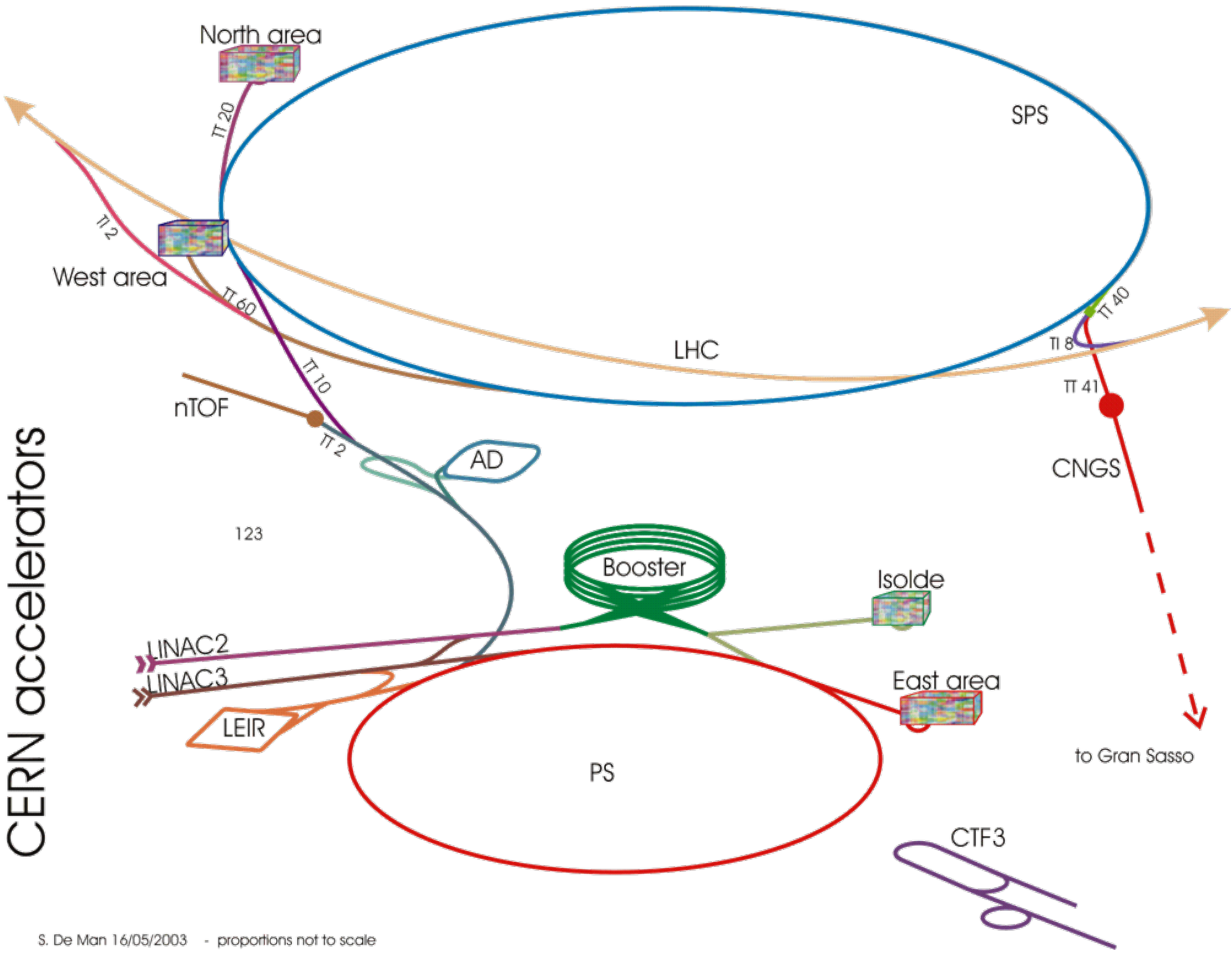
REX-ISOLDE: the radioactive ion beam post-accelerator at CERN

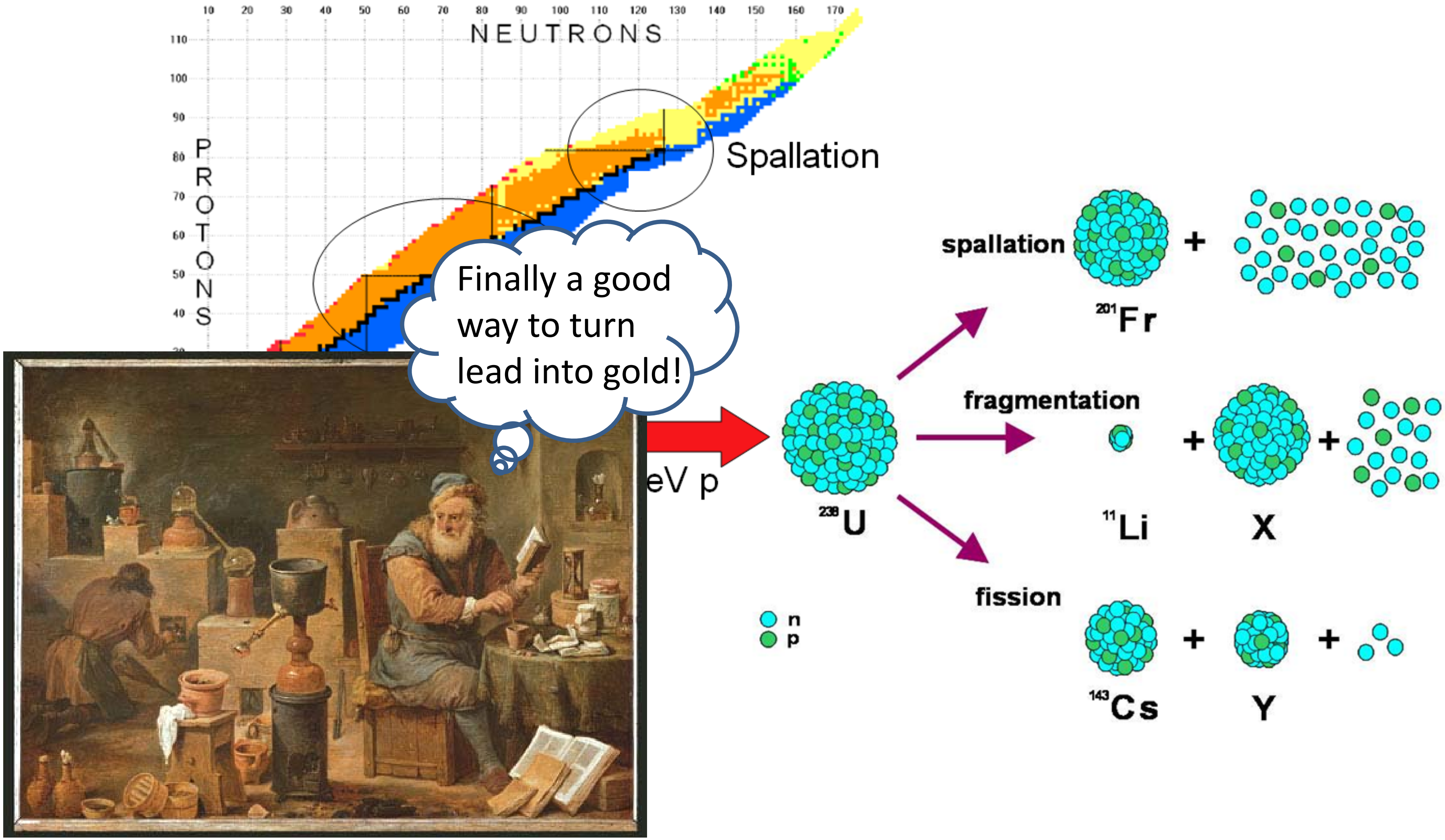
- **REX and ISOLDE**
- **Operational experience - Beam purification techniques**
- **HIE-ISOLDE and projects**

