The ATLAS Multi-User Upgrade & Potential Applications

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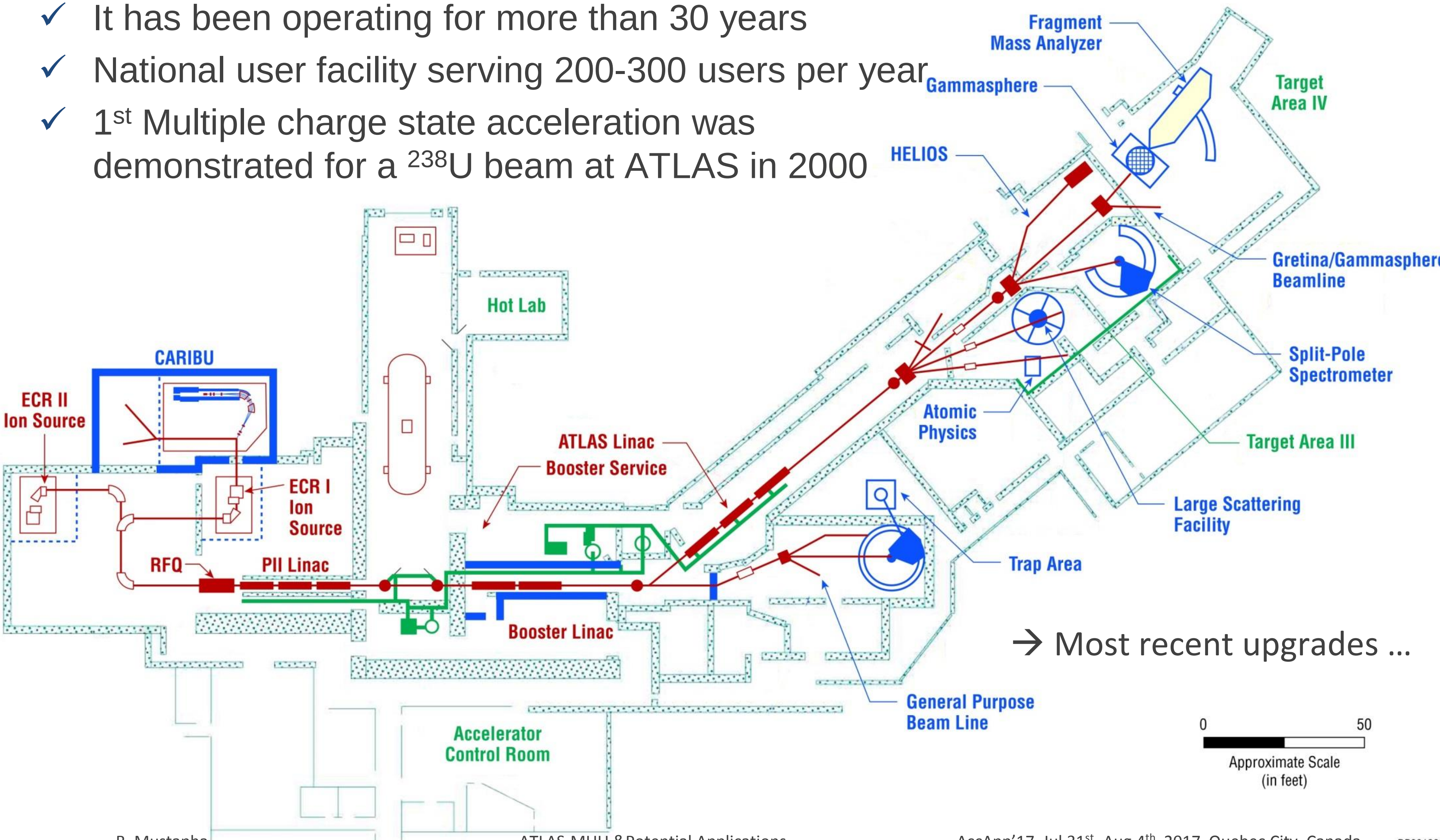
ANS AccApp'17 Topical Meeting
Jul 31st-Aug 4th, 2017, Quebec City, Canada

Outline

- A Brief Introduction to the ATLAS Linac at Argonne
- Recent Upgrades to the ATLAS facility
- Increased Beam Demand & The Need for Multi-User Capabilities
- Simultaneous Two-Beam Acceleration with Pulsed CARIBU-EBIS
- The ATLAS Multi-User Upgrade
  - Scope & Proposed Implementation
  - Beam Optics & Technical Solution
- Potential Applications
  - Material Irradiation with Heavy Ions at ~1 MeV/u
  - Isotope Production with Light Ions at ~ 7 MeV/u

ATLAS: Argonne Tandem Linac Accelerator System

- ✓ 1st Superconducting heavy-ion linac in the world
- ✓ It has been operating for more than 30 years
- ✓ National user facility serving 200-300 users per year
- ✓ 1st Multiple charge state acceleration was demonstrated for a ^{238}U beam at ATLAS in 2000

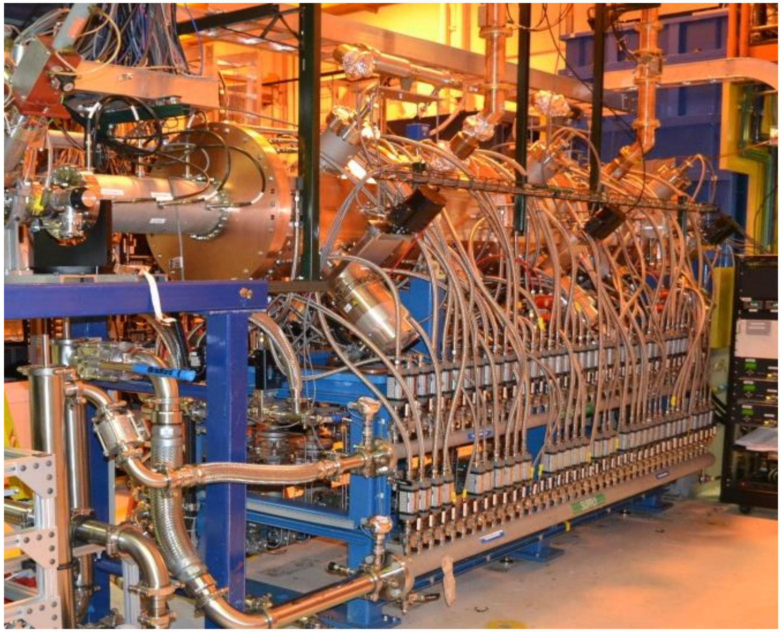


→ Most recent upgrades …

Recent Upgrades (2014): Efficiency & Intensity Upgrade

New CW 60 MHz RFQ

- ✓ Split-coaxial with trapezoidal modulations
- ✓ Output matcher for axis symmetric beam
- ✓ In routine operation since early 2013



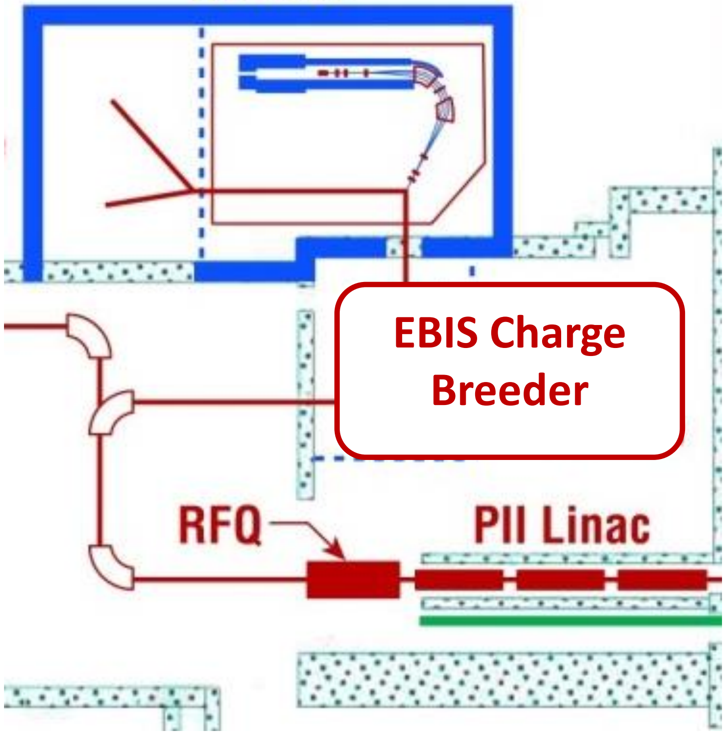
New SC Module

- ✓ 7 β ~ 0.77 QWR and 4 solenoids
- ✓ Capable of delivering 17.5 MV
- ✓ Replaced 3 old SC modules
- ✓ In routine operation since early 2014

