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Particle control in the sustained spheromak physics experiment

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Abstract

In this paper we report on density and impurity measurements in the sustained spheromak physics experiment (SSPX) which has recently started operation. The SSPX plasma is sustained by coaxial helicity injection for a duration of 2 ms with peak toroidal currents of up to 0.5 MA. Plasma-facing components consist of tungsten-coated copper to minimize sputtering. The surfaces are conditioned by a combination of baking at 150°C, glow discharge cleaning, titanium gettering, and pulse-discharge cleaning with helium plasmas. In this way we achieve density control with $n_e \sim 1\text{–}4 \times 10^{20}$ m^{-3}. However, gas input has only a weak effect on plasma density; injector current is the dominant factor. Conditioning reduces the impurity radiation to the point where it is no longer important to the energy balance, so that the lifetime of the spheromak discharge is ultimately governed by MHD activity, which grows rapidly about 1.5–2.0 ms after helicity injection ends. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Impurity control; Particle recycling

1. Introduction

In this paper we discuss power and particle control for the sustained spheromak physics experiment (SSPX) spheromak device, which began operation in 1999. In spheromaks, a very low aspect ratio ($A \sim 1.1$) toroidal confinement geometry is produced by currents in the plasma itself (the plasma dynamo), rather than by external coils which necessarily link the vacuum vessel; this configuration could lead to smaller, cheaper power plants. Furthermore, DC or AC potentials applied to external electrodes can sustain the spheromak plasma. At present, it is unknown if the spheromak configuration can provide sufficient energy confinement to allow the plasma to be heated to thermonuclear temperatures (10 keV). Recent analysis of previous experimental data [1,2] suggested that adequate core energy confinement could be obtained in these devices and that performance might scale favorably to power reactors. The SSPX device was built to explore this question.

The spheromak plasma in SSPX is confined within an $R = 1.0$ m, $h = 0.5$ m, 1.2 cm thick copper flux conserver which serves to maintain the plasma shape via image currents flowing in it. A cross-section of the device appears in Fig. 1; magnetic flux surfaces for an ideal MHD equilibrium computed with the CORSICA code are included. The confined plasma ($R = 0.31$ m, $a > 0.25$ m) is isolated from the flux conserver by a thin (less than 1cm wide at the midplane) scrape-off layer (SOL) plasma which is connected to the electrode region at the top of the device. The cross-section of the shell was designed to minimize the volume of corner regions having open field lines, so it is everywhere conformal to the magnetic flux surfaces except for a 5 cm high toroidally uniform diagnostic slot encircling the midplane.

In terms of plasma surface interactions and the scrape-off layer plasma, the main issues for the spheromak are as follows. Foremost is impurity generation by the high current discharge in the injector region. Peak surface-normal current density can reach 60 A/cm^2 and if the gas density is too low in this region, the current

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will be maintained by sputtering of the wall material. Secondly, we are concerned about sputtering from the walls of the flux conserver because the scrape-off layer plasma is relatively thin. To mitigate these effects we have coated the copper surfaces with a 100 μm thick layer of plasma-sprayed tungsten. Density control is another issue for present-day spheromak experiments because the short pulse duration precludes real-time feedback and because breakdown requirements in the injector impose a minimum gas injection rate (which depends on injector geometry and gas valve properties) to reach the minimum of the Paschen curve.

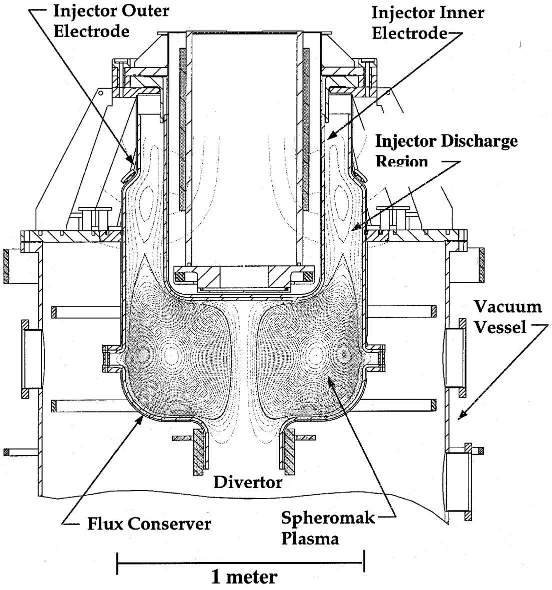

Fig. 1. SSPX with Corsica equilibrium profile.

