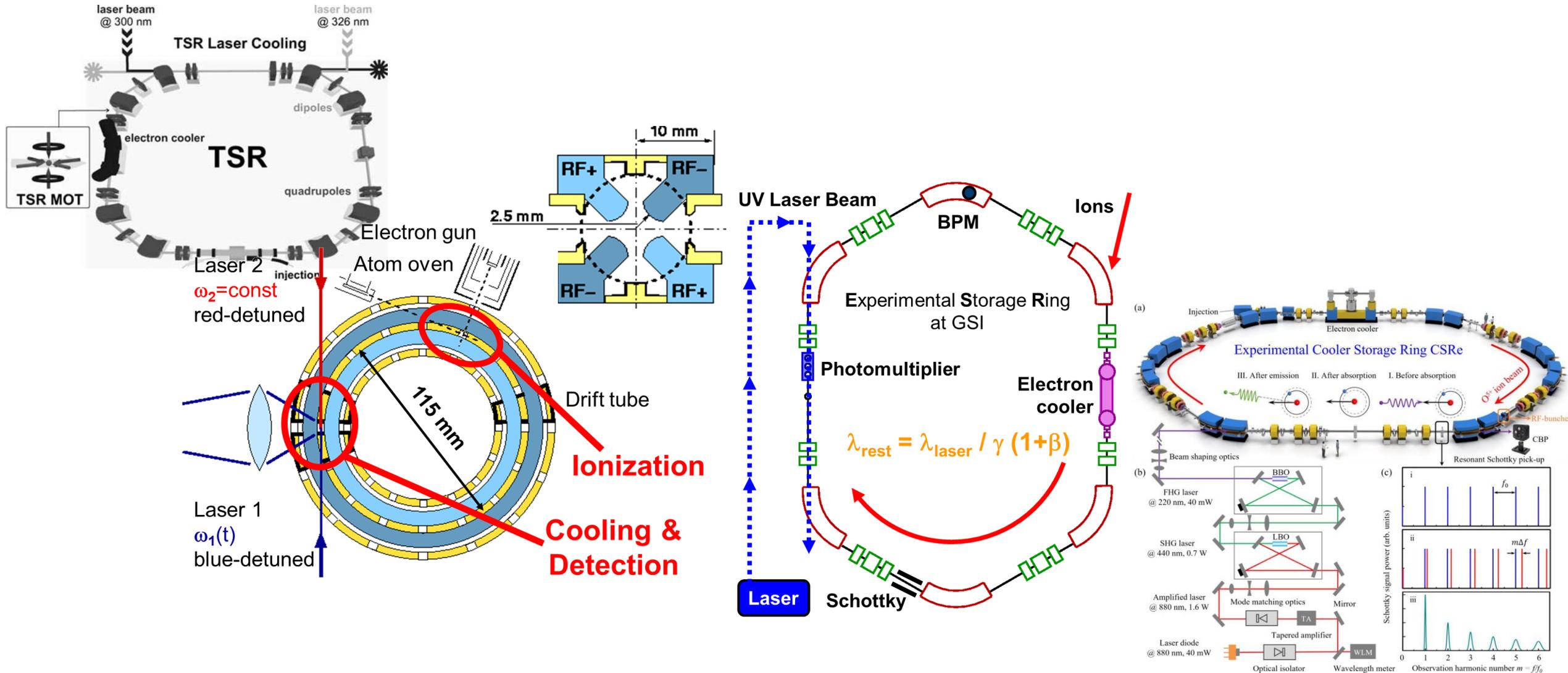# Laser cooling of relativistic ion beams

Michael Bussmann, SIS100 laser cooling collaboration
www.casus.science

A long-term effort

From TSR (and others) to Pallas to ESR to CSRe and beyond

Why laser cooling of relativistic ion beams?

Cold relativistic beams, precision spectroscopy, crystalline beams

- Achieves **higher cooling rates** than other techniques

- Grows **stronger with increasing ion energy** (using more laser power)

- Reaches **smaller longitudinal momentum spread** than other techniques

- Produces interesting **spectroscopic data** „for free" from many ions collectively

- May lead to **beam crystallization**

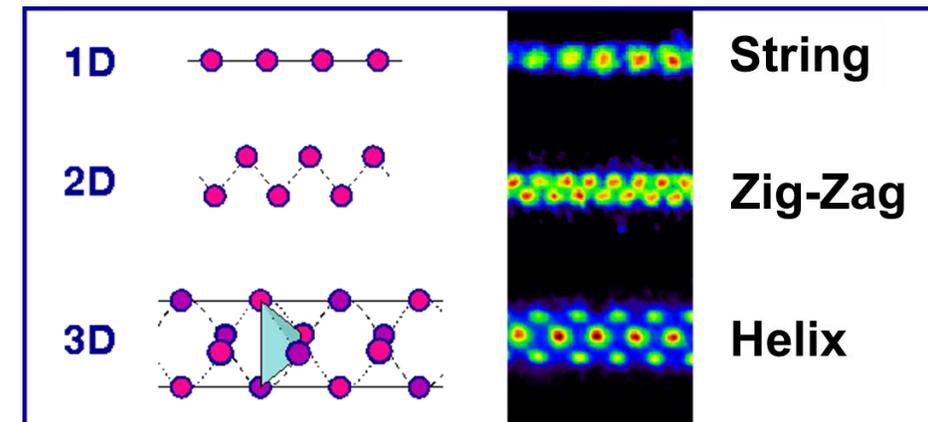$$f_p^2 = Q^2 e^2 n_{beam} / \left(4\pi^2 \varepsilon_0 m_{ion} \right)$$ (plasma frequency)

$$f_\beta^2 = Q_\beta^2 f_{rev}^2 \approx f_p^2$$ (betatron frequency)

$$f_{syn} << f_{rev} \approx f_p / Q_\beta$$ (synchrotron frequency)

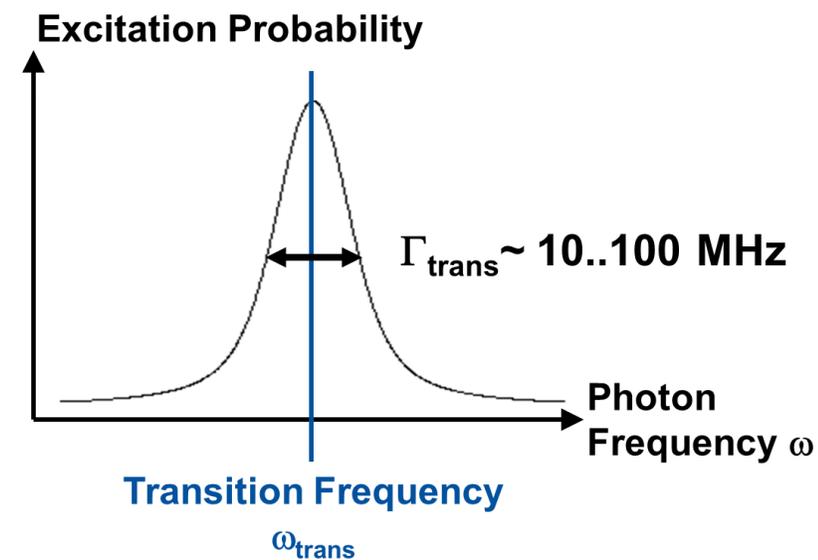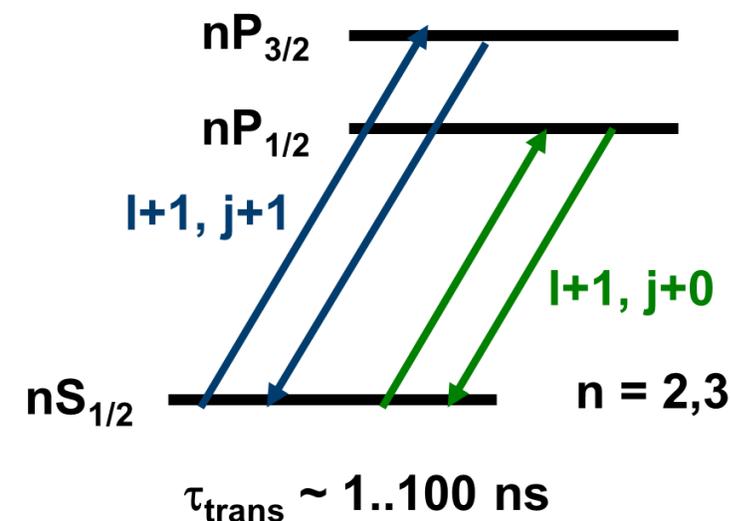# How to laser cool (relativistic) ion beams

Cooling transitions

We need a fast (see below) cooling transition

- Li-like or Na-like, needs a certain charge state Q

λ'_{trans} (transition wave length in rest frame, UV, VUV, ...)

