A new storage ring for ISOLDE

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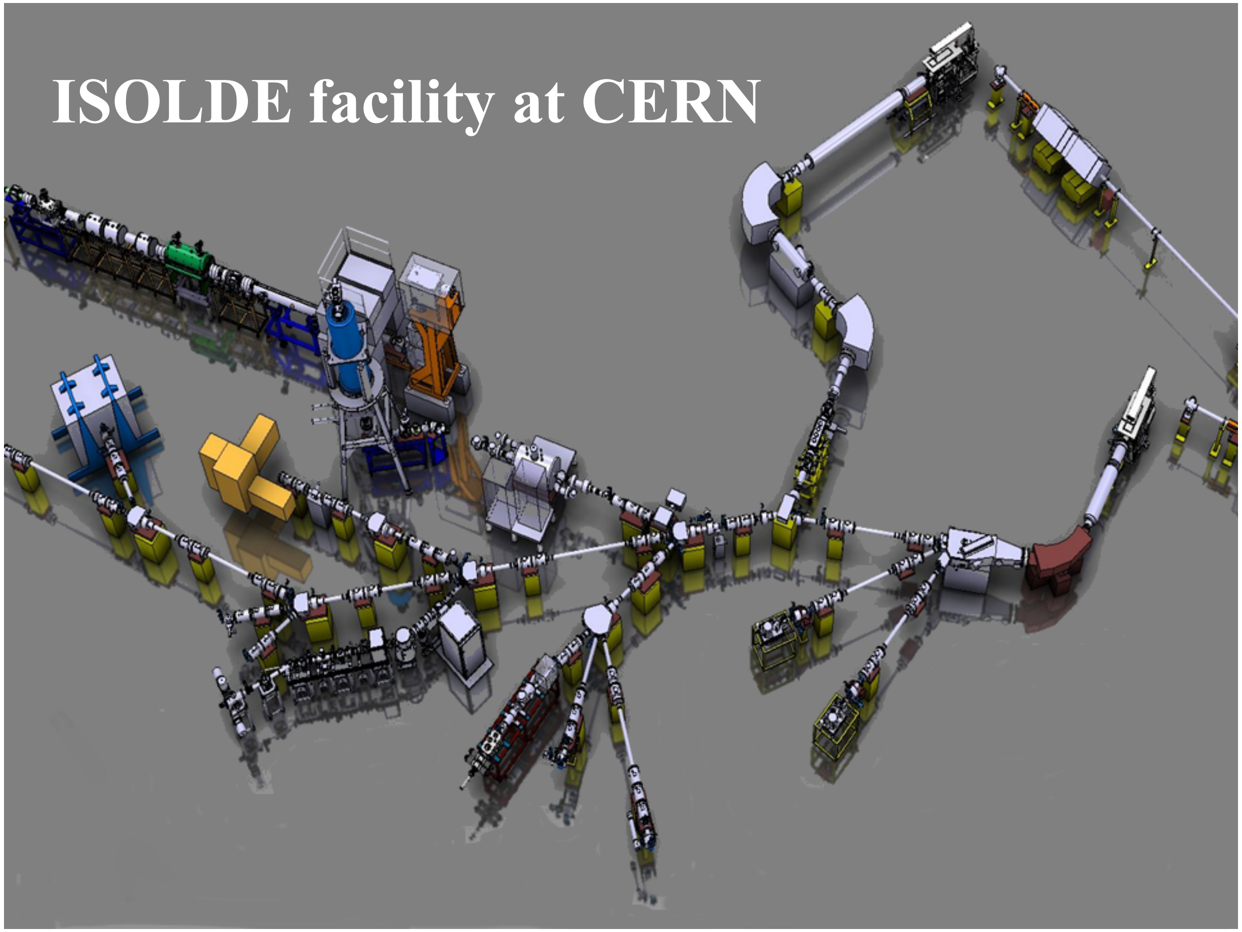
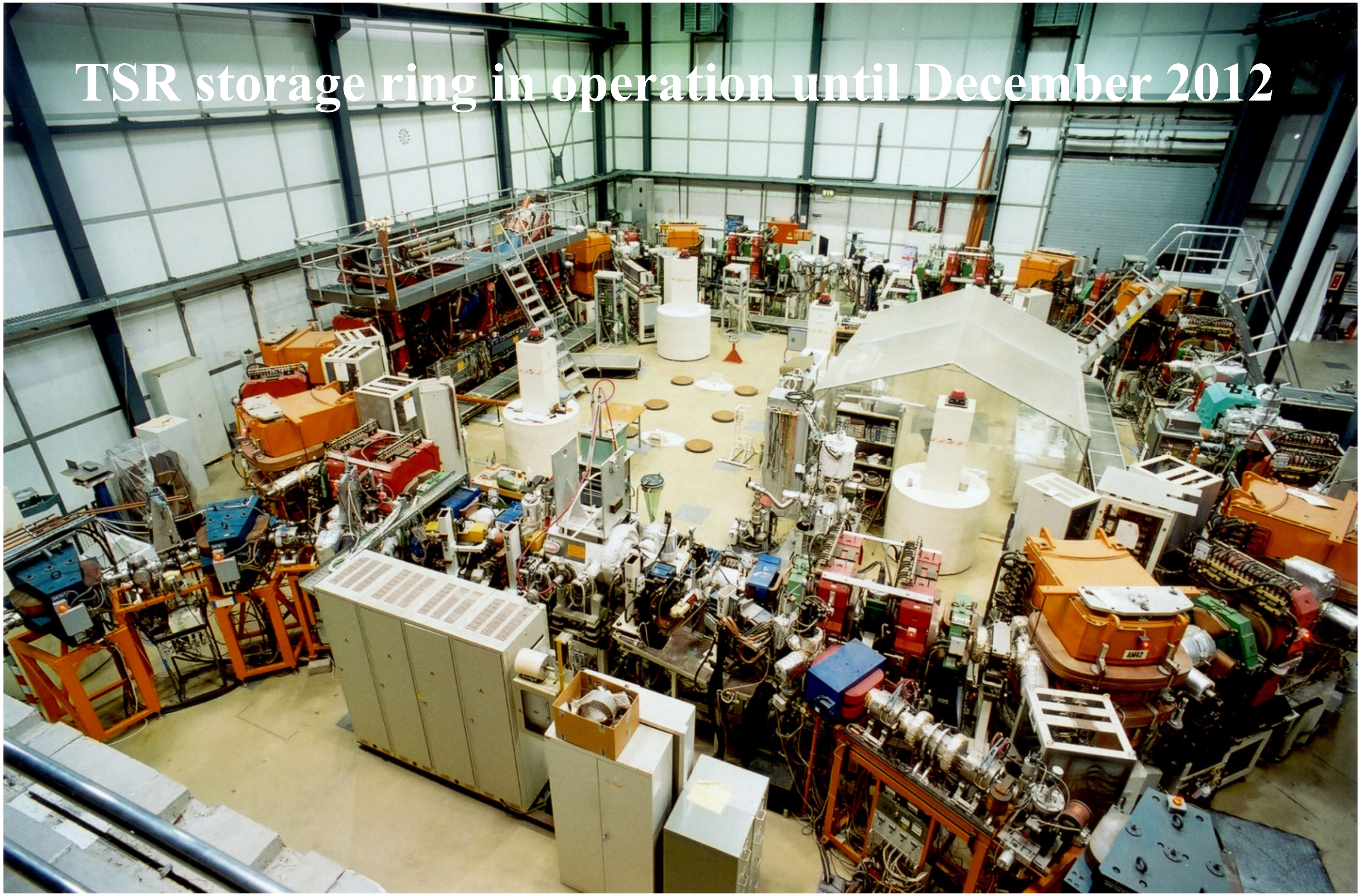


