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RARE ISOTOPE BEAMS AND HIGH-POWER ACCELERATORS*

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Abstract

Facilities for rare isotope beams provide tools for nuclear science research and tools for applications ranging from fundamental nuclear structure and dynamics to societal benefits in medicine, energy, material sciences and national security. State-of-the-art rare isotope facilities can be based on an isotope separation on-line (ISOL) approach using mostly high-power proton beams striking a thick target where the isotopes are produced in the target, or an in-flight fragment separation (IF) approach using high-power heavy ion beams striking upon a thinner target where the isotopes continue out of the target followed by fragment separation. This tutorial class introduces high power hadron accelerators as driver machines for rare isotope production, summarizing the key design philosophy, physical and technical challenges, and current world-wide development status. As an example, the Facility for Rare Isotope Beams (FRIB) project is used to illustrate the process of establishing such facilities.

MOTIVATION

The primary goals of studies using rare isotope beams are to (1) understand the origin of elements and model extreme astrophysics environments (nuclear astrophysics); (2) develop a comprehensive model of atomic nuclei (nuclear structure); (3) use atomic nuclei to test fundamental symmetries and search for hints of new particles (fundamental physics); and (4) explore new applications of isotopes and solutions to societal problems including medicine, energy, material sciences and national security (applications). Such studies may answer basic questions such as: (1) How does subatomic matter organize itself and what phenomena emerge? (2) How did visible matter come into being and how does it evolve? (3) Are the fundamental interactions that are basic to the structure of matter fully understood? (4) How can the knowledge and technological progress provided by nuclear physics best be used to benefit society? Current research has demonstrated that to answer such challenging questions, studies at the extremes of neutron and proton number are necessary [1].

A chemical element is a species of atom having the same number of protons in their atomic nuclei. Isotopes are variants of a particular chemical element which differ in neutron number and, consequently, in nucleon number. There exist nearly 300 stable nuclei in natural environment. As shown in Fig. 1, more than 3000 nuclei have been discovered in laboratories – the so called rare isotopes [2]. There are an unknown number (predicted 5000 ~ 12,000) of nuclei in the unexplored territory to be discovered. For exploration on the broad frontiers of nuclear studies discussed above, we must deal with a diverse selection of isotopes both near and far from the more common, stable isotopes found in nature.

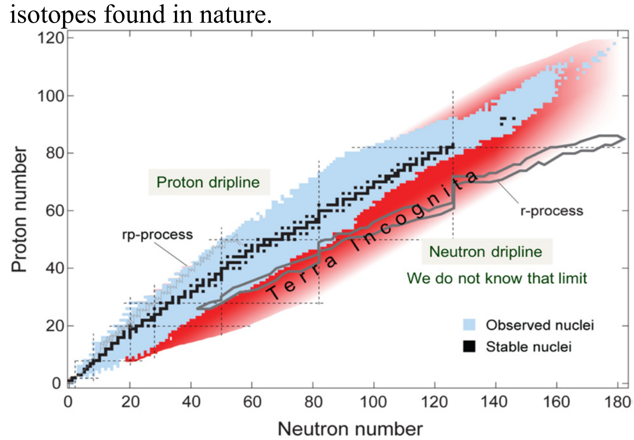

Figure 1: Chart of elements and isotopes showing about 300 stable nuclei found in natural environment (black), more than 3000 nuclei discovered in the laboratories (blue), and unknown number in the unexplored territory (red).

APPROACHES

Although human beings have mined and crafted elements like copper as early as 7,000 B.C., rise of modern chemistry and the discovery of many more elements occurred as late as 1700's and further accelerated with the discovery of Dalton's atomic theory (1804) and Mendeleev's periodic table (1869). In 1910, F. Soddy discovered isotopes and a new dimension of atomic nuclei was revealed. In 1934, F. Joliot and I. Curie made the first "artificial" isotopes by bombarding B, Mg, and Al with alpha particles from Po. The rate of new isotope discovery peaks upon introduction of new experimental methods: mass spectroscopy, accelerators, and reactor, as shown in Fig. 2 [2].

