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Complementarity of New RNB Facilities and Their Technological Challenges

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Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Science goals drive technological developments for ever more capable radioactive beam facilities

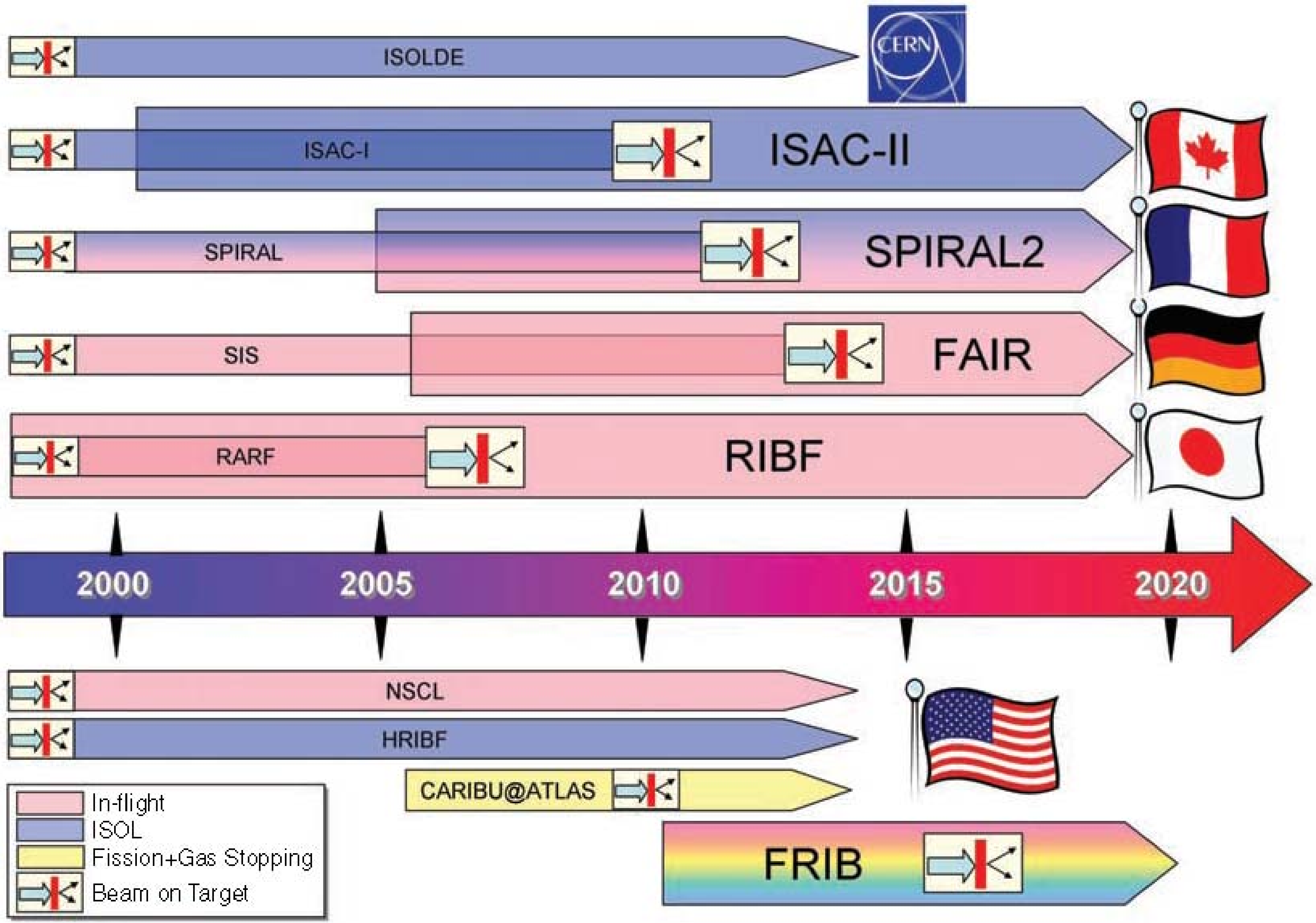
- Pushing the intensity frontier is a very high priority
- Physics requires beams are needed at a wide range of energies
- Some research demands very high quality reaccelerated beams
- Some research demands the most exotic beams even at the expense of intensity or quality
- Some research demands specific radioactive beam species even if they are refractory or chemically active

- **No single facility can fulfill all these needs**
- **A wide variety of techniques and technologies are required**

Isotope production reaction mechanisms

- **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
  - Can use a "2-step" neutron-generator method
- **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 ^{18}O, ^{82}Kr, & ^{238}U at 200-2000 MeV/u; typical targets Be or C
- **Niche mechanisms:**
  - **Low energy, ~Coulomb barrier, heavy ion fusion**
    - *Can produce isotopes at the proton drip line, e.g. ^{100}Sn*
    - *Synthesis of new elements has used this mechanism*
  - **Deep inelastic collisions**
    - *Beam energies somewhat above the Coulomb barrier*
    - *Produces rare isotopes that are more neutron-rich than the beam*
  - **Spontaneous fission – produces unqiue species of fission products**

World-wide facilities – from the U.S. National Academies' report



Next-generation facilities in the works or being proposed (driver beam power ≳ 50 kW)

- ISAC at TRIUMF in Vancouver, Canada
  - Operating
- RIBF at RIKEN in Waco, Japan
  - Operating
- SPIRAL2 at GANIL in Caen, France
  - Under construction
- FAIR at GSI in Darmstadt, Germany
  - Under construction
- FRIB in the U.S.
  - Project initiated at MSU in 2009
- EURISOL in Europe
  - Concept development phase; Design Study complete 2009

Important developments are also associated with several lower power projects

- E.g.: SPES; EXCYT; CARIBU; HIE-ISOLDE; Texas A&M RIB upgrade; Gas-filled and vacuum separators at RIKEN, the LBNL 88” cyclotron, Jyväskylä, GSI, HRIBF, and ATLAS; storage rings for radioactive fragments ESR at GSI and CSR at HIRFL/Lanzhou

- ~30-40% of the papers at this conference are related to technology development to improve radioactive beam facilities or techniques

