A 2-stage, 5-MW FFAG

R. Kustom
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Abstract

The Fixed-Field Alternating Gradient (FFAG) accelerator has DC-excited magnets whose field strength varies with radius as $B_o(R/R_o)^k$, where B_o is the injection field, R_o is the injection radius, and k is a constant which is called the field index.

Typically, injection energy into an FFAG is between 250 and 400 MeV and extraction energy is between 1100 and 2200 MeV. Because of the DC-excited magnetic fields, the FFAG can be operated with repetition rates as high as 250 to 400 Hz. The optimum repetition rate for neutron-scattering users is usually lower, 30-100 Hz. Techniques such as internal stacking, an external stacking ring, or staged FFAGs for lowering the extraction rate will be discussed. A 2-stage design will be described which uses a 100 Hz, 250 to 800 MeV machine and a 50 Hz, 800 MeV to 2000 MeV machines. With additional installed RF, the machine could be designed to operate at even higher repetition rates to deliver multi-megawatt beams to more than one target facility.

I. Introduction

Conceptual designs for a 5-Megawatt FFAG accelerator have considered using relatively low energy (250-350 MeV) linac injectors at a high repetition rate (250 Hz) with internal stacking at an intermediate energy[1] or an external isochronous storage ring to store several bunches[2] in order to lower the repetition rate on the target. Another option is suggested here. The proposal is to use two FFAG accelerators; the first operates at a 100-Hz repetition rate at the first RF harmonic and the second FFAG operates at a 50-Hz repetition rate on the second RF harmonic. With this configuration, two one-bunch extractions from the first FFAG are injected into two waiting buckets in the second FFAG.

The concept which is outlined in this paper is not represented as a design since one has not been done. What is presented is the basis on which the design would be pursued using components that have been designed for previous machines.

II. 2-stage FFAG Parameters

The proposed facility layout is shown in Figure 1. Injection into the first FFAG would be at 400 MeV with a 100-Hz repetition rate. The first, or low energy, FFAG would accelerate the beam to 800 MeV at a 100-Hz repetition rate. The injection radius would be about 12.0 meters and the extraction radius would be about 12.7 meters. There would be 16 sector magnets each of which would provide the field strength along the particle orbit shown in Figure 2[3]. The variation of magnetic field with radius would be

$$B = B_o \left(\frac{R}{R_o}\right)^k$$

where R_0 is the injection radius, B_0 is the magnetic field at injection, and k is a constant known as the field index. The value of k for the first machine would be between 12 and 13. The betatron tunes would be 3.25 in the horizontal plane and 2.75 in the vertical plane. The inside height of the vacuum chamber at the injection radius would be about 20 centimetres. The injected charge would be 1.58 x 10^{14} protons per acceleration cycle. This would result in a betatron tune depression of 0.17 assuming a bunch factor of 0.375 and a form factor of 1.35, which corresponds to reasonably uniform painting in the horizontal plane and parabolic in the vertical plane.

The RF frequency would swing from 2.835 MHz at injection to 3.16 MHz at extraction. The peak voltage required would be 40 kilovolts which allows operation at a 30° phase stable angle.

The second stage FFAG would take the beam from 800 MeV to 2 GeV. The first bunch from the low energy FFAG would either be 1) injected into one of the two RF buckets in the second stage FFAG and held in a stationary orbit until the second bunch from the low energy FFAG is injected into the other RF bucket, or 2) accelerated very slowly to keep the particles in the bucket until the second bunch is injected. Then, the two bunches would be accelerated in about 10 milliseconds to 2 GeV and both extracted in one turn into the spallation target.

The injection radius for the proposed second stage would be about 36 meters and the extraction radius about 37.3 m. The number of sectors would be between 24 and 26, the field index, k, about 18, the horizontal tune would be 5.25, and the vertical tune 4.25.

The RF frequency at injection would be 2.16 MHz and at extraction would be 2.43 MHz. The peak RF voltage would be 280 kilovolts, which would allow for operation at a phase stable angle of 30°.

