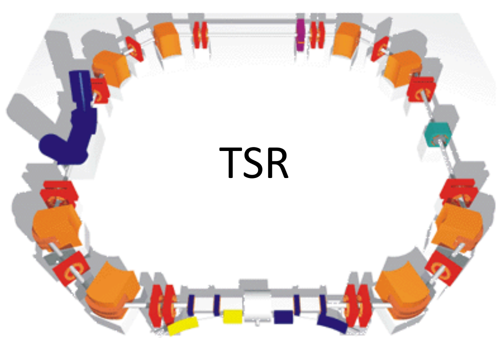
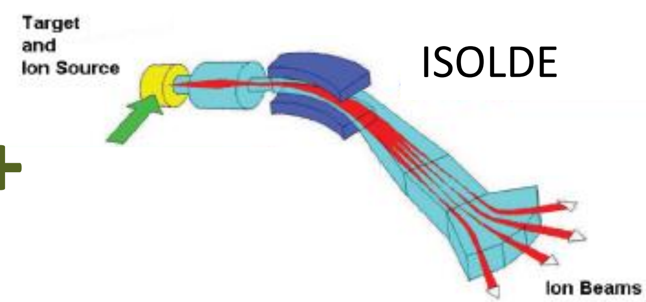
TSR ISOLDE



+



= True?

Fredrik Wenander, ISCC 31/3-2014

High-energy and low-energy storage rings

Easy access to highest charge states

Storage Rings for Physics with Exotic Nuclei

High-energy

- ESR @ GSI
- CSRe @ IMP

- RI-RING @ RIKEN
- CR @ FAIR
- HESR @ FAIR

- NESR @ FAIR
- RESR @ FAIR
- HIAF

Low-energy

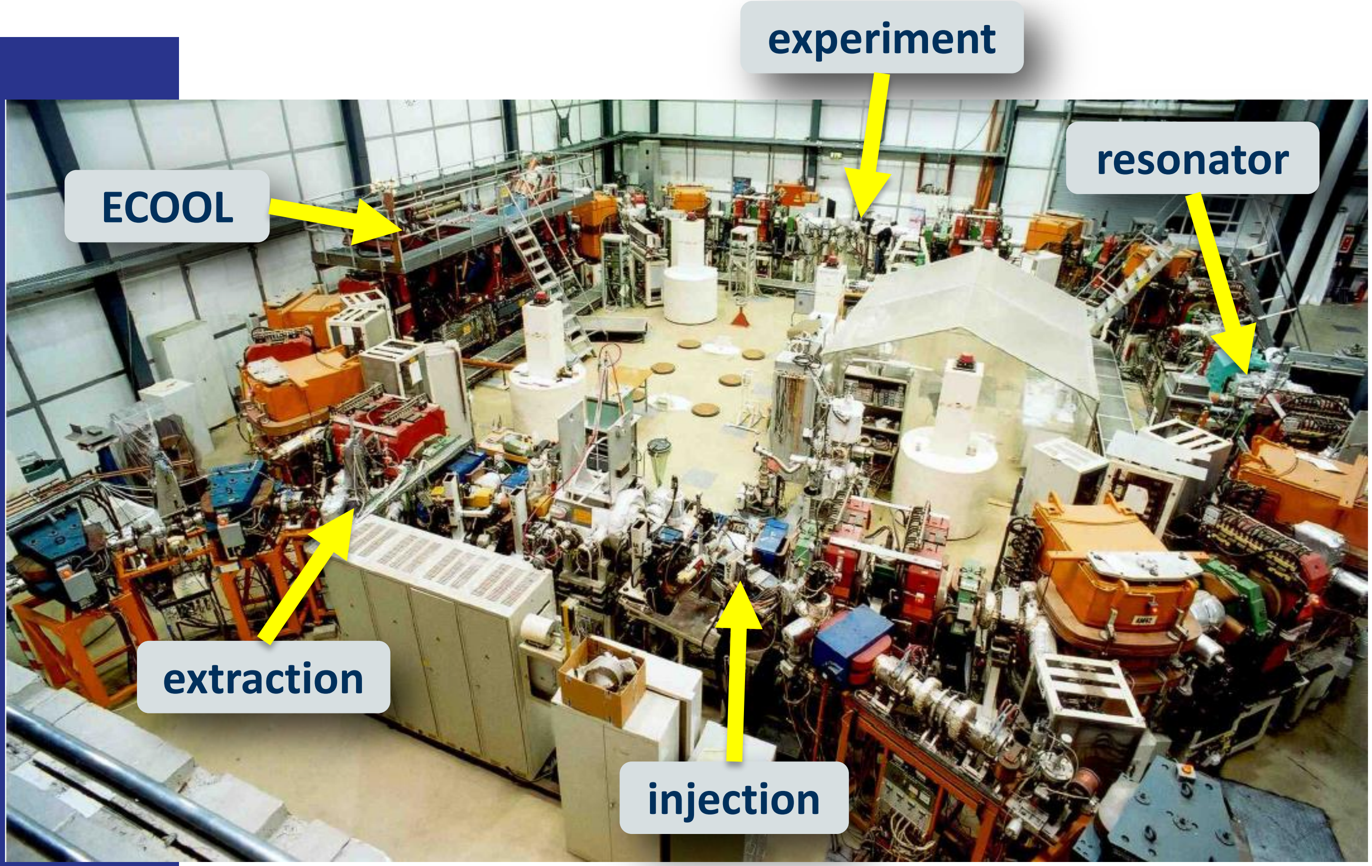
- TSR @ ISOLDE
- CRYRING @ ESR

RI beams originates from opposite side of the energy spectrum

Highly-charged ions at low-energies

Courtesy Y. Litvinov

Test Storage Rings 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)

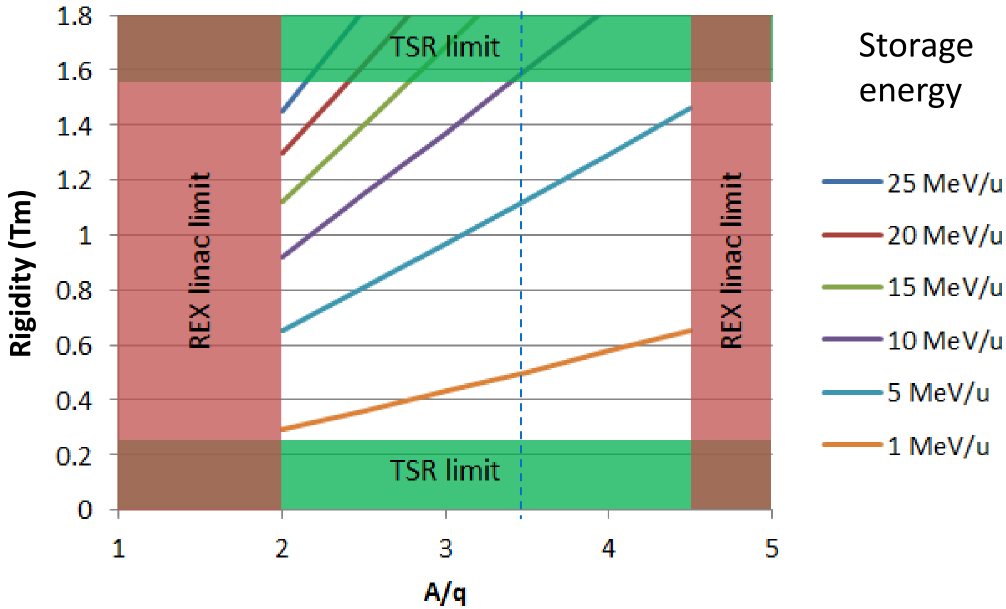
Circumference: 55.42 m
Vacuum: ~few 1E-11 mbar
Acceptance: 120 mm mrad

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

Machine performance

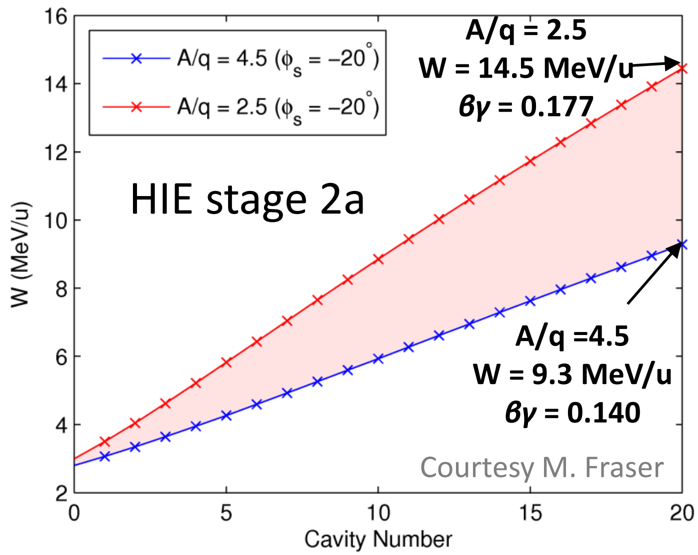
Ring beam energy



TSR magnetic rigidity range: 0.25-1.57 Tm

REX linac 2<A/q<4.5

Lifetime studies and nuclear structure studies using decay at 5 MeV/u



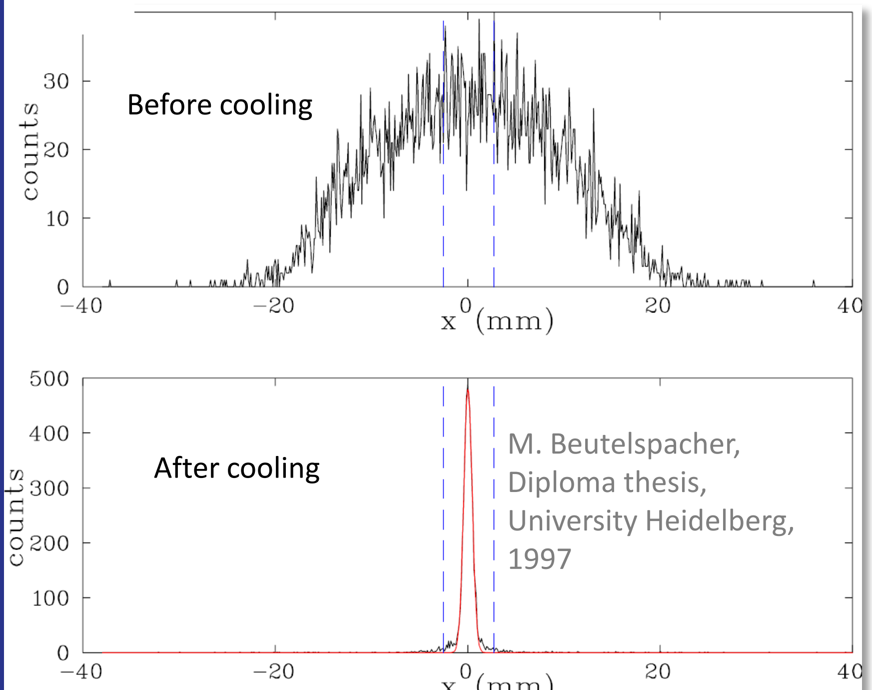
☺ Beam can be accelerated (and decelerated) inside the ring