D. VOULOT, *CERN*

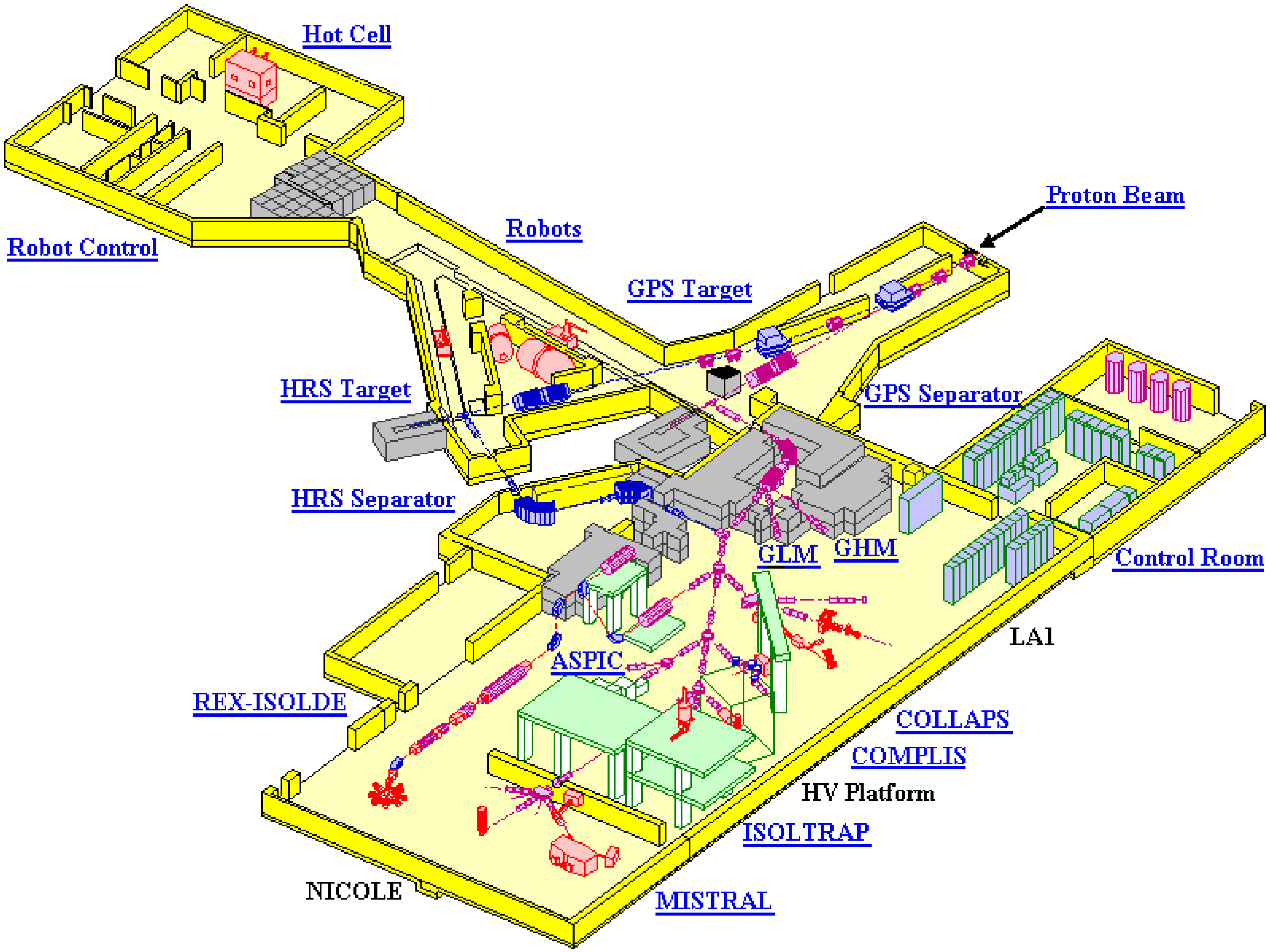
ISOLDE at CERN



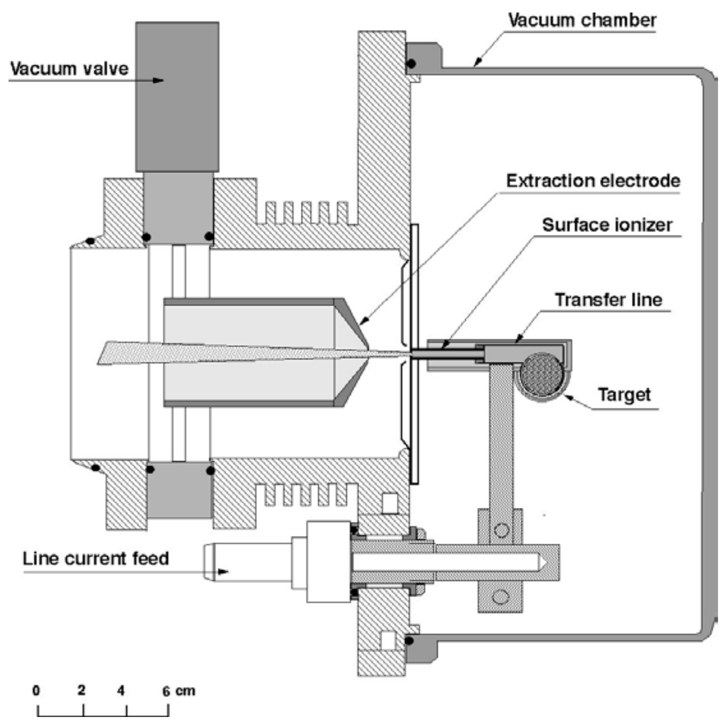
Rare isotopes production



ISOLDE layout



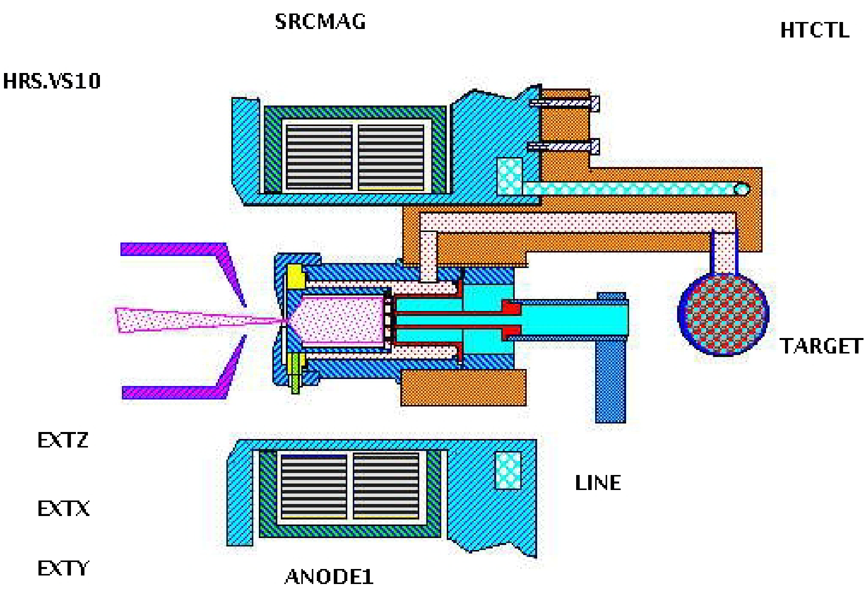
ISOLDE target-ion source



T = 2000 ˚C, HT ≤ 60 kV
Water-cooled flange and connectors

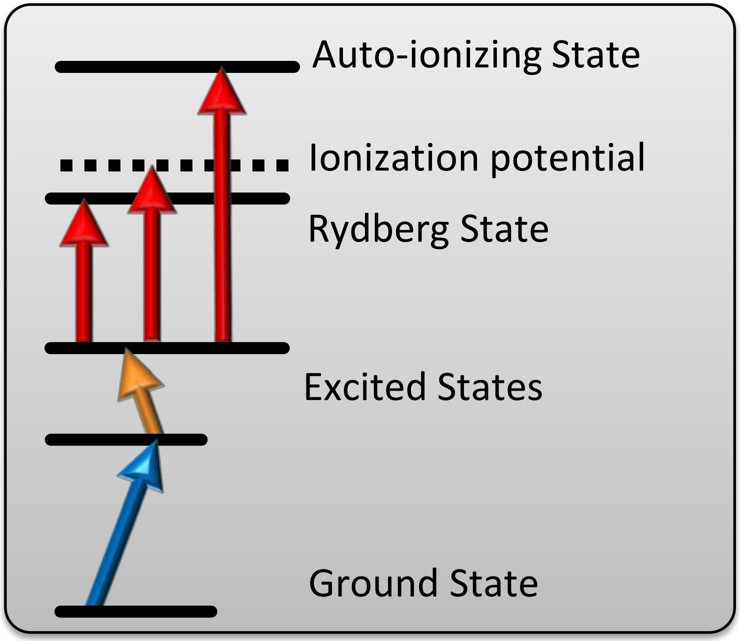
Target-ions source: many possible combinations

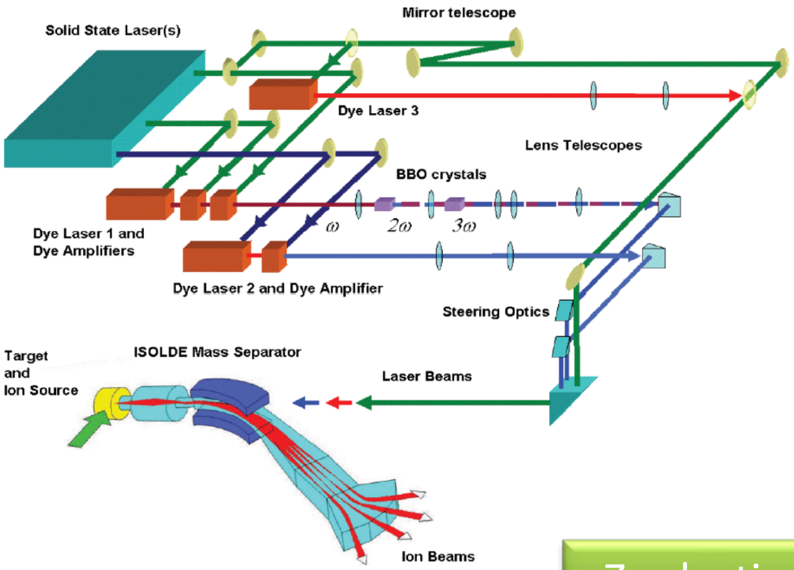
- Different materials
  - Need high density for production
  - Large surface for effusion
  - -> powder, foils, liquid metal
  - -> Pb, UC, Ta, Oxydes, Carbides...
- Different transfer lines
  - Temperature
  - Chemical properties
- Different ion sources
  - Surface
  - Plasma
  - RILIS



* Custom made targets * About 30 units per year

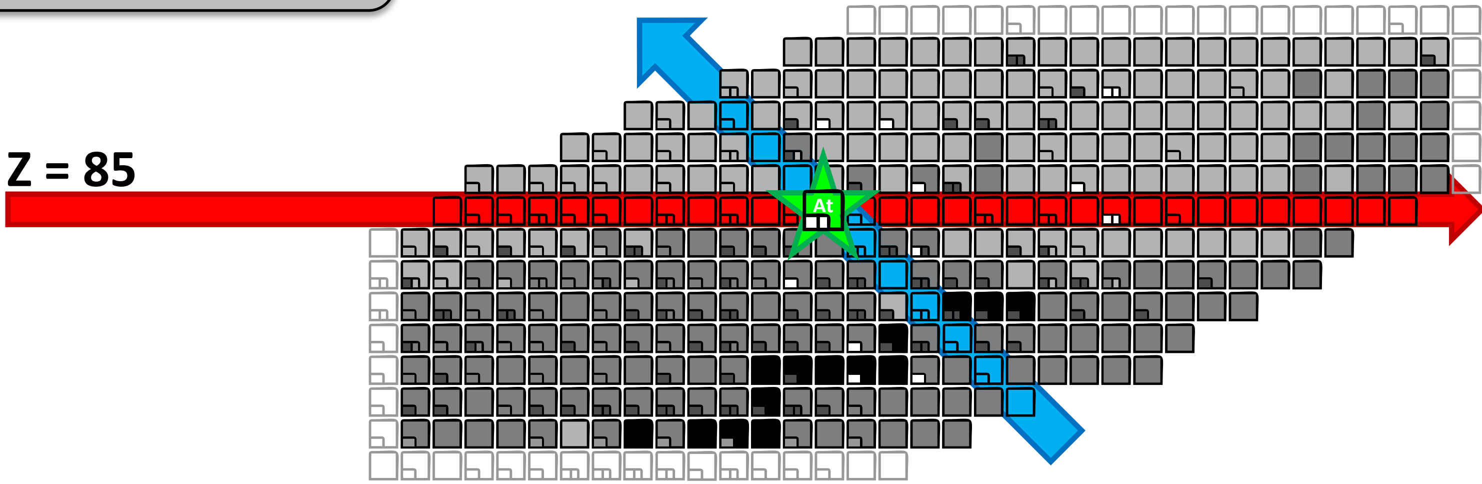
The Resonance Ionization Laser Ion Source (RILIS)





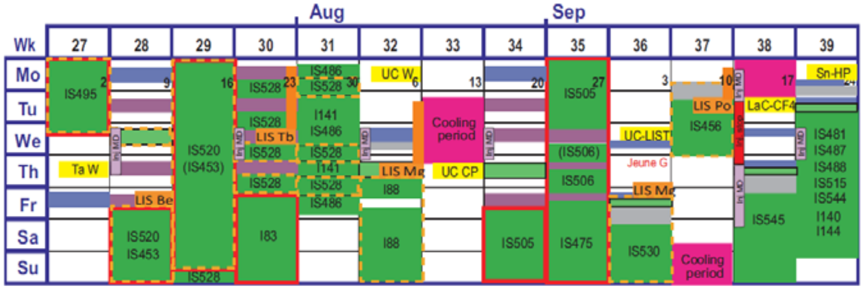
Z selective

Laser tuned to Z = 85



Magnet set to A = 205

Courtesy RILIS team


Aug
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Wk
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IS528
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I141
I183
UC W
Cooling period
UC CP
LIS Mg
I88
IS505
(IS506)
IS506
IS475
UC-LIST
Jeune G
IS530
LIS Po
IS456
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Sn-HP
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I140
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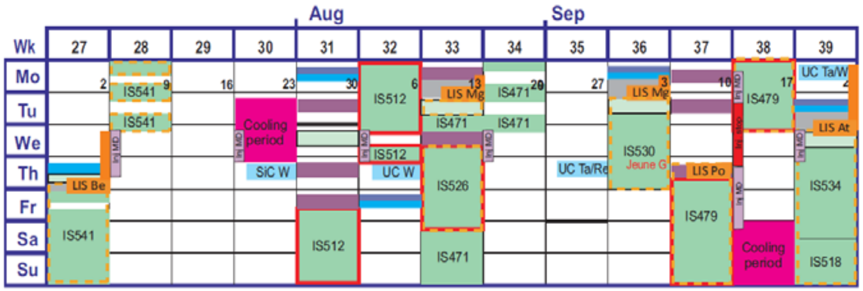
Ta W
LIS Be
LIS Tb

Aug
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Cooling period
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IS512
UC W
LIS Mg
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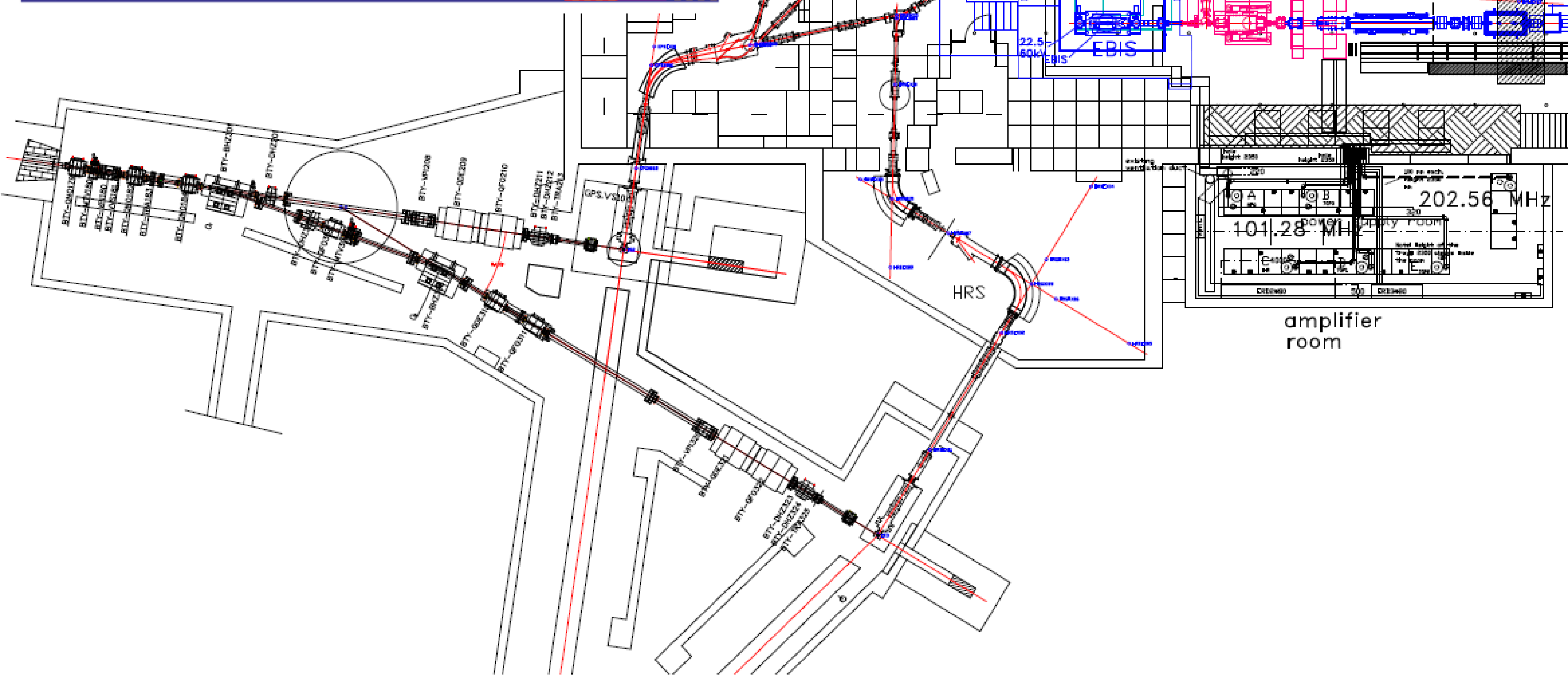
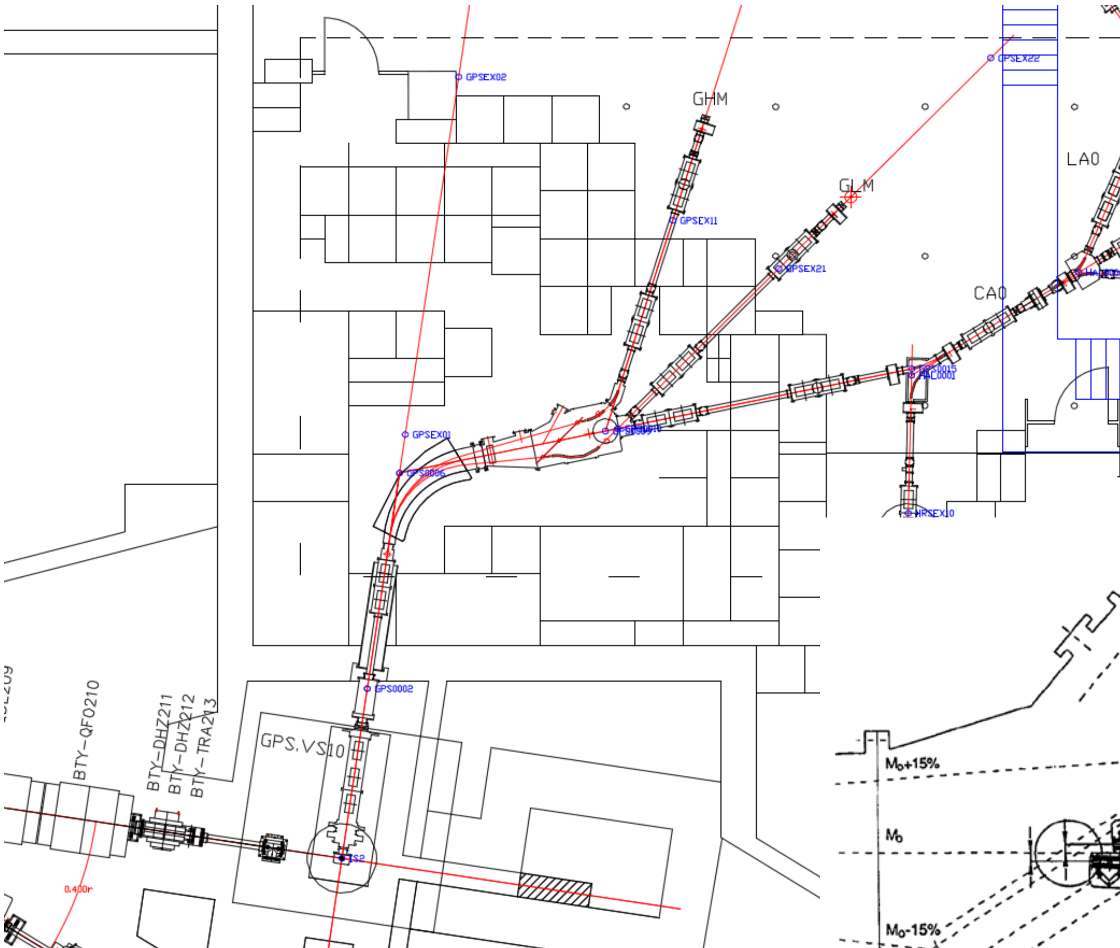
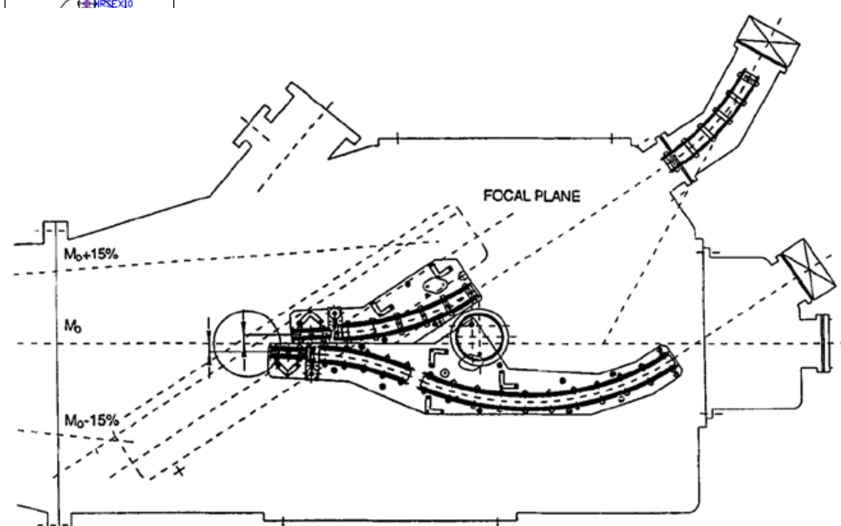

