INJECTION AND CAPTURE OF ELECTRONS IN THE UCI STELLATRON

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Summary
An \( L = 2 \) stellatron accelerator is under experimental study. The stellarator field has a strength of up to 10 kG and a rotational transform angle \( \psi \approx 0.1 \). Electrons are injected from either a thermionic emitter or a field-emission cathode placed inside the torus. Typically, a 20 kV, 2-4 \( \mu \)s pulse is applied to the hot cathode which emits \( \approx 3 \) A. A 2 MeV, 200 A beam is formed due to betatron acceleration which immediately follows the injection. The injection voltage is raised to 60 kV with the cold cathode emitting \( \approx 30 \) A for \( \approx 0.4 \) \( \mu \)s. A significant increase in beam current is not observed. A beam in excess of 500 A is generated by injecting plasma and electrons simultaneously at the beginning of the stellarator field and starting the betatron acceleration after the plasma has diffused throughout the torus.

Introduction
There has been increasing interest in cyclic acceleration of multikiloampere electron beams[1]. Old ideas of plasma betatrons have been revived since a 2 kA electron ring was accelerated from 1 MeV to 3.3 MeV[2]. On the other hand, new devices operating with vacuum background have been extensively studied theoretically. A modified betatron[3,4] and stellatron[5] are typical examples of them. While many advantages are claimed with these innovations, some problems are also introduced. One of the major problems is electron trapping. An experiment has been run on a modified betatron[6] which was converted to a stellatron last year. In this paper, we report on the dependency of beam current upon injection parameters in the UCI stellatron.

Apparatus
The schematic of the experimental apparatus is shown in Fig. 1(a). A pair of vertical field coils and the center solenoid produce a betatron field that allows the control of \( \langle \psi \rangle / B \). Here, \( B \) is the local field strength and \( \langle \psi \rangle \) is the average field inside the electron orbit. The toroidal magnetic field is generated by 24 equally separated coils and has an azimuthal uniformity of \( \pm 2\% \) on the minor axis of the torus. Four helical windings are nested inside the toroidal field coils at \( 7.5 \) cm from the minor axis of the torus. They are connected so that the current alternates in adjacent windings. Parameters of these fields are summarized below.

<table>
<thead>
<tr>
<th>Field Type</th>
<th>Rise Time</th>
<th>Peak Field</th>
<th>Field Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical field</td>
<td>100 ( \mu )s (0 to peak)</td>
<td>0.4 kG on the minor axis</td>
<td>0.3</td>
</tr>
<tr>
<td>Toroidal field</td>
<td>80 ( \mu )s (0 to peak)</td>
<td>0.8 kG on the minor axis</td>
<td></td>
</tr>
<tr>
<td>Rotating quadrupole</td>
<td>90 ( \mu )s (0 to peak)</td>
<td>30 kA</td>
<td></td>
</tr>
</tbody>
</table>

The toroidal and quadrupole fields yield an \( L = 2 \), \( m = 12 \) stellarator field. Here, \( \lambda \) is the pole number and \( m \) is the azimuthal mode number. The rotational transform angle \( \psi \) is typically 0.1. Combined with the vertical field, the quadrupole field gives an alternating field index which is as large as 100 at \( B = 100 \) G and a field generated by wires wound around the torus which is used to artificially spill the beam electrons.

The top view of the torus is shown in Fig. 1(b). The torus is made of glass and lined with stainless steel mesh. The major and minor radii are 41 cm and 4 cm, respectively. The torus is evacuated with a cryogenic pump. Three types of electron injectors are illustrated in Fig. 2. The cathode of the thermionic injector (Fig 2(a)) is a stranded wire coated with a 50%-50% mixture of zirconium carbide and lanthanum hexaboride. A variable width negative pulse of up to 30 kV is applied to it. Figure 2(b) shows a cold cathode with carbon fibers as the emitter[7]. The emission initiates when a negative pulse of 30 kV is

FIG. 1. (a) Schematic of UCI stellatron and (b) Top view of the torus.

FIG. 2. Electron injector.
applied. In Fig. 2(c), Thornel fibers are embedded in a 5 mm diam hole to assure directionality and to restrict the emissive area. The pulse generator used for the cold cathode consists of a pulse forming network and a pulse transformer. The injection voltage and the emission current are \( \lesssim 60 \text{ kV} \) and \( \lesssim 30 \text{ A} \), respectively. The effective duration of injection is typically 0.4 \( \mu \text{s} \). A small plasma source is also installed in the torus: either a flashboard or a tip of 1/4" diam solid coaxial cable. It is driven by a 0.1 \( \mu \text{F} \) capacitor at a charging voltage of \( \sim 5 \text{ kV} \). Typically, the current flows for 5 \( \mu \text{s} \) (a half cycle of the sinusoidal wave). Accelerated electron beams are diagnosed with a Rogowski loop and various kinds of X-ray detectors. An electrostatic probe monitors oscillations and a plane probe collects charged particles impinging on it.

