Cooling Activities at the TSR Storage Ring

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The TSR Storage Ring

TSR: shut down December 2012

ECOOL

RF-system
diagnostics

injection/extraction

experiments
TSR experiments with a reaction microscope

Reaction microscope tool to measure the dynamic of charge transfer/ionization processes between a stored ion beam and an neutral beam. For some experiments, very short ion bunches are required.

⇒ investigation of short bunch creation at the TSR
Bunch length compression with electron cooling

longitudinal phase space
damping of synchrotron oscillation

bunch profile before electron cooling
bunch profile before electron cooling

separatrix
closed orbit

Δϕ [rad]
Δv [rel. units]

Δv = v - v_e
electron cooling force
Fe[Δv]
Measured bunch profile with electron cooling

Measured bunch profile

- Fit parabola profile

Bunch length as a function of resonator voltage \( I = 20 \, \mu A \)

- Fit: \( w = \frac{158.8}{U^{0.34}} \)

Beam

- \( ^{12}C^6^+ \) \( E = 50 \, \text{MeV} \)
- \( I = 45 \, \mu A \)
- \( U = 795 \, \text{V} \)
- \( W = 20 \, \text{ns} \)

Measurement with capacitive pick up

For \( R \to \infty \): \( U \sim I \)

Bunch length as a function of intensity \( U = 795 \, \text{V} \)

- Fit \( w = 6.35 \cdot I^{0.31} \)
Space charge limitation of bunch length

**bunch profile with electron cooling**

![Graph showing bunch profile with electron cooling](image)

**effective acceleration voltage:**

\[
U_{\text{eff}}(\Delta \phi) = U \cdot \sin(\Delta \phi + \phi_s) + U_s(\Delta \phi)
\]

with \(U_s(\Delta \phi) = E_s(\Delta \phi) \cdot C_0\)

\(C_0\) - circumference

**space charge limit**

\[
\eta = \frac{\Delta f / f}{\Delta p / p} > 0 \quad U_{\text{eff}}(\Delta \phi) = 0 \quad \Rightarrow \quad w = C_0 \frac{3^{3/2} (1 + 2 \ln(R/r)) I}{\sqrt{3^2 \pi^2 c^4 \varepsilon_0 \gamma^2 h^2 \beta^4 U}}
\]

\(\phi_s = 0^0\)

**parabola profile:** only distribution to compensate the synchrotron motion of each ion
Space charge limitation
comparison theory and measurements

space charge limit: parabola profile

\[ w = C_0 \frac{3^{\frac{1}{3}} \sqrt{\frac{R}{r}}}{\sqrt{\frac{2^4 \pi^2 c^4 \varepsilon_0 \gamma^2 h^2 \beta^4 U}} \left( 1 + 2 \ln \left( \frac{R}{r} \right) \right)} \]

\( I \) – intensity, \( U \) - resonator voltage

bunch length as a function of resonator voltage \( U \) \( \text{I}=20 \ \mu\text{A} \)

fit: \( w = \frac{158.8}{U^{0.34}} \)

theory calculated for \( r=2\sigma=2 \ \text{mm} \)
\( R=100 \ \text{mm} \)

bunch length as a function of intensity \( I \) \( U=795 \ \text{V} \)

fit: \( w = 6.35 \cdot I^{0.31} \)

theory calculated for \( r=2\sigma=2 \ \text{mm} \)
\( R=100 \ \text{mm} \)
Operation of the storage ring at $\eta<0$ ring

f- revolution frequency
p- momentum

at $\eta = \frac{\Delta f / f}{\Delta p / p} < 0$

effective acceleration voltage:
$U_{\text{eff}}(\Delta \phi) = U \cdot \sin(\Delta \phi + \phi_s) + U_s(\Delta \phi)$
with $U_s(\Delta \phi) = E_s(\Delta \phi) \cdot C_0$ $C_0$ - circumference

at $\eta = \frac{\Delta f / f}{\Delta p / p} < 0$

space charge voltage $U_s(\Delta \phi)$ doesn’t compensate resonator voltage $U \cdot \sin(\Delta \phi + \pi)$

no space charge limit at $\eta<0$ !!!!

$\Rightarrow$ operation of the storage ring at $\eta<0$
to achieve smaller bunch length
The slip factor $\eta$ of a storage ring

To get the $\eta$ parameter negative the orbit length of ions with positive momentum deviation has to increased by increasing the dispersion $D_x(s)$ inside the dipole magnets.