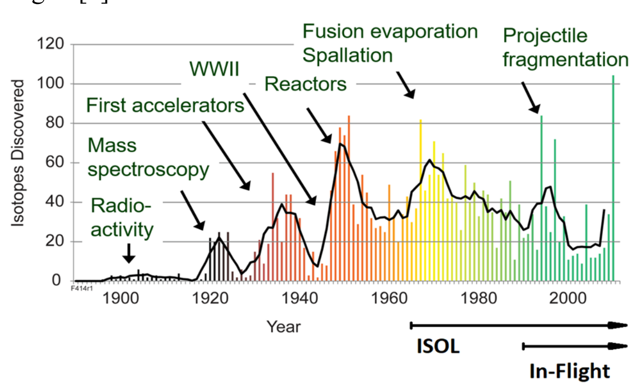

Figure 2: Annual discovery of new isotopes by various kinds of experimental methods [2].

During the recent decades, discoveries of new isotope have primarily relied on two accelerator-based methods: the isotope separation on line (ISOL) used since around

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1965 and in-flight fragmentation separation (IF) used since around 1990 [3].

As illustrated in Fig. 3(a), the ISOL method uses high-energy light projectiles (e.g. proton, deuteron, or neutron beams) to bombard a thick target (e.g. uranium carbides; or with a catcher). The nuclear-reaction (e.g. spallation, fission) products are stopped and then transported into an ion source providing element separation through chemical selection and ionization. Upon extraction, the wanted isotopes are then obtained through electromagnetic separation before they are reaccelerated (Fig. 4, (a)).

The IF method as illustrated in Fig. 3(b) uses high-energy heavy projectiles (e.g. uranium beams) to bombard a thin target of relatively light element (e.g. graphite). The reaction (e.g. fragmentation, fission) products retain high velocities determined by the reaction kinematics. The wanted fragments typically exhibit a narrow momentum distribution and a substantial part of them may be directly collected through a fragment separator. A major advantage of an in-flight separator is that the limits in half-lives for the separated rare isotopes are determined only by the time-of-flight through the optical system (Fig. 4 (b)).

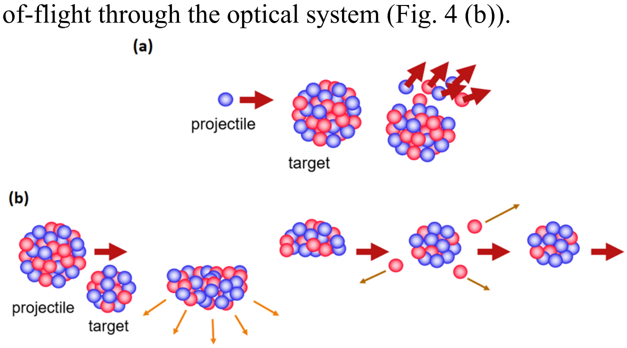

Figure 3: Sketch of (a) ISOL and (b) IF reaction mechanisms.

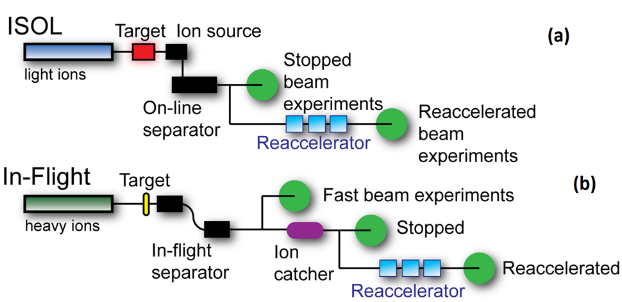

Figure 4: Illustration of (a) ISOL and (b) IF acceleration and separation layout.