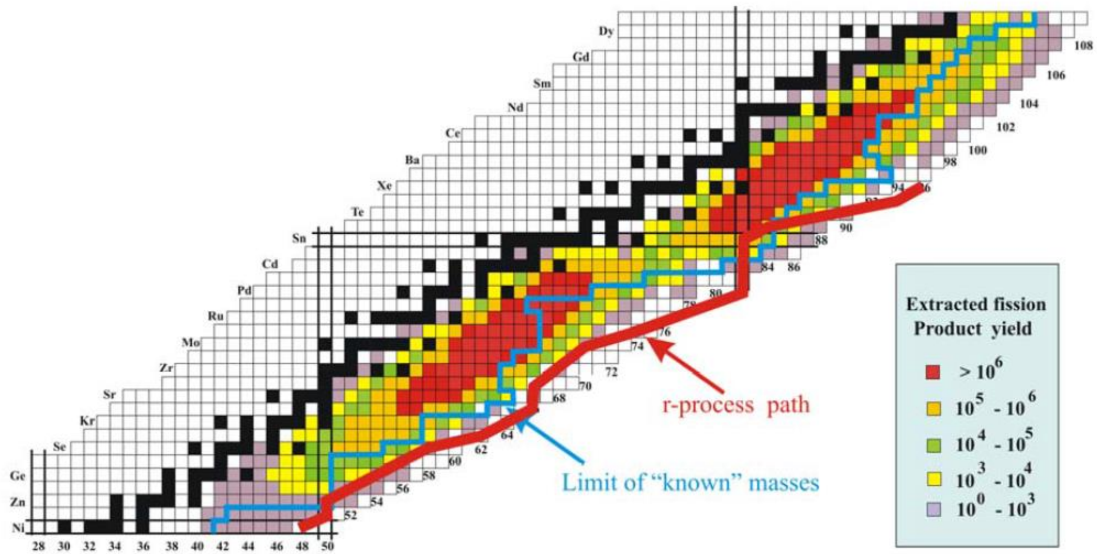
- ✓ New RFQ: Transmission increased from 50% to 80% → Efficiency & Reliability
- ✓ New SC Module: Acceleration of 10x more intense beams → Intensity

Recent Upgrades (2016): CARIBU - EBIS

CARIBU : CAlifornium Rare Isotope Breeder Upgrade



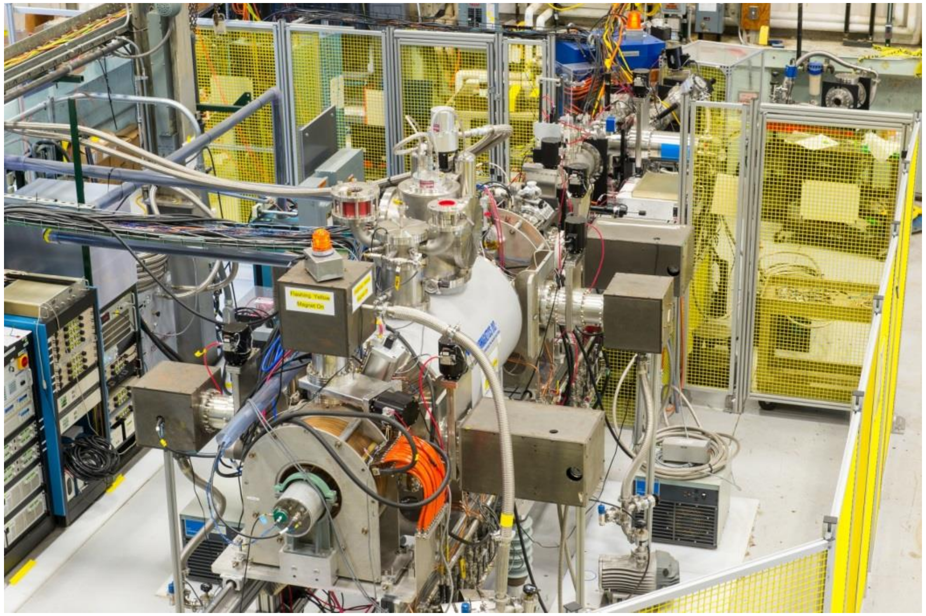
Map of radioactive beams from a ^{252}Cf source



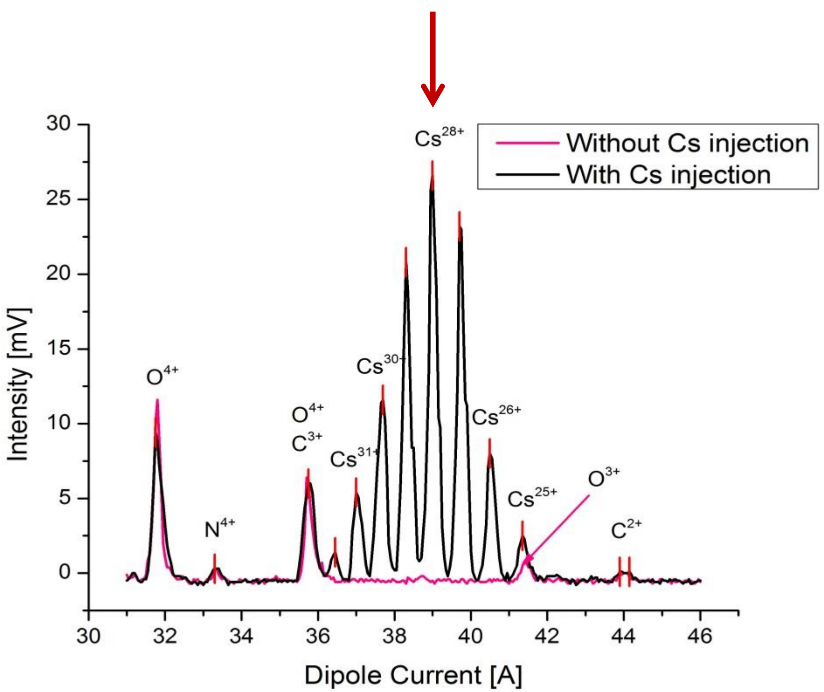
G. Savard et al, ANL

- ✓ Radioactive beams from a Californium Source
- ✓ The ions are collected, separated and cooled to form a beam
- ✓ An ECR charge breeder was originally used for breeding and injection to ATLAS
- ✓ An EBIS charge breeder was developed for higher efficiency and better purity
- ✓ The EBIS was successfully installed and commissioned in 2016

EBIS Source Installation & Performance



Cs^{28+}, A/Q=4.75



- ✓ The CARIBU-EBIS has replaced the original ECR breeder
- ✓ It enhanced both the intensity and purity of CARIBU radioactive beams
- ✓ Successfully commissioned online: Cs transmission efficiency > 70 %
  with single charge state breeding efficiency > 20%
- ✓ It is now being routinely used to breed CARIBU beams for injection to ATLAS

