Rare Isotope Beams at MSU - Present and Future

The NSCL at MSU

Fast beams from projectile fragmentation

Thermalized beams

Reacceleration

Future opportunities

Georg Bollen
National Superconducting Cyclotron Laboratory
and Department of Physics & Astronomy
Michigan State University

MICHIGAN STATE UNIVERSITY

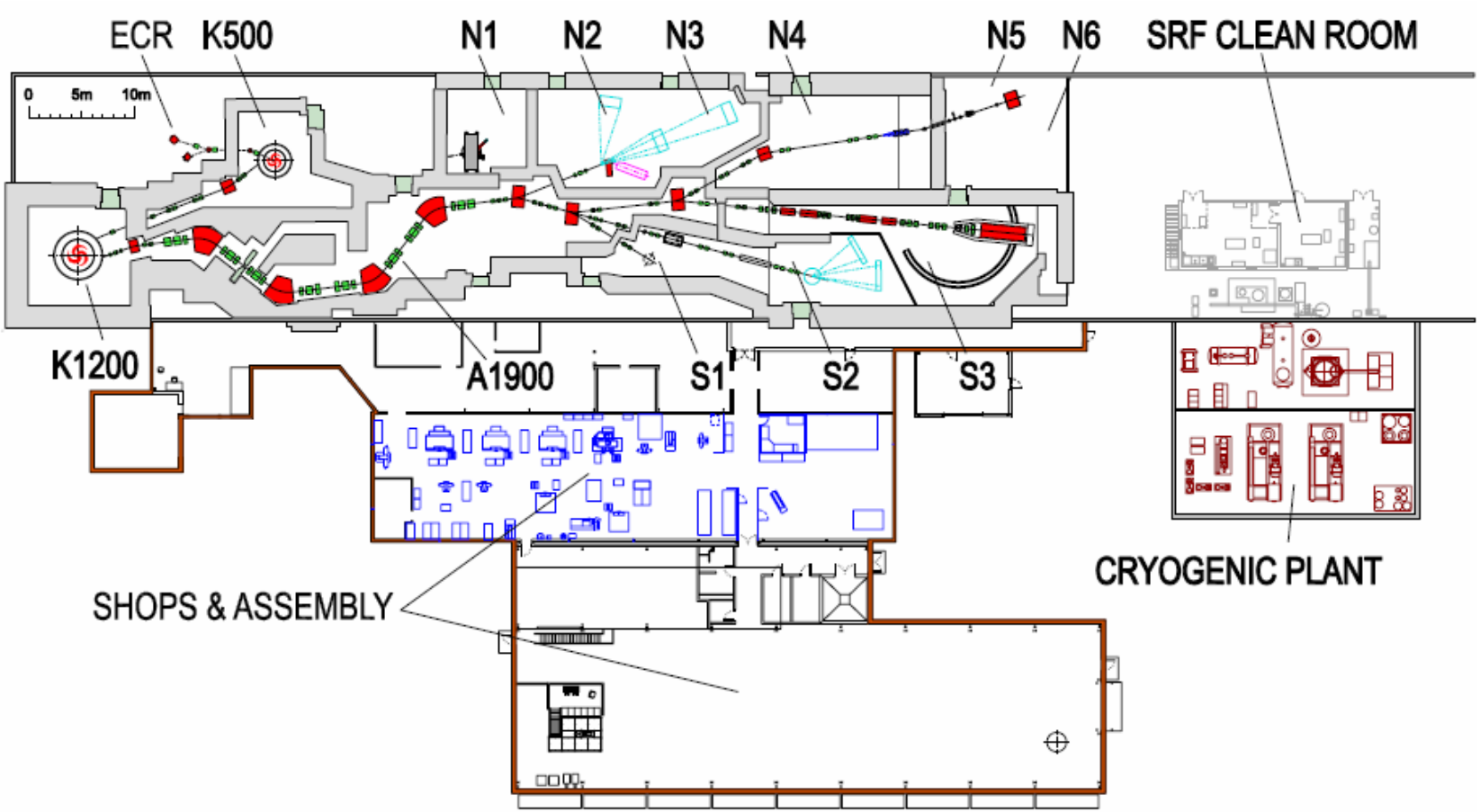
The National Superconducting Cyclotron Laboratory at Michigan State University

Premier national user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

314 employees, incl. 61 undergraduate and 60 graduate students, 29 faculty – over 700 users

Coupled Cyclotron Facility (CCF)

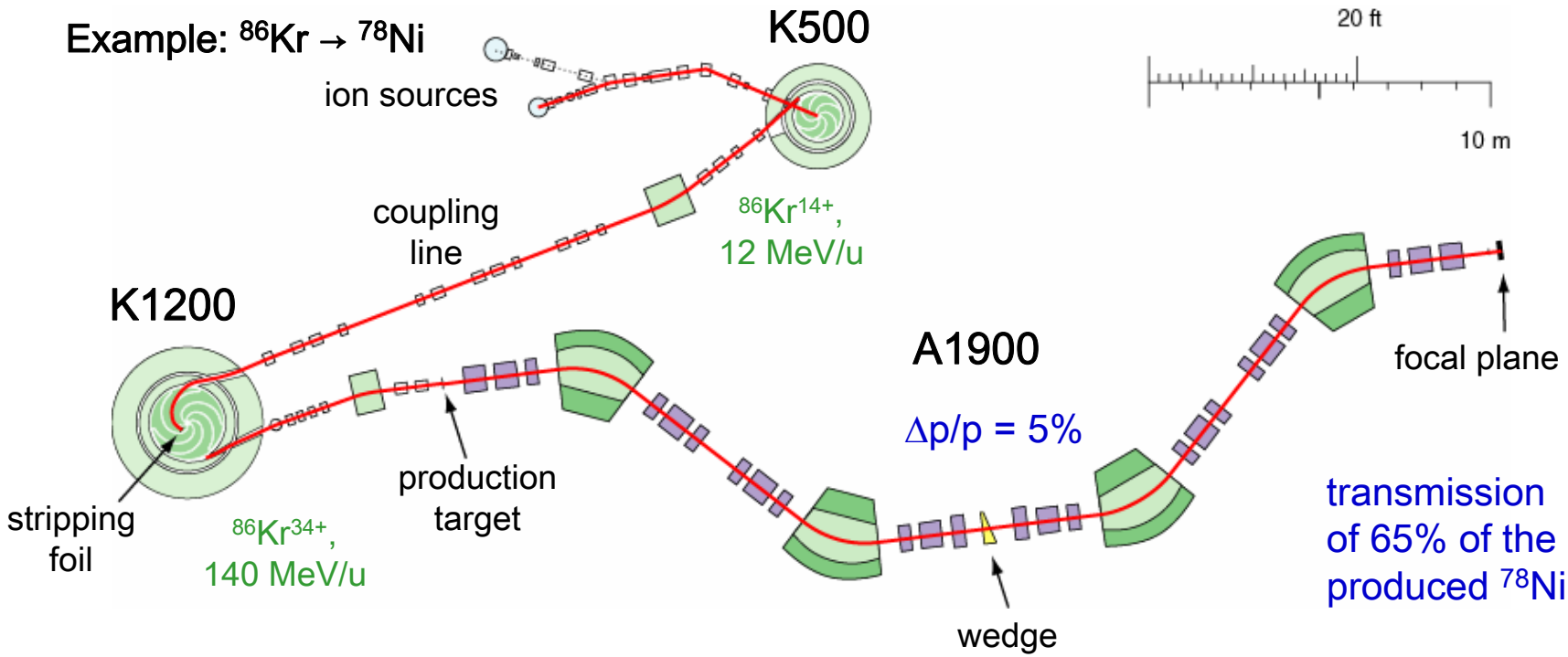
Commissioned in 2001. Vault and beam-line reconfiguration in 2007



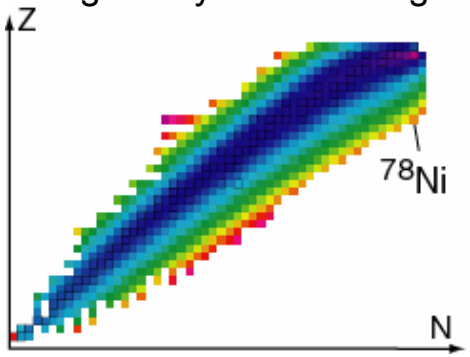
Experimental apparatus:

A1900 fragment separator, 92-inch chamber, S800 magnetic spectrograph, large aperture sweeper magnet spectrograph, large area (2×2 m^2) position sensitive neutron detectors, segmented Ge and Si-strip-CsI arrays, β-NMR and β-counting station, LEBIT: gas cell (1 bar He) for stopping rare isotopes, 9.4 Tesla Penning Trap, RF-separator, …

