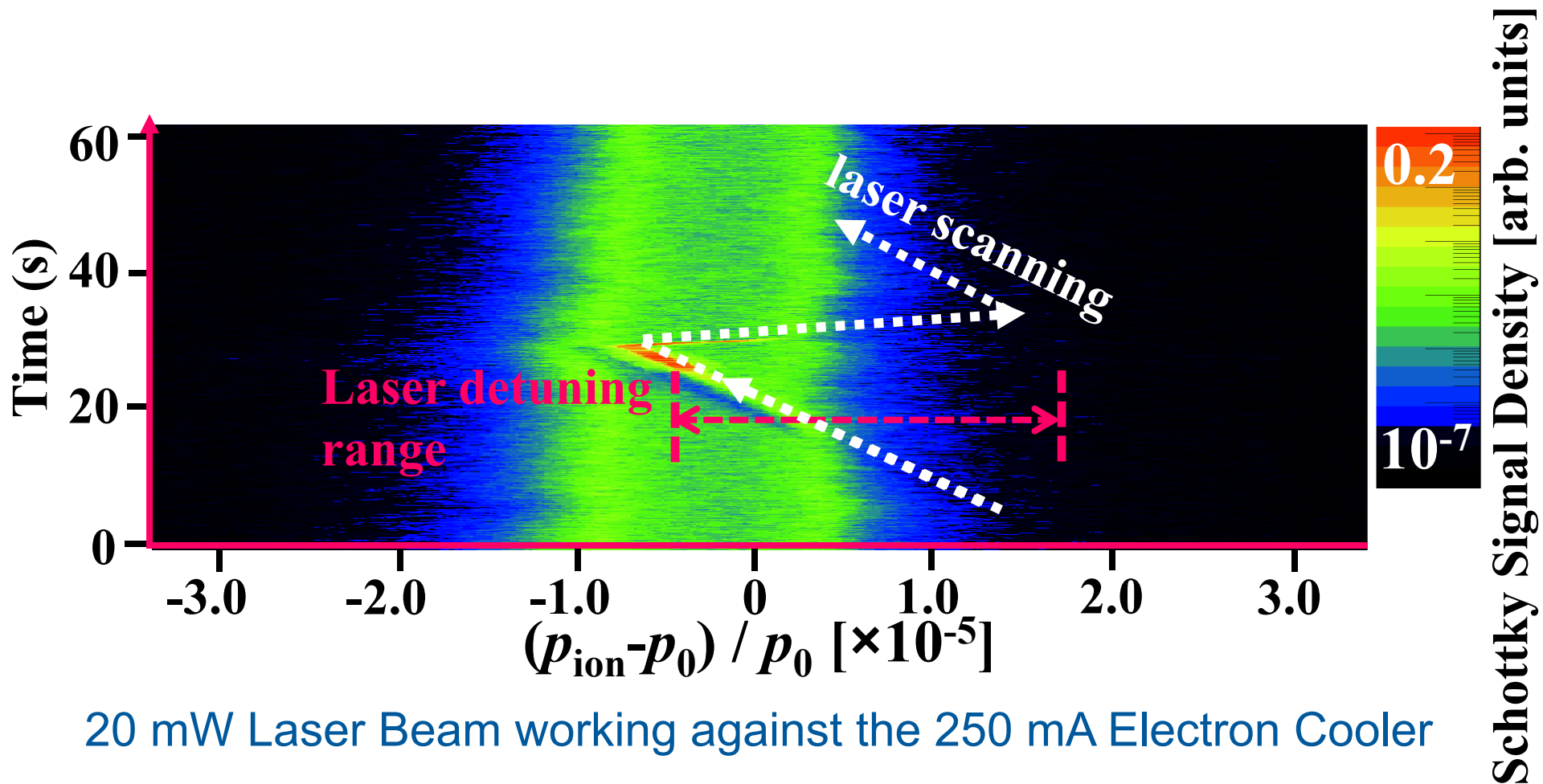
The in-beam mirror concept



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



Laser cooling force increases with beam energy



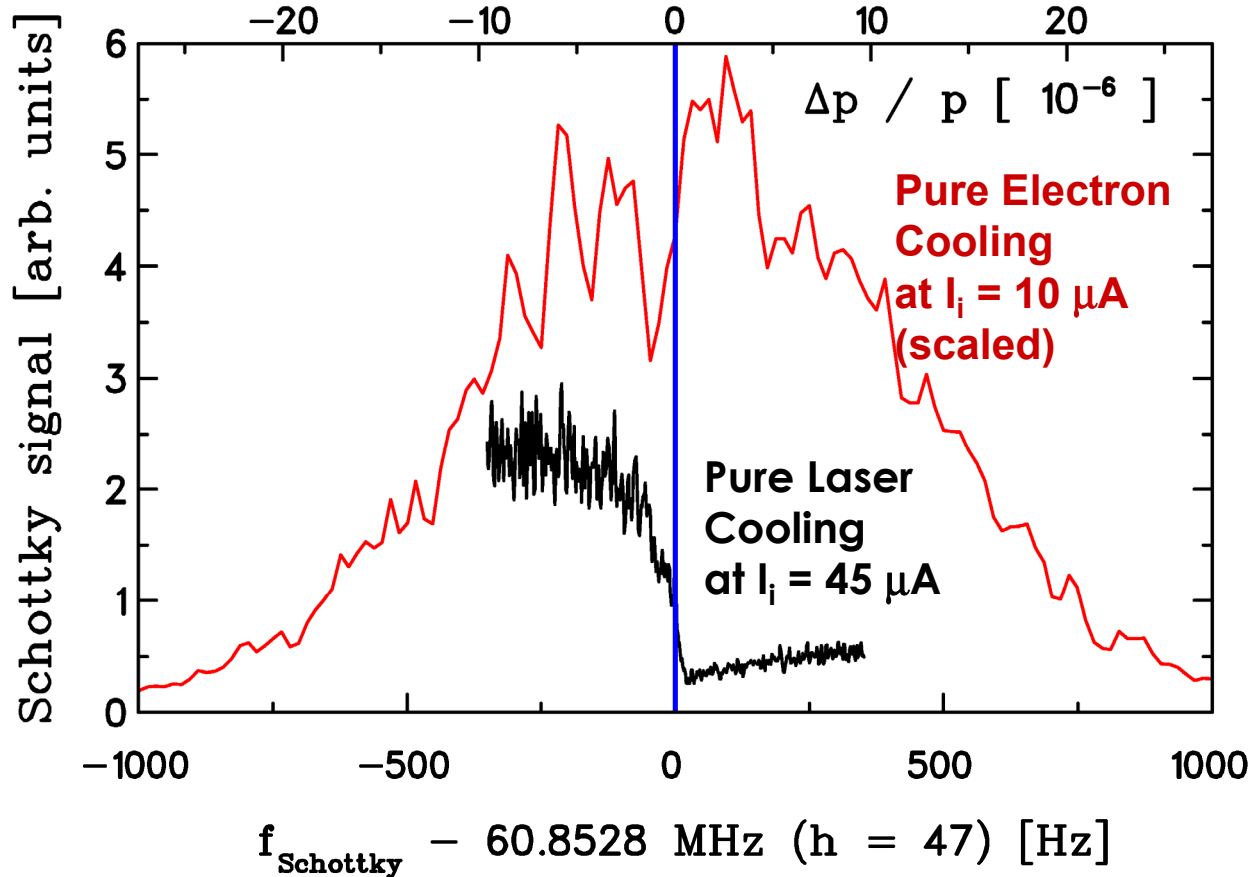
20 mW Laser Beam working against the 250 mA Electron Cooler

