Systematic Measurements with Electron Cooled Bunched Heavy Ion Beams

Regina Heß, C. Dimopoulou, M. Steck
GSI Helmholtzzentrum für Schwerionenforschung GmbH

COOL Workshop 2017 Bonn
18. – 22.09.2017

Motivation & Methods

- **Simultaneous** non-destructive monitoring of **full 6D phase space** of stored ion beam (bunched or coasting) during electron cooling

- Bunch length measurement with better time resolution with new fast current transformer (FCT).
- Parallel measurement of the transverse emittances using ionization profile monitors (IPM).
- Control of beam intensity via DC current transformer.
- Optimize cooling force before each measurement series:

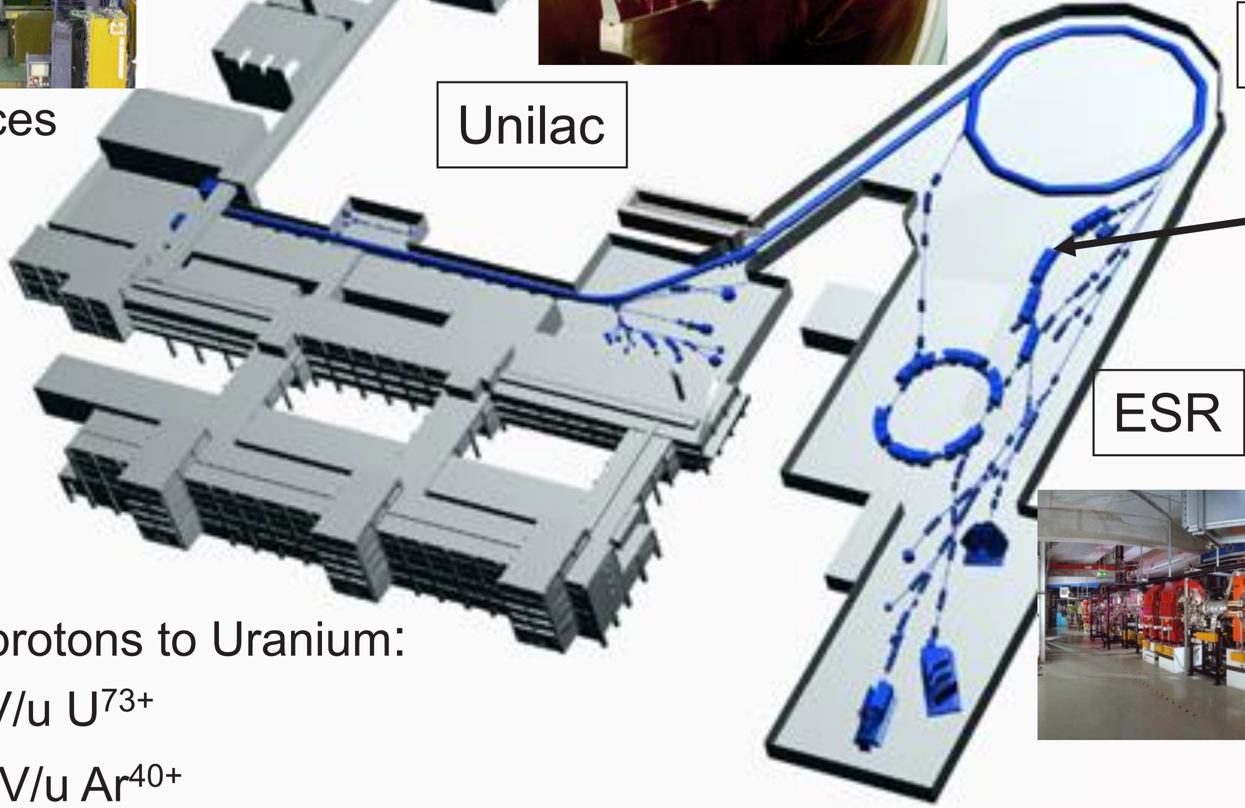
  electron steerers tuned to minimize x,y sizes/emittances of ions;

  cooler voltage finely tuned for minimum bunch length in the RF bucket.

- Systematic data for several ion species, different beam energies, as a function of (bunched) beam intensity and electron cooling current.

The GSI accelerator complex

ion sources



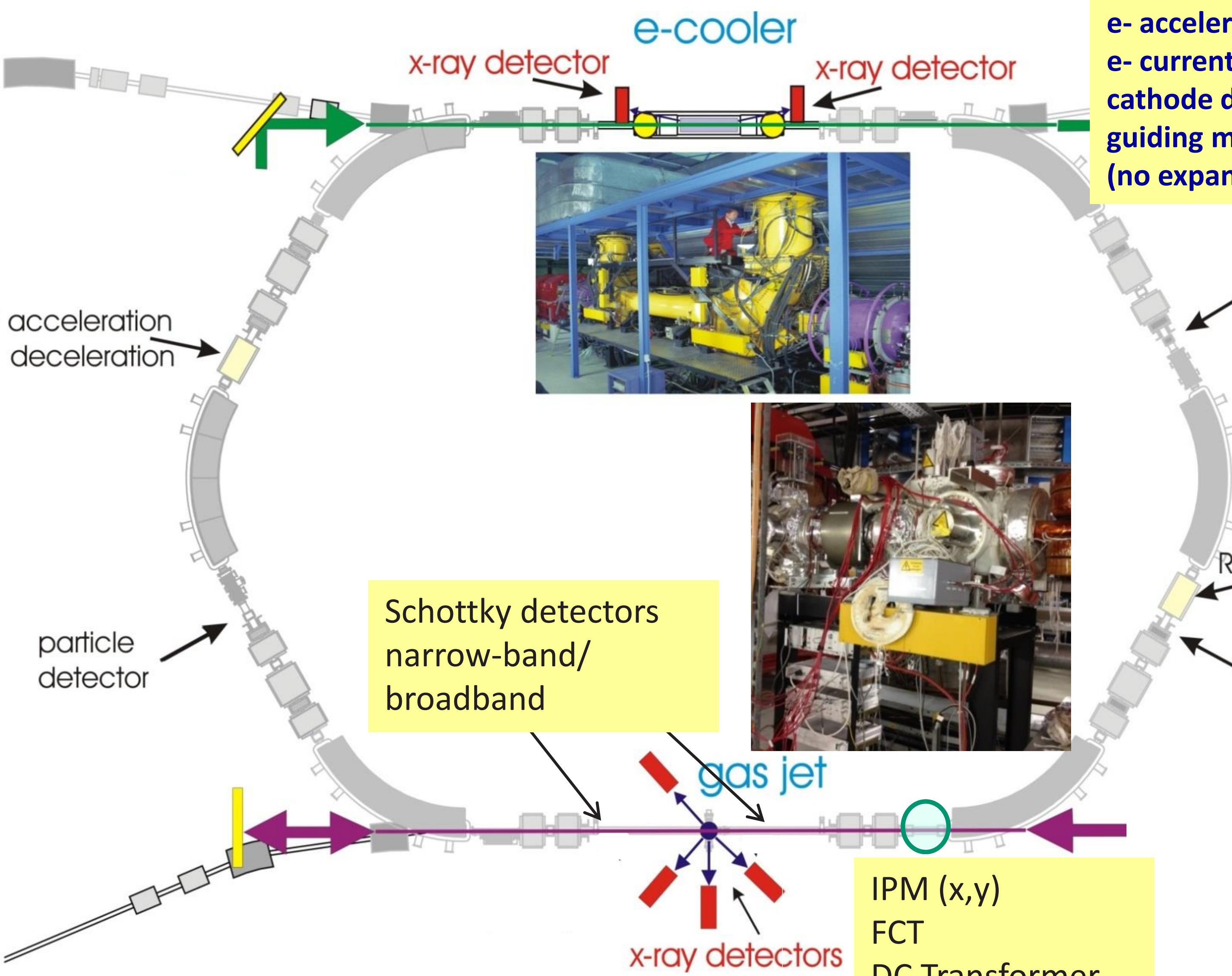
All ions from protons to Uranium:

- 4×10^9 1 GeV/u U^{73+}
- 5×10^{10} 1 GeV/u Ar^{40+}

Secondary ion beams (rare isotopes) after FRS

ESR Storage Ring

e- accelerating HV 2-220 kV (± 1 V)
e- current 0-1 A
cathode diameter 2 inch
guiding magnetic field
(no expansion) 0.02-0.1 T