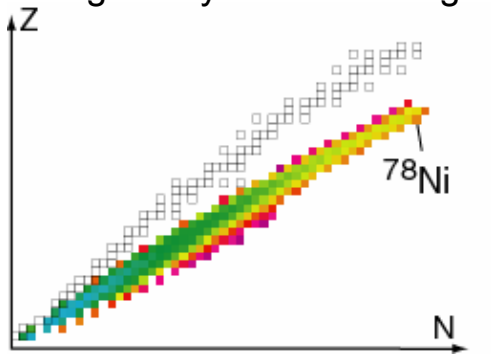
In-Flight Production of Rare Isotopes



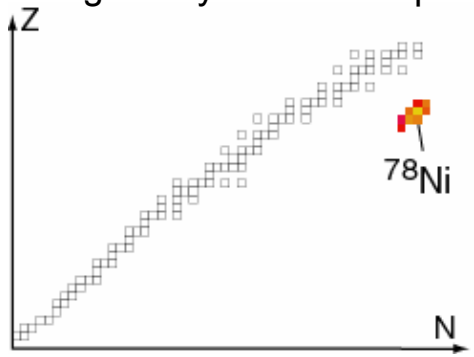
fragment yield after target



fragment yield after wedge

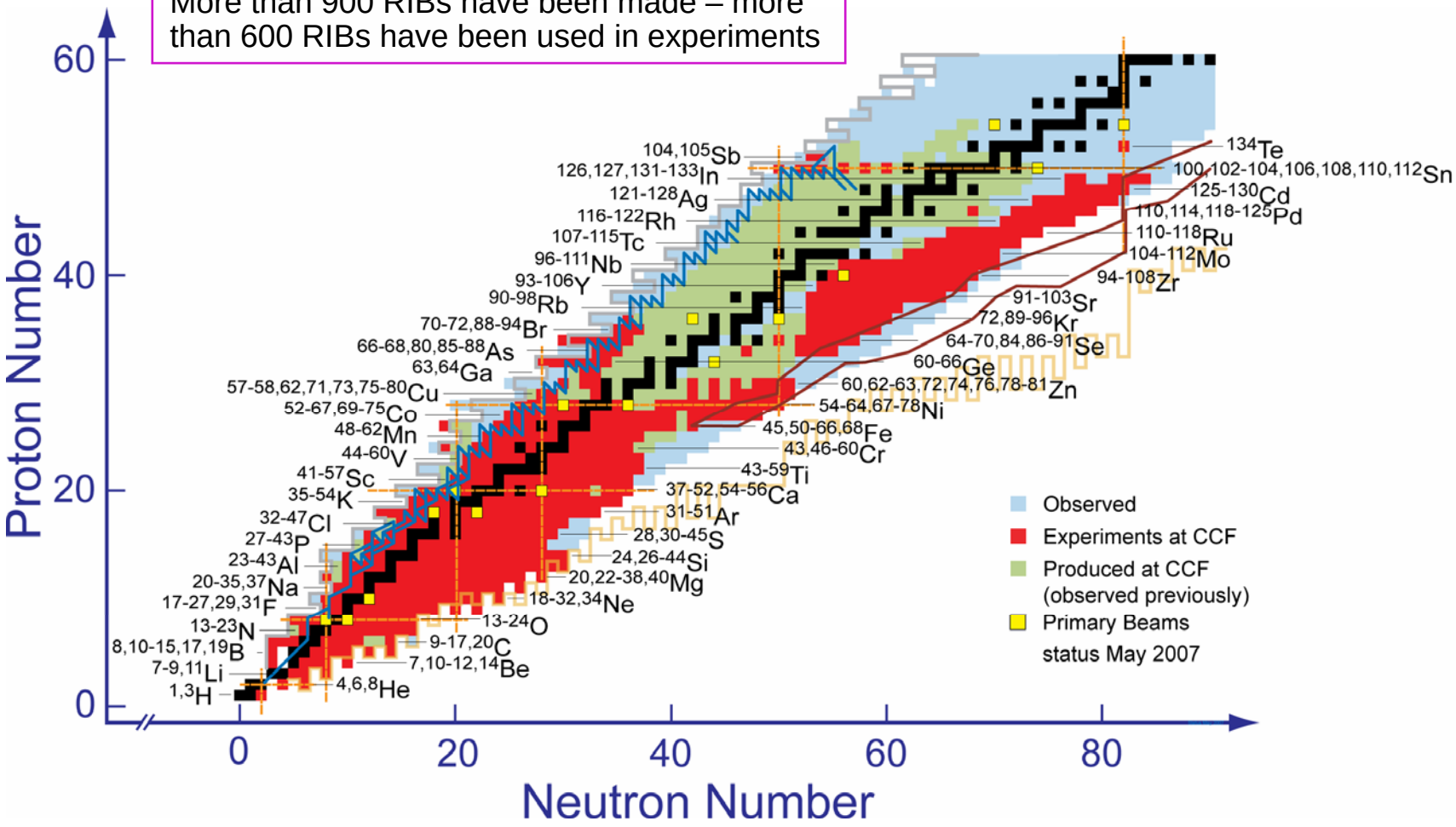


fragment yield at focal plane



Rare Isotope Beams at NSCL

More than 900 RIBs have been made – more than 600 RIBs have been used in experiments



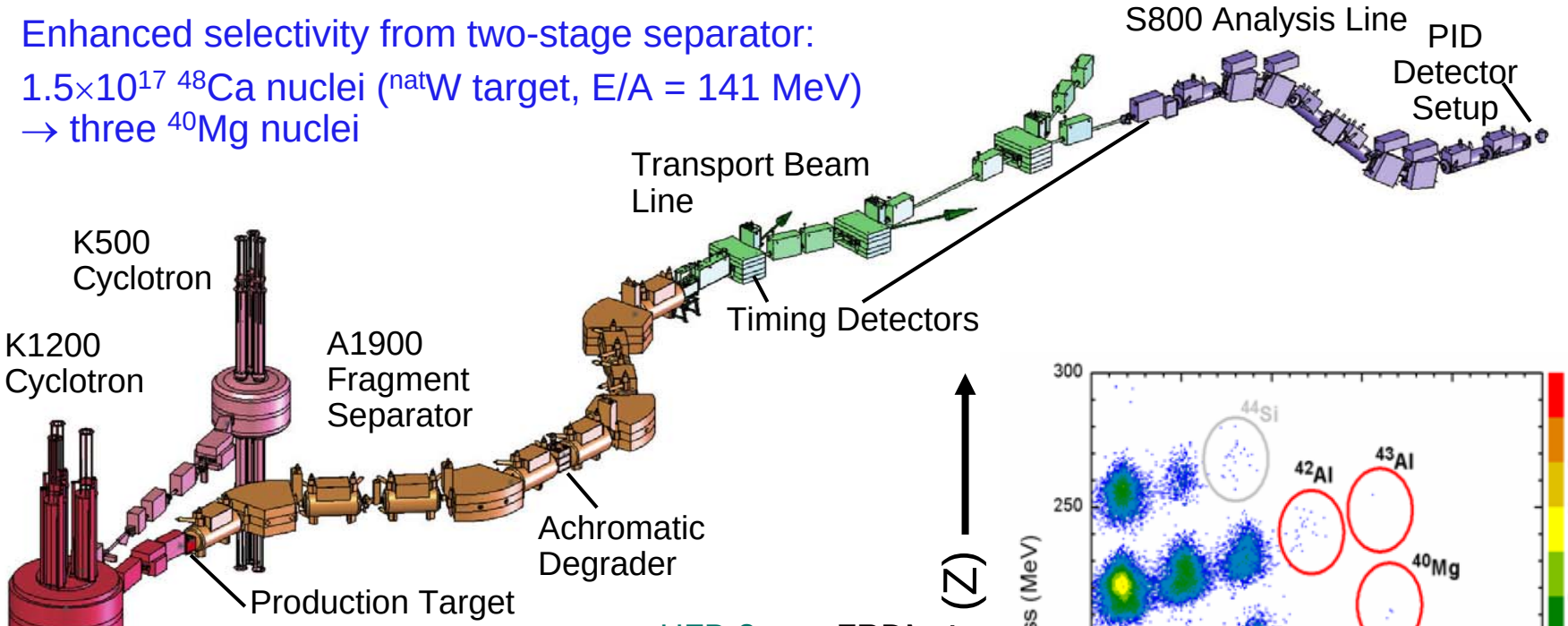
Multi-facetted science program: nuclear structure studies, nuclear reactions, nuclear astrophysics, fundamental interaction tests, and applications using **fast rare isotope beams** and **thermalized beams** (new).

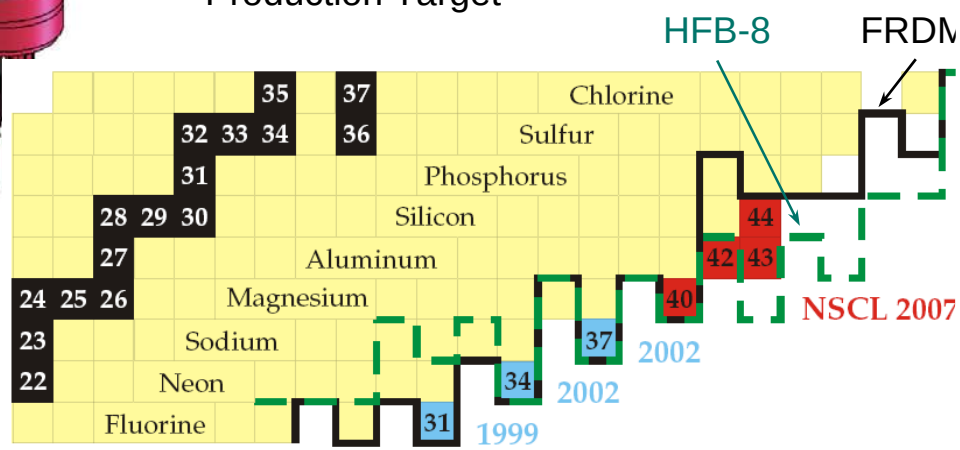
Discovery of ^{40}Mg, ^{42,43}Al, and ^{44}Si

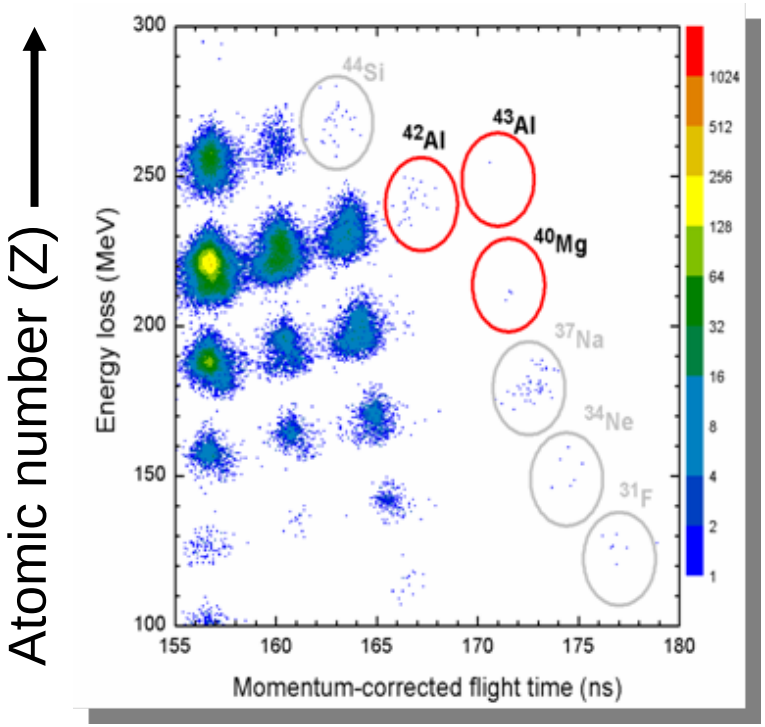
Enhanced selectivity from two-stage separator:

1.5×10^{17} ^{48}Ca nuclei (^{nat}W target, E/A = 141 MeV)

$\rightarrow$ three ^{40}Mg nuclei







Mass number (A) $\rightarrow$

T. Baumann et al., Nature 449 (2007) 1022

O. Tarasov et al., Phys. Rev. C75 (2007) 064613

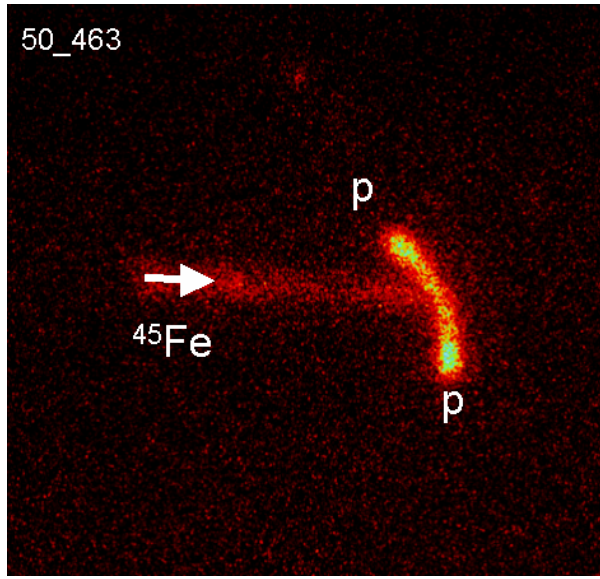
Exotic decays – Search for di-proton decay

M. Pfützner (Warsaw) et al.

K. Miernik et al., PRL99(2007)192501

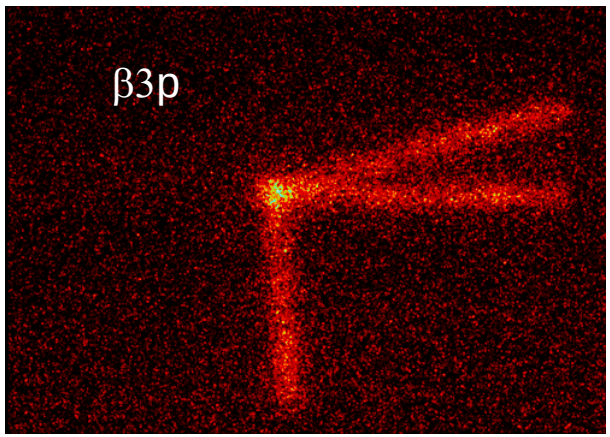
^{45}Fe known 2-proton ground state emitter.

