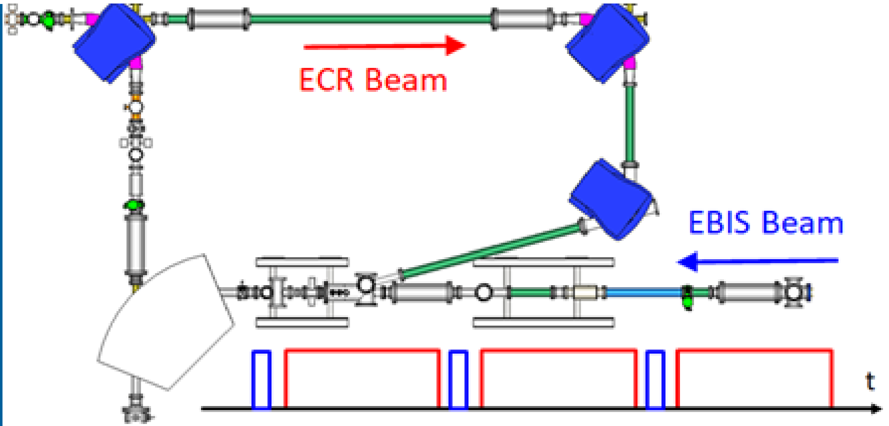
IPAC'21 (VIRTUAL), CAMPINAS, BRAZIL, MAY 24-28, 2021

Argonne NATIONAL LABORATORY

THE MULTI-USER UPGRADE OF THE SUPERCONDUCTING ION LINAC, ATLAS



BRAHIM MUSTAPHA

Physics Division
Argonne National Laboratory

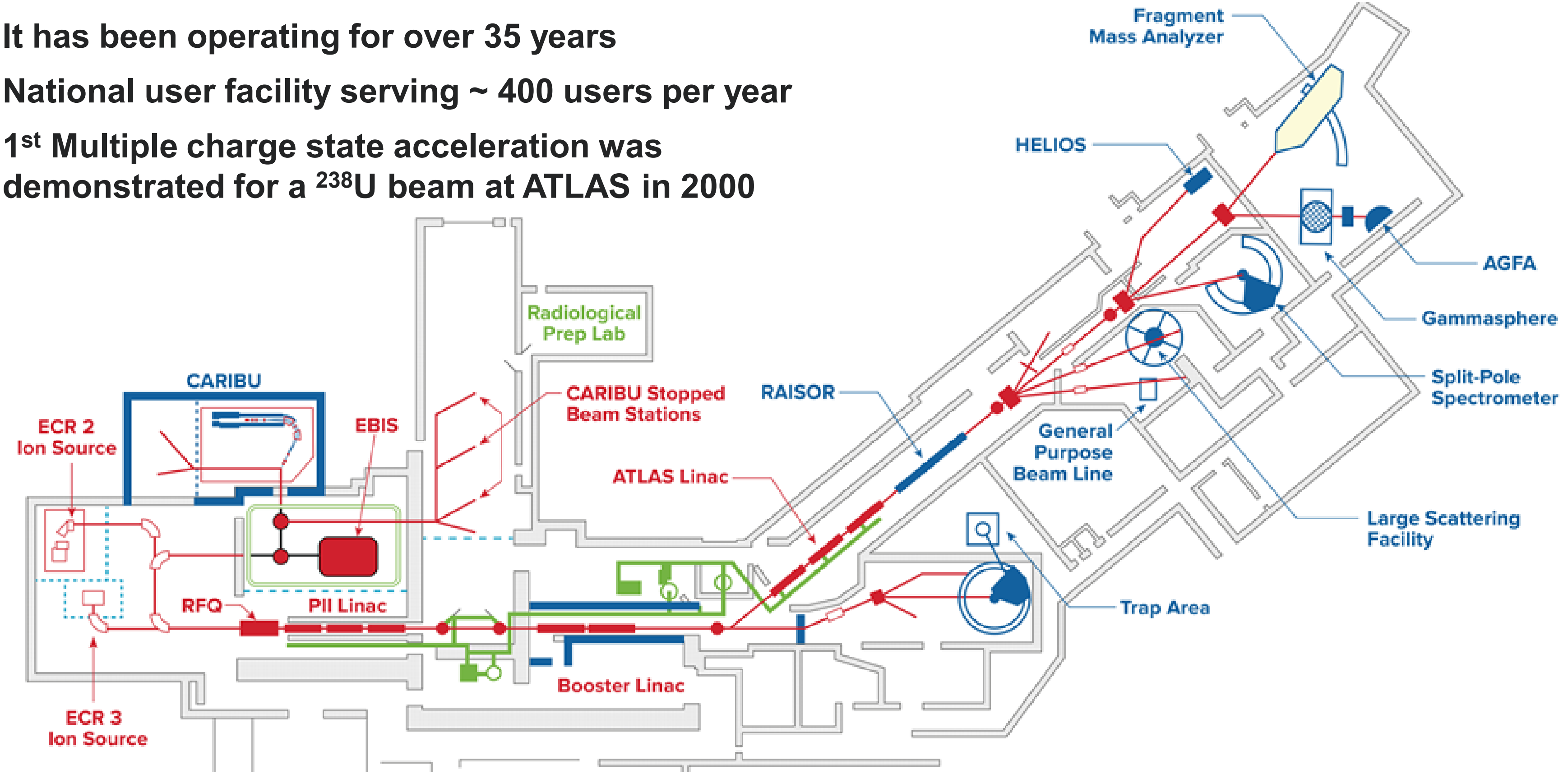
Presentation/Discussion date:
Wednesday, May 26th, 2021

Outline

- Overview of ATLAS & Multi-Charge-State Ion Beam Acceleration
- The Need for and Purpose of the ATLAS Multi-User Upgrade
- The Opportunity and Potential Impact
- Concept, Scope, Requirements, Solution and Implementation
- Application: ATLAS Material Irradiation Station – (New beamline)
- Other Applications: Isotope R&D, Radiobiology & Imaging
- Summary

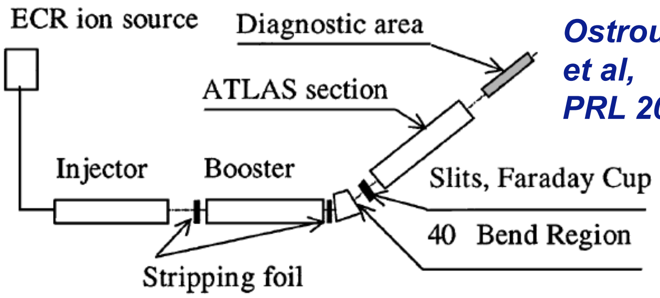
ATLAS: Argonne Tandem Linear Accelerator System

