Laser Cooling of Relativistic Ion Beams
Recent Results and Future Perspectives

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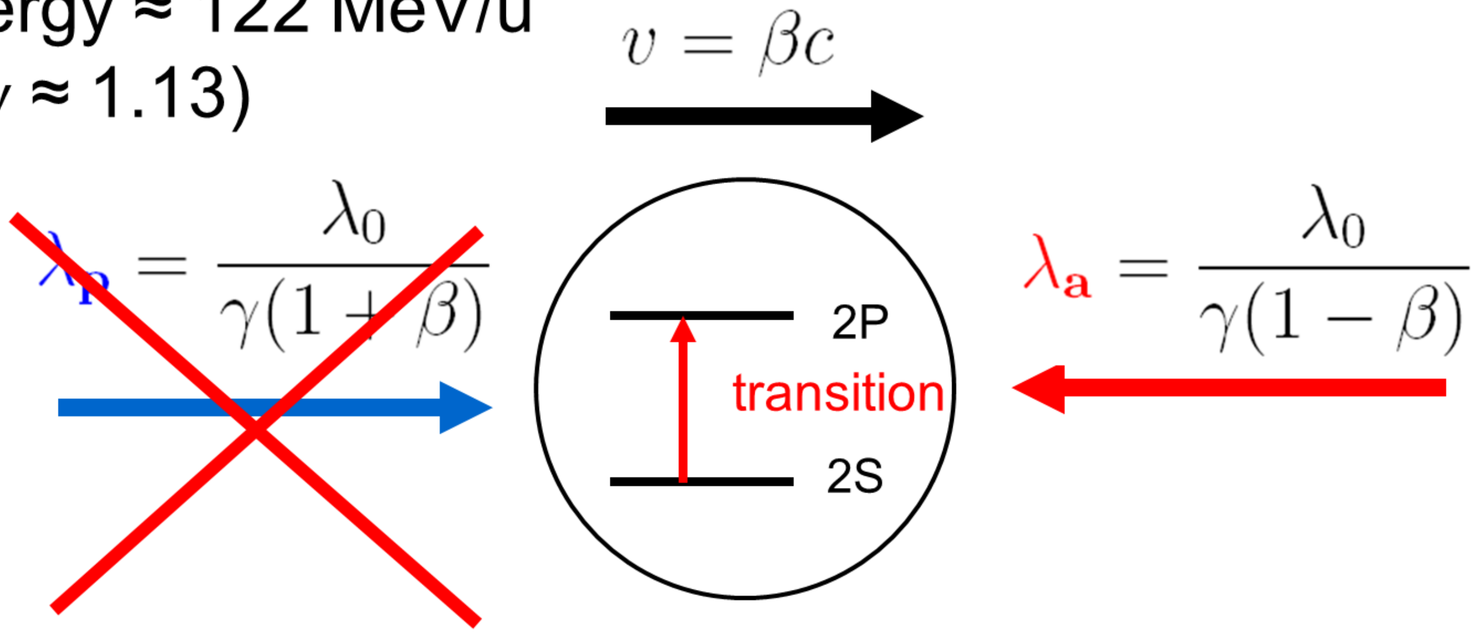
Atomic Physics at Relativistic Beam Energies

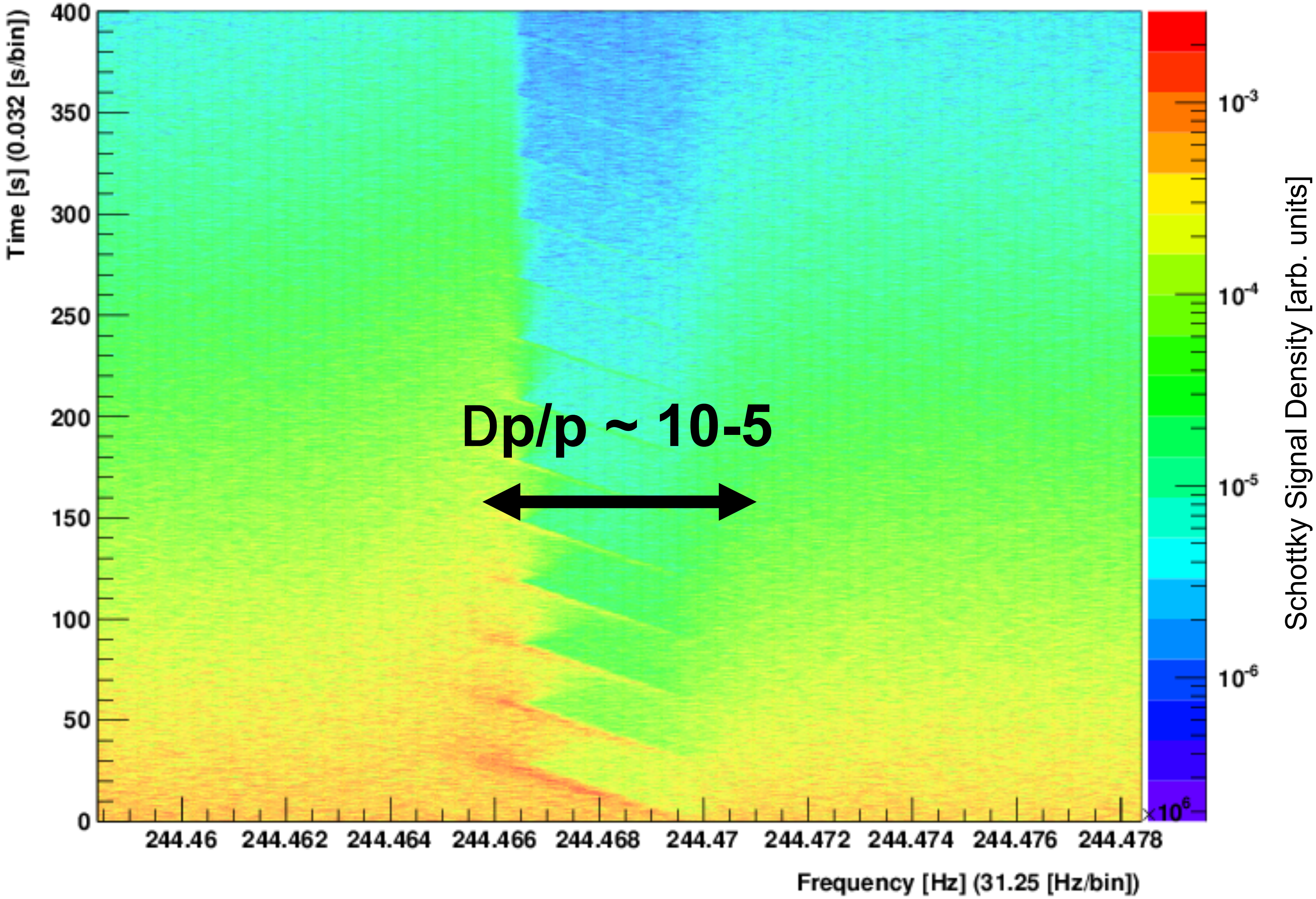
Laser Cooling at Relativistic Energies – Relativistic Doppler Shift

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

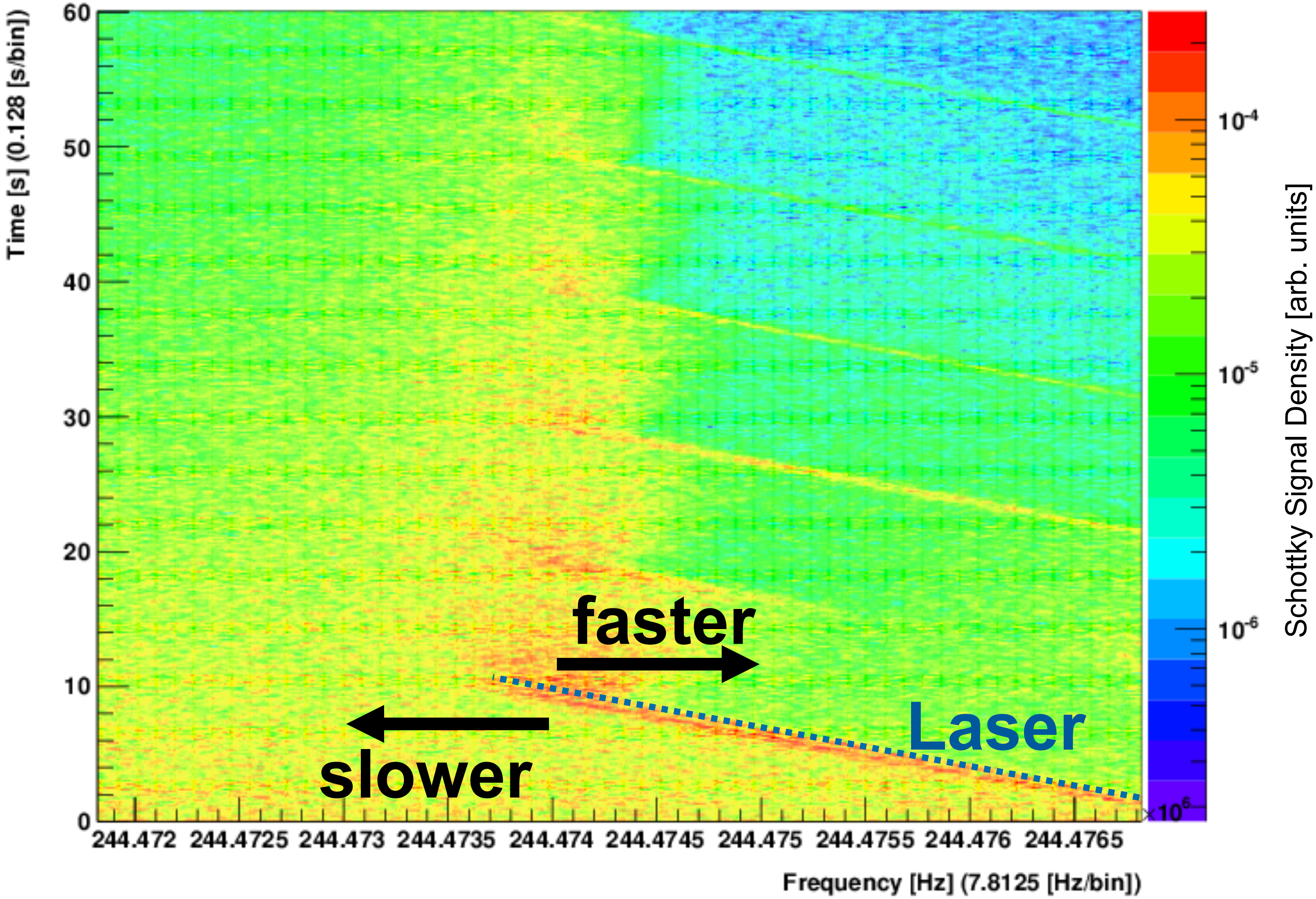


λ_p=93 nm λ_0=155 nm λ_a=257 nm

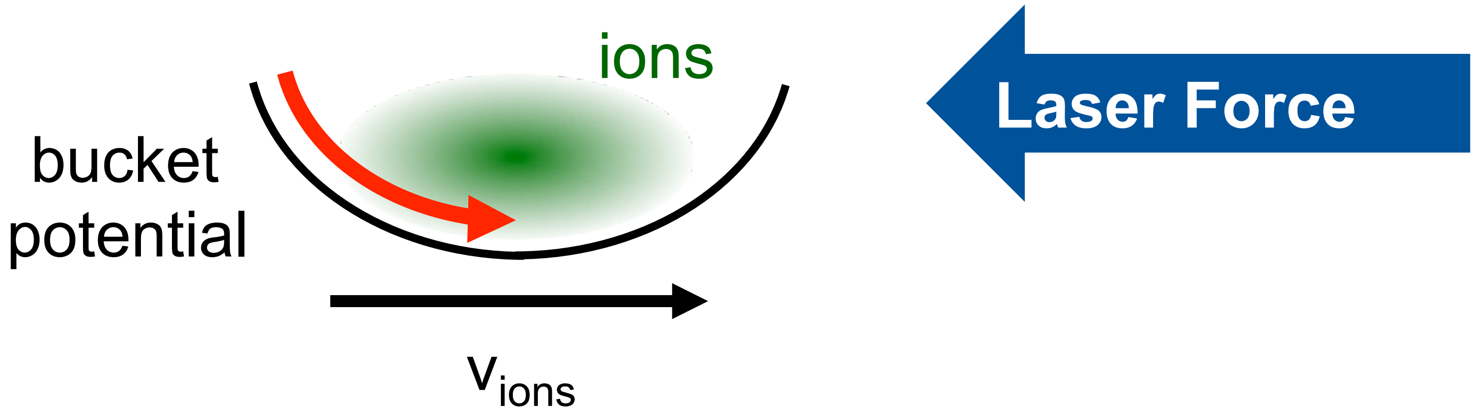
Scanning Laser Frequency with a Coasting Ion Beam



