STATUS OF ECR ION SOURCES FOR CARBON-ION RADIOTHERAPY IN JAPAN

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Abstract

For the five Japanese carbon-ion treatment facilities the carbon beams are being produced with ECR ion sources of two types, both developed at NIRS. These sources satisfy all medical requirements. A study has been initiated for understanding the performance deterioration following long periods of carbon operation.

HISTORY AND GEOGRAPHY

Presently in Japan five carbon-ion radiotherapy (C-RT) facilities are situated. The Heavy Ion Medical Accelerator in Chiba (HIMAC), the Hyogo Ion Beam Medical Centre (HIBMC) and the Gunma University Heavy-ion Medical Centre (GHMC) are already under operation. Over 1100 patients have been treated by three facilities in 2011. The Saga Heavy Ion Medical Accelerator in Tosu (SAGA-HIMAT) and the Ion-beam Radiation Oncology Centre in Kanagawa (i-ROCK) are under construction.

The HIMAC project at the National Institute of Radiological Sciences (NIRS) was promoted by the Japanese government as a research project under the first "Comprehensive 10-year Strategy for Cancer Control [1984-1993]." HIMAC is the first medical dedicated carbon facility in the world[1], and has successfully treated close to 7000 patients with 140-400 MeV/u carbon beams since 1994. The clinical result at HIMAC clearly shows the effectiveness and safety of C-RT[2], therefore the newer Japanese facilities have chosen carbons as well for treatment, all being produced in ECR ion sources.

HIBMC is the first proton and carbon combined facility, and was mainly funded by a local government. In order to reduce the running cost and the risk of interruption due to troubles, two ECR ion sources with the same structure are utilized to produce proton and carbon ions. HIBMC is also the first commercial C-RT facility with the permission under the Japanese regulation law of medical instruments, and start the treatment since 2001.

Under the third 10-year Strategy [2004-2013], the government promotes development of downsizing technologies. NIRS designed a hospital-specified C-RT facility and developed prototypes of various components. The feature of the design is an exhaustive optimisation for treatment by carbon beams[3]. This realized a cost-effective and reliable facility's design. The ECR ion source was also renewed under this concept. GHMC was constructed as a demonstration facility by the government, and start the treatment since 2010[4].

Table 1 shows existing and planned ECR ion sources for C-RT in Japan. Type N, H, and K mean NIRS-ECR, NIRS-HEC and Kei-series described in the next section. Figure 1 shows their locations. SAGA-HIMAT is funded by a consortium of a local government and private companies[5]. i-ROCK belongs a local government.

Table 1: Chronology of ECR Ion Sources at Carbon-Ion Radiotherapy Facilities in Japan

Name	Type	Facility	Launch
NIRS-ECR	N	HIMAC	1993
NIRS-HEC	H	HIMAC	1997
ECR1	N	HIBMC	1999
ECR2	N	HIBMC	1999
KeiGM	K	GHMC	2009
Kei2	K	HIMAC	2010
KeiSA	K	SAGA-HIMAT	*2012(plan)*
?	K	iROCK	*2015(plan)*

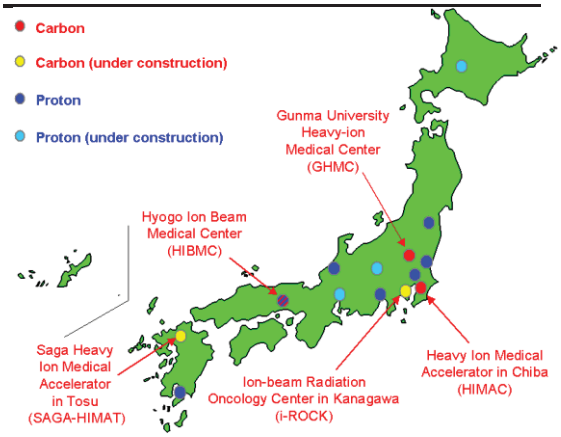

Figure 1: Geographical distribution of carbon-ion radiotherapy facilities in Japan.

