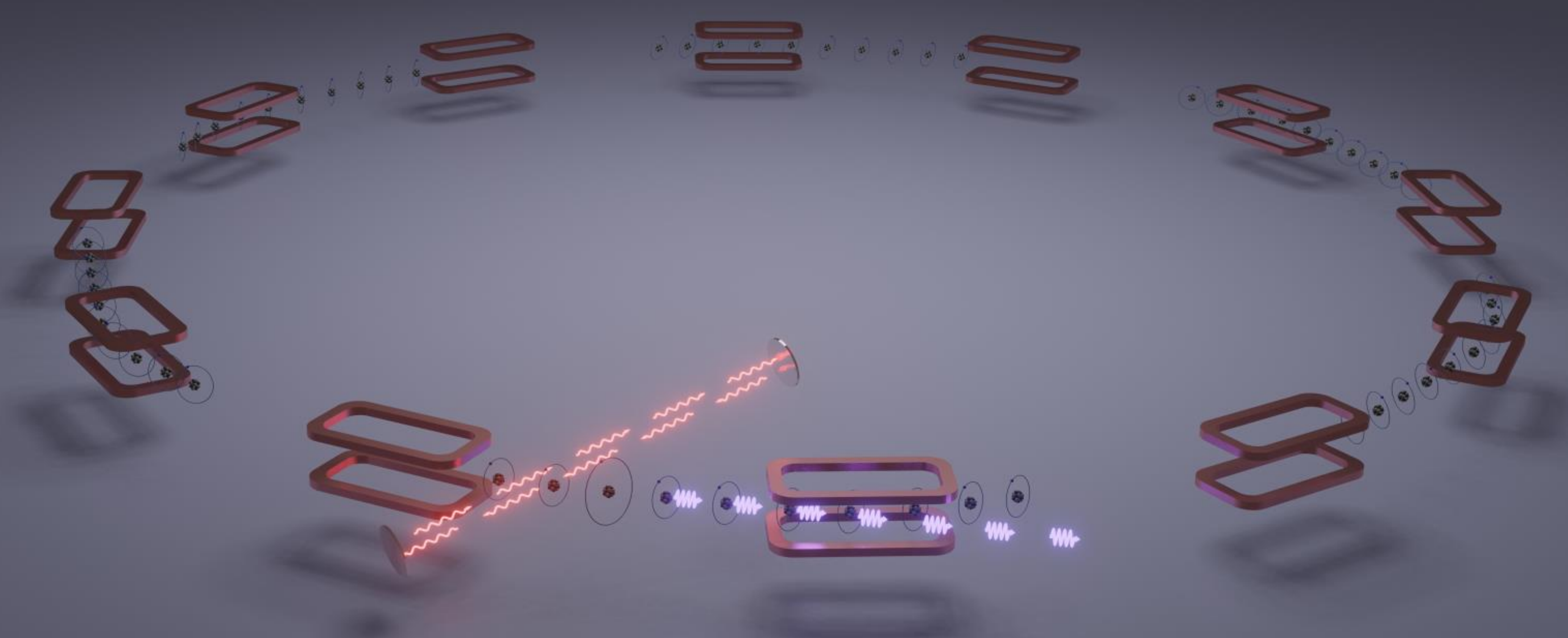
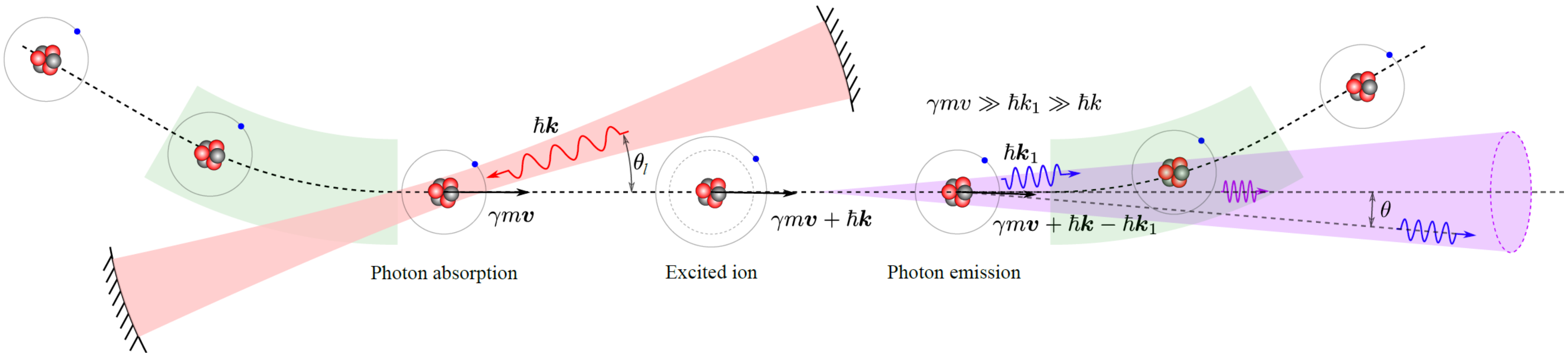
Лазерное охлаждение ультрарелятивистских ионов и проект Гамма-Фабрики в ЦЕРНе

Алексей Петренко, ИЯФ СО РАН, 09.12.2021

онлайн-семинар «Новые методы ускорения частиц и экстремальные состояния материи»





The process of excitation is resonant, its cross-section ~ λ'^2 while for the Compton scattering the cross-section ~ r_e^2. (for H-like Pb λ'=18 pm >> r_e = 2.8 fm).
The ion energy loss due to the emission of the photon is very small while in the inverse Compton scattering source the electron loses significant fraction of its energy and is lost from the circulation.

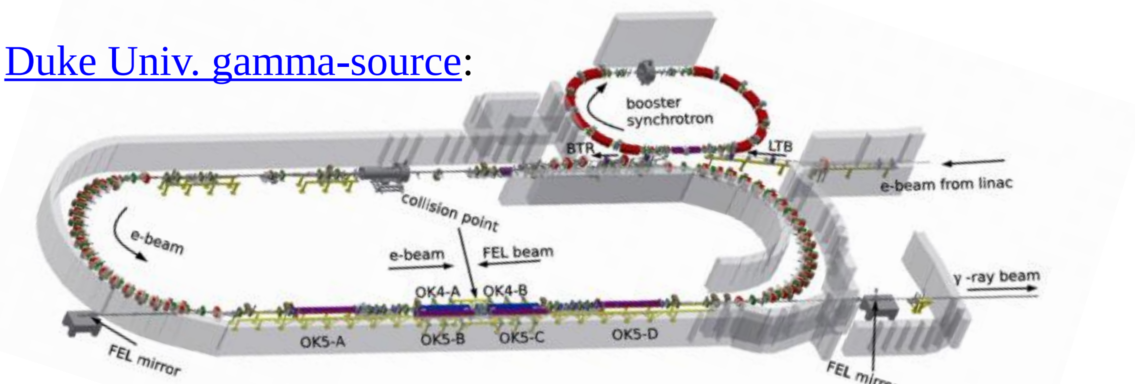
Facility	Lab.	p^+ energy	Max. photon energy
LHC	CERN	6.5 TeV	Pb^{81+} + 12.6 eV → 373 MeV
SPS	CERN	450 GeV	Ti^{21+} + 11.7 eV → 2.1 MeV
RHIC	BNL	255 GeV	Cl^{16+} + 11.8 eV → 0.74 MeV
NICA	JINR	12.6 GeV	Li^{2+} + 10.2 eV → 0.83 keV
SIS 100	GSI	29 GeV	B^{4+} + 10.2 eV → 6.4 keV
SIS 300	GSI	87 GeV	Ne^{9+} + 12.1 eV → 86 keV
SC-SPS	CERN	1.3 TeV	Kr^{35+} + 11.4 eV → 15 MeV
HE-LHC	CERN	13.5 TeV	U^{91+} + 7.8 eV → 0.96 GeV
FCC-hh	CERN	50 TeV	U^{91+} + 2.1 eV → 3.5 GeV

TABLE XI. Survey of the existing (first three lines) and future relativistic heavy-ion facilities. The maximum photon energy is given assuming hydrogen-like ions interacting with a primary laser beam in the optical range (down to 100 nm). With a dedicated FEL used as a primary source of higher energy photons (+ heavier ion) the maximum secondary photon energy can be increased further.

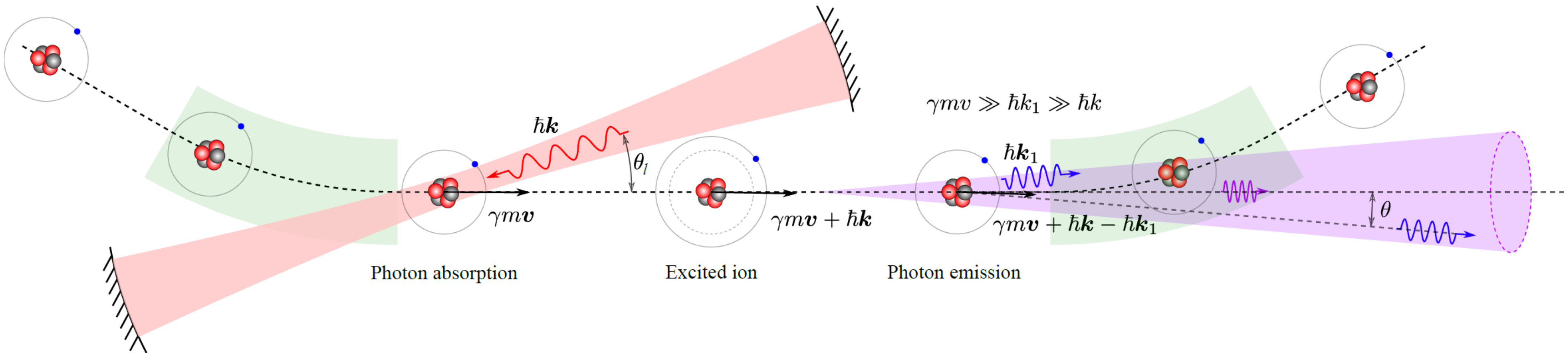
The fluxes are limited mainly by the ring RF power and can be ~10^{17} photons/sec (3 MW at 200 MeV) -- direct conversion of RF power into gamma radiation.

Typical max. fluxes of existing gamma sources based on inverse Compton scattering ~ 10^9 photons/sec.

Duke Univ. gamma-source:



Expanding Nuclear Physics Horizons with the Gamma Factory. D. Budker et al.



The full-scale Gamma Factory will extract MWs of gamma radiation from the LHC beam in a single interaction point. (By the way, the beam energy loss due to SR in LEP was 11 MW).

H-like Pb in the LHC example: 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 $\hbar\omega_{1,max} = 402$ MeV,

typical angle of emission $\theta_1 \sim 1/\gamma \sim 0.3$ mrad.
Typical transverse kick due to gamma emission:
$p_x/p_z \sim \hbar\omega'/p_z c \sim 69$ keV/567 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 MeV / 567 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.

