

MICHIGAN STATE  
UNIVERSITY

Advancing Knowledge.  
Transforming Lives.

# ReA3



**Marc Doleans**  
**(On behalf of the ReA3 team)**

# Building addition

- Office building (~100 staff + conf. rooms)



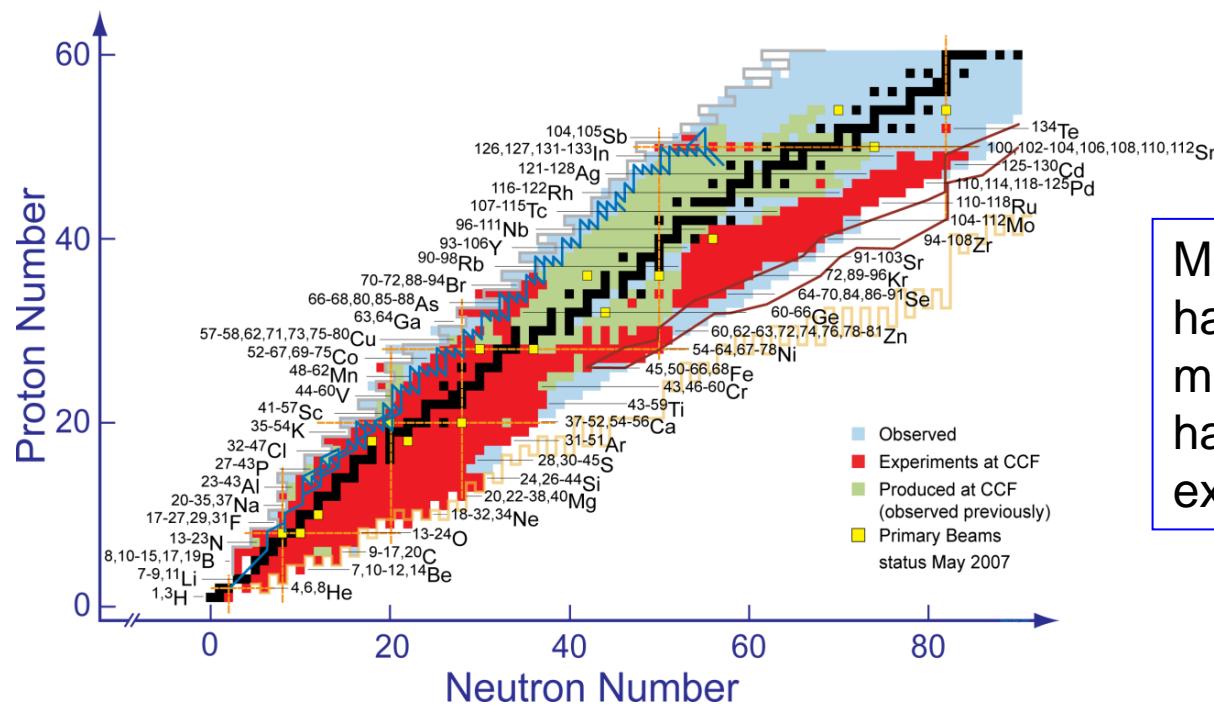
- ReA3 Experimental area



- 9100 sqft

# Why reaccelerated beams at the NSCL?

- NSCL is a user facility based on rare isotope production by projectile fragmentation and projectile fission
  - NSCL has successful program with stopped beams – LEBIT facility for Penning trap mass spectrometry of projectile fragments – laser spectroscopy under preparation

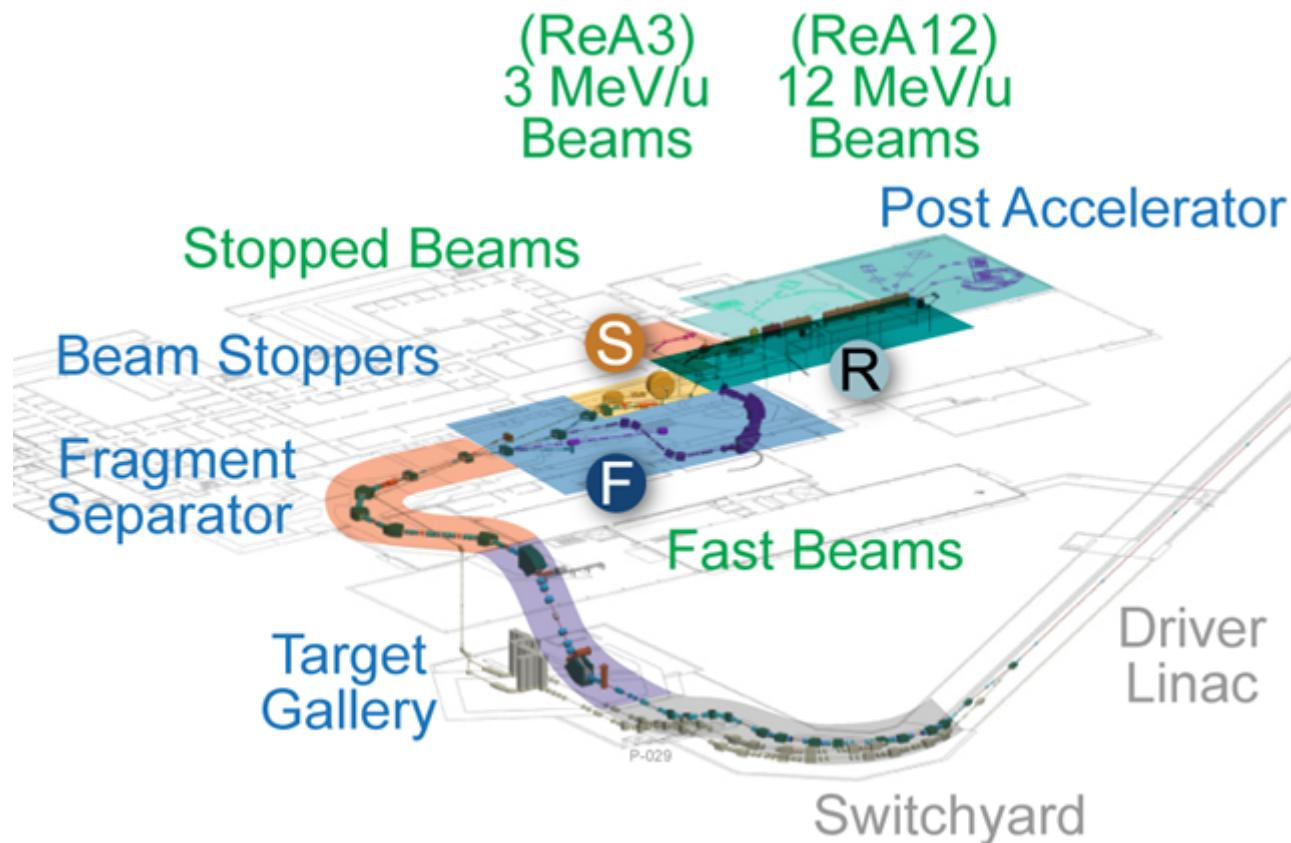


More than 900 RIBs have been made – more than 600 RIBs have been used in experiments

- ReA3 opens new science opportunities with rare isotopes produced by projectile fragmentation
  - Nuclear astrophysics: key reactions at near-stellar energies
  - Nuclear structure via Coulomb excitation or transfer reactions

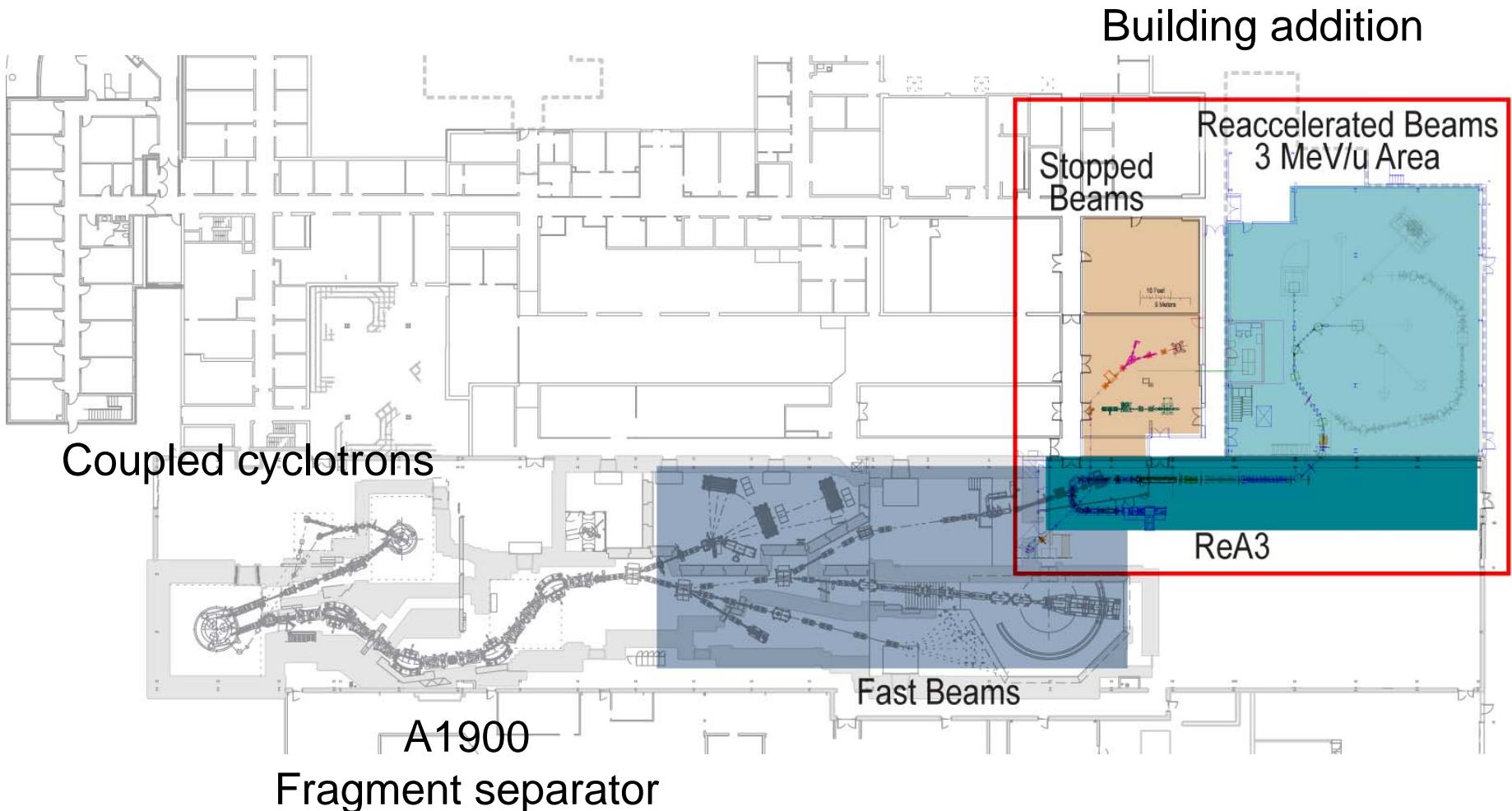
# Reaccelerated beams at FRIB at MSU

- FRIB includes fast (F), stopped (S), and reaccelerated beams (R).
- ReA3 provides pioneering beams for research in one of the pillars of FRIB.
- ReA3 will allow the user community to develop programs and techniques in reaccelerated beams before FRIB will come into operation.



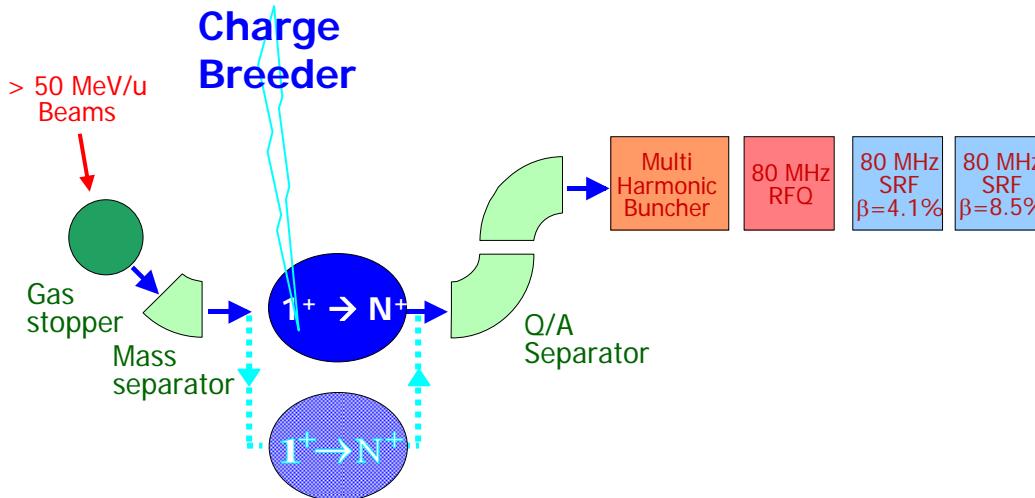
# ReA3 at the Coupled Cyclotron Facility

- Coupled cyclotrons primary beams : ~ 150 MeV/u
- ReA3 beams : Up to 3 MeV/u for Q/A=1/4



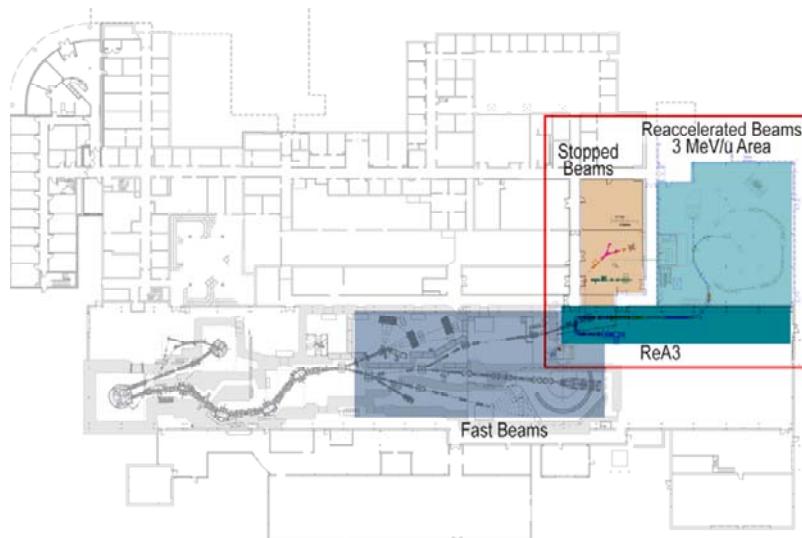
# ReA3 – concept and overview

- Goal: provide optimized reaccelerator for maximum science reach



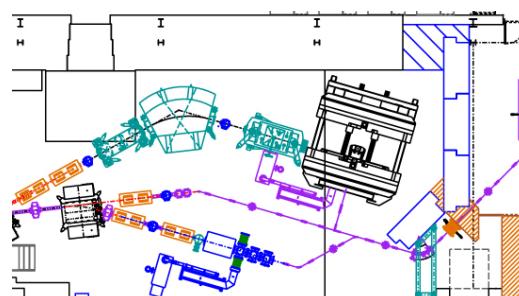
- Next generation gas stopping
  - Various optimized stopping techniques
  - Multiple stations in future to avoid single-point failure
- Advanced n+ reacceleration scheme to maximize science reach; best achieved with an EBIT charge breeder
  - Maximize efficiency by avoiding stripping losses
  - Provide variable duty factor to tailor beam to experiments
  - Deliver clean beams to avoid background and ambiguities
- Sufficient and expandable space for experiments