L'ISOLDE
TIMENT 170
IS303
H.V. PLATFORM
IS302
TRAP
IS304
COLL. LASER EXPT
ASPIC IS318
Penning-
trap
HV-cage
60kV
electronics
trap
mass-
separator
Linac
EBIS
22.5
60kV
GPS
HRS
202.56 MHz
101.28 MHz
power supply room
amplifier
room

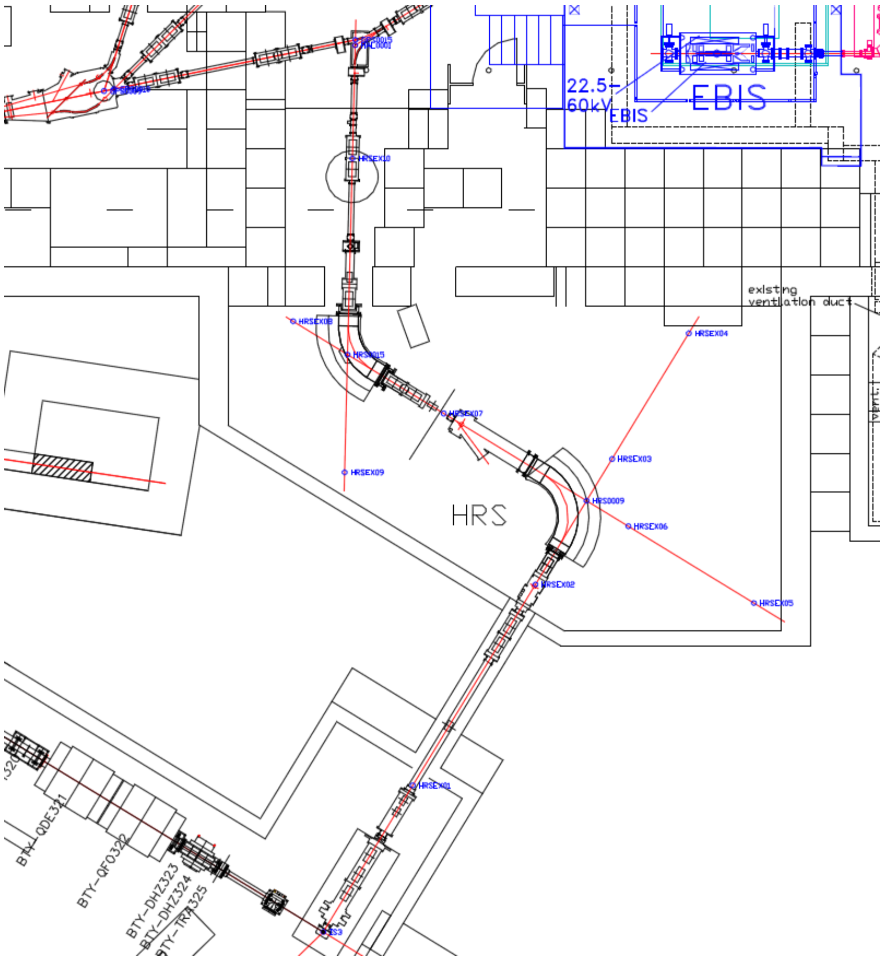
GPS



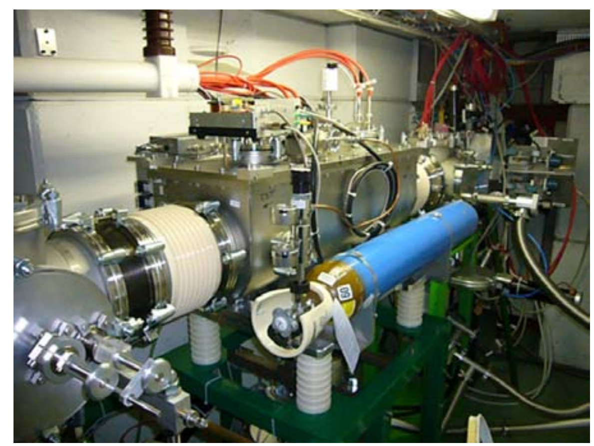
General purpose separator
* 70 deg magnet
* m/Δm = 2500
* 1 central beamlines + 2 parasitic beamlines GHM/GLM



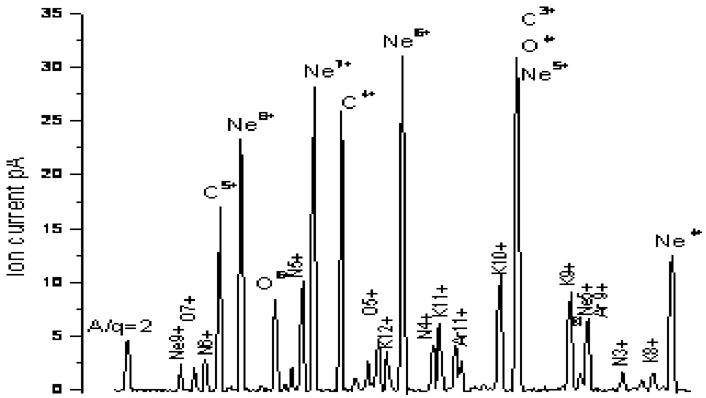
HRS



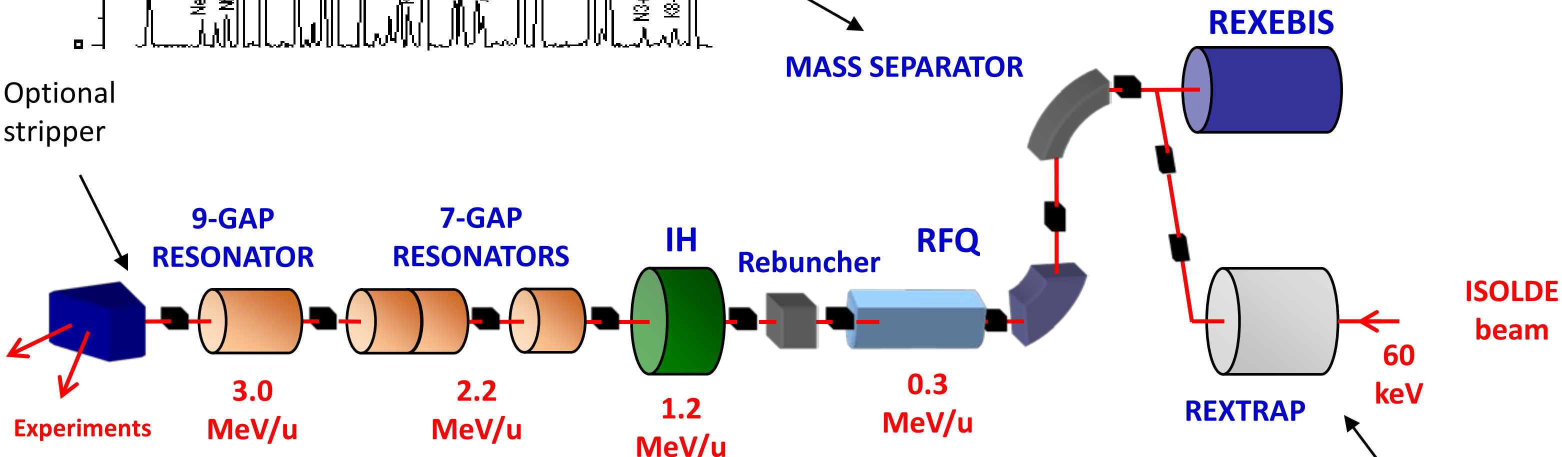
High resolution separator
* Two magnets 90 and 60 deg
* m/Δm = 5000 (aim was 30000)
* Can be used for isotopic separation
* RFQ- cooler buncher



REX-Isolde overview

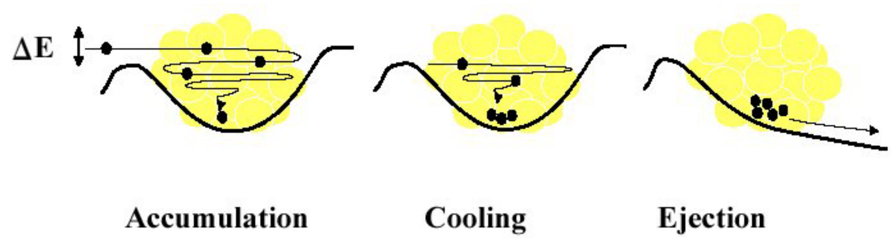


* charge breeding
* 1+ ions to n+



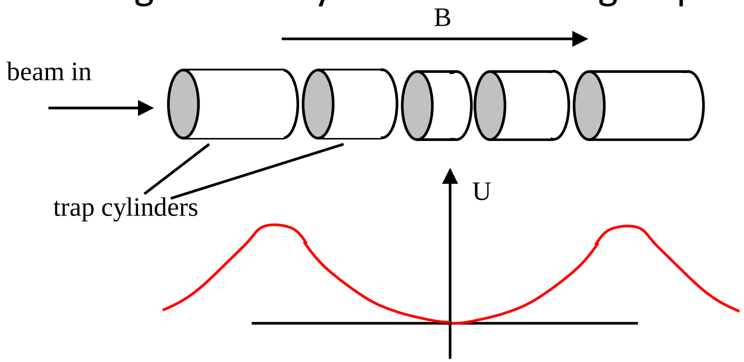
* longitudinal accumulation and bunching
* transverse phase space cooling

