Cooling of relativistic heavy ion beams

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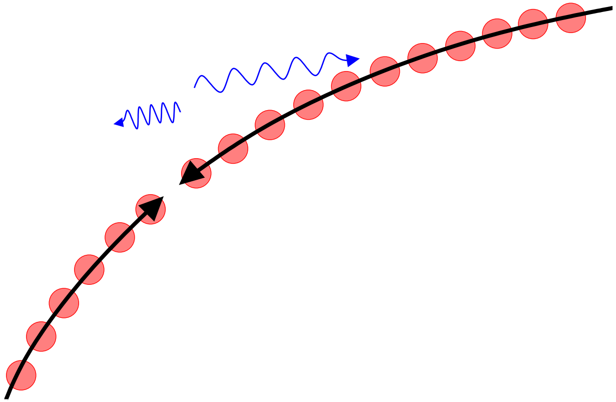
in collaboration with the atomic physics group of GSI

Workshop on Atomic Physics Research at the Future GSI Facility 12/2002

http://www.ha.physik.uni-muenchen.de/uschramm/



- *Motivation*
  (relativistic crystalline beams)
- *Status of present experiments*
  (low energy)
- *Near future plans (at ESR)*
- *Cooling techniques and ideas*

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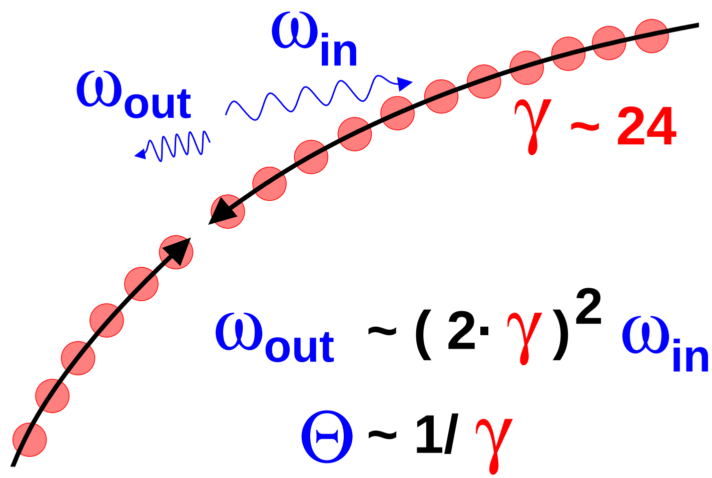
Motivation

- **Crystalline beams at relativistic energies:**

  a) improved phase space density (x 10^6 ?)

  b) intriguing scattering properties

  - ***x−ray emission (photon scattering)***
  - ***forward emission***
  - ***Mößbauer−like recoil free (?)***
  - ***pulse compression***



- **Crystalline beams of exotic species:**

  a) improved phase space density (x 10^6 ?)

  - ***collider applications for radioactive beams ?***

- **Technical aspects of large rings:** ***c) high tune, high periodicity***

  - ***favourable for beam crystallization***

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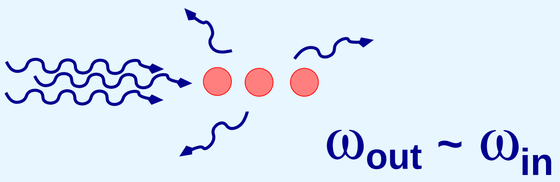
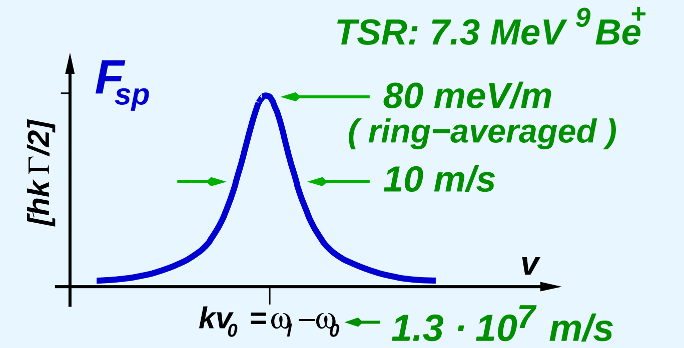
Laser cooling of non−relativistic beams

