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Injection, trapping, and acceleration of an electron beam in a stellatron accelerator

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The UCI modified betatron [Phys. Rev. Lett. **53**, 266 (1984)] was converted into a stellatron accelerator by the addition of helical quadrupole coils to the betatron configuration. An experimental study of the injection, trapping, acceleration, and disruption of a beam in this apparatus has been conducted. The stellarator field applied was of up to 10 kG and with a rotational transform of $\tau \approx 0.1-0.15$. Electrons were injected from a thermionic emitter typically operated by applying 20 kV, 2–4 μ sec pulses to the hot cathode, which emitted ~ 3 A. A beam of ~ 200 A was trapped in the torus and accelerated by the betatron field applied immediately after the injection. The beam life was extended by increasing the toroidal field. The beam current suffered a partial disruption after it reached its peak value. After that the beam lost electrons gradually, accompanied by generation of x rays, until the entire beam was lost close to the peak of the accelerating betatron field. Electron energies of up to ~ 4 MeV were reached. The dependence of the beam current and its lifetime, upon the applied fields and injection conditions, was explored.

I. INTRODUCTION

There has been considerable interest during the last few years in accelerators capable of delivering intense electron beams at high energies.¹ The modified betatron^{2,3} and the stellatron⁴ are two compact configurations of such accelerators and extensive theoretical studies²⁻⁹ have been carried out exploring their parameters.

Experiments have been conducted on the modified betatron at the University of California, Irvine,¹⁰ which accelerated a circulating beam of 200 A to ~ 1.0 MeV (starting with ~ 20 keV electrons). A larger device is under study at the Naval Research Laboratory.¹¹

The UCI modified betatron was converted to an $l = 2$ stellatron⁴ by the addition of four helical windings around the torus. It was expected to stabilize the beam against the drift to the torus wall and hence to permit acceleration to higher energies.

With the stellatron, a beam current of ~ 200 A was trapped and electrons were accelerated up to ~ 4.0 MeV when a hot cathode injection was employed. This was achieved because the beam lasted for a longer time in the chamber and continued to be accelerated.

Further experiments on the stellatron included different injection methods, such as the use of a cold cathode injector and/or plasma guns, and some experiments on beam extraction. They are described elsewhere.¹²⁻¹⁴

In Sec. II of this paper we describe the apparatus and the diagnostics used in the experiment. In Sec. III the experimental results are presented, in particular the dependence of the beam current, the beam life, and the electron energies upon the experimental parameters is discussed. The experiment is summarized in Sec. IV.

II. THE EXPERIMENTAL SETUP

A. Apparatus

As mentioned before, the UCI experimental stellatron is based on the UCI modified betatron.¹⁰ Figure 1 is a schematic drawing of the stellatron, and Table I summarizes the major parameters of the apparatus.

A pair of Helmholtz coils together with the center solenoid produce the vertical betatron field and the magnetic flux needed for the acceleration. They also facilitate control of $\langle B \rangle / B$. Here, B is the local field strength at the electron orbit and $\langle B \rangle$ is the average field inside the the electron orbit.

The toroidal magnetic field is generated by a set of 24 coils equally separated around the major diameter of the glass torus.

An additional set of four helical windings completes the configuration of the stellatron. The helical windings, made of $\frac{1}{4}$ in. diam Phosphor-bronze stranded wire, are nested inside the toroidal field coils at 7.5 cm from the minor axis. The wires are connected in series so that the current alternates in adjacent windings. They produce, together with the toroidal field, a stellarator-type field with $l = 2$, $m = 12$, where l and m are the pole number and the azimuthal mode number, respectively.

The vacuum chamber is a glass torus, made of two halves with rubber O-rings in between. It is evacuated with a cryogenic pump. A stainless steel screen liner inside the torus provides a conductive wall to the apparatus.

The electron injector used in the experiments described here employs a hot cathode. A negative voltage pulse, of up to 30 kV and a variable width, was applied to it. Figure 2 is a drawing of the injector. The cathode is a stranded tantalum wire coated by a 50%–50% mixture of zirconium carbide and lanthanum hexaboride.

The different coil sets can be activated independently.