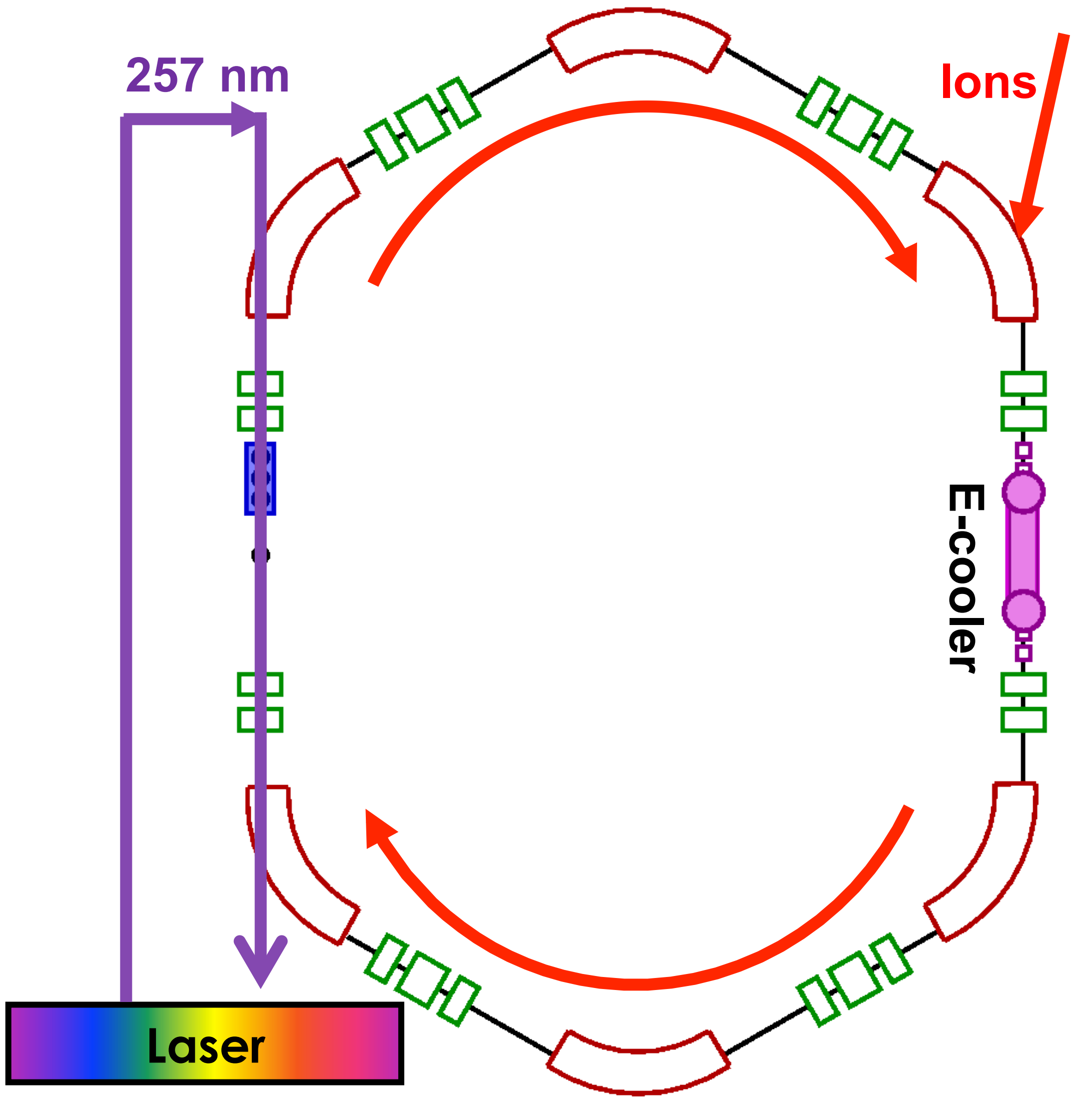
Laser „pushes“ the Ion Beam in Momentum Space to lower Velocities



Bunching the Ion Beam counteracts the Laser Force



C^{3+} Laser Cooling Setup (ESR, CSRe)



C^{3+}

E_{beam} = 122 MeV/u

= 1.47 GeV

(b = 0.47, g = 1.13)

f_{rev} = 1.295 MHz

Solid laser (cw)

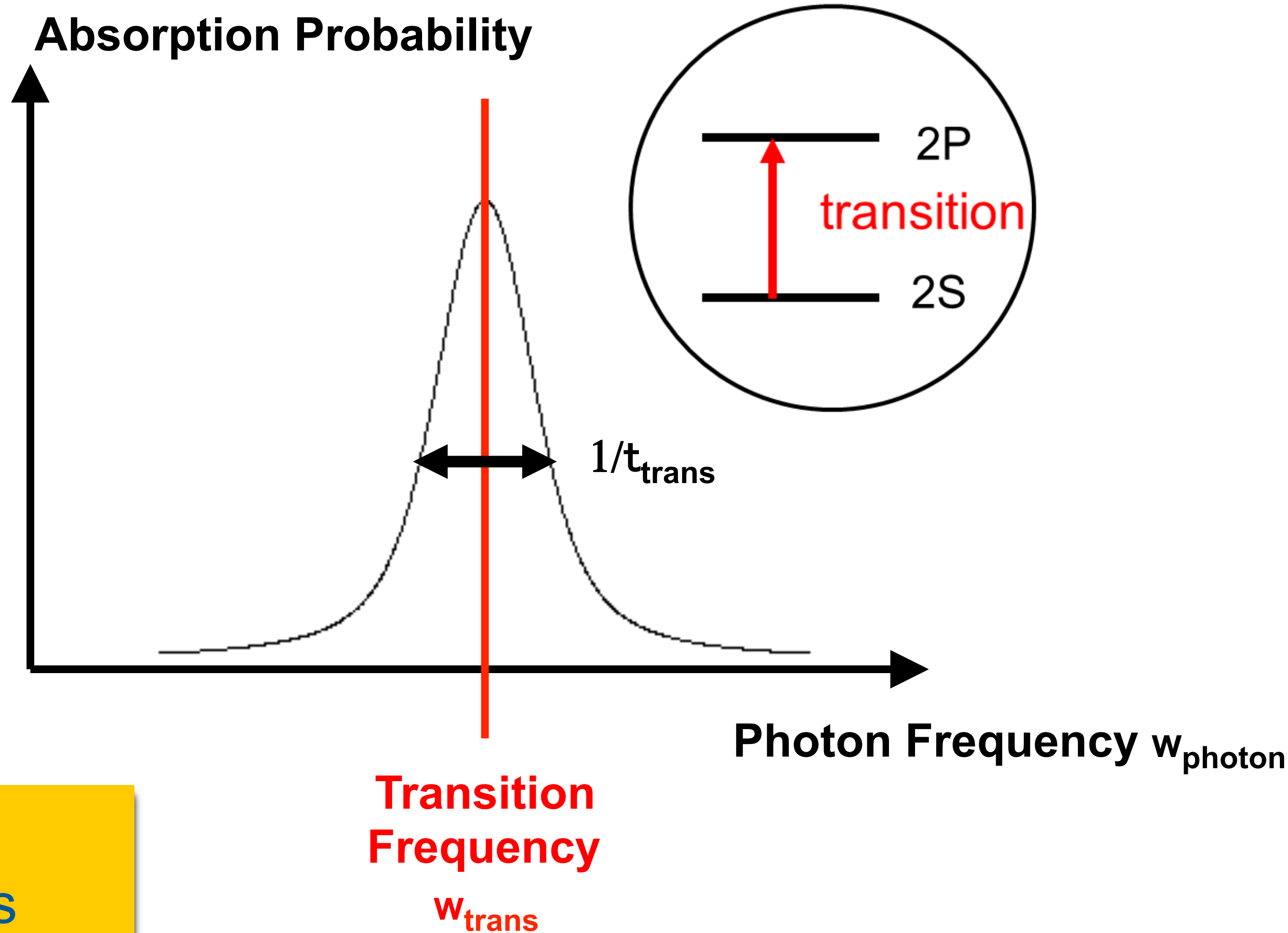
l_{laser} = 257 nm

$2S_{1/2} \rightarrow 2P_{1/2}$

l_{rest} = 155.07 nm

t_{rest} = 3.8 ns

Line Shape determines the Probability of Photon Absorption



C^{3+}

t'_{trans} = 3.8 ns

$\hbar k'_{trans}$ = 8 eV/c

l'_{trans} = 155 nm

Scattering Rate of Photons is directly proportional to Line Shape

$$R'(\delta') = L'(\delta') / \tau'_{trans} = \frac{1}{2\tau'_{trans}} \frac{S'(1/\tau'_{trans})^2}{4\delta'^2 + (1/\tau'_{trans})^2 (1+S')}$$

$$\delta' = \omega'_{photon} - \omega'_{trans} - \Delta p'_{ion} k'_{phot} / m'_{ion}$$

S‘	~ 1	: Saturation Parameter (S > 1 does not increase cooling!)
t'_{trans}	~ ns	: Lifetime of the Transition (determines minimum cooling time!)
d‘		: detuning between laser light and atomic transition (photon frequency in rest frame!)

C^{3+} @ ESR, CSRe

gt'_{trans} = 4.3 ns

t_{rev} = 772.2 ns

N_{scat} = t_{rev}/gt'_{trans} = 179

Saturation Intensity > 1, depends on Relativistic Effects and Transition

$$S' = \frac{I'_{laser}}{I'_{sat}}$$

$$I'_{sat} = \frac{2\pi^2 hc}{3\tau'_{trans}\lambda'^3_{trans}} = P'_{sat} / \left(\pi w'^2_{laser}\right)$$

I'_{sat} : Saturation Intensity
(laser power depends on the ion beam diameter)

I'_{sat} for C^{3+} : Laser Spot Size = Ion Beam Diameter
(we need between 1 mW to 100 mW)