$\eta = \frac{\Delta f / f}{\Delta p / p} = \frac{1}{\gamma^2} - \alpha$ with $\alpha = \frac{\Delta C_0 / C_0}{\Delta p / p} = \int \frac{D_x(s)}{\rho(s)} ds$

$\Delta x = D_x \frac{\Delta p}{p}$

Increasing of the orbit length decreases revolution frequency.

$TSR \quad \alpha = 1.58 \quad \leftrightarrow dipole: \quad \overline{D_x} = 14 \text{ m}$

for $^{12}\text{C}^{6+} \quad E = 50 \text{ MeV}$

$\eta = -0.59$
The slip factor of the TSR at negative $\eta$

**Schottky frequency as a function of the magnetic field (main dipole)**

$$f_{\text{Schottky}} = h \cdot f_0$$

ion: $^{12}\text{C}^6^+$
E=50 MeV

**Schottky frequency as a function of cathode voltage**

$$f_{\text{Schottky}} = h \cdot f_0$$

ion: $^{12}\text{C}^6^+$
E=50 MeV

measurement of $\gamma_{tr}$

$$\alpha = \frac{\Delta C/C}{\Delta p/p} = \frac{\Delta f_{\text{Schottky}}/f_{\text{Schottky}}}{\Delta B/B} \Rightarrow \alpha = 1.58$$

ion velocity constant

main dipole field

$$\Rightarrow \eta = \frac{1}{\gamma^2} - \alpha = -0.59$$

average dispersion in the main dipole magnets

$$<D_x> = 14 \text{ m}$$

cathode voltage increases ion velocity faster ion lower revolution frequency

$\eta$ is negative !!!

$$\eta = \frac{\Delta f_0/f_0}{\Delta p/p} \approx 2 \cdot \frac{U_{\text{cath}}}{f_0} \cdot \frac{\Delta f_0}{\Delta U_{\text{cath}}} = -0.62$$
Electron cooled bunches at negative and positive $\eta$

slip factor: $\eta = \frac{\Delta f / f}{\Delta p / p}$

beam: $^{12}\text{C}^{6+}$ $E = 50$ MeV

bunch length measured at $\eta = -0.59$

measurement

fit

$\text{I} = 2.9$ $\mu$A  
$U = 651$ V

Gaussian distribution

comparison: corresponding Gaussian bunch length $\sigma^*$ with same half width as parabola distribution: $\sigma^* = \frac{w}{2\sqrt{\ln(2)}} = 0.6 \cdot w$

bunch length measured at standard mode $\eta = 0.91$

measurement

fit

$\text{I} = 45$ $\mu$A  
$U = 795$ V

Parabola distribution
Measured bunch length at $\eta=-0.59$

Comparison of measured bunch length at $\eta=-0.59$ and at the TSR standard-mode ($\eta=0.91$)

<table>
<thead>
<tr>
<th>$U_0,[V]$</th>
<th>$I_0,[\mu A]$</th>
<th>$\sigma_{\eta&lt;0},[\text{ns}]$</th>
<th>$\sigma^*,[\text{ns}]$</th>
<th>$\frac{\sigma^*}{\sigma_{\eta&lt;0}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>5.8</td>
<td>4.73</td>
<td>16.39</td>
<td>3.47</td>
</tr>
<tr>
<td>102</td>
<td>4.4</td>
<td>3.87</td>
<td>11.97</td>
<td>3.09</td>
</tr>
<tr>
<td>204</td>
<td>3.6</td>
<td>3.71</td>
<td>8.95</td>
<td>2.41</td>
</tr>
<tr>
<td>409</td>
<td>3.7</td>
<td>3.47</td>
<td>7.18</td>
<td>2.07</td>
</tr>
<tr>
<td>651</td>
<td>2.9</td>
<td>3.03</td>
<td>5.71</td>
<td>1.88</td>
</tr>
</tbody>
</table>

$\Rightarrow$ shorter bunch length (factor $\approx 2-3.5$) are archived at $\eta<0$ for the same $U$ an $I$ compared to the standard mode with $\eta>0$

$\sigma^* = 0.6 \cdot w$
Self Bunching at $\eta < 0$

**pick-up voltage**

- with beam, without rf $U_0=0$, ECOOL on
- without beam, without rf, ECOOL on

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**Gaussian Fit**

- $I \approx 2 \mu A$
- $\sigma = 4.5$ ns

beam: $^{12}\text{C}^6+$

E = 50 MeV
Pick-up signal measured at $f=1$ MHz ($h=2$) as a function of time

- **At** $t=0$ s and start electron cooling
- **Start** self bunching
- **$t \approx 0.150$ s**
- **Creation of bunches** (beam lifetime: $\tau \approx 1400$ s)
- **Decay** with time constant $\tau_d \approx 6$ s
- **Observation frequency** $f = 1.0$ MHz

