New Developments and Capabilities at the Coupled Cyclotron Facility at Michigan State University

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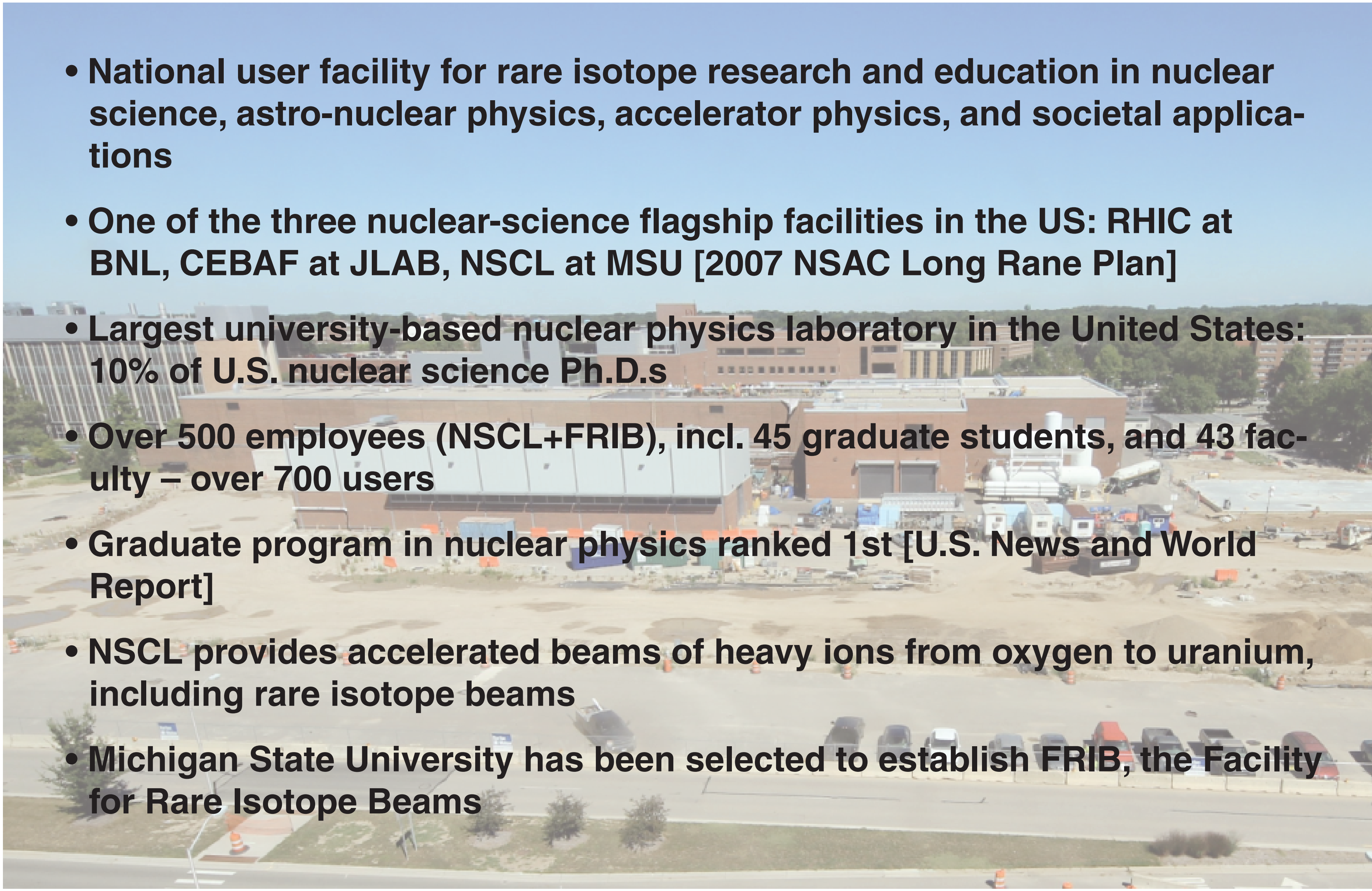
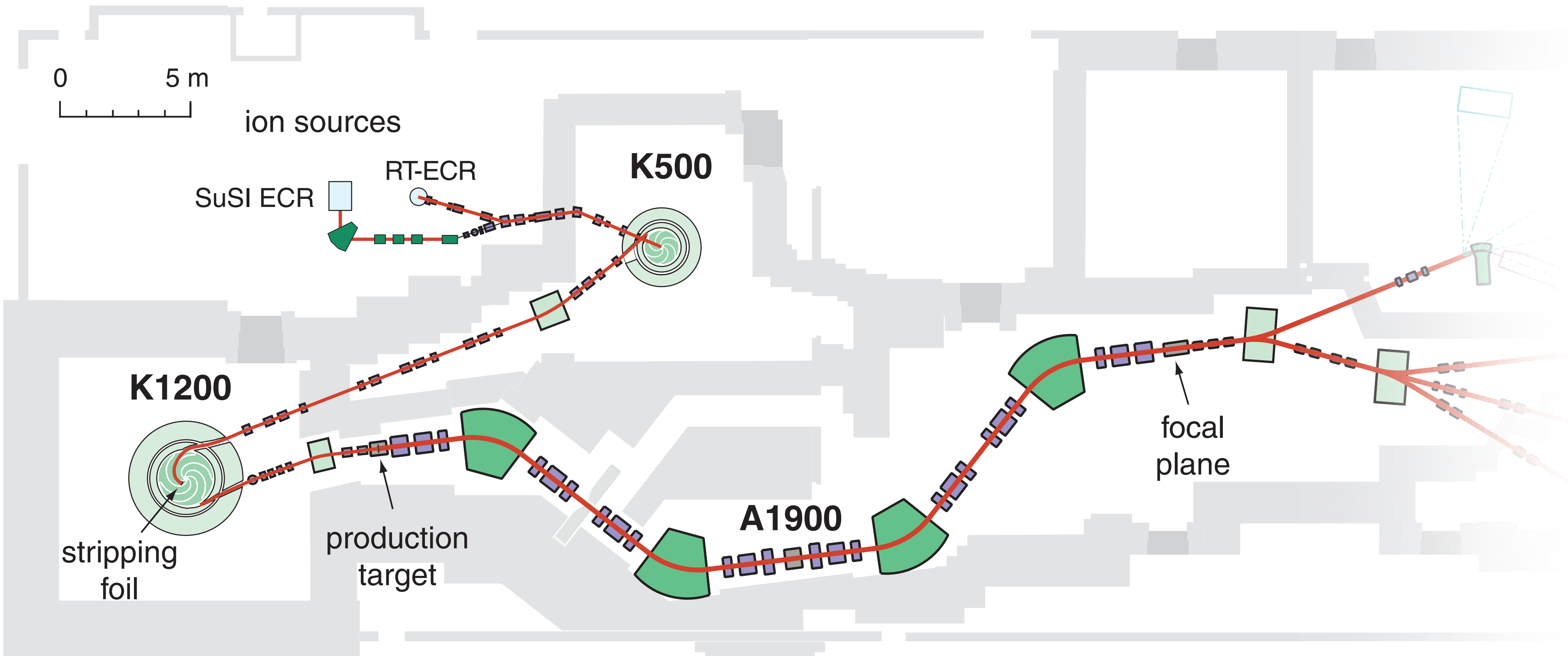
National Superconducting Cylotron Laboratory (NSCL)

NSCL at Michigan State University in East Lansing



- National user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications
- One of the three nuclear-science flagship facilities in the US: RHIC at BNL, CEBAF at JLAB, NSCL at MSU [2007 NSAC Long Rane Plan]
- Largest university-based nuclear physics laboratory in the United States: 10% of U.S. nuclear science Ph.D.s
- Over 500 employees (NSCL+FRIB), incl. 45 graduate students, and 43 faculty – over 700 users
- Graduate program in nuclear physics ranked 1st [U.S. News and World Report]
- NSCL provides accelerated beams of heavy ions from oxygen to uranium, including rare isotope beams
- Michigan State University has been selected to establish FRIB, the Facility for Rare Isotope Beams

Coupled Cyclotron Facility at NSCL



2 ECR ion sources
2 coupled cyclotrons: K500 + K1200
primary beams: oxygen to uranium
K500: 8 - 14 MeV/u, 2-8 eμA
K1200: 100 - 170 MeV/u, up to 2 kW

A1900 fragment separator
to produce rare isotope beams
by projectile fragmentation

NSCL Primary Beam List

Isotope	Energy [MeV/u]	Intensity [pnA]		Isotope	Energy [MeV/u]	Intensity [pnA]
^{16}O	150	175		^{82}Se	140	35
^{18}O	120	150		^{78}Kr	150	25
^{20}Ne	170	80		^{86}Kr	100	15
^{22}Ne	120	80		^{86}Kr	140	25
^{22}Ne	150	100		^{96}Zr	120	1.5
^{24}Mg	170	60		^{112}Sn	120	4
^{36}Ar	150	75		^{118}Sn	120	1.5
^{40}Ar	140	75		^{124}Sn	120	1.5
^{40}Ca	140	50		^{124}Xe	140	10
^{48}Ca	90	15		^{136}Xe	120	2
^{48}Ca	140	80		^{208}Pb	85	1.5
^{58}Ni	160	20		^{209}Bi	80	1
^{64}Ni	140	7		^{238}U	45	0.1
^{76}Ge	130	25		^{238}U	80	0.2

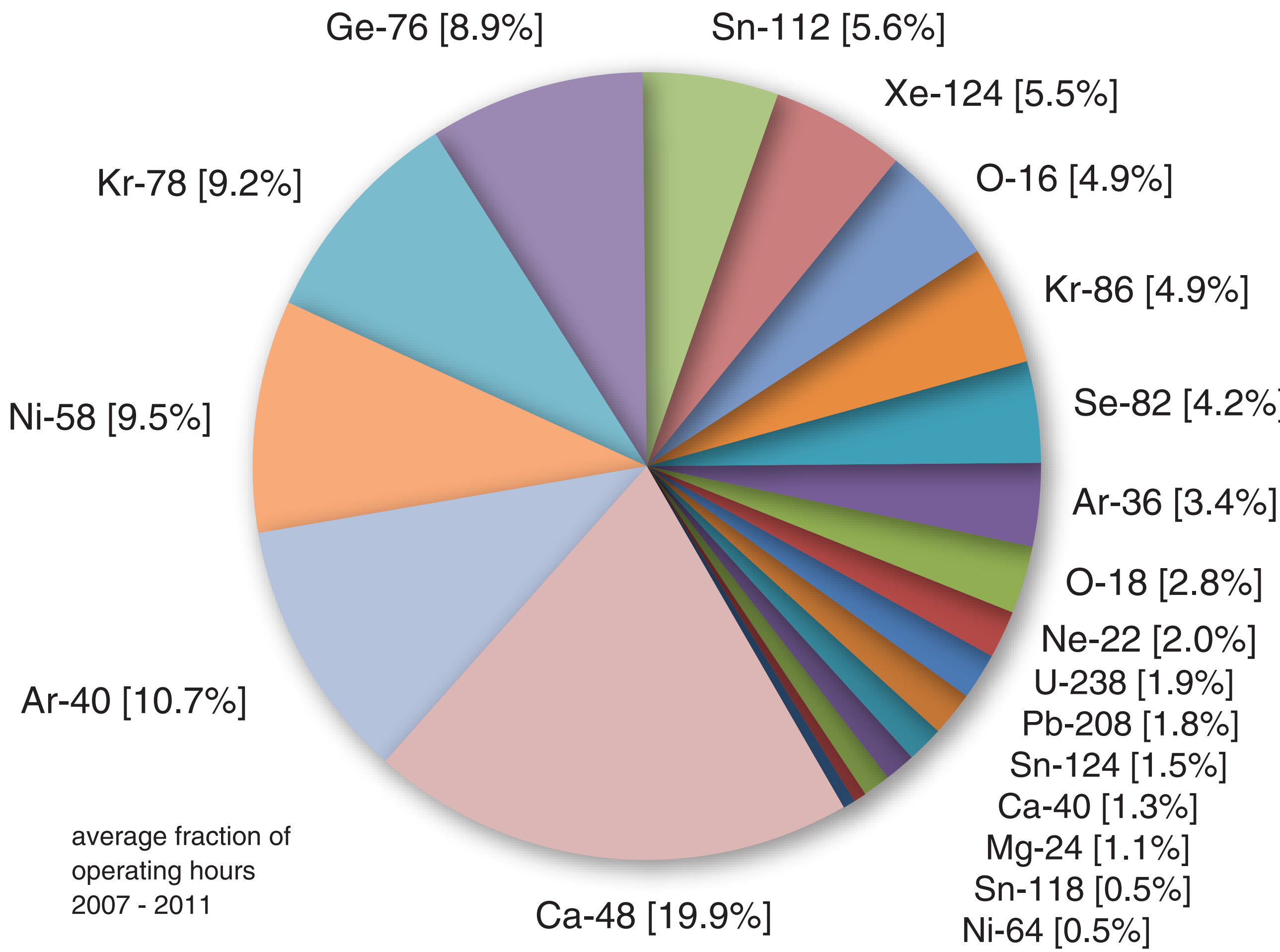
Beam list intensities are typical intensities for experiment planning purposes and are maintainable for extended time periods.

Primary Beam Statistics

Coupled Cyclotron Facility (CCF) delivers a different primary beam every 5 to 7 days, typically 30 beam changes per year.