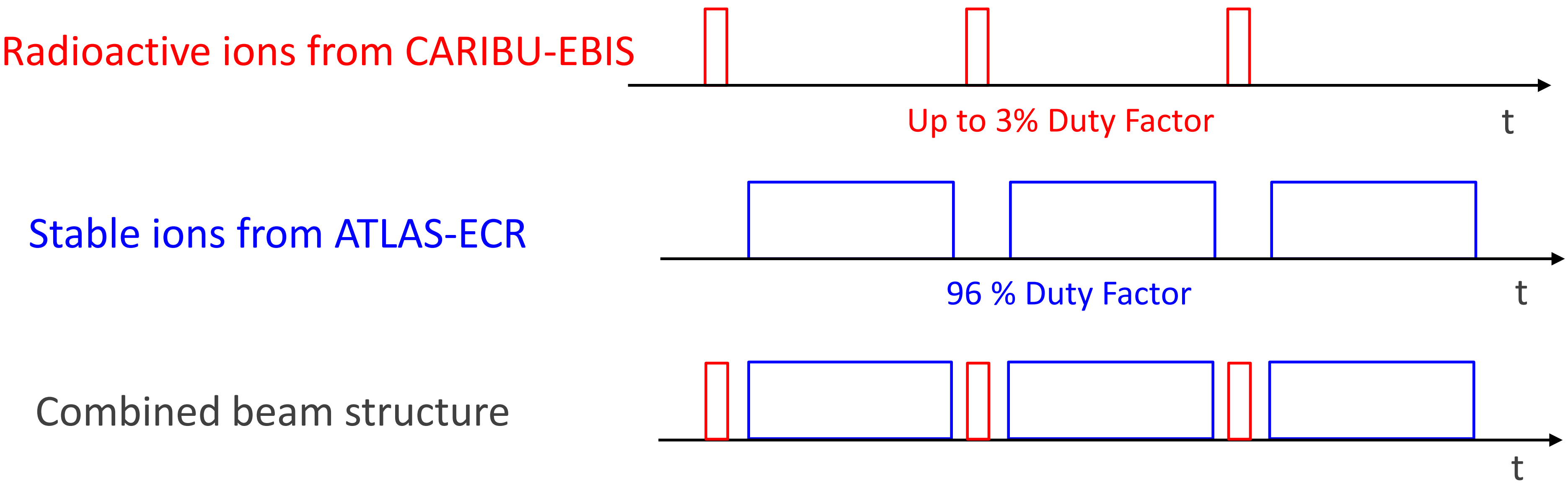
Increased Beam Demand and The Need for Multi-User Capabilities at ATLAS

- ✓ In the past few years, the requested experimental beam time significantly exceeded the 5500 hours that ATLAS deliver yearly.
- ✓ With CARIBU online and the closing of other user facilities, the demand for beam time is more than doubling …
- ✓ Low intensity beams (CARIBU & In-flight) and the search for low cross section channels (FMA & AGFA) will require longer experimental run periods, putting more pressure on available beam time.

➢ There is an immediate need for multi-user capabilities

❖ Analysis of recent ATLAS operations with accelerated CARIBU beams shows that a multi-user upgrade could deliver ~ 50% more beam time for the nuclear physics experimental program and potentially up to 100% if other applications were added.

The Possibility with Pulsed Beams from CARIBU-EBIS



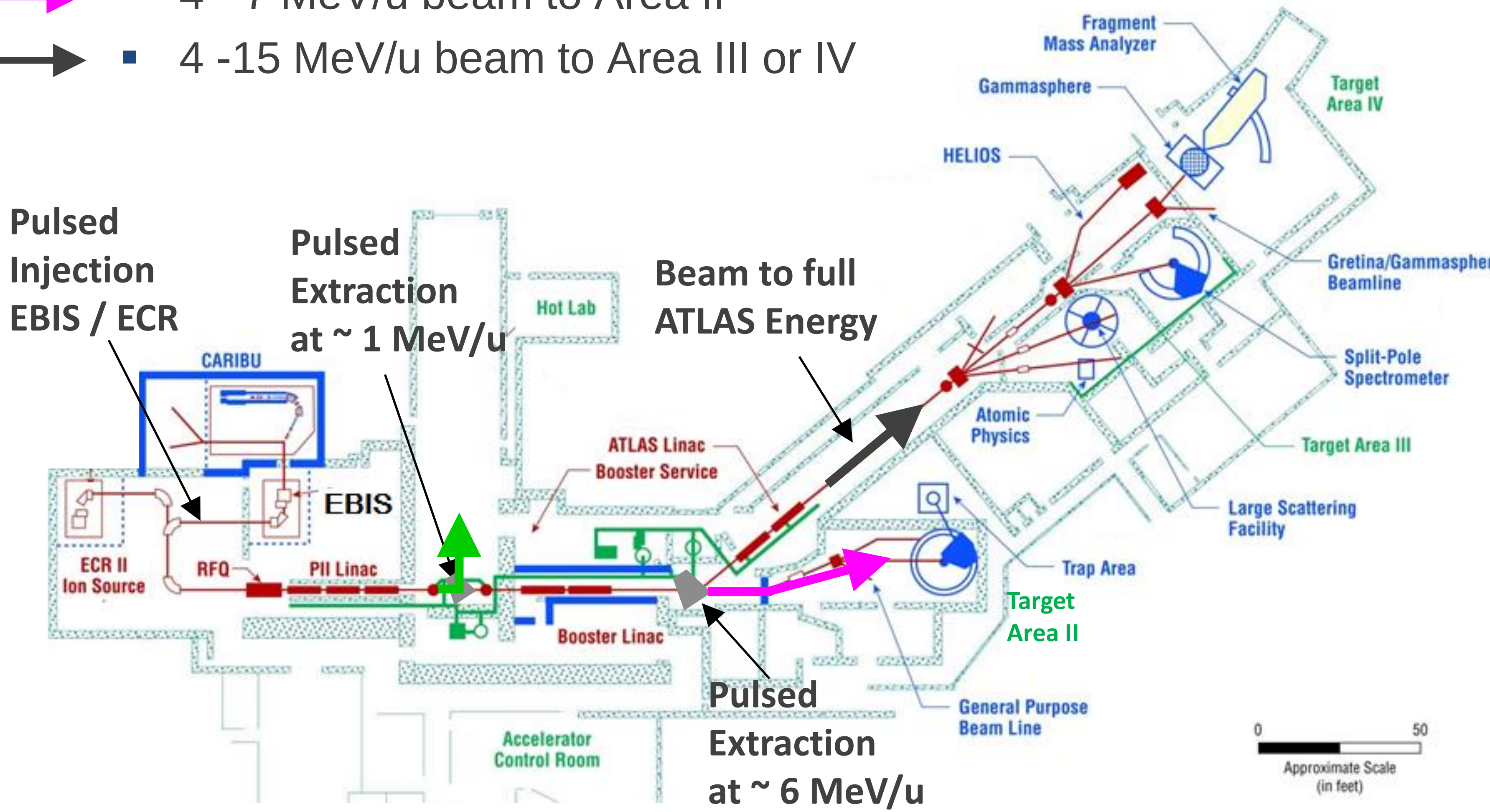
- ✓ EBIS beam is ~ 10 μs to ~1 ms pulse up to 30 Hz repetition rate → < 3 % DF
- ✓ DC beam from ECR could be injected into ATLAS in the remaining 97% DF
- ✓ CARIBU beam masses range from 80 to 170 with Z ranging from 30 to 70
- ✓ The highest charge-to-mass ratio they could be ionized to is 1/4.
- ✓ ATLAS accelerates any beam with a charge-to-mass ratio $\geq$ 1/7
- ✓ The useful charge-to-mass ratio range for the multi-user capability is 1/7 to 1/4
- ✓ Higher q/A $\approx$ 1/3 can be achieved if EBIS is operated at 10 Hz