Table 1 lists the parameters for the two FFAG stages.

III. Magnet Design

The design of the magnets for the 2-stage FFAG accelerators would be similar to the magnet designed for a 1500-MeV FFAG[2]. Figure 3 shows the field variation that must be matched in the 1500-MeV FFAG at the extraction orbit. The peak field in the focusing section would be 4.1 T and peak fields in the defocusing section would be 1.9 T. A 6-coil core configuration that provides correct field pattern is shown in Figure 4. Figure 5 shows the required, or target, field over the radius at the plane of symmetry along with that achieved with the 6-coil configuration. Figure 6 shows the target and achieved azimuthal fields at the extraction radius for the same coil configuration. The coil sizes and required excitation currents are listed in Table 2.

Coil 1 in Table 2 corresponds to the large coil that is furthest above (and below) the vacuum chamber. These are the upper and lower coils shown in the upper view of Figure 4. The coordinate x is the radial direction in the FFAG and z is the plane perpendicular to the orbital plane. The coordinate Y is the distance along the beam orbit measured from the median plane of the magnet. The reverse field coils (coil 2) are closer to the vacuum chamber in the top view and straddle coil 1 (the heavy black coil) in the bottom view of Figure 4. A long thin coil (coil 4) is located inside coil 1 and is shown as the smaller rectangle inside coil 1 in the bottom view of Figure 4. Finally, two smaller coils are shown in the upper view (coil 3) at the extraction side of the coils. They are located on each side of the median plane of the coil.

The conductor for the coil would use high purity aluminium (HPAL) stabilizer with NbTi strands as shown in Figure 7. The conductor would be embedded in a high-strength alloy aluminium (HSAL) as shown in Figure 8.

It is proposed that the vacuum jacket and heat shields also be made out of aluminium to minimize the possibility of generating long-life residual radioactivity.

Normal-conducting, aluminium pole-face windings would be placed between the beam vacuum chamber and outer cryostat wall of the sector magnets to fine tune the magnetic field and the beam as a function of radial position in the FFAG.

IV. RF System

The cavities for the FFAG would be a picture frame design using ferrite blocks in a construction technique similar to the RF cavities of the old weak-focusing synchrotrons[4]. The cavities for the second stage FFAG would be about 50% larger than the cavities for the weak-focusing synchrotrons, but basically would not pose any real construction problems. The beam loading, however, requires the use of cathode-follower amplifiers to avoid distortion of the RF bucket. This type of amplifier maintains a low output impedance, 20 to 80 ohms, over a large frequency range[5]. Also, the power tubes must be able to provide sufficient output current to match the peak circulating current of the beam and to be able to supply the peak RF voltage on the cavity. These conditions result in an average power per tube that is only 25 to 50% the cw power rating of the tube.

Typically, twenty cavities with a physical length of 1.25 meters each would be used. Each cavity would generate 14 kV with 0.012 T peak RF field in the ferrite. The active length of ferrite would be about 0.8 m, in the direction of the beam.

References

1. T. K. Khoe and R. L. Kustom, "ASPUN Design for an Argonne Super Intense Pulsed Neutron Source," IEEE Trans. on Nuclear Science, NS-30, No. 4, 1983.

2. R. L. Kustom, "The ASPUN Project," Advanced Neutron Sources 1988, Institute of Physics Conference Series Number 97, Institute of Physics, Bristol and New York, 1989.

3. P. F. Meads, Jr. and G. Wustefeld, "An FFAG Compressor and Accelerator Ring Studied for the German Spallation Neutron Source," IEEE Trans. on Nuclear Science, NS-32, No. 5, 1985.

4. L. A. Klausner, et al., "Zero Gradient Synchrotron RF System," IEEE Trans. on Nuclear Science, Vol NS-12, No. 3, 1965.

5. Thomas W. Hardek and William E. Chyna, "Common Anode Amplifier Development," IEEE Trans. on Nuclear Science, Vol NS-26, No. 3, 1979.