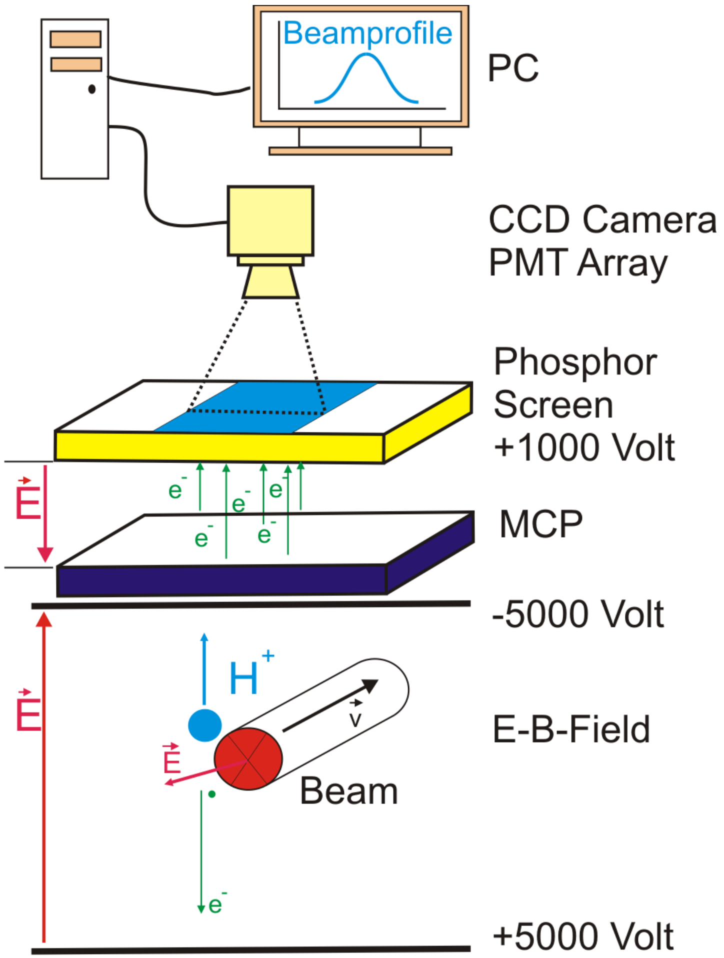


Schottky detectors
narrow-band/
broadband

IPM (x,y)
FCT
DC Transformer

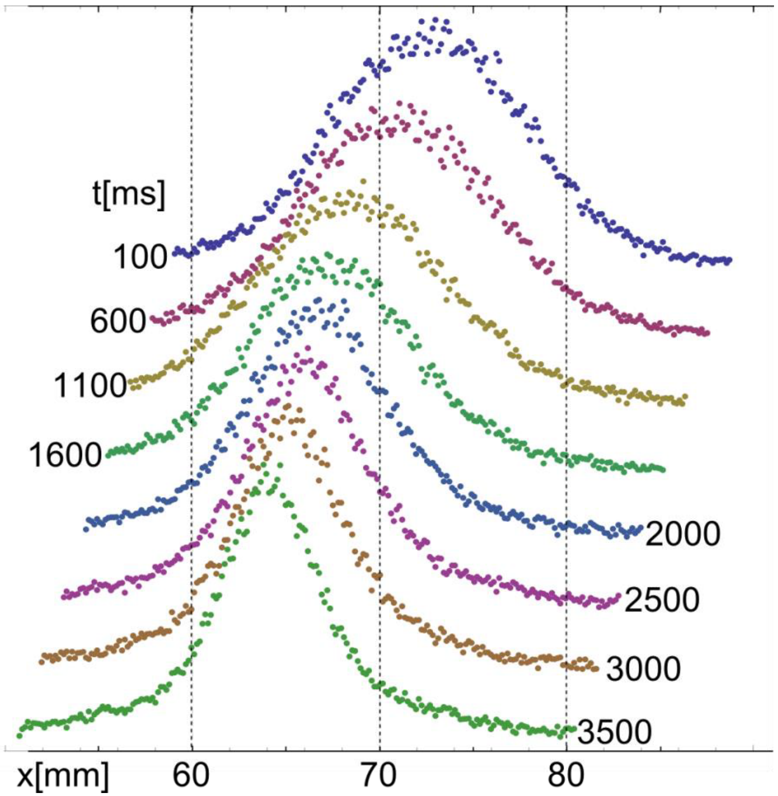
C_{circ}=108 m

Non-destructive diagnostics: transverse



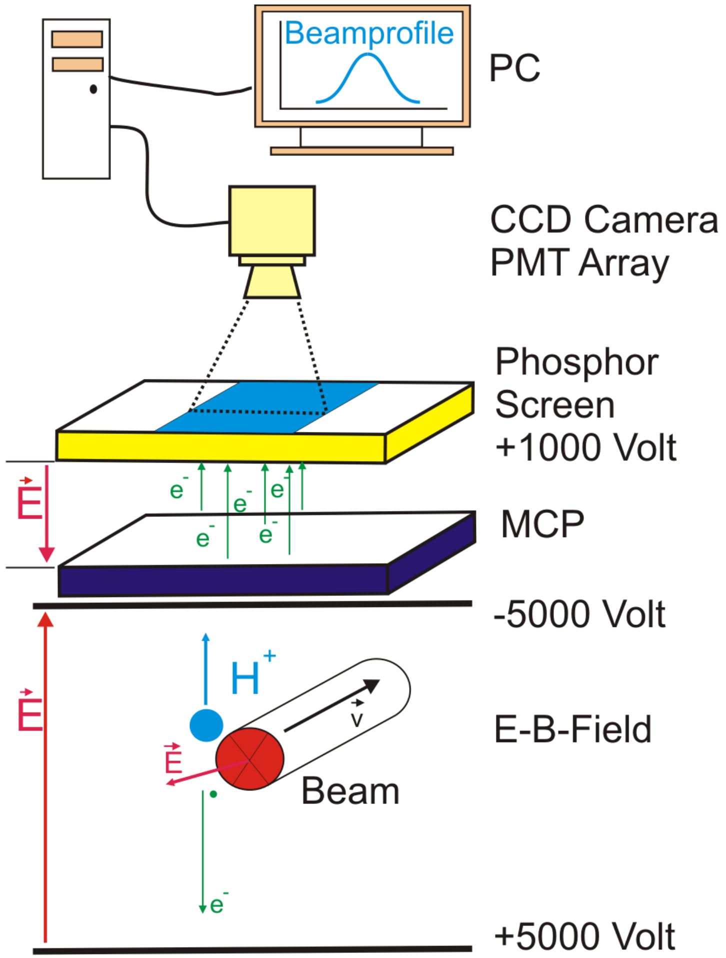
Ionization Profile Monitor (IPM)

Profile of transverse distribution from ionization of residual gas



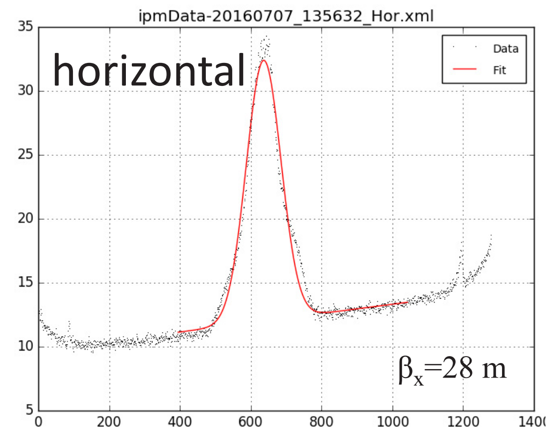
transverse cooling of the beam after injection into ESR

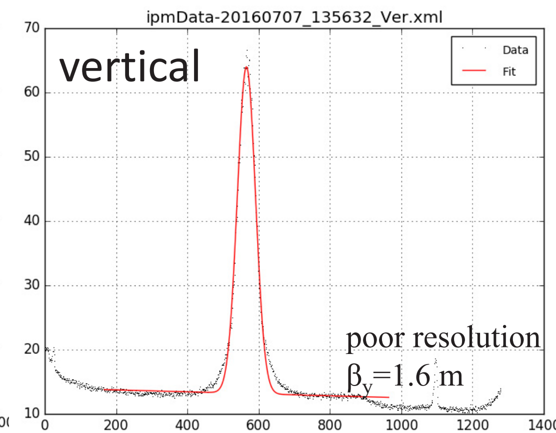
Non-destructive diagnostics: transverse



Ionization Profile Monitor (IPM)