☹ Takes several seconds though

e-cooling

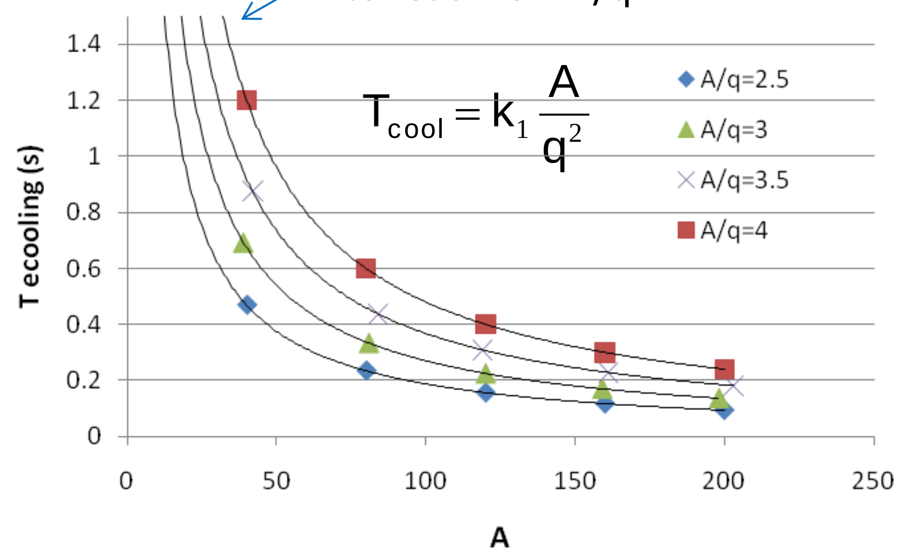
E-cooling needed for:

1. Reducing momentum spread → $\Delta p/p$ ~ 5E-5 (rms); $\Delta p/p$ < 1E-5 (rms) for N<1000
2. Stacking of multi-turn injection
3. Compensate for energy loss in target
4. Reducing beam size



Radial beam extension

Light elements easiest to reach low A/q

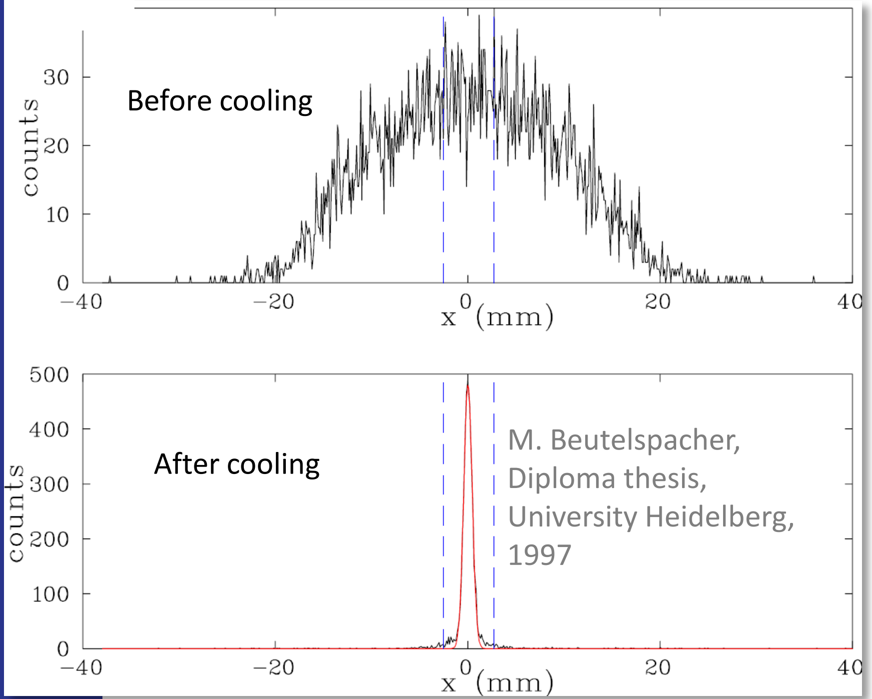


T_{cool} – horizontal cooling time for beam with large diameter

e-cooling

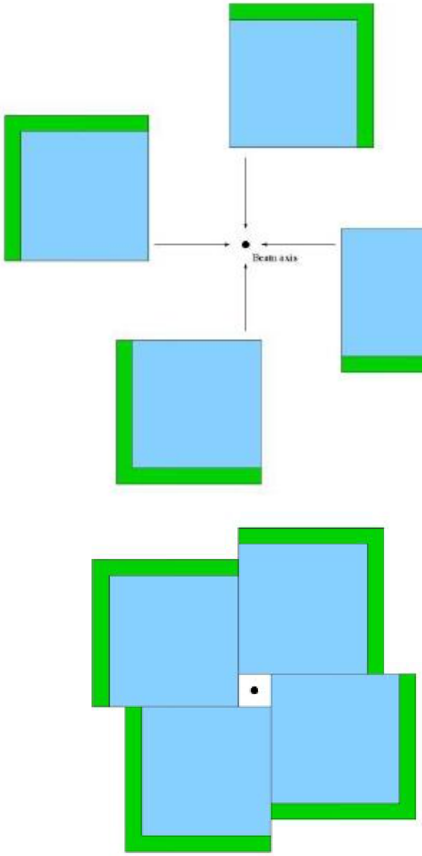
E-cooling needed for:

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



Radial beam extension

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



From T. Davinson and P. Woods

In-ring experiments[1]

* SAS allows for either **electron, gas-jet or no target** to be installed.
* Experimental setups installed on precision rails, moveable in and out from ring.

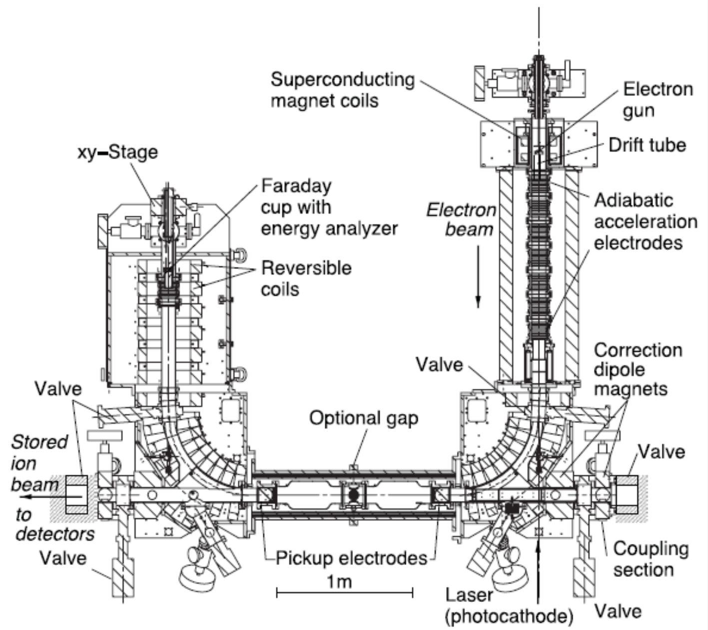


Fig. 83. ETS magnetic and vacuum system in the thermocathode configuration [170].

Electron target section

* Existing, delivered to CERN
* Offers an independent merged cold electron beam dedicated for collision studies

1. See M. Grieser et al., EPJ Special Topics May 2012, vol 207, Issue 1, pp 1-117

In-ring experiments[1]

* SAS allows for either **electron, gas-jet or no** target to be installed.
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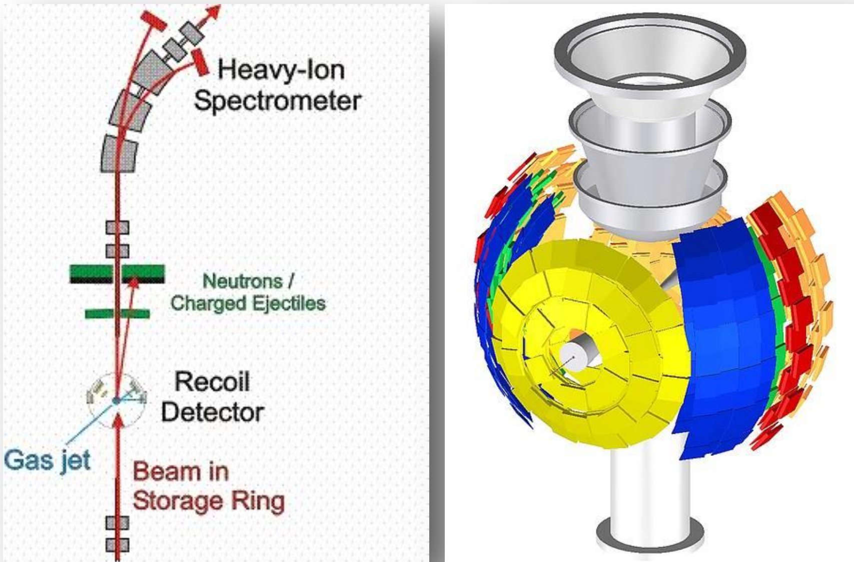


From EXL collaboration

* TSR gas-jet study group being formed

* Offer to borrow UHV detector setup with DSSDs from P. Egelhof

Layout of the new target inlet chamber design with the existing interaction chamber and target dump system for the ESR in Darmstadt.