Table 1

Parameters for 2-Stage FFAG

800-MeV FFAG

Number of Sectors	16
Injection Radius, m	12.0
Extraction Radius, m	12.7
Magnetic Field Index, k	12 to 13
Radial Tune, v_x	3.25
Verticle Tune v_y	2.75
Harmonic Number	1
RF Frequency @ Injection, MHz	2.835
RF Frequency @ Extraction, MHz	3.16
RF Voltage, kV, ϕ_s=30°	40
τ Bunch at Extraction, nsec	158
Q_{inj}	1.58×10^{14}

2000-MeV FFAG

Number of Sectors	24 to 26
Injection Radius, m	36
Extraction Radius, m	37.3
Magnetic Field Index, k	18
Radial Tune, v_x	5.25
Verticle Tune, v_y	4.25
Harmonic Number	2
RF Frequency @ Injection, MHz	2.16
RF Frequency @ Extraction, MHz	2.43
RF Voltage, kV, ϕ_s=30°	280
Q_{ext}	3.16×10^{14}

Table 2

SIX-COIL CONFIGURATION - Dimensions and coil currents

COIL COORDINATES

Coil #	X	Y	Z	X	Y	Z	W/H
1	25.800	.360	1.100	28.800	.402	.500	.400
	28.800	.000	.400	25.800	.000	1.000	.250
2	25.800	.540	.450	28.800	.603	.250	.300
	28.800	.855	.250	25.800	.766	.450	.150
3	27.800	.243	.250	28.800	.251	.250	.080
	28.800	.503	.250	27.800	.485	.250	.100
4	26.000	.113	.250	28.400	.124	.250	.040
	28.400	.000	.250	26.000	.000	.250	.100

COIL CURRENTS (AMPERE-TURNS)

Coil#	Current	J (kA/cm²)*
1	6.449E+06	6.45
2	2.372E+06	−5.27
3	−4.242E+05	5.30
4	−2.462E+05	−6.16

