State of the Art Post Accelerator Facilities

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Content

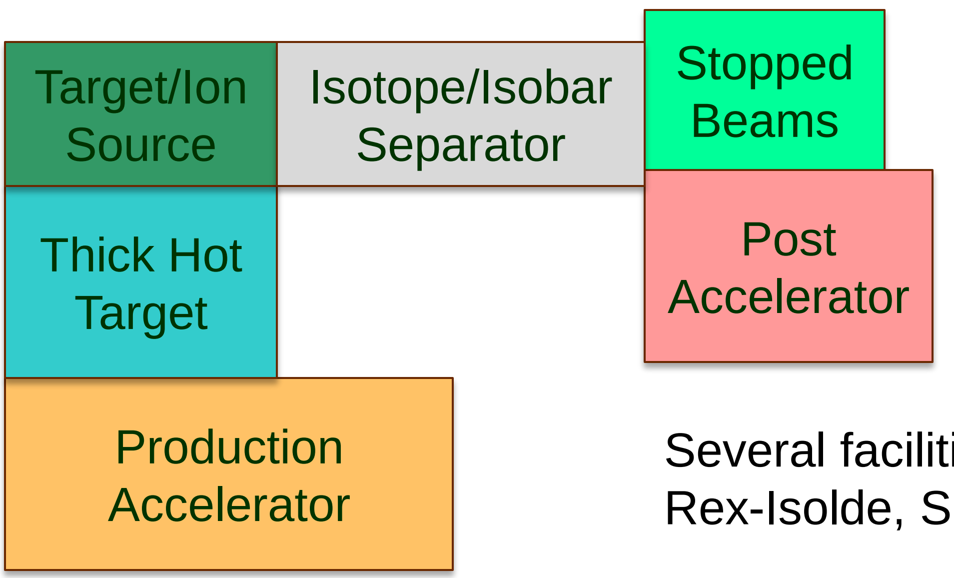
- RIB post accelerators challenges
- Implementations and designs for selected post accelerator facilities
- Coming online soon: ReA (Reaccelerator facility at MSU)
- Design choices for ReA as efficient post accelerator
- ReA commissioning results and status
- Summary

Isotope production reaction mechanisms

Most post accelerator facilities are based on

ISOL –Isotope Separator On-Line (target "spallation"or fission)

- Light ion-induced "spallation"or fission of heavy targets
- Isotopes must diffuse from hot targets and effuse to an ion source
- Typical beams ~100-1000 MeV protons; typical targets Ta & UC
- Photofission using high power electron linac

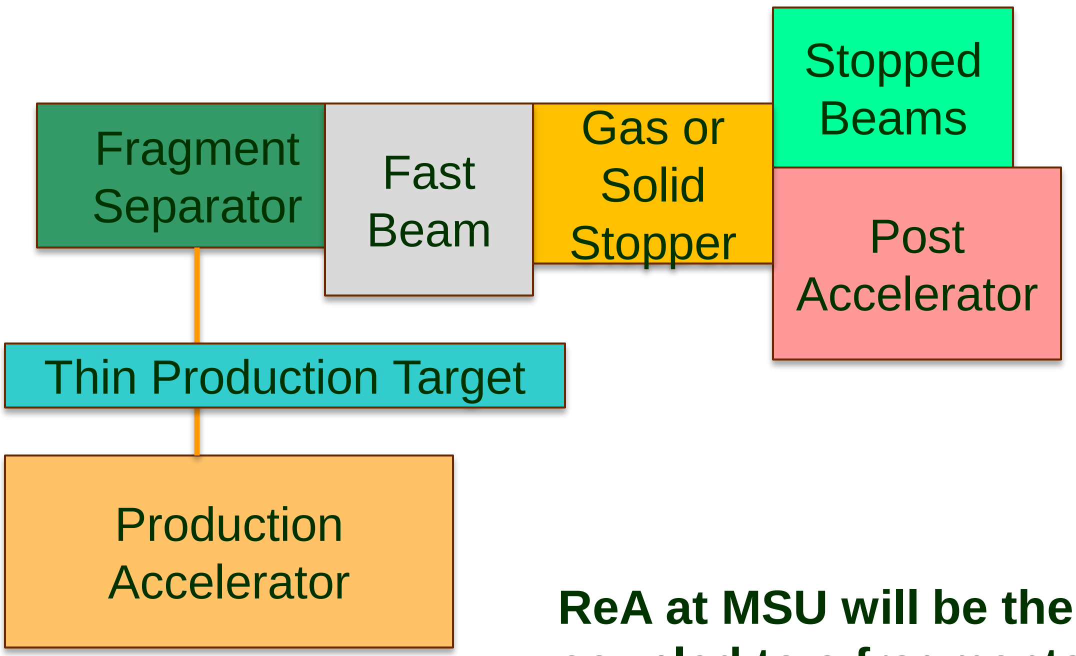


- Very intense beams of many elements, especially noble gases and alkalis
- Weak beams of refractory and chemically active elements

Several facilities around the world:
Rex-Isolde, Spiral, ISAC, EXYPT, SPES,EURISOL …

Isotope production reaction mechanisms

- **In-flight heavy-ion fragmentation or fission on a light target**
  - Fragments of the beam are kinematically forward directed at ~beam velocity
  - Rare isotopes are separated physically; no chemical dependence
  - Typical beams are 18O, 82Kr, & 238U at 200-2000 MeV/u; typical targets Be or C

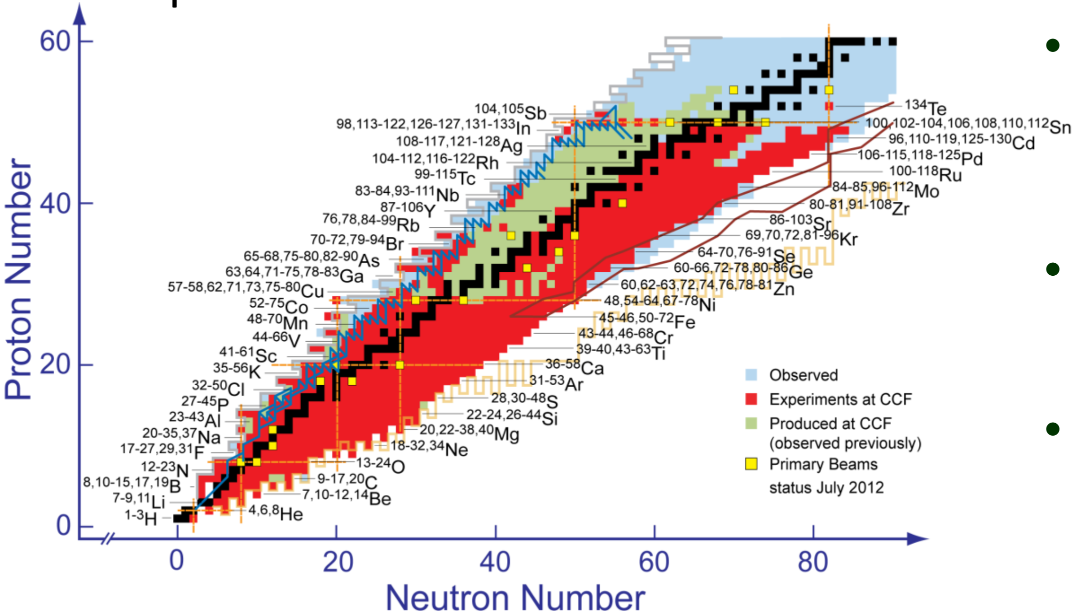


- Separated beams of any species including refractory and chemically active elements and isotopes with very short half-lives, even isomers
- Needs gas catcher or solid stopper for post acceleration

ReA at MSU will be the first postaccelerator coupled to a fragmentation facility

RIB post accelerator are heavy ion accelerator, but come with special requirements/challenges

More than 1000 RIBs Isotopes produced and observed at the Coupled Cyclotron Facility at MSU, more than 830 RIBs used in experiments



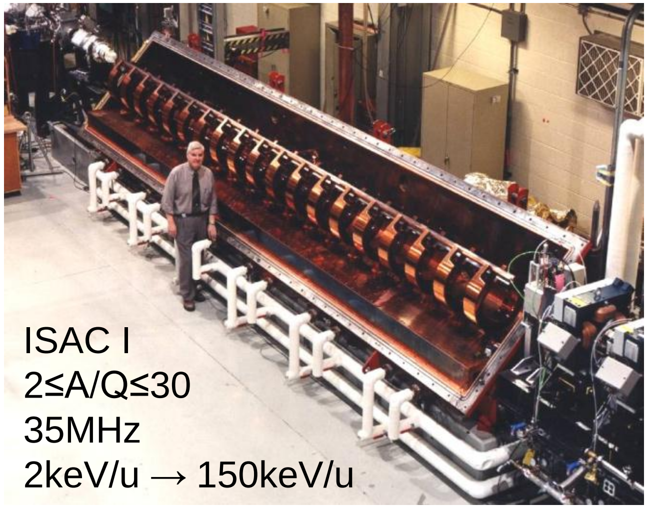
Postaccelerators

- need to accelerate **a wide variety of ions and all masses**
- should be capable of **accelerating all masses fast and with high efficiency**
- Must **control isobaric impurities** (stable and unstable)
- Support a **wide dynamic range**, beam tuning with a few 100 p/s (diagnostics !)

Support wide energy range and energy flexibility

- 100keV to Coulomb barrier for nuclear astrophysics (low energy spread and small transverse emittance)
- Above Coulomb Barrier 5-20MeV/nuc

Challenge: Accelerate all ions efficiently starting from thermal/low energy beams



- **Linac structures** have a **lower limit for injection energies**(focusing and cell size limit)
- **RFQ** utilize quadrupole channel (focusing) with axial modulation (acceleration). Heavy ions requires **low frequency (implies large size)** to keep to a reasonable lengths of acceleration cell ($\beta\lambda$) and quadrupole aperture size (limits A/Q range)
- Typically **RFQ** provide a **fixed energy "step"** (choice must be made for the lowest energy supported by the facility)

For singly charged RIB complex RFQ chains with charge stripping in between are necessary to provide full A/Q range (see for example, P.N. Ostroumov, PAC2005)

High charge state ions (CB) are needed to provide flexible mass and energy range

Challenge: Accelerate all ions efficiently starting from thermal/low energy beams

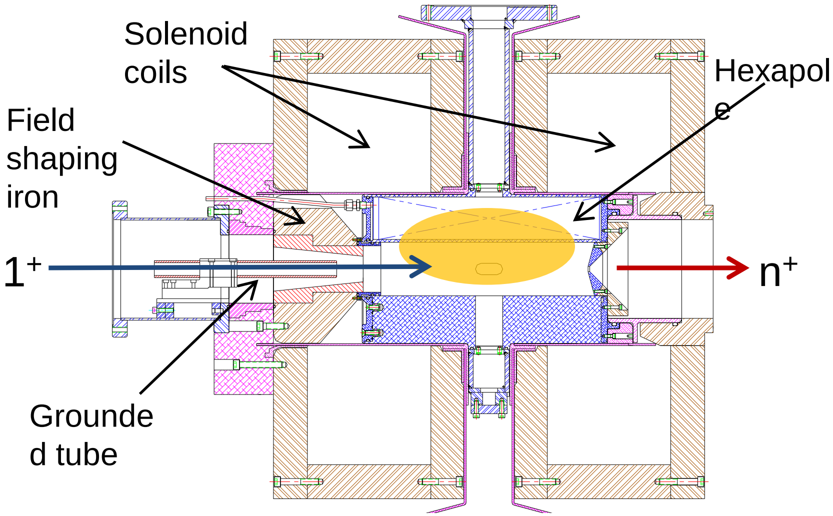
- **Provide great mass resolution and are a very compact solution**
- **Limited A/Q range**
- **Wide energy range is difficult** to achieve with a single machine (complex operation using several higher harmonics)
- **Beam matching** into the **center region** with high efficiency is more difficult compared to a linac
- **Energy upgrades** are much more **difficult** than with a linac

High charge state ions (CB) are needed to provide flexible mass and energy range

Charge breeder for post accelerator facilities - a comparison

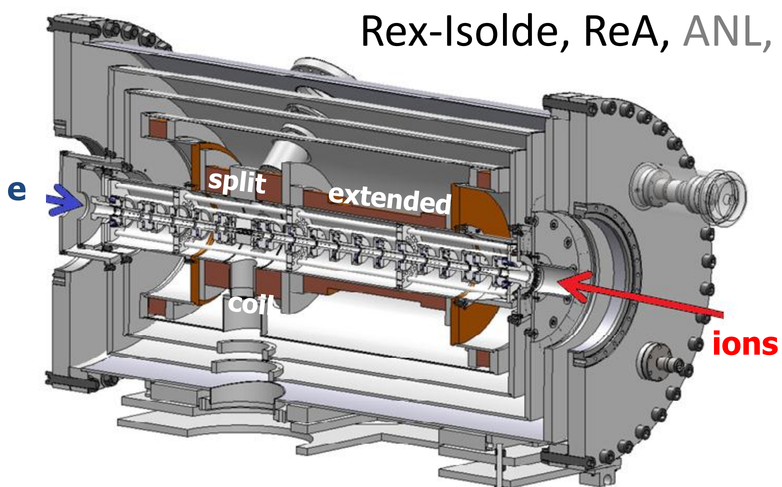
Electron Cyclotron Resonance Sources

ANL, CARIBU, GANIL Spiral, ISAC…



Electron Beam Ion Sources

Rex-Isolde, ReA, ANL, ISAC

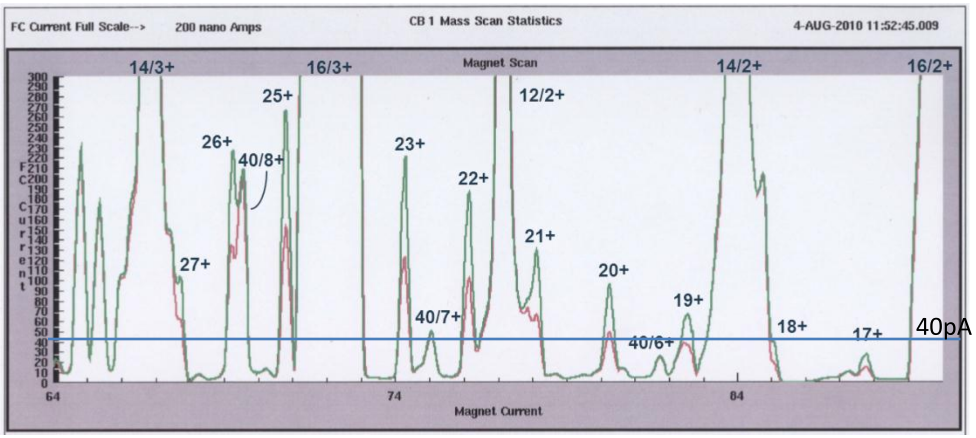


ECR		EBIS/EBIT
Plasma	Confinement	E-beam
<25%	Efficiency	<25%-50%
μA (10^{13} pps)	Injected beam	nA (10^{10} pps)
2- 8	A/Q	2 – 8
100ms-10 sec	Breeding time	20 - 300 msec
pA-nA	Contamination	<pA
CW or pulsed	Operation	Pulsed
Easy		complex
Charge state selection is less flexible		Flexibility in charge state selection