Gas-jet target

* Not existing, being studied
* Targets with thicknesses of $\sim 10^{14}$ atoms/cm^2 for light gases as H_2, d, ^{3}He and ^{4}He

1. See M. Grieser et al., EPJ Special Topics May 2012, vol 207, Issue 1, pp 1-117

Internal gas target

Miniball target thickness 0.1 to 4 mg/cm^2 -> N_{MB_target} ~ 1E19 atoms/cm^2
(^{3}H-loaded Ti, CD_2, Sn, Pd, Ag etc)

To reach the same reaction rate at TSR:

$$N_{TSR\_target} = \frac{N_{MB\_target}}{T_{lifetime}} \frac{C_{TSR}}{v_{projectile}} \frac{d_{dilution}}{\varepsilon_m}$$

Assume:

$T_{lifetime}$=1 s $d_{dilution}\approx 2$ ε_m=0.8
$v_{projectile}$=0.14·c (10 MeV/u)

=> N_{TSR_target}=3E13 atoms/cm^2

Integrated residual gas thickness much smaller
(55.42 m, 5E-11 mbar) => 6.7E9 atoms/cm^2

* Target types: H_2 or He

* To address:
Interaction length ~ 5 mm
ideally 1 mm
Pressure around target

Miniball	TSR
e.g. C_xH_y	Pure gas

Advantage: target purity

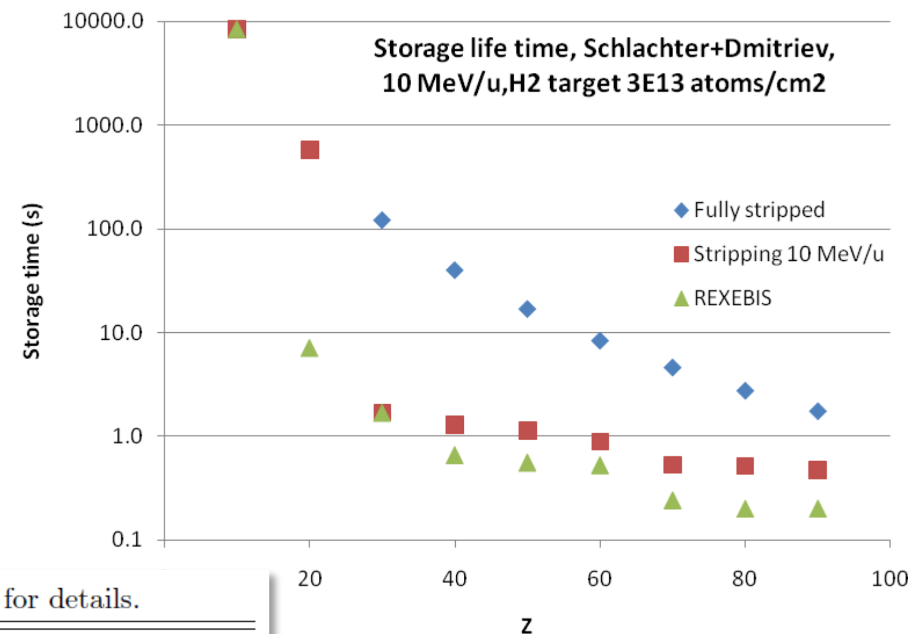
NB. Can't use foils in the ring!

Beam life times

Survival times

* Coulomb scattering, electron capture and stripping
* Residual gas, electrons in the cooler and gas target

Internal gas target



M. Grieser et al., EPJ Special Topics May 2012, vol 207, Issue 1, pp 1-117 ↓

Table 1: Parameters of beams circulating in the TSR. See text for details.

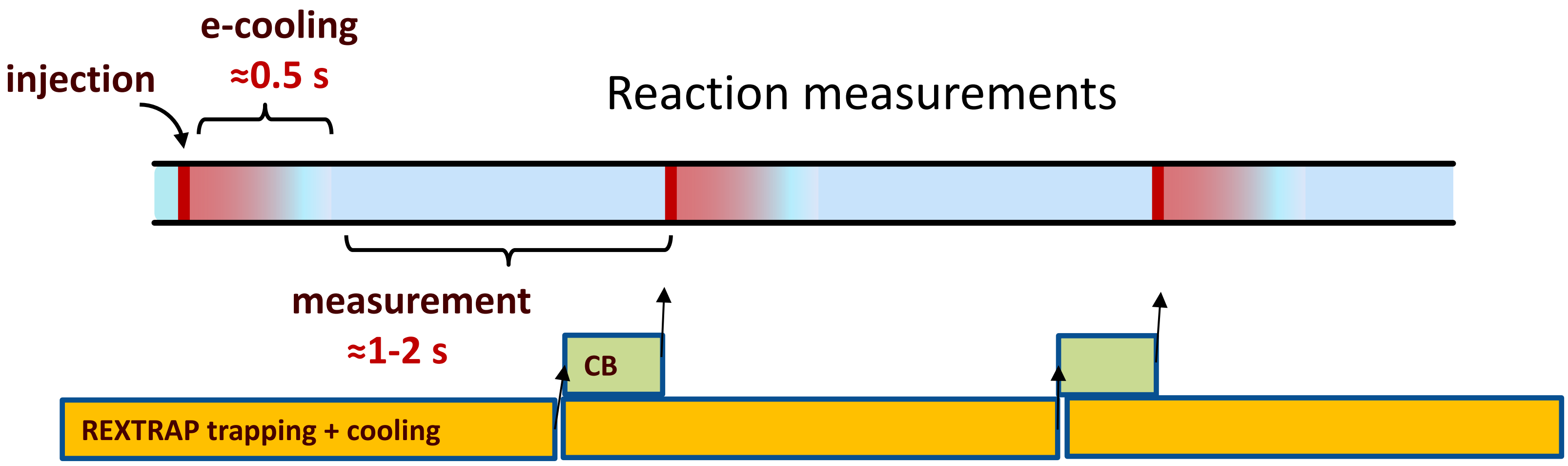
Ion	Nuclear lifetime	Energy (MeV/u)	Cooling time	Beam lifetime in residual gas	H_2 target (atoms/cm^2)	Beam lifetime in target	Eff. target thickness (μg/cm^2)
^{7}Be 3+	(53 d)	10	2.3 s	370 s			
^{18}F 9+	100 m	10	0.7 s	280 s	1×10^{14}	236 s	31000
^{26m}Al 13+	6.3 s	10	0.5 s	137 s	5×10^{14}	23 s	4200
^{52}Ca 20+	4.6 s	10	0.4 s	58 s	5×10^{14}	9.6 s	3000
^{70}Ni 28+	6.0 s	10	0.25 s	30 s	2×10^{14}	12 s	1600
^{70}Ni 25+	6.0 s	10	0.3 s	26 s	2×10^{13}	2.1 s	60
^{132}Sn 30+	40 s	4	0.4 s	1.5 s	1×10^{12}	1.4 s	1.2
^{132}Sn 45+	40 s	4	0.2 s	1.4 s	5×10^{12}	1.6 s	7
^{132}Sn 39+	40 s	10	0.25 s	7.4 s	2×10^{12}	3.6 s	9.5
^{132}Sn 45+	40 s	10	0.2 s	10 s	5×10^{13}	1.3 s	90
^{186}Pb 46+	4.8 s	10	0.25 s	4 s	2×10^{12}	1.5 s	4
^{186}Pb 64+	4.8 s	10	0.13 s	5 s	1×10^{13}	1.7 s	20

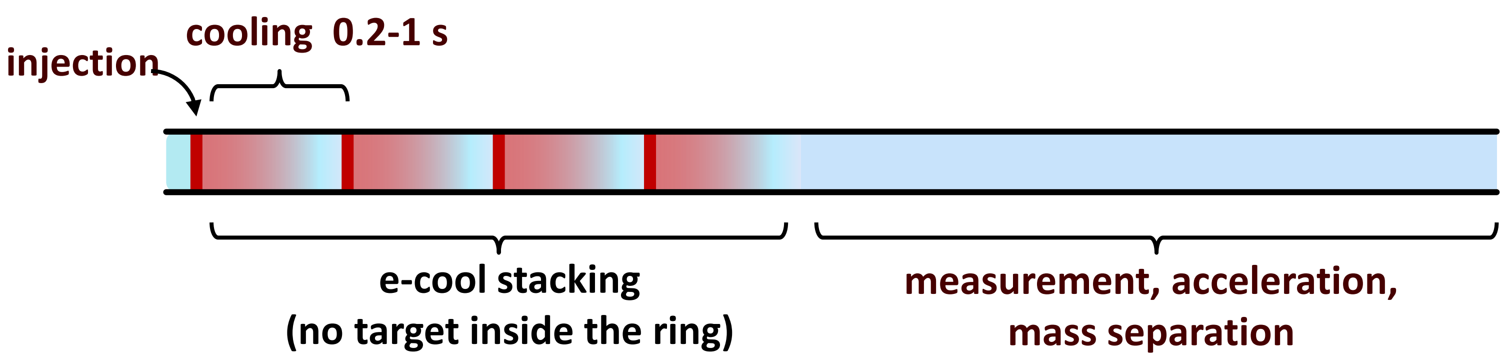
Fully stripped ions
-> improved lifetime

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

~100 ug/cm^2 for direct target

Injection rate

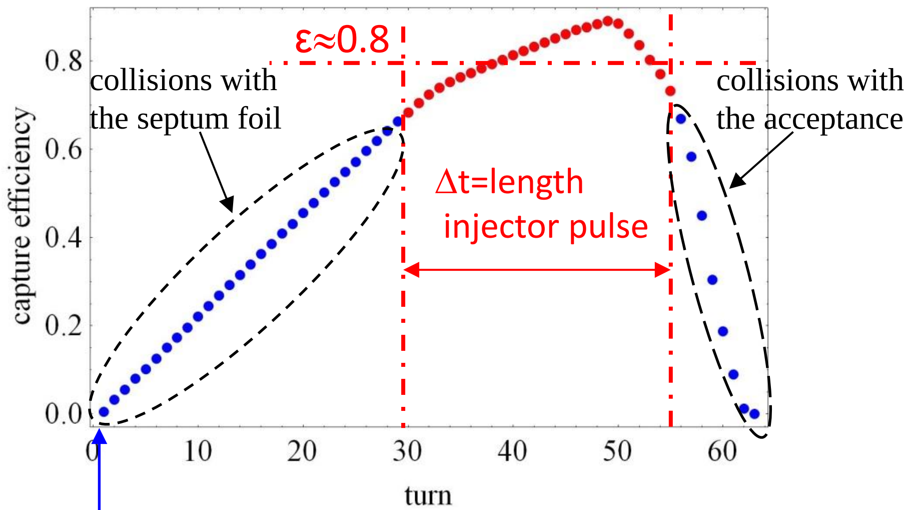




Based on R. Raabe presentation

Ring injection time

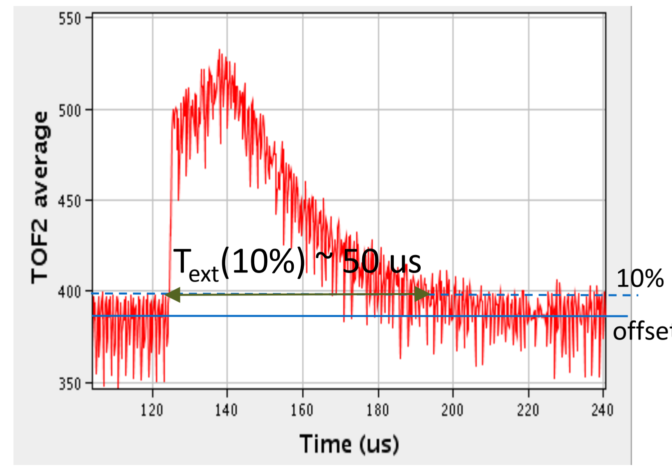
- ***High injection efficiency of outmost importance***
- ***Multi-turn injection***



