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THE DESIGN OF A 10-KV DEUTERIUM-ION EXTRACTOR FOR CONTINUOUS SERVICE

Thomas J. Duffy¹ and J. Alan Paterson²

Abstract

An extractor for accelerating 50 A of deuterium ions to 10 keV for injection into a metal, vapor charge-exchange cell has been designed. The beam-forming electrodes are convection cooled and capable of continuous service.

Introduction

The design presented here is for an extractor to inject positive deuterium ions at low energy (1 to 20 keV) into a metal, vapor charge-exchange cell. The resulting negative-ion beam is post-accelerated to higher energy, neutralized, and injected into a magnetically confined fusion plasma. The extractor is curved to a spherical surface to provide focusing at the post-accelerator.

At this time, negative-ion sources are in the early stages of development, and the optimum system is not yet defined. For charge exchange on cesium vapor, the best system efficiency is realized at about 1 keV, while sodium-vapor charge exchange may offer better overall system efficiency between 10 and 15 keV if improved beam optics are considered.

To satisfy both conditions with the same beam-forming electrode geometry, the accelerator is operated with high decelerating voltage when the low-energy beam is required. This mode of operation results in intense dissipation on all grids.

At high beam energy, increased plasma density and electron temperature in the arc chamber cause increasing dissipation on the upstream side of the extraction grid. At the same time, less well-understood mechanisms, associated with charge exchange and ionization on the background gas in the inter-grid space, increase the dissipation on the downstream side of the extraction grid. A knowledge of these loads is essential for predicting voltage-holding ability, erosion characteristics, and thermal stability.

For the present design, we scale from two prototypes: (1) a four-grid extractor, operating in similar conditions of extraction-current density but a different energy regime; and (2) a three-grid extractor in high decel service, operating without instrumentation to measure dissipation. Both sources are in short-pulse service (heat-sink mode) so extrapolation to long pulse or continuous duty is associated with a low confidence factor. For these reasons, we optimize the heat-transfer capacity of the electrodes and look to limiting conditions of heat flux.

Electrode Geometry, Extraction Current and Beam Optics

Beam energy and extraction-current density are approximately related to one another by the Langmuir-Childs law, $J = kv^3/2d^2 \cdot m^{1/2}$, where J is the extraction-current density, v is the potential difference between the extraction and accelerating grids, d_1 is the distance between the sharp edge of the extraction electrode and the mid-plane of the accelerating grid electrodes, and r is the mass number of the gas

molecule (see Fig. 1). With a fixed set of electrode dimensions, V is the only variable at our disposal and J is matched to V by adjusting the arc density in the plasma chamber. The voltageholding properties of the grid set are a function of the distance between electrodes, the radius of curvature, the gas density and the presence or absence of ions and electrons in the space between electrodes, and material properties.

By setting $J = 0.25 \text{ A/cm}^2$ as the lowest value of interest and 10 keV as the minimum energy for charge exchange in sodium vapor, the upper limit of current density is then set at 0.5 A/cm^2 at 16 keV, a value that is about the maximum at arc chambers of current design can supply. From our experience with a high-decel grid set, now operating, distance c between grids of 1.5 mm is about the minimum for voltage holding on molybdenum electrodes at 16 kV. The actual dimensions of the extraction and accel electrodes are adjusted so distance d_1 will yield the desired extraction-current density while at the same time provide the required mechanical stiffness for an extraction window 10-cm wide. This is accomplished by forming a crown on the extraction grid and bending the accel grid to an elliptical shape. This technique rapidly converges to a limit, however, because stiffness depends on h^3 and because electrostatic forces increase with J , which depends on the constant c as $(c+h)^{-2}$, where c and h are defined in Fig. 1.

Highest extraction-current density with good beam optics are reported where the spacing does not exceed the grid-to-grid spacing d_1 (see Ref. 1). Setting s equal to d_1 fixes grid transparency at 50%, and the total current for a given grid area is determined. In this case, the dimensions are $10 \times 40 \text{ cm}$, and the resulting current is 50 A at 10-kV accel potential.

This total extractor geometry will be evaluated by WOLF code² for beam optics and to determine allowable manufacturing tolerances. Trade-offs, according to the rules outlined above, can be made to meet a particular set of operating conditions.

Fig. 1. Sections through grids of prototype and model, all to same scale.

