Laser cooling of bunched O^{5+} ion beams at the CSRe: Coherent effect and Extraction of momentum distribution

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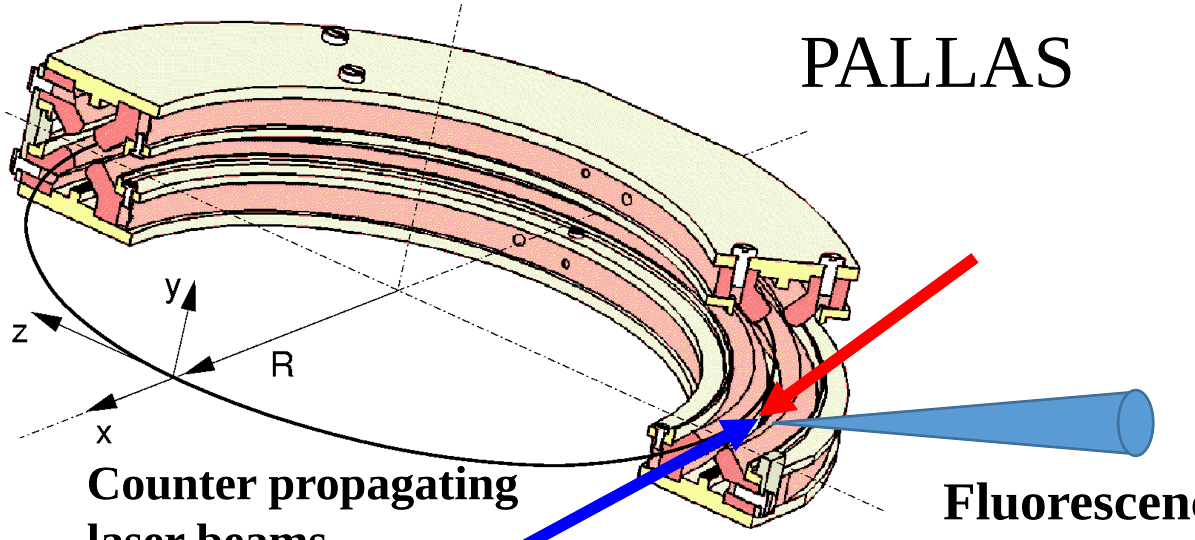
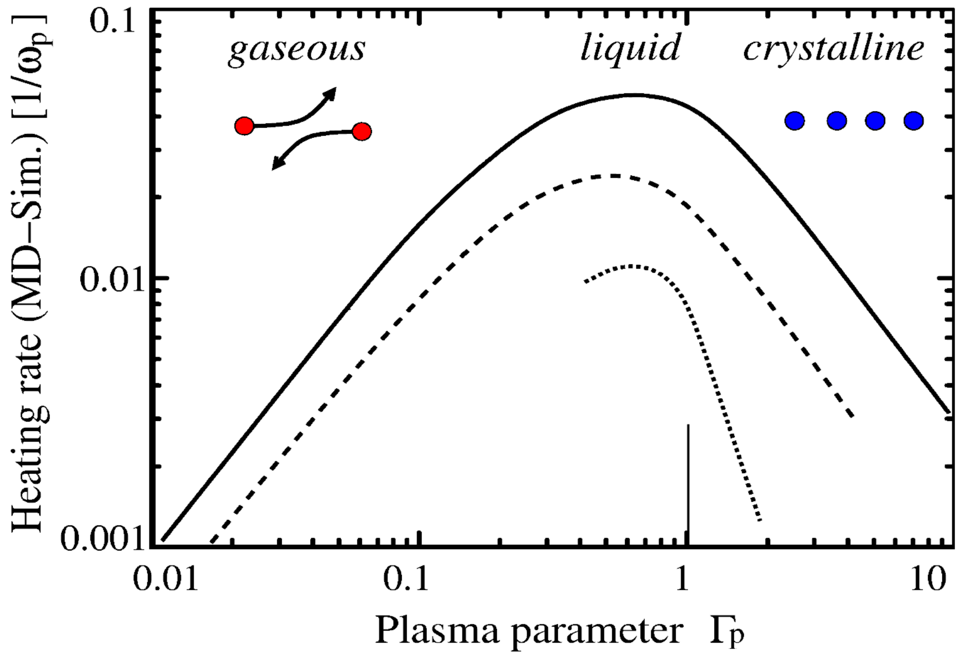
Motivation: Crystalline ion beams

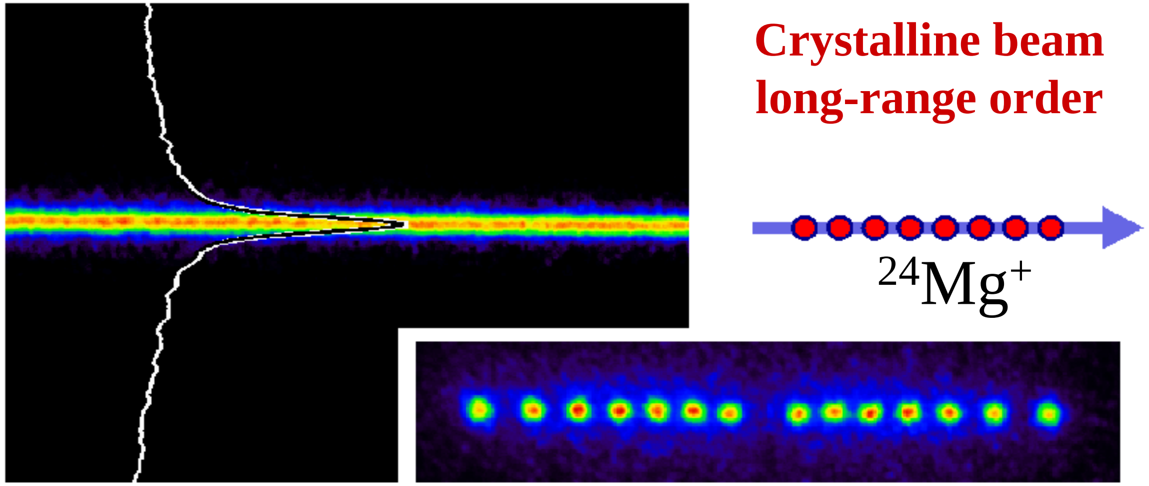


Counter propagating laser beams

Fluorescence detection



$$\Gamma_p = \frac{E_{Coulomb}}{E_{thermal}} = \frac{(Qe)^2}{4\pi\varepsilon_0 a_{ws} k_B T_{ion}}$$



Crystalline beam long-range order

$^{24}Mg^{+}$

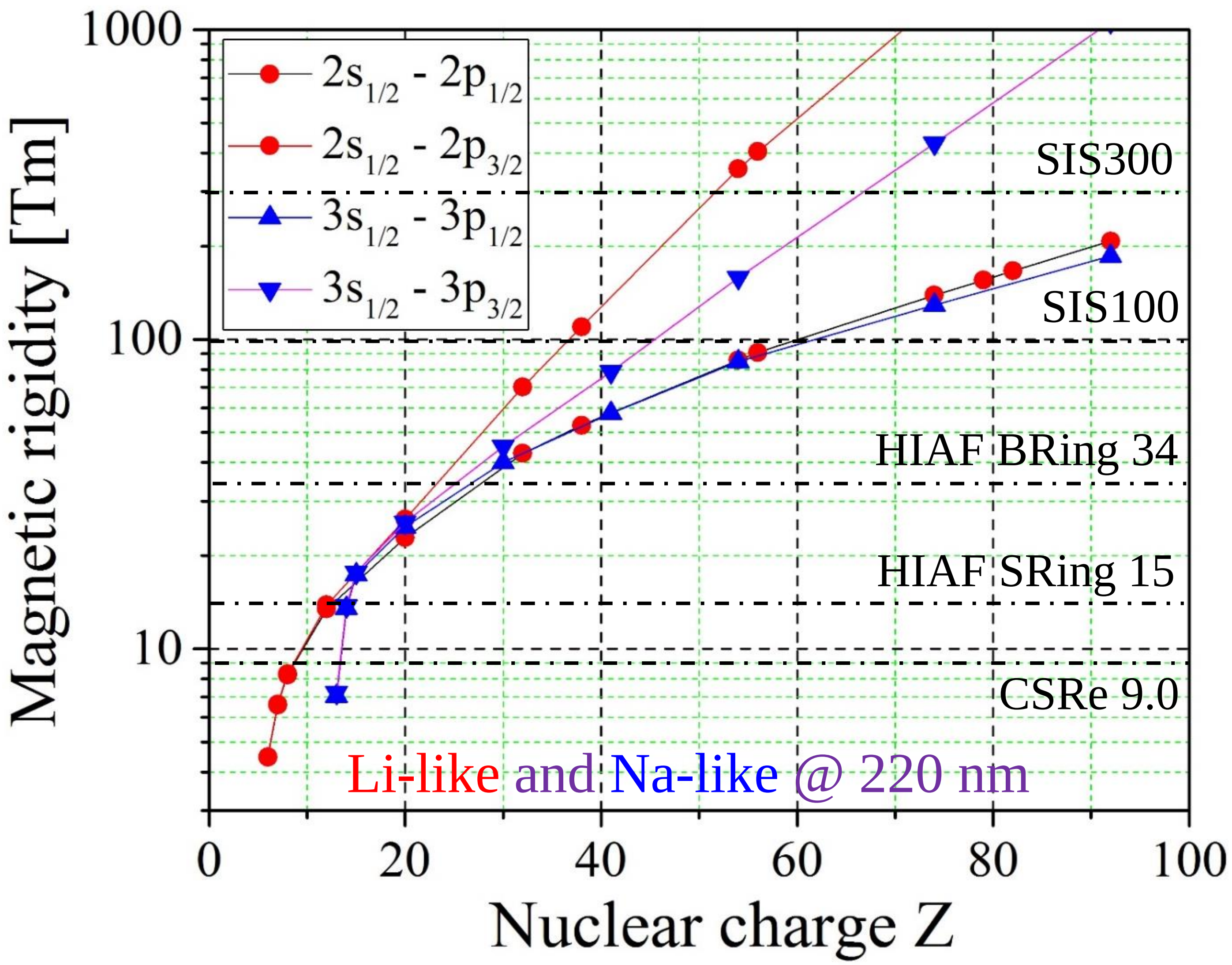
Laser-cooled ions at storage ring:

$^{6,7}Li^{+}$, $^{9}Be^{+}$, $^{24}Mg^{+}$, $^{12}C^{3+}$ $\rightarrow$ $^{16}O^{5+}$

