TSR@ISOLDE

To be, or not to be?

Reflections on the atomic nucleus
Liverpool 2015

Why ISOL + ring?

Advantages

Compared to in-flight storage rings

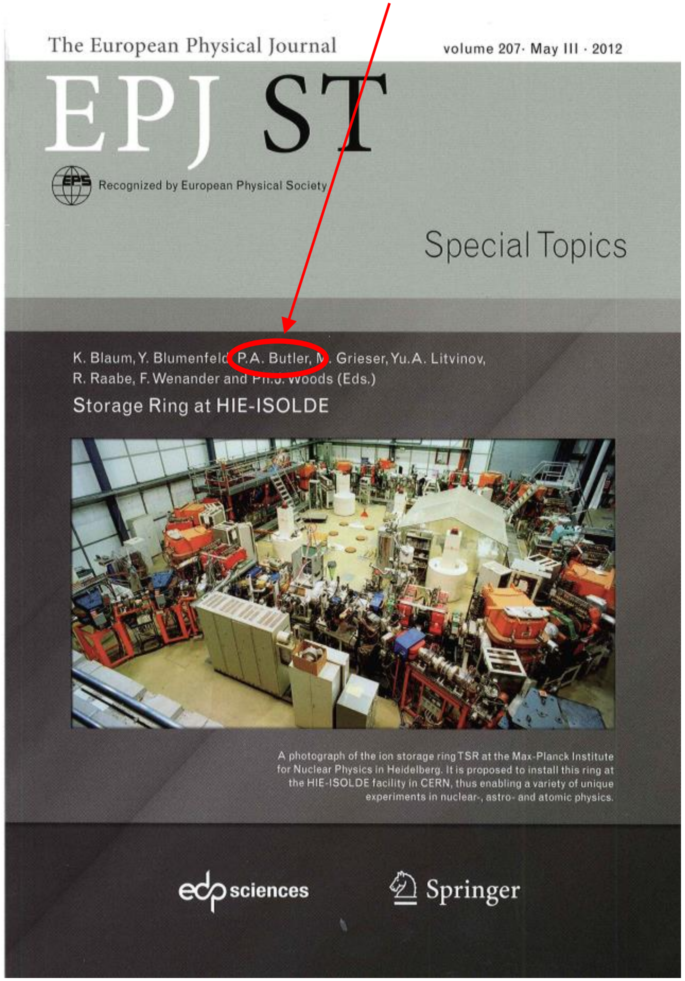
- Higher intensity
- Cooler beams / Shorter cooling time

Compared to direct* beams

- Less background
  (clean target, target container, beam dump)
- Improved resolution
  (smaller beam size, reduced energy straggling in target)
- CW beam
- Luminosity increase for (light) beams

* reaction experiments with non-circulating, ‘thick’ target after linac

The Organiser



The European Physical Journal
volume 207· May III · 2012
EPJ ST
Recognized by European Physical Society

Special Topics

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

World-wide storage rings

Storage Rings for Physics with Exotic Nuclei

Fully-stripped ions

High-energy

ESR @ GSI
CSRe @ IMP

RI-RING @ RIKEN
CR @ FAIR
HESR @ FAIR

NESR @ FAIR
RESR @ FAIR
HIAF

($T_{1/2}$ > 1ms)

Masses, lifetimes

Low-energy

TSR @ ISOLDE
($T_{1/2}$ > 1s)

ESR @ GSI (L.E.)
or
CRYRING @ ESR
($T_{1/2}$ > 1 min or stable)

Reaction and decay studies

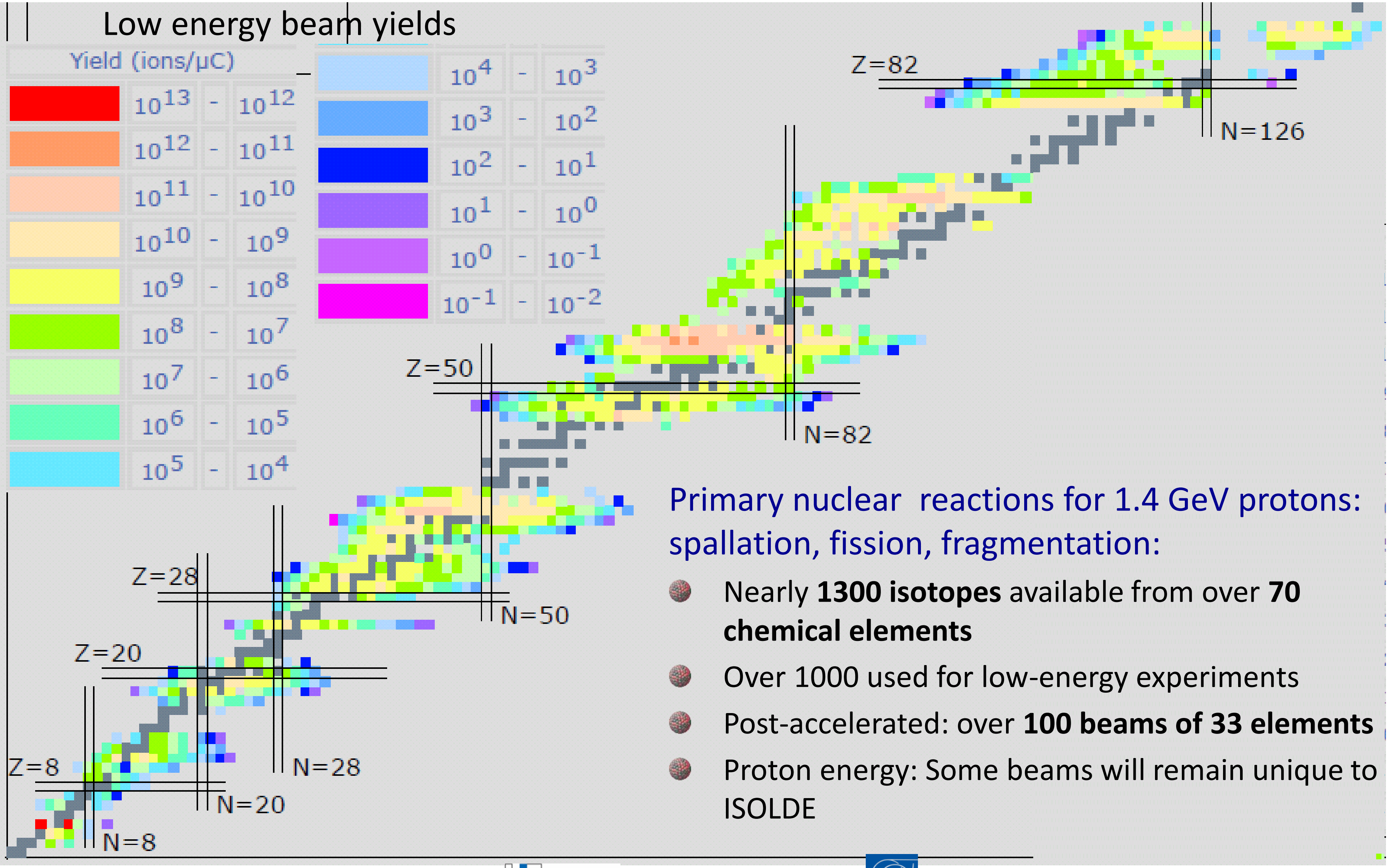
Highly-charged ions

NB. RI beams originates from opposite side of the energy spectrum

Courtesy Y. Litvinov

ISOLDE - a suitable custodian?

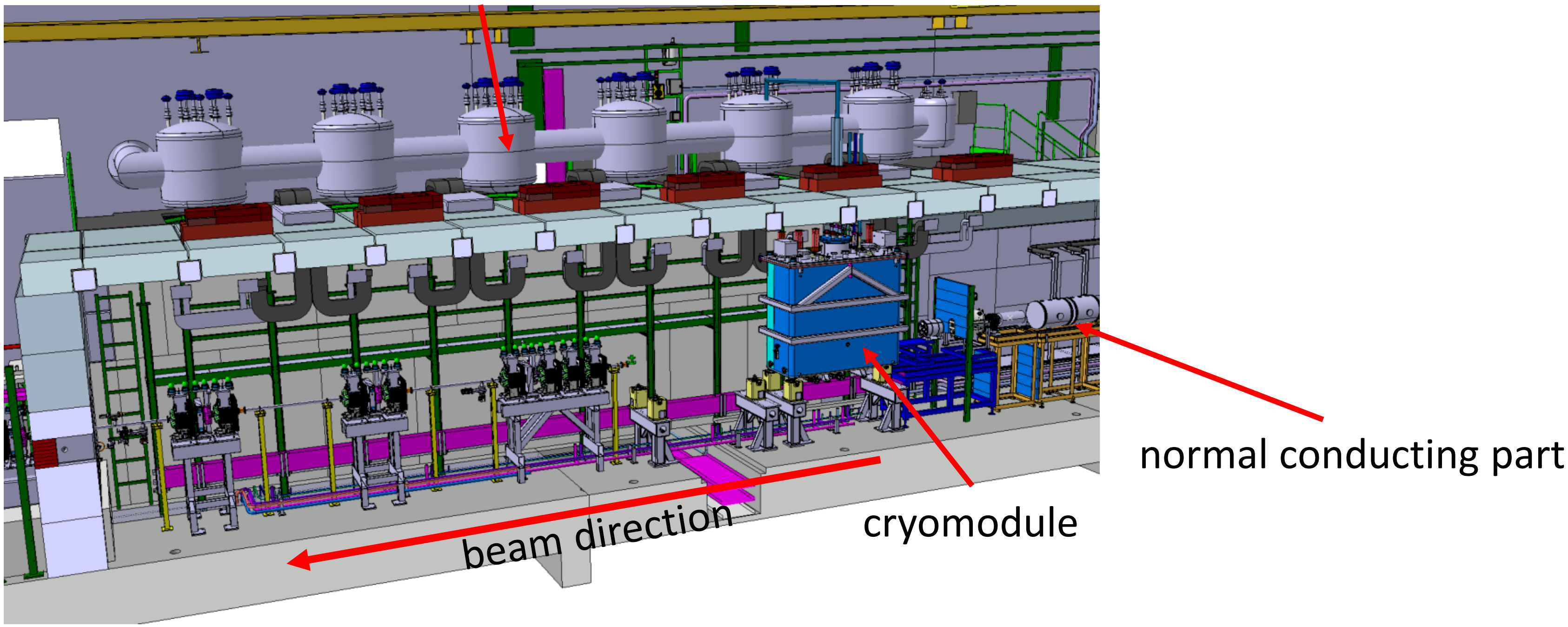
ISOLDE beams



Primary nuclear reactions for 1.4 GeV protons: spallation, fission, fragmentation:

- Nearly **1300 isotopes** available from over **70 chemical elements**
- Over 1000 used for low-energy experiments
- Post-accelerated: over **100 beams of 33 elements**
- Proton energy: Some beams will remain unique to ISOLDE

Energies from post-accelerator



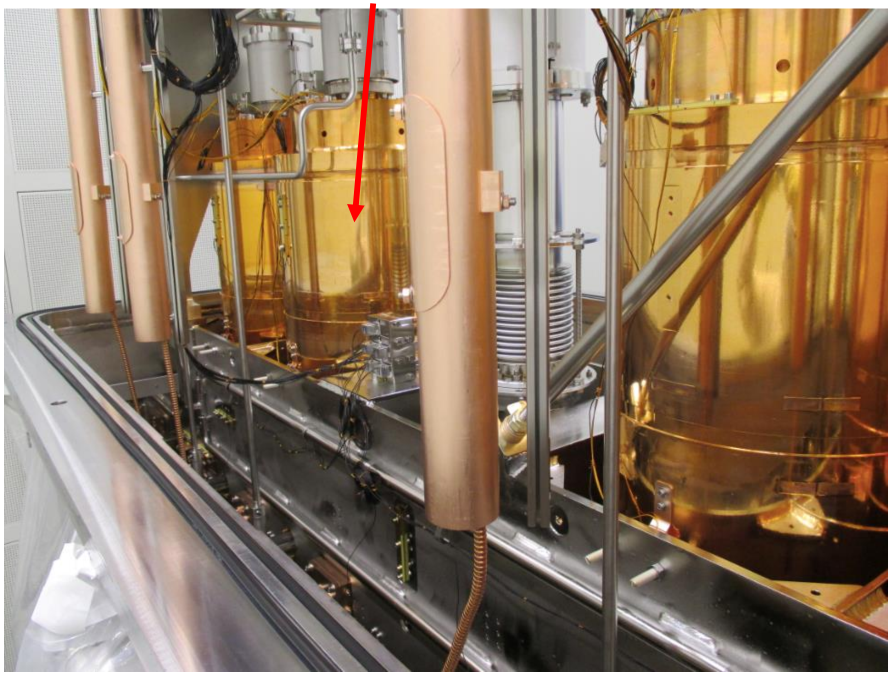
REX-ISOLDE post-accelerator becomes HIE-ISOLDE

HIE-ISOLDE installation schedule
3 MeV/u until 2012

2015: ~4.2 MeV/u (physics in October)

2016: ~5 MeV/u
2017: 10 MeV/u

Energies at post-accelerator



gold-coated cavity

cryo module inside linac tunnel

REX-ISOLDE post-accelerator becomes HIE-ISOLDE

HIE-ISOLDE installation schedule
3 MeV/u until 2012

2015: ~4.2 MeV/u (physics in October)