Complementarity (1): ISOL

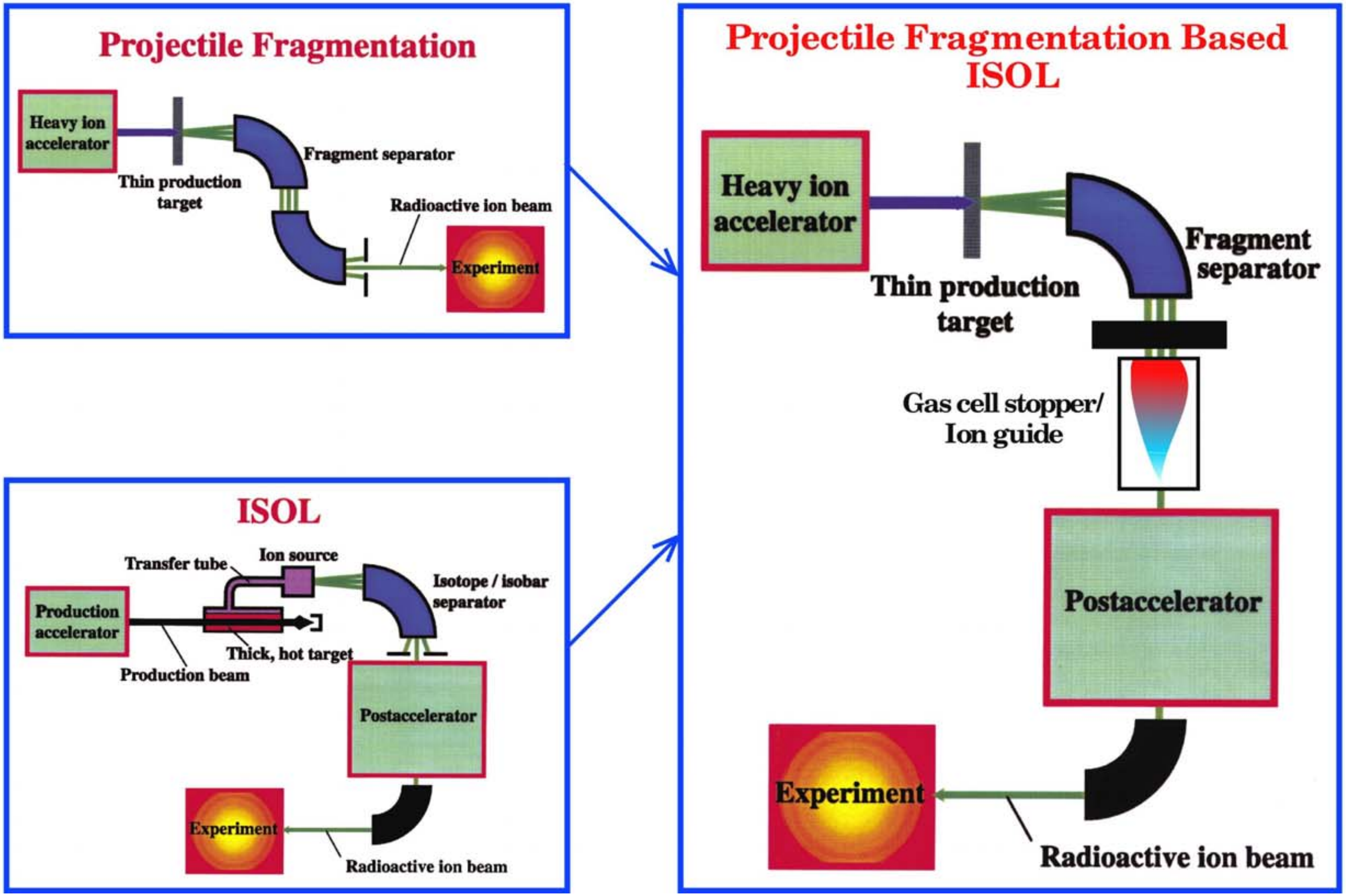
- Light-ion induced spallation and fission
- Very intense beams of many elements, especially noble gases and alkalis
  - Very useful for stopped beams: atom & ion traps and co-linear laser spectroscopy
  - Intense reaccelerated beams with excellent beam quality for detailed reaction and structure studies with rare isotopes including heavy and possibly superheavy elements
- Weak beams of refractory and chemically active elements

Complementarity (2): Fragmentation

- Heavy ion induced in-flight fragmentation or fission
- Provides in-flight beams at high energies
  - Separated beams of any species including refractory and chemically active elements and isotopes with very short half-lives, even isomers
  - Lower quality secondary beams due to kinematic energy spread and divergences
  - High luminosity and excellent particle ID due to high energies and thick targets
- Provides stopped and reaccelerated beams
  - "New paradigm" with helium gas catcher
    - *Fast and efficient extraction of all elements except He*
    - *High quality beams, but intensity limits*
  - Intense beams from solid catchers in special cases, e.g. ^{15}O

Rare Isotope Production Schemes

- Fast Extraction Times (~msec)
- Chemical independence
- Isobar separation



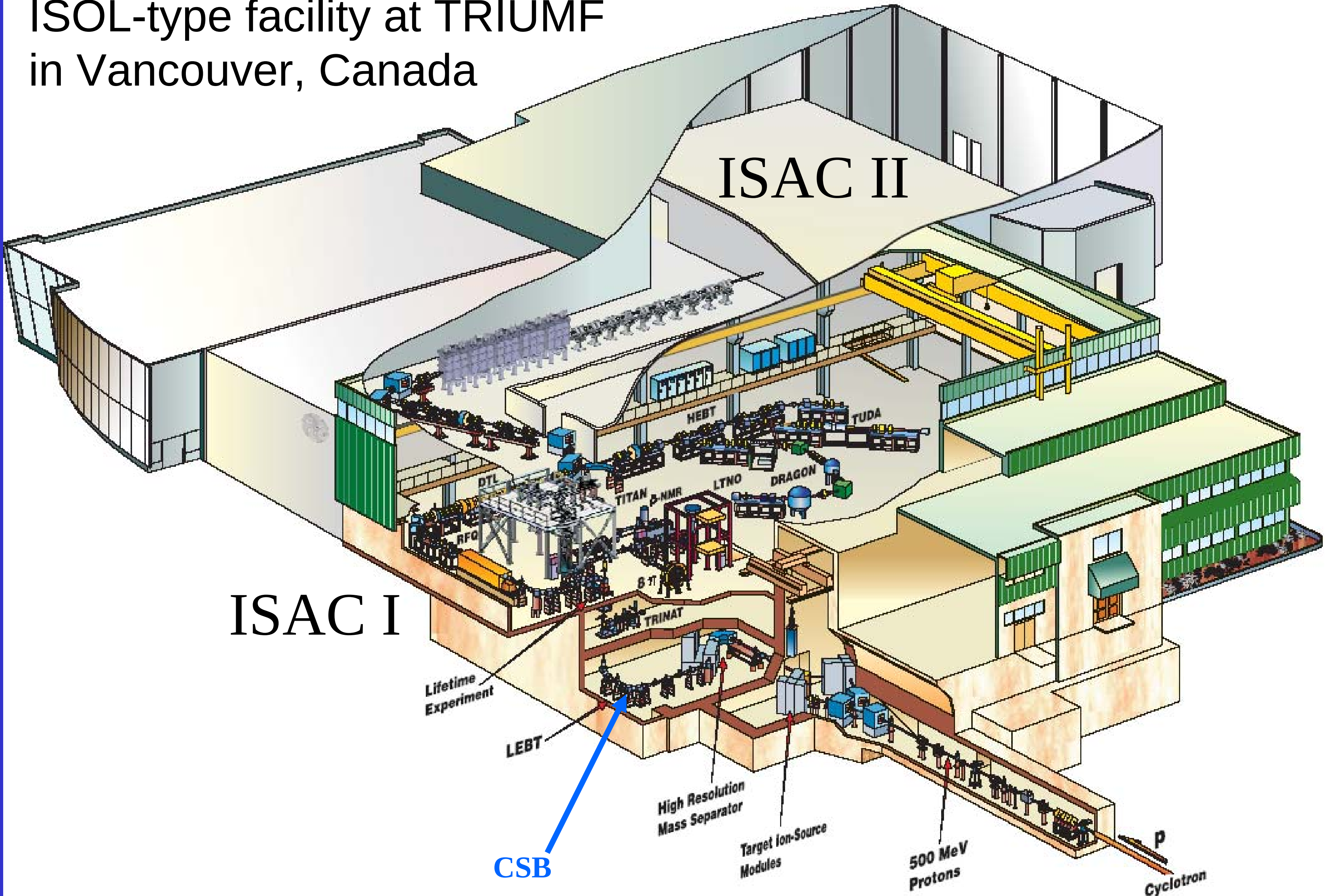
Heavy ion drivers: advantages and limitations