T. Schaetz et al. , Nature 412, 717(2001)

U. Schramm, et al., Progress in Particle 53 (2004) 583

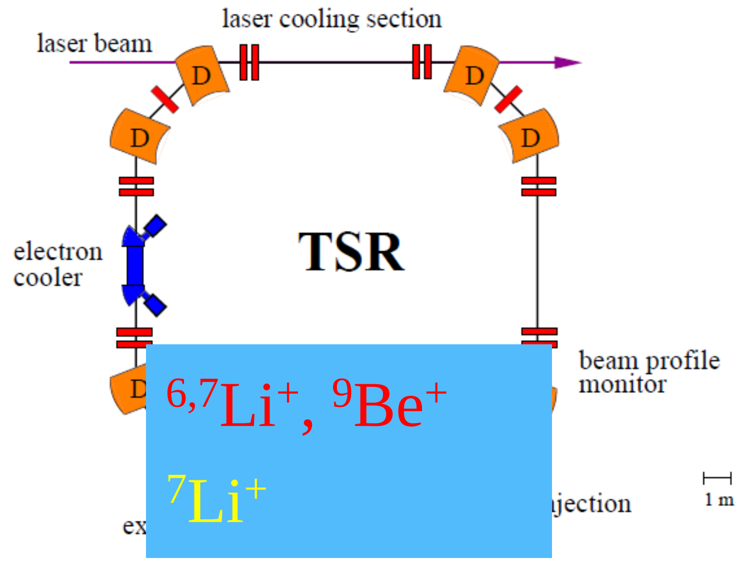
Motivation: Laser spectroscopy @ relativistic energy

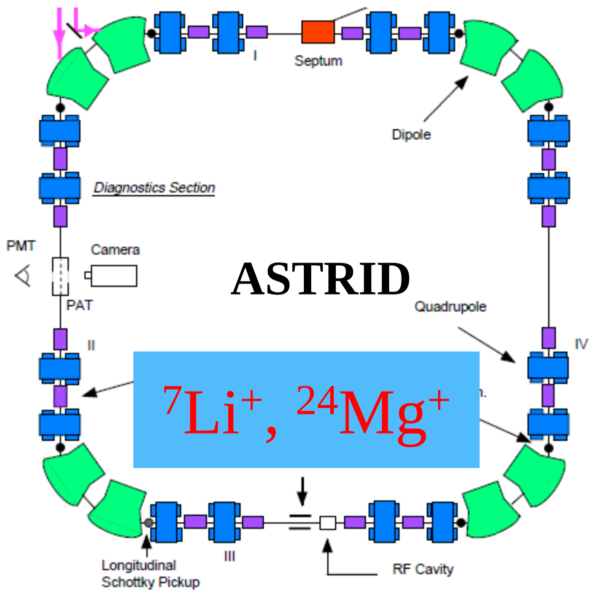


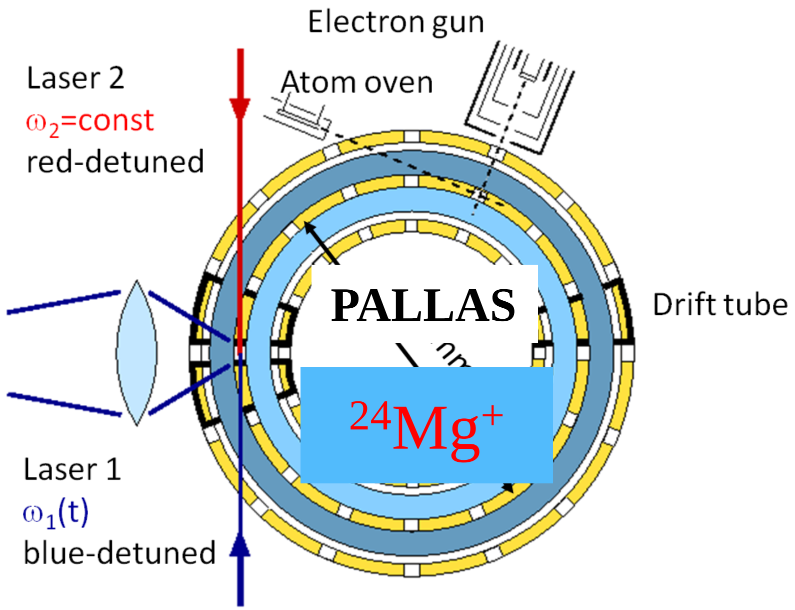
Advantages of laser cooling :

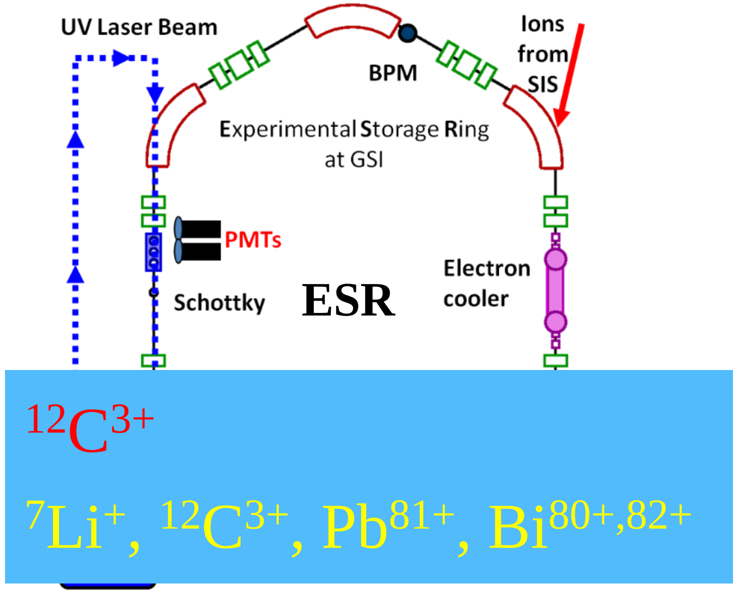
- Fast cooling speed
- Strong cooling force: increases with beam energy $\propto \gamma^2$
- Laser cooling of relativistic ions
- Access to ground state transitions of heavy ions by huge Doppler shift
- Precision laser spectroscopy of HCIs

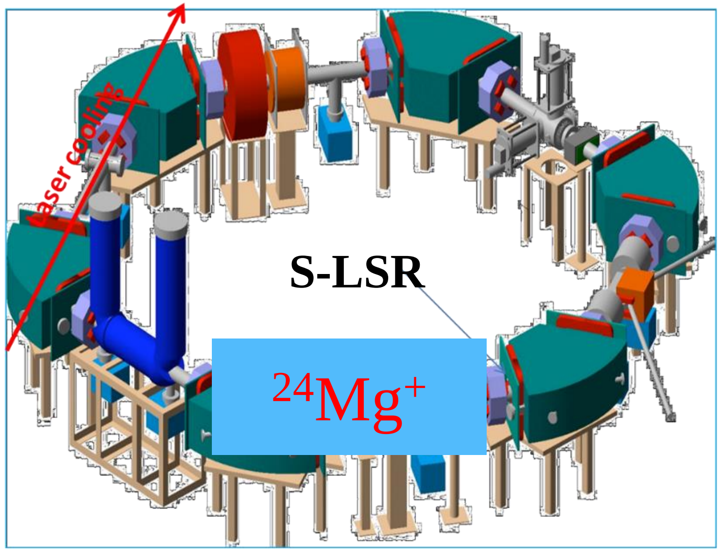
Laser cooling and precision laser spectroscopy @storage rings