- ✓ 1st Superconducting heavy-ion linac in the world
- ✓ It has been operating for over 35 years
- ✓ National user facility serving ~ 400 users per year
- ✓ 1st Multiple charge state acceleration was demonstrated for a ^{238}U beam at ATLAS in 2000



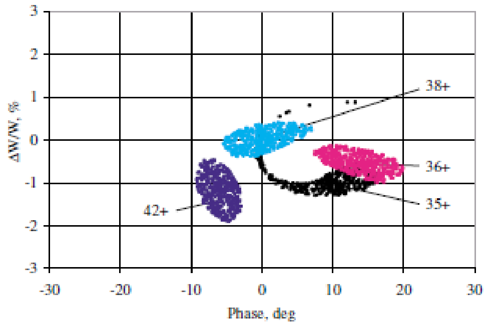
Simultaneous Multi-Charge States Acceleration

^{238}U from PII, stripped and injected to Booster

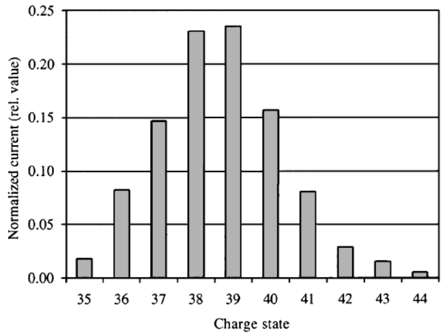


Ostroumov et al, PRL 2001

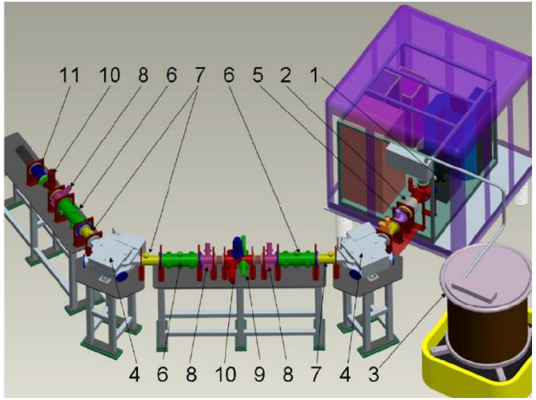
Multiple Q's in Longitudinal PS



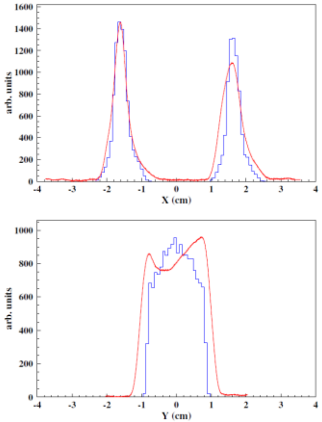
Intensities of accelerated Q's



Test beamline, Bi beam from ECR



Simulation vs. Experiment

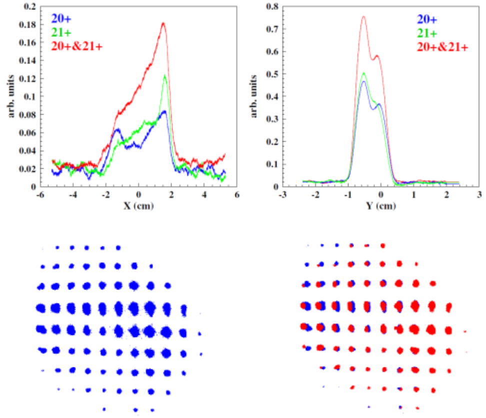


$^{209}Bi^{20+}$

$^{209}Bi^{21+}$

Ostroumov et al, PRST-AB 2009

Experimental Results, 2 Q's overlap

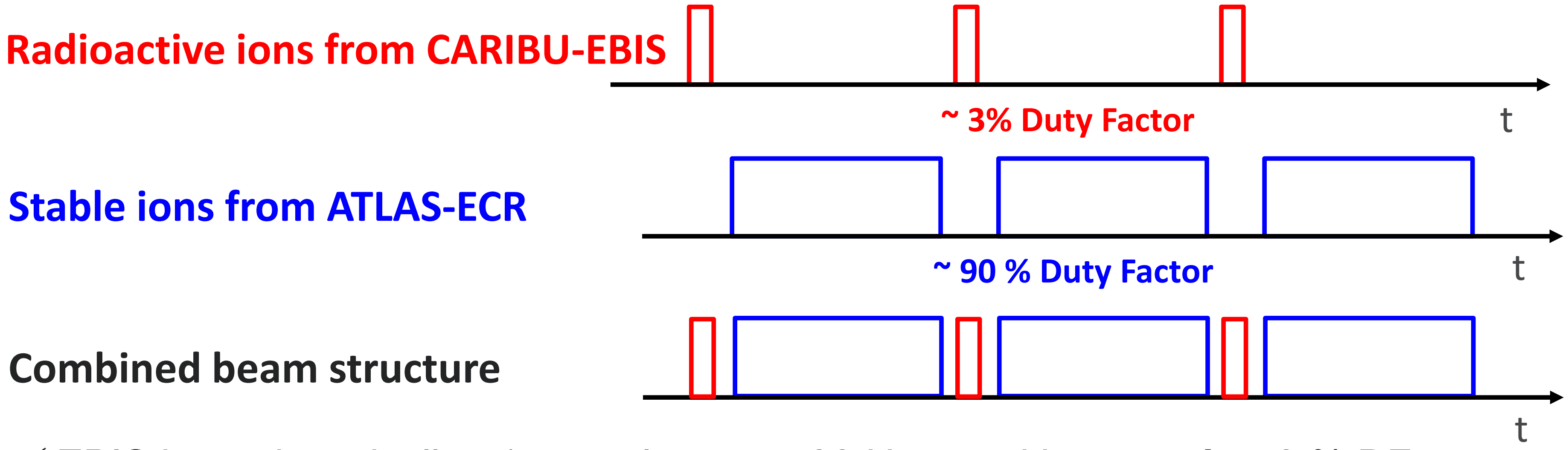


The Need & Purpose of the ATLAS MUU

- The Need
  - Significant competition & increased pressure on ATLAS beam time
  - Increasing demand for longer experiments (> 1 week)
  - Examples: Low intensity RIBs & Low cross section reaction channels
  - Requested beam time significantly exceeds ATLAS's ~ 6000 hours/year
  - ATLAS PAC is typically over-subscribed by a factor of 2-3 …

