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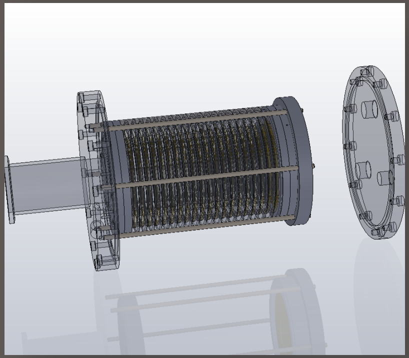
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

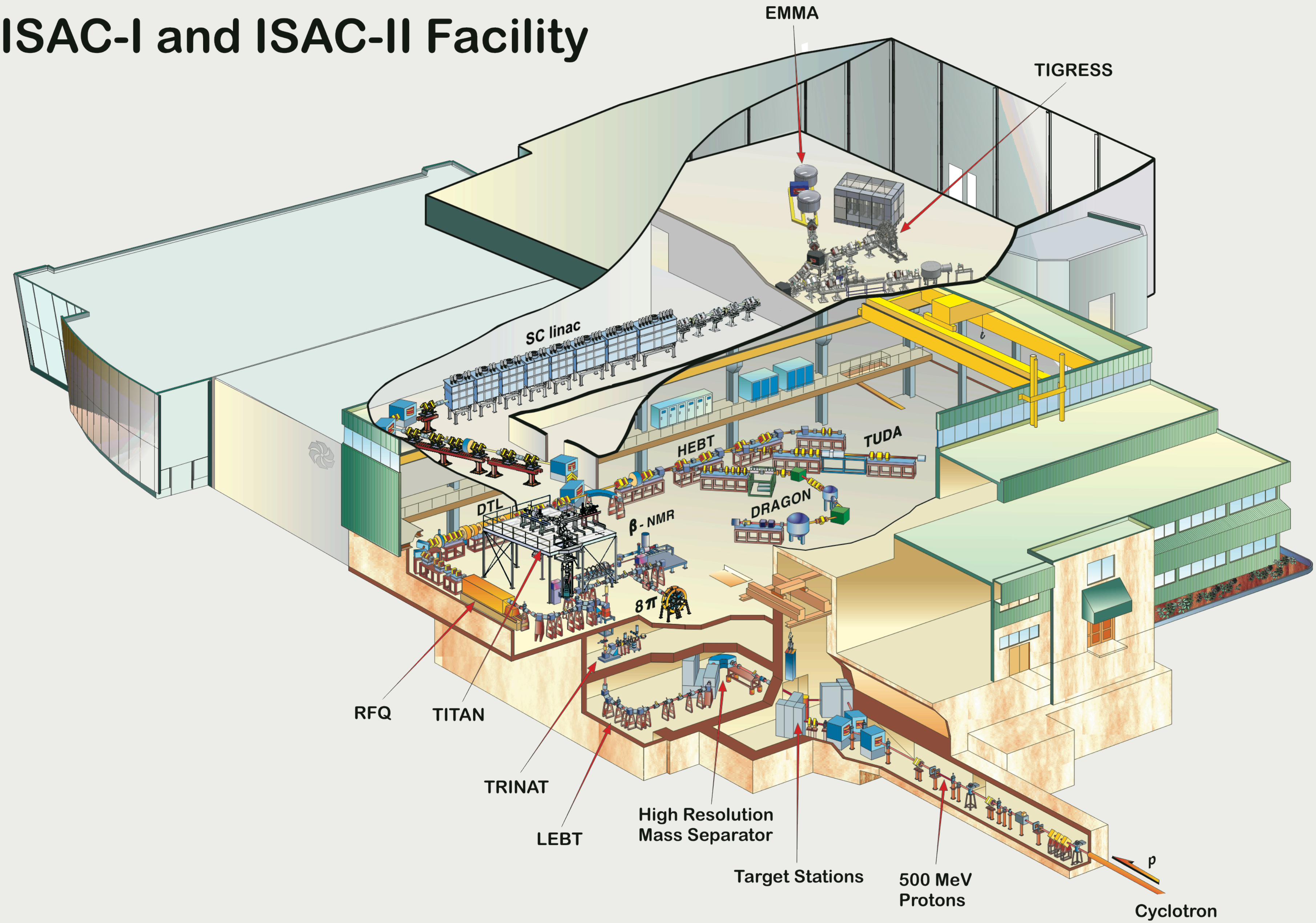
In-flight ion separation using a linac chain

LINAC12, Tel Aviv, IL

Colin Morton | Beam Delivery Group Liaison/Coordinator | TRIUMF
for TRIUMF's High Mass Task Force



ISAC-I and ISAC-II Facility



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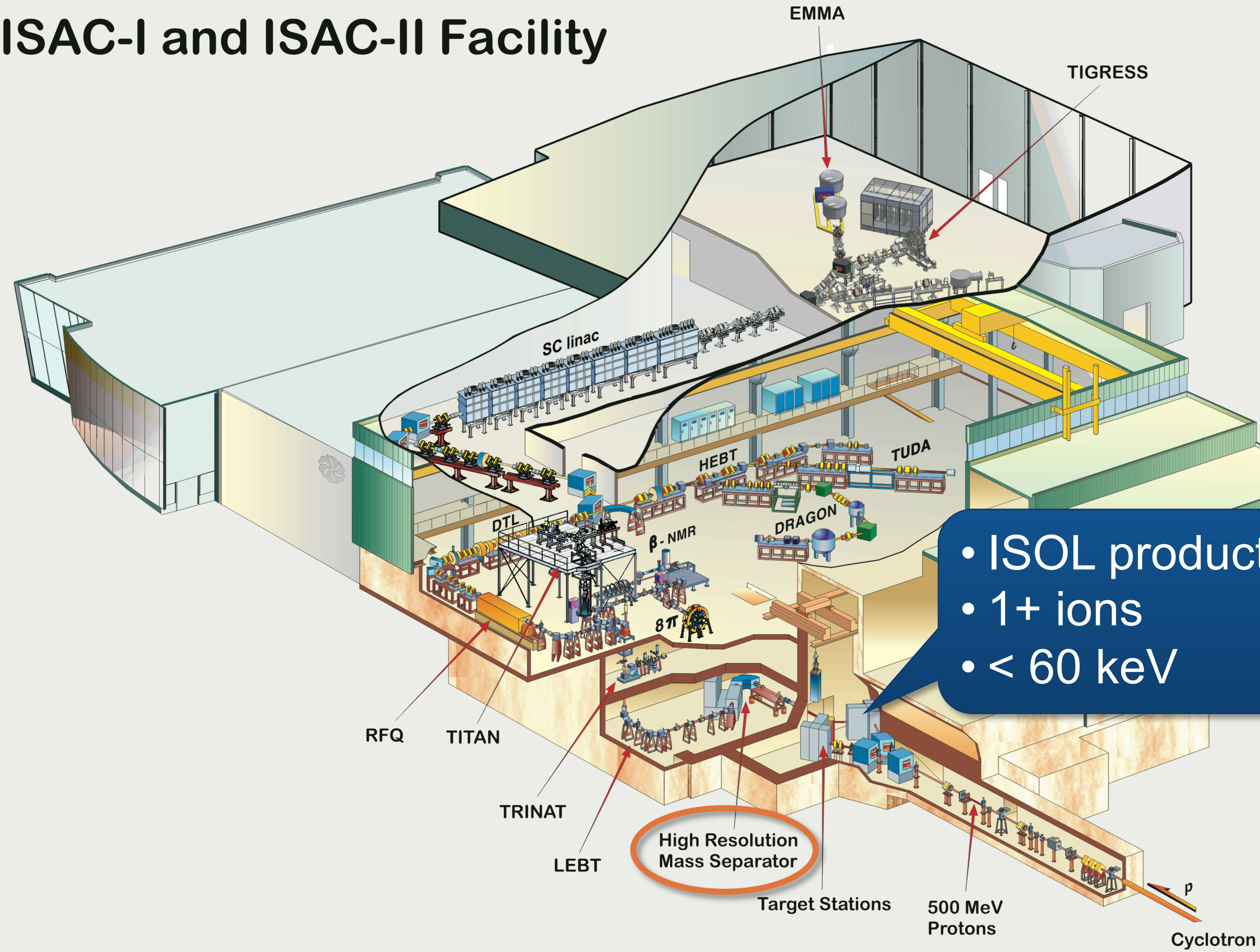
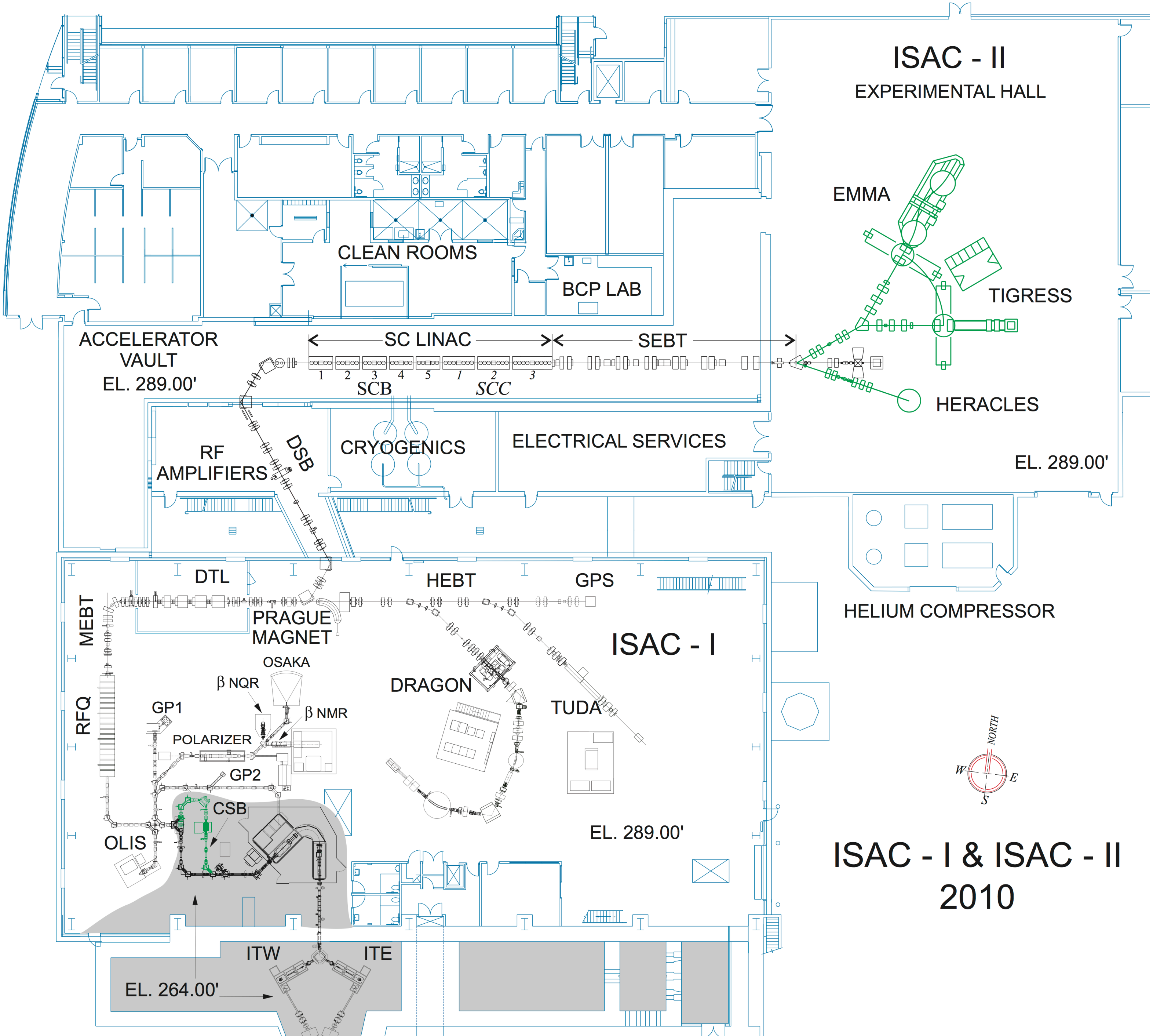
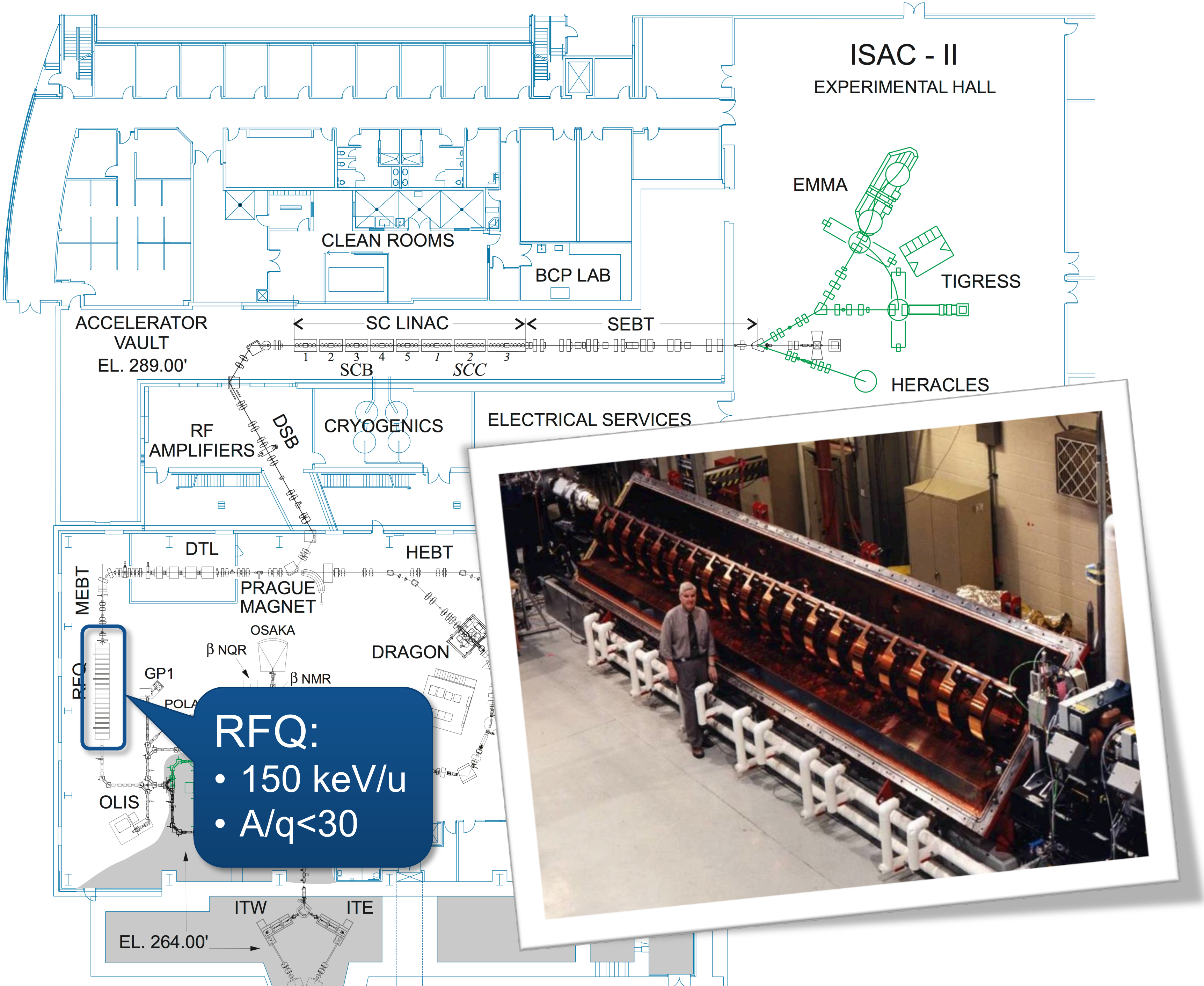
ISAC-I and ISAC-II Facility