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

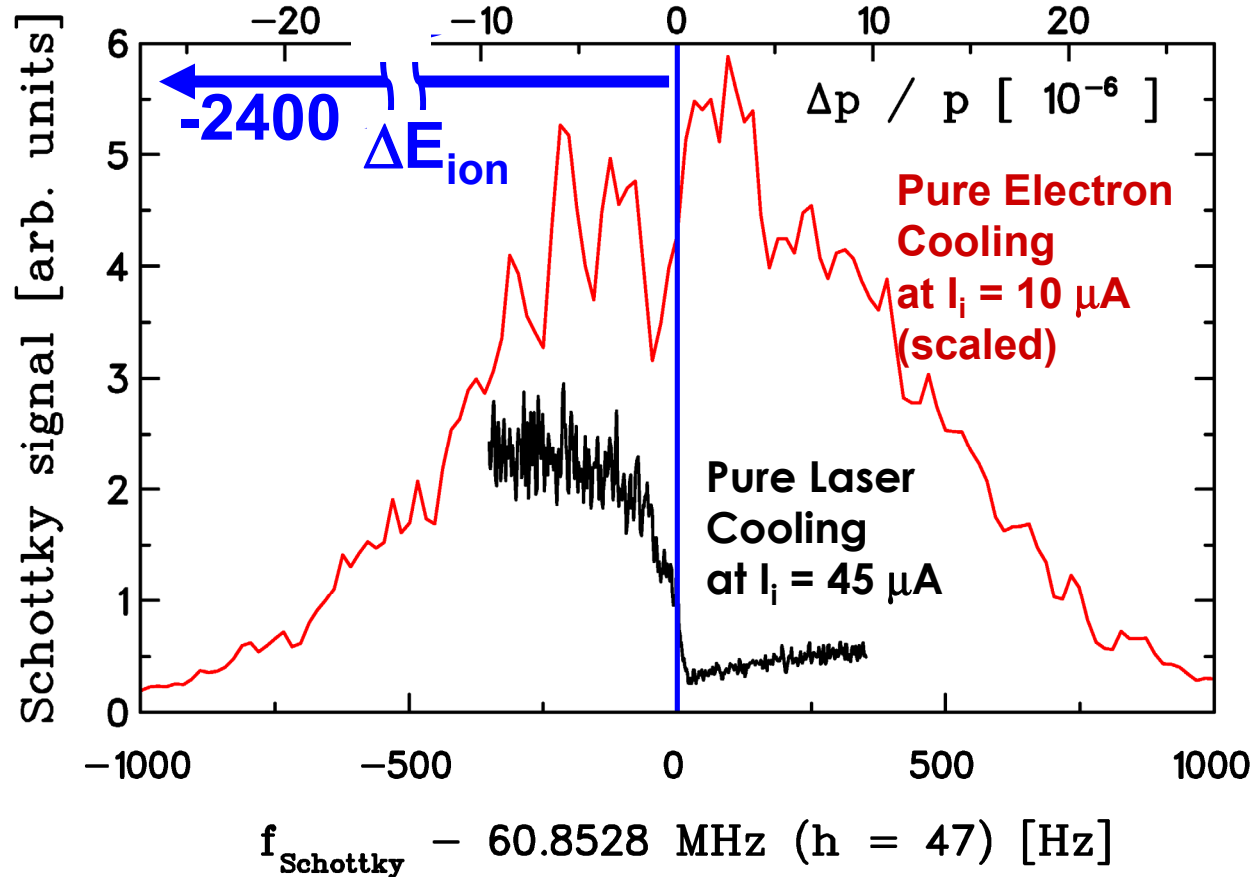
C³⁺ spectroscopy in the old days



- 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

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

C³⁺ spectroscopy in the old days

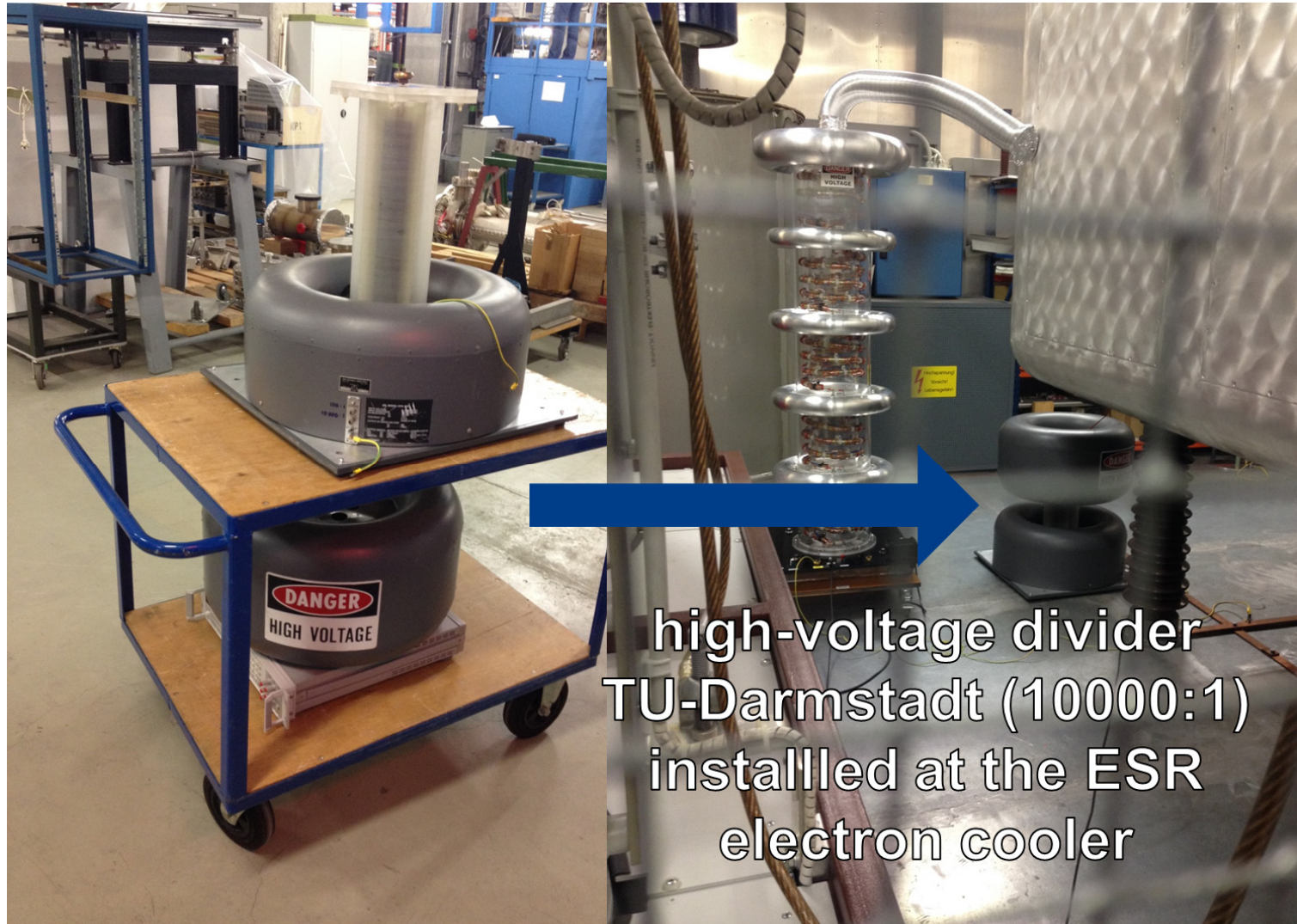


- Mark Doppler-shifted transition in Schottky spectrum (coasting)
- Adjust electron cooled distribution to the same revolution frequency
- Extrapolate to zero ion current to eliminate space charge effects

