A new ISOLDE storage ring - ISR

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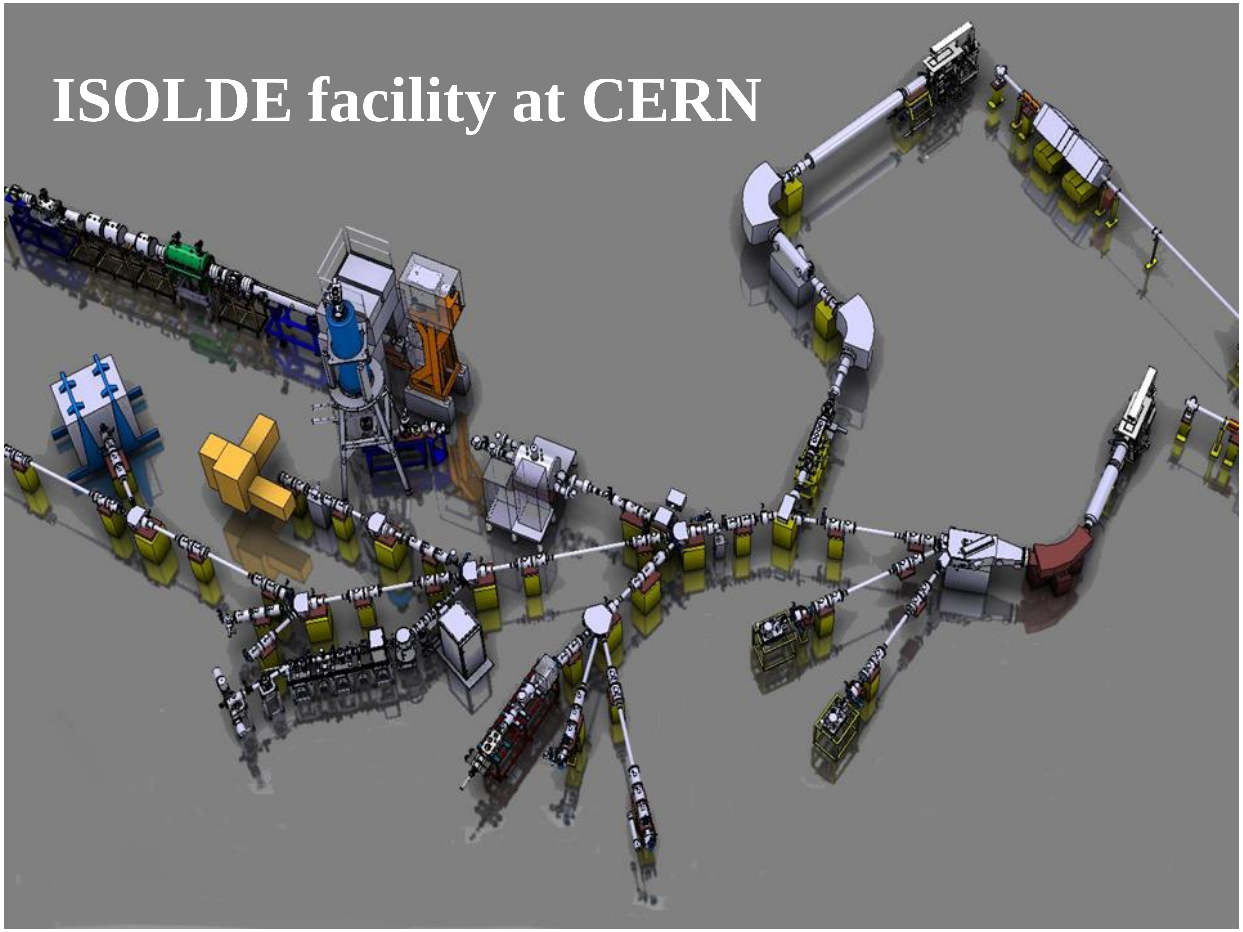
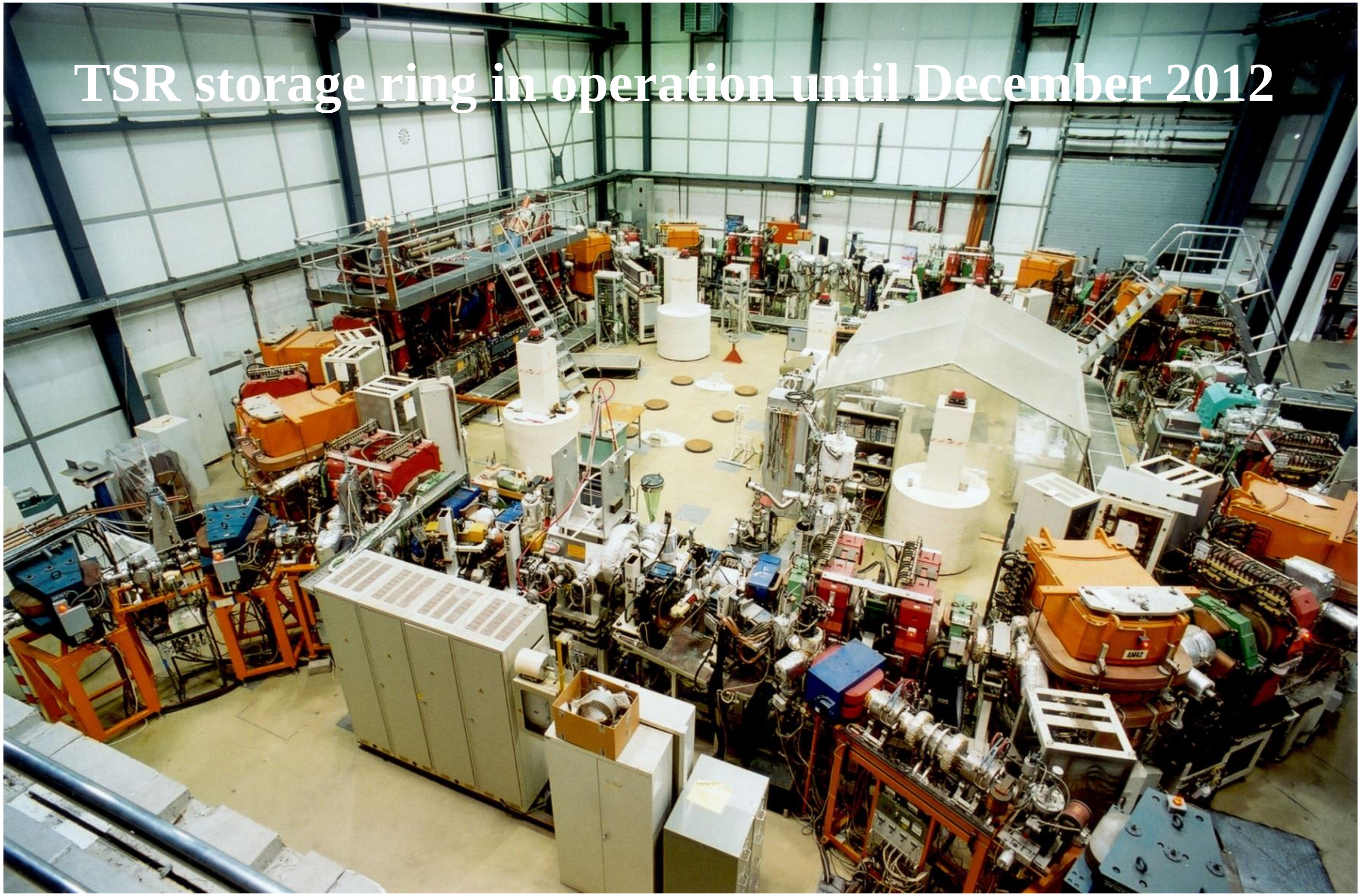


ISOLDE-EPIC workshop, CERN, Geneva, 3rd-4th December 2019

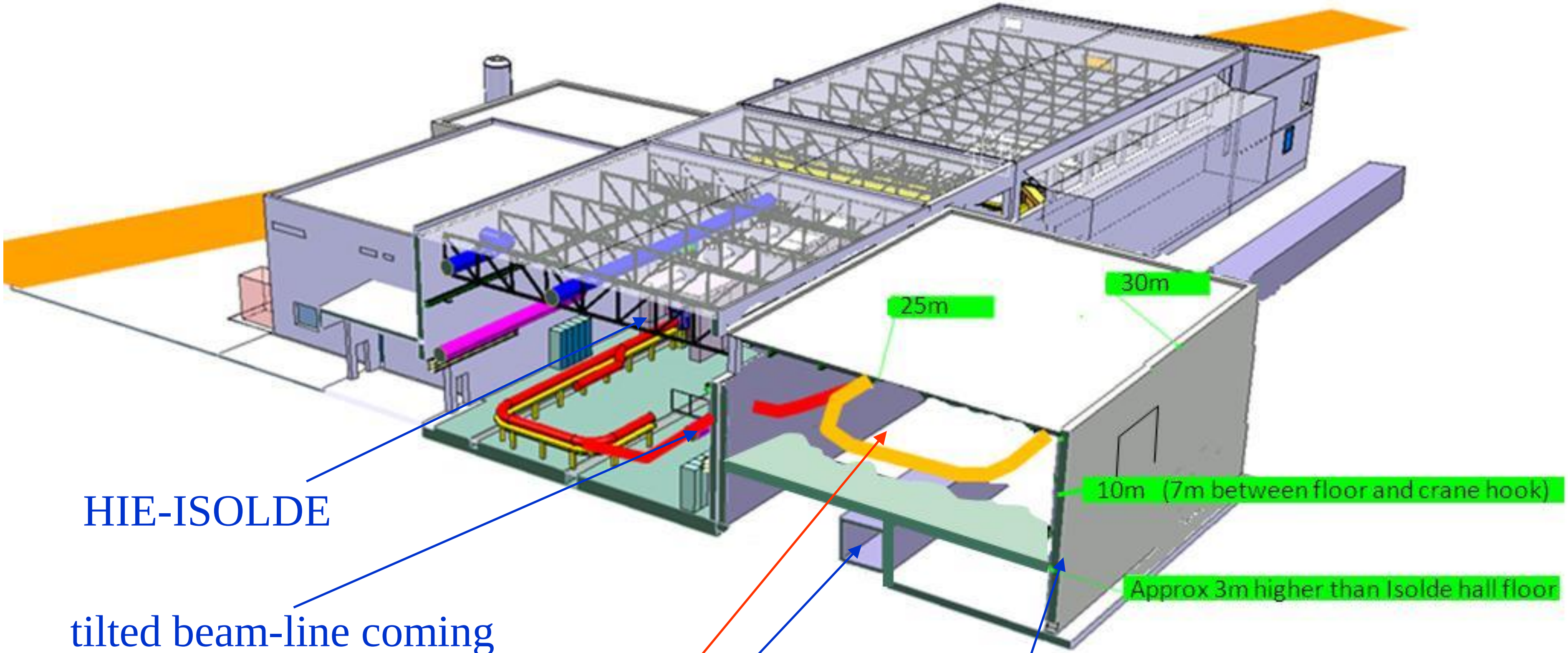
Proposed TSR@ISOLDE project

to store radioactive ions for nuclear physics experiments it was proposed to move TSR located at MPI for nuclear physics to ISOLDE.



TSR storage ring in operation until December 2012

TSR @ HIE-ISOLDE



HIE-ISOLDE

tilted beam-line coming
from the HIE-ISOLDE machine.

possible TSR installation

above the CERN cable-tunnel.

(E. Siesling)

TSR@HIE-ISOLDE building

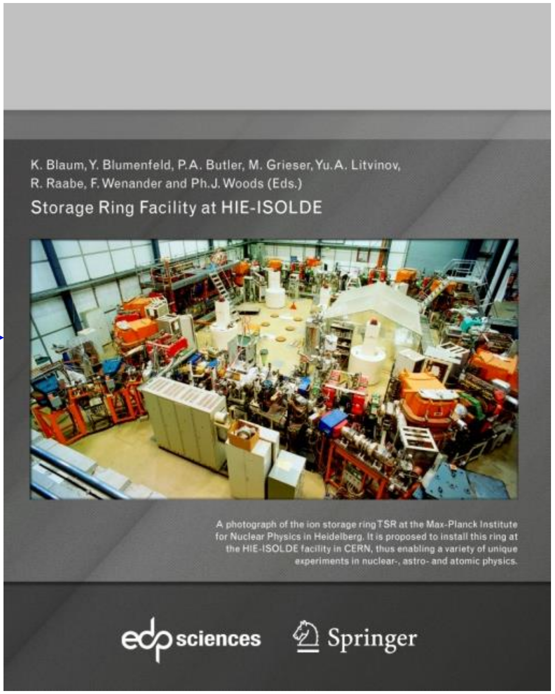
Time-line of the TSR@ISOLDE project

TSR@ISOLDE workshop at MPI-K Heidelberg
evaluated the future for TSR Oct 2010

ISOLDE and Neutron Time-of-Flight Committee endorsed Jan 2012

TSR technical design report **129 co-authors (47 institutions)**

EPJ Special Topics **207** 1-117 May 2012 →



K. Blaum, Y. Blumenfeld, P.A. Butler, M. Grieser, Yu.A. Litvinov,
R. Raabe, F. Wenander and Ph.J. Woods (Eds.)
Storage Ring Facility at HIE-ISOLDE

A photograph of the ion storage ring TSR at the Max-Planck Institute for Nuclear Physics in Heidelberg. It is proposed to install this ring at the HIE-ISOLDE facility in CERN, thus enabling a variety of unique experiments in nuclear-, astro- and atomic physics.

edp sciences Springer

Approved by CERN Research board, May 2012

"The installation of TSR, as an experiment to be included in the HIE-ISOLDE programme, was approved by the Research Board.

The timescale will be defined once the study of its Integration has been completed."

Presentation of the integration study to the CERN Research Board Nov 2013

Several TSR@ISOLDE workshops at CERN: 2012, 2014, 2015

Updated CERN integration study with report to the CERN directorate 2016

CERN director general: decision about the TSR@ISOLDE project is postponed until 2020/2021 (after second LHC upgrade) August/September 2016

Without getting green light from CERN MPIK can not hold the TSR so long at MPIK

Design Criteria of the new storage ring

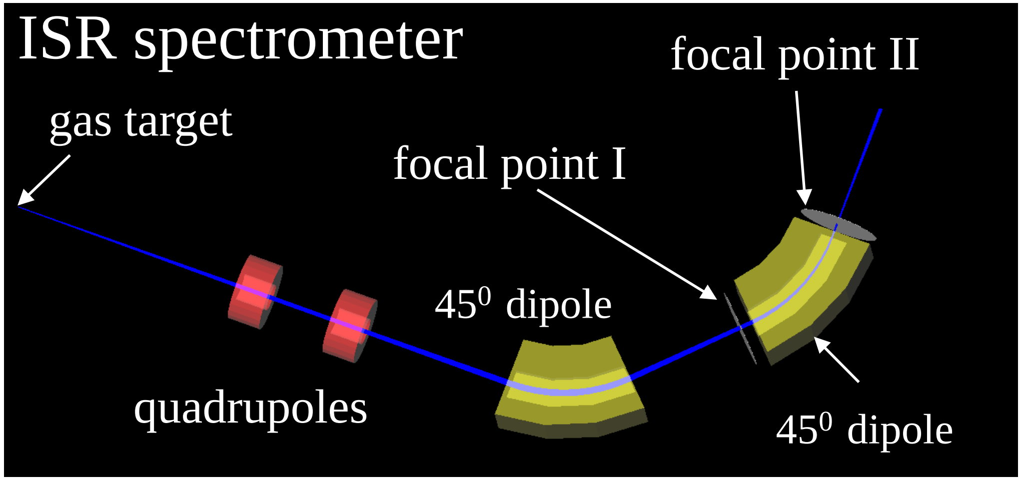
a) storage ring should be able to store ions up to $^{238}U^{72+}$ and 10 MeV/u at the equilibrium charge state obtainable with the HIE-ISOLDE stripper.

⇒ maximum rigidity of the ring: $B\rho_{max} \approx 1.5$ Tm

b.) daughter nuclides with large transfers momenta, produced in nuclear reactions, should be focused at the detector positions

⇒ ISR spectrometer should have focal points in the detector planes

c.) extraction of an cold stored ion beam for an external spectrometer

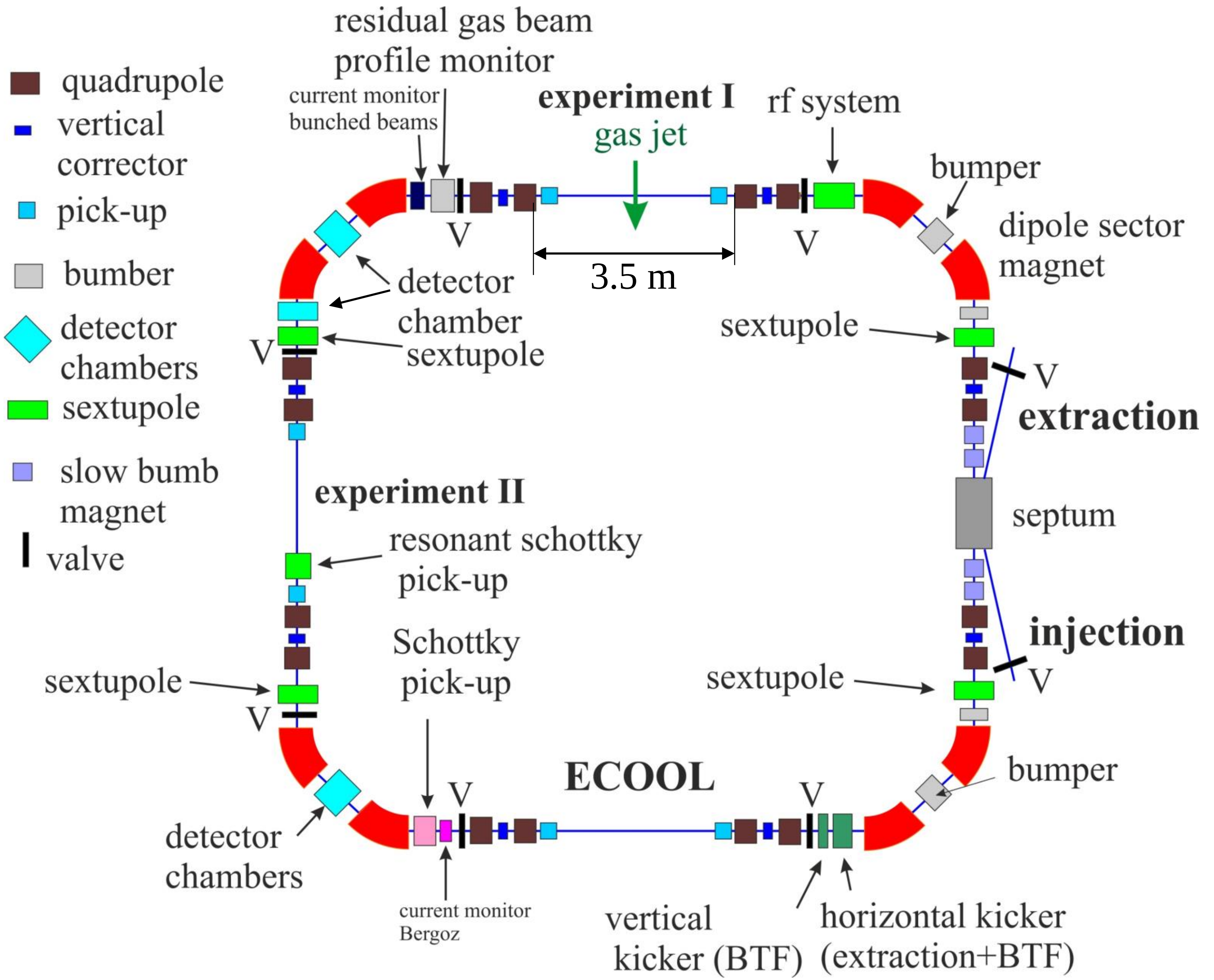


d) storing of heavy daughter nuclei up to a certain rigidity deviation $(\Delta B\rho/B\rho)$ created in nuclear reactions should be possible.

e.) storing ring should be compact to fit in the present HIE ISOLDE hall

Layout of the new storage ring

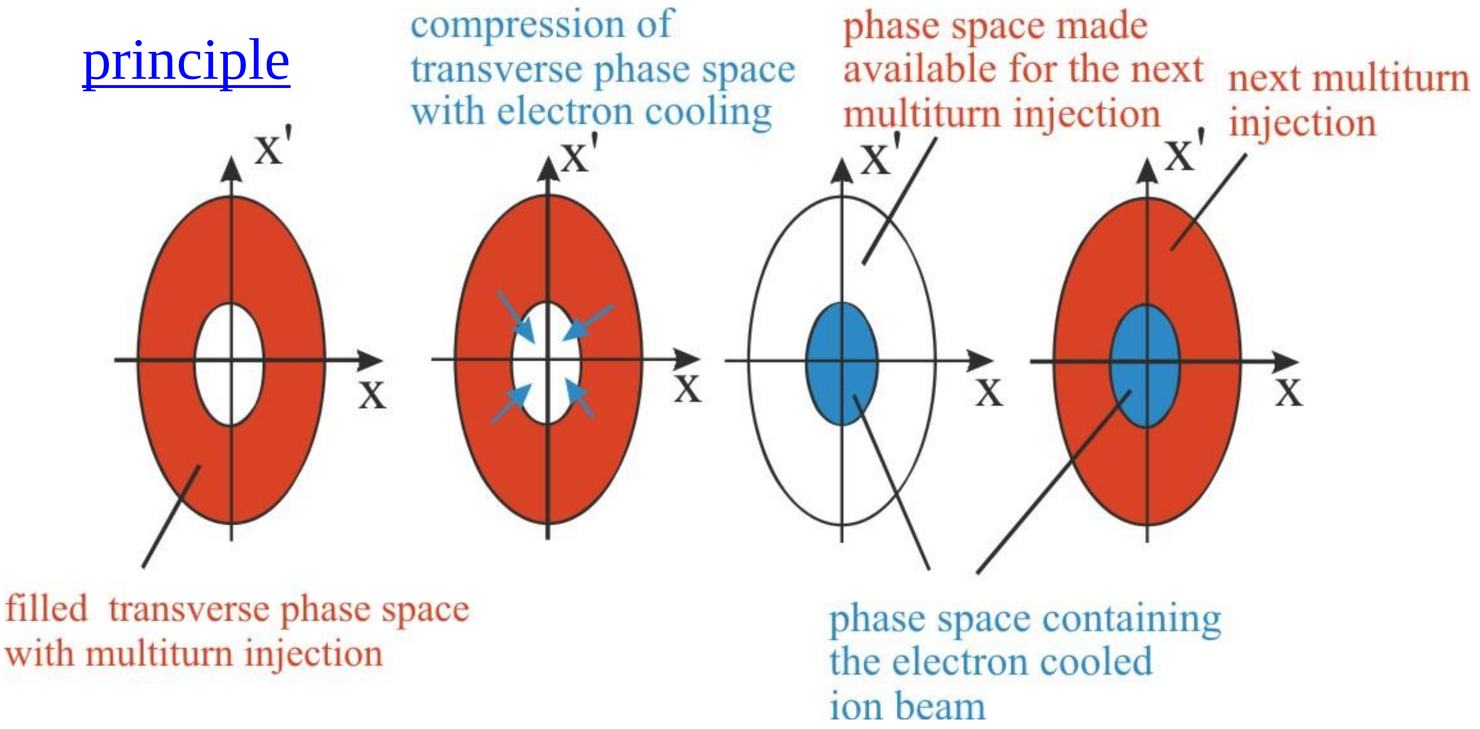
with straight section length L=3.5 m and circumference C=42.4 m



