Diagnostics at CSR (and TSR)

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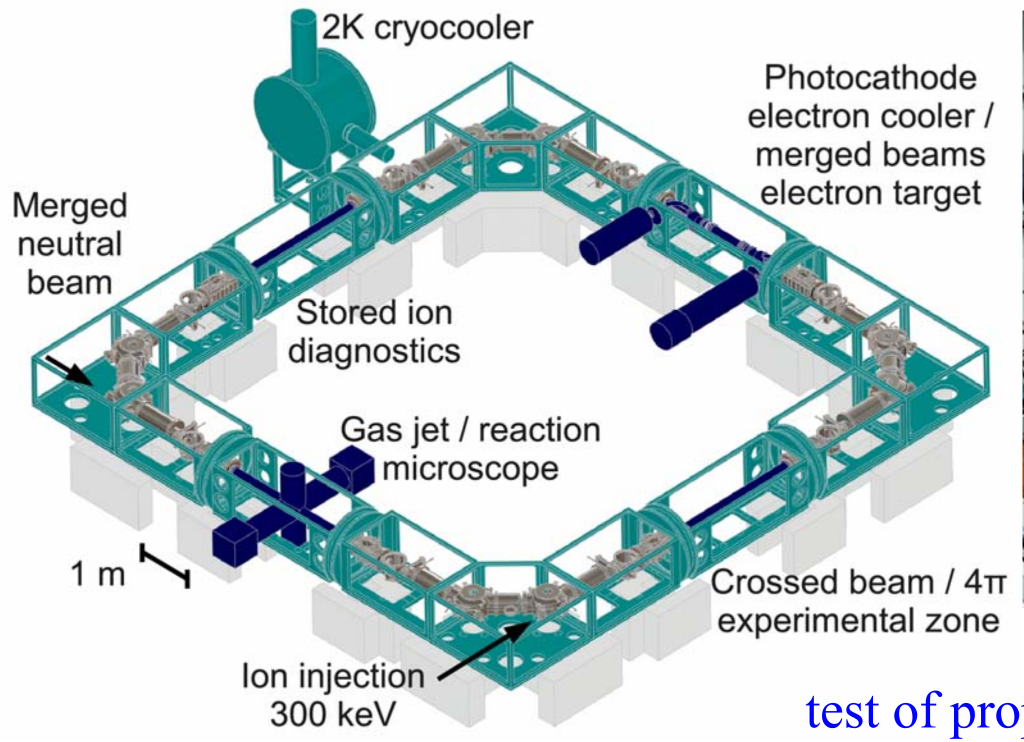
CSR storage ring
under construction

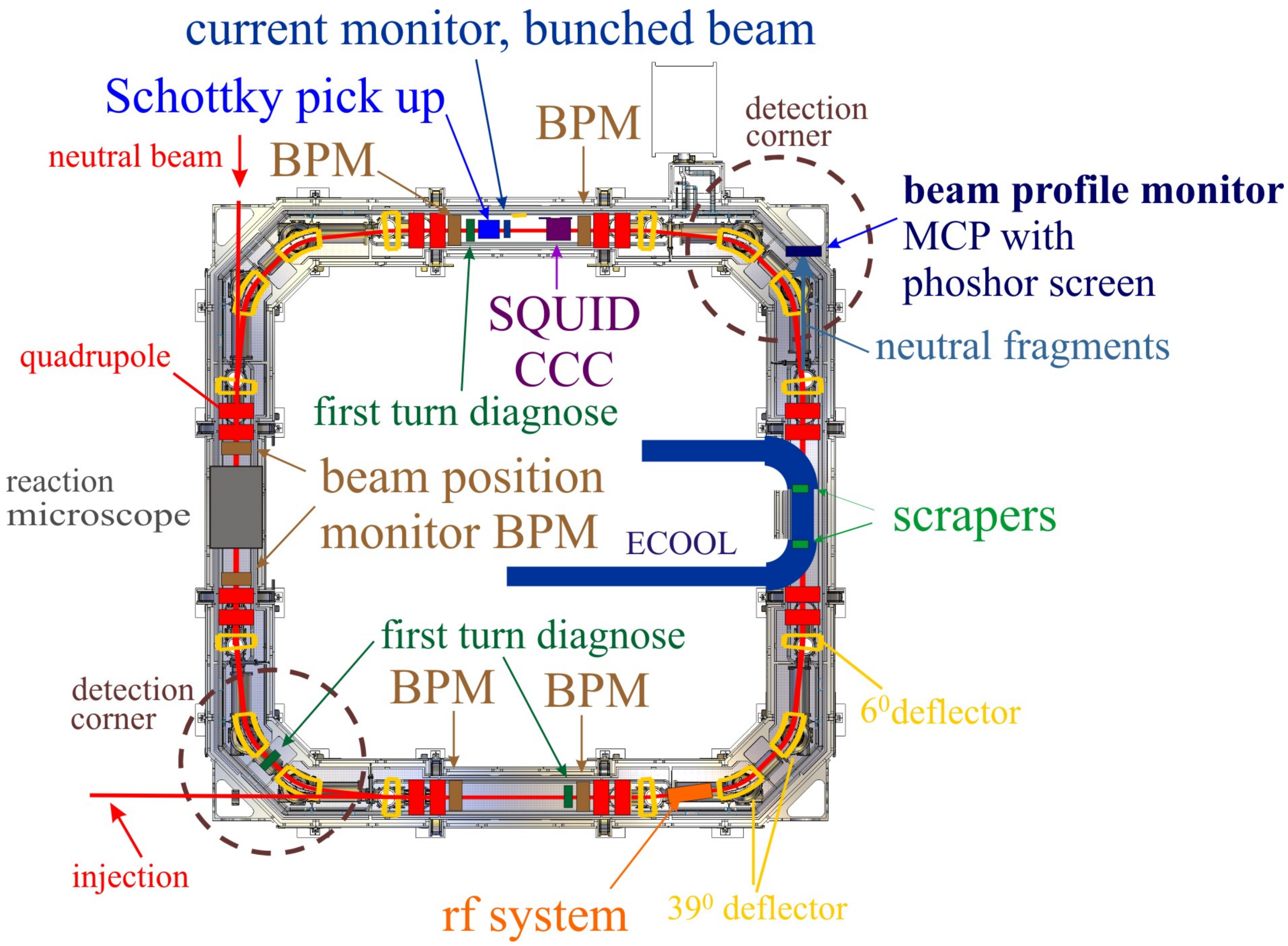


TSR storage ring

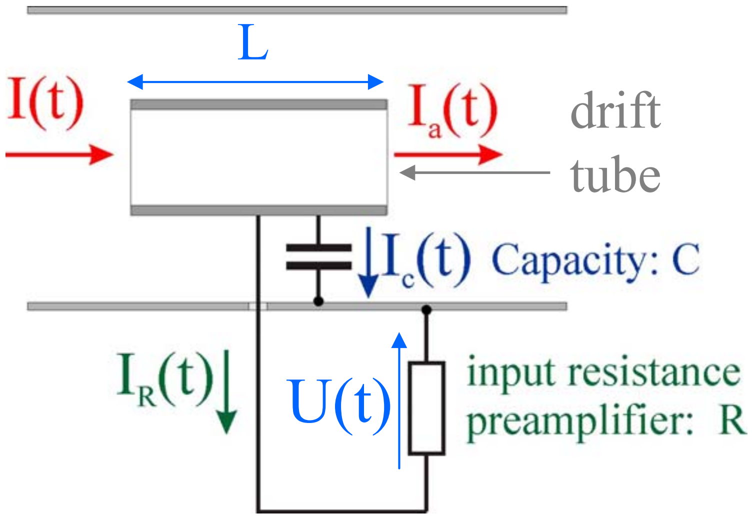
test of properties of diagnostics elements for CSR
investigation of diagnostics procedure for the CSR

DITANET workshop November 24th and 25th

Diagnostic elements of the CSR



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 $l_b >> L$: $I(t - \Delta t) = I(t) - \frac{\partial I}{\partial t}\Delta t = I(t) - \dot{I}(t)\frac{L}{v}$

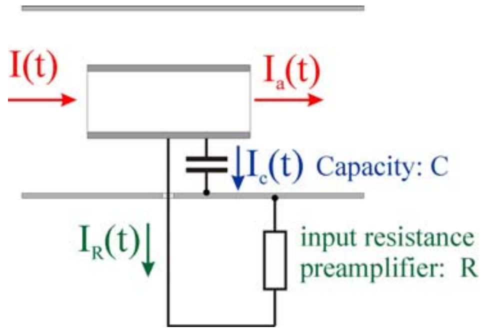
with $I_R(t) = \frac{U}{R}$ and $I_C(t) = C \cdot \dot{U}(t)$ differential equation for drift tube voltage U(t)

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

for $R \rightarrow \infty$ drift tube voltage: $U(t) = \frac{1}{C}\frac{L}{v} I(t) \quad \Rightarrow \quad U(t) \propto I(t)$

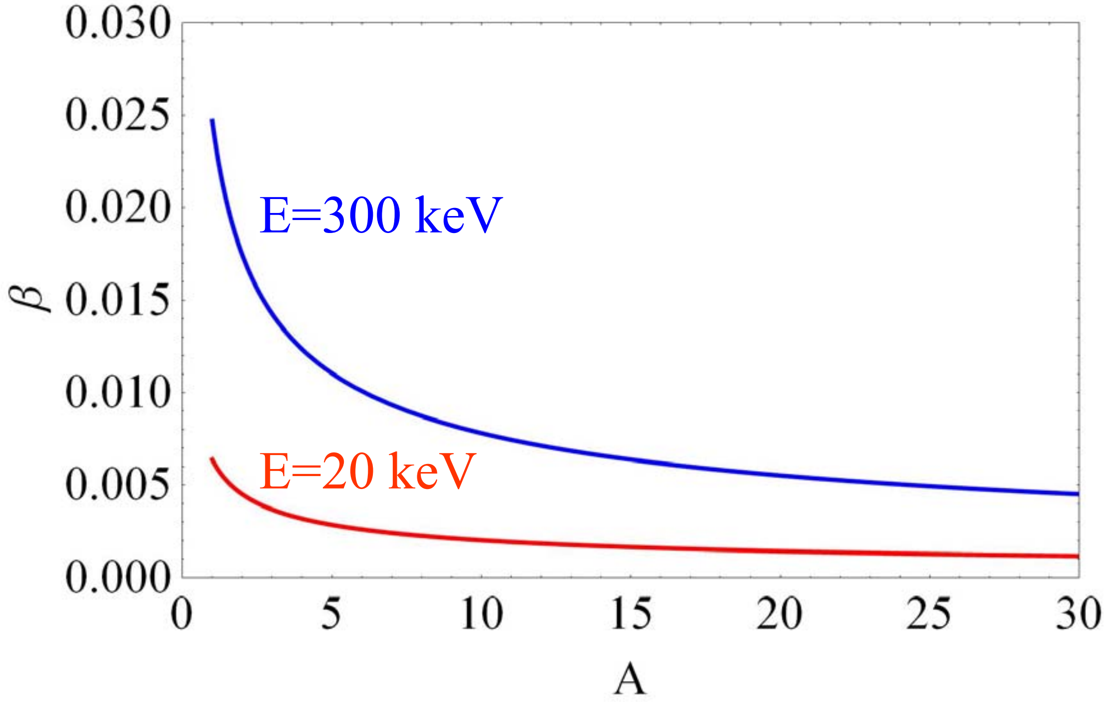
Measurement of the intensity of a bunched ion beam

relation pick up voltage U(t) and stored ion current I(t)



for $R \to \infty$ $$U(t) = \frac{1}{C}\frac{L}{v} I(t)$$ ← ion velocity

ion velocities for singly charge ions at the CSR



very sensitive for a low velocity bunched ion beam !!

