Update on the ATLAS Multi-User Upgrade

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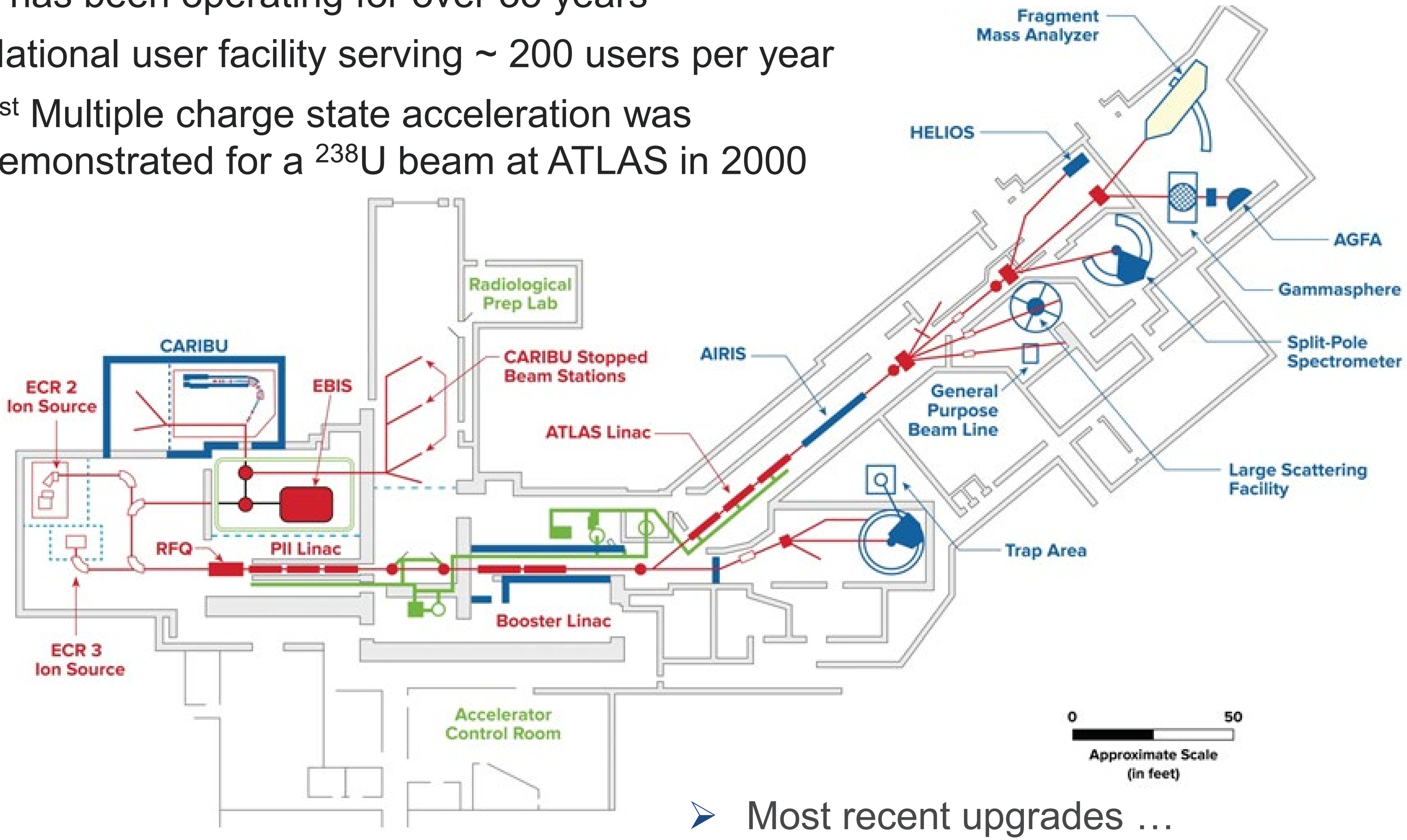
Outline

- ❑ The ATLAS Facility at Argonne and Recent Upgrades
- ❑ The Need for Multi-User Capabilities at ATLAS
- ❑ The Opportunity with Pulsed beams from CARIBU-EBIS
- ❑ Expected Impact: Nuclear Physics & Other Applications
- ❑ Proposed Implementation: Beam Optics & Technical Solutions
- ❑ Operational Considerations
- ❑ 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 ~ 200 users per year
- ✓1st Multiple charge state acceleration was demonstrated for a ^{238}U beam at ATLAS in 2000

