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HIGH FREQUENCY ECR ION SOURCE (60 GHZ) IN PREGLOW MODE FOR BUNCHING OF BETA-BEAM ISOTOPES

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The efficient production of short pulses of radioactive ion beams is one of the key points of the 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 preliminary studies performed during the 6th PCRD is proposed. Ion source main specifications are summarised. A first 60 GHz ECR Ion Source prototype using room temperature coils is presented. The 3D magnetic field structure, along with the mechanical design status is presented. An experimental test using an aluminium coil prototype is presented, showing good agreement with simulation and validating the design. The Prototype is expected to be completed in the early 2009. Experiments at 60 GHz may start in 2010.

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[1] Speaker

1. Summary of Preglow studies

Experiments have been performed on a modified version of the PHOENIX source [1] named PHOENIX V2. Details of the experimental setup are reported in [2]. At the beginning of the RF pulse, for some tunings, a fast and intense extracted beam was observed, associated to a pressure decrease in the source. This peak was named Preglow (PGW) [2, 3] in analogy with the afterglow peak which occurs at the microwave pulse end. The evolution of He and Ne PGWs has been studied as a function of the following parameters: RF frequency (18 and 28 GHz) and power, buffer gas nature and pressure and plasma electrode hole diameter. To evaluate efficiencies, a Leybold calibrated leak TL6 (5×10^{-6} mbar.l.s^{-1}) has been used to inject either ^{3}He or ^{22}Ne isotopes. The technique used to analyze the experimental ionic pulses is described in [3].

Table 1. PGW characteristics of He+ and Ne2+ peaks at 18 and 18 GHz.

	He^{+}18 GHz	He^{+} 28 GHz	Ne^{2+}18 GHz	Ne^{2+}28 GHz
FWHM (µs)	600-1200	100-300	900	350
Bunching efficiency	~5-10%	~1-3%	~3%	~5%

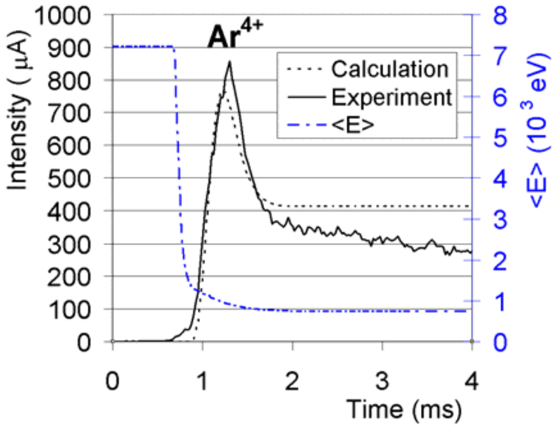

Figure 1. Experimental Ar^{4+} pulse and its numerical fits, along with <E>(t).

Table 1 summarizes examples of PGW peaks characteristics obtained for He^{+} and for a Ne^{2+} for 18 and 28 GHz microwave frequencies. It can be noticed that the Full Width Half Maximum (FWHM) of the PGW peaks decreases with the microwave frequency. This point is of importance since it incites to increase RF frequency to reduce FWHM. The Ne^{2+} global peak ionization efficiency also increases with the RF frequency from 3 to 5%. On the contrary, a lower He efficiency was measured for 28 GHz with respect to 18 GHz. This effect is mainly due to the too low magnetic confinement of PHOENIX V2 at 28 GHz, and to the ion extraction space charge limitation. Indeed, the best results of 3% were obtained with a high pressure in the source and a high extracted ionic current level which could not be properly accelerated through the beam line. This limitation could be avoided with a high voltage extraction system (typically 100 kV). With a better extraction system, He efficiency is expected to be higher at 28 GHz than at 18 GHz heating frequency. Another important fact is observed: the lower the plasma chamber volume, the lower amount of additional buffer gas is necessary to sustain the plasma and the lower the total extracted ionic current. These points are discussed further in the text.

A theoretical 0 dimension plasma model, described in [4], was developed by the Institute of Applied Physics of Nizhniy Novgorod (Russia) in order to describe the PGW mode. This model is based on the 18 and 28 GHz experiments and it enables to simulate 60 GHz plasmas.

Figure 1 represents the experimental and simulated Ar^{4+} PGW peaks, along with the calculated electron energy averaged over the electron energy distribution function (<E>(t)). The microwave frequency influence on the FWHM and on the maximum intensity has been studied by simulation. As observed in experiments, the peak FWHM is expected to decrease with the ECR frequency increase. At a microwave frequency of 60 GHz, the FWHM should be of the order of 100 µs, and the peak currents are expected to increase by a factor 3.

2. Summary of specifications for the Beta Beam pulsed ion source

According to the beta beam baseline scenario [5], the ion source should bunch the beam with a pulse duration as short as possible (~ 50-100 µs) with a pulse repetition rate in the range ~10-25 Hz. The expected radioactive atoms flux ^{18}Ne and ^{6}He from the targets are ~5.10^{13}/s. This flux corresponds to ~8 pµA continuous working (CW) current. Such ionic intensity is very easy to extract from a classical ECRIS in CW mode. The highest peak current, derived from the former duty factor is ~ 16 pmA. Moreover, an unknown amount of other gas species will diffuse from the target; these gases will also be transformed into current. The total extracted current from the source is thus expected to be high. In order to ensure high current, fast ionization and high production efficiency, the Beta Beam pulsed ion source requires high density plasma. A 4th generation ECRIS heated at 60 GHz is the best option. The volume should be as small as possible in order to increase the efficiency. A high voltage (100 kV) is required to extract the high currents.

