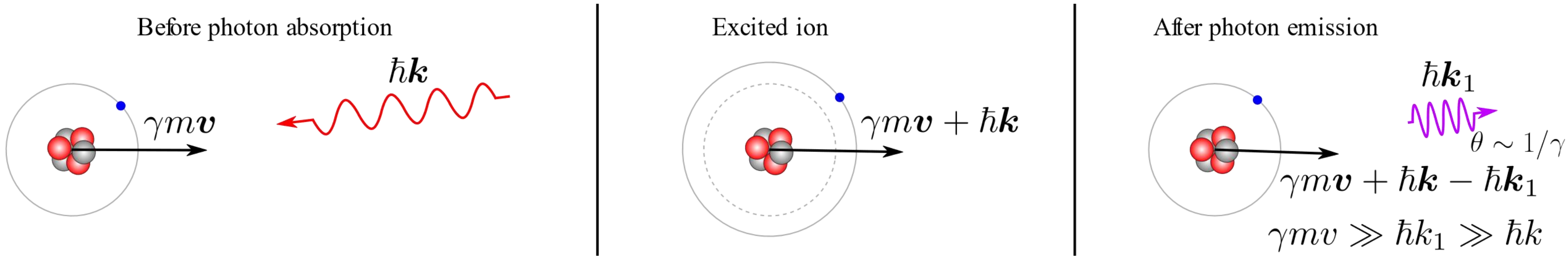
Gamma Factory ion beam dynamics

Alexey Petrenko (Budker INP)

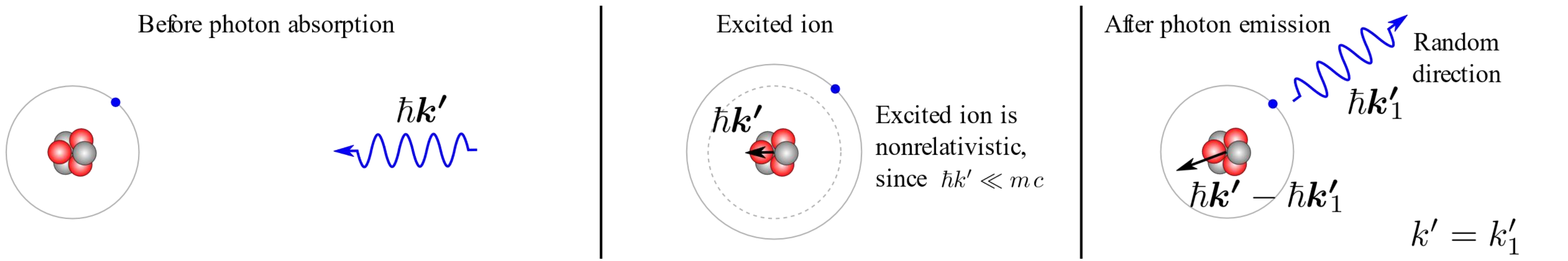
Gamma Factory meeting at CERN, March 26, 2019.

Laser-ion interaction kinematics

In the lab frame:



In the ion's frame:



What is the effect of radiation emission on the ion beam dynamics?

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.

Longitudinal heating: because energy loss per emission is random due to the random direction of photon emission in the ion's frame of reference.

The LHC H-like Pb example:

Ion charge Z = 81, mass A = 208, **γ = 2719**, p_z = 526.5 TeV/c,

$\hbar\omega'$ = 69 keV (Lyman-alpha line), laser **$\hbar\omega$ = 12 eV (98 nm)**,
emitted gamma **$\hbar\omega_{1,max}$= 373 MeV**, typical angle of emission **$\theta_1 \sim 1/\gamma \sim$ 0.3 mrad**.

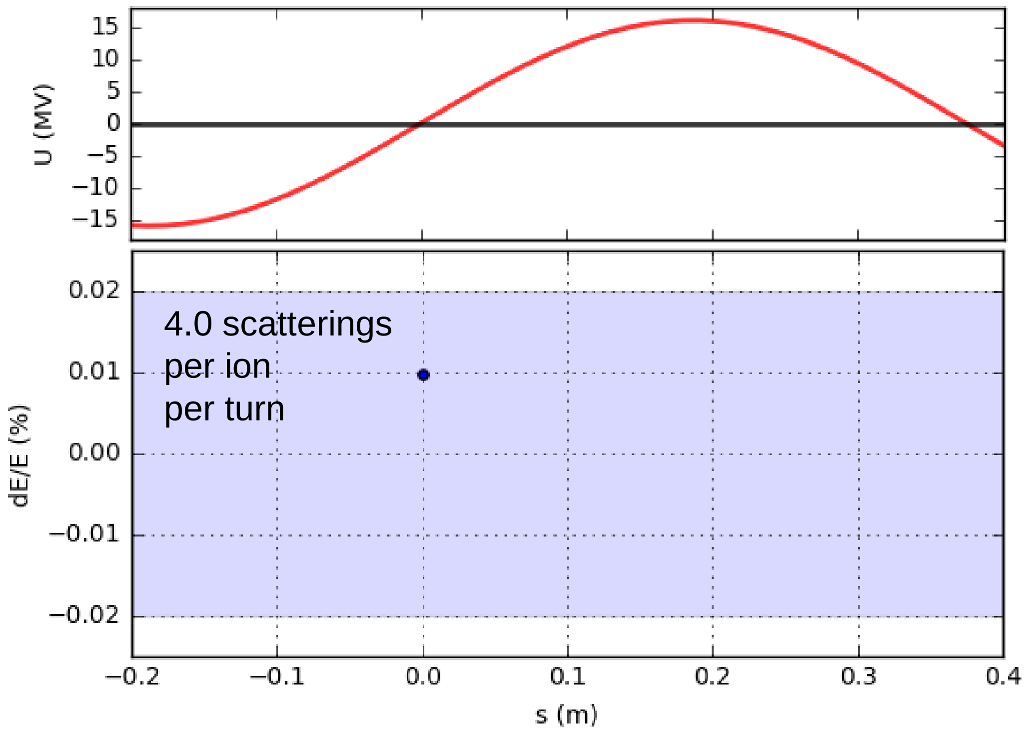
Typical transverse kick due to gamma emission:

$p_x/p_z \sim \hbar\omega'/p_z c$ ~ 69 keV / 527 TeV ~ 10^{-7} mrad.

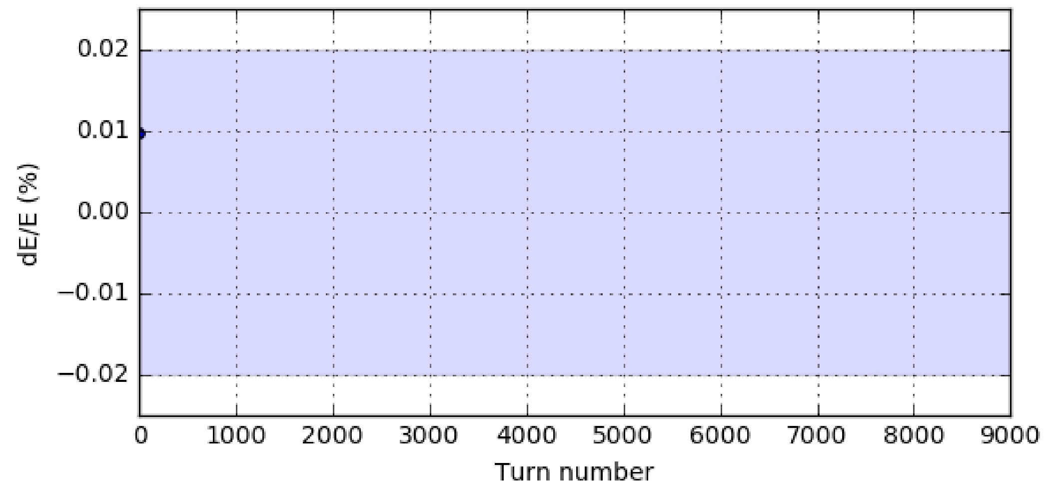
Typical transverse beam parameters at the LHC interaction point for example:
Transverse beam size = 0.026 mm, angular spread = 0.026 mrad (10^5 times higher).

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 / 527 TeV = $3.7 \cdot 10^{-7}$ => $\Delta p/\delta p \approx 300$, and even with one scattering per turn the longitudinal effects will be significant in ~100-1000 turns.