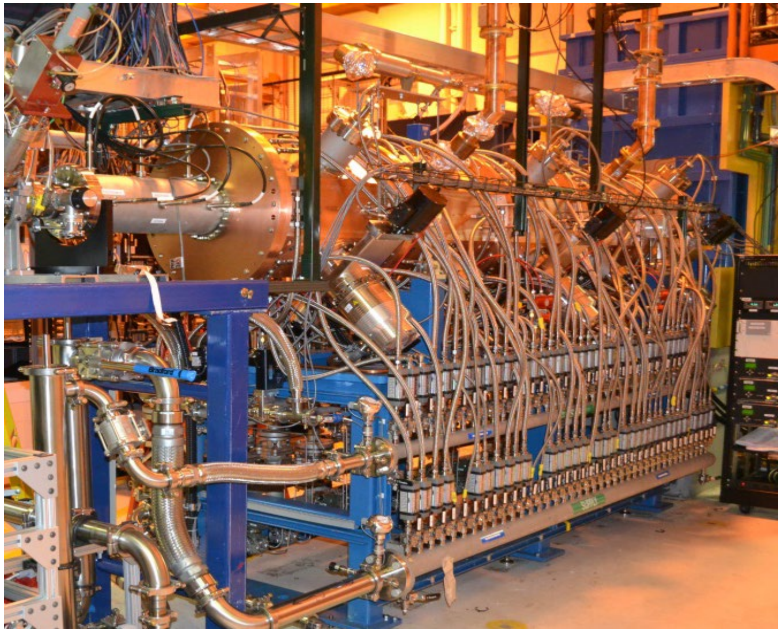


➢ Most recent upgrades …

Efficiency & Intensity Upgrade – Completed in 2014

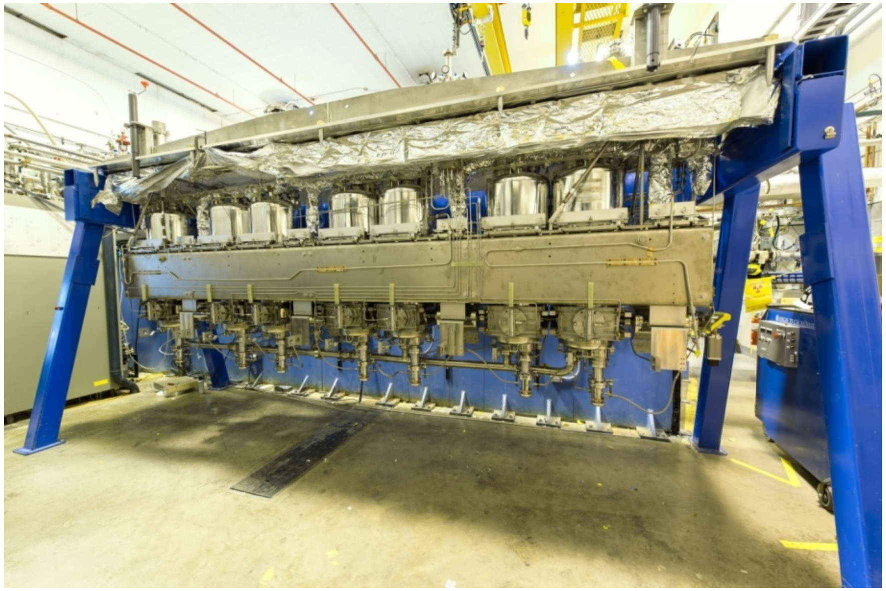
New CW 60 MHz RFQ

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



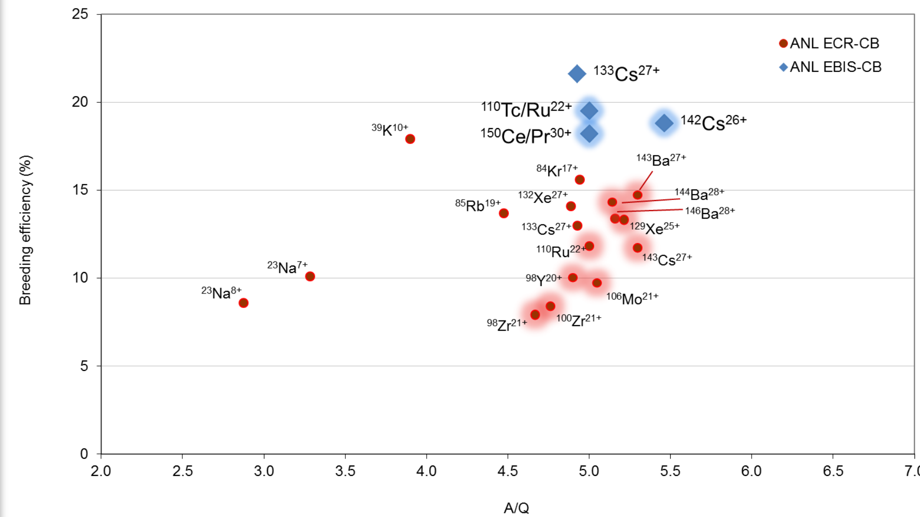
New SC Module

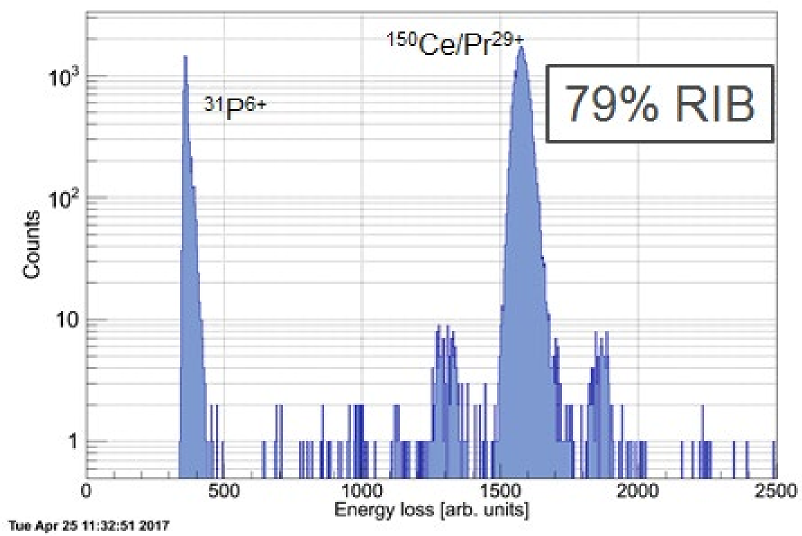
- ✓ 7 β ~ 0.77 QWR and 4 solenoids
- ✓ Capable of delivering 17.5 MV
- ✓ Replaced 3 old SC modules
- ✓ In routine operation since early 2014



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

CARIBU EBIS Charge Breeder – Completed in 2016



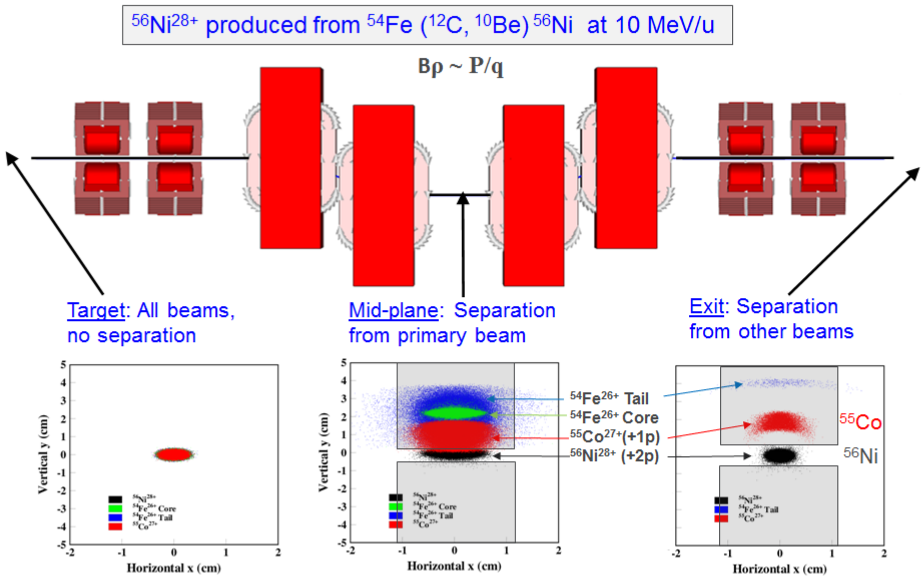


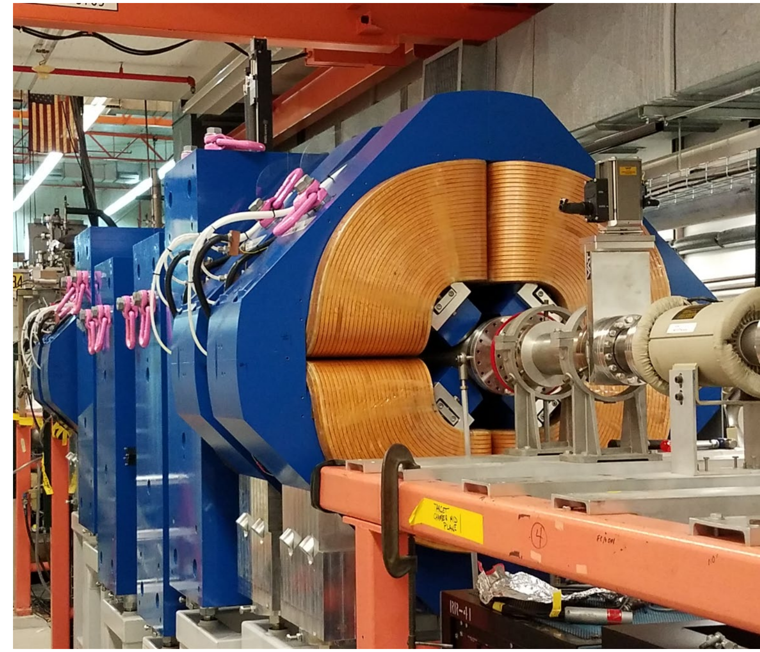
EBIS breeder replacing ECR - CB

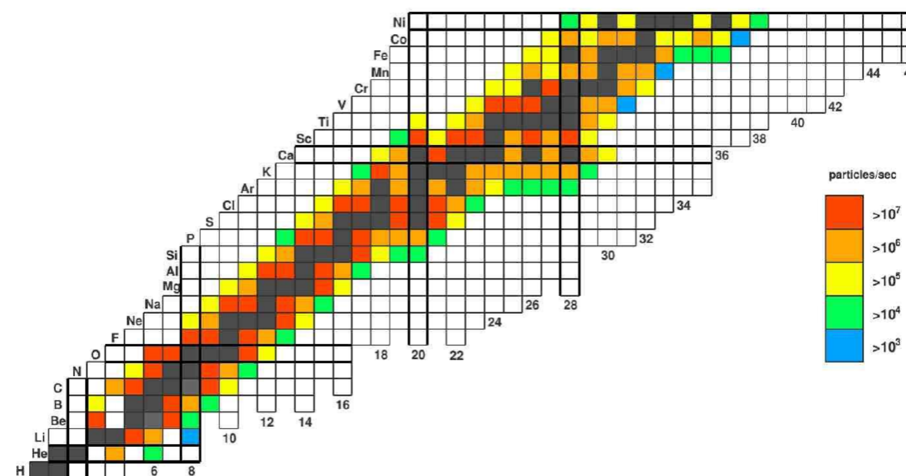
- ✓ Significantly higher beam purity
- ✓ Higher efficiency than ECR-CB
- ✓ Shorter charge-independent breeding time
- ✓ Pulsed operation → Multi-user possibility

R. Vondrasek Talk, Yesterday

AIRIS / RAISOR Separator – Completed in 2018







A Dedicated Inflight RIB Separator

- ✓ Serves all experimental areas
- ✓ Produces wider range of RIB beams
- ✓ Higher intensity RIB beams
- ✓ Higher RIB beam purity

C. Dickerson Talk, Yesterday

The Need for Multi-User Capabilities at ATLAS

- ATLAS is the only US DOE National User Facility for Low-Energy Nuclear Physics Research
  → Enormous competition for & increased pressure on beam time

- Increasing demand for longer experiments (> 1 week)
  - Low intensity RIB beams: from CARIBU and AIRIS
  - Low cross section channels: Heavy elements (FMA and AGFA)