# ReA3 at the Coupled Cyclotron Facility

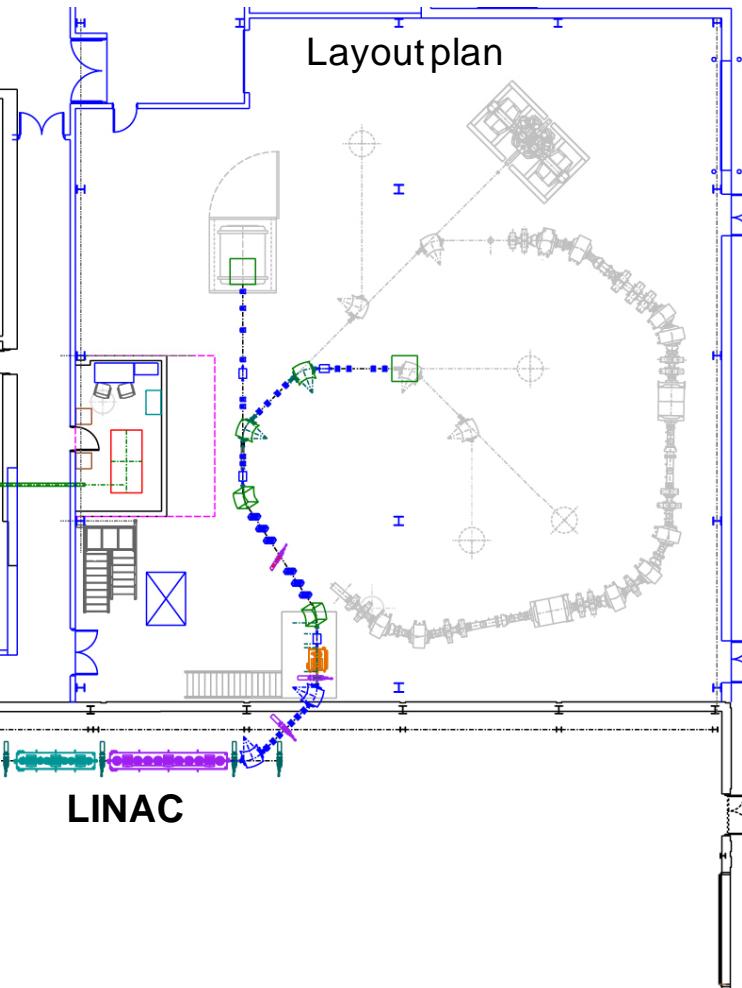


**Stopped beam area**  
- Relocated LEBIT  
- Laser spectroscopy

**N4 – beam stopping vault**



**EBIT  
charge  
breeder**



# Gas cells

- Vault reconfiguration in 2009

- 2 new momentum compression beam lines + solid stopper line
- Opportunity for simultaneous R&D and beam operation for pre-FRIB science (ReA3, stopped beams)

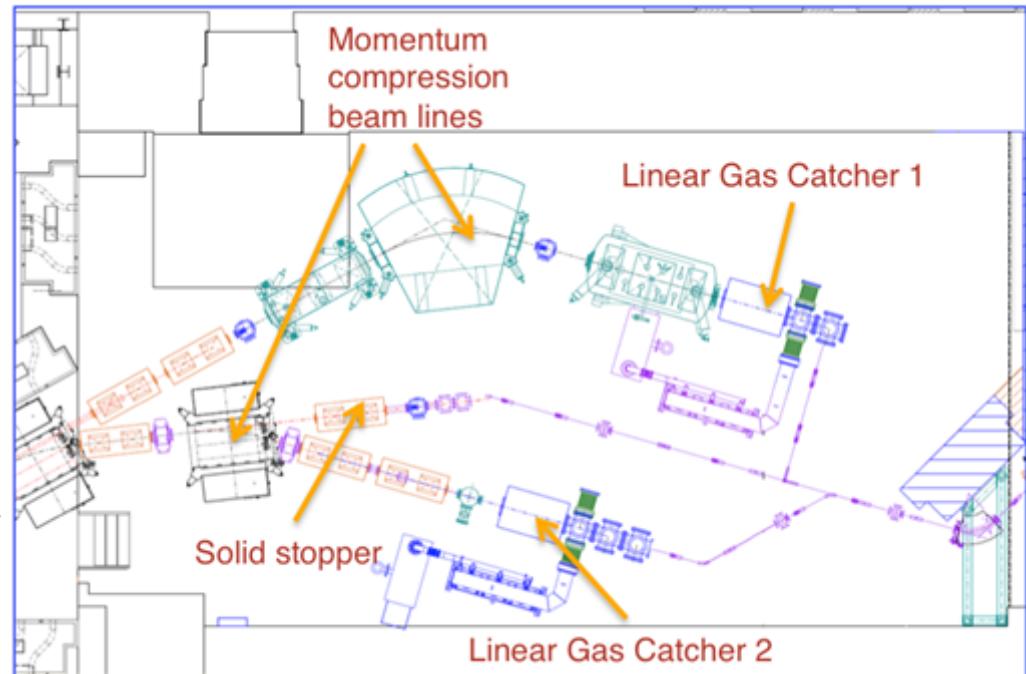
- Phase 1 (before 2012):

- ANL gas catcher and MSU linear cryogenic gas stopper

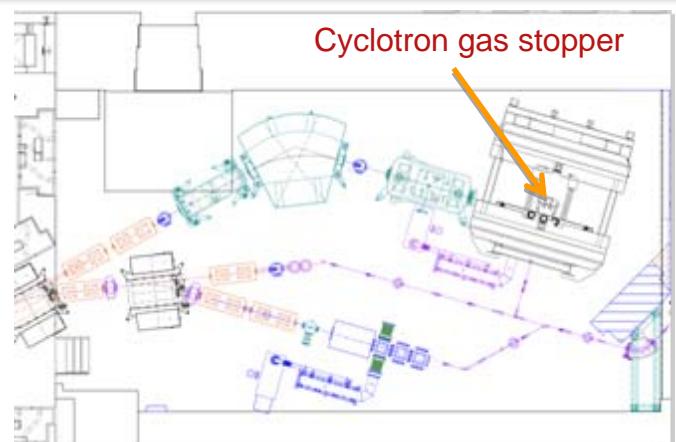
- Phase 2 (after 2012):

- Cyclotron gas stopper and linear gas stopper

*Task leaders: D. Morrissey, G. Bollen  
collaboration with ANL*

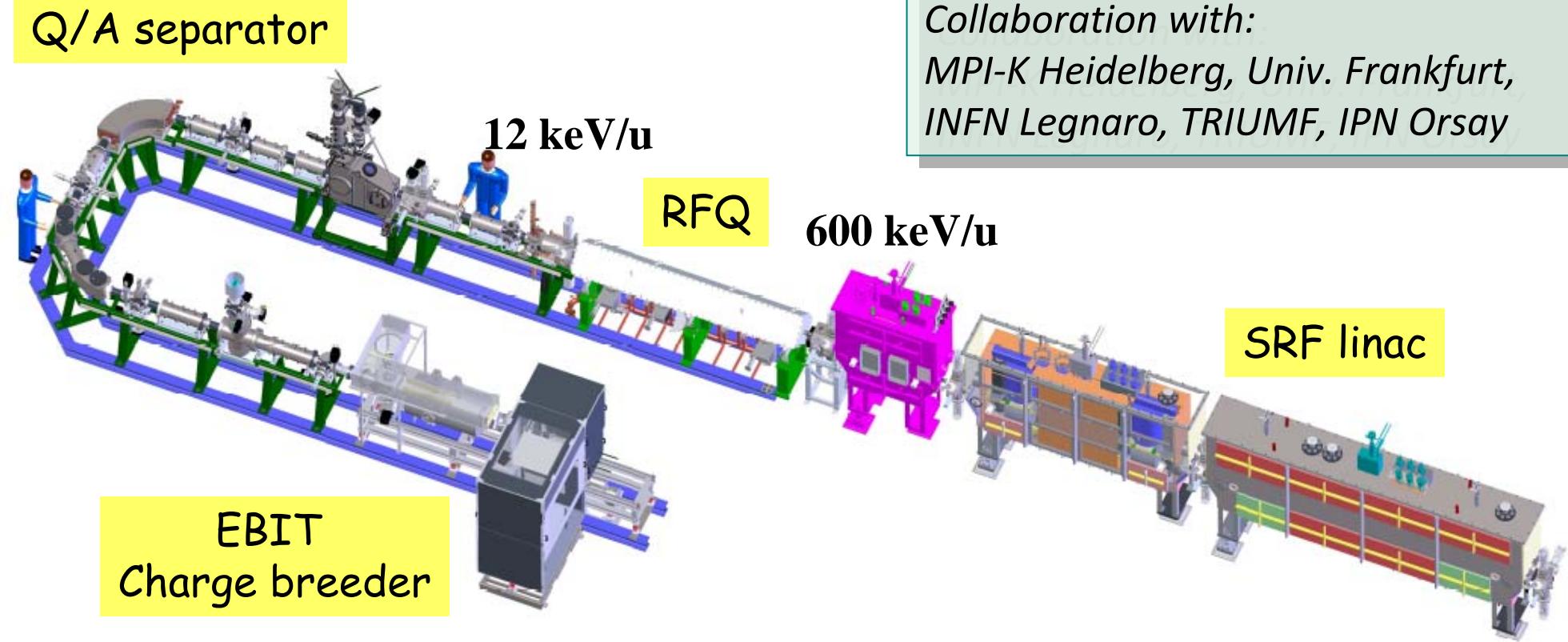


Phase 1



Phase 2

# ReA3 – reacceleration

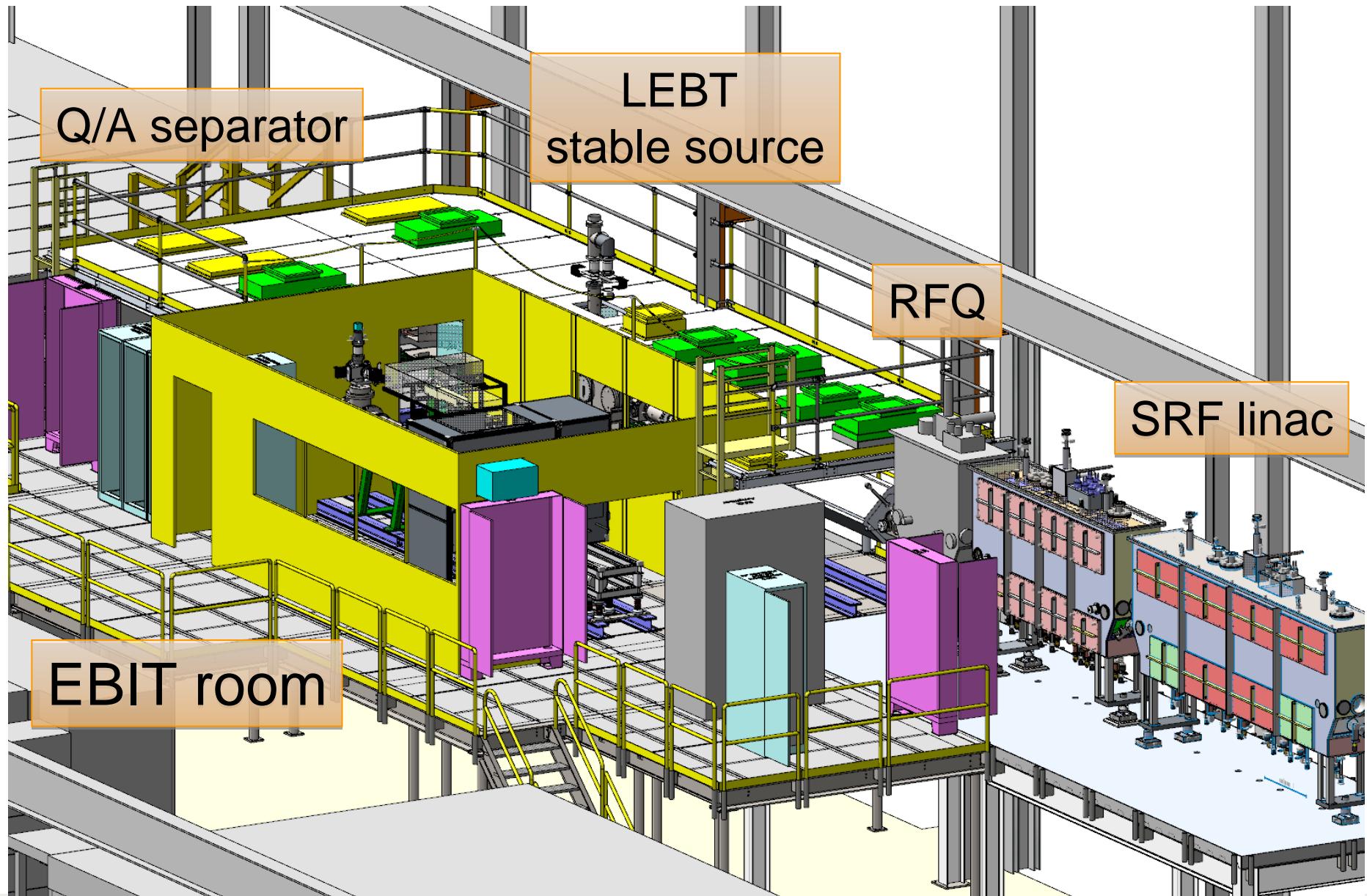


- Compact and efficient re-acceleration
  - EBIT charge breeder & Q/A separator
  - Radio-frequency quadrupole (RFQ)
  - Superconducting linac

*Collaboration with:*  
MPI-K Heidelberg, Univ. Frankfurt,  
INFN Legnaro, TRIUMF, IPN Orsay

**Energy examples:**  
 $^{238}\text{U}$  0.3 – 3 MeV/u  
 $^{48}\text{Ca}$  0.3 – 6 MeV/u

# ReA3 - platform

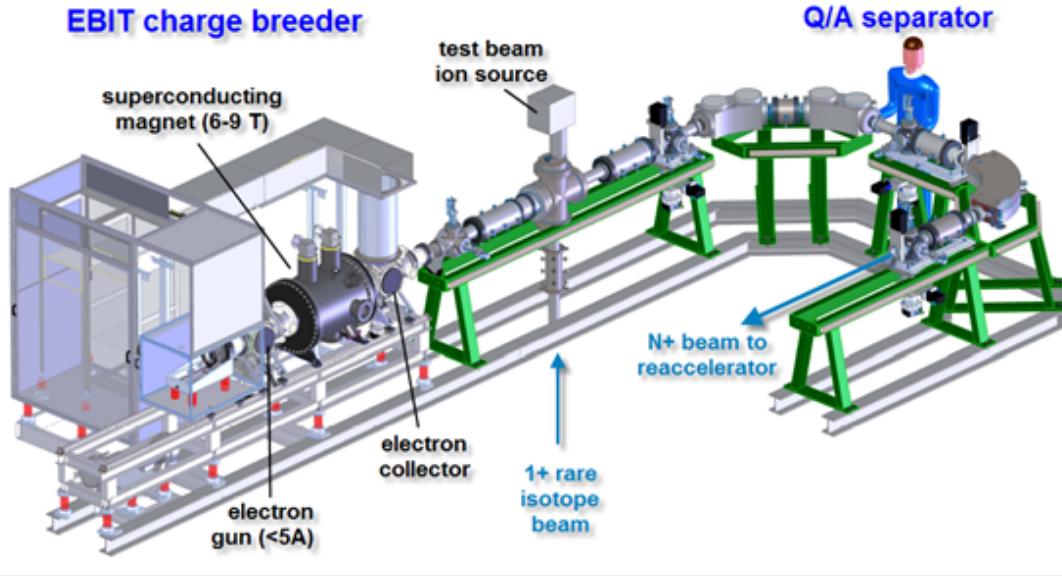


# ReA3 – platform



# High-current EBIT charge breeder

EBIT charge breeder



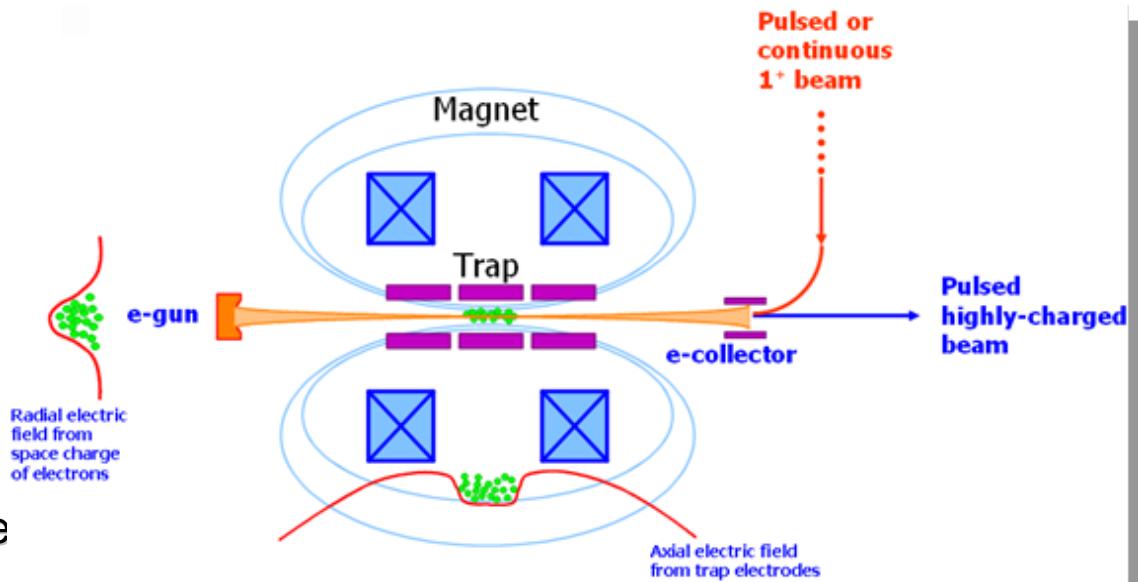
Task leaders: S. Schwarz, G. Bollen

- **High performance :**

- Large trapping region 80 cm
- High e- beam current >2.5 A
- High e- current density > $10^4$  A/cm<sup>2</sup>
- Strong magnetic field 6 T