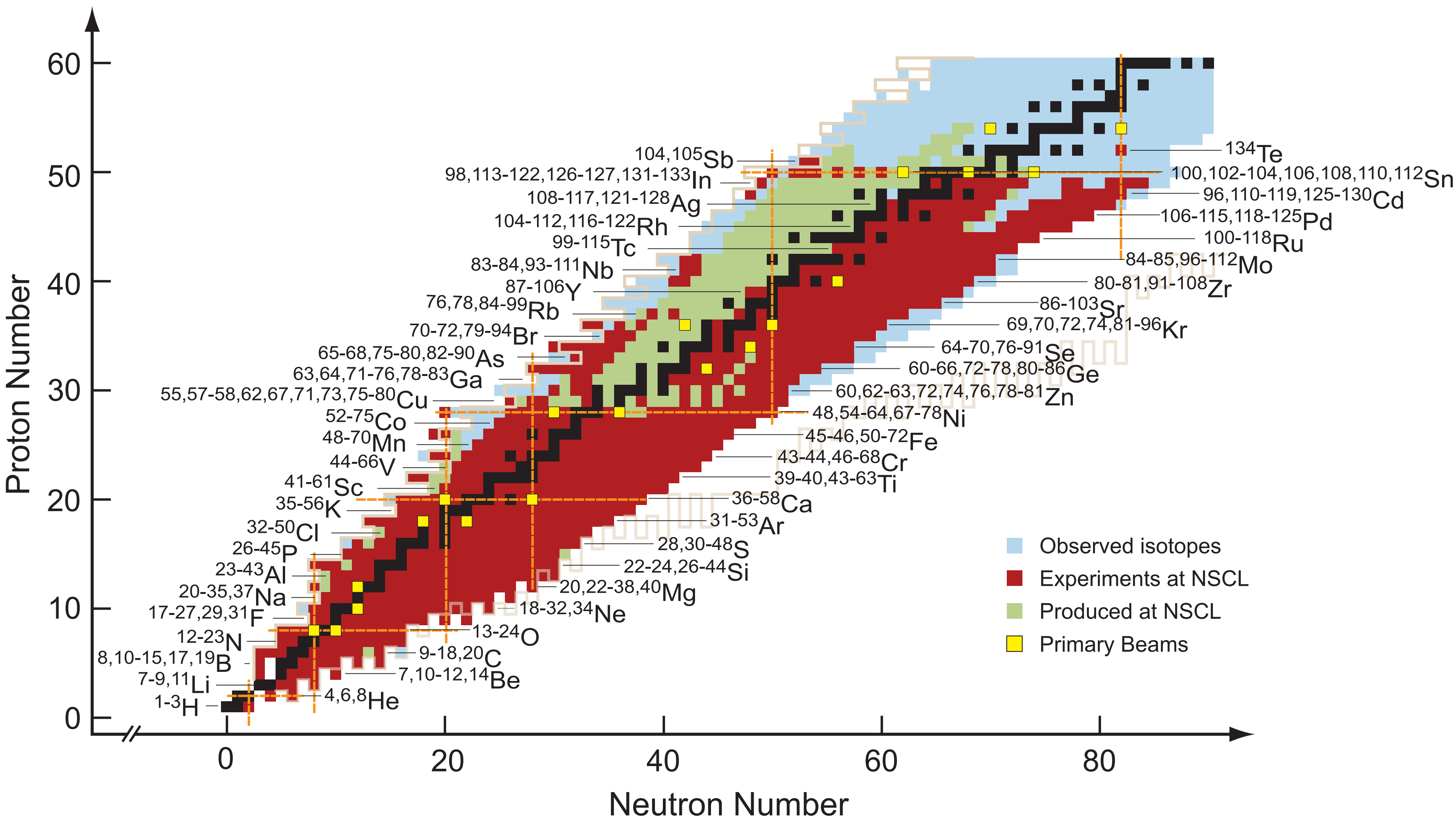
The development of new primary beams (isotope and energy) is driven by user demand.

CCF Primary Beam Isotope Statistics



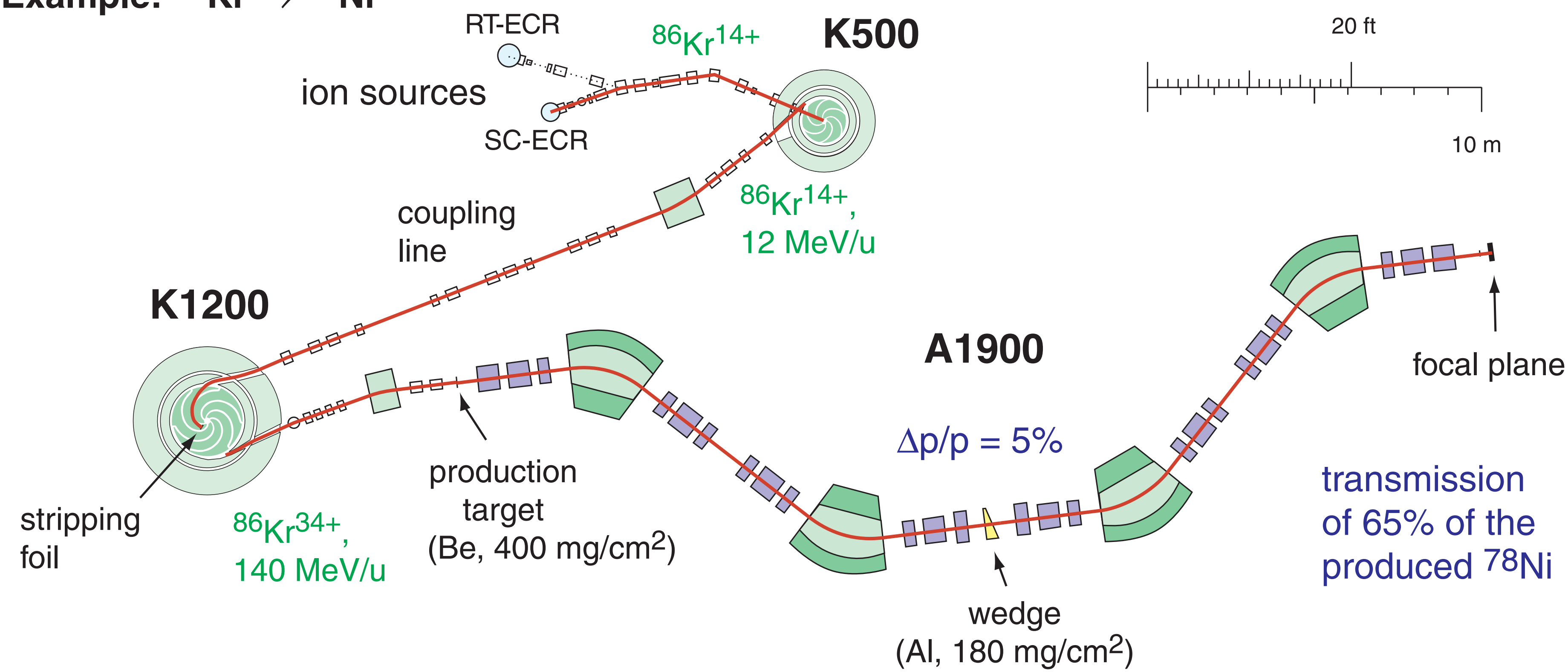
Rare Isotope Beams produced at NSCL

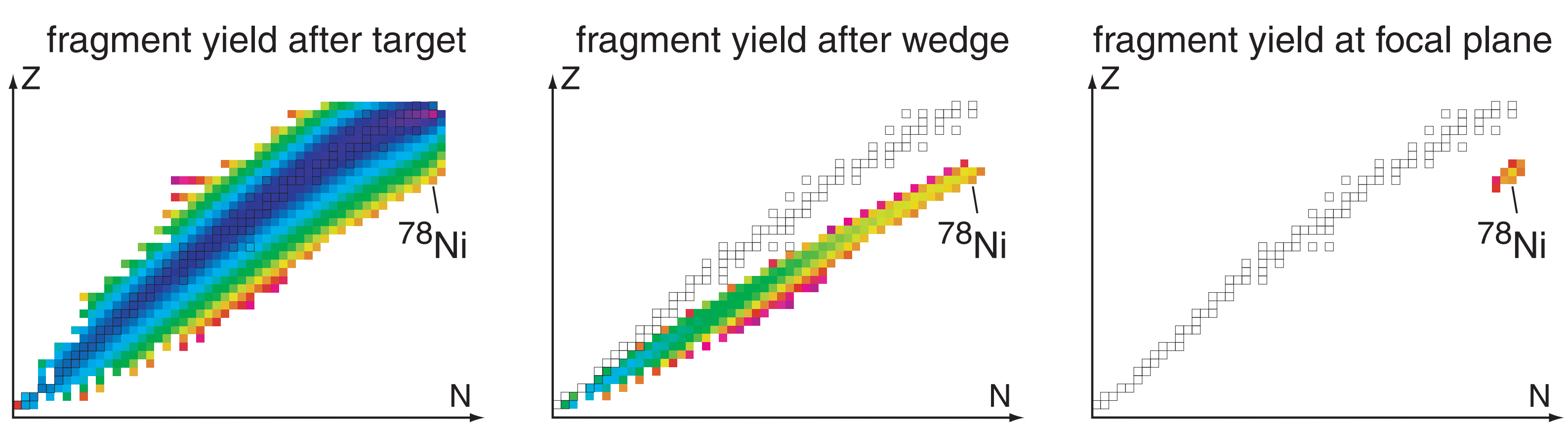
more than 1000 RIBs have been produced (2001-2013)
more than 870 have been used in experiments



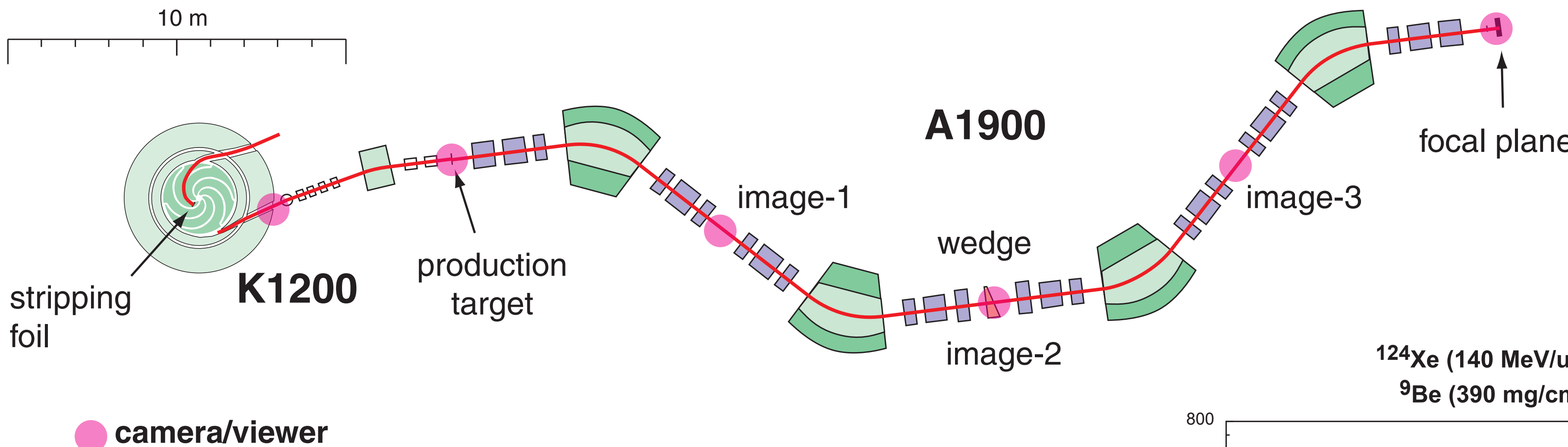
Overview of the Fragment Separation Technique

Example: $^{86}Kr \rightarrow {}^{78}Ni$

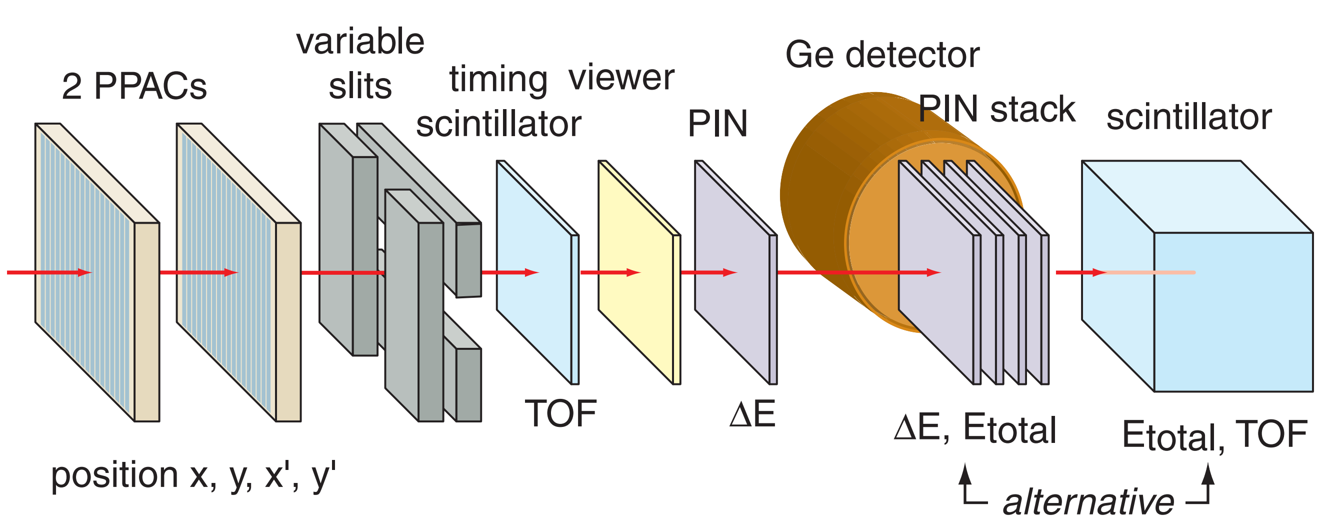




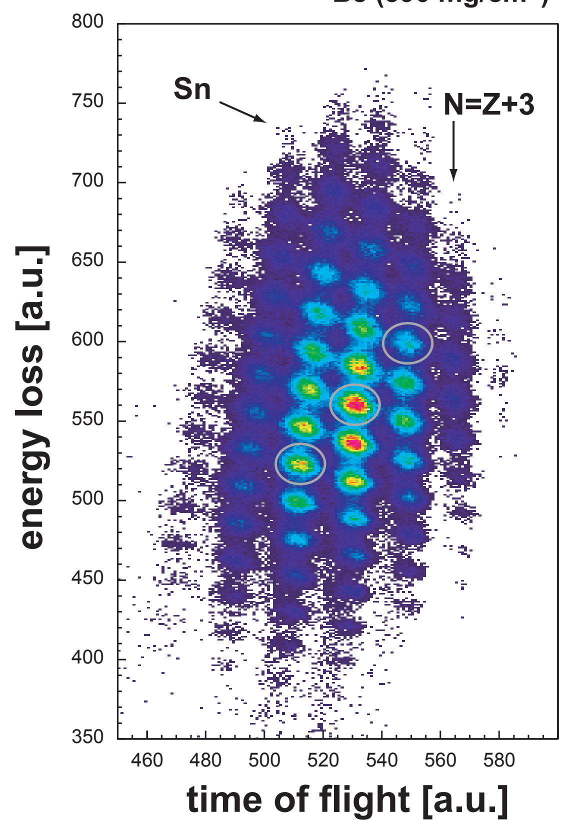
A1900 Diagnostics Setup and Particle Identification