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Estimate of Grid Loading

(a) Extraction-grid Loading Resulting from Ion-source Plasma

Substantial heating of the extraction grid is due to ion bombardment from the plasma chamber. Tests performed at Lawrence Berkeley Laboratory on a 9-by-10-cm, four-grid prototype indicate a total loading from this source of 1.9 kW at 80 kV and 2.2 kW at 100 kV, with arc density adjusted for these extraction voltages.³ The corresponding current density J was 0.116 A/cm² and 0.177 A/cm², respectively. The total electrode area involved was 33.1 cm².

Assuming a linear dependency on plasma density and a constant term for representing radiated power from hot cathode and anode,

$$W_1 \propto Jk_1 + W_r \quad (1)$$

watts/cm² of projected grid area, where W_1 is the dissipation on the upstream side of the extraction grid, k_1 is a constant of proportionality for arc density, and W_r is the radiation load.

Solving for k_1 and W_r in the prototype, we obtain $k_1 = 131$ and $W_r = 43$. Applying this relationship to our model at the peak extraction-current density of $J = 0.5$ A/cm², we find

$$W_1 = 0.5 (131) + 43 = 108 \text{ W/cm}^2$$

An additional heating load that results from increased electron temperature in the arc should be included. These arc chambers characteristically require increased arc voltage at peak density, which with deuterium usually varies from 40 V at lowest density to 50 V at highest density ($J = 0.5$ A/cm²). Our design peak density is 0.5 A/cm². If we assume the test was conducted near 40-V arc drop, then the heating resulting from the arc should be increased by 20% and W_1 should be $108 + (108)(0.2) = 129.6$ W/cm². Then the total heating from the arc chamber side on the extraction grid will be

$$W_1 = 129.6 (0.3) = 38.8 \text{ W/cm}$$

on a unit length basis, where 0.3 cm is the width of individual grid electrodes.

(b) Loading on Downstream Side of Extraction Grid (15-kV Operation)

Ions born on the background gas between grids seek the nearest more-negative grid; they have characteristic energies about equal to half the potential difference between the arc chamber and the grid they strike. Secondary electrons emitted from these surfaces and photo-emitted electrons seek the more positive grids, and they carry an energy equivalent to the voltage difference between the grids involved.

When attempting to scale these effects in the four-grid prototype for two test points (80 and 100 kV) for the plasma grid alone or the gradient grid alone, a good fit is not realized. However, if the effect on both the plasma grid and gradient grid is combined as

$$W_{2p} + W_3 \propto JVk_2 \quad (2)$$

we get good agreement for the two test points, where W_{2p} is the dissipation on the downstream side of the plasma grid, and W_3 is the total dissipation on the gradient grid. The constant k_2 is proportional to gas density, ionization and charge-exchange cross

sections, and path length. This indicates that the contribution of ions on the gradient grid is relatively insignificant; that the loading is almost all due to electrons; and that, if the gradient grid were not present, practically all the dissipation would appear on the plasma grid.

Solving Eq. 2 for k_2 results in $k_2 = 1.14 \times 10^{-2}$ for the prototype. To apply Eq. 2 to our model, k_2 will be reduced by a factor of three to account for the differences in path lengths over which charge exchange and ionization occur. No correction is made for average gas density, and it is assumed that charge-exchange and ionization cross sections are linearly proportional to energy. The loading on the downstream side of the extraction grid W_2 is:

$$W_2 = (0.5)(1.5 \times 10^4)(1.14 \times 10^{-2}/3) = 28.5 \text{ W/cm}^2$$

or 8.55 W/cm of grid electrode. And the total load on the extraction grid at 15 kV is:

$$W_0 = W_1 + W_2 = 47.25 \text{ W/cm}$$

(c) Loading on the Accelerating Grid (15-kV Operation)

Following the arguments presented in (b), each electron that finds either the plasma grid or the gradient grid would be produced by the collision of an ion or a photon with a more-negative grid. Assuming that all the dissipation on the suppressor grid is due to ion bombardment at half energy, we would predict the loading on the suppressor to be one-half the loading on the plasma and gradient grids. In the prototype, the value of this loading was actually less. Therefore, in the model we will use ($W_0/2$) as a design: point loading.

Operation as a 1-keV Extractor

When operated as a low-voltage extractor, the extraction grid is at ground potential; the accelerating grid is at -15 kV, to establish the extraction current density J ; and the decelerating grid is at -1 kV. The resulting beam is at 1 keV with respect to ground. We have a prototype operating in short-pulse service in these conditions; the power supply drain to the accel grid is 2 A.

