ASTERICS, a new 28 GHz electron cyclotron resonance ion source for the SPIRAL2 accelerator

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Abstract. A new A/Q=7 injector is under development for the SPIRAL2 accelerator at Caen, France (NEWGAIN project). A new 28 GHz superconducting electron cyclotron resonance ion source named ASTERICS is under design for this project. The source features a modern cryostat and a large plasma chamber (91 mm radius and 600 mm length). The physical and technical motivations for a larger plasma volume are detailed and estimates of expected beam intensities enhancement are discussed. The source will mainly produce metallic ion beams: the concept of a temperature-controlled liner (up to 900°C) to stabilize high vapor pressure metal re-evaporation in the source is presented. The preliminary design of the ion source and its superconducting magnet are described.

1. The NEWGAIN injector and its beam requirements

A new M/Q=7 (mass over charge) injector named NEWGAIN is under development at the SPIRAL2 accelerator at GANIL [1], Caen France, completing the existing M/Q=3 one. The main project goal is to extend the ions acceleration range to heavy ions masses, up to uranium, with intensities on target up to 10 pμA. The injector includes a high voltage platform (HVPF) equipped with a new electron cyclotron resonance ion source (ECRIS) named ASTERICS (acronym of Advanced Spiral2 Electron cyclotron Resonance Ions source at Caen with Superconducting Magnets) and a short analysis beam line to select and analyse the beam of interest. Next, a low energy beam transfer line (LEBT) injects the beam into a radiofrequency quadrupole (RFQ). An interconnection between the existing M/Q=3 and the new M/Q=7 injectors LEBT will allow to inject ions from the existing PHOENIX V3 ECRIS [2] toward the new RFQ. The input energy required in the RFQ is E $\geq$ 10 keV/Q. The maximum voltage of beam extraction is 70 kV, decomposed into 50 kV maximum for the sole HVPF and 20 to 40 kV for the ion source. This last voltage range for the source is expected to bring tuning flexibility during operation. The main beam requirements for the SPIRAL2 physics are summarized in Table 1. The ion beam intensities requested for intermediate masses up to xenon is 13 pµA at the source, to ensure 10 pµA on target. The high mass to charge ratio of the new injector relaxes the mean charge state required for medium mass metallic ions in the range 10+ to 12+. Such charge states and intensities are easy to obtain with a modern 18 GHz ECR plasma. On the other hand, the beam intensitiy for heavy masses with M$\geq$100, like uranium, up to 10 pμA at the source requires its operation at 28 GHz. Such a record intensity on one charge state has been demonstrated with the VENUS source [3], but it is unlikely that this production level could be sustained for a long period. Experiences done with the VENUS source demonstrated the feasibility to run for long term U^{34+} beam with an intensity of 6 pμA. And this is why the production level of 10 pμA is planned to be reached with the co-acceleration of a second charge state (U^{33+}) in the VENUS-FRIB ion source at Michigan State University [4]. The challeging uranium ion beam requirement of the NEWGAIN injector pushed the project team to develop a new original 28 GHz ECR ion source, rather than a copy of an existing ECRIS. The choices for the ion source design are motivated in the next section.

Table 1. Ion beam characteristics required for the NEWGAIN injector. Intensities (I) at the source are in unit of μA and particule μA (pμA), emittance are in unit of 1 σ normalized root mean square π.mm.mrad.

elem.	I (pμA)	I (μA)	ion	$\epsilon^*_{1\sigma}$
Ca	13	143	Ca^{11+}	≤ 0.2
Cr	13	143	Cr^{11+}	≤ 0.2
Ti	13	143	Ti^{11+}	≤ 0.2
Ni	13	130	Ni^{10+}	≤ 0.2
Zn	13	156	Zn^{12+}	≤ 0.2
Xe	13	336	Xe^{28+}	≤ 0.15
Bi	12	360	Bi^{30+}	≤ 0.15
U	6-10	204-350	U^{34+}	≤ 0.15

Table 2. Main parameters of ASTERICS compared to VENUS-FRIB. L, R and V are respectively the plasma chamber length, radius and volume. The Min-B value at wall indicated is the one obtained with the axial magnetic profile 3.7-0.3-2.5 T.