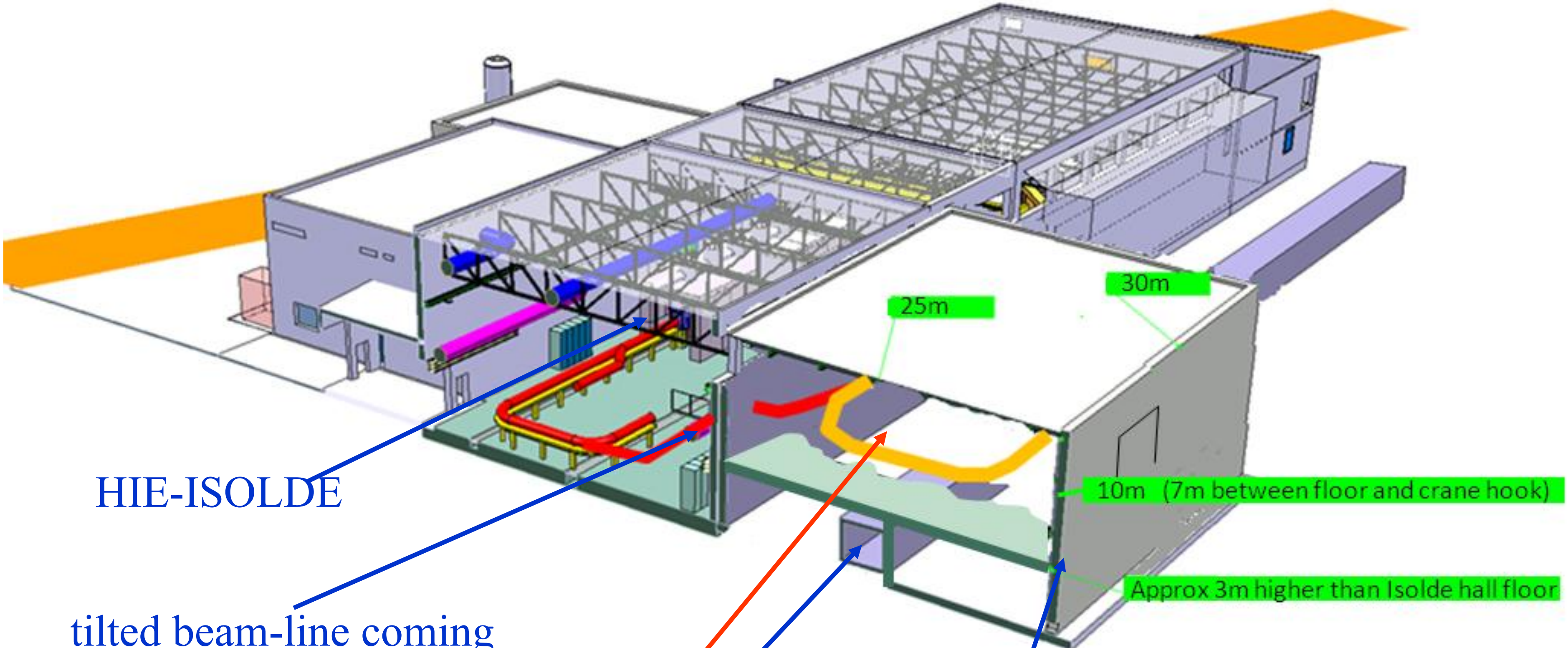
NARRS workshop, GSI, Darmstadt, 13th-15th March 2018

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 @ 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 →

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

<u>MPIK cannot hold TSR at MPIK until 2020/2021 without getting green light from CERN</u>

Design Criteria of the new storage ring

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

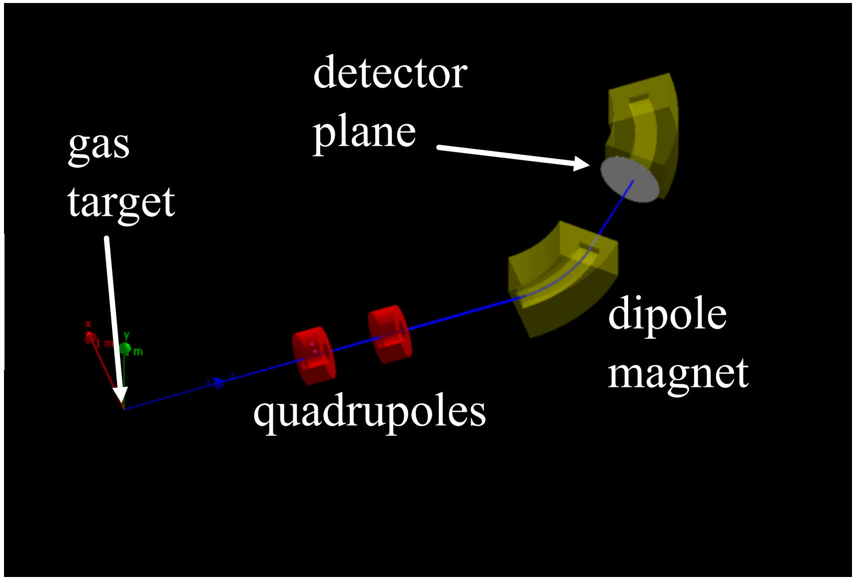
$\Rightarrow$ maximum rigidity of the ring: $B\rho_{max} \approx 1.5$ Tm