closed orbit at the septum foil

$\Delta t \approx 25$ turns
typically ≈ ***33 μs*** at 10 MeV/u

Input from M. Grieser



TOF after REX charge breeder

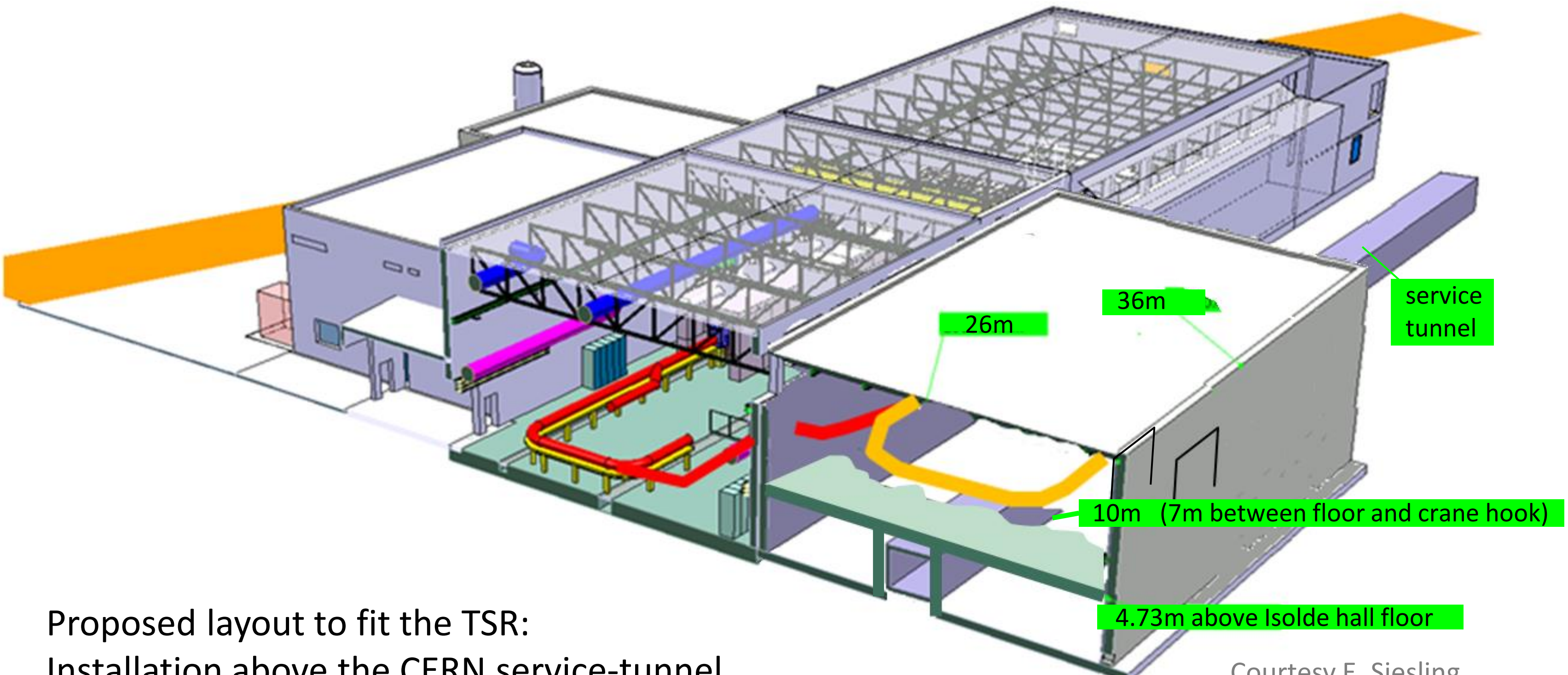
Adapt EBIS $T_{extraction}$ to fit beam pulse into transverse acceptance

$$T_{extraction} = N_{turn}\frac{C_{TSR}}{v_{injection}} \approx \frac{A_{TSR\_geo}}{\varepsilon_{REX\_geo\_x}}\frac{C_{TSR}}{v_{injection}} = \frac{A_{TSR\_geo}}{\varepsilon_{REX\_norm}}\cdot\frac{C_{TSR}}{c}$$

Beam-line layout

Building layout

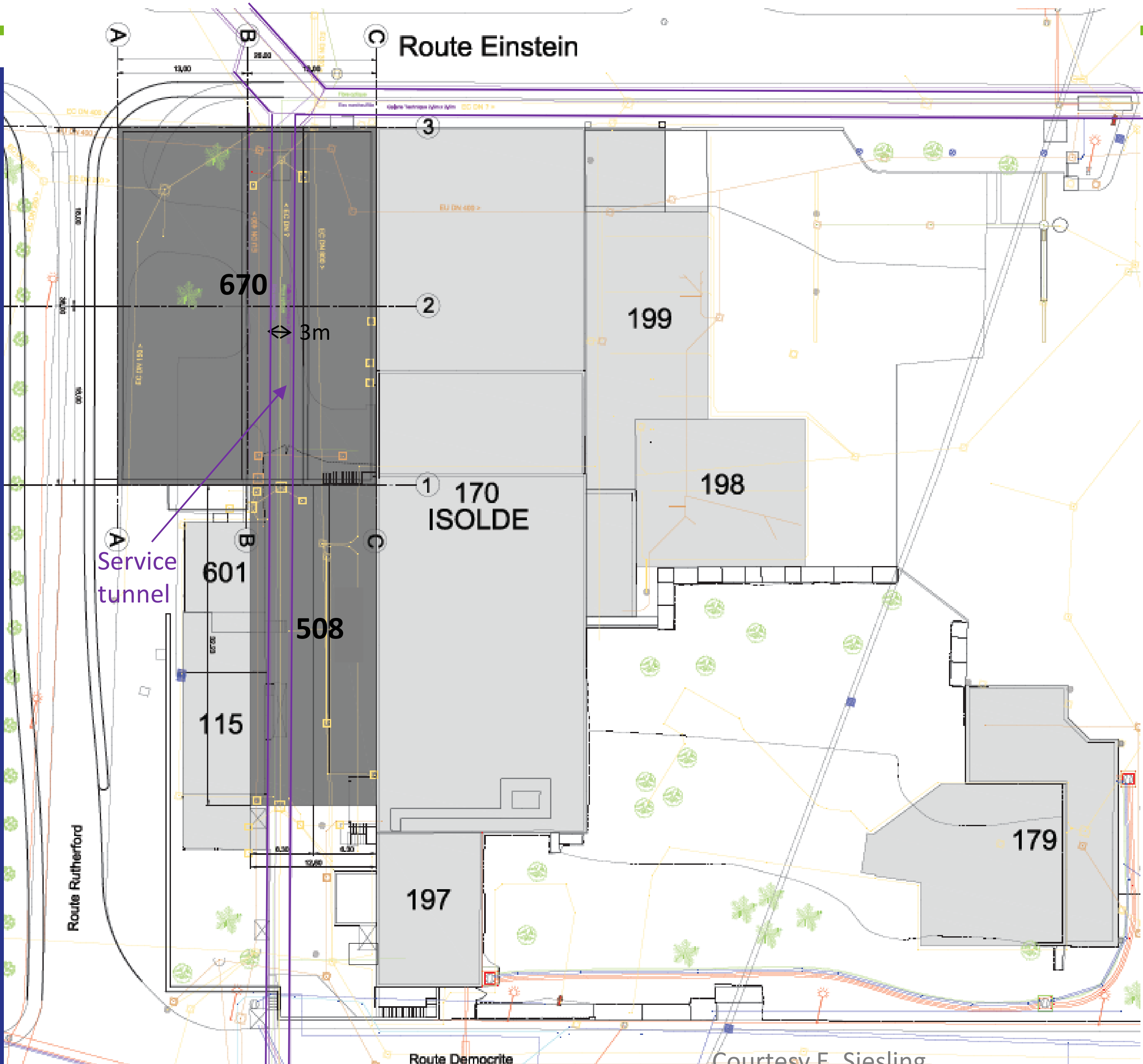
Presently at MPI-K, Heidelberg, a large hall is housing the TSR with enough space around it for experiments and equipment that need to be close to the ring. The basement underneath the ring is used for power supplies and other necessary equipment.



