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MODIFICATION OF THE FLEXIBLE PLASMA TRAP FOR HIGH-INTENSITY METAL ION BEAMS PRODUCTION

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Abstract

NQSTI (National Quantum Science and Technology Institute) is the enlarged partnership on QST established under the National Recovery and Resilience Plan (NRRP) funded by the European Union – NextGenerationEU. In this framework, there is a growing interest in the availability of mA beams of singly charged (1+) metallic ions to realise quantum devices. To satisfy this request, the joint INFN Laboratories LNS and LNL proposed to modify the Flexible Plasma Trap (FPT), installed at LNS, thus transforming it into a simple mirror Electron Cyclotron Resonance Ion Source (ECRIS). This contribution describes the various technical solutions that will be adopted, foreseeing novel radial RF and gas/metal injection systems, focusing particularly on the design and simulations of a flexible extraction system capable of handling different beam intensities and ion species. Specifically, the project targets the production of high-intensity beams of singly charged ions such as Fe^{+}' and Ba^{+}, highlighting the versatility and innovation of the proposed modifications.

INTRODUCTION

Within the NextGeneration EU project NQSTI (National Quantum Science and Technology Institute), the scope of the Task 3.1 of Spoke 3 is to develop novel atomic/molecular systems to extend coherence time in quantum system. In fact, there is an active field of research in the quantum technologies concerning the measure of the permanent electric dipole moment of specific molecules' electrons in a solid matrix, looking for evidence of CP violation [1]. This atomic-embedding in low-temperature solid matrix conventionally resorts to glow discharge chamber and electrostatic elements to select and transport ions to be embedded [2]. The two INFN Laboratories LNL and LNS have studied novel techniques to produce isotopically enriched metallic ion beams (iron, barium), with intensities in the mA range end energies of tens of keV. This will be accomplished by proper modifications of the Flexible Plasma Trap (FPT) [3], installed at LNS and used to date for fundamental studies of magnetically confined plasmas, thus turning it into a simple mirror Electron Cyclotron Resonance Ion Source (ECRIS) [4]. This contribution describes the innovative technical solutions adopted, with greater emphasis to the design of the extraction system through numerical simulations. Finally, preliminary results of the beam optics studies will be also reported.

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UPGRADES OF THE FLEXIBLE PLASMA TRAP

The Flexible Plasma Trap (FPT) is an ECR plasma-based facility present at the INFN-LNS to trap ionised particles in plasma and perform in-plasma interdisciplinary measurements. The FPT magnetic field is provided by means of three solenoids, which allow the tuning of the field profile. The plasma can be generated in both simple mirror and quasi-B-flat configuration, adequately tuning the coils currents. The RF power up to 500 W is injected through a WRD 350 waveguide entering radially the trap [5], at frequencies from 3 to 7 GHz, leaving the longitudinal axis to the access of plasma diagnostics. As being a trap, ions' extractions have never been attempted and thus no extraction system has been developed so far. The modifications to the Flexible Plasma Trap (FPT) have been focused on implementing innovative metal/radiofrequency injection and beam extraction systems, which are crucial for upgrading FPT to an ion source and optimizing the production of singly charged metallic ion beams. With reference to Fig. 1, the key upgrades include the following listed below.

Radial RF and Gas/Metal Injection

The FPT will be equipped with a radial injection of radiofrequency (RF) through a WRD 475, working at 5-7 GHz, and a radial gas/metal injection system. This will improve the power coupling to the plasma, as well as the efficiency of metals ionisation, thus increasing the intensity of the extracted beam.

Advanced Diagnostic Systems

Plasma and extraction conditions will be monitored through a Langmuir probe and an optical emission spectroscopy (OES) quartz window. These diagnostic tools will allow for precise assessment of plasma parameters, thus facilitating the optimization of the source.

Flexible Extraction System

A three-electrode (accel-decel) extraction system has been designed to produce beams with suitable quality for isotopic selection. We conceived a flexible design that enables the extraction gap to be adjusted without breaking the vacuum, adapting the system to the specific requirements of the produced beam (a more detailed description will be given in the next section).

