The Cryogenic Storage Ring CSR

electrostatic storage ring with
circumference≈35 m
first beam stored: March 2014
cryogenic operation: since April 2015
first electron cooled ion beam: June 2017

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744. Wilhelm and Else Heraeus seminar

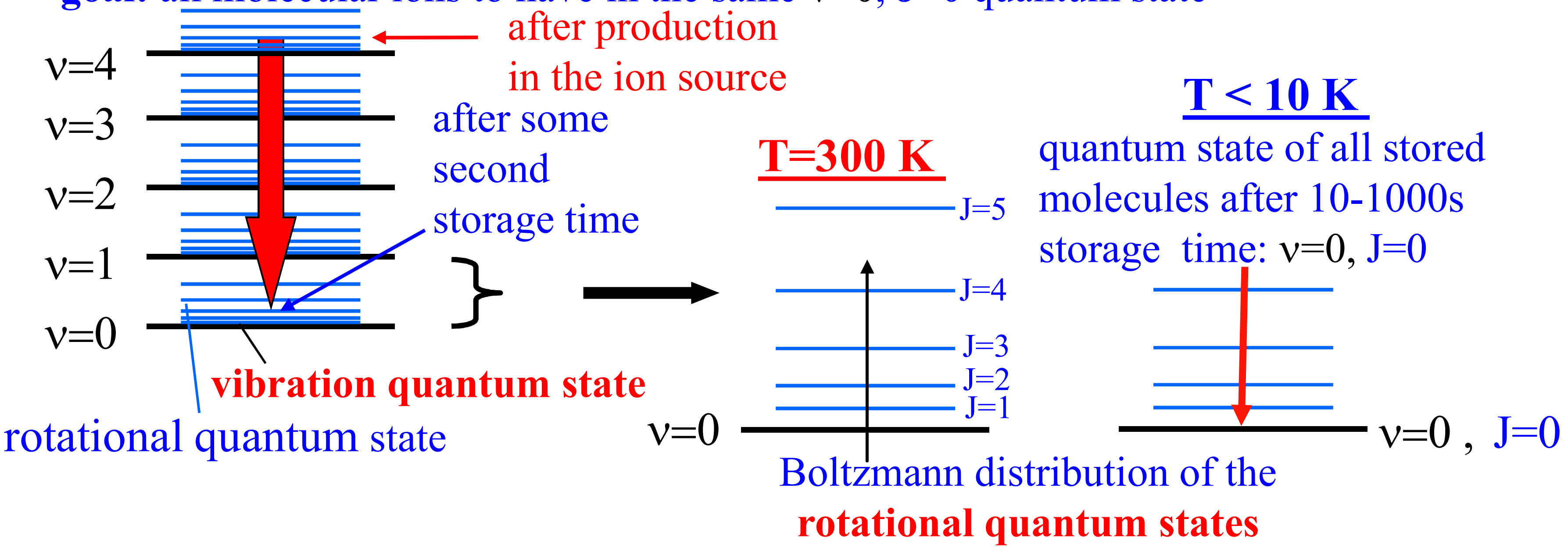
Towards Storage Ring Electric Dipole Moment Measurements

29th-31th March 2021

Purpose of the CSR

main research field: <u>molecular ion physics</u>

goal: all molecular ions to have in the same **ν=0**, **J=0** quantum state



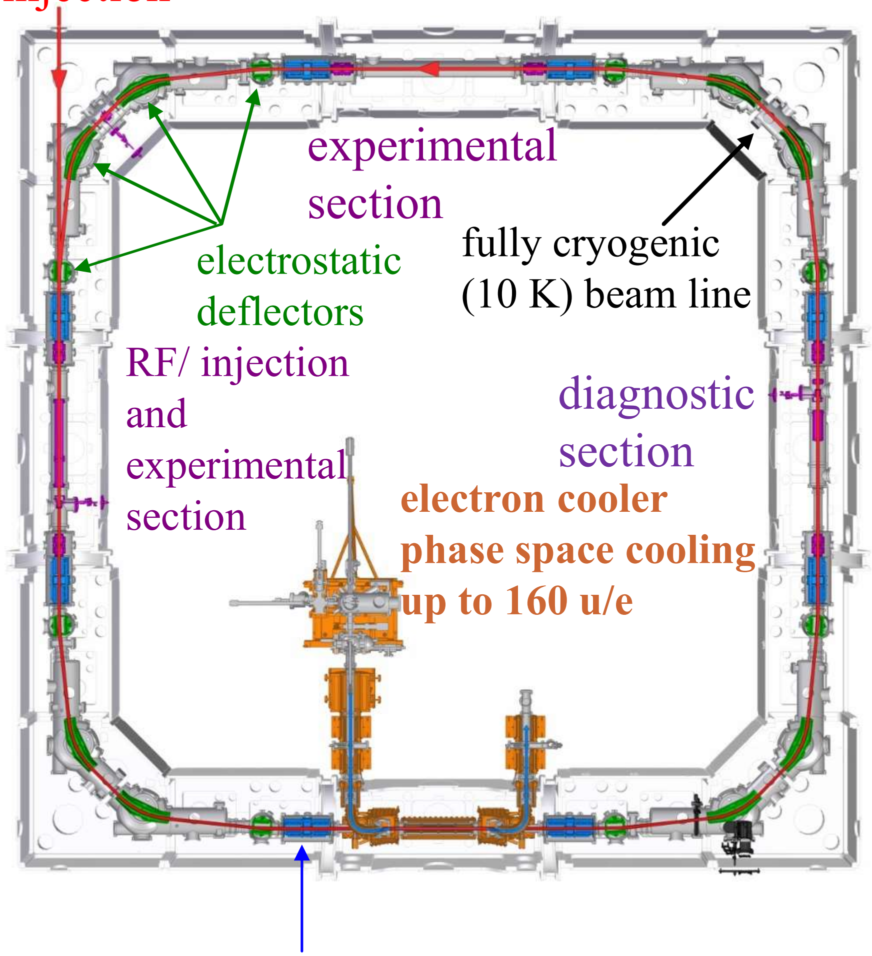
quantum state of all stored molecules after 10-1000s storage time: ν=0, J=0

Boltzmann distribution of the **rotational quantum states**

to get all molecular ions in the same molecular quantum state (ν=0, J=0) the molecular ions have to be stored at **T<10 K**

⇒ a new **C**ryogenic **S**torage **R**ing (**CSR**) at MPIK Heidelberg
in opposite to other storage rings it is an **electrostatic storage ring**

Overview of the CSR



injection

experimental section

electrostatic deflectors

fully cryogenic (10 K) beam line

RF/ injection and experimental section

diagnostic section

electron cooler phase space cooling up to 160 u/e

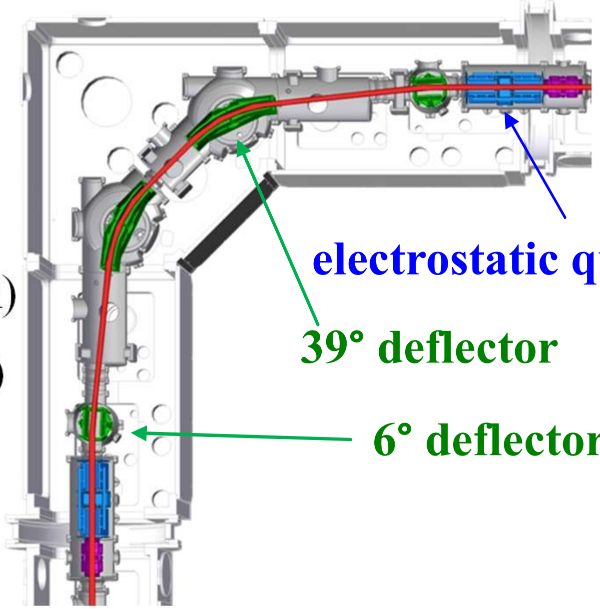
electrostatic quadrupole duplet

circumference: 35.12 m
beam energy: (20-300)·q keV
temperature: 10-300 K
residual gas densities:
(at $\overline{T} \approx 10$ K): <100 molecules/cm^3

with electron cooling
m/q range: 1 -160
(at E/Q=300 kV)
lowest rigidity: p^+, H^- at E/Q= 20 kV
$B\rho$=0.02 Tm

Electrostatic beam optics Elements

- 4-fold symmetric storage ring
  all CSR corner sections identical
- 8 pairs of **quadrupoles** (±10 kV, ∅ =100mm)
- 8 **6°- electrostatic deflector** (±30 kV, g=120mm)
- 8 **39°-electrostatic deflector** (±30 kV, g=60mm)
- 8 vertical electrostatic deflectors

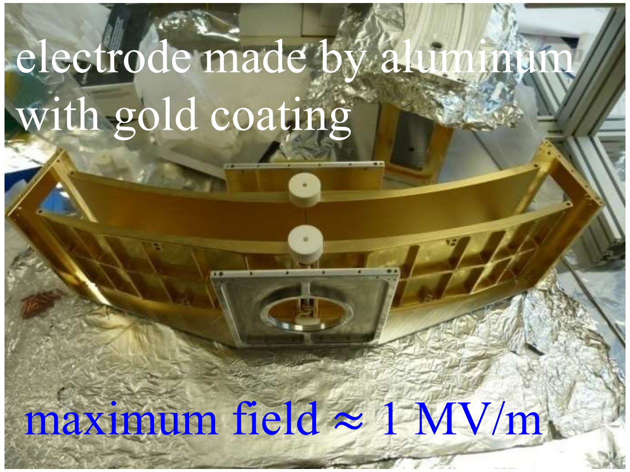


electrostatic quadrupoles

39° deflector

6° deflector

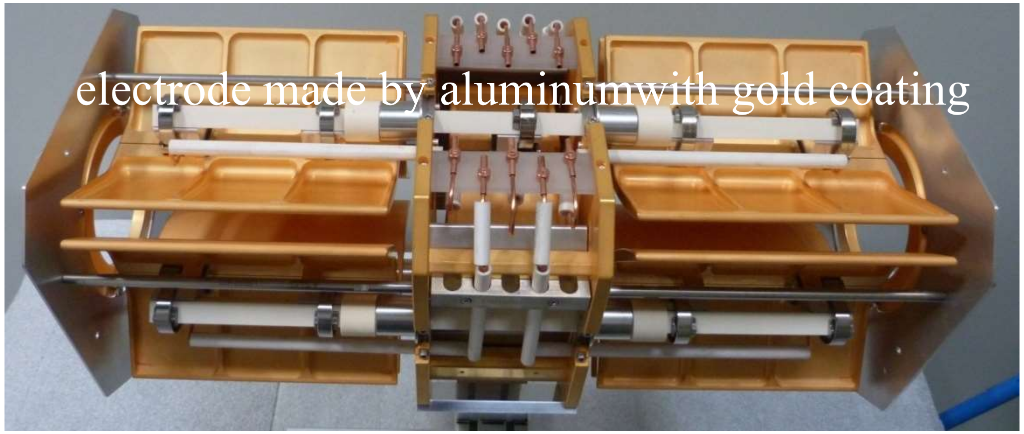
39^0 cylindrical deflector



electrode made by aluminum with gold coating

maximum field ≈ 1 MV/m

electrostatic quadrupoles with vertical steerer

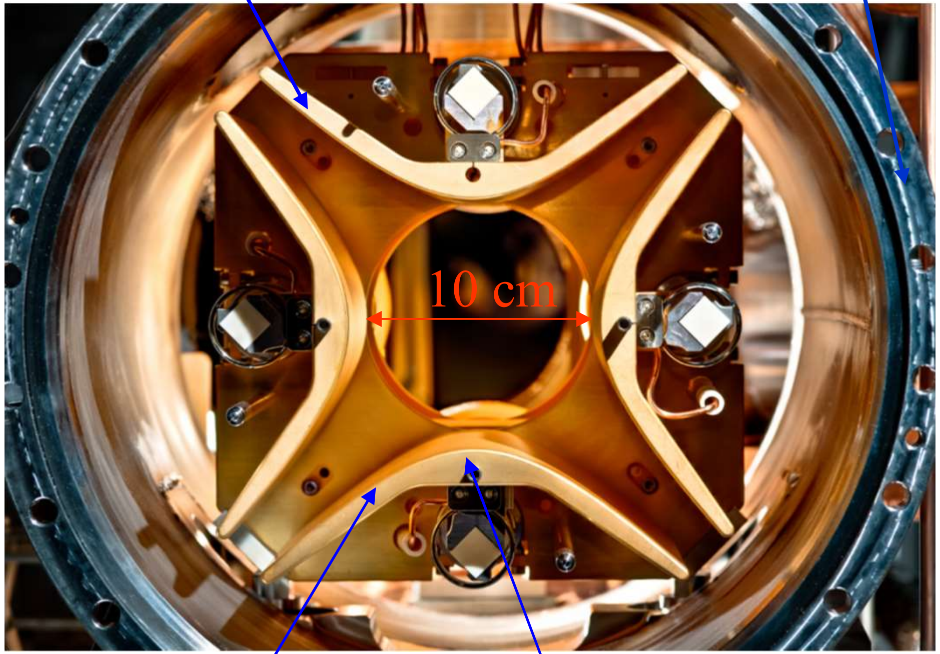


electrode made by aluminumwith gold coating

Electrostatic Quadrupole of the CSR

quadrupole electrode

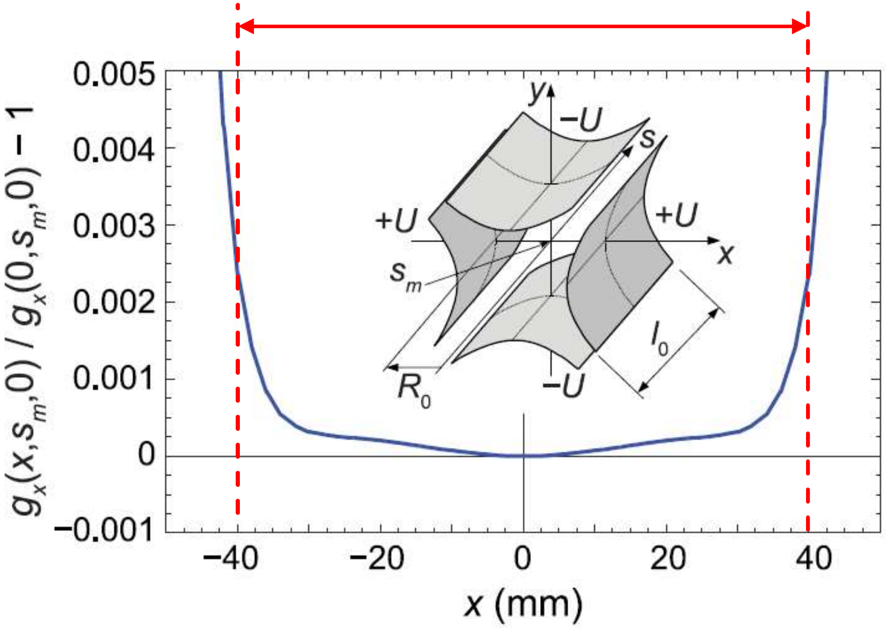
inner vacuum chamber



quadrupole electrode

hyperbolic shape

maximum electrode voltage: $U_{max}=\pm 10\text{kV}$



Relative deviation of the field gradient in the CSR focusing quadrupole. l_0=200 mm