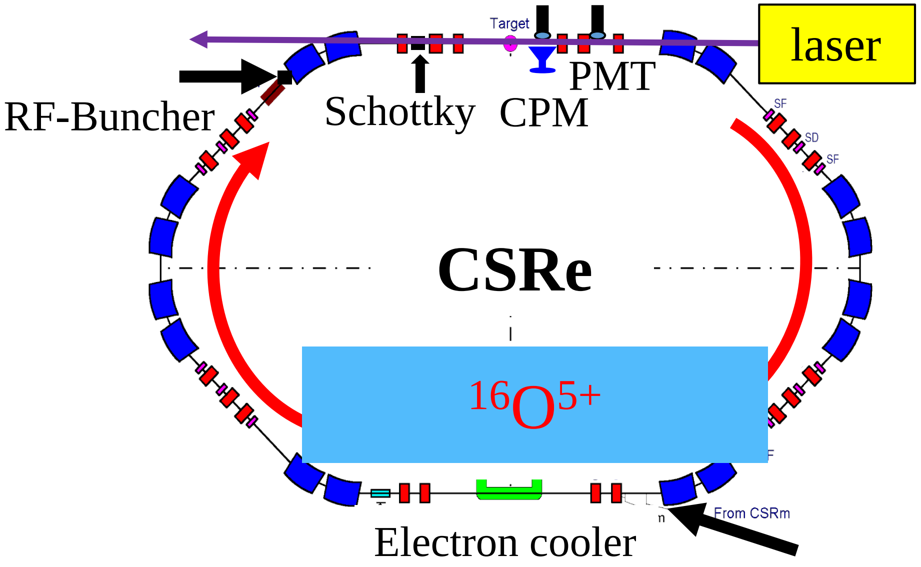




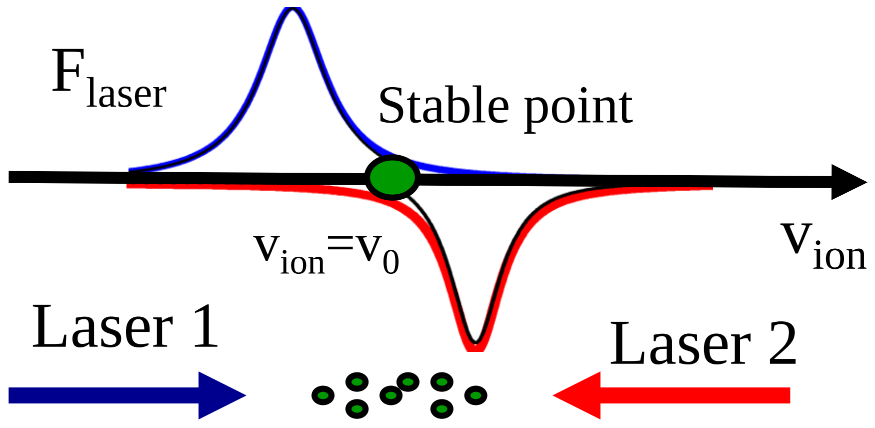




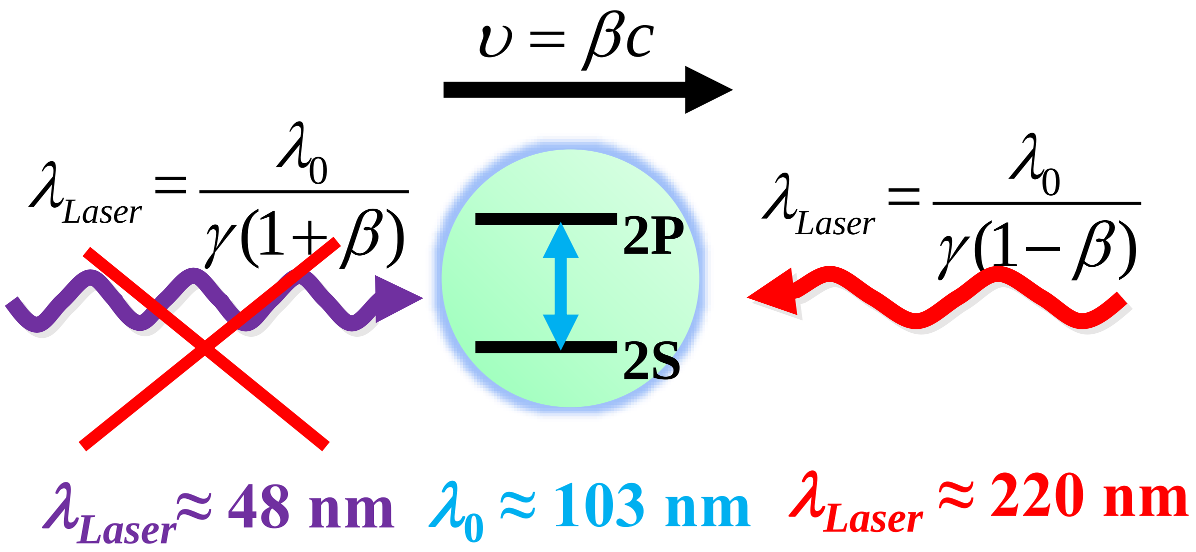


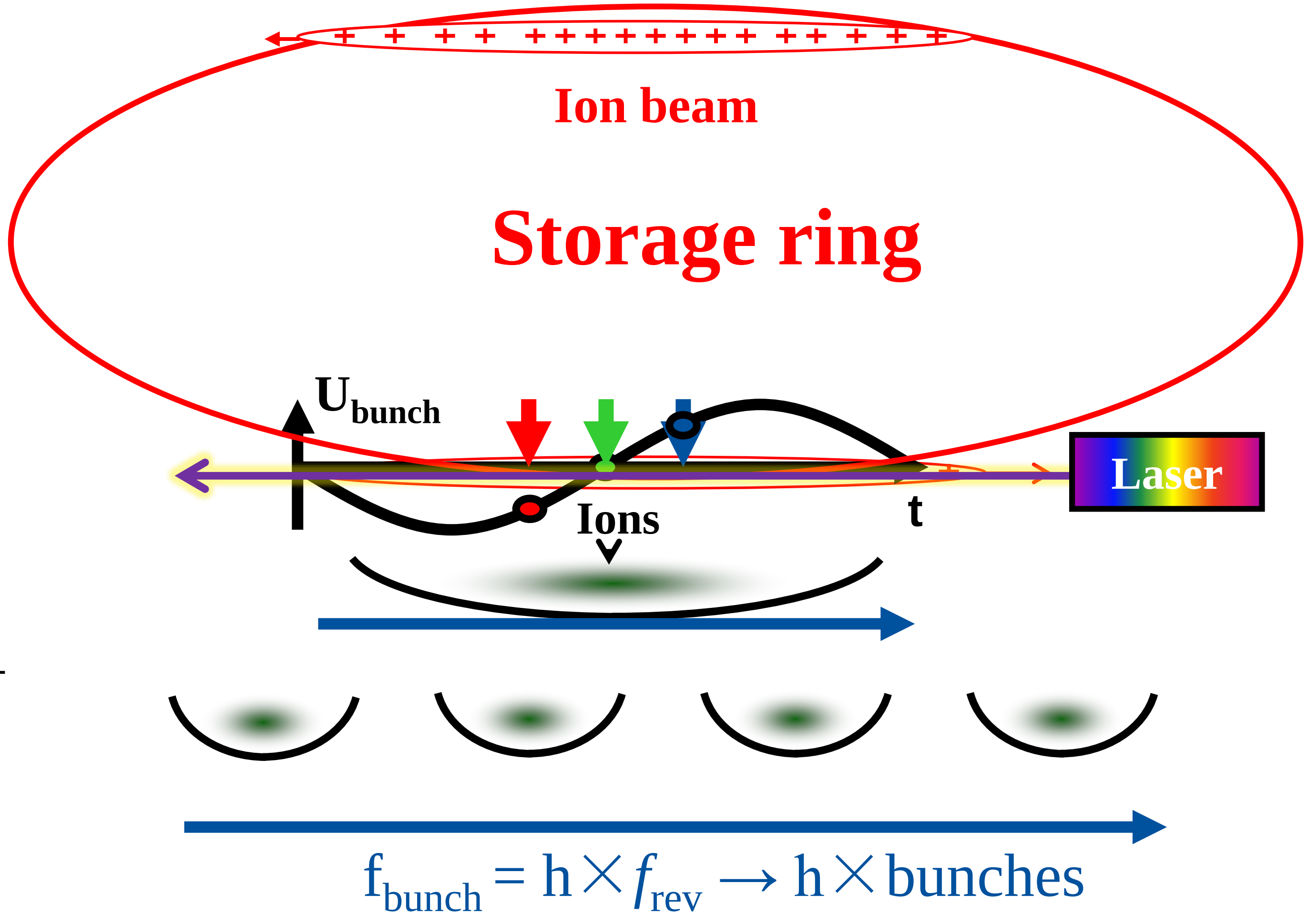


Principle: Laser cooling @ storage rings

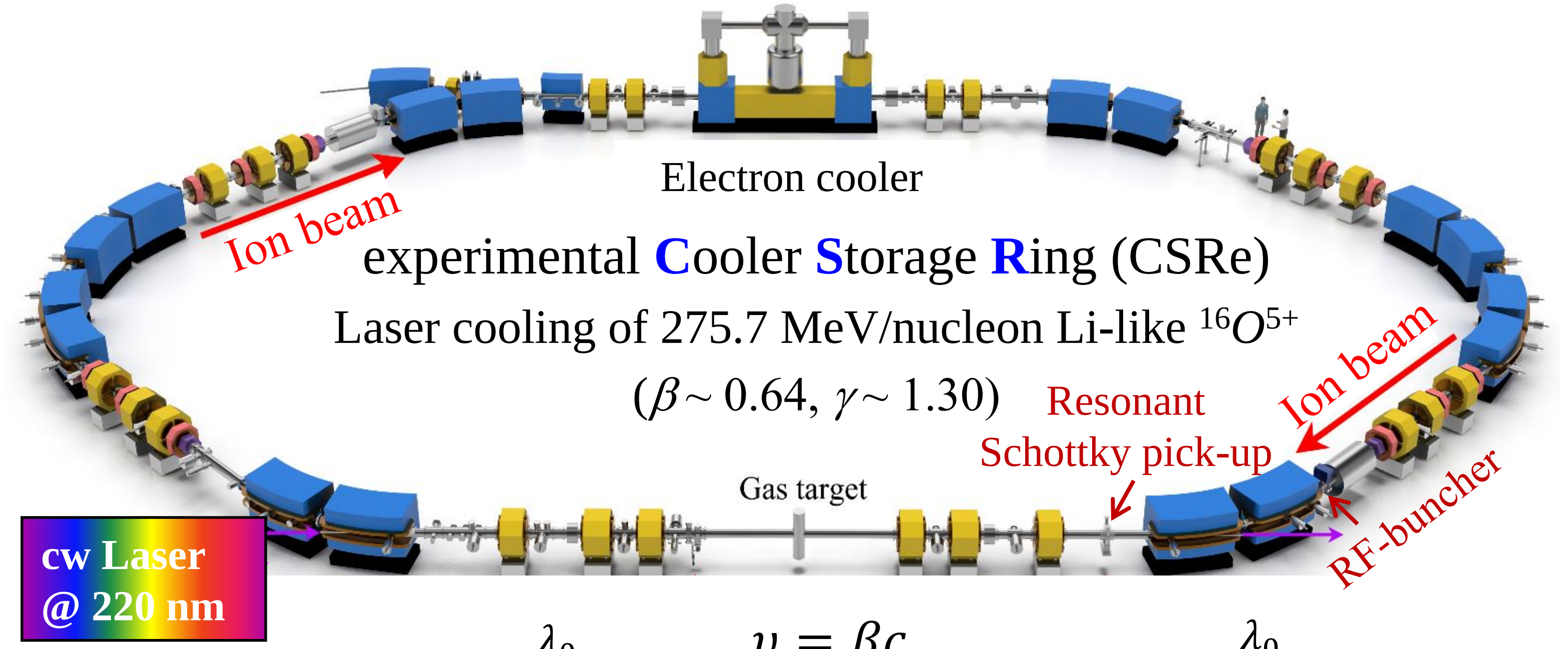


275 MeV/u Li-like $^{16}O^{5+}$
($\beta\approx 0.64$, $\gamma\approx 1.30$)





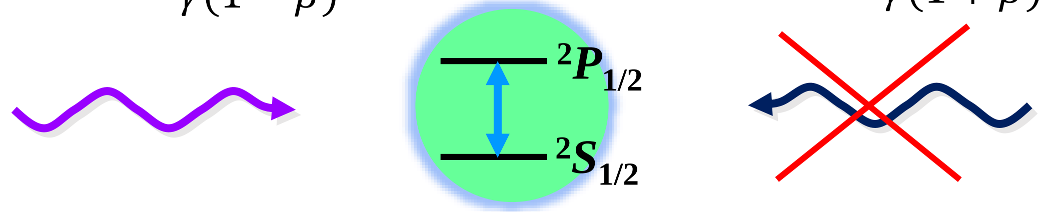
Experimental setup & parameters



$$\lambda_{Laser} = \frac{\lambda_0}{\gamma(1-\beta)}$$

$$\upsilon = \beta c$$

$$\lambda_{Laser} = \frac{\lambda_0}{\gamma(1+\beta)}$$



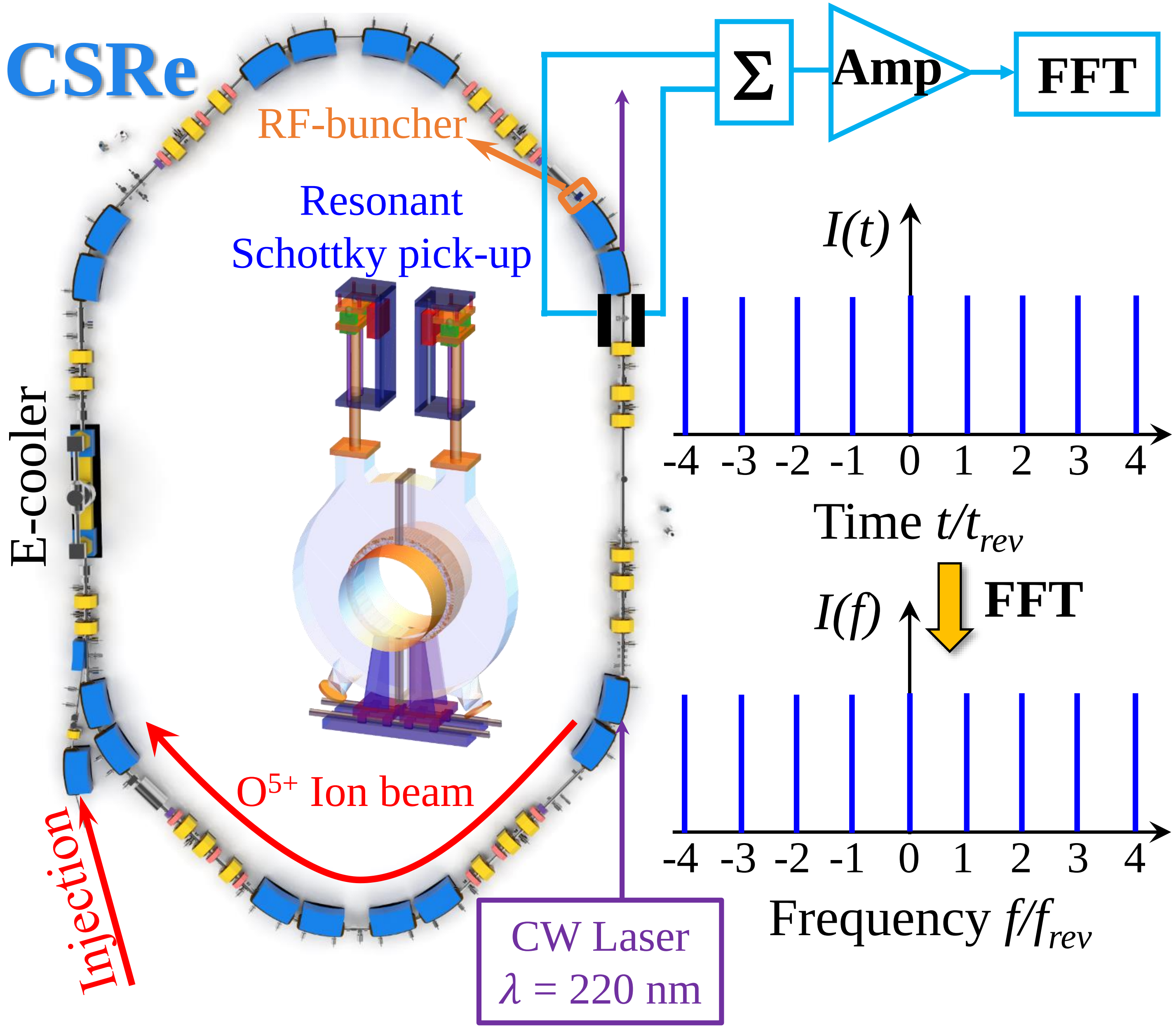