ECOOL Stacking

A combination of multi-turn injection and electron cooling stacking can be used to fill the storage ring with particles

principle



particle number N(t):

$$\frac{dN(t)}{dt} = n_r N_{inj} - \frac{N(t)}{\tau}$$

N_{inj}-injected particle number per injection
$n_r = 1/T_C$- injection rate
τ- total lifetime

equilibrium ion number N_0 : $N_0 = n_r \tau N_{inj}$

Space charge limit due to incoherent tune

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

$-\Delta Q$ - possible incoherent tune shift for B=1 at TSR: $\underbrace{-\Delta Q \approx 0.065\text{-}0.1}$

new storage ring (ISR) has similar possible incoherent tune shifts

for an **electron cooled ion beam**:

$$\varepsilon \propto \left(\frac{q^4}{A^2}\frac{N_s}{\lambda_{Cool}}\frac{1}{\beta^3}\right)^{0.44} \qquad \lambda_{cool} \propto n_e \frac{q^2}{A} \qquad n_e \propto \beta^2$$

⇒ scaling law

$$N_s = \text{const}\frac{(A^{33}/E^5)^{1/28}}{q^2}$$

E-ion energy in MeV

A-ion mass

q-ion charge state

TSR experiments with $^{12}C^{6+}$:

const≈$7\cdot10^9$

Measured and calculated space charge limit of an electron cooled ion beam at the TSR

Ion	E (MeV)	measured N_s	calculated N_s
p	21	$5.4\cdot10^9$	$4.1\cdot10^9$
$^{16}O^{8+}$	98	$9.4\cdot10^8$	$1.3\cdot10^9$
$^{12}C^{6+}$	73	$1.7\cdot10^9$	$1.7\cdot10^9$
$^{32}S^{16+}$	195	$9.5\cdot10^8$	$6.3\cdot10^8$
$^{35}Cl^{17+}$	293	$5.1\cdot10^8$	$5.8\cdot10^8$

Space charge limit for some selected ion beams

Space charge limit of an electron cooled ion beam $$N_s = \text{const}\,\frac{(A^{33}/E^5)^{1/28}}{q^2}$$

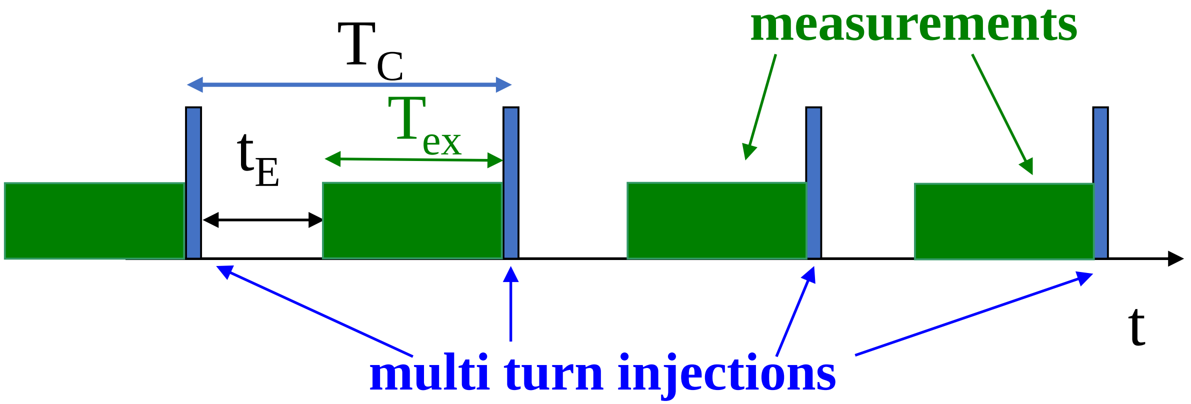
beam	energy (MeV/u)	q	Ns
$^{7}Be^{3+}$	8	3+	$5\cdot10^9$
$^{86}Kr^{36+}$	10	36+	$3\cdot10^8$
$^{96}Ru^{39+}$	10	39+	$3\cdot10^8$
$^{196}Hg^{64+}$	10	64+	$2\cdot10^8$
$^{232}Th^{71+}$	10	71+	$2\cdot10^8$
$^{238}U^{72+}$	10	72+	$2\cdot10^8$

green: equilibrium charge states after the HIE-ISOLDE stripper

Result: For the equilibrium charge state after the HIE-ISOLDE stripper at 10 MeV/u the space charge limit is about: $\mathbf{N_s \approx 2\cdot10^8}$

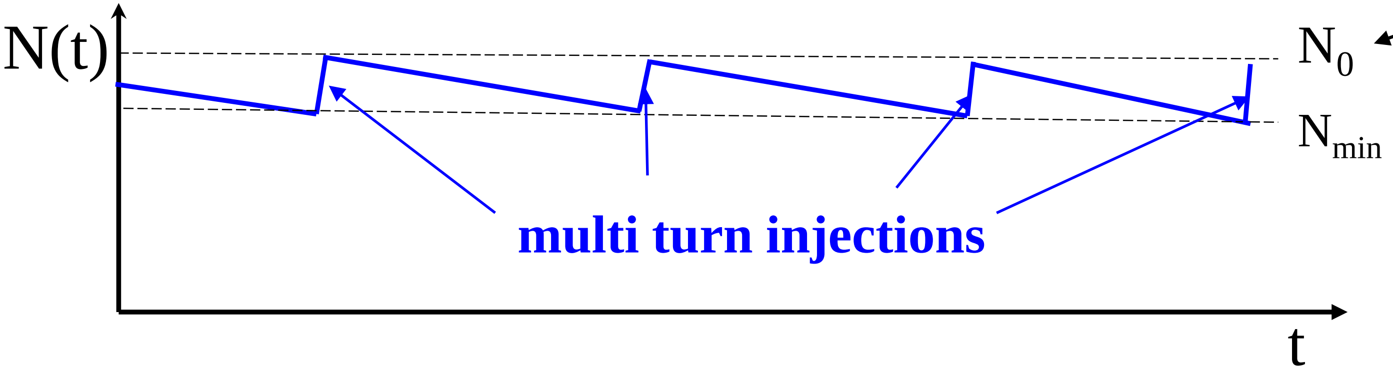
Remark: For some ion species the space charge limit may not be reached due to the limitation of the injected ion number N_{inj}

Injection and measuring scheme



T_c- cyle time
= inverse repetion
rate n_r of the multiturn
injection
t_E- electron cooling time
T_{ex}-measurement time

Stored ion number N(t)



initial ion number
in the cycle time T_c

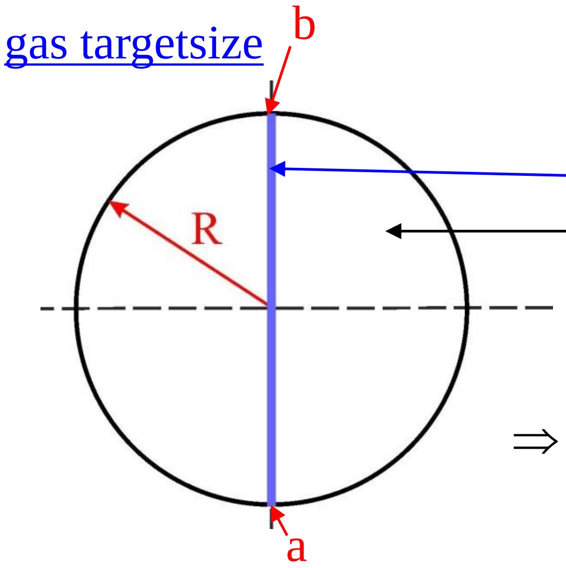
Luminosity

$$L(t) = \frac{R(t)}{\sigma}$$

R(t)- reaction rate
σ- cross section for a reaction
with the gas target

Luminosity dependency on target radius R

gas targetsize



zero emittance ion beam interacting with a gas target

ion beam with ε=0 mm·mrad and Δp/p=0

gas target with radius R

target thickness $W=\int_a^b n_t \cdot ds$ n_t-gas target density

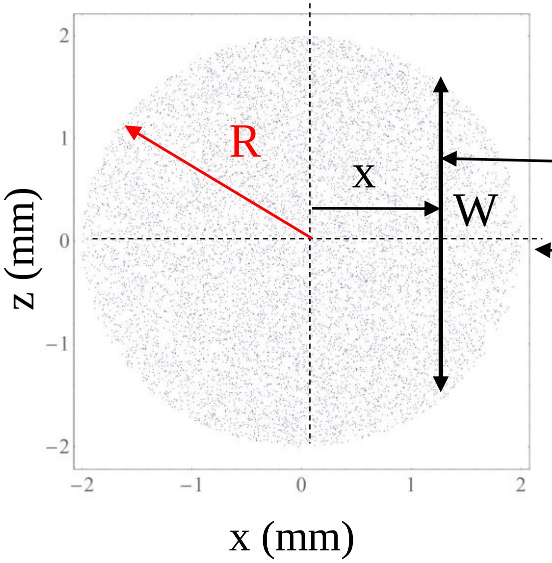
$$\Rightarrow \text{Luminosity:} \boxed{L_0 = \frac{R_0}{\sigma} = f_0 \cdot N_0 \cdot \int_a^b n_t \cdot ds}$$

R_0-reaction rate at t=0 s

σ-cross section

f_0-revolution frequency

N_0- number of ions



$$w = 2 \cdot \sqrt{R^2 - x^2}$$

real ion beam interacting with the gas target with radius R

target thickness w depends on horizontal ion position x

ions outside the gas target will not react

modification of maximum possible luminosity:

$$L_{eff} = \eta \cdot L_0$$

ion beam gas target interaction parameter: η≤1

The ion beam gas target interaction parameter η

η depends on:

a.) stored ion beam size, characterized by the horizontal and vertical beam emittance $\varepsilon_x, \varepsilon_y$, ring TWISS parameter, dispersion D_x and ion beam momentum spread $\Delta p/p$

b.) target radius R

c.) possible horizontal ion beam displacement x_d

parameter:

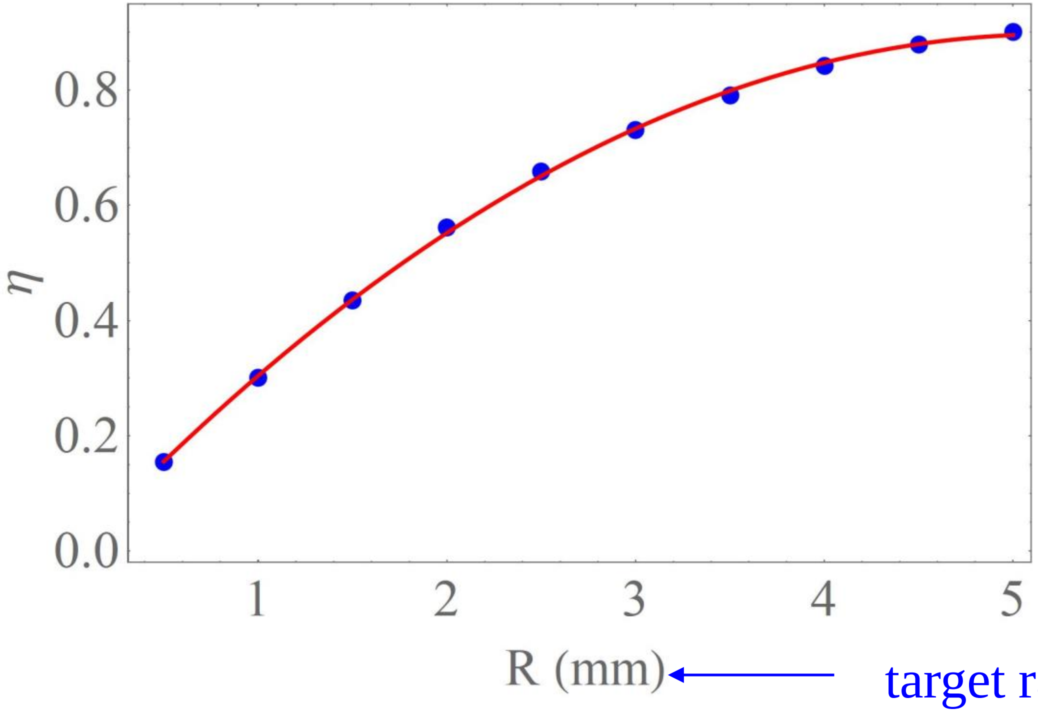
$\varepsilon_x, \varepsilon_y = 0.5$ mm·mrad

$\sigma_p/p = 2 \cdot 10^{-4}$

$D_x = 0$ m

$x_d = 0$ m

standard mode



target radius

Time averaged luminosity $\overline{L}$

$$\overline{L} = \frac{\int_{t_E}^{T_c} \overbrace{\eta \cdot L_0}^{\text{luminosity at t=0 s}} \cdot e^{-t/\tau} dt}{T_c}$$

T_c-cycle time
t_E-electron cooling time
N_0- number of initial ions
τ-total life time
τ_t-target life time
τ_v-life time in the ring vacuum
τ_{ECOOL}-ECOOL life time

with $L_0 = f_0 \cdot N_0 \cdot \int_a^b n_t \cdot ds$ (luminosity of a an ion beam with $\varepsilon=0$ mm·mrad and $\Delta p/p=0$)

and $\frac{1}{\tau} = \frac{1}{\tau_t} + \frac{1}{\tau_v} + \frac{1}{\tau_{ECOOL}}$ $\longleftarrow$ total life time τ

The ion beam gas target interaction parameter η determined the gas target life time τ_t

$$\tau_t = \frac{1}{\eta \cdot \sigma \cdot f_0 \int_a^b n_t ds}$$

σ –cross section for ion loss in the gas target
f_0 - revolution frequency

Time averaged luminosities

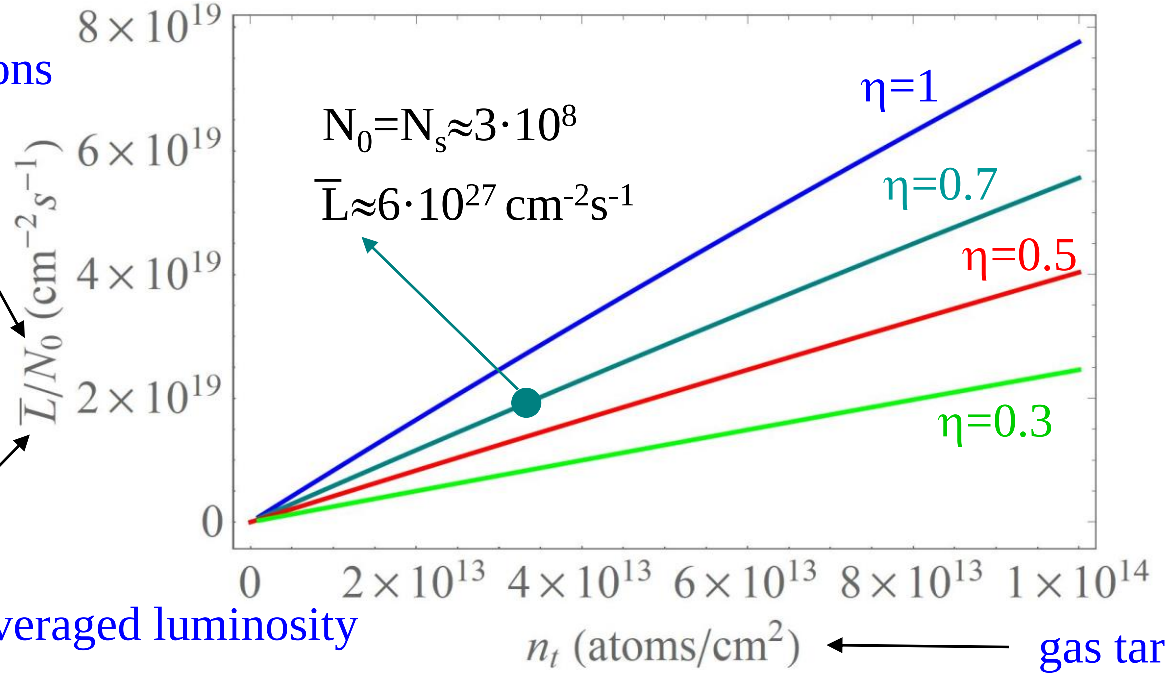
Parameter: beam $^{86}Kr^{36+}$ E=10 MeV/u target: H_2

cycle time T_c = 2 s

p=$5 \cdot 10^{-11}$ mbar vacuum life time with ECOOL :T_v=100 s

t_E=0.3 s start of the measurement after injection

N_0 - initial number of ions



$N_0=N_s\approx3\cdot10^8$

$\bar{L}\approx6\cdot10^{27}\ cm^{-2}s^{-1}$

$\bar{L}$ time averaged luminosity

gas target thickness

in case of $^{86}Kr^{36+}$:

$$\boxed{\bar{L} \approx \eta \cdot \frac{T_c\text{-}t_E}{T_c} f_0 \cdot N_0 \cdot \int_a^b n_t \cdot ds}$$

where total lifetime $\tau >> T_c$

here N_0-stored ion number

$$N_0 = \frac{\tau}{T_C} N_{inj}$$

injected ion number

$\bar{L}$ for $^{238}U^{72+}$ and He-target

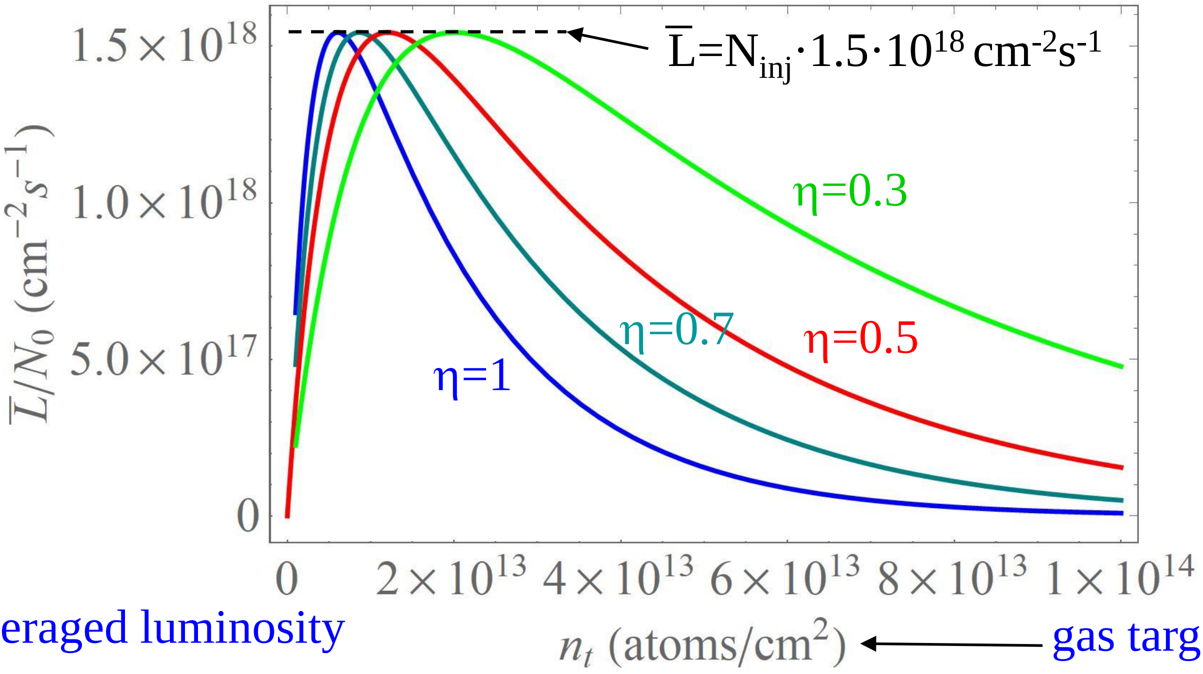
Parameter: beam $^{238}U^{72+}$ E=10 MeV/u   target: He

cycle time $T_c = 2$ s

p=$5\cdot10^{-11}$ mbar   vacuum life time with ECOOL :T=19 s

t_E=0.3 s start of the measurement after injection

N_0 - initial number of ions



$\bar{L}=N_{inj}\cdot1.5\cdot10^{18}$ cm^{-2}s^{-1}

$\bar{L}$ time averaged luminosity

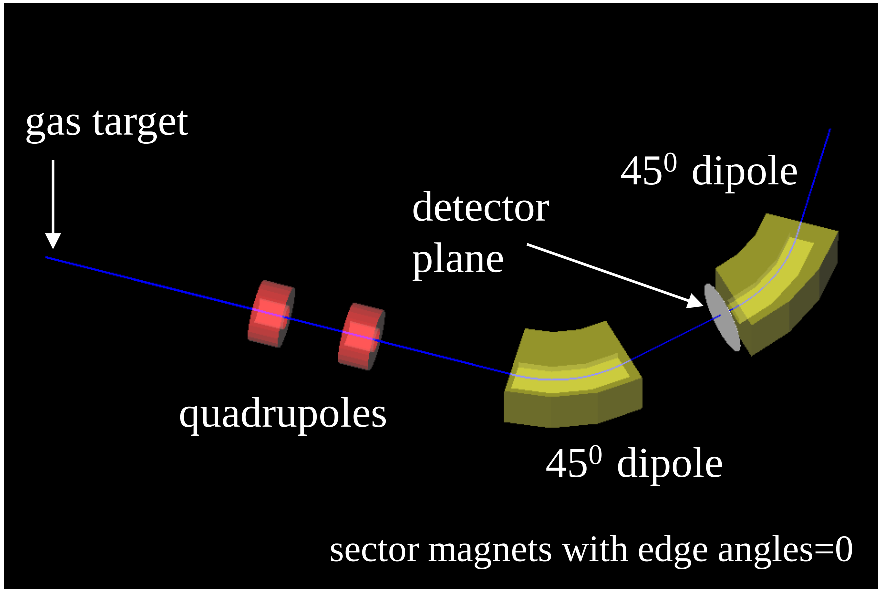
gas target thickness

in case of $^{238}U^{72+}$:   total life-time << T_c

here $N_0=N_{inj}$ injected ion number !!!!