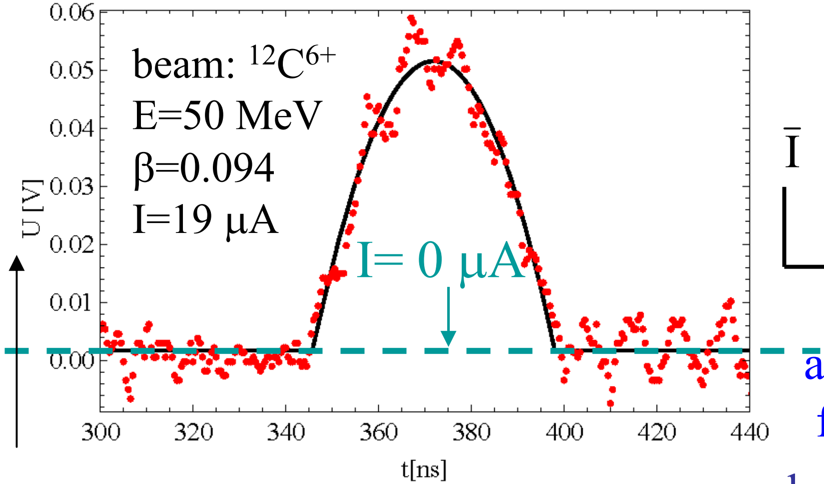
typically TSR velocity ß=0.1

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)



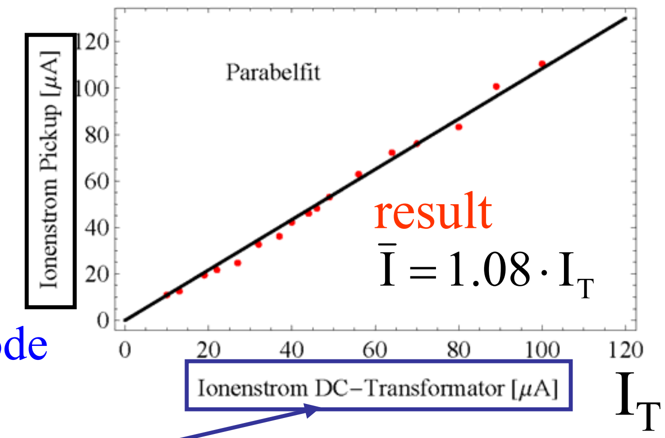
amplification: factor $V_a = 15.14$

determination of the beam current

$$\bar{I} = \frac{C \cdot v}{L \cdot V_a} \frac{\int_{-T/2}^{T/2} U(t) \cdot dt}{T}$$

amplification factor

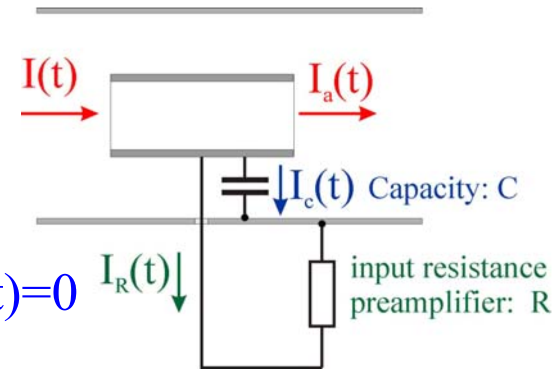
rf periode



beam current measured with beam current transformer

attention: due to $\frac{U(t)}{R}$ no DC can be measured with a pick up

differential equation of the pick up voltage: $\frac{L}{v} \dot{I}(t) = C \cdot \dot{U}(t) + \frac{U(t)}{R}$



⇒ we have to know where the region in the signal where I(t)=0

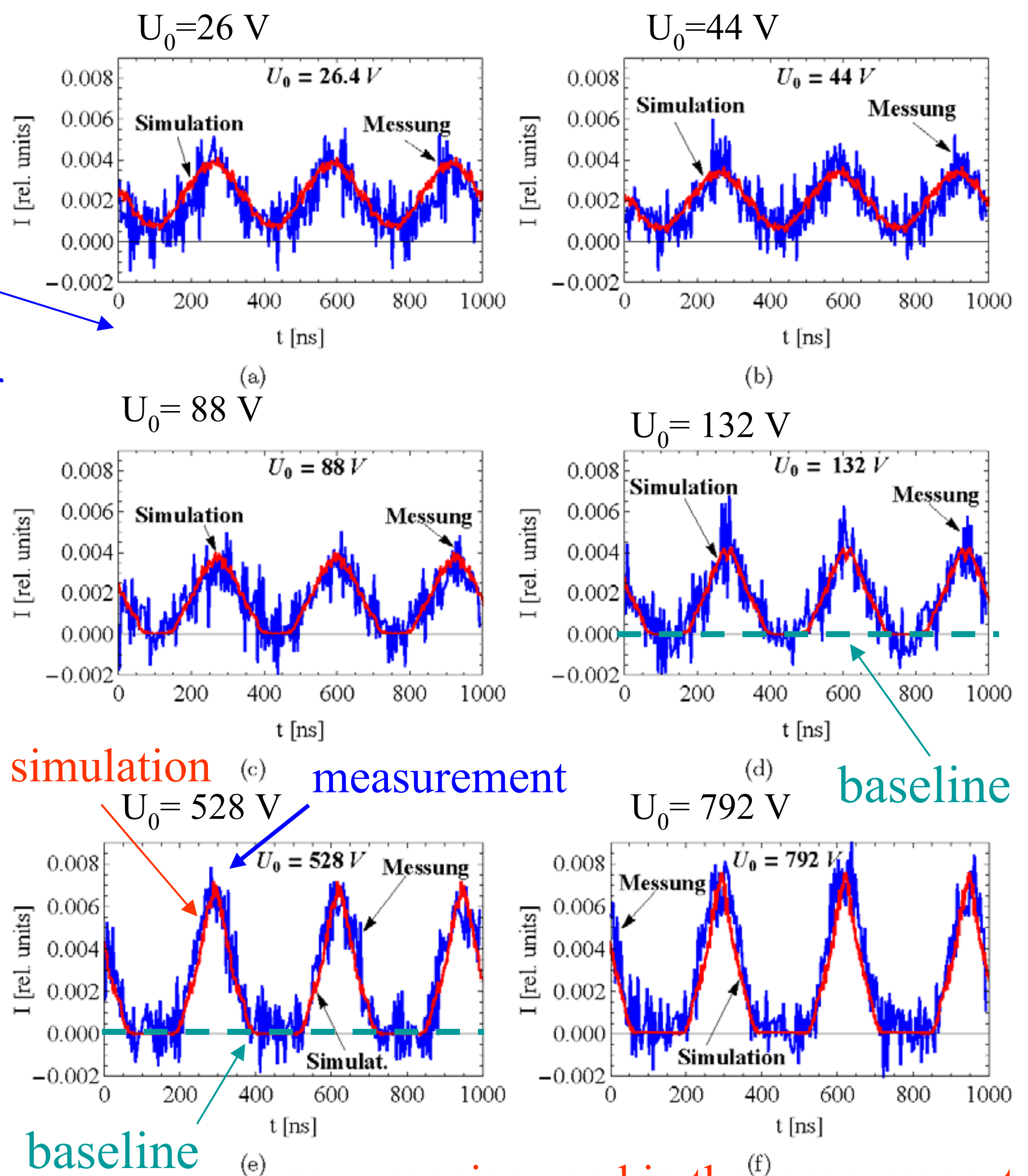
⇒ base line has to shift where I=0 !!!

Measurement of the intensity of a bunched ion beam

1. there are region with I(t)=0 ?
2. where are the region with I(t)=0 ?
   for baseline (I=0) construction

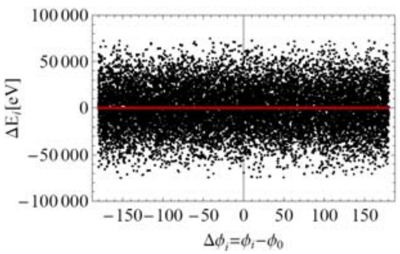
measurements and simulations for comparison were performed

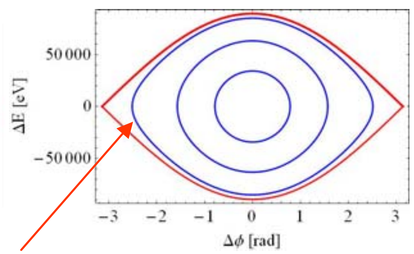
beam : $^{12}C^{6+}$ 50 MeV



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

bucket size at the final resonator voltage U_0=100V





rf bucket

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

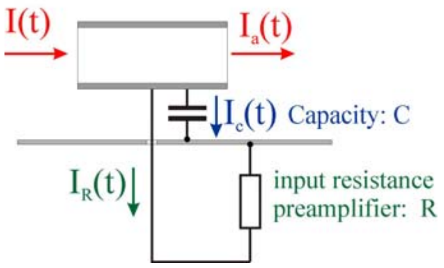
$$A_b > A_{beam}$$

A_b-rf bucket area

A_{beam}- longitudinal phase space area of the injected beam

no averaging used in the measurements

Spectrum of the pick-up signal



bunched ion current periodic function
with period T (T is rf periode)
$\Rightarrow$ pick up signal can be expressed in a Fourier row:

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

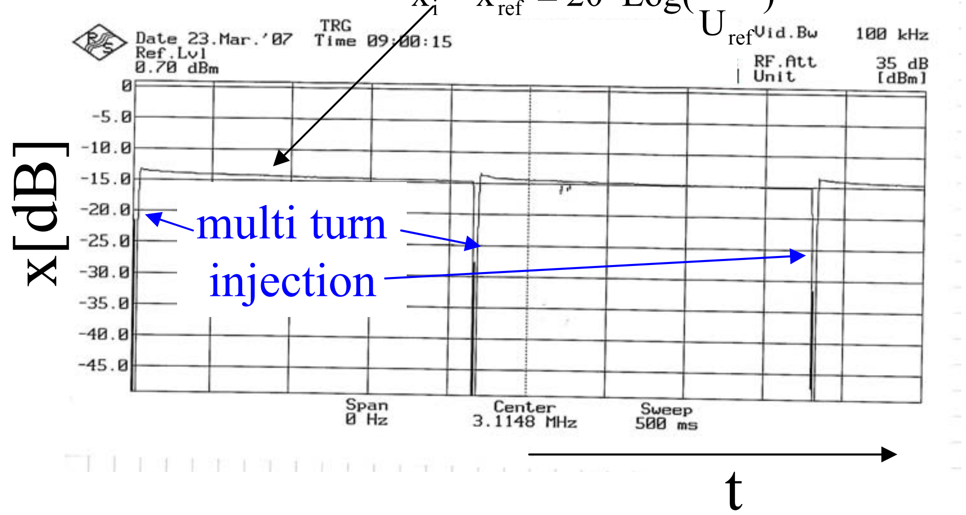
where $\hat{U}_n = \sqrt{a_n^2 + b_n^2} \propto \bar{I}$ ← stored intensity