FIGURES OF MERIT

Figure 5 shows the examples of ISOL (black) and IF (magenta) facilities worldwide based on both accelerators and reactors. The figures of merits of these radioactive beam facilities are high efficiency, selectivity and sensitivity and short delay times [3]. The final aim is the production of rare isotope beams that are intense and pure with good optical quality, proper timing characteristics, and energies varying essentially from rest (~ meV/u) to the highest attainable energies (~ GeV/u). Regarding driver accelerator facilities that produce the charged projectile beams, the leading figure of merit is the beam power on the production target.

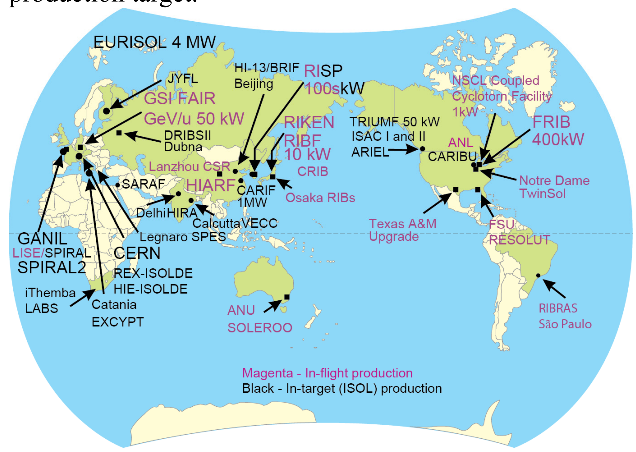

Figure 5: Examples of ISOL and IF facilities worldwide.

POWER-FRONTIER ACCELERATORS

Modern rare isotope facilities demand high power hadron accelerators. Figure 6 shows examples of high-power hadron facilities worldwide [4]. During the past decades, accelerator-based neutron-generating facilities like SNS [5], J-PARC [6], PSI [7] and LANSCE [8] advanced the frontier of proton beam power to 1 MW level, as shown in Fig. 1 with the beam-on-target power as the product of the average beam current and the beam kinetic energy. For heavy ion, the power frontier will be advanced by more than two-order-of-magnitudes to 400 kW with the construction of the Facility for Rare Isotope Beams (FRIB) currently underway at Michigan State University [9].

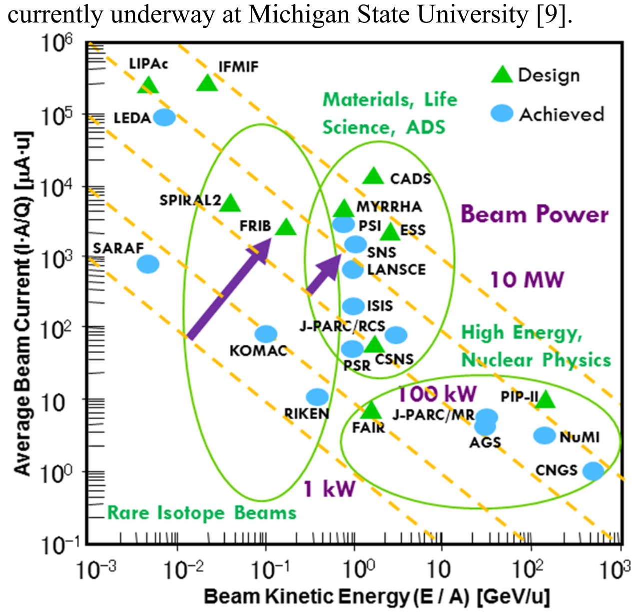

Figure 6: Hadron accelerator power frontier [4].