Courtesy E. Siesling

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

Building layout



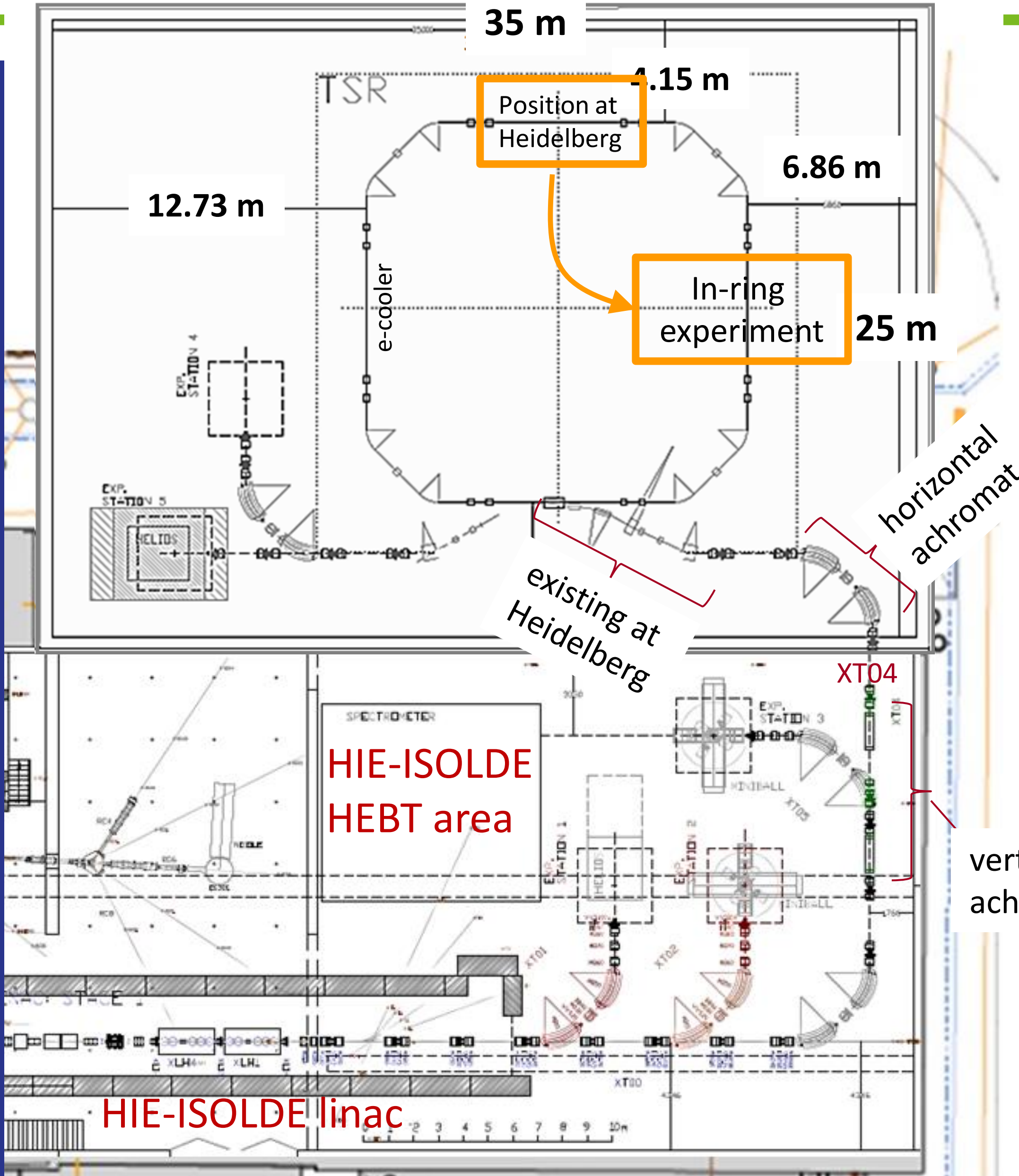
TSR building 670:
Taken in account at the construction of the new user building 508.

Water station:
Water station and cooling tower to be integrated in the ISOLDE area.

Roads:
Adaptation of the Route Rutherford and corner with Route Einstein. Move of the ramp giving access to the premises to the Route Democrite side.

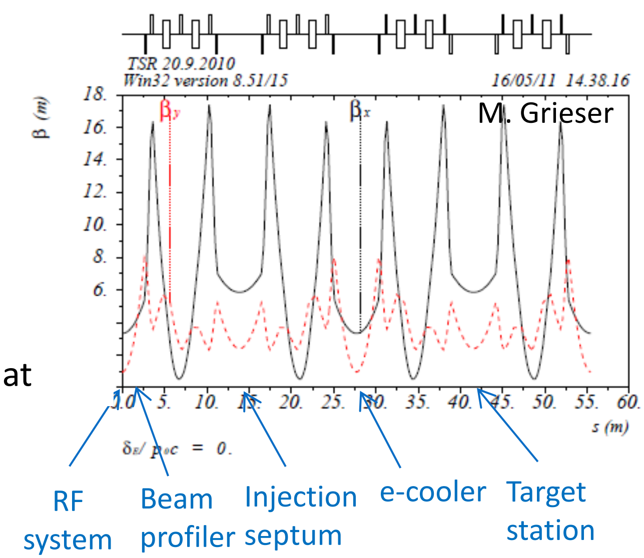
CERN service tunnel:
Construction above the tunnel creating two separate basements to house TSR equipment racks and power supplies.

Beam-line layout



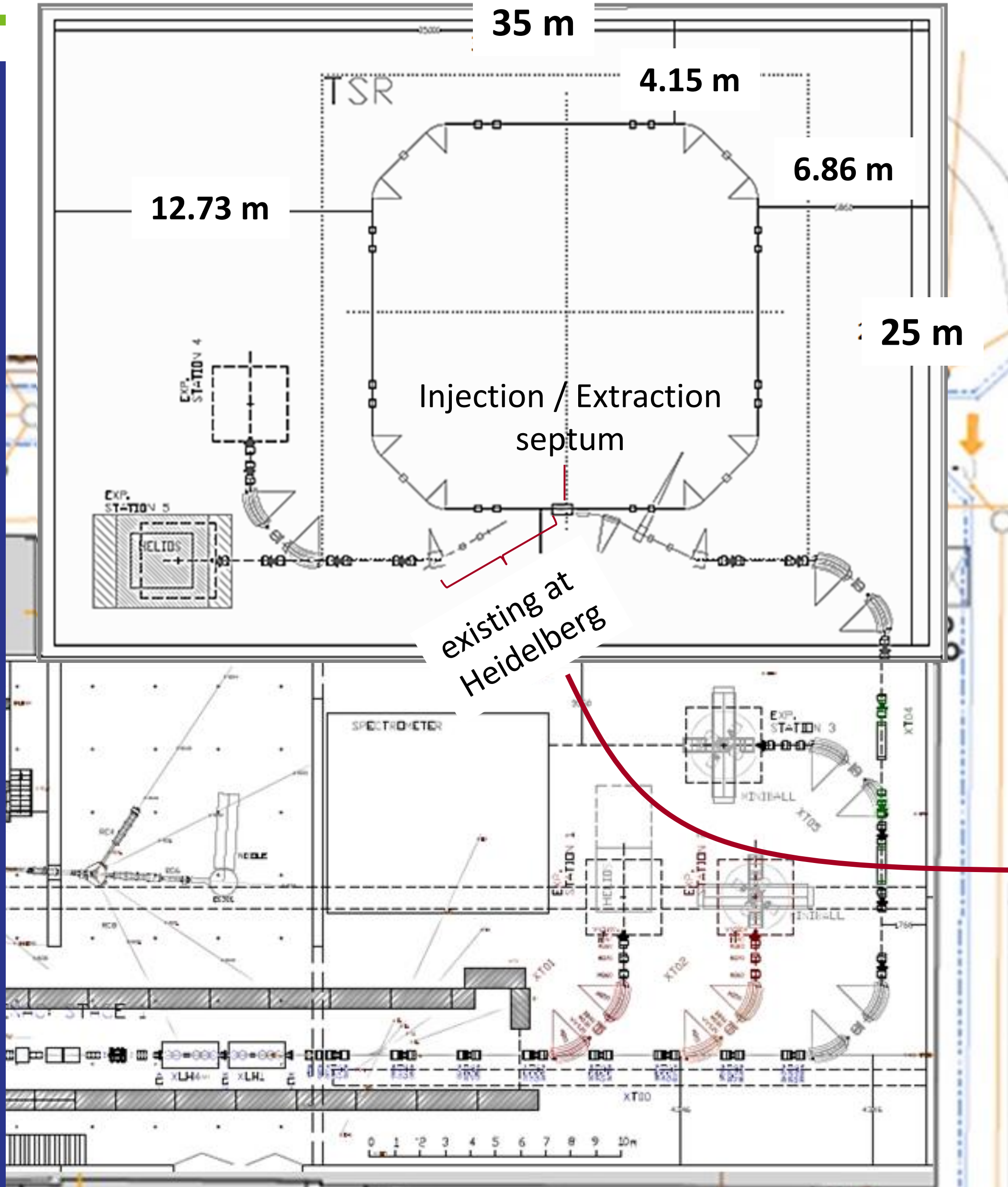
1. Achromatic injection line
   * Links HIE-ISOLDE to TSR ring via XT04
   * Considers HIE-ISOLDE and TSR floor level difference of 4.73 m

2. Standard HIE-EBIT elements



Heidelberg layout

Extraction lines

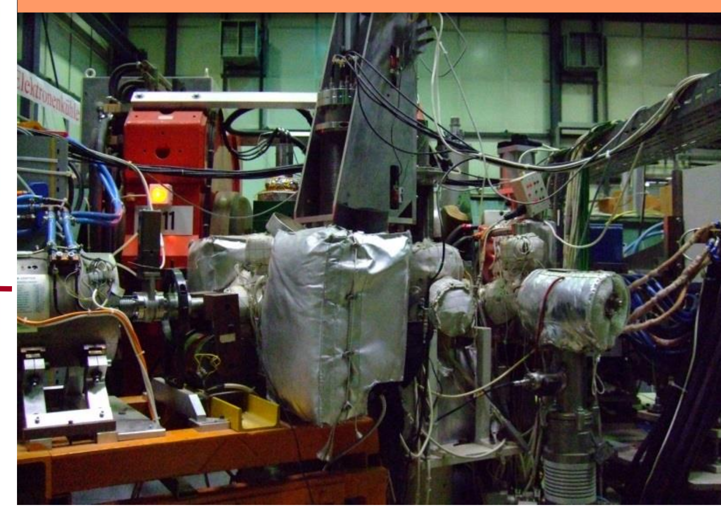


* Tentative layout for two experimental stations.

* Tolerated stray magnetic field at ring from experiments
$\int B_{stray} ds < 10^{-4}\ Tm$

* Beam optics study initiated.

**** Awaiting feedback from physics community.***



CERN input: A. Parfenova, D. Voulot, B. Goddard, M. Fraser

ISOLDE

Charge breeder upgrade

Charge states out of REX

Benefits from high q

- Rigidity TSR
- Storage lifetimes
- Cooling times
- Experiments

Charge breeding times for a selection of elements of relevance for TSR@ISOLDE experiments

Ion	Z	q	A/q	Breeding time (ms)
^{7}Be	4	3	2.33	20
^{18}F	9	9	2	100
^{70}Ni	30	25	2.33	350
^{132}Sn	50	39	3.38	700 *
^{182}Pb	82	53	3.43	1000 *
^{182}Pb	82	64	2.84	EBIS upgrade needed

* to be tested

☺ REXEBIS charge breeder capable of producing sufficiently low A/q (or beam rigidity for < 10MeV/u) for most elements

TSR@ISOLDE implications for charge breeder

Experiment	Species	State	Charge breeder requirements
Astrophysical p-process capture	Zn through* Yb	bare	E_e~150 keV, J_e ~1-2x10^4 A/cm^2 ***
Atomic effects on nuclear half-lives	Cu Sn Tl **	H/Li-like	E_e~100 keV, J_e ~1-2x10^4 A/cm^2 ***
DR on exotic ions	Lu U Th	Li/Na-like	E_e~100 keV, J_e ~1-2x10^4 A/cm^2 ***
Atomic data for supernova explosions	Fe Si	1^+ to H-like	Not limiting any charge state
Atomic data for fusion research	W	q>22	Not limiting till H-like