How are the protons correlated? Di-proton (^{2}He) or p+p?

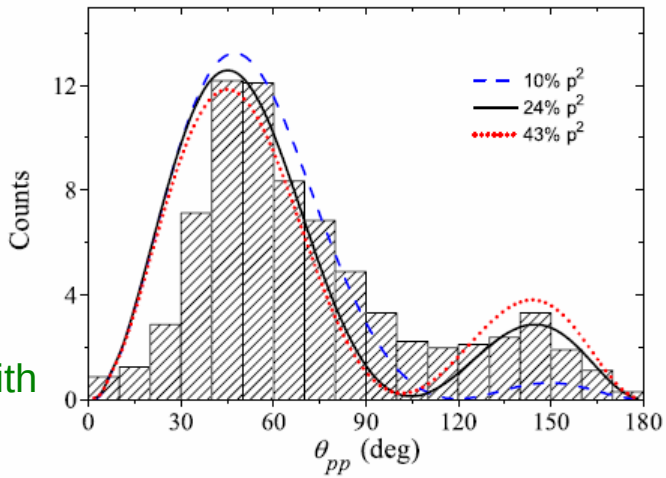


Experiment with optical time projection chamber

- **First direct angular and energy correlation measurement in 2-proton decay**
- **First observation of β-delayed 3-proton decay**



87 2p-events
38 β-delayed events

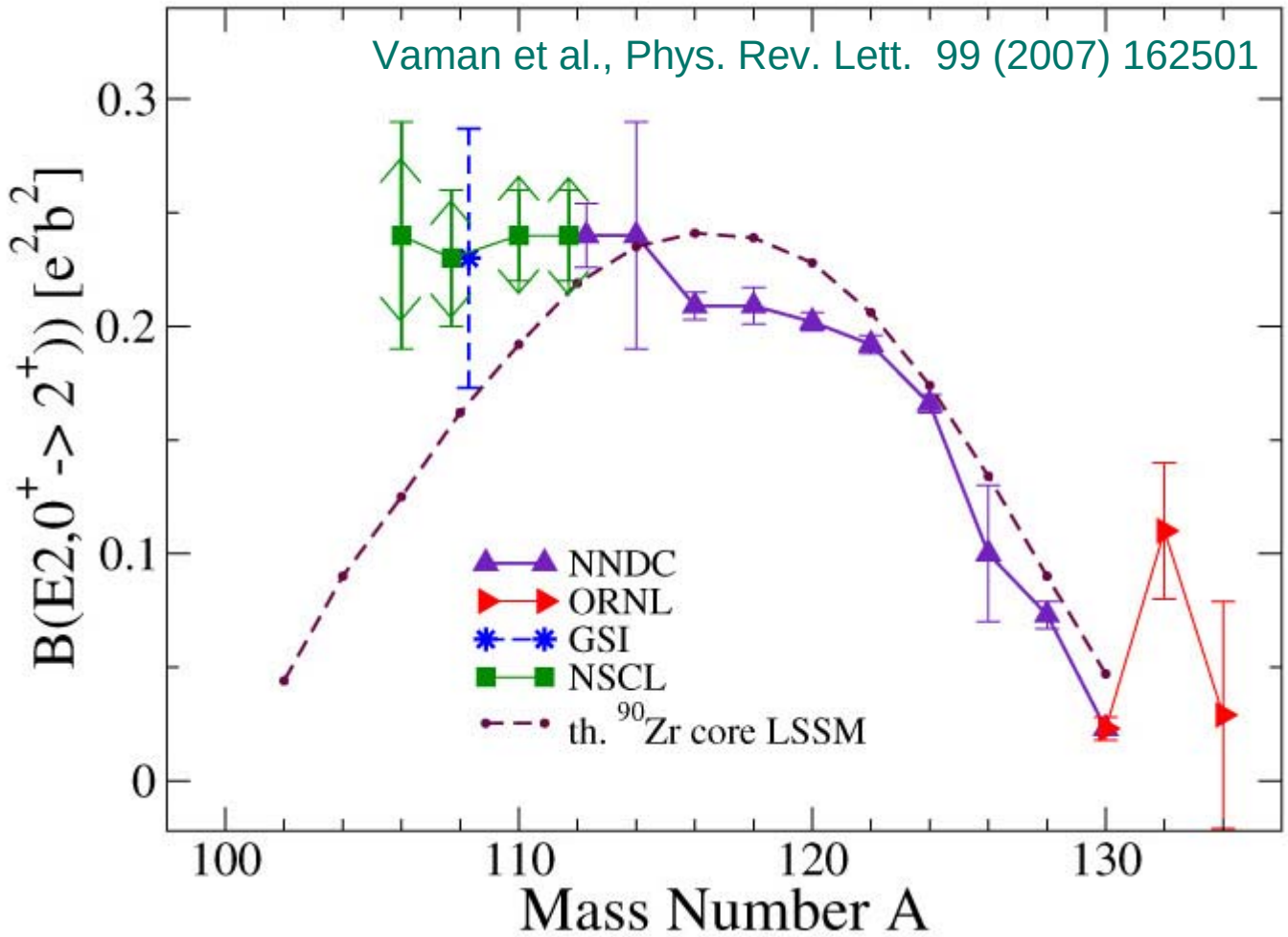


Good agreement with 3-body model
(Grigorenko & Zhukov)

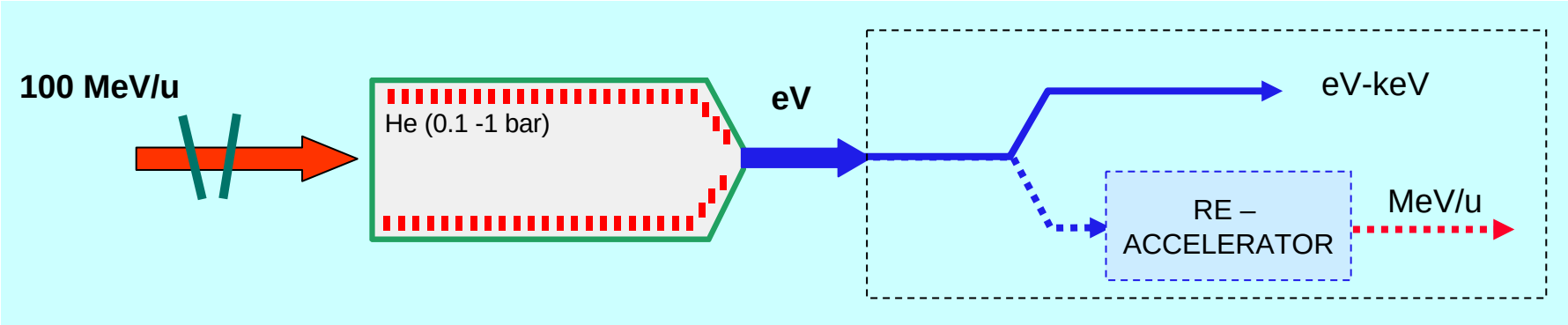
Breaking of Z=N=50 Core Near ^{100}Sn?

Coulex of neutron-deficient Sn isotopes

Nearly constant B(E2) values in $^{106\text{-}112}$ Sn are not expected from state of the art shell model calculations, but could be explained if $g_{9/2}$ protons from within the Z = 50 shell contribute to the structure of low-lying states in this region.



Experiments with thermalized beams from projectile fragmentation



Rare isotope production via relativistic projectile fragmentation and in-flight separation

- Fast – no element selectivity – short beam development times

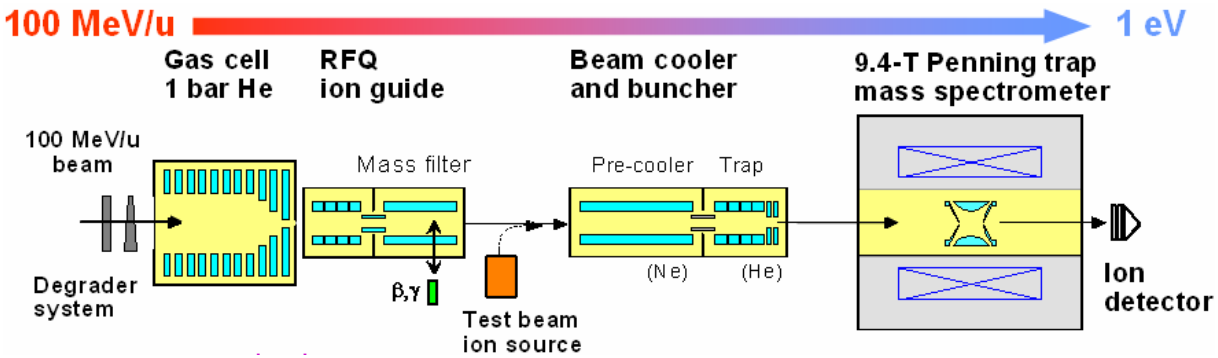
Gas stopping opens door for precision experiments with low-energy beams

