

## Advanced Electron Beam Ion Sources (EBIS) for 2-nd generation carbon radiotherapy facilities

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## TECHNICAL REPORT

## Advanced Electron Beam Ion Sources (EBIS) for 2-nd generation carbon radiotherapy facilities

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**ABSTRACT:** In this work we analyze how advanced Electron Beam Ion Sources (EBIS) can facilitate the progress of carbon therapy facilities. We will demonstrate that advanced ion sources enable operation of 2-nd generation ion beam therapy (IBT) accelerators. These new accelerator concepts with designs dedicated to IBT provide beams better suited for therapy and, are more cost efficient than contemporary IBT facilities. We will give a sort overview of the existing new IBT concepts and focus on those where ion source technology is the limiting factor. We will analyse whether this limitation can be overcome in the near future thanks to ongoing EBIS development.

**KEYWORDS:** Instrumentation for heavy-ion therapy; Instrumentation for hadron therapy; Instrumentation for particle-beam therapy

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## 1 Motivation

IBT compared to X-ray treatment offers a significant advantage owing to the peaked energy deposition for charged particles (Bragg peak). This reduces the collateral dose received by healthy tissues in front and behind the tumor. The prominence of the Bragg peak is higher for heavier ions compared to protons. In addition, heavier ions deposit a significantly higher amount of energy in the cells, and have stronger relative biological effect (RBE) [1] owing to a higher frequency of double-strand DNA breakups. Ion RBE is especially enhanced in the area of the Bragg peak. This makes IBT the method of choice for treating patients with radiation-resistant tumors. It is estimated that for a population of 10 million the annual number of patients requiring IBT amounts to 4500 [1]. Contemporary IBT facilities, such as HIMAC in Japan [2] and HIT in Germany [3], are designed to treat 800 and 750 patients a year, respectively. Compared to the incidence of IBT-relevant cancer cases this translates to up to 6 IBT facilities per 10 million people, creating demand for 300 IBT facilities within the European Union alone. Even though a significant number it is a small fraction compared to 20 000 X-ray radiotherapy facilities in service worldwide at the moment.

The therapeutic advantages of IBT compared to protons come with higher costs for larger and more complex equipment, as well as higher operational costs. Carbon ions must have a higher energy of 425 MeV/u compared to 250 MeV/u for protons for the same penetration depth of 33 cm [4]. On top of that, bare carbon has twice the mass-to-charge ratio of protons. This makes a total difference in beam rigidity of about a factor of 3 higher for carbon compared to protons, thus requiring larger and more expensive machines.

While radiotherapy protons are typically accelerated by cyclotrons with a diameter of 3–5 meters, carbon ions require synchrotrons of some 20 meters in diameter. For best dose delivery a gantry allowing multidirectional treatment of the patient is an essential component of a therapy complex. Due to the rigidity limitations, carbon gantries are large in size, heavy, and expensive in both construction and operation. The carbon ion gantry at HIT [5], the only one worldwide,

exceeds the weight of the HIT synchrotron itself. The complete gantry weighs 700 tons, of which 570 tons are rotating [6]. As the gantry makes up the dominating part of the treatment facility cost, less effort has been devoted to new cost-efficient designs of the actual accelerator.

The situation is likely to change with recent advances towards compact and less expensive superconducting (SC) gantries. Several new optics schemes for superconducting gantries have been suggested [7, 8]. The classical optics in a SC variant reached the conceptual design phase in the Etoile project [9] and at JINR [10]. At HIMAC [11] the first SC ion gantry passed the technical design stage and is being built [12], as of 2015 the gantry is mounted with SC magnets cooled down [13]. With a maturing SC gantry technology the focus of the construction cost will be back at the accelerators.

Apart from financial reasons present day machines have limited abilities to follow the progress in the beam delivery methods. A clear disadvantage of cyclotrons is the beam being extracted at a constant energy. In contemporary synchrotrons the beam is extracted by long spills of about 1 s. The energy can be changed between spills. Also extraction of ions of varying energy can be realized in existing synchrotrons with successive deceleration and partial extraction of a single spill with energy shift requiring about 100 ms [14]. Higher frequency of energy change of about 30 Hz can be achieved with a specially designed ion Rapid Cycling Medical Synchrotron (iRCMS) [15], which is better suited for raster tumor scanning, but remains a bulky, high maintenance and expensive option.

