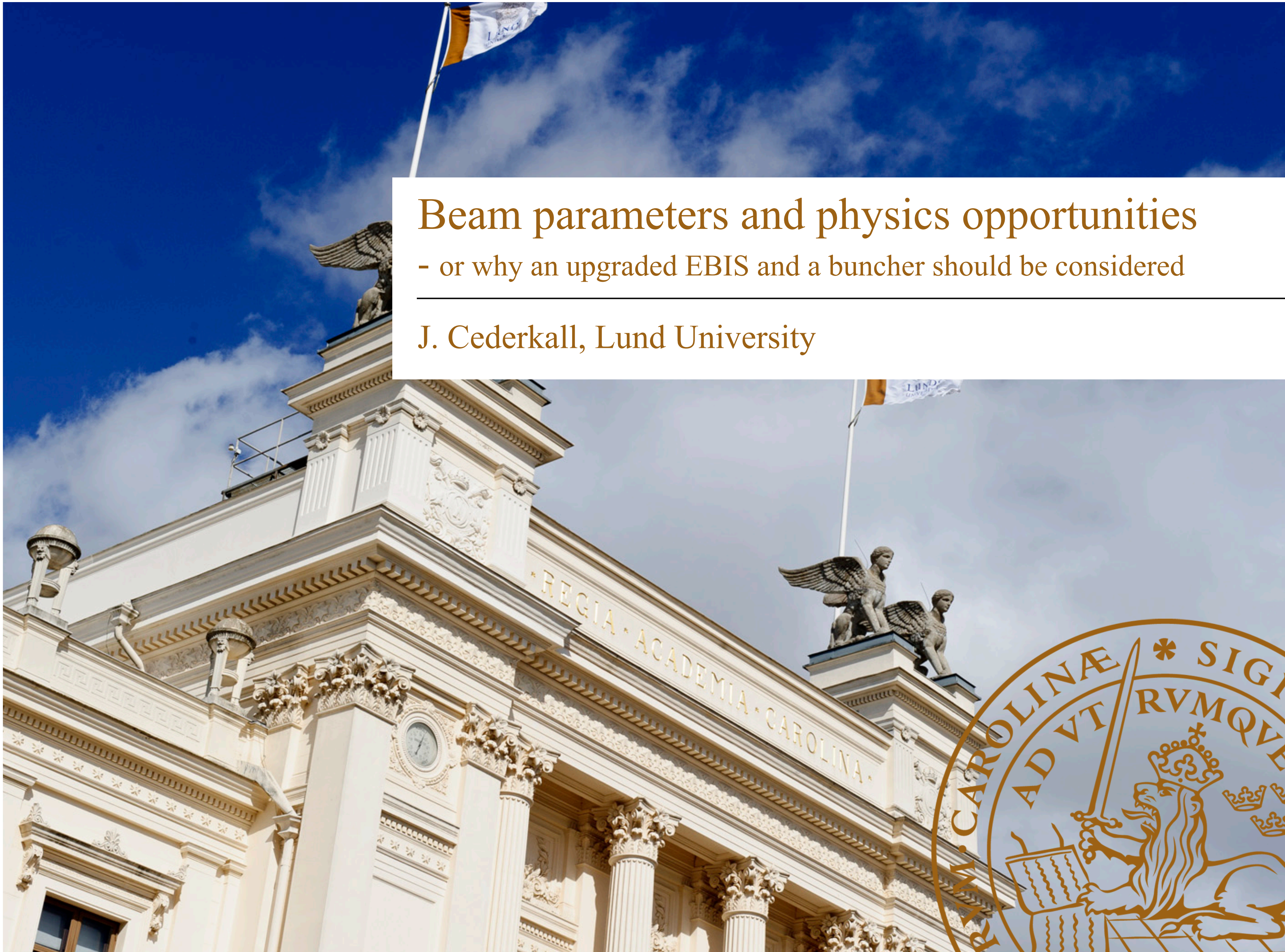


Beam parameters and physics opportunities

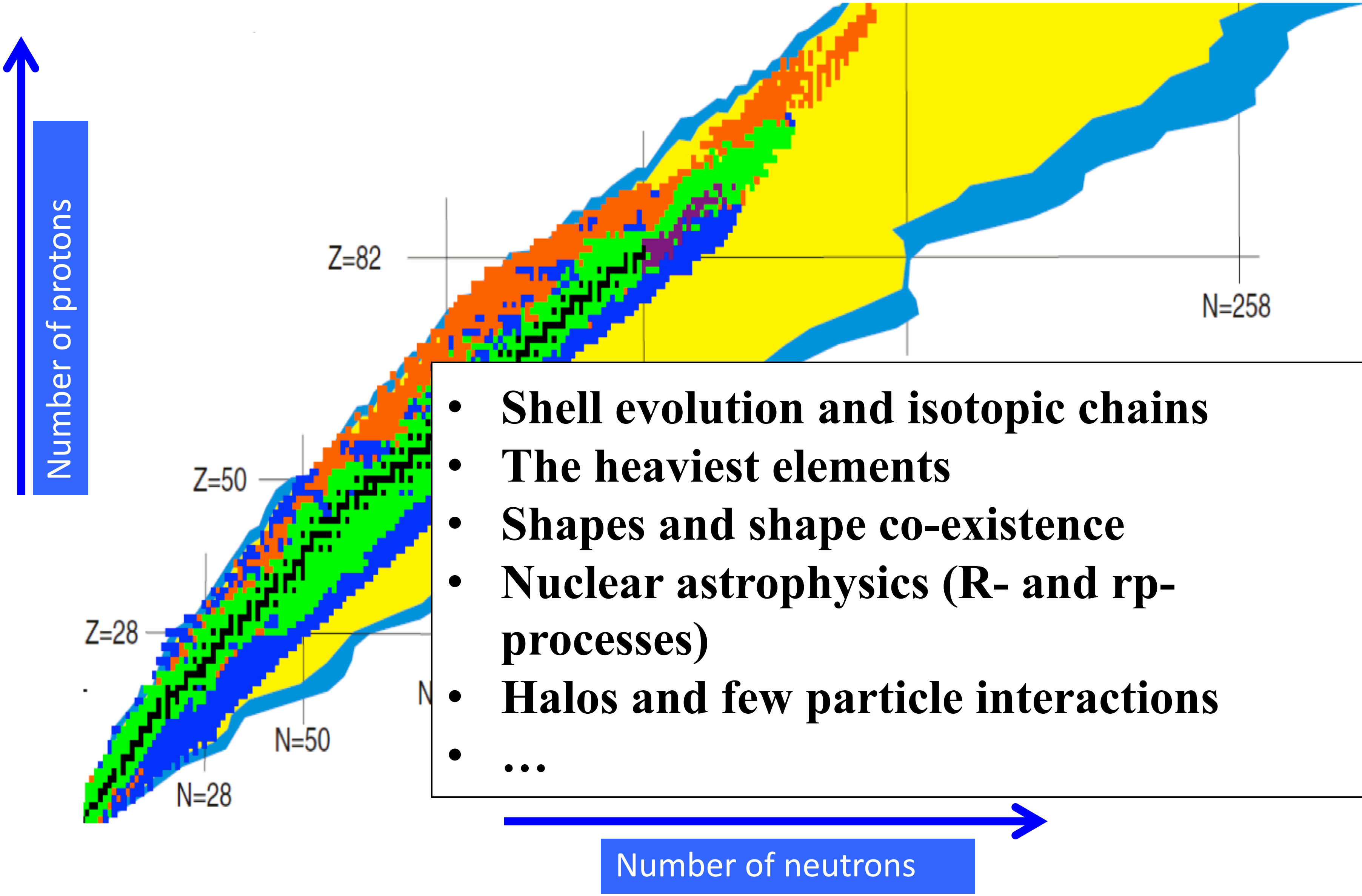
- or why an upgraded EBIS and a buncher should be considered

J. Cederkall, Lund University

What has been achieved? What is next?

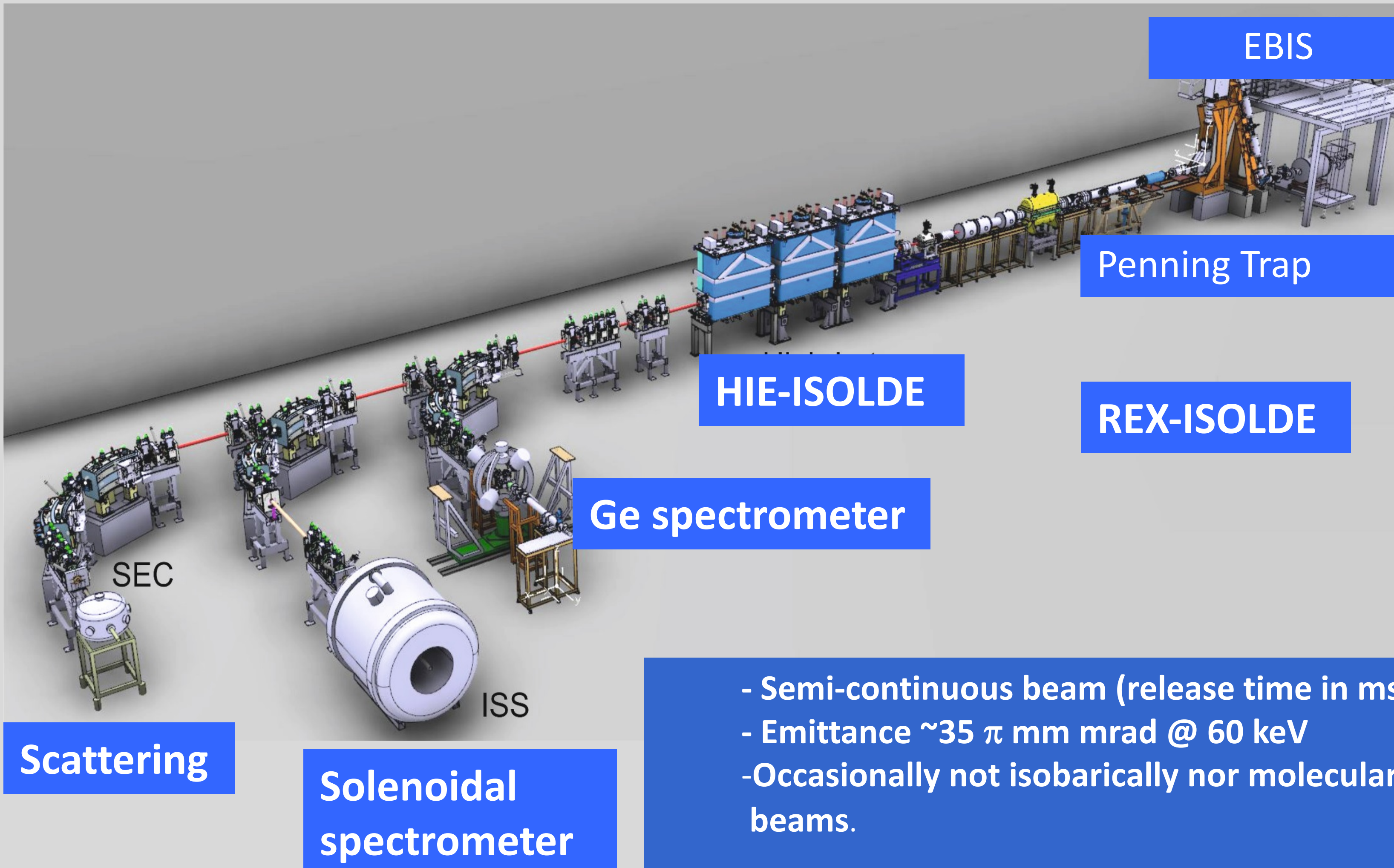
- **Some goals for HIE-ISOLDE with attempt at a combined physics–and-machine view**
- **What is the current status?**
- **What can we do next?**
- **Which generic developments could/should we focus on?**

Some physics for accelerated RIBs



- **Shell evolution and isotopic chains**
- **The heaviest elements**
- **Shapes and shape co-existence**
- **Nuclear astrophysics (R- and rp-processes)**
- **Halos and few particle interactions**
- **…**

REX-ISOLDE and HIE-ISOLDE (evolution…)



- Semi-continuous beam (release time in ms range)
- Emittance ~35 π mm mrad @ 60 keV
- Occasionally not isobarically nor molecularly clean beams.

HIE-ISOLDE energy upgrade TDR, Y. Kadi (ed).

Table 1.1: Requested beam characteristics at HIE-ISOLDE.

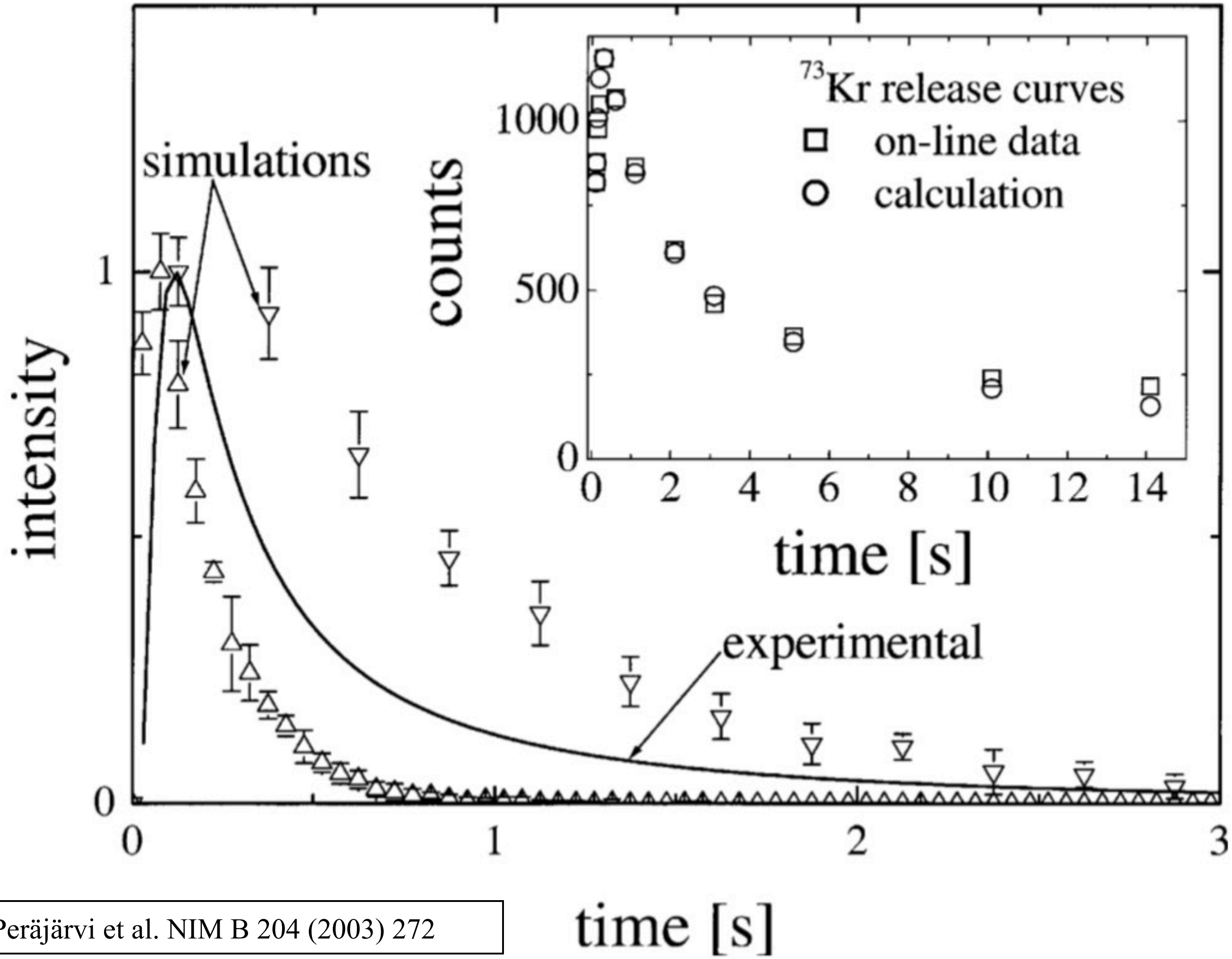
Beam parameter	**Description or value**
Energy	continuous from < 0.7 to at least 10 MeV/u
Beam spot diameter	$< 1 - 3$ mm FWHM
Beam divergence	$< 1 - 3$ mrad FWHM
Micro-bunch structure[a]	no requirement of micro-bunching to bunch at < 1 ns FWHM with ~ 100 ns bunch spacing
Macro-bunch structure[a]	longer pulse lengths or cw operation
Energy spread	$< 0.1\%$
Absolute energy resolution[b]	no specific details given

[a] The time structure of the beam is determined by the charge breeder and the REX front end, see Figure 2.4.

[b] No system currently exists to measure the absolute beam energy; time-of-flight systems are being discussed.

CERN-2018-002-M

Effusion, diffusion and decay



K. Peräjärvi et al. NIM B 204 (2003) 272

The combined time structure

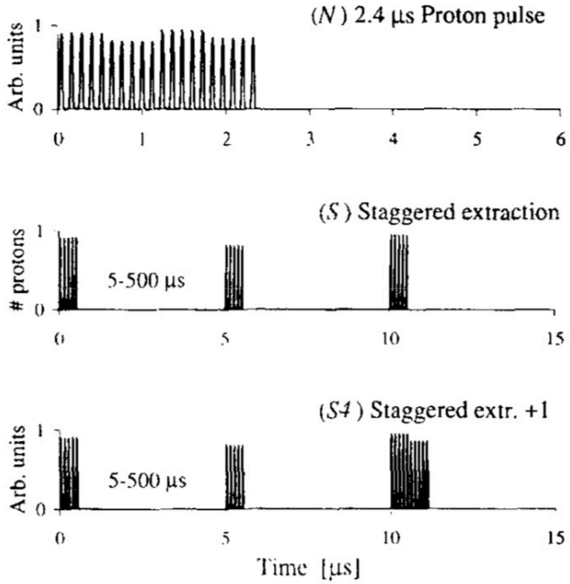


Fig. 1. The time structure of the PS-BOOSTER proton pulses is illustrated. A standard proton pulse (*N*) contains up to 3×10^{13} protons distributed in 20 bunches over 2.4 µs. In the staggered mode (*S*) three groups of 5 bunches are extracted at time intervals ranging from 5 to 500 µs (maximum pulse intensity: 2.2×10^{13} ppp). The maximum proton pulse intensity is obtained by immediate extraction of the last synchrotron (S4).

Semi-continuous beams already from the primary target.

