Laser cooling of calcium beam in the SPS for the high-luminosity LHC with isoscalar ion beams

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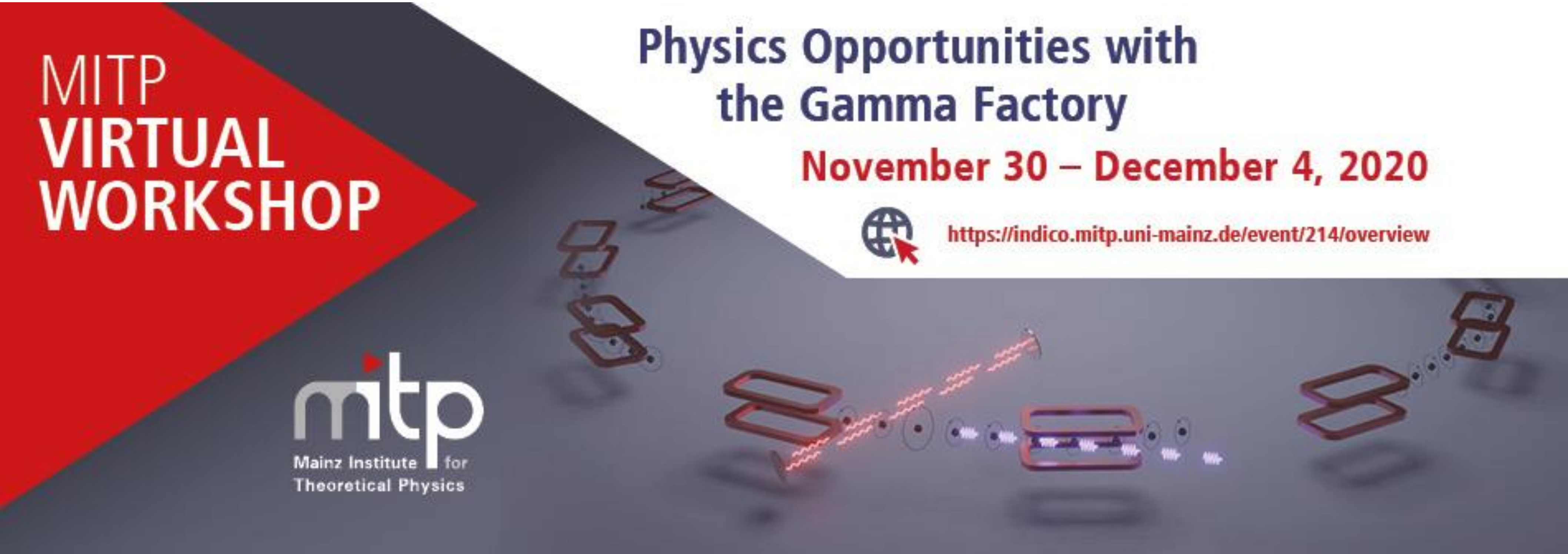

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Review

High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams☆

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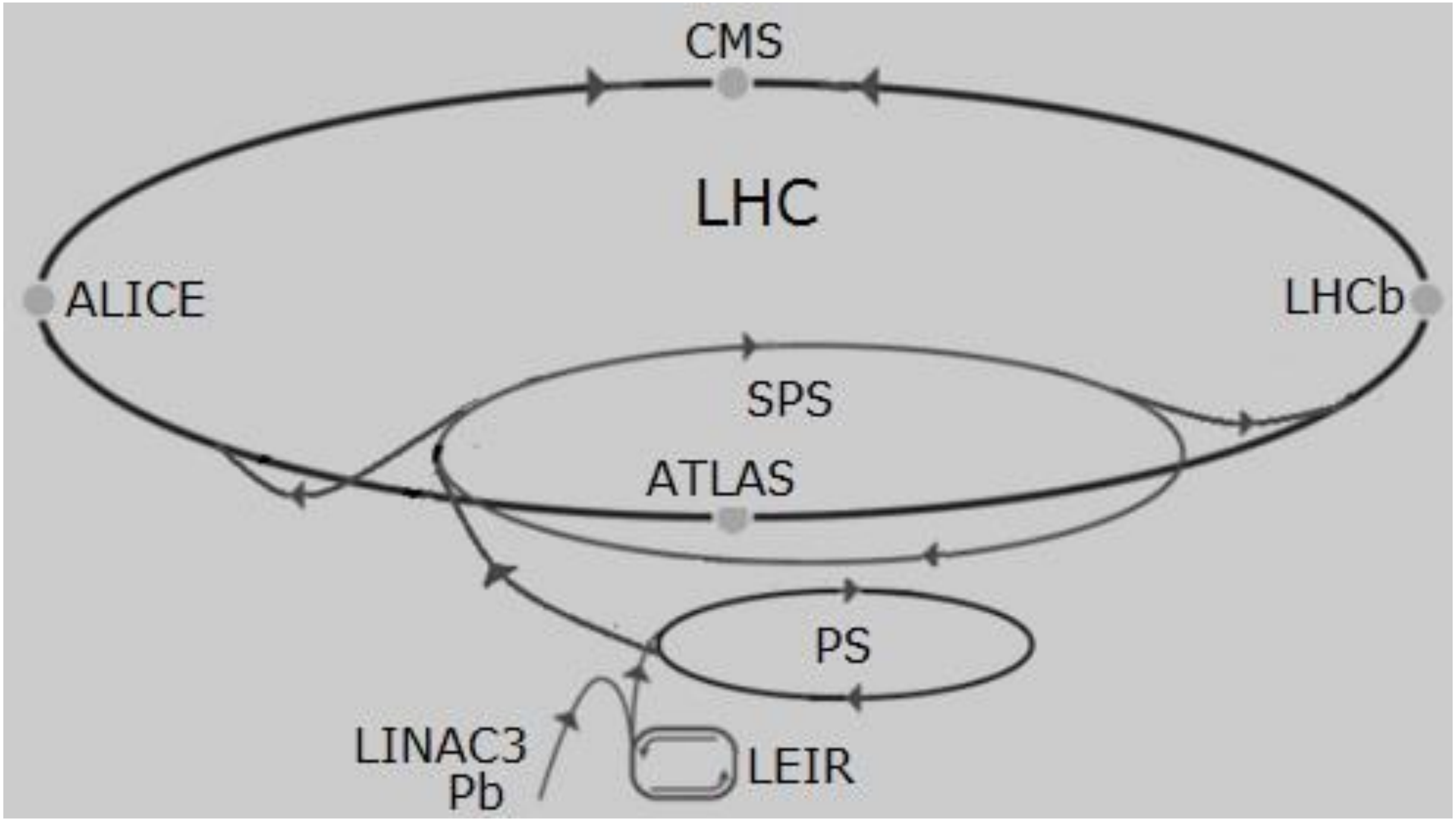
A B S T R A C T

The existing CERN accelerator infrastructure is world unique and its research capacity should be fully exploited. In the coming decade its principal *modus operandi* will be focused on producing intense proton beams, accelerating and colliding them at the Large Hadron Collider (LHC) with the highest achievable luminosity. This activity should, in our view, be complemented by new initiatives and their feasibility studies targeted on re-using the existing CERN accelerator complex in novel ways that were not conceived when the machines were designed. They should provide attractive, ready-to-implement research options for the forthcoming *paradigm-shift* phase of the CERN research. This paper presents one of the case studies of the *Gamma Factory* initiative (Krasny, 2015) – a proposal of a new operation scheme of ion beams in the CERN accelerator complex. Its goal is to extend the scope and precision of the LHC-based research by complementing the proton–proton collision programme with the *high-luminosity* nucleus–nucleus one.