$\lambda_{Laser} \approx$ **220.0 nm**

$\lambda_0 \approx$ **103.8 nm**

$\lambda_{Laser} \approx$ **48.9 nm**

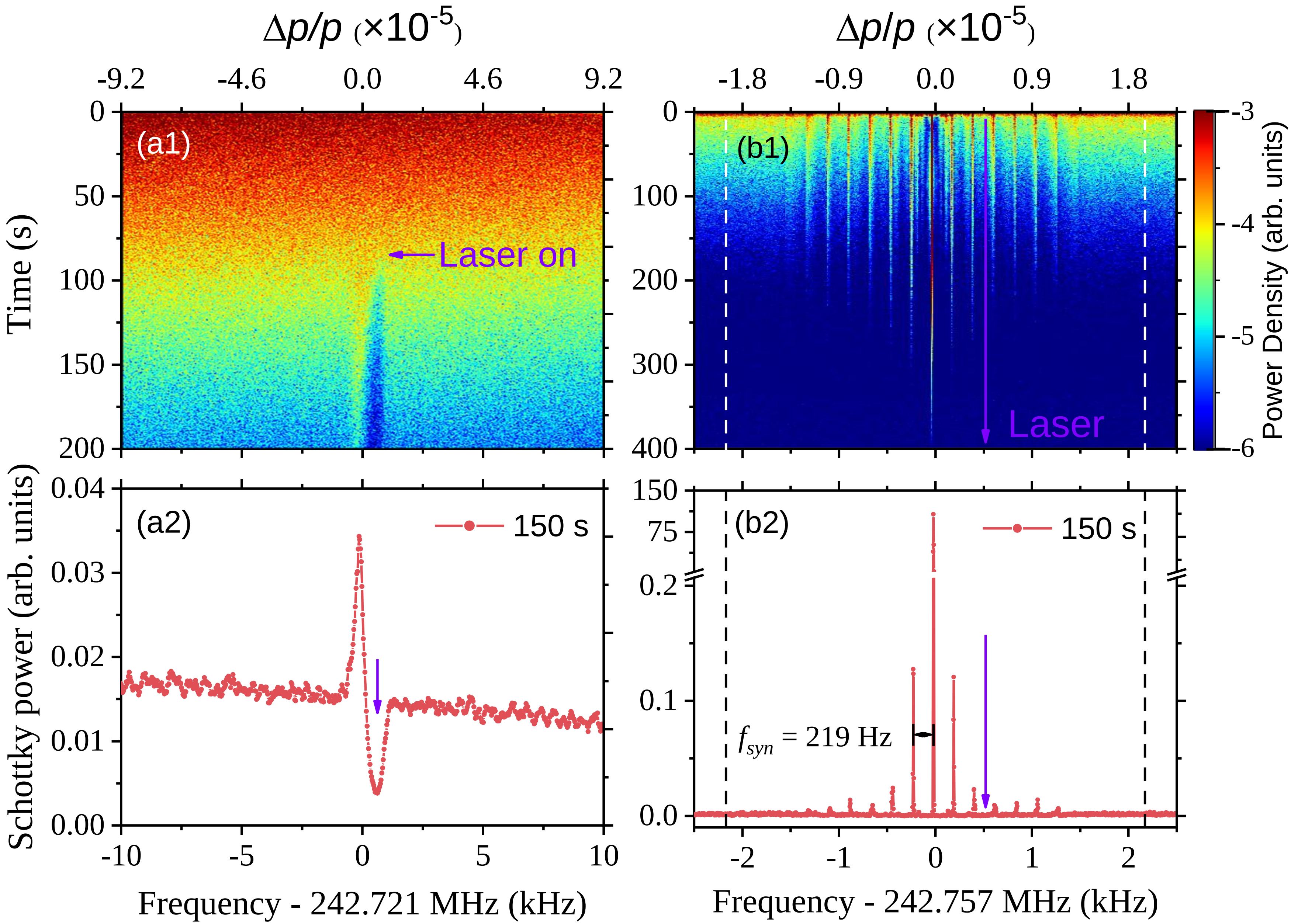
CSRe parameters	
Circumference	128.80 m
Max. magnetic rigidity $B\rho$	9.4 Tm
Ion species	$^{16}O^{5+}$
Beam energy E	275.7 MeV/u
Relativistic β, γ	0.636, 1.296
Revolution frequency	1.48 MHz
Transition energy γ_t	2.629
Splitting factor η	0.45
Beam lifetime	~35 s
Transition $2s_{1/2} - 2p_{1/2}$	103.76 nm
Resonance energy	11.95 eV
Lifetime of spontaneous emission τ	2.44 ns
CW laser system	
Laser wavelength	220 nm
Laser power	40 mW
Scanning range	20 GHz

