Diagnostics at CSR (and TSR)

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CSR storage ring
under construction

TSR storage ring

CSR storage ring
under construction

TSR storage ring

test of properties of diagnostics elements for CSR
investigation of diagnostics procedure for the CSR

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Diagnostic elements of the CSR

- **current monitor, bunched beam**
- **Schottky pick up**
- **neutral beam**
- **quadrupole**
- **reaction microscope**
- **first turn diagnose**
- **beam position monitor BPM**
- **ECOOL**
- **scraper**
- **beam profile monitor**
- **MCP with phosphor screen**
- **neutral fragments**
- **injection**
- **rf system**
- **60° deflector**
- **390° deflector**
- **detection corner**
Measurement of the intensity of a bunched ion beam

current of the stored ion beam
\[ I_a(t) = I(t - \Delta t) \]

after the drift tube flight time inside the drift tube

node theorem:
\[ I(t) = I_a(t) + I_R(t) + I_C(t) \]
\[ \Leftrightarrow I(t) = I(t - \Delta t) + I_R(t) + I_C(t) \]

With bunch length \( l_b \gg L \):
\[ I(t - \Delta t) = I(t) - \frac{\partial I}{\partial t} \Delta t = I(t) - \dot{I}(t) \frac{L}{v} \]

with \( I_R(t) = \frac{U}{R} \) and \( I_C(t) = C \cdot \dot{U}(t) \) differential equation for drift tube voltage \( U(t) \)
\[ \frac{L}{v} \dot{I}(t) = C \cdot \dot{U}(t) + \frac{U(t)}{R} \]

for \( R \to \infty \) drift tube voltage:
\[ U(t) = \frac{1}{C \cdot v} L I(t) \quad \Rightarrow \quad U(t) \propto I(t) \]
Measurement of the intensity of a bunched ion beam

relation pick up voltage $U(t)$ and stored ion current $I(t)$ for $R \rightarrow \infty$

$$U(t) = \frac{1}{C} \frac{L}{V} I(t)$$

ion velocities for singly charge ions at the CSR

![Graph showing ion velocities for E=300 keV and E=20 keV]

very sensitive for a low velocity bunched ion beam!!

typically TSR velocity $\beta = 0.1$

at the CSR the current sensitivity is improved by a factor $>10$

compared to the TSR
Measurement of the intensity of a bunched cooled ion beam profile of an electron cooled bunched ion beam

TSR measurement (no averaging)

beam: $^{12}$C$^{6+}$
$E=50$ MeV
$\beta=0.094$
$I=19 \mu A$

$U(t)$ $+\cdot=\frac{I}{RL}$

attention: due to no DC can be measured with a pick up
differential equation of the pick up voltage:

$$\frac{L}{V} \dot{I}(t) = C \cdot \ddot{U}(t) + \frac{U(t)}{R}$$

⇒ we have to know where the region in the signal where $I(t)=0$
⇒ base line has to shift where $I=0$ !!!

determination of the beam current

amplification factor

result

$I = 1.08 \cdot I_T$

beam current measured with beam current transformer

amplification: factor $V_a = 15.14$
Measurement of the intensity of a bunched ion beam

1. are region with I(t)=0?
2. where are the region with I(t)=0?

for baseline (I=0) construction measurements and simulations for comparison were performed

longitudinal phase space of the injected beam at \( U_0=0 \) V

bucket size at the final resonator voltage \( U_0=100 \) V

to get region in the signal with I(t)=0
the rf bucket size at the final resonator voltage after bunching has to fulfill:

\[ A_b > A_{\text{beam}} \]

\( A_b \) - rf bucket area
\( A_{\text{beam}} \) - longitudinal phase space area of the injected beam

for baseline (I=0) construction measurements and simulations for comparison were performed:

- \( U_0=26 \) V
- \( U_0=44 \) V
- \( U_0=88 \) V
- \( U_0=132 \) V
- \( U_0=528 \) V
- \( U_0=792 \) V

no averaging used in the measurements
Spectrum of the pick-up signal

bunched ion current periodic function
with period \( T \) (\( T \) is rf period)

\[ \Rightarrow \text{pick up signal can be expressed in a Fourier row:} \]

\[
U(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cdot \cos(n \omega t) + b_n \sin(n \omega t) \\
a_n = \frac{2}{T} \int_{-T/2}^{T/2} U(t) \cdot \cos(n \omega t) dt \\
b_n = \frac{2}{T} \int_{-T/2}^{T/2} U(t) \cdot \sin(n \omega t) dt
\]

where \( \hat{U}_n = \sqrt{a_n^2 + b_n^2} \propto I \) stored intensity

measured with a spectrum analyzer has always its maximum value at \( n=1 \)

measurement of \( \hat{U}_1 \) as a function of time during optimization of the injection (TSR)

\( \hat{U}_1 \) is determined by the bunch length !!