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FIG. 1. A schematic drawing of the UCI stellatron.

Their relative triggering time is controlled and set through delayed triggering units.

B. Diagnostics

The diagnostics of the experiment included $\vec{B}$ loops, a Rogowski coil to measure the beam current, x-ray detectors, a pinhole x-ray camera, and an electrostatic probe. The $\vec{B}$ loops were used to monitor the magnetic field. Usually, integrated signals were recorded, with an integration time constant long enough with respect to the measured pulse.

The beam current was measured in the experiment by an air core Rogowski coil. It had about 340 rectangular turns wound back and forth on a polycarbonate frame, made of two halves and placed around the minor radius of the glass torus. The signal was integrated by an external RC integrator with a time constant of $410 \mu\text{sec}$. Its sensitivity had been calculated and measured by comparison to commercial probes.

The Rogowski coil operated in the experiment in the vicinity of high magnetic fields, which caused a large pickup signal in the probe. A great part of this spurious signal was subtracted by the use of small compensation loops that picked up the field and were adjusted to cancel the pickup of the Rogowski coil. However, it did not cancel the Rogowski coil pickup completely. Therefore, in order to measure the beam current, the machine was usually operated twice under the same conditions except that in the second discharge, only the magnetic fields were applied while the injector was not fired; the pickup signal was recorded and could be subtracted from the real signal.

A few x-ray detectors were used to monitor the x rays produced when the beam hit the wall or the injector. A 1.5 in. $\times$ 2 in. NaI(Tl) detector attached to a 10 stage 2 in. photomultiplier tube, and one or two NE102A plastic scintillators attached to similar PMT's had been used regularly during the experiments. The plastic scintillators have better time response; hence they were used whenever timing of the

TABLE I. Major parameters of the UCI stellatron.

Vacuum chamber (glass torus)	
Major radius	41 cm
Minor radius	4 cm
Screen liner	Stainless steel 12 mesh/inch
Vacuum	$\sim 10^{-7}$ torr
Electron injector (thermionic electron source)	
Filament	~ 4 cm long
Voltage	0–30 kV
Pulse width	0–5 μsec
Emission current	3–4 A (typically)
Toroidal field	
Rise time	80 μsec (0 to peak)
Peak field	12 kg (on the minor axis)
Azimuthal uniformity	$< \pm 2\%$ (measured)
Vertical field	
Rise time	$\sim 100 \mu\text{sec}$ (0 to peak)
Peak field	0.5 kG (on the minor axis)
Field index	0.3–0.8 (inside the torus)
Helical windings field	
Rise time	90 μsec (0 to peak)
Peak current	30 kA
l	2 (quadrupole)
Periods around the torus	6
τ	0.1 (typically)

x rays was important. The PMT's output was usually fed to an emitter follower preamplifier that drove a 50Ω cable, and was recorded on an oscilloscope. The detectors were placed at a distance of 2–5 m from the glass torus, shielded by a cylindrical lead housing ~ 5 cm thick. A small PIN silicon x-ray diode was used as another x-ray detector. It was mounted, in a $\frac{7}{8}$ in. hole in a lead brick that served as a collimator, at ~ 15 cm from the glass torus. This detector was used mainly to get spatial information about the x-ray source.

An electrostatic probe^{15,16} measured the currents induced by the motion of the electron beam in the chamber, i.e., the electrostatic oscillations of the beam. The probe was made of a 2 cm $\times$ 3 cm copper plate, placed in an opening in the screen liner and connected through a 50Ω coaxial cable to an oscilloscope.

III. EXPERIMENTAL RESULTS

A. General features

An example of the time sequence of the stellatron operation is given in Fig. 3.

Usually the toroidal and helical coils were activated simultaneously while the timing of the injector and the vertical field was variable with respect to the start of the stellatron field. The beam current increased, as the electrons gained velocity, until it reached a maximum value and became flat, when the velocity approached the speed of light. A decrease in the beam current as a result of loss of beam electrons was then observed, accompanied by x-ray generation. An x-ray pulse that appeared later in time indicated the termination of the beam. Electrostatic oscillations were observed during the early period of the acceleration, occasionally followed by a steep descent of the beam current after which these oscillations damped.