$\Gamma'_{trans} = 1/\tau'_{trans}$ (natural line width in rest frame)

$\tau'_{trans} = \tau_{trans}/\gamma \quad < \quad T_{rev} = \beta c / C = f_{rev}^{-1}$

(transition life time)   (beam revolution time in lab. frame)

$nP_{3/2}$

$nP_{1/2}$

I+1, j+1

I+1, j+0

$nS_{1/2}$ n = 2,3

$\tau_{trans} \sim 1..100$ ns

Excitation Probability

$\Gamma_{trans} \sim 10..100$ MHz

Photon Frequency ω

Transition Frequency ω_{trans}

How to laser cool (relativistic) ion beams
Photon absorption and emission

$$\lambda'_{trans} \equiv \lambda'_{laser} = \lambda_{laser} / ((1+\beta)\gamma)$$

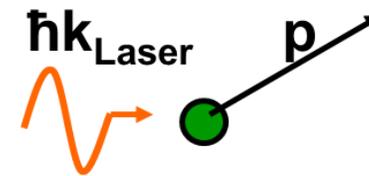(transition wave length in rest frame vs laser wavelength in lab. frame)

$$\gamma_{res} \xrightarrow{\beta \to 1} \lambda_{laser} / (2\lambda'_{trans})$$ (matching energy)

$$\gamma \leq \gamma_{B\rho} = \sqrt{(B\rho Qe/(m'_{ion}c))^2 + 1}$$
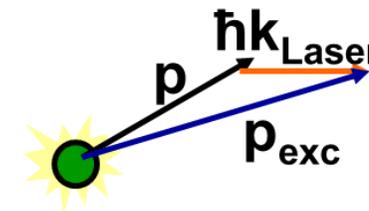

Excite an Atom by absorbing a Photon

$$p'_{phot} = \hbar k'_{phot} = h / \lambda'_{phot} = (1+\beta)\gamma h / \lambda_{phot}$$

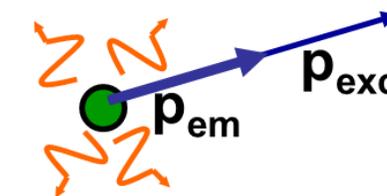$$= (1+\beta)\gamma p_{phot} \xrightarrow{\beta \to c} 2\gamma p_{phot}$$

(photon momentum in rest/lab. frame)

Photon Momentum changes Atomic Momentum in Direction of the Laser

Emission of Photon in random Direction Avering means net Reduction of Atomic Momentum

How to laser cool (relativistic) ion beams

Saturation intensity and cooling rate

$$\delta' = \omega'_{Doppler} - \omega'_{trans}$$

(detuning in rest frame)

$$\omega'_{Doppler} = \omega'_{phot} - \vec{p}'_{ion} \cdot \vec{k}'_{phot} / m'_{ion} \qquad \omega'_{trans} = 2\pi c / \lambda'_{trans}$$
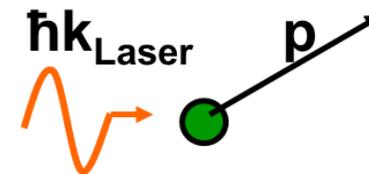
(Doppler shift and transition freq.)

$$I'_{sat} = \pi h c / \left(3 \lambda'^3_{sat} \tau'_{sat} \right)$$
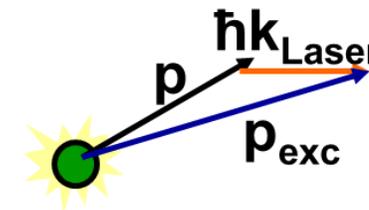
(saturation intensity)

ħk$_{Laser}$ **p**

Excite an Atom by absorbing a Photon

$$S'_0 = I'_{laser} / I'_{sat}$$

(saturation parameter)

p **ħk$_{Laser}$**

p$_{exc}$

Photon Momentum changes Atomic Momentum in Direction of the Laser

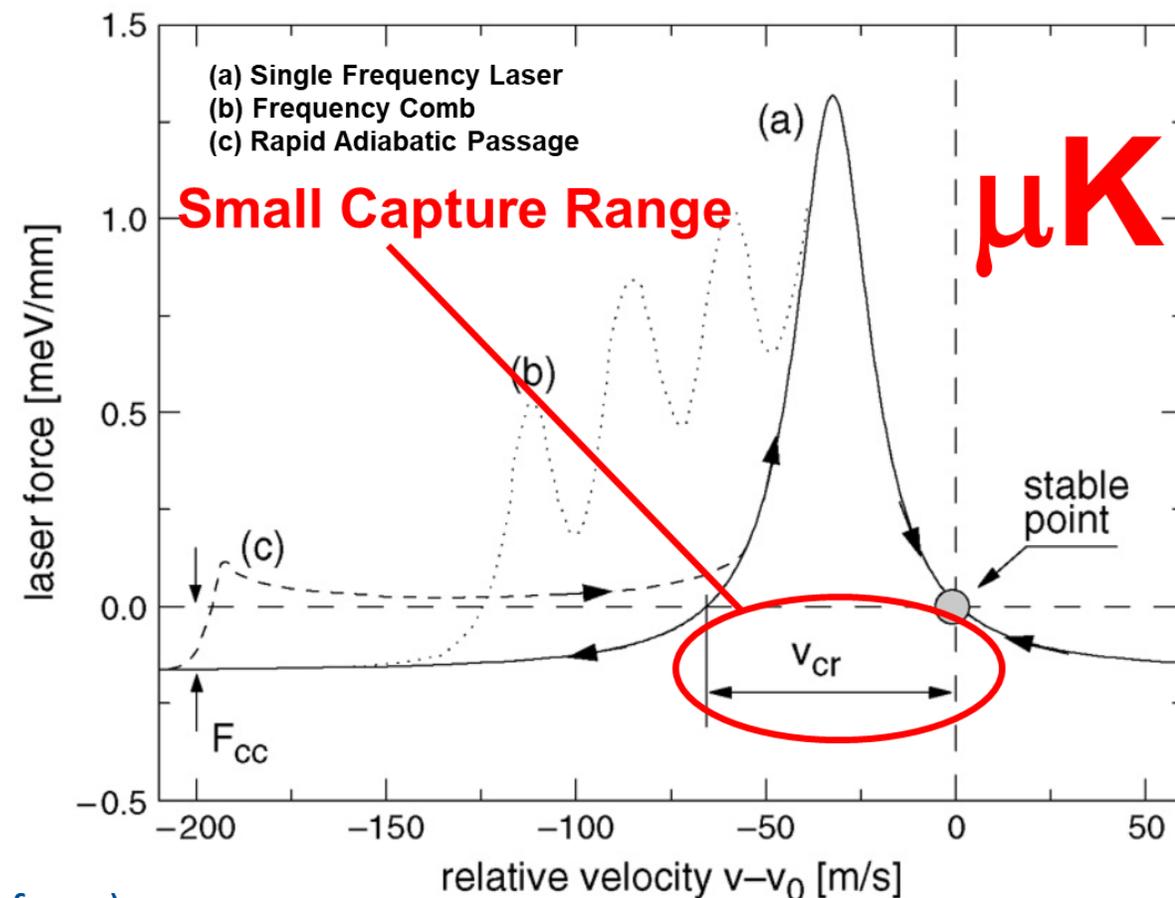$$R' = \Gamma'_{trans} \cdot L'$$

(scattering rate)

$$= \Gamma'_{trans} \cdot \frac{1}{2} \frac{S'_0 \left(\Gamma'_{trans} / 2 \right)^2}{\delta'^2 + \left(1 + S'_0 \right) \left(\Gamma'_{trans} / 2 \right)^2}$$

p$_{em}$ **p$_{exc}$**

Emission of Photon in random Direction Avering means net Reduction of Atomic Momentum

How to laser cool (relativistic) ion beams

Averaged laser force

$$\vec{F}'_{laser} = \vec{p}'_{phot} R'$$
(averaged laser force in rest frame)

$$= \frac{S'_0 (\Gamma'_{trans} / 2)^3}{\delta'^2 + (1 + S'_0)(\Gamma'_{trans} / 2)^2} \hbar \vec{k}'_{phot}$$

$$\left| \vec{F}'_{laser,\max} (\delta' = 0) \right| = \frac{h \Gamma'_{trans}}{2 \lambda'_{phot}} \frac{S'_0}{(1 + S'_0)}.$$

$$\xrightarrow{S'_0 \rightarrow \infty} \frac{\Gamma'_{trans}}{2} \frac{h}{\lambda'_{phot}} = \frac{p'_{phot}}{2 \tau'_{trans}}$$
(maximum laser force)

