Title
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Publication Date
1990-04-01

LBL-28924

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the Workshop on the Science of
Intense Radioactive Ion Beams,
Los Alamos, NM, April 10–12, 1990, and
to be published in the Proceedings

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April 1990

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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This work was supported by the Director, Office of Energy Research, Office of High Energy & Nuclear Physics, Nuclear Physics Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

PRODUCTION OF HIGH INTENSITY RADIOACTIVE BEAMS

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Invited paper presented at the Workshop on the
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Abstract

The production of radioactive nuclear beams world-wide is reviewed. The projectile fragmentation and the ISOL approaches are discussed in detail, and the luminosity parameter is used throughout to compare different production methods. In the ISOL approach a thin and a thick target option are distinguished. The role of storage rings in radioactive beam research is evaluated. It is concluded that radioactive beams produced by the projectile fragmentation and the ISOL methods have complementary characteristics and can serve to answer different scientific questions. The decision which kind of facility to build has to depend on the significance and breadth of these questions. Finally a facility for producing high intensity radioactive beams near the Coulomb barrier is proposed, with an expected luminosity of $\sim 10^{39}$ cm^{-2} s^{-1}, which would yield radioactive beams in excess of 10^{11} s^{-1}.

1. Introduction

One of the central thrusts of nuclear science is the understanding of the properties of nuclear matter. Thanks to modern accelerator technology we are able to make almost all stable nuclei react with each other, giving rise to a plethora of phenomena involving electroweak and strong interactions, and creating new nuclei at the limits of stability. After more than three decades of heavy ion experiments, however, the limitations of our tools have become apparent. To explore the equation of state of nuclear matter and to search for phase transitions higher energies are necessary, and proposals are underway to address these topics. On the other hand, many open questions remain with regard to nuclear matter at moderate excitation energies; some of the most fascinating ones involving nuclei with extreme N/Z ratios. Many of these nuclei can not be synthesized with stable beams and targets and it was therefore proposed during the NSAC long range planning process last year [Nit89] to build a National High Intensity Radioactive Beam (RNB) Facility. There are several methods available to produce such beams and the purpose of this contribution to the workshop is to compare these approaches and to develop a working concept that may serve as a basis for further discussions. Table 1 gives an overview of several RNB facilities that are presently operating or in an advanced

Table 1. Radioactive beam facilities.

Project (Location)	Production Method, Instrument	Mass/Energy Range	Status
BEVALAC (LBL, Berkeley)	Fragmentation, Separator	$(A < 100)$ 30–500 MeV/u	Operating
SIS 18/ESR (Germany)	Fragmentation, Achromat, Storage Ring	$A < 238$ 5–500 MeV/u	1990/91
Hadron Project (INS, Tokyo)	Fragmentation, 1 GeV p + ISOL + Postacceleration	$A < 238$ 1–1000 MeV/u	Proposed
Meson Facility (Moscow)	Spallation, ISOL + Postacceleration	$A \leq 150$ $E \leq 600\ Q^2/A$	Proposed
TISOL/TRIUMF (Vancouver)	500 MeV p + ISOL + RFQ + LINAC	$A < 60$ ≤ 1 MeV/u	Operating/ Proposed
GANIL (Caen)	Fragmentation, Achromat, v-Filter	$A \leq 100$ (?) $E \leq 50$ MeV/u	Operating
CYCLONE I/II (Louvain)	30 MeV p + ISOL + Cyclotron	$A \leq 40$ (?) $E \leq 110\ Q^2/u$	Operating
ISOLDE (CERN)	Spallation, 600 MeV p + ISOL + Postacceleration	$A \leq 27$ $E \leq 1.4$ MeV/u	Proposed
TOFI LANL (Los Alamos)	Fragmentation, $B\rho$/ToF	$A \leq 60$ (?) $E \approx 4$ MeV/u	Operating
RPMS/A1200 (MSU)	Fragmentation, Achromat	$A < 100$ (?) $E = 1200\ Q^2/A$	Operating/ Planned
RIPS (RIKEN, Japan)	Fragmentation, Achromat	$A \leq 100$ (?) $E = 1300\ Q^2/A$	Proposed
RMS (NSRL, Rochester	Transf. Reactions, Recoil Separator	$A \leq 50$ (18 MV)	Operating
Daresbury (England)	CN Reactions, Recoil Separator	$A \leq 238$ (22 MV)	Operating
SC Solenoid (U. of Michigan, U. of Note Dame)	Transf. Reactions, SC Solenoid	$A \leq 40$ $E \leq 5$ MeV/u	Operating
QSBTS (LLNL, Livermore)	Transf. Reactions, Quadrupoles	$A \leq 20$ (12 MV)	Operating

proposal stage. (There is in addition a facility in Osaka that produces RNBs via transfer reactions.) Details and references on most of these facilities can be found in Ref. [Con89]. Included in Table 1 are some facilities that do not use RNBs to induce secondary reactions but are geared towards the study of the nuclear properties of the RNBs themselves. Figure 1 gives a schematic representation of the two principal RNB production methods: the ISOL approach and projectile fragmentation. In the following chapters we intend to compare the different production methods and comment on the quality of RNBs that they produce. The main characteristics we will try to evaluate are: 1. Intensity, 2. Energy, and 3. Beam quality (i.e., energy/momentum spread, transverse emittances, and beam purity). Information on recent developments in the emerging field of RNB research can be found in Ref. [Con89]. This was also the source of much of the data used in this contribution.

