MSU Re-accelerator

The Reacceleration of Low Energy RIBs at the NSCL

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Outline

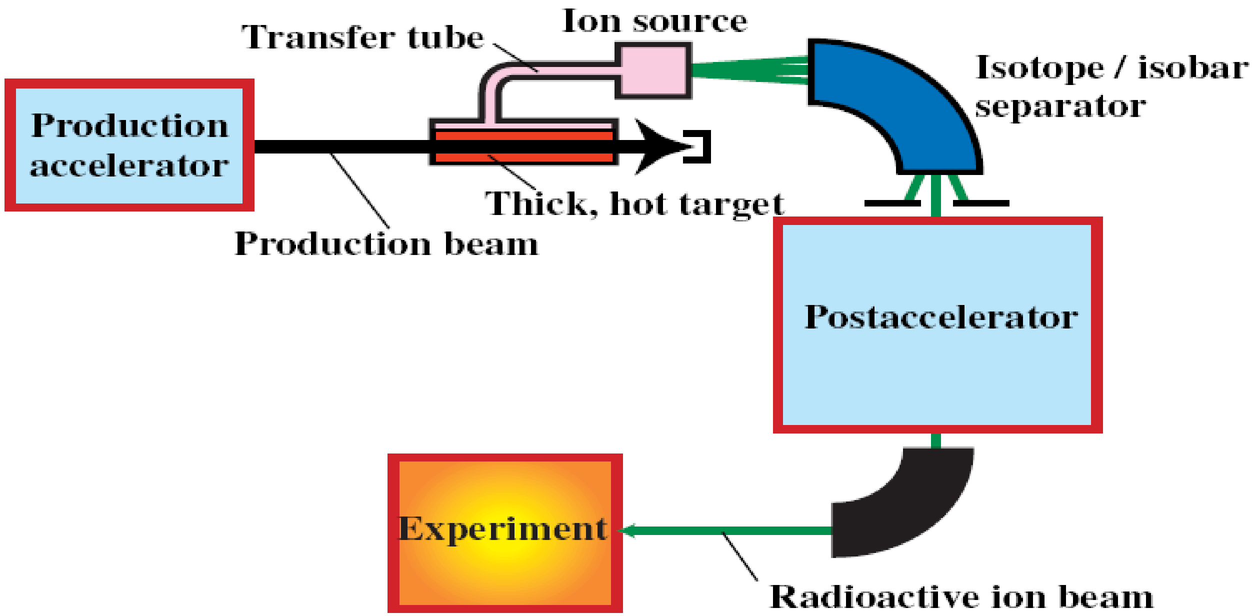
- Low-Energy Rare Isotope Beams (RIBs) production
- Planned Low-Energy RIBs Facility at NSCL
- Re-accelerator
  - Design considerations
  - Accelerator system
  - Beam dynamics
  - Current status and future plan
- Summary

Low-Energy RIB Production

- **Strong demand from nuclear science for high quality low-energy RIBs for:**
  - **Precision mass measurements & Laser spectroscopy**
  - **Precision decay studies & Low energy coulomb excitations**
  - **Transfer reaction studies of astrophysical reactions**
- **Two RIB production methods**
  - **Isotope Separation On-Line (ISOL)**
    - Produced at ~ rest
    - REX-ISOLDE & TRIUMF
  - **Projectile Fragmentation**
    - Produced at ~ 50 MeV/u
    - NSCL/MSU

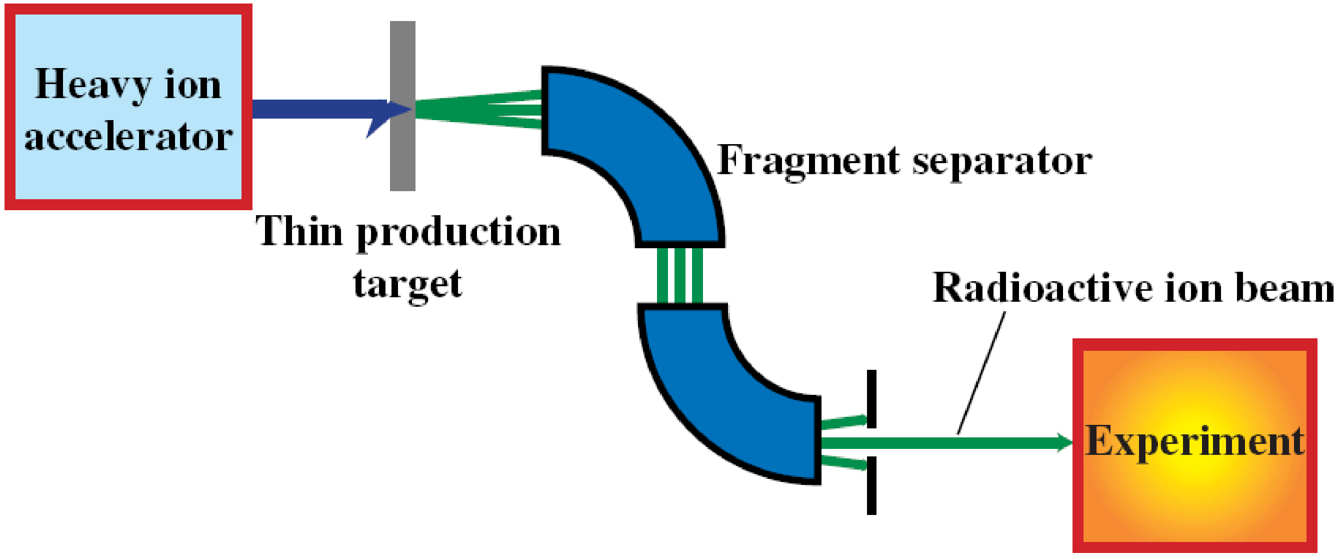
ISOL Facility Concept

- High beam quality and low beam energy
- Limited to longer life time (τ > 1s)
- Isotope extraction and ionization efficiency depend on chemical properties of element
- The most neutron-rich isotopes will have too low intensities and too short lifetimes to be suitable for re-acceleration

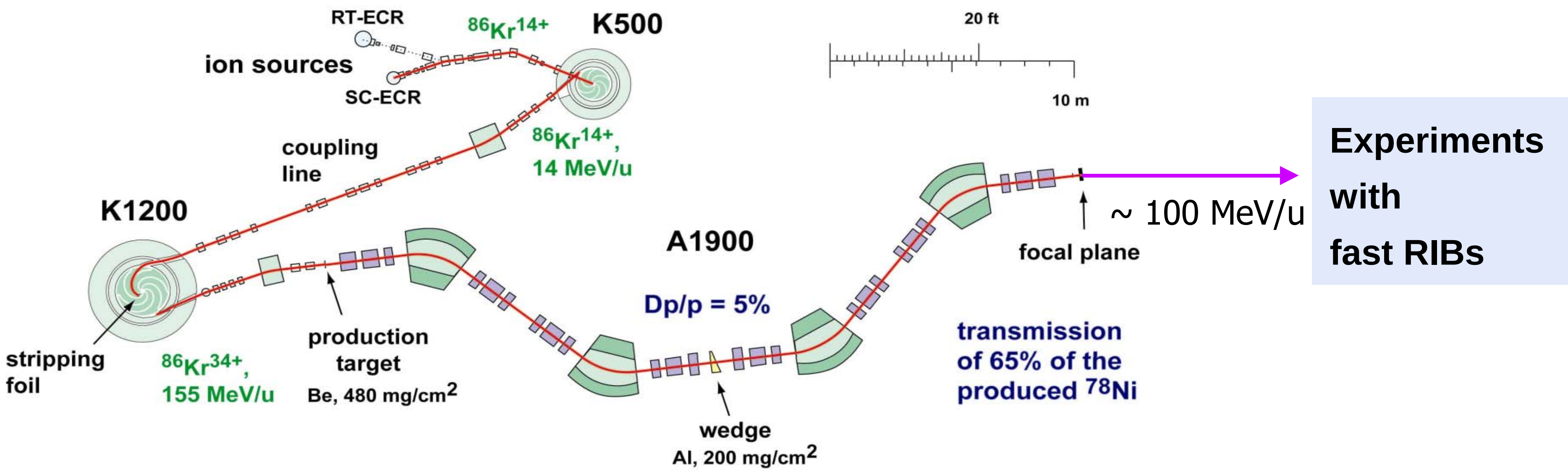


Projectile Fragmentation Facility Concept

- **Modest beam quality and high beam energy (E/A > 50 MeV/u)**
- **Suitable for short-lived isotopes ($\tau > 10^{-6}$ s)**
- **Physical method of separation, no chemistry**
- ***Low-energy beams are difficult (emittance too large)***