- ISOL production
- 1+ ions
- < 60 keV

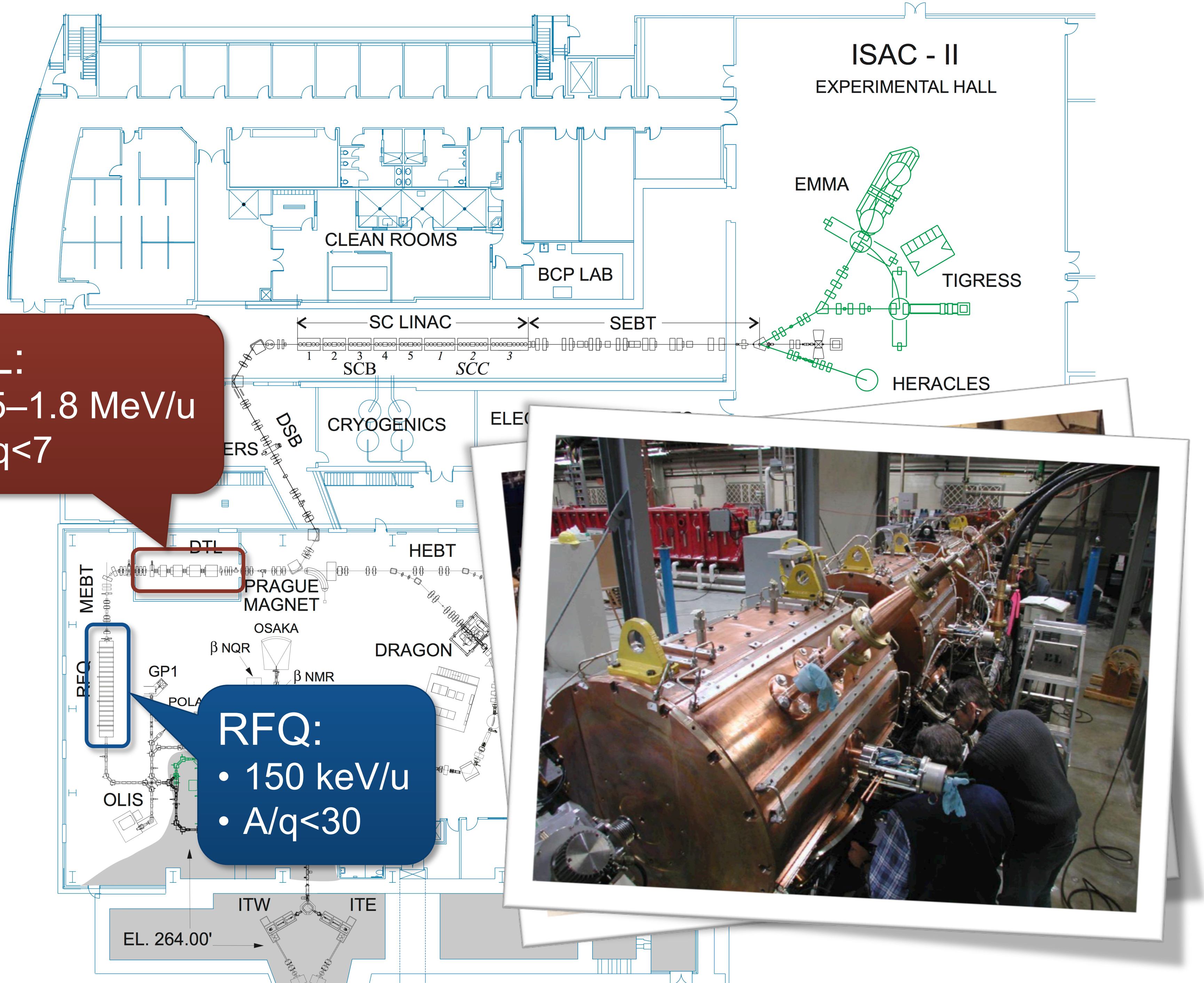


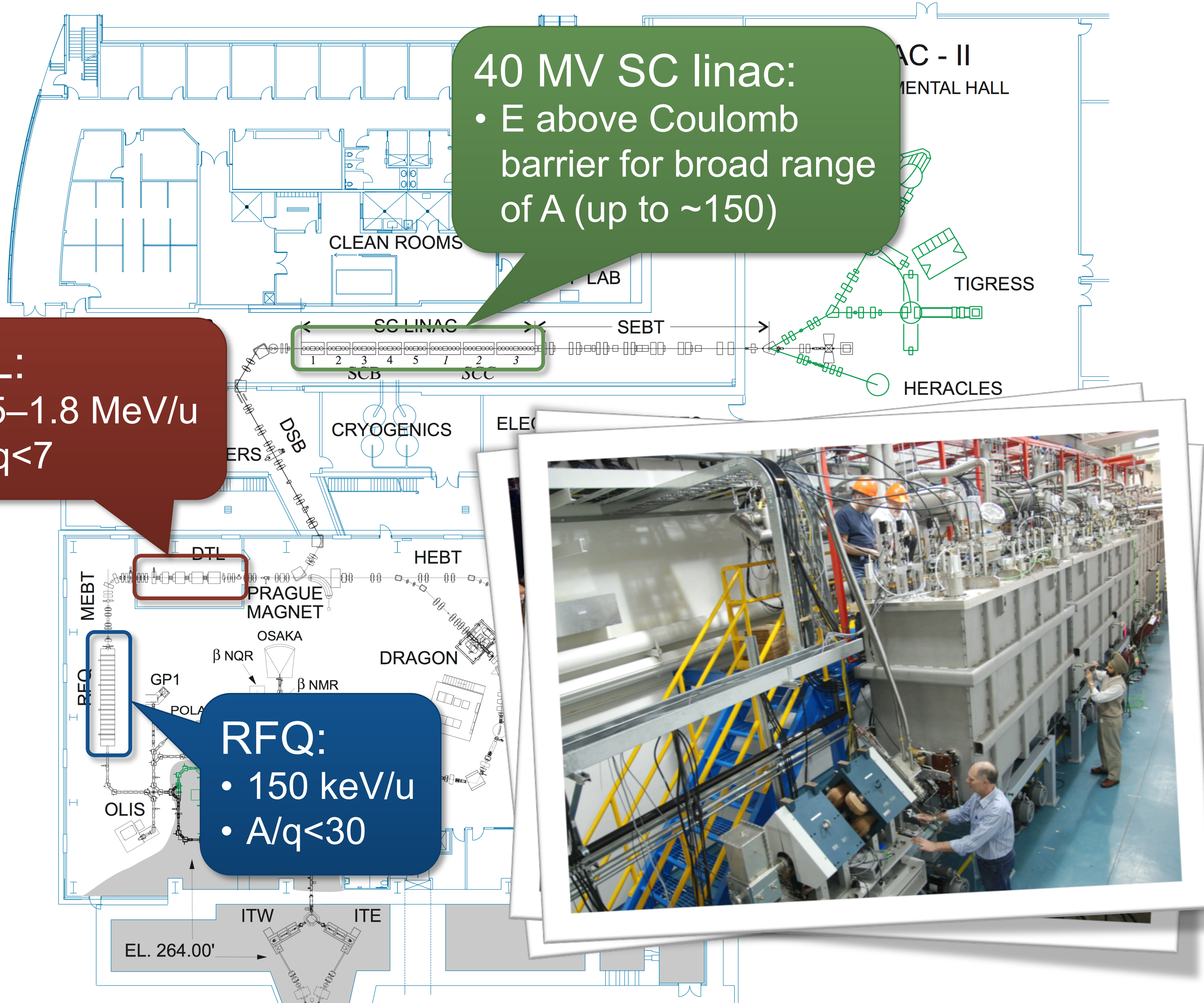
ISAC - I & ISAC - II
2010


ISAC - II
EXPERIMENTAL HALL
EMMA
TIGRESS
HERACLES
CLEAN ROOMS
BCP LAB
ACCELERATOR
VAULT
EL. 289.00'
SC LINAC
SEBT
SCB
SCC
RF
AMPLIFIERS
DSB
CRYOGENICS
ELECTRICAL SERVICES
DTL
HEBT
MEBT
PRAGUE
MAGNET
OSAKA
β NQR
β NMR
DRAGON
GP1
RFQ
OLIS
ITW
ITE
EL. 264.00'
RFQ:
• 150 keV/u
• A/q<30