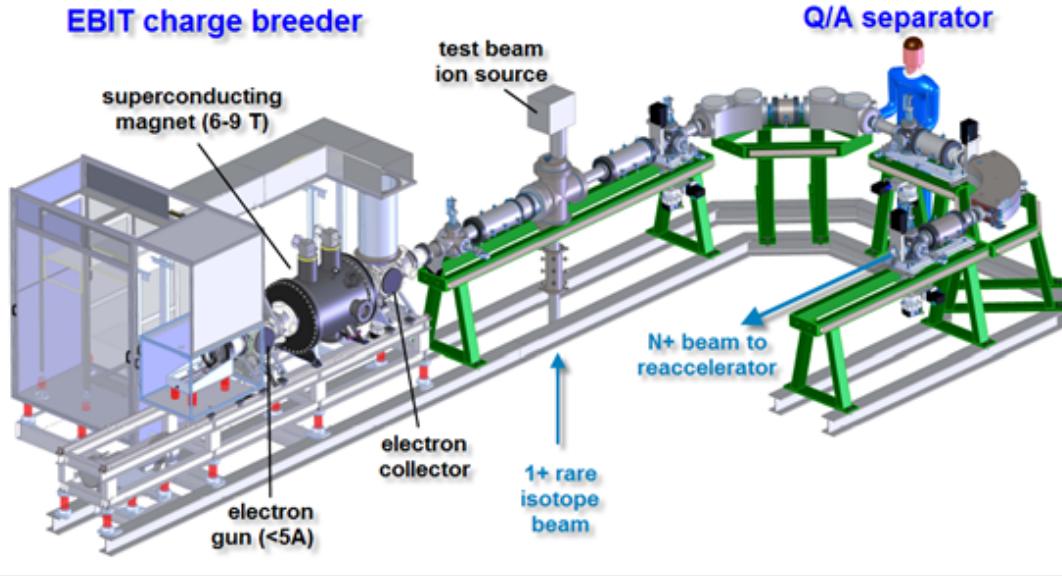
- **Features:**

- Continuous injection of ions
  - » high capture rate
- Variable extraction duty cycle
  - »  $\mu$ s pulse to quasi-continuous
- Short breeding time (<10 ms)
- Highest efficiency
  - » > 50% in a single charge state



# High-current EBIT charge breeder

EBIT charge breeder

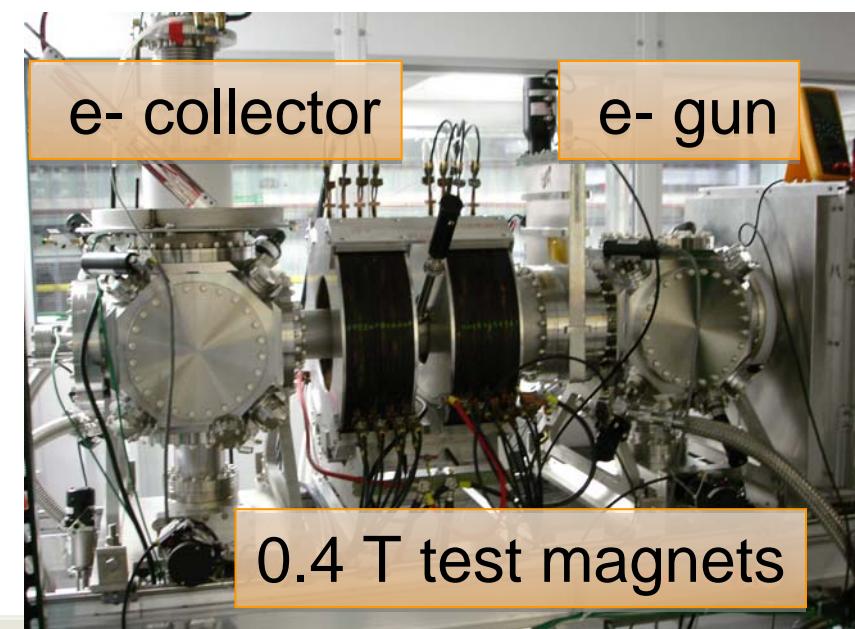


Task leaders: S. Schwarz, G. Bollen

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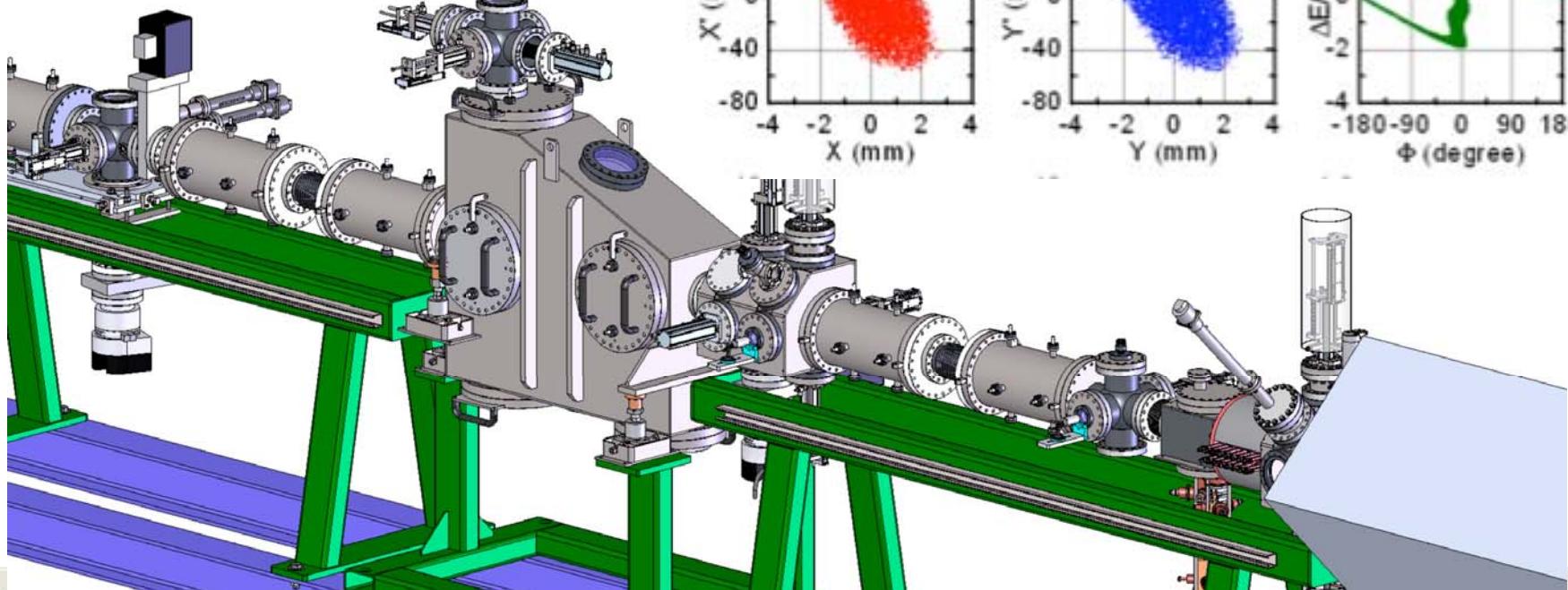
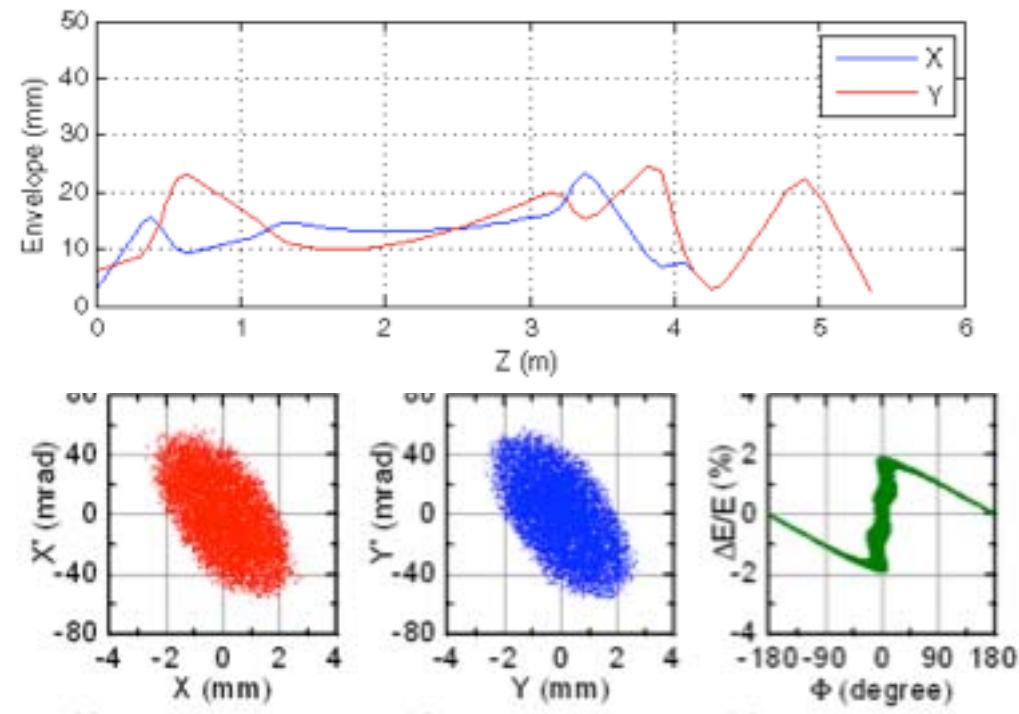
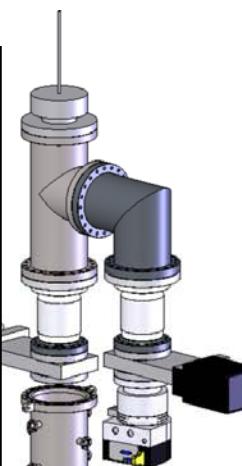
- EBIT charge breeder concept successfully used at REX-ISOLDE CERN
- RHIC-EBIS provides intense pulses of highly-charged heavy ions
- Preliminary tests with temporary 0.4 T solenoid magnets achieved 0.3 A with 98% transmission to the collector



# LEBT – beam dynamics

## Design beam Parameters

Energy	12 keV/u
Q/A	0.2 – 0.4
$\varepsilon_{x,y}$ (100%)	0.6 $\pi\text{-}\mu\text{m}$
$\Delta E$	$\pm 0.2 \%$

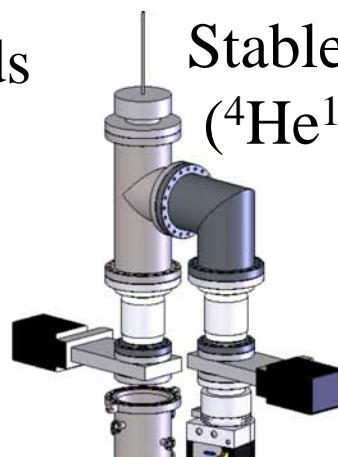


# LEBT

Electrostatic quads



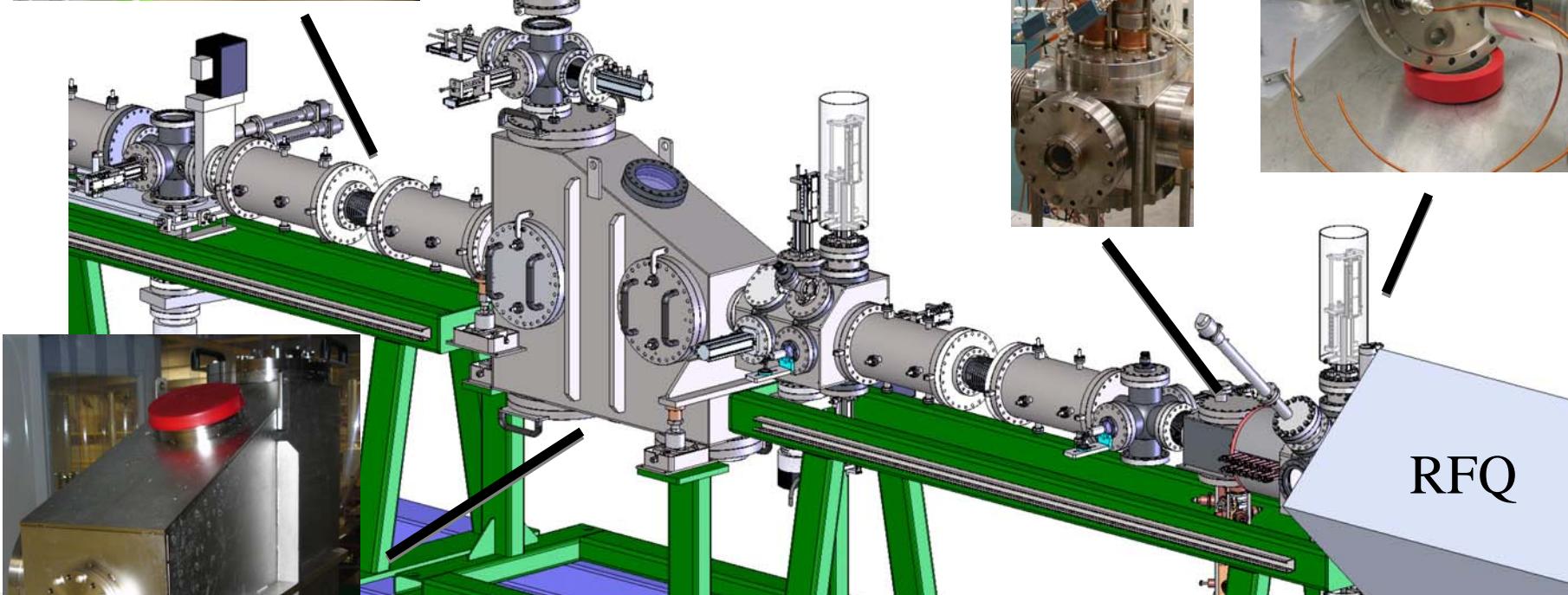
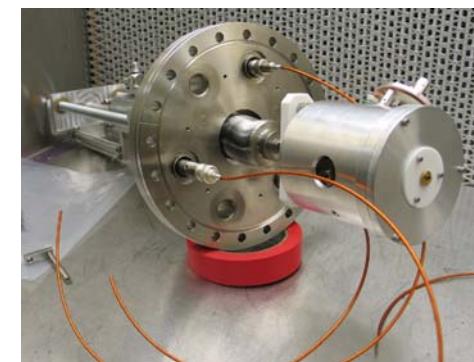
Stable Ion Source  
( $^4\text{He}^{1+}$ )



