The FFAG as an Accelerator for High Intensity Proton Beams

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Abstract

The requirements are discussed for an FFAG using high intensity proton beams ($2.5 \cdot 10^{14}$ particles per pulse) suitable for an average beam power of 5 MW and an acceleration from 800 MeV to 2.5 GeV with a pulse rate of 50 Hz. The lattice is a radial type FFAG with iron magnets excited by super conducting coils. The basic input parameters are: Stripping injection of H^- at 800 MeV, acceleration on the 1^{st} harmonic (1.1-1.2 MHz), and extraction by kicker at 2.5 GeV. Dynamic apertures are calculated using the code ORBIT. A first estimate of the technical feasibility is discussed.

1. BASIC DESCRIPTION OF THE ACCELERATOR

The general properties of the FFAG for intense proton beams have been discussed in an earlier paper[1]. The basic parameters of an FFAG have been recommended at a workshop[2] in Müden. This is an FFAG with an injection energy of 800 MeV, 50 Hz repetition rate and a beam power of 5 MW at the extraction energy of 2.5 GeV. Basic parameters of this machine are given in Table 1. From the average 5 MW beam power follows the $2.5 \cdot 10^{14}$ particles per bunch.

Table 1
General Specification for the 2.5 GeV FFAG

Beam Power	5	MW
Average Beam Current	2	mA
Energy at Injection	800	MeV
Energy at Extraction	2500	MeV
Average Radius at Injection	36.31	m
Average Radius at Extraction	38.00	m
Field Index k	16.95	
Repetition Rate	50	Hz
Number of requested Particles	$2.5 \cdot 10^{14}$	per puls
Bρ at Injection	4.88	Tm
Bρ at Extraction	11.03	Tm
Peak Magnet Field at Injection	2.31	T
Peak Magnet Field at Extraction	5.0	T
Cell Length	9.95	m

The 24 sector FFAG configuration is based on a super conducting magnet with a maximum field of 5.0 Tesla and a minimum field of -1.7 Tesla. The injection is at an average radius of 36.3 m, and extraction occurs at an average radius of 38 m. The requested field index k describes the radial field through $B/B_0=(R/R_0)^k$, it is related to the transition energy by $\gamma_{tr}=\sqrt{k+1}$. To work safely below transition requires $k>>12$. The chosen field index results in a radial distance from the injection orbit to the extraction orbit of 1.71 m. Each of the 24 cells has a length of 9.95 m, of which 7.94 m is the approximate length of the straight section. Injection will be done by charge exchange of H^- ions from an 800 MeV linac or another FFAG as it has been proposed by R.L. Kustom and G. Bauer[3].

2. THE LATTICE

The optical parameters are optimised to yield the maximum acceptance at the requested field index. The tunes are horizontal Q_x=4.78 and vertical Q_y=3.29. Table 2 shows further parameters.

Table 2
Lattice Parameters for the 2.5 GeV FFAG

Horizontal Tune Q_x	4.78
Vertical Tune Q_y	3.29
Horizontal Phase Advance per Cell	71.70 degree
Vertical Phase Advance per Cell	49.35 degree
β_{xmax}/R	0.2967
β_{xmin}/R	0.1778
β_{ymax}/R	0.3206
β_{ymin}/R	0.2893
Laslett Tune Spread ΔQ	0.2
Emittance, normalised	243 π mm mr
Emittance at Injection	156 π mm mr
Beam Diameter	87 mm

The program ORBIT[4] was originally written during 1983-1985 to study FFAGs for the German SNQ program. It has been extended to allow automatic adjustment of the field index and the geometry of the magnets. The β-functions scale with the momentum and machine radius, which is a consequence of the FFAG general scaling property[5]: All orbits are photographic enlargements of a reference orbit. The integration method of Bulirsch-Stoer[6] has been implemented in the ORBIT Code. It is faster for high accuracy than the 8th order Runge-Kutta method. For the estimation of he dynamic aperture 512 sectors usually have been calculated. The horizontal and vertical planes are coupled. But the dynamic apertures are very large as shown in Figure 1.

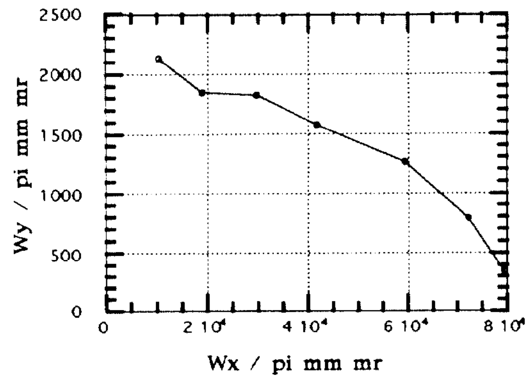

Figure 1: Dynamic aperture for the 2.5 GeV FFAG. The tunes are Qx=4.78, Qy=3.29 at a field index of k=16.69

3. THE MAGNETS

Vertical focusing in a radial type FFAG is done primarily by the alternating gradient created by the presence of negative gradient magnets. A pure radial machine becomes reasonably compact if strong magnetic fields of up to 5 T are used, as was shown in earlier work[7]. First design studies for the magnet have been done using the programs MAFIA[8] and PROFI[9]. Basic magnet data are given in Table 3.