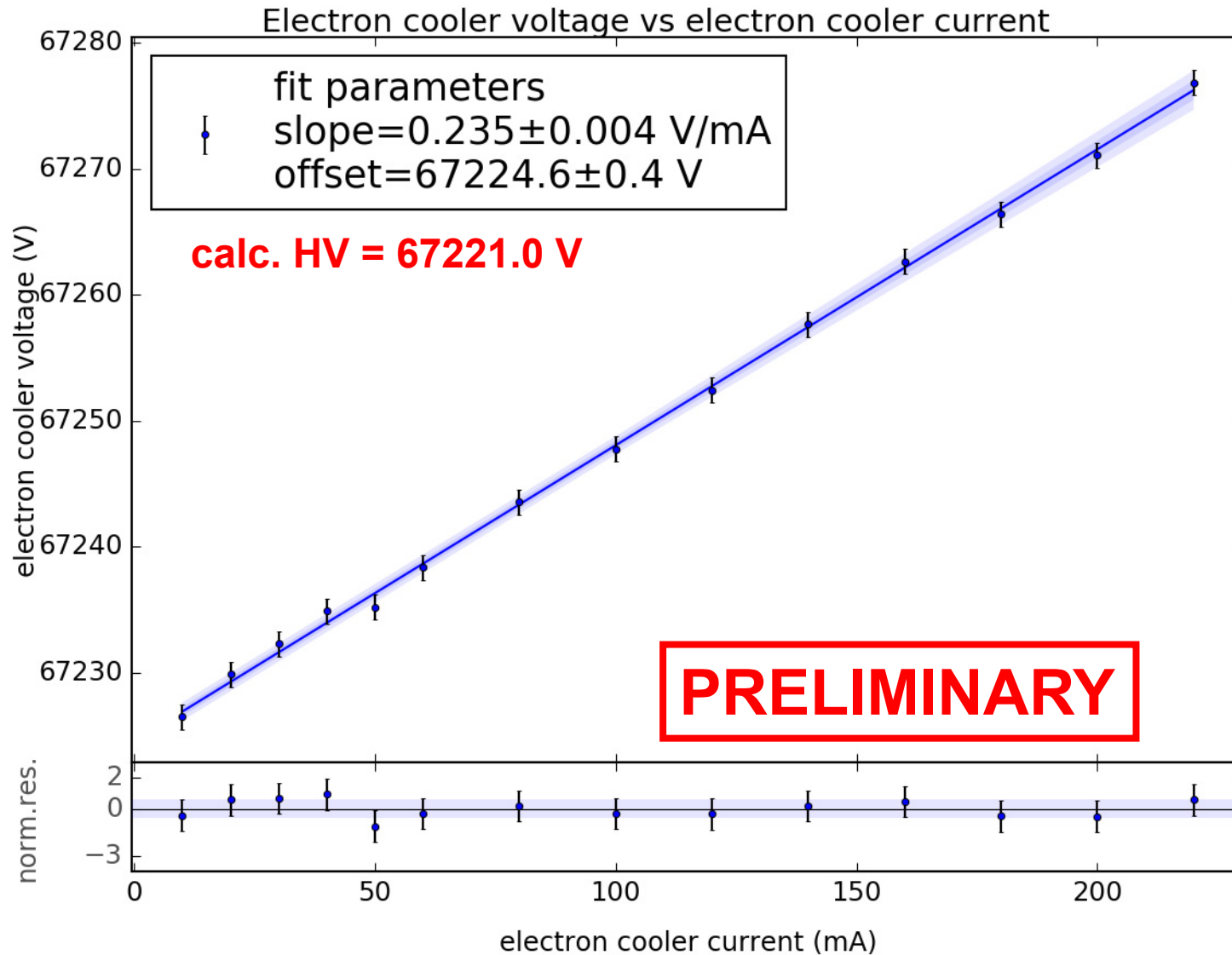
Uncertainty in absolute ion energy

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

Nörtershäuser group effort for increasing voltage accuracy



Preliminary results with PTB-calibrated electron cooler voltage

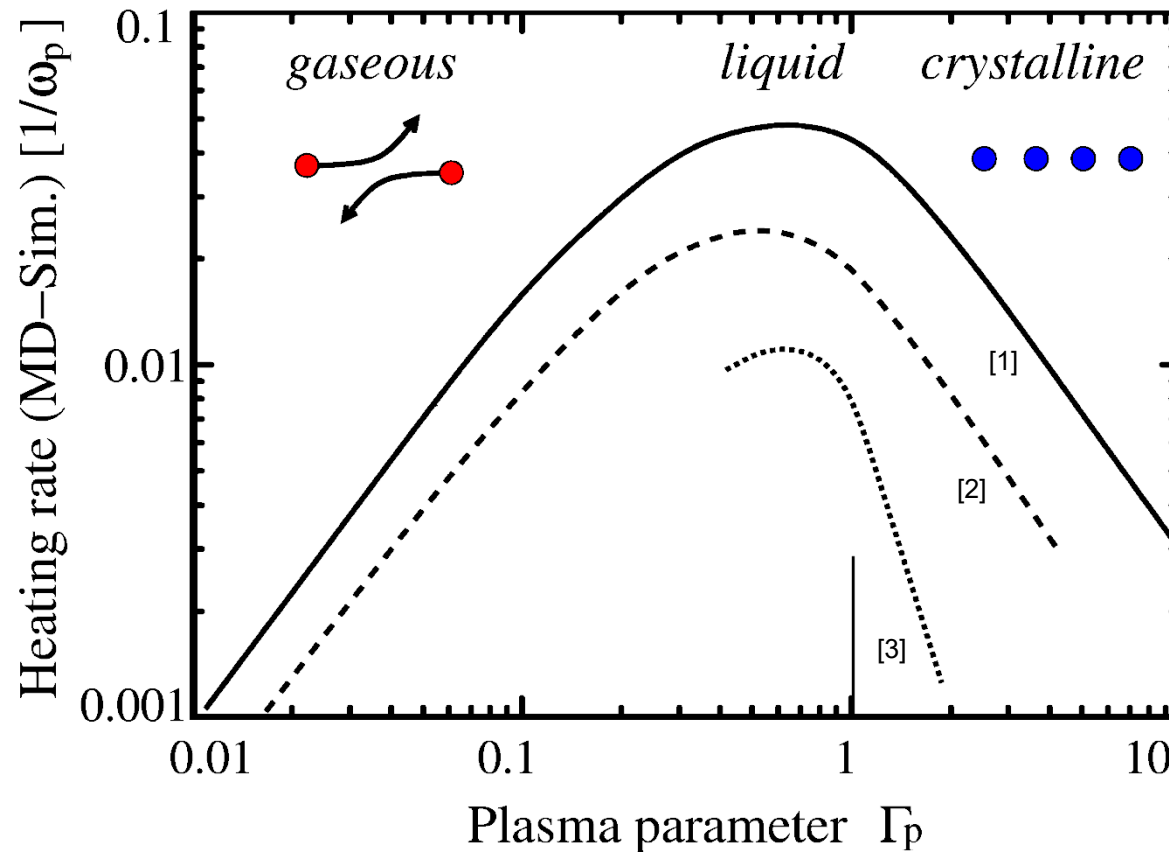


Spectroscopy

- 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!)



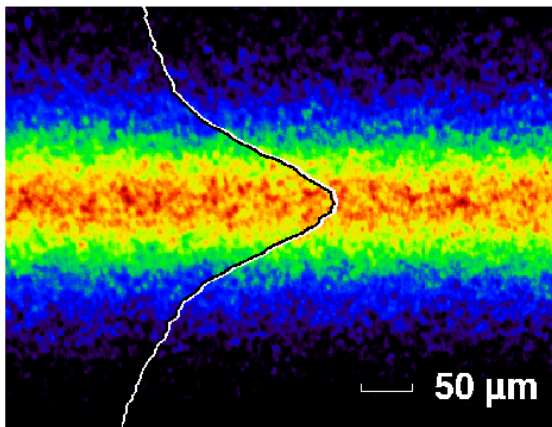
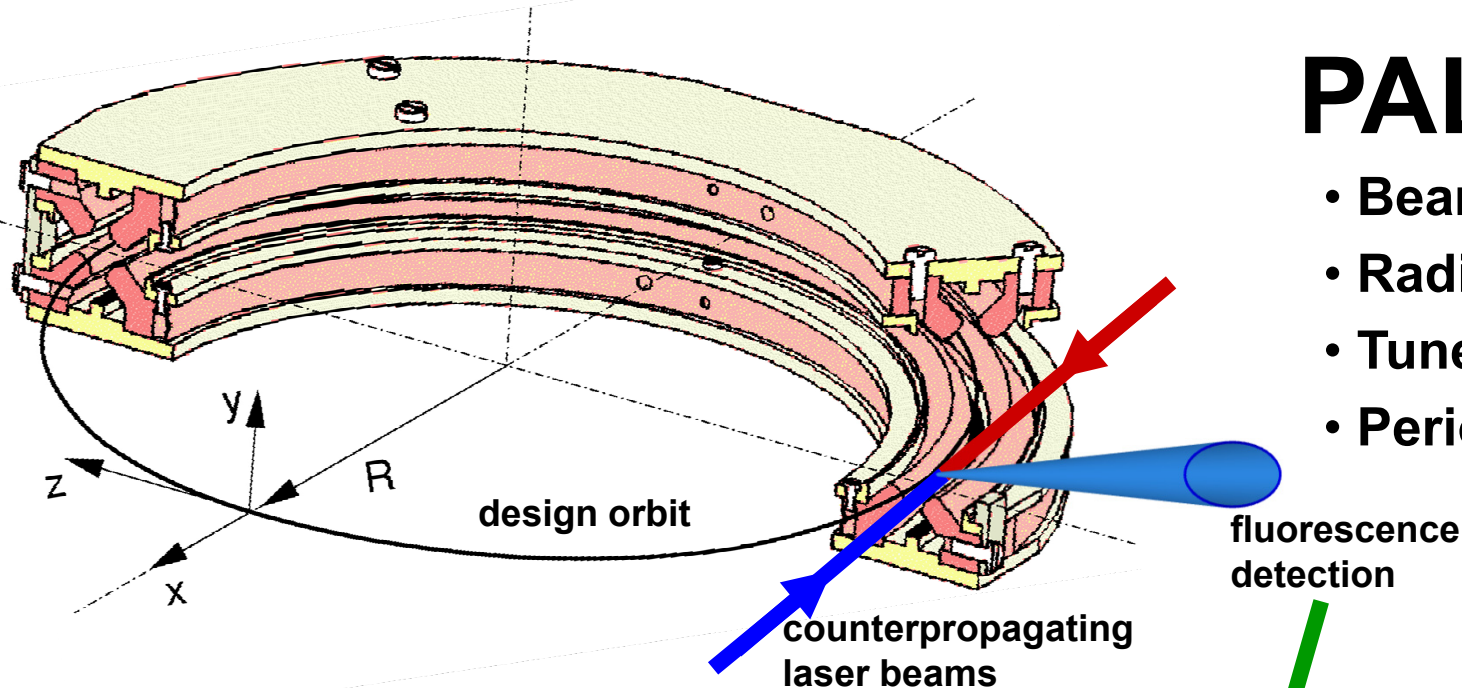
$$\Gamma_P = \frac{E_{\text{Coulomb}}}{E_{\text{thermal}}} = \frac{Z_{\text{ion}}^2 e^2}{4\pi\epsilon_0 a_{\text{WS}} \cdot k_B T_{\text{ion}}}, \quad a_{\text{WS}} = \left(\frac{4}{3} \pi n_{\text{ion}} \right)^{-\frac{1}{3}}$$