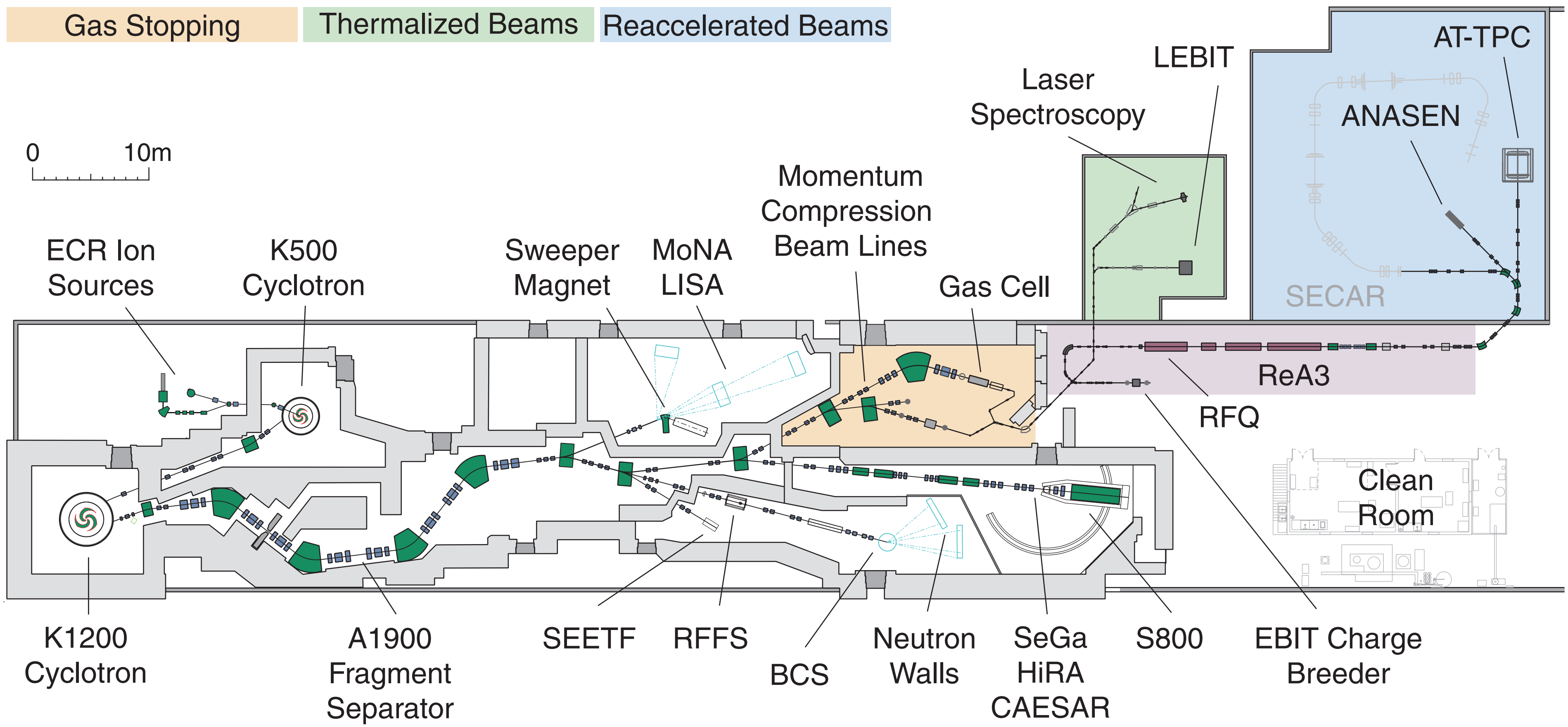
Detector Setup in Focal Plane Box



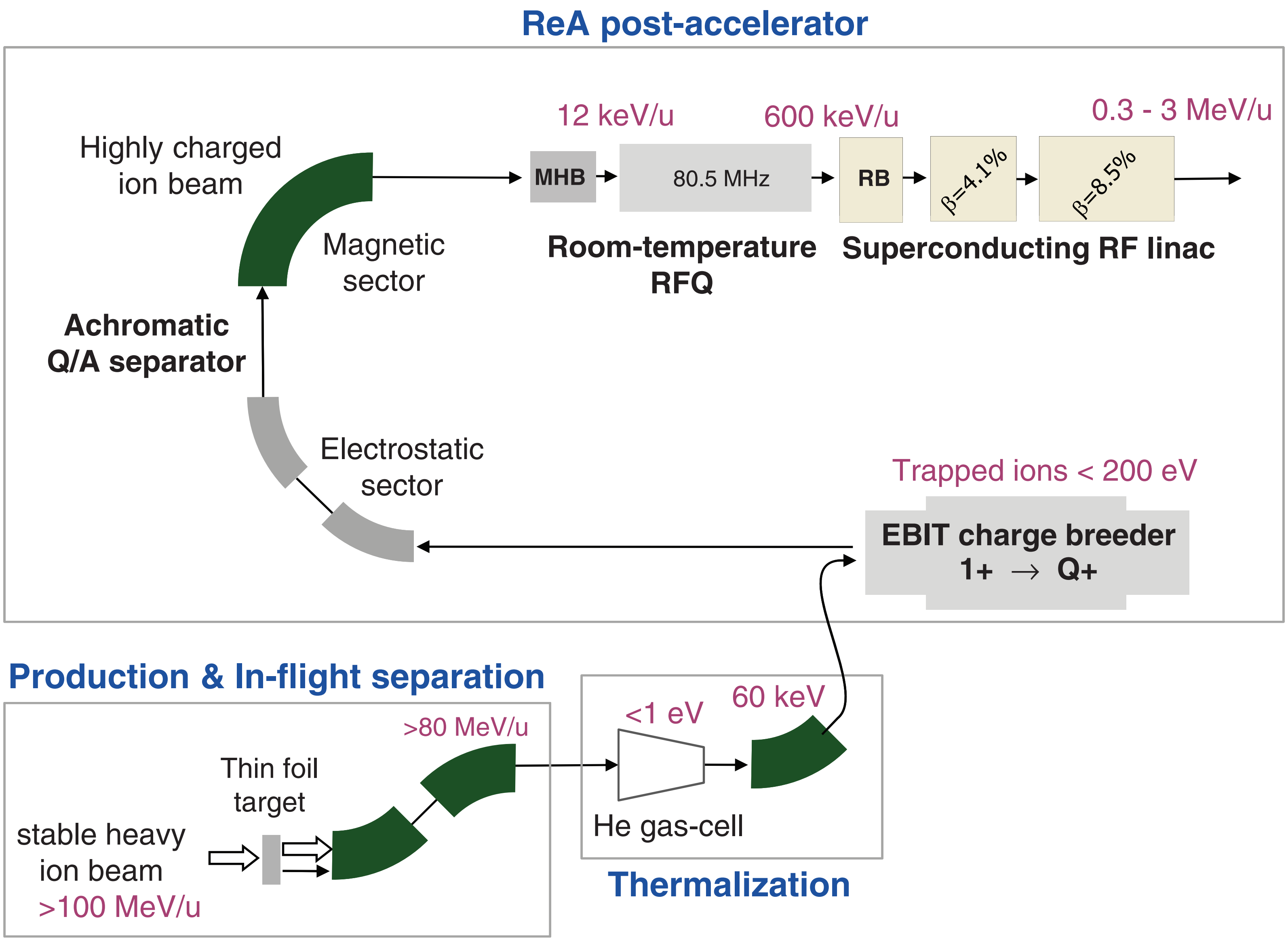
^{124}Xe (140 MeV/u) +
^{9}Be (390 mg/cm^{2})



NSCL's Experimental Facility Plan



The Reacceleration Concept

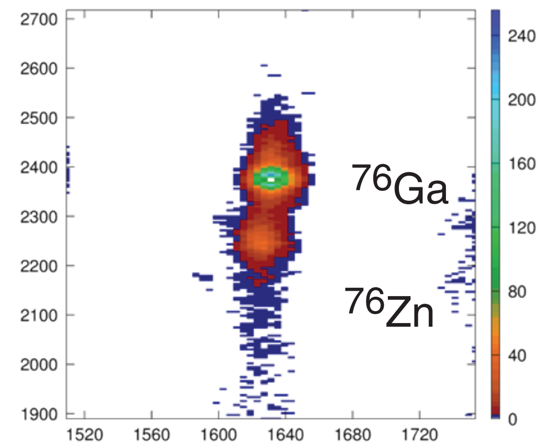


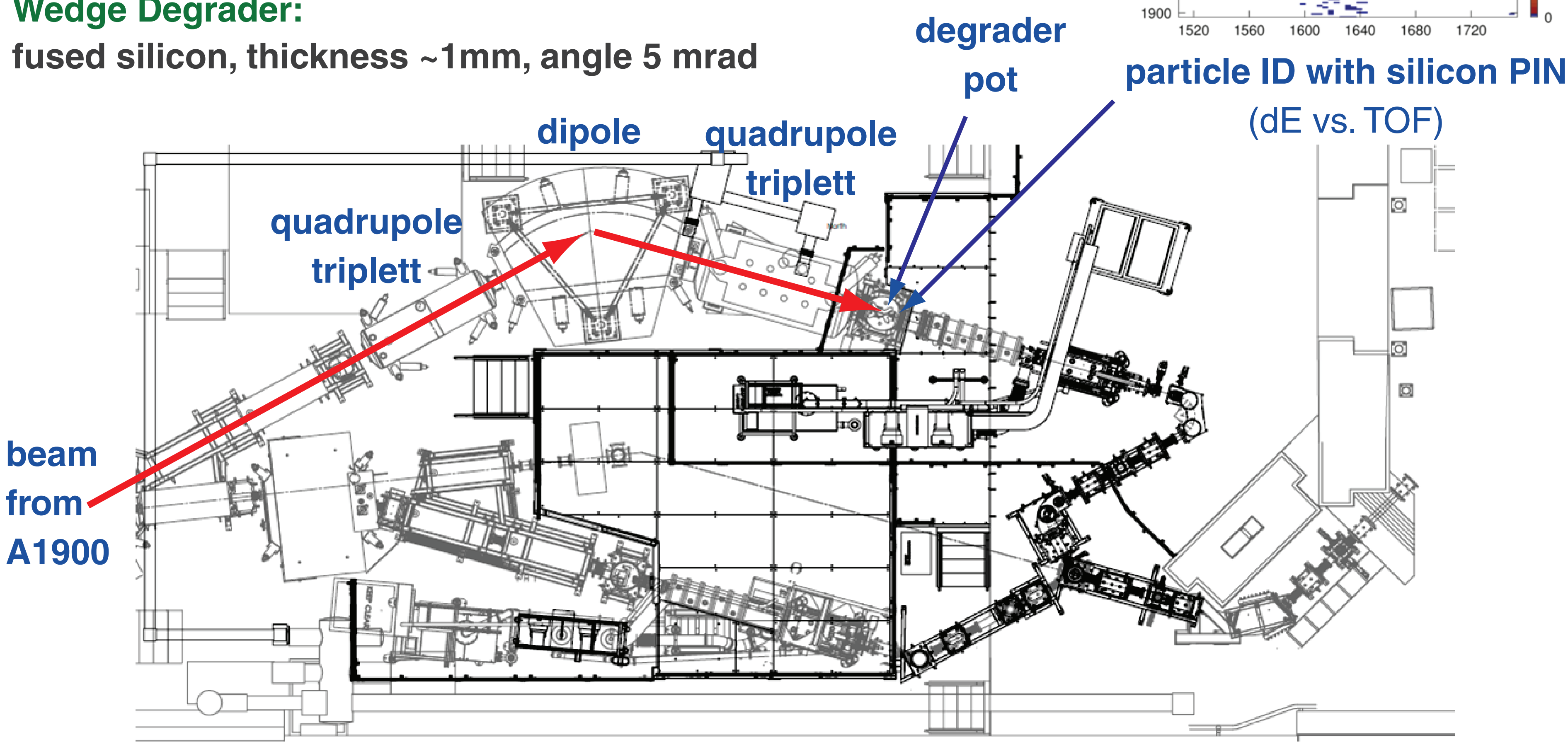
Gas Thermalization – Momentum Compression

Rare isotope beams from A1900 fragment separator go through a momentum compression stage based on magnetic elements and variable and wedge-shaped solid degraders before injection into gas cell.

