Thermalization of fast rare isotope beams – from linear gas cells to cyclotron gas stoppers

G. Bollen
National Superconducting Cyclotron Laboratory NSCL
Michigan State University

- **Low-energy beams at the NSCL**
- **Limitations of present stopper concepts**
- **The cyclotron gas stopper**
- **Perspectives**

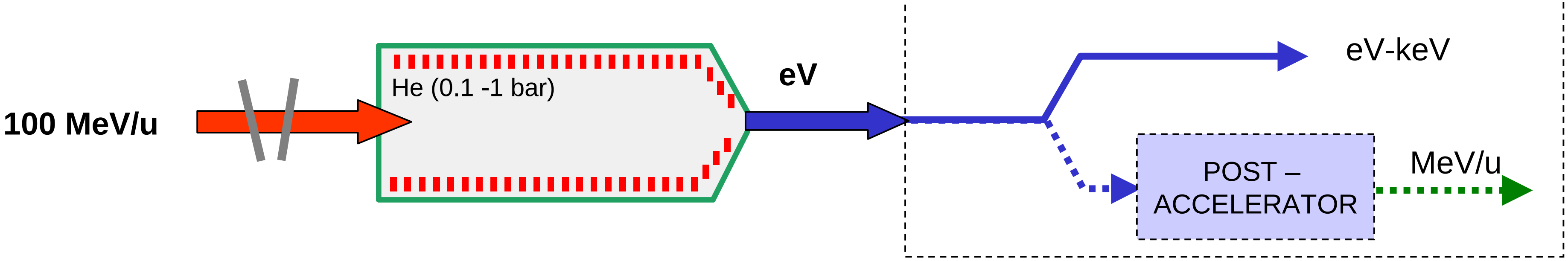
MICHIGAN STATE UNIVERSITY

Low-Energy Beams from Fast-Beam Fragmentation

Benefits of relativistic projectile fragmentation and in-flight separation

- Fast
- No element selectivity
- Short beam development times

New facilities and upgrades promise high intensities



Gas stopping → new opportunities with precision (ISOL-type) experiments

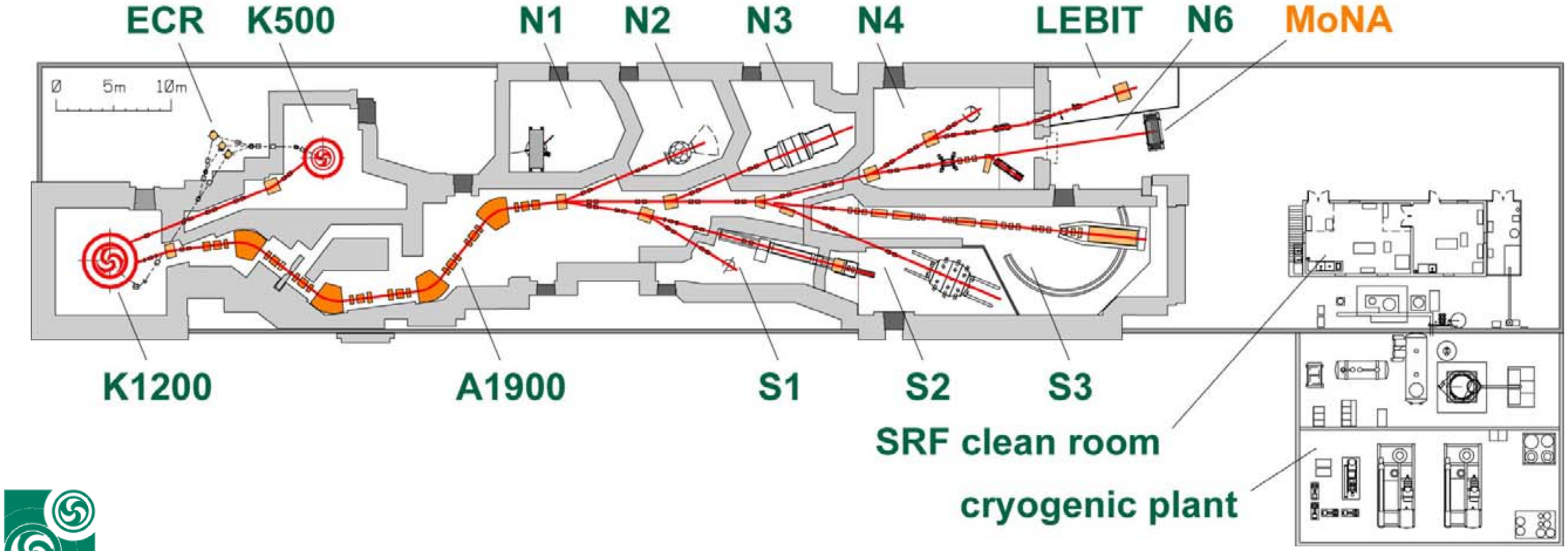
- Mass measurements
- Laser spectroscopy
- Experiments with post-accelerated beams

Planned for
next-generation RIB Facility in the US
FAIR/GSI, RIBF/RIKEN

Stopping of beams >50 MeV/u tested at NSCL, RIKEN, GSI(ANL)

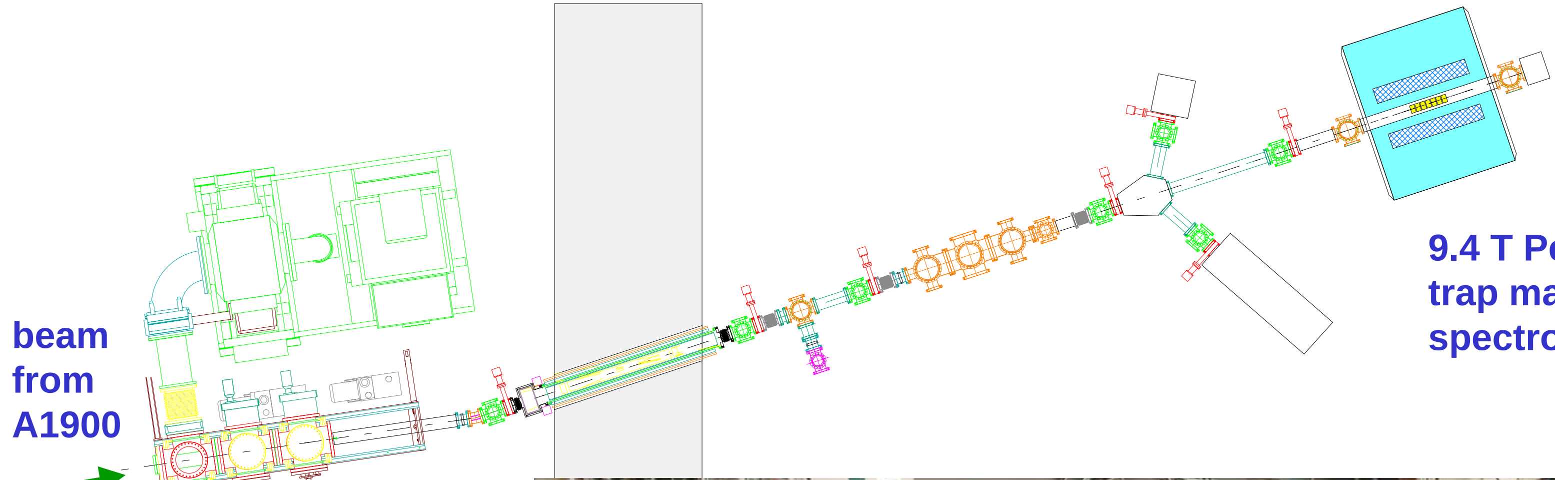
First stopped-beam experimental program with LEBIT at NSCL

National Superconducting Cyclotron Laboratory



Premier rare isotope science facility in the US

Low Energy Beam and Ion Trap Facility LEBIT

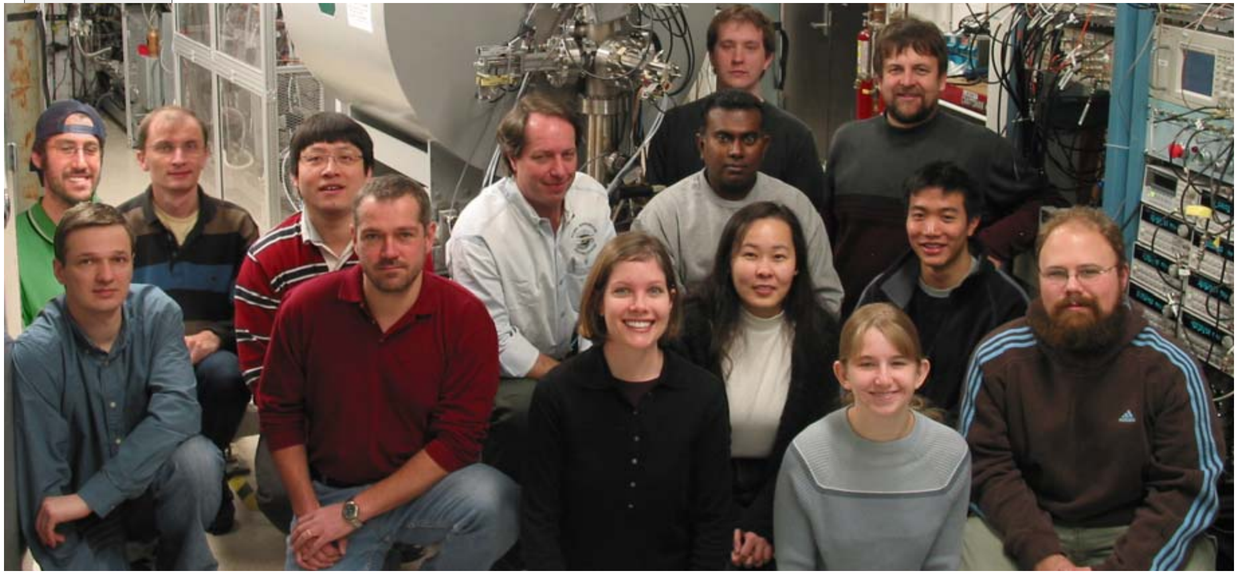


beam
from
A1900

gas stopper

9.4 T Penning
trap mass
spectrometer

Started in 2000



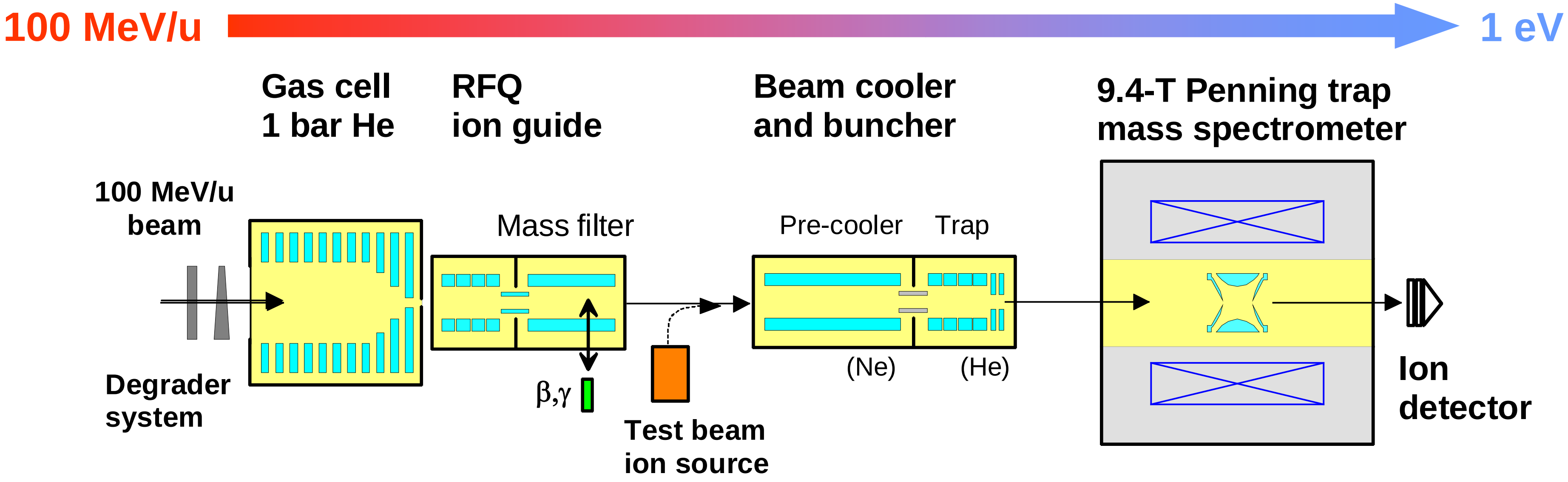
D. Davies, E. Kwan, A. Kwiatkowski, G. Pang, A. Prinke, R. Ringle, J. Savory, P. Schury, C. Sumithrarachchi, *T. Sun*