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

$\Rightarrow$ small maximum dispersion function D_x of the storage ring

dispersion at the gas jet D_x=0 m to avoid a excitation of betatron oscillation of daughter nuclei

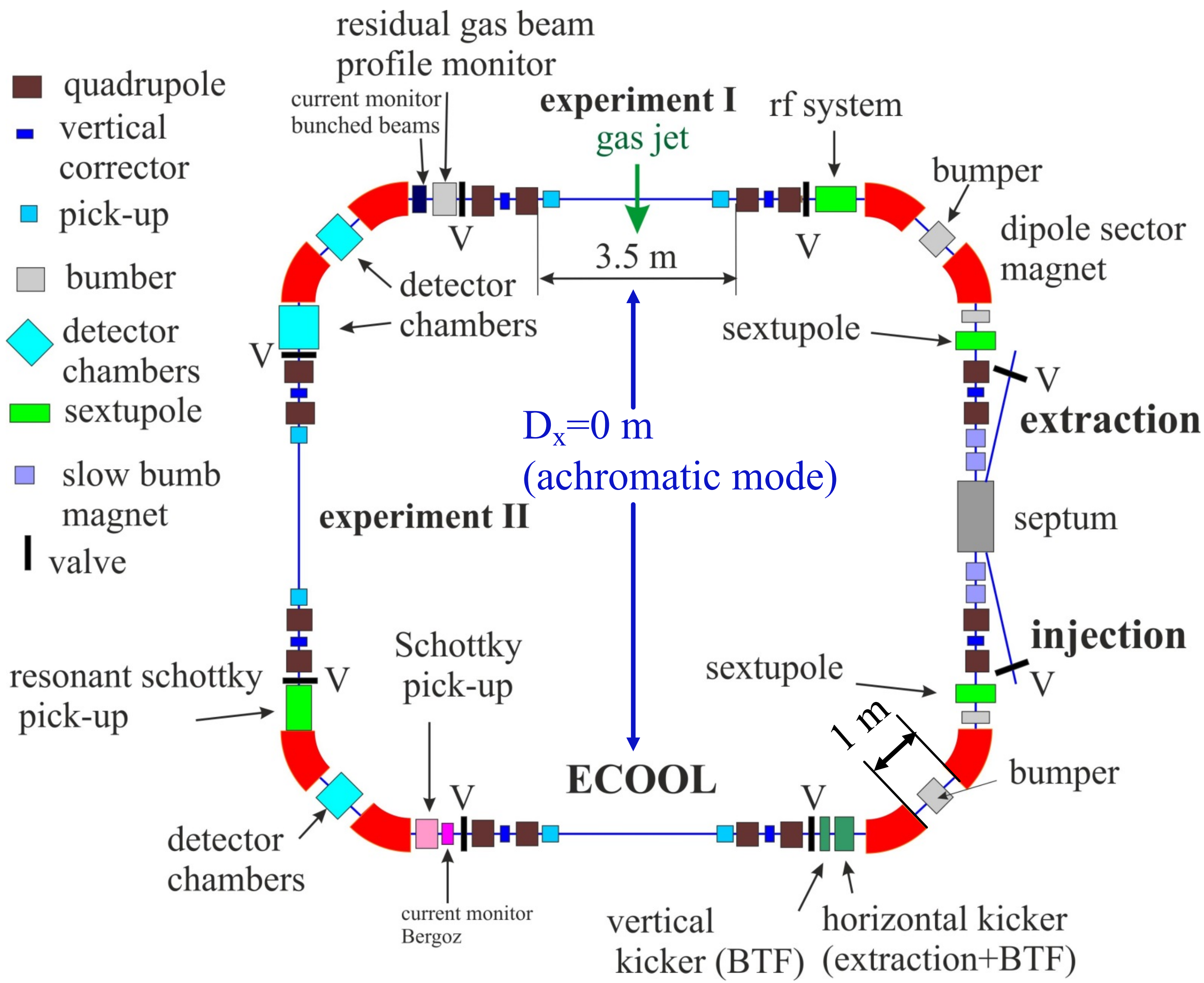
c.) daughter nuclides with large transfers momenta produced in nuclear reactions should be focused at the detector position



d.) storing ring should be compact to fit in the present HIE Isolde hall

Layout of the new storage ring

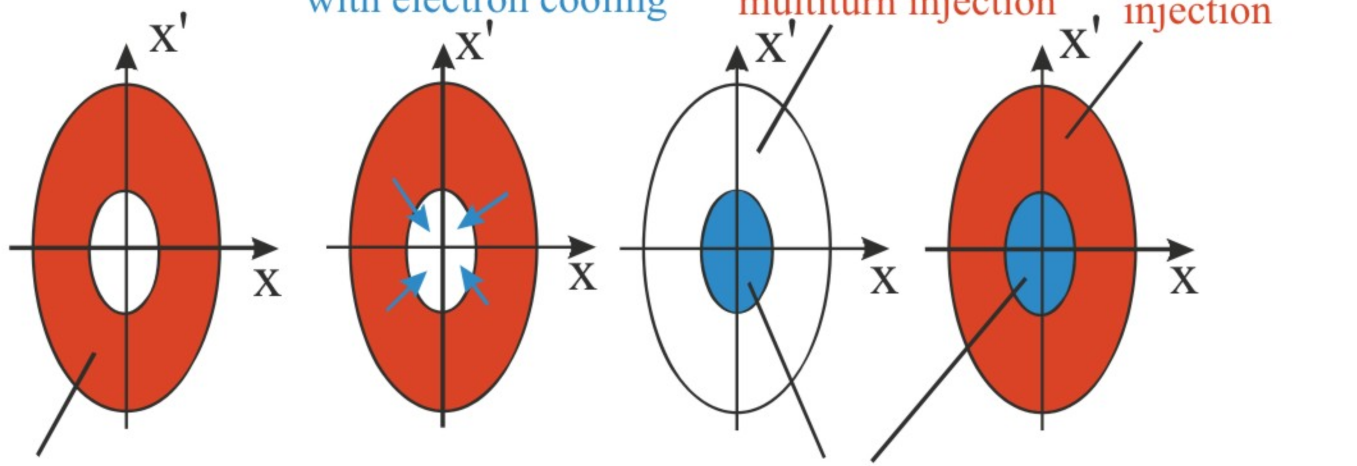
with straight section Length L=3.5 m and circumference C=42.4 m