DTL:
- 1.5–1.8 MeV/u
- A/q<7

RFQ:
- 150 keV/u
- A/q<30





40 MV SC linac:

- E above Coulomb barrier for broad range of A (up to ~150)

DTL:

- 1.5–1.8 MeV/u
- A/q<7

RFQ:

- 150 keV/u
- A/q<30

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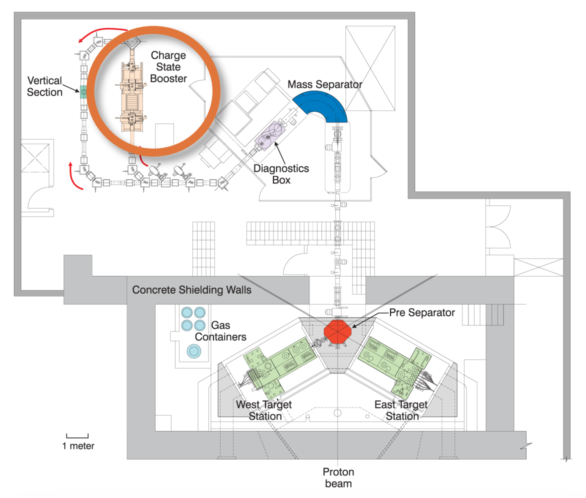
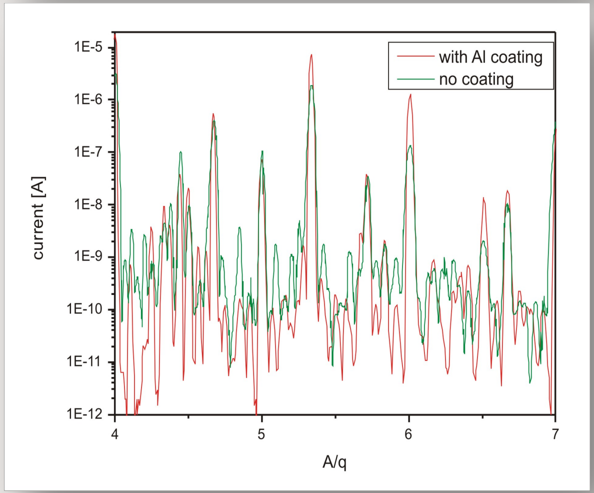
Why in-flight separation?

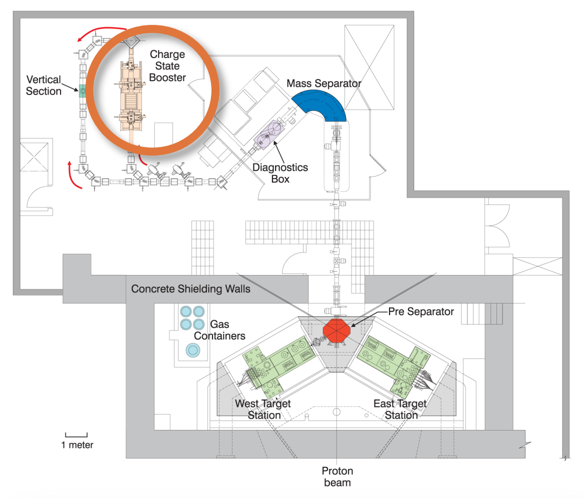
- **High-mass beam delivery**
  - RFQ requires A/q<30; q=1 ⇒ **A<30 limit**
  - Need to increase q, lower A/q before acceleration
- Charge State Booster (CSB)
  - ECR-based charge breeder
  - Boosts RIB to high charge states, A/q < 7
  - **10s to 1000s of pA of stable-beam background**

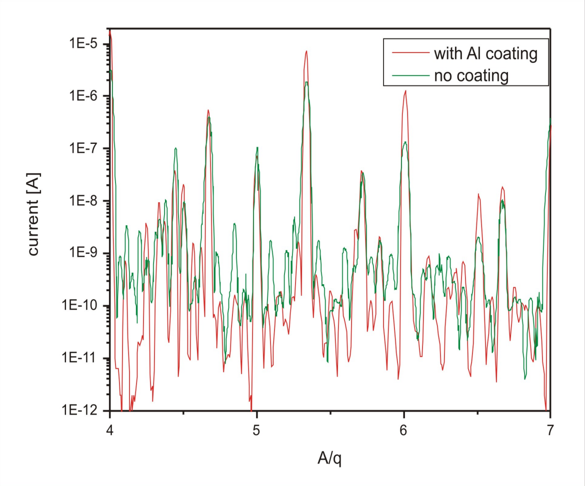




Why in-flight separation?

- RIB are vulnerable to contamination
  - Low count rates – 10^3/s or less
- Measurable stable-beam currents can render many experiments impossible
- **In-flight separation is needed to provide the necessary beam purity for experiments**



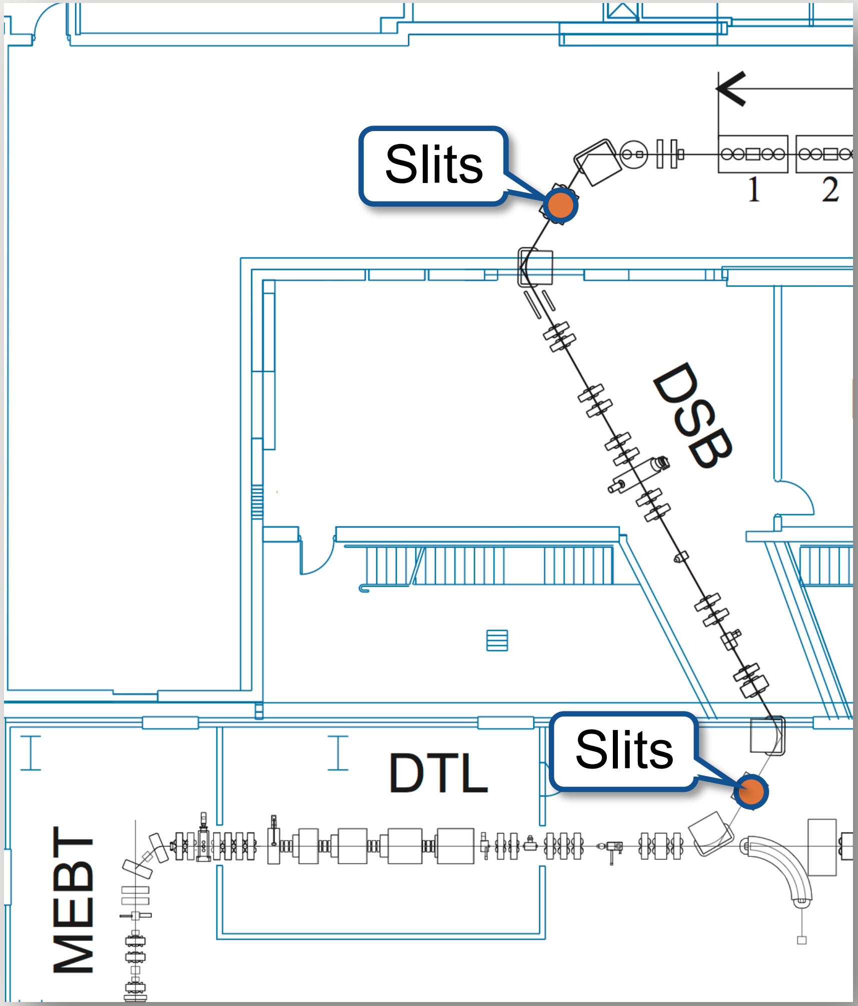


Challenges

- Tunes have to be established with contaminated beams before they can be purified
  - **Can't lose RIB component**
- ISAC was not designed as a mass separator
  - Operation outside initial design envelope
  - The techniques needed to use existing infrastructure for beam purification have had to be developed
- One advantage? A long linac chain – **several possible locations for A/q separation**

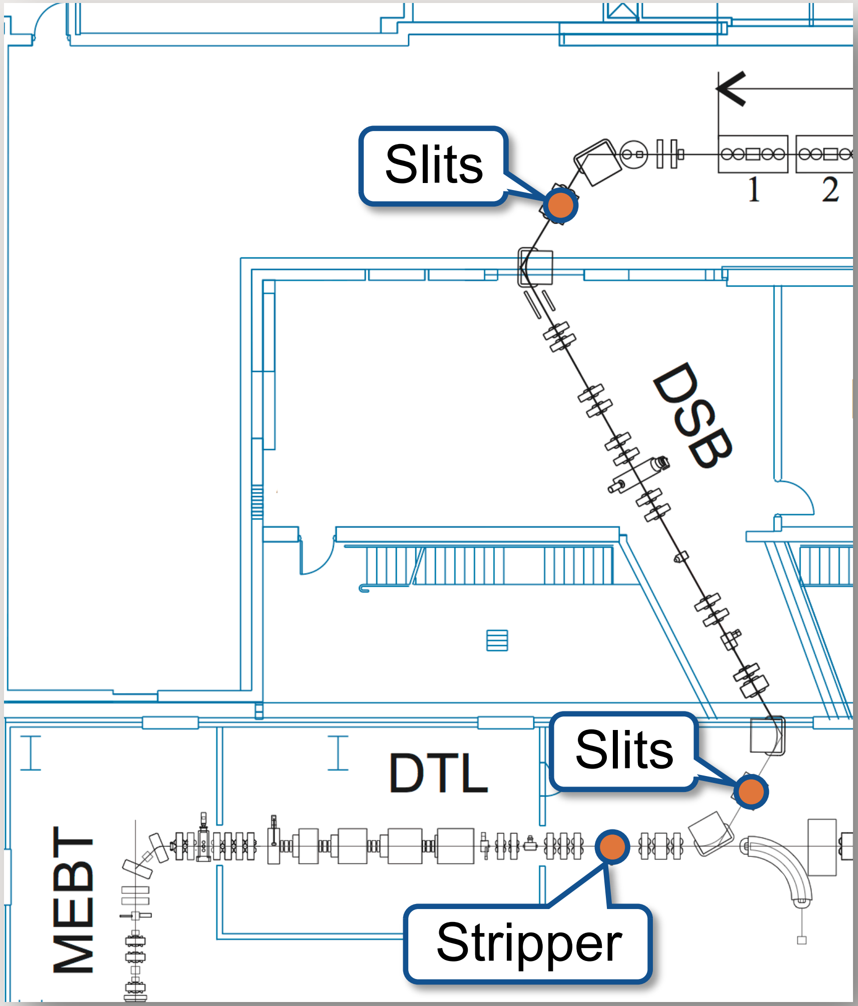
A/q selection in DSB (S-bend)

- S-bend between DTL and SC linac
- Common ion velocity; beam energy of 1.5 MeV/u ± 0.2%
- Slits in dipole sections can separate A/q with ~1/500 resolution