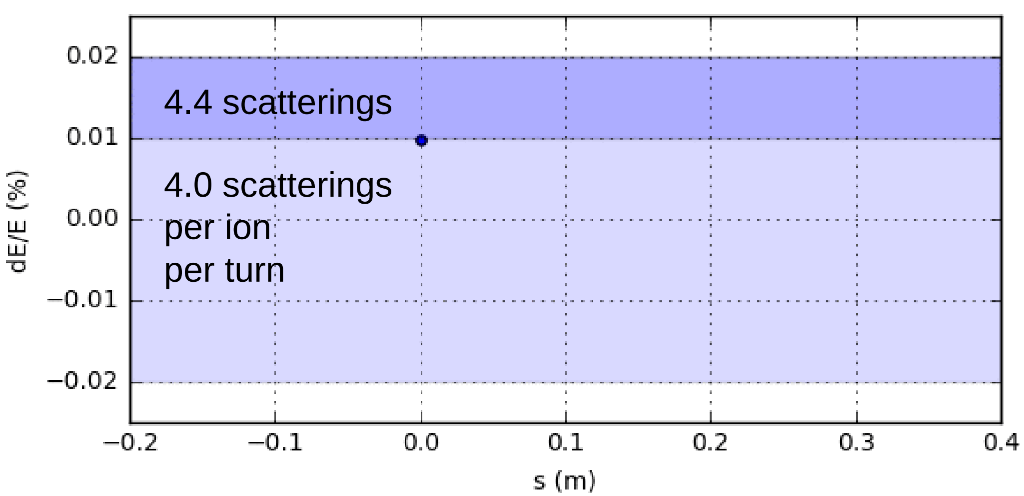
Longitudinal laser cooling is important to stabilize the ion motion:

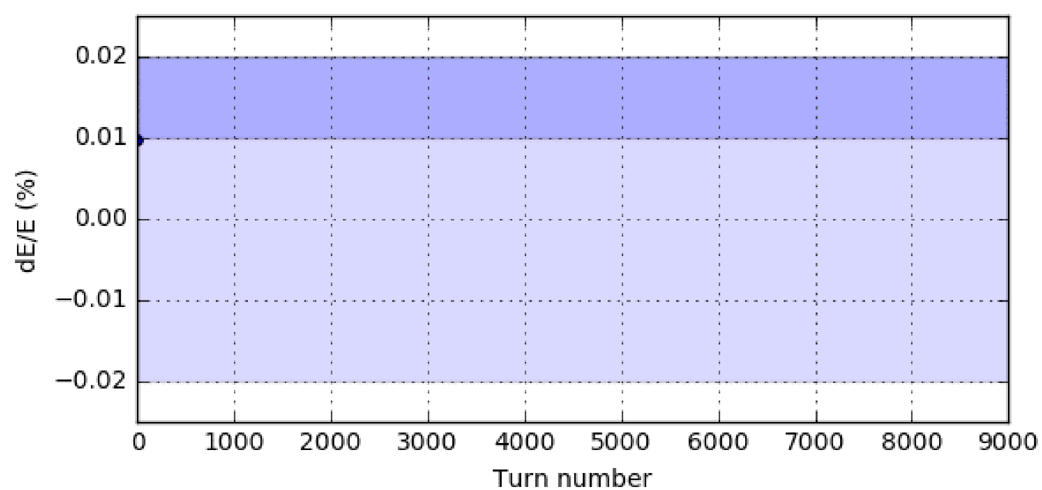


The important effect of photon emissions on ion beam dynamics is in the energy loss of the partially stripped ion. This energy loss is randomly distributed from 0 to 400 MeV in this case of Pb ion with one remaining electron in the LHC. This randomness excites uncontrolled growth of synchrotron oscillations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





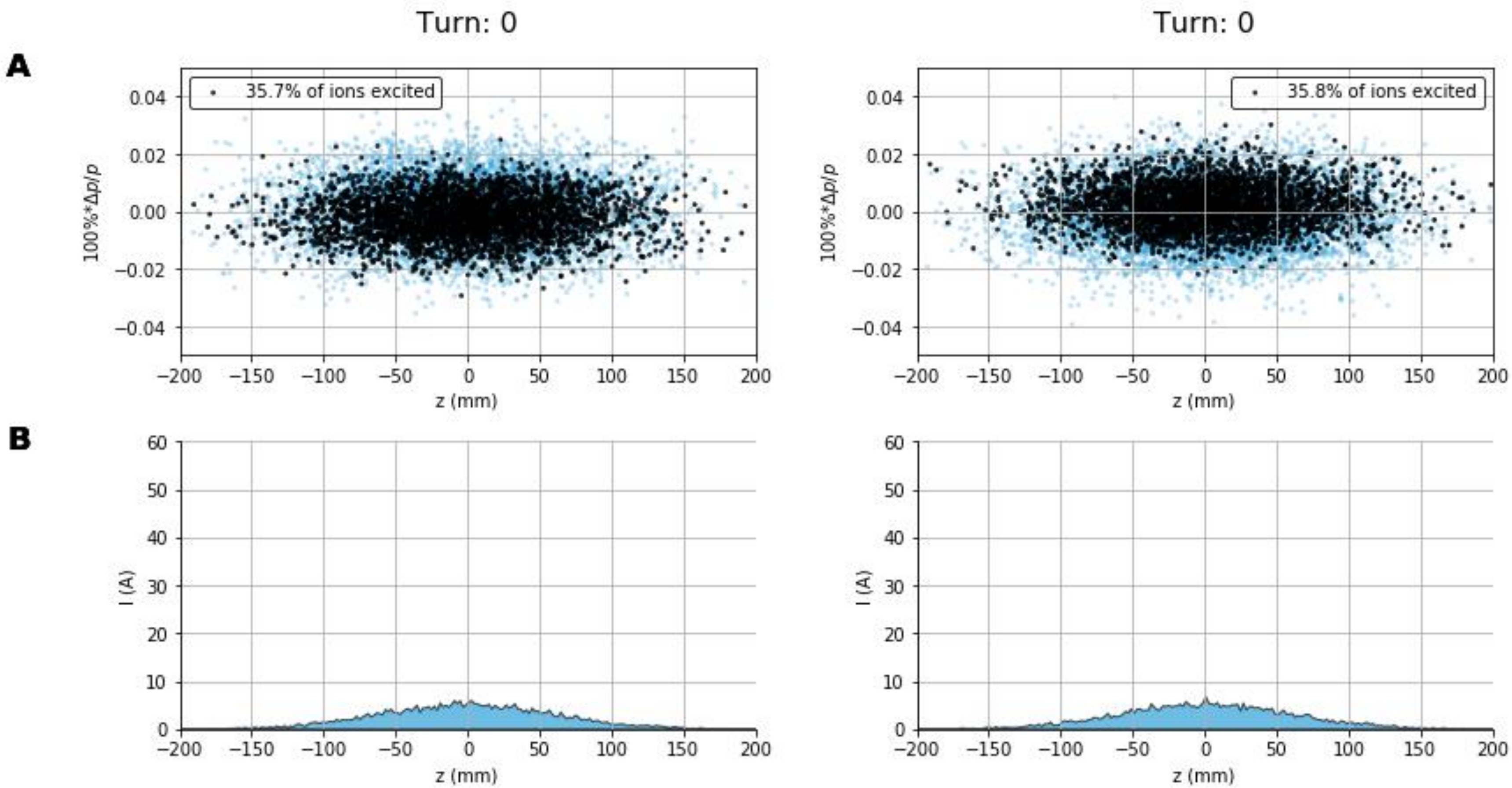
Simulation details: http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

The longitudinal beam dynamics is quite sensitive to imbalance of energy radiated at $\Delta p>0$ vs $\Delta p<0$:

Fourier-limited Gaussian laser pulse with $\sigma(\Delta\omega/\omega) = \sigma(\Delta p/p)$ centered on $p_0(1\pm0.5\Delta p/p)$

Laser waist size $w_0 = 2\sigma_{x,y} = 40$ µm, energy = 42 µJ.

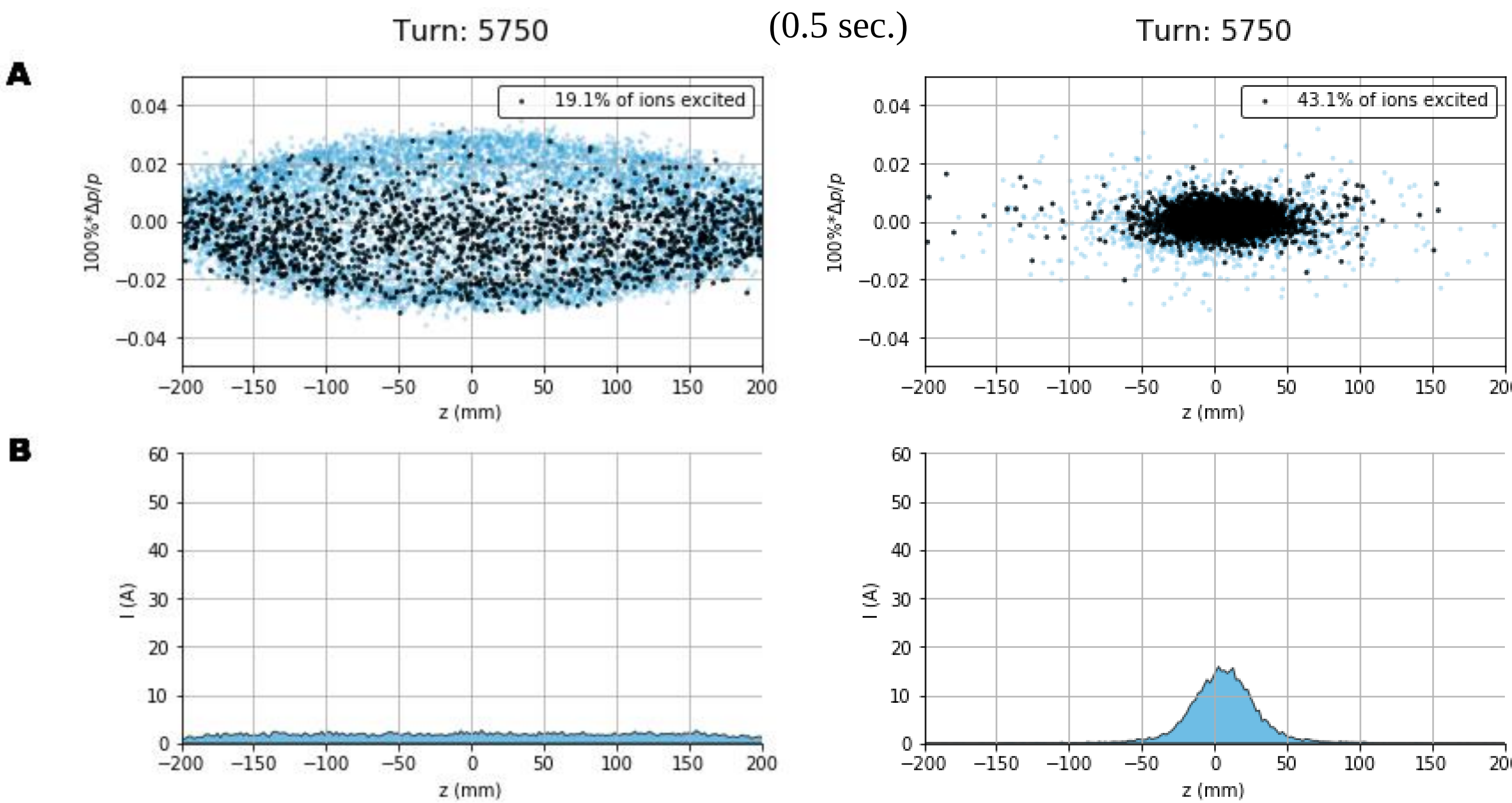
Slightly shorter central laser wavelength: Slightly longer central laser wavelength:



Black dots – excited ions, blue dots – not excited ions.