2. Production Methods

2.1 PROJECTILE FRAGMENTATION

Projectile Fragmentation (PF) becomes a significant reaction mechanism at heavy ion beam energies of ~50 MeV/u to several GeV/u. It is characterized by a peripheral interaction of the projectile with the target nucleus that leaves the projectile with much of its initial momentum and only a small angular spread. Details of this mechanism are discussed in a separate contribution to this workshop [She90]. Inherent in this reaction mechanism is that it produces a wide variety of nuclei with a large spread in A, Z and N/Z ratios, and it is in almost all cases necessary to employ a beam purification step before the RNBs can be used for secondary reactions or be studied themselves. Due to overlapping charge-to-mass ratios a purely magnetic separation is insufficient and a profiled energy degrader has to be introduced between the separator magnets, which leads to the concept of a "momentum loss achromat" [Sch87]. Even then, the beam purity may not be sufficient to study isotopes with extreme N/Z ratios that are produced with orders of magnitude lower cross sections than nuclei near β-stability. The LISE group at GANIL, for example, is therefore planning to add a Wien-type velocity filter after their achromatic spectrometer [Mue89] to suppress unwanted particles that overload the detection system and limit the primary beam intensity. The advantages of projectile fragmentation for the production of RNBs are: short separation times (~μs), no chemical selectivity, simple production targets (no large amounts of radioactivity), high product collection efficiency (≥50%) and reliable operation. (Some of these advantages are lost when the RNBs are decelerated in a storage ring.) The disadvantages are: low primary beam intensity compared to p, d and ^{3}He beams, target thickness limited by acceptable momentum spread Δp/p, high energies (300–1000 MeV/u) necessary to obtain fully stripped ions (q = Z) in the projectile fragment separator, poor emittance (depending on production mechanism), moderate beam purity, large momentum/energy spread, and deceleration/cooling difficult without intensity loss.

To compare different RNB production methods the concept of "luminosity" L in units of $\text{cm}^{-2}\ \text{s}^{-1}$ will be used, which is the product of beam intensity times effective target thickness. This eliminates the cross section dependence of the yield, which is justified in particular for the comparison between the PF and the spallation and fragmentation