Profile of transverse distribution from ionization of residual gas





σ = 4.5 mm
$\varepsilon_x(2\sigma) = 2.9 * 10^{-6}$ m

σ = 2.2 mm
$\varepsilon_y(2\sigma) = 1.2 * 10^{-5}$ m

$$\varepsilon_{x,y} = \frac{(2\sigma_{x,y})^2}{\beta_{x,y}}$$

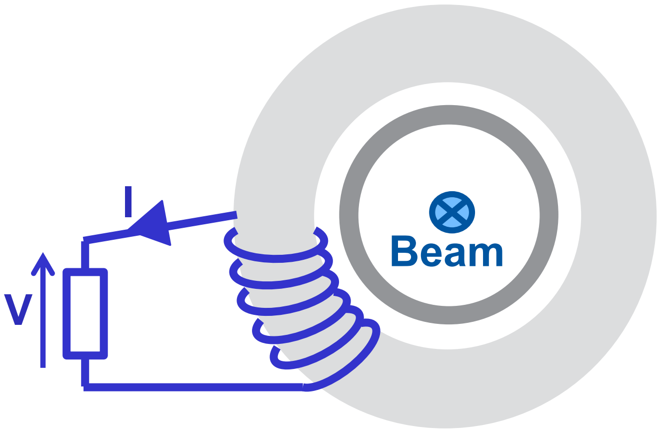
(dispersion at IPM negligible)

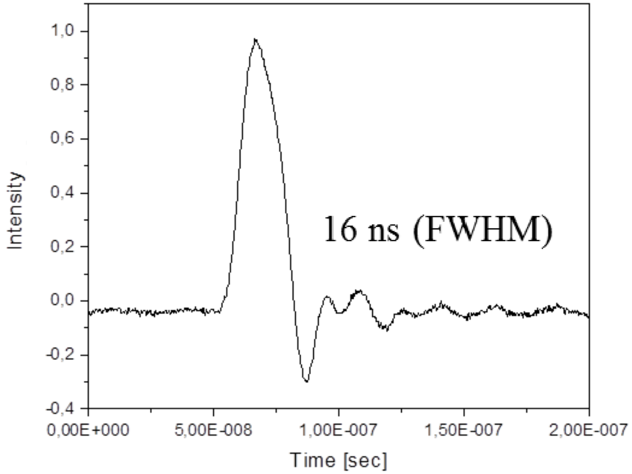
example: C^{6+} @ 122 MeV/u
bunched (RF = 300V)
and electron cooled (I_e = 250 mA)

Non-destructive diagnostics: longitudinal

Fast Current Transformer (FCT)

Determination of momentum spread (for bunched beam)





good time resolution (from measurement): down to 7ns (better than with typical beam position monitor in sum mode)
for shorter bunch lengths time resolution starts to be influenced by intrinsic resolution

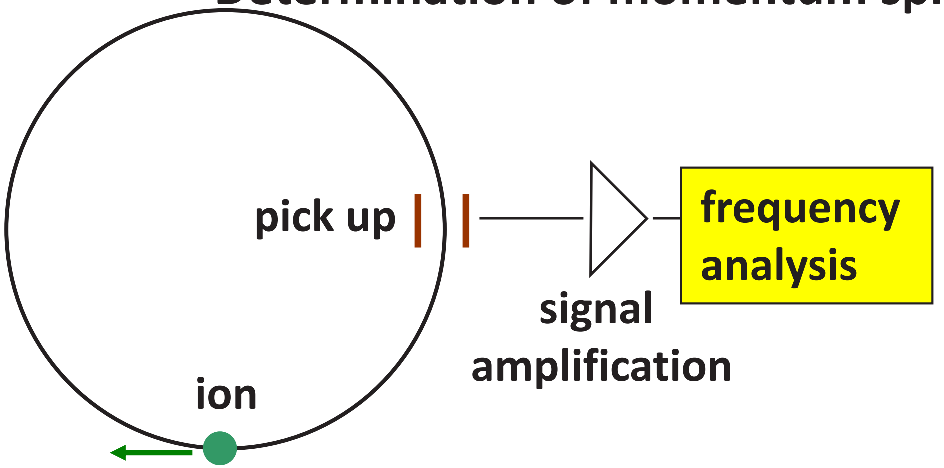
$$\frac{\sigma_t}{T_{rev}} = \sqrt{\frac{\beta_0{}^2 \eta E_{0\,tot}}{2\pi Q h \hat{V}}}\,\frac{\sigma_p}{p}$$

example: C^{6+} @ 122 MeV/u
bunched (RF = 300V)
and electron cooled (I_e = 250 mA)

Non-destructive diagnostics: longitudinal

Schottky noise longitudinal diagnostics

Determination of momentum spread (here for coasting beam)

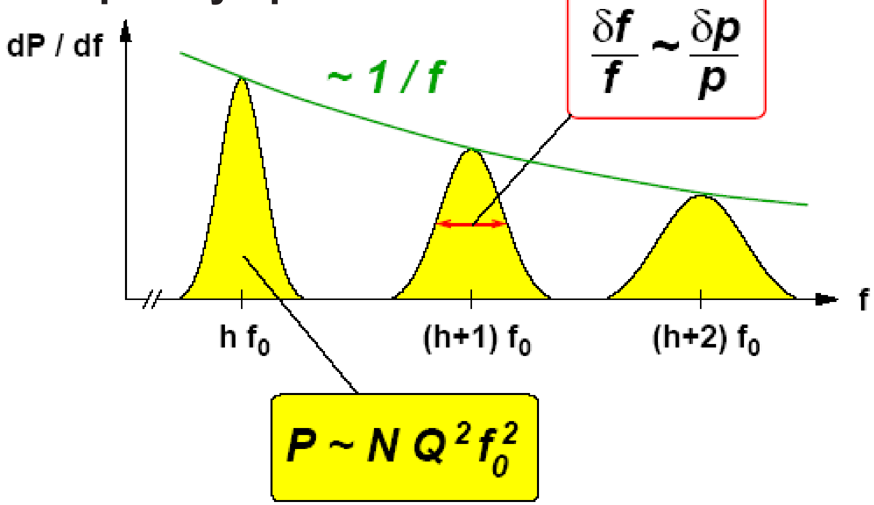


$$\frac{\Delta p}{p} = \frac{1}{\eta}\frac{\Delta f}{f}$$

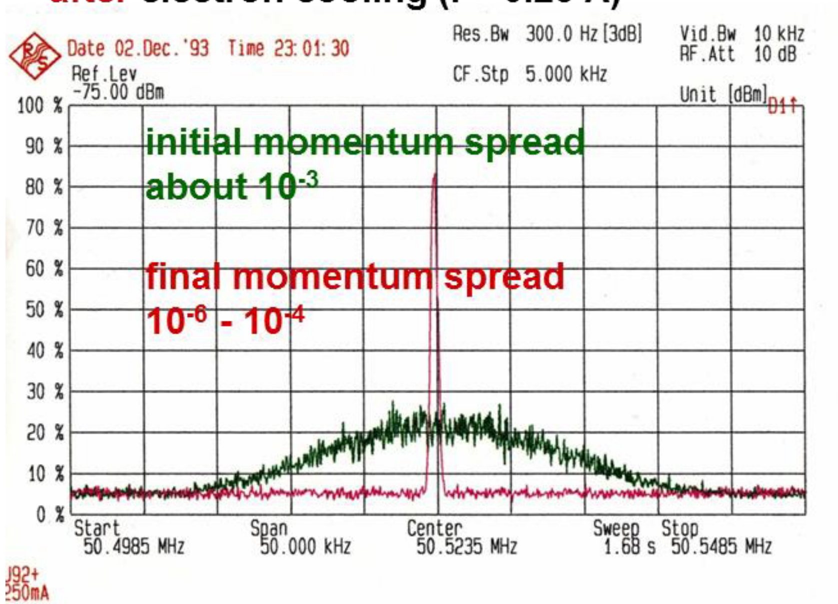
momentum compaction factor η

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}$$

frequency spectrum



U^{92+} at 300 MeV/u before and after electron cooling (I = 0.25 A)