Schottky system @ HIRFL-CSRe

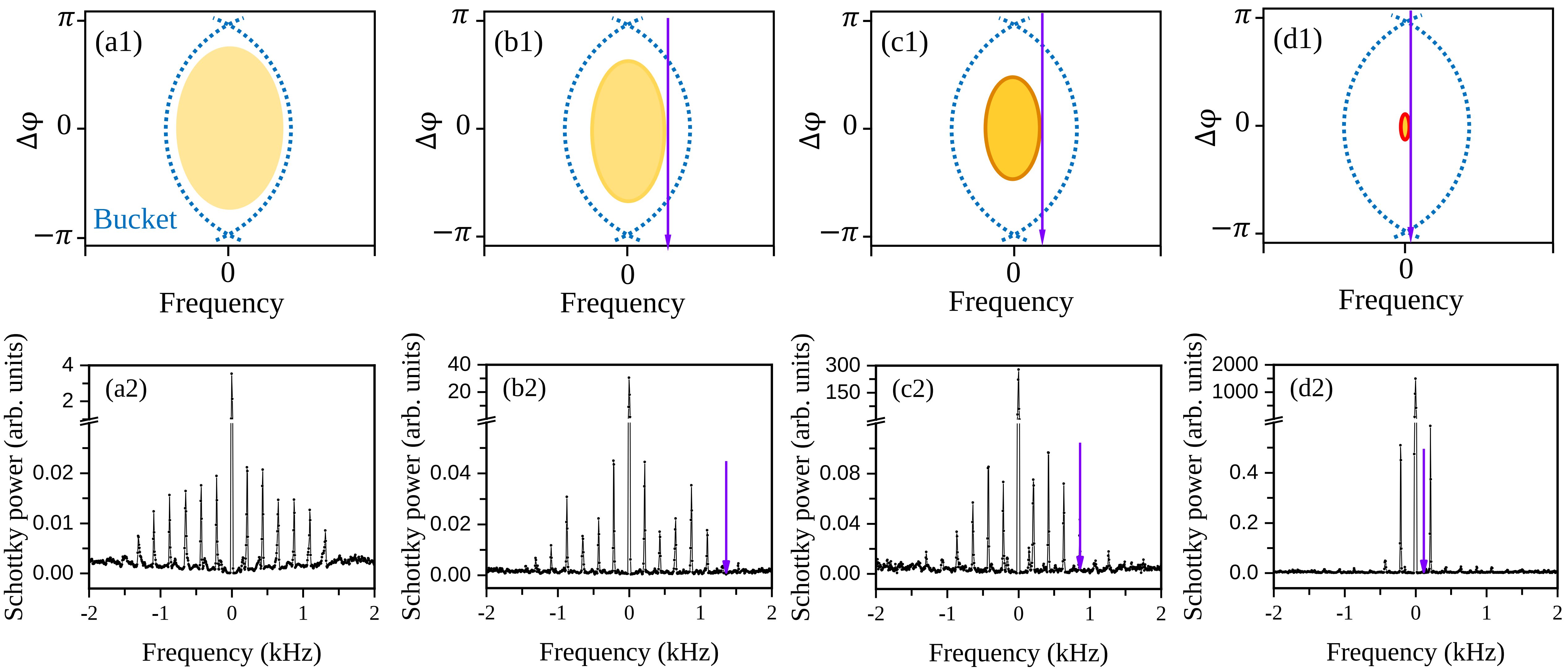


Resonant Schottky pick-up

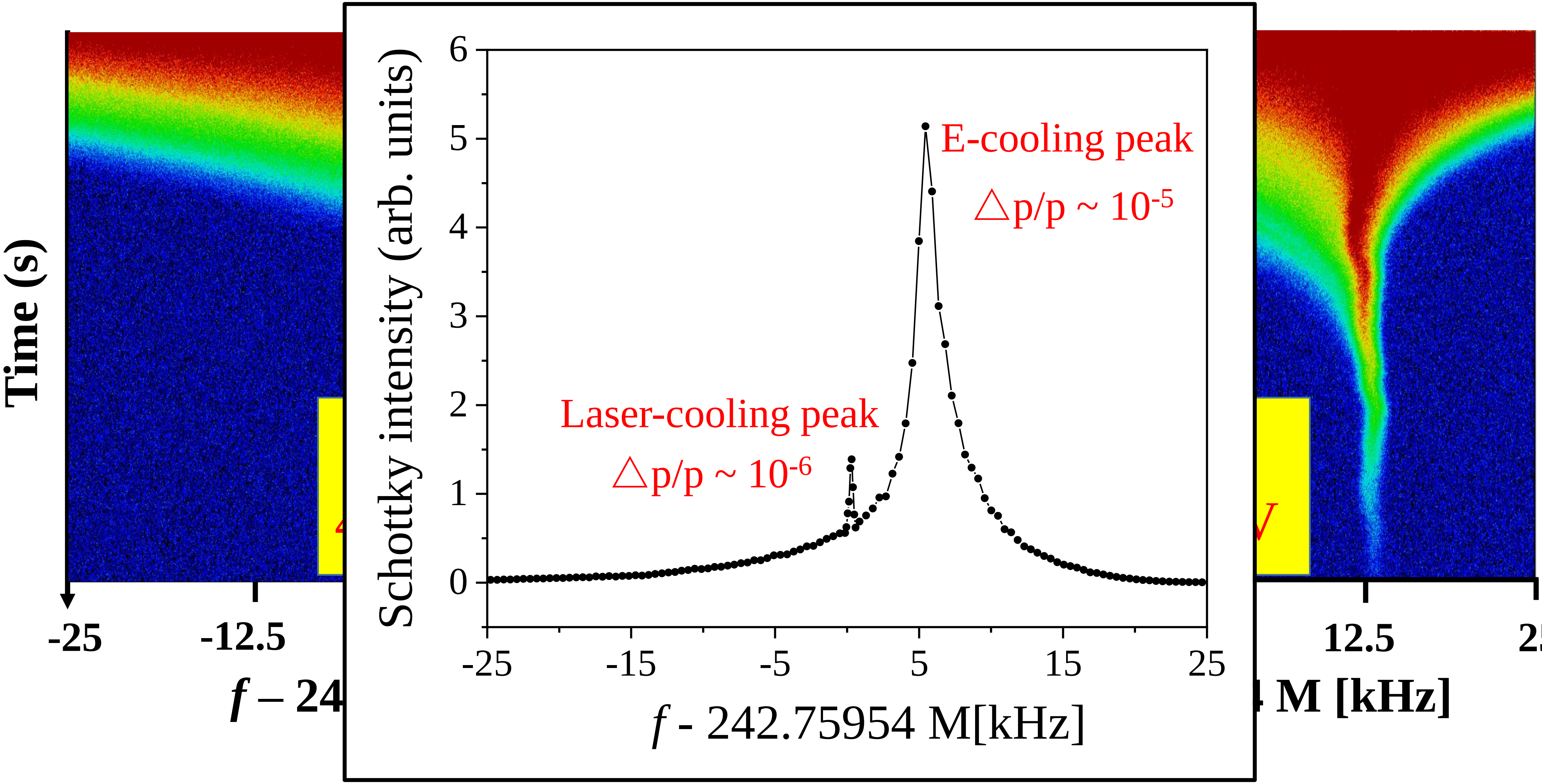
Experimental results @ laser cooling of O^{5+} ion beams



Laser cooling of bunched $^{16}O^{5+}$ ion beams



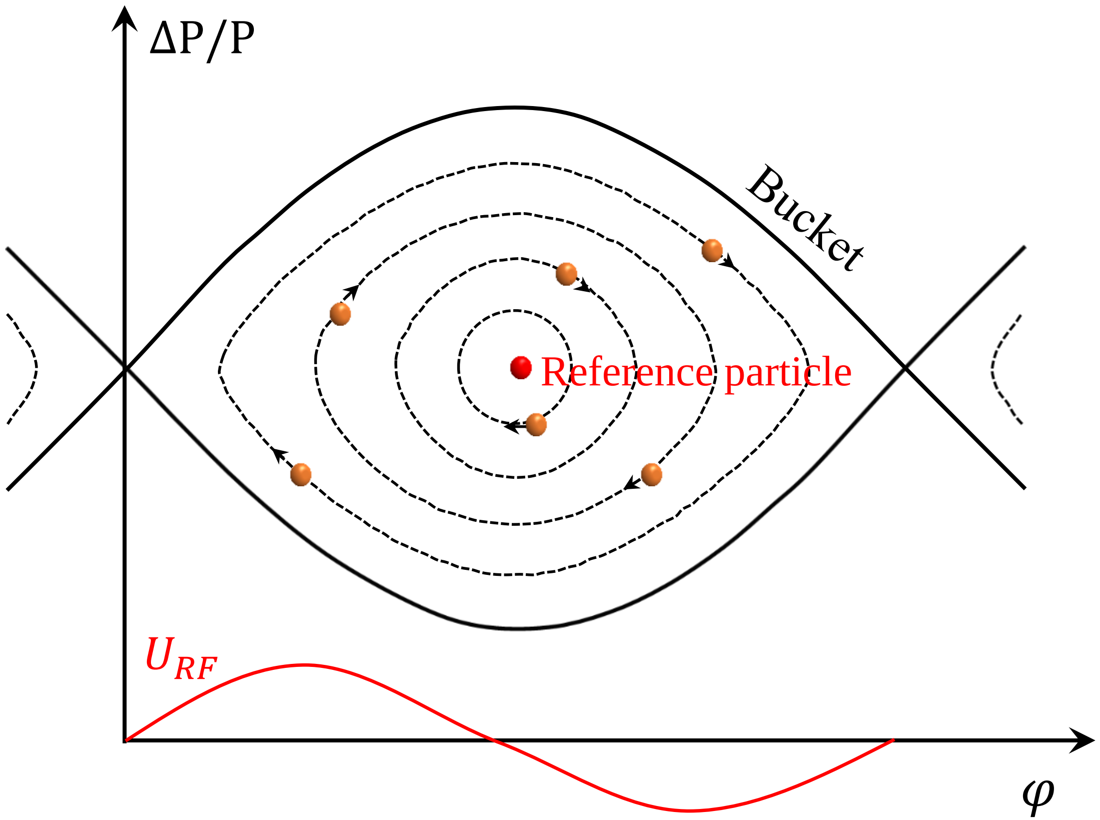
Laser cooling by CW laser and E-cooler



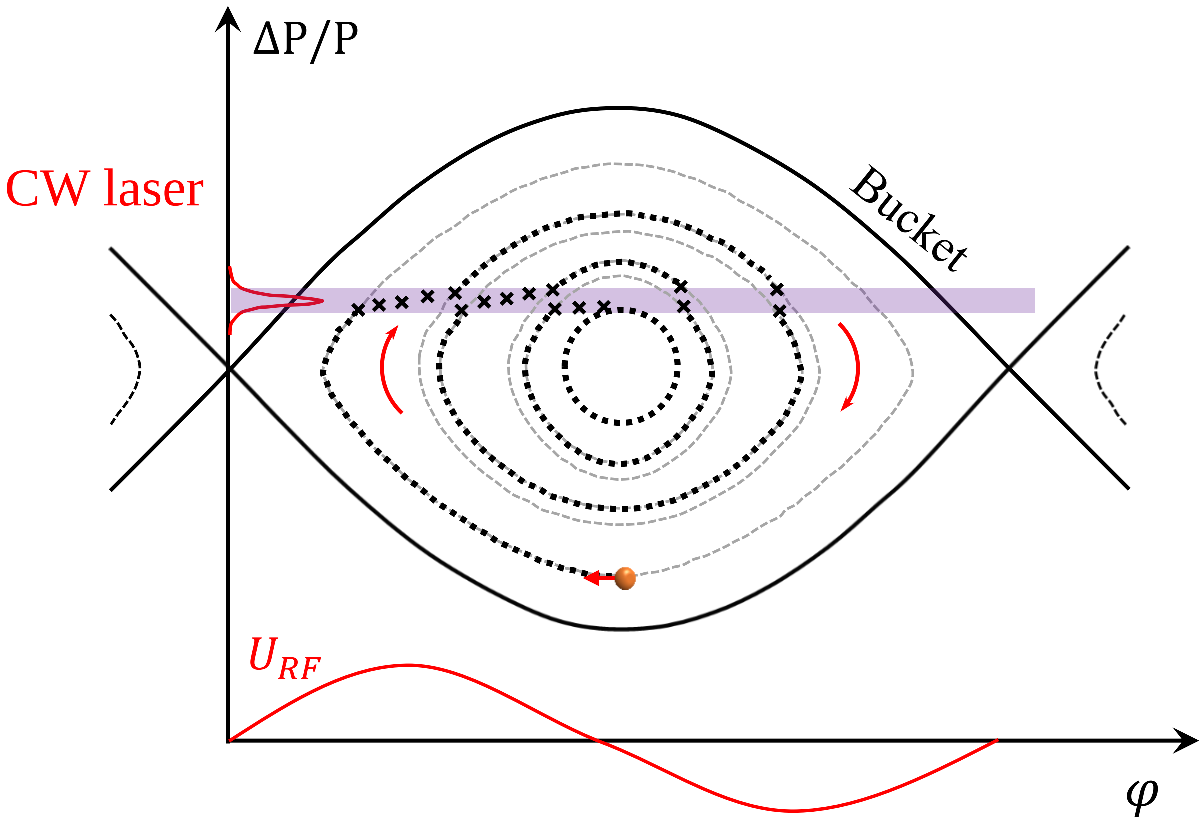
Simulation method: phase space tracking

The motion of ions in the phase space

The motion of bunched ions in the longitudinal phase space



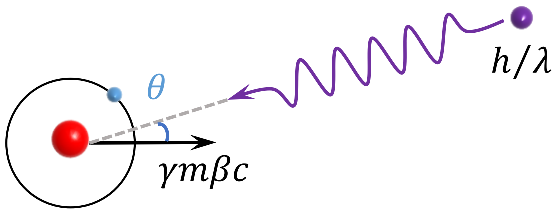
The trajectory of bunched ions under fixed laser in the longitudinal phase space