In the rest of this paper we summarize the basic features of typical SSPX spheromak plasmas (Section 2), discuss particle balance and density control in Section 3, and in Section 4 show how improved surface conditioning has reduced impurity radiation and improved performance.

2. Spheromak formation experiments

Spheromak plasmas have four distinct phases: breakdown, formation (or ejection), sustainment, and decay. These features are illustrated by data from SSPX in Fig. 2. Breakdown occurs when the gas pressure in the injector exceeds that required for Paschen breakdown; the presence of an initial magnetic field modifies this threshold significantly. In SSPX we increased the radius

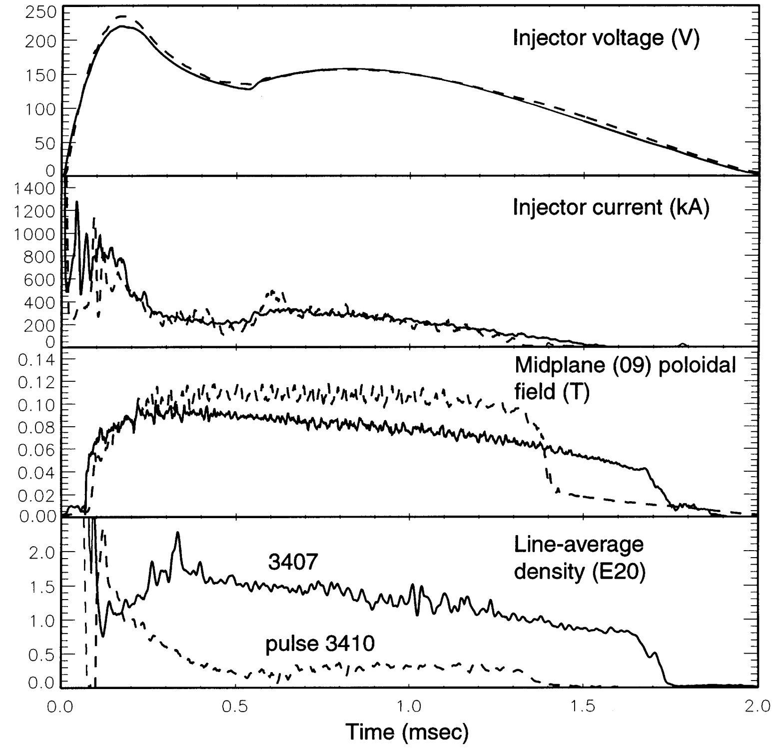

Fig. 2. Sustained plasmas above (3407-solid) and below (3410-dashed) the threshold current. (top) injector current; (upper mid) gun voltage; (lower mid) edge poloidal field; (bottom) line-average plasma density.

of the coaxial source by about a factor of three over previous experiments and also widened the radial gap in order to improve the drive efficiency [3]. As a result, significantly more gas input is required for breakdown than in other devices and higher volume-average densities are obtained. We have managed to reduce the required gas input about a factor of four by creating a Penning discharge configuration in the injector.

Following breakdown, the plasma current rises sharply during the formation phase, which in SSPX lasts until about 0.2–0.3 ms. During this time, if the radial current is large enough, the plasma in the injector will accelerate out into the flux conserver region to form a spheromak plasma; the discharge then enters the sustainment phase. If no additional energy is supplied to the injector, then the spheromak disconnects from the injector and the current decays on a timescale consistent with resistive dissipation of the magnetic fields. Given additional energy input from the sustainment bank, the spheromak plasma can be sustained for longer periods. When the radiative losses are low, the decay is very gradual and the discharge usually terminates abruptly due to MHD activity. In dirty plasmas the fields decay steadily in about 0.5 ms.