Charge breeder for post accelerator facilities - a comparison

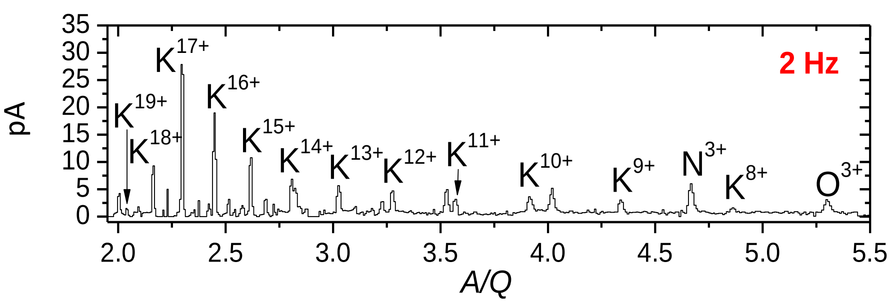
Electron Cyclotron Resonance Sources background peaks limit purity level of CB beams

ANL, CARIBU



R. Vondrasek, ICIS 2011

Electron Beam Ion Sources background peaks are reduced to pA levels, clean A/Q can be selected



MSU EBIT, A. Lapierre, CAARI2012

ECR		EBIS/EBIT
Plasma	Confinement	E-beam
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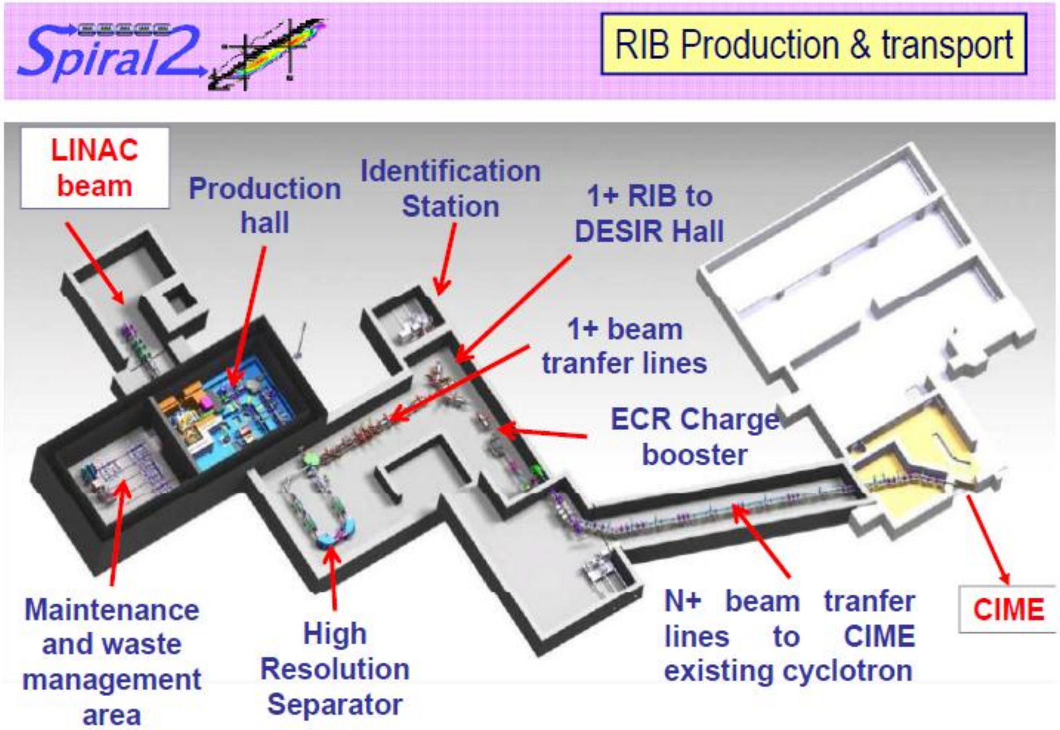
µA (10^{13} pps)	Injected beam	nA (10^{10} pps)
2- 8	A/Q	2 – 8
100ms-10 sec	Breeding time	20 - 300 msec
pA-nA	Contamination	<pA
CW or pulsed	Operation	Pulsed
Easy		complex
CS is less flexible		Flexibility in CS

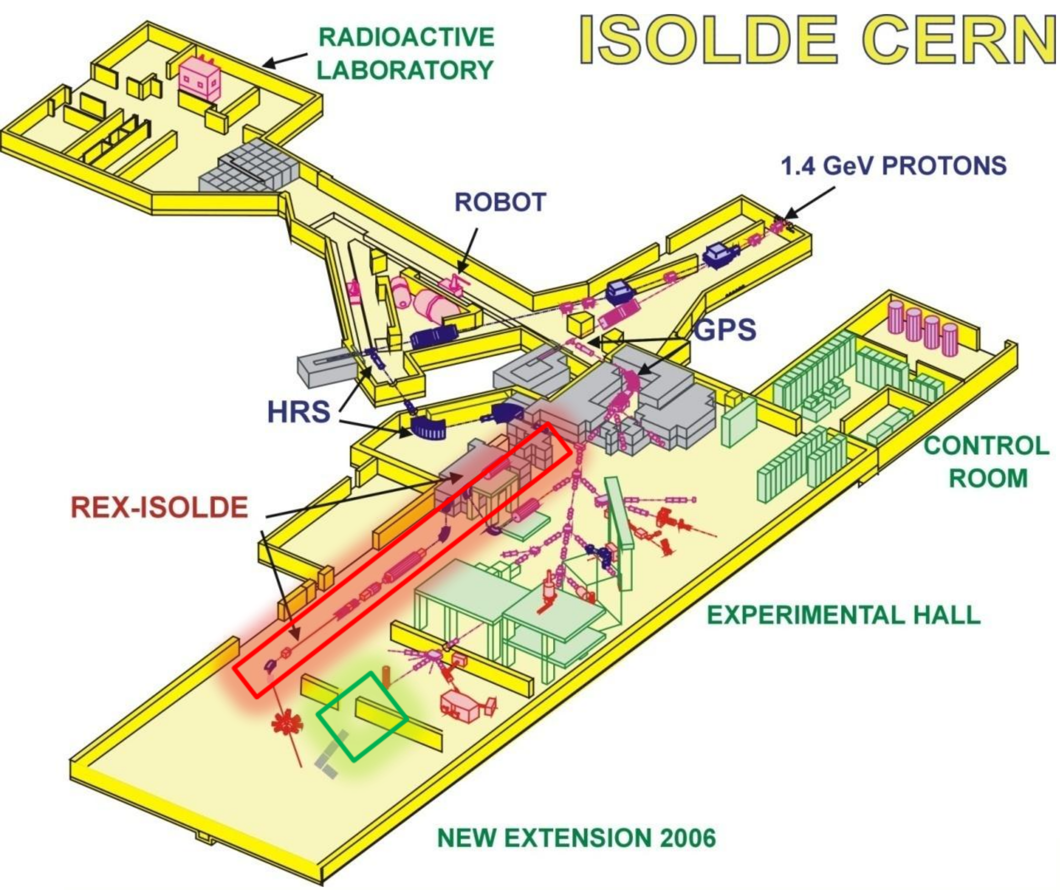
Spiral – GANIL – ISOL+ECR CB+ Cyclotron



Impurity Issues from ECR CB are addressed with the high mass resolution from Cime (>10000)

Wide mass range/energy is achieved by using 2,3,4,5, harmonics for cyclotron acceleration, 1.7MeV/n-25MeV/n

Slide Courtesy F. Wenander

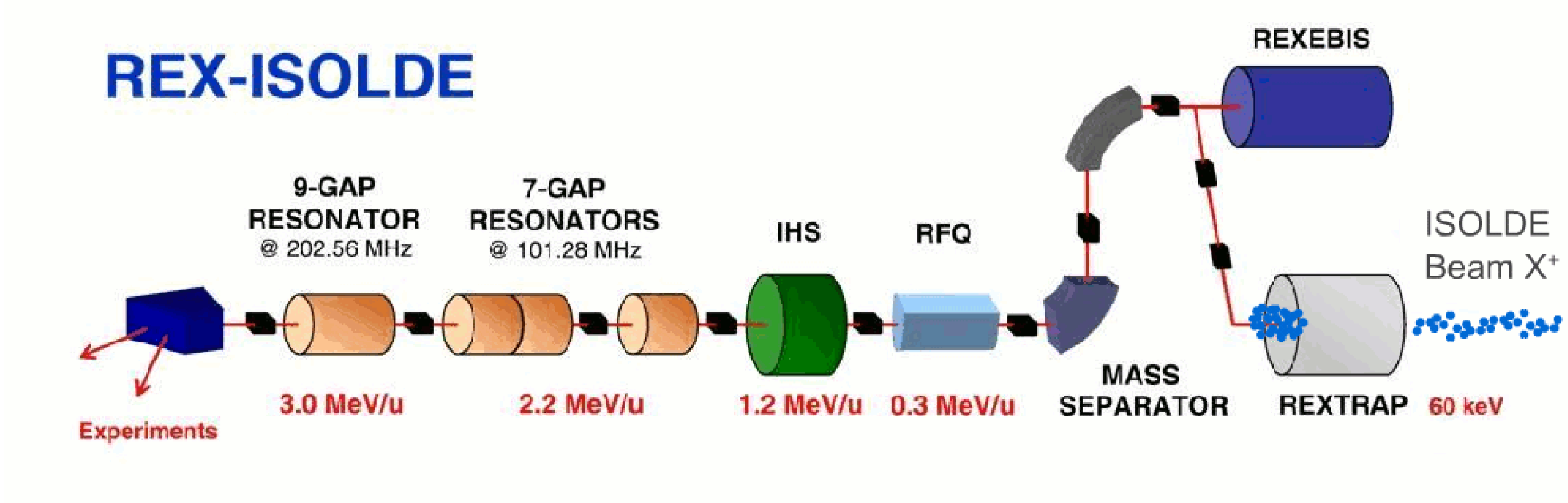


ISOL-Penning Trap-EBIS-LINAC

32 different radioactive elements for physics
~100 isotopes accelerated
~100 beam times
~<10% contaminates

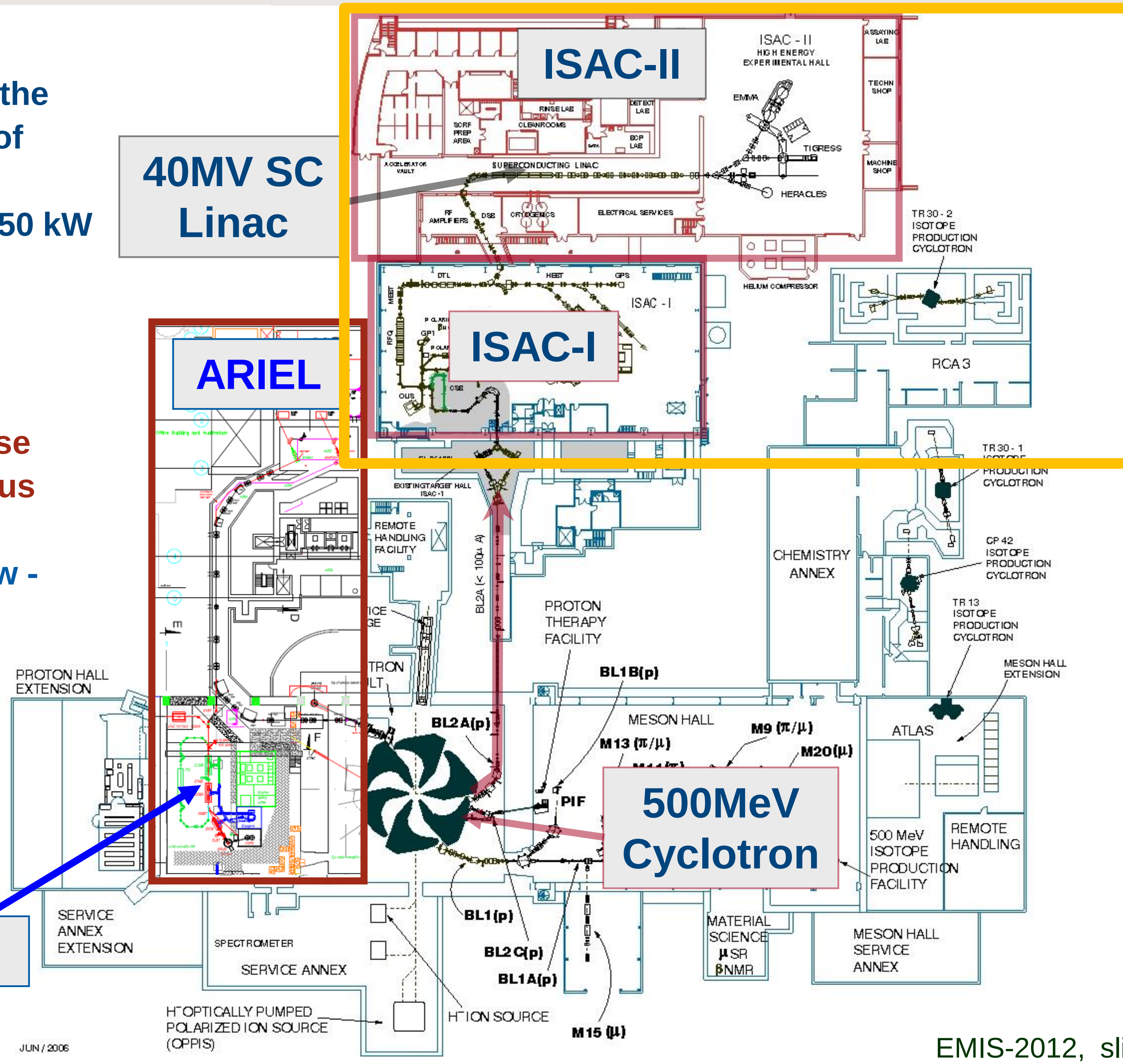
REX-ISOLDE

Post accelerator to 3 MeV/u
Room temperature Linac
First experiment 2001
HIE upgrade with SRF Linac (2015)



TRIUMF/ISAC Facility

- World class ISOL facility for the production and acceleration of rare isotope beams (RIB)
- Highest power driver beam (50 kW protons)
- 40MV SC heavy ion post-accelerator – fully variable in energy
- Now adding ARIEL to increase from one to three simultaneous beams
- Add e-Linac (50MeV 10mA cw - 1.3GHz SC linac)



