

THE RADIATRON: A HIGH AVERAGE CURRENT BETATRON FOR INDUSTRIAL AND SECURITY APPLICATIONS*

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Abstract

The fixed-field alternating-gradient (FFAG) betatron has emerged as a viable alternative to RF linacs as a source of high-energy radiation for industrial and security applications. For industrial applications, high average currents at modest relativistic electron beam energies, typically in the 5 to 10 MeV range, are desired for medical product sterilization, food irradiation and materials processing. For security applications, high power x-rays in the 3 to 20 MeV range are needed for rapid screening of cargo containers and vehicles. In a FFAG betatron, high-power output is possible due to high duty factor and fast acceleration cycle: electrons are injected and accelerated in a quasi-CW mode while being confined and focused in the fixed-field alternating-gradient lattice. The beam is accelerated via magnetic induction from a betatron core made with modern low-loss magnetic materials. Here we present the design and status of a prototype FFAG betatron, called the Radiatron, as well as future prospects for these machines.

CONVENTIONAL BETATRON

Betatron accelerators were introduced in the early 1940's, and soon found common application in research, medicine and industry. From the viewpoint of industrial applications, betatron acceleration is still attractive because it avoids the expense and complication of using high-power RF.

The conventional betatron [1] is a fixed-orbit circular induction accelerator. A changing magnetic field confines and focuses the particles, while also generating an azimuthal electric field which accelerates the particles. The condition relating the rate of change of the magnetic flux through the circular orbit, $\dot{\Phi}$, and the local (at the design trajectory radius R) bending field $B_z(R)$ to maintain this equilibrium orbit is

$$\dot{\Phi} = 2\pi R^2 \dot{\bar{B}}_z, \text{ or } \bar{B}_z = 2B_z(R) + C, \quad (1)$$

where \bar{B}_z is the average is over the interior of the orbit, and C is a constant.

Equation 1 is termed the betatron condition. In early betatrons the accelerating and bending fields were created by a single dipole, with a shaped gap to create the proportionality at the desired radius. Later, the functions of the accelerating core and the bending field were separated to reduce the energy needed to drive the core [2]; core biasing — setting C in opposition to the

direction of increase in B_z — also allowed improvement in the total available acceleration. The correct proportionality between the core and bending fields in such devices was maintained by connecting the coils of the bending and accelerating magnets in parallel.

Despite these and other improvements, the average current capability of the conventional betatron was limited by several factors:

- The transverse focusing is weak.
- The duty cycle is limited to a few percent — current may only be injected during a small portion of the betatron cycle because the bending fields change in time.
- The momentum acceptance of the device is very low — there is a narrow range of equilibrium orbits of differing momenta allowed in the machine at a given time.
- The cycle rate is limited by the rapid increase of eddy current losses at higher frequency.

FFAG BETATRON

FFAG accelerators were independently proposed by Ohkawa [3], Symon [4], and Kolomensky [5] in the 1950's and several electron accelerators were built by the Midwestern Universities Research Association (MURA) in the 1950's and 1960's as prototypes for future high energy proton accelerators [6,7,8]. The scaling FFAG, in which the tunes are constant throughout the acceleration cycle, has a vertical magnetic field in the device midplane given by

$$B(r, \varphi) = B_0 (r/r_0)^k f(\varphi), \quad (2)$$

where k is a constant, and $f(\varphi)$ is a periodic function describing the azimuthal variation of the field around the accelerator. Creating the radial variation with field index k requires either current distributions on the pole faces, or shaping of the magnet poles, or a combination of these two approaches. There are two principle types of azimuthal variation $f(\varphi)$: radial and spiral. The radial type are plain “pie slice” shaped sectors, whereas the spiral type include a spiral angle to add edge focusing.

Applying FFAG focusing to the betatron, the functions of acceleration and focusing are separated, and the focusing field is kept fixed in time (not ramped). FFAG focusing increases the current capability of the betatron in the following ways:

- There is an large increase in the maximum duty factor, since the fixed-in-time guide field allows long-pulse injection. As electrons are being

accelerated, moving to outer orbits, more particles are being continuously injected and accelerated.

- The focusing is strong, thus the size of the beam is better controlled, allowing more current to be loaded into the machine.
- There is a wide spectrum of stable orbits, for all momenta from injection to extraction, so a wide range of injected momenta will be accepted and accelerated.
- The charge in the accelerator is spread out over many orbits in a sheet, reducing the space-charge effects.

One final advantage of the FFAg betatron is that the issue of eddy current losses is confined to the betatron core. This simplifies the cooling and minimizes the portion of the accelerator that must be made from special materials (e.g. laminations). In particular, the core may be made of advanced, nanocrystalline magnetic materials such as Finemet [9], which has very low core loss and comparatively high saturation (see Table 1). Using Finemet for the betatron core allows cycling at very high frequency (> 10 kHz), thus the acceleration rate is very fast, further mitigating space charge effects.