Sample of Possible Simultaneous Stable and RIBs

A/Q	ATLAS stable beams	CARIBU beams
4.000	$^{20}Ne^{5+}$, $^{28}Si^{7+}$, $^{36}Ar^{9+}$	$^{84}Se^{21+}$, $^{88}Kr^{22+}$, $^{92}Sr^{23+}$, $^{101}Mo^{25+}$, $^{105}Ru^{26+}$
4.143	$^{58}Ni^{14+}$	$^{83}As^{20+}$, $^{95}Y^{23+}$, $^{104}Tc^{25+}$, $^{112}Pd^{27+}$, $^{117}Cd^{28+}$
4.167	$^{50}Ti^{12+}$	$^{88}Br^{21+}$, $^{91}Rb^{22+}$, $^{101}Zr^{24+}$, $^{105}Ru^{25+}$, $^{117}Cd^{28+}$
4.200	$^{63}Cu^{15+}$	$^{89}Rb^{21+}$, $^{97}Sr^{23+}$, $^{105}Mo^{25+}$, $^{109}Rh^{26+}$, $^{113}Ag^{27+}$
4.238	$^{89}Y^{21+}$	$^{89}Kr^{21+}$, $^{97}Sr^{23+}$, $^{102}Zr^{24+}$, $^{111}Rh^{26+}$, $^{119}Cd^{28+}$
4.308	$^{56}Fe^{13+}$	$^{94}Kr^{22+}$, $^{100}Sr^{23+}$, $^{113}Rh^{26+}$, $^{126}Sn^{29+}$, $^{143}Ce^{33+}$
4.364	$^{48}Ti^{11+}$, $^{74}Ge^{17+}$	$^{92}Kr^{21+}$, $^{105}Nb^{24+}$, $^{109}Tc^{25+}$, $^{119}Pd^{27+}$, $^{149}Nd^{34+}$
4.375	$^{35}Cl^{8+}$	$^{100}Y^{23+}$, $^{109}Tc^{25+}$, $^{127}Sn^{29+}$, $^{132}I^{30+}$, $^{159}Gd^{36+}$
4.444	$^{40}Ca^{9+}$, $^{102}Ru^{23+}$, $^{120}Sn^{27+}$	$^{89}Br^{20+}$, $^{112}Rh^{25+}$, $^{139}Xe^{31+}$, $^{157}Sm^{35+}$, $^{156}Eu^{35+}$
4.471	$^{76}Ge^{17+}$	$^{90}Br^{20+}$, $^{99}Sr^{22+}$, $^{135}Te^{30+}$, $^{128}Cs^{31+}$, $^{161}Gd^{36+}$
4.538	$^{59}Co^{13+}$	$^{91}Rb^{20+}$, $^{105}Zr^{23+}$, $^{123}Cd^{27+}$, $^{131}Te^{29+}$, $^{146}Pr^{32+}$
4.875	$^{78}Kr^{16+}$	$^{93}Y^{19+}$, $^{102}Mo^{21+}$, $^{132}Sn^{27+}$, $^{141}I^{29+}$, $^{162}Eu^{34+}$
4.900	$^{98}Mo^{20+}$	$^{98}Sr^{20+}$, $^{108}Mo^{22+}$, $^{117}Pd^{24+}$, $^{136}Sb^{28+}$, $^{161}Sm^{33+}$
…		
5.714	$^{80}Se^{14+}$	$^{91}Kr^{16+}$, $^{97}Zr^{17+}$, $^{109}Ru^{19+}$, $^{131}Sb^{23+}$, $^{143}Ba^{25+}$
6.432	$^{238}U^{37+}$	$^{83}Se^{13+}$, $^{90}Kr^{14+}$, $^{97}Sr^{15+}$, $^{103}Zr^{16+}$, $^{141}I^{22+}$
6.615	$^{86}Kr^{13+}$	$^{86}Se^{13+}$, $^{92}Rb^{22+}$, $^{100}Sr^{23+}$, $^{105}Zr^{24+}$, $^{106}Nb^{24+}$
6.667	$^{180}Hf^{27+}$	$^{87}Br^{13+}$, $^{94}Kr^{14+}$, $^{100}Sr^{15+}$, $^{101}Y^{15+}$, $^{107}Nb^{16+}$
6.709	$^{208}Pb^{31+}$	$^{88}Se^{13+}$, $^{88}Br^{13+}$, $^{94}Rb^{14+}$, $^{100}Y^{15+}$, $^{107}Nb^{16+}$
6.742	$^{209}Bi^{31+}$	$^{87}Se^{13+}$, $^{87}Br^{13+}$, $^{95}Rb^{14+}$, $^{102}Y^{15+}$, $^{108}Nb^{16+}$
6.793	$^{197}Au^{29+}$	$^{89}Se^{13+}$, $^{89}Br^{13+}$, $^{95}Rb^{14+}$, $^{102}Y^{15+}$, $^{108}Nb^{16+}$
7.000	$^{133}Cs^{19+}$	$^{84}As^{12+}$, $^{98}Rb^{14+}$, …

Potential Scope of ATLAS Multi-User Capabilities

- 1-1.5 MeV/u beam to Tandem Vault
- 4 - 7 MeV/u beam to Area II
- 4 -15 MeV/u beam to Area III or IV