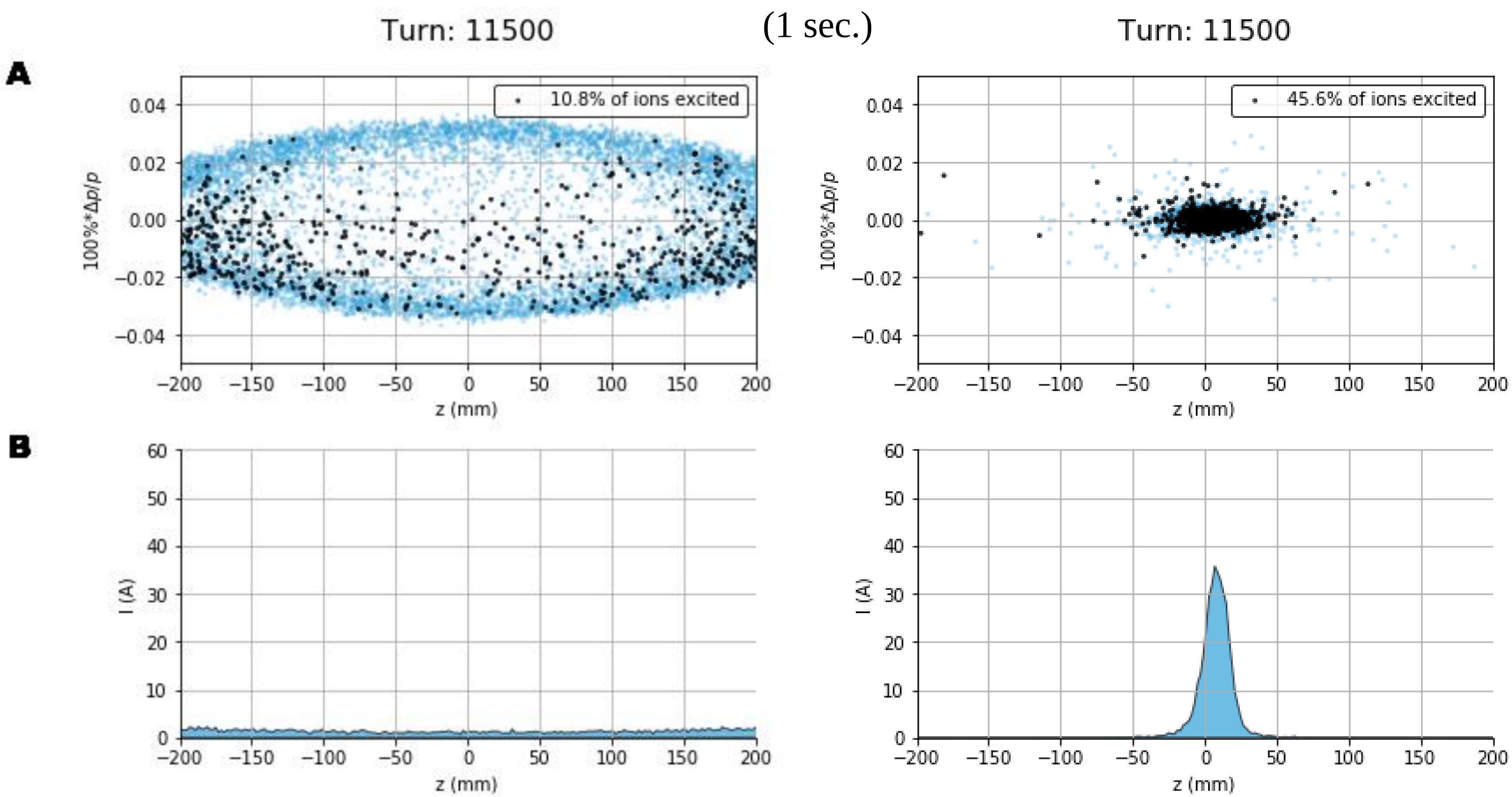
The longitudinal beam dynamics is quite sensitive to imbalance of energy radiated at $\Delta p>0$ vs $\Delta p<0$:

Fourier-limited Gaussian laser pulse with $\sigma(\Delta\omega/\omega) = \sigma(\Delta p/p)$ centered on $p_0(1\pm0.5\Delta p/p)$
Laser waist size $w_0 = 2\sigma_{x,y} = 40$ µm, energy = 42 µJ.



The longitudinal beam dynamics is quite sensitive to imbalance of energy radiated at $\Delta p>0$ vs $\Delta p<0$:

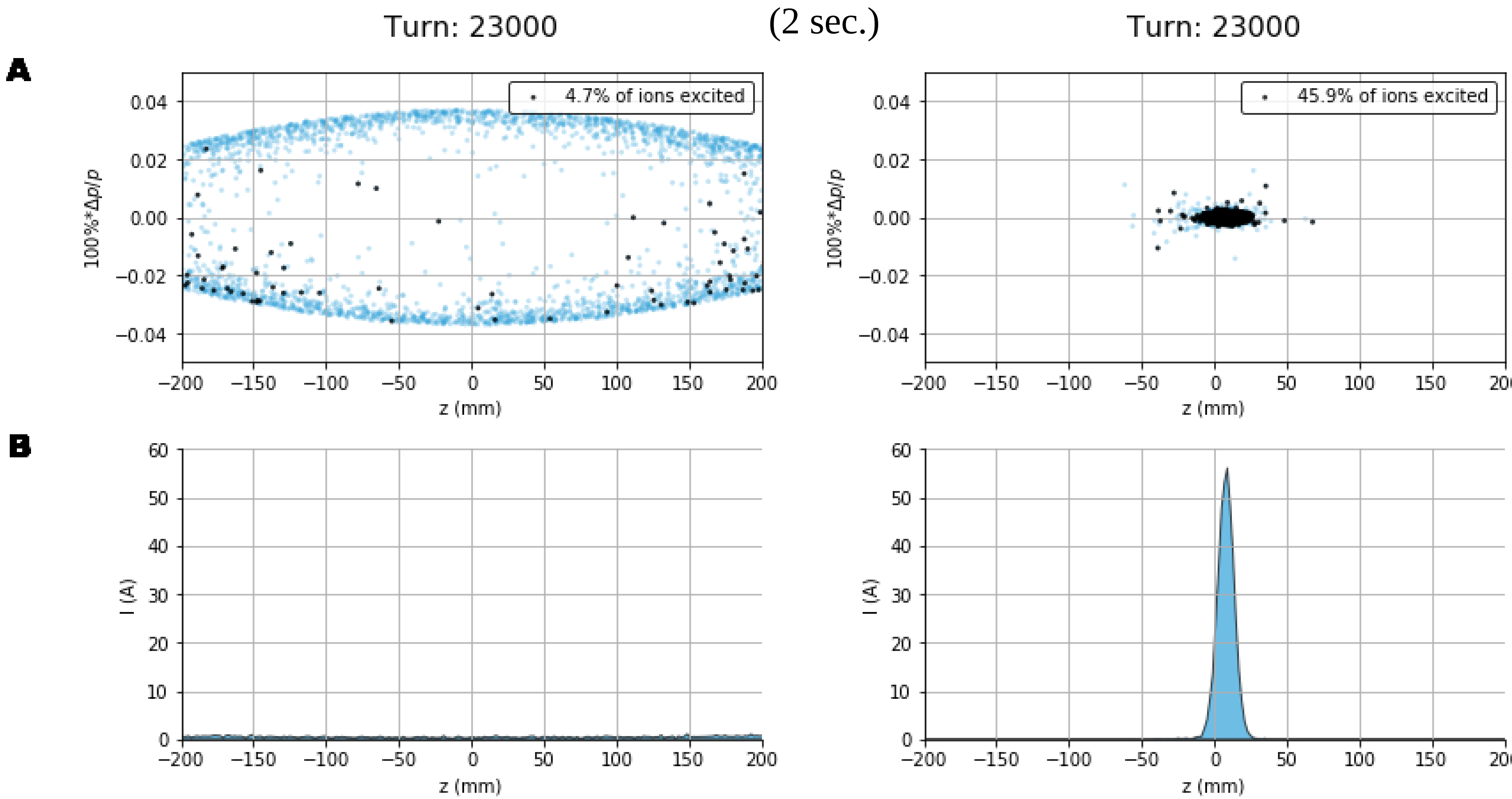
Fourier-limited Gaussian laser pulse with $\sigma(\Delta\omega/\omega) = \sigma(\Delta p/p)$ centered on $p_0(1\pm 0.5\Delta p/p)$
Laser waist size $w_0 = 2\sigma_{x,y} = 40$ µm, energy = 42 µJ.