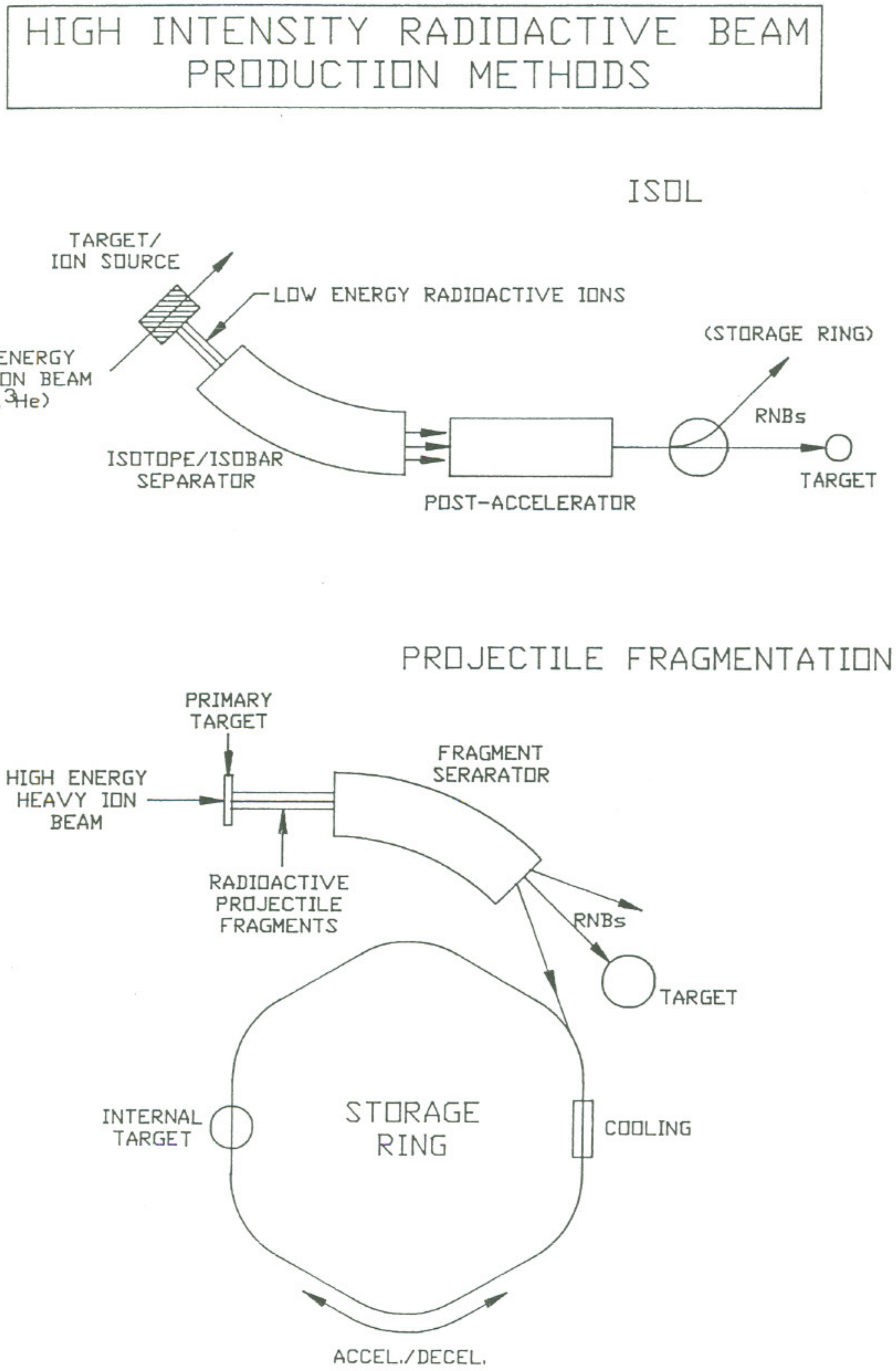

Figure 1. Schematic representation of two approaches to the production of high intensity radioactive beams: the ISOL method (top) and the projectile fragmentation method (bottom). (For details see text.)

reactions used in the on-line isotope separator (ISOL) techniques, which will be discussed later, since one is the kinematic inverse of the other and the cross sections are, therefore, in most cases similar. Actual yields Y can be obtained from $Y = \sigma L$ (s^{-1}) where σ is the cross section in cm^2. It should be emphasized that luminosity is only one of several important criterial for evaluating RNB facilities; others being: energy, beam purity, time structure, transverse emittances, and (A,Z) ranges. In Table 2 the production luminosity L_p is calculated for different PF facilities and operating parameter ranges; it reaches a maximum of 3×10^{-35} $cm^{-2}s^{-1}$ for the fragment separator at GSI (GSI/FRS). A special case is the U. of Michigan-U. of Notre Dame facility (UM-UND) that produces RNBs via transfer reactions, where the luminosity is limited due to delicate thin targets and consequently low primary beam intensity. This is, however, often compensated by relatively large resonant cross sections. The last row in Table 2 shows the principal parameters of a potential future PF facility discussed in these proceedings [She90] where the luminosity is increased by one order of magnitude over GSI/FSR by increasing the primary beam intensity correspondingly.

2.2. STORAGE RINGS

Thus far the only way to decrease the energy of secondary beams has been to interpose degraders in the beam path. These not only degrade the energy but unfortunately also the beam emittance. A more elegant (and costly) way is being realized at GSI where the PF separator FRS is coupled to an experimental storage ring ESR. The full momentum bite of $\Delta p/p = 2\%$ of the FRS can be injected into the ESR.

Table 2. Examples of radioactive beam production by projectile fragmentation and transfer reactions. Ranges of primary beam energy E_p, intensity I_p, and target thickness t are given and the RNB production luminosity L_p is calculated.

Facility	E_p(MeV/u)	I_p(s^{-1})	Target	t(g/cm^2)	L_p($cm^{-2}s^{-1}$)
Bevalac	200–1000	10^9–10^{10}	^{9}Be	2–5	10^{32}–3×10^{33}
GSI/FRS	100–1000	10^7–5×10^{11}	^{12}C	0.1–10	5×10^{28}–3×10^{35}
MSU/A1200	45–100	3×10^{11}	^{6}Li	0.5–1.5	$(2–5)\times10^{34}$
GANIL/LISE	30–95	10^{10}–2×10^{12}	^{58}Ni/^{181}Ta	0.2–0.4	8×10^{30}–10^{34}
UM-UND	2–3	~6×10^{10}	TiH_2	~10^{-3}	~3×10^{28}
Future Facility[a)]	300–1000	6×10^{12}	^{9}Be	4–18	$(2–7)\times10^{36}$

a) Under discussion.

