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THE RACETRACK INDUCTION ACCELERATOR

C.W. Roberson
Naval Research Laboratory
Washington, DC 20375

A racetrack induction accelerator is a new high current-high voltage cyclic accelerator using a long pulse induction module from an induction linac. The geometry is shown in figure 1. The geometry is an oval racetrack shaped toroid similar to a Model C Stellarator[1]. In one leg of the racetrack a 2 microsecond long linear induction accelerator module is inserted[2]. The voltage gain of a particle as it goes around the racetrack is approximately

$$V_{final} = \frac{T}{\tau} V_m$$

Where T is the time the induction module is on, τ is the time it takes an electron to go around the racetrack and V_m is the voltage gain per pass through the induction module. For the racetrack shown in figure 1, τ = 42 ns, T = 2 μs at 400-500 kV, then the voltage gain can be as high as 18-23 MeV. Since the beam goes around 47 times, gaining the energy across the gaps each time we can increase the beam energy to 20 MeV in only 2 microseconds with what was previously a one half MeV single pass module. This is done by taking advantage of the relative time it takes electrons to go around the racetrack as compared to the time the voltage is on in the induction module.

The linear induction module is designed to operate with a 2 kA load. This high current poses a problem for the transport of the beam around the racetrack. A beam can be transported along an axial magnetic field if[3]

$$n < \gamma B^2/8\pi^2 mc^2$$

where n is the beam density, B is the magnetic field, γ the relativistic factor, m the electron mass and c the speed of light. A 2.5 kG magnetic field is sufficient to stabilize a 1 kA/cm^2 beam density when the beam energy is 1 MeV. This relationship is approximately correct in the racetrack configuration, however other problems may be encountered as a result of the cyclic motion.

Some of the toroidal field coils are shown in figure 1. The use of toroidal magnetic fields in the accelerator introduces an new effect; vertical particle drifts in the bends of the racetrack. This in fact is the major problem that must be solved for the racetrack to operate as a high current accelerator.

There are distinct drifts that affect the stability of the beam in the bends. The $\bar{E} \times \bar{B}$ drift arising from the self electric field of the beam, the drift due to the gradient of the magnetic field in the radial direction and the drift due to the curvature of the magnetic field. If the beam is centered the $\bar{E} \times \bar{B}$ drift only causes rotation about the axis of the beam, the gradient drift is small compared to the curvature drift since it is proportional to $v^2_\perp$ while curvature drift is proportional to $v_\parallel^2$ where these are perpendicular and parallel components of velocity.

The curvature drift is

$$\bar{v}_{DC} = \frac{\gamma m}{q} \frac{\beta^2 c^3}{R^2} \bar{R} \times \bar{B} \qquad (1)$$

The magnetic field is in the toroidal direction, hence the drift is vertical, or in the z direction, out of the plane of the racetrack. For a 1 MeV beam, going around a 1 meter radius of curvature bend with a 2.5 kG magnetic field, the curvature drift is in excess of 500 cm/μs. This is clearly a problem during the 2 μs acceleration time. This drift can be canceled if we add a B_z field, perpendicular to the orbit. This causes a drift

$$v_z = \frac{c}{q} \frac{\bar{F}_\perp \times \bar{B}_\phi}{B^2} = \frac{v_\parallel B_z \times B_\phi}{B_\phi^2} = \frac{v_\parallel B_z}{B_\phi} \qquad (2)$$

where the $F_\perp$ comes from the Lorentz force due to the parallel velocity with the B_z field.

If we chose the magnitude and sign such that $v_z = -v_{DC}$, then the curvature drift will be canceled. The vertical magnetic field required to do this is

$$B_z = \frac{\gamma\beta mc^2}{qR} \qquad (3)$$

or $\omega_c = qB/\gamma mc = \beta c/R$. The field required is that which gives the Larmor orbit equal to the radius of curvature of the bends in the absence of the toroidal magnetic field. The curvature drift is canceled because particles with this orbit exert no centrifugal force on the curved toroidal field lines, hence there is no curvature drift.