The longitudinal beam dynamics is quite sensitive to imbalance of energy radiated at Δp>0 vs Δp<0:

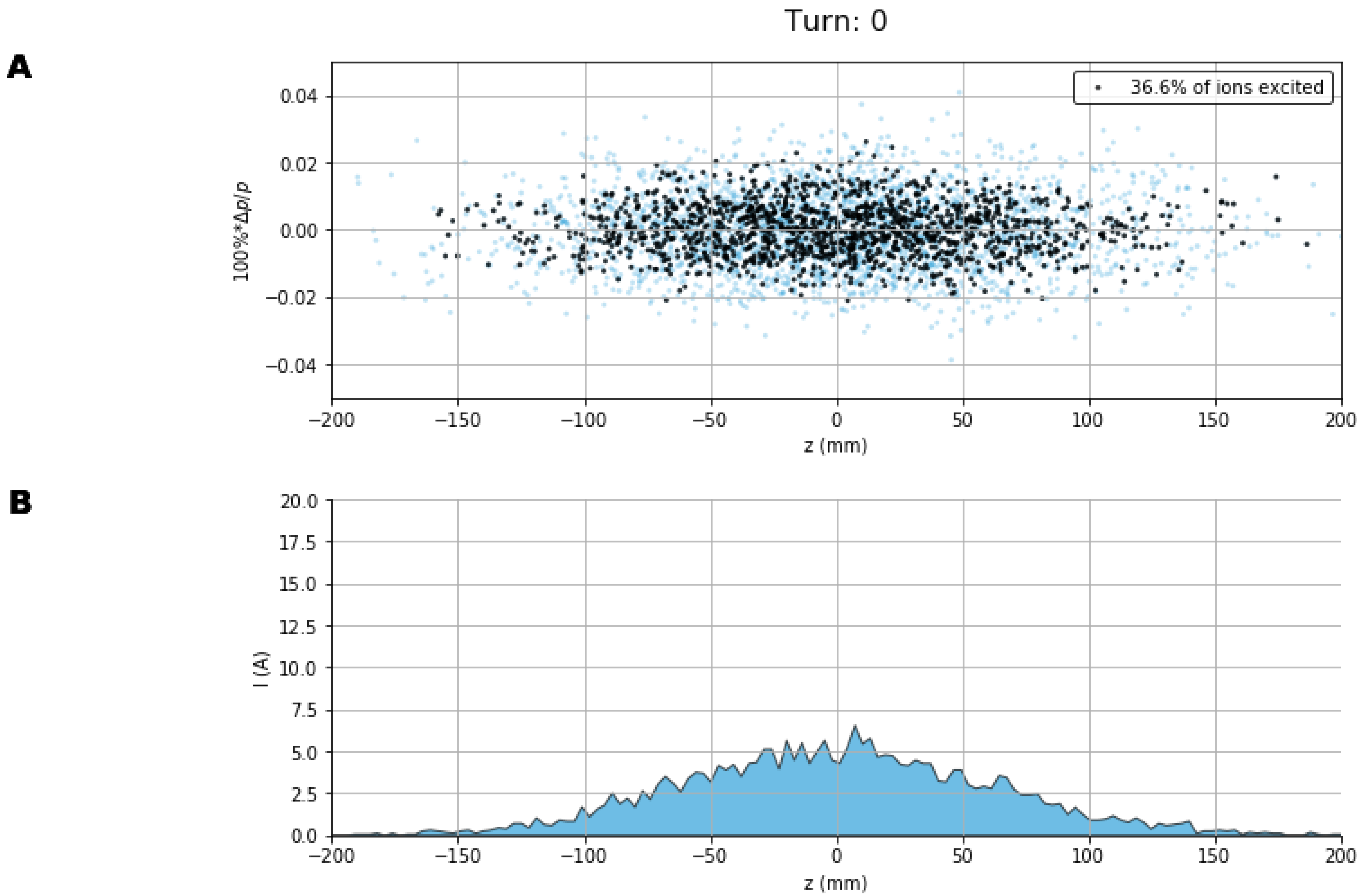
Fourier-limited Gaussian laser pulse with $\sigma(\Delta\omega/\omega) = \sigma(\Delta p/p)$ centered on $p_0(1 \pm 0.5\Delta p/p)$
Laser waist size $w_0 = 2\sigma_{x,y} = 40$ µm, energy = 42 µJ.

(2 sec.)

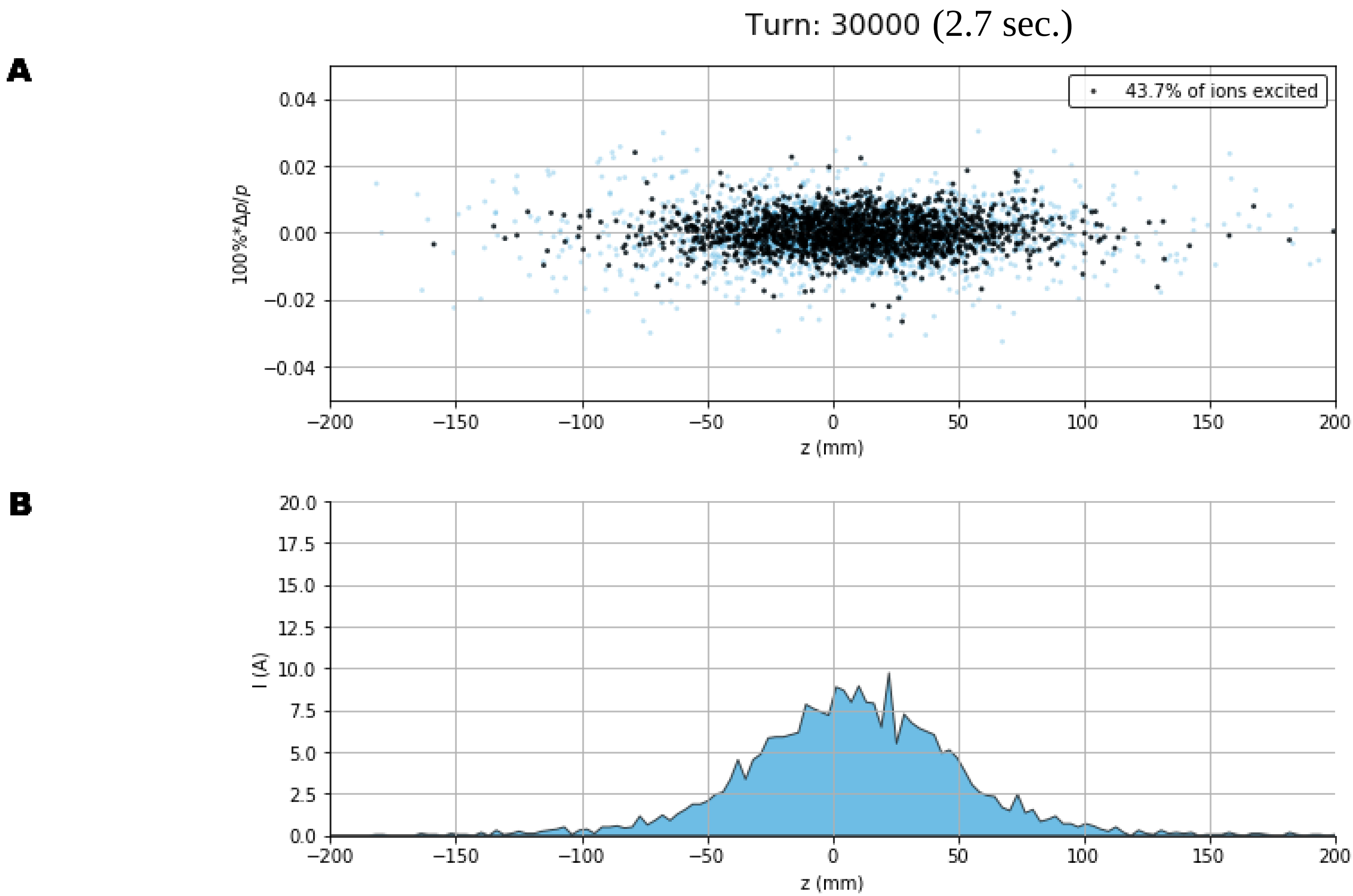


Maybe a good approach would be to introduce heating in the middle while limiting the Δp growth with a barrier. This can be done by alternating the cooling and heating regimes or using a laser with a complicated frequency profile (or two lasers).

Fourier-limited Gaussian laser pulse with $\sigma(\Delta\omega/\omega) = \sigma(\Delta p/p)$ centered on $p_0(1+0.05\Delta p/p)$
Laser waist size $w_0 = 2\sigma_{x,y} = 40$ μm, energy = *42* μJ.