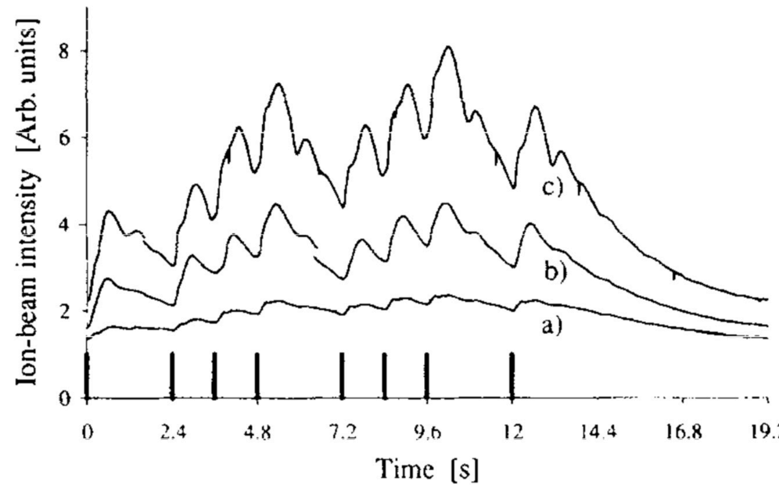


Fig. 6. The ionic current of ^{190}Hg as recorded with a 0.5 mm metallic needle is shown for different proton beam intensities in the staggered mode (a) 9×10^{12}, (b) 1.5×10^{13} and (c) 2.1×10^{13} proton per pulse. The parameters of the release function from which the release time is calculated were fitted to these data. The timing of the 8 proton pulses in the 19.2 s cycle is shown.

J. Lettry et al. NIM B 126 (1997) 170

The pulse structure

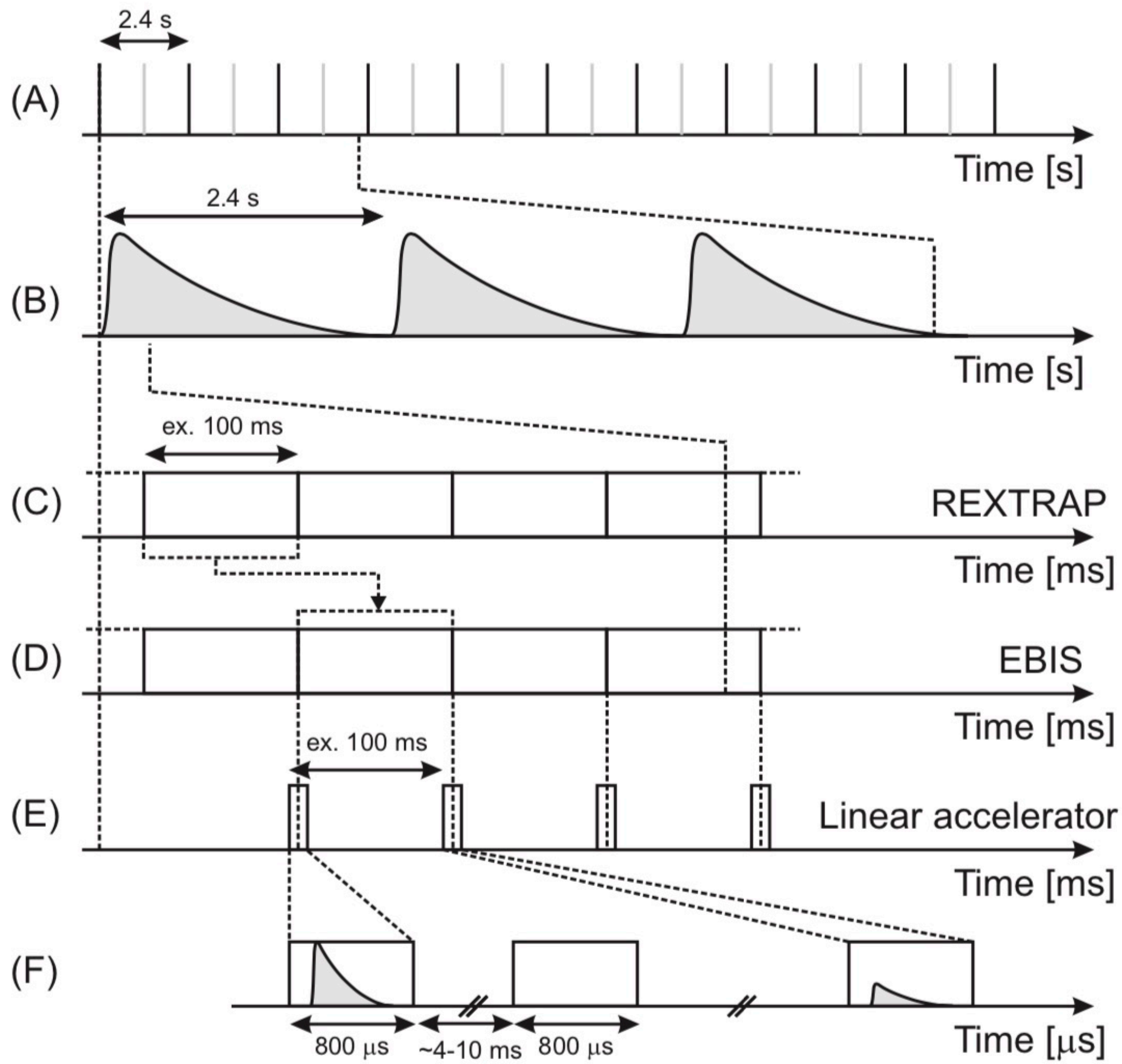
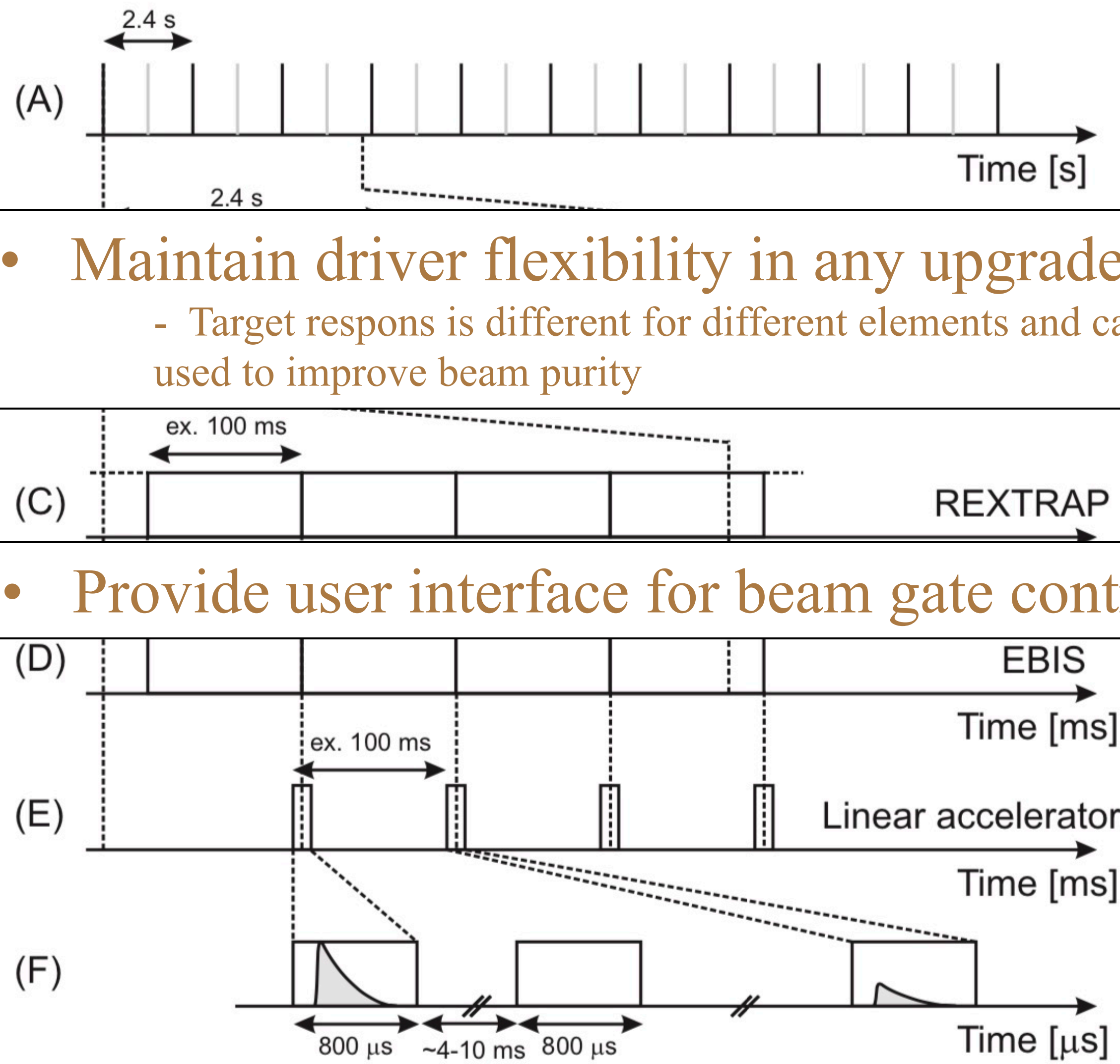


Fig. 2.4: REX beam time structure. Figure courtesy of J. van de Walle.

HIE-ISOLDE upgrade TDR CERN-2018-002-M Y. Kadi, M. A. Fraser A. Papageorgiou-Koufidou (eds.)

The pulse structure



- Maintain driver flexibility in any upgrade
  - Target respons is different for different elements and can be used to improve beam purity

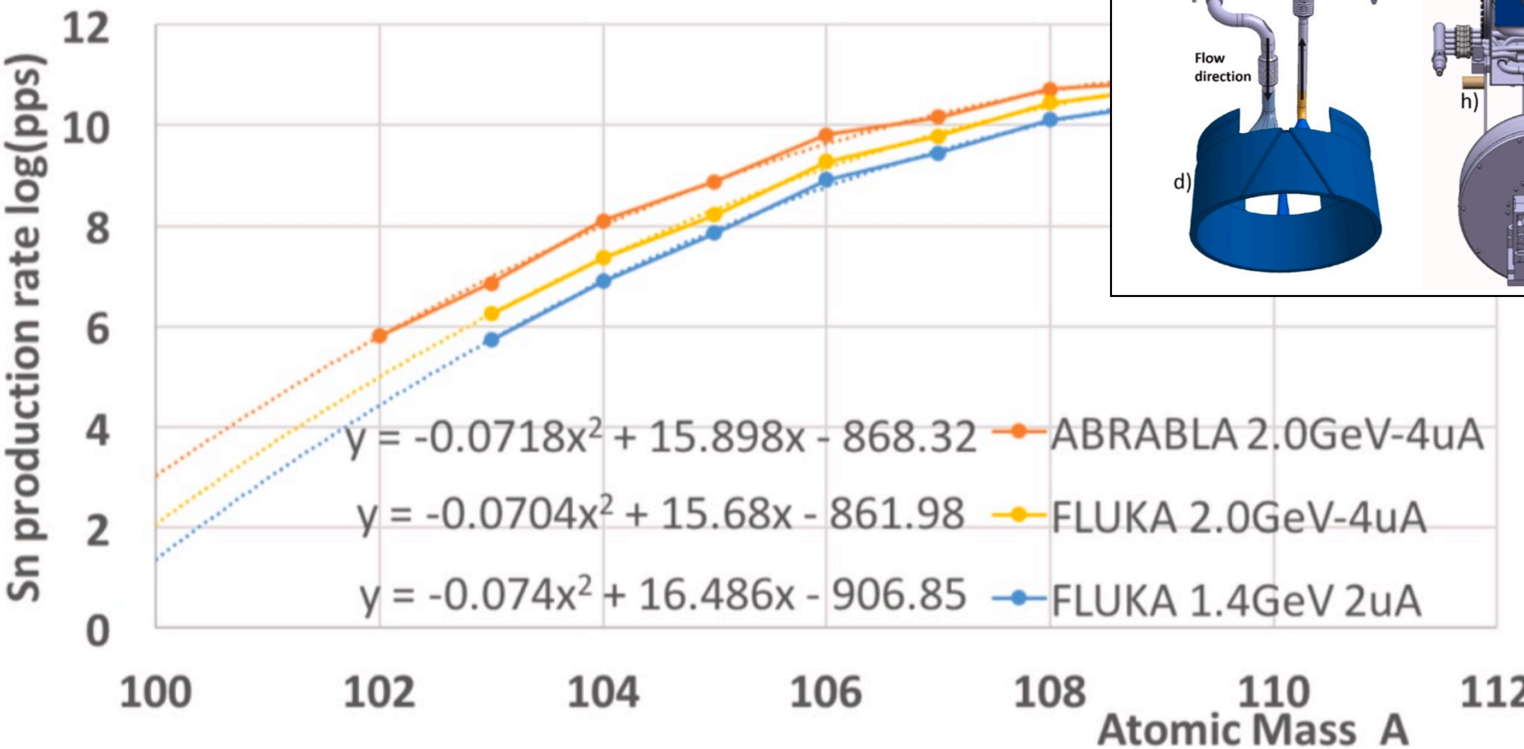
- Provide user interface for beam gate control

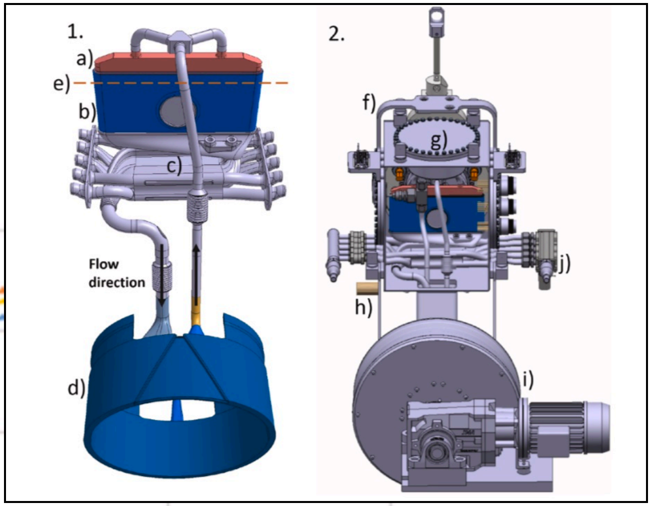
Fig. 2.4: REX beam time structure. Figure courtesy of J. van de Walle.

HIE-ISOLDE upgrade TDR CERN-2018-002-M Y. Kadi, M. A. Fraser A. Papageorgiou-Koufidou (eds.)

Target development for future improved yields?

LIEBE target

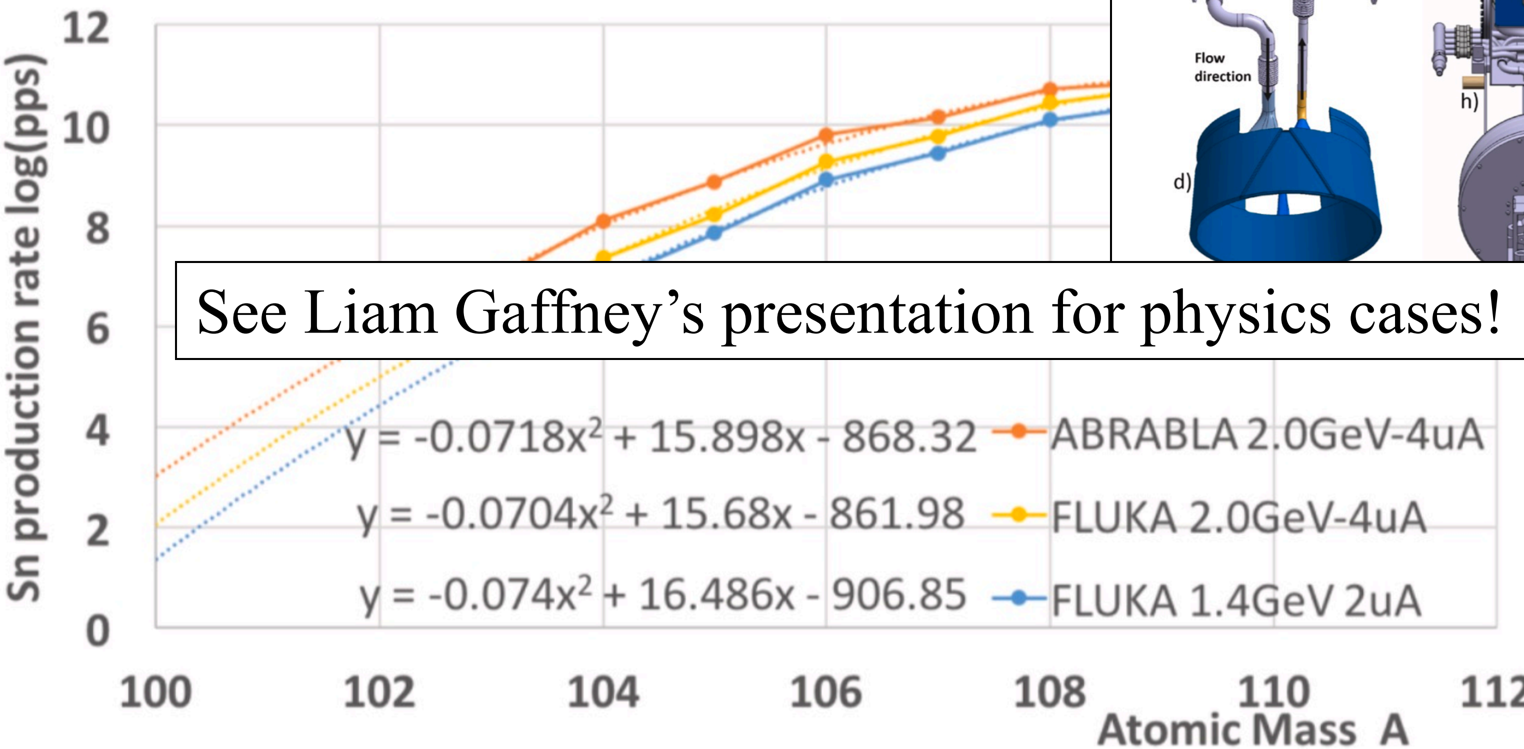


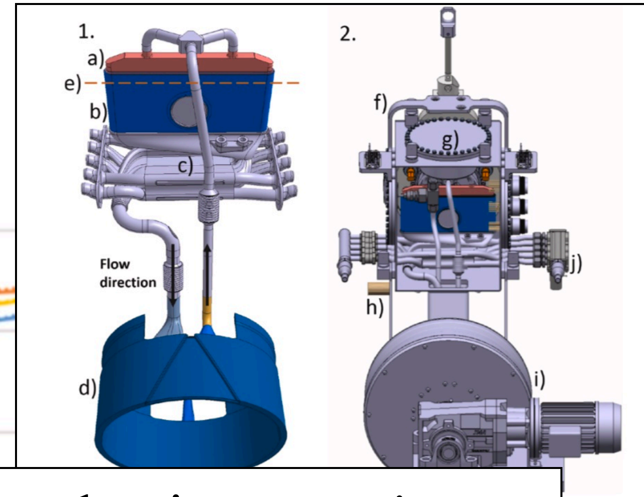


F.Boix Pamies, T.Stora, E.Barbero et al. NIM B https://doi.org/10.1016/j.nimb.2019.06.043

Future Improved Yields?

