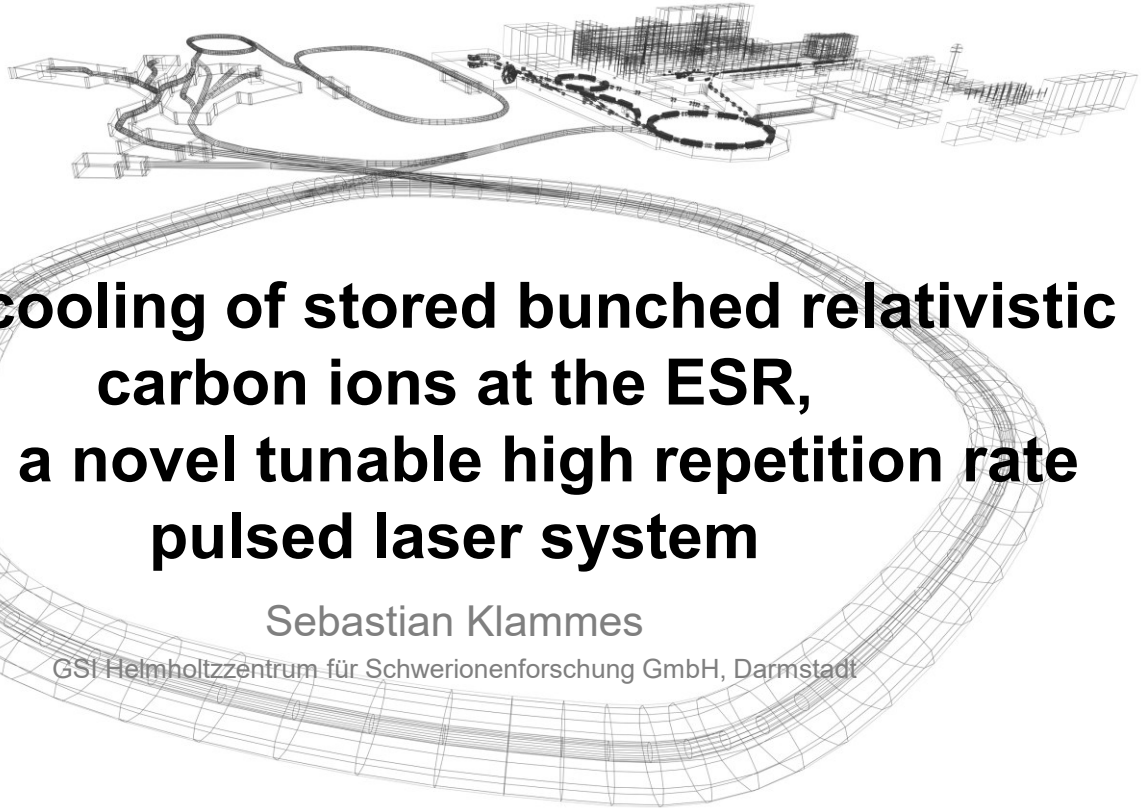


Laser cooling of stored bunched relativistic carbon ions at the ESR, using a novel tunable high repetition rate pulsed laser system

Sebastian Klammes

GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt

Laser cooling collaboration

- GSI

  Sebastian Klammes, Thomas Kühl, Peter Spiller, Markus Steck, Thomas Stöhlker[1], Danyal Winters

  ([1]also HI Jena & Uni Jena)

- HZDR, TU Dresden

  Michael Bussmann[2], Markus Löser, Mathias Siebold, Ulrich Schramm

  ([2]also CASUS Görlitz)

- TU Darmstadt

  Lewin Eidam, Jens Gumm, Daniel Kiefer, Benedikt Langfeld[3], Thomas Walther[3]

  ([3]also HFHF Frankfurt am Main, Campus Darmstadt)

- Uni Münster

  Volker Hannen, Ken Ueberholz, Christian Weinheimer

- IMP-CAS, Lanzhou, China

  Dongyang Chen, Zhongkui Huang, Xinwen Ma, Hanbing Wang, Weiqiang Wen

➢ **SIS100 laser cooling work package**

Contents

- Motivation: laser cooling in accelerators
- Principle of laser cooling
- Experimental setup
- Results from laser cooling at GSI / ESR (2021)

Contents

- Motivation: laser cooling in accelerators
- Principle of laser cooling
- Experimental setup
- Results from laser cooling at GSI / ESR (2021)

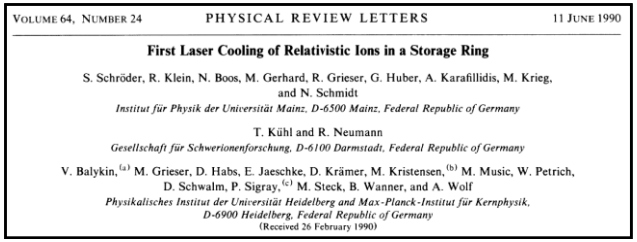
Motivation for laser cooling

- interdisciplinary
  - accelerator, atomic research and laser physics
- fundamental aspects of very cold ion beams
  - coupling, ordering
- advantages of cold ion beams
  - low momentum spread, low emittance, short bunches
- worldwide unique @ SIS100

  opportunity: laser spectroscopy
  - find transition, measure transition preciseley

we do not aim for crystalline ion beams
nor for transverse cooling!

Historical background of laser cooling in accelerators



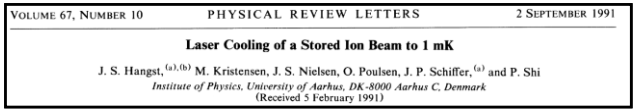
VOLUME 64, NUMBER 24 PHYSICAL REVIEW LETTERS 11 JUNE 1990

First Laser Cooling of Relativistic Ions in a Storage Ring

S. Schröder, R. Klein, N. Boos, M. Gerhard, R. Grieser, G. Huber, A. Karafillidis, M. Krieg, and N. Schmidt
Institut für Physik der Universität Mainz, D-6500 Mainz, Federal Republic of Germany

T. Kühl and R. Neumann
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Federal Republic of Germany

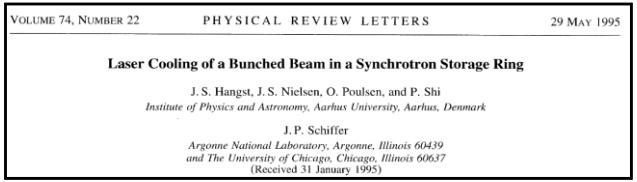
V. Balykin,[(a)] M. Grieser, D. Habs, E. Jaeschke, D. Krämer, M. Kristensen,[(b)] M. Music, W. Petrich, D. Schwalm, P. Sigray,[(c)] M. Steck, B. Wanner, and A. Wolf
Physikalisches Institut der Universität Heidelberg and Max-Planck-Institut für Kernphysik, D-6900 Heidelberg, Federal Republic of Germany
(Received 26 February 1990)



VOLUME 67, NUMBER 10 PHYSICAL REVIEW LETTERS 2 SEPTEMBER 1991

Laser Cooling of a Stored Ion Beam to 1 mK

J. S. Hangst,[(a),(b)] M. Kristensen, J. S. Nielsen, O. Poulsen, J. P. Schiffer,[(a)] and P. Shi
Institute of Physics, University of Aarhus, DK-8000 Aarhus C, Denmark
(Received 5 February 1991)

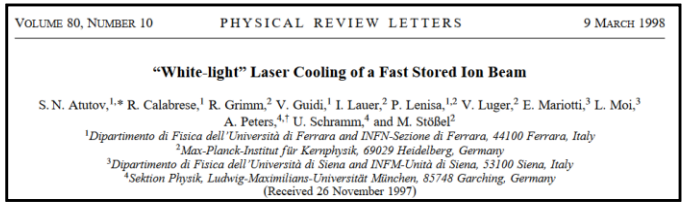


VOLUME 74, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY 1995

Laser Cooling of a Bunched Beam in a Synchrotron Storage Ring

J. S. Hangst, J. S. Nielsen, O. Poulsen, and P. Shi
Institute of Physics and Astronomy, Aarhus University, Aarhus, Denmark

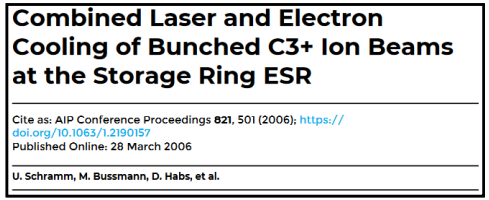
J. P. Schiffer
Argonne National Laboratory, Argonne, Illinois 60439
and The University of Chicago, Chicago, Illinois 60637
(Received 31 January 1995)



VOLUME 80, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1998

"White-light" Laser Cooling of a Fast Stored Ion Beam

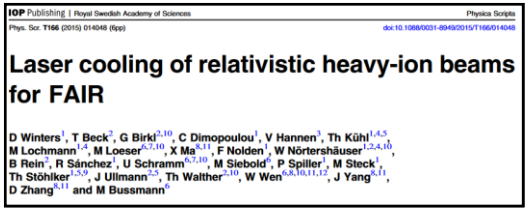
S. N. Atutov,[1,*] R. Calabrese,[1] R. Grimm,[2] V. Guidi,[1] I. Lauer,[2] P. Lenisa,[1,2] V. Luger,[2] E. Mariotti,[3] L. Moi,[3] A. Peters,[4,†] U. Schramm,[4] and M. Stößel[2]
[1]*Dipartimento di Fisica dell'Università di Ferrara and INFN-Sezione di Ferrara, 44100 Ferrara, Italy*
[2]*Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany*
[3]*Dipartimento di Fisica dell'Università di Siena and INFM-Unità di Siena, 53100 Siena, Italy*
[4]*Sektion Physik, Ludwig-Maximilians-Universität München, 85748 Garching, Germany*
(Received 26 November 1997)