Several alternative accelerator concepts were recently proposed to address both the construction cost challenge and offer beams better suited for therapy. These accelerators are specifically developed for IBT already taking into account clinical experience from the first carbon machines and compatible with the modern and future therapy strategies. Therefore, in this paper we call such accelerators 2-nd generation IBT accelerators. The key features of such accelerators are reduced footprint and higher accuracy of dose delivery achieved by using such technique as multi-painting. Multi-painting is an irradiation technique where every single voxel of the irradiated tumor is visited by the beam multiple times. Multi-painting increases the treatment quality by reducing the statistical error in the delivered dose especially for moving organs [16]. Realization of multi-painting requires adjustable ion beam energy and possibility to steer the beam quickly between spots. The latter can be done either using a continuous beam and steering with the beam turned on, or a pulsed beam with high enough repetition rate of some hundreds of Hz [16], so that any voxel will be visited multiple times within reasonable therapy-session time of a few minutes.

In this paper we will limit ourselves to already well developed concepts ready to soon be constructed. We will not touch upon more exotic concepts such as dielectric wall or laser driven accelerators [17]. While promising to be even more cost efficient and compact these need longer R&D phase and will likely be the base for the 3-rd generation IBT machines. We will look at such new IBT accelerator concepts as cyclinac [18–20], linac [21], iRCMS [15] and FFAG [22, 23], which allow to adjust the ion-beam energy between the high frequency pulses. While all of these machines have certain advantages, such as cyclinac and FFAG allowing easily combined proton and carbon treatment, not all of them are good candidates according to above mentioned criteria of reduced footprint, compatibility with modern beam scanning technique and required R&D. FFAG is a circular machine with rather complex structure including several concentric accelerating rings covering the full energy range. Thus it does not provide significant advantage in terms of footprint and construction cost as compared to present day synchrotrons. Known proposals of iRCMS

feature the repetition rate of tens of Hz which falls in between of the continuous beam of a standard synchrotron and hundreds of Hz required for multi-painting. There is also no benefit in footprint compared to classical synchrotron. Therefore, only linac-based models can be both compact and provide multi-painting scan capabilities for both proton and carbon ion operation [19]. The critical technology for compact linac-based design is the high-gradient cavities. This technology relies on massive R&D performed for the Compact LInear Collider (CLIC) at CERN, for example, hence the research phase can be significantly shortened [24]. The construction price for alternative accelerator designs is expected to be lower owing to the simpler structure. Furthermore, a linac-based design offers a more compact machine leading to lower costs for civil construction, shielding and utilities.

Some critics state, that linac-based designs are inferior to synchrotrons due to lower quality of multi-painting or longer treatment times at the same quality. These critics, however, neglect the fact that choice between two possible IBT options will be made not based on the time it takes to treat a single patient. The decision will be based on the cost of a patient treatment taking into account the facility construction and running costs compared to its throughput. If we take as an example the successful HIT facility we see 119 M€ construction budget [25], ~20 M€/year running costs [26] and about 750 patients a year [3] throughput. Such construction and operation costs are close to early projections [27] based on detailed cost breakdown, even though patient throughput assumed in the calculation was never achieved. As a result there is plenty of room for alternative options to be competitive even with longer treatment times for individual patients if other advantages cover for it. Here we mean first of all lower maintenance downtime, lower running and construction costs. While providing impeccable treatment quality synchrotrons struggle to become profitable, which is illustrated by Siemens withdrawal from 250 M€ NRoCK project in 2011 (see p. 373 in [28] ) and economic struggles with first private-operated therapy centrum in Marburg [29, 30] based on the same IONTRIS™ design by Siemens.

At the moment only linac-based designs seem as realistic alternatives to synchrotrons. In our overview of the ion source requirements for the alternative accelerators we will cover a few other types to provide a wider context.

