Considerations for the implementation of experiments

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Half life of $^{7}Be^{3+}$

$$^{7}Be^{3+} + e^{-} \rightarrow {}^{7}Li^{3+} + \nu_e$$ estimated $\tau \approx 100$ d

K-shell electron

Number of stored $^{7}Be^{3+}$ and $^{7}Li^{3+}$ ions as a function of time

$$\frac{dN_{Be}}{dt} = -\frac{N_{Be}}{\tau} - \frac{N_{Be}}{\tau_{Be}}$$

$$\frac{dN_{Li}}{dt} = \frac{N_{Be}}{\tau} - \frac{N_{Li}}{\tau_{Li}}$$

N_{Be}- number of Be ions
τ- nuclear lifetime
τ_{Be}- Be lifetime in residual gas/cooler
N_{Li}- number of Li ions
τ_{Li}- Li lifetime in residual gas/cooler

$\Rightarrow$ number of stored $^{7}Li^{3+}$ ions as a function of time

$$N_{Li}(t) = \frac{N_0}{\tau} \frac{\tau_{Be}\tau_{Li}}{\tau_{Li} - \tau_{Be}} \left(e^{-\frac{t}{\tau_{Li}}} - e^{-\frac{t}{\tau_{Be}}} \right)$$

N_0- initial number of $^{7}Be^{3+}$ ions

nuclear life time

remark: $^{7}Li^{3+}$ not distinguishable from $^{7}Be^{3+}$

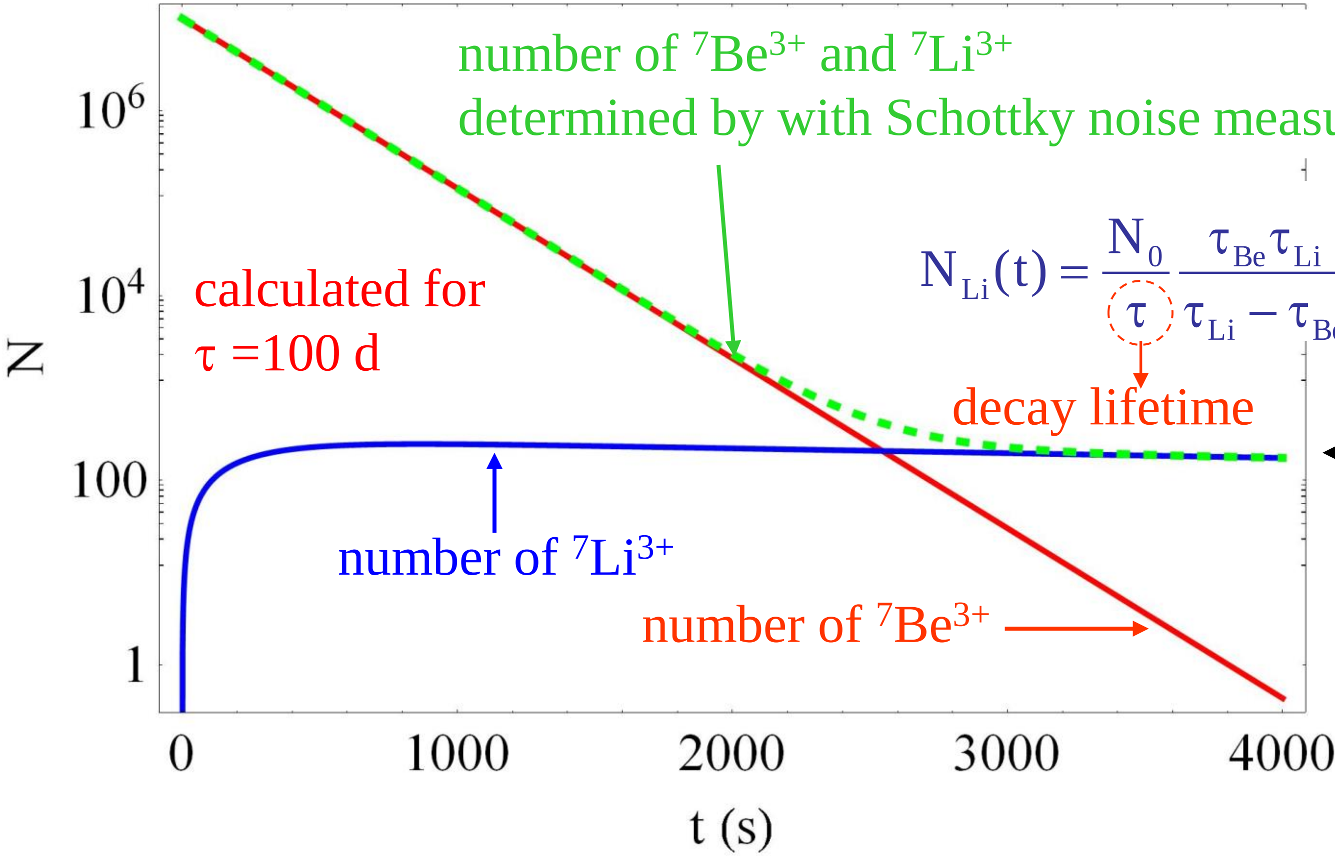
measurement of: $N_{Li}(t)+N_{Be}(t)$, N_0, τ_{Li}, $\tau_{Be} \Rightarrow \tau$

Half life of $^{7}Be^{3+}$

$$^{7}Be^{3+} + e^{-} \rightarrow {}^{7}Li^{3+} + \nu_e$$ estimated $\tau \approx 100$ d

K-shell electron

example: **$N_0 = 10^7$ $^{7}Be^{3+}$** E=56 MeV $\Rightarrow$ τ_{Be}= 240 s , τ_{Li}= 8400 s (for p=5·10^{-11} mbar)

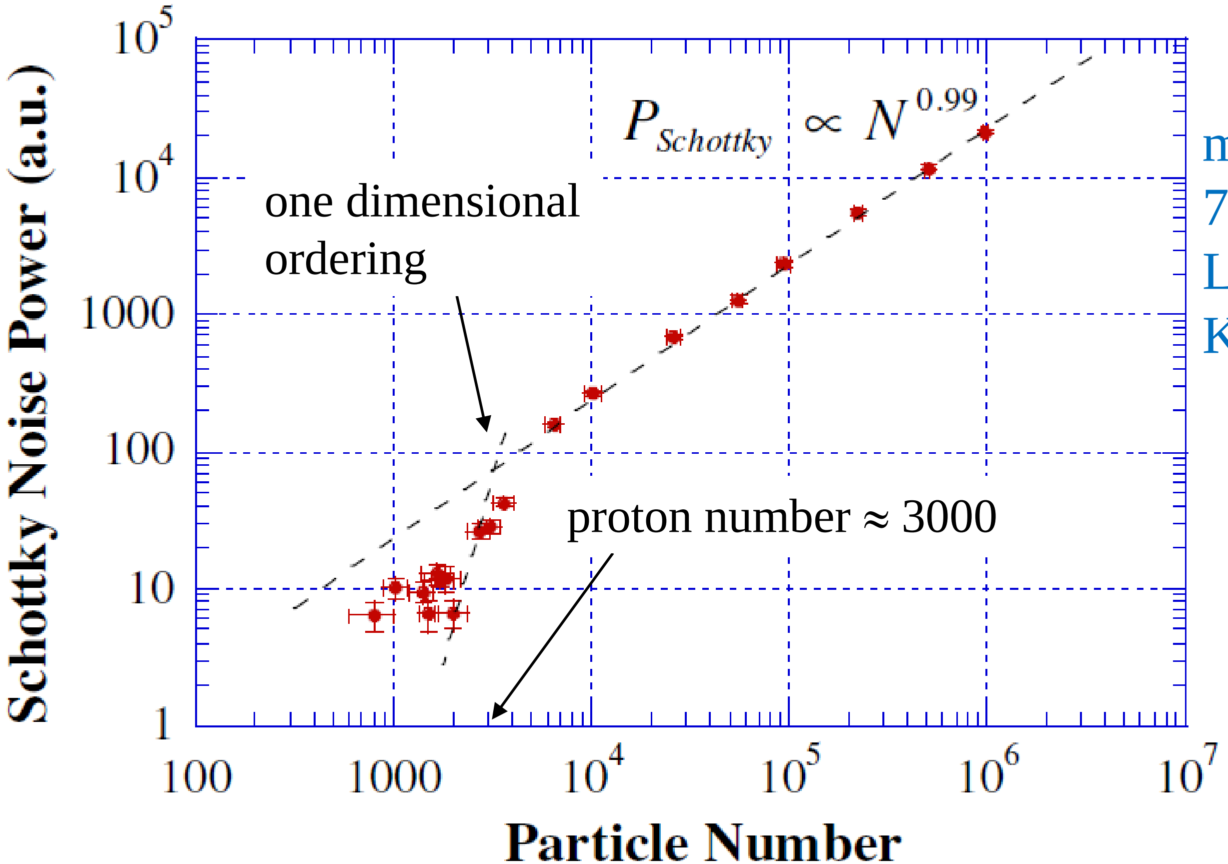


$$N_{Li}(t) = \frac{N_0}{\tau} \frac{\tau_{Be}\tau_{Li}}{\tau_{Li} - \tau_{Be}} \left(e^{-\frac{t}{\tau_{Li}}} - e^{-\frac{t}{\tau_{Be}}} \right)$$

← **N_{Li}=174**

not possible to distinguish between $^{7}Li^{3+}$ and $^{7}Be^{3+}$ ions !

Schottky noise power and particle number



measured with 7 MeV protons, LSR storage ring Kyoto university

Schottky noise as a function of proton number, measured at the LSR storage ring (Kyoto University) , T. Shirai et al. PRL 98, 204801 (2007)

phase transition observed in many storage rings at ion numbers: 1000-3000

To determine particle number from Schottky noise: number of particles **N>3000**

Lifetime determination of $^{7}Be^{3+}$

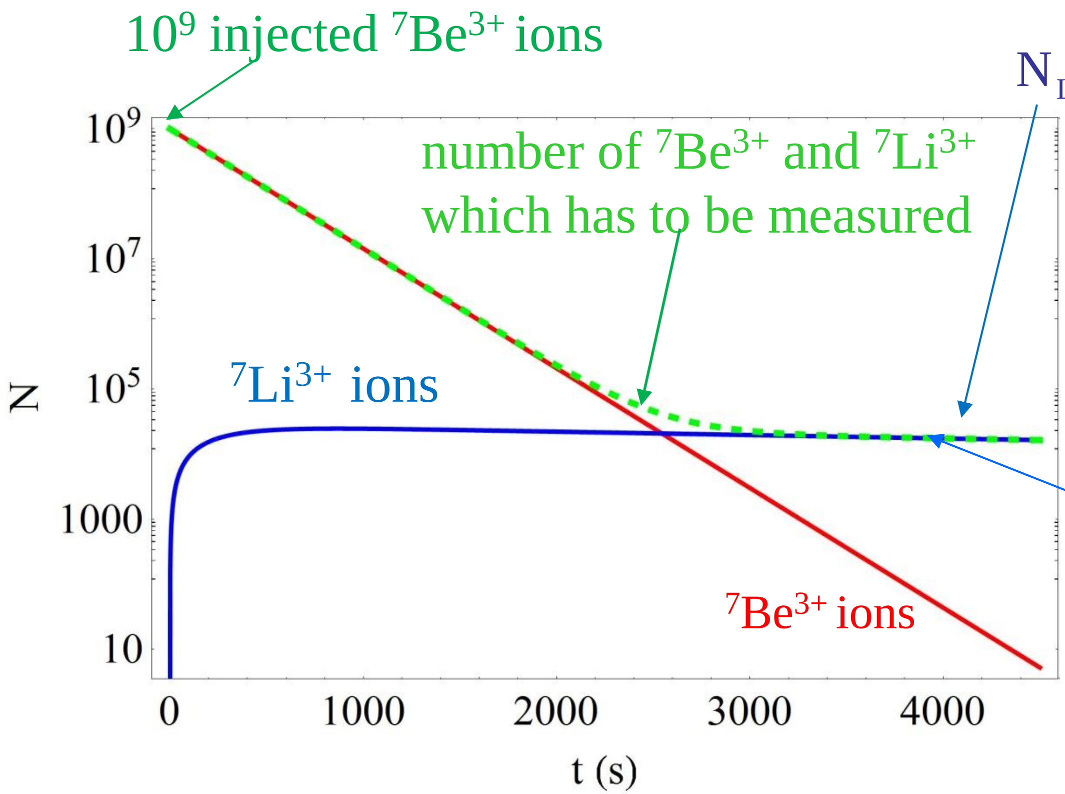
Accumulate 10^9 ions:

10^8 ions injected with multi turn injection and 10 ECOOL stacking cycles

filling time ≈ 30 s

$$N_{Li}(t) = \frac{N_0}{\tau} \frac{\tau_{Be}\tau_{Li}}{\tau_{Li} - \tau_{Be}} \left(e^{-\frac{t}{\tau_{Li}}} - e^{-\frac{t}{\tau_{Be}}} \right)$$

decay lifetime



N_{Li}=17400

remark: 10^9 $^{7}Be^{3+}$ ions are much below the **space-charge limit:** N=5.8·10^9

this means the life-times τ_{Be} and τ_{Li} should not effected by the beam intensity !