aperture: ± 5cm

dynamical aperture: ± 4 cm

Cryostat of the CSR

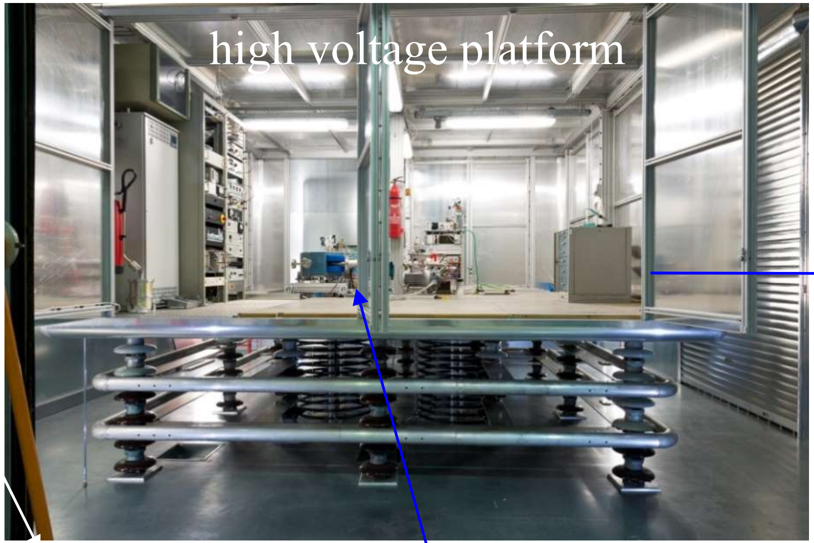
isolation vacuum
ca. 10^{-6} mbar

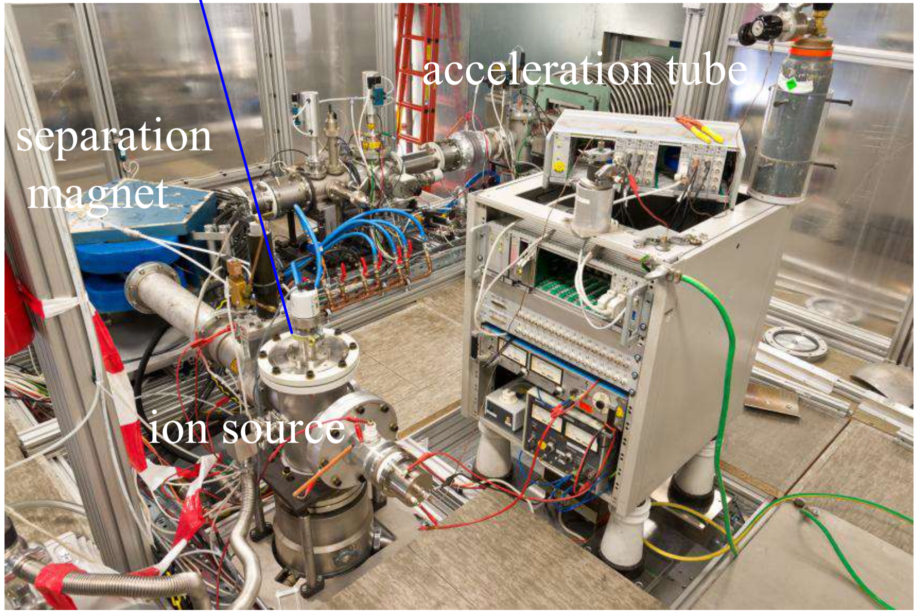
isolation
vacuum chamber

at cryogenic conditions
$n \leq 100$ molecules/cm^3

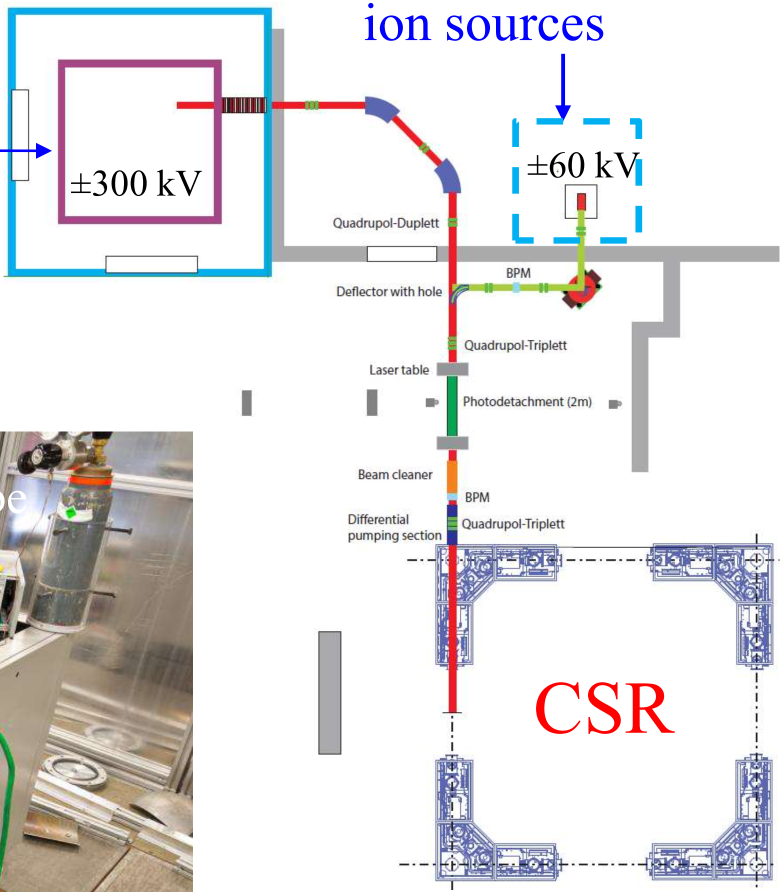
CSR main injector

CSR main injector: ion source on a high voltage platform: ±300 kV





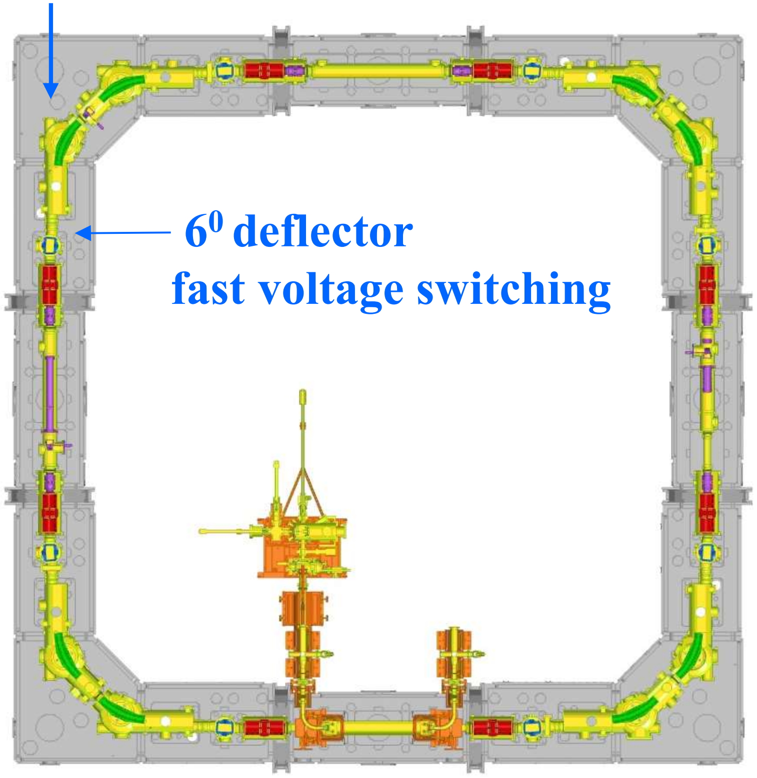
± 60 kV platform with positive and negative ion sources