## 2 EBIS application for 2-nd generation IBT

### 2.1 2-nd generation IBT requirements on the ion sources

Regardless of the accelerator type the average rate of irradiation is dictated by the medical considerations. For carbon therapy the typical value is about  $3 \times 10^8$  particles per second. The intensity and time structure of an ion source can be defined from that value and expected beam transmission of the accelerator. A summary of the required number of particles per pulse and pulse repetition rate for several accelerator proposals is given in table 1. As we see, the 2-nd generation concepts require intensive pulses with a high repetition rate. While this poses no major problem for proton-based accelerators, it is a challenge for heavier ions. The challenge is a result of several requirements to be satisfied simultaneously. The pulse from the source must be intensive enough to provide therapeutic dose and cover all the transmission losses in the beam delivery system. In some designs (FFAG, cyclinac) only a percentage fraction or less of the beam intensity at source will be delivered to the target.

**Table 1.** Injection requirements for some 2-nd generation IBT accelerator types. Intensity at the source in particles per pulse (ppp).

Accelerator	Injection	Source intensity, ppp	Rep. rate, Hz	Pulse width, $\mu\text{s}$
FFAG [23]	$\text{C}^{4+}/\text{C}^{6+}$	$0.58 \times 10^8$ – $4.3 \times 10^8$ <sup>1</sup>	200	0.25
iRCMS [31]	$\text{C}^{4+}/\text{C}^{6+}$	$2.7 \times 10^7$	30	0.9 <sup>2</sup>
Cyclinac [18] and linac	$\text{C}^{6+}$	$1 \times 10^8$	300–400 <sup>3</sup>	1.5

The second requirement concerns the integral pulse intensity, which should be fitted in a short pulse typically of a microsecond scale. Such limitation comes from the RF pulse length in linac-based devices or typical revolution time in circular machines at injection energy, which is the time-scale to perform single-turn injection. This creates an obstacle for ion sources performing well in DC mode but having no means to provide pulses with high instantaneous intensity, such as Electron Cyclotron Resonance Ion Source (ECRIS). The third requirement is to have pulses with high enough repetition rate from tens to hundreds of Hz. This poses a challenge for intensive pulsed sources which have certain intrinsic time limitations (laser ion source, EBIS). While covering these three base challenges an ion source must also provide appropriate beam emittance, energy spread, contamination level and stability. We will give a performance overview of potential ion sources in the next section.

## 2.2 Performance overview of laser and ECR ion sources

Let us compare the performances of modern ion sources of potential interest for the 2-nd generation IBT facilities. We will consider 3 types of ion sources proposed and tested for IBT: laser ion sources, ECRIS and EBIS.

Laser ion sources based on terawatt power lasers are capable of producing rather intensive pulses of several MeV ions including bare carbon [32]. In NIRS-led study [33] a laser ion source provided a beam sufficient for IBT pulse-intensities of about  $10^9$  ions. However, this scheme is only relevant to low repetition-rate synchrotrons and requires a complicated injection scheme. The terawatt laser has a repetition rate of 10 Hz, below any relevant injection rate. The beam is produced with  $\pm 5\%$  energy spread, which is reduced to  $\pm 1\%$  by a dedicated phase rotation system. The obtained beam still has too large energy spread to be used for IBT, and the injected beam needs to be cooled by a dedicated electron cooler to an energy spread of  $\pm 0.1\%$  [34]. For an electron cooler an energy spread of  $1\%$  is large and challenging to deal with [35]. An experiment modelling such electron cooling was performed on TSR storage ring at MPIK (Heidelberg, Germany) and predicted electron cooling time of about 0.6 s [35]. Therefore, the use of laser ion sources is possible only with 1-st generation slow-cycling synchrotrons and unsuitable for 2-nd generation IBT facilities.

ECRIS is the workhorse of operating synchrotron-based IBT facilities [36]. ECRIS is typically used to produce a DC beam, or afterglow pulses, of  $\text{C}^{4+}$  ions for subsequent electron stripping to  $\text{C}^{6+}$ . This scheme is not applicable to some of the 2-nd generation IBT designs requiring direct

<sup>1</sup>Number provided in [23], gives estimation significantly higher than derived from dose delivery rate and system transmission of 2.2/2.6 % for  $\text{C}^{4+}/\text{C}^{6+}$  given in [23].

<sup>2</sup>Depending on the type of used cyclotron and linac frequency.

<sup>3</sup>Single turn injection.