* Positive current denotes a force directed towards the center of the FFAG

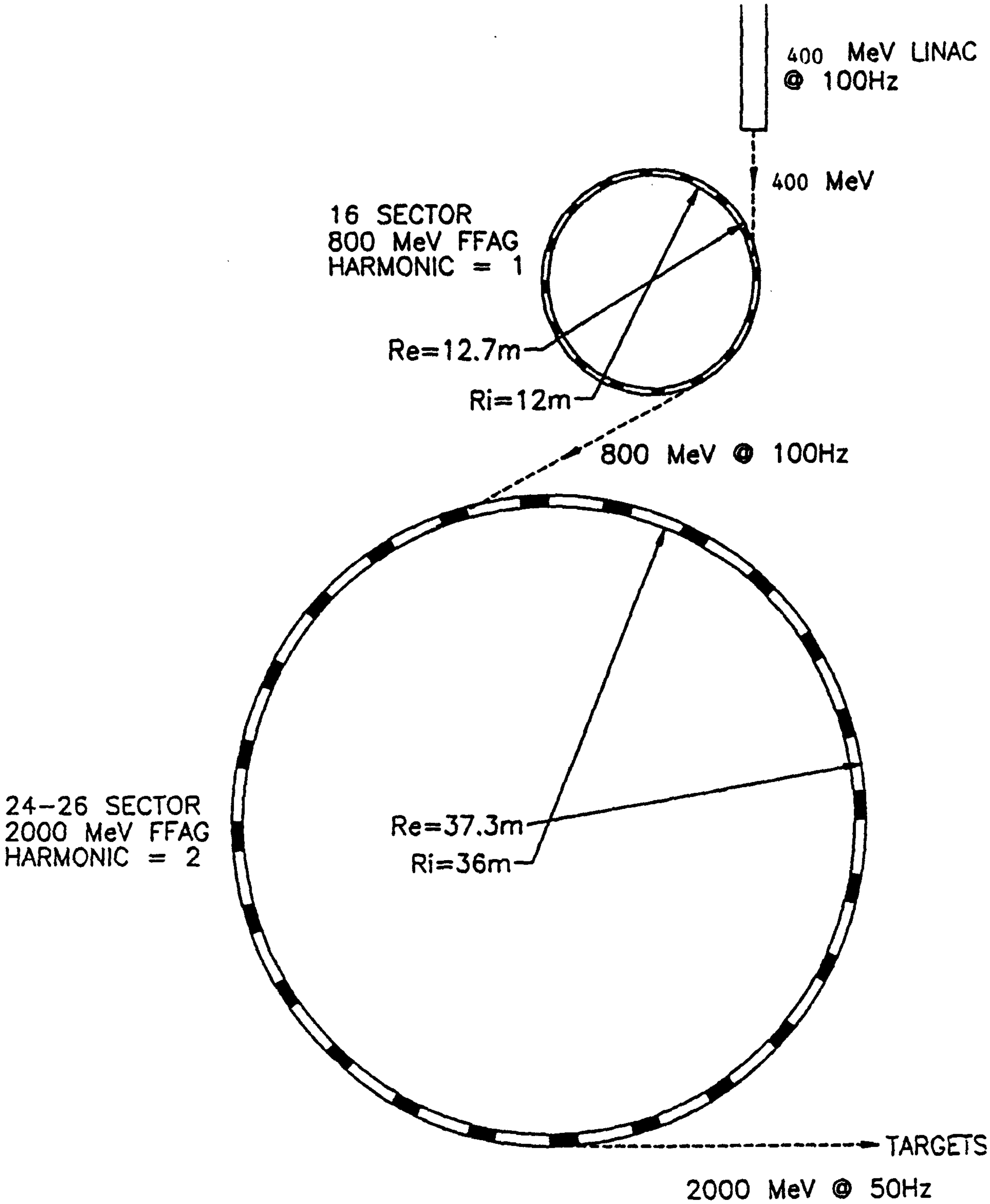


Figure 1 - Layout of 2-stage 5 MW FFAG

