Laser cooling of the SPS ion beams – the Xenon case

Acknowledgements: D. Gamba, G. Franchetti, A. Petrenko, W. Krasny

Peter Kruyt

March 25th 2024

Outline

- Laser cooling introduction
- Xenon cooling rates
- Xenon vs IBS
- Comparison with lead and calcium
- Conclusions

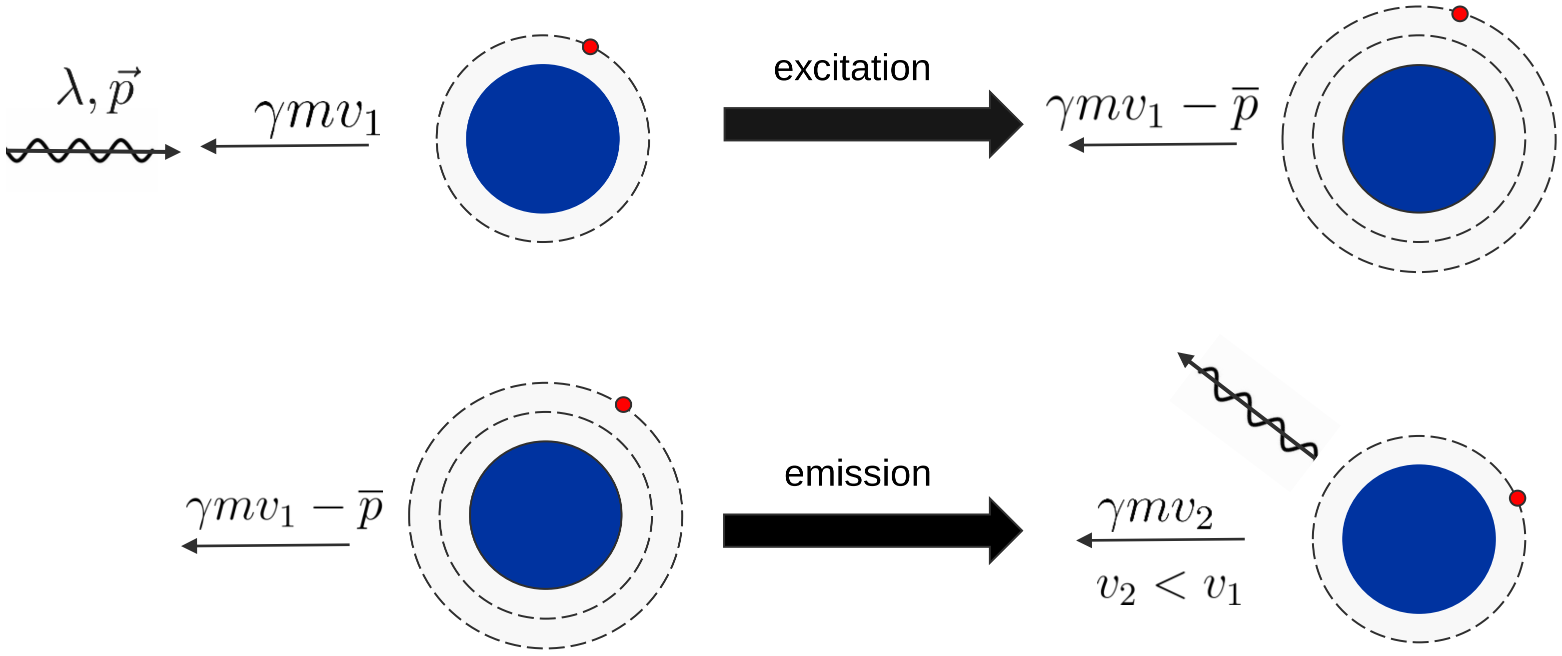
Laser cooling: excitation & emission

Step 1: excitation

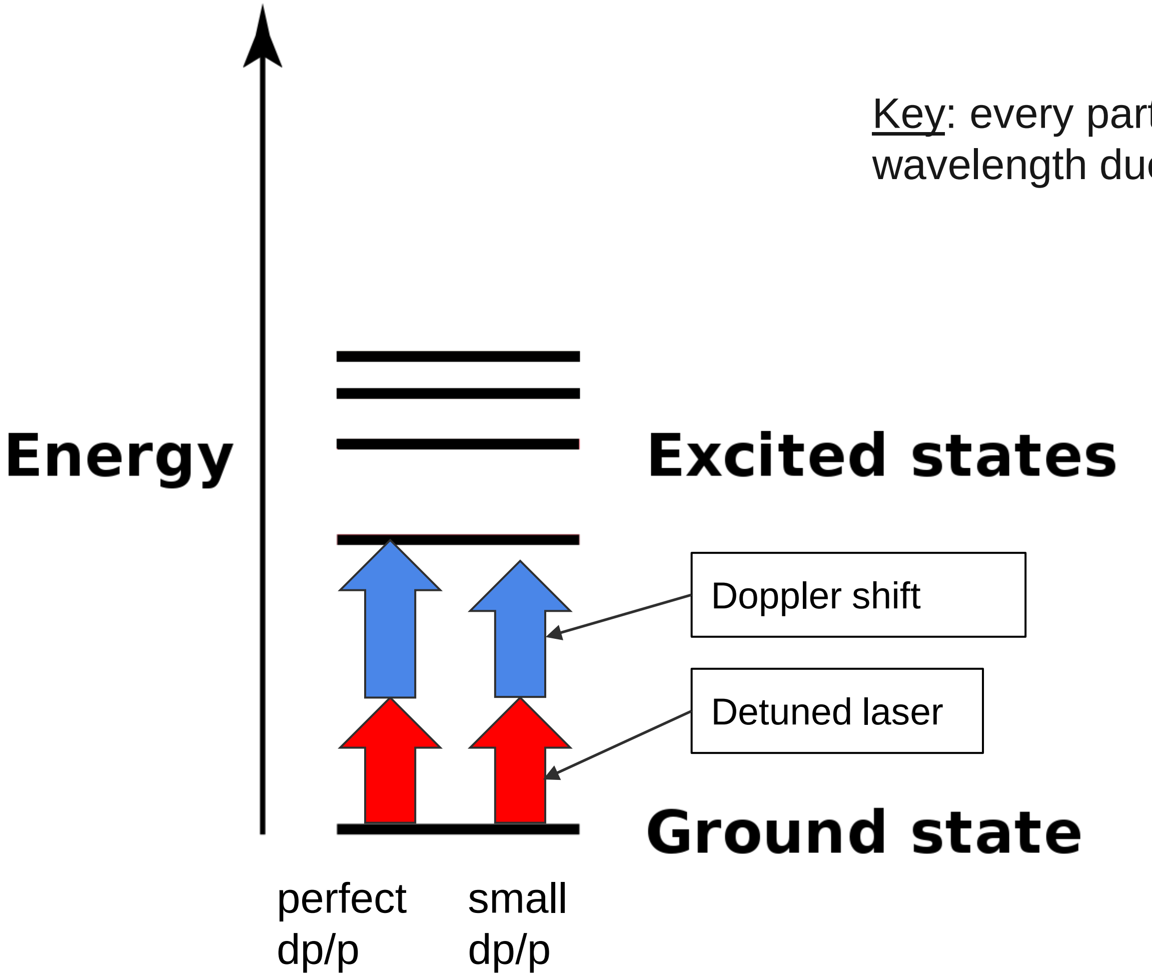
Laser cooling: excitation & emission

Step 1: excitation

Step 2: emission



Laser cooling: Doppler shifting



Key: every particle experiences a different laser wavelength due to Doppler shift

Conclusion: Only excite narrow band of dp/p

Studied ions

Progress in Particle and Nuclear Physics 114 (2020) 103792

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Review

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

M.W. Krasny [a,b,*], A. Petrenko [c,b], W. Płaczek [d]

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ARTICLE INFO

Article history:
Available online 26 May 2020

Keywords:
HL-LHC
Gamma Factory
ion beams
laser cooling
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Standard Model

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 $L_{NN} = 4.2 \times 10^{34}\ \mathrm{s^{-1}cm^{-2}}$ 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.

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Property	Pb^{79+}	Xe^{51+}	Ca^{17+}
Mass Number (A)	208	129	40
Atomic Number (Z)	82	54	20
Charge (e)	79	51	17
Beam intensity(1e8)	1.90	4.20	27.7
Excited Lifetime (ps)	76.6	3	0.43
Transition Energy (eV)	230	492	661
Lorentz factor γ	96	152	205
Laser wavelength (nm)	1031	768	768

(Doppler shift scales with γ)

Laser wavelength + Doppler shift -> Transition energy

Studied ions

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(Doppler shift scales with γ)

Laser wavelength + Doppler shift -> Transition energy

Results will only cover cooling with single laser

Xenon simulations

- Code: laser cooling module was developed in Xsuite (CERN beam dynamics code) [1]
- Excitation: solve Optical Bloch Equations (OBE)
- Emission: particle loses energy based on emission angle

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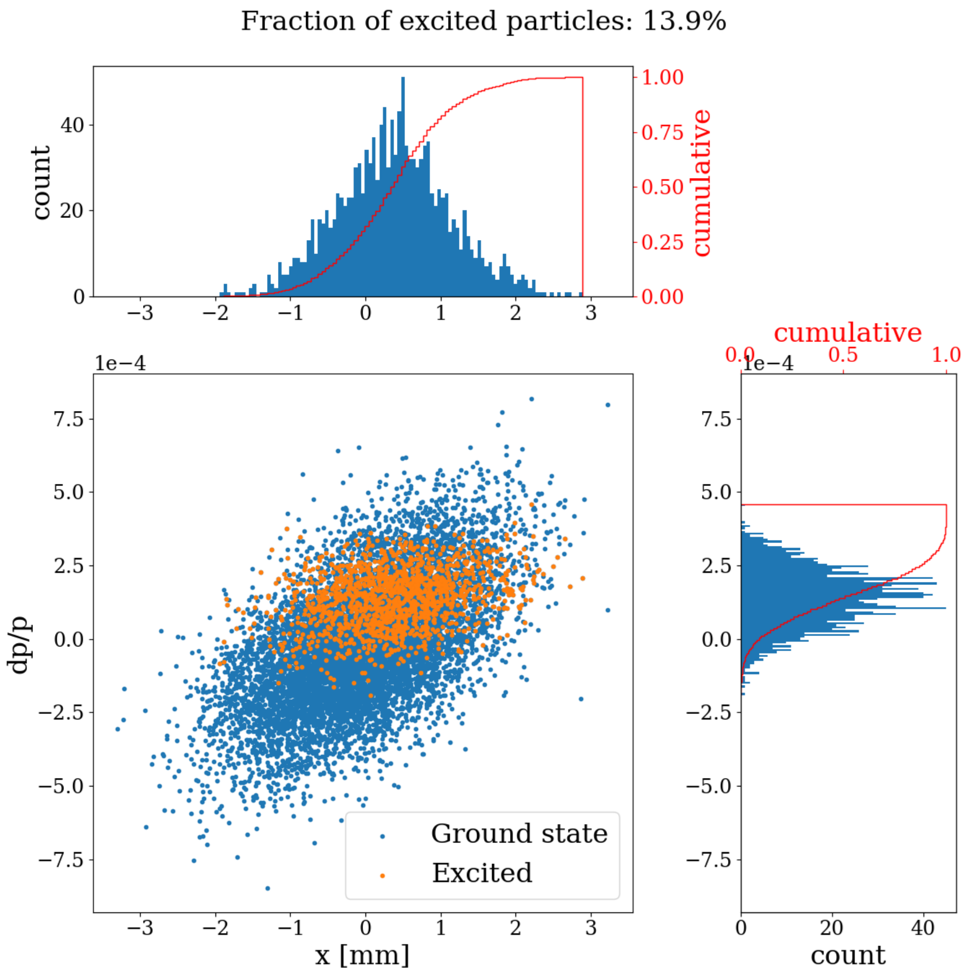
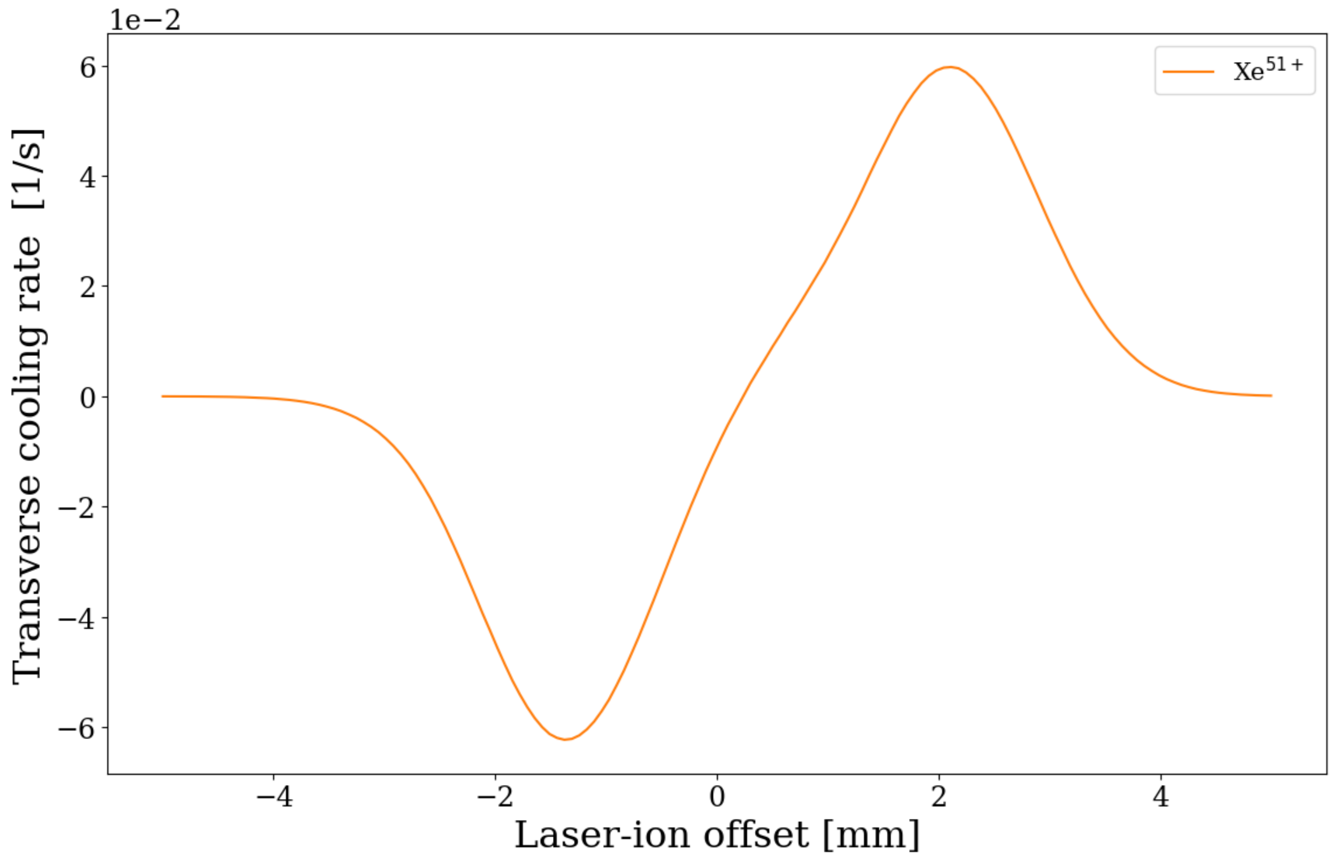


Longitudinal cooling + horizontal cooling thanks to coupling with dispersion (2.4m)

Optimal transverse cooling

cooling rate = -a

$$\epsilon_n = \epsilon_0 e^{-at}$$



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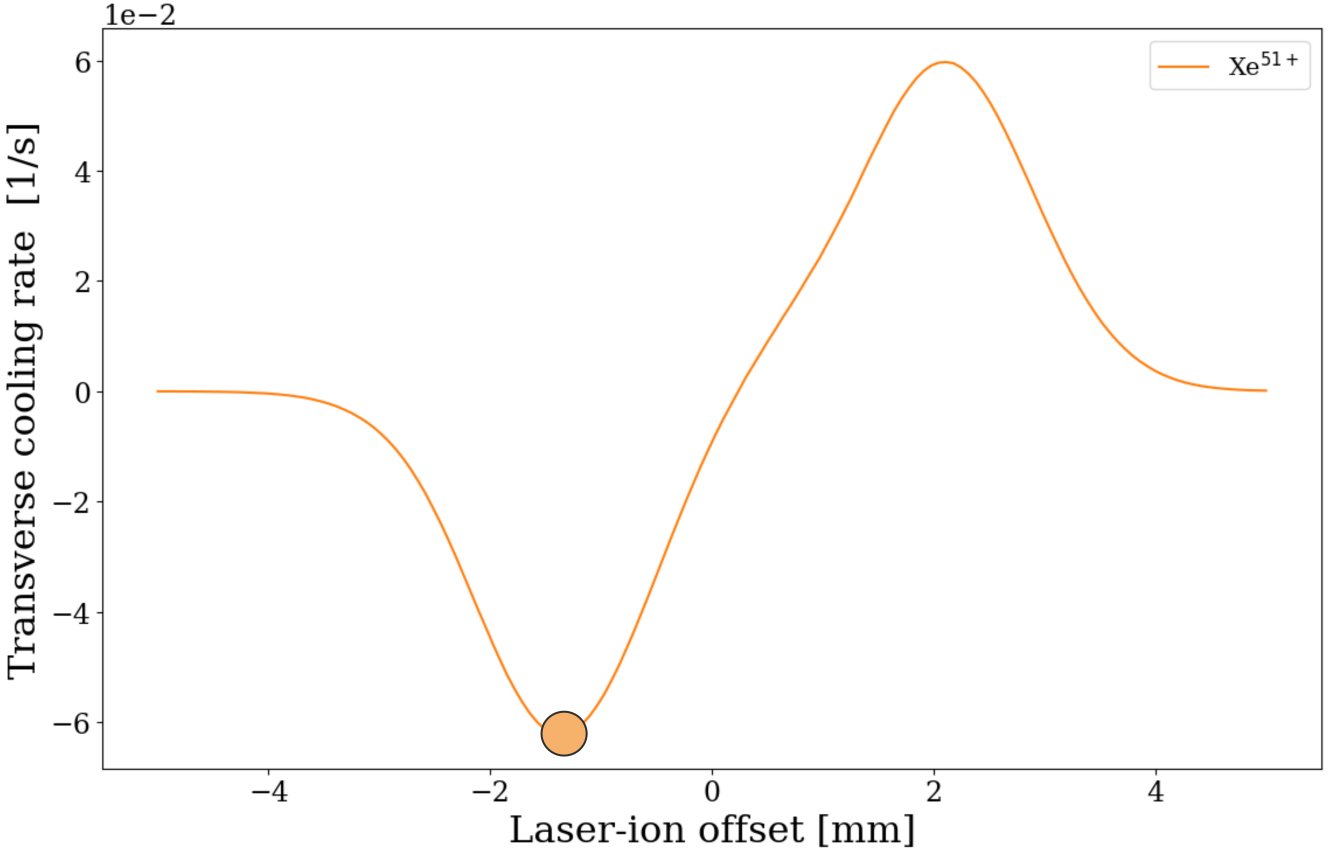

