Summary of Radioactive Beam Facilities Worldwide

E. Blackmore, August 22.2011

This summary is my perspective on the present radioactive beam facilities and the significant new projects underway. I am obviously most familiar with ISAC at TRIUMF but I have been on some reviews of the US facilities and have visited several European facilities. Rather than starting from scratch I looked for a good general review of ISOL/In Flight Facilities and found one by Mats Lindroos (ISOLDE then) in EPAC04 – see link below:
http://accelconf.web.cern.ch/accelconf/e04/TALKS/TUXCH01.PDF

There is an excellent summary of the ISOL technique, the history of development of ISOL facilities and some mention of IFF(In-flight facilities). Although it is a little out of date it is a good starting point because of its historical perspective.

There are 3 tables in the presentation that I include here for discussion purposes.

First generation ISOL RNB facilities

Location	RIB Starting Date	Driver	Post-accelerator
Louvain-la-Neuve Belgium	1989	Cyclotron p, 30 MeV, 200 μA	Cyclotrons K = 110, 44
SPIRAL: GANIL Caen, France	2001	2 cyclotrons heavy ions up to 95 A MeV, 6 kW	cyclotron CIME K = 265, 2–25 A MeV
REX ISOLDE: CERN Genève, Switzerland	2001	PS booster p, 1.4 GeV, 2 μA	Linac 0.8-3.1 A MeV
EXCYT Catania, Italy	2004	K=800 cyclotron heavy ions	15-MV tandem 0.2–8 A MeV
HRIBF Oak Ridge, USA	1997	Cyclotron p, d, α, 50-100 MeV, 10-20 μA	25-MV tandem
ISAC-I: TRIUMF Vancouver, Canada	2000	Cyclotron p, 500 MeV, 100 μA	Linac up to 1.5 A MeV

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ISOL facilities

The important parameters for an ISOL facility are beam energy, power on target, ion source capabilites and energy reach of the post accelerators. Most drivers use protons but some have deuterons and alphas. Obviously the suite of scientific instruments and the scientists using them are also important.

TRIUMF has the highest beam power at present on an ISOL target with several target/ion source combinations that can handle up to 100 μA. Most of the RIB production is by spallation and fragmentation reactions on moderately heavy targets eg Ta, TiC, SiC etc. but there is increased use of actinide (uranium) targets for neutron rich fission reactions and some heavy nuclides such as radon and francium from spallation. Radioactive species produced in the target diffuse out of the heated target and are ionized in an ion source optimized for a particular beam. The ion source designs are crucial in delivering high RIB production rates and different types eg surface, plasma, ECR, RLIS (resonant laser), FEBIAD are used. Not all elements can be produced and ionized eg. refractory elements. The other important parameter is lifetime of the target and ion source as it should be long compared to the time to change targets which can be 1-2 weeks because of remote handling, hot cells and new target conditioning.

So far uranium carbide targets for fission or spallation at TRIUMF and elsewhere are operating at lower currents either because of accelerator current limitations or to imposed restrictions while learning how to measure and control the alpha emitters and other reliability issues. HRIBF-ORNL and ISOLDE also have experience with these UCx targets with production using 40-50 MeV protons and currents of 10-20 μA at HRIBF and energies of 1.3 GeV at ISOLDE. The lower energy requires the use of thinner targets so there is a corresponding loss in RIB production.

The second slide shows planned upgrades or new facilities:

ISOL RNB: Intermediate facilities

Location	RIB Starting Date	Driver	Post-accelerator
SPIRAL-II: GANIL Caen, France	2008	SC linear accelerator LINAG deuterons up to 40 MeV heavy ions up to 15 A MeV	cyclotron CIME $K = 265$, 2–25 A MeV
MAFF Munich, Germany	2008	Reactor 10^{14} n/cm^2.sec	Linac up to 7 A MeV
SPES Legnaro, Italy	2008 (Initial phase)	SC proton linac	ALPI linac
ISAC-II TRIUMF	2007	Cyclotron p, 500 MeV, 100 μA	Linac up to 6.5 A MeV
ISOLDE upgrade CERN	2008	PS booster p, 1.4 GeV, 10 μA	Linac up to 5 A MeV

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TRIUMF is now operating a SC linac post accelerator capable of accelerating radioactive beams to 6.5 A MeV. ISOLDE still operates at the original 2-3 μA at 1.3 GeV and the REX linac has energies of 2.2 A MeV but there are plans for HIE-ISOLDE which will increase the proton current with LINAC4 and replace the REX linac with SC cavities capable of 5.5 A MeV by 2014 and 10 A MeV by 2016 (according to a recent schedule).