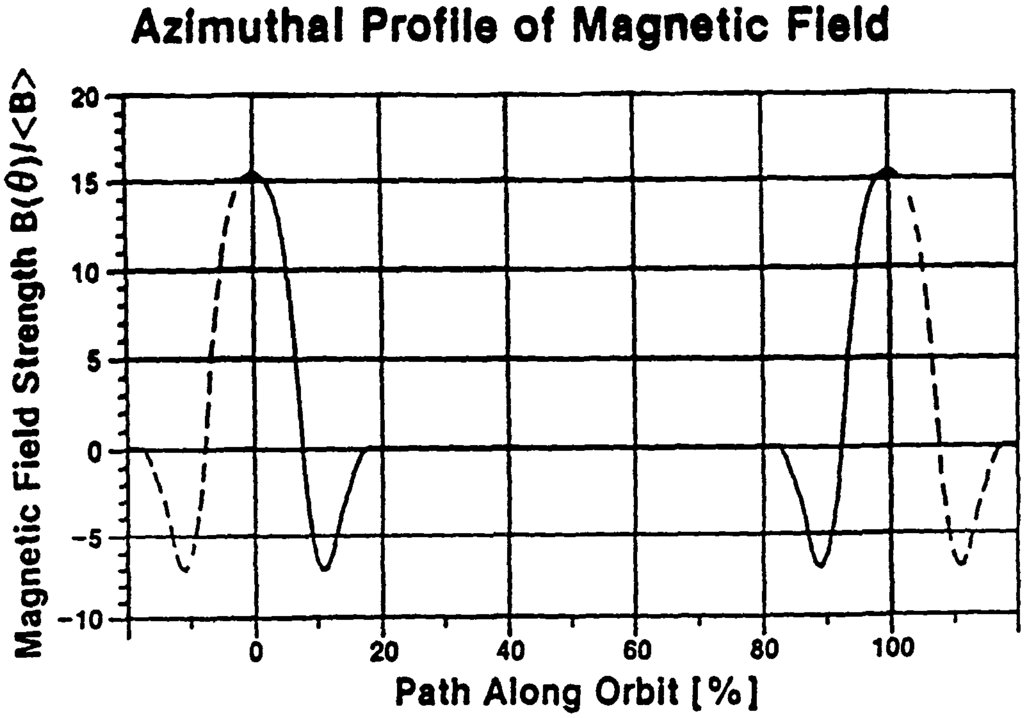


Figure 2 - Magnetic Field Strength along particle orbit through one sector of FFAG