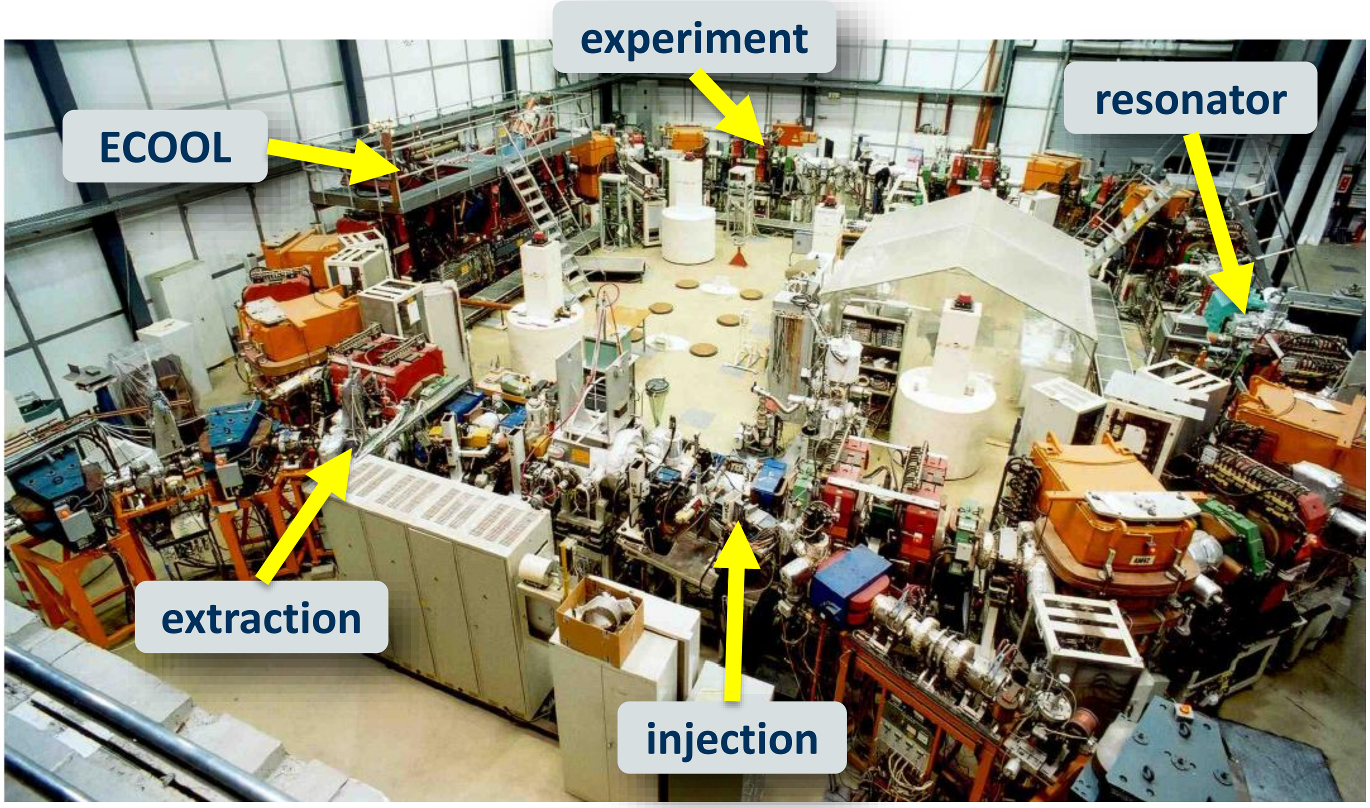
2016: ~5 MeV/u
2017: 10 MeV/u

The ring and its beam characteristics

The following two sections are based on presentations given by Manfred Grieser, MPI-K Heidelberg at TSR workshop

Courtesy of M. Grieser

Test Storage Ring at Heidelberg



Courtesy MPI-K

* In operation since 1988

* Mainly for atomic physics studies and accelerator development

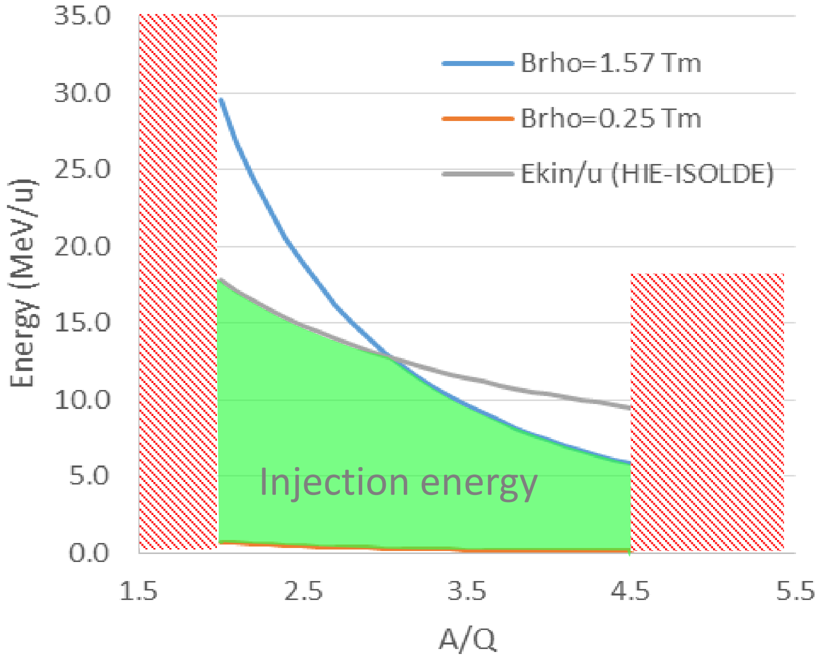
* One nuclear physics experiment – FILTEX (internal polarized H_2 gas target)

Circumference: 55.42 m
Vacuum: **~few 10^{-11} mbar**
Acceptance: 120 mm mrad

Multiturn injection: mA current
Electron cooler: transverse T_{cool} in order of 1 s
RF acceleration and deceleration possible
Typical energy $^{12}C^{6+}$: 6 MeV/u

www.mpi-hd.mpg.de/blaum/storage-rings/tsr/index.en.html

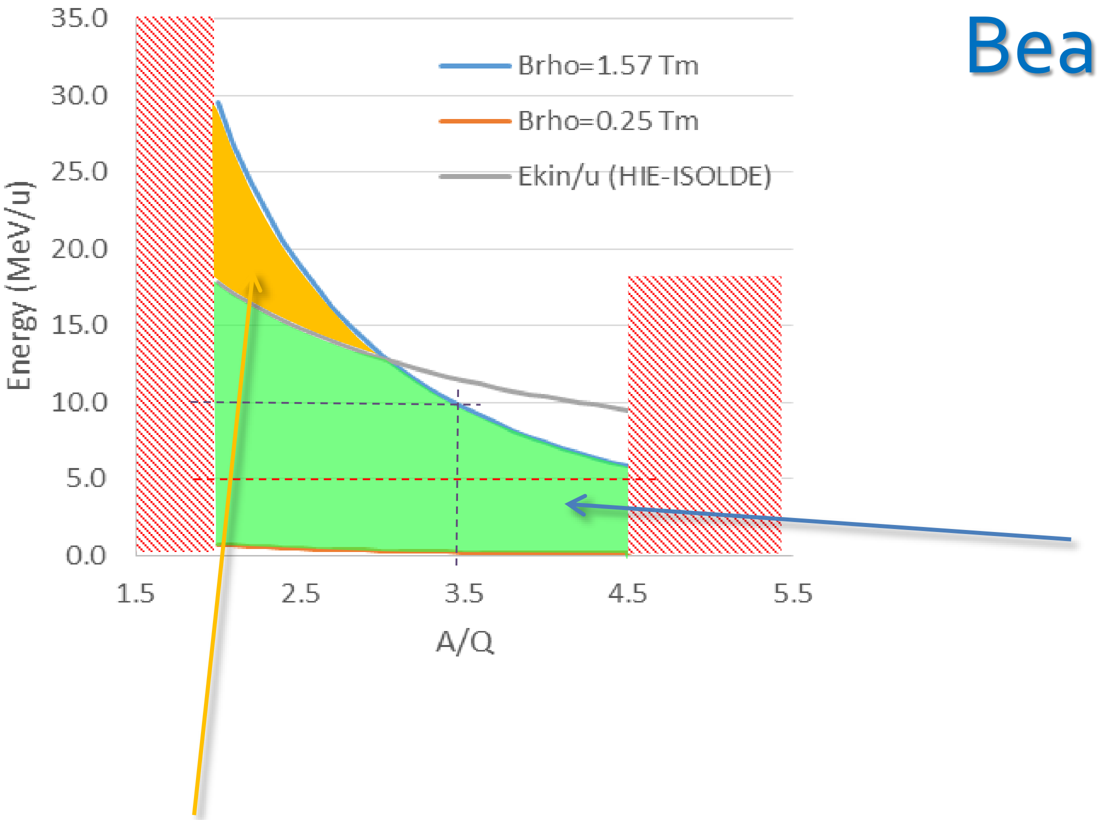
Beam energy ring



TSR magnetic rigidity range: 0.25-1.57 Tm

REX linac 2<A/q<4.5

Beam energy ring



Pending achievable A/Q inside charge breeder

5 MeV/u sufficient for lifetime and nuclear structure studies

Beam can be accelerated (and decelerated) inside the ring

Upgrade at CERN will allow ramping time < 1 s

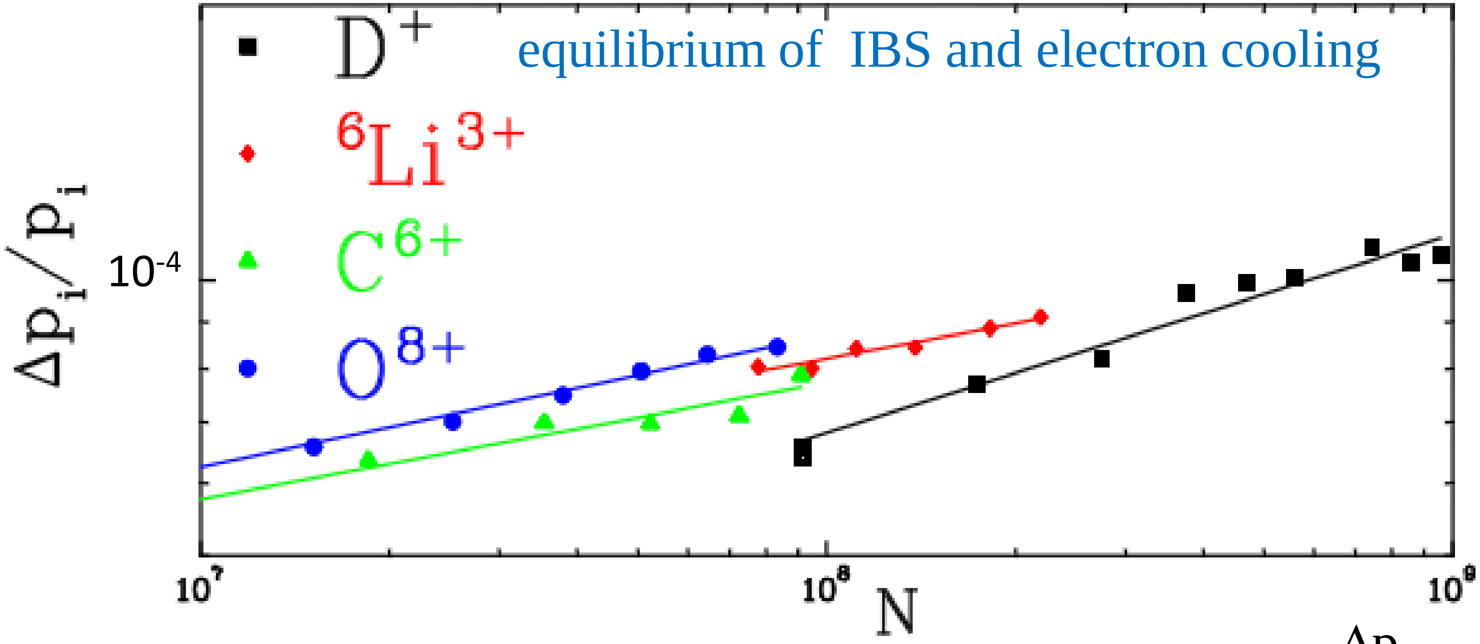
e-cooler – energy spread

e-cooling needed for:

1. Reducing momentum spread → $\Delta p/p \sim 5\cdot10^{-5}$ (rms)

$$\frac{\Delta p_{rms}}{p_i} = \frac{1}{2}\frac{\Delta E_{rms}}{E}$$

HIE-ISOLDE $\Delta p/p \sim 1\cdot10^{-3}$ (rms)



M. Grieser, TSR workshop 2014

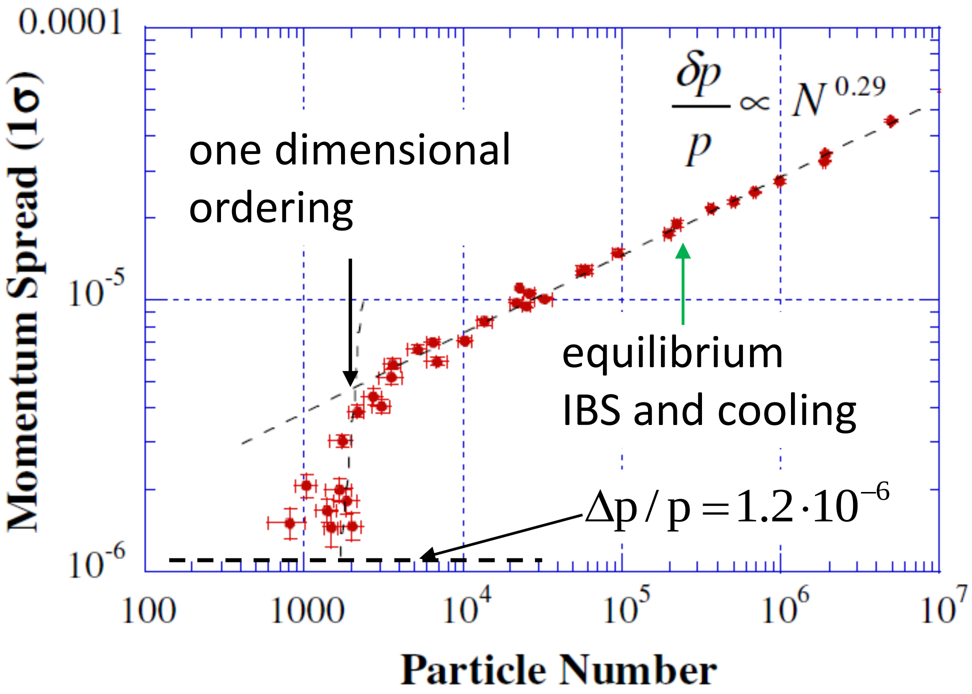
particle number scaling: $\frac{\Delta p}{p} \sim N^{\alpha}$

e-cooler – energy spread

e-cooling needed for:

1. Reducing momentum spread → $\Delta p/p \sim 5\cdot10^{-5}$ (rms)

HIE-ISOLDE $\Delta p/p \sim 1\cdot10^{-3}$ (rms)



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

T. Shirai et al. PRL 98, 204801 (2007)

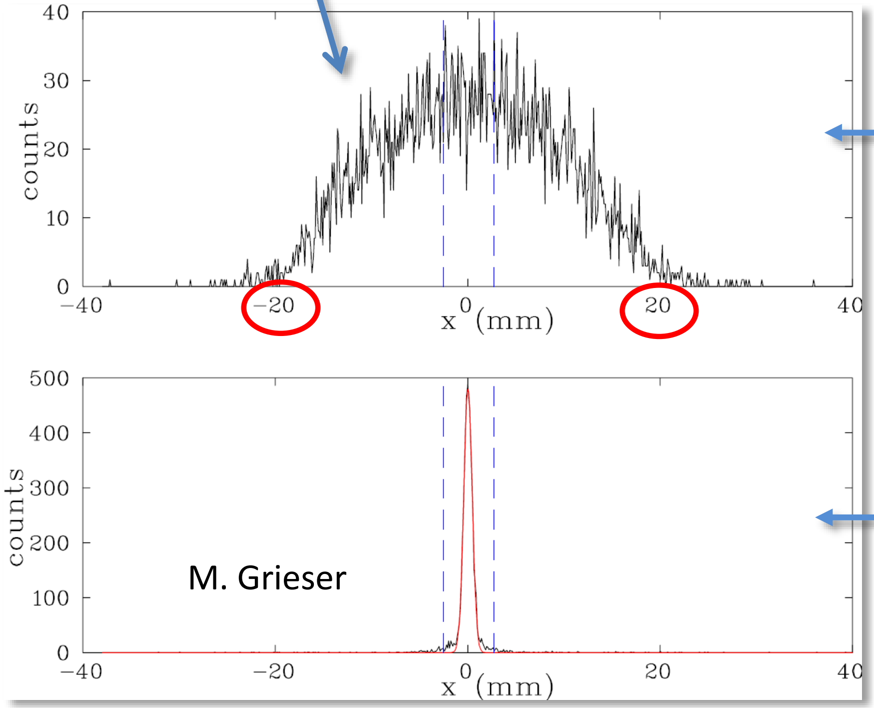
M. Grieser, TSR workshop 2014

e-cooler – transverse ε

e-cooling needed for:

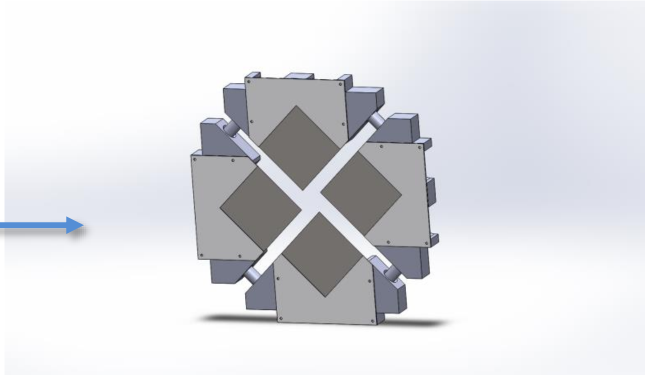
1. Reducing momentum spread
2. Reducing beam size / transverse emittance

Assembly of 4 movable DSSD positioned
up- or downstream of target point

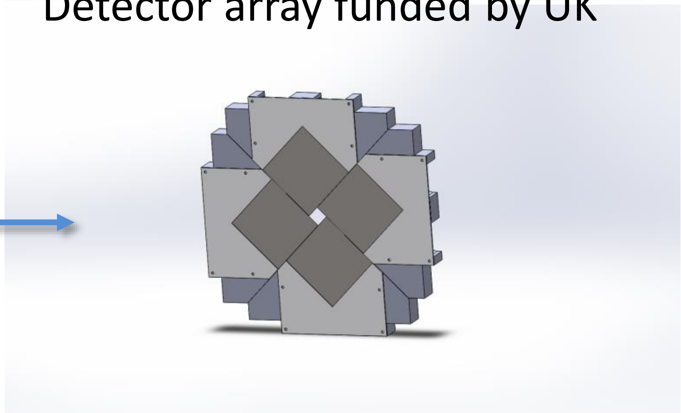


M. Grieser

Radial beam extension



Detector array funded by UK

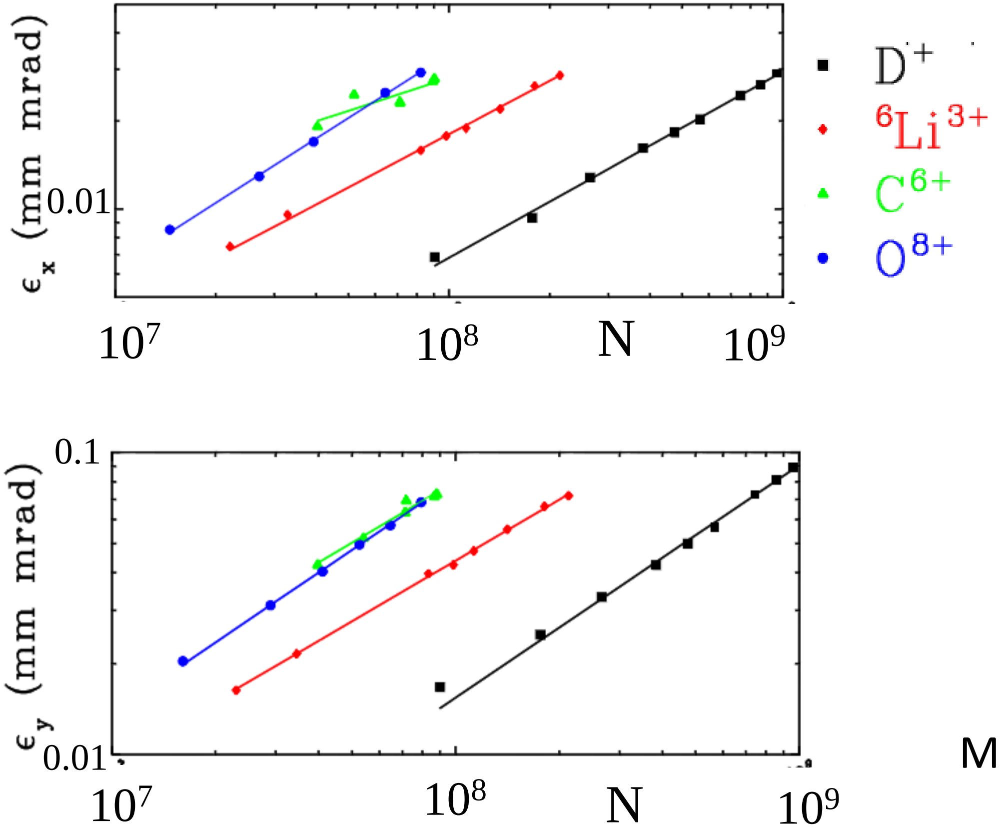


T. Davinson and P. Woods

e-cooler – transverse ε

e-cooling needed for:

1. Reducing momentum spread
2. Reducing beam size / transverse emittance



beam width

$$\varepsilon_{x,y} = \frac{\sigma^2_{x,y}}{\beta_{x,y}}$$

beta function

M. Grieser, TSR workshop 2014

e-cooler properties

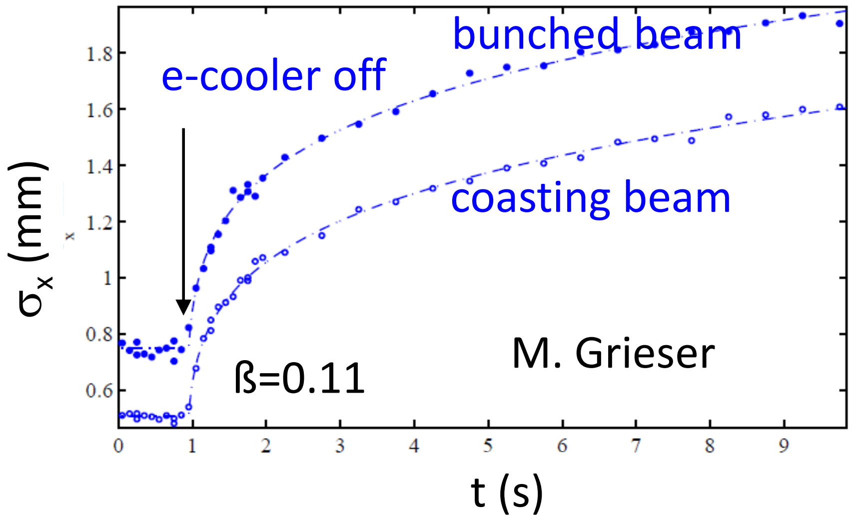
e-cooling needed for:

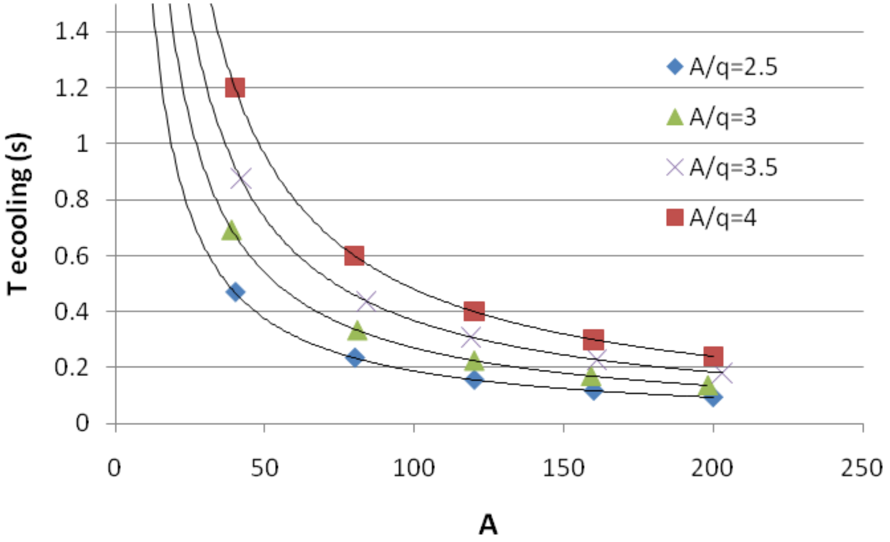
1. Reducing momentum spread
2. Reducing beam size / transverse emittance
3. Stacking of multi-turn injection
4. Compensate for energy loss in in-ring target

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

in the velocity range
0.03<ß<0.16

horizontal beam profile





T_{cool} – horizontal cooling time for beam with large diameter

Maximum ring intensities

Space charge limit in TSR

- Incoherent space-charge tune shift
- Transverse instabilities

$$I_{limit} = const\,\frac{(A^{19}\cdot E^{9})^{1/28}}{Q}$$

E (MeV), I (uA), const=279

$$I_{TSR} \approx T_{lifetime}\,\frac{\varepsilon_m}{d_{dilution}}\,\frac{v_{projectile}}{C_0} < I_{REX} >$$

C_0 = ring circumference

ε_m=0.8, $d_{dilution}$=2

$T_{lifetime}$ = storage life time

$<I_{REX}>$ = ISOLDE ion current * REX efficiency

Information from M. Grieser,
TSR workshop 2014

TSR intensities Exp. Theory

Ion	E [MeV]	Intensit [μA]	Stability limit [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
$^{45}Sc^{18+}$	178	380	1087
$^{56}Fe^{22+}$	250	70	1
$^{56}Fe^{23+}$	260	128	1
$^{58}Ni^{25+}$	342	600	1147
$^{63}Cu^{25+}$	290	280	1150
$^{63}Cu^{26+}$	510	100	1326
$^{74}Ge^{28+}$	365	110	1234
$^{80}Se^{25+}$	480	100	1590
$^{80}Se^{31+}$	506	<1	1304
$^{197}Au^{50+}$	695	3	1651

~ 1 mA

close to the limit

stability limit not reached

Storage lifetime

$$\frac{1}{T} = \frac{1}{T_{radioactive\_decay}} + \frac{1}{T_{storage}}$$ 1/e-lifetime

Consider:
- **residual gas** (composition H_2=93.4%, C=2.2%, N=0.7%, O=3.3%, Ar=0.3%)
- **target gas**

$$\frac{1}{T_{storage}} = \underbrace{\frac{1}{T_{ms}}}_{\text{Coulomb multi scattering}} + \underbrace{\frac{1}{T_{ss}}}_{\text{Coulomb single scattering}} + \underbrace{\frac{1}{T_{st}}}_{\text{e- stripping}} + \underbrace{\frac{1}{T_{cap}}}_{\text{e- capture}}$$

Storage lifetime

$$\frac{1}{T}=\frac{1}{T_{radioactive\_decay}}+\frac{1}{T_{storage}}$$

1/e-lifetime

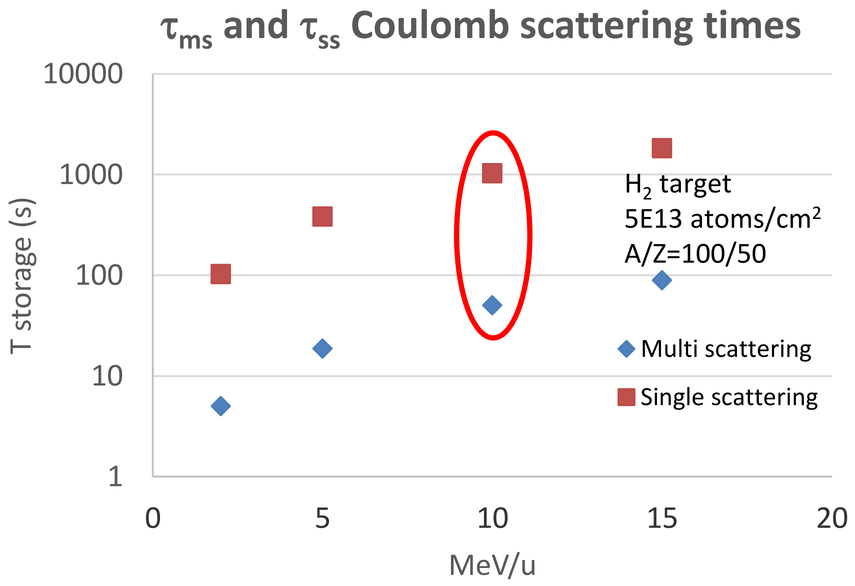
Consider:

- **residual gas** (composition H_2=93.4%, C=2.2%, N=0.7%, O=3.3%, Ar=0.3%)
- **target gas**
- **e-cooler**

$$\frac{1}{T_{storage}}=\frac{1}{T_{ms}}+\frac{1}{T_{ss}}+\frac{1}{T_{st}}+\frac{1}{T_{cap}}\boxed{+\frac{1}{T_{RR}}+\frac{1}{T_{DC}}}$$

radiative and
di-electronic
recombination
inside to e-cooler

Scattering and e-cooler lifetimes



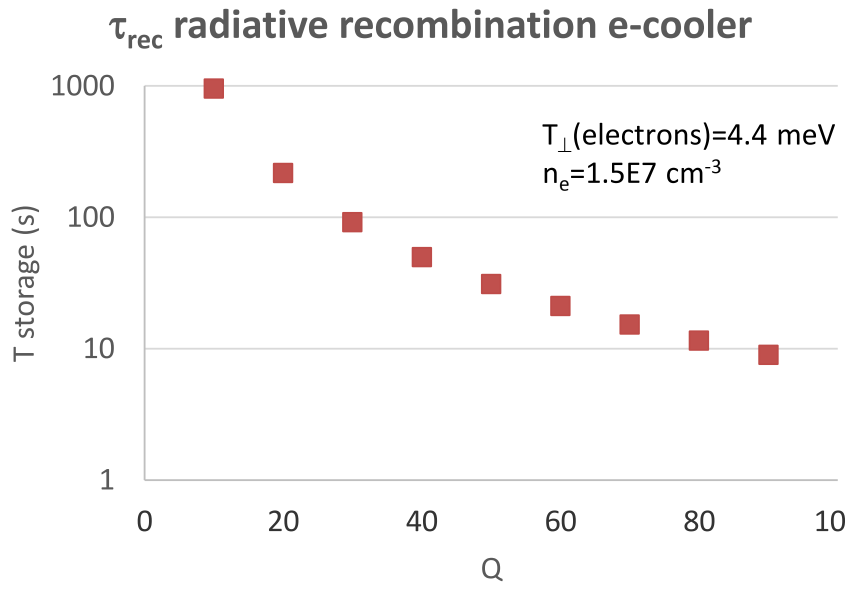
τ_{ms} and τ_{ss} Coulomb scattering times

$$\tau_{ms} \propto \frac{v_{proj}^3 Q_{proj}^2}{\rho_{gas} A_{proj}^2 \ln\left(\frac{const \cdot A}{Z_{gas}^{1/3} v_{proj}}\right)}$$

* $\tau_{ss}=20.5*\tau_{ms}$

* ms avoided by e-cooling

* residual gas ms and ss lifetime are longer



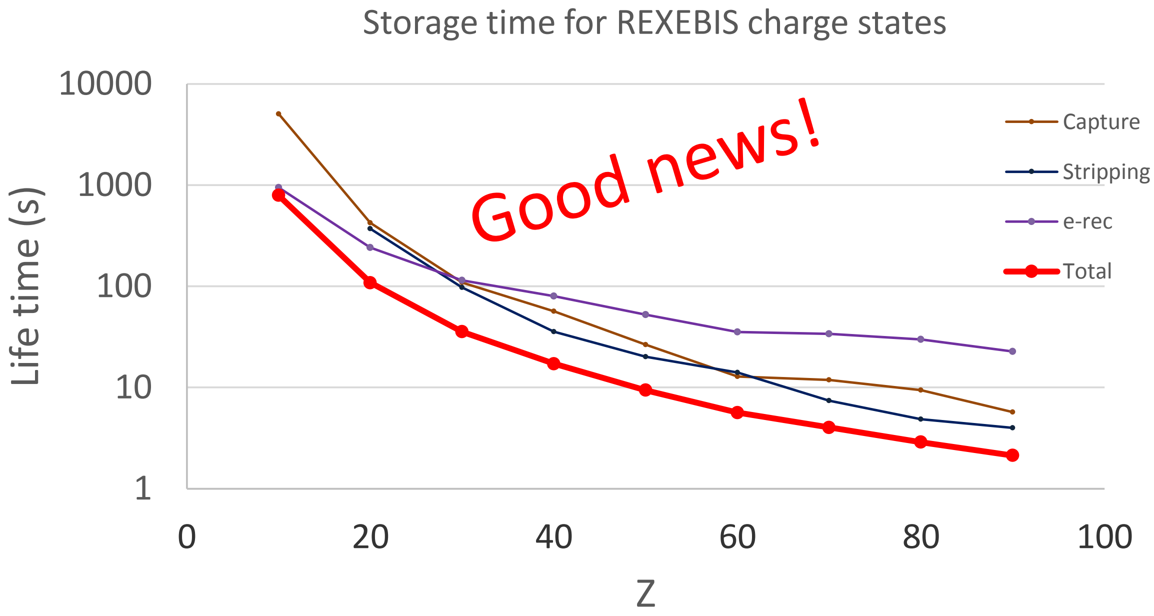
τ_{rec} radiative recombination e-cooler

$$\tau_{rec} \propto \frac{1}{n_e Q_{proj}^2} \cdot \frac{1}{\ln(const1 \cdot Q_{proj}^2) + const2 \cdot Z_{proj}^{-2/3}}$$

* di-electronic recombination generally a factor 1.5-5 higher than RR for electron-ion energies <10 meV

A. Wolf et al, Nucl Instr Meth A441 (2000) 183-190

Total storage lifetimes



10 MeV/u
H_2 target, $5 \cdot 10^{-13}$ atoms/cm^2
e-cooler
$1.5 \cdot 10^7$ cm^{-3} 4.4 meV,

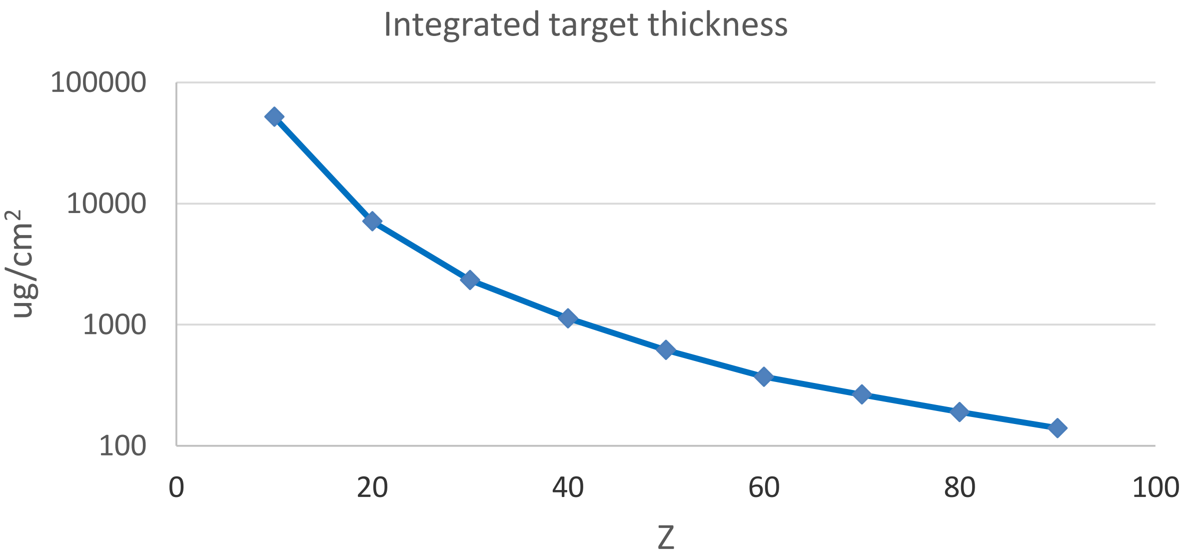
Schlachter formula for $\sigma_{capture}$
Franzke extrapolation for $\sigma_{stripping}$

NB! Calculation excludes contribution from residual gas as the integrated thickness is much smaller (55.42 m, $5 \cdot 10^{-11}$ mbar)
=> $6.7 \cdot 10^9$ atoms/cm^2

Integrated target thickness

Effective target thickness:

(gas target thickness) x (revolution frequency) x (lifetime)

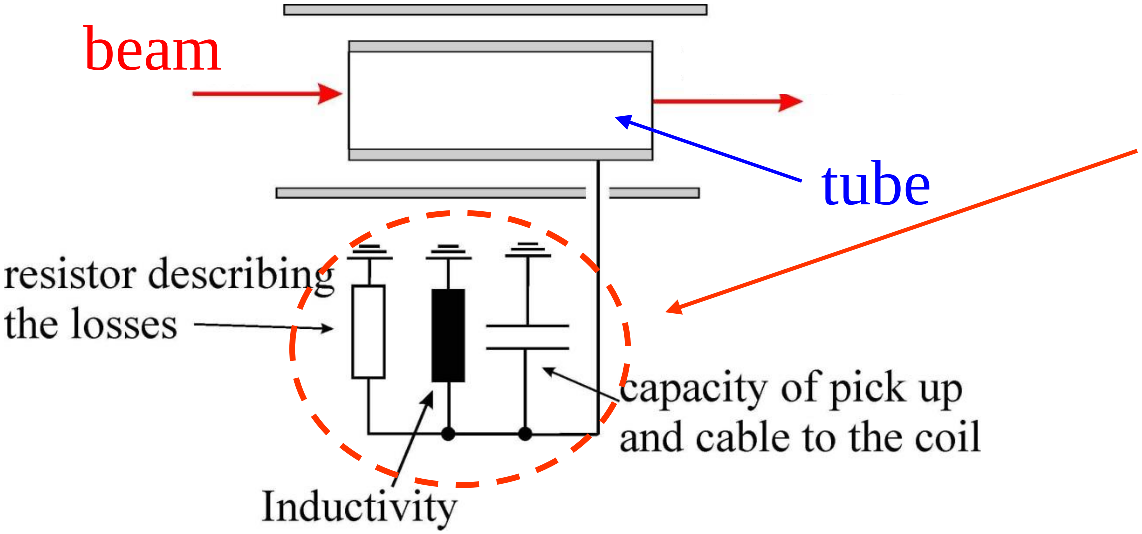


Compare with ~100 ug/cm^2 for direct target

NB 1. $\sigma_{cap} = 1.1 \cdot 10^{-8} \frac{q^{3.9} Z_{gas}^{4.2}}{(E/A)^{4.8}} [cm^2] \quad \Rightarrow \quad \tau_{target,He} = \frac{\tau_{target,He}}{18.4}$

NB 2. Can’t use foils in the ring!

Schottky pickup sensitivity



resonant at the observed Schottky band n

Schottky voltage power spectrum

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

Schottky spectrum visible if:

$$P_0(n) > U^2_{r,Qw}\cdot\Delta f = \alpha^2(Qw)\,U^2_{r,Qw=1}\cdot\Delta f$$

amplifier noise

amplification of noise at resonant measurement

Schottky pickup sensitivity

Q - ion charge

Q_w - Q value of **LC** circuit

$Q_w = 263$, $\alpha(Q_w=263) = 65$

N - number of ions

n - harmonic number of revolution frequency

$U_{r,Qw=1} = 0.5\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ amplifier noise

L = 0.35 m pick-up length

C=300 pF total capacity

C_0=55.42 ring circumference

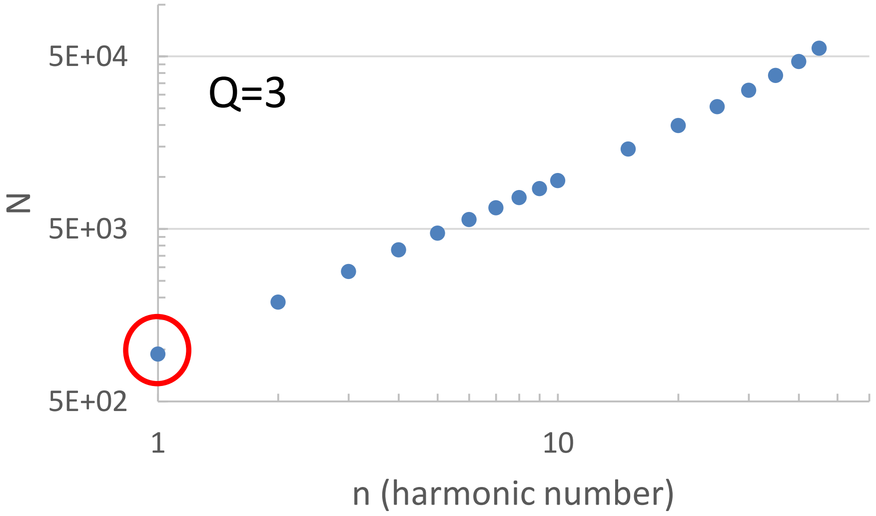
$\eta = 0.9$ (standard mode)