M. Facina, *J. Huikari*, C. Bachelet, M. Block, C. Folden III, C. Guenaut

LEBIT trappers and helpers

G. Bollen, D.J. Morrissey, S. Schwarz

Low Energy Beam and Ion Trap Facility LEBIT



100 MeV/u → 1 eV

Gas cell
1 bar He

RFQ
ion guide

Beam cooler
and buncher

9.4-T Penning trap
mass spectrometer

100 MeV/u
beam

Degrader
system

Mass filter

β,γ

Test beam
ion source

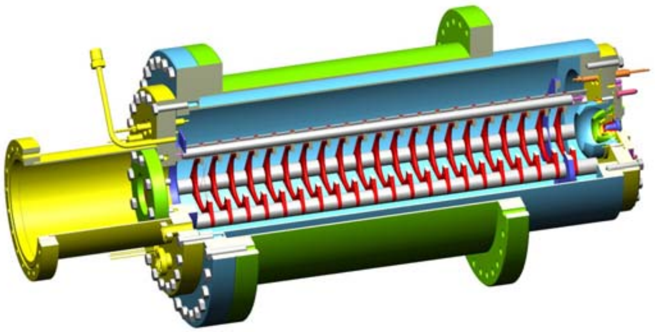
Pre-cooler (Ne)

Trap (He)

Ion
detector

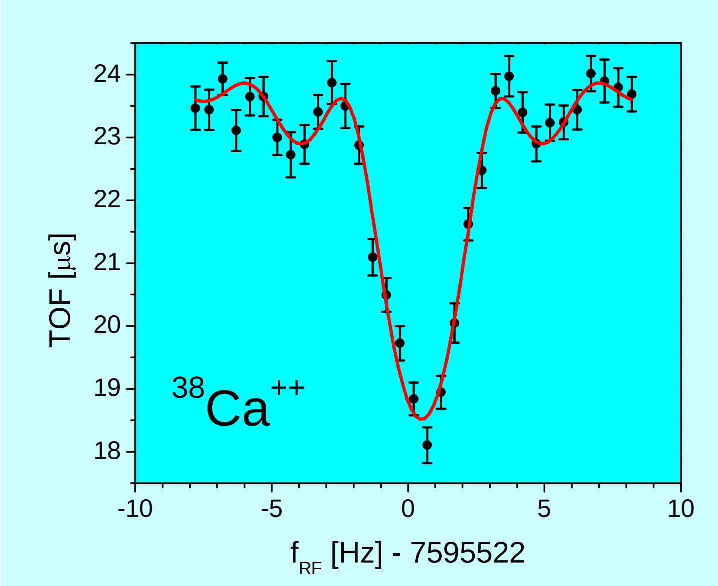
- Stopping and extraction of rare isotope beams (100 MeV/u) from fast beam fragmentation

Mass measurements since May 2005
^{33}Si, ^{34}P, ^{37}Ca, ^{38}Ca, ^{40}S, ^{41}S, ^{42}S, ^{43}S, ^{44}S, ^{65}Ge, ^{66}Ge, ^{66}As, ^{67}As, ^{80}As, ^{81m}Se, ^{81g}Se

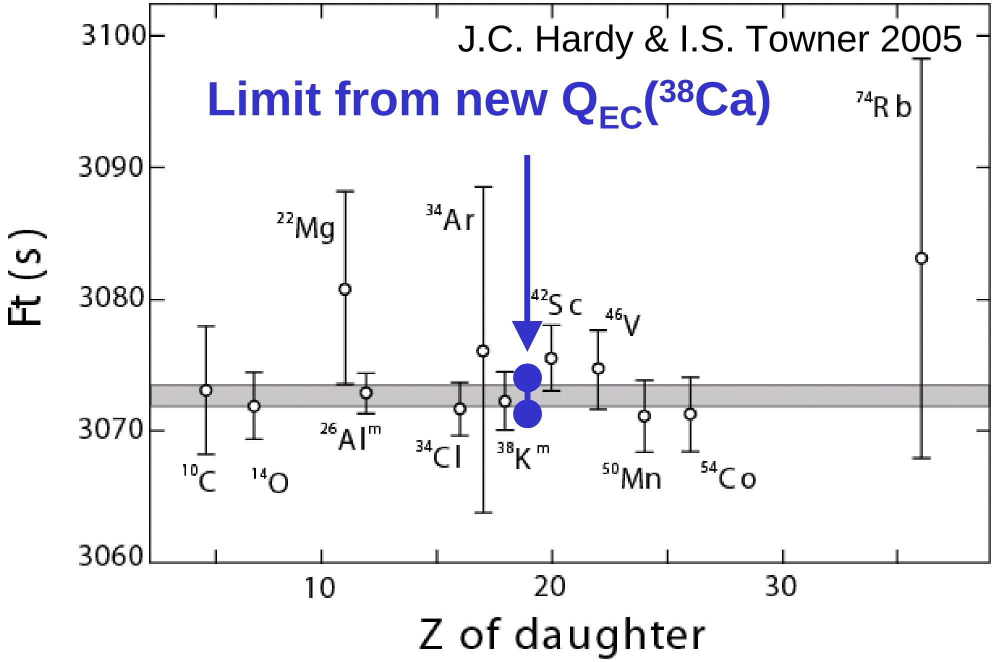


First LEBIT Results

Super-allowed beta emitter ^{38}Ca – a new candidate for test of CVC



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


J.C. Hardy & I.S. Towner 2005

Limit from new Q_{EC}(^{38}Ca)

LEBIT: $\delta m = 280$ eV → **10 fold improvement of Q_{EC} value**

Partial half-life *t* still required

$T_{1/2}$ needs to be improved

Branching ratio unknown

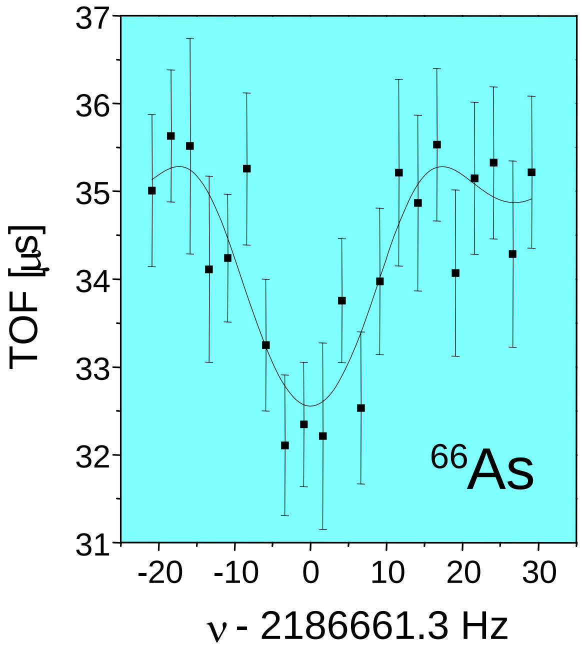
TAMU: J.C. Hardy in progress

ISOLDE: B. Blank et al. in progress

First LEBIT results

Masses close to N = Z = 33: ^{65}Ge, ^{66}Ge, ^{66}As, ^{67}As, ^{69}Se

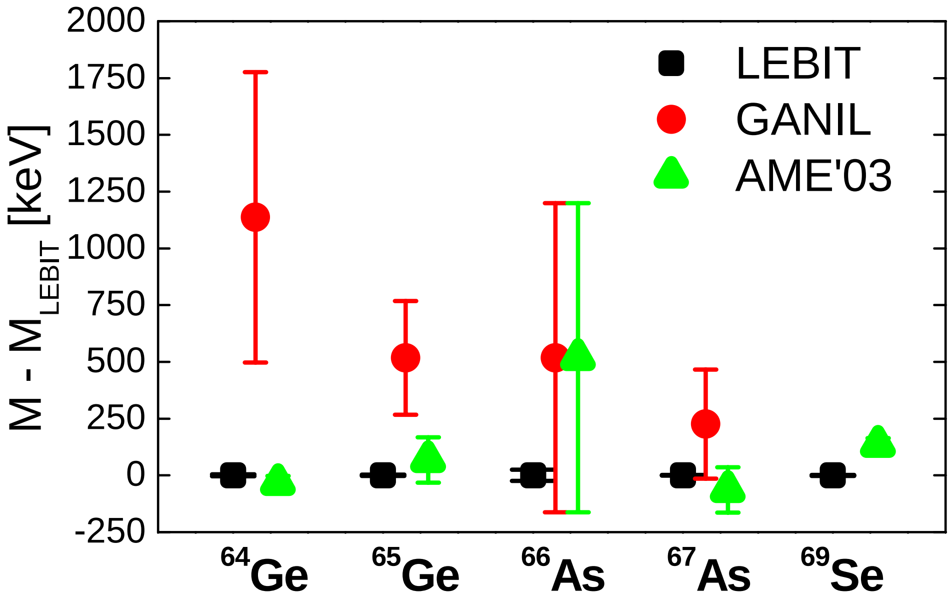
Example: short half-life



$T_{1/2}$ = 96 ms

P. Schury et al., PRC in preparation

Mass comparison

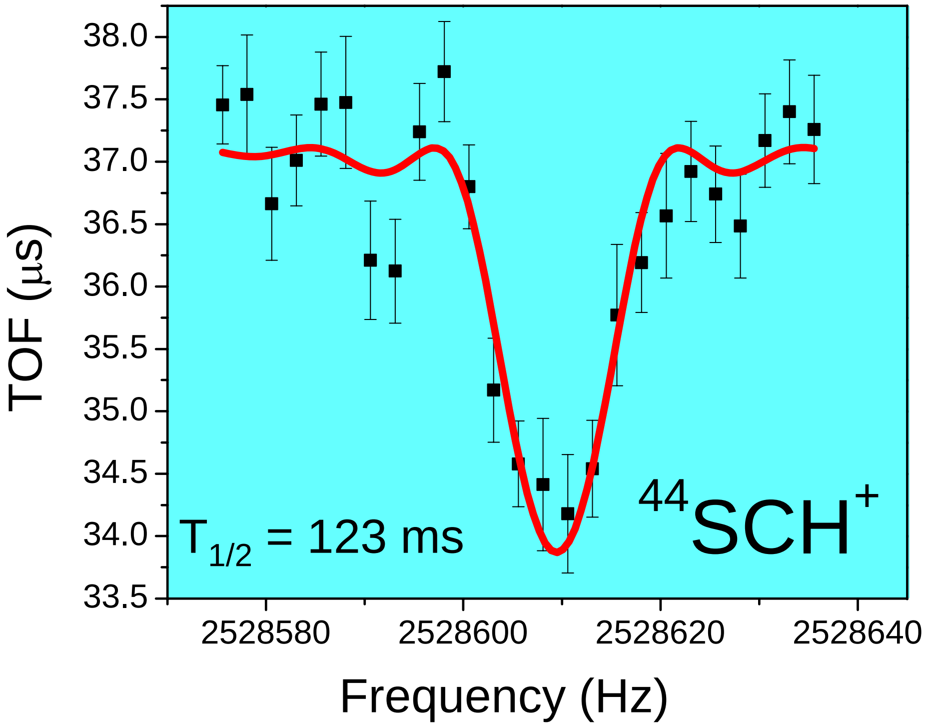


- **20-fold improved masses in region critical to rp-process**
- **Improved effective lifetime for waiting point nucleus ^{68}Se**

