New xenon results of Phoenix at 28 GHz

T. Thuillier, J.L. Bouly, J.C. Curdy, T. Lamy, C. Peaucelle, P. Sole, P. Sortais, J.L. Vieux-Rochaz, D. Voulot

NEW XENON RESULTS OF PHOENIX AT 28 GHZ

T. Thuillier, J.-L. Bouly, J.-C. Curdy, T. Lamy, C. Peaucelle, P. Sole, P. Sortais*, J.-L. Vieux-Rochaz, D. Voulot, ISN, Grenoble, France

Abstract

The classical PHOENIX 28 GHz electron cyclotron resonance ion Source (ECRIS) has been developed to prospect high pulsed multi charged lead ion (MCI lead) beams for the Large Hadron Collider (LHC) [1,2]. The goal of the experiment is to reach 1 emA pulses of Pb^{27+} during 0.4 ms with a 10 Hz repetition rate. This high beam current is one order of magnitude higher than the ones available nowadays. The strategy to take up this challenge is based on an increase of the radio frequency (RF) to 28 GHz and an increase of the RF power density.
A new high acceptance, high resolution analysing beam line has been coupled to PHOENIX in order to study efficiently the intense beams delivered by the source. Thus, 0.6 emA of Xe^{20+} has been measured in the afterglow (AFG) among 9 emA analysed in the Faraday Cup (FC). The lead production is under study and a preliminary beam of 0.6 emA of Pb^{24+} AFG has already been obtained. The cross check of a 3D beam simulation program and measured beam characteristics enables to estimate the beam emittance to be ~ 200π mm.mrad. The project of development of an upgraded version of PHOENIX is presented (a new ECRIS named A-PHOENIX).

1 THE CLASSICAL PHOENIX 28 GHZ SOURCE

The PHOENIX 28 GHz ECRIS has already been presented [3,4]. For completeness, a summary of its specifications are recalled here. See Fig.1 For an overall view of the ECRIS. The PHOENIX source is based on an extrapolation of ECR4 performances at 14 GHz RF injection [5]. ECR4 provides ~100 eμA of Pb^{27+} in AFG mode at CERN. The LHC project needs to increase beam luminosity and 1 emA is required for Pb^{27+} AFG. The PHOENIX strategy to increase the ion beam by a factor of 10 has been developed in [4].

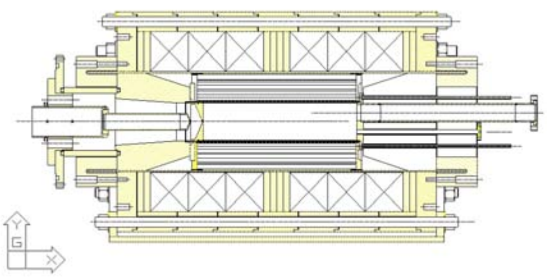

Fig. 1 : PHOENIX General Structure.

A first factor of 3 to 4 in total ionic current is expected through the frequency doubling from 14 to 28 GHz. A second multiplication factor comes from a medium magnetic confinement structure that increases plasma leakages and hence total ionic current (see the large bold B=1 Tesla line in Fig. 2). In parallel, to maintain the charge state distribution in a weak magnetic confinement, a high RF power density is required to feed the plasma with energetic electrons. Here, the 1.2 litre volume of PHOENIX plasma chamber enables to launch up to 8 kW/litre of RF with the present gyrotron.

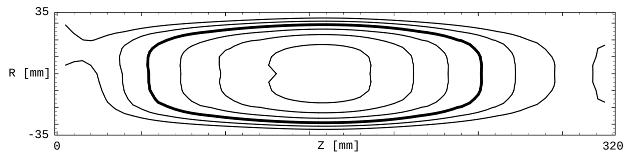

Fig. 2 : iso B surfaces in PHOENIX plasma chamber (B=1 Tesla is the bold line).

2 THE NEW HIGH CURRENT ANALYSING BEAM LINE

2.1 The new beam line

A new, high acceptance, high resolution beam line has been designed and installed during winter 2001 to analyse the high currents provided by PHOENIX (see Fig. 3). Ions are extracted at 60 kV via a movable monogap puller and, due to the space charge, expands rapidly into the ∅100 mm line.