ECOOL Stacking

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

principle



particle number N(t):

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

N_i-injected particle number per injection

n_r- injection rate

τ- total lifetime

Luminosity with ECOOL stacking

In the equilibrium: $dN(t)/dt = 0$
number of stored ions N_0 ($N_0 \leq N_s$):

$$N_0 = n_r \tau N_i$$

N_0 determines the luminosity L:

$$L = \frac{R}{\sigma} = N_0 f_0 n_t = n_r \tau n_t N_i f_0$$

$$\tau \sim \frac{1}{n_t}$$

N_0 - equilibrium particle number
N_s -space charge limit
R- reaction rate
σ- cross section
N_i-injected number of ions with multi-turn injection
n_t- target thickness
n- target density $n_t = \int n ds$
f_0 -revolution frequency
n_r-injection rate $n_r = 1/T$
T- time between two injections

for large n_t the total life time τ given by the target thickness n_t:

$$L = \frac{R}{\sigma} = \text{const} \frac{N_i}{T}$$

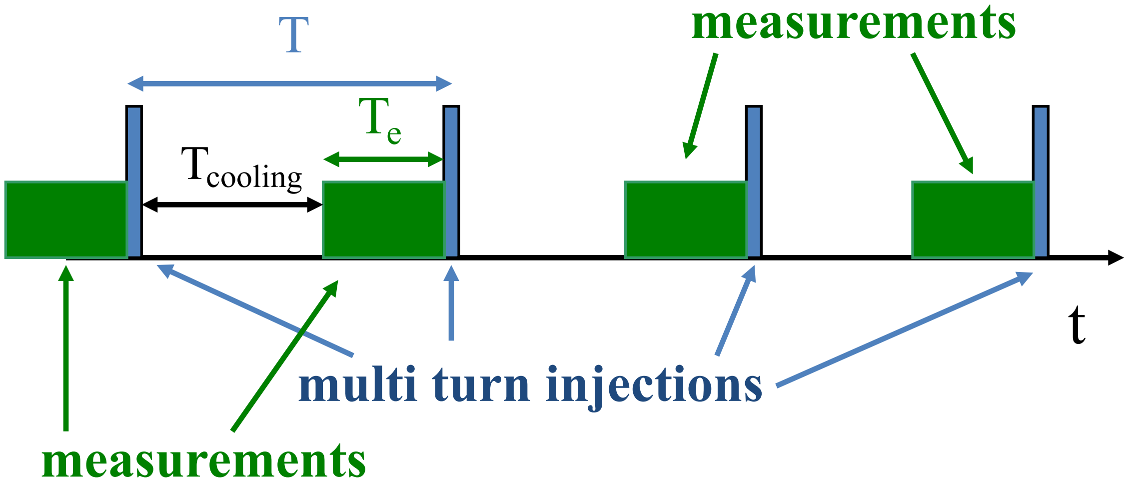
N_i ← number of ions per multi turn injection
T ← time between two multi turn injections

const ↑ independent of target thickness !

Effective Luminosity

-continuous injection cycle
-measurement starts after the cooling time $T_{cooling}$ of the injected ions and ends before the next multi-turn injection takes place

injection and measuring scheme



Luminosity is reduced by factor $\eta = T_e/T$
$\Rightarrow$ effective Luminosity L_{eff} :

$$L_{eff} = \frac{R}{\sigma} = \eta N_0 f_0 n_t = \eta \frac{\tau}{T} f_0 n_t N_i$$

below space charge limit $N_0 \leq N_s$ N_s-space charge limit

N_0-total number of stored particles
N_i-injected particle number per multi-turn injection
T- time between two injections
τ- total lifetime
f_0-revolution frequency

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: $-\Delta Q \approx 0.065\text{-}0.1$

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

for an electron cooled ion beam:

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

incoherent tune shift for an electron cooled ion beam

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

E-ion energy in MeV
A-ion mass
q-ion charge state

TSR experiments: const $\approx 7\cdot 10^9$

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

Ion	E (MeV)	measured N_s	calculated N_s
p	21	$5.4\cdot 10^9$	$4.1\cdot 10^9$
$^{16}O^{8+}$	98	$9.4\cdot 10^8$	$1.3\cdot 10^9$
$^{12}C^{6+}$	73	$1.7\cdot 10^9$	$1.7\cdot 10^9$
$^{32}S^{16+}$	195	$9.5\cdot 10^8$	$6.3\cdot 10^8$
$^{35}Cl^{17+}$	293	$5.1\cdot 10^8$	$5.8\cdot 10^8$

$\Rightarrow$ maximum possible Luminosity for $N_0 = N_s$

Effective Luminosity of some selected ions

$L_{eff} = \eta N_0 f_0 n_t$ calculated for the space charge limit ($N_0=N_s$) and a beam life time τ=1-1.5s

$\eta=0.5$

beam	Energy (MeV/u)	q_s	N_s	target	n_t (atoms/cm²)	τ (s)	N_i/T (1/s)	L_{eff} (1/cm²s)
$^{86}Kr^{36+}$	10	36+	$3\cdot10^8$	H_2	$9\cdot10^{14}$	1.5	$3\cdot10^8$	$2\cdot10^{29}$
$^{96}Ru^{39+}$	10	39+	$3\cdot10^8$	H_2	$4\cdot10^{14}$	1	$3\cdot10^8$	$8\cdot10^{28}$
$^{196}Hg^{64+}$	10	64+	$2\cdot10^8$	H_2	$5\cdot10^{13}$	1.5	$2\cdot10^8$	$8\cdot10^{27}$
$^{232}Th^{71+}$	10	71+	$2\cdot10^8$	H_2,D_2	$5\cdot10^{13}$	1	$2\cdot10^8$	$8\cdot10^{27}$
$^{238}U^{72+}$	10	72+	$2\cdot10^8$	H_2,D_2	$3\cdot10^{13}$	1.5	$2\cdot10^8$	$5\cdot10^{27}$
$^{232}Th^{71+}$	10	71+	$2\cdot10^8$	He	$3\cdot10^{12}$	1	$2\cdot10^8$	$4\cdot10^{26}$
$^{238}U^{72+}$	10	72+	$2\cdot10^8$	He	$2\cdot10^{12}$	1	$2\cdot10^8$	$3\cdot10^{26}$

proton capture reactions (first three rows)

fission reactions (last four rows)

injection charge state
green: bare ion
black: equilibrium charge state after HIE-ISOLDE stripper