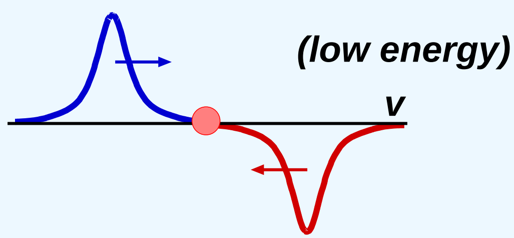
non−relativistic regime





- ***Longitudinal acceleration***
- ***Doppler tuned Lorentzian velocity dependence***
- ***Diffusive transverse heating***

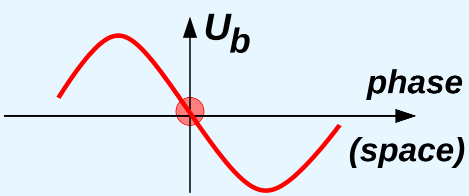
Second counter−propagating laser :

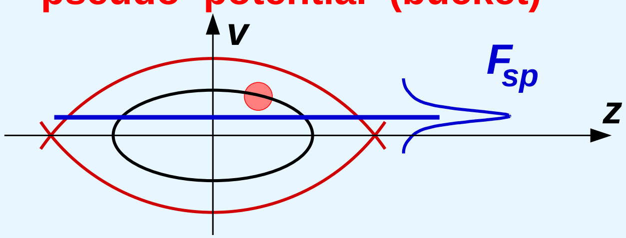


- ***Force of counter−propagating laser beam counteracted by bunching force −> dissipative force and recycling***

synchronous velocity $v_s = C \cdot f_b / h$

pseudo−potential (bucket)





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The rf quadrupole storage ring

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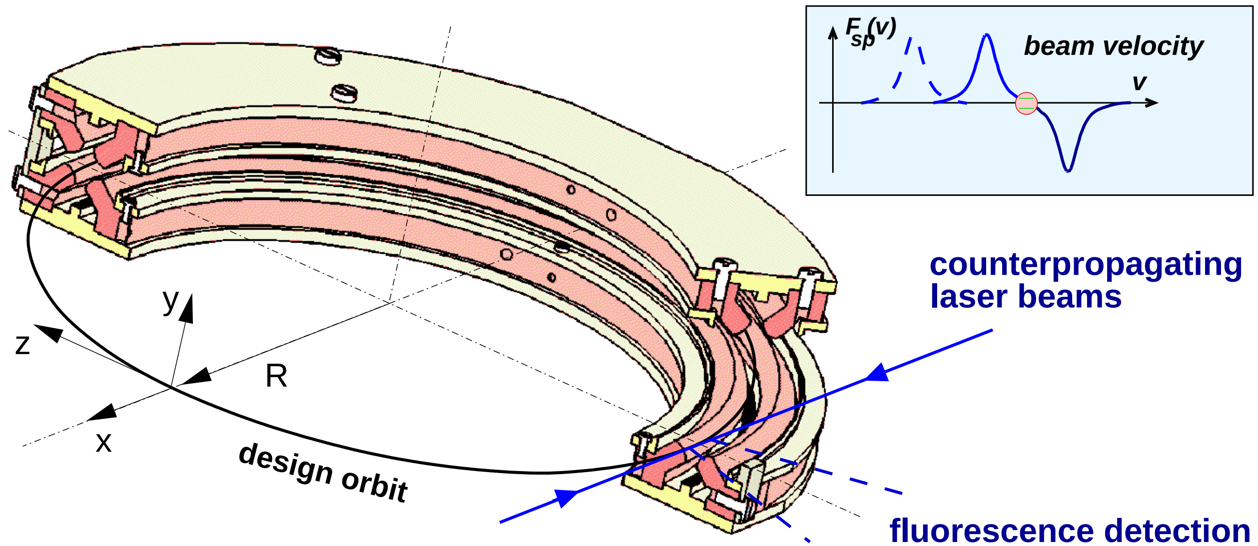
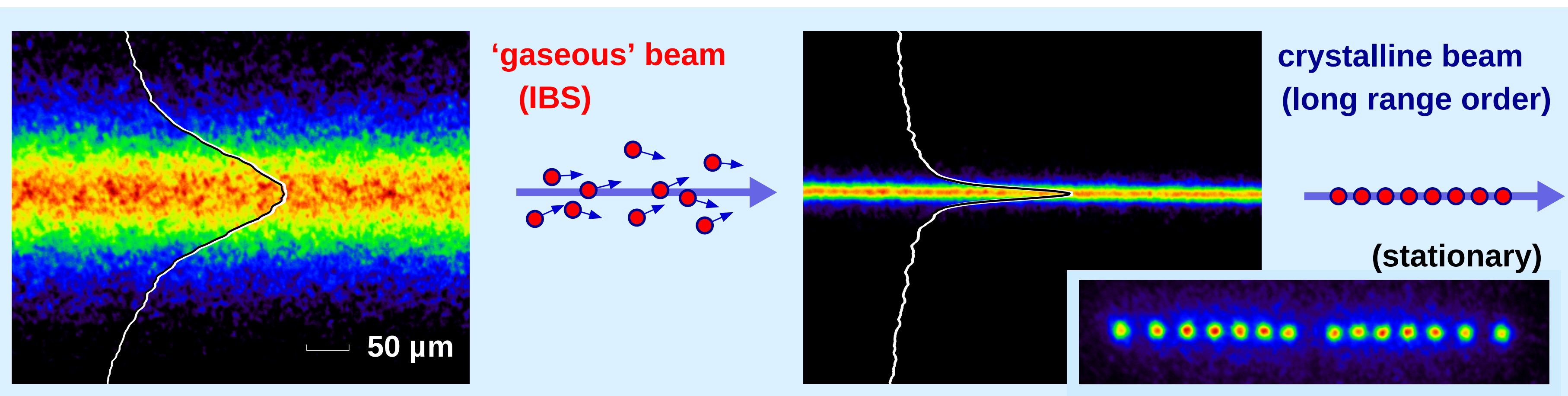
Beam energy : ~eV