Space charge limit due to inchoherent tune

maximum possible stored ion number: $N = \frac{A}{q^2}\frac{2\pi}{r_p}\cdot B\cdot\beta^2\cdot\gamma^3\cdot\varepsilon\cdot(-\Delta Q)$

$-\Delta Q$ - possible incoherent tune shift TSR: $-\Delta Q \approx 0.065$-0.1 for B=1

with $I = q\cdot e_0\cdot N\cdot f_0$ and $\varepsilon \propto \left(\frac{q^4}{A^2}\frac{N}{\lambda_{Cool}}\frac{1}{\beta^3}\right)^{0.44}$ $\lambda_{cool} \propto n_e\frac{q^2}{A}$ $n_e \propto \beta^2$ (α_{ex}=const)

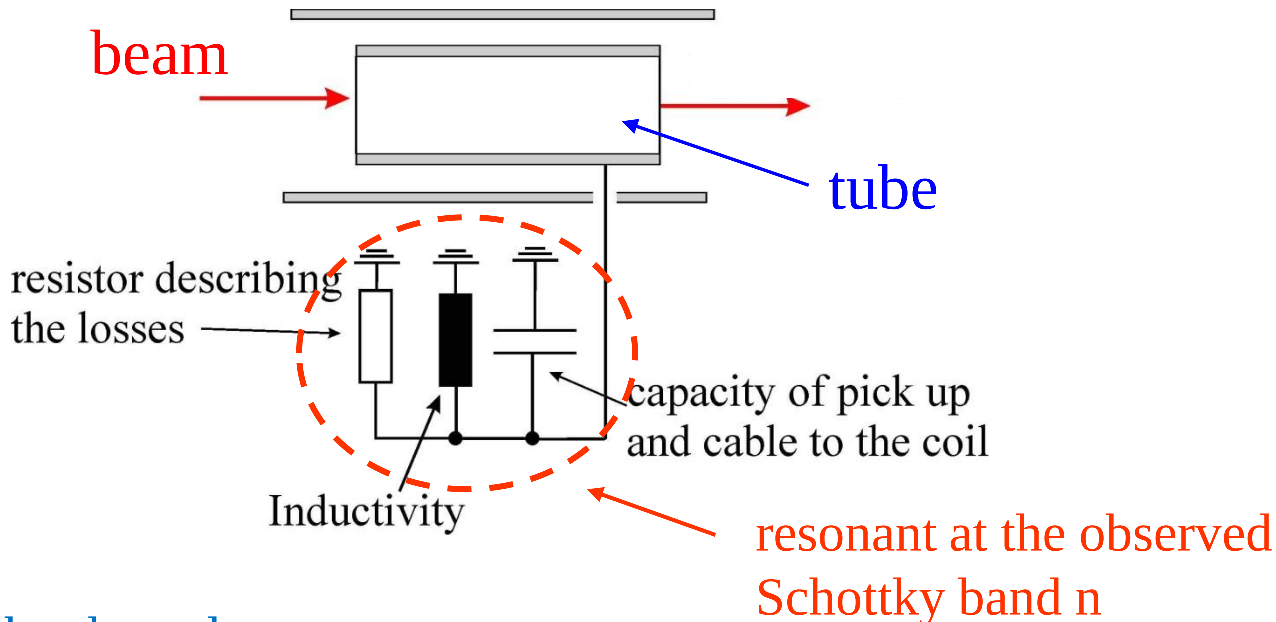
intensity limit: $I = const\frac{(A^{19}\cdot E^9)^{1/28}}{q}$ const is calculated from the $^{12}C^{6+}$ data:

Ionm	E [MeV]	Intensity [μA]	calculation I[μA]
p	21	1000	740
$^{16}O^{8+}$	98	750	1000
$^{12}C^{6+}$	73	1000	1000
$^{32}S^{16+}$	195	1500	999
$^{35}Cl^{17+}$	293	1000	1130

stability limit incoherent tune shift $I \approx 1$ mA

space charge limit $^7Be^{3+}$ (E=56 MeV) : I=1.3 mA ⇔ N=5.8 10^9

TSR@ISOLDE Schottky pick-up



Schottky voltage power spectrum

$$\overline{P}_0(n) = \hat{U}^2(n)\frac{N}{2} = \left(Q_w \frac{\sqrt{2}}{\pi}\frac{1}{n}\frac{Q}{C}\sqrt{1-\cos(n\,2\pi\frac{L}{C_0})}\right)^2 \frac{N}{2}$$

power spectrum of a single ion

n- harmonic number of revolution frequency

Q-ion charge

Q_w- Q value of **LC** circuit

N- number of ions

Detection Limit Schottky pick-up at TSR@ISOLDE

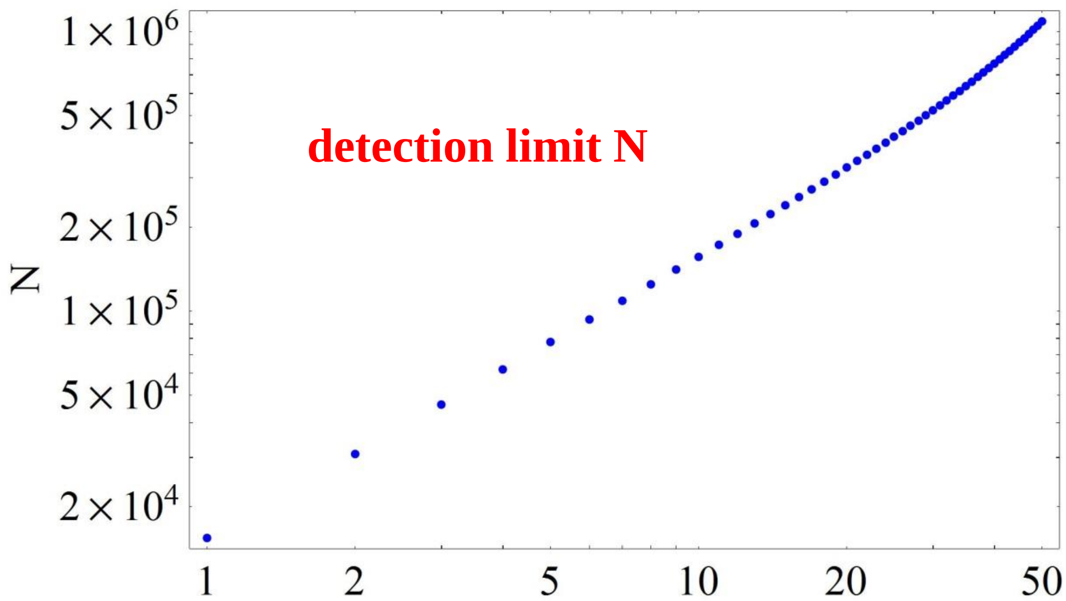
Schottky Spectrum is visible if: $\overline{P}_0(n) > U^2_{r,amplifier} \cdot \Delta f_{Schottky}$ ← frequency spread of Schottky signal:

$$\Delta f_{Schottky} = \eta \, \Delta p / p \, n f_0$$

Schottky power ← amplifier noise

$$\overline{P}_0(n) = \hat{U}^2(n)\frac{N}{2} = \left(Q_w \frac{\sqrt{2}}{\pi}\frac{1}{n}\frac{Q}{C}\sqrt{1-\cos(n\,2\pi\frac{L}{C_0})}\right)^2 \frac{N}{2}$$

For Q_w=1 (non resonant measurement) it follows:



harmonic number → n

Input

ion $^7Li^{3+}$ E=56 MeV

Q_w=1 non resonant measurements

pick-up length: L=0.35 m

C=300 pF

η=0.9 (standard mode)

revolution frequency: $f_0=0.7\ 10^6$ Hz

amplifier noise: $0.5\,nV/\sqrt{Hz}$

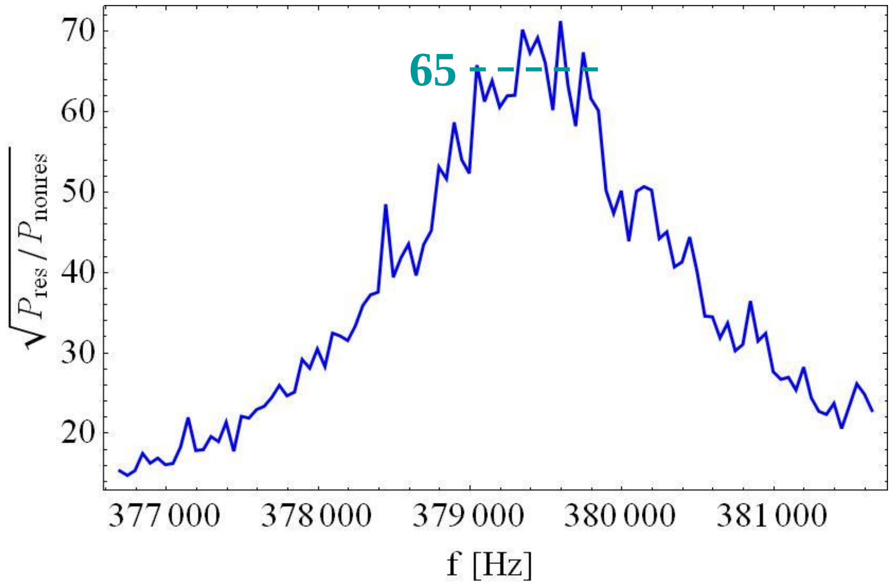
full momentum spread width:

$\Delta p/p = 2 \cdot 10^{-5}$

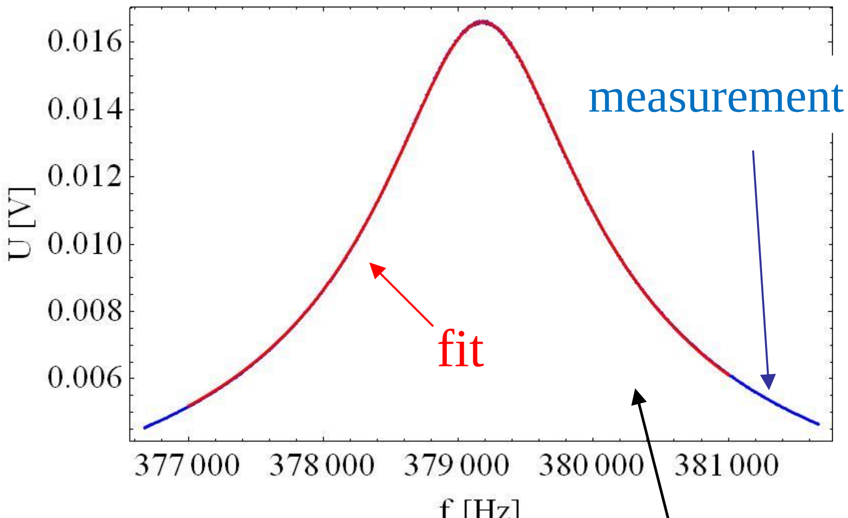
Improvement of noise signal ratio at resonant measurement

P_{res}- noise of preamplifier (resonant measurement)
$P_{nonresonant}$- noise of pre amplifier (non resonant measurement)
pre amplifier: ULNA

pre amplifier noise



Q_w value measurement



Q_w value : Q_w**=263**

$$\Rightarrow \text{improvement of SNR} = \frac{Q}{\sqrt{P_{res}/P_{nonres}}} = \frac{263}{65} = 4$$

detection limit $N \sim \frac{1}{SNR^2} = \frac{1}{16}$ $\Rightarrow$ detection limit for $^7Li^{3+} \approx 1000$ ions (n=1)

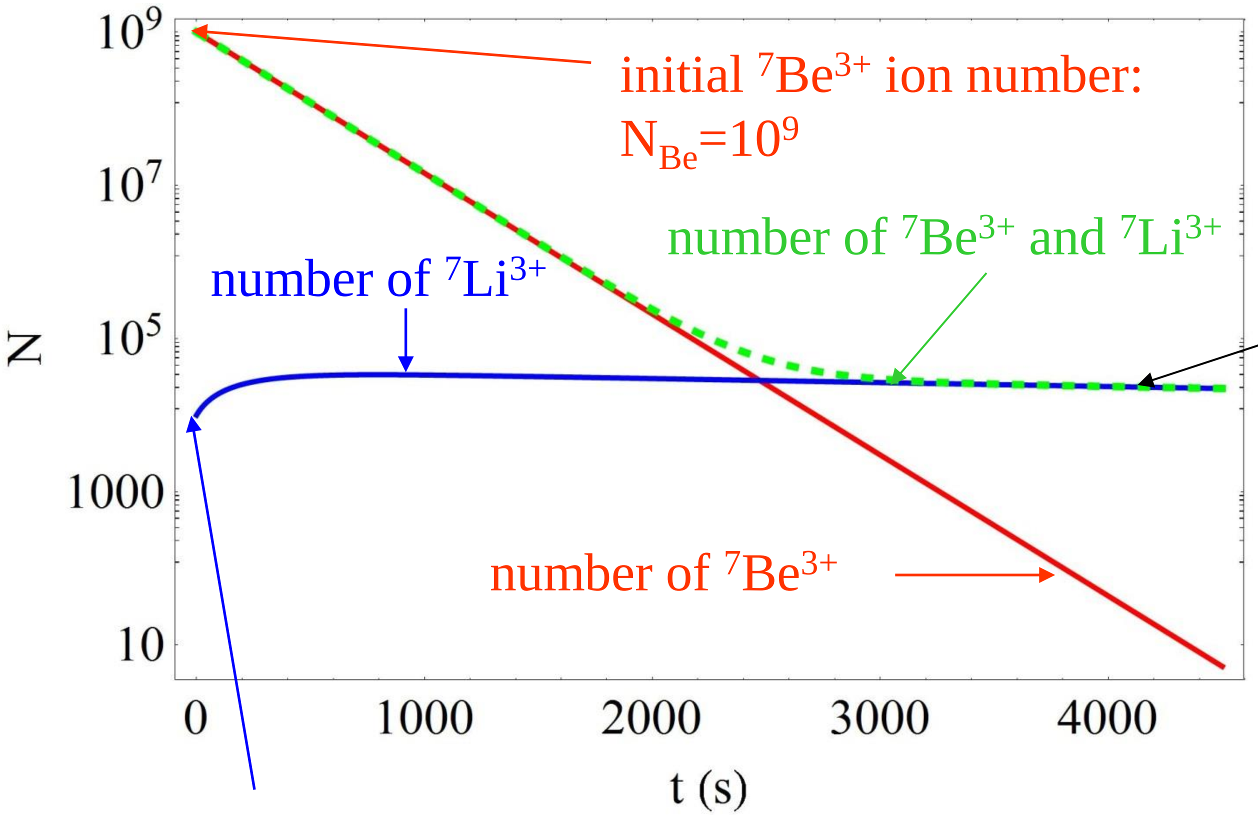
remark: to measure $^7Li^{3+}$ ion number of ≈ 20000 >> detection limit of ≈ 1000

Contamination of the $^7Be^{3+}$ beam with $^7Li^{3+}$ ions

$$^7Be^{3+} + e^- \rightarrow {}^7Li^{3+} + \nu_e$$ nuclear life time $\tau \approx 100$ d

example: $N_0 = 10^9$ $^7Be^{3+}$ E=56 MeV $\Rightarrow$ τ_{Be}= 240 s , τ_{Li}= 8400 s (for $p = 5 \cdot 10^{-11}$ mbar)

contamination of the $^7Be^{3+}$ beam: **10^4 $^7Li^{3+}$** ions



$$\frac{N_{Li}(t=0\,s)}{N_{Be}(t=0\,s)} = 10^{-5}$$

N_{Li}=23600

without contamination:

N_{Li}=17400

$\Rightarrow$ error in the lifetime τ determination **≈ 35 %**

initial $^7Li^{3+}$ ion number: $N_{Li}=10^4$

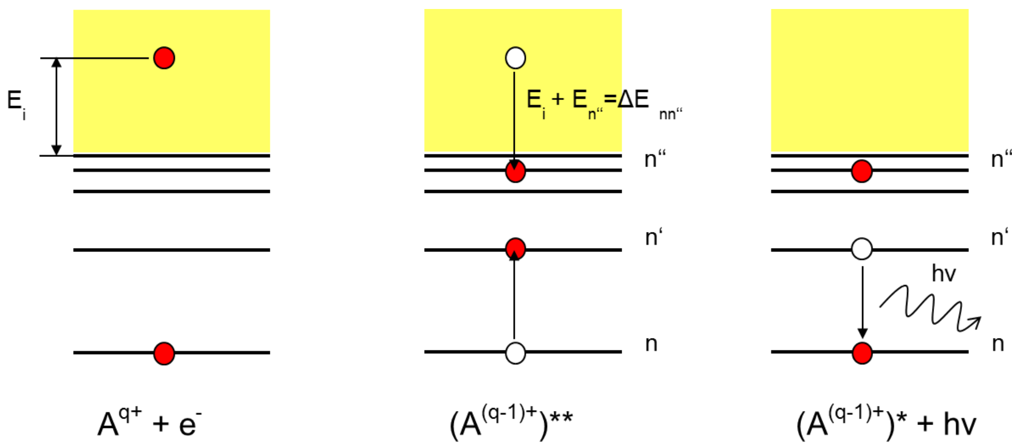
initial $^7Be^{3+}$ ion number: $N_{Be}=10^9$