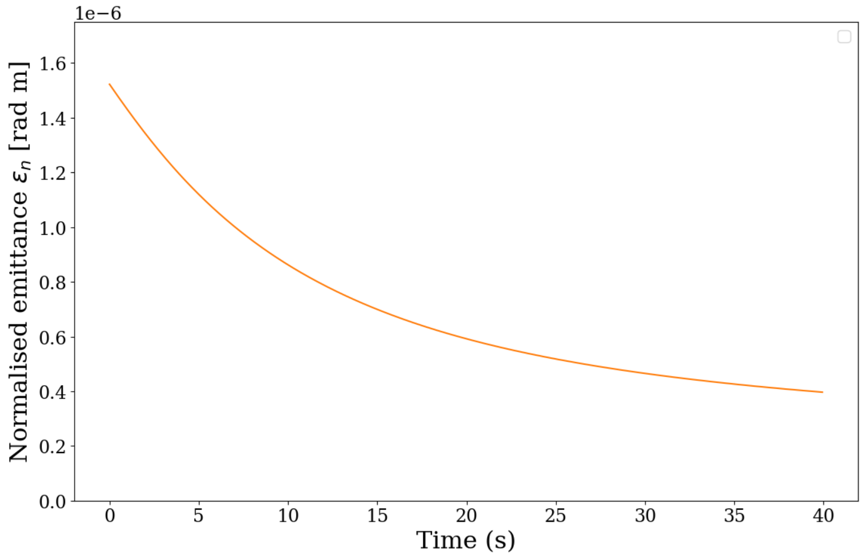

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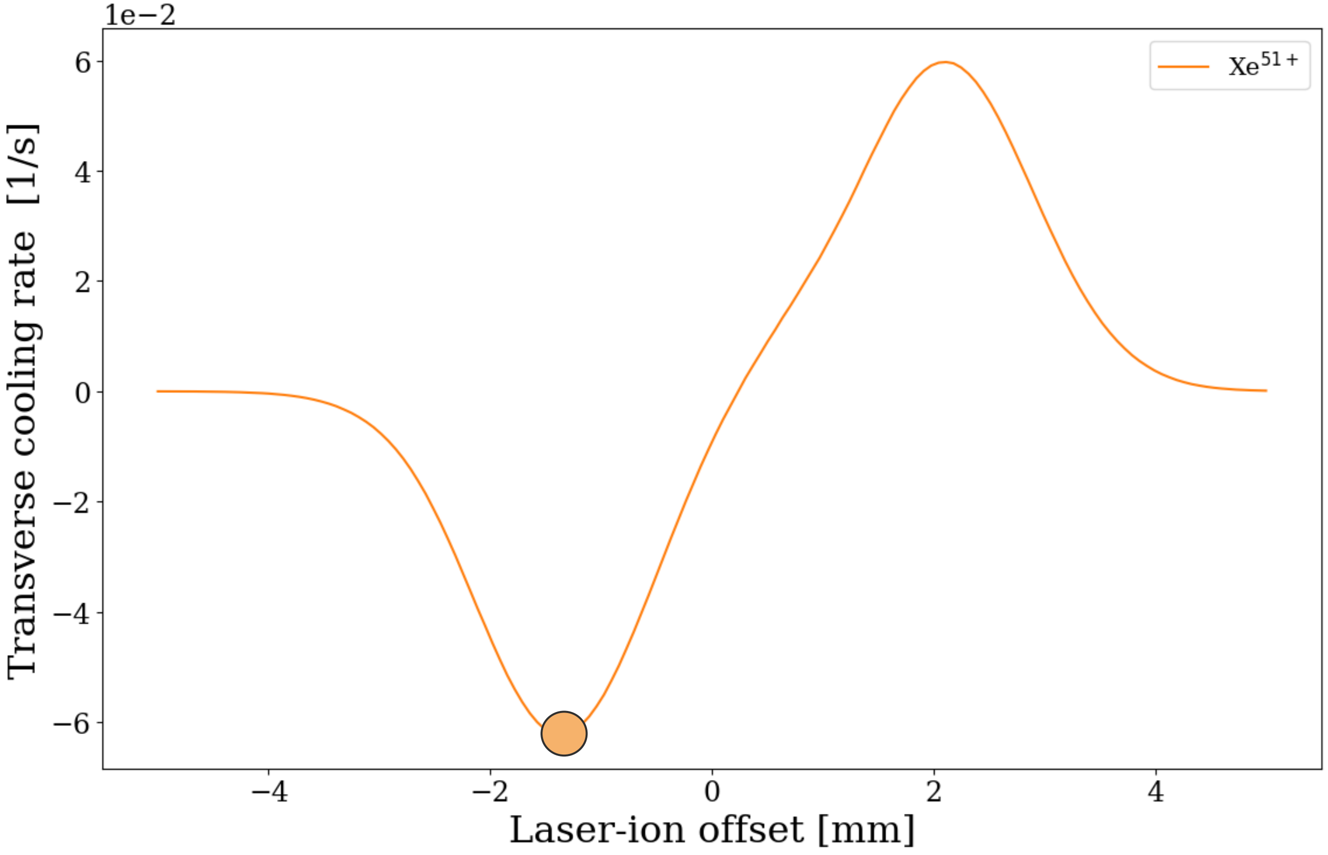

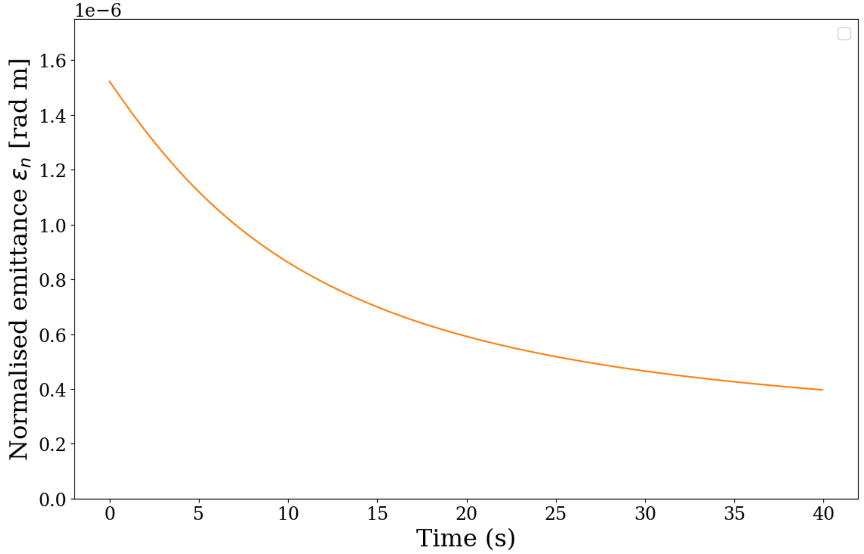

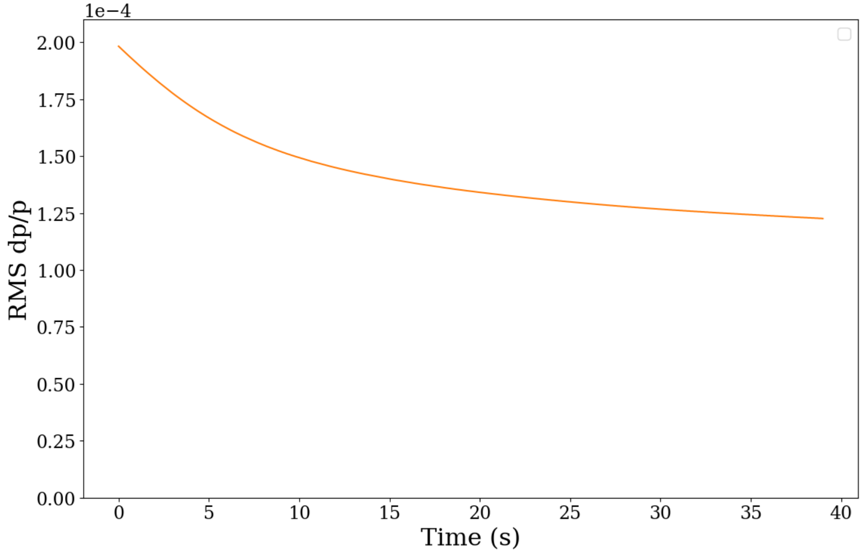

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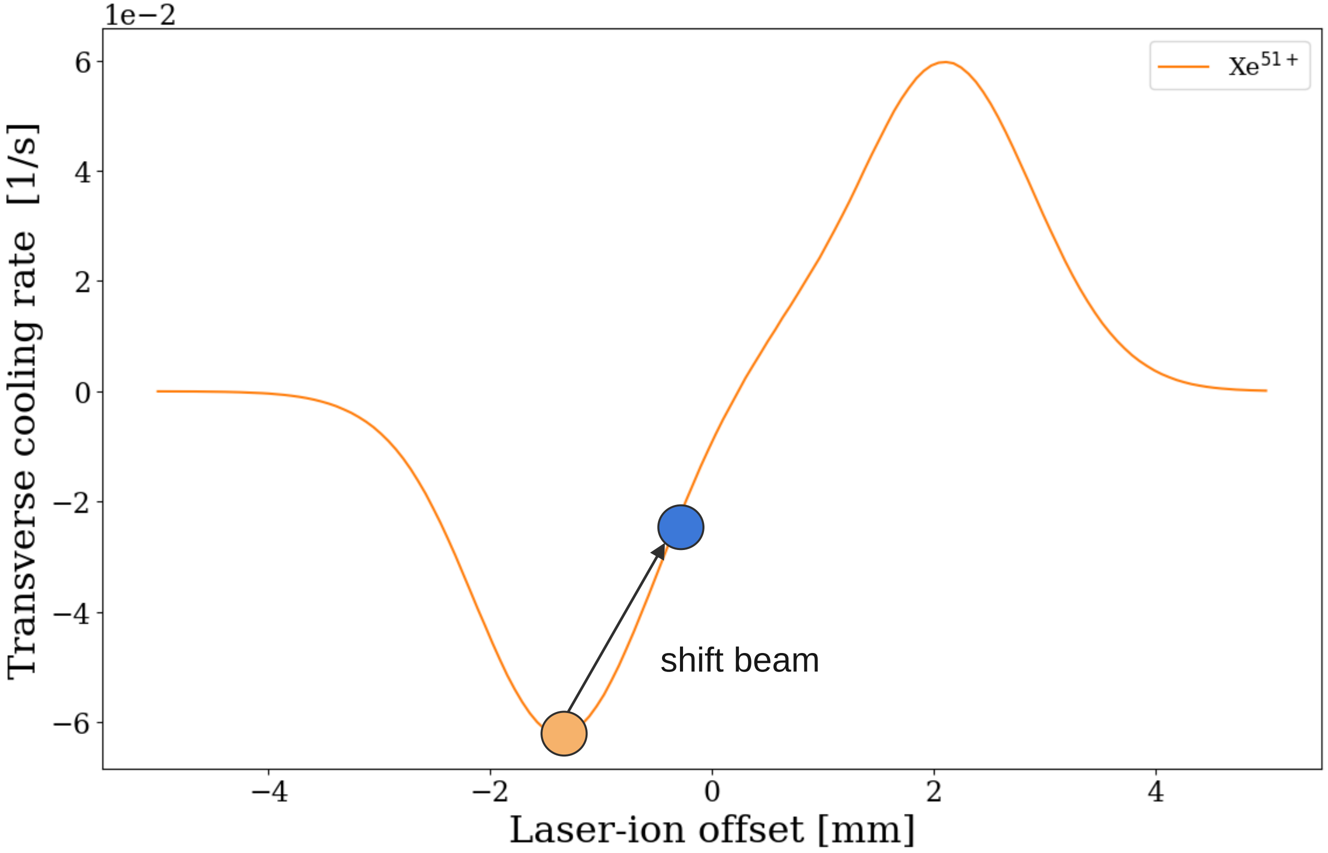

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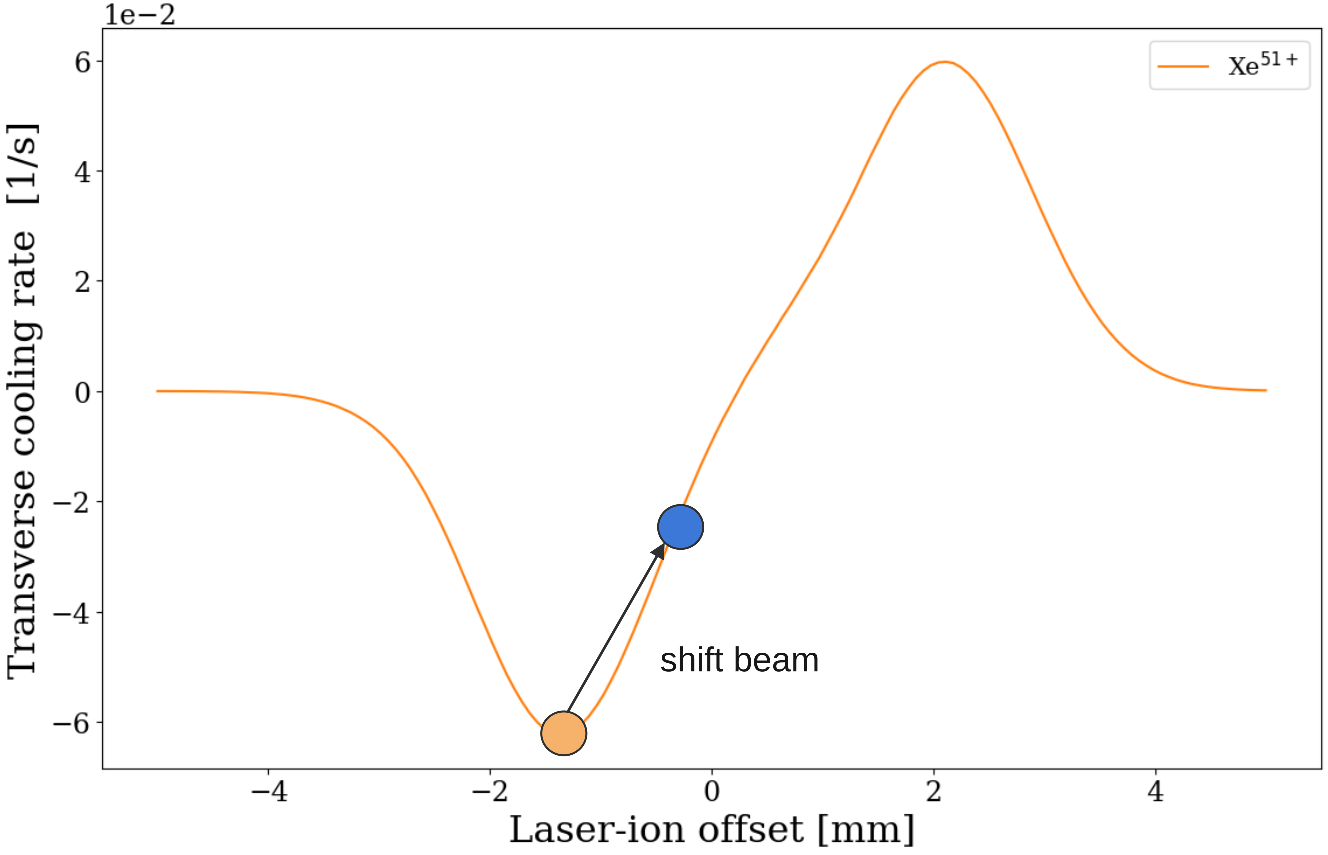

