RIBF AND OTHER RADIOACTIVE ISOTOPE BEAM FACILITIES

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Abstract

Aimed to explore many unknown properties of unstable nuclei, the RIKEN Radioactive Isotope Beam Factory (RIBF) began operation at the end of 2006 as the first of several next-generation RI beam facilities planned worldwide. To date, the design intensity for light ions has been achieved, and the intensity of ^{48}Ca beams is steadily increasing. For very heavy ions such as uranium, a new injector system RILAC2 is now under construction to realise an increase in intensity of two orders of magnitude. The present status of RIBF is described, and other next-generation RIB facilities that will begin operation in the near future are outlined. The future scope of RIBF is discussed in comparison with other in-flight facilities.

INTRODUCTION

In the mid-1980s, the exotic behaviour of light radioactive isotopes (RIs) such as the neutron halo structure of ^{11}Li [1] were discovered by using radioactive isotope beams (RIBs). Since then, RIBs have become indispensable tools for studying nuclear physics. Systematic studies on short-lived RIs have been performed at so-called first-generation RIB facilities worldwide since the 1980s. Extensive physics research has been carried out, and many technical innovations have been achieved to date [2]; however, the first-generation RIB facilities were not fully dedicated to the production of high-intensity RIBs. In spite of their importance in understanding nucleosynthesis in the universe, the RIs on the presently assumed rapid-neutron-capture-process path were difficult to access using the first-generation facilities because of insufficient beam intensity. Therefore, intensity upgrades at existing RIB facilities were proposed in the 1990s. For a comprehensive understanding of fundamental nuclear physics and nuclear astrophysics, a broad research programme is needed, including measurements of masses, half-lives, decay properties, energy spectra and reaction cross sections. Accordingly, two types of RIB facilities, namely, isotope separation on-line (ISOL) and in-flight facilities, should be constructed on a regional basis [3]. RIBF, which succeeded in producing its first beam at the end of 2006, is the first of the next-generation in-flight facilities.

ISOL AND IN-FLIGHT TECHNIQUE

The ISOL technique was first developed in Copenhagen in 1951 [4]. In the ISOL technique, light ions such as protons or deuteron impinging on a thick target kept at high temperature produce RIs via fission, spallation or fragmentation reactions. The RIs diffusing out of the target are guided into an ion source, usually being ionised to be the 1+ state, and are then extracted from the ion source. Mass separation of the RIs is performed with an analyser magnet, and the selected RIs are reaccelerated. A charge breeding technique before reacceleration is widely used to obtain a higher energy RIB. For more details, see Ref. [5].

The other technique is the in-flight separation. The pioneering work on this technique was performed for fission products in 1958 [6], and the in-flight technique was then applied to high-energy heavy-ion beams in the late 1970s at the BEVALAC accelerator [7]. In this technique, RIs are produced at a thin target via a projectile fragmentation reaction or projectile fission. They are kinematically focussed within a small forward angle and are directly used as a beam of RIs after in-flight separation such as the ΔE-TOF-Bρ method if the energy of the projectile ions is sufficiently high, for example, more than 100 MeV/nucleon. For more details of the in-flight technique, see Ref. [8].

The ISOL and in-flight techniques are thought to be complementary. In the ISOL technique, higher beam intensity is more accessible for protons or deuterons than heavy ions, and a thick target can be used. Hence, the in-target yields of RIs are higher than those obtained by the in-flight technique. The quality of the reaccelerated beam is as high as that of the primary beam. The RIBs obtained via the ISOL technique are thus suitable for precise nuclear spectroscopic studies. However, the processes of separation from the target, transportation into the ion source and ionisation depend on the chemical properties of the RI of interest, the target material and the ion-source material. Also, RI separation from the target requires at least several tens of milliseconds. Hence, refractory ions and extremely short-lived RIs are difficult to produce with high efficiency in the ISOL technique.

The in-flight method does not require an additional post accelerator and is not sensitive to the chemical properties of the RI of interest. RI production and separation is completed during the flight time (< 1 μs) of ions. Hence, short-lived RIs and isomers can be easily handled through this technique. In contrast, the beam quality is poor due to the recoil momentum of RIs from the target and a modern fragment separator with a large aperture is required [8]. RIBs with energy of several hundreds of megaelectronvolts per nucleon are suitable for reaction-scheme studies because the reaction mechanisms become simpler in this energy region.