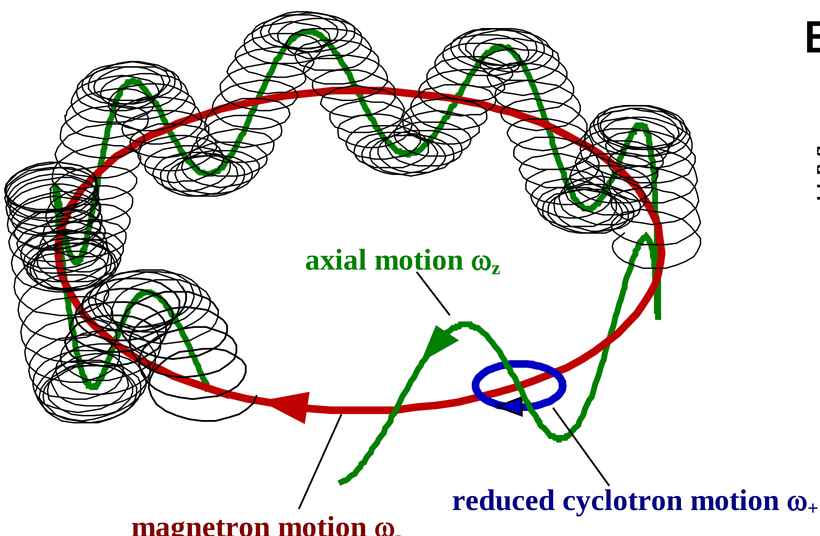
* 6 cavities
* 300 keV/u to 3 MeV/u



Penning trap basics

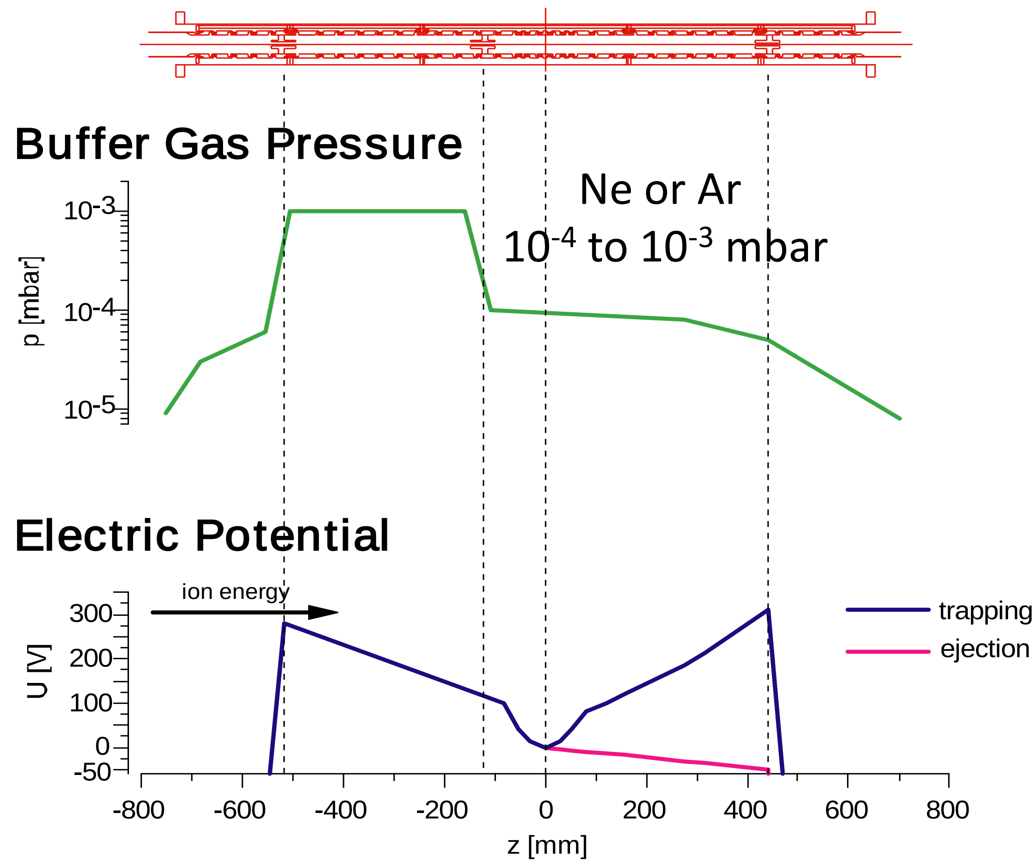
gas filled cylindrical Penning trap





Ion motion inside a Penning trap at low ion density

Trapping Electrodes

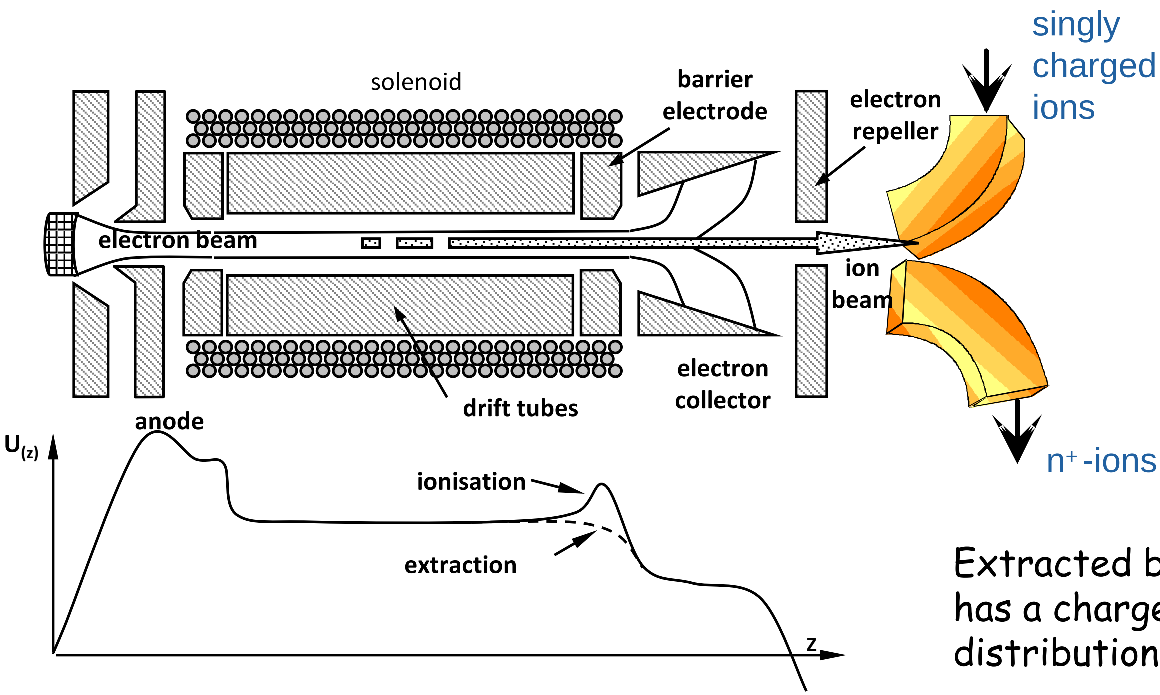


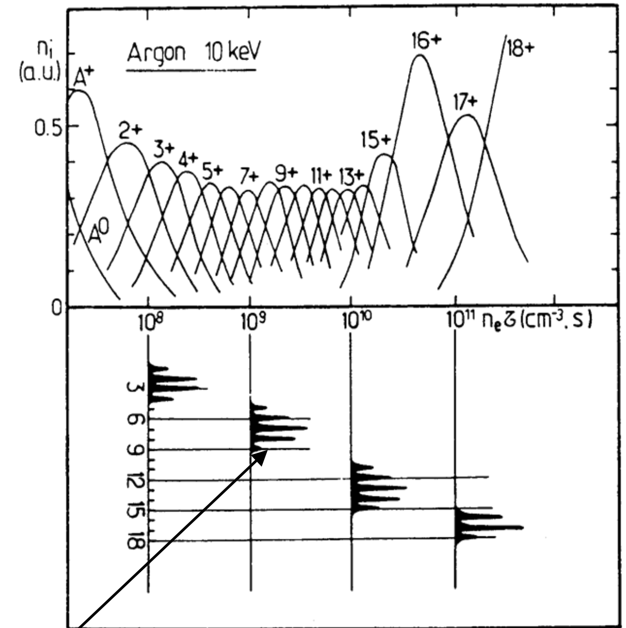
- Use RF excitation to couple the different motions
- Need 20 ms for cooling
- Trapping up to few seconds

Courtesy F. Wenander BE/ABP

EBIS basics

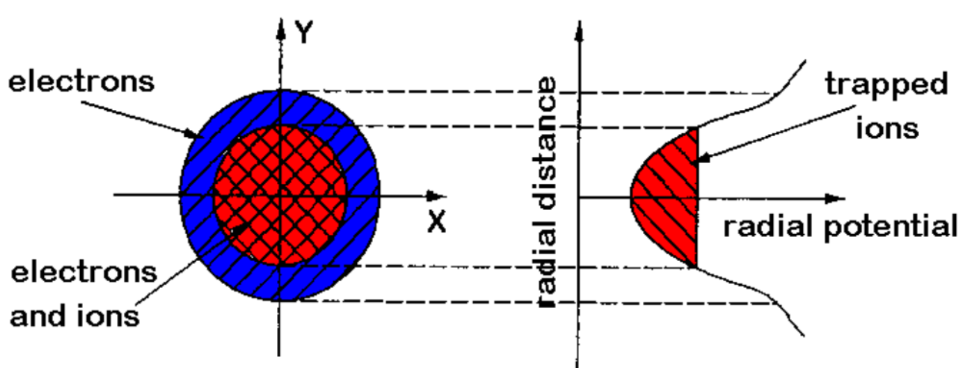
Electron beam ion source





Charge development for stepwise ionisation

Extracted beam has a charge state distribution

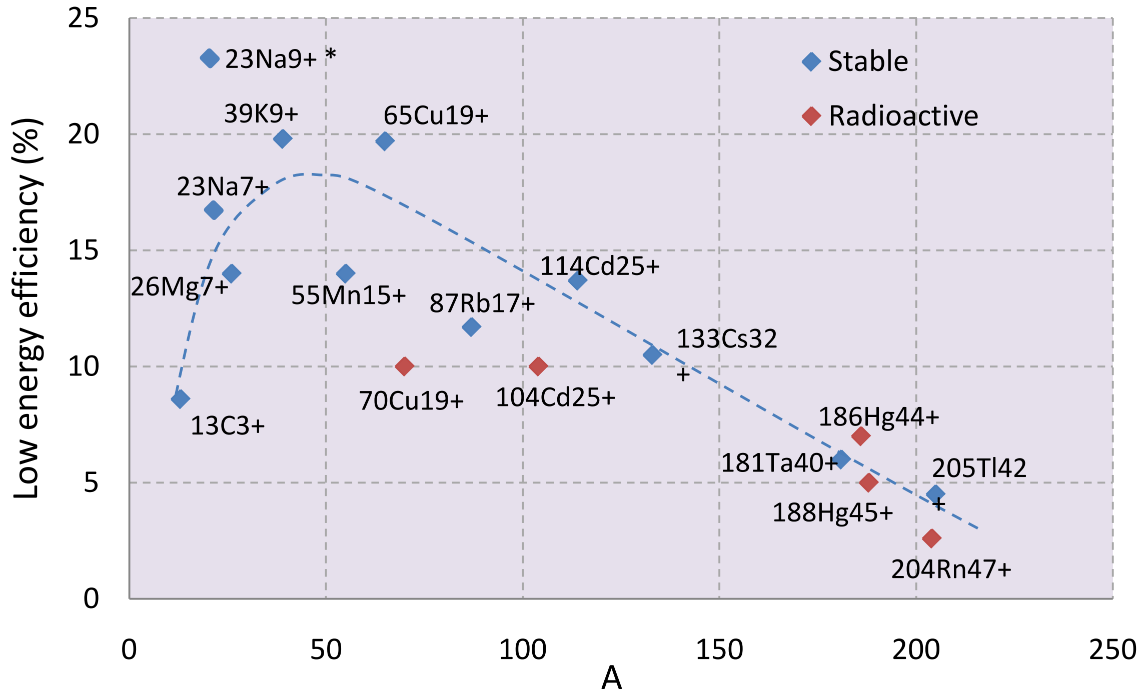


* Produces multiply charged ions
* Ions are trapped in a magneto-electrostatic trap
* Ionisation by e^- bombardment from an mono-energetic e^- beam

Courtesy F. Wenander BE/ABP

Present performance

Efficiency = Trap+EBIS+REX mass separator



* REX low energy= 2-16 %

* Depends on:
  mass, A/q, experience

* Linac transmission x 0.6-0.9

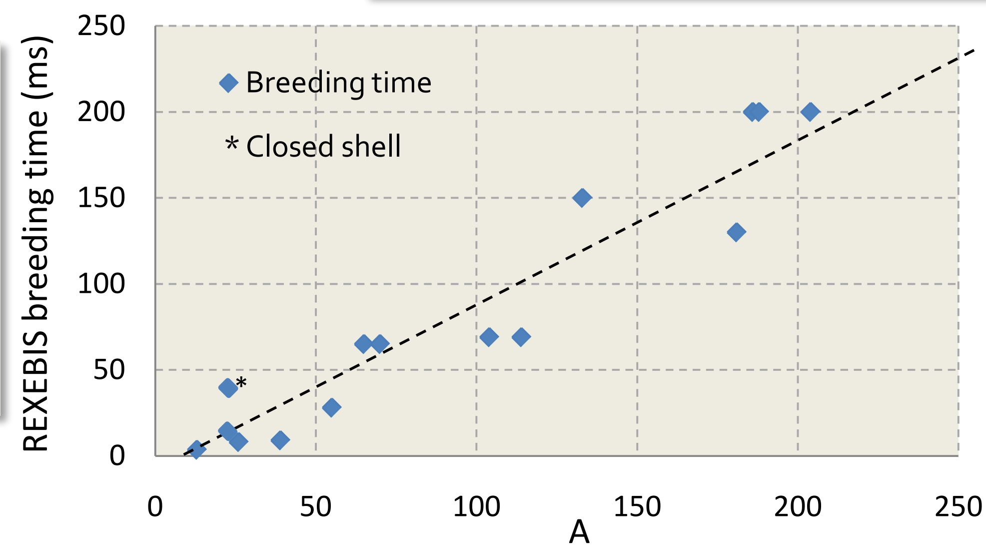
* A<20 ions still difficult

* Heavy ions low efficiency:
  charge exchange?
  heating losses? *under investigation*
  broader CSD?