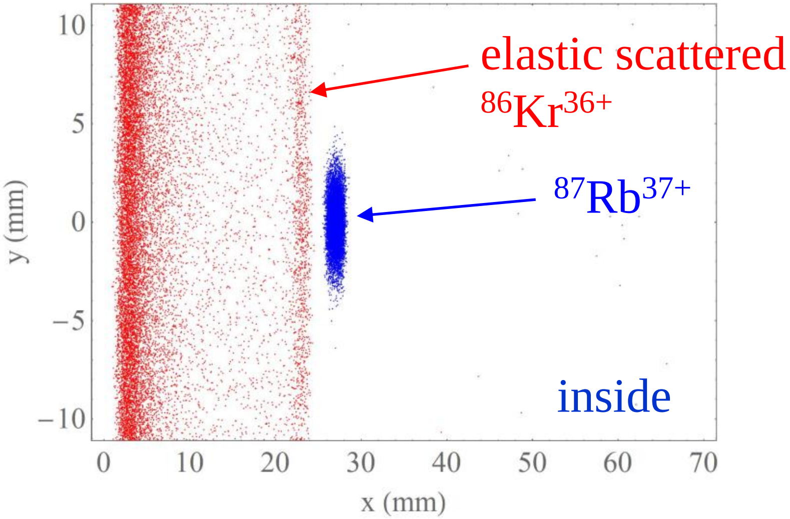
ISR Spectrometer

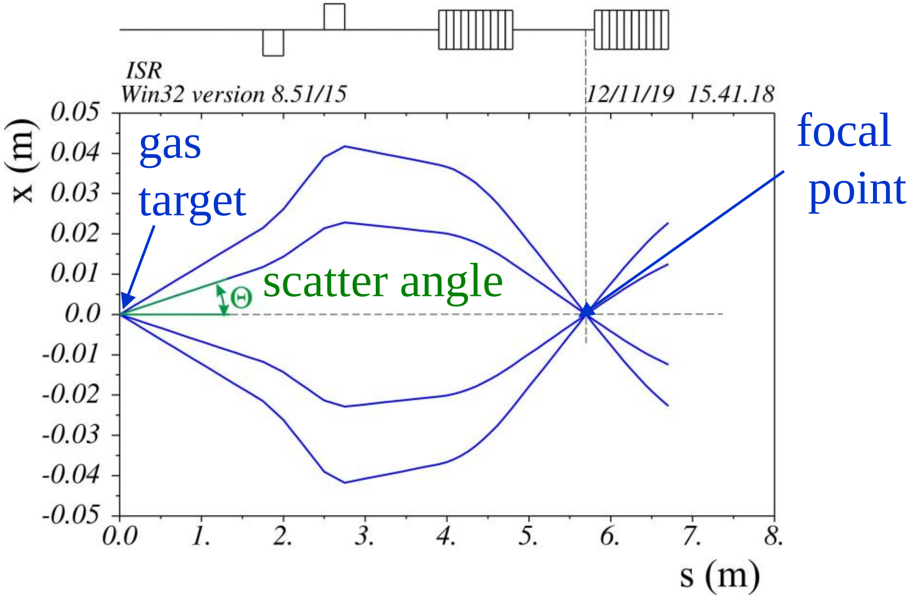
spectrometer



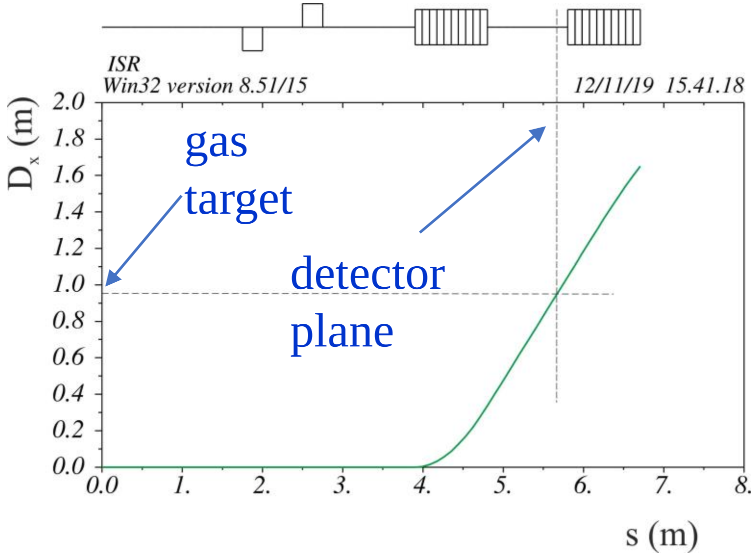
Example: proton pick-up reaction

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





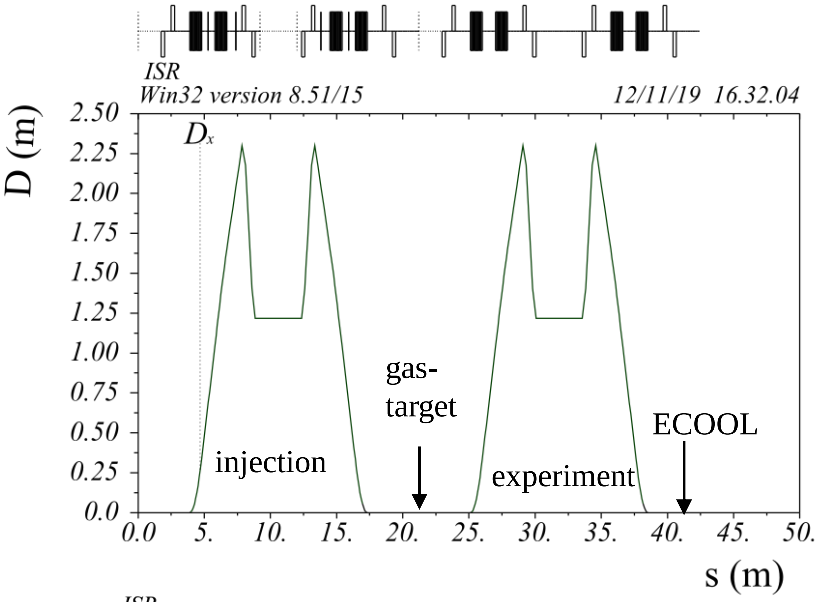
spectrometer dispersion



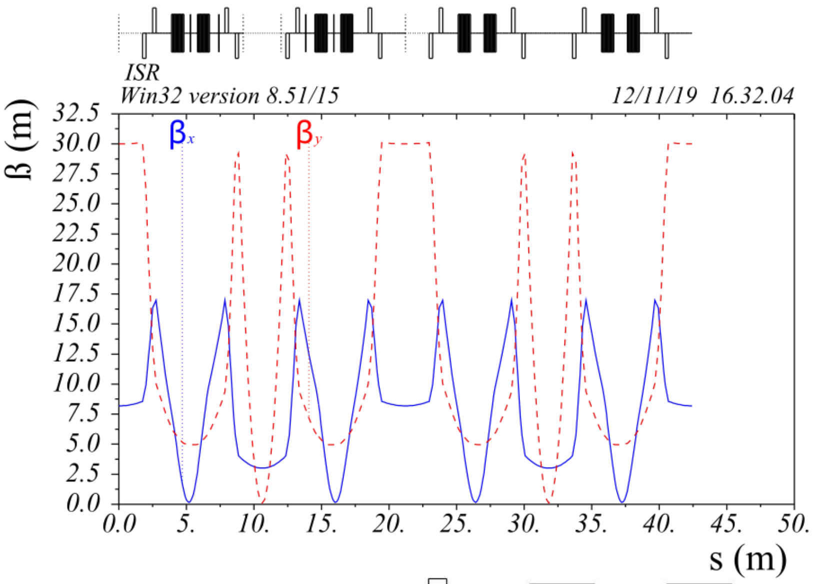
Standard-Mode of the ISR ring

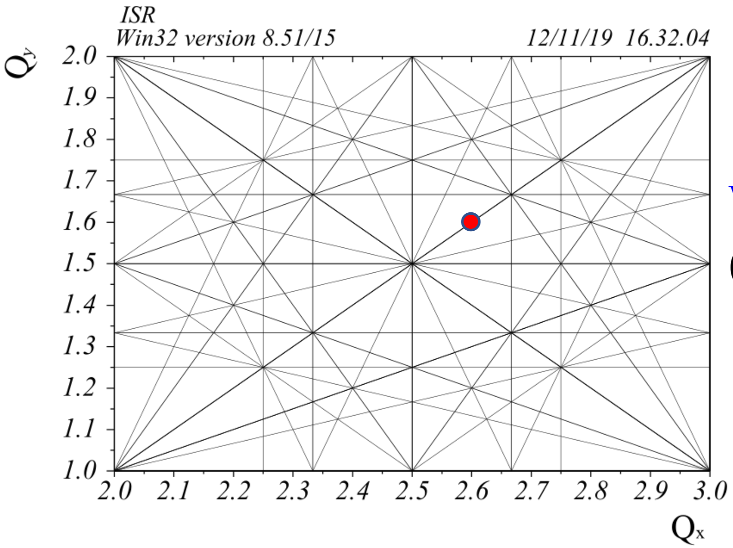
Dispersion

=achromat



Beta functions

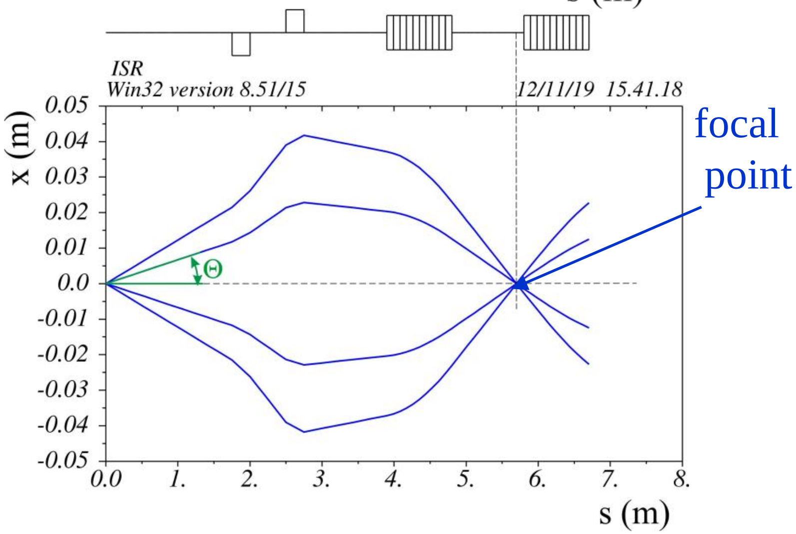




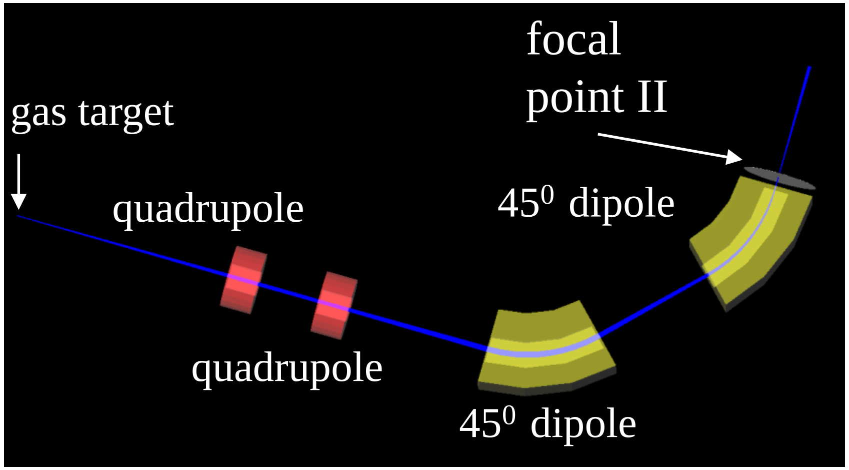
Working diagramme

working point

(Q_x=2.6, Q_y=1.6)

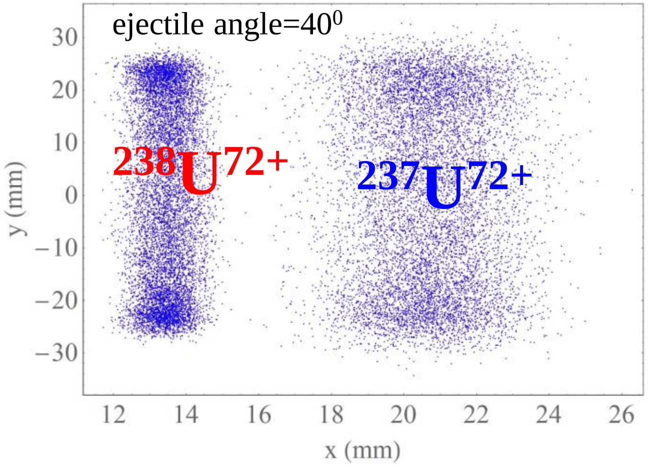


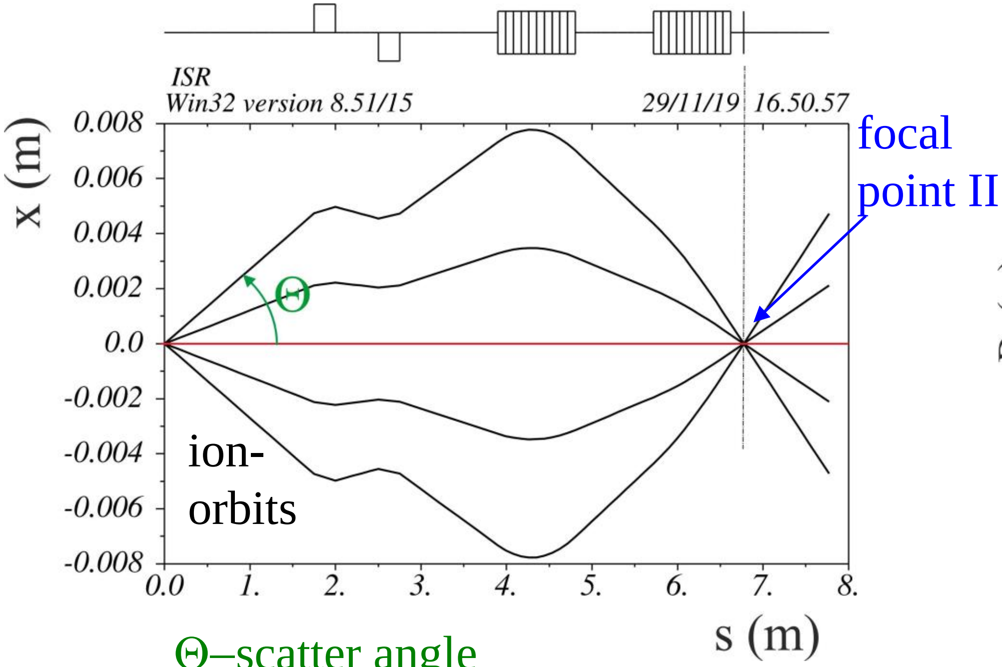
Focal point II of the ISR Spectrometer



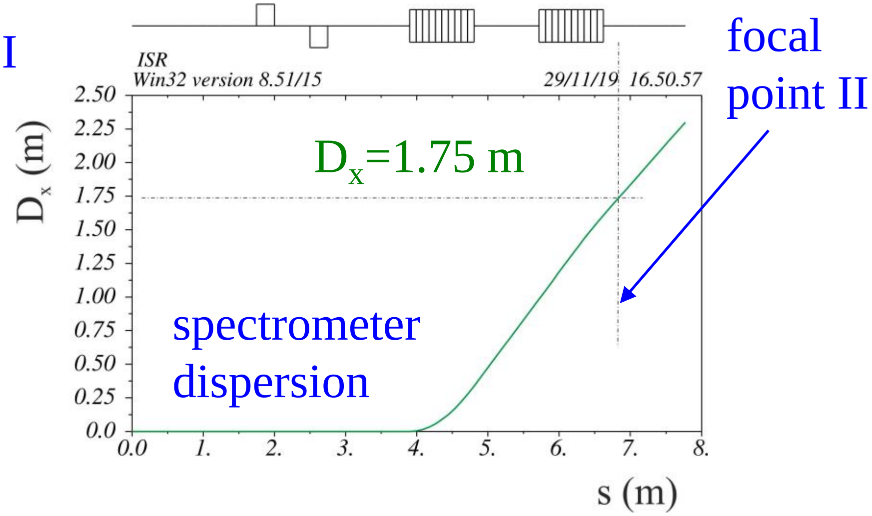
separation of reaction residues

$$^{238}U^{72+} + d \to (^{238}U^{72+})^* + d' \qquad (^{238}U^{72+})^* \to \begin{cases} ^{238}U^{72+} + \gamma \\ ^{237}U^{72+} + n \end{cases}$$



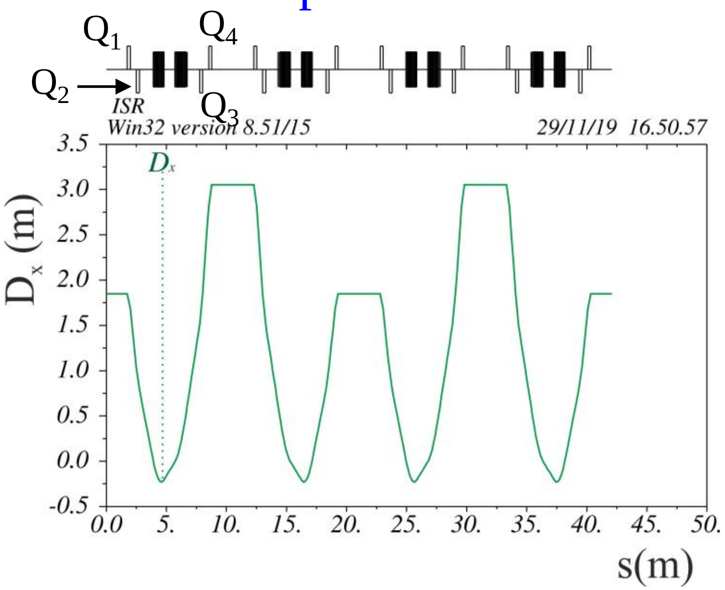


Θ–scatter angle

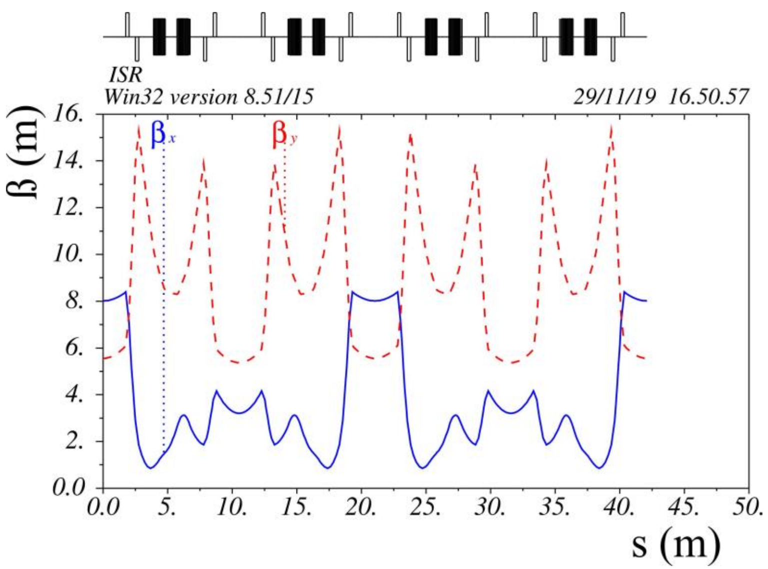


ISR Mode for focal-point II operation

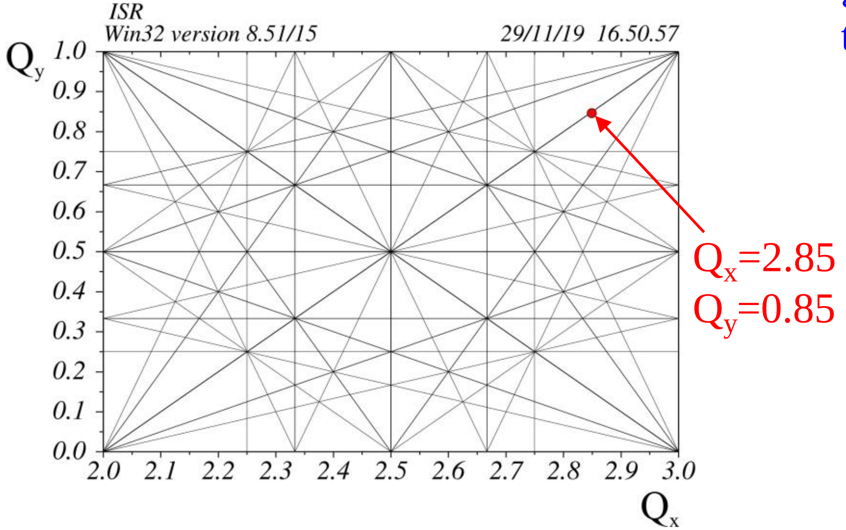
ISR dispersion



ISR β functions

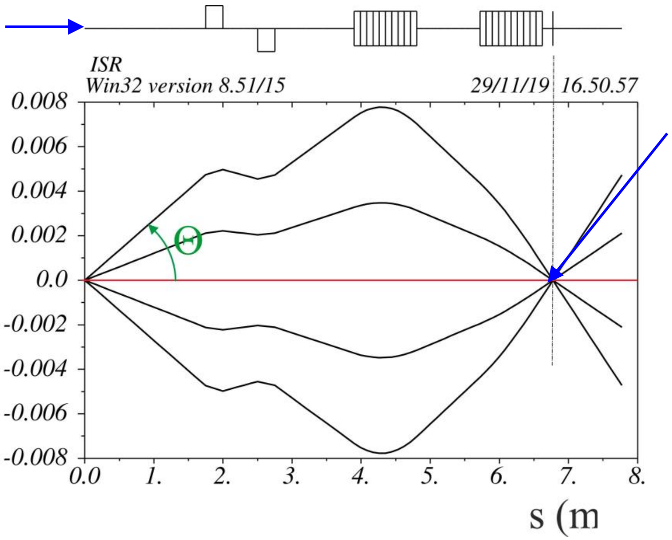


working point



Q_x=2.85
Q_y=0.85

gas-
target



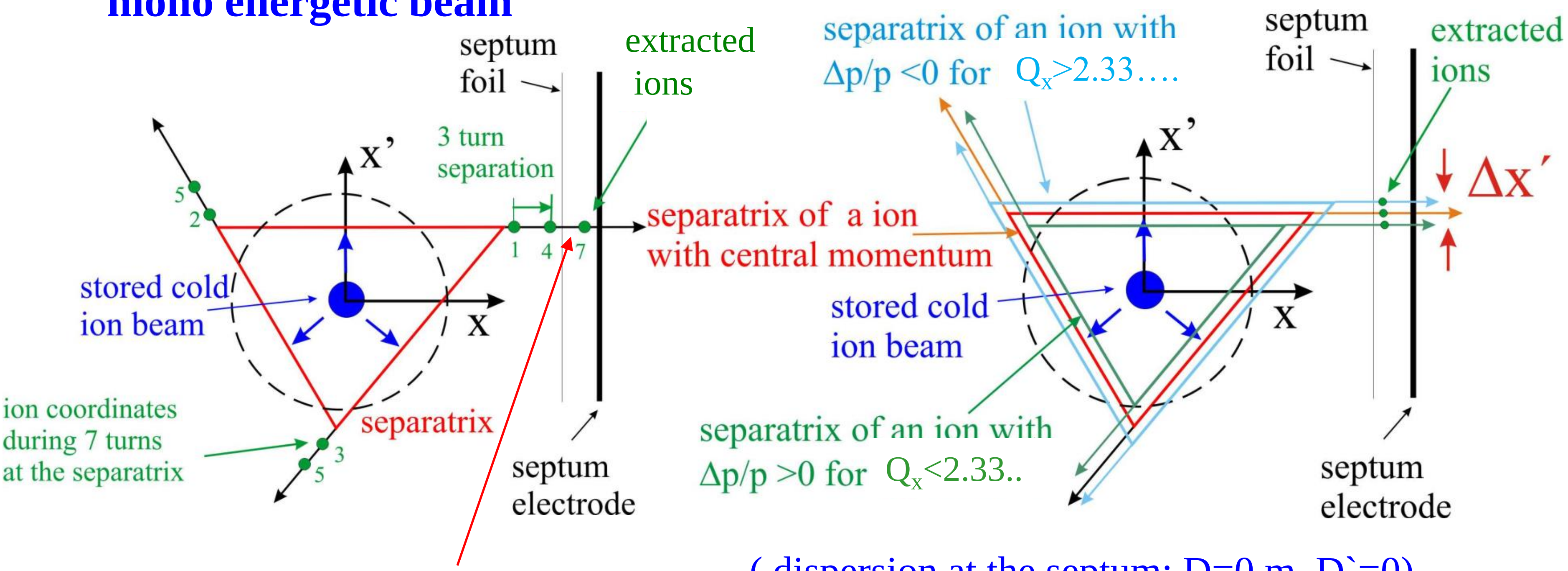
focal
point II

Slow Extraction

horizontal emittance of slow extracted beam is determined by the extraction method and momentum spread Δp/p

mono energetic beam

beam with momentum spread



ions are extracted along a straight line in the transverse phase space

$\Rightarrow \varepsilon_x=0$!

