A 60 GHZ ELECTRON CYCLOTRON RESONANCE ION SOURCE FOR PULSED RADIOACTIVE ION BEAM PRODUCTION

T. Thuillier, L. Latrasse, T. Lamy, C. Fourel, J. Giraud,
Laboratoire de Physique Subatomique et de Cosmologie, CNRS/IN2P3-UJF-INP Grenoble,
53 rue des Martyrs, 38026 Grenoble CEDEX, France

C. Trophime, P. Sala, J. Dumas, F. Debray,
Laboratoire des Champs Magnétiques Intenses, CNRS
25 rue des Martyrs, B.P. 166, 38042 Grenoble CEDEX 9 France

Abstract

The efficient production of short pulses of radioactive ion beams is a key point of the long term CERN beta-beam project. A strong R&D effort in the field of ion sources is required to reach this challenging objective. A summary of the pulsed beta-beam ion source specification is proposed. A discussion follows on the ion source technologies suitable for this demanding project. The proposed solution foreseen (a 60 GHz ECRIS), uses a cusp magnetic configuration based on water cooled copper coils. The 3D magnetic field structure, along with the mechanical design status is presented. An experimental test with an aluminium prototype shows a good agreement with simulation and validates the design.

THE BETA-BEAM PROJECT

The neutrino physicist community is currently discussing the next generation neutrino beam factory. Nowadays, several projects are still under competition. The Beta-Beam is a project studied by the CERN [1]. The baseline scenario is to generate, ionize, and then accelerate Radioactive Ion Beams (RIB) ~5×10^{13}/s ^{18}Ne or ^{6}He to high energies (with a Lorentz factor γ>100). These nuclei which undergo a β decay are stored in a long race track decay ring to produce intense neutrino beams (see Figure1, blue arrows). The goal of these beams is to study the neutrino oscillations properties and give constraints on the mixing angle θ_{13}.

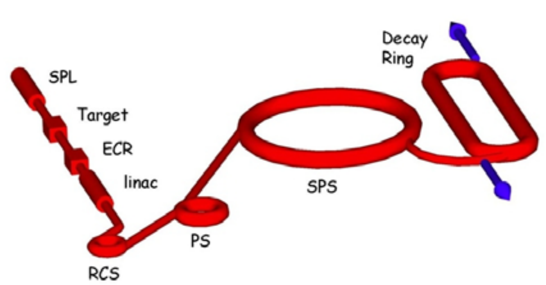

Figure 1: Baseline scenario of the beta-beam accelerator.

The radioactive elements are expected to be produced in the future EURISOL facility. The primary beam, delivered by a proton LINAC, induces nuclear reactions in a set of target stations. Radioactive Gases effuse from the target to the ion source through a high conductance cooled pipe to filter gas and condensable contaminants. The ion source should bunch the beam in order to inject ions as efficiently as possible in the 3 synchrotrons rings included in the project.

SPECIFICATIONS FOR THE PULSED ION SOURCE

Pulsed Ion beam Current specifications

Consider an ideal source able to ionize the RIB of interest with 100% efficiency. If the ion extraction is performed in continuous working (CW) operation, the 5×10^{13} /s ^{18}Ne flux would result in a 8 pμA extracted CW beam. Such ionic intensity is very easy to extract from a classical Electron Cyclotron Resonance Ion Source (ECRIS). The Beta-Beams pulse width at the source extraction is expected to be <50 μs, with a frequency repetition rate f=1/T ranging within the 10 to 25 Hz range. The highest peak current, derived from these values is ~16 pmA. Moreover, other gases will be extracted from the target and ionized in the source. Thus, an unknown number of contaminants will be added to the peak current.

High radioactivity environment constraints

The ^{18}Ne and ^{6}He half lives $T_{1/2}$ are respectively 1.67s and 0.807s. The time for a radioactive atom to exit the target and reach a classical ion source located several meters away already approximately reduces the initial atoms flux by a factor 0.4. A key parameter for the project is to design an efficient ion source located as close as possible to the target in order to minimize the radioactive decay losses. Moreover, the source should hold radiation damages for a long time (~1 month). Consequently, the ion source mechanical parts shall not contain permanent magnets, plastic gaskets; even radiation damage on glass fibre may cause problems. Due to the high radiation level, the maintenance of the ion source will not be possible and its cost per unit will have to be moderate, since it may be necessary to change it periodically.