RI BEAM FACTORY

The accelerator complex at RIBF consists of an 18-GHz electron cyclotron resonance (ECR) ion source [9], a folded-coaxial radio frequency quadrupole (RFQ) [10], a

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variable-frequency heavy-ion linac (RILAC) [11], a K=70 MeV injector AVF cyclotron [12] and four ring cyclotrons. The specifications of the ring cyclotrons are listed in Table 1. RILAC, AVF and one of the four ring cyclotrons (RRC) [13] were used in our previous facility, and now serve as the injector complex of RIBF. The three ring cyclotrons newly constructed for the RIBF project are fixed-frequency Ring Cyclotron (fRC) [14], Intermediate-stage Ring Cyclotron (IRC) [15] and the world-first Superconducting Ring Cyclotron (SRC) [16].

Table 1: Specifications of RIBF Cyclotrons. In bottom row, the number of acceleration cavities is shown (FT=flat-top cavity).

	fRC	IRC	SRC
K-number (MeV)	570	980	2600
Number of sectors	4	4	6
Velocity gain	2.1	1.5	1.5
Number of trim coils	10	20	4 + 22
Frequency range (MHz)	54.75	18 -38	18 - 38
RF system	2 + FT	2 + FT	4 + FT

Various acceleration modes are available in the RIBF accelerator complex. The basic scheme is a variable-energy mode that uses RILAC, RRC, IRC and SRC in series. The variable-energy mode is able to accelerate ions such as ^{48}Ca up to at least 345 MeV/nucleon. Since the variable-energy mode cannot accelerate ions heavier than krypton to the same velocity as lighter ions, an additional cyclotron fRC is inserted between RRC and IRC. Because fRC operates at a fixed frequency, the energy is set to 345 MeV/nucleon. The third mode, which is used to accelerate extremely light ions, such as deuteron and nitrogen, uses the AVF cyclotron as an injector and only two ring cyclotrons (RRC and SRC). This is also a variable-energy mode. Upstream of the AVF cyclotron, a polarised ion source is installed; consequently, polarised deuteron beams can be accelerated to energies of 250–440 MeV/nucleon to study the nuclear three-body force [17].

Table 2: Operation Statistics (hours) of RIBF Accelerator cComplex. The third column includes all the operation times including beam tuning, commissioning and so on.

Year	User run	RIBF operation	Reliability
2007	414	1845	
2008	496	2051	0.68
2009	1129	3036	0.68
2010	907	1820	0.86

Operation Statistics

Operation statistics are summarised in Table 2. The yearly operation time was limited by the approved budget. The reliability index is defined as the ratio of actual beam service time to a scheduled beam service time. Operations required to maintain certain beam intensity, for example, replacement of a charge stripper and conditioning of RF cavities after a several days of operation under a high magnetic field, are not counted as scheduled operations and thus decrease the reliability index. Hence, our reliability goal is 90%. In the latest experiment performed from June 21 to July 1, 2010, the reliability was 92%.

Present Performance

The obtained beam intensities are summarised in Table 3. The design intensity of 1 pμA was achieved for 320 MeV/nucleon ^{4}He and 345 MeV/nucleon ^{18}O beams in the first acceleration tests. Beam intensities for these light ions are limited by current radiation safety regulations. For ^{48}Ca ions, which have many excess neutrons and are suitable for production of neutron-rich RIs, the maximum beam intensity is 0.23 pμA. This is limited by the beam-loss-induced heat load of ~300 W at the beam extraction device installed in SRC. The emittance of a ^{48}Ca beam at SRC injection is within the acceptance [18]; thus, this low intensity may be due to insufficient optimisation of the operational parameters of SRC, particularly the low operating voltage of the flattop resonator. A beam-halo scraper or emittance-definition slits just before the SRC injection might be needed to achieve the design intensity.