Radius: 57 mm

Tune: ~50

Periodicity: ~800





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"intense" crystalline beams
focusing conditions

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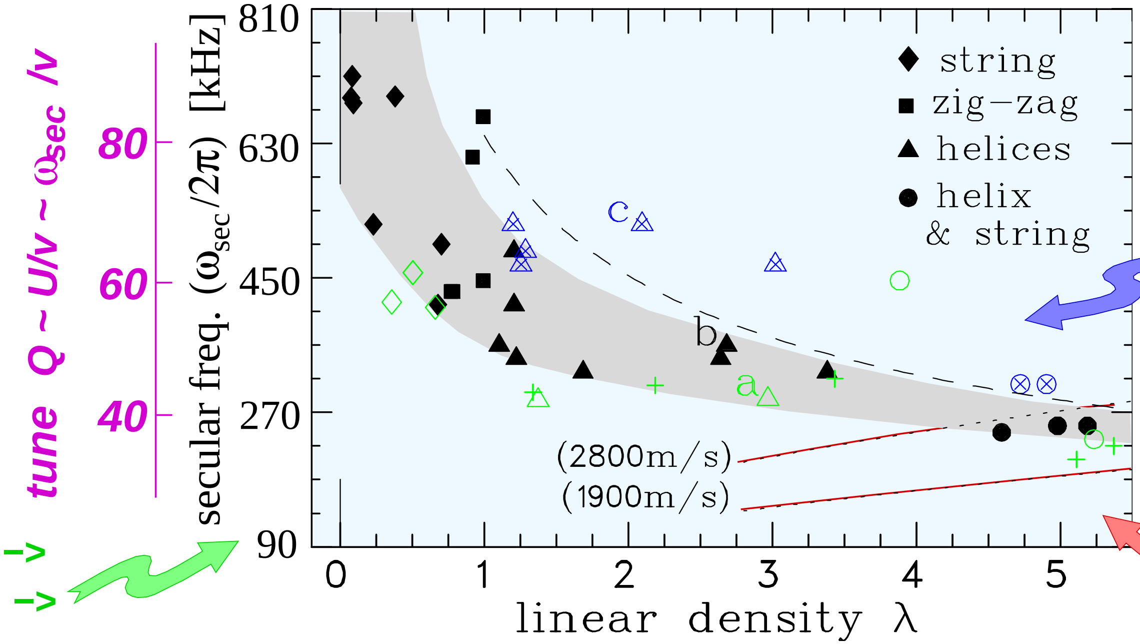
reduced coupling for lower – dimensional structures