FIG. 2. The hot cathode electron injector. (a) front view, (b) side view, and (c) position inside the torus.

The details about the injection and trapping process, the acceleration and the loss of the beam, and their dependence on the experimental parameters are discussed hereafter.

B. Injection and trapping

A beam was formed and sustained in the stellatron when the thermionic injector was activated for a short pulse of 1–5 μsec , near the start of the vertical magnetic field. A long pulse injection (or a continuous injection as in the case of the UCI modified betatron experiment¹⁰) caused an early disruption of the beam.

In Fig. 4, the injector emission current, the start of the vertical field, and the x-ray signals are shown for two cases. In the first one, the injection and the vertical field started almost together while, in the second, the injection started about 12 μsec before the vertical field. A beam was formed and sustained even if the injection pulse ended before the vertical field started. This is seen in Fig. 4(b), where an x-ray signal, measured about 60 μsec after the start of the vertical field, indicates the formation of a beam although the injection in this case ended about 8 μsec before the vertical field

started. This was observed also for longer delays between the start of the injection and the vertical field and it evidently showed that electron trapping occurred without the presence of the vertical field.

It was also noticed that the stellarator field (toroidal and helical) did not need to be in the rising phase at the time of the injection for the trapping to take place, but it had to be above a certain value. Electrons were trapped and accelerated in cases when the injection and the vertical field were fired at the peak of the stellarator field or even when it was in its declining phase. However, maximum beam current and maximum beam life were achieved when the injection and the vertical field were activated when the stellarator field reached about 70% of its peak value. As mentioned before, this was not a severe condition for trapping.

C. Beam current formation and acceleration

The beam current, measured with the Rogowski coil, is shown in Fig. 5, where the two traces are the beam current and the residual pickup of the magnetic field of the machine. The difference between the two traces is the actual beam current shown in Fig. 5(b). The increase of the current follows the increase in $\beta(t)$, the electron velocity, with time

FIG. 3. Typical time sequence of the operation of the stellatron and of the appearance of the signals.

Upper Trace: Emission Current
Lower Trace: B_V X-Ray Signals

FIG. 4. The timing of the injection and the start of the vertical field followed by the generated x-ray signal for two cases. (a) Injection and vertical field start together. (b) Injection starts $\sim 12 \mu\text{sec}$ before the vertical field.

FIG. 5. A beam current oscillogram as measured by the Rogowski coil. (a) Upper trace: beam current and noise pickup (95 A/div, 20 μsec/div) and lower trace: noise pickup (95 A/div, 20 μsec/div); (b) the net beam current—the difference between the above traces.

[here $\beta(t) = v(t)/c$, where v is the electron's velocity and c is the speed of light] until the velocity approaches c .

The start of the beam, measured by the Rogowski coil, was found to occur at different values of B_v (the vertical magnetic field) in the range 5 to 25 G while the matched field for 20 keV electrons was 12 G. Hence, trapping and accelerating electrons occurred despite the fact that there was a momentum mismatch between the electrons and the vertical field at injection. A significant momentum mismatch continued to exist during the acceleration because the betatron condition ($\langle B_v \rangle / B_v = 2$) was violated in many of the measured cases. The conditions for operation were chosen so that the beam life, determined from the time the x-ray signal appeared, was the longest. It was found that $\langle B_v \rangle / B_v$ was ≈ 2.35 on the minor axis of the torus for this to happen. Under these conditions the stellarator-type field contained the electron beam and could tolerate the momentum mismatch.

On many occasions electrostatic oscillations appeared close to the time the beam current reached its peak value. With some experimental parameters the growth of the oscillations was followed by a decrease in the beam current (loss of electrons). As the current decreased the oscillations damped and a smaller beam continued to be accelerated. The beam current signal became flat and later it started to decrease because of a loss of electrons. This was accompanied by the generation of x rays, from which the timing and the place of the beam disruption was learned. The frequency of the oscillations followed linearly the gyration frequency of the electrons around the major axis of the torus. The gyration frequency was calculated assuming that the electrons were accelerated by the measured one-turn loop voltage. The oscillation frequency was slightly smaller (by about 10%) than the gyration frequency.