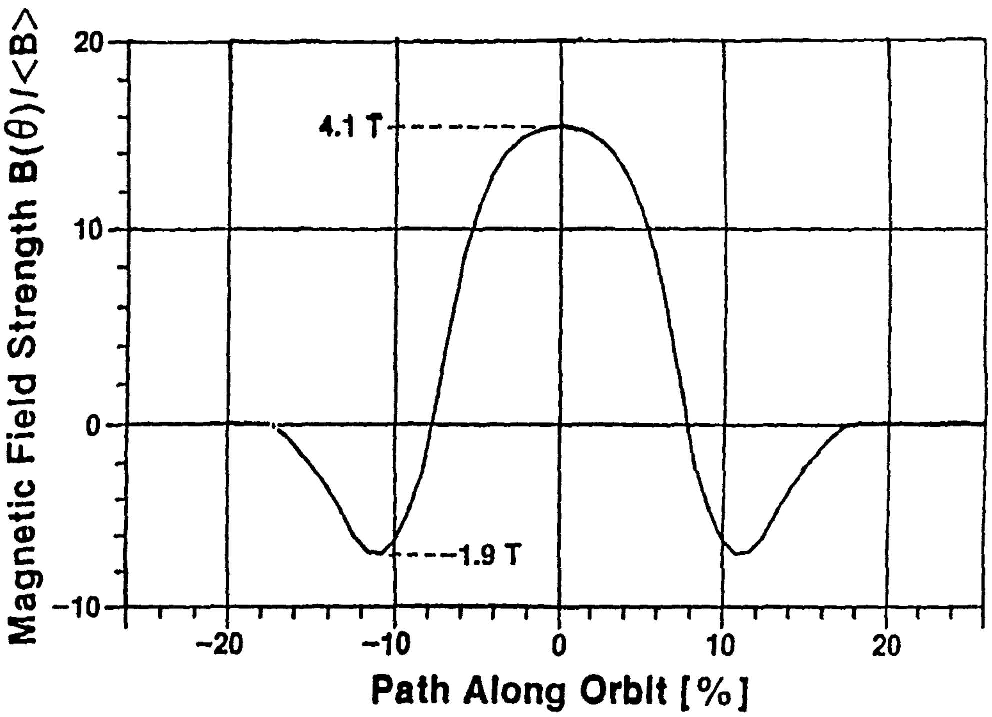


Figure 3 Azimuthal profile of magnetic field along the path of one cell

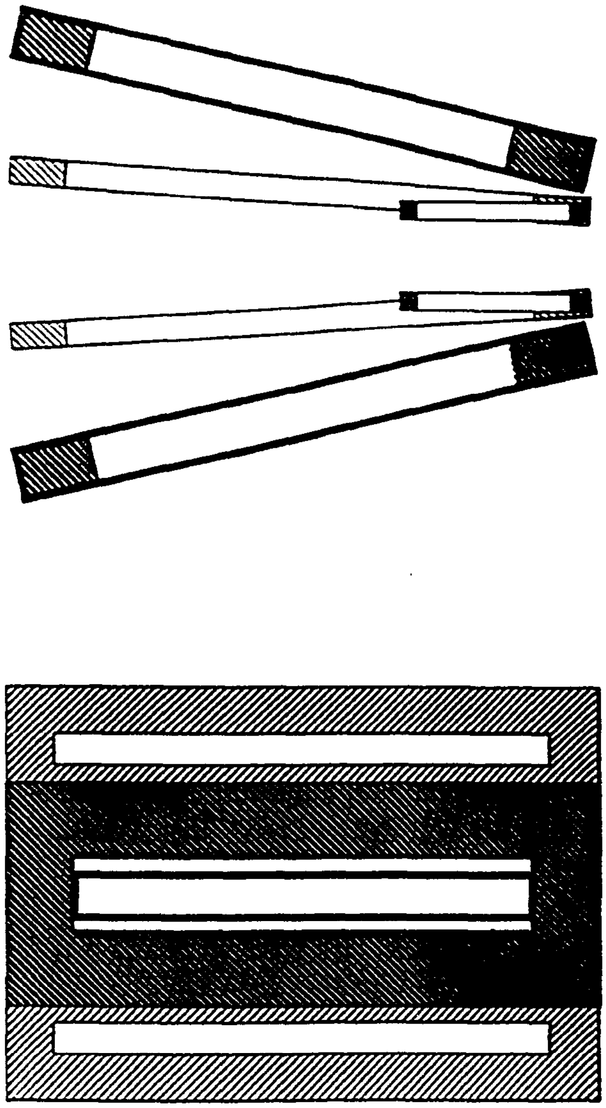


Figure 4

6 COIL–CONFIGURATION for a 1500-MeV FFAG - top view is looking in the direction of the beam and bottom view is looking down on the beam. The left side is the injection radius and the right side is the extraction radius.

