A CONCEPTUAL DESIGN OF AN ECR SOURCE FOR AN ISOL FACILITY

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Recent reports have indicated the feasibility of producing and accelerating intense radioactive ion beams (RIB) of low Z elements.^{1,2} There is a great deal of interest¹ in nuclear astrophysics to use such an accelerated RIB for studying rates of reactions involving reactants with short half-lives. This makes it desirable to consider the use of highly efficient ion sources with on-line isotope separators (ISOL) to improve the effective yield leading of radioactive beams. It has been demonstrated that high (1+) ionization efficiencies can be obtained for many gases using an ECR source.³ Similar values should be possible for other materials in the low Z region. This report presents conceptual plans for the development of an ECR source coupled to a 500 MeV proton based ISOL at TRIUMF.

1. INTRODUCTION

It has been known for many years that exploding events like supernovae and novae occur from time to time in our galaxy and others. These explosive events reprocess the accumulated material of stars back into the interstellar space and thus contribute significantly to the present isotopic composition as observed in the solar system.

In many of these events the temperatures and densities become so high that radioactive nuclei produced by fusion from their stable progenitors can themselves undergo nuclear reactions. Since nuclei are constantly undergoing fusion and other reactions in the stellar environment, it is important to know the reaction rates when radioactive species are involved. Only then can one calculate the energy generation in explosive stellar events and the isotopic composition of the stellar medium at a particular temperature as well as for the ejected material.

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Stellar reaction rates are in most cases difficult to calculate with any degree of accuracy by various present theoretical approaches. So they have to be carefully determined experimentally as it has been done for stable nuclei for the last 35 years. But stellar rates have not been determined for unstable nuclei due to the present unavailability of radioactive beams in sufficient intensity and with the correct energy to perform these measurements.

In this context important reactions in the low Z regime are:

¹³ N (p,γ)	¹⁴ O	T _{1/2} (¹³ N) = 10 min
¹⁴ O (α,p)	¹⁷ F	T _{1/2} (¹⁴ O) = 71 sec
¹⁵ O (α,γ)	¹⁹ Ne	T _{1/2} (¹⁵ O) = 2 min
¹⁸ Ne (α,p)	²¹ Na	T _{1/2} (¹⁸ Ne) = 1.7 sec
¹⁹ Ne (p,γ)	²⁰ Na	T _{1/2} (¹⁹ Ne) = 17 sec

But in addition, knowledge of the rates for many (p,γ) and (α,p) reactions involving A > 20 unstable species, leading to ⁵⁶Ni and beyond is necessary for these complicated isotopic networks.

2. ACCELERATED RADIOACTIVE BEAMS FROM AN ISOL

This goal to determine such nuclear rates involving radioactive heavy ion beams as well as some other possible applications have led to the TRIUMF-ISOL proposal⁴ in which a postaccelerator is coupled to an On-Line Separator facility (ISOL). This facility is proposed to be located on the present TRIUMF 4A beamline using targets of up to 100 g/cm² and up to 100 μA of the 500 MeV proton beam. The radioactive nuclei of choice will then diffuse out of the heated target and be ionized with some efficiency (see below) in a coupled ion source, all being at the extraction potential.

The ion beam will then be mass analyzed and transported to the entrance of an accelerator. At present, calculations² have been done for an RFQ-(room temperature) LINAC combination to further accelerate these singly charged, mass A < 60, ions. This design is presented in Fig. 1.

The calculations of this configuration have indicated² that a transmission through the accelerator of up to 86% can be reached, if no stripper has to be inserted (A < 20). Other concepts of possible postaccelerators are also under consideration.¹ The final energy of the ions has been agreed upon¹ to be 1.5 MeV/amu. From the exit of the accelerator the ions will be transported to the experimental stations. An adequate time-energy spread structure at the experiment will be achieved by allowing either bunching or debunching.