LIEBE target

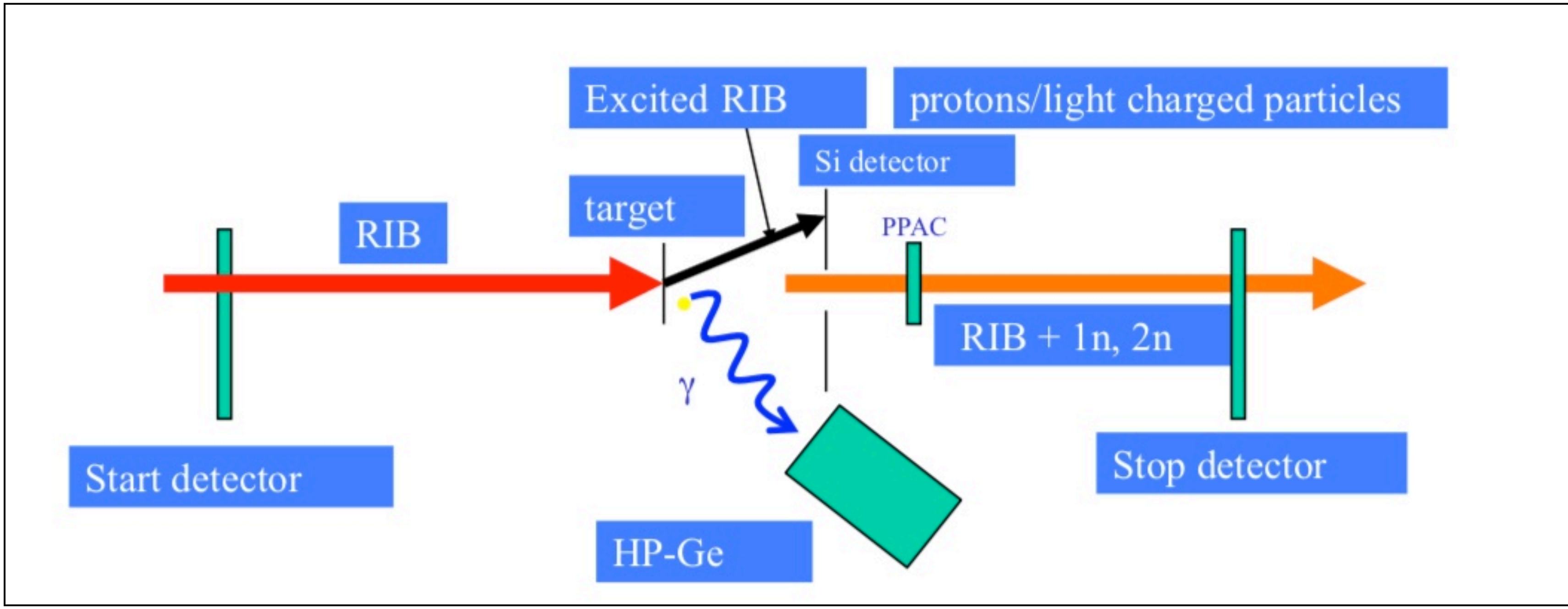


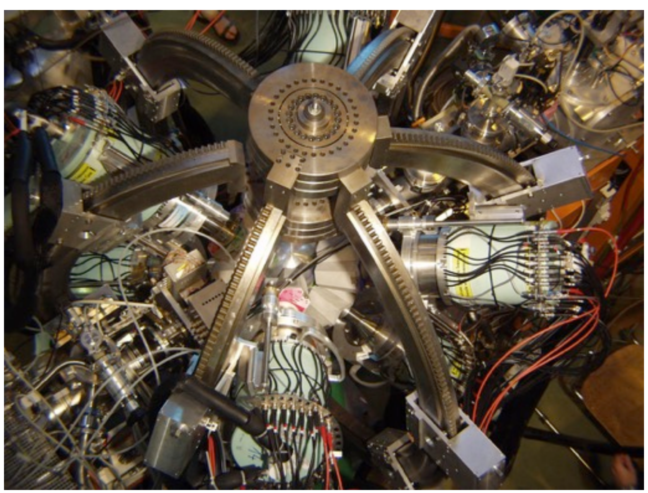


See Liam Gaffney's presentation for physics cases!

F.Boix Pamies, T.Stora, E.Barbero et al. NIM B https://doi.org/10.1016/j.nimb.2019.06.043

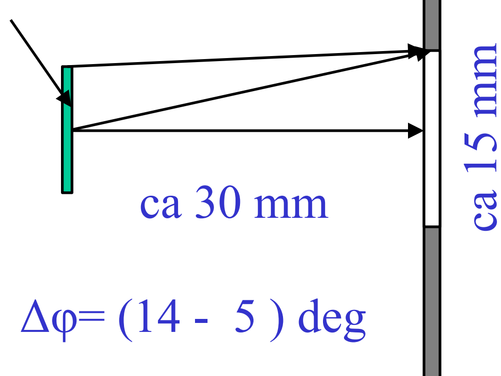
The principle



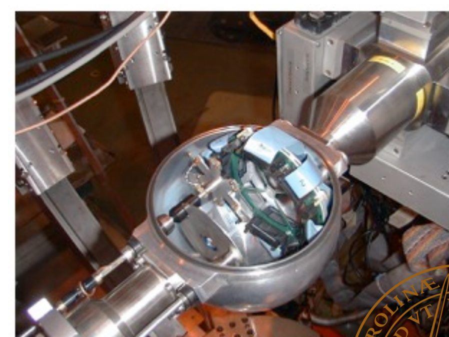


Worst case:

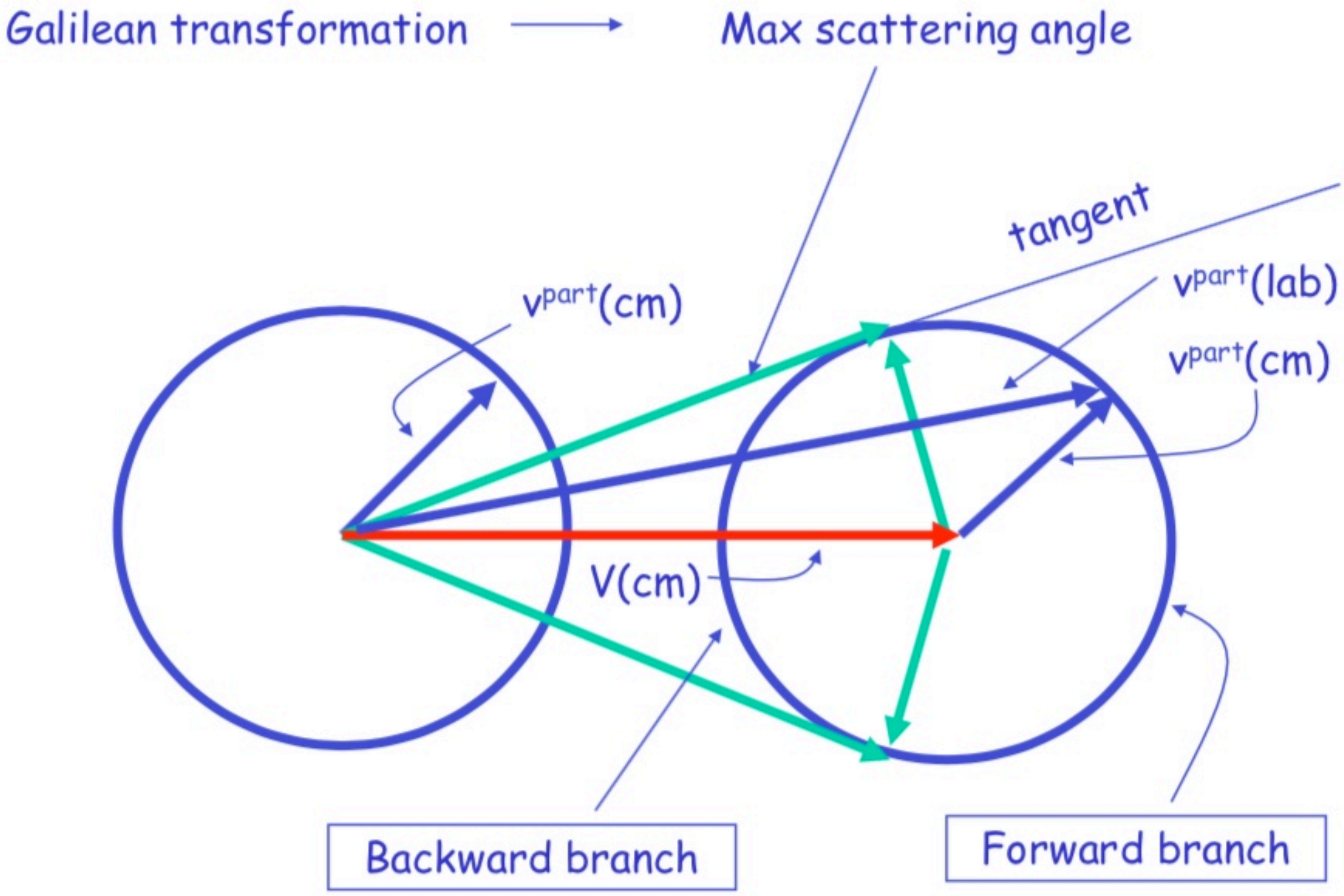
assume ca 10 mm



$\Delta\varphi$= (14 - 5) deg



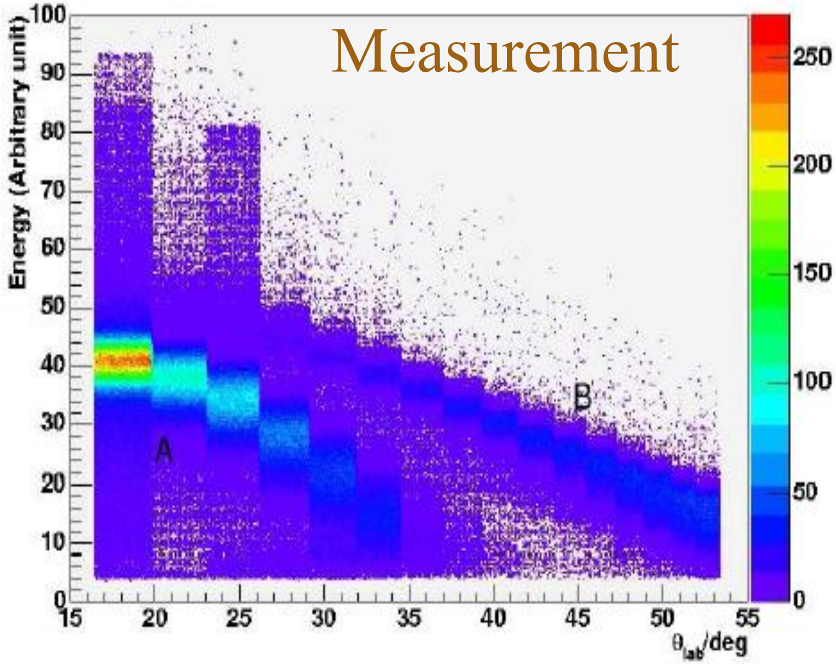
Kinematics

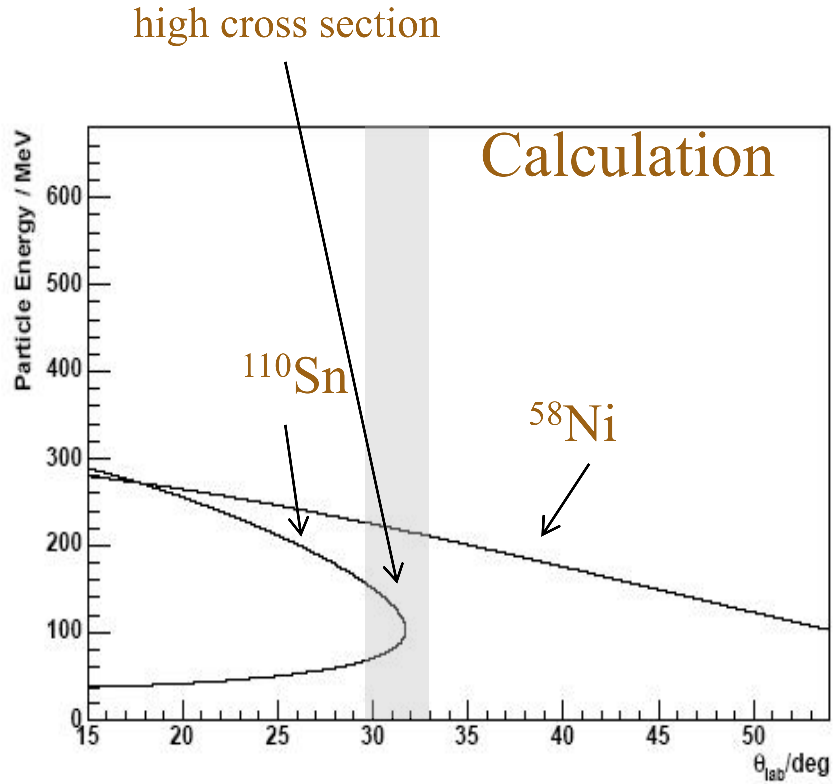


Galilean transformation
Max scattering angle
tangent
v^{part}(cm)
v^{part}(lab)
v^{part}(cm)
V(cm)
Backward branch
Forward branch

Kinematics I

$^{110,108,106}Sn$ on ^{58}Ni at 2.8 MeV/u

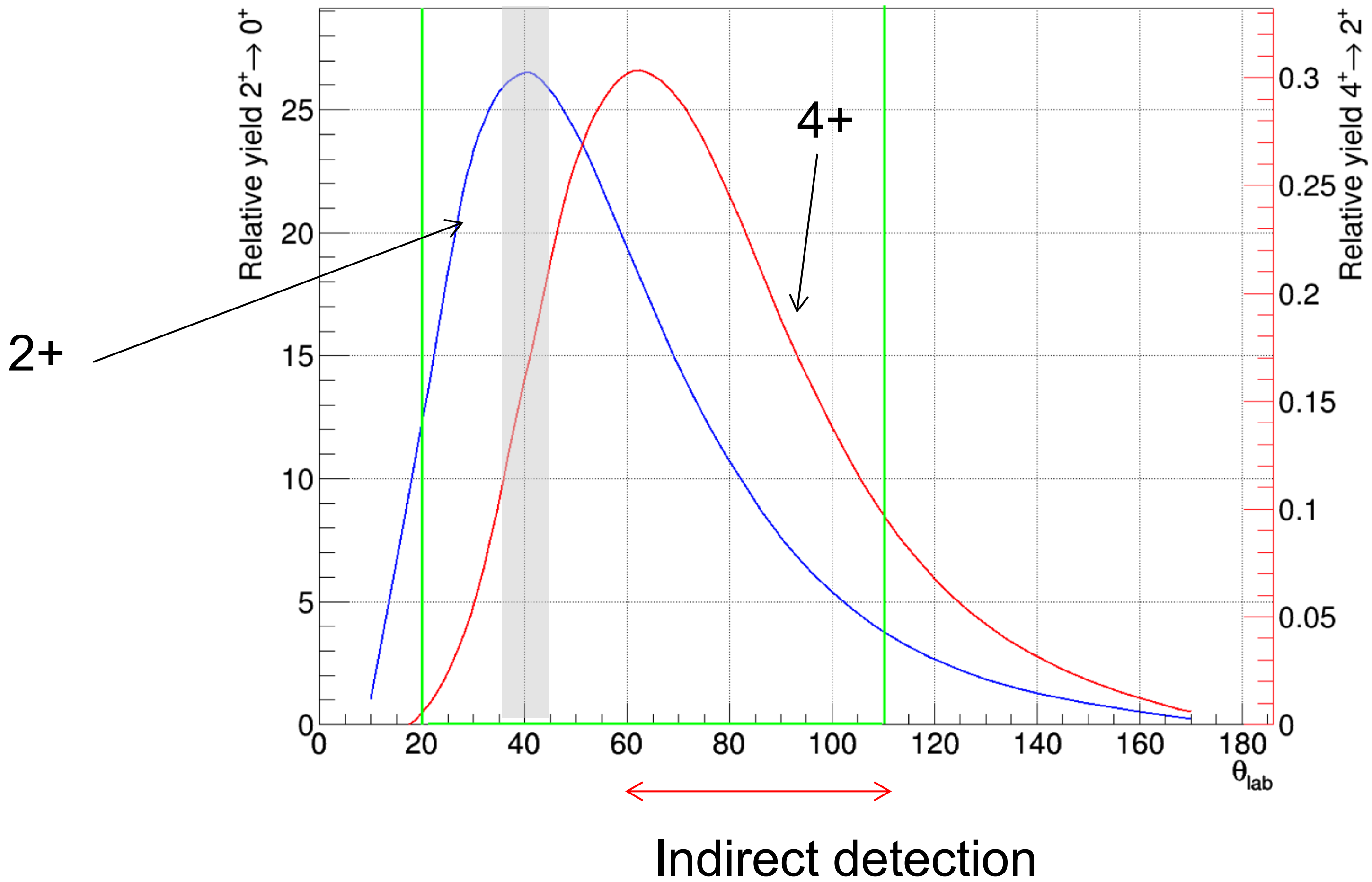




Energy in lab vs scattering angle

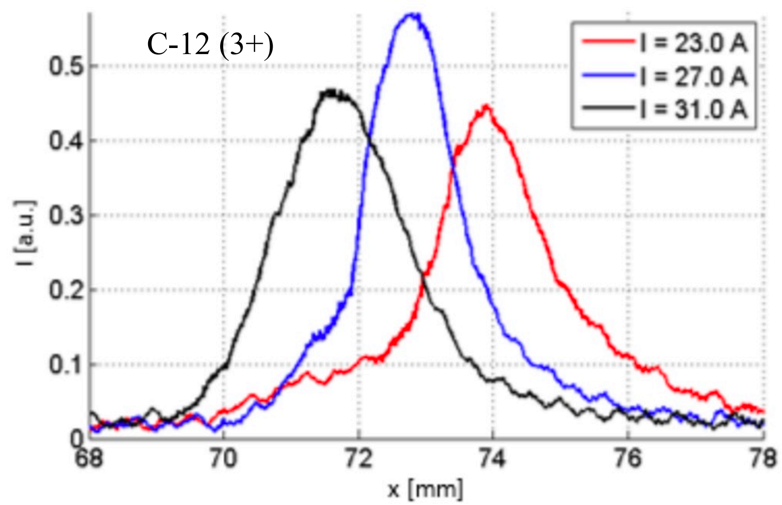
Cross section for a 2^+ and 4^+ excitation