C^{3+} @ ESR, CSRe

$(1+b)^{-3}g^{-4}I'_{sat}$ = 9.2 W/cm^2 / ((1+0.47)^3×1.13^4)
= 17.9 mW/mm^2

Force = Momentum Transfer Rate

$$\omega'_{photon} - \omega'_{trans} - p'_{ion} k'_{phot} / m'_{ion}$$

$$\vec{F}'(\partial') = \pi\hbar\vec{k}'_{phot} \times R'(\partial')$$

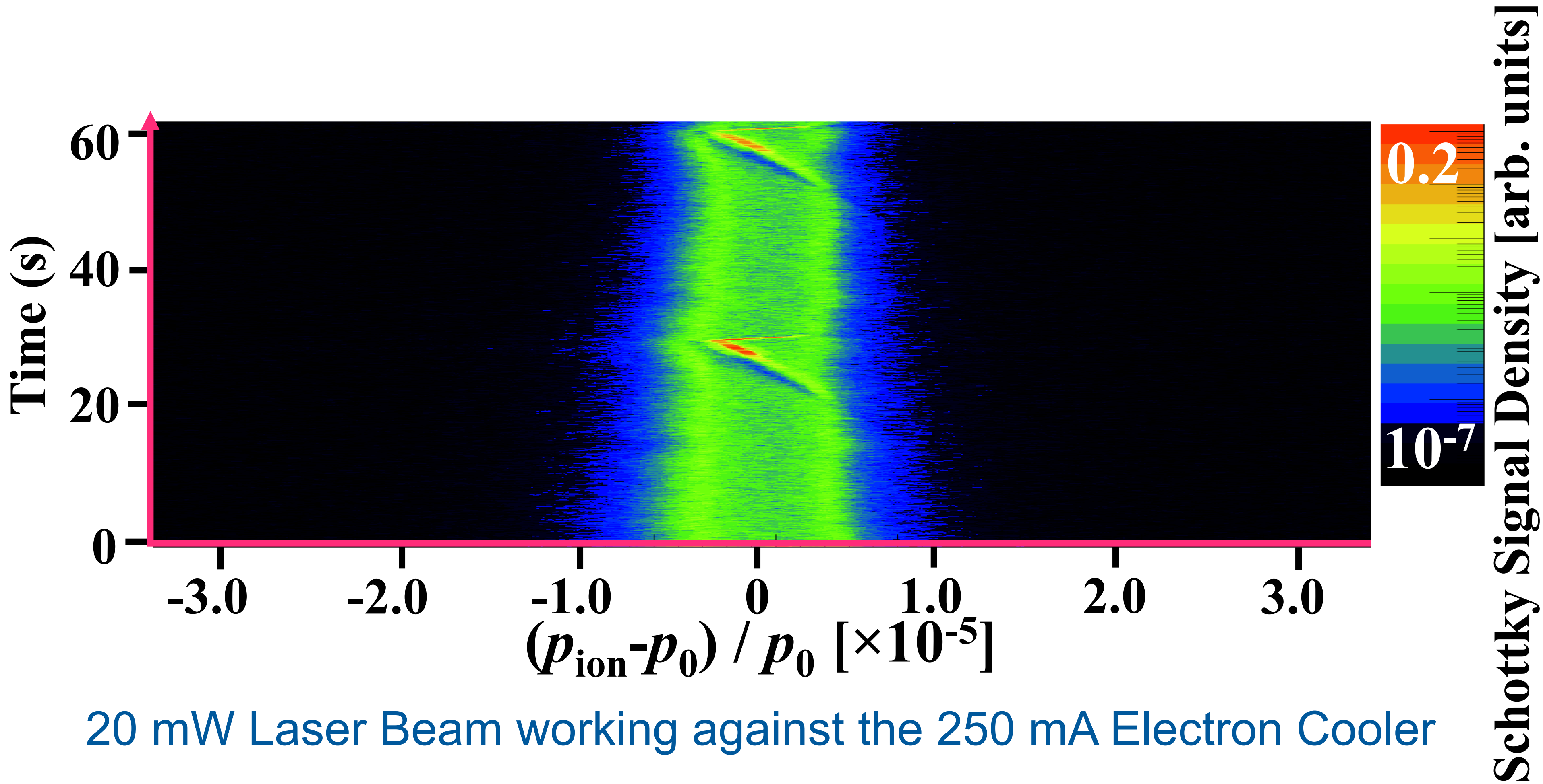
Photon Momentum

Scattering Rate

C^{3+} @ ESR, CSRe

l_{phot}	$= g(1+b) l'_{trans}$	= 257 nm
t_{trans}	$= g t'_{trans}$	= 4.3 ns
$F(0)$	$= h/(2\, l_{phot}\, t_{trans})$	= 1.87 eV / m

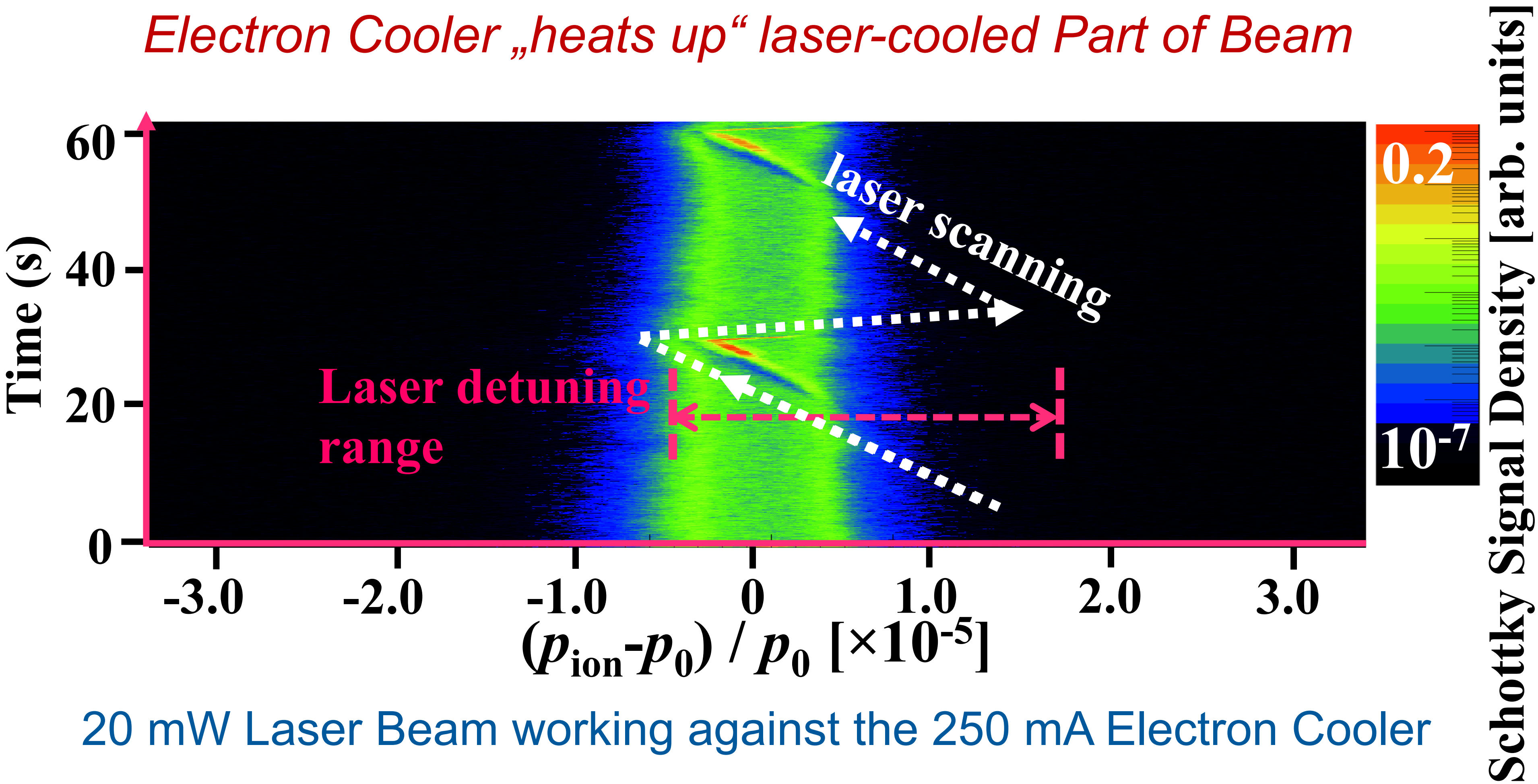
Laser Cooling Force vs. Electron Cooling Force (Coasting Beam)



20 mW Laser Beam working against the 250 mA Electron Cooler

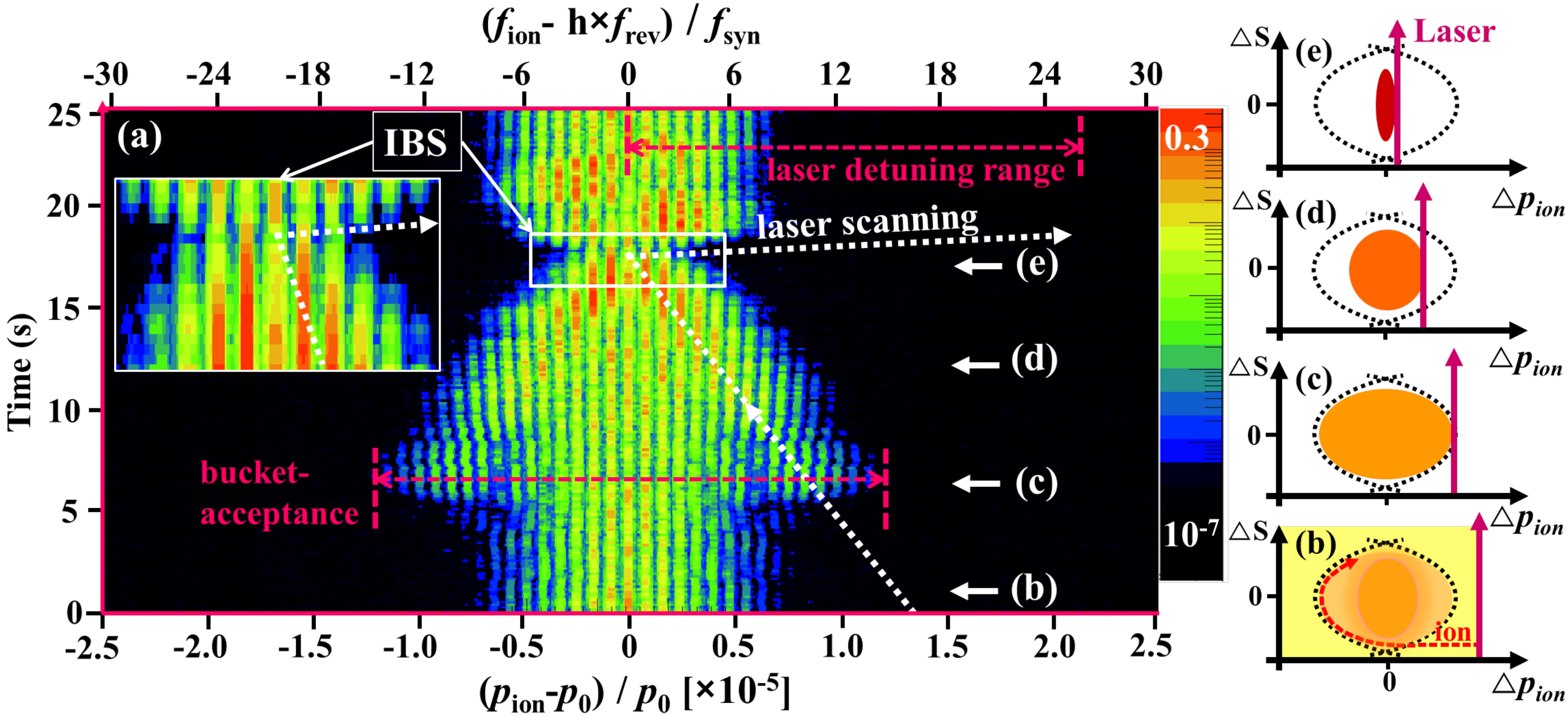
Laser Cooling Force vs. Electron Cooling Force (Coasting Beam)