- Synchrotrons such as the GSI FAIR facility
  - The least expensive path to high energies, over 1 GeV/u heavy ions
  - Space charge limits intensities due to pulsed beam structure
  - Pulsed beam structure is ideal for injecting storage rings for internal beam physics
  - Pulsed beam structure leads to difficult target technology
  - Well suited to pulse-to-pulse beam species and energy switching
- CW cyclotrons such as RIKEN
  - Less expensive than superconducting linacs up to a few 100 MeV/u heavy ions
  - Space charge limit is low due to lack of longitudinal focusing of internal beam
  - Acceptance is low, making multiple charge state acceleration impossible, thereby further limiting intensity
- CW superconducting linacs such as FRIB
  - Relatively expensive per volt of acceleration
  - Very large transverse and longitudinal acceptance: enables multi-q beams, high intensities, and a wide range of ion species
- FFAG: new ideas being developed, applicability and cost factors currently unknown

Complementarity (3): other methods

- Heavy ion fusion
  - Not traditionally considered for RIB facilities, but intensities up to 100 pμamps (SPIRAL2) open new possibilities
    - *"^{100}Sn factory" – yields in the 1-10 ions per second*
    - *Detailed studies of separated heavy and superheavy elements*
    - *Decay spectroscopy, studies in atom/ion traps, chemistry following separation*
- Spontaneous fission plus gas catcher (CARIBU, ^{252}Cf)
  - Good yields of species not populated by U fission
  - Many refractory species well suited to the gas catcher

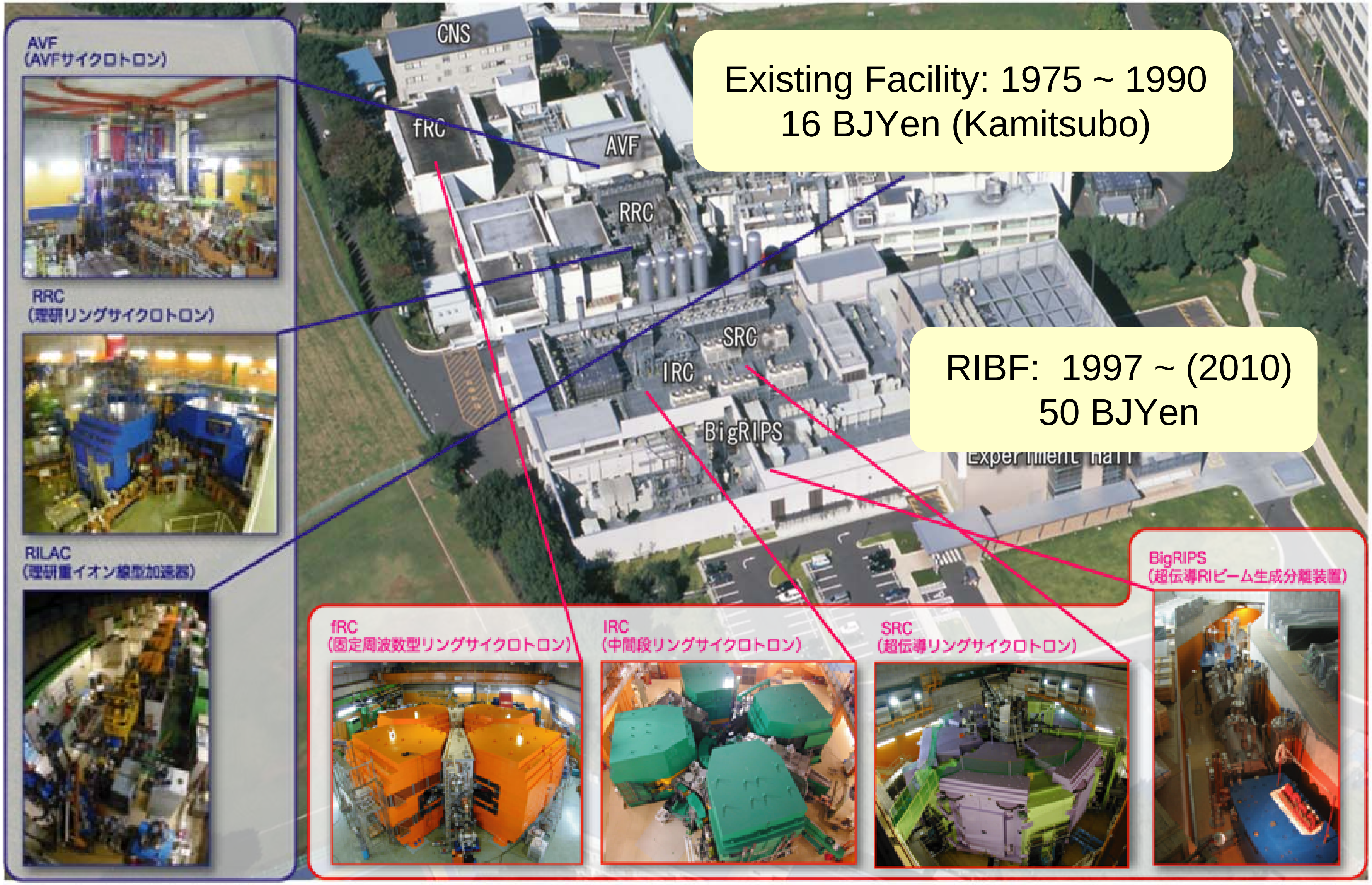
ISOL-type facility at TRIUMF in Vancouver, Canada



Some technological challenges for ISAC-II

- Upgrade for high intensity actinide targets
  - On-going series of tests to document degree of radiological migration/contamination to determine intensity limits
  - Planning a high power photo-fission option with new electron-beam driver
- Broaden the variety of RIBs
  - On-going development of the ion source portfolio
    - *Recently implemented FEBIAD source*
    - *New laser resonance ionization source*
    - *Developing ECR-based 1+ ISOL source*