3. Density control

The performance of spheromaks is sensitive to the plasma density and impurity content since low temperature resistive plasmas have lower confining magnetic fields and corresponding worse confinement than hotter plasmas because the fields are produced by currents in the plasma. A key measure for the spheromak is the quantity I/N (equivalently j/n), which can be related to the ratio of ohmic heating input power to impurity radiation loss power. Various authors have shown [4] this to be equivalent to the Murakami limit for tokamak density. As long as j/n is greater than about 10^{-14} A-m, the ohmic heating will exceed the impurity radiation loss and the electron temperature will be transport limited. The exact value depends on the impurity species, but not very strongly on the impurity concentration since ultimately, both the resistivity and radiative losses scale together with Z_{eff}. Unlike the tokamak, no disruptive density limit is observed in the spheromak; rather, steady state low temperature plasmas with $P_{\mathrm{rad}} \sim P_{\mathrm{ohmic}}$ are produced.

In SSPX, we fuel the plasma by either a static prefill or localized gas puffing in the coaxial injector region about 250 μs before the high voltage is applied; the short delay between gas and voltage helps keep most of the gas up in the injector region. Using a prefill produces spheromaks in which the plasma density is comparable to or higher than the initial neutral gas density (about $4–6 \times 10^{20}$ m^{-3} line average density). Fueling with a short gas pulse just before firing the capacitor banks produces better spheromak plasmas with lower density. The resulting plasma density does not depend strongly on the size of the gas puff and at best, represents only about 50% of it (assuming uniform plasma density in the flux conserver); this is consistent with data from other spheromaks [5]. The density does depend on the peak formation current.

The evolution of the density after formation depends on whether the current in the spheromak (as opposed to the injector current) is sustained or is decaying. Without sustainment, the density will decay rapidly down to a low-level plateau, which is maintained during the spheromak decay. The plateau density is most likely sustained by recycling on the flux conserver wall since it does not depend on the size of the initial gas puff, but does increase with the spheromak field strength (confinement). It is not likely that gas flux through the diagnostic slot plays a significant role, since even with a high prefill pressure of 10^{-3} Torr, the particle flux ($\sim 10^{22}$ atoms/s) is about an order of magnitude less than the loss rate obtained using the 0.5 ms density decay rate at the end of the pulse ($N/\tau_{\mathrm{p}} > 10^{23}$/s).

In sustained spheromaks the density depends strongly on whether the sustaining current is above the spheromak formation threshold, expressed as $\lambda = I/\psi$, where I is the current and ψ is initial vacuum magnetic flux threading the injector region. If below threshold, then there is only a weak dependence on λ since most of the current and plasma remain in the injector region. As the current rises above the threshold, the injector plasma is swept out into the main chamber so that the spheromak density can be maintained at a high level. This behavior is evident from the data of Fig. 2, which shows how the density varies between two discharges which differ only by the initial magnetic flux. For pulse 3407 the flux has been lowered so that the current remains above the 100 kA threshold value, while for 3410 the field has been increased to raise the spheromak threshold current to 190 kA, which is higher than the discharge current. In this case, the density decays away rapidly to values similar to those for decaying spheromaks. A similar threshold current for maintaining spheromak density was observed in the CTX device [6].

Global particle balance studies show that less than 1% of the hydrogen fueling gas is retained in the tungsten walls after a plasma pulse. However, due to the porous nature of the tungsten surface, it takes many minutes for the hydrogen to be pumped away after it diffuses back to the surface and this leads to higher recycling. Therefore, we have used titanium gettering to trap the hydrogen more effectively and reduce the recycling. With gettering, we have lowered the density during the decay phase by almost an order of magnitude so that the value of j/n rose from 10^{-15}

A-m to above 10^{-14} A-m. We have not yet quantified the improvement for sustained plasmas, though j/n is well above 10^{-14} A-m. With gettering, the impurity radiation has dropped significantly, as discussed in the following section.

4. Wall conditioning for impurity control

In SSPX we rely primarily on a 100 μm thick layer of plasma sprayed tungsten on the copper flux conserver to minimize sputtering and reduce impurity concentrations. It turns out, however, that these layers can have up to 20% porosity [7] and can absorb high levels of water. Surface analysis [8] shows concentrations of oxygen and carbon typical of metal surfaces with a measured oxide layer thickness at the surface of 15 nm. Heating of the tungsten during plasma discharges would lead to a slow release of oxygen to the surface of the tungsten.

