LINEAR ACCELERATORS FOR EXOTIC ION BEAMS

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Abstract

One of the new frontiers in nuclear science is the use of exotic ion beams. In the past, nuclear reaction studies were restricted to the use of stable projectiles or a few long-lived isotopes. The possibility of producing intense exotic ion beams opens a wide variety of research opportunities in nuclear astrophysics, nuclear physics, material sciences, etc. This field has grown considerably in the past ten years owing to progress in the production techniques of isotopic separation on-line and in particular in the field of heavy-ion accelerators. One of the breakthroughs is the possibility to accelerate very low energy heavy-ions using a low frequency RFQ at the front end of a linear accelerator.

This paper will review exotic ion beam facilities, based on the ISOL method, using or proposing a linear accelerator as a post-accelerator.

1 INTRODUCTION

The opportunities offered by beams of exotic nuclei for research in the areas of nuclear physics, nucleosynthesis and nuclear astrophysics, and for critical tests of fundamental symmetries, are very exciting. The worldwide activity in the installation of different types of facilities for exotic nuclei reflects the strong scientific interest in the corresponding physics.

The choice of the post accelerator depends on the physics program, which defines the energy and mass range, duty factor and pulse characteristics of the desired ions. This paper reviews only exotic ion beam facilities using LINAC's as post-accelerators. One LINAC has already being built for exotic beam applications, this is the prototype of the JHF E-arena at INS-Tanashi, now, KEK-Tanashi. Two more LINAC's are under construction: one at ISOLDE-CERN and the other at ISAC-TRIUMF. Proposals for second generation exotic ion beams facilities based on the ISOL method which have selected a LINAC as post-accelerator are: JHF E-arena, Argonne National Laboratory, Oak Ridge National Laboratory, Munich and ISAC2 at TRIUMF. A proposed upgrade of the accelerator of the BRNBF in Beijing will also be mentioned.

2 EXISTING RIB LINAC FACILITIES

2.1 E-arena Prototype at Tanashi

A prototype radioactive ion beam facility has been built at KEK-Tanashi. The main components are: target/ion source, mass separator, RFQ and IH linear accelerators. The exotic species are produced using the ion beams extracted from the INS SF cyclotron. The exotic ions are then accelerated to energy ≤ 1 MeV/u through a split-coaxial RFQ (SCRFQ) and an interdigital-H type (IH) linacs. The project is regarded as a prototype of the more ambitious RIB facility for the E-arena in the proposed Japanese Hadron Facility (JHF). The main accomplishments were:

1) Test off- and on-line of target/ion-source systems, ECR, plasma and surface ion sources;
2) Off- and on-line beam tests of the ISOL system as well as the construction of the beam-transport system;
3) Construction and operation of a 25.5 MHz split-coaxial 4-rod RFQ;
4) Construction and operation of a 51 MHz IH linac composed of 4 tanks;
5) Construction and operation of the stripping and matching section between the RFQ and the IH LINACs.
6) Pilot experiments with exotic beams.

2.1.1 Split-Coaxial RFQ LINAC

The split-coaxial RFQ is designed to accelerate ions with charge-to-mass ratio (q/A) ≥ 1/30 from 2 to 172 keV/u. The split coaxial resonant cavity was invented by R. W. Müller[1] and development and investigation took place in several institutes: GSI[2], Frankfurt[3], and Argonne[4].

Various kinds of electrode structure have been proposed: modulated vanes, circular rods, drift tubes with fingers. At INS they selected modulated vanes. In order to achieve easy assembly of the vanes and a stable mechanical structure, a multi-electrode cavity is employed. Two opposite electrodes are fixed and electrically grounded at one end of the cavity. The other opposite electrodes are fixed and grounded at the other end of the cavity. That is, the electrodes are supported at only one point.

The module length, 0.7 m, was determined so that the drop of the vanes due to gravity may not exceed 35µm, with the cavity diameter not exceeding 1m. By introducing spacer rods, it was possible to align the vanes with accuracy better than ± 40 µm before installation into the unit-cavity tank.

The cavity, comprising 12 module cavities, is 0.9 m in diameter and 8.6 m long. The measured resonant resistance is 25.55 ± 0.44 kΩ. The measured unloaded Q-value is 5800. The nominal vane voltage is 109 kV for q/A ≥ 1/30 ions. This corresponds to an input power of 240 kW. The maximum duty factor is 30%.