–> stronger confinement required

far earlier than bullk mode excitation is expected

(P > 2·$\sqrt{2}$ ·Q)



coupling of micro–motion into thermal energy

$\Gamma_{app} \sim 1/\lambda \cdot (P/Q)^2$

(Schiffer 1995)

weak focusing ->
weak coupling ->
insufficient sympathetic cooling

($Q^2 > 250 \cdot \lambda$)

the influence of (velocity dependent) bending shear comes into reach

- *no principle arguments prohibit the crystallization*
- *direct transverse cooling should allow crystalline beams in a wider range*

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Laser cooling and heating
of crystalline beams

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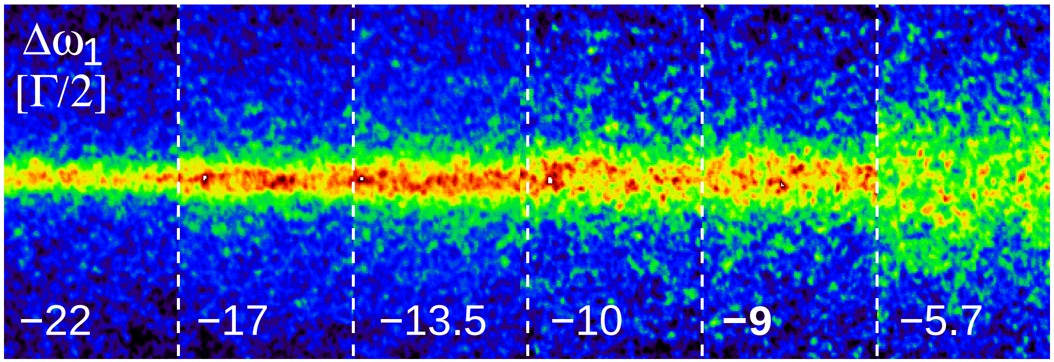

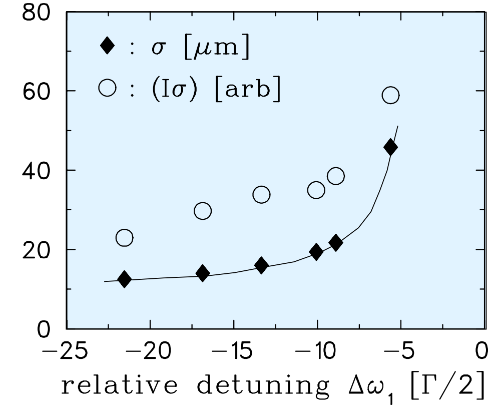

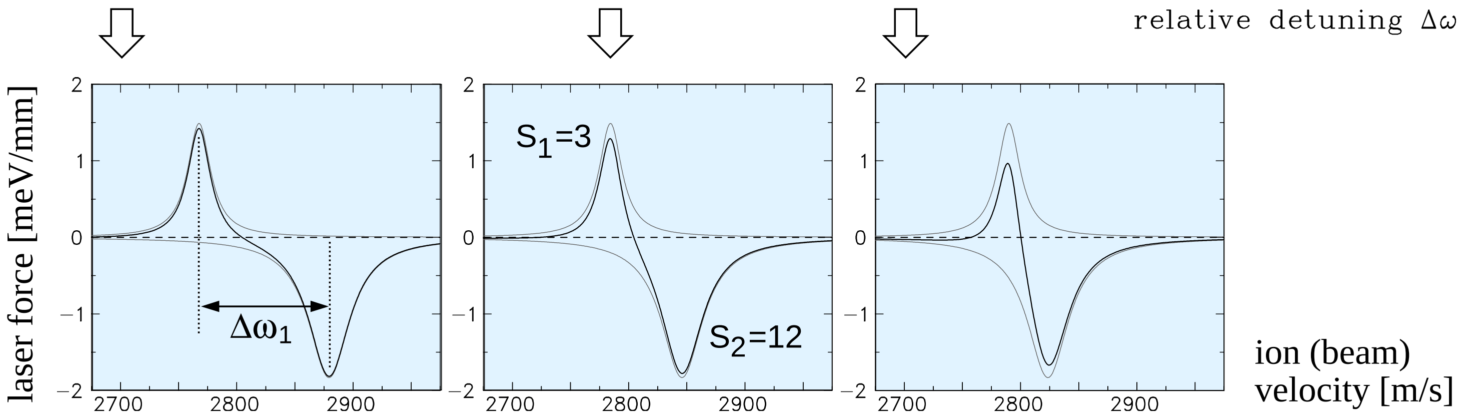

Tuning the cooling laser too close to resonance leads to an increase in the beam radius

velocity diffusion (3D) ~ scattering rate <−> cooling rate (1D) ~ force gradient

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Bunched ion beams
spatial profiles (dilute bunched beams)