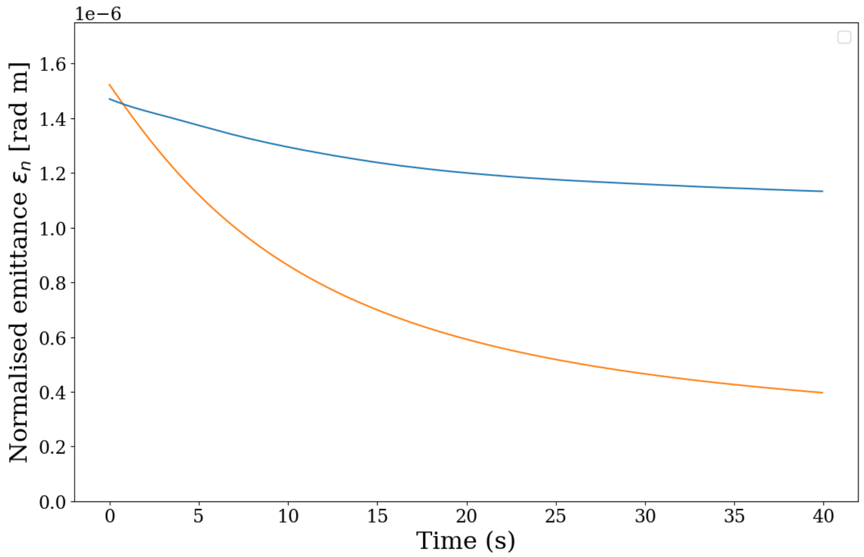

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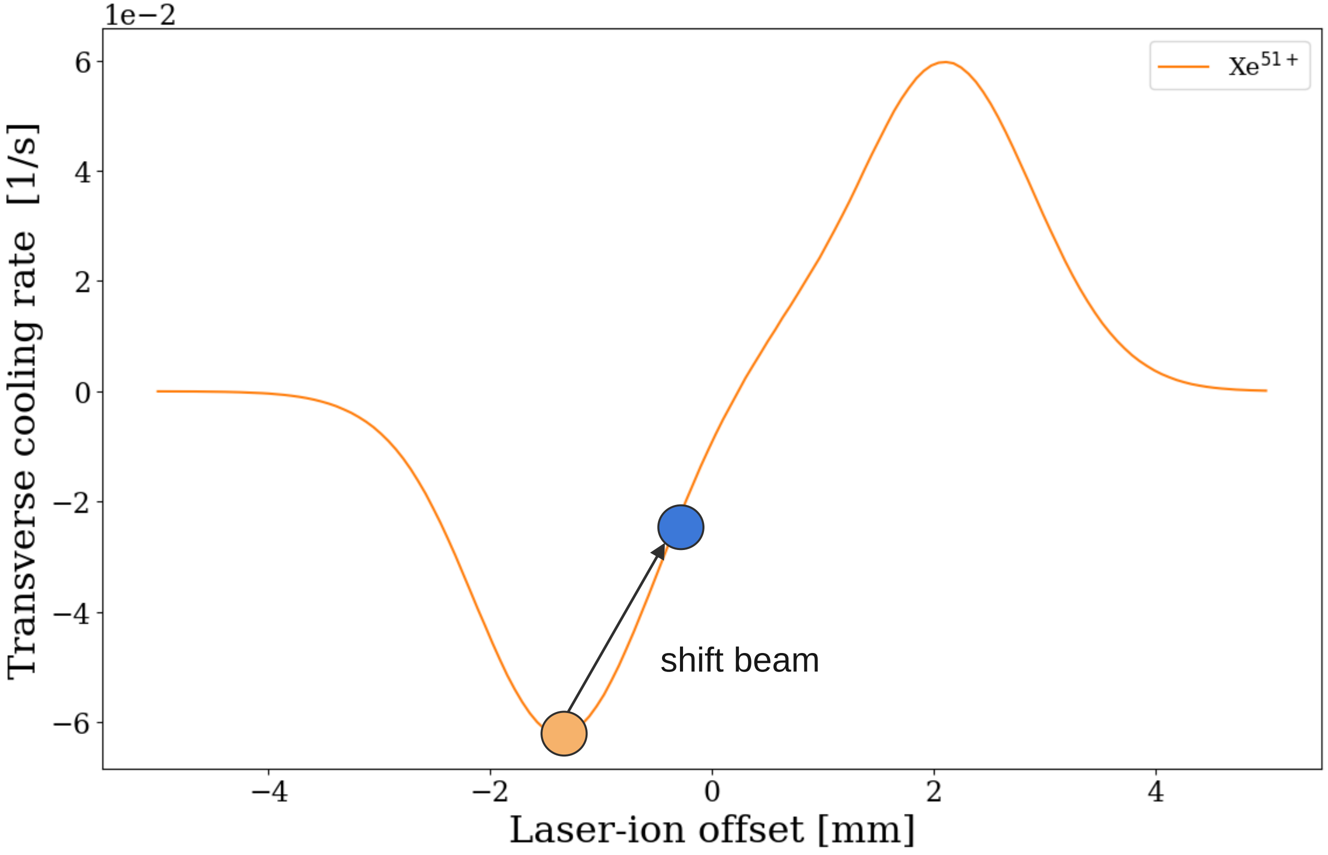
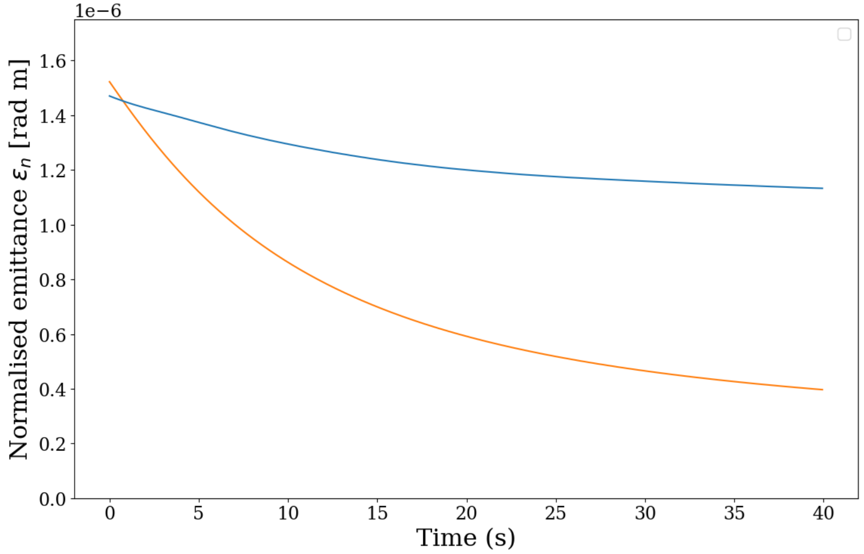
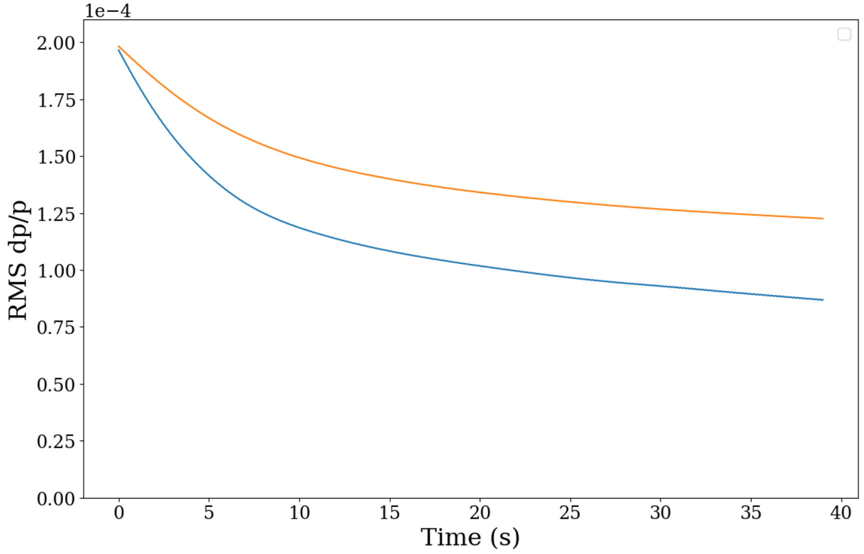
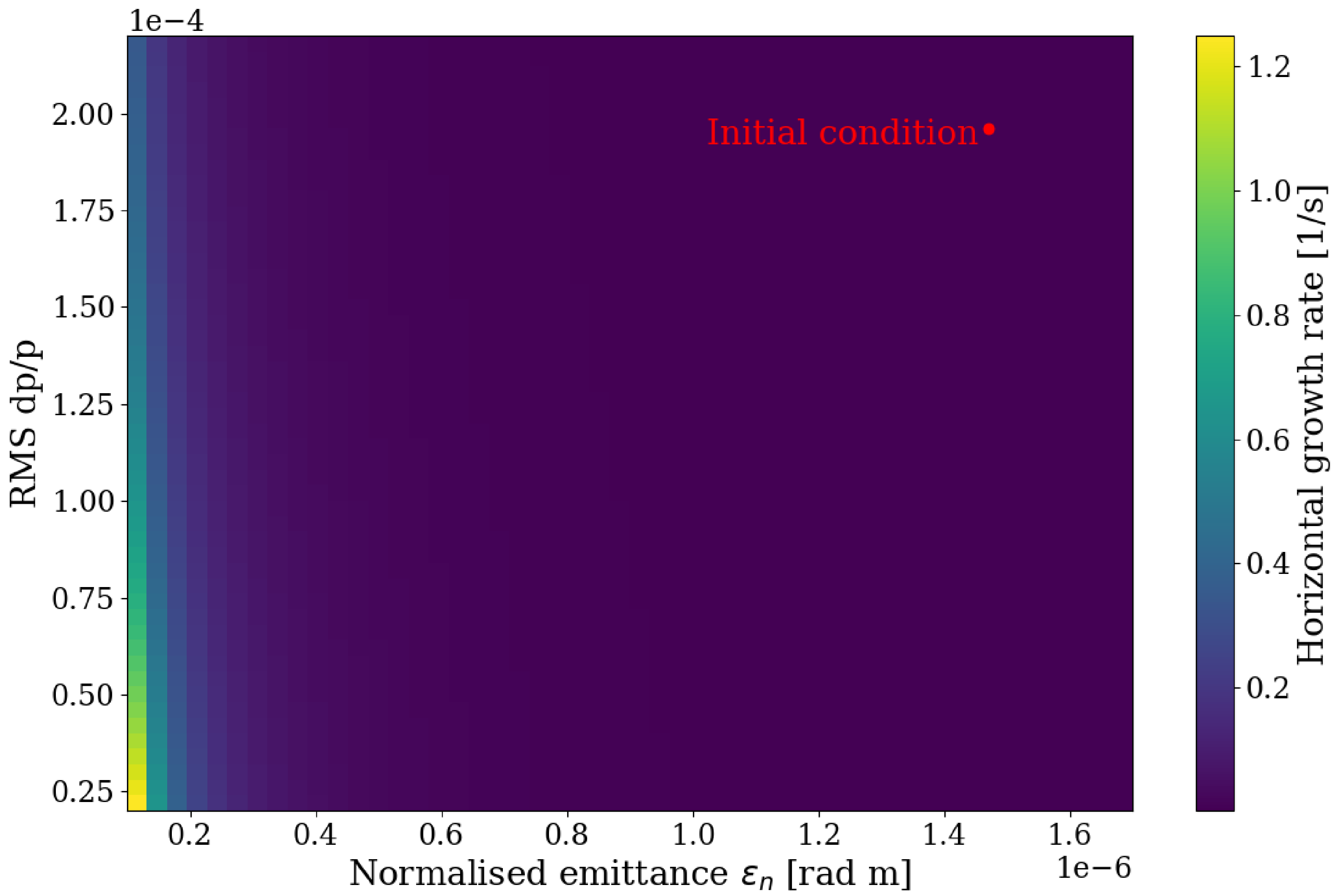






Conclusion: trade-off between longitudinal and transverse cooling

Xenon IBS growth rates

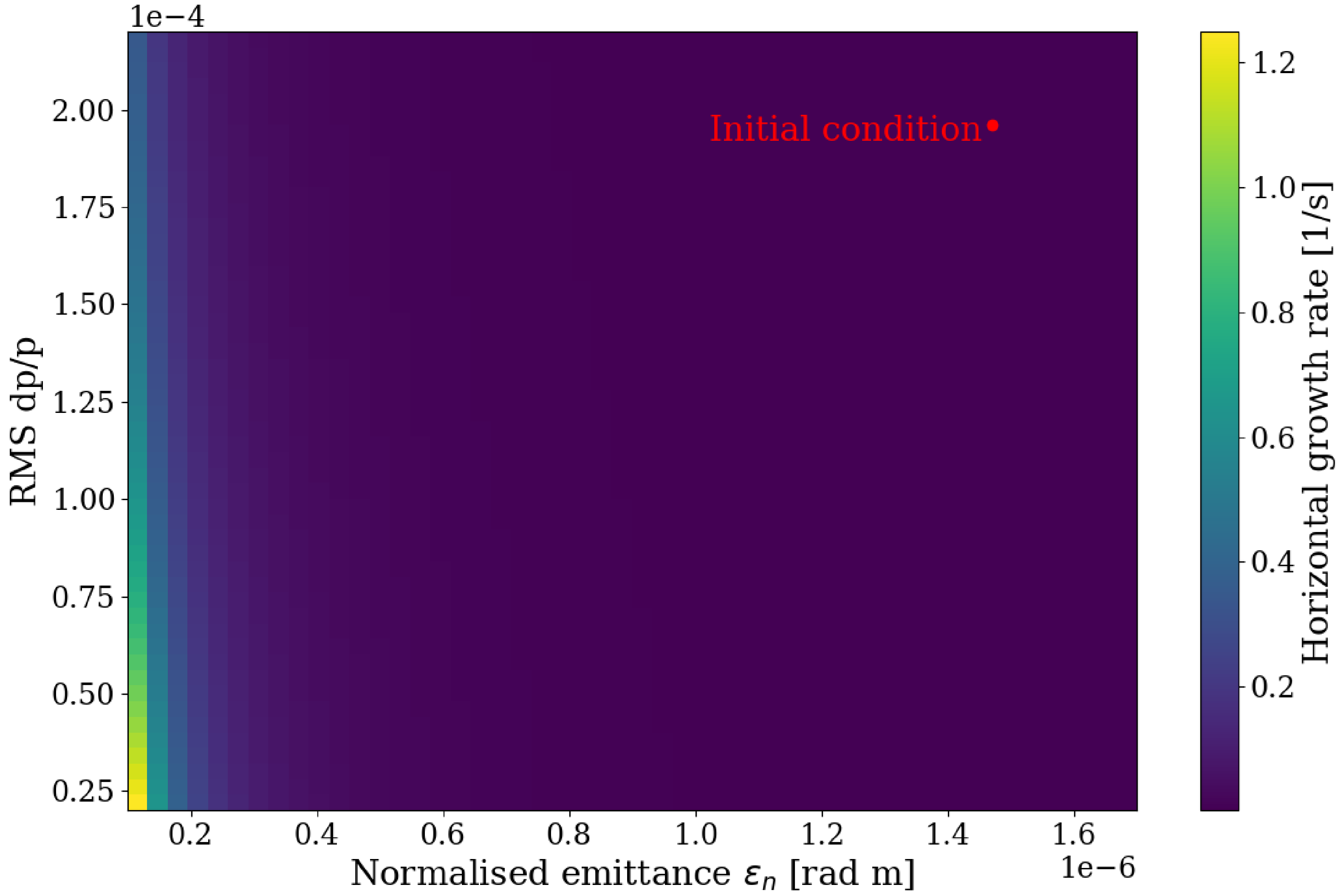


- Compute IBS growth rates for different dp/p and emittance

growth rate = b

$$\epsilon_n = \epsilon_0 e^{bt}$$

Xenon IBS growth rates



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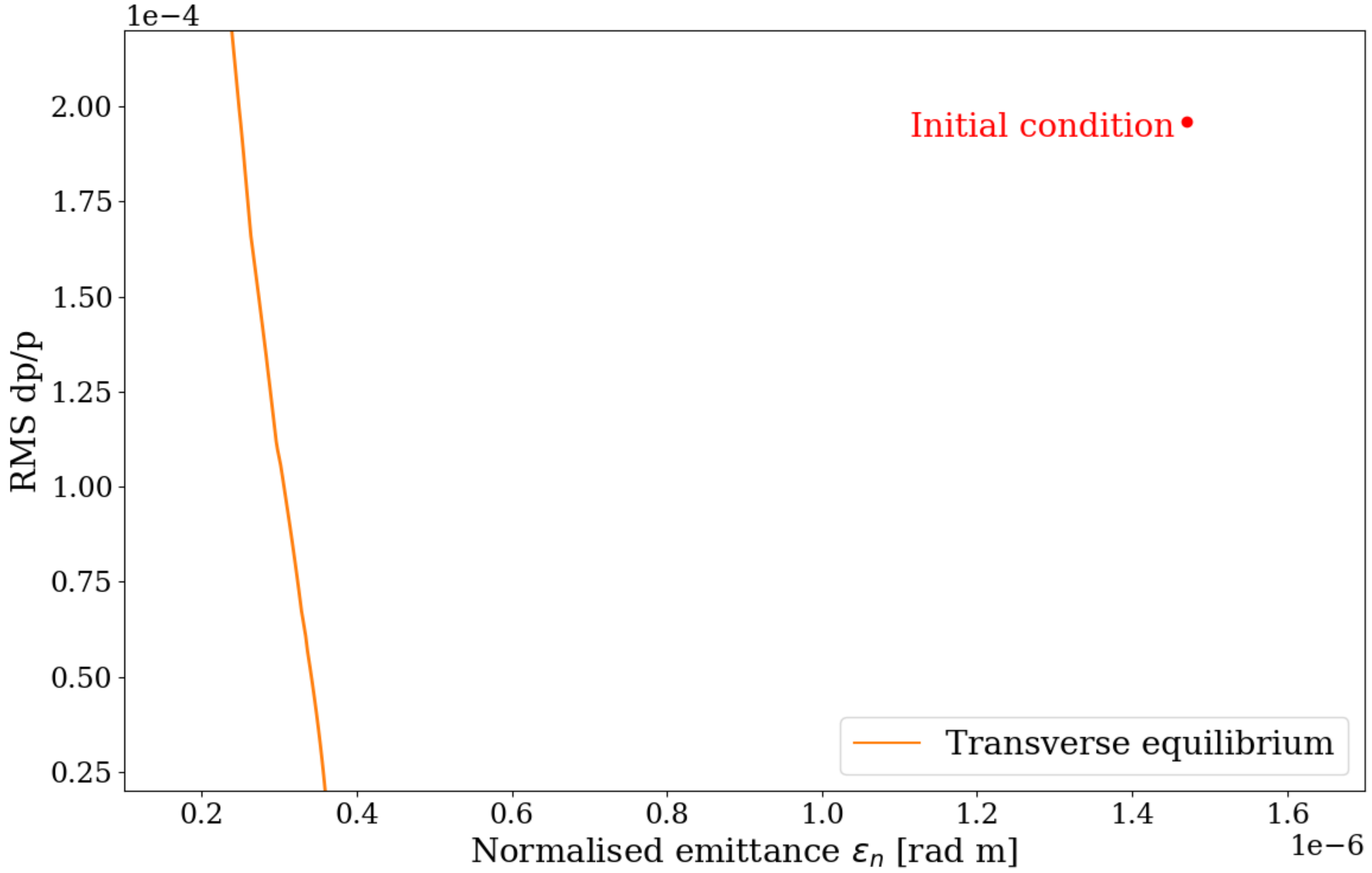
<u>Question</u>: when does cooling reach equilibrium?