	VENUS	ASTERICS	unit
L	500	600	mm
R	72	91	mm
V	8.1	15.6	liters
B_{wall}	1.85	1.97	T
L_{ECR}	178	205	mm
R_{ECR}	50	58	mm
V_{ECR}	1.17	1.85	liters

2. Motivations for a large ECR plasma volume ion source

The difficulty to produce 10 pμA of uranium on a single charge state in the existing ECRIS operated at 28 GHz incited the project team to design an ion source with a larger plasma volume. The motivations for this choice are itemized below and elaborated later in the text:

(i) For a given plasma density and electron temperature, the ion beam current for an ECRIS is proportional to the plasma volume.

(ii) A larger diameter plasma chamber increases the production of high charge state (U^{34+} vs U^{33+}).

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(iii) A large plasma chamber allows to install thick dedicated system to optimize and control metal atom re-evaporation from the plasma chamber wall.

Regarding (i), fig. 1 presents a compilation of Ar^{12+} currents measured in various ion sources operated at 18 GHz, frequency at which many ion sources have been developed [6, 7, 8]. The currents are plotted as a function of the product $L_{ECR}.R^2_{ECR}$ where R_{ECR} and L_{ECR} are respectively the radius and length of the ECR zone of these ions source. Because modern ion sources have a similar minimum-B magnetic confinement and follow the usual magnetic scaling laws [5], one can consider that the ECR volume V is proportional to $L_{ECR}.R^2_{ECR}$. Furthermore, the RF power density per unit of volume is approximately constant for all the sources considered (of the order of 0.5 $W.cm^{-3}$).the vertical error bars stand for possible specific effects like power coupling, magnetic field limitation, use of gas mixing or not, wall effect, etc that can scatter the ion production from an ECRIS model to another. One can see that the trend remains linear while V increases by a factor 4. The item (ii) is widely acknowledged in the community and it is unnecessary to elaborate on it (see for instance [9]). A larger ECR volume also increases the capture efficiency of metal vapors emitted from an oven in a cone [10]. The main activity of the ASTERICS source will be the production of metallic isotopic ion beams in the mass range 40-100 with medium charge states (see Table 1), for which the plasma heating with a 2kW 18 GHz RF emitter will be sufficient. The motivation for item (iii) is that several metals of interest have a vapor pressure sufficiently high (example ^{48}Ca) to consider the use of a hot liner to enhance the yield of the metal to ion conversion and reduce the metal consumption rate (metal isotope ca be very expensive). The conceptual design and motivation of a thermo-regulated liner is discussed later in the text. The beams of low vapor pressure metals like uranium will be produced at 28 GHz frequency. Thanks to the longer and larger ECR plasma (+19% and + 28 % respectively wrt existing ECRIS), the U^{34+} beam intensity is expected to reach 8-9 pμA for long run operation and 10 pμA is targeted as a long term prospect.

3. ASTERICS ion source preliminary design

The ASTERICS ion source and superconducting magnet designs are done by LPSC and CEA-Irfu respectively, under the specifications and the follow-up of the GANIL experts. The HVPF design managed by LPC Caen, is not presented in this work. The hexapole-in-coil magnet design was chosen for this project because the bladder and key technique [13], mitigating the risk on the hexapole assembly, has already been successfully implemented with this configuration. The VENUS-FRIB magnet [13] was considered as the starting design point of the ASTERICS magnet and next oversized to enlarge both the plasma chamber length and radius (see table 2), keeping the same system structure. A benefit from the source enlargement is the improvement of the last closed iso-B line from 1.85T (VENUS-FRIB) to 1.97T (ASTERICS) for a comparable magnetic field profile, as can be seen in fig. 3 (see the caption for the plots details). The main reason for this is the longer distance between the axial coils which relaxes their unwanted radial magnetic component, locally opposing to the hexapole radial field. The ASTERICS superconducting magnet design has been presented in detail in [11, 12]. The axial magnetic profile used to design the magnet is 3.7-0.1-2.5 T while the radial magnetic field intensity at wall is 2.4 T when the hexapole is energized alone. Fig. 4 proposes a cutaway view of the magnet in its cryostat (preliminary design). The magnet is classically thermalized by a liquid helium bath which level is sustained by a set of 6 cryocoolers cold heads equipped with condensation fins, providing a total cooling power of 10.8 W to balance the onset of indirect x-ray heating from the ECRIS plasma.