DESCRIPTION OF SOURCES AND THE STATUS OF OPERATION

Four types of ion sources have experiences of C-RT; a 10GHz ECR ion source called 'NIRS-ECR', an 18GHz ECR ion source called 'NIRS-HEC', and 'Kei-series', and finally one PIG ion source called 'NIRS-PIG', which for the production of carbon ions, NIRS-PIG at HIMAC is being used temporally only[6]. The main purpose of NIRS-HEC is to produce heavier ions like Fe for

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fundamental researches[7]. Therefore we summarize here the most important types: NIRS-ECR and Kei-family

The NIRS-ECR Type

NIRS-ECR has a closed ECR zone with 10 GHz microwave shown in Figure 2[8]. The plasma chamber has an inner diameter of 70 mm and an inner length of 160 mm. Typical operational parameters for C^{4+} production are as follows. CH_4-gas is used to supply the carbon. The vacuum pressure in the plasma chamber was estimated to be around 3×10^{-4} Pa. The axial mirror fields at the injection side, the bottom of minimum B, and the extraction side are set to 0.8, 0.25 and 0.6 T, respectively. The radial sextupole field is 0.8 T on the chamber wall. The microwave is fed into the chamber through the open end of rectangular waveguide, which is simply connected with the end plate of chamber for the microwave shielding. Usually, the microwave power (typically 600 W) is operated in pulsed mode, but continuous wave mode is also available. The pulse width of 2 ms is enough for supplying beams, and the shorter duty cycle gives better reproducibility at the start up. The extraction voltage of 24 kV is applied to the plasma chamber matching injection into the NIRS RFQ linac. The distance between the plasma and the extraction electrodes is around 25 mm optimised to the beam transport.

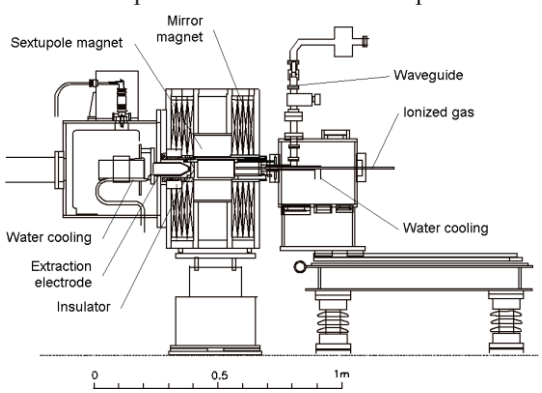

Figure 2: Schematic view of NIRS-ECR ion source.

NIRS-ECR does not need maintenance and beam tuning for the daily treatment, usually. The reproducible beam is realized with loading well-established parameters which were stored in the control system. The running time reached about 6000 hours in 2011. Since a few serious accidents occurred with the microwave amplifier, we replaced the klystron amplifier to a travelling wave tube amplifier. The present 10 GHz NEC amplifier did not give any trouble in the last 8 years. At present, small electronics circuits are routinely replaced every several years to prevent troubles. During last few years, we clean up the source including the plasma chamber once per year. However, we did not take care of the inside of source during a period of over 4 years; thus our experience is proving that such type of maintenance is strictly not necessary.

At HIBMC, the production of proton and carbon beams is required with the same ion sources and a common beam transport line and injector linacs. In order to improve the transmission efficiency, H_2^+ molecular ion beams with the higher energy of 35 keV/u are necessary to reduce the space charge effect between ion sources and the RFQ linac. Two copies of NIRS-ECR (with small modifications) were installed on the high voltage platform shown in Figure 3. The beams are extracted from the source with 25 kV from the plasma chamber and are accelerated from the high voltage platform with 45 kV and 80 kV for H_2^+ and C^{4+}, respectively[9].

ECR1 and ECR2 are usually assigned for each ion species. However, it is easy to exchange their roles for a scheduled maintenance and so on. The beam intensities at the front of RFQ for H_2^+ and C^{4+} are about 1300 and 400 eμA, respectively. These intensities are four times higher than required. The microwave amplifiers were also replaced from the old klystron to the same TWT as used for the NIRS-ECR.

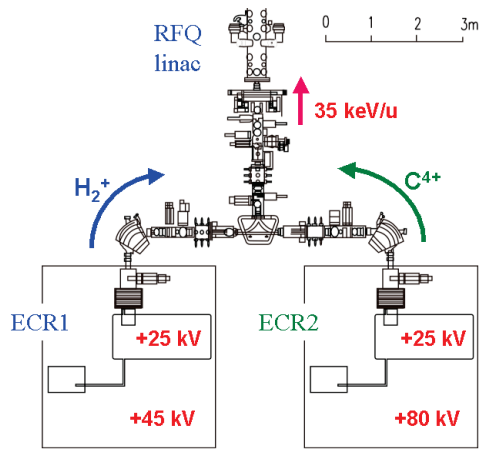

Figure 3: Layout of the high voltage platform at HIBMC.