- Mass measurements
- Laser spectroscopy
- Experiments with re-accelerated beams

Gas stopping of fast beams is challenging

Experiments with thermalized beams

Low Energy Beam and Ion Trap Facility LEBIT



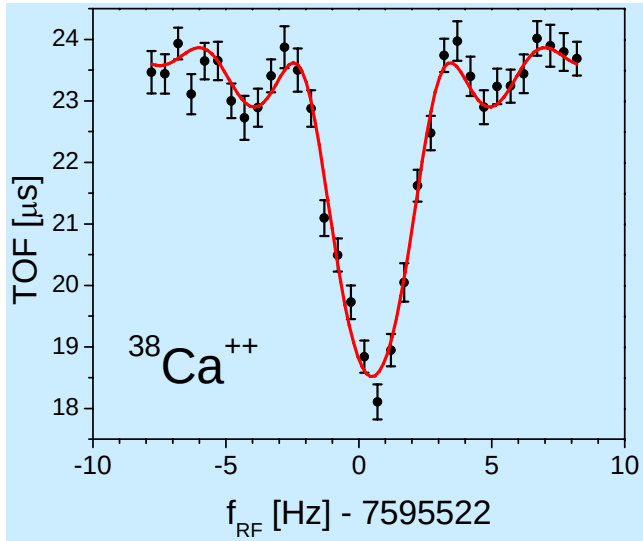
2005: First demonstration that fast projectile fragments can be thermalized and used for precision experiments

^{38}Ca: $0^+ \rightarrow 0^+$ β^+-emitter

ME_{LEBIT} = -22058.53(28) keV

δm = 280 eV, $\delta m/m = 8 \cdot 10^{-9}$

new candidate for the test of the conserved vector current (CVC) hypothesis



G. Bollen et al., PRL 96 (2006) 152501

LEBIT results since 2005

NSCL

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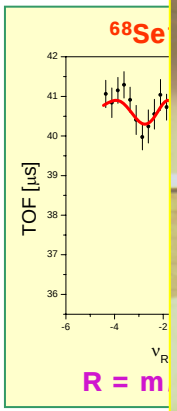
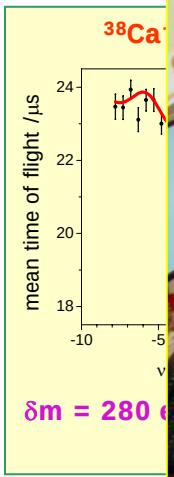
Advancing Knowledge. Transforming Lives.

rp-proc



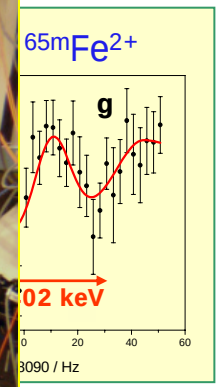
R = m

CVC tes

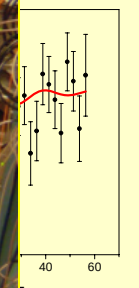


δm = 280

somer



0 ms



^{33}Si, ^{29,34}P, ^{37,38}Ca, $^{40\text{-}44}$S, $^{63\text{-}65}$Fe, $^{64\text{-}66}$Co, ^{63,64}Ga, $^{64\text{-}66}$Ge, $^{66\text{-}68}$As, ^{80}As, $^{68\text{-}70}$Se, ^{81}Se, ^{70m,71}Br

PRL 96 (2006) 152501, PRC 75(2007)055503, PRC 75 (2007) 055801

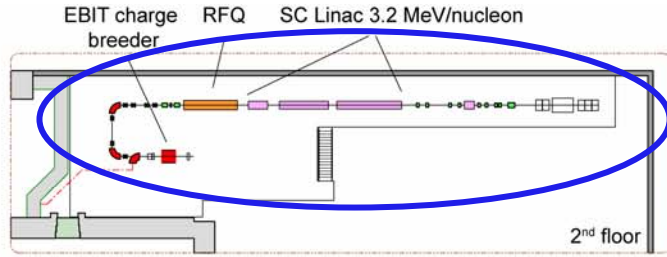
New opportunities with thermalized beams

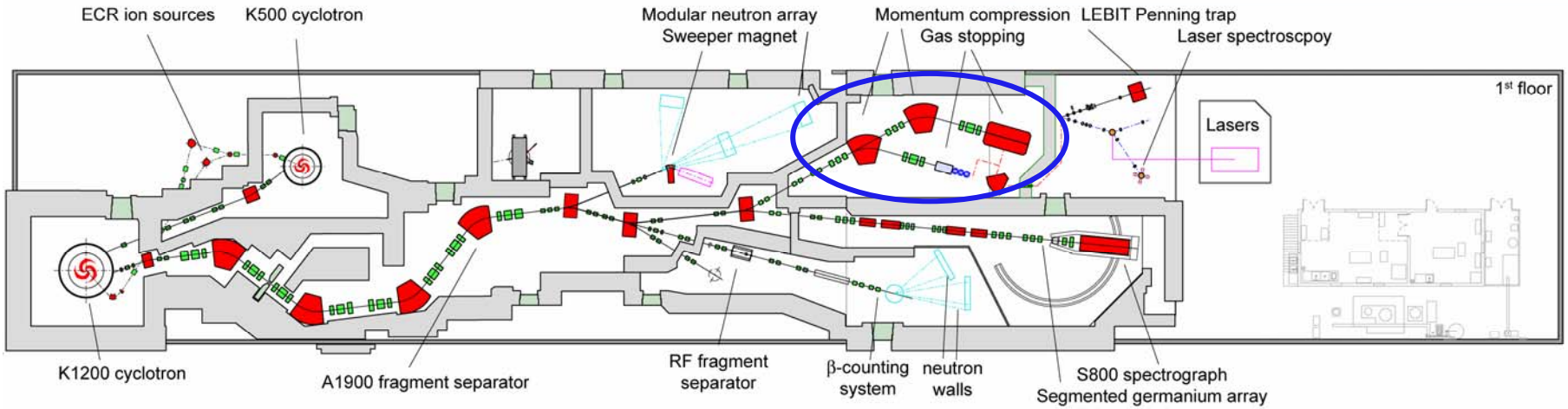
Laser spectroscopy of rare isotopes from projectile fragmentation

- Radii, moments

Re-acceleration of thermalized beams up to 0.3 – 3.2 MeV/u

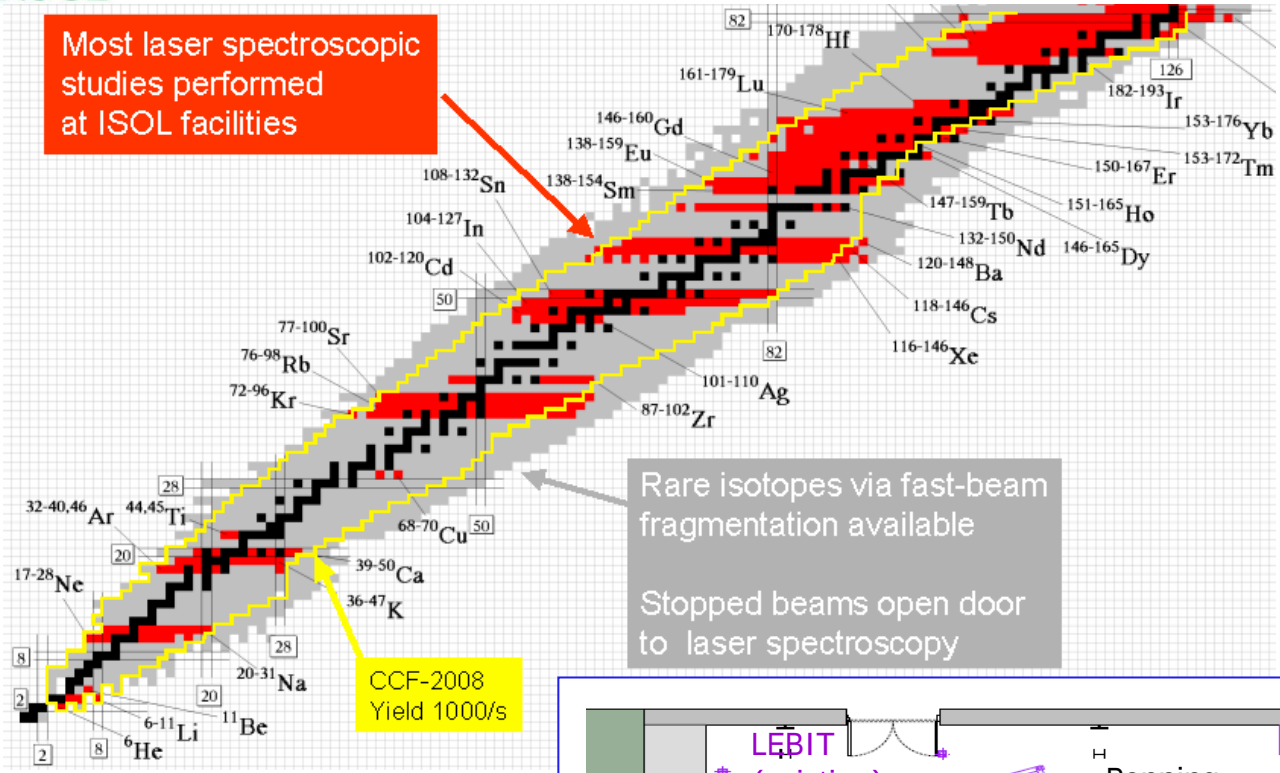
- Low-energy reactions important for nuclear astrophysics
- Transfer reactions, Coulomb excitation for nuclear structure studies



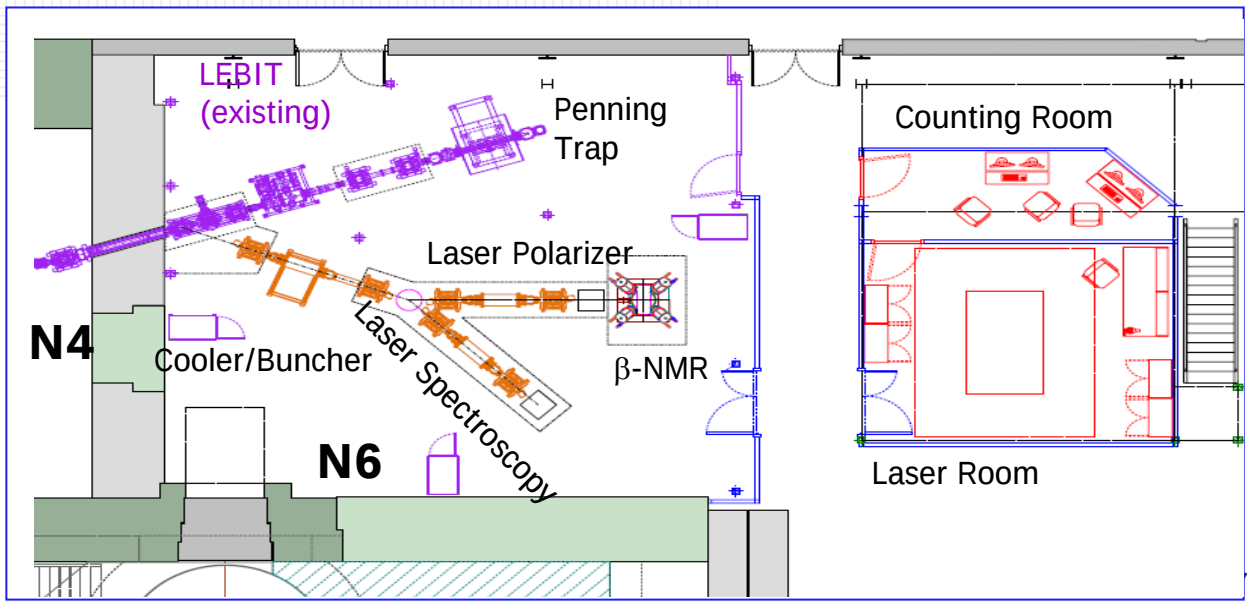


NSCL near future

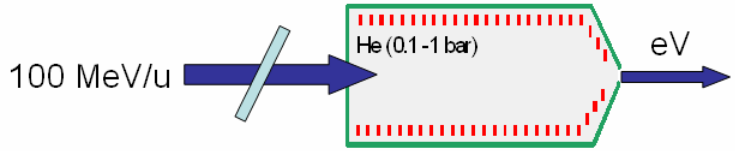
Laser Spectroscopy at the NSCL



H.-J. Kluge and W. Nörtershäuser, Spectrochim. Acta B, 58 (2003)