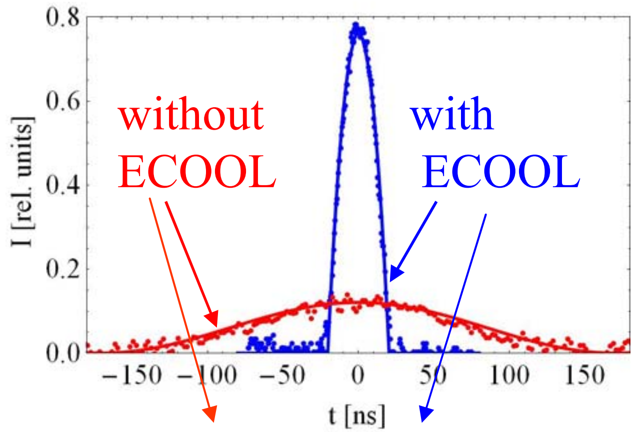
measured with a spectrum analyzer   has always its maximum value at n=1

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 !!

$$x_i - x_{ref} = 20 \cdot Log\left(\frac{\hat{U}_1}{U_{ref}}\right)$$





$\hat{U}_{1b} < \hat{U}_{1EC}$

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 $\hat{U}_1 \propto \bar{I}$

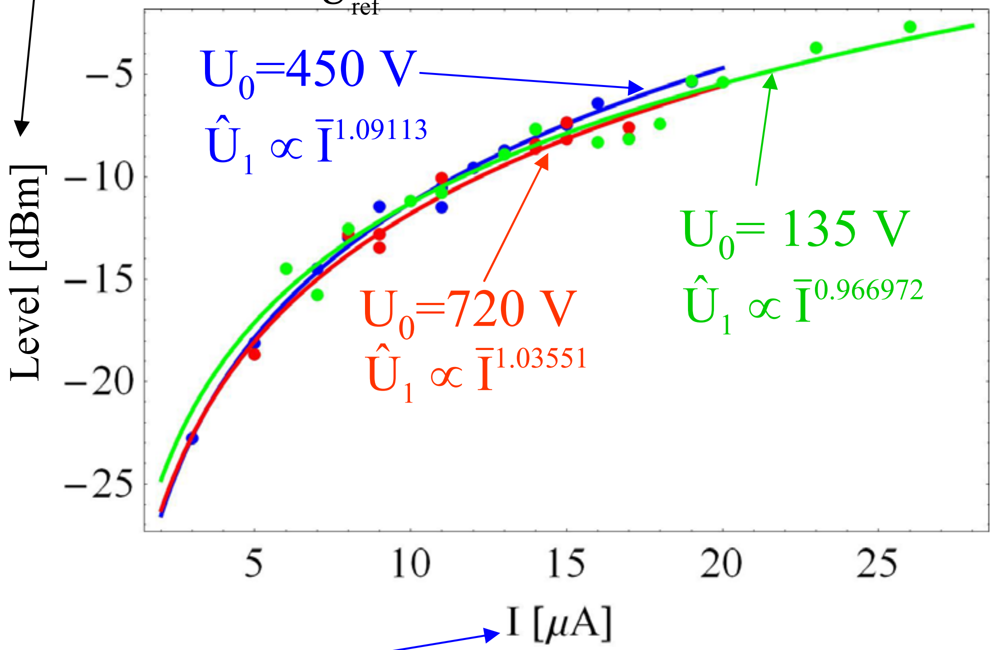
first Fourier U_1 component of the pick up signal as a function of the intensity

Measurement of an electron cooled ion beam

$^{12}C^{6+}$ E=50 MeV ion beam at $f = f_{rf} = 3.05$ MHz

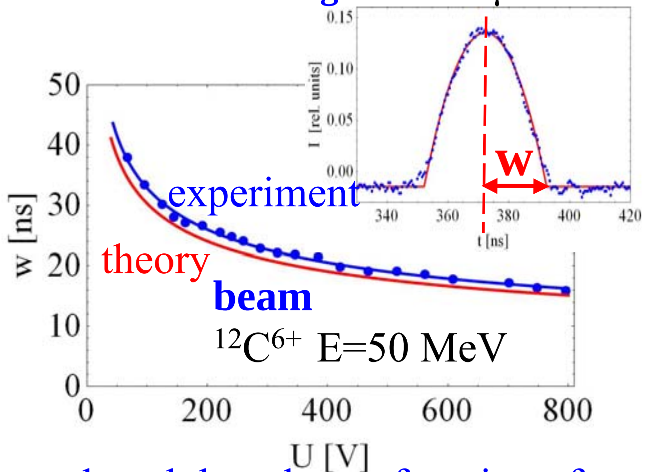
$$x_1 - x_{ref} = 20 \cdot \mathrm{Log}\left(\frac{\hat{U}_1}{U_{ref}}\right)$$

U_0-resonator voltage

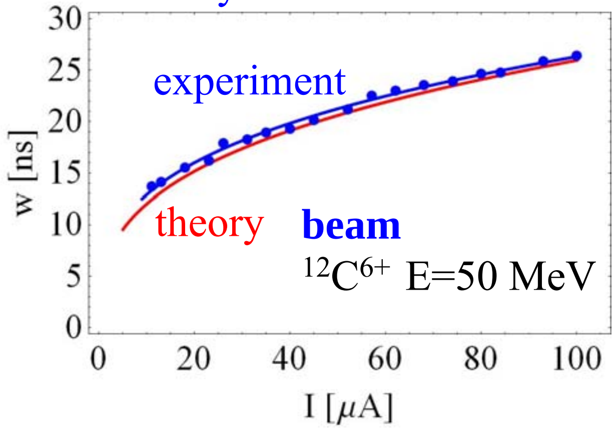


beam current measured with beam current transformer

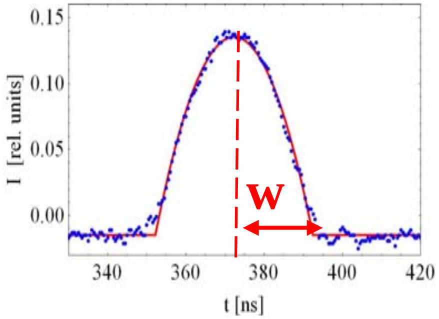
bunch length as a function of resonator voltage U I=20 μA



bunch length as a function of intensity I U=795 V



Spectrum of the pick up voltage for a electron cooled bunched ion beam



for $R \rightarrow \infty$ spectrum cooled bunched beam

$$\hat{U}_n = \frac{V_a L}{v C} \hat{I}_n \qquad \hat{I}_n = \frac{6 \bar{I} (\sin(n w \omega) - n w \omega \cos(n w \omega))}{n^3 w^3 \omega^3}$$

$w << T_{rf}$ Taylor expansion

at rf frequency n=1

$$\hat{U}_1 = \frac{V_a L}{v C}(2\bar{I} - \frac{1}{5}\bar{I}(\omega w)^2 + ...) \overset{w << T_{rf}}{=} \frac{V_a L}{v C} 2\bar{I}$$

at second harmonic n=2

$$\hat{U}_2 = \frac{V_a L}{v C}(2\bar{I} - \frac{4}{5}\bar{I}(\omega w)^2 + ...) \overset{w << T_{rf}}{=} \frac{V_a L}{v C} 2\bar{I}$$

$\hat{U}_1$ and $\hat{U}_2$ has the same intensity

if $w<<T_{rf}$

$\Rightarrow$ experimental proof that the condition $w<<T_{rf}$ is fulfilled

$$\hat{U}_1 = \frac{V_a L}{v C} 2\bar{I} \Leftrightarrow \bar{I} = \frac{v C}{V_a L} \frac{\hat{U}_1}{2}$$

example:

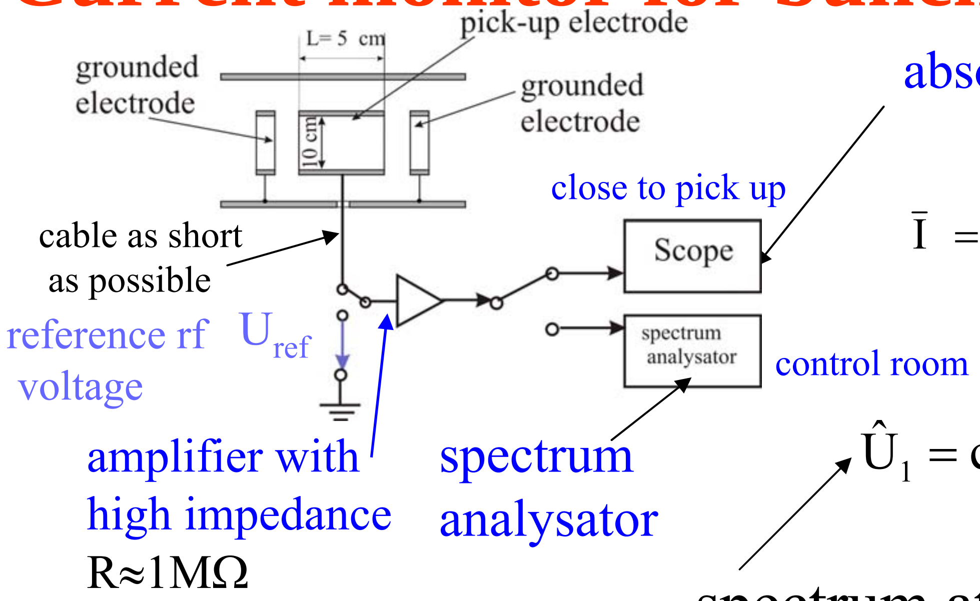
consider signal direct at the pick-up V_a=1, ß=0.01, L=5 cm, C=100 pF

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

easily to measure with a spectrum analyzer

current sensitivity $\bar{I} < 10\,nA$ if the bunched ion beam is cooled

Current monitor for bunched ion beams at the CSR



absolute intensity measurement

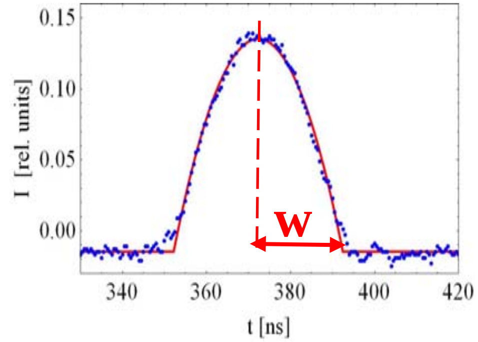
$$\bar{I} = \frac{C \cdot v}{L \cdot V_a} \frac{\int_{-T/2}^{T/2} U(t) \cdot dt}{T}$$

$$\hat{U}_1 = \text{const} \cdot \bar{I}$$

average ion current

spectrum at rf frequency

electron cooled ion bunch



uncooled bunched ion beam

const: depends on the amplitude of the rf used for bunching $\hat{U}_1 \approx \frac{V_a L}{v C} \bar{I}$ if $A_b > A_{beam}$

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 !