^{7}Li ion detection by using dielectronic recombination

$$^{7}Be^{2+} + e^{-} \rightarrow {}^{7}Li^{2+} + \nu_e$$

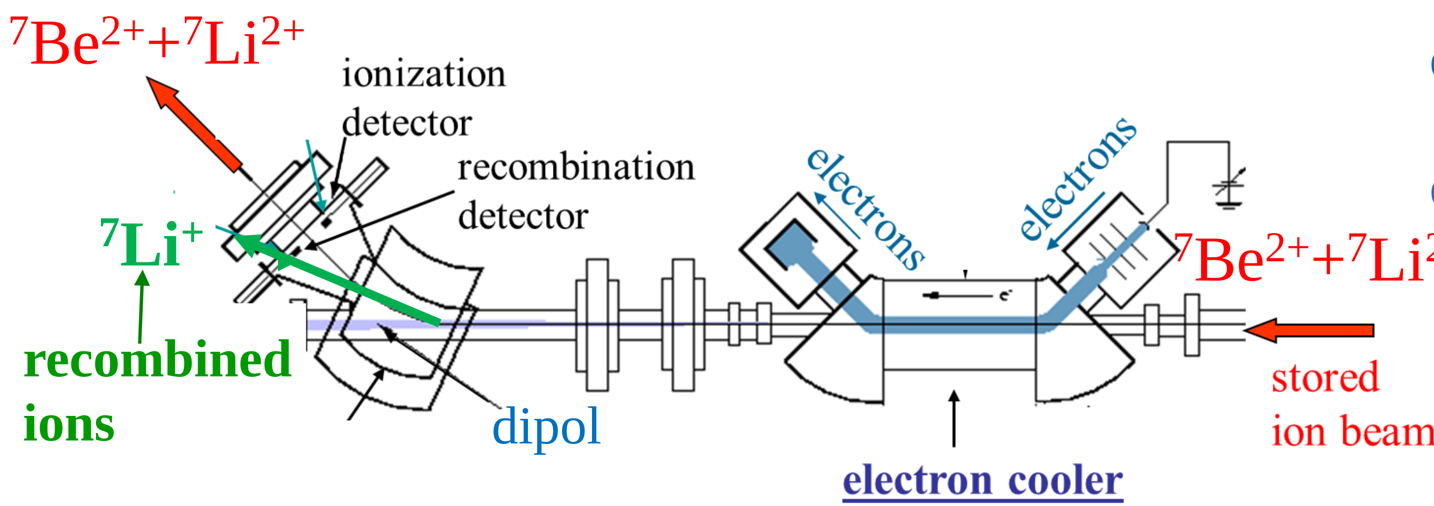
proposal by Stefan Schippers

K-shell electron



dielectronic recombination:

measuring electron capture in the cooler at dedicated, ion specific, resonance energies. Detector counting rate proportional to number of $^{7}Li^{2+}$ ions. Experiment has to be done with injected $^{7}Be^{2+}$ ions.



counting rate

electron density

$n_e = 5 \cdot 10^{7}\ 1/cm^{3}$

electron temperature

$T_{\parallel} = 0.2$ meV

$T_{\perp} = 20$ meV

ion intensity

$N = 10^{4}\ {}^{7}Li^{2+}$ ions

R ≈ 0.5 1/s

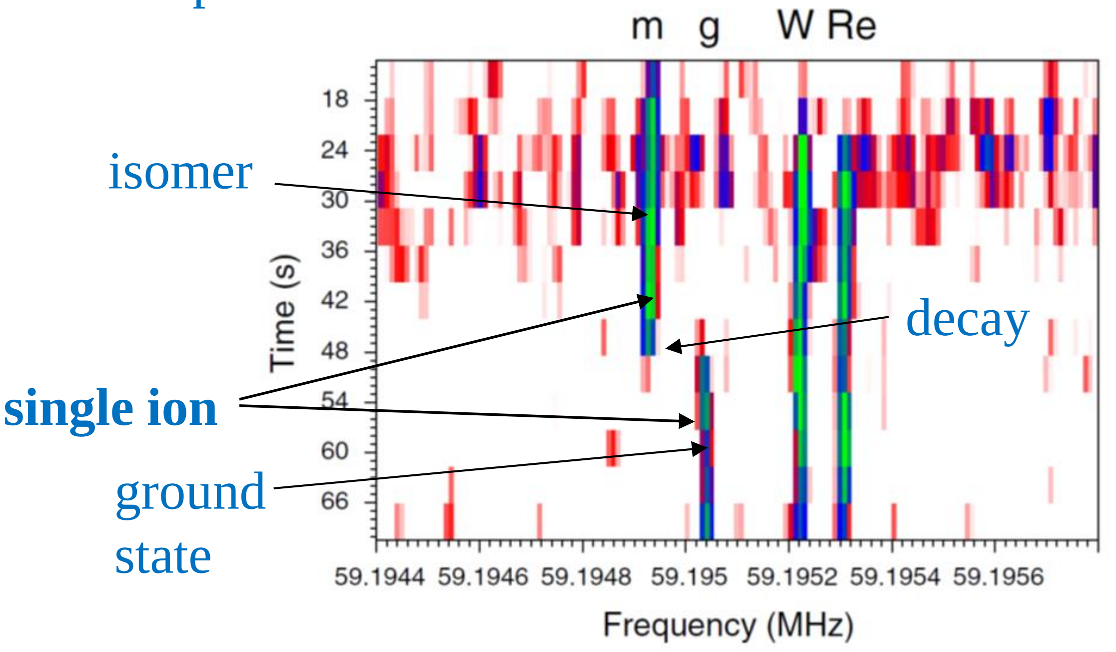
possible problem: electron capture of $^{7}Be^{2+}$ in the residual gas, which is very low

Long-lived isomeric states

Nuclear isomers are metastable excited stated with half live from ns to years

Isomers can be measured with Schottky noise analyses

example: isomeric state measurement of $^{187}Ta^{73+}$



Single ion detection:
Observing in the Schottky spectra the decay of an isomeric state of $^{187}Ta^{73+}$.
ref. M. W. Reed,
PRL 105, 172501 (2010)

GSI: so far **singly ion detection** with charge states q≥59@400 MeV/u,
S.Sanjari private comminication and P. Kienle et al. Physics Letters B 726 (2013)

TSR@Isolde: Isomers will have smaller charge states q compare to isomers stored at ESR storage ring.

Schottky power: $P_{Schottky} \sim q^2$ q- ion charge state

⇒ single ion detection and measuring of isomeric state very challenging

Single ion detection

Single ion: power voltage spectrum:

$$P_0(n) = \hat{U}^2(n) = \left(Q_w \frac{\sqrt{2}}{\pi} \frac{1}{n} \frac{Q}{C} \sqrt{1-\cos(n\,2\pi \frac{L}{C_0})} \right)^2$$

Q_w- Q value of oscillator
Q_w=1 non resonant measurement

spectrum is visible if: $P_0(n) > U^2_{r,Qw} \cdot \Delta f_{bandwidth} = \alpha^2(Qw)\, U^2_{r,Qw=1} \cdot \Delta f_{bandwidth}$

n harmonic number of f_0

amplifier noise

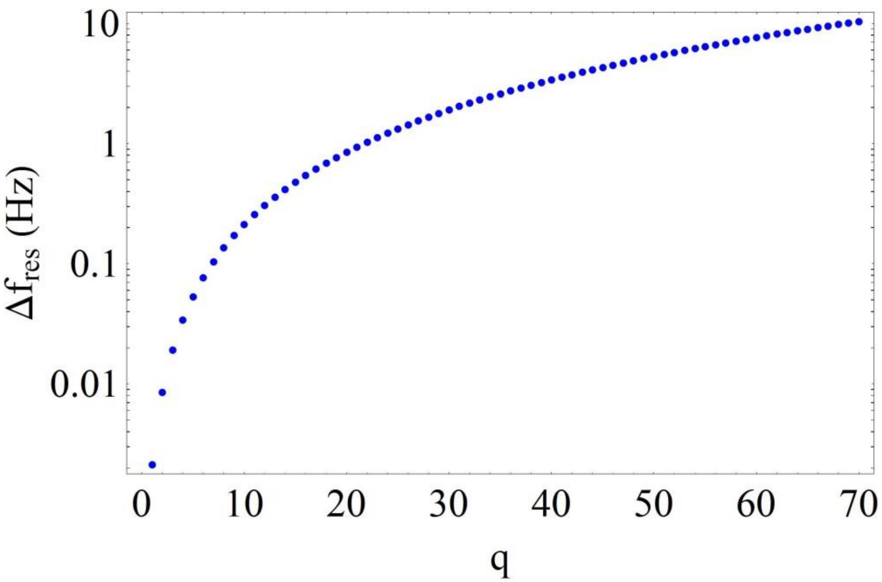
measuring band width

amplification of noise at resonant measurement

Input

amplifier noise $U_{r,Qw=1} = 0.5\,nV/\sqrt{Hz}$
measurement: Q_w= 263, $\alpha(Q_w=263)=65$
pick-up length: L=0.35 m
total capacity: C=300 pF
circumference C_0=55.42 m
harmonic number: **n=50**
ion charge: Q=q·e

relatively high harmonic number **n** was chosen to get larger Δf splitting of the individual lines in the spectrum



necessary band width to measure a single ion as a function of the ion charge state q

Mass measurements in storage rings

revolution frequency f_0 in first order

$$\frac{\Delta f_{Schottky}}{f_{Schottky}} = \frac{\Delta f_0}{f_0} = -\alpha \frac{\Delta(m/Q)}{(m/Q)} + \left(\frac{1}{\gamma^2} - \alpha\right)\gamma^2 \frac{\Delta v}{v}$$

determined by electron cooling

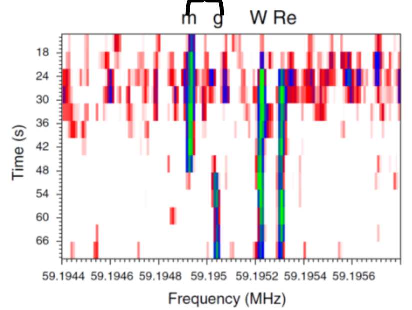
momentum compaction:

$$\alpha = \frac{\Delta C/C}{\Delta p/p} = \frac{1}{\gamma_{tr}^2} \approx \frac{1}{Q_x^2}$$

horizontal tune

slip factor: η

isochronous mode: **$\eta=0$**



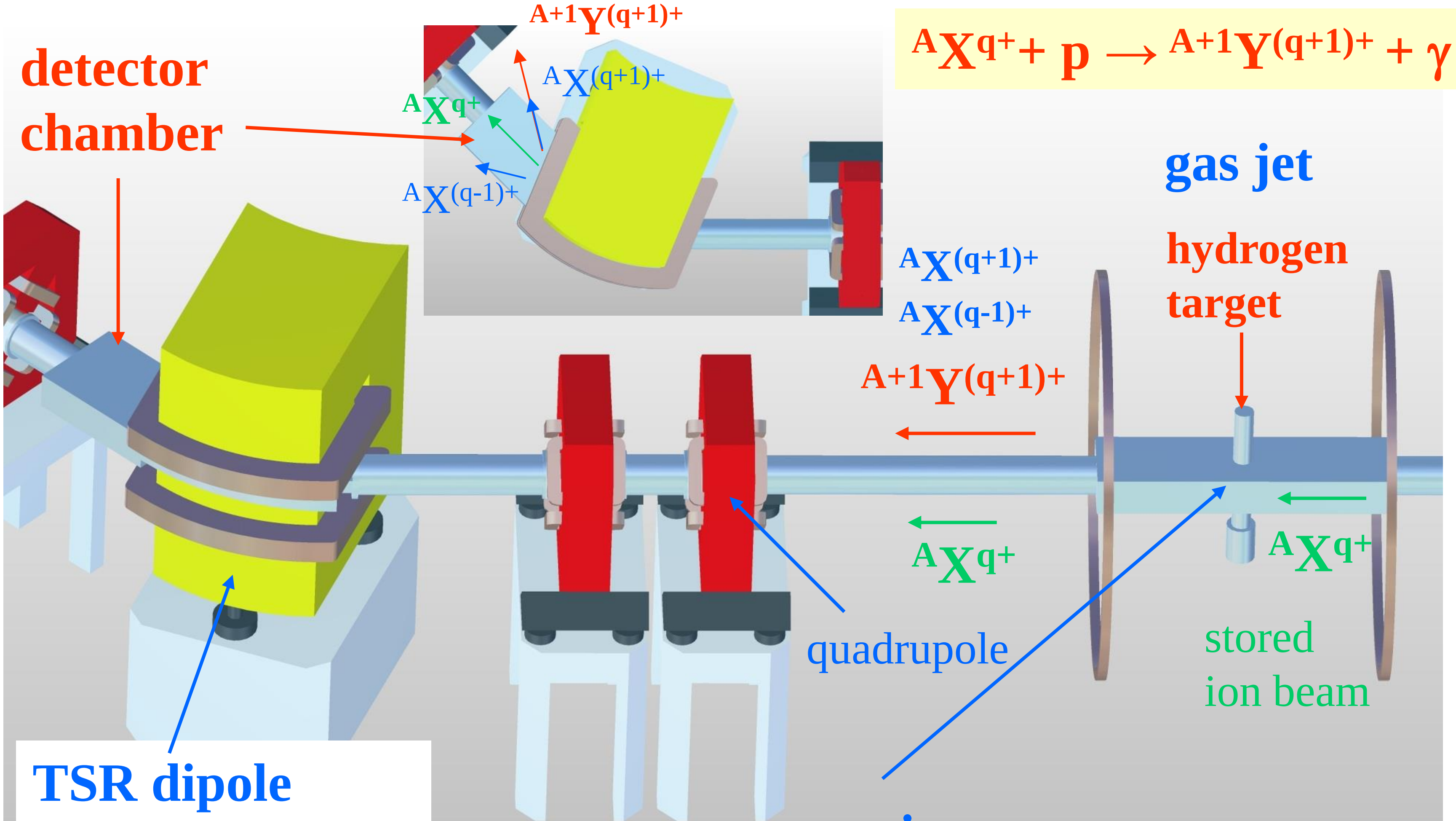
an isomeric state of ^{187}Ta.
ref. M. W. Reed,
PRL 105, 172501 (2010)

ESR/GSI: high energies: $\gamma \approx 1.3$, slip factor can set up to $\eta=0$
operation in synchronous mode possible

TSR@ISOLDE: energies $\gamma \approx 1 \Rightarrow$ for $\eta=0$: $Q_x \approx 1$ strongest resonance
in a storage ring, TSR operation at $Q_x \approx 1$ not possible
no synchronous mode possible
ref. M. Grieser et al., CERN 94-03 (1994)

many ions: Schotty spectrum width: $\Delta f_{Schottky} = \eta \, \Delta p/p \, n f_0$
more difficult to measure Schotty spectrum
at low ion numbers: $\overline{P}_0(n) > U^2_{r,amplifier} \cdot \Delta f_{Schottky}$

Proton capture reaction for the astrophysical p-process



TSR dipole

separation of $^{A+1}Y^{(q+1)+}$, $^{A}X^{(q+1)+}$ and $^{A}X^{(q-1)+}$ from the stored ion beam $^{A}X^{q+}$

reactions

nuclear: $^{A}X^{q+} + p \rightarrow {}^{A+1}Y^{(q+1)+} + \gamma$

ionization: $^{A}X^{q+} \rightarrow {}^{A}X^{(q+1)+} + e$

recombination: $^{A}X^{q+} + e \rightarrow {}^{A}X^{(q-1)+} + e$

Separation of $^{A+1}Y^{(q+1)+}$ and $^{A}X^{(q+1)+}$

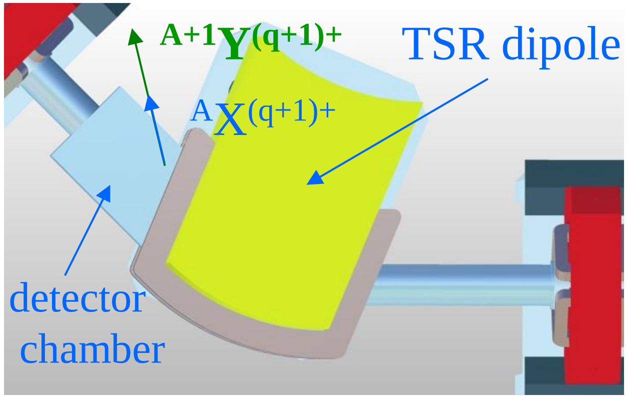
1. Nuclear reactions $^{A}X^{q+} + p \rightarrow {}^{A+1}Y^{(q+1)+} + \gamma$

momentum conservation $A \cdot m_0 \cdot v_p = (A+1) m_0 \cdot v$

v_p-projectile velocity
v- velocity of $^{A+1}Y^{(q+1)+}$

$$\Rightarrow \quad v = \frac{A \cdot v_p}{(A+1)}$$

rigidity $^{A+1}Y^{(q+1)+}$ $\Rightarrow \quad B\rho = \frac{p}{Q} = \frac{A}{(q+1)e_0} m_0 v_p$