Table 1: Core loss and Saturation of Magnetic Materials

Material	Core Loss (kW/m ³) at 100 kHz, 0.2 T	Saturation Induction (T)
Si Steel	8000	1.9
Mn-Zn Ferrite	500	0.5
Fe Amorphous alloy (Metglas)	2000	1.6
Co Amorphous alloy	300	0.6
Nanocrystalline alloy (Finemet)	400	1.2

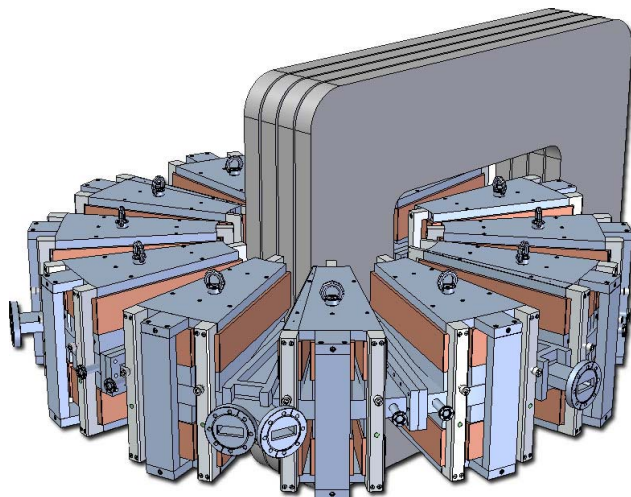


Figure 1: A CAD rendering of the Radiatron accelerator.

THE RADIATRON

RadiaBeam Technologies is currently fabricating a prototype FFAg betatron for industrial applications, which we call the Radiatron (see Figure 1). The accelerator will fit within a footprint of about 2 x 2 m and weigh about 2000 kg. Additional specifications are listed in Table 2 below.

Table 2: Radiatron Specifications

Energy (inj/ext)	45 keV / 5 MeV
Radius (inj/ext)	30 cm / 67 cm
Sector type	Radial sector FDF triplet
Number of Sectors, <i>N</i>	12
Field index, <i>k</i>	3
Injected current	20 mA
Tune (hor/ver)	2.3 / 1.6
Injection period	24 μs
Core cycle period	100 μs
Acceleration period	26 μs
Acc. Period Duty Cycle	47%
Total Period Duty Cycle	24% (at 10 kHz)

Lattice and Magnets

The lattice was designed initially using a simple thin-lens matrix model. We then proceeded to develop a single-particle tracking program in Mathematica [10] to allow the investigation of complex magnet geometries and field shapes.

After initial design was complete, ICOOL [11] was used to study error tolerances and to import magnetic field maps. These steps confirmed appropriate lattice design and stable working point and set limits for alignment errors.

The magnet achieves a quasi-scaling FFAg field via pole-shaping. Iterative modifications to the pole geometry were performed in order to match the path-integral of the field in each F and D to the ideal. Considerable difficulty was encountered in trying to optimize the field at the inner radius. In order to solve this problem, and allow flexibility to adjust the field later, we have designed and simulated correction coils to place in the magnet gap. We plan to build a set of two prototype magnets and perform further simulations with the measured field maps.

Components

Most of the components – magnets, vacuum chamber, and diagnostics – are being fabricated by RadiaBeam. The magnets have complex pole-face geometries that will be CNC machined. The vacuum chamber will be made of non-magnetic stainless steel with metal seals. The electron gun, the core and the power supply have been purchased from select suppliers. The diagnostics consists

of two innovative, combined wire-scanner and pickup electrode probes which are mounted on a custom feedthrough. We also will install faraday cups at the injection location and the extraction arm.

Experiment

The prototype Radiatron will be installed and commissioned in the PEGASUS laboratory at UCLA. This facility does not contain sufficient shielding to run the accelerator at full duty-cycle (24 kW), therefore it will be run in “burst mode” to demonstrate the high-power capabilities. The experimental goal will be to achieve high-current, high-duty cycle acceleration to 5 MeV and to extract the beam with high efficiency.

Most components are either complete or currently being fabricated. The magnets will be fabricated after the

prototype test is complete. We plan to commission the accelerator later this year.

Conclusion

The Radiatron holds the potential to be a robust, high-power accelerator for industrial applications. Because it uses magnetic induction, rather than RF power, for acceleration, the systems involved will be more reliable and less expensive. RadiaBeam is currently building a prototype of the Radiatron. Our goal is to license the technology or supply the machines through a partnership with a larger company.

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