Table 3: Beam Intensities achieved at RIBF

Ion	Energy (MeV/A)	Intensity	Date
^{4}He	320	1 pμA	09/10/31
^{18}O	345	1 pμA	10/6/17
^{48}Ca	345	0.23 pμA	10/5/31
^{86}Kr	345	33 pnA	07/11/04
^{238}U	345	0.8 pnA	09/12/19

The major challenges for accelerator technology at RIBF are the realisation of the world-first superconducting ring cyclotron and the stable operation of multi-step ring cyclotrons. SRC serves well as a good isochronous cyclotron without any performance degradation compared with other room-temperature ring cyclotrons [18]. The transmission efficiencies for multi-step acceleration are shown in Fig. 1. An example of the beam stability for an experiment conducted in May–June, 2010, is also shown in Fig. 2, where beam intensities measured by a Faraday cup and beam bunch signals measured by a pickup electrode installed downstream of SRC were continuously analysed with a lock-in amplifier. The present stability is achieved through stabilisation of RILAC [19] and is now at an acceptable level for daily experiments. Stability of the major components of the ring cyclotrons, such as power supplies and RF resonators, fulfil the design requirements. A remaining problem is further temperature stabilisation of the sector magnets of the three room-temperature ring cyclotrons. We have experienced sizable drifts of magnetic fields from well-tuned isochronous fields after a large change of the outdoor air temperature.

The maximum intensity obtained for a uranium beam is 0.8 pnA. This corresponds to less than 0.1% of our goal. The reasons for this result are as follows. First, the existing 18-GHz ion source is not suitable for high-intensity production of $^{238}U^{35+}$ ions. Second, the vacuum pressure of RILAC is not sufficiently low for the acceleration of low-energy $^{238}U^{35+}$ ions. Hence, construction of a new injector system called RILAC2 is now in progress. RILAC2 consists of a 28-GHz superconducting ECR ion source [20], an RFQ and a room-temperature linac [21]. Test operations of the new ion source using an 18-GHz RF source resulted in high-intensity beams as expected [22]. The new injector linac with improved vacuum pressure and higher acceleration-voltage gradients than RILAC is designed to obtain a 70% transmission efficiency, which surpasses the present system by a factor of 1.7. The beam commissioning of RILAC2 is scheduled for December 2010.

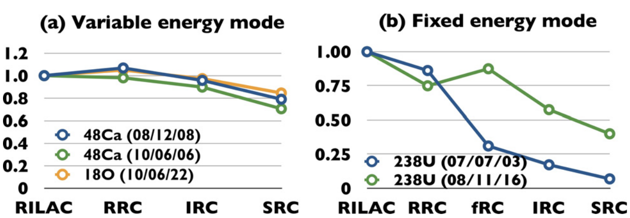

Figure 1: Transmission efficiency of RIBF cyclotron complex. Output intensity of the cyclotrons relative to that of injector RILAC is shown. Charge-stripping efficiency is excluded from the present plot. Error from beam intensity monitors is thought to be 10% and is not calibrated in the present plot.

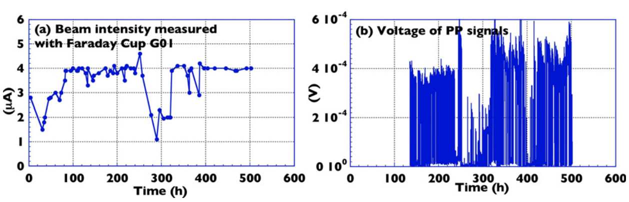

Figure 2: Stability of 345 MeV/nucleon ^{48}Ca beam extracted from SRC. Observed beam intensity measured with a Faraday cup is shown in (a). Points show measured values; the line is only a guide for the eye. Beam bunch signals measured with a phase-pick (PP) electrode are continuously analysed with a lock-in amplifier. Voltages of the second harmonic component of the signals are shown in (b). A decrease in beam intensity around T = 300 h was caused by a user's request.

A two-step charge-stripping scheme adopted for uranium acceleration is also problematic. Carbon foil (0.3 mg/cm^2) is installed before fRC injection to obtain a 71+ state. A carbon disk (14 mg/cm^2) is also used before IRC injection in order to obtain an 86+ state. The degradation in beam quality after passing through these two foils has exceeded our assumption in the design stage. In particular, the carbon foil becomes seriously stretched and wrinkled after being irradiated for 15 h with the present low-intensity uranium beam [18]. It results in large energy spread of the beam. Therefore, the use of a fixed carbon foil is not realistic for higher-intensity uranium beams after introduction of RILAC2. To overcome the problem, we have begun research and development to utilise a gas stripper of light elements such as hydrogen and helium in collaboration with Brookhaven National Laboratory. In addition, a rotating carbon foil stripper system [23], which had been developed before beam commissioning, has recently seen improvements in its rotating speed.