(a) Single Frequency Laser
(b) Frequency Comb
(c) Rapid Adiabatic Passage

Small Capture Range

μK

How to laser cool (relativistic) ion beams

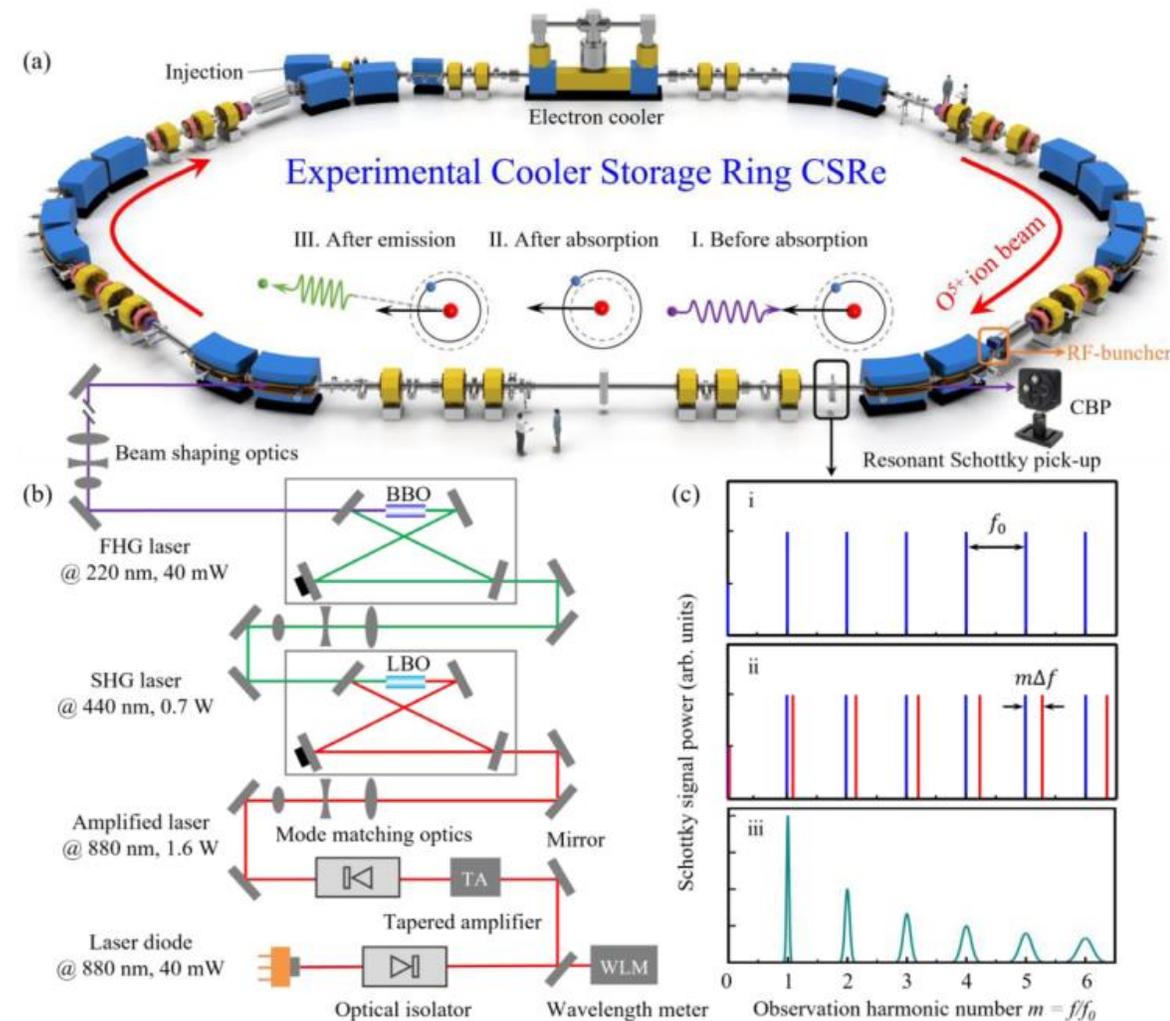## Laser force acceptance and maximum cooling rate

$$\Delta p'_{l,acc} = \sqrt{(1 + S'_0)} \Gamma'_{trans} \lambda'_{trans} m'_{ion} / 2\pi$$

(laser force momentum acceptance)

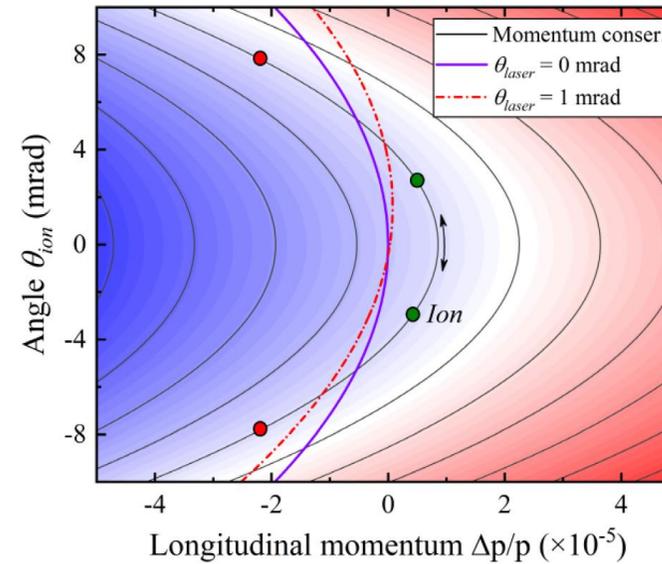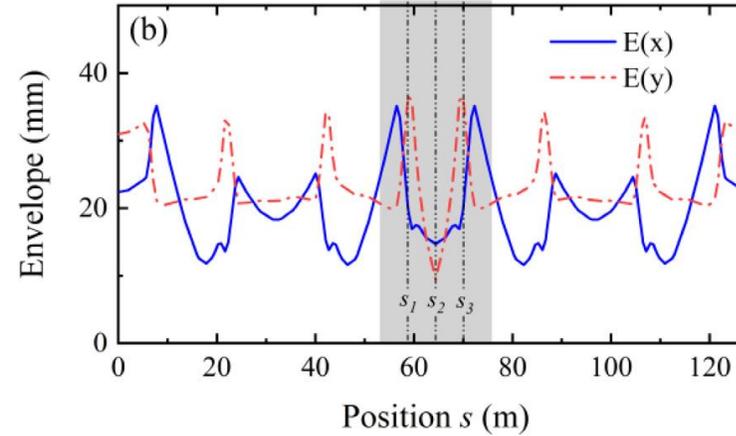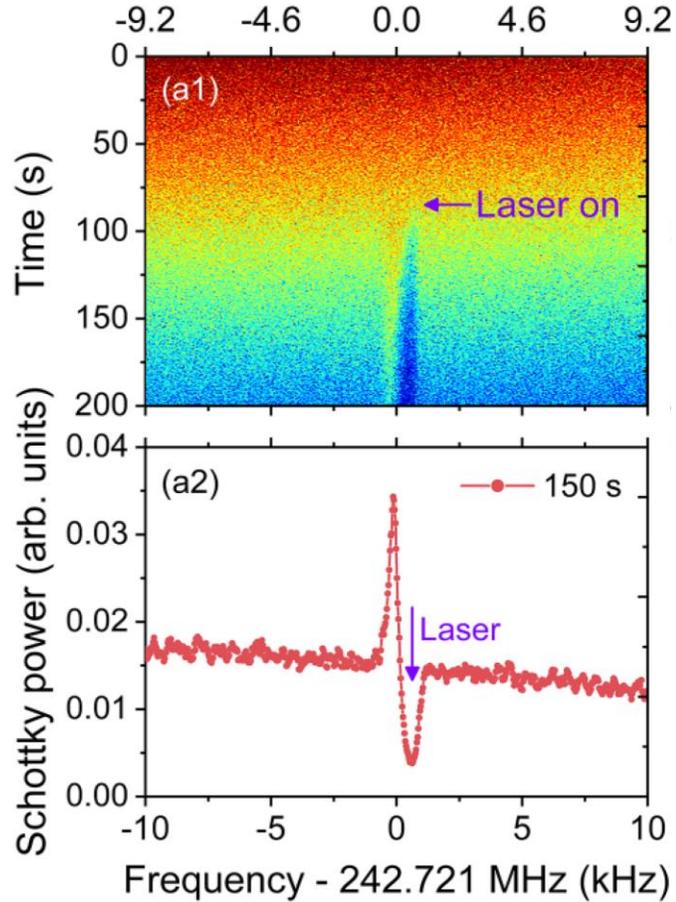$$T'_{Doppler} = \frac{\hbar \Gamma'_{trans}}{2k_B}$$

(minimum temperature)

$$R_{cool} = f_{recoil} / 2$$

(maximum cooling rate)