Latest LEBIT results

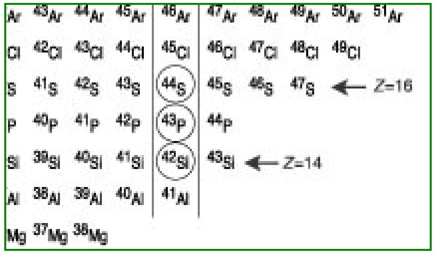
Towards N = 28 in vicinity of Z = 14: ^{40}S, ^{41}S, ^{42}S, ^{43}S, ^{44}S

< 2 weeks old



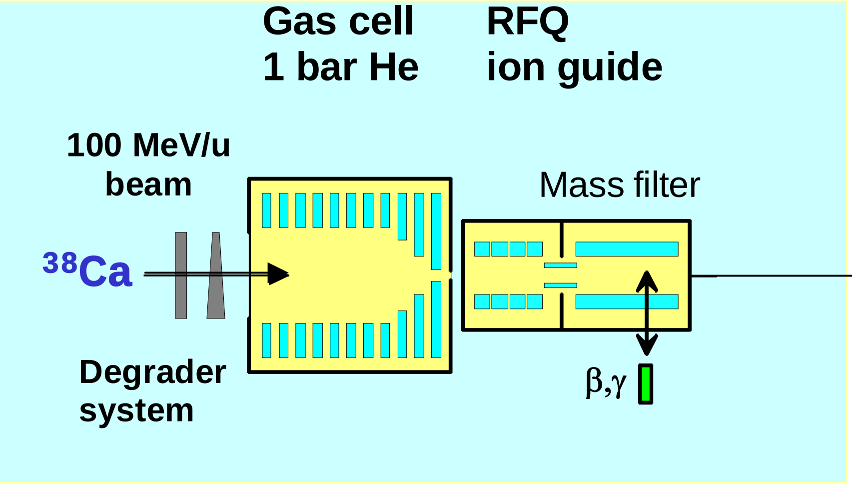
Beam rate into gas cell < 30/s

Expected accuracy δm ≈ 5 keV

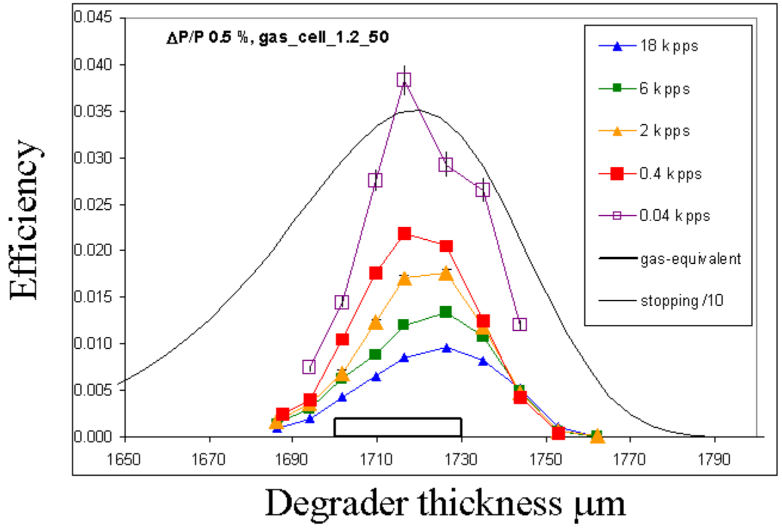


Ar	^{43}Ar	^{44}Ar	^{45}Ar	^{46}Ar	^{47}Ar	^{48}Ar	^{49}Ar	^{50}Ar	^{51}Ar	
Cl	^{42}Cl	^{43}Cl	^{44}Cl	^{45}Cl	^{46}Cl	^{47}Cl	^{48}Cl	^{49}Cl		
S	^{41}S	^{42}S	^{43}S	^{44}S	^{45}S	^{46}S	^{47}S	← Z=16		
P	^{40}P	^{41}P	^{42}P	^{43}P	^{44}P					
Si	^{39}Si	^{40}Si	^{41}Si	^{42}Si	^{43}Si	← Z=14				
Al	^{38}Al	^{39}Al	^{40}Al	^{41}Al						
Mg	^{37}Mg	^{38}Mg								

NSCL linear gas stopping cell

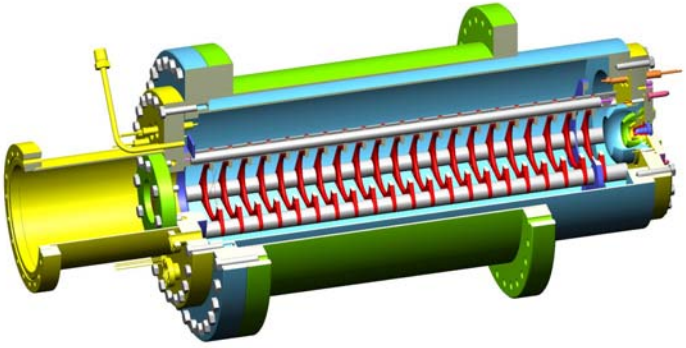


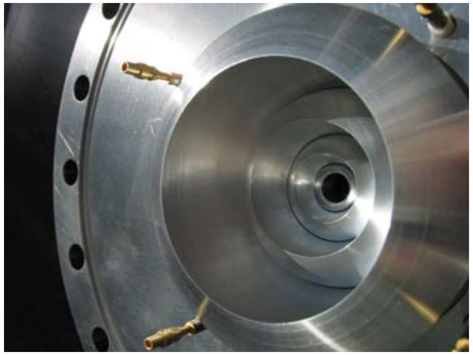
Stopping and total efficiency



- **Beam momentum compression**
- **Cell: 1 bar He, length =50 cm**
- **Electrostatic guiding fields**

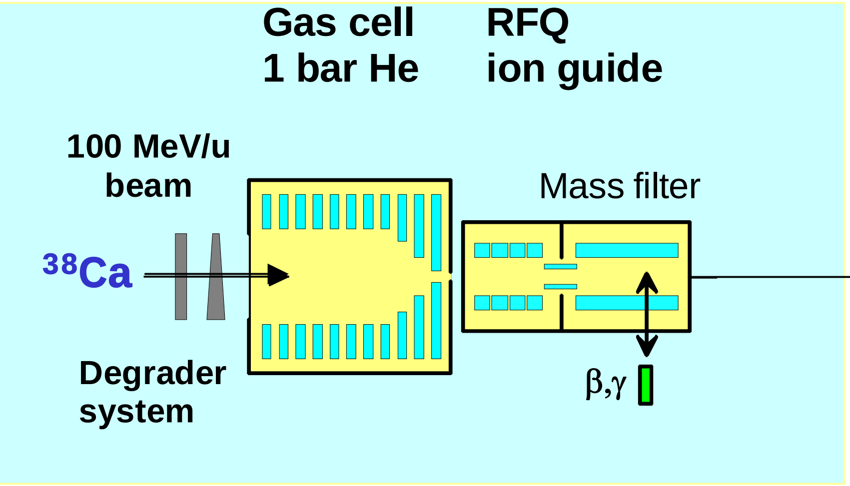
Rate-dependence observed

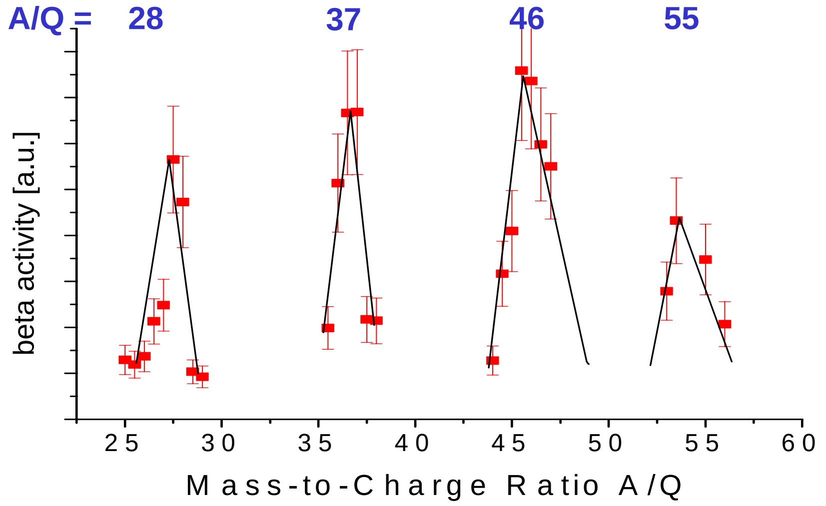




L.Weissman et al.
NIM A522 (2004) 212, NIM A531 (2004) 416,
Nucl. Phys. A746 (2004) 655c, NIM A540 (2005) 245

NSCL linear gas stopping cell





Mass filter scan of beta activity

UHV + multi-step gas purification

Molecular sidebands $[^{38}Ca(H_2O)_n]^{2+}$

Chemistry remains important

Stable (molecular) ion beams

10^6-10^7 (He^+-e^- pairs)/ion + charge exchange with gas impurities

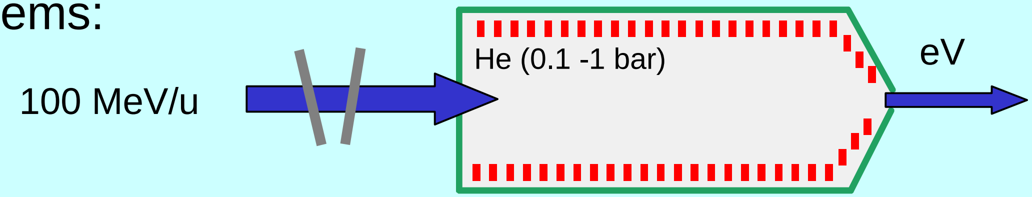
Radioactive molecular sidebands

$^{A}Ca(H_20)^+$, $^{A}AsHe^+$, $^{A}SCH_3$, $^{A}SiCH_3$, $^{A}PN_2$, ^{A}GeH

Several purification steps in LEBIT, for example CID in cooler/buncher

Stopping of intense beams in linear gas cells

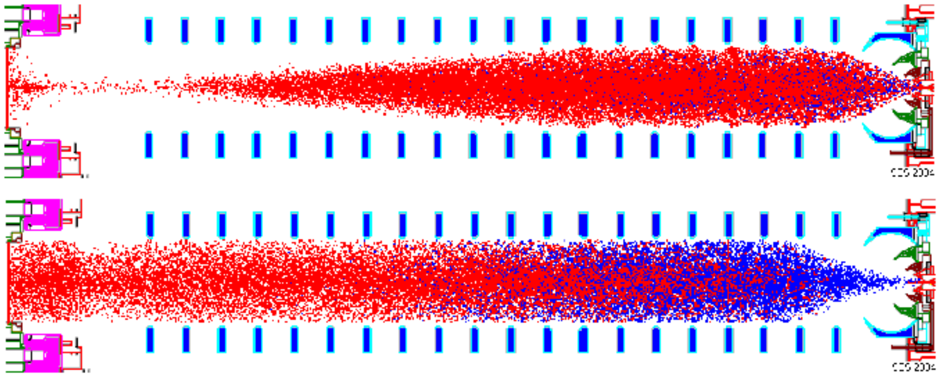
Present systems:



E > 50 MeV/u tested at
NSCL, RIKEN, GSI(ANL)

NSCL gas cell (L=50 cm, p_{He}=1000 mbar)

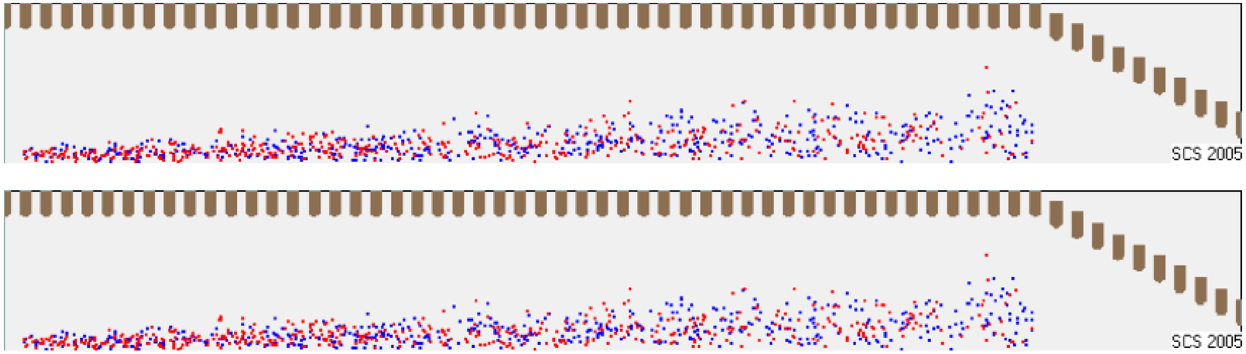
PIC simulations
(S. Schwarz)