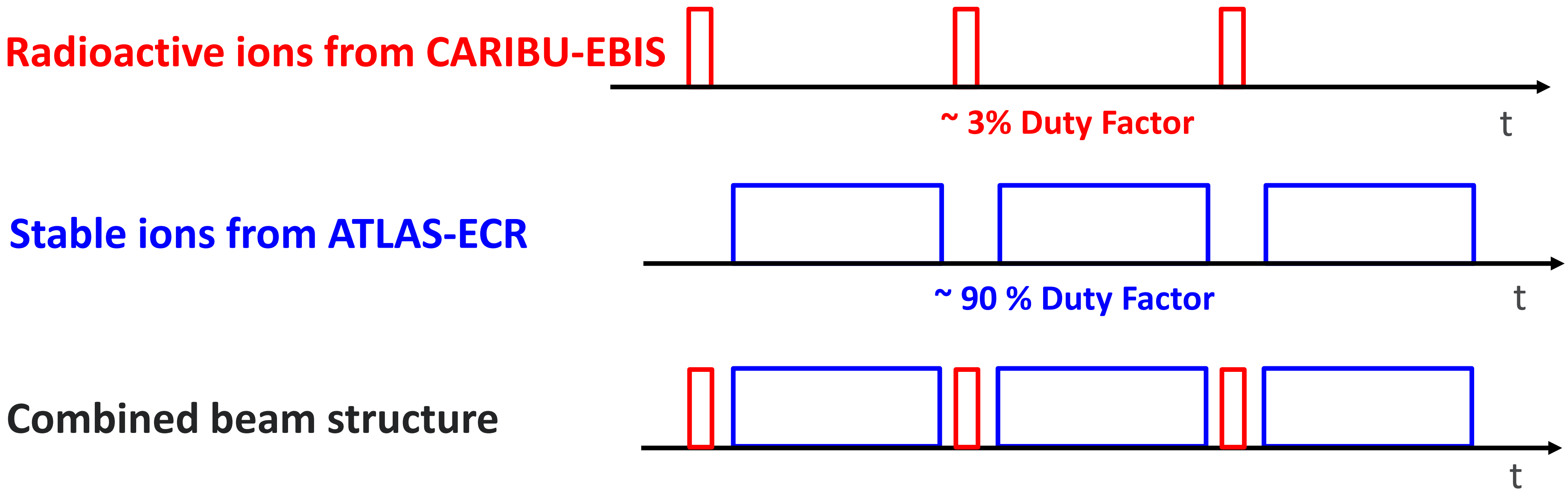
- In the past few years, the requested experimental beam time significantly exceeded the ~ 5500 hours ATLAS delivers every year

- ATLAS PAC is over-subscribed by a factor of 2-3 …

➢ There is a clear need for multi-user capabilities at ATLAS …

The Possibility with Pulsed EBIS Beams

The Possibility with Pulsed Beams from 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
- ✓ CARIBU beam masses range from 80 to 170 with Z ranging from 30 to 70
- ✓ The highest charge they could be ionized to, corresponds to $A/q \geq 4$
- ✓ ATLAS accelerates beams with A/q ratios ≤ 7
- ✓ The useful range of A/q ratios for multi-user capability is 4 - 7
- ✓ Lower $A/q \approx 3$ can be achieved with longer breeding time (10 Hz rep. rate)

Sample of Possible Simultaneous Stable and RIBs

For every stable beam typically produced at ATLAS, there are several RIB candidates …

List shown is for A/q within 1%

Accepted range is up to 2%

A/Q	Stable ATLAS 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	$^{98}Mo^{20+}$	$^{98}Sr^{20+}$, $^{108}Mo^{22+}$, $^{117}Pd^{24+}$, $^{136}Sb^{28+}$, $^{161}Sm^{33+}$
4.923	$^{64}Zn^{13+}$	$^{83}Se^{17+}$, $^{93}Y^{19+}$, $^{117}Ag^{24+}$, $^{132}I^{27+}$, $^{166}Tb^{34+}$

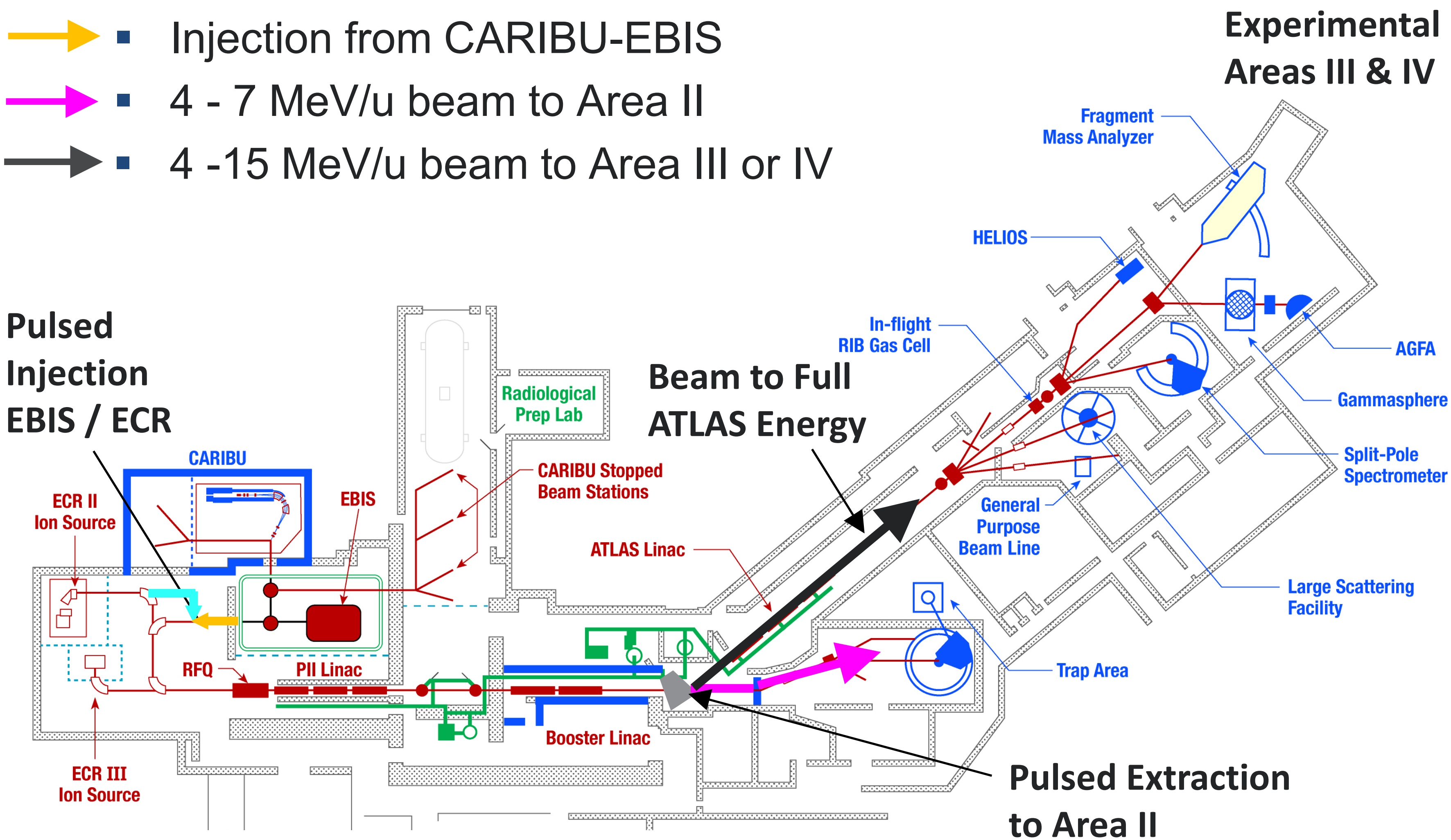
More Examples of Possible Simultaneous beams

A/Q	Stable ATLAS beams	CARIBU beams
5.000	$^{40}Ar^{8+}$, $^{60}Ni^{12+}$, $^{90}Zr^{18+}$, $^{130}Te^{26+}$	$^{85}Se^{17+}$, $^{110}Mo^{22+}$, $^{124}In^{25+}$, $^{141}I^{28+}$, $^{159}Pm^{32+}$
5.280	$^{132}Xe^{25+}$	$^{105}Ru^{20+}$, $^{126}In^{24+}$, $^{137}I^{26+}$, $^{153}Pr^{29+}$, $^{165}Tb^{31+}$
5.565	$^{128}Xe^{23+}$	$^{95}Y^{17+}$, $^{105}Tc^{19+}$, $^{134}Sn^{24+}$, $^{144}Xe^{26+}$, $^{149}La^{27+}$
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	$^{238}U^{37+}$	$^{83}Se^{13+}$, $^{90}Kr^{14+}$, $^{97}Sr^{15+}$, $^{103}Zr^{16+}$, $^{141}I^{22+}$
6.615	$^{86}Kr^{13+}$	$^{86}Se^{13+}$, $^{92}Rb^{22+}$, $^{100}Sr^{23+}$, $^{105}Zr^{24+}$, $^{106}Nb^{24+}$
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	$^{209}Bi^{31+}$	$^{87}Se^{13+}$, $^{87}Br^{13+}$, $^{95}Rb^{14+}$, $^{102}Y^{15+}$, $^{108}Nb^{16+}$
6.792	$^{197}Au^{29+}$	$^{89}Se^{13+}$, $^{89}Br^{13+}$, $^{95}Rb^{14+}$, $^{102}Y^{15+}$, $^{108}Nb^{16+}$
7.000	$^{133}Cs^{19+}$	$^{84}As^{12+}$, $^{98}Rb^{14+}$, …