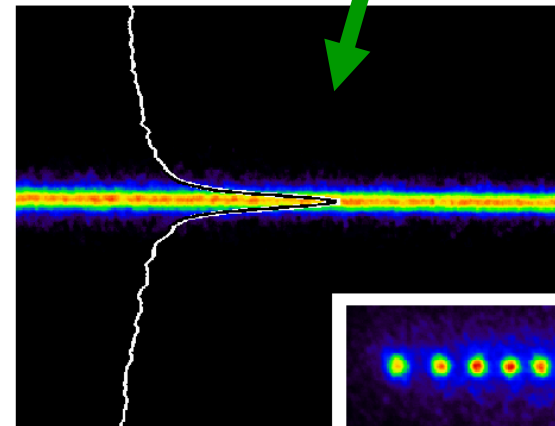
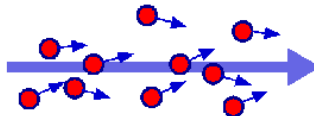
„Crystalline“ ion beams at the eV RFQ storage ring PALLAS

PALLAS

- Beam energy $\sim$ eV
- Radius 57 mm
- Tune 50
- Periodicity 800



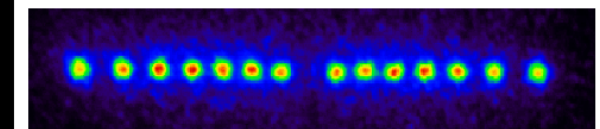
'gaseous' beam
IBS-dominated



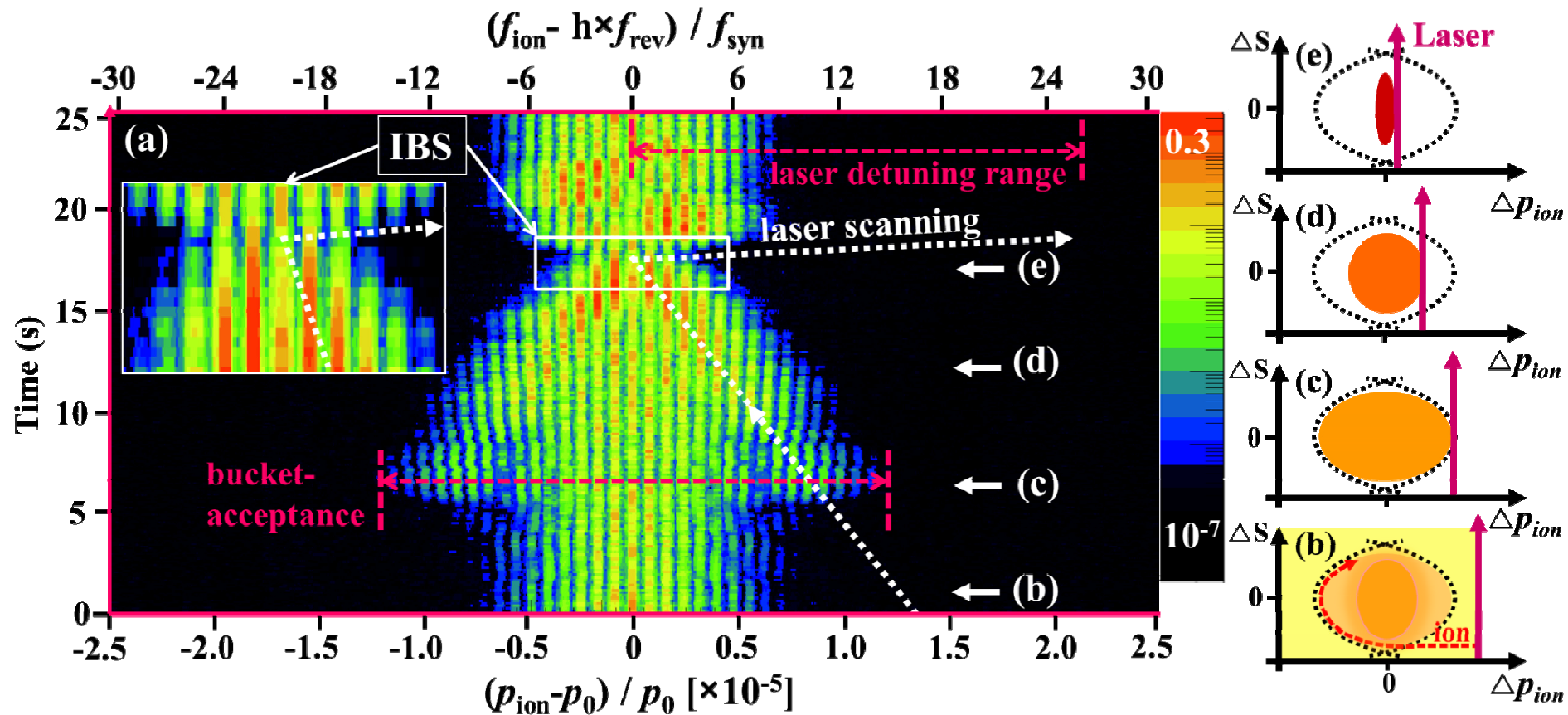
crystalline beam
long-range order



(stationary)