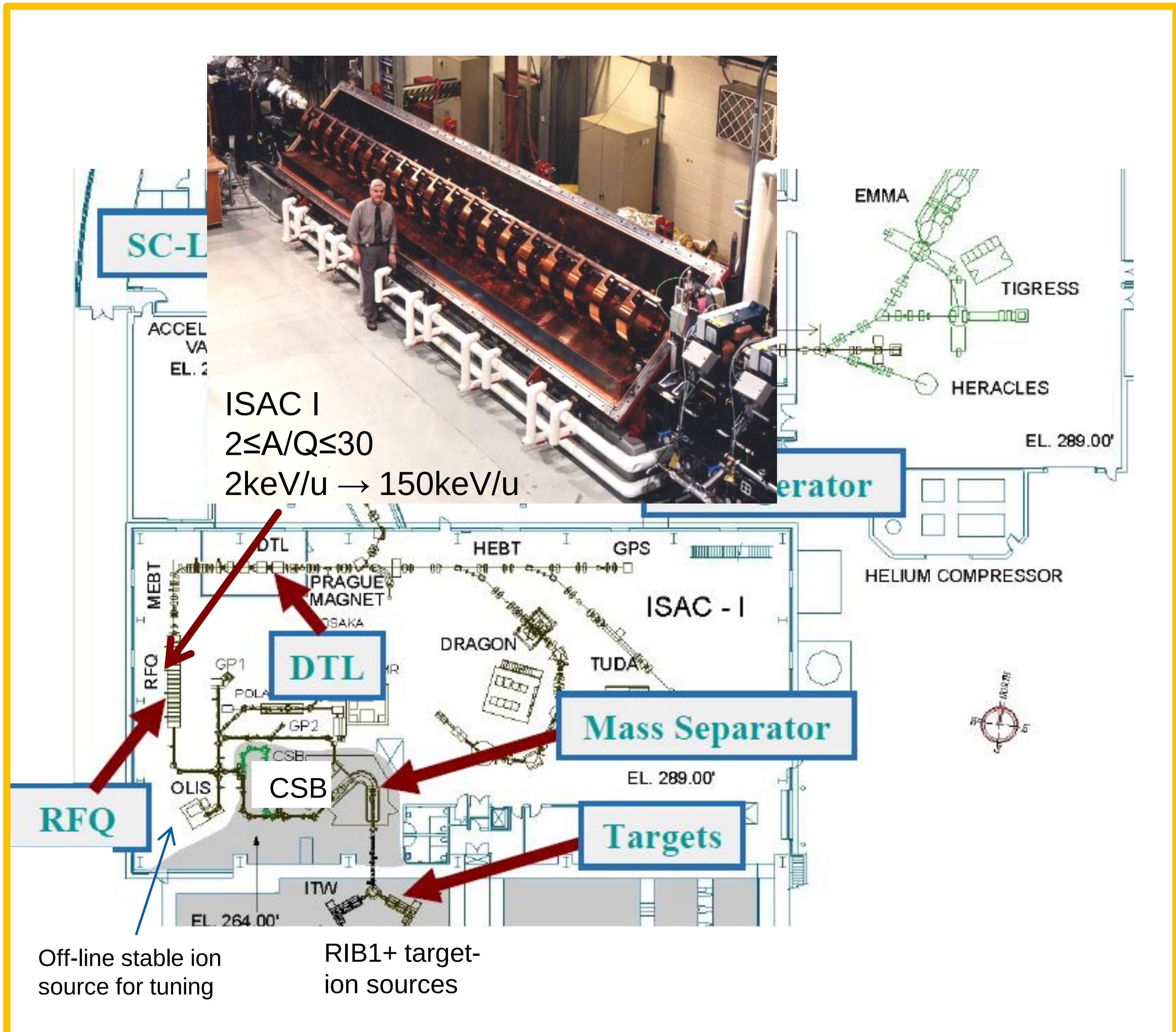
Slides Courtesy of Bob Laxdal

ISAC Postaccelerator Facility

- World class ISOL facility for the production and acceleration of rare isotope beams (RIB)
- Highest power driver beam (50 kW protons)
- Heavy mass RIB produced with actinide targets (10kW)
- 40MV SC heavy ion post-accelerator – fully variable in energy

Challenges:

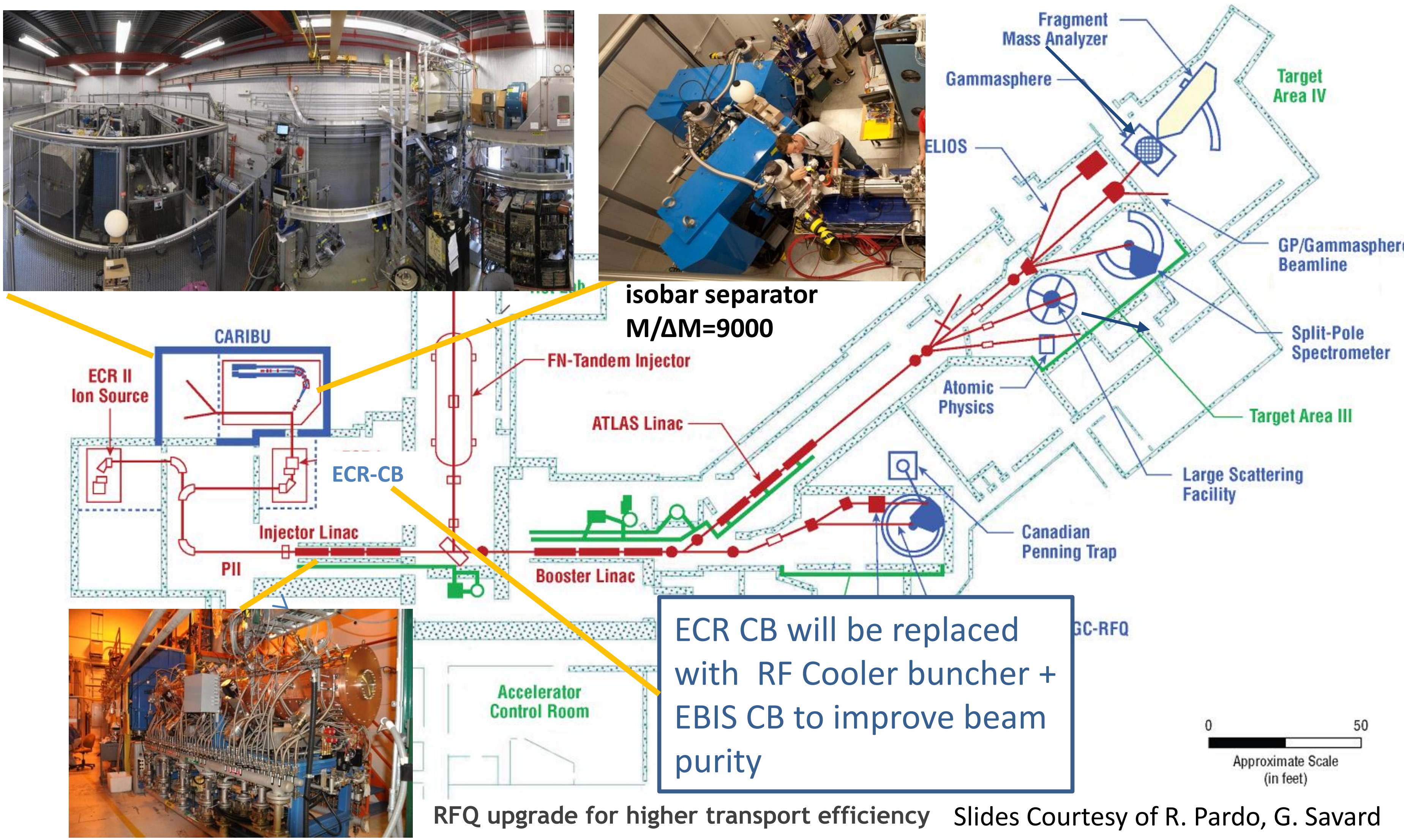
- A/q acceptance of RFQ imposes limit of A<30
- Charge State Booster (ECRIS) needed to reach A>30
- Chief problem – stable contaminants from CSB overwhelming RIB
- Plans are to use to add an EBIT CB



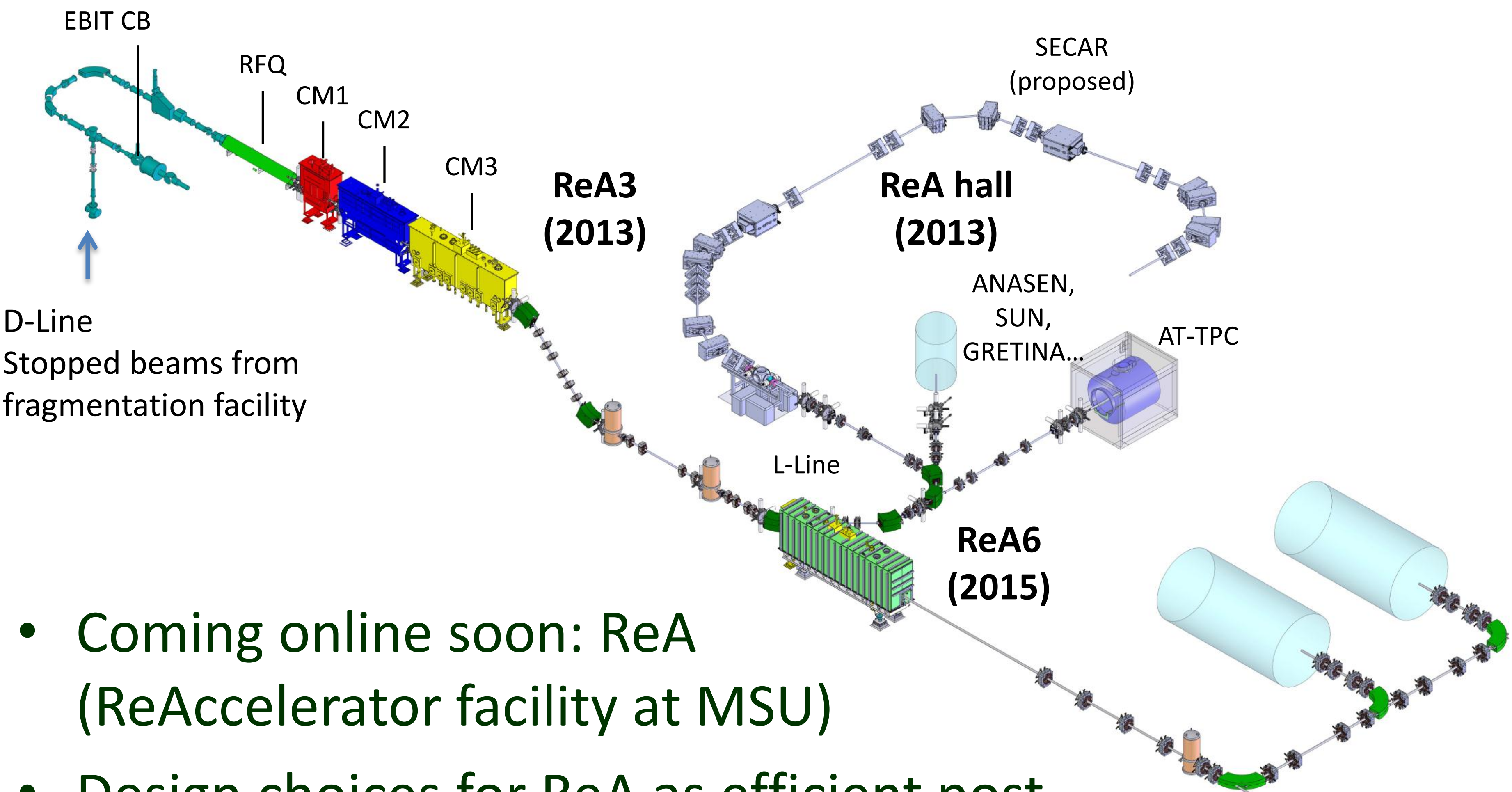
Slides Courtesy of Bob Laxdal

CARIBU uses a ^{252}Cf source for "production" and ATLAS as post accelerator (neutron rich heavy ions)

- Stopped beams - Masses, decay spectroscopy, laser spectroscopy (over 60 masses measured)
- Post-acceleration energy up to 12 MeV/u - Single particle structure, gamma-ray spectroscopy



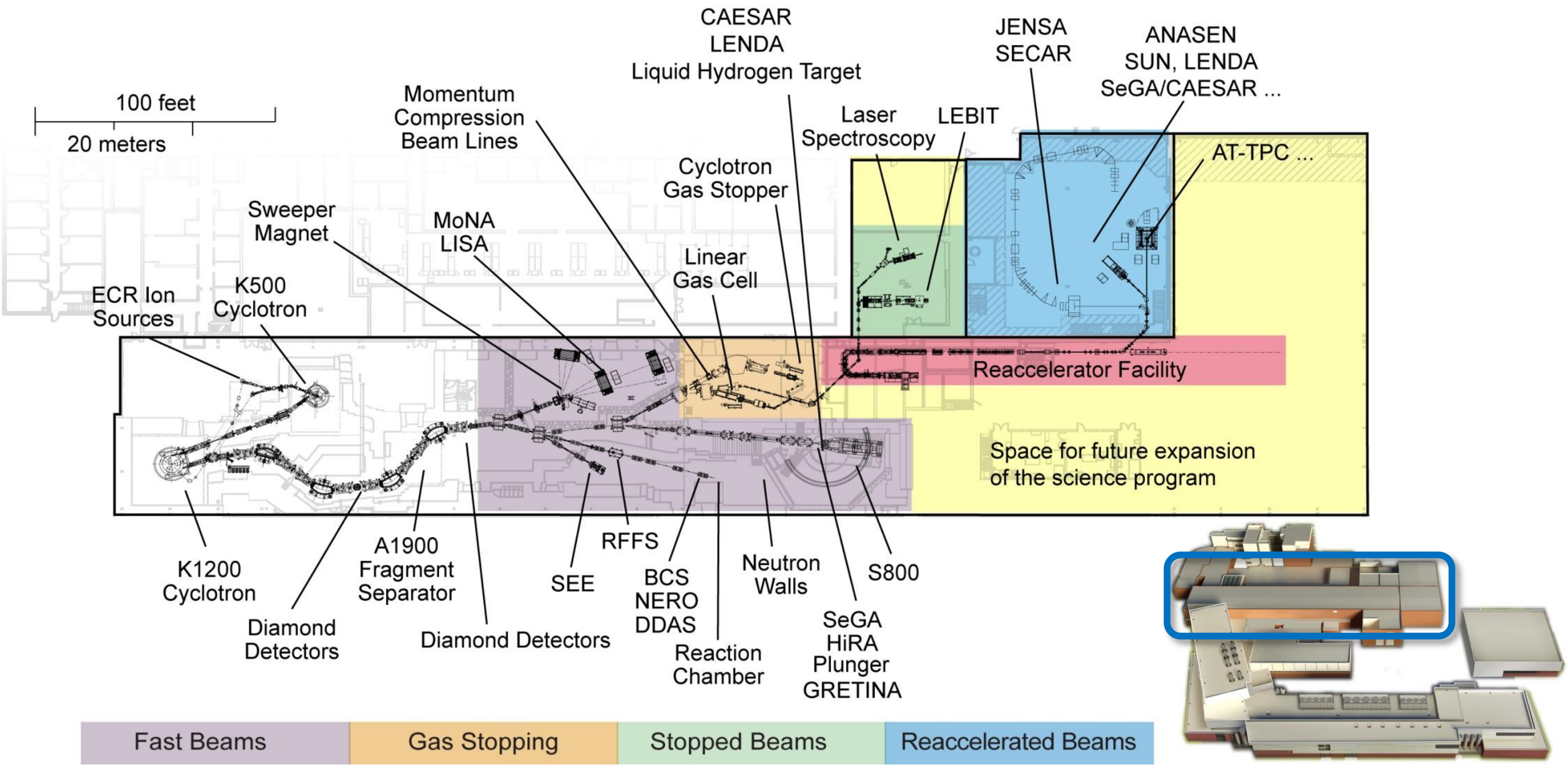
Slides Courtesy of R. Pardo, G. Savard



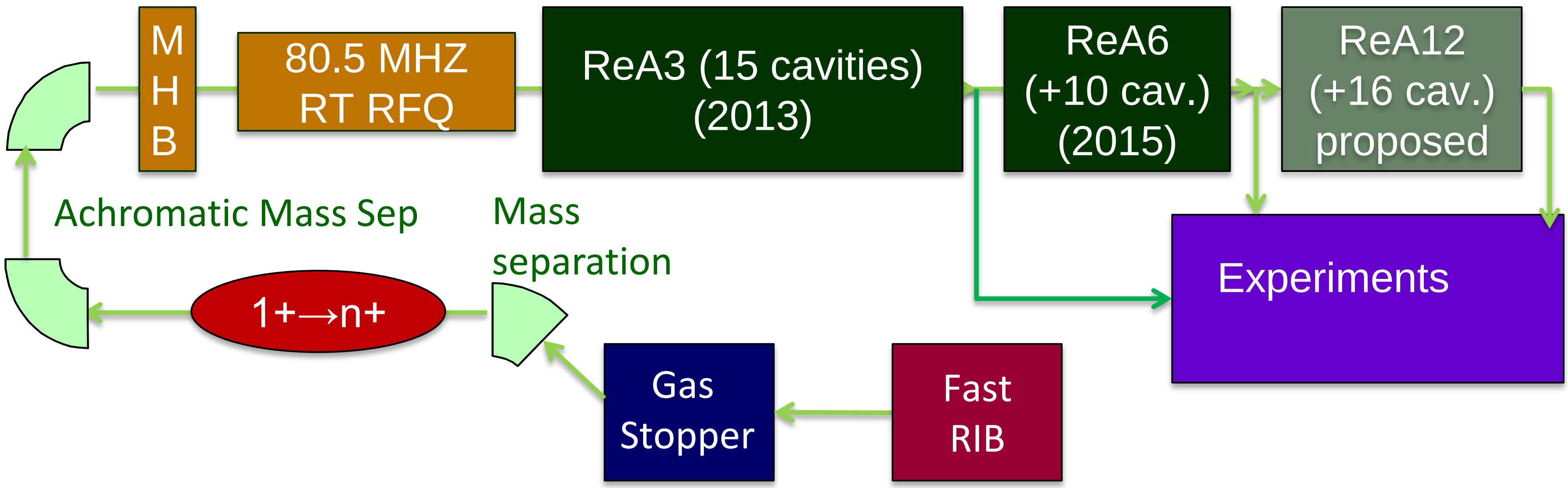
- Coming online soon: ReA (ReAccelerator facility at MSU)
- Design choices for ReA as efficient post accelerator
- ReA commissioning results and status

