ELECTRODE DESIGN OF THE ESS-BILBAO ACCELERATOR PROTON EXTRACTION SYSTEM*

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Abstract

The goal of extracting high proton currents from the ECR source of the ESS-Bilbao Accelerator has required comprehensive and systematic studies to find the appropriate geometric parameters for the electrode extraction system. Electrostatic and beam dynamics simulations are used to achieve a complete optimization of the accelerating electrode shapes, gap distances, and extraction electrode apertures, in order to ensure the extraction of a 70 mA proton beam from a 3.75 mm aperture radius. For the accelerating electrode shapes two different designs were mainly analyzed; the first is based on a Pierce geometry; and the second on a spherically convergent layout. Both designs consist of a tetrode system comprising a plasma electrode fed at 75 kV, followed by a puller system formed by a grounded extraction electrode separated to a certain distance from the plasma chamber, an electron repeller electrode fed at -3 kV; and finally, a fourth electrode at ground potential.

INTRODUCTION

The ESS-Bilbao project aims to build an accelerator able to produce high current proton beams [1]. The extraction system, which intrinsically determines the current of the beam and its quality, is a critical part of the ECR source where strong magnetic solenoidal field traps the plasma such that it is further ionized by means of a 2.7 GHz and 1.2 kW klystron [1]. In fact, an optimal electrode shaping is fundamental to extract a well focalized beam with high current and low emittance. An extraction system with four electrodes in a tetrode configuration seems very suitable for extracting high current proton beams in good conditions. The performance of this kind of extractors in similar ECR sources was already demonstrated numerically and experimentally by the Sherman [2] investigations which are used as a reference in this analysis. To design the shapes of the accelerating electrodes two different approaches are taken; firstly, the analytic derivation of Pierce [3]; and secondly, by considering the space charge dominated beam flowing between a concentrically spheric electrode geometry [4]. The Pierce geometry is often used by space charge dominated extraction systems where undesired forces, specially coming from radial electrostatic fields and from the longitudinal component of the magnetic field produced on the ECR solenoids can be more easily minimized [5]. On the other hand, using spherically shaped electrodes could contribute to improve even further the charged particle flow and to extract higher currents than the Pierce layout.

It is expected that the new ESS-Bilbao ECR ion source will deliver a current density at the injection plane around 2500 A/m^2. In fact, similar sources like SILHI [6] and LEDA [2] have already provided plasma densities of 2470 A/m^2 and 2590 A/m^2, respectively. Higher currents could be extracted by increasing the aperture; however, it would also deteriorate the emittance and the probability of charge transfer in the extraction system because of higher residual gas pressure. Moreover, the maximum field strength is also reduced if the aperture is increased [5].

The well-known POISSON-SUPERFISH [7] software from LANL is used to calculate the electrostatic fields by solving the Laplace equation for well defined boundary conditions. The GPT [8] code is used to solve the equation of motion with a 5^{th} order embedded Runge-Kutta solver.

The aim of these simulations is to obtain an electrode system capable of extracting, accelerating, and delivering a high quality proton beam from the plasma chamber to the LEBT system. Moreover, the normalized rms emittance at the LEBT position must be kept about 0.2 π-mm-mrad in order to get an acceptable matching to the elements downstream the accelerator, in particular the RFQ [9]. The extraction system geometry that delivers the best beam parameters calculated at 530 mm from the source (LEBT first solenoid position) is selected.

ELECTRODE SYSTEM GEOMETRY ANALYSIS

The extraction system is principally composed of a 75 kV plasma electrode and an extraction grounded electrode placed downstream at a certain accelerating gap distance, so that the electric field strength $\mathbf{E}$ is mainly given by the voltage applied to the plasma electrode and the distance d_{gap} between the plasma and the extraction electrode. The extraction electrode is followed by another electrode fed at -3 kV to be used as a repeller for the low energy electrons that could be attracted to the plasma potential. The tetrode system is completed with a ground electrode placed next to the electrode repeller to limit the -3 kV potential. The repeller and its associated grounded electrode delimits a maximum radius and a certain longitudinal distance where the beam has to go through without hitting the electrodes.