Initial conditioning consisted of baking to 150°C to remove water and hydrogen, followed by glow discharge cleaning (GDC) to remove surface hydrocarbons and oxides. Prior to bake out, water was the dominant gas in the vacuum chamber representing ~80% of the total pressure. Baking at 150°C for ~100 h reduces the partial pressure of water by an order of magnitude. Hydrogen GDC after the bake produces only a modest further reduction in water content due to the limited pumping speed (500 l/s) and high backfill pressures (30 mTorr) needed to clean the injector region.

Even with baking and GDC the partial pressure of water can increase significantly after the start of plasma operation, sometimes equalling the partial pressure of the hydrogen fuel gas. Other gases (methane, carbon monoxide and carbon dioxide) are also produced during these discharges. Water and volatile gas production during plasma discharges is attributed to the reduction of tungsten compounds (i.e., tungsten oxide) by hydrogen. Further details of the volatile gas production mechanisms and wall conditioning techniques are presented elsewhere [8].

Helium shot conditioning and titanium gettering further reduce impurities and lead to improved plasma performance. The partial pressure of water decreases an order of magnitude after 6–10 helium discharges, as measured with a residual gas analyzer (RGA). Therefore, we typically follow the helium shot conditioning with the application of a 10 nm thick coating of titanium (gettering) onto the plasma facing surfaces of the flux conserver. The gettered surface pumps and buries water and the volatile gas species, thereby reducing the impurity levels in the plasma.

We characterize the impurity radiation, line emissions in the 100–1600 Å spectral region are using an absolutely calibrated SPRED spectrograph [9,10]. The spectrograph has a tangential view of the magnetic axis through the midplane and provides a time-integrated spectrum of the discharge. A pair of monochrometers having a similar view of the plasma as the SPRED provide, time-resolved line emissions in the 300–5500 Å spectral region. Time-resolved intensities of impurity emissions from the UV spectral region are obtained by cross-calibrating the monochrometers with the SPRED instrument. Before helium shot conditioning and gettering, a typical spectrum shows many low-*Z* impurities (carbon, nitrogen and oxygen). Tungsten and other metallic lines have not been observed. After helium shot conditioning and gettering, the Li-like CIV (1550 Å) emission has decreased a factor of 10 and all of the lower charge states of carbon have burned through and are not radiating. Similar behavior is seen for nitrogen. For oxygen, the Li-like OVI (1032, 1038 Å) has increased a factor of three and the Be-Like (OV) lines at 630 Å and 760 Å have decreased; the lower charge states of oxygen have also burned through. The ratio of OVI to OV in the non-gettered discharge is <1, whereas in the case with gettering this ratio is 10 indicating a hotter, cleaner plasma.

Spectroscopic determination of the radiated power and an estimate of the temperature (T_e) in the region of impurity emissions are obtained from the measured line brightness. Taking advantage of the strong temperature dependence of the excitation rates of Li-like transitions in carbon, nitrogen, and oxygen we estimate the electron temperature (T_e) in the ungettered case to be on the order of 25 eV, compared with $T_e \sim$ 50–60 eV after gettering. The total radiated power in this spectral region is also determined from the measured brightness. For the ungettered discharge shown in Fig. 2 (dashed), assuming uniform emissivity over the plasma volume, the total radiated power determined spectroscopically is ~140 MW. With gettering, the radiated power is ~50 MW. For these discharges the total injected power is 480 MW, with 240 MW coupled to the spheromak plasma so that the spectroscopically determined radiated power represents ~70% of the total ohmic input power in the ungettered case and ~20% in the case with gettering.

We have also measured the total radiated energy directly from a bolometer mounted at the midplane with a full horizontal cross-sectional view of the plasma. Fig. 3 shows the fraction of radiated energy to injector input energy for an ensemble of discharges with gettering only and with gettering and helium shot conditioning. Discharges with helium shot conditioning radiate a factor of 4 less energy than discharges with only gettering and the edge poloidal field decay time has increased a factor of 2. Based on the measured resistive decay time [11], we estimate that the average electron temperature is $\geqslant$50 eV compared to ~25 eV for discharges without conditioning (see Fig. 4).