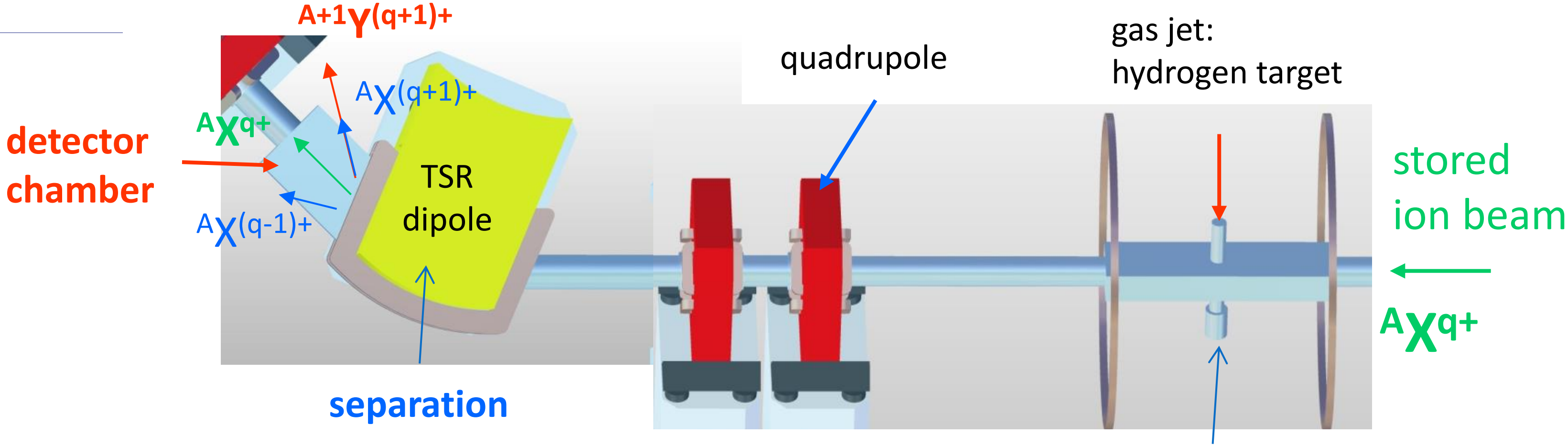
Courtesy A. Shornikov

* After Z=60 the abundance of bare state will drastically drop

** Only Li-like Tl with acceptable abundance

*** Assumed an injection repetition rate of 1 Hz

Pick up reaction at TSR



Reactions

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

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

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

Issue

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

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

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

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

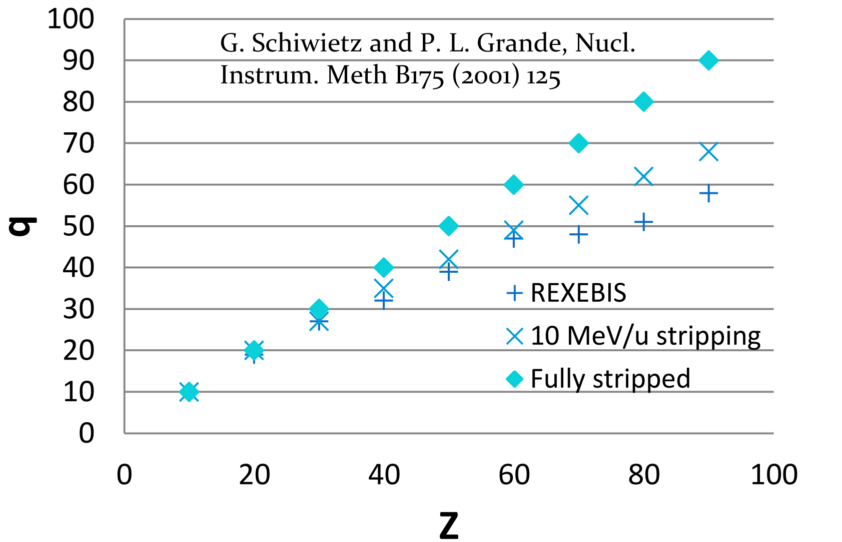
Dead-time /pile-up due to high flux $^{A}X^{(q+1)+}$

Charge states out of REX

☹ But some experiments might require:

* Fully stripped to Z~60

* Few-electron system, e.g. for Th/U

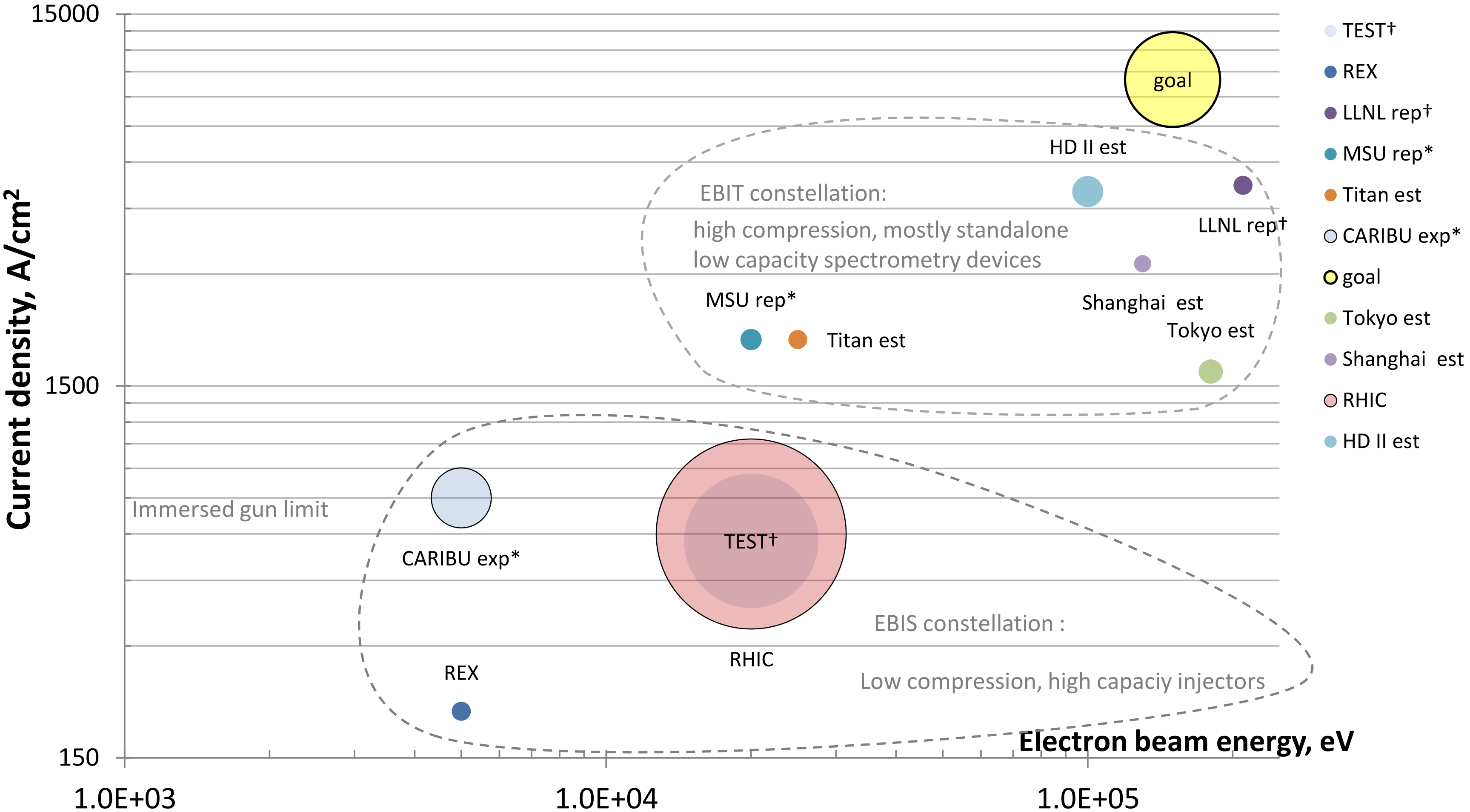


Estimated attainable charge states in REXEBIS and after stripper foil as a function of ion Z

Design parameters HIE-ISOLDE / TSR@ISOLDE breeder

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

No such breeders available



rep - reported, est - estimated, * - in commissioning phase † - discontinued

Bubble size represents electron current

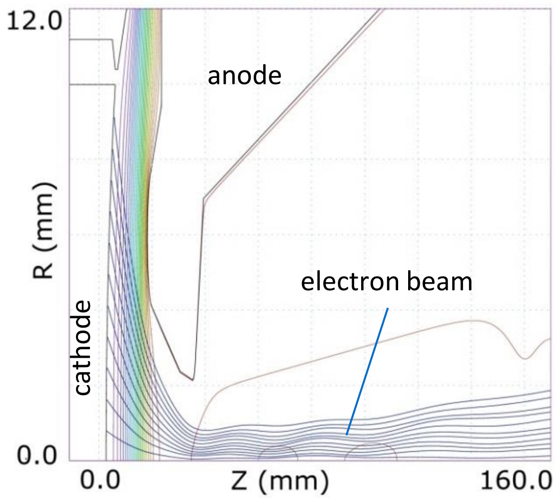
Courtesy A. Shornikov

How we are addressing them

High Energy Current and Compression (HEC²) electron gun project
Requirements compared to simulations