Combined Laser and Electron Cooling of Bunched C3+ Ion Beams at the Storage Ring ESR

Cite as: AIP Conference Proceedings **821**, 501 (2006); https://doi.org/10.1063/1.2190157
Published Online: 28 March 2006

U. Schramm, M. Bussmann, D. Habs, et al.



IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta
Phys. Scr. T166 (2015) 014048 (6pp) doi:10.1088/0031-8949/2015/T166/014048

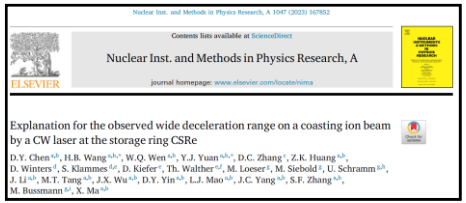
Laser cooling of relativistic heavy-ion beams for FAIR

D Winters[1], T Beck[2], G Birkl[2,10], C Dimopoulou[1], V Hannen[3], Th Kühl[1,4,5], M Lochmann[1,4], M Loeser[6,7,10], X Ma[8,11], F Nolden[1], W Nörtershäuser[1,2,4,10], B Rein[2], R Sánchez[1], U Schramm[6,7,10], M Siebold[6], P Spiller[1], M Steck[1], Th Stöhlker[1,5,9], J Ullmann[2,5], Th Walther[2,10], W Wen[6,8,10,11,12], J Yang[8,11], D Zhang[8,11] and M Bussmann[6]

Nuclear Inst. and Methods in Physics Research, A 887 (2018) 103–113
Contents lists available at ScienceDirect
Nuclear Inst. and Methods in Physics Research, A
journal homepage: www.elsevier.com/locate/nima

Cooling rates and intensity limitations for laser-cooled ions at relativistic energies

Lewin Eidam[a,*], Oliver Boine-Frankenheim[a,b], Danyal Winters[b]

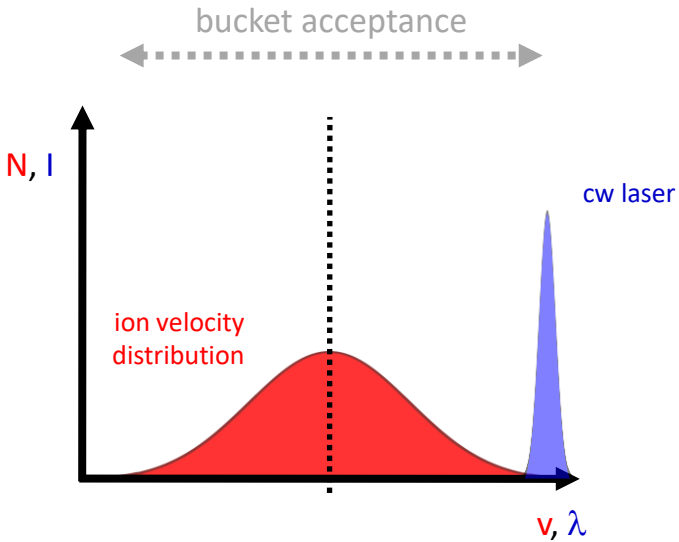


Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167852
Contents lists available at ScienceDirect
Nuclear Inst. and Methods in Physics Research, A
journal homepage: www.elsevier.com/locate/nima

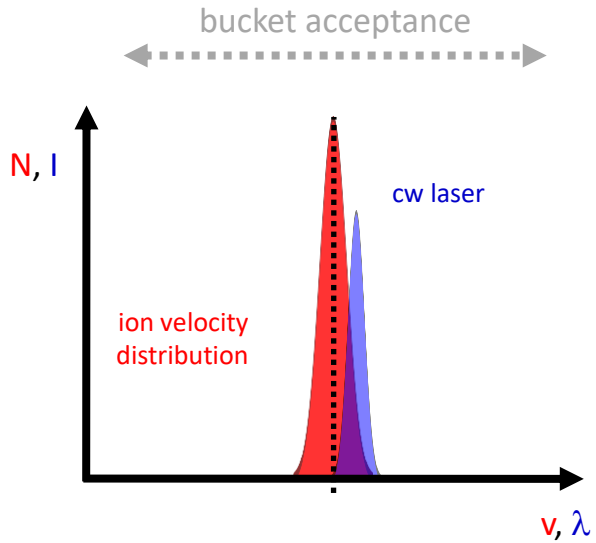
Explanation for the observed wide deceleration range on a coasting ion beam by a CW laser at the storage ring CSRe

D.Y. Chen[a,b], H.B. Wang[b,c,*], W.Q. Wen[a,b], Y.J. Yuan[a,b,c], D.C. Zhang[c], Z.K. Huang[a,b], D. Winters[d,e], S. Klammes[d,e], D. Kiefer[e,f], Th. Walther[e,f], M. Loeser[g], M. Siebold[g], U. Schramm[g,h], J. Li[a,b], M.T. Tang[a,b], J.X. Wu[a,b], D.Y. Yin[a,b], L.J. Mao[a,b], J.C. Yang[a,b], S.F. Zhang[a,b], M. Bussmann[g,i], X. Ma[a,b]

Laser cooling of relativistic ions



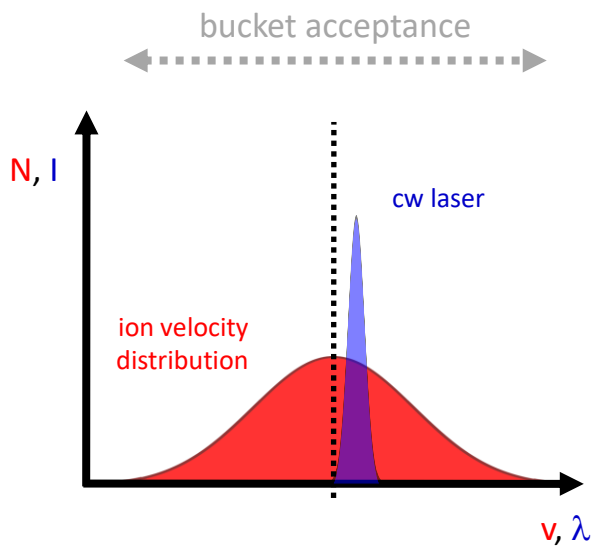
Laser cooling of relativistic ions



final momentum spread $\frac{\Delta p}{p}$ & minimum bunch length depends on intensity effects of the ion beam:

- **intra beam scattering**
- **space charge**

Laser cooling of relativistic ions



final momentum spread $\frac{\Delta p}{p}$ & minimum bunch length depends on intensity effects of the ion beam:

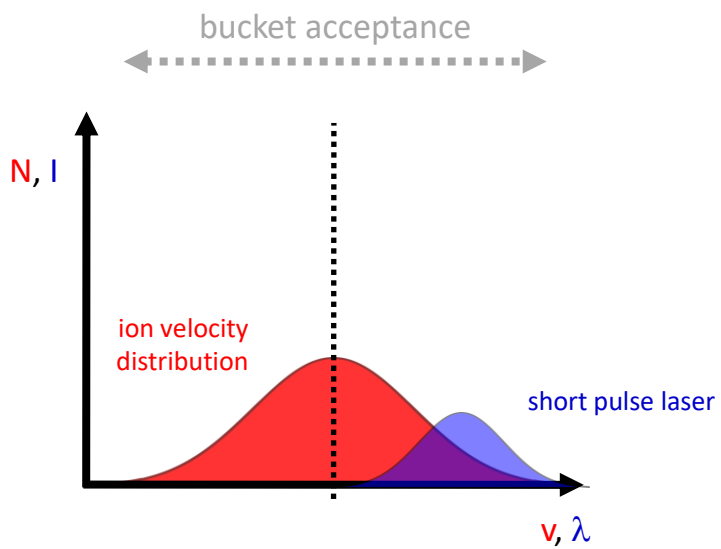
- **intra beam scattering**
- **space charge**

beam dynamics or collective effects could broaden the ion velocity distribution

- new laser scan needed!