RIKEN RI Beam Factory (RIBF), Nishina Center, Japan

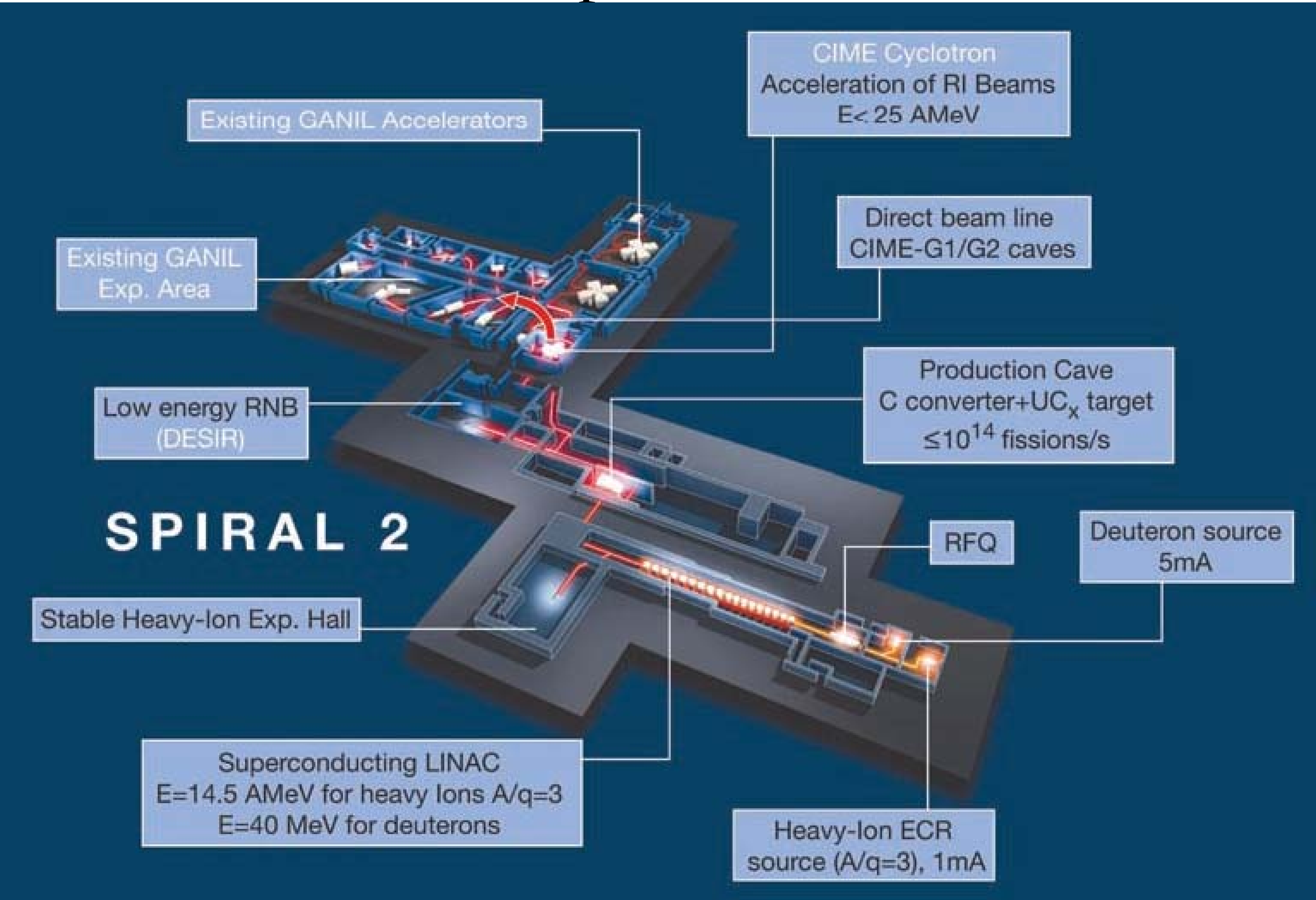


Prof. Y. Yano, CAARI, 2006

Some technological challenges for RIKEN

- Improving transmission efficiencies
  - See papers Mo 10 & 11
- On-going development of strippers, especially for uranium beam
  - Includes possible test of liquid lithium stripper in collaboration with Argonne and MSU
  - Recently developed gas stripper that works well for beams with Z ~ Xe and lower
- Reconfiguring injection scheme with new linac to enable independent superheavy element program
- Commissioning new SC ECR ion source to increase uranium beam intensity

GANIL Spiral 2, France

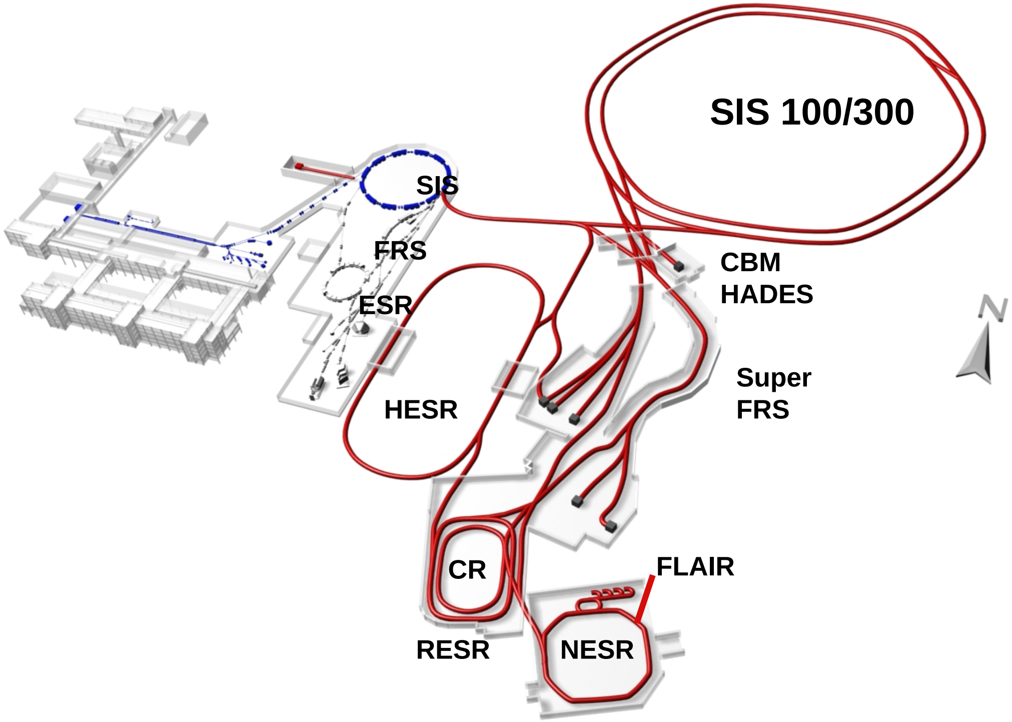


Some technological challenges for SPIRAL-2

- Developing concept for q/m = 1/6 injector to increase intensities expected for heavier beams over those currently expected with 1/3 injector
- Investigating concepts for the neutron converter for use with 200-kW deuteron beams
  - Testing rotating carbon wheels (Legnaro and Novosibirsk)
  - Considering heavy water convertor with aluminum windows
- Developing plan for cost effective implementation of the high power ISOL target area
  - See papers Mo 13 and F 1

International FAIR Project: Germany

Ground breaking was 11/2007!