In the figure:
- Multi turn injection
- Without ECOOL
- With ECOOL

\[ x_i - x_{\text{ref}} = 20 \cdot \log\left( \frac{\hat{U}_1}{U_{\text{ref}}} \right) \]
Measurement of the intensity of a stored bunched cooled ion beam

\( \hat{U}_1 \), for an electron cooled ion beam in the space charge limit almost independent of the bunch length \( \hat{U}_1 \propto \bar{I} \)

**first Fourier \( U_1 \) component of the pick up signal as a function of the intensity**

Measurement of an electron cooled ion beam

\(^{12}\text{C}^6+\ E=50\ \text{MeV}\) ion beam at \( f = f_{rf} = 3.05\ \text{MHz} \)

\[ x_1 - x_{\text{ref}} = 20 \cdot \log\left( \frac{\hat{U}_1}{U_{\text{ref}}} \right) \]

\( U_0 \)-resonator voltage

- \( U_0 = 450\ \text{V} \), \( \hat{U}_1 \propto \bar{I}^{1.09113} \)
- \( U_0 = 135\ \text{V} \), \( \hat{U}_1 \propto \bar{I}^{1.03551} \)
- \( U_0 = 720\ \text{V} \), \( \hat{U}_1 \propto \bar{I}^{0.966972} \)

Beam current measured with beam current transformer

**bunch length as a function of resonator voltage \( U \)**

- \( I = 20\ \mu\text{A} \)
- \( \text{experiment} \)
- \( \text{theory} \)
- \(^{12}\text{C}^6+\ E=50\ \text{MeV} \)

**bunch length as a function of intensity \( I \)**

- \( U = 795\ \text{V} \)
- \( \text{experiment} \)
- \( \text{theory} \)
- \(^{12}\text{C}^6+\ E=50\ \text{MeV} \)
Spectrum of the pick up voltage for a electron cooled bunched ion beam

\[
\hat{U}_n = \frac{V_a}{\sqrt{C}} \hat{I}_n \quad \hat{I}_n = \frac{6}{n^3 w^3 \omega^3} (\sin(n w \omega) - n w \omega \cos(n w \omega))
\]

\(w \ll T_{rf}\) Taylor expansion

at rf frequency \(n=1\) \(w \ll T_{rf}\)

\[
\hat{U}_1 = \frac{V_a L}{\sqrt{C}} (2 \bar{I} - \frac{1}{5} \bar{I} (\omega w)^2 + ...) = \frac{V_a L}{\sqrt{C}} 2 \bar{I}
\]

at second harmonic \(n=2\) \(w \ll T_{rf}\)

\[
\hat{U}_2 = \frac{V_a L}{\sqrt{C}} (2 \bar{I} - \frac{4}{5} \bar{I} (\omega w)^2 + ...) = \frac{V_a L}{\sqrt{C}} 2 \bar{I}
\]

example:

consider signal direct at the pick-up \(V_a=1, \ \beta=0.01, L=5 \ \text{cm}, C=100 \ \text{pF}\)

\(\bar{I} = 10 \text{nA} \Rightarrow \hat{U}_1 = 3 \mu \text{V} \) pick-up voltage without amplification

easily to measure with a spectrum analyzer

current sensitivity \(\bar{I} < 10 \text{nA} \) if the bunched ion beam is cooled

\(\hat{U}_1 , \hat{U}_2 \) has the same intensity

\(\text{if } w \ll T_{rf}\)

\(\Rightarrow\) experimental proof that the condition \(w \ll T_{rf}\) is fulfilled

\[
\hat{U}_1 = \frac{V_a L}{\sqrt{C}} 2 \bar{I} \iff \bar{I} = \frac{\sqrt{C} \hat{U}_1}{V_a L 2}
\]
Current monitor for bunched ion beams at the CSR

absolute intensity measurement

\[ \hat{I} = \frac{C \cdot V}{L \cdot V_a} \int_{-T/2}^{T/2} U(t) \cdot dt \]

\[ \hat{U}_1 = \text{const} \cdot \hat{I} \]

\[ \hat{U}_1 \approx \frac{V_a L}{v C} \hat{I} \] if \( A_b > A_{\text{beam}} \)

For an electron cooled bunched ion beam absolute intensity measurement is possible to intensities \( \hat{I} < 10 \text{nA} \), depending on the ion velocity, by measuring \( \hat{U}_1 \)

- **Uncooled bunched ion beam**
  - const: depends on the amplitude of the rf used for bunching

- **Cooled bunched ion beam**
  - const: independent on rf voltage for bunching and bunch length, but const depend on ion velocity, taking into account this dependency it is possible to determine from \( U_1 \) the absolute stored ion current!