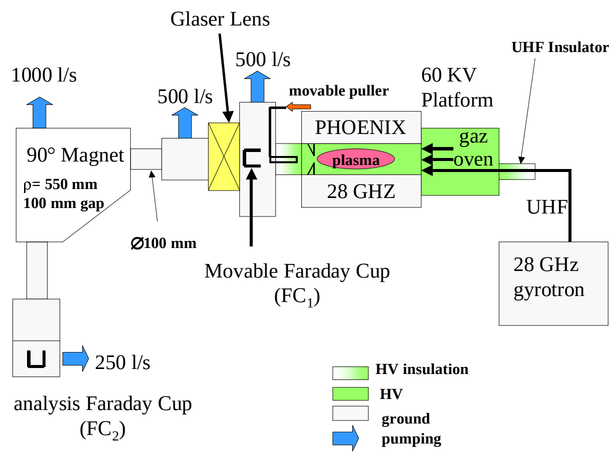

Fig 3 : Sketch of the high current PHOENIX bench.

A movable Faraday cup is located at the exit of the puller to measure the total current delivered by the ECRIS. The beam is then focused by a Glaser Lens with Bmax=1.4 T and FWHM ~ 120 mm, placed the nearest possible from the movable puller. Next, the selected ion enters quasi parallel in a large acceptance 90° bending

* sortais@isn.in2p3.fr

magnet with a curvature radius ρ=550 mm and a 100 mm gap. The 3D magnetic structure has been calculated with RADIA† [6] and used to build a 3D magnetic data map used in the simulation program presented in section 3.3.

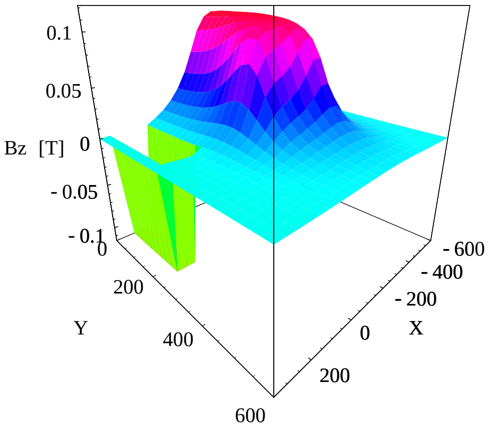

Fig 4 : example of the Bz magnetic field map given by RADIA in the mid-plane gap of the bending magnet.

The beam focuses after the analysing magnet to a set of movable slits and a Faraday Cup to measure MCI currents. The vacuum is insured by a set of turbomolecular pumps, with pumping speed indicated in Fig. 3.

2.2 The data analysis program

The analysis of the MCI currents produced by PHOENIX is performed on a PC with an A/D converter data card enabling current pulses sampling rate at 250 kHz. The acquisition software has been developed under LABVIEW and is triggered at the beginning of the RF pulses injected into PHOENIX. The use of this technique enables to record time resolved MCI spectrum and provides a powerful tool to analyse the dynamics of the ECR plasma during the discharge.

3 INTENSE BEAM PRODUCTION

3.1 Very high current densities production

The first experiments were dedicated to show the ability of PHOENIX to produce very high ion current densities in order to prove the plasma capability to deliver high particle flux. The measurements consisted in using a ∅2 mm extraction hole to insure the transmission through the beam line to be 100% ; thus, ion extraction and transport troubles were avoided permitting to focus on the ECRIS plasma characteristics.

It has been possible to observe densities from 20 to 40 emA/cm^2 with O, Ar and Xe (~3 emA of total current analysed), so roughly 10 times more current than in a standard 14.5 GHz ECRIS. Table 1 reports some remarkable densities observed. Hydrogen experiment at 30 kV has given a measured total current density of ~200 emA/cm^2 with ~140 emA/cm^2 on H^+, while ~100 emA/cm^2 total current density of N has been extracted with ~30 emA/cm^2 on N^{3+}.

Table 1 : Example of high current densities measured with PHOENIX 28 GHz in a ∅2 mm extraction hole.