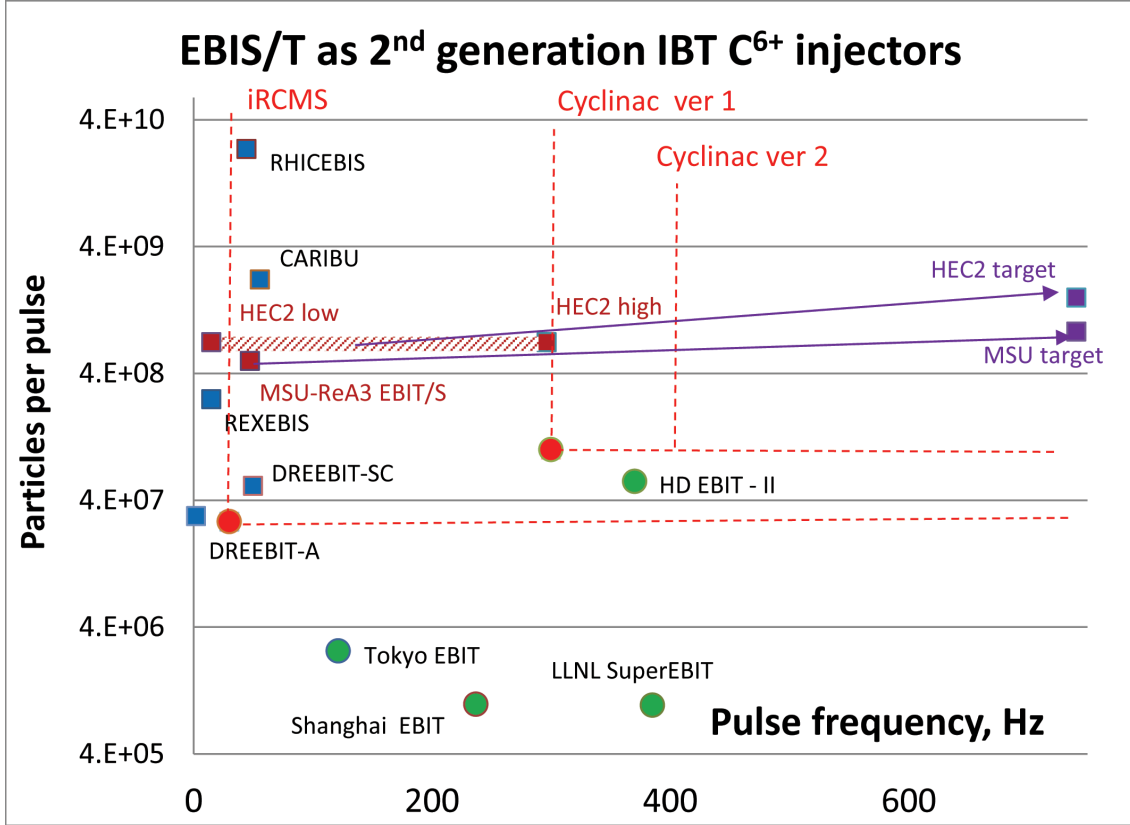
low-energy  $C^{6+}$  injection, such as cyclinac. Moreover, the stripping process increases the beam emittance due to additional scattering. The extraction of a DC beam means the instantaneous current is low and multi-turn injection into the accelerator is required. Even in afterglow mode, with an extraction pulse length of a few 100  $\mu s$ , single-turn injection is not possible, but multi-turn injection into a large acceptance ring has to be used.

