Reacceleration of Rare Isotope Beams at Heavy-Ion Fragmentation Facilities

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Facility for Rare Isotope Beams
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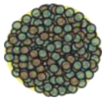
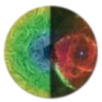
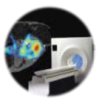
Nuclear Science Major Themes for Reaccelerated Isotope Beams



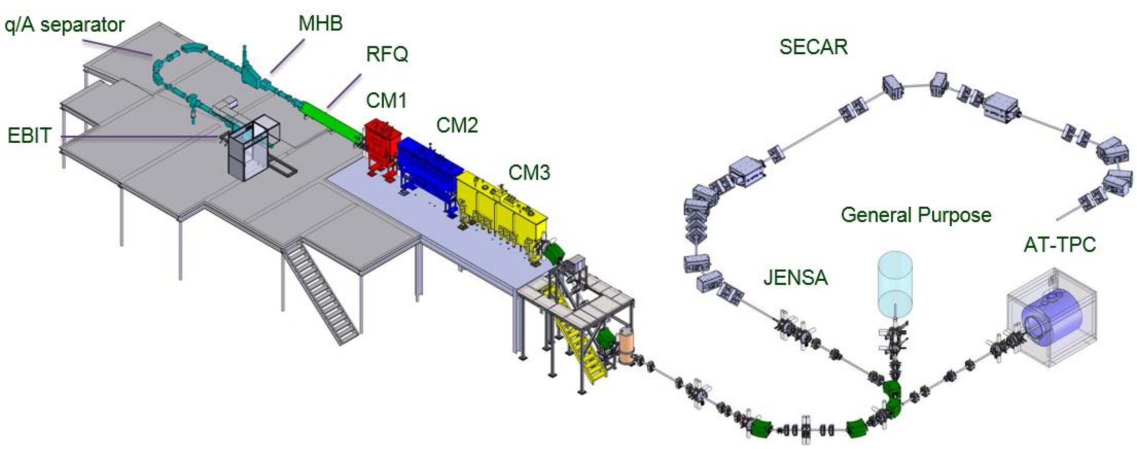
- Properties of nuclei via transfer reactions, Coulomb excitation for nuclear structure studies
  - Develop a predictive model of nuclei and their interactions
  - Many-body quantum problem



- Astrophysical processes via low-enery reactions
  - Origin of the elements in the cosmos
  - Explosive environments: novae, supernovae, X-ray bursts …



- Applications via variable beam energies
  - Bio-medicine, material sciences



Reaccelerator ReA at National Superconducting Cyclotron Laboratory (NSCL)

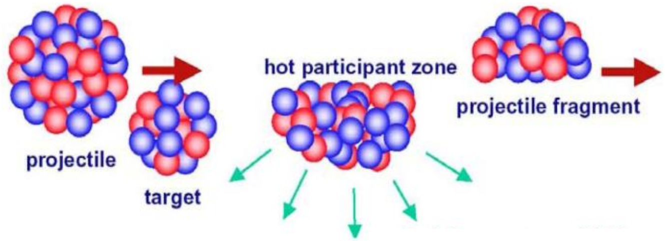
- 2010: RFQ commissioning started
- 2011: CM1 first beam acceleration
- 2011: CM2 first beam acceleration
- 2012: first 1+→n+acceleration
- 2013: First experimental hall beam line
- 2013: First rare isotope experiment
- 2014: EBIT coil fails
- 2014: ReA3 Beam Lines complete
- 2014: EBIT magnet returns
- 2015: CM3 full energy acceleration
- 2015: ReA RIB program starts

U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

Need of Rare Isotope Beams from keV to GeV

Heavy Ion Fragmentation Facilities can Deliver Beams in a Wide Energy Range

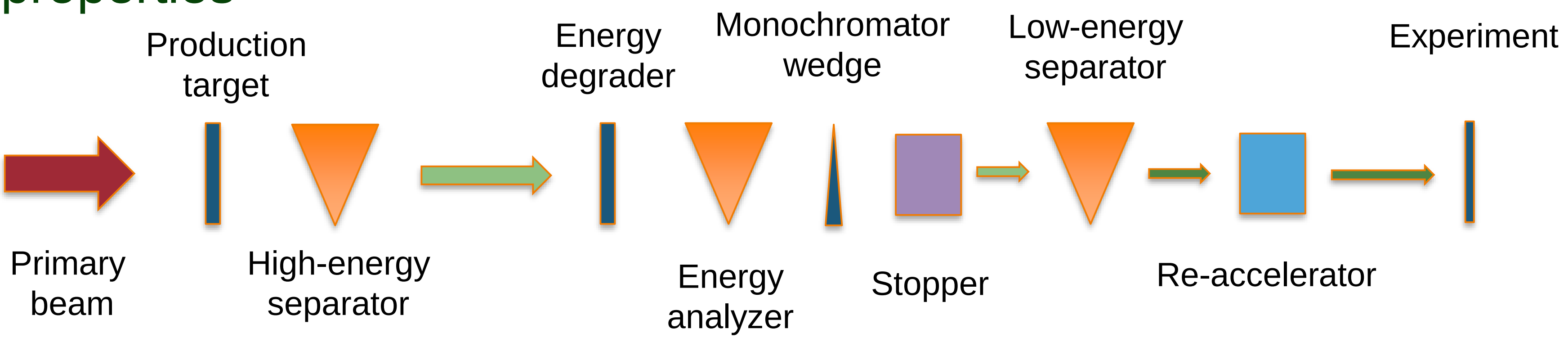
- Heavy-ion fragmentation facilities are designed to offer high energy beams: the primary beam velocity is maintained



- Heavy-ion fragmentation is extremely fast and chemically independent
  - Virtually not lifetime limited
- Beam properties provided by these facilities are governed by reaction properties and separator characteristics
- Beam emittance can be improved to a certain extent in the separator at the cost of beam intensity
- Beam energy can be reduced by using degraders down to limits given by energy and angular straggling

A Solution is: Stopping and Reacceleration

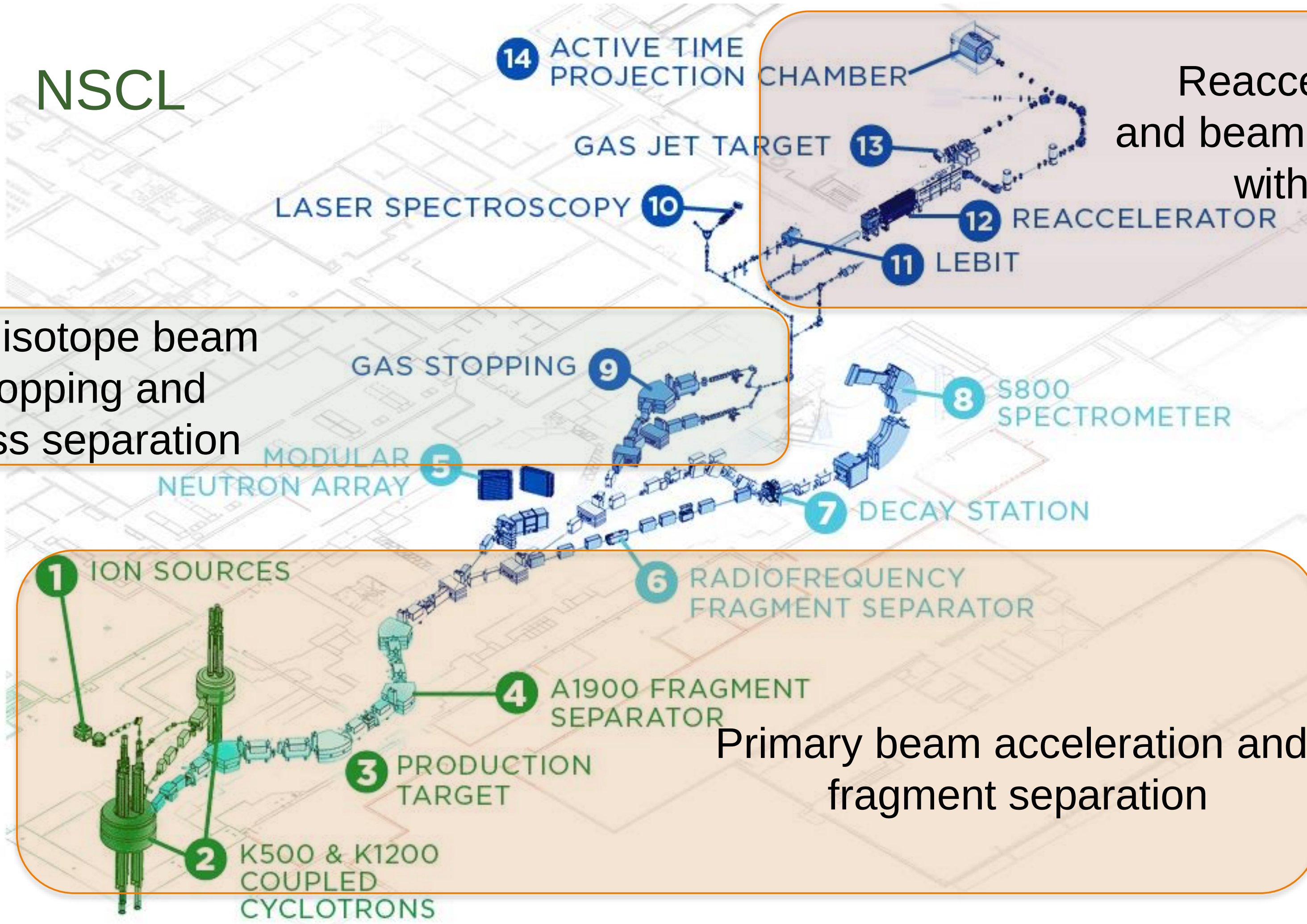
- Stopping and reacceleration extends research capabilities of heavy-ion fragmentation facilities to much lower energies, whilst improving beam properties