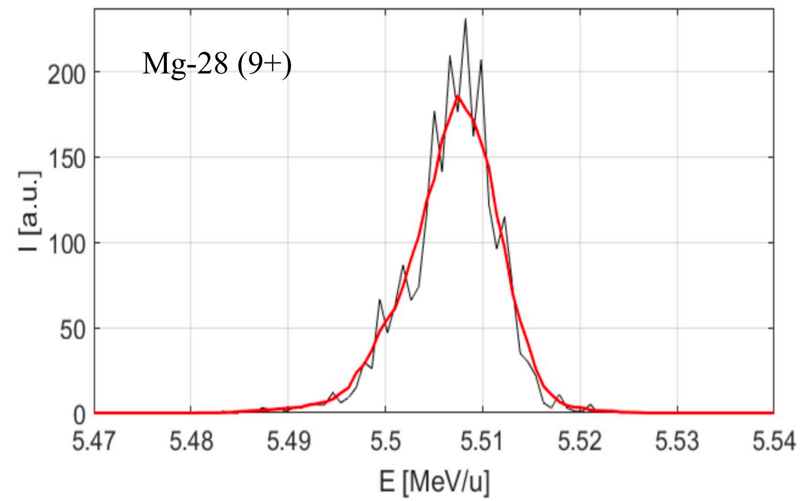
Sn-110 and Pb-206

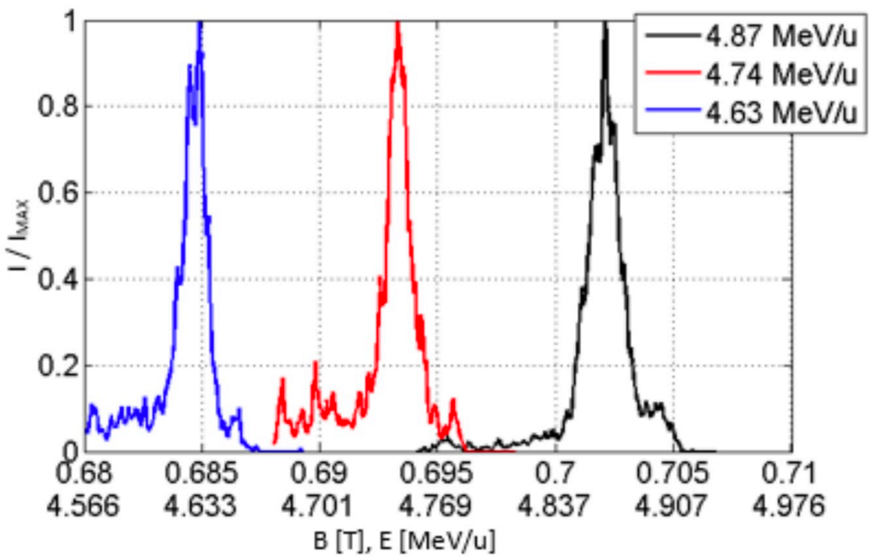


Energy spread and beam spot size

HIE-ISOLDE TDR CERN-2018-002-M Y. Kadi, M. A. Fraser A. Papageorgiou-Koufidou (eds.)





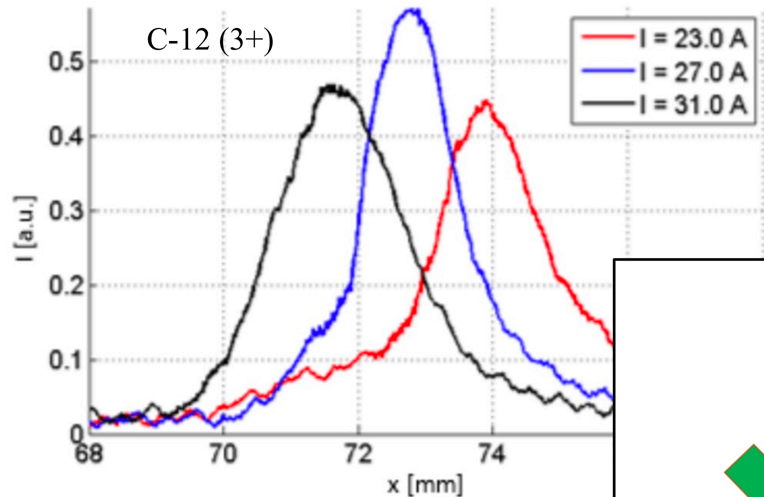


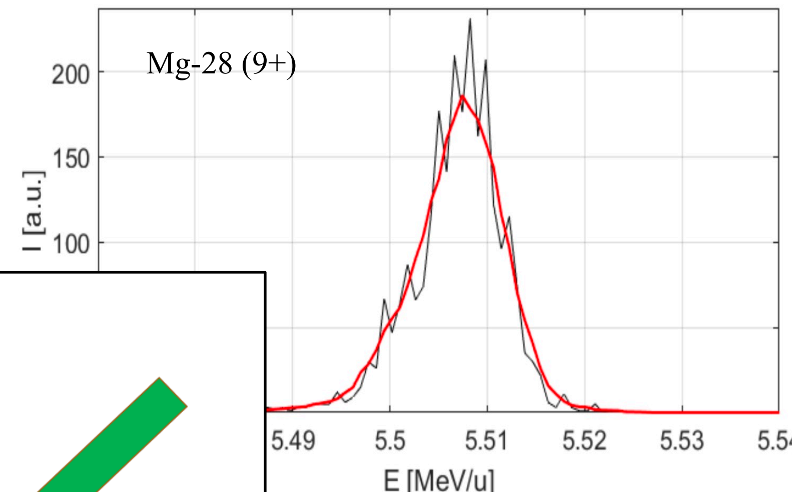
	Nominal Energy [MeV/u]	Measured Energy [MeV/u]	Energy Spread [%]
66Ni16+	4.5	4.47	0.2
9Li3+	6.9	6.72	0.5
132Sn31+	5.5	5.49	0.4
78Zn20+	4.3	4.27	0.3

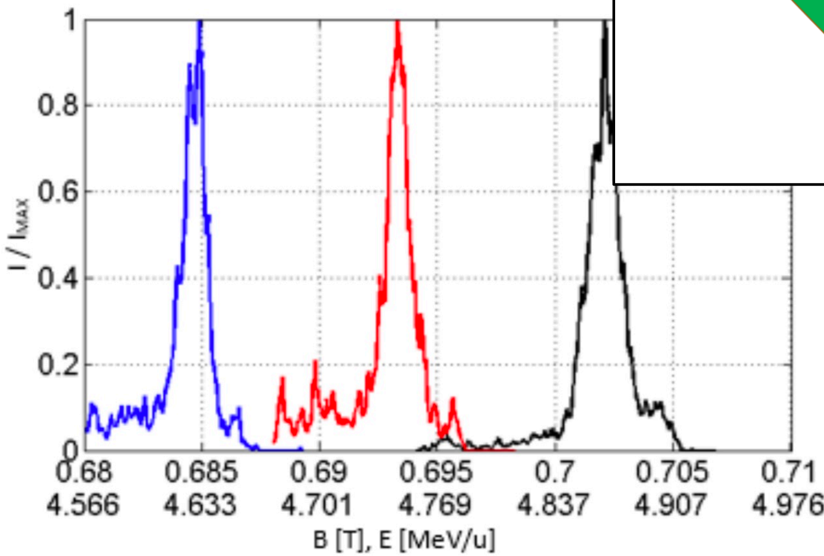
J … odriguez el al. priv comm.

Energy spread and beam spot size

HIE-ISOLDE TDR CERN-2018-002-M Y. Kadi, M. A. Fraser A. Papageorgiou-Koufidou (eds.)







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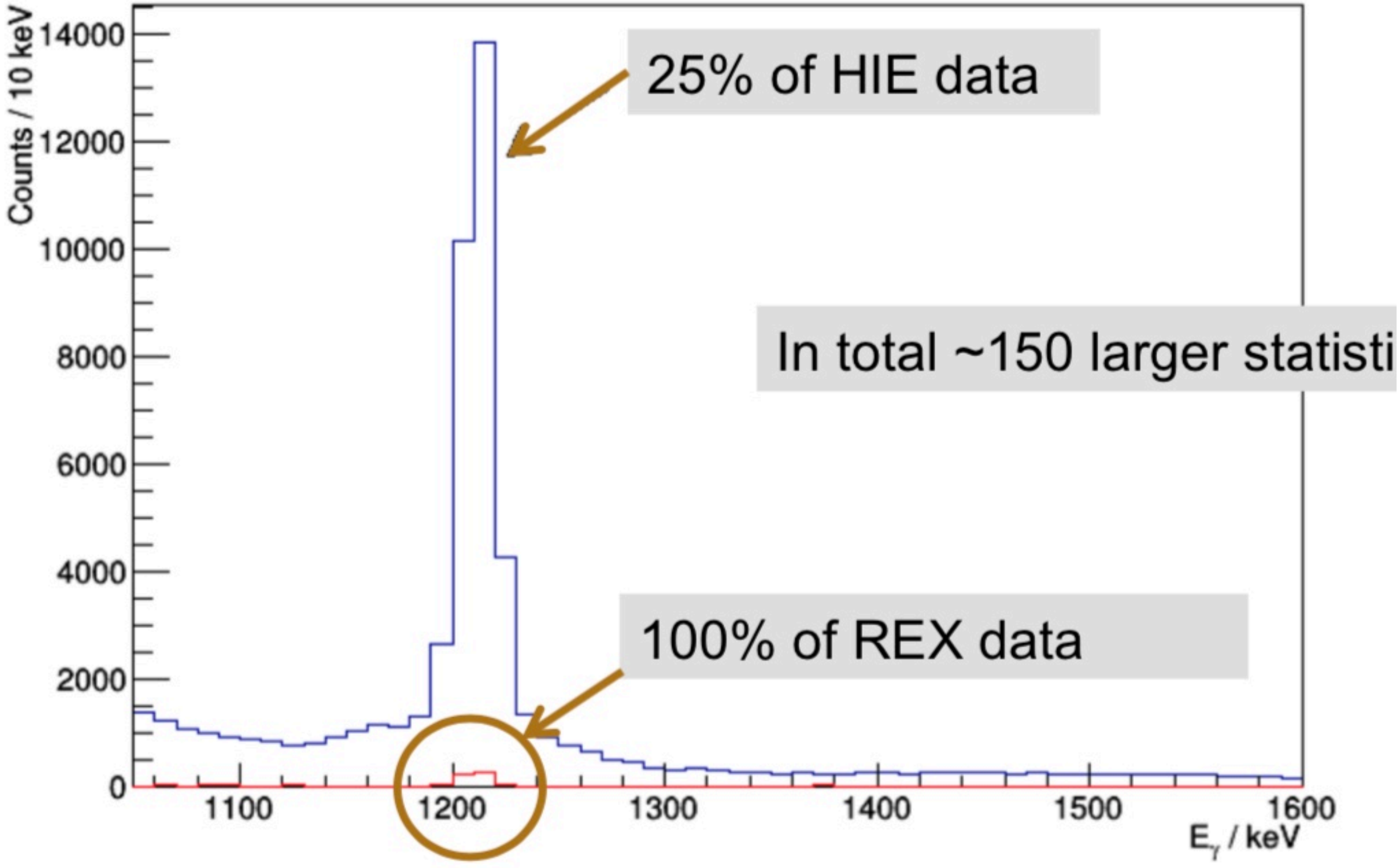
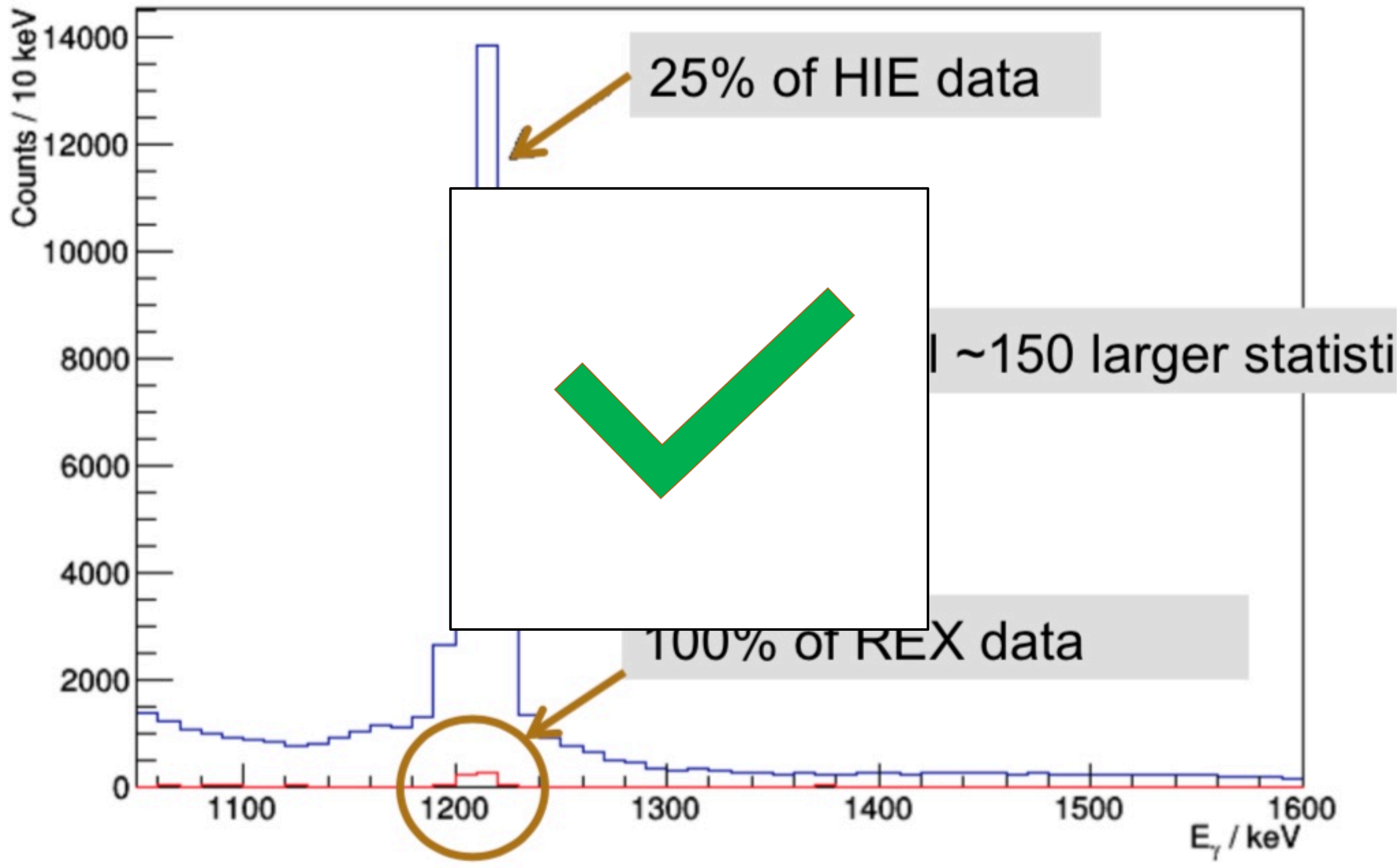
J. A. Rodriguez Rodriguez el al. priv comm.