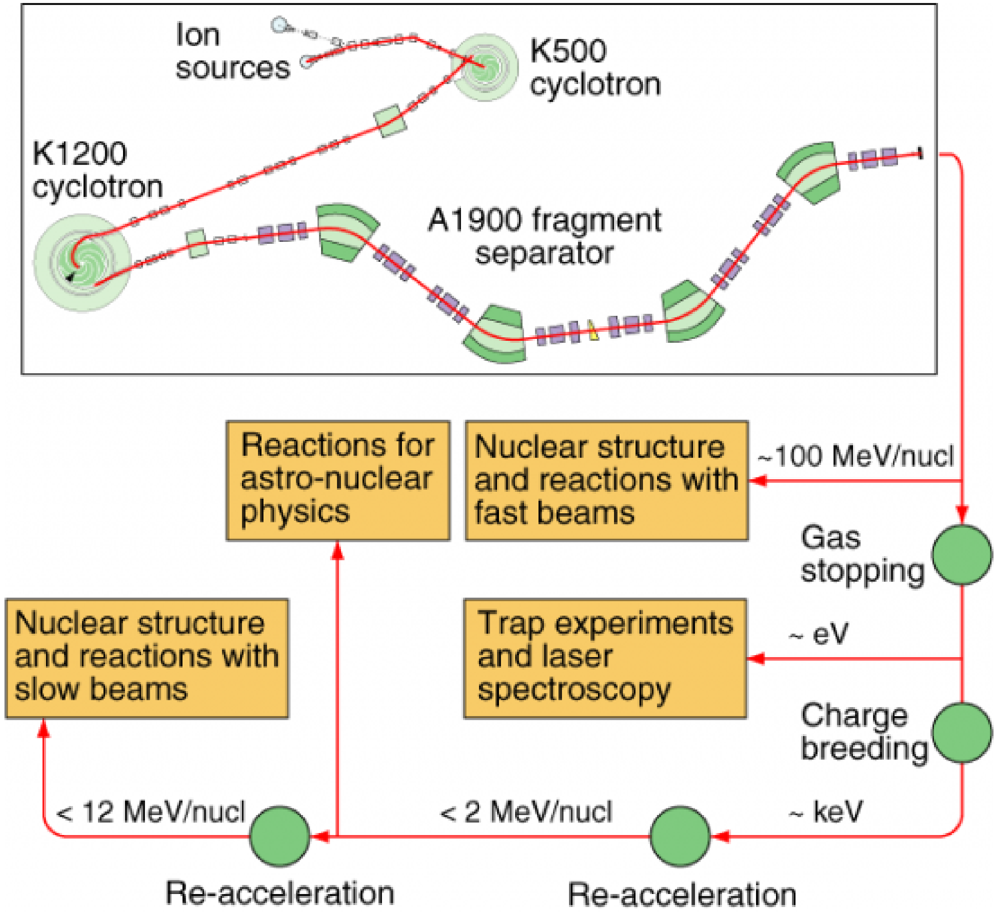


Fast RIBs Production at the NSCL



- **In-flight particle fragmentation method**
  - **Coupled cyclotrons produce high energy primary beams**
  - **Production target produce RIBs at velocity**
  - **A1900 Fragment Separator separate RIBs in-flight**
  - **Experiments performed with fast RIBs**
    - Nuclear structure/Nuclear reactions

Low-Energy RIBs at the NSCL

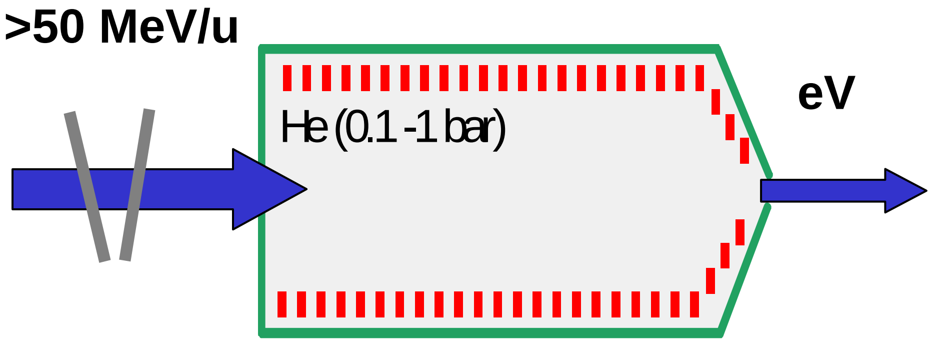


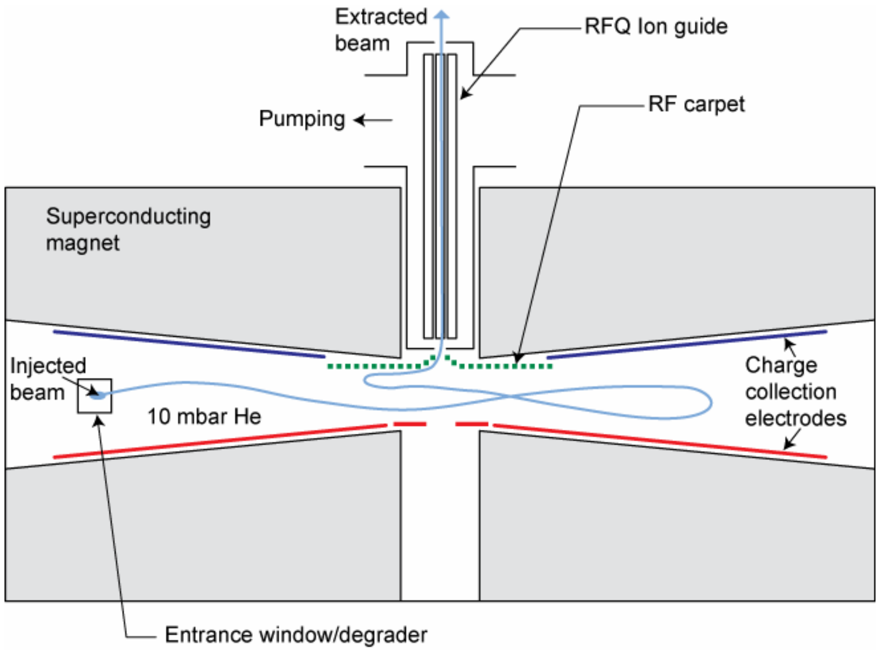
- **Prototype facility planned for stopping and re-accelerating RIBs produced and separated in-flight**
- **Important step toward a next-generation rare-isotope facility in the United States**
- **Three key steps:**
  - **Gas stopping**
  - **Charge breeding**
  - **Re-acceleration**

Gas Stopping Method

- **Linear Gas Cell – works but has limitations**
  - **Intensity-dependent extraction efficiencies**
  - **Extraction time of ~100 ms**
  - **Low stopping efficiencies for light beams**
- **"Cyclotron" Gas Stopper – under development**
  - **Shorter extraction times**
  - **Higher beam rate capability**