Table 1 shows some high-power hadron accelerators at design, construction, and operation stages. They are intended for high-energy physics (AGS [10], SPS [11], MI [12], J-PARC/MR [6], PIP-II [13] for neutrino, Kaon and Muon physics), nuclear physics (TRIUMF/ISAC [14], RIKEN [15], SPIRAL2 [16], FAIR [17], FRIB, HIAF [18],

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RAON [19] for rare isotope physics; FAIR for antiproton physics; LANSCE), basic energy science and applications (LANSCE, PSI, SNS, J-PARC/RCS [6], ISIS [20], SARAF [21], SPIRAL2, CSNS [22], ESS [23] for neutron sources; KOMAC [24] for proton applications), radioisotope production (SARAF), material neutron irradiation (IFMIF and its validation prototype LIPAc [25]), and accelerator driven subcritical systems (CiADS [26] and MYRRHA [27] for nuclear waste transmutation and power generation). Other operating or proposed projects in the world include ISOLDE [28], GANIL [29], GSI [30], NSCL [31], LEDA [32], PSR [33], CPHS [34].

ACCELERATOR DESIGN CHOICES

The desired beam structure on target largely determines the driver accelerator type: (1) continuous-wave (CW) or long-pulsed ones, and (2) short-pulsed ones. Accelerators in the first category are generally in two configurations as illustrated in Fig. 7 (a) linac driven and (b) cyclotron driven. Accelerators in the second category are generally in two configurations as illustrated in Fig. 7 (c) linac and synchrotron driven, and (d) full-energy linac and accumulator driven. Synchrotrons and accumulators are used downstream of the injector accelerators to produce pulsed beams on target. When pulsed operation is not required, cyclotrons and linacs are used to reach high beam power at high beam duty factors.

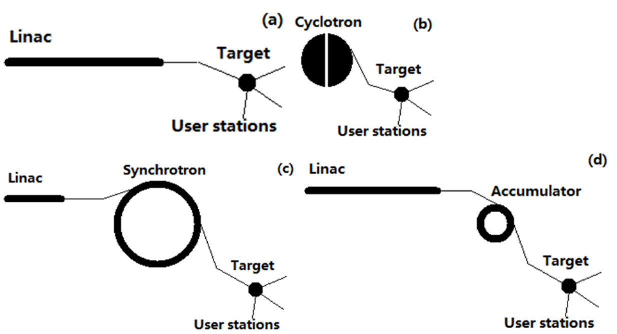

Figure 7: Common high-power accelerator layout of long pulse or CW driven by (a) linac and (b) cyclotron and short pulse driven by (c) synchrotron and (d) accumulator.

The type of primary beams is largely determined by the facility purpose. Rare isotope production using the ISOL method requires proton or deuteron beams (ISOLDE, GANIL, TRIUMF/ISAC2). Rare isotope production using the IF method requires heavy ion beams (RIKEN, GSI, GANIL, FRIB/NSCL). Neutron production at high energy using the spallation process prefers high intensity proton beams. Neutron production at lower energy favors deuteron beams. In synchrotron and accumulators for proton beams, the injector linac accelerates H^- beams for multi-turn injection to reach high peak intensity on target.

Key to the design and operations of a high-power accelerator is to actively and passively control the beam loss [35]. Passive measures of loss control include beam collimation and shielding. Uncontrolled losses must be kept below a level (about 1 W/m for protons around 1 GeV and less stringent for heavy ions) to facilitate hands-on maintenance. Personnel protection system is designed against radiation exposure under both normal and fault machine conditions [36].

KEY TECHNOLOGIES

Cutting edge technologies continuously developed for accelerator systems have sustained continuous growth in beam intensity and power (Fig. 8). High-power operations have been made possible by various types of accelerators: linac, cyclotron, synchrotron and accumulator. During the past decade, superconducting RF related technology has becoming indispensable for next generation accelerators.

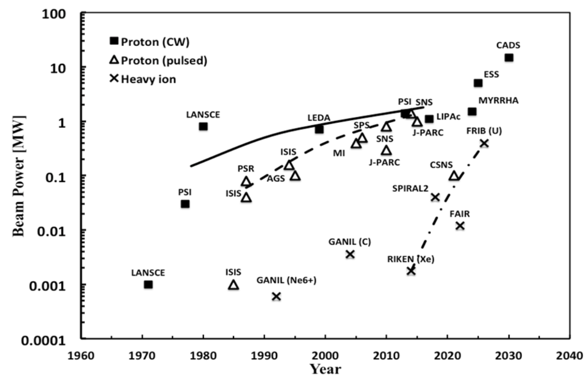

Figure 8: Hadron accelerator beam-power evolution [4].