A_b- rf bucket area

A_{beam}- longitudinal phase space area of the injected beam

for $w \ll T$ $\hat{U}_1 = \frac{V_a L}{v C} 2 \cdot \bar{I}$

rf periode

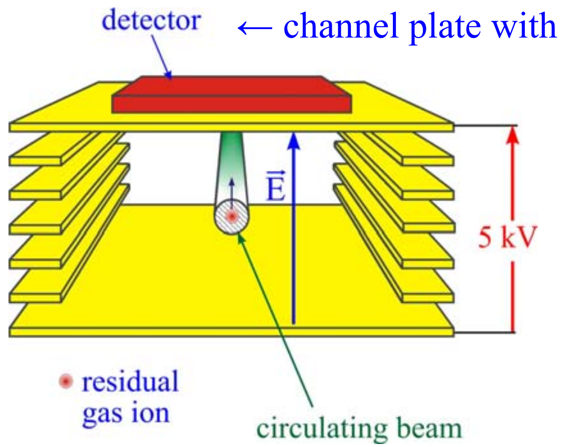
V_a-amplification factor of the amplifier

C- capacity of the pick-up with cable to amplifier

v- ion velocity

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

Residual gas beam profile monitor



counting rate

$$R = \eta \cdot \sigma \cdot n \cdot v \cdot N$$

$$\eta = \frac{l_D}{C_0}$$

l_D ← detector length

C_0 ← Circumference of the storage ring

σ- cross section for ionization

n- residual gas density

v- ion velocity

N- particle number

example TSR

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

$n \approx 10^6 \ 1/cm^3$

$I = 1 \mu A$

$R \approx 200$ 1/s

CSR: $n < 10^4 \ 1/cm^3$

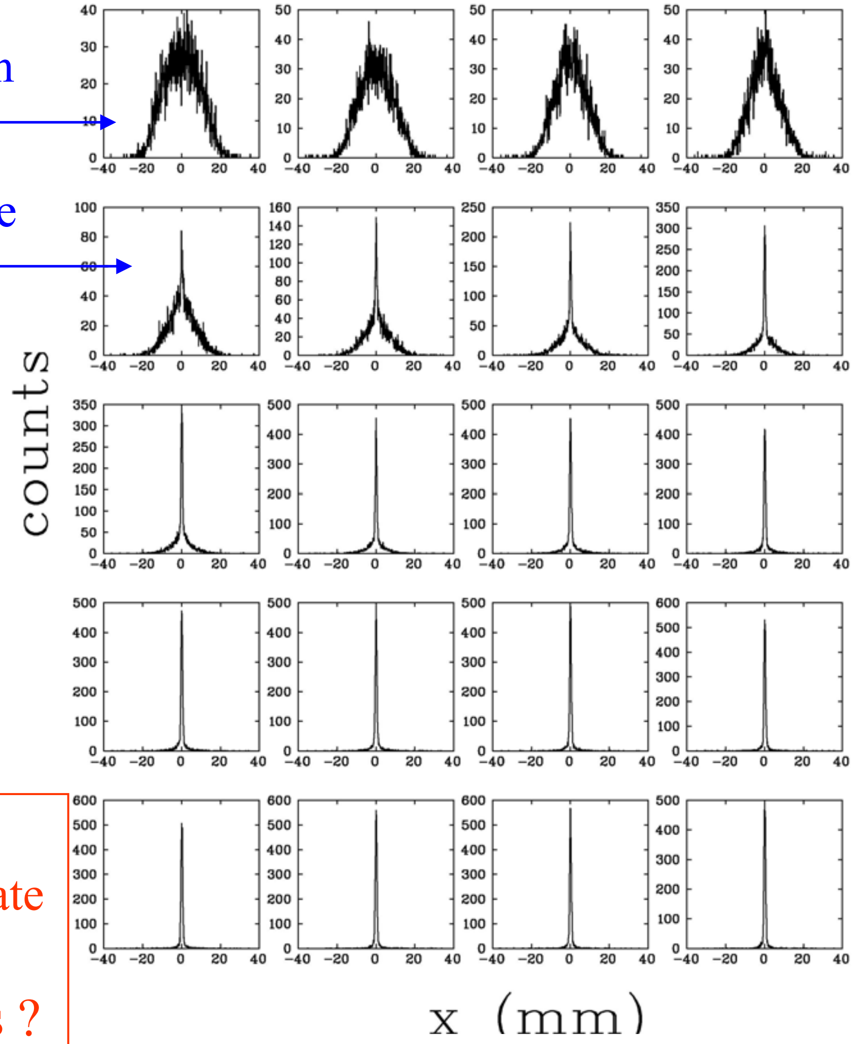
⇒almost no counting rate

other possibilities for profile measurements ?

measured beam profile for $^{12}C^{6+}$ E=73 MeV ions during electron cooling

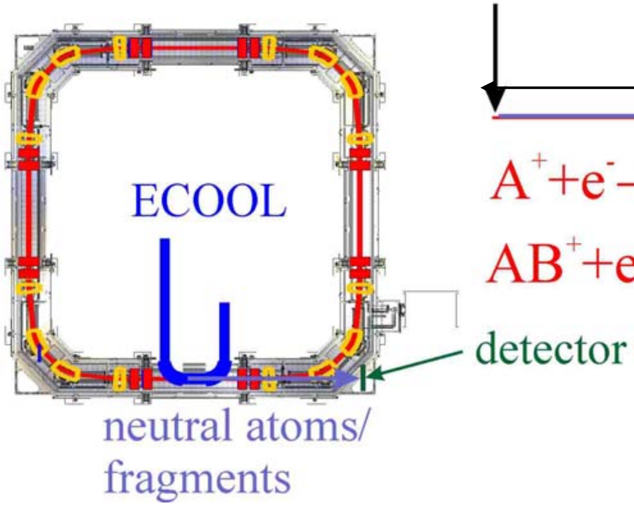
after multiturn injection →

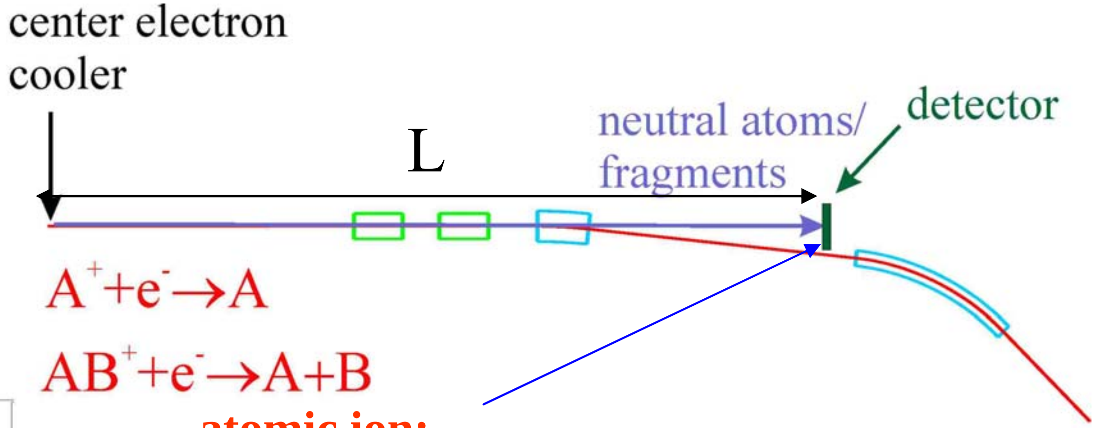
measuring time per frame: → Δt=100 ms



total measuring time: 2s

Beam profile measurements for singly charged ions and molecules





$A^{+}+e^{-}\rightarrow A$

$AB^{+}+e^{-}\rightarrow A+B$

atomic ion:
measurement of the neutral particle position

molecular ion:
center of mass coordinate of the fragments are measured

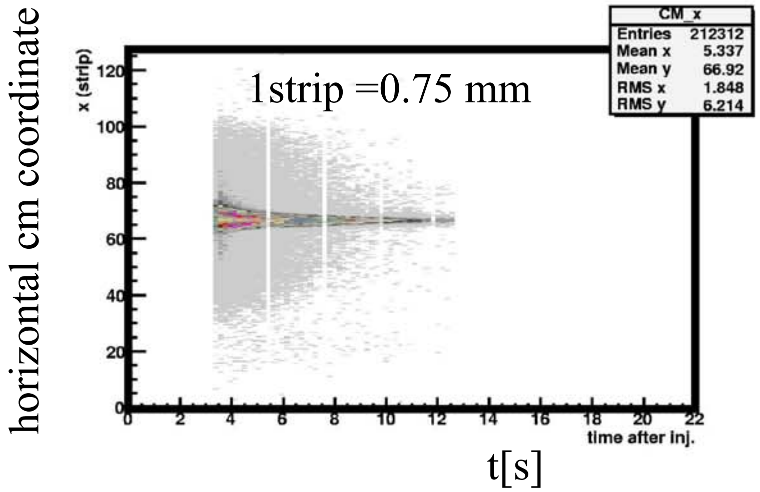
relation between ion beam size at the cooler σ_E and at the detector position σ_D

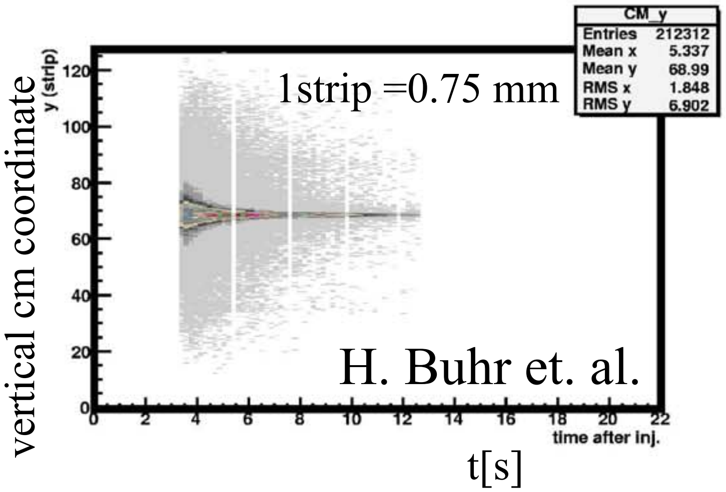
$$\sigma_D = \sigma_E\sqrt{1+\frac{L^2}{\beta^2}}$$