$$f_{recoil} = h / \left(2m'_{ion} \lambda'^2_{trans} \right)$$

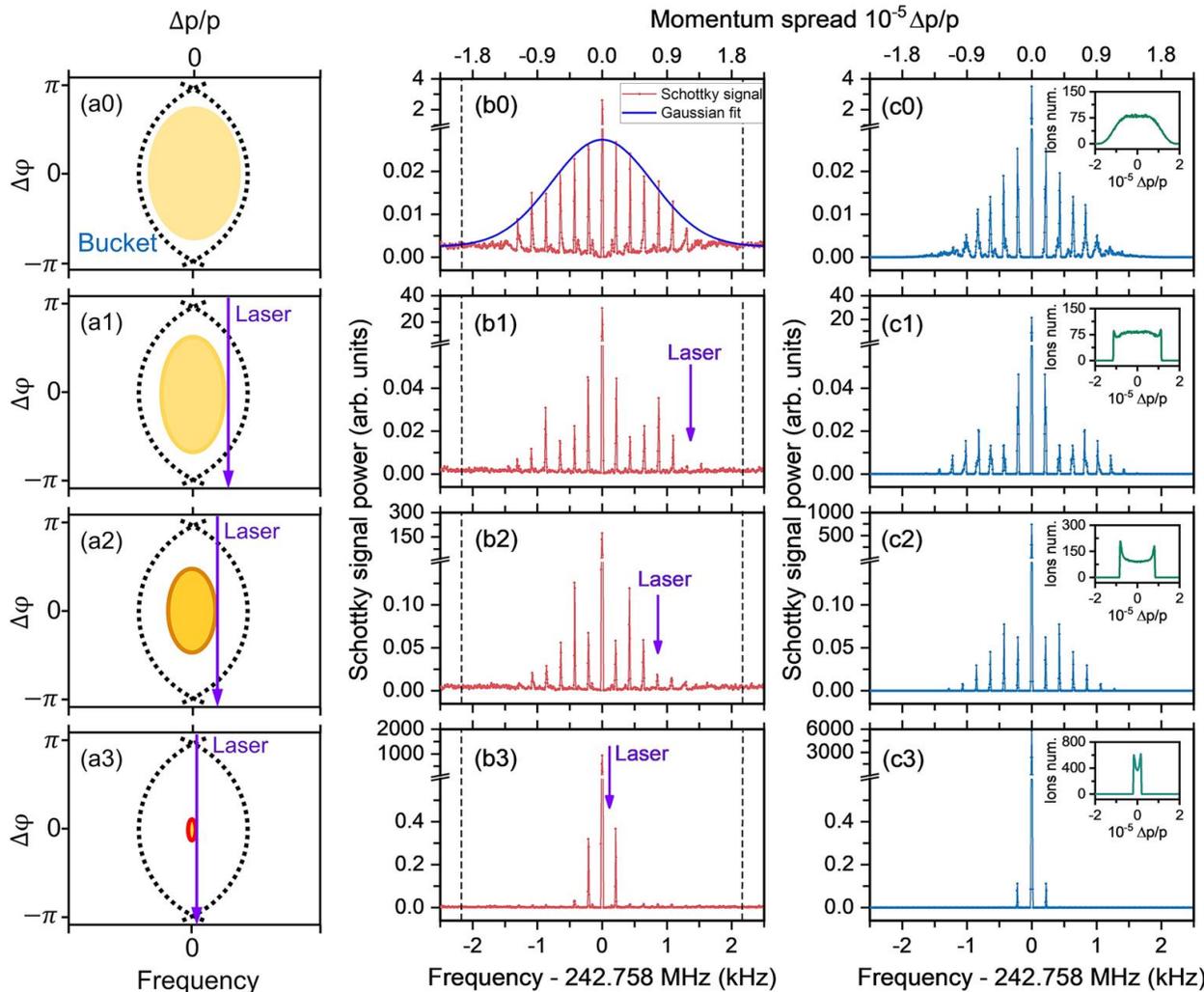## Relativistic coasting beams need more than lasers

How to laser cool (relativistic) ion beams

Betatron oscillations broaden the effective laser force acceptance

How to laser cool (relativistic) ion beams

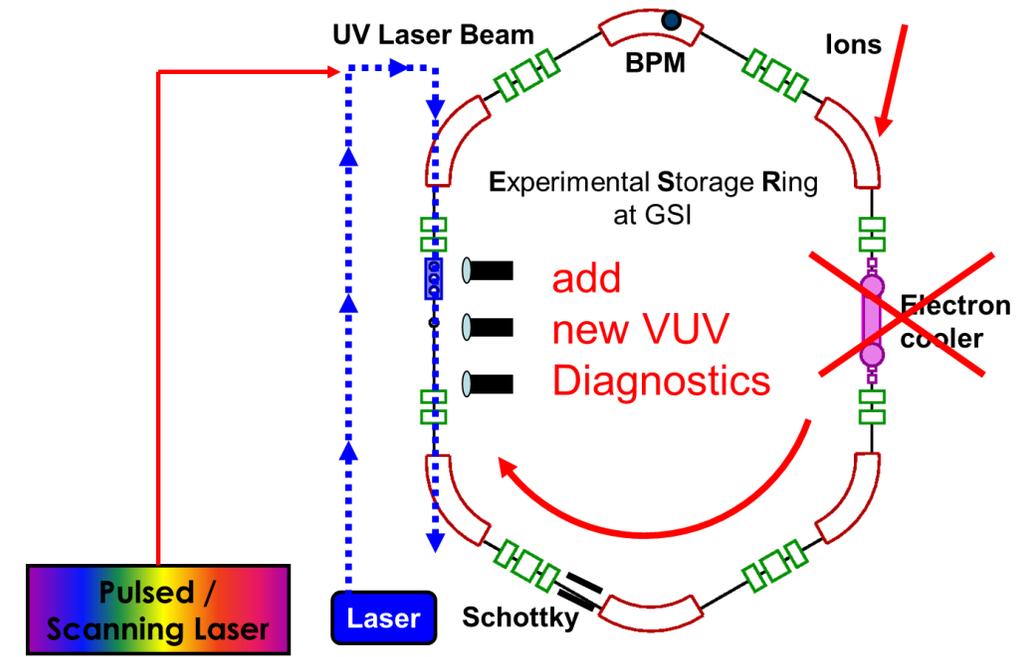## Using the bucket force on a bunched beam to counteract the laser force

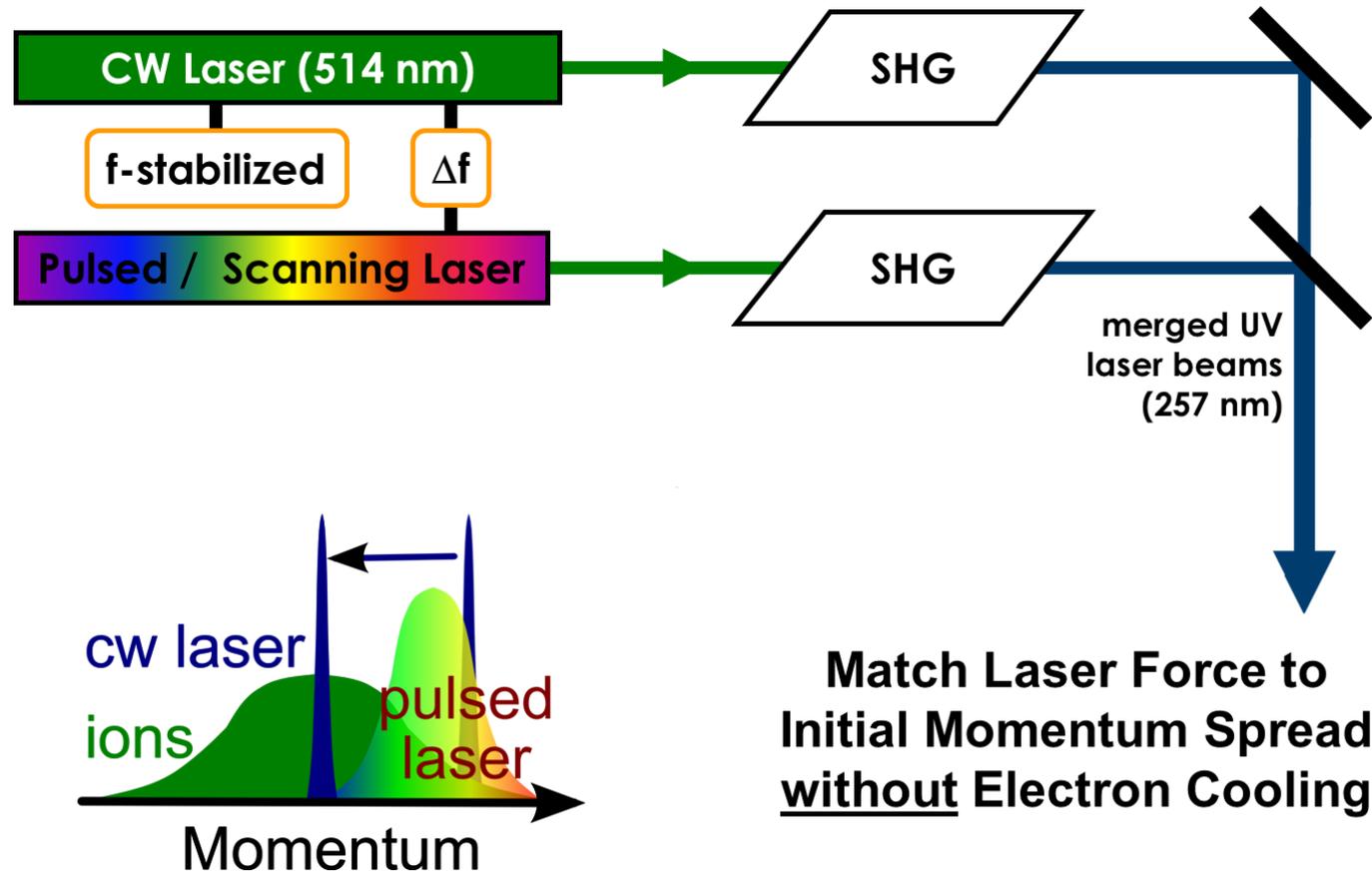$$\Delta f_{scan} = \frac{\beta}{2} \frac{\Delta p_{ion,hot}}{p_{ion}} \frac{c}{\lambda_{trans}}$$

$$= \frac{\beta}{2} \frac{\Delta p_{ion,hot}}{p_{ion}} \frac{c}{(1+\beta)\gamma} \frac{1}{\lambda'_{trans}}$$