✓ **The overlap between Stable and RIB Beams offers a lot of flexibility …**

Scope of the Proposed Multi-User Upgrade

- 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



Potential Impact / Gain from ATLAS MUU

Potential Impact / Gain based on PAC-Approved Experiments with CARIBU beams available

- **We analyzed PAC-approved experiments that ran during the first GRETINA campaign for potential overlap between stable beams and CARIBU beams**

- **Analysis procedure and criteria for beam overlap**
  - Source: One beam from ECR-2 & One beam from CARIBU
  - Mass-to-charge ratio: Both beams with A/q > 3.5
  - Energy: One beam at Booster & One beam at ATLAS energy (only Booster energy beams can run in Area–II)
  - Experimental equipment: Area-II has limited operational equipment → Added hypothetical case: GRETINA located in Area-II

- **Findings**
  - ✓ With a gamma ray detector (GT/GS) located in Area-II, the potential overlap is ~ 40%, limited only by the approved days of CARIBU beams

Nuclear Physics Programs to Benefit from ATLAS MUU

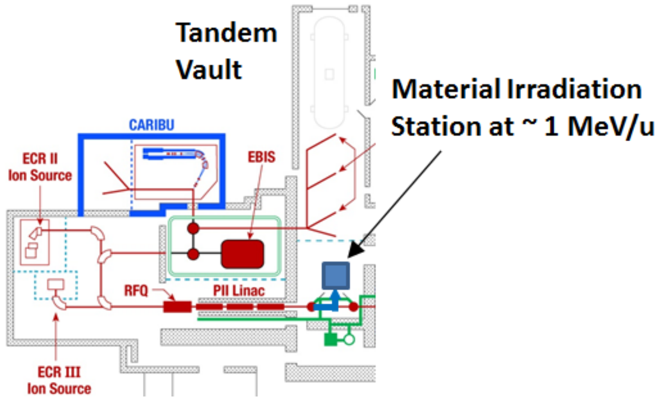
- ✓ **Heavy element program (Z >100)** (AGFA separator + Digital GS)
- ✓ **Decay spectroscopy & super-heavy program** (AGFA + DSSD)
- ✓ **Astrophysics capture reaction program** (AIRIS + MUSIC)
- ✓ **High resolution spectroscopy of nuclei** (CARIBU and AT-TPC)
- ✓ **Coulomb excitation studies** (CARIBU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

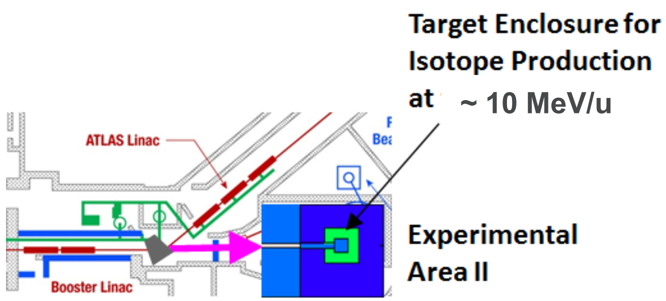
Potential Applications with the ATLAS MUU!

✓ Material Irradiation at PII energies ~ 1 MeV/u



- Fission fragment – like beams
- Stable or from CARIBU
- Good overlap & Flexibility

✓ Isotope Production at Booster / ATLAS energies



- High current light ion beams
- Limited overlap with CARIBU beams

✓ Radiobiology Studies at Booster / ATLAS energies

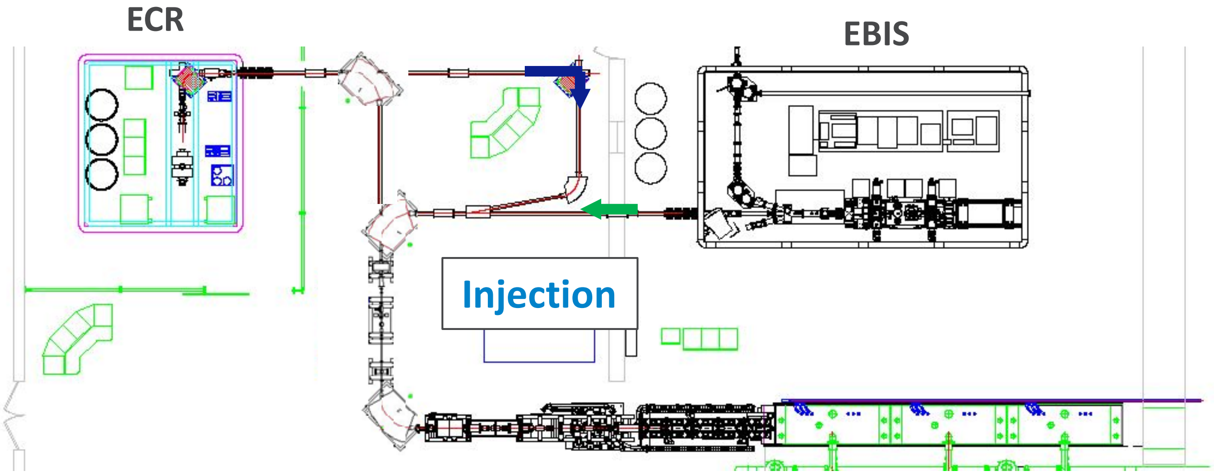
- Study radiobiological effects of different ion beams: proton, helium, carbon, … at the Bragg peak for comparative ion beam therapy
- Also, limited overlap with CARIBU beams

Requirements & Proposed Implementation

Requirements for Two-Beam Injection

➢ Pulsed injection in the LEBT

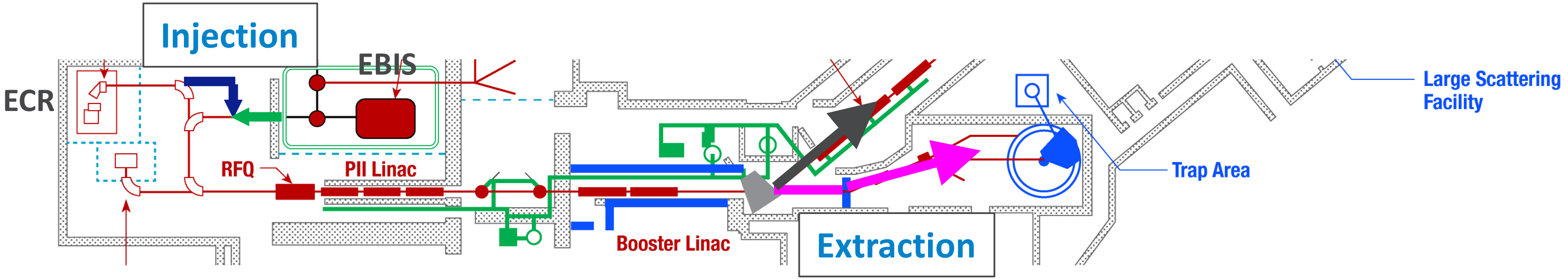
- ✓ Properly combine in time two beams with close A/q ratios
- ✓ Maximize the overlap in phase space – Achromatic beam transport & high order corrections
- ✓ The machine tuned for the average A/q to maximize acceptance of both beams.
- ✓ Similar to two-charge state acceleration in FRIB, except that the two beams are coming from different platforms which should be set to match the required velocity at the RFQ for both beams