(dispersion at the septum: D=0 m, D`=0).

⇒ divergence Δx’ of extracted beam

horizontal beam size Δx is given by the three turn separation at septum position

with Δx’>0 $\Rightarrow \varepsilon_x>0$

Measured emittance of the slow extracted beam

experiment done at the TSR

beam: $^{12}C^{6+}$ E=73.3 MeV

Measured emittances of the slow extracted beam :

number of injected ions: N= $2.7 \cdot 10^5$ (I=0.15 μA)

horizontally: $\varepsilon_{x,\sigma}=0.25 \pm 0.05$ mm·mrad

vertically $\varepsilon_{y,\sigma}= 0.275 \pm 0.025$ mm·mrad

stored ion beam: $\varepsilon_{y,\sigma}= 0.245 \pm 0.019$ mm·mrad

emittance definition: $\varepsilon_{\sigma} = \frac{\sigma^2}{\beta} = \varepsilon_{rms}$

momentum spread of slow extracted beam:

was not measured

cooled stored beam

$N=4 \cdot 10^7$

$\varepsilon_{x,\sigma}= 0.02$ mm·mrad

$\varepsilon_{y,\sigma}= 0.04$ mm·mrad

measured for

$^{12}C^{6+}$ E=73.3 MeV

and $n_e=8 \cdot 10^6$ cm^{-3}

-During the extraction process electron cooling is switched off resulting in a larger emittance compare to a continues electron cooled ion beam

Modifying the slow extraction scheme

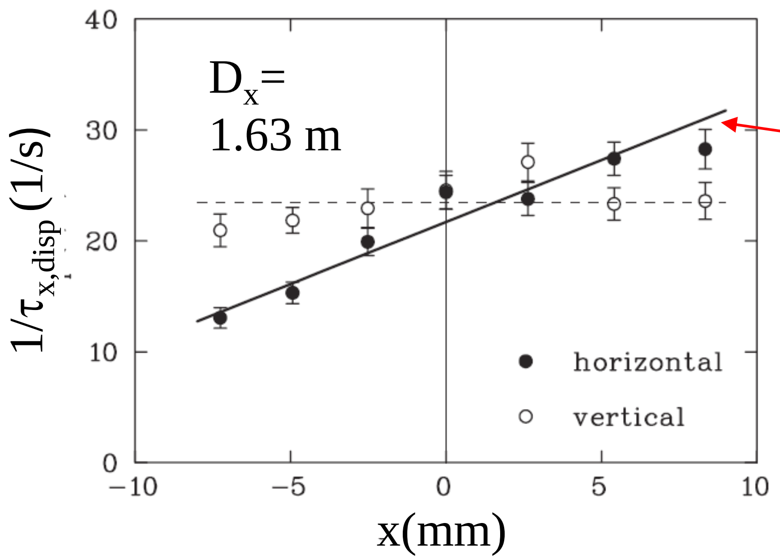
-electron **cooling has to be permanent on** to cool the vertical and longitudinal degree of freedom during the extraction process

-horizontal electron cooling has to switched off , or can be used to heat the beam for the slow extraction process

⇒combination of slow extraction with **dispersive electron cooling**

In the **dispersive electron cooling** process horizontal cooling rate is transferred in the longitudinal degree of freedom.

Dispersive electron cooling is realized by shifting the electron beam towards the ion beam and applying a dispersion in the electron cooler



x horizontal position of the ion beam to the center of the electron beam

Horizontal and vertical cooling rate

measured at the TSR with 73 MeV $^{12}C^{6+}$

$$\frac{1}{\tau_{x,disp}} = \frac{1}{\tau_{x,0}} + \eta_c \frac{\alpha_D D_x}{p_0} \alpha_{\|} \cdot x$$

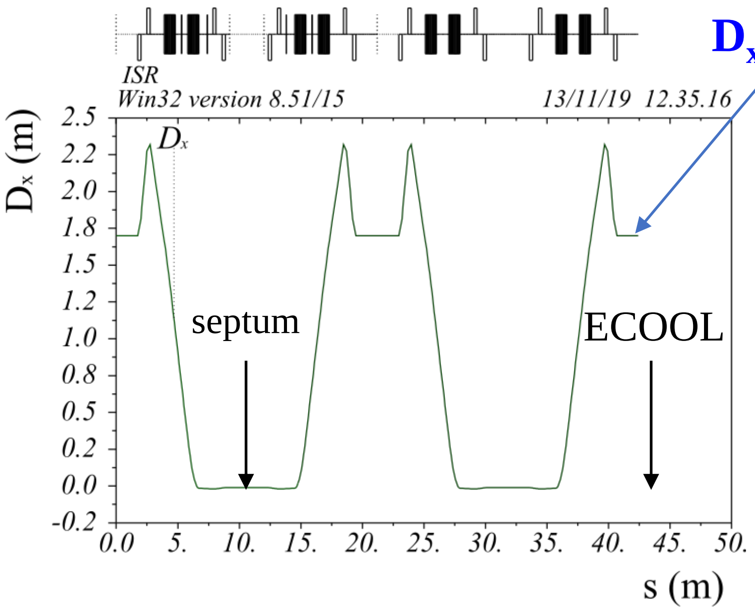
$$\alpha_D = e^2 n_e/(4\varepsilon_0 m_e v_0)$$

$$n_e = 8\cdot 10^6\,cm^{-3} << n_{e,max} = 5.6\cdot 10^7\,cm^{-3}$$

⇒ switching off horizontal electron cooling or to use horizontal heating is possible by increasing the electron density n_e

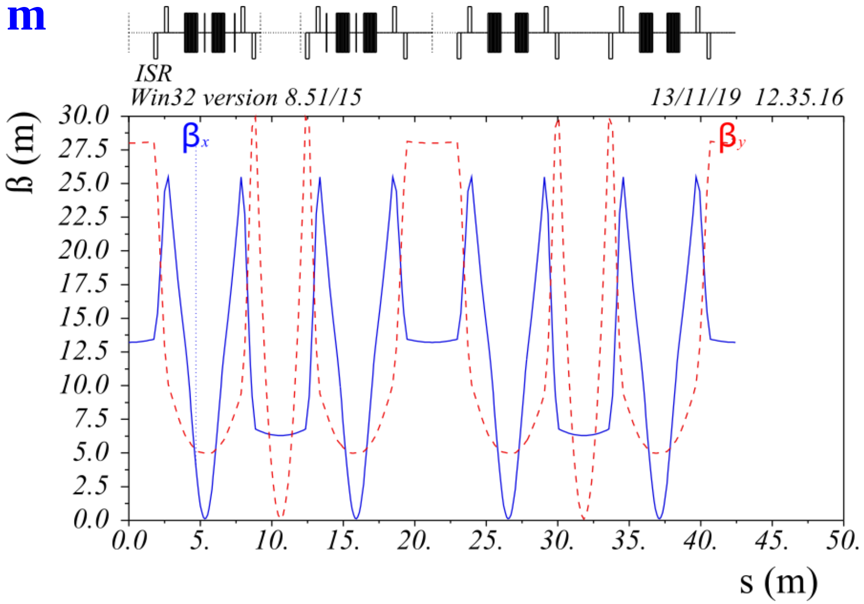
Slow cold extraction mode

dispersion

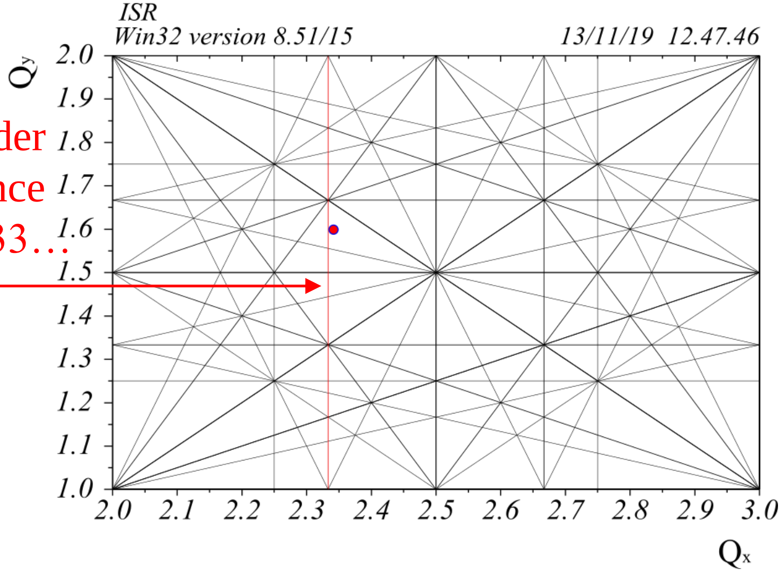


D_x=1.7 m

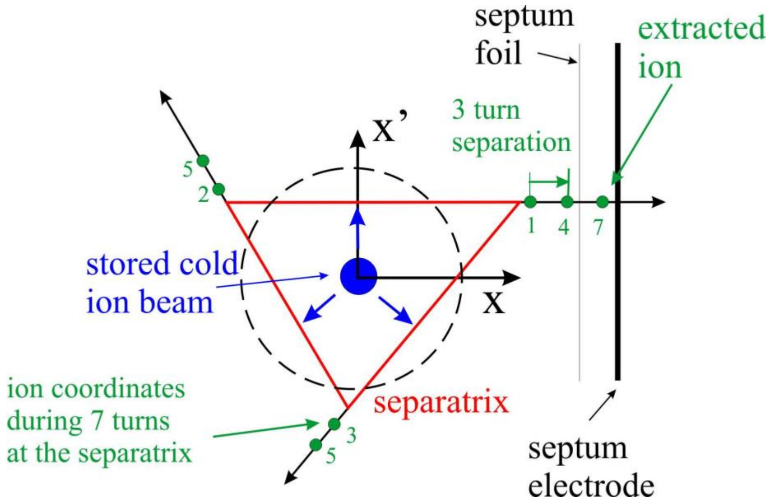
ß functions



third order resonance Q_x=2.333…



working point
Q_x=2.34
Q_y=1.6



Storing of daughter nuclei produced in nuclear reactions

proton pick-up reaction $^{A}\mathbf{X}^{q+} + \mathbf{p} \rightarrow {}^{A+1}\mathbf{Y}^{(q+1)+} + \gamma$

stripping: $^{A}\mathbf{X}^{q+} + \mathbf{gas} \rightarrow {}^{A}\mathbf{X}^{q+1} + \mathbf{e}$

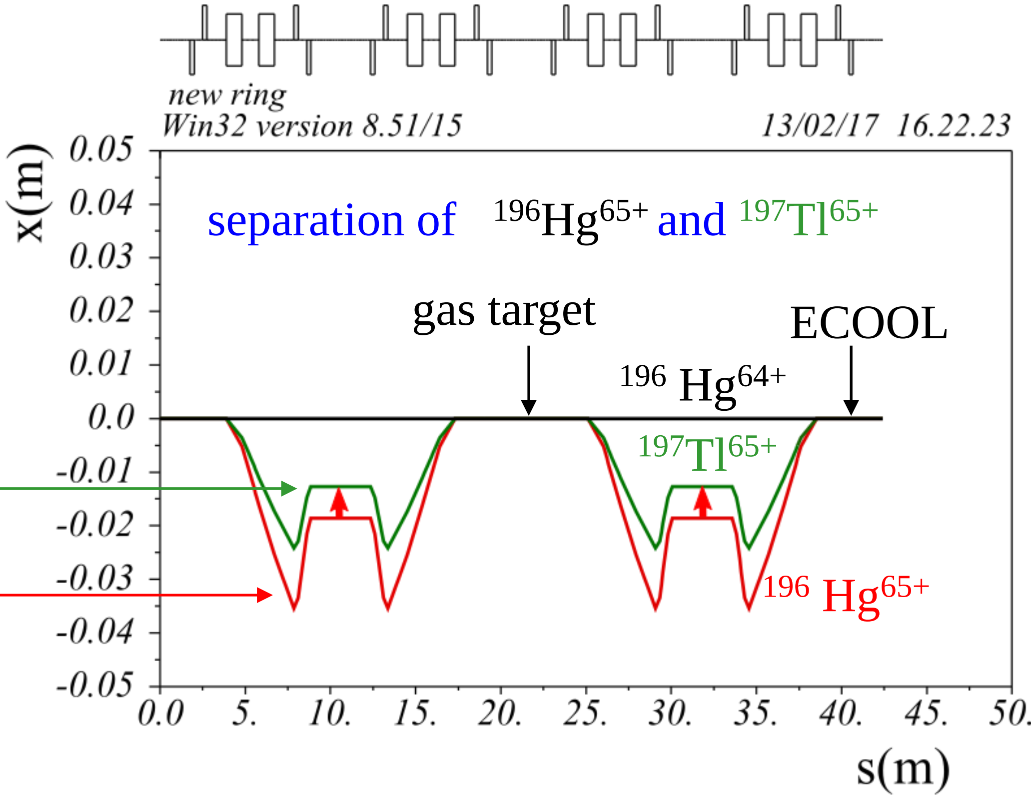
cannot separated with the ISR spectrometer

daughter nuclei $^{A+1}Y^{(q+1)+}$ and stripped ion $^{A}X^{q+1}$ ions have the same magnetic rigidity Bρ and cannot separated at the detector plane !

By storing the daughter nuclei $^{A+1}Y^{(q+1)}$ and electron cooling the daughter nuclei can be separated from the stripped ions $^{A}X^{q+1}$.

example:

$^{196}\mathrm{Hg}^{64+} + p \rightarrow {}^{197}\mathrm{Tl}^{65+} + \gamma$

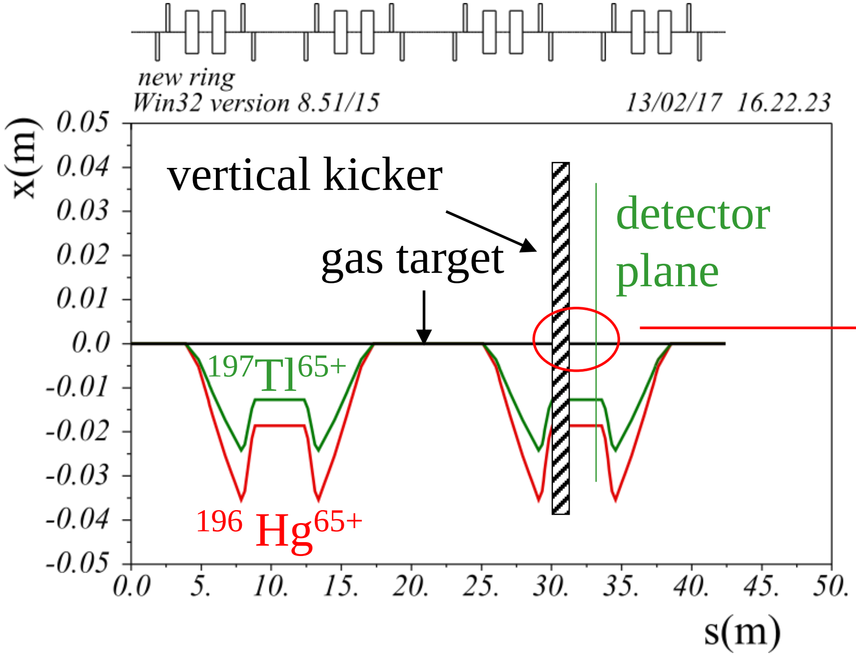


$^{197}\mathrm{Tl}^{65+}$ after ECOOL

$^{196}\mathrm{Hg}^{65+}$ and
$^{197}\mathrm{Tl}^{65+}$ direct after production

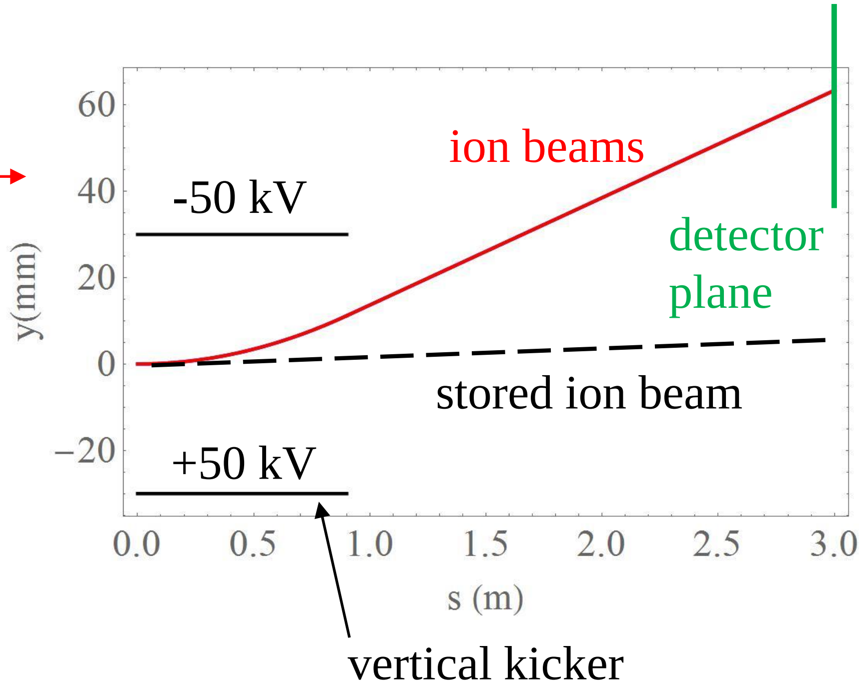
Direct Detection of the produced daughter nuclei

$$^{196}\mathrm{Hg}^{64+} + p \rightarrow {}^{197}\mathrm{Tl}^{65+} + \gamma$$



A vertical kicker is used to kick the stored ion beam towards the detectors

second experimental straight section II



In the equilibrium

number $N_{d,0}$ of $^{196}\mathrm{Tl}^{65+}$: $N_{d,0} = \bar{L}\tau_d\sigma$

example: lifetime daughter nuclei: τ_d=3.5 s

average luminosity: $\bar{L} = 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

cross section: σ=0.02 barn

$N_{d,0}$=70

Multi Charge operation of the TSR

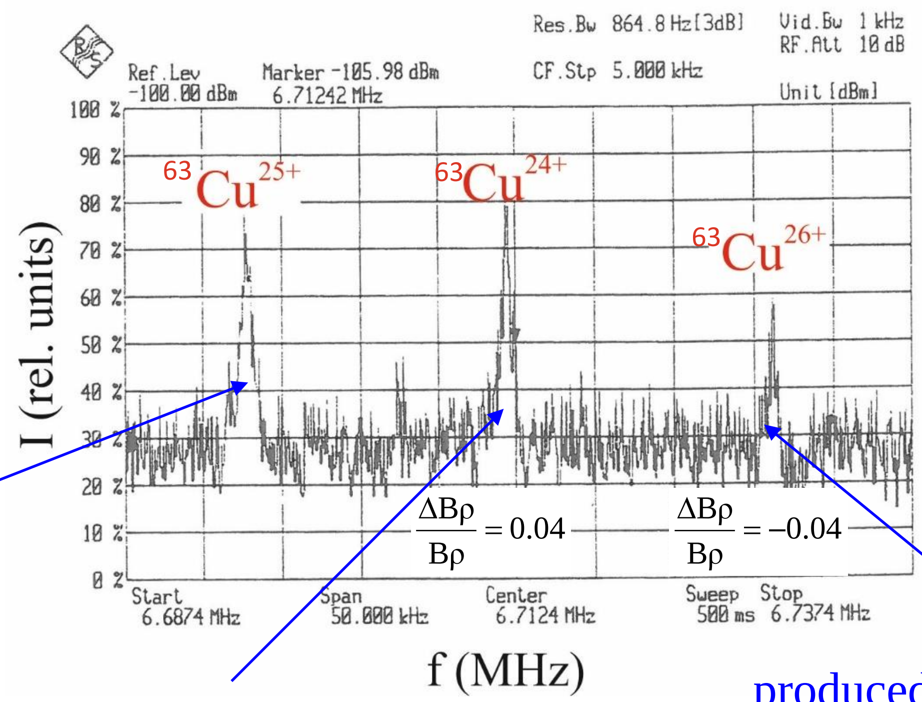
- Storing also daughter nuclei after production needs a relative large momentum acceptance of the storage ring
- At the TSR it was shown that several beams with different rigidities can be stored at the same time

Confirmation of the multi charge operation at the TSR

Schottky noise measured 12 s after injection

dispersion in the cooler:

D_x=0.3 m



$$\frac{\Delta B\rho}{B\rho} = 0.04$$

$$\frac{\Delta B\rho}{B\rho} = -0.04$$

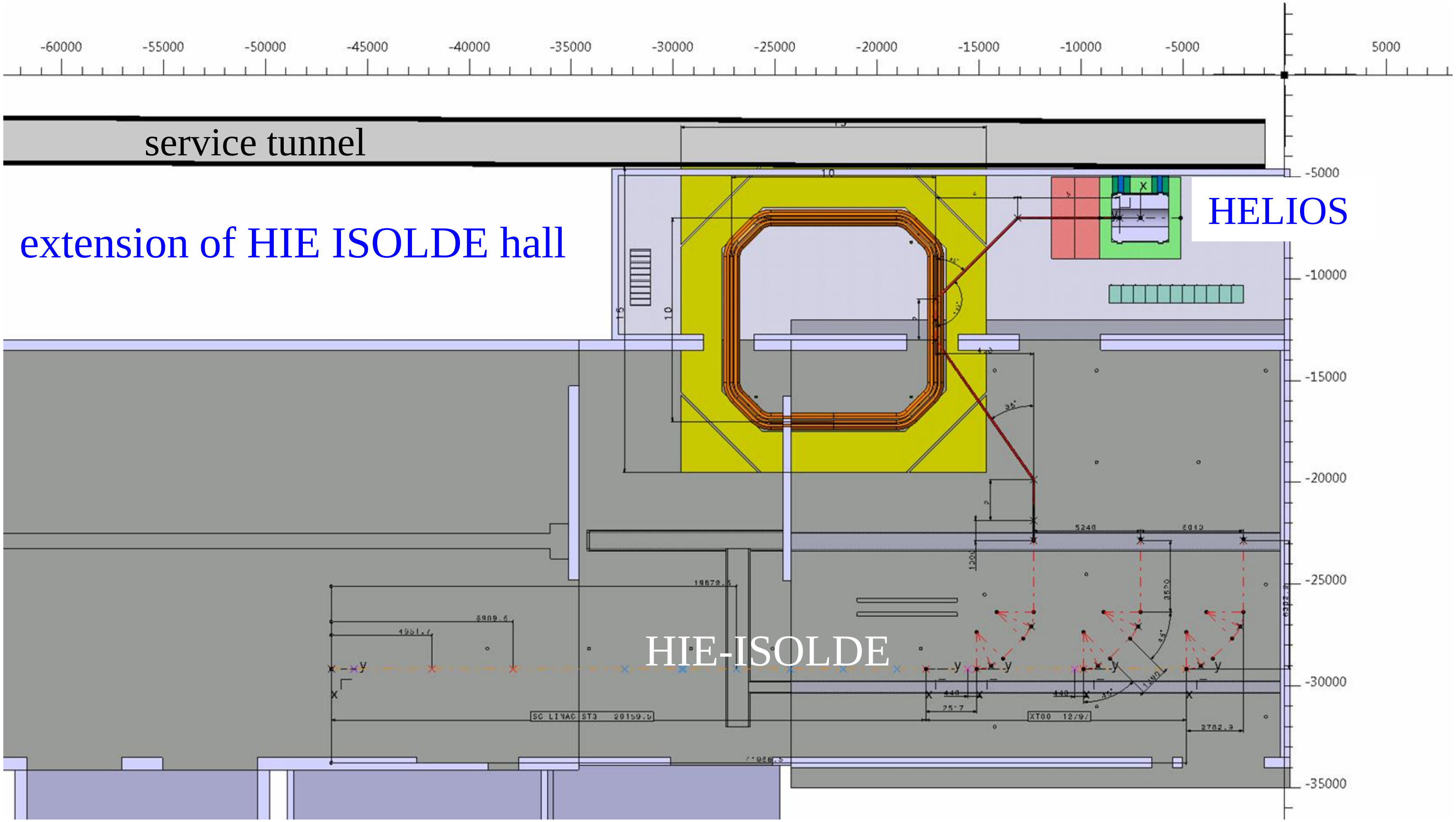
injected ion beam
E=266 MeV

produced by electron capture
visible already 2-3 s after injection

produced by stripping
detectable 8 s after injection

Possible location of the new storage at HIE-ISOLDE

transparency from Erwin Siesling and Stephane Maridor, CERN



Acknowledgement

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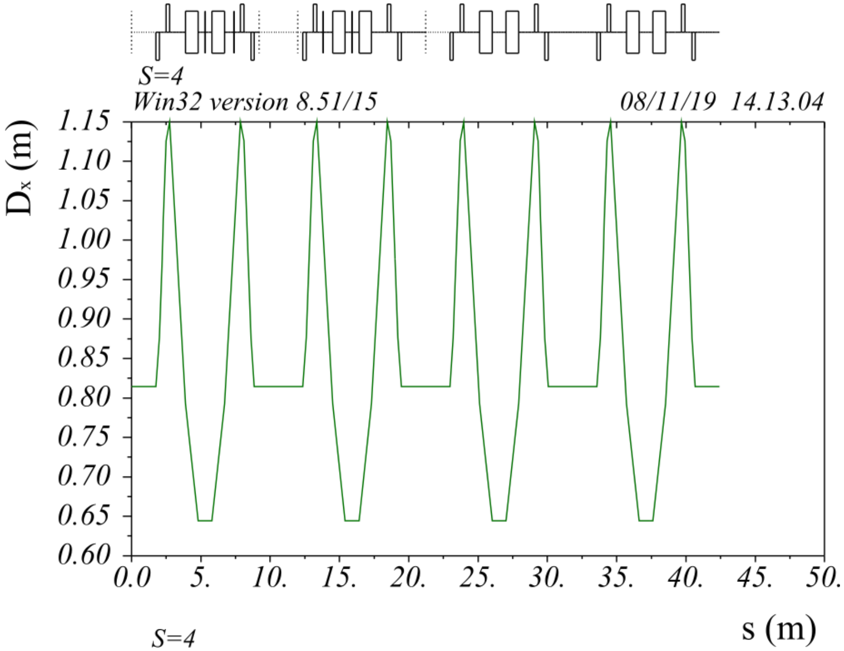
Beatriz Jurado, CENBG, Gradignan
Stephane Maridor, CERN, Geneva
Akira Noda, NIRS, Chiba
Erwin Siesling, CERN, Geneva
Fredrik Wenander, CERN, Geneva

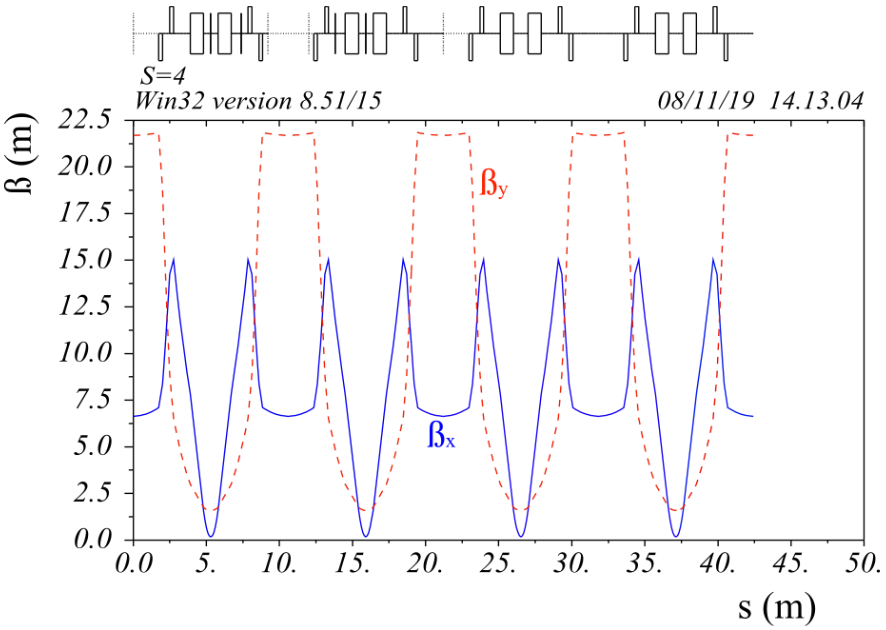
Appendix

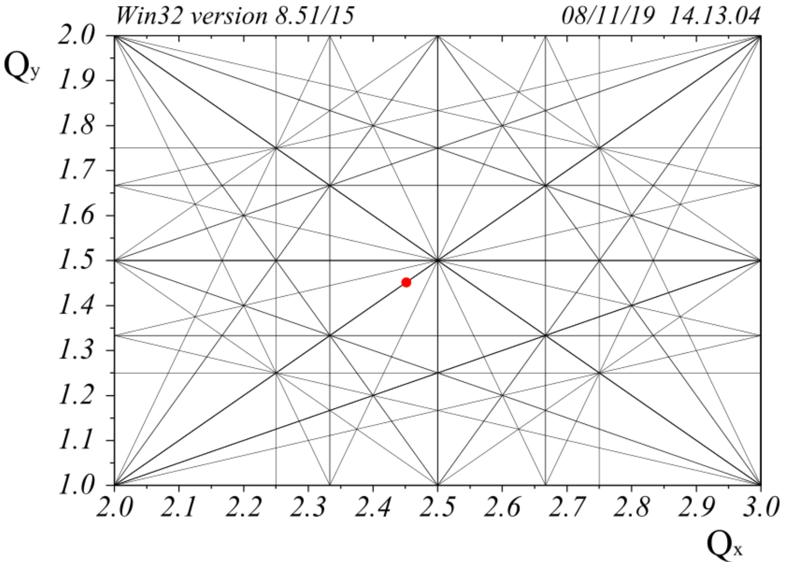
ISR lattice for S=4

dispersion



ß functions





working point

Q_x=2.45,Q_y=2.45

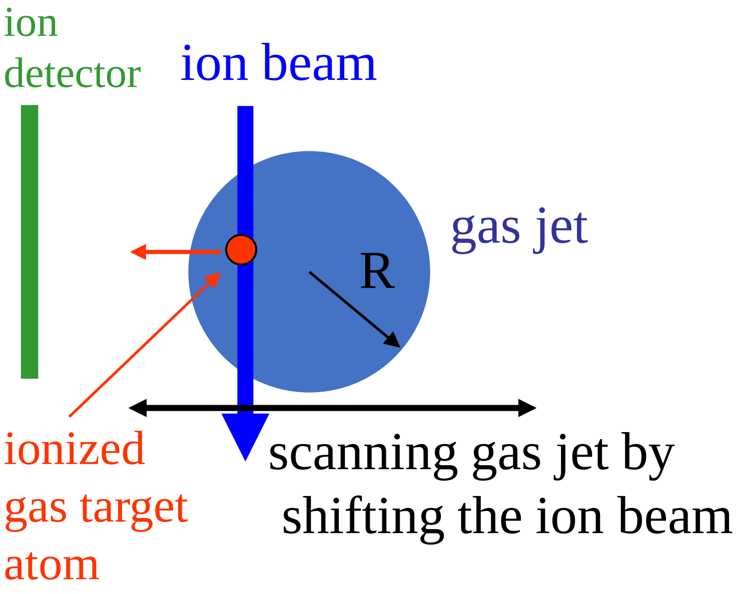
Target thickness profile of an gas jet

R_{ex}- counting rate ion detector reaction microscope

R_{BPM} counting rate beam profile monitor

(ion beam intensity normalization)

schematic assembly



ion detector

ion beam

gas jet

R

ionized gas target atom

scanning gas jet by shifting the ion beam

measured at TSR with 50 MeV $^{12}C^{6+}$ for an Ne gas jet target

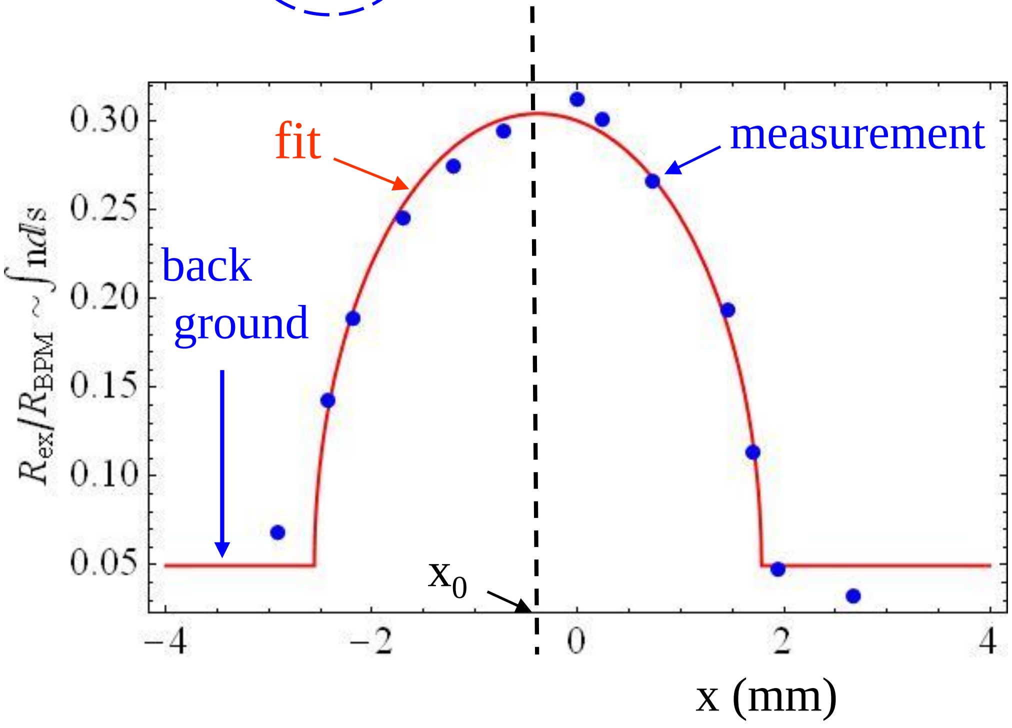
$$\frac{R_{ex}}{R_{BPM}} \propto \int n \cdot ds$$

target thickness

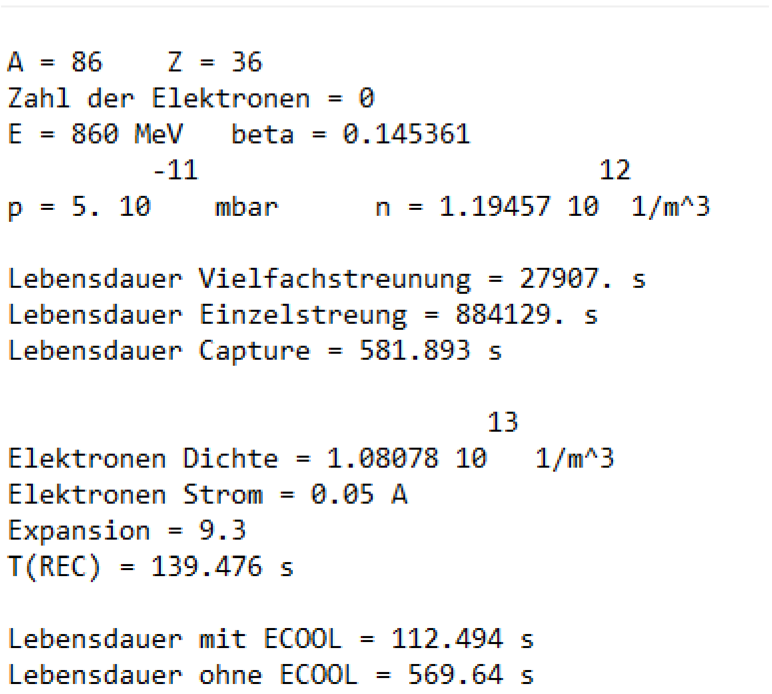
fit function for homogeneous gas density distribution:

$$R_{ex}/R_{BPM} \square \sqrt{R^2\text{-}(x\text{-}x_0)^2}$$

fits very well for a **homogeneous target density distribution**

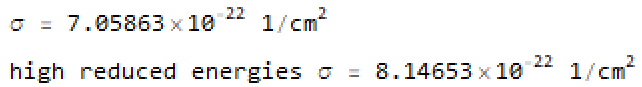


Life time $^{86}\mathrm{Kr}^{36+}$ with H_2 target



```
A = 86     Z = 36
Zahl der Elektronen = 0
E = 860 MeV    beta = 0.145361
         -11                          12
p = 5. 10     mbar       n = 1.19457 10  1/m^3

Lebensdauer Vielfachstreunung = 27907. s
Lebensdauer Einzelstreung = 884129. s
Lebensdauer Capture = 581.893 s


                                    13
Elektronen Dichte = 1.08078 10    1/m^3
Elektronen Strom = 0.05 A
Expansion = 9.3
T(REC) = 139.476 s

Lebensdauer mit ECOOL = 112.494 s
Lebensdauer ohne ECOOL = 569.64 s
```

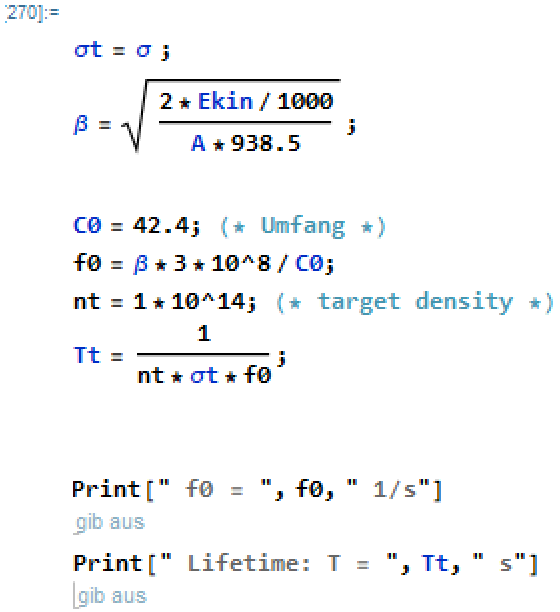
electron cature gas target



$\sigma = 7.05863 \times 10^{-22}$ 1/cm^2

high reduced energies $\sigma = 8.14653 \times 10^{-22}$ 1/cm^2

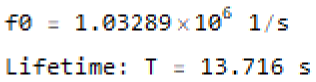
Target Lebensdauer



```
270]:=

σt = σ;
β = Sqrt[(2 * Ekin / 1000) / (A * 938.5)];

C0 = 42.4; (* Umfang *)
f0 = β * 3 * 10^8 / C0;
nt = 1 * 10^14; (* target density *)
Tt = 1 / (nt * σt * f0);


Print[" f0 = ", f0, " 1/s"]
gib aus
Print[" Lifetime: T = ", Tt, " s"]
gib aus
```

$$\beta = \sqrt{\frac{2 * \mathrm{Ekin}/1000}{A * 938.5}};$$

$$Tt = \frac{1}{nt * \sigma t * f0};$$



```
f0 = 1.03289×10^6 1/s
Lifetime: T = 13.716 s
```

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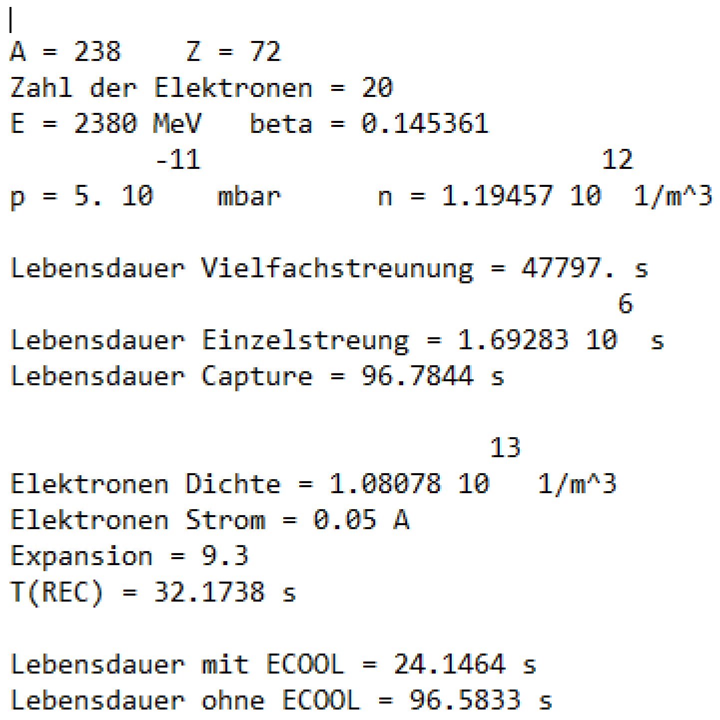
Life time $^{238}U^{72+}$ with a He target



```
|
A = 238    Z = 72
Zahl der Elektronen = 20
E = 2380 MeV   beta = 0.145361
          -11                         12
p = 5. 10     mbar        n = 1.19457 10   1/m^3

Lebensdauer Vielfachstreunung = 47797. s
                                             6
Lebensdauer Einzelstreung = 1.69283 10   s
Lebensdauer Capture = 96.7844 s

                                     13
Elektronen Dichte = 1.08078 10    1/m^3
Elektronen Strom = 0.05 A
Expansion = 9.3
T(REC) = 32.1738 s

Lebensdauer mit ECOOL = 24.1464 s
Lebensdauer ohne ECOOL = 96.5833 s
```

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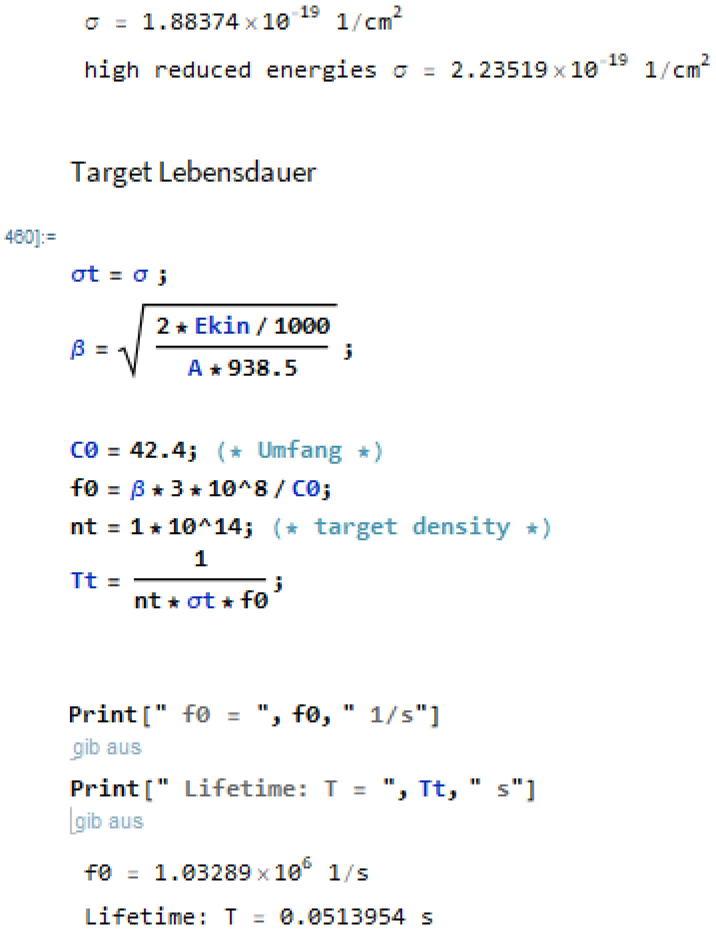
electron cature gas target



$\sigma = 1.88374\times10^{-19}$ 1/cm^2

high reduced energies $\sigma = 2.23519\times10^{-19}$ 1/cm^2

Target Lebensdauer

460]:=

$\sigma t = \sigma$;

$\beta = \sqrt{\frac{2 * Ekin / 1000}{A * 938.5}}$;

C0 = 42.4; (* Umfang *)

f0 = β * 3 * 10^8 / C0;

nt = 1 * 10^14; (* target density *)

$Tt = \frac{1}{nt * \sigma t * f0}$;

```
Print[" f0 = ", f0, " 1/s"]
gib aus
Print[" Lifetime: T = ", Tt, " s"]
gib aus
```

$f0 = 1.03289\times10^{6}$ 1/s

Lifetime: T = 0.0513954 s

Remark: $$\frac{1}{T_{total}} = \frac{1}{T_{cap}} + \frac{1}{T_{strip}} + \frac{1}{T_{rec}} + \frac{1}{T_{target}}$$

Q=72+ is a equilibrium charge state, therefore $T_{strip}=T_{cap}$

ECOOL

The ISR electron cooler

based on the very compact electron cooler at LSR storage ring

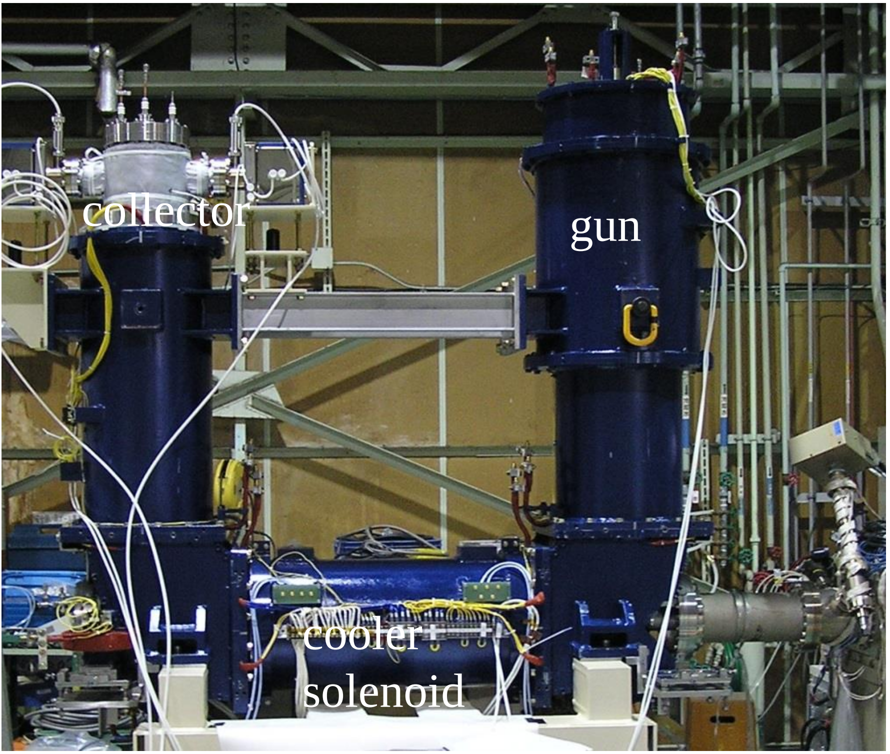
to cool ions with up to 10 MeV/u an electron cooler with electron energies up to 5 keV is required

should be reduced for 10 keV/u

parameter of S-LSR cooler, Kyoto university

Electron Energy	1-5	[keV]
Electron Beam Current	0.05-0.4	[A]
Gun Perveance	2.2	[µP]
Cathode Radius	15	[mm]
Expansion Factor	1-3	
Max Field at Cooling/Gun Solenoid	0.5/1.5	[kG]
Field quality in cooling solenoid	10^{-4}	
Toroid Angle	90	°
Toroid Radius	0.25	[m]
Cooler Solenoid Length	0.8	[m]
Effective Cooling Section Length	0.5	[m]
β-function at cooling section	1.7/2.4	[m]