2.1.2 Medium Energy Beam Transport (MEBT)

The MEBT system between the SC-RFQ and the IH LINAC comprises a charge stripper (Carbon foil of 10 $\mu g/cm^2$), a rebuncher and two quadrupole doublets. Since a frequency of 25.5 MHz is required for the rebuncher, a double-coaxial resonator with 6 gaps was developed to maintain the size of the cavity small and the power low.

2.1.3 Interdigital-H type LINAC

The Interdigital-H LINAC is composed of four tanks. It accelerates ions with charge-to-mass ratio ≥ 1/10 from 172 to 1053 keV/ nucleon. In order to obtain high shunt impedance, the accelerating mode is π-π, and no transverse focusing element is installed into the drift tubes. The operating frequency is twice the RFQ frequency. Each gap length between drift tubes is equal to one half of the first cell length. Both end structures of the cavity, *i.e.*, the magnetic flux inducer and the gaps between end-wall and ridges are determined experimentally so that the longitudinal field distribution becomes flat over the cavity. The synchronous phase is –25° to assure a stable longitudinal motion.

The tuning of the cavities is achieved using three kinds of tuners: a capacitive tuner (C-tuner), an inductive end-tuner (End L-tuner) and an inductive piston tuner (L-tuner). The C-tuner is a manually movable disk facing a ridge; The L-tuner is moved automatically to compensate for the frequency shift.

The first acceleration of an exotic ion beam has been carried out successfully on Mach 14th, 1997 at the INS prototype E-arena.

2.2 ISAC-TRIUMF

2.2.1 RFQ

A cw radio-frequency quadrupole provides the initial acceleration of the ion beam delivered by the ISOL. The total length of the vane-shaped rods is 7.60 m. Given that the radioactive ion beam intensity will be small, space charge can be neglected. A truncated Yamada-style recipe was used for the vane profiles. Due to a requirement from the experimenters for 86 ns time structure, beam bunching is achieved in an external, quasi-sawtooth pre-buncher. The shaper and gentle buncher portions of the RFQ are omitted, leading to substantial shortening. The pre-buncher is located in the LEBT section ~ 5 meters from the RFQ. A 4-rod split-ring RFQ structure has been chosen because of its relatively high specific shunt impedance, its mechanical stability, and the absence of voltage asymmetries in the end region[6]. It is a variation of the 4-rod RFQ built by Schempp[5]. The thermal and dynamic stability have been measured and are well within tolerance[7]. The final RFQ will be composed of 19 modules, but in order to test the beam dynamics and the injection of a bunched beam into the RFQ a 7-ring-RFQ section has being built installed in the 8 m long tank and tested first.

A $^{14}N^+$ beam test with the ISAC split-ring 4-rod RFQ has been successfully completed in June 1998. 7 of the 19 rings were installed for a final beam energy of 54 keV/u. The RFQ was operated in continuous wave (cw) mode. Operation at the nominal peak voltage of 74 kV was achieved in July 1998. This allowed the acceleration of $^{14}N_2$ (q/A = 1/28). The beam transmission was 80% at the nominal voltage in perfect agreement with PARMTEQ calculations. The energy spread of both bunched and unbunched ^{14}N and $^{14}N_2$ beams was measured and showed good agreement with PARMTEQ calculations.

2.2.2 Stripper and matching section

The charge-state selector is composed of a symmetric QQDDQQ section. A four-quadrupole system and a 35 MHz $\lambda/4$ rebuncher provide transverse and longitudinal match into the DTL. Provision is also made for installation of a rebuncher between the RFQ and the stripping foil to produce an upright ellipse for the longitudinal emittance at the stripping foil.

Several options for the 35 MHz $\lambda/4$ rebuncher were investigated. It is likely that a spiral $\lambda/4$ will be used.

2.2.3 Drift-Tube Linac

The drift tube linac is required to accelerate, in cw mode, ions with a charge to mass ratio ≥ 1/7 from 0.15 MeV/u to a final energy variable between 0.15 and 1.5 MeV/u. An IH structure[8] is chosen because of its very high shunt impedance. A *separated function* DTL concept has been adopted[9]. Five independently phased IH tanks operating at Φ_S = 0º provide the main acceleration. Longitudinal focusing is provided by independently phased three-gap split-ring resonator structures positioned before the second, third and fourth IH tanks. When operating at full voltage the beam dynamics resembles that of a so-called 'Combined 0° Synchronous Particle Structure'[8]. To reduce the final energy, the last IH tanks may be turned off while voltage and phase of the last powered tank are varied. The split-ring resonators are all designed for β = 0.023 and are effective over the whole DTL velocity range. They also permit the beam to be kept well bunched over the entire energy range.