The reason for extracting  $C^{4+}$  from ECRIS is twofold. First, ECRISes operate at a rather poor vacuum, meaning that when the beam is extracted the carbon ions have to be separated from residual gas ions originating from the ionization volume. If  $C^{4+}$  is extracted and accelerated, it can be magnetically separated from other species, while  $C^{6+}$  would be contaminated by not magnetically separable  $N^{7+}$  and  $O^{8+}$ . The second reason to use the injection of  $C^{4+}$  with stripping is the production rate. The widely used ECRIS Supernanogan by Pantechnik can produce 200  $e\mu A$  of  $C^{4+}$  [36], while the production rate of  $C^{6+}$  is about 3  $e\mu A$ . Recent more advanced sources [37] demonstrate up to 780/7.8  $e\mu A$   $C^{4+}/C^{6+}$  respectively, which is still significantly below the required values. The injection window for accelerators listed in table 1 is in the range of 0.25 to 1.5  $\mu s$ . If one chops the DC beam from an ECRIS it gives yields of  $3.1 \times 10^8$  to  $1.8 \times 10^9$  of  $C^{4+}$  and only  $3.1 \times 10^6$  to  $1.8 \times 10^7$  of  $C^{6+}$  per pulse assuming the most advanced ECRIS. As we see an ECRIS can provide sufficient intensity for systems using  $C^{4+}$  injection, while injection of proper intensity of  $C^{6+}$  is beyond reach.

### 2.3 Design parameters and performance of EBIS

In early 90-s EBISes have been first proposed as an alternative ion source for carbon therapy synchrotrons [38]. Compared to contemporary used ECRIS, an EBIS offers a simplified injection line without a stripper stage. EBISes have a short extraction pulse and can be operated with a high repetition rate. Thanks to the short and intensive pulse the synchrotron can be filled with single- instead of multi-turn injection, with less losses and radiation activation of the injection septum as a result. Single-turn injection furthermore allows for a reduction in the ring acceptance, and therefore in the aperture of the magnets, which reduces the cost of the ring construction [39]. In a 1994 review of heavy ion sources for IBT Sato et al. [40] mentioned that an EBIS/RFQ injector proposed in [38] “is the most simple system among various combinations which are capable of providing relativistic heavy-ion beams for radiation therapy”, however the technological limits, especially on the EBIS side, require further development to make it feasible. Work on improving EBISes for IBT applications was pursued through 1990-s in the group led by R. Becker [41, 42]. The early experiments with EBIS for synchrotron injection were later continued [43, 44] and recently reached a commissioning stage at HIT [45] where for example an emittance reduction by a factor of 9 compared to an ECRIS was demonstrated [46]. In parallel, EBIS injectors were also studied for alternative accelerator concepts such as cyclinac [18].

For modern EBISes the production of high repetition  $C^{6+}$  pulses is not a standard request. The notable exception are DREEBIT-A and DREEBIT-SC. For these two we use experimental data on fast production of bare carbon ions [44] in our further analysis. For other machines we assess their performance based on the properties of the electron plasma in respective devices. We take the EBIS/EBIT data from the following sources: RHIC EBIS — [47], CARIBU EBIS- [48], REX EBIS — [49], ReA3 EBIT at MSU — [50], DREEBIT-A, DREEBIT-SC — [44], LLNL EBIT — [51], and others — [52]. Here we make no distinction between EBISes and EBIS-like ion traps



**Figure 1.** Comparison of injection requirements and performance of several EBIT and EBIS devices. Cyclinac version 1 and 2 show two design scenarios of cyclinac, version 1 with SCENT cyclotron and 3 GHz linac, version 2 with K480 cyclotron and 5.7 GHz linac [20].

EBITs. An EBIT is generally a low-capacity experimental device for in-trap studies often not meant to provide extracted ions and lacking related design features.

For the estimation of the repetition rate we make the following assumptions. The desired charge state is reached after a series of successive ionization steps. The ionization cross-section is calculated using the Lotz formula [53]. We calculate the cross-sections for a 20 keV electron beam energy for all the devices. Production of  $C^{6+}$  at this energy requires an ionization factor of  $13.5 C/cm^2$ . The ionization factor is a product of the required electron current density  $J_e$  and the ionization time  $\tau$ . From the known  $J_e$  for each machine we can calculate the required breeding time  $t$ , i.e. the maximum repetition rate of the machine.

We estimate the pulse intensity in the following way. From the known electron current, length of the trapping region and the electron energy we find the total negative space charge of the electron beam. Conservative values for the space-charge neutralization and extraction efficiency of 30% and 70% are assumed, and approximately 30% of the carbon ions are in the desired charge state 6+. Using this approach we have analyzed several EBIS/T presently operational, decommissioned or under development. The summary is presented in figure 1.