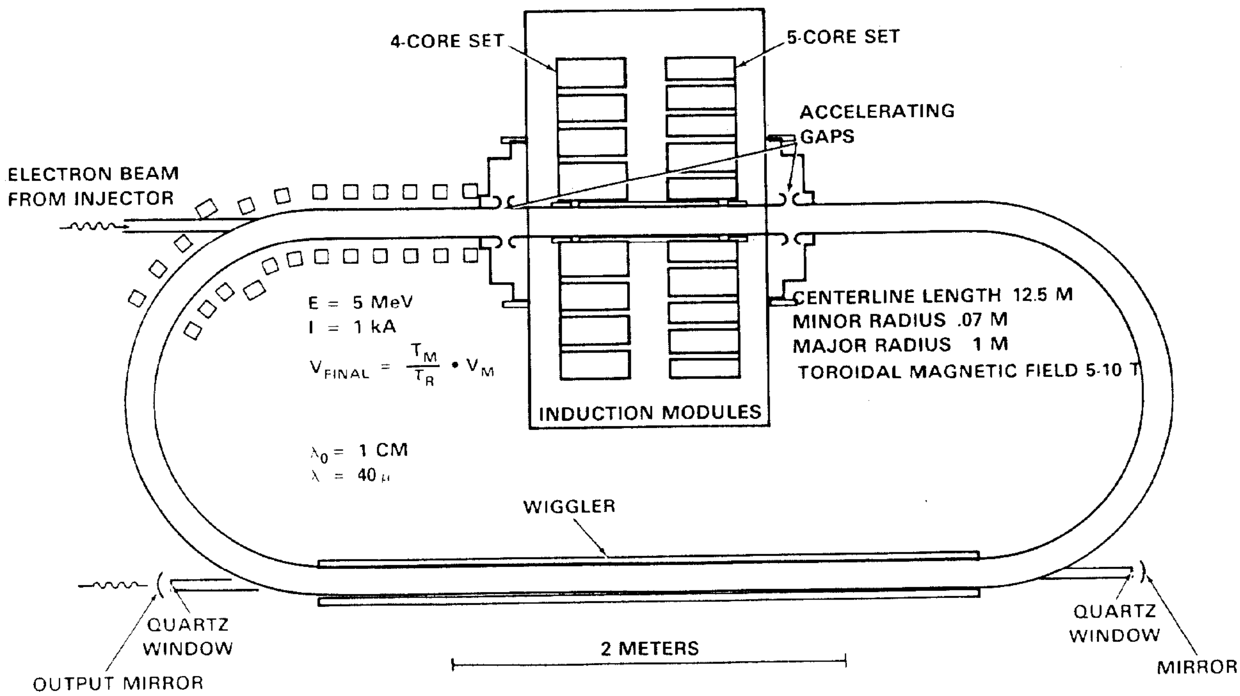
The vertical field provides a solution to drifts only at one energy. To maintain an equilibrium as the particles are accelerated we would have to make the B_z field time dependent.

$$B_z \simeq \alpha_0 \left(1 + \frac{qV_0}{mc^2}\right) + \frac{\alpha E_n(t)}{mc^2} \qquad (4)$$

where $\alpha = \beta mc^2/qR$, V is the injection voltage, E_n is the energy gained after n revolutions. Hence we must have a constant B_z for the initial beam energy but after the acceleration is turned on we must add a time dependent field.

$$B_{zo}(t) = \frac{\alpha E_n}{mc^2} = \frac{\alpha q}{mc^2} \sum_{n=0}^{N} v_n(t) \simeq \frac{\alpha q}{mc^2} \int_0^T \frac{v(t)dt}{L/v} \qquad (5)$$

where B_{zo} is the magnetic field at the output of the induction module, L is the length around the racetrack and v is the velocity.



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Since the acceleration occurs in a short distance (1 meter) the vertical field at the input must differ from the output of the acceleration region by

$$B_{iz}(t) = B_{oz}(t) - \alpha q V_n \qquad (6)$$

where V_n is the voltage on the nth revolution.

Hence the vertical magnetic field must not only be time dependent to keep the particles in the racetrack, it must also be space dependent because the energy is gained in a local region. As the energy is increased from 0.5 MeV to 20 MeV the B_z field must be increased from about 30 gauss to over 500 gauss in 2 μs.

The above configuration provides for an equilibrium orbit around the racetrack, however no stability is obtained. A few percent error in the B_z field will cause the beam to drift out of the accelerator. One possibility is to provide a gradient in the vertical magnetic field. This could be done with two conducting wires above the center of the drift tube with current flowing in the opposite direction. The magnetic field would be stronger near the top. If the curvature drift at the center of the drift tube becomes too strong, the beam will drift into a stronger region of the vertical field where it is again stabilized. If the curvature drift is too weak it will drift down to a weaker B_z field where it becomes stabilized. However the gradient in B_z introduces a drift in the radial direction. The next step is to add a pair of conducting wires below the center line of the vacuum chamber with current flowing in the direction opposite to the upper two wires. Now since B_z is in opposite direction in the lower half plane, the beam drift will be upward for both the curvature drift and v_z drift in the lower half plane. With this configuration we should have a range of energies over which the particle orbits are stable in the curved sections of the racetrack. We have in fact constructed a quadrupole magnetic field. Such configurations have drift surfaces that are ellipses due to the combined vertical and radial drift velocities. The ellipse is shifted from the center due to the curvature drift. If we now twist the quadrupole into a helix as it goes around the bend we have the configuration of a ℓ = 2 stellerator. Run away electrons of 1 MeV energies have been observed in a racetrack stellerator. Hence it is possible to run such configurations over a wide range of energies with time independent magnetic fields. This possibility is under investigation theoretically and computationally at NRL for the configuration shown in figure 1.

One of the applications for a high current-high voltage beam is to drive free electron lasers. The wavelength is inversely proportional to the voltage squared. The Raman mode FEL has a gain that is proportional to the beam density to the one fourth power and an efficiency that is proportional to the beam density to the one half power. The racetrack configuration has a straight section in which a wiggler can be placed. The FEL is then operated without taking the beam out of the system and will be on as long as the beam is circulating. Hence we have the possibility of variable wavelength operation over a wide range during the acceleration phase, single frequency operation during the post acceleration phase, which can last as long as the beam can be confined.

In summary the concept presented takes an existing high current long pulse induction module and inserts it into a racetrack configuration with a toroidal magnetic field to realize a high voltage-high current cyclic accelerator. This configuration is advantageous for FEL operation and has the possibility of very long pulse length (10-100 μs) FEL outputs.

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References

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