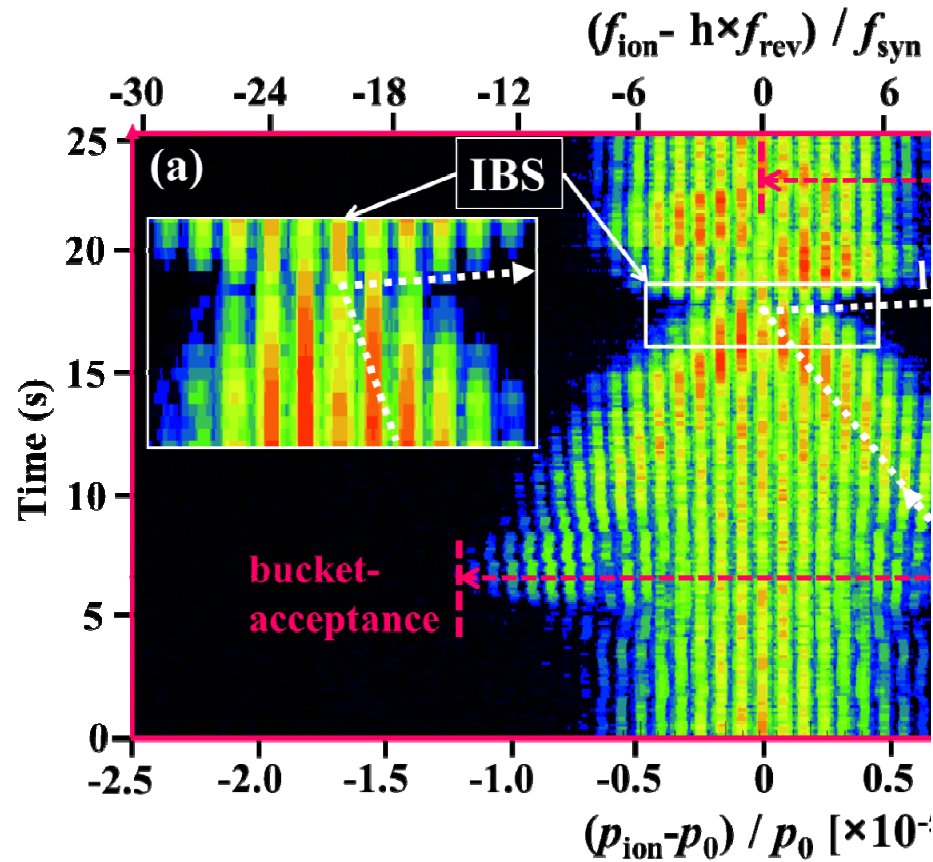


Schottky measurements of bunched laser cooled C^{3+} beams

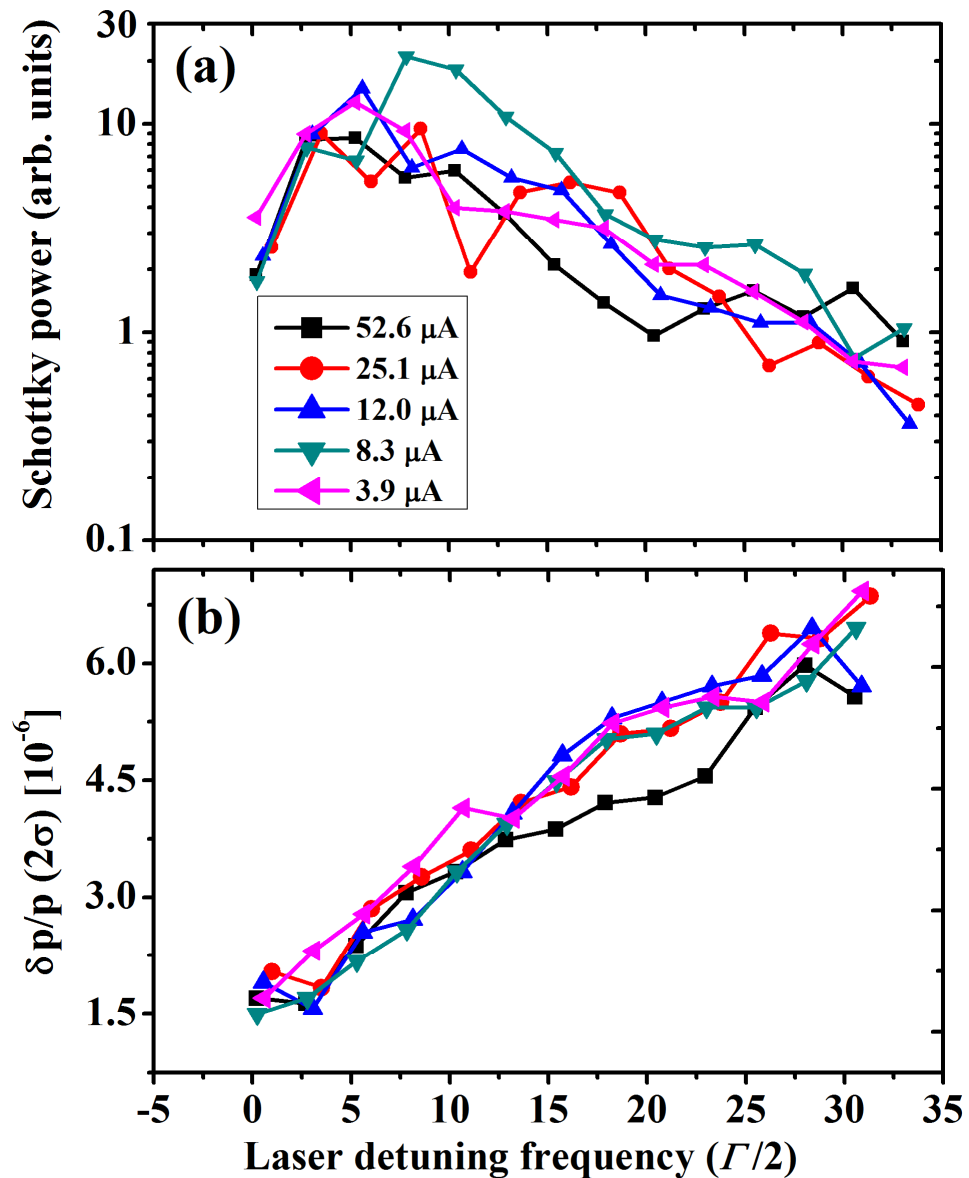


PRELIMINARY

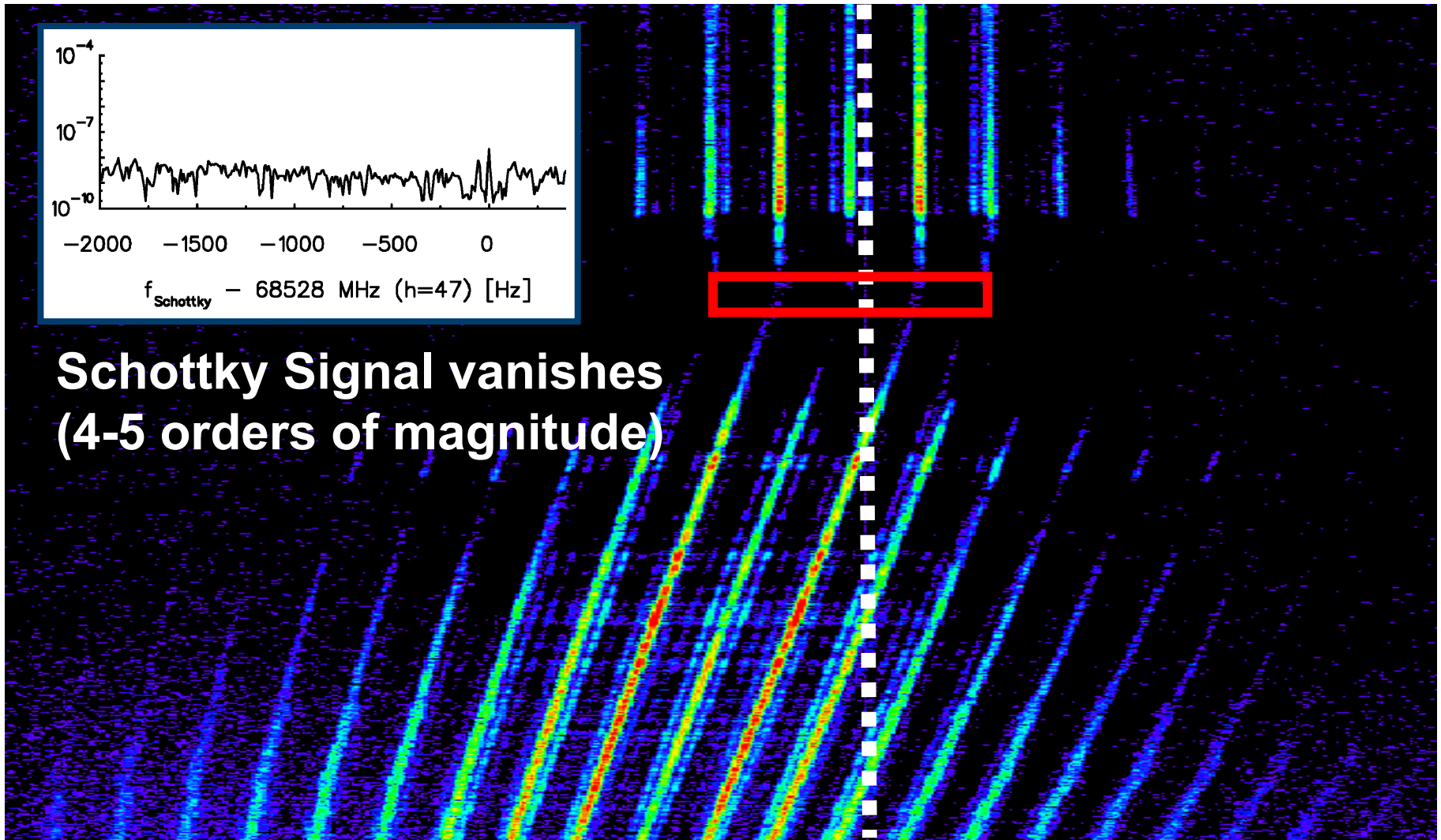
Schottky measurements of bunched laser cooled C^{3+} beams



