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EBIS, AN OPTION FOR MEDICAL SYNCHROTRONS*

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Abstract

Light ion beams have been used for cancer therapy for about twenty years; several dedicated facilities are presently either planned or under construction. In addition, several synchrotrons designed for other purposes are now considered for medical applications as well. A medical synchrotron needs a preaccelerator to produce and inject a range of different light ions, preferably fully stripped, into the ring. The size, cost and complexity of the preaccelerator depend on the performance of its first element, the ion source, and these features will be optimized if the source itself produces fully stripped ions. An EBIS (Electron Beam Ion Source) is capable of producing fully stripped light ions up to argon with intensities sufficient for medical applications. As it has been pointed out in the past, this source option may require just one stage of preacceleration, an RFQ linac, thus making it very simple and compact. The AGS Department has a separate project already under way to develop a very high intensity EBIS for our nuclear physics program. It is, however, our plan first to construct and test an intermediate size device and then to proceed to the design of the final, full scale device. Parameters of that intermediate model are close to those that would be needed for a medical synchrotron. This paper describes the BNL program and considers parameters of EBIS devices for possible use in synchrotron facilities serving as sources of high energy light ions for cancer therapy.

1. Introduction

Although the advantages of high energy, light ion beams in the treatment of cancer have been known for quite some time, clinical trials started less than twenty years ago, at Lawrence Berkeley Laboratory, using helium ions from their synchrocyclotron and, a few years later, heavier ions from the LBL Bevalac. A few thousand patients have been treated so far. The results seem to justify further research in this area and presently there are a number of facilities under consideration or construction [1,2].

A synchrotron is very flexible regarding the choice of ion species, beam properties and energy modulation on a pulse-to-pulse basis. However, for a dedicated synchrotron located in a hospital environment it is very important to be simple, reliable and easy to operate and maintain. An ion source, producing fully stripped ions, would greatly contribute to these features because the preaccelerator may thus become very compact and efficient [3]: a single stage RFQ linac, with no need for stripping foils. Existing EBIS devices have not been designed specifically for applications in medical synchrotron facilities but their performance as pulsed sources of fully stripped light ions (although the available data are very limited) justifies their consideration for that purpose. The beam intensities of such ions, when delivered to a patient, should be of the order of 10^9 particles per second, less for heavier species [1,2,4]. Several EBIS devices have already achieved yields close to this level; e.g., DIONÉ at Saclay, on the synchrotron SATURNE, has produced 10^9 fully stripped nitrogen ions with a short confinement time of only 30 ms and at a reduced electron beam current [5]. The Stockholm EBIS is serving in the injector for the synchrotron CRYRING; it has produced $\approx 3.6 \times 10^8$ fully stripped neon ions per pulse, again operating at half of the maximum electron beam current [6]. The same source has been tested with argon and it

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has produced a charge state distribution with a peak in the fully stripped state [7] and a yield of 4.7×10^7 ions per pulse.

The Brookhaven EBIS program is directed toward a possible application in the RHIC preinjector [8,9], although a medical option was considered as well [10]. The present scenario for RHIC is based on one of BNLs tandem accelerators injecting ion beams up to gold into the AGS Booster [11]. As an alternative, more compact and easier to operate and maintain, we are considering an EBIS followed by an RFQ and a superconducting linac, which in our case is necessary to reach the required injection energy into the AGS Booster [8-10]. We are in the process of putting into operation and performing first tests on the Super-EBIS [12], a device designed to produce extremely high charge state heavy ions, and which we obtained on a long term loan from Sandia Laboratories. However, its design electron beam current is far below the value needed for RHIC and we plan to upgrade it in two steps [9]. The intermediate device would operate with electron beam currents of 1-2 A; it will, of course, serve primarily to produce heavy ions up to uranium as a test device for RHIC, but it should also be capable of delivering light ion beams of any species required by a medical synchrotron, in a fully stripped state. The second phase will be devoted to the design of a high intensity EBIS as required by RHIC.