Figure 5 **FIELD AT PLANE OF SYMMETRY FOR THE 6-COIL DESIGN**

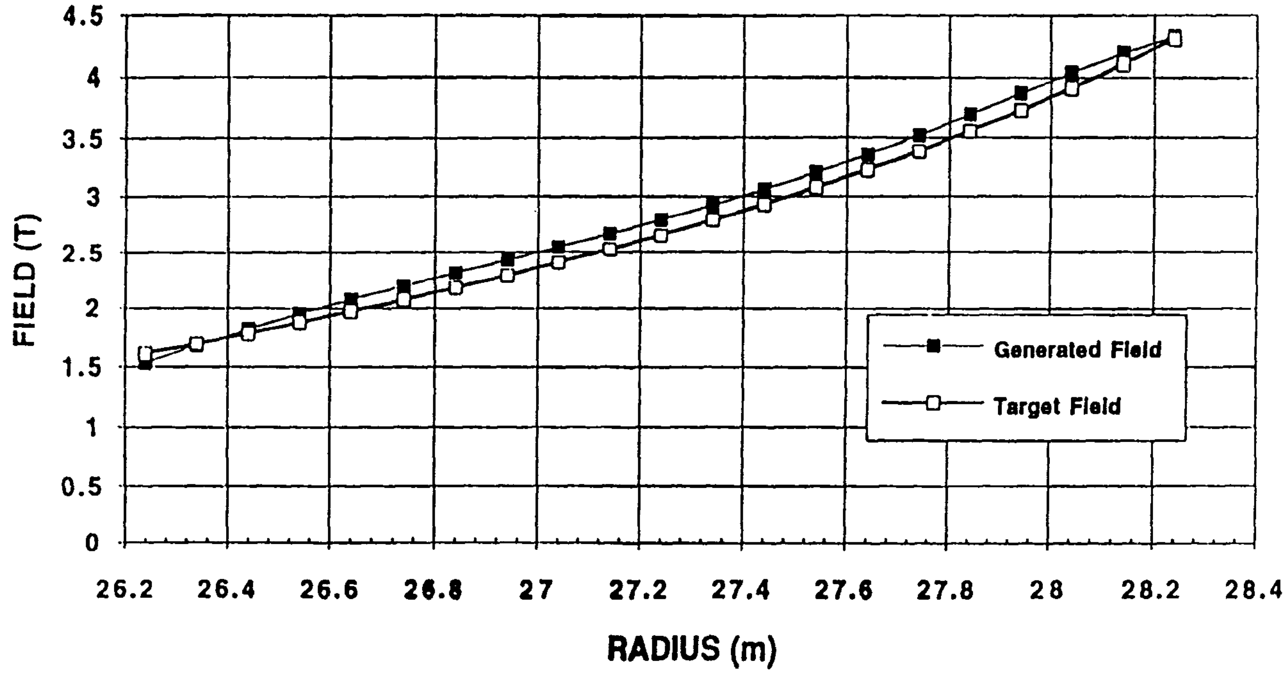
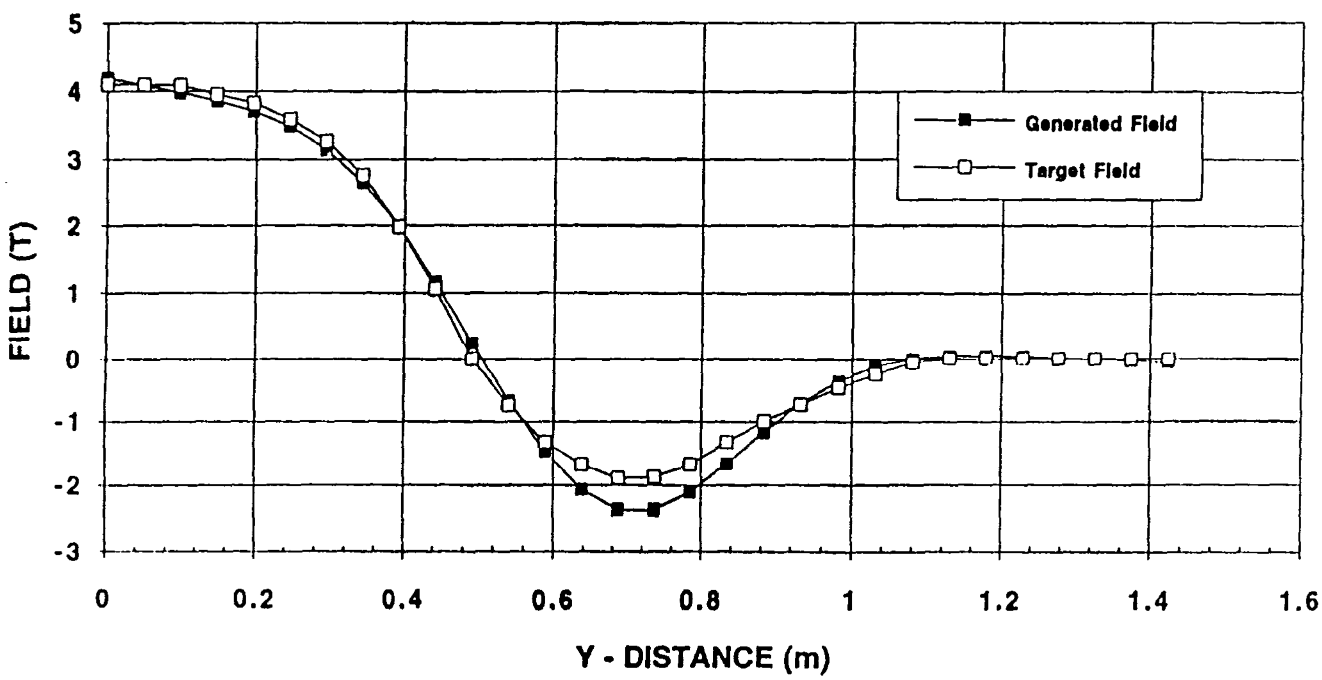