* Trap time excluded; same as the breeding time (at least 20 ms) →

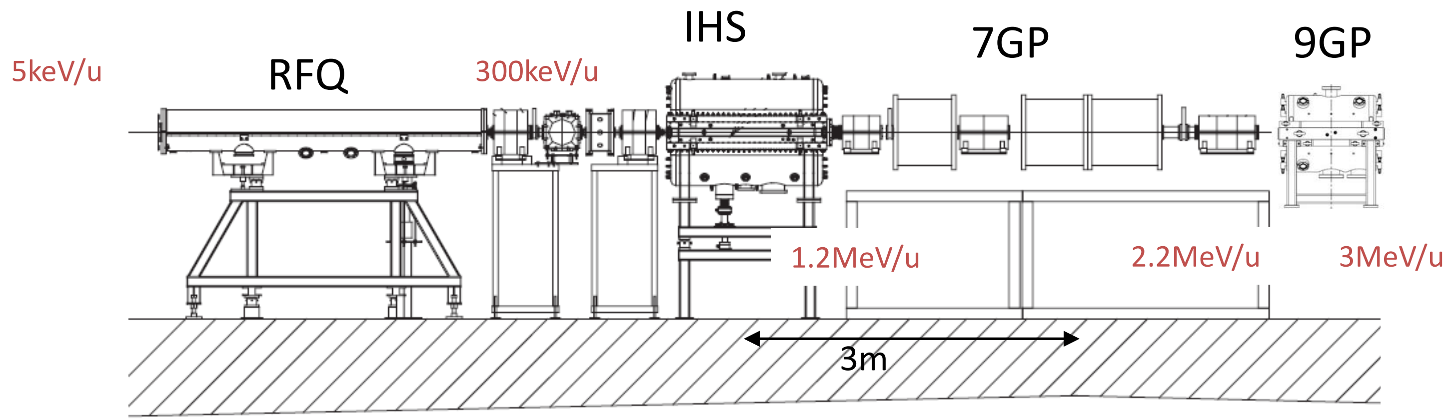
* T_{breed} depends on A/q & injection condition
  (High efficiency -> short breeding time)

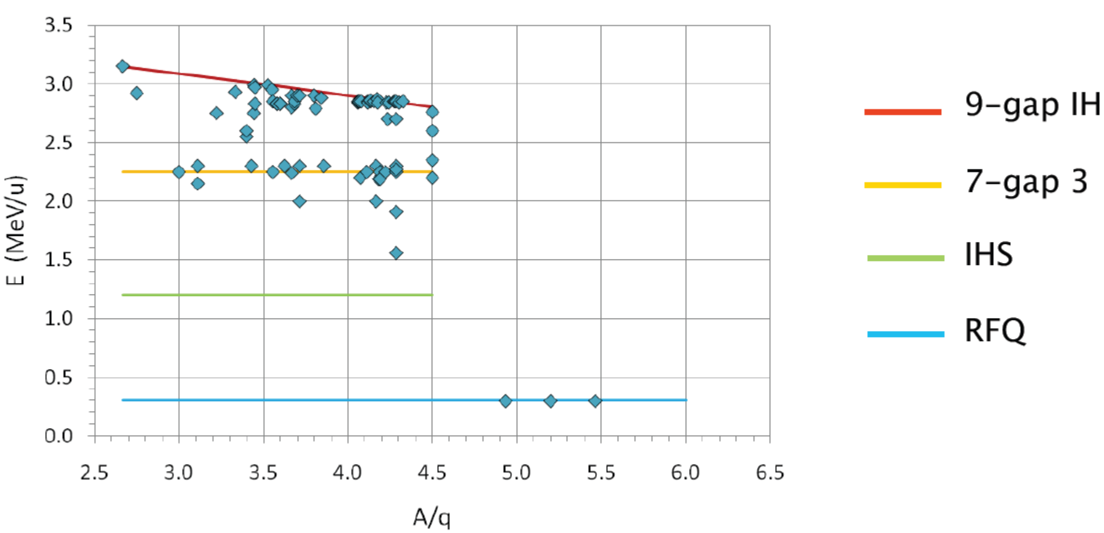
* Half-lives down to some 10 ms



Courtesy F. Wenander BE/ABP

REX linac





<u>Linac:</u>

Length	11 m
Freq.	101 MHz (202 MHz for the 9GP)
Duty cycle	1ms 100 Hz (10%)
Energy	max. 3 MeV/u
A/q	2.0 - 4.5
Trans.	90% (lower for highly charged beams)

Present experimental program at REX-ISOLDE

Focus of experimental program at REX-ISOLDE:

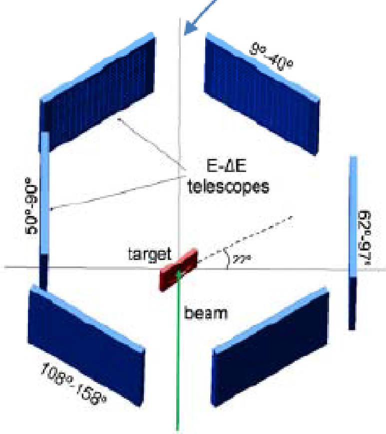
- Coulomb excitation
- few-nucleon transfer reaction studies
- fusion evaporation studies
- light particle elastic scattering

using radioactive beams
Z=3 to 88, up to 3 MeV/u

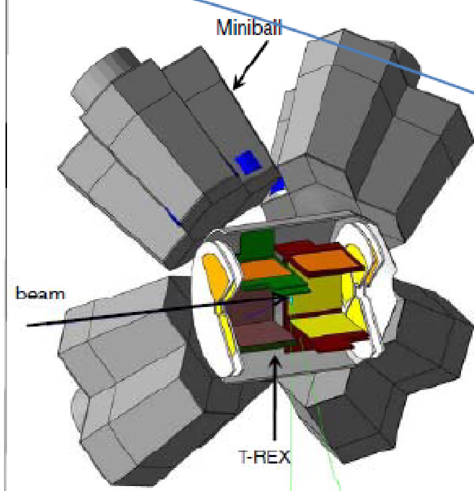
Miniball
Low-multiplicity Ge array + Si pixel particle detectors for Doppler correction

2nd beam line
Mobile experiments, e.g. scattering chamber

β-NMR experiment
Test to produce polarized beams using tilted foils method



Setup for scattering experiments of light nuclei, e.g. ^{11}Be



T-REX silicon barrel detector with Miniball germanium array for few-nucleon transfer reaction experiments

REX physics reference: P Van Duppen and K. Riisager, J. Phys. G: Nucl. Part. Phys. 38 024005 (2011)

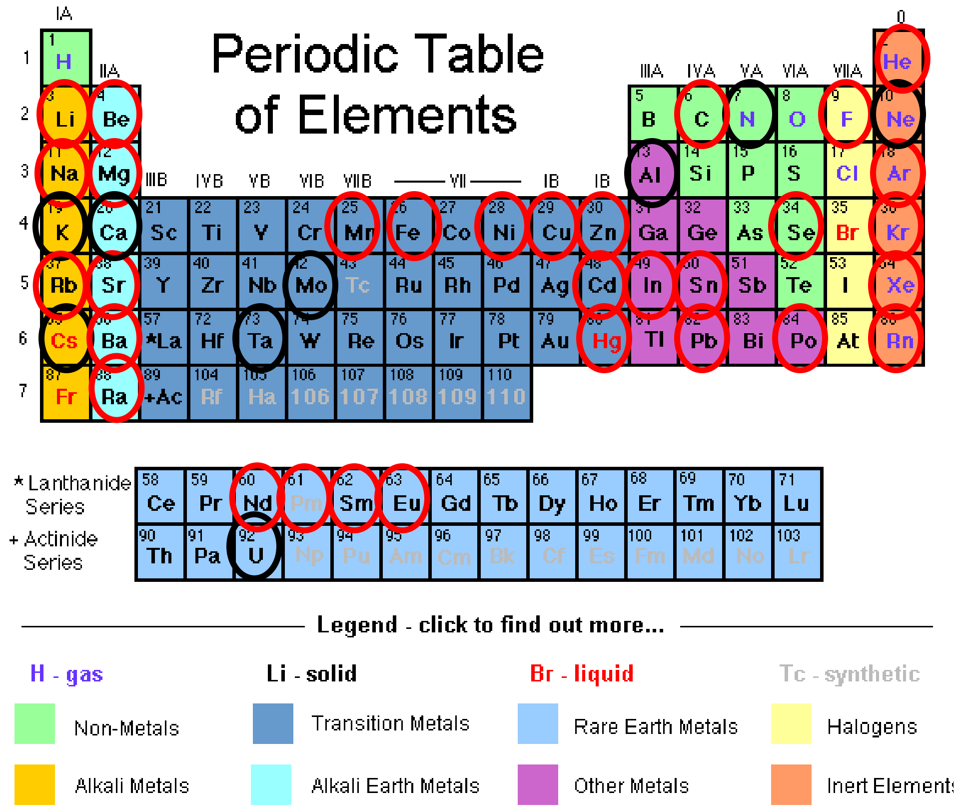
Miniball reference: 'The Miniball at REX-ISOLDE', J. Van de Walle., EPJ to be published

Courtesy F. Wenander BE/ABP

^{6}He
^{8,9,11}Li
^{10,11,12}Be
^{10}C
^{17}F
^{21,24,25,26,27,28,29,30}Na
^{28,29,30,31,32}Mg
^{44}Ar
^{61,62,63}Mn
^{61,62}Fe
^{66,68}Ni
^{67,68,69,70,71,73}Cu
^{72,74,76,78,80}Zn
^{70}Se
^{72,88,92,94,96}Kr
^{93,95,97,99}Rb
^{96,98}Sr
^{100,102,104,122,123,124,126,128}Cd
^{108}In
^{106,107,108,109,110}Sn
^{138,140,142,144}Xe
^{140,142,148}Ba
^{140}Nd
^{148}Pm
^{140,142,153}Sm
^{156}Eu
^{182,184,186,188}Hg
^{186,188,190,192,194,196,198}Pb
^{196,198,200,202,206}Po
^{202,204,208,220,221}Rn
^{224}Ra

REX beam collection

2001-2012



>100 radioactive isotopes of 31 elements

A selection of stable elements charge bred

ISOLDE Statistics 2011

ISOLDE Shifts (8h):

Scheduled: 471.5

Delivered: 329.5 (+134 for machine development and test)

REX-ISOLDE: 147 (45%)

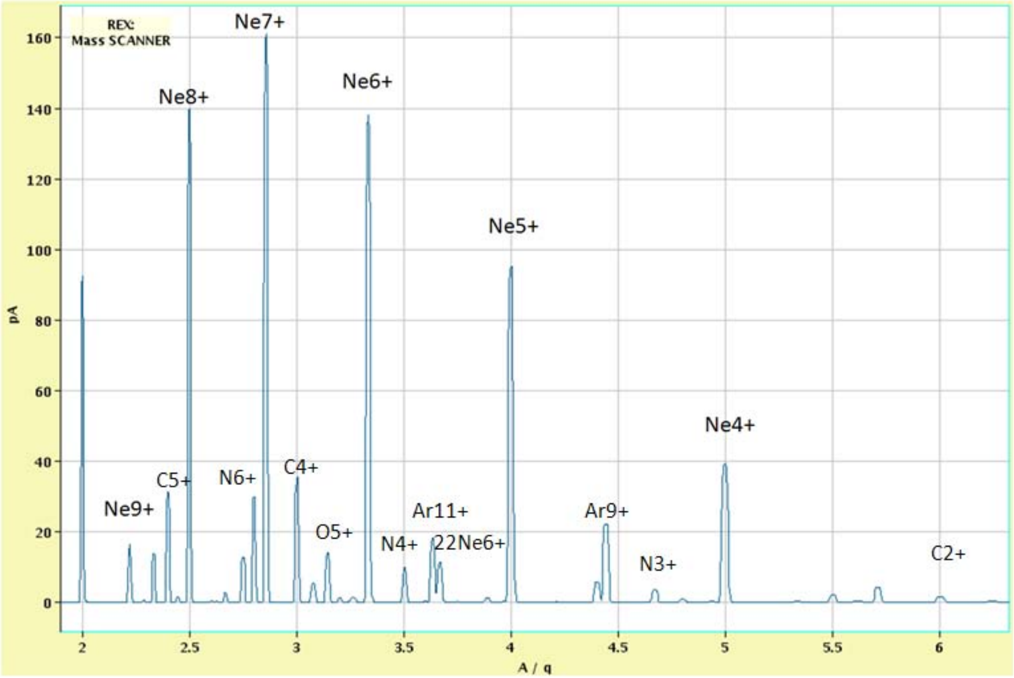
Category	Percentage
Nuclear structure using reactions	28%
Nuclear structure from ground-state properties and beta-decay	22%
Nuclear astrophysics	1%
Fundamental interactions	3%
Solid-state physics	12%
Biophysics and medicine	4%
total INTC and LOI RIB shifts	**71%**
Target and ion source development and Coordinator's reserve	29%

Use of pilot beams

- Some/most radioactive beams are too low to see on conventional beam diagnostics (FC and profilers): few pps to few pA
- Use stable beams to set-up the charge breeder and linac
  - Need same element (or similar) and similar mass for the EBIS
    - e.g. Use 238U for Ra beams, stable Cu (mass marker) for Cu isotopes
    - Sometime use several pilot beams
  - Need close-by A/q for the linac
- Use linear scaling of the linac to go from pilot to radioactive beam
    - Only works well for small A/q change

Beam cleaning with REX

- ISOLDE
  - isobars/molecules
  - stable or radiogenic
- EBIS rest gas
  - Ne (REXTRAP buffer gas), C, N, O, Ar (leaks), La, B (electron gun),Al, Zr, Ti (NEGs, vacuum chamber)...
  - But EBIS = very low background <1e-10 mb



* Large palette of cleaning tools within ISOLDE: RILIS, HRS, chemical selection, molecular beams...
* REX versatility offers many possibilities

Proper choice of charge state, some examples:

- 80Zn
  - Ar and Ne on even charge states => q = 2n + 1
  - Need A/q between 2 and 4.5 for the linac => q > 17
  - Low charge states = higher efficiency and higher efficiency
- 12Be 23.6 ms half-life

  -> need short breeding time to minimise decay losses

  For Ttrap=31 ms and Tbreed=28.7 ms the hold-up time is approximately 31/2+28.7=44 ms => transmission = 28%

  For this period and breeding time we have 9.3% for stable beam => 2.6% transmission (incl decay losses)

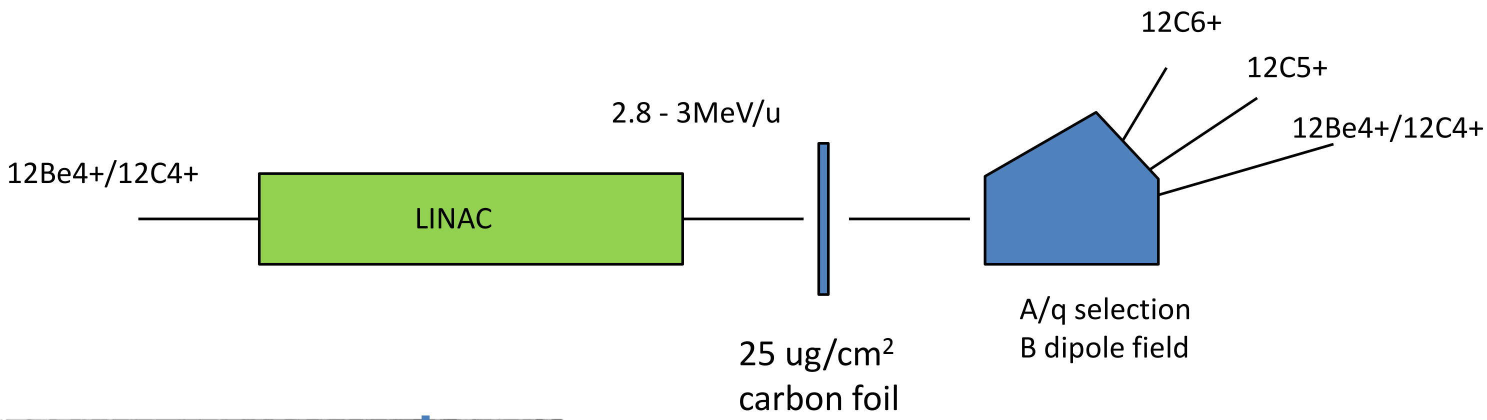
  For Ttrap=21 ms and Tbreed=18.7 ms the hold-up time is approximately 21/2+18.7=29 ms => transmission = 43%

