THE EBIS AS AN INJECTOR FOR HEAVY-ION LINACS*

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Summary

The Electron Beam Ion Source (EBIS), because of its high-charge states and pulsed operation, is ideally suited as an injector for a heavy-ion linac operating at a low duty factor. Although presently in use with conventional linacs, the low emittance and the large yield of highly charged ions in each pulse make the EBIS even more interesting as an injector for the new linac accelerating structures, such as the alternating-phase-focusing (APF) structure, or the radio-frequency quadrupole (RFQ) structure. These new structures could be used with an EBIS to produce a small, efficient, low-duty-cycle accelerator. Coupled to a conventional linac, the resulting accelerator could be used for heavy-ion medical therapy, or nuclear physics, or, it could be used as an injector for a synchrotron or storage ring.

Introduction

The EBIS, 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 that 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. The ionization rate of the ions is dependent on the current density of the electron 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.

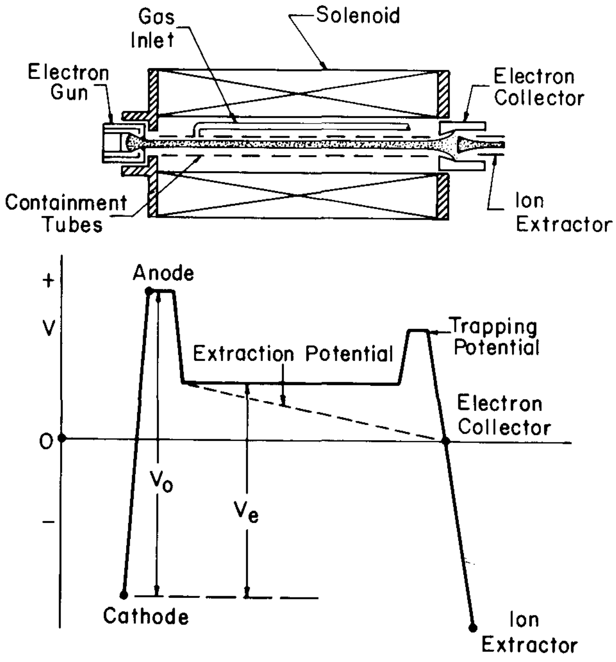

Fig. 1 Schematic of the EBIS.

The ion source configuration was introduced in Dubna[1] and it is currently being studied in Frankfurt, Giessen, Orsay, Cern, Kyushu University, and Texas A&M University.[2] Recent results on the latest version of the EBIS at Orsay,[3] have shown spectra containing N^{+7}, Ne^{+10}, A^{+18}, and Kr^{+44} ions. With an electron beam of only 250 mA at 4.3 keV, this EBIS produced 3×10^9 particles/pulse of Ne^{+10} with a confinement time of only 7 ms. The normalized emittance of this source was measured to be 1.2π mm-mrad and the energy spread of the extracted ions was estimated to be 1.4 %/q, where q is the charge of the ions. Figure 2 gives the projected yields from this source operating at the design goal of a 2-A, 10-kV electron beam.[4] These results are for operation of the source with the maximum repetition rate possible and are misleading for low-duty-cycle operation, because of the vanishing duty cycle required for the high-charged, very heavy ions. The projected yields for each pulse of this ion source are given in Table I for several different, fully stripped ions.[5] The calculated confinement period to achieve these charge states is shown and the experimental confinement times given in recent data[3] are shown for N^{+7} and Ne^{+10}.

This EBIS, called CRYEBIS because of the superconducting solenoid and cryogenic pumping, will soon be mounted in a 375-kV high-voltage dome and will be used with a conventional 100-MHz linac to produce beams at 5 MeV/nucleon for injection into the Saturne II synchrotron.[5] Fully stripped ions ($q/m = 0.5$) up to Ne^{+10}, as well as polarized H^+ ions, will be injected