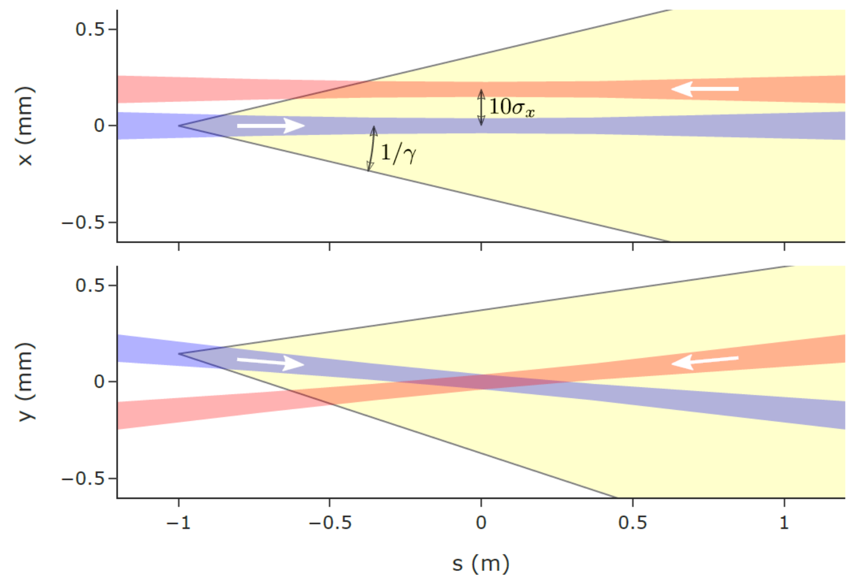


FIG. 27. The typical LHC interaction point (IP) configuration compared to a $1/\gamma$ cone of gamma-radiation. The diameter of the beams in this picture is $4\sigma_{x,y}$ (at the IP $\sigma_{x,y} \approx 19\ \mu$m). The beams are separated by $10\sigma_x \approx 0.2$ mm horizontally in order to avoid stripping of the PSI due to collisions with counter-propagating ion or proton beam.

Expanding Nuclear Physics Horizons with the Gamma Factory.
D. Budker et al.

[Recent short review of the Gamma Factory Project in general](#):

THE GAMMA FACTORY PROJECT AT CERN: A NEW GENERATION OF RESEARCH TOOLS MADE OF LIGHT*

W. Płaczek[a], A. Abramov[b], S.E. Alden[b], R. Alemany Fernandez[c]
P.S. Antsiferov[d], A. Apyan[e], H. Bartosik[c], E.G. Bessonov[f]
N. Biancacci[c], J. Bieroń[a], A. Bogacz[g], A. Bosco[b], R. Bruce[c]
D. Budker[h,i], K. Cassou[j], F. Castelli[k], I. Chaikovska[j], C. Curatolo[l]
P. Czodrowski[c], A. Derevianko[m], K. Dupraz[j], Y. Dutheil[c]
K. Dzierżęga[a], V. Fedosseev[c], N. Fuster Martinez[c], S.M. Gibson[b]
B. Goddard[c], A. Gorzawski[n,c], S. Hirlander[c], J.M. Jowett[c]
R. Kersevan[c], M. Kowalska[c], M.W. Krasny[o,c], F. Kroeger[p,s]
D. Kuchler[c], M. Lamont[c], T. Lefevre[c], D. Manglunki[c], B. Marsh[c]
A. Martens[j], J. Molson[c], D. Nutarelli[j], L.J. Nevay[b], A. Petrenko[q,c]
V. Petrillo[k], S. Redaelli[c], Y. Peinaud[j], S. Pustelny[a], S. Rochester[r]
M. Sapinski[s], M. Schaumann[c], R. Scrivens[c], L. Serafini[k]
V.P. Shevelko[f], T. Stoehlker[p], A. Surzhykov[t], I. Tolstikhina[f]
F. Velotti[c], G. Weber[p], Y.K. Wu[u], C. Yin-Vallgren[c], M. Zanetti[w,l]
F. Zimmermann[c], M.S. Zolotorev[y], F. Zomer[j]

[a]M. Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland
[b]Royal Holloway University of London Egham, Surrey, TW20 0EX, United Kingdom
[c]CERN, Geneva, Switzerland
[d]Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Region, Russia
[e]A.I. Alikhanyan National Science Laboratory, Yerevan, Armenia
[f]P.N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
[g]Center for Advanced Studies of Accelerators, Jefferson Lab, USA
[h]Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany
[i]Department of Physics, University of California, Berkeley, USA
[j]LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
[k]Department of Physics, INFN — Milan and University of Milan, Milan, Italy
[l]INFN — Padua, Padua, Italy
[m]University of Nevada, Reno, Nevada 89557, USA
[n]University of Malta, Malta
[o]LPNHE, University Paris Sorbonne, CNRS–IN2P3, Paris, France
[p]HI Jena, IOQ FSU Jena, Germany
[q]Budker Institute of Nuclear Physics, Novosibirsk, Russia
[r]Rochester Scientific, LLC, El Cerrito, CA 94530, USA
[s]GSI, Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[t]Braunschweig University of Technology and Physikalisch-Technische Bundesanstalt, Germany
[u]FEL Laboratory, Duke University, Durham, USA
[w]University of Padua, Padua, Italy
[y]Center for Beam Physics, LBNL, Berkeley, USA

(Received March 5, 2020)

* Invited talk presented by W. Płaczek at the 45[th] Congress of Polish Physicists, Kraków, September 13–18, 2019.

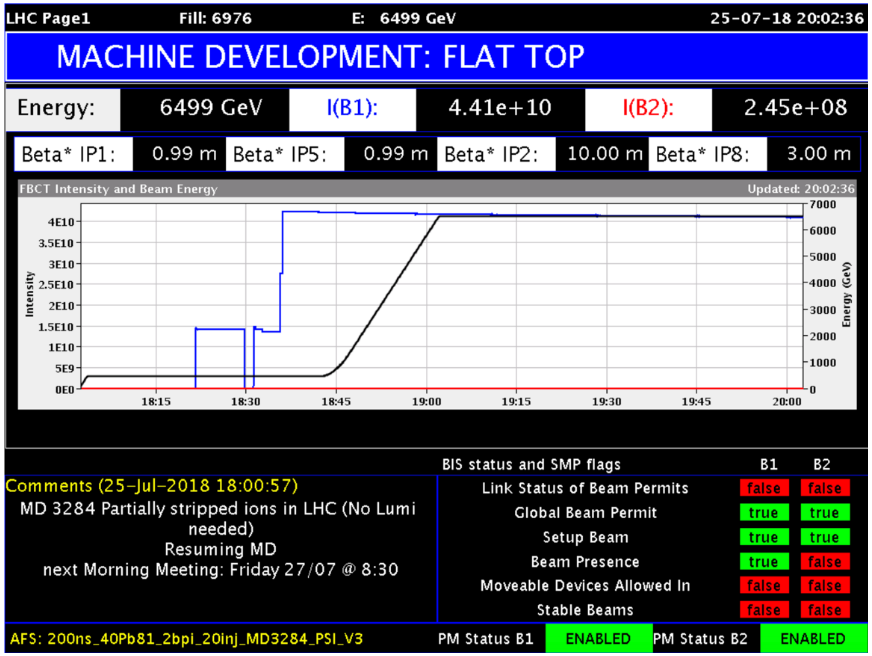
CERN homepage:
https://pbc.web.cern.ch/gfpop-mandate

Physics Beyond Colliders

Recent papers:

- Expanding Nuclear Physics Horizons with the Gamma Factory
- Atomic Physics Studies at the Gamma Factory at CERN
- Probing ALPs at the CERN Gamma Factory
- Radioactive ion beam production at the Gamma Factory
- High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams
- Gamma Factory Searches for Extremely Weakly-Interacting Particles
- Vacuum birefringence at the Gamma Factory
- Local Lorentz invariance tests for photons and hadrons at the Gamma Factory
- Resonance photoproduction of pionic atoms at the proposed Gamma Factory
- Collimation of partially stripped ions in the CERN Large Hadron Collider

First Partially Stripped Ions in the LHC (H-like Pb):



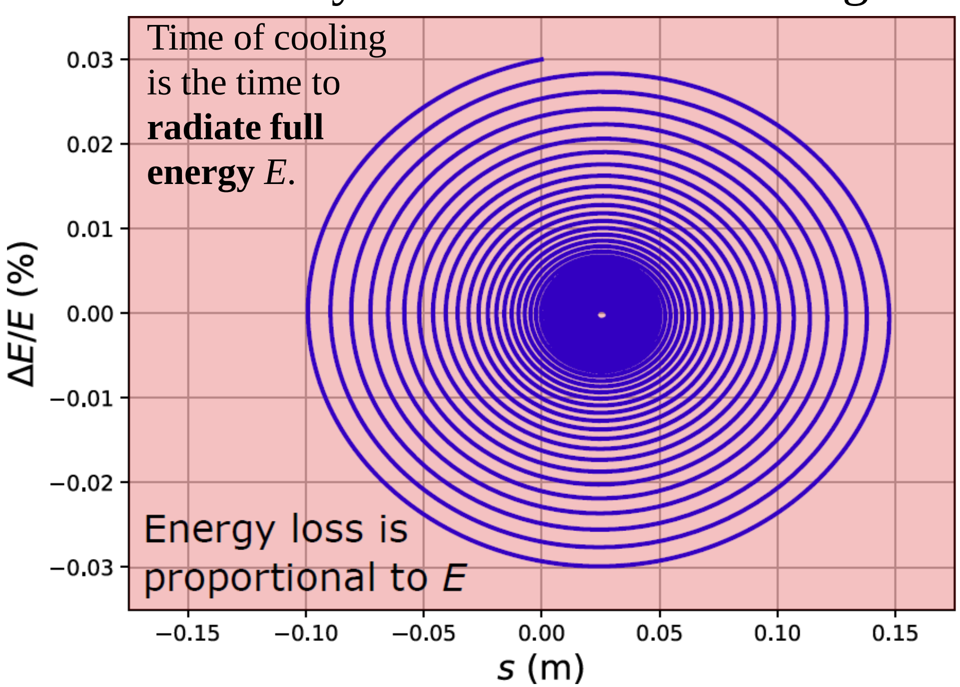
GF study group is open to everyone willing to contribute to this initiative!

Beam cooling/heating is an effect of multi-turn laser-ion interaction

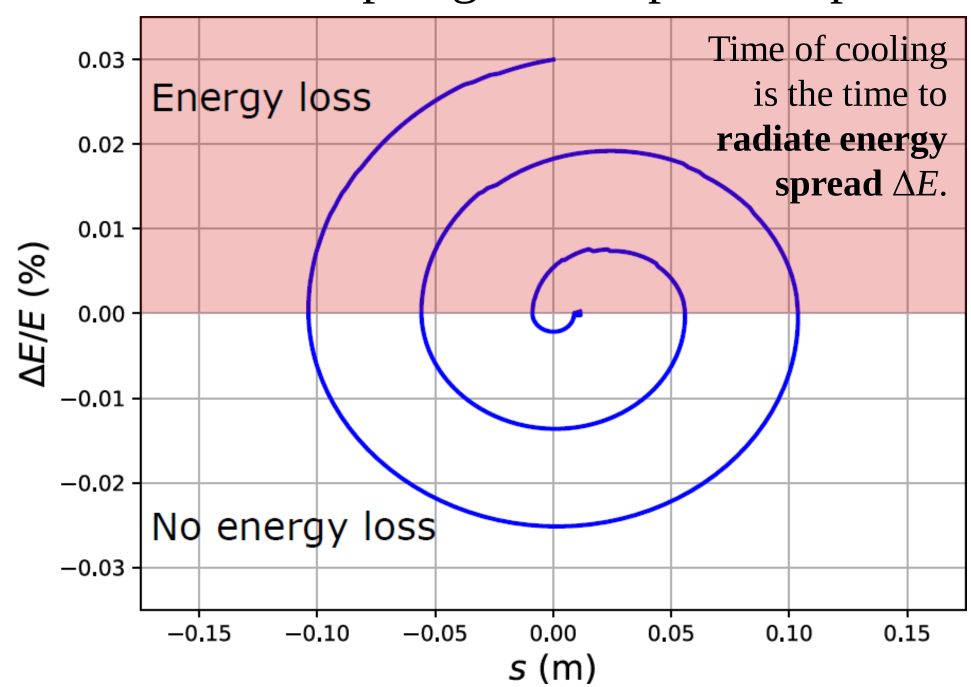
Since the ion is losing only a tiny fraction of its energy the laser-ion interaction can happen over multiple turns (while in the Compton gamma source electron is lost due to recoil).