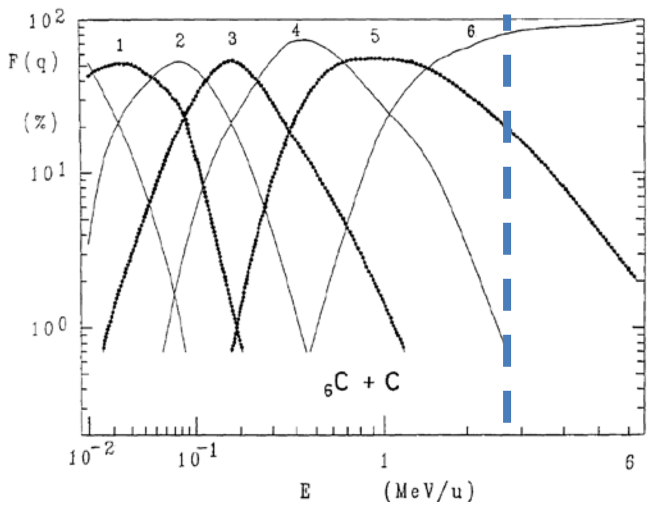
  For this period and breeding time we have 6.1% for stable beam => 2.6% transmission (incl decay losses)

  Run at the shorter period time to reduce the instantaneous rate at the experiment
- Closed-shell breeding

  Breeding efficiency is enhanced for closed-shell e.g. 123Cd30+ (Ar-like)

Stripping foils

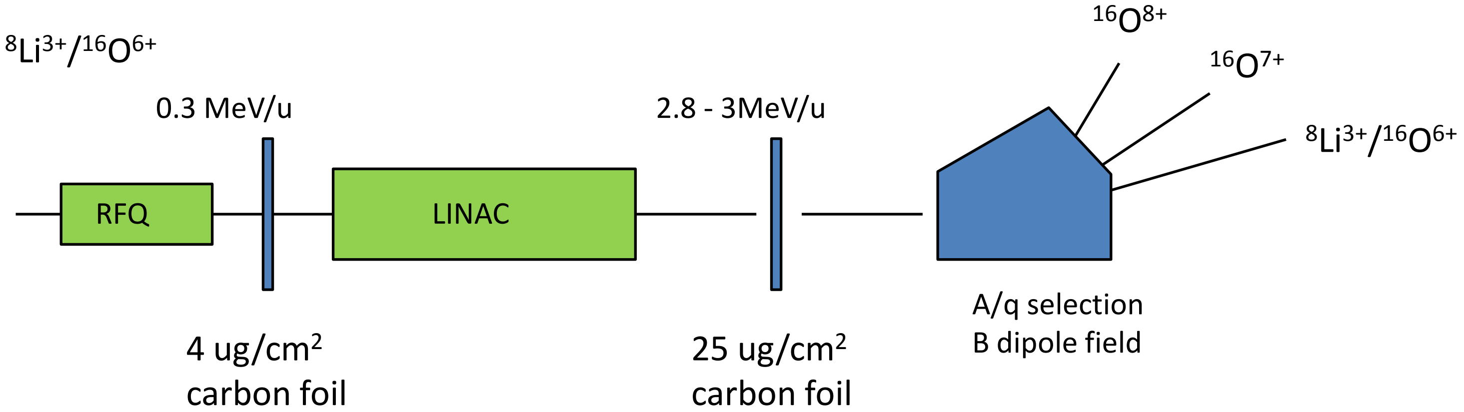




Shima et al, Atomic data and nuclear data tables, 51, 173-174 (1992)

- Efficiency can vary from few % to 100% depending on the case
  - * ideal case 10C/20Ne: fully stripped 10C has no Ne contamination -> 100% separation
  - * 11Be/22Ne -> some 22Ne will remain as 8+
- Only works for light beams (charge state distribution)
- Energy straggling significant at low energy -> need to retune the optics

Double stripping



Use differential energy loss in the thin foil to separate Li and O with energy filtering in the linac (O is injected at the wrong energy -> lower transmission)

- $^{8}Li/^{16}O$ ratio increased by a factor 13
- Beam intensity decreased by a factor 3 -> can only be used in case of sufficiently intense beams

Undesired for: ^{80}Zn ($t_{1/2}$=537 ms)
– also got ^{80}Ga (T_{trap}=80 ms, T_{breed}=78 ms)

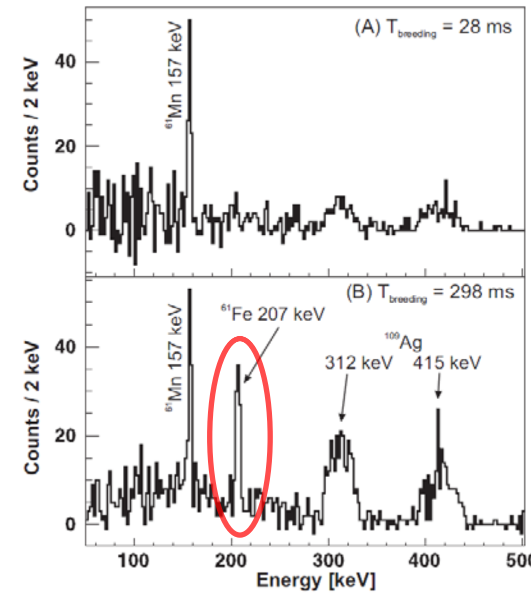
In-trap decay

for better or for worse

The idea: *Let easily produced elements decay in REX low-energy part prior to acceleration to provide post-accelerated beams of difficultly produced elements*

previously used at ISOLTRAP; A. Herlert et al., New J. Phys. 7 (2005) 44

Doppler corrected Coulex spectra (Miniball)



J. Van de Walle et al.: European Physical Journal A 42 (2009) 401

Tested first time at REX-ISOLDE with ^{61}Mn ($T_{1/2}$=675 ms; 1.7x10^6 atoms/s)

T_{trap}	T_{breed}	Result
200-1100 ms	28 ms	no Fe detected at Miniball
300-1100 ms	298 ms	57(7)% Fe detected agrees with predictions

Courtesy F. Wenander BE/ABP

The HIE-ISOLDE project

- A general upgrade for ISOLDE
- High intensity (design study)
- HIE-LINAC
  - R&D activities for the linac (started in 2008)
  - Approved CERN project 2010
  - 5.5 MeV/u (stage 1) 2015 / 10 MeV/u (stage 2) 2016-2018
  - 36.5 MCHF, 50% financed through external collaboration

A superconducting linac?

“an array of small independent resonating cavities, equipped with their own small RF amplifier “

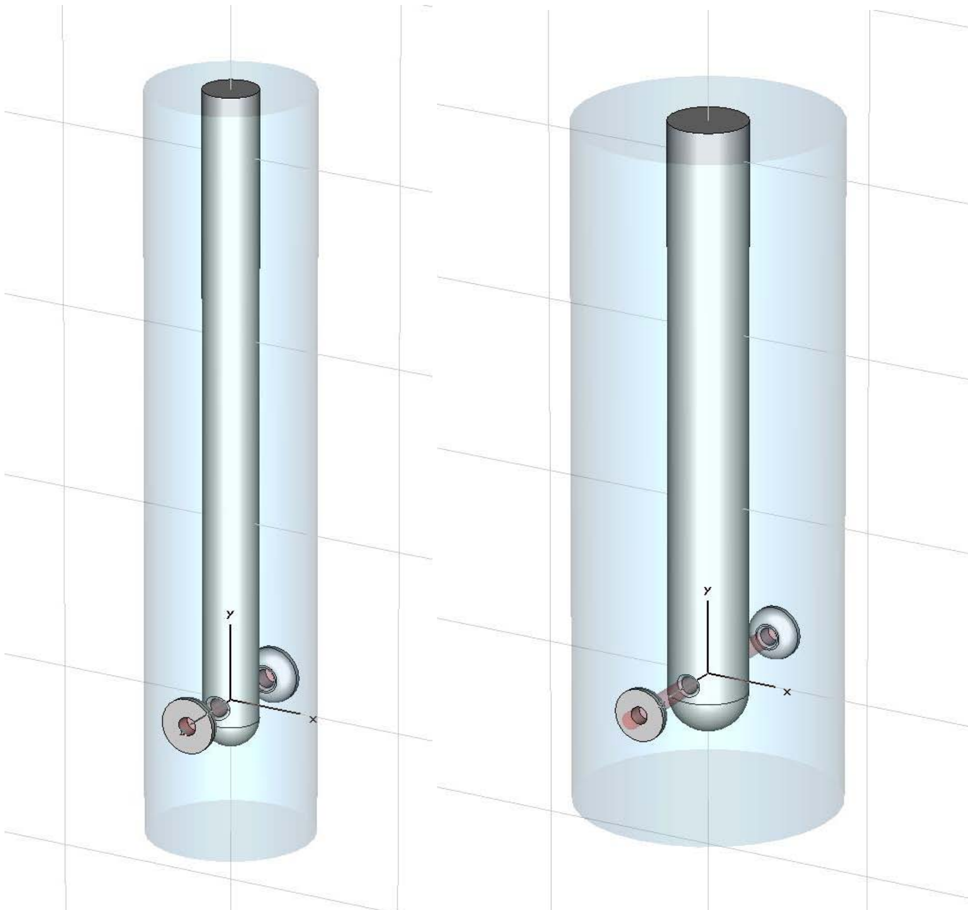
-> No high power amplifier (7W of RF)

-> Very high accelerating gradient

-> Short + independent cavities = high flexibility

-> CW operation

SC quarter-wave cavities

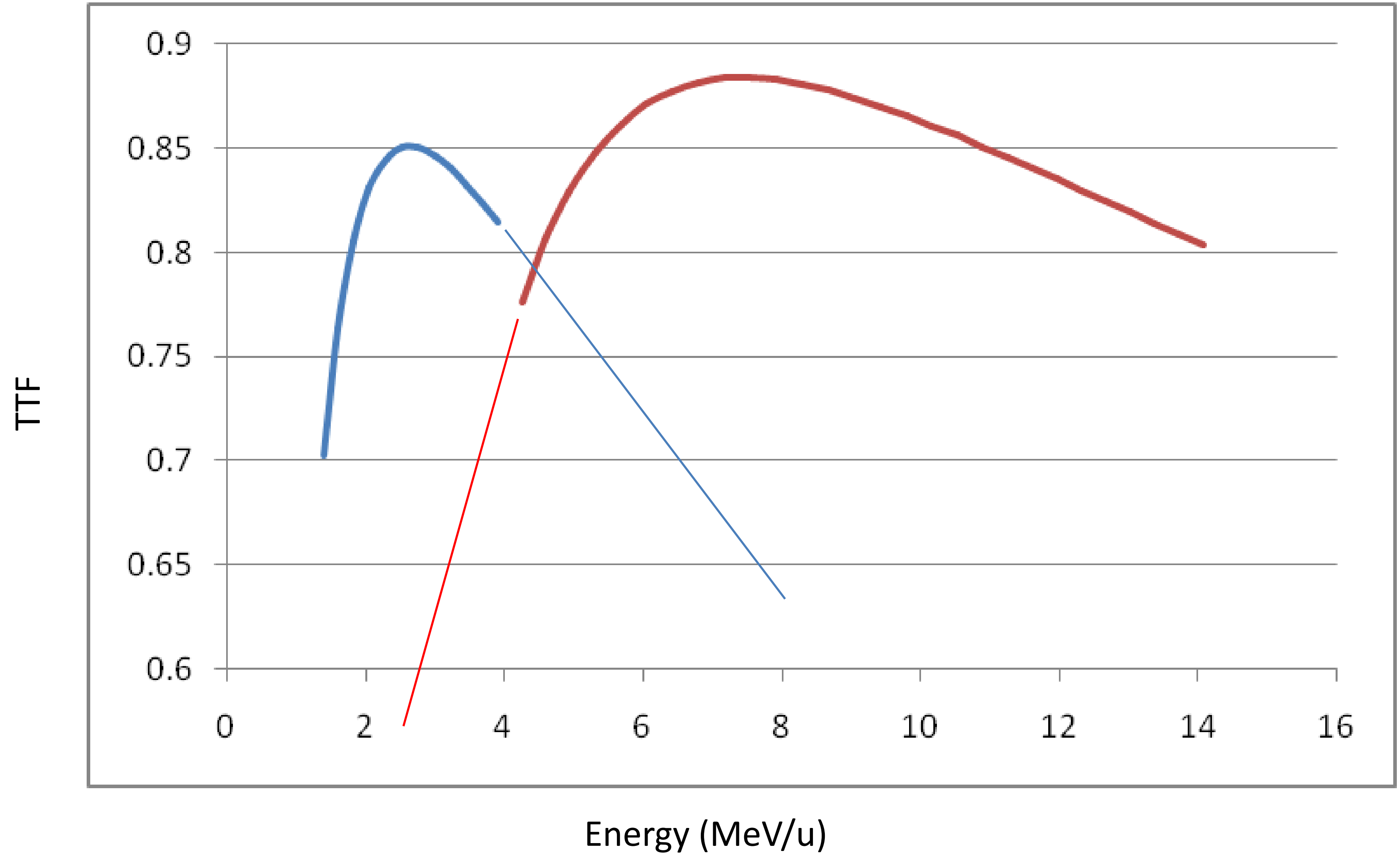


Low β Highβ

f (MHz)	101.28	101.28
β 0	6.3%	10.3%
Gradient Ea (MV/m)	6	6
Inner Cond. Diam (mm)	50	90
Outer Cond Diam (mm)	195	300
Mechanical Length (mm)	215	320
Gap length (mm)	50	85
Beam Apert. Diam. (mm)	20	20
U/Ea^2 (J/(MV/m)^2)	73	207
Ep/Ea	5.4	5.6
Hp/Ea (Oe/MV/m)	80	100.7
Rsh/Q (Ohm)	564	548
Q0 min for 6 MV/m at 7W	3.2 10^8	5 10^8
TTF max	0.85	0.9
No. of cavities	12	20