The extracted ion beam current can be either limited by emission or by space-charge. For space-charge limitations and considering an infinite and planar emission area of ions with zero initial longitudinal velocity, the maximum ex-

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tracted current carried by protons can be approximated by the Child-Langmuir law [10]:

$$I_{C-L} = \frac{4}{9}\pi\epsilon_0\sqrt{\frac{2e\xi}{m}}\left(\frac{r_{ap}}{d_{gap}}\right)^2 V_p^{3/2} \qquad (1)$$

where V_p is the plasma electrode potential drop, $\xi = 1$ the ion charge state, $S = r_{ap}/d_{gap}$ the aspect ratio between the r_{ap} plasma chamber aperture radius and the d_{gap} accelerating extraction gap distance [5]. Figures 1 and 2 respectively show the extractable current and current density at different gap distances for a V_p=75 kV and plasma potentials for a d_{gap}=14 mm calculated from equation (1) where r_{ap}=3.75 mm. The inset figures show the extractable current and current density approximated region of interest within values already achieved in currently working ECR sources [2, 6].

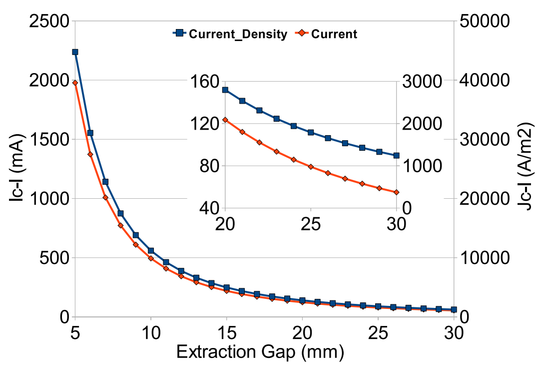

Figure 1: Langmuir extractable current and current density versus extraction gap distances for a 75 kV plasma potential.

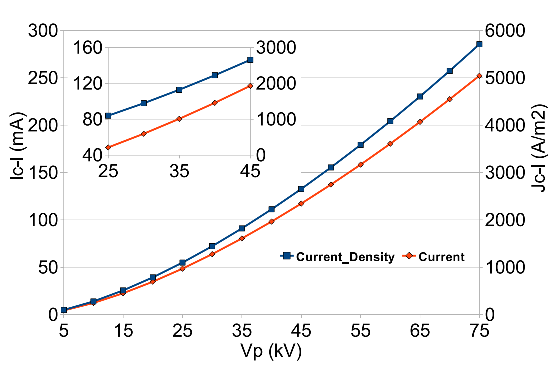

Figure 2: Langmuir extractable current and current density versus plasma electrode voltages for a 14 mm extraction gap.

Pierce Extractor Geometry

An analytic self-consistent solution to solve the Laplace equation for a space-charge flow problem can be calculated when the particle velocity through the accelerating gap is non relativistic. The analytic derivation of Pierce [3] gives a self-consistent electrostatic solution for electrodes when the source is placed at z=0 and the extraction electrode at z=d. The electrostatic potential through the gap can be expressed as:

$$\frac{\phi(x,y,z)}{V_p} = \left(\frac{z}{d_{gap}}\right)^{3/4} \qquad (2)$$

In order to get the right electrode shaping, equation (2) can be solved from considering some specific boundary conditions. In particular, a Pierce solution for plasma electrode shape is found as:

$$\frac{4\theta}{3} = \frac{\pi}{2} \qquad (3)$$

Equation 3 estimates a plasma electrode angle inclination of $\theta = 22.5$ degrees with respect to the source vertical plane. On the other hand, the extraction electrode shape can be calculated as:

$$\left(\frac{\rho}{d_{gap}}\right)^{3/4} \times \left(\frac{4\theta}{3}\right) = 1 \qquad (4)$$

where d_{gap} is the extraction gap distance and ρ the radial polar coordinate. The extraction electrode shape varies as a function of the accelerating gap length and the plasma electrode angle has to be optimized within a certain range of angular values in order to obtain a self-consistent solution.

Spherical Extractor Geometry

A different tetrode system based on a spherically convergent electrode architecture is also investigated [4]. The aim of analyzing this geometry is to improve even further the beam parameters in comparison with the Pierce geometry.