**Graphical Details:**
- **Pick-up voltage**
- **Time span:** $\Delta t = 1$ $\mu$s
- **Intensity (dBm)**: $-10$ to $-50$
- **Time (s):** 0.0 to 3.0
- **Zero span mode**
Deceleration of ion beams

demand of highly charged ions at low velocities for experiments with a reaction microscope

Example: deceleration of $^{12}\text{C}^{6+}$ ions: energy: 73.3 MeV → 9.7 MeV
$B\cdot\rho$: 0.71 Tm → 0.26 Tm

beam rigidity as a function of time

declaration cycle:
increase of bunch length and beam size
⇒ two electron cooling steps:
1. after injection before ramping
2. at the final energy to provide good beam quality for the experiment

almost linear decrease of beam rigidity and beam velocity
Horizontal beam $\sigma_x$ beam width during deceleration

beam: $^{12}\text{C}^{6+}$ $E=73.3$ MeV $\rightarrow$ 9.7 MeV

final energy $E=9.7$ MeV

start electron cooling

calculation taking into account IBS

pre electron cooling ($E=73.3$ MeV)

final beam width at $E=9.7$ MeV

ECOOL off and start deceleration

horizontal beam width ($i=x$)

$$\sigma_i(t) = \left( \sigma_{i,0} + \frac{D_i}{\alpha(k-1)} \left( \frac{1}{\beta_0^{1-k} - \beta(t)^{1-k}} \right) \right)^{\frac{1}{\gamma}} \sqrt{\frac{\beta_0}{\beta(t)}}$$

with $\beta(t) = \beta_0 + \alpha t$ and $\alpha = (\beta_f - \beta_0)/T$; $\kappa=3\quad \gamma=5.9$ (bunched beams)

heating term: $D_i \propto N \frac{q^4}{A^2}$
IBS studies with $^{12}\text{C}^{6+}$ ions at the initial energy of 73.3 MeV

IBS rates:  
$$ \frac{1}{\sigma_i} \frac{d\sigma_i}{dt} = c_i \frac{q^4 N}{A^2 \beta^3} \varepsilon_x \varepsilon_y \Delta p/p \cdot h \cdot l_{\text{eff}} \quad \text{i=x,y,} \frac{\Delta p}{p} $$

if in the IBS process starting from the equilibrium between cooling and IBS:

$$ \sigma_x \sim \sigma_y \sim \Delta p/p \sim l_{\text{eff}} $$  

effective bunch length

then we get:  
$$ \frac{1}{\sigma_i} \frac{d\sigma_i}{dt} = \frac{1}{\beta^\kappa} \frac{\bar{D}_i}{\sigma_i^\gamma} $$

for a bunched beam, where $\gamma \approx 6$, $\kappa \approx 3$  

$$ \bar{D}_i \sim \frac{q^4 N}{A^2 h} $$

solution for $\beta$ is constant:  
$$ \sigma_i(t) = \left( \sigma_{i,0}^\gamma + \gamma \frac{\bar{D}_i}{\beta^\kappa} t \right)^{\frac{1}{\gamma}} $$

horizontal beam width

IBS measurement at TSR  
E=73.3 MeV  
bunching at $h=6$  
I=50 $\mu$A
Beam width during deceleration

beam with due to IBS at a constant velocity:

$$\frac{1}{\sigma_0} \frac{d\sigma_i}{dt} = \frac{1}{\beta^\kappa} \frac{\tilde{D}_i}{\sigma_i^\gamma}$$

in the deceleration process: \( \beta(t) = \beta_0 + \alpha \cdot t \) \( \beta_0 \) initial velocity

\( \Rightarrow \) beam width during deceleration:

$$\sigma_i(t) = \sqrt{\frac{\beta_0}{\beta(t)}} \left( \sigma_{i,0}^\gamma + \frac{\gamma \tilde{D}_i (\beta_0^{1-\kappa} - \beta(t)^{1-\kappa})}{\alpha(\kappa - 1)} \right)^{\frac{1}{\gamma}}$$

\( \kappa \approx 3 \)

change of the beam size due to Lioville

determined at initial energy for particle number \( N \)

\( \tilde{D}_i \sim \frac{q^4}{A^2} \frac{N}{h} \)

ECOOL on

ECOOL off

stop deceleration

start deceleration

calculated beam width during deceleration with \( \kappa=3 \)
Acknowledgement

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