– cw laser does not interact with all ions simultaneously

Laser cooling of relativistic ions



width of laser force: $\sigma_{laser} \propto \frac{1}{\tau_{pulse}}$

lowest attainable momentum spread: $\frac{\Delta p}{p} \propto \sigma_{laser}$

Contents

- Motivation: laser cooling in accelerators
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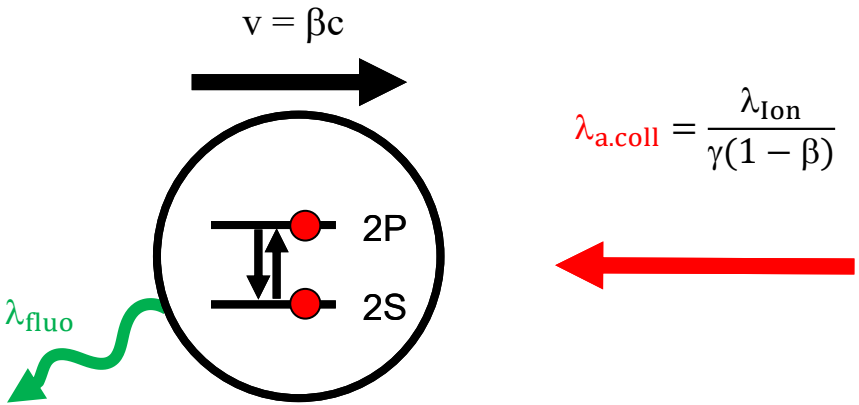
Principle of laser cooling of relativistic bunched ion beams

ESR experiment (2021):
$^{12}C^{3+} \rightarrow \beta \approx 0.47, \gamma \approx 1.13$

one laser:
only deceleration possible!



$$\lambda_{a.coll} = \frac{\lambda_{Ion}}{\gamma(1-\beta)}$$

$\lambda_{Ion} \approx 155$ nm

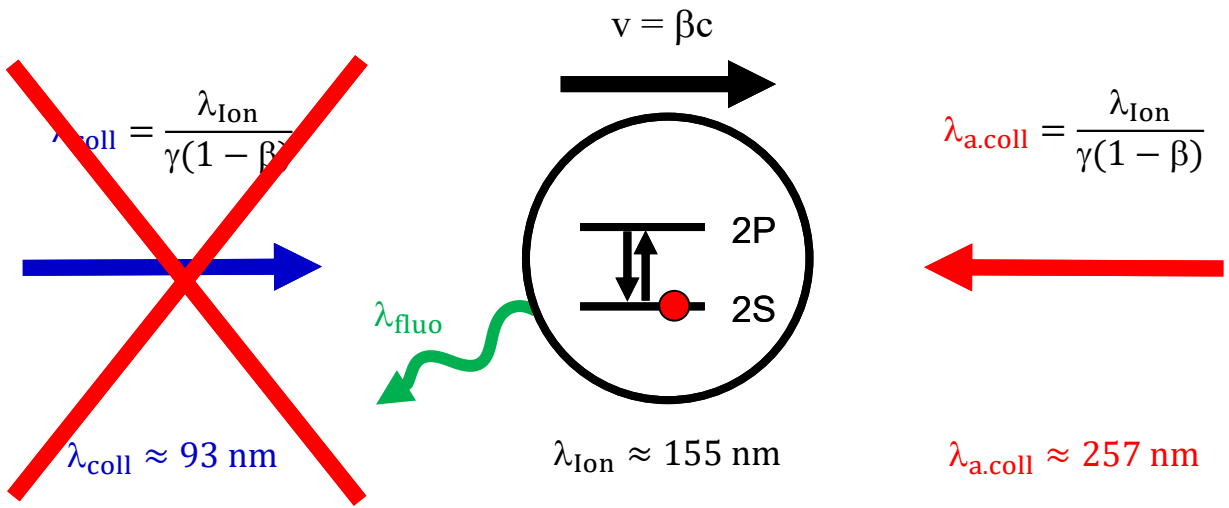
$\lambda_{a.coll} \approx 257$ nm

The ion absorbs many directional momenta from the photons and decays each time with a random recoil, averaging out to zero.

Principle of laser cooling of relativistic bunched ion beams

ESR experiment (2021):
$^{12}C^{3+} \rightarrow \beta \approx 0.47, \gamma \approx 1.13$

one laser:
only deceleration possible!

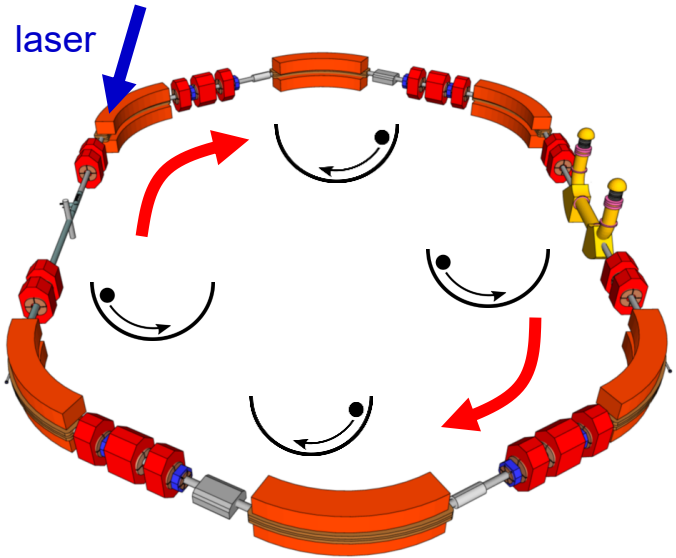


not feasible yet

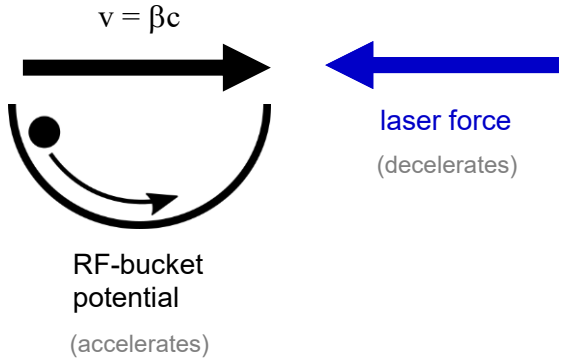
The ion absorbs many directional momenta from the photons and decays each time with a random recoil, averaging out to zero.

Counteracting RF-Bunching vs. laser force

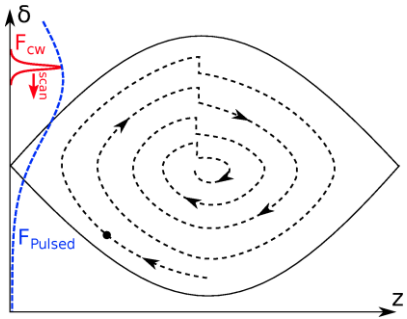
$$f_{bunching} = h \cdot f_{rev} \rightarrow h \text{ bunches}$$



with kind permission of R. Sánchez. GSI Darmstadt (private communication, 2022)



➢ damping of synchrotron oscillations to the velocity dependent equilibrium



L. Eidam, O. Boine-Frankenheim, D. Winters
Nucl. Instr. Meth. A A **887**, 102 (2018)

Contents

- Motivation: laser cooling in accelerators
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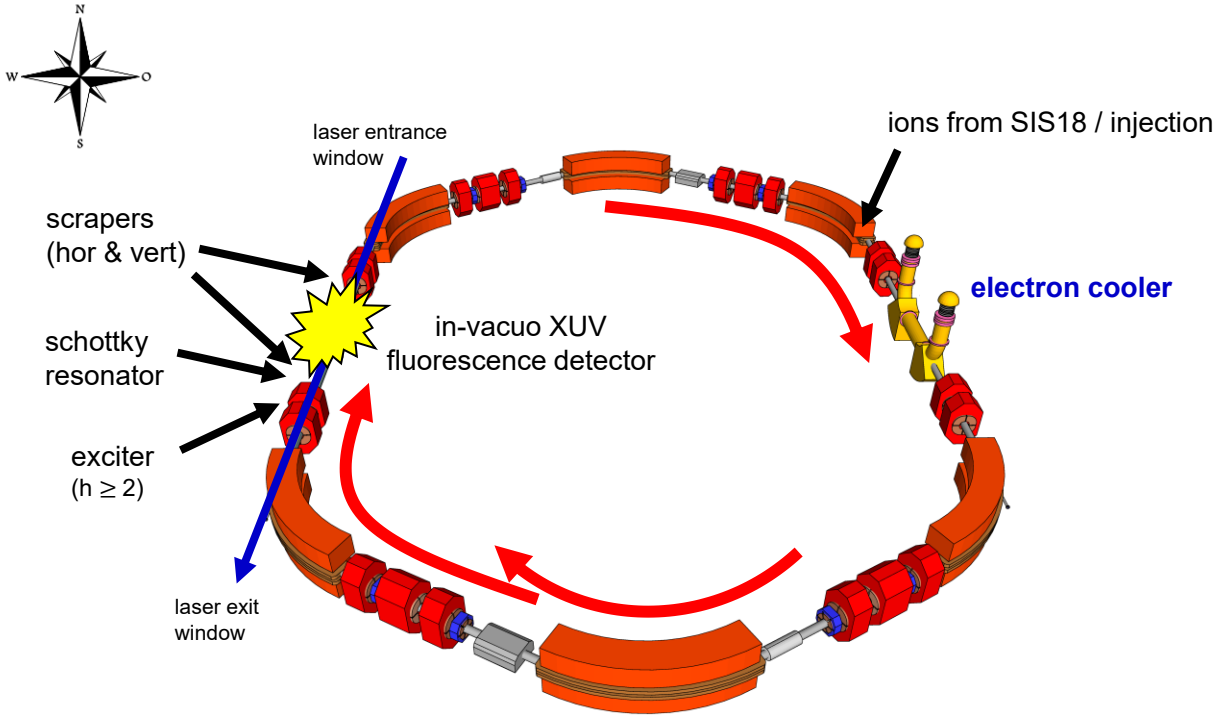
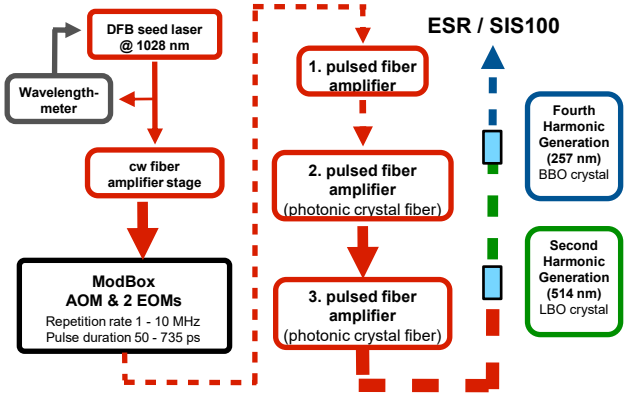
Experimental setup for laser cooling at the ESR