Primary Beams

- 10^{12}/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- Factor 100-**1000** over present intensity
- 2(4)x10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{92+}$ up to 35 GeV/u
- up to 90 GeV protons

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor **10 000** in intensity over present
- Antiprotons 0 - 15 GeV

Storage and Cooler Rings

- Radioactive beams
- e^- – A (or Antiproton-A) collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons
- Polarized antiprotons(**?**)

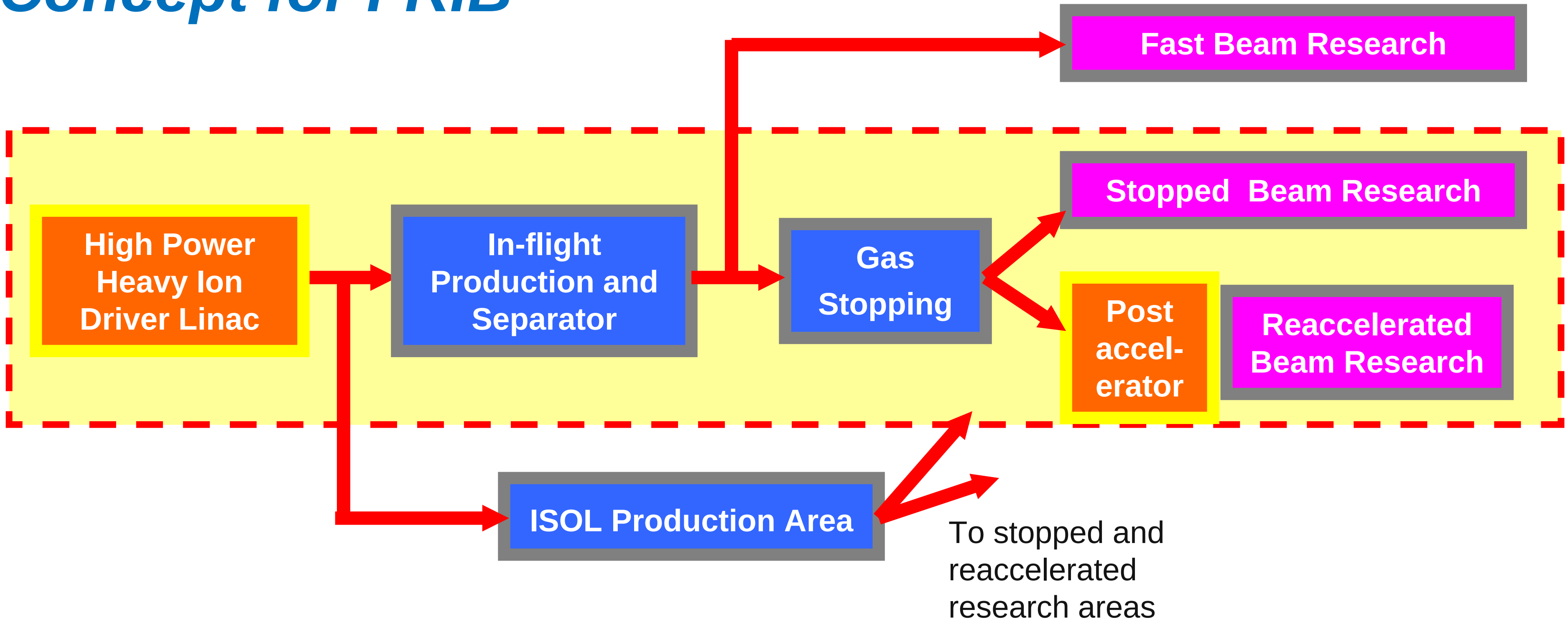
Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets

Some technological challenges for FAIR

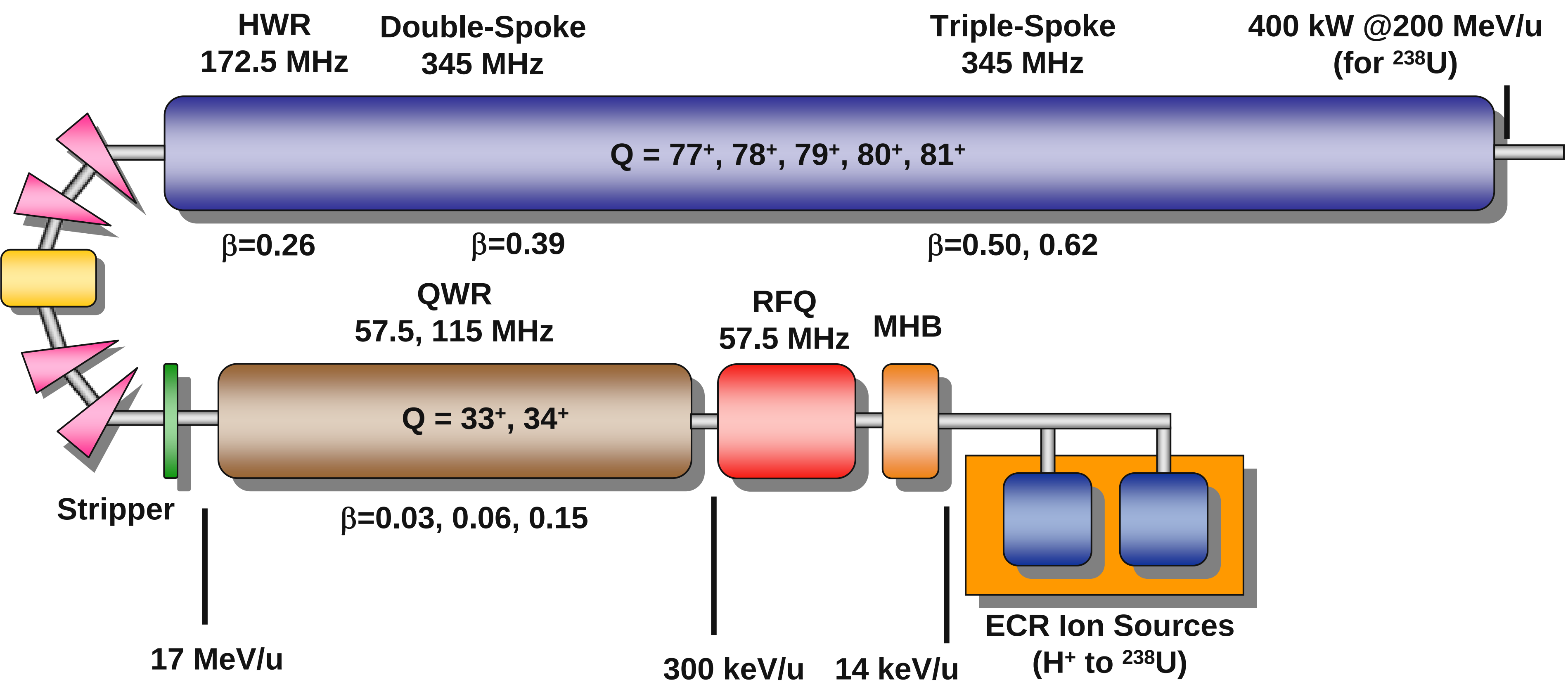
- Improve ion source feed material efficiency to enable cost-effective use of rare separated isotopes for beams such as ^{48}Ca
- Mitigate vacuum excursions that occur in SIS18 with intense beam injection
- Develop Super-FRS target concept to use fast-extracted beams from SIS100
  - Pulsed beams are essential for fragment accumulation in the storage ring
  - Intense pulsed beams cause destructive pressure waves in solid or liquid targets