The Coupled Cyclotron Facility at National Superconducting Cyclotron Laboratory at Michigan State University

Fast, stopped, and (soon) reaccelerated radioactive ion beams

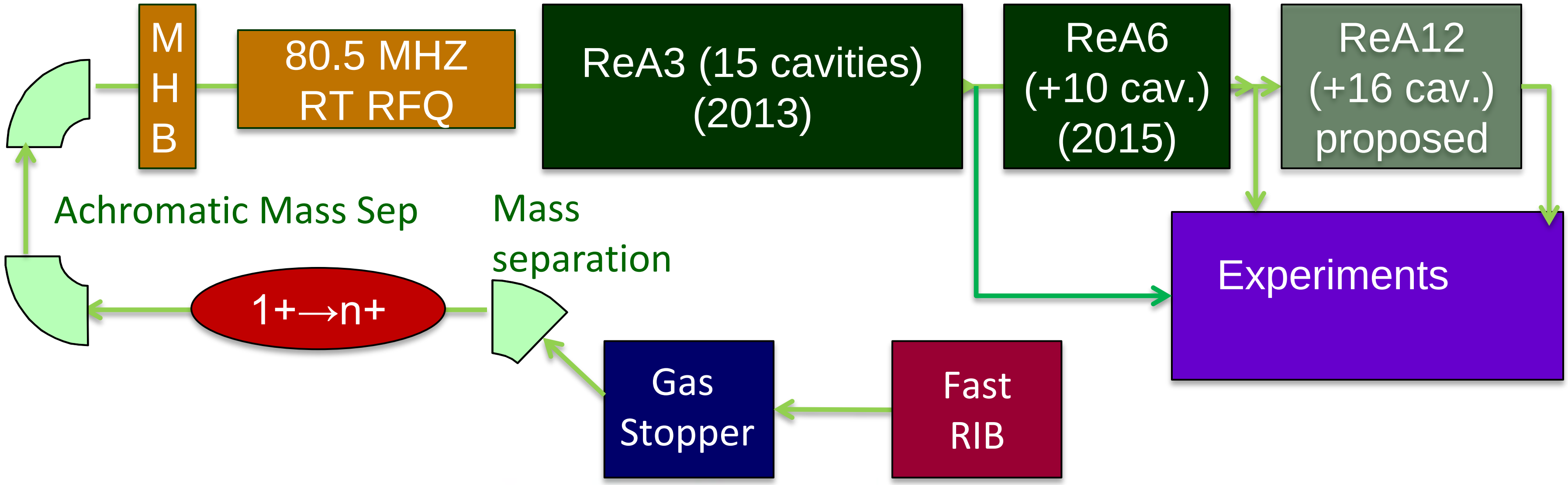


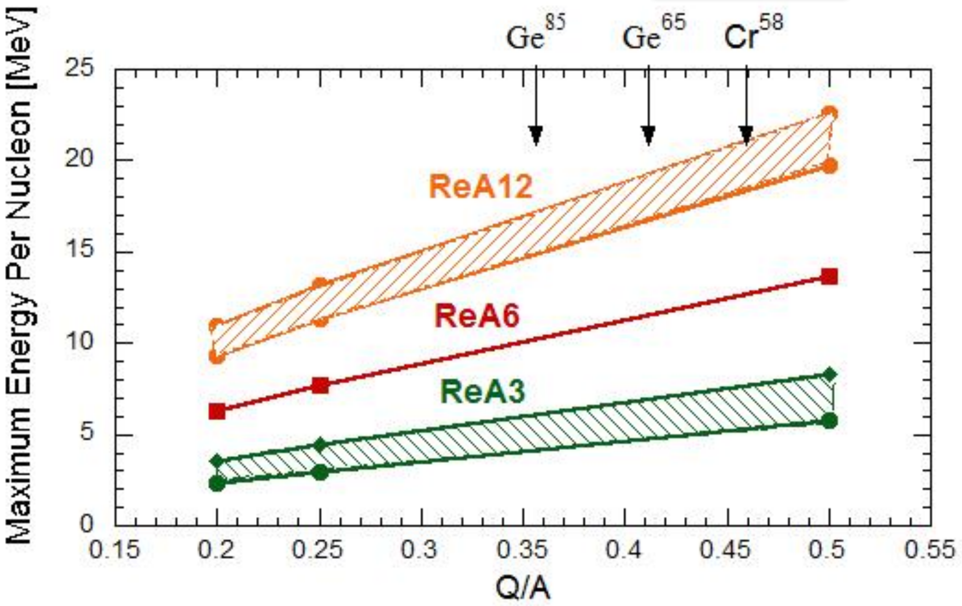
ReA Concept: Fragmentation Facility-Gas Stopper - EBIT CB coupled with SC Linac



Requirements and Design Choices		
Ion efficiency for all elements	> 20 %	EBIT charge breeder + high efficiency linac
Beam rate capabilities	10^8 ions/sec	Hybrid EBIS/T charge breeder
High beam purity		A1900, EBIT CB, Q/A
Low energy spread, short pulse length	1keV/u, 1nsec	Multiharmonic external buncher and tight phase control in SRF linac

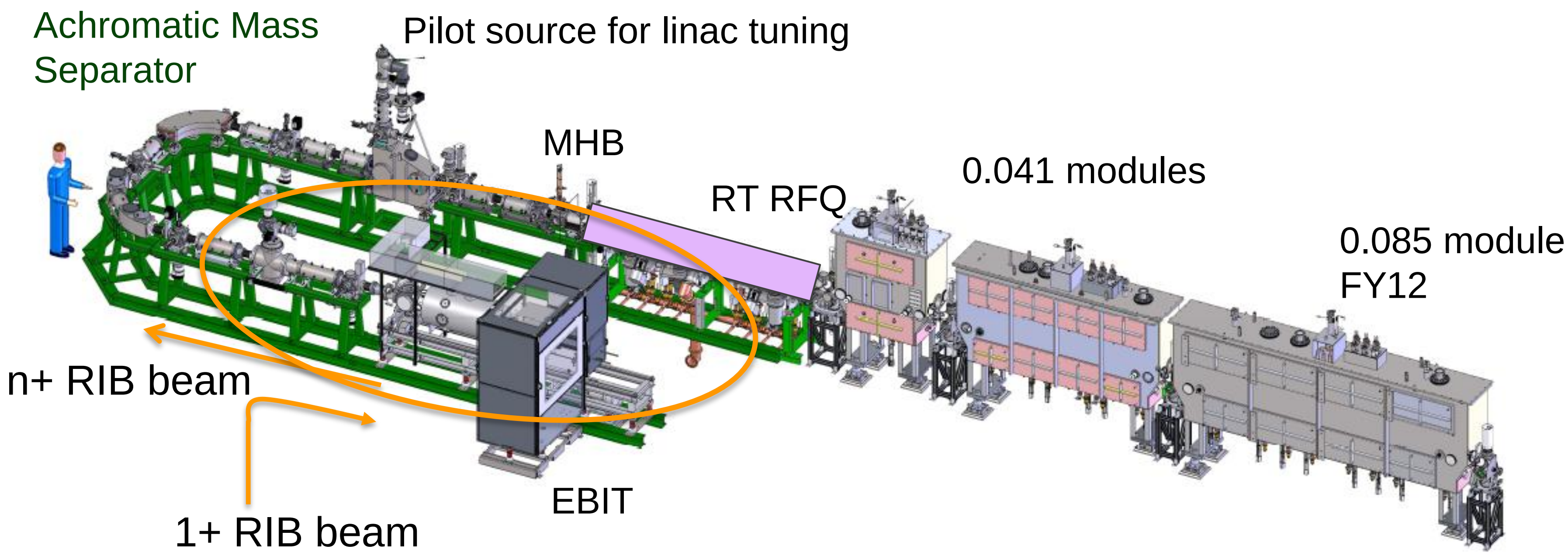
ReAccelerator facility is build in several phases, energy can be upgraded by adding cryomodules



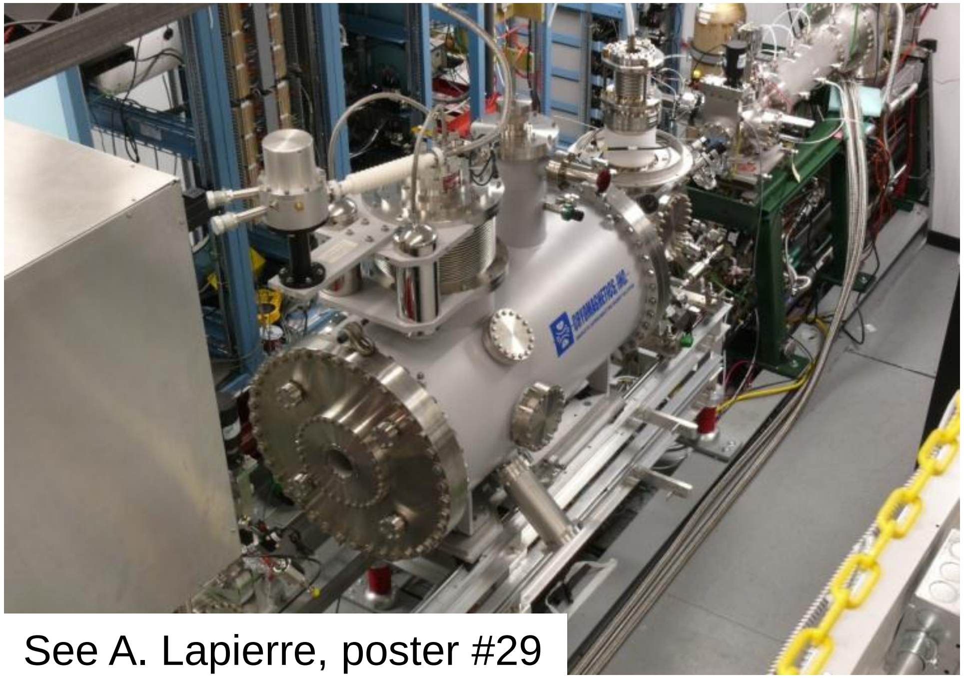


Min Energy : 300keV/u
Max Energy: see graph

ReA Design Choices: EBIT CB



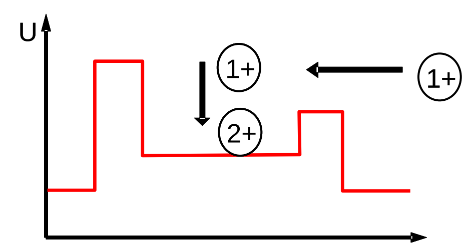
EBIT Charge Breeder: Hybrid Design to maximize capture efficiency and minimize breeding time



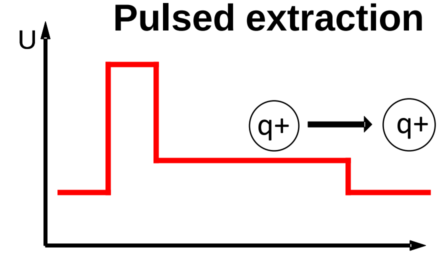
See A. Lapierre, poster #29

EBIT: Key *design* parameters:
- magnetic field: up to 6 T
- I_e= 0.5…5 A, E_e < 30keV
- current density: up to ~10^4 A/cm^2
- 4K trap system
- 0.5 < A/Q < 0.2
- HV: 60kV ⇔ 24…48 kV

Over-the-potential barrier injection



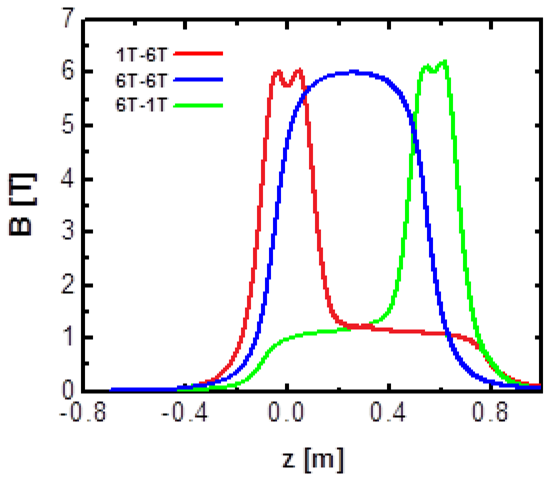
Pulsed extraction

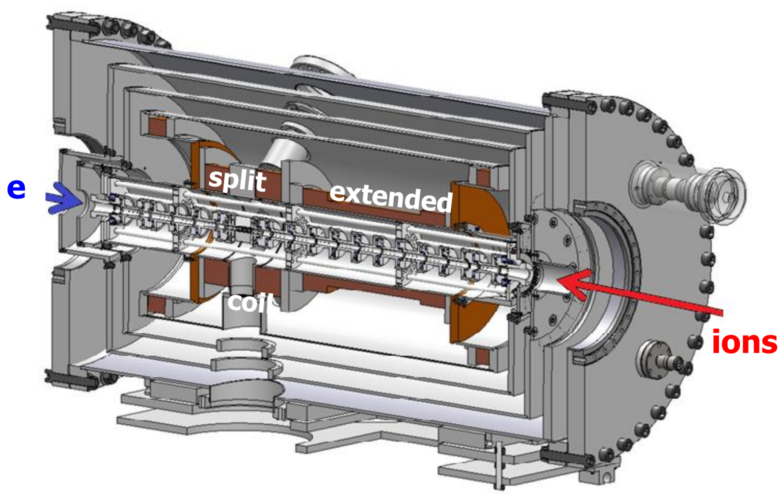


Requirements of a charge breeder for ReA:
- ▶ Breeding time < 50 ms (for short-lived isotopes)
- ▶ Efficiency: 20% - 50 % (for inj.-breeding-extrac.)
- ▶ Charge capacity: up to 10^{10} positive charges
- ▶ Low contamination level…

EBIT Charge Breeder: Hybrid Design to maximize capture efficiency and minimize breeding time