The red circles represent minimum requirements of a certain accelerator class and the dashed red lines indicate the parameter area where a suitable ion source should operate (above and to the



right from corresponding lines). In this analysis we exclude FFAG. As mentioned earlier, there are significant discrepancies between references regarding required intensity; also the injection window of 0.25 microseconds is below reach for most of the considered EBIS/T.

The green circles show EBITs. These devices typically operate at low electron-currents and have short trapping regions, which limit their pulse intensity to low levels. On the other hand, thanks to their high-compression electron-guns, they can reach rather high current densities, i.e. a high pulse repetition frequency. Unfortunately, these guns are typically used at electron energies in excess of 100 keV, which is too high for efficient production of  $C^{6+}$ . At the same time, operating at lower energies may be difficult as it sets harder constraints on the divergence of the electron beam, which at lower energies may fail to enter the high magnetic field region without excessive losses. Therefore pure EBITs are of little interest as ion injectors for IBT.

A series of blue squares shows existing EBISes using immersed-flow electron guns with beams of moderate to high currents and long trapping regions. These sources of highly charged ions operate at the relevant electron energy with proven stability and reliability. Unlike small-scale devices (EBITs or compact EBISes such as DREEBIT-A), high-capacity EBISes, such as RHIC-EBIS, CARIBU, REXEBIS, can not only ionize a target gas but also accept the external injection of  $1+$  ions from a primary source owing to their significant transverse acceptance. The importance of this option can be demonstrated with the following example. Let us consider an EBIS with an electron current of 200 mA, equal to that of REXEBIS or DREEBIT-A, and a trapping region to 0.7 meters, equal to that of REXEBIS and more than ten times longer than that of DREEBIT-A. Let the working gas pressure be  $3 \times 10^{-9}$  mbar, as found optimal at DREEBIT-A for carbon ion production. If we take the first ionization cross-section for carbon and use the above motivated values for final charge-state abundance of 30% and extraction efficiency of 70%, we will find that  $6.2 \times 10^9$  ions can be extracted per second. At 200 Hz extraction frequency it means  $3.1 \times 10^7$  ions per pulse. This is sufficient for iRCMS but is not enough for a cyclinac or linac as shown in figure 1. Hence, the primary ionization constraint will require either higher electron current for gas ionization, or higher electron current in order to accept intensive pulses of externally produced and injected primary ions.

While fulfilling even the toughest IBT requirements for the pulse intensity, modern high-intensity EBISes have a major limitation in the attainable repetition rate. Due to the immersed-flow gun design these machines have the current density limited by the emission density of the cathodes and the magnetic compression ratio. The latter is constrained by the magnetic field strength in the ionization region. Both are unlikely to be increased and have reached their practical limitation in the newest CARIBU charge breeder. Despite of their large capacity, contemporary EBISes are therefore neither suitable for injection into high repetition rate 2-nd generation IBT accelerators.

Two devices presently under development and indicated by dark red squares are aiming to bridge the gap between high intensity and high repetition rates (the target values for both are shown by purple squares). These are the ReA EBIT [54] at NSCL-MSU and the HEC<sup>2</sup> [55] project carried out by BNL and CERN. The ReA EBIT/S pursues the idea of upscaling the EBIT type electron optics (green circles) and employing it at lower energy. The HEC<sup>2</sup> project downscales [56] the electron optics used for X-band RF-tubes and adjusts it to EBIS applications. Both projects have demonstrated first electron beams and production of highly charged ions [57]. However, in neither of the cases the design values of the electron current density were achieved using the initial gun

designs due to limitations related to electron loss currents. The electron current density has been established at NSCL by observing X-ray emission from ions inside the electron beam via radial ports in the solenoid. From the electron beam radius the current density could be derived [58]. The HEC<sup>2</sup> does not have such a gap in the solenoid, thus the current density estimations have only lower and upper limits (HEC<sup>2</sup> low and HEC<sup>2</sup> up) indicated in figure 1, and were obtained from simulations and observed production of highly charged ions originating from the residual gas. The dark red hatched area corresponds to the uncertainty in current density. Both projects have revised their electron gun designs in order to achieve higher levels of electron beam current and beam compression (MSU — [50], HEC<sup>2</sup> — [59–61]). The modified designs are now being implemented. If successful, either of the machines will outperform the requirements of all studied IBT accelerator types. Even a partial success of either project will make the use of new accelerator types feasible and open new opportunities for 2-nd generation IBT.