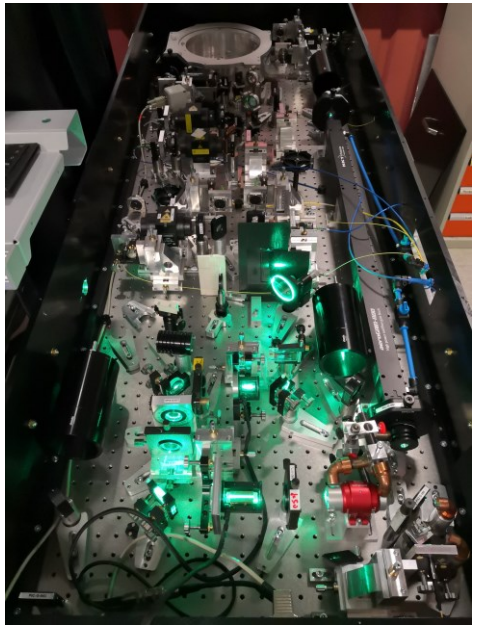


with kind permission of R. Sánchez. GSI Darmstadt (private communication, (2022)

Long Pulse Laser System (TU Darmstadt)

- tunable distributed feedback laser (DFB) as seed laser @ 1028 nm
- transform limited pulses with **1-10 MHz repetition rate** and **50-735 ps pulse duration**
- multi-stage pulsed fiber amplifiers to generate up to **60 W average IR power**
- two single pass stages to generate 514 nm and **257 nm**
- up to **4.1 W UV power** (115ps, 10 MHz) could be demonstrated

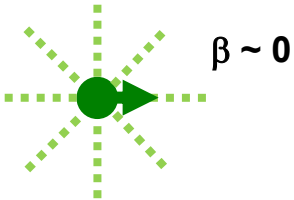




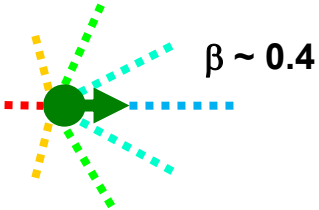
BMBF funding:
group of
Prof. Thomas Walther
(TU Darmstadt)

➢ successful demonstration of the first broadband laser cooling at ESR during G-PAC approved (A^-) experiment in 2021

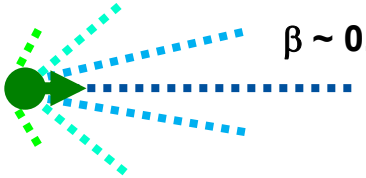
Moveable in-vacuo XUV fluorescence detection system



β ~ 0

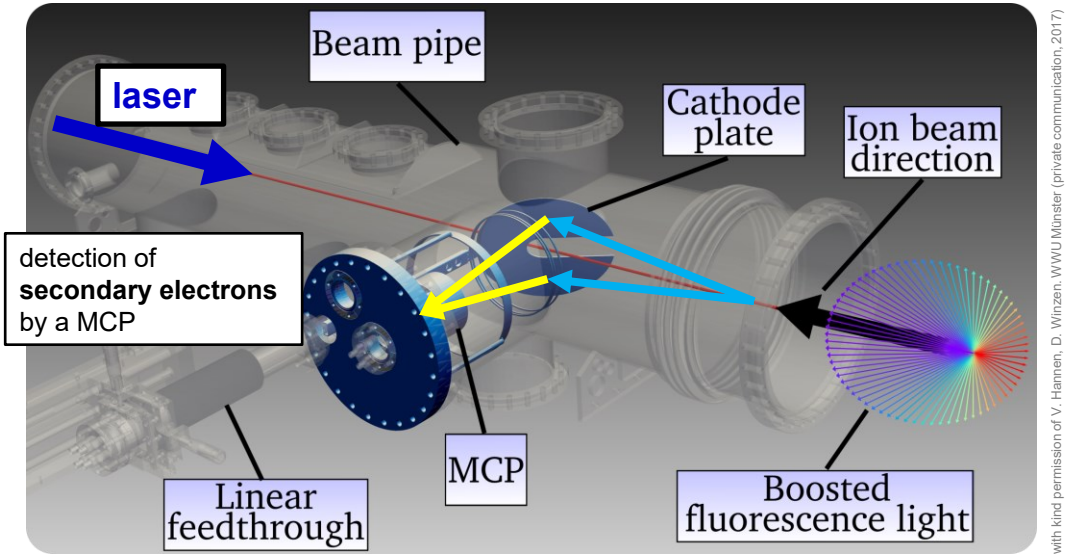


β ~ 0.4



β ~ 0.8

BMBF funding:
group of
Prof. Christian Weinheimer
(Uni Münster)



with kind permission of V. Hannen, D. Winzen, WWU Münster (private communication, 2017)

Contents

- Motivation: laser cooling in accelerators
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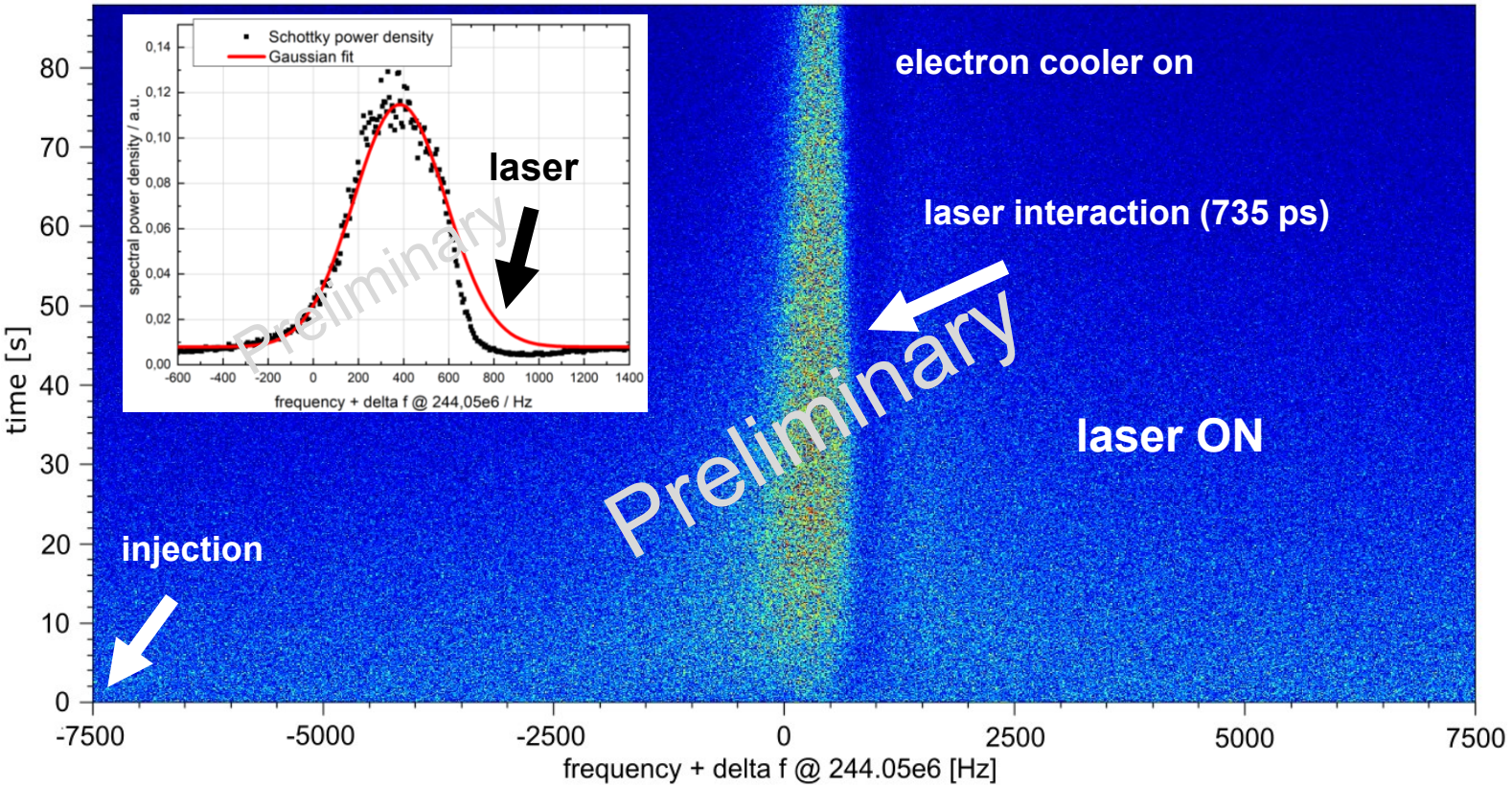
C^{3+} Beam Experiment at the ESR (11.5.2021 – 16.5.2021)