Element	Extraction Voltage [kV]	Total Current density [A/cm^2]	I n+ [emA]
H^+	30	~200	4.5
N^{3+}	48	~100	0.9

3.2 Heavy ion pulses production

The experiments are performed at a repetition rate of 10 Hz and pulse duration varies between 10 and 20 ms, depending on the source tuning. The results presented here were done with a ∅12 mm plasma electrode, an acceleration gap of 45 mm with an extraction voltage of 55 kV.

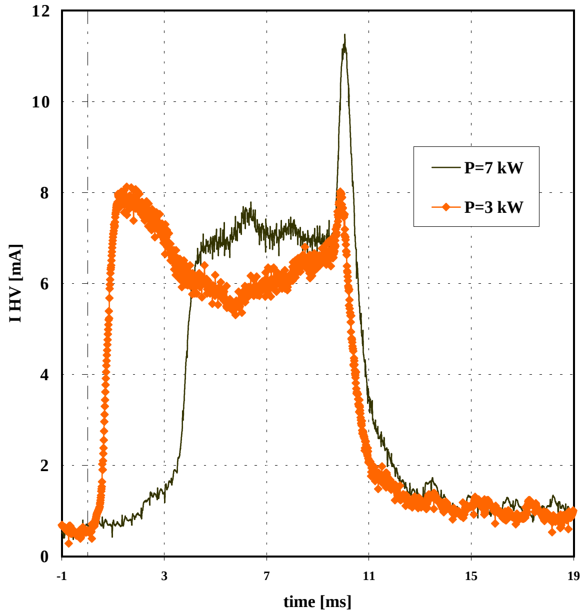

Fig. 5 : Example of the ECRIS HV current evolution with RF power in PHOENIX 28 GHZ (Xe+O_2 mixing).

At RF power below 3-4 kW, the average charge of the plasma is low as expected (see section 1), and a total ionic peak current occurs at the beginning of the RF discharge, like on Fig. 5. When RF power increases (P ≥ 4-5 kW), the plasma confinement increases as well and this first peak decreases progressively. At this stage, the total current remains small for several ms, then MCI extraction amplifies to reach an equilibrium value in the range of 5 to 10 emA, depending on the tuning, while the average charge state increases with time. At the RF stop, a strong AFG occurs with a total current between 10 and 15 emA for Xe.

Fig. 6 shows a typical and very stable lead tuning of PHOENIX with $^{208}Pb^{24+}$~500 µA. The AFG time structure was in this case of 280 µs FWHM.

† Partial copyright of ©Mathematica

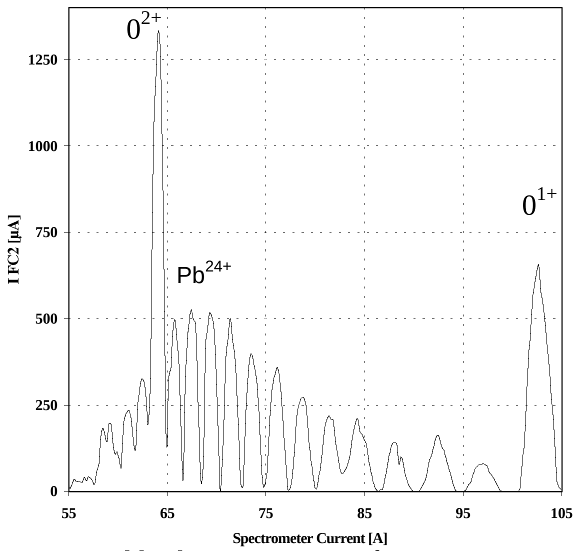

Fig. 6 :typical lead AFG spectrum of PHOENIX 28 GHz.

Table 2 summaries best PHOENIX tuning achieved with AFG xenon (612 eµA) and preliminary result of lead beam production (600 eµA). IFC_2 is the measured intensity for each element after the bending magnet. IFC1 is the total ionic current at the exit of the puller, while $\Sigma\, IFC_2$ is the sum of the charge state currents reaching FC_2 and IHV is the total current on the High Voltage power supply. These results, which should be improved, validate the PHOENIX strategy to produce high beam currents with a classical ECRIS and medium magnetic field confinement.

Table 2 : Heavy MCI currents produced in AFG mode with PHOENIX.