Flexible B-field distribution





See A. Lapierre, poster #29

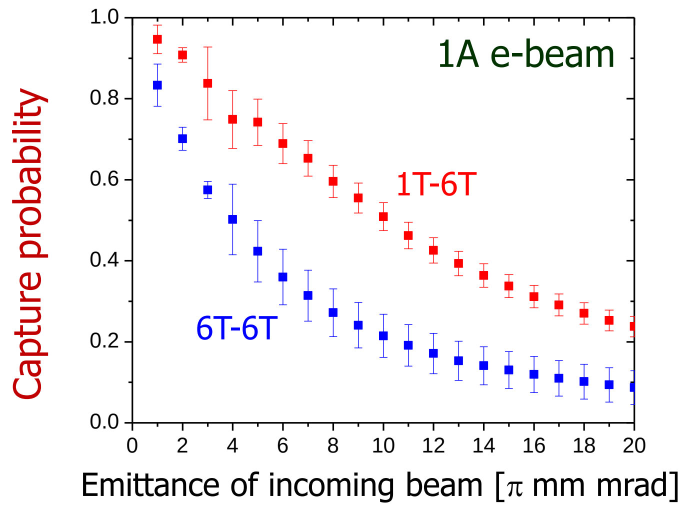
Extended low-field region (solenoid):

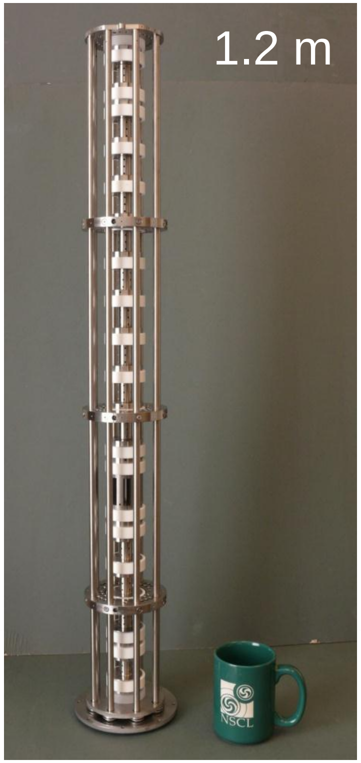
To ionize 1+ ion before a roundtrip: increase e-beam diameter for high electron-ion beam overlap upon injection
→ High capture probability

Short high-field region (Helmholtz coils):

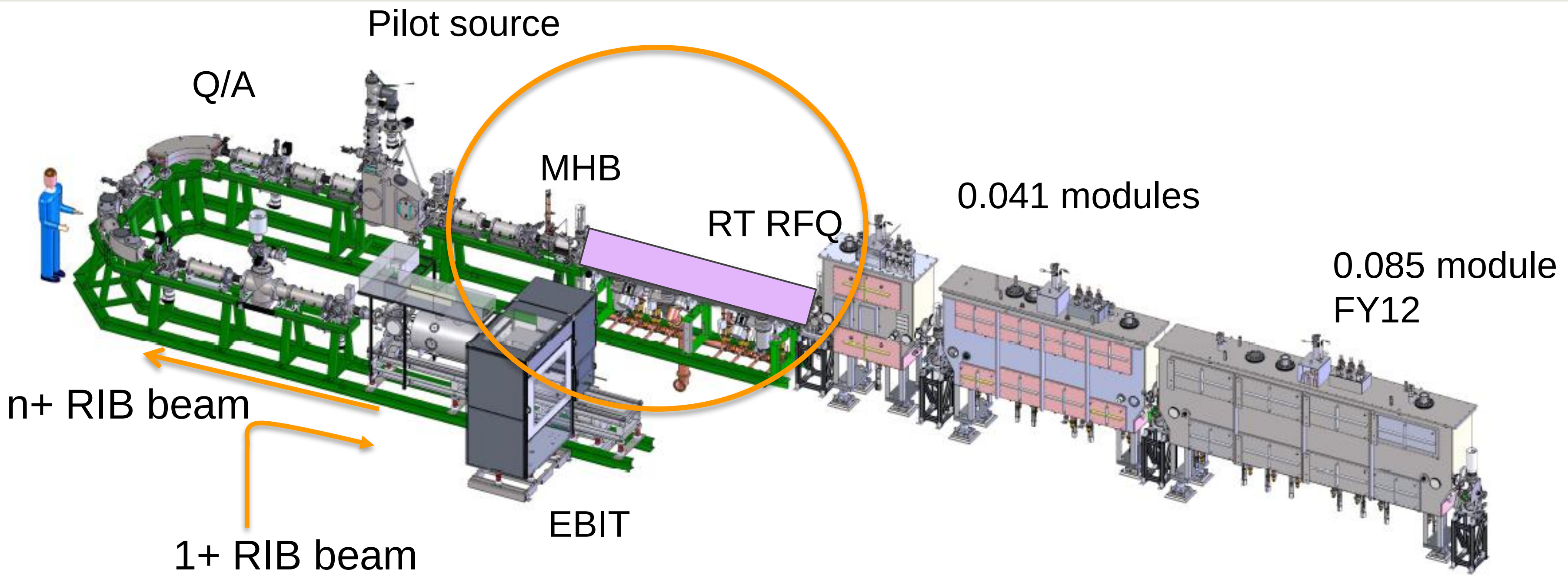
Reduce e-beam diameter for high current density
→ High charge states and fast charge breeding

Simulation of Capture efficiency





ReA Design Choices: MHB+ RT RFQ

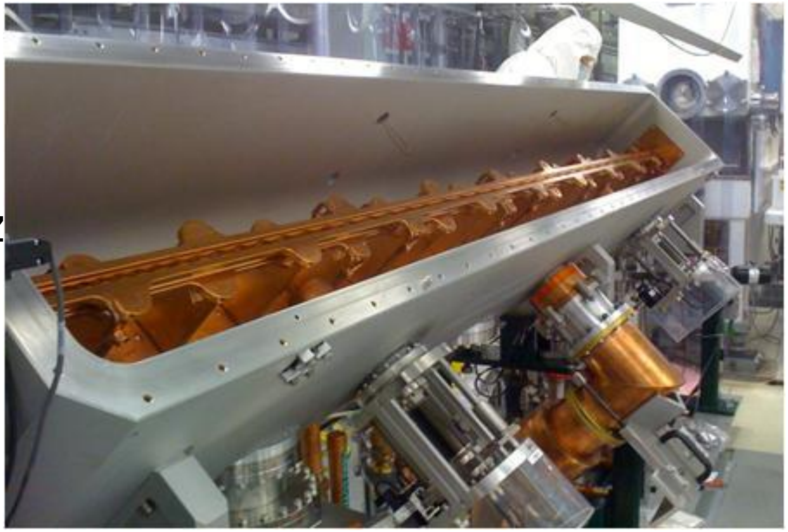


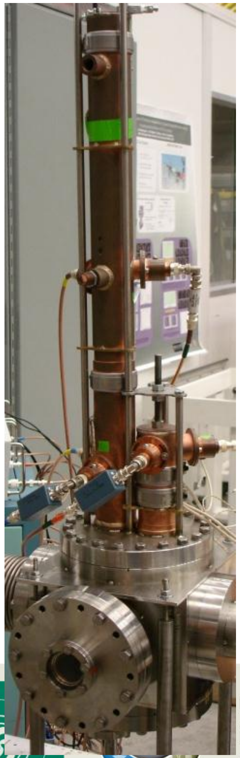
RFQ and Multiharmonic Buncher

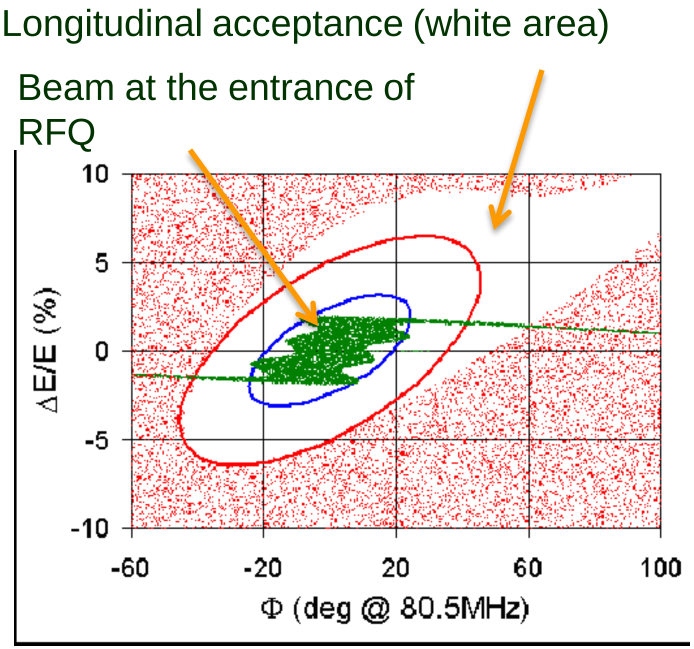
- 80.5 MHz RF frequency
- External bunching to reduce RFQ length and energy spread of the beam
- Compact design relying on high charge states from EBIT (0.5 < Q/A < 0.2)
  (2 < A/Q < 5)

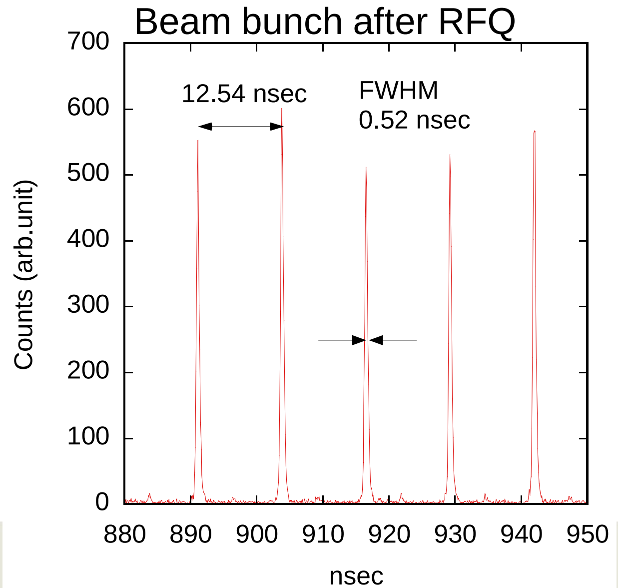
Room Temperature Radio Frequency Quadrupole (RFQ)

– Pulsed operation (160kW, 25%)
– Energy Boost: 12 keV/u - 600 keV/u
– 4-rod structure, 92 cells, 3.3 m long
– Buncher : 80.5MHz, 161MHz, (241.5 MHz
– Nom 82 % beam captured measured
– Beam emittance within specification

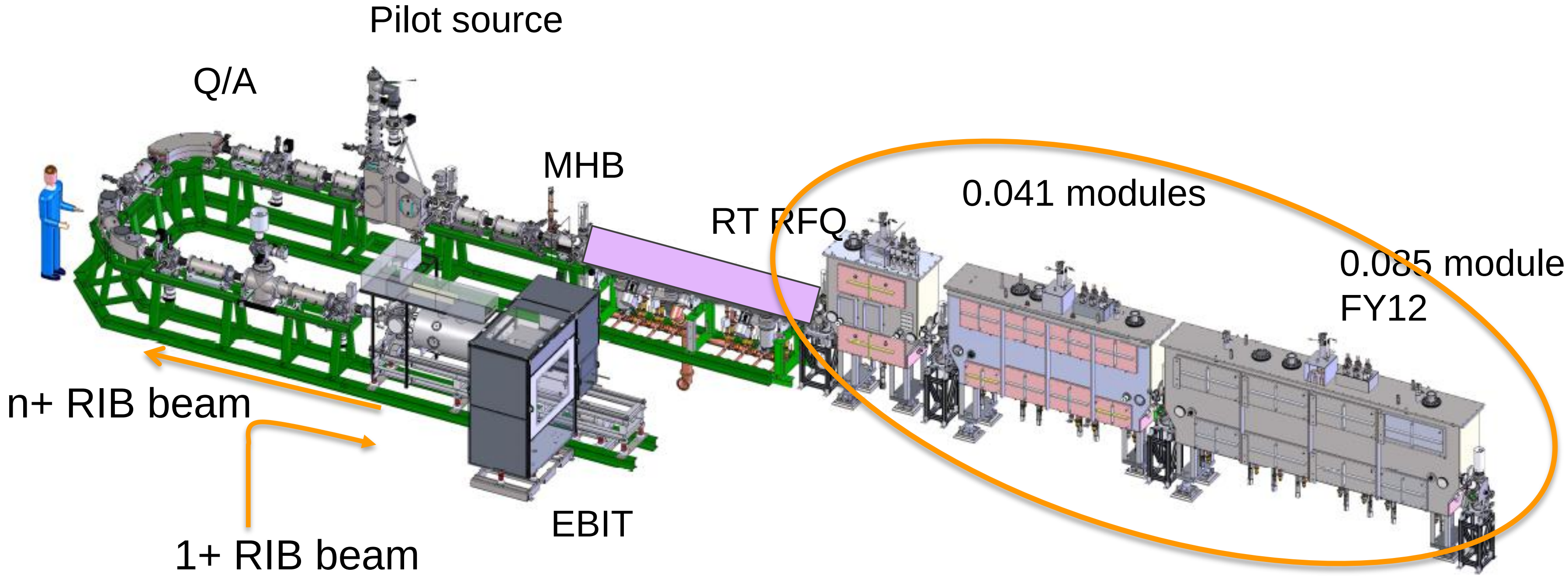








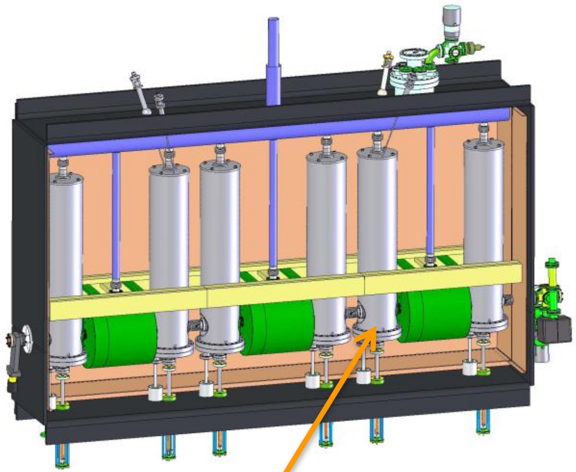
ReA Design Choices: SC-Linac



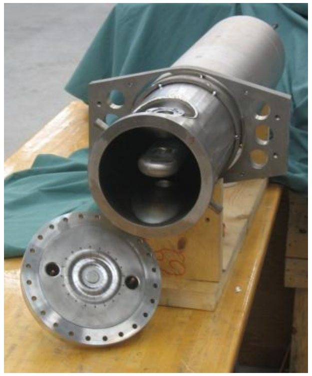
SRF LINAC

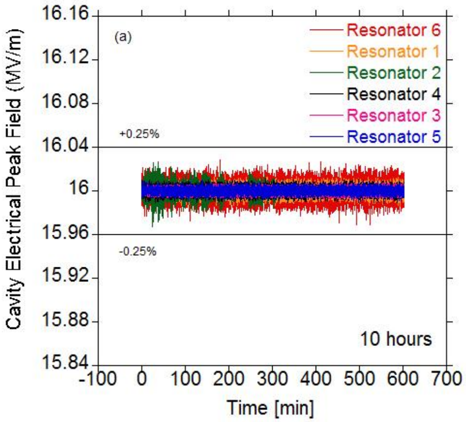
- 80.5 MHz RF frequency
- Flexible energy range (deceleration 300keV/u to maximum linac energy in small steps