Superconducting RF (SRF)

For hadrons, SRF technology is first extensively used in the SNS linacs for the high energy-efficiency, high accelerating gradient, and operational robustness [37]. For pulsed operations, resonance control by means of fast tuners and feedforward techniques is often required to counteract Lorentz force detuning [38], and the need of higher order mode damping is to be expected [39]. FRIB as a heavy ion continuous-wave (CW) linac extends SRF to low energy of 500 keV/u. 330 low-β (from 0.041 to 0.53) cavities are housed in 46 cryomodules. The resonators (at 2 K temperature) and magnets (at 4.5 K) supported from the bottom to facilitate alignment and the cryogenic headers suspended from the top for vibration isolation (Fig. 9) [40]. High performance subsystems including resonator, coupler, tuner, mechanical damper, solenoid and magnetic shielding are necessary [41].

Figure 9: Partially assembled FRIB β=0.53 SRF cryomodule.

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Table 1: Major Parameters of Some Proton and Heavy Ion Accelerators at Design, Construction and Operation Stage

Project	Status	Primary Beam	Sec. Beam	Accel. Type	f_{rep} [Hz]	Beam Duty	Target Type	Energy [MeV/u]	Ave. Power [MW]
AGS	Achieve	p	μ, K	LN/SR	0.5	5e-7;.5 ^{t}	Ni; Pt	24000	0.1
SPS	Achieve	p	ν	LN/SR	0.17	3.5e-6 ^{t}	C	400000	0.5
MI	Achieve	p	ν	LN/SR	0.75	1.e-5 ^{t}	C	120000	0.4
J-PARC MR	Achieve	p	ν, K, π	LN/SR	0.4;0.19	2e-6;.4 ^{t}	C; Au	30000	0.5; 0.05
	Goal	p	ν, K, π	LN/SR	0.9;0.19	4e-6;.4 ^{t}	C; M ^{r}	30000	1.3; > 0.1
LANSCE	Achieve	p, H^{-}	π, μ, n	LN	100	0.15	C ^{r}	800	0.8
PSR	Achieve	p	n	LN/AR	20	0.08 ^{i}	W	800	0.08
RIKEN	Achieve	d to U	RIB	LN/CY	CW	1	Be	345-400	0.007-0.002
	Goal	d to U	RIB	LN/CY	CW	1	Be	345-400	0.08 (U)
TRIUMF	Achieve	p	RIB	CY	CW	1	ISOL	520	0.05-0.08
PSI	Achieve	p	n, μ	CY	CW	1	C ^{r}, Pb	590	1.4
SNS	Achieve	p	n	LN/AR	60	0.06 ^{i}	Hg ^{l}	>940	1.4
	Goal	p	n	LN/AR	60	0.06 ^{i}	Hg ^{l}	1300	2.8
J-PARC RCS	Achieve	p	n, μ	LN/SR	25	0.02 ^{i}	Hg ^{l}	3000	0.5-0.92
	Goal	p	n, μ	LN/SR	25	0.02 ^{i}	Hg ^{l}	3000	1
ISIS	Achieve	p	n, μ	LN/SR	40; 10	0.01 ^{i}	W	800	0.16; 0.04
	Goal	p	n, μ	LN/SR	40; 10	0.01 ^{i}	W	800	0.45; 0.05
SARAF	Achieve	p; d	n; -	LN	CW; 1	1	SST;Li ^{l}	3.9; 2.8	0.0039; -
	Goal	p, d	n, RIB	LN	CW	1	Li ^{l}; Be	40; 20	0.2
KOMAC	Achieve	p	-	LN	10	0.005	-	100	0.01
FRIB	Constru.	p to U	RIB	LN	CW	1	C ^{r}	>200	0.4
FAIR	Constru.	p to U	RIB, $\bar{p}$	LN/SR	0.2;0.5	<0.25 ^{i}	M ^{r}; Ni	1e3;3e4	0.012;0.001
SPIRAL2	Constru.	p,d,A/q≤3	RIB, n	LN/CY	CW	1	C ^{r}	33,20,14	0.2,0.2,0.04
RAON	Constru.	p to U	RIB	LN/CY	CW	1	C	>200	0.4
HIAF	Constru.	p to U	RIB	LN/SR	CW; 5	1 ^{i}	C ^{r}, M ^{r}	834,9300	0.009; 0.01
CSNS	Achieve	p	n	LN/SR	25	0.01 ^{i}	W	1600	0.08
	Goal	p	n	LN/SR	25	0.01 ^{i}	W	1600	0.5
LIPAc	Constru.	d	n	LN	CW	1	Li ^{l}	4.5	1.1
PIP-II	Design	p	ν, μ	LN/SR	15	0.15 ^{i}	C; Al	1e5; 800	1.2; 0.1
ESS	Constru.	p	n	LN	14	0.04	W ^{r}	2000	5
IFMIF	Design	d	n	LN	CW	1	Li ^{l}	20	2 x 5
CiADS	Constru.	p	n	LN	CW	1	Pb-Bi ^{l}	500	2.5
MYRRHA	Constru.	p	n	LN	CW	1	Pb-Bi ^{l}	600	1.5 – 2.4