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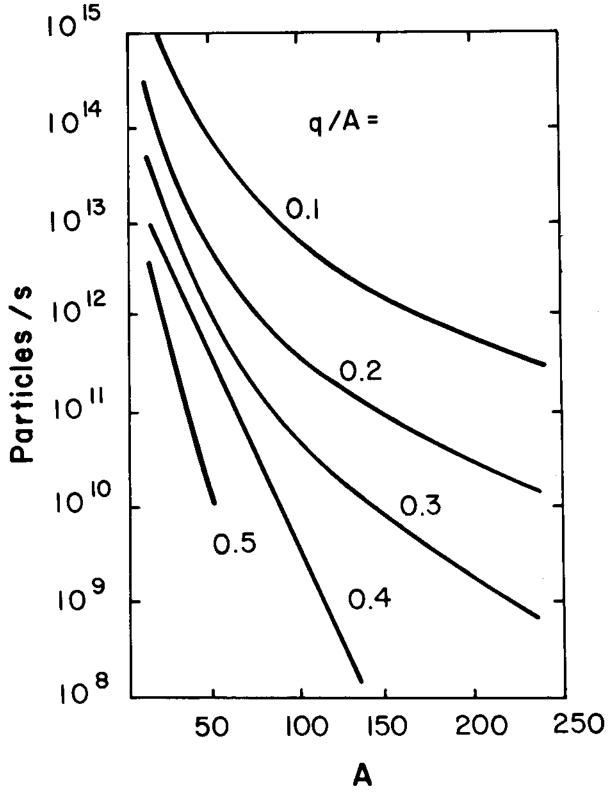


Fig. 2 Projected yields of CRYEBIS.

into the linac from the ion source with the use of a buncher system.

Two such cryogenic EBIS's have been built by Donets and his co-workers in Dubna. These sources have been used to study the time evolution of charge states in nitrogen, oxygen, neon, argon, and xenon.[6] For all ions except xenon, fully stripped nuclei were observed; and in the case of xenon, the highest charge state observed was Xe^{+37}, with the peak intensity being at Xe^{+33}. In addition, the first of these sources (KRION-I) was used with a conventional linac and a 600-kV injector, to inject carbon and oxygen nuclei at 10 MeV/nucleon into the Dubna synchrophasatron.[7] Carbon ions accelerated to 4.2 GeV/nucleon were used in high-energy heavy-ion experiments.

Proposed System

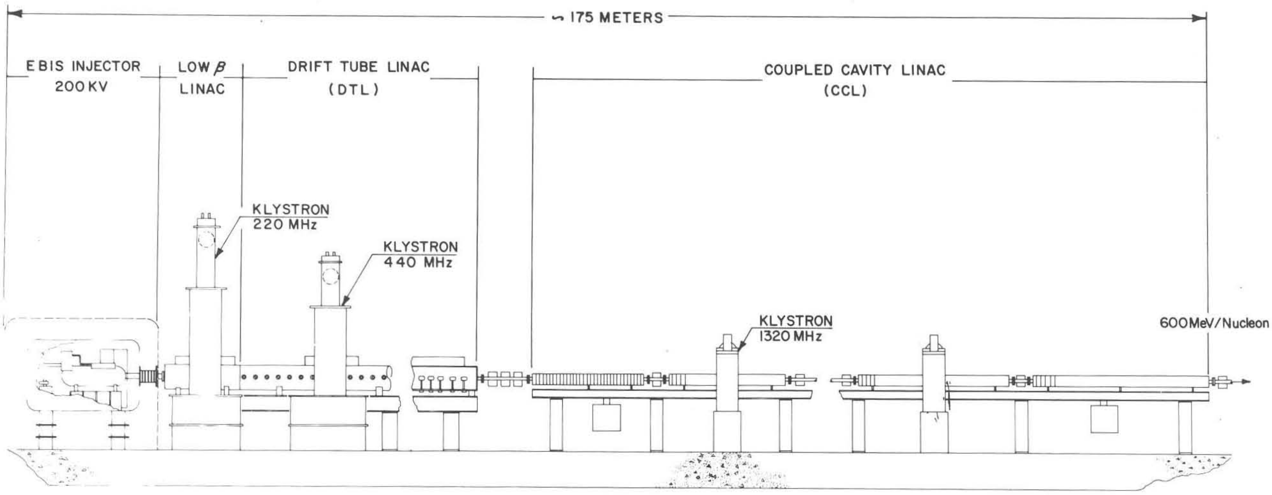
A conservative extension of the present experimental results from the EBIS, yields a very interesting heavy-ion accelerator system when combined with the new linac structures being studied by the Accelerator Technology Division, of the Los Alamos Scientific Laboratory (LASL). Programs such as the Pion Generator for Medical Irradiation (PIGMI) Study[8] could have a significant impact on the cost and size of a low-duty-cycle linac for heavy ions, if these new technical innovations are put to use with an EBIS as the linac injector. Figure 3 shows an adaptation of the PIGMI technology to a low-duty linac for heavy ions. This system, designed specifically for injection of fully stripped ions up to calcium (q/m = 0.5), would only be 50 meters longer than the proposed 650-MeV proton linac, and would use the rf and control systems already developed for the proton machine. The low-beta section necessary to accelerate the ions to 1 MeV/nucleon for injection into the drift-tube linac could be either an APF or an RFQ.