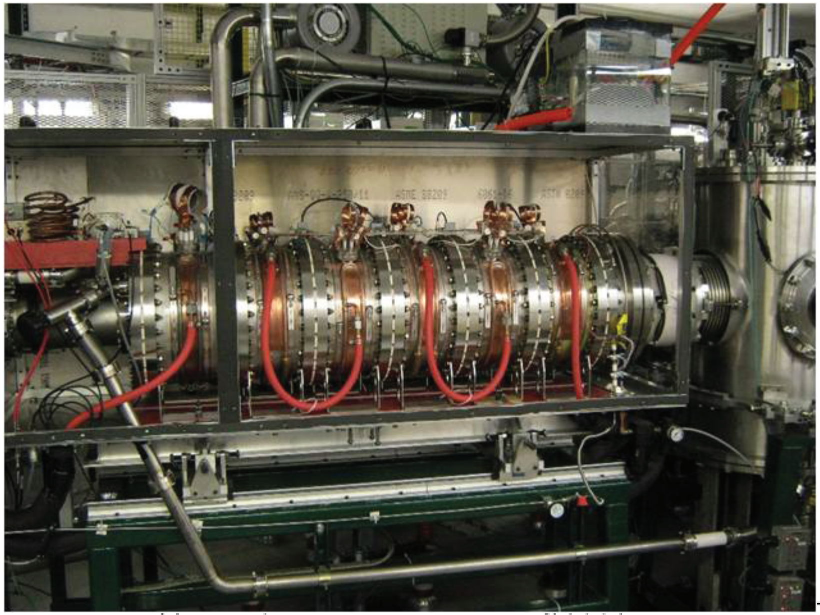
Rotable Degraders:
aluminum, thickness ~0.2 - 1.5 mm, angle 0-45 deg

Wedge Degrader:
fused silicon, thickness ~1mm, angle 5 mrad





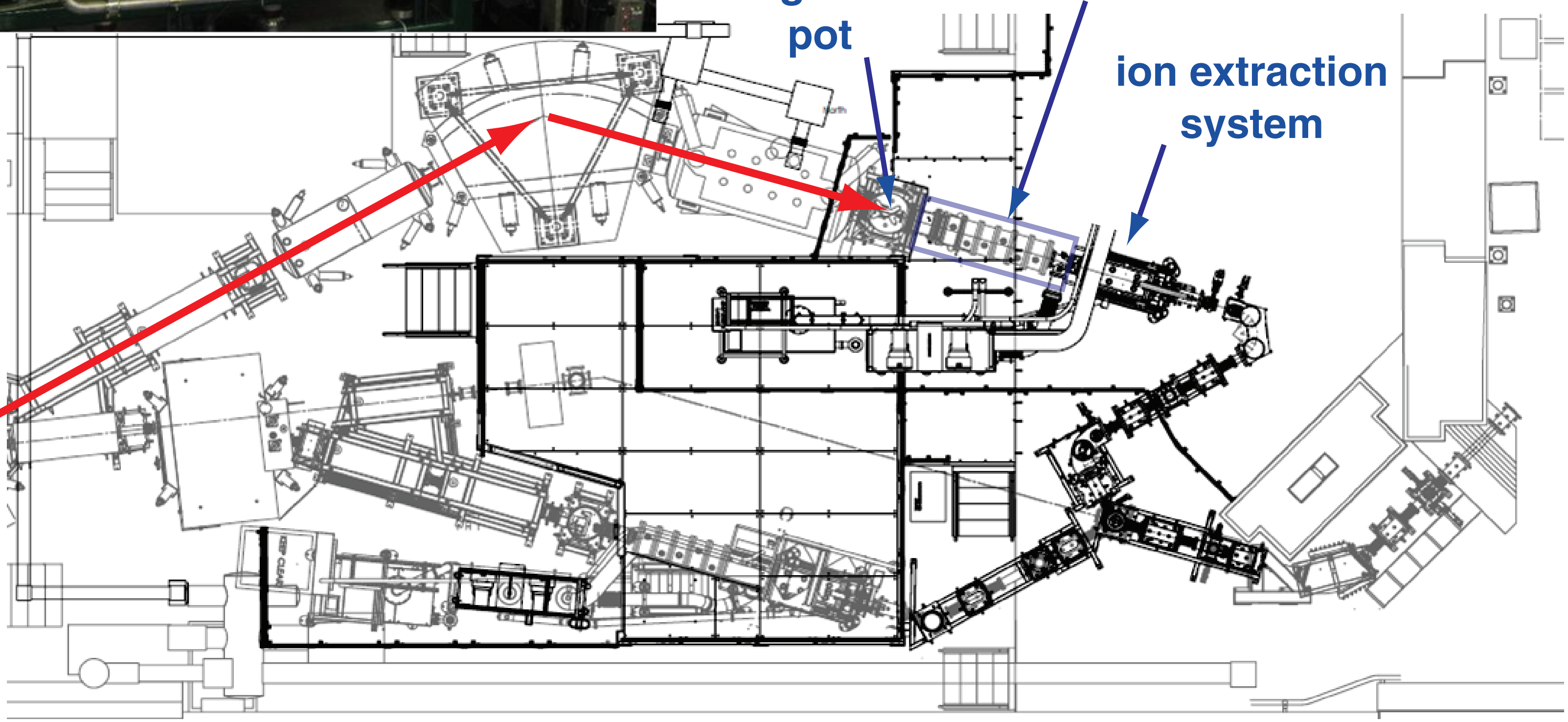
Gas Thermalization – Gas Catcher



120 cm gas catcher from Argonne National Lab operates with helium at ~100 mbar and -5°C

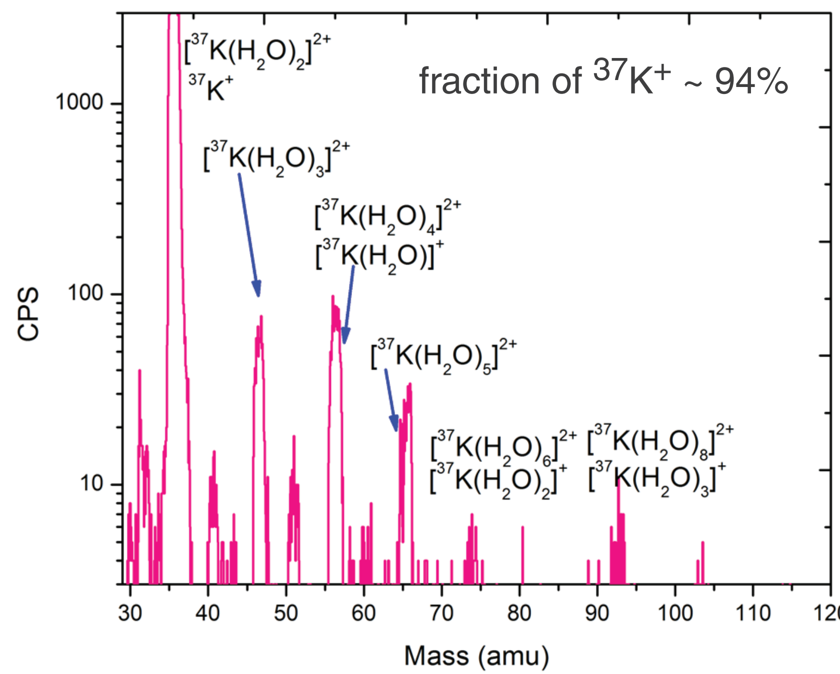
gas catcher mounted on high-voltage platform with variable potential up to 60 kV

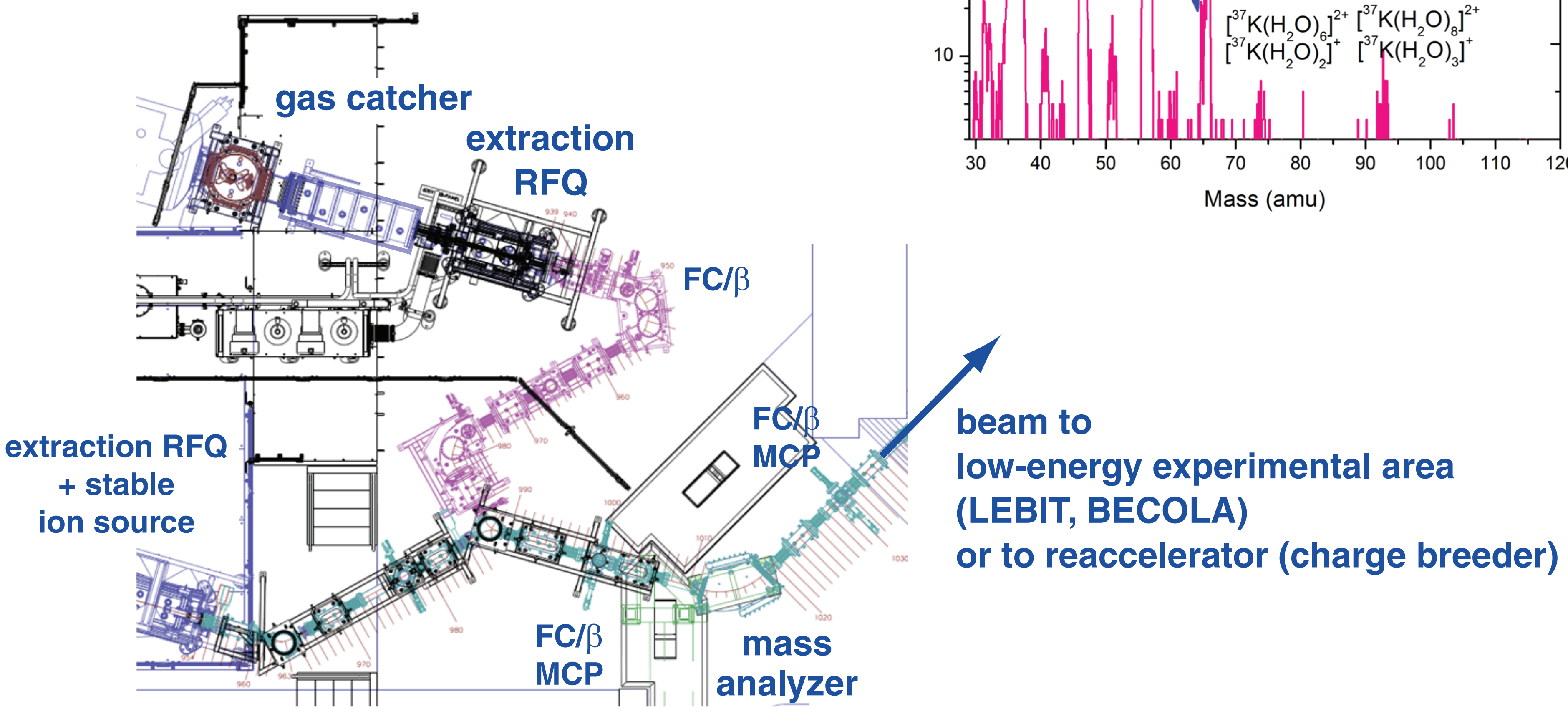
total extraction efficiency: ~10%



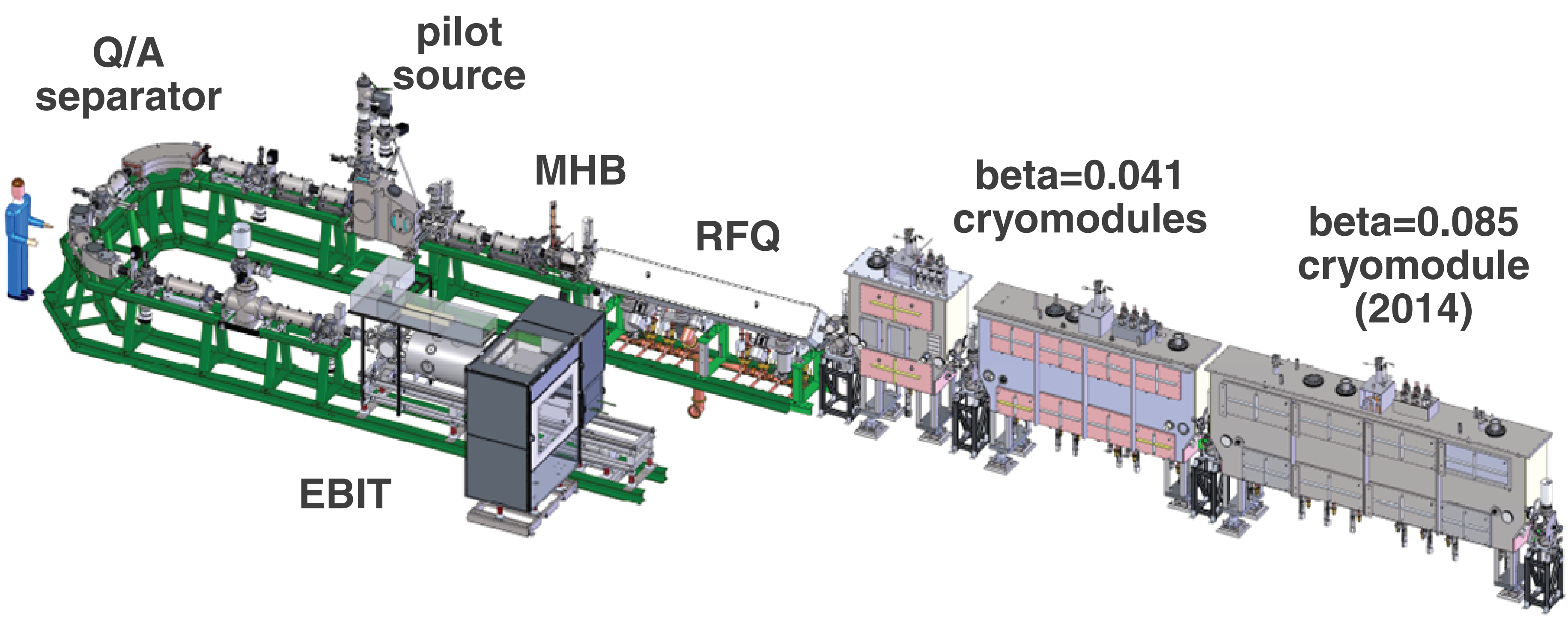
Gas Thermalization – Extraction

- ions are extracted in 1+ and 2+ charge states
- mass analyzer allows to select single mass
- activity can be detected with beta-decay counter
- extraction efficiency into single mass depends on chemistry with impurities