coasting ion beam

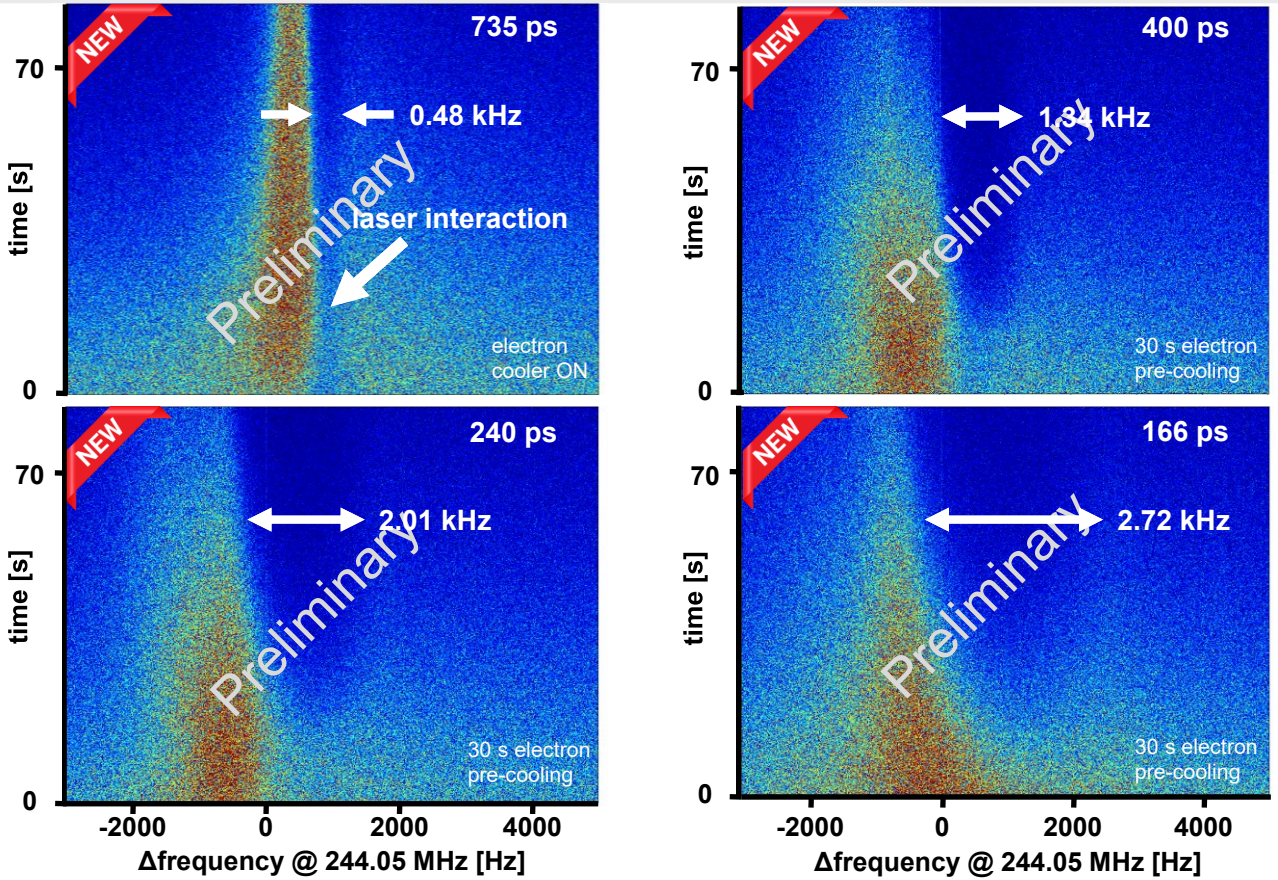
Coasting C^{3+} ion beam - laser pulse interaction



Coasting C^{3+} ion beam – effect of laser pulse duration

laser rep. rate:
~ 9 MHz

schottky images
@ 244 MHz

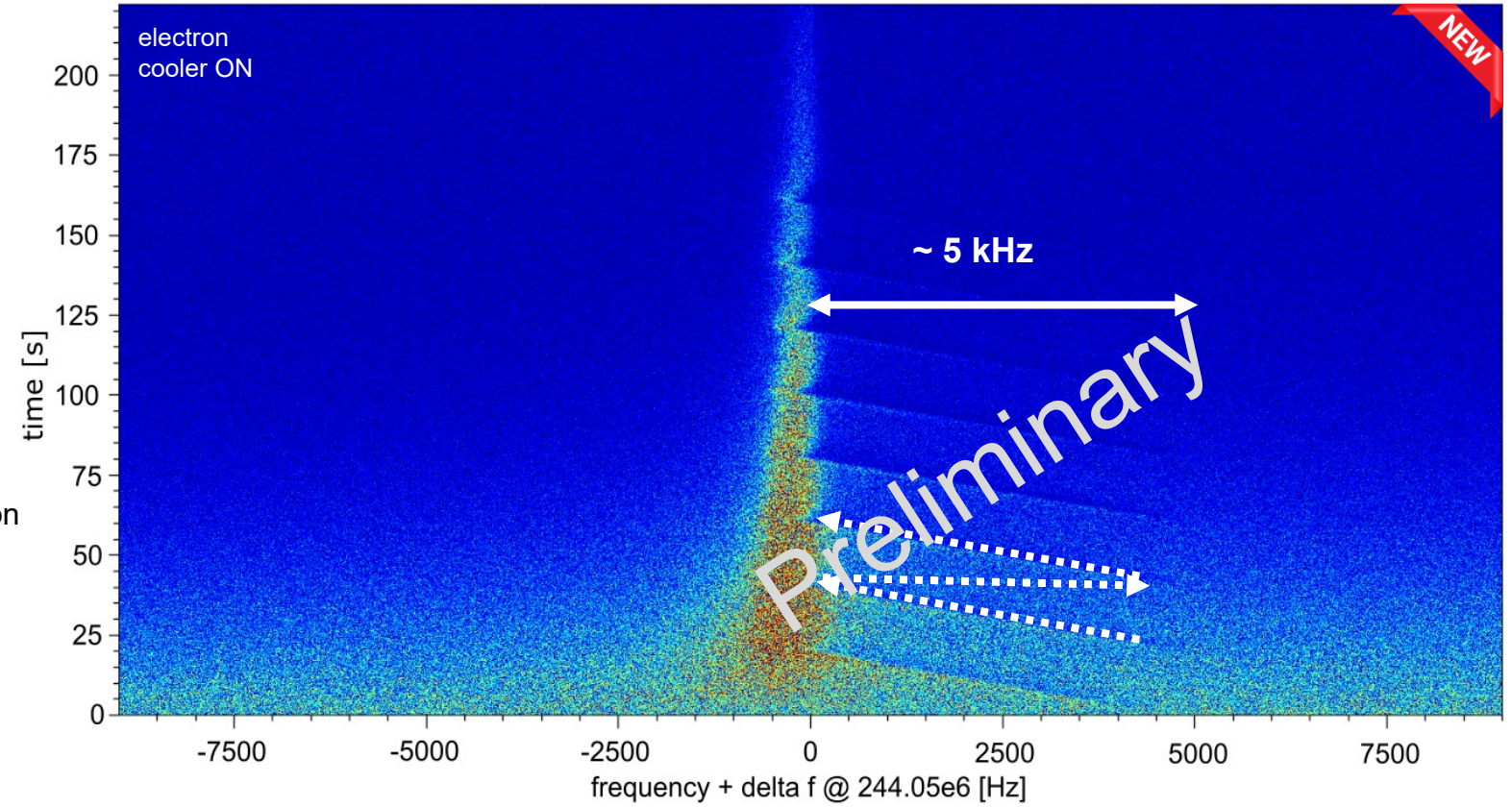


Coasting C^{3+} ion beam - sawtooth scan

laser rep. rate:
~ 9 MHz

schottky images
@ 244 MHz

735 ps pulse duration

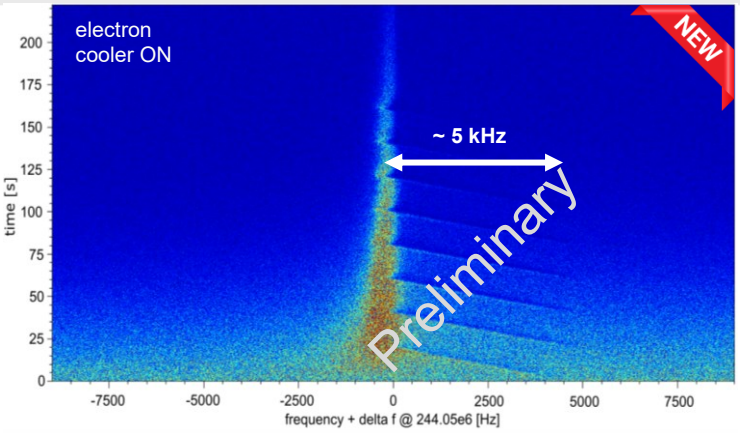


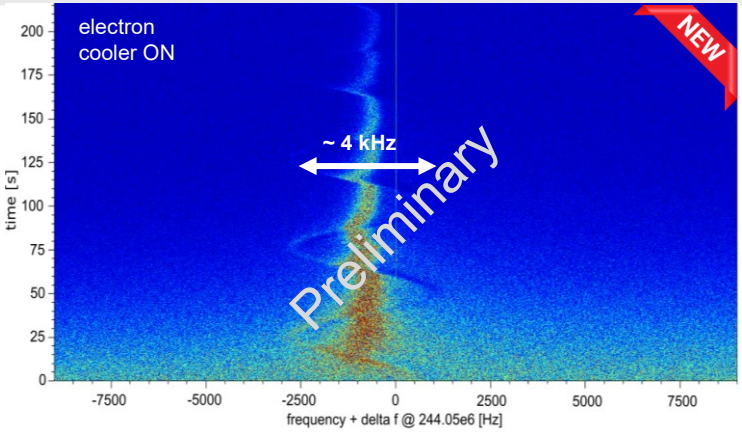
Coasting C^{3+} ion beam - different user defined laser scans