Multi-harmonic  
buncher



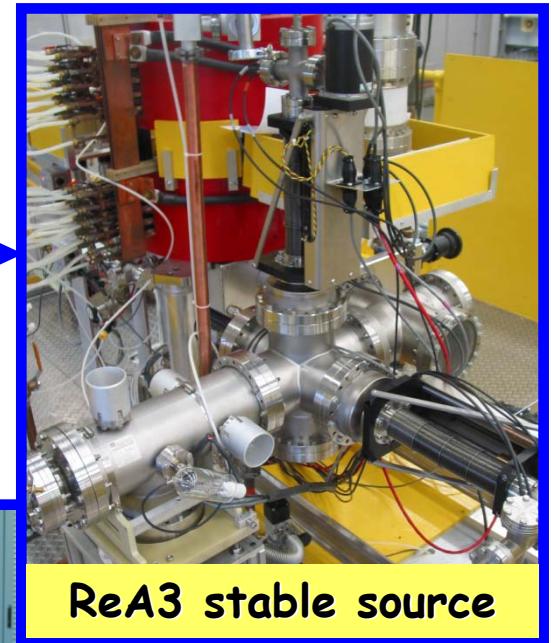
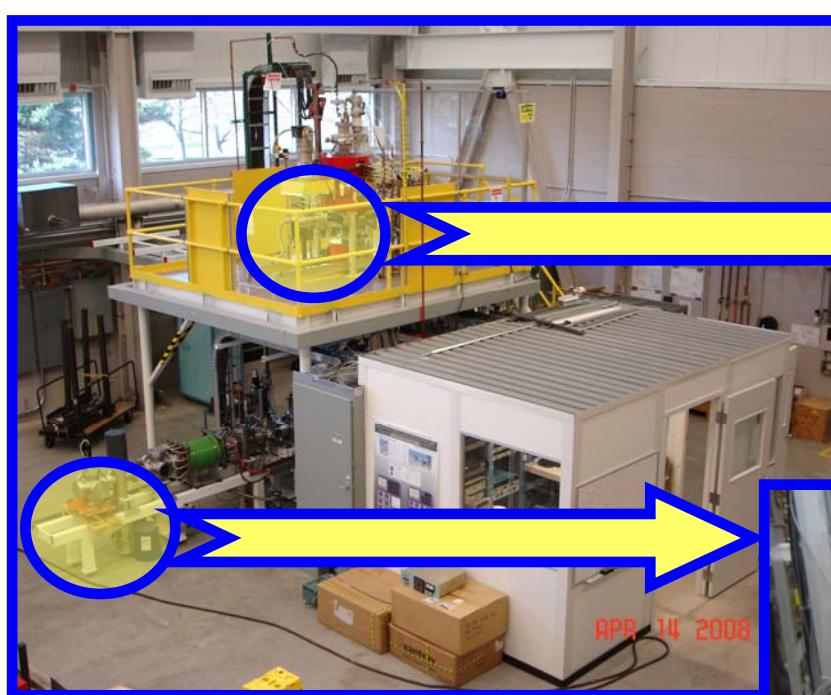
Bunch length  
monitor



Department of Energy Office of Science  
National Science Foundation  
Massachusetts Institute of Technology

MAY

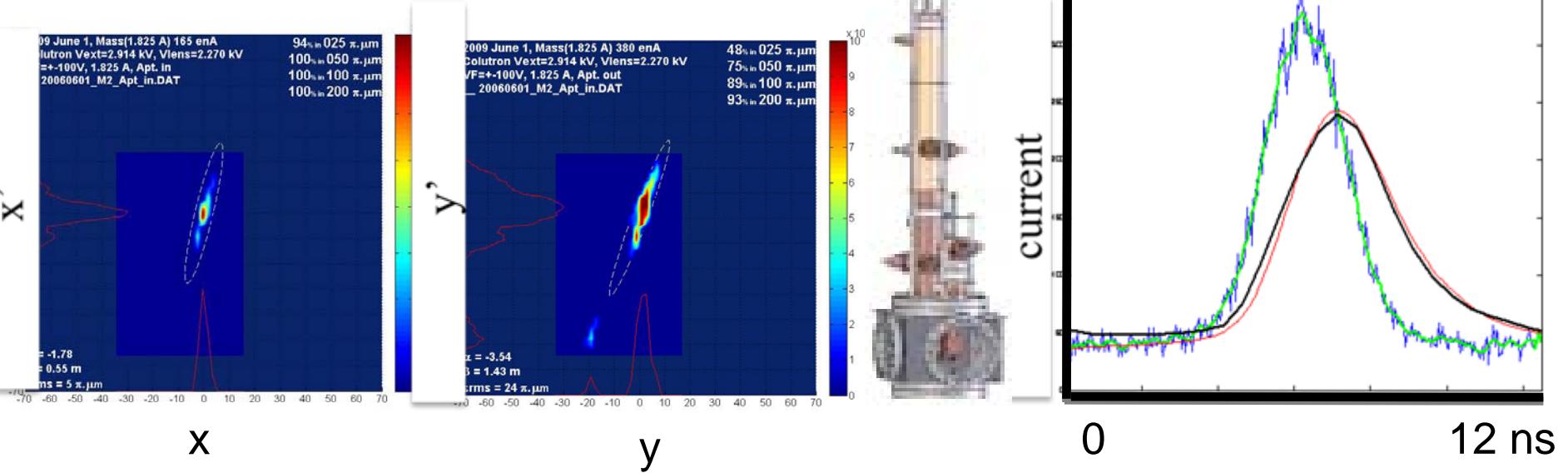
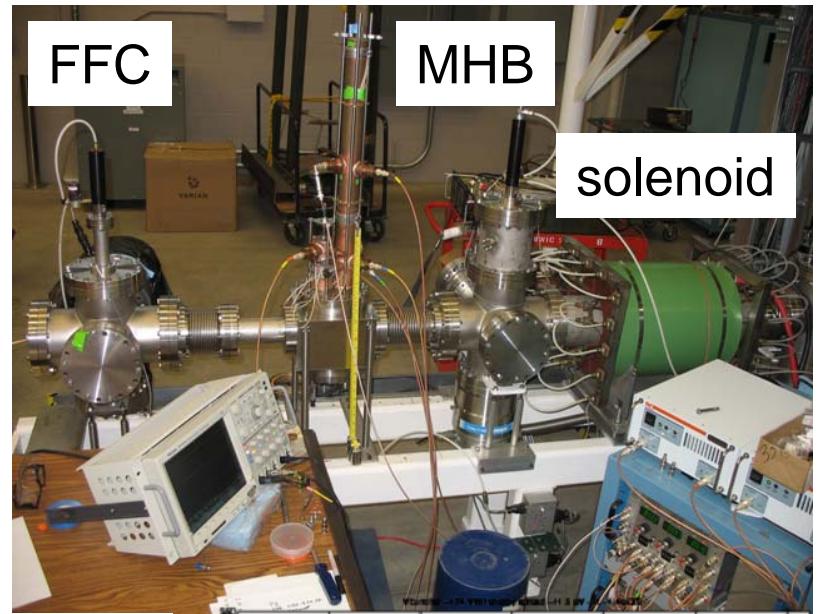
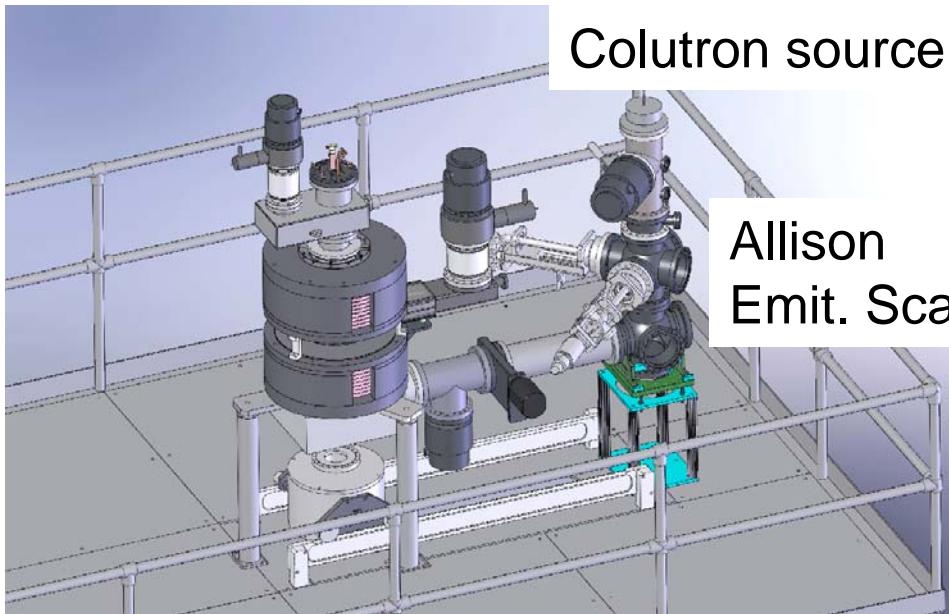
# ReA3 – hardware tests at ArtemisB



- **Artemis-B ECR test-stand**

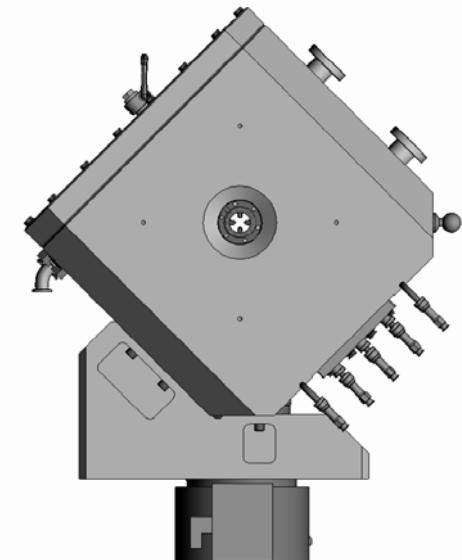
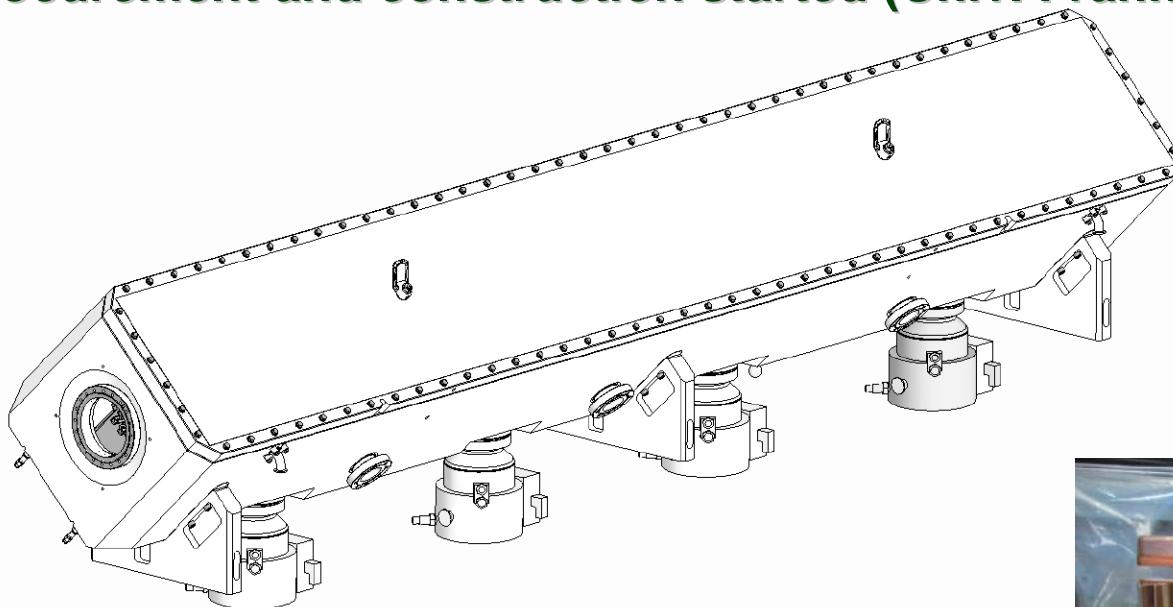
- ECR R&D
- Beam dynamics R&D
- ReA3 R&D

# LEBT – hardware test



# RFQ

- Beam simulations and electrode design completed (MSU)
- Mechanical design completed
- Procurement and construction started (Univ. Frankfurt)

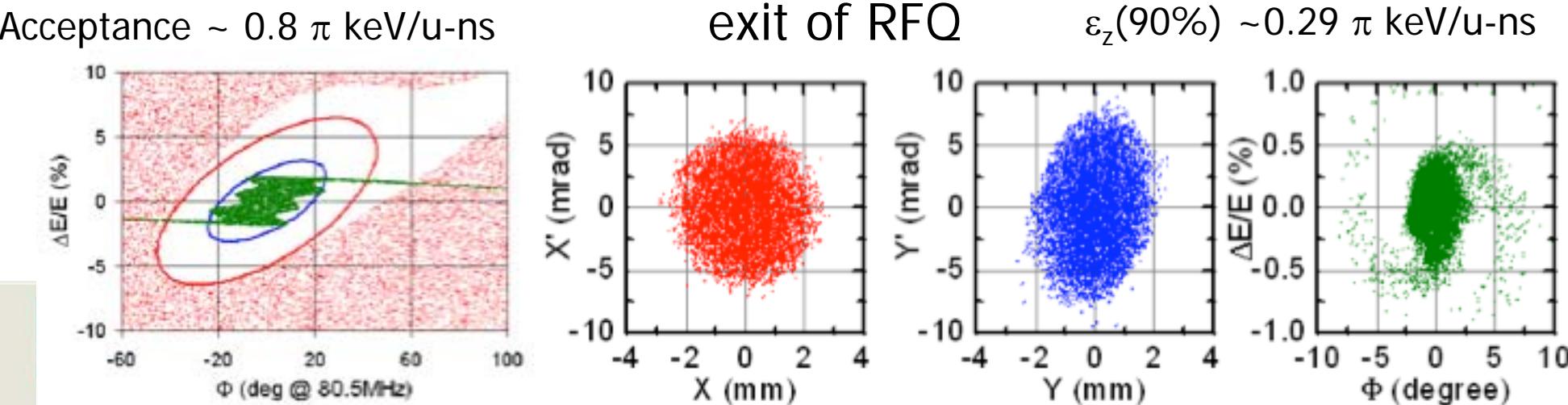


- Injection energy: 12 keV/u
- Extraction energy: 600 keV/u
- Power (CW): ~150 kW

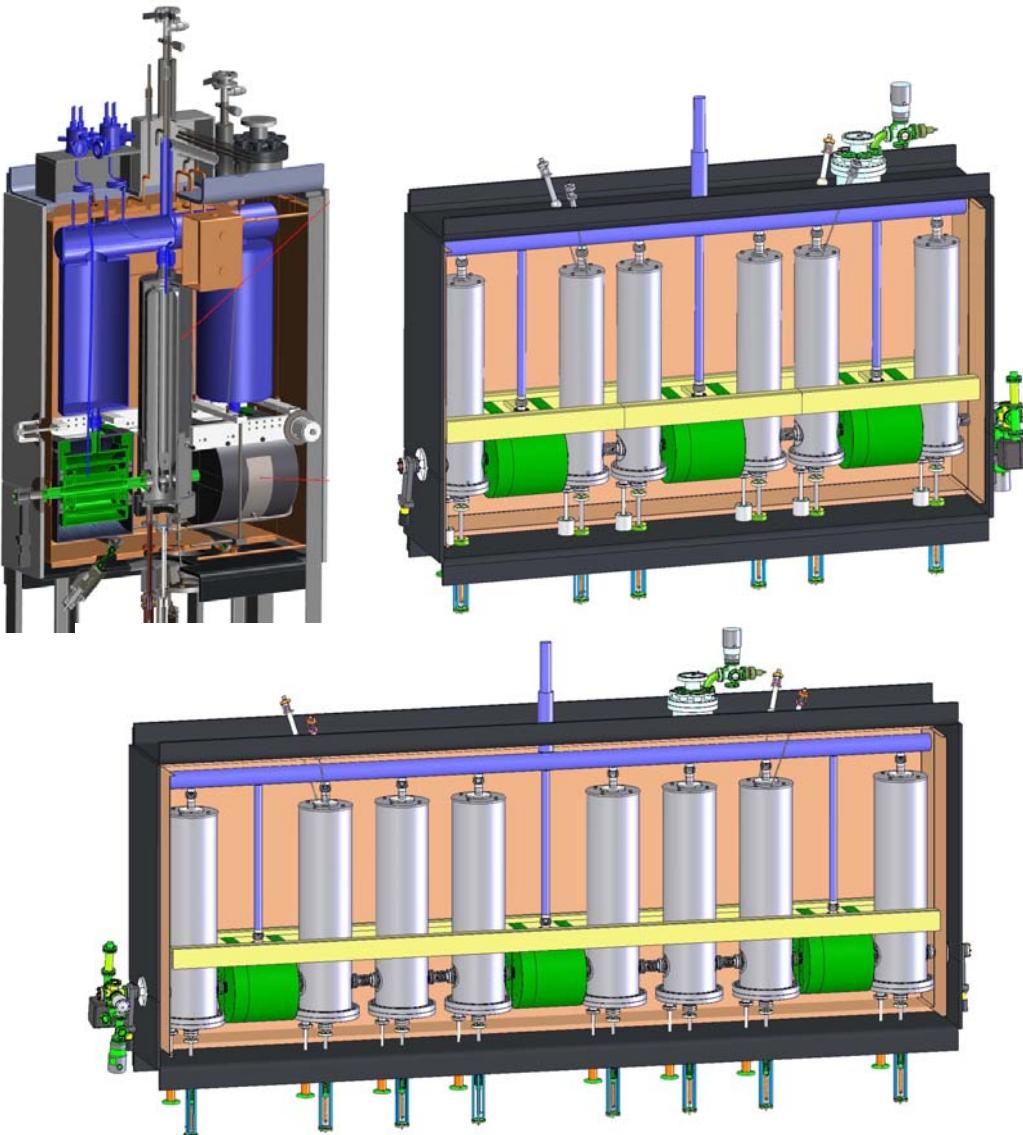


# RFQ – parameters

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 ( $E_{\text{kilpatrick}}$ )	1.6
Number of cells	94
Synchronous phase (degree)	-20
Modulation factor	$1.15 \rightarrow 2.58$
Average radius (mm)	7.3
Tip radius (mm)	6.0
Focusing strength	4.9



