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INCREASING THE BEAM BRIGHTNESS OF A DUOPLASMATRON PROTON ION SOURCE*

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Abstract

The LANSCE accelerator facility operates with two independent ion injectors for H^+ and H^- particle beams. The H^+ ion beam is formed using a duoplasmatron source followed by a 750 keV Cockroft-Walton accelerating column. Formation of an optimal plasma meniscus is an important feature for minimizing beam emittance and maximizing beam brightness. An experimental study was performed to determine optimal conditions of extracted H^+ beam for maximizing beam brightness. Study was based on measurements of beam emittance versus variable beam current and extraction voltage. Measurements yielded 0.52 as the best ratio of beam perveance to Child - Langmuir perveance for maximizing beam brightness. As a result of optimization, beam brightness was increased by a factor of 2.

ION SOURCE AND BEAMLINE

The existing H^+ ion source is a duoplasmatron with a Pierce extraction geometry [1]. The source (see Fig. 1) has been operated successfully for many years at LANSCE [2]. Originally developed for production of 50 mA proton beam, the source was modified for production of a less intense, but brighter beam [3]. The Pierce anode was replaced with a modified electrode with an aperture radius of R = 2.5 mm. The extraction electrode was moved closer to the ion source. The extraction distance is now d =10.78 mm. Details of internal structure of LANSCE duoplasmatron are given in [2, page 28]. Presently the source delivers a proton beam current of I = 15 mA at 60 Hz x 625 μsec pulse length using 1.3 std cc/min gas flow. The source is mounted on a Cockroft-Walton accelerating column at 750 kV potential with respect to ground. The H^+ beamline (see Fig. 2) is equipped with two slit-collector emittance measurement stations. TAEM1 station is placed after the 750 keV Cockroft-Walton accelerating section, while TAEM2 is placed after the 81° bending magnet. An additional emittance measurement station, TDEM1, is common for both H^+ and H^- beams and is placed in front of Drift Tube Linear accelerator. Beam current is measured with 5 beam current monitors along the beamline. The beamline is operated at typical pressure of $9 \cdot 10^{-7}$ Torr.

CHARACTERISTICS OF EXTRACTED BEAM

Optimal operation of the accelerator facility critically depends on the emittance of the beam extracted from the ion source. An intrinsic limitation in particle-source beam-emittance comes from the finite value of plasma temperature in the ion source and from the value of longitudinal magnetic field at extractor. Normalized emittance of the beam, extracted from a particle source with aperture radius R and plasma ion-temperature T with magnetic field B at extractor is estimated as [4]

$$4\varepsilon_{rms} = 2R\sqrt{\frac{kT}{mc^2} + \left(\frac{eBR}{4mc}\right)^2} \quad . \qquad (1)$$

Besides emittance determined by Eq. (1), additional sources contributing to beam emittance are:

- irregularities in the plasma meniscus extraction surface
- aberrations due to ion-source extraction optics
- optical aberrations of the focusing elements of the Low Energy Beam Transport
- non-linearity of the electric field created by the beam space charge
- beam fluctuations due to ion-source instability or power regulation.

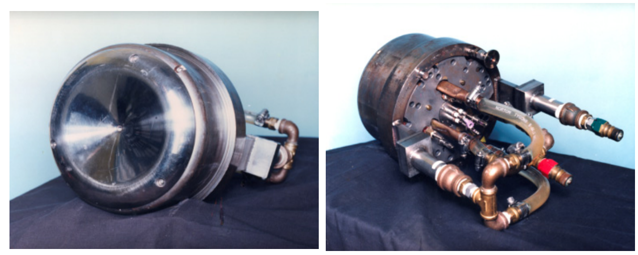

Figure 1: Side view of assembled LANSCE duoplasmatron ion source with Pierce electrode.

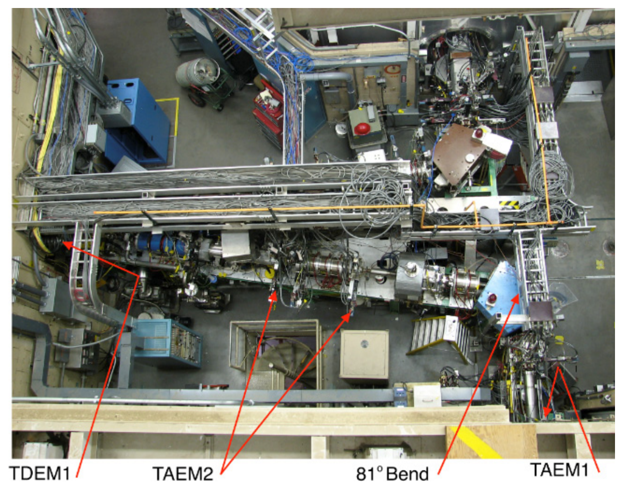

Figure 2: Layout of 750 keV H^+ Low Energy Beam Transport of LANSCE.