R = 10^3/s

R = 10^7/s

Large gas catcher (L=1.5 m, p_{He}=300 mbar)



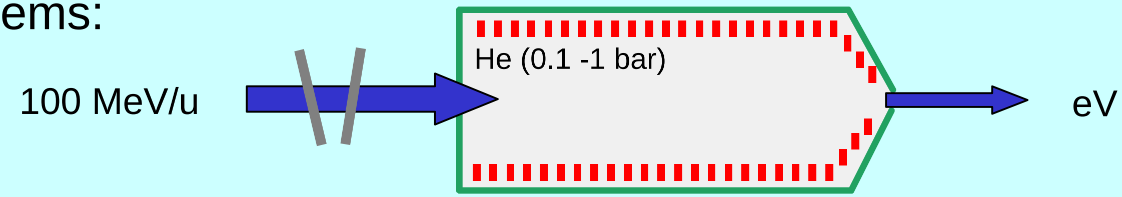
R = 10^4/s

R = 2 x10^7/s

red dots – He, blue dots – fragments

Stopping in linear gas cells

Present systems:



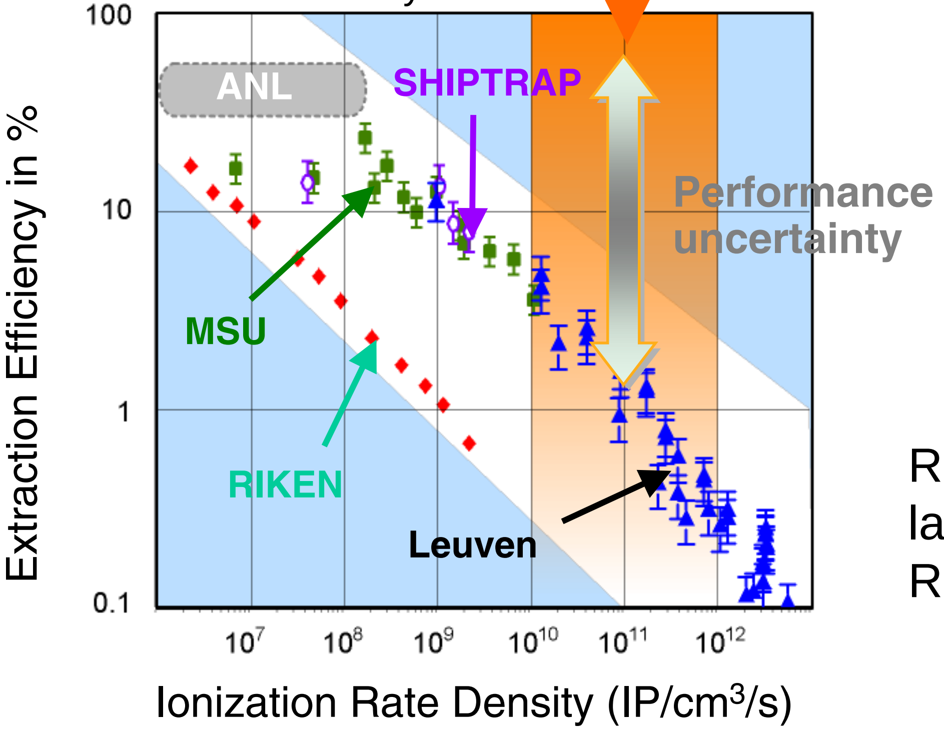
100 MeV/u

He (0.1 -1 bar)

eV

1) Intensity-dependent extraction efficiencies limit experimental opportunities

D. J. Morrissey



Beam rate 10^9/s (next generation facility)

Ionization 10^6-10^7 IP/ion

Linear cell stopping volume

V = 10,000 – 30,000 cm^3

R&D:

larger linear gas cells (benefit limited)

RF wall carpets (complicated, vacuum)

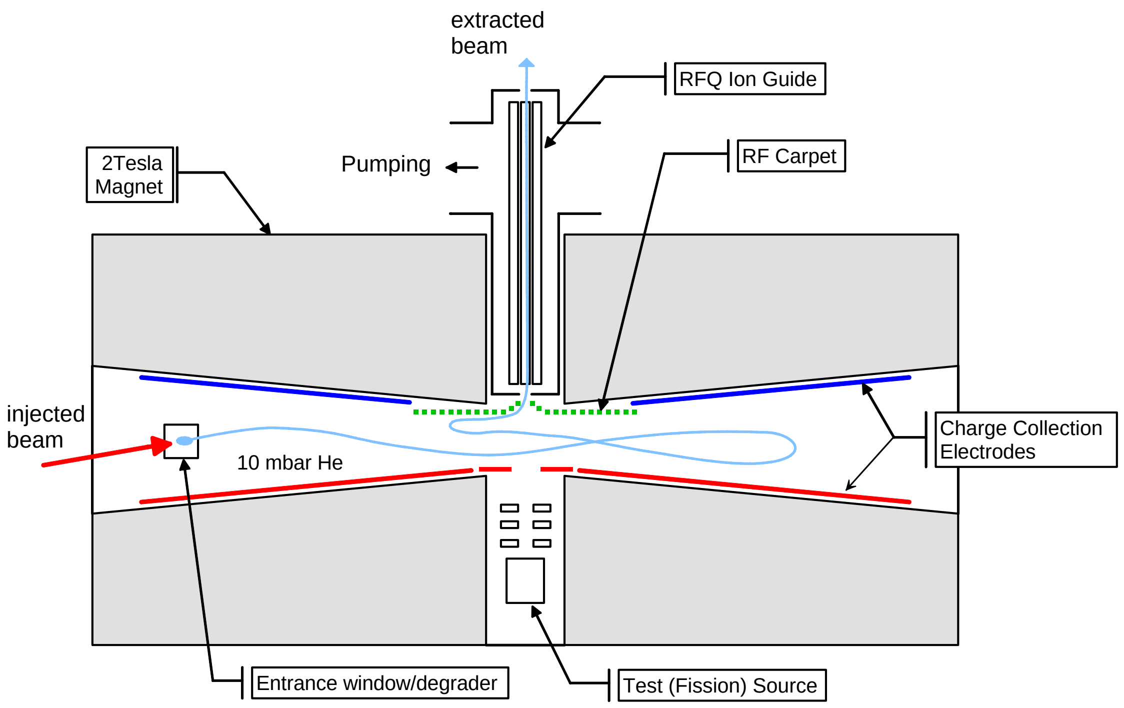
2) Extraction times of 10- 200 ms do not match advantages of fast RIB production

Cyclotron Gas Stopper Concept

Principle: Gas-filled weakly-focusing cyclotron magnet + RF guiding techniques

Expectations:

- **Long stopping path**
  - **→ low gas pressure**
- **Low pressure**
  - **→ fast extraction**
- **Large volume**
  - **→ reduced space-charge effects**



Exotic atom studies in a cyclotron trap for antiprotons, pions, and muons

L.M. Simons, Hyperfine Interactions 81 (1993) 253

Proposal for a cyclotron ion guide with RF carpet

I. Katayama, M. Wada, Hyperfine Interactions 115 (1998) 165

A Study of Gas-Stopping of Intense Energetic Rare Isotope Beams

G. Bollen, D.J. Morrissey, S. Schwarz, NIM A550 (2005) 27

First MC simulations

Simulation

Lorentz force, stopping power, charge changing collisions, small angle multiple-scattering

Cyclotron gas stopper

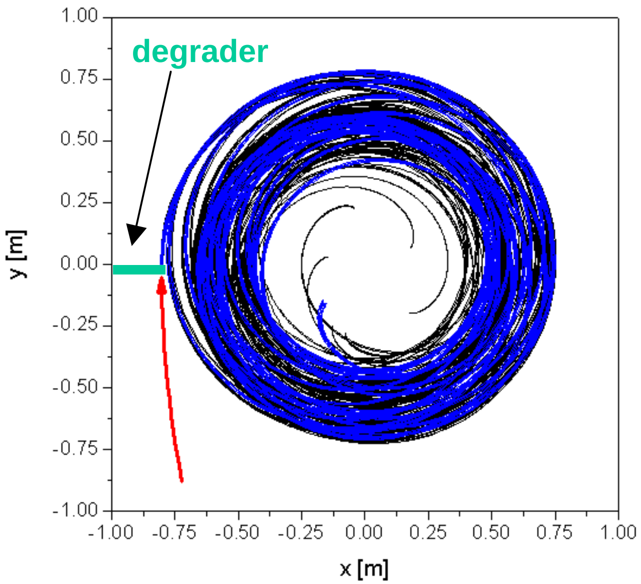
$B = 2$ T; $n = 0.2$, $r_{inj} = 0.75$ m

$p_{He} = 10$ mbar

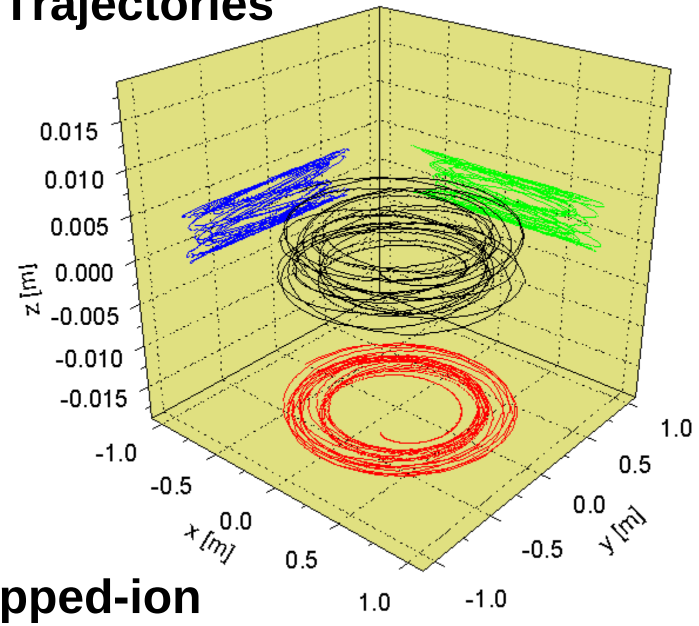
Beam

100 MeV/u ^{78}Br on 2.6mm Al → 610 MeV ^{78}Br

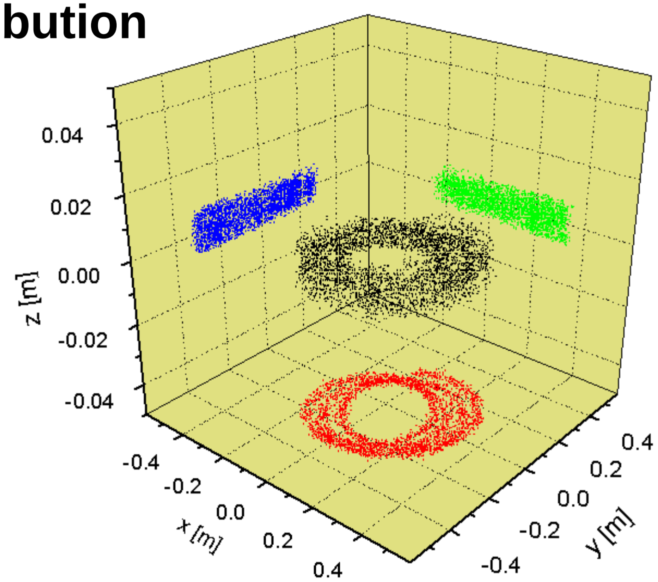
$\Delta E/E = 20\%$; width = 10 mm ; div =10 mrad