One of the main objectives of the ESR is to cool the "hot" RNB beams stochastically and via momentum exchange with a "cold" electron beam, and to decelerate them to lower energies. While this will produce beams with excellent longitudinal and transverse emittances, the time scale for cooling and deceleration is on the order of 0.1 to a few seconds and hence nuclei with short half-lives will be lost. Furthermore, it is estimated that phase space density considerations will limit the beam intensity from the FRS that can be cooled stochastically to $10^7\ s^{-1}$. If deceleration to Coulomb barrier energies is desired the e^-–cooling may limit the beam intensity to $10^6\ s^{-1}$ [Mun90]. For internal target experiments these beam intensities are boosted by a factor $\sim 2 \times 10^8$ due to the circulating beam and multi-turn injection, which yields effective beam currents of up to $2 \times 10^{15}\ s^{-1}$. For uncooled beams intensities up to $2 \times 10^{16}\ s^{-1}$ are expected [Mun89]. With an internal target density of $\sim 2 \times 10^{14}\ cm^{-2}$ a maximum target luminosity L_T of $4 \times 10^{30}\ cm^{-2}s^{-1}$ can be achieved. The luminosity gain G for an experiment using the internal target in the ESR ($\sim 2 \times 10^{14}\ cm^{-2}$) versus a single pass experiment with an external target is about $G \approx 7 \times 10^{-2}\ A/\rho$ where A is the external target mass number and ρ its density in g/cm^2. For a thin 10 mg/cm^2 carbon target this works out to $G \approx 80$, which is significant considering in addition the good emittance properties of the internal beam. It is obvious that for thicker external targets the advantages of the storage ring will diminish. Table 3 taken from Ref. [Muh89] gives a summary of expected efficiencies for primary and secondary reactions at the GSI facility.

2.3 ISOL METHOD

The on-line isotope separator ISOL method takes a complementary approach to the production of RNBs: a high energy beam of light particles (p, d, or ^{3}He) impinges on a heavy target and produces radioactive nuclides via spallation, fission, or target fragmentation. If the target is thin the recoiling nuclei emerge from the target and can be collected on aerosol particles suspended in a He gas atmosphere, and transported to a

Table 3. Efficiencies for primary and secondary reactions at GSI.

Fragment production	Target (carbon)	0.1 – 10	g cm^{-2}
	SIS Beam	$10^7 - 5 \times 10^{11}$	s^{-1}
	Luminosity	$5 \times 10^{28} - 2 \times 10^{35}$	s^{-1} cm^{-2}
Single pass experiments with secondary beams	Target (lead)	100	mg cm^{-2}
	Secondary Beam	$50 - 10^8$	s^{-1}
	Luminosity (100mg/cm^2)	$10^{21} - 10^{29}$	s^{-1} cm^{-2}
Stored beam experiments in ESR (100 bunches circulating)	Gas Target	2×10^{14}	cm^{-2}
	Effective Beam	$10^{10} - 2 \times 10^{16}$	s^{-1}
	Luminosity	$2 \times 10^{24} - 4 \times 10^{30}$	s^{-1} cm^{-2}

collection device or introduced into an ion source as shown in Fig. 2. The ion source serves as the first stage of an acceleration process that is common to all ISOL/RNB methods since the recoil velocities in the light ion reactions are too low to be of any practical use for inducing secondary reactions. The acceleration process will be discussed below. The basic idea behind the thin target approach is that the reduced target thickness is compensated by a very intense primary beam: up to 1 mA of 800 MeV protons from LAMPF, for example [Tal90].

In the thick target ISOL approach the primary beam intensities are about an order of magnitude lower and the targets are ~10^4 times thicker. The recoils stop in the hot target, diffuse to the surface from which they desorp, and enter an ion source for acceleration. Table 4 shows several operating or proposed RNB facilities and their operating parameters. Special mention should be made of the RNB facility at Louvain where intense beams of ^{13}N are being produced with a low energy proton beam (30 MeV) of up to 0.5 mA current on a 1 g/cm^2 ^{13}C target. A similar facility EB-88 is being proposed for the 88-Inch Cyclotron at LBL.

EB-88

Comparing the thin to the thick target app
noted: intense primary beam, simple target c
target diffusion/ desorption problems, and r
Some of the disadvantages of the thin target a
target thickness is further reduced for spallation
may cause reduced beam purity and ion source cc
transported, efficient He-jet/ion source coupling is
load will affect the efficiency, in particular for charg

Advantages of the thick target methods are: thick
beams, high beam purity (element dependent), and