- Reacceleration of beams is a complex multi-step process
  - Needs careful optimization of each of them to provide high efficiency
- Two-step separation grants extra beam purity
- This technique is presently employed at NSCL and could be implemented at other heavy-ion fragmentation facilities as well

NSCL First and Only Facility to Stop and Reaccelerate Rare Isotope Beams Produced by Heavy-Ion Fragmentation

NSCL



Reacceleration and beam distribution with ReA

Rare isotope beam stopping and mass separation

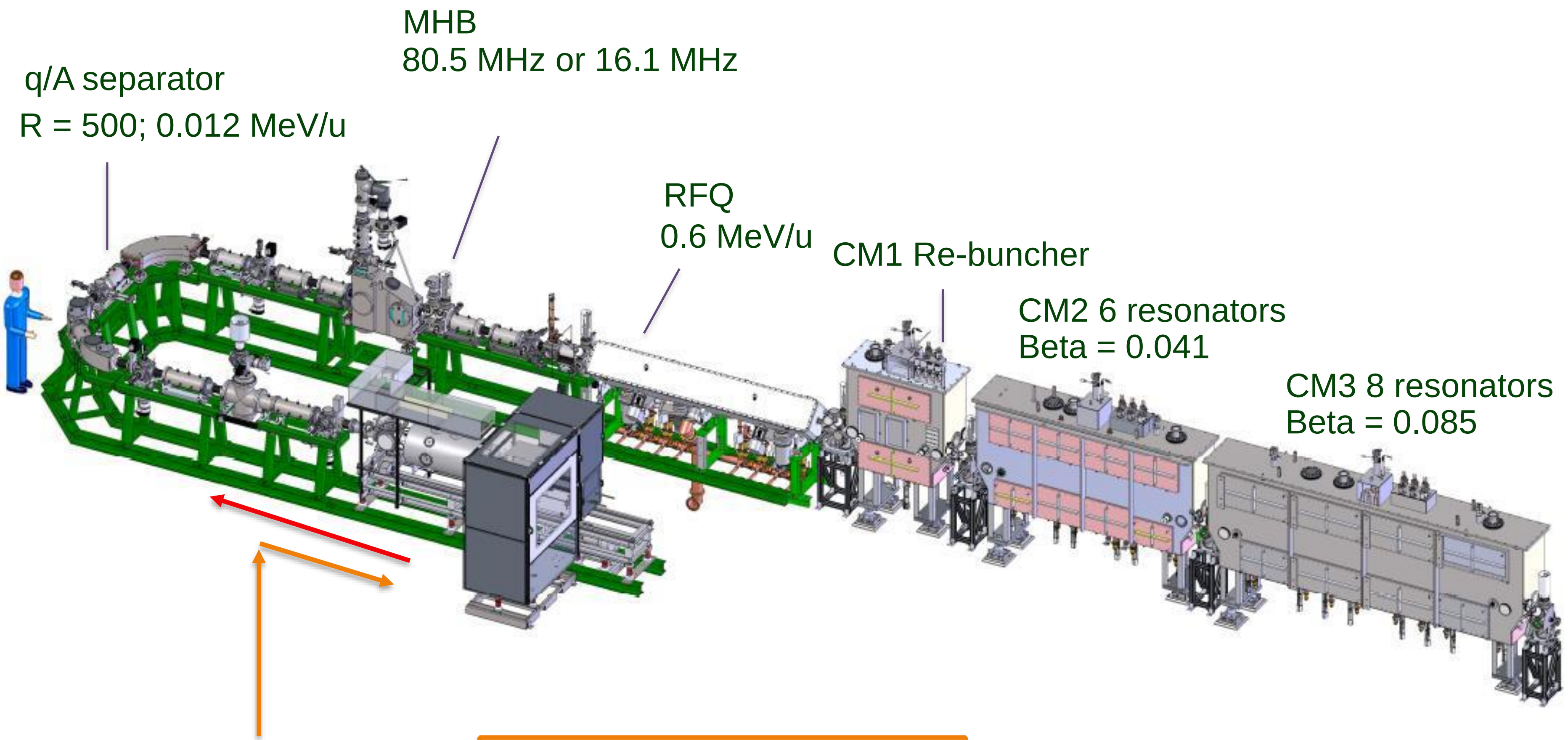
Primary beam acceleration and fragment separation

ReA Rare Isotope Beams Delivered for Successful Experiments

Isotope	Energy (MeV/u)	Beam rate on target (pps)	Subject
^{22}Mg	5.0	1.2E3	Astrophysics: ^{22}Mg(α,p)^{25}Al
^{34}Ar	1.63 - 1.71	5.1E3	Astrophysics: ^{37}K(p,α)^{34}Ar, etc.
^{37}K	4.6	5.7E3	Astrophysics: ^{34}Ar(α,p)^{37}K
^{45}K	4.65	7.8E4	Fusion: Fusion-Fission ^{45,49}K + ^{181}Ta
^{46}Ar	4.65	1.0E3	Nuclear Structure: IAS ^{46}Ar + p
^{46}K	4.14 - 4.68	1.0E4	Fusion: ^{46}K + ^{208}Pb
^{47}K	2.66 - 2.96; 4.6	1.6E4	Nuclear Structure: ^{47}K + p (^{48}Ca) Astrophysics: Fusion ^{47}K + ^{28}Si
^{75}Ga	4.0	1.8E3	Astrophysics: neutrino wind, ^{75}Ga(α,n)
^{72}Se	4.0	1.6E3	Nuclear Structure: Coulomb excitation

- Complete available ReA beam list with 121 isotopes can be found at: http://www.nscl.msu.edu/users/beams.html

Example: ^{37}K Reaccelerated Beam
Using the Re-accelerator ReA3



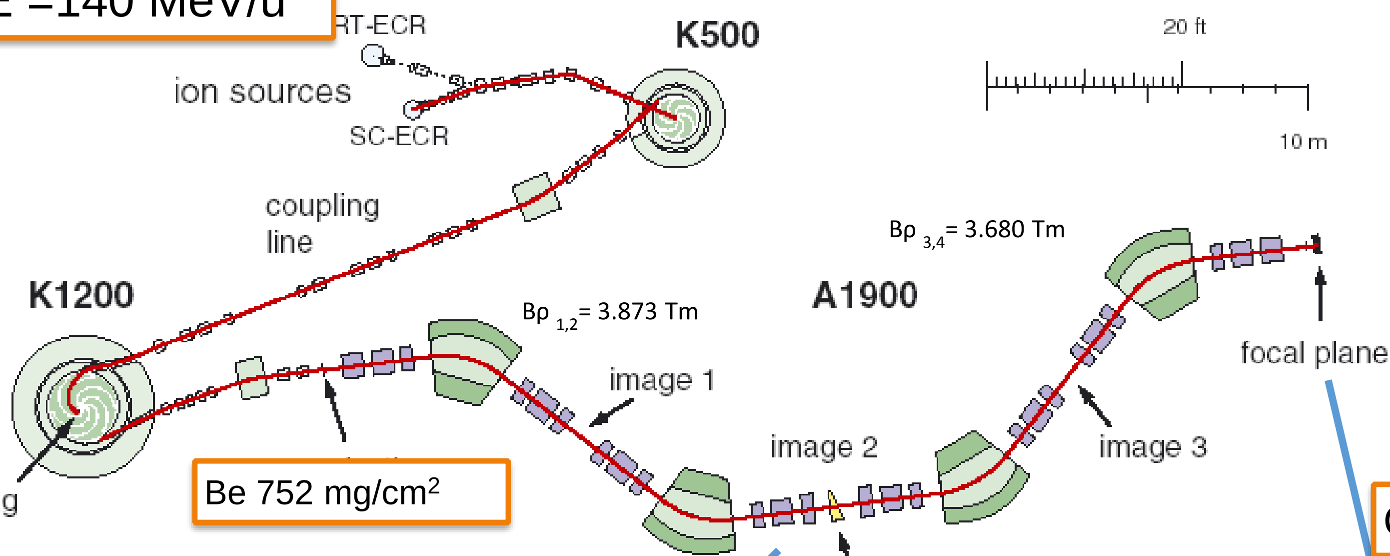
0.3 MeV/u < E < 6 MeV/u
E = 12 x q/A for q/A ≤ 4