Results I

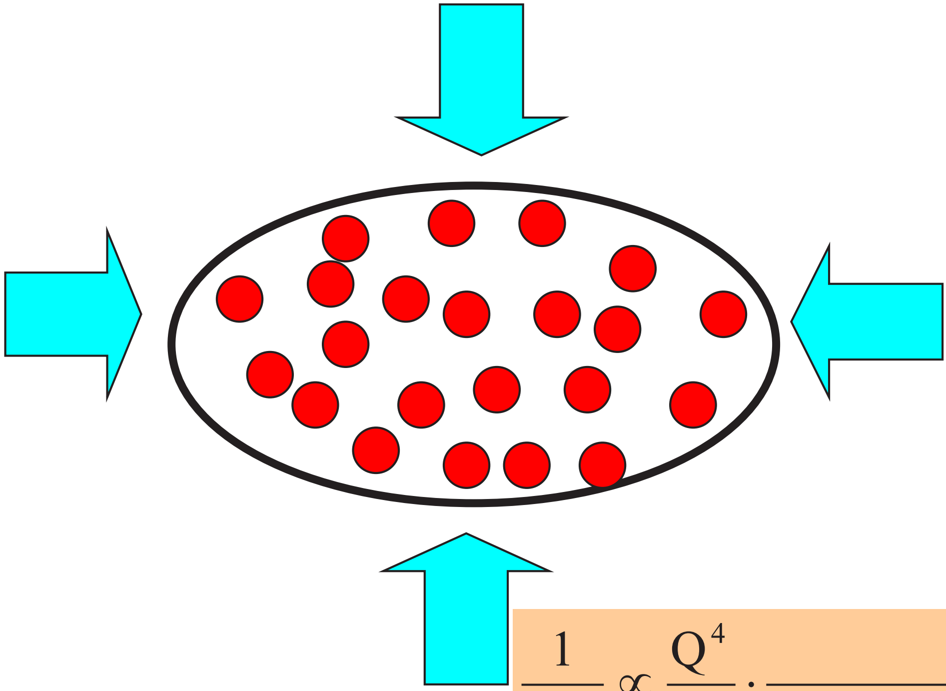
- **6D phase space** interplay between electron cooling and intrabeam scattering

  Previously: coasting beams →

  Now: also for bunched beams

Electron Cooled Beams in Equilibrium with Intrabeam Scattering (IBS)

The intrabeam scattering (IBS) is the multiple Coulomb scattering of charged particles in the beam



$$\frac{1}{\tau_{cool}} \propto \frac{Q^2}{A} \cdot \frac{n_e}{\beta_0^3 \gamma_0^5 \theta_{rel}^3} \cdot \frac{l_{cool}}{C_{circ}}$$

$$N = \frac{I_{ion}}{Qef_{rev}}$$: ion intensity

$$B = \frac{h\, T_{Bunch(4\sigma t)}}{T_{rev}}$$: bunching factor

$$\frac{1}{\tau_{IBS}} \propto \frac{Q^4}{A^2} \cdot \frac{N}{\beta_0^3 \gamma_0^4 \varepsilon_x \varepsilon_y (\Delta p/p)(h \cdot T_{bunch})} = \frac{Q^4}{A^2} \cdot \frac{N/B}{\beta_0^3 \gamma_0^4 \varepsilon_x \varepsilon_y (\Delta p/p) \cdot C_{circ}}$$

Equilibrium $$\frac{1}{\tau_{cool}} = \frac{1}{\tau_{IBS}}$$

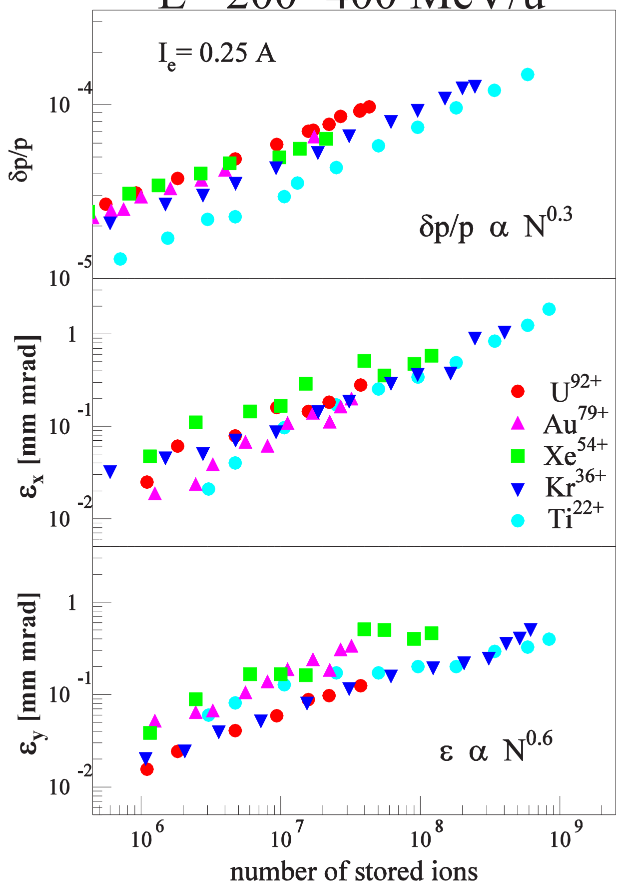
Equilibria Electron cooling ←→ IBS

Coasting beams

Steck et al. Ref. [1-3]
1990-today

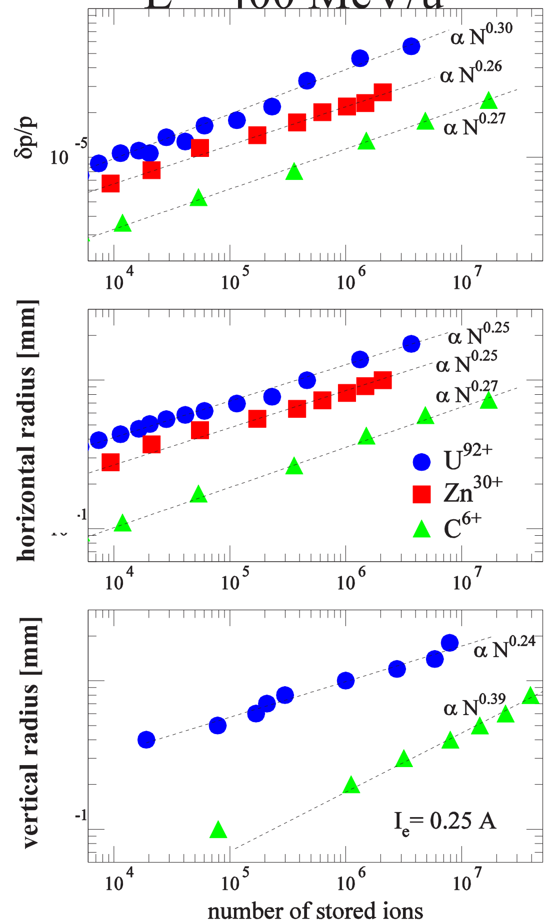
by non-destructive methods (particle detectors, profile monitor)