D. Beam current dependence on the experimental parameters

1. Beam current dependence on the injection voltage

Using the hot cathode injector, the injection voltage was changed in the range of 15–28 kV without noticeable change in the maximum beam current. This measurement was repeated for a few sets of the other parameters such as the strength of the vertical magnetic field and the type of the injector. This is shown in Fig. 6. As long as only the injector voltage was changed the peak current hardly changed. This might indicate that the limitation on the beam current was probably not the electrostatic limit.¹⁷

2. Beam current and the timing of the injection

Figure 7 shows an example of the beam current versus the relative timing ΔT (the delay of the injector pulse with respect to the vertical field). It seemed that maximum current was achieved if the injector started together with or up to 4 μsec after, the vertical field had started. Similar behavior was seen on some other measurements in which some of the experimental parameters, such as the maximum B_v or the injector geometry, were different.

From these results it was also apparent that electrons were trapped in the stellarator field and stayed there for several microseconds with no need to apply the vertical field, as mentioned above.

3. The injector position inside the torus

Experiments had been conducted with different types of injectors, either nondirectional or unidirectional, and the results were similar as to the beam current and beam lifetime. However, changing the position of the hot filament inside the torus affected the accelerated beam current in the torus. Figure 8 shows the peak current achieved with three injec-

FIG. 6. Peak beam current as a function of injection voltage for a few sets of experimental parameters.

FIG. 7. Dependence of peak beam current on the injection timing. Here, ΔT is the delay of the start of the vertical field relative to the injection pulse.

tors, which were mainly different from each other by the distance of the filament from the screen liner. The parameters of the experiment were the same for all injectors except for the timing between the injector voltage and B_v , which was optimized for each case to get maximum current. It is apparent that the beam current reached about 200 A when the cathode projected about 2 cm into the torus.

Another effect related to the position of the injector was that the current was larger (by about 20%) when the filament was almost perpendicular to the median plane of the torus, compared to the case where it was in the plane.

FIG. 8. Beam current dependence on the position of the injector's cathode inside the torus. Here, X is the distance of the cathode from the screen liner.

4. The beam current and the stellarator field

The beam current changed as the toroidal and helical fields were changed in the apparatus. These parameters were scanned as follows.

(i) Electrons were injected into different stellarator fields by changing the relative timing between the injection and the toroidal and helical fields, while the fields were in their rising phase. The beam current was measured. It was found, as mentioned earlier, that for an early activation of the injector, when the toroidal field reached only $\sim 3-4$ kG, the trapped beam was much poorer than for an injection into a toroidal field of ~ 6 kG or more. Injection into larger fields did not improve the beam significantly. This implies that the stellarator field should be above a certain value at the time of the injection in order to get maximum beam current.

(ii) The timing of the injection and the start of the vertical field with respect to the stellarator field was kept constant, while the amplitude of the toroidal field and the current in the helical windings were changed over a moderate range of each parameter. The beam current and the x-ray signal were recorded. It was found that as the toroidal field was increased the electron beam lasted longer (for a given helical field). It was also seen that if the toroidal field was not changed (but it was ~ 9.0 kG or more at its peak value) then an increase of the helical field, so that the rotational transform $\epsilon \geq 0.1$, would cause an increase in the accelerated beam current. This is shown in Fig. 9 where the accelerated beam current is plotted versus the rotational transform for a variety of other experimental parameters. The toroidal field was the same (~ 9.4 kG at the peak) in all the cases shown in this figure.

(iii) As mentioned before, the four helical windings were connected in series and carried the same current. The

FIG. 9. Beam current dependence upon rotational transform, for some different experimental settings.

direction of the current could be changed in successive wires by changing the connections on the capacitor bank. By doing this the helical field phase rotated by about 90° . This fact was meaningful mostly at the injector position, since in one case the electrons at the injector felt a focusing force and in the other case a defocusing force. This can be seen in Fig. 9 when comparing the (O) data points to the (X) data points, where the only difference between the operating conditions was the reverse in direction of the current in the helical windings. It was clear that the trapped current was larger by up to a factor of 2 when the injector position was closer to the focusing plane than to the defocusing plane. A simulation of an electron beam in a field similar to the one in this experiment was carried out by Hughes and Godfrey.¹⁸ Their simulation predicted that the electron oscillations had a much smaller amplitude when they were injected into a focusing stellarator field, which is in agreement with the above results.