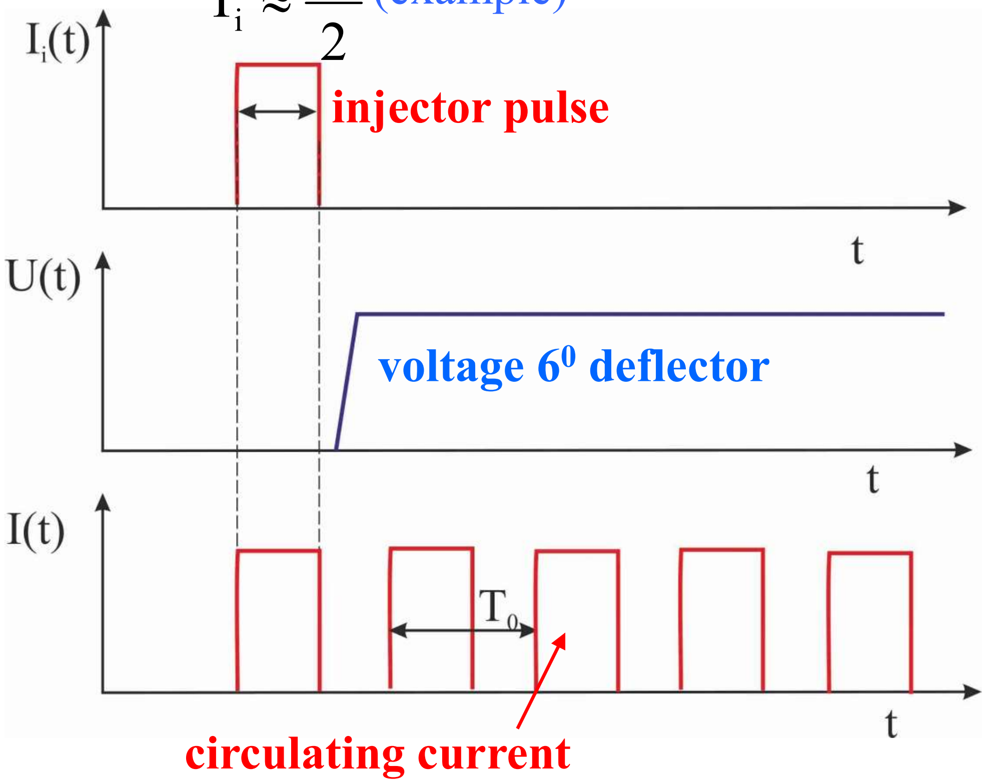


Single Turn injection

T_0-revolution time
T_i-injector beam pulse length

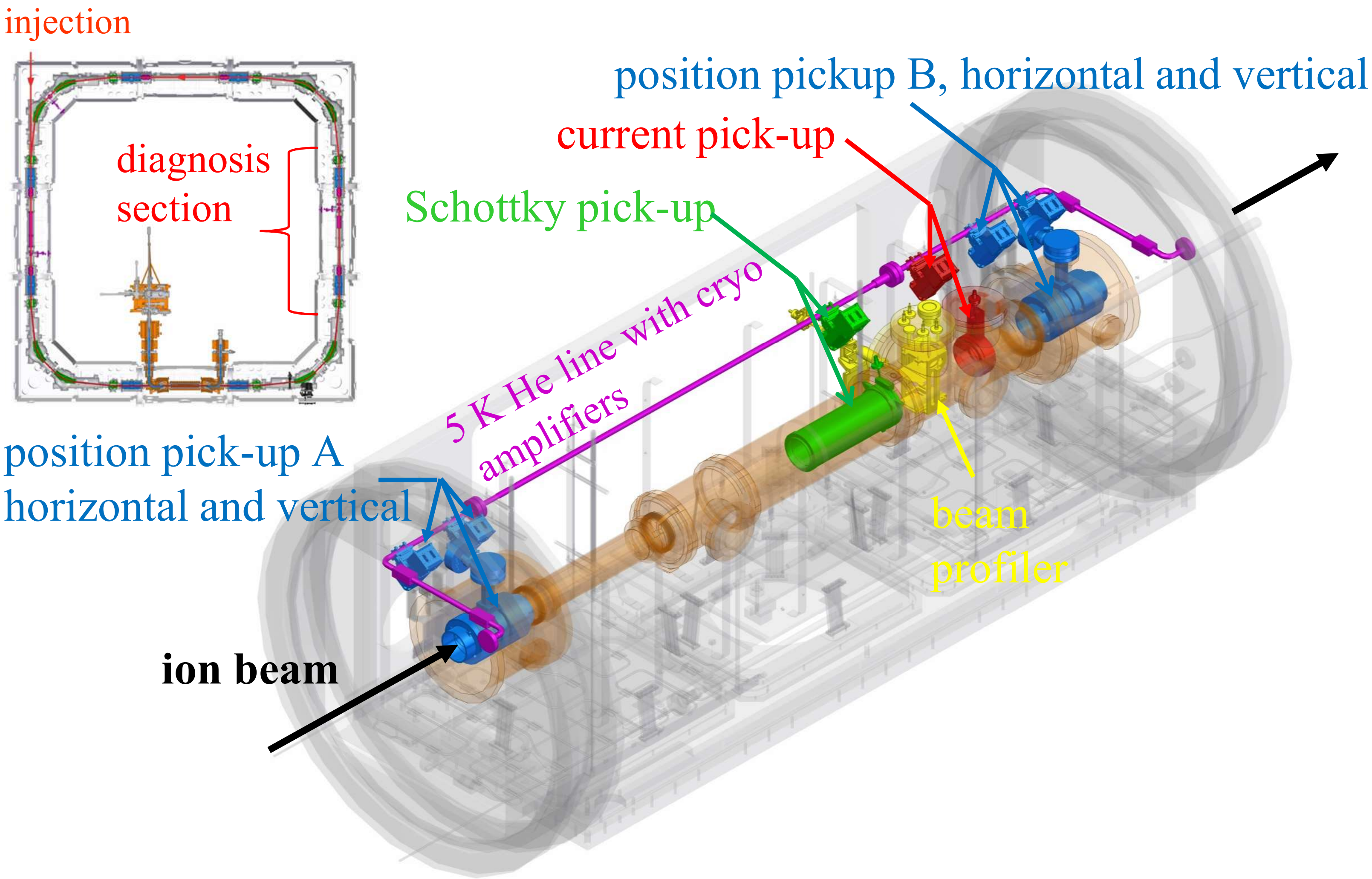
$$T_i \approx \frac{T_0}{2} \text{ (example)}$$





The diagnosis section

Most of the diagnosis elements are located at the diagnosis section



injection

diagnosis section

position pickup B, horizontal and vertical

current pick-up

Schottky pick-up

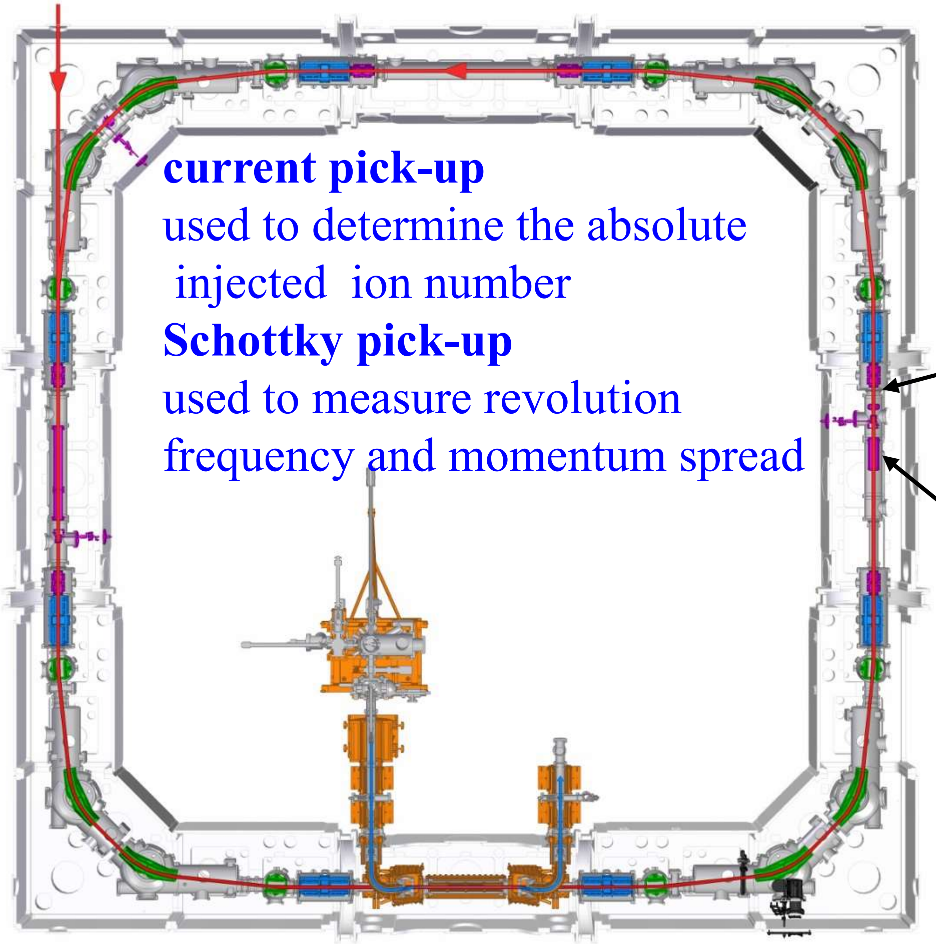
5 K He line with cryo amplifiers

position pick-up A horizontal and vertical

beam profiler

ion beam

The current and Schottky pick-up

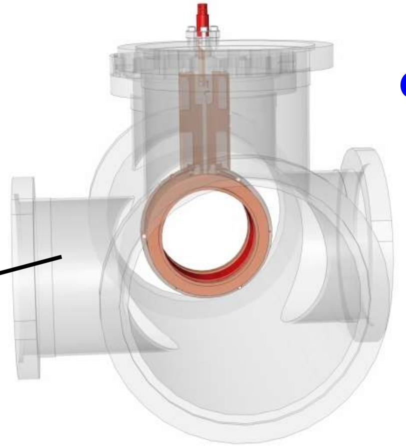


current pick-up

used to determine the absolute injected ion number

Schottky pick-up

used to measure revolution frequency and momentum spread

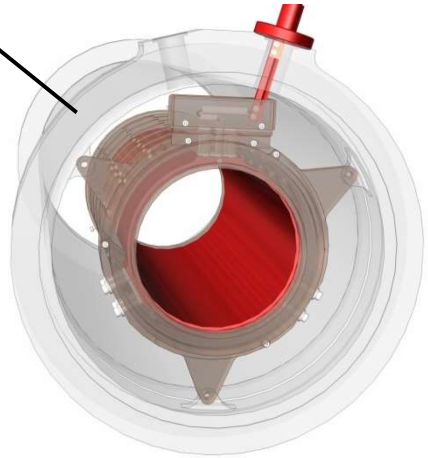


current pick-up

tube:

L= 3.0 cm

ϕ =10 cm



Schottky pick-up

tube:

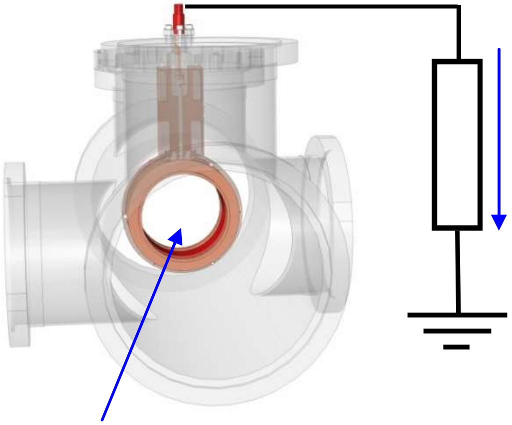
L= 34 cm

ϕ =10 cm

Current pick-up

-used to measure the **absolute number** of the injected ion number (pulsed beam)

-sensitivity 10^6 singly charged ions



$$U(t) = \frac{X_u}{C}\frac{L}{v}I(t)$$

X_u- signal amplification

L- pick-up length

v-velocity

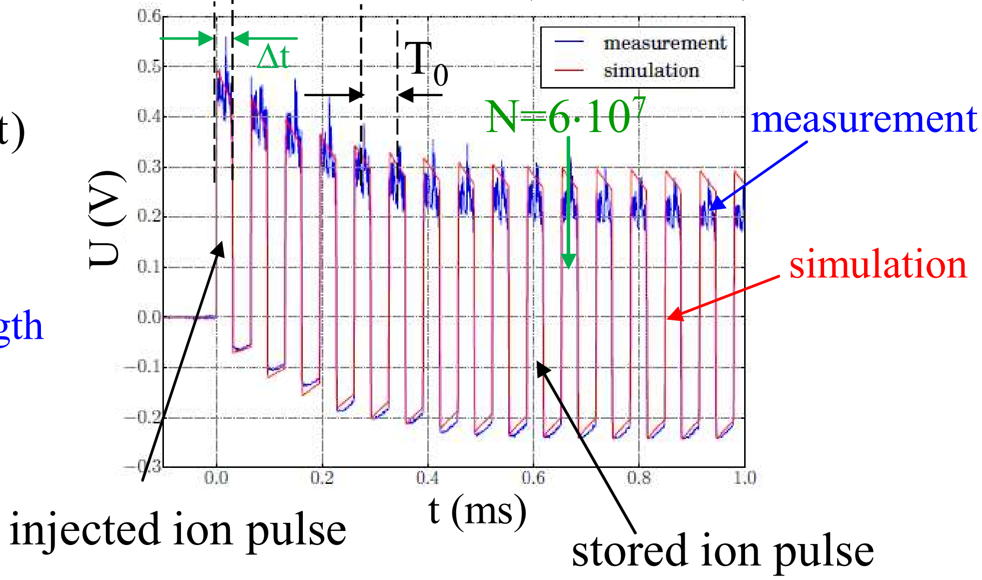
C- capacity

tube: ϕ=10 cm, L=3.0 cm

integration over one pulse

$$N = \frac{1}{qe}\int_{t_1}^{t_2} I(t)dt = \frac{1}{qe}\frac{Cv}{L}\int_{t_1}^{t_2}\frac{U(t)}{X_u}dt$$

measured current signal of an $^{40}Ar^+$ ions (E= 60 keV)



T_0- revolution time

pulse length Δt is set up with an chopper located in the transfer line to the CSR

Schottky noise spectrum

Schottky pick-up

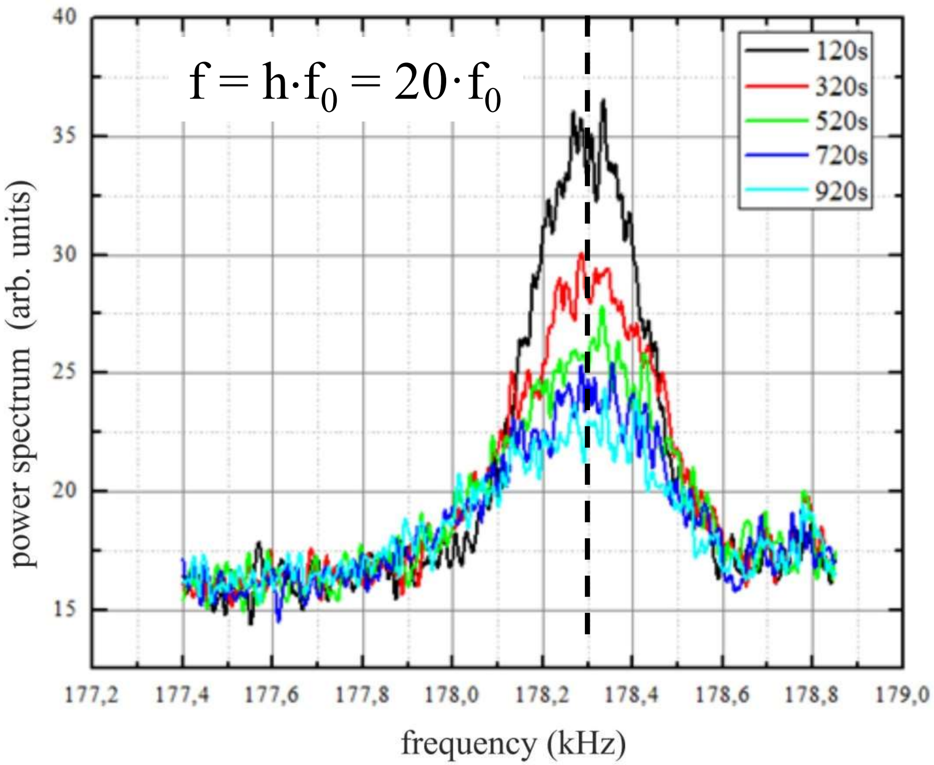
slip factor

$$\eta = \frac{\Delta f / f}{\Delta p / p} = 1 - \frac{1}{\gamma_{th}^2} = 0.7$$

CSR standard mode

(non relativistic approach)