Requirements for Beam Extraction after Booster

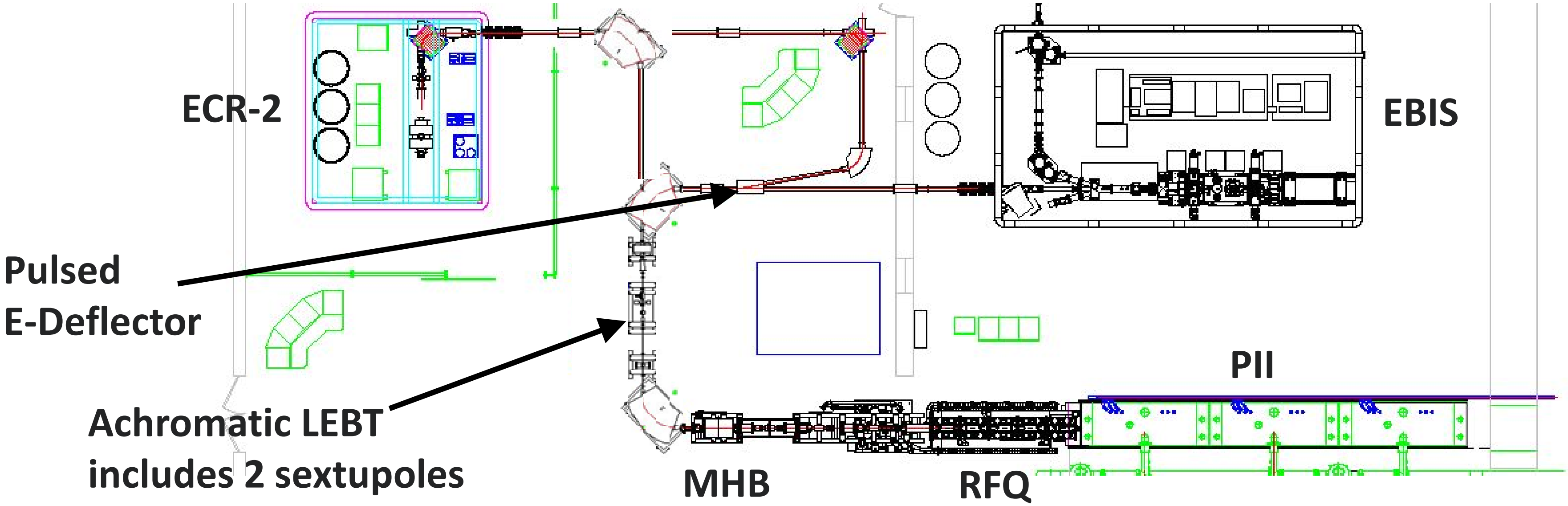
➢ Pulsed extraction after the Booster

✓ Switch either radioactive or stable beam to either Area II or Area III&IV
✓ Fit into the available space (significant constraint)
✓ Accommodate existing re-buncher close to center of beam line
✓ Accommodate existing beam diagnostics
✓ Compatible with potential future upgrades

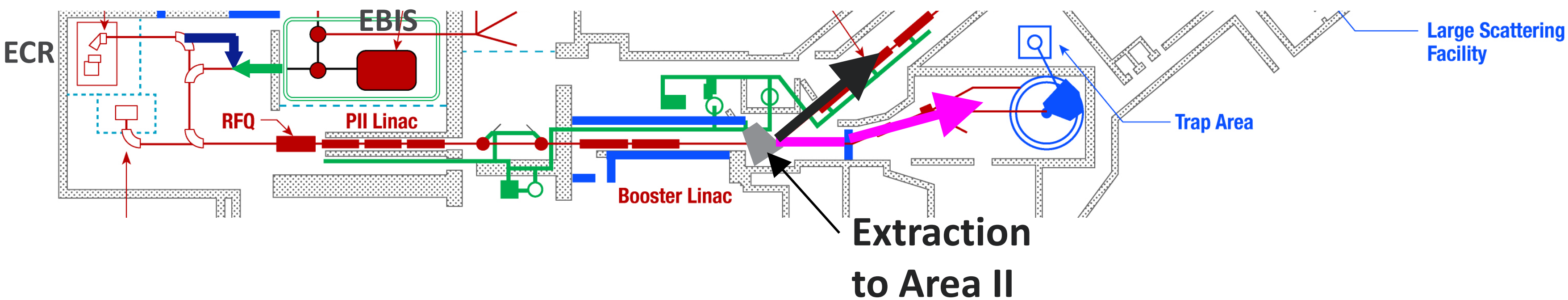


Proposed Implementation

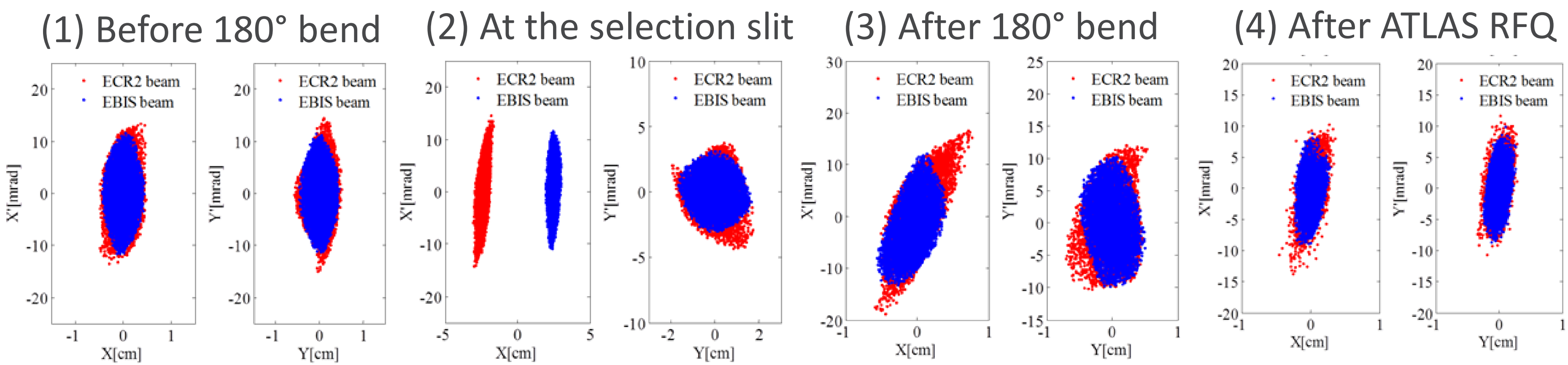
1) Modification to the Front-end / Injection



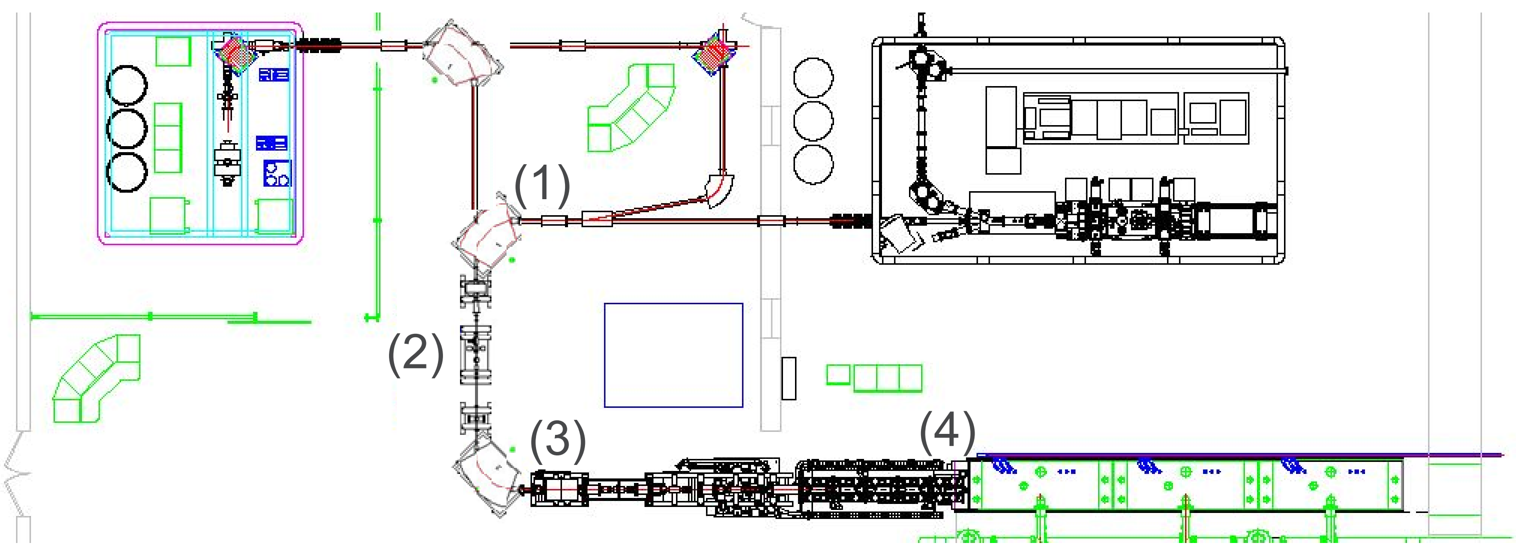
2) Extraction added after the Booster section