Notation: LN for Linac; CY for Cyclotron; SR for Synchrotron; AR for Accumulator; C for graphite; M for metal; RIB for rare isotope beams; Superscripts r for rotating and l for liquid targets, i for linac beam duty and t for beam duty on target.

Large-scale Cryogenics

An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems is key to efficient SRF operations. The FRIB refrigeration system adopts the floating pressure process – Ganni Cycle [42] for efficient adaptation to the actual loads. Distribution lines are segmented and cryomodules are connected with the U-tubes to facilitate stage-wise commissioning and maintenance (Fig. 10). The 4-2 K heat exchangers are housed inside the cryomodules for enhanced efficiency.

Loss Detection and Machine Protection

Machine protection is crucial to the availability of the high-power accelerators. FRIB adopts multi-time scale, multi-layer approaches: the fast protection system (FPS) is designed to prevent damage from acute beam loss by quickly activating the beam inhibit device; the run permit system (RPS) continuously queries the machine state and

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provides permission to operate with beam; the even slower but highly sensitive RPS prevent slow degradation of SRF system under small beam loss [43].

Figure 10: FRIB cryoplant operating at both 4.5 K and 2 K. Segmented distribution lines are connected to the refrigeration system with the U-tubes.

Challenges remain for intense low-energy heavy ion beams due to the low detection sensitivity and high power concentration/short range. Innovative techniques include the halo monitor ring for high-sensitivity loss detection and current monitoring modules for critical magnet power supply inhibition. ADS machines like MYRRHA demand mean-time-between-failure of trips exceeding 3 s to be longer than 250 h [25].

High-power Charge Stripping

Intense heavy ions at low energies may cause severe damage on stripping material. Innovative stripping mechanisms are under development worldwide. RIKEN uses helium gas with differential pumping (Fig. 11) [44]. Plasma windows are being tested to establish a high gas density [45]. FRIB uses a liquid lithium film moving at ~50 m/s speed. Tests with a proton beam produced by the LEDA source demonstrated that power depositions similar to the FRIB uranium beams could be achieved without destroying the film (Fig. 12) [46].

Injection of intense H^- beams into rings require sophisticated charge stripping designs [35]. Innovative schemes like laser stripping are tested [47]. Stripping can also be used to split H^- beam to multiple beam lines [48].