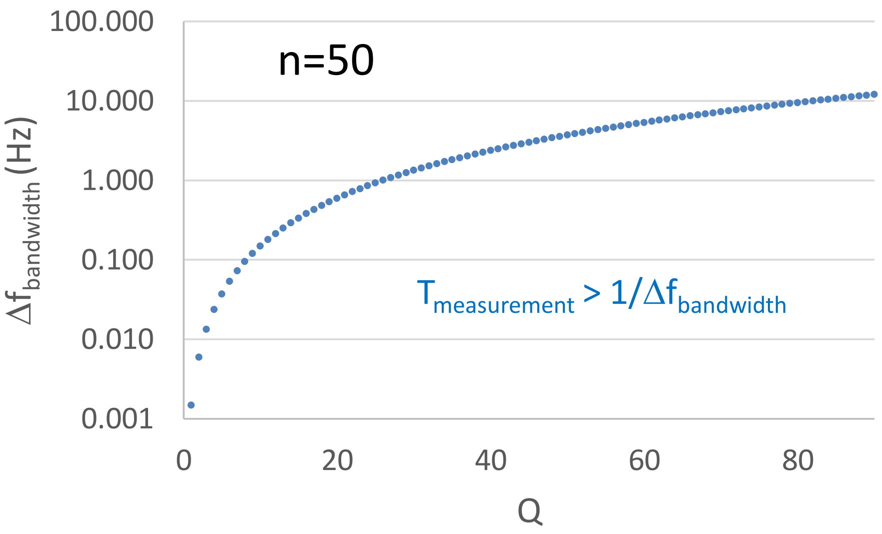
$f_0 = 0.7\ 10^6$ Hz revolution frequency

$\Delta p/p = 2\cdot 10^{-5}$ full momentum spread width

$$\Delta f = \begin{cases} \Delta f_{Schottky} = \eta\, \Delta p / p\, n f_0 \\ \quad \text{for multiple particle detection} \\ \Delta f_{bandwidth} \\ \quad \text{for single particle detection} \end{cases}$$

Based on information from M. Grieser, TSR workshop 2014





$T_{measurement} > 1/\Delta f_{bandwidth}$

Experimental matters to keep-in-mind

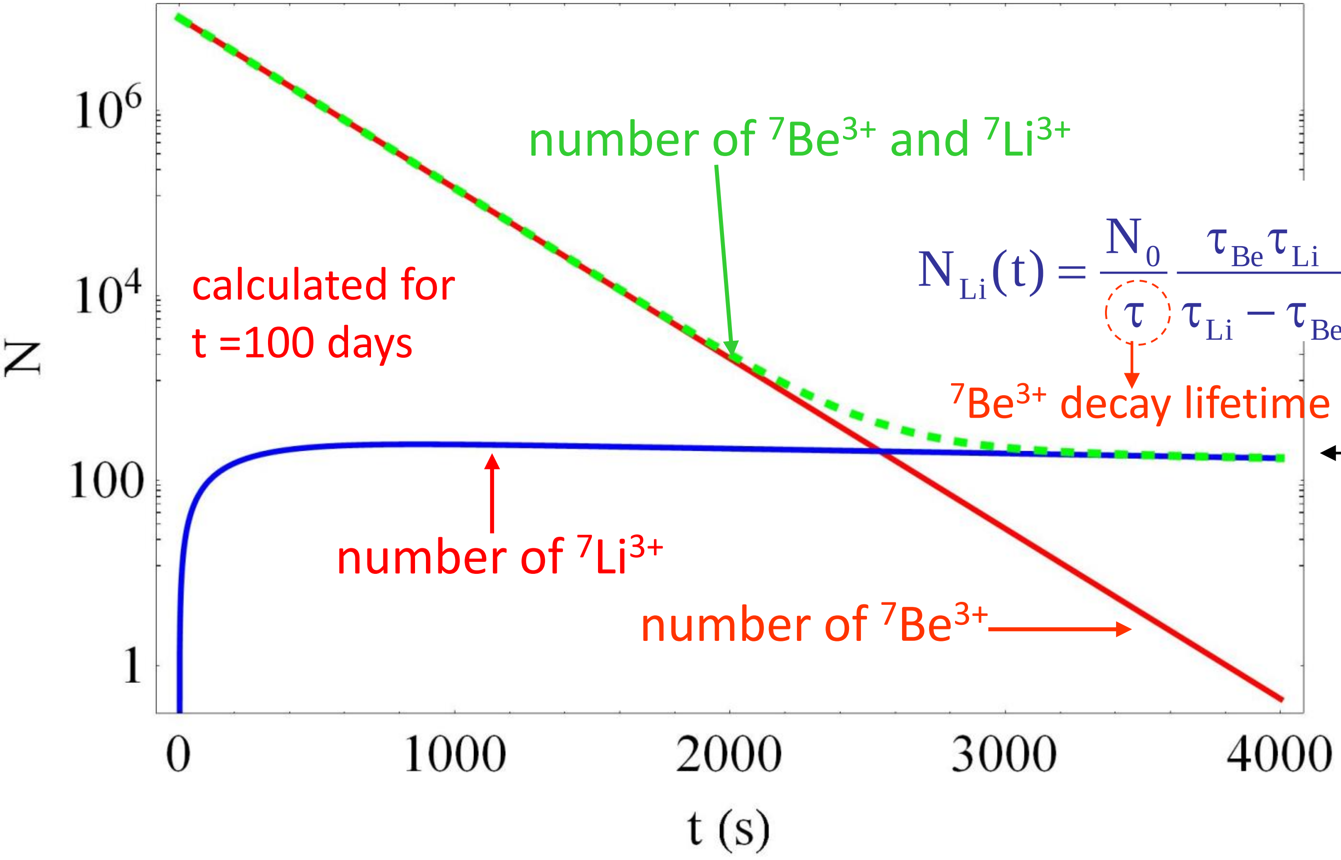
M. Grieser, TSR workshop 2014

^{7}Be^{3+} decay measurement

$$^7\mathrm{Be}^{3+} + e^- \rightarrow {}^7\mathrm{Li}^{3+} + \nu$$

Example: $N_0=10^7$ ^{7}Be^{3+} injected

At 8 MeV/u ⇒ τ_{Be}= 240 s , τ_{Li}= 8400 s storage life-times



number of ^{7}Be^{3+} and ^{7}Li^{3+}

calculated for
t =100 days

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

^{7}Be^{3+} decay lifetime

N_{Li}=174

number of ^{7}Li^{3+}

number of ^{7}Be^{3+}

M. Grieser, TSR workshop 2014

$^{7}Be^{3+}$ decay measurement

Accumulate 10^9 ions:

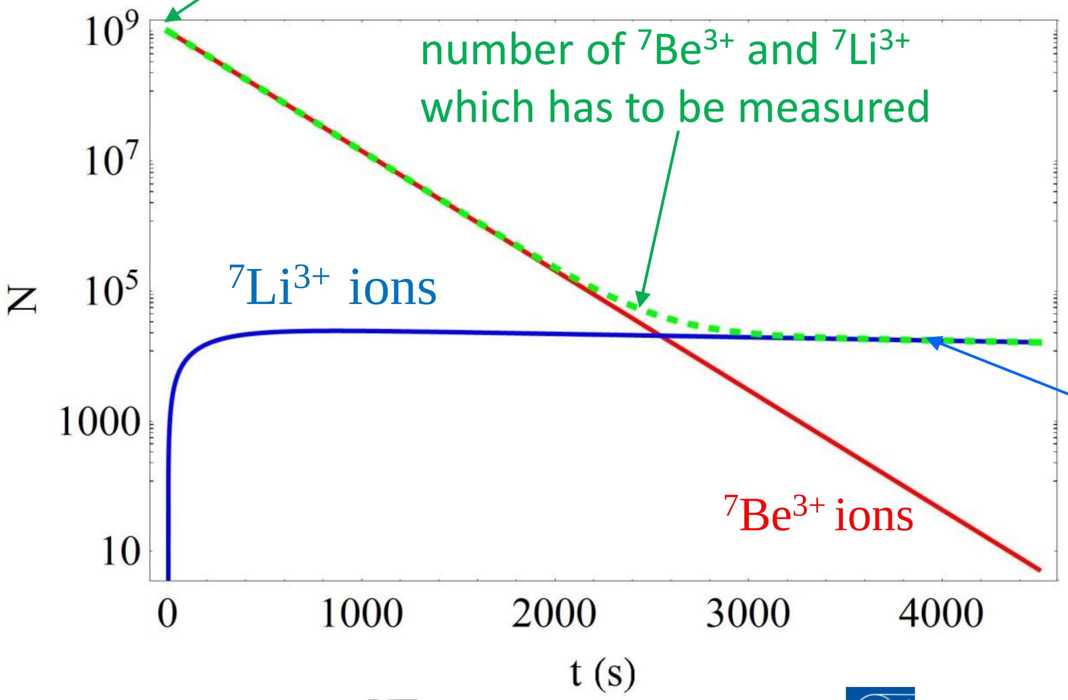
10^8 ions injected with multi-turn injection and 10 e-cool stacking cycles

filling time ≈ 30 s

Assure $\tau_{1/2} > T_{\text{cool stacking}}$

Assure I_{ring} < space charge limit, otherwise storage life-time modified

10^9 injected $^{7}Be^{3+}$ ions



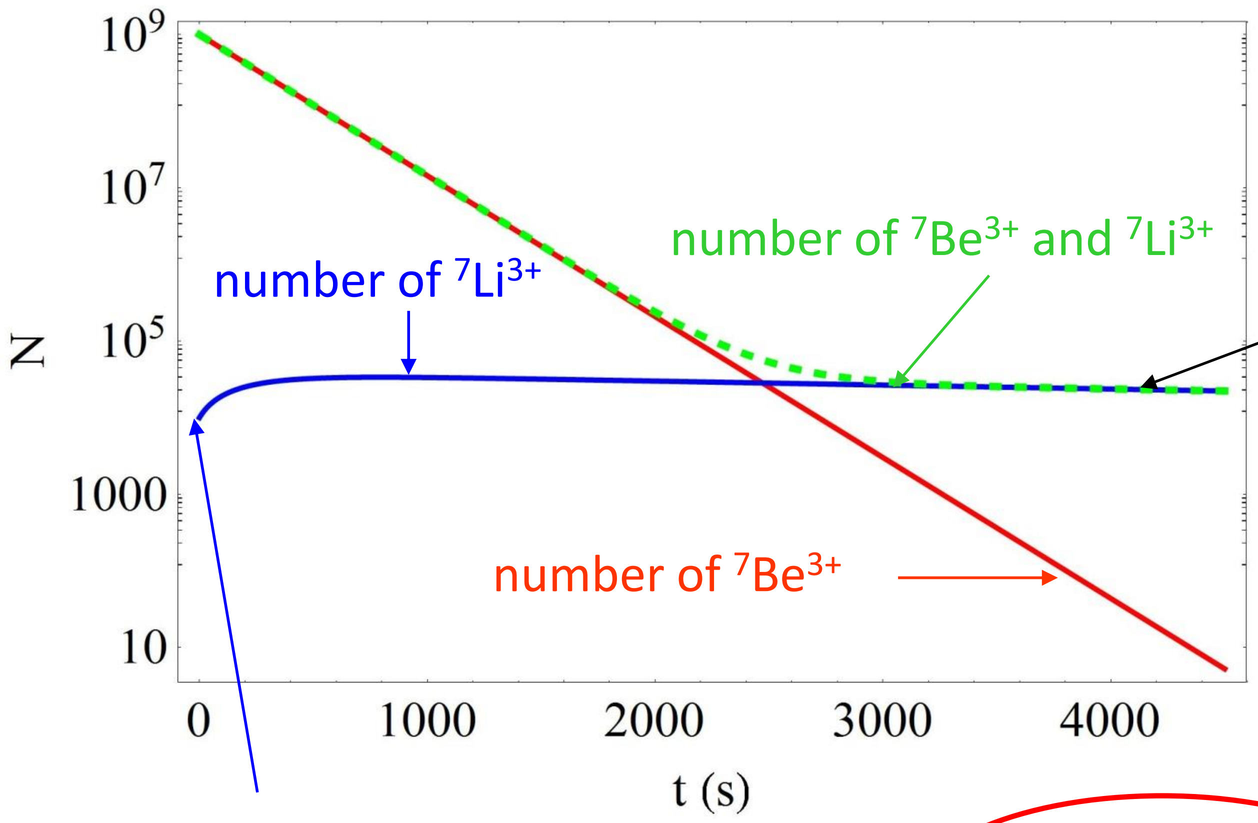
number of $^{7}Be^{3+}$ and $^{7}Li^{3+}$ which has to be measured

$^{7}Li^{3+}$ ions

$^{7}Be^{3+}$ ions

$N_{Li}=17400$ √

$^7Be^{3+}$ decay measurement



number of $^7Be^{3+}$ and $^7Li^{3+}$

number of $^7Li^{3+}$

number of $^7Be^{3+}$

with contamination

N_{Li}=23600

without contamination

N_{Li}=17400

⇒ error in the lifetime

τ determination ≈ **35%**

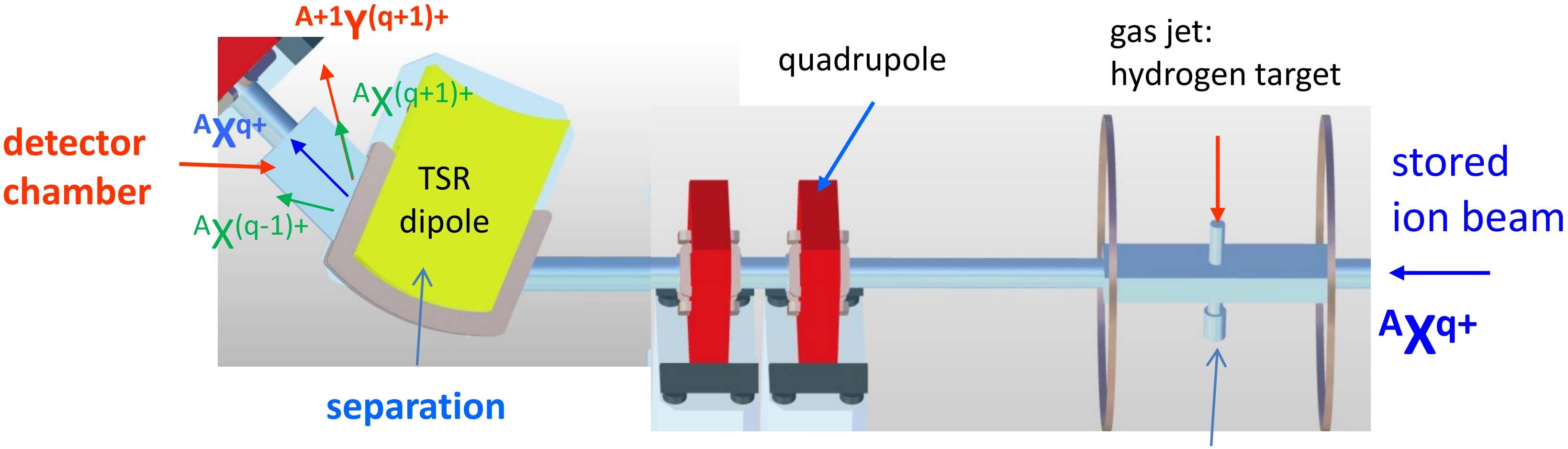
initial $^7Li^{3+}$ ion number: N_{Li}=10^4