E. Beam disruption—timing and position

As mentioned before, the beam current suffered a loss of electrons shortly after it reached its peak value. There was a sudden decrease in the beam current that was observed in some cases, while in others the beam current became flat with no significant loss of electrons. The sudden drop in the current was accompanied by electrostatic oscillations. After that, the beam lost electrons gradually. This loss started at about 40–50 μsec after the start of the beam although earlier or later starts had also been observed. The x-ray pulse was detected simultaneously with the loss of electrons and usually the peak of the x-ray signal was measured toward the end of the beam life.

In Fig. 10, the vertical magnetic field is plotted versus time for a few experimental settings, and the time when the peak of the x-ray signal appeared is marked. It is seen that as the maximum of the vertical field was higher, the beam ter-

FIG. 10. Timing of the beam disruption on some vertical field slopes.

minated earlier. However, unlike the results of the modified betatron experiment,¹⁰ the value of B_v at the termination time was higher on the steeper slope. In the modified betatron experiment, the beam disrupted at a constant value of B_v . Since the change of the vertical field was proportional, in both experiments, to the change in the magnetic flux, the disruption of the beam in the stellarator experiment at higher B_v showed that the electrons reached higher energy before disruption.

The x-ray detectors were used to locate the spatial position of the x-ray source. Measurements with radiation dosimeters, which were distributed around the torus close to the glass chamber, helped to determine roughly the locations of the x-ray sources. Further measurements with a collimated silicon PIN detector and x-ray pinhole camera photography located the sources more accurately. It was found that the beam was skimmed off at the injector gradually. The injector was the deepest obstacle inside the torus and it seemed that the major radius of the beam increased during acceleration and electrons hit the injector. There was another location where electrons hit the wall. It was determined by the above measurements, but it was later related to a field error in the toroidal field near that point. When the field error was removed the beam disruption occurred solely at the injector.

F. Electron energy

The electron energy in the stellarator experiment was estimated from measurements of the one-turn loop voltage and from the time the beam current terminated as seen through the x-ray measurement. The energy gained by the electrons during their acceleration was calculated from the known one-turn voltage as a function of time and is plotted in Fig. 11. There are two slopes for each setting of the vertical

FIG. 11. Electron energy as estimated from the one-turn loop voltage as a function of time, marked with the beam's termination time.

field, indicating the uncertainty in the energy calculation because of the fact that the initial energy (and hence the momentum) of the electrons when the acceleration starts varies between 0 and the injection energy (20 keV). The timing of the beam termination is marked on the same graph, for different settings of the vertical magnetic field, i.e., for different values of the one-turn voltage. From that figure the maximum energy was estimated to be about 4 MeV. It can also be seen that the energy electron gained in $\sim 50 \mu\text{sec}$ (when the beam current was at about 200 A) was more than 2 MeV.

In the modified betatron experiment,¹⁰ the beam energy was determined by the x-ray absorption method. This method was not applicable in the stellatron experiment mainly because it was found to be inaccurate and less reliable for energies higher than 2 MeV. On the other hand, it was noted that the energy estimated from the one-turn voltage measurements agreed quite well with the absorption curve method. Hence, the energy estimate presented above is quite reliable.

It is seen in Figs. 10 and 11 that beam termination occurred in this experiment close to the maximum of the vertical field. As mentioned before, the energy the electrons reached by termination was higher when the applied accelerating field was larger.

IV. SUMMARY AND DISCUSSION

The conversion of the modified betatron to a stellatron was shown to stabilize the beam inside the torus. Beam currents of ~ 200 A were trapped and accelerated to more than 2 MeV and somewhat smaller currents reached ~ 4 MeV, which was close to the limit of the acceleration capability of the betatron field capacitor bank.

