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THE ADVANTAGES OF COMBINING AN EBIS WITH THE PIGMI TECHNOLOGY*

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Summary

The Electron Beam Ion Source (EBIS) produces highly charged heavy ions by electron impact ionization of ions electrostatically trapped within a dense energetic electron beam. Because of its pulsed operation and the highly charged ions produced, the EBIS is ideally suited as an injector for a high-gradient, low duty-cycle linac such as that being developed at the Los Alamos Scientific Laboratory (LASL) in the program to design a Pion Generator for Medical Irradiation (PIGMI). This combination of new technologies would produce an efficient, small heavy ion linac useful in a variety of research and practical applications.

Introduction

This paper describes briefly the design for a heavy ion linac that utilizes an EBIS injector and the linac technology that is being developed by the Accelerator Technology Division at LASL in the PIGMI program. The goal of this study is to present a conceptual design of an accelerator that is an extension of the PIGMI concept, from protons to ions with a charge-to-mass ratio of 0.5. It would be capable of accelerating fully stripped ions from deuterons to calcium. The system proposed here would meet the energy and intensity requirements for heavy ion medical therapy and radiography, and would be useful in high-energy heavy ion physics. The low-energy portion of such an accelerator would have applications in low-energy atomic and nuclear physics in addition to being suited as an injector for a synchrotron.

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Fig. 1. Schematic of the EBIS.

EBIS Injector

The EBIS, shown schematically in Fig. 1, consists of a very dense energetic electron beam magnetically confined within a series of insulated cylindrical electrodes along the axis of a solenoid. The space charge of the dense electron beam creates a radial potential well that traps ions as they are created by ionization of atoms injected into the electron beam. A potential distribution applied to the insulated electrodes prevents the axial escape of the ions, so they become highly ionized by successive electron impact ionizations. The ions are trapped within the electron beam until the production of a desired charge state has reached its optimum, and then the ions are extracted by lowering the axial potential on the output end of the source. The total positive charge in the ion source cannot exceed the negative charge in the electron beam, and the ionization rate of the ions is dependent on the current density of the beam. Thus, the total ion current extracted from the source in each pulse is proportional to the electron beam current, while the confinement period to achieve a particular charge state is inversely proportional to the electron beam current density.

This ion source configuration was introduced in Dubna¹ and is currently being studied at many laboratories.² The most recent results³ from Dubna have shown the production of Xe^{48+} in KRION-2, the latest of two cryogenic EBIS's built by Donets and his co-workers. These sources have been used to study the time evolution of charge states in nitrogen, oxygen, neon, and argon,⁴ in addition to the latest xenon study. In all the previous studies, fully stripped nuclei have been observed, and the step-by-step ionization mechanism has been verified. In addition, the first of these two sources (KRION-1) was used with a 600-kV injector and a conventional linac to inject carbon and oxygen nuclei at 10 MeV/nucleon into the Dubna synchrophasatron.⁵ Carbon ions accelerated to 4.2 GeV/nucleon were used in high-energy heavy ion experiments.

The latest version of a cryogenic EBIS at Orsay, France, called CRYEBIS I, has been built to provide fully stripped ions up to Ne^{10+} (10^{10} particles/pulse) for the Saclay synchrotron Saturne II and is described elsewhere in this conference.⁶ Previously reported results⁷ have shown spectra containing N^{7+} , Ne^{10+} , A^{18+} , and Kr^{34+} ions. With an electron beam of only 250 mA at 4.3 keV this source produced 3×10^9 particles/pulse of Ne^{10+} with a confinement time of only 7 ms. For nitrogen, 5×10^9 particles/pulse of N^{7+} were obtained with an electron beam of 190 mA and an energy of 3.8 keV with a confinement time of only 6 ms. The technological difficulties in achieving routine operation with this source have been solved, and this source is soon due to go into operation on the 375-kV high-voltage platform at Saclay for injection into Saturne II. The transmission from the source to Saturne is very low with the conventional 100-MHz drift-tube linac; therefore, plans are to build a 7-m-diam ring, MIMAS, to store the ions from CRYEBIS and accelerate them for injection into Saturne.⁸ A new source, CRYEBIS II, is now being designed at Orsay for use in atomic physics,⁹ capable of producing fully stripped ions up to Xe^{54+} , and other ions as high as U^{90+} .