3D-Trajectories

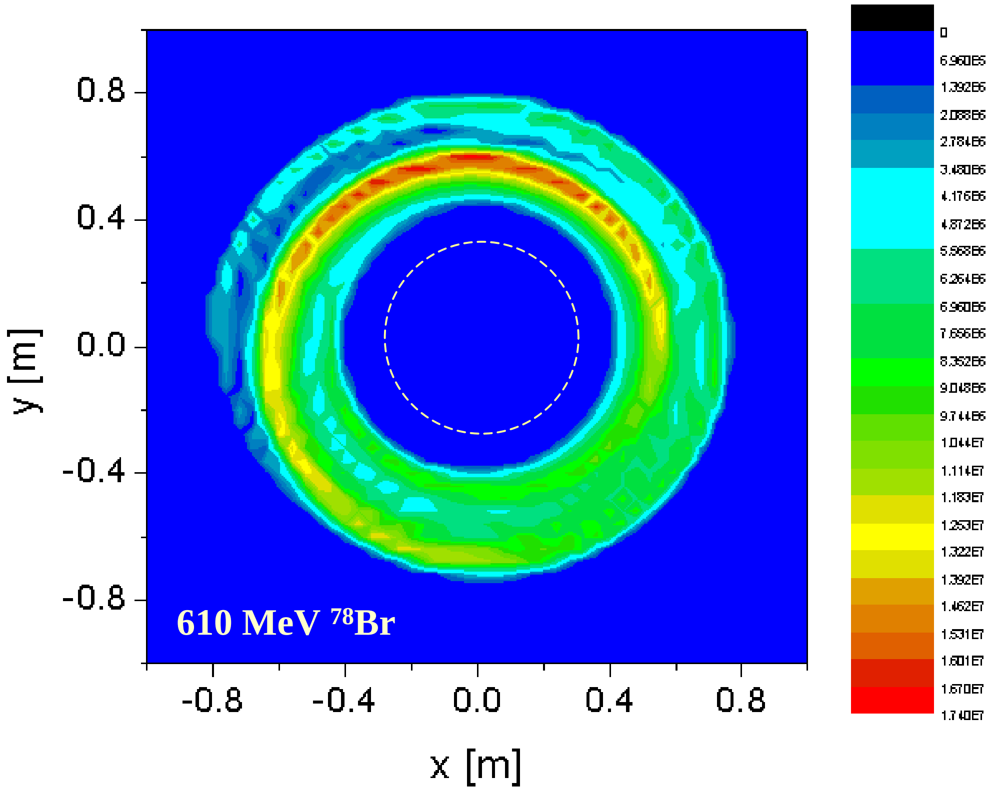


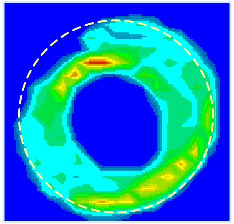
Stopped-ion distribution



Minimizing space charge effects

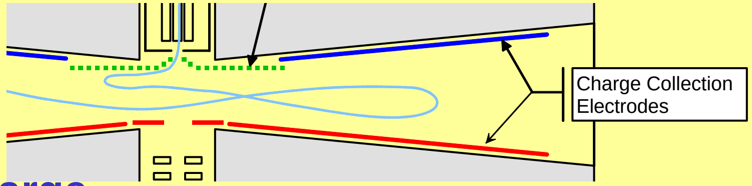
Energy loss density





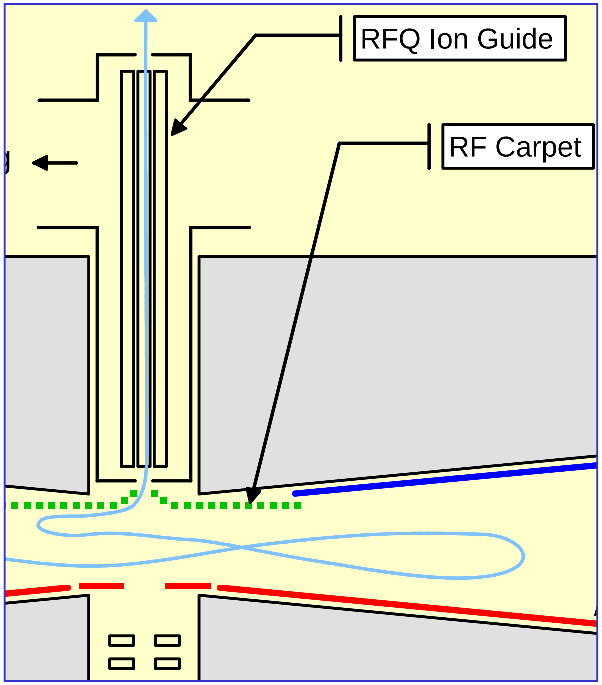
Stopped-ion distribution

- Ions accumulate in center, separated from region of highest ionization
- He$^+$ and e$^-$ can be collected efficiently up to 10^8 incoming ions/s
- Ions with E > 1 MeV don’t care about space charge

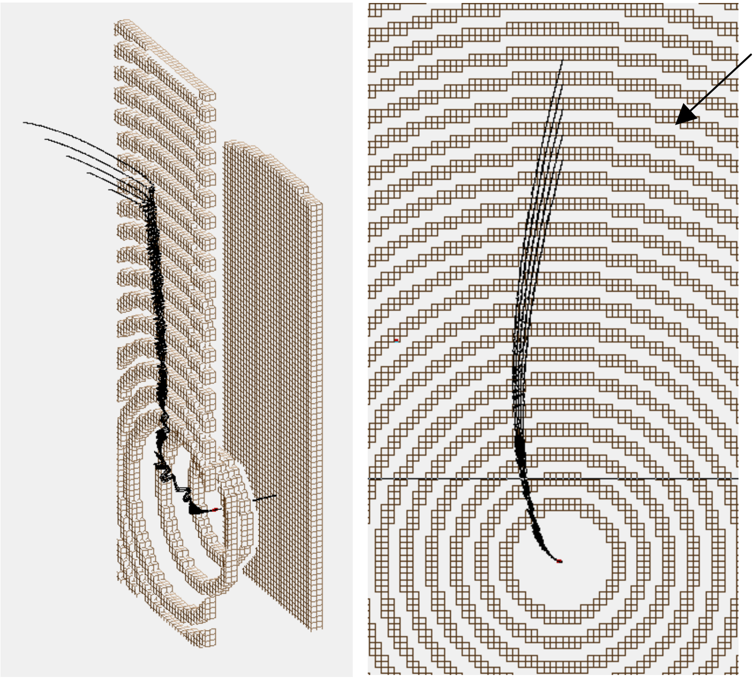


Ion extraction

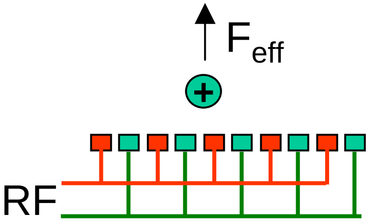
RF carpet + RF ion guides for stopped-ion collection and extraction



Simulations → RF carpets in 2 Tesla field



RF 400V; 1.5MHz
DC gradient 20V/cm
Spacing 1 mm, 0.5 mm thick



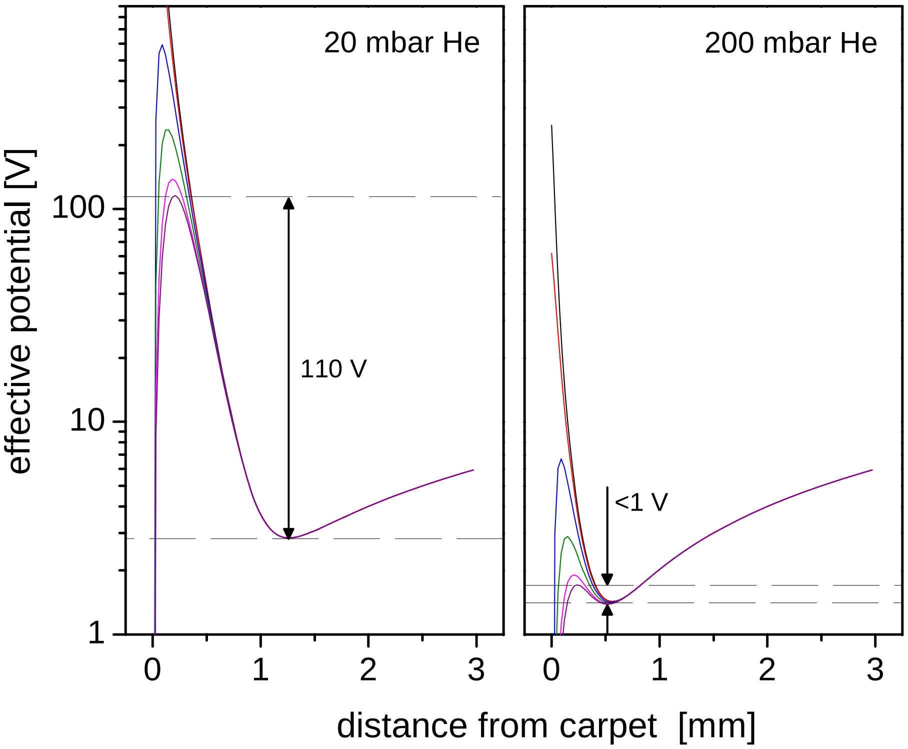
Low gas pressure (10 mbar compared to 200 - 1000 mbar in present systems) →

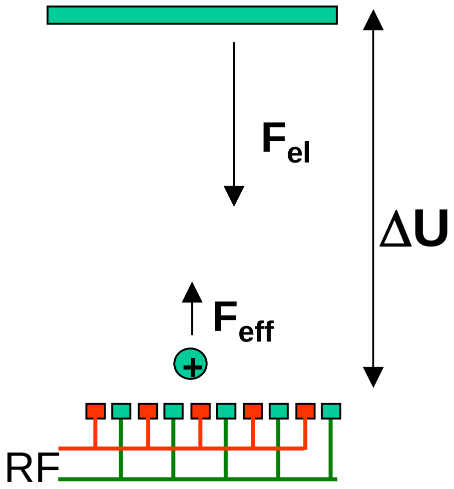
Time for collection onto carpet and transport over 50 cm is < 5 ms !