Beam on target: 5.7E3 pps

ReA3: A.C.C. Villari et al., IPAC 2016 – IPAC 2016, p.1287

Rare Isotope Production via Projectile Fragmentation

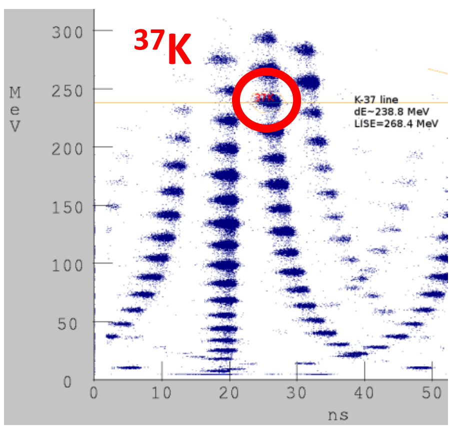
^{40}Ca; E =140 MeV/u



Be 752 mg/cm²

Clean of mass 37

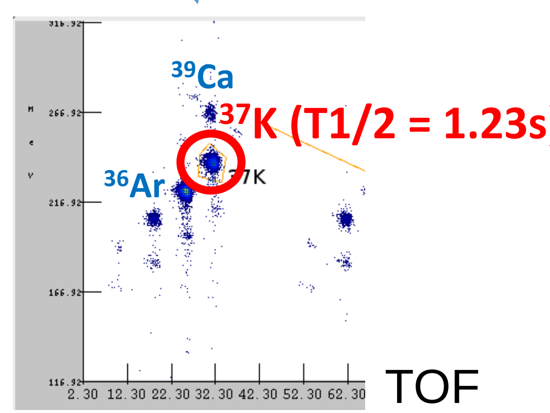
Wedge Al 240 mg/cm²



DE

TOF

Beam: 9.3E6 pps

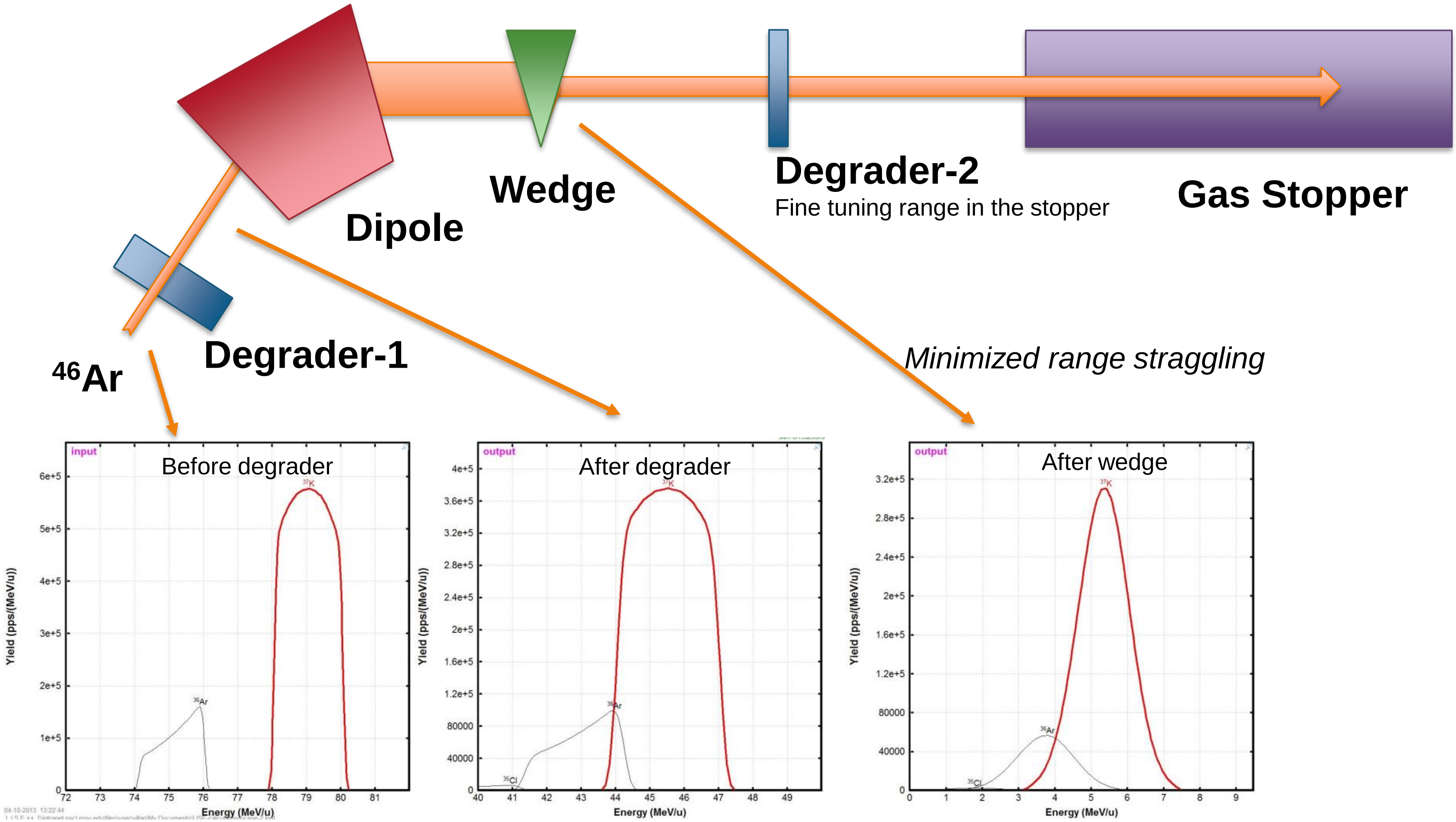


DE

TOF

Degrade Energy Using Monochromator Technique

Momentum Compression Reduces Range Straggling

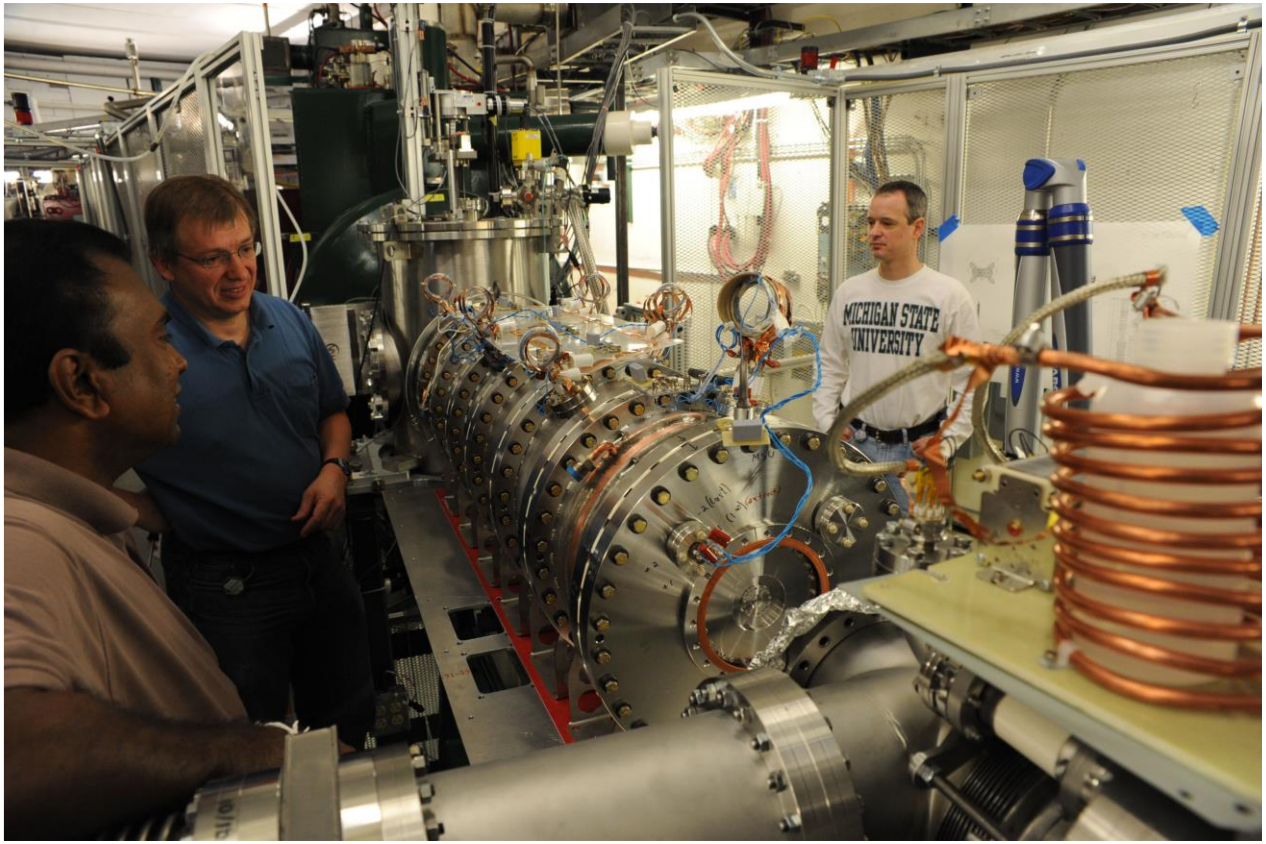


Energy distribution

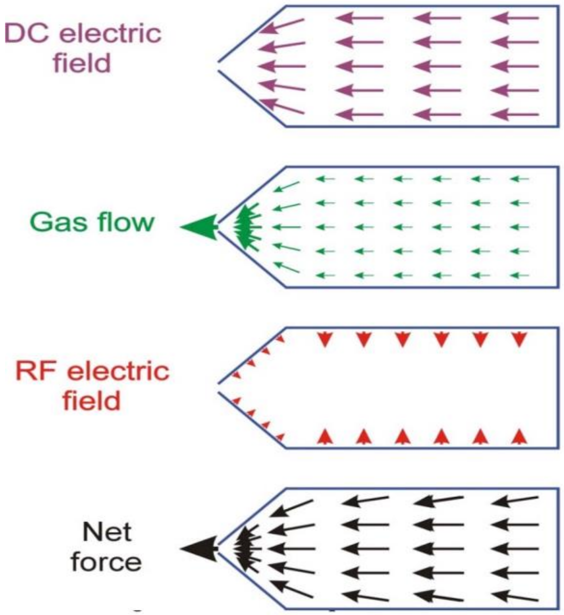
The method: H. Geissel, et al., NIM A282 (1989) 247