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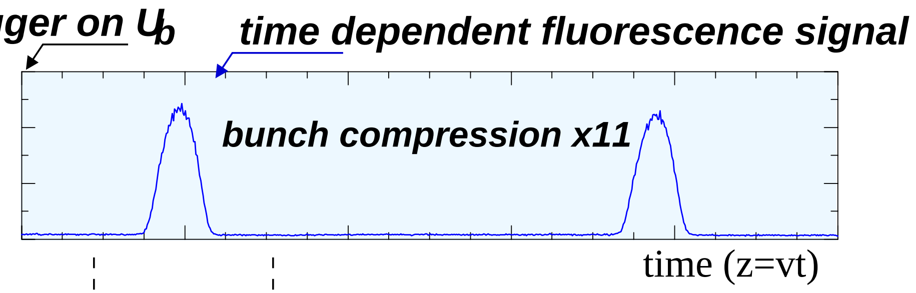
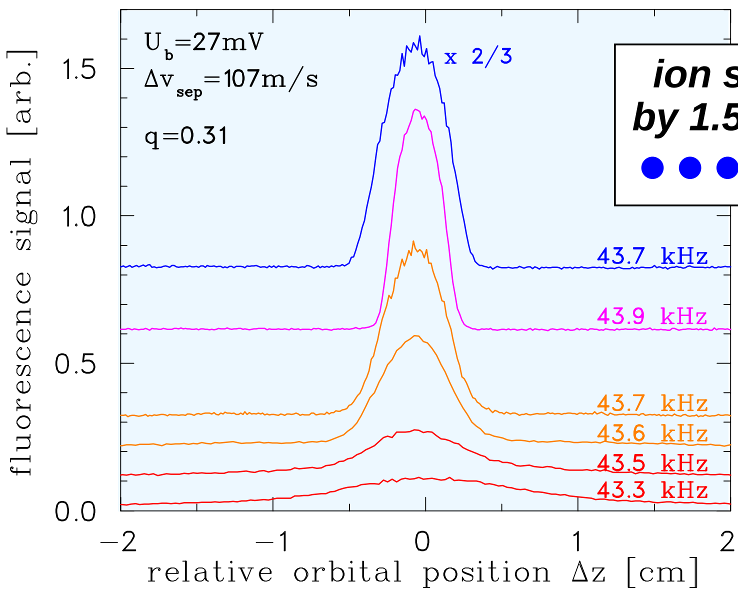


N ~ 3000 ions
a ~ 7.6 μm
$\bar{\lambda}$ ~ 0.5 (full width)

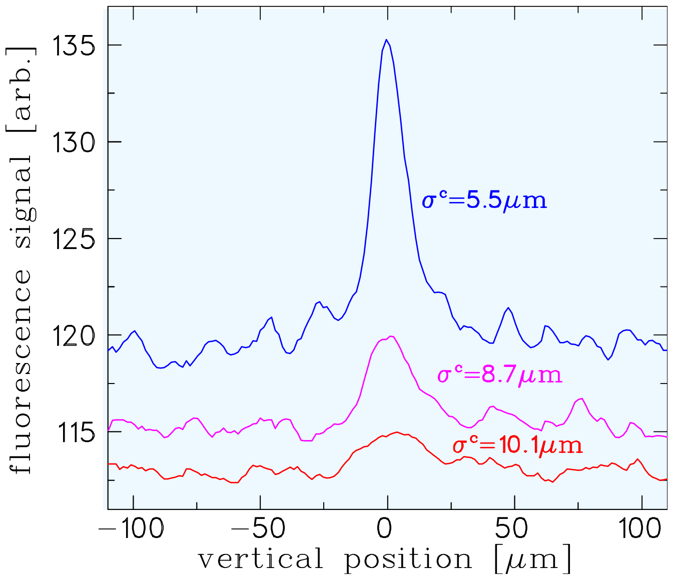
varied detuning (cooling strength)

longitudinal profiles



ion string longer by 1.5 and brighter

corresponding transverse profiles



crystalline bunches are shorter by a factor of two to three compared to the usual space charge dominated bunches (neglecting correlations)

!

