

# HIGH-CURRENT PROTON AND DEUTERIUM EXTRACTION SYSTEMS

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## Abstract

The PBGUNS code is used to explore and optimize high-current extraction system designs for hydrogen and deuterium beams extracted from plasmas. Two subjects are explored: first, the PBGUNS simulations are used to evaluate an analytic procedure for determining suitable plasma electrode shapes for hydrogen-ion beams. Experimental confirmation for this procedure was found in the high-current proton Low-Energy Demonstration Accelerator project at Los Alamos. A second subject is to determine via numerical simulations an initial design for a high-quality deuterium ion beam that could be extracted from a microwave ion source. This work builds on many years experience in design and testing of high-current extraction systems for proton and H<sup>-</sup> injectors.

## INTRODUCTION

Radio-frequency quadrupole (RFQ) development has progressed to the degree of accelerating 100-mA proton beams in continuous wave (cw) mode [1] to 6.7 MeV output energy. The 100-mA cw RFQ accelerator required development of a high current proton source [2] whose extraction beam optics were sufficiently controlled for injector beam matching to the RFQ. The proton beam extraction optics design was carried out by application of combined analytic and numerical codes. The first section of this paper gives a comparison of the numerical [3] and analytic [4, 5] procedure results. The modelling yields plasma and extraction electrode shapes appropriate for 140-mA, 75-keV proton beam. The second section applies the design technique to 75-keV, 154-mA H<sup>+</sup> and 75-keV, 30-mA d<sup>+</sup> sources.

## ANALYTIC AND NUMERICAL SIMULATION COMPARISON

A test case for establishing the consistency of numerical simulation and the analytic model is developed here. The numerical code used in this comparison is PBGUNS [3], and is commercially available [6]. The code uses the successive over-relaxation technique to arrive at a self consistent solution for beam formation from a plasma. The 2-D cylindrically symmetric option is used here, where the z coordinate is along the beam direction, and r is in the radial or transverse beam direction. The plasma is characterized by an electron temperature (kT<sub>e</sub>) in a Maxwellian distribution. A non-zero ion temperature (kT<sub>i</sub>) may be introduced for the extracted plasma positive ions, thus providing a model for finite beam emittance effects. This latter analysis is reserved for the following

section where practical high-current ion sources are discussed. Implied in the analytic model formulation is the kT<sub>i</sub> = 0 eV assumption. The numeric procedure yields a prediction for the plasma boundary or meniscus that separates the high electric field region of the acceleration gap from the plasma. The code also yields many (> 1000) trajectories whose coordinates in (r,r') phase space are available for emittance calculation and other dynamic comparisons. The r' (= dr/dz) variable is a measure of the trajectory angle from the axial direction z.

The analytic model [4,5] discussed here assumes a spherically convergent relationship between the beam forming plasma and extraction electrodes. The plasma electrode is characterized by an emission aperture with radius R<sub>em</sub> and the extraction electrode has an aperture

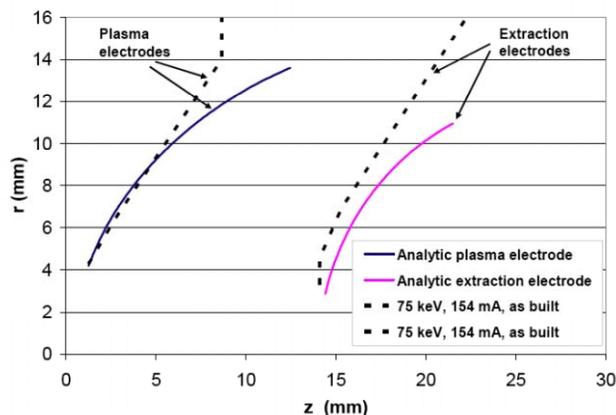


Figure 1: The solid curves are the plasma and extraction electrode shapes predicted from the analytic model [5]. The dashed electrodes are discussed in the applications section.