For an electron cooled bunched ion beam absolute intensity measurement is possible to intensities \( \hat{I} < 10 \text{nA} \), depending on the ion velocity, by measuring \( \hat{U}_1 \)
Residual gas beam profile monitor

counting rate

\[ R = \eta \cdot \sigma \cdot n \cdot v \cdot N \]

- \( \eta = \frac{l_D}{C_0} \) detector length
- \( C_0 \) Circumference of the storage ring
- \( \sigma \) - cross section for ionization
- \( n \) - residual gas density
- \( v \) - ion velocity
- \( N \) - particle number

example TSR
beam: \(^{12}\text{C}^6+\ E=50\ \text{MeV}\)
\( n \approx 10^6\ \text{1/cm}^3\)
\( I = 1\ \mu\text{A}\)
\( R \approx 200\ \text{1/s}\)

measured beam profile for \(^{12}\text{C}^6+\ E=73\ \text{MeV}\) ions during electron cooling
after multturn injection
measuring time per frame: \( \Delta t=100\ \text{ms}\)

csr: \( n < 10^4\ \text{1/cm}^3\)
⇒ almost no counting rate
other possibilities for profile measurements?

total measuring time: 2s
Beam profile measurements for singly charged ions and molecules

atomic ion: measurement of the neutral particle position
molecular ion: center of mass coordinate of the fragments are measured

relation between ion beam size at the cooler $\sigma_E$ and at the detector position $\sigma_D$

$$\sigma_D = \sigma_E \sqrt{1 + \frac{L^2}{\beta^2}}$$

TSR measurements with 3 MeV COD$^+$ molecules

H. Buhr et. al.
Beam-profile measurement using the reaction microscope

Heavy ions are used in experiments using a reaction microscope for scanning the gas jet.

**Principle:**
- Measuring counting rate as a function of beam-position.
- The CSR is rampable: each element is controlled by a function generator. Time-dependent periodic scans are easily possible.

**TSR experiment:**
- Proof of principle, opposite way, scanning the gas-jet with an ion beam with small diameter to determine the profile of the gas-jet.
Gas jet profile of the reaction microscope

**schematic assembly**

- ion detector
- ion beam
- gas jet

**ionized atom**

**neon gas jet**

from the measured lifetimes $T_0, T_g \Rightarrow T_t$

\[
\frac{1}{T_g} = \frac{1}{T_t} + \frac{1}{T_0}
\]

Schlacter

\[
\frac{1}{T_t} = n_t \cdot \sigma \cdot f_0
\]

\[n_t = \int n \cdot ds = 1.3 \cdot 10^9 \text{ } 1/\text{cm}^2\]

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**Rex-counting rate ion detector reaction microscope**

**R_{BPM}** counting rate beam profile monitor (current normalization)

\[\frac{R_{ex}}{R_{BPM}} \propto \int n \cdot ds\]

lifetime measurement $T_g$

lifetime measurement outside the gas jet: $T_0$

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**fit**

measured at TSR with 50 MeV $^{12}\text{C}^6^+$

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**back-ground**

ion beam position $\Delta x [\text{mm}]$
Measurement of the beam profile with a scraper

Measurement are done by deceleration the stored ion beam to the scraper position.

Distance to the scraper is decreased.

Intensity decrease due to ion collisions with the scraper.

Beam width is determined from the intensity decrease.
Measurement of the position and beam profile position

profile measurements with $^{24}$Mg$^+$ ions, E=40 keV at S-LSR university of Kyoto

intensity measured by measuring the spectrum of the bunched ion beam spectrum analysator span 0 mode resolution $\gg$ frequency shift

number of stored ion as a function of time

beam loss determined by the life time
beam starts to collide with the scraper

$N(t) = \begin{cases} 
    a_0 + D_x \frac{\alpha}{f \eta} t & \text{for } a_0 + D_x \frac{\alpha}{f \eta} t \geq 0 \\
    N_{off} & \text{for } a_0 + D_x \frac{\alpha}{f \eta} t < 0 
\end{cases}
$

fast method to measure the beam profile for an ion beam with short lifetime!

beam position without applying a frequency ramp $a_0 = x$

from the fit
beam size: $\sigma$
beam position: $a_0$
Beam position monitor of the CSR

Beam position monitor pick up cutting into two parts:

$U_1$ (inner vacuum chamber), $U_2$ (grounded shielded chamber)

$40\, \text{K shield}$

$\approx 35\, \text{cm}$ to improve the sensitivity of the beam position monitoring beam position system is resonant

$x = S_{\text{cal}} \frac{U_2 - U_1}{U_1 + U_2}$

scaling factor of the pick-up

$U = U_1 + U_2$

influenced voltage between plate and chamber

preliminary mechanical design of the CSR beam position monitor

$U_1$, $U_2$

cut

$F = \frac{1}{2 \cdot \pi \sqrt{L(C_v + C_k + C)}}$

details: talk of Felix Laux

$C_k$, $C_v$, inductivity

$C$, diode

coupling capacity

pick up capacity +cable capacity

$U_0$

pick-ups

cryo-pump

suspension

inner vacuum chamber

grounded shielded chamber
Scintillators not sensitive enough for 20 keV, nA beams
⇒ “Beam Profiler” developed for REX ISOLDE: $10^2$ pps – mA

First turn diagnose at the CSR beam viewer at CSR prototype

example
10 pA He$^+$
10 keV,
Ø 15 mm
two of these beam viewer are used in front and behind the CTF
The Schottky pick up of the CSR

single ion interaction with the Schottky pick up

\[ I_i(t) = Q \sum_n \delta(t - nT) \]

\[ I_{i,a}(t) = I_i(t - \Delta t) = Q \sum_n \delta(t - nT + \Delta t) \]

\[ \Delta t = \frac{L}{v} \]

L - pick up length

v - ion velocity

\[ T - revolution time of the ion \]

Fourier row Schottky band

\[ I_i(t) = Q \left( \frac{a_0}{2} + \sum_{n=1}^{\infty} \frac{2}{T} \cos(n \omega_0 t) \right) \]

\[ I_{i,a}(t) = Q \left( \frac{a_0}{2} + \sum_{n=1}^{\infty} \frac{2}{T} \cos(-n \omega_0 \Delta t) \cdot \cos(n \omega_0 t) + \frac{2}{T} \cdot \sin(-n \omega_0 \Delta t) \sin(n \omega_0 t) \right) \]

current into LC circuit

\[ \Delta I_i(t) = I_i(t) - I_{i,a}(t) \quad \text{with} \quad \omega_n = n \omega_0 \]

\[ \Delta I_i(t) = Q \frac{2}{T} \sum_{n=1}^{\infty} \left( (1 - \cos(\omega_n \Delta t)) \cos(\omega_n t) + \sin(\omega_n \Delta t) \sin(\omega_n t) \right) \]
Spectrum of the Schottky signal coming from a single ion

\[ \Delta I_i(t) = Q \frac{2}{T} \sum_{n=1}^{\infty} \left( (1 - \cos(\omega_n \Delta t)) \cos(\omega_n t) + \sin(\omega_n \Delta t) \sin(\omega_n t) \right) \]

\[ \Rightarrow \text{spectrum of } \Delta I_i \quad \omega_n = n \omega_0 \]

\[ \hat{\Delta I}_i(\omega_n) = \frac{2Q}{T} \sqrt{\left(1 - \cos(\omega_n \Delta t)\right)^2 + \sin^2(\omega_n \Delta t)} = \frac{2\sqrt{2}Q}{T} \sqrt{1 - \cos(\omega_n \Delta t)} \]

\[ \hat{\Delta I}_i(\omega_n) \text{ is maximum at } \omega_n \Delta t = \pi, 3\pi, \ldots \]

\[ \hat{\Delta I}_i(\omega_n) \text{ is } 0 \text{ at } \omega_n \Delta t = m \cdot \pi \quad \Delta t = \frac{L}{v} \]

\[ \omega_n = 2\pi n f_0 \]

resonant at \( f_n \)

\( f_n = n f_0 \)

revolution frequency of the ion

integer number
Spectrum of the Schottky signal coming from a single ion

signal on LC circuit from a single ion:

\[ \hat{U}_i(\omega_n) = \frac{Q_w}{\omega_n C} \frac{2\sqrt{2}Q}{T} \sqrt{1 - \cos(\omega_n \frac{L}{V})} \]

⇒ signal from a single ion proportion to the Q-value \((Q_w)\) of the LC circuit!