TABLE I
YIELD PER PULSE FOR FULLY STRIPPED IONS

Ion	Confinement Time Calculated (ms)	Confinement Time Experimental (ms)	Particles per pulse (10^{10})
C^{+6}	5.6	--	2.6
N^{+7}	9.6	6.0	2.5
O^{+8}	16	--	1.8
Ne^{+10}	40	7.0	2.2
Ca^{+20}	500	--	1.1

The advantage of using an EBIS as the injector in such a system is clearly seen in the study of these low-beta structures. A comparison of a heavy-ion APF proposed by Swenson,[9] and the combination of an EBIS and an APF of approximately the same length and gradient is shown in Table II. An increase in the charge state by a factor of 4 reduces the injector voltage from 1 MV to the inexpensive, manageable, 250 kV presently being used in the PIGMI injector.[10] With the same input energy, gradient and cavity length, the number of cells in the APF are less, and the energy gain is four times greater. The heavy-ion beam would, however, have to be injected into the APF through a buncher system, such as the one used in the PIGMI system.

The alternate solution to the low-beta acceleration in this scheme is the RFQ, an accelerating structure first proposed by Kapchinskii and Teplyakov,[11] which is currently being studied at LASL. Preliminary calculations have shown this structure capable of very high capture efficiency, without the aid of a separate bunching system. The beam dynamics in this structure are described in more detail elsewhere in this conference.[12] The results of a beam dynamics calculation for a Ne^{+10} beam injected into a 200-MHz RFQ from a 200-kV injector are shown in Fig. 4. A modest yield of 10^{10} particles/pulse was assumed to be extracted from an EBIS during 50 μs. With a normalized emittance of 1.2π mm-mrad, 98% of the ions was captured and accelerated to 1 MeV/nucleon, within a 5.3-m structure. The parameters of this RFQ structure are given in Table III. At a repetition rate of 120 Hz, this combination of EBIS and RFQ could produce an accelerated beam of ~2 μA.



LINAC PARAMETERS

FREQUENCY	LOW β SECTION	220 MHz
	DTL SECTION	440 MHz
	CCL SECTION	1320 MHz
GRADIENT	DTL SECTION	6 MV/m
	CCL SECTION	8 MV/m
TRANSITION ENERGY	LOW β/DTL	1 MeV/Nucleon
	DTL/CCL	150 MeV/Nucleon

BEAM PARAMETERS

INJECTOR VOLTAGE	200 kV
INJECTION ENERGY	100 keV/Nucleon
FINAL ENERGY	600 MeV/Nucleon
PEAK BEAM CURRENT	600-800 μA
PULSE LENGTH	50 μs
REPETITION RATE	30-120 Hz
AVERAGE BEAM CURRENT	1-5 μA

Fig. 3 Heavy-ion linac utilizing EBIS and the PIGMI technology.