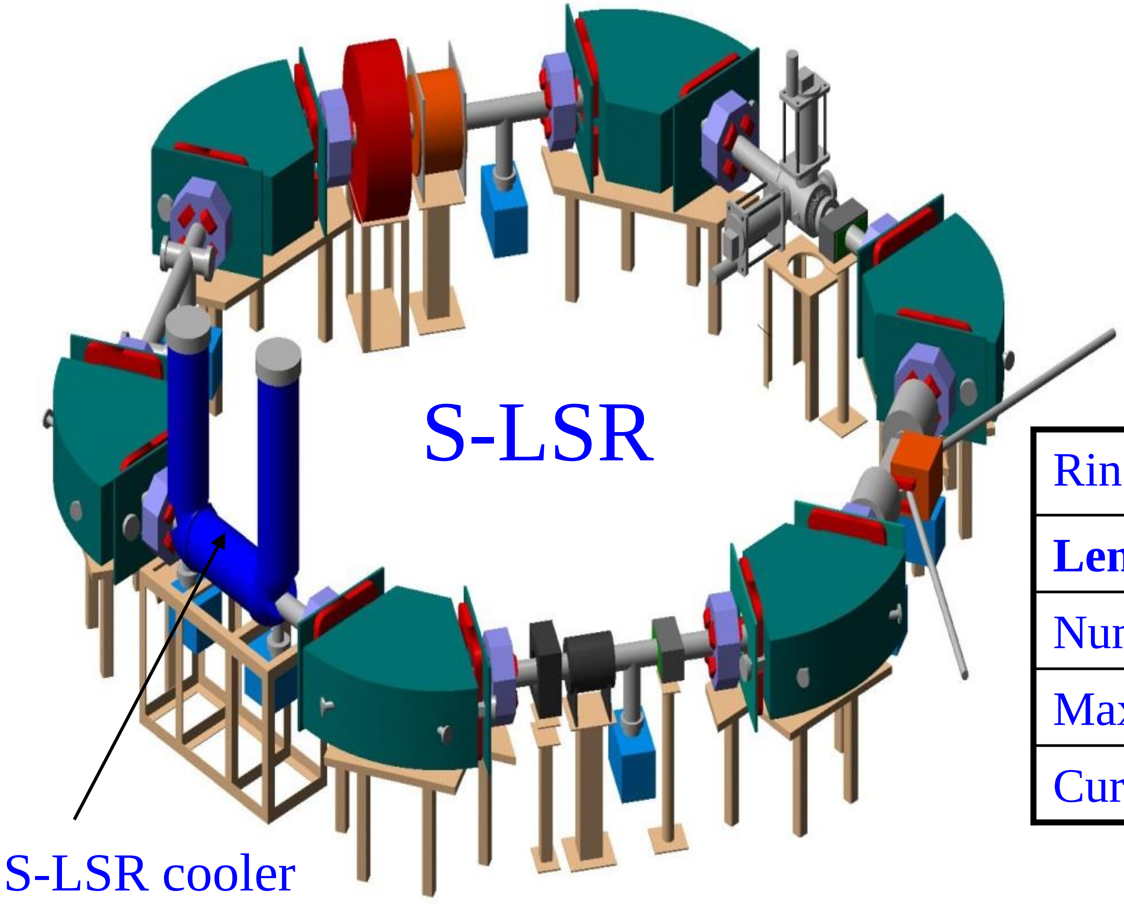
S-LSR cooler



should be increased to **1.5 m**

remark: ELENA (CERN) cooler is also based on the S-LSR cooler

The S-LSR Ring



parameter of S-LSR ring

Ring Circumference	22.557 m
Length of Straight Section	**1.86 m**
Number of Periods	6
Maximum Bending Field	0.95 T
Curvature Radius	1.05 m

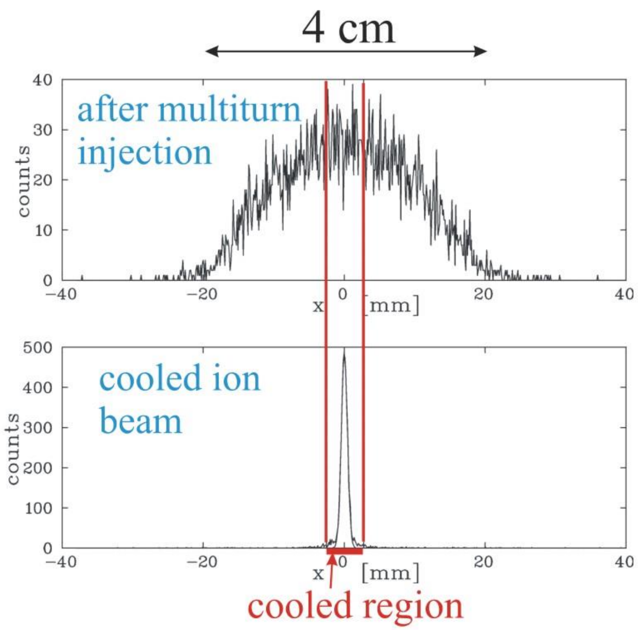
⇒ cooler should fit in a straight section of L= 3.5 m.

-to decrease cooling time length of cooler solenoid should be increased.

-two beam position monitors may be possible to place in the same straight section.

Cooling time T_{cool} of a multiturn injected ion beam

TSR measurements



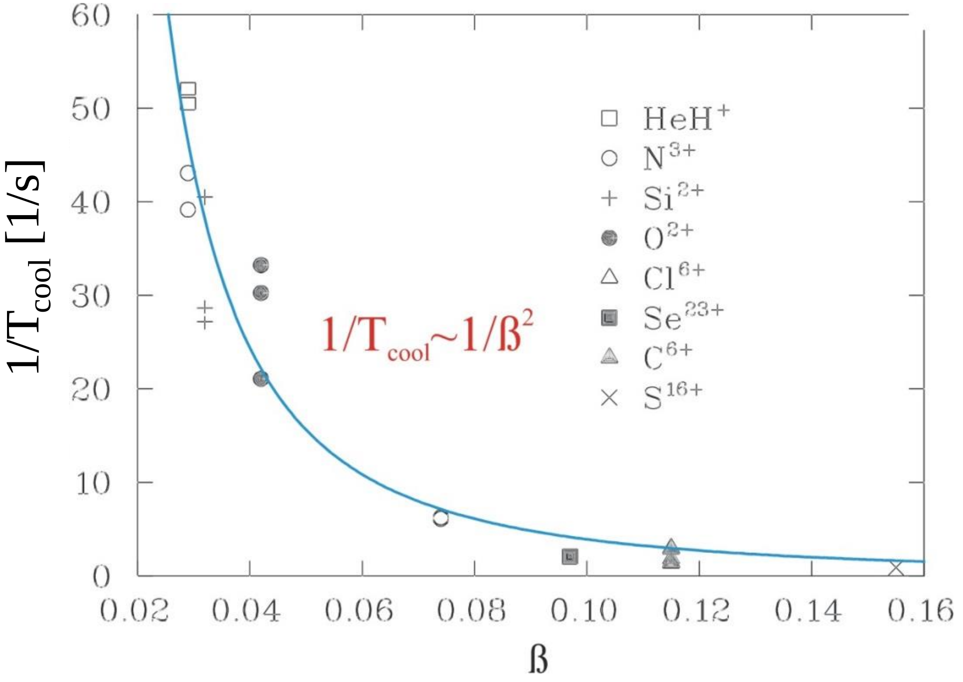
definition of transverse cooling time

The cooling time is the time it takes to cool 80% of the particles outside the cooled region into the marked region

$$T_{cool} \approx \text{const} \cdot \frac{A\,ß^2}{q^2\,n_e} \quad (\,0.03<ß<0.16\,)$$

inverse cooling time $1/T_{cool}$ as a function of ß

normalized to q^2/A and $n_e=10^8\ \text{cm}^{-3}$

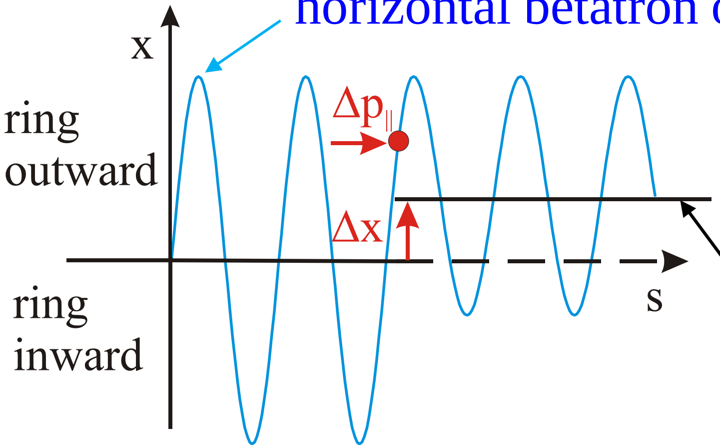


$\Rightarrow$ for $\alpha_{ex}=9.6$ and per $=1$ μperv

$$T_{cool} \approx \frac{A}{q^2}\cdot 3\,\text{s} \quad \text{because} \quad n_e \propto \beta^2$$

Dispersive cooling

Principle of dispersive cooling

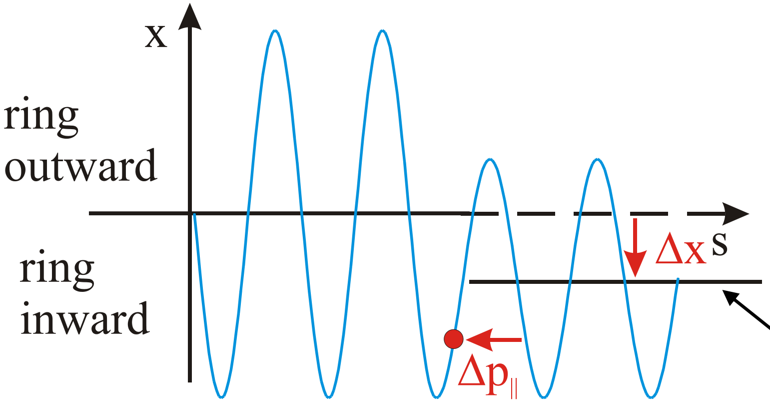


horizontal betatron oscillation of an ion

positive momentum transfer
$\Delta p_{\parallel}$ at x>0 damping of the
horizontal betatron oscillation

new closed orbit

$\Delta x = D_x \cdot \Delta p_{\parallel} / p_{\parallel}$ D_x-dispersion



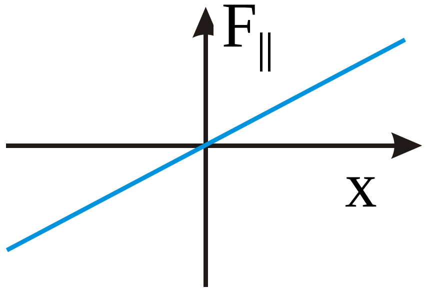
negative momentum transfer
$\Delta p_{\parallel}$ at x<0 damping of the
horizontal betatron amplitude

new closed orbit

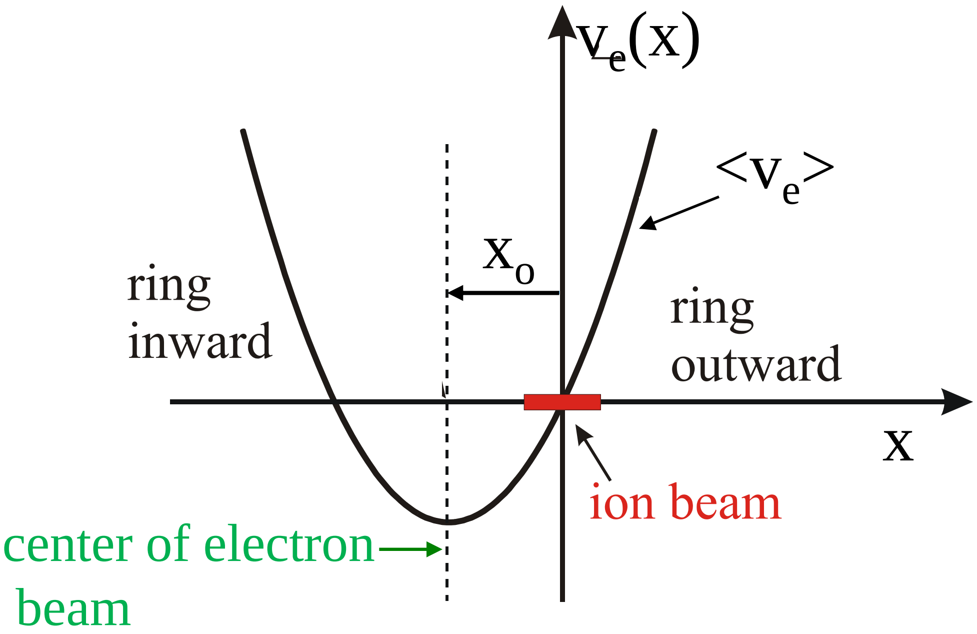
⇒gradient $dF_{\parallel}/dx$ of the longitudinal friction force
can damp or excite the horizontal betatron amplitude

Realization of dispersive electron cooling

gradient of the longitudinal friction force $F_\parallel$



velocity distribution $v_e(x)$ of the electron beam



creating a horizontal gradient of the longitudinal electron cooling force by displacing the electron beam by x_0:

$x>0$: $<v_e> \; > \; v_{ion}$ $F_\parallel>0$

$x<0$: $<v_e> \; < \; v_{ion}$ $F_\parallel<0$

change of the horizontal cooling rate:

$$\Delta_x = -\frac{1}{\sigma}\frac{d\sigma}{dt} = \Delta_{0,x} + \Delta_{D,x}$$

$$\Delta_{D,x} \propto n_e \, \alpha_\parallel \, D_x \, x_0$$

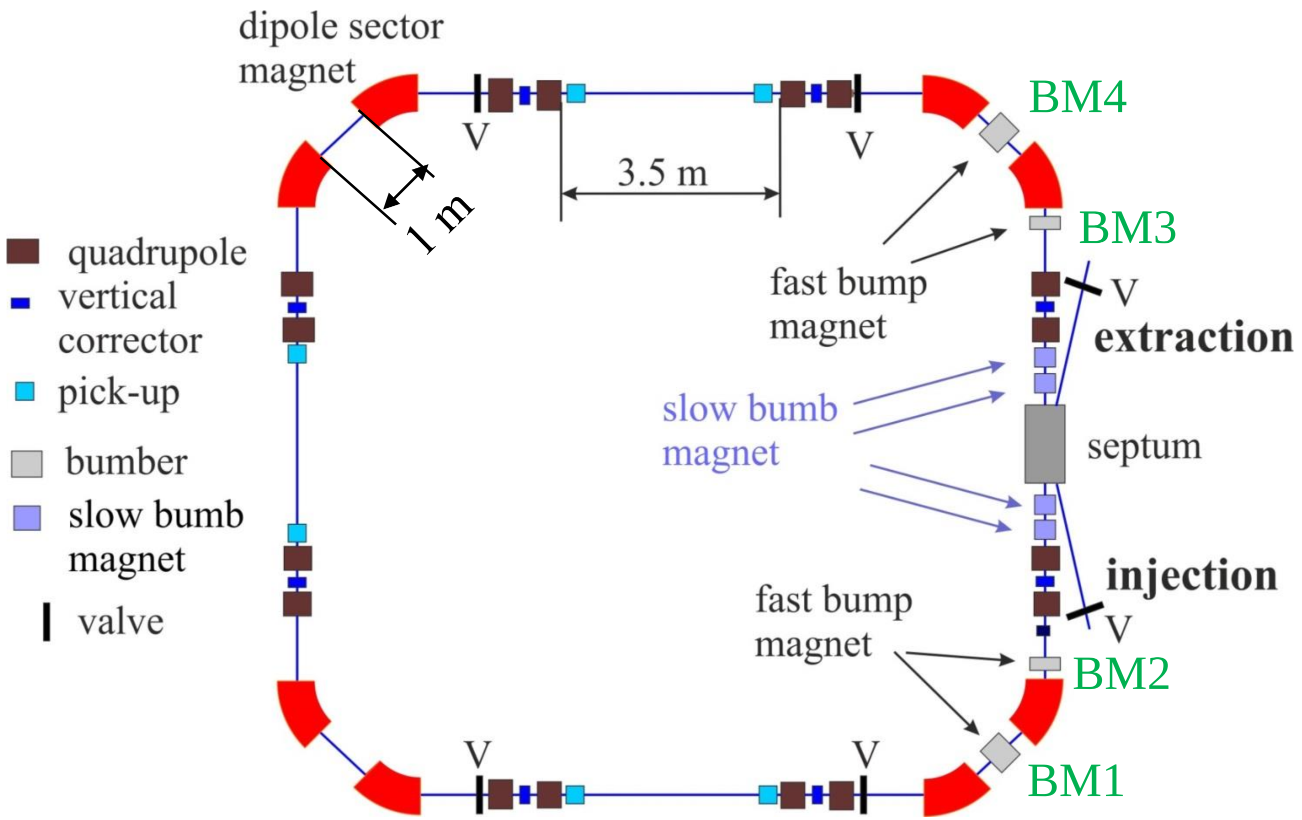
$\alpha_\parallel$ – longitudinal cooling decrement:

$$\alpha_\parallel = -\frac{\partial F_\parallel}{\partial \Delta v_\parallel}$$

D_x- dispersion in the electron cooler for dispersive cooling D_x=1.63 m

Multi turn Injection

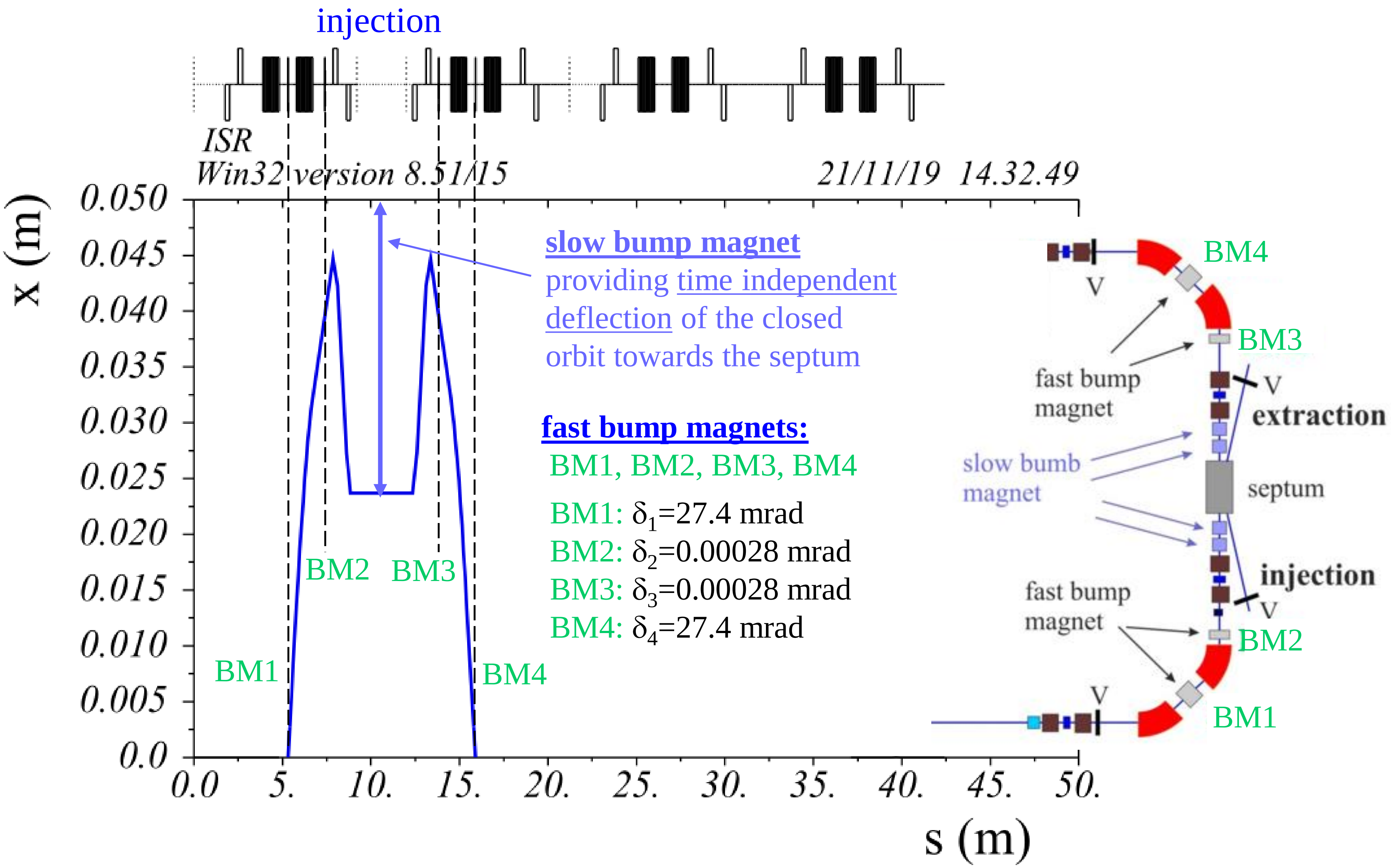
Magnet system for multi-turn injection



slow bump magnets: providing a time independent closed orbit shift towards the electrostatic septum of Δx≈2.5 cm

fast bump magnets: providing a fast shift of the closed orbit towards the electrostic septum of Δx ≈ 2.5 cm, BM1,BM4 large fast bump magnets, BM3,BM4 small fast bump magnets

Injection orbit (standard mode)