Beam Collimation

Collimators are indispensable to reduce uncontrolled beam loss for hands-on maintainability [49]. Collimation can be performed in both the transverse and longitudinal phase space (momentum cleaning and beam gap cleaning). Charge stripping is often used for H^- and partially stripped heavy ions for efficient collimation. Multi-stage collimations are used on fully stripped beams like protons.

For heavy ions, beams of unwanted charge states need to be removed downstream of the stripper. Such "charge selector" must sustain high power, low energy beams of short range. The FRIB charge selector, designed to absorb ~42 kW of heavy ions at 12 – 20 MeV/u, consists of two rotating graphite discs similar to the FRIB target [50].

Target and Remote Handling

The production target design is chosen based on secondary-beam requirements. High-power primary beams often demand non-stationary targets like circulating liquid or rotating solid targets. For pulsed neutron production at MW level, both SNS and J-PARC/RCS use liquid mercury. Target pitting issues are largely mitigated by vessel surface treatment, mercury flow and bubble controls. For lower-energy neutron production both SARAF [51] and IFMIF use liquid lithium while SPIRAL2 prefers a rotating carbon wheel. MYRRHA's ADS target uses liquid Pb-Bi eutectic [52]. For IF RIB production FRIB needs to focus 400 kW of heavy ion beam onto an area of 1 mm diameter (~60 MW/cm^3). A radiation-cooled multi-slice graphite target of 30 cm diameter rotates at 5000 rpm [50]. While neutron targets are designed to absorb most beam power, FRIB's RIB target is designed to absorb ~25% power; targets for high-energy physics (ν, μ, K) typically absorb <5% power.

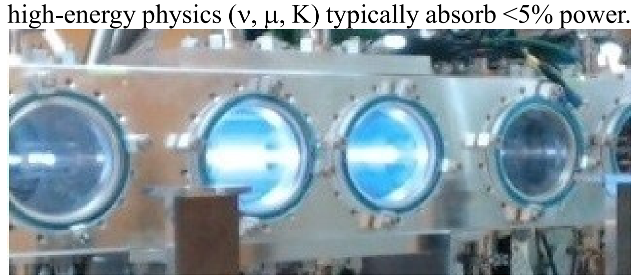

Figure 11: Test of He gas charge stripper using Uranium beams at RIKEN [44].

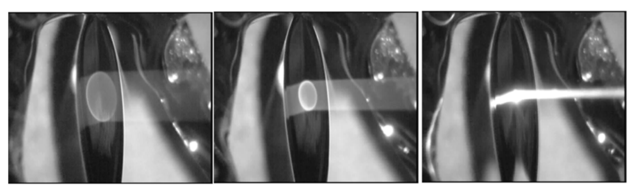

Figure 12: Liquid lithium film intercepting a proton beam of ~ 60 kV for beam power survival test [46].

FACILITY FOR RARE ISOTOPE BEAMS

FRIB is designed with IF as the baseline and ISOL as an upgrade potential for rare isotope productions. The FRIB baseline construction scope includes a driver linac that can accelerate all stable isotopes including uranium above the energy of 200 MeV/u with beam power of 400 kW striking the IF target for rare isotope production and in-flight fragment separation [9]. The upgrade paths include upgrading the energy above 400 MeV/u and adding a light ion injector for the driver linac to simultaneously accelerate multiple ion species and charge states like $^{3}He^{+}$ and $^{238}U^{78+}$. Proton beams above 600 MeV can be made to strike an ISOL target operating in parallel with the IF target. In 2019, the first segment of the linac was commissioned accelerating beams of Ne, Ar, Kr and Xe all above 20 MeV/u [53].

FUTURE PERSPECTIVES

The worldwide quest for rare isotope beams for nuclear science and applications is driving the development of new

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generation high-power hadron accelerator facilities. Global efforts are readying the technologies and designs meeting the requirements of user facilities with high reliability, availability, maintainability, tunability, and upgradability.

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