Electron Cooler „heats up“ laser-cooled Part of Beam

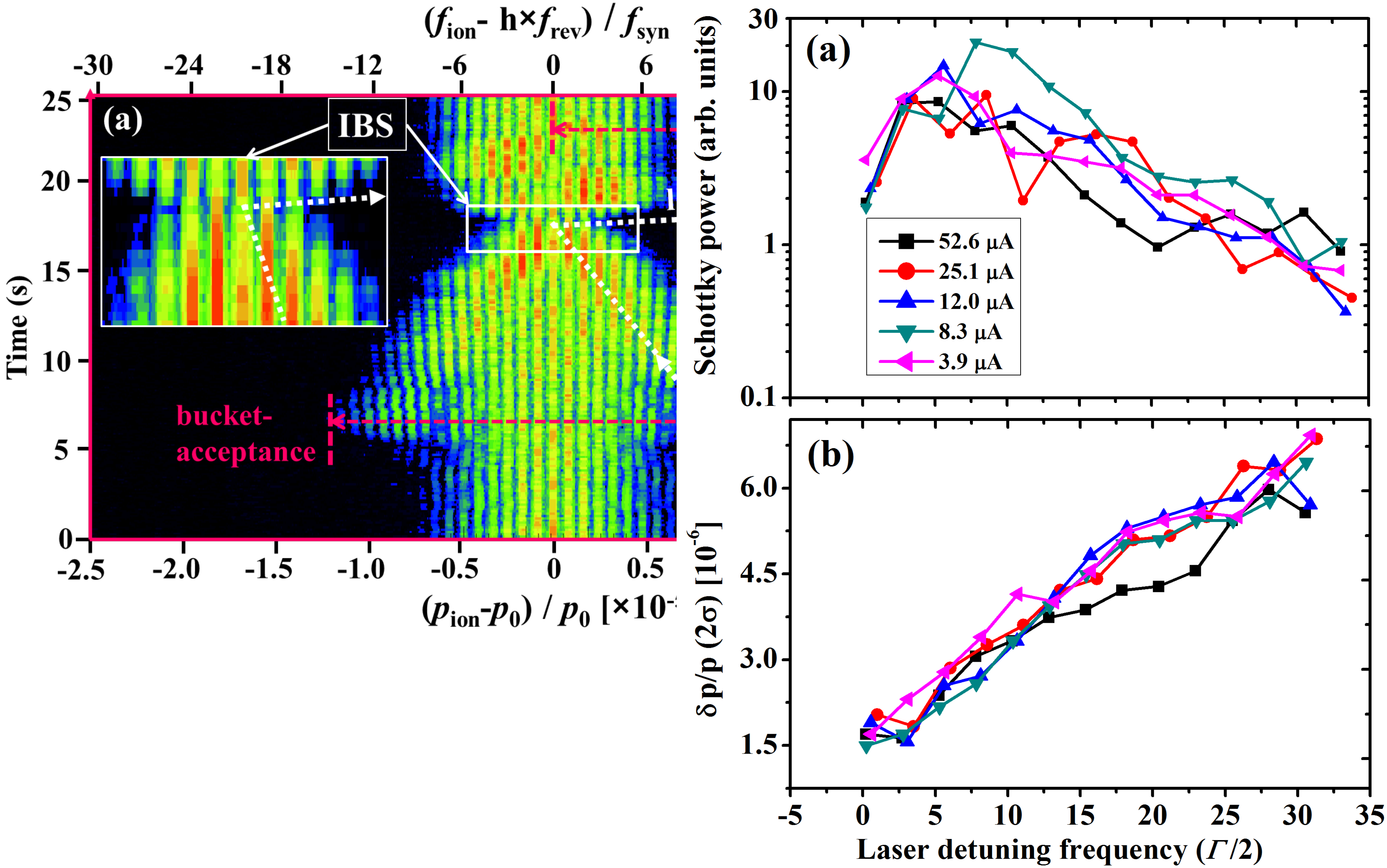


20 mW Laser Beam working against the 250 mA Electron Cooler

Schottky Measurements of Bunched Laser Cooling

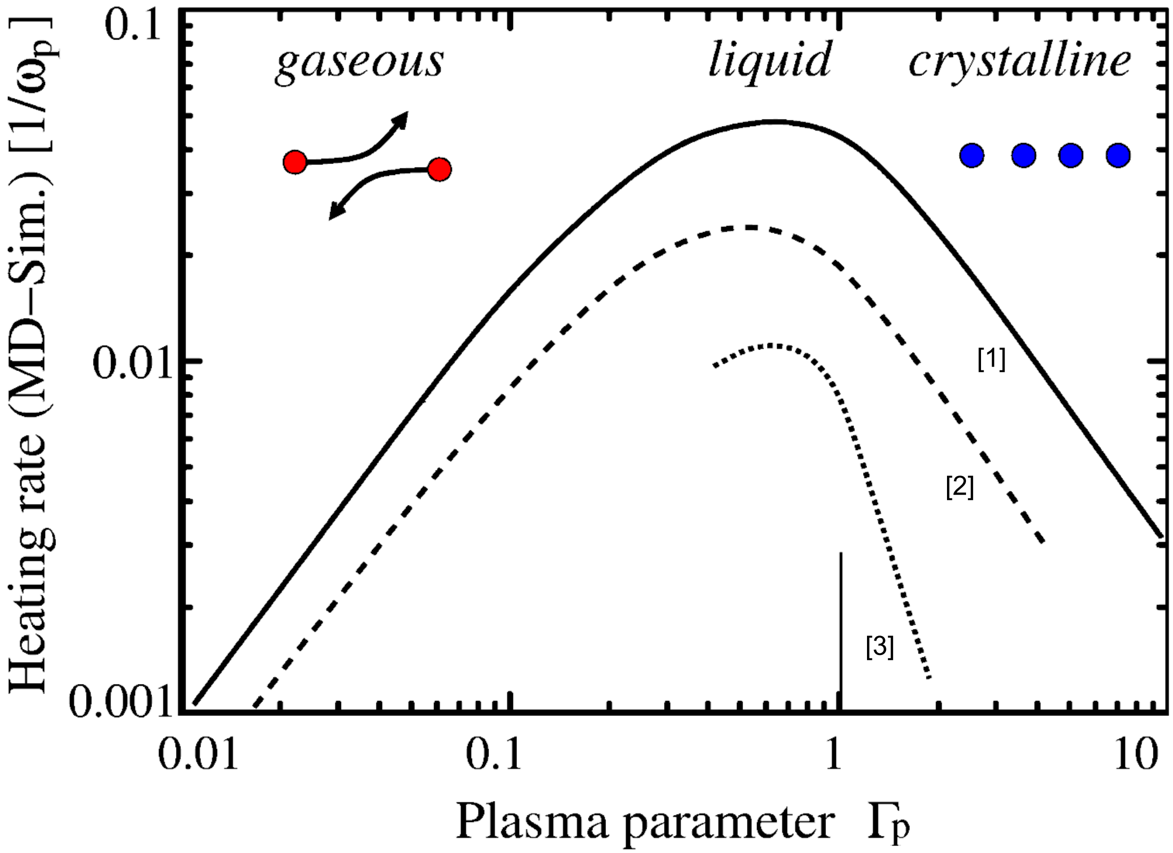


Schottky Measurements of Bunched Laser Cooling



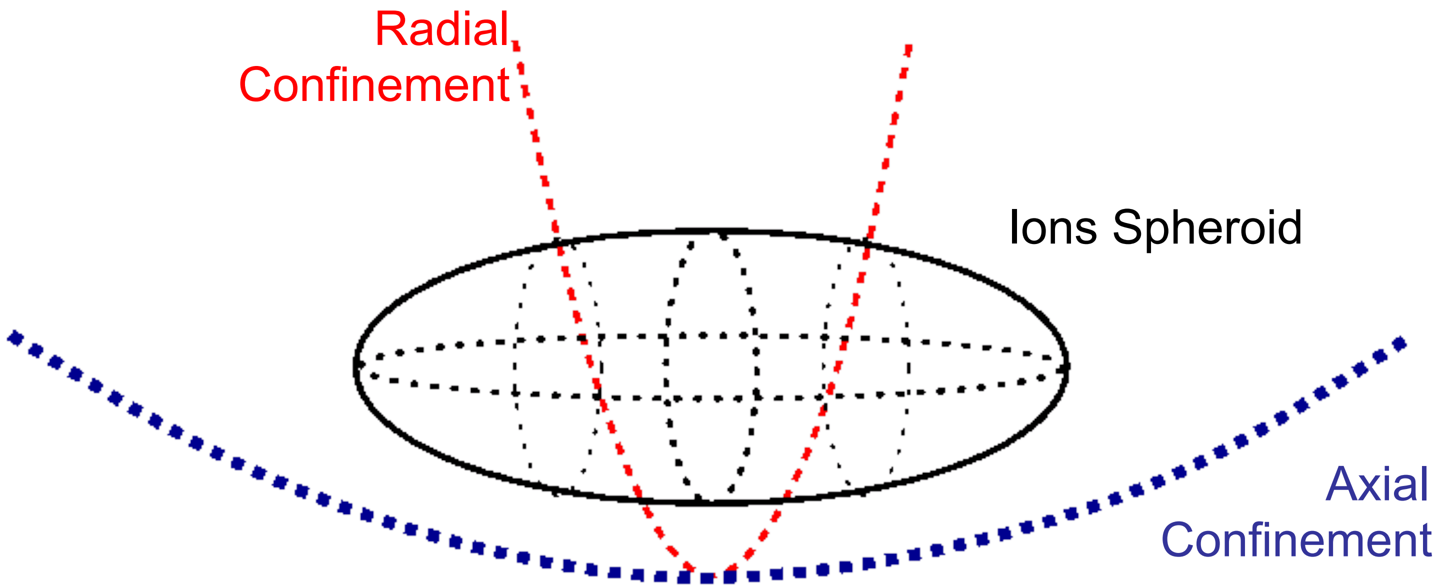
The Beam as a Strongly Coupled OCP

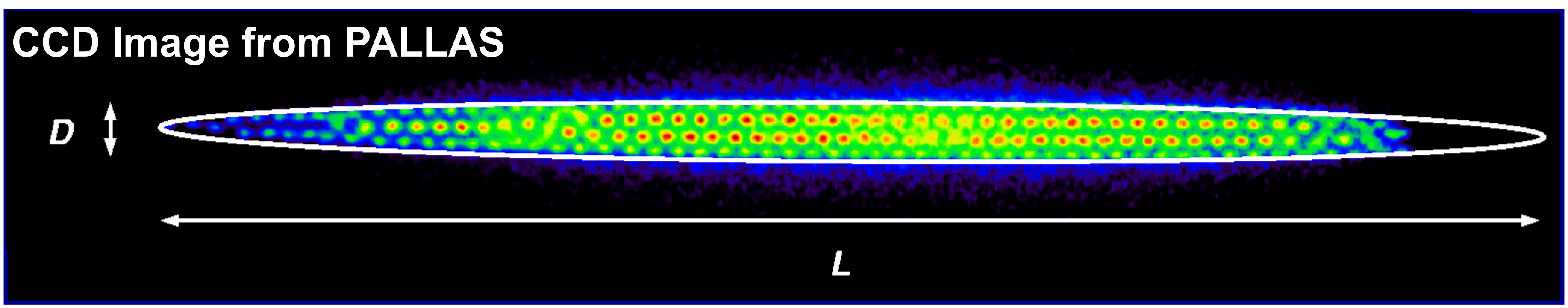
With increasing Coupling, IBS increases (but not forever!)



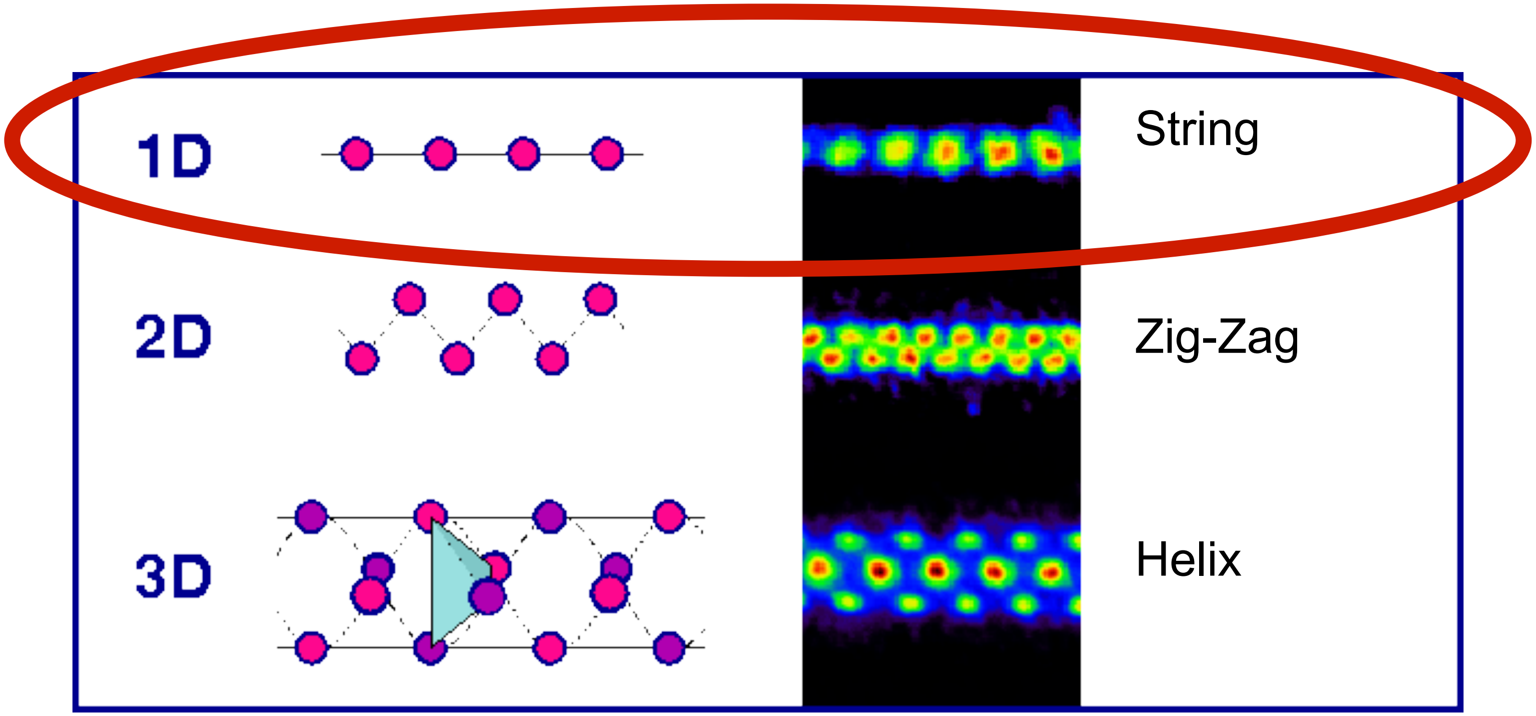
$$\Gamma_P = \frac{E_{\text{Coulomb}}}{E_{\text{thermal}}} = \frac{Z_{ion}^2 e^2}{4\pi\varepsilon_0 a_{\text{WS}} \cdot k_{\text{B}} T_{\text{ion}}}, \quad a_{WS} = \left(\frac{4}{3}\pi\, n_{ion}\right)^{-\frac{1}{3}}$$

How would a Crystalline Beam look like?