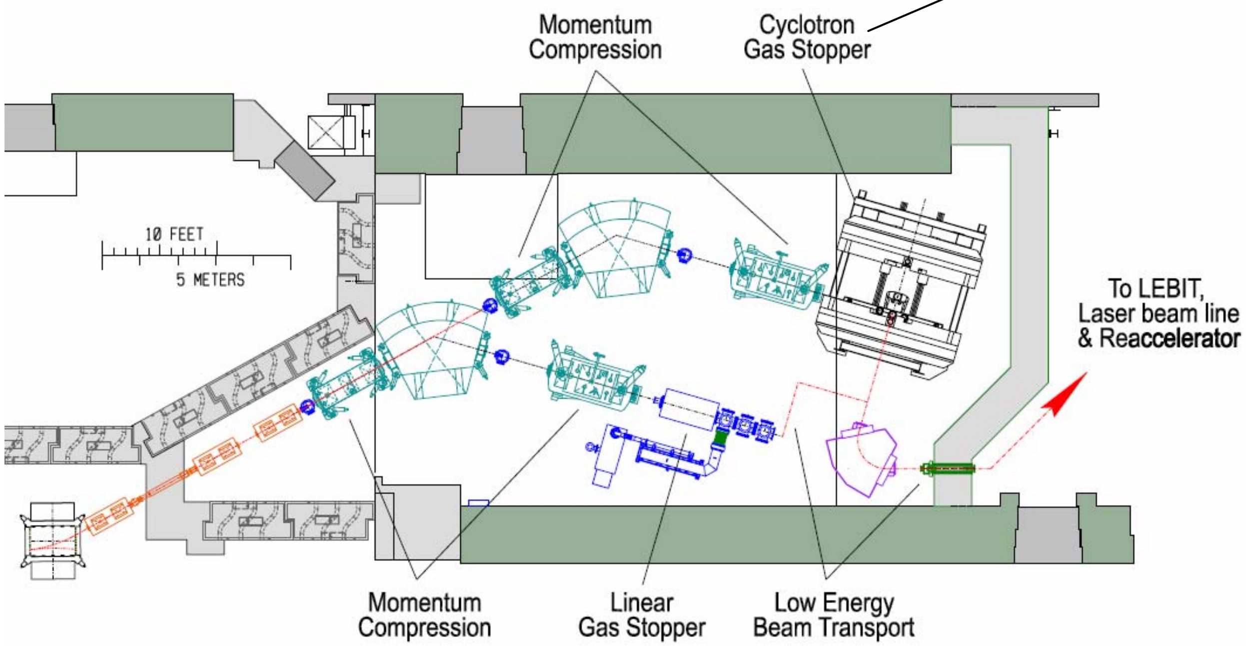
Georg Bollen/NSCL User Workshop 2007

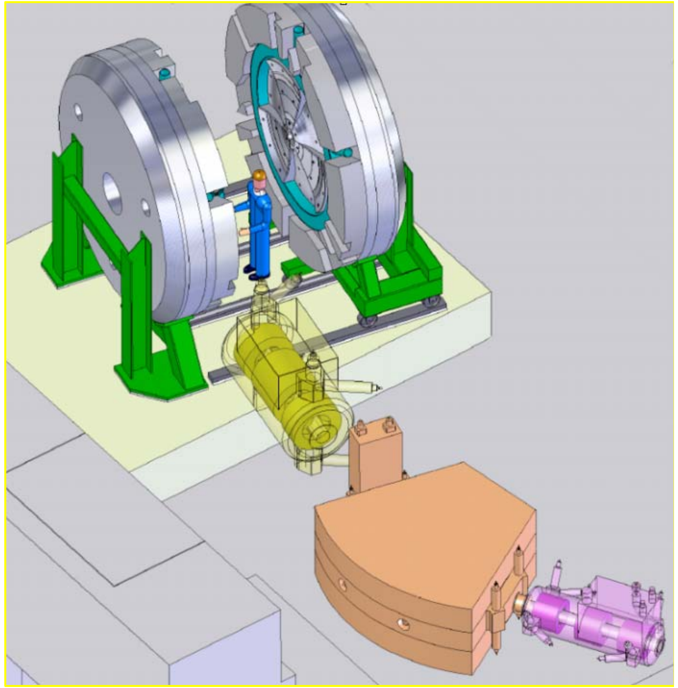


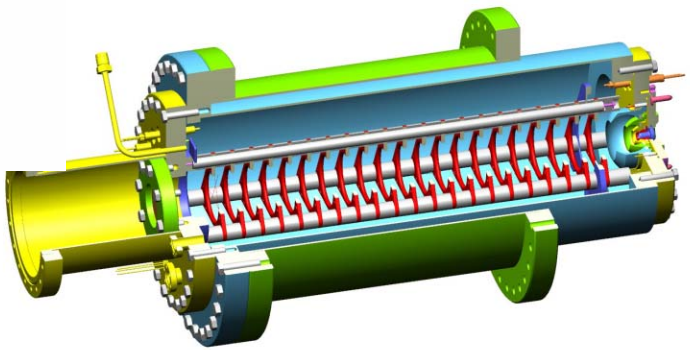


NSCL Gas Stopping Plan

• Possibility of both stopping methods at the NSCL

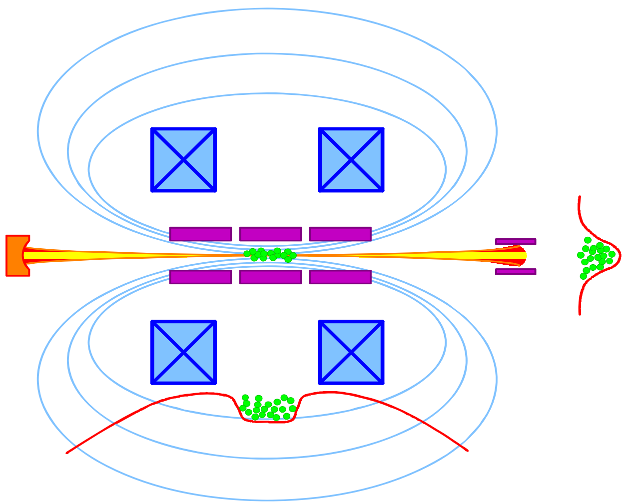


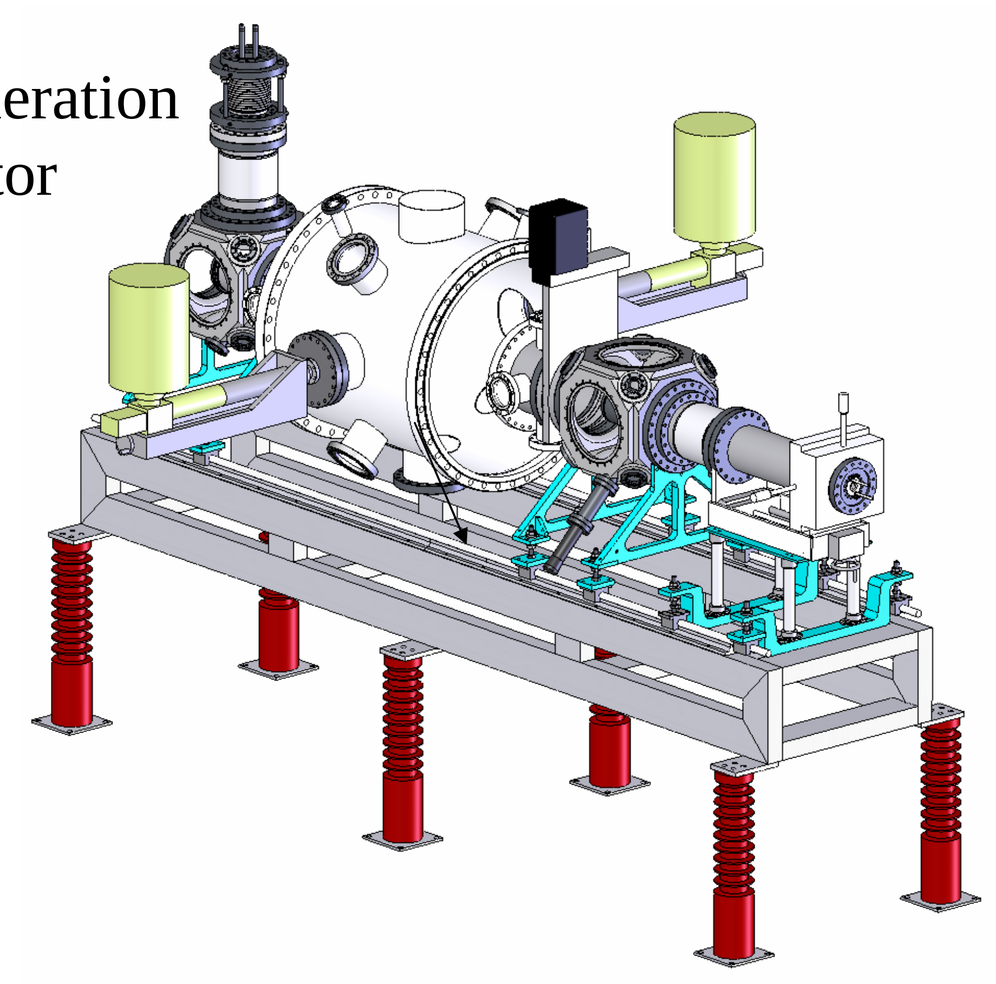




Electron Beam Ion Trap (EBIT) Charge-Breeder

- Charge breeder
  - 1+ → N+
  - More efficient acceleration
  - Electron gun/collector
  - Solenoid
  - Trap electrodes
  - 60 kV platform





MSU Reaccelerator Beam Specifications

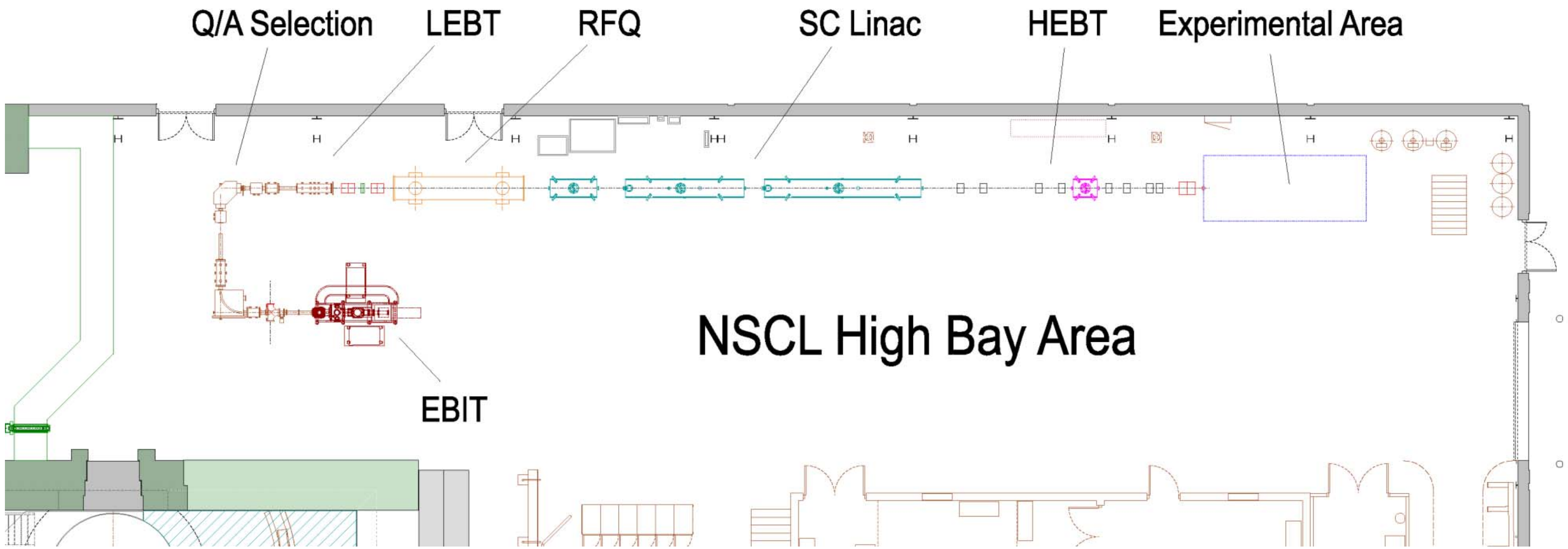
Input Beam Parameters *(From EBIT)*	
Energy	12 keV/u
Q/A	0.2 – 0.4
Transverse Emittance (normalized)	0.6 π mm-mrad
Energy Spread	± 0.2 %
Output Beam Parameters *(On target)*	
Energy Variability	From 0.3 to 3.0 MeV/u
Bunch Width on Target	~ 1 ns
Energy Spread on Target	~ 1 keV/u
Beam Size on Target	~ 1 mm