Under these conditions of operation, ions born in the inter-grid space, which do not have enough energy to escape, seek the most negative surface, the accel grid. The current that the power supply furnishes is a combination of the secondary-electron current, resulting from ion bombardment, and the ion current. If we assume a secondary-electron coefficient of unity, then the power supply must have furnished one electron to the secondary-electron current and one electron for each ion that struck the grid. If we further assume that the loading to the extraction grid is about equal to that on the decelerating grid, then the electron current to each of these grids is 1/4 or 0.5 A. The dissipation on each of these grids then is $P = IV = 7.5$ kW in the prototype. These grid arrays consist of 21 electrodes, each 7-cm long, so the dissipation per unit length is 51 W/cm of electrode.

The dissipation on the accelerating grid is the same as on the extraction grid, because current to this grid is 1/2, if we assume an average ion energy of $V/2$. However, there is reason to believe that the ion energy is considerably lower than this value so the actual dissipation is smaller.

In the model then, the dissipation on the extraction grid on the downstream side will be the same as the prototype multiplied by the area ratio of the beam-lets. The area ratio is 1.51:1, and the loading will

Table I. Main design features of extractor.

Parameter	Operations at:	
	15 keV	1 keV
Extraction current density, J max	0.5 A/cm ²	0.5 A/cm ²
Total extracted beam	100 A	100 A
Dissipation per electrode, extraction grid	470 W	1.2 kW
Total dissipation, extraction grid	31.5 kW	80 kW
Total dissipation all grids	63 kW	150 kW
Coolant flow rate per electrode	5.9 g/s	5.9 g/s
ΔT Water	19 K	47 K
ΔP Water (manifold to manifold)	10 atm	10 atm
Max. surface temp. rise	42.5 K	82 K
Design point max. heat flux (hot side average)	130 W/cm ²	171 W/cm ²
Critical heat flux (boiling begins)	304 W/cm ²	304 W/cm ²
Thermal distortion at design point	4×10^{-3} cm	2×10^{-3} cm

be $W_2 = (1.51)(51) = 77$ W/cm. The total loading is:
 $W_1 + W_2 = 77 + 38.8 = 116$ W/cm on a unit length basis.
 The peak thermal flux is on the downstream side and is
 171 W/cm².

Grid Thermal Distortion and Heat Transfer

The accommodation of electrode expansion in these structures is critical to successful operation and to acceptable beam optics. A problem is caused by the end connections. These slender members elastically deform beyond acceptable limits when minute end forces and moments are applied. The effects are most detrimental in low-energy extractors where characteristic dimensions are small. To solve these problems, we placed both the supply and return manifolds at the same end of the electrode, so the member is fixed at one end only and the opposite end is free but guided. This arrangement provides nearly the same degree of fixity at both ends (see Figs. 2 and 3) and provides the highest available stiffness without end restraint.

The trade-off is that Reynolds numbers tend toward laminar flow when coaxial tubes are used unless a high water velocity is employed. Lower velocities lead to low heat transfer coefficients, high film ΔT 's, and high electrode temperatures. Boiling is suppressed, however, by making the outer tube the supply and the inner tube the return. These considerations are critical only in the case where the extractor is used as a high decel source, where dissipation on all grids may be as high as 1 to 2 kW/electrode. Under these conditions, the pressure drop across the system would necessarily be high (30 to 40 atm) to assure fully developed turbulent flow.

Our laboratories have permanently installed circulating-water systems with about 6 atm available head. The purity and electrical conductivity of this water is adequate for the system described here. Initially, at least, we will simply add a booster pump and additional filtration to these facilities to assure appropriate hydrodynamic conditions.

Conclusions

A summary of the main design features of the described extractor is shown in Table I. Included are estimates of the more important design parameters with regard to flow conditions and heat transfer. We believe the margins of safety are adequate to assure successful operation at the design point conditions.

This extractor design is the first of its kind and is based on inadequate experimental data. Hopefully, the extractor will be used to obtain the design data required for further extension of the scaling techniques outlined here. These data could also lead to a better understanding of the physics involved.

Fig. 2. An extraction-grid electrode from extractor (see Fig. 3).

Fig. 3. The extractor after assembly.

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