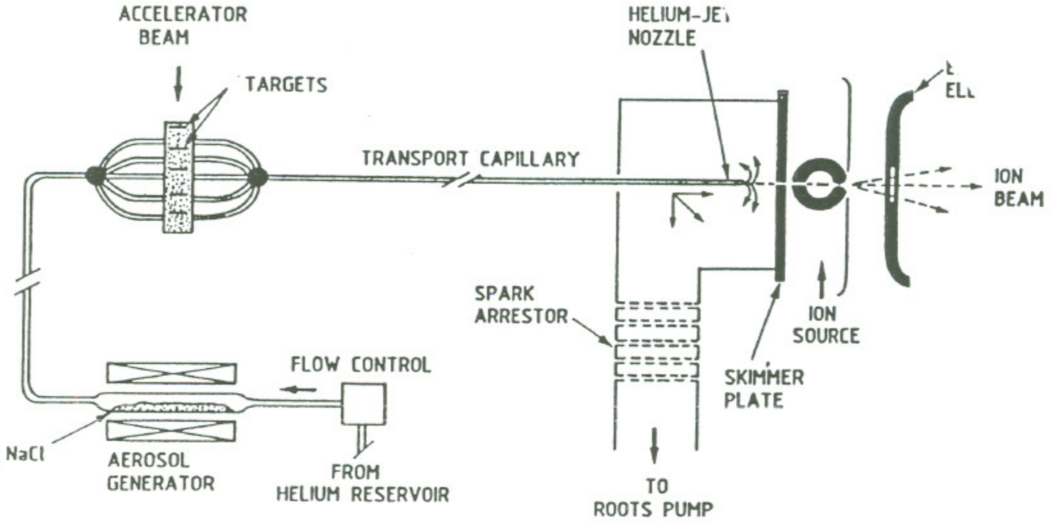

Figure 2. Schematic representation of the thin target version of the ISOL method for RNB production. Only the first three stages involving the target, the He-jet and the ion source are shown. The isotope/isobar separation, acceleration and storage ring would be similar to the scheme shown in Fig. 3.

Table 4. Examples of radioactive beam production via the ISOL method, using spallation, target fragmentation and fission reactions. Ranges of primary beam energy E_p intensity I_p and target thickness t are given, and the production luminosity L_p is calculated.

Facility	Beam	E_p(MeV)	$I_p(s^{-1})$	Target	t(g/cm^2)	$L_p(cm^{-2}\ s^{-1})$
Louvain	p	30	3×10^{15}	^{13}C	1	$\leq10^{38}$
TISOL	p	500	$(1–2)\times10^{12}$	a)	1–15	$3\times10^{33}–2\times10^{35}$
(Proposed)	p	500	3×10^{13}			$\sim3\times10^{36}$
ISOLDE	p, ^{3}He	600/910	2×10^{13}	b)	3–170	$\leq10^{37}$
(Proposed)	p, ^{3}He	600/910	3×10^{13}	c)		$(1–7)\times10^{37}$
JHP (Proposed)	p	1000	$\sim6\times10^{13}$	b)	50–300	$\sim2\times10^{37}–10^{38}$
Moscow (Proposed)	p		$\sim10^{15}$	b)	10–100	$(1–3)\times10^{38}$
EB-88, LBL (proposed)	p	30	3×10^{15}	b)	1	$\leq10^{38}$
Future Facility$^{d)}$ (Thin Target)	p	800	6×10^{15}	Th	$\sim5\times10^{-2}$	$8\times10^{35}–2\times10^{36}$
Future Facility$^{d)}$ (Thick Target)	p, d, ^{3}He	500–1000	1×10^{15}	b)	50–300	$10^{38}–10^{39}$

a) Targets of ^{48}Ti, ^{93}Nb, ^{90}Zr, ZrC, SiC, and UO/C heave been used; b) A variety of targets can be used; c) Production of light RNBs; d) under discussion.

designs. Some of the disadvantages are: yield strongly dependent on target/radioactive-product chemistry, and large amounts of unwanted radioactivity and high radiation fields are generated.

As was done for the PF method in Table 2, the production luminosities L_p for the different ISOL based RNB facilities were calculated and are shown in the last column of Table 4. The high luminosities of $\sim 10^{38}$ $cm^{-1}s^{-1}$ for the low-primary-beam-energy facilities (Louvain, EB-88 LBL) should be particularly noted, since it results in the production of intense RNBs near β-stability. In a suggested facility that will be discussed in greater detail below, using the thick target approach, a production luminosity of 10^{39} $cm^{-2}s^{-1}$ can be obtained (last row in Table 4).

The luminosity in the thin target approach is $\sim 10^3$ smaller than in the thick target case. Assuming that ion source and post-acceleration efficiencies would be the same this would result in similarly reduced final beam intensities. Table 5 gives a summary of the qualitative comparison between the two ISOL methods and the PF method.