- The Purpose
  - Relieving the pressure on beam time and accomplish more physics by serving two users at a time, allow more time for some applications
  - When running CARIBU Beams, the machine is "empty" ~ 90% of the time while operating CW → Take advantage of that time (Economic!)
  - Demonstrate multi-user capabilities that can be a model for similar facilities …

The Opportunity with Pulsed CARIBU-EBIS



- ✓ EBIS beam is typically ~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
- ✓ Considering 2 x 1 ms switching time, the useful ECR duty cycle can be ~ 90%
- ✓ CARIBU beams are typically charge-bred to corresponding A/q ≥ 4, ATLAS accelerates beams with A/q ratios ≤ 7 → The useful range of A/q overlap is 4-7

Combining ECR Stable beams with CARIBU RIBs

- ✓Table shows beams overlap within 1% of A/q ratio
- ✓Flexibility:
  Overlap between stable and RIBs offers a lot of flexibility. Also, EBIS allow charge state selection
- ✓Potential Impact / Gain:
  based on a study of a recent run period showed ~ 40% potential overlap, limited only by the number of days of RIBs

A/Q	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	$^{58}Ni^{14+}$	$^{83}As^{20+}$, $^{95}Y^{23+}$, $^{104}Tc^{25+}$, $^{112}Pd^{27+}$, $^{117}Cd^{28+}$
4.364	$^{48}Ti^{11+}$, $^{74}Ge^{17+}$	$^{92}Kr^{21+}$, $^{105}Nb^{24+}$, $^{109}Tc^{25+}$, $^{119}Pd^{27+}$, $^{149}Nd^{34+}$
4.538	$^{59}Co^{13+}$	$^{91}Rb^{20+}$, $^{105}Zr^{23+}$, $^{123}Cd^{27+}$, $^{131}Te^{29+}$, $^{146}Pr^{32+}$
4.875	$^{78}Kr^{16+}$	$^{93}Y^{19+}$, $^{102}Mo^{21+}$, $^{132}Sn^{27+}$, $^{141}I^{29+}$, $^{162}Eu^{34+}$
5.000	$^{40}Ar^{8+}$, $^{60}Ni^{12+}$, $^{90}Zr^{18+}$	$^{85}Se^{17+}$, $^{110}Mo^{22+}$, $^{124}In^{25+}$, $^{141}I^{28+}$, $^{159}Pm^{32+}$
5.280	$^{132}Xe^{25+}$	$^{105}Ru^{20+}$, $^{126}In^{24+}$, $^{137}I^{26+}$, $^{153}Pr^{29+}$, $^{165}Tb^{31+}$
5.600	$^{84}Kr^{15+}$	$^{100}Nb^{18+}$, $^{111}Tc^{20+}$, $^{117}Cd^{21+}$, $^{141}Xe^{25+}$, $^{147}La^{26+}$
5.643	$^{79}Br^{14+}$, $^{107}Ag^{19+}$	$^{96}Rb^{17+}$, $^{107}Nb^{19+}$, $^{119}Cd^{21+}$, $^{135}Te^{24+}$, $^{151}Nd^{27+}$
5.714	$^{80}Se^{14+}$	$^{91}Kr^{16+}$, $^{97}Zr^{17+}$, $^{109}Ru^{19+}$, $^{131}Sb^{23+}$, $^{143}Ba^{25+}$
6.432	$^{238}U^{37+}$	$^{83}Se^{13+}$, $^{90}Kr^{14+}$, $^{97}Sr^{15+}$, $^{103}Zr^{16+}$, $^{141}I^{22+}$
6.709	$^{208}Pb^{31+}$	$^{88}Se^{13+}$, $^{88}Br^{13+}$, $^{94}Rb^{14+}$, $^{100}Y^{15+}$, $^{107}Nb^{16+}$
6.792	$^{197}Au^{29+}$	$^{89}Se^{13+}$, $^{89}Br^{13+}$, $^{95}Rb^{14+}$, $^{102}Y^{15+}$, $^{108}Nb^{16+}$
7.000	$^{133}Cs^{19+}$	$^{84}As^{12+}$, $^{98}Rb^{14+}$, …

Nuclear Physics Programs to Benefit from the ATLAS MUU

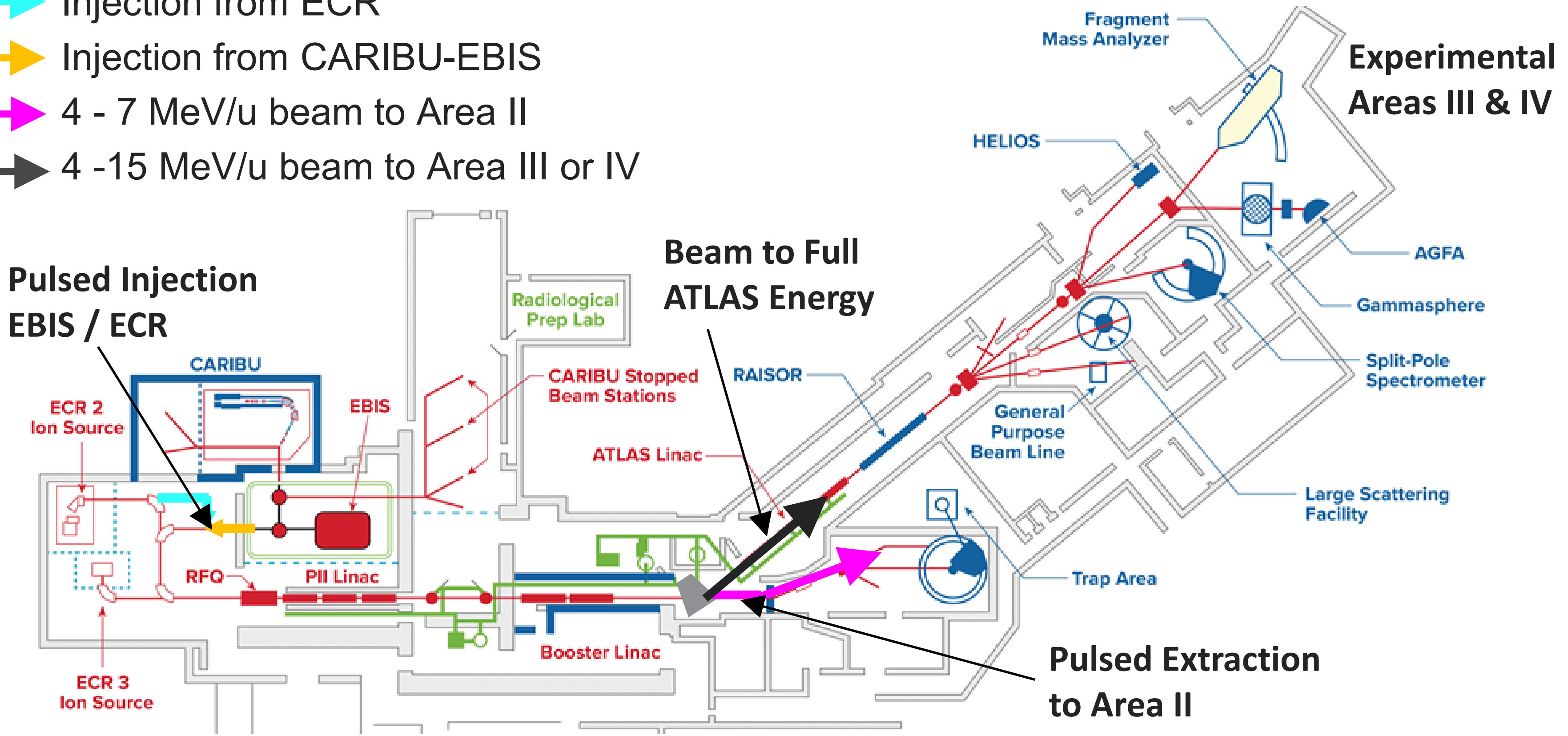
- ✓ **Heavy element program (Z >100)** (AGFA separator + Digital GS)
- ✓ **Decay spectroscopy & super-heavy program** (AGFA + DSSD)
- ✓ **Astrophysics capture reaction program** (AIRIS + MUSIC)
- ✓ **High resolution spectroscopy of nuclei** (CARIBU and AT-TPC)
- ✓ **Coulomb excitation studies** (CARIBU + GRETINA & CHICO-II)
- ✓ **Single particle structure studies** (CARIBU + HELIOS)
- ✓ **High resolution single particle structure** (AIRIS + HELIOS)