2. Ionization projectile: $^{A}X^{q+} \rightarrow {}^{A}X^{(q+1)+} + e$

rigidity $^{A}X^{(q+1)+}$ $\quad B\rho = \frac{p}{Q} = \frac{A}{(q+1)e_0} m_0 v_p$

$\Rightarrow$rigidities of $^{A}X^{(q+1)+}$ and $^{A+1}Y^{(q+1)+}$ are equal

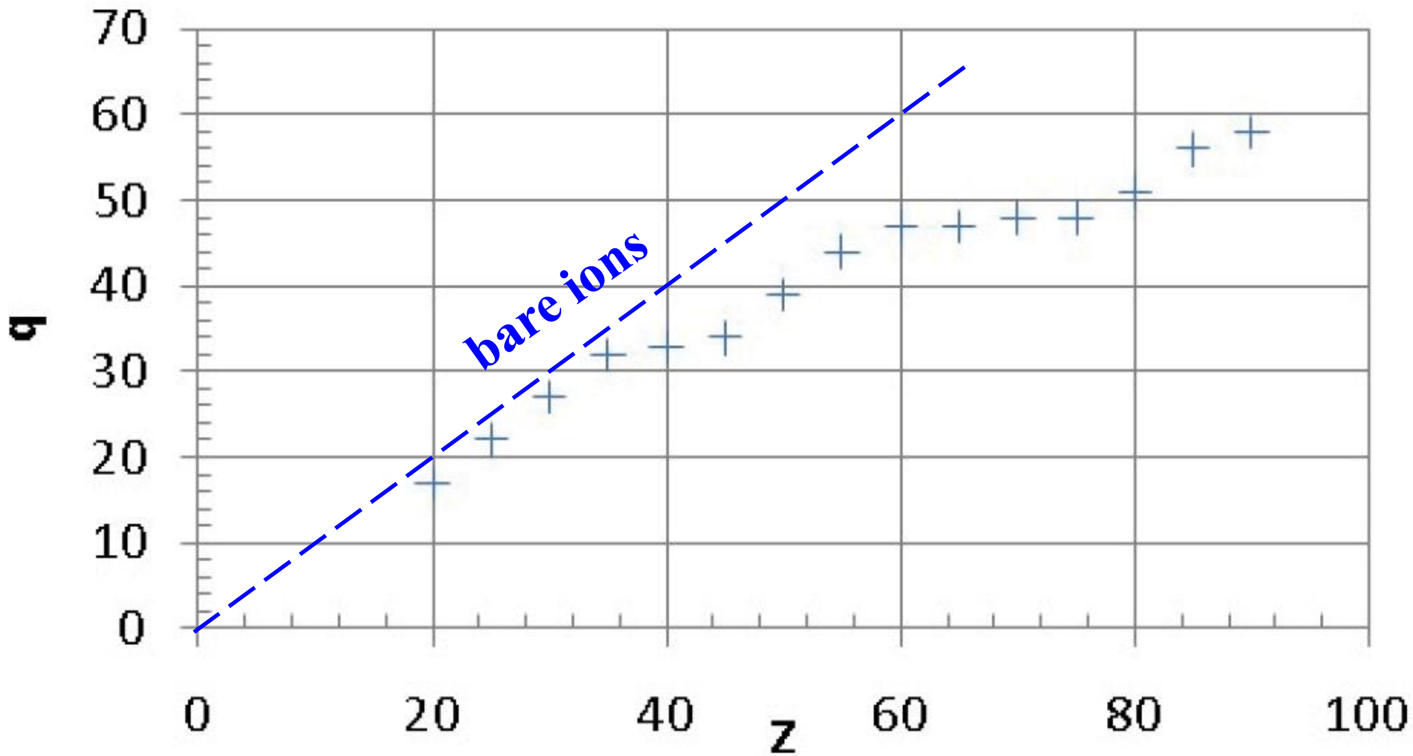
$\Rightarrow$ $^{A}X^{(q+1)+}$ and $^{A+1}Y^{(q+1)+}$ **can not separated with magnetic fields !**

$\Rightarrow$ $^{A}X^{(q+1)+}$ and $^{A+1}Y^{(q+1)+}$ ions are one same detector position

$\Rightarrow$**experiment has to carry out with bare $^{A}X^{q+}$ ions !**

Charge State in REXEBIS

Estimated attainable charge states in REXEBIS as a function of ion Z (ref. TSR@Isolde TDR)



Z of relevant ions to study astrophysical p process: **Z>40**

⇒ stripping process after HIE-ISOLDE linac !

example: **^{96}Ru (Z=44)** E=10 MeV/u equilibrium charge state after stripping:

charge state → ; charge distribution →

q	42	43	44
ε	0.985	$1.4\cdot10^{-3}$	$6\cdot10^{-5}$

← bare ion (44)

calculated with LISE 9.7.1

Upgrade of REXEBIS

A new EBIS, producing much higher charge states is under investigation at CERN

Design parameters HIE-ISOLDE / TSR@ISOLDE breeder

	Charge breeder	REXEBIS
Electron energy [keV]	150	5
Electron current [A]	2-5*	0.2
Electron current density [A/cm^2]	1-2x10^4	100
Trap pressure (mbar)	~10^{-11}	~10^{-11}
Ion-ion cooling needed	YES	NO
Extraction time (us)	<30	>50

↑ new TSR@Isolde charge breeder

With the new TSR@Isolde charge breeder bare ions up to Z=60 should be possible

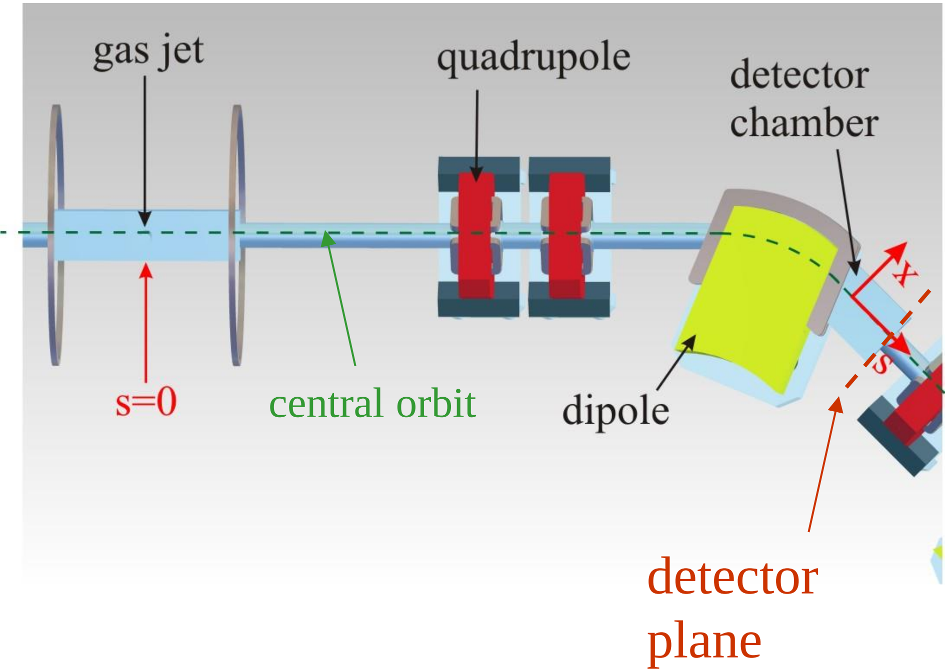
Much more details about this project was given by Fredrik Wenander during this workshop

Pick up reaction with a stored $^{86}Kr^{36+}$ ion beam

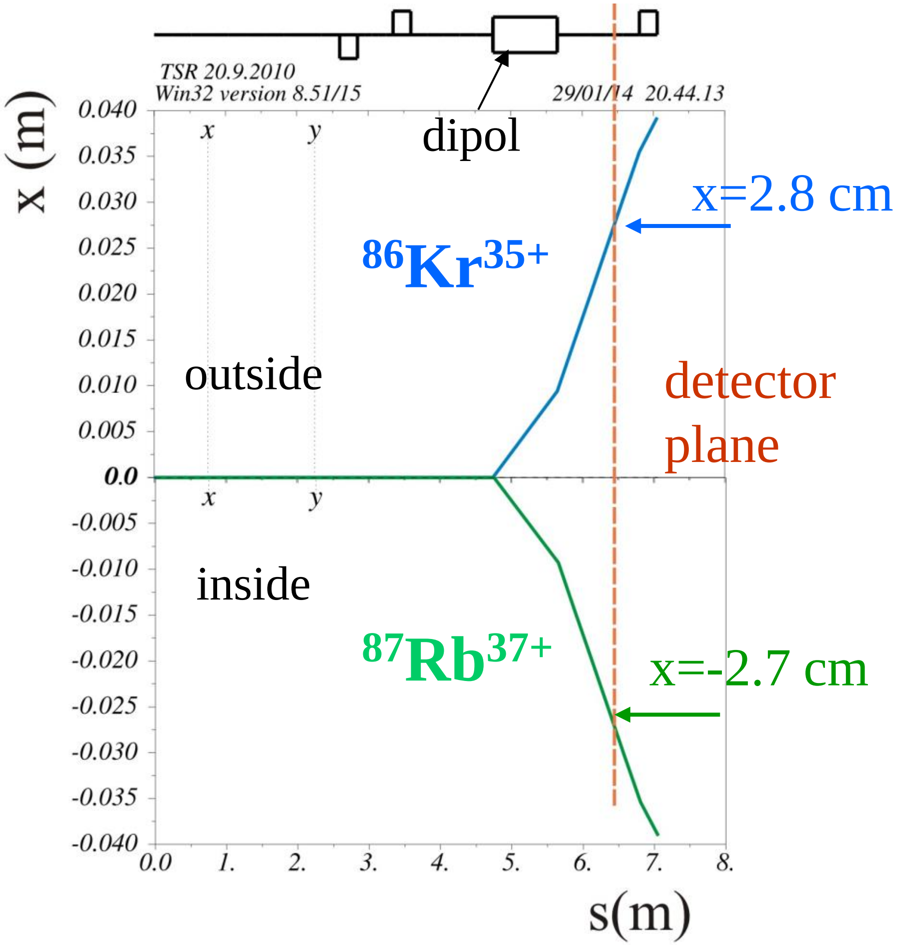
$$^{86}Kr^{36+} + p \rightarrow {}^{87}Rb^{37+} + \gamma$$

recombination: $^{86}Kr^{36+} + e \rightarrow {}^{86}Kr^{35+}$

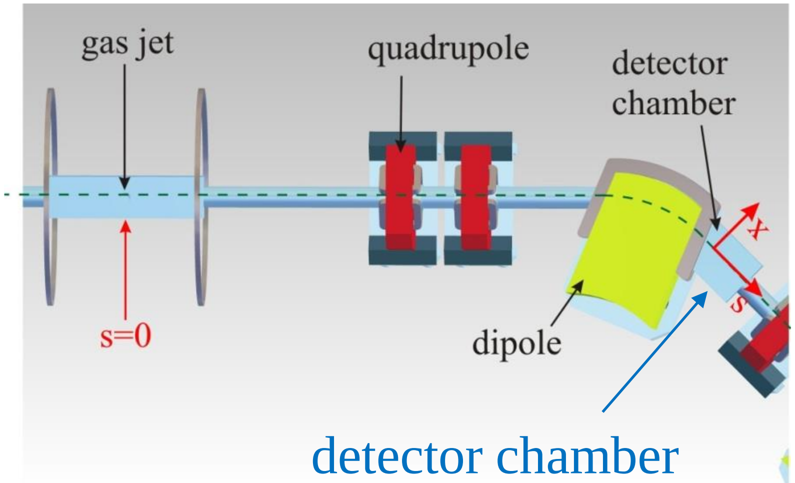
reference system



ion orbits of $^{87}Rb^{37+}$ and $^{86}Kr^{35+}$



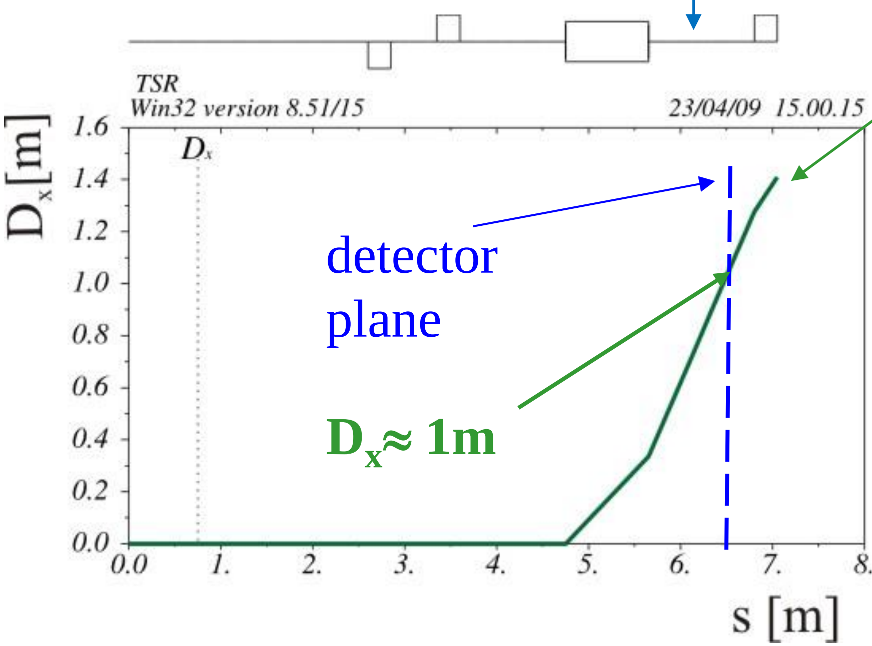
First Order calculation of ion trajectories



$$x = D_x \frac{\Delta B\rho}{B\rho} \qquad B\rho = \frac{p}{Q} = \frac{m \cdot v}{Q}$$

$$\text{with} \quad \frac{\Delta B\rho}{B\rho} = \frac{\Delta m}{m} + \frac{\Delta v}{v} - \frac{\Delta Q}{Q}$$

$$\Rightarrow \quad x = D_x \cdot \left(\frac{\Delta m}{m} + \frac{\Delta v}{v} - \frac{\Delta Q}{Q} \right)$$



x – horizontal position

D_x – dispersion Function

Δm – mass deviation to central particle with mass m

Δv – velocity deviation to central particle with velocity m

ΔQ - charge deviation to central particle with charge Q

Reaction Rate

if ion beam width $\sigma_t > \sigma_{beam}$

then $R = \sigma \cdot n_t \cdot f_0 \cdot N$

$$n_t = \int_0^l n \cdot ds \approx 10^{14}\, 1/cm^2$$

projected target density

R reaction rate
σ_t - target width
σ_{ion} ion beam width
σ cross section
n target density
n_t target thickness
f_0 revolution frequency
N **number of stored ions**