R<sub>ex</sub> through which the extracted beam passes (R<sub>em</sub> > R<sub>ex</sub> for convergent cases). The two electrodes are separated by a gap g. The solid lines in Fig. 1 show analytic model predictions for plasma and extraction electrode shapes for the following parameters: R<sub>em</sub> = 4.2 mm, R<sub>ex</sub> = 2.9 mm, and g = 13.2 mm. Input beam parameters for the hydrogen-ion beam are 95% proton and 5% H<sub>2</sub><sup>+</sup> fraction, 75-keV final energy, and 140-mA accelerated current. These beam parameters are close to the experimental conditions reported in [2].

A PBGUNS simulation for these input electrodes and beam conditions is shown in Fig. 2. The spatial extent for the simulation is R<sub>max</sub> = 20 mm and Z<sub>max</sub> = 60 mm. The mesh resolution is 0.1mm. The maximum z extent of the plasma electrode has a spherical cap, and then terminated by a short linear section to R = 20 mm. This is considered good high voltage design practice, and this termination has little effect on the predicted beam properties. The third electrode is the electron trap with -3 kV potential

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relative to ground. The fourth electrode is at ground potential, and serves to terminate the strong electric fields in the beam transport region. The effect of the 75-keV internal beam space charge is reduced to 5% at approximately  $z = 33$  mm, in accordance with experimental measurements [7]. Plasma parameters are  $kT_e = 8$  eV, the initial ion drift energy = 12 eV, and  $kT_i = 0$  eV, and the current density at the injection plane is  $J = 259$  mA/cm<sup>2</sup>. The proton/H<sub>2</sub><sup>+</sup> fraction is 95/5% as per analytic simulation.

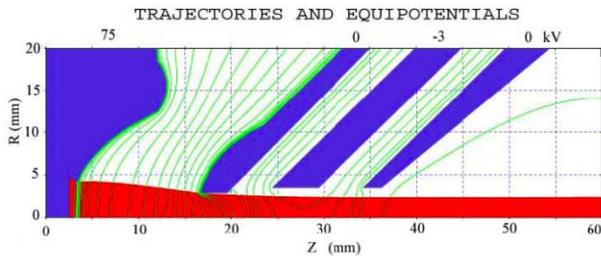


Figure 2: PBGUNS simulation for the 75-keV, 140-mA analytic model electrode configuration shown in Fig. 1. The electrode potential (kV) relative to ground is given along the top of the figure.

The results from the PBGUNS numerical simulation are that 144-mA current is accelerated to 75 keV before beam interception is predicted to occur on the extraction electrode. This is in good agreement with the analytic design current. Figure 3 shows the predicted phase-space plot at  $z = 33.3$  mm. Most of the phase-space trajectory coordinates have  $r' < 5$  mrad. The predicted rms normalized emittance is 0.074 ( $\pi$ mm-mrad). Most of this emittance likely arises from the emission aperture edge. The PBGUNS numerical simulation of the electrode profiles predicted by the analytic method thus gives a predicted high quality hydrogen-ion beam.

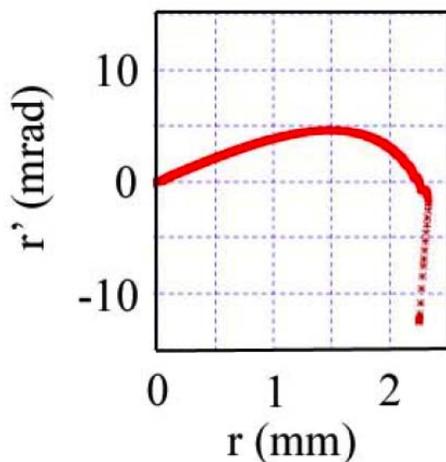


Figure 3: Phase-space distribution for the predicted trajectories of the Fig. 2 simulation at  $z = 33.3$  mm. The plasma ion temperature is  $kT_i = 0$  eV in this simulation.