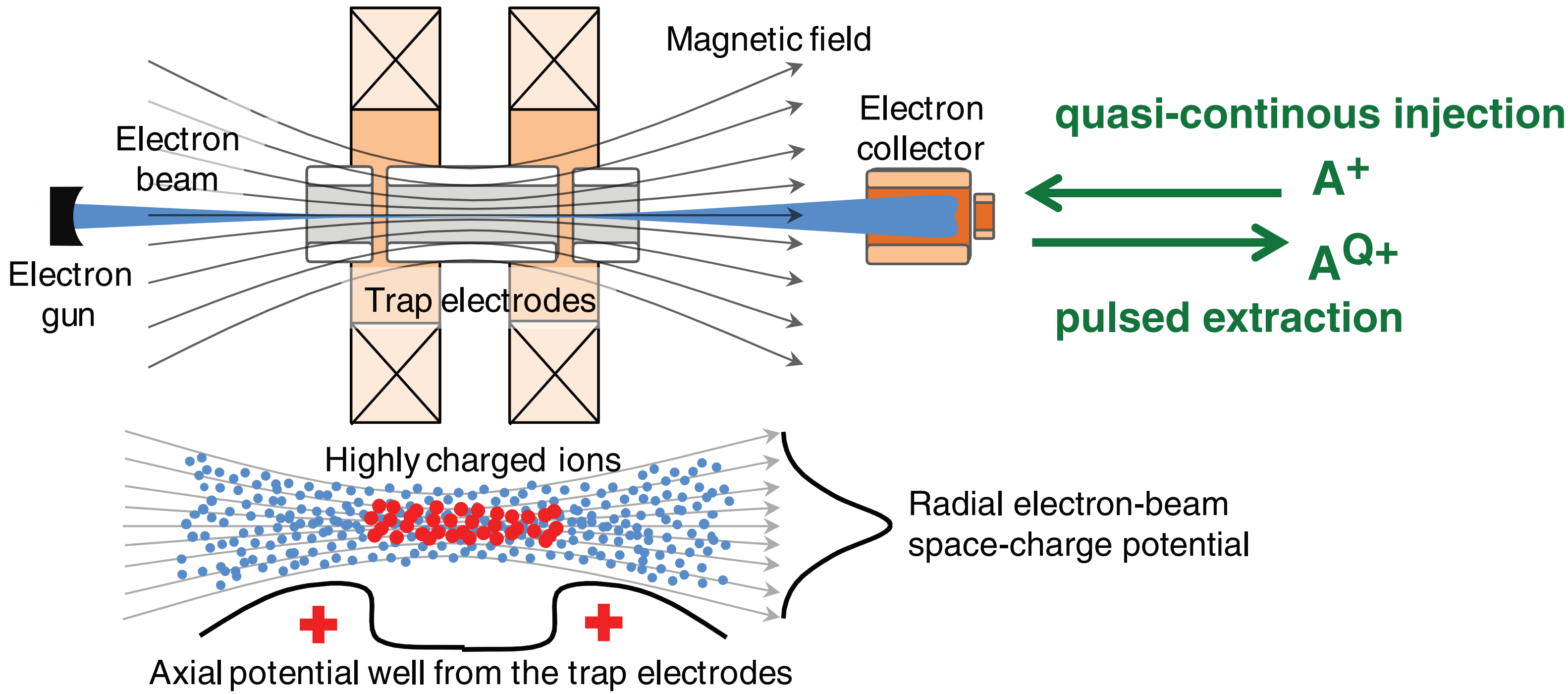
ReA Reaccelerator Layout



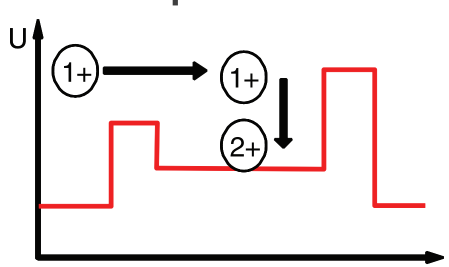
EBIT charge breeder
Q/A mass separator
multi harmonic buncher (MHB)
room-temperature RFQ
2 beta=0.041 cryomodules with 2 + 6 QWR
1 beta=0.085 cryomodule (to be installed in 2014)

EBIT Charge Breeding Principle

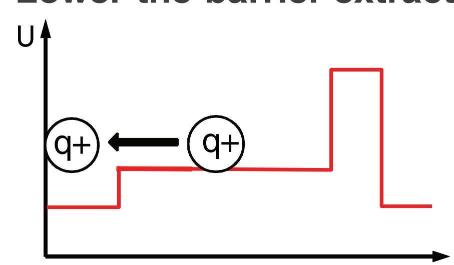
- Singly charged ions quasi-continuously injected in the high-current density electron beam
- Ions trapped by trap electrodes & the e-beam space-charge potential
- Highly charged produced by electron-impact ionization (i.e., charge breeding)
- Pulsed extraction of highly charged ions



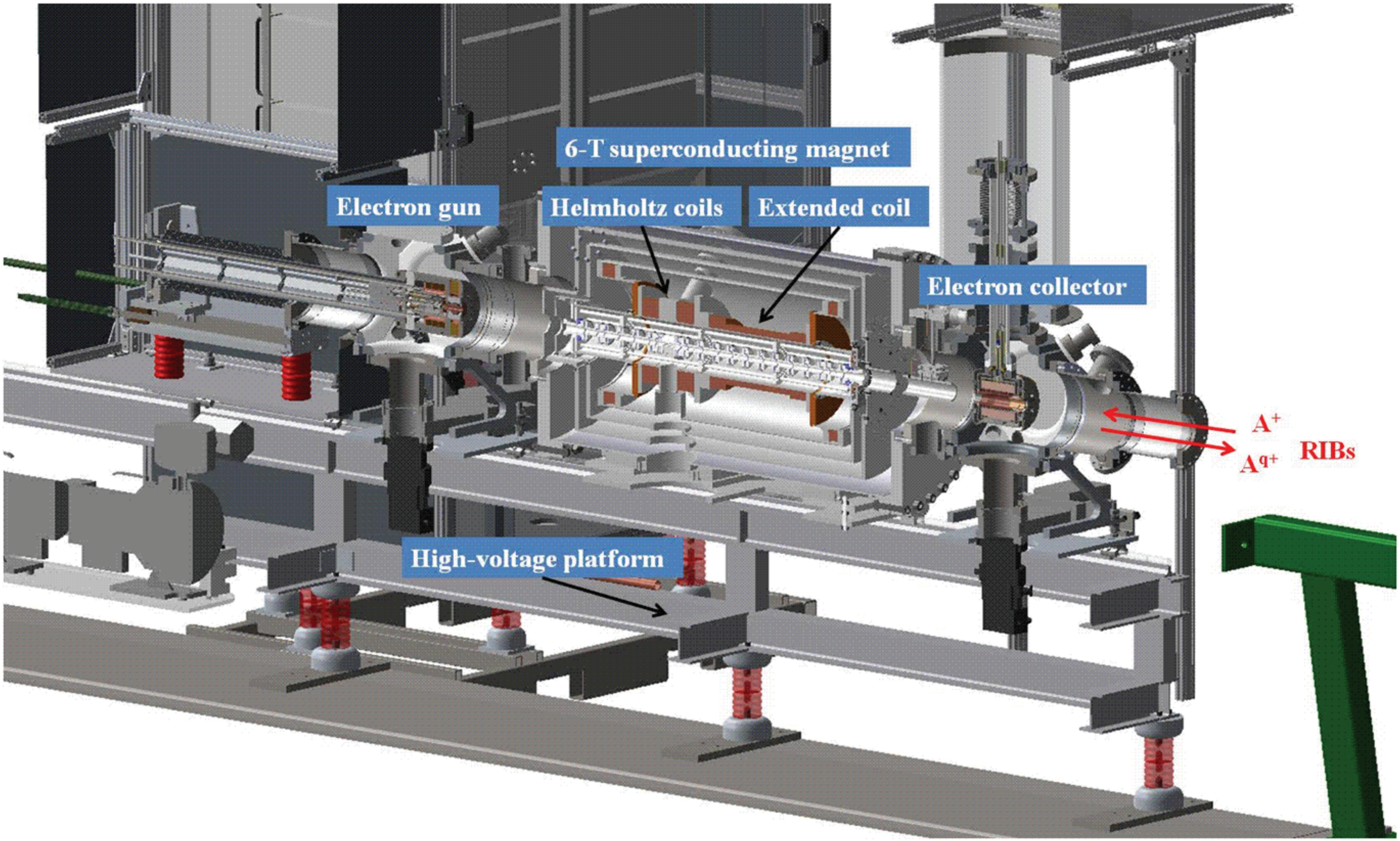
Over-the-potential barrier injection



Lower-the-barrier extraction



The ReA EBIT Charge Breeder



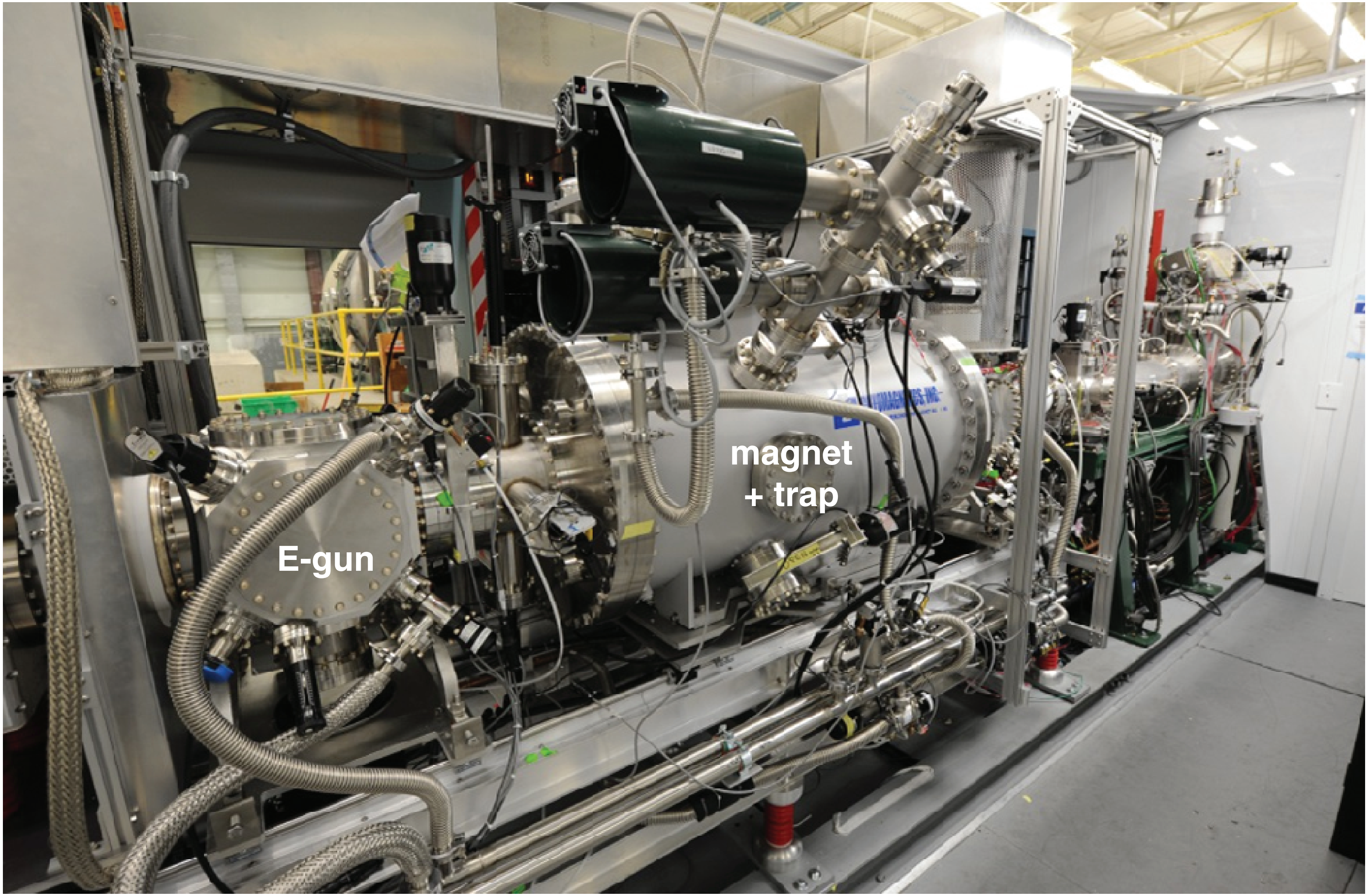
Requirements for ReA charge breeder:

- Breeding time < 50 ms (for short-lived isotopes)
- Efficiency: 20% - 50 % (inject.-breeding-extract.)
- Charge capacity: up to 10^{10} positive charges
- Low contamination level…

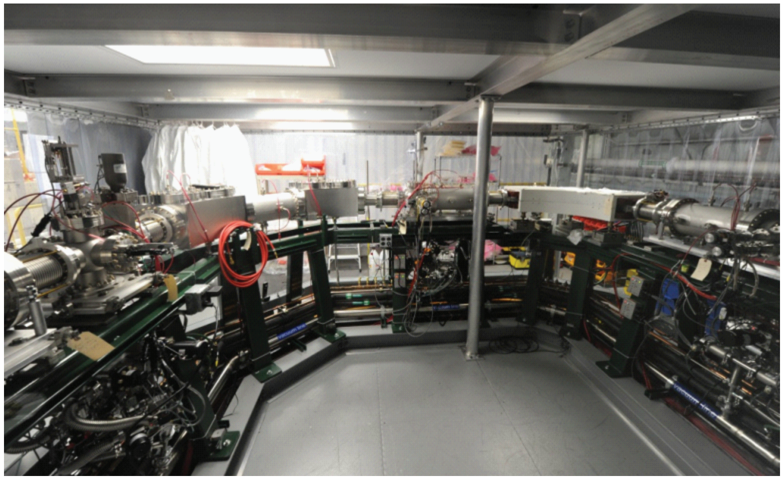
Key design parameters:

- High electron current: up to 2.4 A (large cathode)
- E-beam energy <30 keV (e.g. Ne-like U^{82+})
- Current density (6 T): ~10^4 A/cm^2
- Reduced contamination: 4-K trap structure

ReA EBIT Charge Breeder

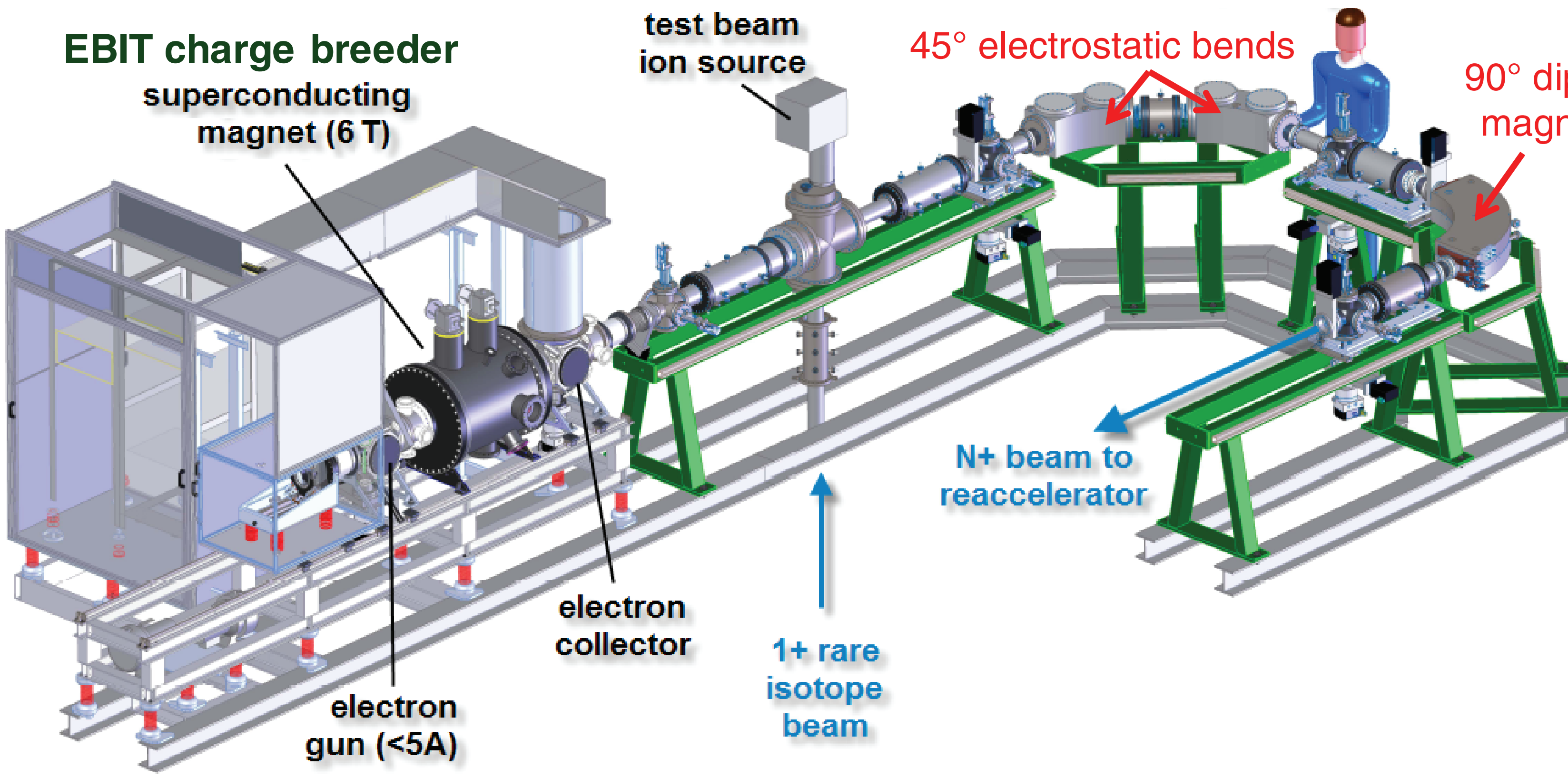


Q/A Mass Separator



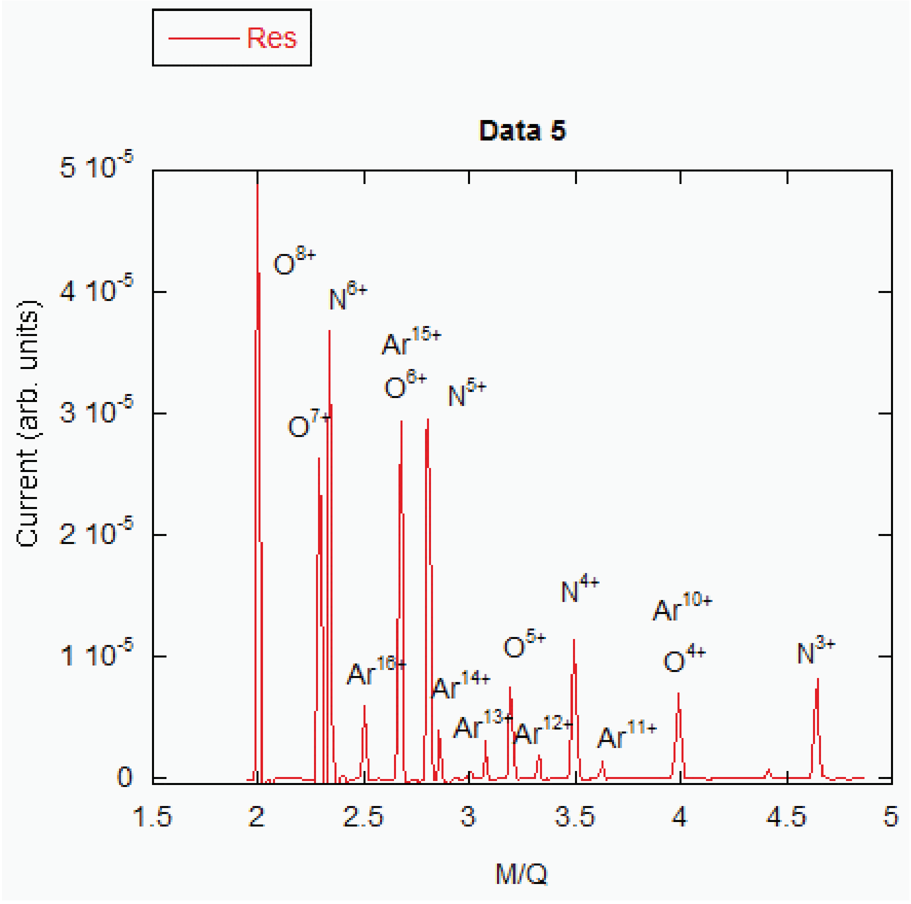
Design parameters:

- Resolving power ~100 at 120 π mm mrad
- Achromatic within $\Delta E/E$ ~ 3%
- Accept EBIT beams of large energy spread

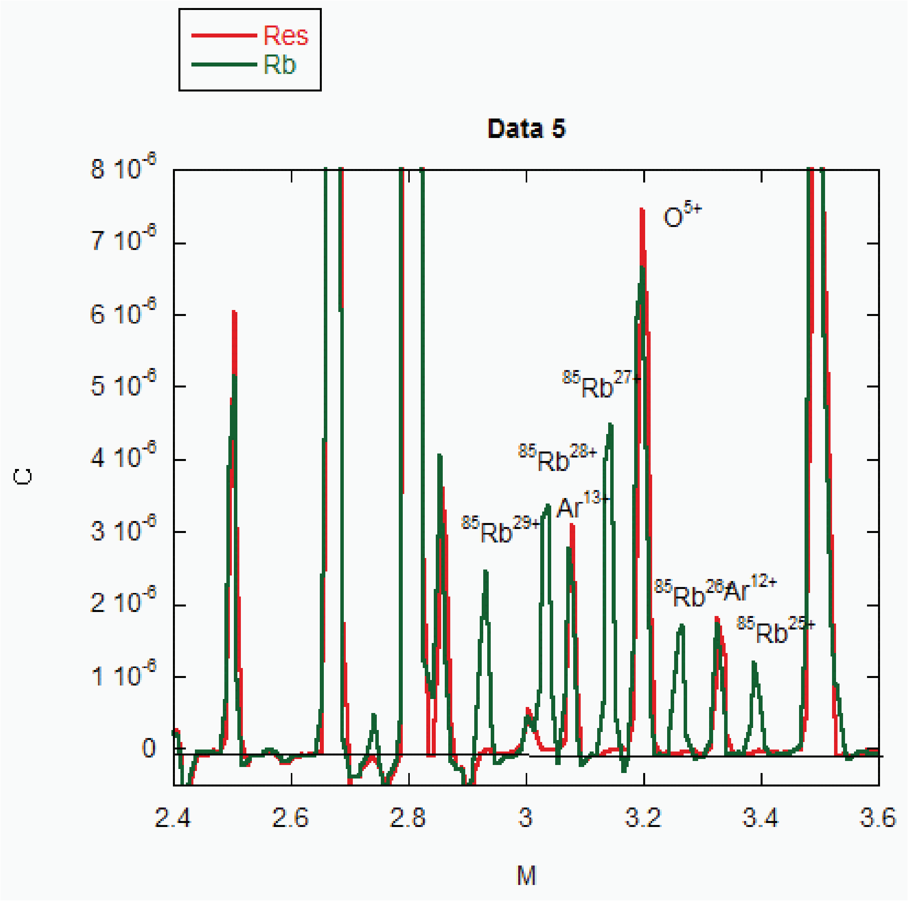


EBIT Commissioning Results

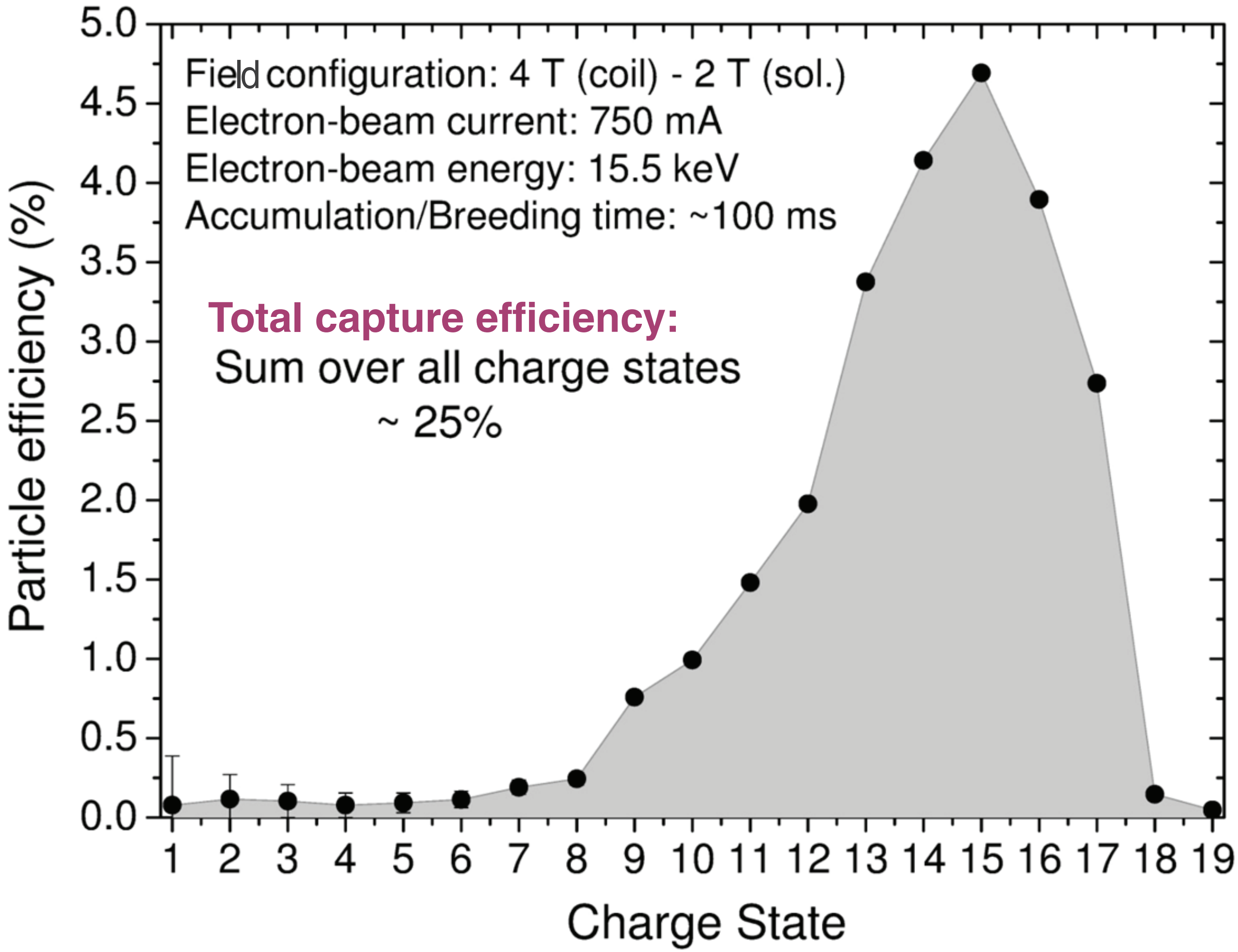
Residual Gas - no EBIT injection



Charge-bred ^{85}Rb from ion source

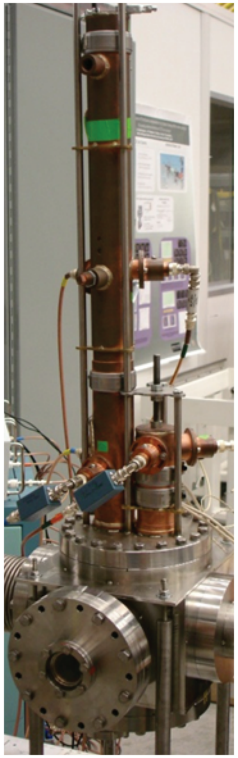


EBIT Charge Breeding Efficiency



Total capture efficiency is in good agreement with expected capture efficiency (~30%) for an electron beam current density of ~350 A/cm^2