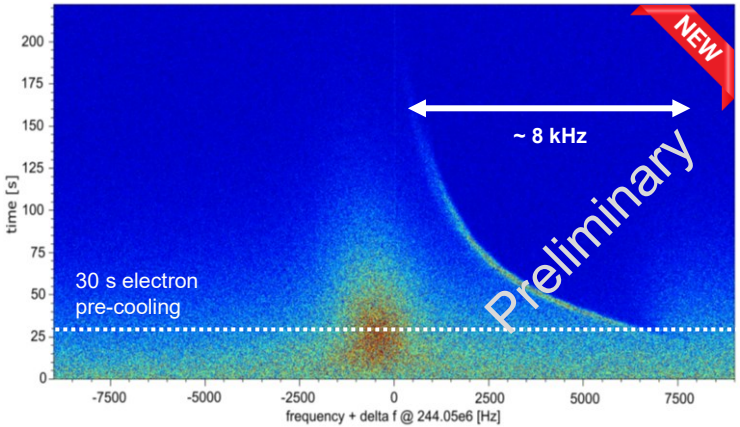
laser rep. rate:
~ 9 MHz

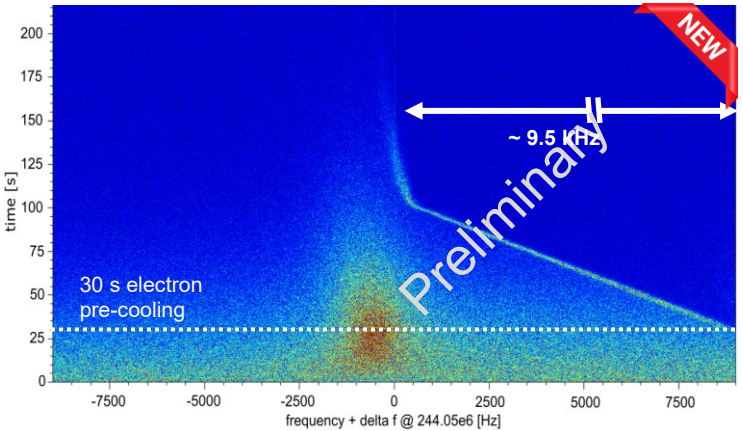
schottky images
@ 244 MHz

735 ps pulse duration

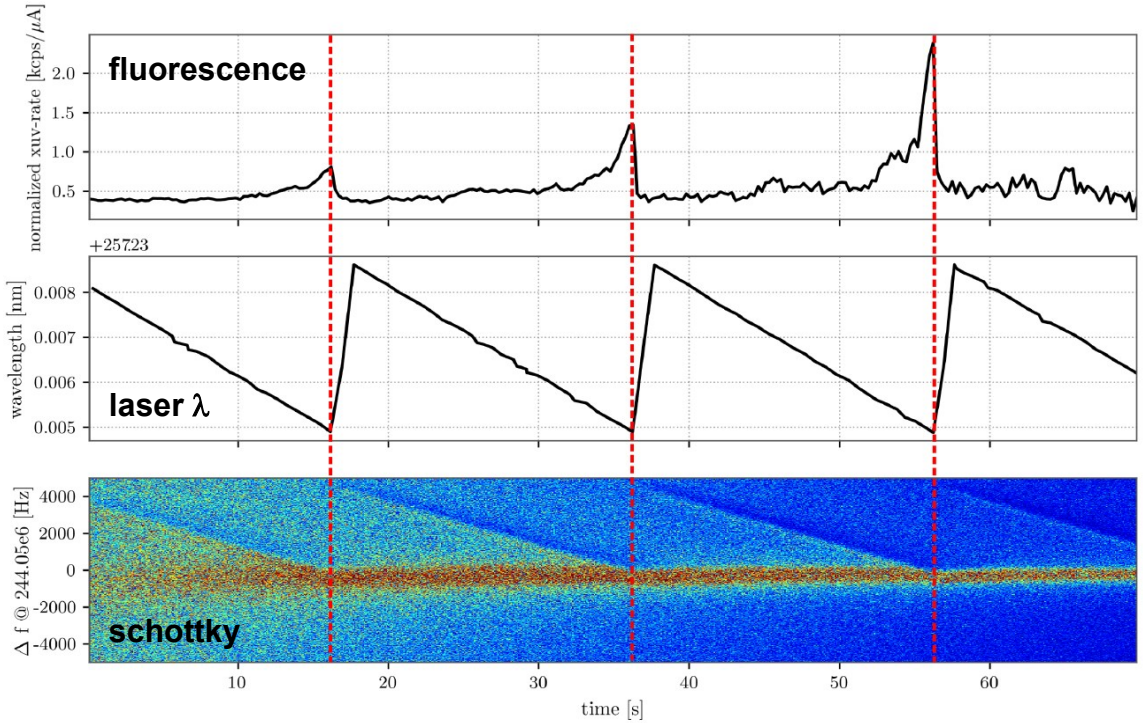








Fluorescence detection during sawtooth scan



Ueberholz, K.; Bozyk, L.; Bussmann, M.; Eizenhöfer, N.; Hannen, V.; Horst, M.; Kiefer, D.; Kiefer, N.; Klammes, S.; Kühl, T.; Langfeld, B.; Loeser, M.; Ma, X.; Nörtershäuser, W.; Sánchez, R.; Schramm, U.; Siebold, M.; Spiller, P.; Steck, M.; Stöhlker, T.; Walther, T.; Wang, H.; Weinheimer, C.; Wen, W.; Winters, D. XUV Fluorescence Detection of Laser-Cooled Stored Relativistic Ions. *Atoms* **2023**, *11*, 39. https://doi.org/10.3390/atoms11020039

Figure 2. Laser scans of an electron-cooled coasting ion beam of $^{12}C^{3+}$ ions at the ESR plotted as a function of time. **Top:** the rate of the fluorescence photons detected by the XUV detector, **middle:** the laser wavelength, **bottom**: the Schottky spectrum.

C^{3+} Beam Experiment at the ESR (11.5.2021 – 16.5.2021)

bunched ion beam

Laser pulse - ion bunch timing

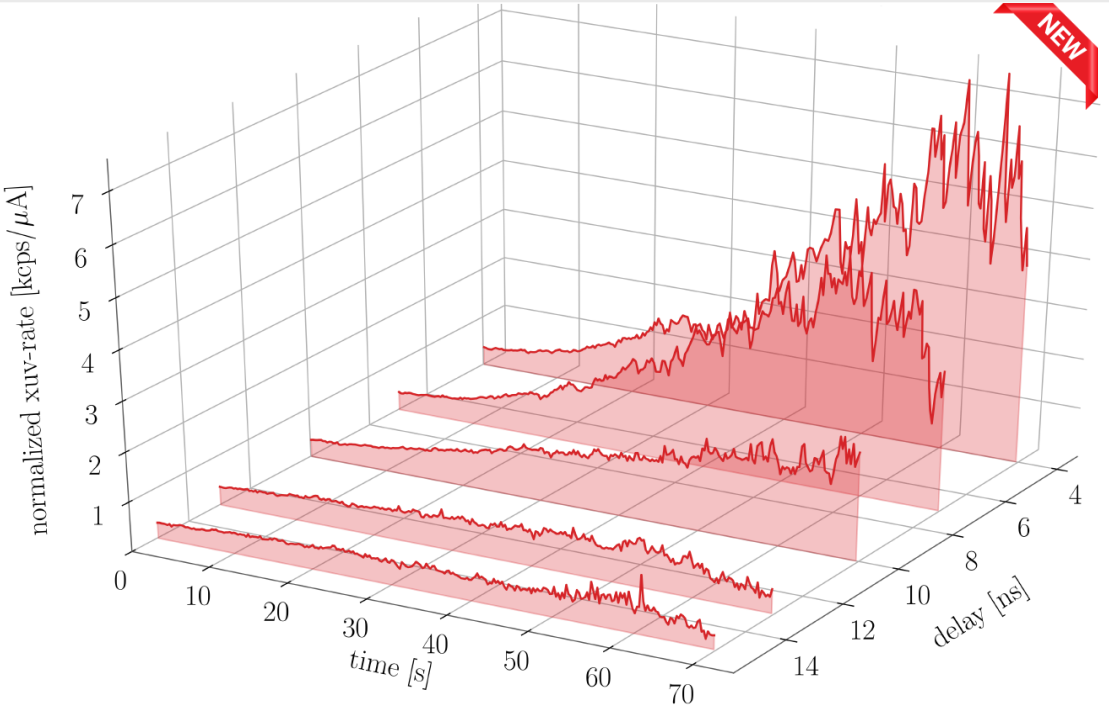


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Figure 3. Fluorescence rate of $^{12}C^{3+}$ ions plotted as a function of the delay of the laser pulses with respect to the ion bunches, as detected by the XUV detection system at the ESR. For these measurements, there were 7 ion bunches stored in the ESR, the repetition rate of the laser pulses was ∼9 MHz, and the laser wavelength was 257.235 nm.