ABSTRACT

The existing CERN accelerator infrastructure is world unique and its research capacity should be fully exploited. In the coming decade its principal *modus operandi* will be focused on producing intense proton beams, accelerating and colliding them at the Large Hadron Collider (LHC) with the highest achievable luminosity. This activity should, in our view, be complemented by new initiatives and their feasibility studies targeted on re-using the existing CERN accelerator complex in novel ways that were not conceived when the machines were designed. They should provide attractive, ready-to-implement research options for the forthcoming *paradigm-shift* phase of the CERN research. This paper presents one of the case studies of the *Gamma Factory* initiative (Krasny, 2015) – a proposal of a new operation scheme of ion beams in the CERN accelerator complex. Its goal is to extend the scope and precision of the LHC-based research by complementing the proton–proton collision programme with the *high-luminosity* nucleus–nucleus one. Its numerous physics highlights include studies of the exclusive Higgs-boson production in photon–photon collisions and precision measurements of the electroweak (EW) parameters. There are two principal ways to increase the LHC luminosity which do not require an upgrade of the CERN injectors: (1) modification of the beam-collision optics and (2) reduction of the transverse emittance of the colliding beams. The former scheme is employed by the ongoing high-luminosity (HL-LHC) project. The latter one, applicable only to ion beams, is proposed in this paper. It is based on laser cooling of bunches of partially stripped ions at the SPS flat-top energy. For isoscalar calcium beams, which fulfil the present beam-operation constrains and which are particularly attractive for the EW physics, the transverse beam emittance can be reduced by a factor of 5 within the 8 seconds long cooling phase. The predicted nucleon–nucleon luminosity of $L_{NN} = 4.2 \times 10^{34}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$ for collisions of the cooled calcium beams at the LHC top energy is comparable to the levelled luminosity for the HL-LHC proton–proton collisions, but with reduced pile-up background. The scheme proposed in this paper, if confirmed by the future Gamma Factory proof-of-principle experiment, could be implemented at CERN with minor infrastructure investments.

The LHC lead injector chain:



https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.lhc_pb_collisions

There are several ways to cool high-energy hadron beams

1. Synchrotron radiation cooling

For protons and ions occurs naturally at very high energies. Takes hours. For the AWAKE-like PWFA applications probably practical only starting from the energy of High-Energy LHC (a project to upgrade LHC to 12-16 TeV).

2. Optical stochastic cooling

Was seriously considered for the Tevatron. Can be applied for protons in the LHC (for luminosity leveling and beam halo control). The test experiment with electrons is under construction at Fermilab. For details see: V. Lebedev. Optical Stochastic Cooling (2012).
V. Lebedev and A. Romanov. Optical Stochastic Cooling at IOTA Ring (2015).
E. Bessonov, M. Gorbunkov, A. Mikhailichenko. Enhanced optical cooling system test in an electron storage ring (2008) – fast version of optical stochastic cooling.

4. Coherent electron cooling V. Litvinenko and Ya. Derbenev, PRL **102**, 114801 (2009).

3. Laser cooling of partially stripped ions

Well-developed at low-energy. Cooling is faster at high energy because the energy radiated by the ion grows as γ^2. Never tested above few 100 MeV/u. Also interesting as an intense source of gamma-photons: see the talks of W. Krasny on The Gamma Factory Initiative.

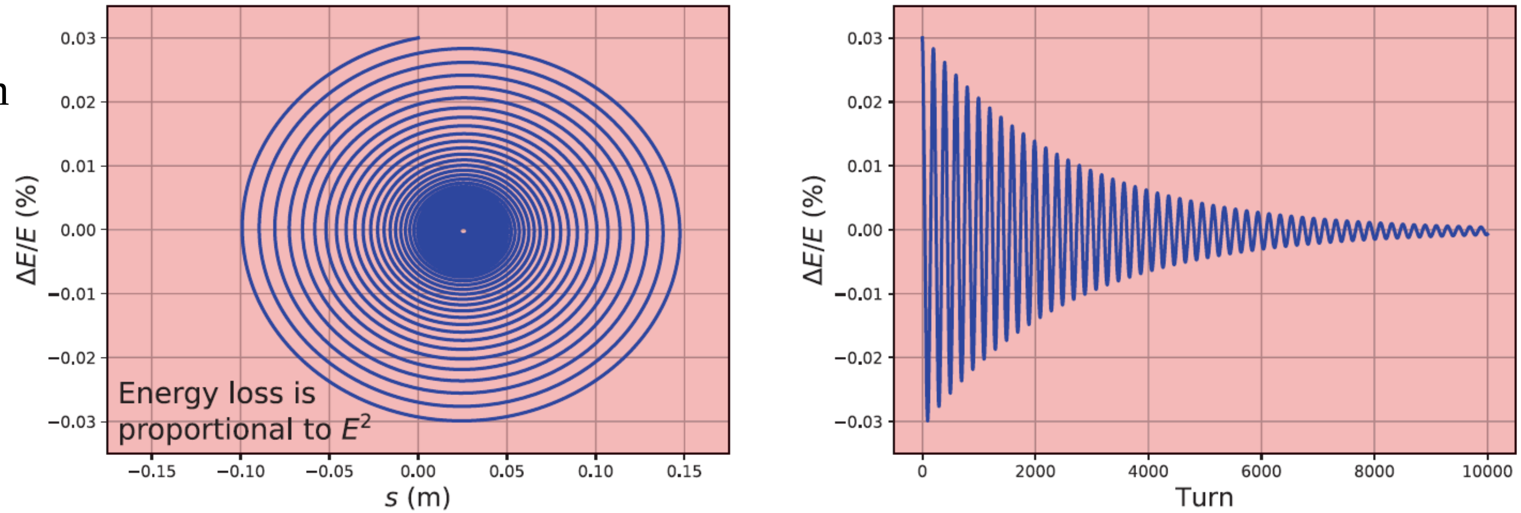
Broad-band cooling vs fast cooling (SPS):

The natural width of the absorption line (~10^{-6}) typically << Doppler shift due to energy spread (~10^{-4})

See: E. G. Bessonov and K.-J. Kim. Radiative Cooling of Ion Beams in Storage Rings by Broad-Band Lasers,

1. Broad-band laser covers the full spectrum of particle energies:

Cooling in all planes. The time of cooling is the time to **radiate full ion energy** E.



See: E. G. Bessonov, R. M. Feshchenko Stimulated Radiation Cooling. RuPAC'2008.

Broad-band laser with a sharp low-frequency cut-off:

Much faster cooling, but only longitudinal. Time of cooling is the time to **radiate energy spread** ΔE.