The first ISAC-IH-DTL tank has been built and is waiting for copper plating. Cooling channels are machined in bulk copper material to assure efficient cooling.

2.3 REX-ISOLDE

REX-ISOLDE is a first generation RIB project aimed at exploring the possibility of an efficient post acceleration of exotic ions based on LINAC after charge breeding with a trap-EBIS system.

The LINAC complex is composed of a 4-rod RFQ, an IH-structure and three seven-gap spiral resonators. To match the phase spread of the ion beam out of the RFQ to the longitudinal phase acceptance of the IH-structure a three-gap split ring resonator is used. The maximum duty cycle is 10% with a maximum repetition rate of 50 Hz.

To reduce the cost of the LINAC a charge-to-mass ratio of 1/4.5 was chosen. Highly charged ions can be produced using an Electron Cyclotron Resonance Ion Source (ECRIS) or an Electron Beam Ion Source (EBIS). For a RIB facility it is essential to get high efficiency charge state breeding from 1+ to n+ ions and in a short time compared to the half-life of the nucleus considered.

2.3.1 REX-ISOLDE charge breeding scheme

In the REX-ISOLDE scheme a Penning trap is used for accumulation, cooling, and bunching[10]. The Penning trap is however limited in the number of particles which can be trapped. The maximum ion density for the REX-Penning trap is estimated for A = 140 at 10^6 ions/mm^3, which correspond to some 10^8 ions per accumulation cycle.

The Penning trap is located on a high voltage platform an the same potential as the singly charged ion source at the ISOLDE target. The transfer line consists of two electrostatic benders and two electrostatic quadrupole doublets. The confinement time required to reach a charge-to-mass ratio larger than 1/4.5 is less than 20 ms. The EBIS magnet has a magnetic field of 2 T with an homogeneity of about 2.5‰ along the confinement length of 0.8 m. The ions ejected from the EBIS are mass analyzed with a magnetic achromat composed of two 90° dipoles.

2.3.2 The 4-rod RFQ

The ions are accelerated from 5 to 300 keV/u by a 4-rod RFQ. This RFQ is similar to the one used for the High-Current -Injector at Heidelberg[11] and the GSI HLI-RFQ[5]. The results from these two RFQ show that about a quarter of the power is dissipated on the ground plate of the resonator. The new REX-RFQ will have additional cooling of the ground-plate, which must have a better electrical contact to the stems along the entire structure. Furthermore, for the cooling of the electrodes a new stem design has been made at Hiedelberg. The main characteristic of the new design is that channels for cooling water are now completely inside the stem.

Regarding the particle dynamics, they add to the present design a so-called “matching out section” at the high-energy end of the RFQ. The focusing strength is reduced stepwise at the last cells of the accelerator. This leads to decreased beam divergence at the exit of the RFQ and thus reduces the required field gradients of the following matching section between the RFQ and the IH LINAC.

2.3.3 REX-MEBT

The beam dynamics concept of the 0° synchronous phase of the IH structure requires a small longitudinal phase spread and a converging beam in both transverse directions at the entrance of the IH-LINAC. Thus, the matching section includes a rebuncher and two quadrupole triplets. The three-gap split-ring rebuncher operates at the RFQ’s frequency with a gap-voltage of 50 kV.

2.3.4 REX-IH LINAC

The IH-structure is a short version of the GSI HLI-IH-structure[12]. The energy gain required is about 0.9 MeV/u, which corresponds to 5 MV absolute voltage. The IH-structure uses the “Combined Zero Degree Structure” beam dynamics concept developed by Ratzinger[8]. A new approach of the REX-IH resonator is the possibility to vary the final energy between 1.1 and 1.2 MeV/u by adjusting the gap voltage distribution via two capacitive plungers and by adjusting the RF-power level in the resonator[13].

2.3.5 REX-7-Gap Resonators

The final energy of 2.2. MeV/u at the target is achieved by three 7-gap spiral resonators. These type of resonators were developed and built first at the Max Plank Institute in Heidelberg for the High-Current-Injector[14]. The resonators have a single resonance structure, which consists of a copper half shell and three arms attached to both ends of the shell. The resonators are optimized for synchronous particle velocities of 5.4%, 6.0% and 6.6%. The total resonator voltage is about 2 MV for a power consumption of 90 kW. The output of the IH structure is matched with a triplet lens to the first 7-gap resonator. Between the first and second 7-gap resonator there is a doublet for transverse focusing.