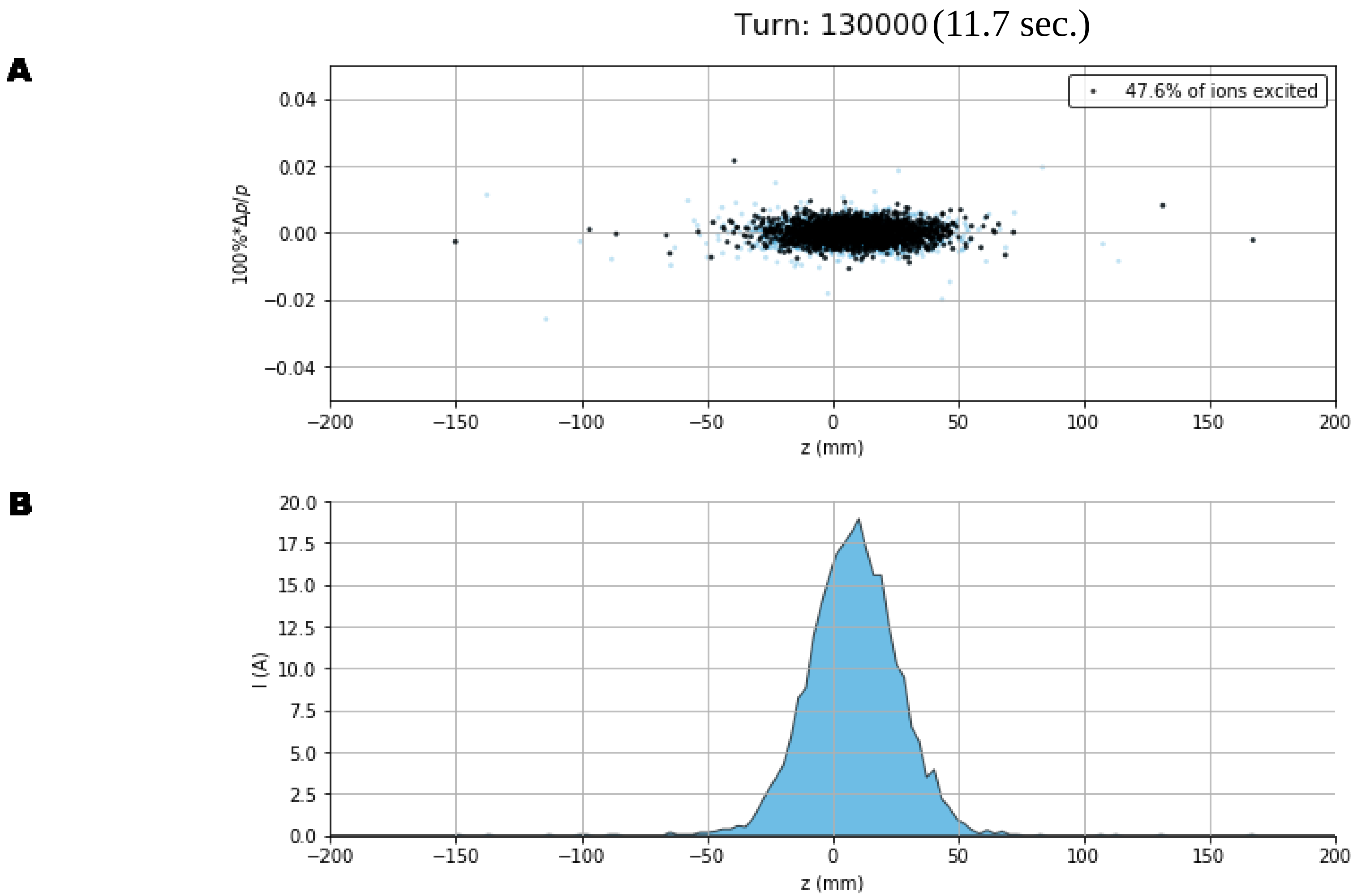


Fourier-limited Gaussian laser pulse with $\sigma(\Delta\omega/\omega) = \sigma(\Delta p/p)$ centered on $p_0(1+0.05\Delta p/p)$
Laser waist size $w_0 = 2\sigma_{x,y} = 40$ μm, energy = *42* μJ.

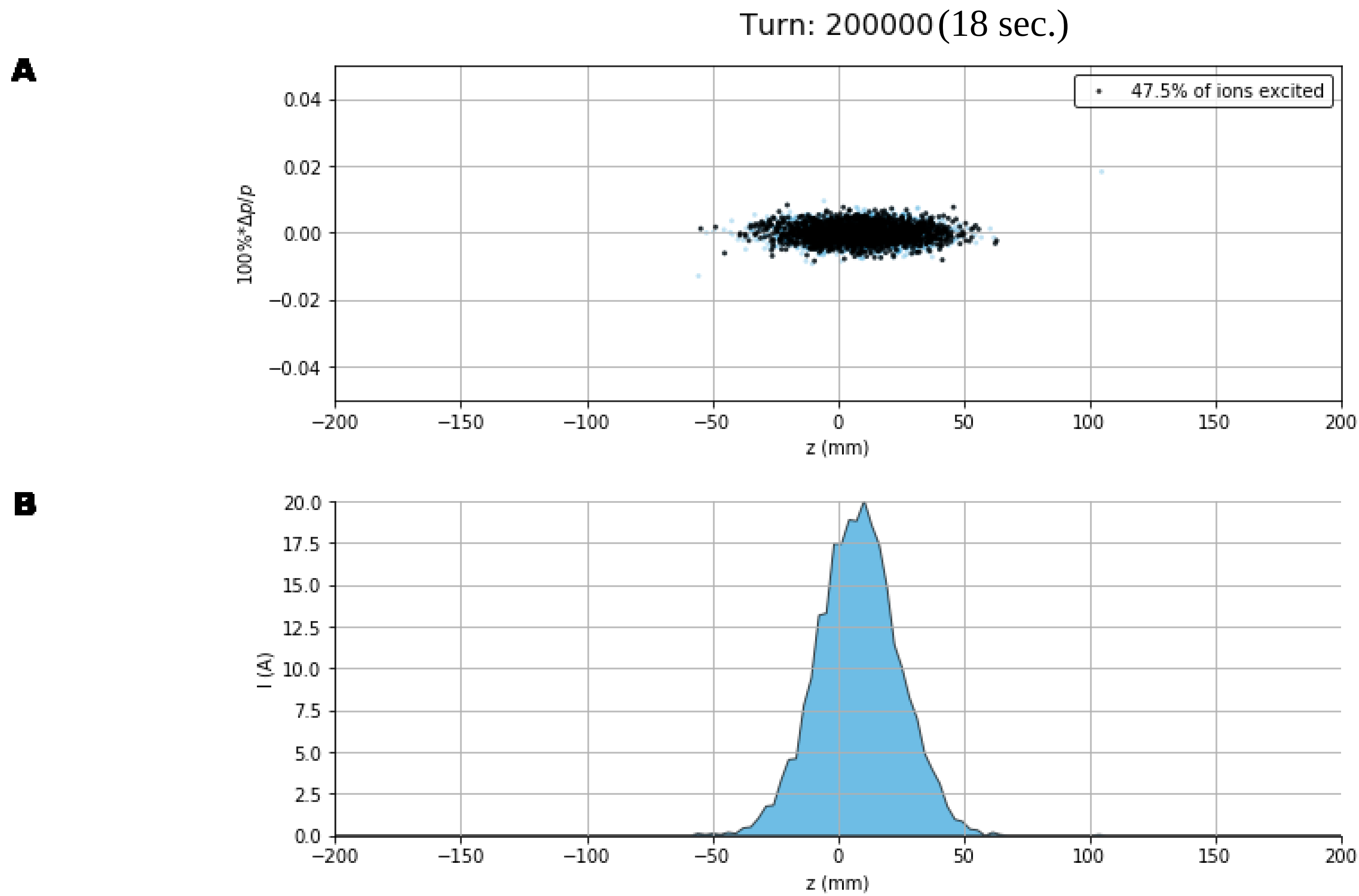


Fourier-limited Gaussian laser pulse with $\sigma(\Delta\omega/\omega) = \sigma(\Delta p/p)$ centered on $p_0(1+0.05\Delta p/p)$

Laser waist size $w_0 = 2\sigma_{x,y} = 40$ µm, energy = 42 µJ.



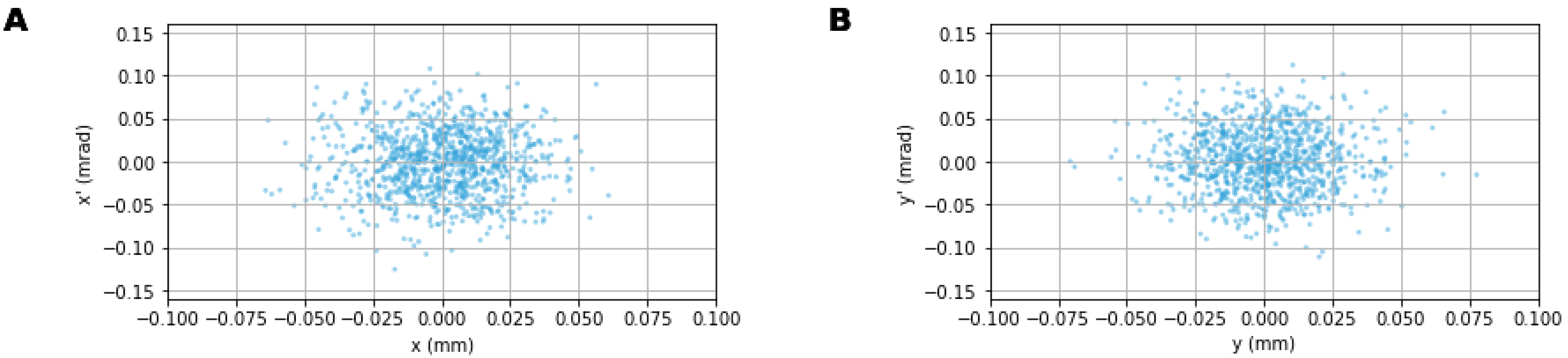
Fourier-limited Gaussian laser pulse with $\sigma(\Delta\omega/\omega) = \sigma(\Delta p/p)$ centered on $p_0(1+0.05\Delta p/p)$
Laser waist size $w_0 = 2\sigma_{x,y} = 40$ µm, energy = *42* µJ.