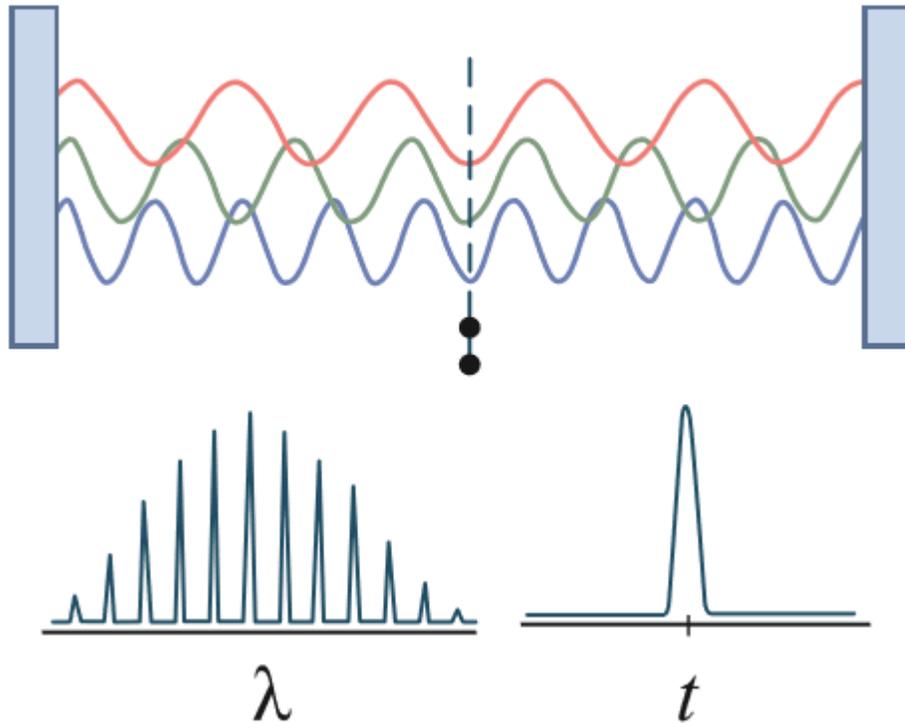(detuning range in lab. frame needed to cool an ion beam with a given momentum spread)

How to laser cool (relativistic) ion beams

Using pulsed lasers for broadband cooling of ion beams

How to laser cool (relativistic) ion beams

A pulsed laser is many cw lasers working in parallel

$$\Delta f_{BW} = \frac{\beta}{2} \frac{\Delta p_{ion,hot}}{p_{ion}} \frac{c}{(1+\beta)\gamma} \frac{1}{\lambda'_{trans}}$$

(bandwidth of laser pulse needed to cool ion beam)

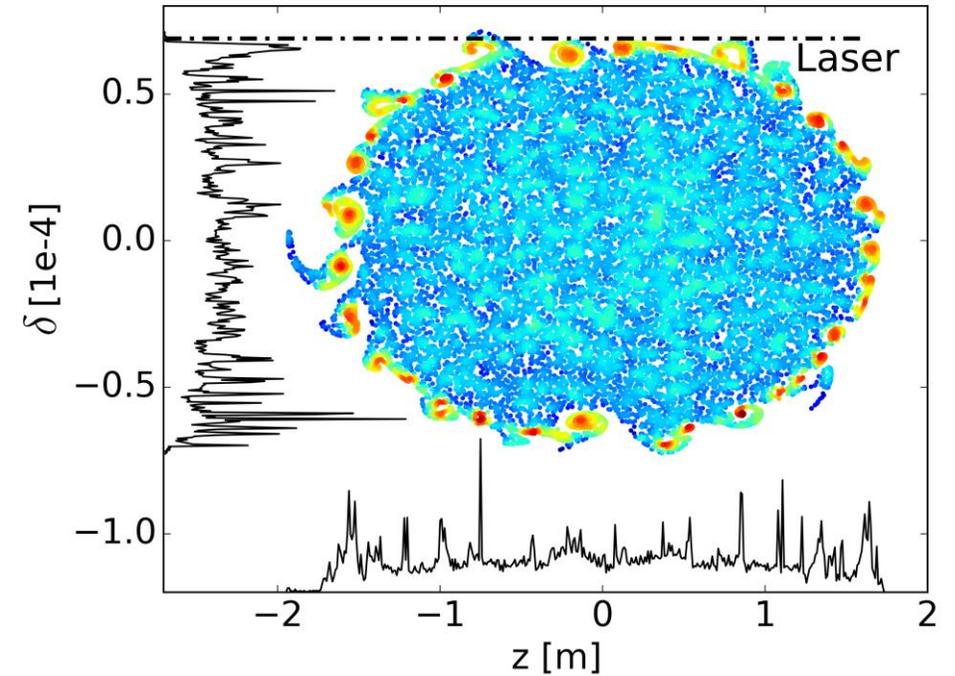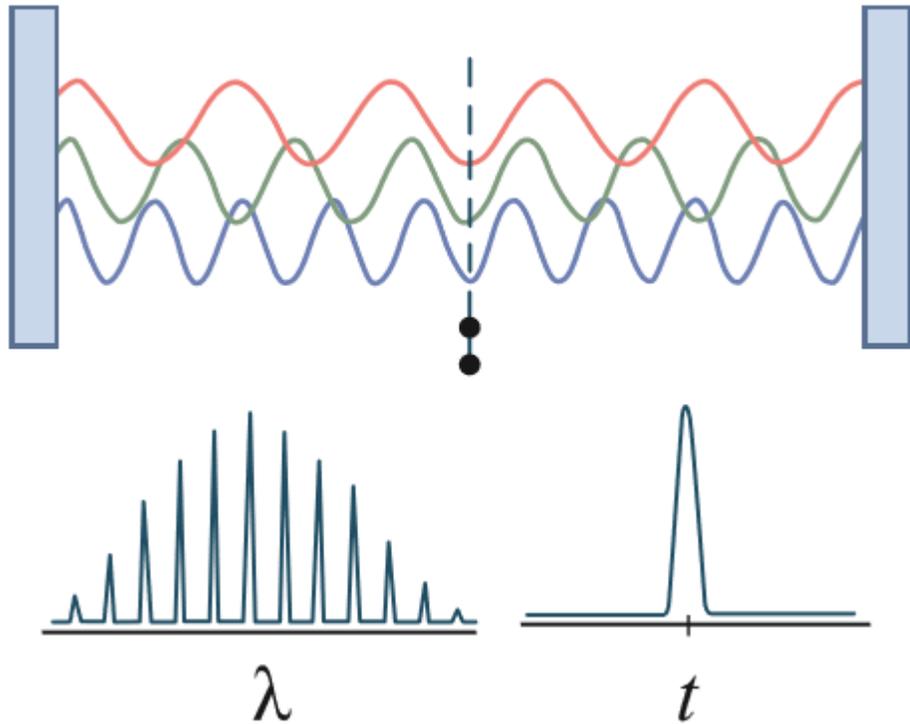$$\tau_{pulse} = \frac{2s_{tb} p_{ion} (1+\beta)\gamma \lambda'_{trans}}{\beta c \Delta p_{ion,hot}}$$

(laser pulse duration)

$$\Delta f_{BW} \tau_{pulse} = s_{tb} \approx 0.5$$

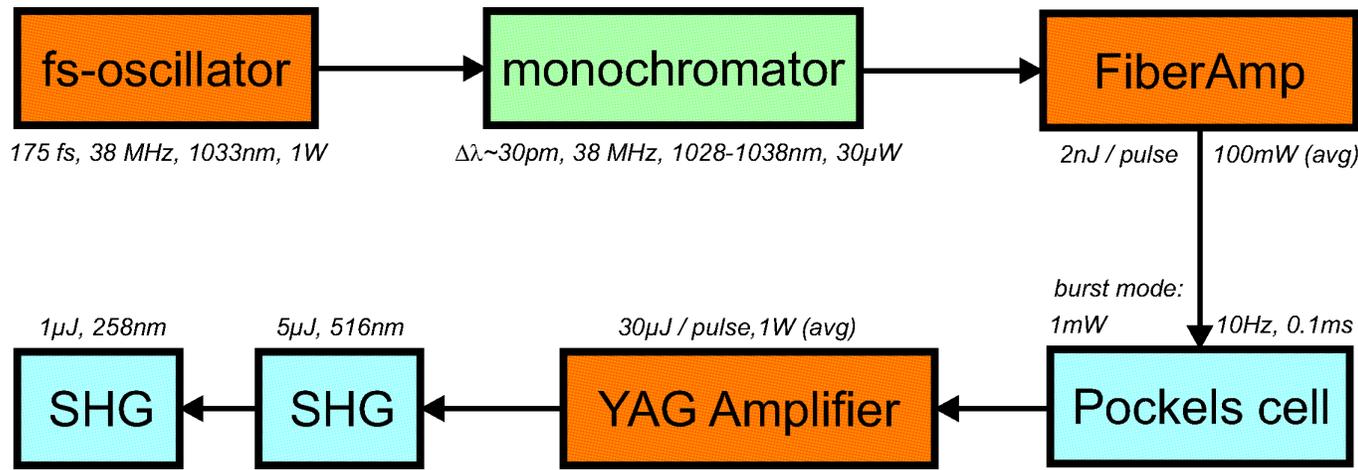# How to laser cool (relativistic) ion beams

Pulsed laser cooling prevents instabilities for intense ion beams

PhD Thesis Lewin Eidam

For intense beams pulsed laser cooling also prevents the microwave instability predicted for cw laser cooling