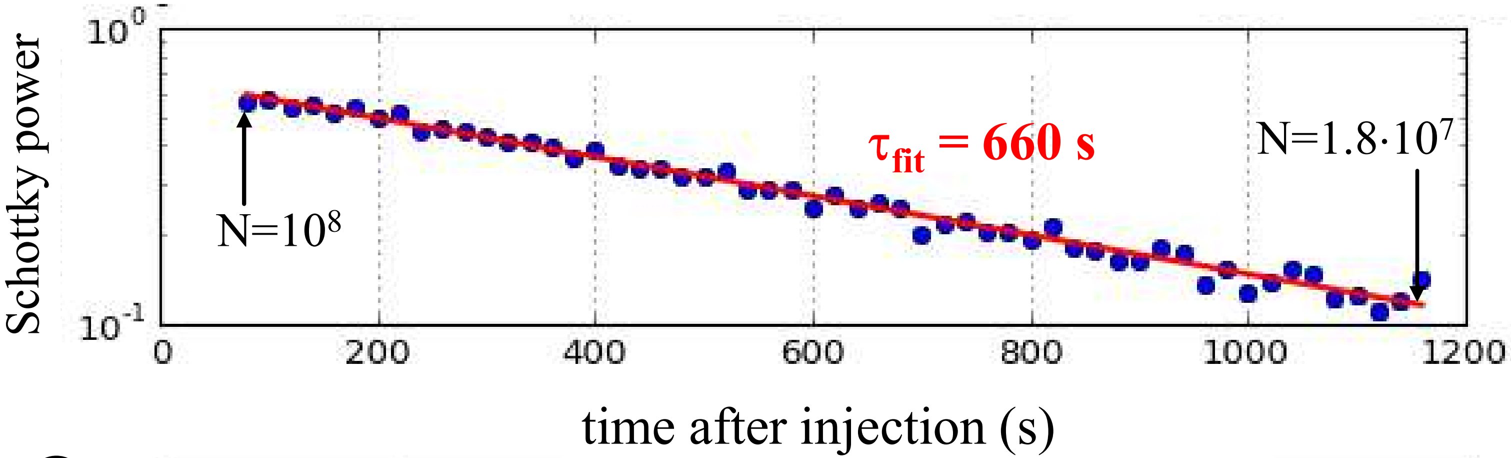
Time development of the Schottky noise spectrum (60 keV Co_2^- ions)



Lifetime Measurements of a stored Co_2^- beam with Schottky noise analysis

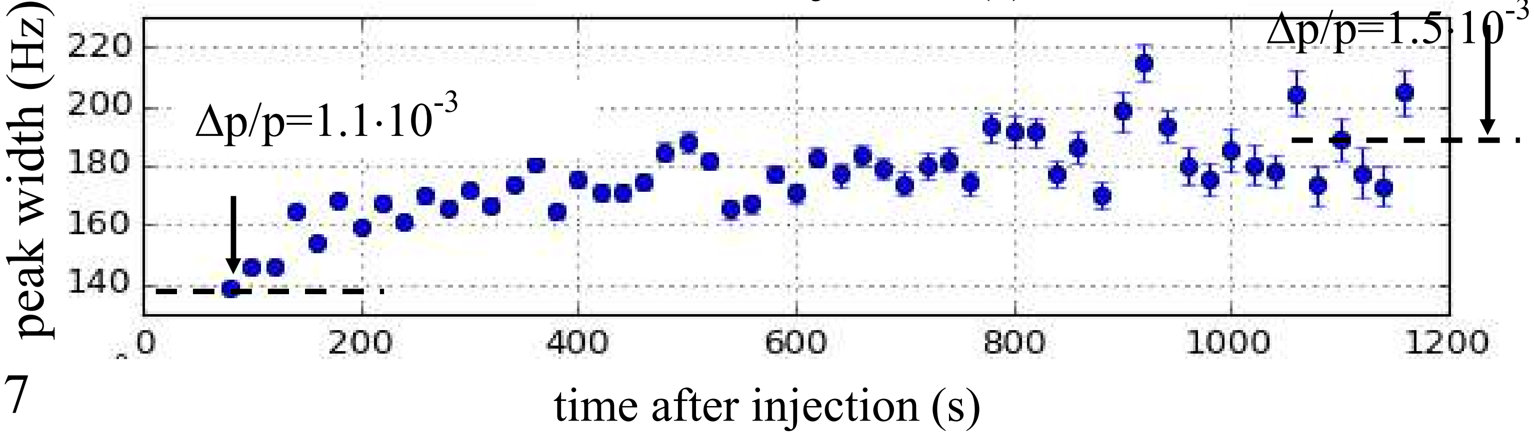
observation frequency:

$$f = h\cdot f_0 = 20\cdot f_0$$



due to noise on the electrodes increasing of Δp/p

$$\eta = \frac{\Delta f / f}{\Delta p / p} = 1 - \frac{1}{\gamma_{th}^2} = 0.7$$



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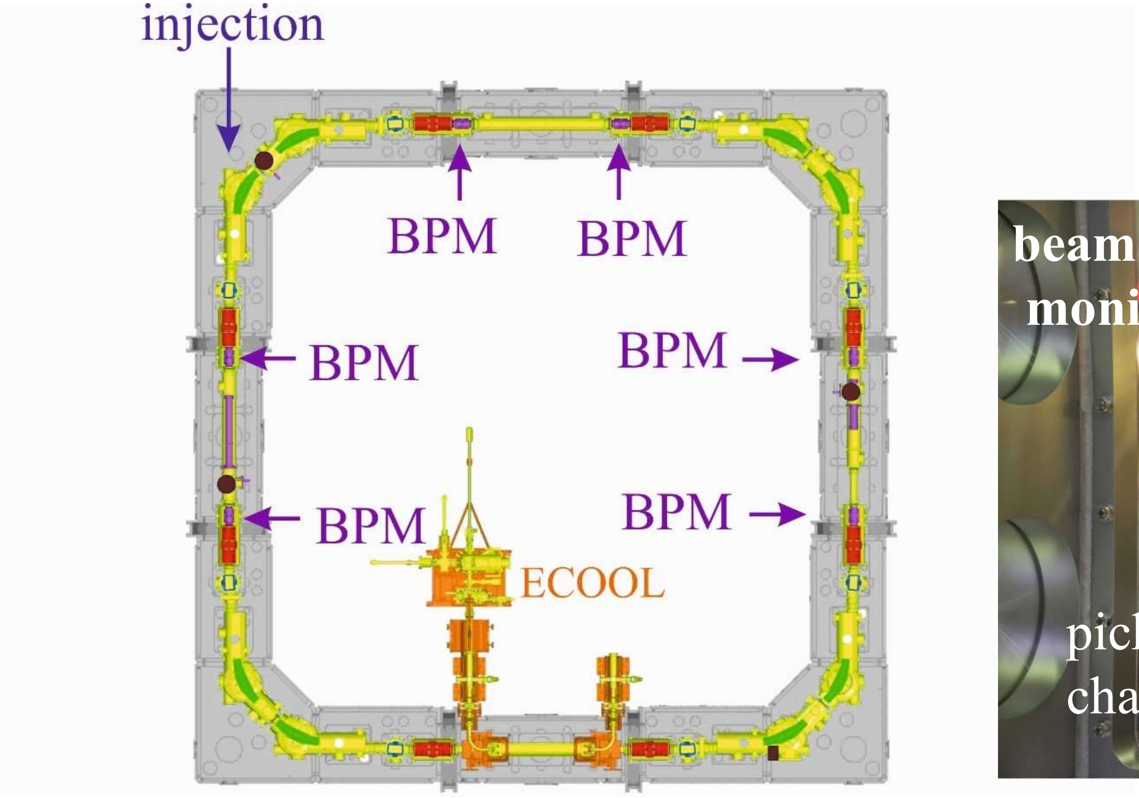
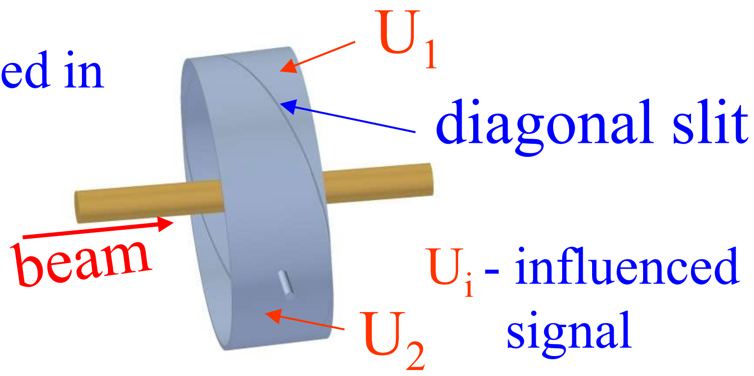
longest measured life time in the CSR: Ag_2^- : τ=2500 s E=60 keV

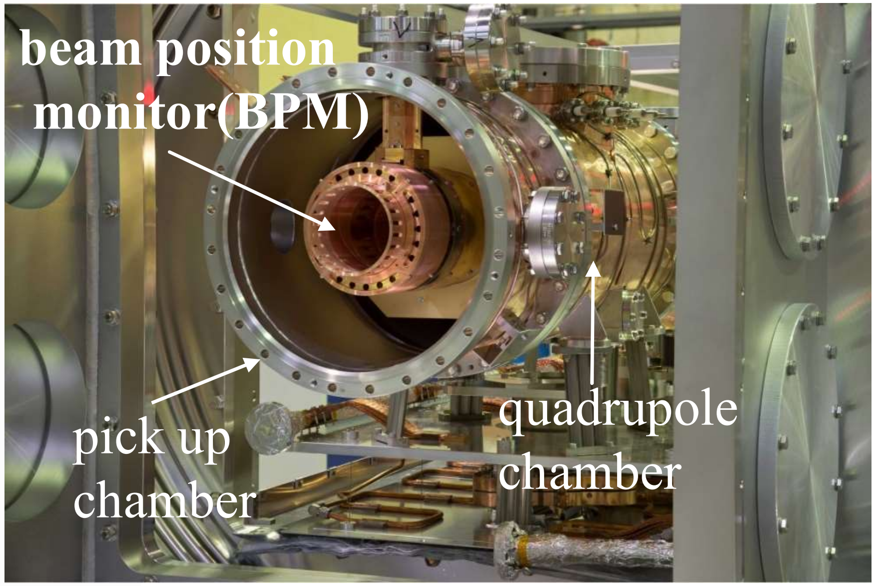
Beam Position Monitor (BPM)

CSR has 6 horizontal and
6 vertical position pick ups (BPM)



tube divided in
two parts



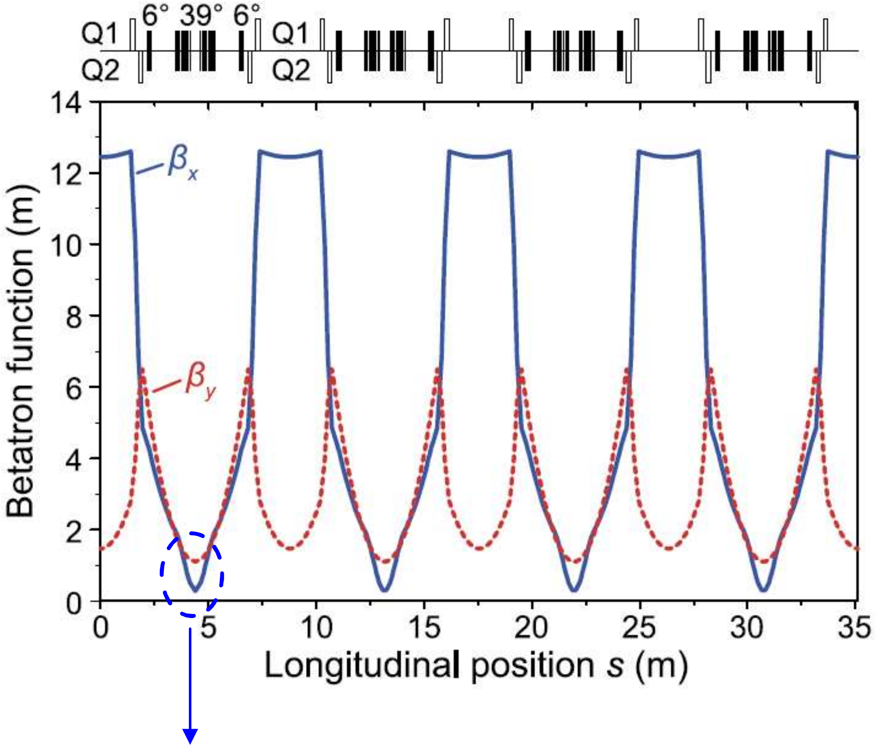


Calculated CSR lattice of the standard mode

-most experiments at the CSR are carried out with the standard mode

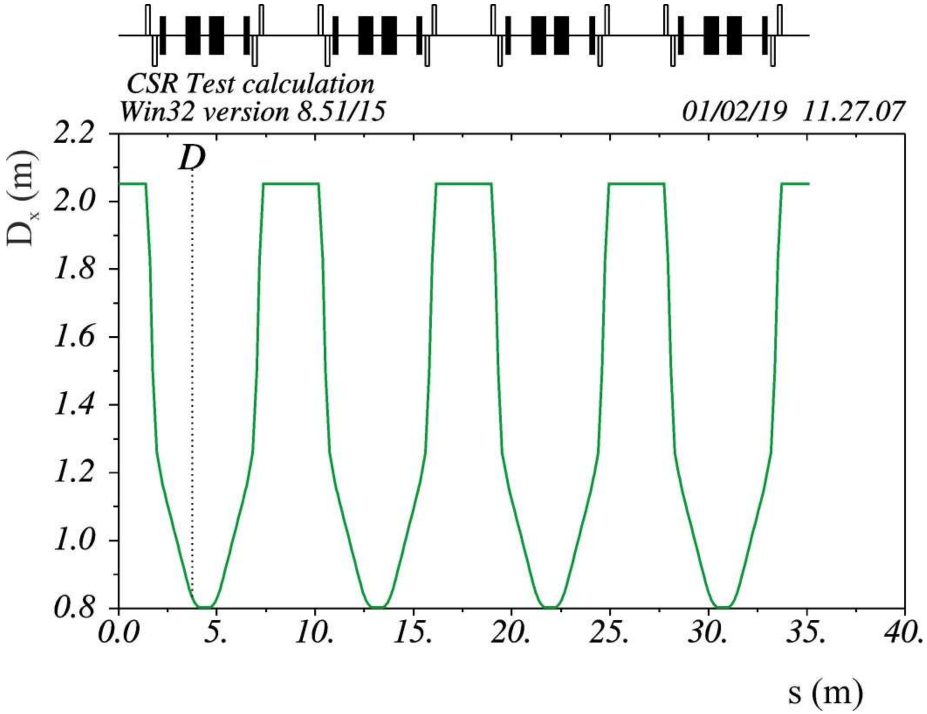
Standard mode of the CSR with super-periodicity 4