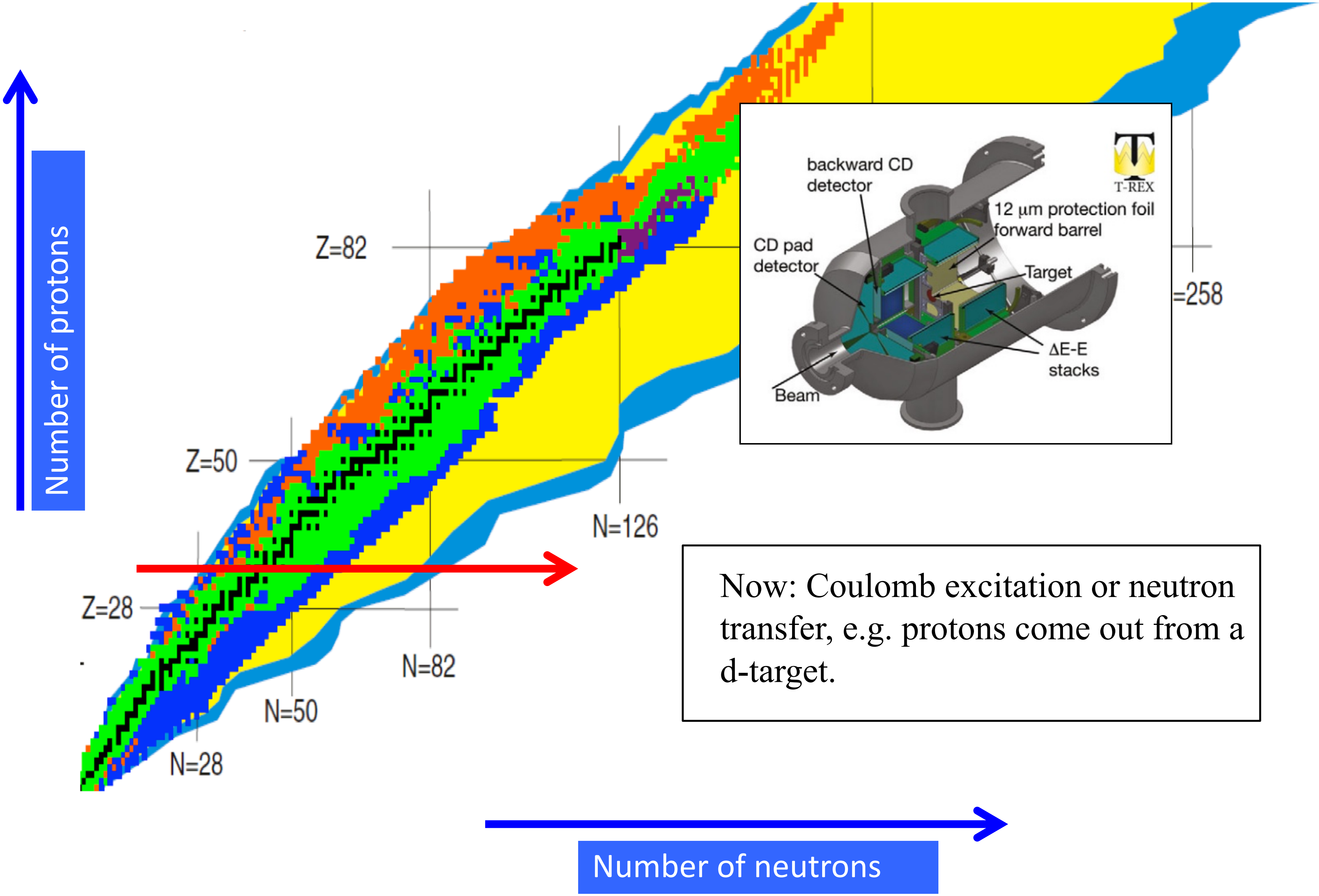
Statistics now and then



Statistics now and then



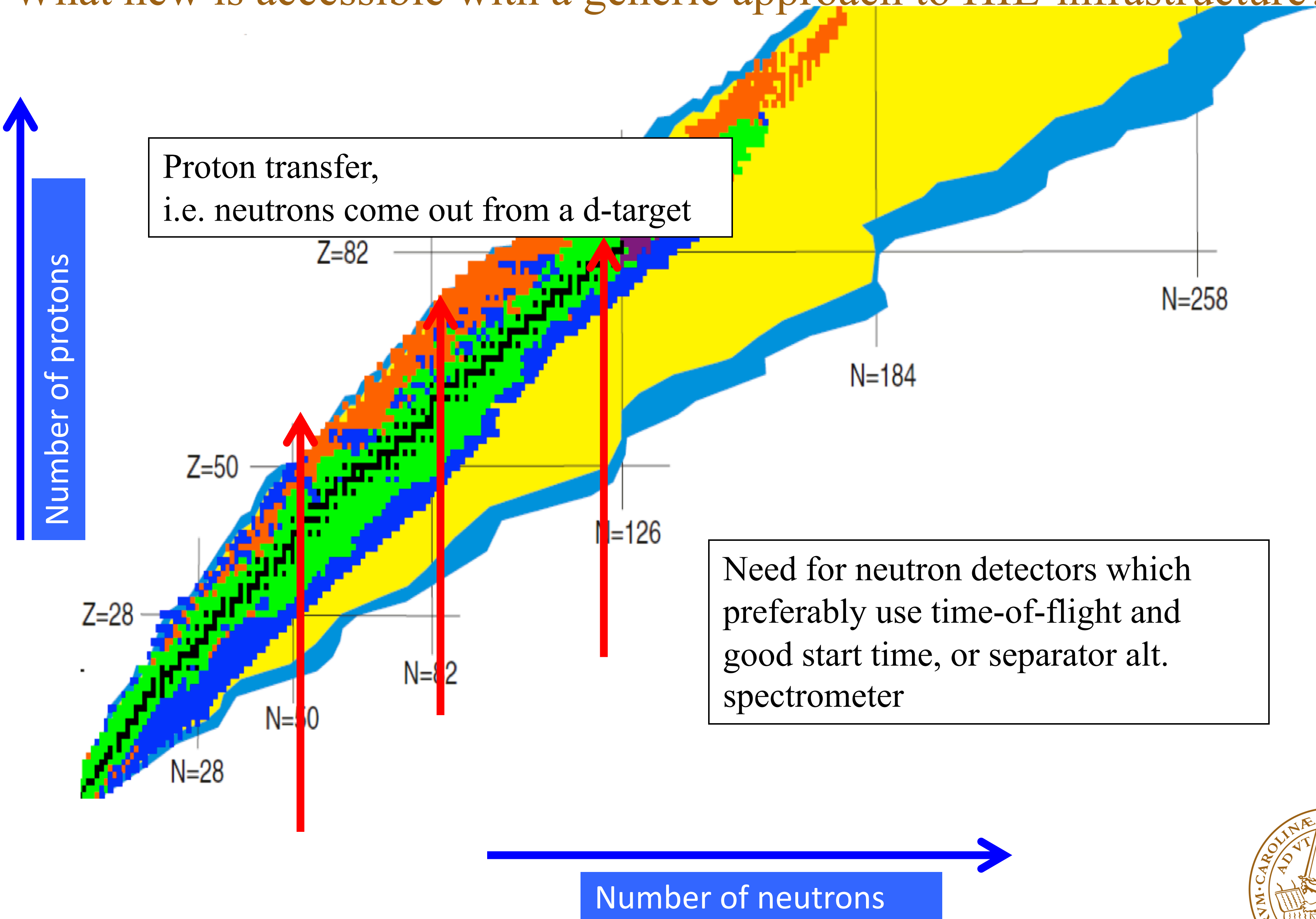
What is accessible with a generic approach to HIE-infrastructure?



Now: Coulomb excitation or neutron transfer, e.g. protons come out from a d-target.

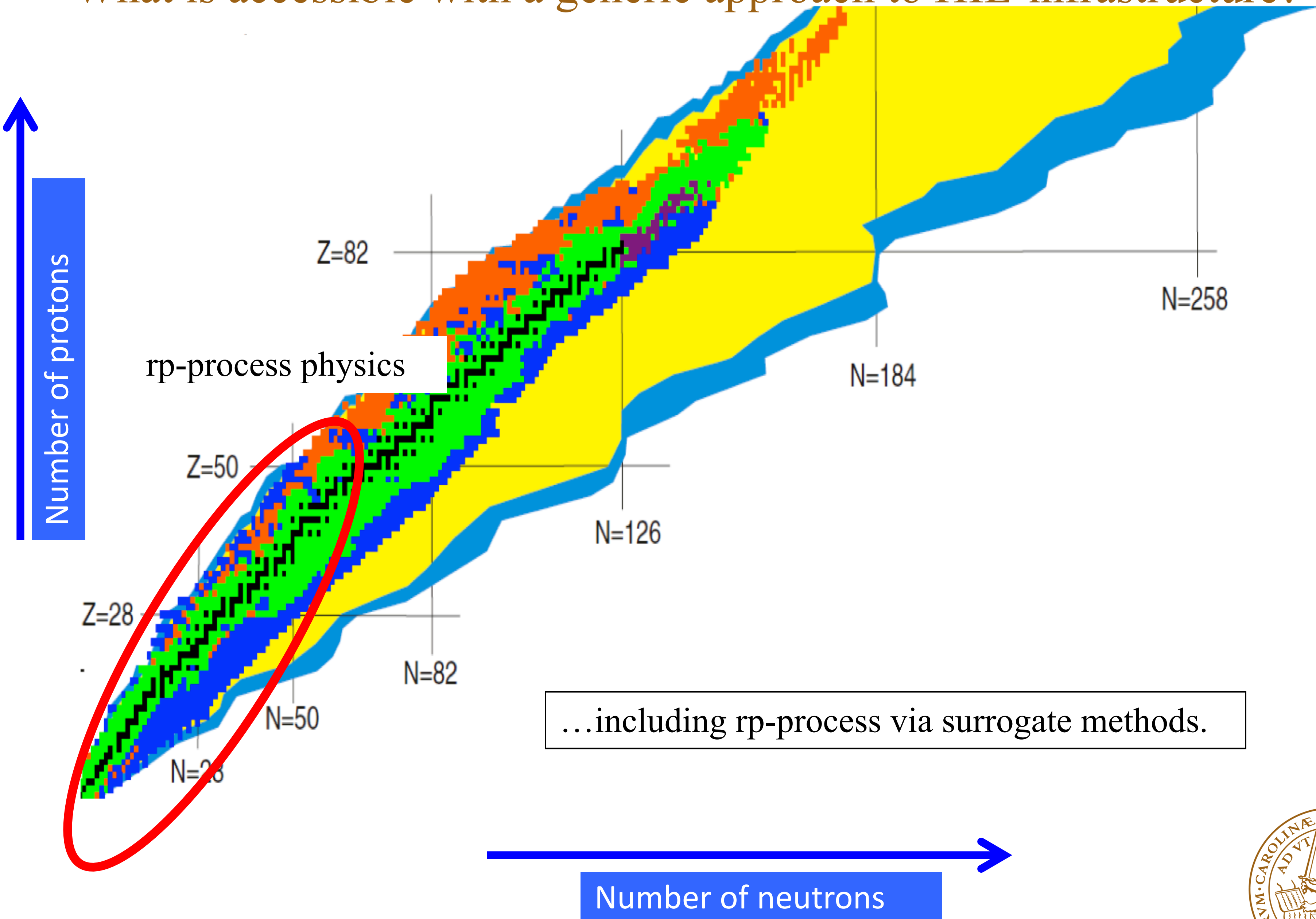
What new is accessible with a generic approach to HIE-infrastructure?

Proton transfer,
i.e. neutrons come out from a d-target



Need for neutron detectors which preferably use time-of-flight and good start time, or separator alt. spectrometer

What is accessible with a generic approach to HIE-infrastructure?



Single particle dominated states

For two particles outside a core:

$$
\begin{aligned}
H &= \underbrace{\sum_{k=3}^{A}[T_k + U(\vec{r}_k)] + \sum_{k=3}^{A}\sum_{l=k+1}^{A} W(\vec{r}_k,\vec{r}_l) - \sum_{k=3}^{A} U(\vec{r}_k)}_{H_{core}} \\
&+ \underbrace{\sum_{k=1}^{2}[T_k + U(\vec{r}_k)]}_{H_0^1+H_0^2 \;\; independent \;\; motion} + \underbrace{\sum_{k=1}^{2}\sum_{l=k+1}^{A} W(\vec{r}_k,\vec{r}_l) - \sum_{k=1}^{2} U(\vec{r}_k)}_{H_{12} \;\; interaction}
\end{aligned}
$$

$$
\begin{aligned}
H_{12} &= \underbrace{\sum_{l=3}^{A} W(\vec{r}_1,\vec{r}_l) - U(r_1)}_{\approx 0} + \underbrace{\sum_{l=3}^{A} W(\vec{r}_2,\vec{r}_l) - U(r_2)}_{\approx 0} + W(\vec{r}_1,\vec{r}_2) \\
&= V(\vec{r}_1,\vec{r}_2)
\end{aligned}
$$

Single particle dominated states

$$E = \langle \Phi^0_{J,T} | H | \Phi^0_{J,T} \rangle = \underbrace{\langle \Phi^{core}_{J,T} | H_{core} | \Phi^{core}_{J,T} \rangle}_{Binding\ energy\ of\ core}$$

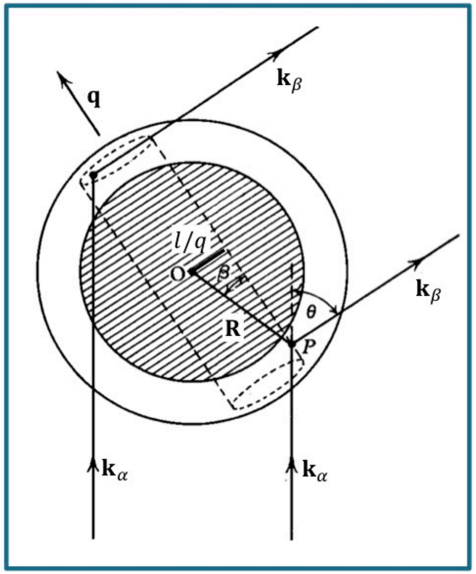
$$+ \underbrace{\langle \Phi^{\alpha_1,\alpha_2}_{J,T} | H_1 + H_2 | \Phi^{\alpha_1,\alpha_2}_{J,T} \rangle}_{E1+E2\ single-particle\ energies} + \underbrace{\langle \Phi^{\alpha_1,\alpha_2}_{J,T} | V(\vec{r}_1, \vec{r}_2) | \Phi^{\alpha_1,\alpha_2}_{J,T} \rangle}_{Interaction\ energy,\ two-body\ matrix\ element}$$

Transfer reactions

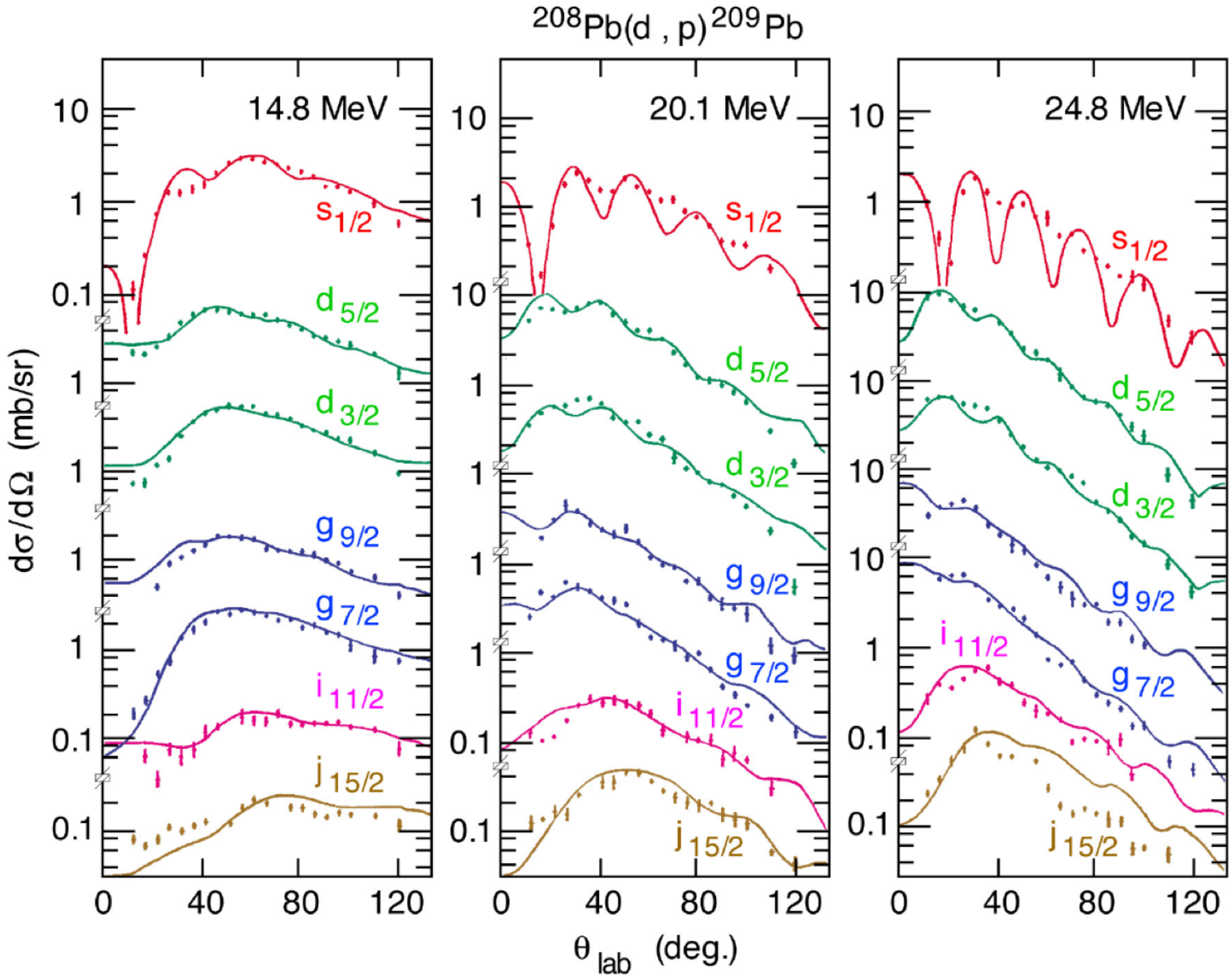
Angular momentum transfer: **l** = **q** x **R,** with q the transferred momentum.