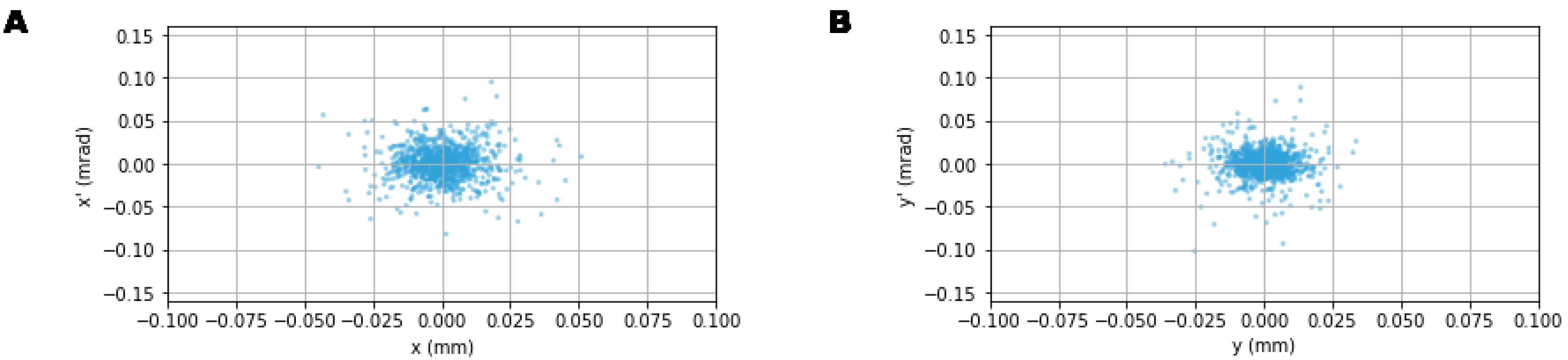
Transverse cooling is much slower:

Turn: 0

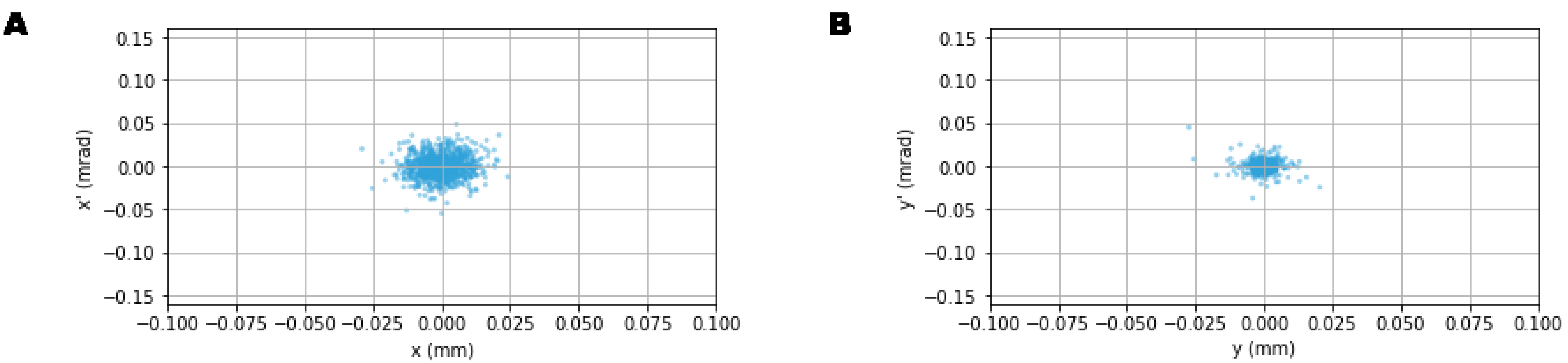
https://anaconda.org/petrenko/lhc_psi_beam_vs_laser



Turn: 10000000 (15 min.)



Turn: 20000000 (30 min.)



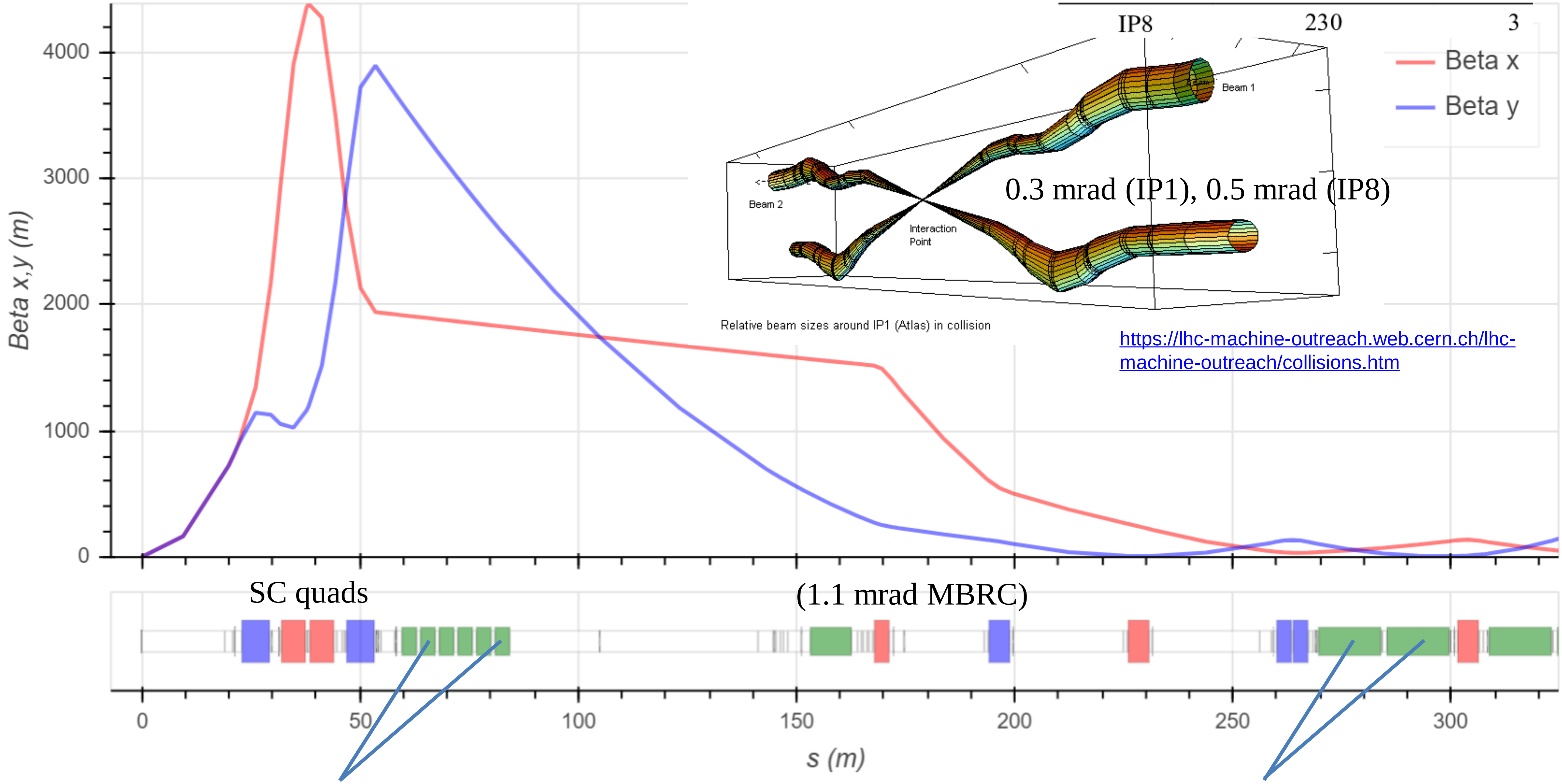
Cooling time ~ time to radiate the full ion energy: 530 TeV / (0.5 * 190 MeV) = 5.6e6 turns (8.5 min)

Interaction region:

http://accelconf.web.cern.ch/accelconf/ipac2013/papers/mopwo046.pdf

Beam Energy	Interaction Point	Half crossing angle [μrad]	β* [m]
4TeV	IP1	145	0.6
	IP2	90	3
	IP5	145	0.6
	IP8	230	3

Beta-function at the center of the IP1 (ATLAS) = 0.6 m.



Relative beam sizes around IP1 (Atlas) in collision

0.3 mrad (IP1), 0.5 mrad (IP8)

https://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/collisions.htm

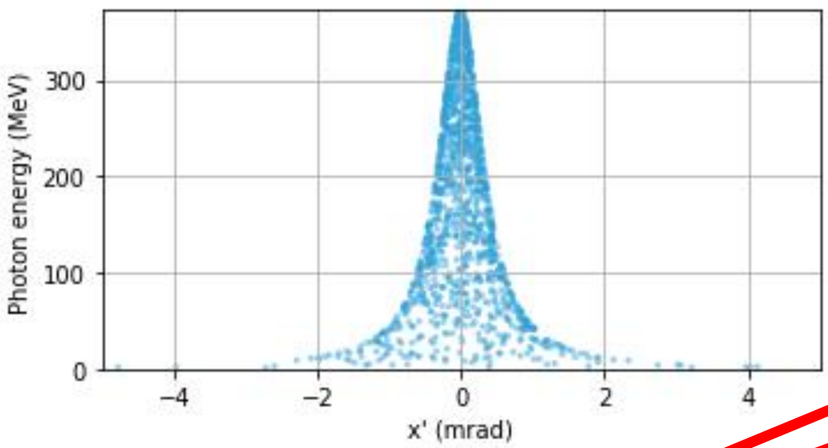
Normal-conducting dipoles (0.19 mrad each, 1.13 mrad with 6 dipoles)

(5.1 mrad Main Dipoles)

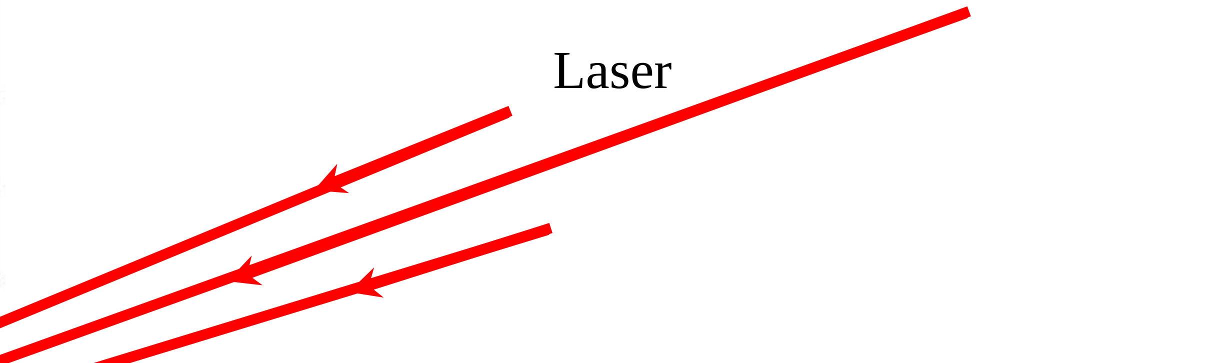
https://apetrenko.blob.core.windows.net/lhc/LHC_optics.html