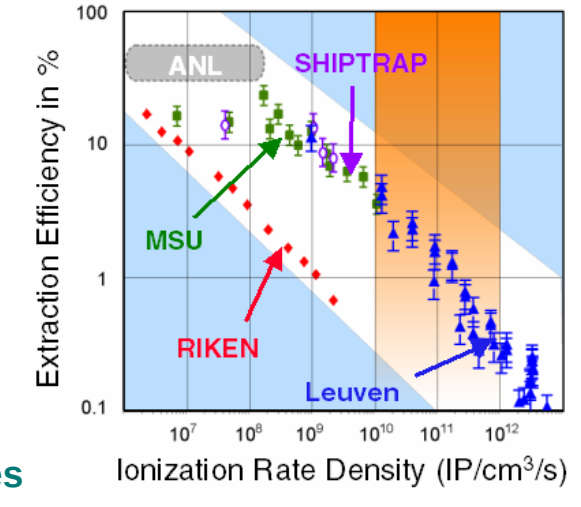


Gas stopping at > 50 MeV/u



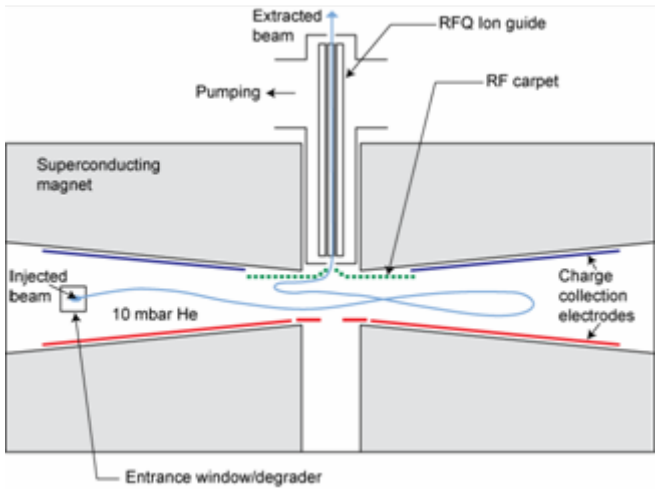
Linear stoppers - present systems

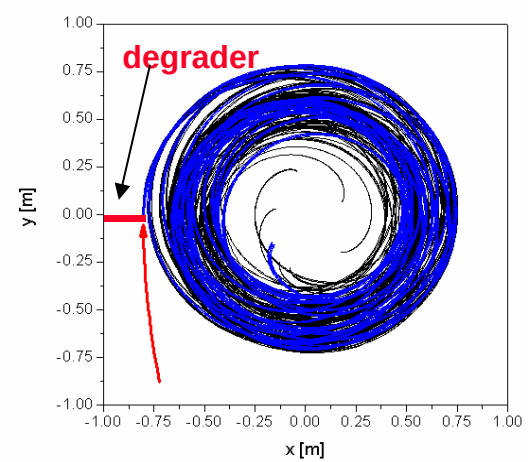
- They work! Experiments at NSCL and RIKEN.
- Intensity-dependent extraction efficiency limits
- Average extraction times of ≈100 ms

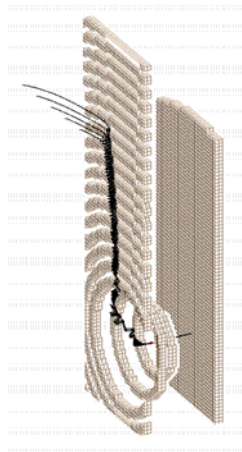


Advanced Concept – the Cyclotron Gas Stopper

Gas-filled cyclotron magnet combined with RF ion guiding techniques



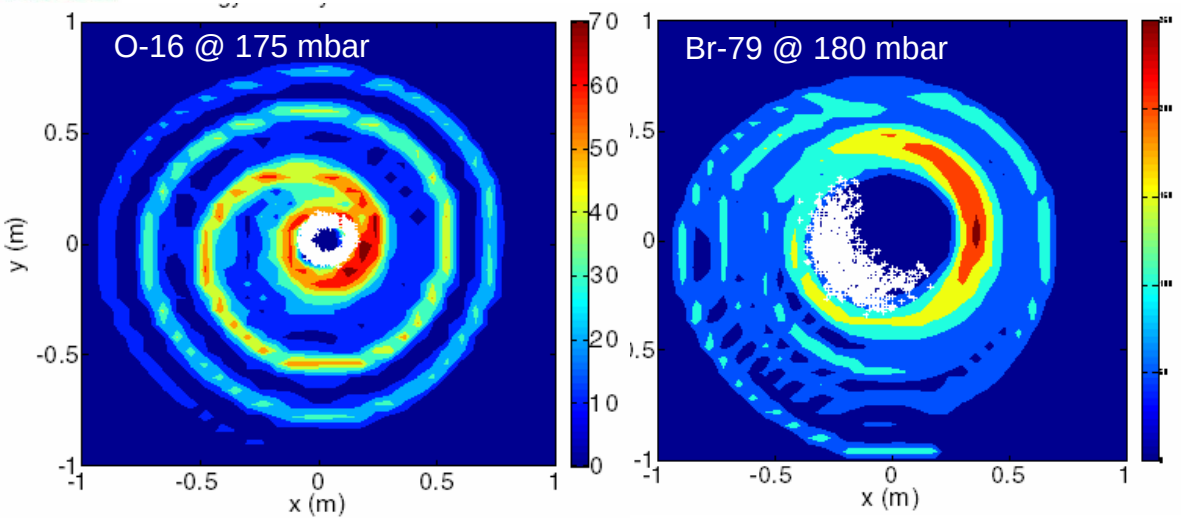


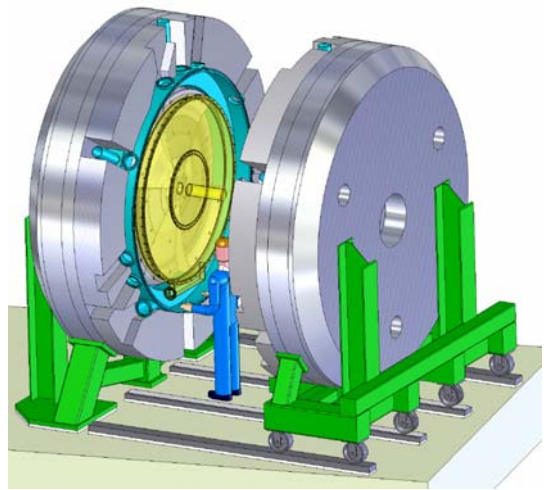


Faster extraction – higher beam rate capability – better stopping of light beams

G. Bollen, D.J. Morrissey, S. Schwarz, NIM A550 (2005) 27, C. Guénaut et al., Hyperfine Interactions 173 (2006) 35,
G. Pang et al., Proc. PAC07, 2007

Cyclotron Gas Stopper

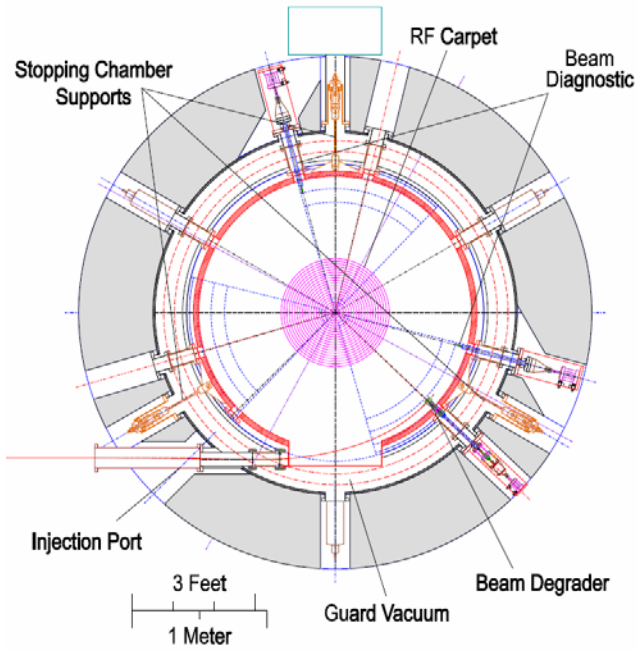




Extensive simulations to evaluate and optimize performance – incorporating

- E-m forces
- Stopping power, energy and angular scattering
- Evolution of charge states (largest uncertainty)
- Detailed PIC simulations of space charge effects