- ➢ **Most / All of these programs require long experimental runs, limited at this time but would run with the ATLAS-MUU**

- ➢ **More beam time from the ATLAS-MUU will help these programs reach their full potential.**

Concept & Scope of the ATLAS MUU

- Injection from ECR
- Injection from CARIBU-EBIS
- 4 - 7 MeV/u beam to Area II
- 4 -15 MeV/u beam to Area III or IV

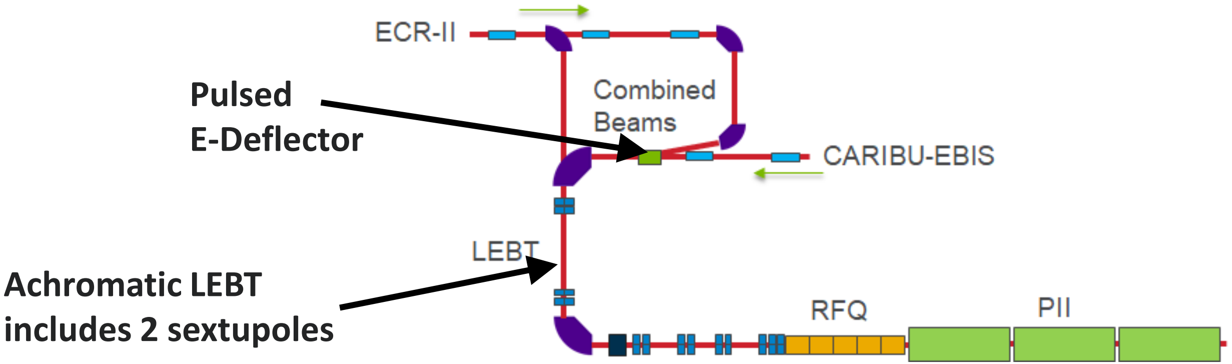


Requirements: Two Beam Injection & Extraction

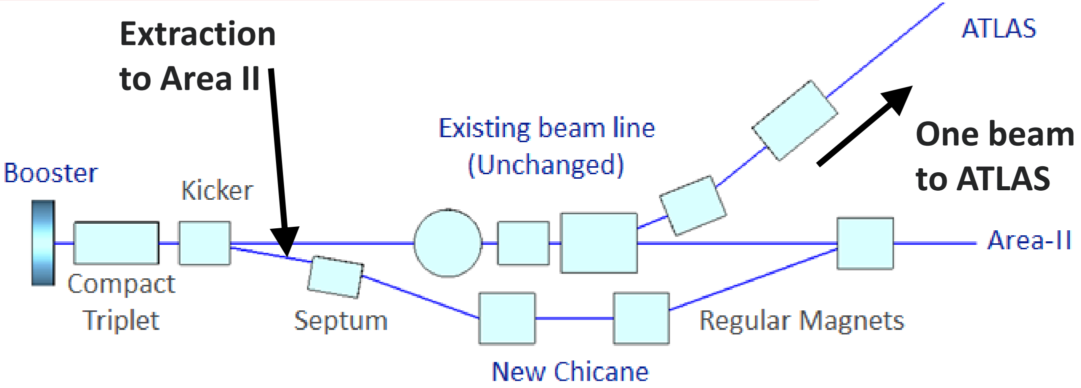
- Pulsed injection in the LEBT
  - ✓ Properly combine two beams with ~ 1 ms switching time
  - ✓ Maximize the overlap of the two beams in phase space
  - ✓ Match velocities of both beams for injection to the RFQ
  - ✓ Have proper beam diagnostics, especially for weak beams
- Pulsed extraction after the Booster
  - ✓ Switch either beam to Area II, the other to ATLAS and Area III&IV
  - ✓ Fit into the available space, this is a major constraint
  - ✓ Maintain single beam operation: Keep existing elements & diagnostics
  - ✓ Compatible with potential future upgrades

Technical Solution

1) Modification to the Front-end / Injection



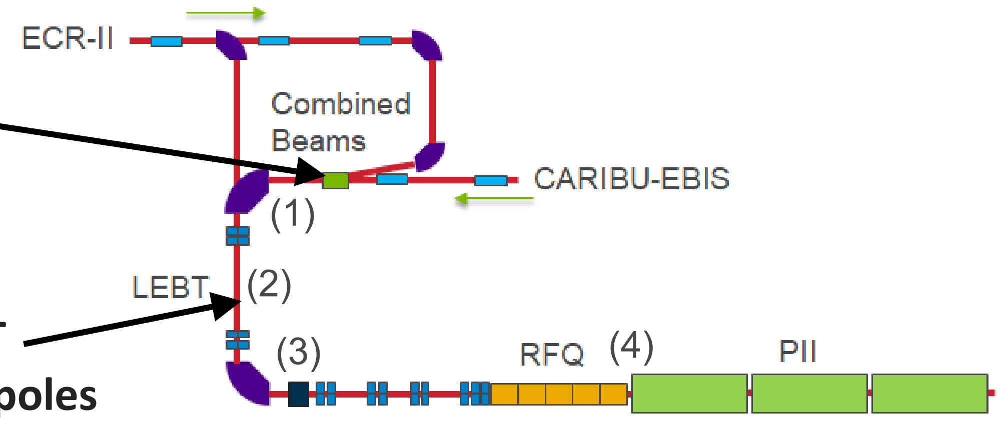
2) Extraction added after the Booster section