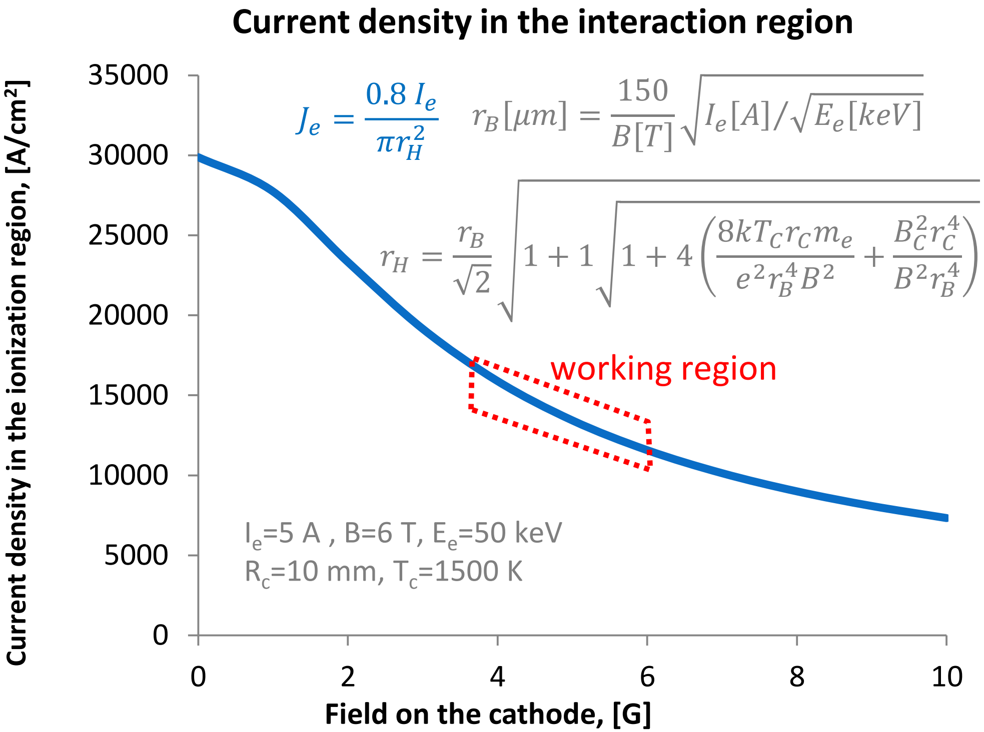
Matching two focusing systems

Very laminar electron flow,
high electrostatic compression



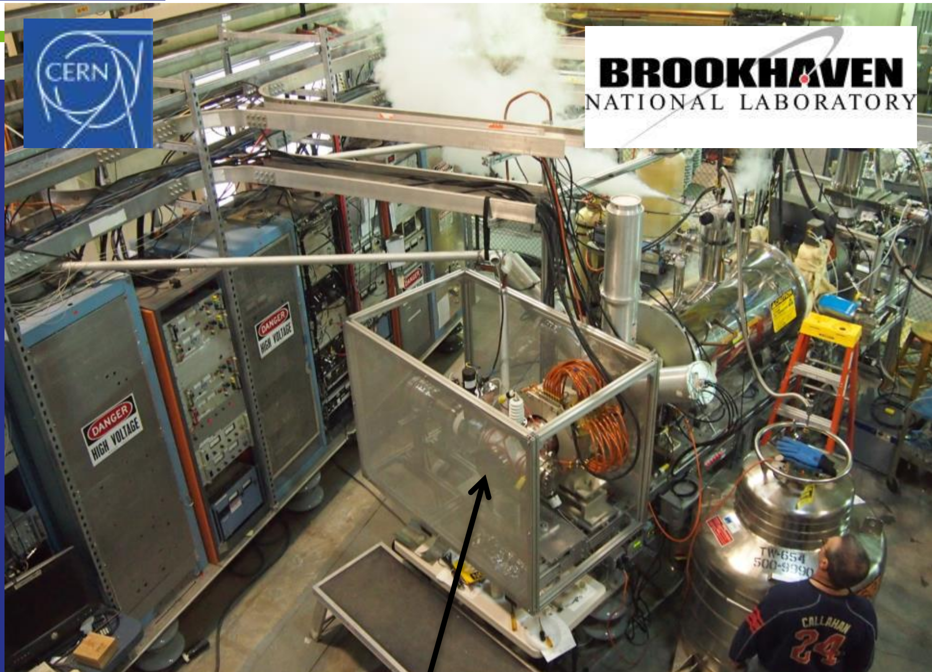
A. Pikin, E. N. Beebe, and D. Raparia, Rev. Sci. Instr. 84 033303 (2013)

Influence of B field leaking

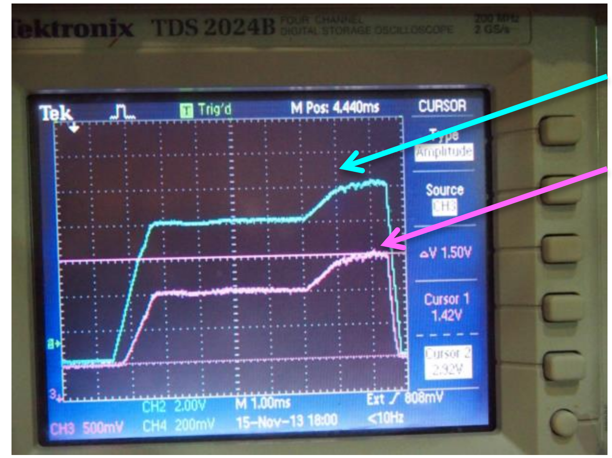


HEC² designed at BNL is now a collaborative effort between BNL and CERN

HEC^2 prototype tests at BNL



First beam time – 08.11.2013-15.11.2013



Anode voltage

Extracted current (1V=1A)

NB: pulsed electron beam

Prototype gun design by BNL, built by CERN being tested at BNL by joint team at BNL TEBIS

Scenario	E_e, keV	I_e, A	J_e, kA/cm^2
HEC^2 ultimate spec	150	5	10-20
Achieved in 1-st run	30	1.54	tba
REXEBIS	5	0.4	0.2

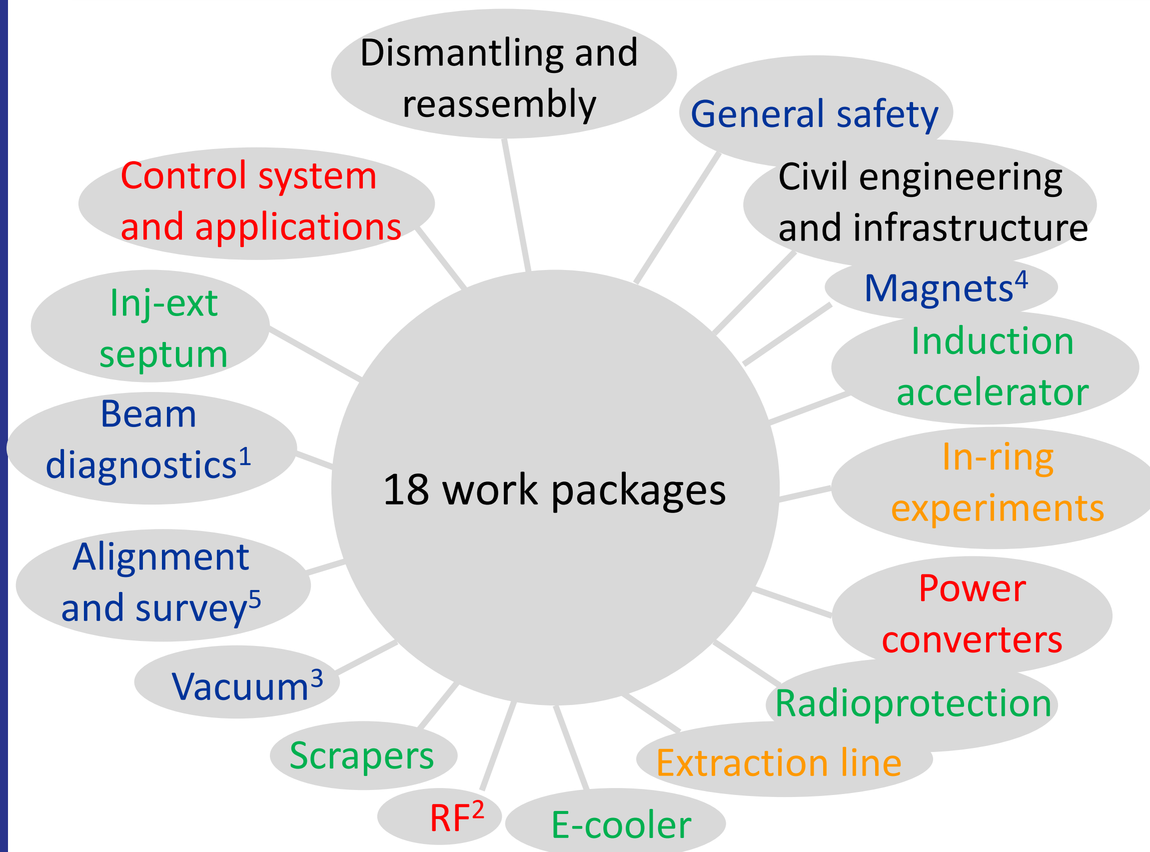
* These activities supported by HIE-ISOLDE design study will continue in 2014

* Hopefully a continuation within ENSAR2

Technical integration study

Technical integration study

Two approaches 1. CERN homologation (full-fledged ‘standardization’)
2. Keep-system-as-is (low-budget option with minimal changes)



1. Obsolete electronics
   Improve sensitivity
2. Change for Finemet® type
3. Exchange bakeout system
4. Improve electrical safety
5. External targets on elements

Red: fully replaced
Blue: complemented and improved
Green: accepted or minor upgrades
Orange: not part of costing

Recommendations by CERN specialists

Technical integration study - conclusions

- ✓ The radiological concern of importing the ring is minimal.
- ✓ Well advanced civil engineering plan with associated infrastructure exists.
- ✓ No technical show stoppers for the implementation – standard solutions identified.

CERN integration proposal

a. First cost and manpower estimate believed to be conservative. *However, no contingency included.*

b. Most CERN groups have insisted on hardware changes and CERN standardization and discourage a 3 years transition period.

Total cost and manpower for transfer and integration into a CERN facility:

15.2 MCHF   27.5 FTE (man year)

Keep-system-as-is

a. Would need to keep all subsystems as they are since many are interlinked with the control system.

b. Would have limited / no support by CERN groups; longer dependence on MPIK Heidelberg.