3. Comparison Between Projectile Fragmentation and ISOL Method

A comparison between the PF and ISOL methods is difficult since the two are essentially complementary. For the purpose of this discussion we will assume that the parameters for the two hypothetical facilities shown in the last rows of Tables 2 and 4 are realistic. We will further assume that the PF luminosity is reduced to the range of $(1\text{–}4) \times 10^{36}$ $cm^{-2}s^{-1}$ due to transmission losses through the separator and that the ISOL luminosity is reduced by $(.5\text{–}5) \times 10^{-2}$ due to losses in the ion source, the isotope/isobar separator, stripping and acceleration, giving an effective luminosity range of 5×10^{35} – 5×10^{37} $cm^{-2}s^{-1}$. This brings the two luminosities much closer together and the expected beam intensities could be similar within an order of magnitude. However, the beam characteristics would be very different! The projectile fragment beam would be in the energy range of 300–1000 MeV/u with a relatively large momentum spread and transverse emittance, depending on the production mechanism, while the post-accelerated ISOL beam would have an energy of ~10 MeV/u with the beam quality of a modern normal or superconducting LINAC, for example. The physics that can be addressed by the two devices is very different and the decision which kind of facility to build has to depend on the significance and breadth of the scientific questions that can be answered.

It was pointed out earlier that if the PF beam is to be decelerated to the Coulomb barrier the maximum beam intensity, in the ESR for example, is limited to $\sim 10^6$ s^{-1}. At a PF luminosity of 4×10^{36} this corresponds to a production cross section of ~0.3 μb. At this cross PF section the ISOL facility would deliver similar beams of 1×10^5 – 1×10^7 s^{-1}. At cross sections larger than ~0.3 μb the ISOL facility would, however, produce larger beams than the storage ring since it does not have any saturation characteristics. For cross sections of, say, 10 mb near β-stability this can amount to a factor 5×10^3 to 5×10^5 higher intensity in the ISOL case over the storage ring operated as a "cooler"/decelerator. Even taking the increased luminosity of internal target experiments in the storage ring into account there is still a significant advantage of the ISOL approach for beams near the Coulomb barrier. The highest luminosity is, however, obtained when the ISOL approach is combined with a storage ring. This will be discussed in the next chapter. In Table 6 a comparison between a future PF and an ISOL based high intensity RNB facility is attempted.

Table 5. Comparison of different high intensity RNB production methods

Production Method	Advantages	Disadvantages
Projectile Fragmentation	• Short separation times (~μs)[a)] • No chemical selectivity • Simple production target (no large amounts of radioactivity) • High product collection efficiency (≳50%) • Reliable operation	• Low primary beam intensity compared to p, d, ^{3}He • Target thickness limited due to momentum spread $\Delta p/p$ • Poor emittance (depending on production mechanism) • Moderate beam purity • Large momentum/energy spread • Deceleration/cooling difficult without intensity loss[b)] • Tertiary reactions
ISOL (thick target)	• Thick targets • Intense primary beams • High beam purity (element dependent) • Excellent beam quality (emittance) • Low energy spread • Experience in target/ion source design	• Yield strongly dependent on target/product chemistry • Large amounts of unwanted radioactivity, high radiation fields, robots • Delay due to diffusion/desorption (element dependent) • Post-acceleration necessary
ISOL (thin) He-jet (target)	• Intense primary beam (~1 mA) • Simple target design • No target diffusion/desorption problems • Ion source is in a low radiation field • Rare target materials can be used • Excellent beam quality • Low energy spread • Not chemically selective	• Thin targets, effective target thickness is further reduced for spallation products • Not chemically selective, reduced beam purity, ion source contamination • Delay due to sweep-out and transport • High ion source gas load, low yield for charge states $q > 1$ (ECR) • Volatile species cannot be transported • Efficient He-jet/ion source coupling is difficult • Post-acceleration necessary

a) No advantage when storage ring is used; b) ions can not be shared except in a ring.

Table 6. Performance comparison between a future PF and an ISOL based RNB facility.

	PF	PF + Ring (100 turns)	ISOL (thick target)	ISOL + Ring (3000 turns)
Energy range (MeV/u)	300–1000	10–500	0.001–10	~1–10
Momentum width (%)	1–5	~0.001a)	~0.1	~0.001a)
Emittance (πmm•mrad)	~20	0.1a)	0.2–1	0.01(?)a)
Production Luminosity L_p ($cm^{-2}s^{-1}$)	$(2–7)\times10^{36}$	—	$10^{38}–10^{39}$	—
Target Luminosity L_t ($cm^{-2}s^{-1}$)	$3\times10^{30} – 10^{31}$b)	$\leq4\times10^{30}$c)e) $\leq4\times10^{28}$a)e) $\leq4\times10^{29}$e)f)	$2\times10^{28}–2\times10^{30}$d)	$\sim10^{31}–10^{32}$c)e) $\sim10^{30}–10^{31}$a)e)

a) e^--cooled.

b) production cross section: $\sigma_p = 10$ mb, transmission: 50%, target: Pb 100 mg/cm^2.

c) uncooled.

d) production cross section: $\sigma_p = 10$ mb, acceleration efficiency $(.5–5)\times10^{-2}$, target: Pb 1 mg/cm^2.

e) internal target: 2×10^{14} cm^{-2}.

f) stochastically cooled.