Figure 6 **FIELD AT OUTER RADIUS FOR THE 6-COIL DESIGN**



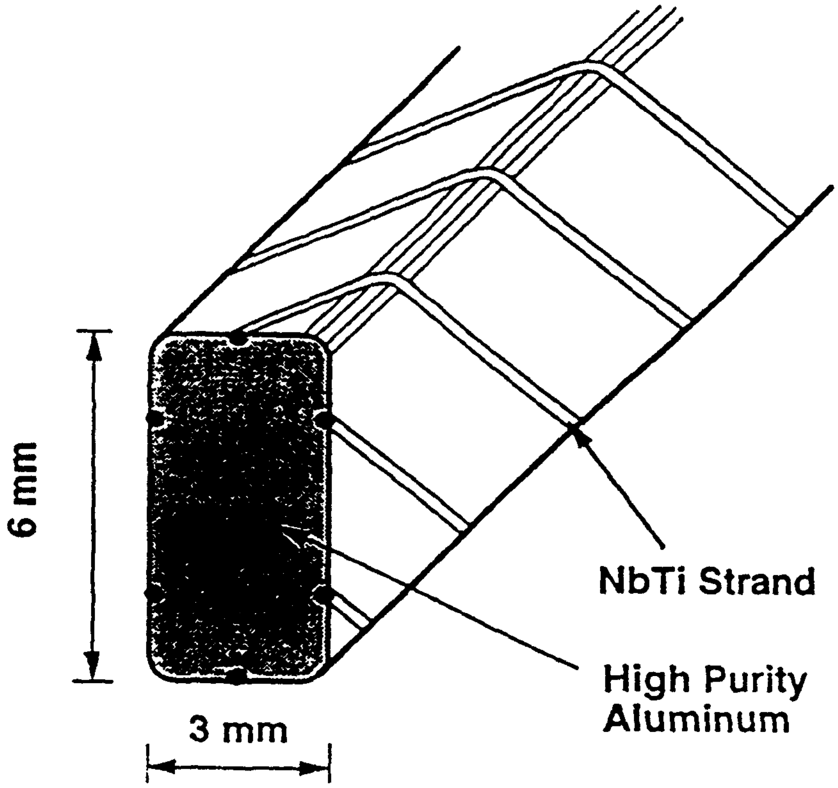


Figure 7 5 KA HPAL Stabilized Conductor

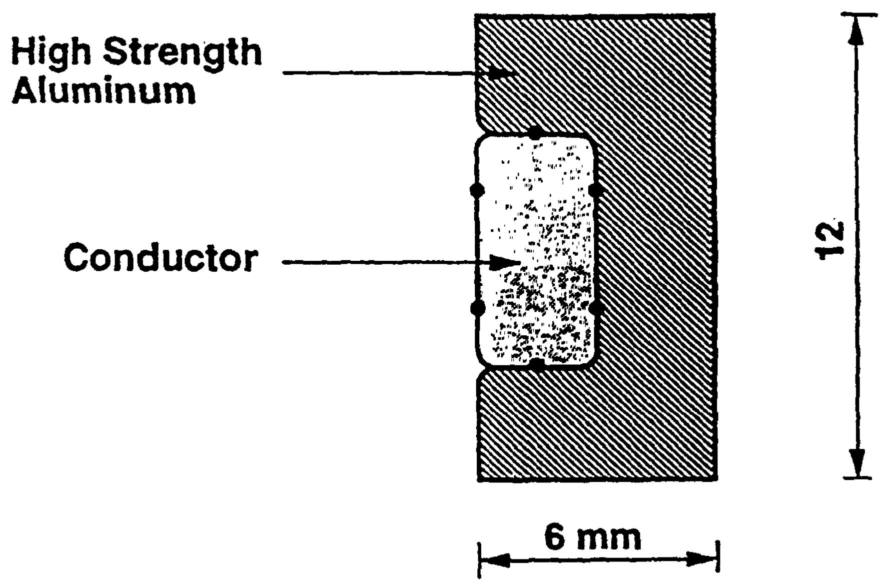


Figure 8 CONDUCTOR EMBEDDED IN HSAL STRUCTURE