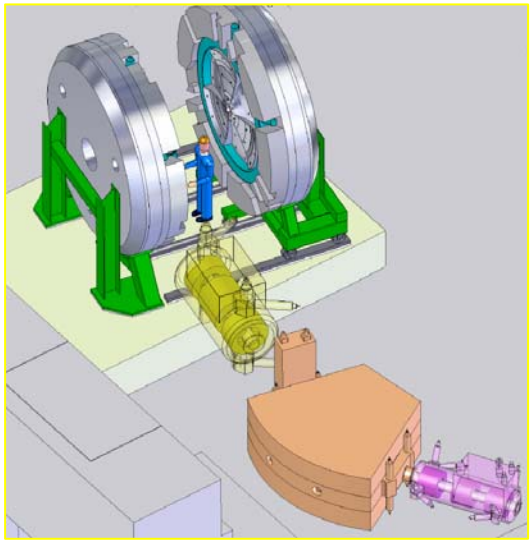
Mechanical and magnet design studies

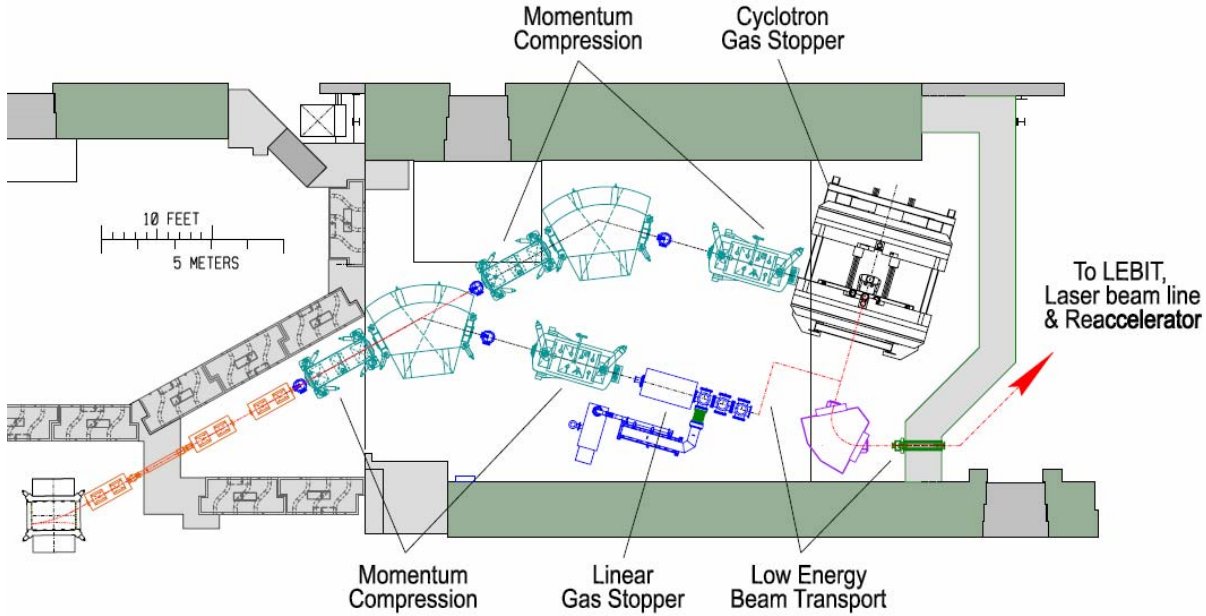


Best system for light and medium-heavy isotope beams

- Stopping efficiencies > 80%
- Higher beam rate capability than linear stoppers
- Extraction times well below 50 ms

Gas Stopping Overall strategy

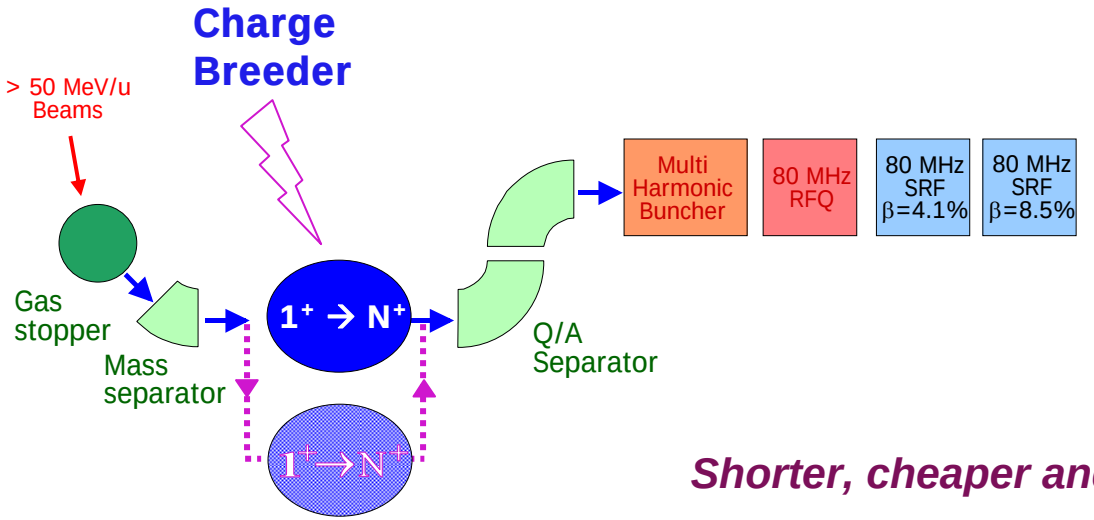




Gas stopping at high energies needs sustained R&D effort – important for the NSCL and future facilities

- Continue study of cyclotron gas stopper and next-generation linear gas-stopper concepts (cryogenic, RF carpets)
- Install two gas stopping beam lines in vault, equip one by 2009

The MSU N+ reacceleration concept



- **Only one frequency – 80 MHz**
- **All RF cavities on ground potential**
- **No strippers**
- **Variable duty cycle**

Shorter, cheaper and better performance

- **EBIS/EBIT charge breeding** (ε >50%) **is the method of choice over ECRs** (ε <10%) for reacceleration of beams with rates as expected for ISF and similar facilities
- An **EBIS/EBIT based N+ scheme promises significant efficiency gains** over conventional 1+ schemes

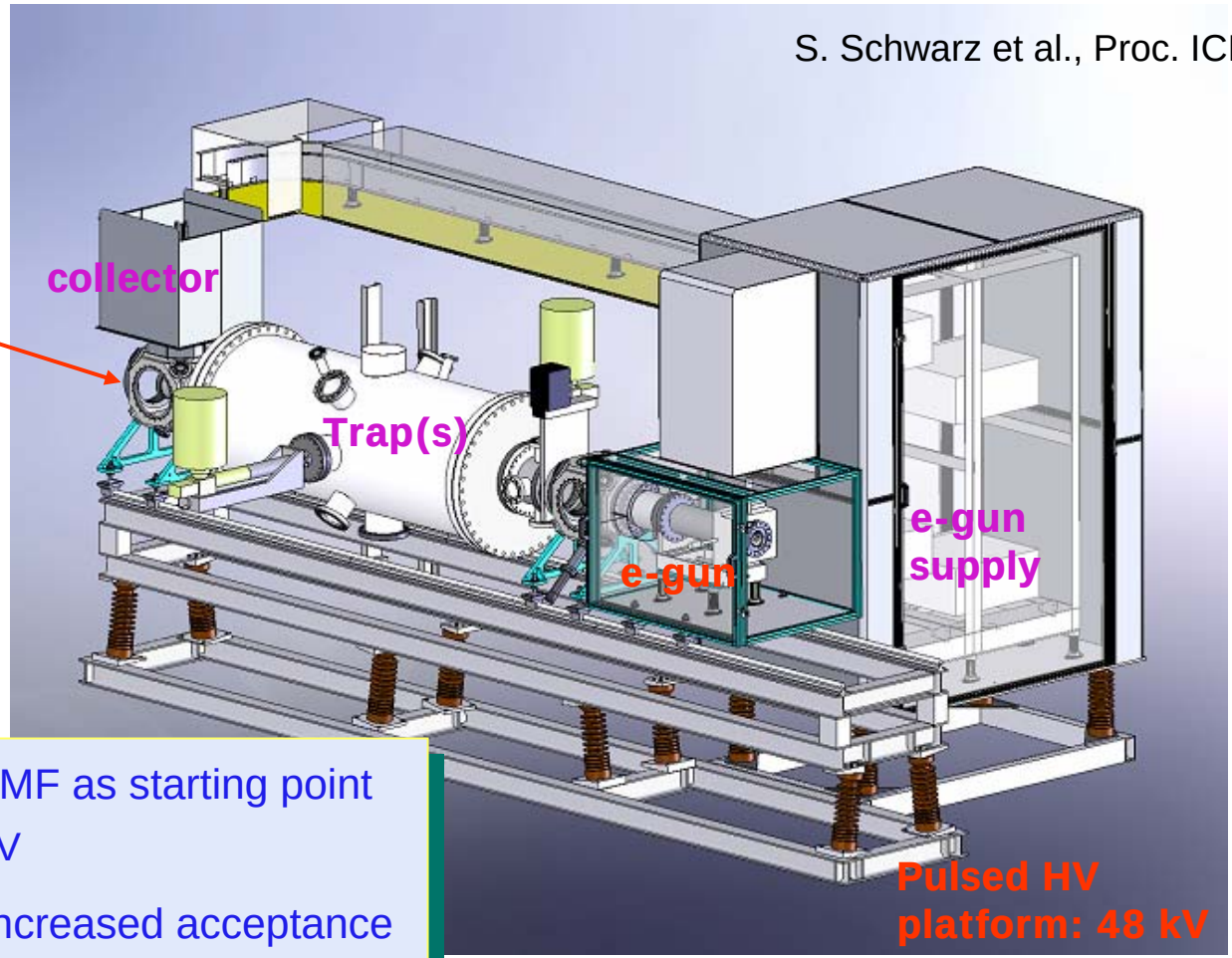
	N+ scheme	1+ scheme	Gain ε(N+)/ε(1+)
ε (A<40)	> 55% (1 CS)	40% (1-2 CS)	1.5 3
ε (A=100)	> 45% (1 CS)	16% (3 CS)	3 10
ε (A=200)	> 35% (1 CS)	12% (4 CS)	3 12
Beam rate	> 10^9/s	>> 10^9/s	Multi-Cs 1 Cs