MSU Reaccelerator and RIA/ISF

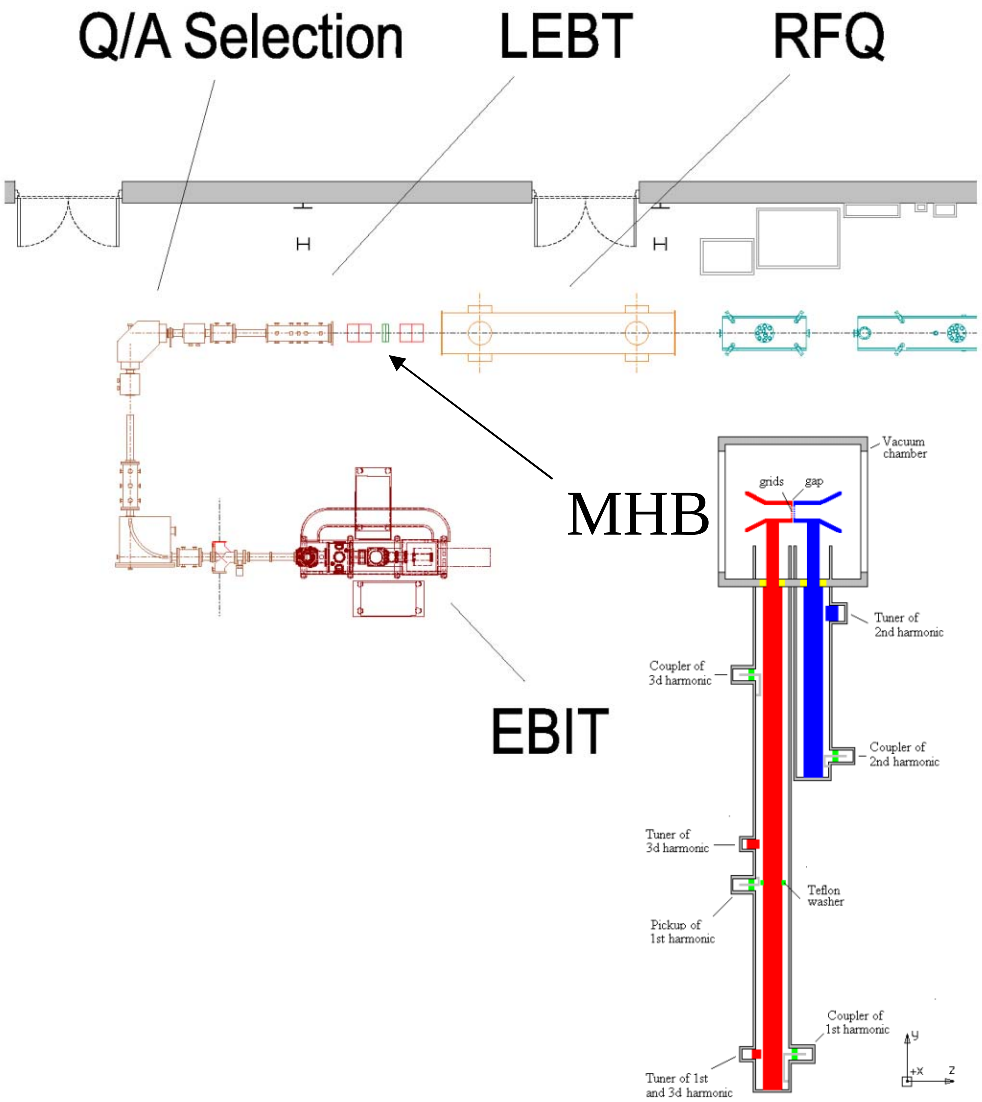
- **Design benefits from past RIA driver linac R&D efforts**
  - **Many similar components**
  - **Design experience**
  - **Beam simulation tools**
  - **SRF cavity and cryomodule prototyping**
- **Design and construction of the MSU reaccelerator will provide valuable experience for the future MSU Isotope Science Facility (ISF)**

MSU Reaccelerator Layout

- **Low Energy Beam Transport (LEBT)**
- **Radio Frequency Quadrupole (RFQ)**
- **Superconducting (SC) Linac**
- **High Energy Beam Transport (HEBT)**



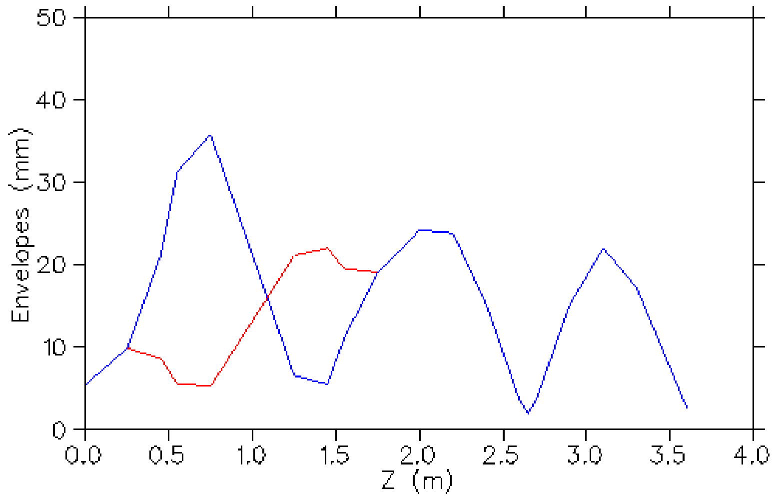
Low Energy Beam Transport



- **Transport, bunch and match RIBs into RFQ**
  - 4 electrostatic quadrupoles
  - 2 Superconducting solenoids
  - Multi-harmonic buncher (MHB)
    - Three harmonics
    - High bunching efficiency: ~ 82%
    - Two λ/4 resonators

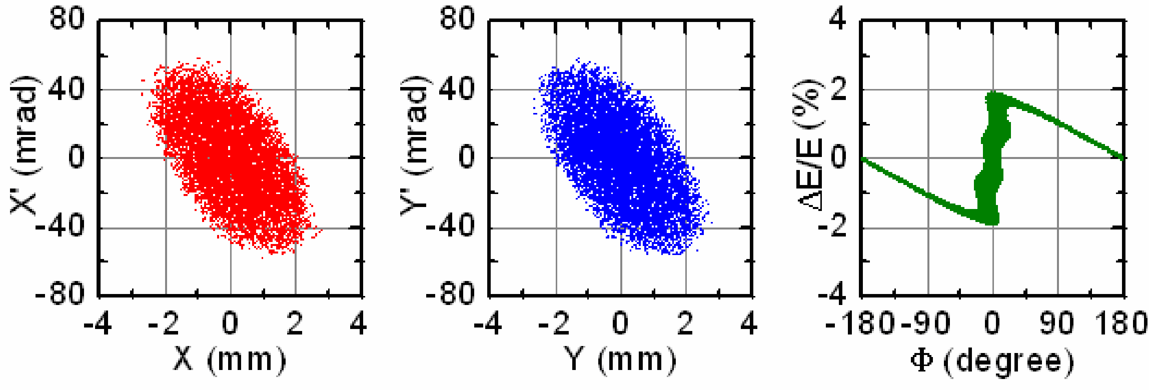
Low Energy Beam Transport

Beam simulated using RIAPMTQ



Beam envelopes in the LEBT

Horizontal, vertical and longitudinal phase spaces at the exit of the LEBT



Reaccelerator RFQ

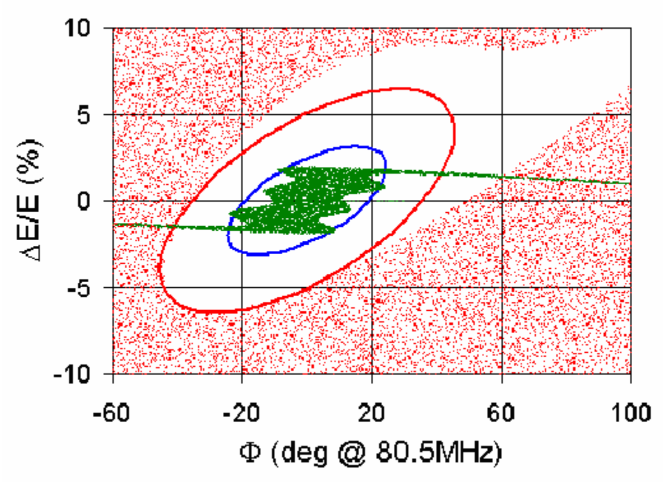
- **CW operation**
- **Room temperature structure**
- **Achieve small longitudinal emittance**
  - **~0.25 π kev/u-ns**
  - **External multi-harmonic buncher**
- **Enhanced acceleration efficiency**
  - **Shortened gentle bunching section**
- **Frequency: 80.5 MHz**
- **Length: 3.5 m**
- **Input energy: 12 keV/u**
- **Output energy: 600 keV/u**