At present, for the development and testing of certain target materials as well as ion sources, a test on-line isotope separator (TISOL) is under construction at TRIUMF. The subsequently described ECR source is planned to fit into this configuration, while it is not planned to make its design compatible to the final ISOL facility.

The ISOL / Post - Accelerator

Fig. 1. The proposed TRIUMF-ISOL facility using a RFQ - room temperature LINAC combination.

3. AN ON-LINE ECR SOURCE

3.1 Ionization-Efficiencies-in-Comparison

While the production of radioactive elements using an on-line target is now a fairly well established technique for a great variety of species,⁵ the absolute yield which can be achieved as an ion beam is often suppressed by the low efficiencies of the ion sources used in these separators. Thus it would be highly desirable to develop an ion source which would yield efficiencies above 10% for many elements. In fact, many experimental investigations concentrate on the alkali elements, since only for them the highly efficient surface ionization source is available. In any case, for the future TRIUMF-ISOL post-accelerator facility,^{1,2} high currents (nA) of many low Z elements for experiments in the realm of nuclear astrophysics will be mandatory. Thus the development of a highly efficient ion source for these elements has to be of high priority.

Recent progress in the development of ECR sources to be used in the isotope separation for medical purposes has led to impressive numbers regarding the ionization efficiencies (1⁺ states) of such a source.⁶ Table 1 shows a comparison of efficiencies at on line separators⁷ and the reported ECR values.

Table 1: Ionization efficiencies achieved on-line and with an off-line ECR source

Element	Ioniz. Eff. On-Line %	ECR Eff. %
Helium	0.5	?
Lithium	50 ⁺	?
Beryllium	0.1	?
Carbon	0.23	15 ⁺⁺ (OO)
Nitrogen	0.01	26
Oxygen	?	54
Neon	0.7	34
Sodium	50 ⁺	?
Magnesium	0.1	?
Aluminum	0.1	?
Chlorine	1	?
Argon	5	?
Potassium	100 ⁺	?
Xenon	?	58

+ surface ionization source
++ non optimized

Besides these impressive numbers for a specific ECR source, obviously only the ionic efficiencies (in the single charge state) for some elements have been determined. Thus it is necessary to continue this kind of work at other laboratories. In addition, only gaseous elements have been ionized so far in this specific ECR source.⁶ Further advancements into low temperature condensing elements has to be contemplated. Finally technical problems in using such a source on-line in a high radiation environment at an isotope separator have to be solved.

3.2 Details of the On-Line Source

It is planned to begin with the present Karlsruhe ion source design⁵ on-line in combination with a target box coupled to the insertion end of the ion source body. The conceptual set-up for such a configuration is shown in Fig. 2.

3.2.1 The Source

It is proposed to use ferromagnetic material (iron yoke) to enhance the magnetic field of the coils and reduce the power consumption as well as the material necessary. The design is planned to be similar to the one for the coils of the TRIUMF H⁻ polarized ECR source,⁸ but with shortened and more widened coils.

Fig. 2. The conceptual design of an on-line ECR source

The magnetic field on the symmetry axis of the borehole has to be increased relative to the Karlruhe source due to the increased RF frequency envisaged (see below). It is felt that the radiation hardness of the coil wire insulation is not a problem for TISOL operations.

The field strength of the Samarium Cobalt magnets probably has to be increased to 0.5 T at the surface due to the increase in RF frequency. Such a surface field strength is not contradictory to the specifications of the suppliers. The actual field strength as well as the radial depth of the hexapole has to be explored in detailed field calculations as now in progress. Aluminum bars could substitute some outer parts of the hexapole. In fact, a later expansion of the quartz tube radius and the hexapole inner diameter seems to be easier in a configuration where the hexapoles do not fill up the whole available radial space.

