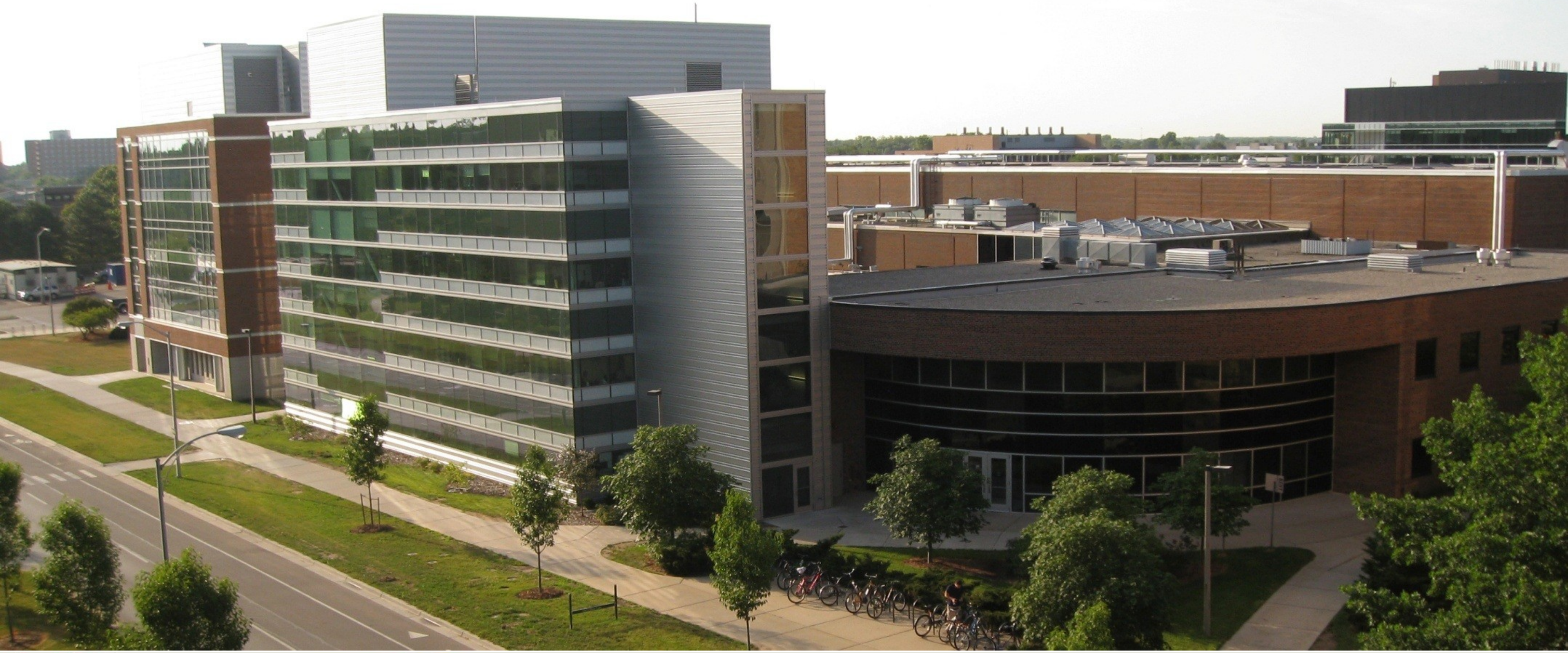
Penning Trap Mass Measurements of Rare Isotopes from Projectile Fragmentation at NSCL Now and FRIB in the Future

Georg Bollen
Facility for Rare Isotope Beams
Michigan State University

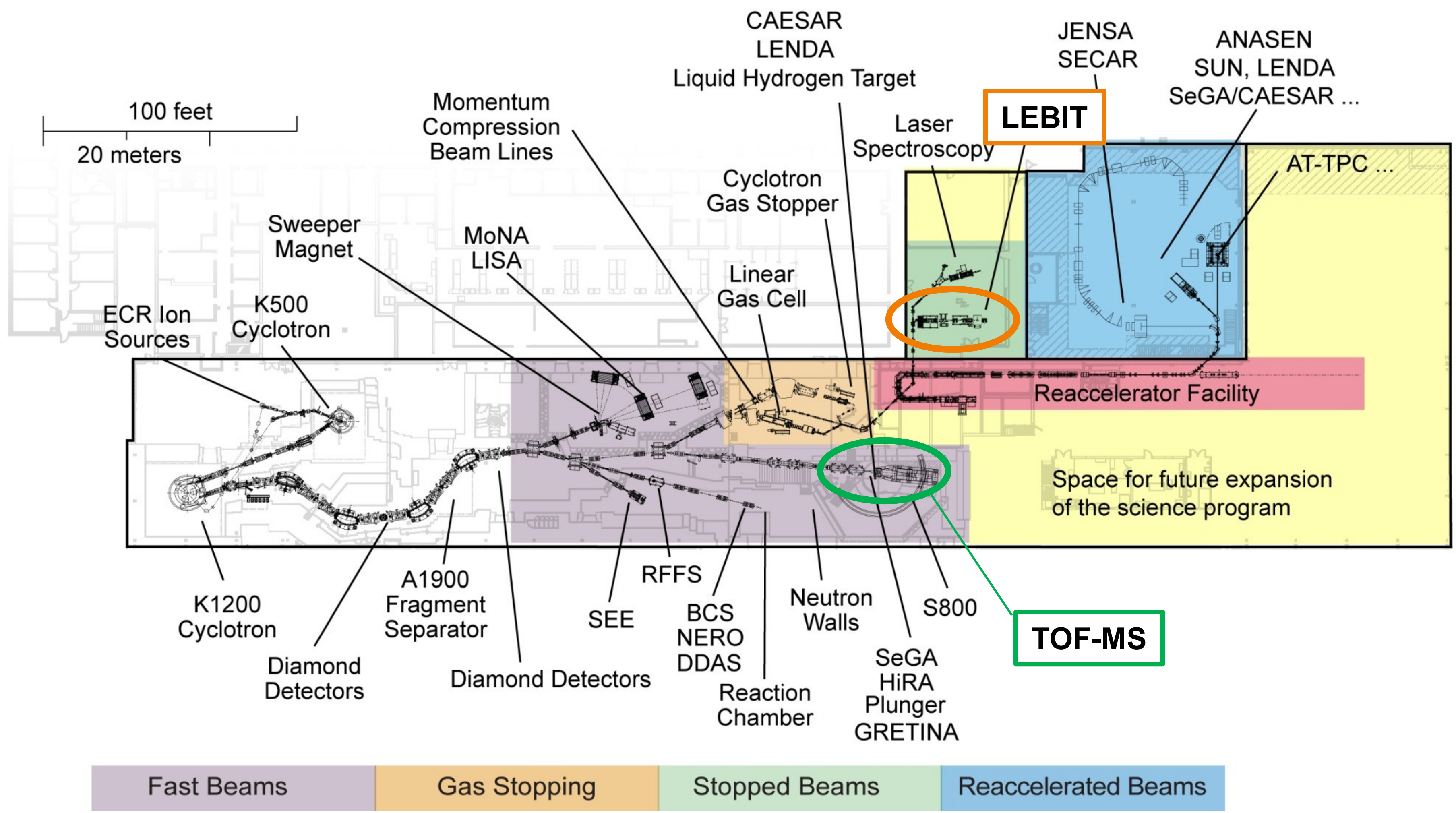


NSCL FRIB

Outline

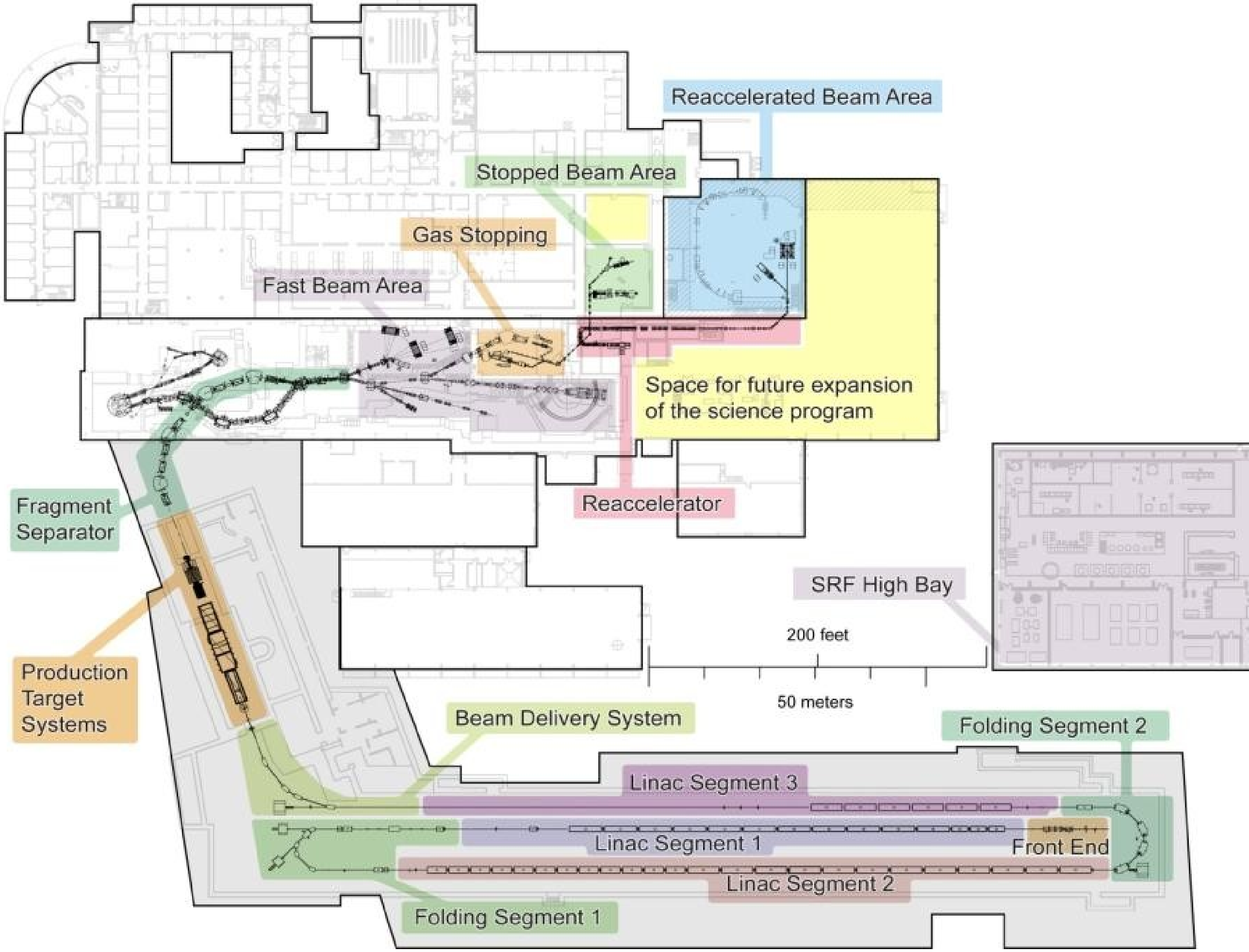
- Introduction – NSCL and FRIB
- Thermalized beams from projectile fragmentation at the NSCL
- Mass measurements with the LEBIT facility at NSCL
  - Masses for the rp-process
  - Masses of n-rich isotopes
- New developments
- Facility for Rare Isotope Beams (FRIB)
  - Perspectives for mass measurements
- Summary

National Superconducting Cyclotron Laboratory
Premier Rare Isotope Beam Facility in the US

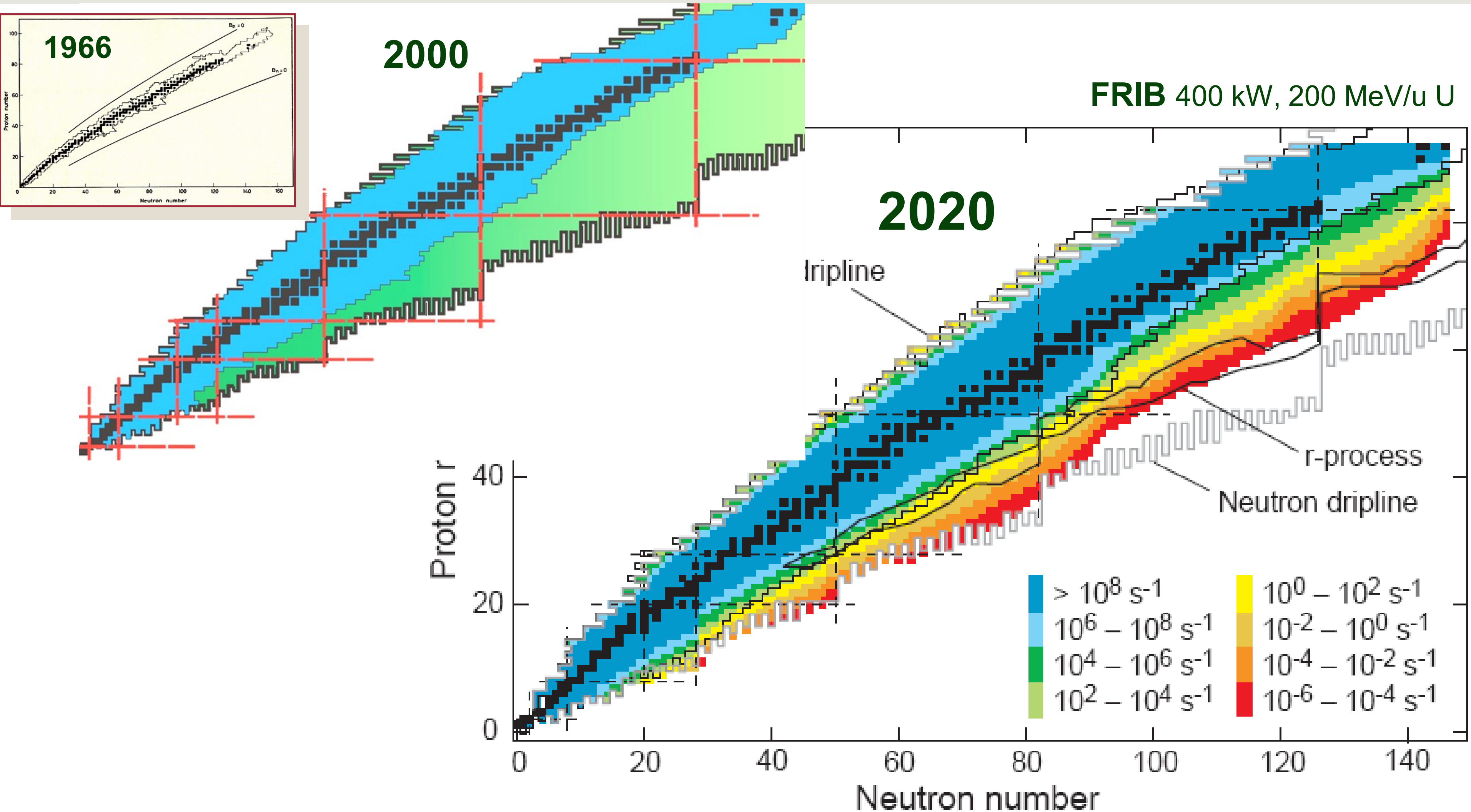


FRIB - Facility for Rare Isotope Beams at MSU
World-leading next-generation rare isotope beam facility