Stop Beam Using Linear Gas Stopper

Linear gas stopper operated at room temperature



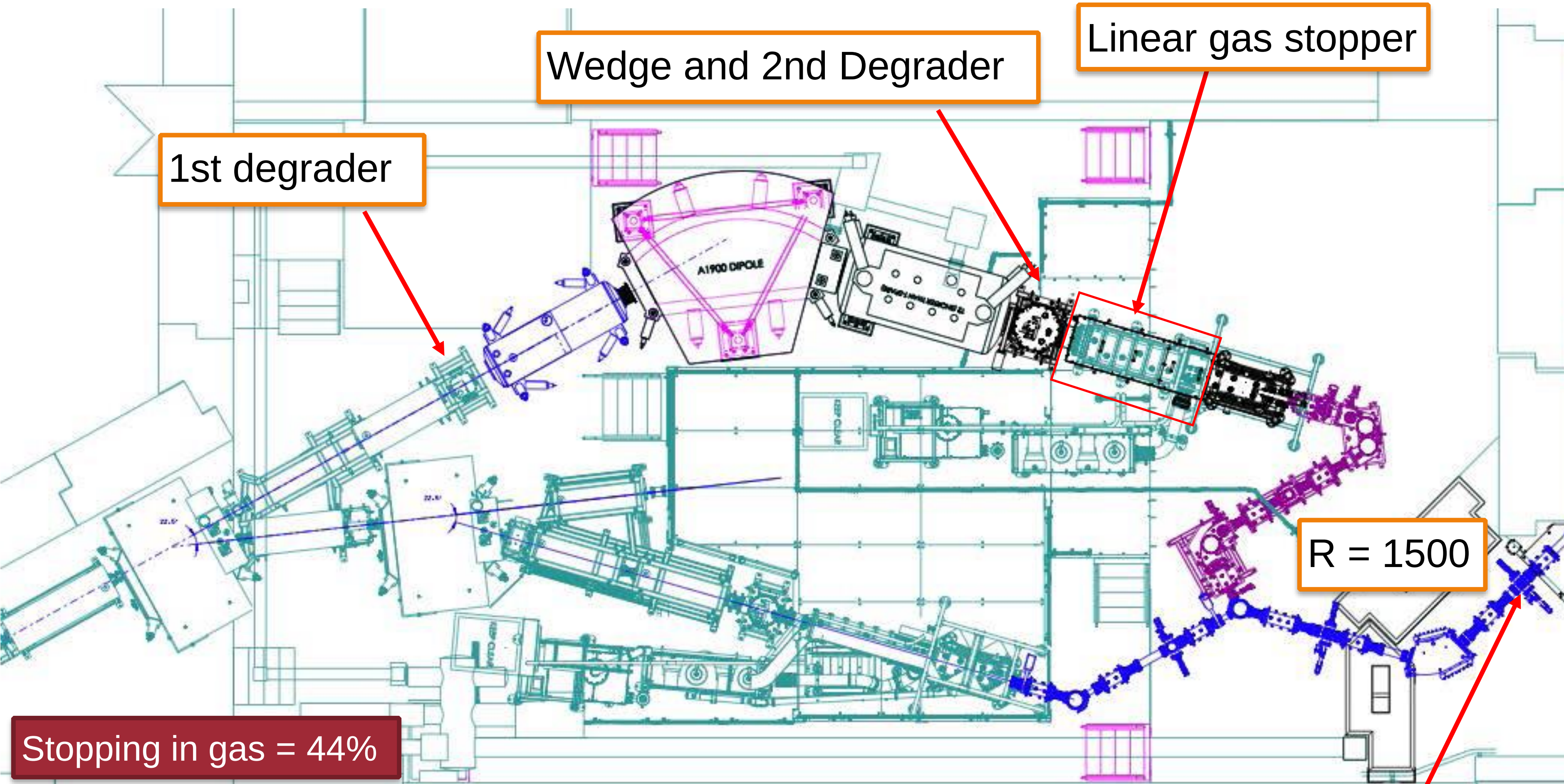
Gas Stopper built by ANL



Courtesy Guy Savard, Chandana Sumithrarachchi

Chandana Sumithrarachchi talk, this session

Stopping, Extracting, and Mass Separation



Stopping in gas = 44%

Extracting from gas stopper = 8%

Transport / separation = 80%

Beam OUT: 2.6E5 pps

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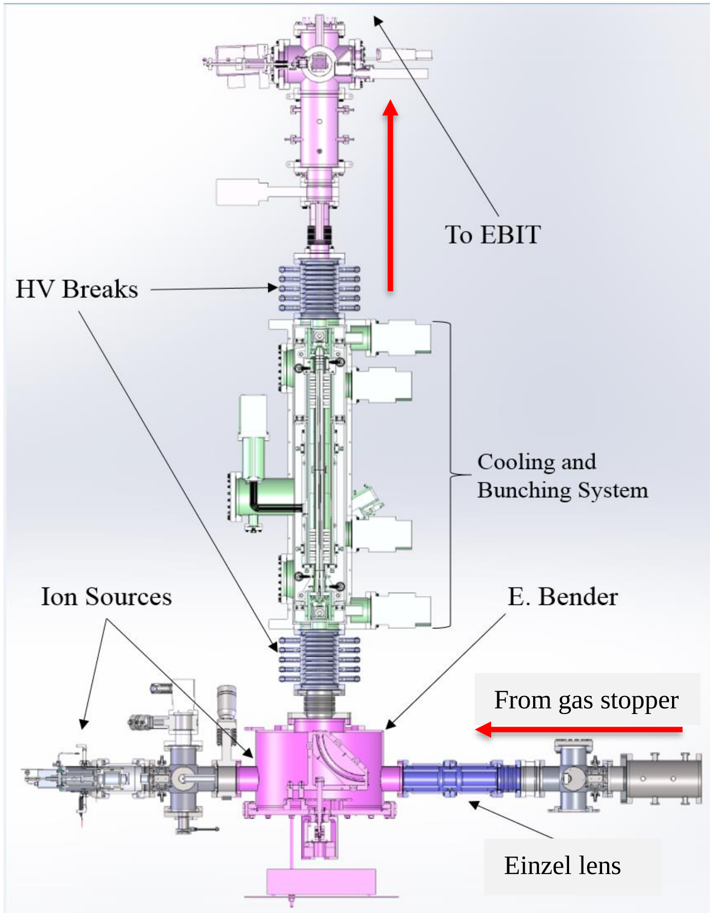
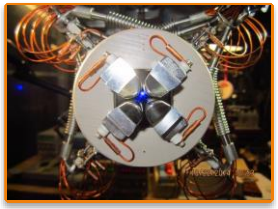
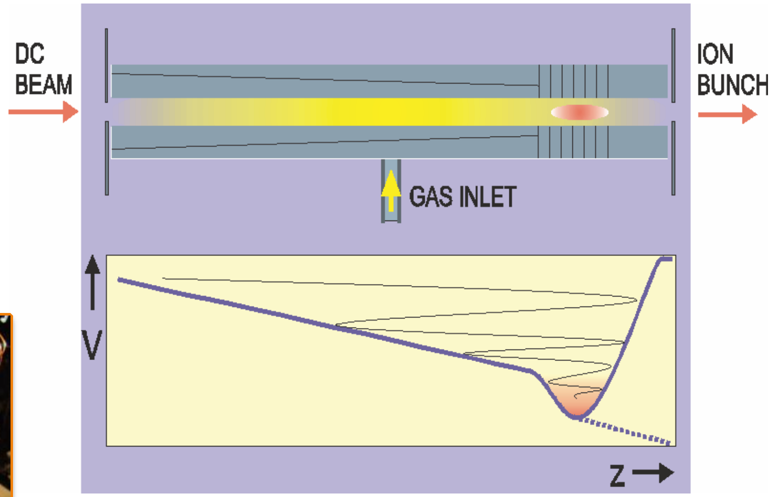
Cooler-Buncher Prepares Injection Into Electron Beam Ion Trap





Bunching the beam

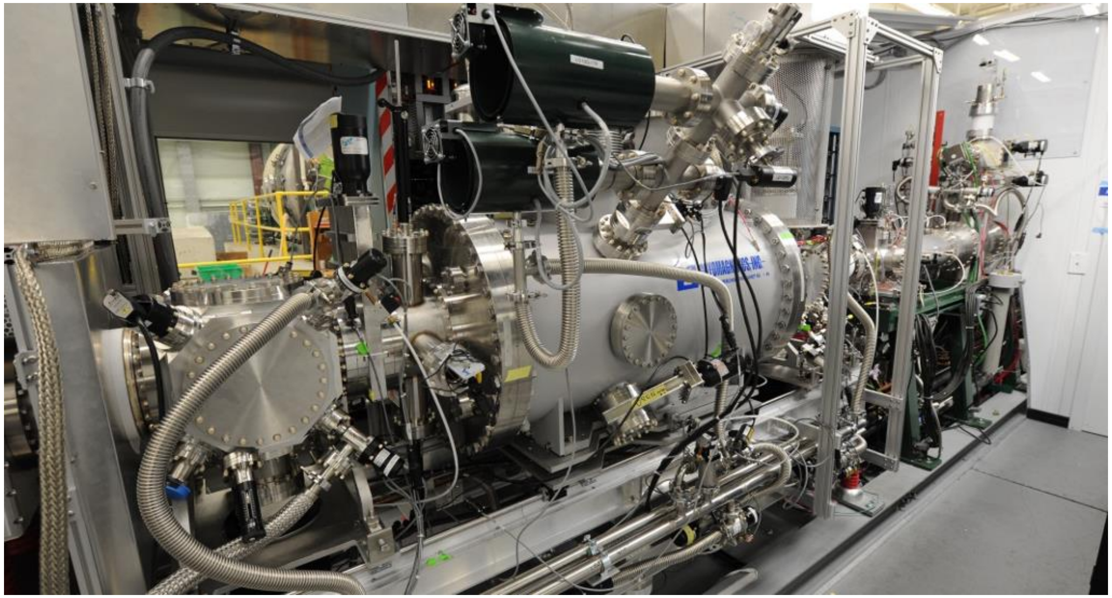


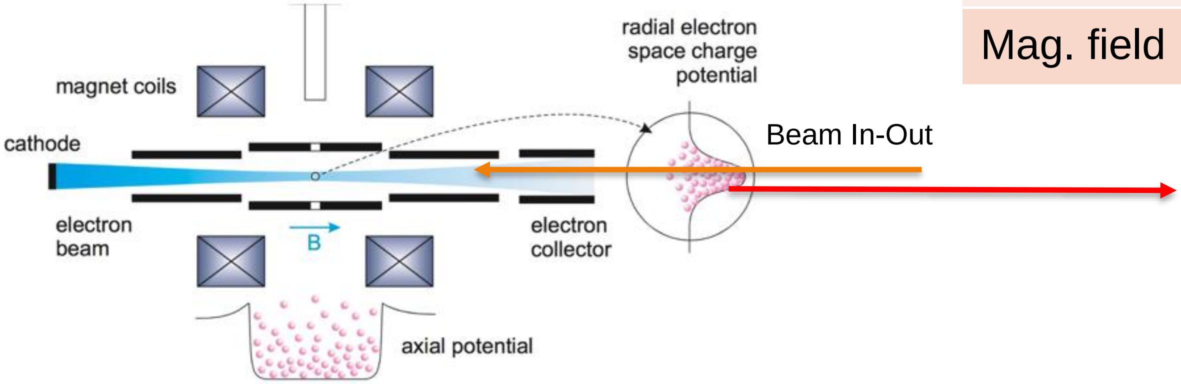
Transport and injection efficiency = 50%