E= 200 -400 MeV/u



by destructive scraping

E = 400 MeV/u



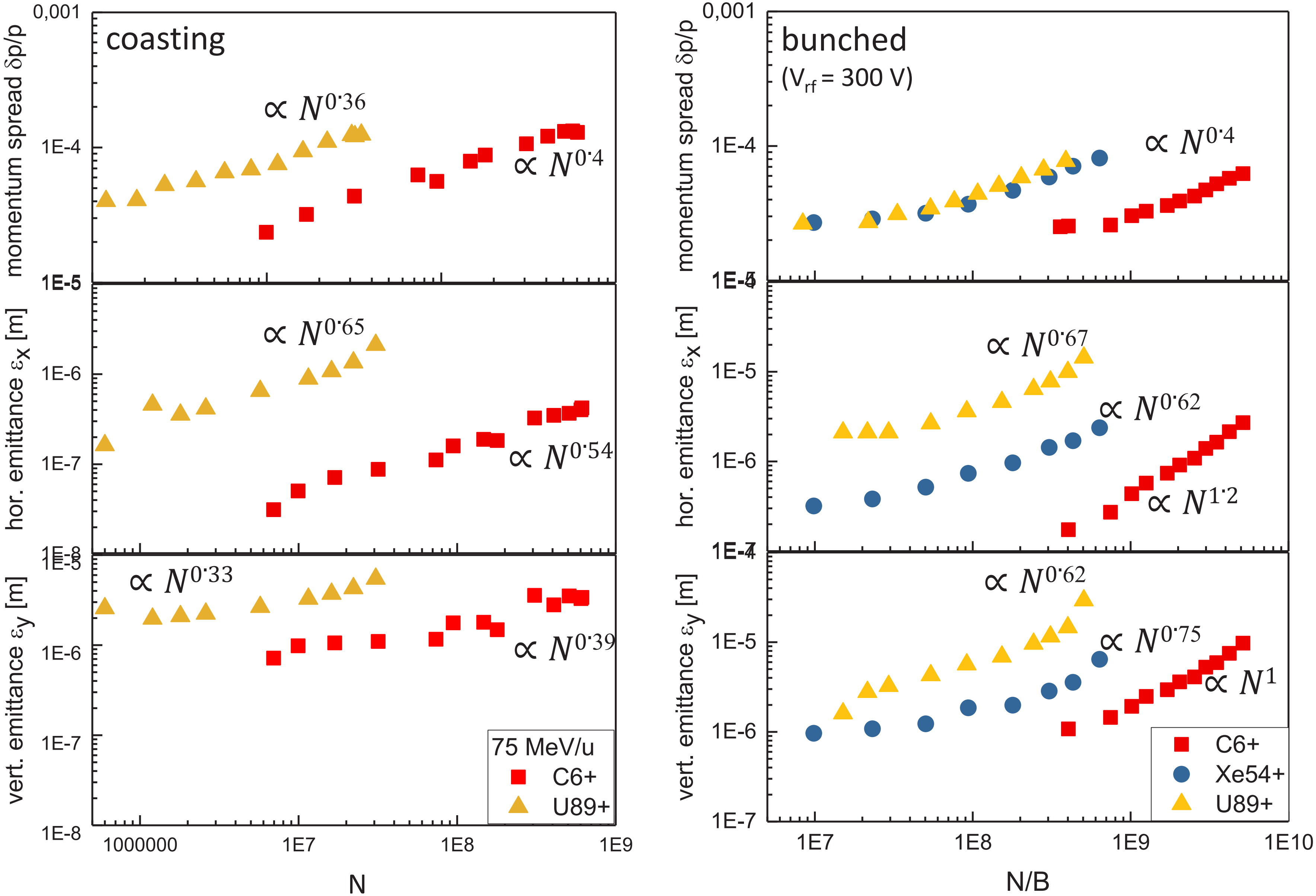
$\delta p/p \ \alpha \ N^{0.3-0.4}$

$\varepsilon_{x,y} \ \alpha \ N^{0.5-0.6}$

Due to IBS: total phase space volume increases with ion beam intensity & charge

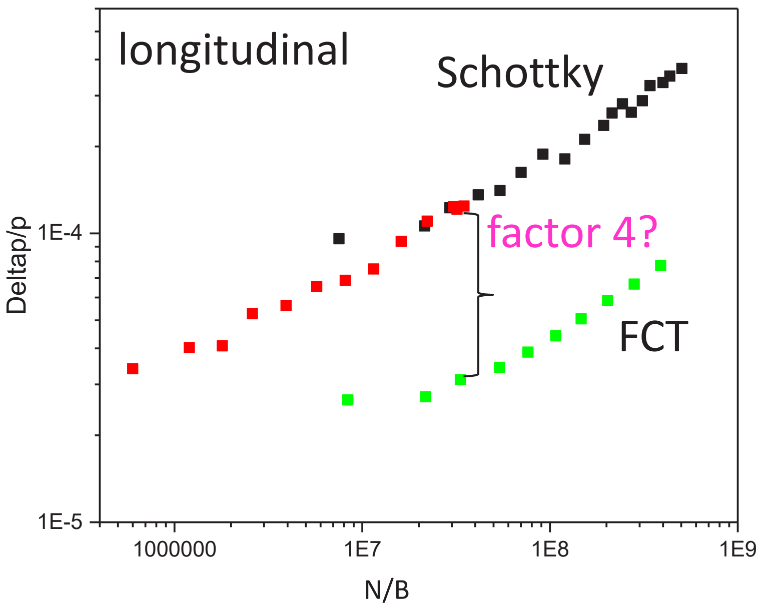
equilibria Electron cooling ←→ IBS:

Comparison C, Xe, U @ 75 MeV/u

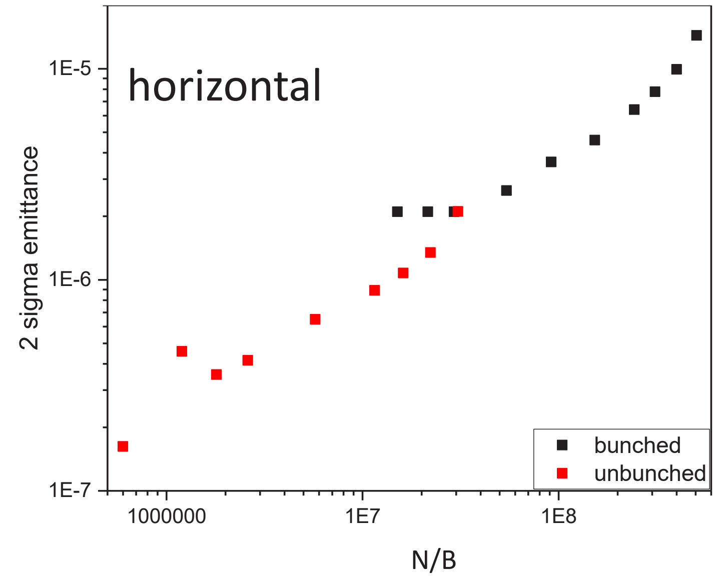


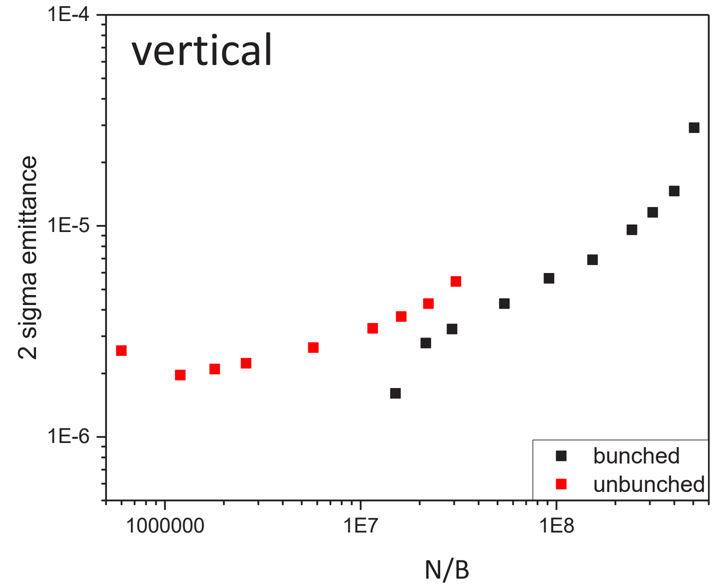
Equilibria scaling with ion intensity

Example: U^{89+} 75 MeV/u

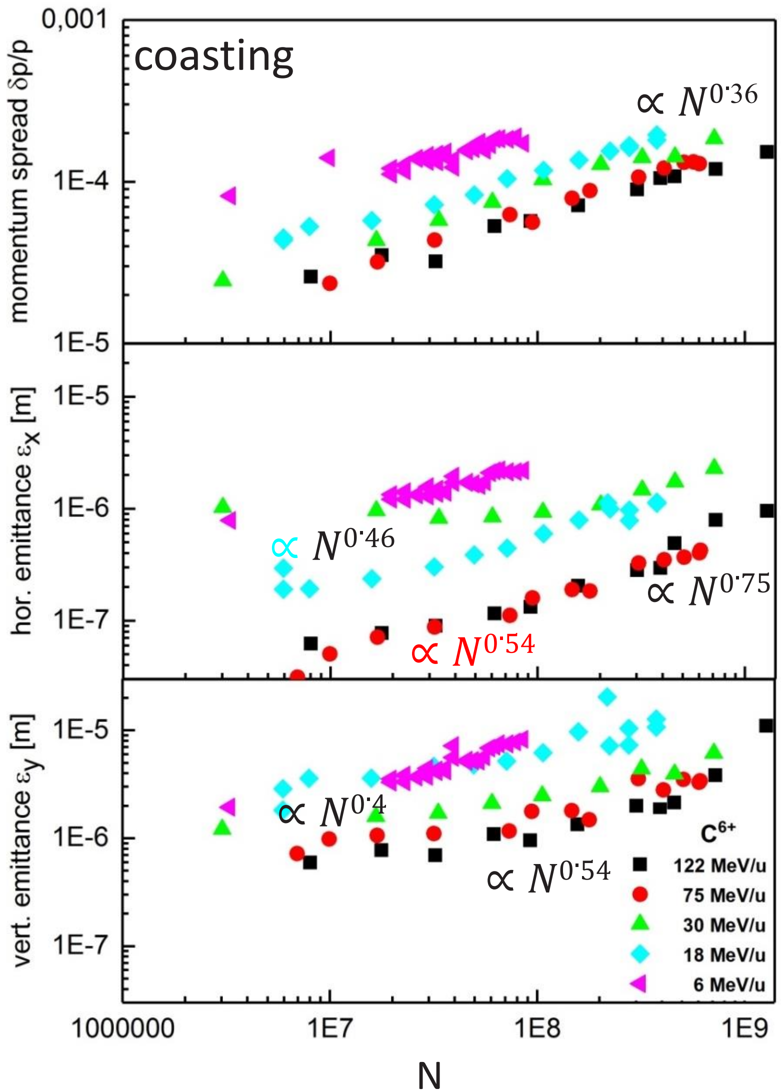


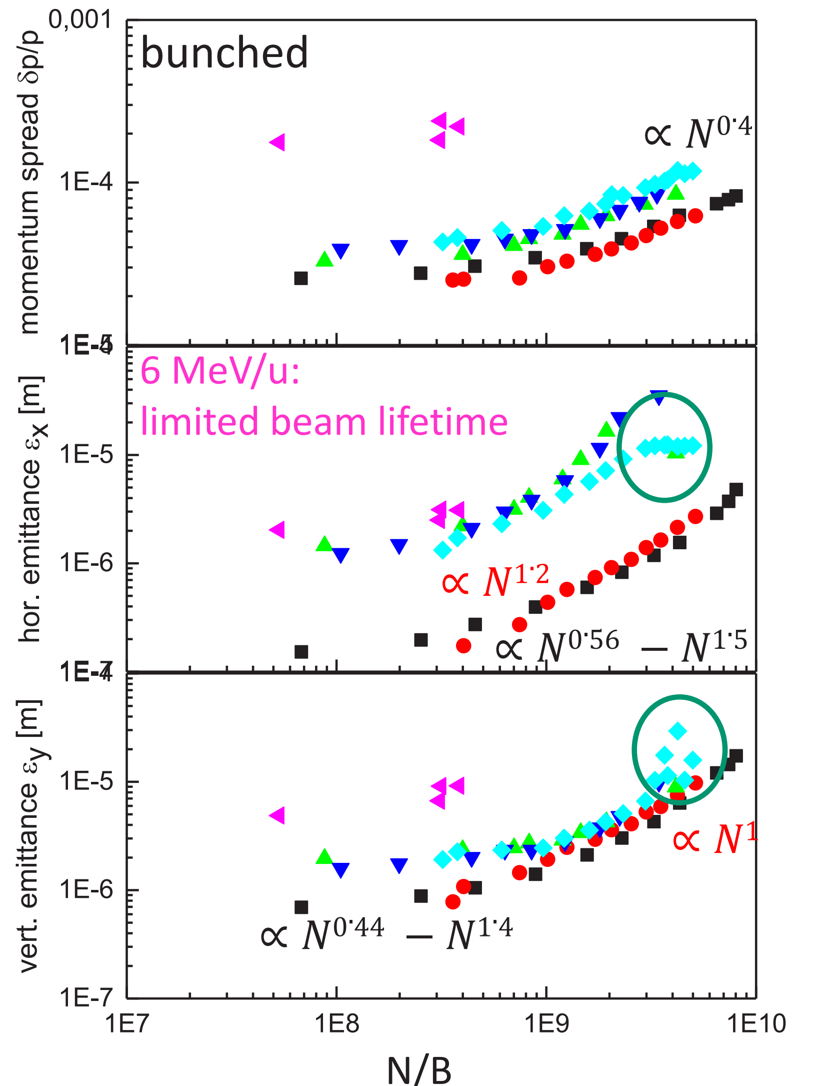
lower intensity region: coasting beam
higher intensity region: bunched beam





Results Carbon all Energies



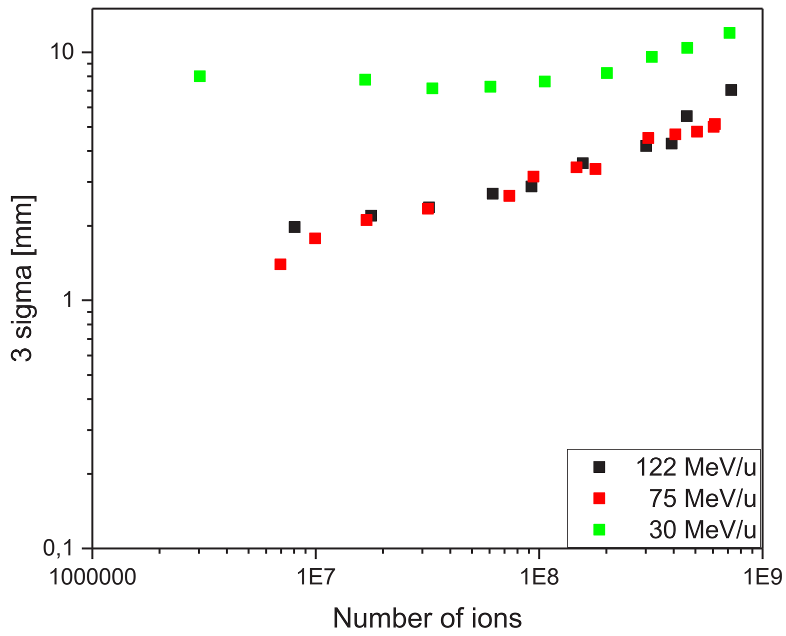


The electron density has been kept at $n_e = 5\cdot10^6\ cm^{-3}$

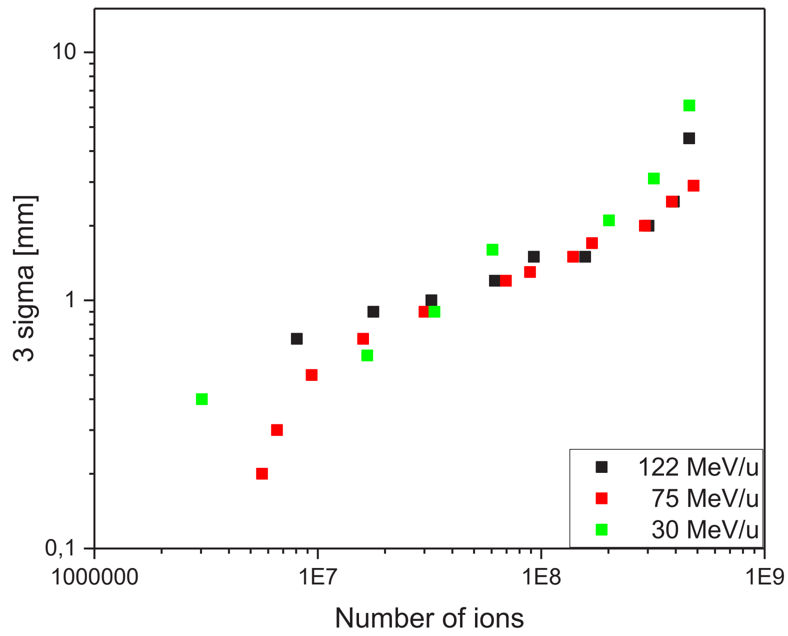
30 MeV/u?