Longitudinal cooling: because energy loss grows with the 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.
Longitudinal heating: because the ion energy loss is random (defined by the random angle of photon emission in the ion's frame of reference).

Energy of laser photons is distributed uniformly and match all ion energies:

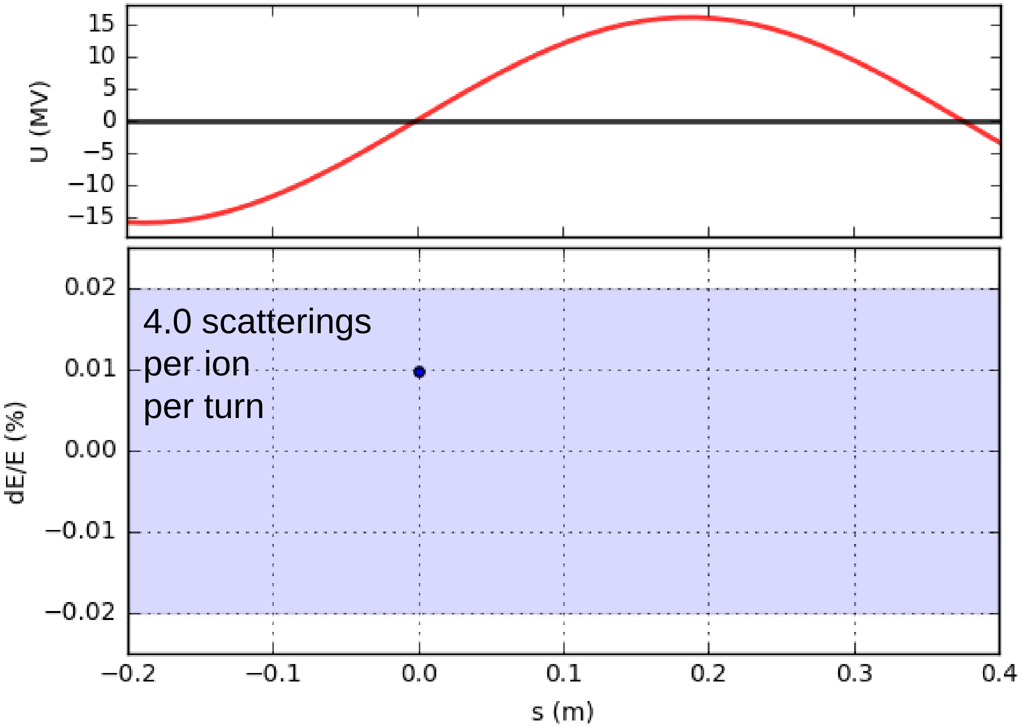


Longitudinal cooling can be much faster with a sharp edge in the photon spectrum:

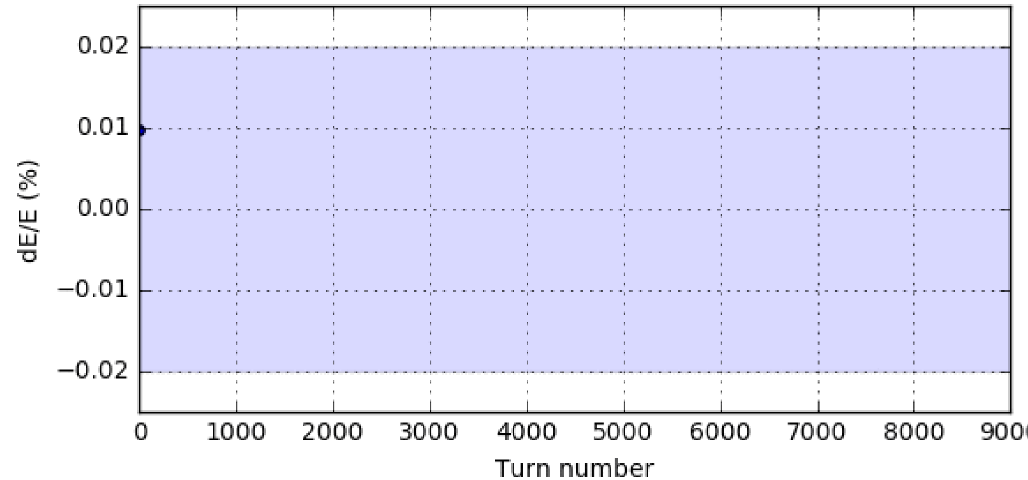


E. G. Bessonov and K.-J. Kim. Radiative Cooling of Ion Beams in Storage Rings by Broad-Band Lasers, PRL, 1996.
E. G. Bessonov, R. M. Feshchenko Stimulated Radiation Cooling. RuPAC'2008.

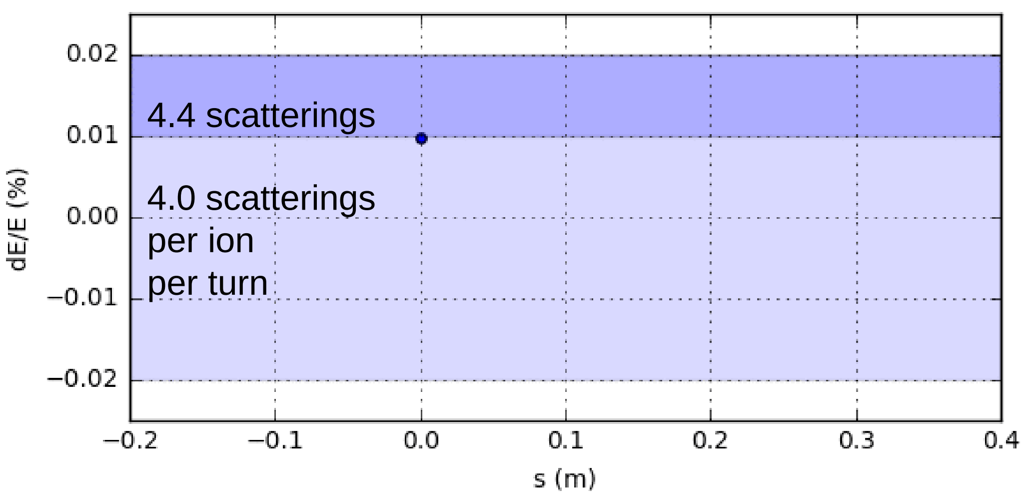
Longitudinal laser cooling is important to stabilize the ion motion:

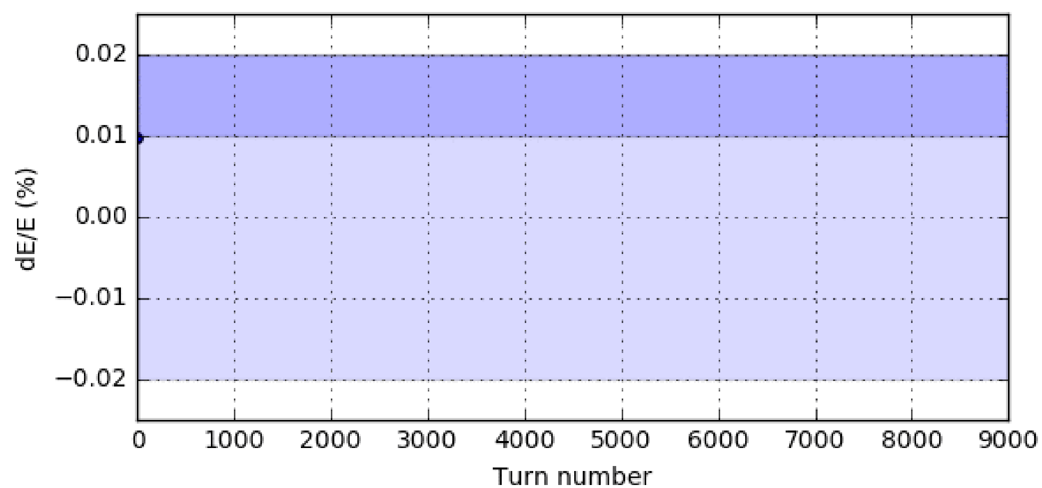


The important effect of photon emissions on ion beam dynamics is in the energy loss of the partially stripped ion. This energy loss is randomly distributed from 0 to 400 MeV in this case of Pb ion with one remaining electron in the LHC. This randomness excites uncontrolled growth of synchrotron oscillations leading to a loss of ion from the RF-bucket:



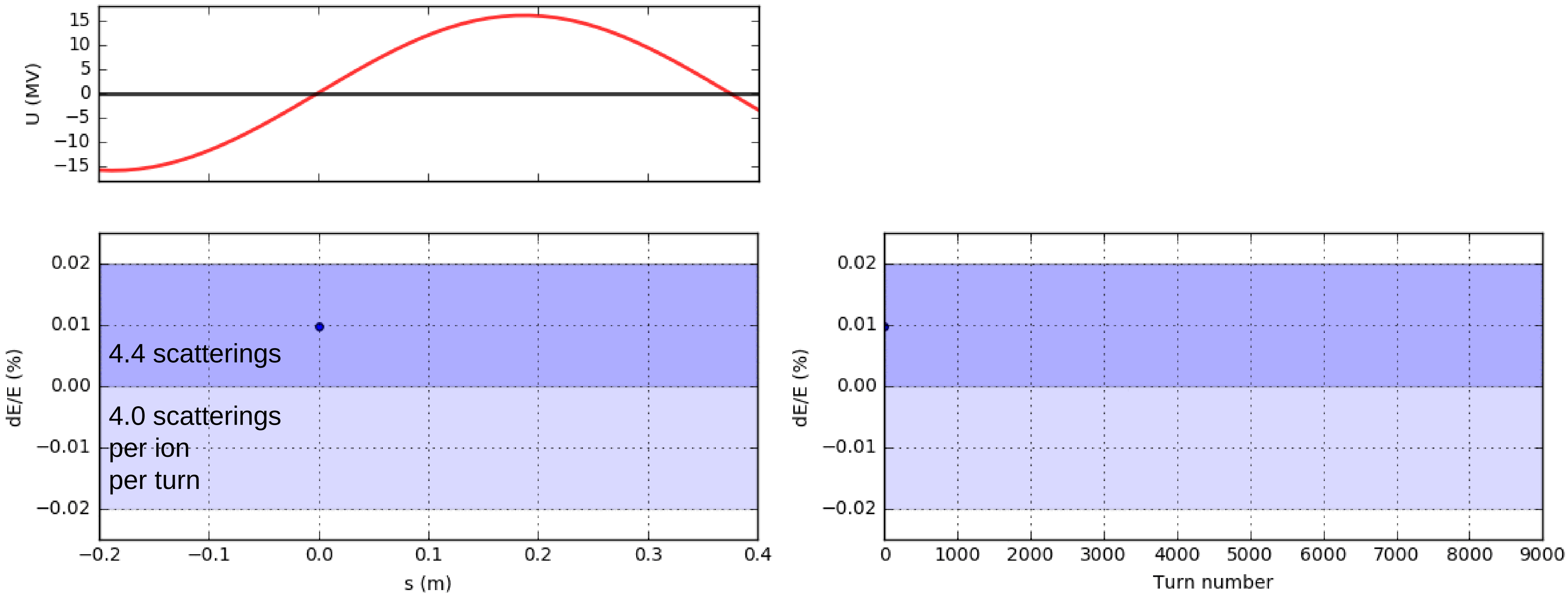
The synchrotron oscillations can be stabilized by a small change in the spectral distribution of the laser beam (or by adding another low-power laser):