Cooling and bunching efficiency > 90%

Beam OUT: 1.2E5 pps

Electron Beam Ion Trap Charge Breeder



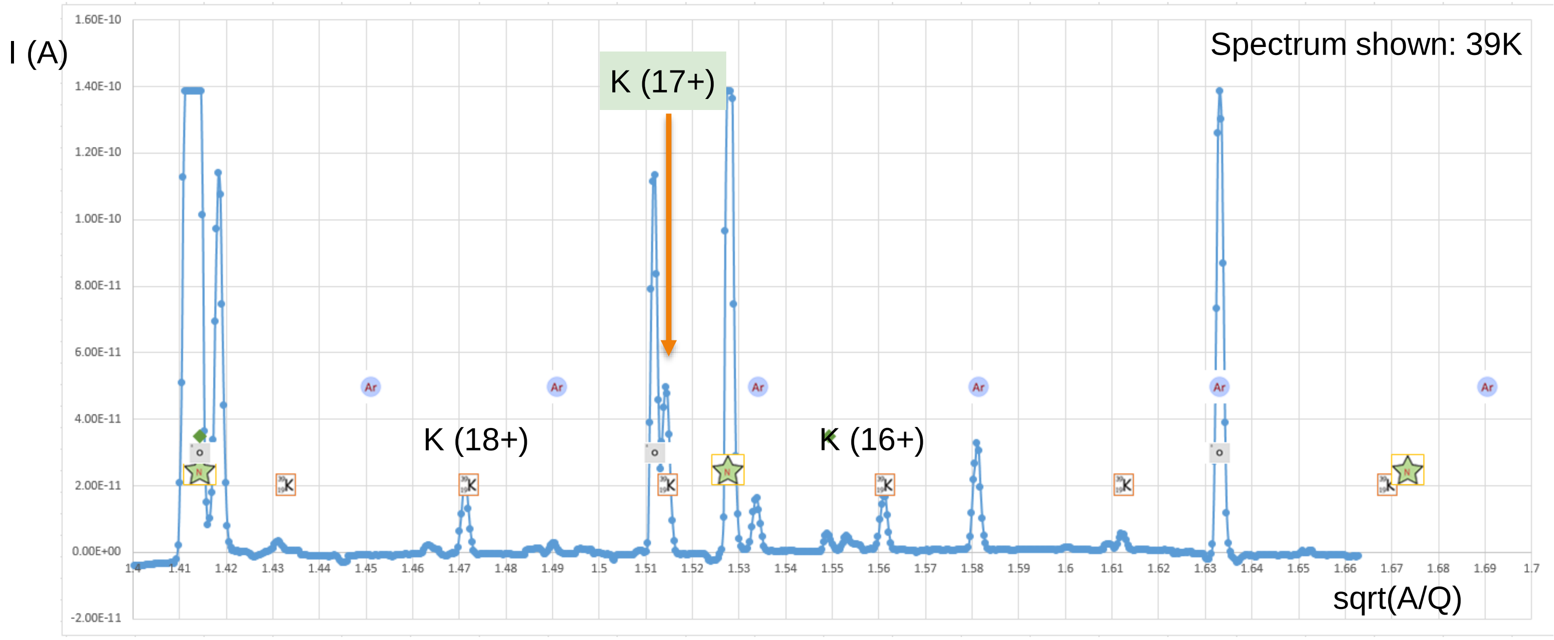


Specification	Value
Ejection energy	12 keV/n
Ch. State efficiency	10-25%
Ejection pulse length	<125 ms
E-beam current	< 400mA
Mag. field	4 T

A. Lapierre et al., Phys. Rev. Acc. Beams 21, 053401 (2018)

A/Q Spectrum of Ions Extracted from EBIS

- Charge state is chosen depending on final energy and contaminants
- EBIT is tuned to maximize the charge state needed for the run, in this case K (17+)



On-line run, ^{37}K

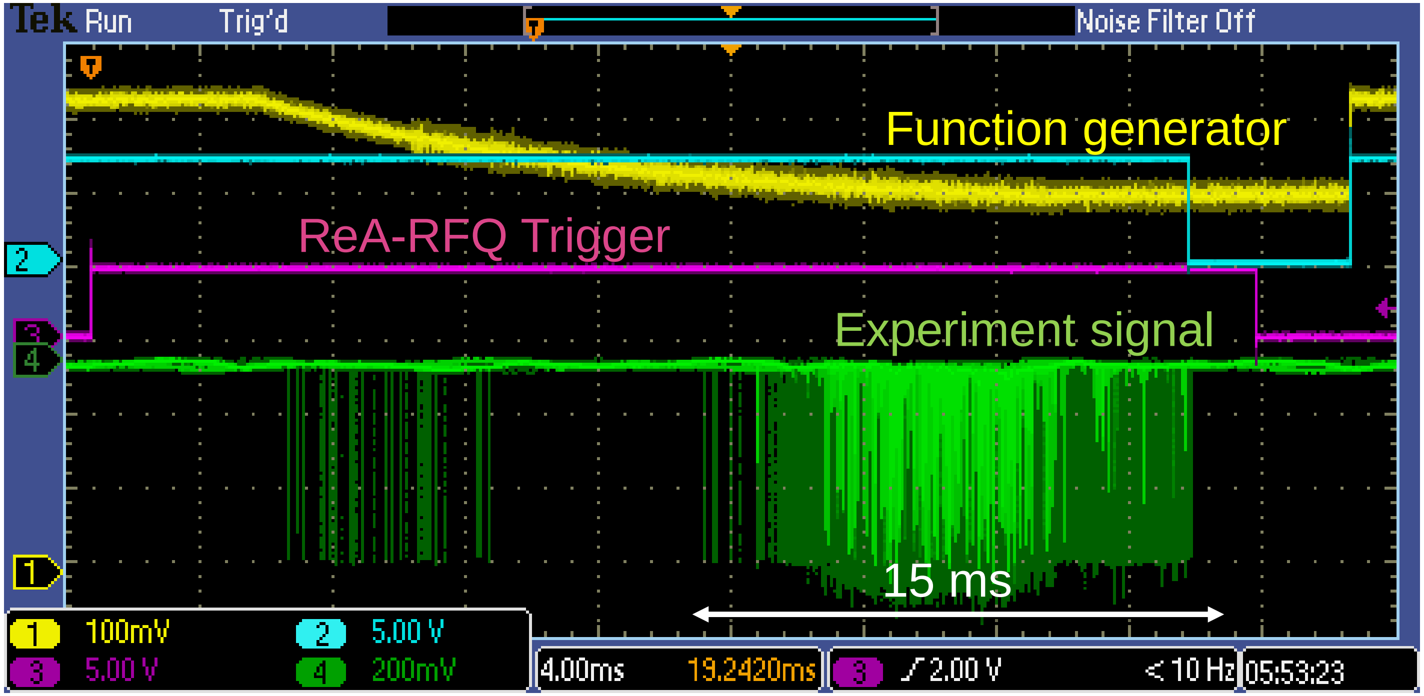
Injection/extraction = 64%

Breeding to 17+ = 15%

Beam OUT: 1.1E4 pps

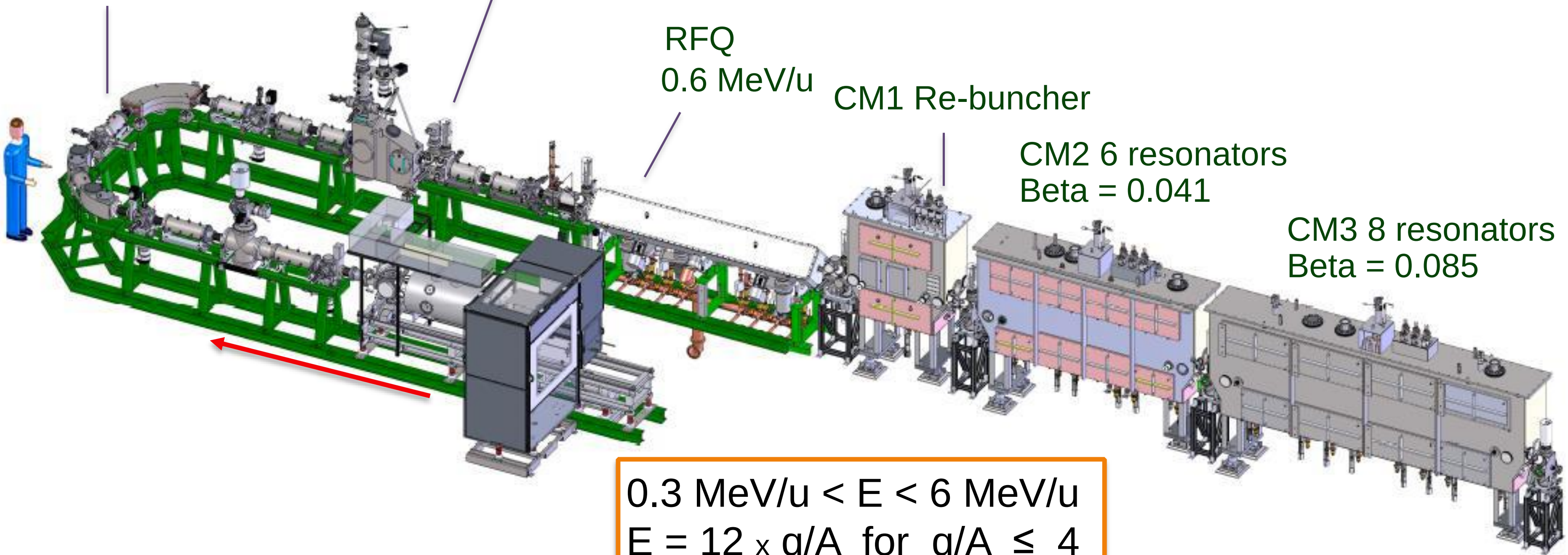
Time Structure of Beam can be Tailored to Experiment Needs