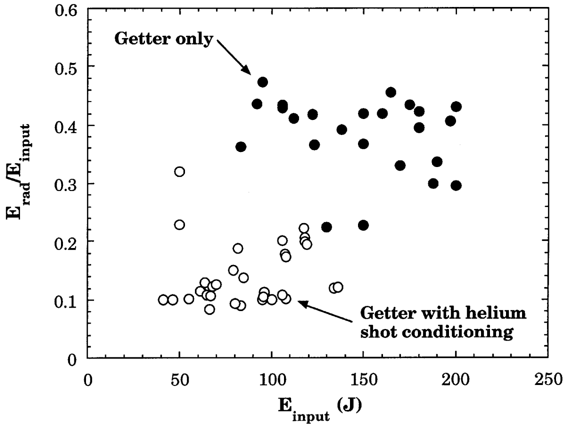

Fig. 3. Fraction of total input energy radiated during discharges with titainium conditioning (●) and with helium discharge and titainium gettering (○). E_{rad} is measured with a thermistor that views a full radial cross-section of the plasma at the midplane. Helium shot conditioning along with gettering decreases the total radiated energy as much as factor of 4.

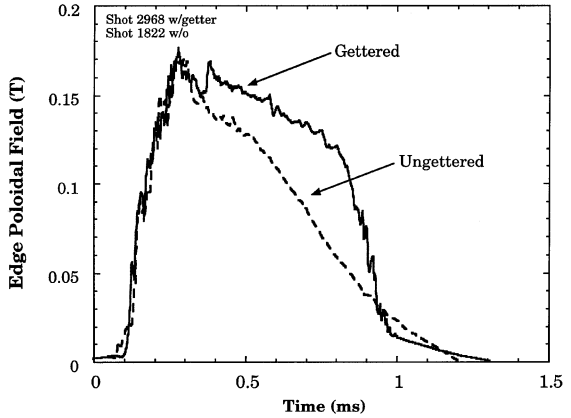

Fig. 4. Edge poloidal field decay times increase a factor of two with gettering and helium shot conditioning.

5. Summary

In this paper we have considered density and impurity control for the SSPX spheromak. Presently, we are relying on a plasma-sprayed tungsten coating to reduce sputtering coupled with baking, hydrogen glow discharge cleaning and titanium gettering to reduce surface impurities and hydrogen recycling. With this combination we have been able to significantly reduce the concentration of carbon and nitrogen in the plasma and have lowered the density by more than a factor of 2. In this way we are able to increase j/n by more than an order of magnitude (to $>10^{-14}$ A-m) and achieve burnout of most low-Z impurities. From the density and impurity behavior of the discharge, we conclude that the injector plasma is the main source of plasma ions and impurities, though most of the impurities are generated during the early formation phase. Future application of boron or lithium coatings is being studied to further decrease the oxygen content in the plasma.

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References

[1] T.K. Fowler, J.S. Hardwick, T.R. Jarboe, Comments Plasma Phys. Controll. Fus. 16 (1994).
[2] E.B. Hooper, J.H. Hammer, C.W. Barnes et al., Fus. Technol. 29 (1996).
[3] M.R. Brown, A. Martin, Fus. Technol. 30 (1996) 300.
[4] S. Ortolani, G. Rostagni, Nucl. Intrum. and Meth. 207 (1983) 353.
[5] W.C. Turner, E.H.A. Granneman, C.W. Hartman et al., J. Appl. Phys. 52 (1981).
[6] C.W. Barnes, T.R. Jarboe, G.L. Marklin et al., Phys. Fluids B 2 (1990).
[7] C. Garcia-Rosales, P. Franzen, H. Plank et al., J. Nucl. Mater. 233–237 (1996) 803.
[8] D. Buchenauer, B.E. Mills, R.D. Wood et al., these proceedings.
[9] B.C. Stratton, R.J. Fonk, K. Ida et al., Rev. Sci. Instrum. 57 (1986) 2043.
[10] R.J. Fonk, A.T. Ramsey, R.V. Yelle, Appl. Optics 21 (1982) 2115.
[11] C.W. Barnes, T.R. Jarboe, I. Henins et al., Nucl. Fus. 24 (1984) 267.