Example of Combining Two Beams in the LEBT



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



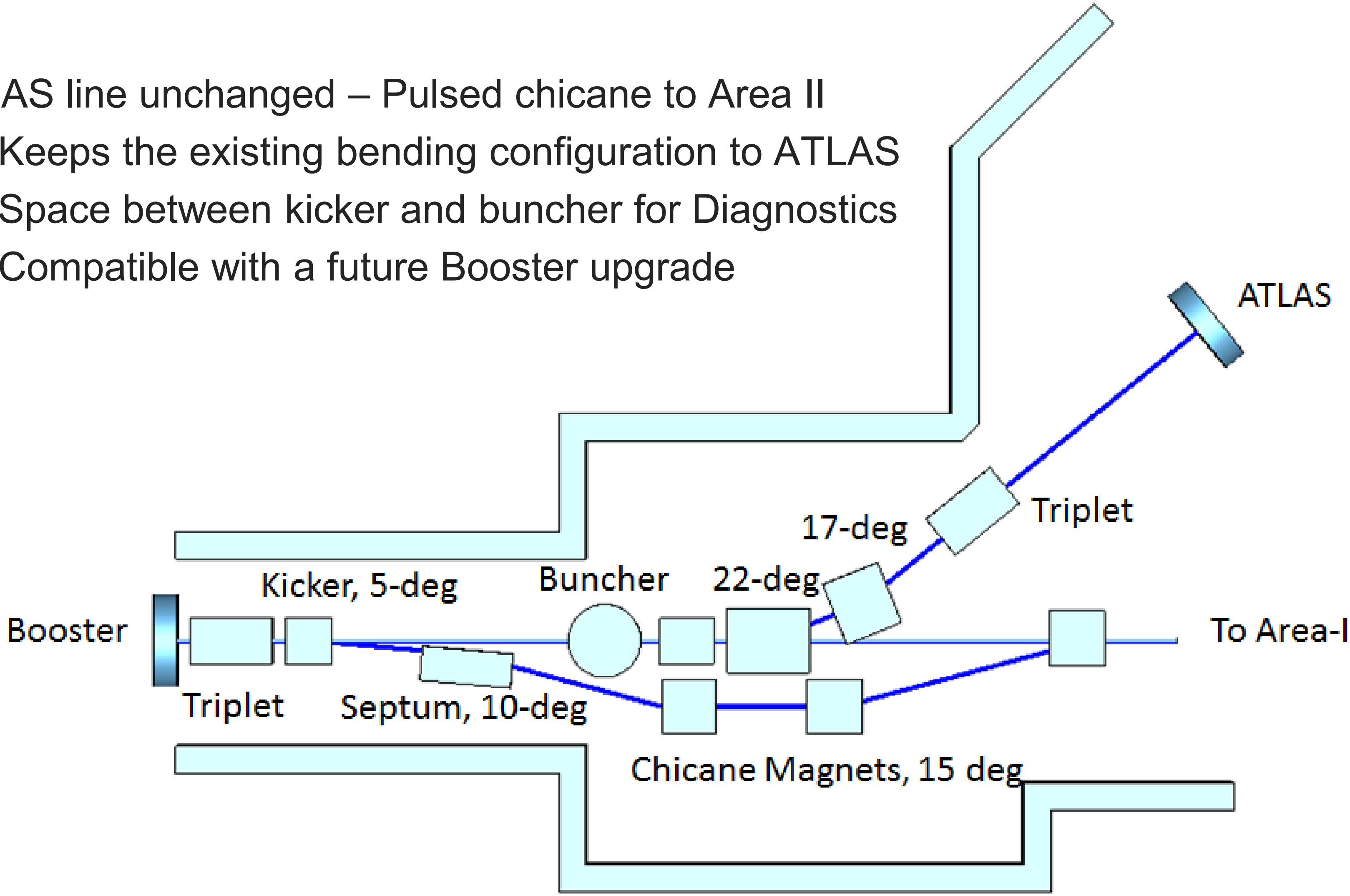
$^{132}Sn^{27+}$ from CARIBU-EBIS

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

~ 2 % in A/q

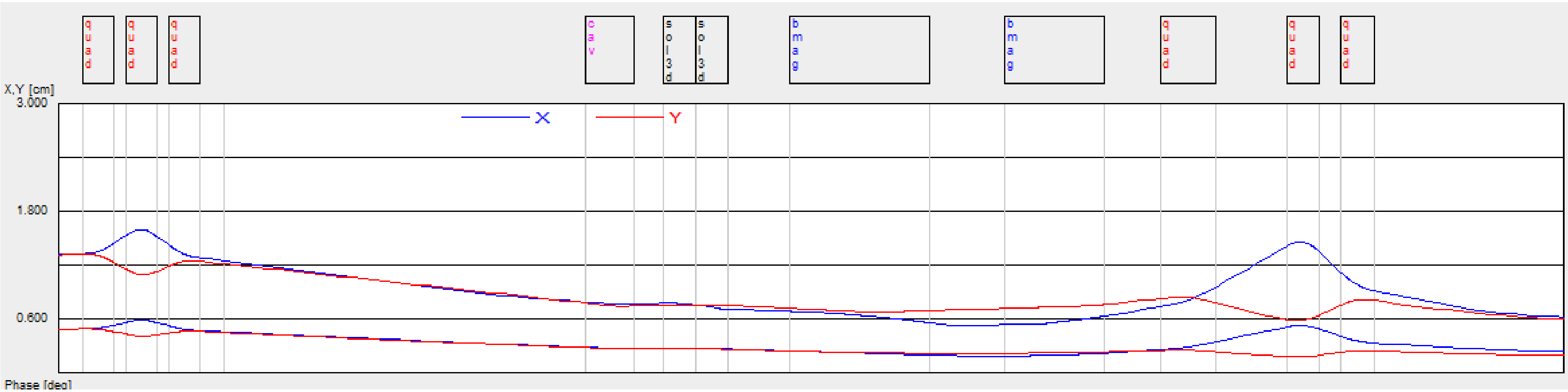
Booster Switchyard: Optimum Solution

- ✓ ATLAS line unchanged – Pulsed chicane to Area II
  - Keeps the existing bending configuration to ATLAS
  - Space between kicker and buncher for Diagnostics
  - Compatible with a future Booster upgrade

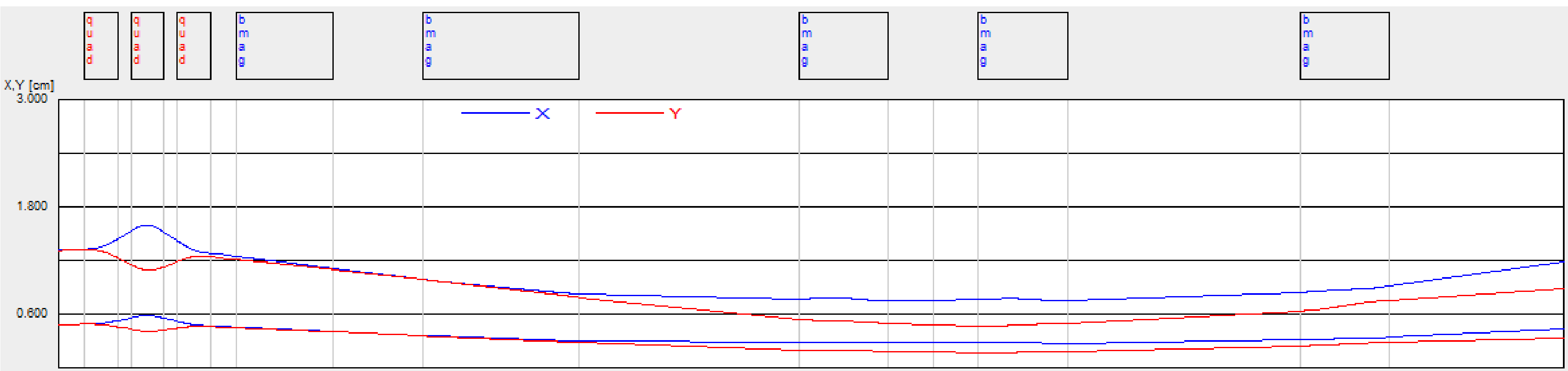


Booster Switchyard: Beam Optics Solution

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



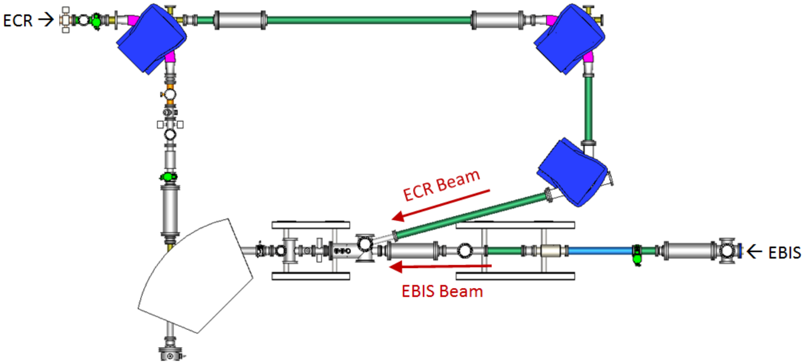
Beam to **Area II** through a new chicane made of a kicker, a septum and 3 regular magnets



Key Components - Preliminary Design

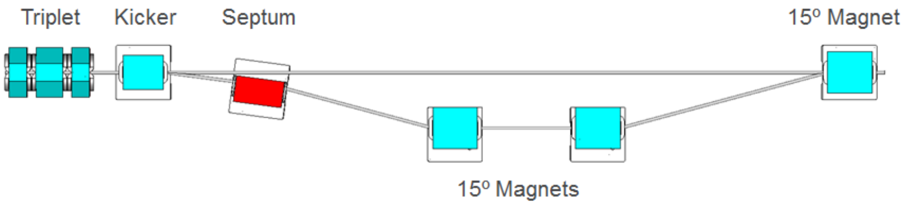
Key Components for the Multi-User Upgrade