Stretched Extracted Beam From Electron Beam Ion Trap



- Function generator is used to elongate EBIT extraction pulse
- Tuning is done using experiment detector and suppressing pile-ups

Example: ^{37}K Reaccelerated Beam
Using the Re-accelerator ReA3



0.3 MeV/u < E < 6 MeV/u
E = 12 x q/A for q/A ≤ 4

Acceleration/transport efficiency = 50%

Beam on target: 5.7E3 pps

ReA3: A.C.C. Villari et al., IPAC 2016 – IPAC 2016, p.1287

Fast Method Available to "Blindly" Tune Rare Isotope Beams

- Use of Pilot Beams
  - Use a pilot beam for phasing the LINAC and transport to the experiment: at ReA, we use a Si detector in the end of the LINAC
  - Tune pilot beam with the same beta of the final beam and scale the gradients of all resonators and the magnetic rigidity of all optical elements to the rare isotope beam

- Example:
  - Pilot beam $^{40}Ar(18^{+})$ M/Q = 2.22 E=4.46 MeV/u
    Desired beam: $^{37}K(17^{+})$ M/Q = 2.18 E=4.46 MeV/u
    Scaling factor: 0.98

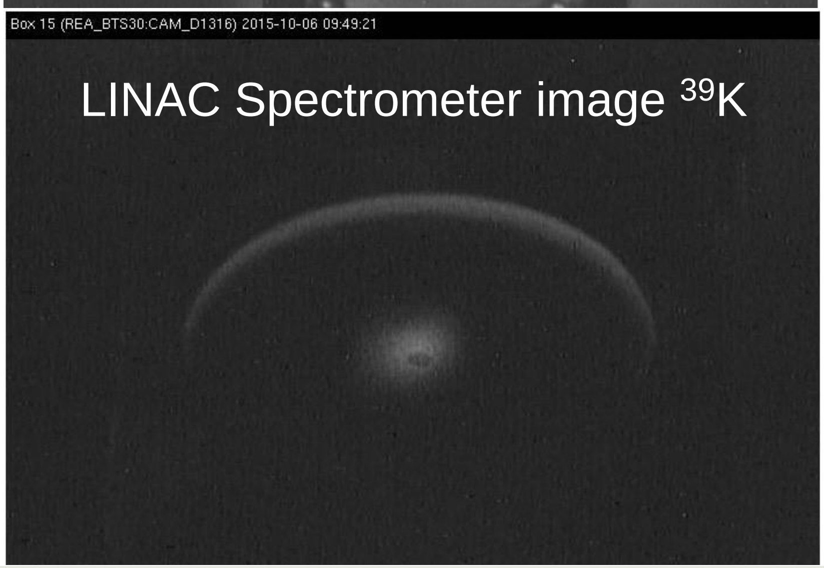
- Time needed to tune EBIT + LINAC + transport with pilot beam: 24 h

- Parallel tuning of A1900 and gas stopper: 16 h

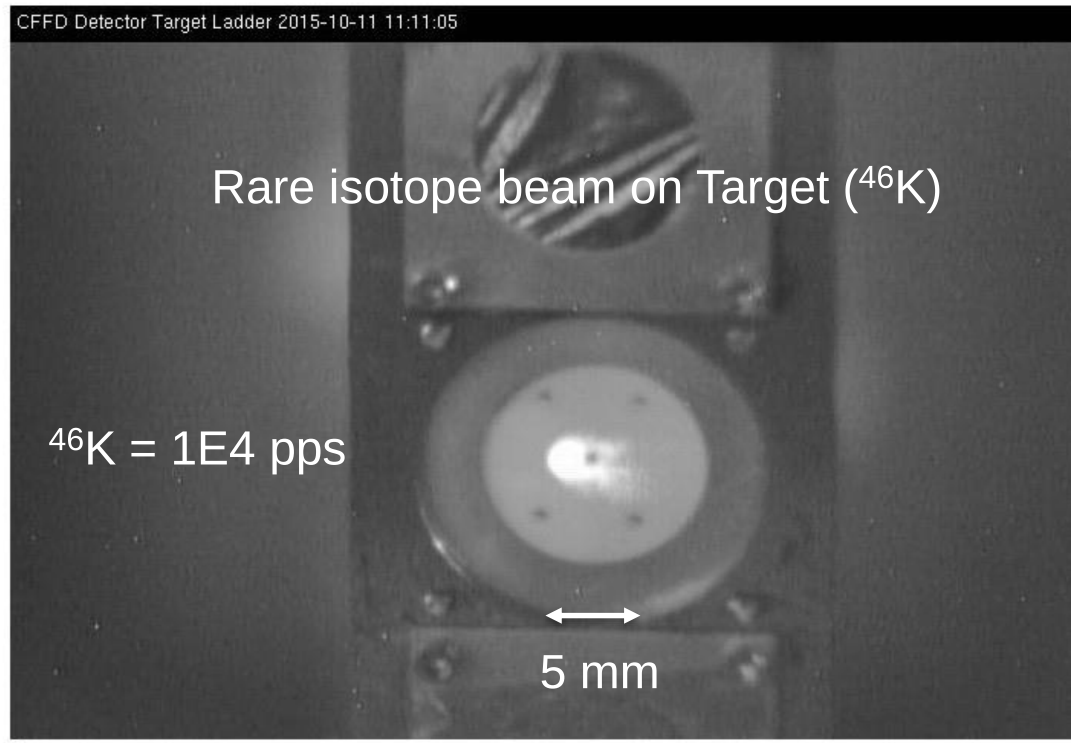
- Switch to final beam: 2 - 3 h

- Switching beams with up to 16% difference in beta was demonstrated

Example: ^{46}K Reaccelerated Beam
Pilot and Rare Isotope Beams on target



After scaling the whole LINAC and beam lines the beam is in position



E = 4.68 MeV/n; resolution = 0.5% (FWHM); accuracy = 0.5%
Beam size = 2 mm (FWHM); Divergence = 5 mrad (FWHM)

Overall Efficiency Ranges
Where are the bottle necks?

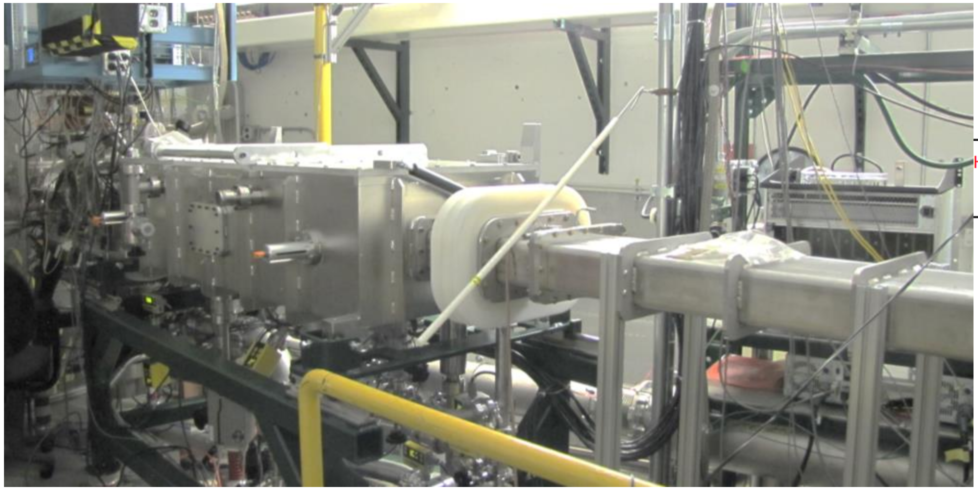
- Efficiencies of each step reveal where improvements are needed
- Stopping, extracting from gas and breeding are the most important

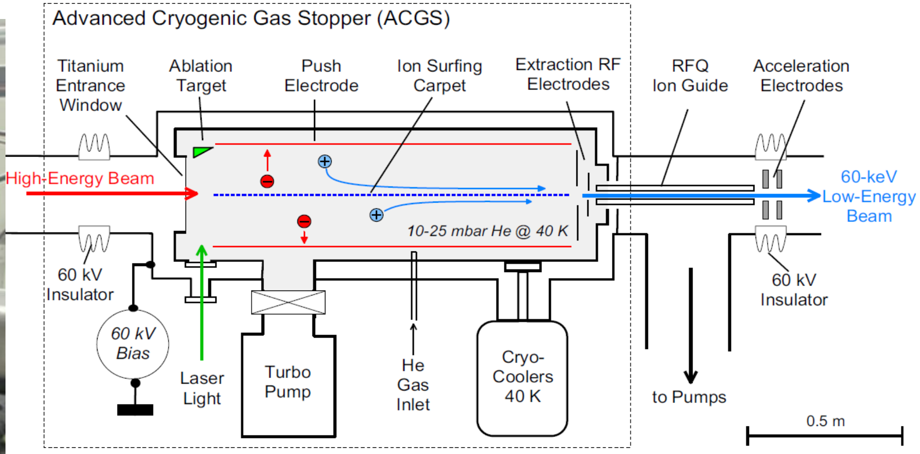
Step	Efficiency
Stop in gas	30-90%
Extract from gas, cool, and mass separate	1-20%
Transport and inject in Buncher	50-80%
Bunch and extract	90%
Inject/extract in charge breeder	40-70%
Charge breeding	10-30%
Accelerate, transport	40-60%
BEST today	1.6%

Improving the Stopping Facility - I
Advanced Cryogenic Gas Stopper (ACGS)

- Advanced Cryogenic Gas Stopper (ACGS) with improved performance compared to present linear stoppers:
  - Novel geometry reduces space charge effects (>10x higher beam rate capability expected)
  - MSU-developed ion surfing technique for fast extraction (2x faster)
  - Cryogenic operation provides cleaner beams (in-situ gas purification)