cooling	IBS
$\epsilon_n = \epsilon_0 e^{-at}$	$\epsilon_n = \epsilon_0 e^{bt}$

Xenon equilibrium



Assume cooling rate same everywhere

cooling

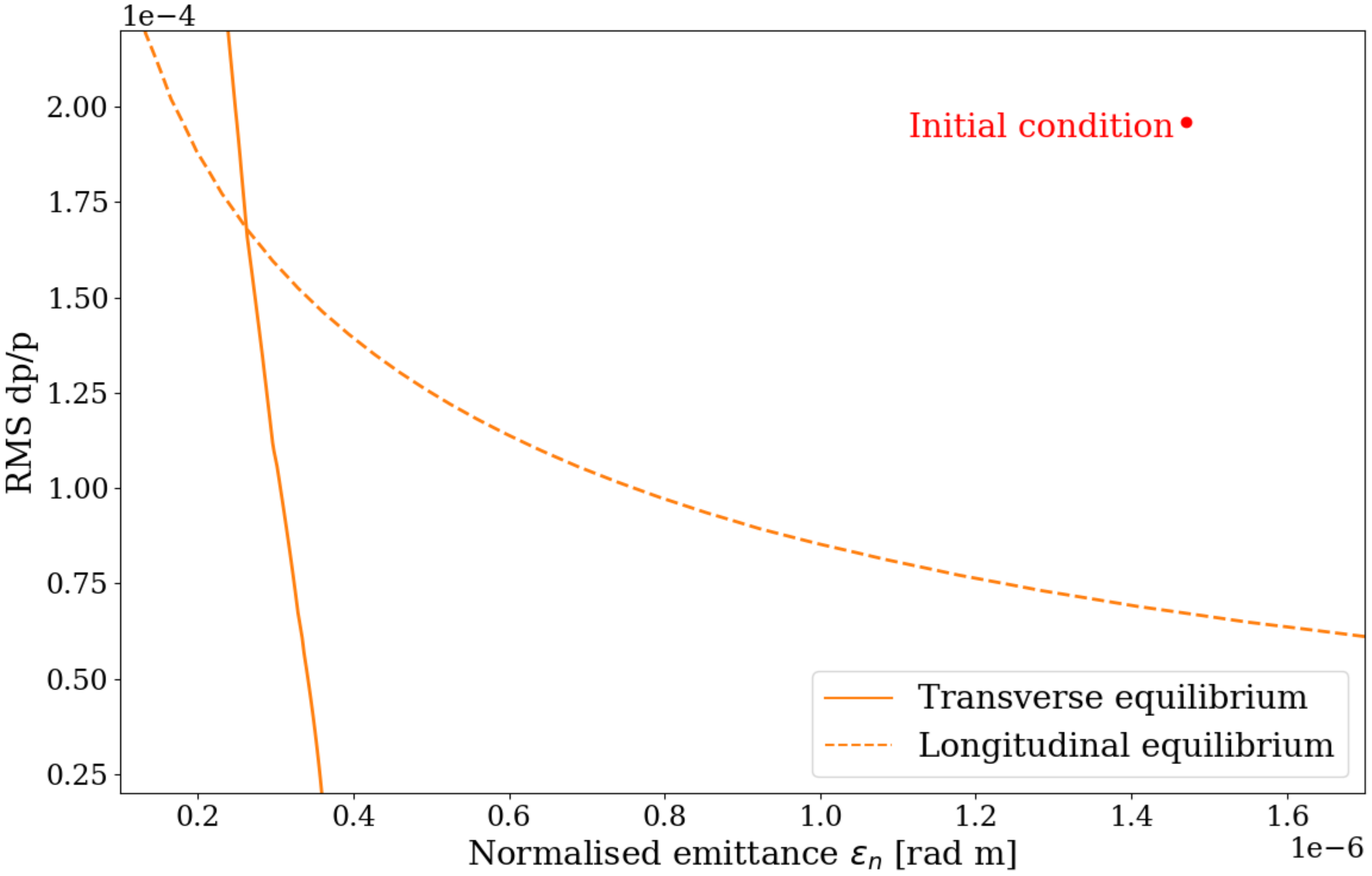
$$\epsilon_n = \epsilon_0 e^{-at}$$

IBS

$$\epsilon_n = \epsilon_0 e^{bt}$$

Equilibrium:
IBS growth rate = laser cooling decay rate

Xenon IBS growth rates



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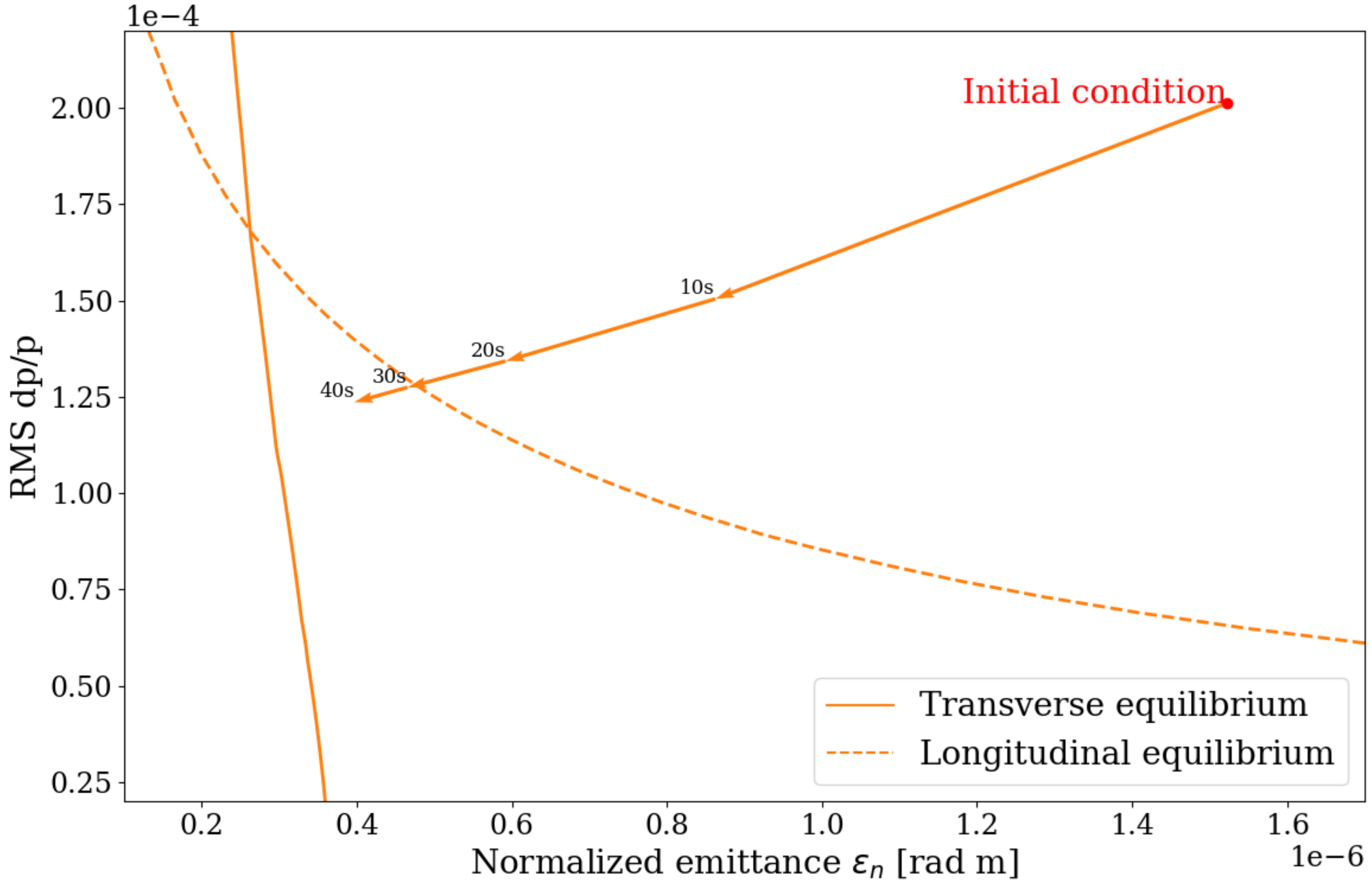
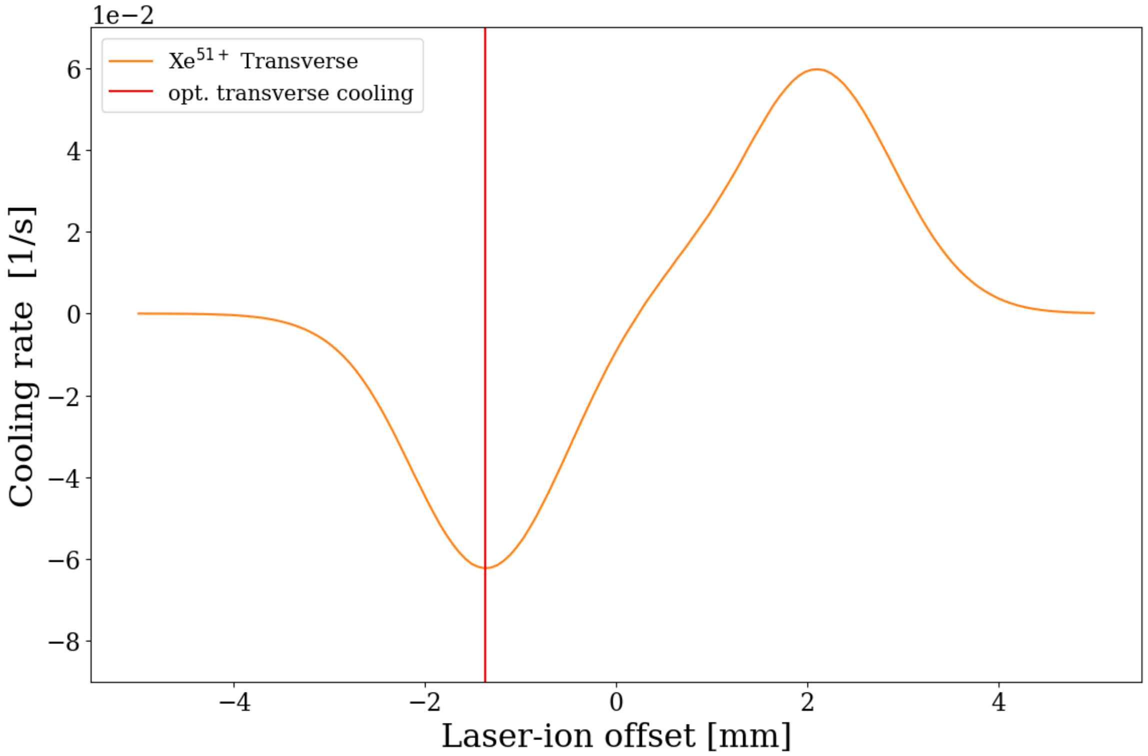


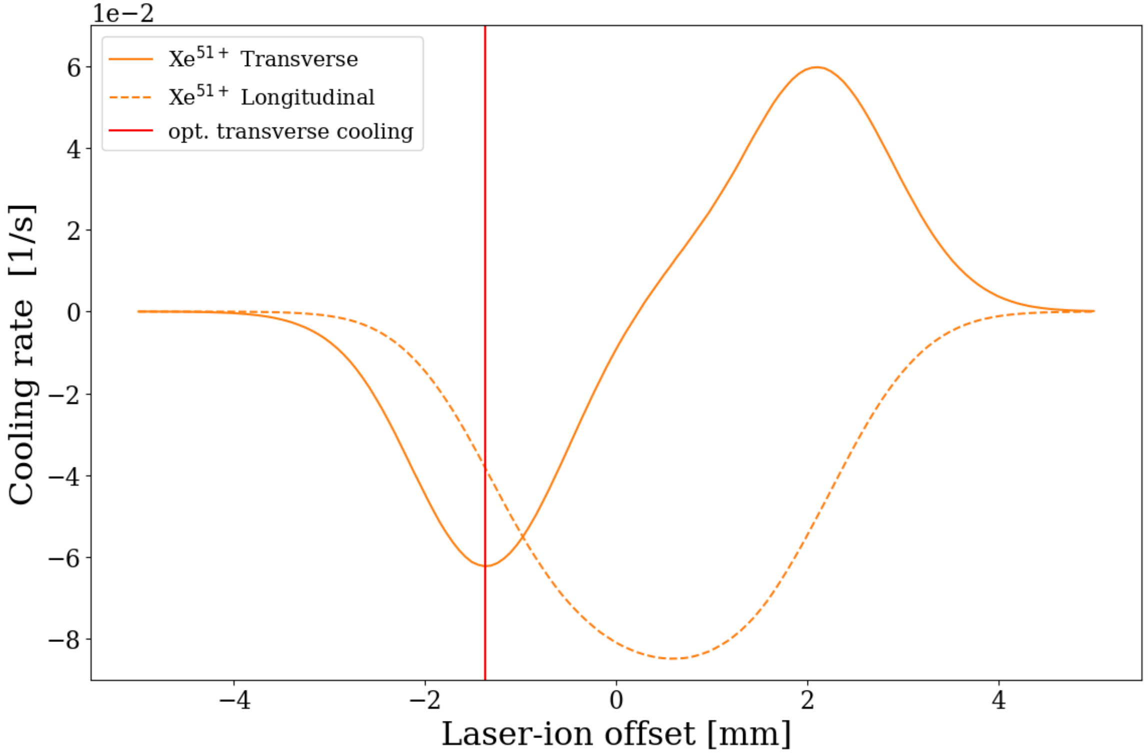
Conclusion: longitudinal plane is the constraint

Optimise Xenon cooling



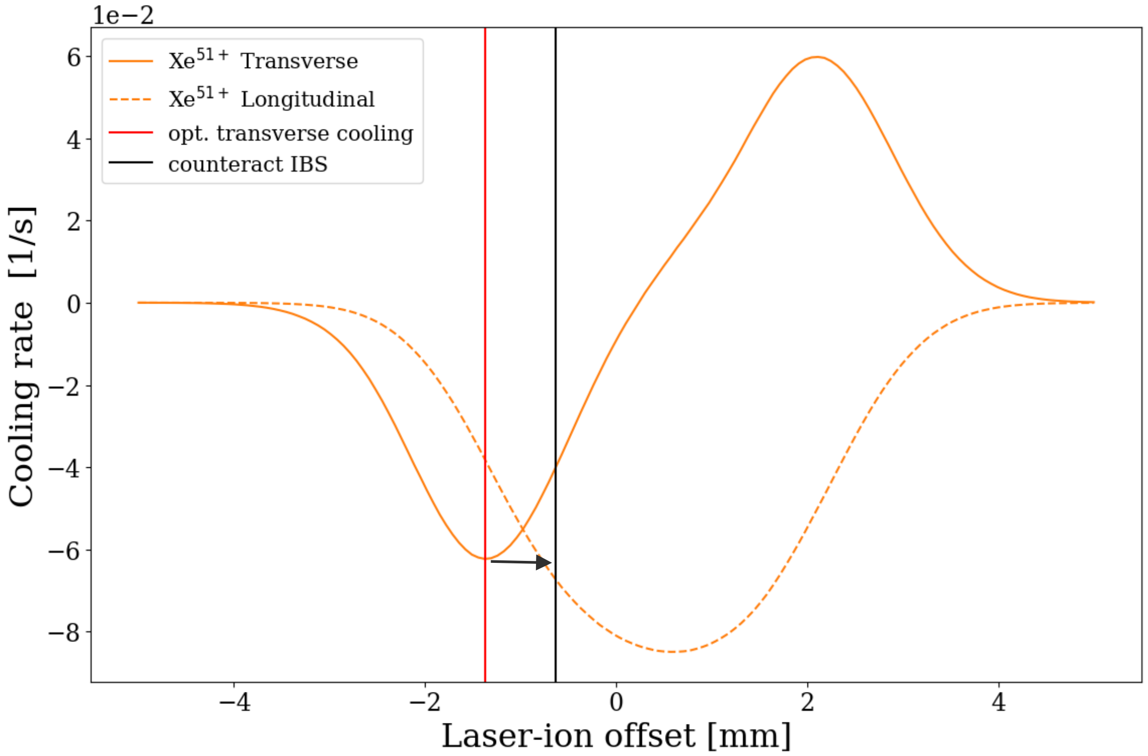
How to circumvent longitudinal constraint?