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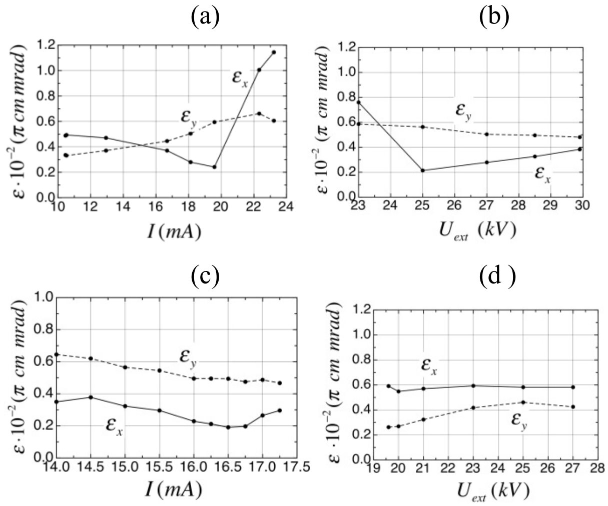

Figure 3: Normalized rms beam emittance at (a) U_{ext} = 27 kV, (b) I = 18.5 mA, (c) U_{ext} = 22 kV, (d) I = 14.5 mA.

Contribution of the above factors results in an effective beam emittance larger than the beam emittance defined by Eq. (1). Irregularity of emitting surface (plasma meniscus) can be controlled by variation of applied extraction voltage between Pierce electrode and extraction electrode [5]. Initial divergence (convergence) of the beam due to curvature of plasma meniscus is estimated from the spherical diode Child-Langmuir law as [6]

$$\theta = 0.625\ S\,(\frac{P_b}{P_o} - 1)\,, \tag{2}$$

where $S = R/d$ is the ratio of extraction radius to extraction gap (aspect ratio of extractor), P_b is the beam perveance

$$P_b = \frac{I}{U_{ext}^{3/2}}\,, \tag{3}$$

where I is the beam current and U_{ext} is the extraction voltage, and P_o is the Child-Langmuir perveance:

$$P_o = \frac{4\sqrt{2}\pi}{9}\varepsilon_o\sqrt{\frac{q}{m}}\ S^2\ . \tag{4}$$

Negative values of θ correspond to convergence of the beam (concave meniscus). The ratio of beam perveance to Child-Langmuir perveance (matching parameter) is given by

$$\eta = \frac{P_b}{P_o} = \frac{9}{\sqrt{2}S^2}\frac{I}{I_c}(\frac{mc^2}{qU_{ext}})^{3/2}\,, \tag{5}$$

where $I_c = 4\pi\varepsilon_o mc^3/q =$ 3.13 x $10^7 A/Z$ [Amp]. The parameter η is used to characterize conditions for optimization of extracted beam quality. Experimental studies of beam divergence and beam emittance indicate the existence of a value for η where beam emittance is minimized [7].

EXPERIMENTAL SETUP AND RESULTS

The purpose of this study was to find conditions for maximization of beam brightness. A series of beam emittance measurements were performed at TAEM2 emittance measurement station with different values of beam current and extraction voltage. The ion source generates additional components H_2^+ / H_3^+ which are removed from the primary proton beam by a 81^o bending magnet. The value of proton beam current was controlled by arc current of the ion source. The following sets of beam emittance measurement were undertaken:

(a) Variation of I = 10… 24 mA at U_{ext} = 27 kV
(b) Variation of U_{ext} = 24 ….30 kV at I = 18.5 mA
(c) Variation of I = 14… 17.5 mA at U_{ext} = 22 kV
(d) Variation of U_{ext} = 19.5 ….27 kV at I = 14.5 mA.

Results of the measurements are presented in Fig 3. In all measurements, the threshold of 2% out of peak value of beam distribution is added to remove experimental noise in phase space distribution. Root-mean-square (rms) normalized beam emittance $\varepsilon_{x\_rms} = (\beta\gamma)\sqrt{<x^2><x'^2> - <xx'>^2}$ (similarly in y -direction) is calculated through experimentally determined second-order moments of beam distribution. It is seen that one of beam emittances has a minimum $\varepsilon_{rms\_\min} \approx (2....2.5)\cdot 10^{-3}\pi\, cm\, mrad$ which corresponds to maximum beam brightness. Random variation of measured beam emittance under fixed values of beam parameters and transport channel parameters is within $\pm 0.5\%$. The reason for observable difference in beam emittances is unknown.