N_s-space charge limit of an electron cooled stored ion beam

n_t -target thickness calculated for a beam life time: τ=1-1.5s

required injection rate (ions/s) for $N_0=N_s$

remark: H_2, D_2, He target: limitation of $n_t \approx 10^{14}$ atoms/cm²
all required injection rate N_i/T for the space charge limit N_s maybe can not be reached

Proton capture reaction for the astrophysical p-process

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

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

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

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

daughter nuclide / stripped ion — **same rigidity !!!!!**

$\Rightarrow$ 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

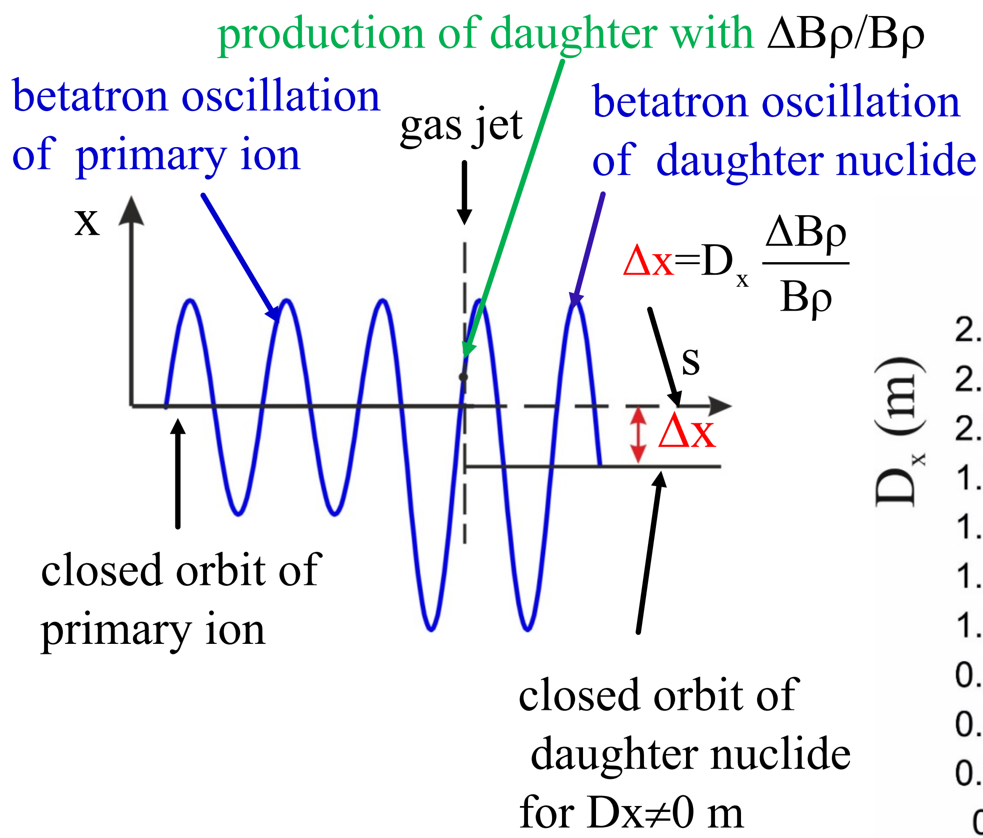
$\Rightarrow$**a) experiment has to carry out with bare $^{A}X^{q+}$ ions**
$\Rightarrow$**b) bare ions for heavy systems $^{A}X^{q+}$ cannot produce by stripping at 10 MeV/u !**
looking for solutions to separate $^{A}X^{(q+1)+}$ from $^{A+1}Y^{(q+1)+}$:
accumulate $^{A}X^{(q+1)}$ in the storage ring and separation with electron cooling

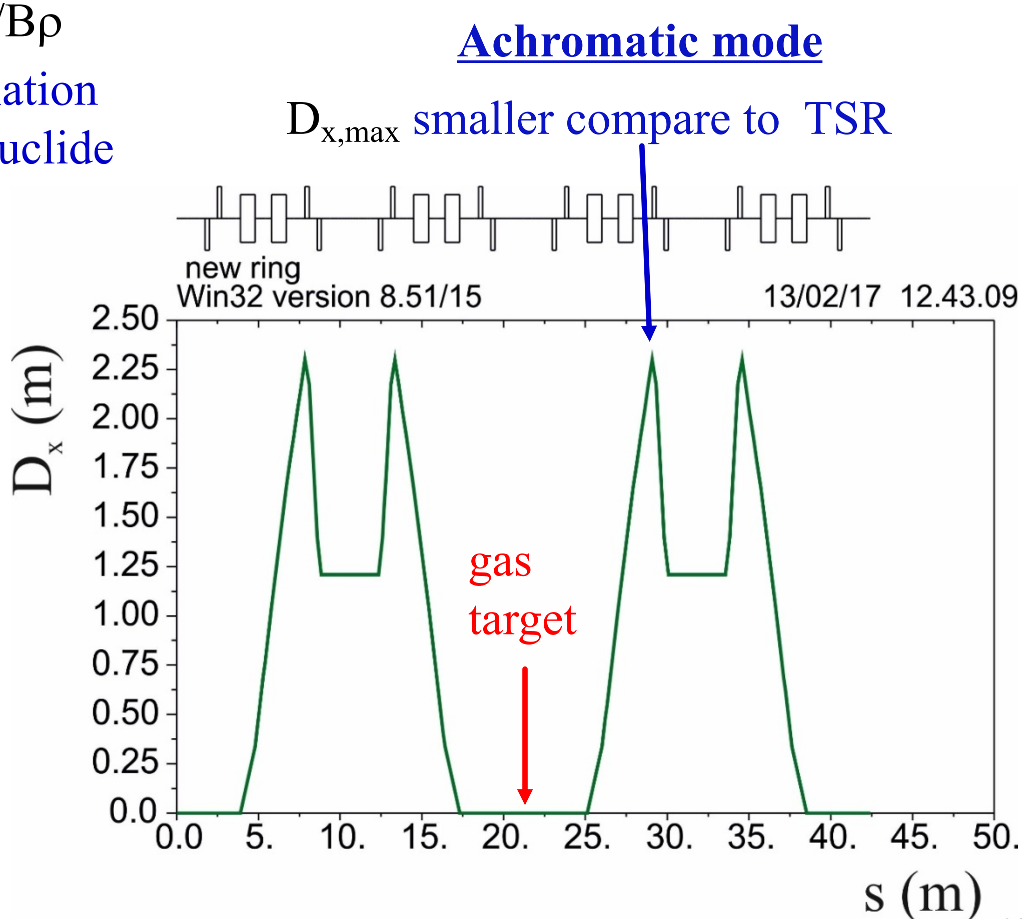
Proton pick up reactions by storing daughter nuclei