2. Electron Beam Ion Sources - EBIS

In an EBIS, multiply charged ions are produced by electron impact on ions in a magnetically confined electron beam of proper energy. The ions are confined radially by the space charge of the electron beam and axially by the potentials on the electrodes of the trap. A cycle of operation in the pulsed mode, which is the only relevant mode for use on synchrotrons, consists of a short injection pulse (either atoms or ions in a low charge state), followed by a confinement period to build up the desired charge state distribution, and ending with the expulsion of ions from the source. The duration of the ion pulse can be adjusted in a wide range, down to 10 μs and below, by properly biasing the electrodes in the trap. This is one of the advantages of an EBIS, because a single turn injection of the whole bunch of ions into the synchrotron ring becomes possible. For an EBIS, the maximum number of positive charges that the trap can store equals the number of electrons in the trap

$$Q^+_{max} = 1.05 \times 10^{13}\ I_e V_e^{-1/2} L \qquad (1)$$

where I_e and V_e are electron beam current and voltage, resp., and L the length of the trap. However, in a real device the neutralization of the electron space charge by positive ions will be less than complete; also the selected charge state will be only part of the distribution. The available number of ions in the desired charge state N_q will rather be

$$q\ .\ N_q = Q^+_{max}\ k_1 k_2 \qquad (2)$$

where k_1 is the neutralization degree and k_2 the relative charge state abundance. Values for k_1 between 0.3 and 0.5 are routinely achieved, while for fully stripped light ions k_2 can reach values above 0.5 [6,13]. There are two other important parameters, electron beam current density, J, and the confinement time τ; their product $J\tau$ determines the evolution of the charge state distribution [13]. To get a feeling about the values for J and τ, we can quote experimental results for fully stripped nitrogen ($J\tau \approx 15$ A.s/cm^2; ref.13), and calculated values for fully stripped neon and argon, resp. ($J\tau \approx$ 30 A.s/cm^2, and $J\tau \approx 300$ A.s/cm^2, resp.; ref. 12). There is a trade-off between the electron beam current density and confinement time; also the repetition rate of the synchrotron may limit the confinement time and, thus, may determine the current density.

3. Medical synchrotron requirements and EBIS parameters.

The required beam intensity at a position close to the patient is often defined as that intensity which would result in a dose of 5 Gy/min delivered to a volume of 2 ℓ [1,4], at the full beam energy. The corresponding values, in particles per second, are shown in Table I; they can be considered as upper limits, because many tumors will be smaller than 2 ℓ or be situated closer to the surface, requiring a lower beam intensity and ion energy. Also, a tumor can be successfully treated even with somewhat lower beam intensity, but over a correspondingly longer irradiation time. The transmission efficiency between the source and the position where the beam has to be delivered, cannot be much better than 50%; the second row in Table I shows the required yields from the source itself, again in particles per second. However, if the synchrot.on repetition rate is different from 1 Hz, the source yields will have to be corrected to take this into the account.

Table I

	C	N	O	Ne	Ar
Beam intensity at target	$1x10^9$	$9x10^8$	$7x10^8$	$5x10^8$	$2x10^8$
Source intensity	$2x10^9$	$1.8x10^9$	$1.4x10^9$	$1x10^9$	$4x10^8$
Super-EBIS upgrade	$3.7x10^9$	$3.2x10^9$	$2.8x10^9$	$2.2x10^9$	$1.2x10^9$

For illustration purposes only, we shall now estimate basic parameters of a few EBIS devices, that could be used in a preinjector for medical synchrotrons. In all cases it will be assumed that the electron beam neutralization efficiency is 50% and that 50% of the extracted beam is in the fully stripped state.

a) BNL upgrade of the Super-EBIS.