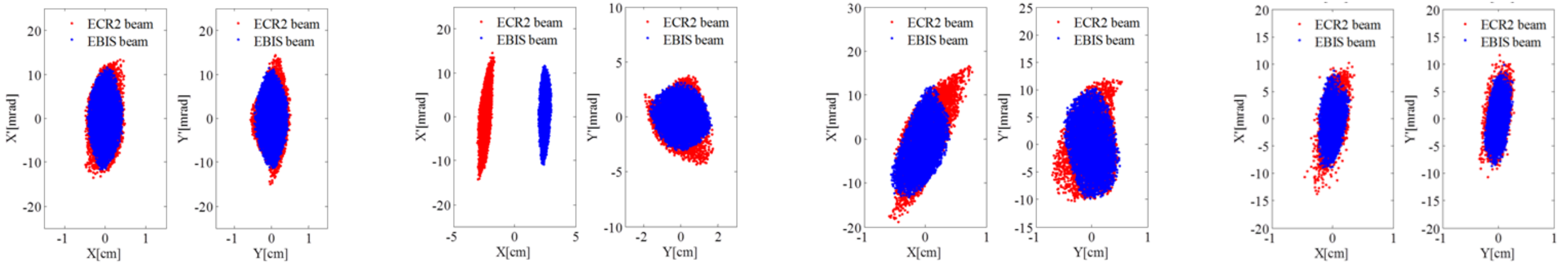
LEBT Injection: Combining Two Beams

Pulsed E-Deflector

Achromatic LEBT includes 2 sextupoles



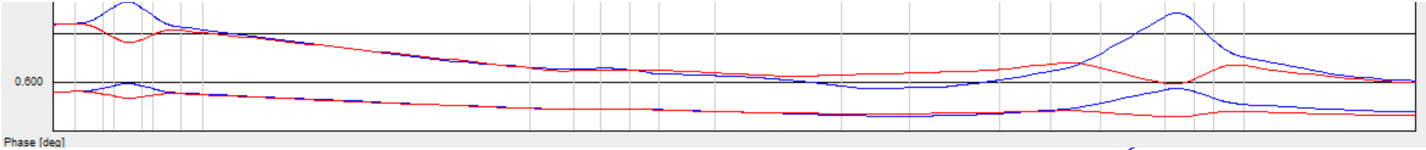
Example: **$^{132}Sn^{27+}$ from CARIBU-EBIS** **$^{48}Ca^{10+}$ from ECR2** **with ~ 2 % in A/q**

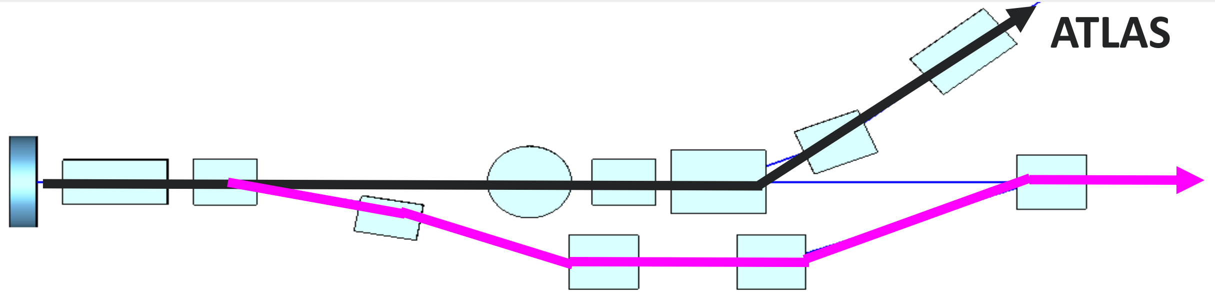


(1) Before 180° bend (2) At selection slit (3) After 180° bend (4) After ATLAS RFQ

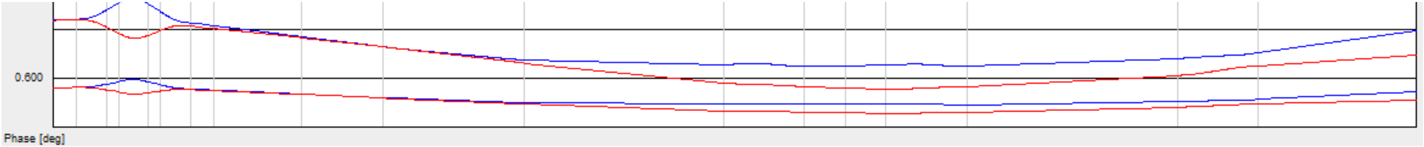
Booster Switchyard: Beam Separation

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



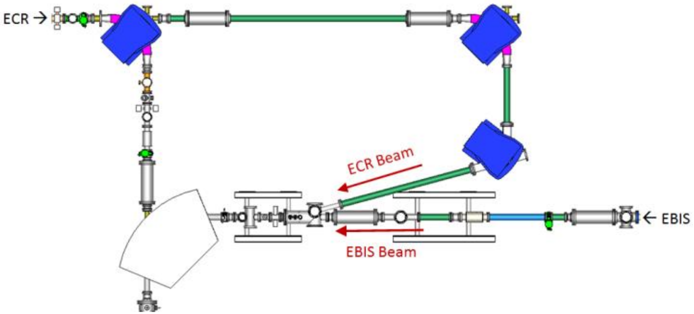


Beam to **Area II** through a new chicane made of a kicker, a septum and 3 regular magnets