DISCUSSION ON THE ION SOURCE REQUIRED

Charge state distribution and RIB efficiency

A physical limit of a RIB ion source efficiency comes from the natural charge state distribution (CSD) generated by the plasma. In an ECRIS dedicated to the production of afterglow pulses, the hot electrons of the plasma along with a high magnetic confinement (τ_c) will favour high charge states ions extraction. The RIB of interest will then be extracted into several beams of different charge states. At best one of these charge states could reach 20% of the total ion CSD. Nevertheless, it is still possible to design a special LINAC or a Fixed-field alternating-gradient accelerator (FFAG) to accelerate several charge states, say 2 or 3, at the same time [2]. In this case, one can expect an increase of the overall maximum efficiency of the RIB ionization to reach ~30-50%. A second possible scenario is based on the studies initiated at IAP Nijni Novgorod. There, a simple ECR magnetic trap (either axial mirror or axial CUSP) is used. Very powerful RF pulses (>100 kW) are used to build fast intense ions pulses. Recent promising results have shown the feasibility to produce very high currents up to 150 mA [3], [4] and very short ions pulses (<100 µs) of low to medium charge states [5]. The ionization efficiency of the method needs to be experimentally investigated. Another third possible scenario is to use a compact source with a low magnetic field to preferably produce low charge state ions. There, the ion charge state distribution follows naturally the Poisson statistics and the 1+ beam can be optimized to reach ~90% of the RIB of interest. Of course a special care must be taken to insure a high level of radioactive atoms ionization efficiency in the plasma.

Source of losses and RIB source foreseen

Let's define the residence time (τ_r) as the duration between the atom injection in the plasma chamber and its extraction through the plasma electrode hole. A necessary condition to insure a negligible radioactive decay of the atoms in the source is to have $\tau_r \ll T_{1/2}$. If the plasma density is high, the ionization time will be low and $\tau_r \sim \tau_c$. Experimental confinement times in ECRIS are roughly in the range $\tau_c \sim$1-100 ms, so $\tau_r \ll T_{1/2}$ is satisfied, provided the plasma to be dense. In pulsed mode, the radioactive atom of interest can either be extracted as an ion beam, or as neutral gas. This last case will occur in case of too low plasma density. The plasma density of the ion source should definitely be as high as possible. Another cause of loss occurs if $\tau_c \ll T$ ($T=1/f$). In this case, the pulsed plasma disappears totally before the next pulse, letting room to natural gas diffusion through the electrode hole. When $\tau_c \sim T$, another source of loss comes from the low charge state afterglow extraction that will continue until the next RF pulse. These losses can be reduced by installing a pulsed valve at gas injection, or by designing an iris able to close the electrode hole on trigger.

The plasma volume is also a critical parameter. We have seen that the foreseen pulsed RIB intensity to be extracted is high (>16 pmA). Assuming the use of an innovative 60 GHz ECRIS, with a plasma density near the cut-off $\sim 4\times10^{13}$ /cm3, the amount of gas required per pulse (for a mean charge $\langle Z \rangle$ plasma) is $\sim 4/\langle Z \rangle \times 10^{16}$ atoms/liter, to be compared with the $\sim 5\times10^{13}$ /s RIB flux. If the plasma volume is large, the radioactive flux could not be sufficient to reach the high density plasma condition and a buffer gas flow will have to be added. The more the buffer gas flow, the higher the extracted pulsed beam intensity, and the higher the difficulties for the ion extraction. So the ion source should have a volume as small as possible in order to minimize the total extracted pulsed ionic current. A small volume is a challenging constraint for a 'standard model' complying ECRIS, since the use of superconducting technology requires a large volume to relax superconductor wire constraints.

The use of a pulsed duo-plasmatron is questionable. This kind of ion source produces naturally 1+ beam with very high intensities and pulse duration can be easily adapted to the requirement. The drawback is the high pressure (~1 mbar) required inside the plasma chamber of the duo-plasmatron that will make RIB filling rather complicated, since they are produced in secondary vacuum. The global ionization efficiency is expected to be in the range of some 1%, but this order of magnitude has to be confirmed experimentally. A duo plasmatron available at LPSC will be tested in the next months to measure properly the ionization efficiency as a function of the duo-plasmatron parameters.