- Rare isotope production via in-flight technique with primary beams up to 400 kW, 200 MeV/u ^{238}U
- Fast, stopped and reaccelerated beam capability
- Mass measurements by TOF-MS and Penning trap MS

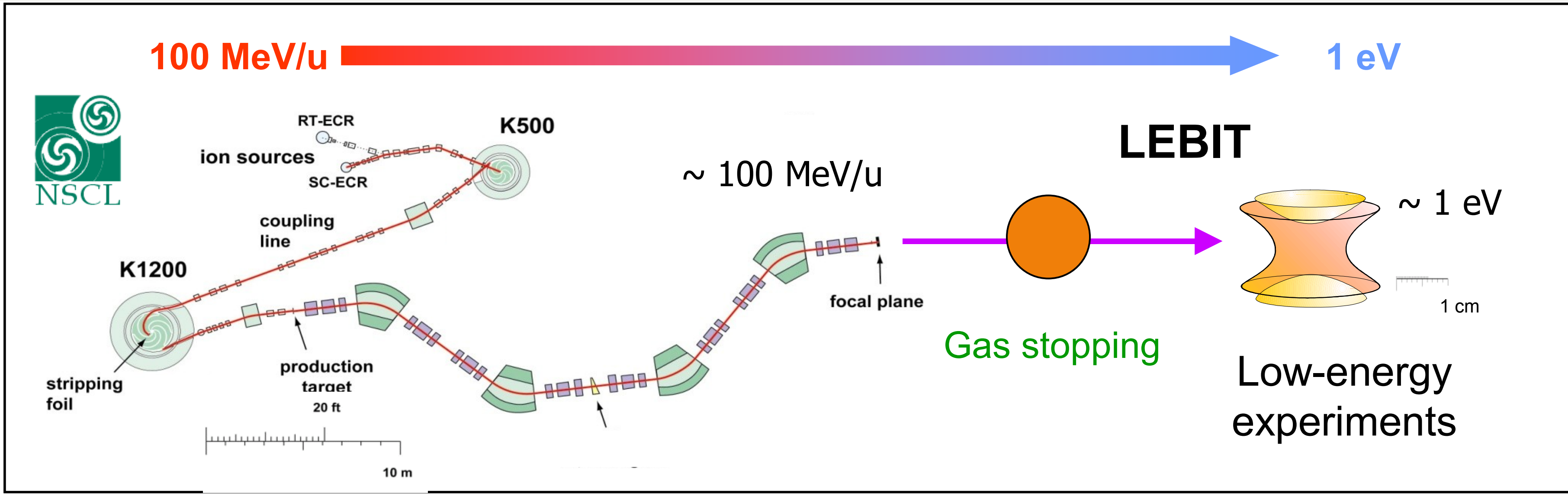


FRIB Production Outlook



FRIB Will Be a Game-changer for Nuclear Astrophysics

Low-Energy “Stopped” Beams from Projectile Fragmentation



Make best use of advantages of projectile fragmentation …

Fast, universal, far reach from the valley of beta-stability

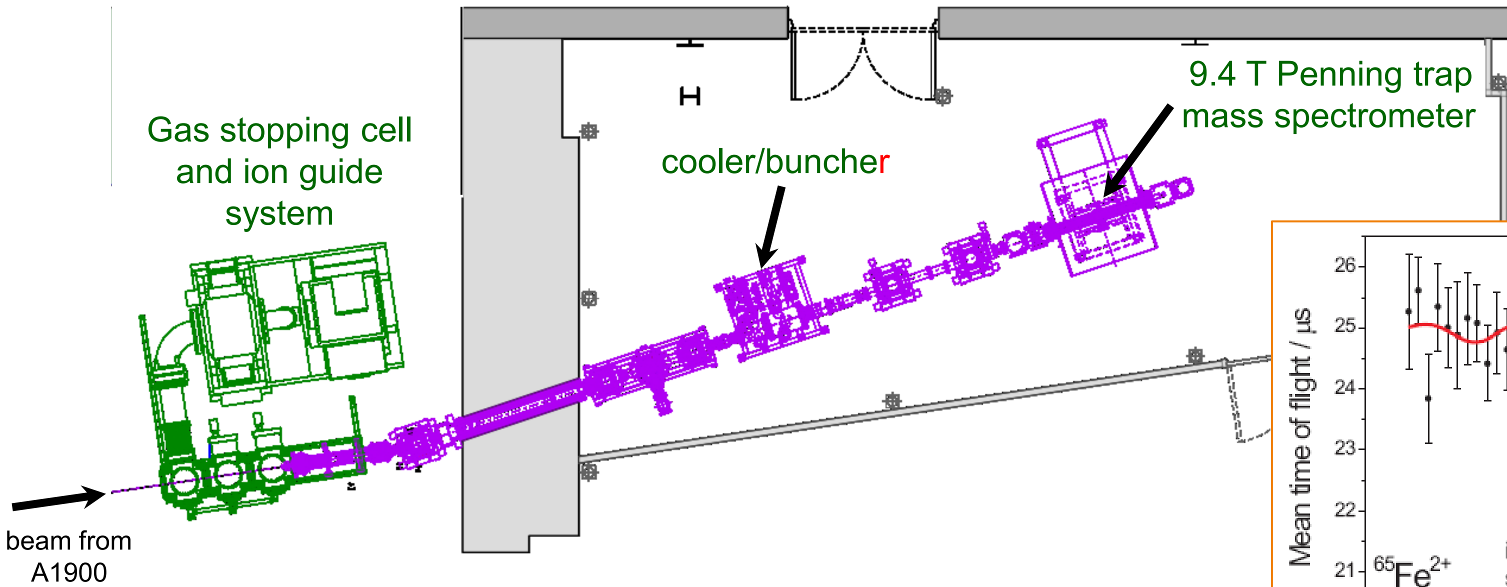
… and of precision experimental techniques developed for low-energy beams

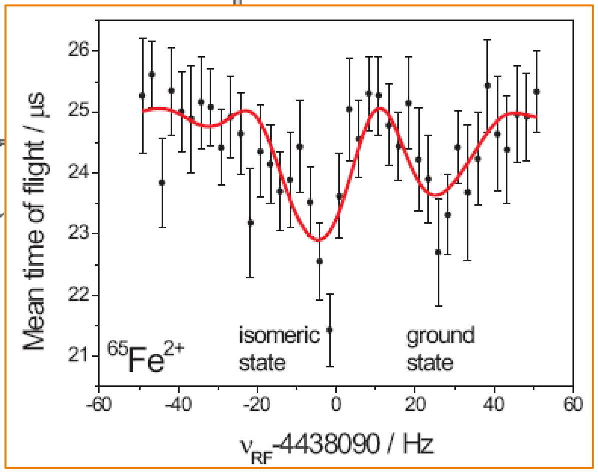
Precision atomic mass measurements

Nuclear properties from atomic spectroscopy

Reaction and nuclear structure studies with reaccelerated beams

Low Energy Beam and Ion Trap Facility LEBIT
Phase I





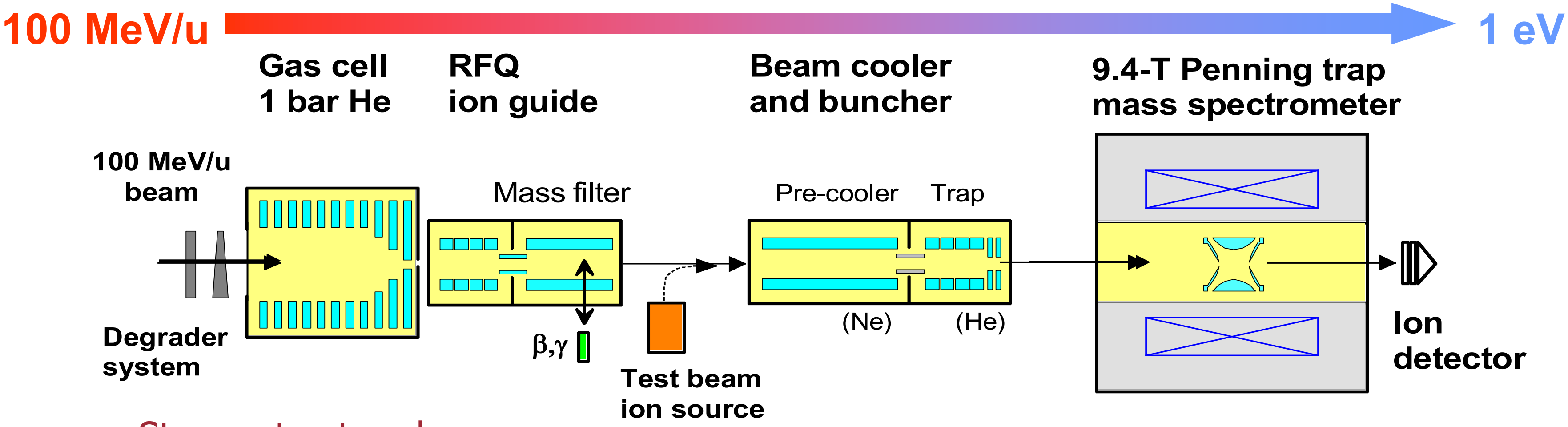
2000: LEBIT project initiated

2004: System complete and functional

2005: First mass measurement of radioactive species - ^{38}Ca

2009: Final mass measurement in this configuration – ^{66}As

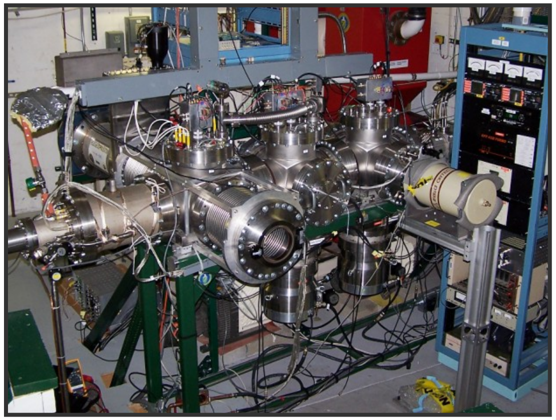
Low Energy Beam and Ion Trap Facility LEBIT

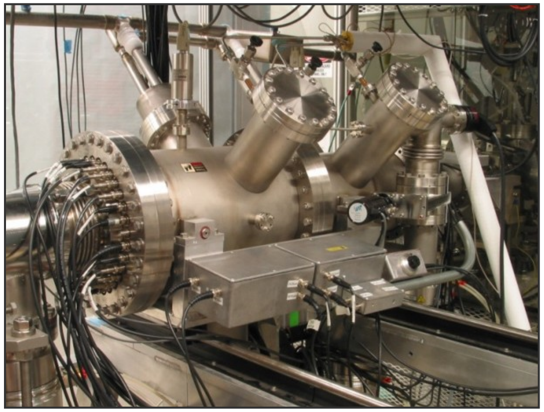


Stop, extract and select
isotope of interest

Accumulate, bunch
(& break molecules)

