The NRL Modified Betatron Accelerator[*]

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Abstract

We have improved the lifetime of the electron beam from a few microseconds to over 700 μs by adding strong focusing windings to our original device. The poloidal bounce orbit of the beam immediately after injection is always in the form of an inward spiral, resulting in the trapping of the beam on the minor axis. The trapped beam current is ~1 kA and is accelerated to an energy in excess of 15 MeV from its injection energy of ~0.6 MeV. Beam energy is inferred from the x-ray signal. Further confirmation is via x-ray attenuation measurements and the detection of photoneutrons from the reaction D(γ,n)H. The loss of the electrons appears to be caused by the excitation of cyclotron resonances.

Introduction

Compact electron accelerators with high-current capability have many potential commercial and defense-related applications. They are presently under development in several laboratories.[1-5] Each of these accelerators incorporates some form of strong focusing to improve the current-carrying capability, and recirculates the beam in order to enhance their effective accelerating gradient and hence achieve a more compact size.

Among these accelerators is the modified betatron[6-8] which is currently under investigation at the University of California, Irvine[2] and also at the Naval Research Laboratory[1] (NRL). In its original form[9] the modified betatron utilizes only two magnetic fields, namely, the strong toroidal magnetic field and the betatron field. The latter is responsible for accelerating the electron beam.

After extensive studies on the NRL device, a substantial amount of information on various critical physics issues of the accelerator concept has been collected. The beam lifetime in the device has been found to be limited to a few microseconds for a wide range of parameters. In order to improve the beam lifetime, the decision was made to install a set of strong focusing windings to the existing experiment. The Stellarator[10] winding configuration (in the form of a rotating magnetic quadrupole) was chosen over the Torsatron[11] configuration (two twisted windings carrying current in the same direction) because it requires less current, produces only a small net vertical field and is compatible with our contemplated extraction scheme.[12,13]

This paper describes the NRL modified betatron accelerator in its latest configuration and presents experimental results obtained after the installation of the strong focusing windings.

Description of the Experiment

The NRL modified betatron comprises a precision electron beam injector, a toroidal vacuum chamber and three different external magnetic fields. The vertical betatron field is a function of time but the toroidal and the strong focusing magnetic fields vary only slightly during the acceleration of the electron ring. As shown in Fig. 1, the coils that generate these three fields are supported by a stiff structure in the form of an equilaterial triangle with truncated vertices. A cross-sectional view showing the relative locations of the different sets of coil and the vacuum chamber is depicted in Fig. 2.

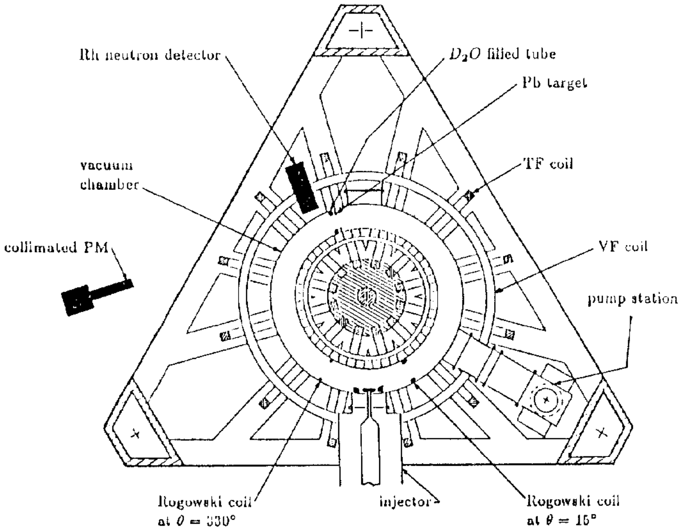


FIG. 1: Schematic plan view of the NRL Modified Betatron.