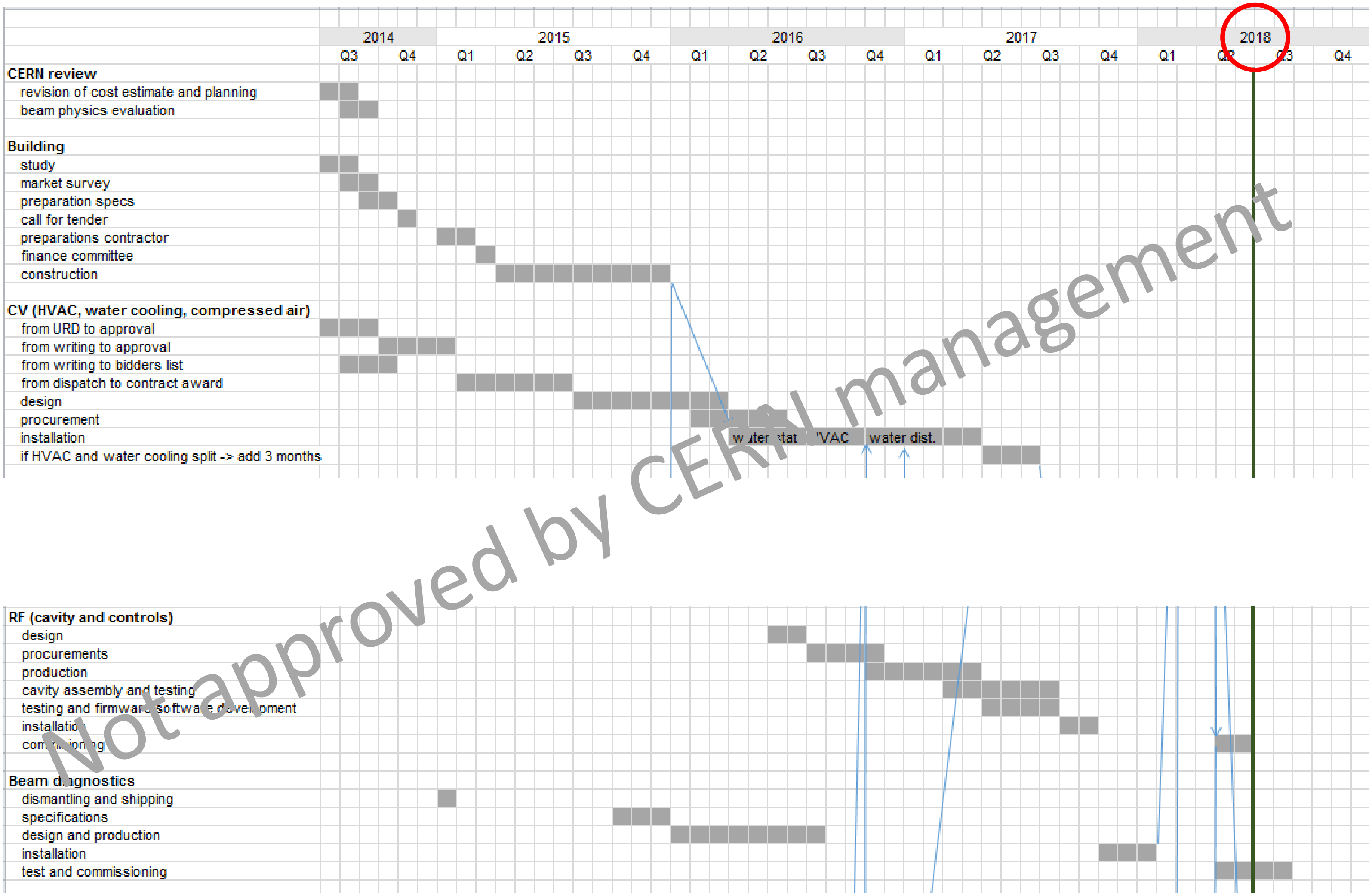
The approximate cost and manpower need for the Keep-system-as-is scenario are:

11.8 MCHF   17.1 FTE (man year)

The cost saving might appear low. Reasons:
** The main cost drivers are the injection line, buildings and infrastructure.*
** Some spares, complementing parts and replacement parts are absolutely necessary.*
** Includes the mandatory electrical protection of magnets connections.*
** Includes sensitivity improvement of the beam diagnostics.*

NB. The figures have not been considered the CERN management

Tentative implementation schedule



Not approved by CERN management

excerpt from 20140328

Past, present and future

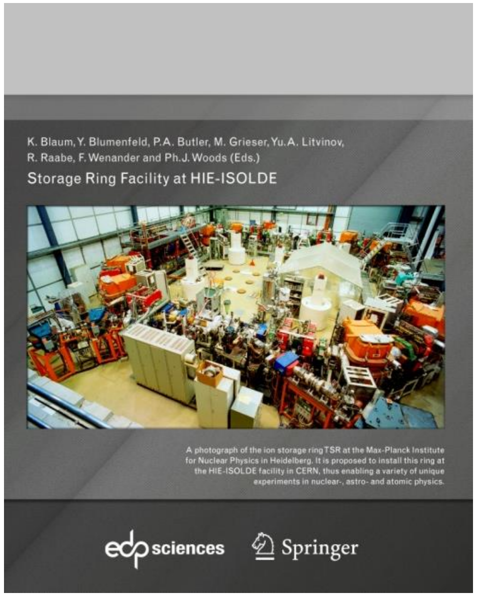
.....

* LoI to the ISOLDE and Neutron Time-of-Flight Committee

  http://cdsweb.cern.ch/record/1319286/files/INTC-I-133.pdf

* TSR at ISOLDE technical design report

  M. Grieser et al., EPJ Special Topics May 2012, vol 207, Issue 1, pp 1-117



* 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

* TSR@ISOLDE workshop at CERN 14/2-2014 – focus on experiments

* Tentative planning for the installation of TSR@ISOLDE handed over to the BE department leader 28/3-2014

Plain sailing?

Operational complexity

ISOL + REX low energy stage + RT + SC LINAC + ring injection + e-cooling + storage

challenges

2 s holding time (or longer) in REXTRAP

< 30 us extraction from REXEBIS + efficient injection

cooling time -> sets lifetime limit

life-time issues

* All for very low beam intensities compared to Heidelberg – not even visible?
* All steps involves unavoidable losses

Optional (complexity)

Gas-jet target

Slow extraction to external setups:

* even longer holding time in REXTRAP required
* will the good longitudinal energy spread be conserved due to RF excitation?
* efficiency <85%

NB! Different from:
rings at in-flight facilities
rings with stable beam

Experimental challenges

Type of experiment	Beam purity	E-cooling time	Efficiency	Storage life-time	Charge breeder upgrade	Detectors	Gas-jet size	Beam emittance
Half-lives of 7Be in different atomic charge states	✓ 1							
In-flight beta-decay of light exotic nuclei		✓ 2a	✓ 2b			✓ 2c		
Laser spectroscopy of rare isotopes with the TSR		✓ 3						
Capture reactions for the astrophysical p-process		✓ 4a		✓ 4b	✓ 4c			
Nuclear structure through inelastic scattering and transfer reactions		✓ 5a		✓ 5b	✓ 5c optional	✓ 5d	✓ 5e	
External spectrometer			✓ 6a					✓ 6b
Long-lived isomeric states					✓ 7			
Atomic effects on nuclear half-lives					✓ 8			
Di-electronic recombination on exotic ions					✓ 9			

1. 7Li contamination from ISOLDE
   14N6+ contamination from REXEBIS

2a. life times: 6He 0.8 s (no e-cool stacking)
8He 119 ms (no e-cool stacking)
Be 13.8 s (e-cool stacking)
2b. REX efficiency for 6He is sub-percent. In addition impossible to store in REXTRAP for long bunching. 8He same problems.
2c. if no e-cooling, force to resolve keV superimposed on MeV

3. e-cooling time set lower life-time limit

4a. life-time needs to be longer than cooling time
4b. electron pick-up in gas-jet limits the storage lifetime
4c. fully stripped ions required

5a. e-cooling time set lower life-time limit
5b. electron pick-up in gas-jet limits the storage lifetime
5c. Higher charge states improve storage life-time
5d. UHV detectors moved out from beam during beam injection
5e. difficulty to arrange well-defined target vertex

6a. losses during injection/extraction
6a. if CW requested, long holding time in REXTRAP required
6b. increased long. momentum during extraction?

7. very high charge state required for Schottky detection

8. very high charge state required for Schottky detection
experimental request for H- or Li-like ions

9. experimental request for Li- or Na-like ions

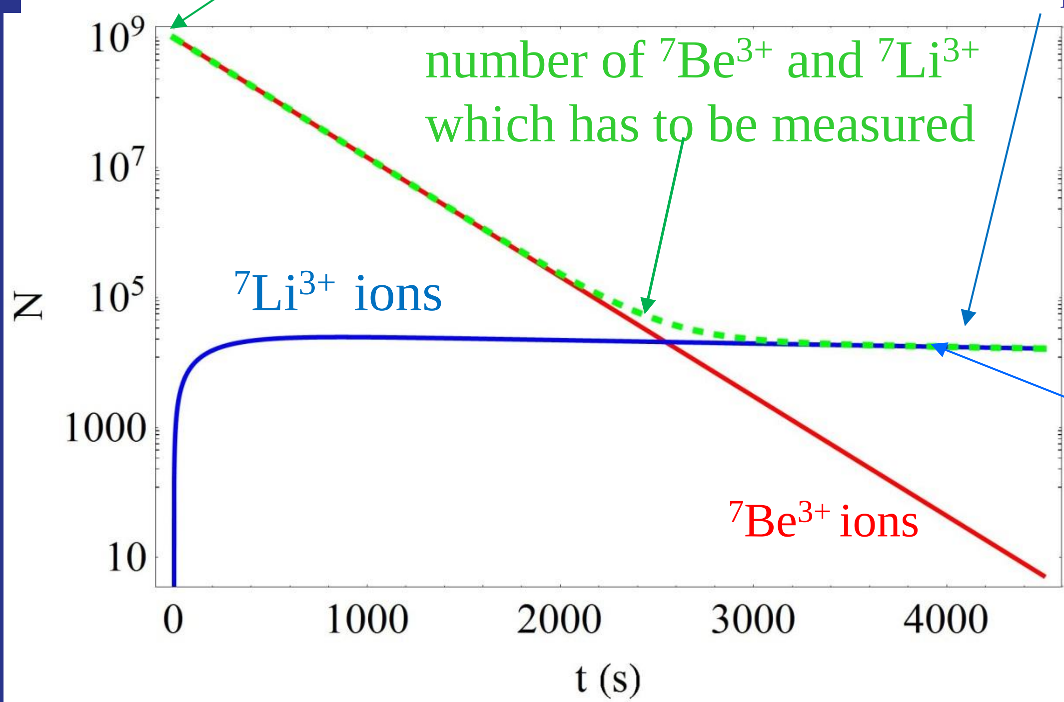
Lifetime determination of $^7Be^{3+}$

Accumulate 10^9 ions:

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

filling time ≈ 30 s

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



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

decay lifetime

$N_{Li}=17400$

Slide from M. Grieser

remark: 10^9 $^7Be^{3+}$ ions is below the **space-charge limit:** $N=5.8\cdot10^9$

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

General conclusions

* The technical aspects of the integration have been studied. No technical showstoppers identified.

* Cost and manpower analysis of the integration has been performed.

* Request feedback from the user community about the layout of the extraction lines and experimental setups.

* Tests of charge breeder upgrade on-going. Concept promising but a *long* way to go.

* Operational and experimental difficulties shouldn’t be underestimated or ignored at this stage.

Personal plead

To continue the HEC2 studies (REXEBIS upgrade) I need:

- work affiliation for A. Shornikov from start of ENSAR2 (1/3-2015 ?) for 30 months
- bridging of his contract between fellowship (terminates 31/12-2014) and start of ENSAR2 (1/3-2015?)

Firm confirmation needed by mid April for me to pursue ENSAR2 proposal