DESIGN OF THE EXTRACTION SYSTEM

The requirements to fulfil the goal of task 3.1, Spoke 3 of the NQSTI project concern the production of a currents

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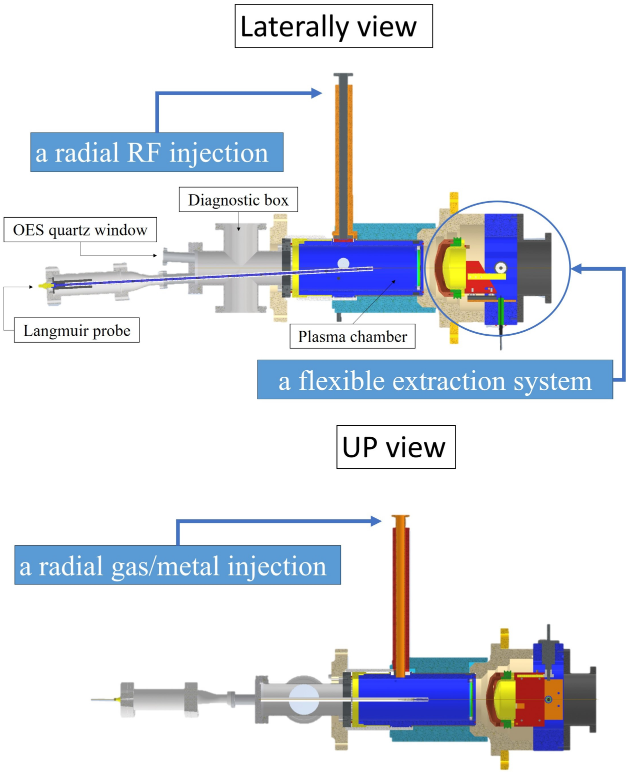

Figure 1: Schematic view of the Flexible Plasma Trap (FPT) highlighting the radial RF injection system and the advanced diagnostic components, the radial gas/metal injection system and the flexible extraction system designed for optimal beam extraction.

≥1 mA of singly charged medium/heavy metallic ions (iron in the first experimental phase, barium in the second one). This level of intensity in known to be a challenge, due to the high contribution of the space charge to the beam quality. This last aspect is very relevant for the project because it influences the ability to reach the desired resolution for isotopes separation, especially for heavy elements (∼1/200 for Barium). In the first experimental phase, we plan to verify the ability of FPT to produce the required intensity by proceeding through a preliminary step, that is the extraction of 5 mA of protons. In that case the FPT will produce a plasma of pure hydrogen. Then, iron will be extracted by creating a helium plasma where iron vapours produced by a resistive oven will flow and be ionized. By keeping the same total extracted current as in the case of hydrogen, it has been reasonably estimated a beam ratio of 80 %–20 % between helium and iron (this last one including all the stable isotopes). The design and construction of an extraction system able to handle the above-mentioned intensities is part of the modification of FPT. Such system should be able to:

- Extract beams with different masses/intensities by employing a common design;
- Produce beams with a quality suitable to reach the required resolution for isotopic separation;
- Employ an extraction voltage not higher than 35 kV to ensure proper high voltage insulation.

The choice fell on a common three electrodes (accell-decel) extraction system, with the possibility to vary the extraction gap without breaking the vacuum to adapt it to the extracted intensity. The design has been validated using the numerical code IBSsimu [6], a Vlasov solver able to solve the Poisson equation including the potentials applied to the electrodes and the space charge generated by the extracted beam, then tracing the motion of a given number of particles resembling the whole beam.