4. A High Intensity Low Energy RNB Facility

Thoughts similar to those presented in the previous chapters have led to the development of a "working concept" for a high intensity low energy RNB facility based on the thick target approach. It should, however, be pointed out that the ideas discussed in this chapter are preliminary and represent the personal opinions of the author at this time (April 1990).

For a future facility the thick target ISOL approach was chosen because, as was shown above, it will produce the highest intensities and the best beam qualities of low energy (0.1–10 MeV/u) RNBs of the methods investigated. The effective luminosity of the proposed facility, i.e., the luminosity after taking losses due to ionization, etc., into account, is expected to be in the range of 5×10^{35} to 5×10^{37} cm^{-2} s^{-1} (2×10^{38} for light ions). This means, in practical terms, that an exotic nucleus that is produced by the interaction of the primary proton beam and the target with, for example, a cross section of 1 mb will be available as a radioactive beam with intensities between 5×10^8 and 5×10^{10} s^{-1} (depending on A and Z) and energies up to 10 MeV/u. (For energies of ~100 keV the intensities may be 10 times higher).

The concept of the facility is shown schematically in Fig. 3. A light particle beam of 500–1000 MeV energy and 100–300 μA intensity traverses a 100–300 g/cm^2 thick target where it looses ~200 MeV of energy and generates ~40 kW of power. The radioactive species emanate from the hot target and undergo a chemical/physical separation step that removes unwanted activities. This is followed by an ion source that produces radioactive ions with charge-to-mass ratios $Q/A \gtrsim 0.01$. The ions are accelerated to an energy of ~100 keV and undergo a coarse separation in an isotope separator. Satellite beams will be available for low-energy RNB research similar to ISOLDE at CERN. The low energy RNB beam is then subjected to further analysis to remove unwanted isobaric nuclei and is injected into a low-β, low Q/A preaccelerator. At an intermediate energy of 1–1.5 MeV/u the RNB ions are stripped and subsequently post-accelerated to the final energy of maximally ~10 MeV/u. They can now be used in "conventional" single pass experiments or injected into a storage ring. The main purpose of the storage ring is to make optimal use of the RNB ions by employing multi-turn injection, cooling and "stacking" of the beam, and having the RNB ions traverse an internal target. The heating of the beam by the internal target and the small energy loss is continuously conpensated by electron cooling. If an accumulation factor of $\sim 10^3$ can be achieved (ESR:10^2, IUCF Cooler: 6×10^3) a significant gain in luminosity for an internal target experiment over an external single-pass target can be expected (c.f. Table 6). The storage ring scheme will, however, only work *efficiently* if a difficult condition can be achieved: the injecting accelerator and the ion source have to be *pulsed* and the radioactive ions should be *stored* between beam pulses. Pulsed operation would also greatly reduce the cost of the accelerator due to lower power requirements. The storage ring could then also function as *stretcher* providing external beams with large duty factors.

There are many questions regarding the operation of the storage ring that remain to be answered, but it should be emphasized that the viability of the presented concept does not depend on the storage ring option.