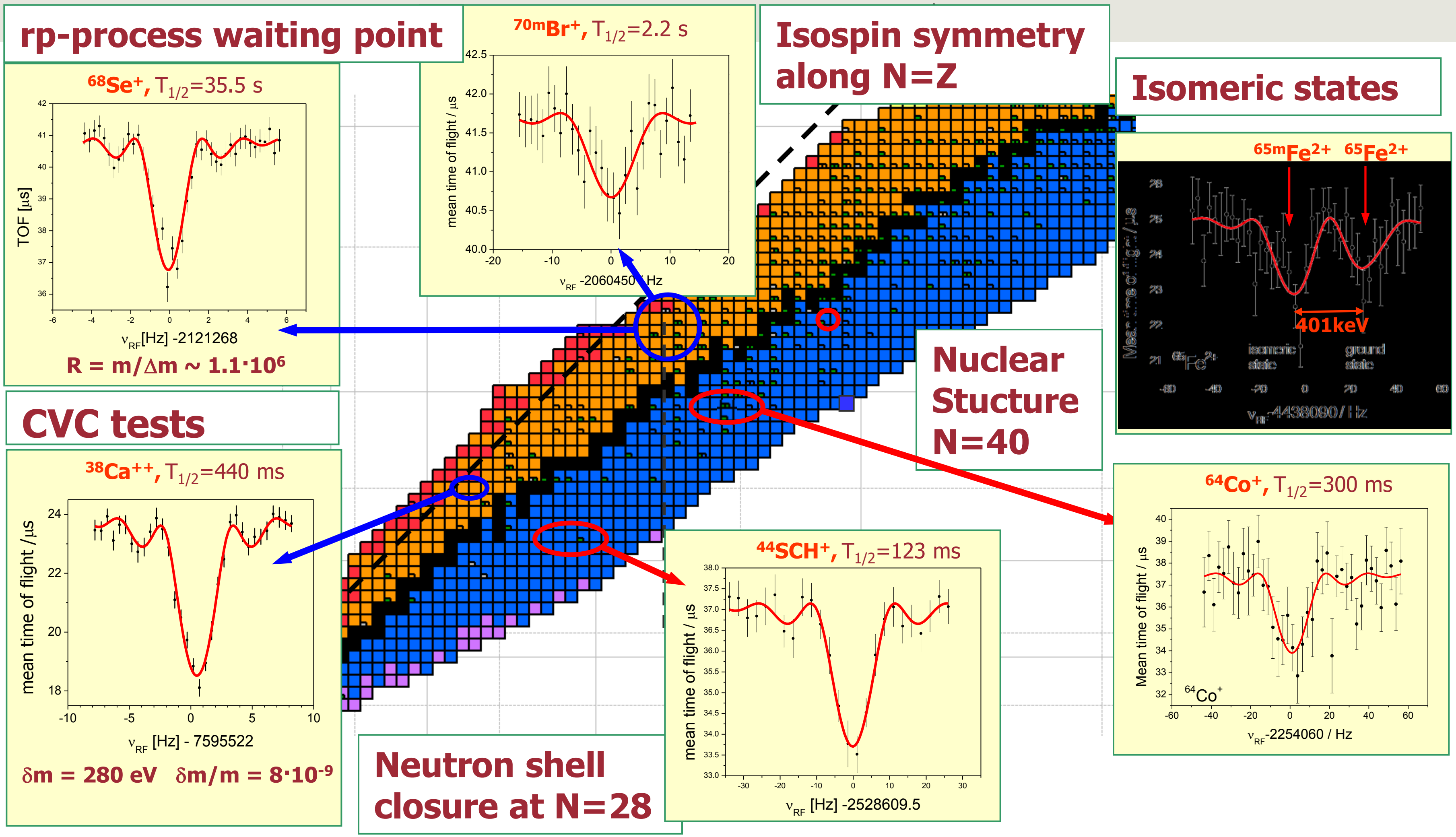
Cyclotron frequency
determination





NSCL FRIB

LEBIT Harvest 2005 - 2009

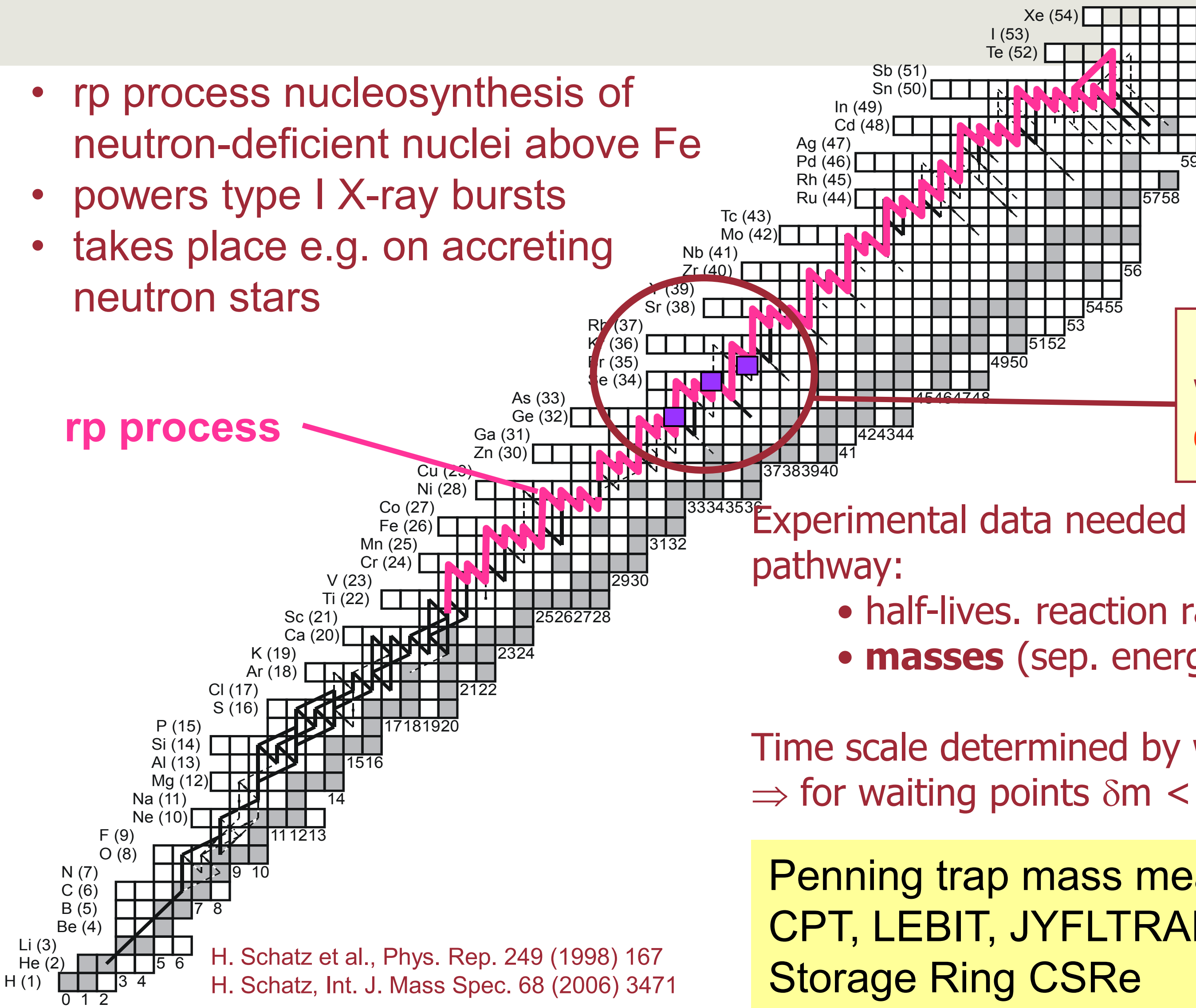


Precise masses for more than 30 isotopes and more than 10 elements

^{32,33}Si, ^{29}P, ^{34}P, ^{37}Ca, ^{38}Ca, ^{40}S, ^{41}S, ^{42}S, ^{43}S, ^{44}S, ^{63}Fe, ^{64}Fe, ^{65}Fe, ^{64}Co, ^{65}Co, ^{66}Co, ^{63}Ga, ^{64}Ga, ^{64}Ge, ^{65}Ge, ^{66}Ge, ^{66}As, ^{67}As, ^{68}As, ^{80}As, ^{68}Se, ^{69}Se, ^{70}Se, ^{81}Se, ^{81m}Se, ^{70m}Br, ^{71}Br

Mass Measurements Relevant for rp Process

- rp process nucleosynthesis of neutron-deficient nuclei above Fe
- powers type I X-ray bursts
- takes place e.g. on accreting neutron stars



H. Schatz et al., Phys. Rep. 249 (1998) 167
H. Schatz, Int. J. Mass Spec. 68 (2006) 3471

Bottlenecks:
Waiting point nuclei
^{64}Ge, ^{68}Se, ^{72}Kr

Experimental data needed to constrain pathway:

- half-lives. reaction rates
- **masses** (sep. energies, Q-values)

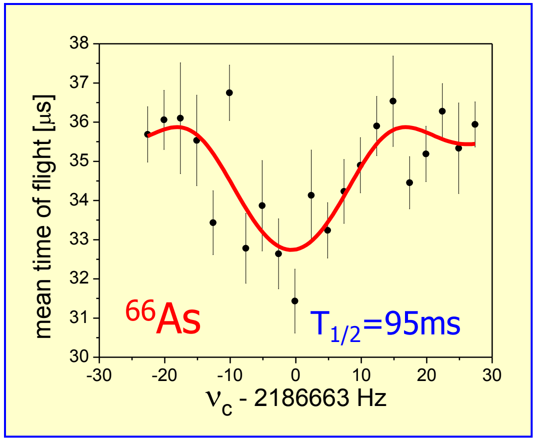
Time scale determined by waiting points
⇒ for waiting points $\delta m < 10$ keV

Penning trap mass measurements
CPT, LEBIT, JYFLTRAP, SHIPTRAP
Storage Ring CSRe

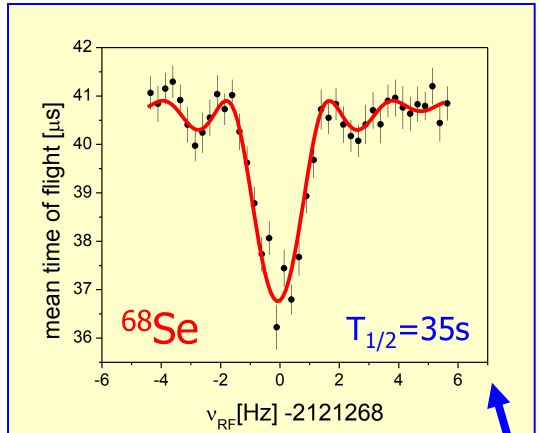
NSCL FRIB

Mass Measurements for Nuclear Astrophysics

^{66}As measured with ≈ 10 ions/hr

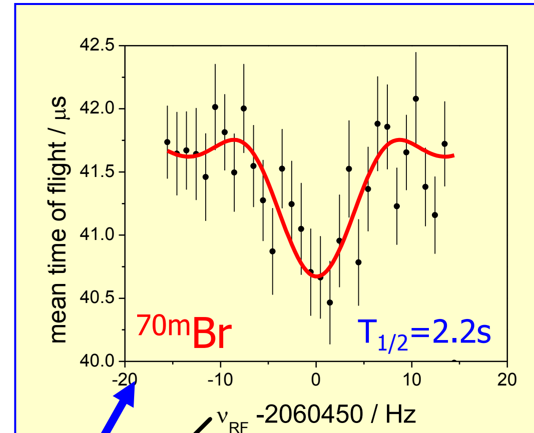


rp process waiting point

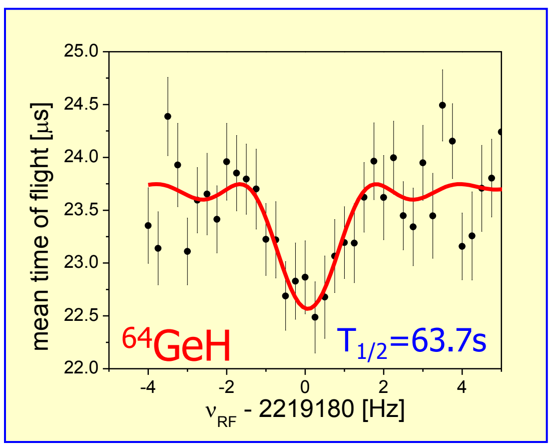


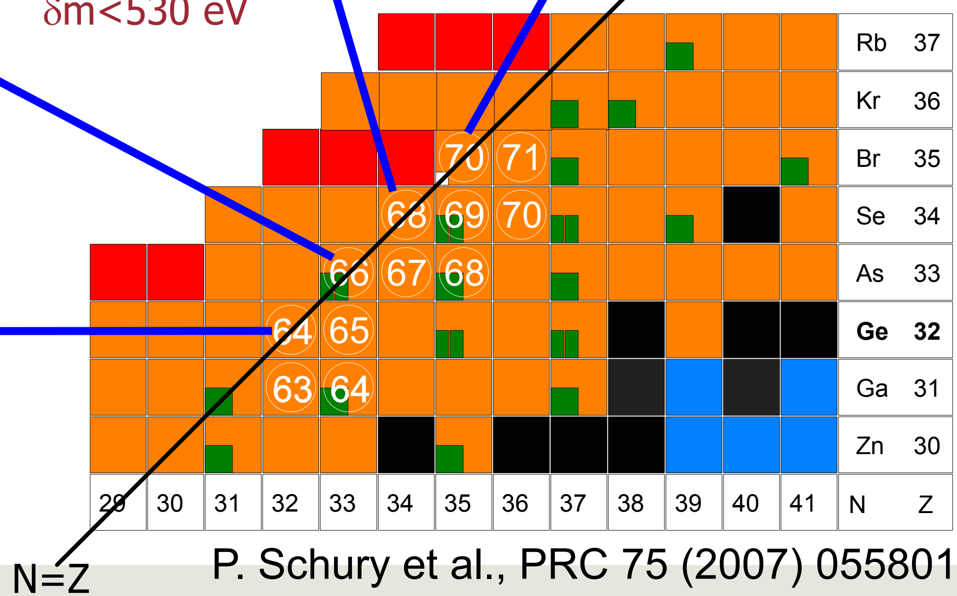
δm<530 eV

Proton drip line nucleus



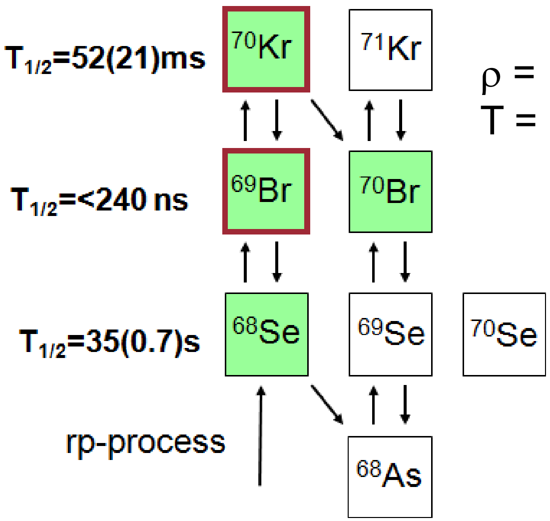
rp process waiting point





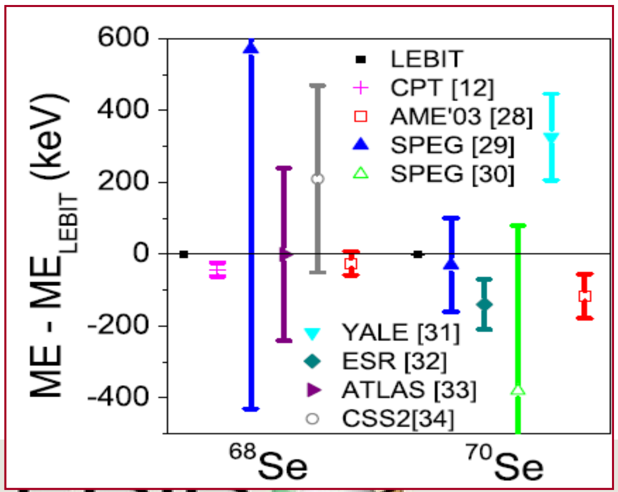
P. Schury et al., PRC 75 (2007) 055801
J. Savory et al., PRL 102, 132501 (2009)