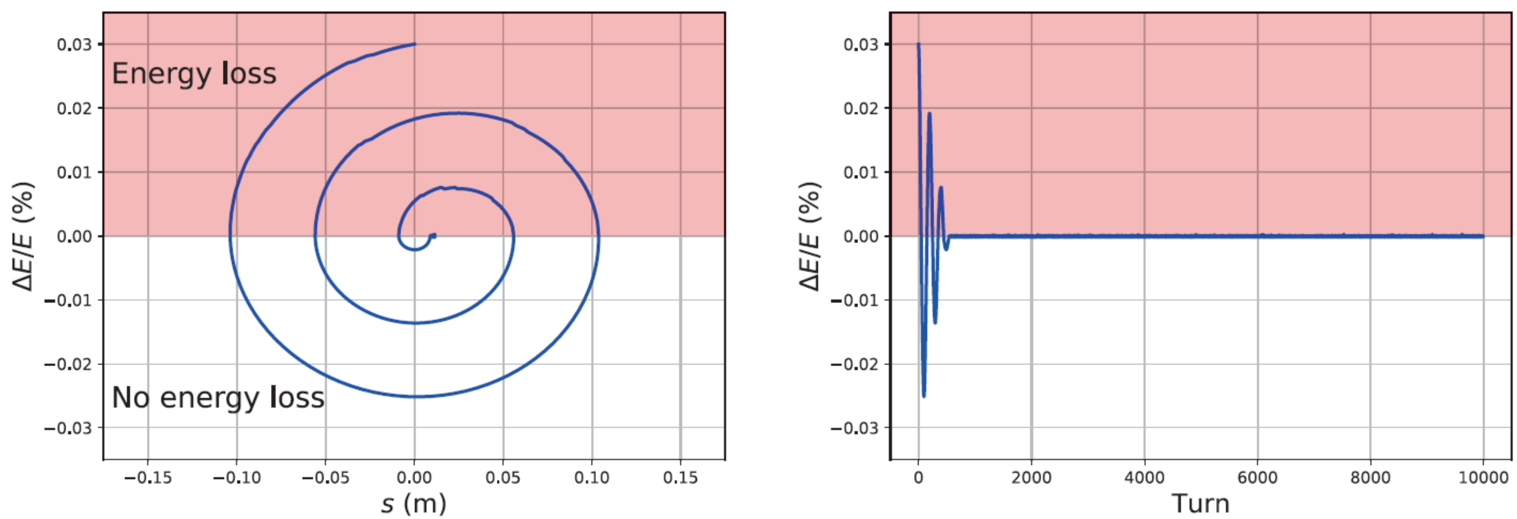


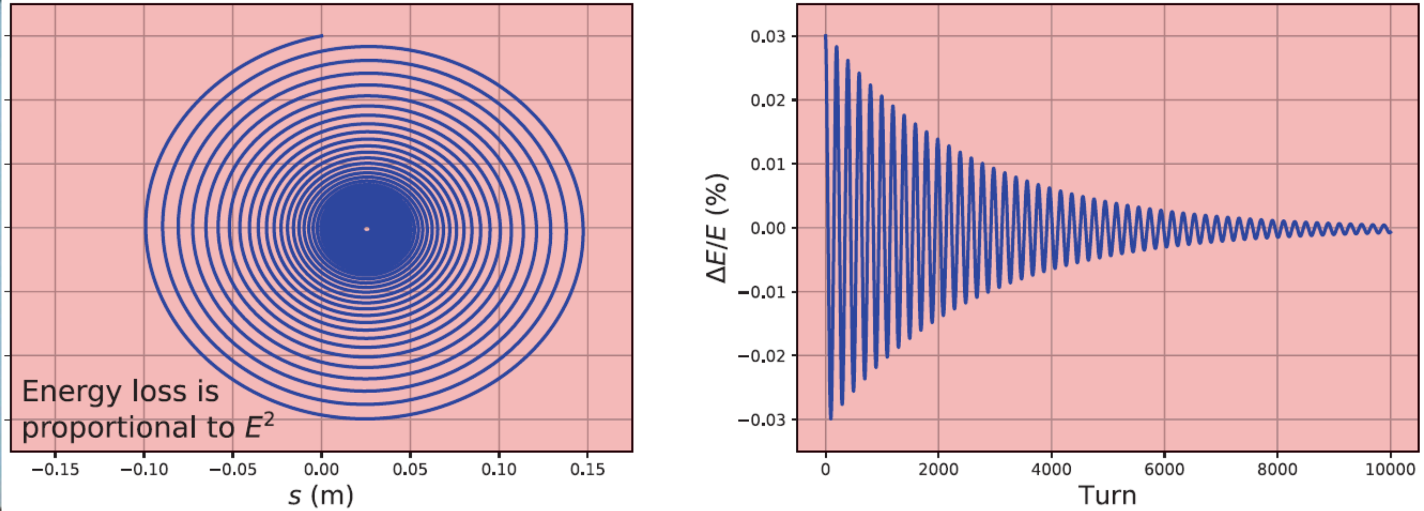
Fig. 6. The evolution of the energy and the longitudinal position of the ion, relative to their central values, as a function of the turn number in the storage ring, for two regimes of the laser cooling. The top plots show the broad-band laser cooling [71] using the laser frequency band which is large enough to excite all the ions, disrespectful of their energies. The bottom plots show the regime of fast cooling [72] using the laser frequency band which has a sharp cut-off, positioned such that the ion absorbs the laser photon only if the ion energy is above its central value.

Broad-band cooling vs fast cooling (SPS):

The natural width of the absorption line (~10^{-6}) typically << Doppler shift due to energy spread (~10^{-4})

See: E. G. Bessonov and K.-J. Kim. [Radiative Cooling of Ion Beams in Storage Rings by Broad-Band Lasers](),

Evgeny Bessonov



See: E. G. Bessonov, R. M. Feshchenko [Stimulated Radiation Cooling](). RuPAC'2008.