details of the construction of a LC circuit with high Q value: talk of Felix Laux
Maxima in the spectrum of a single ion

signal from a single ion

\[ \hat{U}_i(\omega_n) = \sqrt{2} \frac{Q_w}{\pi} \frac{Q}{C} \sqrt{1 - \cos(\omega_n \frac{L}{V})} \]

\[ n = \frac{f_n}{f_0} \quad \text{observation frequency} \]

\[ f_n = n \cdot f_0 \quad \text{revolution frequency} \]

maxima in the signal: \[ \cos(n2\pi \frac{L}{C_0}) = -1 \]

\[ n = \frac{f_n}{f_0} = \frac{1 + 2 \cdot m}{2} \cdot \frac{C_0}{L} \quad \text{circumference of the storage ring} \]

\[ m = 0, 1, 2, 3, \ldots \]

harmonic number \( n \) where \( \hat{U}_i(\omega_n) \) is maximum is determined by the pick-up length \( L \).
Some thoughts about the pick-up length $L$

consider pick-up with capacity $C$
one single ion will produce a voltage during one passage

in our simple model

$$I_c(t) = \begin{cases} Q \delta(t - t_0) & t \leq t_0 \\ -Q \delta(t - (t_0 + \Delta t)) & t > t_0 \end{cases}$$

$$U(t) = \frac{\int_{t_0}^{t_0+\Delta t} I(t') \, dt'}{C}$$

induced charge distribution $\Lambda(s)$

induced charge on the outside of the cylinder

$$Q = \int_{-L/2}^{L/2} \Lambda(s) \cdot ds \quad \Rightarrow U = \frac{Q}{C}$$

voltage rise time:

$$t_{\text{rise}} \approx \frac{\sigma_{\text{rms}}}{v}$$

$\sigma_{\text{rms}}$ - RMS value of $\Lambda(s)$

radius of the tube

RELATIVISTIC $\gamma$

CSR: $\gamma = 1$

induced charge on the outside of the cylinder

$$Q = \int_{-L/2}^{L/2} \Lambda(s) \cdot ds \quad \Rightarrow U = \frac{Q}{C}$$

ion velocity

Electrical field lines from a point charge

CSR: $a = 5 \text{ cm}$ $L \geq 6 \cdot \sigma_{\text{rms}} \approx 20 \text{ cm}$ better $L \approx 35 \text{ cm} \Rightarrow L/C_0 = 0.01$
Schottky signal from a single ion at different $n$

pick up signal of a single ion as a function of $n = \frac{f_n}{f_0}$

for $C = 100 \text{ pF}$

L-pick up length

$C_0$-CSR circumference

$L/C_0 = 0.01 \Leftrightarrow L = 35 \text{ cm}$

$L/C_0 = 0.005 \Leftrightarrow L = 17.5 \text{ cm}$

The resonance frequency of the LC circuit $f_\text{res} = f_n$ should be variable in a certain range to avoid zero signals in the voltage spectrum.
Schottky signal from a single 300 keV proton

protons with 300 keV are the fastest \(\Rightarrow\) low \(n\) for observation can be chosen

\[
\frac{\hat{U}(n)}{Q_w} = \frac{\sqrt{2}}{\pi} \frac{Q}{n} \frac{1}{C} \sqrt{1 - \cos(n 2\pi \frac{L}{C_0})}
\]

for \(C = 100\) pF

\(L/C_0 = 0.01 \iff L = 35\) cm

\[
\hat{U}(n)/Q_w \approx 30\) pV
\]

for \(n = 1\) to \(n = 20\)

\(\Rightarrow\) protons \(E = 300\) keV \(f_0 \approx 200\) kHz

observation frequency \(f_n = 0.2\) - \(4\) MHz

In that frequency range a LC circuit can be build with \(Q_w \approx 1000\) if the LC circuit is cooled down to a temperature \(T \approx 4K\)

\(\Rightarrow\) \(\hat{U} \approx 30\) nV

remark:
In the frequency range: 0.2 - 4 MHz pick up is a pure capacity, as assumed in the calculation, because: \(L << \lambda\)
Tune measurements at the CSR

At low energies there is a large incoherent tune shift

\[ \Delta Q = -\frac{q^2}{A} \frac{r_p N}{2\pi B \beta^2 \gamma^3 \varepsilon} \]

- \( N \) - number of ions
- \( \beta \) - velocity in units of \( c \)
- \( \varepsilon \) - emittance

Distance to “danger” resonances has to be as large as possible.

Important to know horizontal and vertical tune.

Coherent tune is determined by BTF measurements, where the horizontal kicker is one of the 60 deflectors and as a vertical kicker a vertical correction deflector is used. A beam position pick up of the CSR is used for detection the horizontal and vertical oscillations of the beam at \( f = f_0 (n \pm q) \)

- 60 deflectors
- (horizontal kicker)
- deflector for vertical corrections
- (vertical kicker)

[Diagram of deflector system]
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