PRELIMINARY



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



$h = 20$

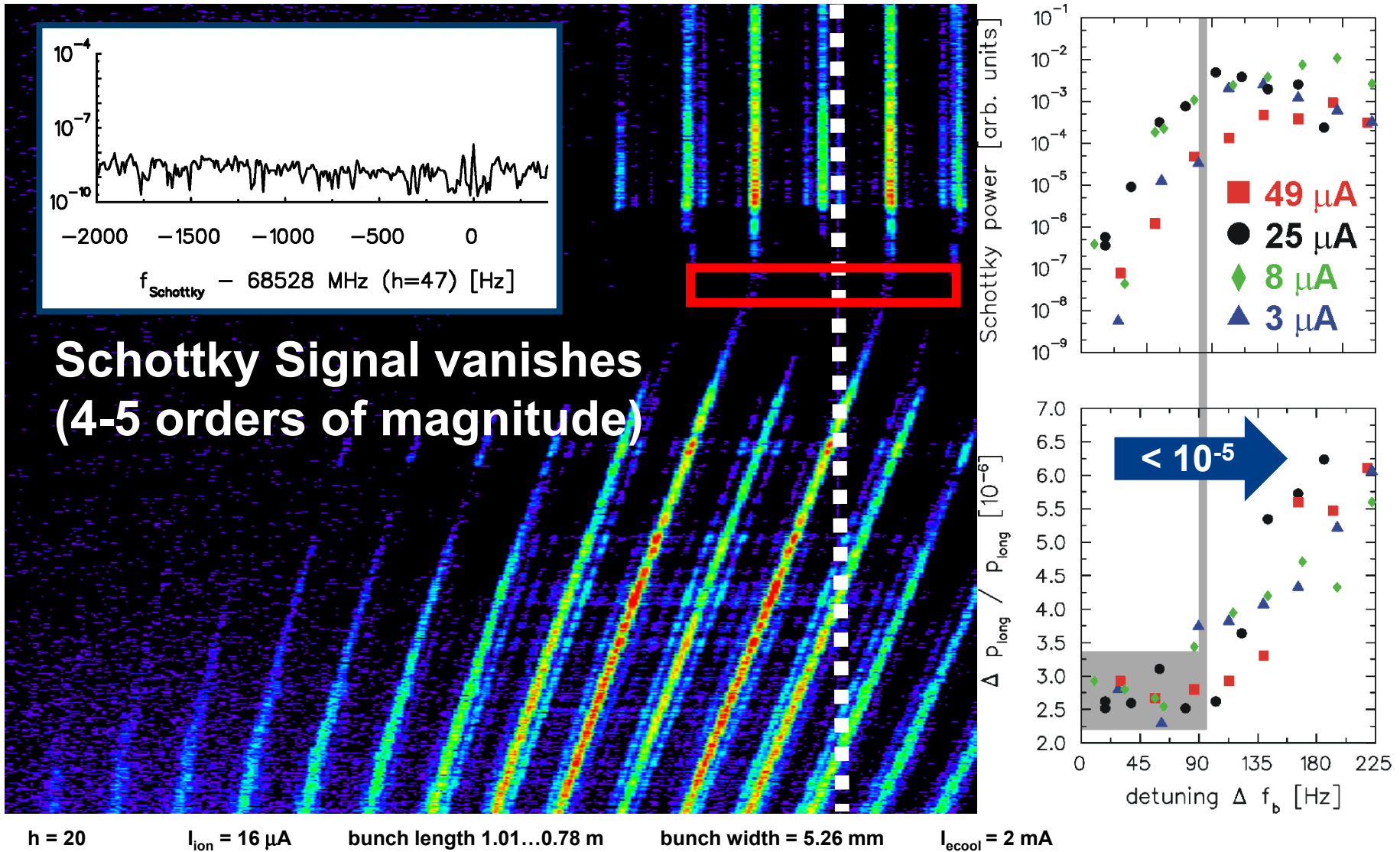
$I_{\text{ion}} = 16 \mu\text{A}$

bunch length 1.01...0.78 m

bunch width = 5.26 mm

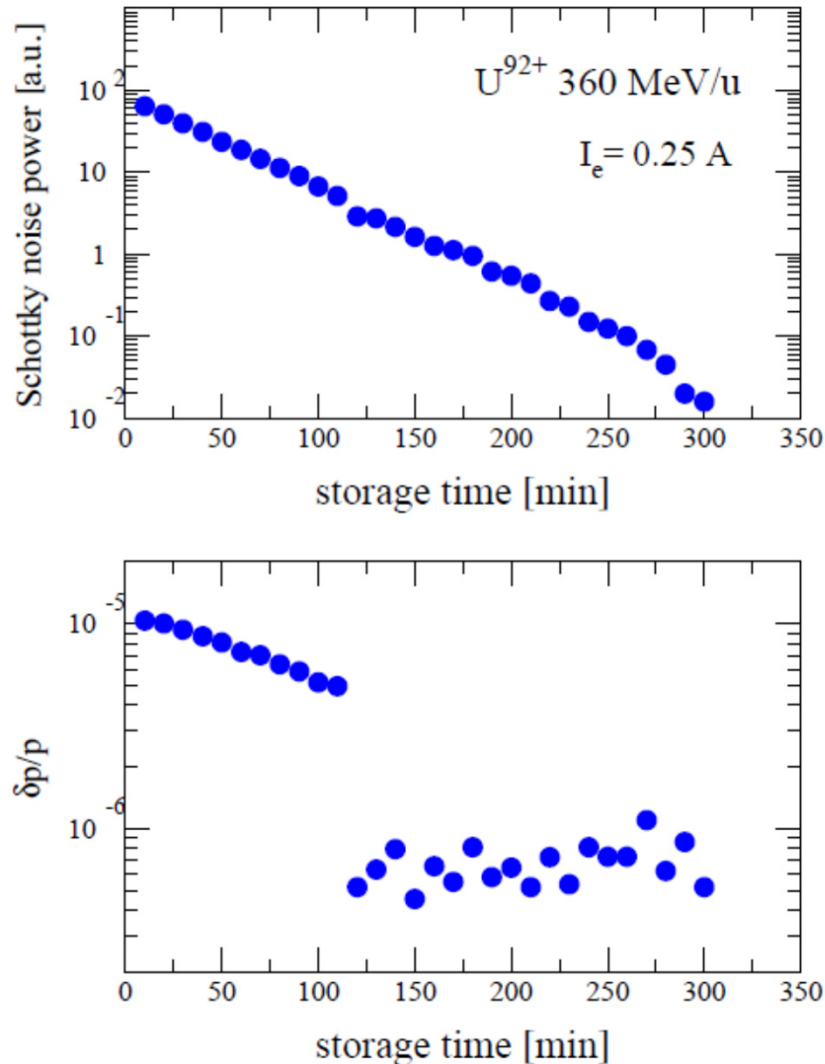
$I_{\text{ecool}} = 2 \text{ mA}$

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

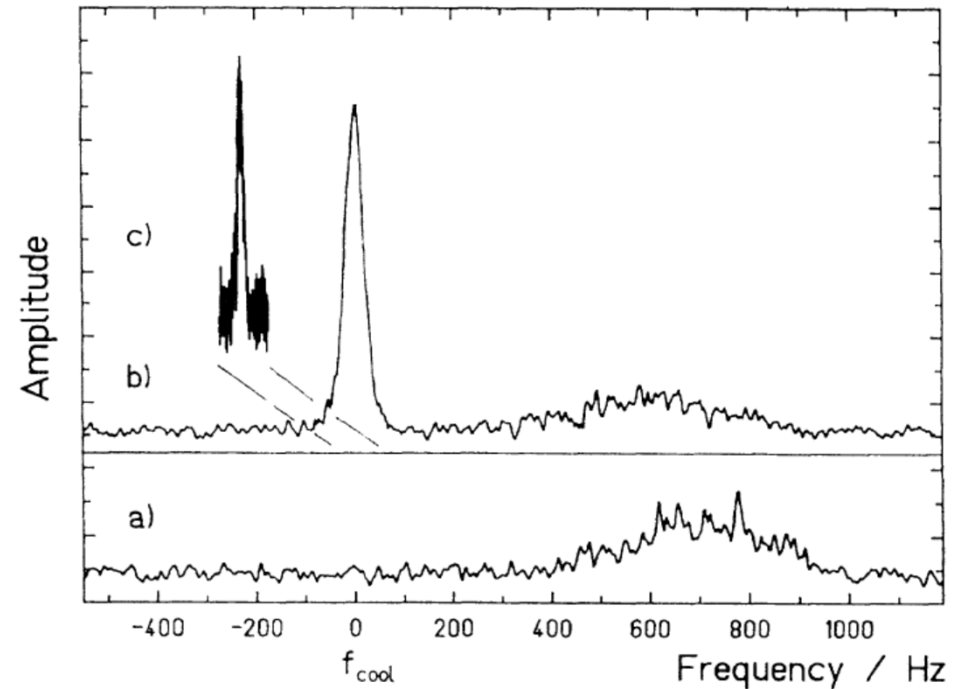


What does zero Schottky signal even mean?