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**

$\Rightarrow$ 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:





Shift of the ion orbits by electron cooling

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

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

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

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

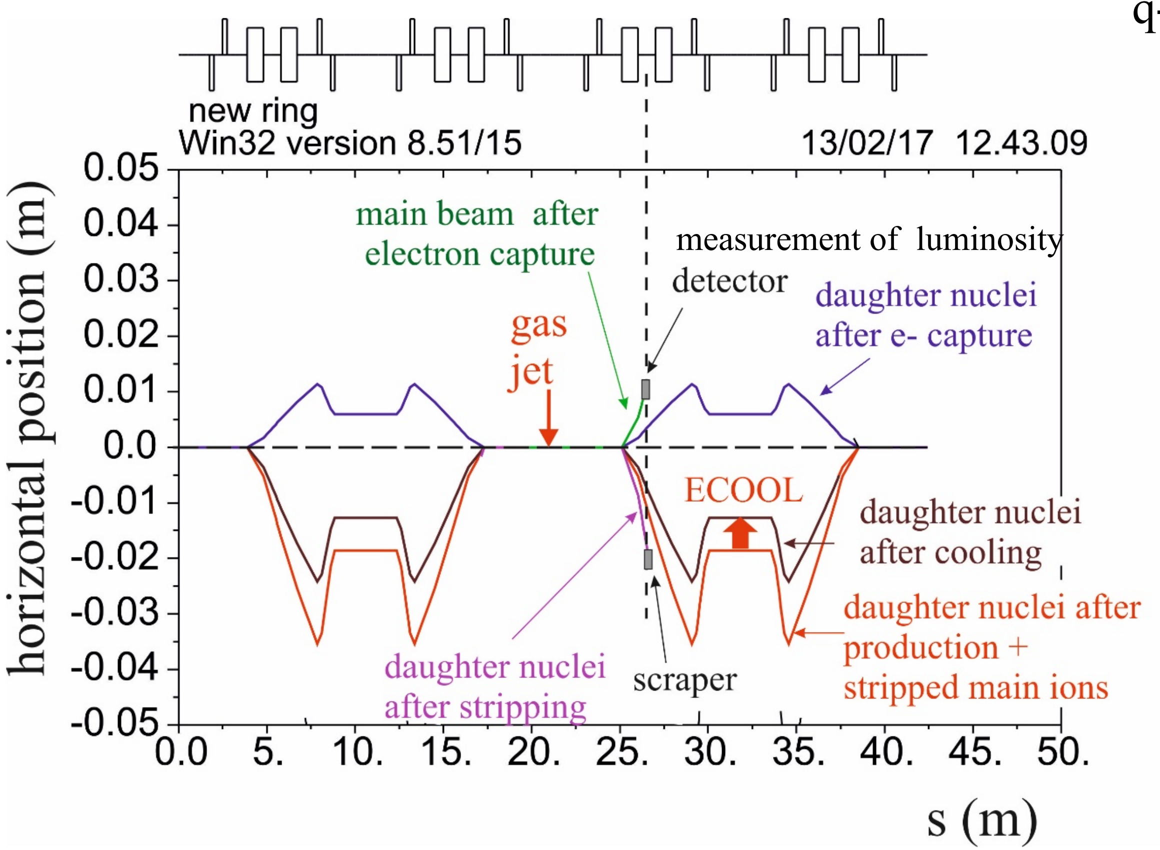
v_e - electron velocity

$v(Hg^{65+})$ – velocity of Hg^{65+}

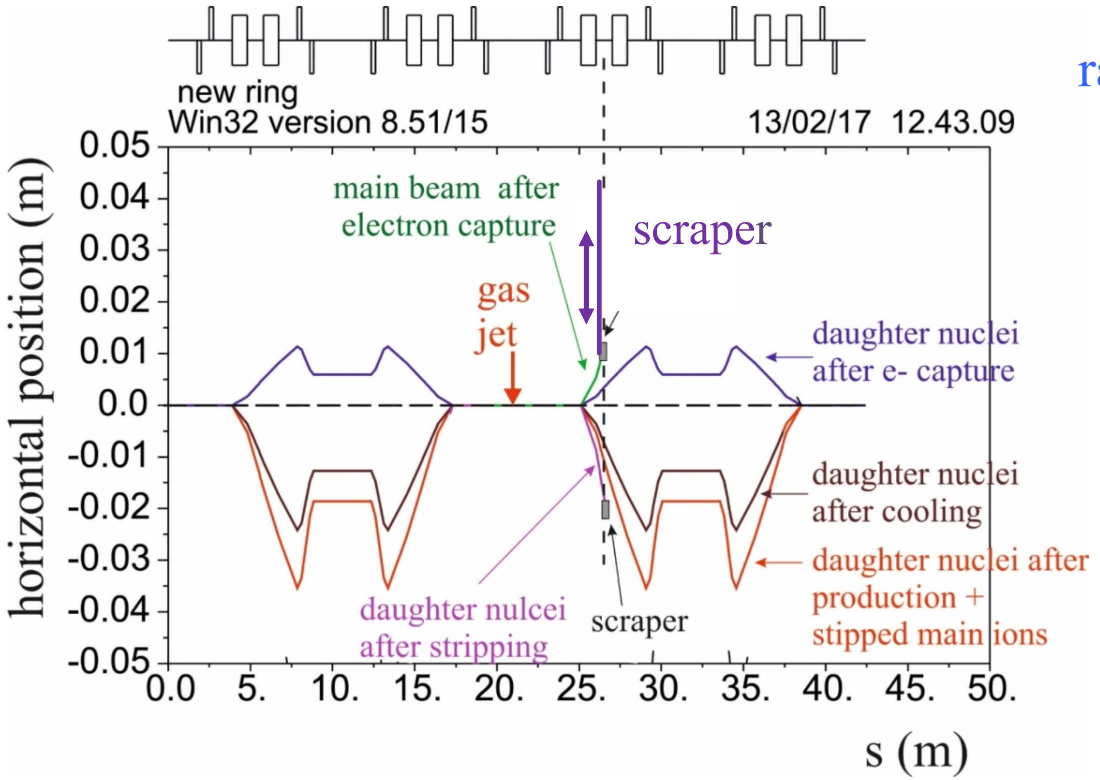
$v(Tl^{65+})$ - velocity of Tl^{65+}

A- mass of main beam

q- charge of main beam



Scraping of electron captured daughter nuclides



rate equation to determine N_d

$$\frac{dN_d(t)}{dt} = L \cdot \sigma - \frac{N_d(t)}{\tau_d}$$

in the equilibrium

cross section

$$\sigma = \frac{N_{d,0}}{L\tau_d}$$

number of accumulated daughter nuclei