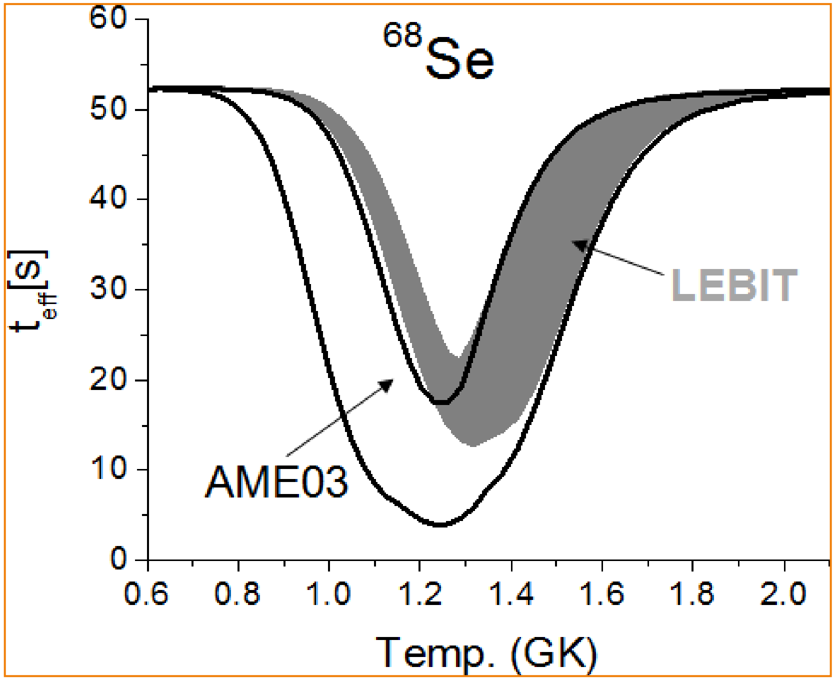
Effective Lifetimes of Waiting Points – Example ^{68}Se



$\rho = 10^6$ g/cm^3
T = [0.5 – 2.2] GK

LEBIT+ Coulomb Displacement Energies. Brown et al. 2002





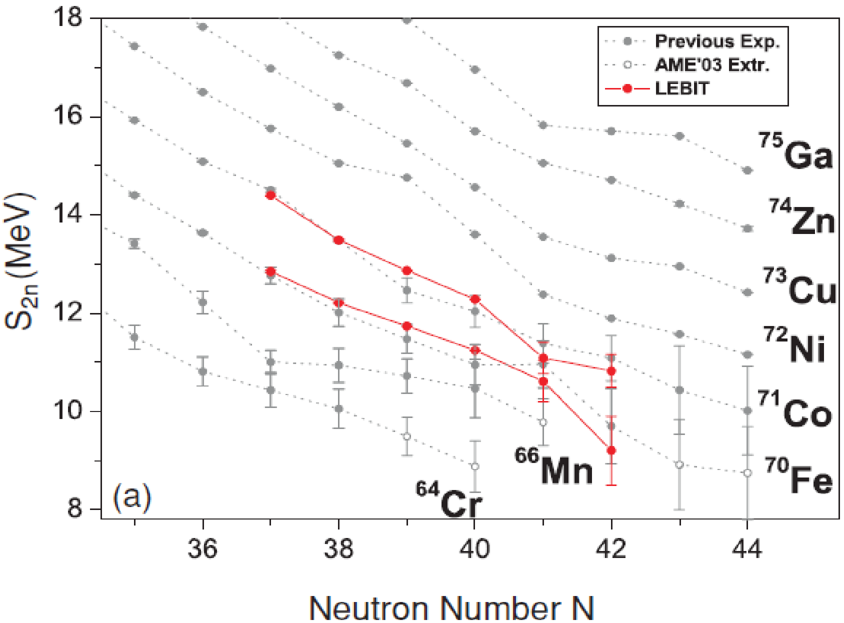
→^{68}Se poses a greater delay

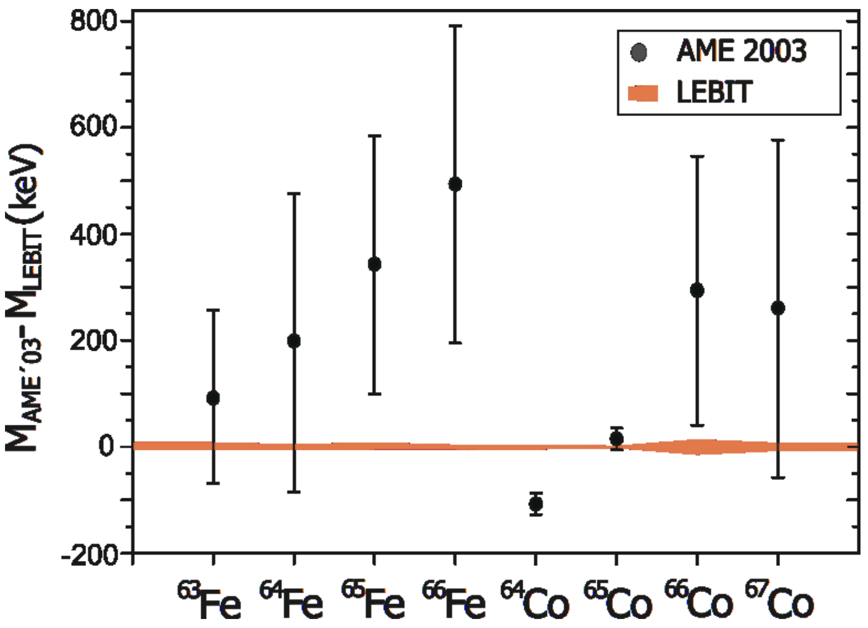
Waiting point nuclei in this region have large impact on tail of x-ray burst light curves

J. Savory et al., PRL 102, 132501 (2009)

Mass measurements on n-rich Fe and Co isotopes
Nuclear structure near N=40, Z=28

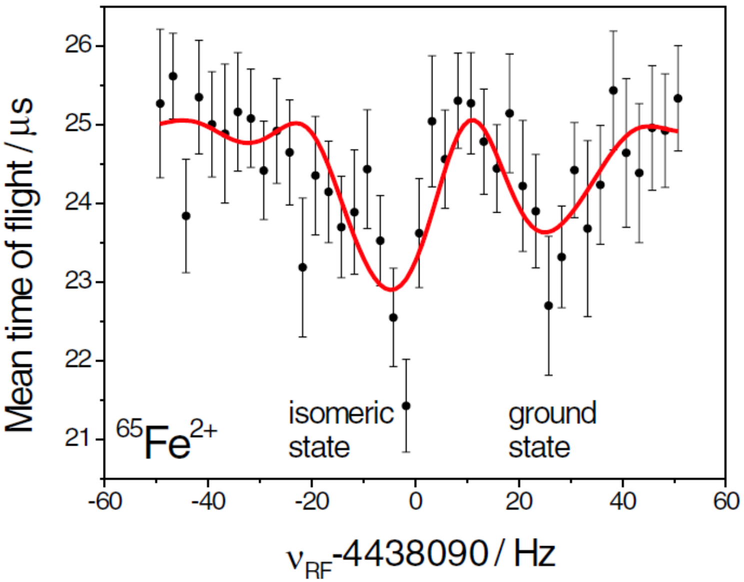
- Significant discrepancies to earlier data
  - Earlier data from TOF-MS (TOFI at LANL)
  - Possible observed systematic trend due to unresolved μs isomers or calibration issue?
- Discontinuities in systematic trend of separation energies – more data required
  - Approved Exp. 10024 to push beyond N=40



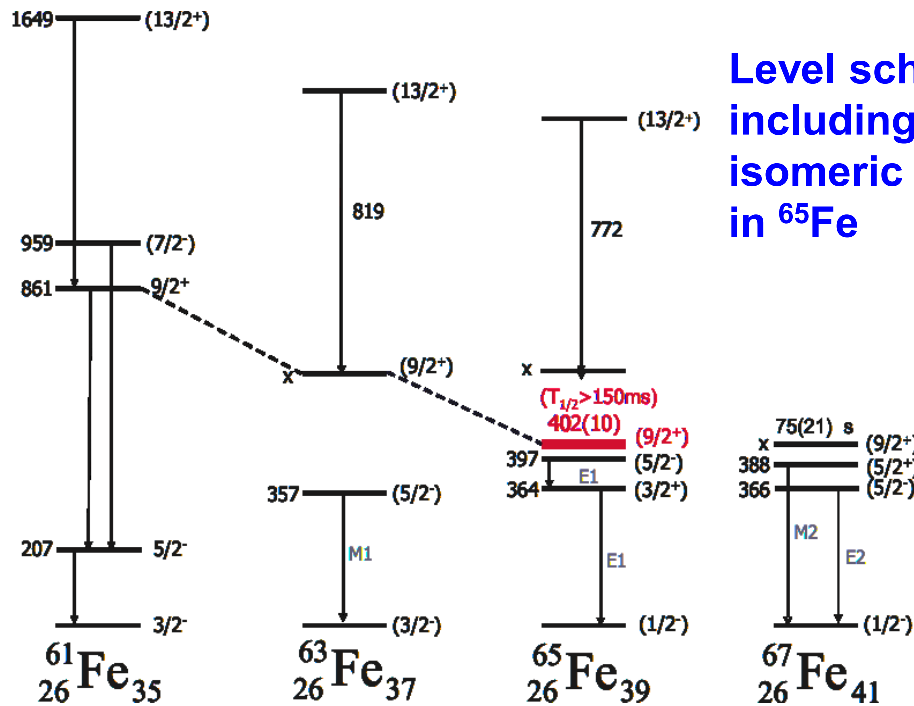


M. Block et al., PRL 100, 012501 (2008)
R. Ferrer et al.. PRC 81 (2010) 044318

First Discovery of New Isomer by Penning Trap Mass Spectrometry



E_x = 402(10) keV
$T_{1/2}$ > 150 ms



Level scheme including new isomeric state in ^{65}Fe

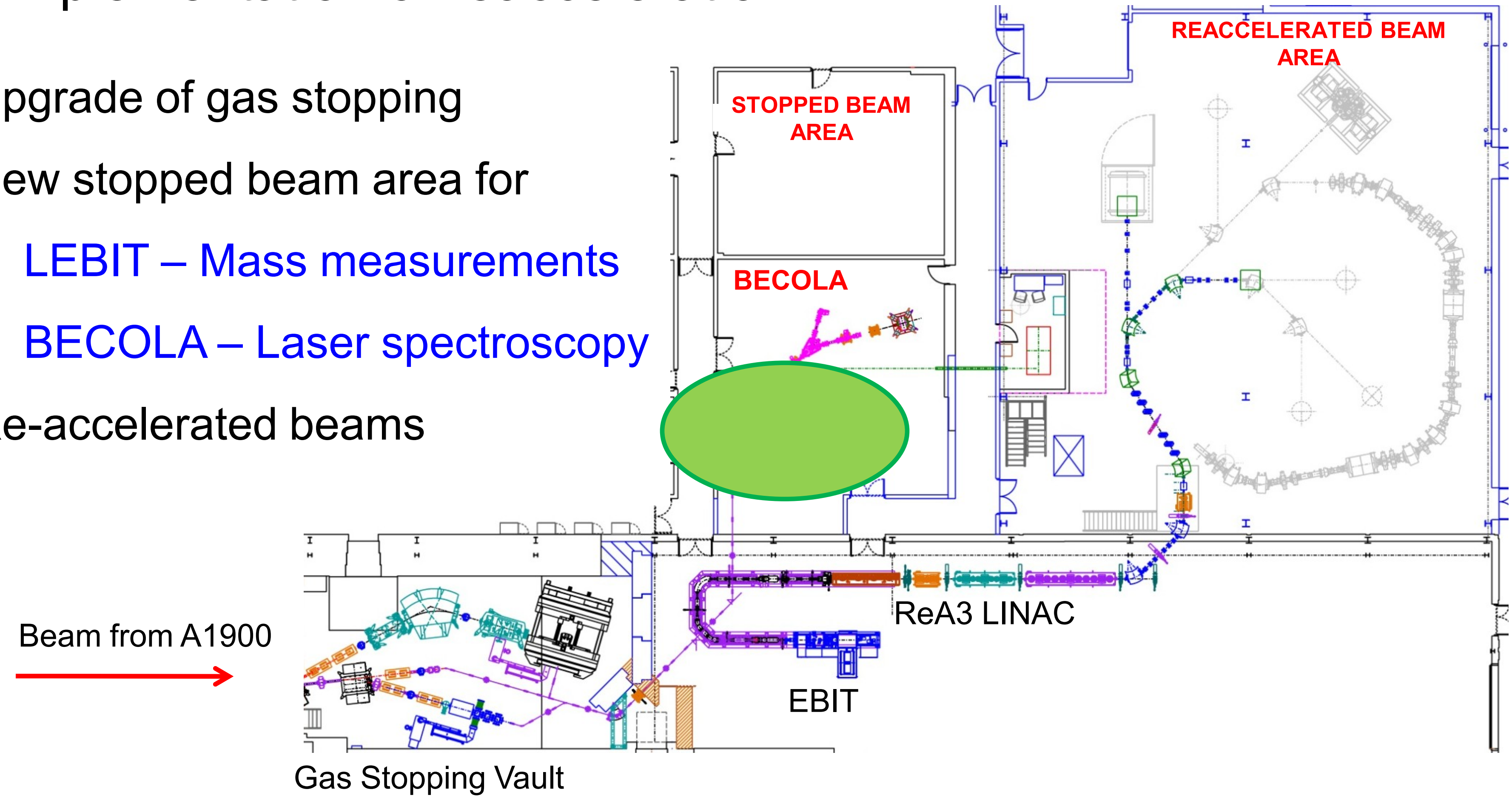
M. Block et al., PRL 100, 012501 (2008)
R. Ferrer et al..PRC 81 (2010) 044318

- Increasing monopole interaction leading to increased deformation could reduce the energy of the $9/2^+$ state

NSCL Moves Forward - Preparing for FRIB

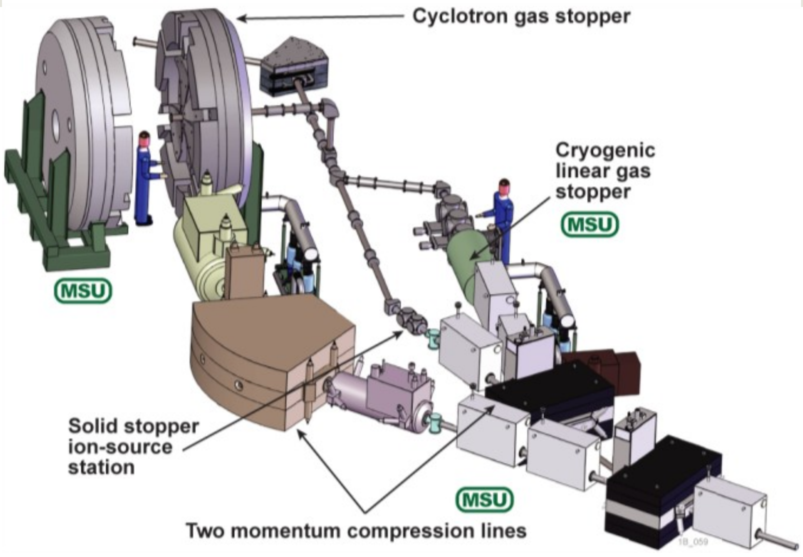
LEBIT success motivated expansion of stopped beam program and implementation of reacceleration