How to laser cool (relativistic) ion beams

Intensity and average power of pulsed laser system

fs-oscillator	→	monochromator	→	FiberAmp

175 fs, 38 MHz, 1033nm, 1W   Δλ~30pm, 38 MHz, 1028-1038nm, 30µW   2nJ / pulse   100mW (avg)

burst mode:
1mW   10Hz, 0.1ms

SHG	←	SHG	←	YAG Amplifier	←	Pockels cell

1µJ, 258nm   5µJ, 516nm   30µJ / pulse,1W (avg)

$$\Phi_{sat} = I_{sat}\tau_{trans} \qquad \text{(fluence at saturation)}$$

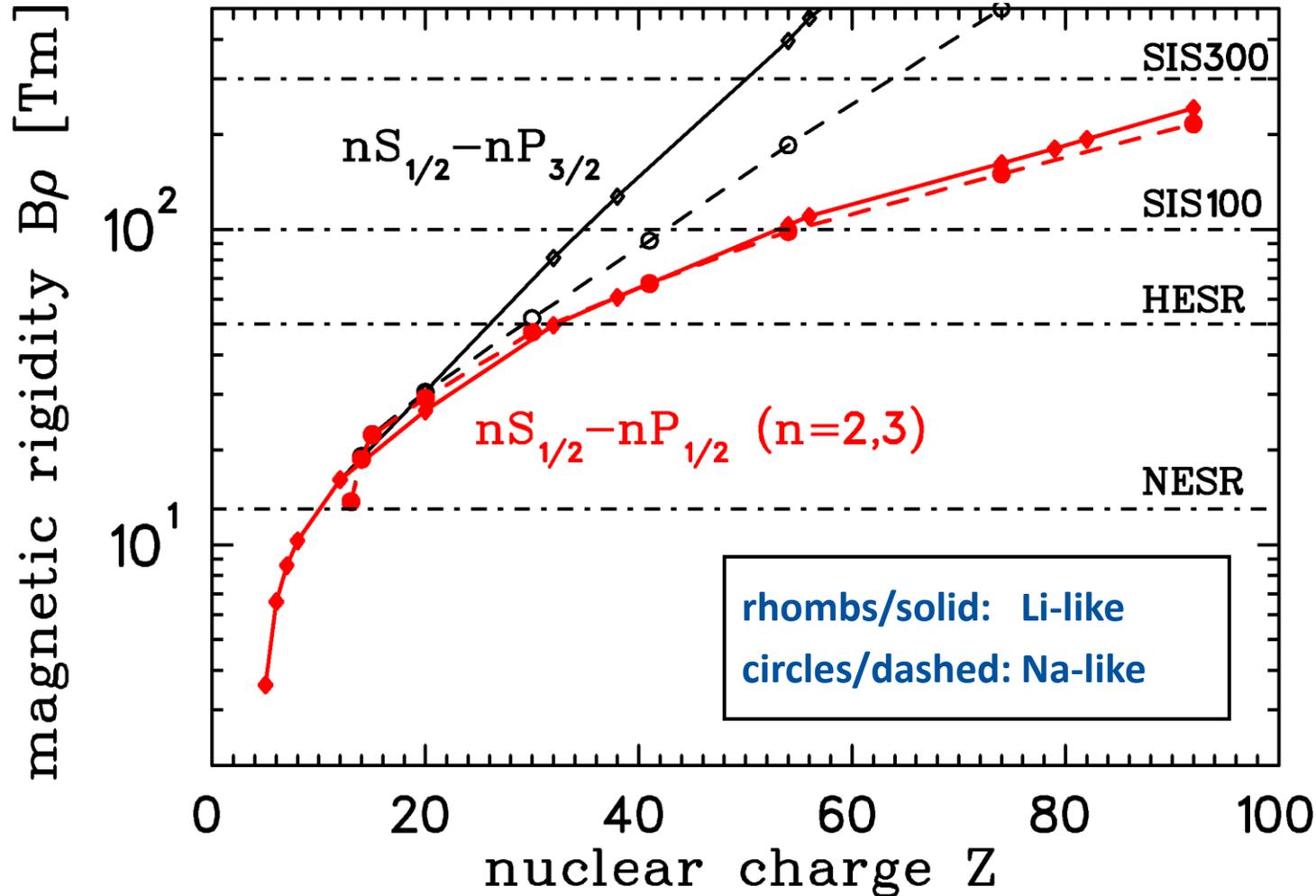$$P_{peak} = E_{pulse} / \tau_{pulse} \qquad \text{(peak intensity)}$$

$$E_{pulse} = \pi w_{laser}^2 \Phi_{sat} \qquad \text{(pulse energy)}$$

$$I_{peak} = P_{peak} / \left(\pi w_{laser}^2\right) = I_{sat}\Delta f_{BW} / \left(s_{tb}\Gamma_{trans}\right) \qquad \text{(peak laser intensity)}$$

$$P_{av} = E_{pulse}R_{rep} \leq \pi w_{laser}^2 I_{sat}\tau_{trans}N_{bunch}f_{rev} \qquad \text{(average laser power)}$$

How to laser cool (relativistic) ion beams

Towards high ion beam energies and highly charged ions

$$F_{laser,\max} = h\Gamma_{trans} / (2\lambda_{laser})$$

$$\overset{\gamma=\gamma_{res}}{\propto} Q^2 \propto \gamma_{res}$$

(maximum laser force in laboratory frame)

$$T'_{Doppler} \propto m'_{ion} \lambda'^2_{trans} \tau'^{-2}_{trans} \propto Q$$
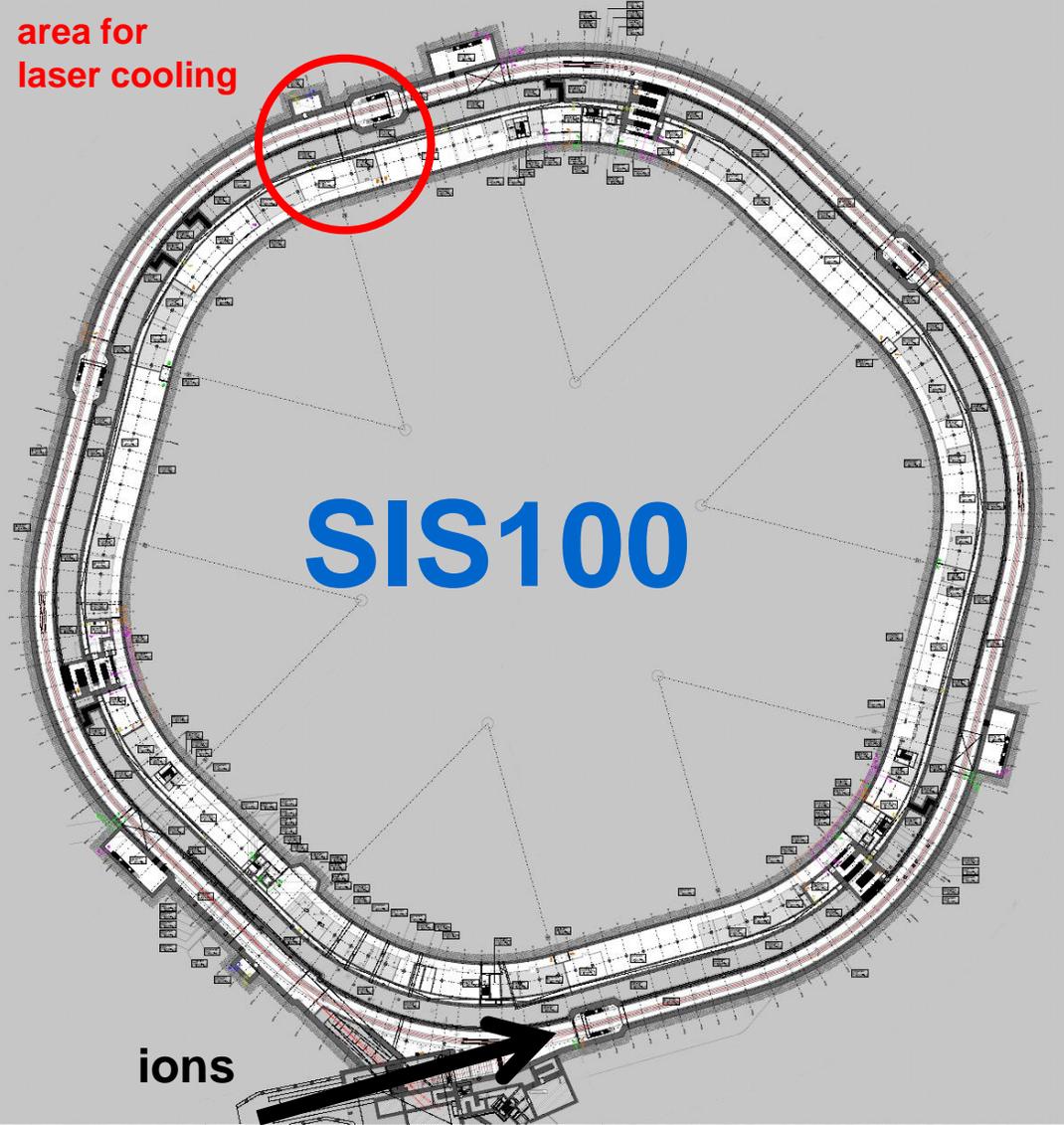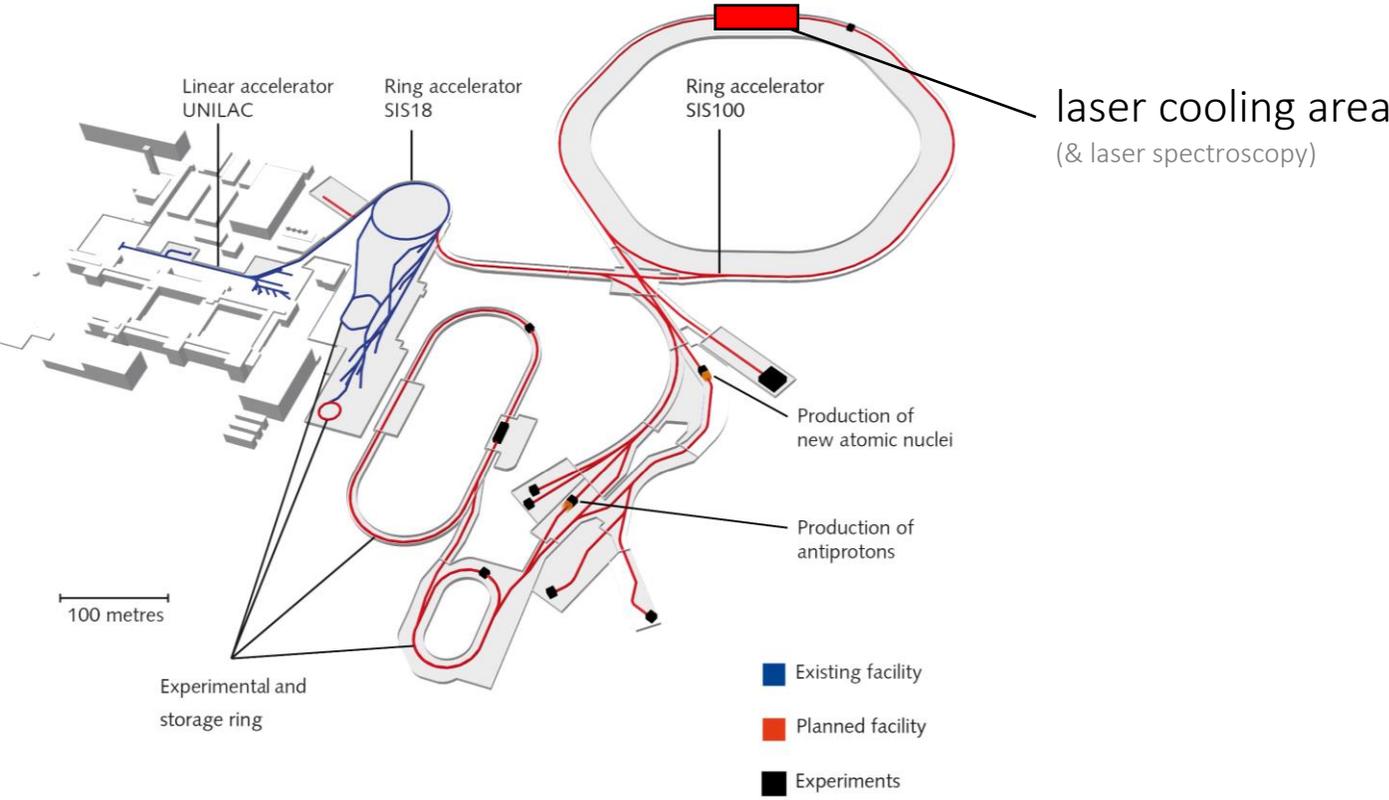
(minimum temperature in rest frame)