**Experimental Results**

(a) General Features

![Diagram](image)

**FIG. 3.** Typical time sequence of operation and signals.

Figure 3 shows the typical time sequence of operation and signals. Usually, the toroidal magnetic field and the helical current start simultaneously. Timing of the vertical field, and also of the injection, is variable with respect to the start of the stellarator field. The beam current increases with time because of increasing electron velocity. As the velocity approaches that of light, the beam signal becomes flat. The decrease in the beam current is due to loss of electrons. It is accompanied by the generation of X-rays at the injector. The behavior of the beam current is nearly independent of the beam intensity, suggesting that the electron loss is essentially a single particle process. The beam is disrupted at any instant when the spiller field is used. This is shown by dotted lines in Fig. 3.

Electrostatic oscillations are observed during the early period of acceleration. The frequency is slightly smaller than that of electron gyration around the torus. Electron gyration is calculated assuming that electrons orbit on the major radius of the torus and are accelerated by the measured one-turn loop voltage. Occasionally a steep descent of the beam current occurs, terminating the oscillations.

(b) Thermionic injection

An electron beam is produced by emitting 2 A or more from the cathode and applying the betatron acceleration. If the injection pulse is too short, naturally the beam is small. On the other hand, a long pulse causes disruption of the beam. The thermionic emitter is operated, near the start of the vertical field, for 1 - 5 \( \mu \text{s} \). Figure 4 shows the beam current versus the relative timing \( \Delta T \) (the delay of the injection pulse from the start of the vertical field). It is seen that electrons are trapped in the stellarator field and stay there for several \( \mu \text{s} \) without the vertical field.

The beam current hardly changes when the injection voltage is varied from 15 to 28 kV. Data are plotted as group I in Fig. 5. Conditions to observe a 200 A beam include the following: the cathode is almost perpendicular to the median plane, the cathode sticks into the torus approximately 2 cm, and the rotational transform angle \( \gamma = 0.1 - 0.12 \).

![Graph](image)

**FIG. 4.** Beam current dependence on injection timing.

![Graph](image)

**FIG. 5.** Beam current dependence on injection voltage.

(c) Field emission cathode

A similar beam is generated with a cold cathode injector. The screen liner serves as the anode. None of the additional anode structures placed closer
to the cathode helps to increase the beam current. The beam is quite weak if breakdown, detected by either the overshoot or ringing of the emission, happens.

The data group II in Fig. 5 is obtained with a cathode shown in Fig. 7(b). Again, the beam current is insensitive to the injection voltage. Here, the emitting side of the cathode points antiparallel to the direction of both the toroidal magnetic field and betatron acceleration. When this happens, the beam current is independent of the direction of acceleration, i.e. clockwise or anticlockwise in Fig. 1(b). The beam in Fig. 5(b) is obtained when the magnetic field is antiparallel to the betatron acceleration. The quadrupole field points outward at the cathode position. If the injector and/or the helical current is reversed, the beam current becomes small, as shown by group IV in Fig. 5. The same figure indicates that the injector geometry influences the beam current. 250 A is reached with a small cathode by adjusting its angle as well as its position. When the betatron acceleration is not applied, the current monitored by the Rogowski loop does not exceed 10 A.

(d) Plasma-assisted beam formation

A runaway process from a tenuous plasma also yields an accelerated beam. In this scheme of operation, a small amount of plasma is injected at the beginning of the stellarator field. (If the plasma source is operated after the toroidal field has reached a few kV, the plasma betatron mode arises and generates a large current and weak X-rays.) The plasma front propagates around to the other side of the torus in approximately 20 μs. The vertical field is applied 20 - 40 μs after this. An accelerated beam of up to 300 A is observed.

The beam current is enhanced by injecting electrons in addition to the plasma. The two sources are located azimuthally apart (Fig. 1(b)), but at the same radial position. The electron injector, the same cold cathode as in the previous section, is operated during the plasma injection. The beam current goes over 500 A, as shown by curve A in Fig. 6. At this level however, the beam current tends to behave as curve C in Fig. 6; the current rises faster and drops sharply ~ 20 μs after the start of acceleration. X-rays appear, corresponding to the descent of the beam signal. Their intensity changes in conjunction with the beam current. The plane probe detects electrons during the electron injection, at the start of acceleration and also when the beam current drops.

FIG. 6. Time dependence of beam current at simultaneous injection of plasma and electrons.

References


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