Horizontal and vertical betatron functions ß$_x$ and ß$_y$ of the CSR standard mode (Q_x,$Q_y \approx 2.6$)



small horizontal beam size in the deflectors

Calculated dispersion function of the standard mode



Mass measurements in an electrostatic storage ring

The revolution frequency f depends on the ion mass m and injection energy E (non relativistic case):

$$\frac{\Delta f}{f}=-\frac{1}{2}\frac{\Delta(m/Q)}{(m/Q)}+\frac{\overset{\text{slip factor}}{\boxed{\eta}}}{2}\cdot\frac{\Delta(E/Q)}{E/Q}$$

ion energy

$$E=\frac{1}{2}m\cdot v(s)^2+Q\cdot\phi(s)$$

$\eta=1-2\cdot\alpha_p \longleftarrow$ in opposite to magnetic storage rings there is an factor 2 in the $\eta-\alpha_p$-relation

η- slip factor

α_p -momentum compaction factor

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

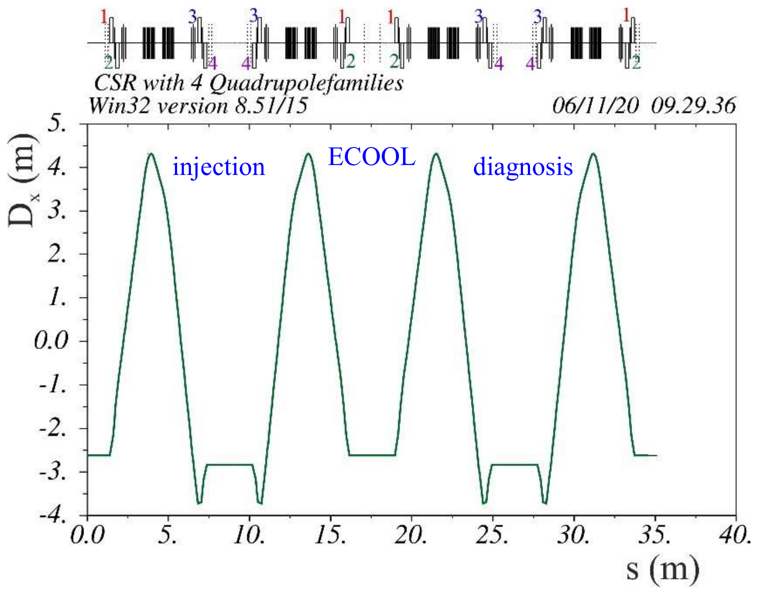
$$\alpha_p=\frac{\Delta C/C}{\Delta p/p}=\frac{\oint\frac{D_x(s)}{\rho(s)}ds}{C}$$

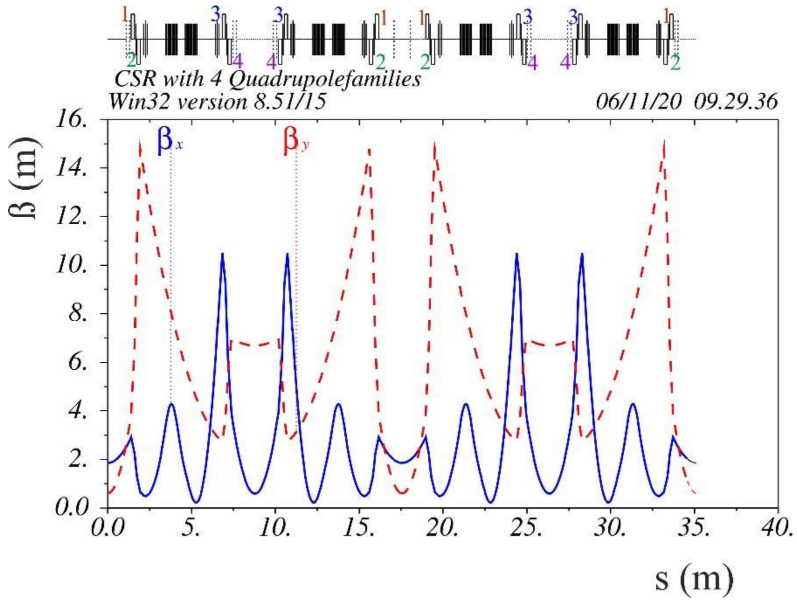
$\Delta p/p$ – momentum deviation of injected ion beam

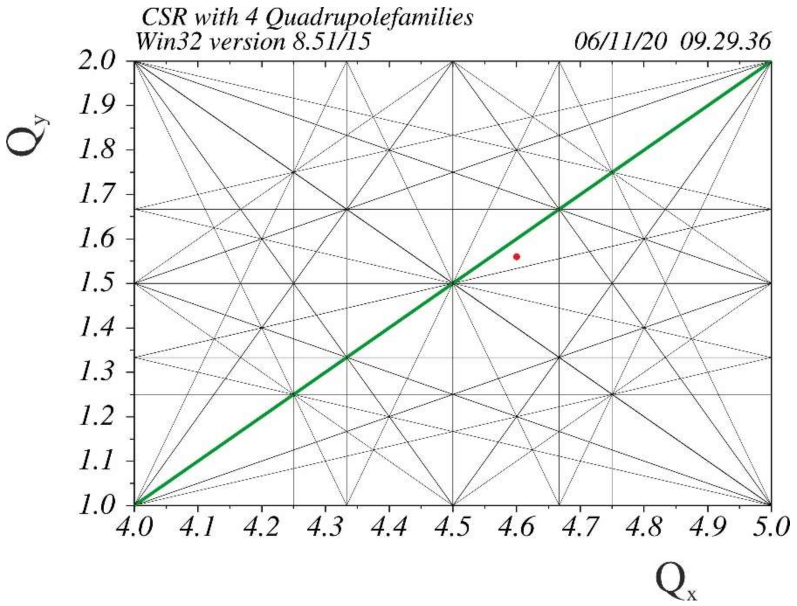
For mass measurements the storage ring has to be operated in an **isochronous mode** with:

$$\eta=1-2\cdot\alpha_p=0$$

Isochronous mode for ion mass measurements







slip factor η

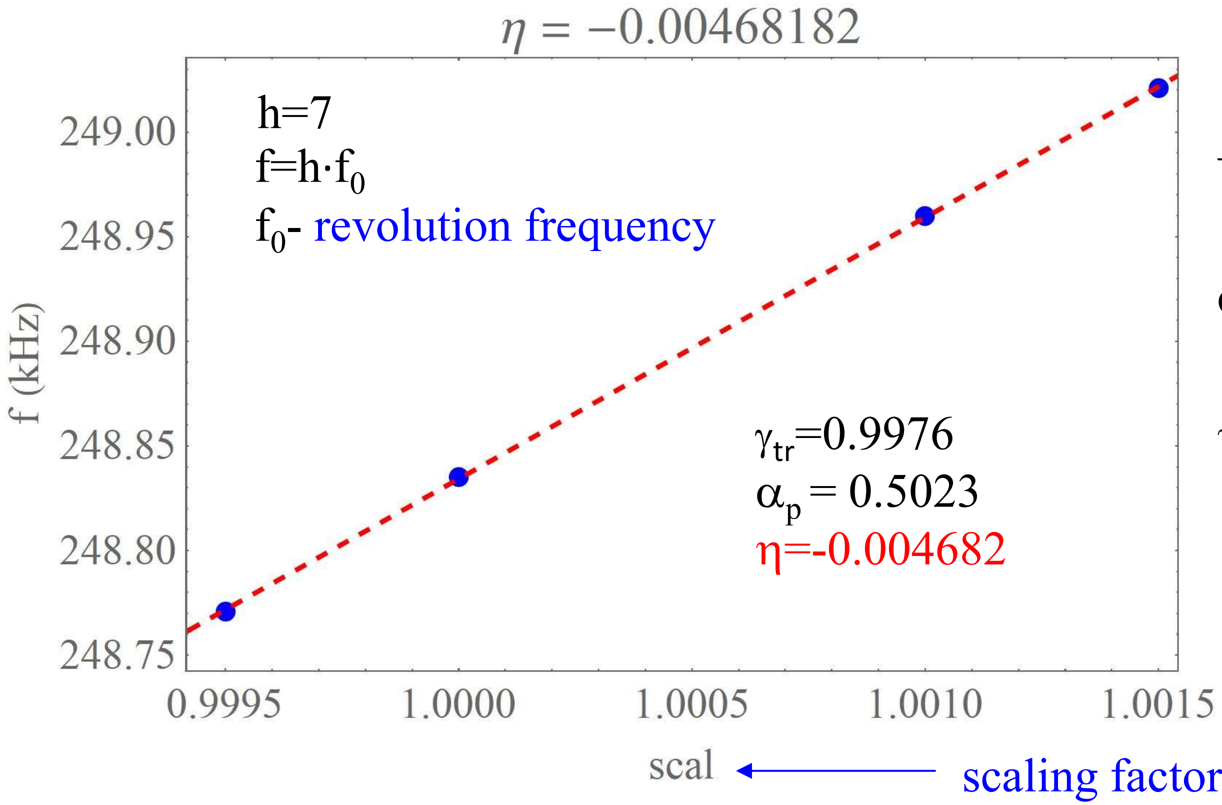
isochronous condition

$$\eta = \frac{\Delta f/f}{\Delta p/p} = 1-2\cdot\alpha_p = 0$$

$$\alpha_p = \frac{\Delta C/C}{\Delta p/p} = \frac{\oint \frac{D_x(s)}{\rho(s)}\,ds}{C} = \frac{1}{2}$$

Typically slip factor used at the mass measurements

Measurement of the slip factor determined with $^{63}Cu^-$ ions (E=250 keV)



h=7

f=h·f_0

f_0- revolution frequency

γ_{tr}=0.9976

$\alpha_p = 0.5023$

η=-0.004682

← scaling factor of all potentials ϕ

$$\frac{\Delta f}{f_0} = \alpha_p \frac{\Delta\phi}{\phi}$$

$$\alpha_p = \frac{\Delta C / C}{\Delta p / p}$$

α_p- momentum compaction

$$\eta = \frac{\Delta f / f}{\Delta p / p} = 1 - 2\cdot\alpha_p = 1 - \frac{1}{\gamma_{tr}^2}$$

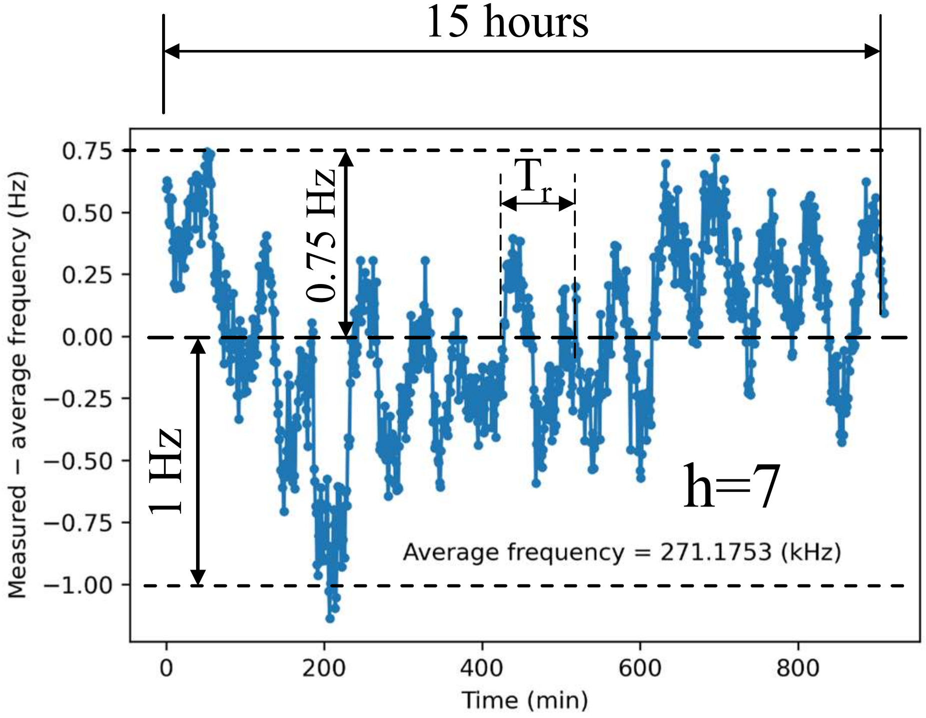
η - slip factor

$\gamma_{tr} - \gamma_{tr}$ parameter

Stability of the measured revolution frequency

If $\eta = \frac{\Delta f/f}{\Delta p/p} \approx 0$ injected pulse length can be keep for seconds