Optimise Xenon cooling



Decrease laser-ion offset to trade transverse cooling for longitudinal cooling

Optimise Xenon cooling



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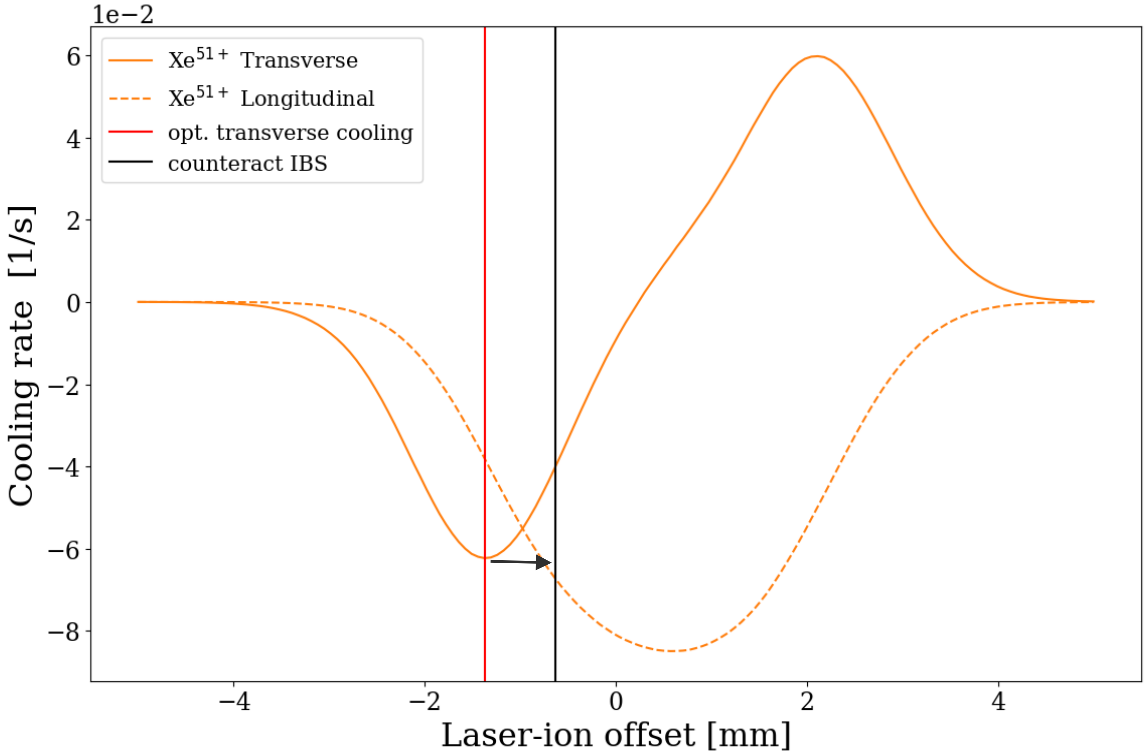

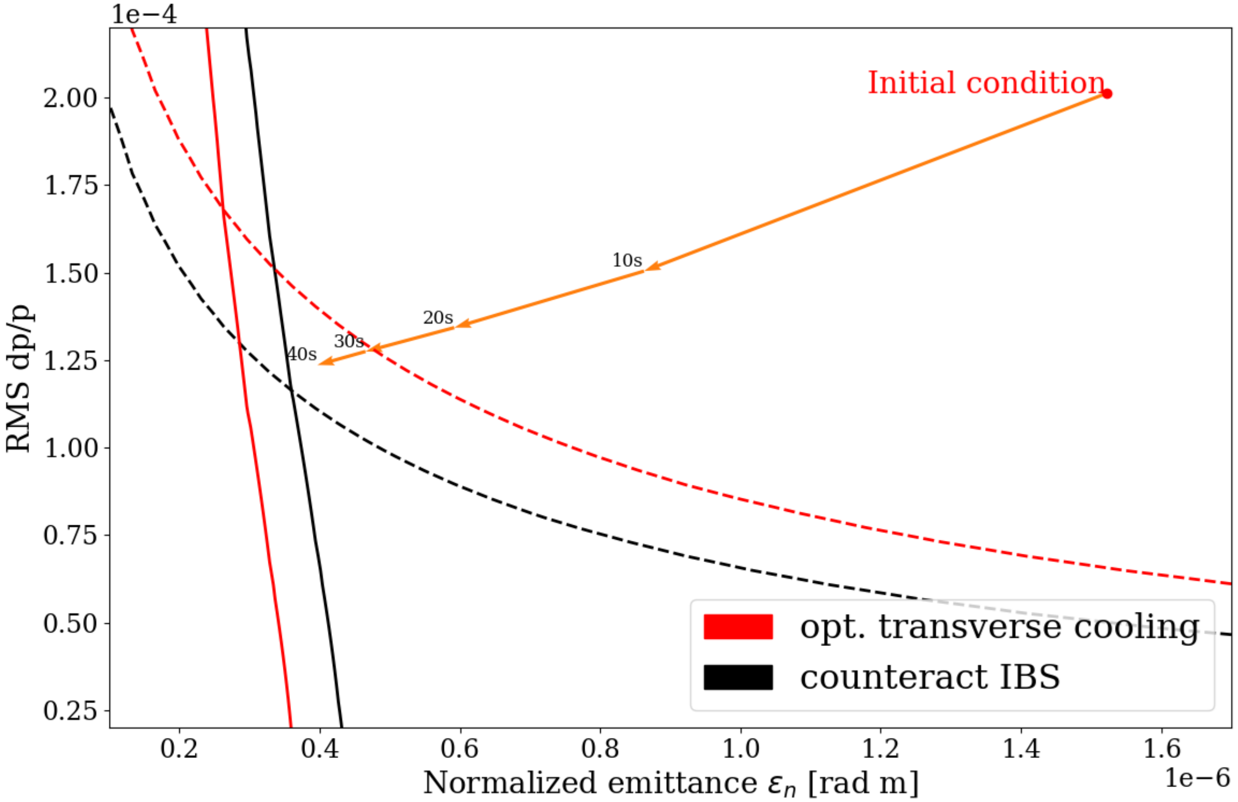

Decrease laser-ion offset to trade transverse cooling for longitudinal cooling

Question: how does Xenon compare to other ions?

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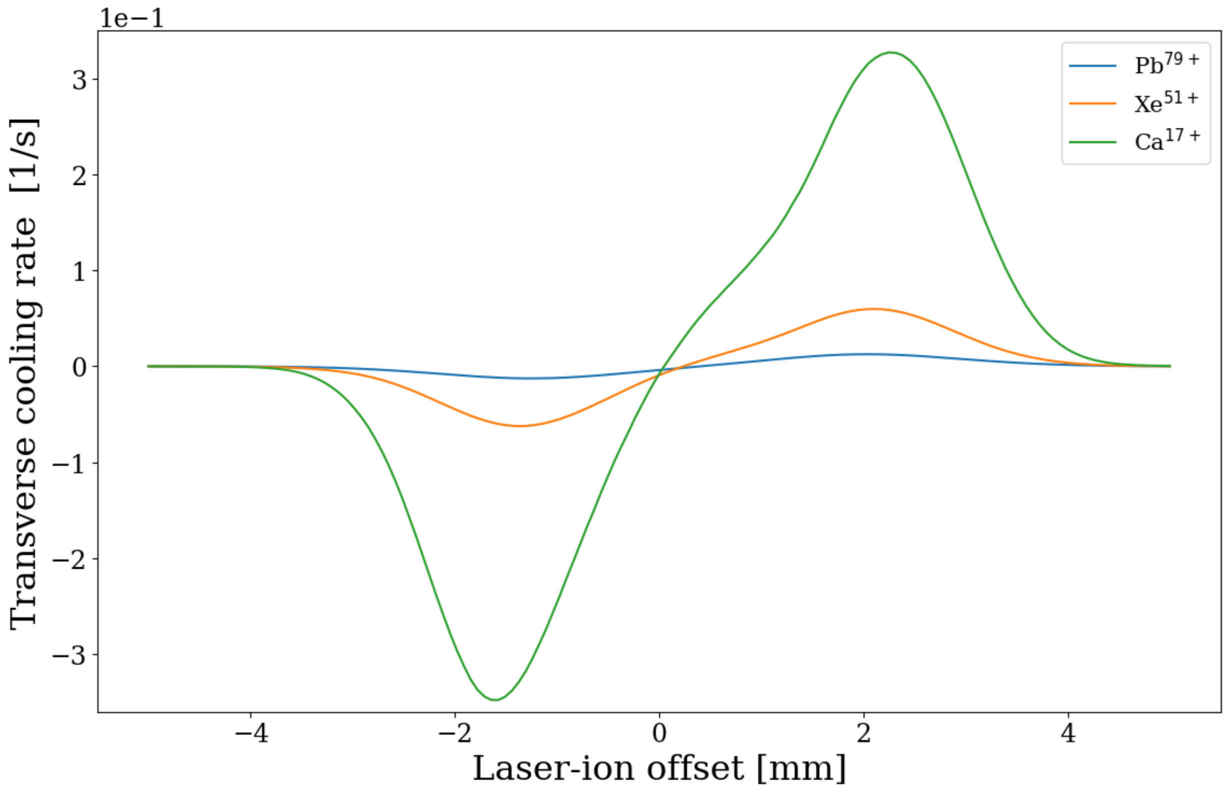
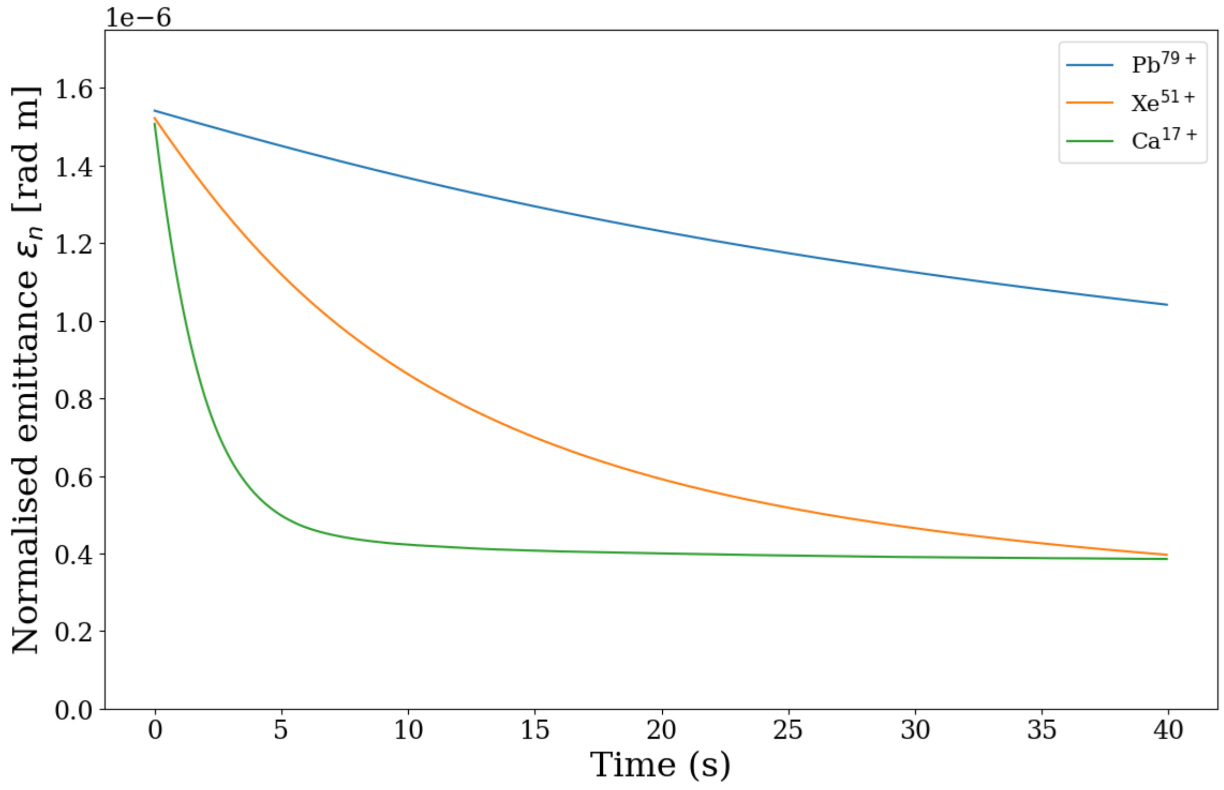
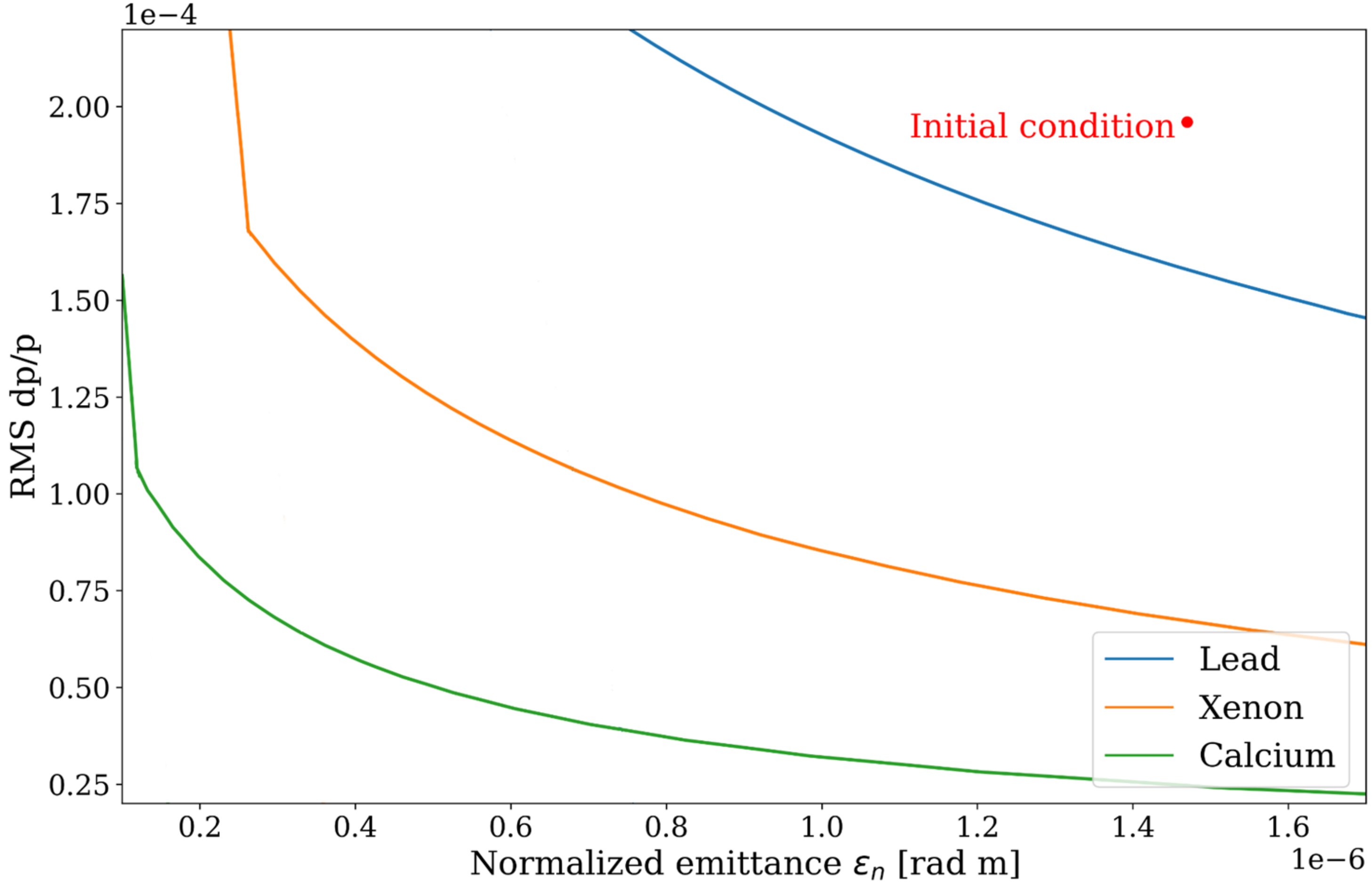




Question: How does this compare to IBS growth rates?

Cooling equilibrium of ions



Summary and outlook

Summary:

- Developed laser cooling tools in Xsuite
- Used tools to estimate cooling rates of xenon,calcium, and lead
- Compared cooling rates against IBS
- Xenon and calcium show small equilibrium emittances

Outlook:

- Simulate lead cooling of Gamma Factory proof-of-principle experiment.

Thanks for your attention & enjoy the workshop!

References

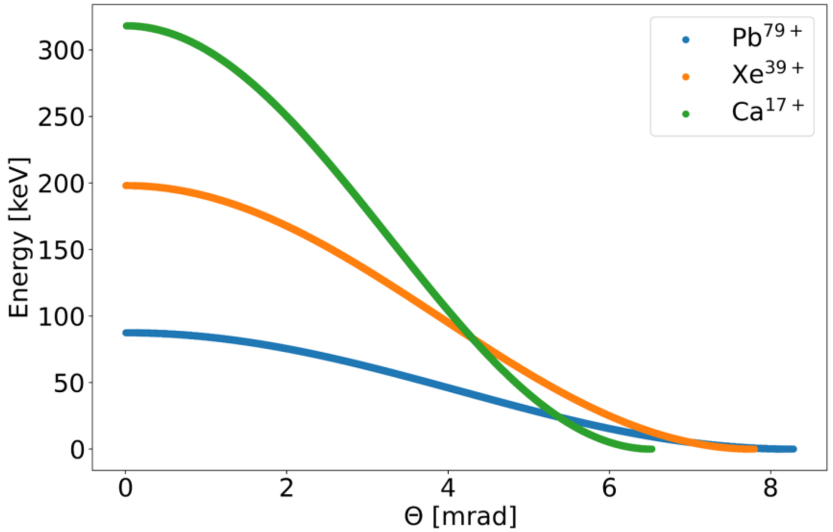
[1] https://github.com/xsuite/xsuite
[2] Chen, D. Y., Wang, H. B., Wen, W. Q., Yuan, Y. J., Zhang, D. C., Huang, Z. K., Winters, D., Klammes, S., Kiefer, D., Walther, T., Loeser, M., Siebold, M., Schramm, U., Li, J., Tang, M. T., Wu, J. X., Yin, D. Y., Mao, L. J., Yang, J. C., … Ma, X. (2023). Explanation for the observed wide deceleration range on a coasting ion beam by a CW laser at the storage ring CSRe. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1047, 167852. https://doi.org/10.1016/J.NIMA.2022.167852

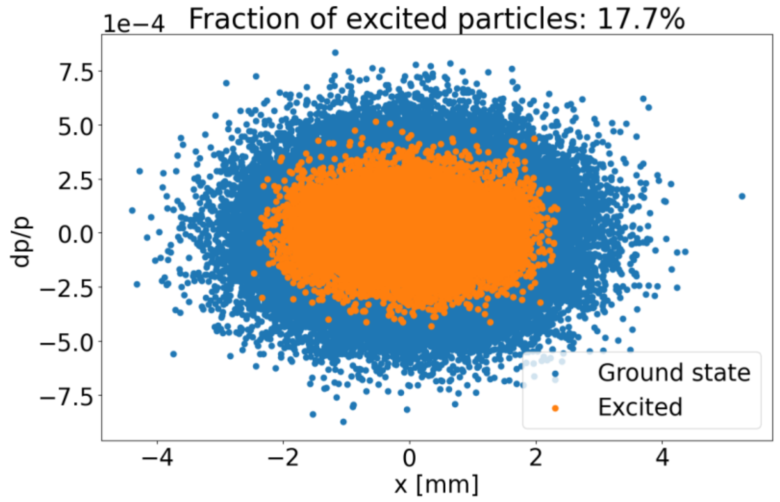
[3] Marcis Auzinsh, Dmitry Budker, Simon Rochester. Optically polarized atoms: understanding light-atom interactions, Oxford University Press, 2010.

