Intense Beam Operation of the MSU/NSCL Cyclotrons*


* Work supported under NSF Grant PHY0606007
Cyclotrons+A1900+Experimental Areas

Described by
Xiaoyu Wu
Later this conference
Cyclotrons + A1900

5 meter scale

RIKEN SRC Scale!
Present Beam Status
Our “Real” Beam List ~ 1000 Entries

more than 1000 RI Bs have been produced (2001-2010)
more than 830 have been used in experiments

$^{46}\text{Ar} \sim 10^7 \text{ pps}$

$^{40}\text{Mg} \sim 10^{-6} \text{ pps}$
(2 / week)
Experimental Demand is Virtually All for Fragment Beams

“Maximum” Primary Beam Power is usually Desired (a task for which these machines were not designed)

Pushing the Limits of what is possible to do with these machines
Fraction of Operating Hours by Accelerated Ion Type

22 Different Ions Available

average fraction of operating hours 2003 - 2008
Demand Influences Development

5 Beams account for ~ ½ the total running time

The most-requested beams generally have the best performance.

\((^{48}\text{Ca}, ^{40}\text{Ar}, ^{78}\text{Kr}, ^{76}\text{Ge}, ^{86}\text{Kr})\)

4 - 7 Day duration runs → Limited Time for “Perfect Tunes”
Cyclotron Beam Intensities - 2010

1) not Peak values
2) not Guaranteed values

Reasonably Achievable

On this list:
P(max) = 1200 W
P(max) = 1 W

What are the Present Limiting Factors?
Power or Loss-Limited Beams (400 – 1200W)

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<td>150</td>
<td>500</td>
<td>1200</td>
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<td>18-O</td>
<td>120</td>
<td>500</td>
<td>1080</td>
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<td>726</td>
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<td>1120</td>
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Danger Zone:
> 1000 W (light)
To
> 300 W (heavy)
Range in Tungsten (Deflector Septum)

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<td>16-O</td>
<td>150</td>
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<td>18-O</td>
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<td>3.2</td>
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<td>3.6</td>
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<td>24-Mg</td>
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<td>3.4</td>
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<td>36-Ar</td>
<td>150</td>
<td>1.8</td>
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<tr>
<td>40-Ar</td>
<td>140</td>
<td>1.8</td>
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<td>1.0</td>
</tr>
<tr>
<td>124-Xe</td>
<td>140</td>
<td>0.7</td>
</tr>
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</table>

~ Factor of 6 in Deposited Energy Density per Watt
## Special Cases: Production Target (Be) Damage

Medium-heavy beams at ~ 1 kW causes damage within the 1 mm dia. impact region

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Rotating Wheel Target being developed
Source-Output-Limited Beams (Ni, Zr, Sn)

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<tbody>
<tr>
<td>58-Ni</td>
<td>160</td>
<td>40</td>
<td>371</td>
</tr>
<tr>
<td>64-Ni</td>
<td>140</td>
<td>15</td>
<td>134</td>
</tr>
<tr>
<td>96-Zr</td>
<td>120</td>
<td>3</td>
<td>37</td>
</tr>
<tr>
<td>112-Sn</td>
<td>120</td>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td>118-Sn</td>
<td>120</td>
<td>3</td>
<td>38</td>
</tr>
<tr>
<td>124-Sn</td>
<td>120</td>
<td>3</td>
<td>44</td>
</tr>
</tbody>
</table>

(However for all Beams, Higher Brightness is a plus)
## Foil-Limited Beam Intensities

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<tbody>
<tr>
<td>208-Pb</td>
<td>85</td>
<td>2</td>
<td>36</td>
</tr>
<tr>
<td>209-Bi</td>
<td>80</td>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td>238-U</td>
<td>80</td>
<td>.3</td>
<td>6</td>
</tr>
<tr>
<td>238-U</td>
<td>45</td>
<td>.1</td>
<td>1</td>
</tr>
</tbody>
</table>

Foil Degradation with 600 enA $^{238}$U$^{30+}$ (7.7 MeV/u) after 15 seconds!
NSCL Stripper Foil Experience

To be discussed in detail by Felix Marti
Later this conference
# Progress since Cyclotrons07

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(Normalized by beam to the same final output power)
Stripping Efficiencies of K1200 Foil

K1200 Transmission percentages are given with the stripping efficiency normalized to 100% to allow comparison between beams of different ions.