Example:
Li-like U^{89+} at $\gamma=25.86$ means scattering of roughly 4 photons per turn
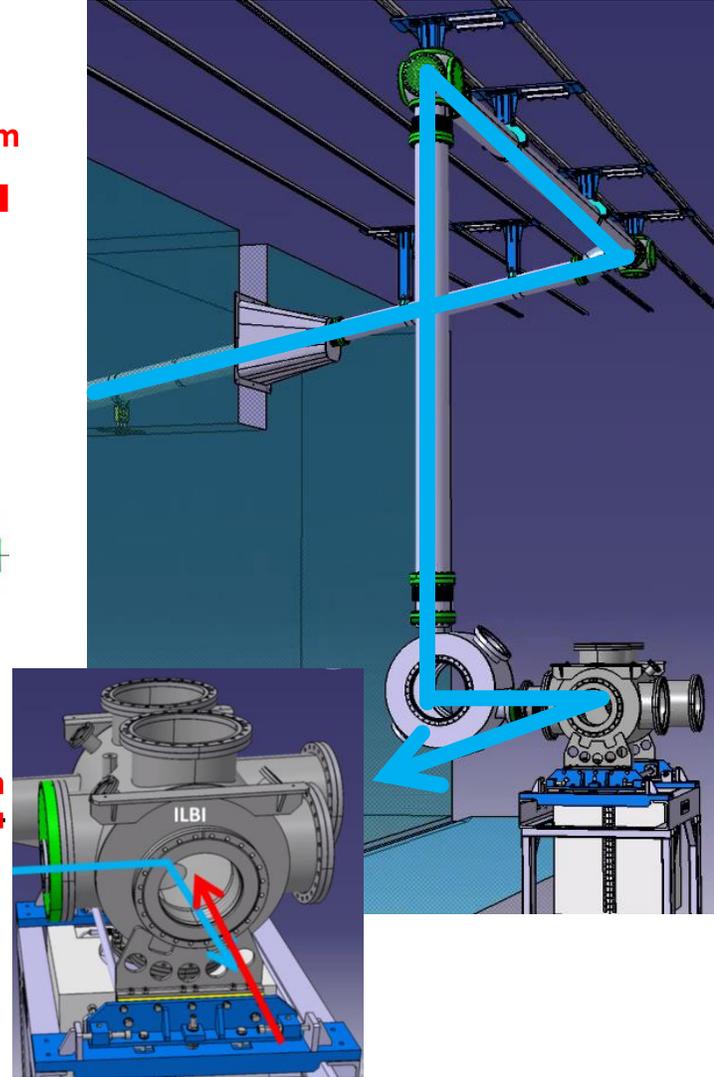
Laser cooling at SIS100
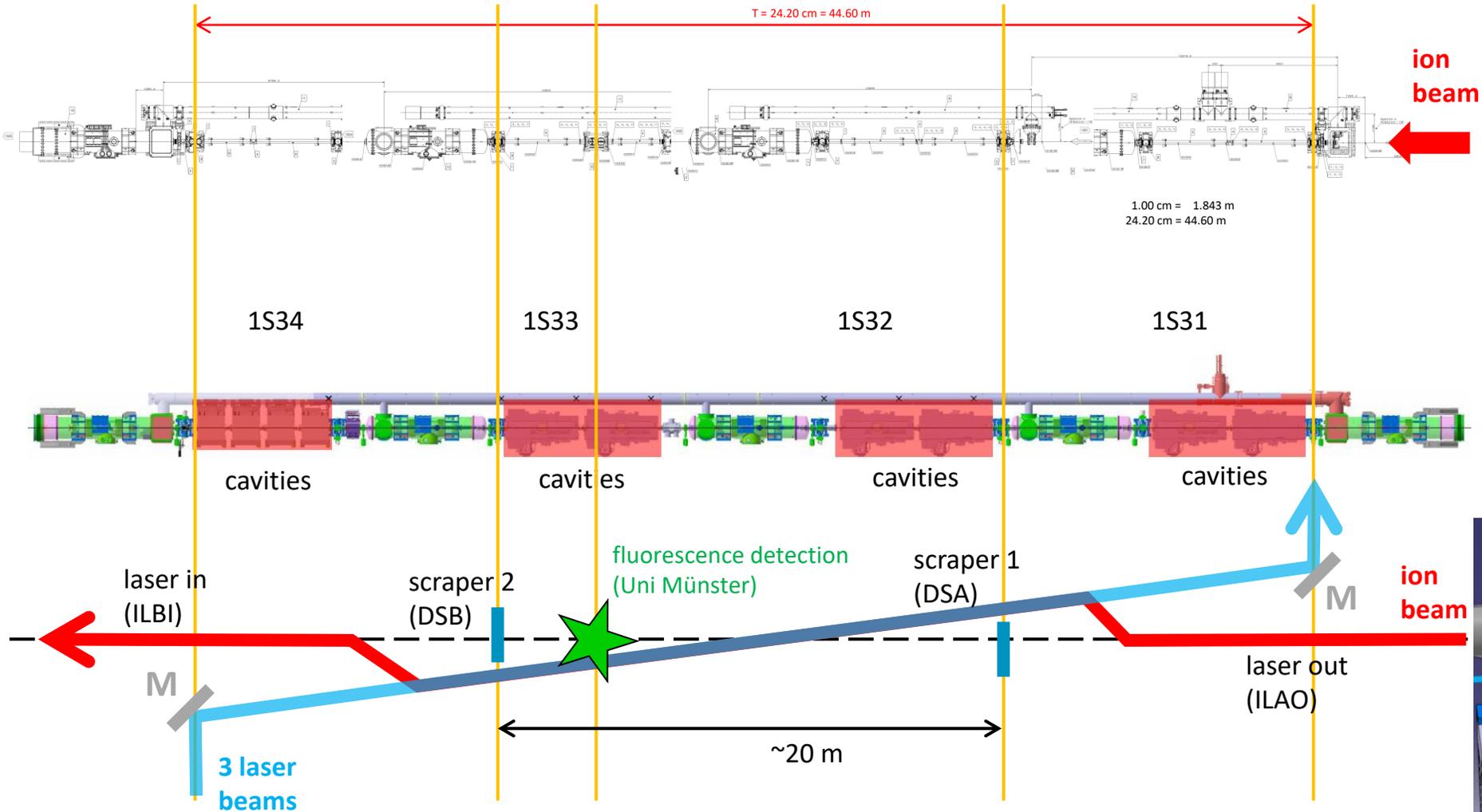
A dedicated laser cooling infrastruture

laser cooling area
(& laser spectroscopy)