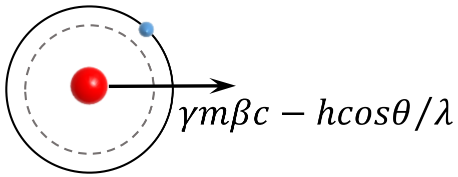
Simulation method

Laser interaction

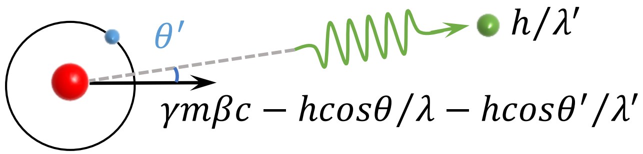
Before absorption



After absorption



After emission

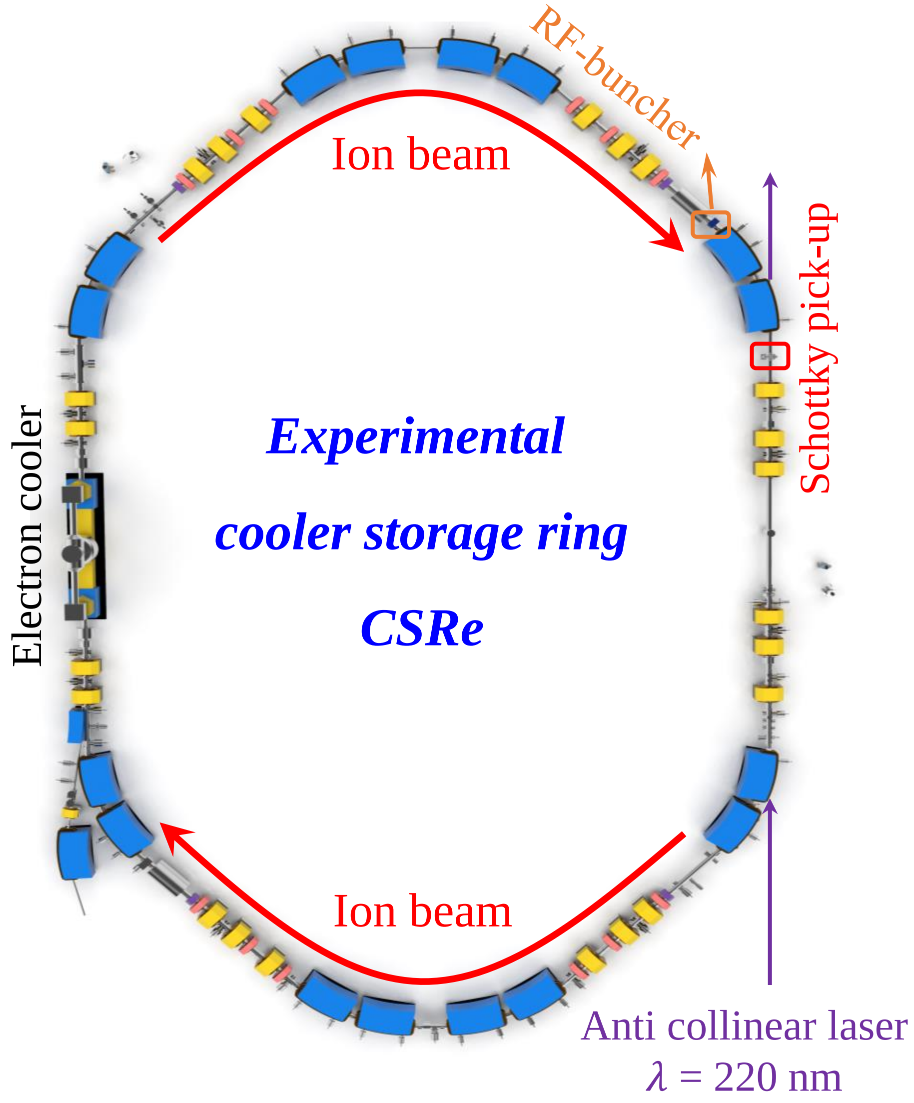


RF-buncher modulation

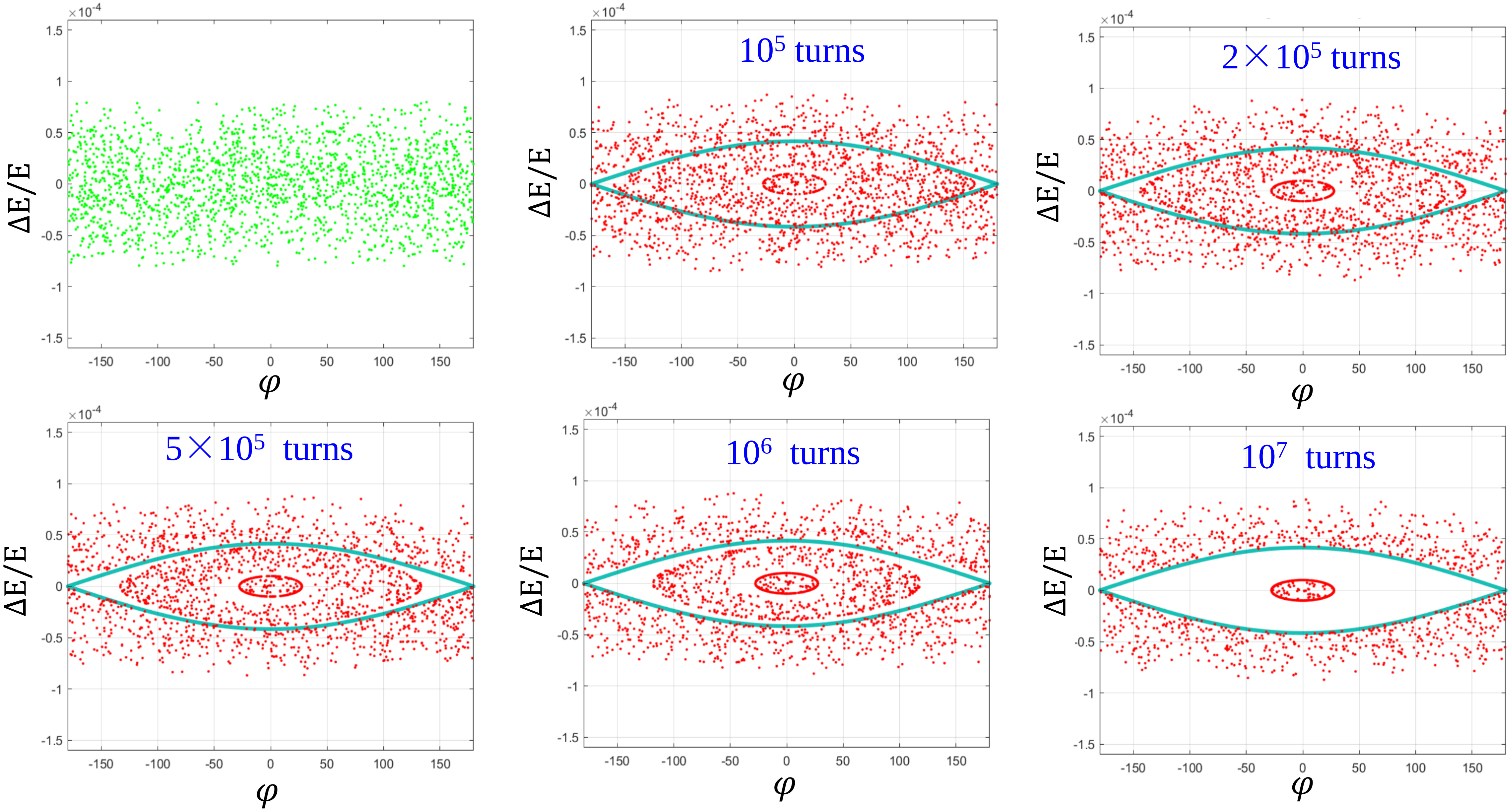
$$\begin{cases} \dot{\delta} = \dfrac{\omega_0}{2\pi\beta^2 E} eV(\sin\phi - \sin\phi_s) \\ \dot{\phi} = h\omega_0\eta\delta \end{cases}$$

6-D motion in storage rings

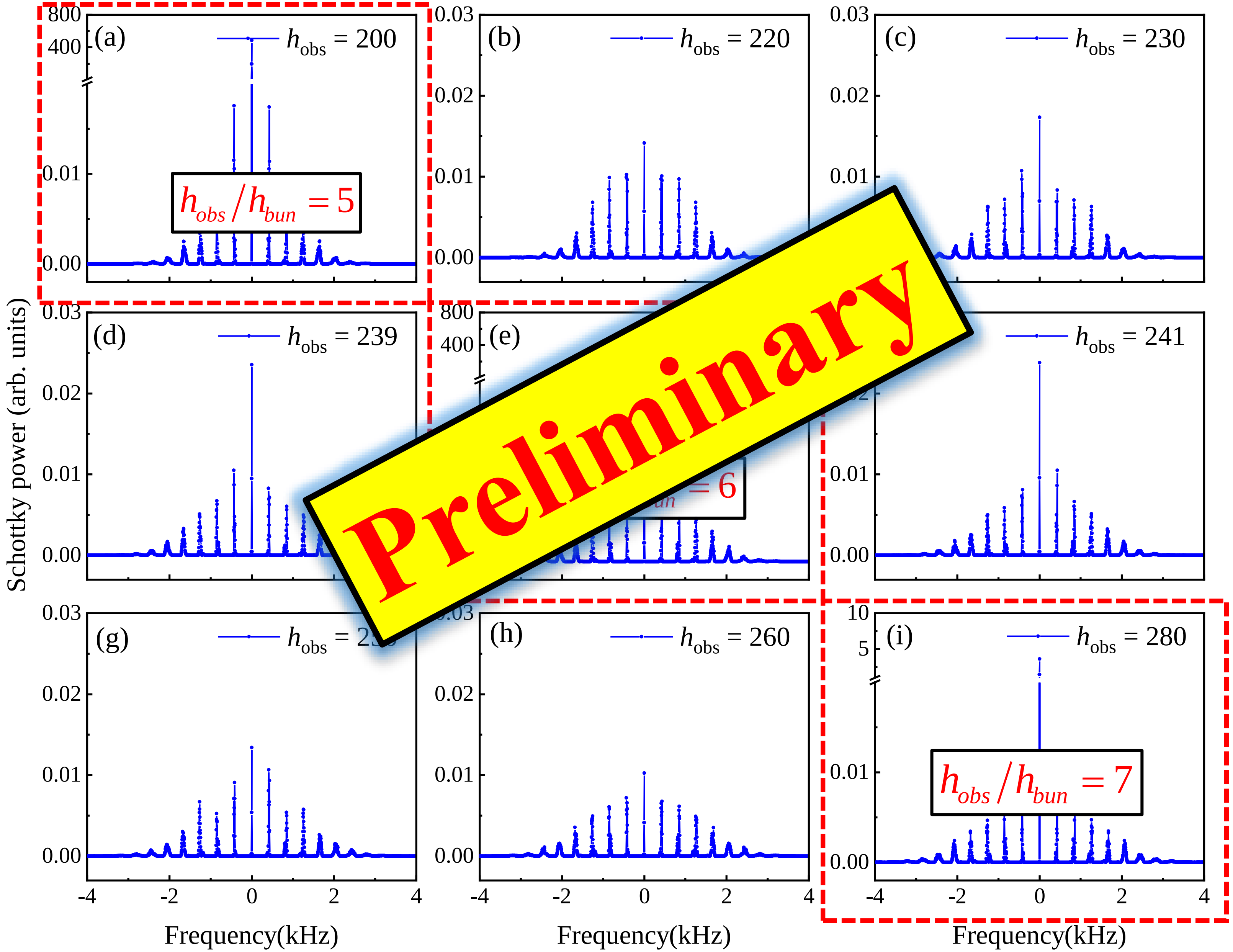
$$\begin{pmatrix} x_2 \\ x_2' \\ y_2 \\ y_2' \\ \delta s_2 \\ \dfrac{\delta p_2}{p_2} \end{pmatrix} = \begin{bmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & 1 & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} x_1 \\ x_1' \\ y_1 \\ y_1' \\ 0 \\ \dfrac{\delta p_1}{p_1} \end{pmatrix}$$