The Poisson equation can be expressed in terms of a space-charge flowing between two concentric spheres as [4]:

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dV}{dr}\right) = \frac{4\pi\rho}{\epsilon_0} \qquad (5)$$

By neglecting the initial velocity, the ion space charge can be substituted in Equation (5) with the following expression:

$$\rho = \frac{I}{4\pi}\sqrt{\frac{m}{2eV_p}} \qquad (6)$$

Equation (5) can be solved in terms of a series, and the solution given by Langmuir-Blodgett for the extractable current is:

$$I_{L-B} = \frac{4\epsilon_0}{9}\sqrt{\frac{2q}{m}}\frac{V_p^{3/2}}{\alpha^2} \qquad (7)$$

where:

$$\alpha = \gamma - 0.3\gamma^2 + 0.075\gamma^3 - 0.01432\gamma^4 + 0.0021609\gamma^5 - 0.00026791\gamma^6 + ... \qquad (8)$$

and:

$$\gamma = Ln\left(\frac{R1}{R0}\right) \tag{9}$$

α is called the Langmuir function and it depends on the aspect ratio, R, between the extraction electrode spherical radius, $R1$, and the plasma electrode spherical radius, $R0$. Figure 3 shows the extractable current and the Langmuir function versus R. By following the Langmuir theory, and in order to have a converging beam, it is necessary to have the emitter outside the collector so that the $R0 > R1$ condition is fulfilled.

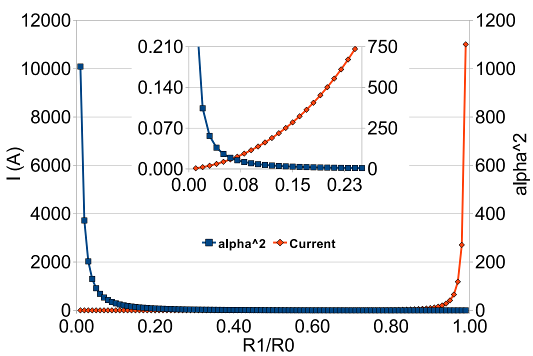

Figure 3: Langmuir function and total current versus the normalized spherical electrode radius.

Results indicate that to extract a 70 mA proton beam through a spherically convergent electrode accelerating system, the R ratio should be about 0.14.

BEAM DYNAMICS

The electrostatic and magnetic fields calculated with POISSON-SUPERFISH are imported to the GPT (General Particle Tracer) software to compute the beam dynamics for a given initial particle distribution.

A fundamental difficulty in the calculations for the space-charge-limited flow is that the electric field gets close to zero values on the plasma surface such that two standard approaches are implemented; the first is to model the plasma meniscus as a continuation of the 75 kV plasma electrode from the 3.75 mm plasma aperture to the axial position, in particular, using a hyperbolic function for the Pierce case, and a spherical radius for the spheric design; the second approach is to place the initial distribution of particles at a certain distance <1 mm from the emission surface [12]. The 70 mA proton beam is allocated in a Gaussian distribution of 1000 macroparticles with an initial energy of $E_0 = 1$ eV. The 2D initial particle distribution is represented as a disk of 3.75 mm radius parallel to the XY plane and with zero longitudinal length. Simulations do not include space charge neutralization or a beam with multi charge states like H^{2+} and H^{3+}. From the ECR plasma chamber solenoids, an axial magnetic field of 0.11 T maximum value at plasma aperture position is also simulated. Beam emittance and radius are calculated from all the surviving particles that successfully pass through an artificial disk of 100 mm (LEBT solenoid) diameter placed at 530 mm (LEBT position) from the source.

The extraction system parameters imposed by project requirements are: the 75 kV plasma electrode potential; the -3 kV electron trap potential; the 5 mm extraction electrode thickness; a separation distance of 5 mm between the extraction and repeller electrodes; the 7 mm extraction electrode thickness; the 5 mm separation distance between repeller and the last grounded electrode; the 5 mm last grounded electrode thickness; and the plasma chamber aperture radius at 3.75 mm; The electron trap and the last grounded electrode have also a 3.75 mm aperture radius. On the other hand, the main parameters to be optimized are: the accelerating gap, the extraction electrode aperture, the Pierce plasma electrode angle, and the spherical electrode radius.

Pierce Electrode System Results

The extraction gap was simulated for distances from 10 mm to 30 mm in 0.1 mm spatial increments. Figure 4 shows the percentage of particles killed and transverse rms emittance versus the extracting gap length. The best beam parameters are found for a 14 mm accelerating gap. Figure 5 represents the beam maximum radius and transverse rms normalized emittance versus the plasma electrode angle. A value of 31 degrees is found as the optimal value, with a rms emittance of 0.2261 π-mm-mrad. In a similar procedure, the extraction electrode aperture radius was also optimized at 2.9 mm. Figure 6 shows the optimum Pierce electrode design and particle trajectories.