Summary and strategy

We have seen that the Beta Beam pulsed Ion Source high plasma density which implies high current extraction. A 4th generation ECRIS is the best option. The volume should be as small as possible in order to limit the total extracted current. The extracted RIB charge state is of secondary importance for the moment: in order to investigate the topic, LPSC team decided to start an ambitious 60 GHz R&D program. The goal is to build several prototypes of 60 GHz innovative magnetic structures and test them in pulsed mode. The structures foreseen may be as simple as a single field gradient or as complex as a minimum-|B| structure. The development of several operational superconducting technologies at 60 GHz is not realistic since it takes a lot of time and requires a lot of money. The collaboration with the Grenoble High Magnetic Field Laboratory (GHMFL) provides an opportunity to make 60 GHz ECRIS R&D for an affordable price and short design time. GHMFL is equipped with a set of 20 MW/20-35 Tesla resistive coils available for fundamental physics studies. The original idea consists in developing different sets of magnetic coils using the helix coil resistive technology [6] invented at GHMFL and test them on site with a new dedicated ECRIS test bench. The 60 GHz prototypes will be dimensioned to comply with the GHMFL electrical power and water cooling systems. Moreover, this technology is usable in a highly radioactive environment, since the magnetic structure is mainly composed of copper, steel and water.

DESIGN OF A 60 GHZ ION SOURCE IN CUSP CONFIGURATION

As a first step, LPSC and GHMFL decided to design an axi-symmetric MHD stable magnetic structure: a cusp. The initial design specifications include the following magnetic properties, illustrated in figure 2:

- a closed 2.1 Tesla 60 GHz ECR zone;
- a 4 Tesla radial mirror;
- 6 Tesla at the injection;
- 3 Tesla at the extraction;
- field lines going through the ECR zone must be connected to the above magnetic mirrors without intercepting the plasma chamber wall;
- a 10 cm mirror length.

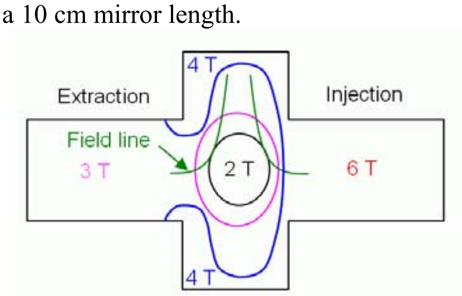

Figure 2: Magnetic field expected in the plasma chamber.

The coil helices are made of copper alloy cylinders into which a helical slit is cut by electro erosion. It is possible to adapt locally the coil current density by changing the helix pitch along the copper coil.

Magnetic simulation

A 2D simulation was performed using both RADIA [7] and Getdp (software developed at Liege University), specially adapted to the helix technique [8]. A flexible solution has been found with a set of 4 radially cooled helices coils, named H1, H2, H3 and H4, presented on figure 3:

- H1, the longest helix, mainly generates the magnetic field at injection. H1 is composed of 3 successive pitch areas (visible on figure 3). The shortest pitch is located on the inner side of the source, close to the largest diameter of the plasma chamber (shoulder), to concentrate the closed ECR zone and generate radial mirror;
- H2 is very short and permits to keep the ECR zone close to the centre of the source and to generate the radial mirror;
- H3 and H4 help to generate the radial mirror in the shoulder;
- H4 mainly produces the extraction magnetic field.

The concentration of a high magnetic field gradient in a 100 mm peak to peak axial cusp rendered the optimization difficult. When the distance between the injection and extraction coils is small, the radial magnetic mirror value is high (sum of radial magnetic components), but consequently the axial magnetic peaks at injection and extraction are reduced (subtraction of the axial magnetic component). A compromise was found when the smaller inner radius of the coils was close to the distance between them. The inner plasma chamber diameter was set to the minimum value possible (60 mm). The corresponding inner coils diameter was set to 80 mm. Below this diameter, the condition concerning the field lines (bullet 5) could not be fulfilled.