GANIL(SPIRAL) is the other major European radioactive beam facility facility operating a complex of heavy ion cyclotrons for stable beam research for nuclear physics as well as putting a few kW of this beam power on an ISOL target for RIB production and post acceleration. However a major new project SPIRAL2 is underway which consists of a deuteron/heavy ion linac as the primary driver (operating at 40 MeV deuteron energy and currents to 5 mA) with the beam sent to a carbon converter to produce neutrons for fission reactions on a nearby uranium target. The fission fragments will be ionized and accelerated in the CIME cyclotron to 25 A MeV maximum energy. This project is scheduled to start beam operation in 2012.

Several other radioactive beam projects envisaged in 2004 are listed below.

Future RNB facilities

Location	Driver	Post-accelerator	Fragment separator	Type of facility
Europe: GSI (Germany)	synchrotron, heavy ions: 1.5 A GeV	-	'Super-FRS'	In-Flight
Europe: EURISOL	protons, 1 GeV, 1-5 MW	CW Linac, up to 100 *A* MeV	-	ISOL
USA: RIA Rare Isotope Accelerator	900 MeV protons heavy ions: 400 *A* MeV, 100 kW	Linac up to 8–15 A MeV	4-dipole Separator	ISOL, In-Flight
JAPAN: RIKEN RIB Factory	Ring-cyclotrons up to 400 *A* MeV (light ions); up to 150 *A* MeV (heavy ions)	-	3 fragment Separators storage & cooler rings	In-Flight

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ISOL facilities

NSCL at MSU, GANIL in France, GSI in Germany and RIKEN in Japan are the primary existing in-flight facilities for radioactive beams. NSCL has two superconducting cyclotrons K500 and K1200 operating in a coupled mode for accelerating light heavy ions to beam powers of about 1 kW. This facility along with some other in-flight facilities has developed the capability to slow down the radioactive beams in an ion catcher or decelerator. This allows the production of radioactive species that cannot be produced by the ISOL process and then slowed down to sufficiently low energies for use in traps or for post acceleration. GANIL as mentioned before has ISOL beams but also IFF beams with a K380 cyclotron with beams up to uranium and beam powers in the few kW range.

GSI has operated the SIS synchrotrons for some time as an IFF and now is developing the FAIR project which will have a component of in flight radioactive beam production using Gev/μ uranium beams and separators. FAIR has many capabilities including antiprotons so it is not clear how much time will be devoted to radioactive beams. However it will have a significant capability in in-flight radioactive beam production at high energy until the other facilities come on line.

RIKEN (RIBF) with its complex of four cyclotrons including a superconducting K2600 cyclotron can deliver ion beams from hydrogen to uranium with energies up to several hundred MeV per nucleon and beam powers up to 6 kW. A new injector linac is being commissioned to produce a significantly higher beam intensity of uranium ions. I believe they had some earthquake damage but are back operating.

The RIA project in the US as envisaged in 2004 has not happened due to its high price tag. Instead a decision was made by DOE to fund a "half-RIA" ie a project in the $550M area and in a competition between Argonne and MSU to host this facility, MSU won and FRIB was approved for construction in 2008. FRIB at that time was planned to consist of:

- A superconducting-RF driver linear accelerator that provides 400 kW for all beams with uranium accelerated to 200 MeV per nucleon and lighter ions with increasing energy (protons at 600 MeV per nucleon)
- Two ECR ion sources for redundancy with space to add a third ECR ion source
- Space in the linac tunnel and shielding in the production area to allow upgrading the driver linac energy to 400 MeV per nucleon for uranium and 1 GeV for protons without significant interruption of the future science program
- Space to add multi-user capability
- One in-flight production target
- Three rare isotope stopping stations (two gas stopping stations and one solid stopper)
- Experimental areas (47,000 sq ft) for stopped beams, reaccelerated beams, and fast beams

There is no ISOL facility in the initial FRIB plan but an intention to leave space for one in the future. The present construction schedule is determined by funding and is presently stated as ending in 2018/2019.

EURISOL was conceived as a design study to develop the technologies for a MW level radioactive beam facility – see www.eurisol.org. I don't know its status for proceeding further. There is a good review of Euopean facilities by Y. Blumenfeld in Nuclear Instruments and Methods in Physics Research B 266 (2008) 4074–4079.