- Upgrade of gas stopping
- New stopped beam area for
  - LEBIT – Mass measurements
  - BECOLA – Laser spectroscopy
- Re-accelerated beams

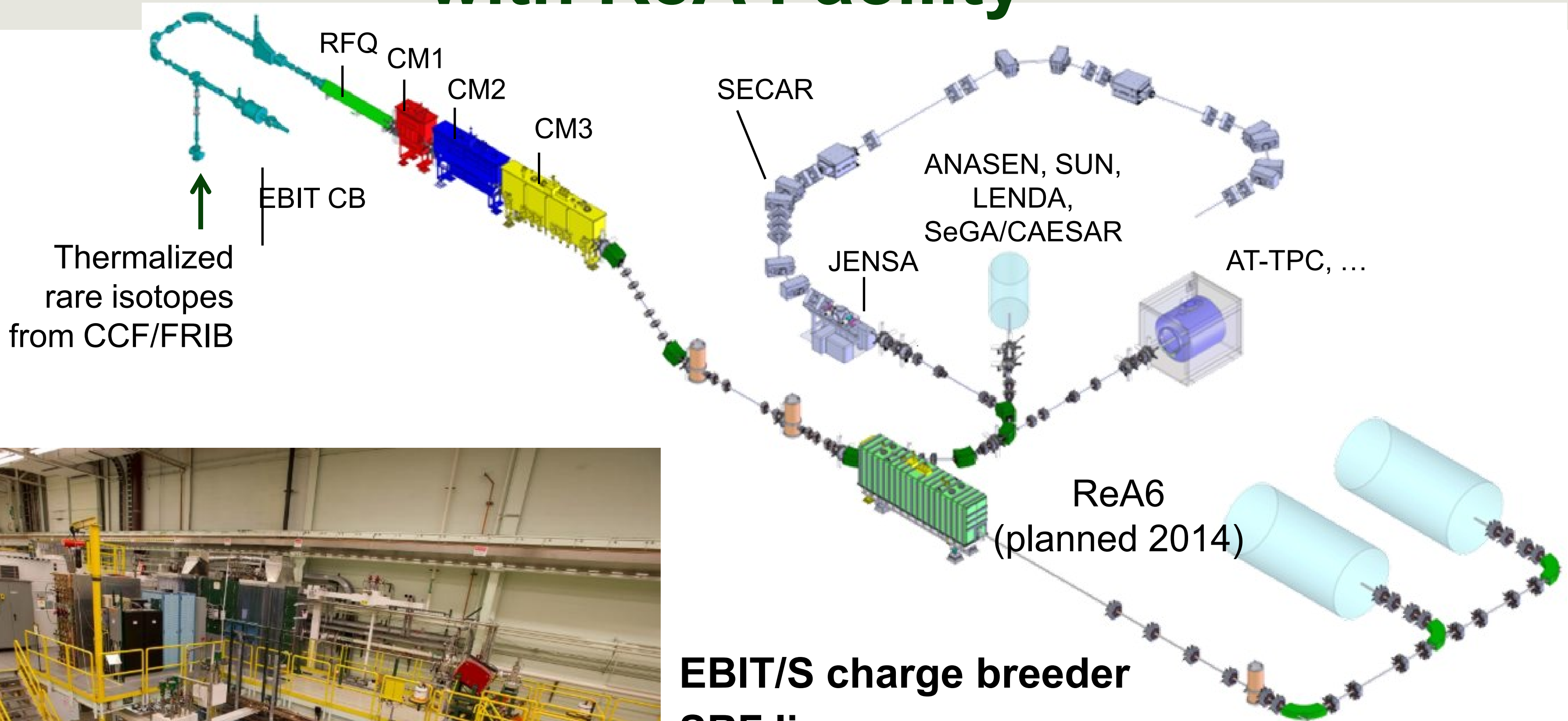


Stopped Beams at NSCL and FRIB
Multifaceted Approach

- Linear gas stopper (heavier ion beams)
- Cyclotron gas stopper (lighter ion beams)
- Solid stopper (certain elements, highest intensity)
- Status
  - Linear gas catcher (ANL) in place and in operation
  - Cyclotron gas stopper construction underway (NSF-funded)



Reaccelerated Beams at NSCL and FRIB with ReA Facility



EBIT/S charge breeder

SRF linac

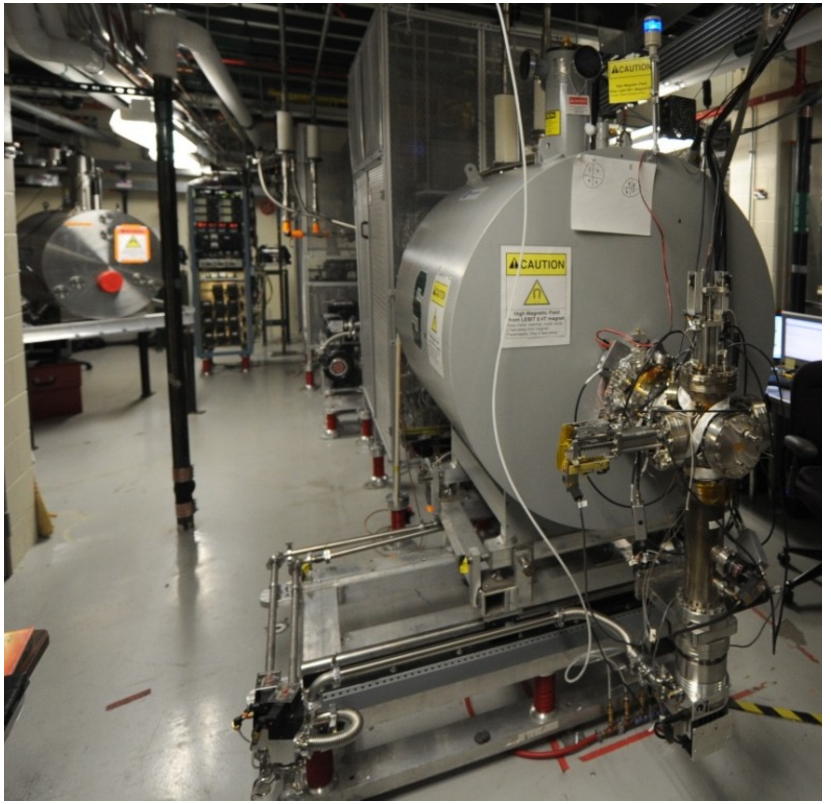
ReA3 – 3 MeV/u for ^{238}U

Expandable to >12 MeV/u for ^{238}U

April 2013: First reaccelerated rare isotope beam ($^{76}Ga^{25+}$)

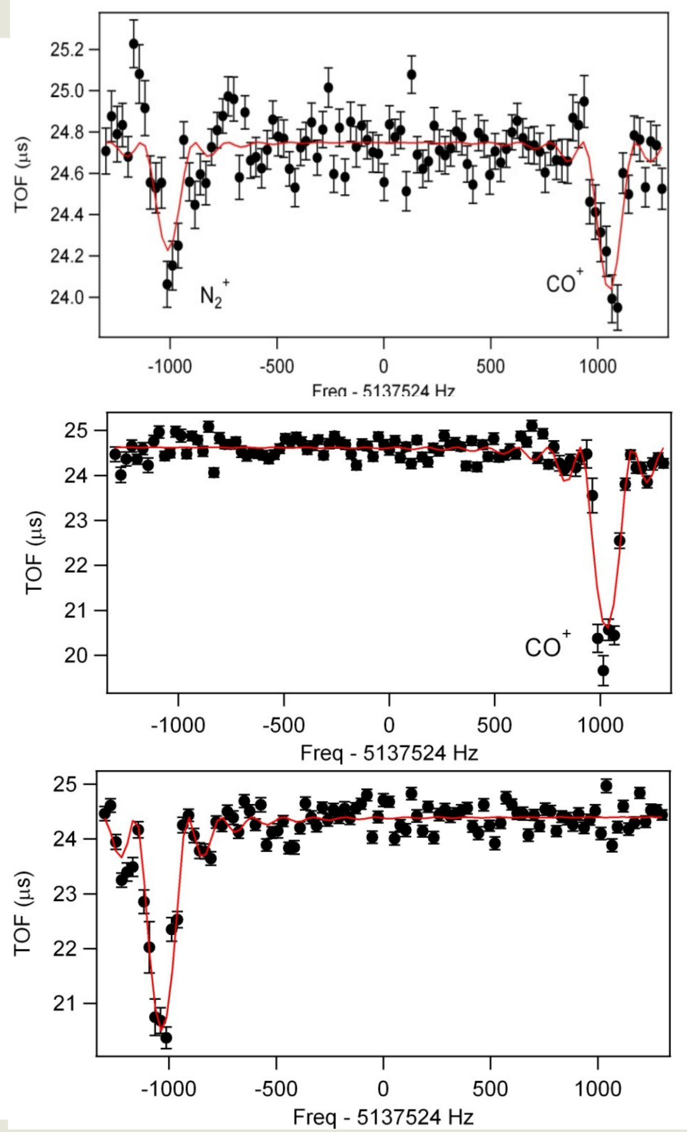
LEBIT Phase II - Back To Life

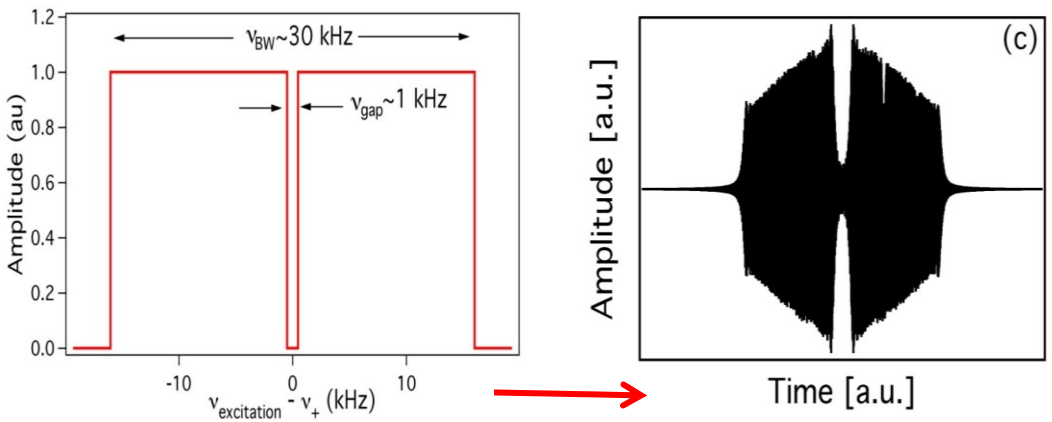
- **LEBIT re-commissioned**
  - High-precision off-line mass measurements
    - $Q_{\beta\beta}$ (^{48}Ca-^{48}Ti): M. Redshaw et al., PRC 86 (2012) 041306
    - $Q_{\beta\beta}$ (^{82}Se-^{82}Kr): D. Lincoln et al., PRL 110 (2013) 012501
    - Q_{2EC} (^{78}Kr-^{78}Se): S. Bustabad et al.PRC (2013) submitted
  - Ready for rare isotopes
    - » Test beam time May 5 (n-rich Fe and Co)
- **LEBIT improved**
  - SWIFT cleaning
    - » Fast undesired ion removal
  - Minitrap magnetometer
    - » Most efficient use of beam time
  - Laser ablation source
    - » Carbon cluster ions for field calibration
    - » Stable and long-lived isotopes
- **Single Ion Penning Trap (SIPT)**
  - Highest sensitive far from stability



SWIFT Cleaning

- Stored Waveform Inverse Fourier Transform (SWIFT)
  - Simultaneous removal of all isobaric contaminant ions from the trap
  - Same excitation scheme for all ions, fast



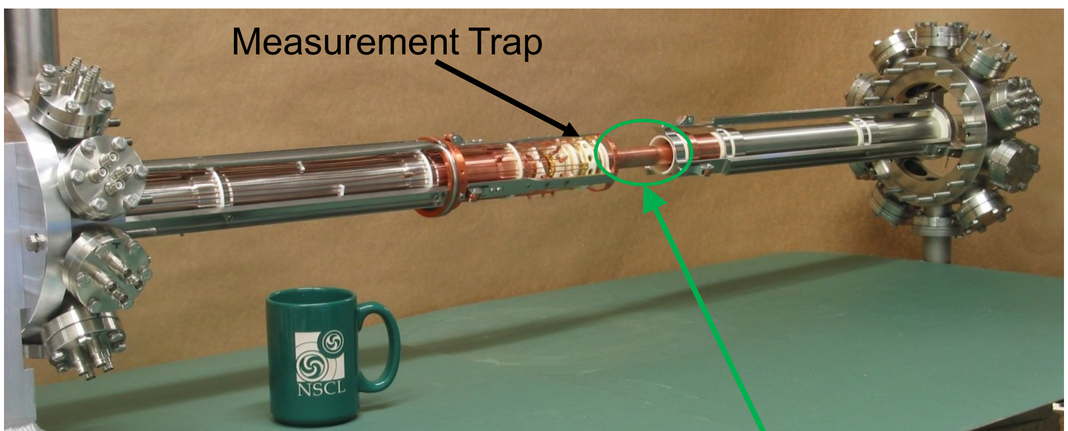


S.Guan and A.G.Marshall, IJMS Ion Proc. 5, **157/158** (1996)

✓ Resolving power demonstrated to 2 x 10^5 with $^{23}Na^+$

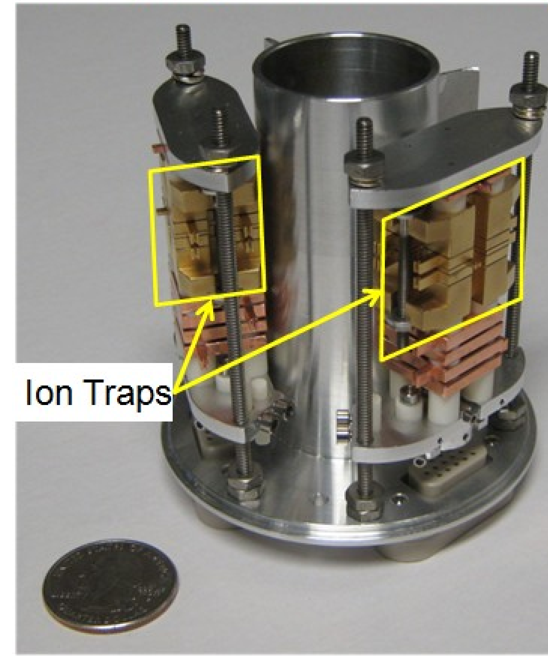
Permanent Magnetic Field Monitoring Miniature Penning Trap (MiniTrap)