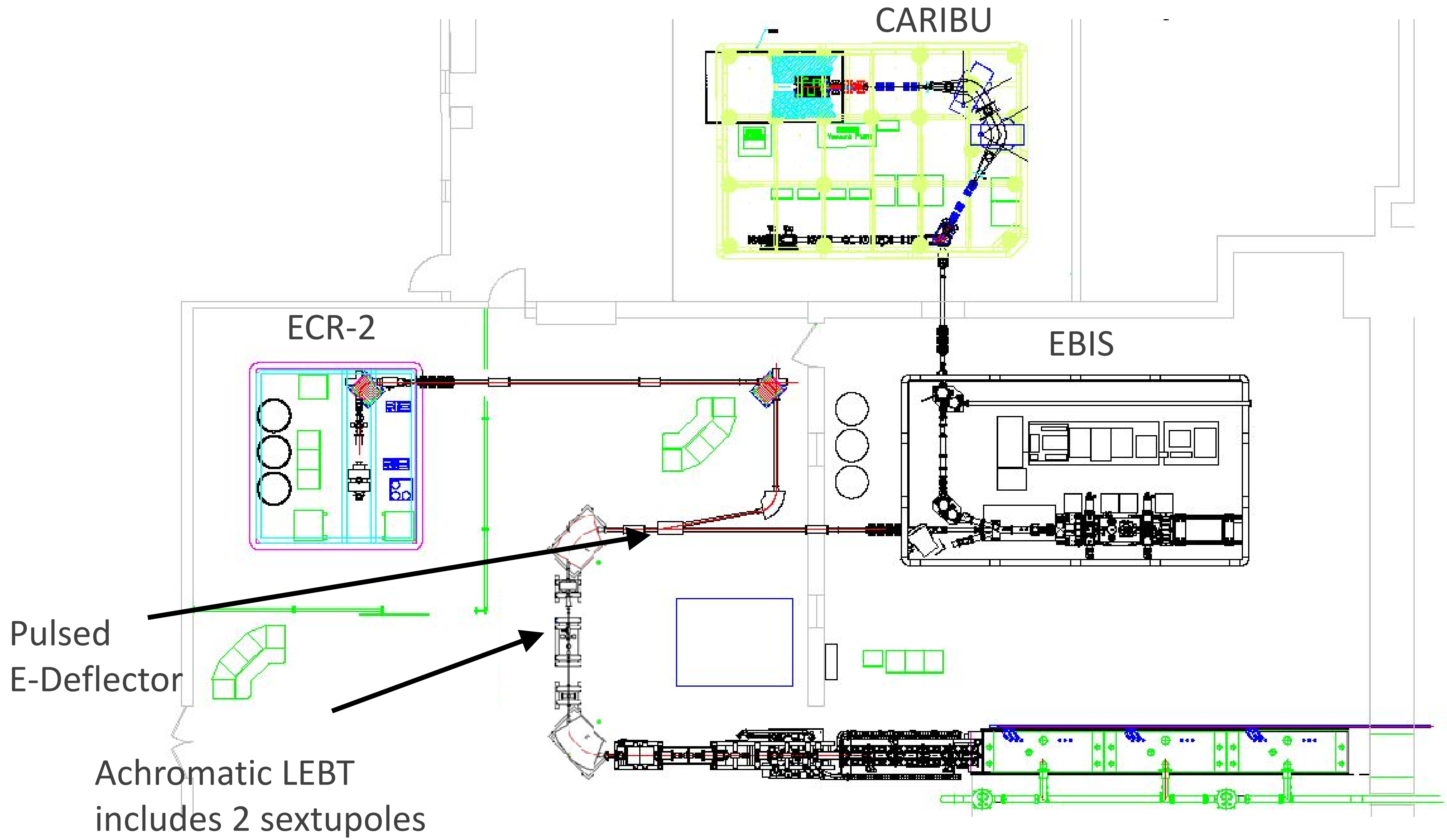


Proposed Implementation of the ATLAS-MUU

- Two Beam Injection in the LEBT
- One Beam Extraction at PII or Booster

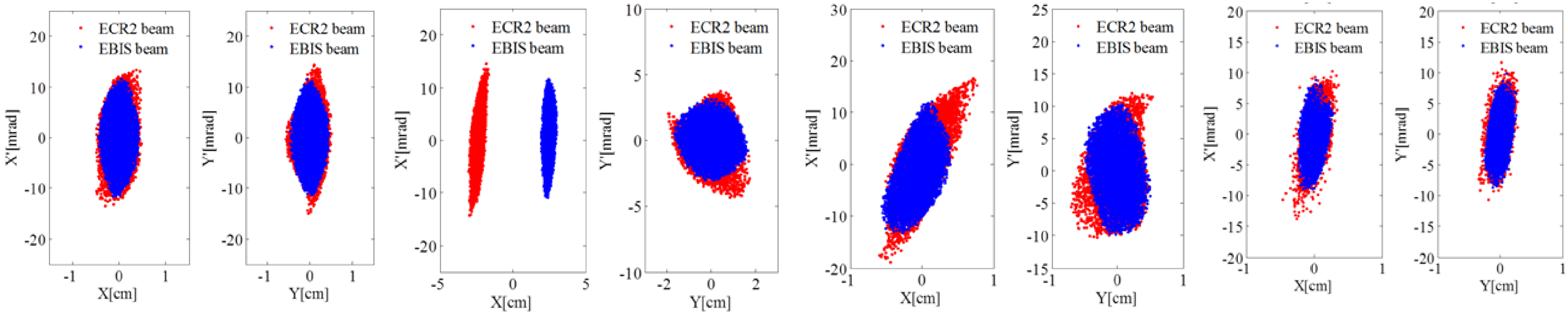
Modified Injection for ATLAS-MUU

✓ Modifications to the Front End

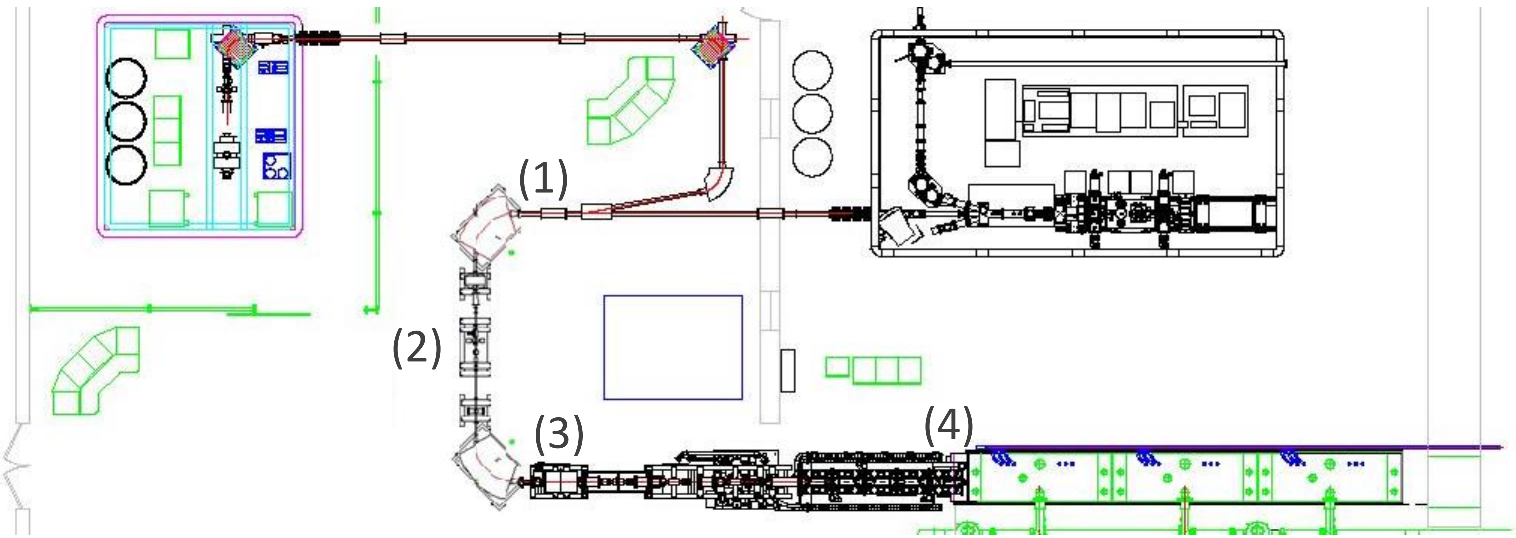


Example of Combining two beams in the LEBT

(1) Before 180° bend (2) At the selection slit (3) After 180° bend (4) After ATLAS RFQ



- ✓ 2 electrostatic sextupoles are needed to maximize the two beam overlap and provide high transmission through ATLAS