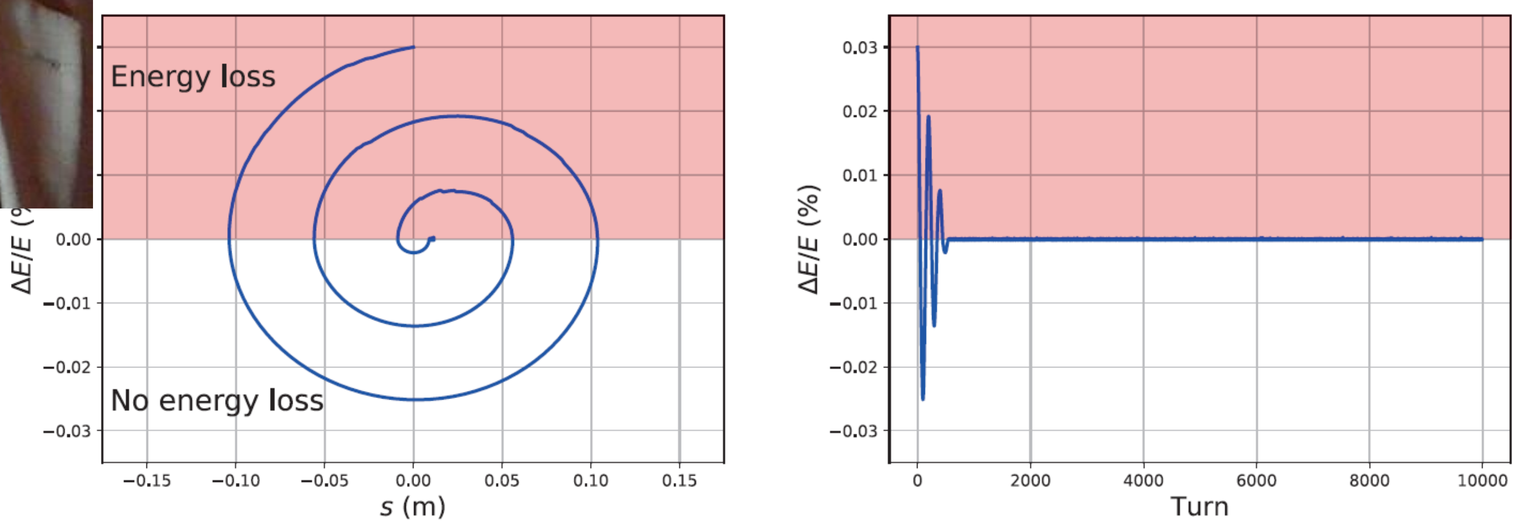


Fig. 6. The evolution of the energy and the longitudinal position of the ion, relative to their central values, as a function of the turn number in the storage ring, for two regimes of the laser cooling. The top plots show the broad-band laser cooling [71] using the laser frequency band which is large enough to excite all the ions, disrespectful of their energies. The bottom plots show the regime of fast cooling [72] using the laser frequency band which has a sharp cut-off, positioned such that the ion absorbs the laser photon only if the ion energy is above its central value.

Transverse cooling via dispersive coupling:

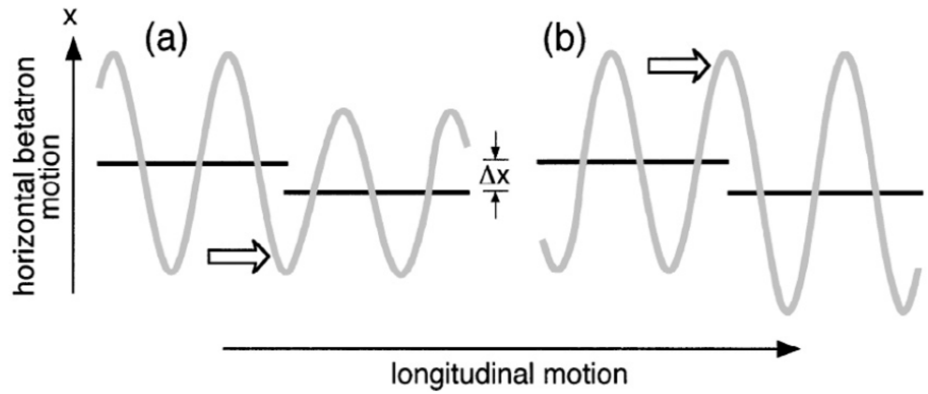


Fig. 7. Horizontal betatron oscillations of a stored ion around the central orbit in a region with positive dispersion. The moment of photon emission and the corresponding change of the central orbit is indicated by the arrow. A reduction of the amplitude of the oscillation occurs when an ion radiates a photon at a negative ($x < 0$) phase of the betatron oscillation (a). If the photon is emitted at $x > 0$ (b), then the amplitude of the betatron oscillations is increased. The transverse cooling will occur if more photons are emitted at $x < 0$ than at $x > 0$.
Source: Adapted from [73].

VOLUME 81, NUMBER 10 PHYSICAL REVIEW LETTERS 7 SEPTEMBER 1998

(I've rearned about this experiment after reading the Lewin Eidam's PhD Thesis which was sent to me by W. Krasny)

Transverse Laser Cooling of a Fast Stored Ion Beam through Dispersive Coupling

I. Lauer,[1] U. Eisenbarth,[1] M. Grieser,[1] R. Grimm,[1] P. Lenisa,[1] V. Luger,[1] T. Schätz,[2] U. Schramm,[2]
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(Received 16 March 1998)

Transverse laser cooling of a fast stored $^9Be^+$ ion beam based on a single-particle force independent of the ion density is demonstrated at the Heidelberg Test Storage Ring. The cooling scheme exploits longitudinal-horizontal coupling through ring dispersion and the transverse intensity profile of the longitudinally merged laser beam. By linear betatron coupling the horizontal force is extended to the vertical degree of freedom resulting in true 3D laser cooling. The observed transverse-cooling mechanism represents an important step towards crystalline ion beams. [S0031-9007(98)07024-0]

Transverse cooling of Li-like Ca beam in the SPS:

Table 1
Parameters of the calcium-beam cooling configuration in the SPS.

Ion beam	$^{40}Ca^{17+}$
m – ion mass	37.21 GeV/c^2
E – mean energy	7.65 TeV
$\gamma_L = E/mc^2$– mean Lorentz relativistic factor	205.62
N – number ions per bunch	4×10^9
σ_E/E – RMS relative energy spread	2×10^{-4}
ϵ_n – normalised transverse emittance	1.5 mm mrad
σ_x – RMS transverse size	0.80 mm
σ_y – RMS transverse size	0.57 mm
σ_z – RMS bunch length	10 cm
Dispersion function	2.44 m
Laser	Pulsed Ti:Sa (20 MHz)
λ – wavelength ($\hbar\omega$ – photon energy)	768 nm (1.6 eV)
σ_λ/λ – RMS relative band spread	2×10^{-4}
U – single pulse energy at IP	2 mJ
σ_L – RMS transverse intensity distribution at IP ($\sigma_L = w_L/2$)	0.56 mm
σ_t – RMS pulse duration	2.04 ps
θ_L – collision angle	1.3 deg
Atomic transition of $^{40}Ca^{17+}$	$2s \rightarrow 3p$
$\hbar\omega_0'$ – resonance energy	661.89 eV
τ' – mean lifetime of spontaneous emission	0.4279 ps
$\hbar\omega_1^{max}$ – maximum emitted photon energy	271 keV

The configuration is very similar to the Gamma Factory Proof-of-Principle experiment.
Many thanks to Aurelien Martens for checking the laser parameters!