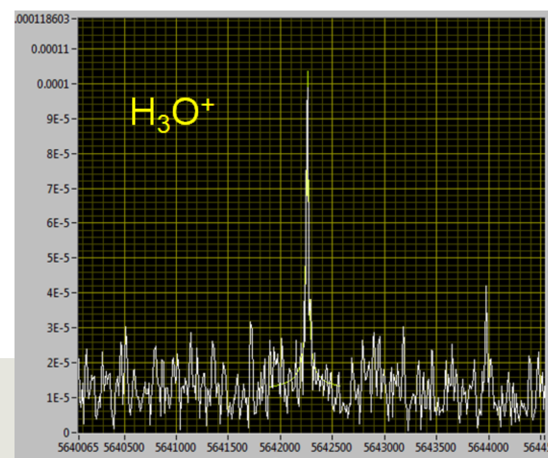
- Best use of beam time by eliminating reference measurements
- Second Penning trap adjacent to the measurement trap to act as a magnetometer
  - Eliminate uncertainty in non-linear magnetic field drifts
  - Obtain desired precision of 1 part in 10^8 by measuring ω_c of H_2 or He ions



Location for MiniTrap Magnetometer

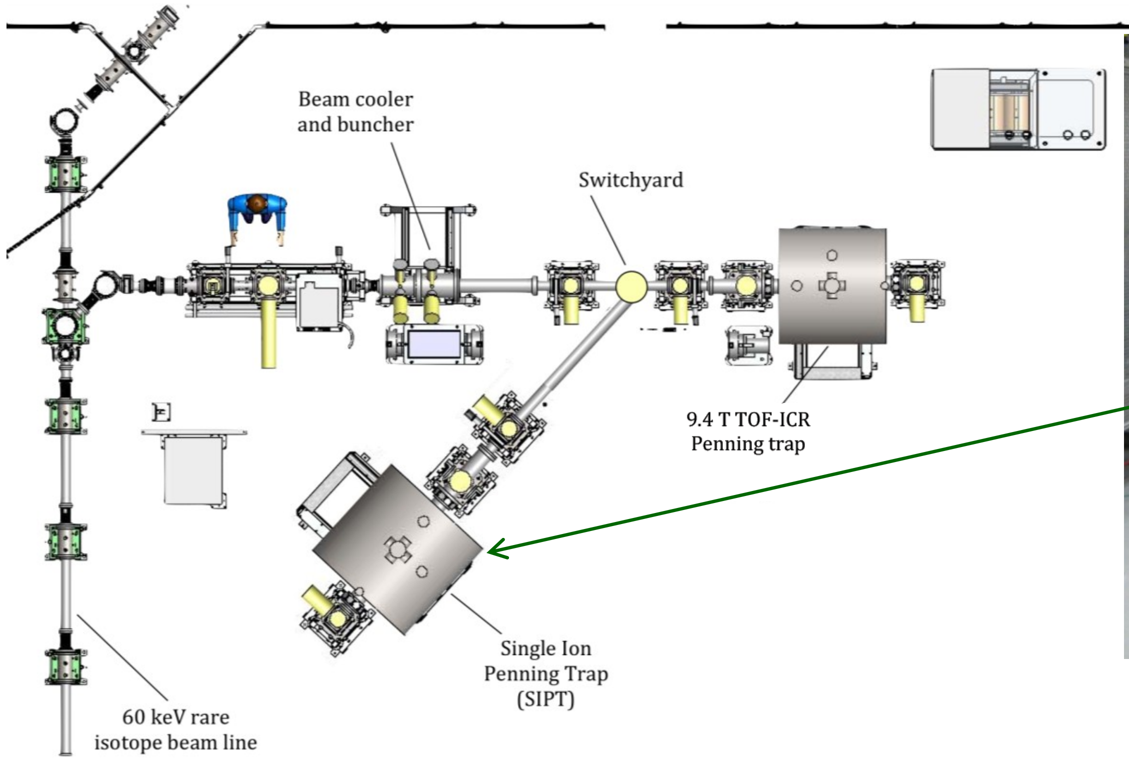
MiniTrap Magnetometer Assembly

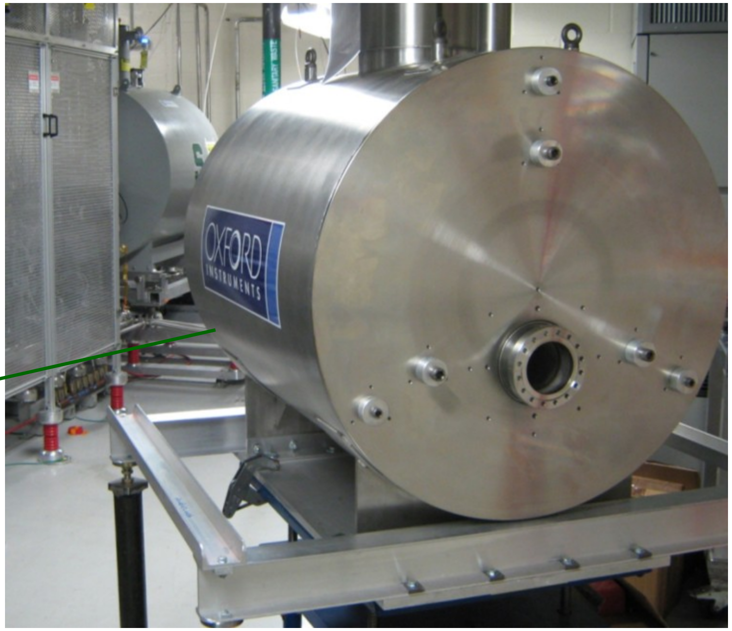




Towards Single Ion Sensitivity using FT-ICR

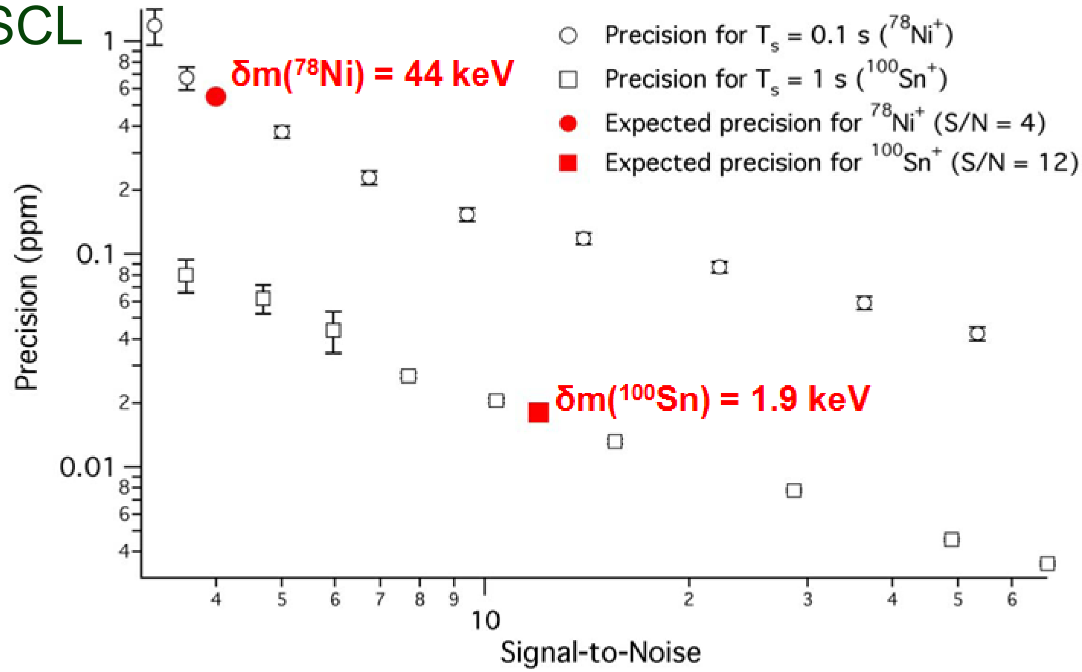
- **Single Ion Penning Trap (SIPT)** for mass measurements with single Ions
- Fourier Transform Ion Cyclotron Resonance FT-ICR technique

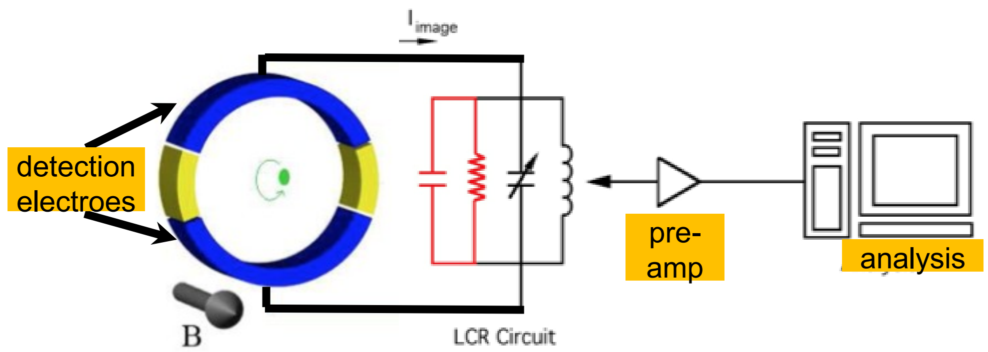


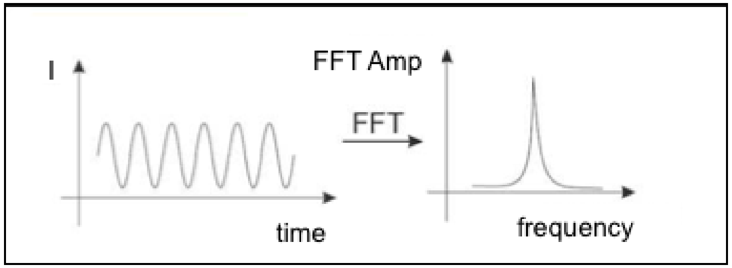


High-precision mass measurements using a single ion with SIPT

- Perform measurements on lowest-rate rare isotopes produced at NSCL and later, FRIB
  - Access to isotopes delivered at rates as low as 1 ion/day
  - ^{78}Ni, ^{100}Sn
- $\delta m/m \sim 10^{-6}$ or better using narrowband FT-ICR
  - Established for high precision measurements of stable isotopes
  - In preparation for SHIPTRAP







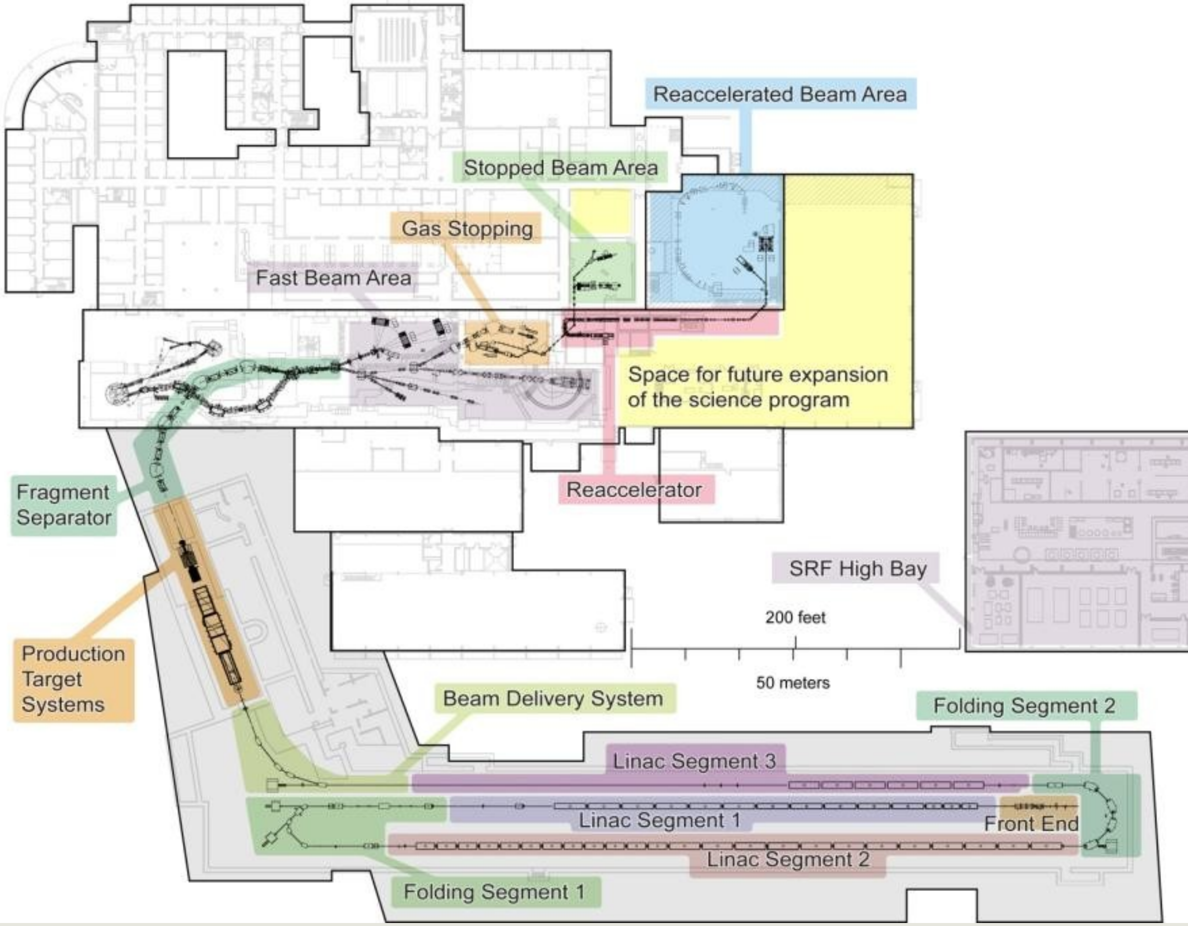
LEBIT Team

B.R. Barquest, G. Bollen, M. Brodeur, S.E. Bustabad, A. Gehring, D.L. Lincoln, D.J. Morrissey, S. Novario, **R. Ringle**, S. Schwarz, C.S. Sumithrarachchi, A. Valverde (MSU)
M. Redshaw (CMU)