ESR, electron cooled, coasting beam
(2001)



TSR, laser cooled, coasting beam
(1990)

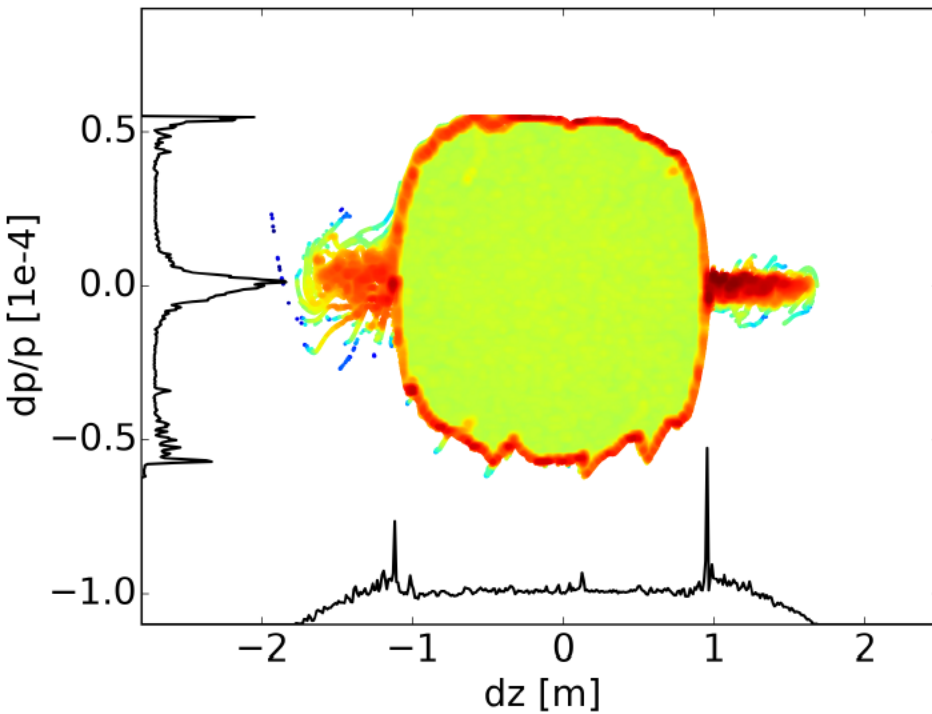


Ultracold ion beams

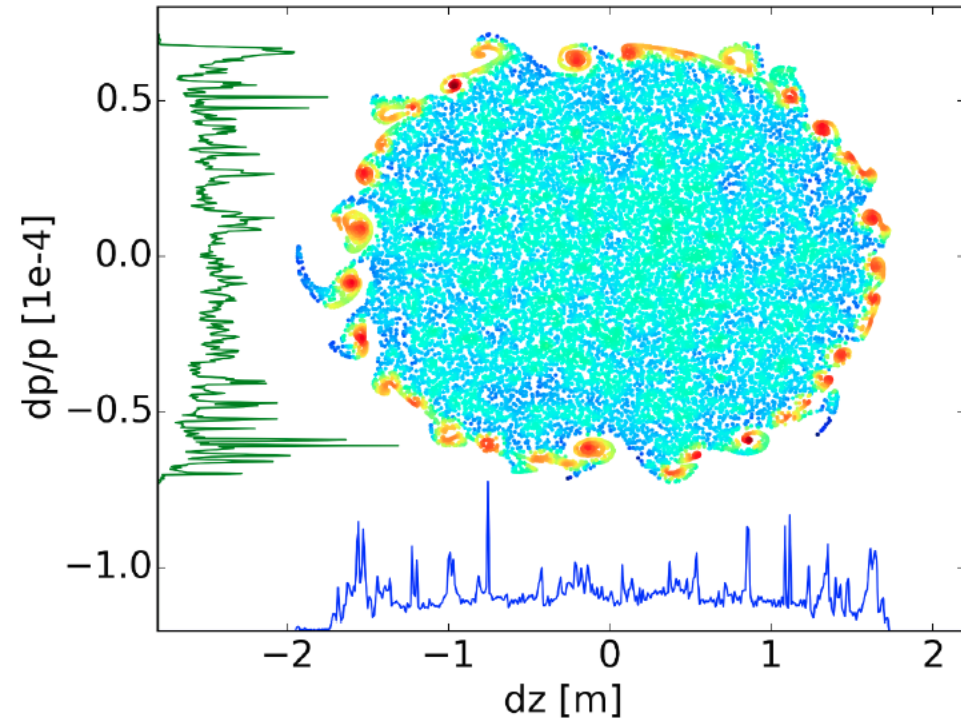
- Unlikely to see crystallization...
- ... but who knows?
- Coupling to transverse degree of freedom needed
- Zero Schottky signal for bunched beams not understood
- Fluorescence detection might give clues

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 ($\sim$ negative mass)
due to high density at the border of
the phase space to where the cw
laser pushes ions with higher
momenta

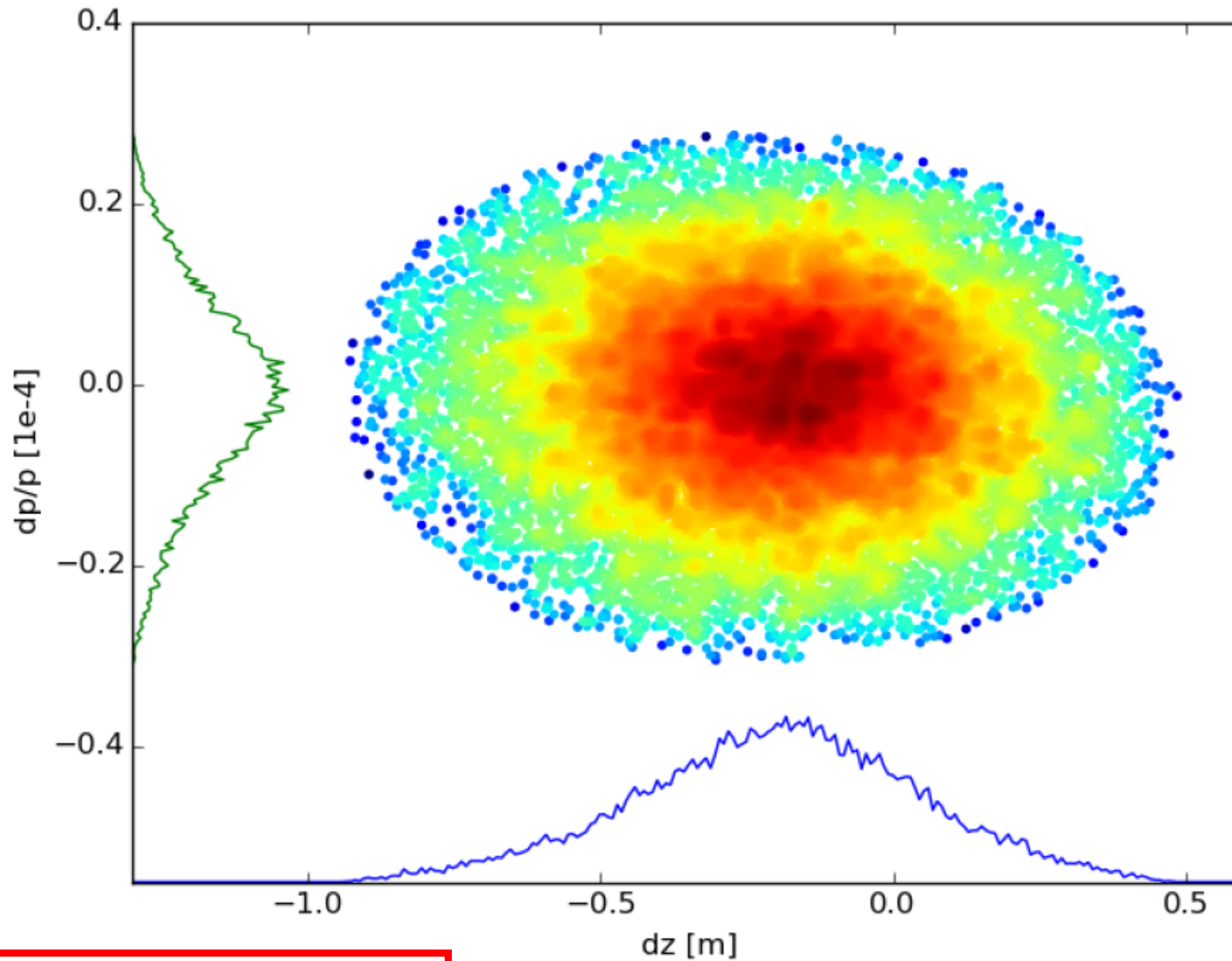
PRELIMINARY

© Lewin Eidam

DRESDEN
concept

HZDR

Both effects suppressed when using pulsed lasers (Simulation!)