RFQ Main Parameters

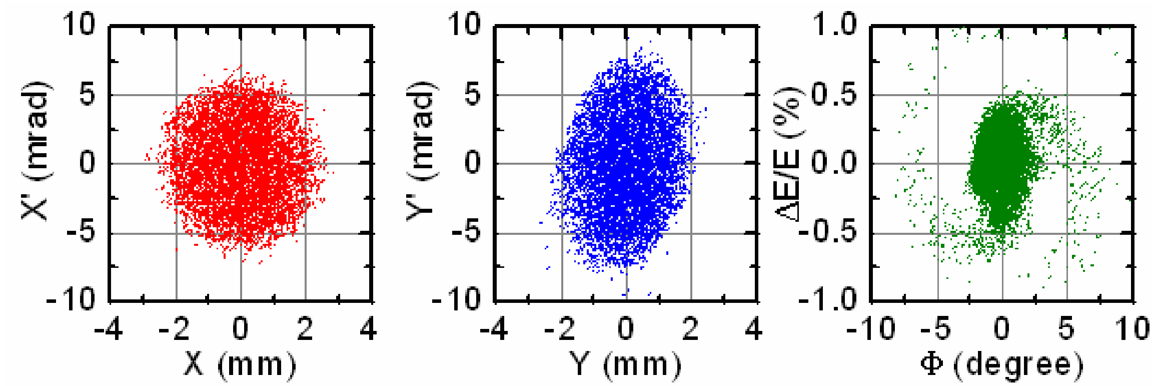
Charge to mass ratio, Q/A	0.2 – 0.4
Max. Intervane voltage (kV)	86.2
Peak electric field (MV/m)	16.7
Peak field ($E_{kilpatrick}$)	1.6
Number of cells	94
Synchronous phase (degree)	-20
Modulation factor	1.15→2.58
Average radius (mm)	7.3
Tip radius (mm)	6.0
Focusing strength	4.9

RFQ Beam Dynamics

The longitudinal acceptance (~ 0.8 π keV/u-ns) and beam phase space at the entrance of the RFQ



Horizontal, vertical and longitudinal phase spaces at the exit of the RFQ



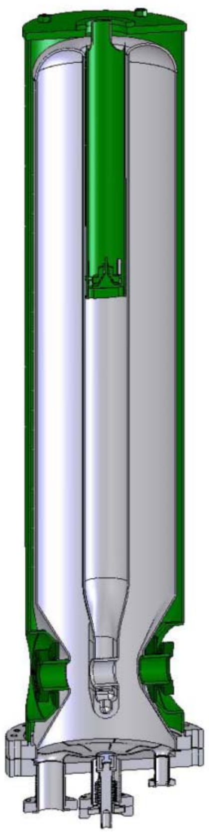
$\varepsilon_z(90\%) = \sim 0.29\ \pi$ keV/u-ns

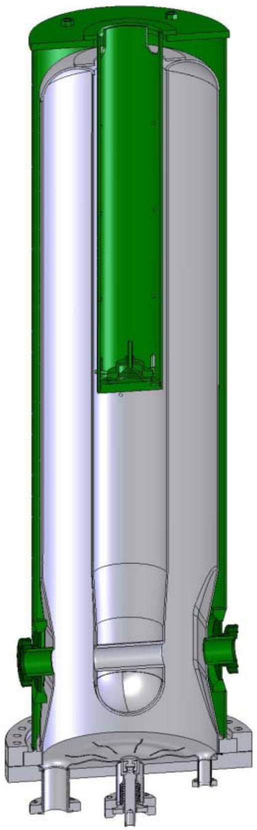
Superconducting Linac

- **Acceleration or deceleration of the RIBs to the desired energy**
  - **RFQ output energy: 600 keV/u**
  - **Final energy: 300 keV/u ~ 3 MeV/u**
  - **Maintain beam quality**
- **SC linac advantages**
  - **Requires very little rf power**
  - **High accelerating gradient for CW operation (100% duty factor)**
  - **Better operational flexibility and availability**

Two SRF Cavity Types Used

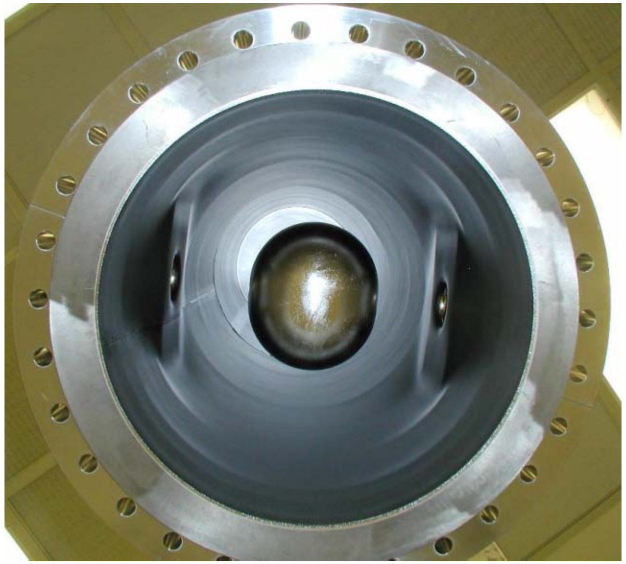
β_{opt}=0.041 β_{opt}=0.085





Type	λ/4	λ/4
Optimum β	0.041	0.085
Frequency	80.5 MHz	80.5 MHz
Epeak	16.5 MV/m	20.0 MV/m
Vacc	0.46 MV	1.18 MV
Eacc	4.84 MV/m	5.62 MV/m
Bpeak	28.2 mT	46.5 mT
Temperature	4.5 K	4.5 K
Length	0.095 m	0.21 m
Aperture	30 mm	30 mm