⇒ easily to detect the stored ion beam my measuring the coherent spectrum.



ripple period $T_r \approx 100$ minutes
Assumption: air condition of the power supplies is causing this period

frequency stability measured over 15 hours:
$\Delta f/f = 1\ \text{Hz}/271175.5\ \text{Hz} = 3.6\ 10^{-6}$

frequency is caused by the stability of the deflector power supplies. A change of all ring potential ϕ is changing the revolution frequency by:

$$\frac{\Delta f}{f} = \alpha_p \frac{\Delta \phi}{\phi} \text{ with } \alpha_p = 0.5$$

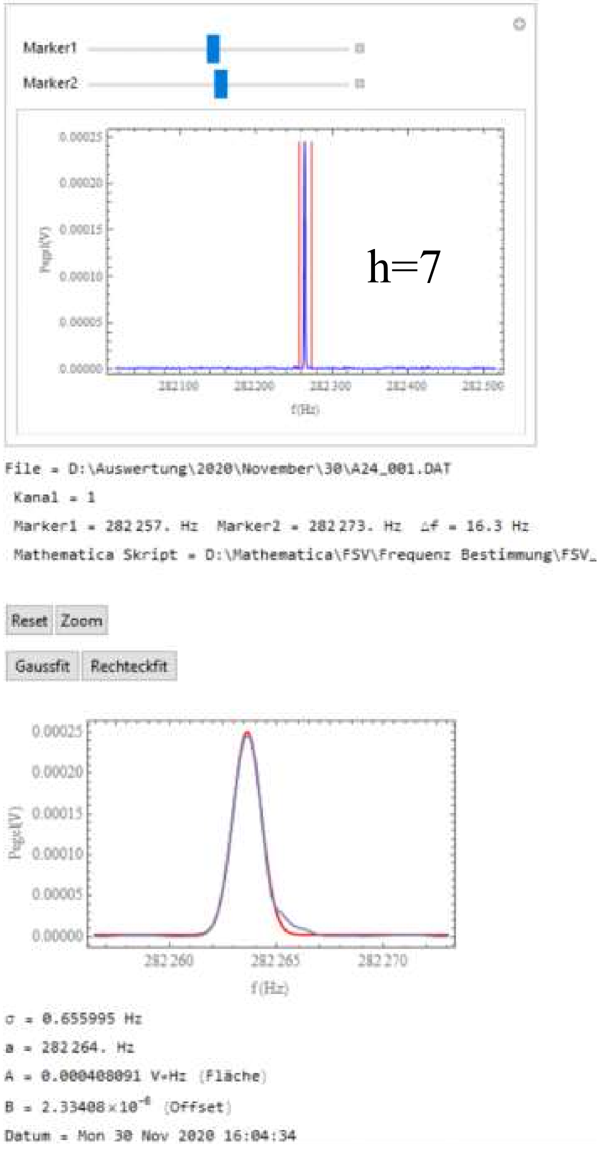
This means we get for the 15 hours stability $\Delta U/U$ of the deflector power supplies (with DAC):

$$\frac{\Delta U}{U} < \frac{1}{0.5} 3.6 \cdot 10^{-6} = 7 \cdot 10^{-6}$$

Mass measurements at the CSR

Reference beam: C_2^-

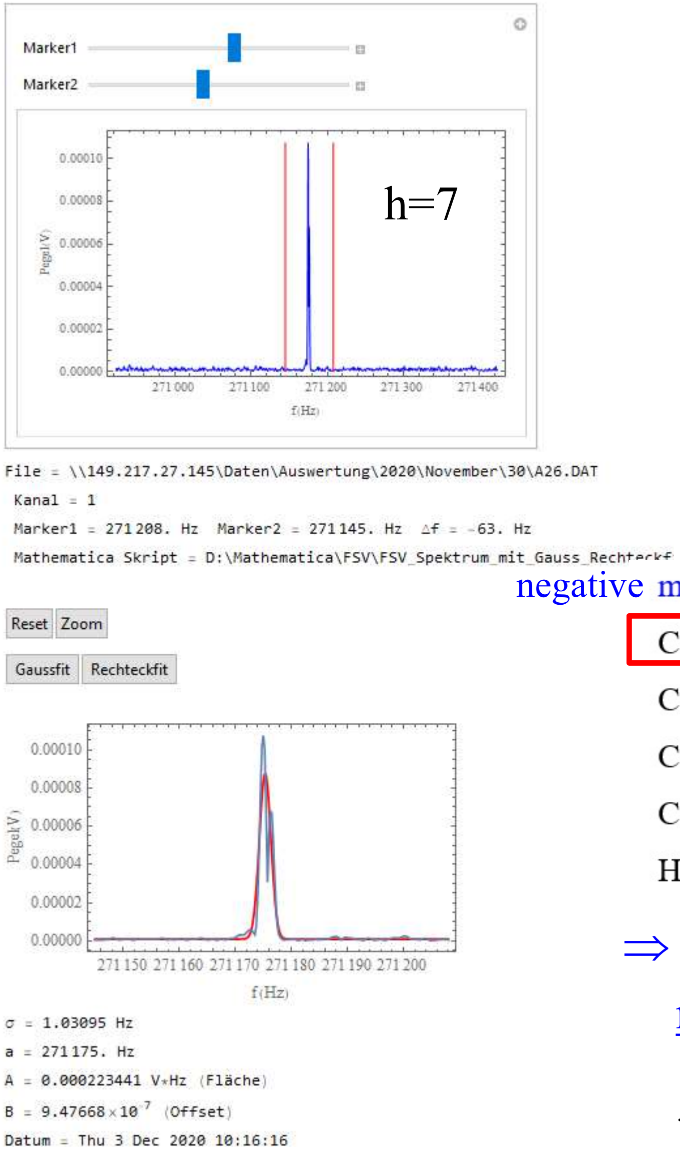
m_{ref}=24.000548 u



```
File = D:\Auswertung\2020\November\30\A24_001.DAT
 Kanal = 1
 Marker1 = 282257. Hz  Marker2 = 282273. Hz  Δf = 16.3 Hz
 Mathematica Skript = D:\Mathematica\FSV\Frequenz Bestimmung\FSV_
```

```
σ = 0.655995 Hz
a = 282264. Hz
A = 0.000408091 V*Hz (Fläche)
B = 2.33408×10^-8 (Offset)
Datum = Mon 30 Nov 2020 16:04:34
```

unknown ion with A=26



```
File = \\149.217.27.145\Daten\Auswertung\2020\November\30\A26.DAT
 Kanal = 1
 Marker1 = 271208. Hz  Marker2 = 271145. Hz  Δf = -63. Hz
 Mathematica Skript = D:\Mathematica\FSV\FSV_Spektrum_mit_Gauss_Rechteckf
```

```
σ = 1.03095 Hz
a = 271175. Hz
A = 0.000223441 V*Hz (Fläche)
B = 9.47668×10^-7 (Offset)
Datum = Thu 3 Dec 2020 10:16:16
```

with

m_{ref}=24.000548

f_{ref}=282264/7 Hz

f=271175/7 Hz

and

$$m=m_{ref}\,\frac{f_{ref}^2}{f^2}$$

we get

m=26.0035 u

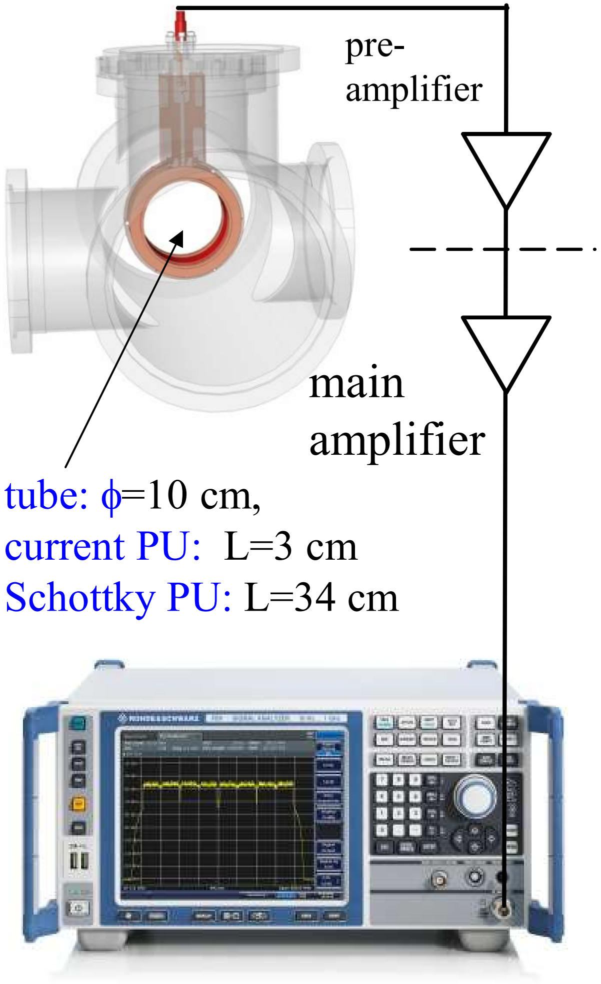
negative molecule	mass
C12-N:	26.0036
C13-C13:	26.0073
C12-C13-H:	26.0117
C12-C12-D:	26.0147
H-C12-C12-H:	26.0162

⇒ molecule is CN^-

mass resolution

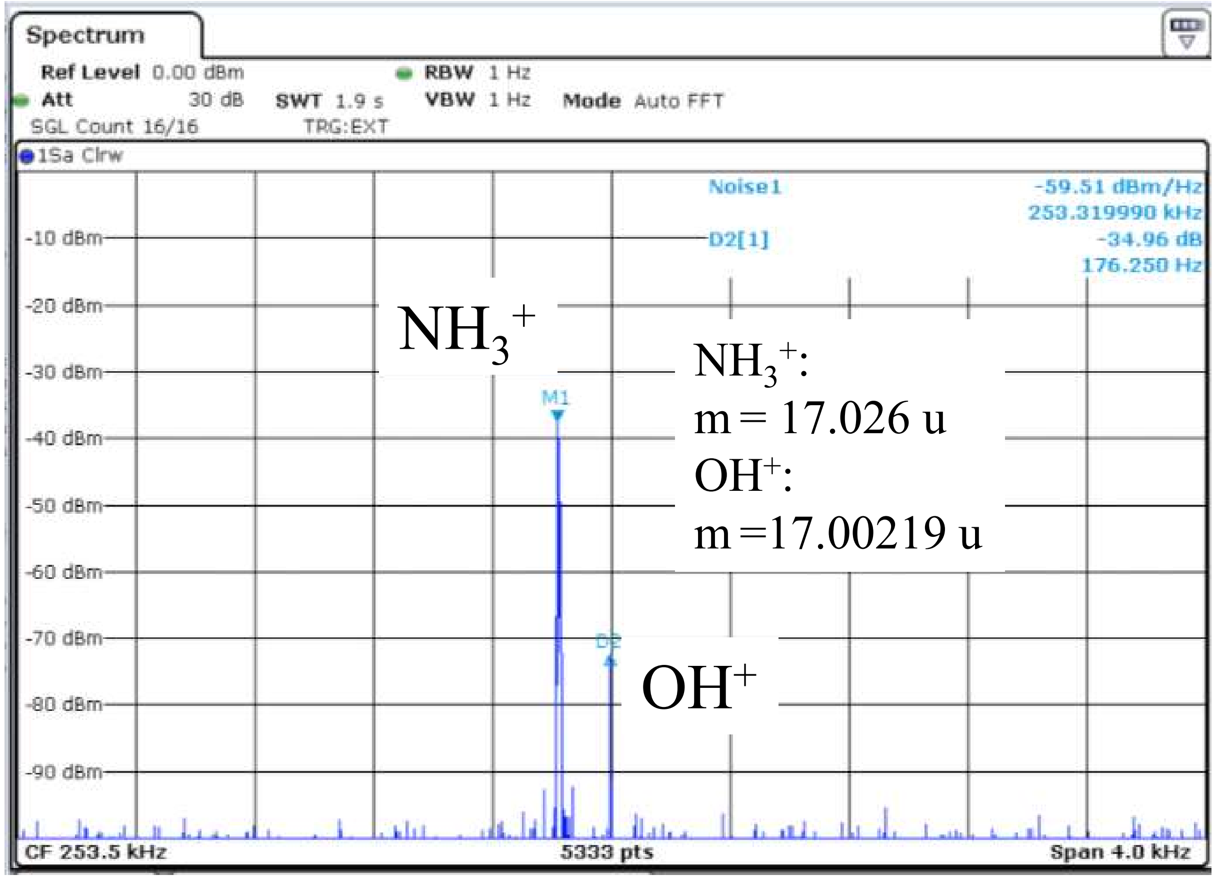
$$\frac{\Delta m}{m} < 3.8\cdot 10^{-6}$$

Mass spectrum of isobars with A=17



tube: ϕ=10 cm,
current PU: L=3 cm
Schottky PU: L=34 cm

spectrum-analyzer


Spectrum

Ref Level 0.00 dBm
Att 30 dB
SGL Count 16/16
SWT 1.9 s
TRG:EXT
RBW 1 Hz
VBW 1 Hz
Mode Auto FFT