## DESIGN APPLICATIONS

### High-current Proton Source.

The design procedure outlined in the previous section was applied to the injector ion source in ref. [2]. This injector was used for several years in 100-mA RFQ operations. The plasma and extraction electrode shapes are shown as dashed curves in Fig. 1. The final ion source parameters are  $R_{em} = 4.3$  mm,  $g = 12.9$  mm,  $R_{ex} = 3.3$  mm, and 75-keV, 154-mA hydrogen ion beam with H<sup>+</sup>/H<sub>2</sub><sup>+</sup> fraction = 90/10%. The PBGUNS trajectory plot for this case is shown in Fig. 4. This simulation includes an 875 G axial magnetic field which decreases slowly with increasing  $z$ . The upper portion of Fig. 4 shows the 875 G axial field profile where the field magnitude is normalized to one. Application of a thermal model to the experimental emittance measurements [2] indicated that the extracted proton plasma temperature  $kT_i$  is approximately 1.5 eV. This ion temperature is included in the Fig. 4 simulation.

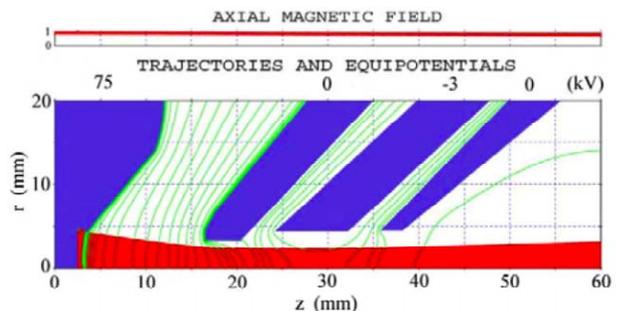


Figure 4: PBGUNS simulation for the 75-keV, 154-mA ion source reported in ref. [2]. The electrode potential (kV) relative to ground is given along the top of the trajectory figure.

Figure 5 shows the phase-space prediction from the Fig. 4 simulation at  $z = 33.3$  mm. The 154-mA beam

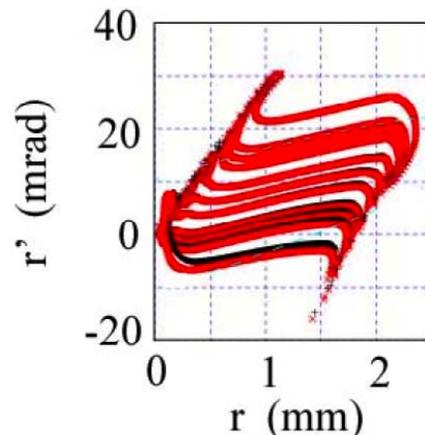


Figure 5: Phase-space distribution from the high-current proton injector simulation.

current is well focussed. The predicted rms normalized emittance is 0.10 ( $\pi$ mm-mrad). The phase-space area (emittance) increase is attributed to the 1.5 eV ion temperature. A revealing experimental observation of the beam quality is that all three electrodes (extraction, electron suppressor, and ground) had operating temperatures  $< 50^\circ\text{C}$  while a cw, 75-keV, 154-mA (11.5 kW) beam was being extracted from the ion source.

*Proposed CW D<sup>+</sup> Ion Source.*

There is interest in high-quality d<sup>+</sup> ion sources for accelerator-based neutron production projects [8]. The analytic model predictions for 75-keV, 30-mA plasma and extraction electrode shapes are shown in Fig. 6.