Cross section ~ 1 mb
Target thickness 100 ug/cm^2 to mg/cm^2
Intensity ~ 10^4 pps

One can show that transferred angular momentum maps onto the scattering angle

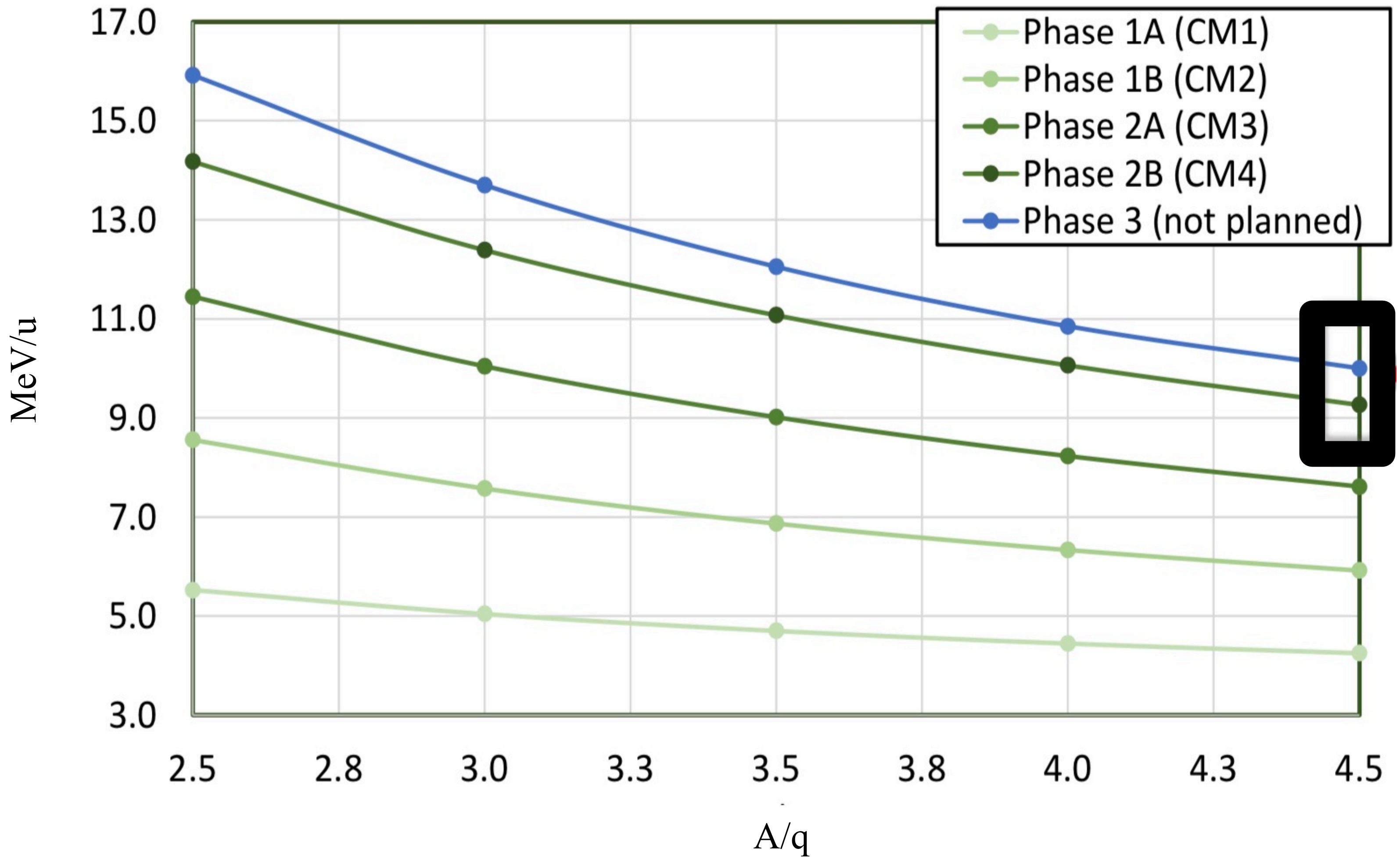


Angular distributions from (d,p)



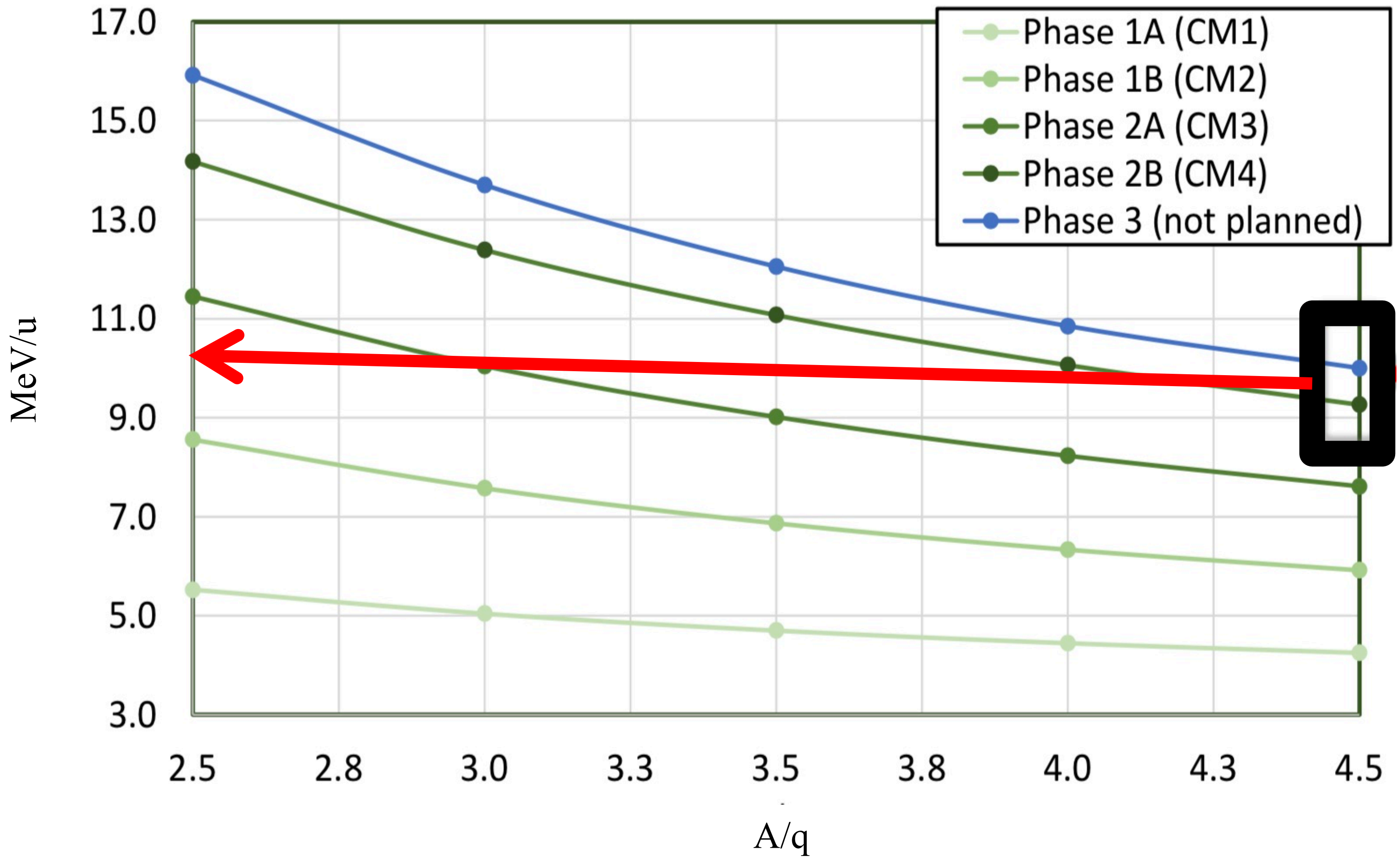
Muehllener et al.
Phys. Rev. 159, 1043 (1967)

Maximum energy



HIE-ISOLDE upgrade TDR CERN-2018-002-M Y. Kadi, M. A. Fraser A. Papageorgiou-Koufidou (eds.)

Maximum energy



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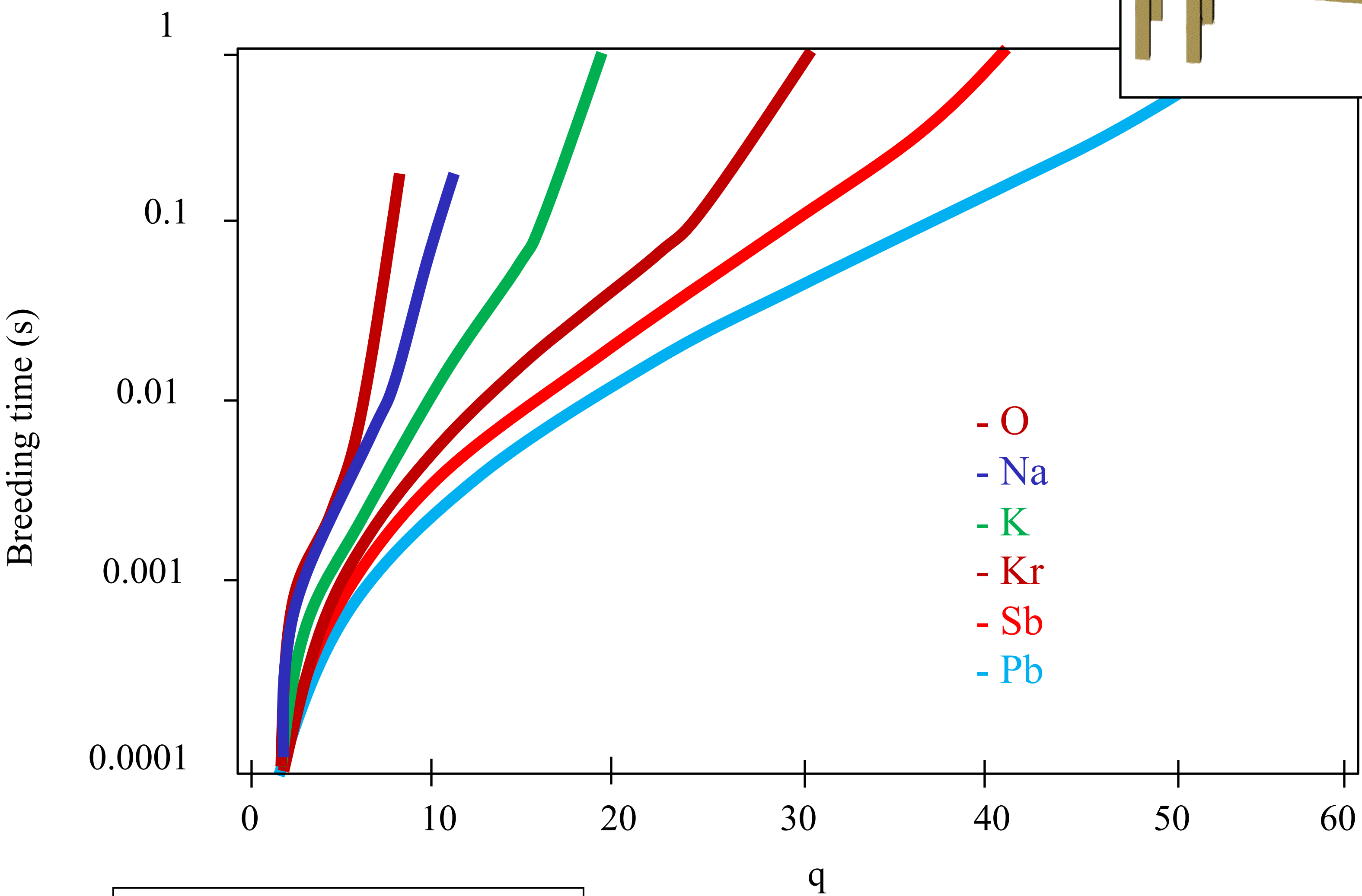
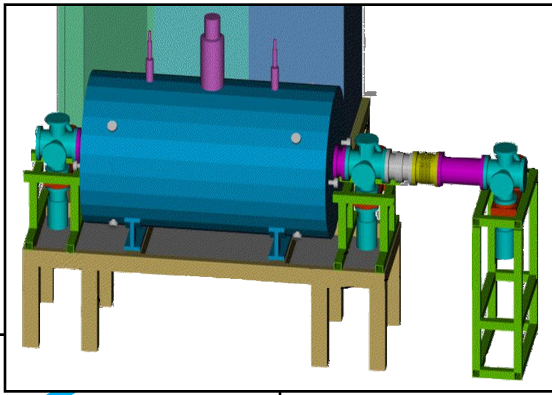
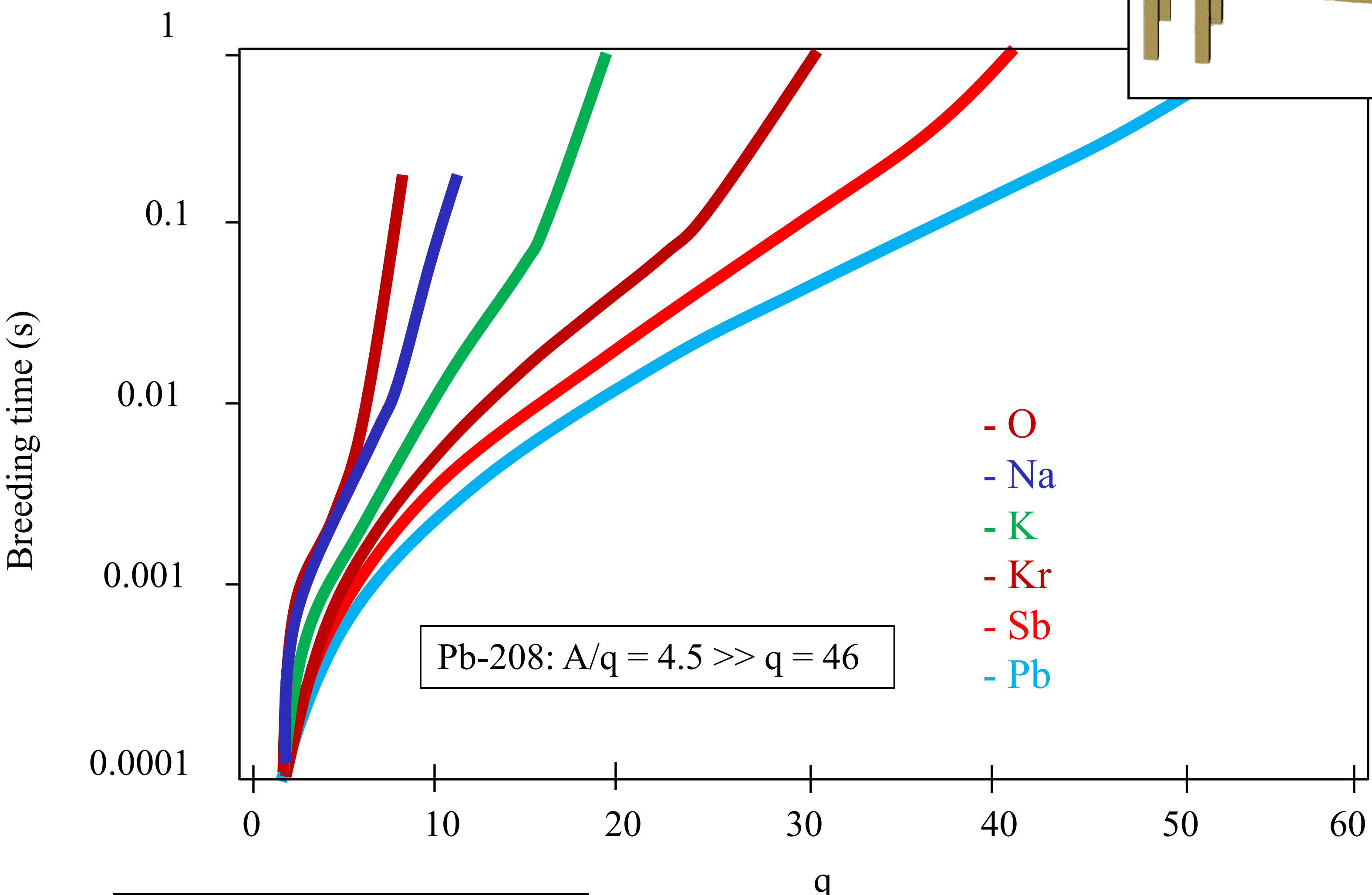
EBIS current situation