Applications

The combination of an EBIS and the PIGMI technology will produce a low-duty, low-cost heavy-ion linac that could find application in a number of areas. A machine, such as the one shown in Fig. 3, would provide the desired dose rate for the requirements in the medical program associated with heavy-ion therapy. In addition, such an accelerator could be used in heavy-ion physics and heavy-ion fusion research. If a storage ring is to be used as a source of high-energy heavy ions for physics or heavy-ion fusion research, such a high-gradient, compact linac appears to be an optimum method for filling the ring.

The beam produced by the low-energy section of such a machine (10 to 20 MeV/nucleon) could be used for low-energy heavy-ion physics, and it would also be ideally suited for injection into a synchrotron designed to produce relativistic heavy ions.

Finally, it is 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 above, that would yield useful beams of all elements up to uranium.

Conclusion

The EBIS, as a new alternate source of heavy ions for linear accelerators, has obviously become more realistic with the recent experimental results from the new cryogenic versions. Combining the EBIS with the new innovations in linac technology discussed at this Conference, will yield an efficient, low-duty-cycle, heavy-ion linac useful in several areas. The new low-velocity linac structures, such as the APF and RFQ, make the use of an EBIS with a conventional drift-tube linac much easier, and much more interesting with regard to accelerated ion yields. This is particularly true with the RFQ, if the capture efficiency is near the calculated values.

Even at the present experimental yields from the EBIS, these new linac structures make a low-duty-cycle heavy-ion linac interesting, but the projected yields from the present EBIS and the projections for a future EBIS make such a linac even more interesting. Thus, because it is ideally suited to the operation of a pulsed linac, the use of the EBIS as an injector for future heavy-ion linacs should be pursued.

TABLE II

HEAVY-ION APF STRUCTURE

	APF w/Conventional Source[9]	APF + EBIS
Injected ion (Tin)	$^{124}Sn^{+9}$ (q/m = 0.072)	$^{124}Sn^{+36}$ (q/m = 0.29)
Injection voltage (MV)	1.0	0.25
Injection energy (MeV/nucleon)	0.072 (β = 0.0124)	0.072 (β = 0.0124)
Final energy (MeV/nucleon)	0.285 (β = 0.0247)	1.14 (β = 0.0494)
Total length (m)	1.0	~1.0
No. of cells	40	32
Axial gradient (MV/m)	3.7 to 7.2	3.7 to 7.2

TABLE III

HEAVY-ION RFQ PARAMETERS

Injection voltage (V_i)	200 kV
Injection energy (W_i)	0.10 MeV/nucleon ($\beta\lambda$ = 2.18 cm)
Frequency (f)	200 MHz
Initial radius (a_i)	0.33 cm
Final energy (W_f)	1.0 MeV/nucleon ($\beta\lambda$ = 6.90 cm
Final radius (a_f)	0.21 cm
Structure length (ℓ)	5.3 m
Final synchronous phase (ϕ_s)	-39°
Peak voltage between electrodes	55 kV

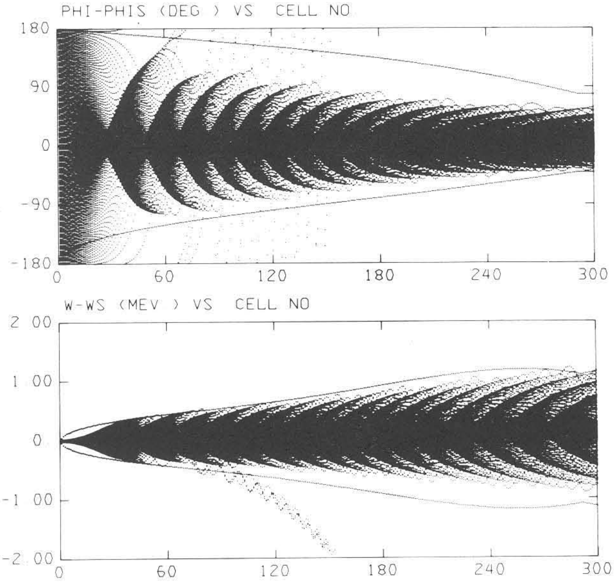


Fig. 4 The RFQ beam dynamics for Ne^{20}.

Acknowledgments

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