M. Wada et al., NIM B 204 (2003) 570: RF carpet in linear gas cell

Ion extraction with rf carpet

Effective potential close to surface





1 MHz, U_{rf} = 200 V, d=1mm

A = 40, Q = 1

Cyclotron stopper

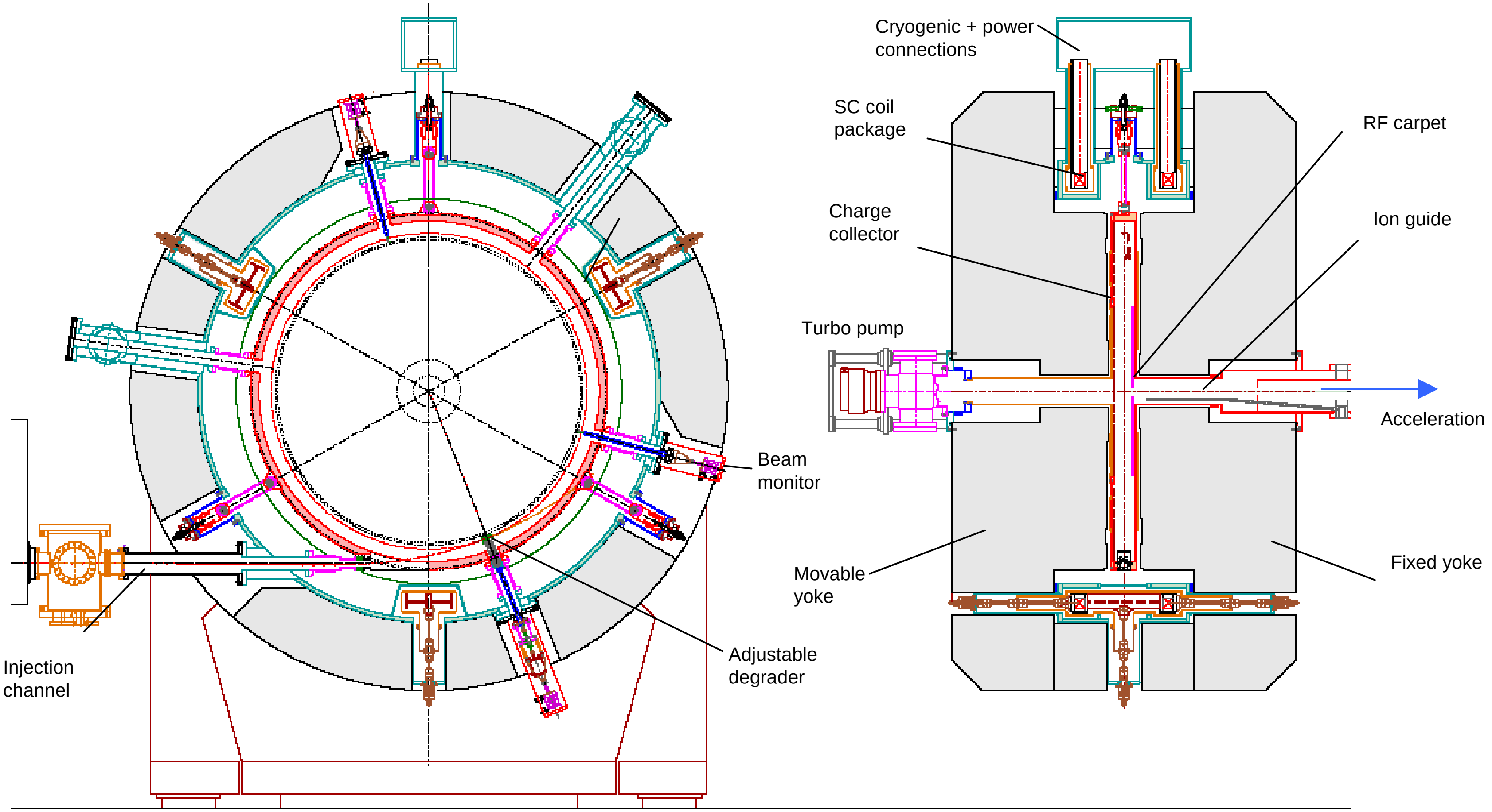
Linear gas cells

NSCL Cyclotron Gas Stopper Project

Superconducting magnet system $B_{max} = 2$ T, $r_{inj} = 0.9$ m, $n < 0.2$

Vertical system with (re)movable yoke, horizontal beam extraction

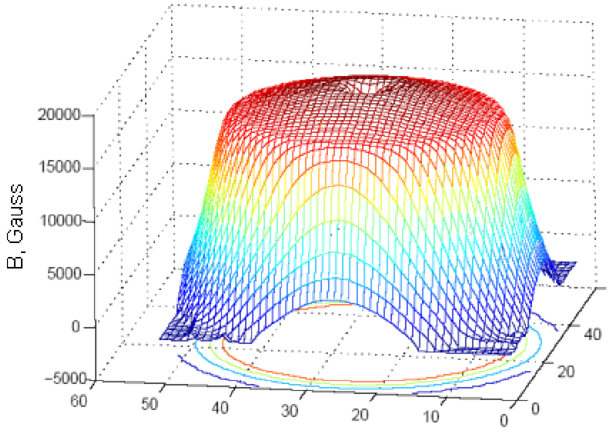
Vacuum chamber in guard vacuum cryogenically cooled



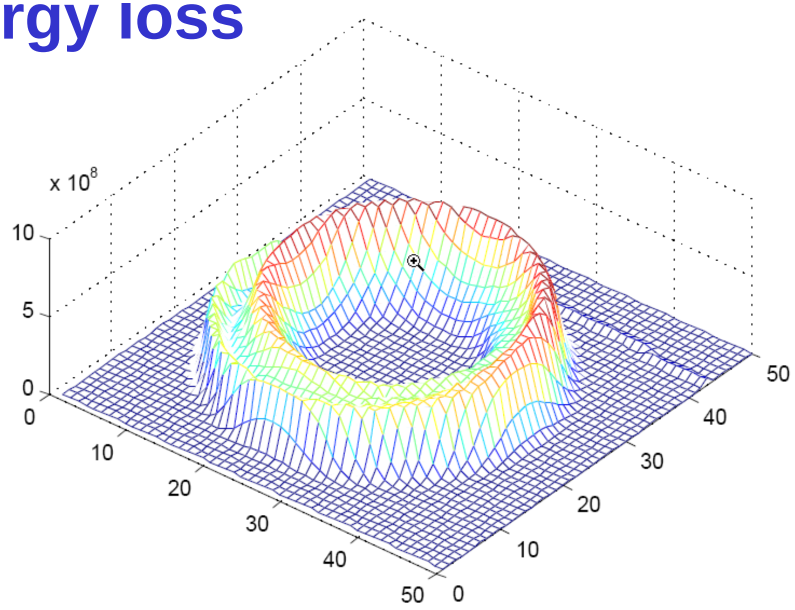
NSCL Project team: G. Bollen, C. Guenaut, D. Lawton, F. Marti, D. J. Morrissey, G. Pang, J. Ottarson, S. Schwarz, A. Zeller

Beam simulation in realistic magnetic fields

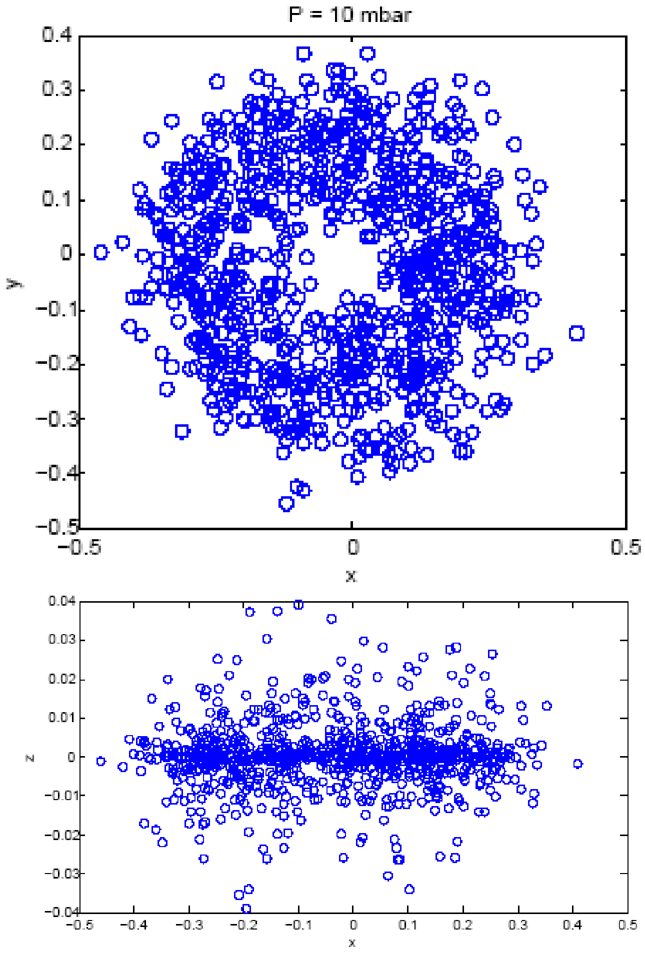
Field



Energy loss



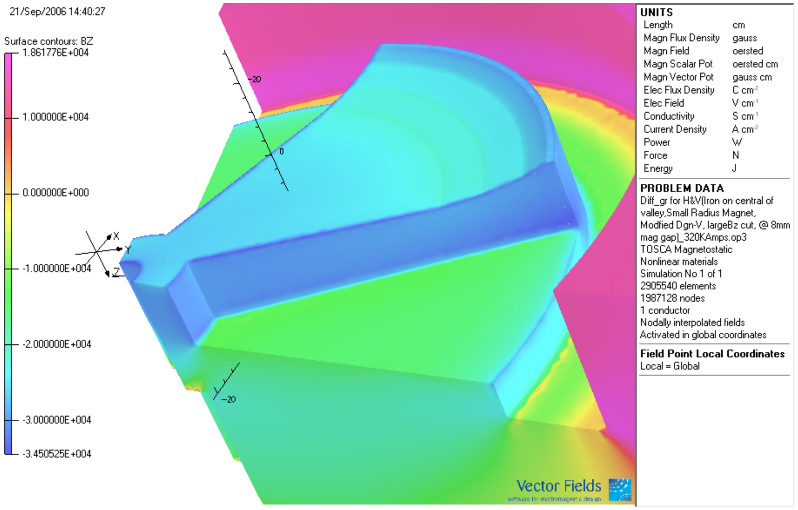
Final positions



10 different magnet systems (S1-S10) considered so far

Realistic simulations – sector fields

Sector field: advantages for beam injection



UNITS

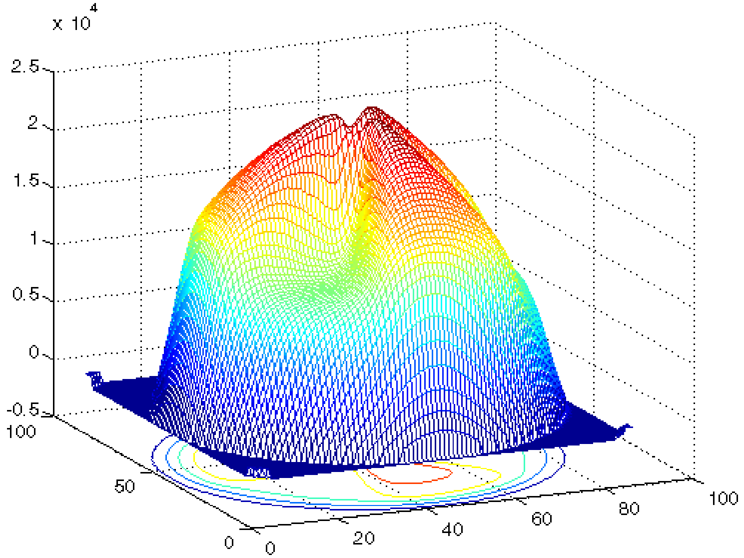
Length	cm
Magn Flux Density	gauss
Magn Field	oersted
Magn Scalar Pot	oersted cm
Magn Vector Pot	gauss cm
Elec Flux Density	C cm^{-2}
Elec Field	V cm^{-1}
Conductivity	S cm^{-1}
Current Density	A cm^{-2}
Power	W
Force	N
Energy	J

PROBLEM DATA

Diff_gr for H&V(Iron on central of valley,Small Radius Magnet, Modfied Dgn-V, largeBz cut, @ 8mm mag gap)_320KAmps.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
2905540 elements
1987128 nodes
1 conductor
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates

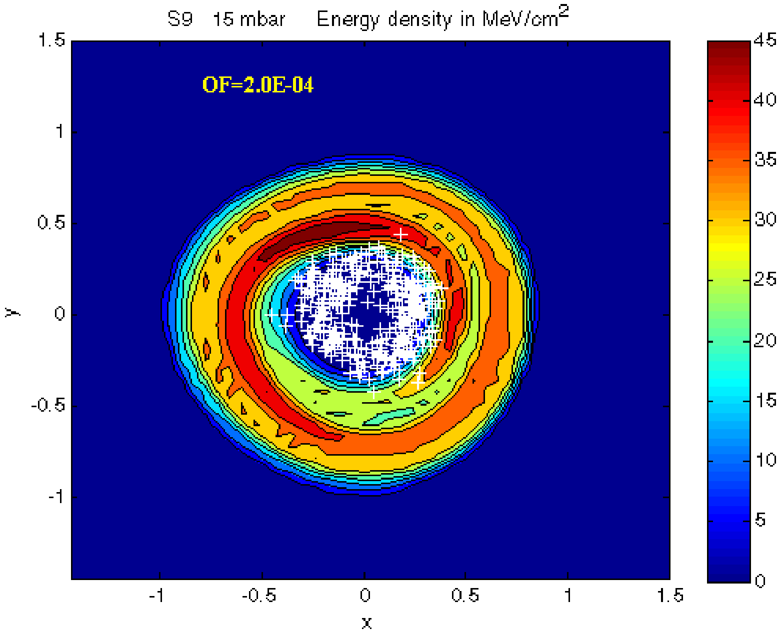
Local = Global



Beam properties after momentum compression:

Bρ = 2.6 Tm, Δp/p = 0.5%,

ε_z = 400 π mm mrad, ε_r = 30 π mm mrad



98% stopping efficiency

NSCL Cyclotron Gas Stopper Project

Status

- Realistic simulations
  Exploration of parameter space (optimum B, shape, p, Bρ)
  ^{70,79,94}Br (done), ^{6,9,11}Li and ^{108,127,144}I.
- Superconducting magnet
  Several system designs performed (S1-S10)
- Mechanical design
  Overall concept for mechanical system developed
  Advanced concept for cryogenic vacuum chamber w. degraders, etc.
- RF carpet
  Basic ion transport simulations, rf carpet test stand will be build
- Towards realization
  Final magnet design and order of coil material before end of 2006.