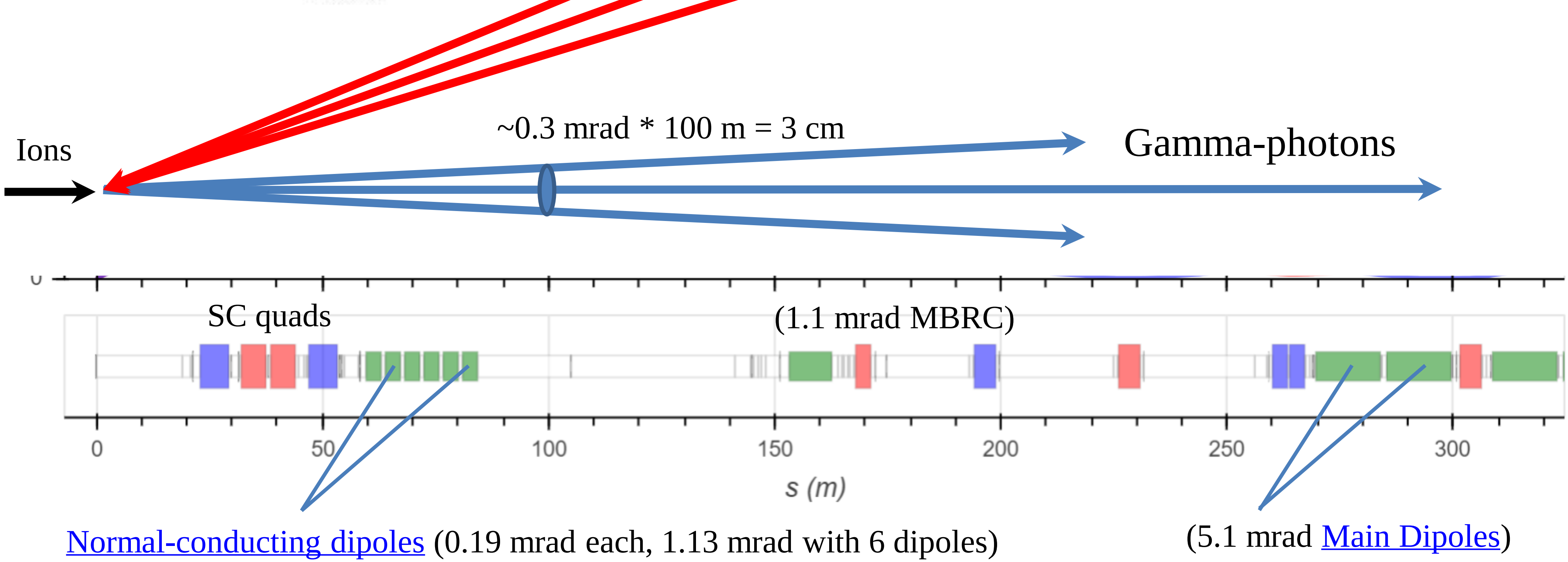
Interaction region:

Angle-energy plot of emitted gamma-photons:

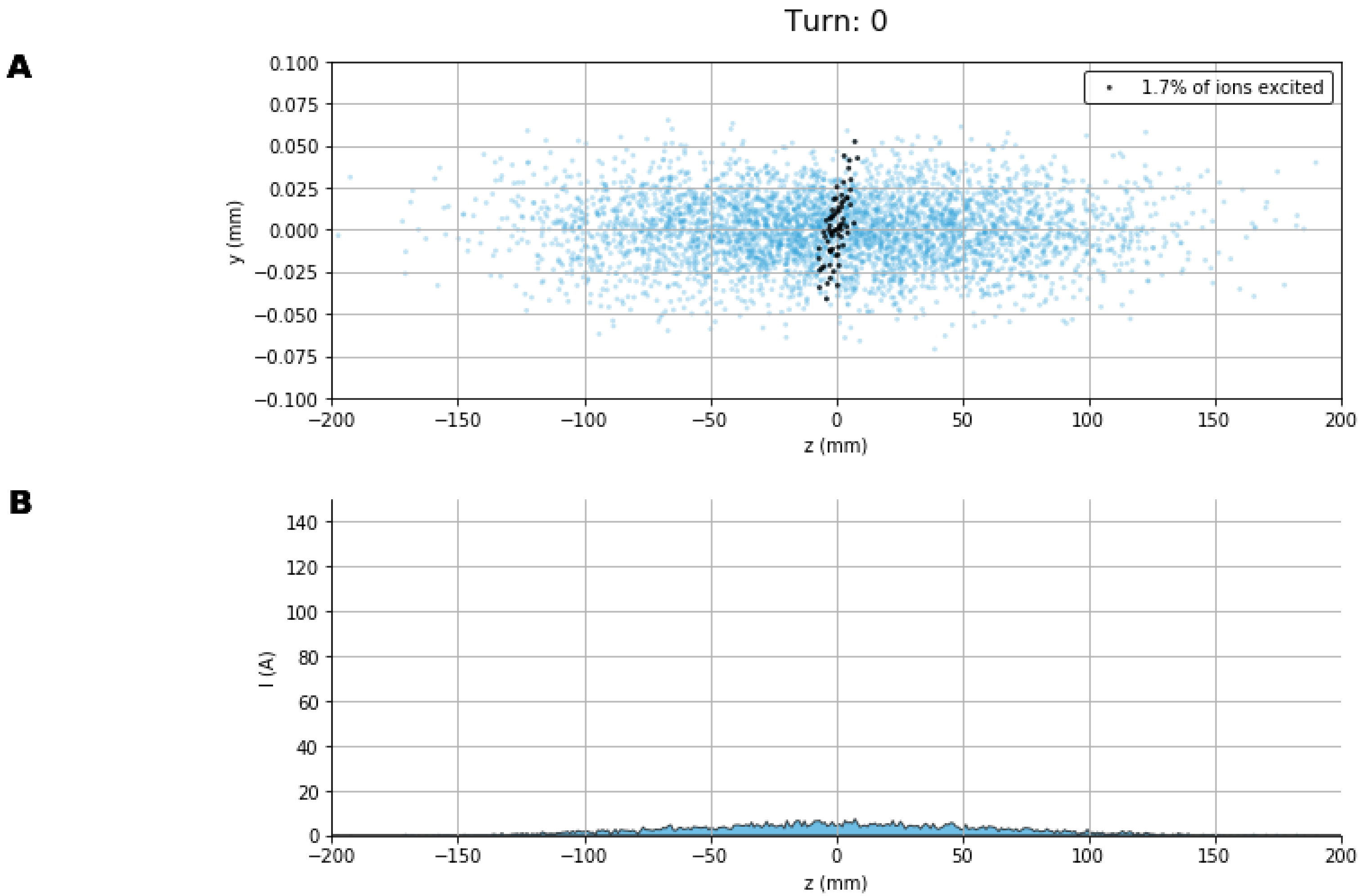


Angular divergence of the laser beam $\theta = \frac{\lambda_l}{\pi w_0} = 0.78$ mrad.