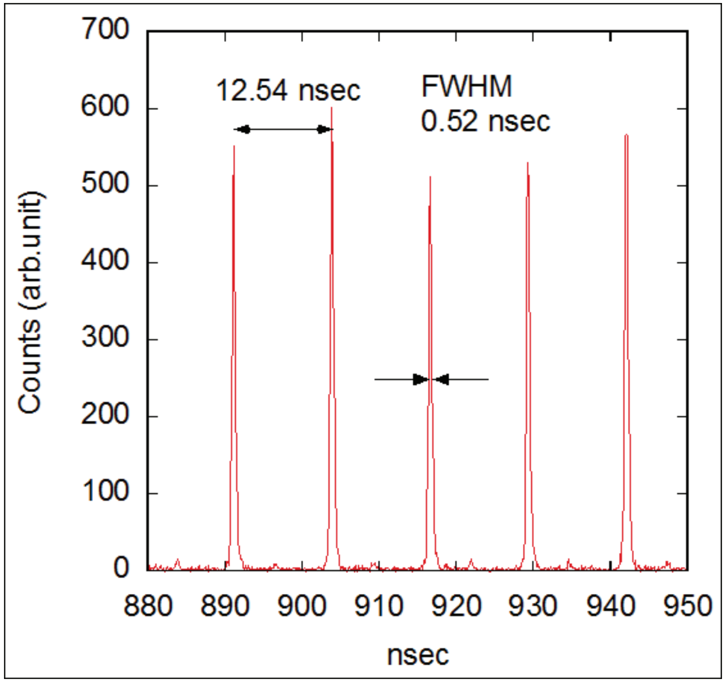
Multiharmonic Buncher and RFQ



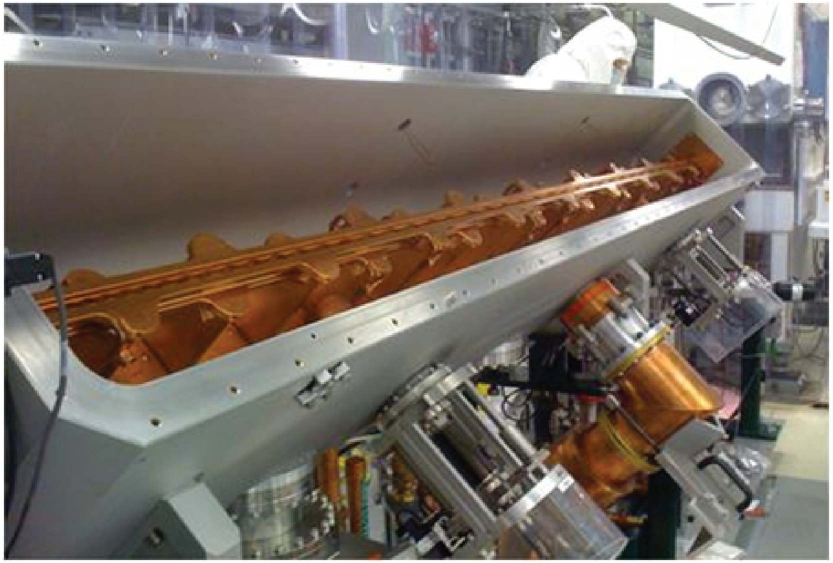
Multiharmonic Buncher (MHB)

Used to achieve beam properties required for nuclear physics experiments:

energy spread: < 1keV/u
bunch length: ~ 1 ns



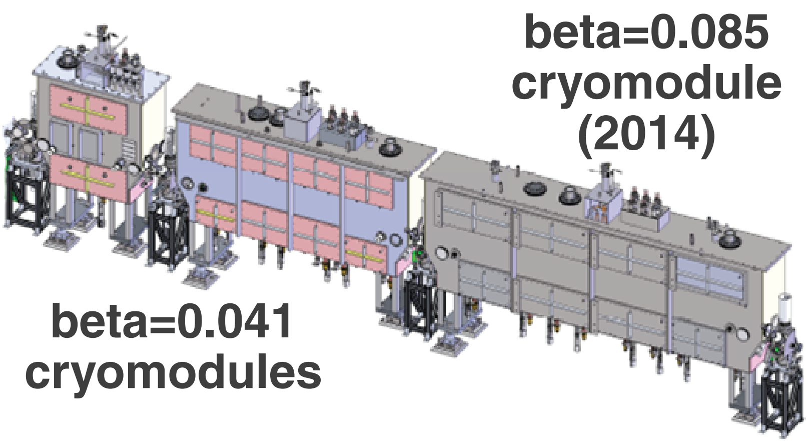
Radio Frequency Quadrupole (RFQ)

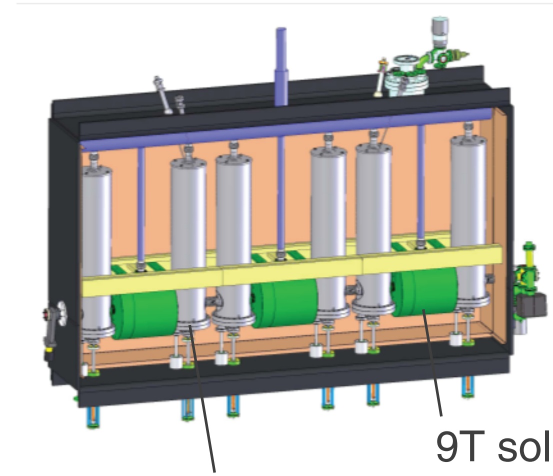


Quadrupole transport channel with longitudinal modulation to achieve accelerating field along the beam direction

Injection energy: 12 keV/u
Extraction energy: 600 keV/u
Operating frequency: 80.5 MHz
Power (CW): ~120 kW

ReA3 Cryomodules





Superconducting Quarter Wave Resonators
Operating frequency: 80.5 MHz

First cryomodule: 2 solenoid, 1 cavity
used for beam matching from RFQ

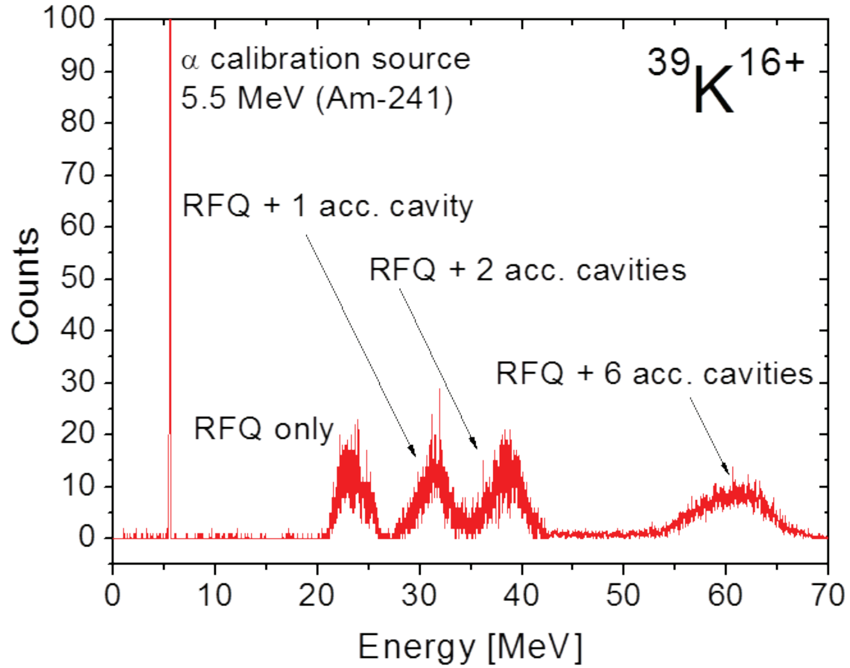
Second cryomodule: 6 accelerating cavities
acceleration up to 1.5 MeV/u (Q/A=0.25)
3 MeV/u (Q/A=0.5)
deceleration down to 300 keV/u

commissioned acceleration voltage: 0.8 MV/cavity
(ReA specifiaction value: 0.45 MV/ cavity)

Reaccelerator Commissioning Results

Reacceleration of charge-bred ^{39}K ions

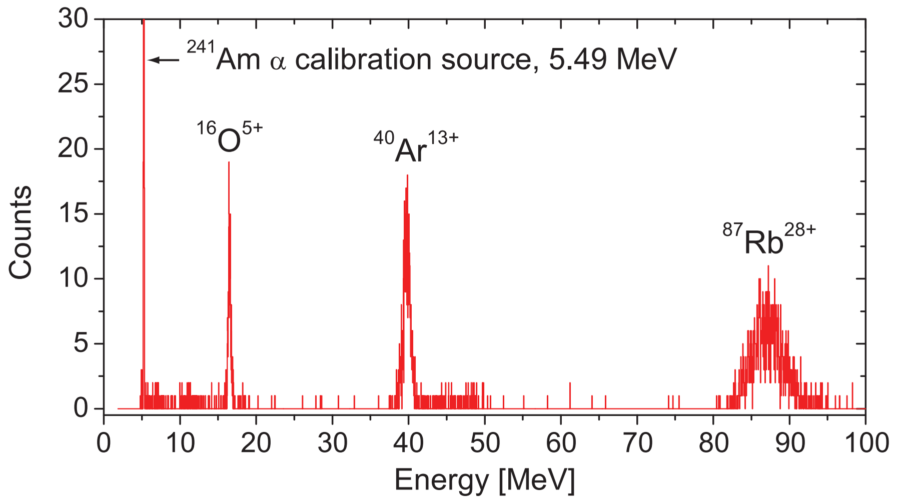
Energy spectrum measured by scattering from a foil into a silicon detector.



Reacceleration of charge-bred ^{87}Rb ions

from an offline source in the gas stopping area.

Residual gas ions (O, Ar) from EBIT with similar A/Q ratio can be used as pilot beams for tuning of the linac and the transport beam lines.



First two cryomodules (beta=0.041) are fully commissioned. Third cryomodule (beta=0.085) will be installed in 2014.

ReA Reaccelerator

Low Energy (ReA3) Experimental Hall

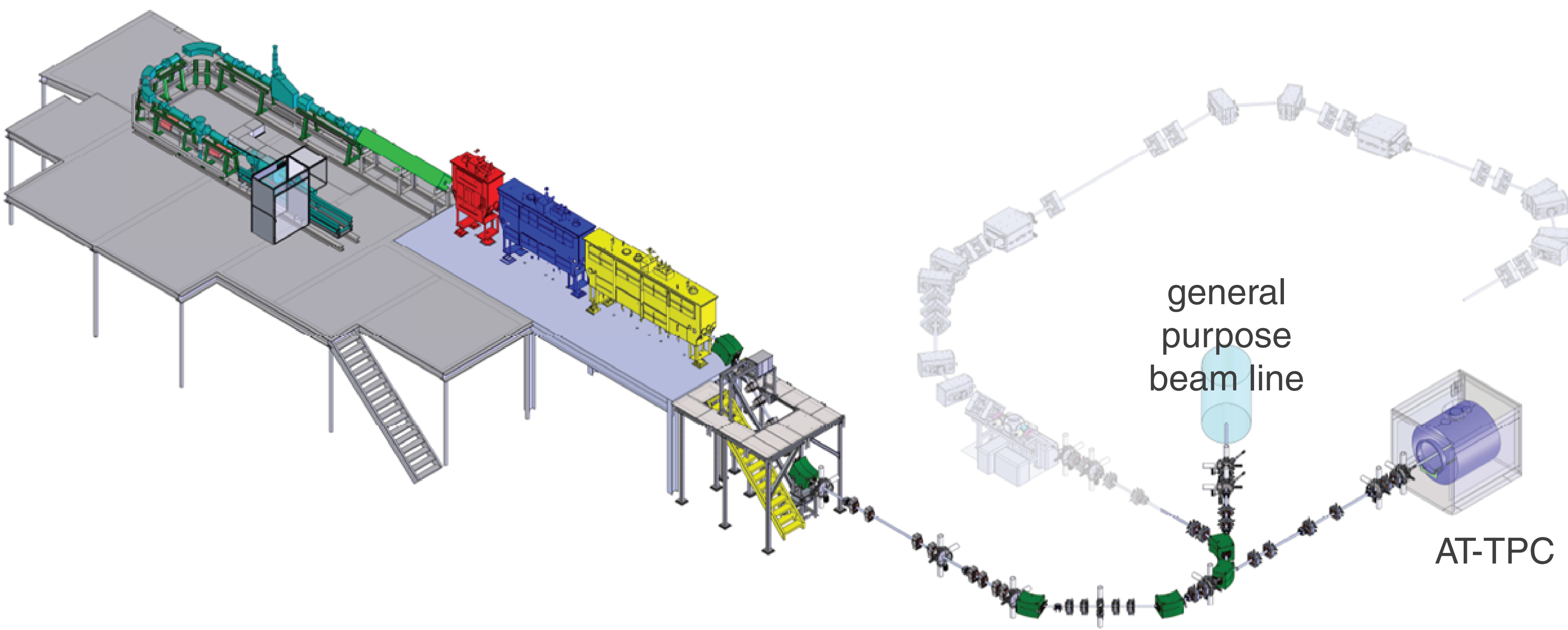
Achromatic beam transport and distribution line from ReA3 platform to multiple experimental end station on ReA3 low energy experimental hall.