# ReA3 – SRF cavities



- 3 cryomodules – 15 cavities

Type	$\lambda/4$	$\lambda/4$
Optimum $\beta$	0.041	0.085
Frequency	80.5 MHz	80.5 MHz
$E_{peak}$	16.5 MV/m	20.0 MV/m
$V_{acc}$	0.46 MV	1.18 MV
$E_{acc}$	4.84 MV/m	5.62 MV/m
$B_{peak}$	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

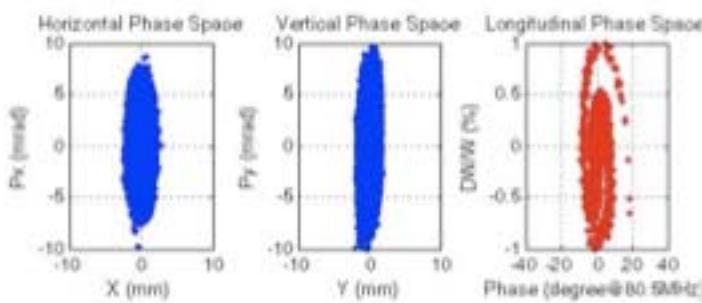
# ReA3 – SRF linac beam energy

	ReA3 Deceleration	ReA3 Acceleration	ReA3 @ FRIB acc. gradients
Ep (MV/m)	16.5/20.0	16.5/20.0	30.0/30.0
Q/A	KE (MeV/u)	KE (MeV/u)	KE (MeV/u)
<b>0.20</b>	0.3	2.4	3.8
<b>0.25</b>	0.3	3.0	4.6
<b>0.50</b>	0.3	6.0	9.4

# Beam phase spaces

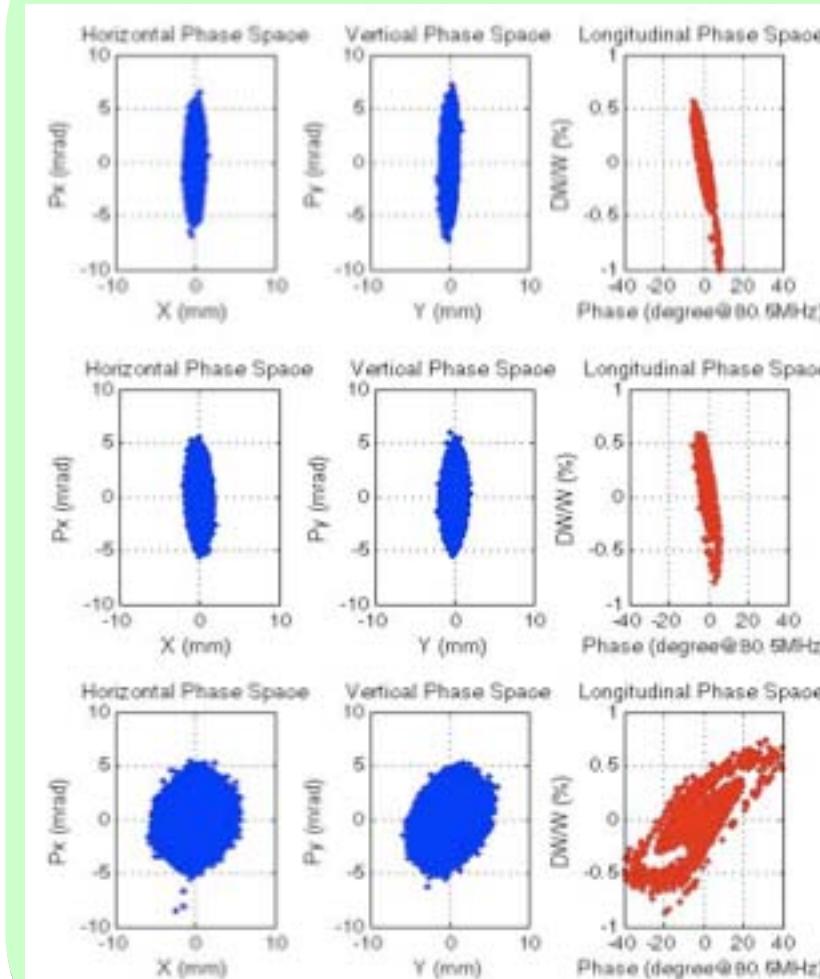
- $Q/A=0.25$

RFQ exit



0.6 MeV/u

LINAC exit



4.6 MeV/u

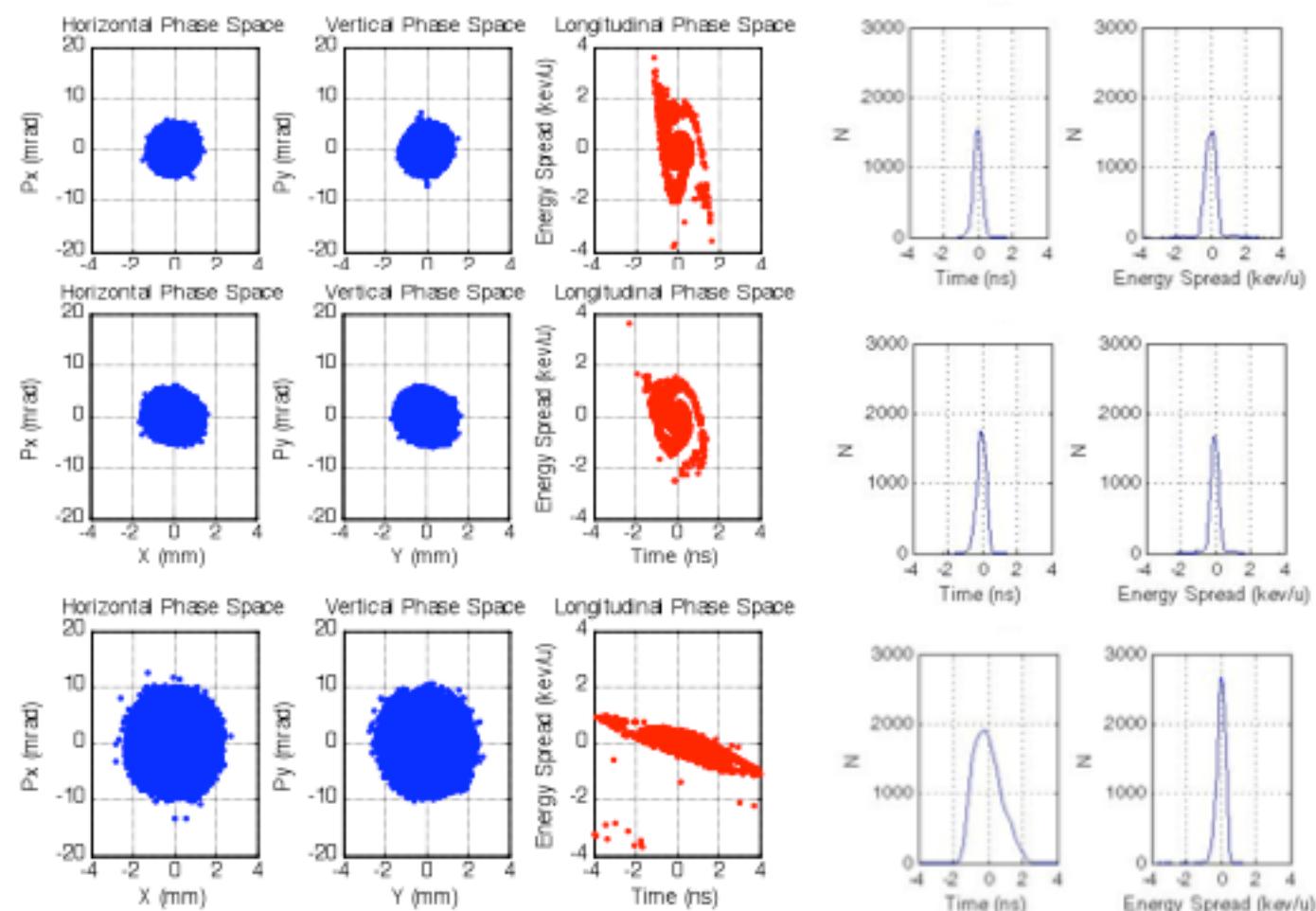
3.0 MeV/u

0.3 MeV/u

# Beam distributions at experiment

- $Q/A=0.25$

4.6 MeV/u



0.3 MeV/u

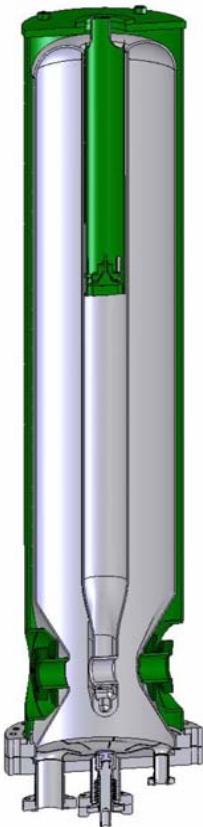
2-4 mm

1-2 ns – keV/u

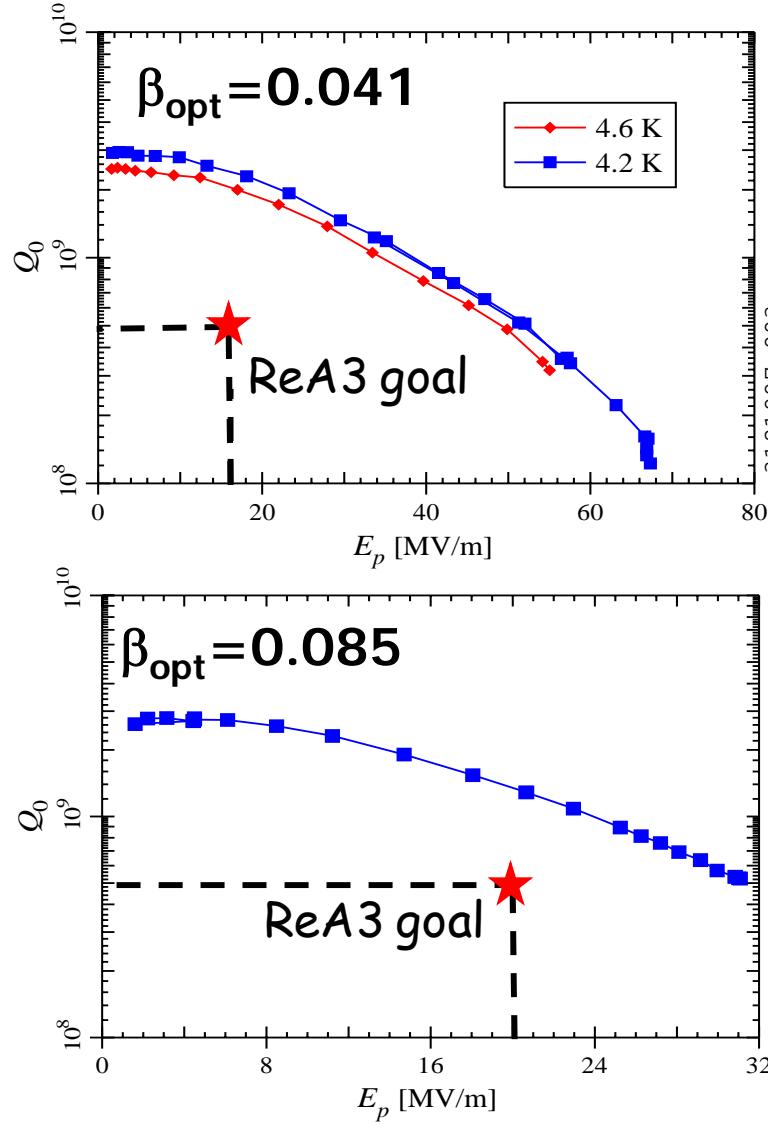
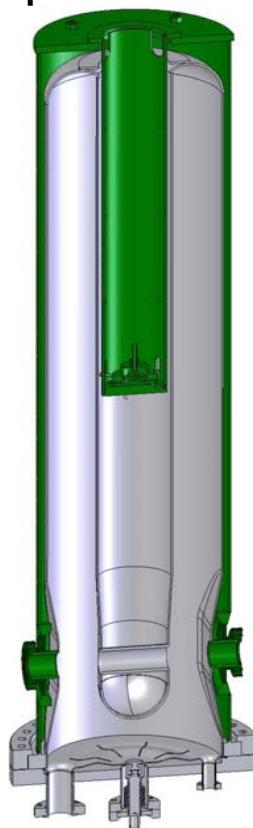
# ReA3 – SRF cavity prototypes