Laser cooling at SIS100

20m overlap vs. 1084m circumference (2%, 277,000 times a second)

Laser cooling at SIS100

The SIS100 laser cooling collaboration

Michael Bussmann (Helmholtz-Zentrum Dresden – Rossendorf, CASUS)

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Benedikt Langfeld (TU Darmstadt)

Ulrich Schramm (Helmholtz-Zentrum Dresden – Rossendorf)

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Dr Mathias Siebold (Helmholtz-Zentrum Dresden – Rossendorf)

Dr Peter Spiller (GSI Helmholtzzentrum für Schwerionenforschung GmbH(GSI))

Thomas Stöhlker (GSI Helmholtzzentrum für Schwerionenforschung GmbH(GSI))
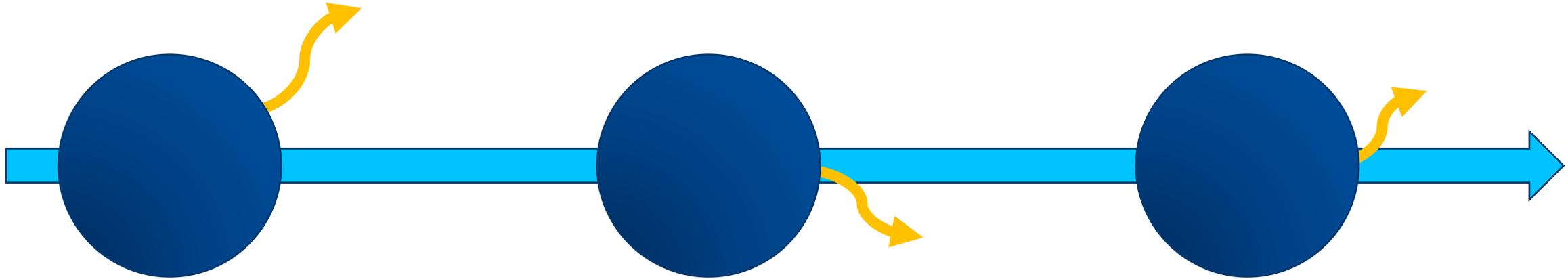
Ken Ueberholz (Universität Münster(UMs-IKP))

Thomas Walther (TU Darmstadt)

Danyal Winters (GSI Helmholtzzentrum für Schwerionenforschung GmbH(GSI))
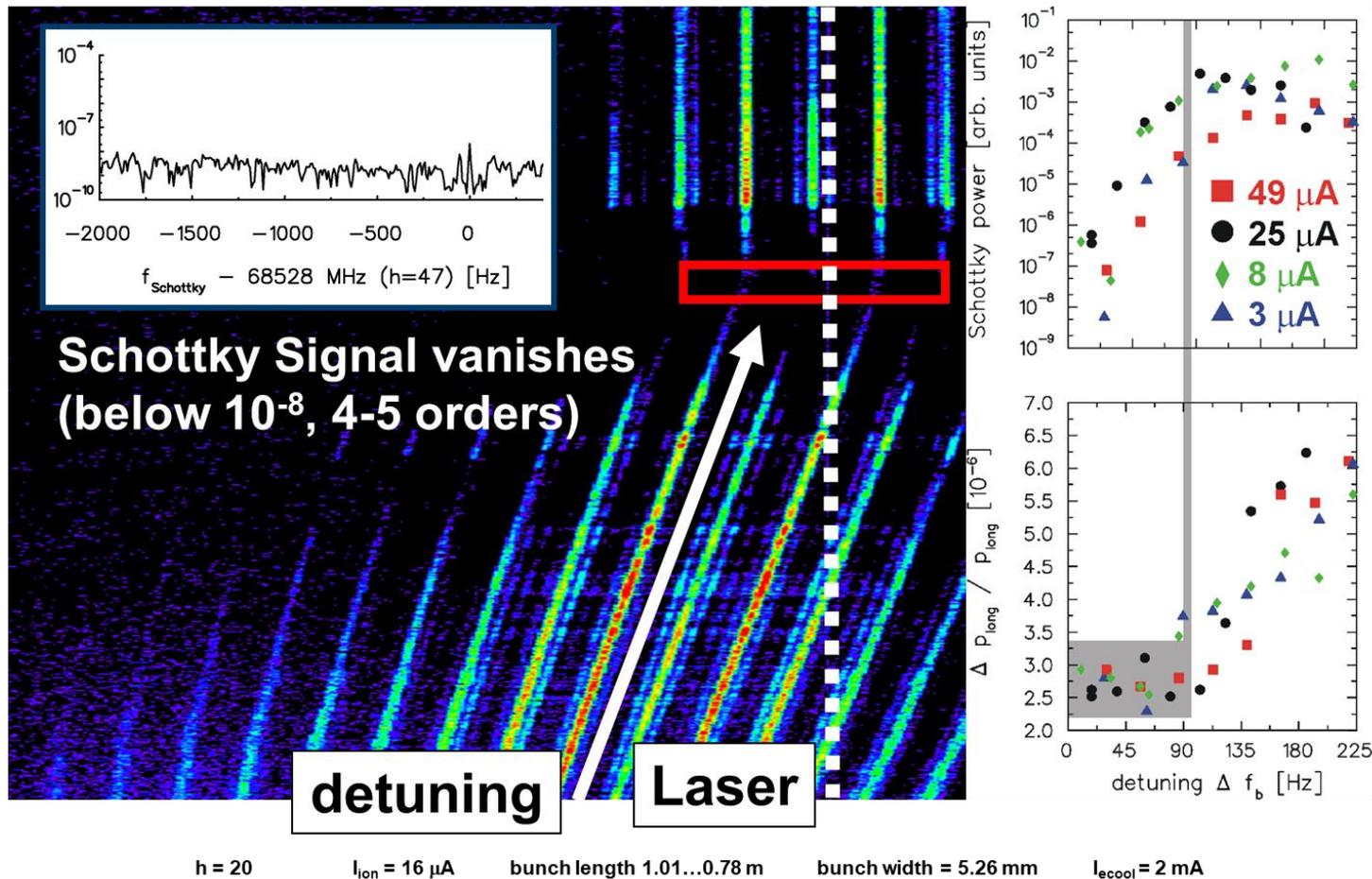
Fun with fluorescence
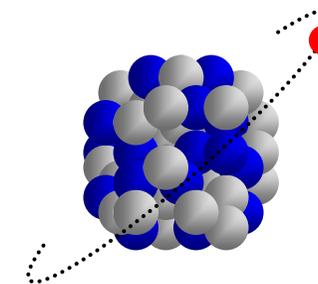## Photon time of flight

- Depends on orbit, at best transversally cold beam

- Depends on lifetime, at best the lifetime is much shorter than one roundtrip

- Few photons in a single roundtrip, so must accumulate – beam lifetime, magnet stability

- Larger ion distances help, so shallow buckets should help

- Synchronization of laser pulse and bunching could make photon arrival correlations visible

Why cooling relativistic ion beams with lasers is fun
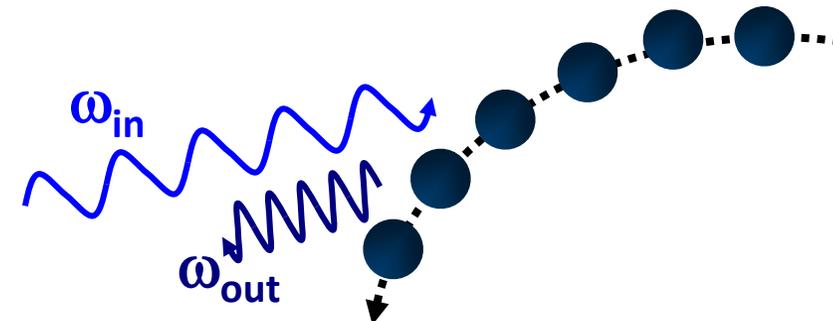
Precision spectroscopy meets ultracold ion beams

Schottky Signal vanishes (below 10^{-8}, 4-5 orders)

detuning   Laser

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

Transition wavelengths for HCI known with less than 10^{-4} precision

Intrinsic Properties of heavy, 'few-electron' Ions

Measure absolute transition wavelength

$$\omega^2_{rest} = \omega_{laser} \cdot \omega_{X\text{-}ray}$$

ω_{in}

ω_{out}

Lorentz transformation