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What have we learned so far ...

✓ **no fundamental arguments against crystallizing an ion beam found (crossing of resonances when betatron motion is frozen out)**

- ***reduce heating in gaseous phase :*** ***'smooth' lattice, minimize envelope modulation***
- ***stabilize crystalline beam :*** ***high betatron (secular) frequency, tight focusing but at high periodicity (P >> Q)***

⤷ ***large synchrotrons seem very favourable (SIS 200)***

- ***provide strong transverse cooling*** ***(in addition to the longitudinal)***

⤷ ***(dispersive cooling)***

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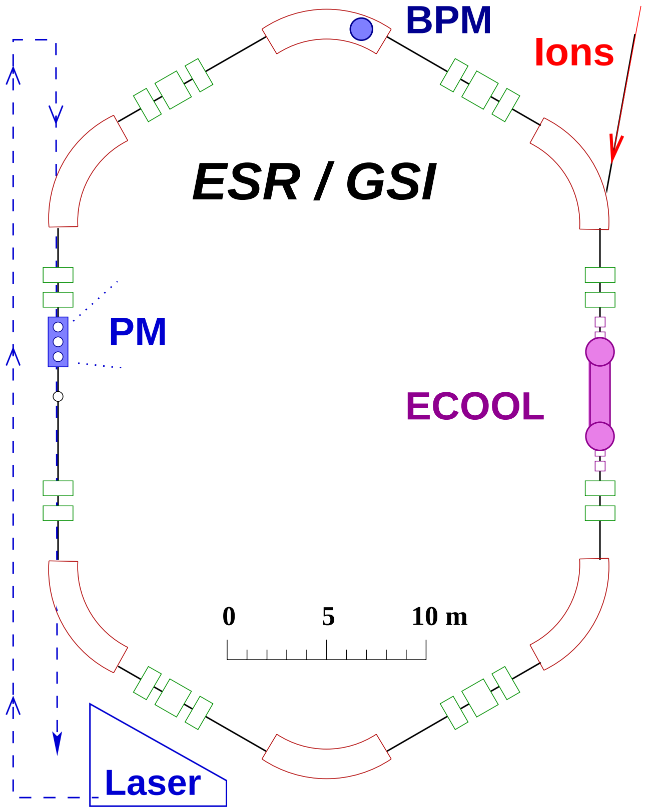
Cooling of C^{3+} beams at the ESR

Lithium-like C^{3+} ions:

λ ~155 nm Doppler-shifted to

~514/2 nm at β ~0.47 (120 MeV/u)

(existing laser technology)



- ***Motivating experiments by M. Steck***
- ***Simultaneous (transverse) electron and (longitudinal) laser cooling***
- ***Higher charge state facilitates beam crystallization***
- ***First step towards relativistic beams***

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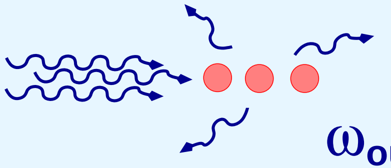
Laser cooling of relativistic beams

non–relativistic regime



$\omega_{out} \sim \omega_{in}$

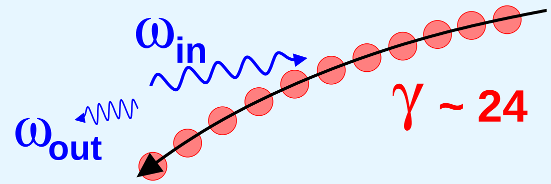
Longitudinal acceleration

Diffusive transverse heating

Doppler tuned Lorentzian velocity dependence

Counteracted by bunching force
–> dissipative force and recycling

relativistic regime



$\omega_{out} \sim (2 \cdot \gamma)^2 \, \omega_{in}$

$\Theta \sim 1/\gamma$

- **Forward emission, large energy shift**

  –> energy transfer large ($\hbar\omega_{out}$)
  –> less diffusive heating
  –> Li–like heavy ions

comparison of typical parameters:

photon energy [eV]	**5 – 5.1 – 5.2**	**5 – 240 – 11,500**	
lifetime [ns]	**4**	**0.002**	$(\sim\gamma^{-2})$
cooling force [eV/m]	**1**	**100,000**	$(\sim\gamma^{3})$
energy spread [lab]	10^{-8}	10^{-6}	D.Habs et al., ECOOL'90