There were concerns that the performance of Samarium Cobalt magnets could deteriorate in the high radiation fields at an on-line separator. Using the data from CERN⁹ and TRIUMF¹⁰ a conservative estimate is that the radiation hard CoSm_{17} alloy is able to withstand a total radiation of 10^{10} rads with negligible losses in the field strength. From multiple scattering data for a copper target¹¹ it is estimated that the closest end of the SmCo magnets in the Karlruhe configuration will survive a beam time of about 4 years (1 g/cm^2 , $1 \mu\text{A}$ beam). In the final TRIUMF ISOL facility it is possible that the much higher radiation fields will cause demagnetization of any permanent material close to the target. Longer transfer lines or other means of producing the hexapole field may be necessary.

The microwave frequency is not a critical parameter in ECR sources. Operational values from 2.5 GHz to 28 GHz have been reported, and in any particular case may be determined by the achievable magnetic fields, the dimensions chosen, costs and available equipment.

For the present source an RF frequency of 10 GHz was chosen, given by an available amplifier of 300 W at TRIUMF. The slightly increased magnetic field required (see above) is not likely to cause any problems. Nevertheless the use of lower frequencies may also be tested.

The 300 W, while useful for off-line tests, would not be sufficient for on-line TISOL operation. At Karlruhe, with several meters of transmission line between the RF source and the ion source, 1.5 kW is required. On the TISOL installation even longer transmission line lengths are required (to penetrate the massive shielding blocks) so a minimum power of 2 kW is estimated.

The source body will be constructed similarly to the one of the Karlruhe model, i.e. a stainless steel cylinder of 14 cm diameter and 20.6 cm length with both sides removable. The hexapole stand should be easy to slide into this cylinder.

Since the present results³ for a larger plasma volume (inner quartz tube diameter 34 mm) are more encouraging and need less RF power, it should be developed for this provision. The extraction hole disk will be removable.

The extraction electrode will be movable over 20 mm, while the extraction cone will be exchangeable to allow for several forms and diameters. The details of the moving mechanism are being examined. The extraction electrode should be followed by an einzel lens to allow for a beam transport without considerable losses.

The part of the construction containing the extraction electrode and the einzel lens will have a pumping port which must allow for the gas flows leaving the source. A 450 l/min turbo pump is considered to be sufficient for this requirement. A final gate valve will make the unit self contained.

The entire source will operate at a high tension of 20 kV to simulate actual TISOL operation requirements. This will include both the ion source body as well as the target unit. Insulation plates are necessary for the extraction electrode, the proton beam entrance, and exit window and the target chamber pump.

3.2.2 The Target Unit

The target unit is a container which can be used independently and without any connections to the source. Nevertheless it is possible to couple it to the source body by a quick-coupling flange, directly. The target unit is also at high tension. The unit is divided into two separable parts: The outside target box and the target insert, the latter to be used, given an adequate flange in other vacuum systems as well.

The target box holds the target insert in vacuum and has provisions to move the target out of the proton beam. It connects the ECR body, the proton beam line and the pump, the latter two insulated for the high tension. In addition, an upside "observation port" allows insertion of thermocouples and proton beam monitoring devices. There is a quick coupling to the ECR source body.

The target insert is connected to a flange and the target box via a welded bellow. This allows an extraction of the target from the beam of about 1 in. The moving mechanism has to be further specified, but may consist of air pistons while the outside of the flange is supported by rods.

Additional guidance for the target insert will be given by rods supporting the target carriage plate close at the source. The rods have a sufficient length to ease the insert and extraction of the target unit (not shown in Fig. 2).

The target insert unit is planned to be the most variable part of the whole set up. This way, several different kinds of units can be envisaged, depending on the target material as well as the transfer to the ion source.

Figure 2 displays a so-called "cold transfer line" configuration for gaseous elements using a powder or sintered solid state target. Highly evaporating material is condensed out in this configuration at the side walls of the transfer tube thus achieving elemental selectivity.