Pioneered at REX-ISOLDE

NSCL-EBIT charge breeder

Breeder requirements: breeding times ~ 10 ms, beam intensity 10^9 ions/s

S. Schwarz et al., Proc. ICIS 07



TITAN-EBIT at TRIUMF as starting point

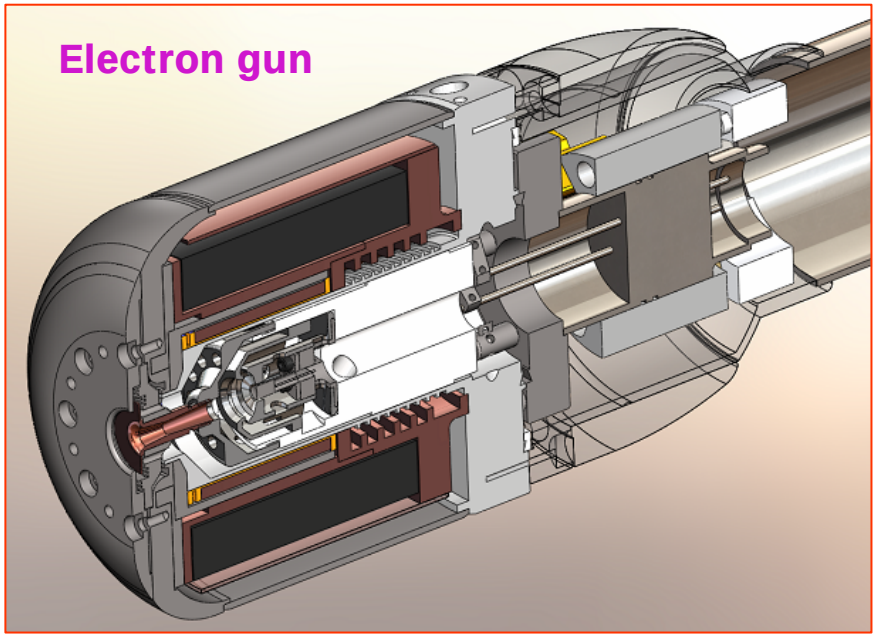
- 10^4 A/cm^2, 6T, 60 kV

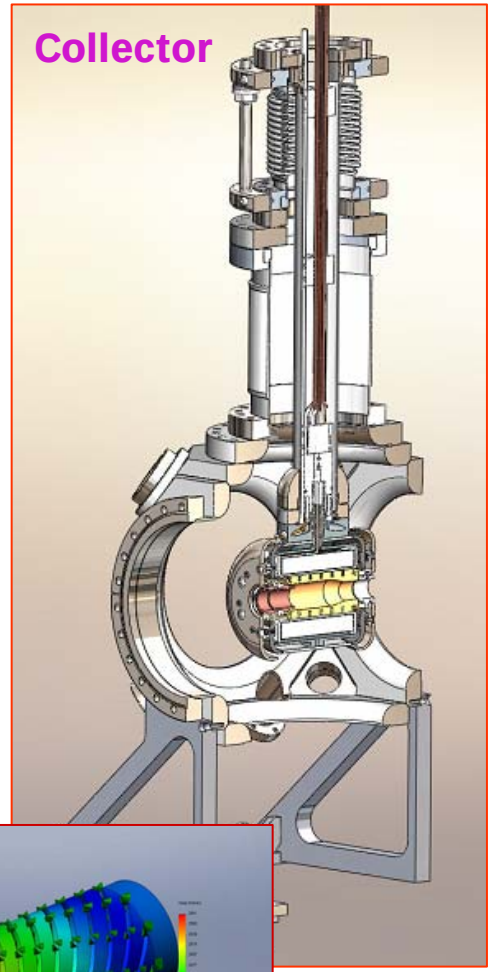
modified design for increased acceptance

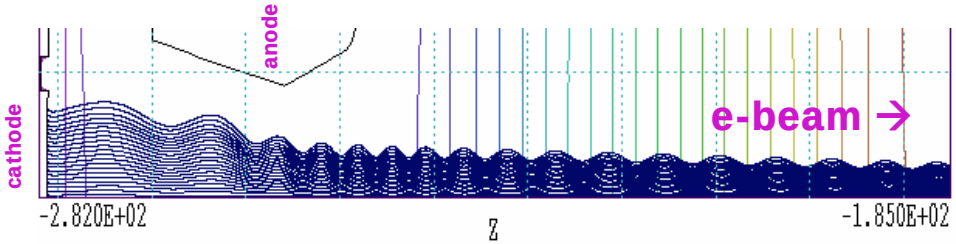
- larger trapping region (40 cm)
- variable B-field configuration (2T + 8T)
- higher current density (<10^5A/cm^2)

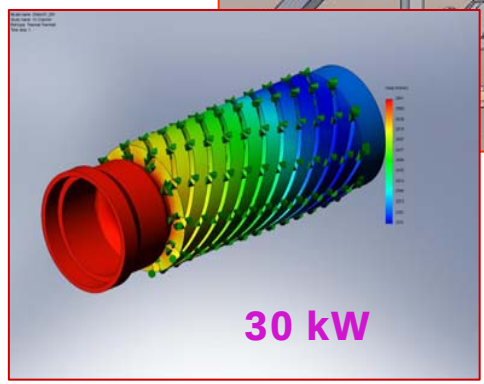
Collaboration with MPI-K/Heidelberg, TRIUMF, GSI

Design + simulation work





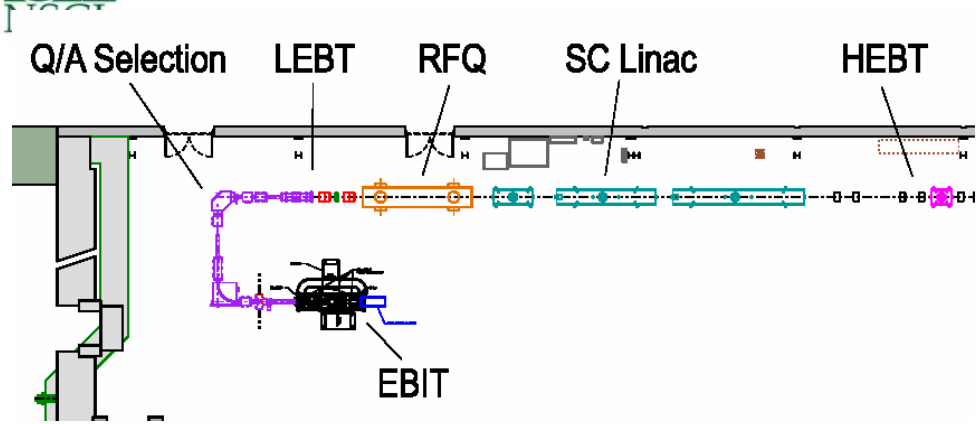




TRICOMP – optics simulation

Dedicated code development:
beam optics + acceptance + charge breeding

Re-accelerator LINAC



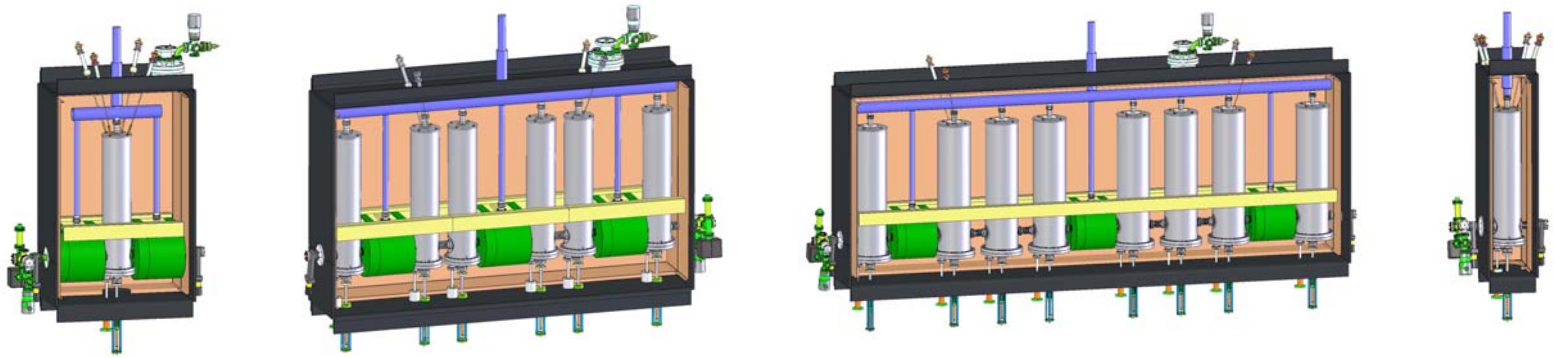
Input Energy	12 keV/u
Q/A	0.2 – 0.4
Emittance (norm.)	0.6 π mm-mrad
Energy	0.3 – 3.2 MeV/u
Energy Spread	± 0.2 %
90% L. Emittance	0.29 π keV/u-ns
Transmission	82%

LEBT with multi-harmonic buncher

Radio frequency quadrupole (RFQ) linac

Superconducting linac: $\lambda/4$ resonators $\beta = 0.041$ and $\beta = 0.085$ ← NSCL RIA design

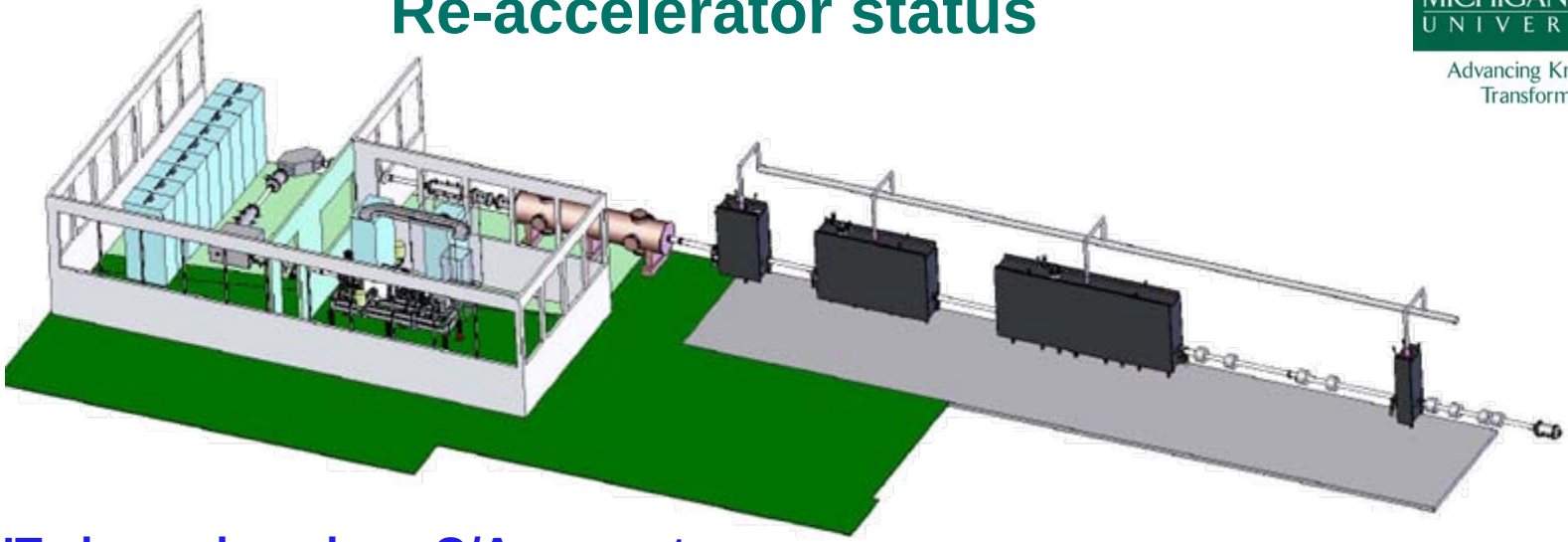
LEBT with re-buncher



Initially RIBs 0.3 - 3.2 MeV/u, upgrade option 12 MeV/u

X. Wu et al., Q. Zhao et al., PAC2007 Proceedings

Re-accelerator status



- **EBIT charge breeder + Q/A separator**
  - Simulations to maximize acceptance, breeding performance ongoing
  - Mechanical design underway
  - Construction of non-critical components started
- **LINAC** (< 3.2 MeV/u)
  - End-to-end optics design performed
  - **RT-RFQ ordered**
  - long-lead items ordered, cavity constr. started, refinements of cryostat design
  - Construction of mezzanine for reaccelerator – spring 2008
- **Experimental area + equipment**
  - Nuclear structure and nuclear astrophysics workshops
  - Discussion about equipment for first experiments ongoing - TPC workshop