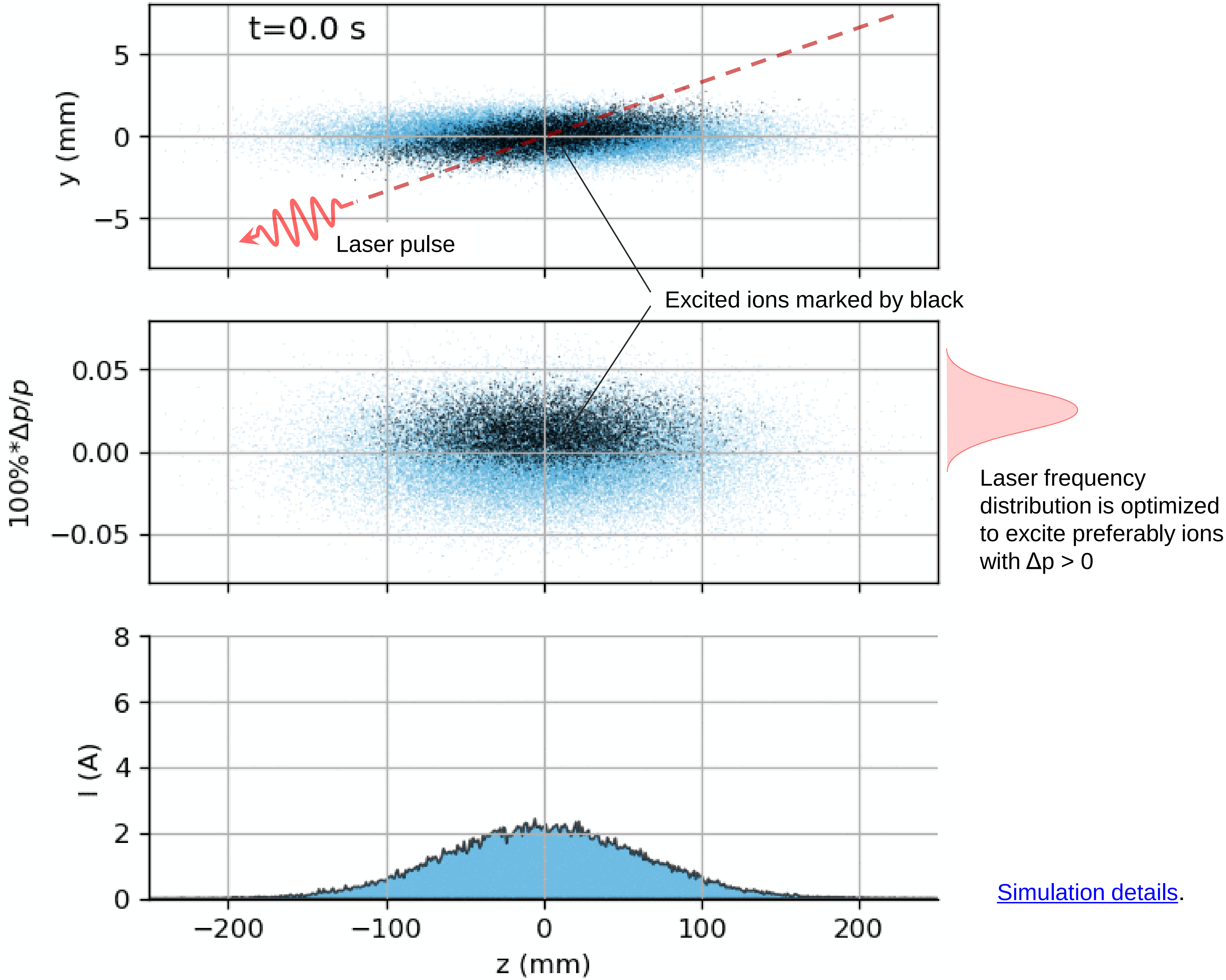
Simulation details: http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

Fast longitudinal cooling



Fast longitudinal cooling idea: E. G. Bessonov, R. M. Feshchenko [Stimulated Radiation Cooling](). RuPAC’2008.

We would like to test this idea with a Li-like Pb beam in the SPS:



[Simulation details](#).

[Gamma Factory Proof-of-Principle Experiment. Letter of Intent.](#) CERN, 2019.

Gamma Factory Proof-of-Principle Experiment at the SPS:

From a recent presentation at Physics Beyond Colliders meeting: https://indico.cern.ch/event/1089151/contributions/4620320/

- Demonstrate integration and operation of a laser and a Fabry-Perot cavity in a hadron storage ring
  - Laser commercially available but limited experience in hadron ring
  - Operation compatible with other ring users
- Benchmark simulations of atomic excitation rates
  - Modelling of laser-ion collisions requires new numerical tools
- Control of ion and photon bunches
  - Control of spatial, time and spectral overlap
- Demonstrate laser cooling of relativistic beams and investigate different approaches
  - Models show different cooling regimes depending on collision scheme
- Investigate feasibility of relativistic atomic physics measurements
  - Accurate and absolute measurement of deep electronic transition energies are highly relevant to fundamental physics

Breakthrough in accelerator physics

Breakthrough in atomic physics

PSI beam	$^{208}\mathrm{Pb}^{79+}$
m – ion mass	193.687 GeV/c^2
E – mean energy	18.652 TeV
$\gamma = E/mc^2$ – mean Lorentz relativistic factor	96.3
N – number ions per bunch	0.9×10^8
σ_E/E – RMS relative energy spread	2×10^{-4}
ϵ_n – normalised transverse emittance	1.5 mm mrad
σ_x – RMS transverse size	1.047 mm
σ_y – RMS transverse size	0.83 mm
σ_z – RMS bunch length	6.3 cm

Gamma Factory Proof-of-Principle Experiment. Letter of Intent. 2019.

Laser	Infrared
λ – wavelength ($\hbar\omega$ – photon energy)	1034 nm (1.2 eV)
σ_λ/λ – RMS relative band spread	2×10^{-4}
U – single pulse energy at IP	5 mJ
σ_L – RMS transverse intensity distribution at IP ($\sigma_L = w_L/2$)	0.65 mm
σ_t – RMS pulse duration	2.8 ps
θ_L – collision angle	2.6 deg
Atomic transition of $^{208}\mathrm{Pb}^{79+}$	$2s \rightarrow 2p_{1/2}$
$\hbar\omega'_0$ – resonance energy	230.81 eV
τ' – mean lifetime of spontaneous emission	76.6 ps
$\hbar\omega_1^{\max}$ – maximum emitted photon energy	44.473 keV

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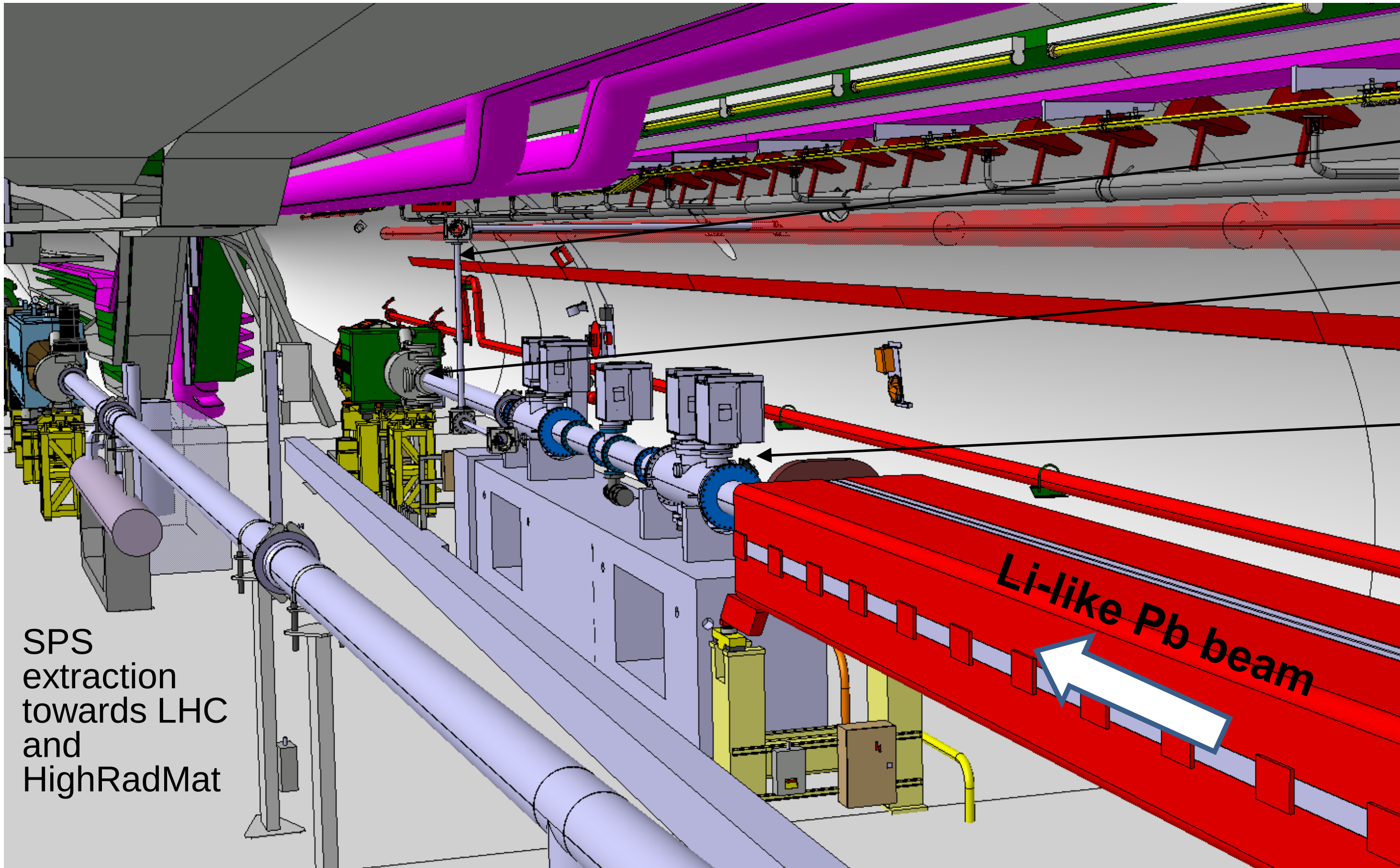

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Gamma Factory Proof-of-Principle Experiment. Letter of Intent. CERN, 2019.