Element	IFC_2 [eµA]	IFC_1 [emA]	$\Sigma\, IFC_2$ [emA]	I HV [emA]
$^{132}Xe^{20+}$	612	12	10	15
$^{208}Pb^{24+}$	600	10	9	11

3.3 Emittance and simulation program

An emittance scanner [7] is under construction at the ISN and is scheduled to be installed on the high current beam line this summer. Meantime, the 3D simulation program of ECR ion extraction and transport, developed at ISN, has been used to put constraints on the beam modelisation and provides an estimate of the real emittance of the beam, using the available experimental Xenon beam parameters :

- total ionic Current in FC_1 versus Voltage extraction,
- width of the n+ beam before FC_2 (measured with movable slits)
- ionic n+ current in FC_2.

The fit result implies that the Xenon beams are within an emittance lower or equal to 200π mm.mrad for an extraction voltage of 60 kV (see Fig. 7). This result should obviously be confirmed by the experimental emittance measurements. It must be underlined that the emittance scanner will enable beam back tracing toward the source extraction hole and will give very interesting information on space charge neutralisation and boundary plasma parameters [8].

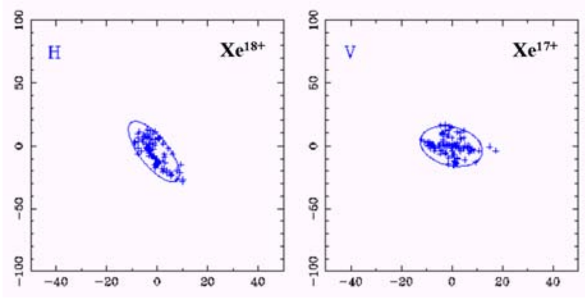

Fig. 7 : Simulation results of the Xe^{18+} and Xe^{17+} emittances fitting experimental beam constraints.

4. THE A-PHOENIX PROJECT

An Advanced version of PHOENIX (A-PHOENIX), is under study. This ECRIS will have a higher magnetic field and will allow higher frequency injection up to 40 GHz. It should also increase the average ion charge state and would allow to save RF power with respect to PHOENIX. The improvement of the FeNdB magnet technology enables to build very high magnetic field sextupoles [9]. The advantage of this technology with respect to a fully superconductive ECRIS is that the inner diameter of the sextupole is a free parameter. Then, it is possible to build a high radial magnetic field ECRIS with an arbitrary plasma chamber volume.

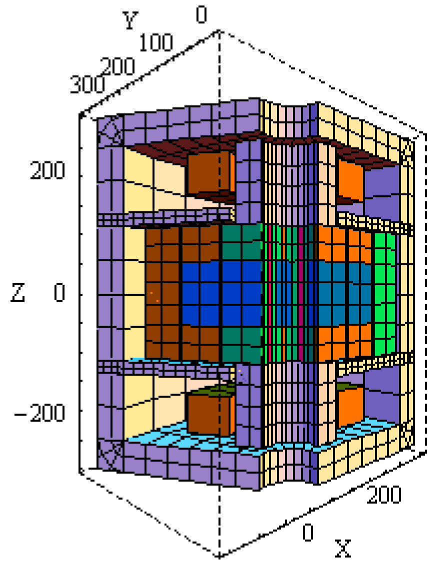

Fig. 8 : Sketch of the A-PHOENIX structure.

Thus, A-PHOENIX will be a compact ECRIS equipped with a classical magnet sextupole and an inner volume of 2 to 3 litre. Concerning the mirror trap of the ECRIS, the improvement of the High Temperature Superconductive (HTS) devices enables to design reliable axial coils for an affordable price. This technology is acting only by thermal conduction for cooling, so no liquid or gas He is necessary. Another advantage comes from the small overall size of the cryostat which holds in a standard room temperature ECRIS coil. Figure 8 represents a sketch of A-PHOENIX as simulated with RADIA‡[6].

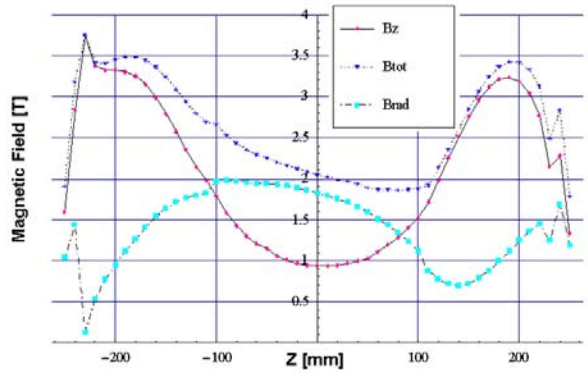

Fig. 9 : magnetic field in A-PHOENIX as a function of Z. B_z, B_{rad} and B_{tot} are respectively the axial, radial and total magnetic field. See text for detail.