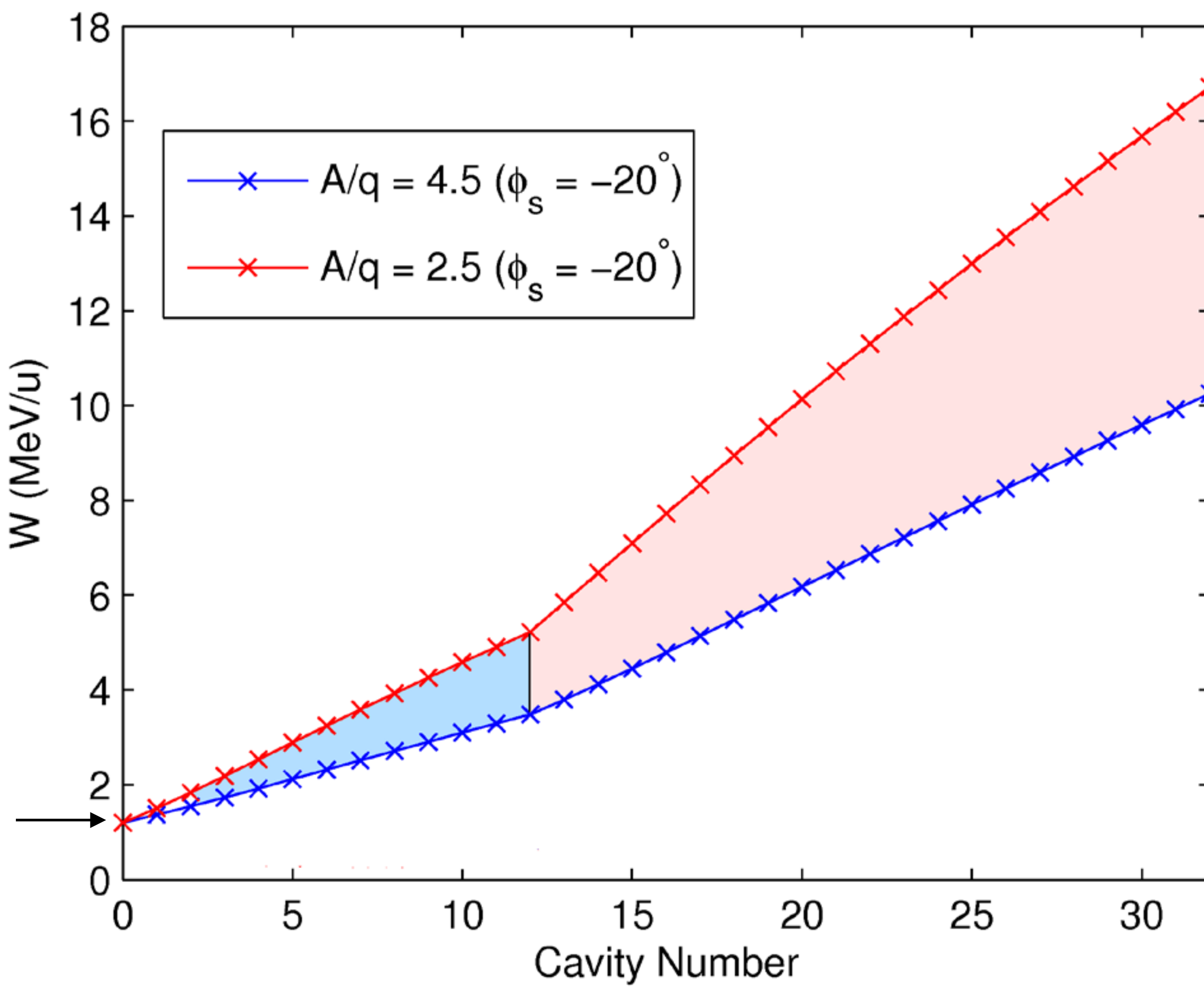
Courtesy HIE-ISOLDE linac working group

TTF vs Energy



Courtesy HIE-ISOLDE linac working group

Energy RANGE: STAGE 2b



A/q = 4.5
W = 16.8 MeV/u
$\beta\gamma$ = 0.187

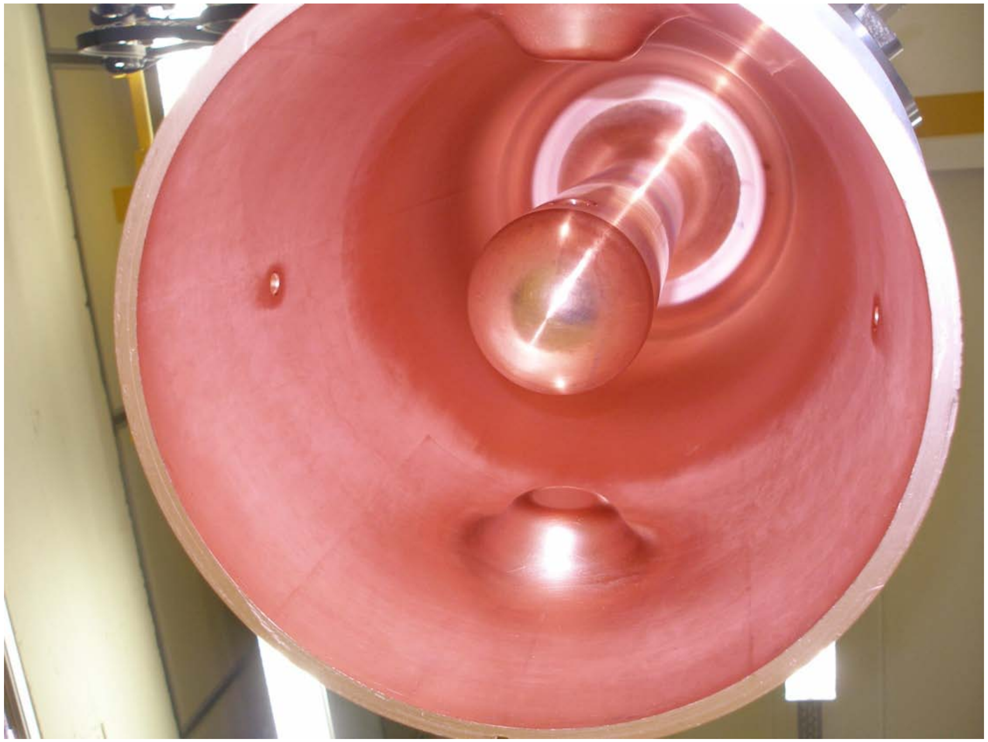
A/q = 4.5
W = 10.2 MeV/u
$\beta\gamma$ = 0.147