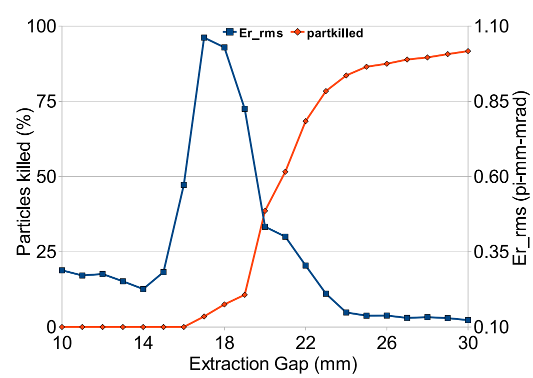

Figure 4: Percentage of lost macroparticles and rms emittance versus extraction gap for the Pierce case.

Spherical Convergent Electrode System Results

Simulations are initially performed by setting an accelerating gap of 13.2 mm [2]. Figure 7 gives the maximum

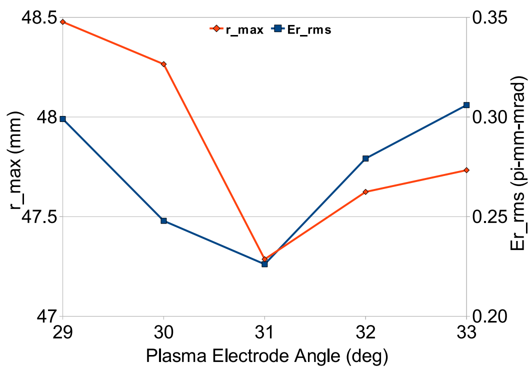

Figure 5: Beam maximum radial length and rms emittance versus plasma electrode angle for the Pierce case.

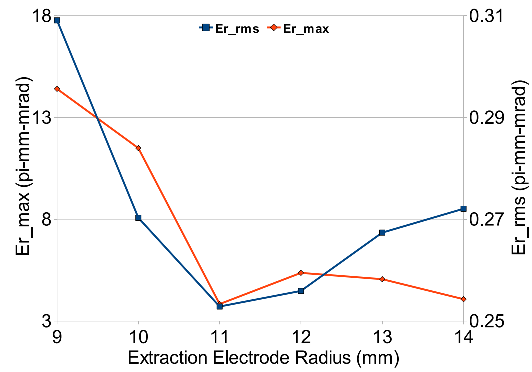

Figure 7: Maximum and rms emittances versus extraction electrode radius for the spherical extractor system.

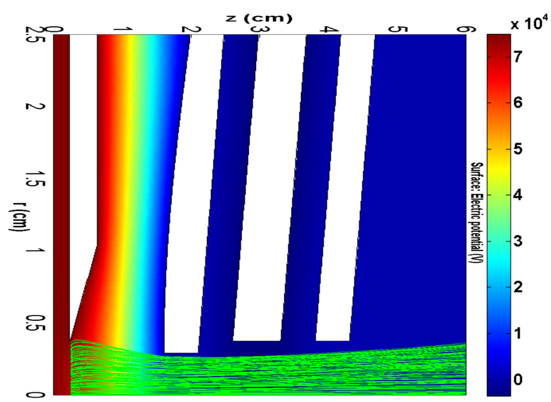

Figure 6: Optimum Pierce electrode system design and particle trajectories.

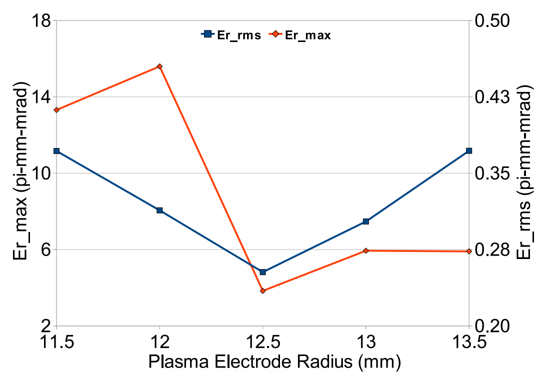

Figure 8: Maximum and rms emittances versus plasma electrode radius for the spherical extractor system.

and rms normalized emittances versus the extraction electrode radius. Results indicate that the optimum extraction electrode radius is R1=11.0 mm. Figure 8 gives the maximum and rms normalized emittances as a function of the plasma electrode radius such that the optimum value is R0=12.5 mm. Once the plasma and extraction spherical radius are optimized, the accelerating gap length is further refined. Figure 9 illustrates the maximum and the rms normalized emittances versus the accelerating gap which optimum value is estimated at 13.0 mm. The extraction electrode radius is also optimized at 3.5 mm. The best design of the spherical extraction system is able to propagate a proton beam up to 530 mm from the source with no lost particles and a 0.2443 π-mm-mrad rms normalized emittance. Figure 10 illustrates the ideal spherical extraction system combined with the particle trajectories.