Transverse cooling via dispersive coupling:

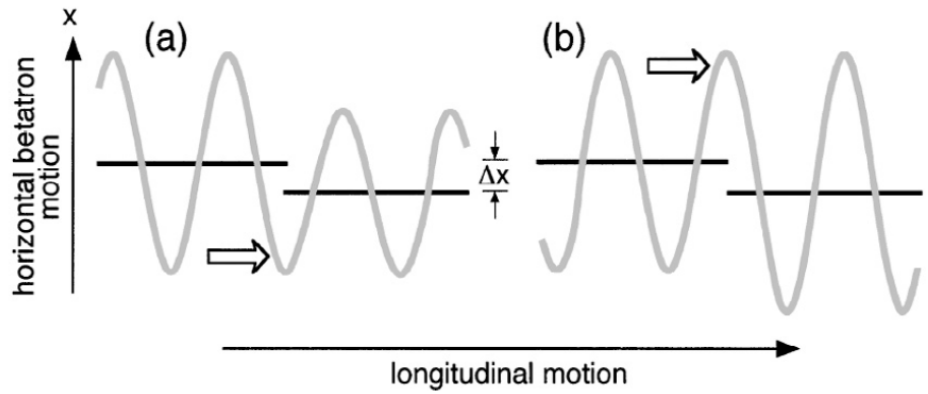


Fig. 7. Horizontal betatron oscillations of a stored ion around the central orbit in a region with positive dispersion. The moment of photon emission and the corresponding change of the central orbit is indicated by the arrow. A reduction of the amplitude of the oscillation occurs when an ion radiates 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] D. Schwalm,[1] and M. Weidemüller[1]
[1] *Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany*
[2] *Ludwig-Maximilians-Universität München, Sektion Physik, 85748 Garching, Germany*
(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:

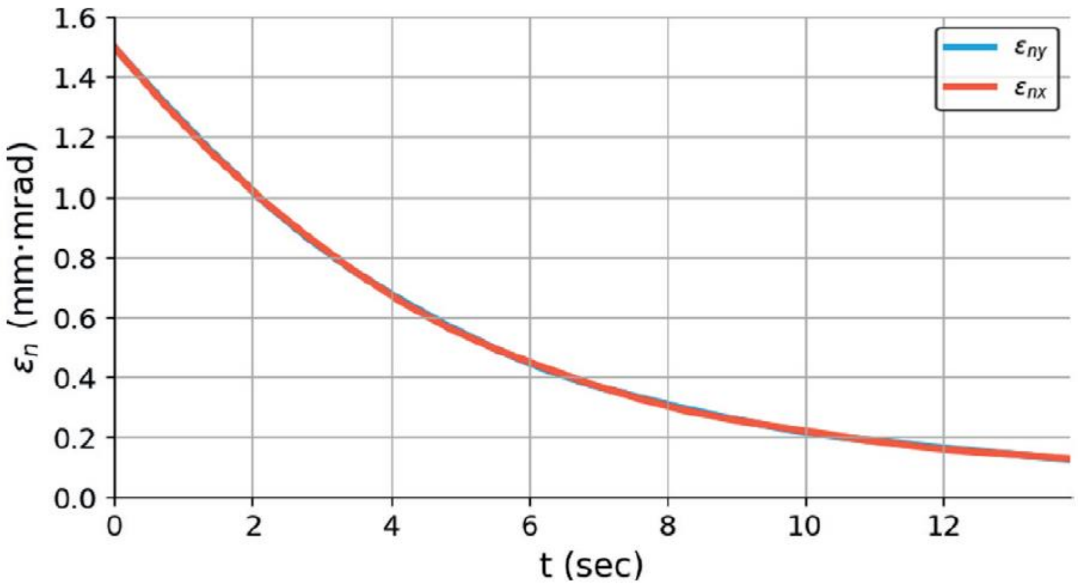


Fig. 11. Transverse cooling speed: the time-evolution curves of the vertical and horizontal emittances are overlapping each other – they are precisely equal when the betatron tunes are on the coupling resonance.

High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams. M. W. Krasny, A. Petrenko, W. Placzek. Progress in Particle and Nuclear Physics 114 (2020) 103792.

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

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. 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).

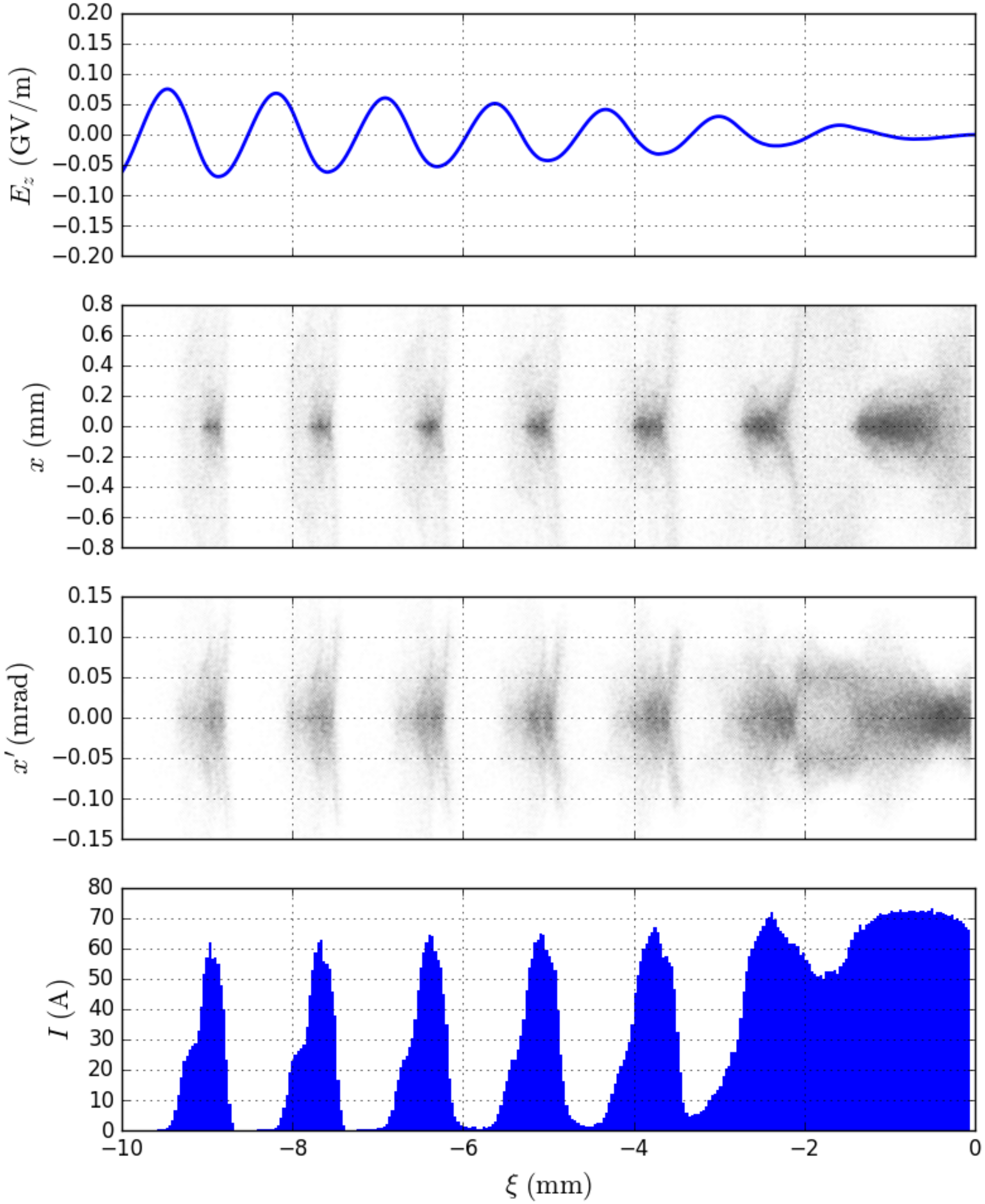
3. Laser cooling of partially stripped ions

Well-developed at low-energy. Cooling is faster at high energy because the energy radiated by the ion grows as γ^2 (assuming different ions/transitions are used). Never tested above few 100 MeV/u.

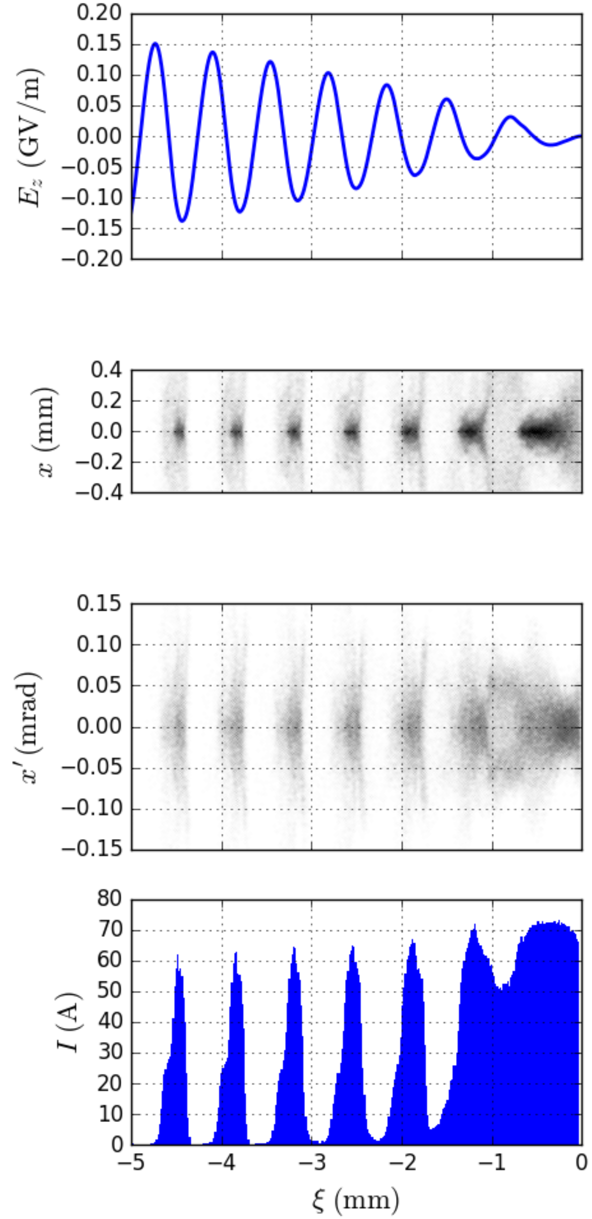
The only low-cost option without large infrastructure investments.

Why ion cooling is interesting for plasma wakefield acceleration: general scaling of PWFA:

$n_{plasma} = 7 \cdot 10^{14}$ cm^{-3}



$n_{plasma} = 4x(7 \cdot 10^{14}$ cm$^{-3})$



2x higher wakefield

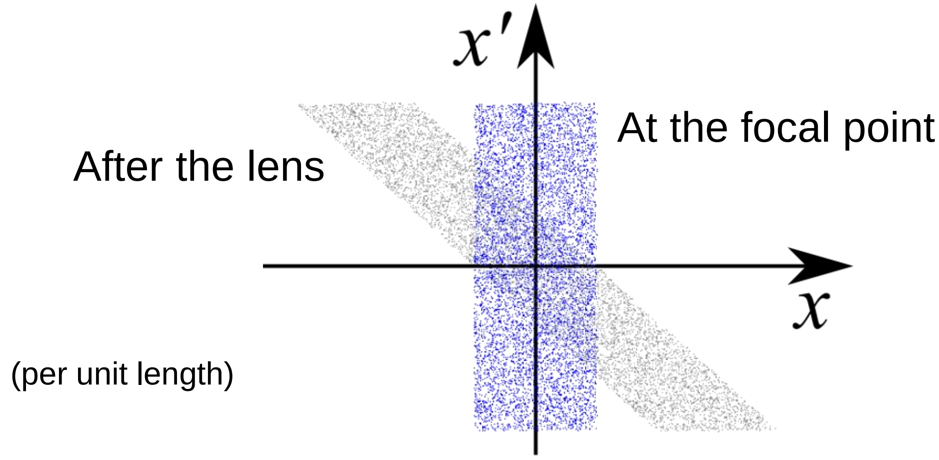
2x smaller transv. size => 4x higher beam density.