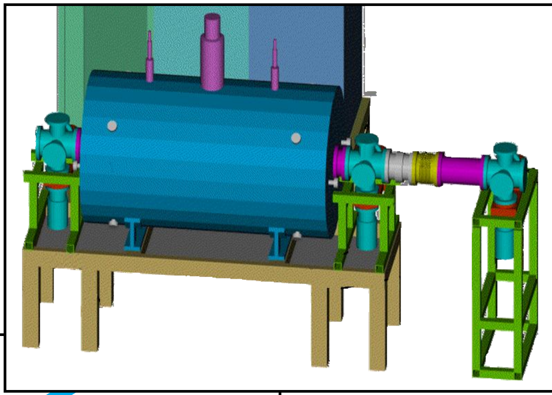




Courtesy F. Wenander

EBIS current situation





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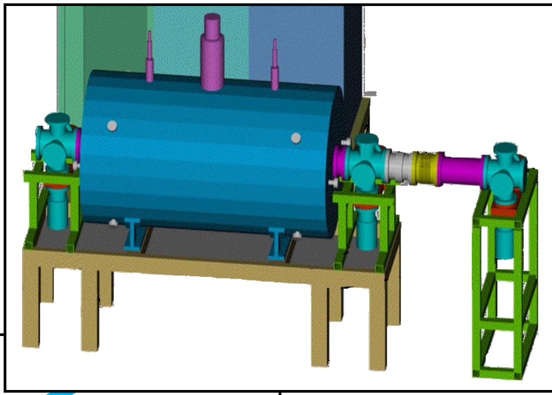
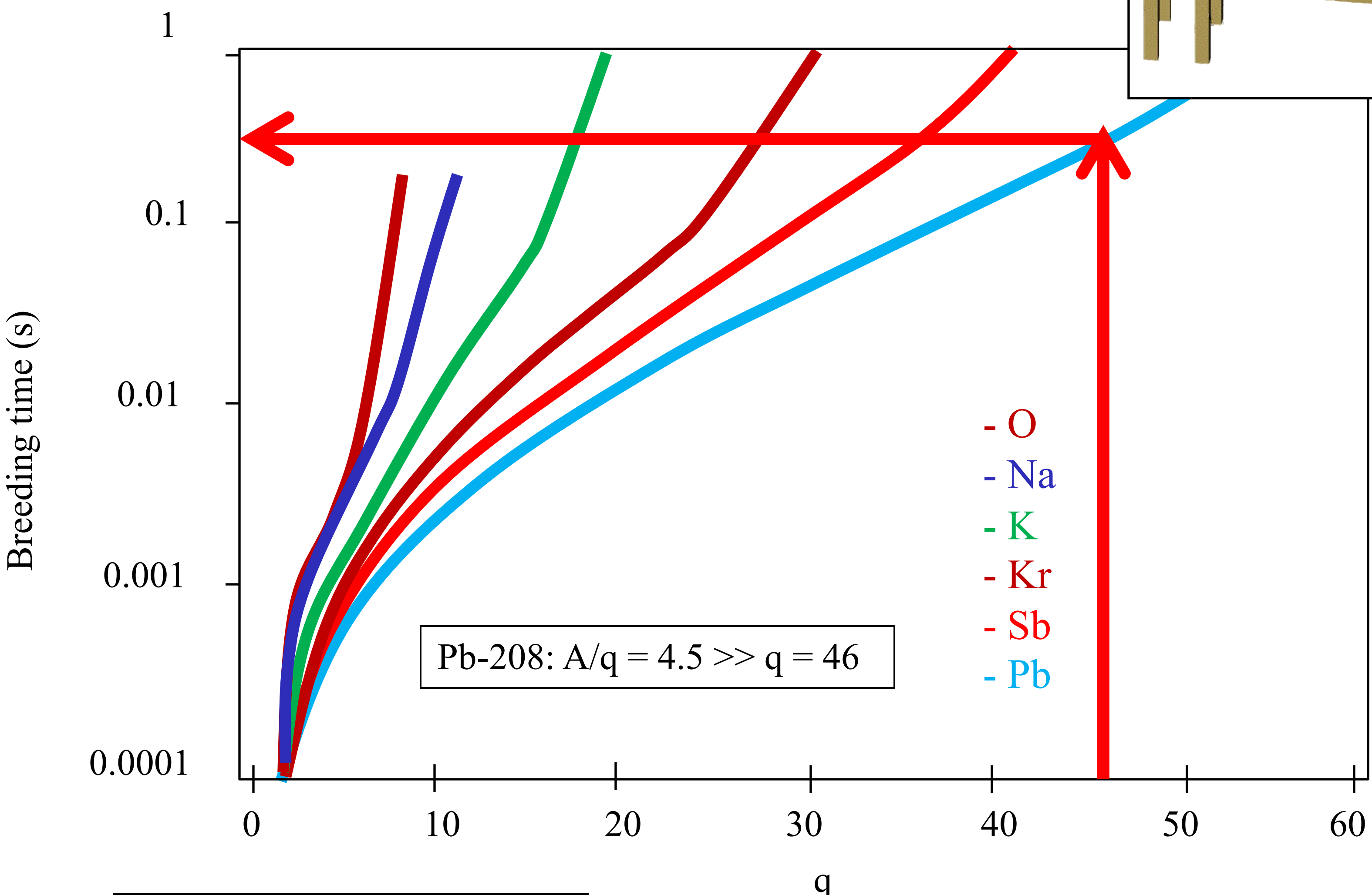
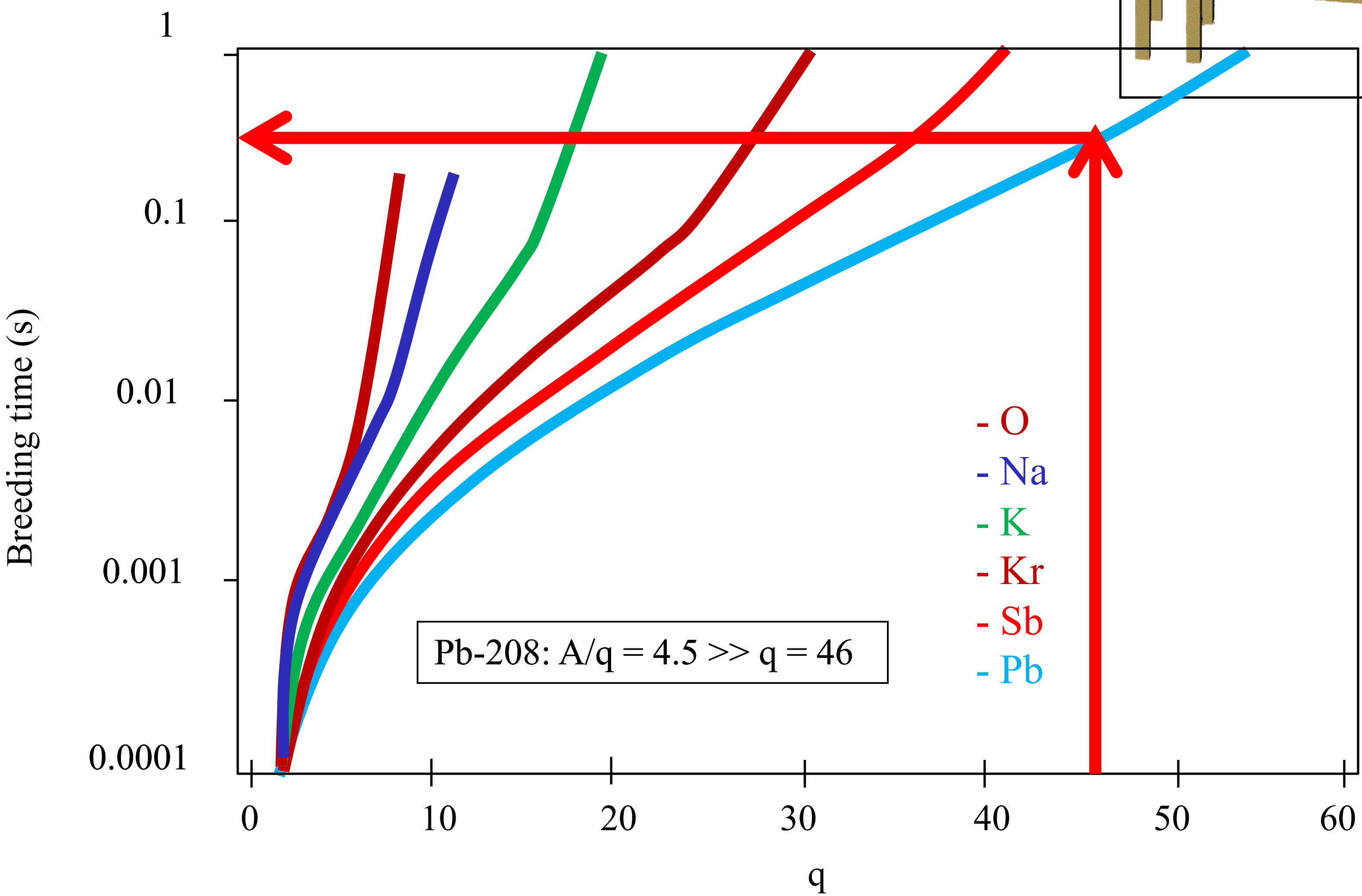
EBIS current situation

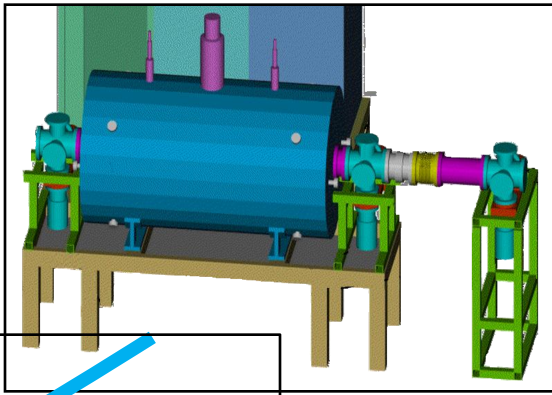




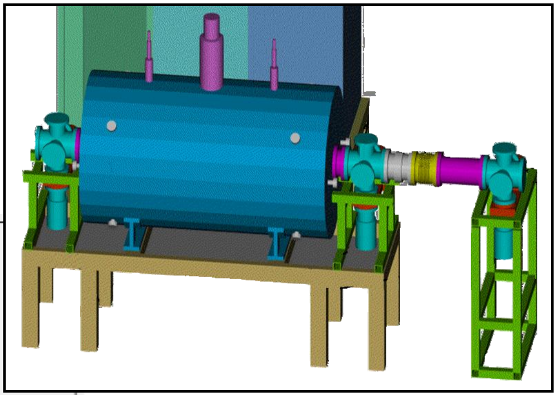
Courtesy F. Wenander

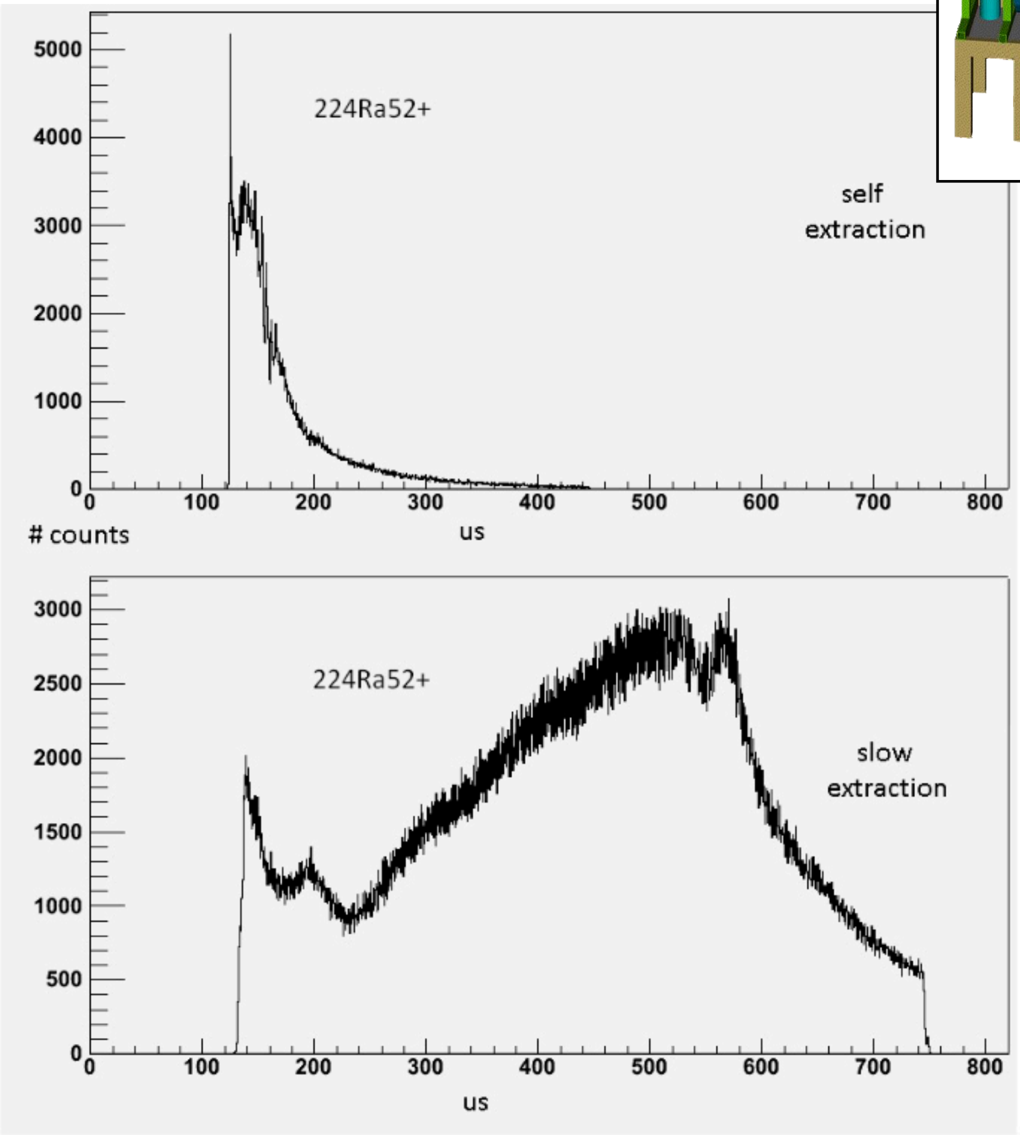
EBIS current situation





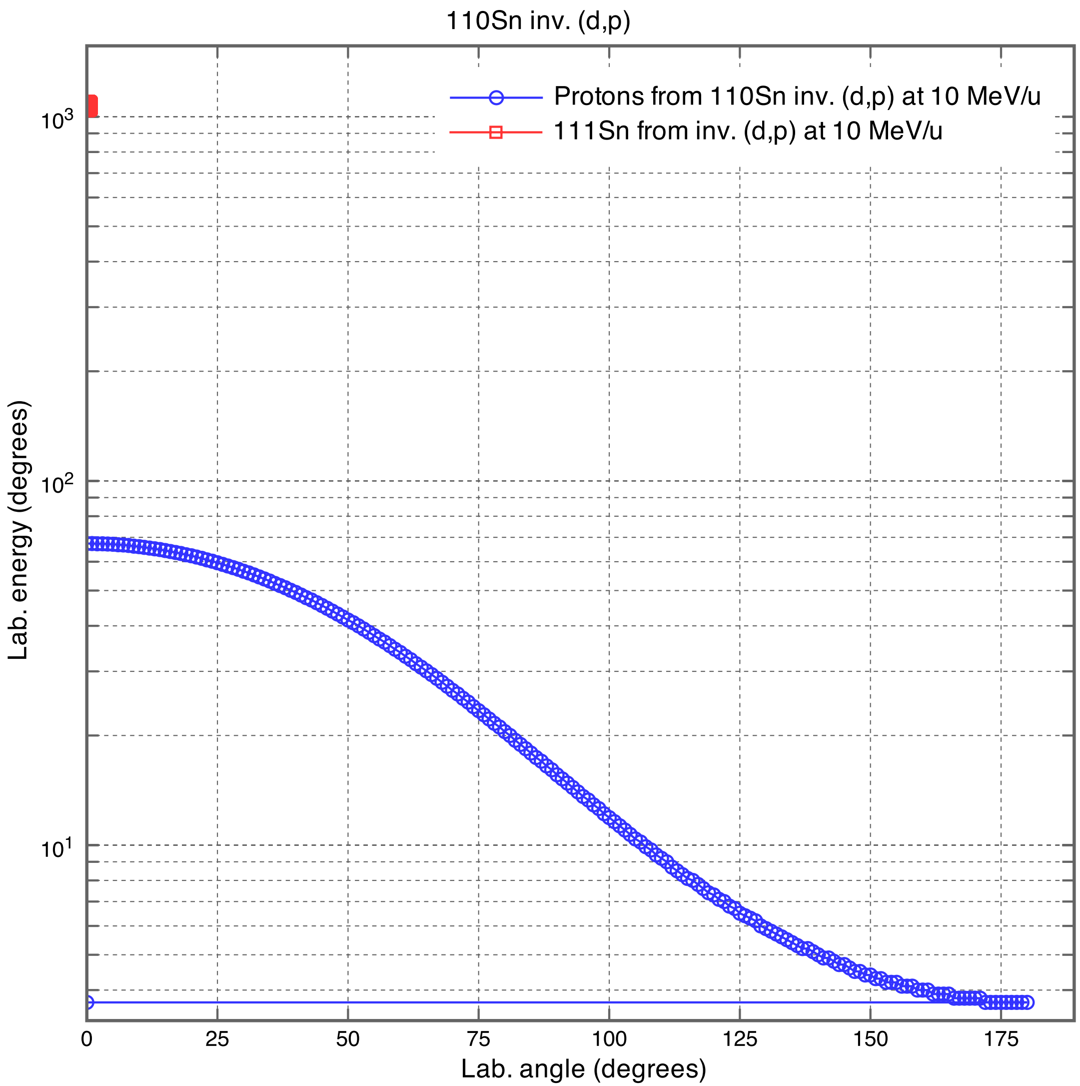
EBIS current situation



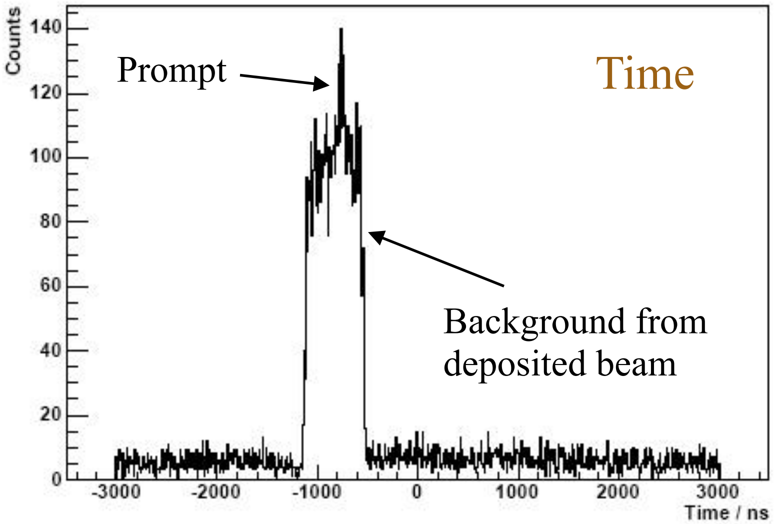


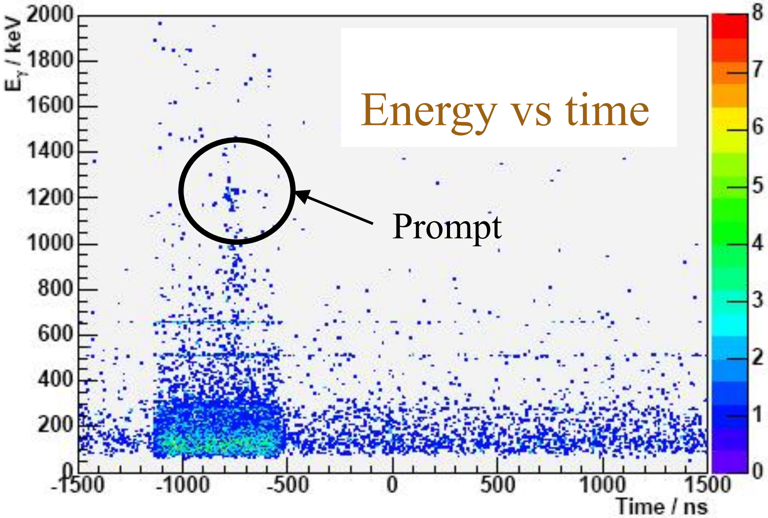
F. Wenander JINST5 C10004 (2010)