## 2.4 Beam purity

In the past, schemes proposing C<sup>6+</sup> injection from a source to an accelerator raised concerns about the beam purity [36]. It was suggested that injection of C<sup>4+</sup> is preferable because of possible contamination of the C<sup>6+</sup> beam with N<sup>7+</sup> and O<sup>8+</sup>. For ECRISes and EBISes working at relatively poor vacuum this poses a significant challenge. The operation experience with today’s EBISes, however, demonstrates that the challenge is manageable.

In the absence of air leaks nitrogen is a minor component of the residual gas composition, while oxygen can come from internal sources. Smaller ionization cross-sections of oxygen compared with carbon will require a 1.4 times longer breeding time to reach bare charge state, so by adjusting the breeding time the fraction of oxygen in the beam can be minimized. Preventive measures such as reducing the partial pressure of oxygen in the ionization region will further improve the purity of the C<sup>6+</sup> beam. For example, the EBIS-A by DREEBIT demonstrated N<sup>7+</sup>/C<sup>6+</sup> and O<sup>8+</sup>/C<sup>6+</sup> ratios in the extracted beam in the range of  $3\text{--}9 \times 10^{-3}$  [43]. EBIS-A is typically working at residual gas pressures of  $1\text{--}3 \times 10^{-9}$  mbar [62, 63]. In experiments with EBIS-A for carbon ions production the optimal value of the working gas pressure (propane) was  $3\text{--}5 \times 10^{-9}$  mbar. EBISes specially aiming to suppress impurities, for instance REXEBIS, demonstrate a base pressure in the lower  $10^{-11}$  mbar region. At the same time the partial pressure of oxygen in normal REXEBIS operation is estimated to  $2 \times 10^{-12}$  mbar [49]. Altogether it brings the contamination level well below tolerable dose uncertainty of the order of 2%. A scheme with the <sup>11</sup>C isotope (see below) as the treatment beam eliminates the isobaric contamination risk completely.

## 2.5 Pulse length

As mentioned in section 2.1 the pulse length might be a critical issue for some ion sources in some applications. Many EBISes were used in applications where the extraction pulse length was not an issue, or it was desired to have it long (up to 800  $\mu$ s at REXEBIS) or continuous in so-called “leaky mode” where ions are escaping over the axial potential barrier from the tail of the thermal energy distribution. Many EBITs dedicated to in-trap spectroscopy didn’t have extraction at all. Therefore it was important to assure that extraction from an EBIS can be fast enough. In applications without strong requirements on the pulse shape EBISes may work in “self-extraction” mode. In this mode the axial potential is lowered and all ions in all charge states escape in axial direction owing to

their kinetic energy. Depending on the trapping region size this process may take up to hundreds of microseconds for slow ions to leave a  $\sim 1$  m trap. The extraction time can be significantly shortened if ions are pushed in axial direction by extraction potentials applied along the drift tube structure. Let us consider typical extraction times relevant to the ion injection into IBT facilities. For a linac-based design the limiting factor is the duty factor of the RF system and the length of the RF pulse. For cyclinac this is 1.5 microseconds [18]. For circular machines the limitation comes from revolution frequency of the beam at the injection energy (energies in case of FFAG with multiple rings). Extracting pulses of such length allows to have simplified single-turn injection, lower emittance of the beam, lower acceptance of the ring, smaller magnets, which eventually leads to significant reduction of construction and running cost. The specified time window for injection into iRCMS is 0.9 [31] — 1.5 [15] microseconds and 0.25 microseconds for FFAG [23].