3. Design of a 60 GHz ion source in cusp configuration

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 structure foreseen may be as simple as a single field gradient to a complex minimum-|B| structure. The development of several operational superconducting technologies at 60 GHz is not realistic since the feasibility of such compact magnetic structures is not proven, and since it is time consuming and very expensive. The collaboration with the Grenoble High Magnetic Field Laboratory (GHMFL) allows making easily 60 GHz ECRIS R&D for an affordable price and reduced design time. GHMFL is equipped with a set of 20 MW/35 T resistive coils available for fundamental physics studies. The original idea consists in developing 60 GHz prototype 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. 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: a closed 2.1 T 60 GHz ECR zone, a 4 Tesla radial mirror; 6 T at the injection; 3 T at the extraction and a 10 cm axial mirror length. Field lines going through the ECR zone must be connected to the magnetic mirrors without intercepting the plasma chamber wall.

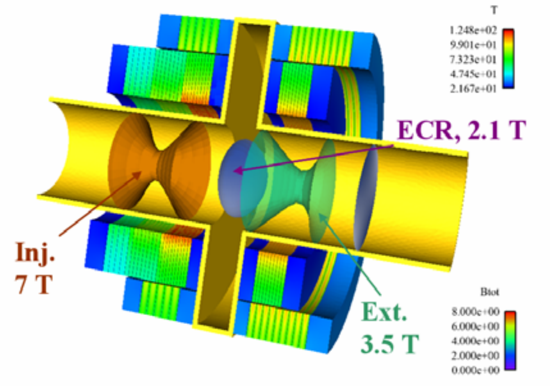

Figure 4: 3D simulation results.

A 2D simulation was first performed using both RADIA [7] and Getdp (software developed at Liege University), specially adapted to the helix technique [8]. A flexible solution was found with a set of 4 radially cooled helices coils. The simulation continued with 3D calculations performed with another code still based on Getdp [9]. It includes thermal analysis (helices water cooling) and exact helices geometry (width of the electro erosion slit). The helices were designed with CATIA and then meshed by SAMCEF Field. The helices conductivity is 90 % of the International Annealed Copper Standard (IACS). 3D simulations gave results in good agreement with the 2D ones. A sectional view of the magnetic structure can be seen in figure 4. There, 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 along with the temperature in the helices. For more visibility, the mirror surface of 4.9 T in the shoulder of the plasma chamber is not represented. These values are above specifications, so more tuning flexibility will be available for the ion source.

An aluminium helix prototype has been machined to experimentally validate the accuracy of the calculations (see figure 5(a)). Figure 5(b) represents a comparison between the calculated 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 peak value and both curves have the same magnetic centre. The test validates the simulation and allows to start the construction of the magnetic structure. A sectional view of the 3D mechanical design is displayed on figure 5(c).

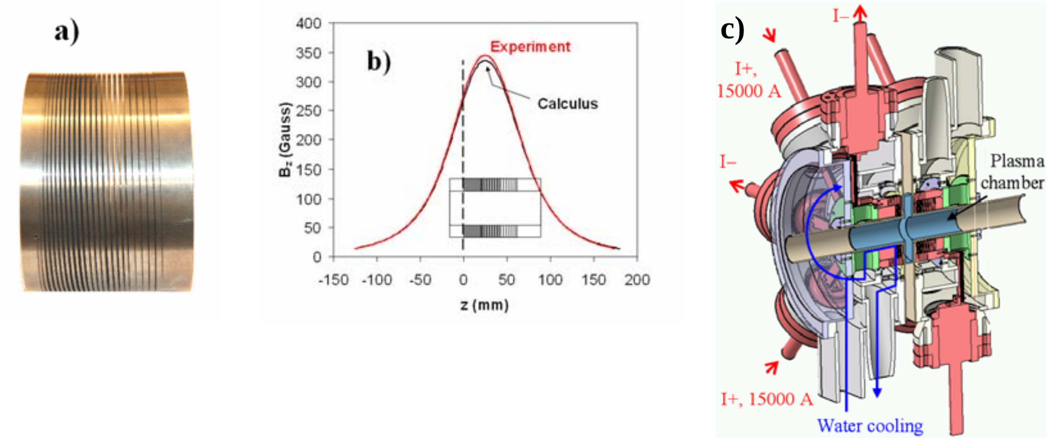

Figure5. a) Aluminium coil prototype, b) Experimental and simulated coil magnetic field on axis, c) 3D mechanical design.

3.1 Engineering design

The current intensity in the cusp is 30000 A; the maximum current density reaches 640 A/mm^2 on the internal radius of the coils, where the helix pitch is only 2 mm. The maximum electrical power needed is estimated to be about 5 MW, depending on the final coils resistivity, so the structure is actively cooled with de-ionized water flow. The inlet water pressure is 2.7 MPa (27 bar), while the outlet one is 0.4 MPa (4 bar). The average water temperature increase is 20°C. The maximum water flow rate is ~ 20 l/s. 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 average temperature of the coils is between 80 and 115 °C, the peak temperature reaches 150 °C and the power needed is 6.5 MW. In these conditions, the maximum hoop stress in the coils is $\sigma \sim 280$ 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.

3.2 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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