XUV Fluorescence Detection of Laser-Cooled Stored Relativistic Ions

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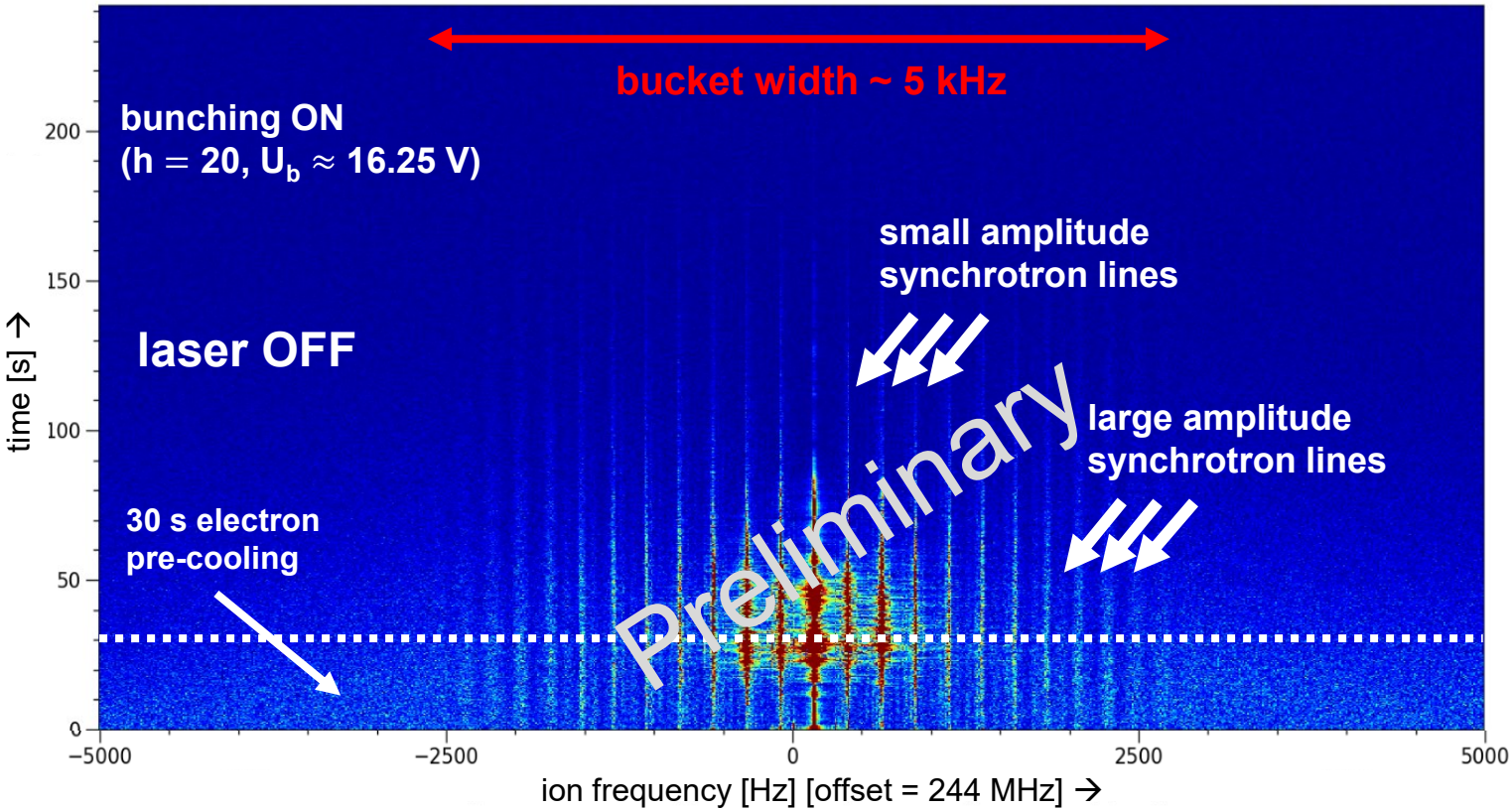
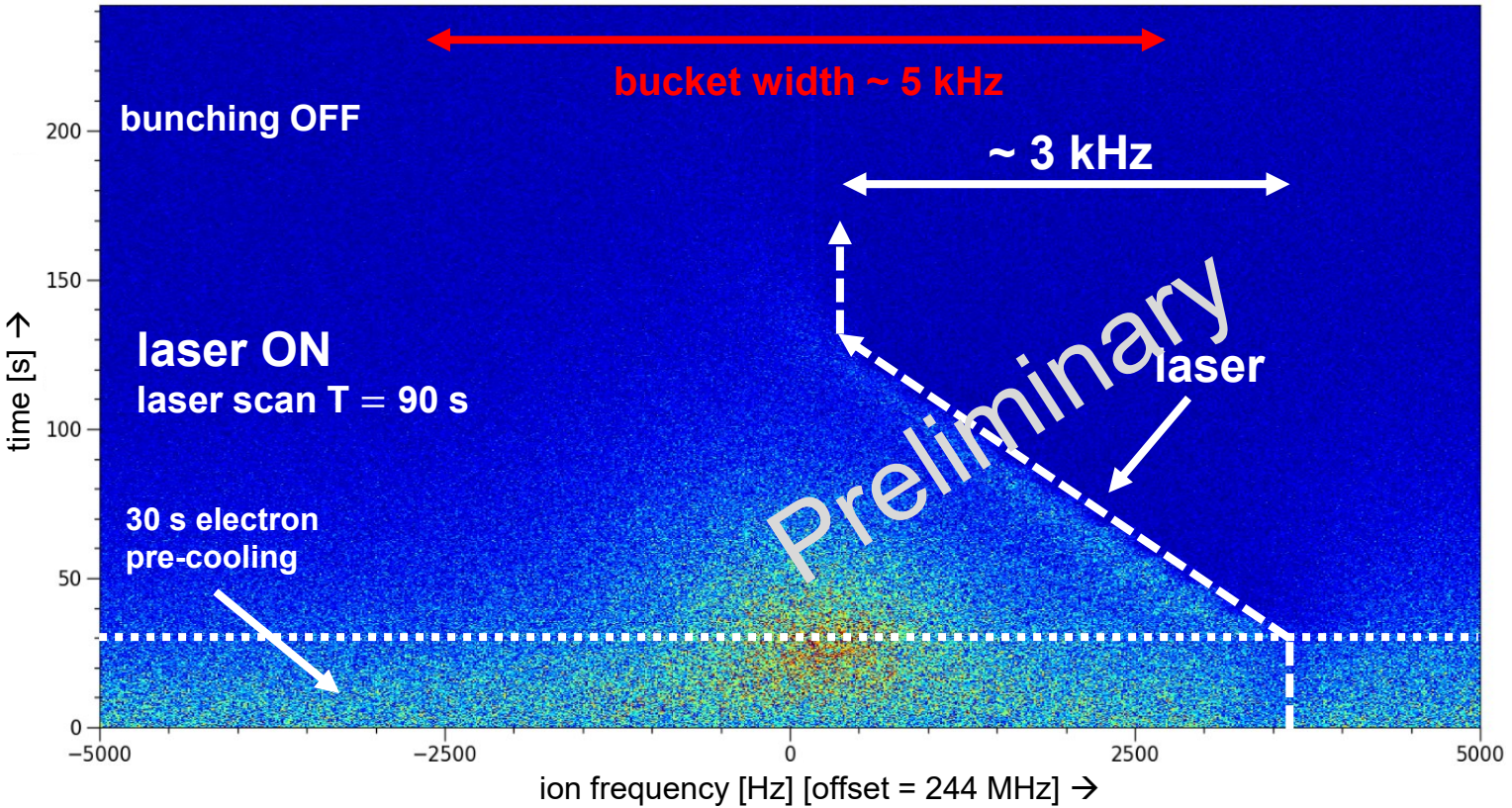
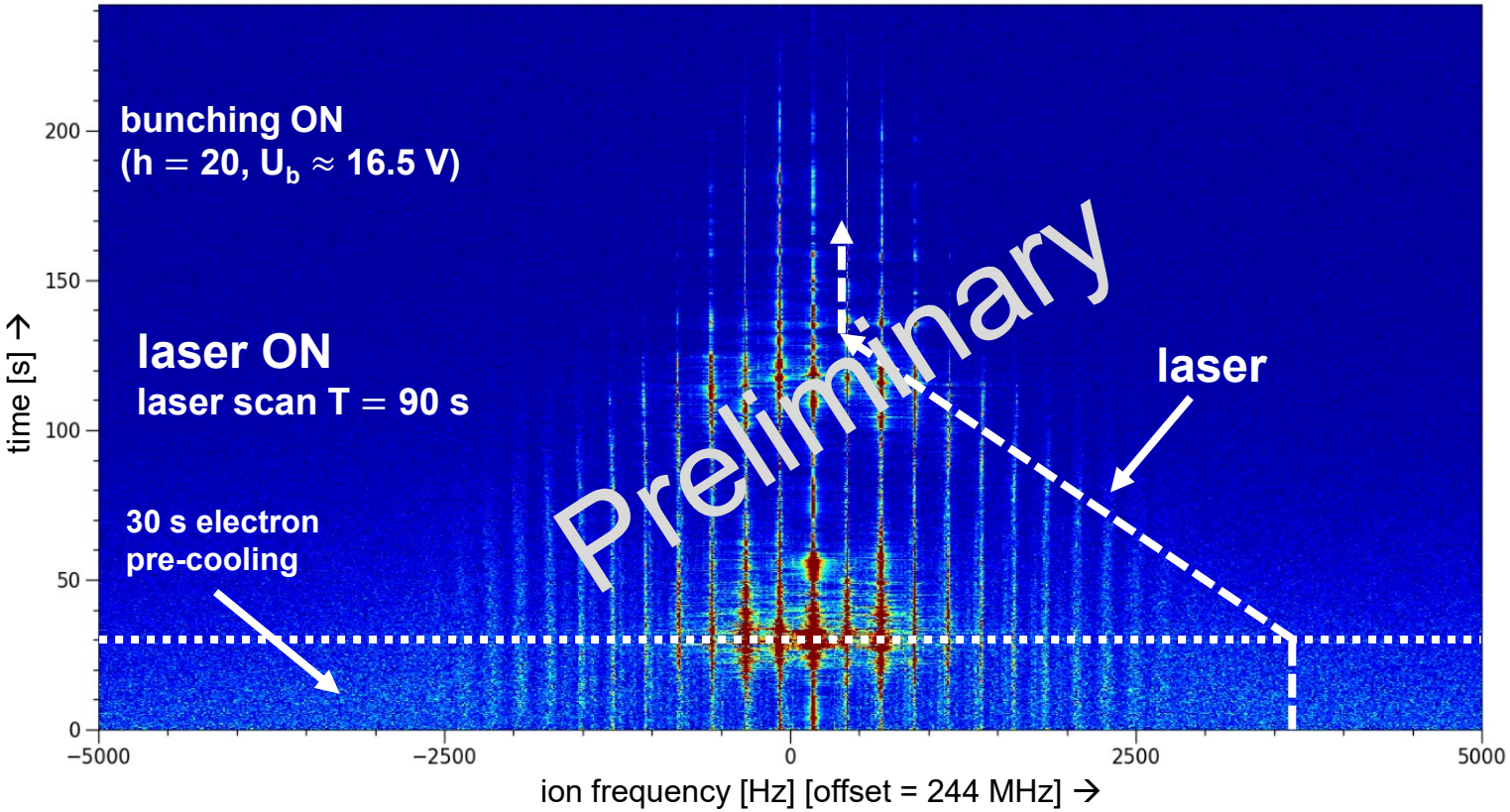
Bunched C^{3+} ion beam