Simulation results: laser cooling process



Simulation results: the coherent effect



Ultra-high power of the central peak appears only:

$$h_{obs}/h_{bun} = \text{Integer}$$

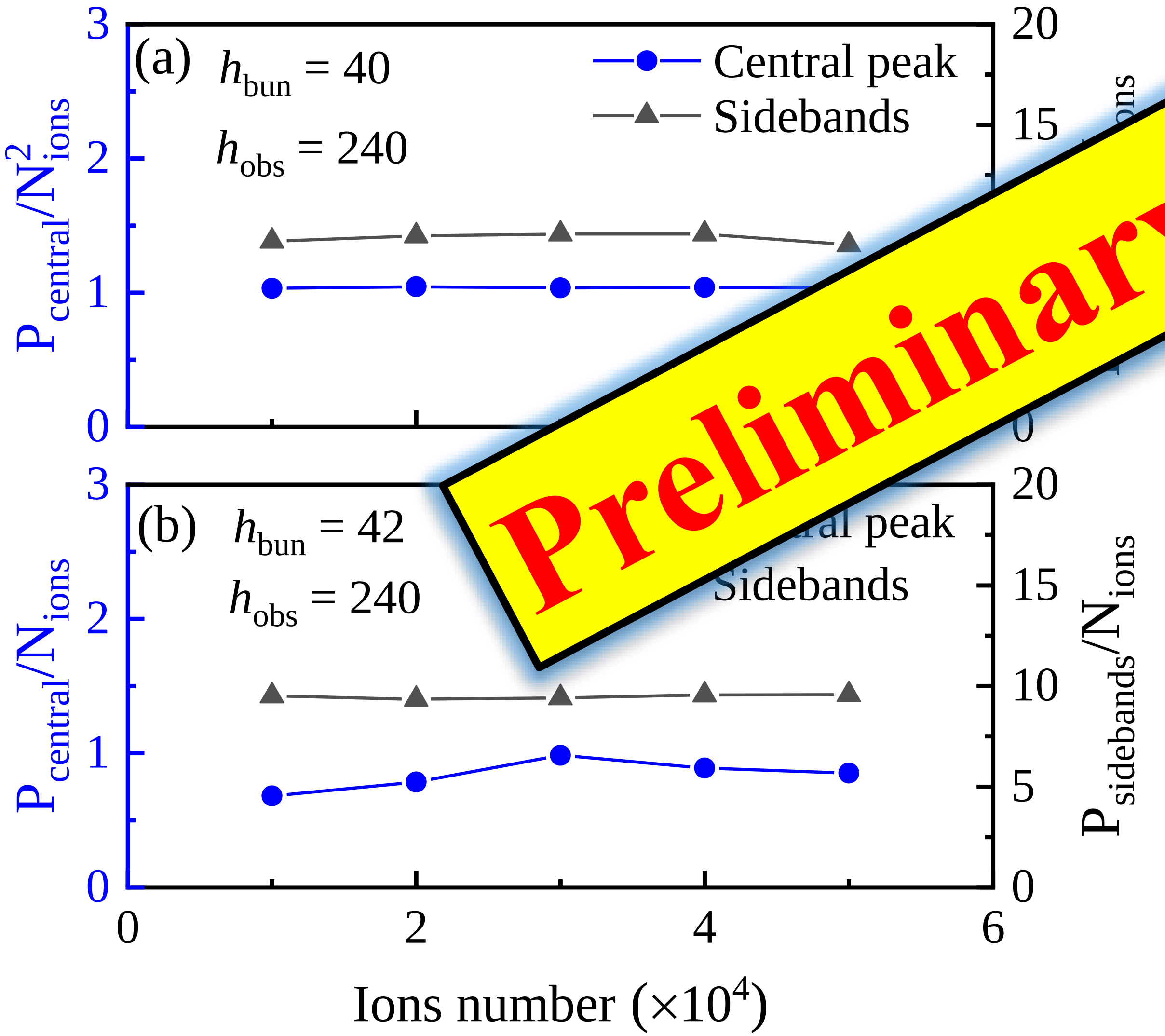
h_{bun}=40, change h_{obs}

h_{obs}: Observation harmonic

h_{bun}: RF-bunching harmonic

Simulation results: the coherent effect

Relationship between the Schottky power and number of ions

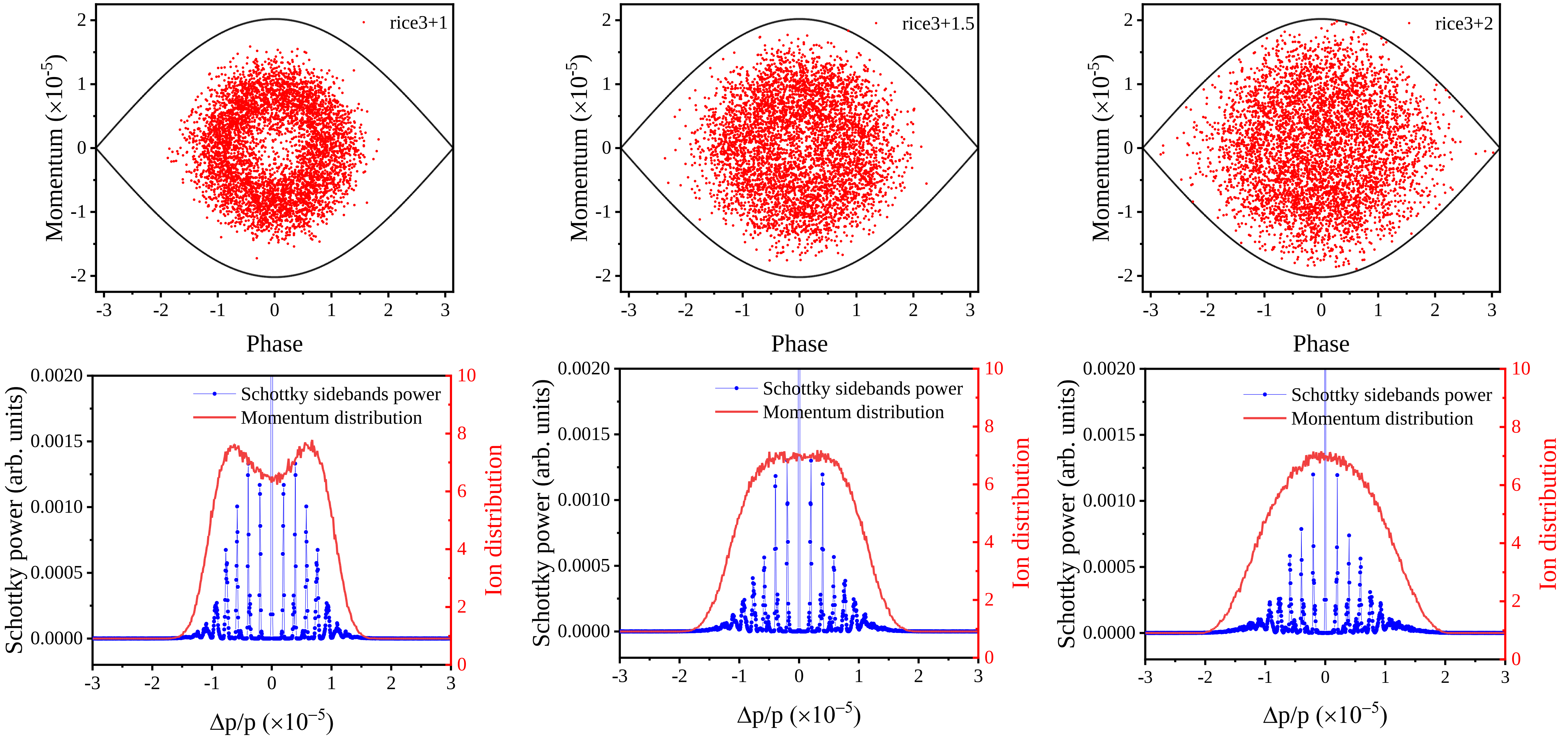


h_{obs}/h_{bun} = / Power	Integer	Non-integer
Power of Central peak	$P_{central} \propto N^2$	$P_{central} \propto N$
Power of Sidebands	$P_{sideband} \propto N$	$P_{sideband} \propto N$