Transverse cooling of Li-like Ca beam in the SPS:

First laser transfers betatron oscillations into energy oscillations (synchrotron oscillations)

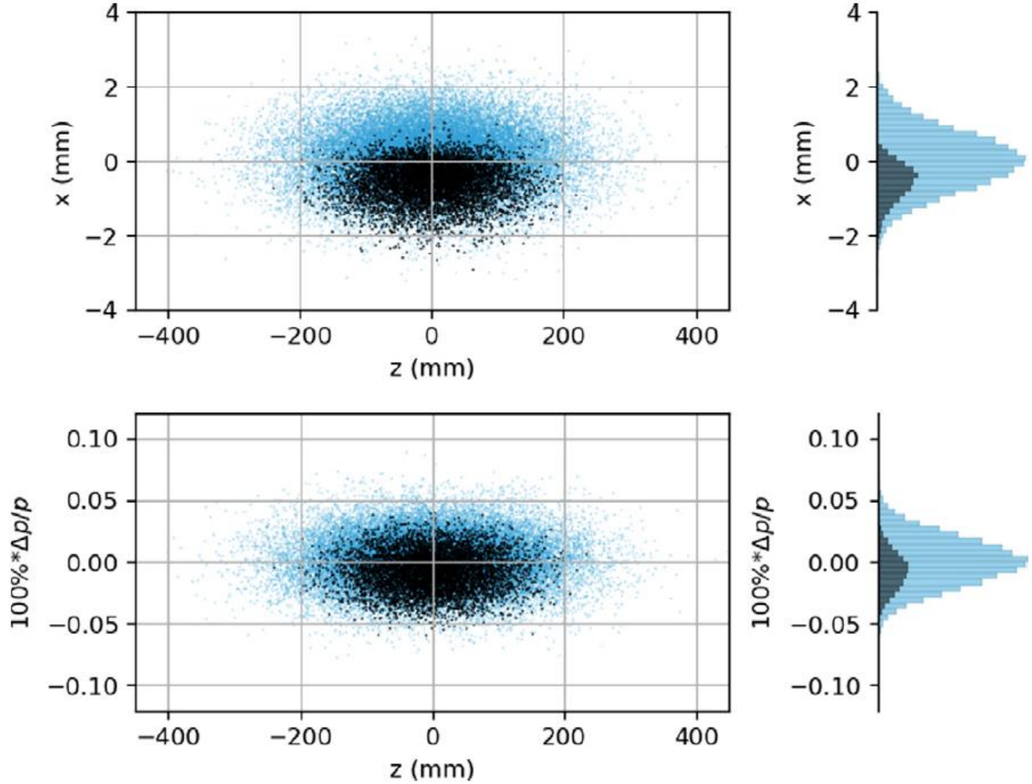


Fig. 9. Distributions of the positions and momenta of the ions interacting with the pulse of the first laser. Excited ions are shown as black dots while non-excited ions are shown as blue dots. The shift of the laser pulse by $-1.4\,\mathrm{mm}$ provides an optimal coupling of horizontal betatron oscillations to synchrotron oscillations, as explained in Fig. 7. About 17% of all ions are excited in each bunch crossing.

Second laser cools the beam in energy (longitudinally)

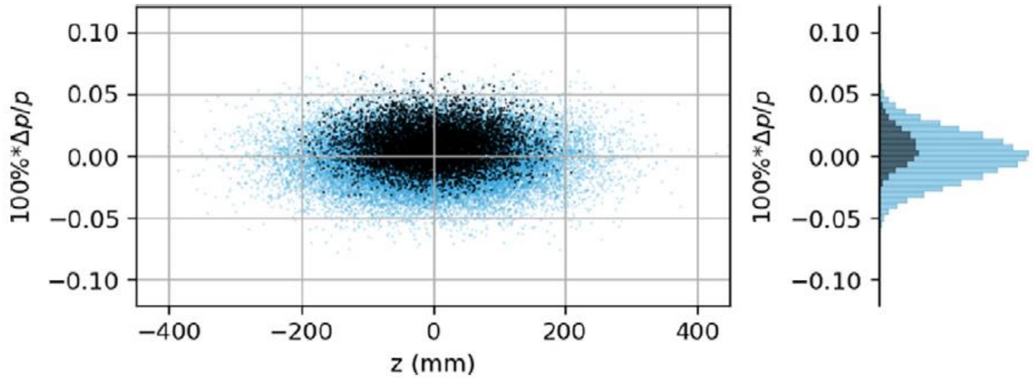
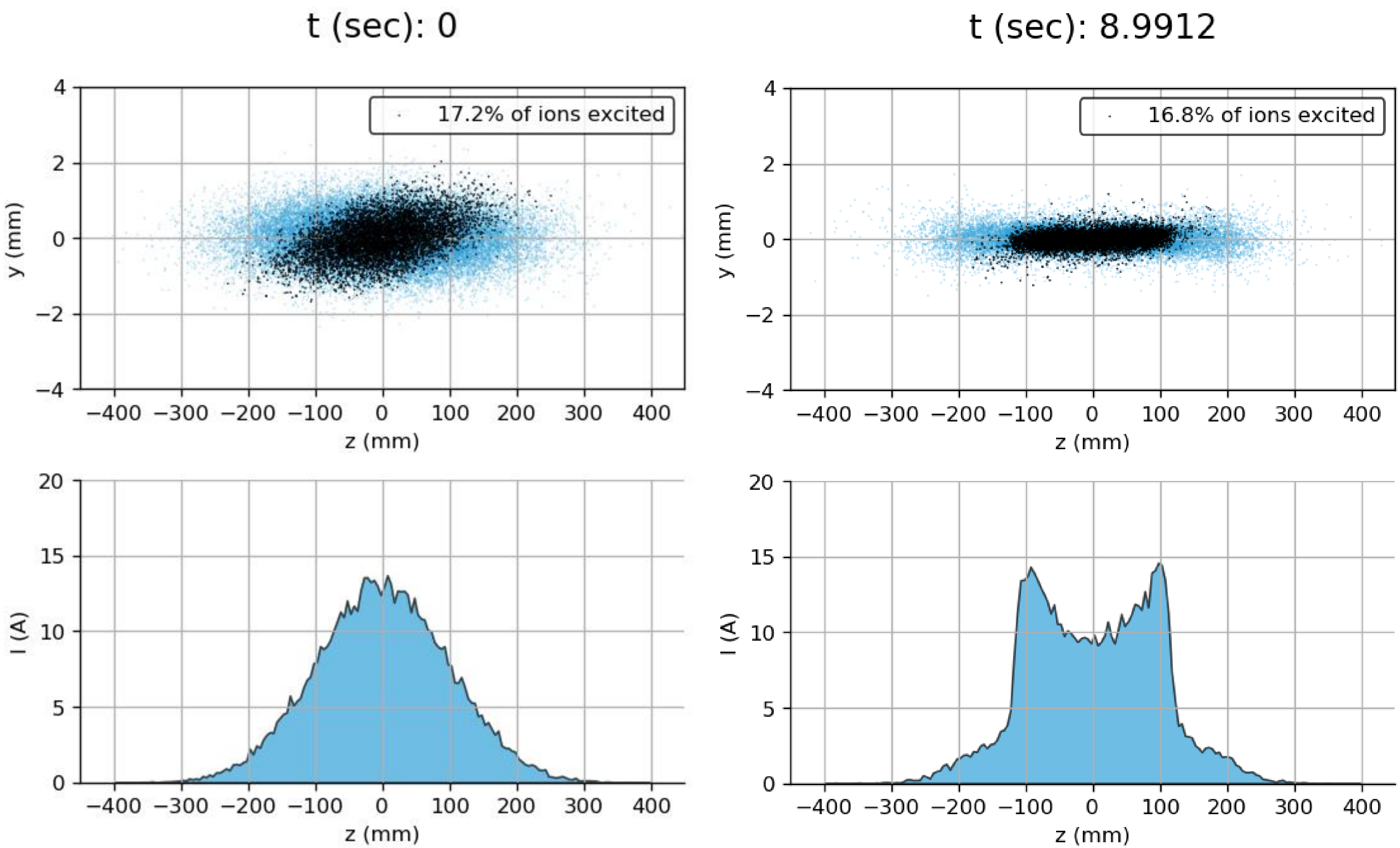


Fig. 10. Distribution of the momentum and longitudinal positions of the ions interacting with the photon-pulse of the second laser. Excited ions are shown as black dots while non-excited ions are shown as blue dots. The laser pulse focal point is aligned with the ion beam centre but its frequency band is shifted to excite the higher-momentum ions, as explained in Fig. 6.