Proposed New/Upgraded Facilities

TRIUMF ARIEL - TRIUMF is constructing a 50 MeV, 500kW superconducting electron linac which will be used for photofission on a uranium target in a new target hall. Radioactive ion beams will be brought to the existing post accelerators and experiments. There is funding for the accelerator and target hall but not for the equipment in the target hall as yet - http://www.triumf.ca/ariel. Photofission has the advantage of less production of alpha emitters so easier target handling but that is also a disadvantage if these isotopes are desired.

HRIBF – Oak Ridge: This is a facility that has been operating since 1997 with production by a 40 MeV, 10 μA proton and light ion cyclotron and post acceleration in a 25 MV tandem. They have considerable experience in UCx targets. They are looking at upgrade paths to replace the 50 year old ORIC cyclotron and are considering both cyclotrons and an electron linac.

SPES – Legnaro: This proposed facility, presently being constructed, is like HRIBF with a 40-70 MeV variable energy proton cyclotron with a current of 200 μA (8 kW) with post acceleration in an SC linac. A Canadian company BEST Theratronics with limited experience in building cyclotrons has been awarded the contract for the cyclotron. However they will get help from CIAE in China which has just built such a cyclotron with some help from TRIUMF – see below. Of relevance to the KoRIA project is the design of UCx targets that can handle high currents and related radiation safety issues.

BFRIB – Beijing, China: The Beijing Radioactive Beam Facility is based on a 100 MeV proton cyclotron CYCIAE-100 (accelerates H- ions with stripping extraction) designed for 250-500 μA. The cyclotron is presently being commissioned and first RIB beams are anticipated in the next year or so. This facility will be close to the capability of the ISOL part of KoRIA.

HIRFL – Lanzou, China: This is an in-flight facility using heavy ion cyclotrons, storage ring and cooler. Heavy ion research has been carried out since 1991 and the radioactive beam line RIBLL has been in operation since about 1993.

VEC-RIB – India: This project was funded in 2007 and consists of a K130 cyclotron and an electron SC linac (like TRIUMF ARIEL) for producing radioactive beams followed by post acceleration – like ISAC-II.

DRIBS – Dubna: This facility at Flerov Laboratory has both an IFF and ISOL capability with U400 and U400M heavy ion cyclotrons with heavy ion energies to 100 A MeV. They also use an electron microtron for photofission production of fission fragment beams. It has been in operation since 2002 but I have not found a good description of how much time is used for conventional RIB research vs. production of superheavy elements which is one of their main interests.

KoRIA – Korea: This project proposes a K100, 70 MeV, 1 mA proton cyclotron for ISOL production of fission fragments using UCx targets, as the initial facility. The main issue here is designing a reliable target/ion source system that can handle 1 mA beams and the necessary nuclear ventilation and shielding to cope with the high rates of volatile radioisotopes, including alpha emitters. The beam power is about a factor 5-10 higher than presently funded projects. The second phase has a SC 200 A MeV heavy ion linac with uranium beam power of 400 kW but with the capability of using this heavy ion/proton beam on the ISOL target for RIB production by spallation and fragmentation. As described the unique feature of the proposal is to use the heavy ion linac for post acceleration of ISOL-produced RIBs. Again the major design issue with the IFF is handling the high beam intensities in the target and separator areas. The IFF is very similar to the FRIB facility at MSU.

There are a number of smaller facilities that I am awre of but have not mentioned: eg. UCL in Louvain-la-Nueve, EXCYT in Catania, Texas A&M, Notre Dame and CARIBU at Argonne based on a ^{252}Cf source.

Comments

This summary shows that there is a worldwide interest in nuclear physics and applications with radioactive beams and many countries are jumping on the bandwagon. At present there is a clear shortage of operating facilities as there is a backlog of users awaiting beam time for their experiments. The reason is that these facilities are essentially a one experiment at a time operation as the beam is optimized for a particular isotope. The situation in 2020 will not be so clear with a half dozen new facilities operating. However any facility with a unique capability will be of interest to the scientific community.

This summary is my understanding of the present status in RIB science and hopefully I am not misrepresenting any of the facilities.

Note: Shortly before finishing this summary I came across a presentation by W. Klemper from Florida State on "Current and New Facilities for Radioactive Beam Physics. It has lots of pretty pictures of the layouts of the different facilities.
http://www.slcj.uw.edu.pl/en/events/IP/kemper.pdf