Concept for FRIB



- In-flight production/gas stopping for stopped and reaccelerated beam research
  - Unique, world-class capability
- Fast-beam research
  - Highest power in the world, farthest reach for rare isotopes
  - Important extension of the scientific reach (5-10% cost increment)
- ISOL production (could be added as an upgrade)

Schematic layout of an FRIB driver linac (400 kW)



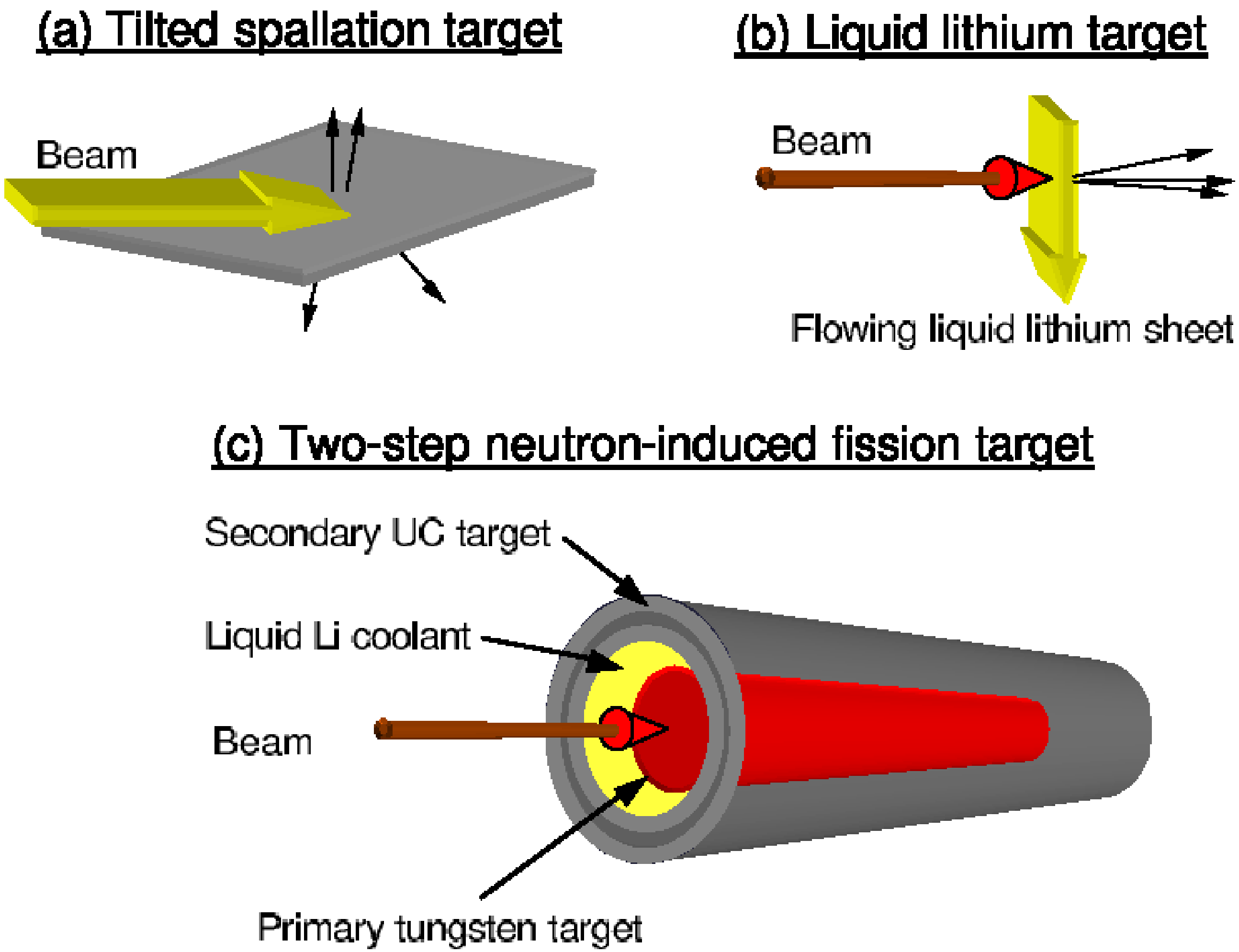
Liquid lithium stripper film development for high power uranium beams

- Experimental demonstration of a high speed liquid lithium thin film is shown
- Film parameters:
  - ~ 5 mm in width
  - ~ 10 mm in length
  - <~ 15 μm in thickness
  - jet velocity of ~ 50 m/s
- An electron-beam diagnostic for rapid-response film thickness monitor has been developed
- Liquid-lithium stripper is essential for FRIB – R&D continues to confirm long term stability and do full beam power tests