LEBT Injection



- Pulsed electrostatic deflector
- 2 electrostatic sextupoles

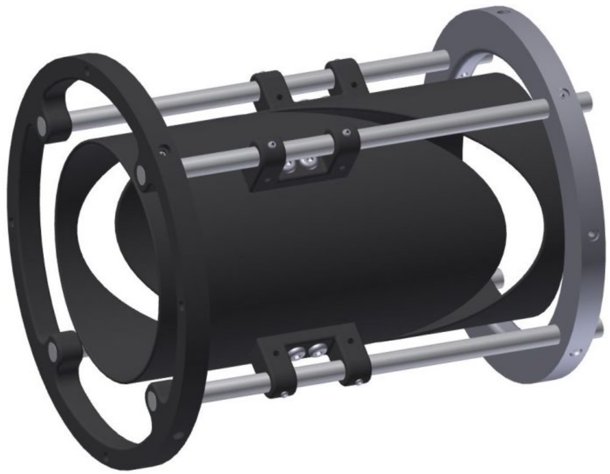
Booster Switchyard

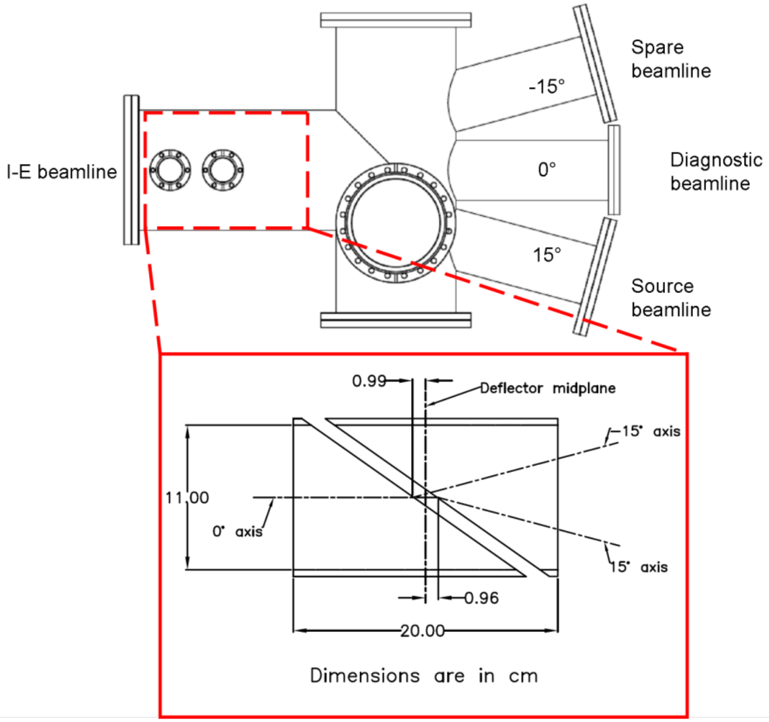


- Compact triplet
- Pulsed kicker-magnet ~ 5°
- Septum-magnet ~ 10°

Pulsed Electrostatic Deflector to Combine Beams

Existing Design – Already in use on EBIS platform



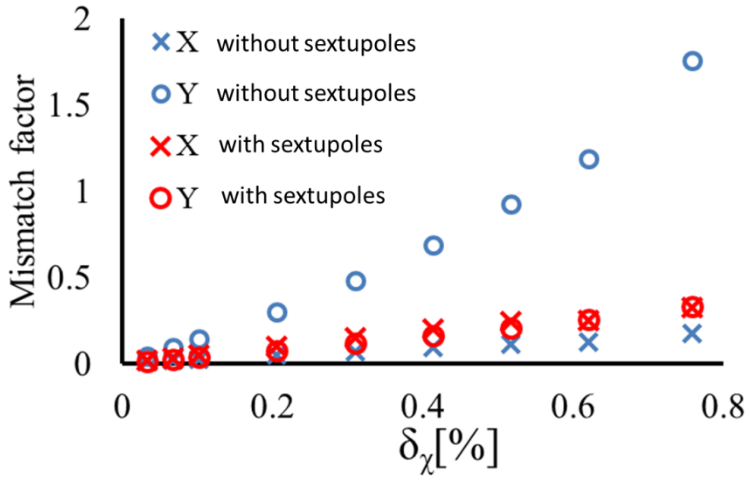


- Merge 30 keV/u stable and radioactive ion beams
- Electrode Voltage +/- 20 kV
- High voltage Belhke switches available for pulsing

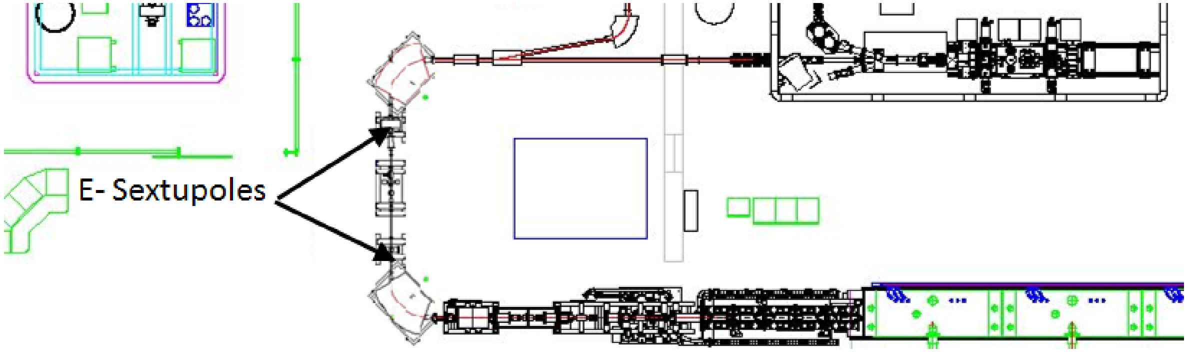
Electrostatic Sextupoles for better Beam Overlap

- ✓ Mismatch factor shows that A/q difference of 1% would double the vertical emittance without sextupole correction
- ✓ Two sextupoles are required to correct aberrations and maximize the overlap of the two beams

$$\chi_{\pm} = \chi_0 (1 + \delta_{\chi})$$



- ➢ Two electrostatic sextupoles in the LEBT to maximize overlap and provide high transmission of both beams



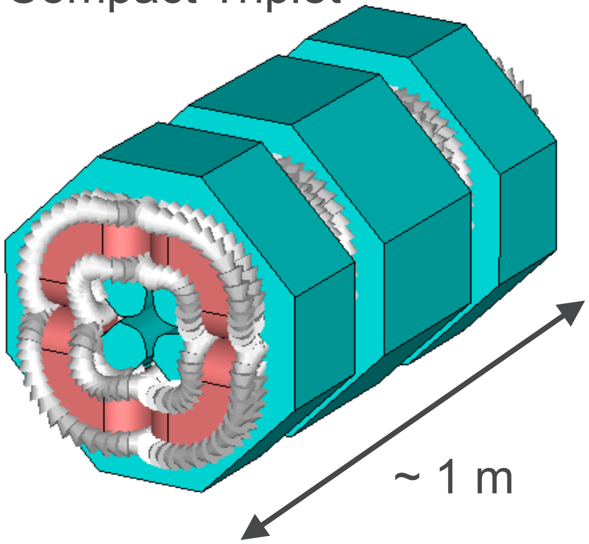
Compact Triplet Specs & Preliminary Design

Compact Triplet Specs

Table 3: Specifications for the compact quadrupole triplet

Parameter	Value	Unit
Effective Length of First & Last lenses	20	cm
Effective Length of Middle lens	40	cm
Spacing between Lenses	10	cm
Triplet Physical Length	1	m
Pole-tip radius	4	cm
Peak Field at Pole-tip	0.5	T

Possible Design of
A Compact Triplet



Kicker Magnet - Design Requirements

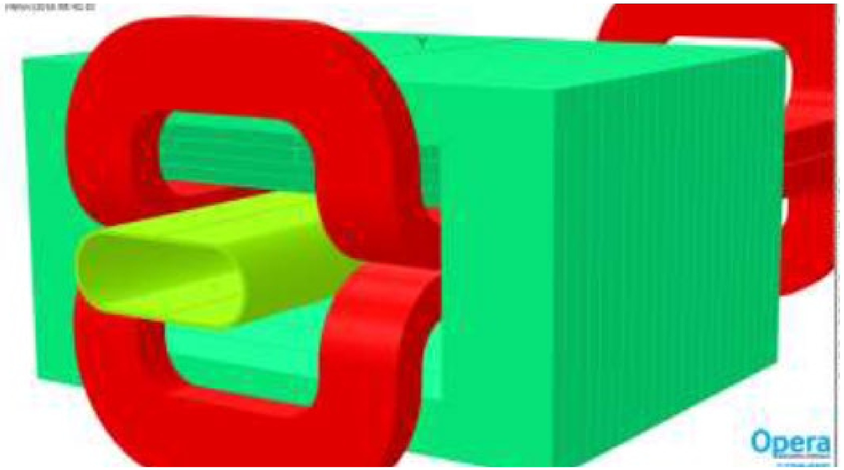
- Main Requirements
- ✓ Should be able to kick a 6.5 MeV/u q/A=1/7 beam by at least 5^o → 0.5 T
- ✓ Rise and fall time of ~ 1 ms or less with 30 Hz rep-rate
- ✓ Two operation modes: 1) 3% ON, 97% OFF and vice versa → ~ DC