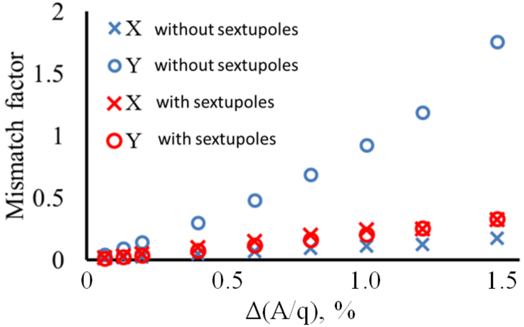


Main Components for the ATLAS MUU

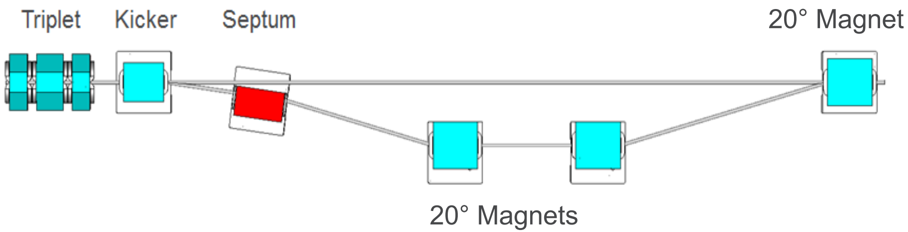
LEBT Injection



- Pulsed electrostatic deflector
- 2 electrostatic sextupoles



Booster Switchyard

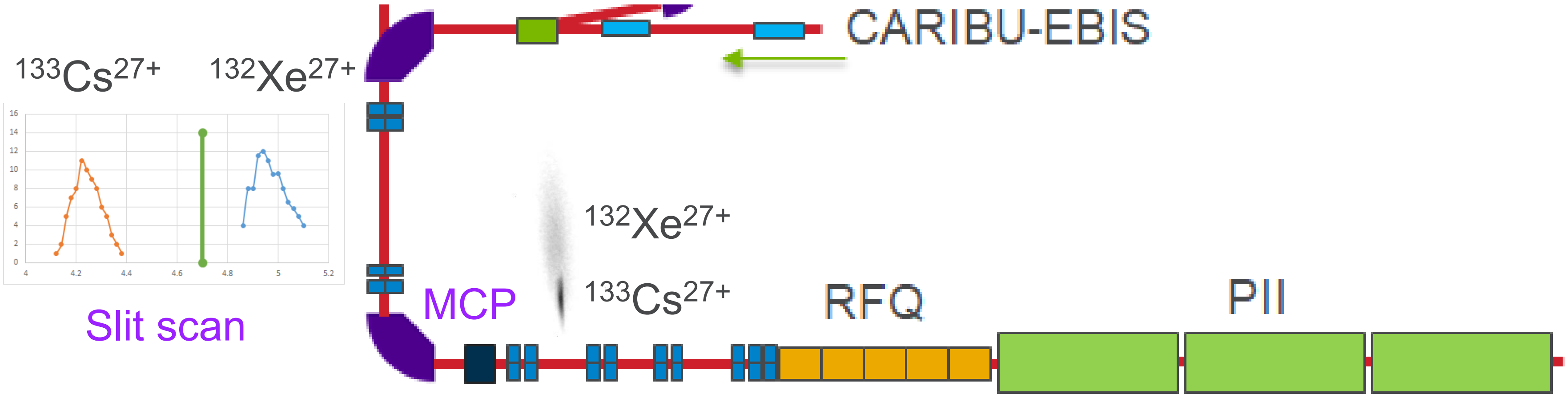


- Compact triplet
- Pulsed kicker-magnet - 10°
- Septum-magnet - 10°

Kicker Magnet – Most Critical Component

- Design Requirements
- ✓ Should be able to kick a 5 MeV/u A/q=6 beam by 10^{o} → ~ 0.7 T (0.5 m)
- ✓ Rise and fall time of ~ 1 ms with 30 Hz rep-rate
- ✓ Two operation modes: 1) 3% ON, 97% OFF and vice versa → ~ DC
- Main Consequences
- ✓ For B ~ 0.7 Tesla, It can't be a Ferrite, It has to be Iron/Steel
- ✓ Very thin laminations required to reduce AC losses from eddy currents
- ✓ Power supply should operate in pulsed and ~ DC modes
- Magnets with Similar Parameters: Very Few …
- ✓ LANL–IPF kicker (0.98 T, 60 Hz, 5 ms rise/fall, excessive losses!)
- ✓ RAL–ISIS kicker (0.86 T, 10 Hz, 12 ms rise/fall, successful!)

Results from a Recent Experimental Test Run



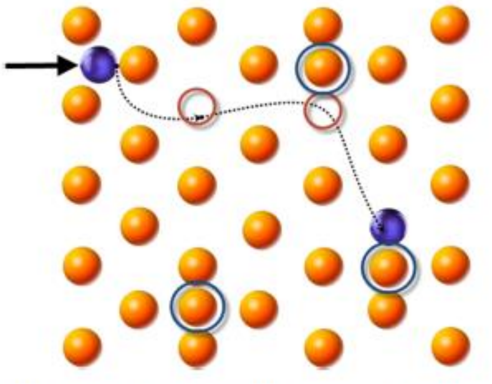
✓Since the ECR/EBIS combiner line is not available (part of project), the test was done using two EBIS beams: $^{133}Cs^{27+}$ and $^{132}Xe^{27+}$

✓Two beams successfully combined, injected and accelerated through RFQ, PII and Booster sections with ~ 70% total transmission