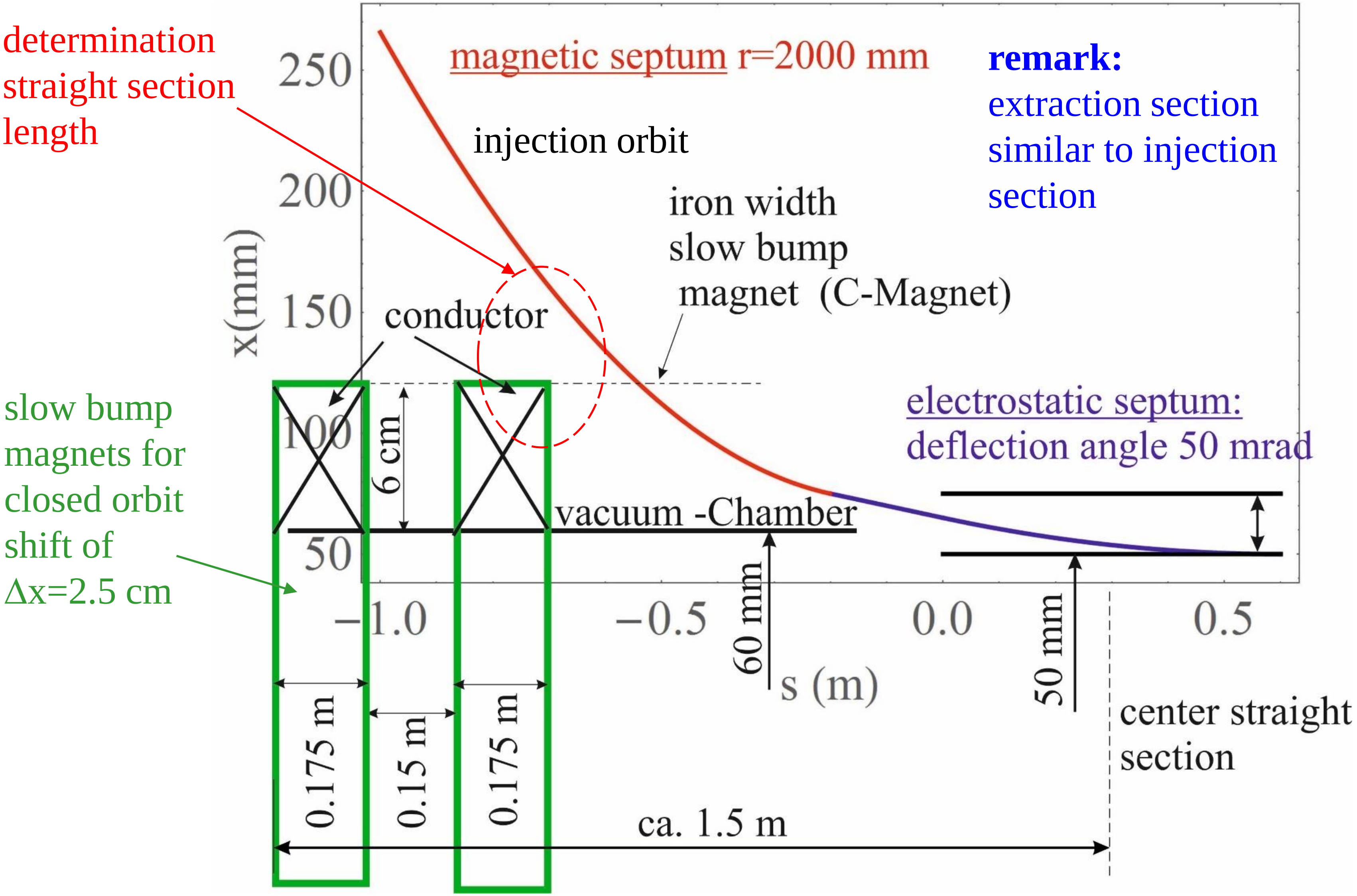


slow bump magnet
providing time independent deflection of the closed orbit towards the septum

fast bump magnets:
BM1, BM2, BM3, BM4

BM1: δ_1=27.4 mrad
BM2: δ_2=0.00028 mrad
BM3: δ_3=0.00028 mrad
BM4: δ_4=27.4 mrad

Place requirements of injection and extraction straight section



remark:
extraction section similar to injection section

length of injection extraction straight section: L ≥ 3 m⇒ **minimum length = 3.5 m**

Preliminary data of the injection components

	electrostatic septum
length	600 mm
gap	25 mm
max voltage U	150 kV
deflection angle	50 mrad
U for 10MeV/u and A/q=3.5	147 kV
E for 10 MeV/u and A/q=3.5	5.88 MV/m

	slow bump magnet
L	175 mm
α	≈ 80 mrad
$B\rho_{max}$	1.5 Tm
B for 1.5 Tm and Δx=2.5 cm	0.66 T
number	4

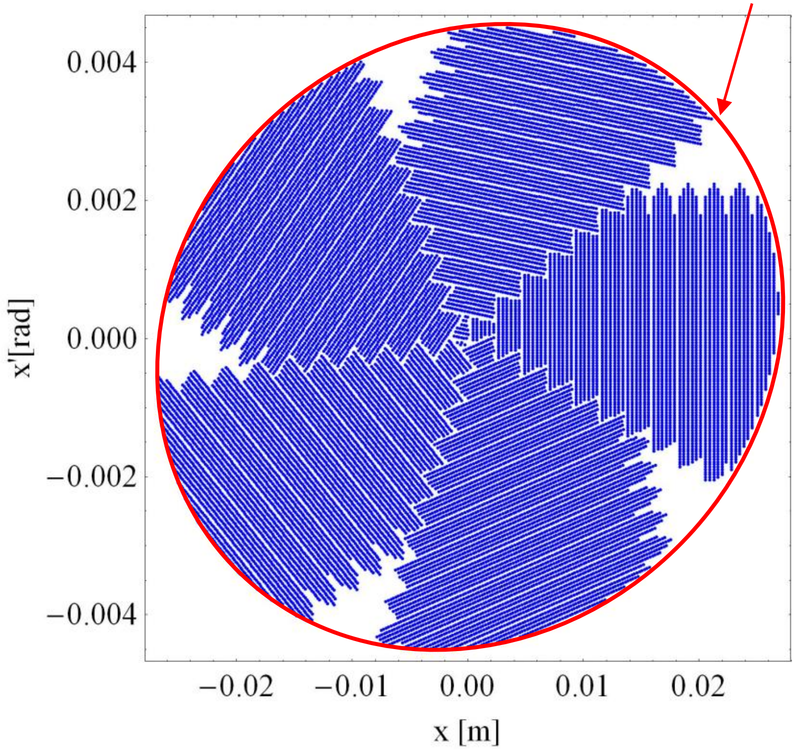
	magnetic septum
r	2000 mm
α	≈ 350 mrad
$B\rho_{max}$	1.5 Tm
B for 1.5 Tm	0.75 T

instead of using two magnetic septum's (like TSR) to simplify the injection

Minimum Length of injection and extraction straight section ≈ 3.5 m

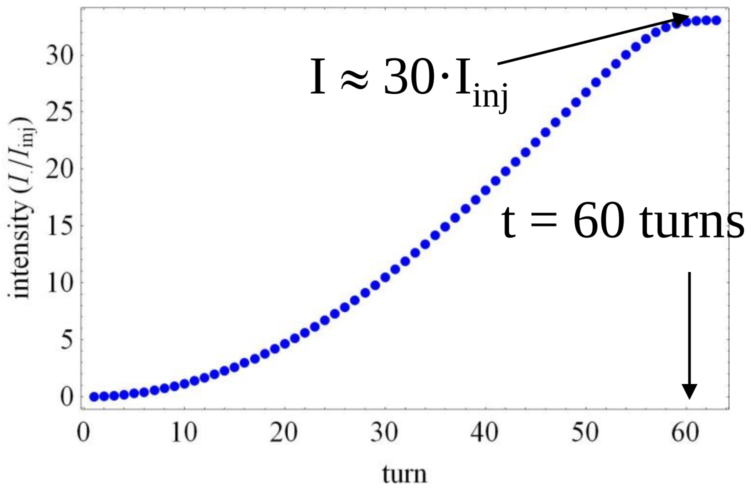
Multiturn injection at TSR@Isolde

transverse phase space



acceptance
A=120 mm·mrad

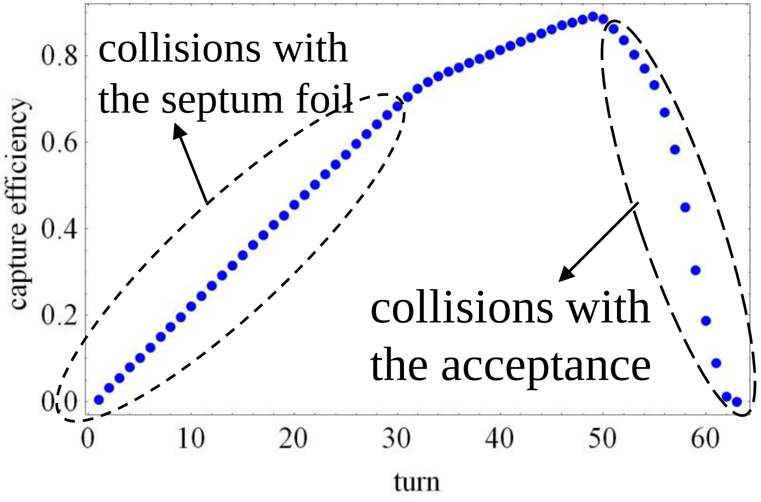
intensity increase



$I \approx 30 \cdot I_{inj}$

t = 60 turns

capture efficiency



collisions with the septum foil

collisions with the acceptance

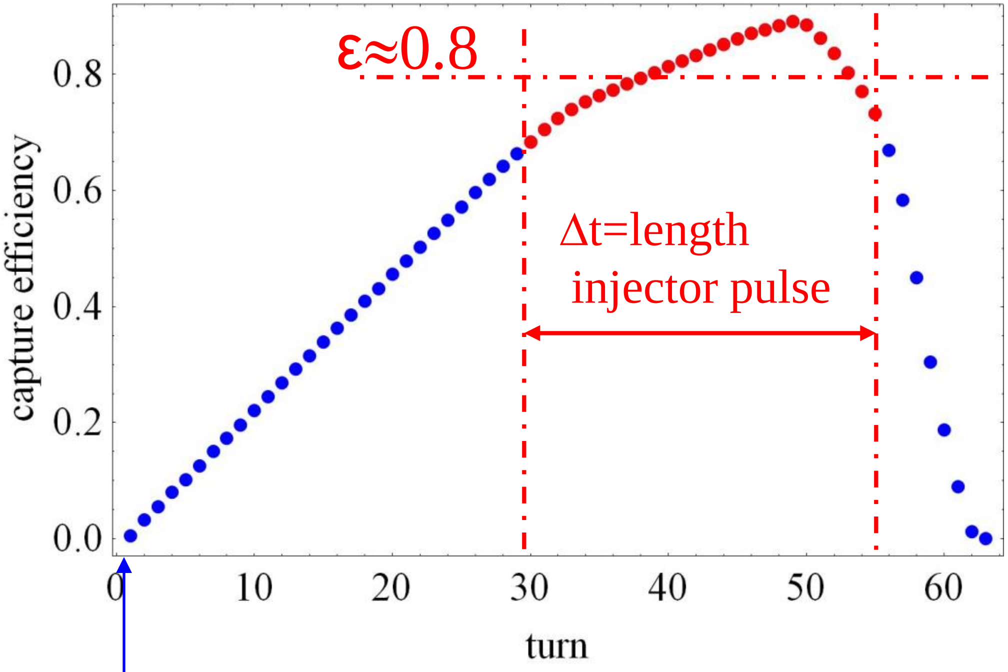
Q_x=2.8
ε= 4 mm·mrad

Hie Isolde beam typically emittance at 10 MeV/u

intensity increase:
$I \approx 30 \cdot I_{inj}$

efficiency ≈ 0.5 for injector beam with pulse length t≈60 turns

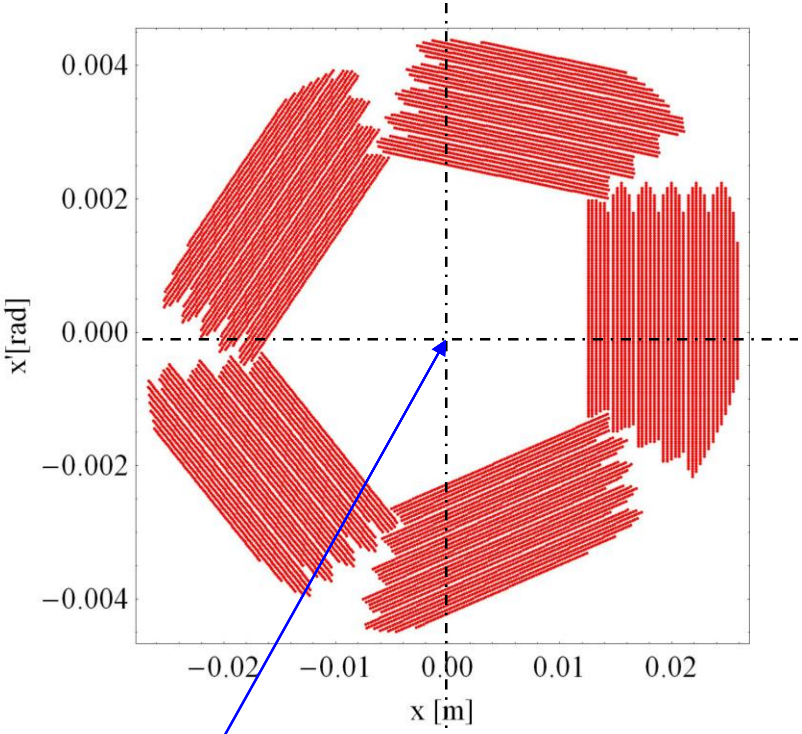
Multiturn injection at TSR@Isolde



closed orbit at
the septum foil

Δt ≈ 25 turns
typically ≈ 30 μs (10 MeV/u)

transverse phase space



closed orbit

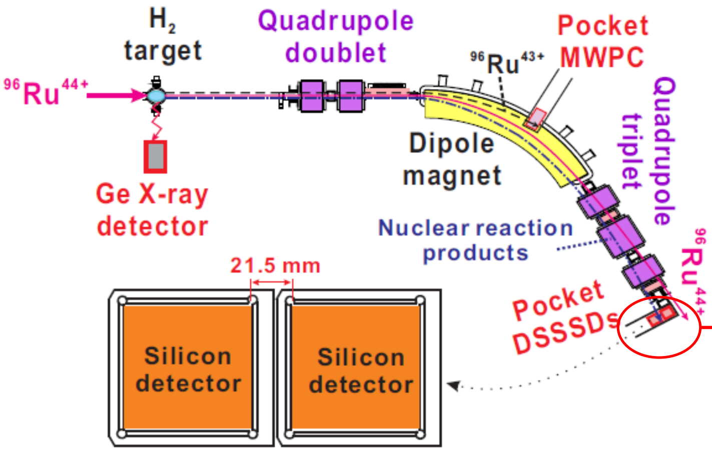
ε= 4 mm·mrad
Q_x=2.8

if Δt ≤ 25 turns ⇒ ≈ 80 % of the injected ions can be captured

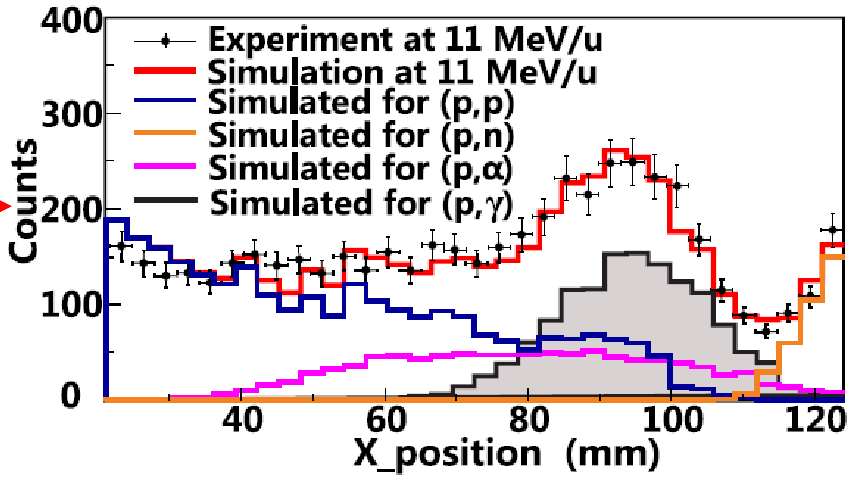
Proton Pick-up reaction

Proton pick-up reaction at ESR

$$^{96}\mathrm{Ru}^{44+} + \mathrm{p} \rightarrow {}^{97}\mathrm{Rh}^{45+} + \gamma$$



horizontal residue distribution



Disadvantages: - no separation of different reactions

-very broad Rutherford scattered ion distribution with interfere with daughter nuclide from p,γ reaction

---

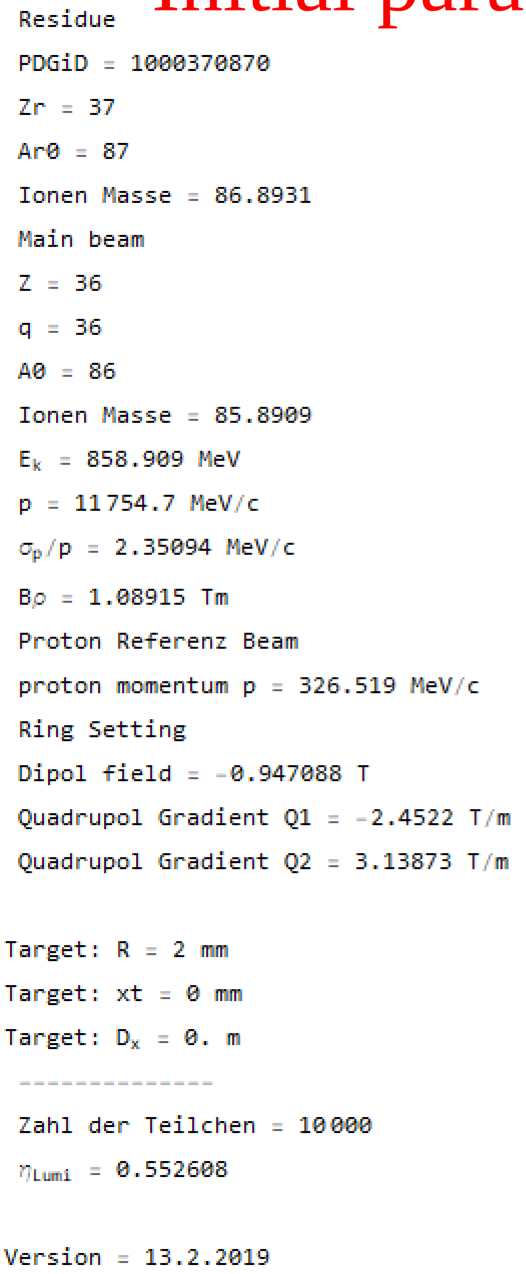
To improve the situation

-To separate Rutherford scatted ions from daughter nuclei a **focal point** at the detector position is required

- Large separation of different reaction products at the detector location

Initial parameters for proton pick-up reaction

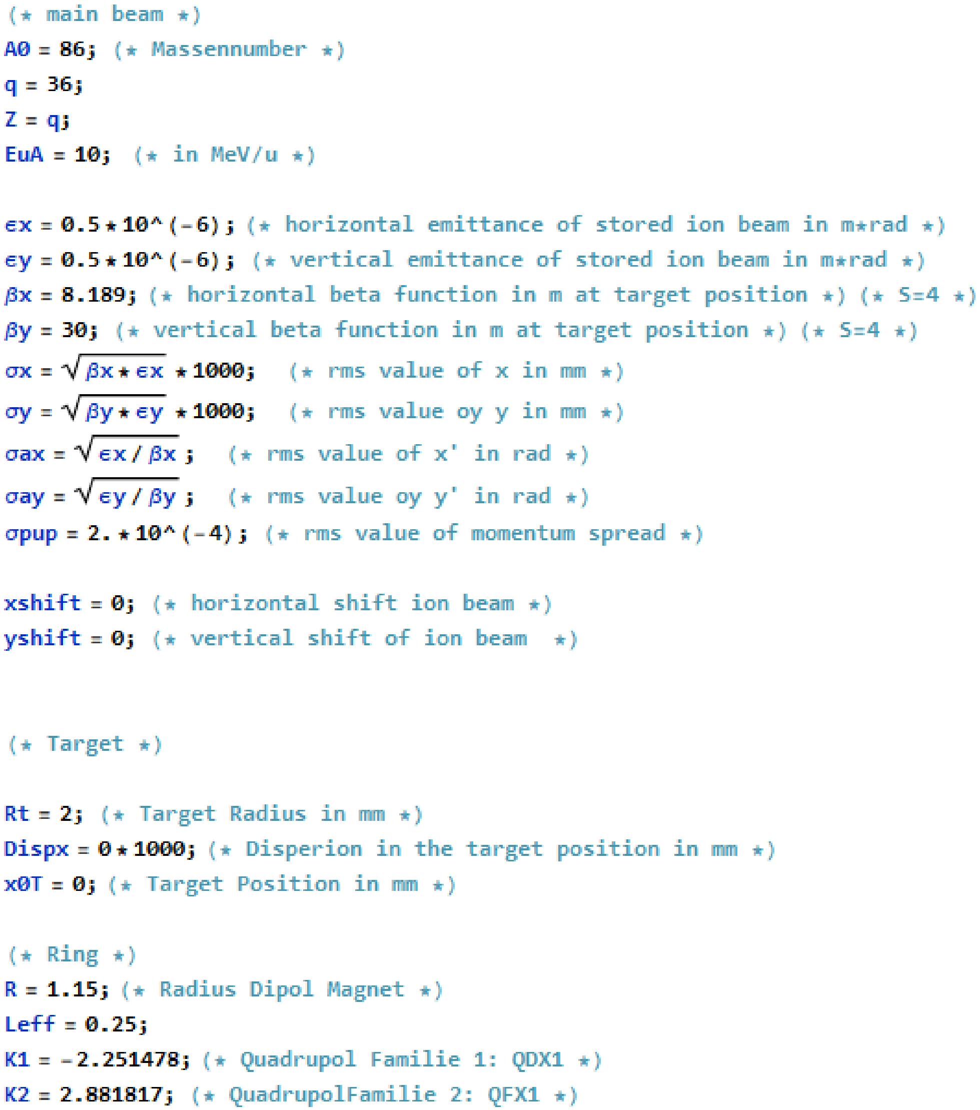
$$^{86}\mathrm{Kr}^{36+} + \mathrm{p} \rightarrow {}^{87}\mathrm{Rb}^{37+} + \gamma$$



```
Residue
PDGiD = 1000370870
Zr = 37
Ar0 = 87
Ionen Masse = 86.8931
Main beam
Z = 36
q = 36
A0 = 86
Ionen Masse = 85.8909
E_k = 858.909 MeV
p = 11754.7 MeV/c
σ_p/p = 2.35094 MeV/c
Bρ = 1.08915 Tm
Proton Referenz Beam
proton momentum p = 326.519 MeV/c
Ring Setting
Dipol field = -0.947088 T
Quadrupol Gradient Q1 = -2.4522 T/m
Quadrupol Gradient Q2 = 3.13873 T/m

Target: R = 2 mm
Target: xt = 0 mm
Target: D_x = 0. m
 --------------
Zahl der Teilchen = 10000
η_Lumi = 0.552608

Version = 13.2.2019
```



```
(* main beam *)
A0 = 86; (* Massennumber *)
q = 36;
Z = q;
EuA = 10;  (* in MeV/u *)

εx = 0.5*10^(-6); (* horizontal emittance of stored ion beam in m*rad *)
εy = 0.5*10^(-6);  (* vertical emittance of stored ion beam in m*rad *)
βx = 8.189; (* horizontal beta function in m at target position *) (* S=4 *)
βy = 30; (* vertical beta function in m at target position *) (* S=4 *)
σx = √(βx*εx) *1000;   (* rms value of x in mm *)
σy = √(βy*εy) *1000;   (* rms value oy y in mm *)
σax = √(εx/βx);   (* rms value of x' in rad *)
σay = √(εy/βy);   (* rms value oy y' in rad *)
σpup = 2.*10^(-4); (* rms value of momentum spread *)

xshift = 0; (* horizontal shift ion beam *)
yshift = 0; (* vertical shift of ion beam  *)


(* Target *)

Rt = 2; (* Target Radius in mm *)
Dispx = 0*1000; (* Disperion in the target position in mm *)
x0T = 0; (* Target Position in mm *)

(* Ring *)
R = 1.15; (* Radius Dipol Magnet *)
Leff = 0.25;
K1 = -2.251478; (* Quadrupol Familie 1: QDX1 *)
K2 = 2.881817; (* QuadrupolFamilie 2: QFX1 *)
```