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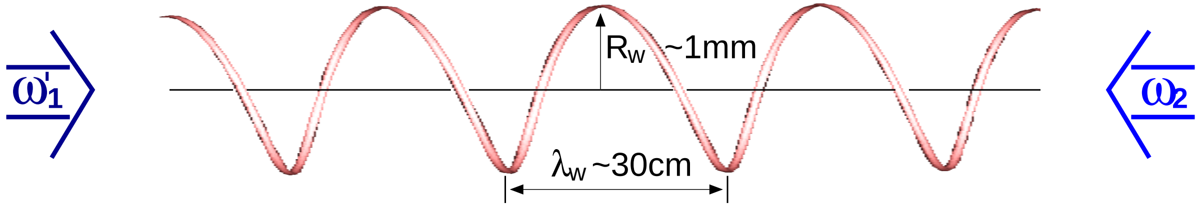
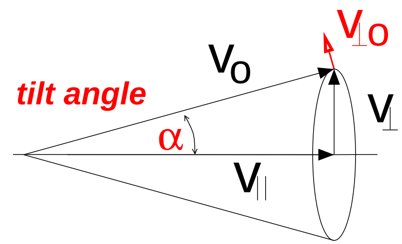
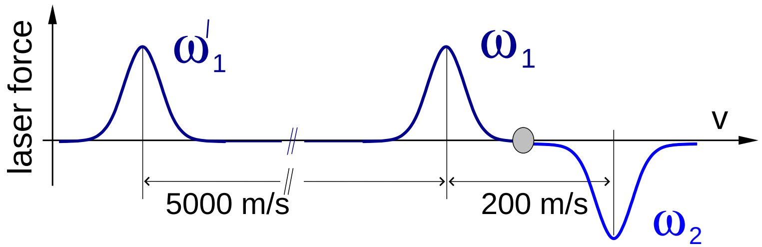
Transverse laser cooling

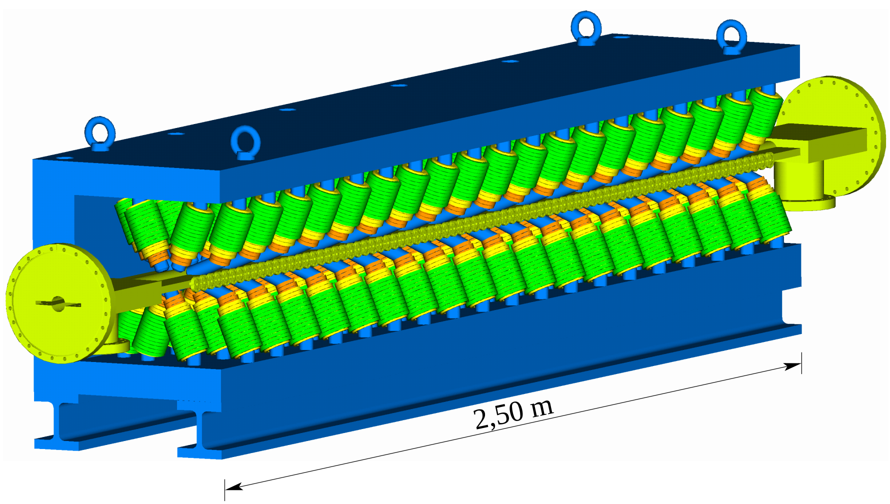
- **Spiral motion: projection of transverse motion into the direction of the beam**







simultaneous cooling of two velocity projections inside and outside the helical wiggler



this idea deserves further investigation ...

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Summary

✓ **no fundamental arguments against crystallizing an ion beam found (crossing of resonances when betatron motion is frozen out)**

- ***reduce heating in gaseous phase :*** ***'smooth' lattice, minimize envelope modulation***
- ***stabilize crystalline beam :*** ***high betatron (secular) frequency, tight focusing but at high periodicity (P >> Q)***

⤷ ***large synchrotrons seem very favourable (SIS 200)***

- ***provide strong transverse cooling*** ***(in addition to the longitudinal)***

⤷ ***laser cooling of relativistic beams seems very promising but clearly intermediate steps should be taken (at GSI)*** !