4. Production of metallic ions and concept of temperature controlled hot liner

The majority of ion beam required from ASTERICS are metallic beams (see tab. 1). A special care is taken to the source design to facilitate their production. The preliminary design of the

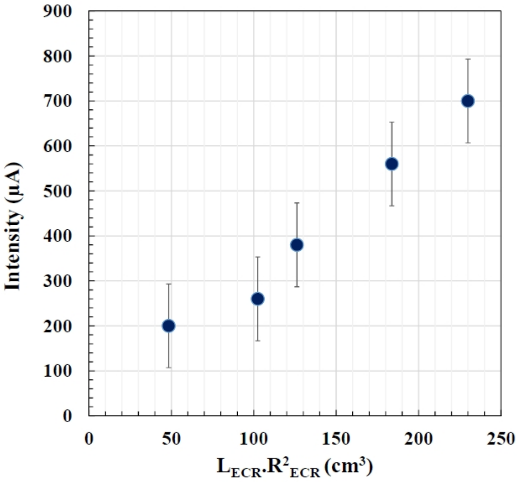

Figure 1. Best Ar^{12+} beam intensity produced in various ion sources as a function of $L_{ECR}.R^2_{ECR}$. From left to rigt: PHOENIX V2, PHOENIX V3, GTS [6], HI-ISI [7],SUSI [8].

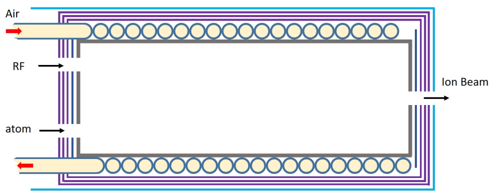

Figure 2. Sketch of the liner concept foreseen to enhance and control the metallic in production in ASTERICS

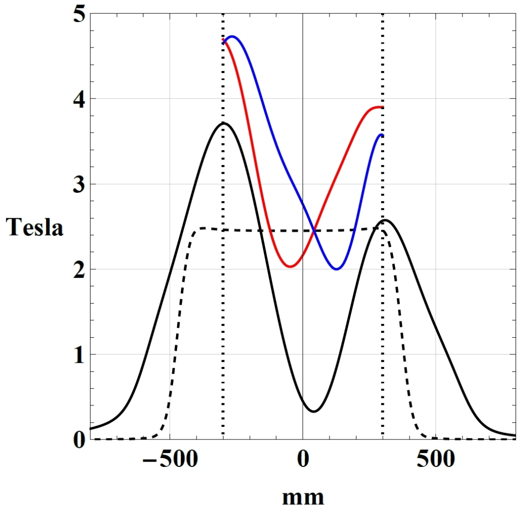

Figure 3. Typical Axial magnetic field profile of ASTERICS (3.7-0.3-2.5T,solid black), maximum hexapole radial field intensity at r =91 mm when the axial coils intensities are set to zero (dashed black). Absolute magnetic field intensity at r =91 mm along two consecutive poles when all the coils are energized (red and blue lines). The spatial limits of the plasma chamber are indicated with vertical black dotted lines.

source injection assembly system is shown in fig. 5. The large inner diameter of the plasma chamber (182 mm) allows to host two feedthroughs for two high capacity ovens (diam. 35 mm, purple rods) along with an 18 mm diam. feedthrough (red rod) for a sputtering system located in the vertical branch of the plasma loss line. It is foreseen to produce the metals with an atom mass ≤ 100 with the 18 GHz frequency, easier to operate and sufficient to produce the intensities required. For heavier masses, the 28 GHz emitter is required. In order to minimize the metal atom consumption of expensive isotopic metals and better control the ion beam stability, it is foreseen to develop hot liners dedicated to the metallic ion beam runs for the elements with a high vapor pressure (e.g. Zn, Ca). When the radial magnetic field is set to 2.2 T at the plasma chamber wall (r=91 mm), its intensity at r=71 mm is 1.34 T, suitable for a safe and reliable 18 GHz operation. The 20 mm gap in radius (between r=71 and r=91 mm) can be used to install a thick hot liner system composed of the following radial layers (see Fig. 2):

(i) a 2 mm thick inner hot liner, made in refractory metal

(ii) a helix of 8/10 (in/out) mm diameter stainless steel tube rolled around (i) in which a controllable air flux passes. the helix both acts as a passive thermal shield or a cooler for the inner hot liner