Stripping Efficiencies are measured for each beam, foil thickness, and foil type with a test setup in the K500 to K1200 coupling line.

\[ {}^{235}\text{U}^{30+} \rightarrow {}^{235}\text{U}^{69+} \]

[ 9% efficiency ]
# Measured Stripping for 600 ugm/cm² Carbon

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<th>⁷⁸Kr</th>
<th>¹²⁴Xe</th>
<th>²³⁸U</th>
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<td>Q₁ → Q₂</td>
<td>3⁺ → 8⁺</td>
<td>8⁺ → 20⁺</td>
<td>14⁺ → 34⁺</td>
<td>19⁺ → 45⁺</td>
<td>30⁺ →</td>
</tr>
<tr>
<td>Efficiency</td>
<td><strong>95%</strong></td>
<td><strong>69%</strong></td>
<td><strong>53%</strong></td>
<td><strong>26%</strong></td>
<td><strong>9%</strong></td>
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(Foil Holder)
Intense Beam Operation of the MSU/NSCL Cyclotrons

Not Very??
1.2 kW of 140 MeV/u $^{48}\text{Ca}$ vs. Stainless Steel

Thickness of Vacuum Chamber wall = 9.5 mm

Range of 140 MeV/u $^{48}\text{Ca}$ in steel = 3.1 mm

From the Operations Log:

“It is possible, but not likely, that this vacuum event was not related to the beam, but this operator doubts it.”
Beam Wins

Event Duration < 20 sec
Range/Energy (re-)Defines “Intense”

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<th>Power</th>
<th>Range in Steel</th>
</tr>
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<td>Proton</td>
<td>590</td>
<td>1 MW</td>
<td>275 mm</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>140</td>
<td>1 kW</td>
<td>3 mm</td>
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(Material Damage effects are also more severe with increasing ion mass.)

These beams must be tuned and run cautiously.
3 Key Elements of Making Intense Beam
Deflectors are a **Major** Concern

**Short Range of Heavy Ions In Materials**

~ 100 kV/cm electric Field In Deflectors

**Full Radius Turn Separation**

(beam center-to-center):

K500 ~ 1.3 mm
K1200 ~ 0.65 mm
Key #1: O₂ Gas Flow during Operation

O₂ flow (in standard cm³/minute) vs. Deflector power supply current (µA)

- 1.0 cc/min
- 25 µA
- 80 µA

Duration: 2.3 Hour
O₂ Gas Flow, Beam Off

Operator stops beam → Current falls slightly

63 uA
O₂ Gas Flow, Beam Off

Flow lowered to more-normal value → Current trends up

(normal: 0.2 cc/min)  0.4 cc/min  73 uA
Deflector voltage set high, but gets into a low volts/high current (corona?) Discharge
“High Pressure Treatment”: Beam & RF Off

12 cc/min

3 uA
Normal Operation Resumed: Time Lost = 20 minutes

0.9 cc/min

3 uA
Key #1: O$_2$ Gas Flow during Operation

Allows Recovery of normal Deflector function

*Without* venting/removal/cleaning

How this works = ?
May be similar to

“Oxygen Plasma Cleaning”

“Oxygen Plasma Cleaning”
Gives
131,000 Google Hits
Useful Aside: Event Reconstruction

EPICS Data Archiver
Saves
~15,000 Parameters
Every 30 seconds
Into Permanent Storage
Key #2: Low Emittance Injection

<table>
<thead>
<tr>
<th>Year</th>
<th>16-Oxygen On K500 Inflector (euA)</th>
<th>Extracted Beam (euA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>100</td>
<td>1.1</td>
</tr>
<tr>
<td>2006</td>
<td>5.0</td>
<td>1.1</td>
</tr>
<tr>
<td>2010</td>
<td>2.1</td>
<td>1.1</td>
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Better transmission through the cyclotron = Many fewer problems
“Don’t inject what won’t extract”
Not easy with ECRIS Beams