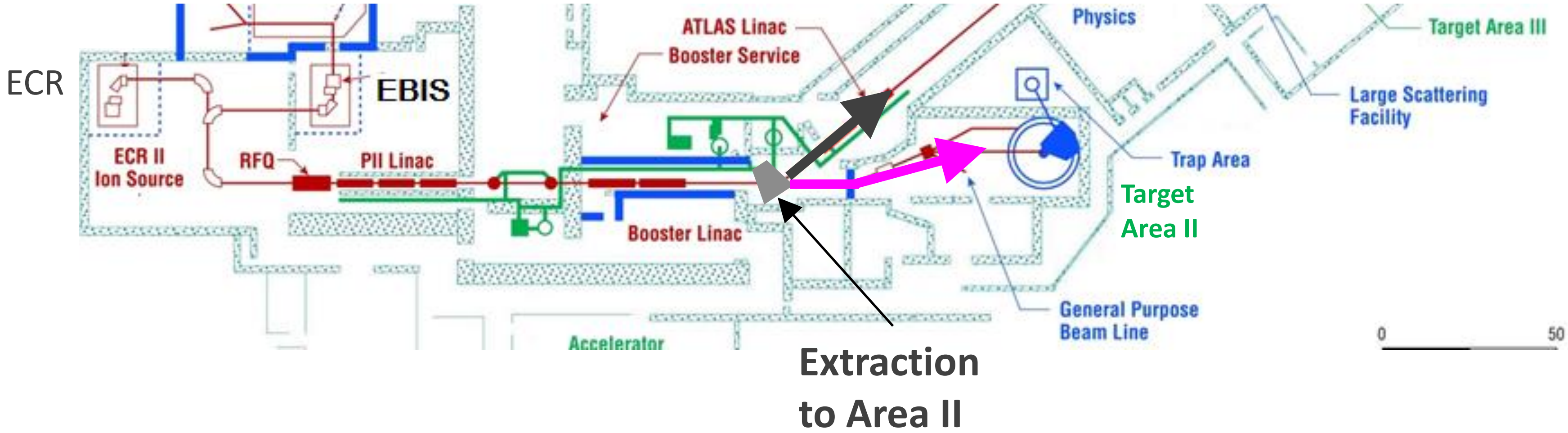


$^{132}Sn^{27+}$ from CARIBU-EBIS

$^{48}Ca^{10+}$ from ECR2

~ 2 % in A/q

Adding a Beam Switchyard after Booster

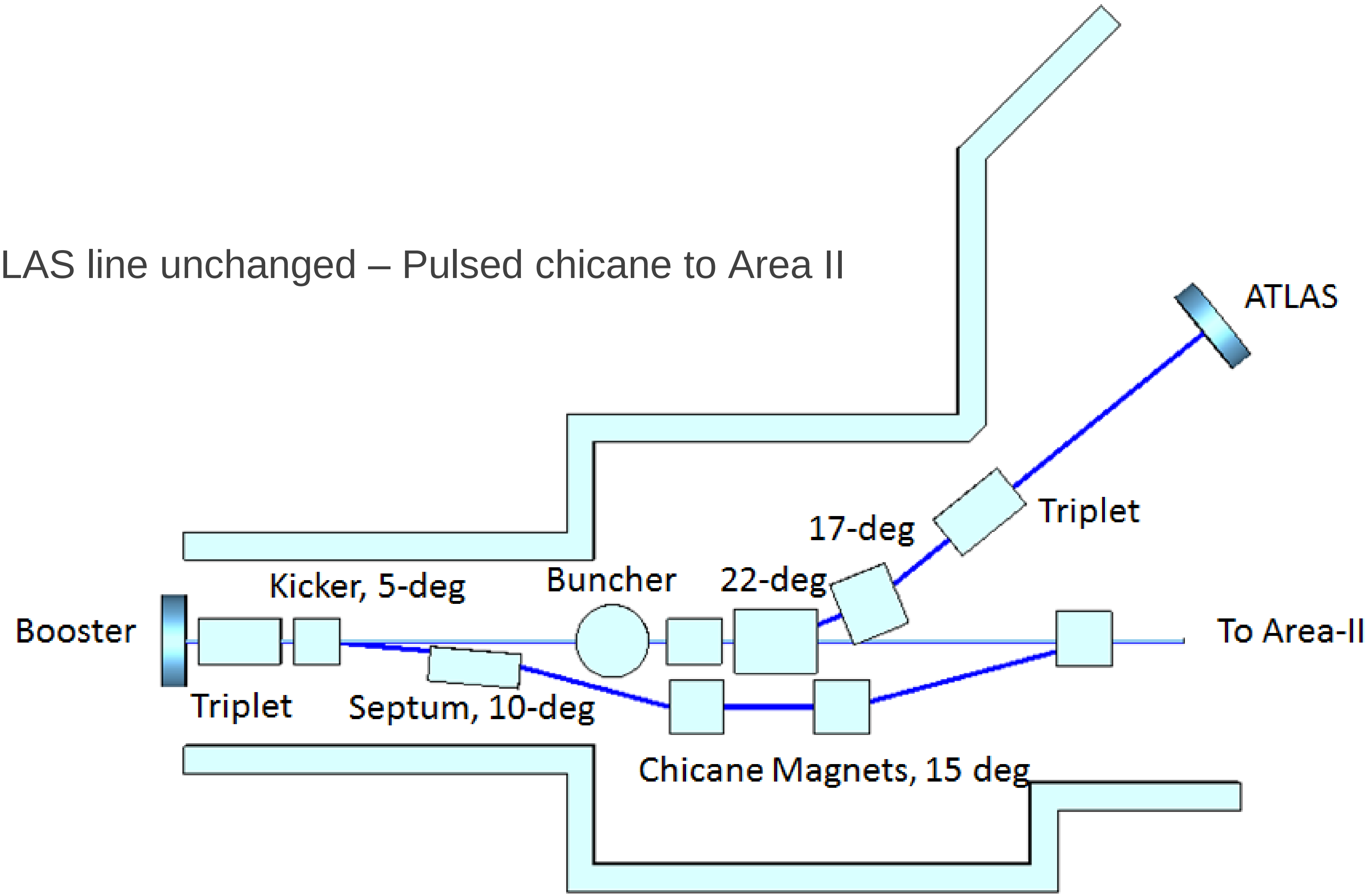


Requirements

- Capable of switching in pulsed mode to send radioactive or stable beams to either Area II or Area III/IV
- Fits into the available space (significant constraint)
- Should accommodate the existing re-buncher cavity in the center of the beam transport line
- Should accommodate existing beam diagnostics
- Compatible with potential future upgrades

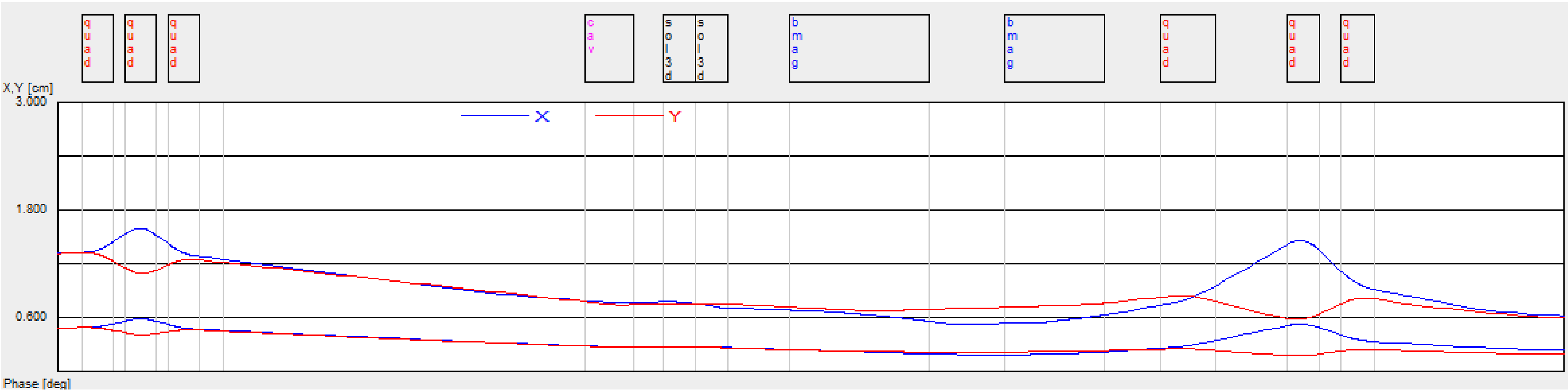
Booster Switchyard: Layout of Pulsed Chicane

- ATLAS line unchanged – Pulsed chicane to Area II

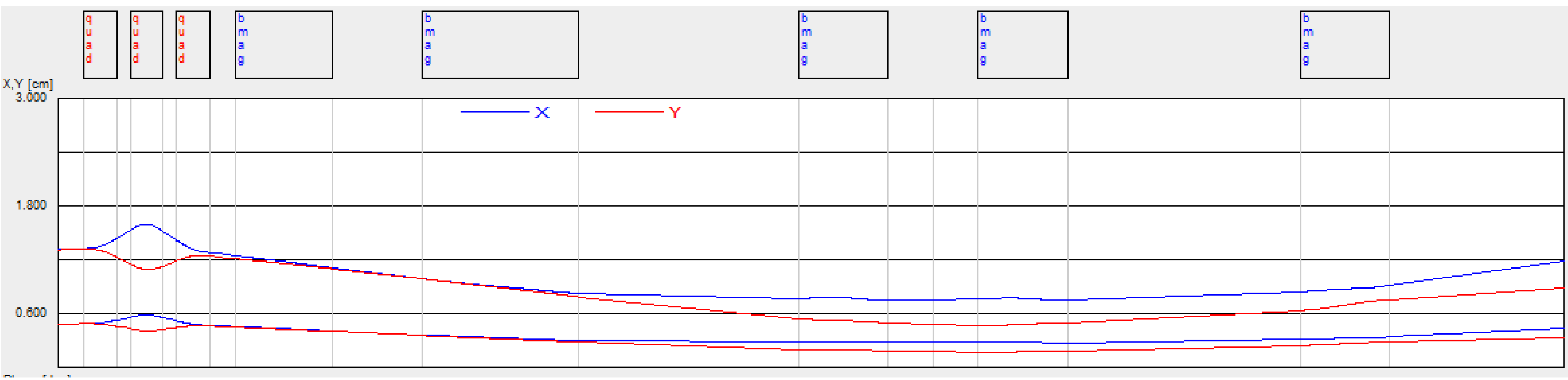


Booster Switchyard: Beam Optics

Beam to **ATLAS** through the original beam line, a compact triplet is inserted right after Booster