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

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

Proton pick-up reactions

M. Grieser, TSR workshop 2014



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

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

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

Reactions

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

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

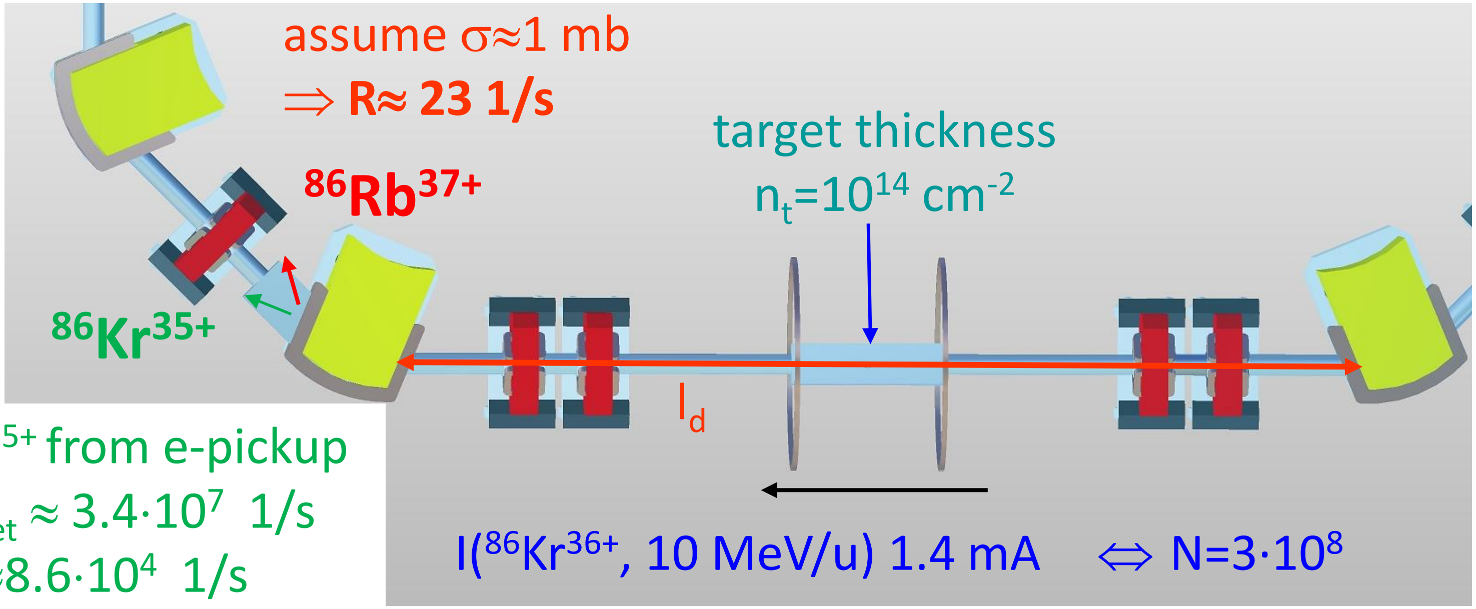
recombination: ${}^{A}X^{q+} + e \rightarrow {}^{A}X^{(q-1)+}$

$\Rightarrow$ experiment has to be carried out with bare ${}^{A}X^{q+}$ ions

M. Grieser, TSR workshop 2014

Proton pick-up reactions

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



assume $\sigma \approx 1$ mb

$\Rightarrow$ **R≈ 23 1/s**

$^{86}\text{Rb}^{37+}$

$^{86}\text{Kr}^{35+}$

target thickness

$n_t = 10^{14}\ \text{cm}^{-2}$

l_d

$I(^{86}\text{Kr}^{36+}$, 10 MeV/u) 1.4 mA $\Leftrightarrow$ $N = 3\cdot10^8$

$^{86}\text{Kr}^{35+}$ from e-pickup

$R_{target} \approx 3.4\cdot10^7$ 1/s

$R_{bg} \approx 8.6\cdot10^4$ 1/s

Particle trajectories in separator magnet

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

dispersion function

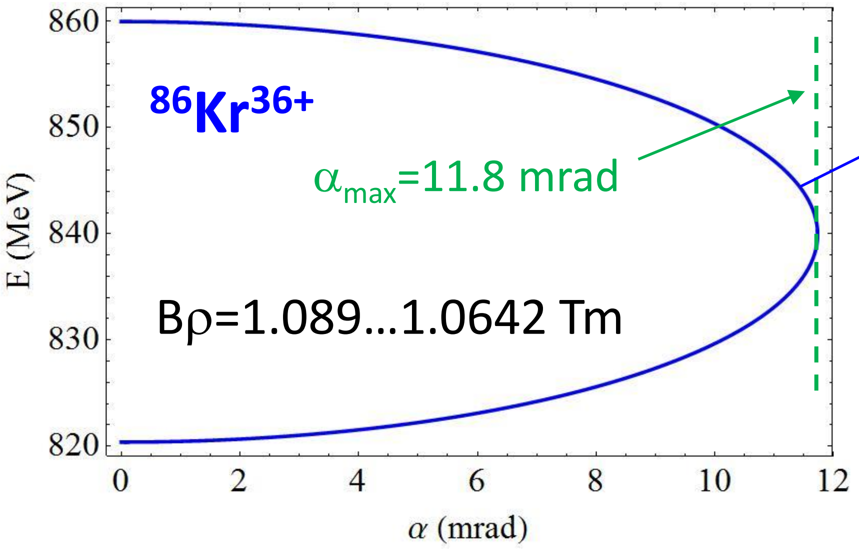
M. Grieser, TSR workshop 2014

Proton pick-up reactions

elastic scattering

$^{86}\mathrm{Kr}^{36+} + p \rightarrow\ ^{86}\mathrm{Kr}^{36+} + p$

energy as a function
of scattering angle



$^{86}\mathrm{Kr}^{36+}$

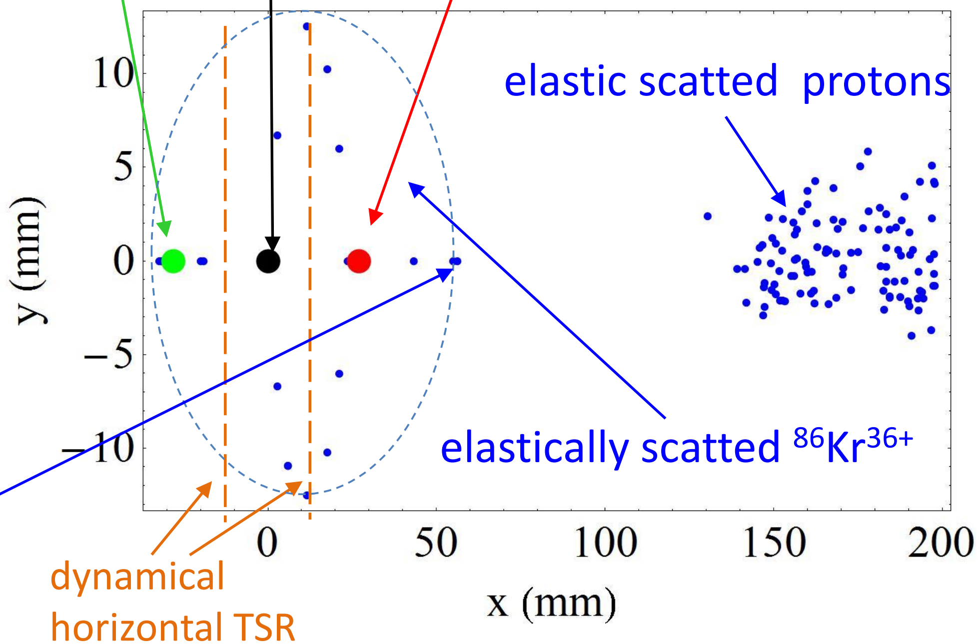
α_{max}=11.8 mrad

Bρ=1.089…1.0642 Tm

center of stored ion beam $^{86}\mathrm{Kr}^{36+}$

center of $^{86}\mathrm{Kr}^{35+}$

center of $^{87}\mathrm{Rb}^{37+}$

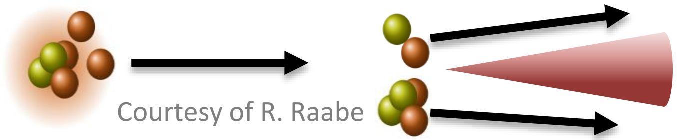


elastic scatted protons

elastically scatted $^{86}\mathrm{Kr}^{36+}$

dynamical
horizontal TSR
acceptance

ions on the detector plane

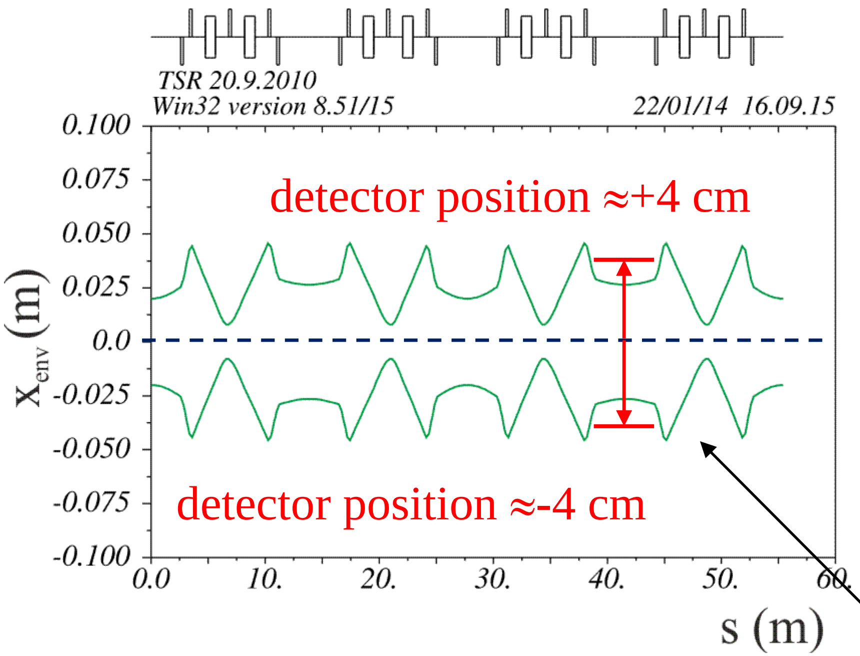


Courtesy of R. Raabe

In-flight decay of light ions

M. Grieser, TSR workshop 2014

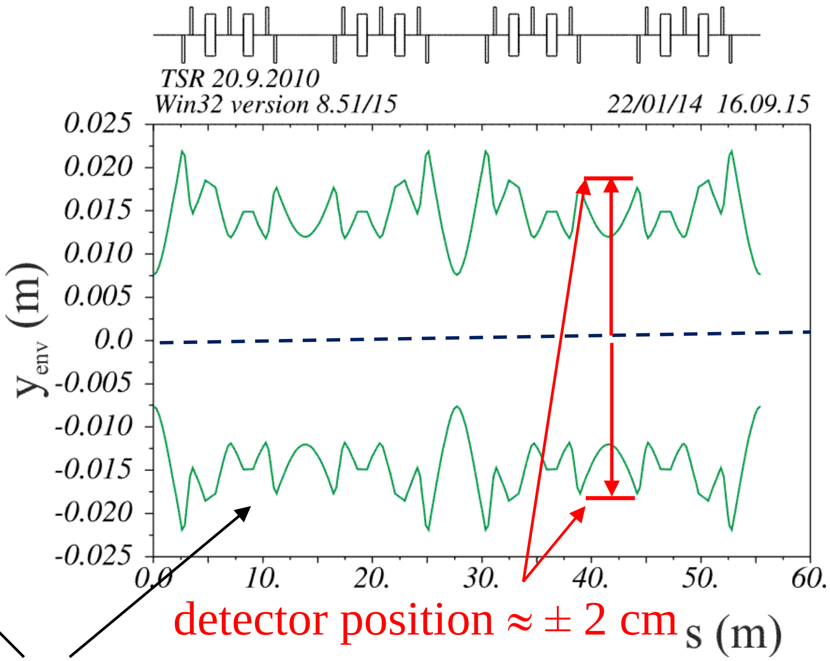
horizontal beam envelope



detector position ≈+4 cm

detector position ≈-4 cm

vertical beam envelope



detector position ≈ ± 2 cm

beam size after multi-turn injection

detector position should be outside the ring acceptance

Courtesy of M. Grieser

In-flight decay of light ions

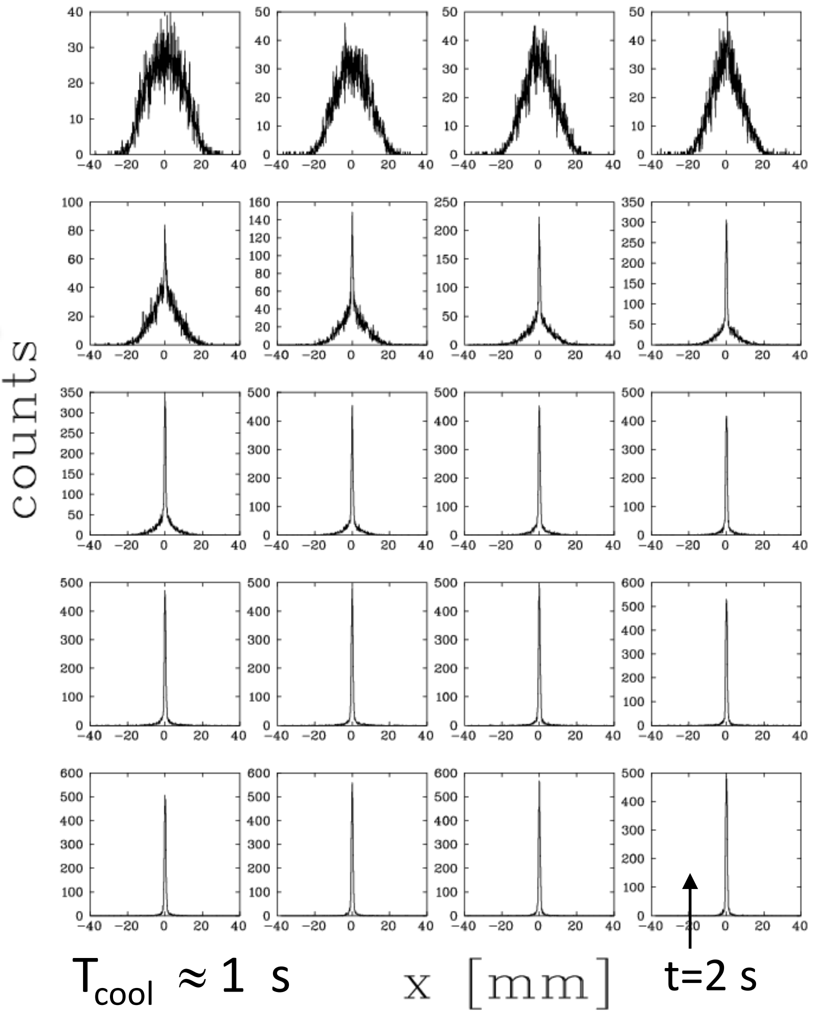
development of a multi-turn injected $^{12}C^{6+}$ beam

If nuclear life-time $\tau_{1/2}$ > cooling time T_{cool}

electron cooling time

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

REX efficiency for gases ^{6}He and ^{8}He is sub-percent. In addition impossible to store noble gases in REXTRAP for long bunching times.