Time for realization and commissioning 2.5 – 3 years

Costs: $3M

Will have large impact on ongoing mass measurement program
Prepare now for new experimental opportunities

Laser Spectroscopy

Ground state properties via laser spectroscopy

- **Charge radii via isotopic shift measurements**

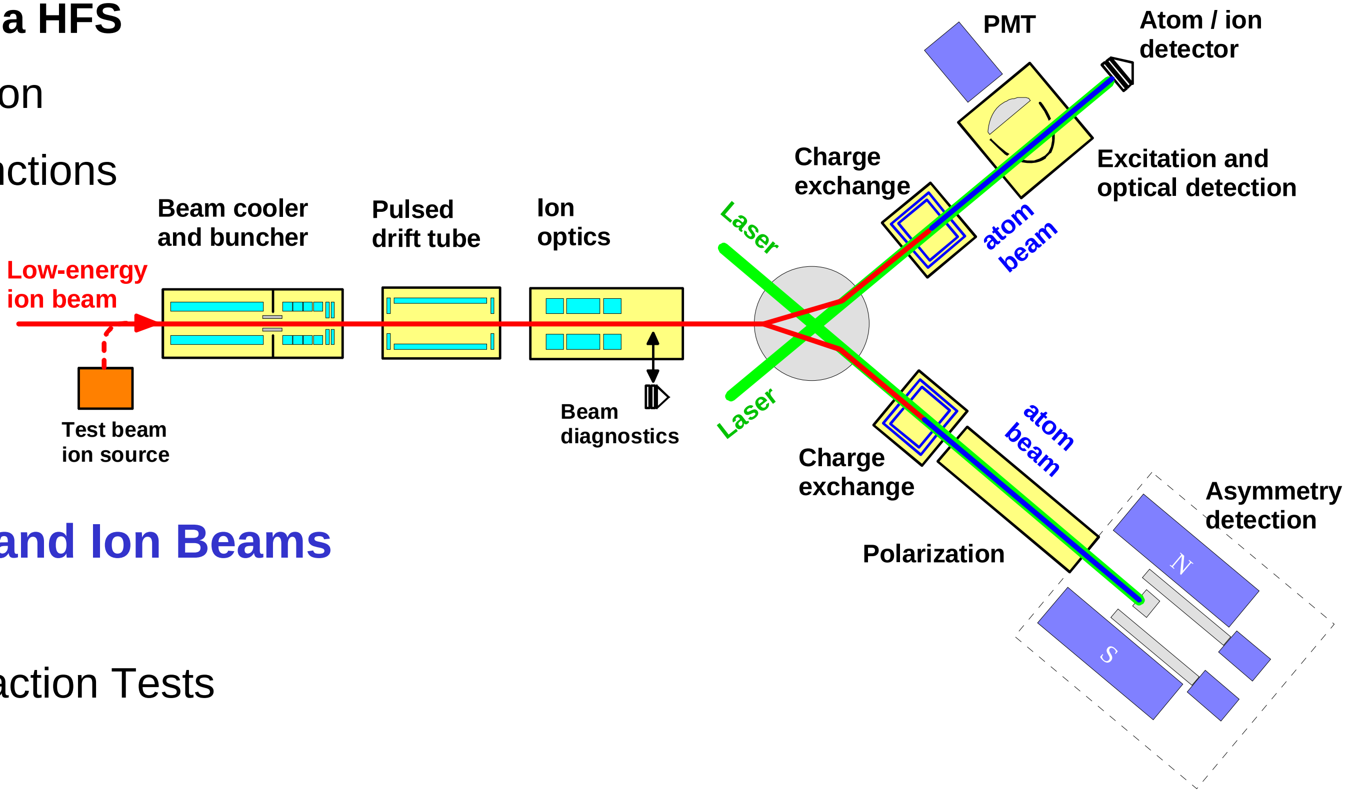
  Skins and Halos - complements matter radius determination

  Nuclear Deformation, Shell Effects

- **Spins & Moments via HFS**

  Nuclear Deformation

  Nuclear Wave Functions



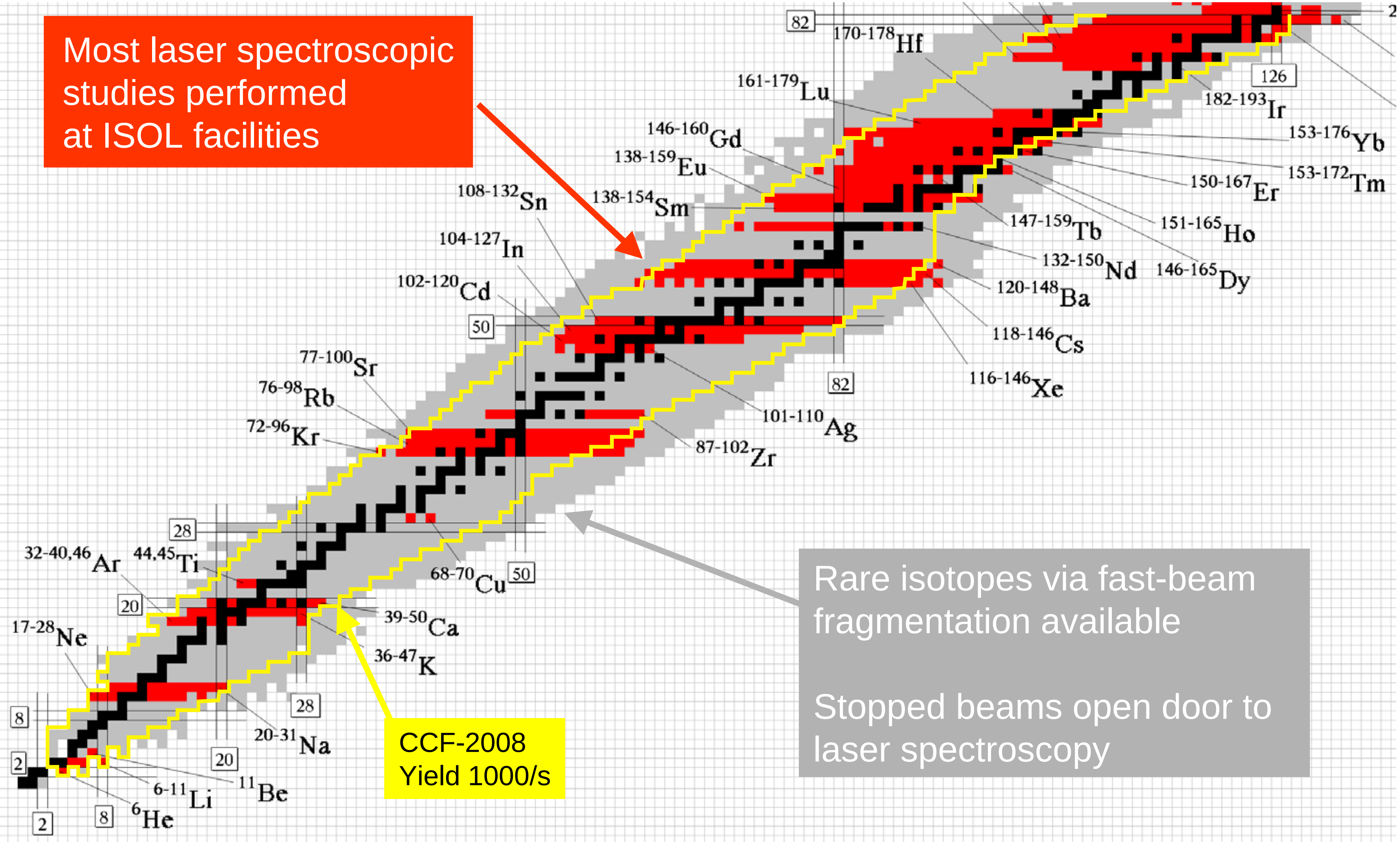
Spin-Polarized Atom and Ion Beams

Moments

Fundamental Interaction Tests

Strong endorsement by NSF

Laser Spectroscopy of Rare Isotopes – Status and Future



Most laser spectroscopic studies performed at ISOL facilities

CCF-2008
Yield 1000/s

Rare isotopes via fast-beam fragmentation available

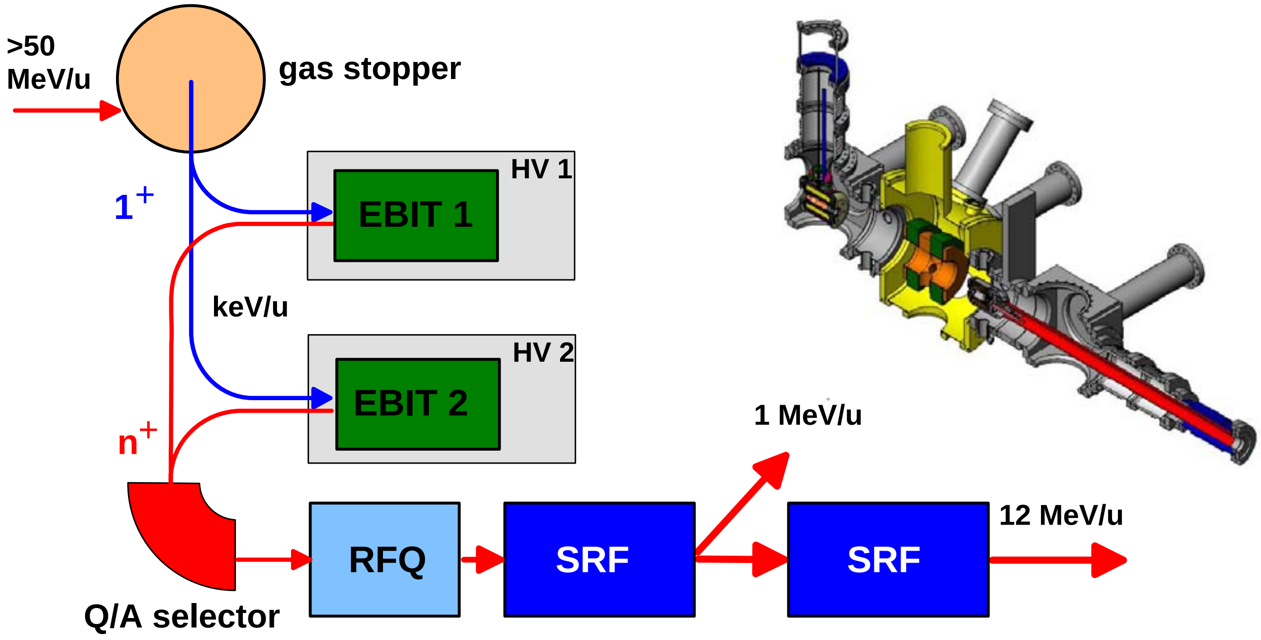
Stopped beams open door to laser spectroscopy

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

NSCL re-acceleration plans

Re-acceleration to 1 MeV/u – 12 MeV/u

- Provide beams nowhere else available in the world
- **high-performance cost-effective post-acceleration scheme**