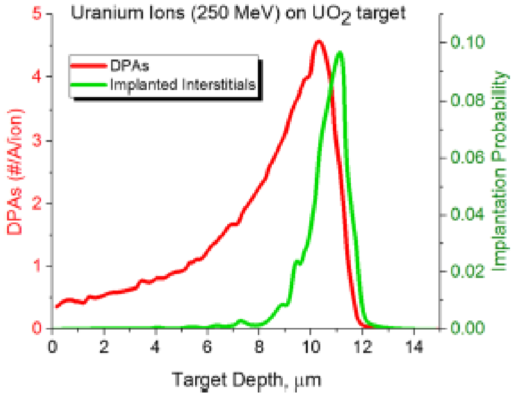
APPLICATIONS

Material Irradiation Studies for Nuclear Energy

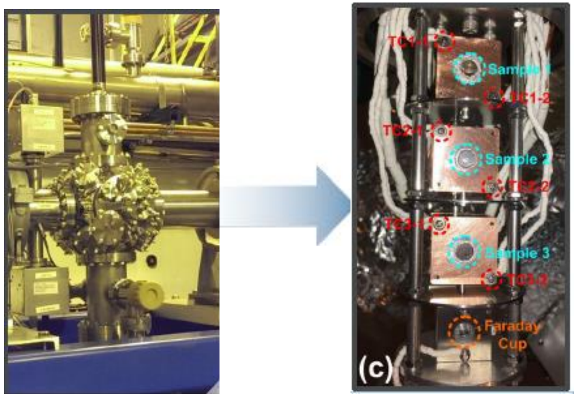
Radiation damage mechanisms



Damage as function of depth



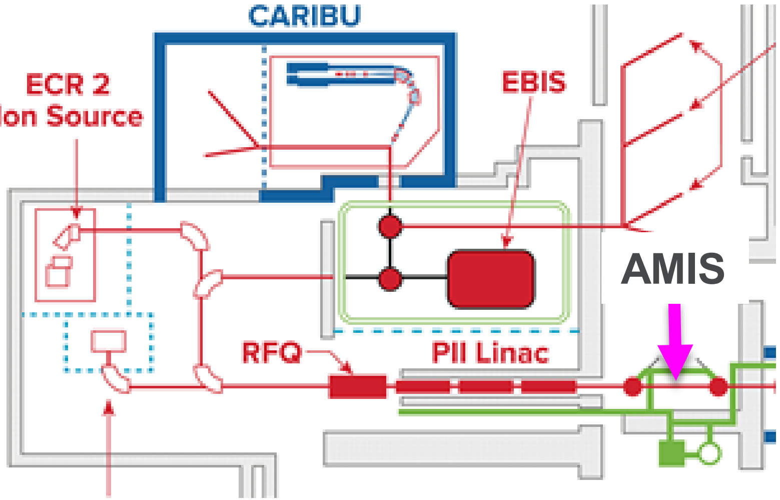
Current Irradiation Station at ATLAS

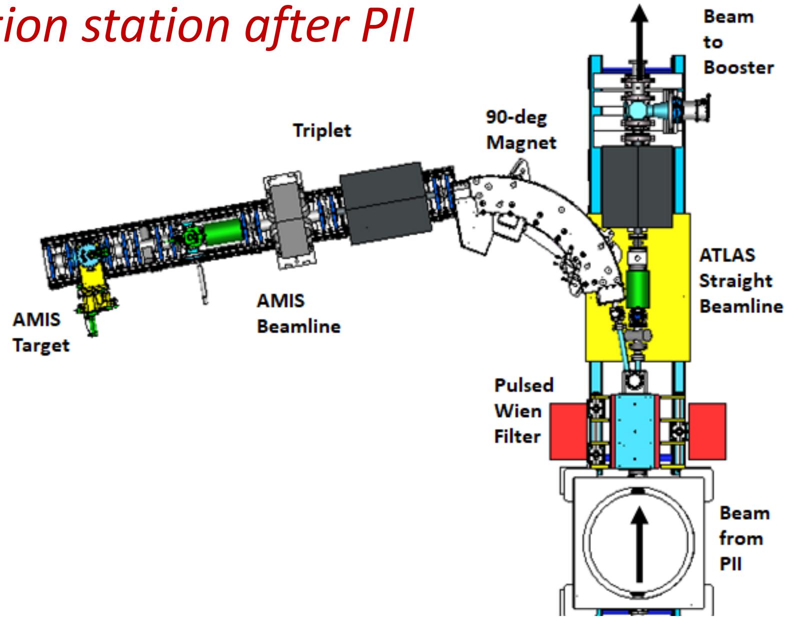


- Low-energy heavy ion beams ~ 1 MeV/u can effectively emulate material damage in nuclear reactors, in both fuel and structural materials
- Damages that could take years in a reactor environment could in principle be reproduced in few days or hours using an ion accelerator
- Following irradiation, materials are analyzed and their robustness and adequacy for nuclear reactor environment is evaluated
- Ref: M. Pellin et al, Journal of Nuclear Materials 472 (2016) 266-271.

AMIS: ATLAS Material Irradiation Station (New)

A dedicated material irradiation station after PII





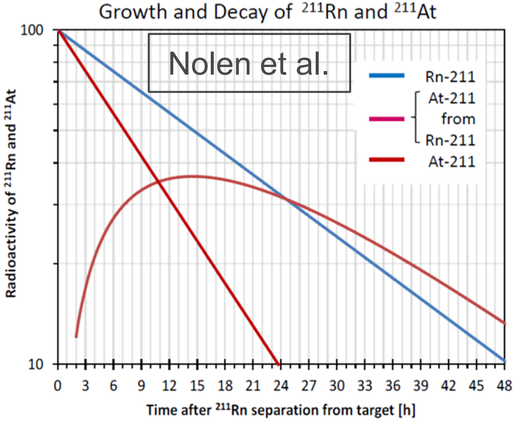
- Pulsed switching using a pulsed Wien filter magnet will allow more beam time by taking advantage of the ATLAS multi-user upgrade
- The new beamline is currently under development, will be completed by end of fiscal year
- Funding: NNSA's Office of Defense Nuclear Nonproliferation