Now let us have a look at the EBISes extraction time. For large EBISes we can take the example of RHIC EBIS where a 1.5 meter long trap is extracted in 10–40 microsecond pulses [64]. This is obviously excessively long for IBT, but so excessively is also the ion capacity of RHIC EBIS. A test demonstrating fast extraction was performed by Becker et al. [41] using a 24 cm trap and a dedicated fast-switchable drift-tube system [65]. In this test the extraction time of 2 microseconds was achieved. This is in general comparable to the described above pulse length of IBT machines. Achieving the same extraction length in longer devices, such as the 75 cm TestEBIS (with HEC2 gun) or the TWINEBIS (offline replica of REXEBIS at CERN retrofitted with a new gun) can be done in one or two ways. If the neutralization level allows, the ions could be collected in a shorter part of the trapping region, i.e. be extracted from a trap of a length comparable to the one used by Becker. Keeping a long trap may be still advantageous in order to improve capture of externally injected ions or ionization from the gas phase. Given 0.1 neutralization assumed in this paper, in good vacuum (low contribution of ionized residual atmosphere) the axial compression of the trap before extraction is a feasible option. Therefore mid-sized EBISes with trap 0.25–0.75 m are capable to fit their pulse within the required time window with acceptable losses for all considered IBT designs apart from FFAG, where most of the extracted ions will be lost.

## 2.6 $^{11}\text{C}$ and other ion beam types

Treatment quality assurance by means of the on-line irradiation control is an important component of radiotherapy. Apart from providing injection of the therapeutic beam, EBISes are a promising tool for the treatment planning and control. For IBT one of the most efficient ways of on-line dose control is Positron Emission Tomography (PET), based on radioactive decay of positron-emitting isotopes in the irradiated region [28]. NIRS-HIMAC pioneered the technique by using an externally produced  $^{11}\text{C}$  ion beam to verify in-vivo the ion range [66] and adjust the treatment plan with stable or radioactive therapeutic ions immediately following the diagnostic irradiation [67]. An R&D program to develop an EBIS-based  $^{11}\text{C}$  injector for the HIMAC synchrotron was later carried out [68].  $^{11}\text{C}$  can be produced off-line by the very same complex (such as proposed for cyclinac [18]), then be extracted and shortly stored. An alternatively way is to use for on-line production an auxiliary device, for instance a medical cyclotron [69], or a medically designed RFQ module [70]. The practical therapeutic application of  $^{11}\text{C}$ -PET aided radiotherapy will be further studied at CNAO (Italy) in the framework of the EU-funded MEDICIS-Promed ITN-program started 2015. In the same program, the possibility of capturing, trapping and charge breeding of carbon

ions produced in ISOL mode will be studied at the CERN ISOLDE complex using the REXEBIS charge breeder [71].

### 3 Conclusion

Over the last decade the carbon IBT technology made a large step towards becoming a market-viable cancer-therapy option for treatment of radiation-resistant tumors. Better understanding of the biological effects of light ion irradiation helped to improve the clinical results. The first facilities such as HIT and HIMAC proved the concept and took necessary steps to establish dosimetry techniques and quality assurance for carbon beam treatment, while progress in superconducting ion gantries opens up possibilities for affordable multidirectional treatment. It shifts the focus back to the cost of the accelerator, its efficiency and reliability to maintain a stable flow of patients. Synchrotrons based on experience from nuclear physics facilities are however high-maintenance and high-cost machines not ideal for the therapy role, neither adapted to a hospital environment. Recently, several types of accelerators, such as iRCMS, FFAG and cyclinac, have been expressly designed for therapy use. Among them linac-based designs provide significant reduction in construction and maintenance cost while enabling advanced dose delivery methods. These accelerators are also the most demanding from the ion source point of view. For linac-based accelerators a suitable ion source matching their injection requirements is a bottleneck problem due to required intensity and repetition rate.

In this paper we have demonstrated how recent advances in the field of EBIS/T technology can address the ion-source problem. Requirements on future EBIS/T devices to be used as charge breeders for ISOL facilities and ion sources for space radiation research are more challenging [72] than a possible use for ion production at IBT facilities. Thus downscaled versions with relaxed design parameters can be utilized for IBT with minimum required R&D. For some of the considered accelerator types, such as linac-based design concepts it has a crucial impact making them technologically feasible. For other new accelerator types, which can be served by modern ECRISes there are multiple possible advantages of using EBISes, which can make such an option worth the investment. The advantages include flexibility of used species, including condensable elements and reduced cost thanks to reduced beam emittance requiring optics with smaller aperture. While for synchrotrons, iRCMS and FFAG EBIS injector is an option to consider, for very promising linac-based concepts an advanced EBIS injector is a prerequisite with no alternative available at the moment.

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