C.B. Reed, et al., ANL

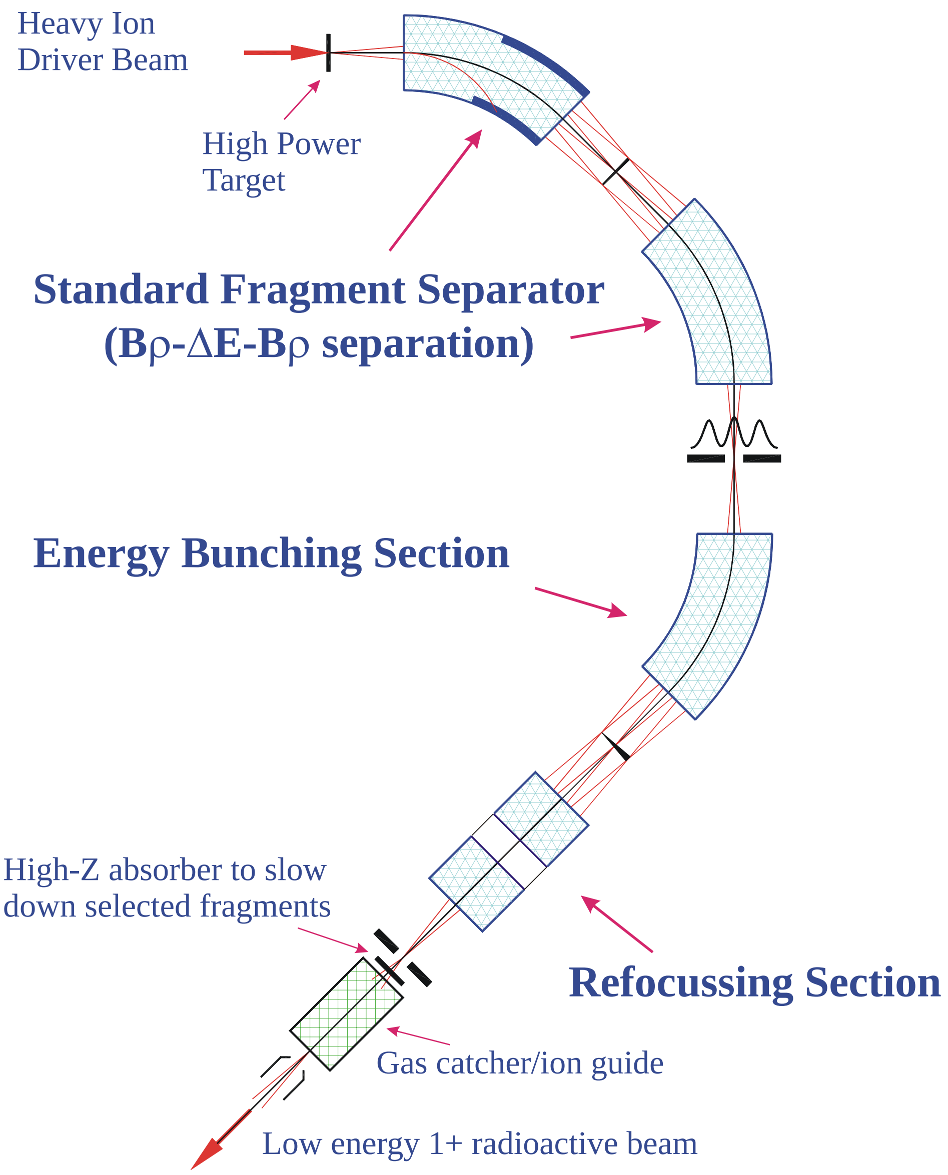
Targets and separation techniques

- A Variety of Targets and Production Mechanisms:

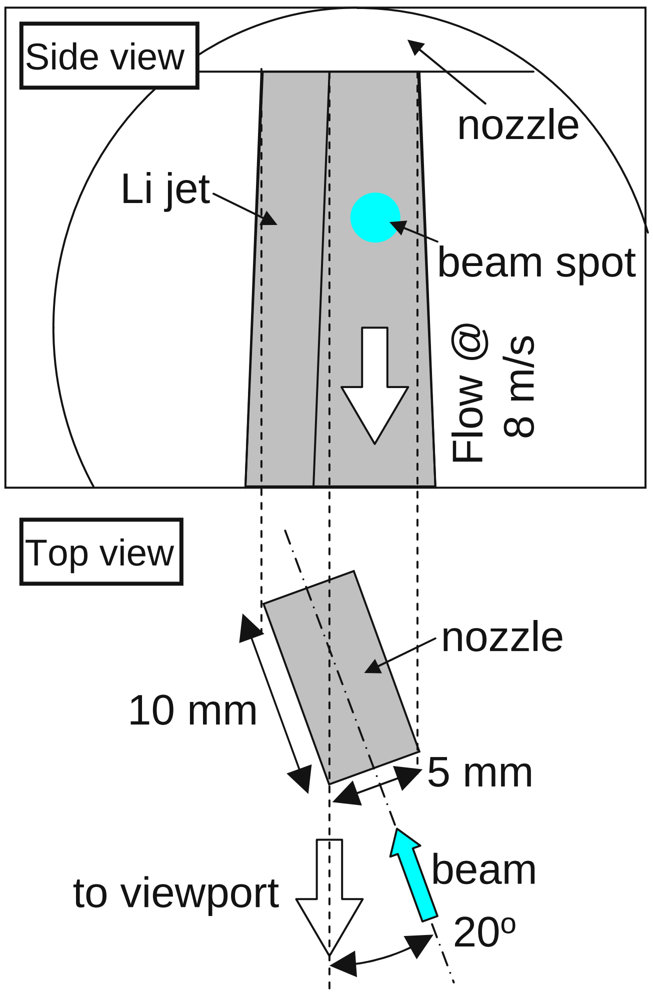


Energy bunching/fast gas catcher concept: challenges

- High power target
- High power beam dumps
- Radiation heating of SC magnets
- Radiation damage of coils and other components
- Beam purity at low energies due to charge state mixing
- Transverse and longitudinal acceptance at low beam energies
- Range bunching for stopping in the gas cell, especially for light ions



High Power Test of a Liquid-Lithium Fragmentation Target



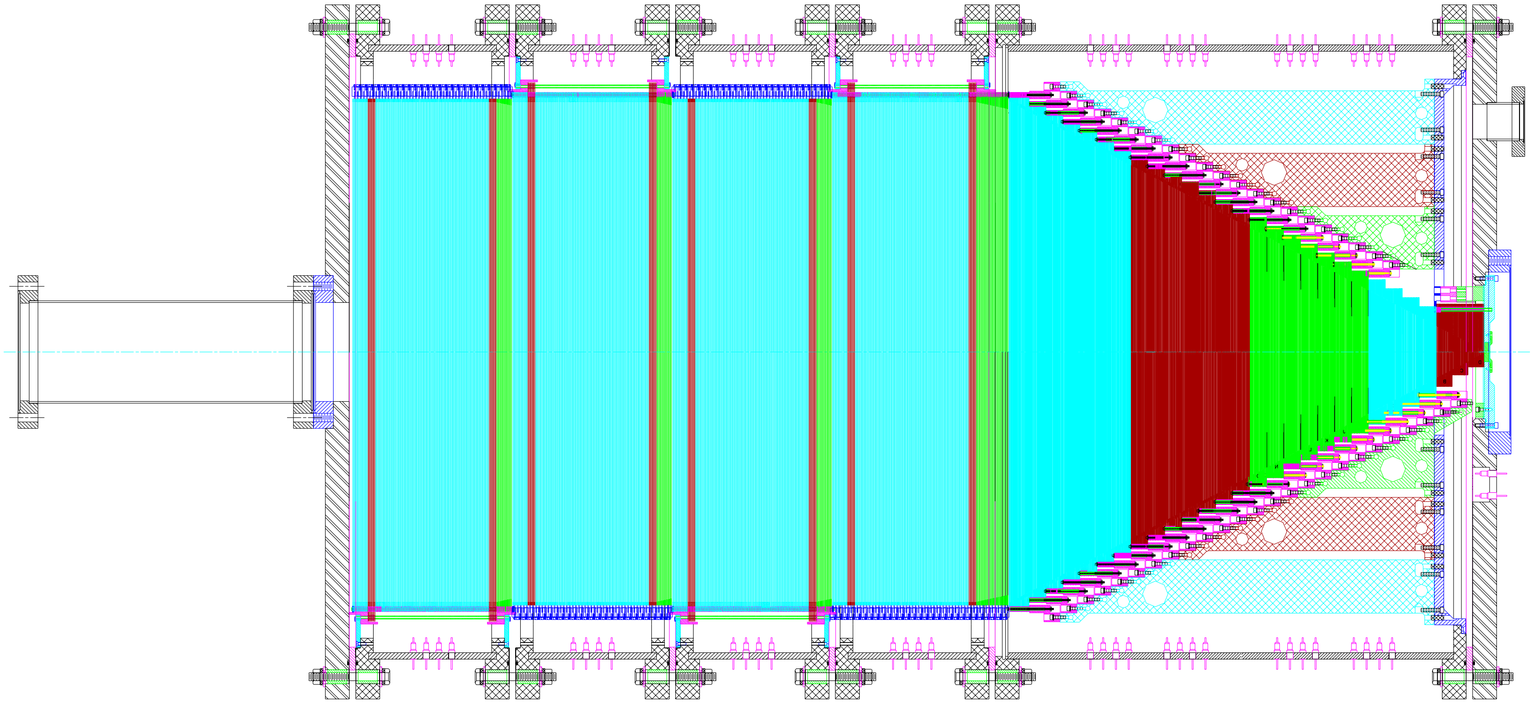
A 20 kW electron beam produces the same thermal load as a 200 kW U beam on the windowless liquid Li target.