L^2 ← distance between cooler and detector

β^2 ← ß function at the cooler position

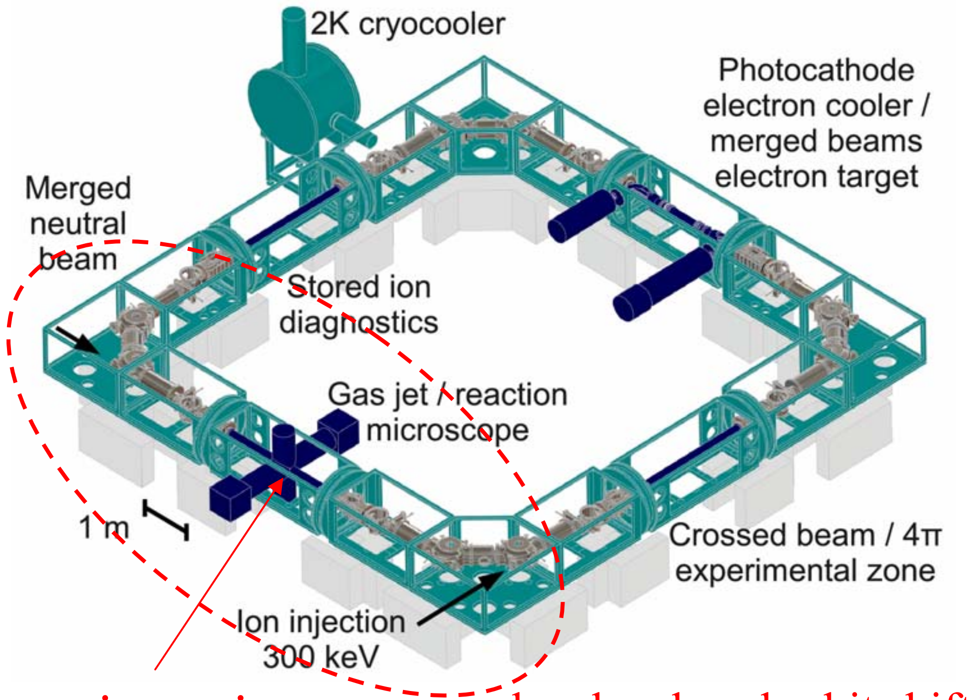
TSR measurements with 3 MeV COD⁺ molecules





Beam-profile measurement using the reaction microscope

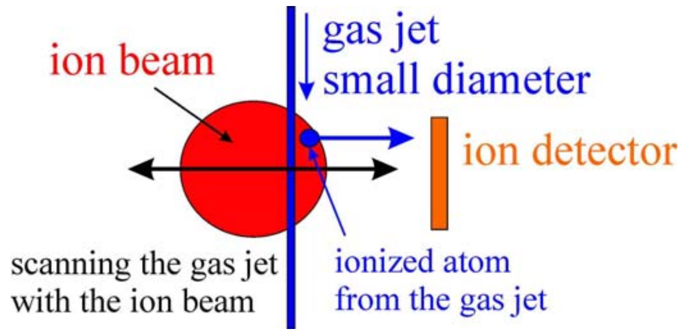
heavy ion are used in experiments using a reaction microscope



reaction microscope

locale closed orbit shift
for scanning the gas jet

principle



measuring counting rate as a function of beam-position

remark:

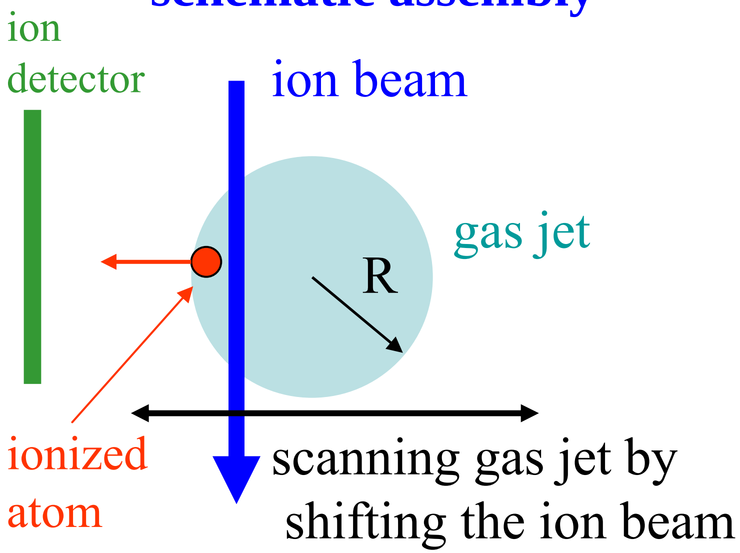
the CSR is ramp able:
each element is controlled by a function generator
time dependent periodic scans are easily possible

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



neon gas jet

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

$$\frac{1}{T_g} = \frac{1}{T_t} + \frac{1}{T_0}$$

Schlachter

$$\frac{1}{T_t} = n_t \cdot \sigma \cdot f_0$$

$$n_t = \int n \cdot ds = 1.3 \cdot 10^9 \;\; 1/cm^2$$

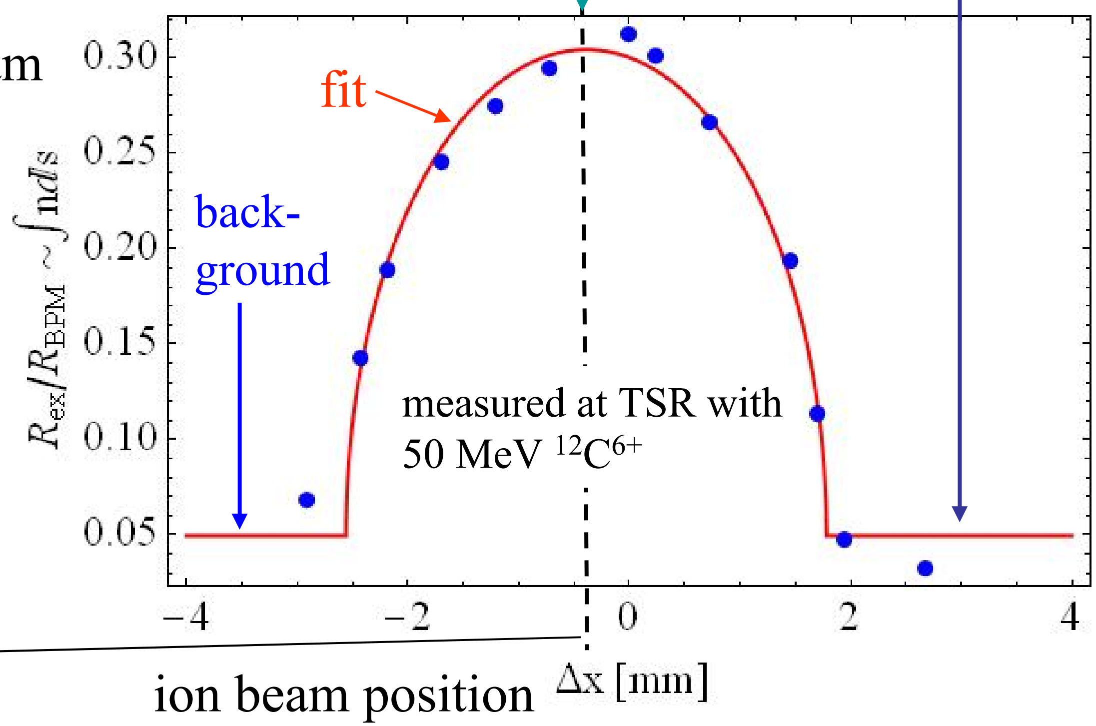
R_{ex}- counting rate ion detector reaction microscope

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

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

lifetime measurement Tg

lifetime measurement outside the gas jet: T_0

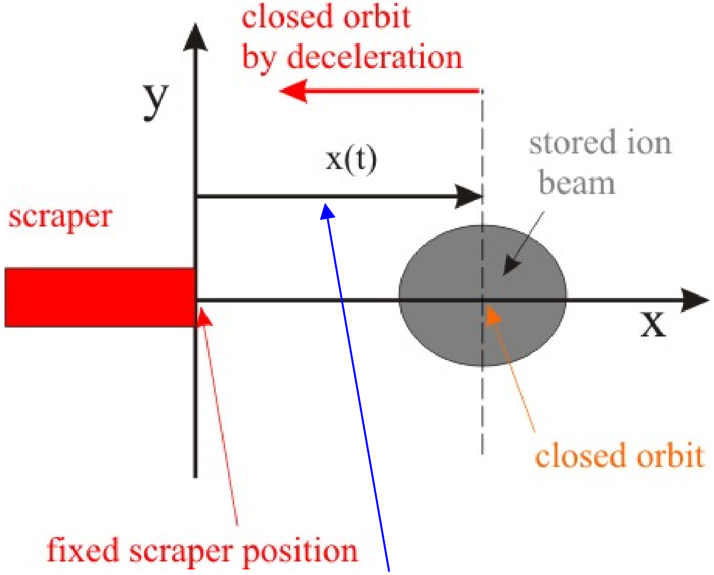


Measurement of the beam profile with a scraper

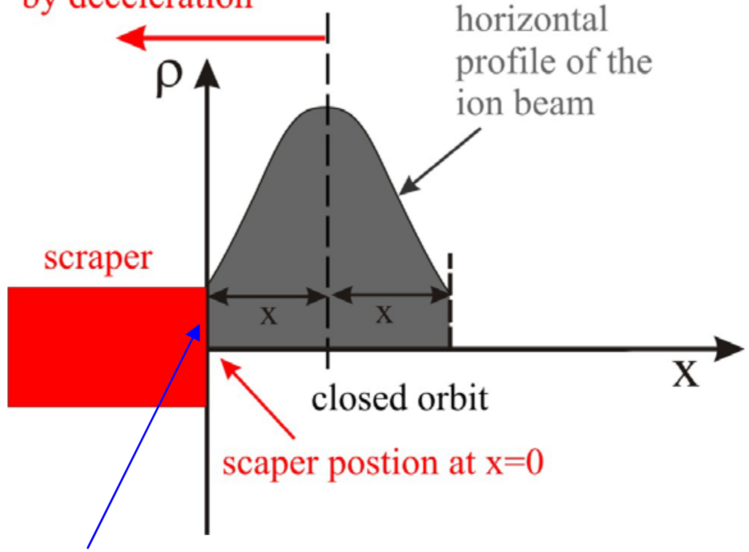
measurement are done by deceleration the stored ion beam to the scraper position

$$x(t) = a_0 + D_x \frac{\alpha}{f \cdot \eta} \cdot t$$

α change of the rf frequency $\alpha = \frac{\Delta f}{\Delta t}$



distance to the scraper is decreased



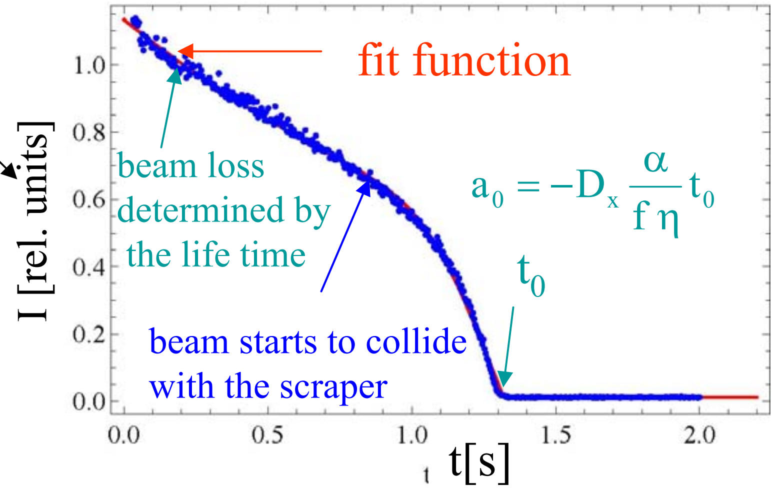
intensity decrease due to ion collisions with the scraper

