Development of a Permanent Magnet Light Ion Source at CEA/Saclay.

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Abstract: In France, the Spiral 2 project dedicated to radioactive beam production is based on a 40 MeV CW deuteron Linac. This installation will allow extending the variety of accelerated particles to very heavy elements. Such beams will open new research domains for the GANIL facility. To inject the requested 5 mA deuteron beam into the Spiral 2 Linac, the performance of the high intensity light ion source (SILHI) allowed us to propose such an ECR source. SILHI, developed at CEA/Saclay, regularly produces high intensity (over 100 mA) proton or deuteron beams through a Φ 9 mm aperture. So for this project, the main modifications of the source design concern the permanent magnets which provide the axial magnetic configuration and the Φ 3 mm aperture. The source produced its first beam (proton) in 2004. This article will report the beam characterization while the source produced D^+ beam with intensity as high as 7.0 mA. Recently, this permanent magnet source has been equipped with the Φ 9 mm plasma electrode. So high intensity proton beams reaching more than 100 mA are now extracted from this source.

I. INTRODUCTION

In the framework of High Power Proton Accelerator (HPPA) development, CEA and CNRS have been working on the IPHI low energy beam demonstrator. The high intensity light ion source (SILHI) has been built first to produce proton beams. Experiments were also devoted to the production of deuterons for irradiation tools. Deuterons are now also needed by the SPIRAL 2 facility [1] and a "low" intensity (5 mA) deuteron source has been studied at CEA/Saclay [2].

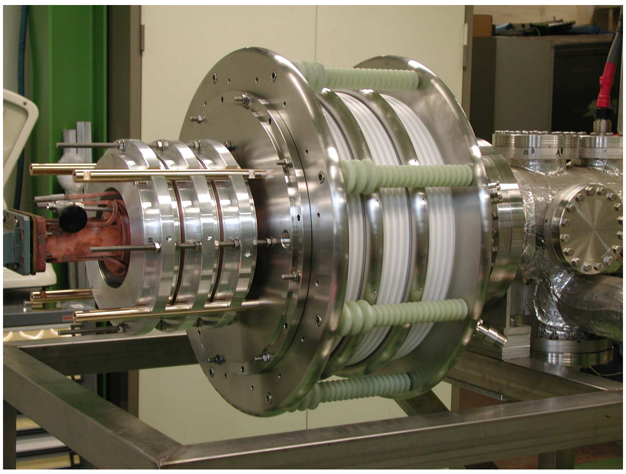

Fig. 1: Permanent magnet source adapted on the Silhi extraction column

The SPIRAL 2 facility will be installed at GANIL in Caen. Its goal consists in extending the possible radioactive beam types. This machine is based on the fission of a Uranium carbide target induced by neutrons. The neutron flow will be produced by interaction of deuteron beam with a Carbon target. SPIRAL 2 requires a maximum of 5 mA - 40 keV continuous wave (cw) D^+ beam with rms normalized emittance lower than 0.2 π mm.mrad. Another operating mode could consist in directly hitting the Uranium carbide target with a 150 µA D^+ beam. So, to fit in with these constraining demands, an ECR source development has been proposed.

A new ECR source equipped with a Φ 3 mm extraction hole has been built with a permanent magnet assembly. The performance of the source satisfies the Spiral 2 requirements with a D^+ beam notably close to 7 mA.

Moreover, to test the capability of such a permanent magnet source, proton beam has been extracted through a Φ 9 mm aperture and the total extracted beam intensity easily reached more than 100 mA.

II. SOURCE DESIGN

A. Magnetic structure

For this new source, electromagnetic simulations suggest the magnetic field be provided by 3 permanent magnet rings [3] (Fig. 1) instead of 2 solenoidal coils on SILHI. In the initial drawings, the plasma chamber with 2 boron nitride disks and the RF power chain followed SILHI design.