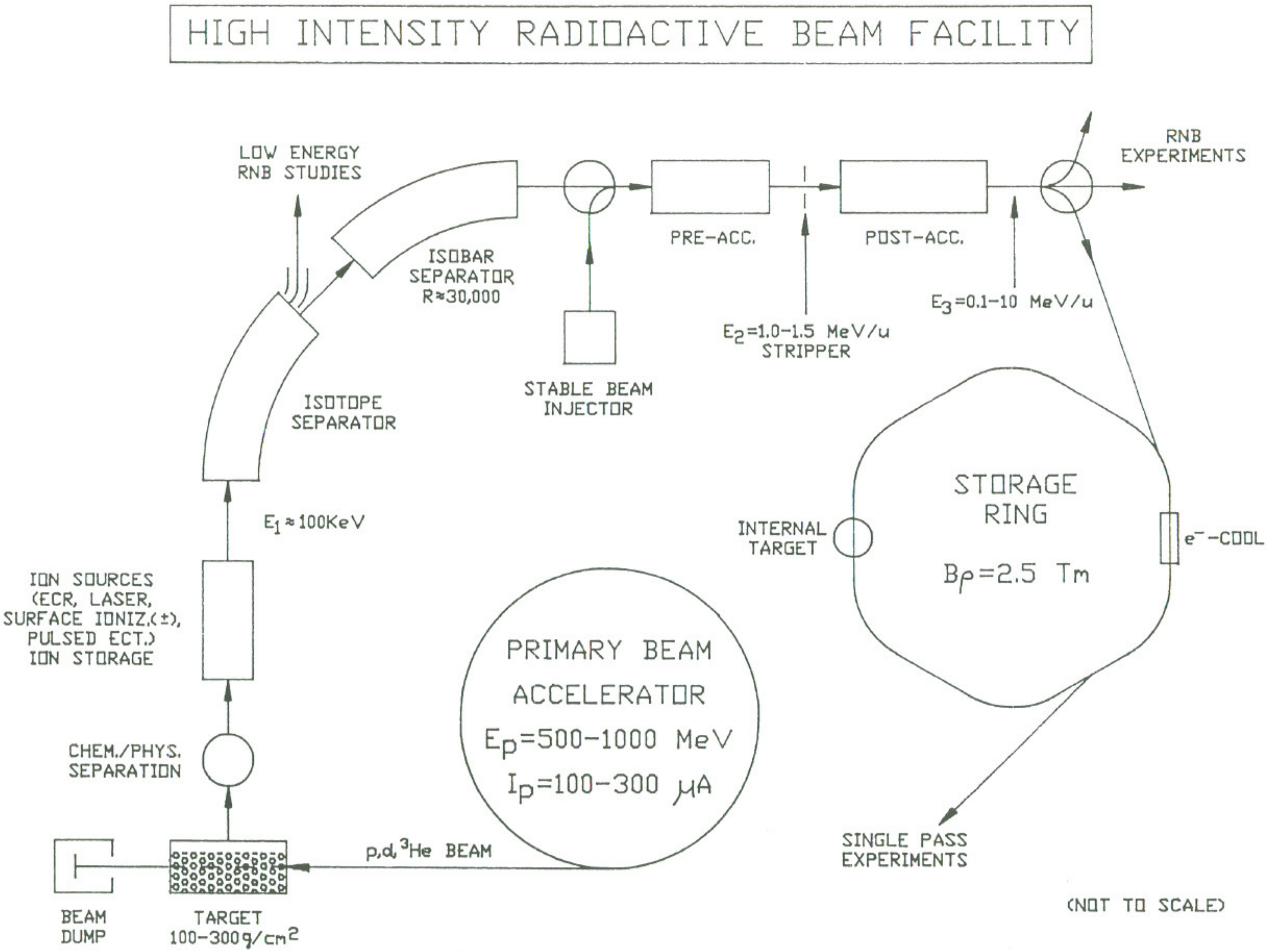

Figure 3. Schematic representation of a proposed high intensity RNB facility based on the thick target version of the ISOL approach. (For details see text.)

Table 7. Technical research and development topics related to a High Intensity RNB Facility.

A. General

- Development of efficient detectors for experiments with low beam intensities
- Exploration of the role of storage rings in RNB research, internal targets, etc.

B. Projectile Fragmentation Method

- Design of a High Energy (300–1000 MeV/u) High Intensity ($\sim 6\times10^{12}\ s^{-1}$) Heavy Heavy Ion Accelerator (~10×SIS18)
- Improvement of secondary beam purification techniques
- Efficient deceleration/cooling techniques

C. ISOL Method (Thick Target)

- Cost effective primary beam production (500–1000 MeV, p, d, ^{3}He; 100–300 μA)
- High beam power targets (≲50 kW)
- Element specific target matrices
- Physical/chemical purification schemes
- Ion source research: high efficiency for low to moderate charge states ($1^+ - 3^+$), high temperature operation, chemical selectivity, laser, pulsed operation, storage capability (traps)
- Charge state boosters: EBIS/ECR, stripping
- Radiation hardened target/ion source components, robotics
- Low-β, low Q/A preaccelerator
- Post-acceleration

D. ISOL Method (Thin Target)

- High intensity (~1 mA) beam studies of thin (multiple) targets, target life time
- Spallation yields
- Physical/chemical purification
- Efficient He-jet/ion source coupling
- High pressure ion source operation (charge states $1^+ - 3^+$)
- Post-acceleration

5. Conclusions

There has been a widespread interest in the nuclear physics community regarding questions that can be addressed with radioactive beams. While several years ago the concept of accelerating radioactive ions was rejected as a "crazy" idea, it has now become possible to produce radioactive beams of sufficient intensity for a wide range of experiments, as discussed at this and several previous workshops, and at the first international conference on this topic [Con89]. The feasibility of such a project has increased dramatically in recent years due to many technological advances: high intensity proton and heavy ion accelerators, superconducting linacs, RFQs, storage rings, electron and stochastic cooling, ECR sources, multi-photon ionization, magnetic separators . . . to mention only a few. There remain, however, several R&D topics specific to a future high intensity RNB facility that need to be addressed. For brevity a list of R&D topics that does, however, not make any claim to completeness is presented in Table 7. The breadth of the necessary research is such that it will require the collaboration of many Laboratories and Universities, and the entire endeavor will benefit greatly from international cooperation.

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