[4] https://www.edinst.com/second-harmonic-generation-microscopy-with-the-rms1000-confocal-microscope/

Backup

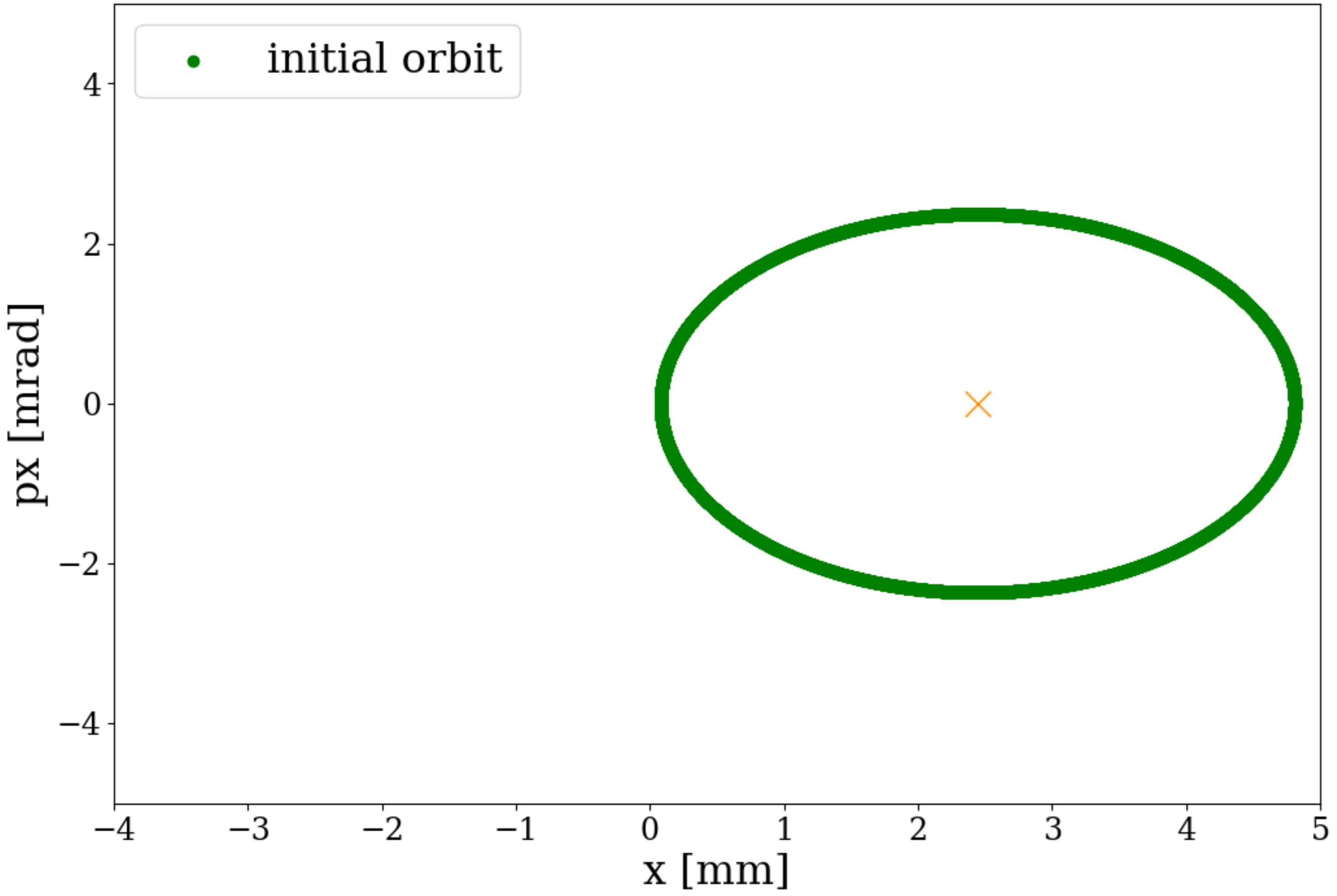
Photon generating mode





Property	Pb^{79+}	Xe^{39+}	Ca^{17+}
Laser Wavelength (nm)	2207.46	1035.17	769.81
Intensity of Ion Beam	1.90×10^8	4.20×10^8	2.77×10^9
Fraction of Excited Particles	16.2%	17.7%	17.7%
Number of Emitted Photons	3.07×10^7	7.43×10^7	4.92×10^8
Maximum Emitted Photon (Kev)	94.91	202.39	272.16

dispersive cooling


initial orbit
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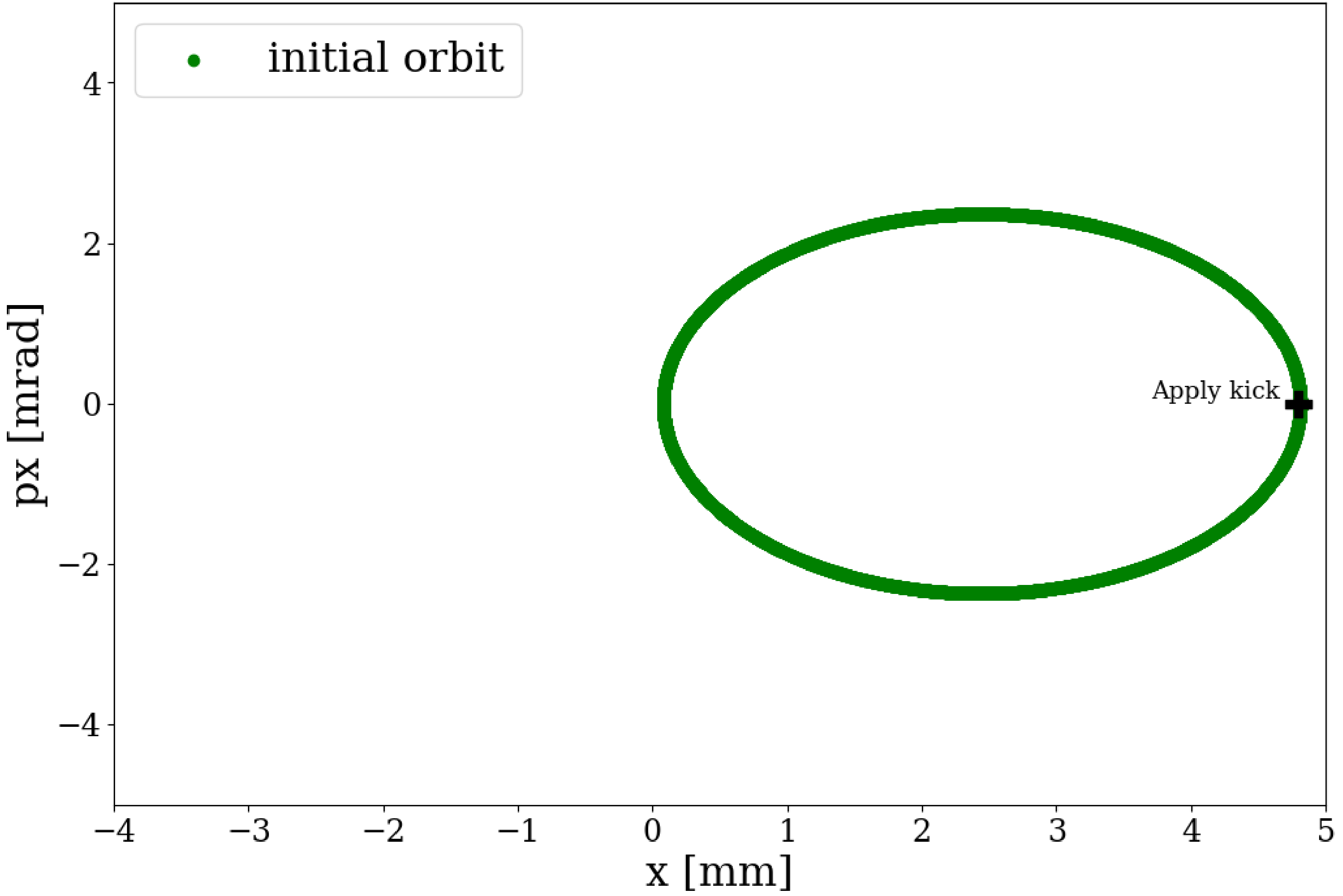
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Apply kick
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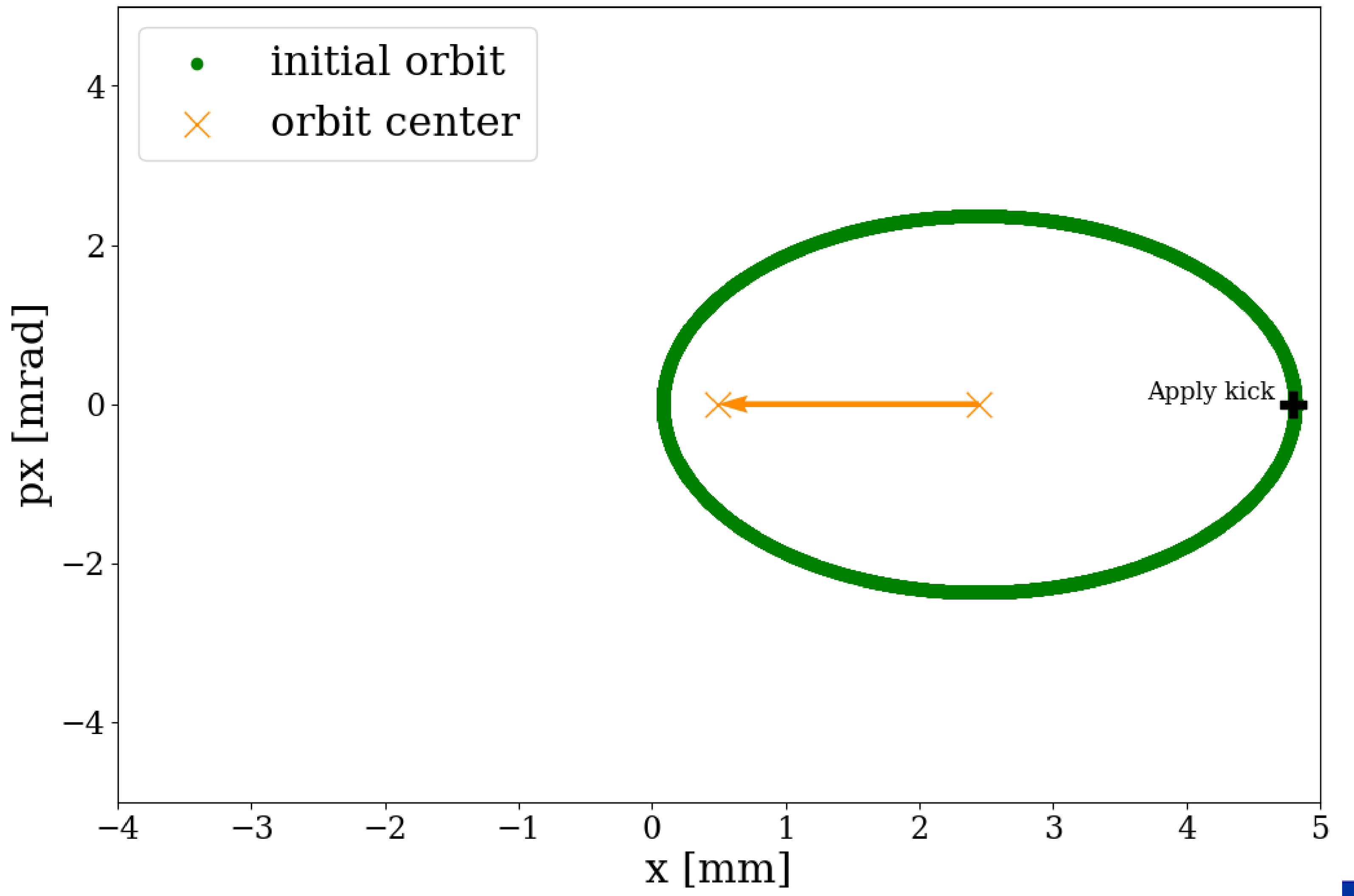
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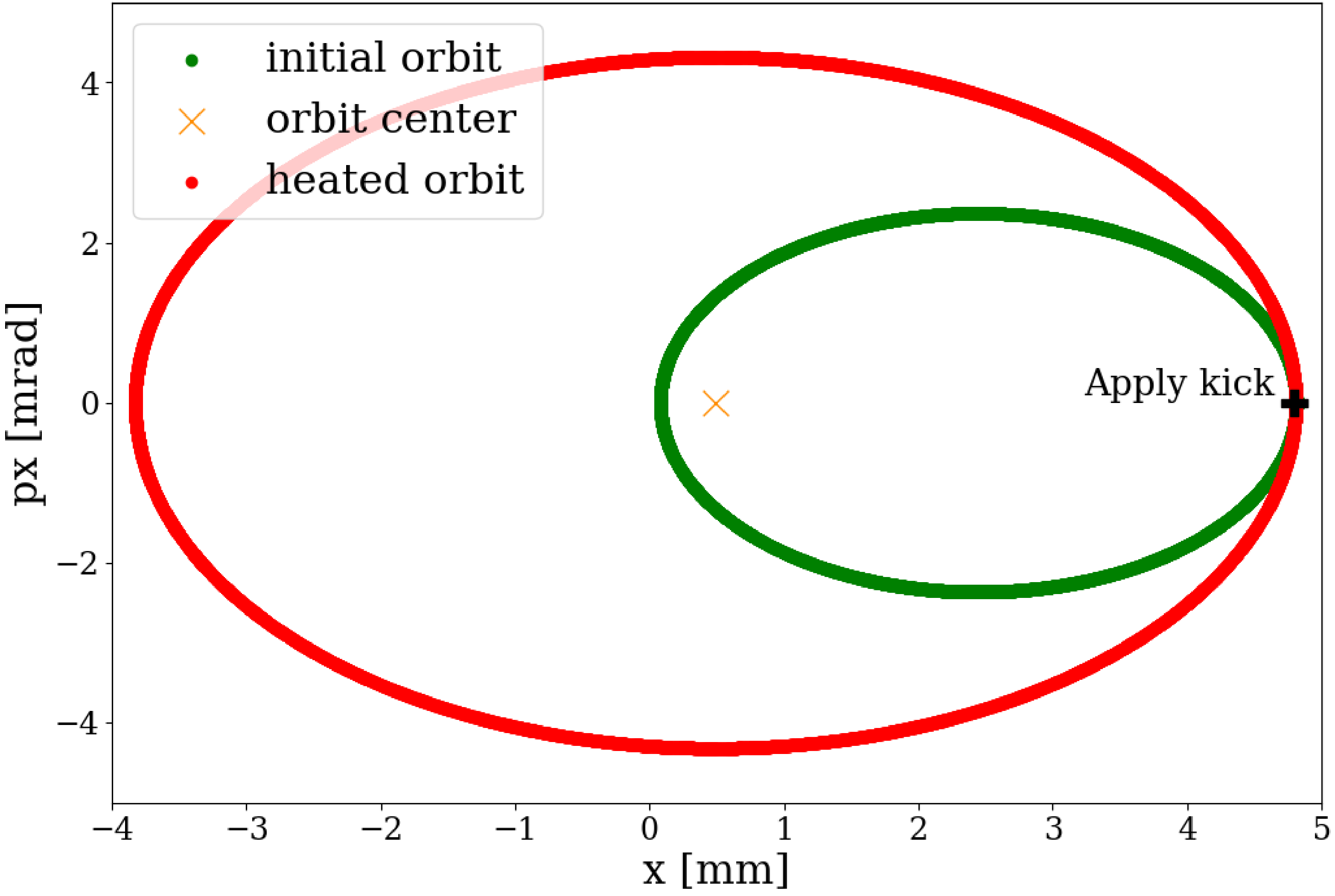
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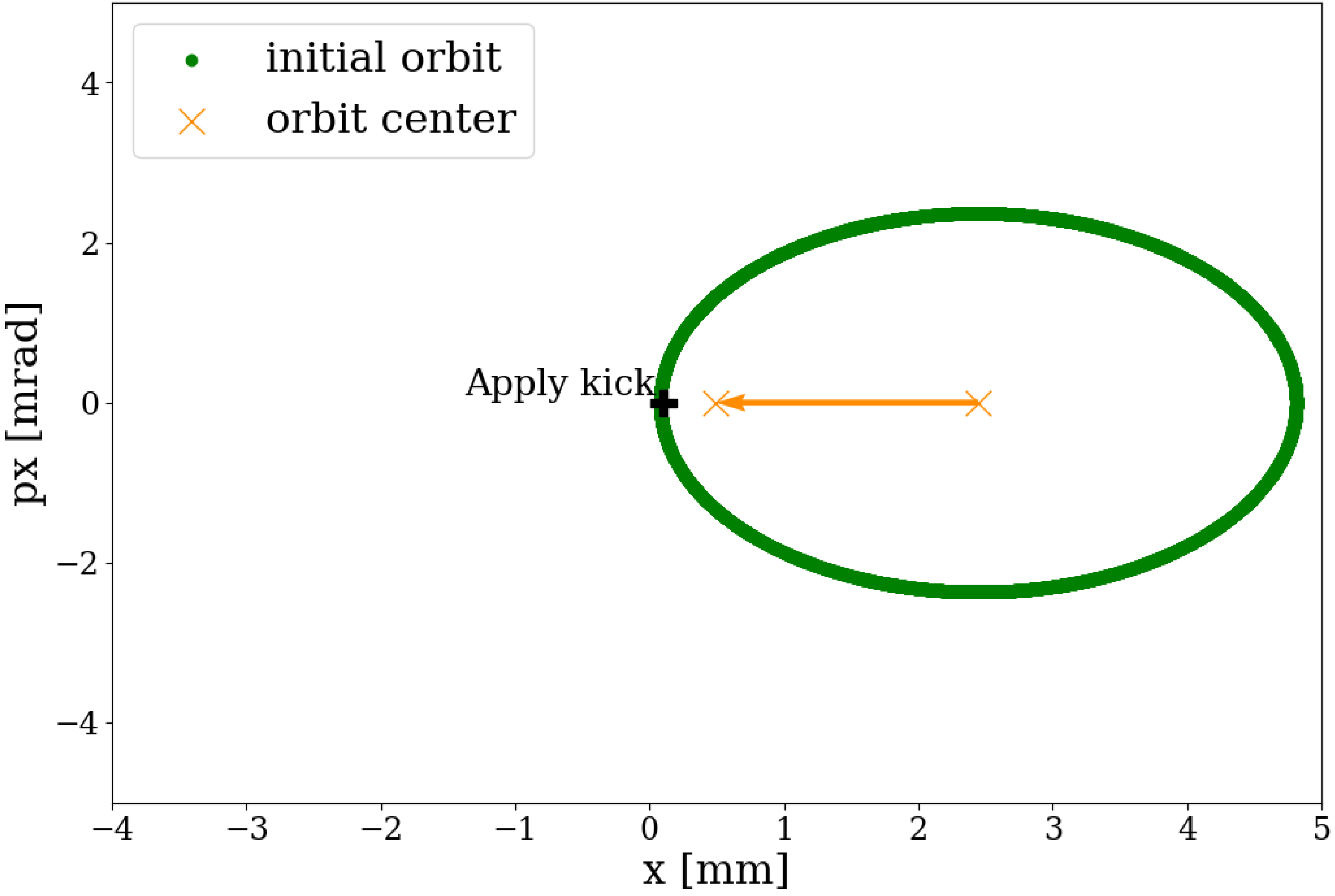
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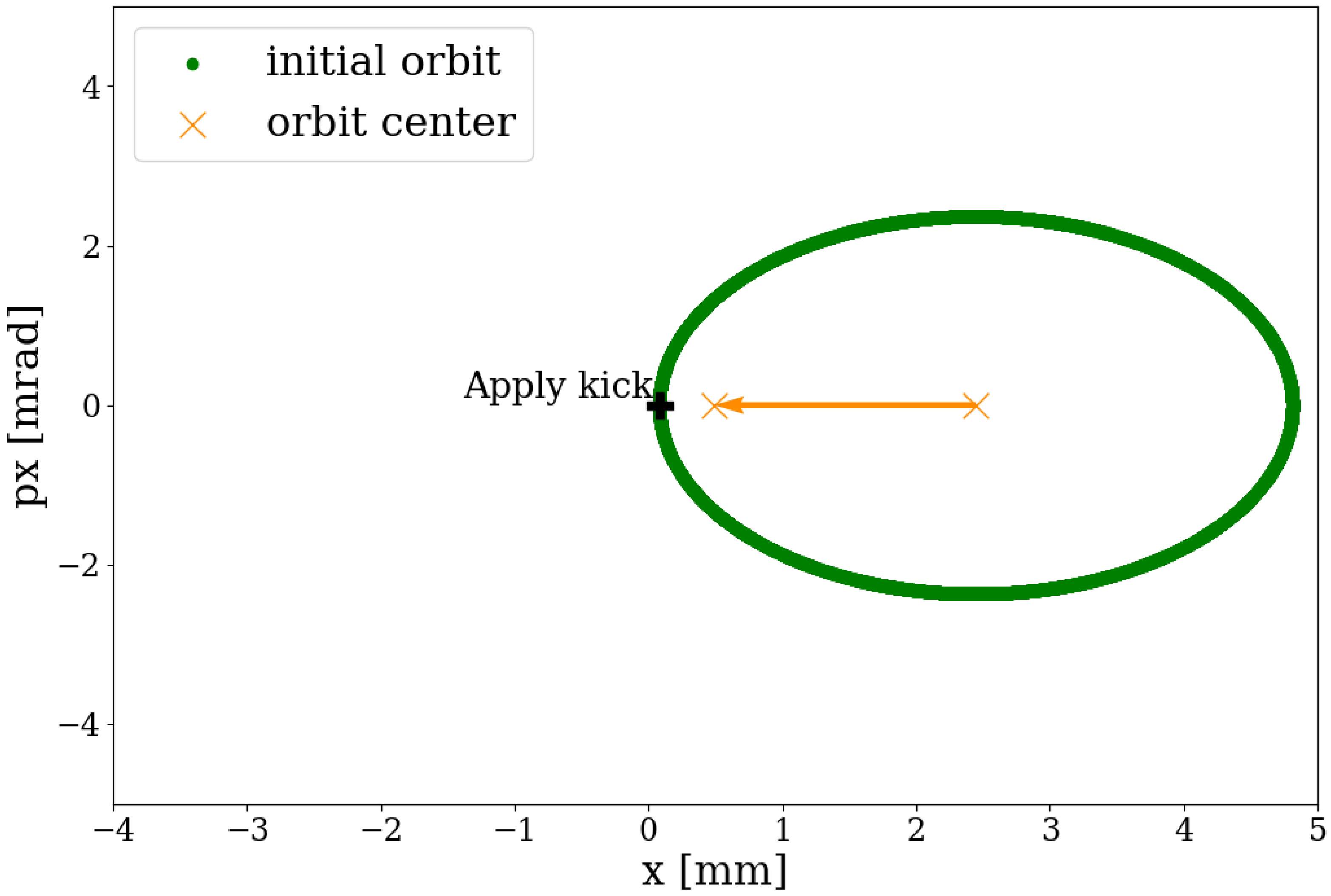
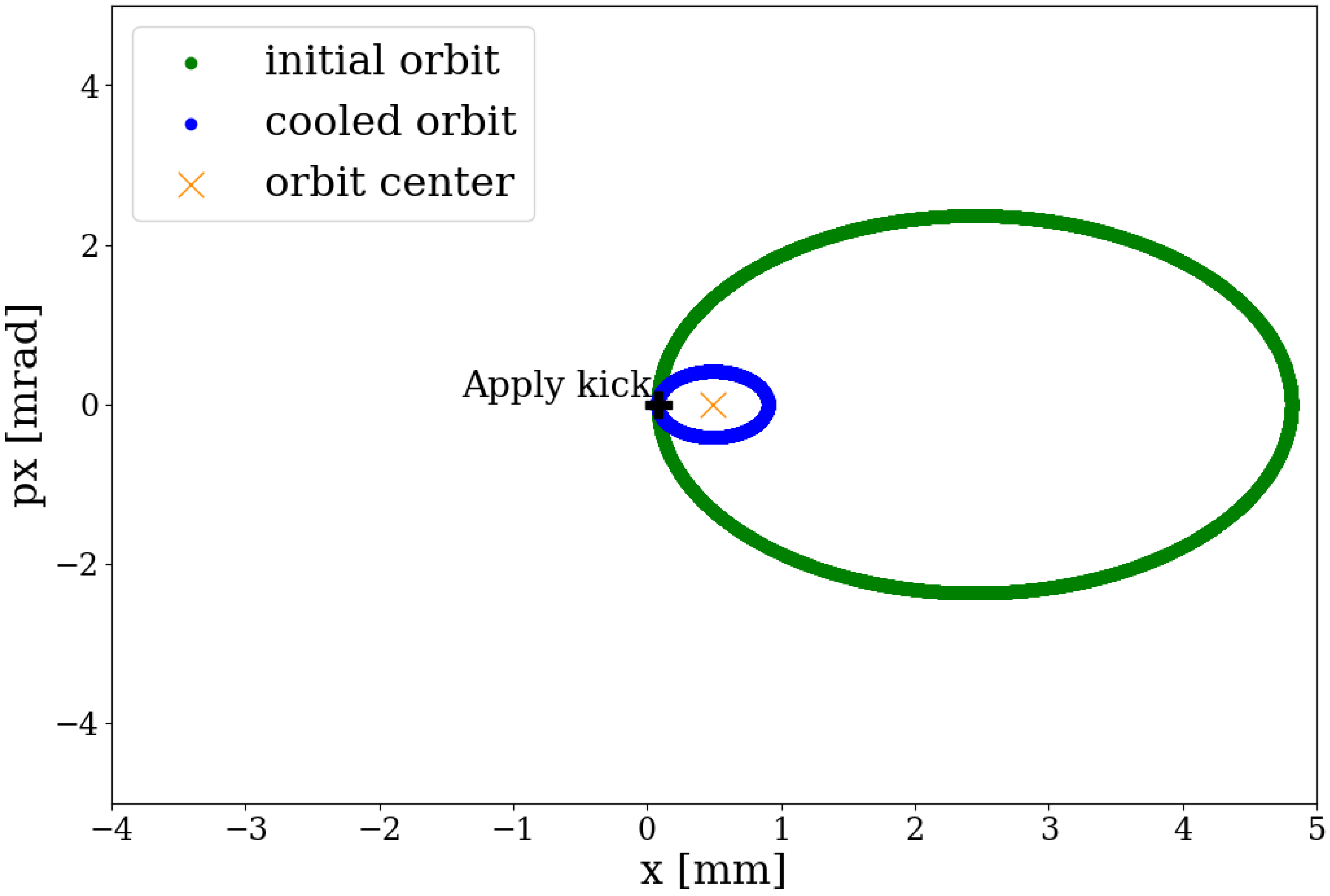
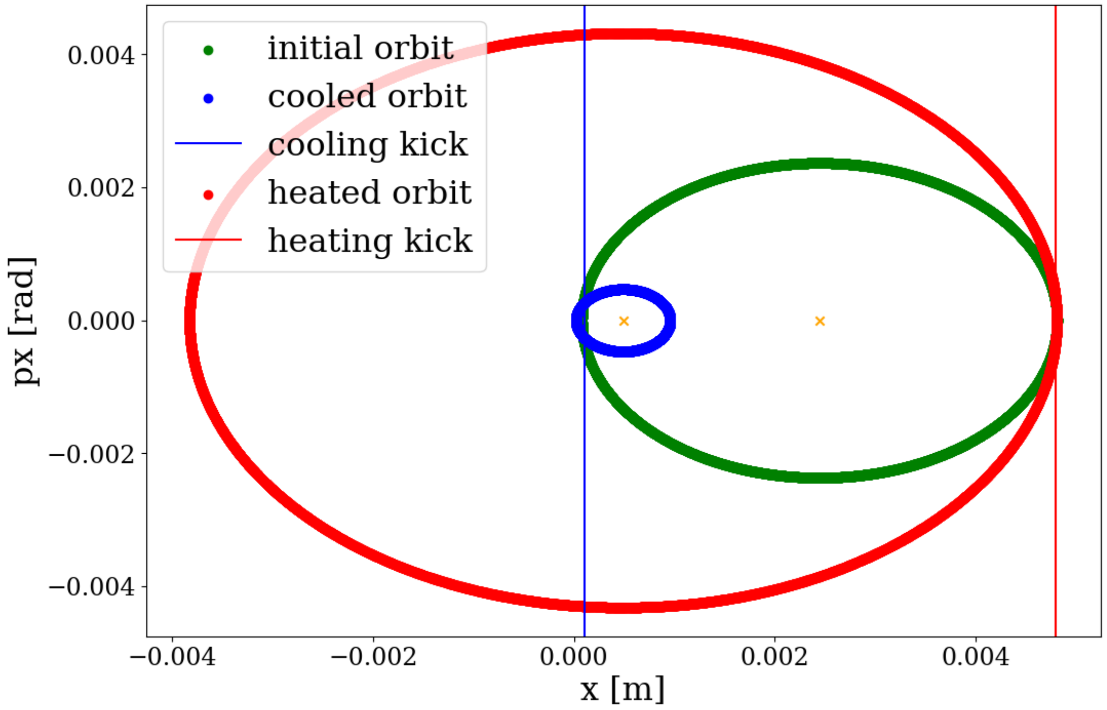
1
2
3
4
5