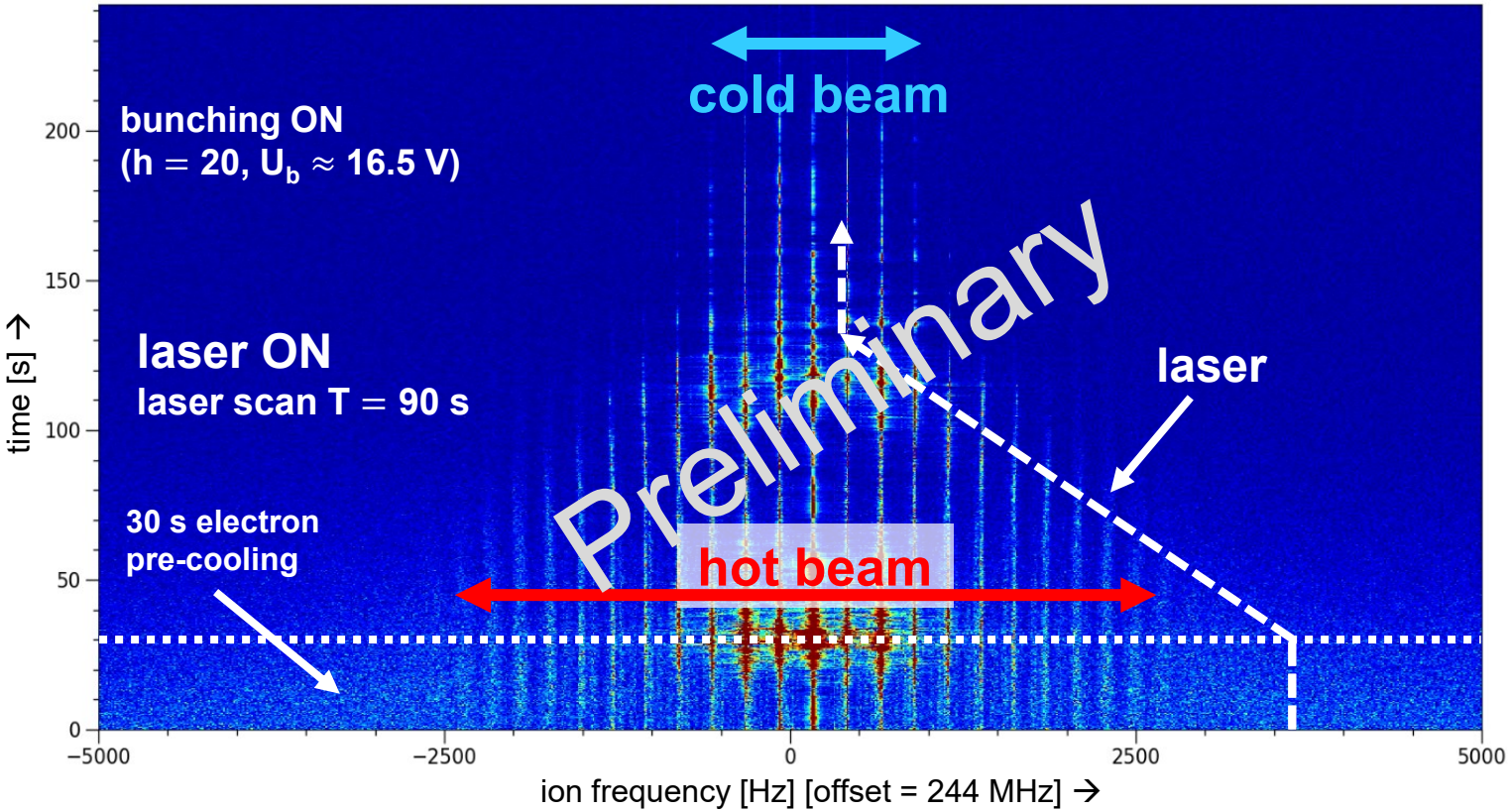
Coasting C^{3+} ion beam - 735 ps pulses, ~9 MHz repetition rate



Broadband laser cooling of relativistic bunched C^{3+} ion beams at the ESR
735 ps pulses, ~9 MHz repetition rate



Broadband laser cooling of relativistic bunched C^{3+} ion beams at the ESR
735 ps pulses, ~9 MHz repetition rate



Outlook

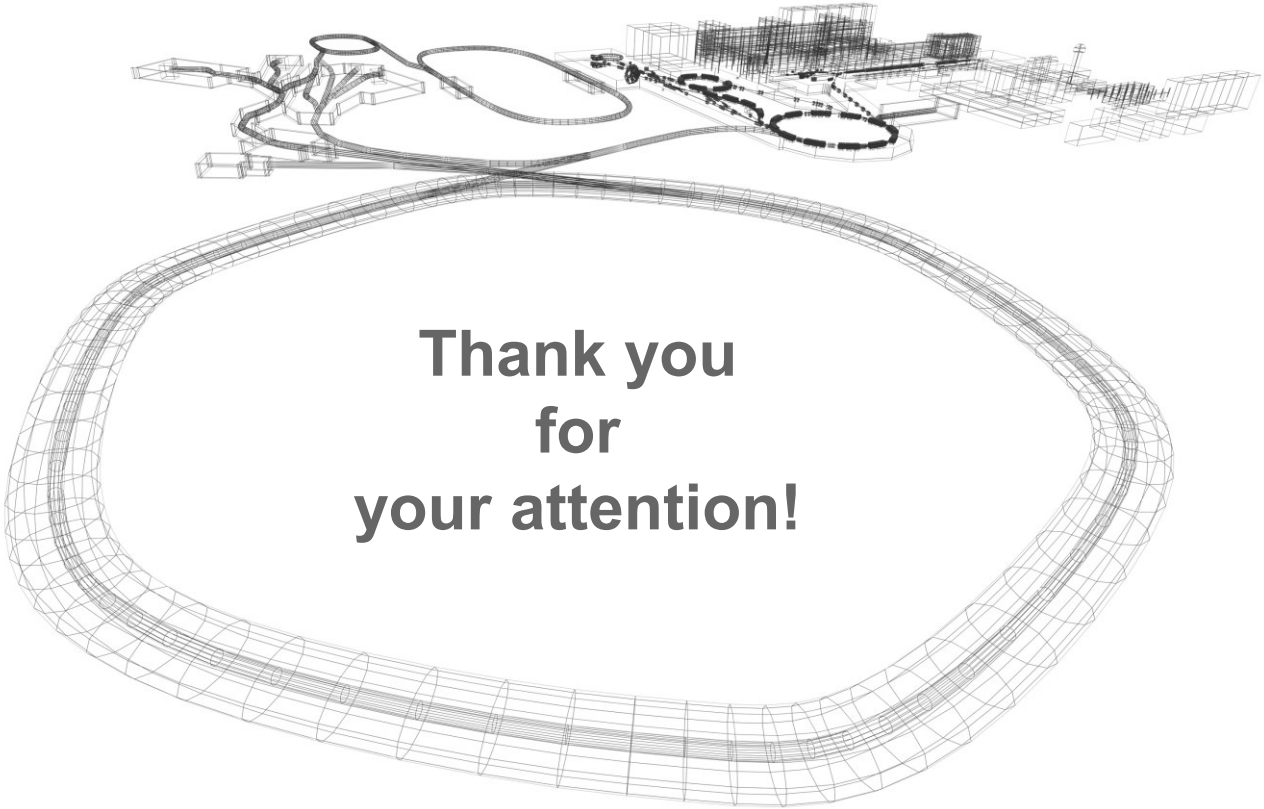
- GSI: demonstrate ’3 beam laser cooling’ at the ESR

GSI Research Proposal | **G-22-00172**

Experiment title: **Exploring the limits of bunched beam laser cooling of relativistic stored ions, using 3 laser beams (pulsed and cw) and new diagnostics**	**Proposal type:** Standard **(ST)**
	Scientific College: G-PAC

GSI/G-PAC rating: A- (G-22-00172-1.1-E)

- Darmstadt & Dresden have already applied for BMBF funding (Juli 2023)
- Code for laser cooling (by Lewin Eidam) will be updated and made suitable for more general use
- FAIR: establish the SIS100 laser cooling facility



Thank you
for
your attention!