NEXT-GENERATION FACILITIES

European RIB Facility Upgrades

The "intermediate–generation" ISOL facilities SPES [24], HIE-ISOLDE [25] and SPRIAL2 [26] are under construction, and the ultimate-generation ISOL facility EURISOL [27] is planned by the European ISOL community. The specifications of these facilities are summarised in Table 4. Within the three intermediate-generation facilities, SPIRAL2 is the facility with the highest RIB intensities. The driver accelerator is a continuous wave (CW)-mode superconducting linac (sc-linac). It accelerates a 5-mA deuteron beam with energy of 40 MeV. The 200-kW deuteron beam produces over 10^{15} neutrons/s at a carbon converter, and the neutrons induce up to 10^{14} fissions/s in a uranium carbide target with a fast release time. The fission products are ionised and mass-separated by an analyser magnet with resolving power of 350. RIs are reaccelerated up to 1~20 MeV/nucleon and purified by the existing K=265 MeV CIME cyclotron after a charge breeding process. The expected intensity of RIBs is 10^6~10^{10} pps, which is one or two orders of magnitude higher than that of existing facilities. This deuteron approach is suitable for producing A=60 to A=140 neutron-rich RIs.

Other production schemes utilising fusion-evaporation, deep inelastic or transfer reactions are accessible with the 14.5 MeV/nucleon heavy-ion beams (M/q=3) accelerated by the sc-linac, which aims to cover a wider area of the nuclear chart. The future GANIL/SPRIAL/SPIRAL2 facility is also capable of being used for at most five simultaneous experiments. SPIRAL2 is scheduled to begin operation in 2012.

The SPIRAL2, SPES and HIE-ISOLDE projects will provide essential knowledge to promote the ultimate ISOL facility EURISOL. Protons accelerated to 1 GeV by an sc-linac will be used as a driver beam. The expected beam power is 5 MW. A mercury converter and a uranium carbide target will be used to produce RIBs with intensities up to 10^{12} pps. The RIs can be used at low energy and can also be reaccelerated by another sc-linac up to 150 MeV/nucleon to induce nuclear reactions. The expected intensity of RIBs is at the level of the present primary beam. Extensive design studies are presently being performed in order to complete EURISOL in the 2020s.

The next-generation in-flight facility in Europe is FAIR [28], which is promoted by Germany and partner countries. The FAIR project covers a wide variety of research fields including atomic, plasma, hadron, antiproton and unstable nuclear physics. FAIR is upgrade of the existing GSI facility, and UNILAC and SIS18 will be used as the injector of the newly constructed heavy-ion synchrotron SIS100. A high-intensity RIB will be produced by a 1.5 GeV/nucleon uranium beam via a projectile-fission reaction. The average intensity of the uranium beam is expected to be 2×10^{11} pps [29]. The uranium beam intensity is not especially high in comparison with other CW-mode next-generation in-flight facilities, but its high energy and modern fragment separator (SuperFRS) will enable efficient production of RIs far from the stability line, as demonstrated at the present GSI facility. Another important feature of FAIR is the introduction of advanced ring families based on the success of the existing experimental storage ring (ESR). A new collector ring (CR) is designed for fast stochastic cooling of RI beams and isochronous mass measurements for short-lived RIs. A new experimental storage ring (NESR) equipped with electron cooling devices will allow precise mass measurements, internal-target experiments and electron-RI scattering experiments. Key technologies of the FAIR accelerator complex include rapid-cycling (4 T/s) superconducting magnets for SIS100, ultrahigh vacuum conditions with control of dynamic pressure increases for SIS100, high RF voltages for fast acceleration, and advanced electron and stochastic cooling techniques for experimental rings. The construction completion is scheduled in 2016 [30].

Future RIB Facility in North America

The advanced ISOL facility ARIEL [31] is under construction at TRIUMF, and a power-front in-flight facility FRIB [32] is proposed in the United States. The ARIEL project is an upgrade of the exiting ISAC facility. It aims to increase annual scientific productivity to two or three times its current level by introducing a superconducting electron linac as a photo-fission driver. A new production target with a new beam transport line from the existing K=500 proton cyclotron is also being planned.

FRIB employs a high-intensity sc-linac as a heavy-ion driver, which accelerates uranium ions up to 200 MeV/nucleon and protons up to 600 MeV with a maximum beam power of 0.4 MW. A high-intensity ECR ion source based on knowledge gained from VENUS [33] and an innovative technique for simultaneously accelerating multi-charge states have enabled a cost-effective proposal for this power-front facility. FRIB is planned to begin operation in 2017.