The target is heated by ohmic resistance heating via two water-cooled feedthroughs capable of carrying a current of at least 1 kA electrical current. The target itself consists of a tantalum or graphite cylinder, which is to be heated up. Inside the cylinder is the material to be bombarded by the proton beam. Maintaining this target at high temperature promotes the release of radionuclides which then diffuse into the transfer line (made out of tantalum or graphite)

and further through the copper cooling block into the inner quartz tube of the ECR source. To cool the transfer line it is clamped in the watercooled copper block which by itself forms the final part of the transfer line. The copper block is electrically insulated from the target carriage plate and can be used as an electrical pole via the low current feedthrough to heat up the transfer line for an initial conditioning or if it should be clogged with highly evaporating material. Further it is also possible to drive out hydrogen off from the tantalum transfer line.

Hydrogen is fed in through the support gas line to transfer the plasma support gas to the ECR source. Hydrogen is the gas of choice for the ECR operation.⁶ On the other hand hydrogen needs careful attention, since tantalum is known to be subject to hydrogen embrittlement at some hundred degrees. Thus cooling of the target and the transfer must be avoided when being exposed to the hydrogen.

Some chemical elements such as nitrogen are known to react with the hot tantalum. For these elements materials other than tantalum must be chosen for the target heater and transfer line or the tantalum must be coated with non-reacting material. Special provisions will be taken so the decoupled ion source end of the unit is mechanically closed when not inserted (lid), to avoid spreading of radioactive contaminations.

3.2.3 Other Provisions of Operating the ECR source

When dealing with gaseous species, the target and the ECR ion source can be separated by some meters. This mode of operation will be tested in the off-line mode, but given targets of high radiation fields, this separation could minimize radiation effects on the ion source.

Another possibility is to use the apparent feature of the source to run with less volatile reaction products. This would require a redesign of the transfer line and the inner quartz tube holder, and the construction of a hot coupling between both. A possible design of a "hot" transfer line could use a rearranged copper block with a wider bore hole clamping to the transfer line in a way that it can be heated up all the way till close to the coupling piece. This coupling piece could be a heated graphite coil/tube to form a connection between the tantalum transfer tube of the target and the inner quartz tube of the source. The quartz tube would slide in the graphite, when the target is retracted. Such a configuration would allow the transfer and ionization of non-gaseous materials.

3.2.4 Summary / Specifications of the TRIUMF On-line ECR Source

Table 2: TRIUMF On-line ECR Source Specifications (TISOL)

Part/Function	Description	Value
Solenoid	2 pieces, watercooled, iron yoke	B = 0.5 T at center of ≥ 15 cm borehole length/coil = 7 cm I = 500 A
RF	power variable amplifier, about 10 meter waveguide	$\nu = 10$ GHz $P < 2$ kW
SmCo hexapole	alloy to be chosen, hexapole stand to be designed	inner diameter: > 52 mm (to be determined) surface field: ≈ 0.5 T
Vacuum	Two pumps, two chambers, support gas to be inserted, outgasing of the target	both 350 l/sec gas flow: $10^{-2}/10^{-1}$ standard ccm/sec H_2
Body	Stainless steel cylinder to be opened at both sides, aircooled, coupling to target box	Diam.: 14 cm Leng.: 23 cm 9 in. fast coupling
HV	Source body and target chamb.	20 kV (TISOL)
Extraction Electrode	movable cone/replaceable Einzel-lens desirable	20 mm range
Target Box	multiport aluminum cylinder, watercooled, target moving mechanism	length: ~ 20 cm
Target Insert	two plate support structure, multiple feedthroughs, cooling block to source	length: ~ 25 cm diam.: ~ 20 cm
Heaters	heater power connected via feedthroughs to target and transfer line	target: I < 1000 A transfer line: I < 500 A
Target	tantalum or graphite cylinder with transfer line, material of choice inserted: $1-100$ g/cm 2	length: 1 - 20 cm transfer line length: ~ 10 cm

4. CONCLUSION

Design features of an on-line ECR source as planned for the TISOL facility at TRIUMF have been presented. At present magnetic field calculations are underway. The static hexapole field is included in these calculations. The design of single components of the system will begin in late spring after the calculations have been finalized.

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