Goal: First reaccelerated beams in 2010

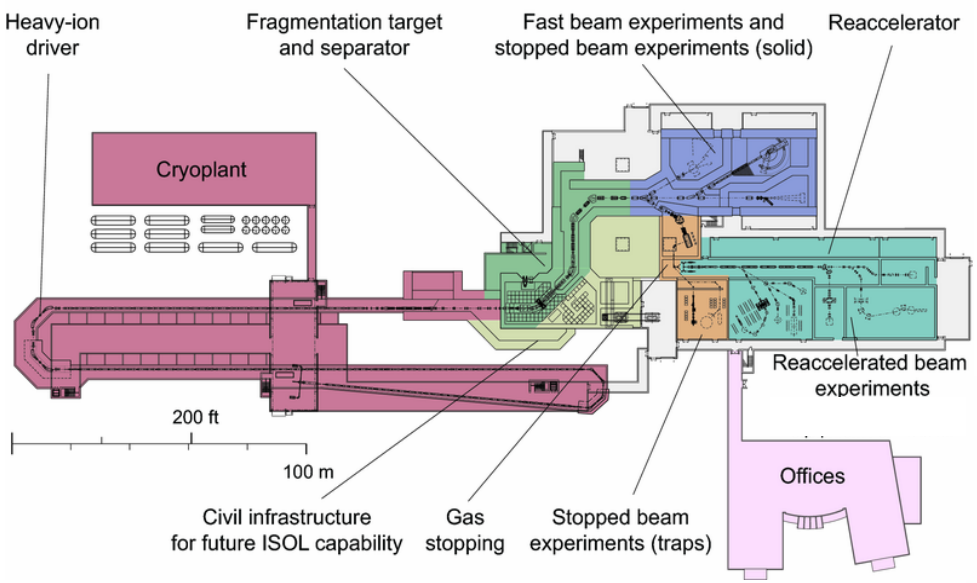
NSCL Long-Range Vision

"Blue Book" proposed building a 200 MeV superconducting linac driver

- 200 MeV linac endorsed by Rare Isotope Science Assessment Committee of the National Research Council of The National Academies (December 2006)
- #2 priority recommendation for the 2007 Long Range Plan for Nuclear Science is "construction of the Facility for Rare Isotope Beams, FRIB, a world-leading facility for the study of nuclear structure, reactions and astrophysics" (May 2007)
- Rare Isotope Beam Task Force recommends "that DOE and NSF proceed with solicitation of proposals for a FRIB based on the 200 MeV, 400 kW superconducting heavy-ion driver linac at the earliest opportunity" (August 2007)
- All recommendations are consistent with the vision laid out in the Blue Book

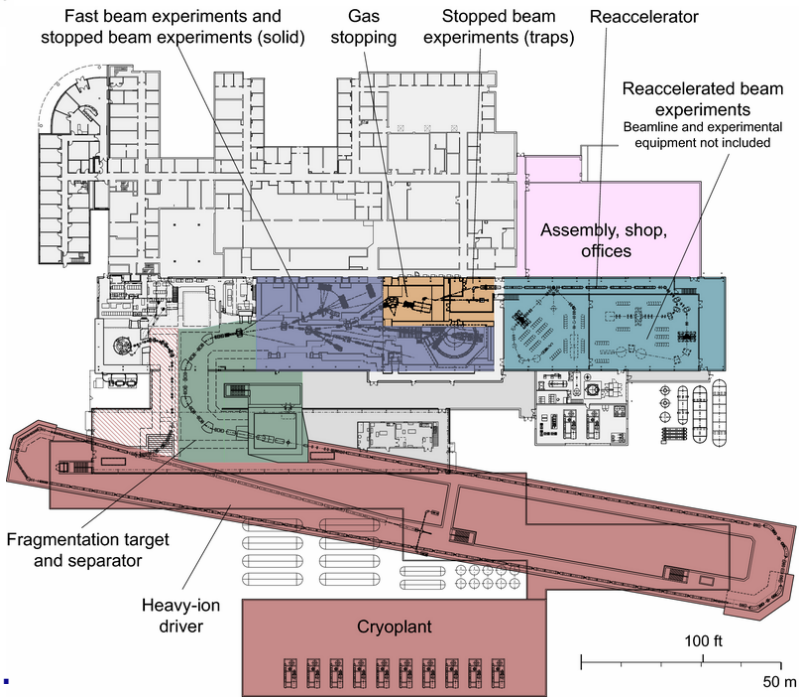
Isotope Science Facility – Options

Heavy Ion Linac; energy/nucleon: > 200 MeV ^{238}U; up to 400 kW beam power



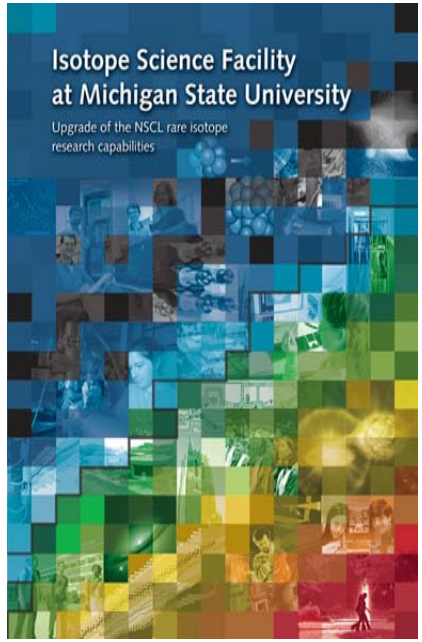
New South Campus Facility allows unconstrained optimization

Layout optimized for staged, science driven upgrade options



Upgrade at NSCL site: constrained by space available, but less costly by ~ $100 M; will need further optimization…

Rare Isotope Beams at MSU – Present and Future



- **NSCL maintains a forefront rare isotope research program**
  - Intense beams far from stability provide far reach + new development: heavier beams
  - Arsenal of powerful instrumentation + new detector developments
  - First facility to perform experiments with thermalized rare isotope beams from projectile fragmentation; advanced gas stopping concepts under study
  - Reacceleration project will provide world-wide unique MeV/u beams
- **MSU well-suited and prepared to house US next-generation RIB facility**

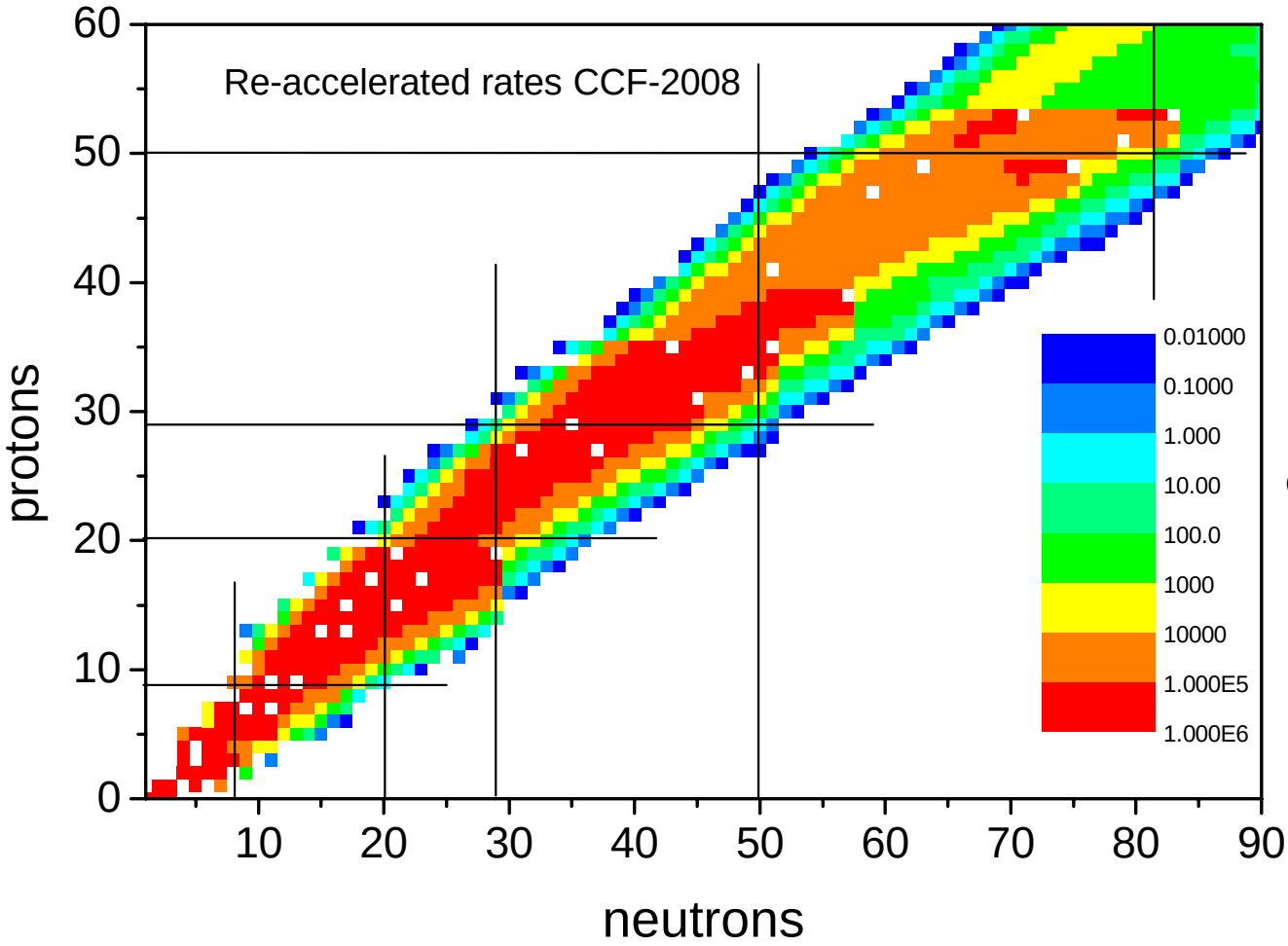
NSCL

MICHIGAN STATE UNIVERSITY

Advancing Knowledge.
Transforming Lives.

NSCL reaccelerated beams

Beams with **variable duty cycle**:from microsecond macro-pulses to quasi-continuous beams



Rates based on very conservative assumptions:

CCF-2008 rates+

$\varepsilon_{stopping}$ = 20% @ 10^6/s

$\varepsilon_{breeding}$ = 60%,

$\varepsilon_{linac+transport}$= 70 %,

t_{delay}= 60 ms

Reliability is important