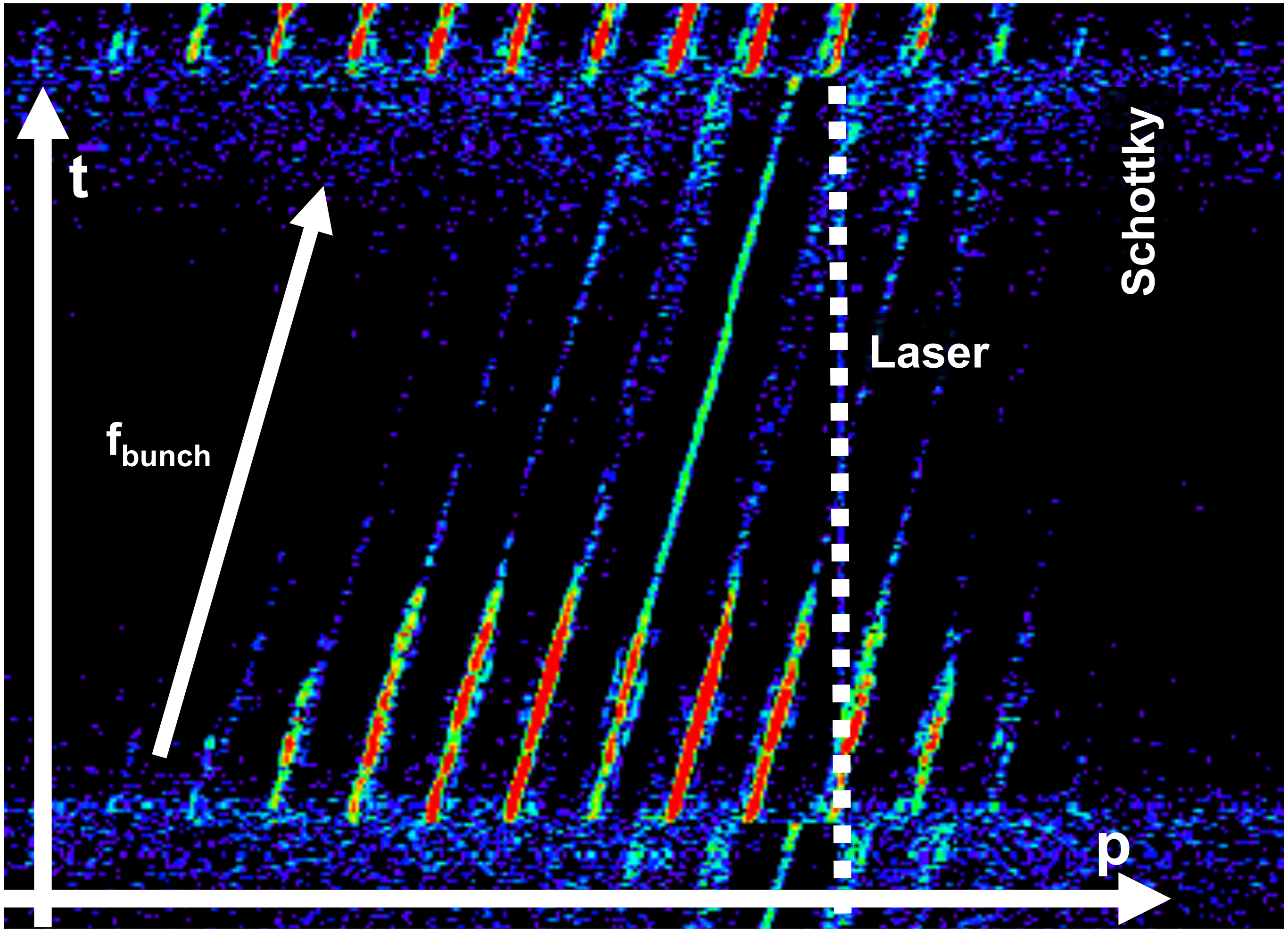
The Structure of Ion Crystals depends on the Confinement Potential

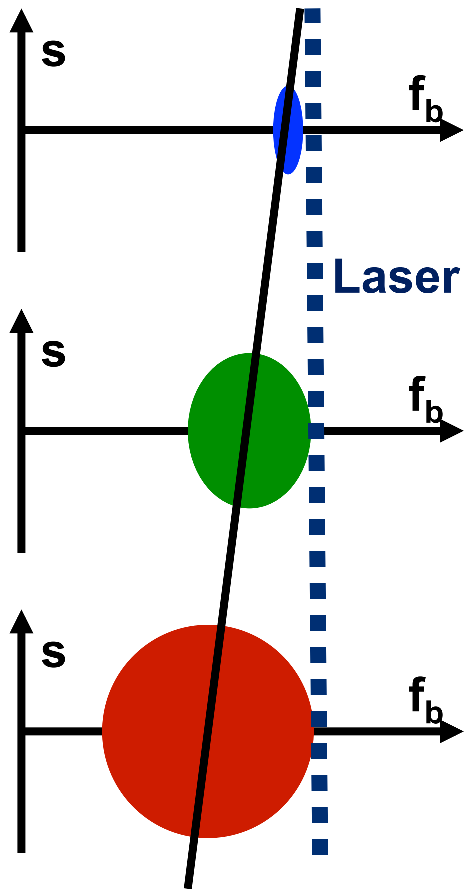


Laser Cooling at ESR

(see Poster by W. Wen for CSRe Activities)

Scanning the Bucket Frequency (2004, 2006)





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

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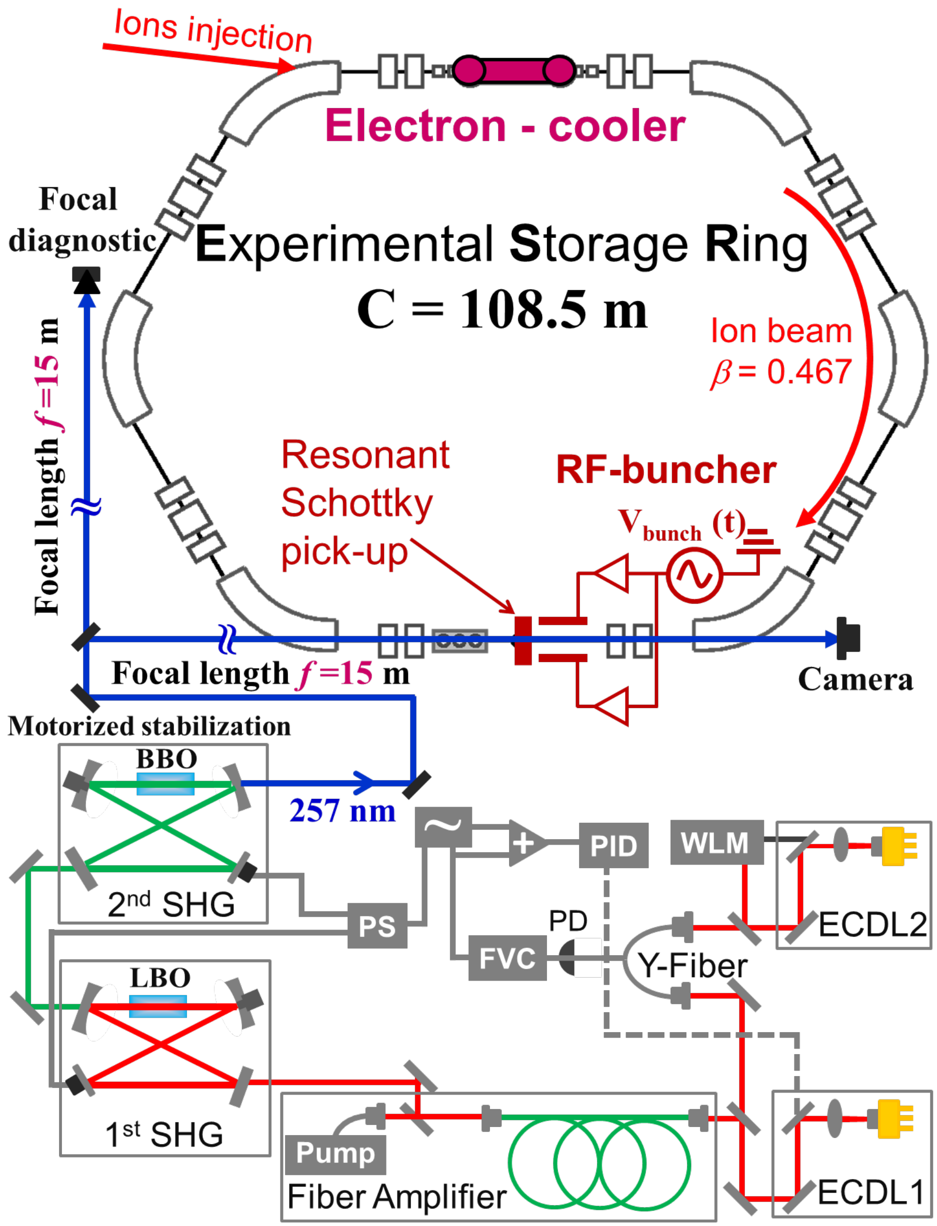
2012 Setup at ESR



C^{3+}

E_{beam} = 122 MeV/u

= 1.47 GeV

(b = 0.47, g = 1.13)

f_{rev} = 1.295 MHz

t_{beam} ~ 100 s

Slip factor = 0.607

Betatron tune = 2.3

Diode laser (cw)