ECOOL stacking to fill the storage ring with ions

$$N = N_{inj} \frac{1}{T_{cool}} \tau$$

N_{inj}- injected particle number
T_{cool}- cooling time:

for $\alpha \approx 10$, $0.03 \leq \beta \leq 0.16$: $T_{cool} \approx \frac{n_{max}}{n} \frac{A}{q^2} \cdot 3s$

n_{max}- maximum possible electron density

τ -life time determined by residual gas pressure/ECOOL (τ_v) and target thickness (τ_t):

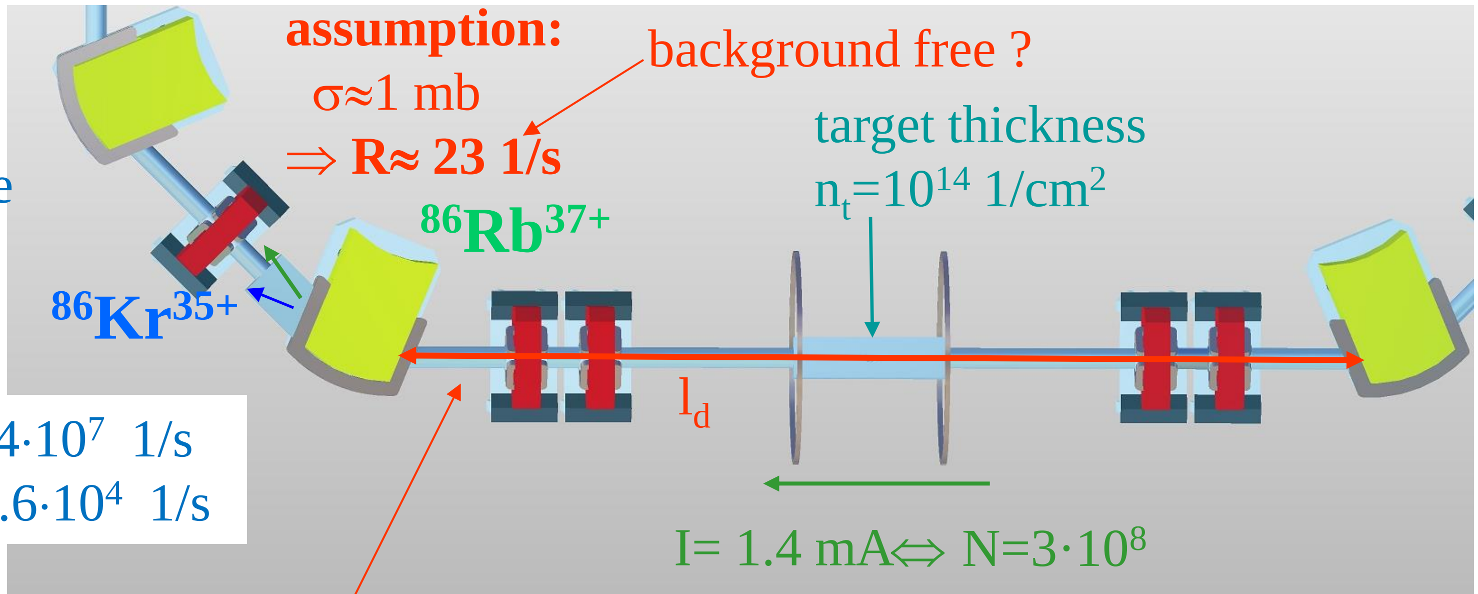
$$\frac{1}{\tau} = \frac{1}{\tau_v} + \frac{1}{\tau_t}$$

example:
for $^{86}Kr^{36+}$ E=860 MeV :
$N_{inj}=5 \cdot 10^7 - 10^8$ ions
$T_{cool} \approx 0.8$ s ($n/n_{max}=0.25$)
$\tau_v \approx 50$ s ($n/n_{max}=0.25$)
$\tau_t \approx 9$ s (electron capture target)
$N \approx 5 \cdot 10^8$ stacking: target on > space charge limit
space charge limit: $N= 3 \cdot 10^8$ ions $\Rightarrow$ with $\sigma=1$ mbarn: **R≈ 23 1/s**

Some remarks on $^{86}Kr^{36+} + p \longrightarrow {}^{87}Rb^{37+} + \gamma$ at the TSR

stored ion beam $^{86}Kr^{36+}$ E=860 MeV

from the target



$R \approx 3.4 \cdot 10^7$ 1/s

$R_{bg} \approx 8.6 \cdot 10^4$ 1/s

Background: electron capture in residual gas, very sensitive to C,N,O…

$\tau_{cap} \approx 581$ s at $p = 5 \cdot 10^{-11}$ mbar and normal TSR residual gas composition

$\Rightarrow$background counting rate for

$$R_{bg} = \frac{l_d}{C_0} \frac{N}{T_{cap}}$$

T_{cap}- capture life time

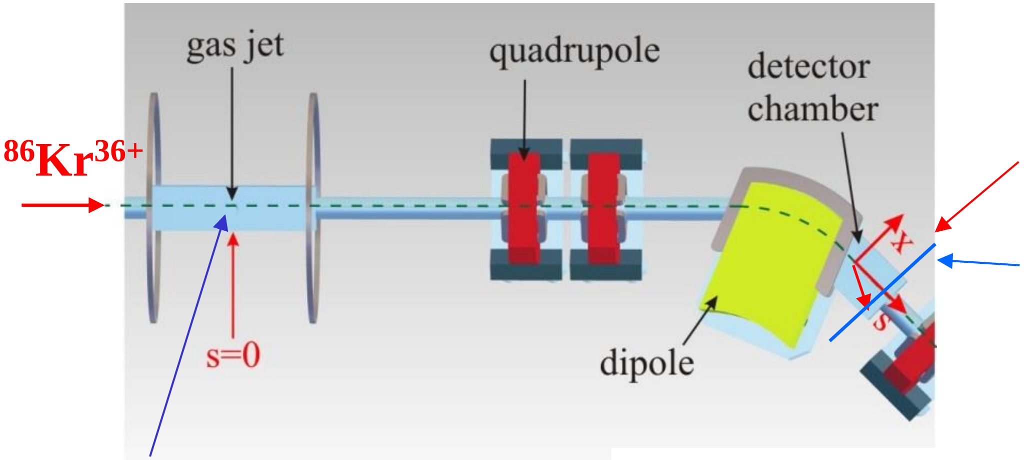
C_0- circumference of the TSR

l_d- distance between two dipole

life time τ of $^{86}Kr^{36+}$ determined by electron capture in the target:

T≈ 9 s

Can scattered ions hit the detector plane on the inside ?

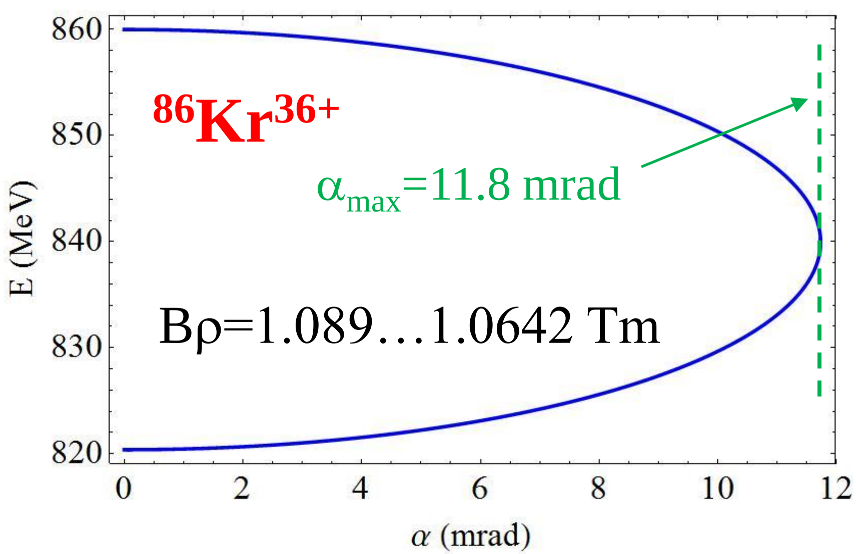


ions produced by a pick up reaction are deflected to the inside of TSR

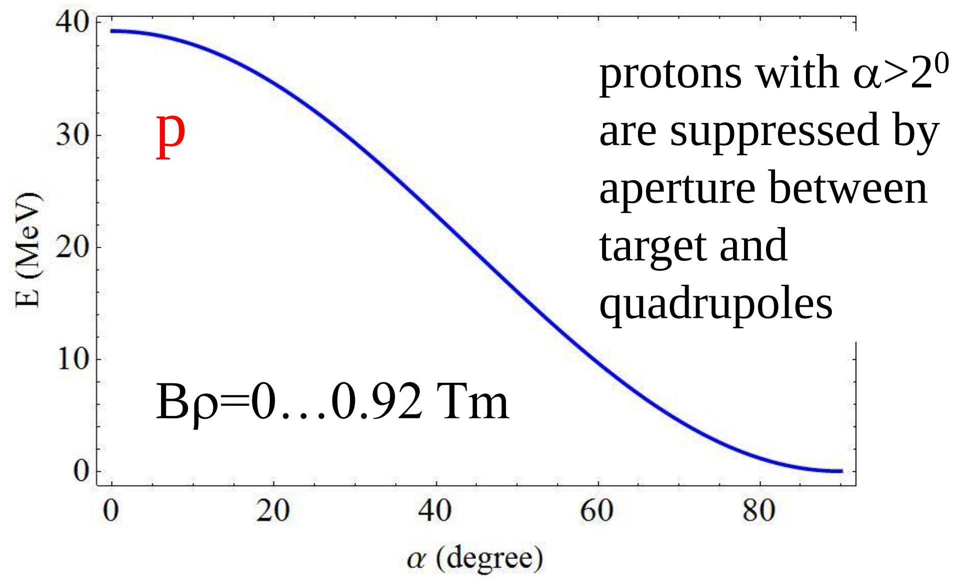
detector plane

gas jet: elastic scattering: $^{86}Kr^{36+} + p \rightarrow {}^{86}Kr^{36+} + p$

energy as a function of scattering angle

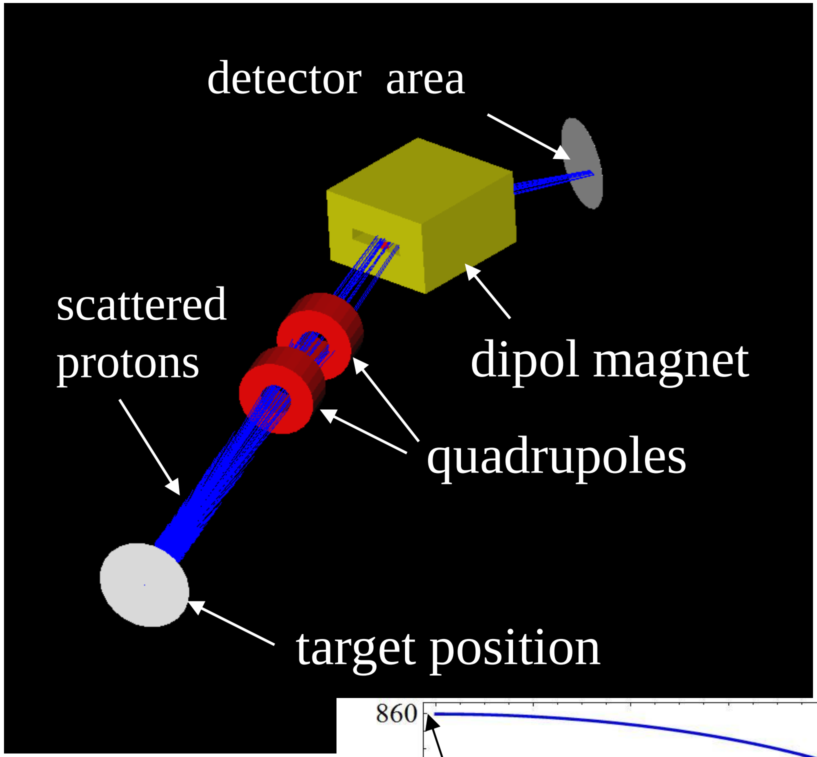


energy as a function of scattering angle

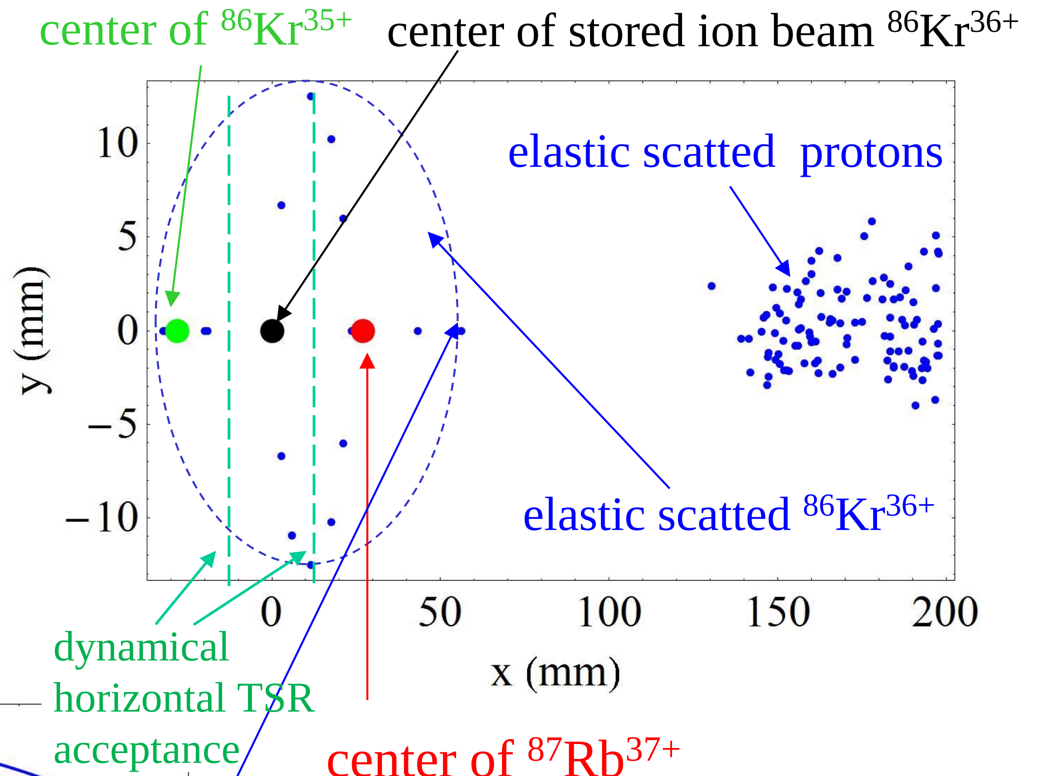


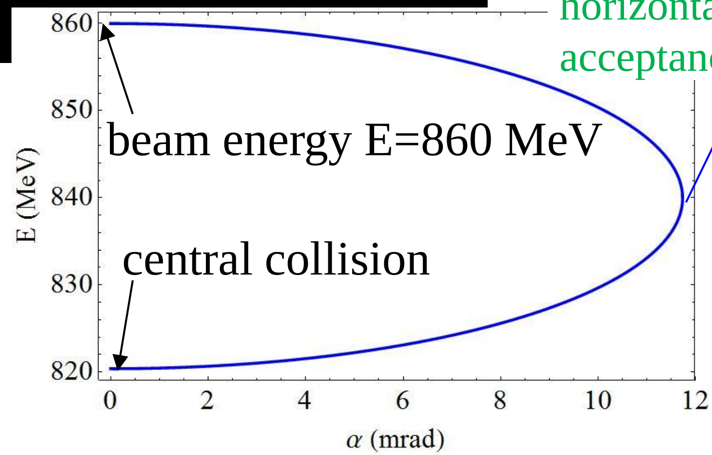
Simulation of elastic scattered ion beam