Figure 4 illustrates variation of horizontal beam emittance at constant extraction voltage U_{ext} = 27 kV. It is clearly seen that the horizontal beam emittance has a minimum at I = 19.6 mA. Lowering of beam current to I = 18.5 mA requires lowering the extraction voltage to U_{ext} = 25 kV in order to maximize beam brightness. Further decreases of beam current require further decrease of extractor voltage to maintain maximum beam brightness. Figure 5 summarizes all measurements illustrating dependence of normalized beam brightness

$$B = \frac{I}{8\pi^2\varepsilon_{x\_rms}\,\varepsilon_{y\_rms}} \tag{6}$$

versus matching parameter, Eq. (5). Random variation in beam brightness due to random experimental uncertainty in beam emittance

$$\left|\frac{\Delta B}{B}\right| = \left|\frac{\Delta\varepsilon_x}{\varepsilon_x} + \frac{\Delta\varepsilon_y}{\varepsilon_y}\right| \tag{7}$$

is within $\pm 1\%$, which is significantly smaller than observable variation of brightness as a function of matching parameter. The average value of the matching

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parameter, where beam brightness reaches it's maximum is:

$$\eta_{opt} = 0.52\ . \tag{8}$$

Based on obtained results, the dependence of extraction voltage on beam current for maximizing beam brightness can be expressed from Eq. (5) as

$$U_{ext} = \left(\frac{I}{P_o \eta_{opt}}\right)^{2/3}\ , \tag{9}$$

where the value of Child-Lengmuir perveance for this source is

$$P_o = \frac{4\sqrt{2}\pi}{9}\varepsilon_o\sqrt{\frac{q}{m}}\left(\frac{R}{d}\right)^2 = 9.16\cdot 10^{-9}\frac{A}{V^{3/2}}\ . \tag{10}$$

Figure 6 is a plot of Eq. (9), together with experimental data.

SUMMARY

The experimental study was done to determine optimal conditions of extracted H^+ beam for maximizing beam brightness. Study was based on measurements of beam emittance versus variable beam current and extraction voltage. Optimal value of matching parameter of 0.52 for this particular source was determined. The best value of matching parameter is expected to be source-dependent, mainly on extraction geometry and plasma temperature. Performed study defines optimal conditions for operation of the beam with maximum brightness.

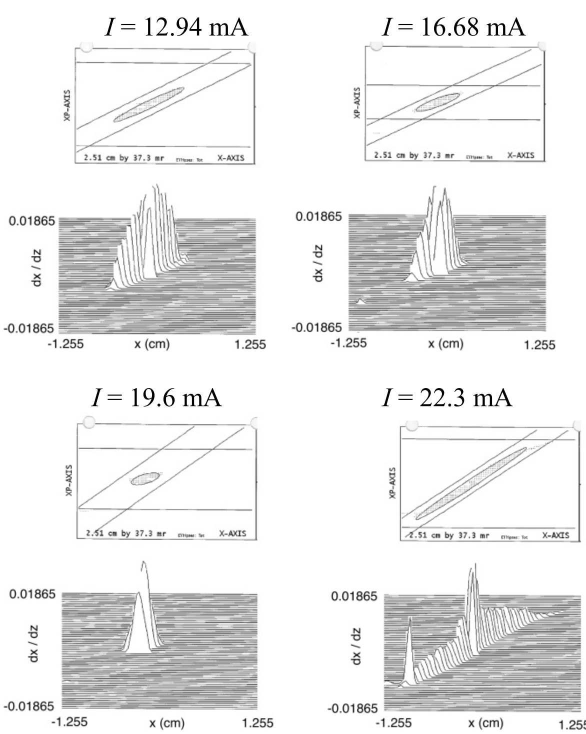

Figure 4: Horizontal beam emittance scans at extraction voltage of U_{ext} = 27 kV for different H^+ beam intensities.

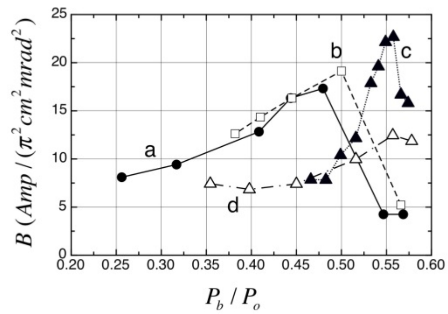

Figure 5: Beam brightness, Eq. (6), as a function of matching parameter, Eq. (5). Curves (a), (b), (c), (d) correspond to experimental setups in Fig. 3.

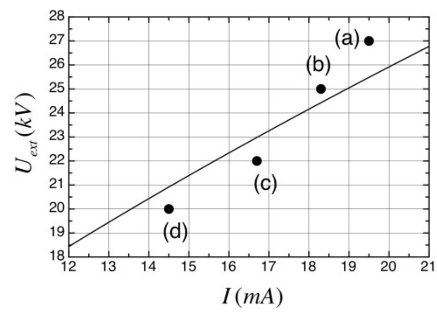

Figure 6: Extraction voltage versus H^+ beam current for maximizing beam brightness: (solid line) Eq. (9), (dots) experimental results (a), (b), (c), (d) corresponding to experimental setups in Fig. 3.

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