- ReA3 design goals exceeded

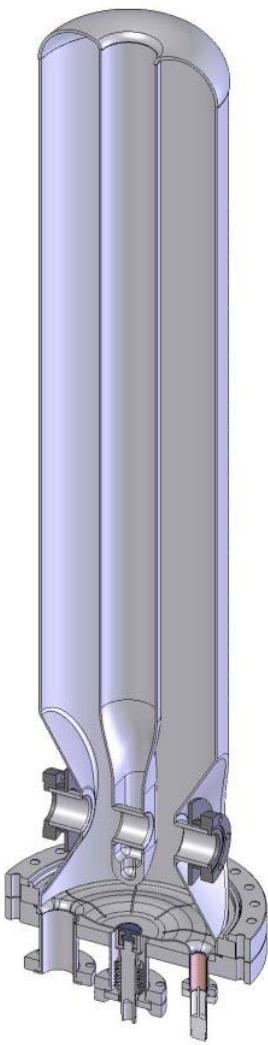
$$\beta_{\text{opt}} = 0.041$$



$$\beta_{\text{opt}} = 0.085$$



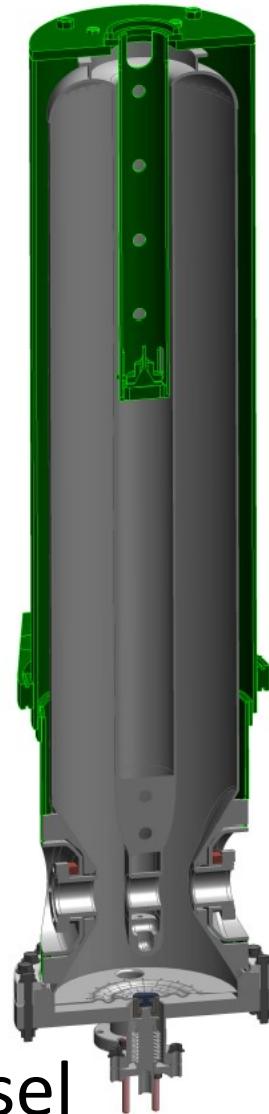
# $\beta = 0.041$ QWR Prototypes



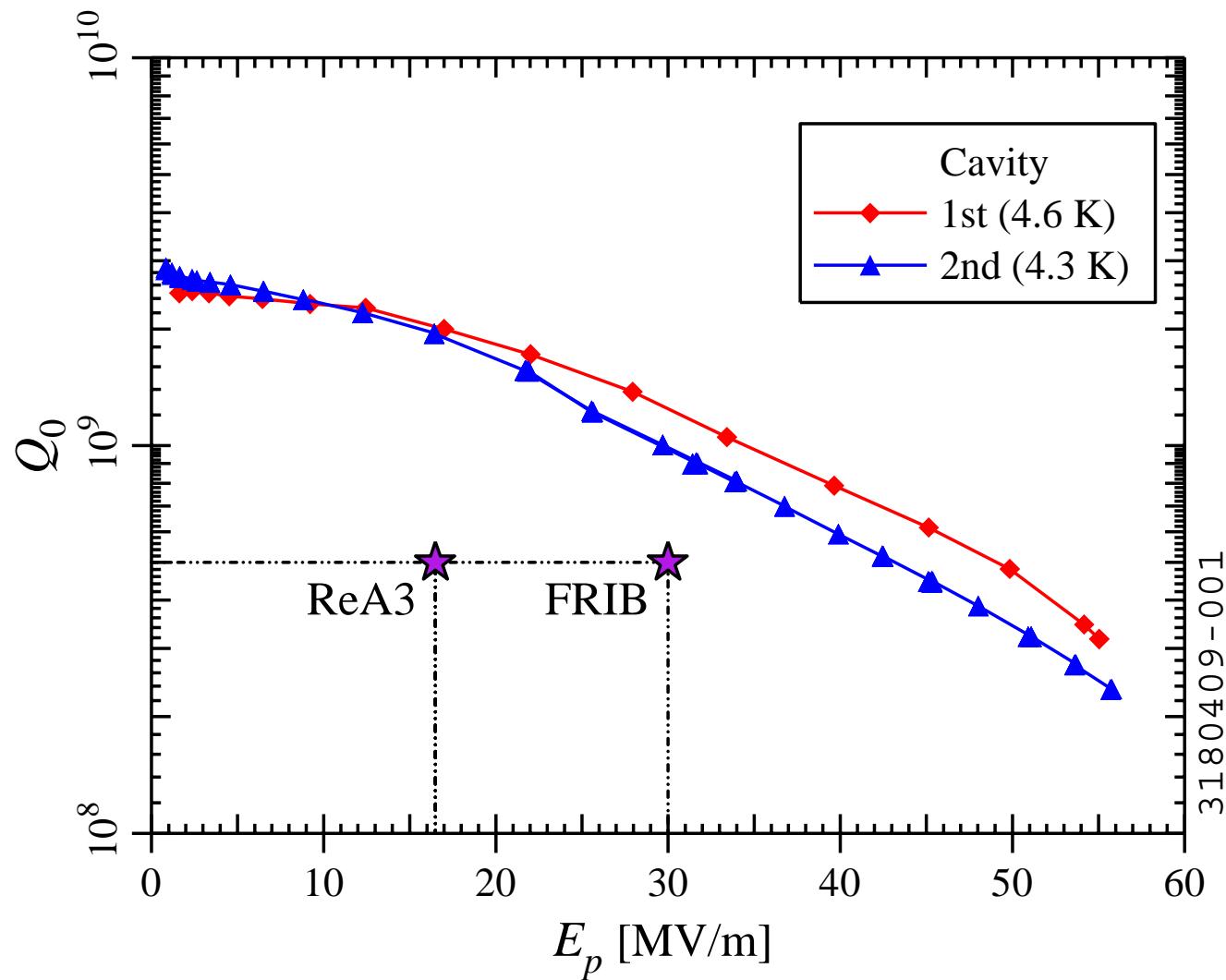
1st cavity  
Unstiffened  
No He vessel



2nd cavity  
Stiffened  
with He vessel

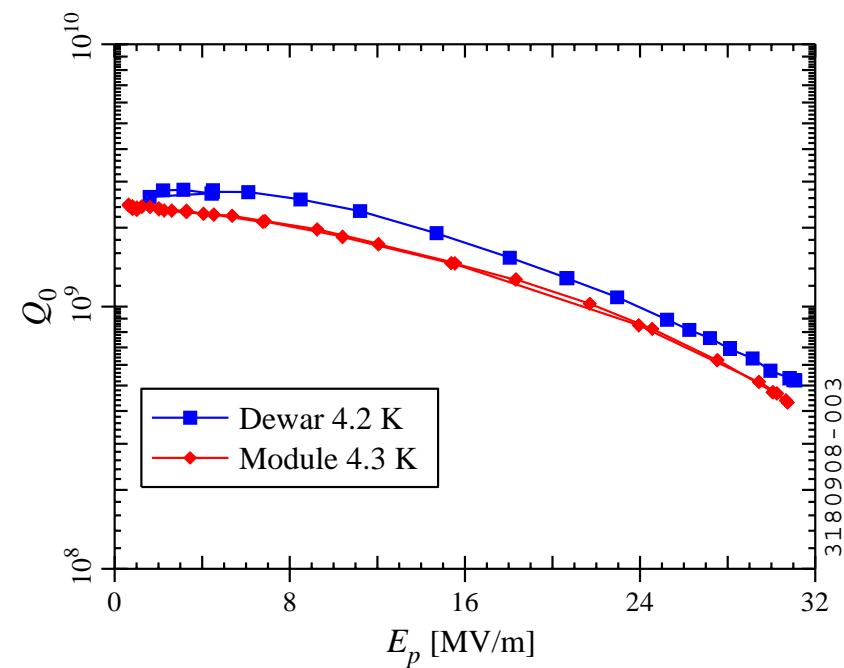


# $b = 0.041$ QWR Prototypes Dewar Testing



- Both cavities exceed design goals

# Systems Tests



- $\beta = 0.085$  QWR
  - Performance in cryomodule is similar to Dewar performance

# Systems Tests



Cold mass



77 K shield



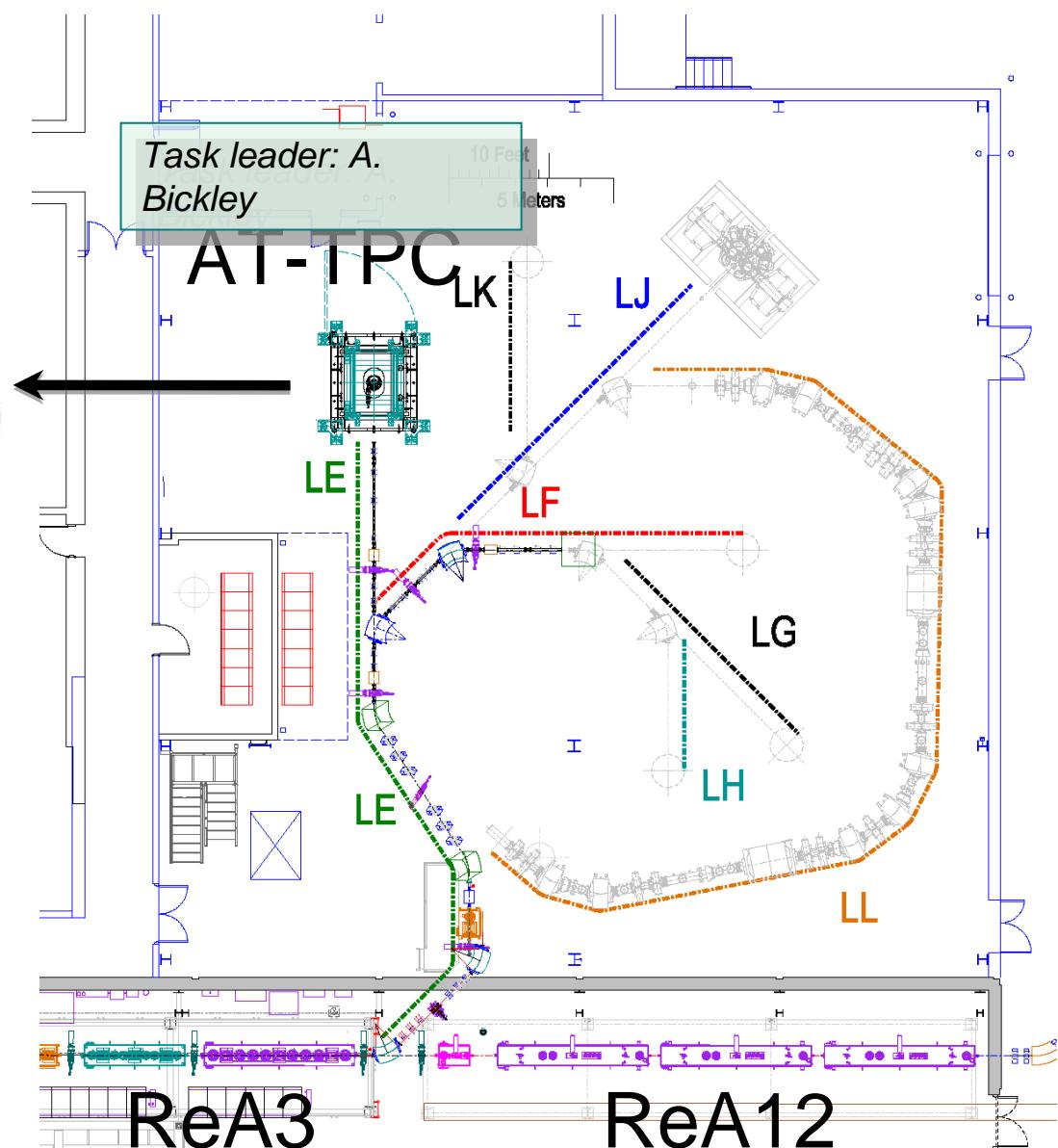
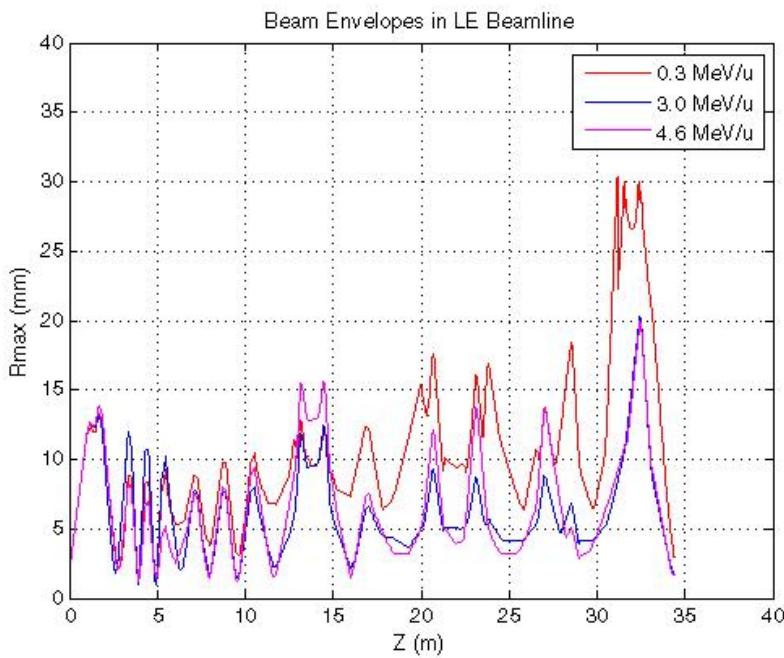
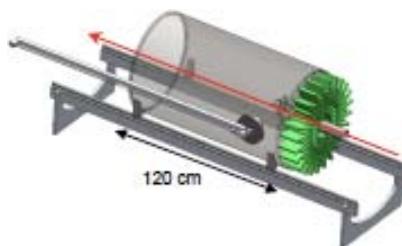
Vacuum vessel

Rebuncher cryomodule for ReA3: assembly in progress

# Possible experimental layout

- Beam delivered to ReA3 experimental area by 2010
- Instruments in preparation

- AT-TPC
- ANASEN
- ...



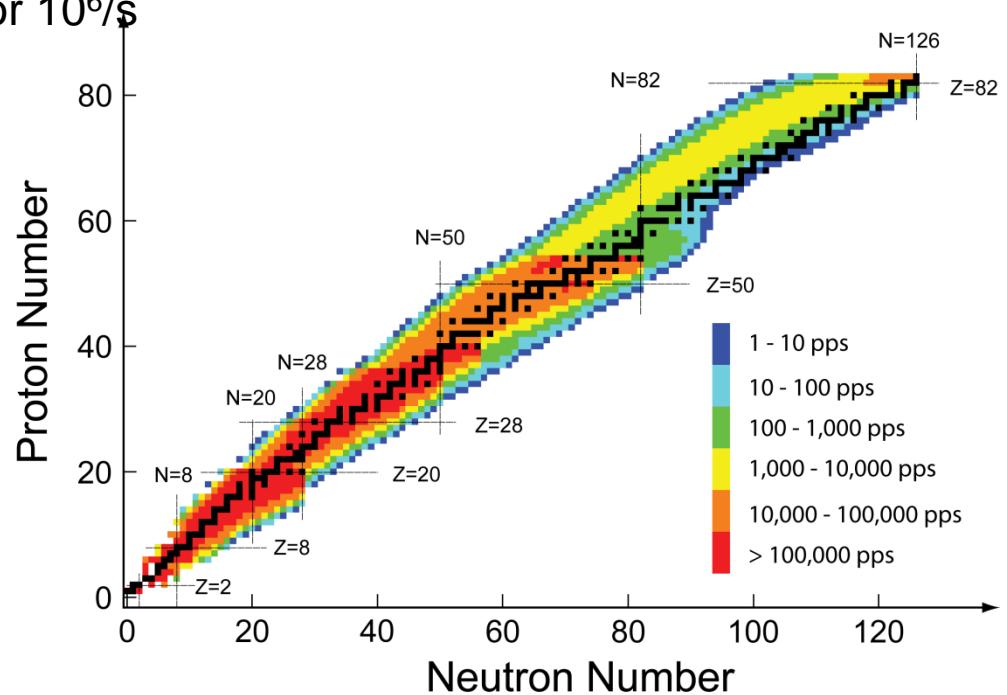
# Conclusion

- ReA3 is a new facility at the NSCL for stopped and reaccelerated radioactive beams coming in 2010
- ReA3 will accelerate uranium beams to  $\sim 3$  MeV/u
- ReA3 will initially use primary beams from the coupled cyclotron facility (<200 MeV/u – 1 kW)
- ReA3 will then use primary beams from the FRIB driver linac (>200 MeV/u – 400 kW)
- An upgrade ReA12 could accelerate uranium beams to  $\sim 12$  MeV/u by adding three cryomodules

# Additional slides

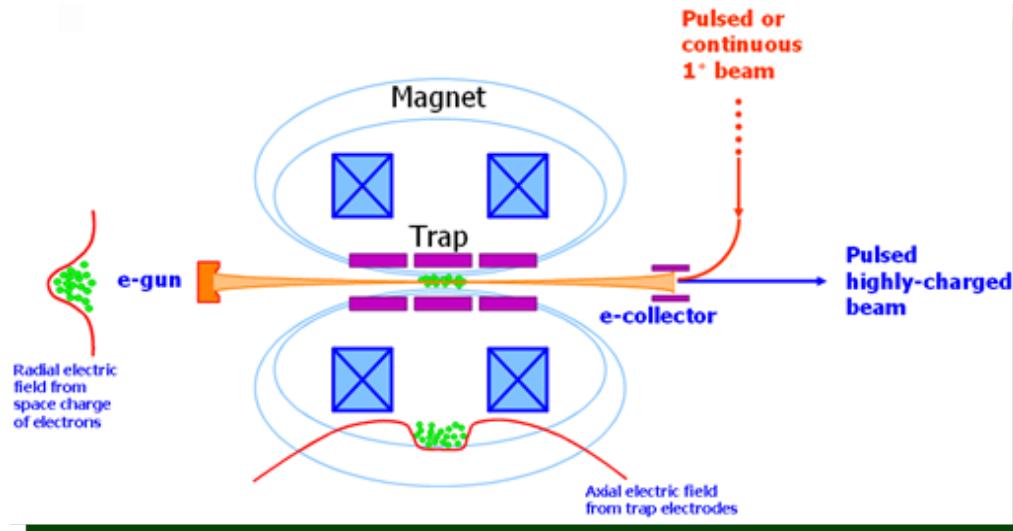
# Beam rate estimate and beam properties