3 PROJECTS AND PLANNED UPGRADES

3.1 Japanese Hadron Facility E-arena

The E-arena is a second-generation exotic ion beam facility based on ISOL and post-accelerator scheme. It aims at new regions in nuclear physics and related fields of science by supplying high-quality intense RIB of energies from nearly zero to 6.5 MeV/u for ion mass up to 240.

The RIB facility will utilize 10 µA from the 3-GeV proton booster synchrotron for the production of unstable nuclei. A wide variety of intense exotic ion beams can be produced via spallation, multi-fragmentation and/or fission process of target nuclei. After selection the exotic ion beam can be accelerated through a heavy ion linac, consisting of a split-coaxial RFQ (SCRFQ), and two IH type linacs, IH1 and IH2. The maximum output energy at each stage being 0.17, 1.05 and 6.5 MeV/u, respectively, with a duty cycle of 30% for q/A equal to 1/30.

The proposed E-arena is a natural extension of the RIB facility at the Institute for Nuclear Study (INS) of Tokyo. The new merits of the E-arena are:

1) Primary accelerator: 3-GeV protons are known to produce exotic nuclei with large probability, while reaction residues produced with low-energy beams available from the K=68 cyclotron, are limited to nuclei close to the stability line.

2) The secondary beam energy: this would be increased, by adding a new IH linac, from 1 to 6.5 MeV/u. Nuclear reactions become therefore possible over the whole region of target nuclides.

3.2 ANL Exotic-Ion-Beams Facility

Argonne National Laboratory proposes a two-accelerator ISOL-type facility to provide intense exotic ion beams at energies required for nuclear structure research and for reactions of astrophysics interest[15]. The heart of the exotic-ion-beam accelerator is the present ATLAS superconducting LINAC[16] which can accelerate ions from protons through Uranium to an energy range from 6 to 15 MeV/u. The ATLAS accelerator complex can presently accelerate ions of $q/A \geq 1/6.6$. The new front end has to accelerate ions of low charge-to-mass ratio $\geq 1/132$ to the energy necessary for efficient stripping to higher charge state, while maintaining excellent beam quality to match the actual ATLAS beam characteristics.

The new front end accelerator can be divided into three distinct sections. A short RFQ1 operating at low frequency will be installed on a high voltage platform. After gas stripping the ions of $q/A \geq 1/70$ will be accelerated by a combination of a second RFQ and a 48 MHz superconducting LINAC. After a second stripper, which will increase the q/A to over 1/6.6, a 72 MHz superconducting LINAC module which match the velocity profile to the present ATLAS LINAC will be installed.

Work started on the room temperature cw RFQ at low frequency. Ions with $q/A \geq 1/132$ call for a 12 MHz frequency range. The selected Split-Coaxial RFQ-structure is a modified version of the MAXILAX built at GSI[1].

The status of the RFQ development is the following; a 2 m prototype section has been constructed and operated cw at the design voltage (100 kV). They are currently preparing a prebuncher and LEBT section for beam tests scheduled for end of August 1998[17].

3.3 ORNL Facility

ORNL operates the Hollifield Radioactive Ion Beam Facility based on the ORIC cyclotron and on the 25 MV tandem accelerator as a post-accelerator. A second-generation ISOL facility based on the utilization of the driver of the Spallation Neutron Source (SNS) is proposed [18]. A decision on the construction of the SNS is expected by late 1998. The scheme for the post-accelerator is not yet finalized; but a low frequency RFQ would be utilized to accelerate low charge-to-mass ratio exotic ions $\geq 1/140$ to an energy suitable for stripping. The second stage would used superconducting quarter-wave resonators similar to the ones developed at Argonne[16].

Three take-off points are foreseen at 1, 6 and 15 MeV/u, which will cover most of the nuclear physics studies.

3.4 ISAC2 at TRIUMF

The aim of ISAC-II is a final energy of 6.5 MeV/u for a mass range up to A = 150[21]. The energy increase can be achieved by adding cavities at the end of the present LINAC. However, the mass limitation comes from the stripping at 0.15 MeV/u. The optimum stripping energy for mass 150 is 400 keV/u. To take these ions from 0.15 to 0.4 MeV/u requires a new LINAC, very similar to the ISAC1 DTL. To reach 6.5 MeV/u from 0.4 MeV/u with A/q = 7 requires a total voltage gain of 42.7 MV. Independently phased superconducting cavities similar to the ones developed at ANL for ATLAS[16] or LNL for ALPI [22] will be used. The maximum energy of particles with $q/A > 1/3$ will be around 15 MeV/u.