Beam width is determined from the intensity decrease

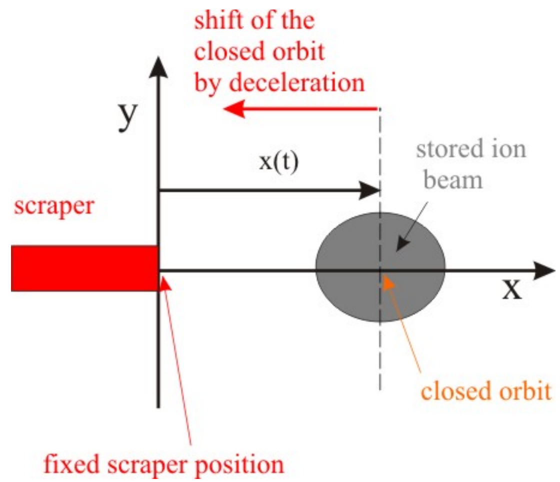
Measurement of the position and beam profile position

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 >>frequency shift



number of stored ion as a function of time



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

fit function

$$N(t) = \begin{cases} N_0 e^{-\frac{t}{\tau}} \mathrm{Erf}\left(\frac{a_0 + D_x \frac{\alpha}{f\eta} t}{\sqrt{2}\,\sigma}\right) + N_{off} & \text{for } a_0 + D_x \frac{\alpha}{f\eta} t \geq 0 \\ N_{off} & \text{for } a_0 + D_x \frac{\alpha}{f\eta} t < 0 \end{cases}$$

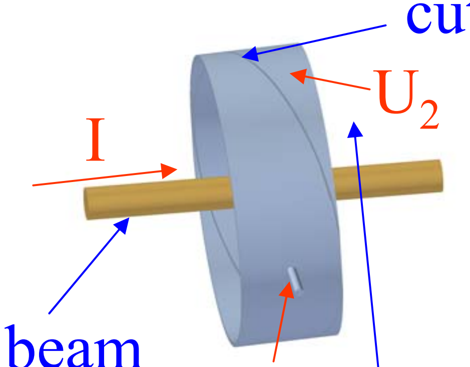
$$\mathrm{Erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt$$

from the fit
beam size: σ
beam position: a_0

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

Beam position monitor of the CSR

beam position monitor
pick up cutting into two parts:



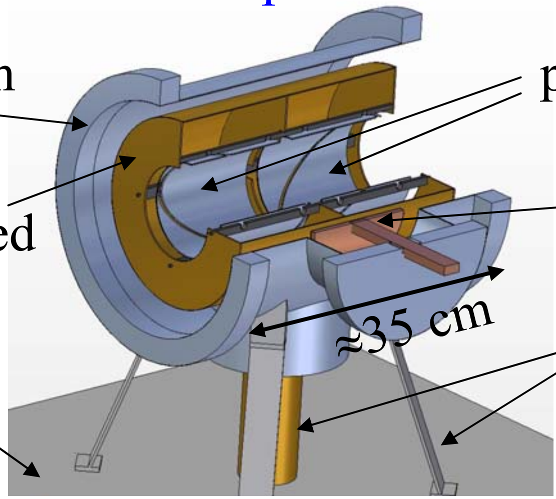
influenced voltage between plate and chamber

position

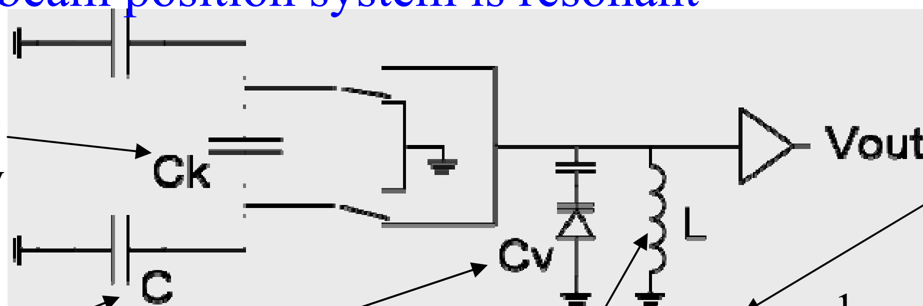
$$x = S_{cal} \frac{U_2 - U_1}{U_1 + U_2}$$

scaling factor of the pick-up

preliminary mechanical design
of the CSR beam position monitor



to improve the sensitivity of the beam position monitoring beam position system is resonant



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

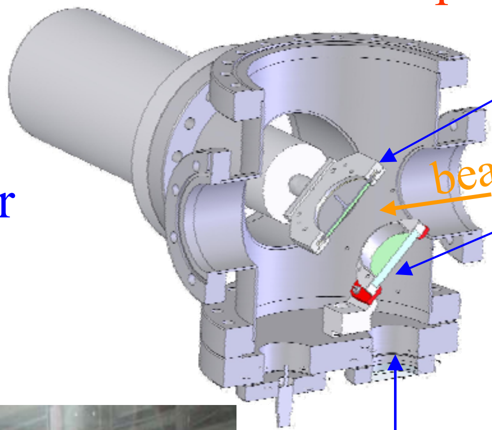
details: talk of Felix Laux

First turn diagnose at the CSR

beam viewer at CSR prototype

Scintillators not sensitive enough for 20 keV, nA beams

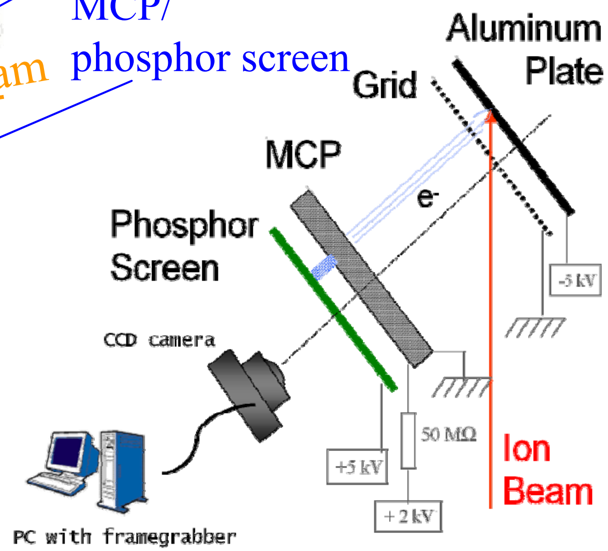
⇒ “Beam Profiler” developed for REX ISOLDE: 10^2 pps – mA

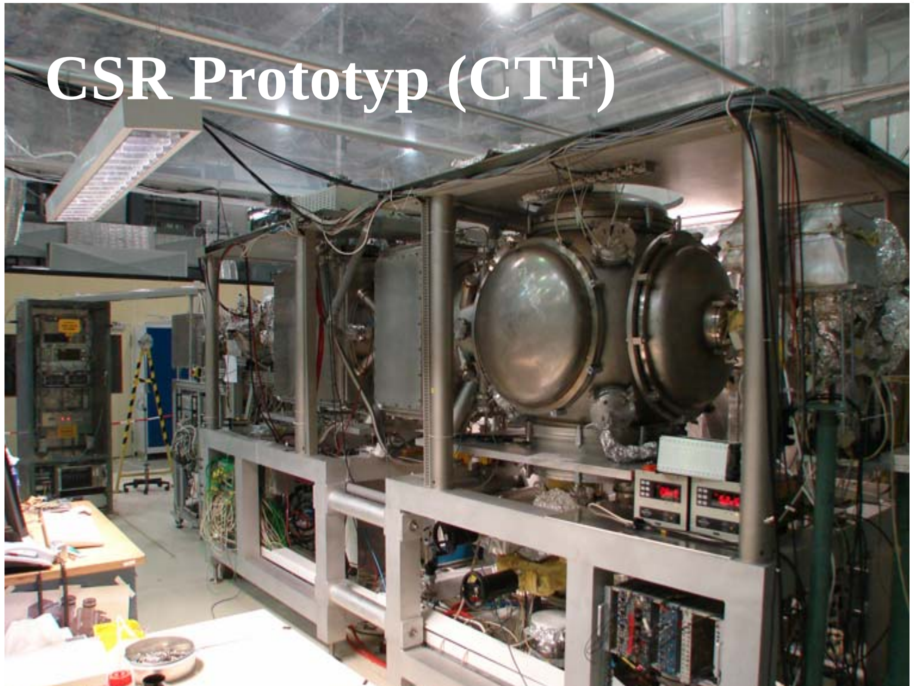


moveable aluminum plate

MCP/ phosphor screen

camera





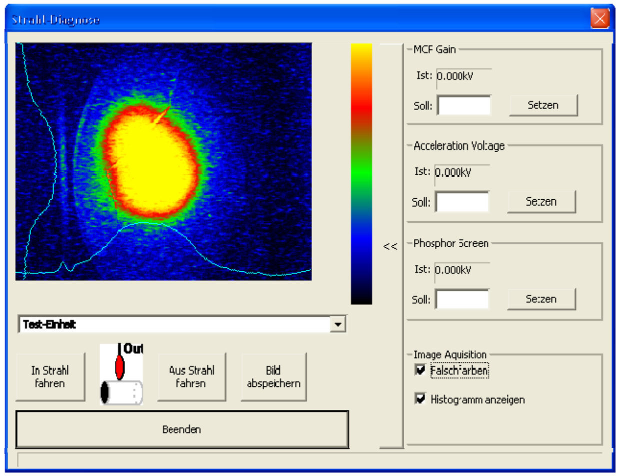
two of these beam viewer are used in front and behind the CTF