Transverse cooling of Li-like Ca beam in the SPS:



Simulation details: https://anaconda.org/petrenko/li_like_ca_in_sps_transv

Transverse cooling of Li-like Ca beam in the SPS:

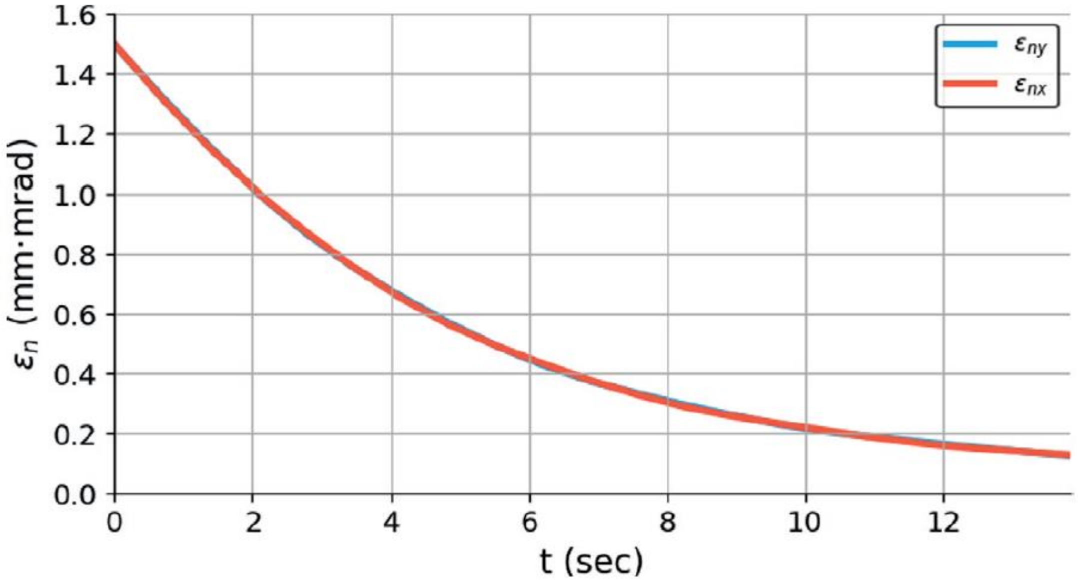


Fig. 11. Transverse cooling speed: the time-evolution curves of the vertical and horizontal emittances are overlapping each other – they are precisely equal when the betatron tunes are on the coupling resonance.

Simulation details: https://anaconda.org/petrenko/li_like_ca_in_sps_transv

Transverse cooling of Li-like Ca beam in the SPS:

Betatron oscillations are fully coupled via the coupling resonance.

Betatron tunes without any skew-quad: **Qx = 26.130, Qy = 26.130,**
Betatron tunes with additional skew-quad: **Qx = 26.134, Qy = 26.126, Qx-Qy=0.0078.**

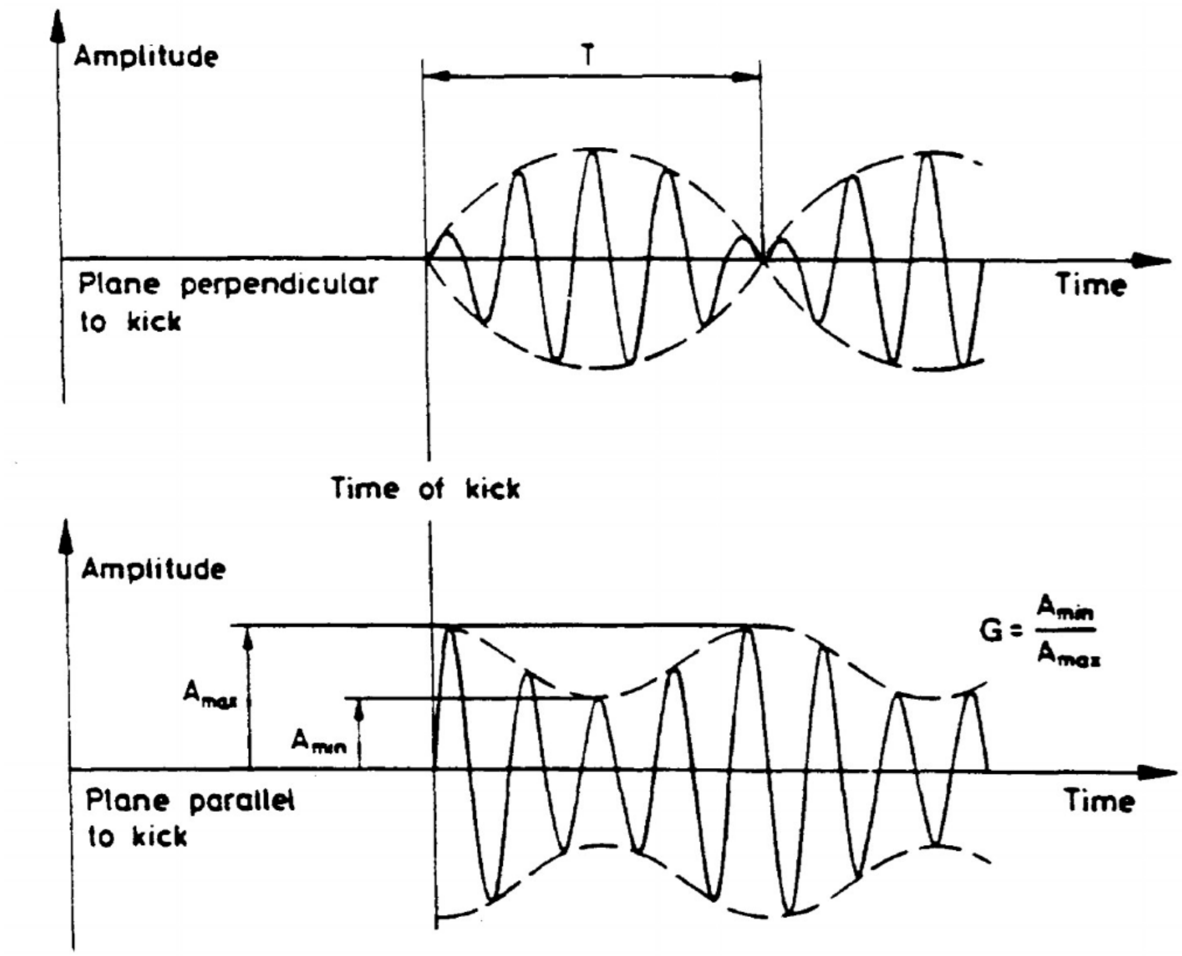


Fig. 1 Coherent oscillations following a horizontal kick

https://cds.cern.ch/record/300856/files/p43.pdf https://indico.cern.ch/event/856751/

Conclusions

It seems possible to apply the deep laser cooling (both longitudinal and transverse!) to the Li-like Ca within few seconds available at the SPS flat top.