total life time of daughter nuclei

example

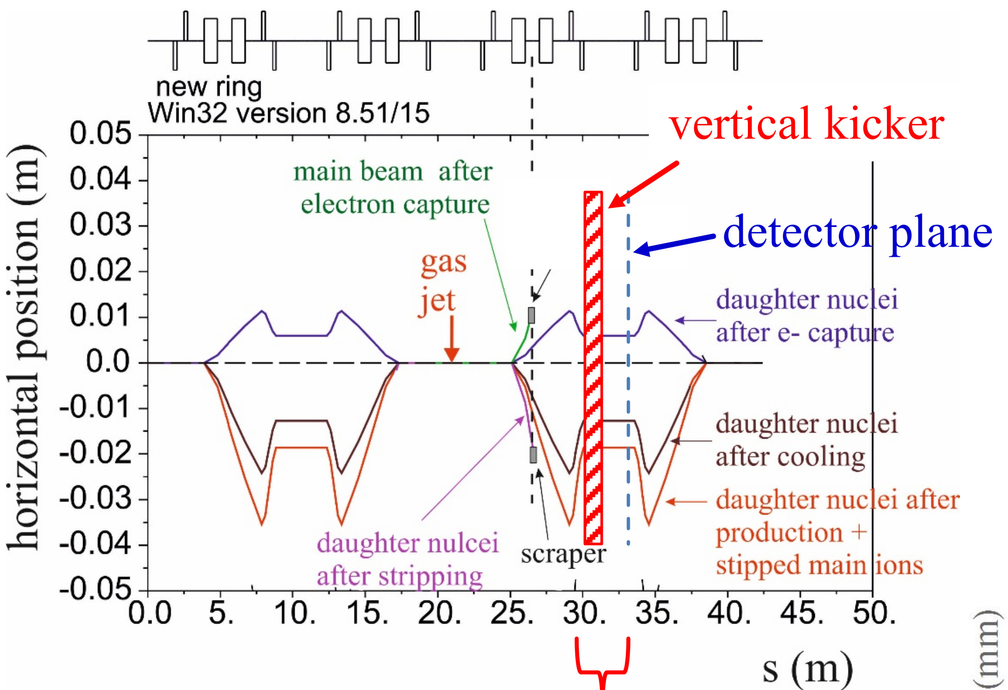
life time should not depend of resonances

beam: $^{196}Hg^{64+}$, $E/A = 10$ MeV/u, $N_0 \approx N_s/6 = 3 \cdot 10^7$, $n_t = 2 \cdot 10^{13}$ atoms/cm^2

$$\Rightarrow L = 2.2 10^{27}\, 1/\text{cm}^2\text{s},\ \tau_d \approx 3.5\,\text{s}$$

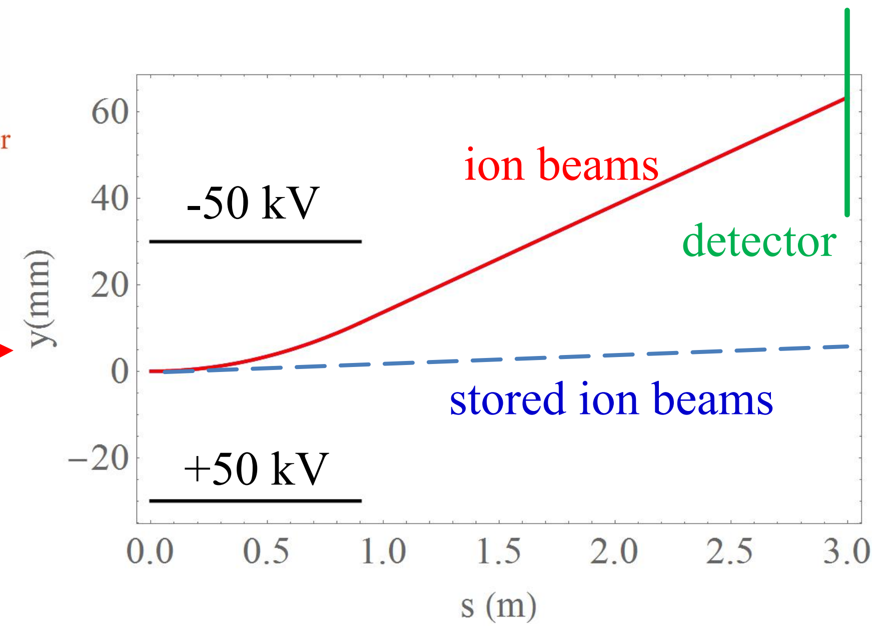
for: $\sigma = 0.01$ barn : $N_{d,0} = \sigma L \tau_d \Rightarrow N_{d,0} \approx 80$

Direct Detection of the produced daughter nuclei



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

<u>second experimental straight section II</u>



After reaching the equilibrium daughter nuclei number given by: $N_{d,0} = L\tau_d\sigma$

The kicker voltage is switched on very quickly with Behlke switches to deflect the stored ion beam to the detectors located above to the stored ion beam, where the switching time $T \ll T_0$ (T_0 -revolution time)