l_{laser} = 257 nm

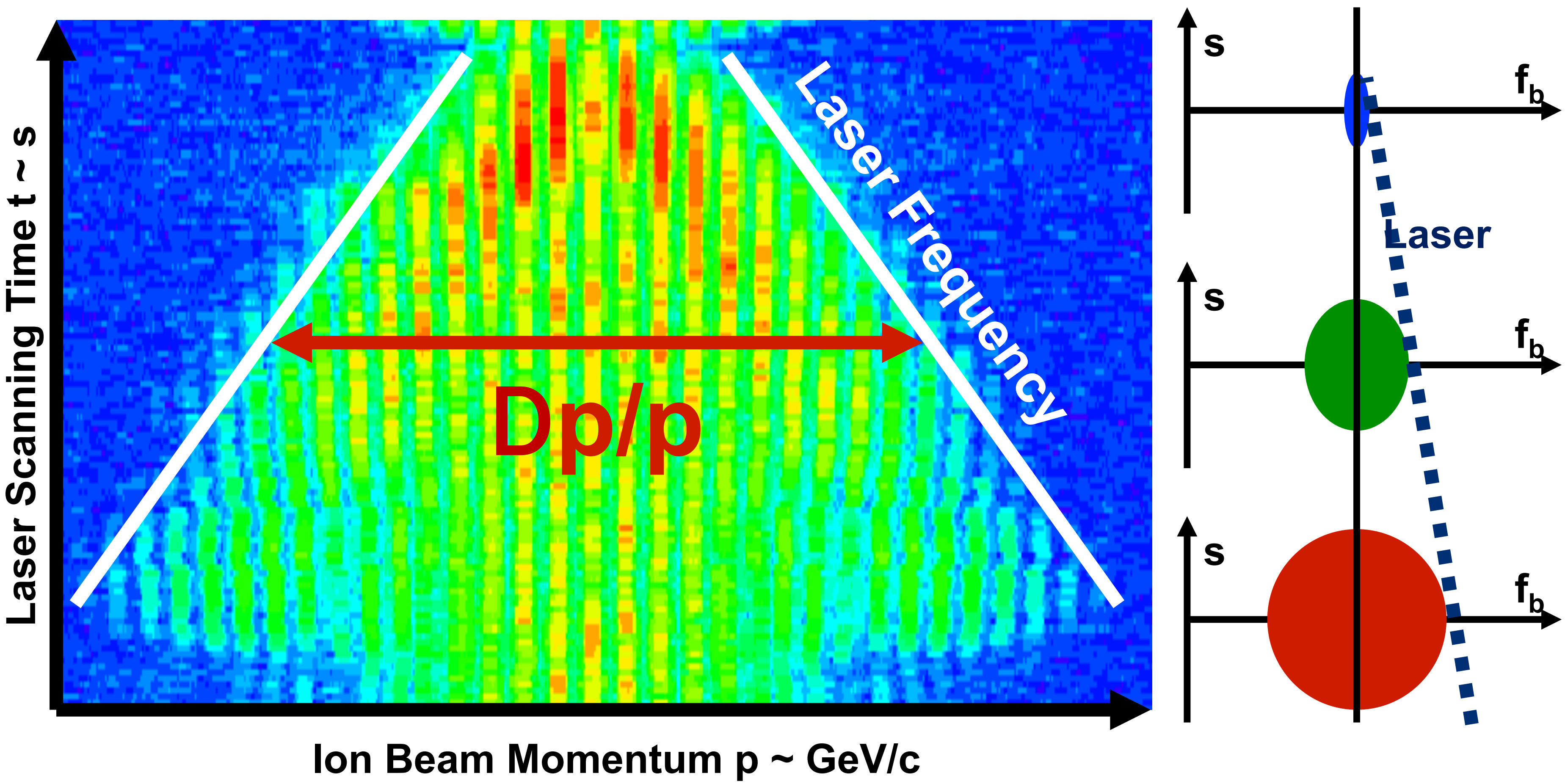
$2S_{1/2} \rightarrow 2P_{1/2}$

l_{rest} = 155.07 nm

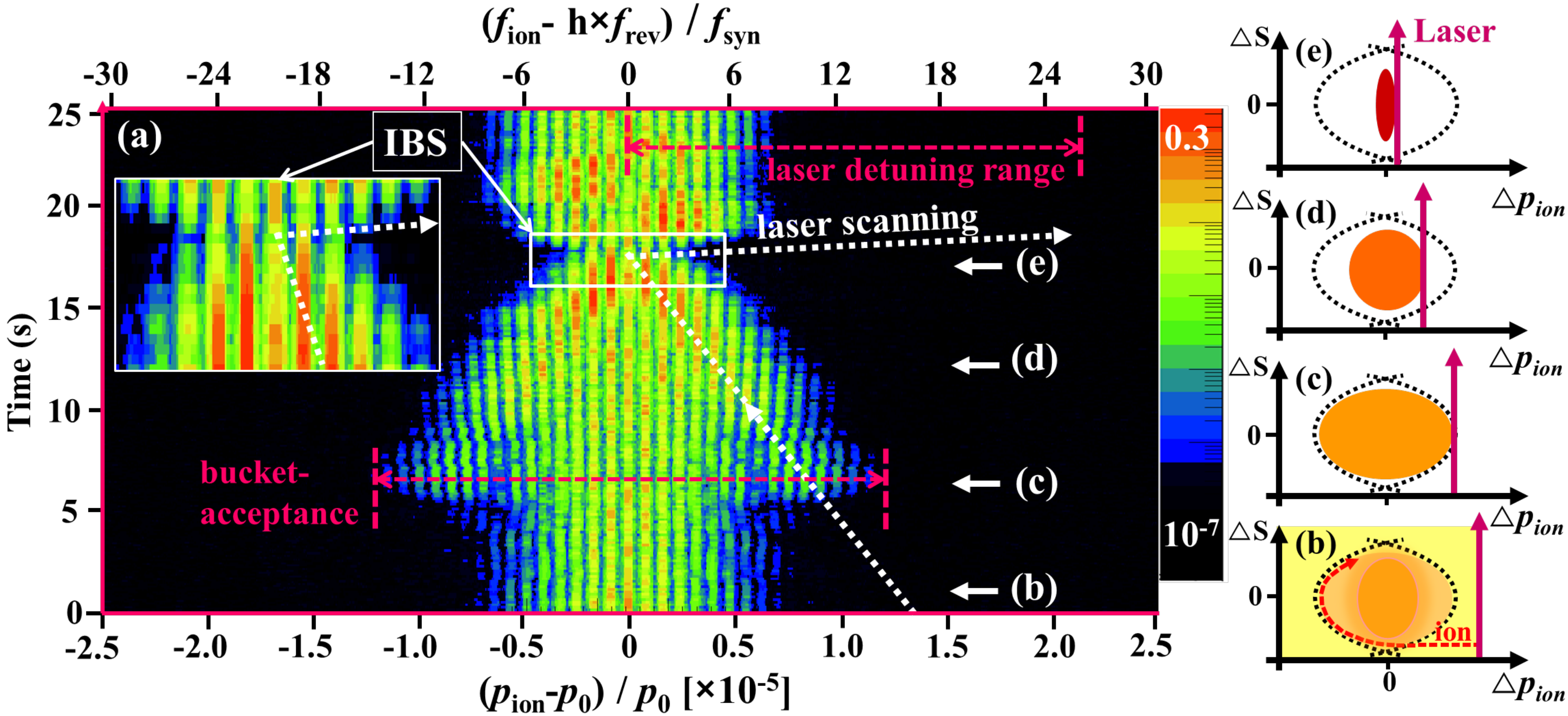
Dp/p ~ 10^{-5}

t_{rest} = 3.8 ns

Scanning the Laser Frequency (2012)



Schottky Measurements of Bunched Laser Cooling



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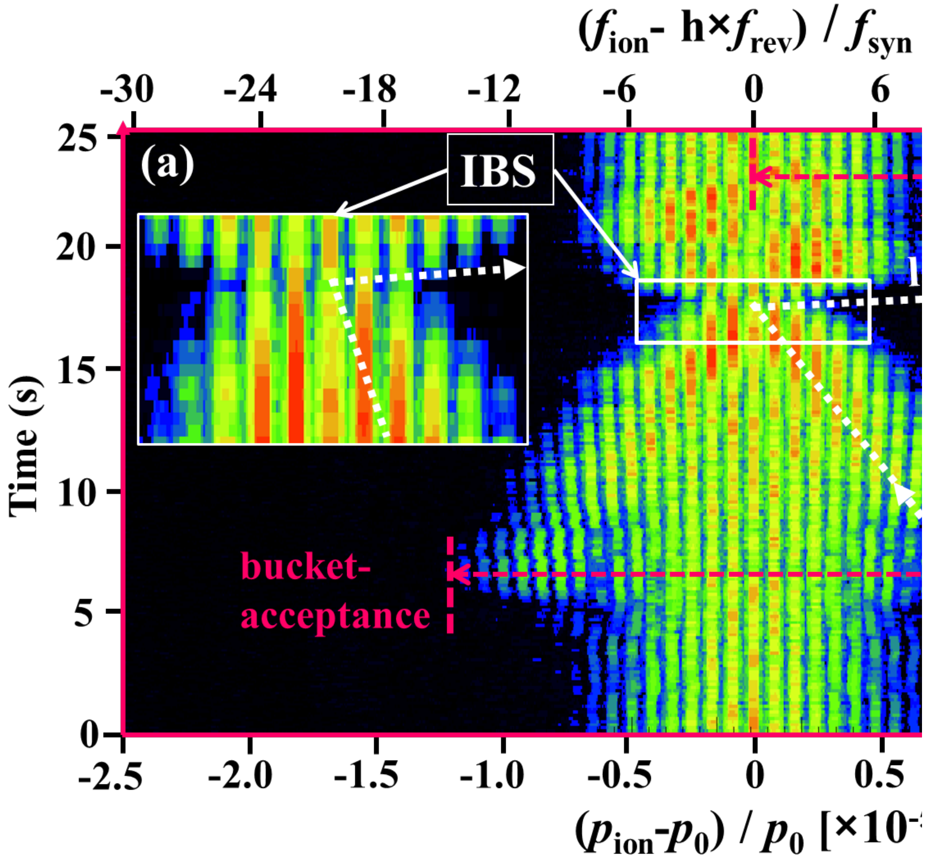
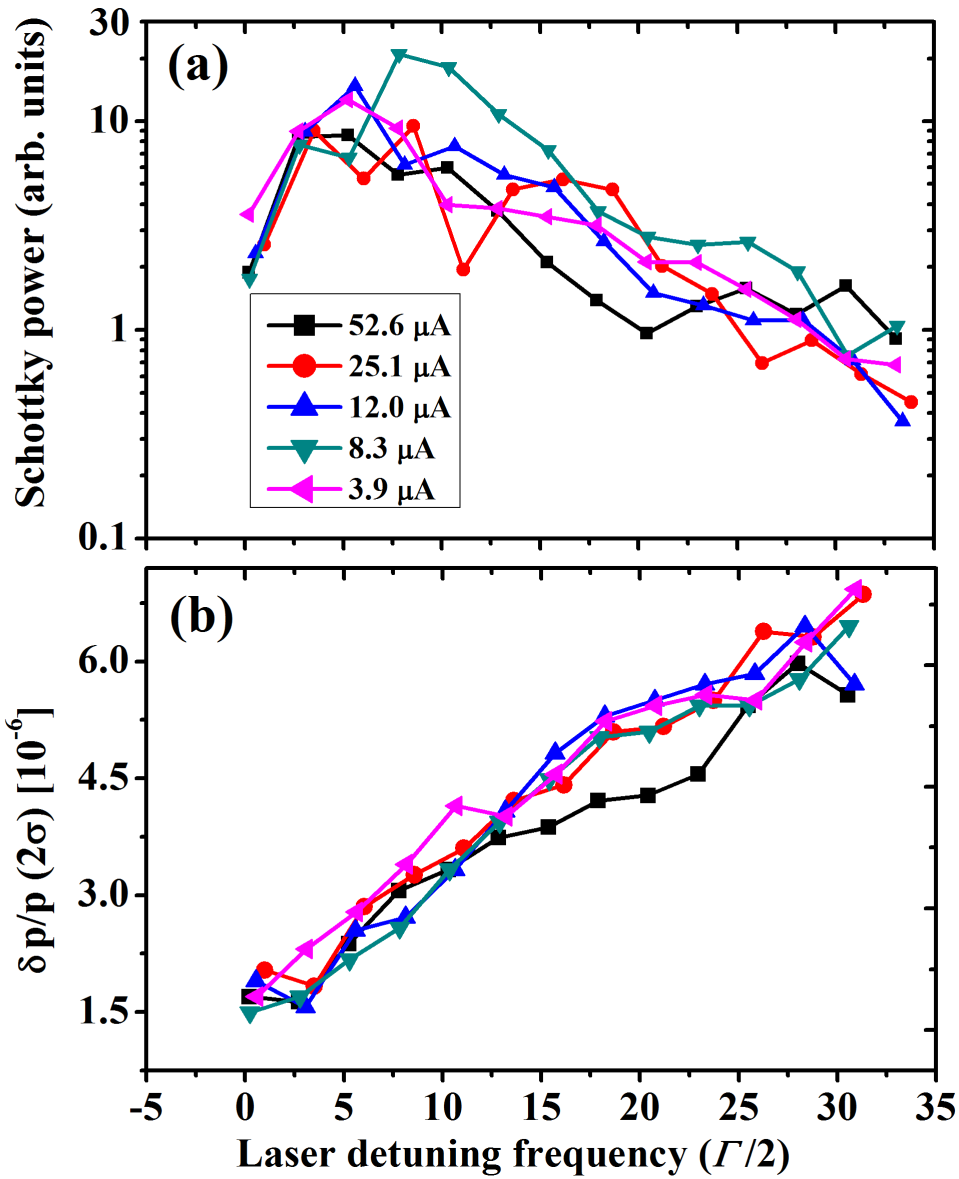
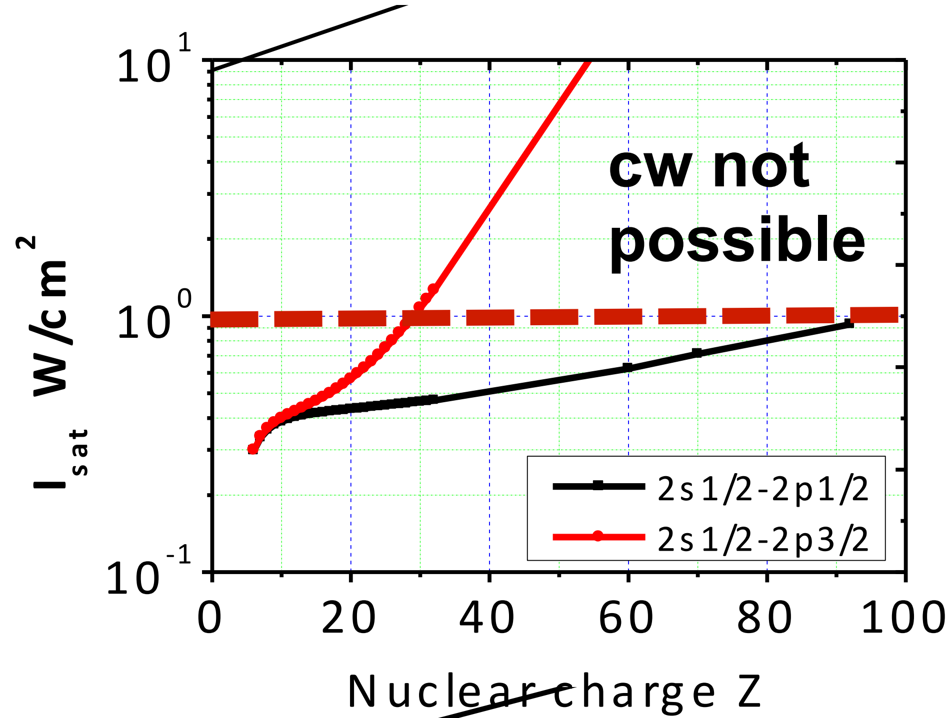
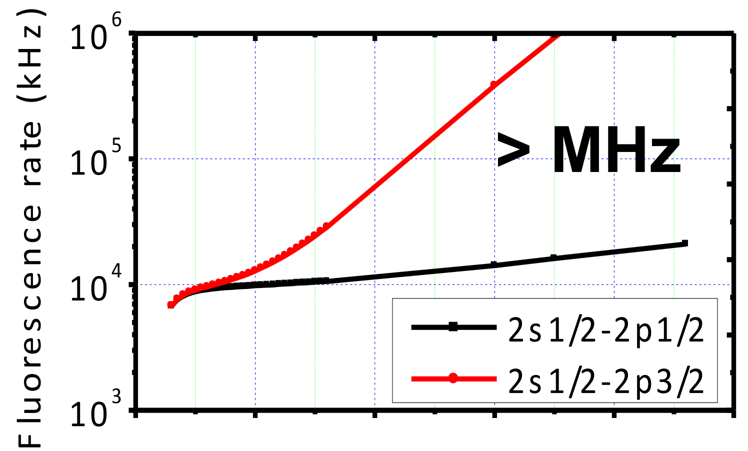
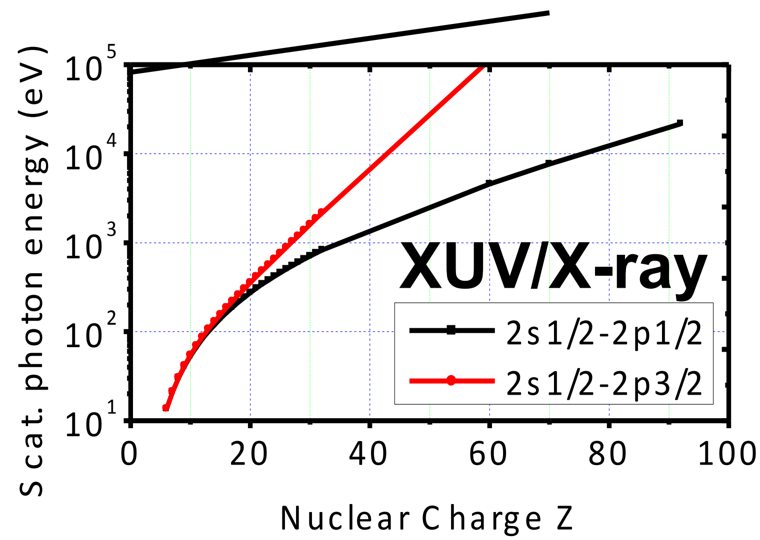