NSCL Image of $^{16}\text{O}^{3+}$
Presented Tokyo 2004

The Beam characteristics from ECRIS’s are a poor match for injection Into Accelerators
Good Emittance can be Achieved
(and it’s vital to do so)

For NSCL Artemis ECRIS techniques see in particular:
J. W. Stetson, NSCL, Proceedings of ECRIS08, Chicago, IL, USA
(JACoW, 2009), THCO-A03, p. 189.

For NSCL SUSI ECRIS techniques see:
G. Machicoane, NSCL, this conference!

ECRIS beam quality is an active area of investigation at
every Heavy-Ion Beam Lab, so there are
many other important references now available
Injection Conditions for Intense NSCL Beams

1) Beam Emittance $< 20 \pi \text{ mm*mr (rms)}$
   (best $< 10 \pi \text{ mm*mr}$) @ 18-27 kV*q keV
   with Intensity of $10-20 \text{ e } \mu \text{ A}$

2) Minimal Beam “Tails”

3) Medium charge state ($\sim 5 < \text{M/Q} > \sim 8$)

($^{40}\text{Ar}^{7+} \sim 10 \text{ e } \mu \text{ A}$
$4 \pi \text{ mm*mr rms}$)
High Emittance Spreads Bunched Phase width thru K500 Inflector

Spiral Inflector widens 100 \( \pi \) mm\( \times \)mrad bunched beam by 40 deg (in 2\textsuperscript{nd} harmonic operation)

Minimized emittance gets Minimal Phase spread

Key #3: Scraper / Collimator

Vertical collimation of the last few orbits

Trims vertical beam blowups caused by the $\nu_r = 2 \nu_z$ resonances present in K500 and K1200

5.6 mm gap

K500 Shown
Perfect $^{40}\text{Ar}^7+$ Beam = No Scraper Losses

K500 Radial Probe Trace

Extraction Radius $\sim 67$ cm

K500 out / K500 in = 62%
100% extraction efficiency

Extracted Beam
“Unclean” Injection $^{208}\text{Pb}^{27+} = \text{Losses}

The low output of $^{208}\text{Pb}$ from Artemis Limited collimation in the Injection Line $\rightarrow$ high emittance

K500 out / K500 in $\sim 25\%$
50% extraction efficiency
Key #3: Scraper / Collimator (K1200)

Off-Center Beam is Cut by the Collimator:
1) Decouples the effect of centering and extraction “bumps”
2) Reduces losses on the Deflector
3) K1200: deteriorating Foil → higher collimator losses
Further Consideration(s)
Source Monitoring & Tuning Using FFT

ECRIS Beam is not Pure DC

Look at a signal taken directly from a Faraday cup or a Wire inserted into the beam path using an FFT-analyzing oscilloscope
$^{40}\text{Ar}^7^+$: Microwave power = 305 W

$I = 65 \, \mu\text{A}$

AC Noise = 2.7%

Frequency = 43 Hz
$^40\text{Ar}^{7+}$: Microwave power = 310 W

- I = 50 $\mu$A
- AC Noise = 1.9 %
- Frequency = 12 Hz
$^{40}\text{Ar}^{7+}$: Microwave power = 315 W

I = 50 uA
AC Noise < 0.1 %
Frequency = ? Hz

Best ??
Importance? “Mode” Influences Injection

Good Beam Thru K500

½ Beam Intensity thru K500 (with similar source output)
Importance? “Mode” Influences Injection

Minor Source Retune

Minor Source Retune

\( \frac{1}{2} \) Beam Intensity thru K500 (with similar source output)
Offers Easy Access to Plasma Condition

Some very provisional comments:

1) Which mode(s) give best Brightness? – Unknown
2) Low Freq. (<100 Hz) → quiet chaos → High Freq. (> 1 kHz)
3) Sensitivity to source parameters greater at high charge state
4) Modes vary among different charges of the same ion
5) Mode shifts may occur at “peaks” of beam output intensity
   (All data taken with a low-pass filter cutoff of 1 MHz)
Wide Foil vs. Narrow Foil ($^{16}\text{O}^{3+} \to 8^+$)
(lightish ions are not fully stopped by the probe at high energy)

Output = 2.4 euA, 720 W
Total Throughput = 42%
Extraction Efficiency = 49%
Deflector Power Loss = 480 W

Output = 5.2 euA, 1560 W
Total Throughput = 66%
Extraction Efficiency = 75%
Deflector Power Loss = 304 W
K1200 Deflector Heating by Unstripped Beam

$^{16}\text{O}^{3+}$ Injected Beam Path

Beam that is
Not stripped
Hits dee edge
Strip $\sim$ harmless
K1200 Deflector Heating by Unstripped Beam

$^{124}$Xe$^{19+}$ Injected Beam Path

Beam that is Not stripped hits Deflector: BAD!

$^{124}$Xe$^{19+}$ Injected Beam Power = 400 W
Summary

- Intensities for many beams ~ 800 – 1000 W
- ECRIS intensity increases (SUSI) → more power-limited beams
- Gradual improvement toward 2000 W (?)
- Experimental Demand is for *much higher* beam power

Major Upgrade Required
Ultimate Upgrade: FRIB Coming ~2018(?)
Bent Linear Accelerator: BLINAC
Logical Progression:
Separated-Sector *Linear* Cyclotron: SSLC
The Cast

**OPERATIONS**
- Peter Miller
- Mathias Steiner
- Andreas Stolz
- Operators!

**ION SOURCE**
- Dallas Cole
- Larry Tobos
- Tommi Ropponen
- Liangting Sun

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- Peter Spaedtke, GSI
- Stefan Adam, PSI
Top View: Compact Machines
(K1200 Extraction Radius = 1 m)
“Magnetic” Phase Compression

(1) Inject with phase error, (2) Bring back to 0 deg
Result: Increasing energy gain/turn

- Phase Compression -
Exhibit A: K1200 Deflector Septum (Tungsten)

(The only such damage noted in the 2007-2010 time period and did not interrupt Beam delivery)
ECRIS Beam Characteristics

1) Transverse Structure
2) Large 2\textsuperscript{nd} Order Aberrations (Triangle)
3) Strong Phase space cross-coupling (beam is correlated)
4) Focusing morphs Triangle into Star
5) Under some conditions, a fractal nature (round cut can redevelop into a triangle-star)
Optical Elements

Artemis-A

Electrostatic Quad Doublets

Solenoids

Dipole 10.5 deg (left)

Dipole 23.0 deg (right)

K500

(Off)
Injection Line (~16.5 m) to K500

Original Configuration (Solenoid)

Electrostatic Q-Triplet Sextupole

4-Jaw Slits

RF Chopper

Improved Dipole

Doublet-Octupole-Doublet

Spherical Bender (2009)

Emittance Scanner

Solenoid Doublet

ECRIS

(K500)
Emittance for 100% Extraction Example

22 Jan-09 40Ar7+ 24.43 kV
12.7 mm; SC Emit31
J33 Slits 5x10 mm
S12=1247 J33=J53=723 N4=418
91% < 0.25 π
98% < 0.50 π
100% < 100 π

α = 0.20
β = 0.55 m
Ε rms = 6 π μm
I meas = 1.6 eμA
Itot = 1.0 eμA (extrapolation)

22 Jan-09 40Ar7+ 24.43 kV
12.7 mm; SC Emit31
J33 Slits 5x10 mm
S12=1247 J33=J53=723 N4=418
100% < 0.25 π
100% < 0.50 π
100% < 100 π

α = 0.51
β = 0.15 m
Ε rms = 2 π μm
I meas = 2.4 eμA
Itot = 1.4 eμA (extrapolation)
Key #1: O₂ Gas Flow during Operation

Beam Time Lost = 20 minutes

2.2 Hours

5 uA