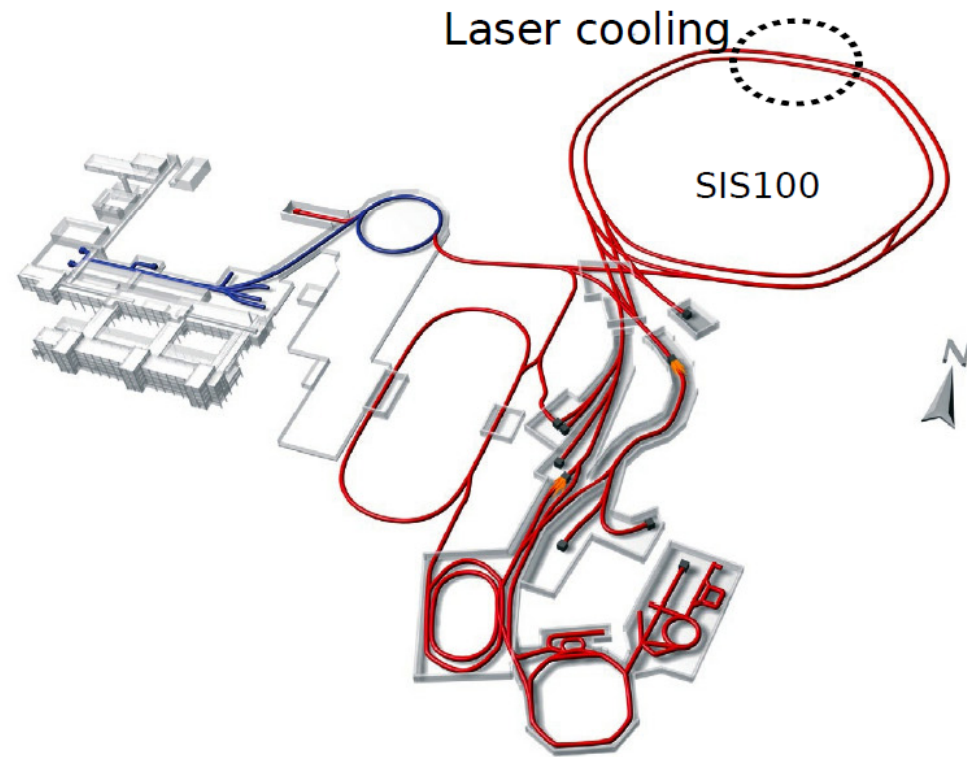
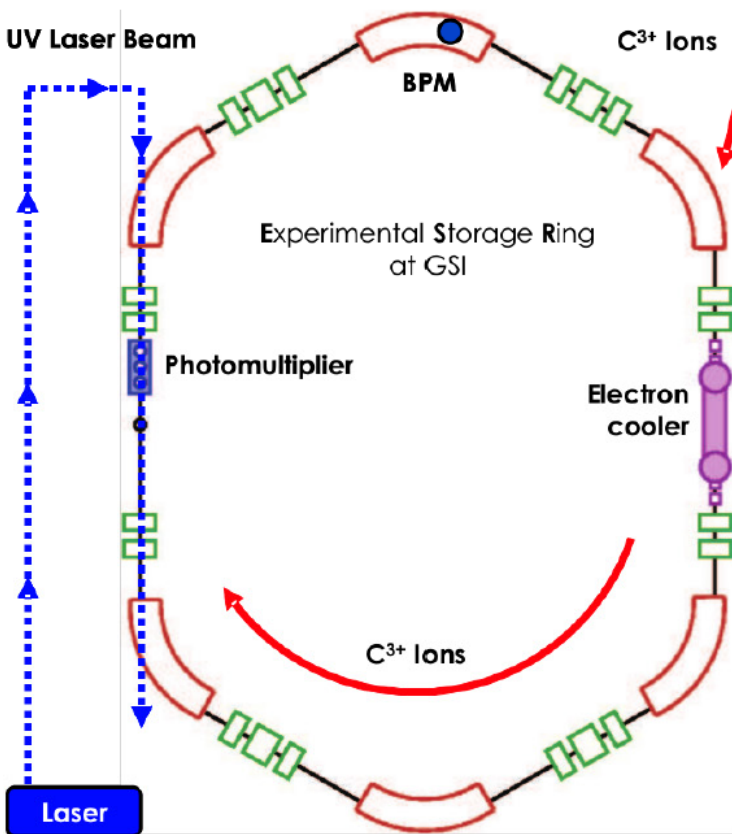
PRELIMINARY

© Lewin Eidam



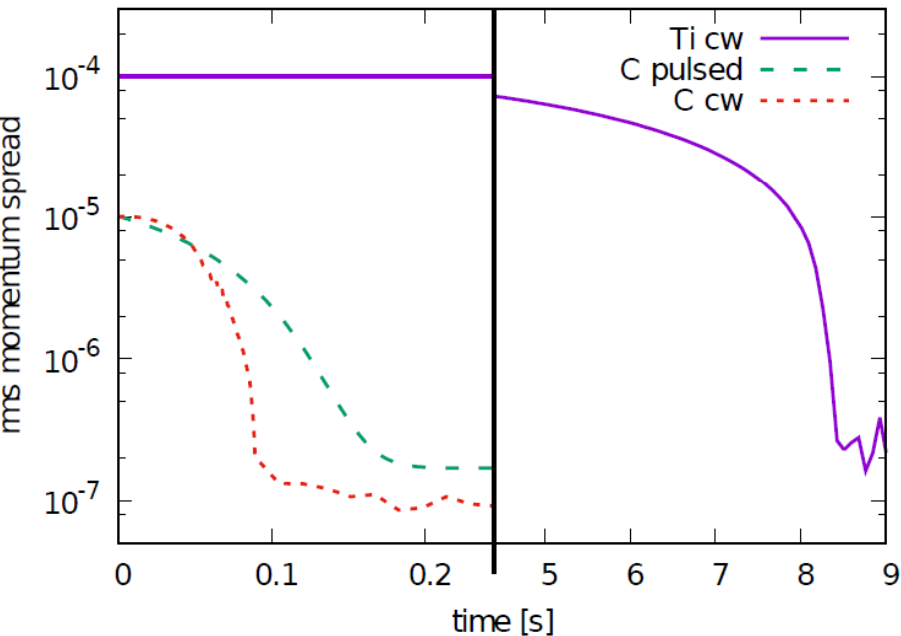
Preliminary cooling times estimates comparing ESR to SIS100

	Ion	T_{rev}	$L_{interact}$	δ_{rms0}	d_{beam}	γ	L_{bunch}
ESR	$^{12}\text{C}^{3+}$	0.8 ms	25 m	10^{-5}	3 mm	1.13	4 m
SIS100	$^{48}\text{Ti}^{19+}$	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}
$^{12}\text{C}^{3+}$	256 nm	20 mW	7.5	$1.5 \cdot 10^{-9}$	$5.8 \cdot 10^{-8}$	0.278
$^{48}\text{Ti}^{19+}$	512 nm	5 W	4.7	$9.3 \cdot 10^{-10}$	$3.9 \cdot 10^{-8}$	$8 \cdot 10^{-5}$



	$^{12}\text{C}^{3+}$	$^{48}\text{Ti}^{19+}$
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

© Lewin Eidam



Thank you!