- Beam rates can be calculated from the NSCL website
- Beam rate estimates – assumptions
  - Predicted beam rates (LISE)
  - Rate dependent stopping and extraction efficiency
    - 1% for  $10^8/\text{s}$  , 5% for  $10^7/\text{s}$  , 20% for  $10^6/\text{s}$
  - Breeding efficiency: 60%
  - Transport efficiency: 70%
  - Delay time for decay losses: 100 ms  
(stopping + breeding)
- Expected beam properties
  - Beam energies:
    - »  $^{238}\text{U}$ : 0.3-3 MeV/u
    - »  $^{48}\text{Ca}$ : 0.3-6.2 MeV/u
  - Beams with variable duty cycle:
    - » from  $\mu\text{s}$  macro-pulses to quasi-continuous beams



Beam rate estimates have large uncertainties (one order of magnitude)

# High-current EBIT charge breeder



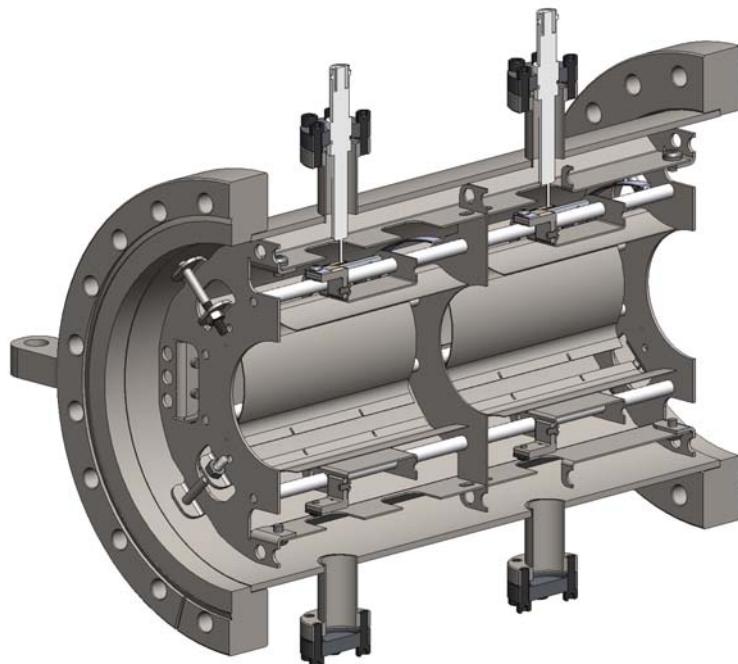
**Large trapping region (40 cm)**  
**High current up to 5 A**  
**High current density ( $>10^4 \text{ A/cm}^2$ )**  
**Strong magnetic field: 6T**  
**Minimum Q/A = 0.2**

Mass range	Efficiency
$A < 40$	> 60%
$A \sim 100$	> 50%
$A \sim 200$	> 40%

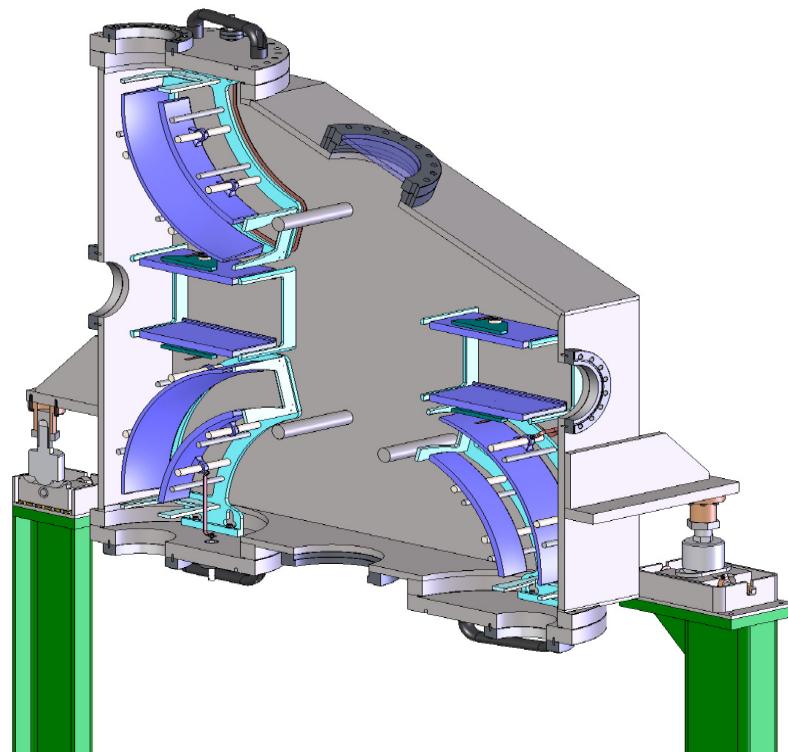
Z	charge state	breeding time [ms]	q/A
1-44 (H-Ti)	fully stripped or He like	2 - 40 ms	0.5-0.4
41-75 (Nb-Re)	Ne-like	20 - 35 ms	0.33-0.35
71-92 (Lu-U)	Ni-like	25 - 40 ms	0.25-0.27

# Electrostatic devices

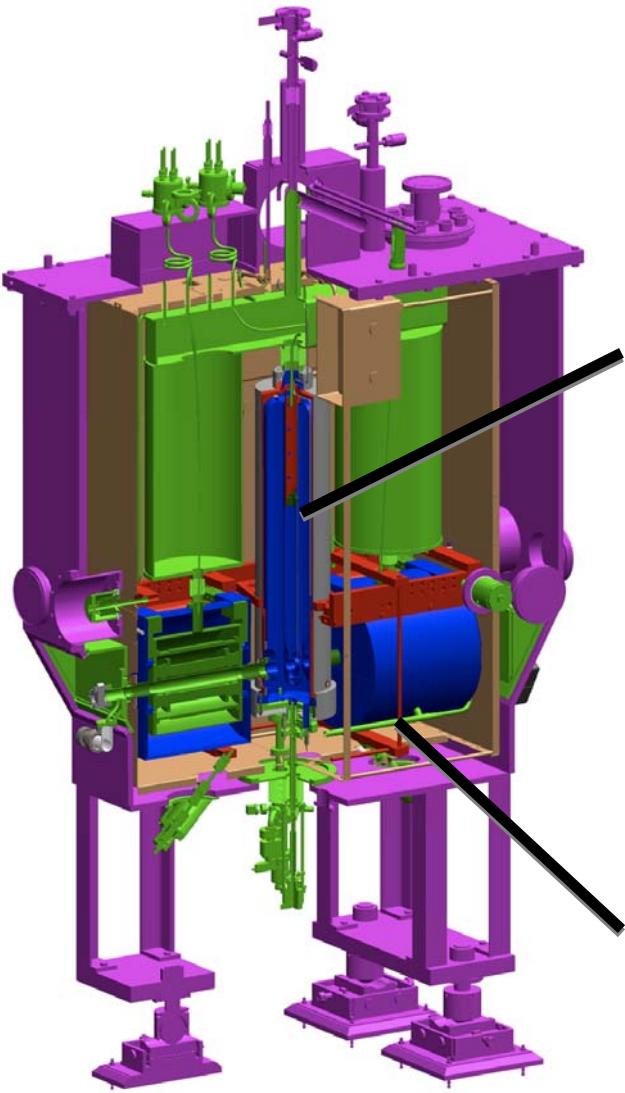
- Quadrupoles
  - Modified from Frankfurt design



- Triple bender
  - $-75^\circ + 15^\circ$



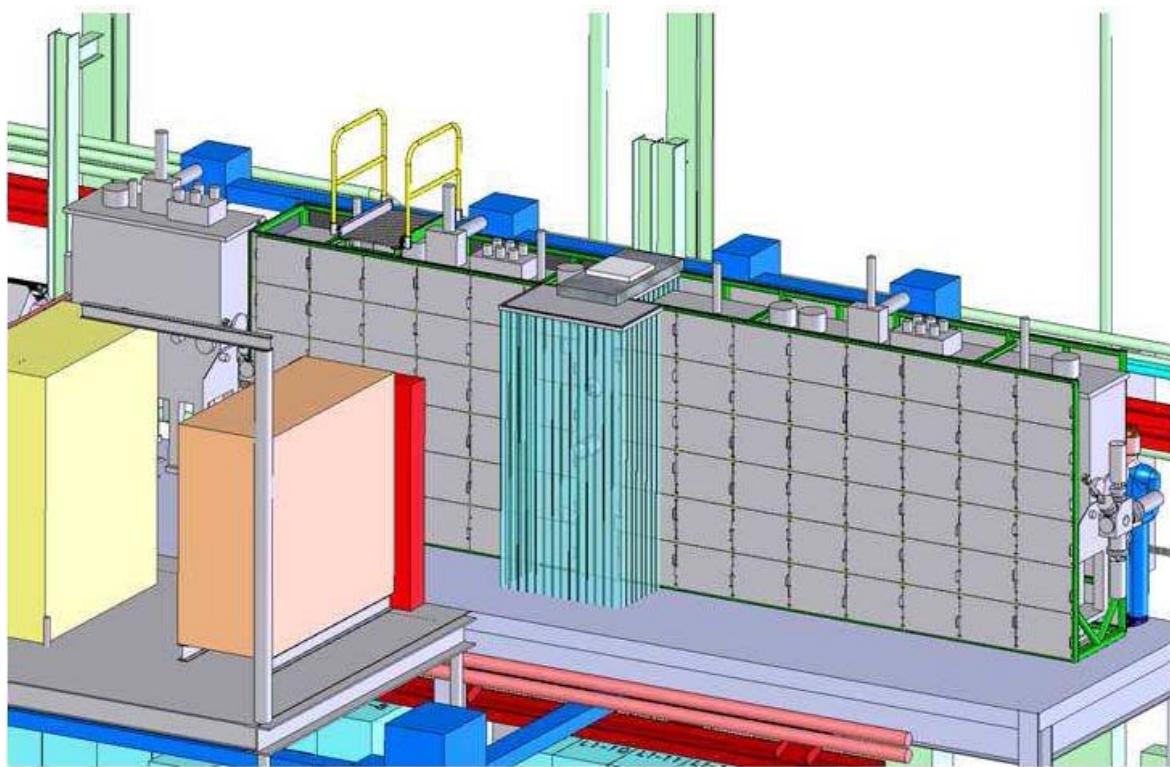
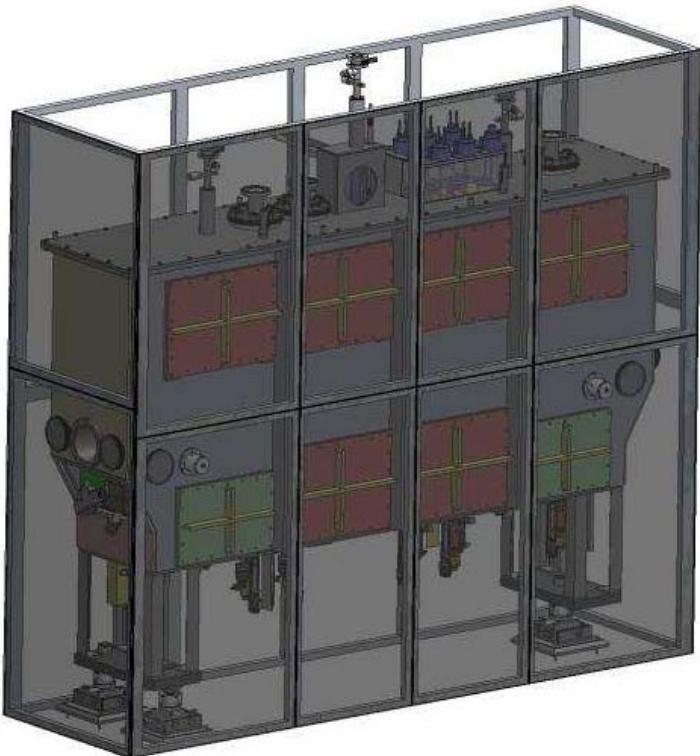
# ReA3 – cryomodule components



# Prototype cryomodule assembly

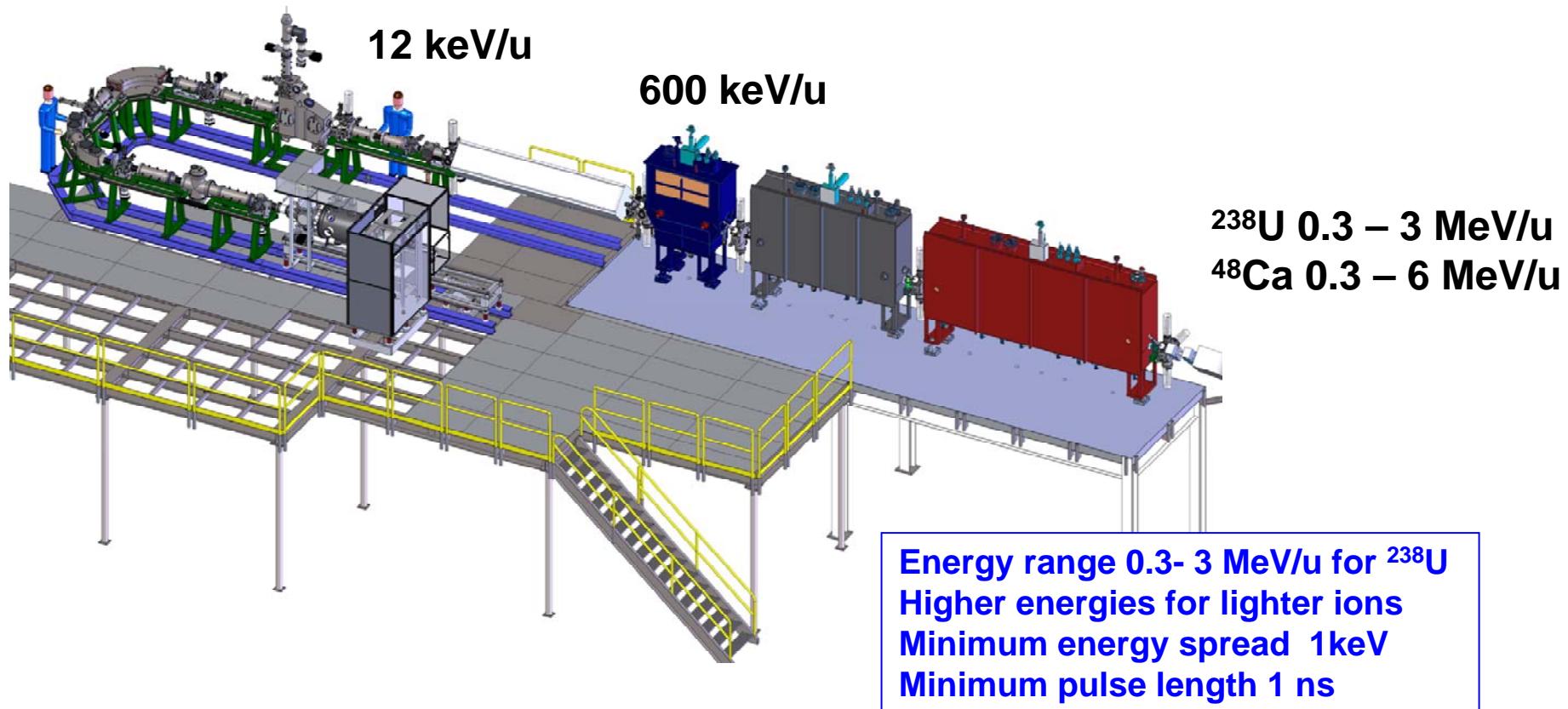


# X-ray shielding



# ReA3 – Platform view

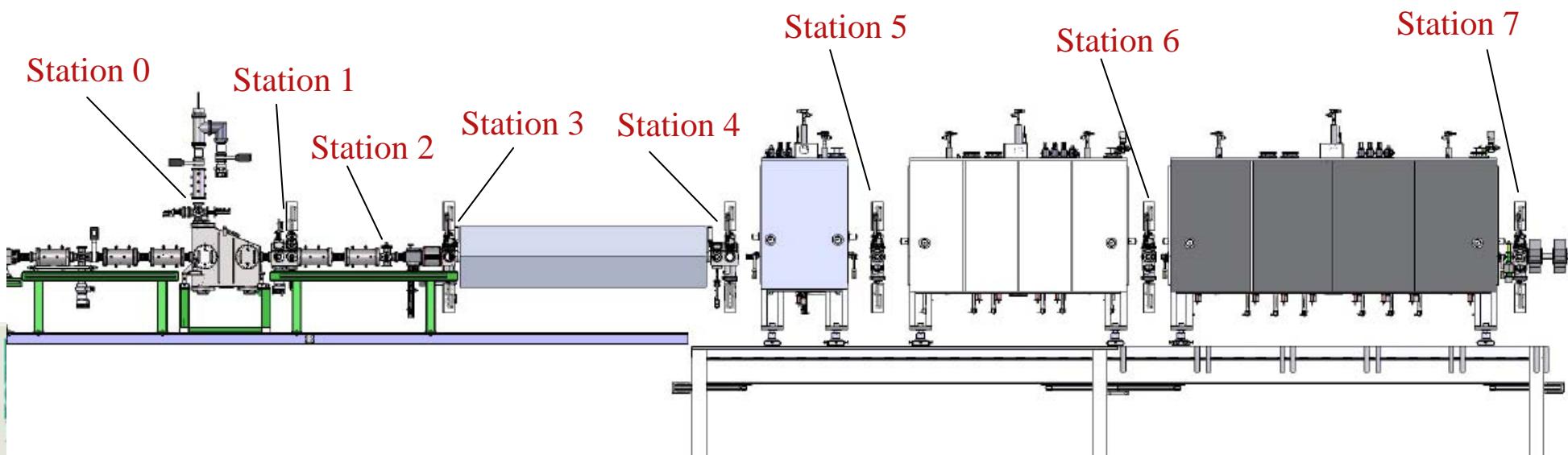
- Modern compact linac
  - LEBT with multi-harmonic buncher
  - Radio frequency quadrupole (RFQ)
  - Superconducting RF linac
  - HEBT with rebuncher