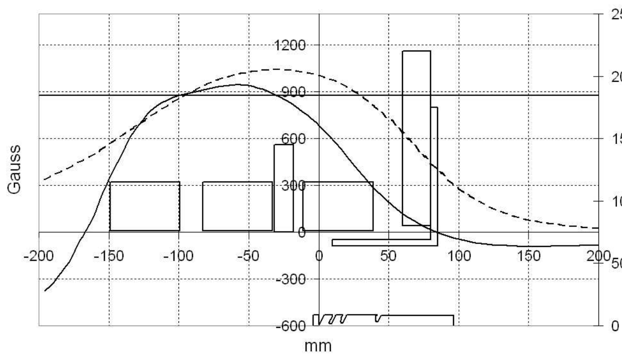

Fig. 2: Axial magnetic field comparison of Silhi and the permanent magnet source

In order to minimize the glow discharge problem magnetic shielding has been inserted between the permanent magnet rings in addition with magnetic shielding between the source and the accelerator column. Such compromise allowed us to reach the 40 kV source potential with the axial magnetic field reported on figure 2 (solid line). On this figure, the horizontal solid line indicates the 875 Gauss limit and shows 2 ECR zones occur in the plasma chamber. The dashed curve represents the computed Silhi axial magnetic field.

B. Preliminary design modifications

Two main reasons led to important modifications after the first hydrogen beam analysis: (i) the beam species measurements showed high level of heavy ions, (ii) while the source was producing low intensity beam (lower 1 mA), plasma instabilities appeared.

So in order to keep very low deuteron beam with no noise, nitrogen and deuterium gas have been simultaneously added in the plasma chamber. In this case, the total extracted beam continuously ranges from 4 to 8 mA and the 2 intermediate electrode complicated extraction system [4] is no more needed. So we decided to directly adapt the permanent magnet source to the large Silhi extraction system [5].

To minimize the impurities, the plasma chamber pumping has been improved. A specific turbomolecular pump has been directly connected on the RF chain.

III. BEAM CHARACTERISATION

To characterise the extracted beam, the source successively operated with hydrogen, deuterium and mixed gas (deuterium and nitrogen). In all following measurements, the source was operating in CW mode and the energy of the extracted beam was fixed at 40 keV.

At low energy, the d,D reaction also leads to 2.45 MeV neutron emission when D^+ ions hit the deuterium molecules at the surface of the target. So the source was first producing hydrogen beams in order to optimize the magnetic configuration by changing the magnet ring position.

After source pressure tuning, the total extracted beam reached 9.2 mA (40 keV) with 800 W of injected RF power. The beam species, measured with the Silhi Wien filter, were H^+ = 71 %, H_2^+ = 12 %, H_3^+ = 1.6 % et 15 % impurities. The source ran in these conditions for 150 hours, with no regulation loop. No beam off occurred and the total current only decreased of 2 % (from 9.2 to 9 mA).

In order to characterise the deuteron beam expected for the Spiral 2 project, deuterium gas was injected in the source. Neutron production was permanently measured with a LB6411 probe located close to the target.

The beam parameters were plotted as a function of the injected RF power. Of course, for each value, the intermediate electrode potential was adjusted to minimise the D^+ beam emittance. Table 1 summarises the source performance while the RF power rose from 300 to 1200 W. In these conditions, the total extracted beam went up from 3.1 to 9 mA.

One could note that the D^+ fraction continuously increased as well as the neutron production. Moreover the D^+ beam intensity reached a maximum of 7 mA, to be compared with the requested 5 mA. Finally, the D^+ beam emittance remained always largely lower than the 0.2 π mm.mrad expected for the Spiral 2 RFQ design.

In addition, in Silhi LEBT, a 6 MHz bandwidth ACCT located 2.25 m downstream the extraction system, allows analysing beam noise. In this case, a 6.1 mA D^+ beam (total current 8 mA) has been checked; a total current equal to 6.5 mA reached the beam stop 5 m far from the plasma electrode and 160 µA rms beam noise (~ 2.5 %) has been observed. Like for Silhi [6], the ACCT showed 19 kHz oscillations are transferred to the plasma from the magnetron RF switched power supply as well as a 50 Hz ripple due to alternative magnetron filament heating.

Table 1: Characteristics of D^+ beam produced by the permanent magnet source equipped with a Φ 3 mm plasma aperture.