Tables 1 and 2 show the optimal geometric and beam dynamics parameters for the Pierce and spherical extraction electrode systems. Figure 11 shows the axial electrostatic fields and potentials.

CONCLUSIONS

The work presented here reproduced some of the results from numerous and methodical simulations required to cover the full spectrum of geometric solutions from two different extraction systems for the ESS-Bilbao ECR source. The extractors were parametrized in basis of the beam dynamic simulations results calculated at 530 mm from the source. The beam transport downstream each of the extraction systems up to the LEBT position was sat-

Table 1: Geometric Parameters for the Extraction Systems

System	Gap [mm]	Plasma Angle [deg]	Ext. Aperture Radius [mm]
Pierce	14.0	31.0	2.9

System	Gap [mm]	R0 [mm]	R1 [mm]	Ext. Aperture Radius [mm]
Spheric	13.0	12.5	11.0	3.5

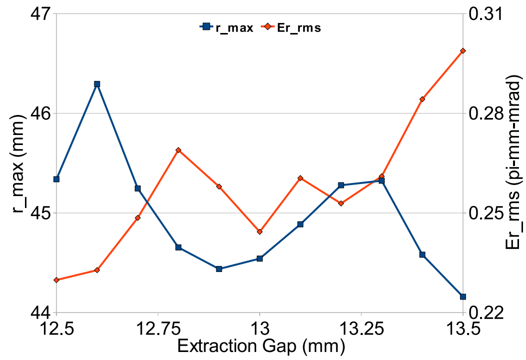

Figure 9: Maximum and rms emittances versus extraction gap distance for the spherical extractor system.

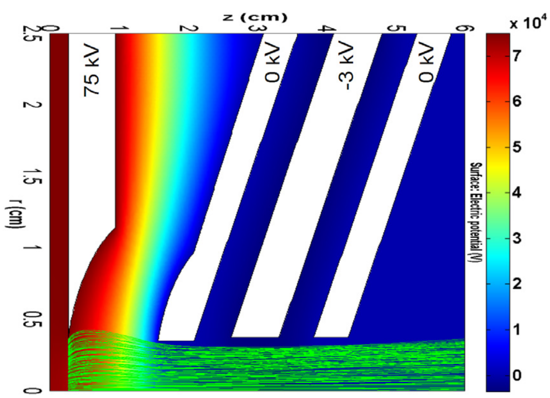

Figure 10: Optimum spherical electrode system design and particle trajectories.

isfactory, even though no space-charge neutralization was included in the simulations.

It would be difficult to make an adequate suggestion about what architecture must be set up in the ECR source since beam parameters are very similar. However, if small geometric parameter variations are introduced in the optimal designs, in general, the Pierce geometry demonstrated a more stable beam dynamics.

Table 2: Optimal Beam Dynamics Parameters for the Extractor Systems

System	r_{rms} [mm]	r_{max} [mm]	ϵ_{rms} [π·mm·mrad]	ϵ_{max} [π·mm·mrad]
Pierce	31.12	47.29	0.2261	6.0020
Spheric	29.10	44.54	0.2443	5.2028

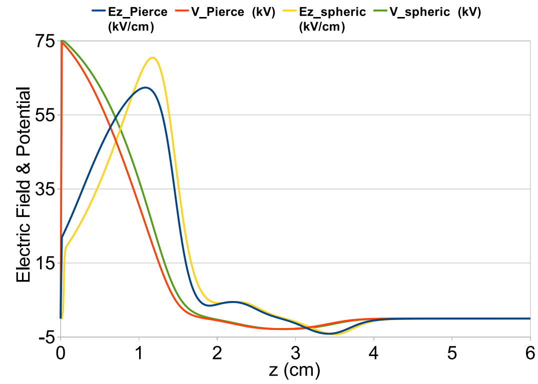

Figure 11: Axial electric fields and potentials of the Pierce and spherical extractor systems.

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