The extraction hole has been fixed to 3 mm in radius, a good compromise between the expected extracted current density and initial beam dimensions. Before proceeding to the design, some preliminary evaluations has been carried out, the first being the contributions to the beam emittance. In fact, the beams of interest for NQSTI will be extracted from a magnetized plasma, so two possible contribution could be expected: the ion temperature and the trap magnetic fringing field at extraction. The latter is a trap's parameter (0.3 T maximum in the case of FPT), while the former is quite difficult to be measured but reasonable values could be guessed. With the use of two handy formulas [7], a comparison between the two contribution has been done considering ion temperatures ranging from 0.1 eV to 10 eV: except for the highest value of the magnetic field and the lowest of ion temperature, the major contribution comes from this last parameter. This made easier the second preliminary evaluation, that is the main extraction system parameters starting from considerations concerning the Child-Langmuir (CL) limit [8]. Normally, it is a good practice to configure the extraction system in order the beam perveance to be a half of the one foreseen by the CL limit: considering the limitations on the voltage applicable and starting from an extraction gap around 30 mm (in order not to have a too high electric field leading to possible sparks), this limit was evaluated for the two steps foreseen for the first experimental phase. For protons, a CL limit of 10 mA is obtained with an extraction voltage of 30 kV, a puller voltage of −3 kV and an extraction gap of 30 mm. For iron, extracting 4 mA of He^+ and 1 mA of Fe^+ (supposed consisting entirely of the mass 54) is equivalent to a proton current of around 15 mA: unfortunately, in this case the CL limit gives an extraction voltage higher than 60 kV for an extraction gap of 27.5 mm, being above the limit of FPT. It has to be pointed out that the CL limit strictly holds for particles generated by a fixed emitter with zero velocity: in the case of the extraction from a plasma particles are emitted with several eV of longitudinal energy, having to satisfy the Bohm criterion [9]. This leads to an increase of the CL limit because the condition of zero electric field at the emitter does not prevent necessarily ions form exiting the plasma. In light of all this, we launched systematic numerical simulations by varying, in the case of hydrogen: the extraction voltage (V_s), the puller voltage (V_p) and the extraction gap (d). All the simulations considered a beam space charge compensation of 90 %.

With the aim at optimizing the beam transport downstream the extraction system, the criteria adopted to choose a proper configuration have been:

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- A RMS emittance (ϵ_{rms}) as low as possible;
- A RMS maximum divergence (x'_{rms} for the x axis, z being the axis of propagation) not higher than 40 mrad;
- The highest beam percentage within four times the rms emittance.

Table 1 shows all the simulated configurations. It has been found that, for voltages equal to or higher than the evaluated CL limit, the beam appeared to be over-focused with a dense core and a rarefied halo: a direct view of this effect is visible in Figs. 2 and 3, showing the 2D plots of the extracted beam for 37 kV/−1 kV/37 mm and 30 kV/−1 kV/30 mm (V_s, V_p, d).

Table 1: Configurations of the Extraction System Simulated for H^+ Extraction

Extraction voltage [kV]	Puller voltage [kV]	Gap [mm]
35	−1	37
30	−1	37
30	−1	35
30	−1	30
20	−1	30

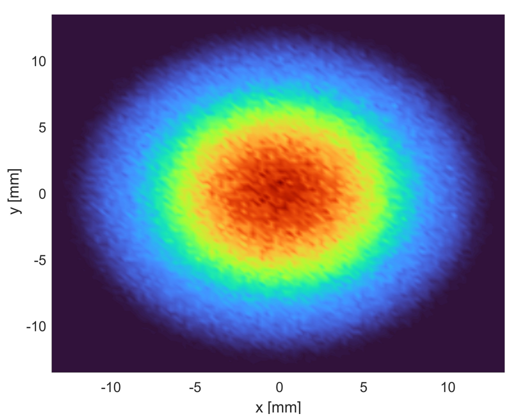

Figure 2: 2D plot of the proton beam extracted at V_s=35 kV, V_p= −1 kV and d=37 mm.