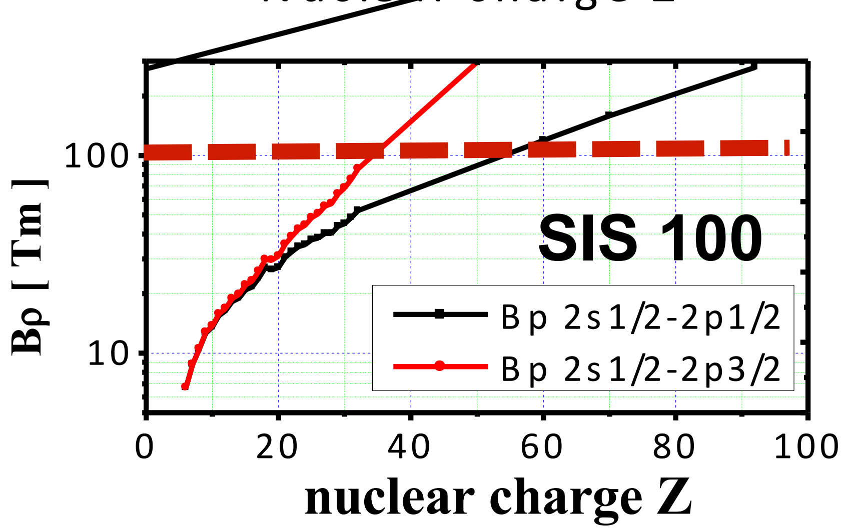


Laser Cooling at Relativistic Energies (l_{laser} = 257 nm, S. Shevelko)





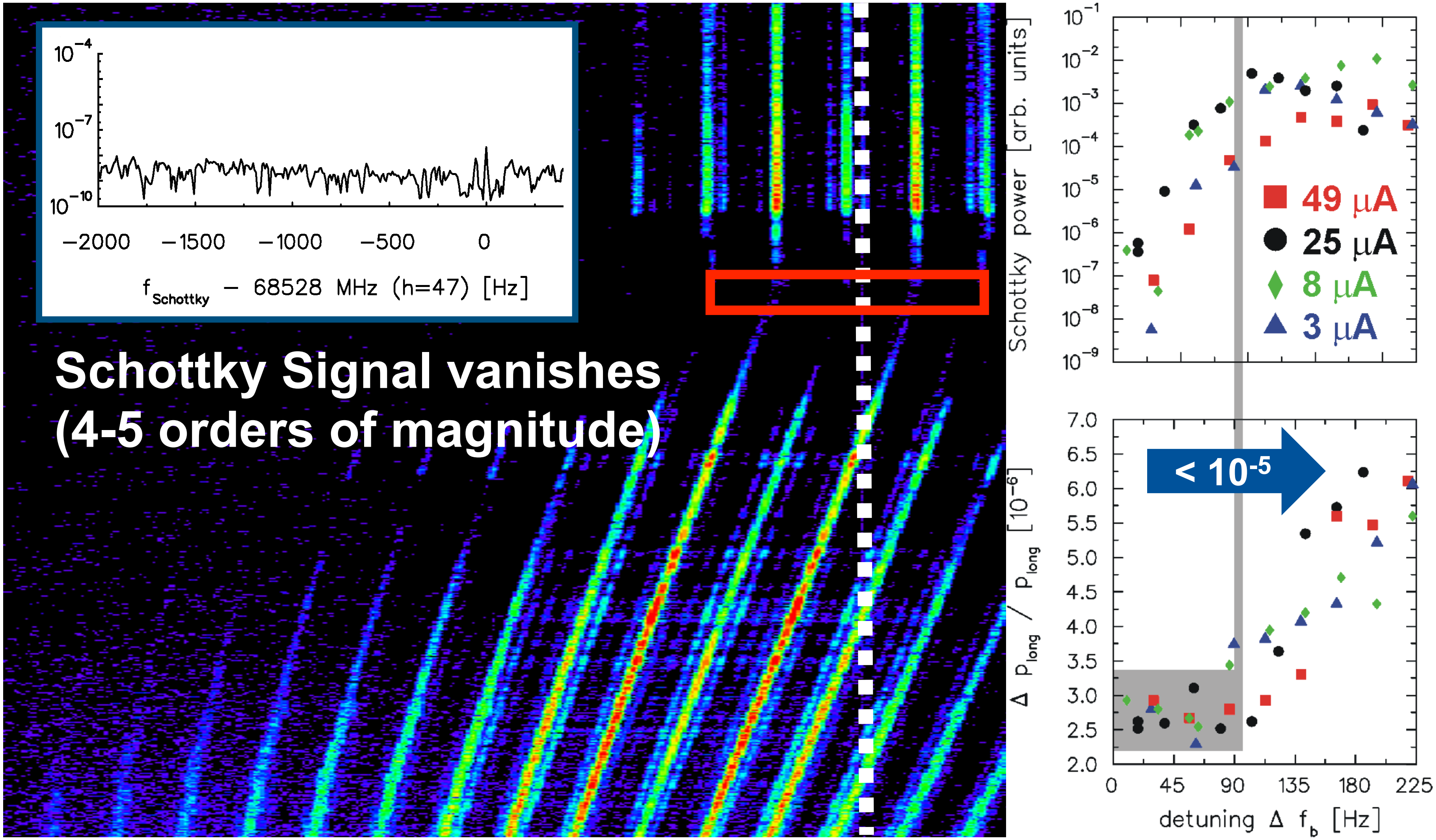




Preliminary

Turn-Key Pulsed Laser System (Dp/p acc. ~ 10^{-4}, MHz repetition rate)

Zero Schottky Signal @ 16 mA (much better vacuum in 2006)



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

„Laser Cooling [at mid-size Ion Storage Rings] is not very active“

M. Steck on Monday (freely interpreted)

„That‘s because there are not many mid-size Rings available“

M. Bussmann

DRESDEN concept

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„But R&D for future Facilities is highly active“

M. Bussmann

DRESDEN concept

German & Chinese Activities in Laser Cooling

- 4 BMBF-funded University Contributions to Laser Cooling (1 x Dresden, 1 x Münster, 2 x Darmstadt) ~ 500 k€
- Chinese NSFC funding for Wen Weiqiang ~ 40 k€
- 1 Beam Time at ESR (2012), 2 at CSRe (2013, 2014) compared to 3 Beam Times between 1998 and 2006
- Dedicated Laser Cooling Project at SIS 100 inside the Helmholtz Program „Accelerator Research & Development“