Compact superconducting linac with 2 types of quarter wave resonators



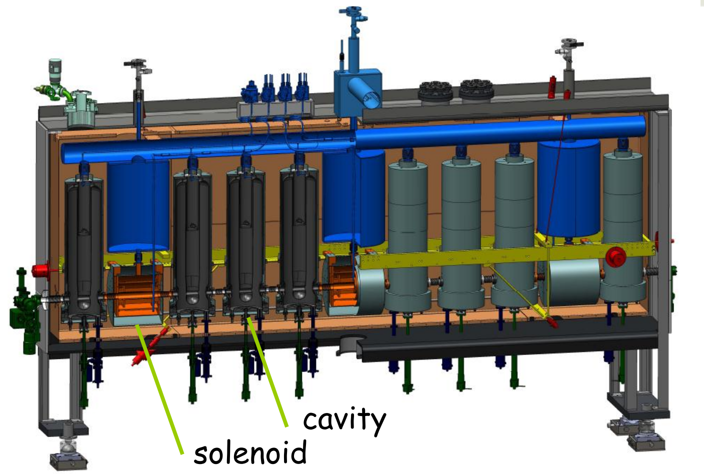
- 7 β=0.041 cavities are in operation since 2010 with excellent performance and stability
- Routinely operated at 160% of the specified gradient





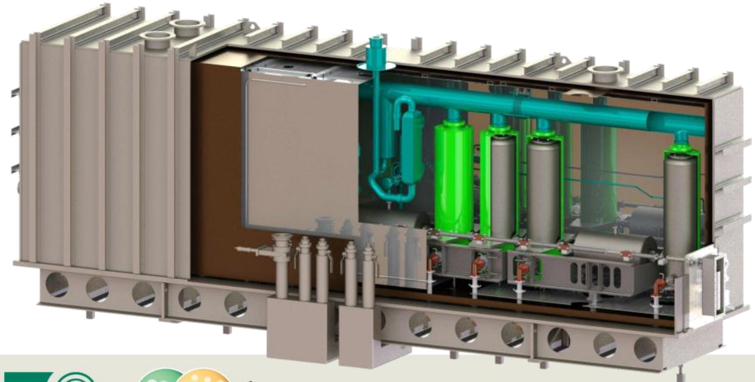
Measured Phase and Amplitude Stability		
Cavity	Phase Std dev (deg)	Amplitude Std dev (%)
82	0.149	0.025 %
84	0.207	0.009 %
85	0.043	0.018 %
88	0.14	0.013 %
89	0.06	0.020 %
91	0.248	0.046 %

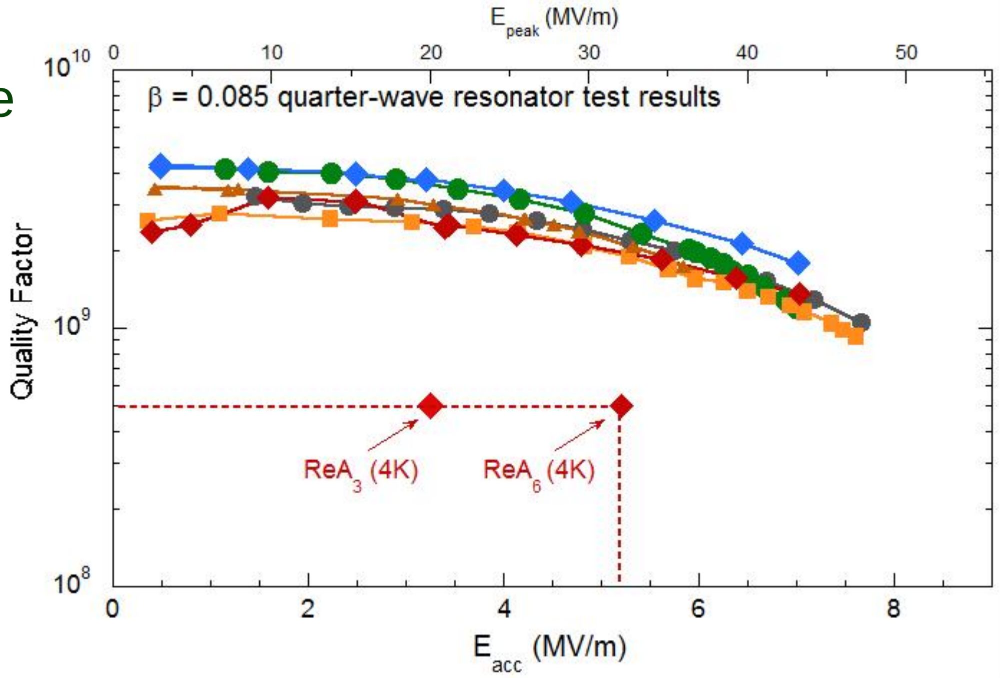
Compact superconducting linac with 2 types of quarter wave resonators



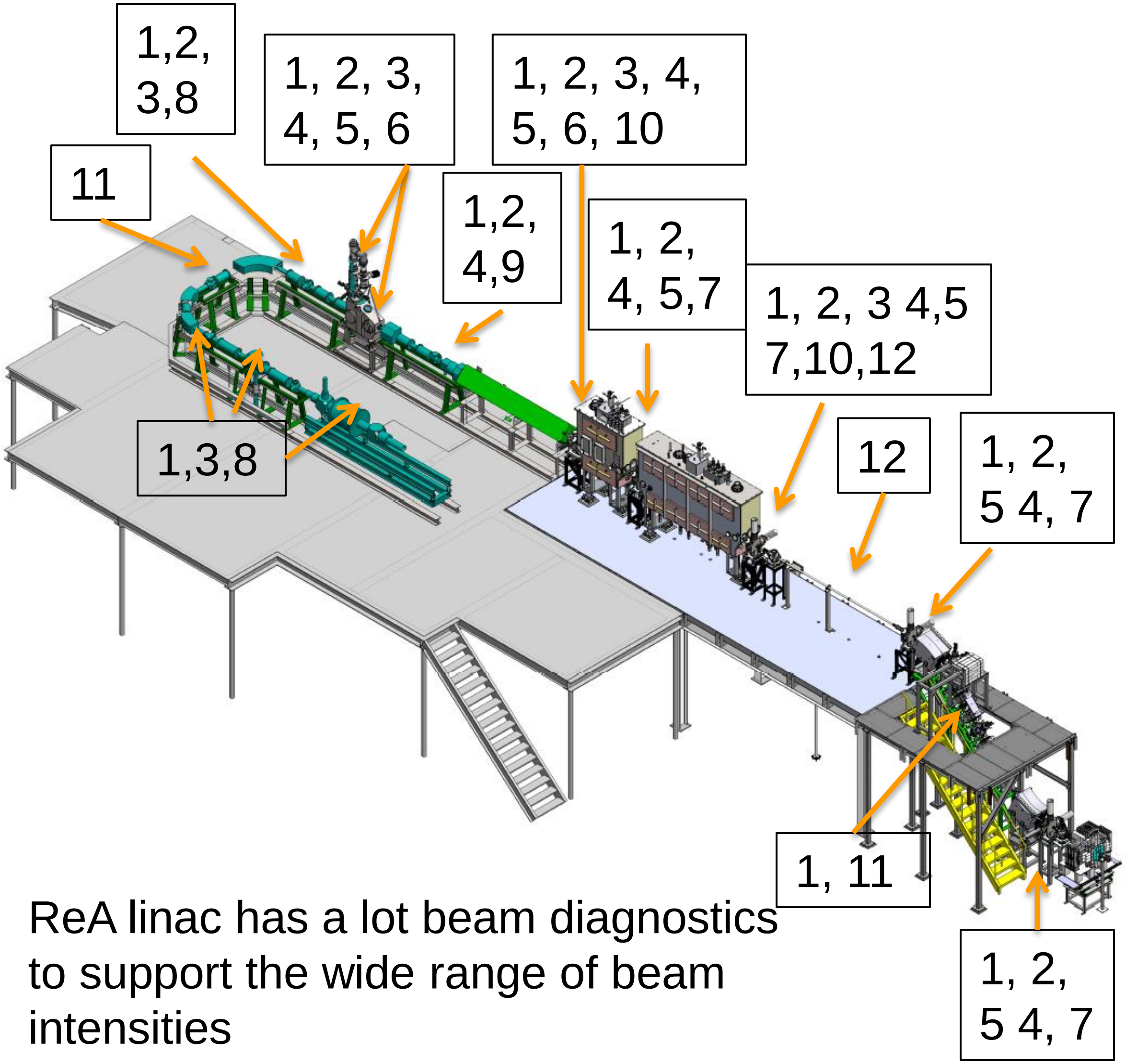
- β=0.085 cavities were redesigned to reliably provide high gradient acceleration fields
- Ten β=0.085 cavities have been completed in November 2012 and are being installed in the final cold mass

- Cryomodule 3 will be installed in the ReAccelerator in April 2013
- Cryomodule 4 under design (2015)





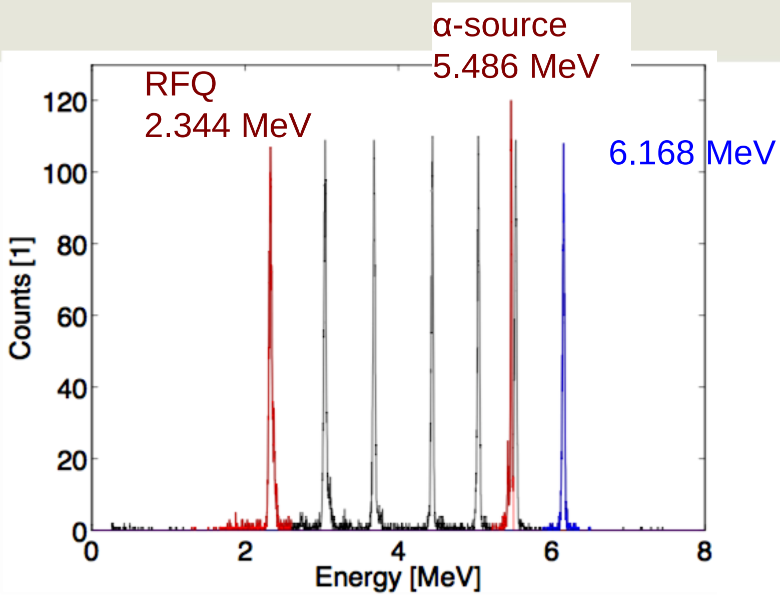
Diagnostic systems are very challenging for RIB post-accelerators (dynamic range 10^2pps to 10^{12}pps)



	Diagnostics
1	FC
2	Slit profile monitor
3	Viewer, MCP or crystals
4	Bunch lengths, timing
5	Slits, aperture
6	Attenuators
7	Detectors (decay, scattering, in beam)
8	MCP, TOF
9	Pepperpot
10	Emittance Scanner
11	Energy defining slits
12	BPM

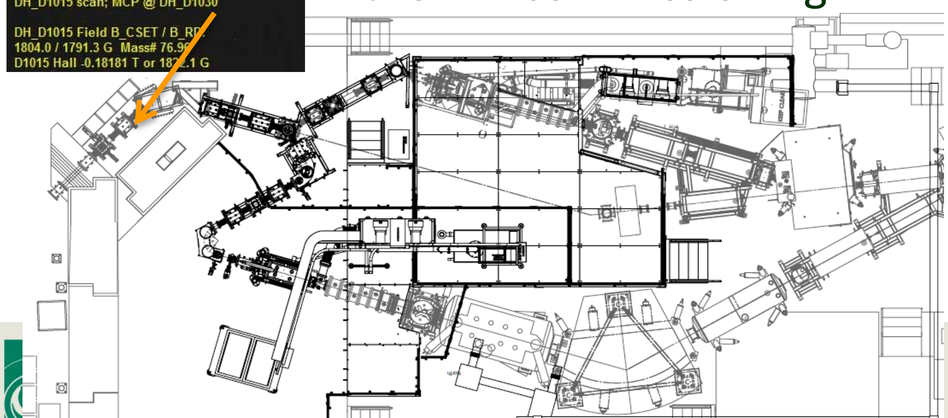
ReA linac has a lot beam diagnostics to support the wide range of beam intensities

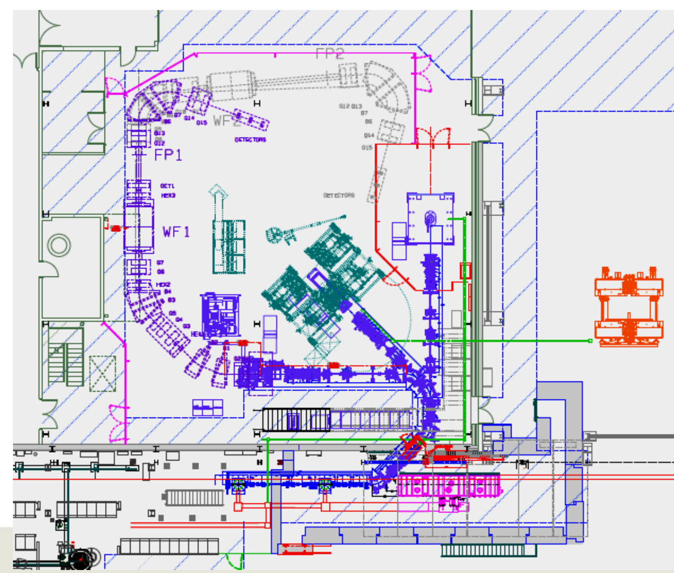
Re-accelerator Commissioning Status



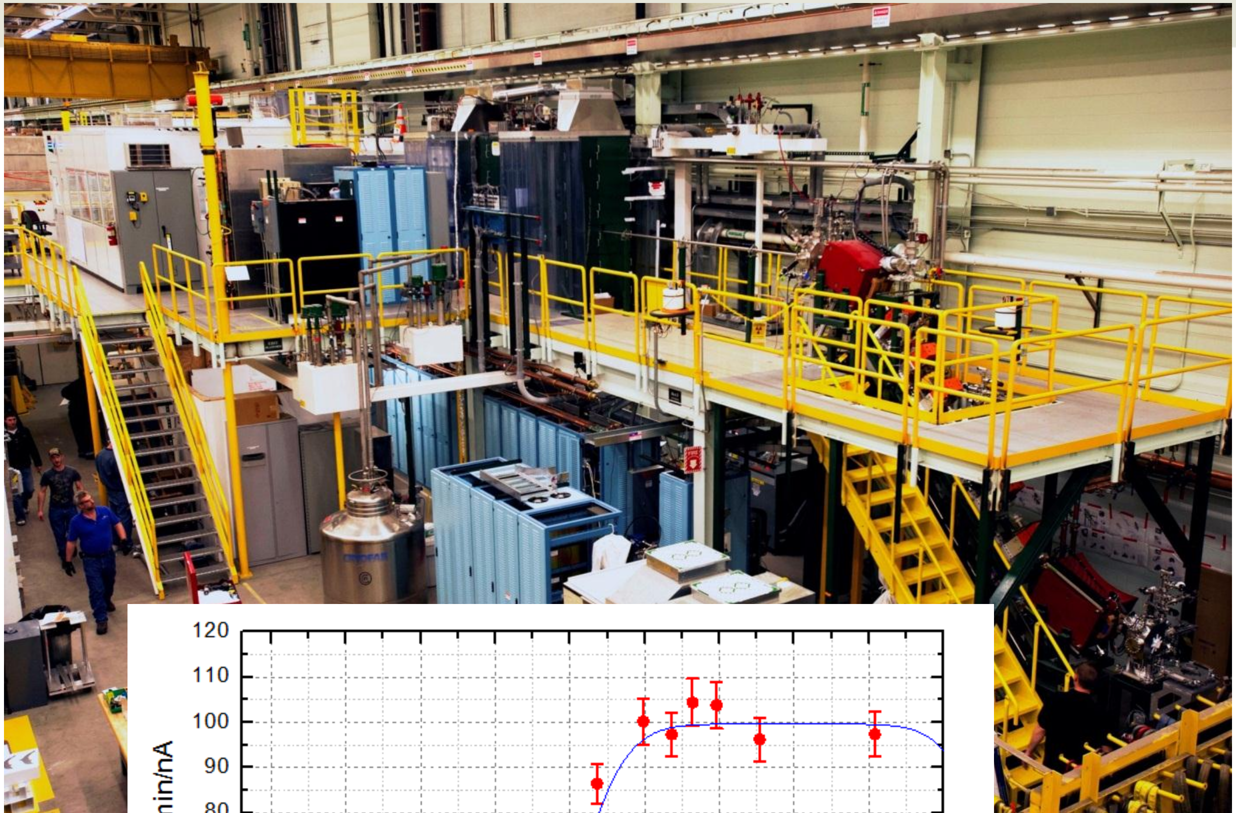
- Beam acceleration through the SRF LINAC using the pilot source has been established as routine operation (H_2, He)
- First 1+/n+ acceleration has been demonstrated with the EBIT source (K^{1+} / K^{16+})
- Next Step: Radioactive ion beam injection…
- Completion of the experimental hall