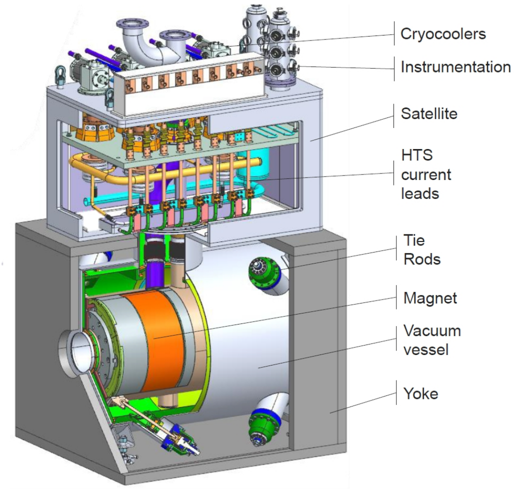

Figure 4. Cutaway view of the preliminary ASTERICS cryostat design, its magnet and the surrounding iron yoke.

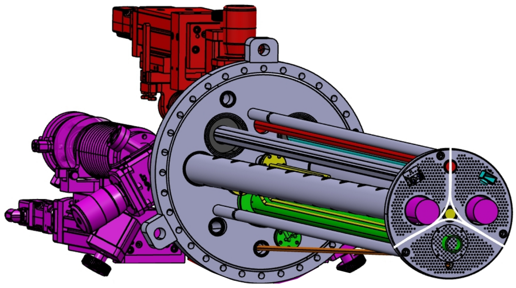

Figure 5. View of the injection assembly preliminary design. The design includes two oven ports (purple), a sputtering shaft (red), one 28 GHz waveguide (green), two 12-18 GHz rectangular wave guide ports (green and grey), a biased disk (yellow).

(iii) a set of concentric 1 mm thick stainless steel cylinders providing further radiation shielding and mechanically centered in the plasma chamber wall by a set of tiny pins. Three layers are displayed on the plot.

In this system, the inner hot liner is directly heated by the plasma and the microwave during the ion source operation. A 2 dimensions thermal simulation has shown that the 3 thermal shield layers allow the inner liner to reach a temperature of 700 and 900°C when the plasma is heated by 1 and 2 kW RF respectively, when no air flux circulates in the tube and the surface emissivity is 0,6. The hot liner thick wall homogenizes the surface temperature by thermal conduction which compensates the anisotropical heating by the plasma (the liner temperature homogeneity is within ∓ 12 °C). The air tube circuit is connected to a 7 bars compressor delivering up to 15 m^3/h. A controllable valve is used to tune accurately the air flux through the pipe. When the air flux reaches 12 m^3/h, the cooling provided by the air decreases the inner liner temperature to 500°C and 700°C for 1 and 2 kW RF respectively. Such a system will allow to better control the re-evaporation of specific metals from the hot liner and avoid unwanted evaporation transients during operation. This is foreseen to balance the risk of metal accumulation on the liner when the oven is on while the RF is off or to compensate for an over evaporation incident of the oven. Removing the thermal shield screens reduces the maximum liner temperature by ≈100°C: the system can thus be adapted to a specific high vapor pressure metal by decreasing the number of thermal screens. If required, a further temperature decrease of the liner can be obtained by directly welding the cooling pipe on the thick liner. A set of temperature sensors are placed on the hot liner, the cooling pipe in the plasma chamber, the inlet and outlet air temperature outside of the source on the air side. The temperature measurements are used to self-adjust the air flow using a feedback loop.

5. Conclusion

This work shows that experimental 18 GHz ECRIS high charge state ion beam intensities are approximately proportional to the ECR zone volume, provided the ECRIS follows the ECR magnetic scaling law [5]. This fact, added with the well establised ECR frequency scaling law

allows to assess that the high charge state ion beam intensities achievable with the new 28 GHz ion source ASTERICS, having a larger ECR zone, will be enhanced by $\approx 28\%$ with respect to existing ECRIS. U^{34+} beam intensity is expected to reach 8-9 pμA for long physics run operation to fulfill the NEWGAIN project need.
The concept of a gas cooled thick hot liner, installed inside the ASTERICS chamber and operated at 18 GHz, studied by thermal simulation, indicates the possibility to reduce the hot liner temperature by 200°C when compressed air is flowing in the cooling system. Instrumented with temperature sensors, this device would allow to dynamically control the liner temperature and consequently control high vapor pressure metallic atom re-evaporation (like calcium) from its surface and mitigate possible ion beam overshoot or collapse, observed in long run operation.

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