Also, a cryogenic EBIS is under construction at Frankfurt,¹⁰ and a cryogenic EBIS has been constructed at the Institute of Plasma Physics in Nagoya, Japan, for atomic physics measurements involving highly stripped ions that are important in a fusion plasma.¹¹

LINAC PARAMETERS

FREQUENCY	RFQ SECTION	440 MHz
	DTL SECTION	440 MHz
	CCL SECTION	1320 MHz
GRADIENT	DTL SECTION	6 MV/m
	CCL SECTION	12 MV/m
TRANSITION ENERGY	RFQ / DTL	1.5 MeV/Nucleon
	DTL / CCL	80 MeV/Nucleon

BEAM PARAMETERS

INJECTOR VOLTAGE	20 kV
INJECTION ENERGY	10 MeV/Nucleon
FINAL ENERGY	530 MeV/Nucleon
PEAK BEAM CURRENT	300-600 μ A
PULSE LENGTH	30 μ s
REPETITION RATE	30-120 Hz
AVERAGE BEAM CURRENT	1-3 μ A

Fig. 2. Heavy ion linac utilizing the EBIS and PIGMI technologies.

PIGMI Technology

A conservative extension of the present experimental results from these cryogenic EBIS's yields a very interesting heavy ion accelerator system when combined with the new linac structures being studied in the PIGMI program. This program is funded by the National Cancer Institute to provide the optimum design of an accelerator for pion therapy; this design is described elsewhere in this conference.¹² The major technical innovations developed in the program over the past four years would have a significant impact on the cost and size of a low duty-cycle linac for heavy ions, particularly when put to use with an EBIS as the injector. The higher frequencies employed have made the accelerator structures smaller and have allowed the use of smaller conventional klystrons as pulsed radio-frequency (RF) power sources. The low duty-factor and the availability of powerful pulsed RF tubes have allowed much higher gradients in the structures than are normally used in ion linacs. The use of permanent magnet focussing in the post-coupled drift-tube linac structure allows a lower power consumption because no power supplies or cooling are required for focussing, and the new disk and washer structure used in the high-energy coupled-cavity linac yields more stability and tuning tolerances to the accelerator while lowering the fabrication costs. In addition, the use of the new radio-frequency quadrupole (RFQ) linac structure, an accelerating structure first proposed by Kapchinskii and Teplyakov¹³ as the low-energy portion of an accelerator, permits a very low injection energy while having a very high transmission for bunching and accelerating the beam to an energy convenient for injection into the drift-tube linac.

A minimum amount of operational adjustment has resulted from this design, and a modest, distributed, MULTIBUS-based microprocessor control system, which uses a small central computer, can be used to handle the

control and diagnostics requirements. Such a system is currently being developed for the PIGMI program and several other accelerator systems at LASL.

Proposed Accelerator

The heavy ion linac proposed by combining the EBIS and PIGMI technologies is shown in Fig. 2. This system, designed for injection of fully stripped ions up to calcium ($q/m = 0.5$) is the optimum design for a low duty-factor heavy ion linac. The maximum charge state for the ions (fully stripped) is attained in the injector by the use of the EBIS; the maximum acceptance possible into the accelerator ($\sim$ unity) is attained by the use of the RFQ; and the maximum accelerating gradient and efficiency is attained in the accelerator (within the limits set by RF sparking) by the use of high frequencies and a low duty-factor. In addition, the low duty-factor in the accelerator system is a perfect match to the low duty-factor required in the EBIS for production of the fully stripped ions. This low duty-factor, combined with the large energy gain attained in the accelerator, minimizes the accelerator length and power consumption.

The accelerator system described above would use a cryogenic EBIS such as CRYEBIS I for the injector. Because of the confinement time of the EBIS for the fully stripped ions required in this facility, the pulse repetition rate for the injector cannot exceed 140 Hz. Because the PIGMI duty factor (0.36%) can be obtained with twice the mains cycle (120 Hz with a 30 μ s beam pulse width), this repetition rate was chosen. Previous experimental data have shown that the ions can be extracted from an EBIS within this required beam pulse duration, so the only development work required for the source is to extend the repetition rate up by a factor of two or three above that obtained already in CRYEBIS I, while maintaining the projected ion yield per pulse.

Fig. 3. The RFO beam dynamics for $q/m = 0.5$ ions.

The use of the RFQ as the low-energy section of the accelerator would enable the ions to be injected with a 20 kV injector voltage. This is approximately the extraction voltage used in an EBIS and can be easily obtained without having to use a large high-voltage dome and accelerating column. The RFQ is capable of accepting ions at this low energy and can accelerate them to several MeV with a very high capture efficiency, without the aid of a separate bunching system. The RFO beam dynamics and structure have been previously described,¹⁴ as well as the experimental results from a structure tested on the PIGMI prototype accelerator.¹⁵ The results of a beam dynamics calculation for a $q/m = 0.5$ beam, injected into a 440 MHz RFQ at 10 MeV/nucleon, are shown in Fig. 3. A yield of 10^{10} particles/pulse was assumed to be extracted from an EBIS during 30 μ s. The experimental measured CRYEBIS I emittance of 1.2π mm-mrad was assumed for this beam, resulting in a capture efficiency of greater than 99% for the structure. The final energy of 1.5 MeV/nucleon is attained with a structure that is only 3.3 m long, with a total peak RF power requirement of only 263 kW. The parameters of this RFQ are summarized in Table I.