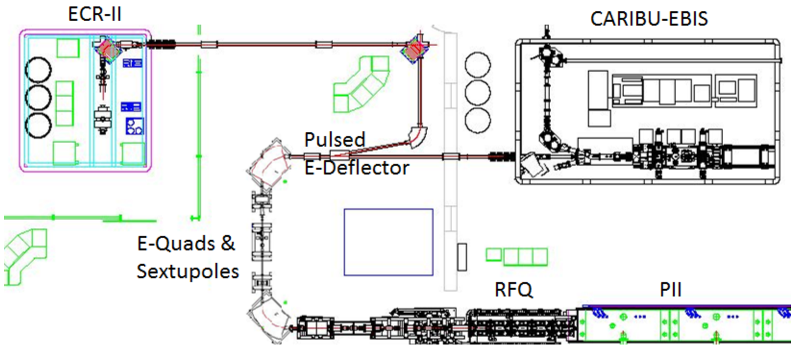


Beam to **Area II** through a new chicane made of a kicker, a septum and 3 regular magnets



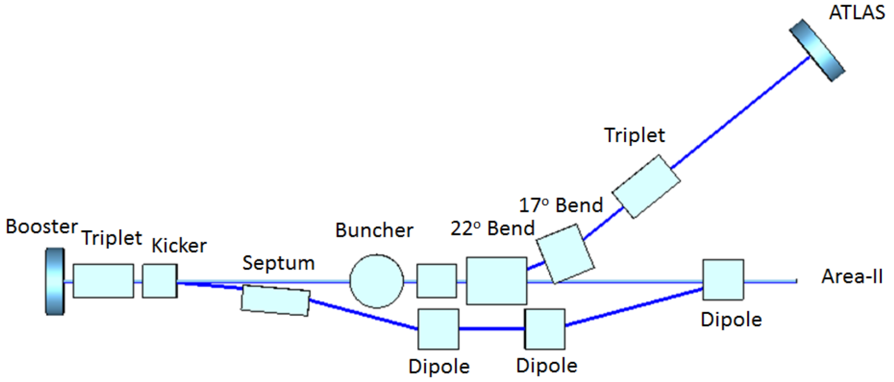
Key Components for the ATLAS MUU

LEBT Injection



- Conventional 75° bending magnet
- 2-3 electrostatic triplets
- Pulsed electrostatic deflector to merge stable and radioactive ion beams
- 2 electrostatic sextupoles

Booster Switchyard



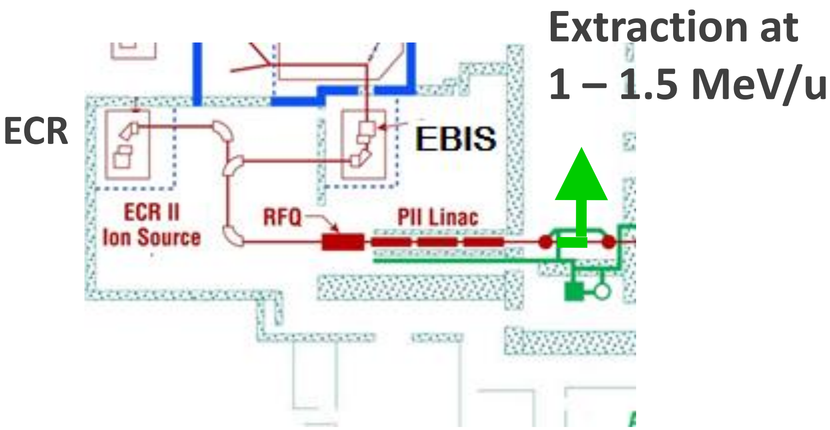
- Booster Switchyard
- Compact triplet
- Pulsed kicker-magnet , 5°
- Septum-magnet, 10°
- Three Conventional 15° bending magnets
- Possibly modified beam instrumentation

Potential Applications

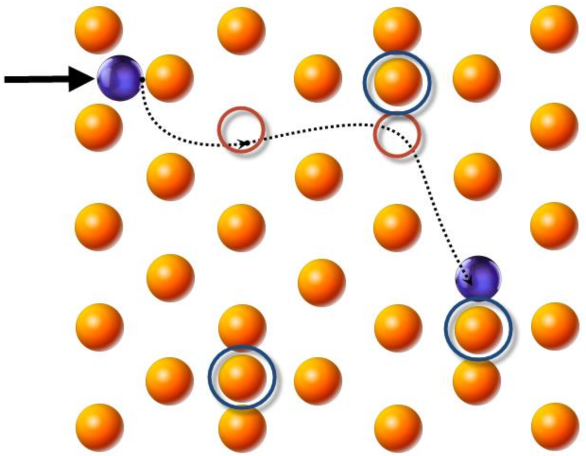
- Material Irradiation at ~ 1 MeV/u
- Isotope Production at ~ 7 MeV/u

Material Irradiation after PII at ~ 1 MeV/u

A new beam extraction at ~ 1 MeV/u

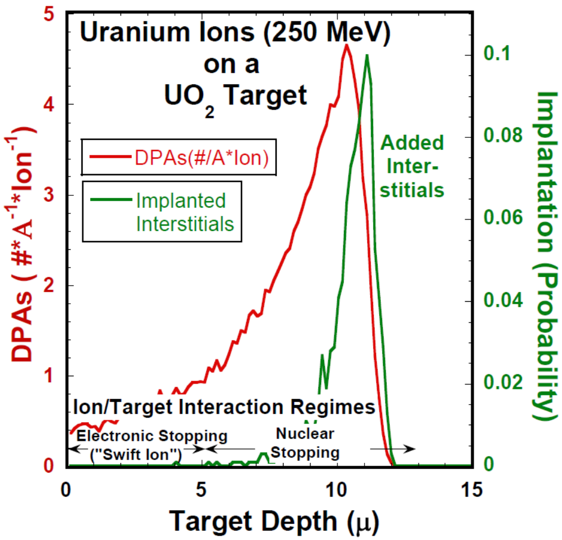


Radiation damage mechanisms in Materials



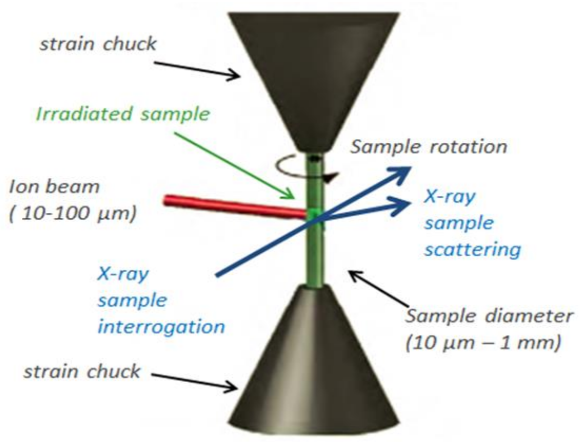
point defects
defect clusters
bubbles
voids
precipitates
solute
segregation
grain boundaries
helium cavities
amorphisation