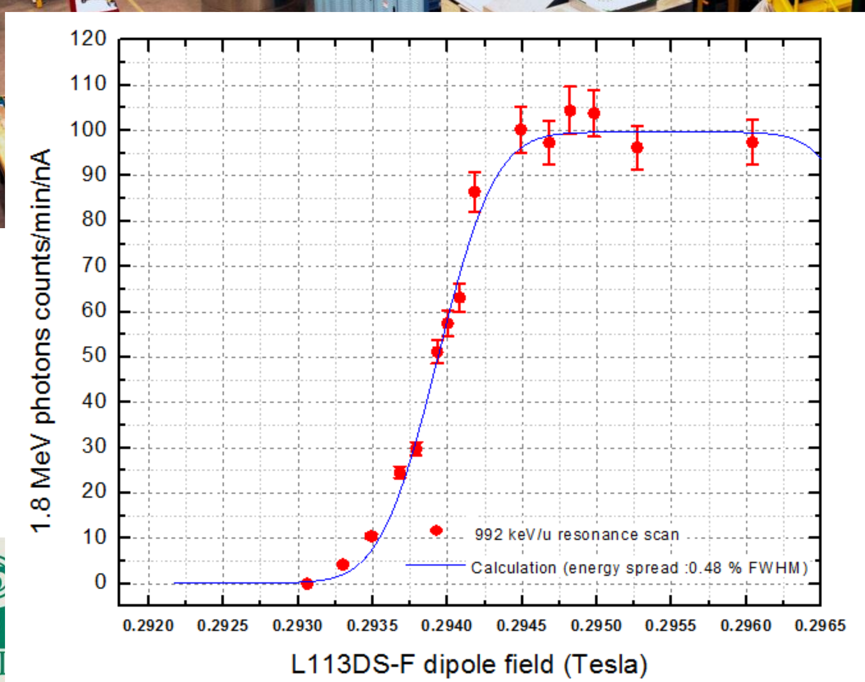
Beam image after N4 analyzing magnet during the RIB commissioning



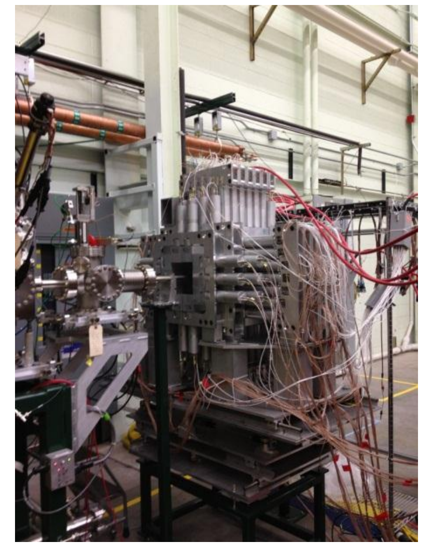


Commissioning Status





CAESAR detector



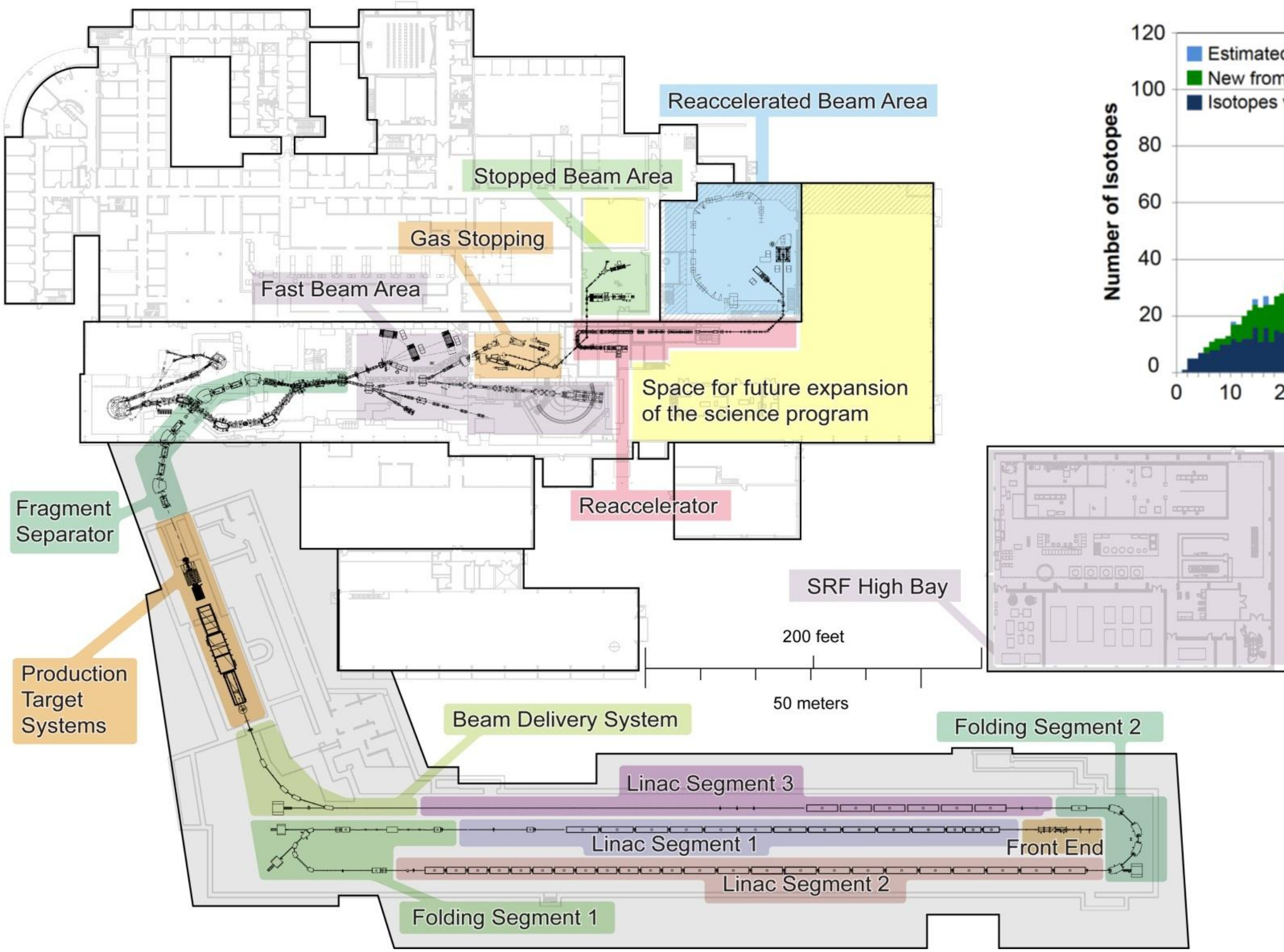
Absolute energy calibration of ReA using 992 keV Al(p,γ) resonance

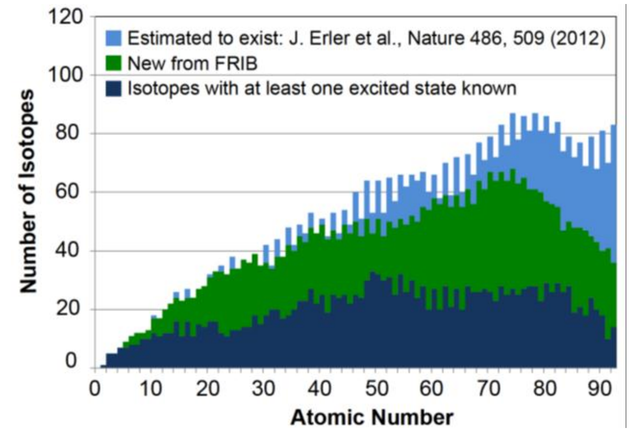
Energy spread is close to predicted value

Summary

- RIB post accelerator are heavy ion accelerator, but come with special requirements/challenges
  - Solution needs to be tailored to the user needs and production facility capability
- ReA is built on the experience of existing post accelerator
  - Commissioning is progressing well, beams below or close to the Coulomb barrier will completed 2013
  - First radioactive ion beam injection is planned in the next few weeks
  - The first energy upgrade for beam energies above the Coulomb barrier is in progress (2015)
- ReA is looking for postdocs to join, and also welcomes collaboration in all forms

When FRIB Driver Becomes Operational the Existing Experimental Areas and ReA will be connected to the FRIB fragment separator





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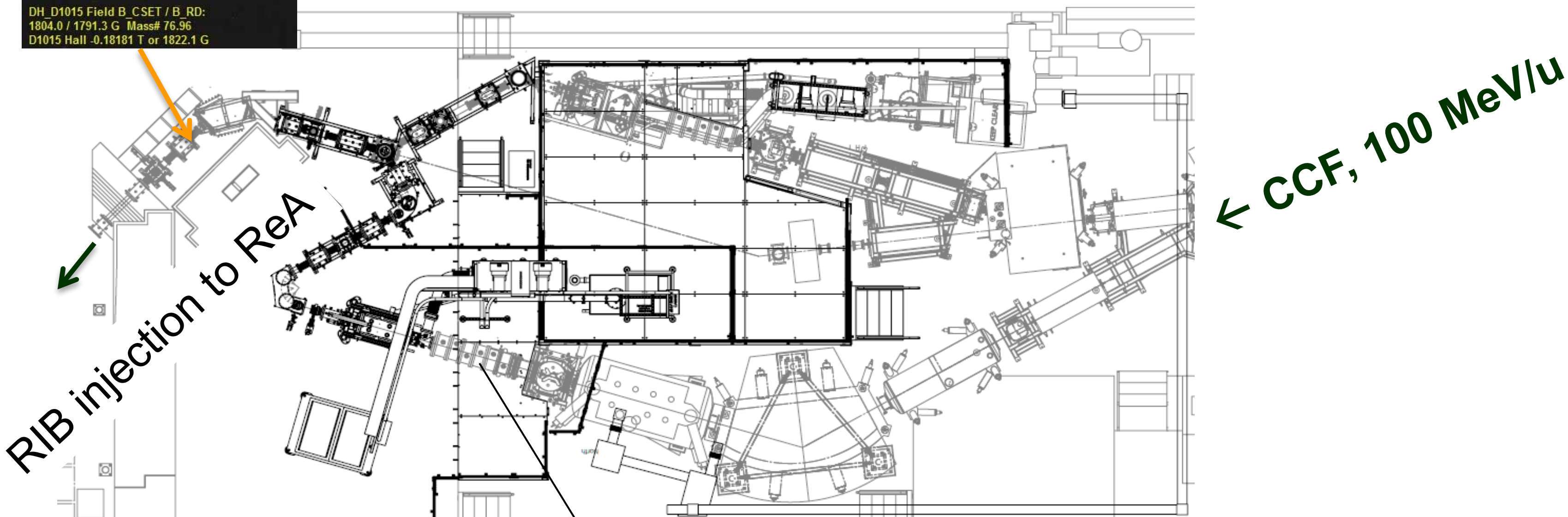
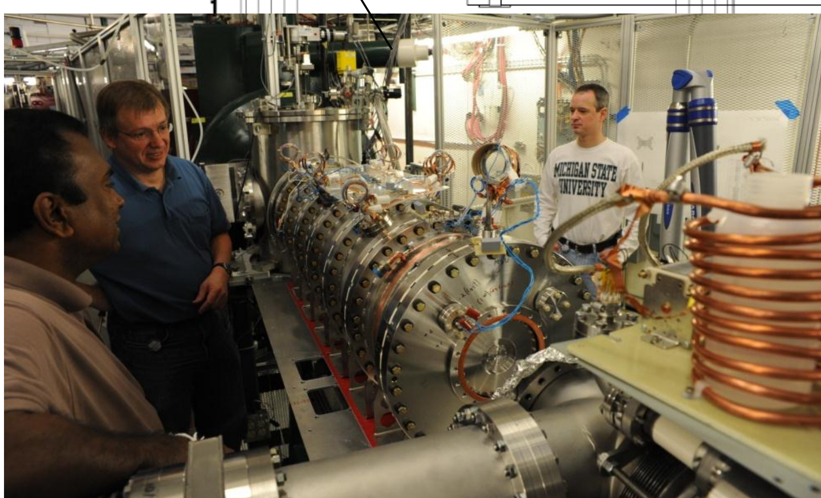
Commissioning Status: Stopped Beam Area

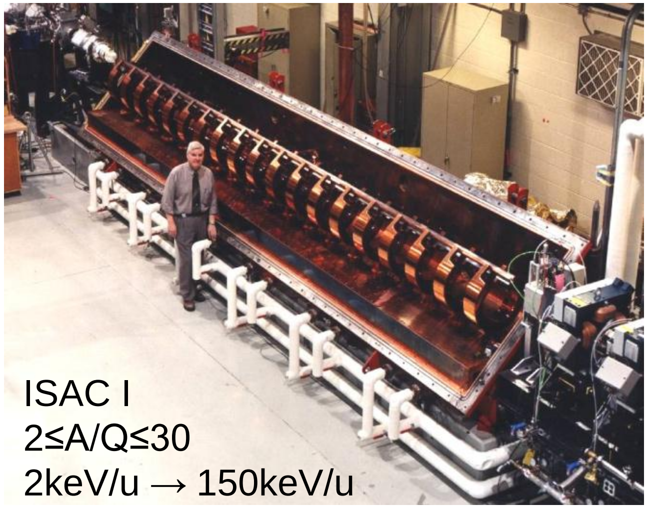
Beam image after N4 analyzing magnet during the RIB commissioning





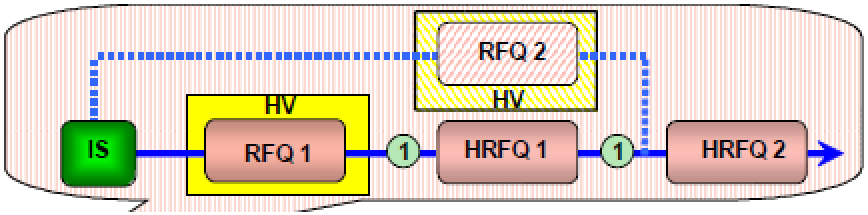
ANL gas stopper (FRIB R&D)
Delivered May 2012
Commissioning runs started 10/2012 using ^{76}Ga

Challenge: Accelerate all ions efficiently starting from thermal beams



- **Linac structures** have a **lower limit for injection energies**(focusing and cell size limit)
- **RFQ** utilize quadrupole channel (focusing) with axial modulation (acceleration). Heavy ions requires **low frequency (implies large size)** to keep to a reasonable lengths of acceleration cell ($\beta\lambda$) and quadrupole aperture size (limits A/Q range),
- Similarly cyclotrons have a limited A/Q range, wide energy range is more difficult to achieve