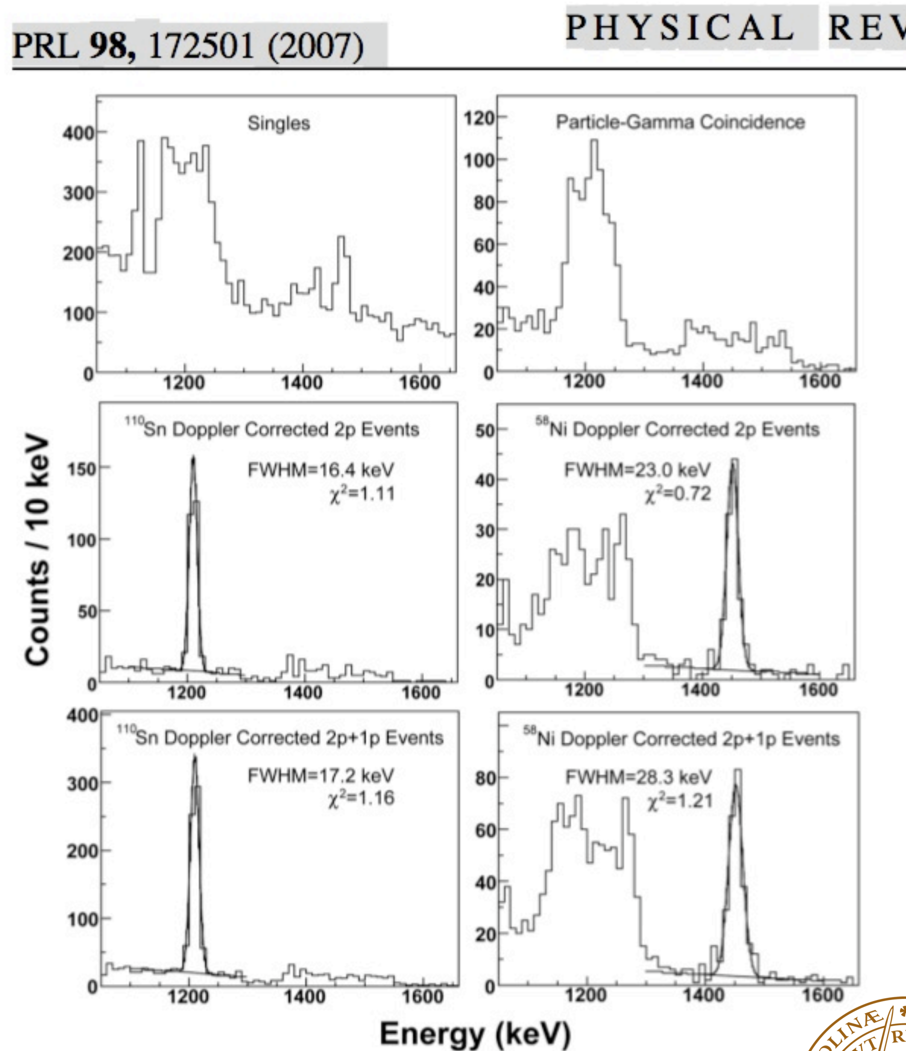
Sn-110, (d,p) kinematics



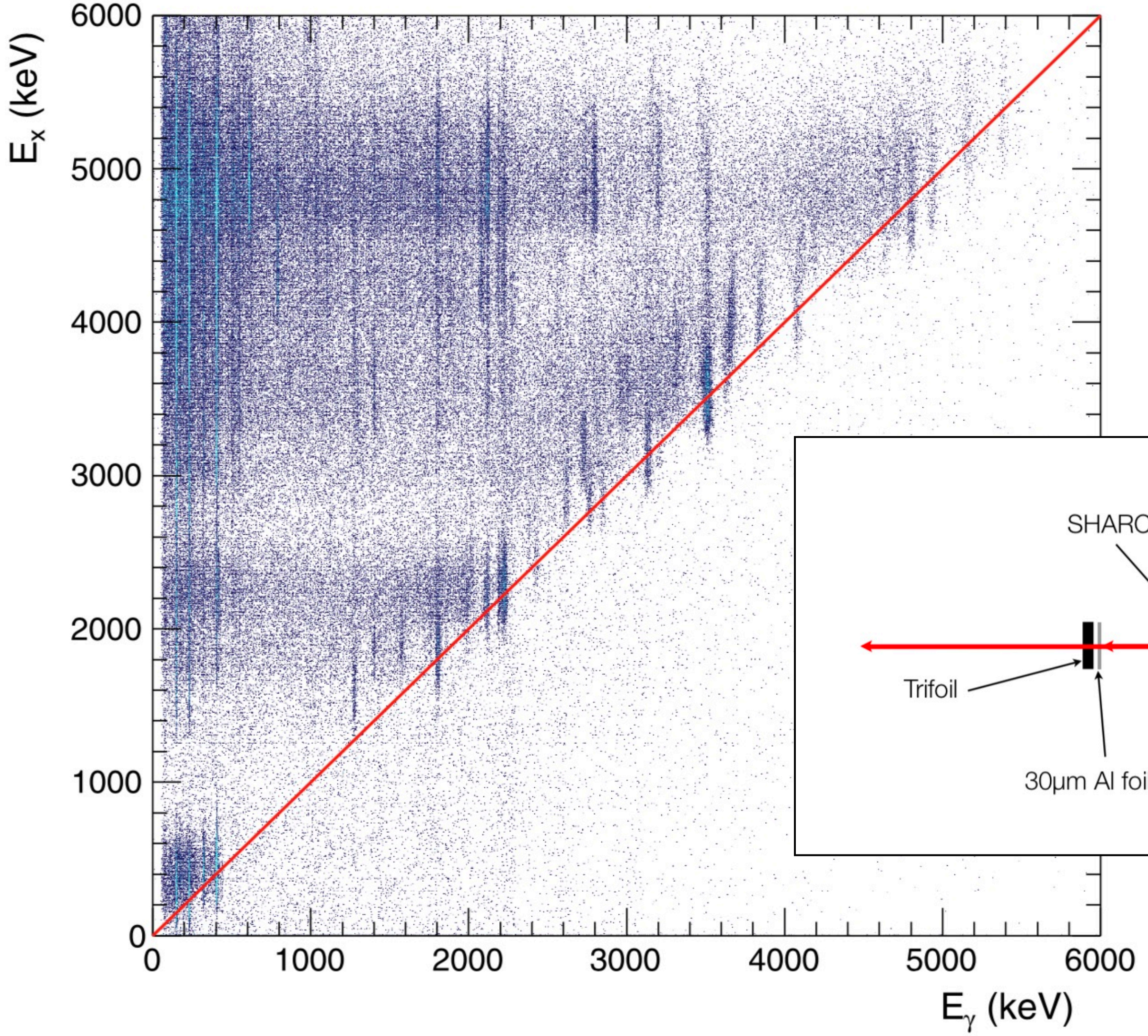
Particle – γ coincidence and Doppler shift

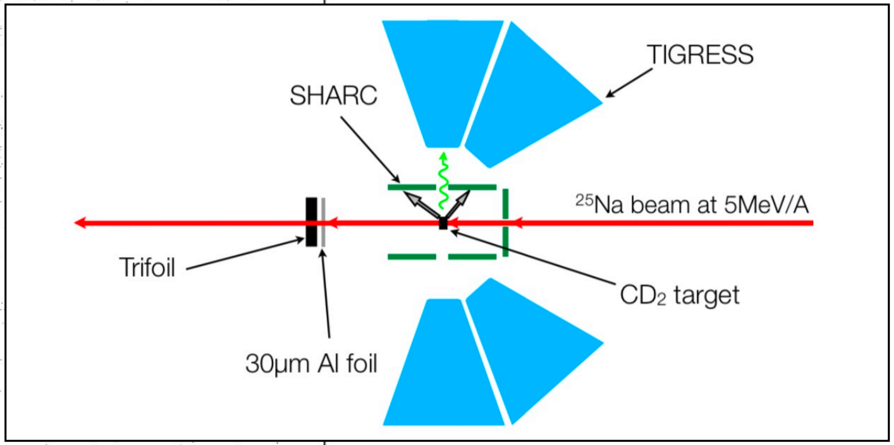






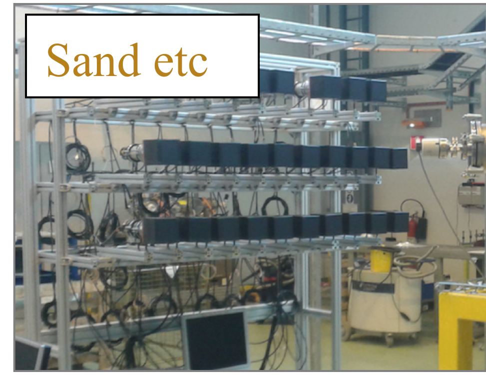
Recoil detection

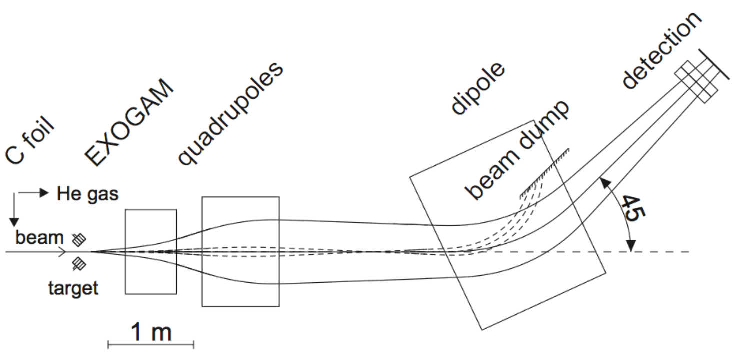




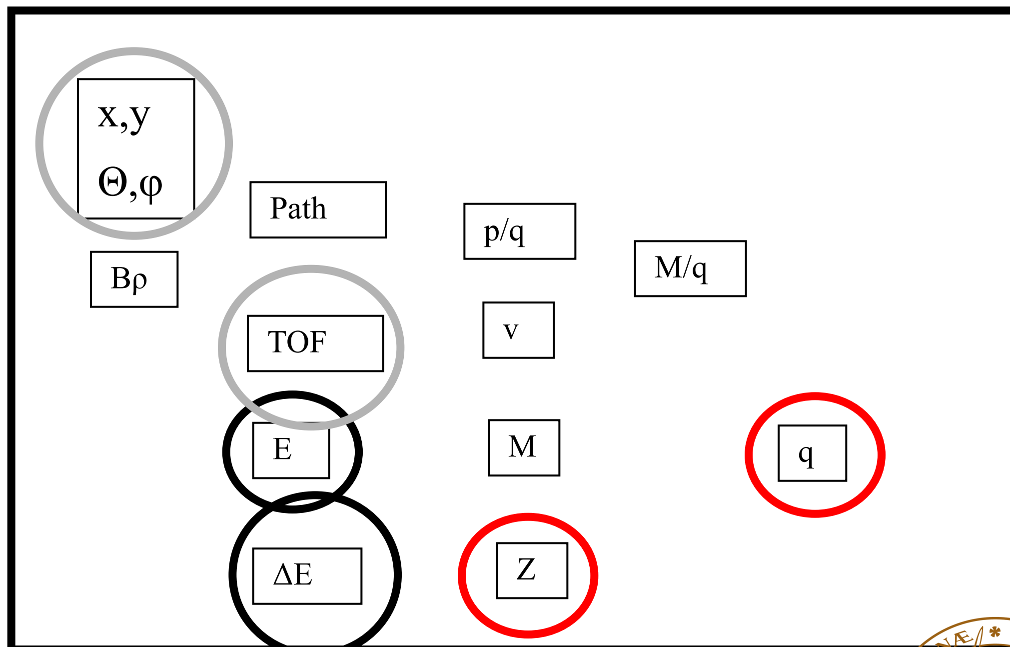
G. Wilson et al.
Physics Letters B 759 (2016) 417–423

TOF spectrometers etc...





M. Rejmund et al. NIMA 621 558 (2010)

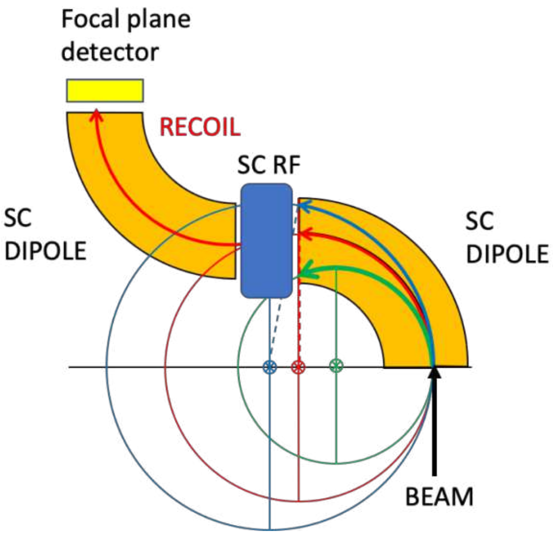


New ideas…

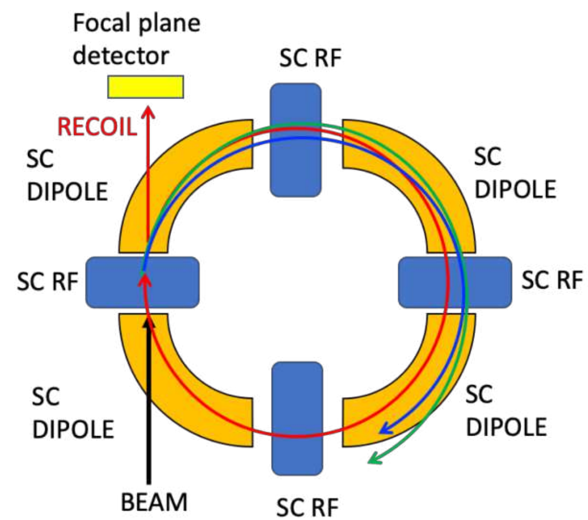
Ismael Bravo, Olof Tengblad

Proposal for a design study using SC elements

Explore new design concept using SC coils and RF cavities. Produce a compact, efficient and high-selectivity recoil separator. Study size, weight, efficiency, selectivity, cost and running cost.



Classical design concept



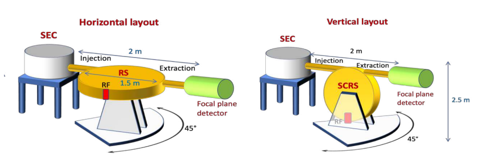
Ring design concept

SC solenoids

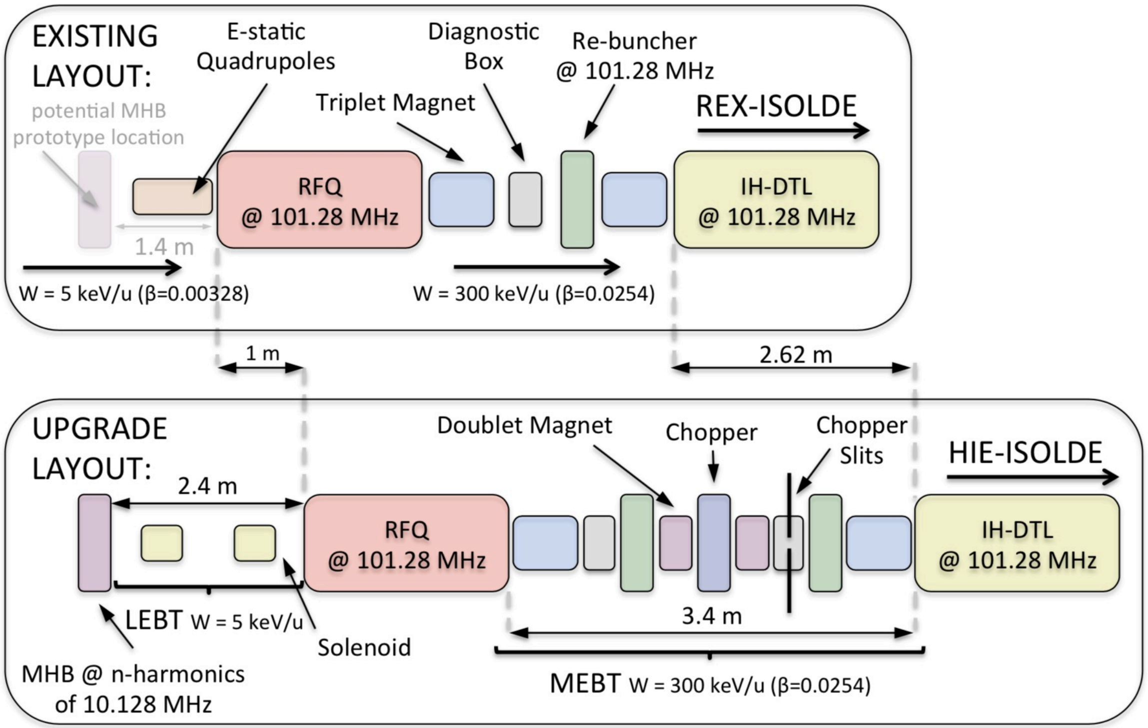
- Combined function magnets for bending and focussing
- High fields ~ 8 T

SC RF cavities

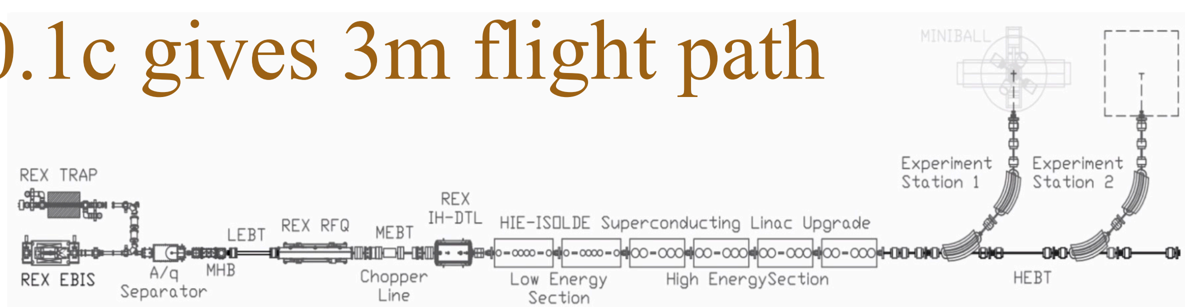
- High gradients ~ 10 MV/m
- HTS materials (> 77 K)
- Rebuncher ~ 10 MHz



100 ns Buncher



@0.1c gives 3m flight path



Resolution in spectrometer and Si-setup

Table 2

Major contributions in keV to the resolution of the excitation energy spectra of single neutron stripping and pickup reactions in inverse kinematics, where the heavy ion is detected in a spectrometer. The detection angle corresponds to 10°_{cm}. The last column is an approximate estimate as a sum in quadrature of the net effect of five non-Gaussian contributions. Other symbols are explained in the text

Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution					Σ_{quad}
			$\Delta\theta$	Δp	E_{stragg}	$\Theta_{1/2}$	dE/dx	
p(^{12}Be, ^{11}Be)d	30	1.07°	172	147	101	74	23	259
p(^{12}Be, ^{11}Be)d	15	1.06°	84	71	99	74	37	169
p(^{77}Kr, ^{76}Kr)d	30	0.16°	1404	811	808	723	56	1952
p(^{77}Kr, ^{76}Kr)d	10	0.10°	334	143	502	570	268	883
d(^{76}Kr, ^{77}Kr)p	10	0.21°	1140	614	2177	1859	1321	3408

Table 3

Major contributions in keV to the resolution of the excitation energy spectra of single neutron pickup and stripping reactions in inverse kinematics, where the light particle is detected in a silicon detector. Symbols as described in text and Table 2

Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution					Σ_{quad}
			$\Delta\theta$	ΔE_f	ΔE_i	$\Theta_{1/2}$	dE/dx	
p(^{12}Be, d)^{11}Be	30	19.0°	136	74	114	96	649	685
p(^{12}Be, d)^{11}Be	15	17.8°	66	72	55	89	984	995
p(^{77}Kr, d)^{76}Kr	30	15.0°	124	55	64	63	186	249
p(^{77}Kr, d)^{76}Kr	10	6.0°	26	24	23	19	775	777
d(^{76}Kr, p)^{77}Kr	10	155.3°	52	93	37	60	1309	1316

What is next?

- **Bunch beam for any form of TOF measurement or timed injection**
  - **time-of-flight dependent detectors (eg. for neutrons)**
  - **spectrometer/recoil separator**
  - **ring**
- **Upgrade EBIS**
  - **reach higher charge states for heavy nuclei quicker**
  - **higher charge states can reduce pressure on accelerator to reach highest voltages for all cavities.**
- **Pre-studies already exists but need to be a priority for next step for the high-energy program together with higher intensity**

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