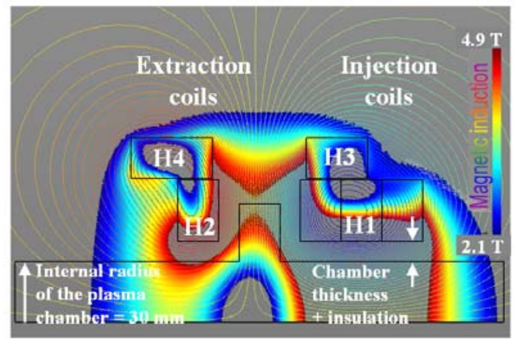

Figure 3: 2D simulation with pitch change configuration of H1. Half of the plasma chamber is represented.

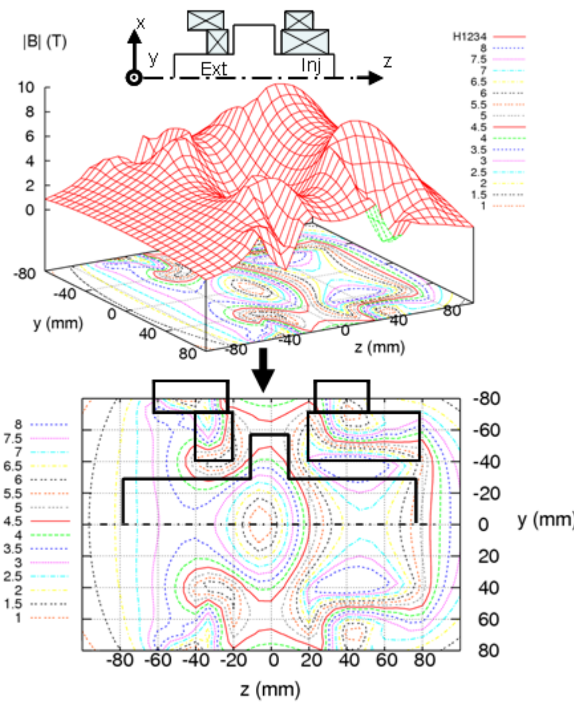

Figure 4. 3D simulation. Magnetic field |B| in the Oy-Oz plane.

A 3D simulation has been performed with another code based on Getdp [9]. It includes thermal analysis (helices water cooling) and exact helices geometry (width of the electro erosion slit) which was not the case in the 2D calculation. The helices were designed with CATIA and then meshed by Samcef Field. The current injected in the coils is 30000 A. The conductivity of the helices is 90 % of the International Annealed Copper Standard (IACS). 3D simulation gave results in good agreements with the 2D ones. Figure 4, represents the magnetic field norm |B| in the Oy-Oz plane as calculated with the 3D simulation. The magnetic field intensity reaches 6.9 T at the injection on the z axis and 3.4 T at the extraction. The radial mirror intensity varies between 4.8 and 4.9 T, due to the imperfect helices symmetry. These results are above the initial specifications, so more flexibility will be available for the injected currents. The magnetic structure can be seen in 3 dimensions using the EnSight 8 software. Thus, in figure 5, the temperature in the helices, the iso-B surface of 7 T at the injection, the iso-B surface of 3.5 T at the extraction and the iso-B of 2.1 T (ECR zone) are represented in the plasma chamber. For more visibility, the mirror surface in the shoulder is not represented.

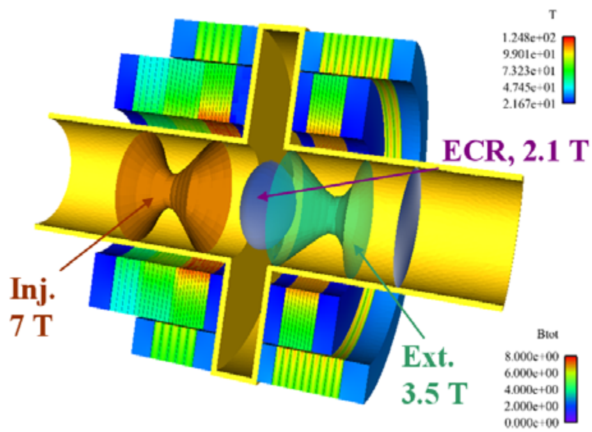

Figure 5. Temperature in the helices and iso-B surfaces of 7 T, 3.5 T and 2.1 T in the plasma chamber.