- ✓ Use heavy-ion beams at ~ 1 MeV/u for irradiation of samples.
- ✓ Deliver mixed beams with the same mass-to-charge ratios (e.g. $^{86}Sr^{15+}$ and $^{132}Xe^{23+}$) to model simultaneous damage from fission fragments.
- ✓ Provide ~ 10 μm beam penetration to avoid surface effects.
- ✓ Provide high damage dose rates (~25 dpa/hour) that will allow rapid material screening. Irradiation times from years to days and hours.
- ✓ Separate nuclear scattering damage and interstitial effects; ion energy deposition and implantation peak at different depths in the sample

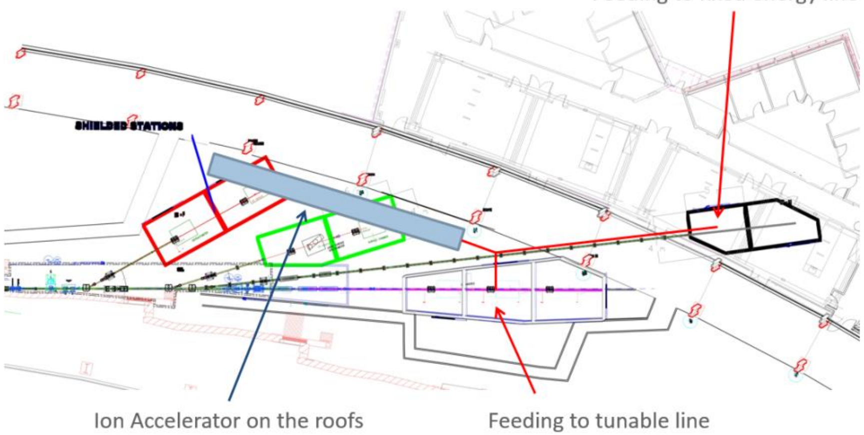


eXtreme MATerial Proposal at ANL - XMAT

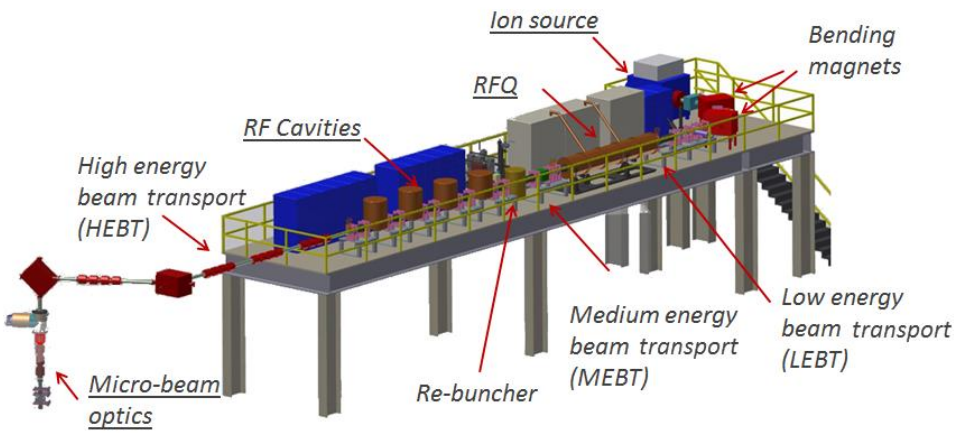
In-situ Imaging of Radiation Damage

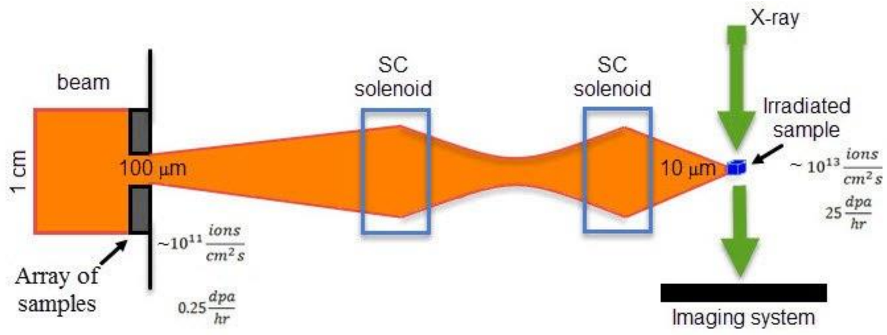


Heavy-Ion Linac at the APS at ANL

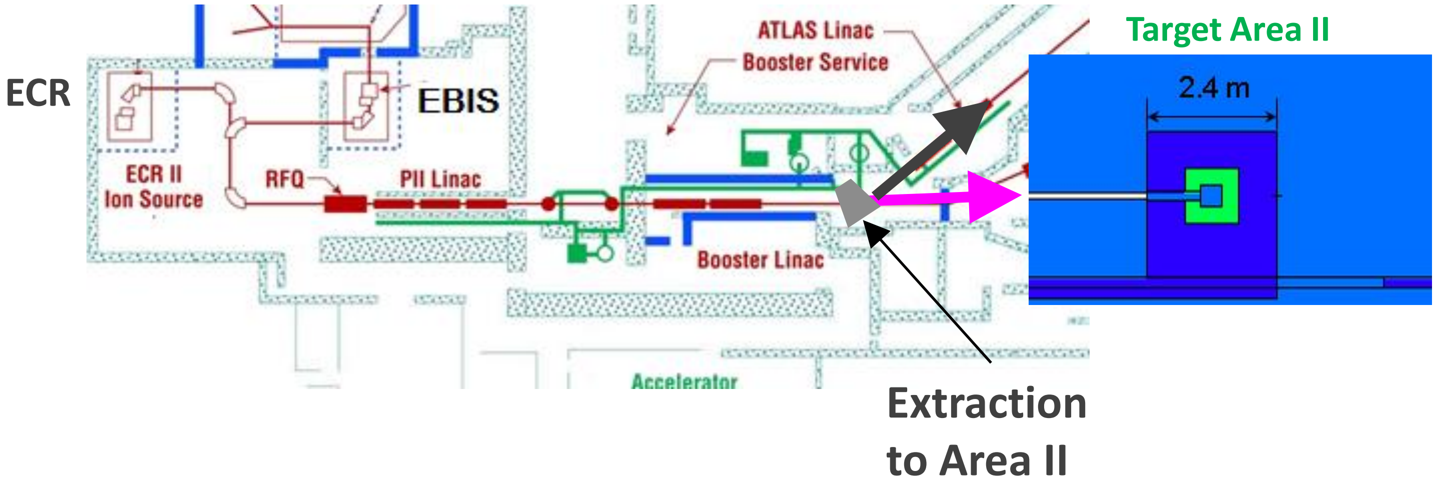


Ref: "Heavy Ion Linear Accelerator for Radiation Damage Studies of Materials"
S. Kutsaev et al, Review of Scientific Instruments, 88, 033302 (2017)





Isotope Production & Other Application at ~ 7 MeV/u



Preliminary

- ✓ 6-7 MeV/u alpha and lithium beams for isotope production R&D
- ✓ Radiobiology effects can be studied with p, 4He, 6Li, and 12C beams at the Bragg peaks
- ✓ Radiation damage of materials can be studied with CARIBU beams such analogs of fission fragments in reactors such as Kr and Xe.

Summary

- We have developed a design concept and a technical solution for the ATLAS Multi-User Upgrade

- Feasibility of the most critical components has been proven

- If implemented successfully the ATLAS Multi-User Upgrade will enhance the experimental nuclear physics program by about 50%

- This upgrade will also make applications such as material irradiation and isotope production possible

- Following the successful implementation of the proposed upgrade and the gained experience from multi-beam operations at ATLAS, more possibilities can be added to enhance the program