elastic scattered protons



ions on the detector plane



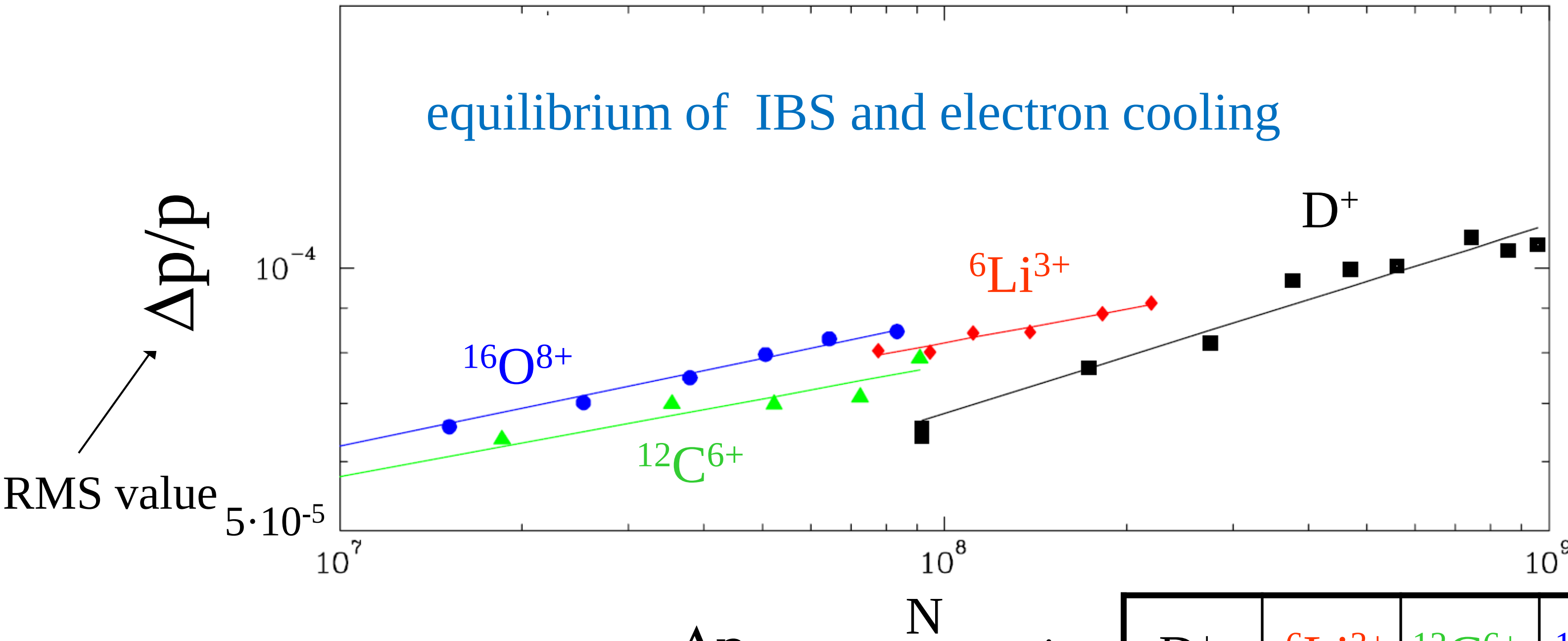


elastic scattered $^{86}Kr^{36+}$ energy E as a function of scatter angle α

Laser Spectroscopy of rare Isotopes

The attainable resolution within the TSR is determined by the longitudinal momentum spread of the stored electron cooled ion beam

At the TSR measured equilibrium momentum spread of electron cooled ion beams as a function of the particle number ($B\rho$=0.71 Tm, ß=0.11, $n_e=8\cdot10^6$ cm^{-3}, B_{cool}=418 Gauss)

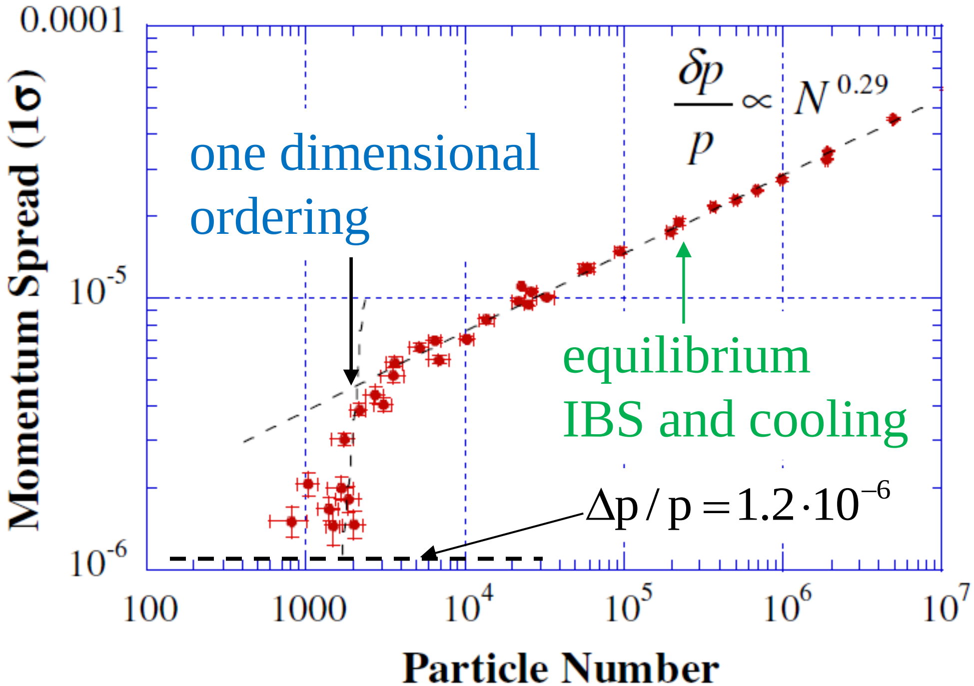


particle number scaling: $$\frac{\Delta p}{p} \sim N^{\alpha}$$

ion	D^+	$^6Li^{3+}$	$^{12}C^{6+}$	$^{16}O^{8+}$
α	0.22	0.13	0.13	0.13

remark: if the ion intensity is very low (N<1000) the ion temperature is given by the electron temperature, resulting in an ion momentum spread $\Delta p/p<10^{-5}$

Momentum spread at very low ion numbers N<1000



Measurement done with 7 MeV **protons** at the LSR storage ring, Kyoto University

Measured momentum spread as a function of the proton number.
T. Shirai et al. PRL 98, 204801 (2007)

momentum jump at ion numbers N=1000-3000 observed at several storage rings

Below N<1000 IBS is suppressed and the ion beam temperature is in equilibrium with the electron beam temperature, therefore the ion momentum spread is given by

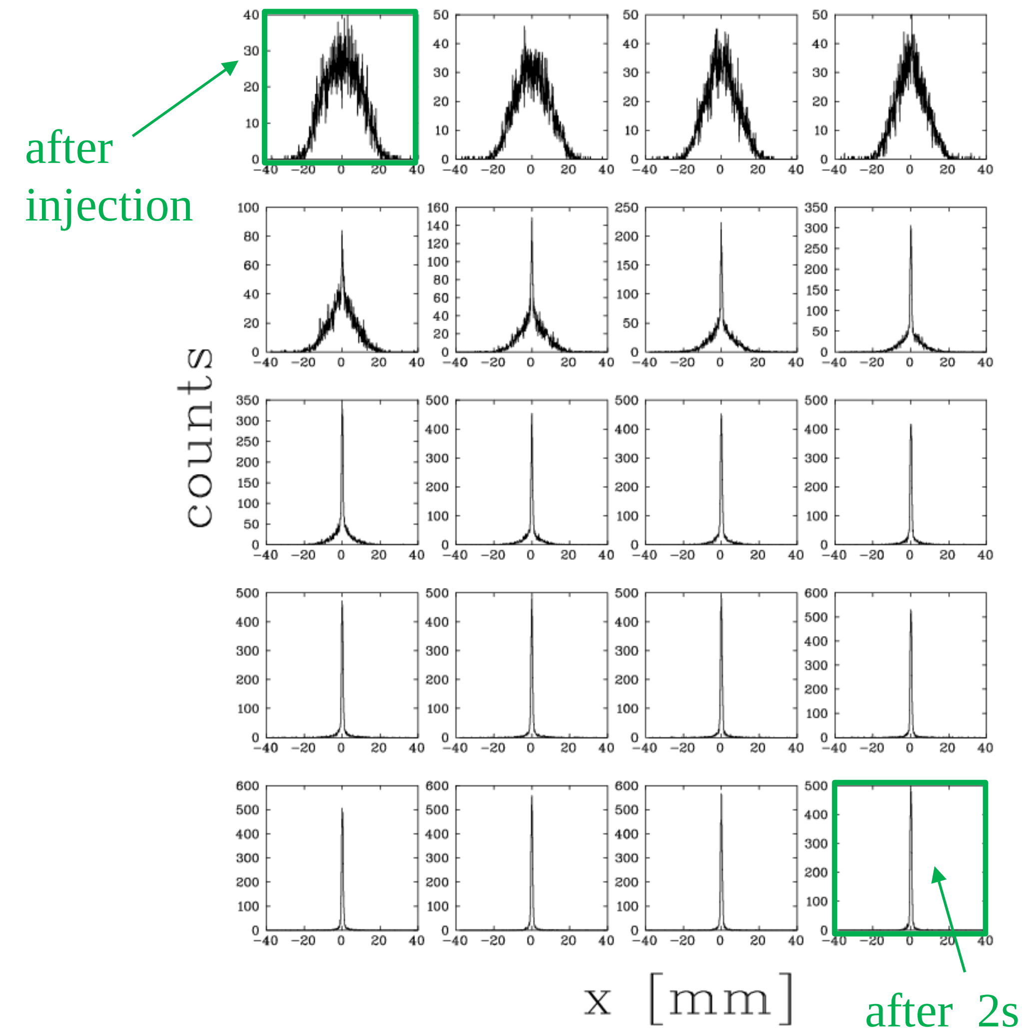
$$\frac{\Delta p}{p} = \frac{\sigma_\parallel}{v_\parallel} = \sqrt{\frac{k_b T_{e\parallel}}{2E}} \quad \text{where} \quad k_B T_{e\parallel} \cong \frac{(k_B T_{\text{cath}})^2}{\beta^2 \gamma^2 m_e c^2} + \frac{e^2 n_e^{1/3}}{4\pi\epsilon_0} \quad \Rightarrow \text{for 7 MeV protons:}$$

$$\frac{\Delta p}{p} = 1.2 \cdot 10^{-6}$$

Laser Spectroscopy of rare Isotopes II

nuclear life time $\tau_n \geq$ cooling time of multi-turn injected ion beam T_{cool}

development of a multi-turn injected $^{12}C^{6+}$ beam



in the velocity range
0.03<ß<0.16

$$T_{cool} \approx \frac{A}{q^2} \cdot 3s$$

proposed ions

ion	T_{cool} (s)	nuclear τ_n (s)	fraction of particles left after cooling
$^{8}B^{3+}$	2.7	0.77	3 %
$^{10}C^{4+}$	1.9	19.3	90 %
$^{16}C^{4+}$	3	0.747	2 %

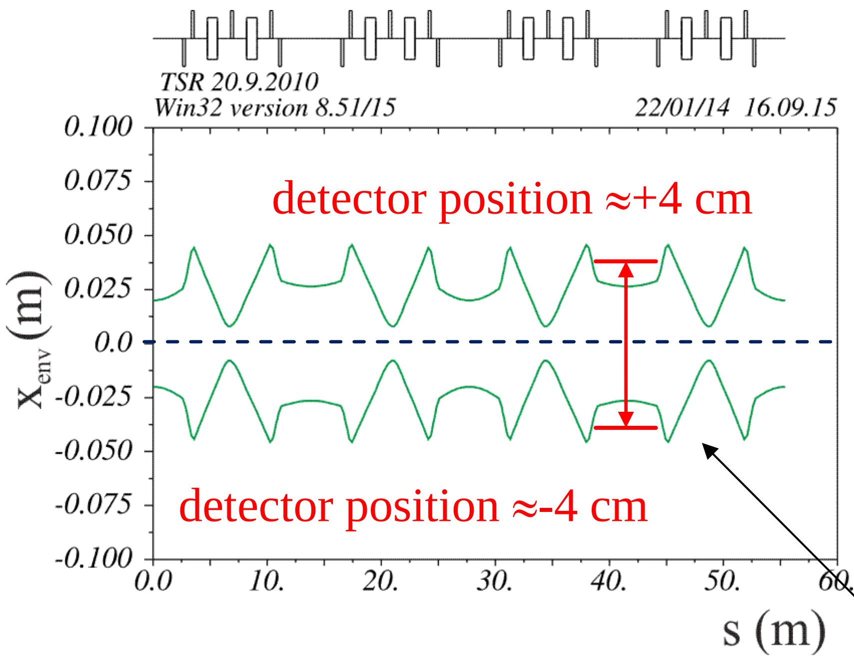
In flight beta-decay of light exotic ions