example

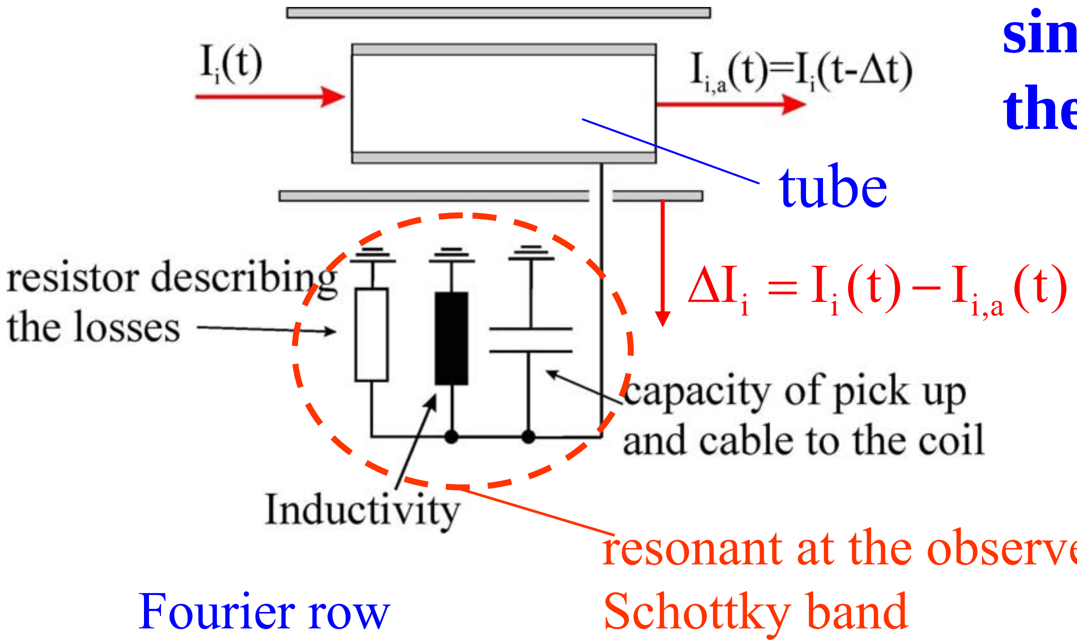
10 pA He^+

10 keV,

∅ 15 mm



The Schottky pick up of the CSR



single ion interaction with the Schottky pick up

flying time through the 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

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

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

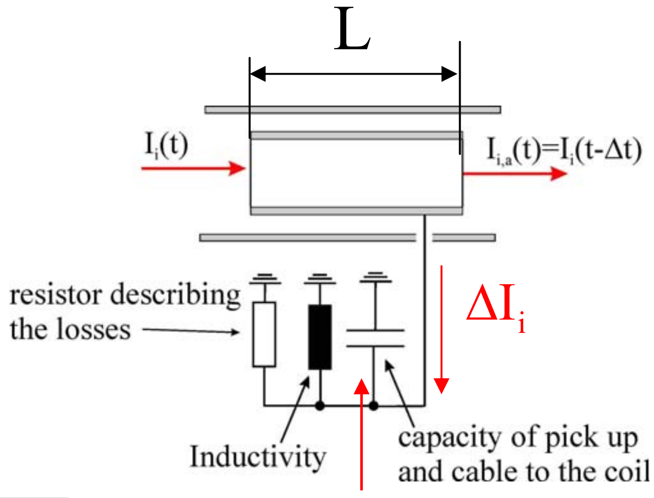
current into LC circuit $\Delta I_i(t) = I_i(t) - I_{i,a}(t)$ with $\omega_n = n\,\omega_0$

$$\Delta I_i(t) = Q\frac{2}{T}\sum_{n=1}^{\infty}\Big(\big(1-\cos(\omega_n\,\Delta t)\big)\cos(\omega_n t) + \sin(\omega_n\,\Delta t)\sin(\omega_n t)\Big)$$

Spectrum of the Schottky signal coming from a single ion

$$\Delta t = \frac{L}{v}$$

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



resonant at f_n

$$f_n = n f_0$$

$\Rightarrow$ spectrum of ΔI_i $\quad \omega_n = n\,\omega_0$

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

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

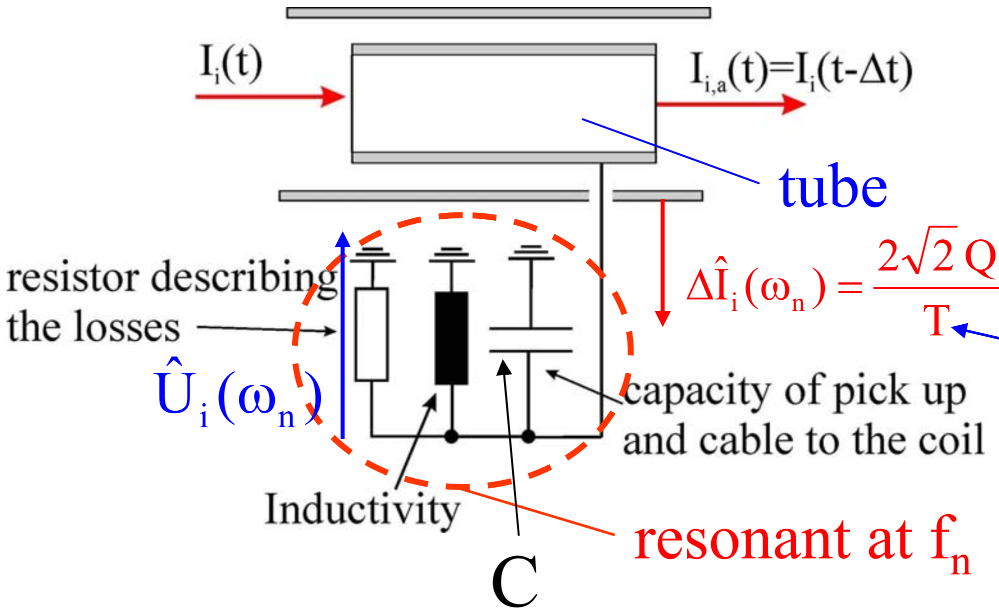
$\Delta\hat{I}_i(\omega_n)$ is 0 at $\quad \omega_n \Delta t = m \cdot \pi \quad \Delta t = \frac{L}{v}$

$$\omega_n = 2\pi n f_0$$

f_0: revolution frequency of the ion

n: integer number

Spectrum of the Schottky signal coming from a single ion



$$\Delta\hat{I}_i(\omega_n) = \frac{2\sqrt{2}\,Q}{T}\sqrt{1-\cos(\omega_n \Delta t)}$$

ion charge

T revolution time

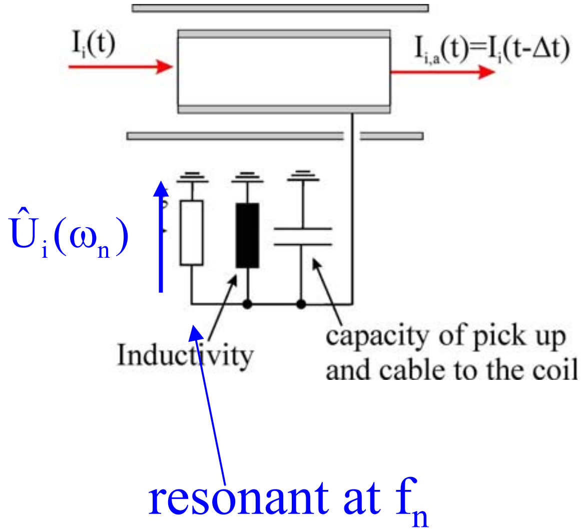
Q value of the LC circuit

signal on LC circuit from a single ion : $\hat{U}_i(\omega_n) = \frac{Q_w}{\omega_n C}\frac{2\sqrt{2}\,Q}{T}\sqrt{1-\cos(\omega_n \frac{L}{v})}$

$\Rightarrow$ 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

$$\hat{U}_i(\omega_n) = \frac{\sqrt{2}}{\pi}\frac{Q_w}{n}\frac{Q}{C}\sqrt{1-\cos(\omega_n \frac{L}{v})}$$

$$n = \frac{f_n}{f_o}$$

f_n ← observation frequency

$f_n = n \cdot f_0$ ← revolution frequency (f_o)

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

$$n = \frac{f_n}{f_0} = \frac{(1+2\cdot m)}{2} \cdot \frac{C_0}{L}$$

C_0 ← circumference of the storage ring

L ← pick-up length

m=0,1,2,3,……

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

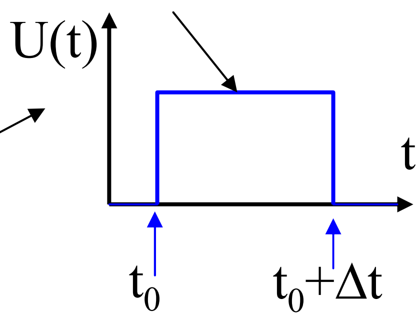
Some thoughts about the pick-up length L

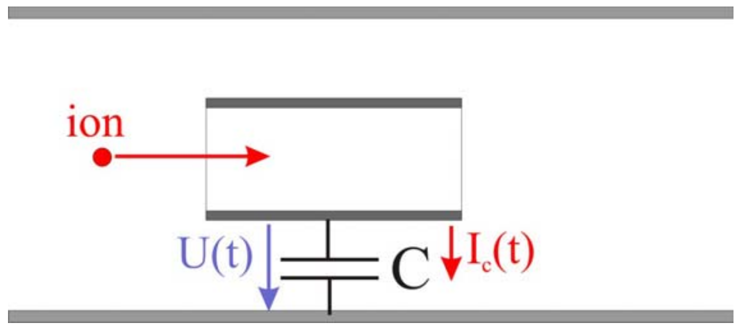
consider pick-up with capacity C
one single ion will produce a voltage during one passage

in our simple model

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

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





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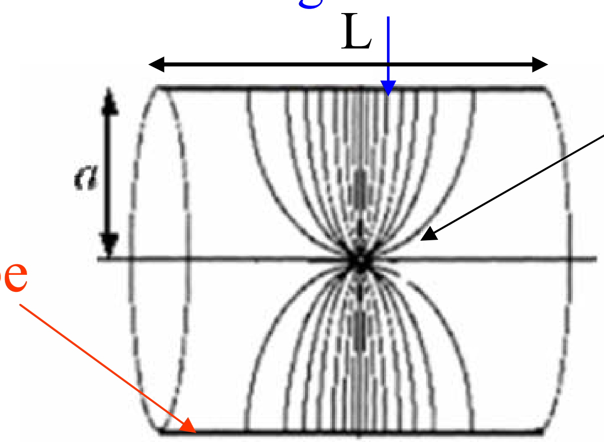
induced charge distribution Λ(s)



ion with charge Q

tube

If $L >> \sigma_{rms}$

Electrical field lines from a point charge

σ_{rms} -RMS value of Λ(s)