Highest rigidity:
W = 10 MeV/u
A/q = 4.5
$B\rho$ = 2 Tm

2.5 < A/q < 4.5
W = 1.2 MeV/u
$\beta\gamma$ = 0.051

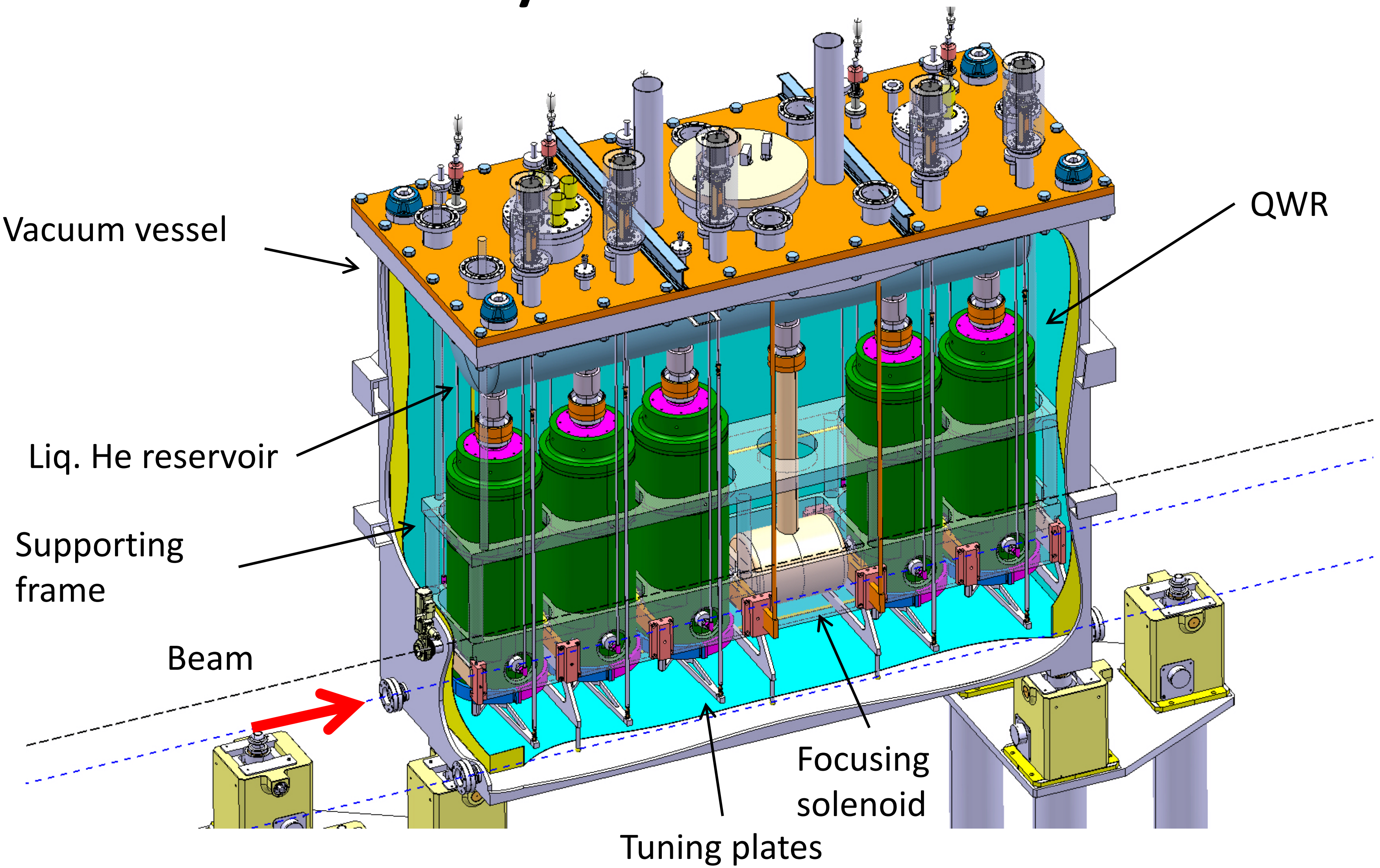
Courtesy M. Fraser BE/RF

HIE-REX Cavity Prototype: Nb sputtered on Cu



Courtesy HIE-ISOLDE linac working group

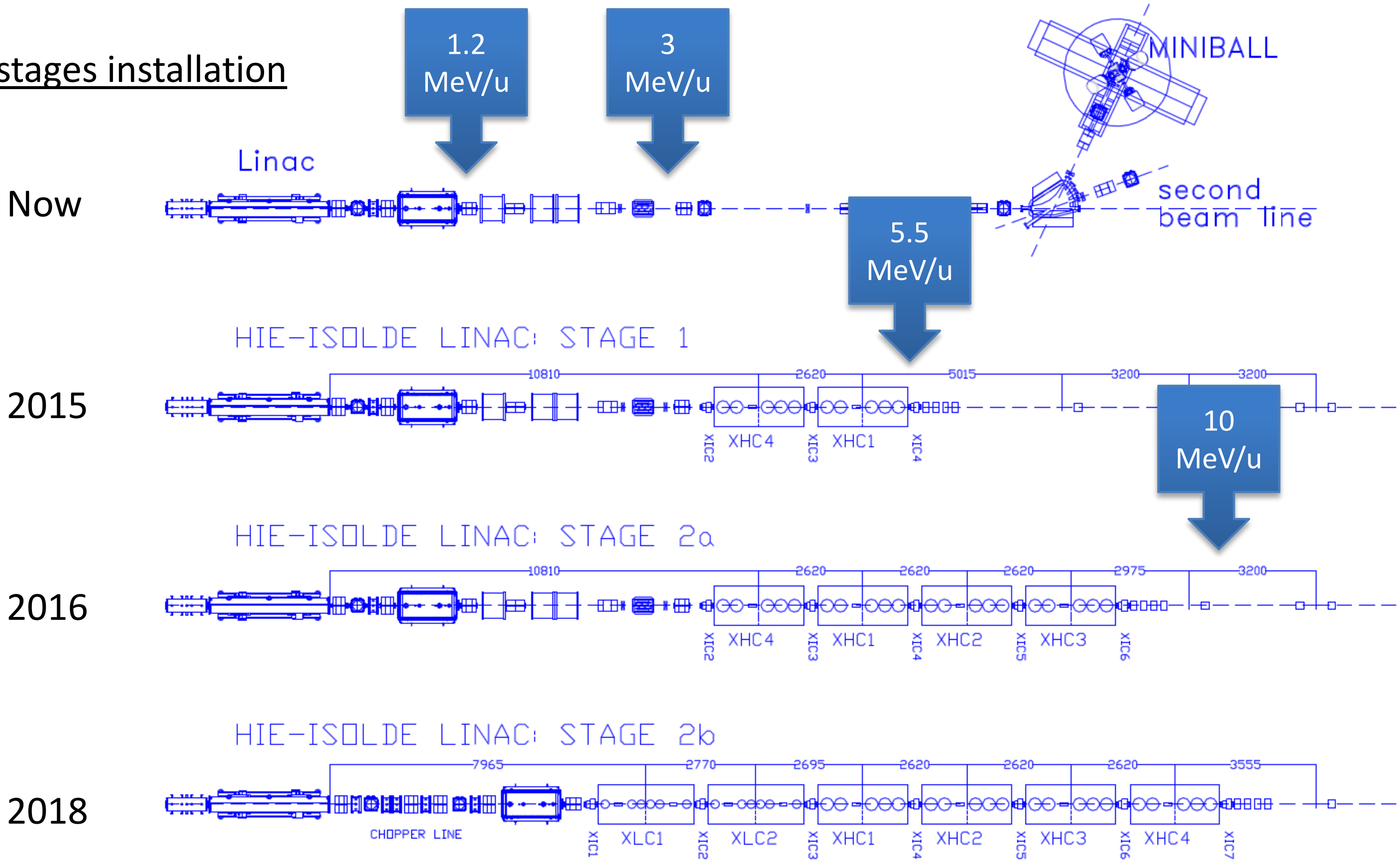
Cryomodule

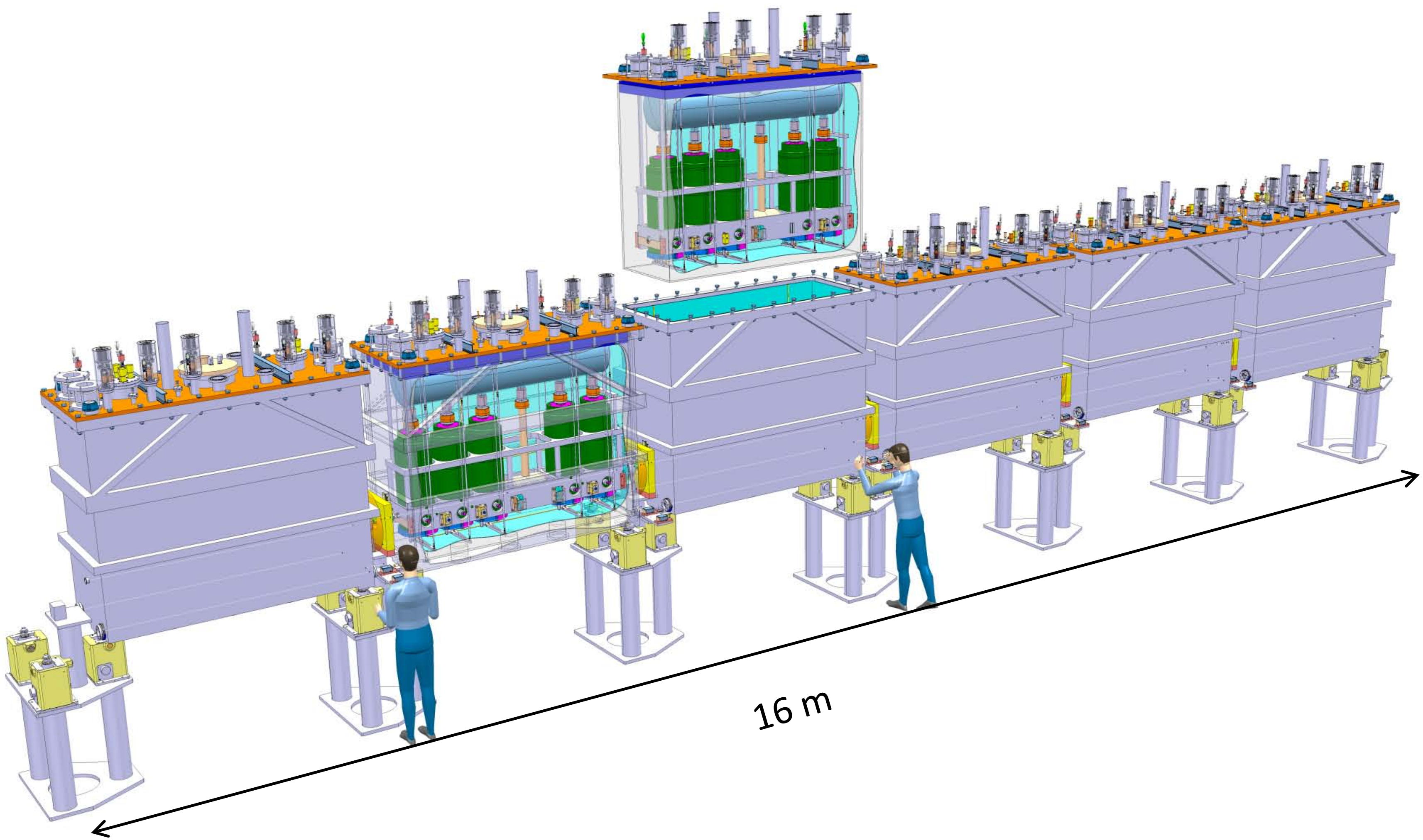


Courtesy HIE-ISOLDE linac working group

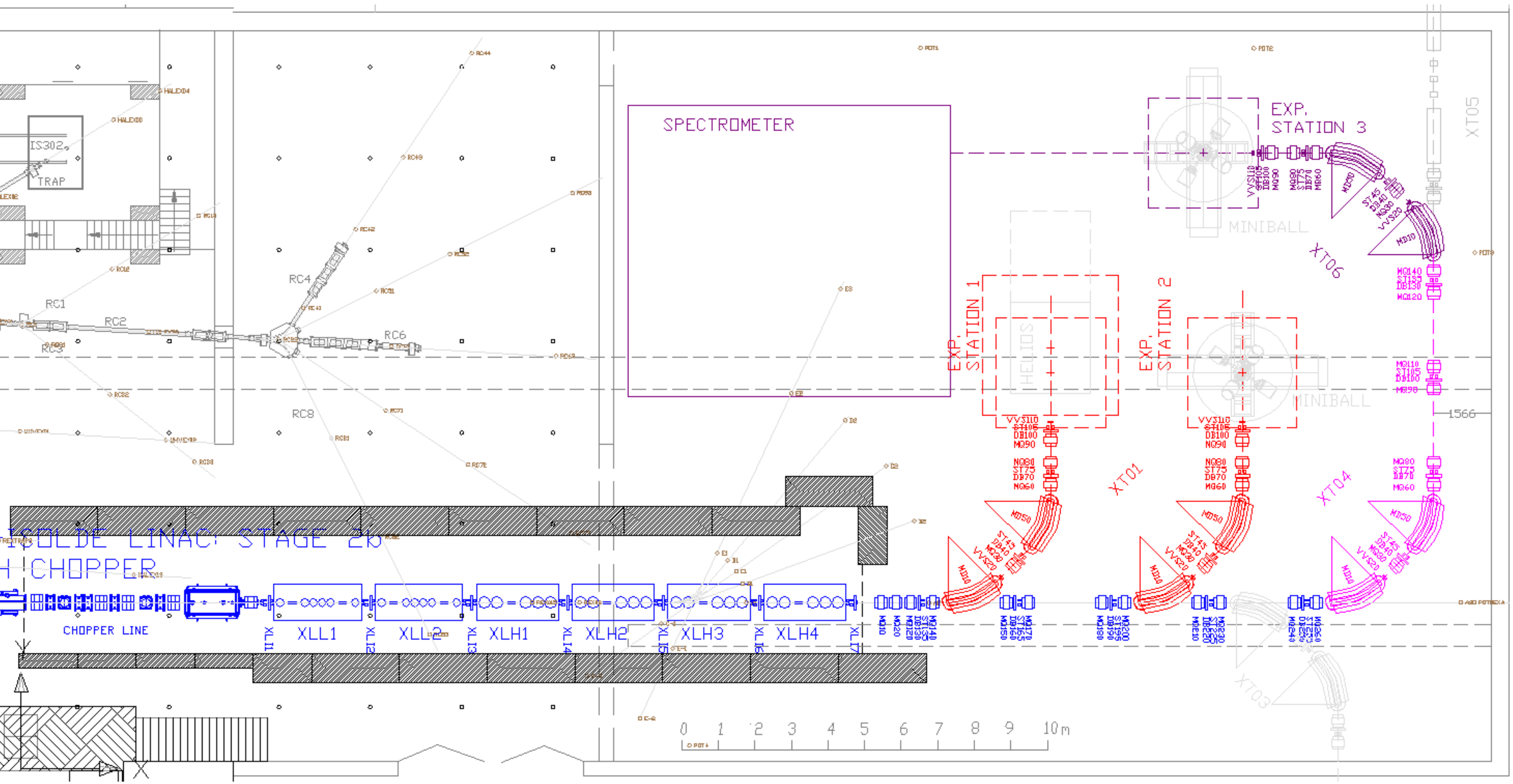
HIE-ISOLDE LINAC - layout

3 stages installation





Courtesy HIE-ISOLDE linac working group



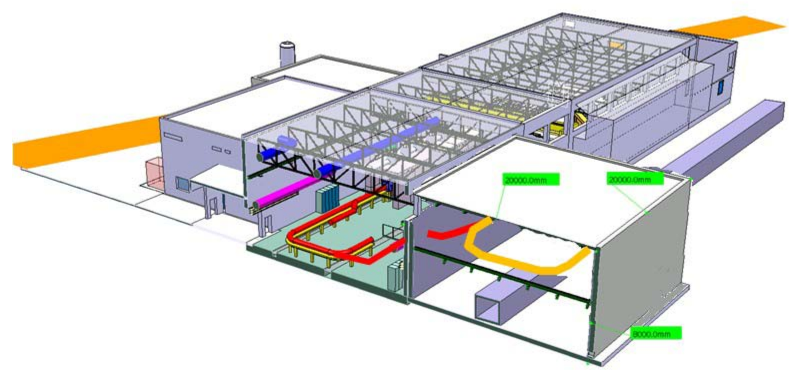
SPECTROMETER
EXP.
STATION 3
MINIBALL
XT05
XT06
EXP.
STATION 1
HELIOS
EXP.
STATION 2
MINIBALL
XT01
XT04
XT03
IS302
TRAP
RC1
RC2
RC3
RC4
RC6
RC8
ISOLDE LINAC: STAGE 2b
CHOPPER
CHOPPER LINE
XLL1
XLL2
XLH1
XLH2
XLH3
XLH4
0 1 2 3 4 5 6 7 8 9 10 m

Beyond HIE-ISOLDE

TSR @ISOLDE

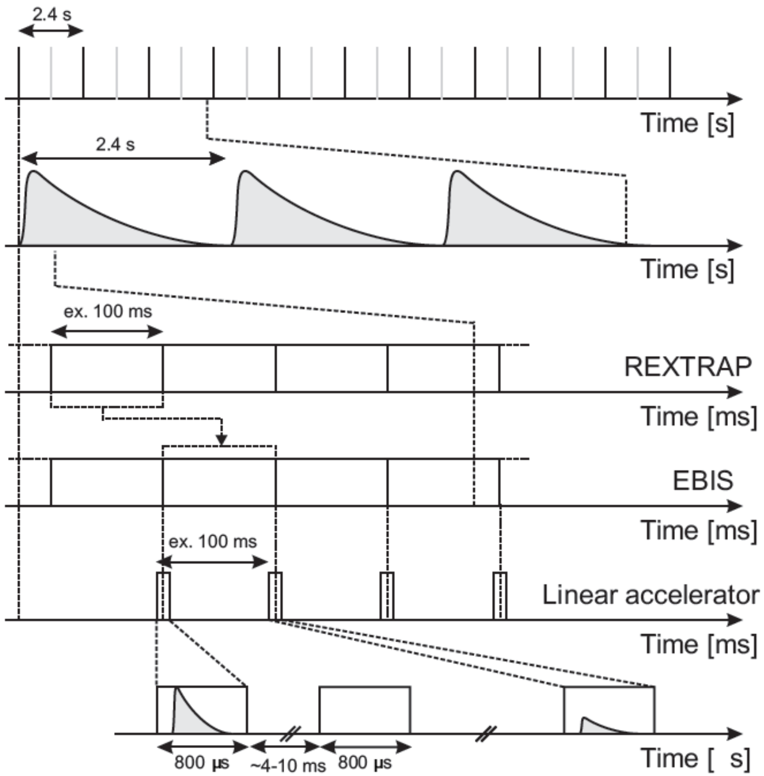
- Heavy-Ion Storage Ring + HIE-ISOLDE
  - No background
  - No energy straggling
  - Cold beam/Smaller beamsize
  - Reduced dead time/CW beam
- Approved by research board May 2012
- Aiming for start-up in 2015 as an experiment, integration as CERN facility in 2018

TSR at MPIK Heidelberg

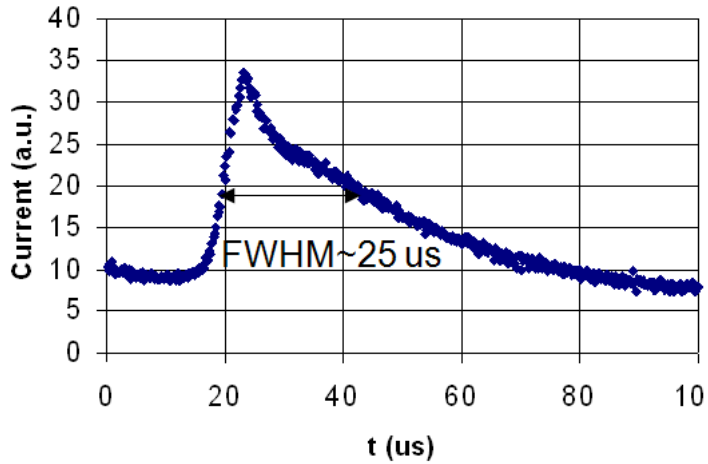


Possible TSR installation

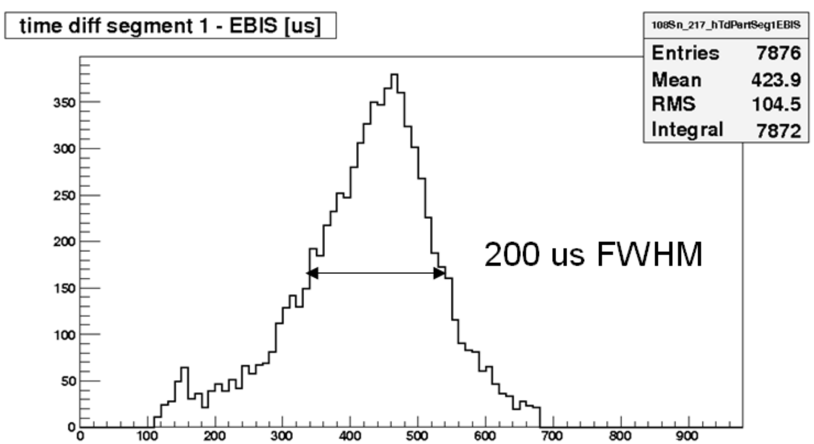
Slow extraction



- Bunched beam = high instantaneous rate -> dead time
- Good signal to noise ratio



normal extraction, 14N4+, measured in front of linac



Slow extraction, 108Sn, measured at Miniball