This was accomplished by injection of electrons in short pulses of $1\text{--}5 \mu\text{sec}$ into the stellarator field. Electrons were trapped in the combined toroidal and helical field even when the vertical field was not operated (although the beam current in that case was small and it terminated after a relatively short time). The compression of the electron cloud by the rising toroidal field, as in the inductive charging^{16,17} injection scheme, did not play an important role in the trapping. Electrons were injected into a high toroidal field in this experiment, and trapping was observed even in cases when injection occurred at the peak or at the decreasing phase of the toroidal field.

Unlike in the modified or conventional betatrons, the beam current did not depend, in this experiment, upon the injection voltage (see Fig. 6) in the range 15–30 kV. At low injection voltages (<20 kV) the electron line density, as estimated from the beam current, was close to the electrostatic limit. The sag in the cathode emission current (see Figs. 4 and 7) verifies it. However, when higher injection voltages were applied the maximum beam current did not increase, which indicates that the limitation on the beam current was probably not the electrostatic limit.

It was found that the experimental conditions for the beam current to reach its maximum value were (a) injection should start within less than $4 \mu\text{sec}$ from the start of the vertical field; (b) the cathode was located ~ 2 cm inside the

torus and was almost perpendicular to the median plane; (c) the helical field near the injector was such that a focusing force acted on the electrons in this area; (d) The rotational transform was about $\epsilon = 0.1\text{--}0.15$.

The growth and damping of the electrostatic oscillations, which appeared at the early phase of the beam's life, were accompanied by a moderate drop in the beam current. The appearance of these oscillations indicated that a collective instability might be responsible for that loss of electrons. The main frequency of the oscillations was found to be very close to the gyration frequency and the drop in electron current happened in all cases when the electrons reached 0.6–1.0 MeV. The experimental data we had were not sufficient to determine the type of the instability and a further search for the mechanisms of that loss was needed. However, very similar behavior was observed in later experiments when the stellatron was operated with plasma injectors and accelerated runaway electron beams (of more than 1 kA).¹⁴ Also, measurements of rf radiation spectra were taken in these experiments,¹⁴ which showed that the radiation intensity was peaked at the gyration frequency and its higher harmonics. In both experiments, the drop in beam current occurred at energies close to the negative mass instability threshold energy¹⁸ (which was ~ 900 keV for the parameters of our experiment). The frequency of the oscillations and their appearance close to the threshold energy suggested that the negative mass instability might be the cause for the loss in beam current and the strong oscillations.

The betatron flux condition during most of the acceleration experiments was $\langle B \rangle / B_0 > 2$. It was set this way in order to get higher beam currents and to extend the beam life. The stellarator field tolerated the momentum mismatch caused by this condition. Also, the final beam energy became higher as the maximum B_z was increased (Figs. 10 and 11). These observations may qualitatively be interpreted as follows. Electrons cross integral, half integral, and other orbital resonances successively as B_z increases with time and the electrons are accelerated. Electron loss due to these resonances is reduced by maximizing the acceleration rate, under the condition that the momentum mismatch is tolerated. Hence the beam passes the resonances without losing many electrons when the acceleration rate is high, but the electron loss is supposedly enhanced near the peak of B_z , where the acceleration rate is small. In addition, the resonances become more dangerous there because they take lower order as B_z increases. The x-ray measurements showed that the gradual loss of beam current and its final termination happened mostly at the injector but when a local perturbation (field error) of the toroidal field existed in the machine it caused the beam to hit a small spot on the torus wall. These observations appear to support the above model. The B_z dependence of the beam's lifetime is attributed to the increase of the relevant betatron tunes with increasing of B_z .

The observation that the beam was terminated when a field error was introduced into the machine implied that adding a perturbation to the stellarator field could be considered as a mechanism of beam extraction.

As mentioned, further measurements, such as a systematic study of the oscillations, were needed in order to deter-

mine the mechanism that limited the beam current. Also, a more refined study of the mechanism of injection and trapping would be important to increase the beam current. Further measurements have already been done and are reported separately.¹²⁻¹⁴

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¹⁸See National Technical Information Service Document No. AD-A151 420 (Mission Research Corporation Report No. AMRC-R-655 by T. P. Hughes and B. B. Godfrey, 1984). Copies may be obtained from the National Technical Information Service, Springfield, Virginia 22161. The price is \$18.95 plus a \$3.00 handling fee. All orders must be prepaid.