This may open some interesting options for the LHC ion program.

Back-up slides

Link to Padua seminar presentation on high-energy laser cooling:

Beam stability and cooling aspects for the partially stripped ions in the storage rings, Padua, 2017

The full-energy Gamma Factory example:

Lead ion with one electron:

Ion charge $Z = 81$, mass A = 208, $\gamma = 2928$, $p_z = 567$ TeV/c,

$\hbar\omega' = 69$ keV (Lyman-alpha line), laser $\hbar\omega = 12$ eV, emitted gamma $\hbar\omega_{1,\mathrm{max}} = 402$ MeV, typical angle of emission $\theta_1 \sim 1/\gamma \sim 0.3$ mrad.

Typical transverse kick due to gamma emission:

$p_x/p_z \sim \hbar\omega'/p_z c \sim 69\ \mathrm{keV}/567\ \mathrm{TeV} \sim 10^{-7}$ mrad.

Typical transverse beam parameters at the LHC interaction point for example:
Transverse beam size = 0.026 mm, angular spread = 0.026 mrad (10^5 times higher).

Typical energy spread in the beam is $\Delta p/p \sim 10^{-4}$, while the average δp_z due to the photon emission is 200 MeV/c => $\delta p_z / p_z = 200\ \mathrm{MeV} / 567\ \mathrm{TeV} = 3.5 \cdot 10^{-7}$ => $\Delta p/\delta p \approx 300$, even with one scattering per turn the longitudinal effects will be significant in 100s of turns.

First of all we should consider the influence of photon emissions on the synchrotron oscillations.

Partially stripped ions in the SPS

D. Manglunki et al. CERN's Fixed Target Primary Ion Programme. IPAC'2016.

Table 1: Charge States and Typical Intensites

Species	**Ar**	**Xe**	**Pb**
Charge state in Linac3	Ar^{11+}	Xe^{20+}	Pb^{29+}
Linac3 beam current after stripping [eμA]	50	27	25
Charge state Q in LEIR/PS	Ar^{11+}	Xe^{39+}	Pb^{54+}
Ions/bunch in LEIR	3×10^9	4.3×10^8	2×10^8
Ions/bunch in PS	2×10^9	2.6×10^8	1.2×10^8
Charge state Z in SPS (fully str.)	Ar^{18+}	Xe^{54+}	Pb^{82+}
Ions at injection in SPS	7×10^9	8.1×10^8	4×10^8
Ions at extraction in SPS	5×10^9	6×10^8	3×10^8
Number of charges:	$9\cdot10^{10}$	$3.2\cdot10^{10}$	$2.5\cdot10^{10}$
Less than in AWAKE	**3x less**	**10x less**	**10x less**

Production efficiency for partially stripped ions can be higher than for the fully stripped ions.

J. Wenninger et al. Energy Calibration of the SPS with Proton and Lead Ion Beams. PAC'2005:

To maximize the frequency difference Δf for the calibration, the lead beam was not stripped in the injection transfer line and injected as Pb^{53+} into the SPS. The lifetime of Pb^{53+} in the SPS was 5.3 seconds at P_{Pb}/Z of 26 GeV/c, limited by the vacuum conditions. The lead ion source is composed of isotopically pure Pb_{208}.

At 450 GeV/c the closed orbit r.m.s in the SPS was 2.0 mm and 1.5 mm for the horizontal and vertical planes. The transverse tunes were set to $Q_h = 26.18$ and $Q_v = 26.14$. The magnetic field in the reference dipole was measured with an NMR probe. The field was stable at 2.0251 ± 0.0002 T during the two days of measurements.

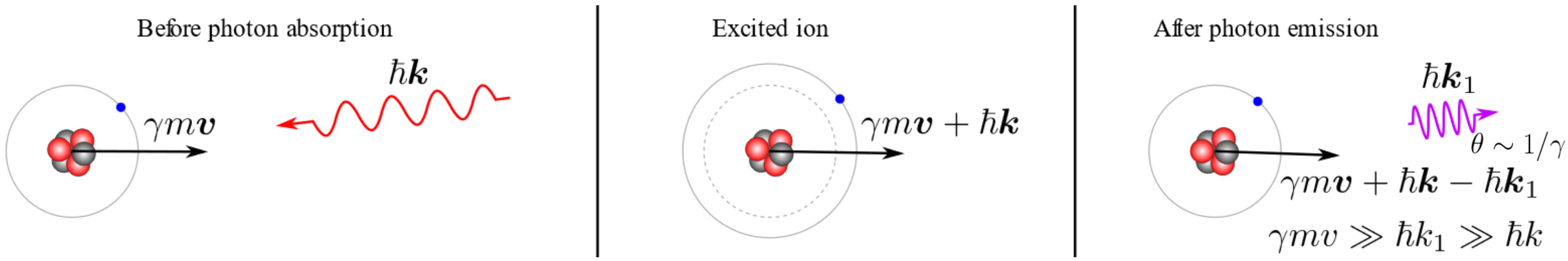
The proton beam intensities corresponded to $\sim 10^{11}$ protons per bunch. The total Pb^{53+} ion beam intensity was only $\sim$ (3-5) $\times$ 10^9 charges.

100x less than in AWAKE.
Maybe could be optimized for high beam charge.

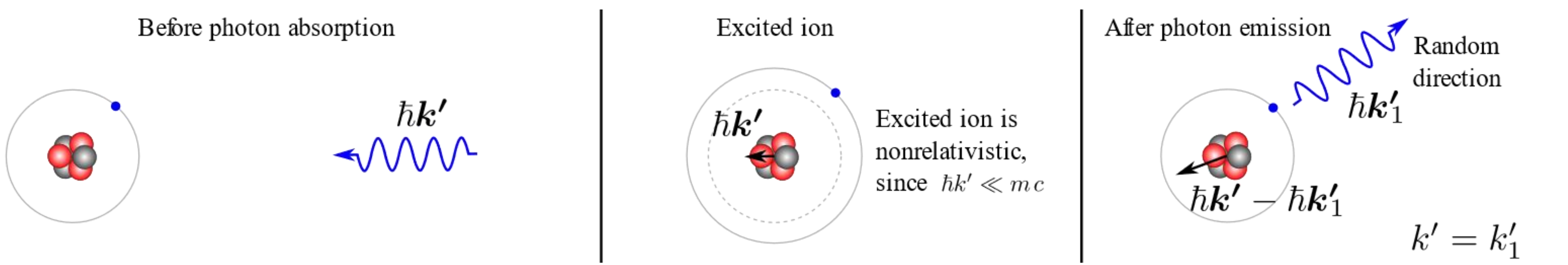
Possible variant: Xe^{47+} (7 electrons left, N-like). γ = 162. Atomic excitation ${}^4S_{3/2} \rightarrow {}^4P_{3/2}$. Krypton laser: 647 nm (1.87 eV) will be converted to gamma-photons with E_{max} = 196 keV. $I_{sat.}$ = $1.7\cdot10^8$ W/cm^2 , decay length = 3.4 cm => with a 1 mm wide beam to have one interaction per turn we need a single laser pulse energy ≈ $1.7\cdot10^8$ W/cm^2 · 0.1·0.1 cm^2 · 3.4 cm / ($3\cdot10^{10}$ cm/sec) ≈ 0.2 mJ => Average laser power ~ $0.2\cdot10^{-3}$ J / (7000 m / $3\cdot10^8$ m/sec) ~ 10 W. (Xe^{47+} suggested by Bessonov and Kim PRL'1996 and in W. Krasny's proposal for gamma-factory test at SPS).