C^{6+} 30 MeV/u coasting beam

IPM



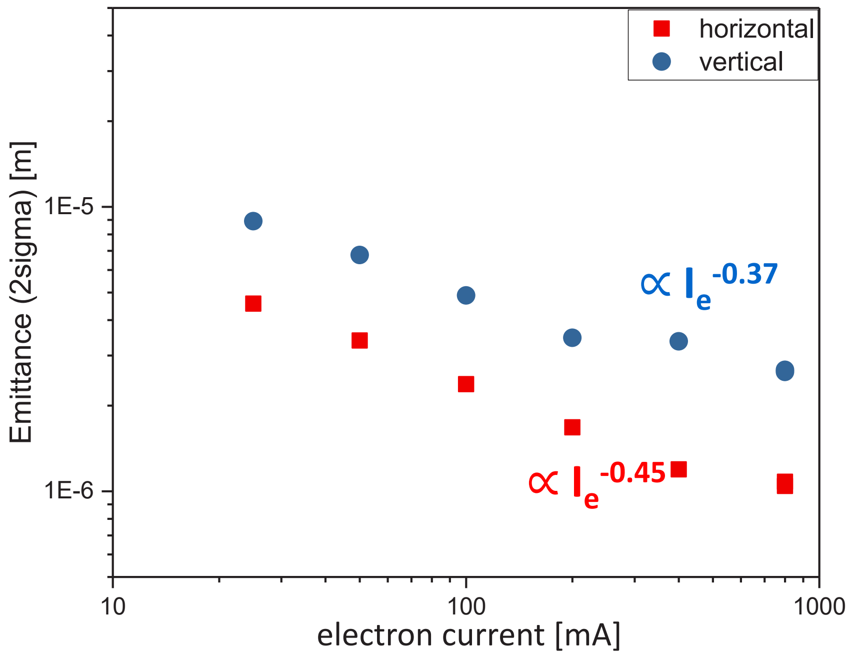
Scraper

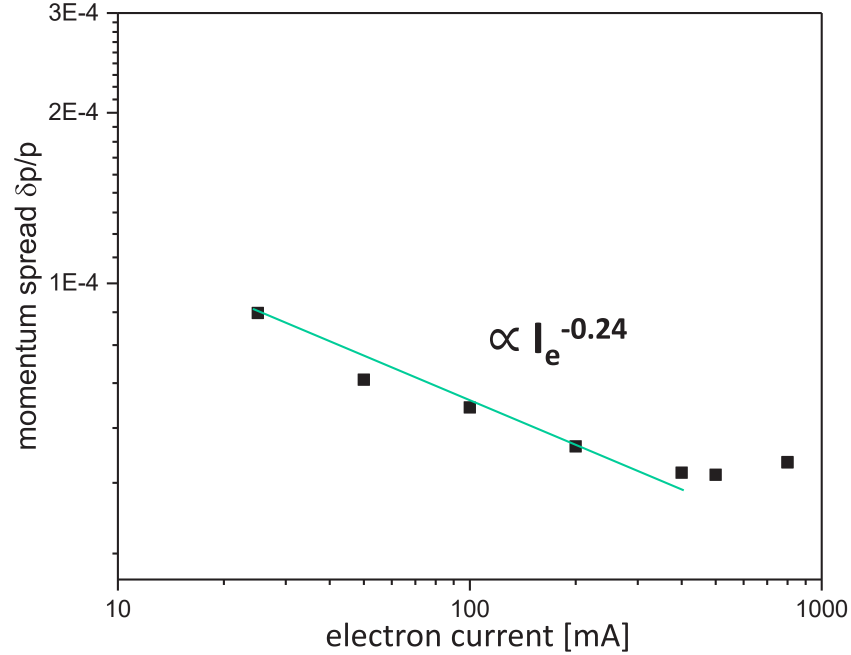


It seems to be a detection effect that leeds to the unexpected behavior of the beam in the horizontal IPM.

Cooler Current Dependence

Xe^{54+} @ 400 MeV/u bunched V_{rf} = 300V





$(\varepsilon_{x,y})_{equil} \propto (N/B)^a\, Ie^{-b}$
a=0.5-0.6 ;
b= 0.1– 0.5

Coasting beam results in the ESR
Ref. [1-3]

$(\Delta p/p)_{equil} \propto (N/B)^a\, Ie^{-b}$
a=0.3-0.4 ;
b= 0.3

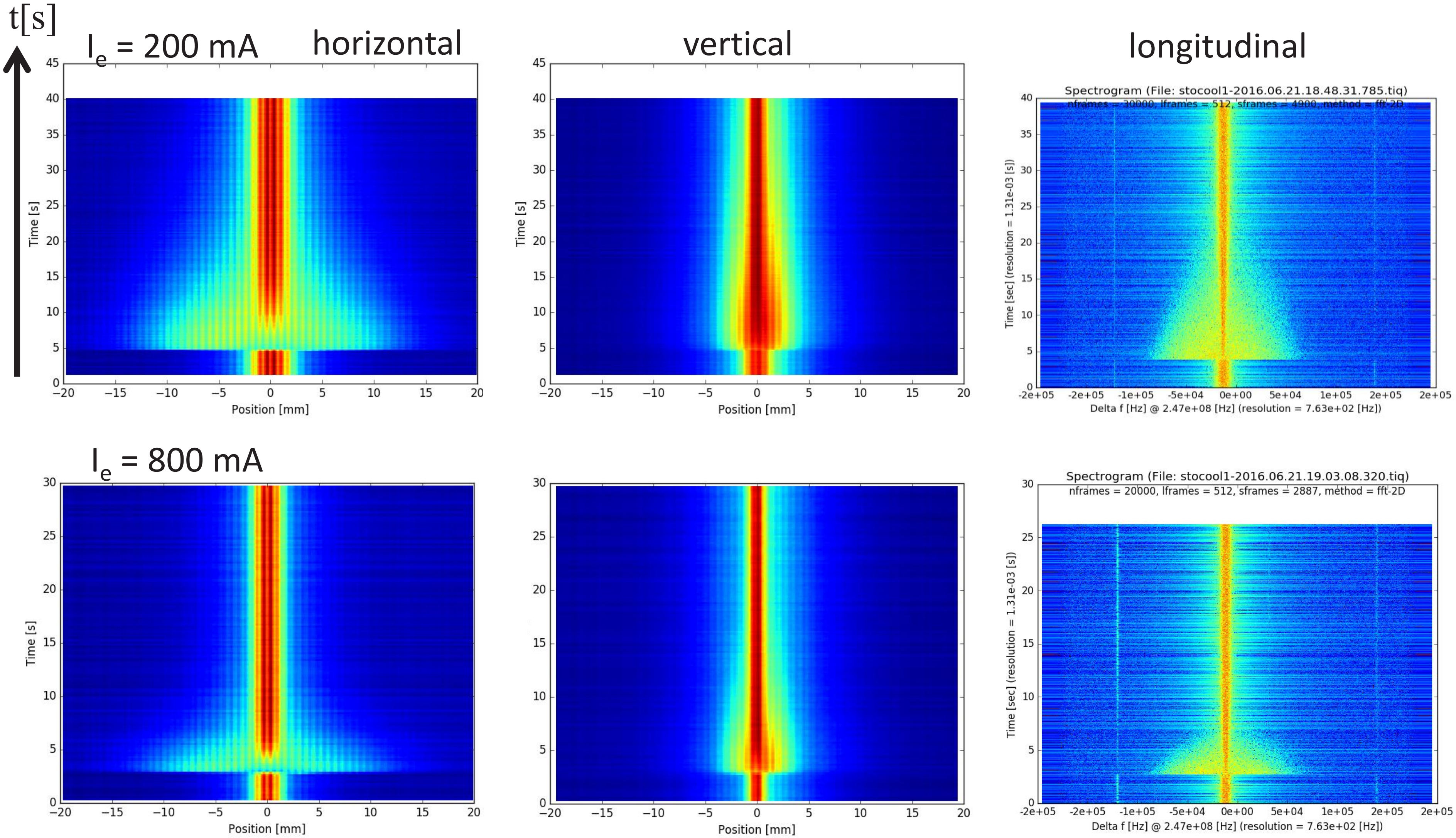
Cooler voltage has been adjusted to the electron cooling current (space charge compensation $\frac{30\, Ie}{\beta}\ (1 + 2ln\frac{b}{a})$)

Results II

- **Simultaneous** information **on cooling force in all 3 planes**: beam evolution of the ion beam after injection with electron cooling