initial orbit
orbit center
Apply kick
px [mrad]
x [mm]
4
2
0
−2
−4
−4
−3
−2
−1
0
1
2
3
4
5


initial orbit
cooled orbit
orbit center
Apply kick
px [mrad]
x [mm]
4
2
0
−2
−4
−4
−3
−2
−1
0
1
2
3
4
5

Transverse cooling example

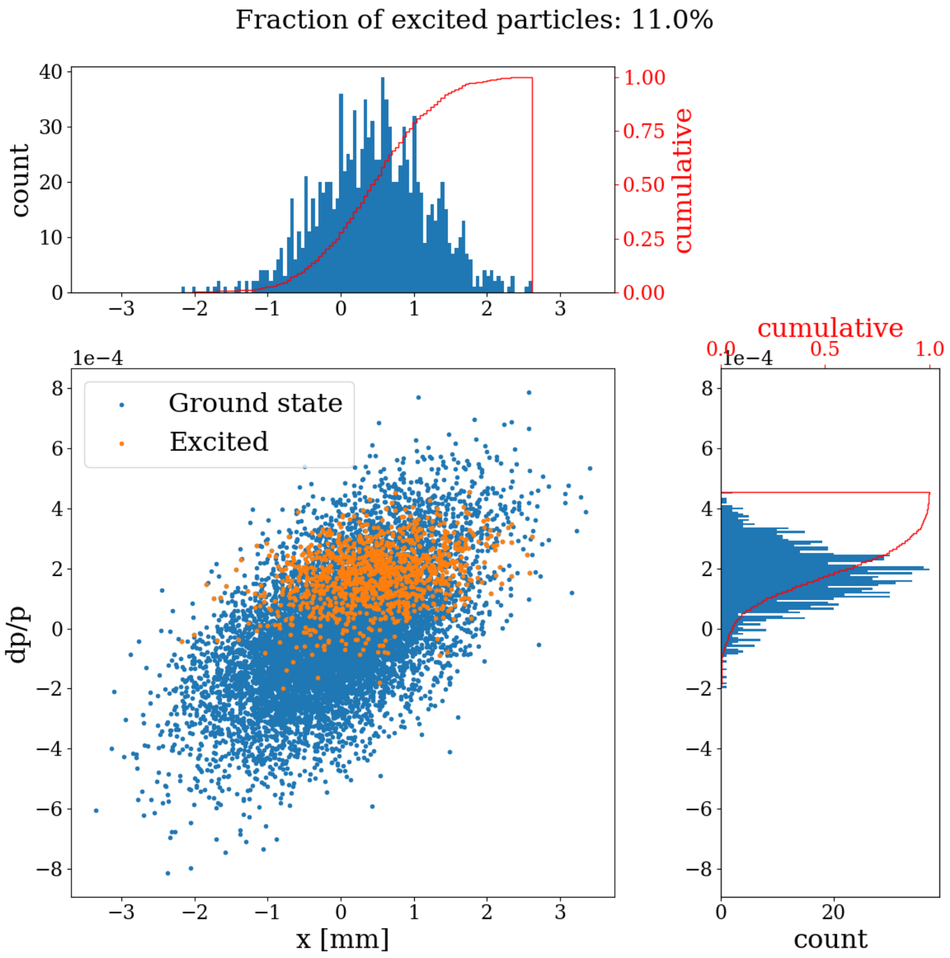
Reducing momentum in dispersive region can heat/cool the beam depending on location of momentum reduction



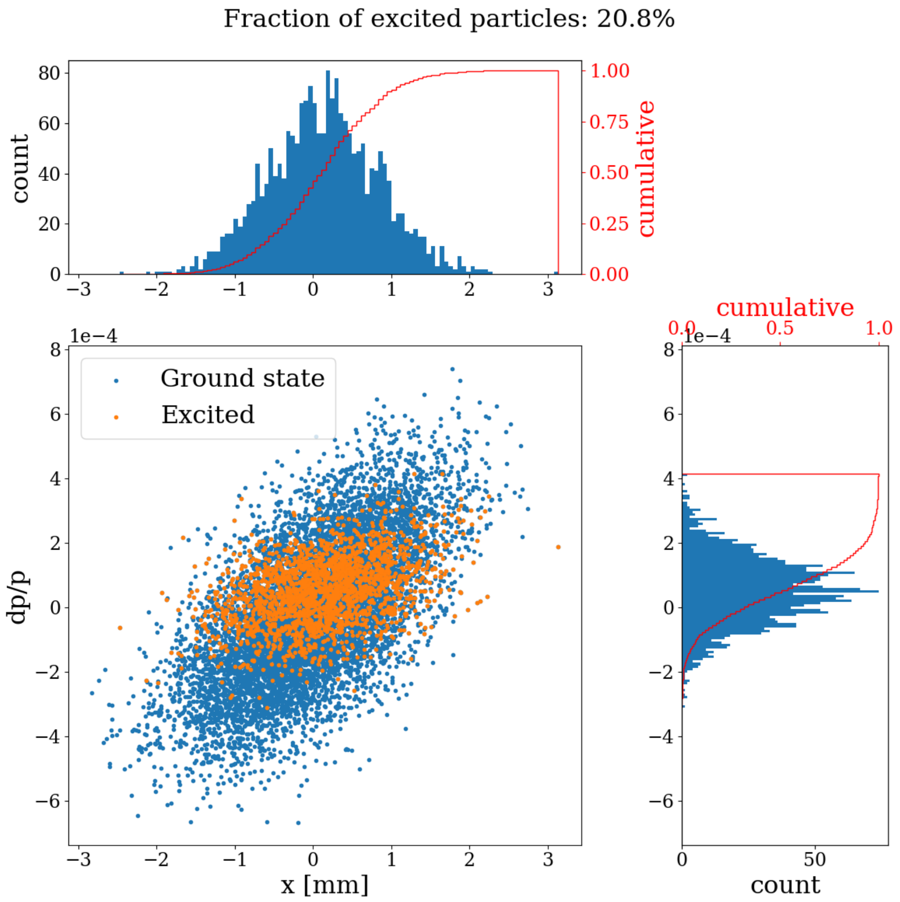
backup

Xenon example

small gamma -> small Doppler shift



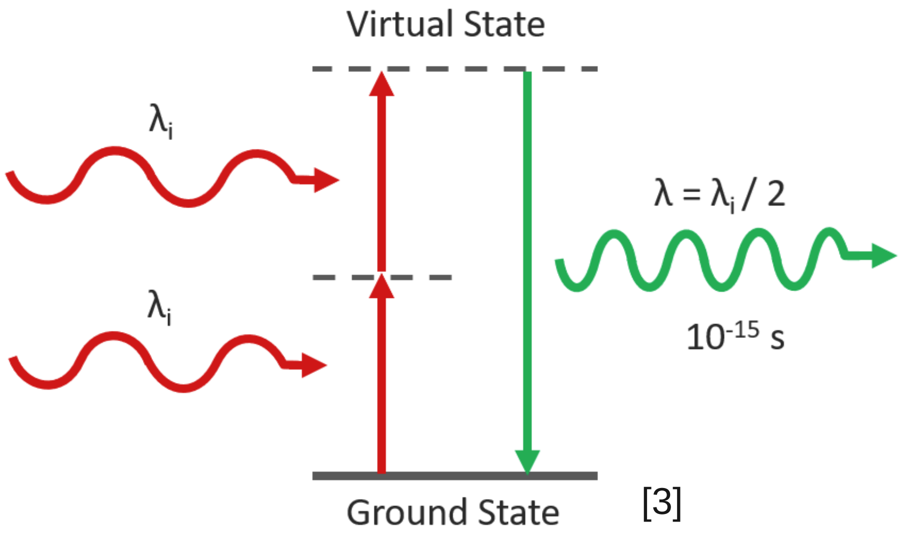
large gamma -> large Doppler shift



Parameter	Value
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
Laser waist radius IP ($\sigma_L = w_L/2$)	1.3 mm
θ_L - Collision angle	2.6°