Power RF	I (total)	**I (D^+)**	D^+	D_2^+	D_3^+	Impurities	Emittance	Neutrons
W	mA	**mA**	%	%	%	%	π mm.mrad	µSv/h
300	3.1	**2**	66	12	2.3	20	0.073	210
500	5.5	**4**	72	9.4	1.1	17.5	0.076	423
700	6.9	**5.2**	75.1	9.1	0.8	15	0.076	538
900	8.0	**6.2**	77.4	8.7	0.7	13.2	0.081	630
1100	8.8	**6.77**	77.2	9.3	0.6	12.8	0.085	694
1200	9	**7**					0.086	

As already mentioned, noisier beam occurred when the RF power was reduced to obtain very low beam current. Table 2 presents the beam species fractions while deuterium and nitrogen gas were simultaneously injected into the plasma chamber. To do this experiment, a second flow controller was installed on the HV platform. For the measurements reported in this table, only the gas mixing changed. The RF power (700 W) and the high voltages (HV source = 40 kV, HV puller = - 35 kV) remained constant. The minimum D^+ intensity was 110 µA (2.7 %) whereas the heavy ion fraction reached close to 95 %. The last line of this table shows the reproducibility of the source behaviour when we come back few hours later. Concerning the emittance, only one measurement was done with such a low D^+ current. The emittance value was 0.079 π mm.mrad with 430 µA D^+ beam current.

Table 2: Deuterium and Nitrogen gas mixing to produce low D^+ beam intensity

D_2 Flow	N_2 Flow	Total beam	**D^+ Current**	D^+	D_2^+	D_3^+	Heavy ions
sccm	sccm	mA	**mA**	%	%	%	%
0.50	0	6.3	**3.9**	62	7.5	0.5	30
0.33	0.05	5.9	**3.4**	57	9.7	0.9	32
0.28	**0.06**	4.5	**1.7**	34	4	0.8	61.3
0.26	0.09	4.1	**0.91**	22	2.2	0.6	75
0.20	0.09	4.3	**0.78**	18	2	1.3	78.6
0.15	0.11	4.1	**0.43**	10.5	1	1.7	86.8
0.10	0.12	4.0	**0.11**	2.7	0.2	2.7	94.3
0.11	0.12	4.0	**0.14**	3.5	0.3	2.7	93.5
0.12	0.12	4.0	**0.19**	4.7	0.2	2.4	92.7
0.28	**0.06**	5.0	**1.7**	33.9	3.8	0.7	61.6

IV. TOWARD HIGH INTENSITY PERMANENT MAGNET SOURCES

Proton beams have been previously produced with the Silhi source equipped with different plasma electrode apertures. The permanent magnet source designed for the Spiral 2 project delivered proton beams with comparable intensity. As the source was installed on the 100 kV Silhi accelerator column, high intensity beam production has been tested.

First, the Φ 3 mm plasma electrode was replaced by a 4.8 mm one. With the source fed with pure hydrogen gas, the total extracted intensity immediately jumped from 9 to 24 mA. Then the classical Φ 9 mm plasma electrode has been installed. The total extracted current easily reached 100 mA for 900 W RF injected power. Of course, beam energy has been increased up to 90 keV to avoid beam losses on the extraction system. In these conditions, the proton fraction was a little bit higher than 75 %. By increasing injected RF power up to 1100 W, the maximum total intensity attained 110 mA. Moreover, the source ran producing 85 mA at 80 keV total beam for 9 days (216 hours). Only 1 beam off occurred during 20 s.

To compare these results with the Silhi ones, the use of coils allows adjusting magnetic field and improving the extracted current. In fact the maximum proton beam produced with Silhi reached 156 mA whereas the optimum obtained with this new source is "only" 110 mA. J. S. C Wills et al. already extracted 60 mA of hydrogen beam through a Φ 5 mm aperture at 450 W RF power [7]. So, magnetic configuration optimisation will be continued to improve this performance. One can already note that the absence of coils, power supplies and control system allows minimising the breakdown rate and improving the source reliability.

V. CONCLUSION

To design ECR light ion sources, the permanent magnet technology can not simply replace a coil magnetic configuration. After several modifications of original design, the new source demonstrated its capability to fit in with the Spiral 2 accelerator requirements. The source, equipped with a Φ 3 mm plasma aperture, effectively produced 6.7 mA D^+ beam at 40 keV with rms normalised emittance lower than 0.2 π mm.mrad. Only 700 W injected RF power is needed to produce the requested 5 mA. Moreover, gas mixing injection allowed producing very low D^+ beams.

In addition, the Silhi extraction column allows installing the Φ 9 mm aperture plasma electrode. Proton beams have been easily produced with intensity as high as 100 mA at 90 keV. Finally, the very high reliability of this permanent magnet source has been demonstrated.

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