Table 4: Second-generation RIB facilities under construction or in the planning stage. For the three in-flight facilities, the energies and beam intensities listed are for uranium ions.

ISOL facilities	**Driver**	**Energy (MeV/A)**	**Power (kW)**	**Post accelerator**
HIE-ISOLDE (Cern/2016)	PS/proton	1400	10	REX upgrade, 10 MeV/A
SPES (INFN Legnaro, Italy/2012)	Cyclotron/proton	40	8	PIAVE-ALPI, 11 MeV/A
SPIRAL2 (GANIL, France/2013)	Sc-linac/deuteron	20	200	CIME cyclotron, 20 MeV/A
EURISOL (> 2020)	Sc-linac/proton	1000	5000	Sc-linac, 150 MeV/A
ARIEL (TRIUMF, Canada/2020)	e-linac + Cyclotron (proton)	50 for e 500 for p	500 for e 100 for p	Sc-linac, 18 MeV/A
In-flight facilities	**Driver**	**Energy (MeV/A)**	**Intensity (pps)**	**Separator**
RIBF (RIKEN, Japan/2006)	SC ring cyclotron	345	6×10^{12}	BigRIPS
FAIR (2016)	SIS100	1500	2×10^{11}	SuperFRS
FRIB (US/2017)	Sc-linac	200	5×10^{13}	3-stage separation

COMPARISON AND FUTURE SCOPE

As mentioned previously, the in-flight technique and the ISOL technique are complementary and it is difficult to compare RIBF with ISOL facilities. Therefore, we will discuss RIBF in comparison with FRIB and FAIR.

Both FRIB and RIBF employ accelerators operating in CW mode and expect similar performance for the ion source. However, the expected intensity for the uranium beam at RIBF is 0.27 pμA assuming that $^{238}U^{35+}$ uranium ions can be produced with intensity of 10 pμA by using the new ECR ion source, that the total charge-stripping efficiency is 4.5% (as already observed) and that the transmission efficiency of all remaining processes is 60%. This number corresponds to 1/30 of the beam intensity expected at FRIB. Half of this great difference results from the two-step charge-stripping scheme adopted at RIBF. The efficiency of the first charge stripper is only 16%. The remaining difference arises from the simultaneous acceleration of multi-charge states proposed for FRIB. The uranium beam intensity expected at FRIB is 1.6 (expressed as the ion-source output intensity averaged over the relevant two charge states), because FRIB is designed to accelerate two charge states (33+ and 34+) simultaneously before a charge stripper and to accelerate five charge states (77+ ~ 81+) up to the final energy, which cover 80% of all the charge states spread in the charge stripping process. In contrast, the total charge stripping efficiency is only 0.045 at RIBF, which means that the two-step charge-stripping scheme adopted at RIBF will become obsolete in the late 2010s. To avoid RIBF becoming a niche facility in the 2020s, one technically possible and modest upgrade plan is the introduction of a K=2300 MeV fixed-frequency superconducting ring cyclotron to replace the existing fRC, which would enable the present first-step charge stripper to be omitted, potentially leading to a 6-fold increase in the intensity of uranium ions. However, this intensity would still be one-fifth of that at FRIB, owing to its proposed multi-charge-state acceleration.

Another important factor to be considered is the energy-per-nucleon dependence of RIB intensity. For secondary neutrons produced by energetic protons, the neutron yield is nearly proportional to the proton beam power. However, this might not be the case for RI production via the in-flight technique. A speculation for a stronger energy-per-nucleon dependence of $E^{2\sim3}$ has recently been discussed for RIs far from the stability line [34], although this has not yet been proved. If true, FAIR, which is based on advanced synchrotron and experimental ring technologies, will be even more productive because of its high-energy nature. Another advantage of the FAIR project is its freedom from the charge-stripper problem, because FAIR uses only a conventional gas stripper before UNILAC injection, which is a well-established approach. Under the assumption that the energy-per-nucleon dependence is $E^{2.5}$, the expected yields of RIs produced by uranium beams with the intensities listed in Table 4 are all within a factor of 3 for FRIB, FAIR and RIBF.