1Sa Clrw

Noise1 -59.51 dBm/Hz
253.319990 kHz
D2[1] -34.96 dB
176.250 Hz

CF 253.5 kHz
5333 pts
Span 4.0 kHz

NH_3^+

NH_3^+:
m = 17.026 u
OH^+:
m =17.00219 u

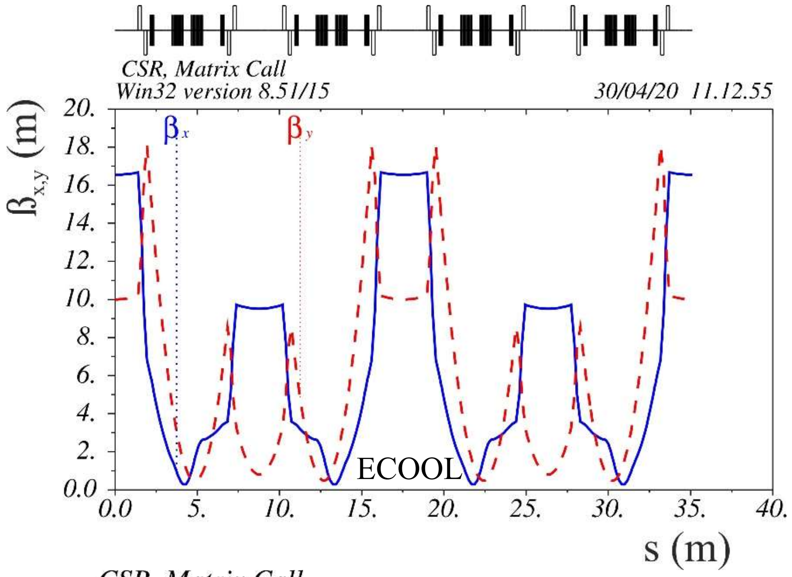
OH^+

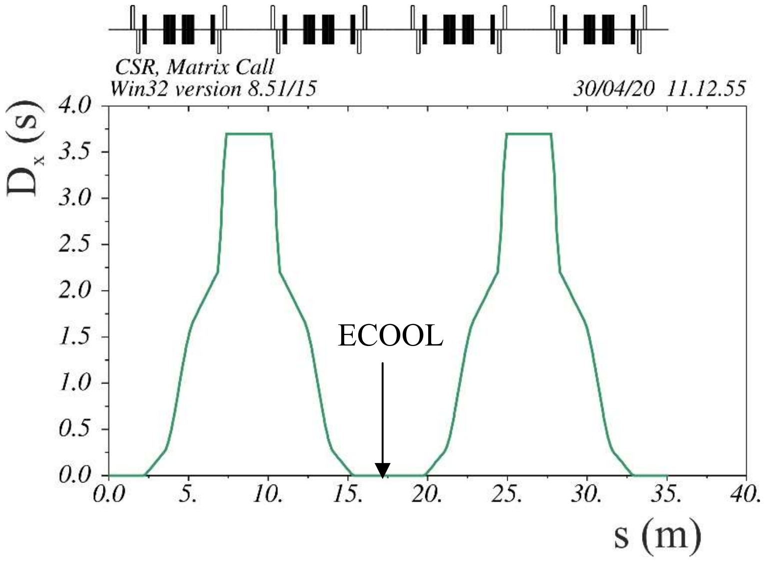
$$\frac{\Delta f}{f} = -\frac{1}{2}\frac{\Delta(m/Q)}{(m/Q)} + \frac{\eta}{2}\cdot\frac{\Delta(E/Q)}{E/Q}$$

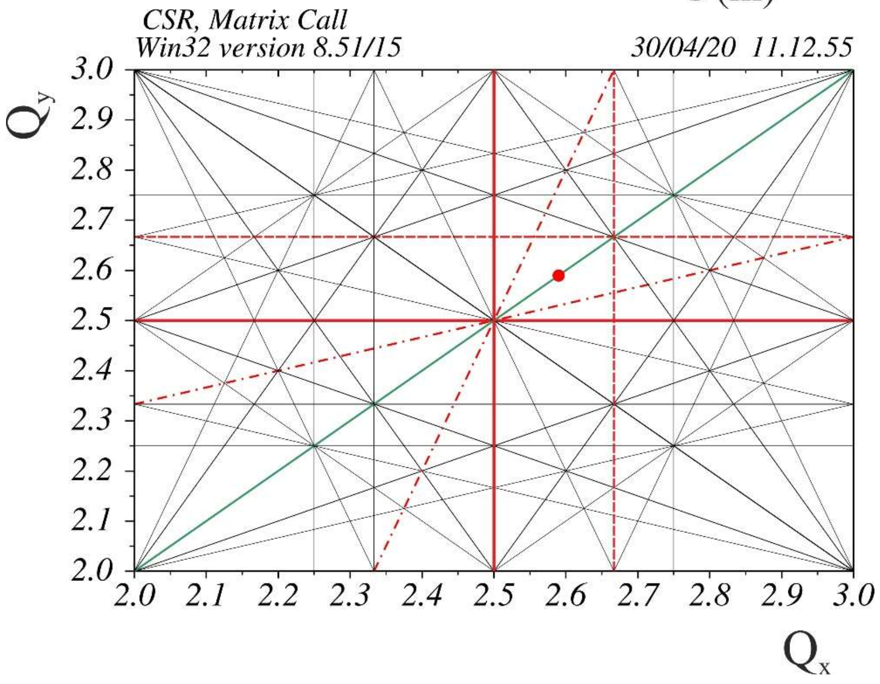
$\eta = 1-2\cdot\alpha_p \approx 0$ (isochronous mode)

CSR achromatic mode for electron cooling

4 quadrupole families







Stability range of electron cooling

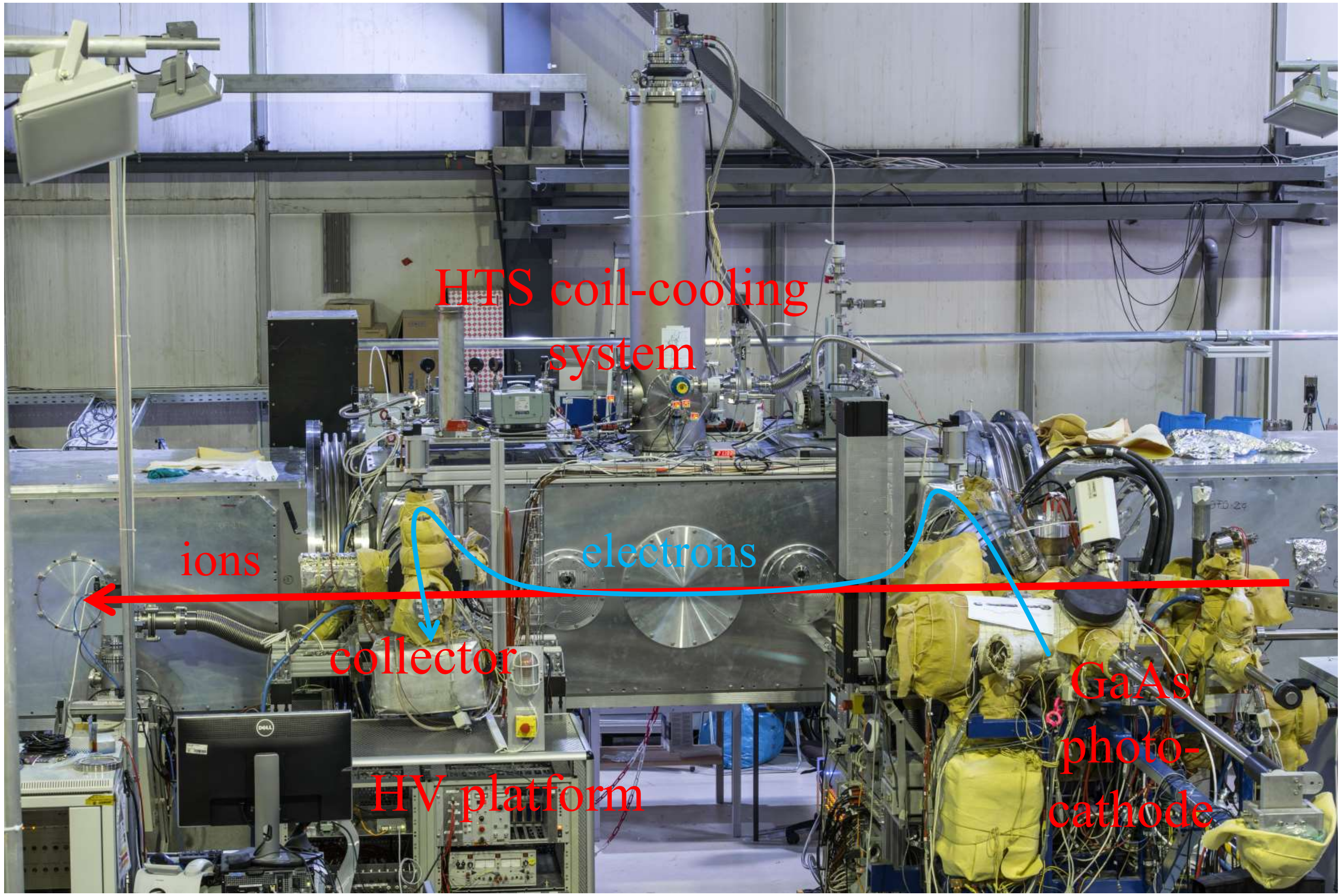
$$-\frac{8E_e\,\varepsilon_0}{D_x\,e^2\,n_e}\,\frac{\Delta_{x,0}}{\Delta_{\|,0}}\,f_b < x_0 < \frac{4E_e\,\varepsilon_0}{D_x\,e^2\,n_e}$$

x_0-horizontal displacement of the ion beam in the electron cooler

To suppress dispersive heating effects
D_x →0 m (ECOOL section)

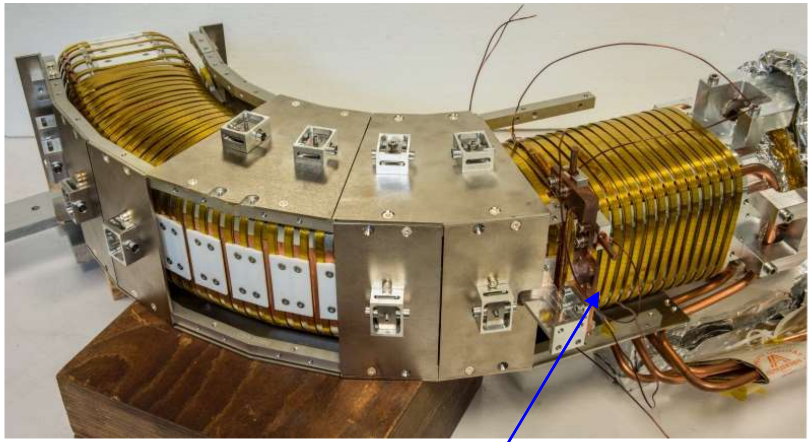
experiments:
attained dispersion D_x in the cooler
D_x=-0.03-0.03 m

The CSR electron cooler



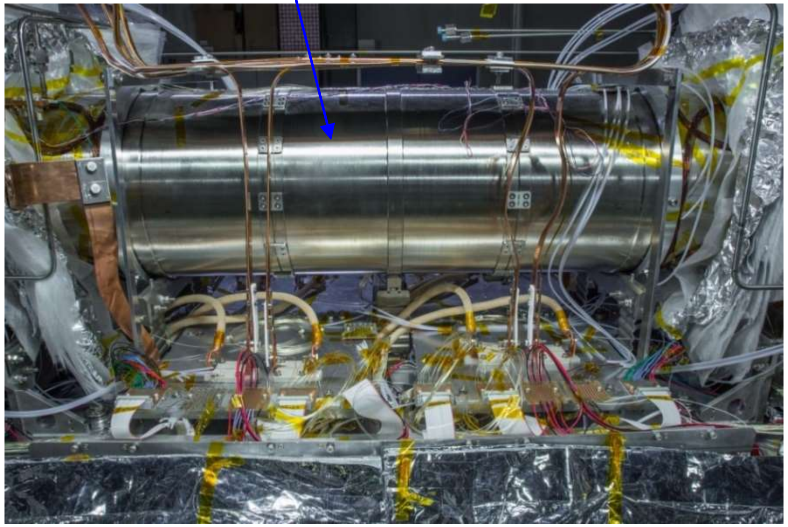
Magnets of the CSR electron cooler

toroid magnet
steering copper coil pairs located inside aluminum body for toroidal drift compensation