Multi Charge operation of the TSR

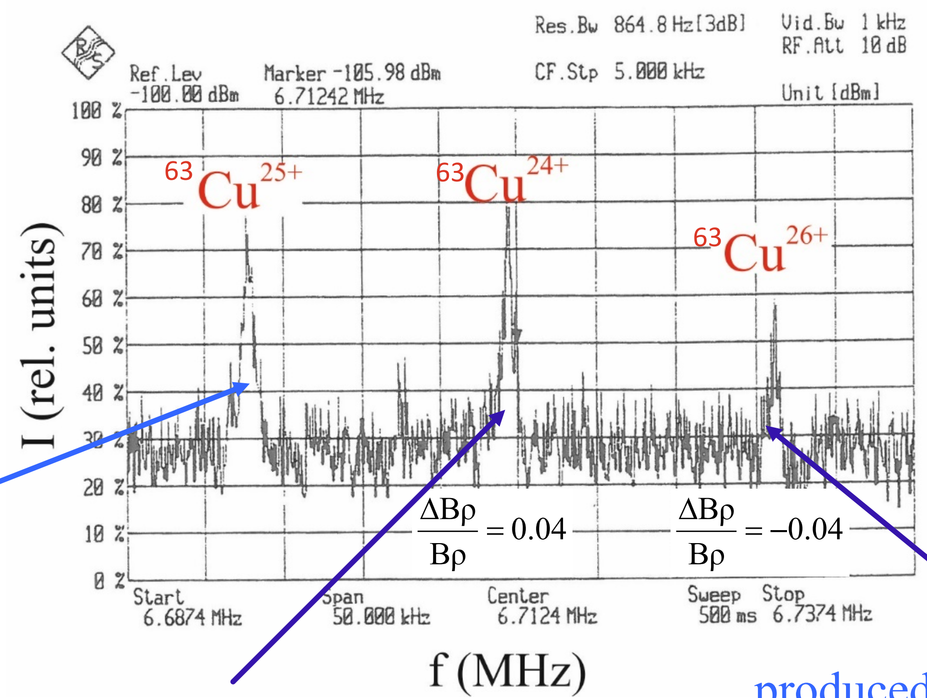
- Storing also daughter nuclei after production needs a relative large momentum acceptance of the storage ring
- At the TSR it was shown that several beams with different rigidities can be stored at the same time

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



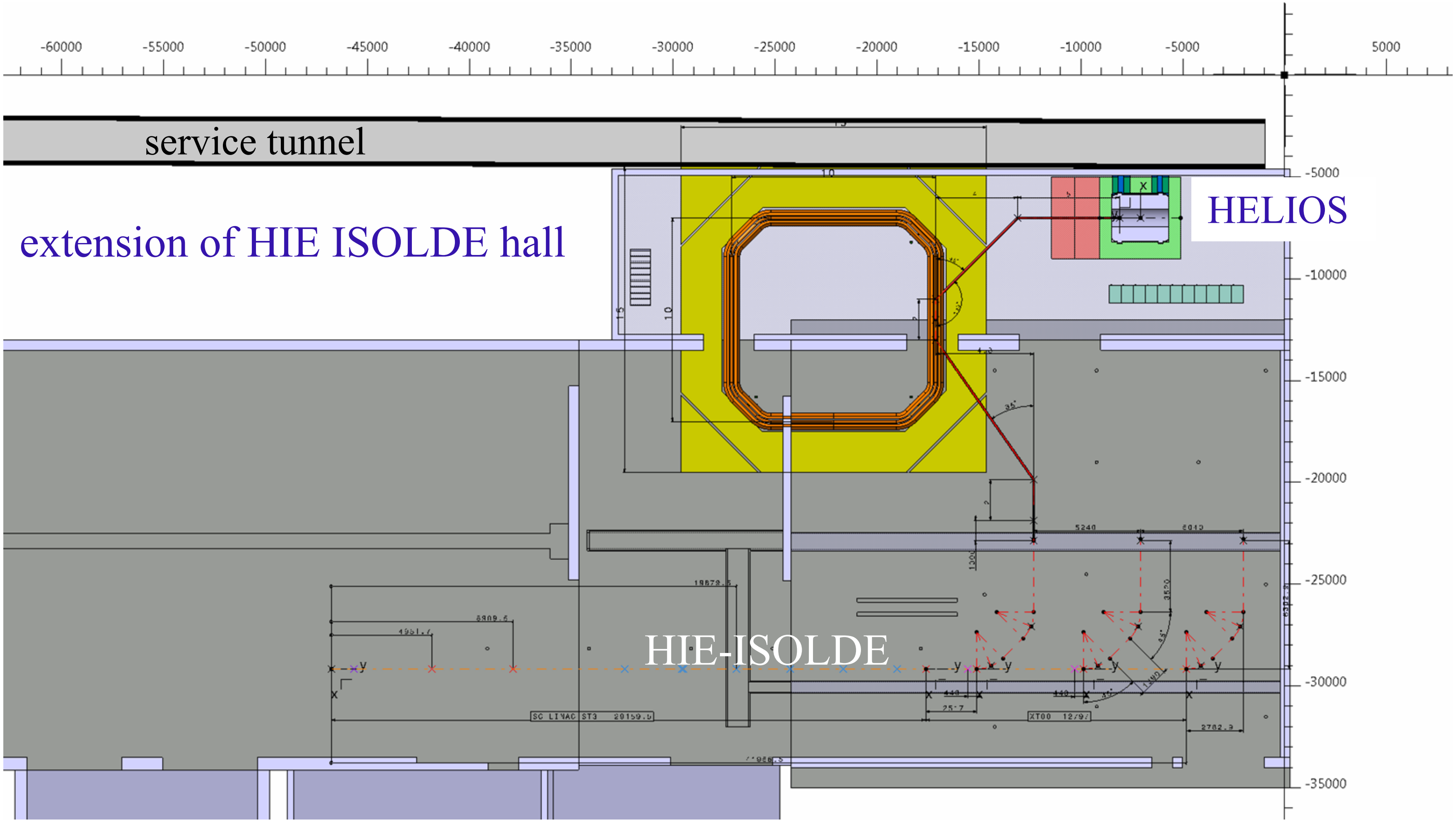
injected ion beam
E=266 MeV

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



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