$$\sigma_{rms} = \frac{a}{\gamma\sqrt{2}}$$

radius of the tube
γ -relativistic γ
CSR: γ=1

induced charge on the outside of the cylinder

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

voltage rise time: $t_{rise} \approx \frac{\sigma_{rms}}{v}$ ion velocity

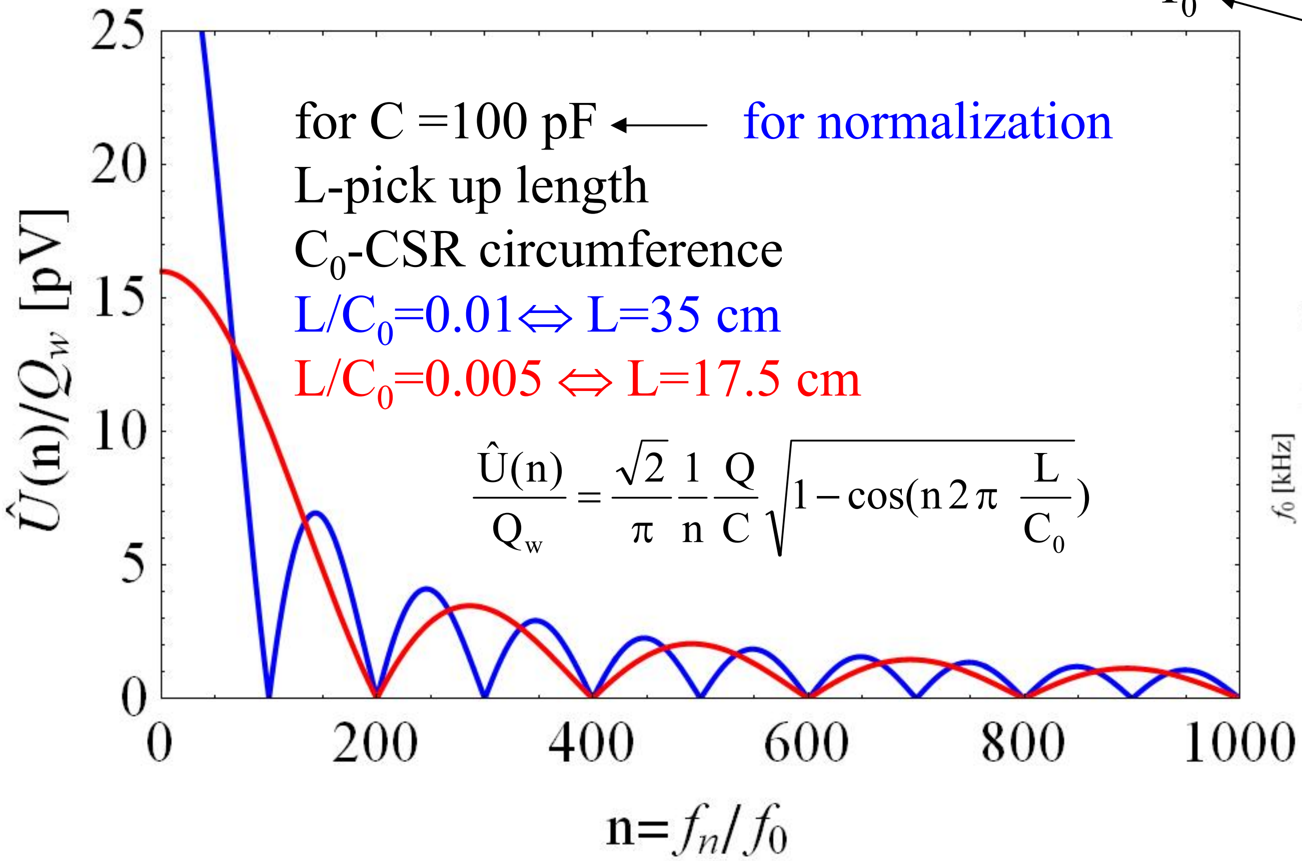
CSR: a=5 cm $L \ge 6\cdot\sigma_{rms} \approx$ 20 cm better L≈35 cm ⇔ $L/C_0 = 0.01$

Schottky signal from a single ion at different n

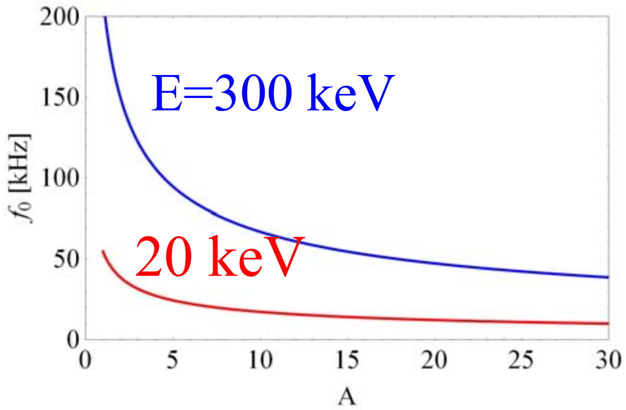
pick up signal of a single ion as a function of $n = \frac{f_n}{f_0}$

f_n ← observation frequency

f_0 ← revolution frequency



f_0 single charge ions

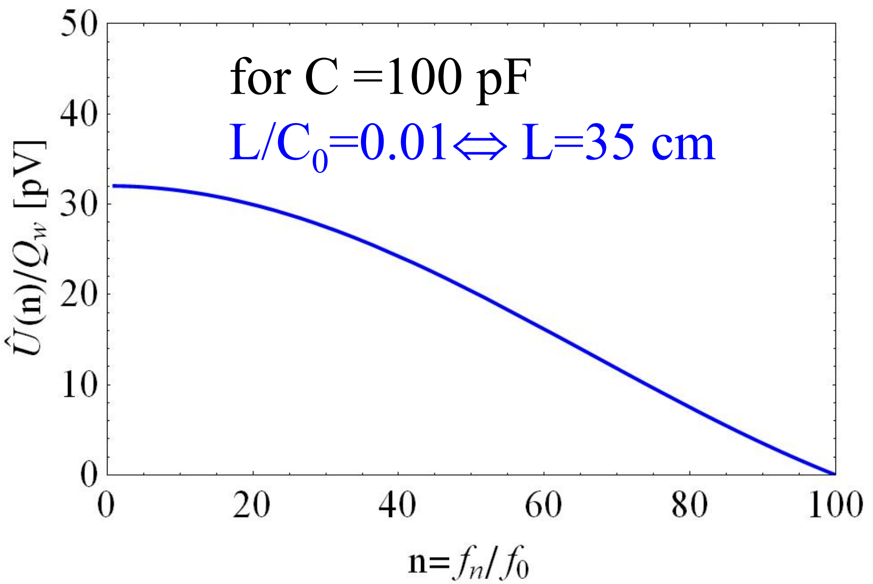


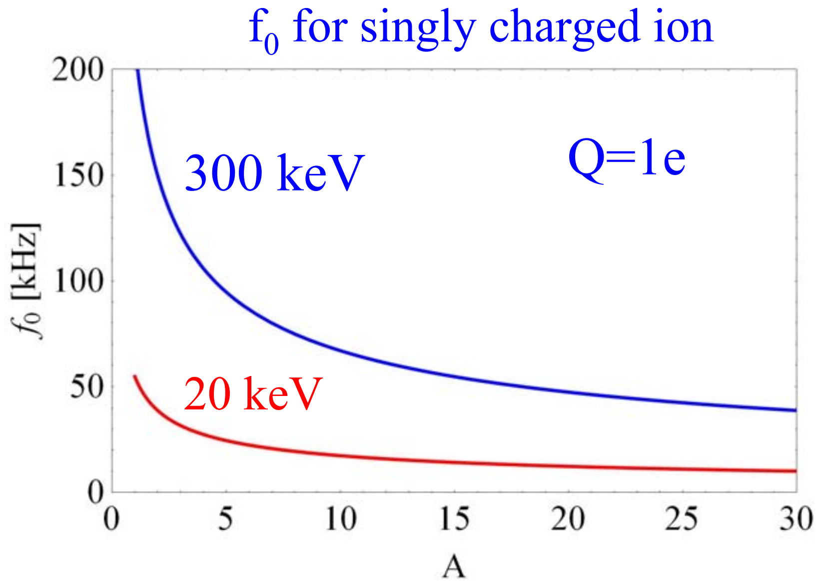
The resonance frequency of the LC circuit $f_{res}= f_n$ should be variable in a certain range to avoid zero signals in the voltage spectrum

Schottky signal from a single 300 keV proton

protons with 300 keV are the fastest ⇒ low n for observation can be chosen

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





remark:
In the frequency range: 0.2-4 MHz pick up is a pure capacity, as assumed in the calculation, because: L<<λ

for n=1 to n=20 $\hat{U}(n)/Q_w \approx 30\,\text{pV}$

⇒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≈4K

⇒ $\hat{U} \approx 30\,\text{nV}$

Tune measurements at the CSR

at low energies there is a large incoherent tune shift

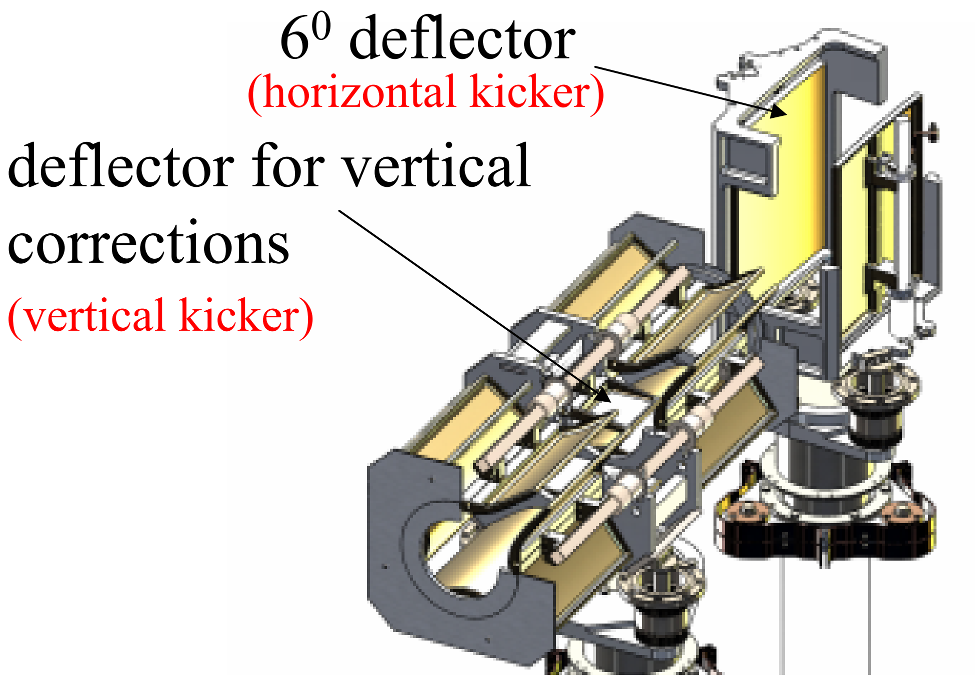
$$\Delta Q = -\frac{q^2}{A}\frac{r_p N}{2\pi B \beta^2 \gamma^3 \varepsilon}$$

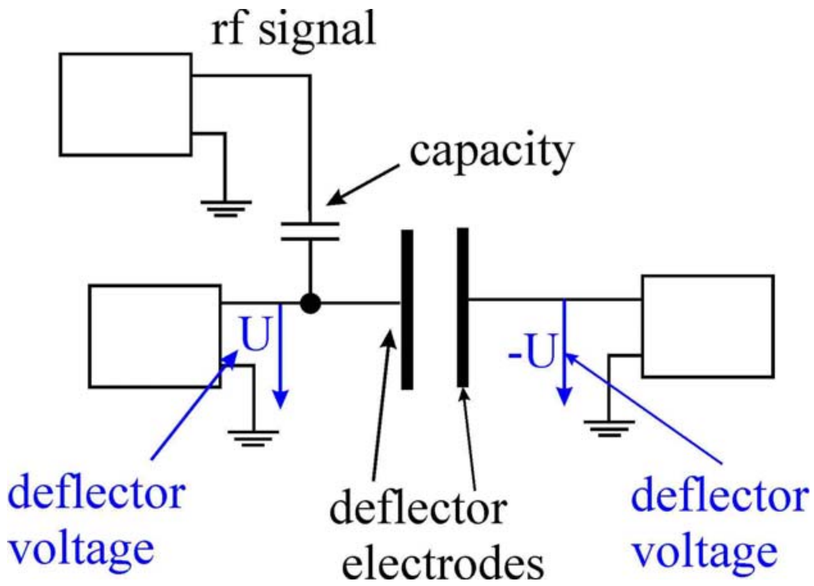
N- number of ions
ß- velocity in units of c
ε -emittance

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 6^0 deflector 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 $f = f_0(n \pm q)$ q- non integer part of the tune





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