FRIB - Facility for Rare Isotope Beams at MSU
World-leading next-generation rare isotope beam facility

- Rare isotope production via in-flight technique with primary beams up to 400 kW, 200 MeV/u ^{238}U

- **FRIB project start in 2009**
- **Detailed design of technical systems started 2012**
- **Start of civil construction planned for 2013**
- **Managed for early completion in 2019**
- **DOE project completion date 2021 (CD-4)**



Facility for Rare Isotope Beams
Existing NSCL will be integrated

FRIB
Southwest View

Ready for Civil Construction to Begin

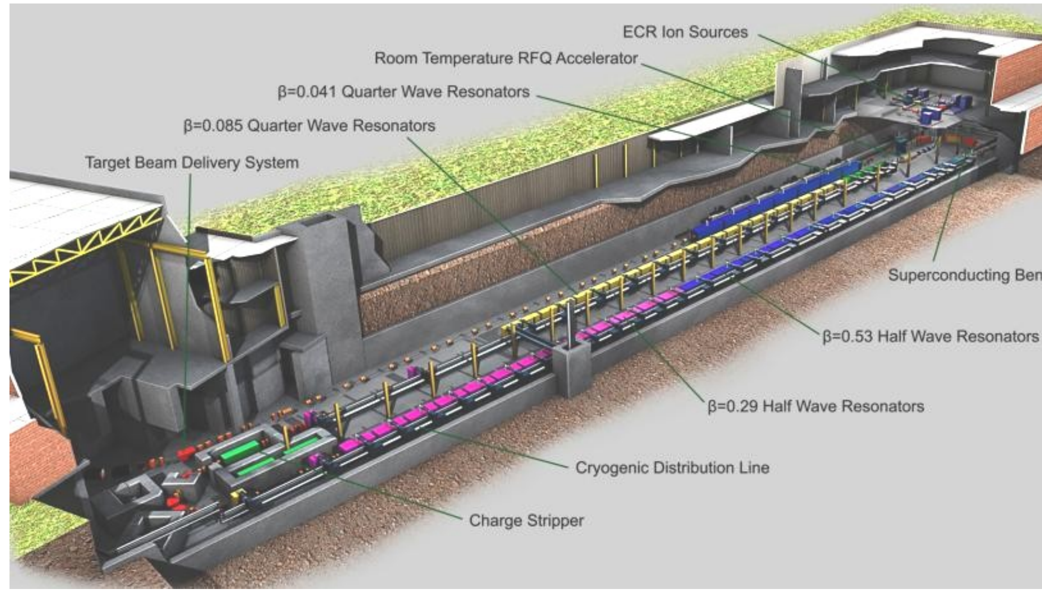
- Site preparation and placement of pilings for earth retention complete
- Ready for start of civil construction upon approval from DOE-SC

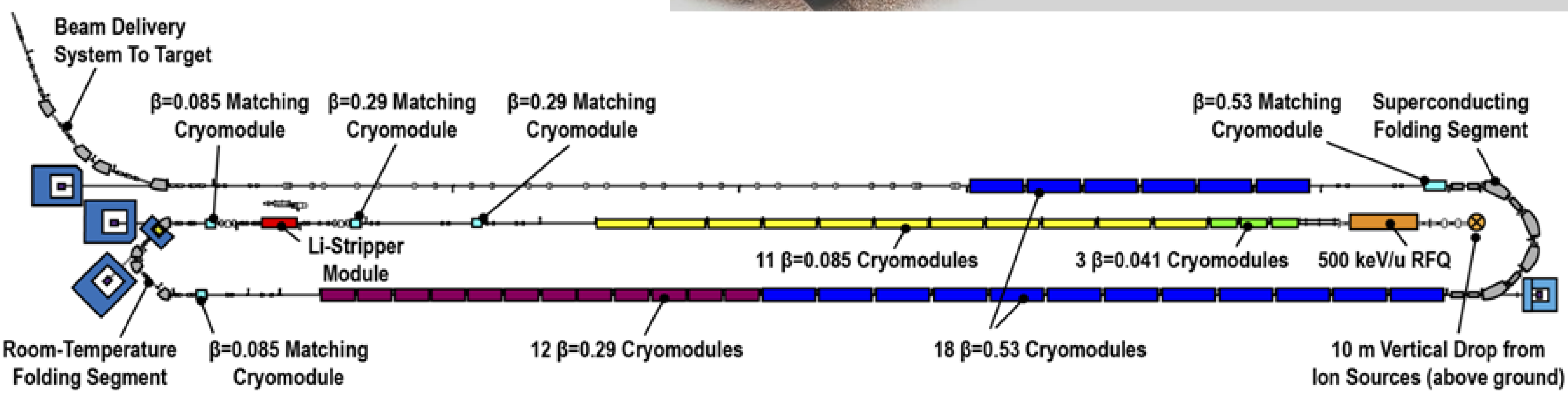
Photo from 25 February 2013; live and time lapse images at frib.msu.edu

NSCL FRIB

FRIB Accelerator Systems
SRF Driver Linac

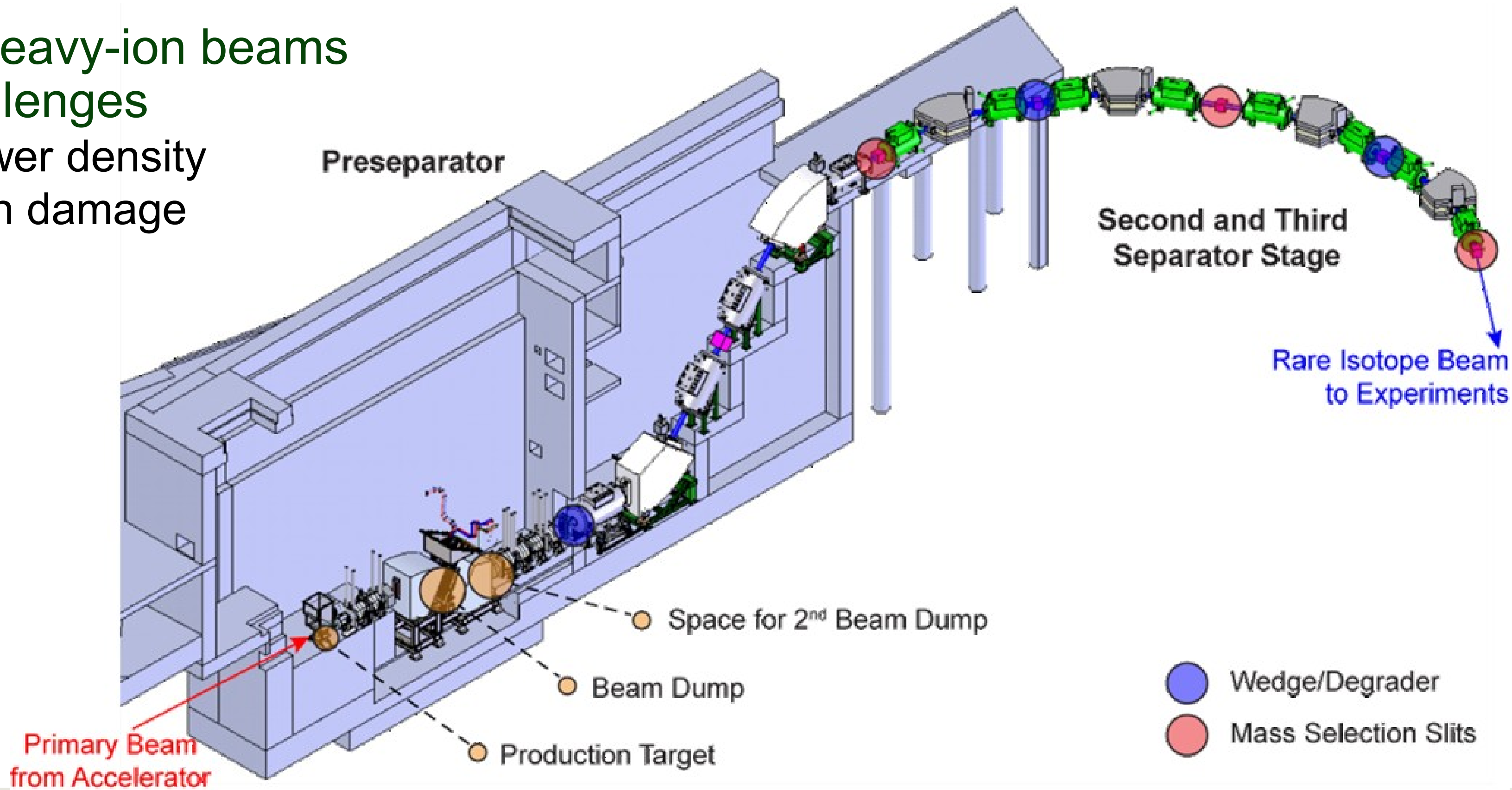
- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400kW
  - Highest power heavy ion accelerator in the world





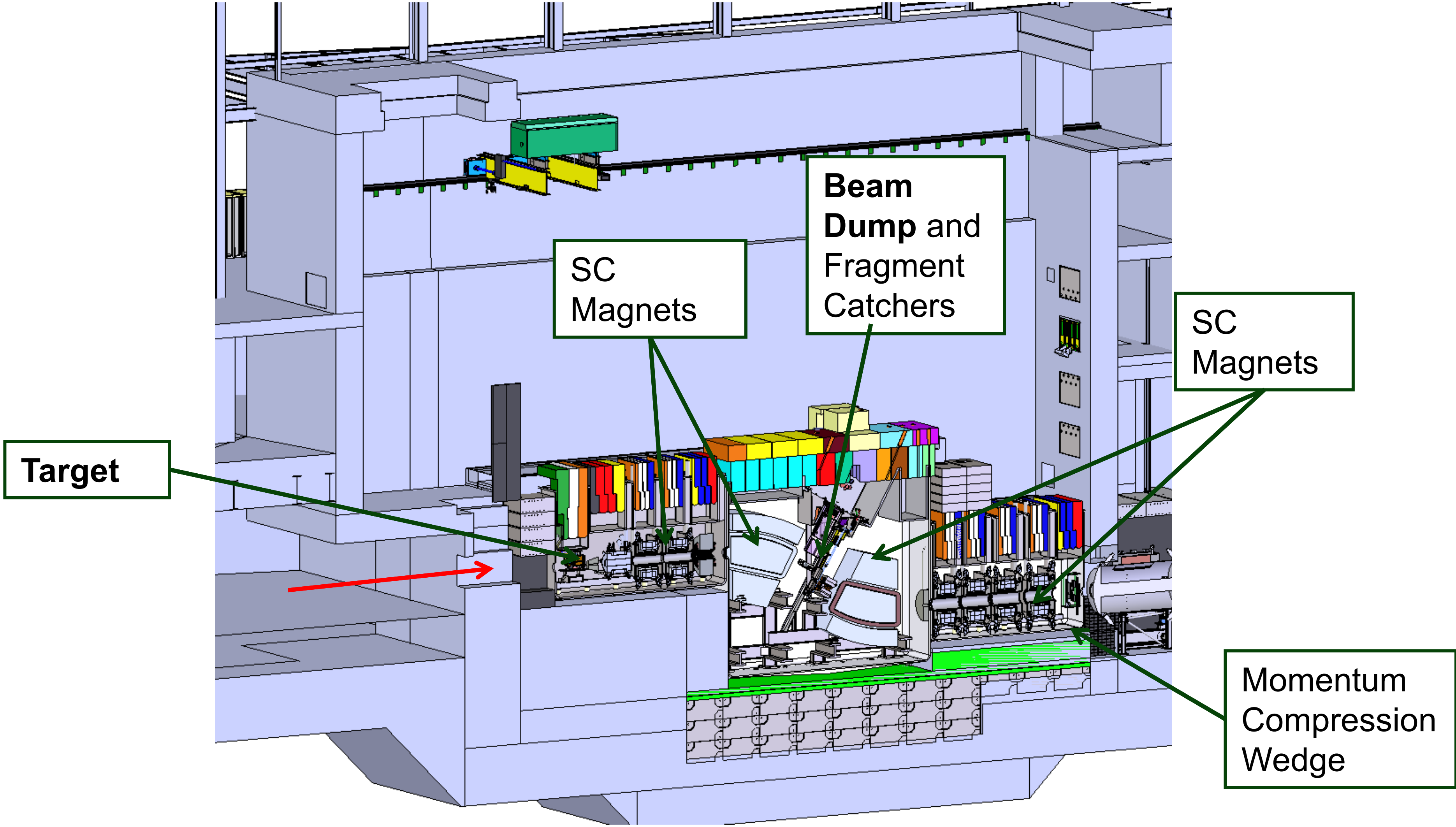
FRIB Experimental Systems
FRIB Rare Isotope Production Systems

- Production of rare isotope beams with 400 kW beam power using light to heavy ions up to ^{238}U with energy ≥ 200 MeV/u
- Three separation stages for high beam purity
- 400 kW heavy-ion beams pose challenges
  - High-power density
  - Radiation damage