In general, the beam intensity obtained from cyclotrons is thought to be less than that from linacs because of the small longitudinal acceptance of cyclotrons. Also, simultaneous acceleration of multi-charge states is impossible for cyclotrons. Hence, it is not a good choice for RIBF to pursue the frontier of driver-beam intensity. A more productive potential strategy may be pursuing additional energy upgrades towards the 1 GeV/nucleon region based on the SRC technology, because the cyclotron is still more cost effective choice than sc-linacs.

REFERENCES

[1] I. Tanihata et al., Phys. Rev. Lett. **55** (1985) 2676.

[2] For example, The Euroschool Lectures on Physics with Exotic Beams Vol. I ~ III were published in Lect. Notes in Phys. **651** (2004), **700** (2006) and **764** (2009).

[3] OECD Megascience Forum, Report on Working Group on Nuclear Physics, January 1999.

[4] O. Kofoed-Hansen, K. N. Nielsen, Phys. Rev. **82** (1951) 96.

[5] H. R. Ravn and B.W. Allardyce, "On-Line Mass Separators",in Treatise on Heavy-Ion Science, Edt. D. A. Bromley, Plenum Press, New York, 1989, ISBN 0-306-42949-7.

[6] B. L. Cohen and C. B. Fulmer, Nucl. Phys. **6** (1958) 547.

[7] T. M. J. Symons, 4th Int. Conf. on Nuclei far from Stability, CERN **81-09** (1981) 668.

[8] D. J. Morrissey and B. M. Sherrill, Lect. Notes. Phys. **651** (2004) 113.

[9] T. Nakagawa et al., Nucl. Instrum. Methods **B 226**, (2004) 392.

[10] O. Kamigaito et al., Rev. Sci. Instrum. **70** (1999) 4523. doi:10.1063/1.1150105.

[11] M. Odera et al., Nucl. Instrum. Methods **A227**, (1984) 187.

[12] A. Goto et al., Proc. 12th Int. Cyclo. Conf. p.51 and p. 439 (1989).

[13] Y. Yano, Proc. 13th Int. Cyclo. Conf. p. 102 (1992).

[14] T. Mitsumoto et al., Proc. 17th Int. Conf. on Cyclotrons and Their Applications, p. 384 (2004).

[15] J. Ohnishi et al., Proc. 17th Int. Conf. on Cyclotrons and Their Applications, p. 197 (2004).

[16] H. Okuno et al., Proc. 17th Int. Conf. on Cyclotrons and Their Applications, p. 373 (2004). H. Okuno et al., IEEE Trans. Appl. Supercond., **18** (2008) 226.

[17] K. Sekiguchi et al., EPJ Web of Conference **3**, 05024 (2010).

[18] N. Fukunishi et al., PAC09, Vancouver, May 2009, MO3GRI01.

[19] K. Suda et al., Cyclotrons'10, Lanzhou, Sep. 2010, MOPCP068.

[20] T. Nakagawa et al., Rev. Sci. Instrum. **79** 02A327 (2008). T. Nakagawa et al., Rev. Sci. Instrum. **81** 02A320 (2010).

[21] O. Kamigaito et al., Proc. of PASJ2-LAM30, WP78, (2006). K. Yamada et al., IPAC'10, Kyoto, May 2010, MOPD046.

[22] Y. Higurashi et al., IPAC'10, Kyoto, May 2010, THPEC060.

[23] H. Ryuto et al., Japanese Journal of Applied Physics **43** (2004) 775.

[24] M. Manzolaro et al., HIAT09, Venice, Italy, June 2008 MO-08.

[25] M. Lindroos et al., Nucl. Instrum. Meth. Phys. Res. **B 266** 4687 (2008). http://hie-isolde.web.cern.ch/hie-isolde/

[26] http://pro.ganil-spiral2.eu/spiral2. M. Leitowicz, Nucl. Phys. **A 805** 519c (2008).

[27] http://www.eurisol.org/site02/index.php.

[28] FAIR Baseline Technical Report, http://www.gsi.de/fair/reports/btr.html.

[29] O. Boine-Frankenheim, IPAC'10, WEYRA01, (2010).

[30] The FAIR modularized start version, GSI, Oct. 2009, http://www.gsi.de/documents/DOC-2009-Nov-124-1.pdf

[31] http://www.triumf.ca/research/future-facilities.

[32] R. C. Yoke, PAC'09, Vancouver, May 2009, M03GRI02.

[33] D. Leitner et al., Nucl. Instrum. Meth. Phys. Res. **B 235** (2009) 486.

[34] N. Aoi, private communication.