Laser-ion interaction kinematics

In the lab frame:



In the ion's frame:

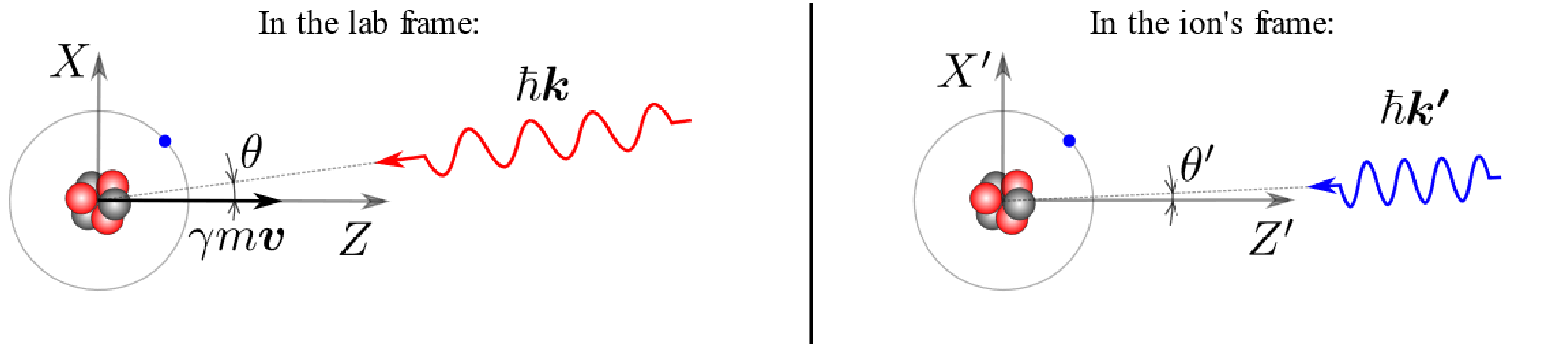


Longitudinal cooling: because energy loss grows with ion energy:

Transverse cooling: because all components of ion momentum are lost due to the photon scattering but only the longitudinal component is restored in the RF resonator.

Heating: because angle of photon emission in the ion's frame is random.
We would like to find an equilibrium between the cooling and heating processes.

Photon absorption



4-vector Lorentz transformation:

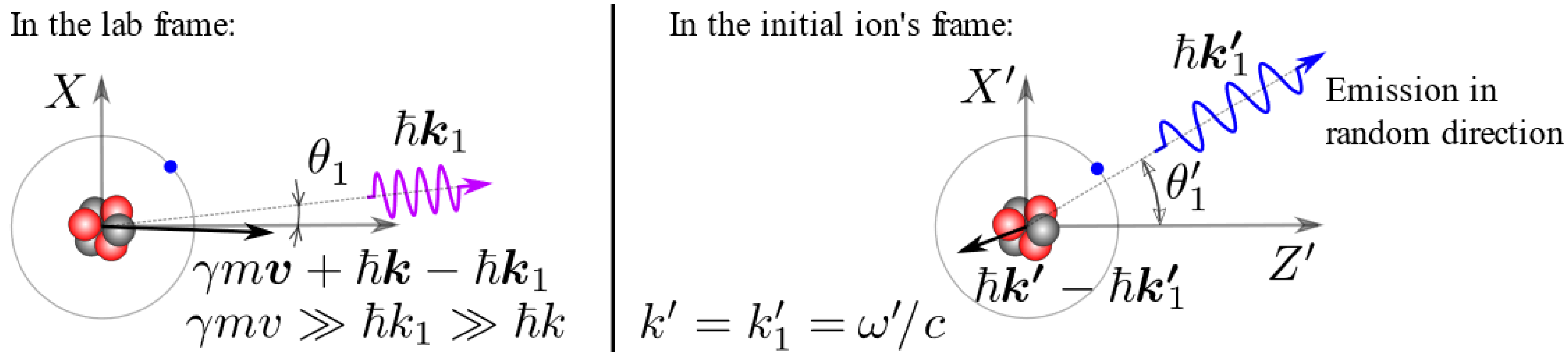
$$\begin{pmatrix} E'/c \\ p'_x \\ p'_y \\ p'_z \end{pmatrix} = \begin{pmatrix} \gamma & 0 & 0 & -\beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\beta\gamma & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} E/c \\ p_x \\ p_y \\ p_z \end{pmatrix}$$

Assuming that $k_x = -k\sin\theta$, $k_y = 0$, $k_z = -k\cos\theta$, and $k = \omega/c$ we can find the incoming photon parameters in the ion's frame of reference:

$$\omega' = (1 + \beta\cos\theta)\gamma\omega \approx \left(1 + \beta - \beta\frac{\theta^2}{2}\right)\gamma\omega \approx 2\gamma\omega.$$

Incoming angular spread in the beam of $\theta \sim 1$ mrad will be translated to a frequency error of only $\sim 10^{-6}$ in the ion's frame of reference. Frequency mismatch is dominated by the energy spread in the ion beam (typically $\sim 10^{-4}$).

Photon emission



Photon emission will occur in a random direction. For simplicity let's assume that the photon was emitted in the same plane (X', Z') at a random angle θ'_1, i.e. $k'_{1x} = k' \sin\theta'_1$, $k'_{1z} = k' \cos\theta'_1$. Then inverse Lorentz transformation gives us the emitted photon parameters in the lab frame:

$$\begin{pmatrix} 1 \\ \sin\theta_1 \\ 0 \\ \cos\theta_1 \end{pmatrix} \frac{\omega_1}{c} = \begin{pmatrix} \gamma & 0 & 0 & \beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \beta\gamma & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} 1 \\ \sin\theta'_1 \\ 0 \\ \cos\theta'_1 \end{pmatrix} \frac{\omega'}{c}.$$

Hence the scatterd photon has the frequency $\omega_1 = \gamma(1 + \beta\cos\theta'_1)\omega' \approx 2\gamma^2(1 + \beta\cos\theta'_1)\omega$.

$$\omega_1 \sin\theta_1 = \omega' \sin\theta'_1 \;\Rightarrow\; \sin\theta_1 = \frac{\sin\theta'_1}{\gamma(1 + \beta\cos\theta'_1)}.$$