German & Chinese Activities in Laser Cooling

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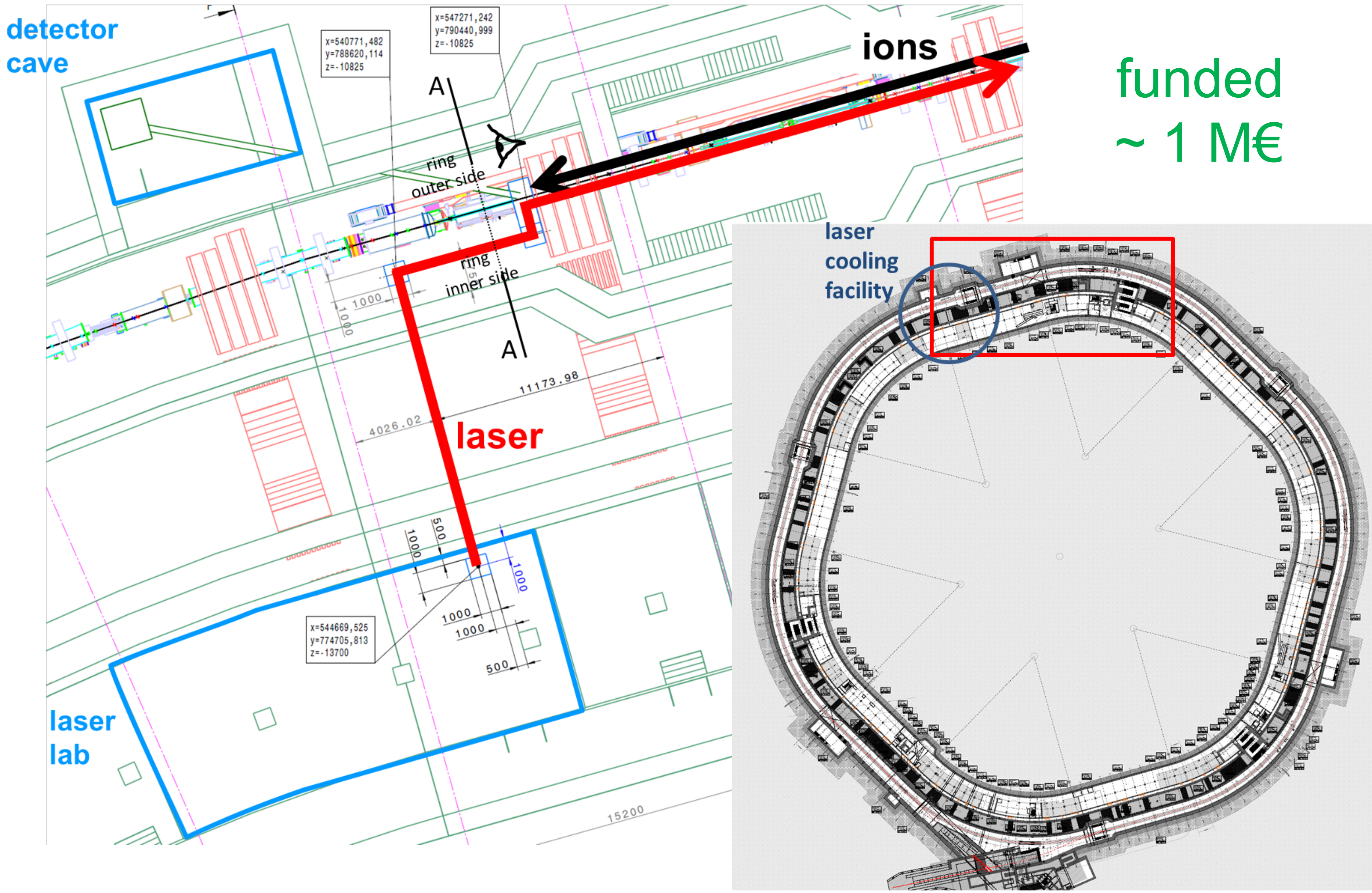
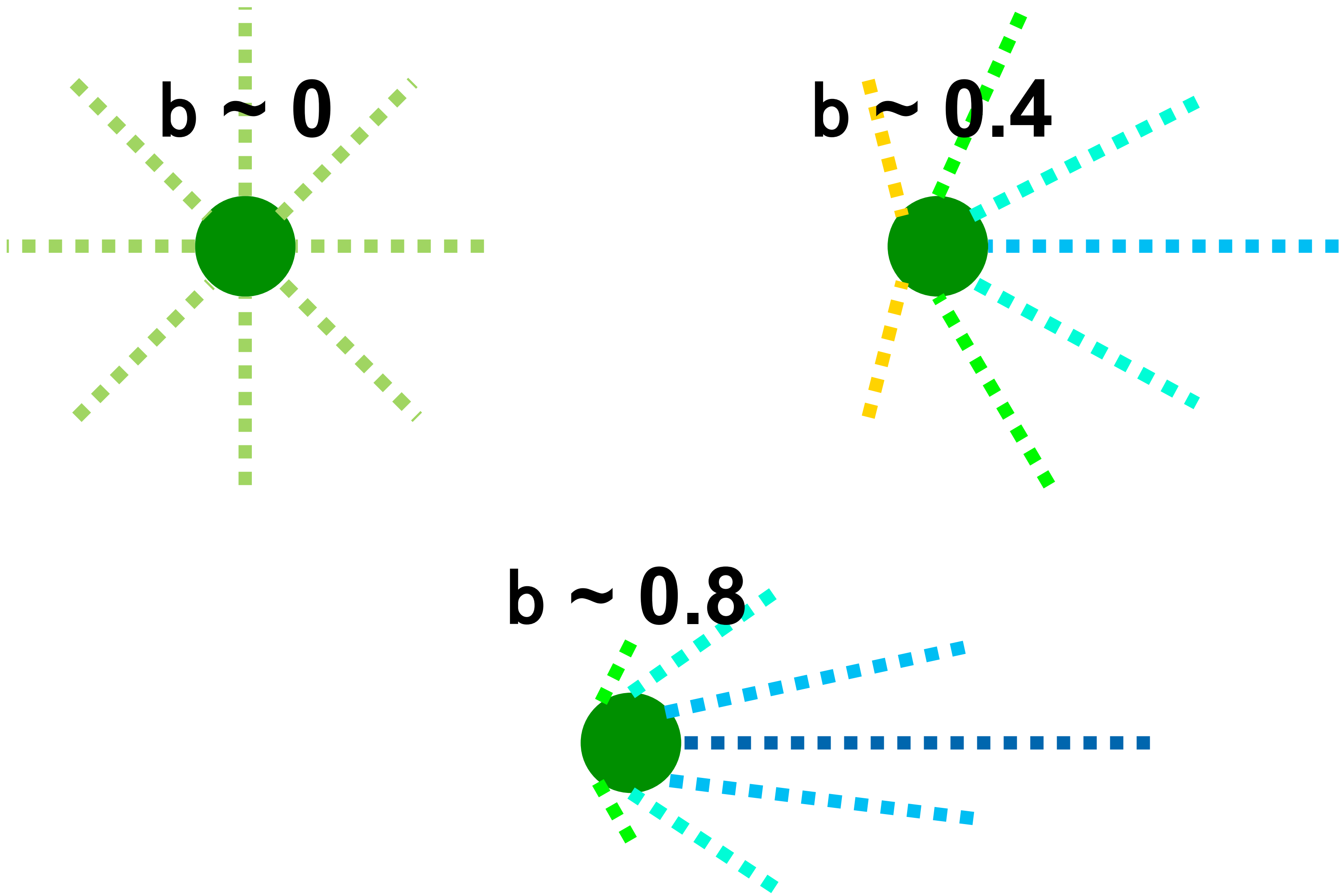
- 1 Beam Time at ESR (2012), compared to 3 Beam Times b
- Dedicated Laser Cooling Proj Helmholtz Program „Accelera

„ARD“ Laser Cooling at SIS 100 (D. Winters, P. Spiller, M. Bussmann)

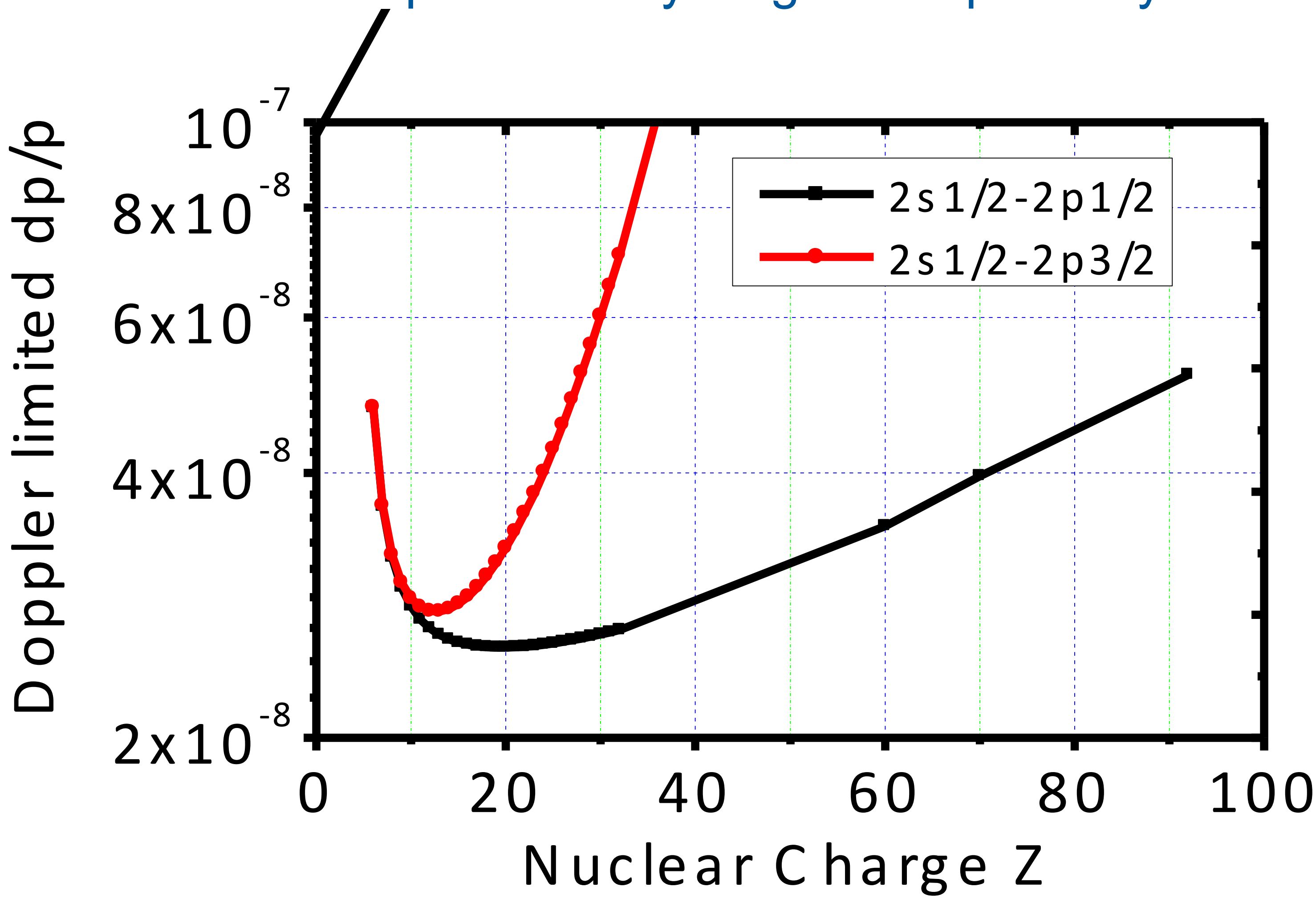


funded
~ 1 M€

Lorentz-boosted Fluorescence (e.g. „Optical Schottky“)



What can we expect if everything works perfectly*?



*hey, one can dream

Preliminary

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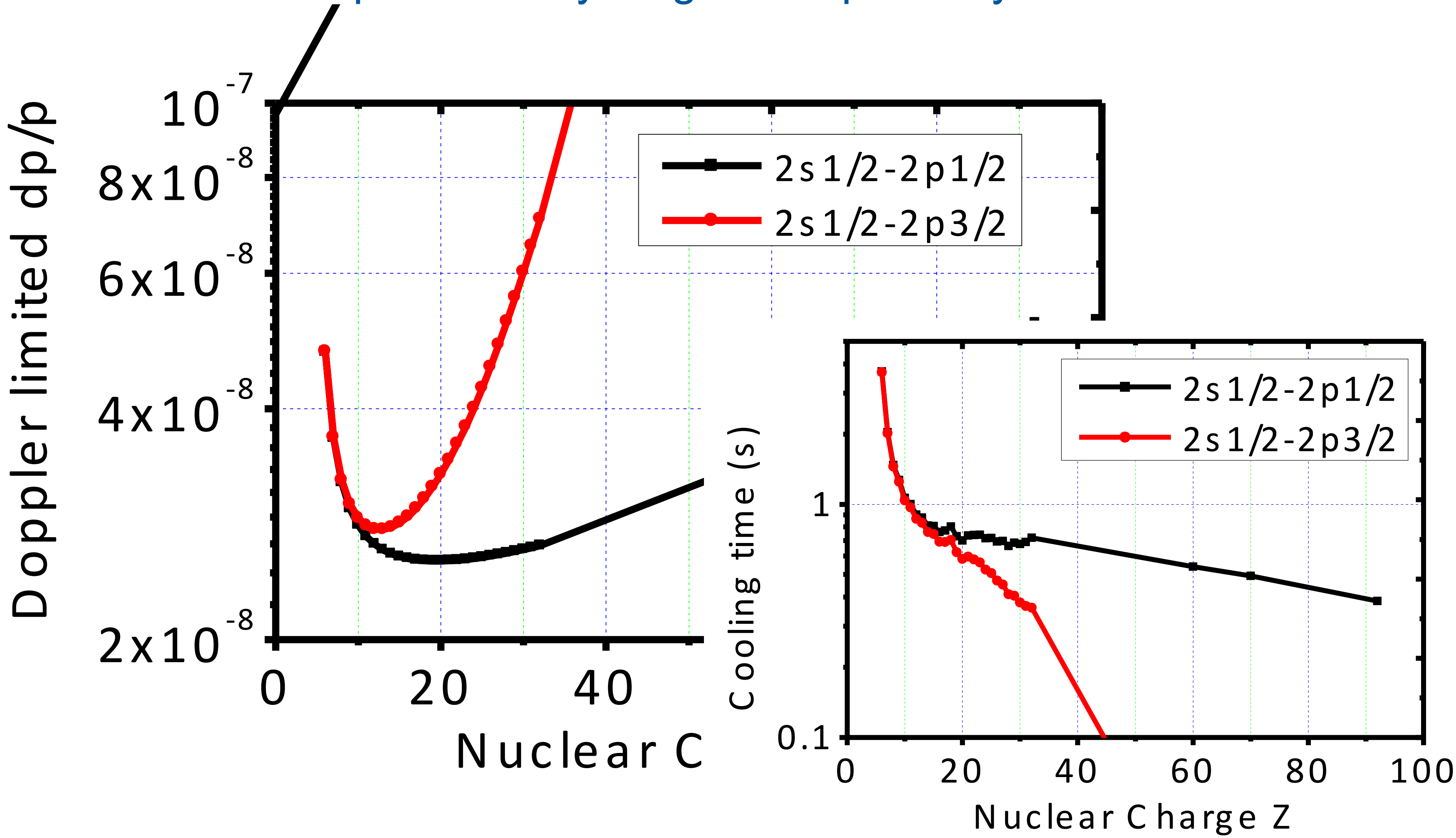

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Preliminary

Thank you!