Systematic Measurements with Electron Cooled Bunched Heavy Ion Beams

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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

All ions from protons to Uranium:
- $4 \times 10^9$ 1 GeV/u $U^{73+}$
- $5 \times 10^{10}$ 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

- Horizontal
  - $\sigma = 4.5 \text{ mm}$
  - $\varepsilon_x(2\sigma) = 2.9 \times 10^{-6} \text{ m}$

- Vertical
  - $\sigma = 2.2 \text{ mm}$
  - $\varepsilon_y(2\sigma) = 1.2 \times 10^{-5} \text{ m}$

**Example:** C$_6^+$ @ 122 MeV/u
- Bunched (RF = 300V)
- Electron cooled ($I_e = 250$ mA)

\[ \varepsilon_{x,y} = \frac{(2\sigma_{x,y})^2}{\beta_{x,y}} \quad \text{(dispersion at IPM negligible)} \]
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

\[
\frac{\sigma_t}{T_{rev}} = \sqrt{\frac{\beta_0^2 \eta E_{0\,tot}}{2\pi Qh\dot{V}}} \cdot \frac{\sigma_p}{p}
\]

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 \( \eta \)

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

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

Initial momentum spread about \(10^{-3}\)

Final momentum spread \(10^{-6} - 10^{-4}\)
• 6D phase space interplay between electron cooling and intrabeam scattering

Previously: coasting beams →
Now: also for bunched beams
The intrabeam scattering (IBS) is the multiple Coulomb scattering of charged particles in the beam.

Equilibrium

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

\[ N = \frac{I_{\text{ion}}}{Q e f_{\text{rev}}} \quad : \text{ion intensity} \]

\[ B = \frac{h T_{\text{Bunch}}}{T_{\text{rev}}} \quad : \text{bunching factor} \]

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

Equilibrium

\[ \frac{1}{\tau_{\text{cool}}} = \frac{1}{\tau_{\text{IBS}}} \]
Coasting beams

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

E = 200 - 400 MeV/u

\[ \frac{\delta p}{p} \propto N^{0.3} \]

\[ \varepsilon_x, \varepsilon_y \propto N^{0.6} \]

by destructive scraping

E = 400 MeV/u

\[ \delta p/p \propto N^{0.3-0.4} \]

\[ \varepsilon_{x,y} \propto N^{0.5-0.6} \]

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

Steck et al. Ref. [1-3] 1990-today
Comparison C, Xe, U @ 75 MeV/u

**Equilibria Electron Cooling ↔ IBS:**

Coasting:
- Momentum spread $\delta/p \propto N^{0.36}$
- Horizontal emittance $\varepsilon_x \propto N^{0.65}$
- Vertical emittance $\varepsilon_y \propto N^{0.33}$

Bunched (V$_{rf}$ = 300 V):
- Momentum spread $\delta/p \propto N^{0.4}$
- Horizontal emittance $\varepsilon_x \propto N^{0.67}$
- Vertical emittance $\varepsilon_y \propto N^{0.62}$

Comparison of 75 MeV/u ions:
- C6+: Red square
- Xe54+: Orange triangle
- U89+: Blue circle

N/B values:
- C6+: Red square
- Xe54+: Orange triangle
- U89+: Blue circle

- N/B values: 1E7, 1E8, 1E9, 1E10
Equilibria scaling with ion intensity

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

Deltap/p vs. N/B

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

Schottky
FCT

horizontal
vertical
The electron density has been kept at $n_e = 5 \cdot 10^6$ cm$^{-3}$
It seems to be a detection effect that leads to the unexpected behavior of the beam in the horizontal IPM.
Cooler Current Dependence

$Xe^{54+} @ 400 \text{ MeV/u}$

bunched $V_{rf} = 300V$

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

Coasting beam results in the ESR

Ref. [1-3]

$\varepsilon_{x,y}^{\text{equil}} \propto (N/B)^a I_e^{-b}$

$a = 0.5-0.6$ ;

$b = 0.1-0.5$

$(\Delta p/p)^{\text{equil}} \propto (N/B)^a I_e^{-b}$

$a = 0.3-0.4$ ;

$b = 0.3$
• **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 $\text{Xe}^{54+} @ 400 \text{ MeV/u}$

$I_e = 200 \text{ mA}$  horizontal

$I_e = 800 \text{ mA}$  vertical

longitudinal
Profiles/Spectrum: injected beam; cooled beam

horizontal

vertical

longitudinal
Cooling times in all 3 planes

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

Longitudinal cooling is 4 times faster than transverse cooling
• 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!