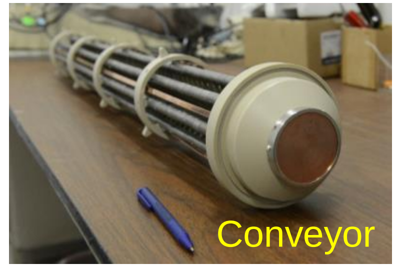
- ACGS Status
  - ACGS is installed and commissioning is on-going

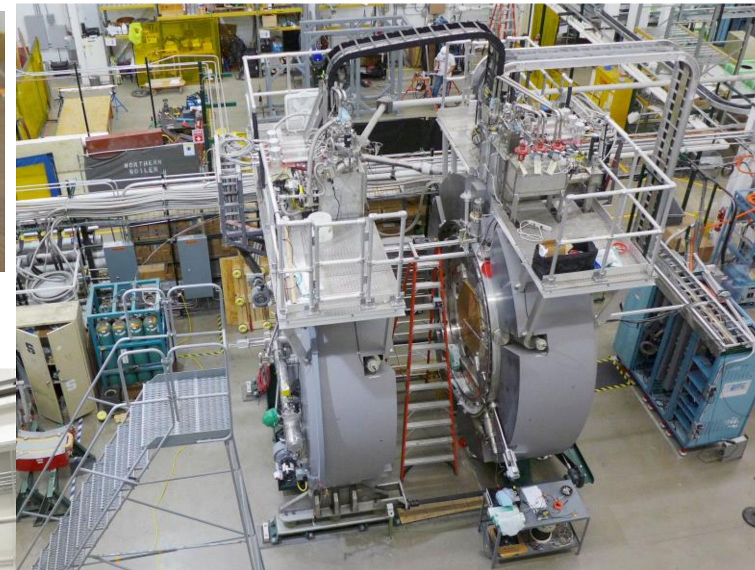


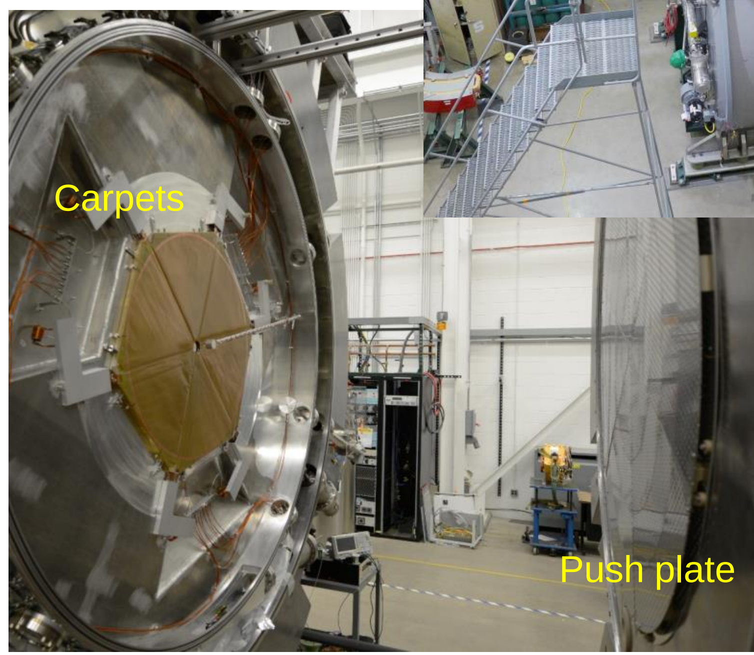


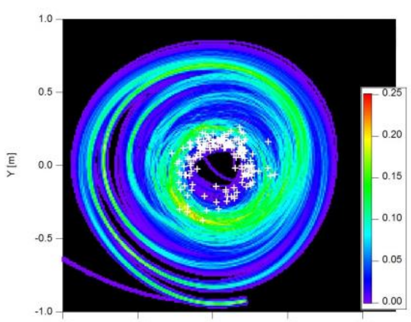
Improving the Stopping Facility – II
The Cycstopper

- **Cyclotron Stopper**
  - Higher efficiency for lighter ions due to accommodation of long stopping paths
  - Large volume, reducing space charge effects
  - Cryogenic operation
- **Status**
  - Magnet construction complete and energized to full field.
  - Ion extraction systems and carpets tested without field
  - Move to final location in N2/N3 to start soon









Stopping simulation in the Cycstopper

Stefan Schwarz, poster 90 / S. Schwarz et al. NIM B 376 (2016) 256

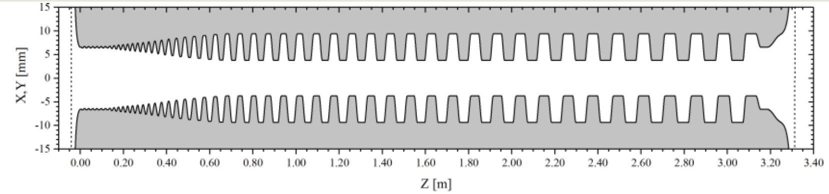
Improving the Charge Breeding Capability
New EBIT

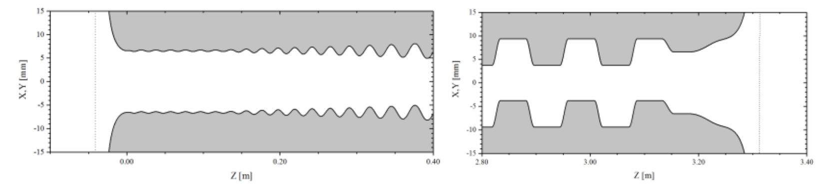
- Goal is to increase efficiency as well as beam rate capability:
  - Charge breeding capacity: > 10^{10} pps (100x better)
  - Faster charge breeding, allowing to achieve fully stripped for light ions
- The new source is the Brookhaven National Laboratory Test Electron Beam Ion Source (EBIS) transferred to NSCL
- The specifications are:
  - Total electron current: > 5 A (10x better)
  - Electron current density: > 250 A/cm^2
  - Magnetic Field: > 5 T
  - Length: 0.7 m
- The new EBIS is planned to be brought into operation in 2019

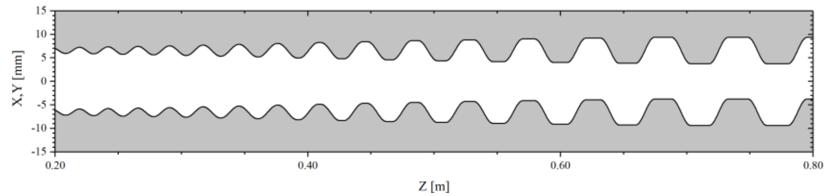
EBIS Magnet being tested at NSCL

Radio Frequency Quadrupole Upgrade
Overcoming present RFQ limitations

- Present RFQ limitations:
  - Maximum RF power limitation due to poor cooling
  - A/Q limited to 4 due to voltage limitation
  - Efficiency achieved in operation for 16.1MHz between 50-60%
- New rod design will
  - Improve reliability and maximum RF power by replacing brazing by electron welding
  - Improve acceleration efficiency to > 80% for 80.5 MHz and 16.1 MHz.
  - Bring maximum A/Q to 5
  - Have 100% duty cycle independently of the A/Q
- Rod fabrication underway at vendor
- Assembly and commissioning in January 2019