A charge state breeder based on an ECRIS will be placed upstream of the 35 MHz RFQ to increase the charge to mass ratio to 1/30 or greater.

The plan is to build and install superconducting modules downstream of DTL1 as they become available. This would allow higher energy-experiments (~ 5 MeV/u) to start before the end of 2003.

3.5 LINAC for the Munich Fission Fragment Accelerator

A Linear accelerator is proposed for the new Munich high flux reactor, FRMII. This LINAC is based on a charge state breeding of singly charged ions coming from the ISOL system. The required charge-to-mass ratio from the CSB is q/A>0,16. The LINAC will operate with a duty cycle of 10% and the final energy will be between 3.7 and 5.9 MeV/u. The LINAC complex will be composed of an RFQ, three IH structures similar to the Lead LINAC at CERN and two 7-gap IH-resonators for the variation of the final energy[20].

3.6 Beijing LINAC

The Beijing Radioactive Nuclear Beam Facility (BRNBF) proposal consists of three accelerators, a compact cyclotron which would deliver 70 MeV proton for the production of radioactive nuclei, an existing Tandem (13 MV) and a superconducting LINAC which will boost the final energy. The superconducting LINAC will use Niobium-sputtered Copper quarter-wave-resonators, currently developed at Peking University[19].

4 DISCUSSION AND CONCLUDING REMARKS

With the new exotic ion beam facilities based on the ISOL method it will be possible to have access to new extreme neutron-to-proton ratios to identify new phenomena and improve our understanding of nuclei, their origin and their properties.

These opportunities are possible because of the development of efficient accelerating structures for very low velocity heavy-ions. All sorts of linear accelerating structures are used or proposed. Both room temperature and superconducting Drift-Tube LINACs are envisaged, see Table 1.

The injection scheme can vary from very low to very high charge-to-mass ratio using Charge State Breeders (CSB). We can highlight four major schemes:

1) High-charge state breeding as used by REX-ISOLDE for experiments with neutron rich isotopes of Na, Mg, K and Ca. The charge-to-mass ratio required is 1/4,5.
2) Medium-charge state breeding as proposed for ISAC2 and E-arena for nuclear physics up to the Coulomb barrier (6.5 MeV/u). The charge-to-mass ratio required are 1/7 and 1/10, respectively. Such a charge-to-mass ratio remove the need for the medium energy stripper.
3) Low-charge state breeding as proposed for ISAC2 for nuclear physics with masses lower then 150 up to the Coulomb barrier (6.5 MeV/u). The charge-to-mass ratio required is 1/30. In that case a medium energy stripper is required.
4) Low-charge-state LINAC injector as proposed by ANL and ORNL for nuclear physics with masses up to 140. Low frequency RFQ and two strippers are used to reach Coulomb barrier energies.

From the available information on the intensity out of the CSB for a given charge state we can say that the fourth option will give a larger final exotic ion beam intensity on target. However, this may also be the most costly option.

Table 1: Summary of the LINAC for Exotic Beams

	q/A	Type	Type	Mass range	E range MeV/u
KEK-Tanashi	.≥ 1/30	SCRFQ (RT)	IH (RT)	6 ≤ A ≤ 30	0.172 to 1.05
REX-ISOLDE	≥ 1/4.5 CSB	4-rod RFQ (RT)	IH, 7-gap (RT)	6 ≤ A ≤ 60	0.3, 0.8 - 2.2
ISAC-I	≥ 1/30	Split-ring 4-rod RFQ (RT)	IH, 3-gap Split-ring (RT)	6 ≤ A ≤ 60	0.15 – 1.5
ISAC-II	≥ 1/30	Split-ring 4-rod RFQ (RT)	IH(RT), QWR (SC)	6 ≤ A ≤ 150	0.15 – 1.5 0.4 – 6.5
E-arena	≥ 1/30	SCRFQ (RT)	IH (RT)	6 ≤ A ≤ 238	0.17 – 6.5
ANL	≥ 140	SCRFQ (RT)	QWR, 3-gap Split-Ring(SC)	6 ≤ A ≤ 238	0.1 – 6.5
ORNL	≥ 140	SCRFQ (RT)	SC-QWR (SC)	6 ≤ A ≤ 238	0.1 – 6.5
BRNBF		Tandem	QWR (SC)	A ≤ 70	≤ 6.5
FRMII	≥ 1/6.5 CSB	IHRFQ (RT)	IH (RT)	A ≤ 100	≤ 6.5

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