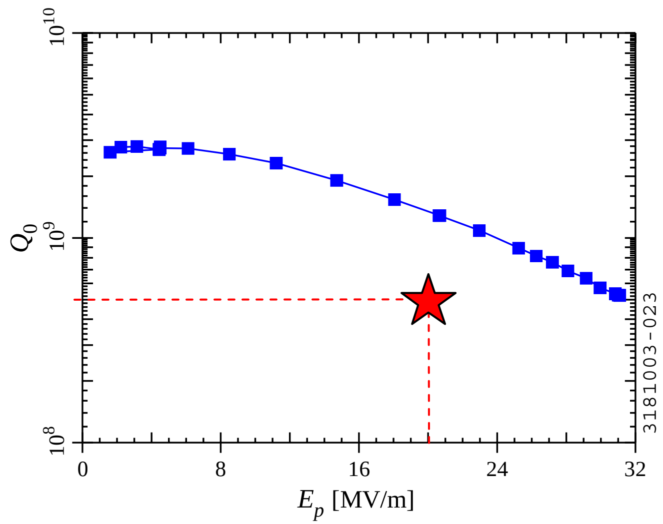
β_{opt} =0.085 Prototype Cavity



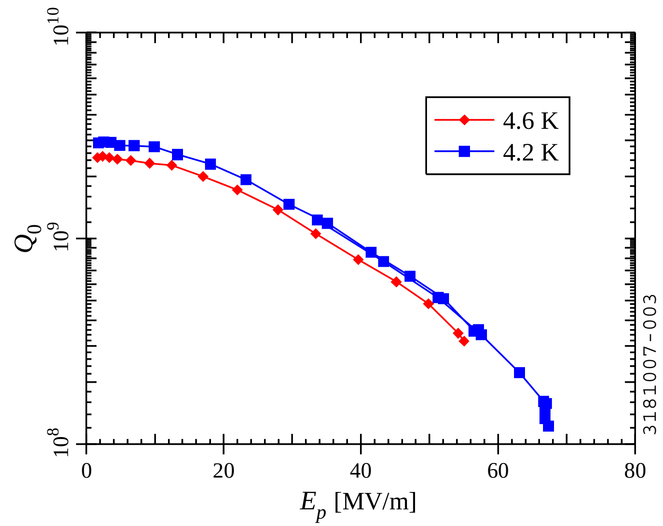
β_{opt} =0.041 Prototype Cavity

SRF Cavity Prototype R&D

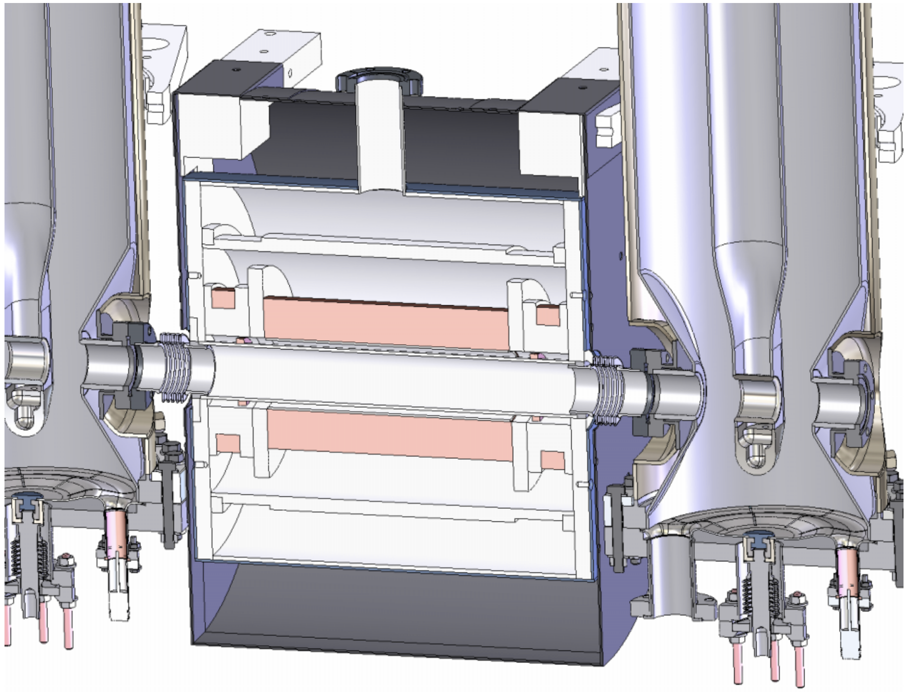
- **QWR** β_{opt}=0.085 prototyped and tested in 2003
  - Q_0: 5×10^8
  - E_p: 20 MV/m



- **QWR** β_{opt}=0.041 prototyped and tested in 2007 – to be presented at Tuesday poster session

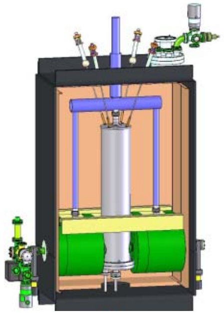


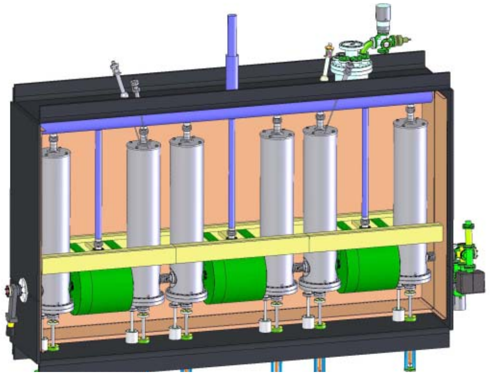
Transverse Focusing – Superconducting Solenoid

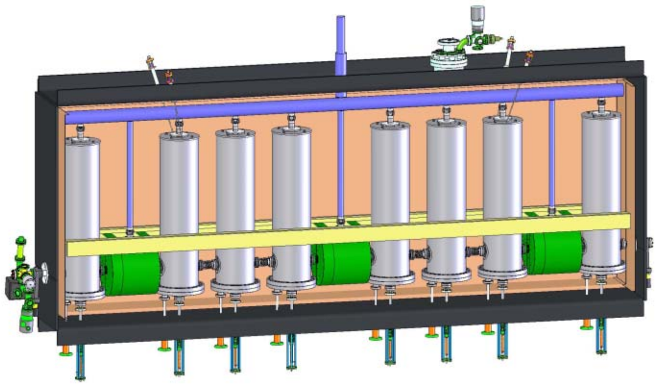


- **Symmetric focusing**
- **Allow more cavities per cryostat**
- **2 dipole corrector coils for central orbit correction**
- **Peak magnetic field: 9T**
- **Adjacent to superconducting cavities**
  - Active end bucking coils and niobium shield to minimize stray magnetic field
  - Obtain ~10^{-6} reduction in B field

Superconducting Linac Cryomodules

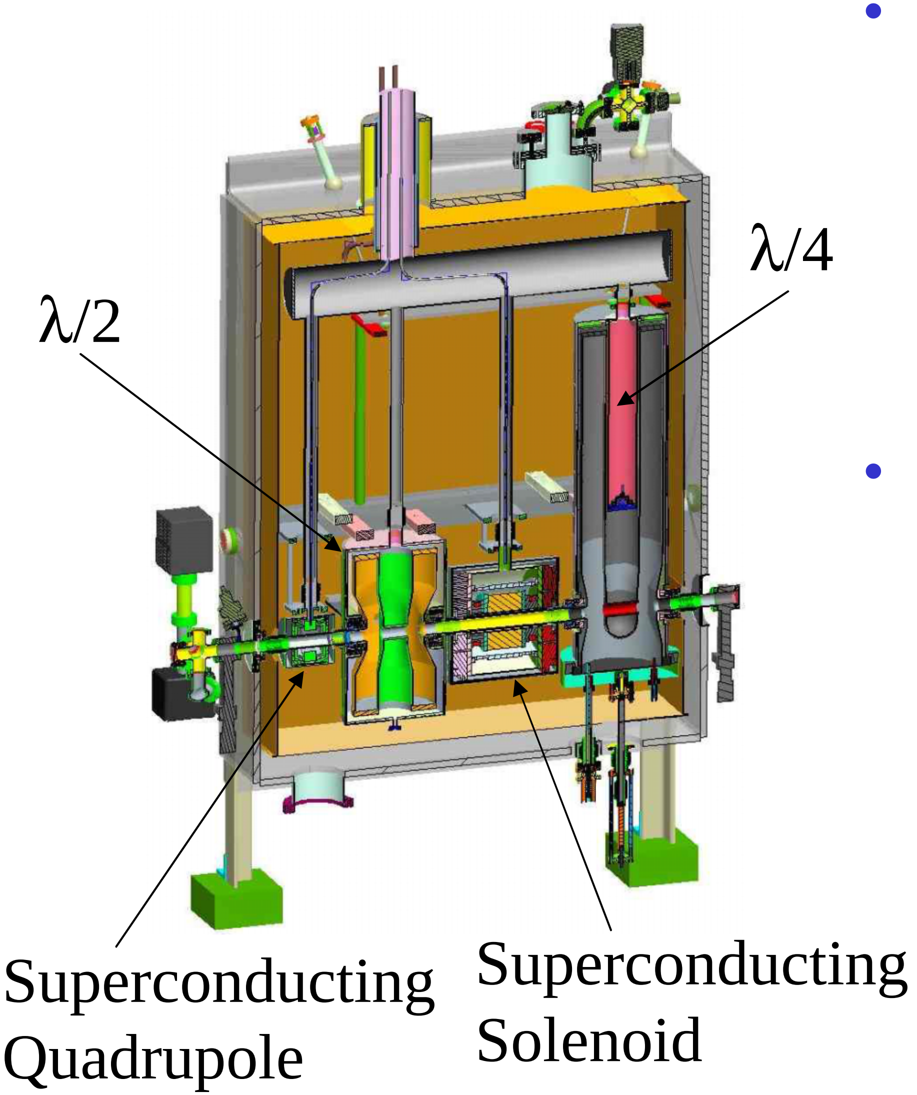






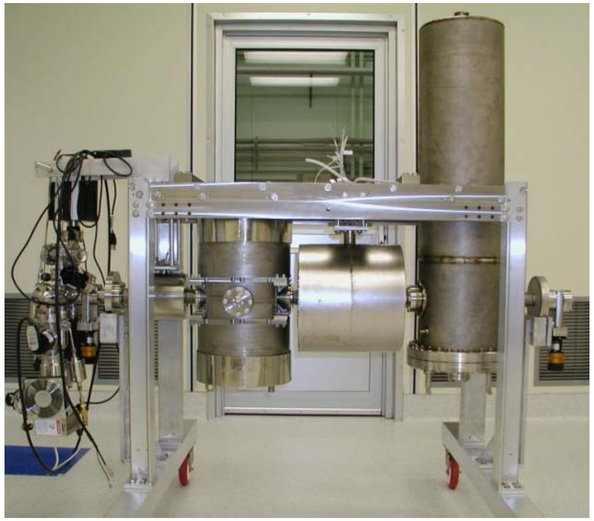
- 1^{st} Cryomodule
  - 2 Superconducting solenoids
  - 1 $\lambda/4$ SC cavity, β_{opt}=0.041
  - Transverse and longitudinal matching
- 2^{nd} Cryomodule
  - 3 Superconducting solenoids
  - 6 $\lambda/4$ SC cavities, β_{opt}=0.041
  - Acceleration/deceleration: 1.2/0.3 MeV/u
- 3^{rd} Cryomodule
  - 3 Superconducting solenoids
  - 8 $\lambda/4$ SC cavities, β_{opt}=0.085
  - Acceleration/rebunching