Although primarily intended as a source of partially stripped, very heavy ions up to uranium, (ratio of the charge to the atomic weight of about 0.2), this device will be tested as a source of fully stripped light ions as well. For nuclear physics applications this EBIS will be running with confinement times up to 100 ms [9], but this could be extended if necessary to achieve fully stripped light ions. The last row of Table I shows calculated yields of fully stripped light ions up to argon, assuming a trap length of 0.6 m, an electron beam current of 1 A, and a voltage of 5 kV (which should be sufficient to fully strip all ions up to argon; the resulting electron gun perveance is relatively high, but achievable with modern designs). For fully stripped neon ions a confinement time of 100 ms would require an electron beam current density of 300 A/cm^2, which is easy to reach, but for fully stripped argon this leads to 3000 A/cm^2, which is excessive; in the latter case one would prefer to run the source with confinement times around 1 s and keep the current density around 300 A/cm^2. The conditions for any ion lighter than neon would, of course, be less stringent.

b) An EBIS Design for the ADROTERAPIA Project.

The ADROTERAPIA (or TERA) project is a feasibility study for a hospital-based hadron therapy facility [4]. The accelerator would be a strong focusing synchrotron with two separate injectors, one for H^- ions and the other for light ions up to oxygen. The repetition rate is assumed to be 2 Hz for H^- ions and 1 Hz for light ions. The light ion injector would consist of a PIG ion source producing a very intense short pulse of O^{2+} ions, followed by an RFQ and a two section drift tube linac. There would be two stripping foils; ions would be injected fully stripped, at an energy of 3 MeV/u.

An EBIS could deliver ion beam intensities as required in this study. If we take from Table I the value $1.4x10^9$ for the number of fully stripped oxygen ions per EBIS pulse, we get from (1) and (2), with k_1=k_2=0.5

for a voltage V_e = 3000 V,

$$I_e L = 0.25 \text{ A.m}$$

This result suggests a tentative EBIS device with a length of L = 0.5 m and an electron beam current of I_e = 0.5 A. A rather low electron beam current density of 100 A/cm^2 would be sufficient so that a standard, room temperature magnet could be used. (For comparison, we can mention the Frankfurt MEDEBIS [3], presently under construction; it has been designed for I_e = 0.165 A, and L = 0.25 m, so that its yield will be below TERA requirements. However, its successful operation will be an important step in the development of room temperature EBIS devices for medical applications.) The source would be followed by an RFQ; there are commercial designs for acceleration of ions with a q/m= 0.5, with the output energy of 1.5 MeV/u. This injection energy is lower than originally designed and it would mean a wider frequency range for the synchrotron rf system, but this should be no problem.

c) Possible EBIS designs for the AUSTRON project.

The AUSTRON project [14] is a feasibility study for an accelerator to serve as a neutron spallation source. The accelerator complex would consist of two preinjectors, one for H^- ions and the other for light ions up to neon, followed by a 70 MeV drift tube linac and a rapid cycling (25 Hz) synchrotron. The primary purpose of the complex is neutron physics, but the possibility of using light ions for cancer therapy is actively pursued as well. The question of how the synchrotron would share its operation between the two modes has not been addressed yet. One possibility is to reserve a time interval (a few minutes per session) exclusively for therapy, and run the machine with a high repetition rate. The source requirements (Table I) would thus be greatly reduced and a rather small and simple EBIS, like the Frankfurt MEDEBIS [3], would be sufficient. The other possibility is to operate the complex with the maximum intensity of light ions to fill an intermediate storage ring. For this mode one would need an EBIS similar to that for the TERA project. The advantage of the latter mode is that the therapy is decoupled from the neutron operation and more beam time is available for neutron physics.

4. Conclusions

A growing interest in the light ion therapy of certain cancers has led to several studies and projects of medical facilities based on synchrotrons. For the best efficiency they would all need injection of a beam of fully stripped ions. An EBIS is a device that is capable to produce such beams with intensities as required for the therapy and in bunches as short as needed for single turn injection. Although at present there are no EBIS sources that would fully satisfy, in all aspects, particular requirements of a medical synchrotron, the performance of devices now in operation is promising enough to warrant their serious consideration as an option for this application.

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