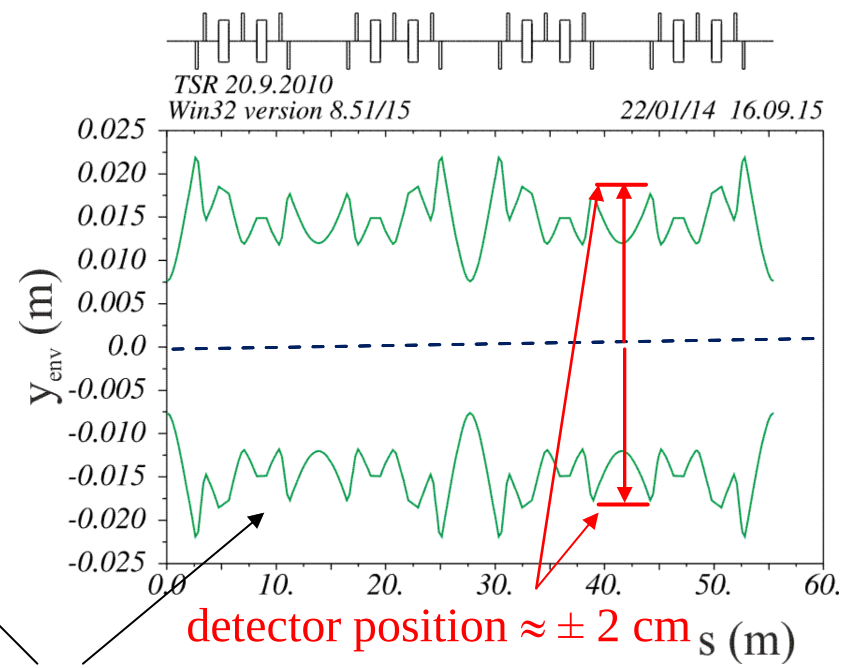
proposed nucleus: $^{6}He^{2+}$, $^{11}Be^{4+}$, $^{16}N^{7+}$ E=10 MeV/A

reaction : $^{6}He \rightarrow \alpha + d$ $\quad ^{11}Be \rightarrow ^{10}Be + p$

measuring: emitted light ions with a detector in appropriate position to the ring

detector position should be outside the ring acceptance





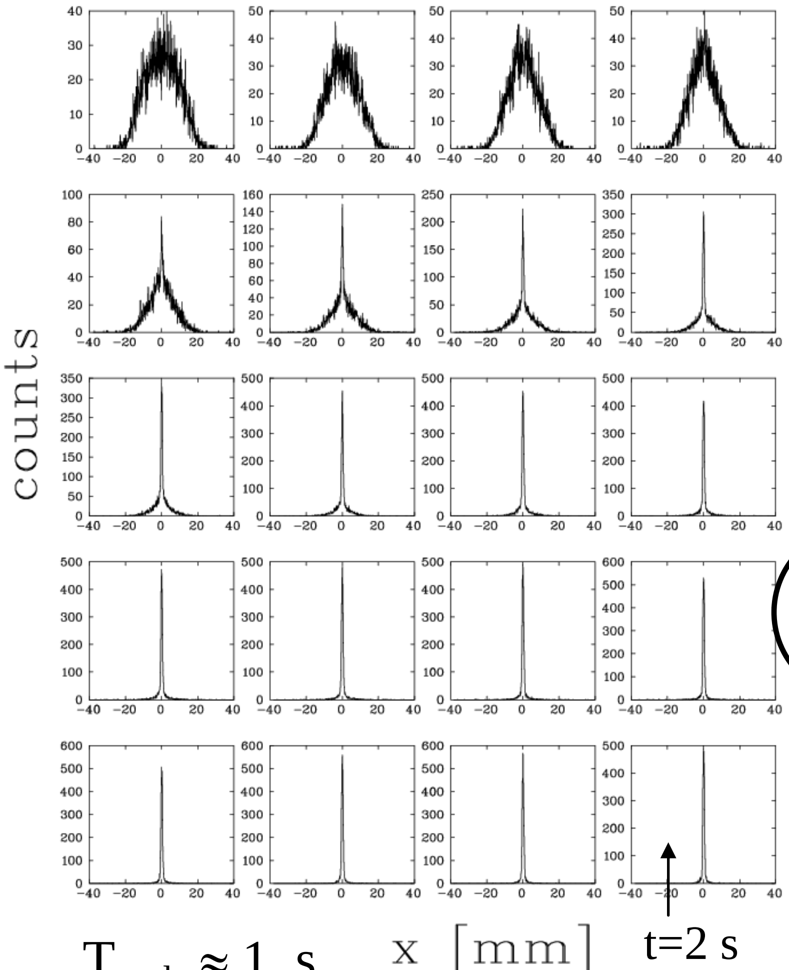
beam size after multi-turn injection

Ricardo Raabe: all detector can place outside the dynamical acceptance of the ring

In flight beta-decay of light exotic ions II

nuclear life-time τ_n > cooling time T_{cool}

development of a multi-turn injected $^{12}C^{6+}$ beam



$T_{cool} \approx 1$ s

electron cooling time

$$T_{cool} \approx \frac{A}{q^2} \cdot 3s$$

fraction of particle left after electron cooling

ion	T_{cool} (s)	nuclear T_n (s)	fraction of particles left
$^{6}He^{2+}$	4.5	0.806	0.4 %
$^{11}Be^{4+}$	2.1	13.8	86 %
$^{16}N^{7+}$	1.0	7.13	87 %

ECOOL stacking can be applied to increase ion intensity

Pilot beam

-A lot of experiments at TSR@ISOLDE are carried out with a very week ion beam not sufficient to set up the storage ring

-to set up the storage ring and cooler: stored intensity $I \approx 1\ \mu A$

⇒ **pilot beam:**

a.) with same magnetic rigidity $B\rho$:

$$B\rho = \frac{p_{pilot}}{Q_{pilot}} = \frac{p}{Q}$$

p- ion momentum

Q-ion charge

⇒ setting of all magnetic fields doesn't change

b.) with approximately the same velocity v:

$$\frac{m_{pilot}}{Q_{pilot}} \approx \frac{m}{Q}$$

m- ion mass

Q- ion charge

⇒ all electrostatic potentials (cooler, septum) are roughly identical

Acknowledgement

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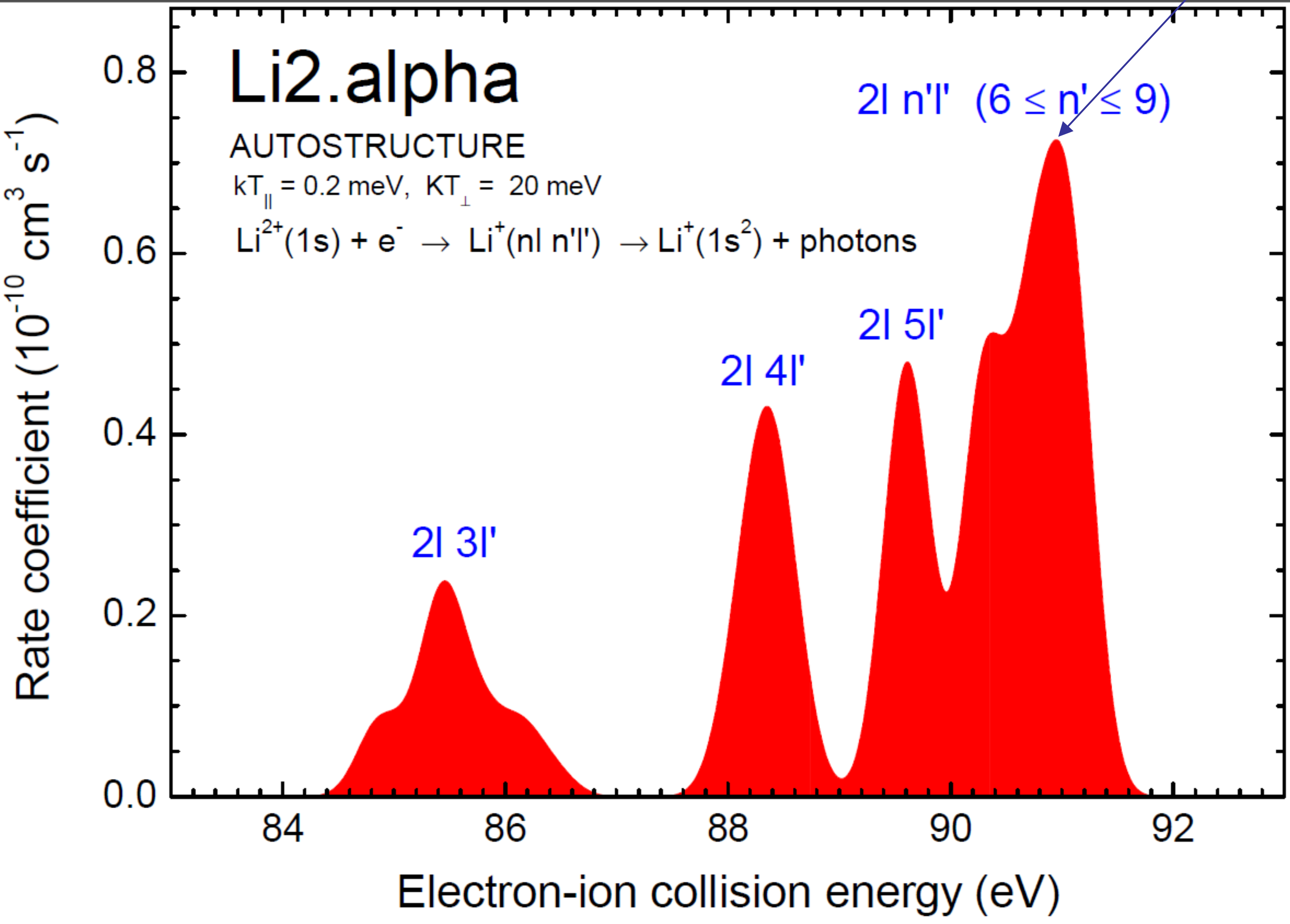
Shabab Sanjari, GSI, Darmstadt
Stefan Schippers, University of Gießen, Gießen
Fredrik Wenander, CERN, Geneva

back-up

Calculated DR resonances for $^{7}Li^{2+}$

calculation done by Stefan Schippers

used resonance



Long-lived isomeric states

Nuclear isomers are metastable excited stated with half live from ns to years

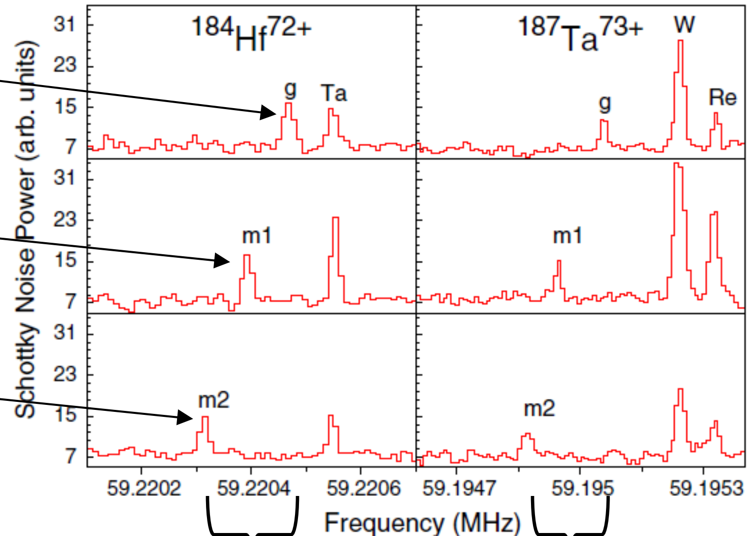
Isomers can be measured with Schottky noise analyses

example: ^{187}Hf ^{187}Ta, measured at ESR/GSI storage ring

ground state

isomer

isomer



single ions single ions

Example of 30th Schottky spectra for A=184 and A=187 isobars and isomers.
ref. M.W. Reed et al. PRL 105, 172501 (2010)

GSI: so far **singly ion detection** with charge states q≥59@400 MeV/u,
S.Sanjari private comminication and P. Kienle et al. Physics Letters B 726 (2013)

TSR@Isolde: Isomers will have smaller charge states q compare to isomers stored at ESR storage ring.

Schottky power: $P_{Schottky} \sim q^2$ q- ion charge state

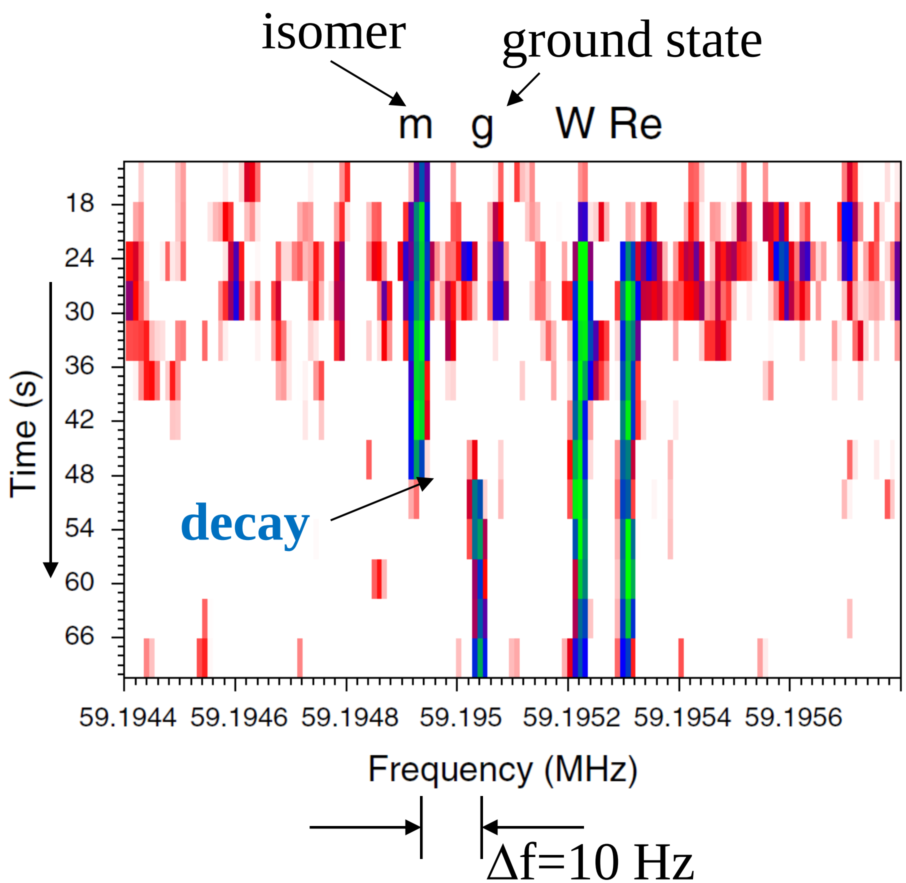
⇒ **single ion detection and measuring of isomeric state very challenging**

Singly ion detection by observing the decay

-To determine the decay time the number of ions in the Schottky spectrum has to be known

-Schottky monitor cannot distinguish is there one, two, three ions in the ring !