- Main Consequences
- ✓ For B ~ 0.5 Tesla, It can't be a Ferrite, It has to be Iron/Steel
- ✓ Very thin laminations required to reduce core losses from eddy currents
- ✓ Power supply should operate in pulsed and DC modes

- Magnets with Similar Parameters: Very Few …
- ✓ LANL – IPF kicker (4 ms rise/fall, didn't work well, significant losses …)
- ✓ RAL – ISIS kicker (12 ms rise/fall, successful, built by Danfysik …)
- ✓ …

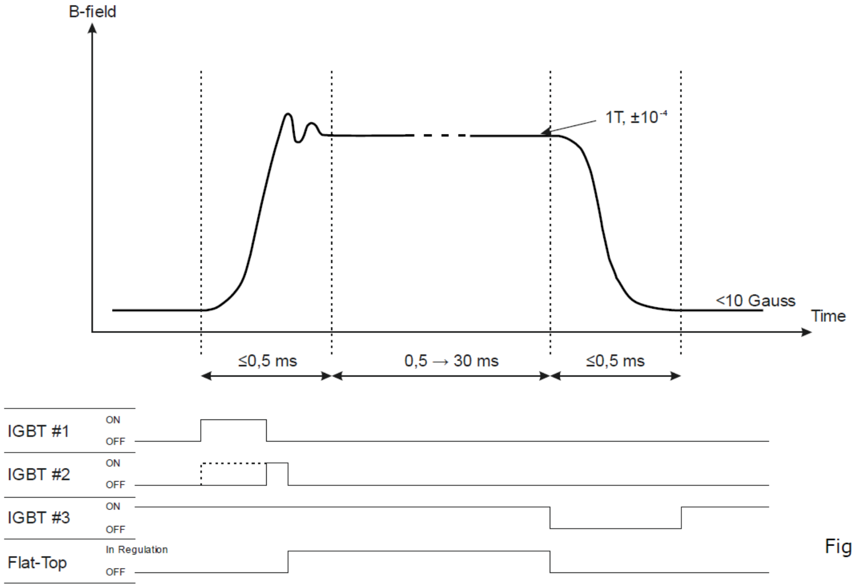
Preliminary Kicker Design - Danfysik

Magnet Design



- Curved Magnet Recommended
- 3 Designs → Racetrack is Best
- 2 Materials → NO20 is best
- Yoke Cooling Required
- Thin steel vacuum chamber recommended
- …

Power Supply Design



Fig

- 3-Stage PS for 0.5 ms and 10^{-4}
- 1st: 0 to 99% Imax in 0.3 ms with 0.5 % error
- 2nd: 99% to 100% in 0.2 ms with 10^{-4} error & transition to flat-top
- 3rd: Low voltage current regulated

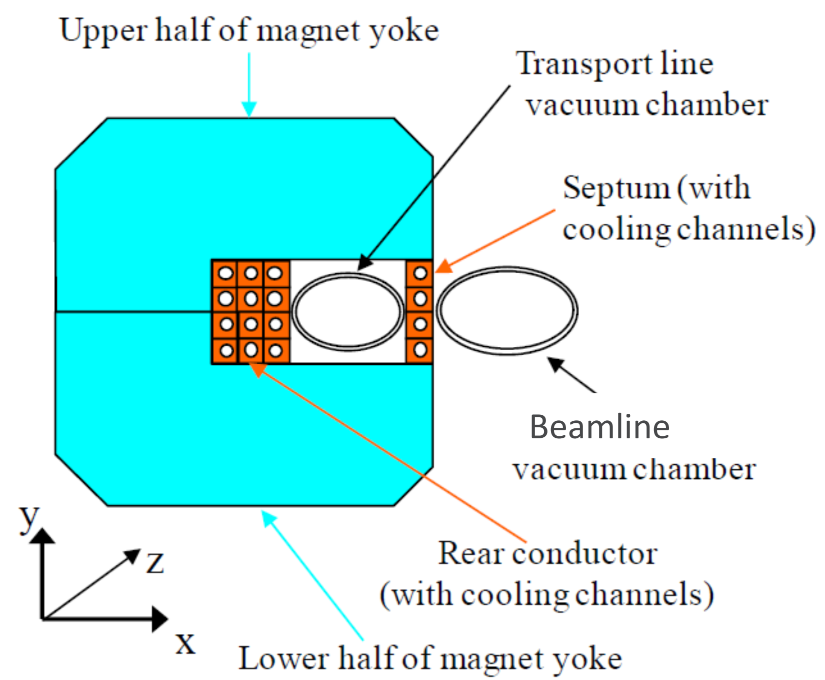
Septum Magnet Specs & Preliminary Design

DC Septum Specs

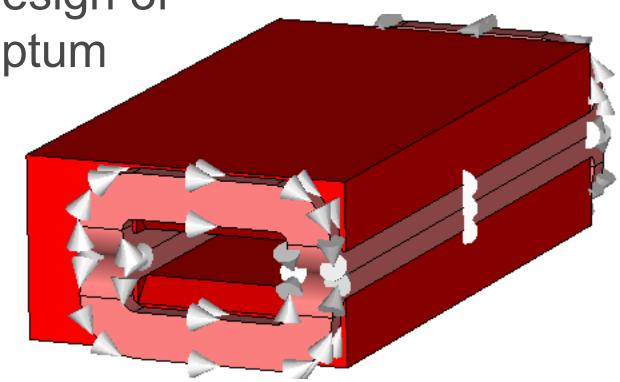
Table 1: Specifications for the septum magnet

Parameter	Value	Unit
Deflection Angle	7.5	deg
Peak Magnetic Field	0.75	T
Bend Radius	3.5	m
Septum Thickness	2	cm
Magnet Full Gap	4	cm
Maximum Physical Length	60	cm
Effective Field Length	46	cm
Width of good field area	7	cm
Field Uniformity over Good Field Area	$< 10^{-3}$	
Max. field seen by non-deflected beam	< 5	Gauss

Principle of A Septum



Possible Design of A Thick Septum



Operational Considerations

Operational Considerations

- Constraints: Two experiments → Two sets of requirements
  - Beam species with compatible A/q (Minimum ~ 4, range: ~ 2%)
  - Beam energies: Area-II beam energy may affect ATLAS beam energy
  - Equipment: Experimental areas must be appropriately equipped

- Flexibility:
  - For every stable beam, there is plenty of compatible CARIBU beams
  - For every CARIBU beam, the charge state from EBIS could be selected (similar intensity) to overlap with the closest stable beam
  - Beam energies: If Area-II energy is fixed, ATLAS section can be set to independently accelerate / decelerate the second beam

- PAC Approval & Scheduling Process
  - Approval by PAC should consider multi-user capability → long runs
  - Simultaneous experiments will be scheduled based on compatibility & approved priority

Operational Considerations: Beam Tuning

- Two Beam Tuning: One from ECR & One from CARIBU-EBIS
  - CARIBU beams are being tuned using a guide beam with similar A/q
  - Stable beam will be used for tuning all lines, because it has a close A/q
  - CARIBU beam will be used to verify the tune to the designated target

- Possible issues / restrictions:
  - Beam stripping can only take place after beam separation
  - Two sources operating, less time for beam development
  - Two beams on targets, limited accessibility to other areas

- Possible solutions: Infrastructure updates
  - Better instrumentation: Diagnostics & interloks
  - Remote control and accessibility
  - Automation

Recent Progress & Future Steps …

- Recent progress …
  - The proposed upgrade has been approved in principle by DOE
  - Project expected to start next year following a review process

- Currently working on / considering …
  - Add chopper to ECR-II line to better define the stable beam profile before combining with CARIBU beam.
  - Weak beam diagnostics and optimized tuning for CARIBU beams
  - New configuration of beam diagnostics after the Booster for MUU
  - Study enhanced Area-II energy flexibility from a single cavity cryostat
  - Ensure compatibility with potential future upgrades …

Summary

- The proposed ATLAS Multi-User Upgrade will significantly 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 new opportunities for other applications
- We have developed a design concept and technical solutions for the proposed multi-user upgrade
- Feasibility of most critical components of the upgrade has been proven
- The proposed upgrade has been approved and expected to start next year …