A/q selection in DSB (S-bend)

- Additional gains are possible with stripping
- Different beam components will have different charge-state distributions
- Final A/q can be chosen to optimize ratio of RIB to stable contaminants



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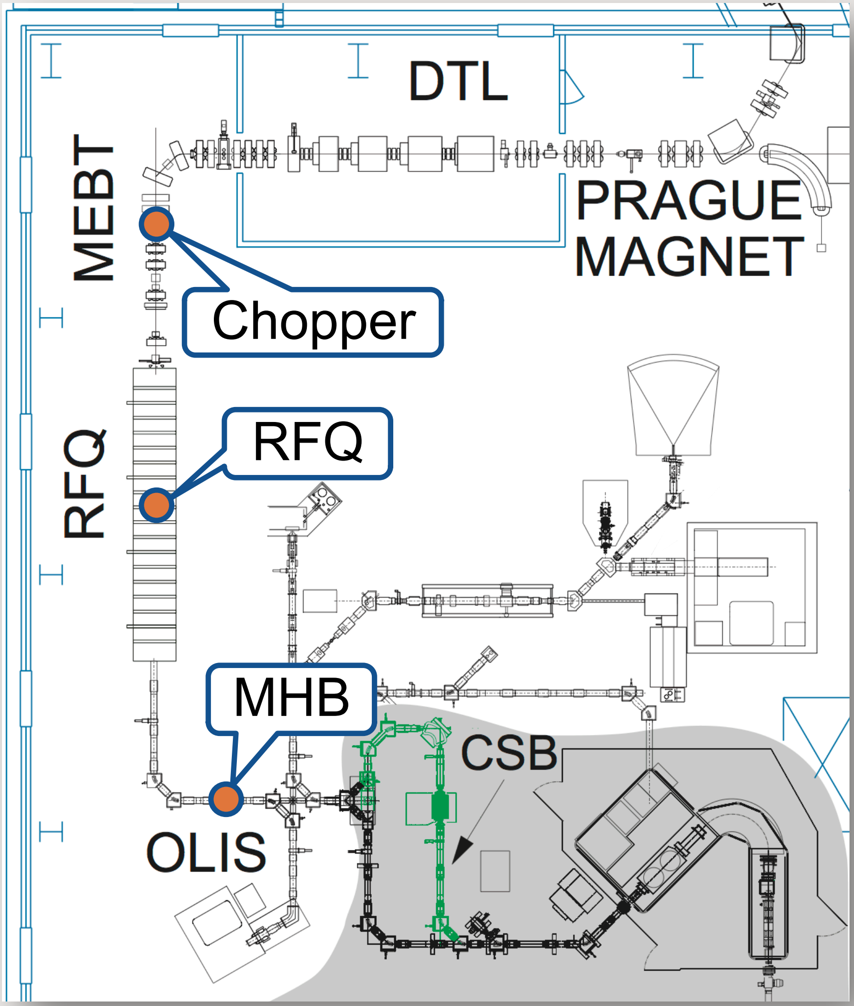
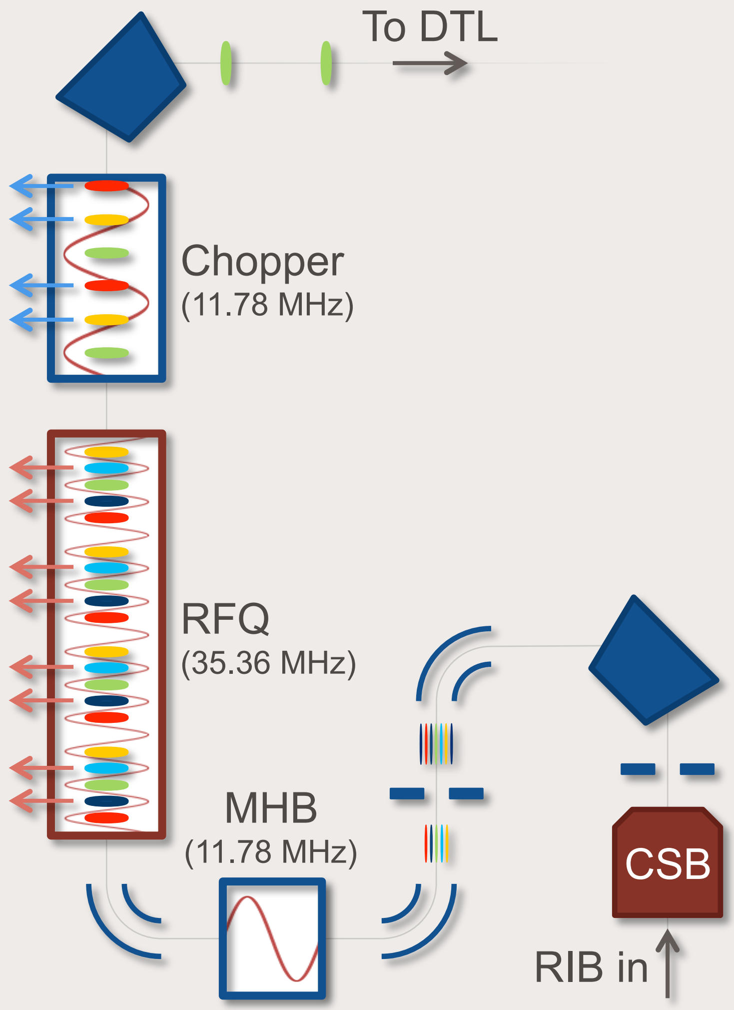
Time-of-flight separation in LEBT



- Ions of different A/q have different velocities, ToF
- RF phase of pre-buncher (MHB), RFQ can be adjusted to accept/reject beam depending on ToF
- **Can use ToF for A/q selection**

Time-of-flight separation in LEBT



- For electrostatic acceleration,

$$E = \frac{1}{2}mv^2 = \frac{1}{2}Am_0v^2 = qV_{bias}, \text{ so } \frac{A}{q} = \frac{2V_{bias}}{m_0v^2}$$

$$\frac{\Delta(A/q)}{A/q} = 2\frac{\Delta v}{v}$$

- Δv results in Δt from MHB to RFQ:

$$\Delta t = \frac{\Delta v}{v}t = \frac{\Delta v}{v}\frac{l}{v}, \text{ so } \frac{\Delta v}{v} = \Delta t\frac{v}{l}$$

- RFQ acceptance:

$$\Delta t_{accept} = \frac{\Delta\varphi_{accept}}{\omega_{RFQ}} = \frac{\pi/4}{\omega_{RFQ}}$$

- Result? **~1/1000 resolution in A/q:**

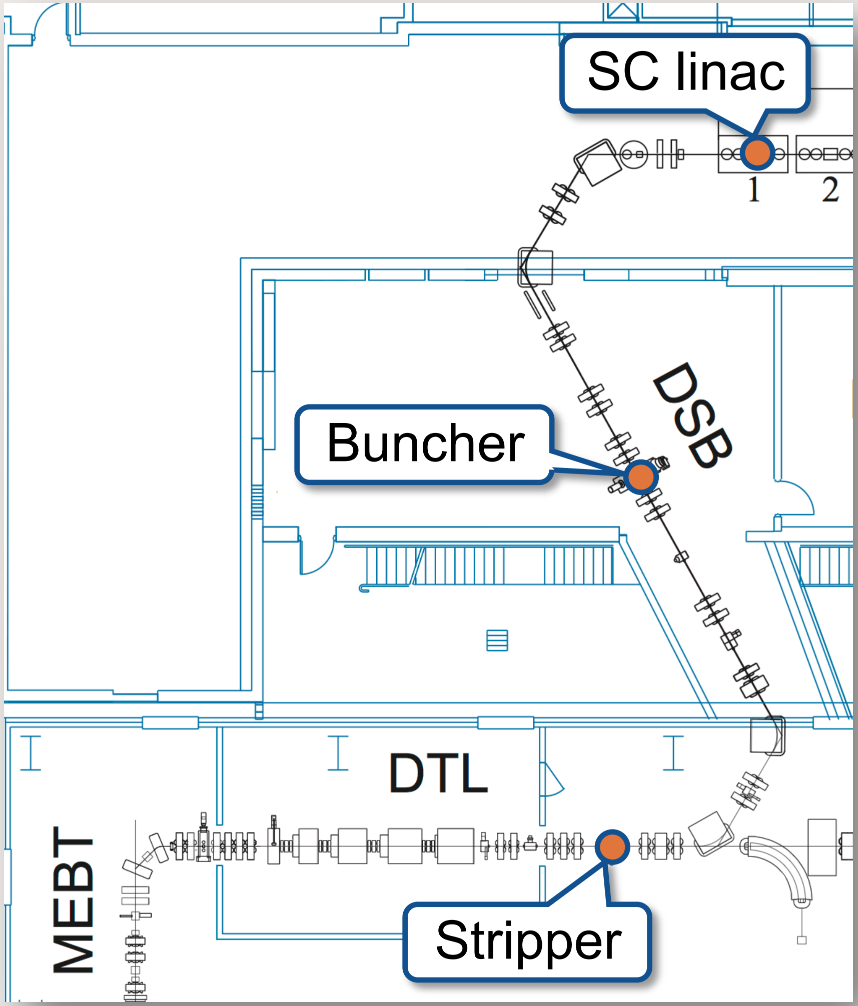
$$\left.\frac{\Delta(A/q)}{A/q}\right|_{accept} = 2\Delta t_{accept}\frac{v}{l} = 2\frac{\Delta\varphi_{accept}}{\omega_{RFQ}}\frac{\beta c}{l}$$

$$= 2\frac{(\pi/4)(0.0021)(3\times10^8\,\text{m/s})}{2\pi(35\times10^6\,\text{s}^{-1})(5.5\text{m})} = 0.08\%$$

Time-of-flight separation in DSB

- Stripping (degrading) introduces a Δv by energy loss
- Δv results in Δt from stripper to buncher
- Result: **~1/800 resolution in v:**

$$\left.\frac{\Delta v}{v}\right|_{accept} = \frac{(\pi/6)(0.056)(3\times10^{8})}{2\pi(106\times10^{6})(10)} = 0.13\%$$