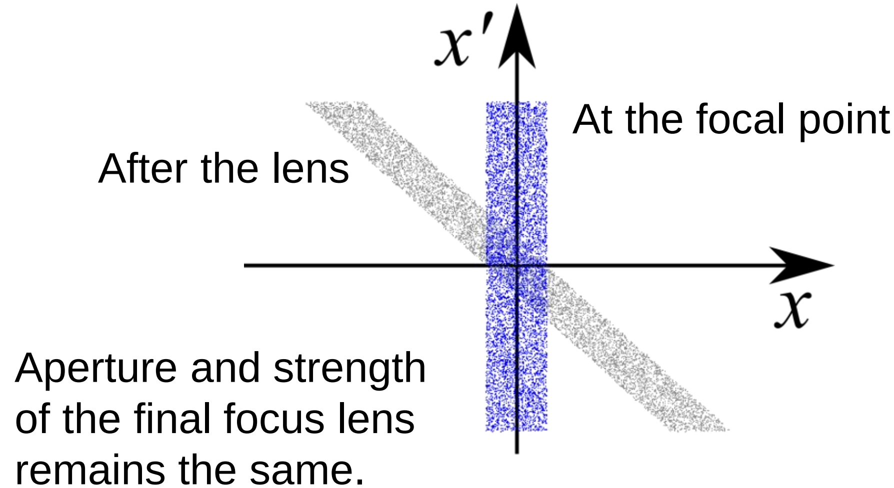
The same angular spread => 2x lower beam emittance required.

The same current => 2x less particles needed to drive 2x higher wake. (Also 2x less accelerated particles).

10x less particles with 10x lower emittance and the same current can potentially drive 10x higher wakefield.
Maximum plasma density is essentially defined by the transverse beam emittance.
Higher peak current is needed to reduce the number of micro-bunches => less strict tolerances on plasma density.

The beam size at the focal point is linearly proportional to the beam emittance (for properly matched beam):





The same scaling applies to a witness beam. This is good for collider luminosity:

$$\mathcal{L} = f\frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

f — frequency of collisions; N_1, N_2 — number of particles in the colliding beams; σ_x, σ_y — transverse sizes of the colliding beams (both beams have the same size).

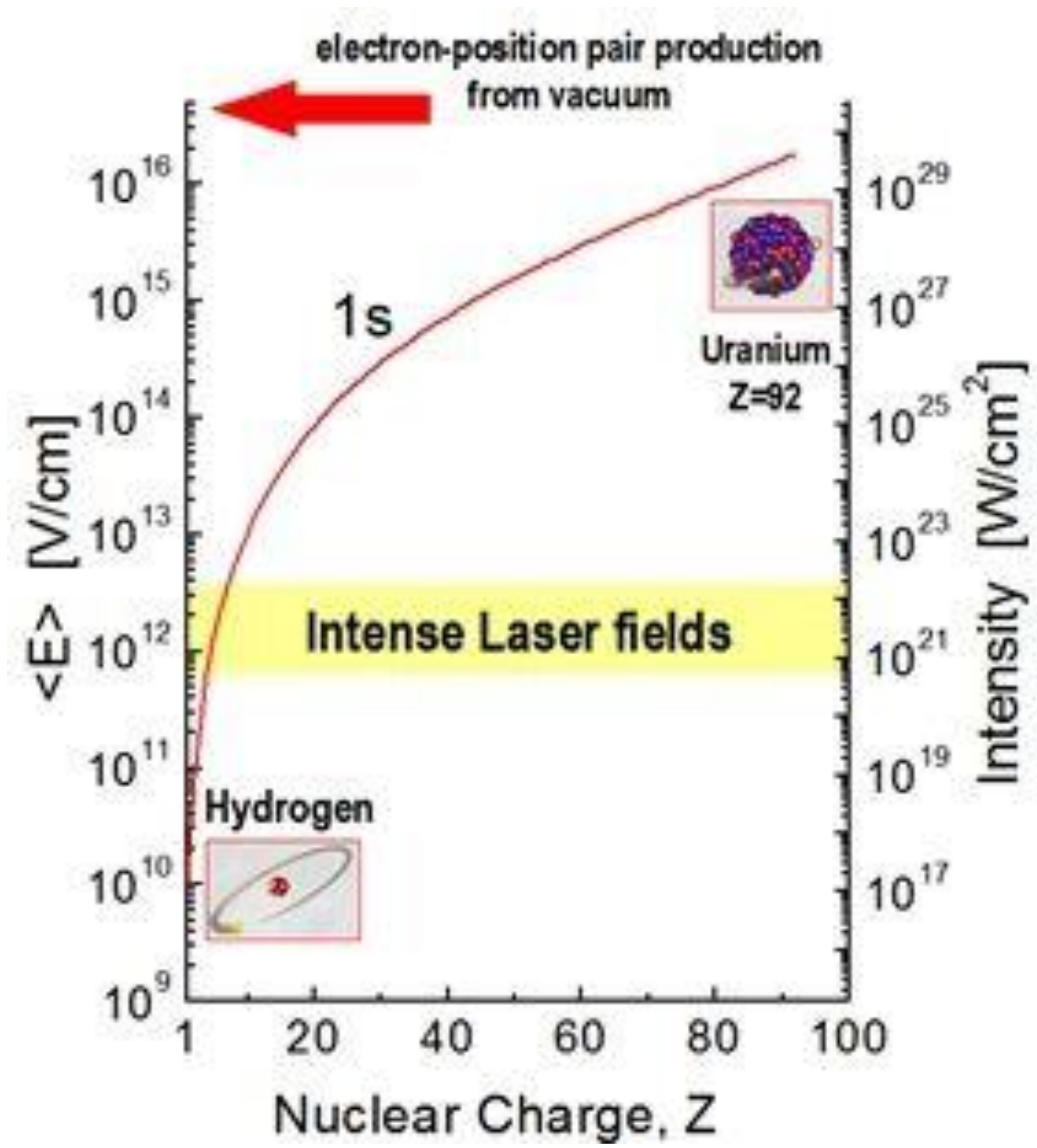
Consider the electron-proton/ion collider for example. If the energy of colliding protons and electrons are the same then electrons will have 2000x higher gamma-factor (and much smaller beam size than colliding protons/ions). Therefore we can assume that the colliding beam size is defined by the proton/ion beam size. In this case **10x smaller emittance (hence 10x smaller size) proton/ion beam will produce 100x higher luminosity.** Cooling is also important for the target proton/ion beam.

The gain in luminosity can be even higher since at low intensity the beam in the ring can be accelerated as a long train of bunches and then extracted bunch-by-bunch. At the high single bunch intensity the number of bunches limited by coupled bunch instabilities.

With a selective fast cooling it might also be possible to cool the bunches one-by-one → first accelerate the maximum possible charge in the SPS/LHC as a long train of bunches and then select small amount of charge from the circulating beam, cool it to the required parameters, and extract the short single bunch towards the high-density plasma accelerator.

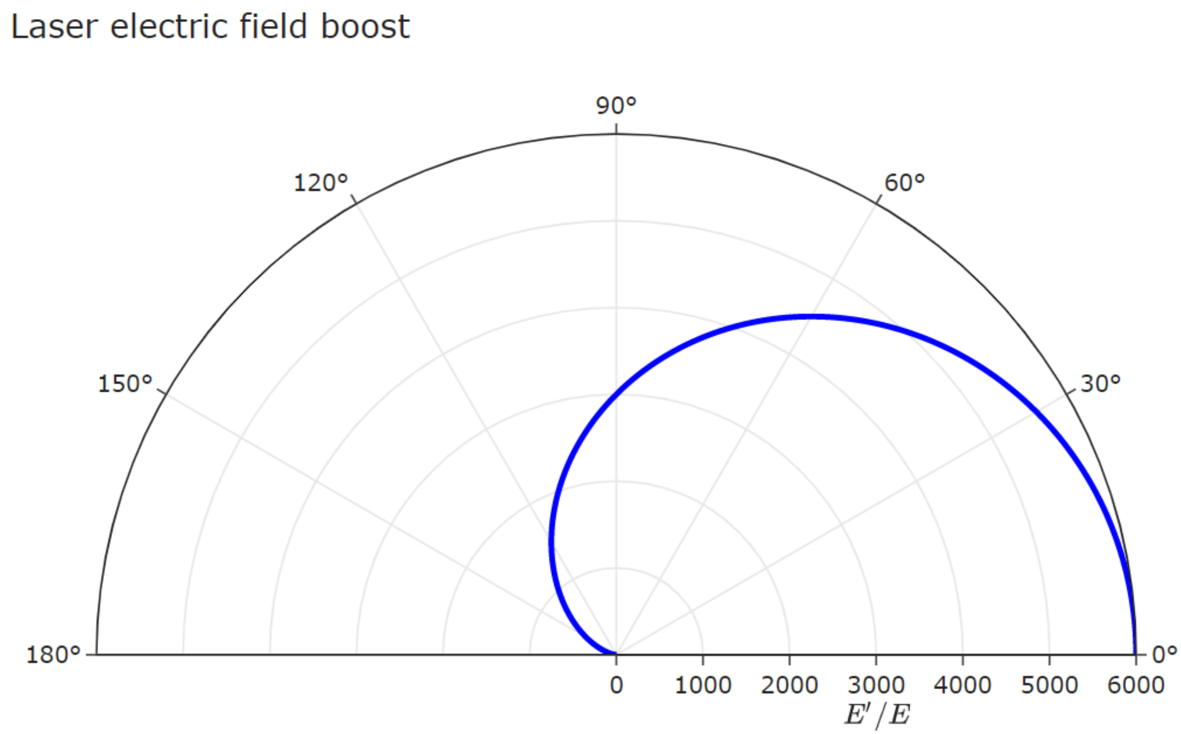
Lorentz boost of the laser field:

Lorentz boost of the laser field to the ion rest frame at the LHC:



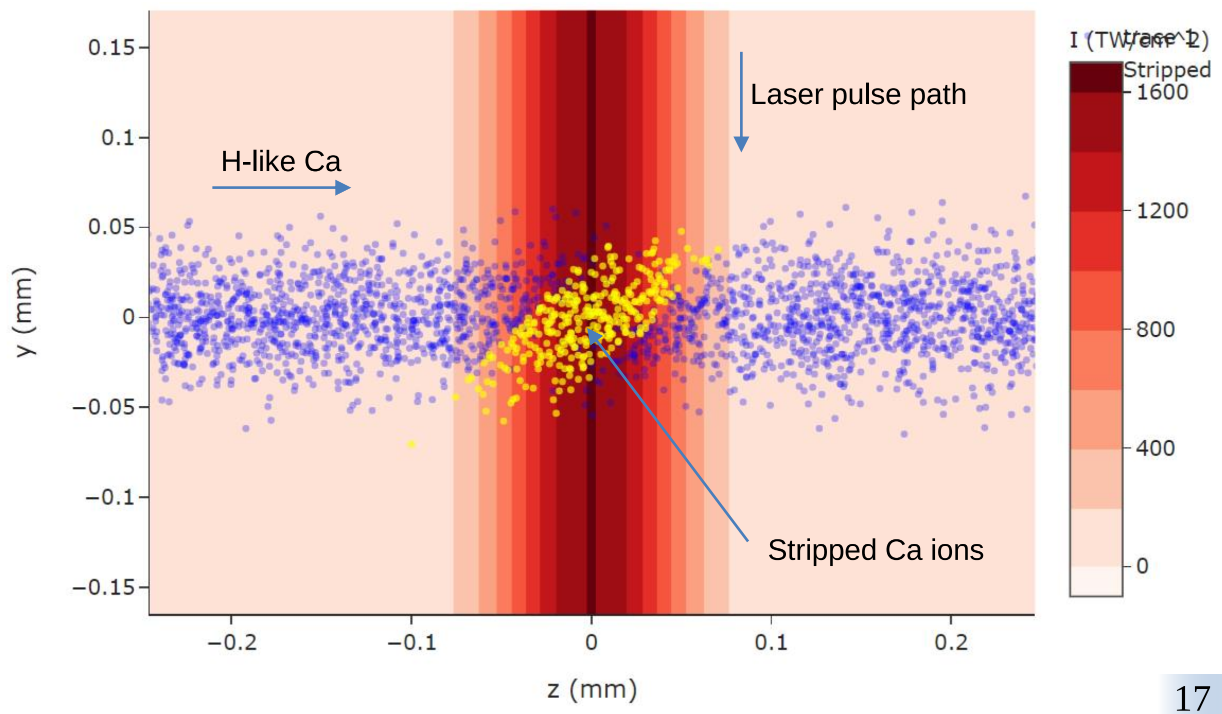
The plot from [T. Stohlker's website](). (2018)

Ion bunch slicing with a short laser pulse:



50 fs long,18 mJ laser pulse focused to w_0 of 75 μm ionizing H-like Ca beam in the LHC at 90-degree angle:

Sequence of such short ion bunches can drive different (plasma / dielectric / metal) wake-field accelerators:



Thanks!

Back-up slides

PWFA-motivation

LHC nominal beam parameters:
(2808 bunches)*(1.15e11 protons)*(7 TeV) = 360 MJ

Fully loaded A320 (80 t) at take-off speed (300 km/h) carries similar amount of kinetic energy (280 MJ).
(However the momentum of the airplane is ~ c/v ~ 10^6 times larger than the LHC beam momentum)

Single LHC proton bunch **(7 TeV, 1.2e11 protons)** carries **130 kJ**
Single SPS proton bunch **(0.4 TeV, 3e11 protons)** carries **19 kJ**
Single ILC electron bunch **(0.5 TeV, 2e10 e+/e-)** carries **1.6 kJ**

Average design beam power of **ILC (11 MW)** is only about **10-20 times higher** than that of **SPS (0.8 MW) and LHC (360 MJ/1000 sec = 0.4 MW)**.

Can we use LHC/SPS beam as a driver to obtain TeV-level (e-/e+/muons) in a single stage?

Such an accelerator probably can't compete with the ILC or CLIC in terms of luminosity but maybe there is some interesting physics at high energy but low luminosity:

A. Caldwell. Collider physics at high energies and low luminosities. Eur. Phys. J. (2014).
A. Caldwell, M. Wing. VHEeP: a very high energy electron–proton collider. Eur. Phys. J. (2016).
-- some electron-proton cross sections grow with energy.

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

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)

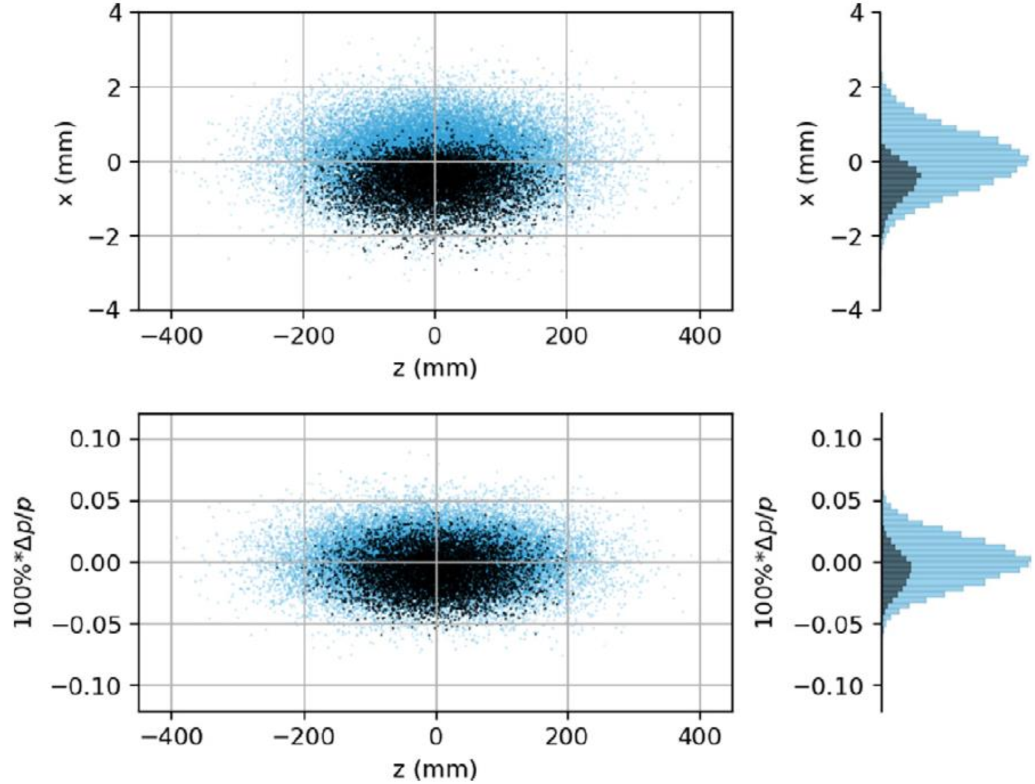


Fig. 9. Distributions of the positions and momenta of the ions interacting with the pulse of the first laser. Excited ions are shown as black dots while non-excited ions are shown as blue dots. The shift of the laser pulse by -1.4 mm provides an optimal coupling of horizontal betatron oscillations to 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)

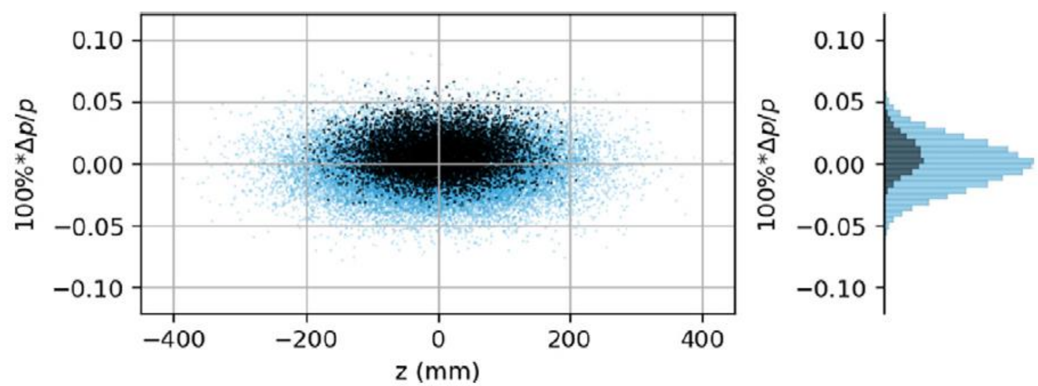
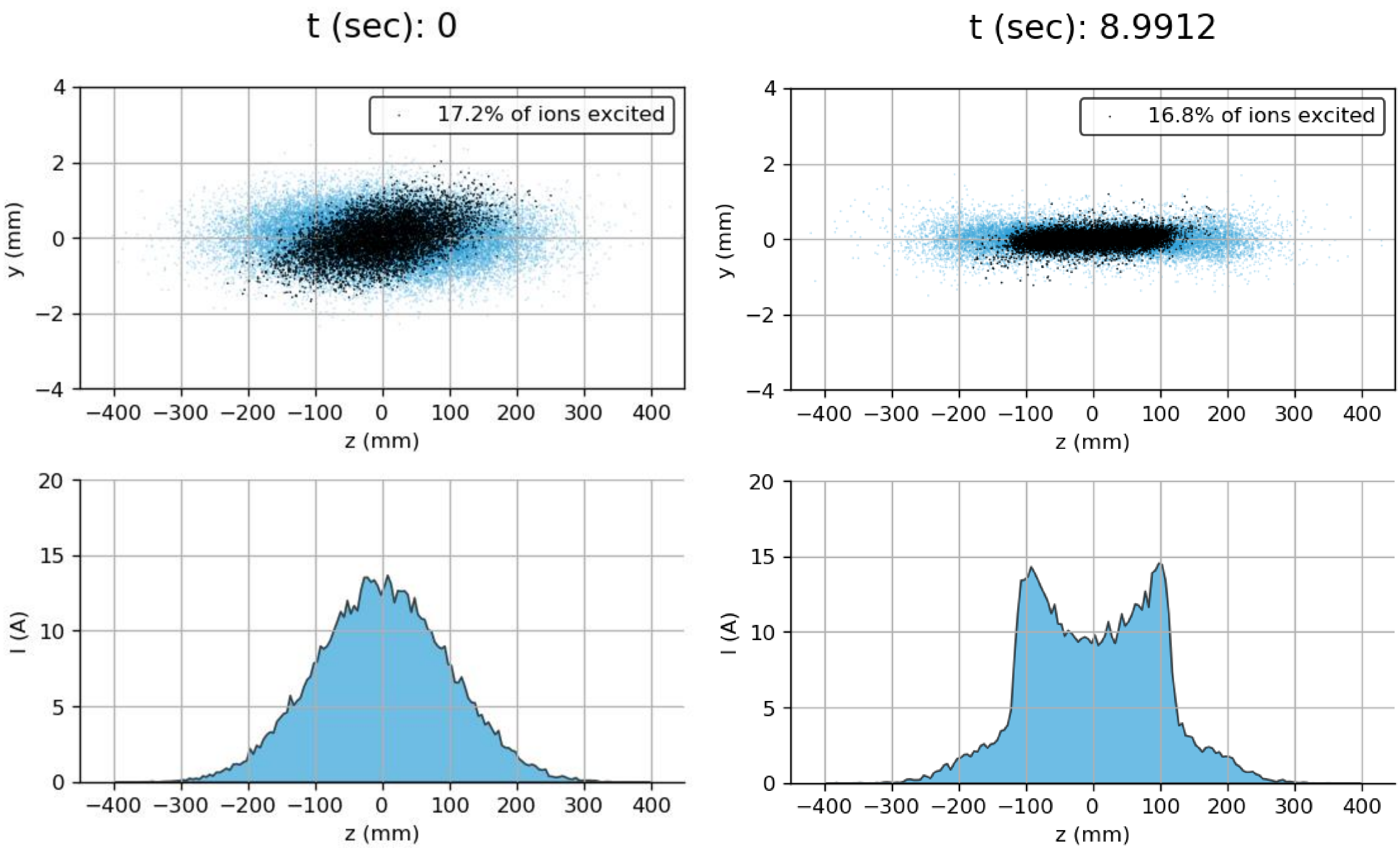