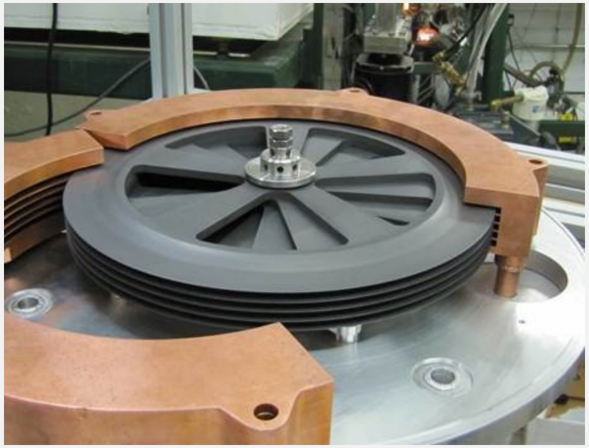
Fragment Separator and Target Facility

Design Meets 400-kW Power Requirement

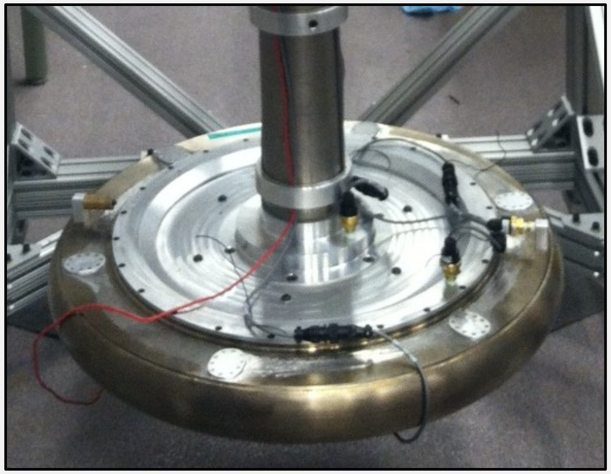


High-power Density Challenge
Production Target and Beam Dump

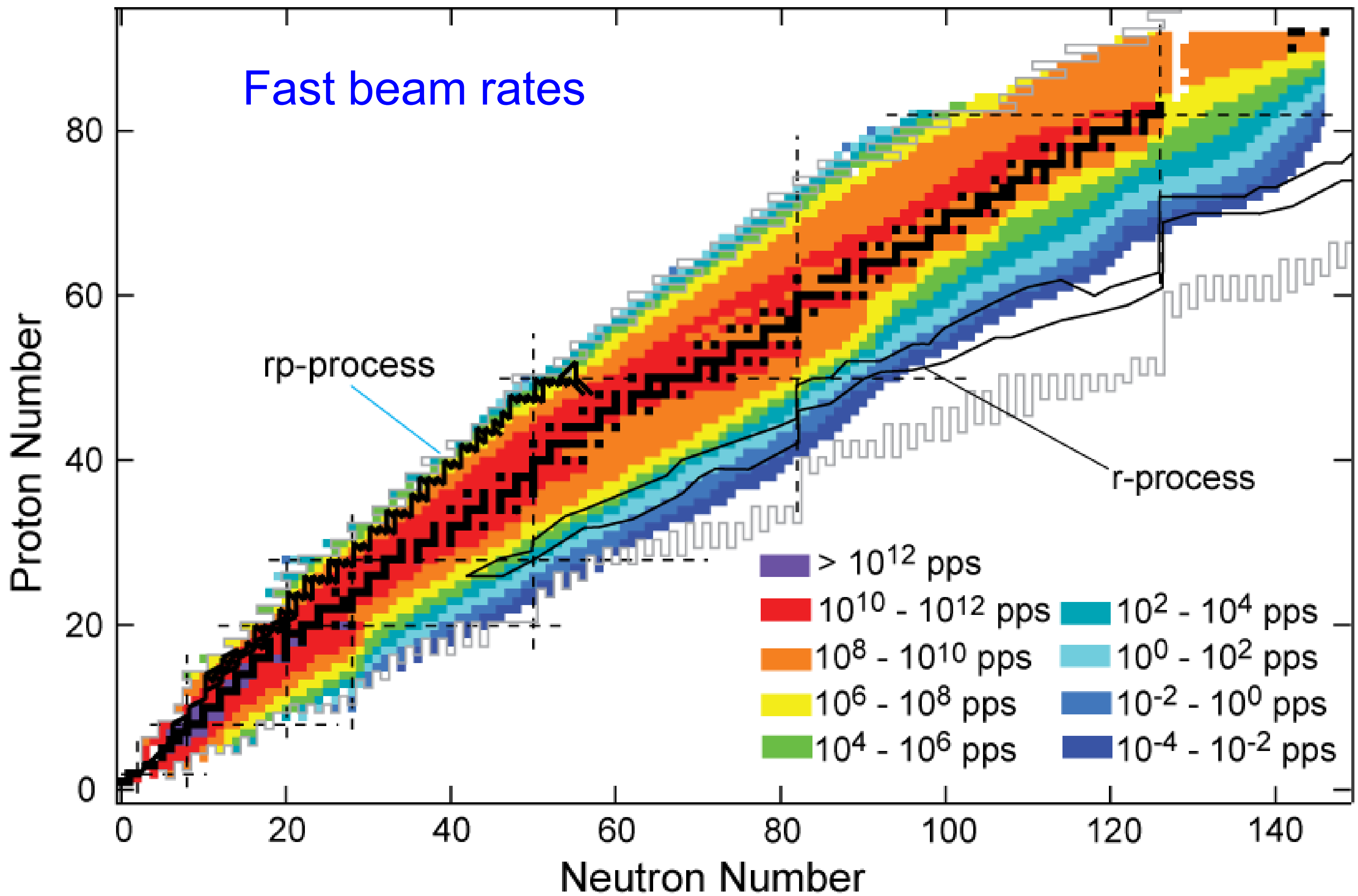
- Production Target
  - 100 kW beam power loss
  - 1 mm beam spot → 60 MW/cm^3 for ^{238}U
  - Desired lifetime of 2 weeks
- Multi-slice rotating graphite target
  - 5000 rpm, 30 cm diameter
  - T_{max} =1900 C, P_{max}/slice=10 kW



- Primary Beam Dump
  - Dissipate 300 kW beam power
  - Desired lifetime of 1 year
- Water-filled rotating Ti drum
  - Beam stops in water
  - 70 cm diameter, 400 rpm, 60 gpm

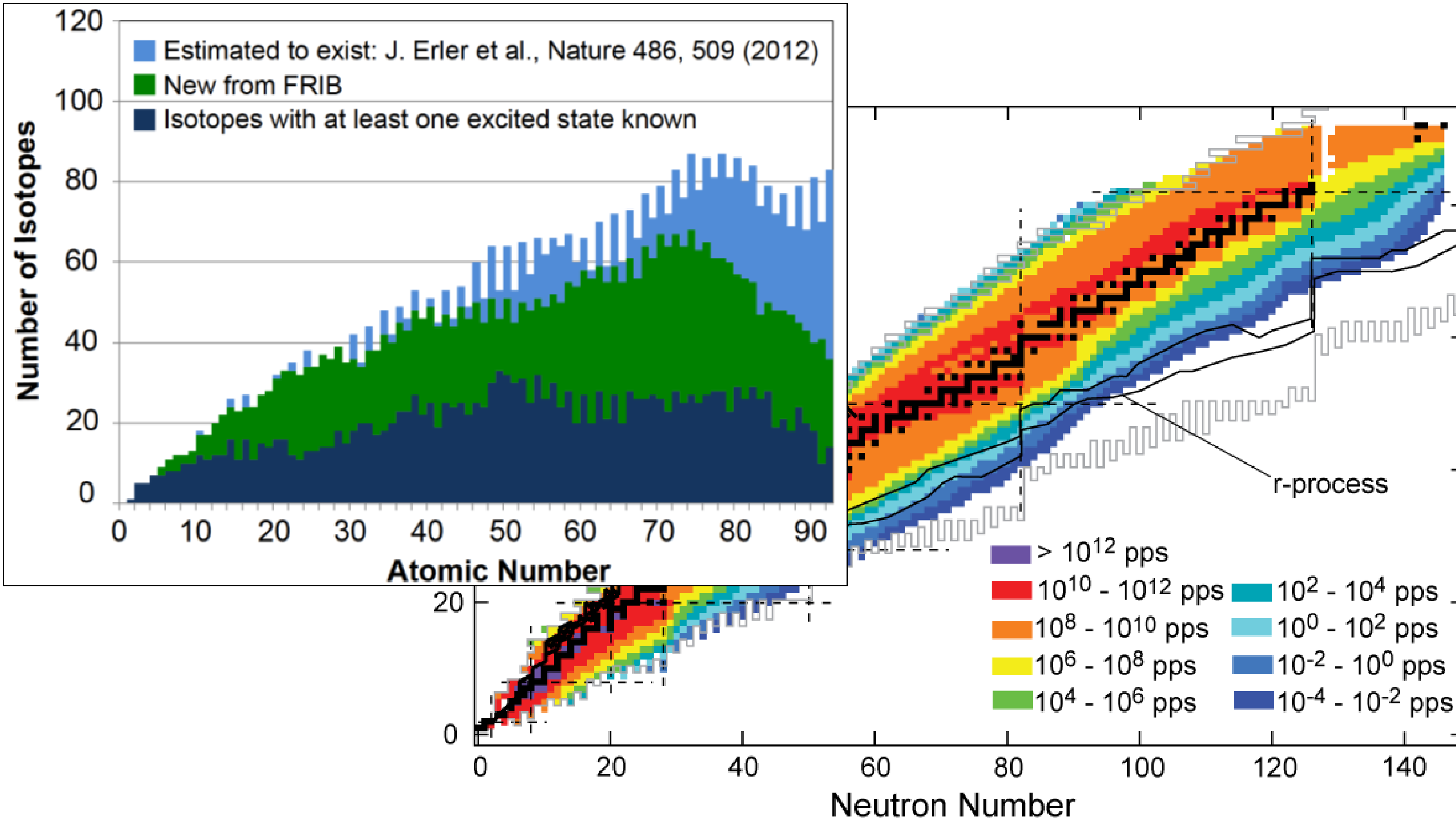


FRIB Rare Isotope Beam Rates
High Beam Rates to Maximize Science Reach



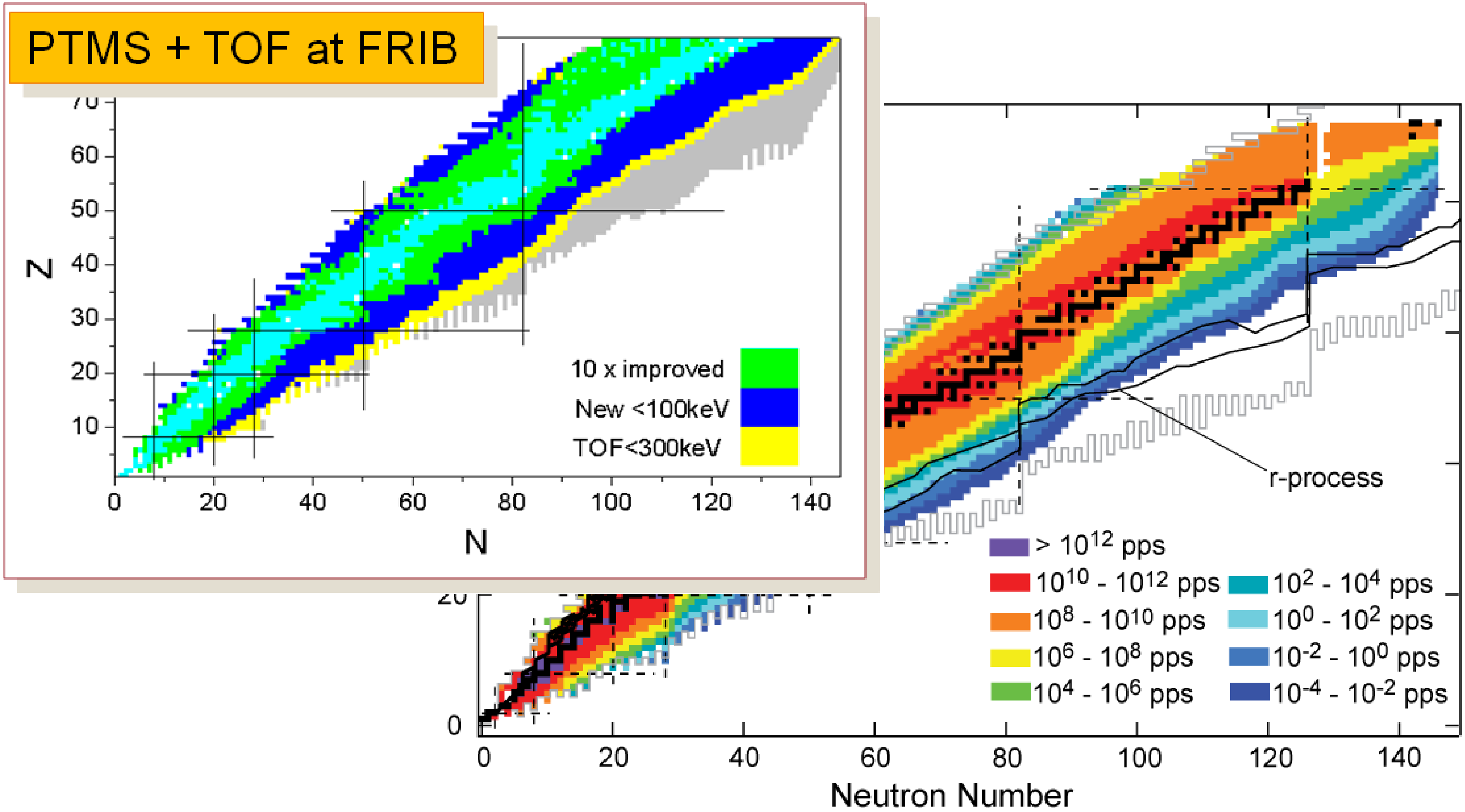
NSCL FRIB

FRIB Beams Will Enable New Discoveries



FRIB

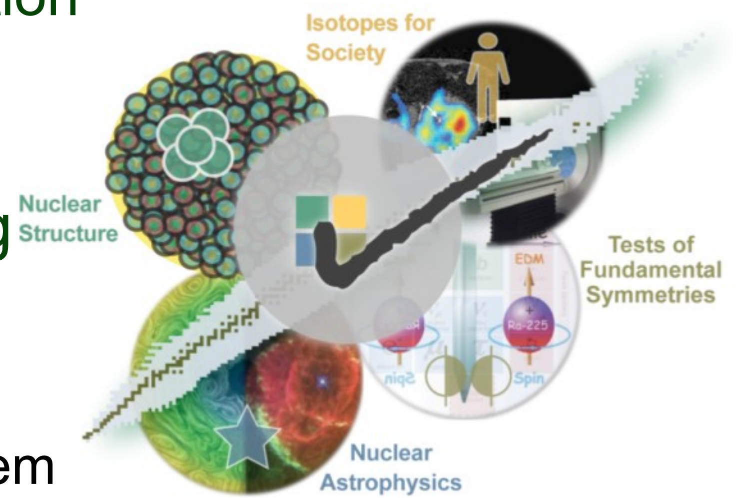
FRIB Opens New Territories to Explore by Mass Measurements



Summary

- LEBIT is first and only Penning trap mass spectrometer for the study of isotopes produced by projectile fragmentation
  - Nuclear Structure
  - Nuclear Astrophysics
  - Fundamental Interactions

- Success triggered expansion of stopped beam program and implementation of reacceleration at NSCL
- New developments at LEBIT aim at reaching farther from stability, preparing for FRIB



- FRIB will enable new discoveries
  - Mass measurements are one way to make them