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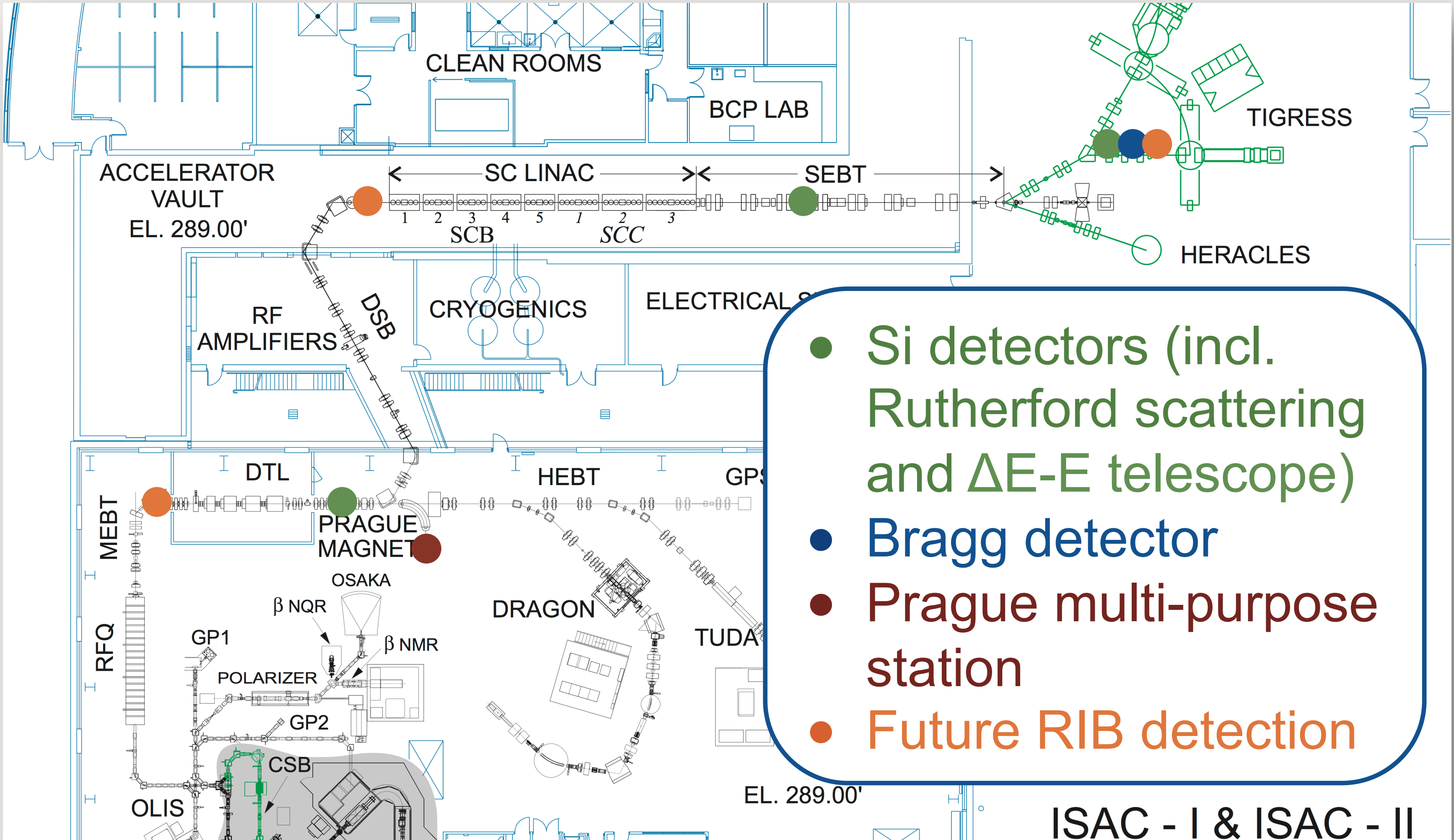
Diagnostics



- Si detectors (incl. Rutherford scattering and ΔE-E telescope)
- Bragg detector
- Prague multi-purpose station
- Future RIB detection

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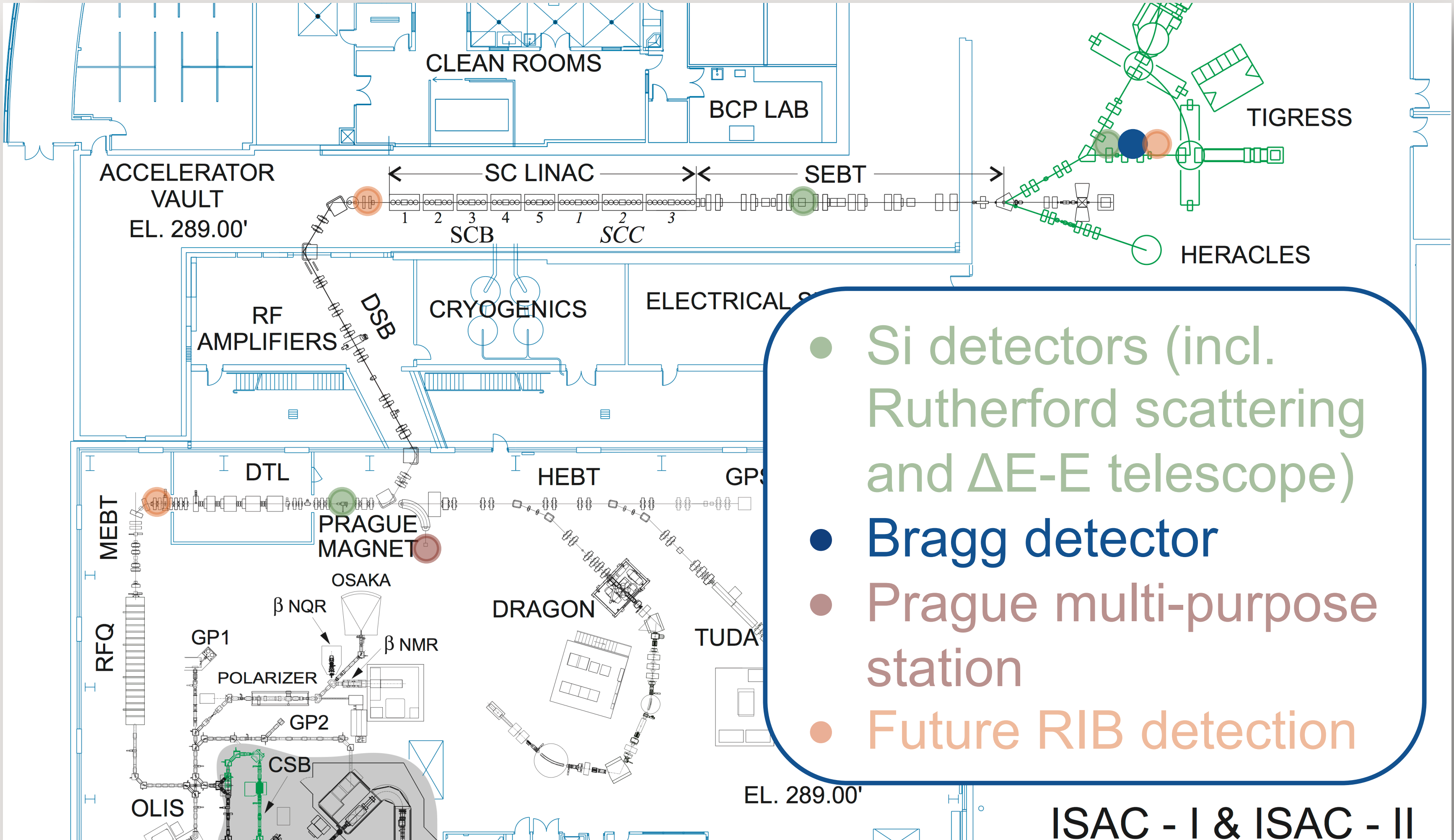
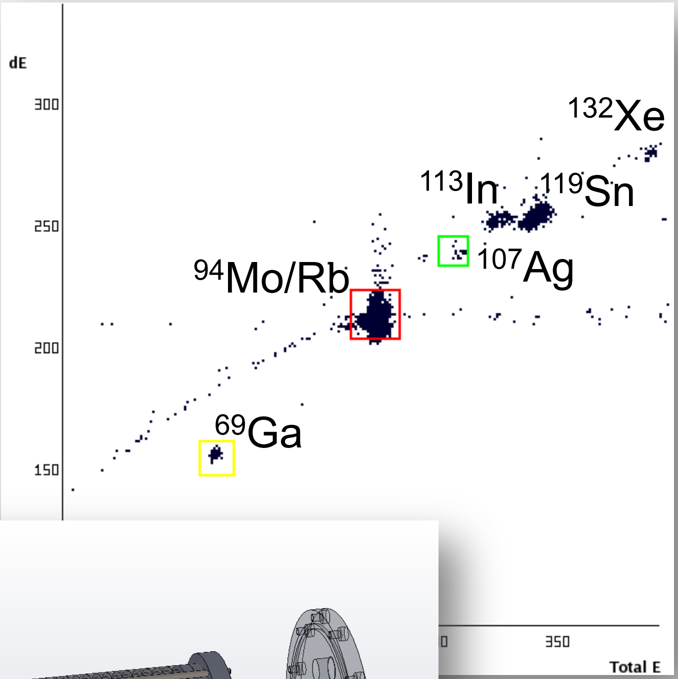
Diagnostics

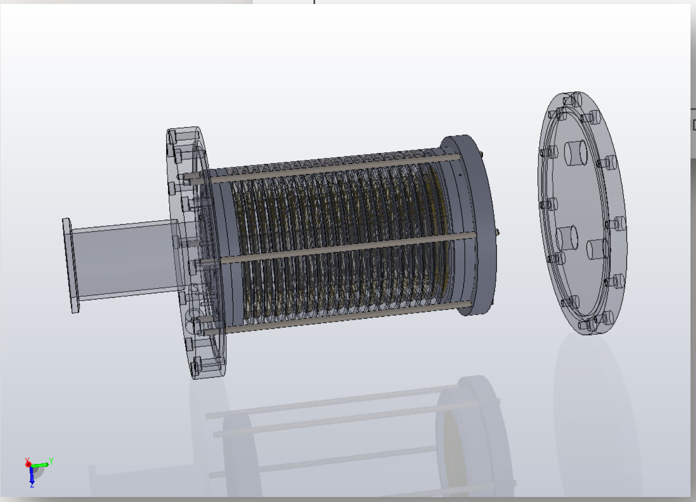


- Si detectors (incl. Rutherford scattering and ΔE-E telescope)
- Bragg detector
- Prague multi-purpose station
- Future RIB detection

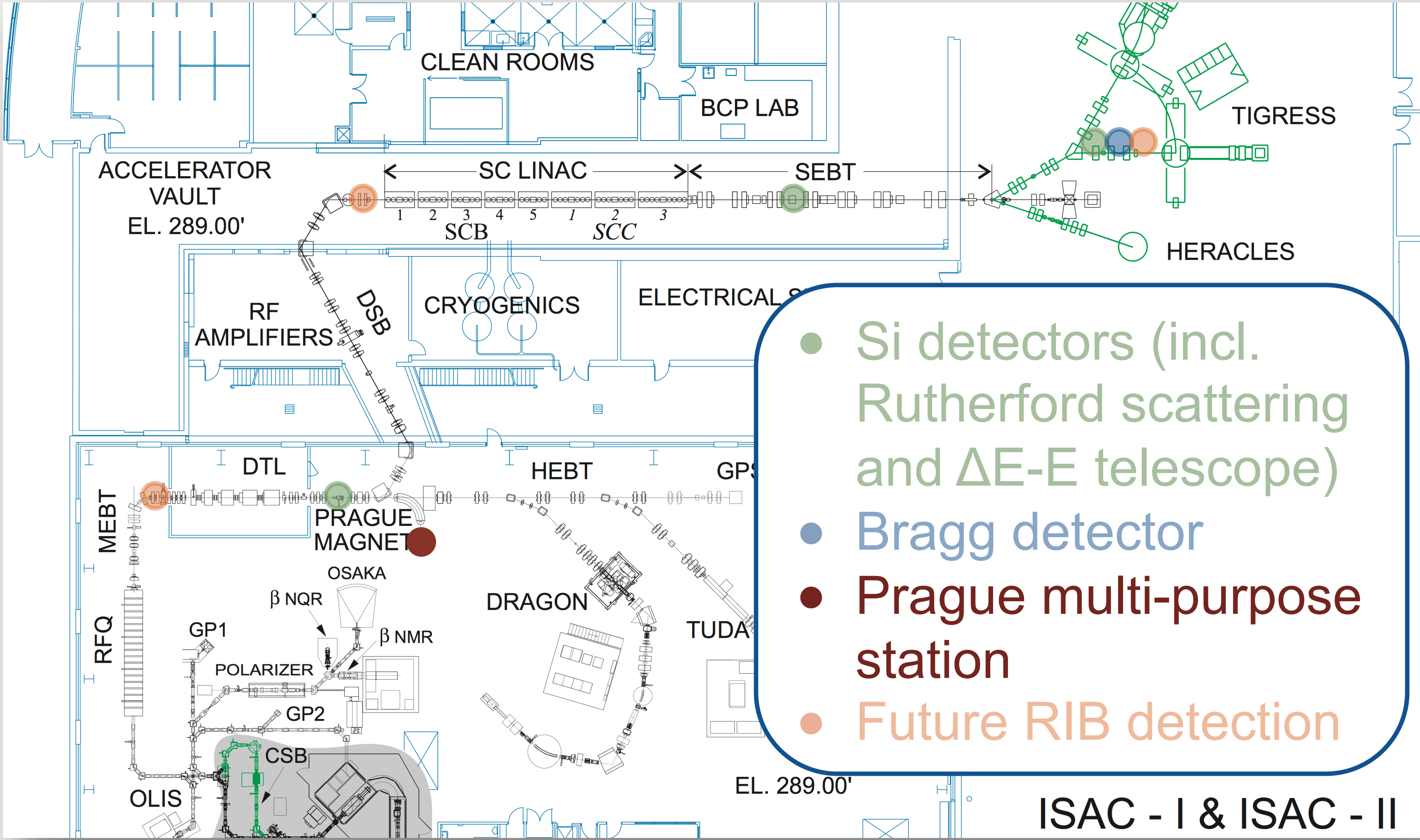
Bragg detector

- Stopping gas counter in ISAC-II experimental hall
- **Particle ID from ΔE-E after acceleration**
- Tolerant of high count rates
- Thickness can be adjusted by varying gas pressure