Fig. 10. Distribution of the momentum and longitudinal positions of the ions interacting with the photon-pulse of the second laser. Excited ions are shown as black dots while non-excited ions are shown as blue dots. The laser pulse focal point is aligned with the ion beam centre but its frequency band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

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.**

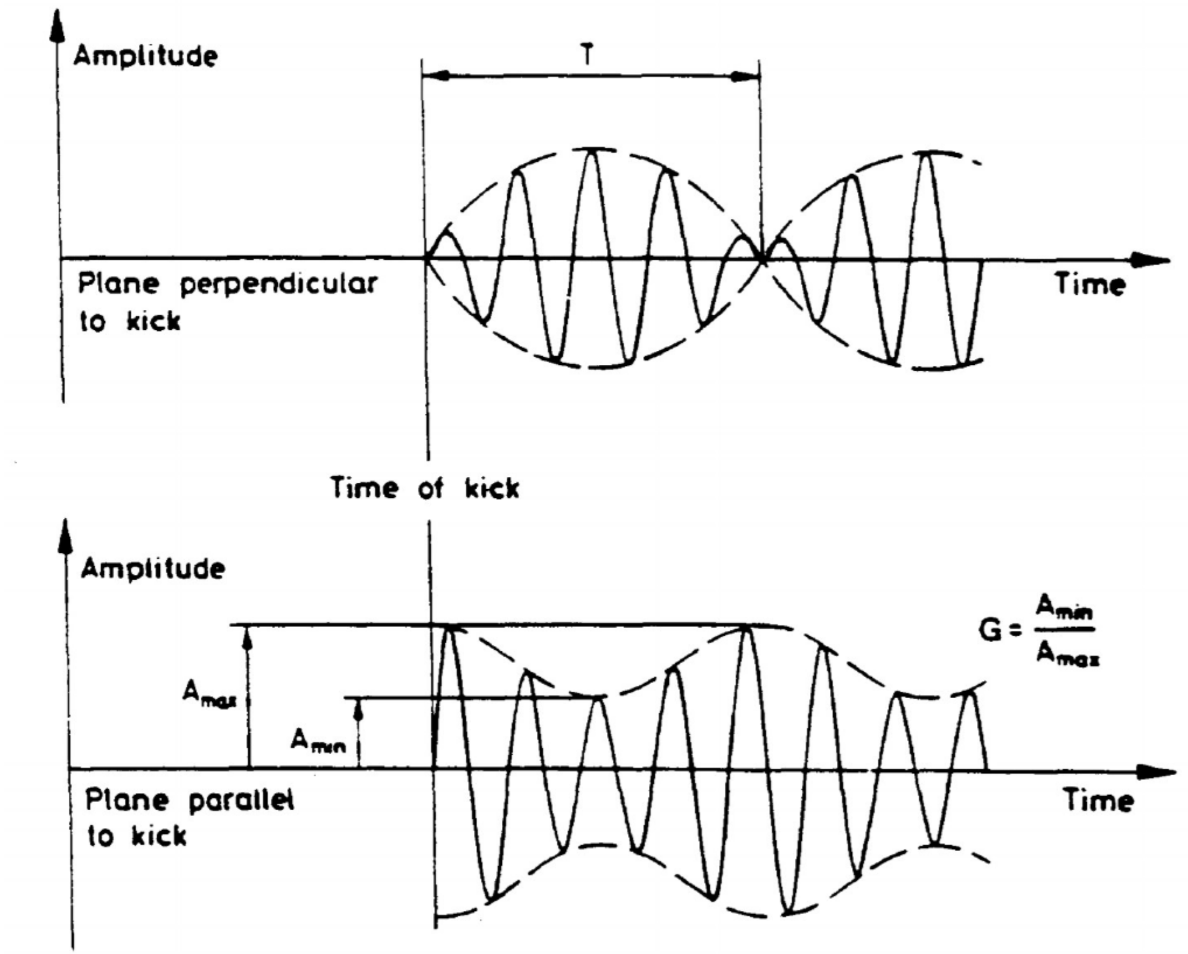


Fig. 1 Coherent oscillations following a horizontal kick

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

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.

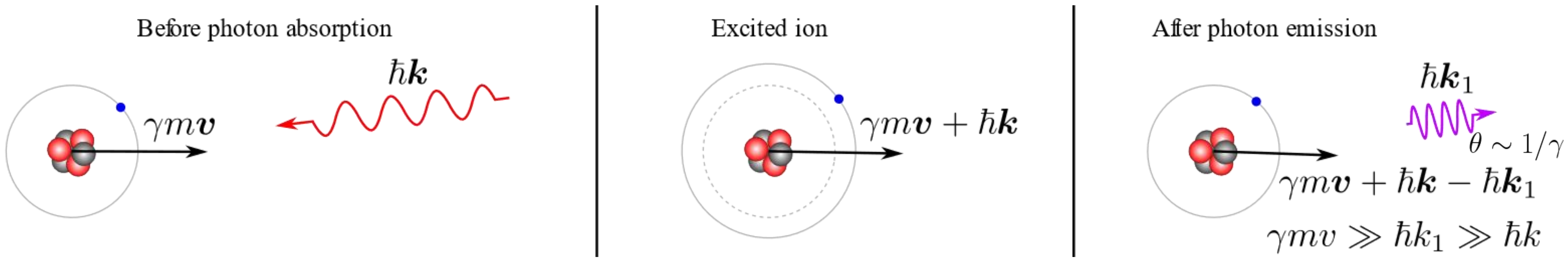
The proton beam intensities corresponded to $\sim 10^{11}$ protons per bunch. The total Pb^{53+} ion beam intensity was only $\sim$ (3-5) $\times$ 10^{9} charges.

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

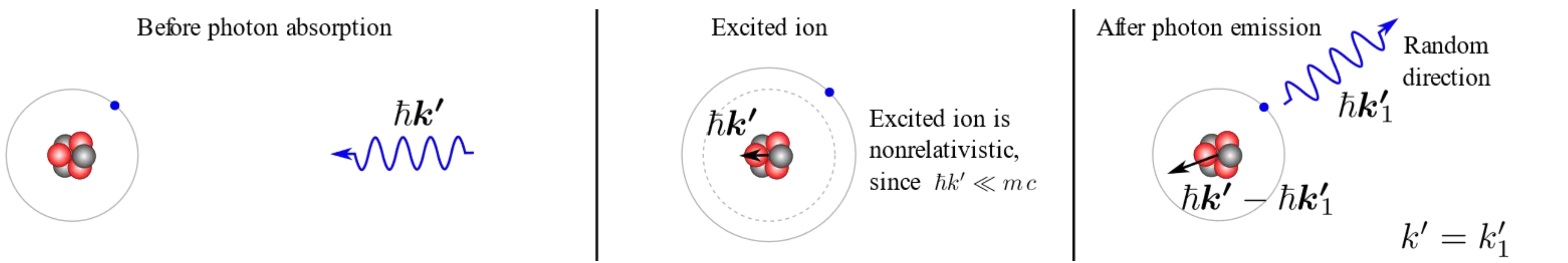
Possible variant: Xe^{47+} (7 electrons left, N-like). γ = 162. Atomic excitation ${}^4S_{3/2} \rightarrow {}^4P_{3/2}$. Krypton laser: 647 nm (1.87 eV) will be converted to gamma-photons with E_{max} = 196 keV. $I_{sat.}$ = $1.7\cdot10^8$ W/cm^2 , decay length = 3.4 cm => with a 1 mm wide beam to have 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:

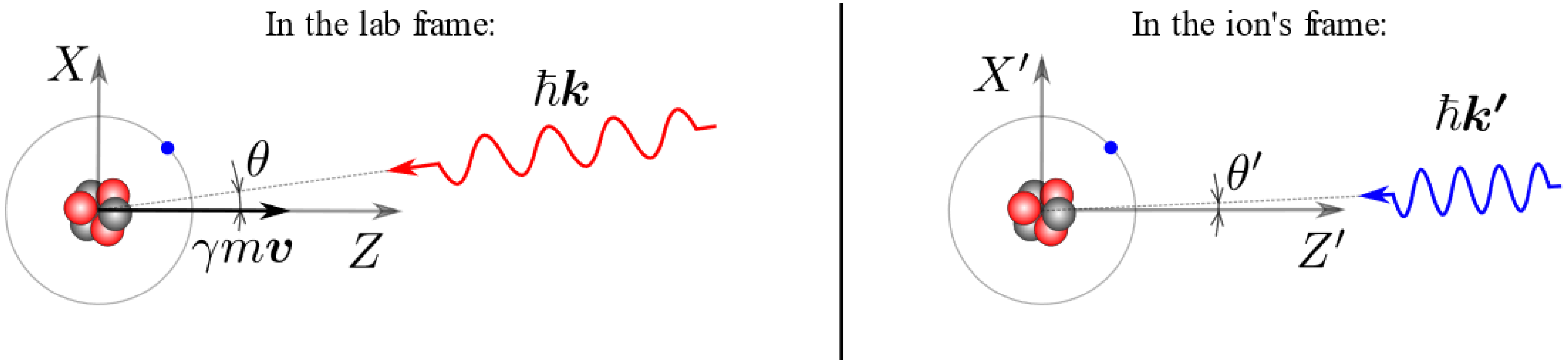


Longitudinal cooling: because energy loss grows with ion energy:

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:

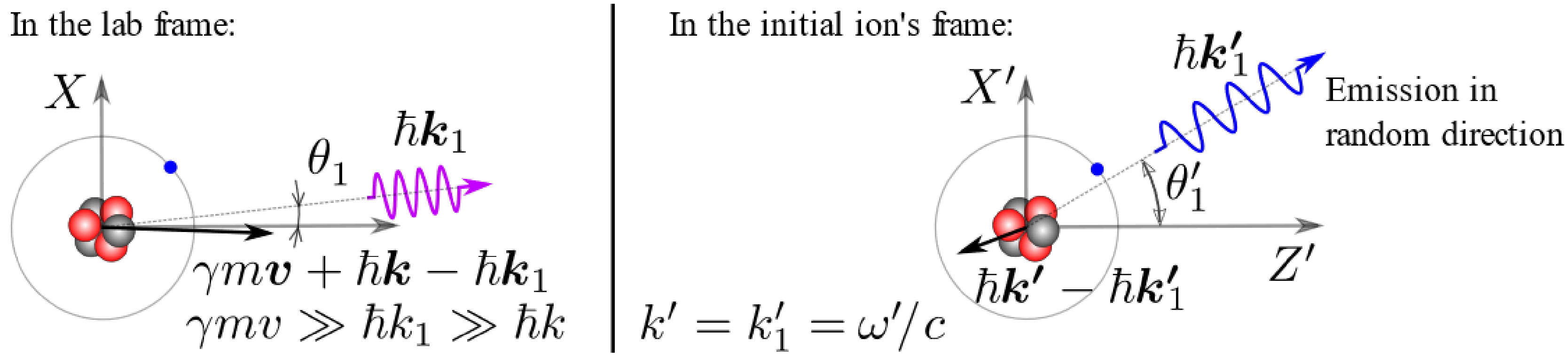
$$\begin{pmatrix} E'/c \\ p'_x \\ p'_y \\ p'_z \end{pmatrix} = \begin{pmatrix} \gamma & 0 & 0 & -\beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\beta\gamma & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} E/c \\ p_x \\ p_y \\ p_z \end{pmatrix}$$

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 $\omega_1 = \gamma(1 + \beta\cos\theta'_1)\omega' \approx 2\gamma^2(1 + \beta\cos\theta'_1)\omega$.

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