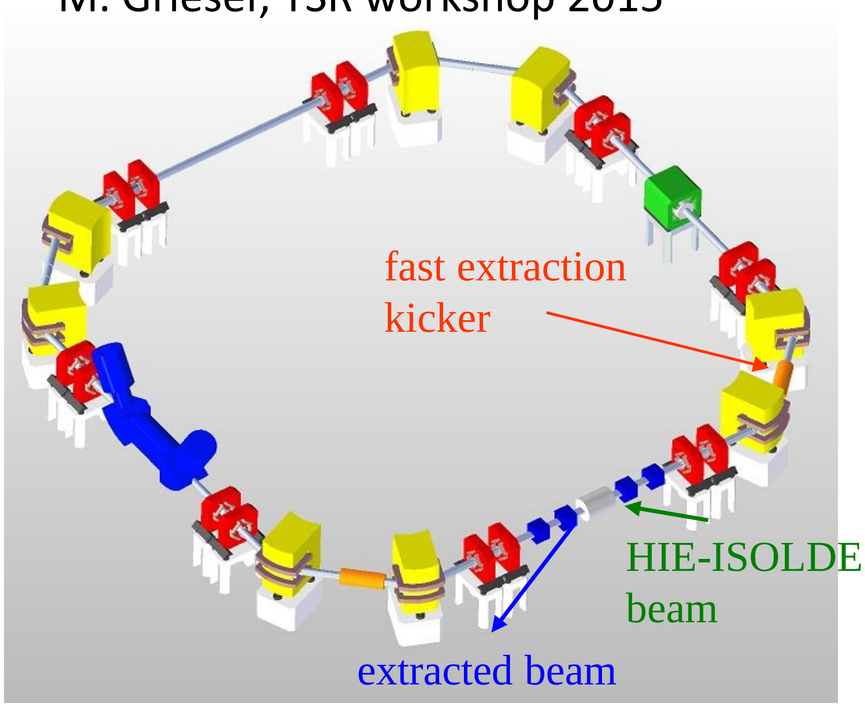
$T_{cool} \approx 1$ s

t=2 s

Externally extracted beam

Beam extraction

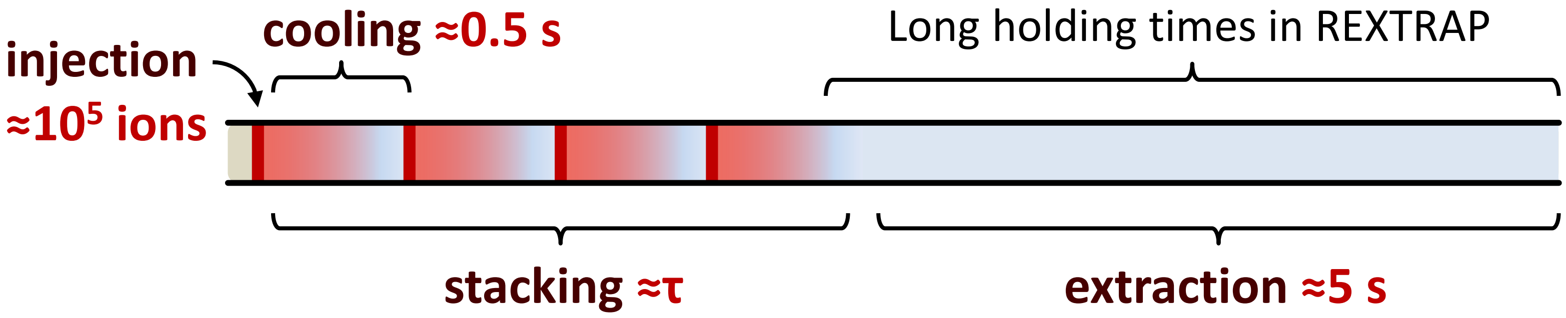
M. Grieser, TSR workshop 2015



Beam extraction to external experiment using either:

* Fast extraction –
≈ revolution time ≈ us bunches

* Slow extraction – bunch lengths up to seconds using horizontal RF noise excitation close to a 3rd order resonance + dispersive electron cooling



injection
≈10^5 ions

cooling ≈0.5 s

Long holding times in REXTRAP

stacking ≈τ

extraction ≈5 s

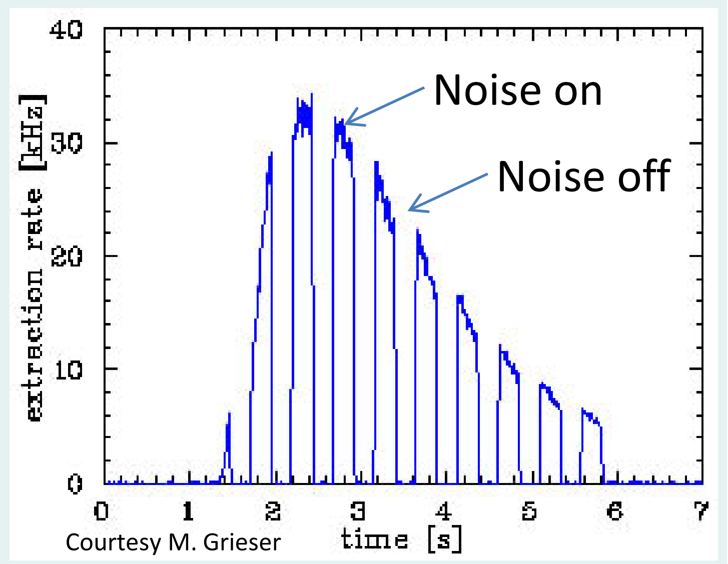
M. Grieser

Extraction types – pros and cons

Slow extraction

+ TSR has a slow extraction system
+ The extraction rate can be controlled by the noise level
+ In combination with dispersive electron cooling the extracted ion beam quality comparable to an electron-cooled in-ring beam
- Dispersive electron cooling not tested in this context

Controlling the extraction rate



Courtesy M. Grieser

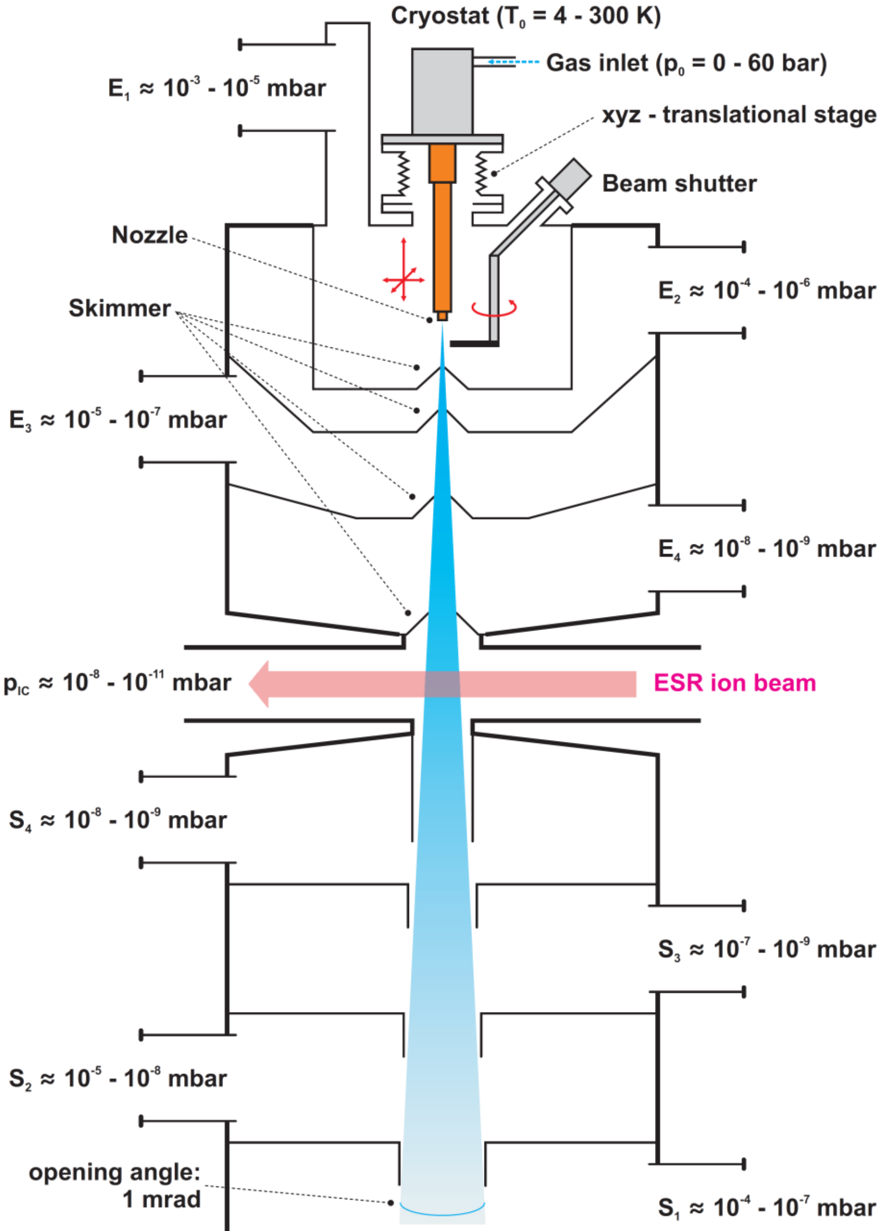
Fast extraction

+ ε and $\Delta p/p$ of extracted beam similar to cooled in-ring ion beam (but need to bunch the beam during e-cooling $\Rightarrow$ some increase of momentum spread and emittance)
- TSR is not equipped with a fast extraction system $\Rightarrow$ extraction system has to be built (estimated cost > 1 Million CHF + 4.4 man year)
- Modification of TSR is required (removing of quadrupole family 3)

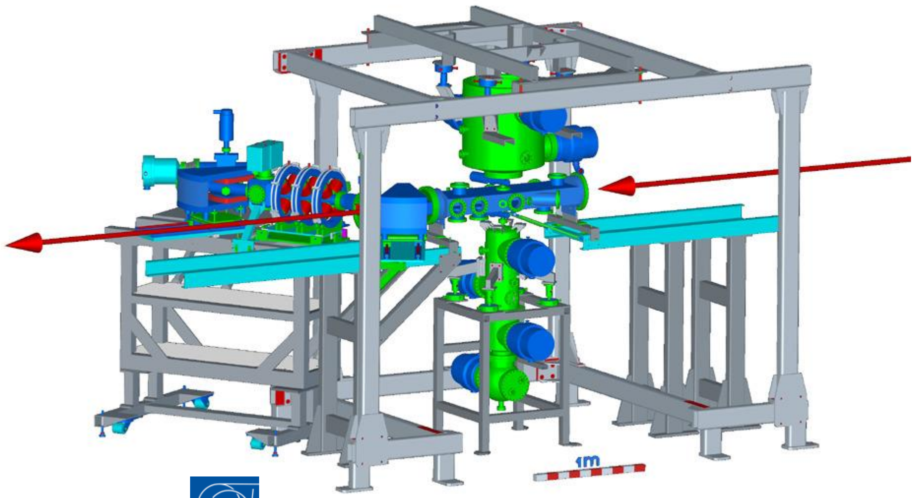
Internal gas target

ESR target layout

Courtesy of N. Petridis

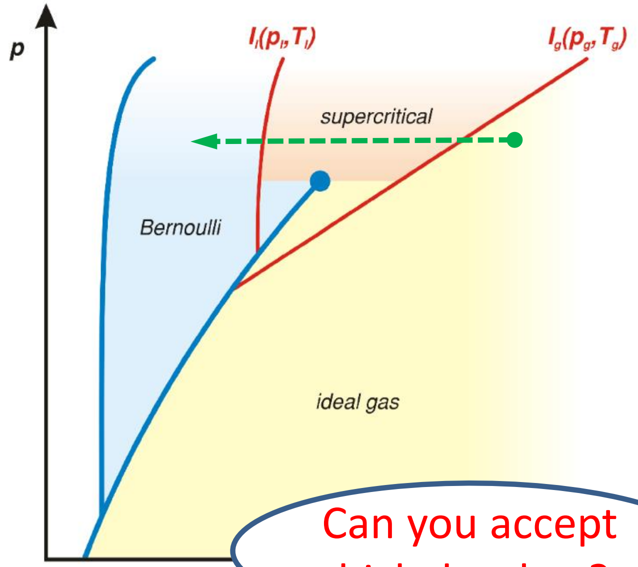


- The cryostat allows the nozzle operation at temperatures down to $T_0 = 4$ K
- The target density can be derived from the pressure increase in the dump pressure chambers $S_1 - S_4$



Gas target performance

Courtesy of N. Petridis



Can you accept thick droplets?