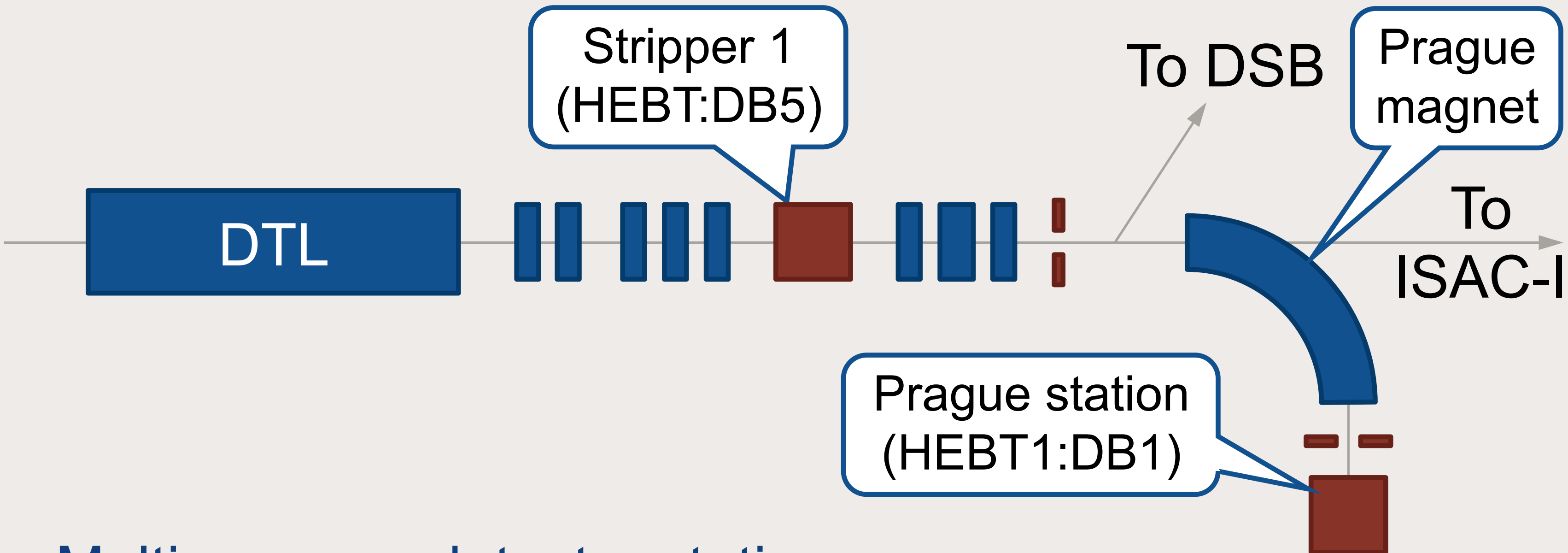


Diagnostics



- Si detectors (incl. Rutherford scattering and ΔE-E telescope)
- Bragg detector
- Prague multi-purpose station
- Future RIB detection

Prague station



- Multi-purpose detector station:
  - Faraday cup, low-intensity purity monitor, beta/gamma counters for RIB identification
- Allows rapid characterization of beams – crucial for development, setup and tuning

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Automatic tune scaling

- EPICS control system application to scale beamline optics and accelerator RF
  - Voltages for electrostatic elements
  - Currents for magnetic quads and steerers
  - Magnetic fields for dipoles (with Hall probe readback)
  - RF amplitudes
- **Allows rapid scaling between A/q – (far) faster and more reliable than manual scaling**

“CSB Assistant”

- Web app to simulate RIB delivery from CSB
- Includes known backgrounds, stripping efficiencies, energy losses in foils, etc.
- **Allows accelerator and beam delivery experts to identify promising initial A/q and to determine strategies for in-flight separation before and while tuning beam**
- A simplified version is available to experimenters for guidance in preparing proposals, etc.
  - http://trshare.triumf.ca/~garns/CSB/

CSB Assistant

trshare.triumf.ca/~garns/CSBExperts/

Charge-State Booster Page

UNDER DEVELOPMENT - PLEASE REPORT ERRORS OR SUGGESTED IMPROVEMENTS

The Charge-State Booster (CSB) is intended to produce radioactive ion beams in charge states greater than 1+. Stable isotopes are also ionized and produced by this device so must be considered when selecting which beam to extract. This page may help identify which charge-state might be the cleanest.

Select CSB liner material: Aluminium

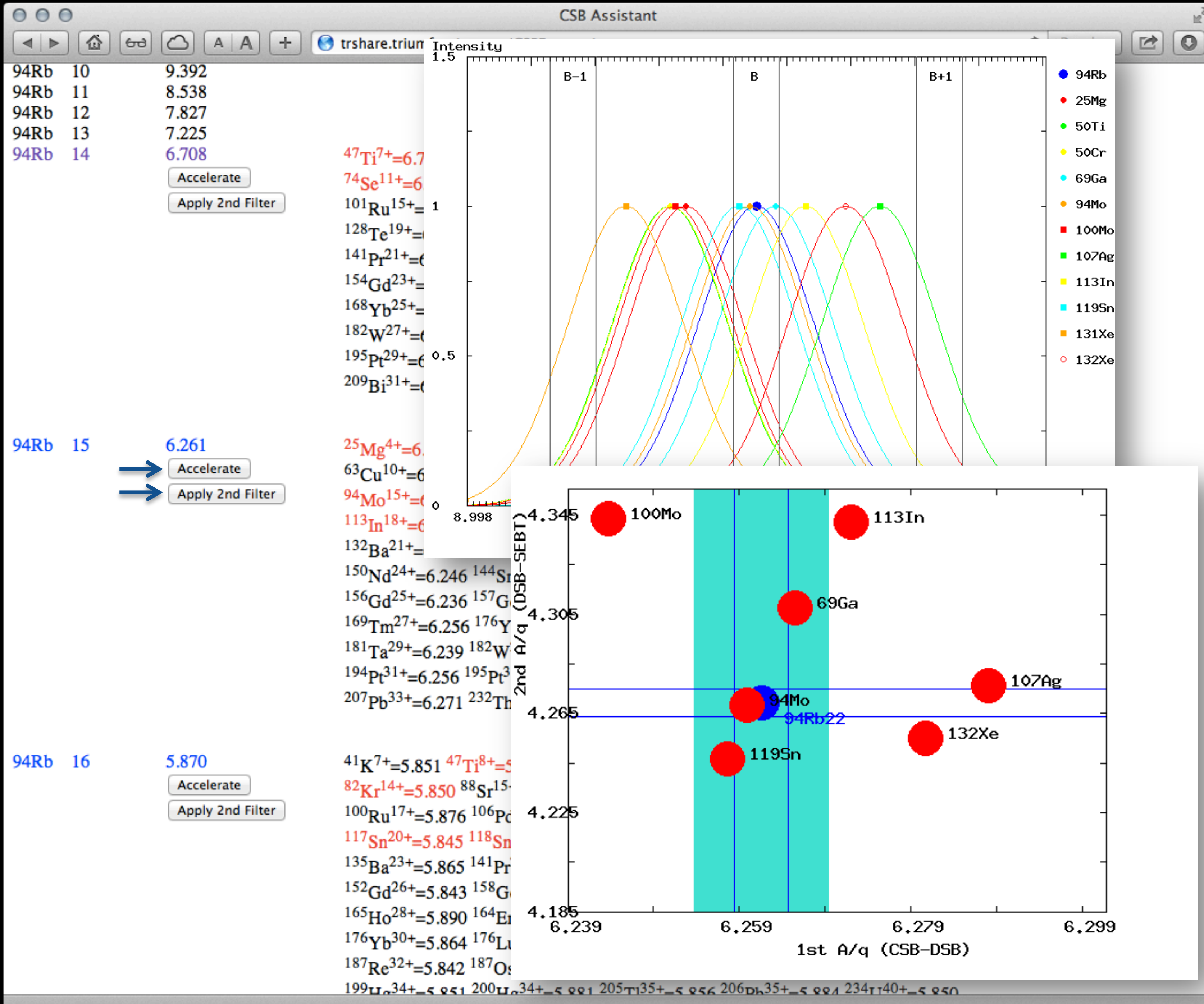
Select Mass and Element: 94 Rb Show A/Q values   or Enter A/Q Value: Show Species

Enter resolving power: 100

Rb has an atomic number: 37
94Rb has an atomic mass of: 93.926405 amu.
You have selected an Aluminium liner for the CSB ECR source.
You have selected a resolving power of 100

Blue font indicates species which can currently be delivered to ISAC II (i.e. have an A/Q value between 5 and 6.4 only).
Purple font indicates species which may be delivered to ISAC II in the future with upgrades (i.e. have an A/Q value between 6.4 and 7 only).
"Possible Companions" includes any stable species with an A/Q value within +/- 0.5% (1/100 resolving power of magnet) of the species of interest. Obviously not all of these stable species will be present and the amount of each species will depend on the operating conditions of the CSB (temperature/pressure etc.) as well as the recent CSB history (i.e. isotopes recently injected into the device).
Red font indicates elements which are known to come from the CSB. (Residual gases and the material of the CSB itself).
The masses used here to calculate A/q values are taken from the AME2003 atomic mass evaluation available at http://www.nndc.bnl.gov/masses.