Parameter	Value
β_x, β_y	54.47, 44.40
α_x, α_y	-1.55, 1.32
γ_x, γ_y	0.06, 0.06
D_x, D_y	2.4, 0.0
D_{px}, D_{py}	0.09, 0.0

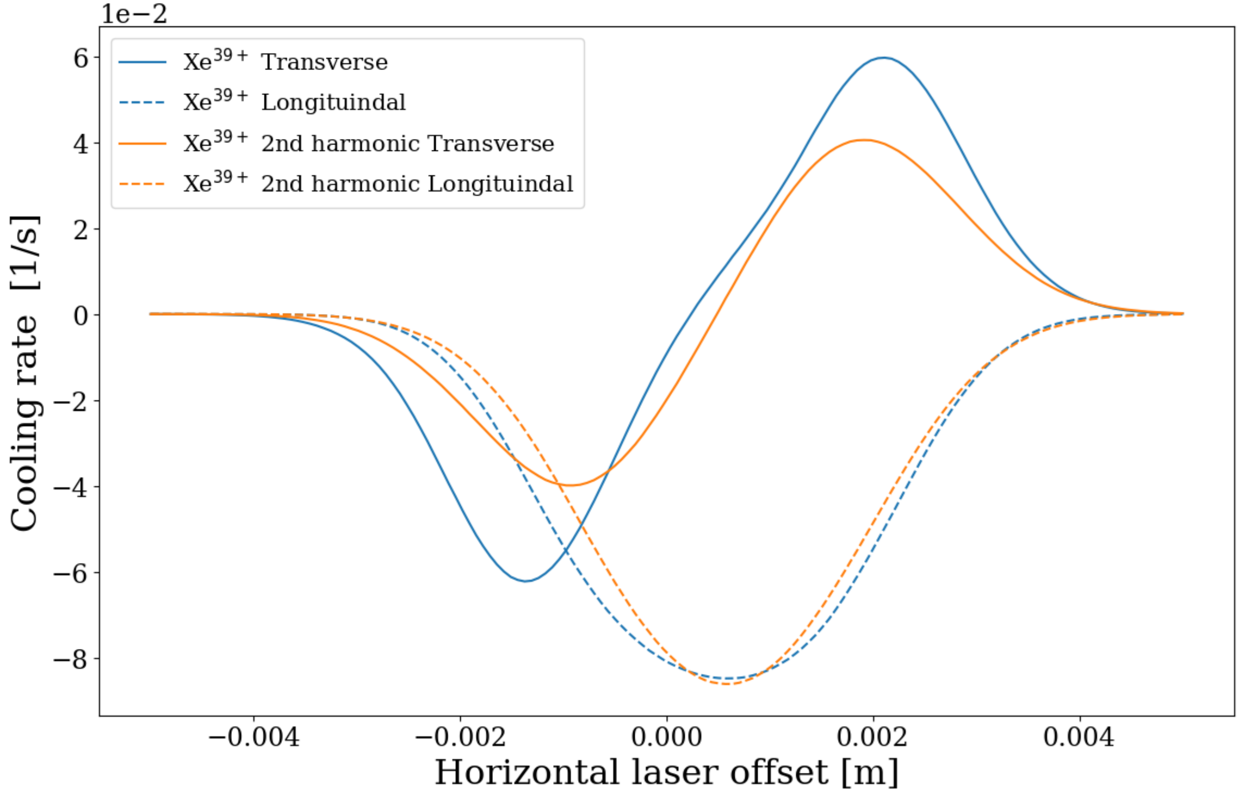
Second harmonics: Xenon

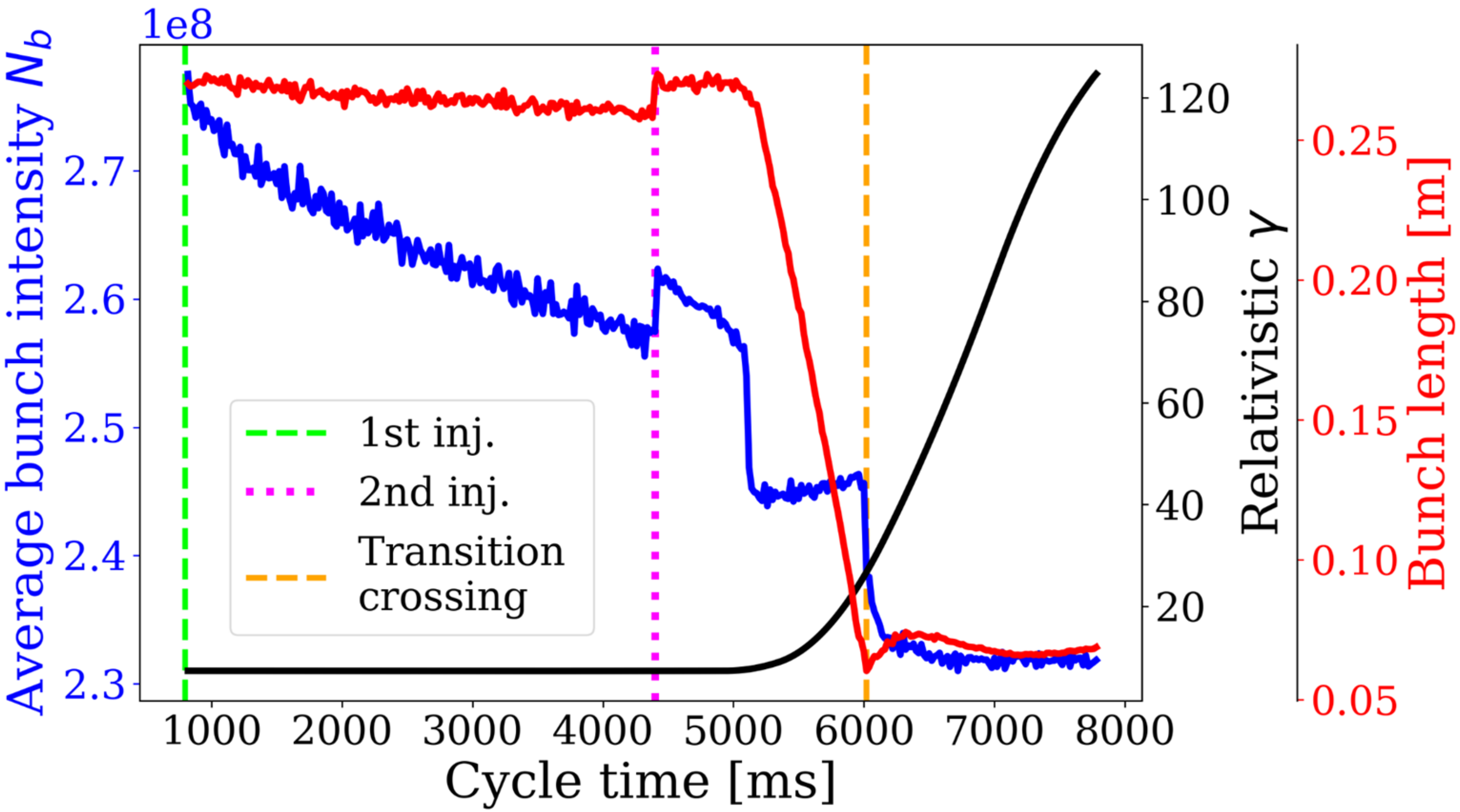


[3]

Property	Xenon	Xenon 2nd harmonic
Excited Lifetime (ps)	3	3
Transition Energy (eV)	492.22	492.22
Lorentz factor	152.5162	102.2579
Laser Wavelength (nm)	768	515
Pulse energy (mJ)	5	2.5

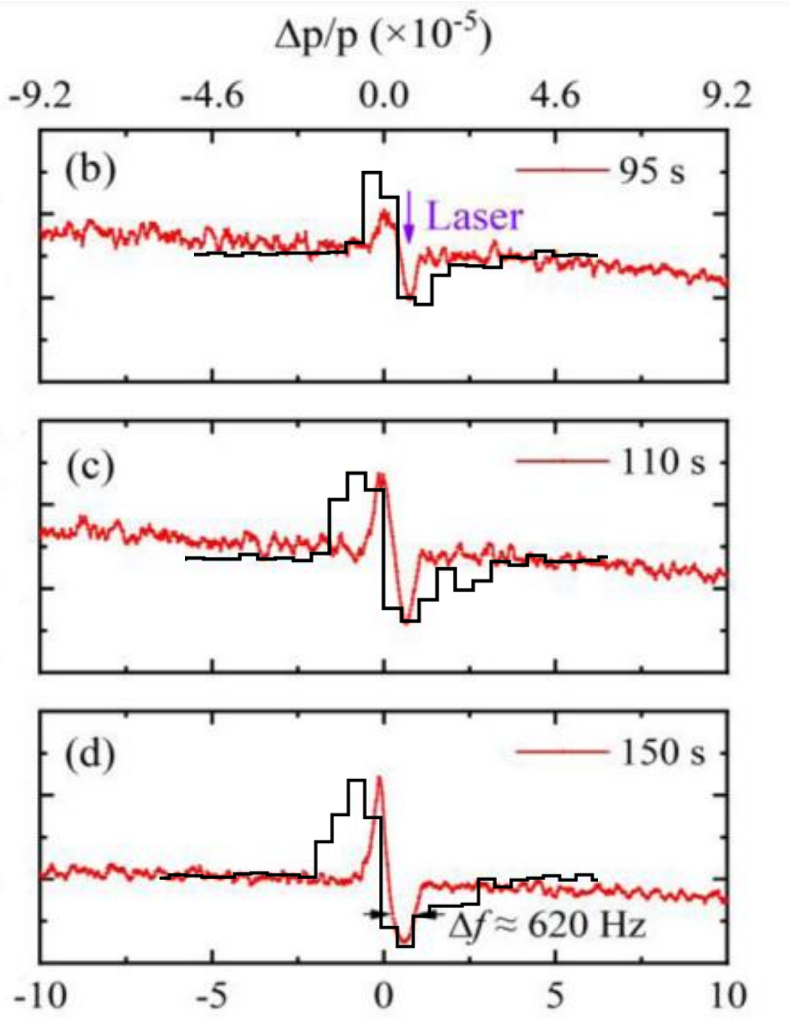
- smaller laser wavelength
- smaller laser pulse energy



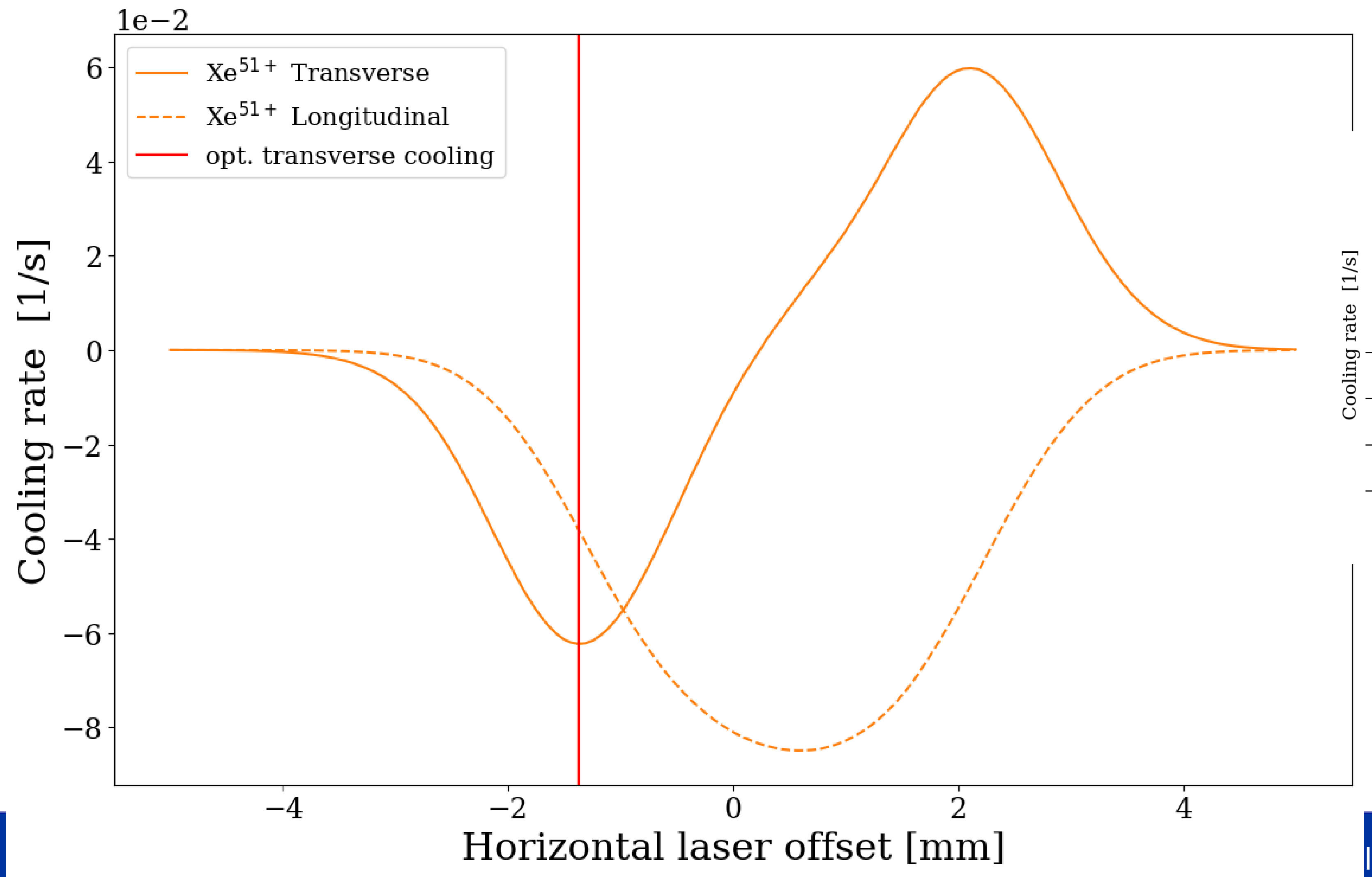

1e8
Average bunch intensity N_b
2.7
2.6
2.5
2.4
2.3
1000
2000
3000
4000
5000
6000
7000
8000
Cycle time [ms]
120
100
80
60
40
20
Relativistic γ
0.25
0.20
0.15
0.10
0.05
Bunch length [m]
1st inj.
2nd inj.
Transition crossing

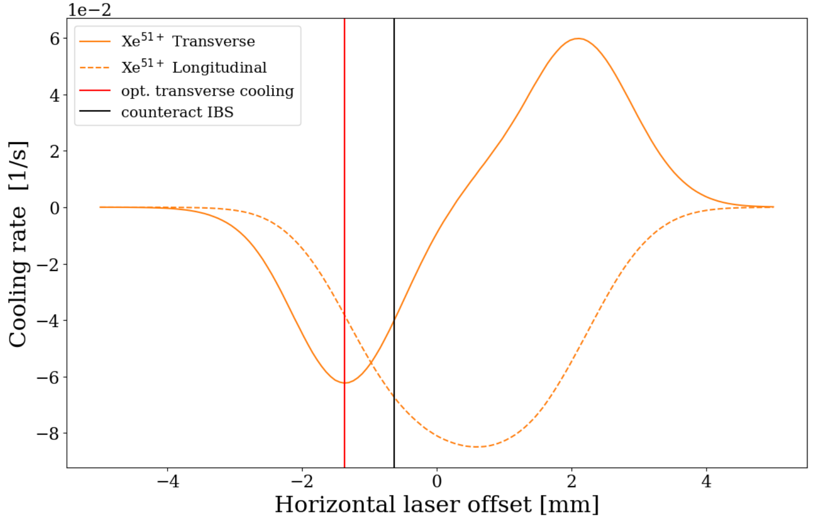
Lanzhou benchmark

- Solve Optical Bloch Equations (OBE)
- Compare with Lanzhou experiment



<u>Results</u>:
Theoretical linewidth = 3.6e-8
Observed linewidth = 5.7e-6
Xsuite linewidth ≈ 5e-6


1e−2
Xe51+ Transverse
Xe51+ Longitudinal
opt. transverse cooling
Cooling rate [1/s]
6
4
2
0
−2
−4
−6
−8
−4
−2
0
2
4
Horizontal laser offset [mm]


1e−2
Xe51+ Transverse
Xe51+ Longitudinal
opt. transverse cooling
counteract IBS
Cooling rate [1/s]
6
4
2
0
−2
−4
−6
−8
−4
−2
0
2
4
Horizontal laser offset [mm]