Superconducting Linac Prototype Cryomodules



- **Prototype cryomodule fabricated**
  - 80.5 MHz β_{opt}=0.085, λ/4 cavity
  - 322 MHz β_{opt}=0.285, λ/2 cavity
  - Superconducting solenoid
  - Superconducting quadrupole
- **Testing in progress**
  - Cavity performance
  - Magnet field effect on cavities
  - RF frequency stability, amplitude and phase controls
  - Will compare with vertical test results

SC Linac Prototype Cryomodules



(a) cold mass

(c) inner MLI

(e) outer MLI

(b) top plate

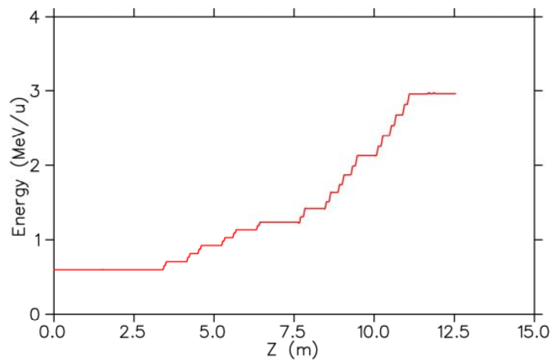
(d) 77 K shield

(f) vacuum vessel

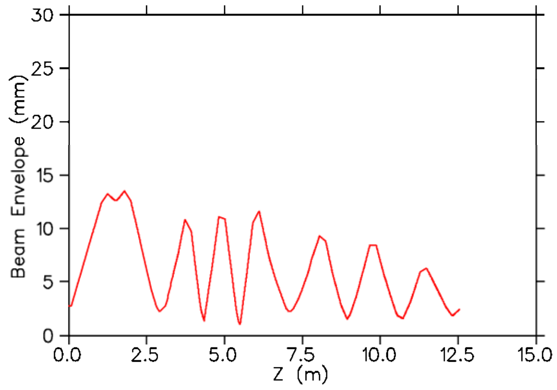
Superconducting Linac Performance - [1]

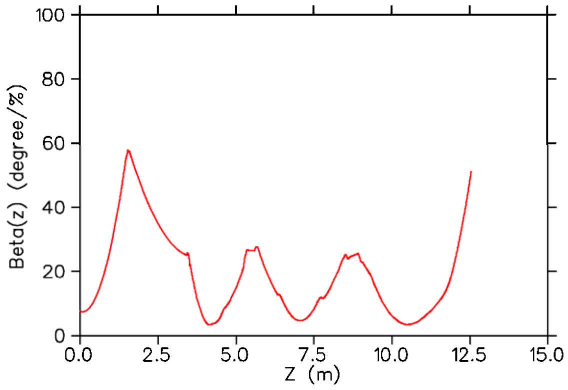
- **Beam simulations using IMPACT (~3 MeV/u)**

Beam energy gains along the SC linac



Beam transverse envelopes and longitudinal beta function along the SC linac

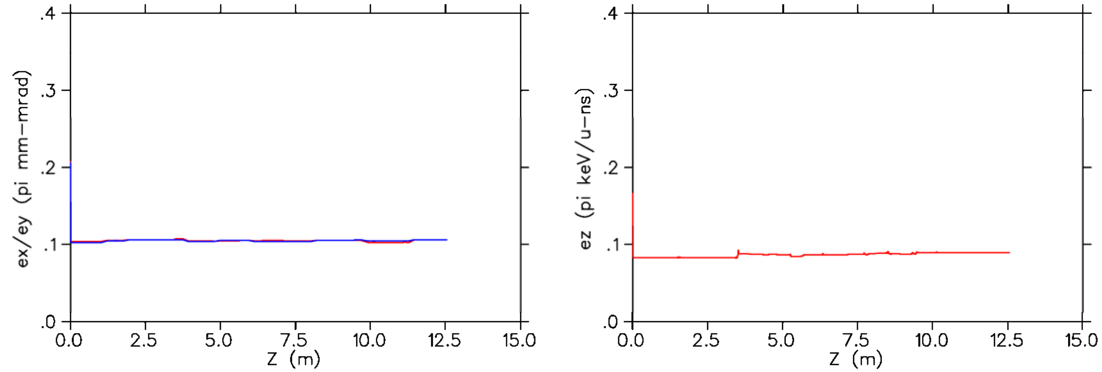




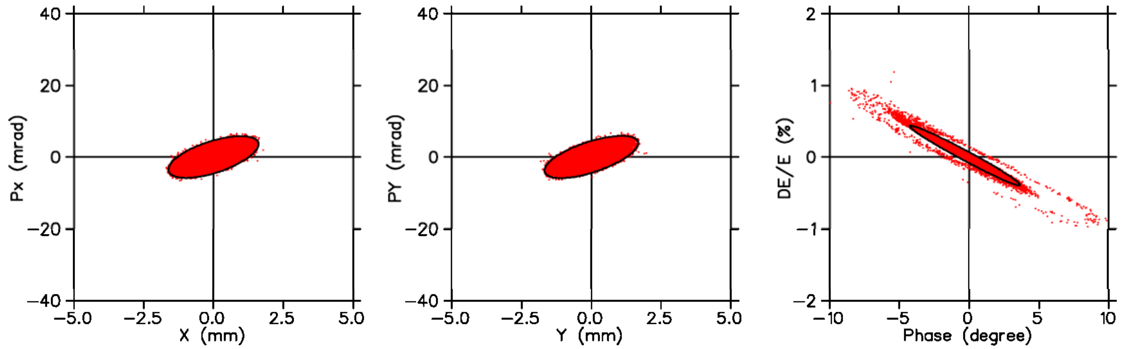
Superconducting Linac Performance - [2]

- **Adequate transverse and longitudinal acceptance**
- **No beam loss**
- **No transverse or longitudinal rms emittance growth**

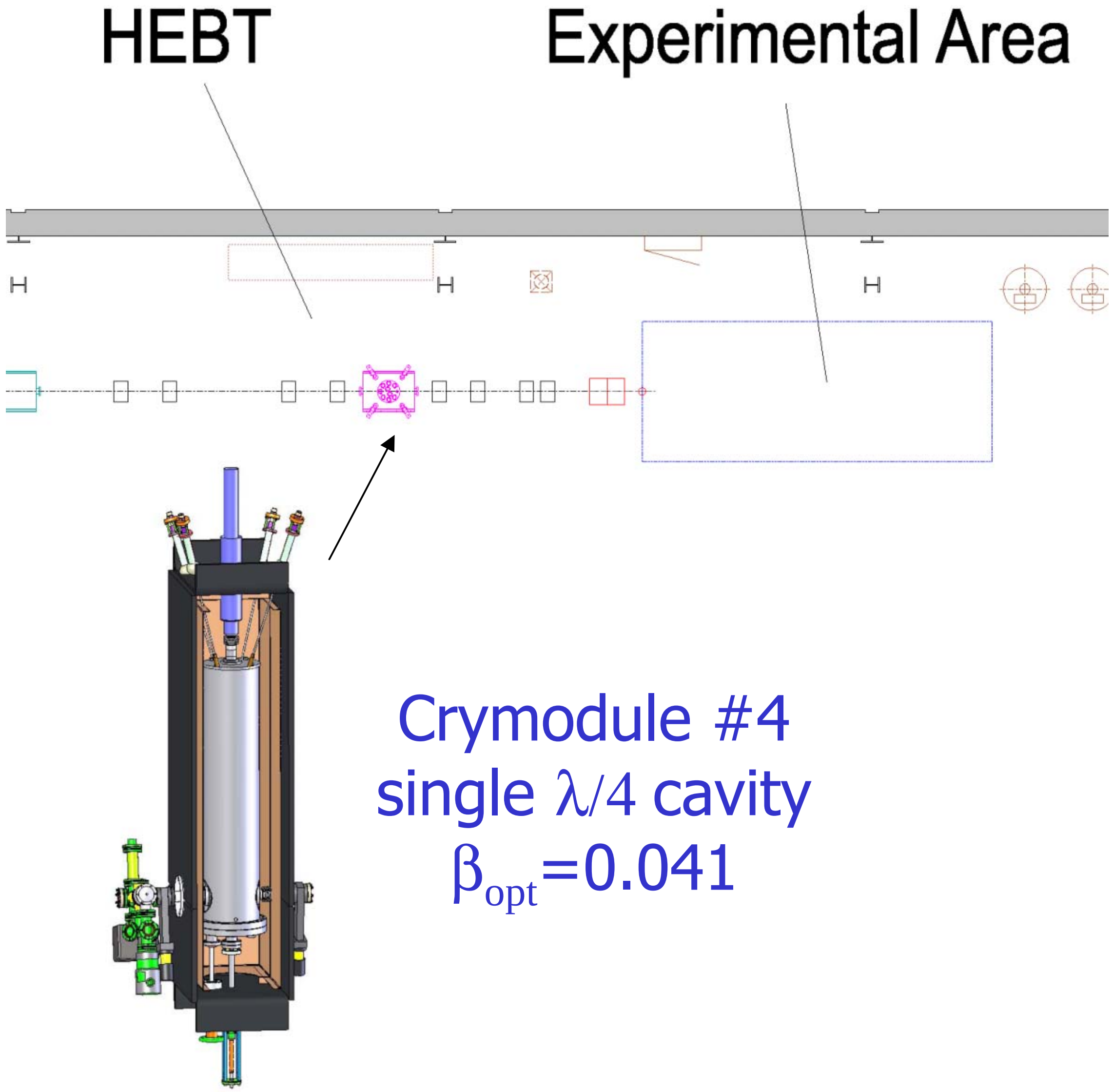
Transverse and longitudinal rms emittances along the SC linac