Species	Charge State	A/Q Value	Possible Companions
94Rb	1	93.926	
94Rb	2	46.963	
94Rb	3	31.308	
94Rb	4	23.481	
94Rb	5	18.785	
94Rb	6	15.654	
94Rb	7	13.418	
94Rb	8	11.740	
94Rb	9	10.436	
94Rb	10	9.392	
94Rb	11	8.538	
94Rb	12	7.827	



CSB Assistant
trshare.trium
94Rb 10 9.392
94Rb 11 8.538
94Rb 12 7.827
94Rb 13 7.225
94Rb 14 6.708
Accelerate
Apply 2nd Filter
94Rb 15 6.261
Accelerate
Apply 2nd Filter
94Rb 16 5.870
Accelerate
Apply 2nd Filter
150Nd24+=6.246
156Gd25+=6.236
169Tm27+=6.256
181Ta29+=6.239
194Pt31+=6.256
207Pb33+=6.271
41K7+=5.851
82Kr14+=5.850
100Ru17+=5.876
117Sn20+=5.845
135Ba23+=5.865
152Gd26+=5.843
165Ho28+=5.890
176Yb30+=5.864
187Re32+=5.842
Intensity
B-1
B
B+1
94Rb
25Mg
50Ti
50Cr
69Ga
94Mo
100Mo
107Ag
113In
119Sn
131Xe
132Xe
100Mo
113In
69Ga
107Ag
94Mo
94Rb22
132Xe
119Sn
2nd A/q (DSB-SEBT)
1st A/q (CSB-DSB)

Recent results

- August 2012 development run:
  - UO_2 production target with FEBIAD ion source – isobaric RI contaminants expected but unavoidable
  - All tools, techniques available for use
  - Goal: **Demonstrate RIB delivery to the ISAC-II experimental hall**
- A=94, 15+ ID'd as most promising case
  - A/q=6.26 beam tuned through ISAC-I
  - Stripped after DTL; charge-state distributions determined at Prague station

Expected beam components

$^{25}Mg^{4+}=6.246$
$^{44}Ca^{7+}=6.279$
$^{50}Ti^{8+}=6.243$
$^{50}V^{8+}=6.243$
$^{50}Cr^{8+}=6.243$
$^{69}Ga^{11+}=6.265$
$^{75}As^{12+}=6.243$
$^{88}Sr^{14+}=6.278$
$^{94}Zr^{15+}=6.260$
$^{94}Mo^{15+}=6.260$
$^{100}Mo^{16+}=6.244$
$^{100}Ru^{16+}=6.243$
$^{106}Pd^{17+}=6.229$
$^{107}Ag^{17+}=6.288$
$^{106}Cd^{17+}=6.229$
$^{113}Cd^{18+}=6.272$
$^{113}In^{18+}=6.272$
$^{119}Sn^{19+}=6.258$
$^{125}Te^{20+}=6.245$
$^{131}Xe^{21+}=6.233$
$^{132}Xe^{21+}=6.281$

- From CSB Assistant:
  - A/q = 6.229–6.233:
    - $^{106}Cd^{17+}$, $^{106}Pd^{17+}$, $^{131}Xe^{21+}$
  - 6.243–6.246:
    - $^{25}Mg^{4+}$, $^{50}Ti^{8+}$, $^{50}V^{8+}$, $^{50}Cr^{8+}$, $^{75}As^{12+}$, $^{100}Ru^{16+}$, $^{100}Mo^{16+}$, $^{125}Te^{20+}$
  - 6.258–6.265:
    - 6.258: $^{119}Sn^{19+}$
    - 6.260: **$^{94}Zr/Mo^{15+}$**
    - 6.265: $^{69}Ga^{11+}$
  - 6.272–6.288:
    - $^{113}Cd^{18+}$, $^{113}In^{18+}$, $^{88}Sr^{14+}$, $^{44}Ca^{7+}$, $^{132}Xe^{21+}$, $^{107}Ag^{17+}$

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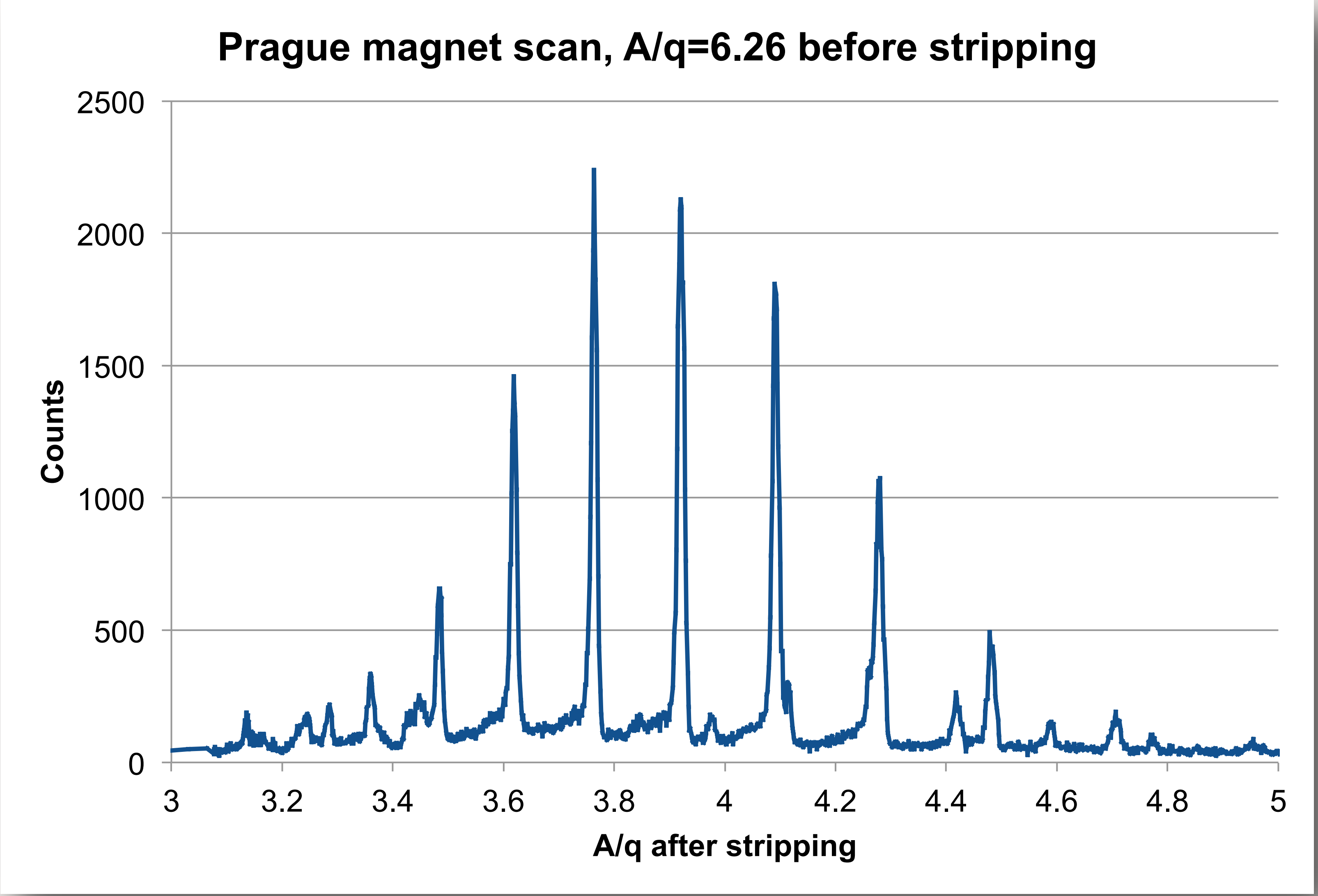
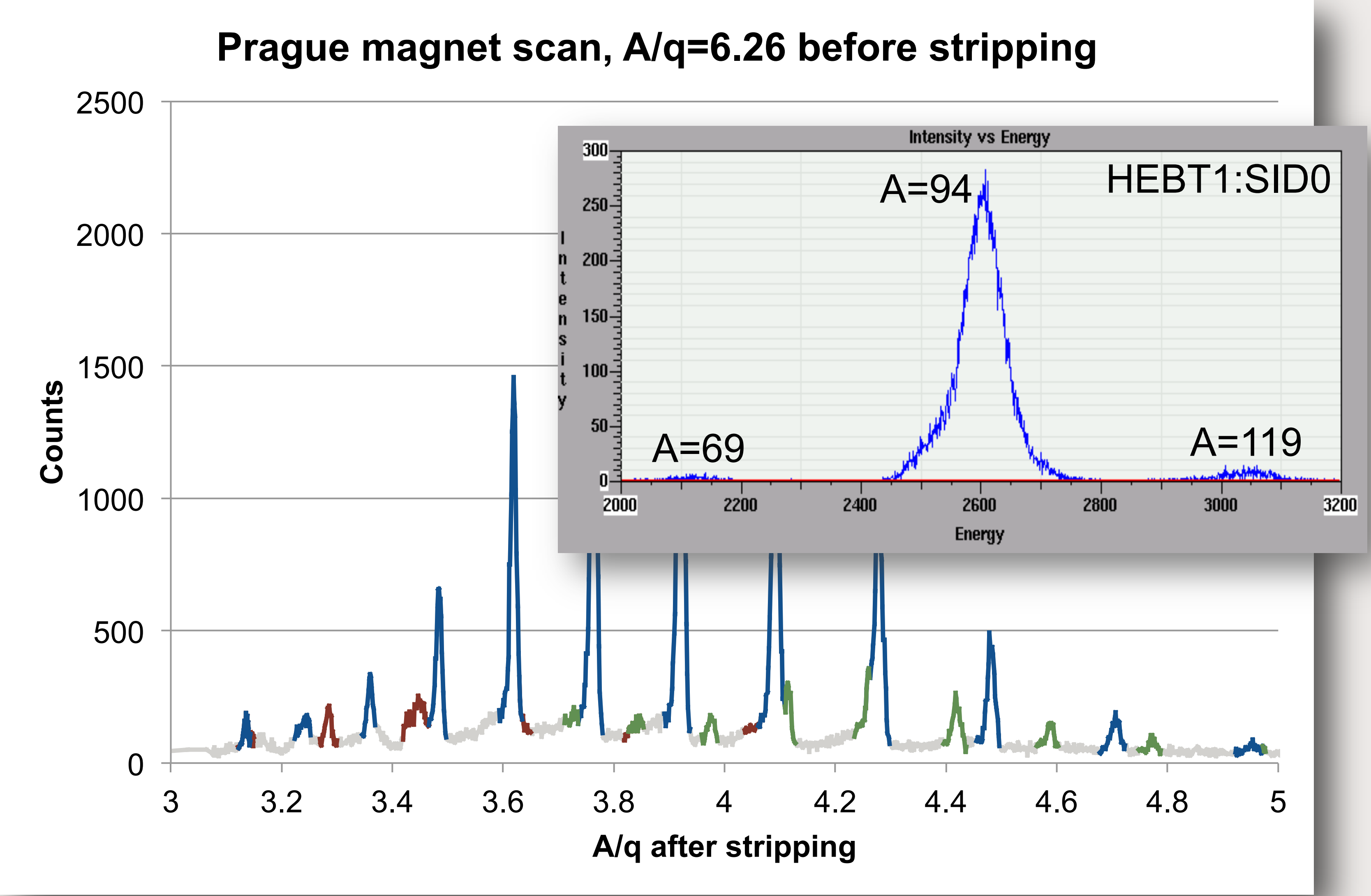
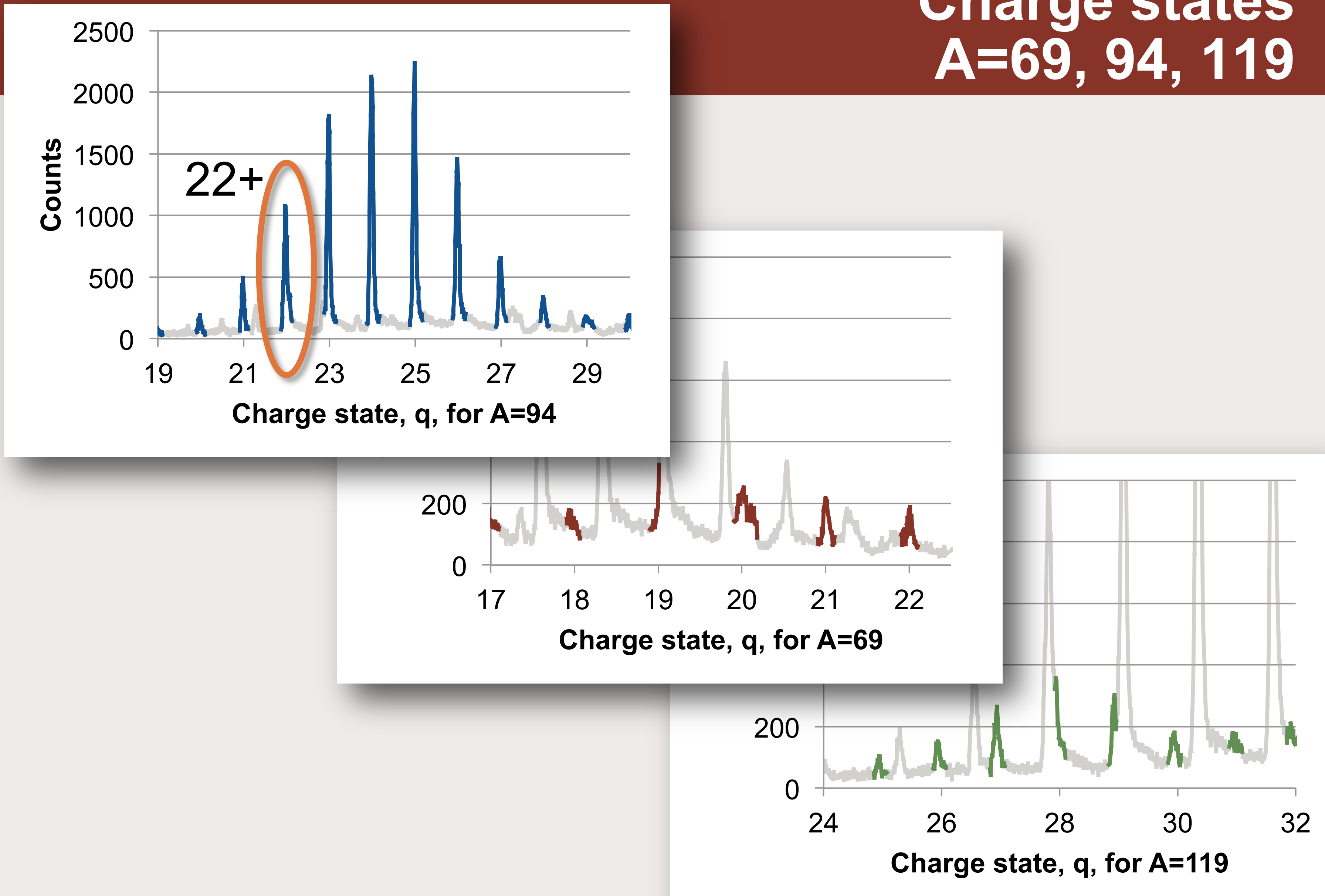
Stripping at 1.5 MeV/u