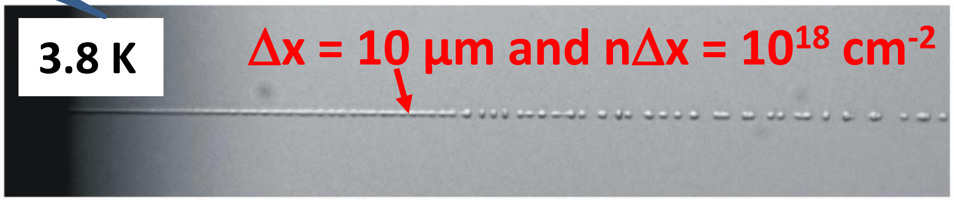
The fluid can be expanded from its gaseous, supercritical or liquid phase, yielding a supersonic jet, cluster or microdroplet beam - **multiphase target.**

Target gas	Area density [cm^{-2}]	T_0 [K]
Helium	1×10^{13}	20
Hydrogen	3×10^{13}	40
Nitrogen	8×10^{12}	130

Currently achievable cluster target densities

Expected n for multiphase target:
10^{10} cm^{-3} – 10^{15} cm^{-3}

Variable target widths down to **1 mm:**
nΔx = **10^{14} cm^{-2}** at **Δx = 0.1 cm**


3.8 K

Δx = 10 µm and nΔx = 10^{18} cm^{-2}

Droplet target (limited distance)

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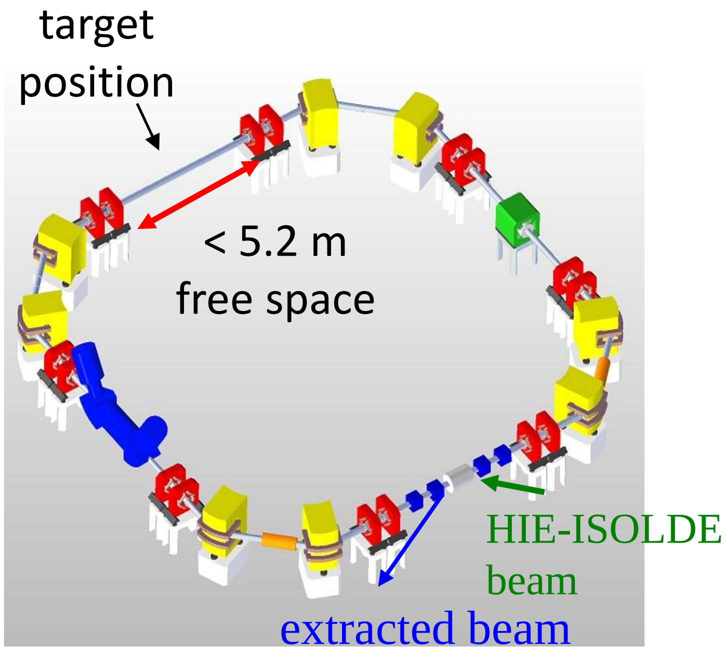
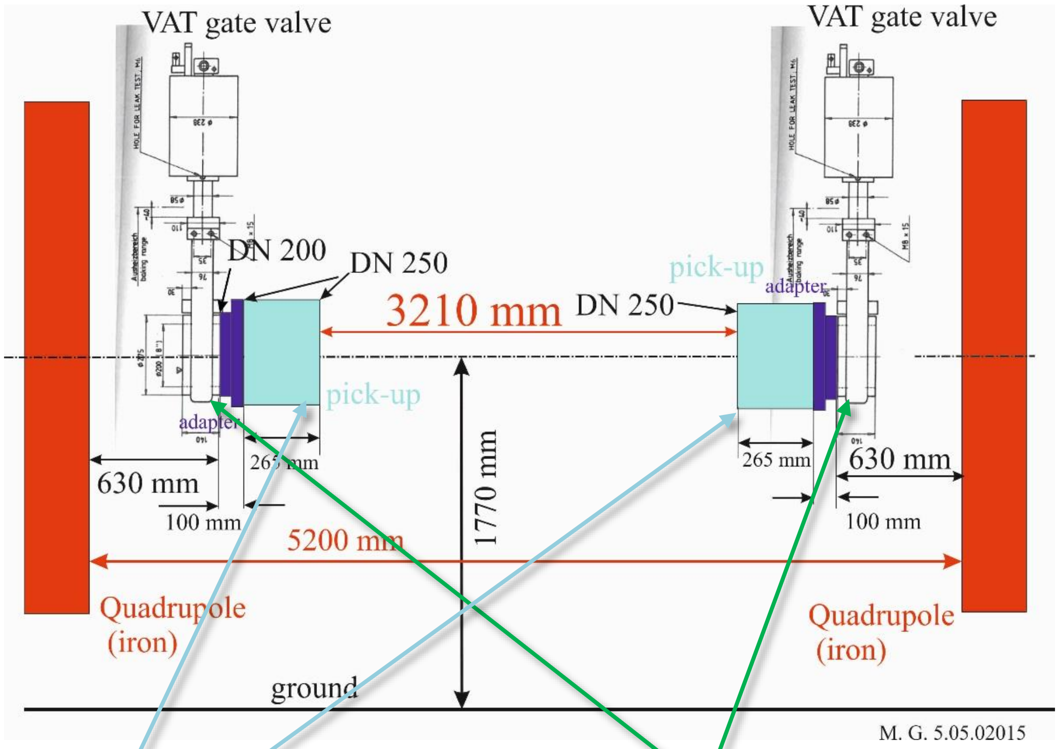
In-ring experimental station

* Experimental setups installed on precision rails, moveable in and out from ring.



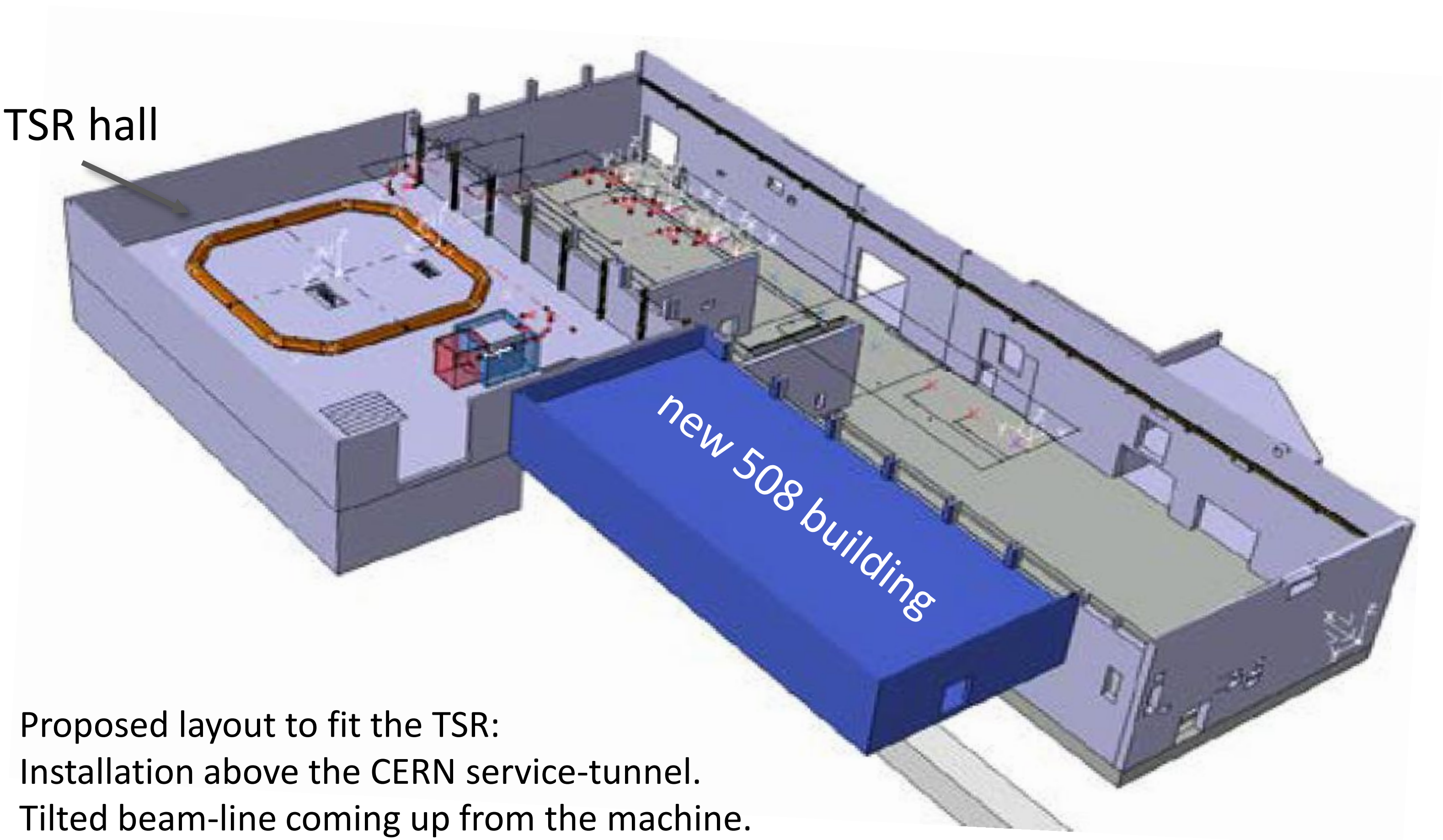


Should (absolutely) avoid removing gate valves

Pick-ups needed for aligning beam correctly at target

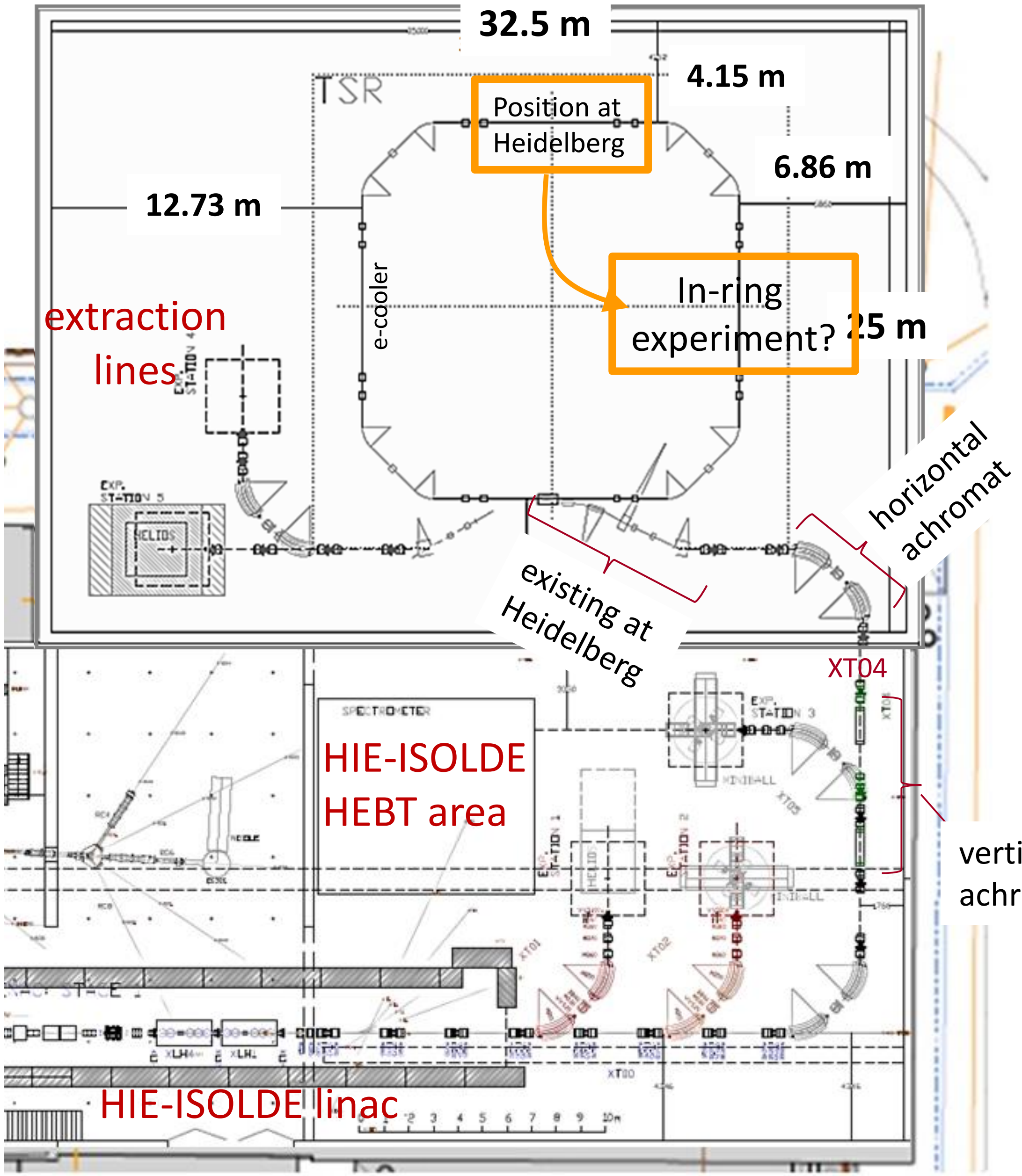
Project progress

Building layout



Proposed layout to fit the TSR:
Installation above the CERN service-tunnel.
Tilted beam-line coming up from the machine.

Beam-line layout



Standard HIE-ISOLDE beam line elements for injection line

Exact position of ring to be defined

Thanks for your attention

…and to Peter for the encouraging support!

Credits to

M. Grieser MPI-K

Experimentalists K. Blaum, P. Butler, R. Raabe, Y. Litvinov, P. Woods…

TSR@ISOLDE collaboration