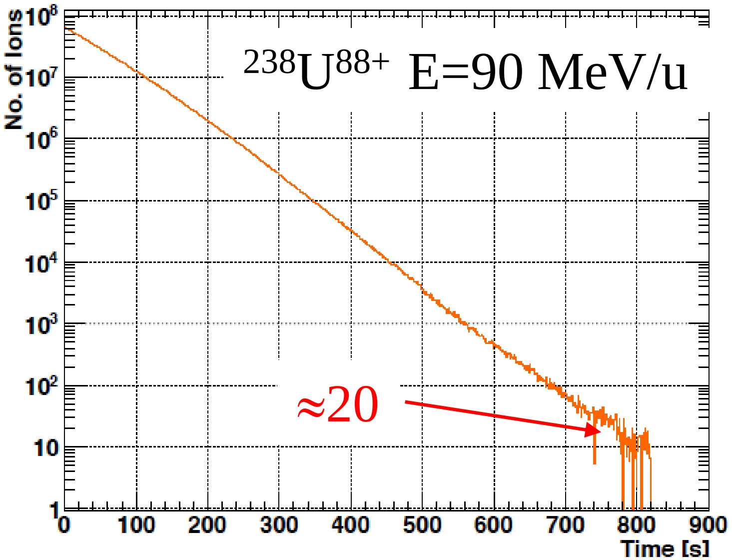
- Is there a decay where the ion goes from the meta stable state in the ground state and only one ion in the meta-stable state is stored then Isomer disappear and ion in the ground state appears:

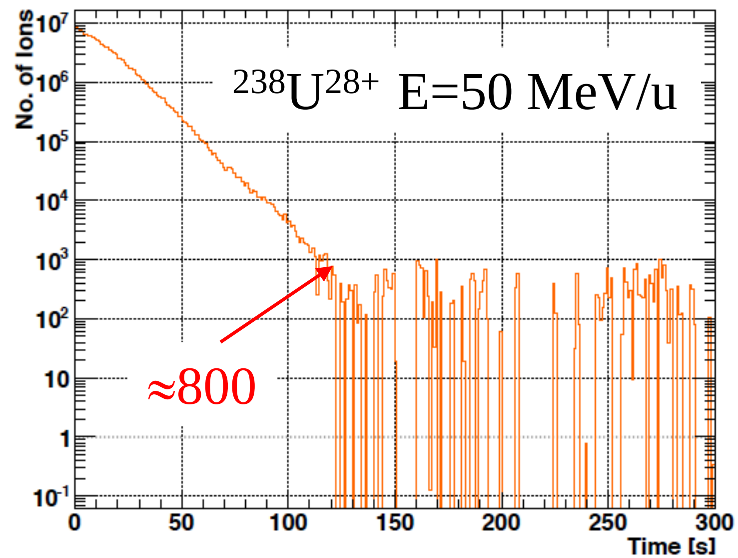


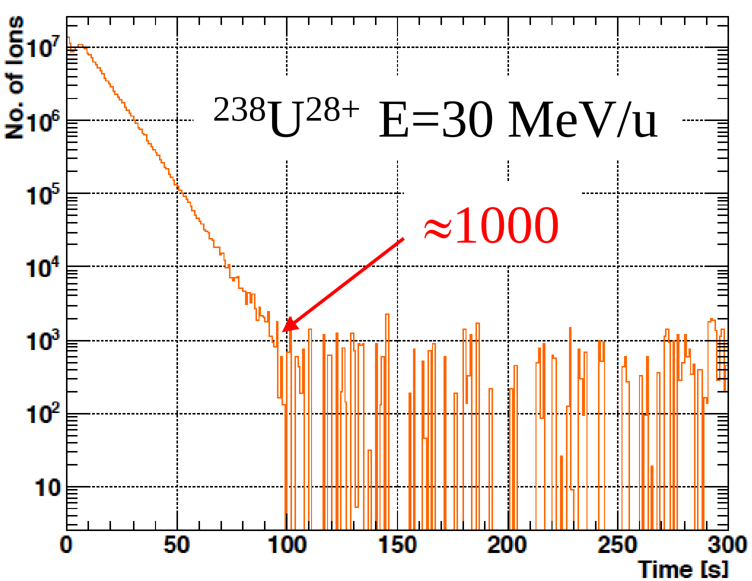
Single ion detection:
Observing in the Schottky spectra the decay of an isomeric state of ^{187}Ta.
ref. M. W. Reed, PRL 105, 172501 (2010)

to get relative large splitting Δf: measurement at relative high harmonic number n

Detection Limit Schottky pick-up (cavity) at ESR ring







Shahab Sanjari, GSI
privat communication

Energy deviation of $^{A+1}Y^{(q+1)+}$ and $^{A}X^{(q+1)+}$

$$\delta E = E_y - E_x$$

$^{A+1}Y^{(q+1)+}$ $^{A}X^{(q+1)+}$

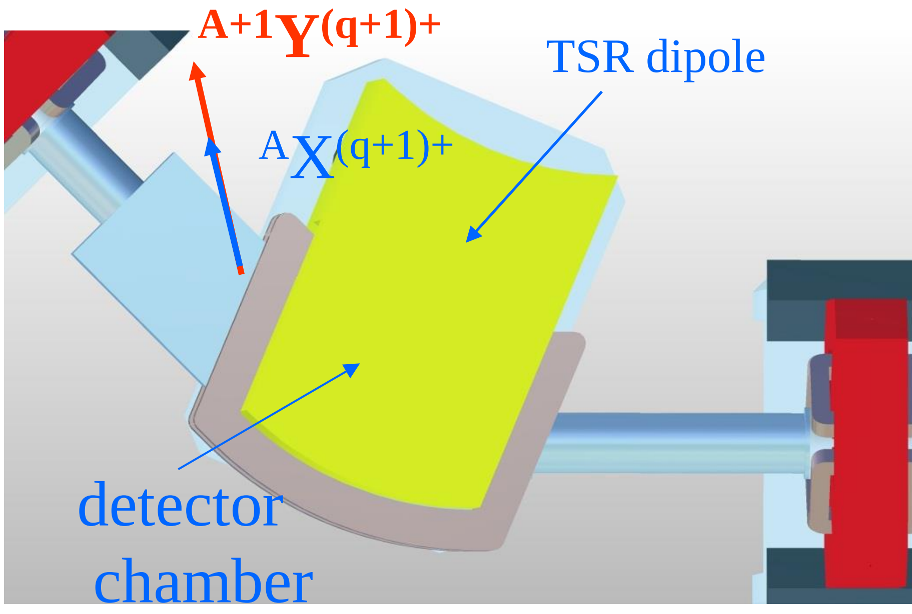
E- energy projectile: $E_x = E$

$$\frac{\delta E}{E} = -\frac{1}{(1+A)}$$

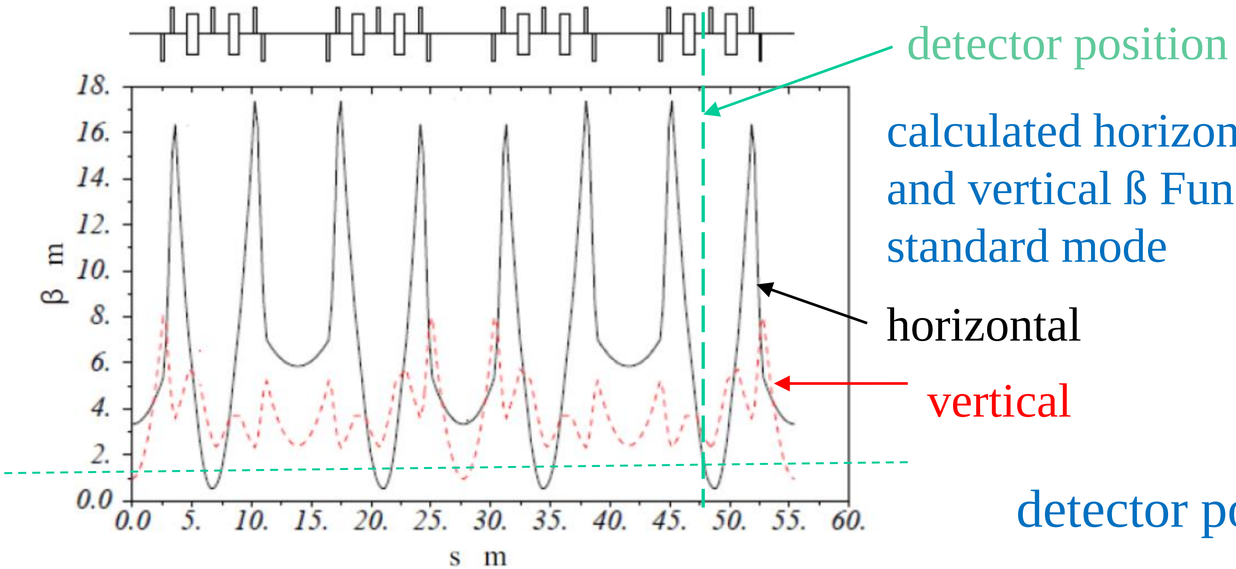
example

$^{A}X^{q+}$: $^{96}Ru^{26+}$

$$\frac{\delta E}{E} = -0.01$$

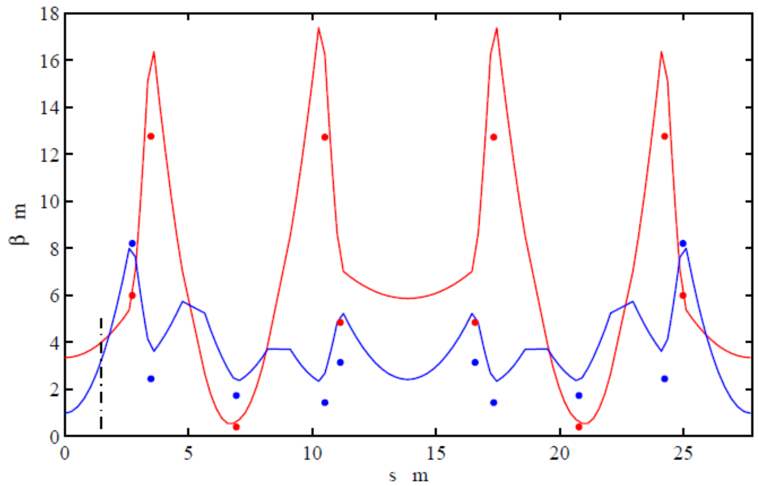


Dynamical Acceptance



calculated horizontal and vertical ß Function of TSR standard mode

measurement



detector position

$\beta_x \approx 1.2$ m

dynamical acceptance

$A_x \approx 120$ mm·mrad

⇒maximal beam width:

$$x = \sqrt{A_x \beta_x}$$

$x \approx 1.3$ cm

Lifetime modification due to gas target

intensity multiplication factor

$$\frac{1}{\tau} = \frac{1}{\tau_v} + \frac{1}{\tau_t}$$

life time due to target density

life-time due to electron capture and residual gas interactions

loss process in the target

1. **electron capture**

Schlachter:

$$\tilde{\sigma} = \frac{1.1 \cdot 10^{-8}}{\tilde{E}^{4.8}} (1 - e^{-0.037\tilde{E}}) \cdot (1 - e^{-2.44 \cdot 10^{-5} \tilde{E}^{2.6}})$$

remark for $H_{2\ \text{target}}$ M=2

$$\tilde{E} = \frac{E / A}{Z_2^{1.25} q^{0.7}} \qquad \sigma_{cap} = M \cdot \frac{\tilde{\sigma} \cdot q^{0.5}}{Z_2^{1.8}}$$

cross section in $1/\text{cm}^2$

E projectile energy in keV, A mass number, Z_2-target atomic number, q ion charge

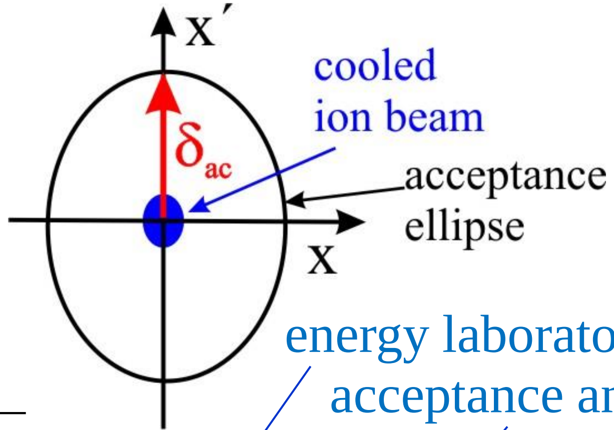
example $^{86}Kr^{36+}$ E=860 MeV

$$\Rightarrow \tau_{cap} = \frac{1}{\sigma_{cap} \cdot n_t \cdot f_0}$$

with $n_t = 10^{14}\ 1/\text{cm}^2\ (H_2) \Rightarrow T_{cap} = 9\ \text{s}\ \ (\sigma = 1.63 \cdot 10^{-21}\ \text{cm}^2)$

Lifetime modification due to gas target II

2. single scattering



-CMS System Rutherford scattering:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\left(\frac{q \cdot Z \cdot e^2}{4 \cdot \pi \cdot \varepsilon_0 \cdot 2 \cdot E_s}\right)^2 \frac{1}{\sin^4(\Theta/2)}$$

energy laboratory system

$$E_s = \frac{m_t}{m + m_t} E$$

acceptance angle laboratory system

$$\tan(\delta_{ac}) = \frac{\sin(\varphi_{ac})}{\cos(\varphi_{ac}) + \frac{m_t}{m}}$$

$\Rightarrow$ cross section for particle loss

$$\sigma_{sc} = \int_{\varphi_{ac}}^{\pi} \frac{d\sigma}{d\Omega} \cdot 2\pi \sin(\Theta) d\Theta = \frac{e^4 \cdot q^2 \cdot Z^2}{64 \cdot \pi \cdot \varepsilon_0^2 \cdot E_s^2} \cot^2\left(\frac{\varphi_{ac}}{2}\right)$$

acceptance angle CMS system

$$\delta_{ac} \approx 5 \text{ mrad}$$

A_x- horizontal acceptance

A_y- vertical acceptance

$ß_x$,$ß_y$ – ß function at the target

$\Rightarrow$ life-time $T_{sc} = \frac{1}{\sigma_{sc} \cdot n_t \cdot f_0}$

$\Rightarrow$ $^{35}Kr^{17+}$ E=860 MeV and $n_t=10^{14}$ 1/cm^2: $T_{sc} \approx 3060$ s (negligible)

Ion momentum spread determined by the transverse electron temperature

ion longitudinal velocity spread $\sigma_{\|}$

$$\frac{1}{2} m \sigma_{\|}^{2} = \frac{1}{2} k_b T \quad T - \text{ion temperature}$$

Ion temperature T given by the electron temperature T_e : $T=T_e$

$$\Rightarrow \frac{\Delta p}{p} = \frac{\sigma_{\|}}{v_{\|}} = \sqrt{\frac{k_b T_e}{2E}} \quad \text{E-ion kinetic energy}$$

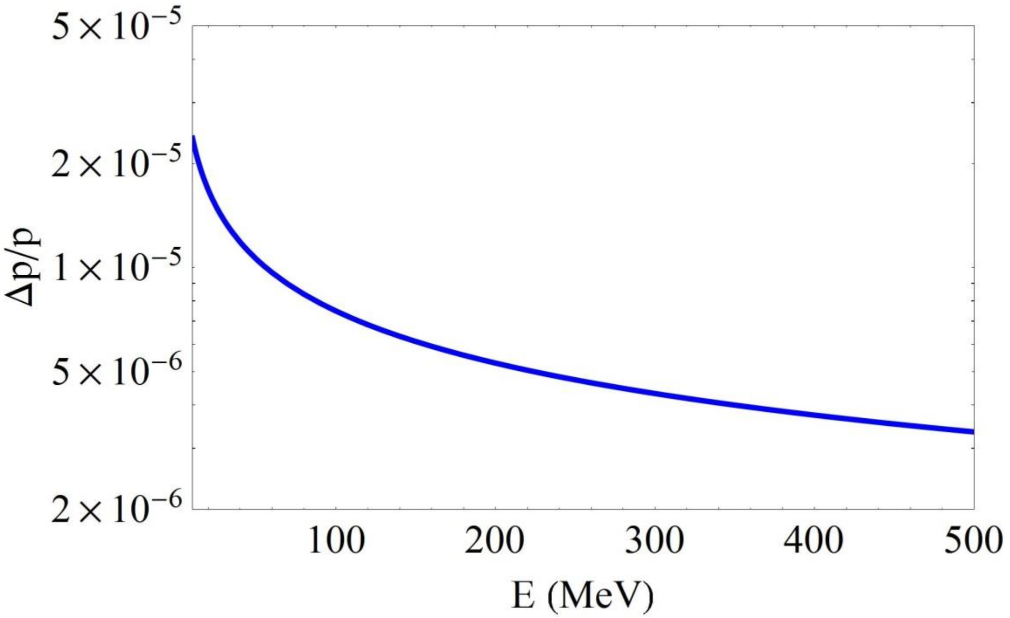
There are a longitudinal $T_{e,\|}$, a horizontal $T_{e,x}$ and vertical electron temperature $T_{e,y}$

where: $T_{e,x} = T_{e,y} > T_{e,\|}$ and $T_{e,x} \approx \frac{T_{cath}}{\alpha}$ $T_{cath} \approx 1300$ K

T_{cath} – cathode temperature, α - expansion factor of electron beam $\alpha \approx 10$

With $T_e \approx T_{e,x}$ we get:

$$\frac{\Delta p}{p} \approx \sqrt{\frac{k_b T_{cath}}{\alpha 2E}}$$



Decreasing the cooling time by emittance reduction

measurement done with $^{12}C^{6+}$ E=73.3 MeV
electron density: $n_e = 1.53 \cdot 10^7$ 1/cm^3