The 2 HTS coils work with a current density of 100 A/mm^2. The axial magnetic field should reach 3 T at the center of the coils and ~0.9 Tesla at the center of the ECRIS. Concerning the radial field, the inner diameter of the sextupole should be ~100 mm, but it is possible to change this value according to the volume desired. The sextupole is mainly composed of 2 parts. The first part is a small external diameter sextupole located under the HTS coils. The second one is located at the center of the source. There, the outer diameter is ~500 mm. The magnets are mounted on three independent concentric crowns with 2 gaps of 4 mm for mechanical magnet standing. The total sextupole is composed of 5 magnets types in order to optimise locally the magnet remanence and its coercivity as a function of the magnetic field intensity "seen" by each magnet. The A -PHOENIX source has been simulated with RADIA [6]. The physical behaviour of the magnets has been taken into account up to 40°C. The magnets design features used in the simulation have been extracted from Vacuum Schmeltze data sheets [10]. See Table 3 for some information about the magnets used.

Table 3 : Typical values of the magnetic properties of the materials used in the sextupole simulation [10].

Material	**Remanence [kG]**	**Coercivity [kOe]**
VACODYM 722 HR	14.7	12
VACODYM 745 HR	14.4	15
VACODYM633 HR	13.5	18
VACODYM655 HR	12.8	23
VACODYM677 HR	11.8	31

The result of the simulation program concerning the expected magnetic field is plotted on Figure 9. The total magnetic field is plotted as a function of Z coordinate (revolution axis of the source). The radius of calculation is r=49 mm, and azimuth corresponds to a purely radial polarised magnet. The radial field intensity reaches 1.8 T in the middle of the source (Z=0 on Fig. 9).

‡ Partial copyright of ©Mathematica

5.CONCLUSION

PHOENIX 28 GHz clearly shows the feasibility to produce very high current densities of MCI using high plasma densities and medium magnetic confinement. The average charge state of the plasma is therefore maintained and the current amplified. The goal is now to enhance the extraction system to manage high current densities with a good reliability and to check experimentally that emittance is ~200π mm.mrad. The success of the PHOENIX strategy incites to go further and to develop A-PHOENIX. This innovative ECRIS will combine a small plasma volume and a strong magnetic field for higher frequency studies, higher average charge state distributions and lower total ionic currents with respect to PHOENIX.

6 ACKNOLEDGEMENTS

This work was supported in part by Grant CERN/GSI/CEA/IN2P3 K598/PS and by European Union under RTD HPRI-1999-50014.

7 REFERENCES

[1] Grant CERN/GSI/CEA/IN2P3 K598/PS
[2] EU RTD HPRI-1999-50014.
[3] Bouly *et Al*., Rev. Sci. Instrum., Vol. 73, No. 2, February 2002 (p. 528).
[4] Bouly *et Al*, Cyclotrons and their applications 2001, AIP Conference Proceeding, Vol. 600, p. 228.
[5] C.E. Hill *et Al*., Rev. Sci. Instrum., 71 (2000) No.2, pt.1-2, pp.863-5.
[6] P. Elleaume *et Al*, presented at the PAC97 Conf. May 1997, Vancouver.
[7] P. Allison *et Al*., IEEE Trans. for Nucl. Sci., Vol. NS-30, No. 4, Aug. 1983.
[8] P. Sortais *et Al*., Proceedings of the 13th International Workshop on ECRIS, 26-28 Feb. 1997, Texas A&M University, Texas USA, p.83.
[9] A. Vassiliev *et Al*., Rev. Sci. Instrum., Vol. 17,# 9, Sept. 2000.
[10] Rare-Earth Permanent Magnets, VACODYM VACOMAX, Company Information Booklet PD-002, Ed. 2000, Vacuumschmeltze GmbH, P.O.B. 22 53, D-63412 Hanau, Germany p.12-22, http://www.vacuumschmelze.de/.