Horizontal, vertical and longitudinal phase spaces at the exit of the SC linac



High Energy Beam Transport – [1]

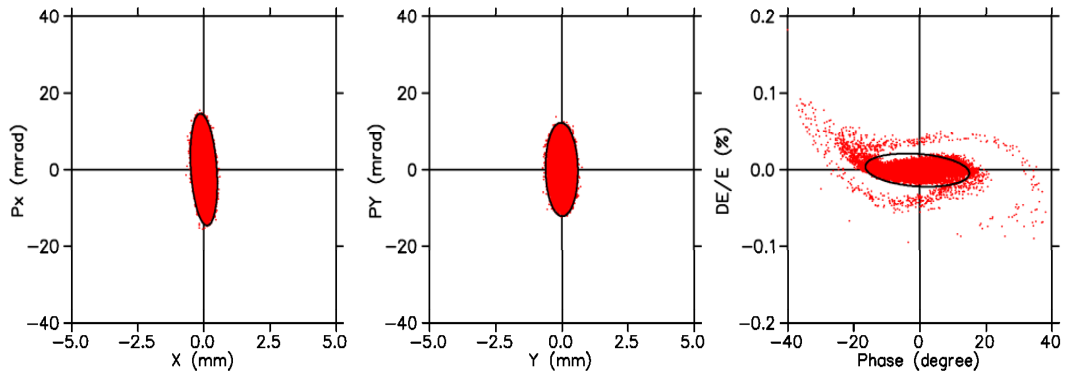


- Achieve the required beam conditions on target
- π-phase advance cell
  - 4 quadrupoles
- Cryomodule
  - Single λ/4 cavity, β_{opt}=0.041
  - Used as rebuncher
- Final focusing
  - 4 quadrupoles
  - Superconducting solenoid

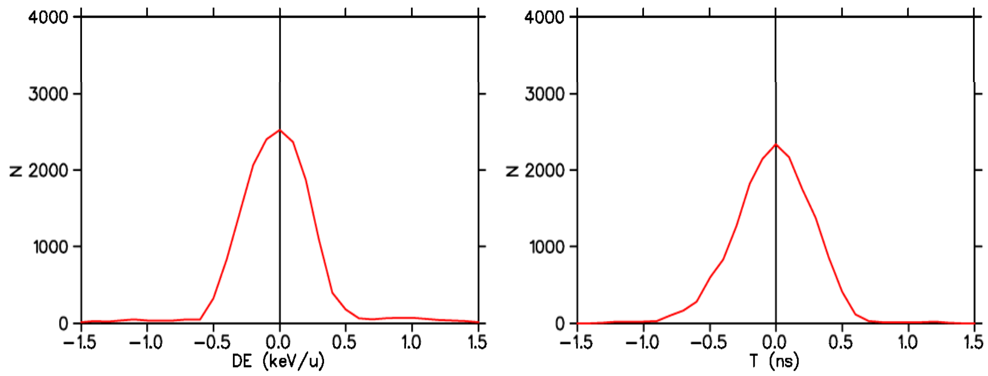
High Energy Beam Transport – [2]

- RIBs accelerated to ~ 3.0 MeV/u
  - ~88% of the RIBs within 1 ns and 1 keV/u

Horizontal, vertical and longitudinal phase spaces on target



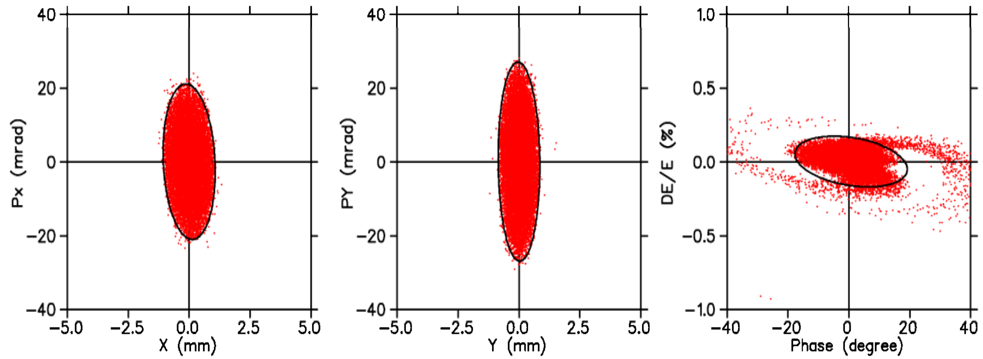
Energy spread and bunch width on target



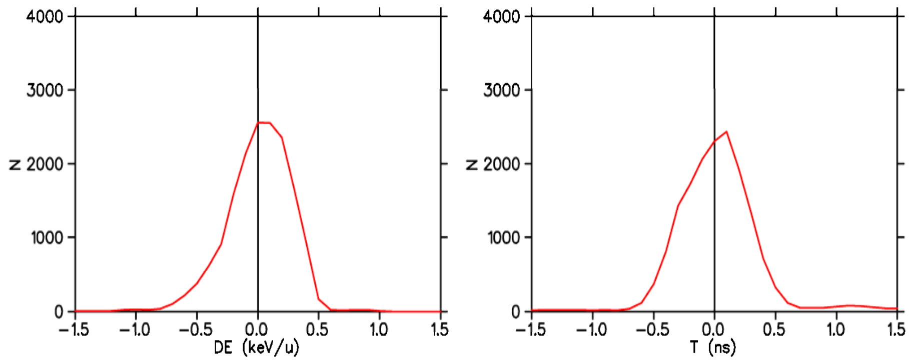
High Energy Beam Transport – [3]

- RIBs decelerated to ~ 0.3 MeV/u
  - ~89% of the RIBs within 1 ns and 1 keV/u

Horizontal, vertical and longitudinal phase spaces on target

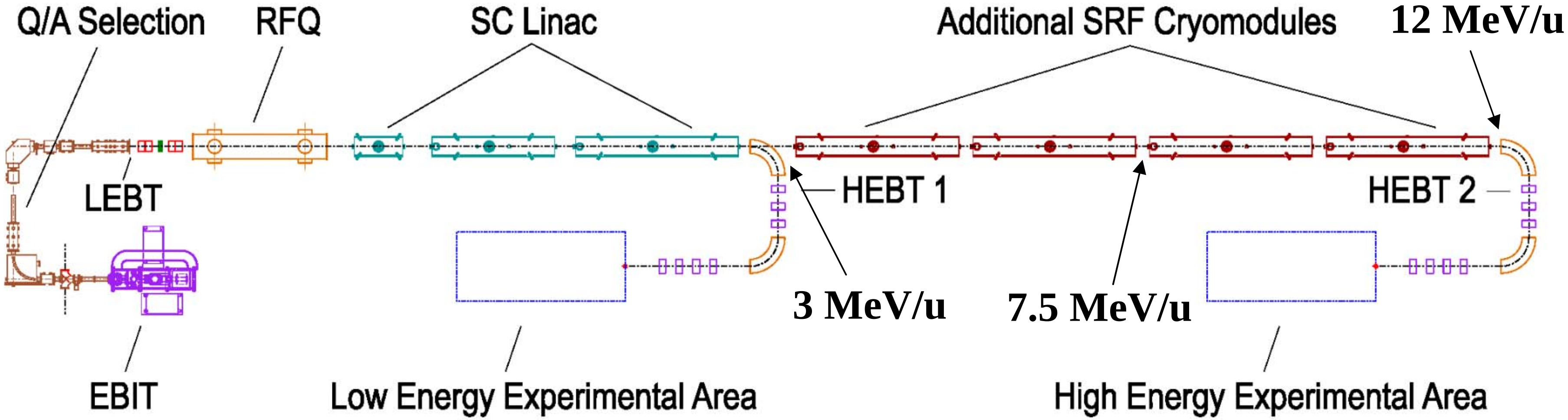


Energy spread and bunch width on target



Future Upgrades Possible

- **Phase I: 0.3 ~ 3.0 MeV/u – In progress**
- **Upgrades: 0.3 ~ 12 MeV/u**
  - Additional SRF cryomodules
  - NSCL High Bay Area expansion
  - New experimental areas



MSU Reaccelerator - Status

- Baseline accelerator system defined
- End-to-end beam simulations performed
- RFQ construction expected to be complete in 2009
- Superconducting cavity & cryomodule prototyping - test and design ongoing
- Experimental apparatus planning - underway
- Studies of beam diagnostics and realistic beam tuning scenarios - ongoing

Planned Low-Energy RIB Facility at the NSCL

- R&D for gas stoppers, EBIT charge-breeder - on going
- The project expected to complete by 2009
- Will be the first facility of creating fast RIBs in-flight, stopping, charge-breeding, and re-accelerating them efficiently and with minimum loss