The final RFQ energy makes the injection into a post-coupled drift-tube linac (DTL) at the same frequency an easy technical task, because the first few drift tubes are long enough to easily use permanent magnet quadrupole focussing. The drift-tube linac in this accelerator is a simple extension of the PIGMI drift-tube linac to $q/m = 0.5$ particles, using the same accelerating gradient and RF source, having a length of 38.5 meters. However, to make the RFQ and drift-tube linac section all powered by one 20-MW RF tube, the transition to the high-energy linac is made at 80 MeV/nucleon, instead of the 125 MeV in PIGMI. This energy is still a reasonable value for making this transition.

The final, and largest, component of the accelerator is the coupled-cavity linac (CCL) that is used as the high-energy portion, which is 118 m long. This linac utilizes the disk and washer structure that has been developed in the PIGMI program, and would accelerate the ions up to 550 MeV/nucleon. It would be powered by

TABLE I

Heavy Ion RFQ Parameters

Injection Voltage (V_1)	20 kV
Injection Energy (W_1)	0.01 MeV/nucleon ($B\lambda = 0.316$ cm)
Frequency (f)	440 MHz
Average Bore Radius (r_0)	0.187 cm
Final Energy (W_f)	1.5 MeV/nucleon ($B\lambda = 3.84$ cm)
Final Radius (a_f)	0.147 cm
Structure Length (l)	3.28 cm
Final Synchronous Phase (ϕ_s)	-30°
Peak Voltage Between Electrodes	56 kV
Peak RF Power (including manifold)	80 kW/m

10 klystrons at 1320 MHz and the peak RF power for this structure would be 180 MW.

Using the PIGMI cost estimate for the accelerator components, we would estimate that the cost for this heavy ion accelerator would be \$13M (1980 US \$), including the cost of the EBIS injector. This does not include the building costs, but such a facility would require only a 10-ft.-square tunnel, with a klystron service gallery building located above it, the same as for the PIGMI accelerator. Not included in this estimate is the engineering cost, probably an additional 35%.

Synchrotron Injector

As mentioned earlier, the beam produced by the low-energy section of such a machine (10-20 MeV/nucleon) could be used for low-energy heavy ion physics, and it would also be suited for injection into a synchrotron designed to produce relativistic heavy ions. However, to extend the mass range beyond calcium, a preliminary design for a 10 MeV/nucleon accelerator for $q/m > 0.4$

ions has been produced. Using an EBIS for the injector, this linac could accelerate ions up to xenon. Table II gives the parameters of this synchrotron injector.

TABLE II

Synchrotron Injector Parameters

Injection Energy	0.02 MeV/nucleon
Beam Pulse Width	60 μ s
Beam Repetition Rate	1 - 60 Hz
Linac Frequency	440 MHz
Final RFQ Energy	2 MeV/nucleon
RFQ Length	6.3 m
RFQ Peak Power	0.5 MW
DTL Length	4.9 m
DTL Energy Gain	4.1 MeV/m
DTL Peak Power	2.3 MW
Transmission	> 99%

Conclusions

The EBIS, as an injector for a heavy ion linac, has obviously become more realistic with the recent results from the new cryogenic versions in Saclay and Dubna. Combining the EBIS with the new linac technology developed at LASL will result in an ideal match of ion source and accelerator, yielding an efficient, low-duty cycle heavy ion linac for medical therapy and physics research. The utilization of the RFQ as the low-velocity section of such a linac makes the use of the EBIS with a conventional DTL much easier, and much more useful with regard to accelerated ion yields. Even at the preliminary yields of fully stripped ions reported from CRYEBIS I this proposed system has promise as a useful accelerator, but the projected design yields from the EBIS sources make such a linac even more interesting. Thus, because these two new technologies can produce a compact, efficient heavy ion linac, this combination should be pursued as an alternative for future heavy ion accelerators.

Finally, it should be obvious from the present EBIS results that a heavy ion linac for physics applications could be designed for a charge-to-mass ratio of 0.2 to 0.3, using the concepts described here, that would yield useful beams of all elements up to uranium. The RFQ for such an accelerator has been designed and is described elsewhere in this conference.¹⁶

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