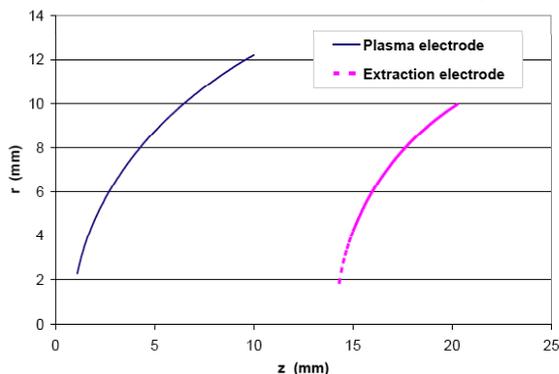


Figure 6: Analytic model predictions for d<sup>+</sup> ion source plasma and extraction electrode shapes.

Other inputs to this extraction system are  $R_{em} = 2.3$  mm,  $R_{ex} = 1.5$  mm,  $g = 13.1$  mm, and deuterium ion fraction =  $d^+/d_2^+ = 87.5/12.5\%$ . The PBGUNS simulation for this extraction system is equal in quality to the proton results shown in Fig. 2. Fig. 7 shows the PBGUNS simulation for these electrode shapes and beam parameters excepting  $R_{ex} = 1.8$  mm and  $kT_i = 1.0$  eV. The plasma electrode is again terminated in a spherical section rather than a sharp corner. The slight increase in the extraction aperture radius is to allow clearance for the 30-mA beam. The predicted rms normalized emittance at  $z = 33.3$  mm is 0.036 ( $\pi$ mm-mrad).

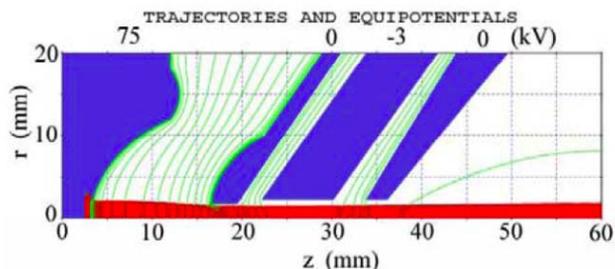


Figure 7: PBGUNS simulation for the 75-keV, 30-mA d<sup>+</sup> source extraction. The plasma and extraction electrode shapes are determined by the analytic model (see Fig. 6).

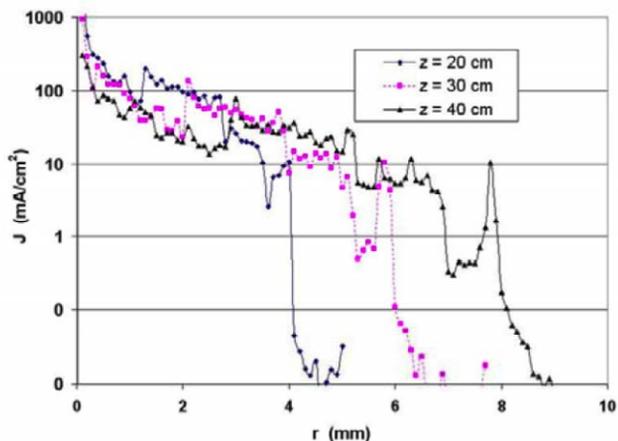


Figure 8: Deuterium ion current densities predicted from PBGUNS simulations at three z locations downstream from the ion source.

In addition to phase-space distribution, one may consider predicted beam profiles at some distance downstream from the ion source as a measure of optical quality. The electrode shapes used in Figs. 6 and 7 is introduced into a PBGUNS model that was extended to  $Z_{max} = 500$  mm. Here,  $kT_i = 1.0$  eV, and the residual beam space charge after the extraction gap is taken to be 5% of the full 30 mA [7]. Predicted beam profiles of the beam current density  $J$  ( $\text{mA}/\text{cm}^2$ ) vs. the radial coordinate are shown in Fig. 8. Rather tightly focused beams ( $r < 10$  mm) are predicted for  $z > 400$  mm using only the extraction electrodes for beam focussing. The deuteron beam power density at  $100 \text{ mA}/\text{cm}^2$  corresponds to  $7.5 \text{ kW}/\text{cm}^2$ .

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