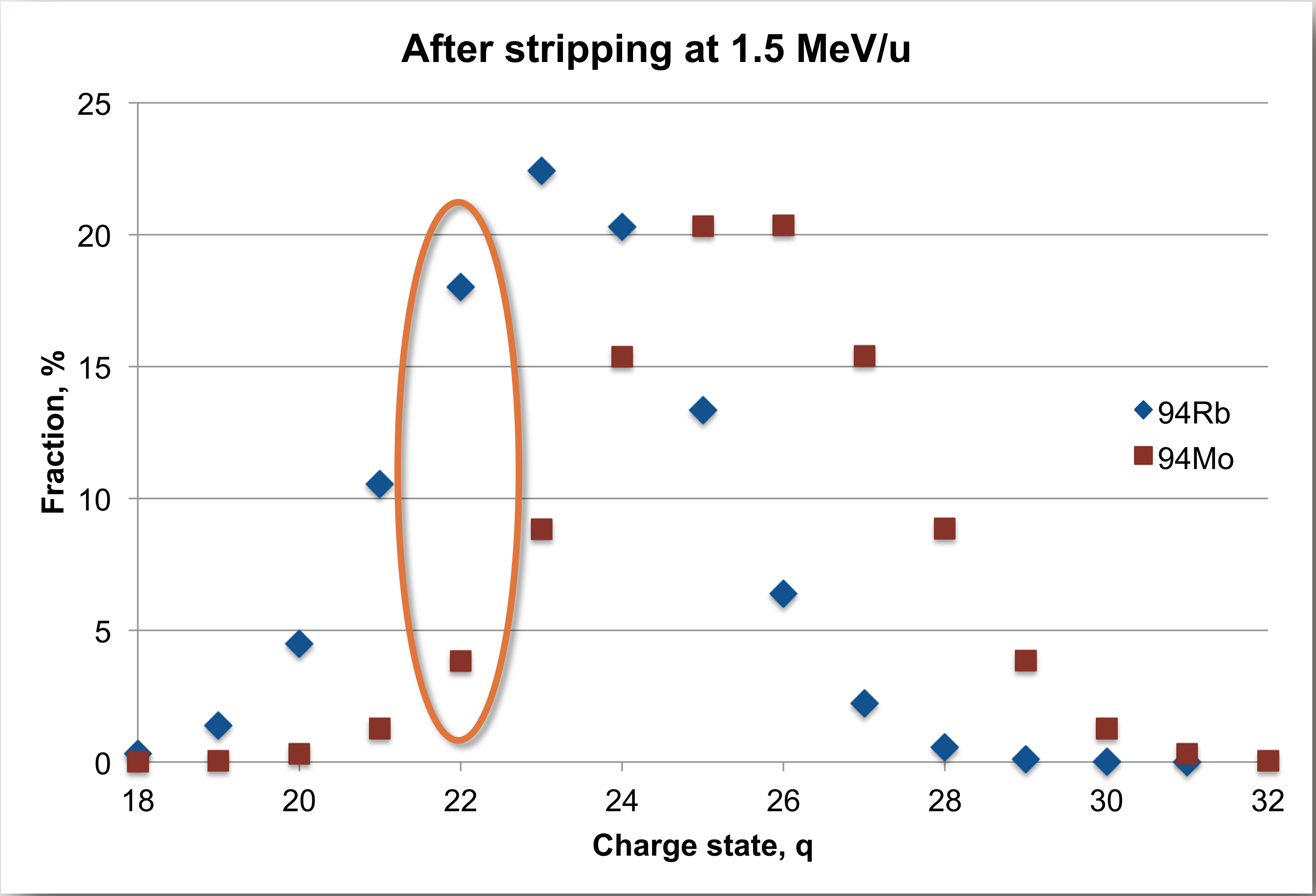
Stripping at 1.5 MeV/u



Charge states A=69, 94, 119



Calculated charge states, A=94



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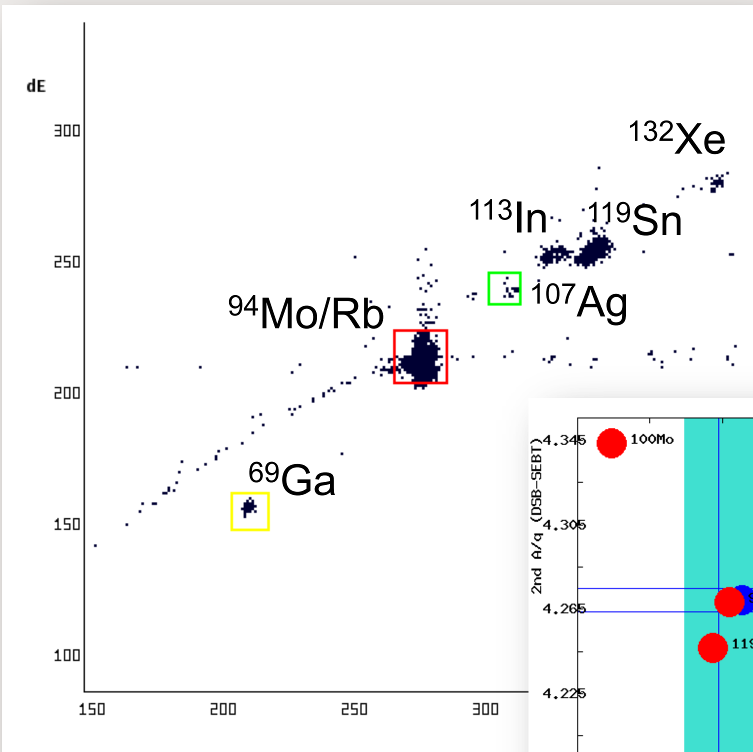
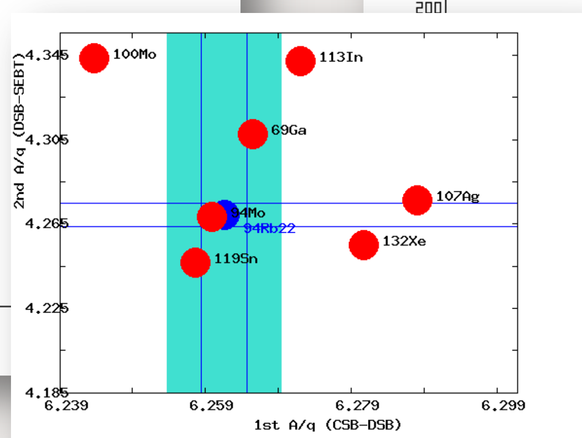
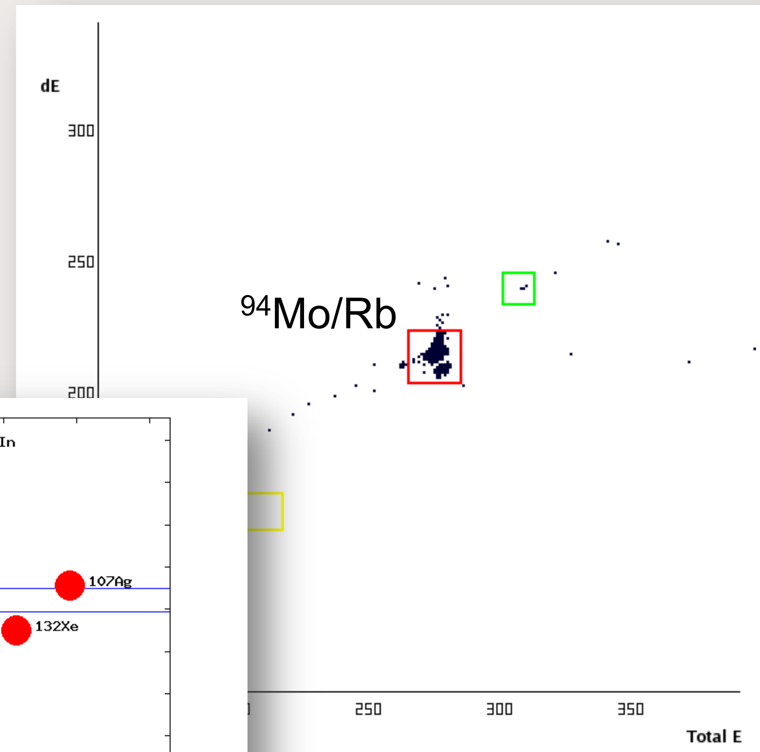
$^{94}Rb^{22+}$ at Bragg detector

Before final filtration





After final filtration



Summary and outlook

- Techniques for in-flight separation using a linac chain *that was not designed for it* have been developed
  - A/q, stripping, time-of-flight
  - New diagnostics and software
- The use of these techniques for beam purification has been demonstrated
  - A=94 from UO_2 target
- Proposals for high-mass experiments will be sought in the next call for submissions (tomorrow)

Acknowledgements

- TRIUMF's High Mass Task Force:
  - Accelerator Division: ACM, **Marco Marchetto**, Bob Laxdal, Friedhelm Ames, Victor Verzilov, Rick Baartman
  - Science Division: Barry Davids, Adam Garnsworthy, Greg Hackman, Peter Bender

Thank you!
Merci