Validation with an aluminium prototype

Since the design includes an innovative small pitch of 2 mm never used before, an H1 aluminum helix prototype has been machined to experimentally test the accuracy of the calculations (see figure 6(a)). Figure 6(b) represents a comparison between the calculated axial magnetic field and the measured axial magnetic field along the coil axis at low current density (144 A injected). z = 0 mm is the beginning of the helix on the thin pitch side. The difference is only of 3 % at the maximum peak value and both curves have the same magnetic center.

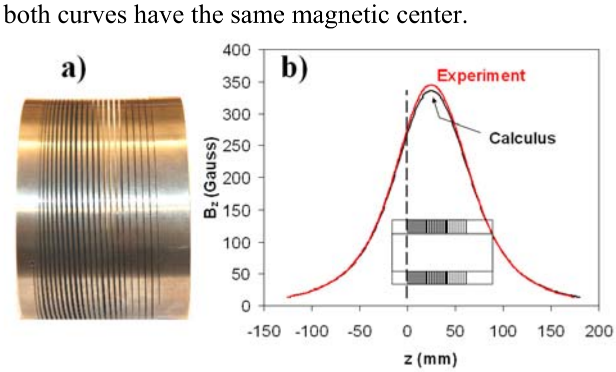

Figure 6. (a) H1 aluminum prototype, (b) Axial magnetic profile of H1.

Engineering design

The current intensity in the cusp has been chosen to be 30000 A Thus, the maximum current density reaches 640 A/mm^2 on the internal radius of H1 and H2, where the pitch is only of 2 mm. The maximum electrical power needed is about 5 MW, depending on the final coils resistivity, so the structure is actively de-ionized water cooled. The inlet water pressure is 2.7 MPa (27 bars), while the outlet one is 0.4 MPa (4 bars). The average water temperature increase is 20°C. The water flow rate is ~20 l/s in the two set of coils. The water speed in the radial helices slit ranges within 30 to 35 m/s, providing a convection heat transfer coefficient h~150 kW/m^2/°C. The average coils temperature varies from 70 to 95 °C while the peak temperature locally reaches 125°C. Pessimist calculations have been performed using a conductivity of 80 % IACS and h~120 kW/m^2/°C for each coil. In this case the mean coils temperature varies between 80 and 115 °C, the peak temperature is 150 °C and the power needed is 6.5 MW. In these conditions, the maximum hoop stress in the coils is σ~280 MPa, far below the copper alloy limit of elasticity (360 MPa). At full current, the two sets of coils repel each other with a force of 600 kN.

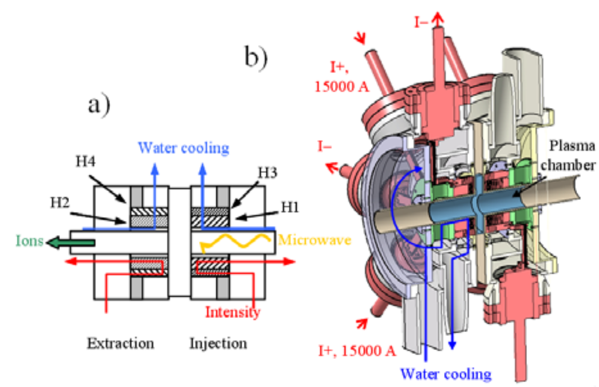

Figure 7. (a) Principle of the source, (b) details of the source.

In case of an extraction coils supply failure (H2+H4), a 50 kN force will arise between H1 and H3 since these two coils have a different magnetic center. The CAD mechanical design of the magnetic structure, taking in account all these data is under progress at LPSC. Figure 7(a) shows the principle of the source and figure 7(b) represents details of the source.

Planning

This first 60 GHz magnetic structure (helices coils in their tanks, electrical and water cooling environment) should be available at the beginning of 2009. The 60 GHz Gyrotron is expected at best for the end of 2009. First experiments of the prototype at a 28 GHz ECR frequency should be done in 2009. The first pulsed beam at 60 GHz is expected in 2010.

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