Reacceleration of Rare Isotope Beams at Heavy-Ion Fragmentation Facilities

Antonio C.C. Villari

National Superconducting Cyclotron Laboratory
Facility for Rare Isotope Beams
Michigan State University

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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-energy 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
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

Primary beam acceleration and fragment separation

Reacceleration and beam distribution with ReA

Rare isotope beam stopping and mass separation

www.nscl.msu.edu
### ReA Rare Isotope Beams Delivered for Successful Experiments

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy (MeV/u)</th>
<th>Beam rate on target (pps)</th>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}$Mg</td>
<td>5.0</td>
<td>1.2E3</td>
<td>Astrophysics: $^{22}$Mg(α,p)$^{25}$Al</td>
</tr>
<tr>
<td>$^{34}$Ar</td>
<td>1.63 - 1.71</td>
<td>5.1E3</td>
<td>Astrophysics: $^{37}$K(p,α)$^{34}$Ar, etc.</td>
</tr>
<tr>
<td>$^{37}$K</td>
<td>4.6</td>
<td>5.7E3</td>
<td>Astrophysics: $^{34}$Ar(α,p)$^{37}$K</td>
</tr>
<tr>
<td>$^{45}$K</td>
<td>4.65</td>
<td>7.8E4</td>
<td>Fusion: Fusion-Fission $^{45,49}$K + $^{181}$Ta</td>
</tr>
<tr>
<td>$^{46}$Ar</td>
<td>4.65</td>
<td>1.0E3</td>
<td>Nuclear Structure: IAS $^{46}$Ar + p</td>
</tr>
<tr>
<td>$^{46}$K</td>
<td>4.14 - 4.68</td>
<td>1.0E4</td>
<td>Fusion: $^{46}$K + $^{208}$Pb</td>
</tr>
</tbody>
</table>
| $^{47}$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](http://www.nscl.msu.edu/users/beams.html)
Example: $^{37}$K Reaccelerated Beam Using the Re-accelerator ReA3

- **q/A separator**
  - R = 500; 0.012 MeV/u
- **MHB**
  - 80.5 MHz or 16.1 MHz
- **RFQ**
  - 0.6 MeV/u
- **CM1 Re-buncher**
- **CM2 6 resonators**
  - Beta = 0.041
- **CM3 8 resonators**
  - Beta = 0.085

1+ ions

0.3 MeV/u < E < 6 MeV/u

$E = 12 \times \frac{q}{A}$ for $q/A \leq 4$

Beam on target: 5.7E3 pps


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Rare Isotope Production via Projectile Fragmentation

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

$^{37}\text{K} (T1/2 = 1.23\text{s})$

Beam: 9.3E6 pps

A1900: D.J. Morrissey et al., NIMB 204 (2003) 90
Degrade Energy Using Monochromator Technique
Momentum Compression Reduces Range Straggling

46\text{Ar} \quad \text{Degrader-1}

Dipole \quad \text{Wedge} \quad \text{Degrader-2}

Fine tuning range in the stopper

Gas Stopper

Minimized range straggling

Before degrader

After degrader

After wedge

Energy distribution

Energy (MeV/\mu\text{A})

Energy (MeV/\mu\text{A})

Energy (MeV/\mu\text{A})


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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
A.C.C. Villari, September 2018 EMIS-2018, Slide 10
Stopping, Extracting, and Mass Separation

1st degrader

Wedge and 2nd Degrader

Linear gas stopper

Stopping in gas = 44%

Extracting from gas stopper = 8%

Transport / separation = 80%

Beam OUT: 2.6E5 pps

R = 1500
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


<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ejection energy</td>
<td>12 keV/n</td>
</tr>
<tr>
<td>Ch. State efficiency</td>
<td>10-25%</td>
</tr>
<tr>
<td>Ejection pulse length</td>
<td>&lt;125 ms</td>
</tr>
<tr>
<td>E-beam current</td>
<td>&lt; 400mA</td>
</tr>
<tr>
<td>Mag. field</td>
<td>4 T</td>
</tr>
</tbody>
</table>

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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+)

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

- q/A separator
- MHB
  - 80.5 MHz or 16.1 MHz
- RFQ
  - 0.6 MeV/u
- CM1 Re-buncher
- CM2 6 resonators
  - Beta = 0.041
- CM3 8 resonators
  - Beta = 0.085

- $0.3 \,\text{MeV/u} < E < 6 \,\text{MeV/u}$
- $E = 12 \times q/A$ for $q/A \leq 4$

- Acceleration/transport efficiency = 50%

Beam on target: 5.7E3 pps


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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

LINAC Spectrometer image $^{39}$K

Rare isotope beam on Target ($^{46}$K)

$^{46}$K = 1E4 pps

E = 4.68 MeV/n; resolution = 0.5% (FWHM); accuracy = 0.5%
Beam size = 2 mm (FWHM); Divergence = 5 mrad (FWHM)
Efficiencies of each step reveal where improvements are needed
Stopping, extracting from gas and breeding are the most important

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

Stoping simulation in the CycStopper

Stefan Schwarz, poster 90 / S. Schwarz et al. NIM B 376 (2016) 256
A.C.C. Villari, September 2018 EMIS-2018, Slide 21
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
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 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...

Space for future expansion of the science program
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

www.frib.msu.edu

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

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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

Georg Bollen
Daniel Crisp
Alain Lapierre
Kasey Lund
Dave Morrissey
Samuel Nash
Ryan Ringle
Stefan Schwarz
Chandana Sumithrarachchi
Tasha Summers
Qiang Zhao
 ACCV

Thank you for your attention