Proton pick-up reaction with stripped ion beam

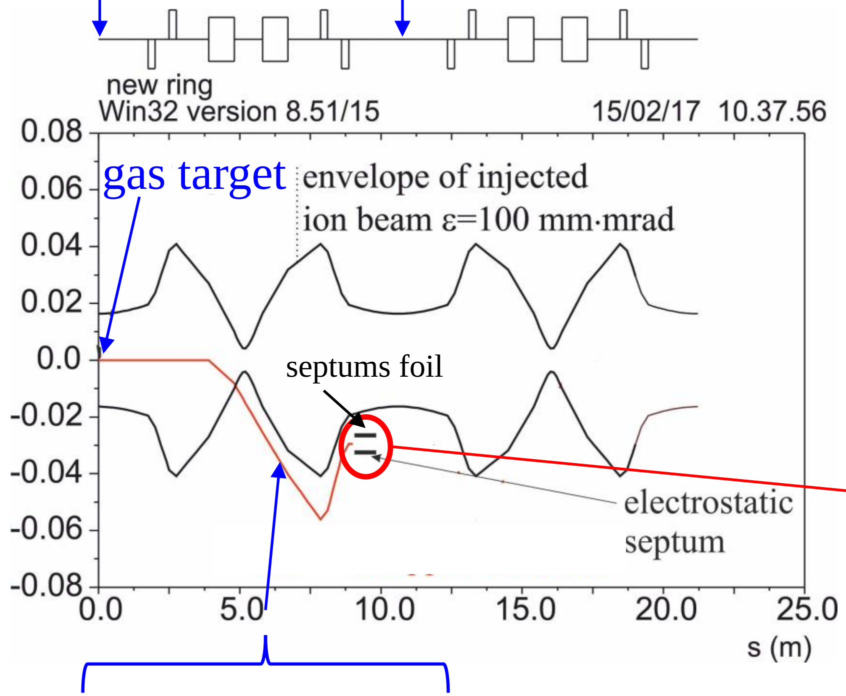
Proton pick reaction with stripped ion beam

example: $^{96}\mathrm{Ru}^{39+} + p \rightarrow {}^{97}\mathrm{Rh}^{40+} + \gamma$ proton pick up reaction

$^{96}\mathrm{Ru}^{39+} + \mathrm{gas} \rightarrow {}^{96}\mathrm{Ru}^{40+}$ stripping reaction

gas target

second experimental straight section



gas target

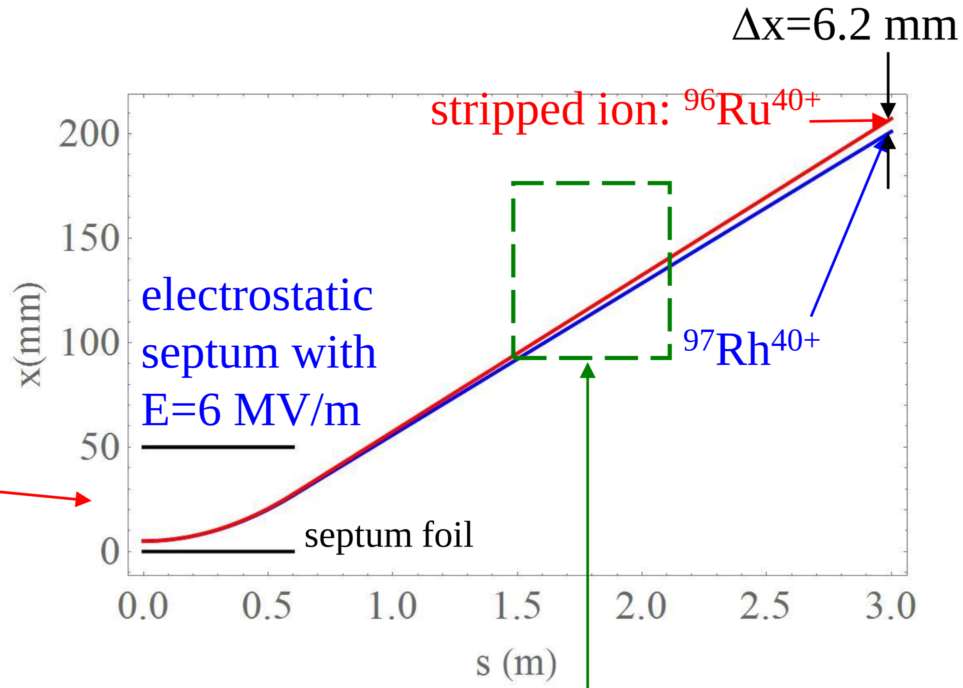
envelope of injected ion beam ε=100 mm·mrad

$^{97}\mathrm{Rh}^{40+}$ + $^{96}\mathrm{Ru}^{40+}$

daughter nuclei

stripped ions

second experimental straight section



electrostatic septum with E=6 MV/m

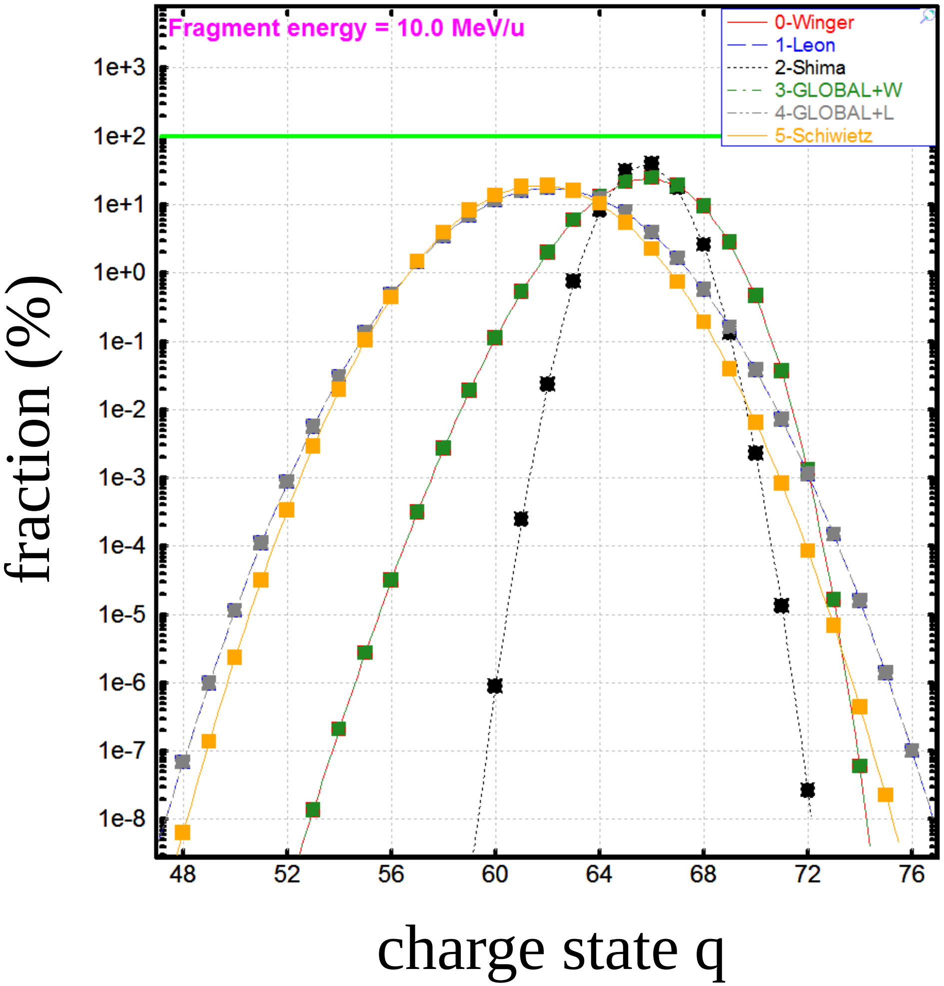
deflection of $^{96}\mathrm{Ru}^{40+}$ + $^{97}\mathrm{Rh}^{40+}$ out the ring with a magnetic septum and separation with an external spectrometer ?

Proton pick up reaction with $^{196}Hg^{+}$

Proton pick-up reaction with Hg

before injection Hg ion beam will be stripped in the HIE ISOLDE stripper at 10 MeV/u

charge state distribution of Hg after stripping at 10 MeV/u



calculated with LISE

equilibrium charge state
q=62-66

assumption
optimum charge state
q=64

Hg is not bare !
number of electrons: 16

yield of the production of $^{196}Hg^{+}$
at **ISOLDE ≈ $7\cdot10^{9}$** ions/μC

⇒ ring can be filled up to
the space charge limit:

$N_s \approx 2.2\cdot10^{8}$ $^{196}Hg^{64+}$ ions for
E= 10 MeV/u

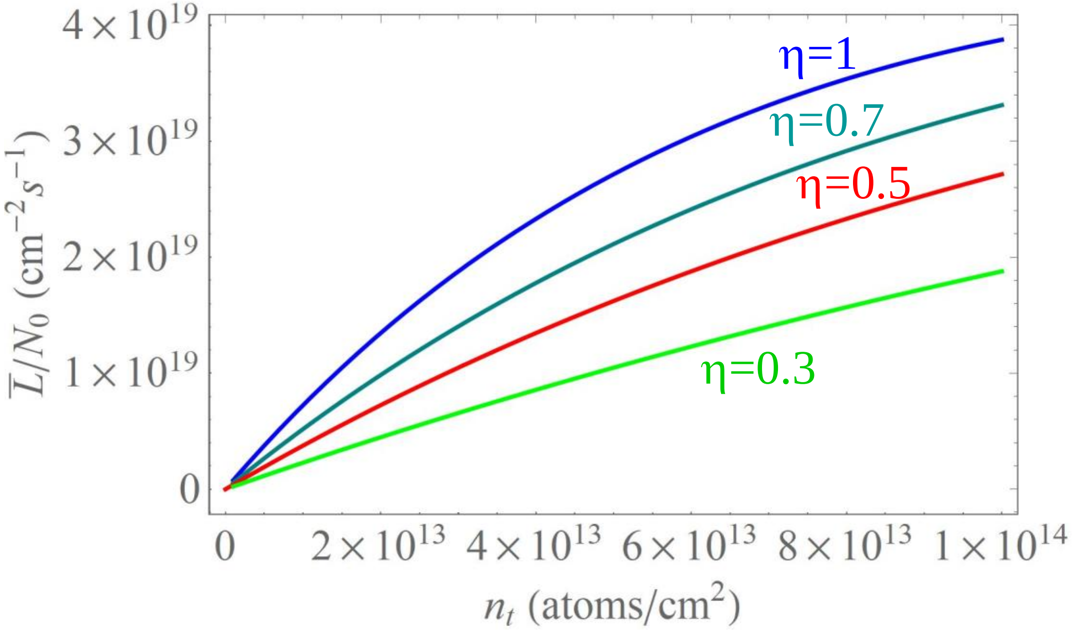
Time averaged luminosity

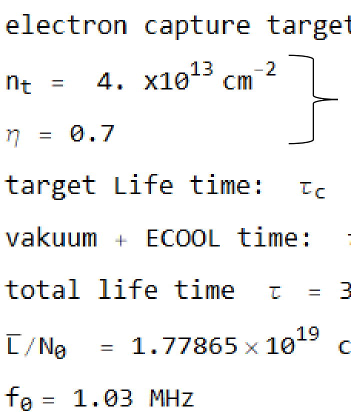
Parameter: beam $^{196}Hg^{64+}$ E=10 MeV/u target: H_2

cycle time T_c = 2 s

$p=5\cdot10^{-11}$ mbar vacuum life time with ECOOL :T_v=10 s

t_E=0.3 s start of the measurement after injection




electron capture target: $\sigma_c = 6.505\times10^{-21}$ cm^2

n_t = 4. x10^{13} cm^{-2}

η = 0.7

reasonable values

target Life time: τ_c = 5.33037 s

vakuum + ECOOL time: τ_r = 10 s

total life time τ = 3.477 s

$\overline{L}/N_0$ = 1.77865×10^{19} cm^{-2}s^{-1}

f_0 = 1.03 MHz

Lifetime should not depend on resonances: $N_0 << N_s$ $N_s \approx 2\cdot10^8$

choose $N_0=5.65\cdot10^7$ $\Rightarrow$ $\overline{L}=10^{27}\,1/(cm^2\,s)$

Storing of the daughter nuclei

Proton capture reaction for the astrophysical p-process

$$^{A}X^{q+} + p \longrightarrow {}^{A+1}Y^{(q+1)+} + \gamma$$

$^{A}X^{q+}$ - stored main ion
q- charge state main beam
A- mass number
$^{A+1}Y^{(q+1)+}$ -daughter nuclide
p- proton from hydrogen target

1. Nuclear reactions

momentum conservation

$$A\, m_0 v_p = (A+1)\, m_0 v$$

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

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

daughter nuclide

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

same rigidity !!!!!

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

stripped ion

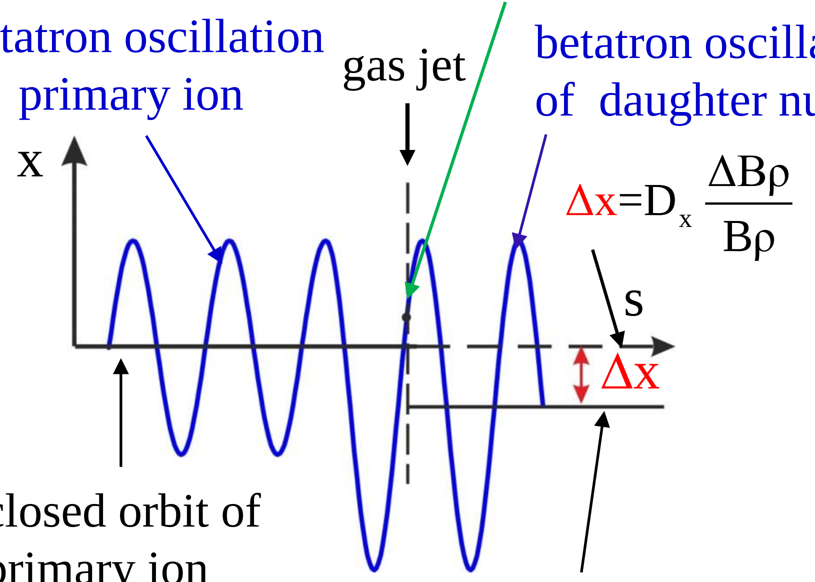
$\Rightarrow$rigidities of $^{A}X^{(q+1)+}$ and $^{A+1}Y^{(q+1)+}$ are equal
$\Rightarrow$ $^{A}X^{(q+1)+}$ and $^{A+1}Y^{(q+1)+}$ **can not separated with magnetic fields !**
$\Rightarrow$ $^{A}X^{(q+1)+}$ and $^{A+1}Y^{(q+1)+}$ ions are at same detector position

Proton pick up reactions by storing daughter nuclei

example: $Hg^{64+} + p \rightarrow Tl^{65+} + \gamma$ 16 electrons are left !

daughter nuclei **Tl^{65+} should be kept and accumulated in the storage ring**

⇒ storage ring has to operate in an achromatic mode with D_x=0 m in the gas target to avoid excitation of betatron oscillations of the daughter nuclei:



production of daughter with $\Delta B\rho / B\rho$

betatron oscillation of primary ion

gas jet

betatron oscillation of daughter nuclide

$$\Delta x = D_x \frac{\Delta B\rho}{B\rho}$$

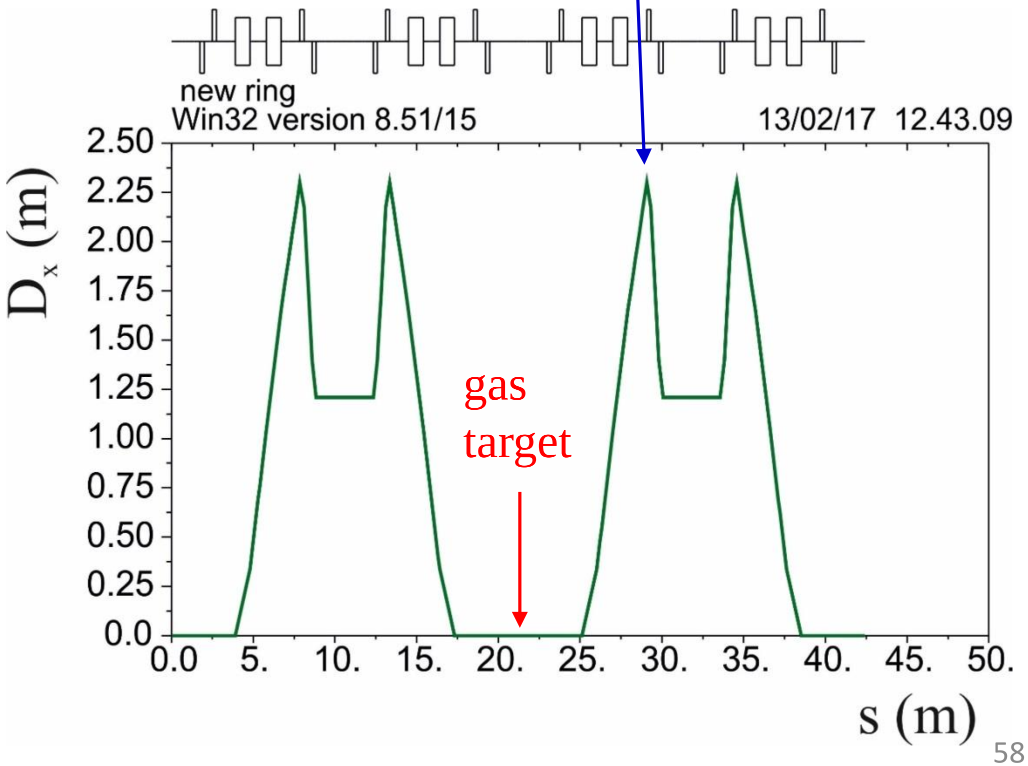
closed orbit of primary ion

closed orbit of daughter nuclide for Dx≠0 m

Achromatic mode

$D_{x,max}$ smaller compare to TSR

gas target



Shift of the ion orbits by electron cooling

reaction: $\mathrm{Hg}^{64+} + p \rightarrow \mathrm{Tl}^{65+} + \gamma$

direct after injection: $v(\mathrm{Tl}^{65+}) < v_e \quad v(\mathrm{Hg}^{65+}) = v_e$

with electron cooling: $v(\mathrm{Tl}^{65+}) \rightarrow v_e \quad v(\mathrm{Hg}^{65+}) = v_e$

change of the rigidity of Tl^{65+}: $\frac{\Delta B\rho}{B\rho} = -\frac{1}{q+1} \rightarrow -\frac{A-q}{A(1+q)}$

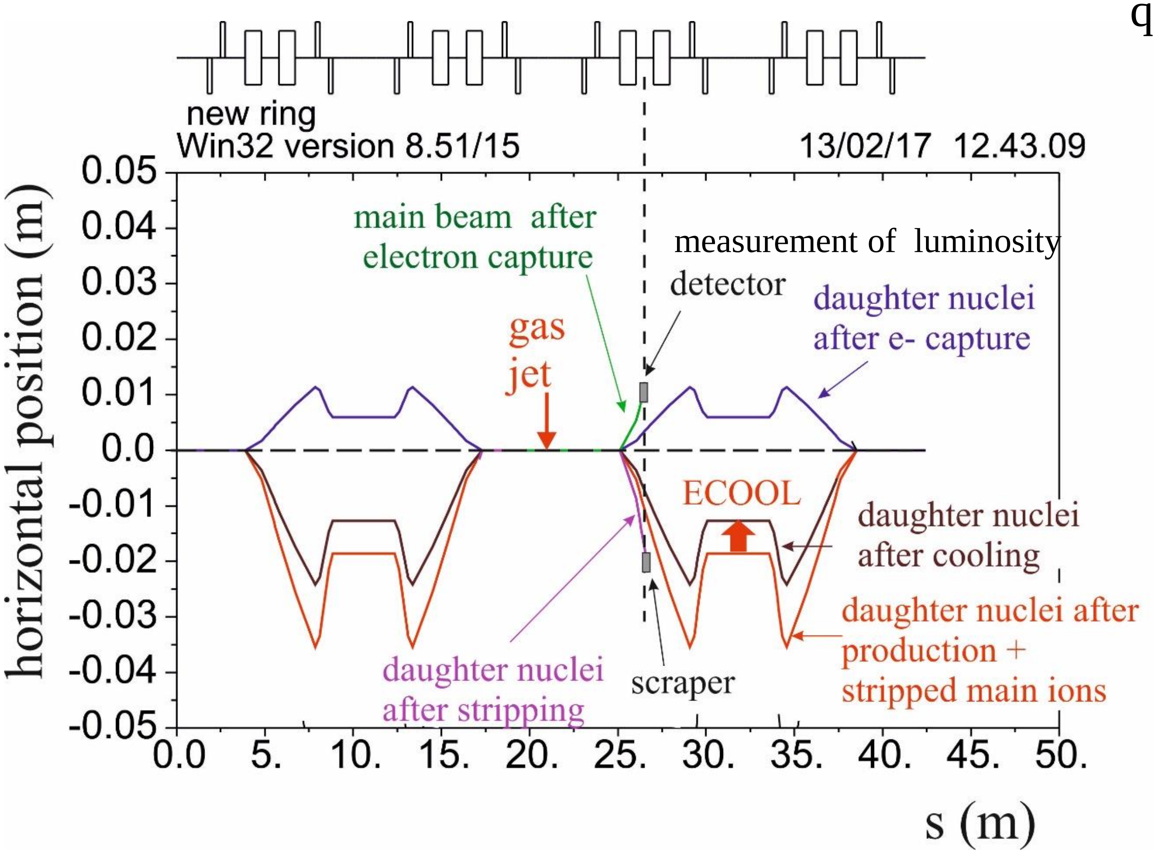
v_e -electron velocity

$v(\mathrm{Hg}^{65+})$ – velocity of Hg^{65+}

$v(\mathrm{Tl}^{65+})$ - velocity of Tl^{65+}

A- mass of main beam

q- charge of main beam



Beam rigidities

for electron cooling with $D_x = 0$ m

m_0- mass unit
e- elementary charge
v- electron velocity
main beam:
A- ion mass
q- ion charge state

ion	rigidity Bρ=p/(q·e)	relative rigidity ΔBρ/Bρ
stored cooled ions	$\frac{m_0 A v}{e q}$	0
stored ions after electron capture	$\frac{m_0 A v}{e(q-1)}$	$\frac{1}{q-1}$
stored ions after stripping	$\frac{m_0 A v}{e(q+1)}$	$-\frac{1}{q+1}$
daughter ions after production	$\frac{m_0 A v}{e(q+1)}$	$-\frac{1}{q+1}$
daughter ions after cooling	$\frac{m_0 (A+1) v}{e(q+1)}$	$-\frac{A-q}{A(1+q)}$
daughter ions after cooling + e capture	$\frac{m_0 (A+1) v}{e q}$	$\frac{1}{A}$
daughter after cooling + stripping	$\frac{m_0 (A+1) v}{e(q+2)}$	$-\frac{-2A+q}{A(2+q)}$

electron cooling

used to measure luminosity

same beam rigidity = same orbit

separation of stripped main beam and daughter ions by electron cooling !

scraping if possible

scraping easily possible