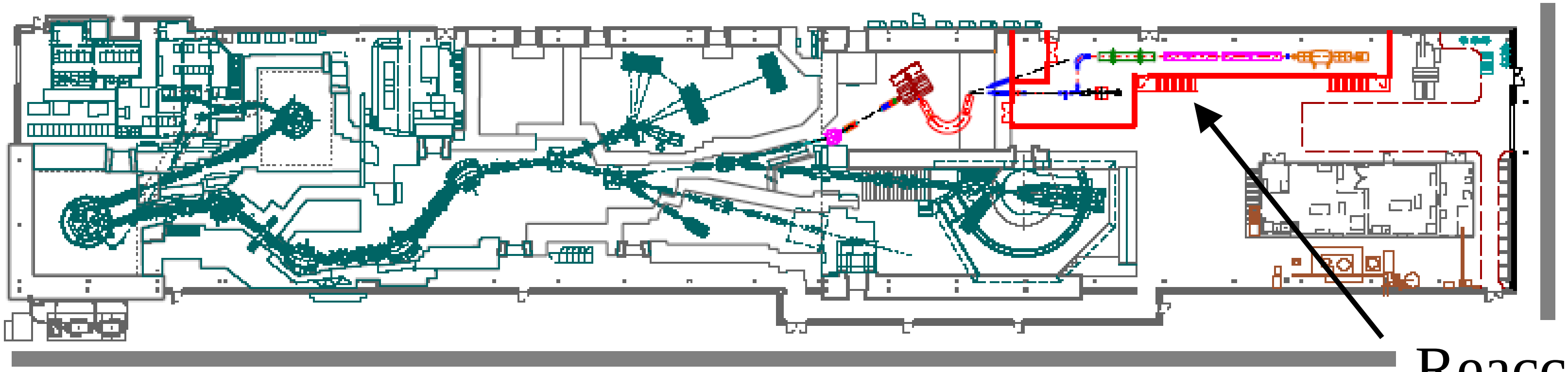
EBIT project started in collaboration with MPI-K Heidelberg and ISAC/TRIUMF

Modified **Titan EBIT**
- larger acceptance
- higher capacity

Low-energy reactions for nuclear astrophysics

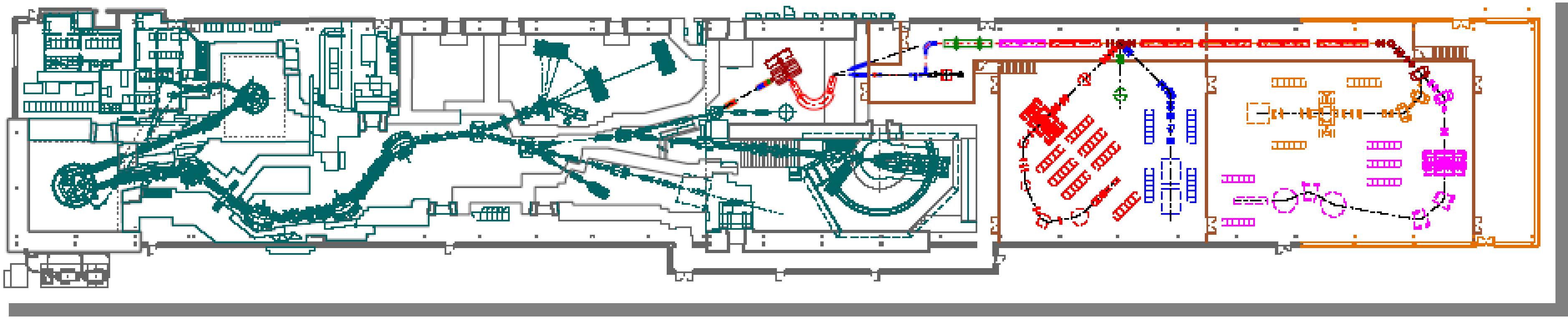
Transfer reactions, Coulomb excitation for nuclear structure studies

NSCL Reacceleration Stage Options



Stage I

Reaccelerated beam area

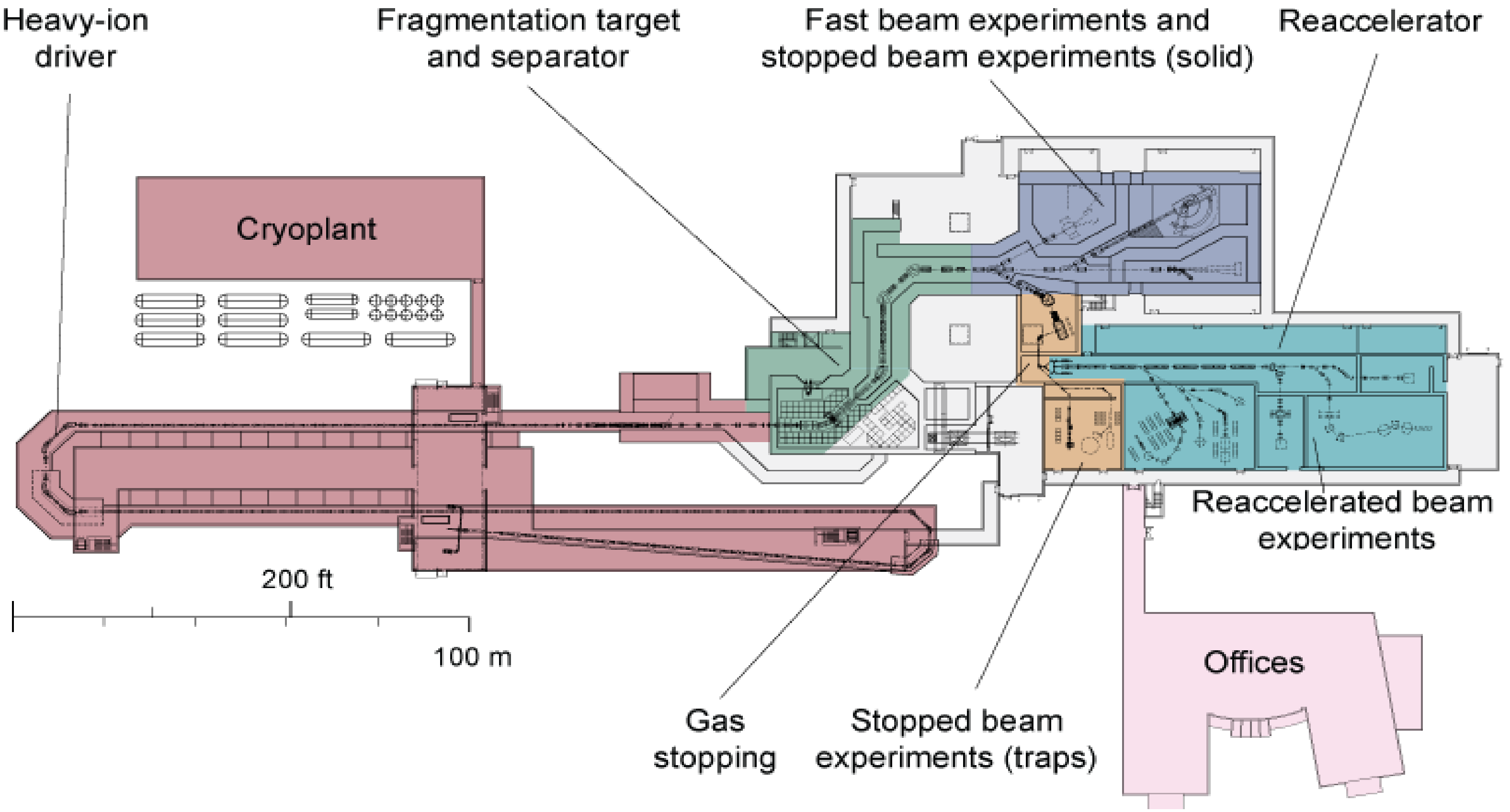


Stage II

ISF (Isotope Science Facility) at MSU

Fast beams, gas stopping, stopped and reaccelerated beams – allows ISOL

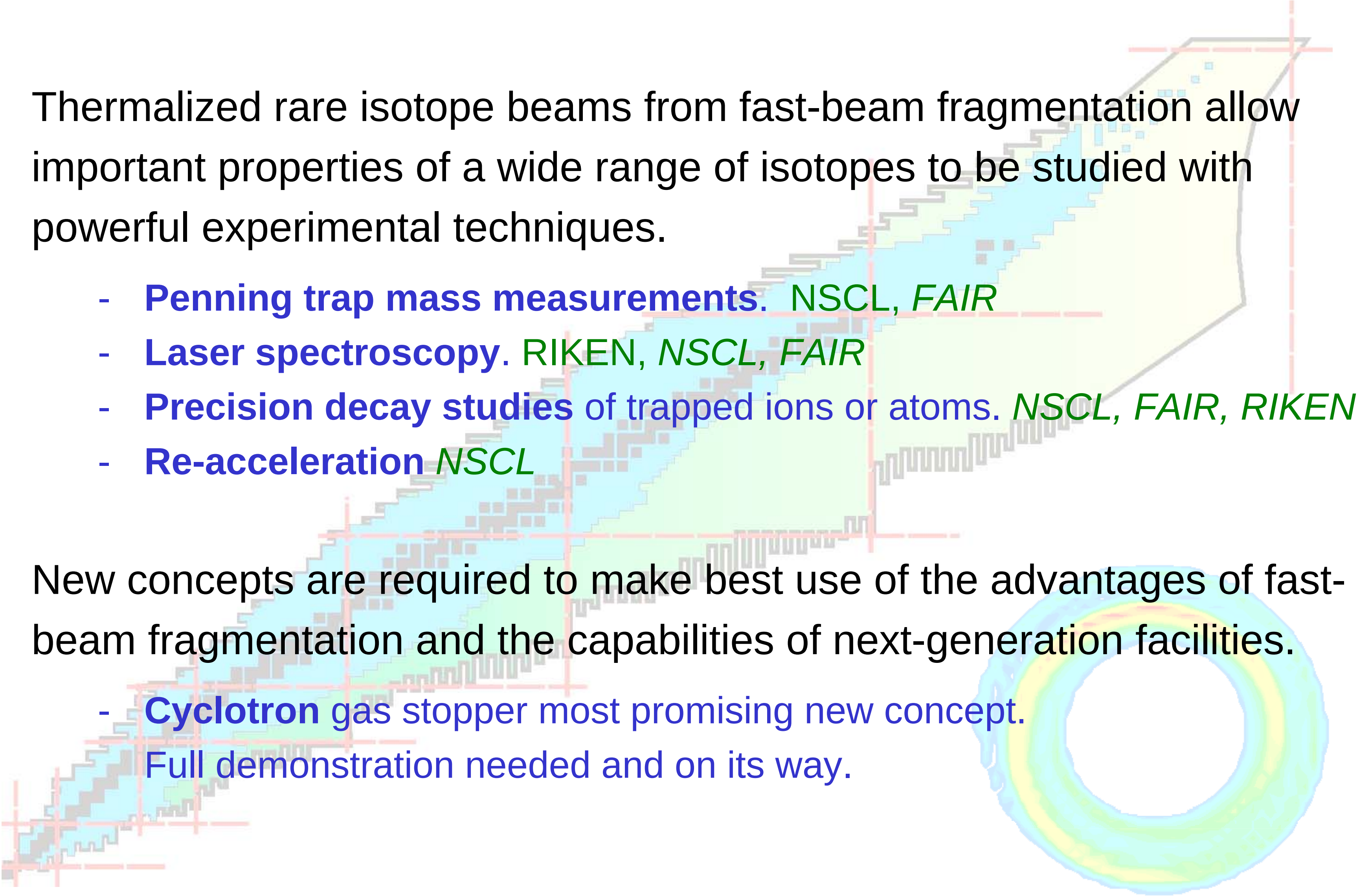
- Energy/nucleon: 200 MeV ^{238}U, 232 MeV ^{129}Xe, 373 MeV ^{3}He, 525 MeV ^{1}H
- 200 - 400 kW beam power possible



Upgrade to RIA capability possible

Georg Bollen, GSI October 06

Conclusions and Summary



Thermalized rare isotope beams from fast-beam fragmentation allow important properties of a wide range of isotopes to be studied with powerful experimental techniques.

- **Penning trap mass measurements**. NSCL, *FAIR*
- **Laser spectroscopy**. RIKEN, *NSCL, FAIR*
- **Precision decay studies** of trapped ions or atoms. *NSCL, FAIR, RIKEN*
- **Re-acceleration** *NSCL*

New concepts are required to make best use of the advantages of fast-beam fragmentation and the capabilities of next-generation facilities.

- **Cyclotron** gas stopper most promising new concept.
  Full demonstration needed and on its way.