Medical Isotope Production R&D at ATLAS

Production of Alpha-emitting ^{211}At using Li beam

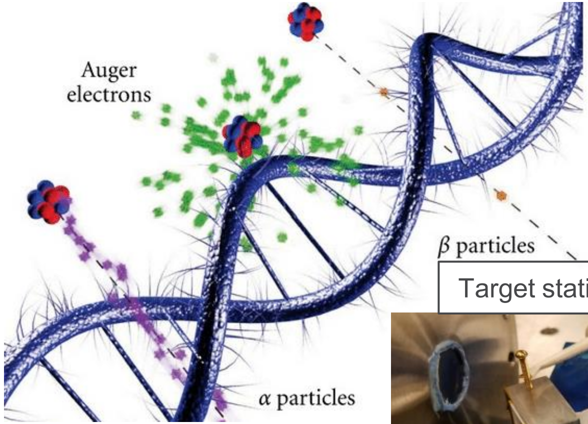
Bismuth oxide target

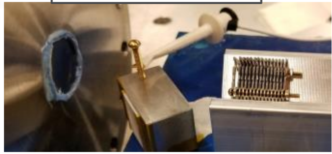
Capturing ^{211}Rn gas



Production through ^{209}Bi (^{7}Li, 5n) ^{211}Rn → ^{211}At

Auger-emitting Isotopes



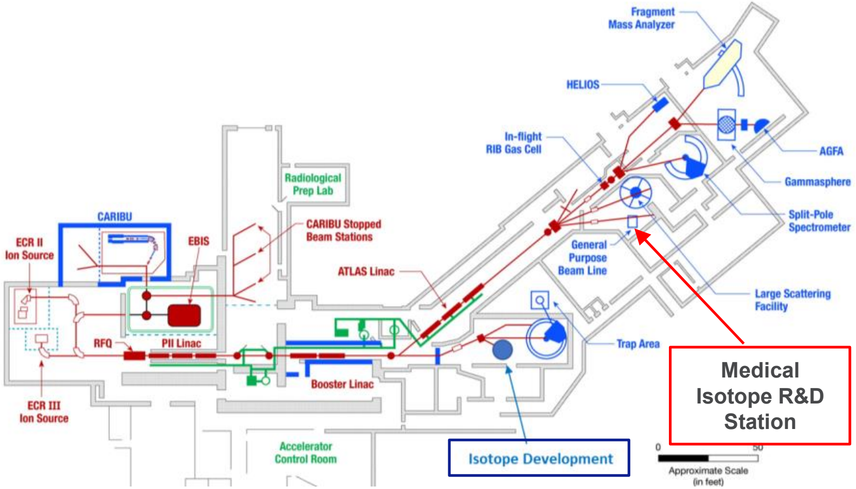


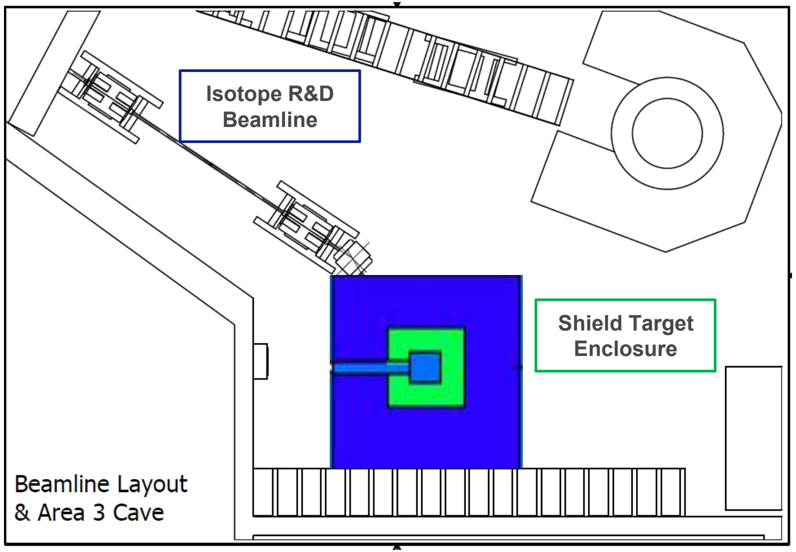
Many possible candidates …

- Light ion beams such as ^{3,4}He and ^{6,7}Li are useful for the production of alpha-emitting and Auger-electron-emitting isotopes
- Many potentially useful isotopes are accessible at ATLAS using such light ion beams.
- The production cross sections are ~1 barn enabling significant yields of isotopes and the useful ion energy range is ~8-15 MeV/u which has excellent overlap with ATLAS capability.

New Beamline for Isotope R&D at ATLAS

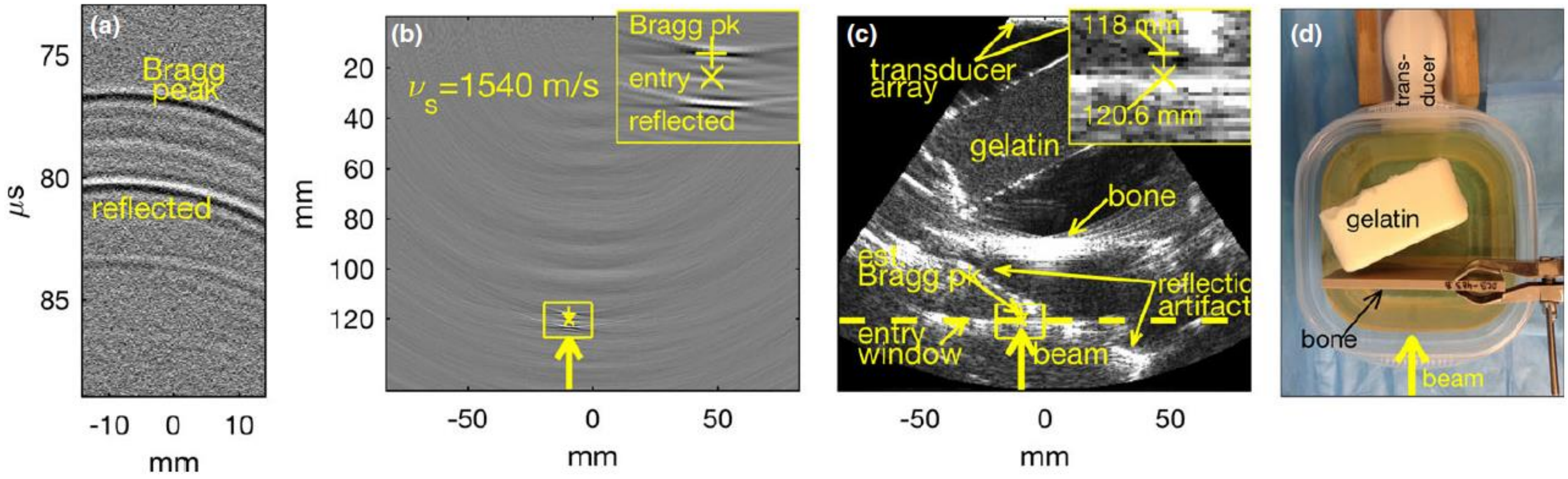
A dedicated beamline and target enclosure





- To maximize overlap with RIB beams in the multi-user mode, the light ions (He, Li) can be accelerated in 1+ charge state up to the Booster, then stripped and accelerated in ATLAS
- In addition to Areas 3 and 4, some Isotope Development can be done in Area 2

Ion Beam Therapy: Thermoacoustic Imaging



S. Patch et al, Med. Phys. 46 (1), January 2019

- Before stopping in media, ions lose a significant part of their energy (Bragg peak), a pressure wave is generated and can be detected if the ion beam is pulsed at a certain rate
- This enables the measurement of the ion beam range to the mm level
- Recent experiments performed at ATLAS with protons, helium, and carbon ions studied the robustness of thermoacoustic range verification to acoustic inhomogeneity in different media

Summary

- The ATLAS Multi-User Upgrade will relieve the pressure on beam time at ATLAS and enhance the capabilities of the facility
- The additional beam time expected from this upgrade will boost the delivery of the nuclear physics program and open-up the opportunity for some applications
- The design concept and technical solution were developed to satisfy the requirements of the multi-user upgrade with minimal interference with single beam operations
- We recently demonstrated the combination and acceleration of two beams with good efficiency all the way through Booster, the beam switching point.
- The project was recently reviewed and approved by the DOE/NP

Thanks to …

- Clay Dickerson, Matt Hendricks, Guy Savard
- Rick Vondrasek, Ben Blomberg
- Jerry Nolen, David Rotsch
- Latif Yacout, Michael Pellin, Heather Connoway
- Sarah Patch, Daniel Santiago
- Peter Ostroumov (now at FRIB)
- …

THANK YOU