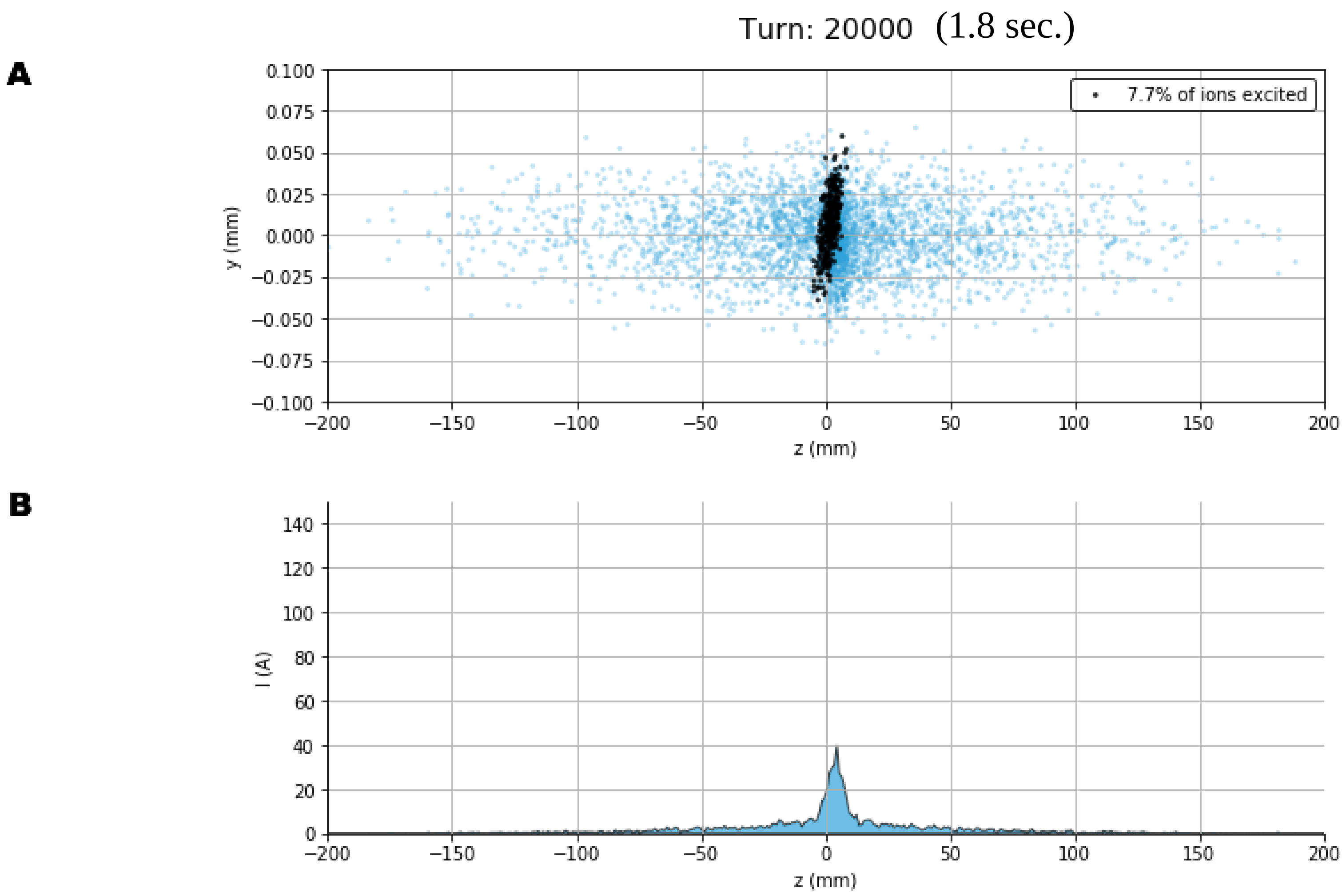




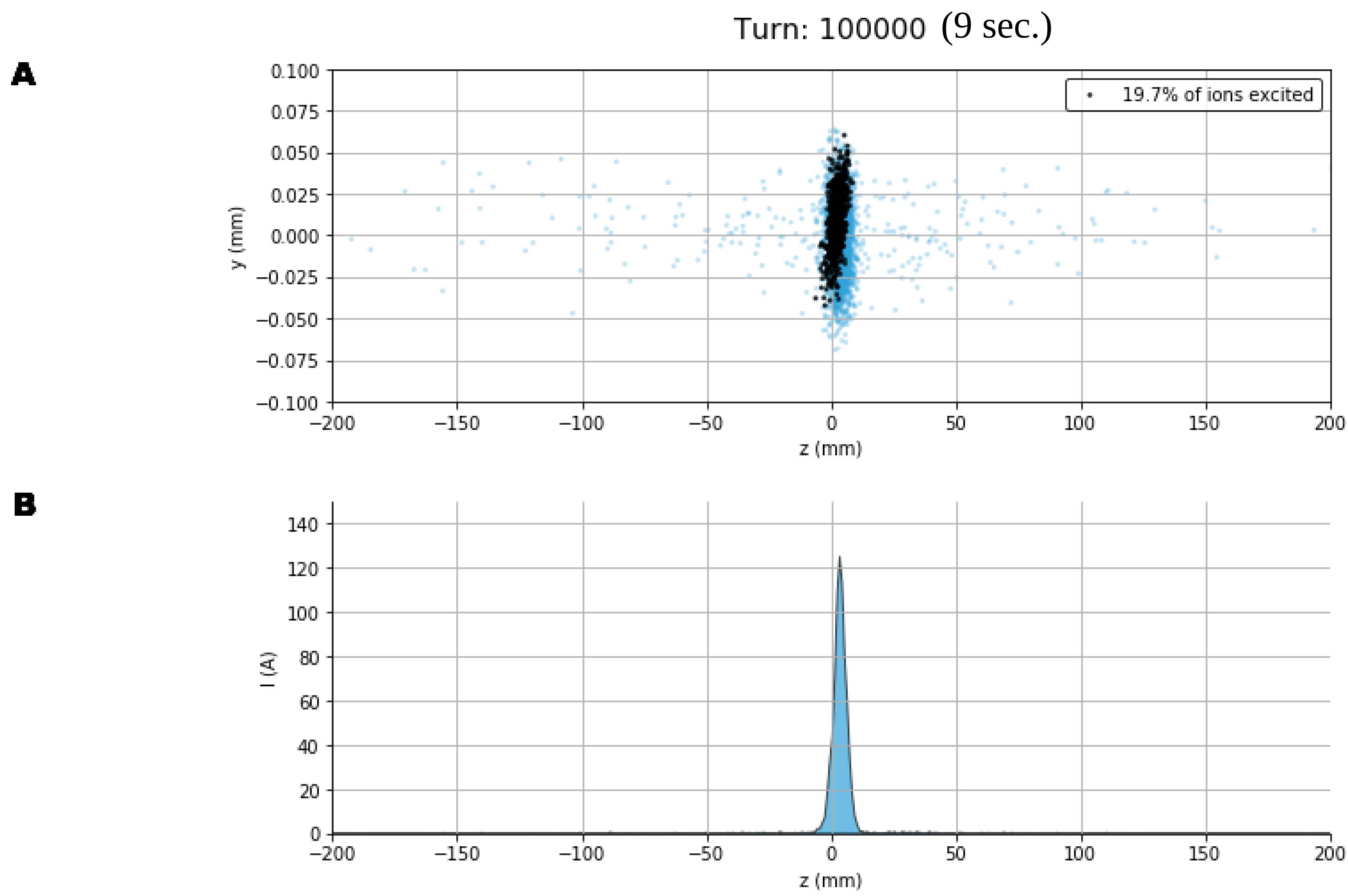
Interaction with 1 degree crossing angle:



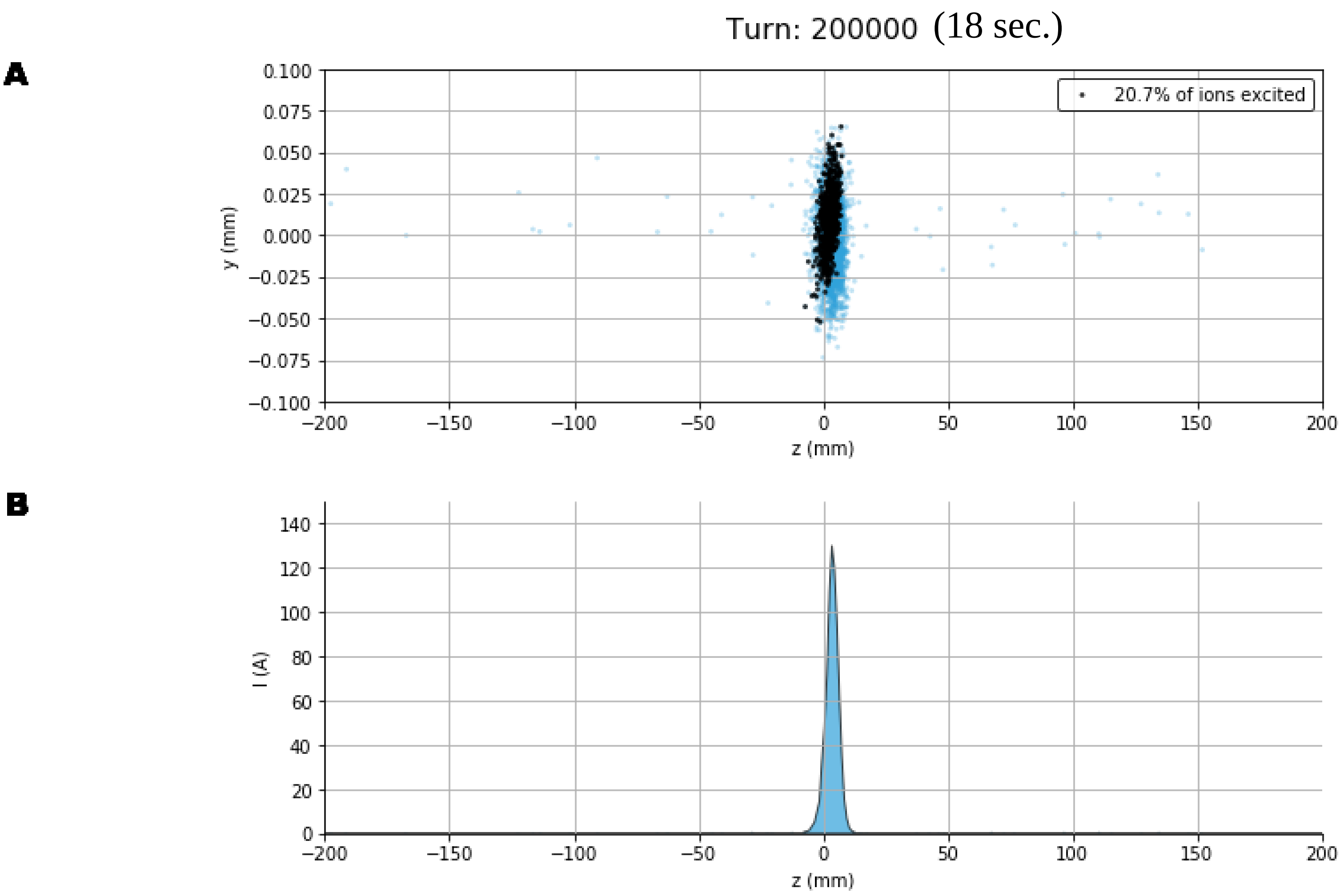
Interaction with 1 degree crossing angle:



Interaction with 1 degree crossing angle:



Interaction with 1 degree crossing angle:



Fast longitudinal cooling allows to compress the bunch and increase the geometric overlap.

Conclusions:

- Understanding and control of the fast longitudinal cooling/heating is critically important for the stable operation of a Gamma Factory.

- Transverse cooling can help to reduce the laser power requirements.

- Longitudinal cooling can be helpful with laser crossing at some angle.

- Questions to study next:

  1) Collective instabilities
  2) Intra-Beam Scattering
  3) Detailed laser-ion beam interaction region including laser input and gamma-radiation output.