Table 3 Magnet Data for the 2.5 GeV FFAG	
Number of Magnets	24
Field extraction	5 T
Field at injection	2.31 T
Flutter	64
Bend Angle total	15 degrees
Positive Bend Angle	30 degrees
Negative Bend Angle	2*7.5 degrees
Vacuum Chamber Clearance horizontal	1.83 m
Vacuum Chamber Clearance vertical	98 mm
Magnet Size radial	2.31 m
Magnet Gap maximum	158 mm
Number of Super conducting Coils per Cell	6
Max. Ampere Turns	2.1 MA
Maximum Thermal Loss per Magnet	20 W
Iron Weight per Magnet	243 t

The azimuthal width of the magnet at the extraction radius is 2.01 m. The magnet is scaling so the azimuthal width is proportional to the radius. The positive portion of each magnet bends the beam by 30 degrees, and each of the two reverse field sections bends the beam by -7.5 degrees in the reverse direction making the total net deflection of the beam through the magnet 15 degrees. First results of the magnetic design show that the requested field shape can be realised using one pair of coils for the positive bending magnet and one pair for each of the two negative bending gully field magnets. The multipole content of the main magnet is given by

$$B(\Delta r) = 3.417 + 1.555\,\Delta r + 0.333\,(\Delta r)^2 + 0.0445\,(\Delta r)^3$$

with $\Delta r = r - r_{av}$ and $r_{av} = 37.154$ m .

The maximum field near the coils will not exceed 5.7 T. This is consistent with standard super conducting technology. The maximum gully field is below 2.2 T. A field shaping by the iron only has been discussed. This would require only two coils for the main magnet. A pure air coil option has been discussed by R.L. Kustom[3].

4. THE RADIO FREQUENCY SYSTEM

The orbit frequency is 1.107 MHz at injection and 1.208 MHz at extraction; the frequency swing is 9 %. We propose to accelerate on the first or second harmonic. The separation between two bunches would be 414 ns (centre to centre), even on the second harmonic that is enough gap for the extraction kick. The basic RF data are given in Table 4 for the acceleration on the first harmonic.

Table 4 RF-System for the 2.5 GeV FFAG		
Cavity Type	Single ended, Ferrite Loaded	
Number of Cavities	16	
Frequency at Injection	1.107	MHz
Frequency at Extraction	1.208	MHz
Harmonic Number	1	
Peak Voltage per Cavity	20	kV
Ferrite Type	Philips 4M2	
Acceleration Gap radial length	1.7	m
Physical Length	1.25	m
Ferrite Area	0.25	m^2
Ferrite Volume	1.6	m^3
Ferrite max. Permeability	100	
Maximum Acceleration	260	kV / turn
Shunt Impedance	3.4	kΩ
RF Power Loss	59	kW

A detailed description of the RF parameters is given in a separate note[10].

5. COST ESTIMATION

A parametric cost estimation has been done to optimise the design in terms of the physical parameters and costs. This cost estimation is done in DM because the system costs for buildings, support structures, electricity, water, etc. are available at the KFA Jülich. The basic cost factors have been taken as follows. - For the magnets: iron and machining 6 DM per kg; super conducting coils 1 MDM per magnet; vacuum and support 430 kDM per magnet. - For shielding and building: 300 DM per m^3 of building; 500 DM per m^3 of shielding material. - For diagnostics: 10 kDM per pick up; 12 MDM for controls. - For electricity: beam to plug efficiency 30 %; electrical installation 1 DM per W; cost factor power 0.25 DM per kWh; thermal efficiency for super conducting losses 700 W electric per W thermal. - For cooling water: installation 1 DM per W; 3 DM per wasted m^3 of water;

overall temperature increase of cooling water is $\Delta T=6$ degree.
- For operation: 5000 h per year. Some additional costs as land, roads, depreciation etc. have not been taken into account because they do not have a strong influence on the machine design.

Table 5
Cost Investment for the 2.5 GeV FFAG

Magnets	50	MDM
Shielding total	24	MDM
RF total	53	MDM
Diagnostics total	21	MDM
Instrumentation	41	MDM
Building	42	MDM
Investment total	231	MDM
Operation:		
Cost of Electricity per Year	26	MDM
Cost of Water per Year	12	MDM

6. SUMMARY

The main attractiveness of the described system are - the better efficiency for the wall plug to beam transformation relative to linacs, - the relaxed requirements on the injector because the adiabatic trapping at injection does not require a chopped beam for injection at 800 MeV, - the activation due to injection losses is smaller than in a linac+compressor solution, because 70 % of the beam power is gained in the FFAG, - the main field is dc (no pulsed magnets), the radial aperture is large, - the dynamic apertures are huge, - the momentum acceptance is very large, - the shimming of the dc magnets is easy.

The FFAG has the possibility to deliver a factor of 2-3 more power by going up with the repetition frequency. As a possible future option the repetition rate could be lowered to 10 Hz by stacking the beam inside the ring before extraction as has been proposed earlier[11]. The FFAG has not been chosen as an option for a future European Spallation Neutron Source because "it became apparent that based on ... rough cost estimates one could conclude, that the FFAG would be more expensive than the other options under discussion."[2] The options mentioned above have not been taken into account for this evaluation.

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