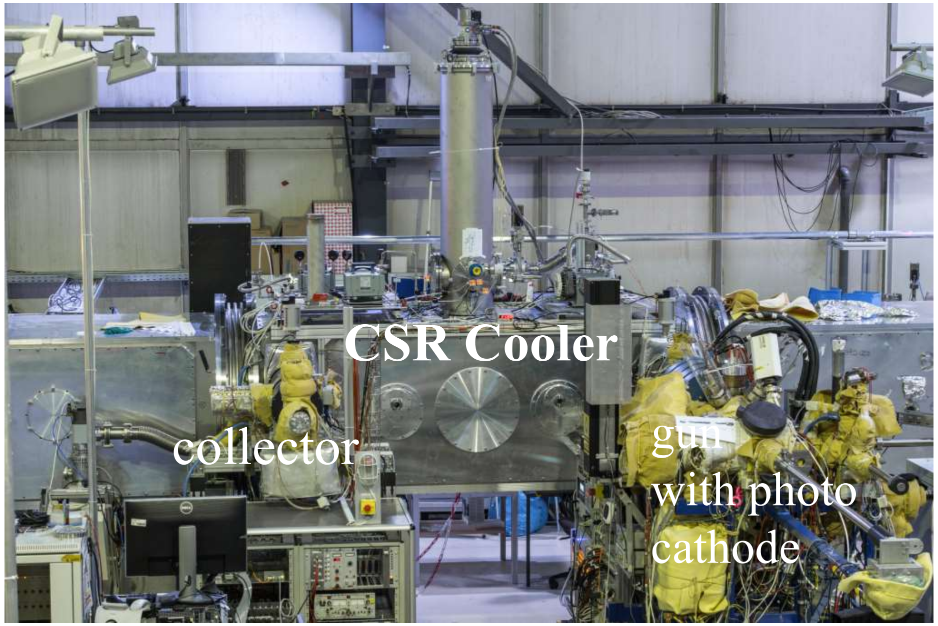
high temperature superconductor

iron shield

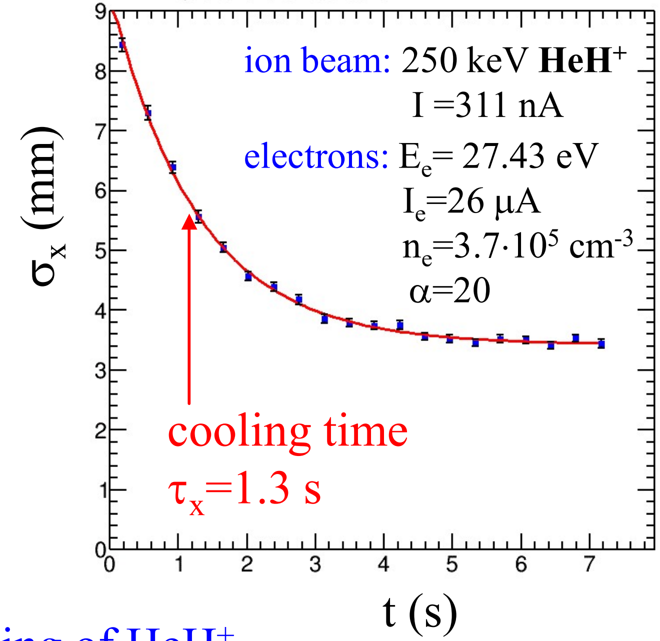


cooling solenoid
High-temperature superconductor attached onto cooled copper strips distributes ≈60 A currents to the magnets

CSR electron cooling



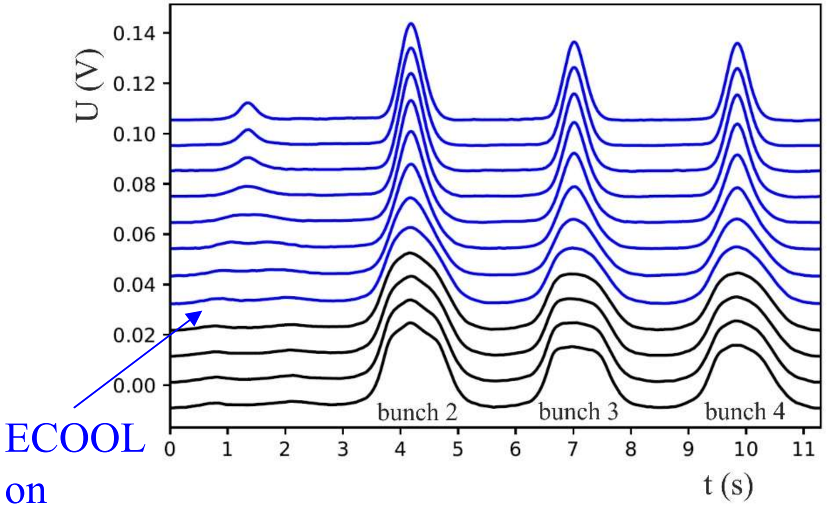
horizontal electron cooling

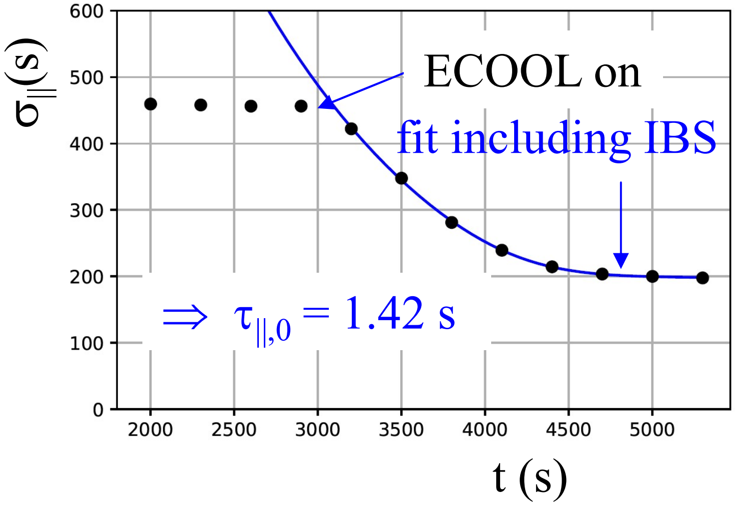


ion beam: 250 keV **HeH$^+$**
I =311 nA
electrons: E_e= 27.43 eV
I_e=26 μA
n_e=3.7·10^5 cm^{-3}
α=20

cooling time
τ_x=1.3 s

Longitudinal electron cooling of HeH$^+$





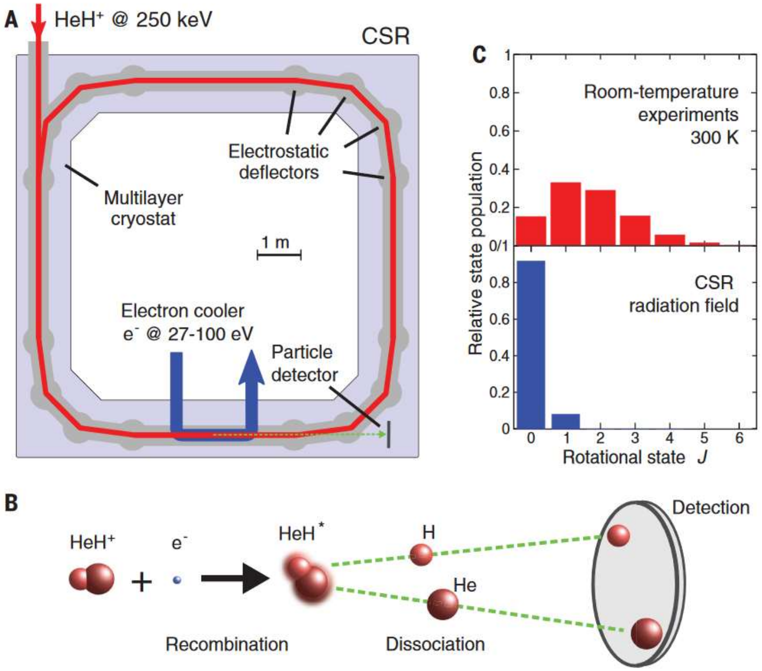
ECOOL on

fit including IBS

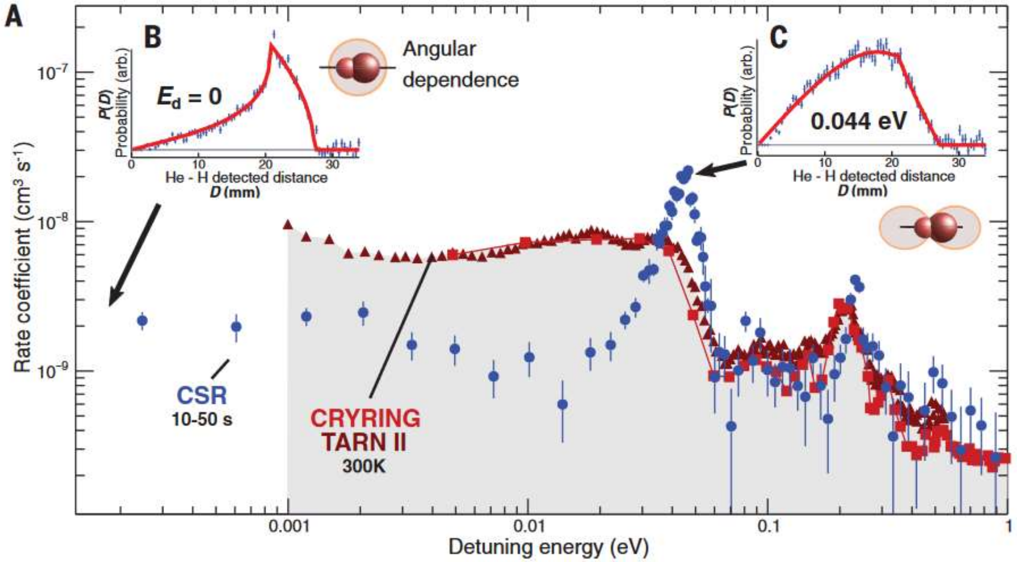
$\Rightarrow \tau_{\parallel,0}$ = 1.42 s

Dissociative Recombination in the cryogenic storage ring

schema



DR spectrum for rotationally cold HeH^+



Science

Quantum-state–selective electron recombination studies suggest enhanced abundance of primordial HeH^+

Oldrich Novotný, Patrick Wilhelm, Daniel Paul, Ábel Kálosi, Sunny Saurabh, Arno Becker, Klaus Blaum, Sebastian George, Jürgen Göck, Manfred Grieser, Florian Grussie, Robert von Hahn, Claude Krantz, Holger Kreckel, Christian Meyer, Preeti M. Mishra, Damian Muell, Felix Nuesslein, Dmitry A. Orlov, Marius Rimmler, Viviane C. Schmidt, Andrey Shornikov, Aleksandr S. Terekhov, Stephen Vogel, Daniel Zajfman and Andreas Wolf

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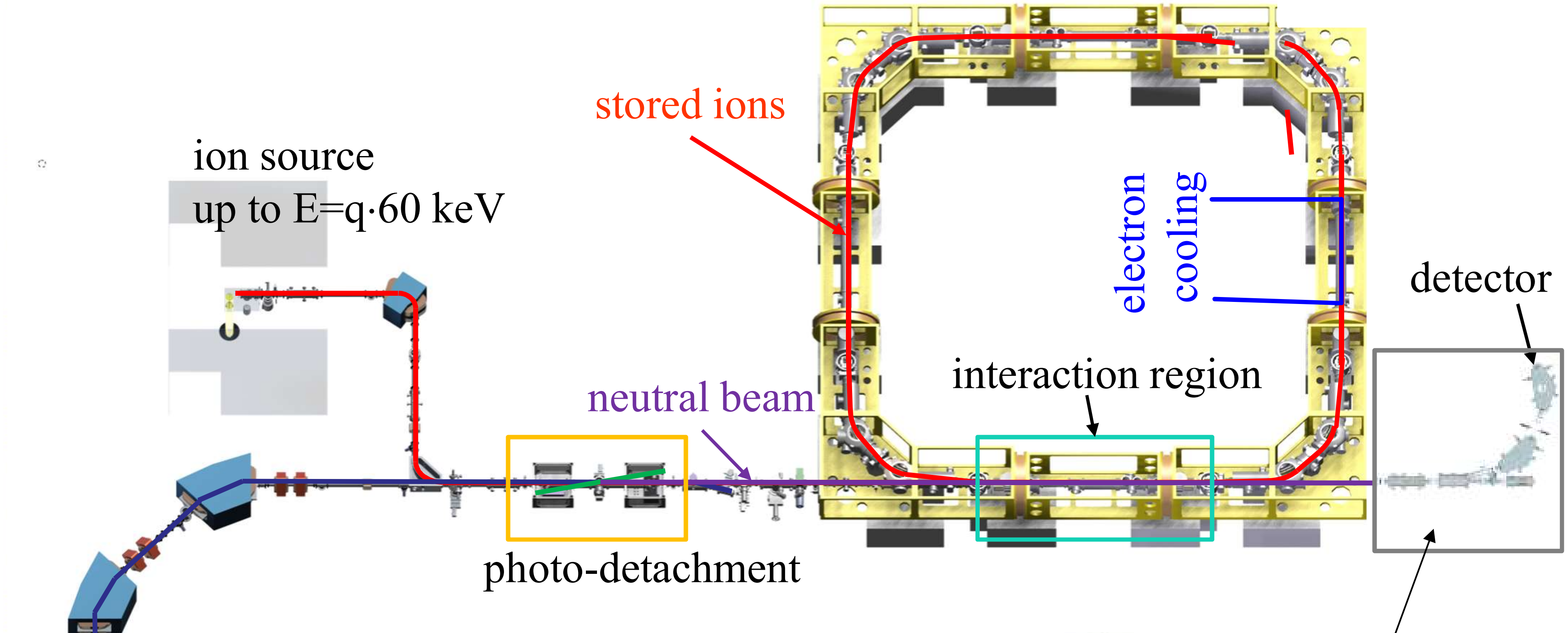
Merged beam experiments



stored ions

ion source
up to E=q·60 keV

electron cooling

detector

neutral beam

interaction region

photo-detachment

spectrometer

ion source up to
E=q·300 keV

Independent Research Group of H. Kreckel

European Research Council

Thanks for your attention!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