Status:

General purpose beam line is fully commissioned.

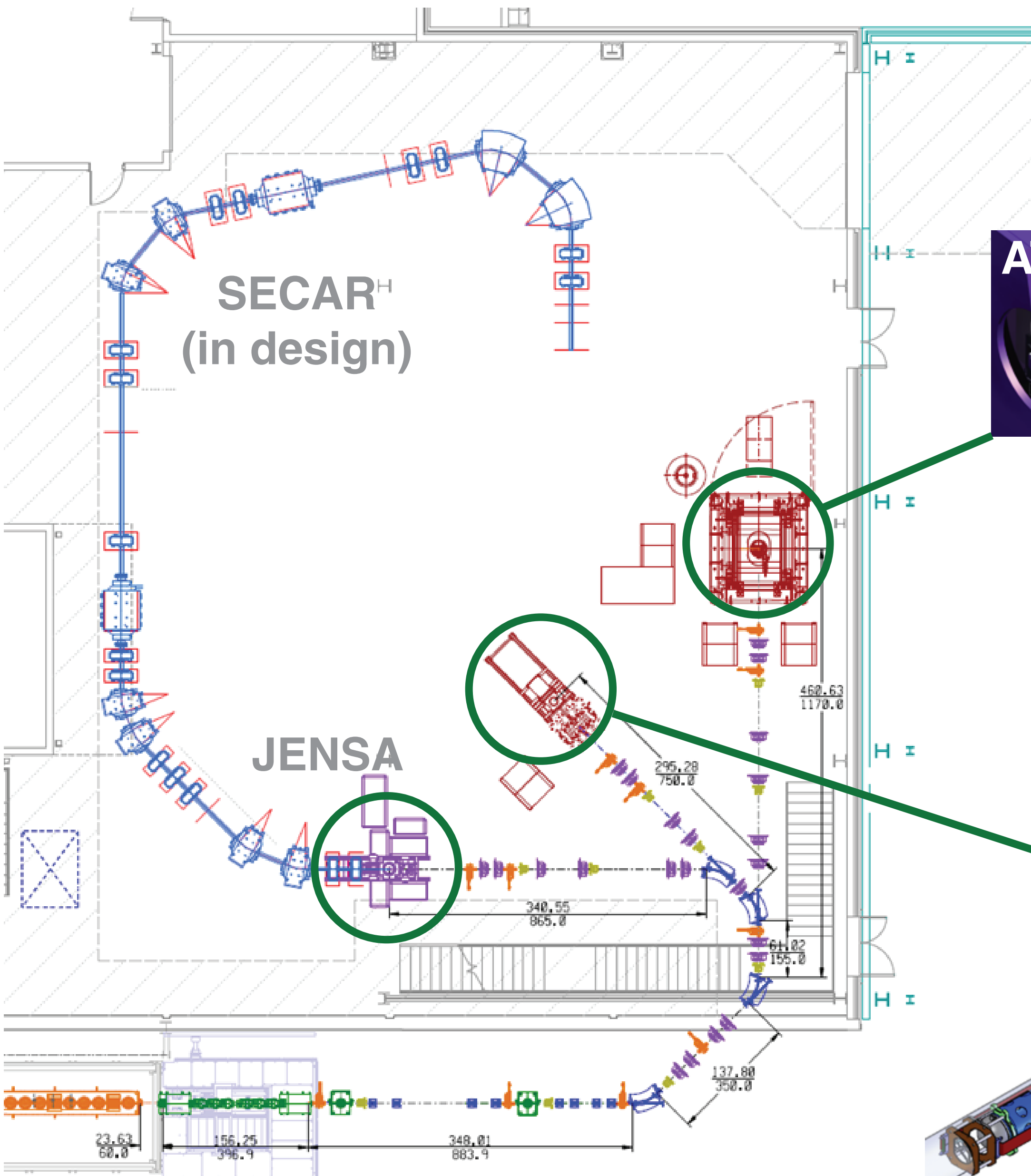
AT-TPC and south beam line will be finished this fall.

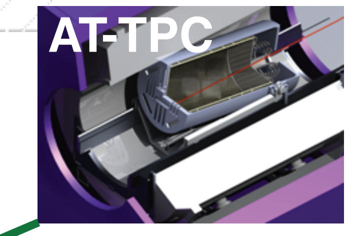
Flexible beam optics allows variuos experimental setups.

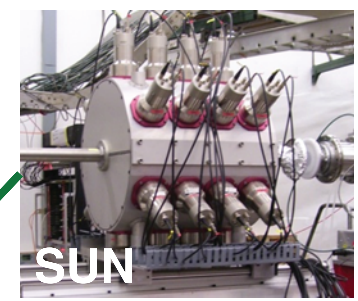


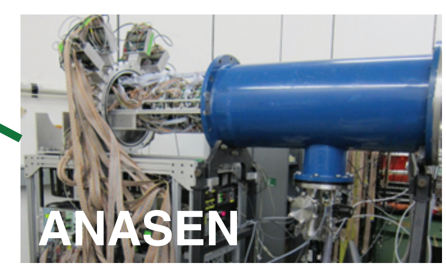
ReA3 Experimental Hall - Equipment

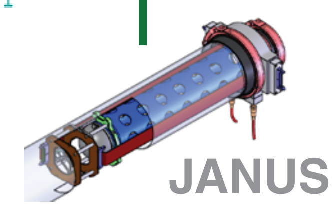
New hall accomodates existing equipment:
LENDA, SeGA, GRETINA and smaller user provided setups.











First Experiment with Reaccelerated Rare Isotope Beam

NSCL experiment 13507 - August 2013

Excitation function of the $^{37}K(p,p)$ reaction, measured with the ANASEN detector

^{37}K (76.7 MeV/u) rare isotope beam, produced by fragmentation of stable ^{40}Ca (140 MeV/u) in A1900 fragment separator
(focal plane rate: ~$9 \cdot 10^6$ pps)

^{37}K transported to gas stopping area.

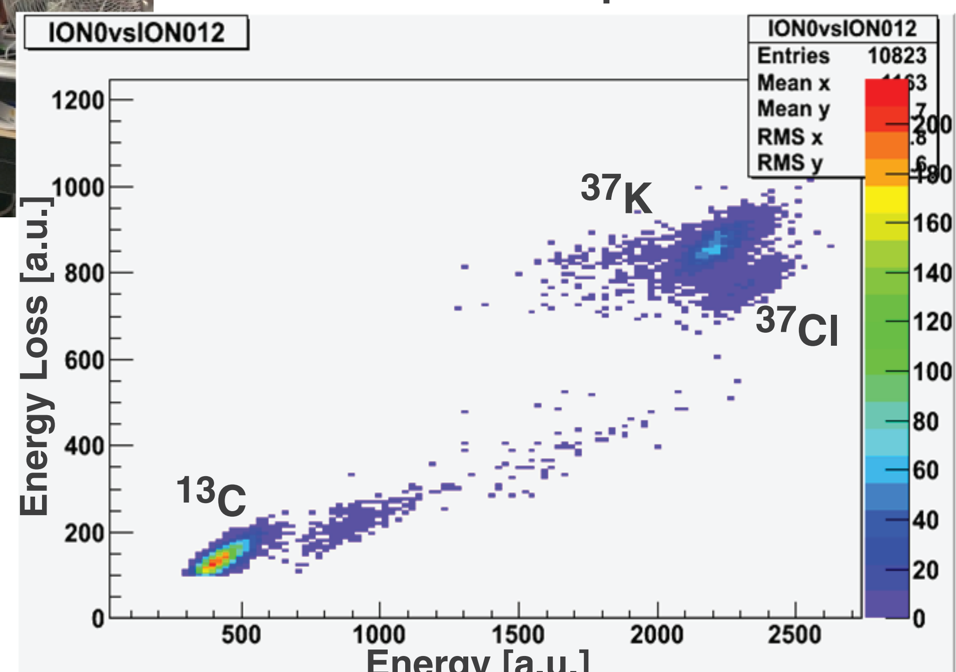
thermalized in ANL gas catcher,

charge bred to $^{37}K^{16+}$ in EBIT charge breeder,

reacclerated with ReA3,

and delivered to ANASEN (rate >500 pps)

Particle ID at experiment location



Conclusion

Reaccelerator facility at NSCL

Substantial progress with commissioning of gas stopping area, EBIT charge breeder, and the ReA3 reaccelerator allow experiments with reaccelerated rare isotope beams.

First user experiment with reaccelerated beam

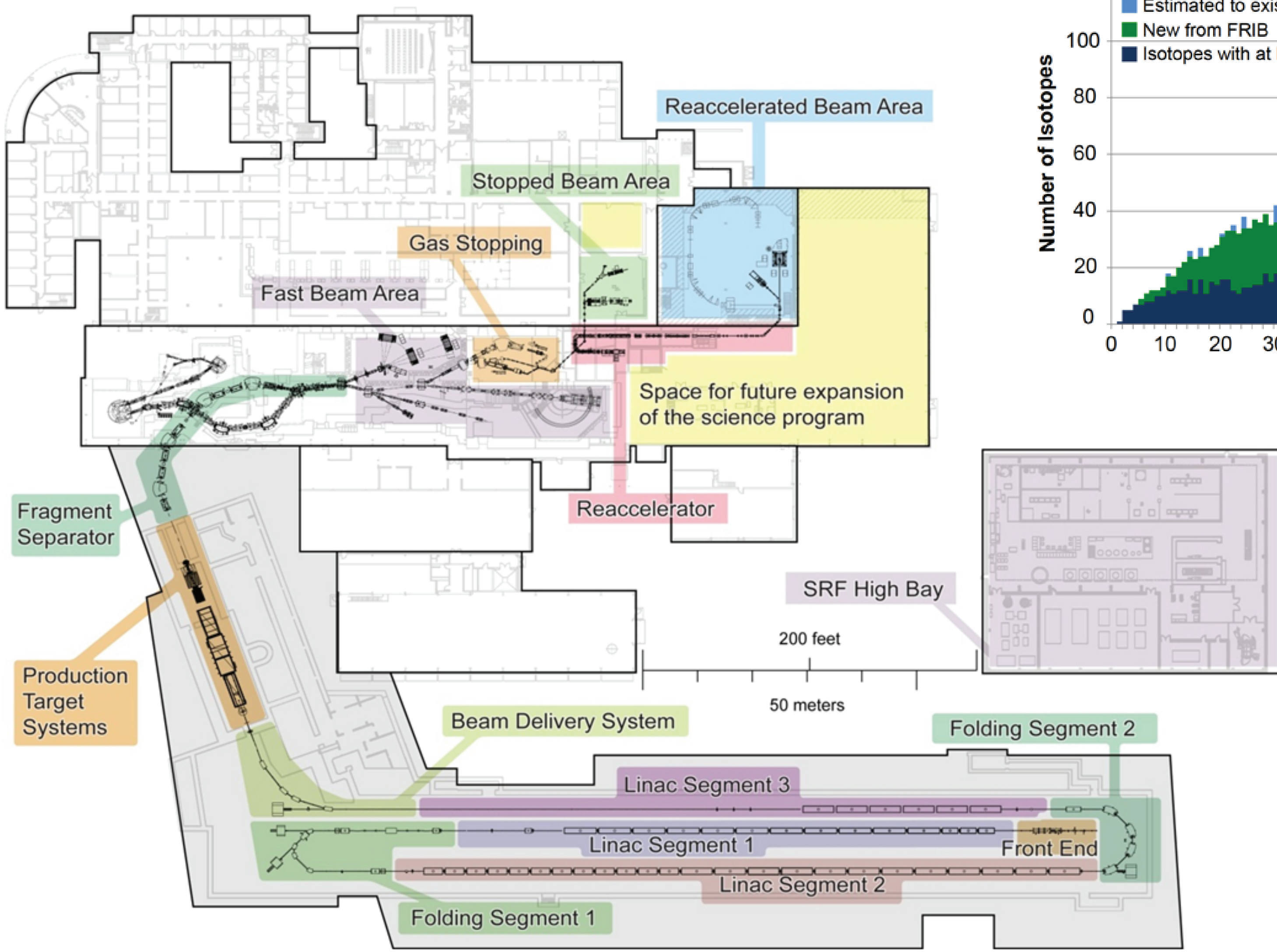
Important milestone reached with delivery of a thermalized and subsequently reaccelerated rare isotope beam to an user experiment.

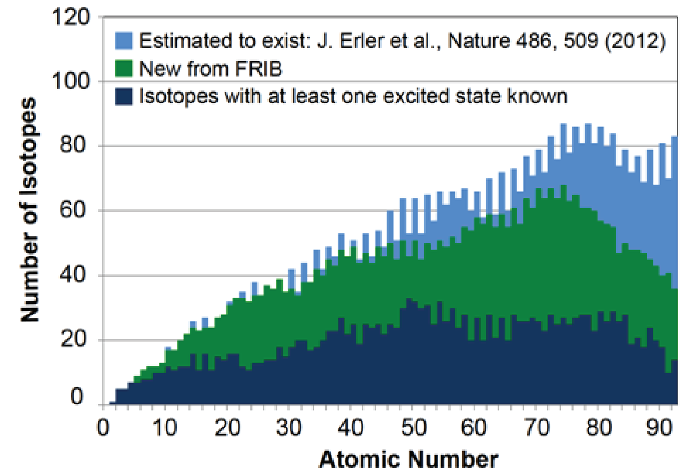
Future commissioning

Commissioning will continue with emphasis on reaching higher gas cell extraction and charge breeding efficiencies.
Installation of third cryomodule in 2014 will allow achieving full energy of the ReA3 reaccelerator.

Outlook into the Future

The newly commissioned areas will become part of FRIB at Michigan State University:





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