# Diagnostics – beam commissioning

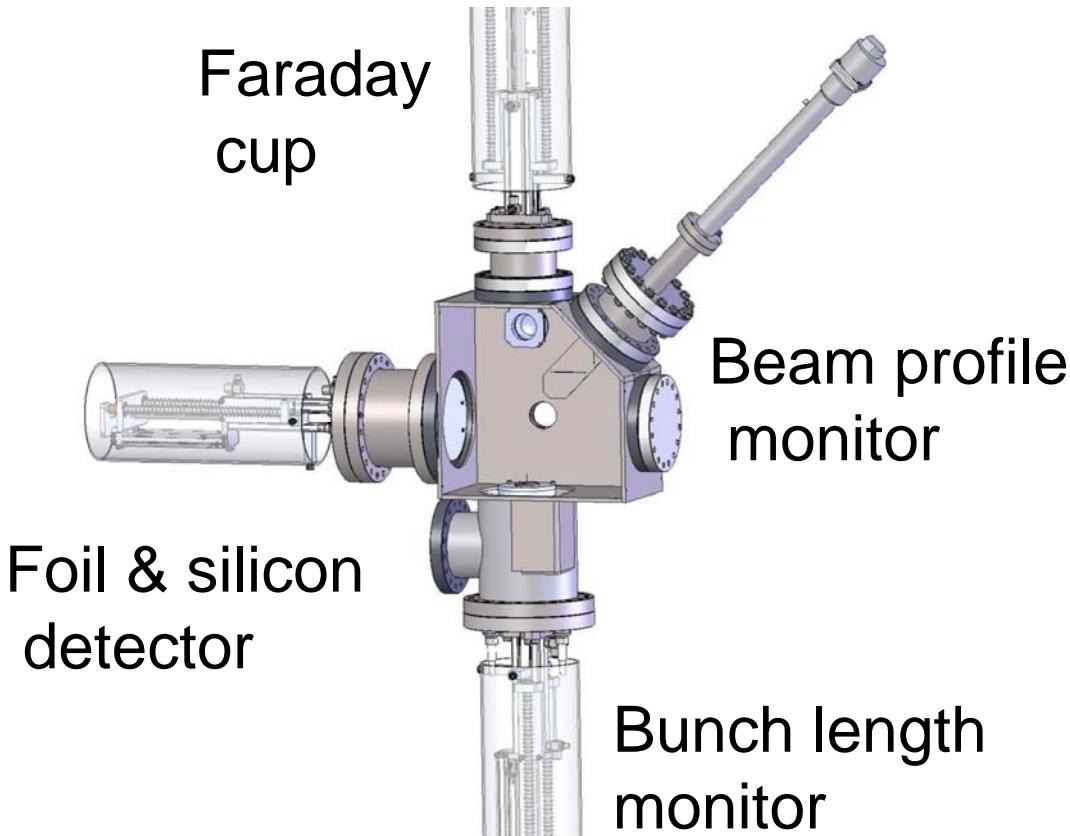
Diagnostics Station	Devices
0	Faraday cup, attenuator, viewer
1	Faraday cup, attenuator, viewer, decay counter, MCP phosphor, emittance scanner
2	viewer
3	Faraday cup, movable slit, timing

Diagnostics Station	Devices
4	Faraday cup, movable slit, timing, 4-jaw slit, attenuator
5	Faraday cup, movable slit, timing, foil and Si det., defining aperture
6	Faraday cup, movable slit, timing, foil and Si det.
7	Faraday cup, movable slit, timing, foil and Si det.

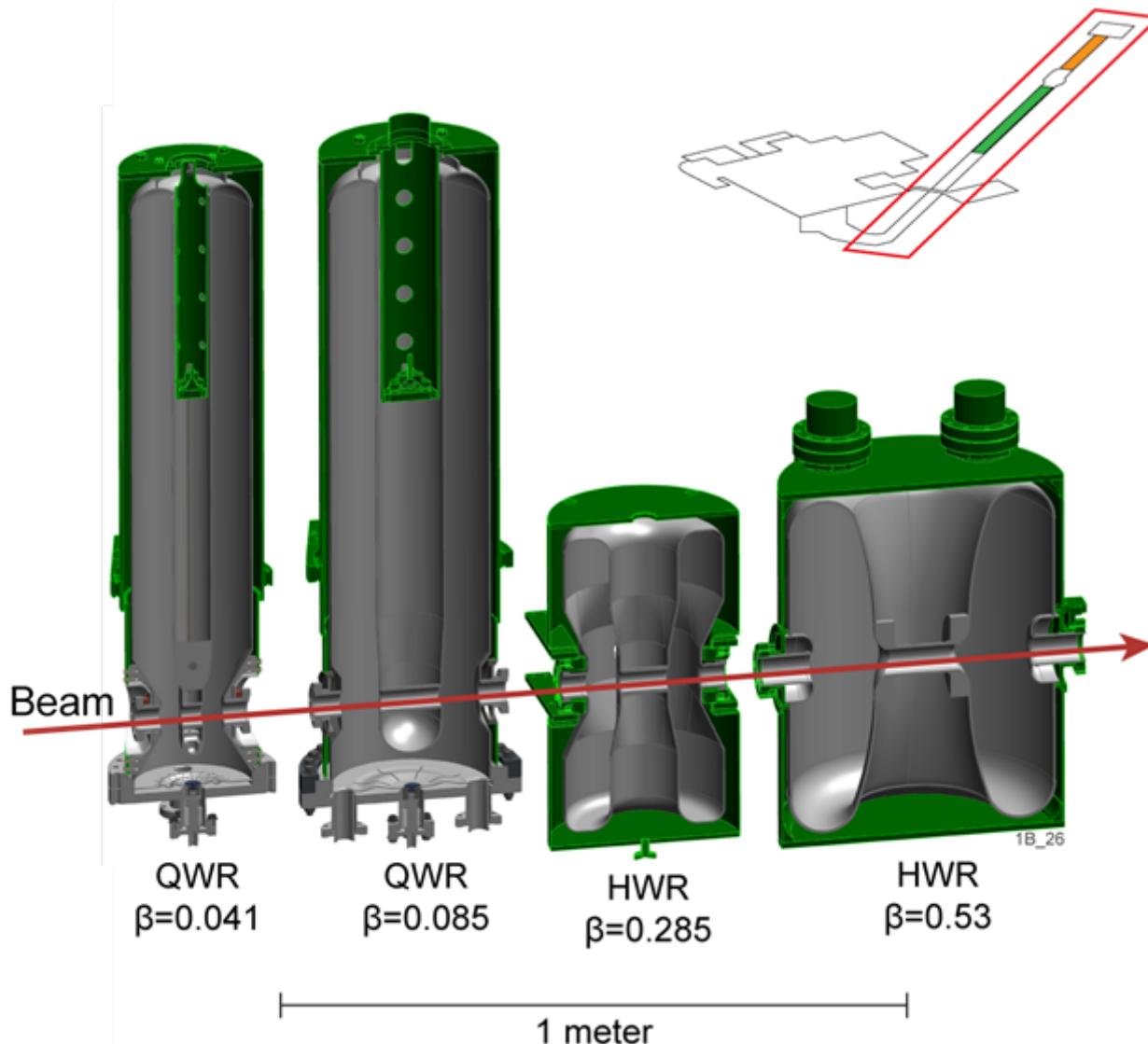


# Beam diagnostic - example

- Beam profile monitors and timing detectors are adaptations from TRIUMF designs



# FRIB– Proposed cavity types



# FRIB – Proposed cavities parameters

Category	Unit	Cavity Types			
		Linac Segment 1		Linac Segment 2	
		$\beta_{\text{opt}} = 0.041$	$\beta_{\text{opt}} = 0.085$	$\beta_{\text{opt}} = 0.285$	$\beta_{\text{opt}} = 0.53$
Cavity type		QWR	QWR	HWR	HWR
Frequency (f)	MHz	80.5	80.5	322	322
Number of accelerating cavities/cryomodule		8	8	6	8
Number of accelerating cryomodules		2	12	12	19
Peak surface electric field ( $E_p$ )	MV/m	30	30	30	30
Peak surface magnetic field ( $B_p$ )	mT	53	67	82	86
Accelerating voltage at $\beta=\beta_{\text{opt}}$ ( $V_a$ )	MV	0.8	1.75	1.9	3.7
Operating temperature ( $T_{\text{ope}}$ )	K	4.5	4.5	2	2
Design quality factor ( $Q_0$ )		$5.0 \times 10^8$	$5.0 \times 10^8$	$8.2 \times 10^9$	$1.3 \times 10^{10}$
Cavity aperture	mm	30	30	30	30
Number of solenoids per accelerating module		7	3	1	1
Solenoid field	T	9	9	9	9
Solenoid aperture	mm	40	40	40	40
Accelerating module length	m	4.7	5.3	3.1	5.37
Cryogenic load per cryomodule at $T_{\text{ope}}$	W	39.7	131.3	25.7	52
Average charge state (for uranium)		33.5	33.5	79	79
Beam current (for uranium)	p $\mu$ A	10.6	10.6	8.3	8.3
Beam power per cavity ( $P_b$ )	W	261	563	1054	2198
Loaded quality factor ( $Q_L$ )		$1.9 \times 10^6$	$4.3 \times 10^6$	$5.7 \times 10^6$	$9.6 \times 10^6$
Cavity bandwidth ( $f/Q_L$ )	Hz	42	19	57	33
Power per RF amplifier	W	700	1500	2900	6000



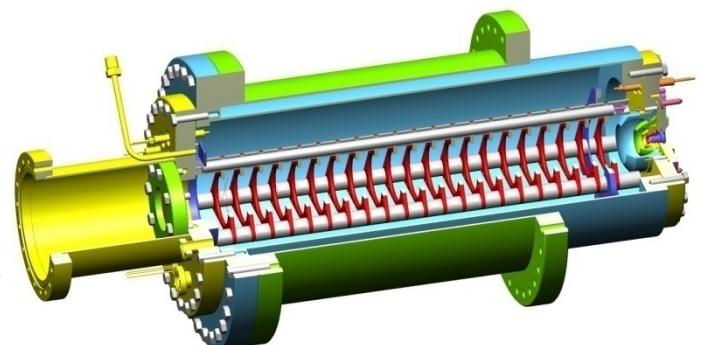
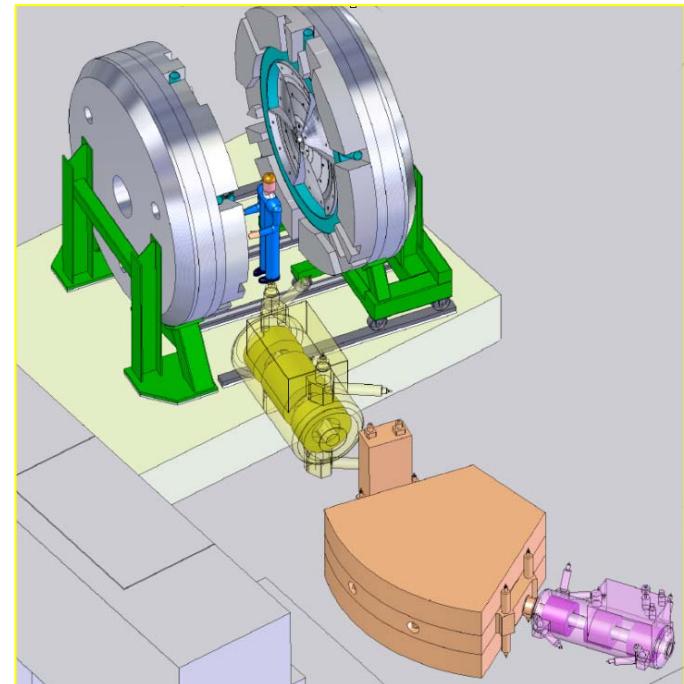
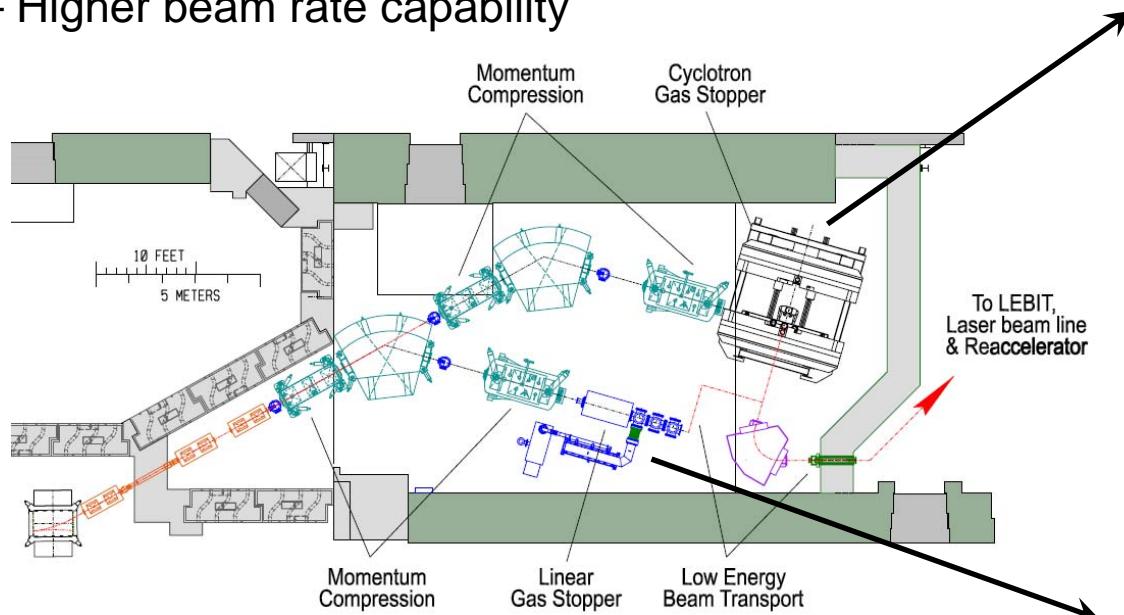
# Gas stoppers - example

- 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



G. Bollen, D.J. Morrissey, S. Schwarz, Nucl. Instr. Meth. A **550** (2005) 27  
F. Marti et al., Cyclotrons-2007 Conference proceedings

# Cyc-stopper

- Characteristics

- Weakly-focusing magnet and rf ion guiding techniques
- Ions injected using a solid degrader
- Slowed in a helium gas at low pressure (~10-200 mbar)
- Longer path compare to linear gas stopper
- Ions extracted with static electric fields, rf carpet and ion guides

- Expected performance

- Fast extraction times (10-100 ms)
- Beam rate limit  $> 10^8$  p/s compatible with next generation facilities
- Capability to stop beams with  $1.75 < A/Z < 3$  and high efficiencies