The Kei Type ECR Ion Source

A compact ECR ion source called 'Kei' source was developed to reduce the size, initial construction cost, and electric power consumption. The design concept was how to reproduce well-established operational parameters of NIRS-ECR including the magnetic configuration by permanent magnets only[10]. Although the inner diameter and length of plasma chamber had to be shrunk to 50 mm and 60 mm, the result was promising. So the next prototype called 'Kei2' was developed to optimise the magnetic configuration and to improve the high voltage insulation[11]. The microwave amplifier was replaced by the same TWT amplifier as used for the NIRS-ECR. The maximum record of C^{4+} finally reached 1emA at extraction voltage of 40 kV. After successfully finishing the tests as a prototype, Kei2 has been installed in 2010 as an additional local injector of HIMAC for the backup of existing injector.

KeiGM was designed for GHMC and its general structure was copied from Kei2. The extraction electrode was simplified down to a fixed position shown in Figure 4. However, this modification also has given an increasing vacuum pressure in operation. Since the vacuum

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condition at the extraction region is more sensitive for a better stability, this effect has to be altered in order acquire an easier operation similar to Kei2.

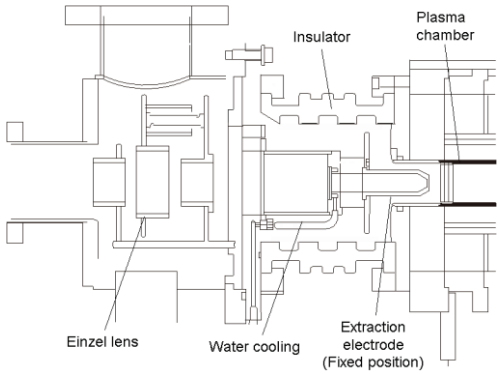

Figure 4: Schematic view of the extraction system of KeiGM.

Since KeiGM is the only ion source installed, it has to supply all beams. In about 4000 hours operation between 2010 and 2012. One of the most serious failures was due to breaking microwave amplifier after 14000 hours operation. The failure had been repaired by replacing. This amplifier was the same type as in the other facilities. There was rarely one accident at seven amplifiers.

KeiSA was manufactured for the installation into SAGA-HIMAT. This facility also adapts a single ion source like GHMC. The structure of KeiSA is completely same as KeiGM and the result of single preliminary test was also same. It will be launched to the linac in 2012.

Figure 5: ECR ion source has been installed in SAGA-HIMAT just before launch.

DIFFICULTY OF CARBON-ION PRODUCTION

Carbon ions are usually produced from gaseous compounds in an ion source. It means many carbon atoms are dissociated and are deposited on the wall. It is well-known from many experiences that such a deposition causes a deterioration of performance. Especially, decreasing of intensity and deterioration of electrical breakdown strength can give serious problems.

Decreasing of Intensity

In order to increase the intensity of highly charged carbon ions like C^{4+}, it's effective to feed hydro-carbonic C_xH_y gases. The other element in the gaseous compound plays the role of mixing gas[12]. On the other hand, carbon deposition is unavoidable with hydro-carbonic gases. Our experience shows that the C^{4+} intensity in several days decreases to about 70 % and further reduces a bit to a somewhat stable regime at say 60 % of the starting level. When the chamber wall is cleaned up, it is recovered to its earlier 100 % level. In order to check the possibility that electric conductive material deposited on the natural dielectric wall would form a Simon short circuit[13], we continuously collect samples for detailed analysis. However, from our preliminary measurements we are not able to draw any firm conclusion.

Electrical Breakdown Strength

We sometimes observed a corona discharge current increasing with increasing operation time. It is supposed that the carbon deposition also causes deterioration of electrical breakdown strength not only on the surface of insulators but also in vacuum between electrodes. However, the mechanism is still not clear. The phenomenon empirically depends on the vacuum pressure at the extraction region. In such a condition, we must find suitable parameters which can operate with better vacuum pressure. It constricts the margin of performance. We study the mechanism for improvement.

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