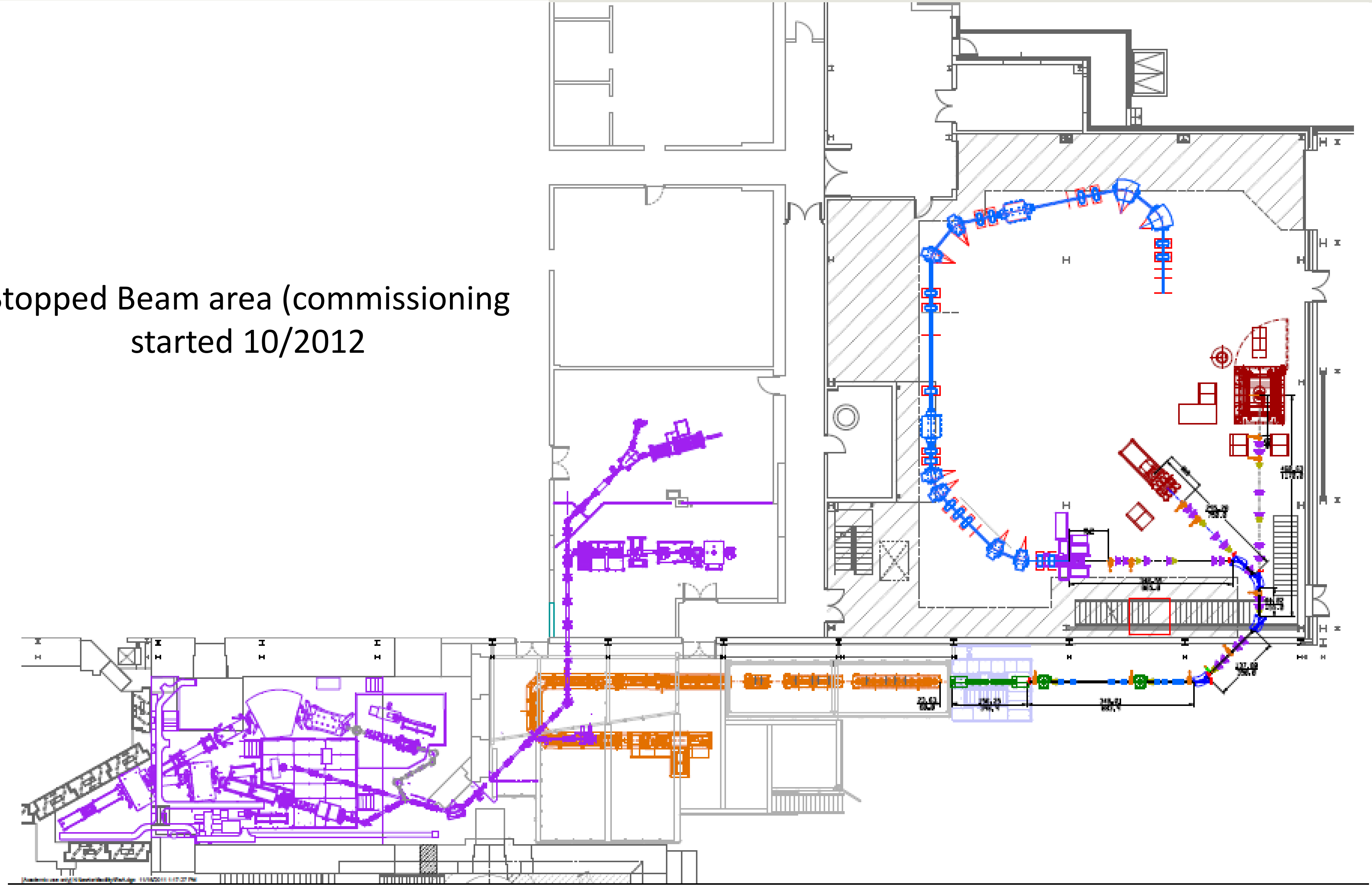
High charge state ions (CB) are needed to provide flexible mass and energy range (or complex RFQ chains with charge stripping in between)



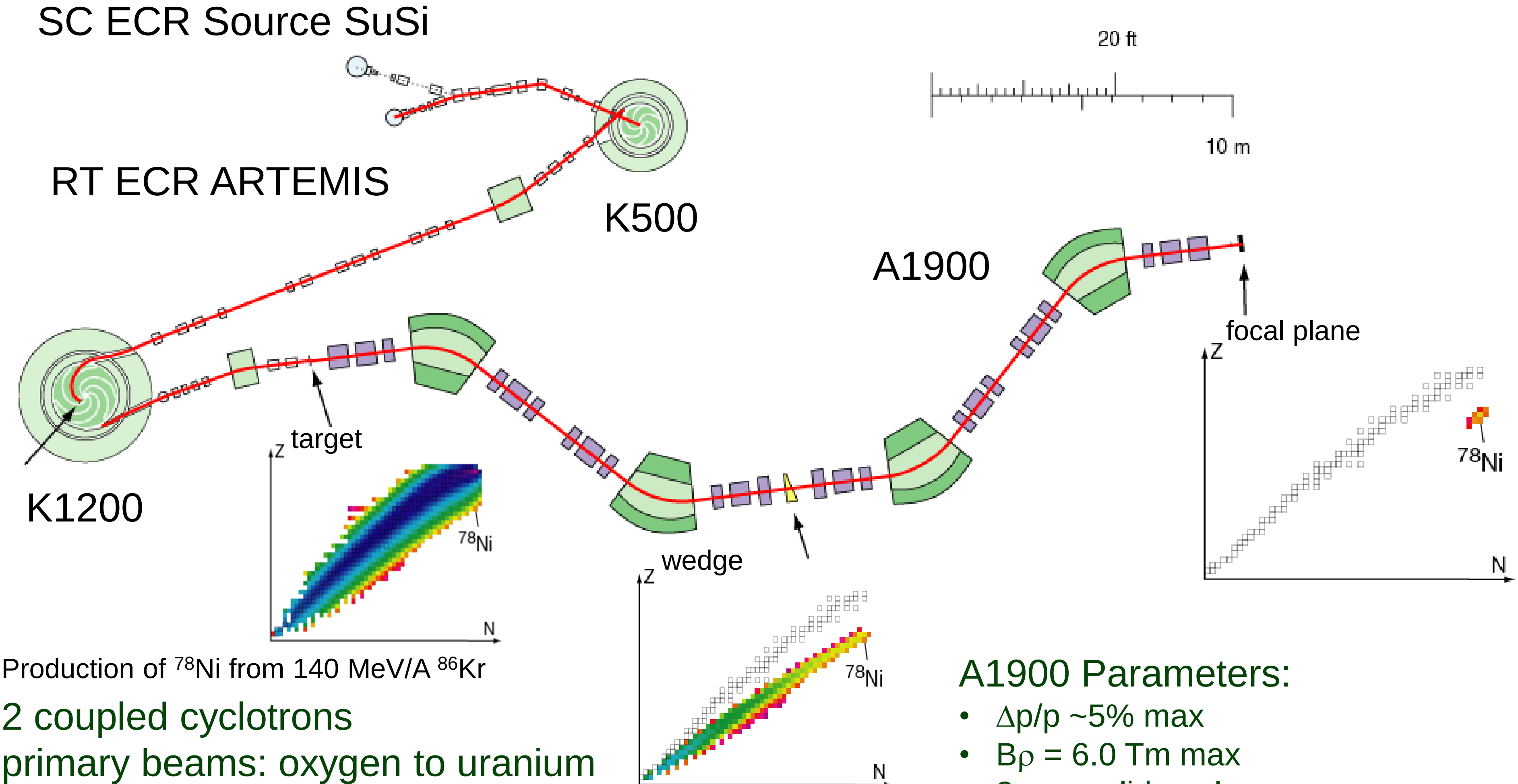
P.N. Ostroumov, PAC2005

ReA at the Coupled Cyclotron Facility (2012)

Stopped Beam area (commissioning started 10/2012



Rare Isotope Beam Production



Production of ^{78}Ni from 140 MeV/A ^{86}Kr

2 coupled cyclotrons

primary beams: oxygen to uranium

K500: 8 - 12 MeV/u, 2-8 eμA

K1200: 100 - 160 MeV/u, up to 2 kW

A1900 Parameters:

- $\Delta p/p$ ~5% max
- $B\rho$ = 6.0 Tm max
- 8 msr solid angle
- 35 m in length

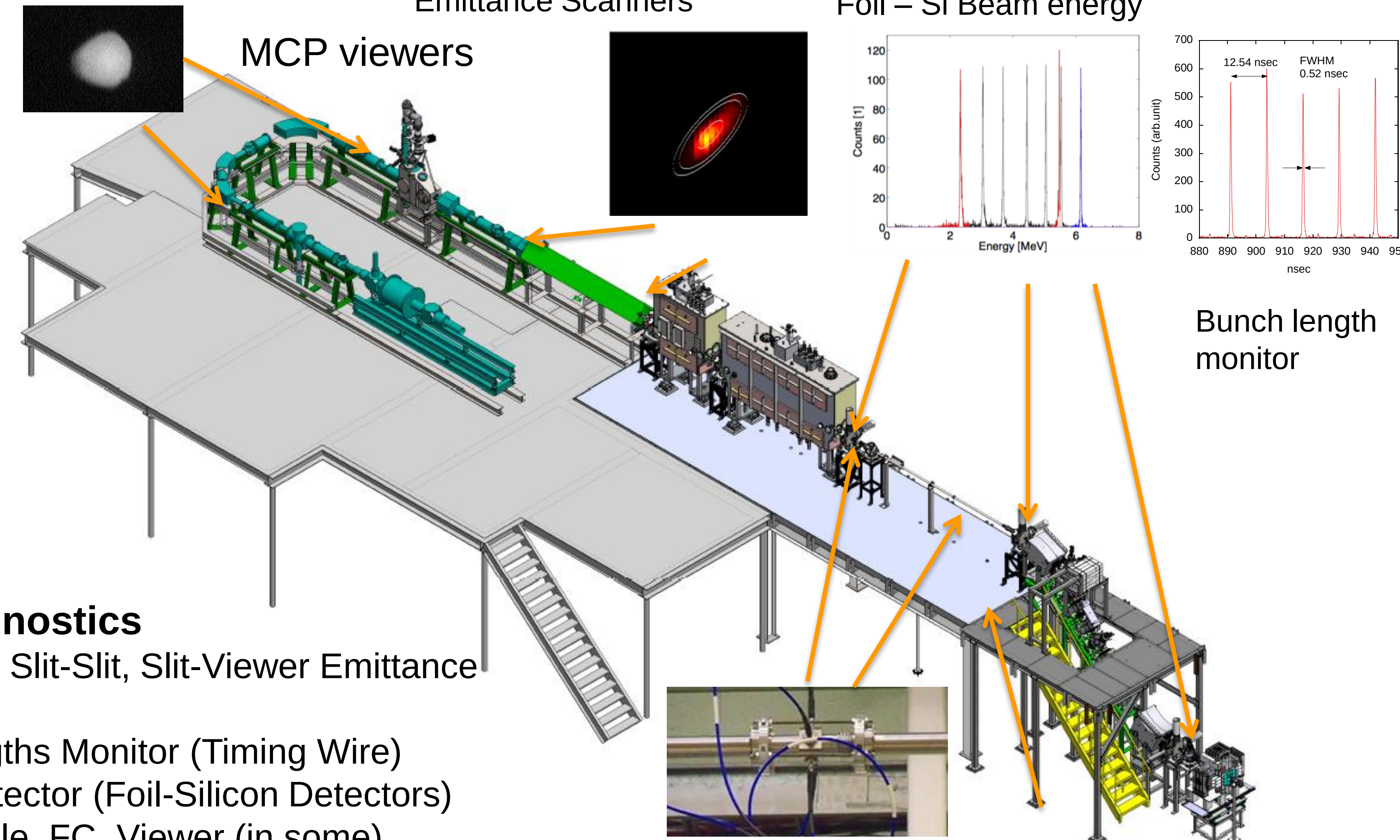
Morrissey *et al.*, NIM B 204, 90 (2003)

ReA Offline test ion source and LINAC is well equipped to benchmark XAL model [2]

Emittance Scanners

Foil – Si Beam energy

MCP viewers



Bunch length monitor

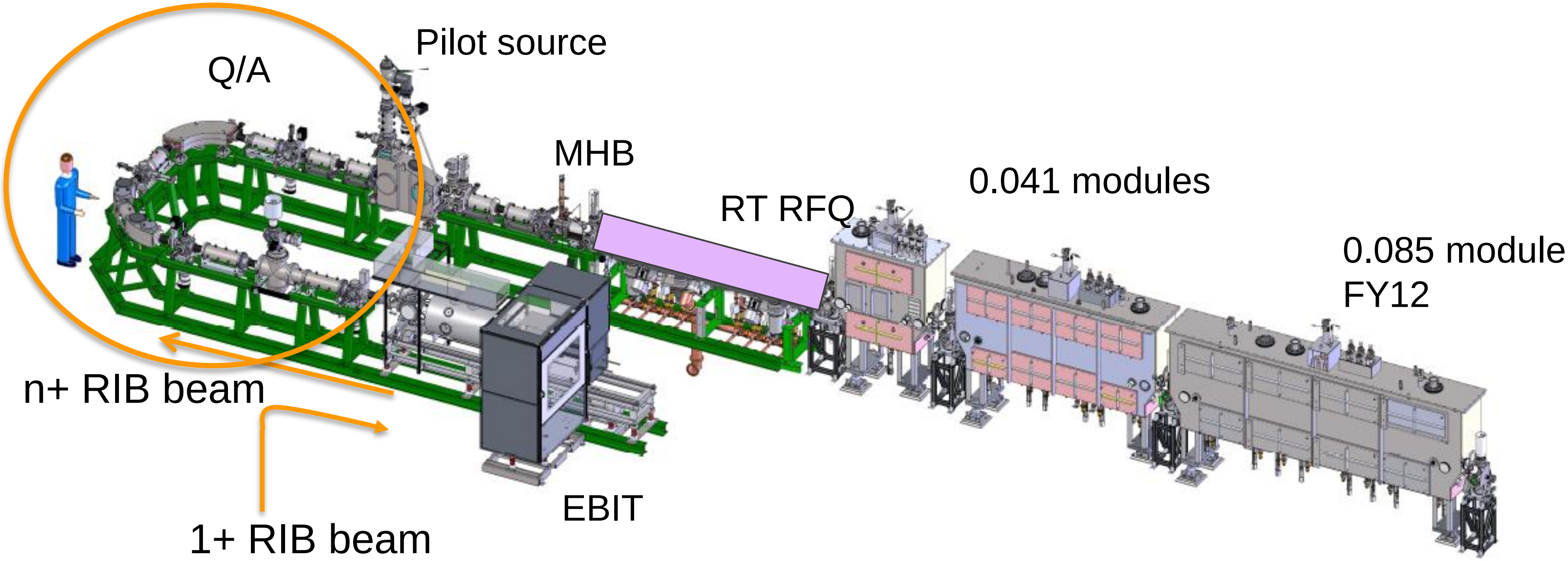
ReA Diagnostics

Pepperpot, Slit-Slit, Slit-Viewer Emittance Scanners
Bunch lengths Monitor (Timing Wire)
Energy Detector (Foil-Silicon Detectors)
Beam Profile, FC, Viewer (in some)
FRIB BPM test installation (will be adapted for use permanently in ReA)

FRIB BPM test installation

Achromatic section with energy resolving slits

ReA Design Choices: A/Q Mass Separator



Achromatic Mass Separator:

- Resolving power ~100 at 120 π mm mrad
- Achromatic within $\Delta E/E$ ~ 3%
- Accept EBIT beams of large energy spread
- Commissioned 2010