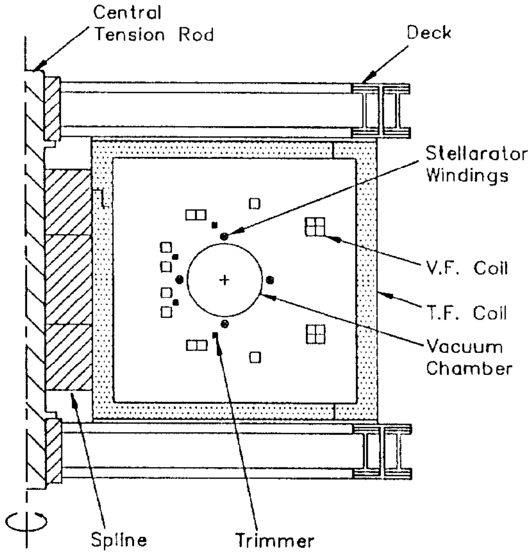


FIG. 2: Cross-sectional view showing the vertical field (V.F.), toroidal field (T.F.) stellarator windings and other structural components.

The betatron[14] magnetic field controls mainly the major radius of the gyrating electron ring and is produced by 18 air core, circular coils connected in series.

The ratio of the average vertical magnetic field $\langle B_z \rangle$ to the local vertical magnetic field on the minor axis B_{z0} can be adjusted over a reasonably broad range. The field index in the region of interest typically ranges from 0.4 to 0.8 which is found to be in very good agreement with the predictions of EFFI,[15] a static 3-D magnetic field code.

Experimental Results

The transverse motion of the beam is studied by monitoring the light emitted from a 10-μm-thick polycarbonate foil that is stretched across the minor cross section of the vacuum chamber[1]. This foil is coated with a thin film of graphite on the upstream side to avoid electrostatic charging and extraneous light from sources behind it. Fig. 3 shows two open shutter photographs of the light emitted as the beam passes through the foil. The light spots near the edges of the photograph are position fiducials produced by a ring of light emitting diodes located approximately 0.7 cm from the vacuum chamber wall. Reflections from the wall are also noticeable near the upper edge of the photograph.

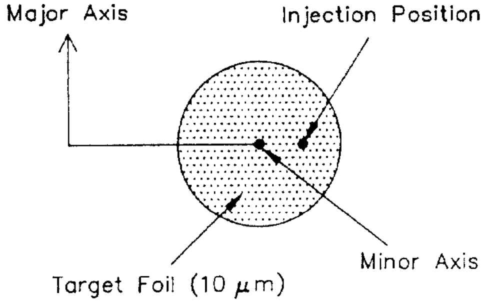
For several combinations of injection parameters the beam consistently spirals from the injection position to the minor axis and is trapped. The transit time of the beam to the minor axis is typically less than 0.5 μsec. In shot #5172 both the beam current and B_θ are low and thus the bounce frequency is high. As the beam spirals from the diode to the minor axis it creates distinct light spots as it passes through the foil. By increasing the beam current and B_θ the bounce frequency is reduced and thus the light spots start to overlap and the spiral becomes continuous as in shot #5214.

The trapping mechanism is presently unknown but is under investigation. A possible candidate is the wall resistivity. However the predicted decay rate from the linear theory[16] for the parameters of the experiment is between 10-20 μsec, i.e., too long to explain the experimental results.

The circulating electron ring current is monitored with two Rogowski coils that are located inside the vacuum chamber. A typical waveform is shown in Fig. 4. Although some losses occur immediately after injection, the circulating current remains practically constant during the first 10 μs. Observations are limited to 10 μs by the signal level and the passive integrator. Active integrators have been designed and built. They are presently being installed, along with our strong focusing upgrade, to extend the current diagnostic.

In the results reported here, the injected electron beam is produced by a diode with a 1.3-cm-diameter carbon cathode disk that is matched to a 1.3-cm-diameter anode aperture. The maximum trapped current is ~1 kA.

The ring lifetime is inferred from the x-rays produced when the beam strikes a 2.5 cm wide, 1 mm thick lead limiter. The x-rays are monitored by a collimated x-ray detector (scintillator/photomultiplier tube) that is housed inside a lead box. The x-rays enter the scintillator through a 1.94 cm diameter hole and the detector is located 10.8 m from the target. A typical waveform of the x-ray monitor is shown in Fig. 5. From the value of B_z field it can be easily computed that the main peak of the x-ray signal corresponds to a particle energy in excess of 15 MeV.