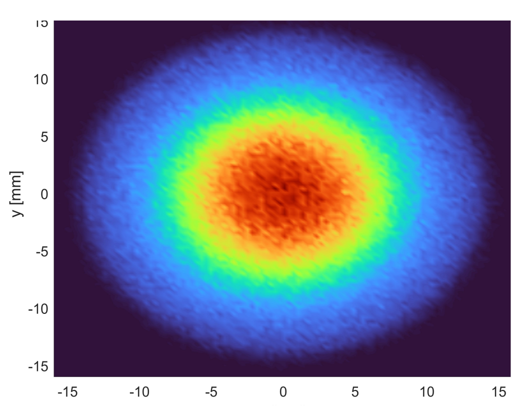

Figure 3: 2D plot of the proton beam extracted at V_s=30 kV, V_p= −1 kV and d=30 mm.

The optimization of the parameters proceeded, with the best results given by the configuration 20 kV/−1 kV/30 mm (V_s, V_p, d): figure 4 shows the beam distribution along the x axis.

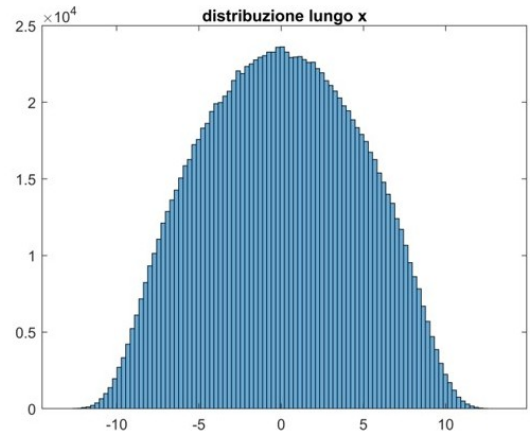

Figure 4: Proton beam distribution along the x axis at V_s=20 kV, V_p= −1 kV and d=30 mm.

It is worth noticing that the beam is very well distributed, resembling almost a Gaussian shape. Concerning the selection criteria, this configuration gave ϵ_{rms} ~8 mm·mrad, x'_{rms}= 26.6 mrad and the 88 % of the beam within 4*ϵ_{rms}. Once the best configuration to extract a proton beam has been found, the numerical study proceeded on the composed beam He^+-Fe^+ starting from V_s=35 kV (the highest possible value) and optimizing V_p and d. Despite the allowed value for V_s was considerably lower than the expected CL limit, good beam properties where found by setting V_p=−5 kV and d=27.5 mm: Figure 5 shows the total beam emittance along the x axis for the Fe^+ beam. It can be clearly seen that both the beam dimension and divergence are fairly small, with a x'_{rms} even smaller than in the case of hydrogen (20.6 mrad) and almost the same percentage within 4*ϵ_{rms}.

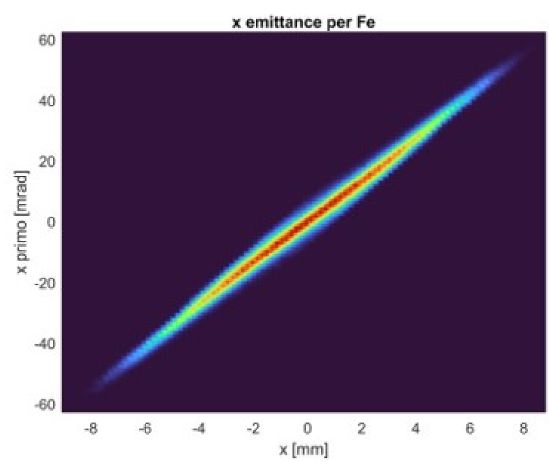

Figure 5: Total emittance along the x axis of a 1 mA Fe^+ beam at V_s=35 kV, V_p= −5 kV and d=27.5 mm.

Starting from the beam parameters found for protons extraction, a preliminary study of the beam optics in the downstream beamline started, to verify the feasibility to reach the required resolving power. The first results (not including the beam space charge) show that, by implementing a magnetic solenoid and an electrostatic quadrupole between FPT and the magnetic selection, the beamline turn out to be flexible enough to handle beams with different characteristics, ensuring a high enough resolving power (1/660 calculated for protons against 1/200 necessary for barium). Further optimizations including the beam space charge will follow and lead to the final design.

ACKNOWLEDGEMENTS

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