Li jet is confirmed stable in vacuum with a U beam equivalent thermal load.

Power density is 8 MW/cm^3 @ 400 kW beam power at 200 MeV/u.

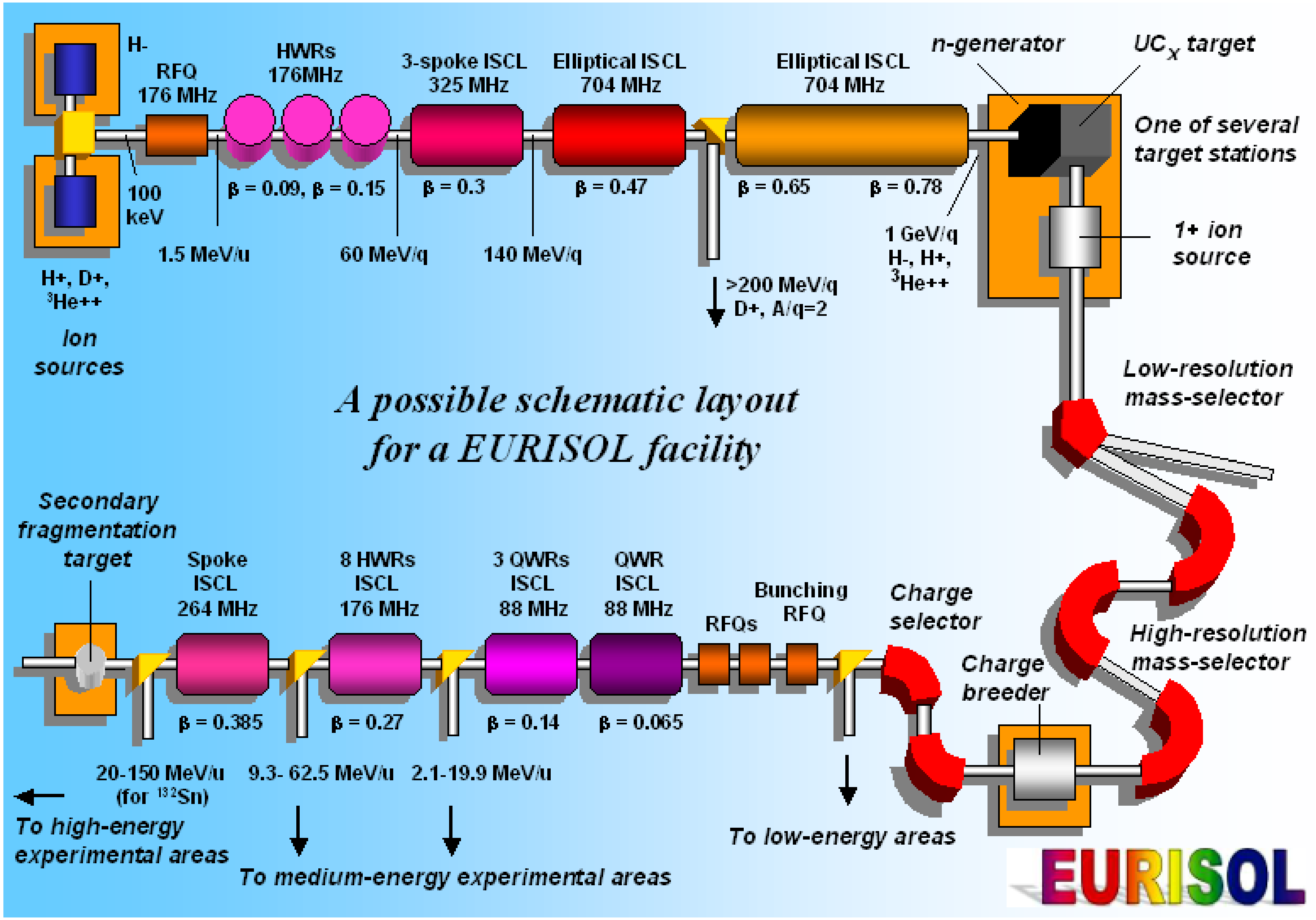
CARIBU gas catcher design (see paper Mo 5)

- **Device similar to the previously developed FRIB gas catcher**
  - **Same operating principle (RF +DC + gas flow)**
  - **Similar construction**
  - **Similar length**
  - **Twice the diameter (50 cm inner diameter)**



EURISOL: a Design Study for a 1-5 MW multi purpose facility

- DS to be completed in 2009 for 1-GeV proton driver and 150 MeV/u post-accel.



Some technological challenges for EURISOL

- Development of multi-megawatt neutron-generator/uranium target concept to achieve 10^{15} fissions per second with efficient isotope extraction
  - Involves investigation of MAFF/PIAVE concepts using 235U with moderator/reflector and mercury “curtain” target
  - Considering multiple target/ion source assemblies around converter and merging the beams
  - Builds on the development of high density, high thermal conductivity uranium carbide by the Legnaro/Gatchina/GANIL collaboration
- Development of direct irradiation ~100-kW ISOL target/ion source systems
- Development of high efficiency charge breeder for post-accel.

Summary

- There is currently world-wide interest in the fundamental nuclear science issues that can be addressed by next-generation radioactive beam facilities.
- The science drivers require a broad-based approach that can only be accomplished with a variety of technologies
- Many technologies are pushing the limits and require on-going R&D and innovation
- Many recent developments in this field are being reported at this conference
- **There is hard work ahead, but also an exciting future in this field!!!**