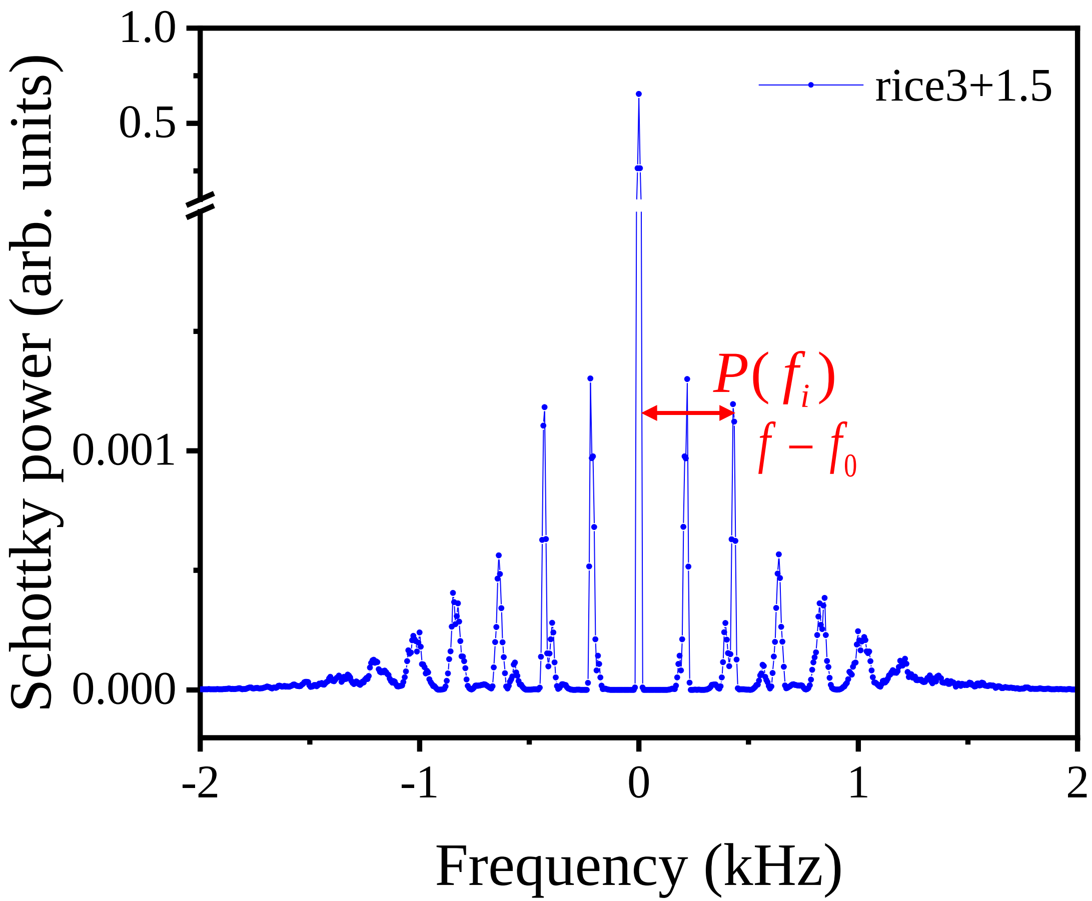
h_{obs}: Observation harmonic

h_{bun}: RF-bunching harmonic

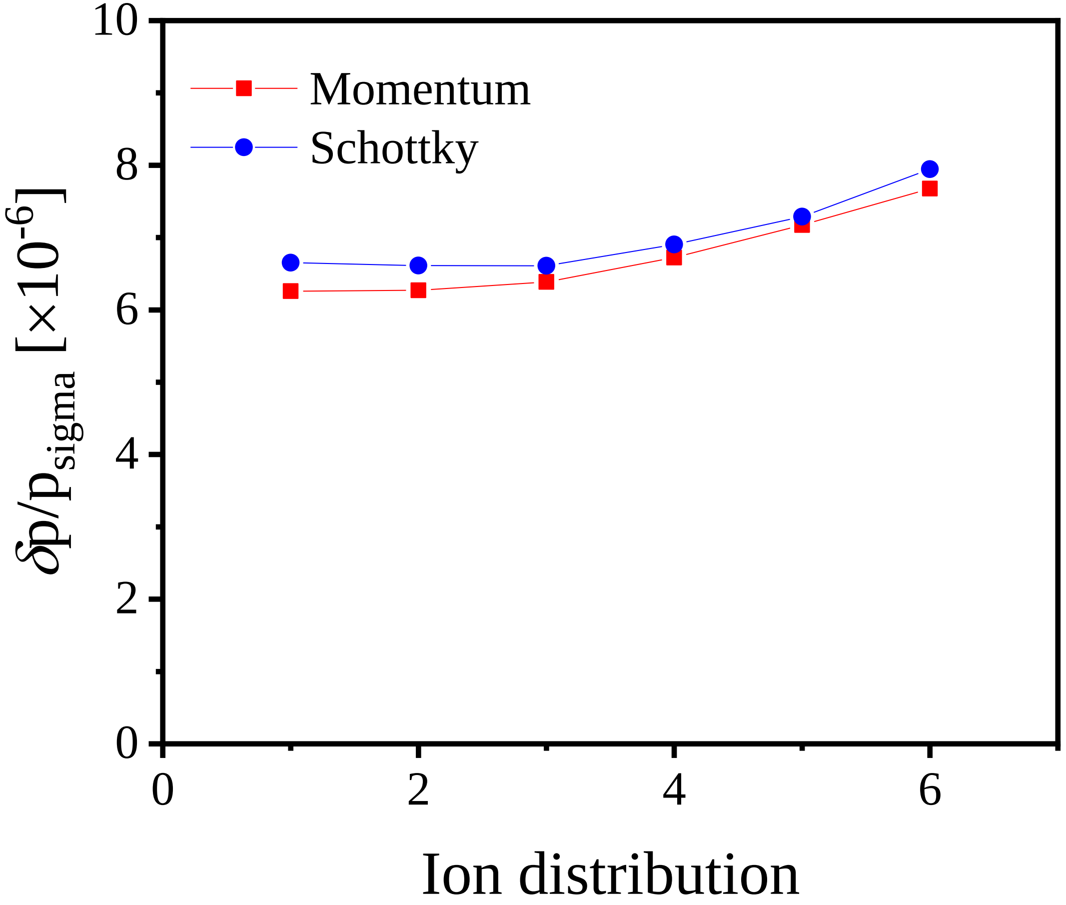
Method 1. Fit the sidebands of the Schottky spectrum



Method 2. Calculate the r.m.s width of the Schottky sidebands



Momentum distribution vs RMS calculation



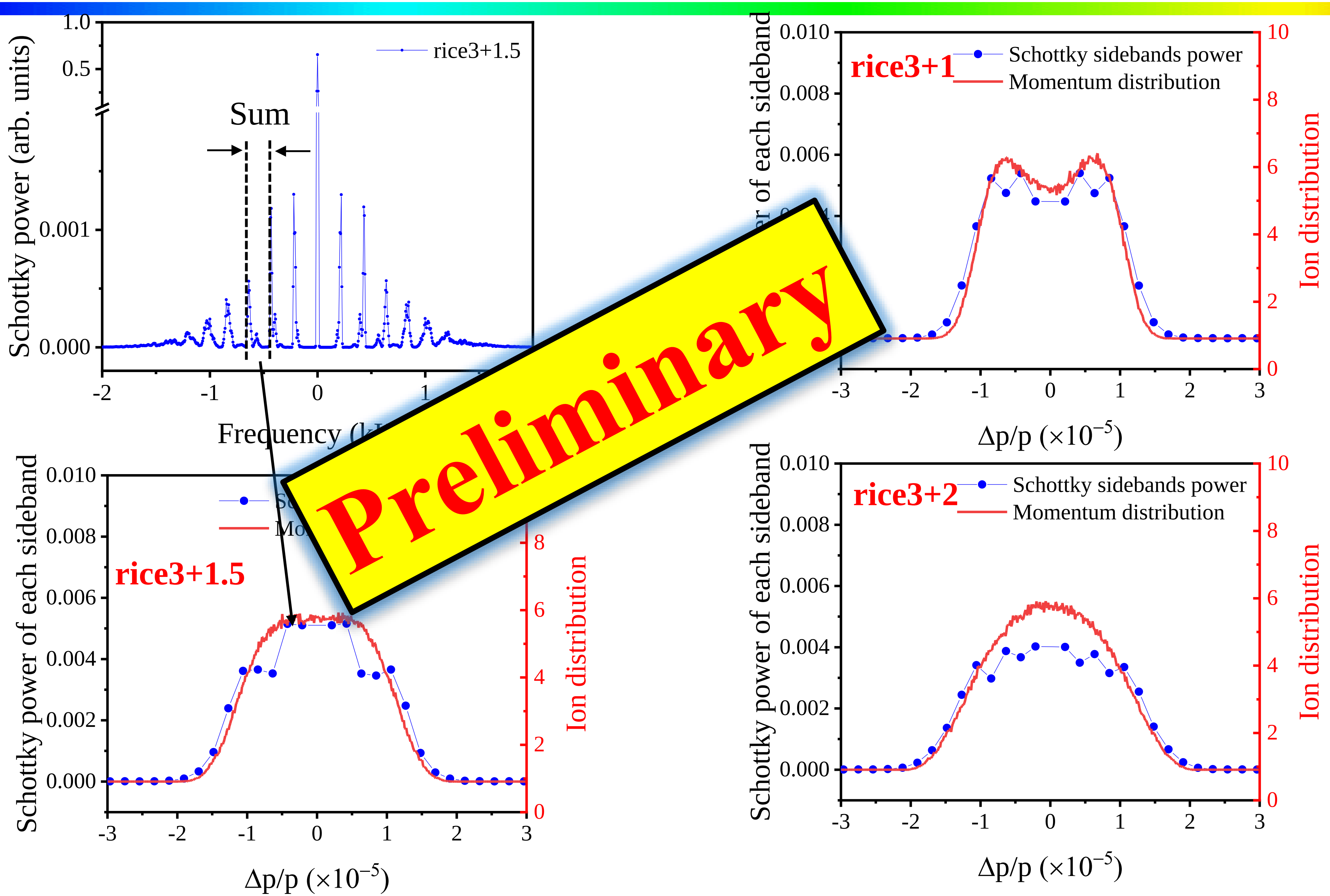
$$\sigma_f^{\ 2} = \int_{-\infty}^{\infty} W(f)(f - f_0)^2 df$$

$$W(f_i) = P(f_i) \Big/ \sum_{i=1}^{N} P(f_i)$$

$$\Rightarrow \quad \frac{\sigma_p}{p} = \frac{1}{\eta} \cdot \frac{\sigma_f}{f}$$

V. Balbekov, Longitudinal schottky spectra of bunched beams, Proceedings of EPAC 2004, Lucerne, Switzerland

Method 3. Sum the Schottky power of each sideband



Summary

1. First laser cooling of $^{16}O^{5+}$ ion beams at the storage rings:

   Highest charge state and energy

   Shortest transition wavelength： 103 nm

   Laser cooling with a CW laser and the electron cooler

2. Simulation of laser cooling of $^{16}O^{5+}$ ion beams at the CSRe.

   Laser cooling process

   Schottky spectrum of laser-cooled bunched $^{16}O^{5+}$ ion beams

   Coherent effect

   Extraction of momentum distribution from Schottky spectrum of bunched ion beams

Acknowledge

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