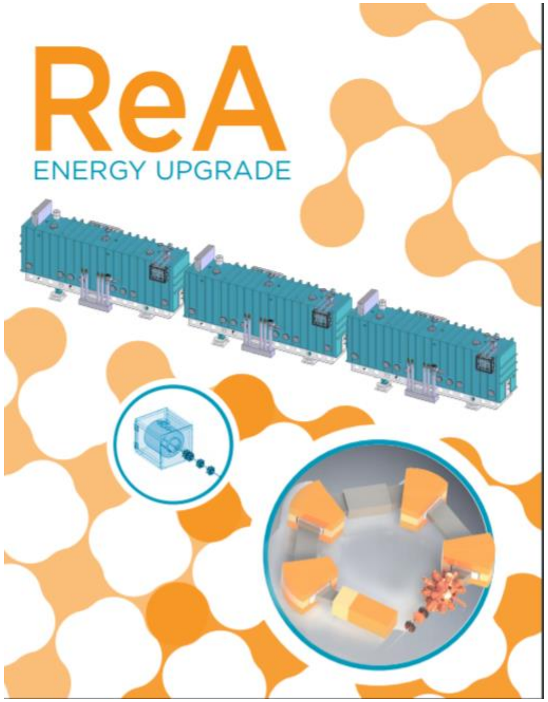


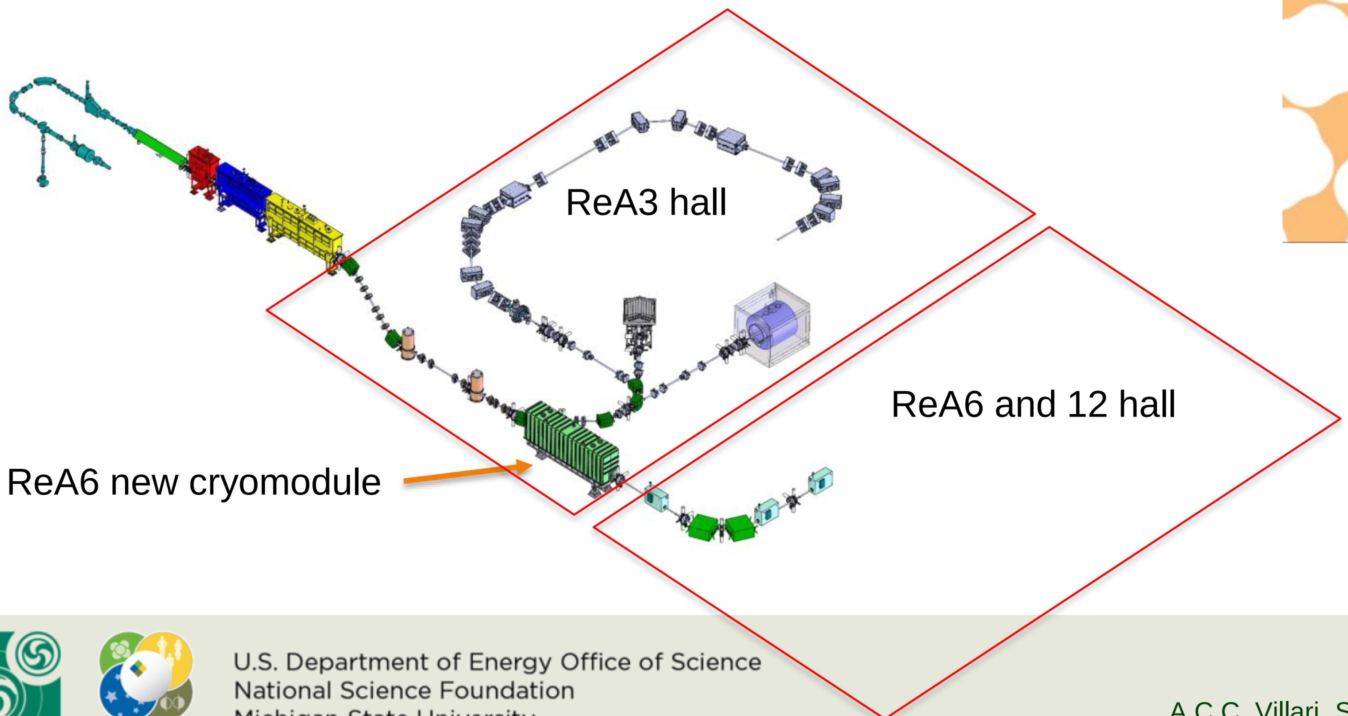


ReA Upgrades

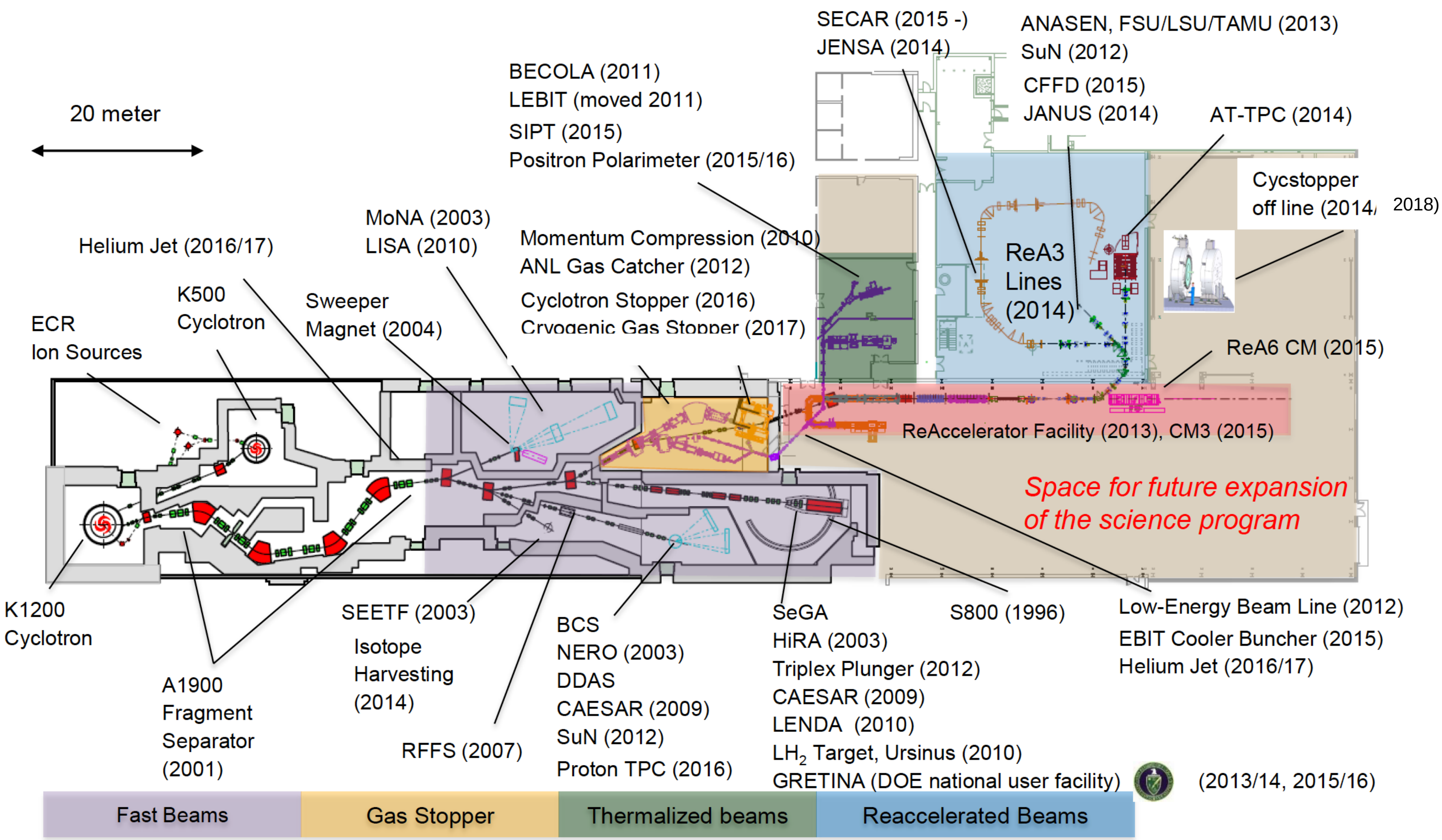
ReA6 Upgrade Ongoing, and ReA12 Upgrade Proposed

- The NSF recognized that ReA6 is a priority, NSCL is working on a minimal implementation
  - Prototype ReA6 cryomodule was completed in CY17 and can be installed after testing of FRIB cryomodules is complete
  - Four of the five magnets shown are available
- ReA12 upgrade (with more two cryomodules) is being planned - a white paper can be found at: http://2016.lecmeeting.org/Iwasaki_ReA_LECM16.pdf



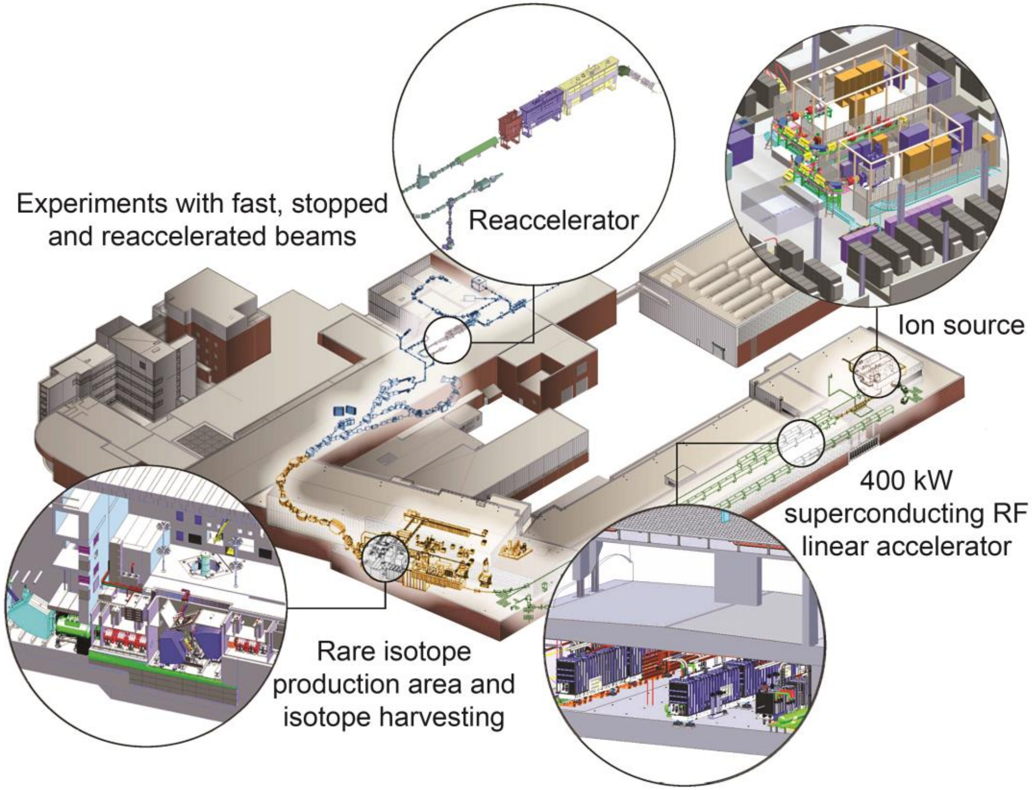


Moving Forward from Present NSCL to…



The Ultimate Improvement
The Facility for Rare Isotope Beams - FRIB

- Rare isotope production via in-flight technique with primary beams up to 400 kW, 200 MeV/u uranium
- Fast, stopped and re-accelerated beam capability
- Multiply rare beam intensities by more than 3 orders of magnitude
- Upgrade options
  - 400 MeV/u for uranium
  - ISOL production – multi-user capability
- Arriving in 2022



Summary

- Nuclear Science needs stopped and reaccelerated beams
- Heavy-ion fragmentation at NSCL combines A1900 separator with a gas stopper and ReA reaccelerator, providing beams from 300 keV/u up to 6 MeV/u
- ReA accelerates rare isotope beams successfully producing science since 2015
- Multi-step process to reaccelerate need careful optimization of each step. Today the maximum efficiency achieved for the whole process is around 0.1-1.0%
- Optimization and upgrades are ongoing at NSCL

The Stop and Reaccelerate Team

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Stefan Schwarz
Chandana Sumithrarachchi
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Qiang Zhao
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Thank you for your attention