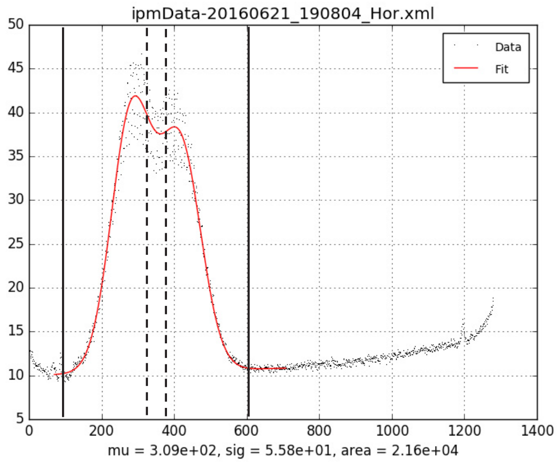
Evolution of the cooling process

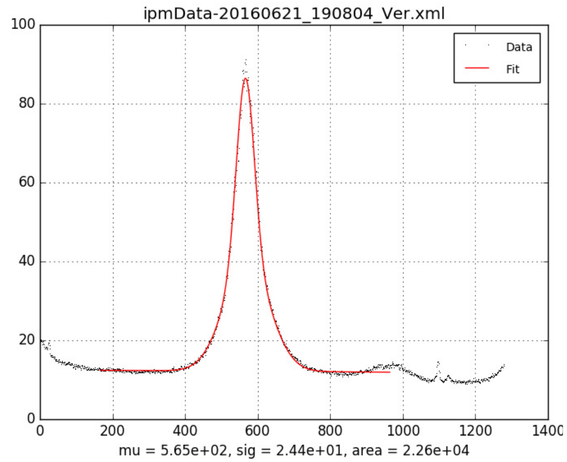
Coasting beam Xe^{54+} @ 400 MeV/u

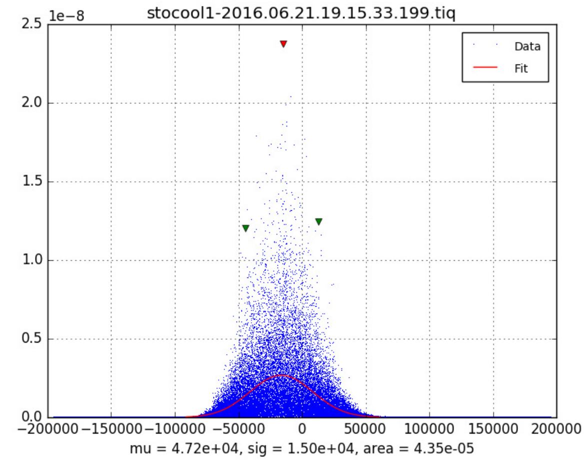


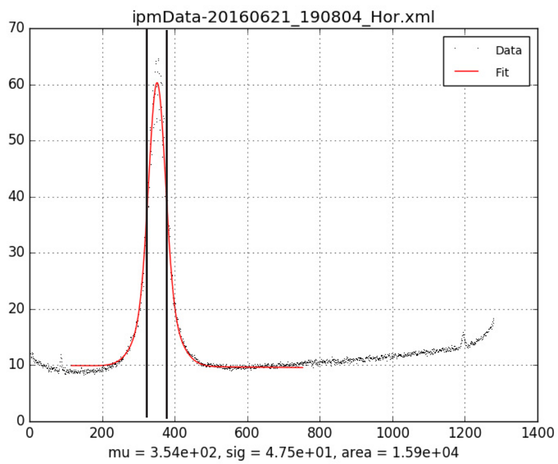
Profiles/Spectrum: injected beam; cooled beam

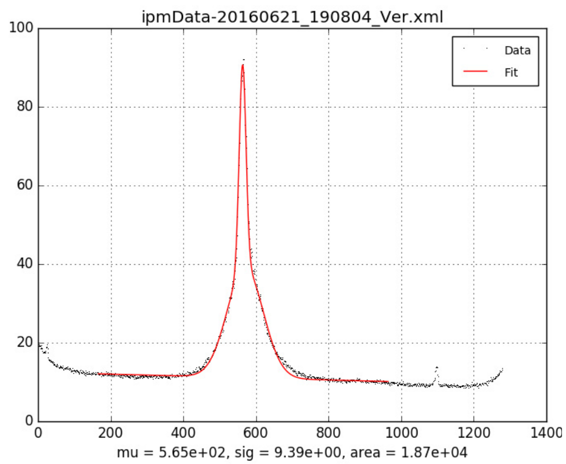
horizontal | vertical | longitudinal

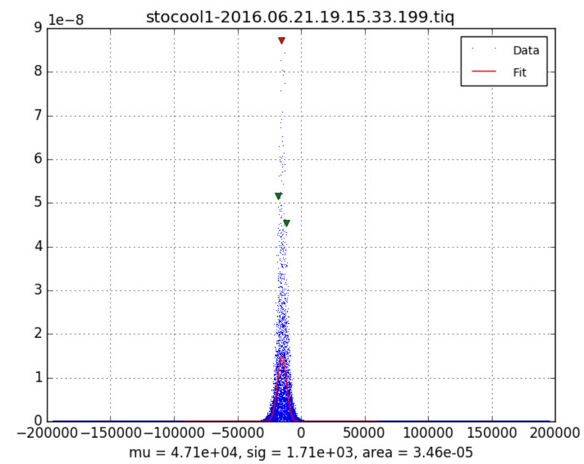




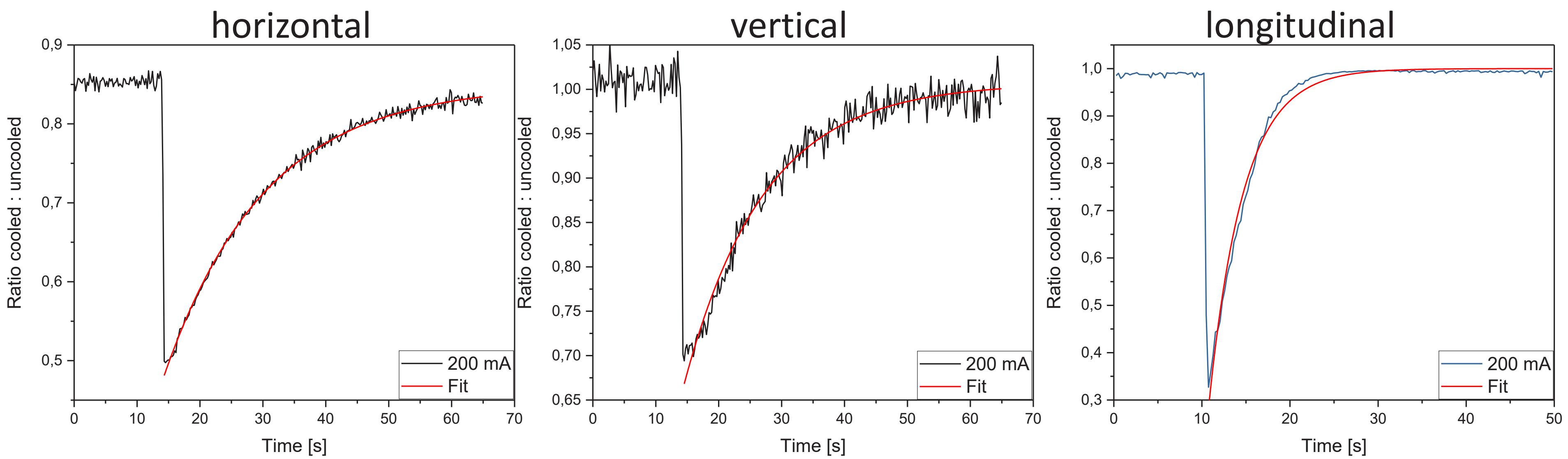


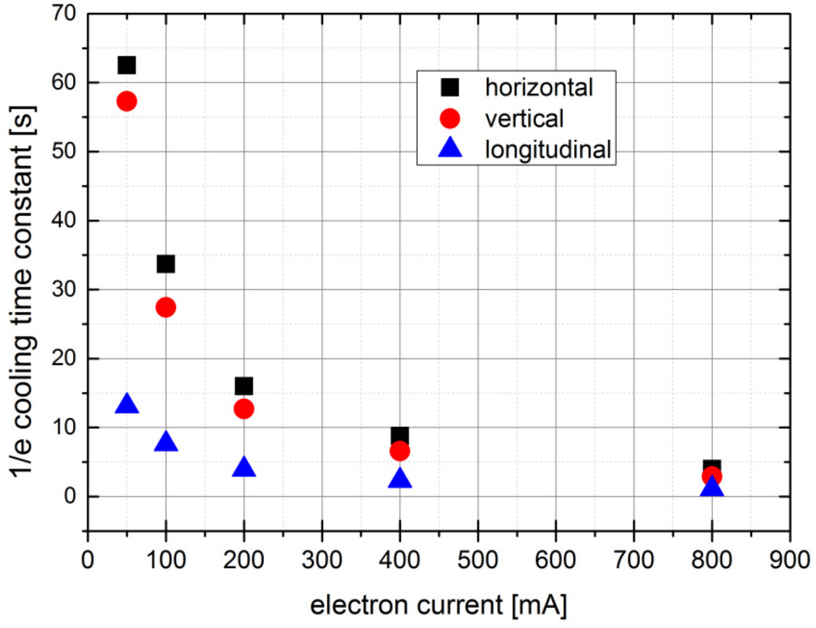






Cooling times in all 3 planes





$\tau_{cool} \propto 1/I_e$ as expected

Longitudinal cooling is 4 times faster than transverse cooling

Summary & Outlook

- Results: FCT worked well, resolution < 10 ns.

Measured bunch lengths (t-domain) seem optimistic: (detector electronics, analysis of ringing...); why factor 4 lower that with Schottky (f-domain)?

- IPMs provide detailed profiles => deduce beam position and shape
- Scaling laws for dependencies on (bunched) ion beam intensity, electron cooling current and cooling time verified in all 3 planes simultaneously.
- Further analysis & interpretation underway (more data)
- Benchmarking with BETACOOL simulations

Thank you for your attention!

[1] M. Steck et al. NIM A 532 (2004) 357
[2] M. Steck et al. Proceedings of the Workshop on Beam Cooling and related topics, Montreux, Switzerland 1993, CERN Yellow Report 94-03 p. 395.
[3] M. Steck et al. Proceedings of EPAC 04, Lucerne, Switzerland p. 1966