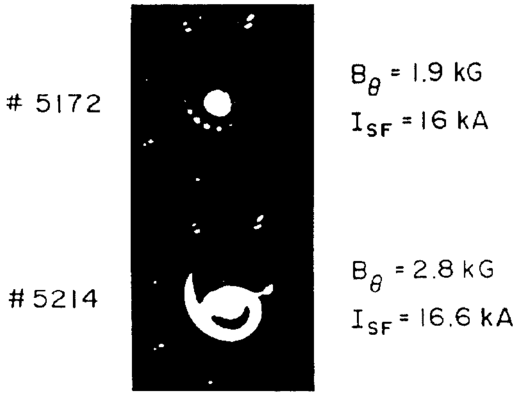


FIG. 3: Open-shutter photographs of the light emitted when the beam passes a 10-μm-thick foil.

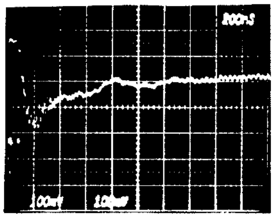


FIG. 4: Current trace from a Rogowski coil located 15° downstream from the diode. 525 A/div.

The spiky shape of the x-ray signal and therefore the beam loss is consistent with the excitation of the cyclotron resonances[17,18] which occur when the ratio $B_\theta/B_z = (2\ell^2 - 1)/2\ell$ where ℓ is an integer. For ℓ values relevant to the data presented in this paper, $\ell \approx B_\theta/B_z$. A plot of B_θ/B_z vs. time is shown in Fig. 5.

The x-ray signal has been studied with the usual attenuation technique. A layer of lead more than 5-cm thick is needed to completely eliminate the signal. A 1.3 cm thick layer does not have any effect on the signal except on the initial spike that is due to the injected beam. In addition to the x-ray attenuation technique the beam acceleration has been confirmed with the photoneutrons produced from the D(γ, n)H reaction. A plastic tube in the form of a ring containing heavy water was inserted behind the limiter. The photons produced on the target photodisintegrate the deuterium and produce neutrons that are monitored with a rhodium activation detector.[19] The number of counts measured during the first minute exceeds seven standard deviations.

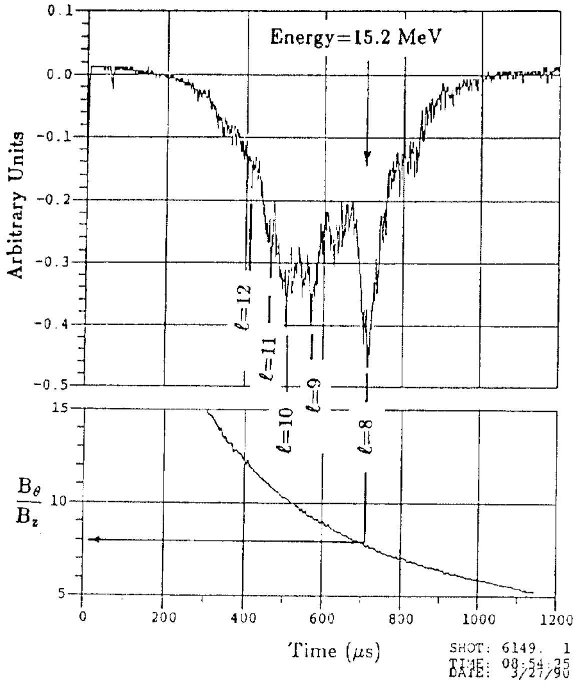


FIG. 5: Top trace is the output of the x-ray detector vs time and the bottom trace is B_θ/B_z vs time.

Summary

We have successfully trapped ~1 kA of the injected beam. The temporal behavior of the x-ray signal is consistent with the excitation of cyclotron resonances. The energy of the electrons at the time of beam loss is over 15 MeV. The strong focusing system is presently being upgraded and work on beam extraction is in progress.

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