DESIGN OF FIXED FIELD ALTERNATING GRADIENT CYCLOTRONS - FFAG - AS ACCELERATORS FOR INTENSE PULSED PROTON BEAMS

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The design principle of FFAG cyclotrons is presented. The FFAG accelerates the beam from 800 MeV up to 2500 MeV. The average beam current is 2 mA. This delivers a beam power of 5 MW at a repetition frequency of 50 Hz. The basic parameters of the system are presented. Options are discussed to raise intensity by stacking, to work at lower or higher repetition rates up to 100 Hz, and to double the output power by adding a second ring. The design is optimized in terms of cost for investment and operation.

1 Introduction

We have investigated the possibility of using an FFAG synchrocyclotron for producing high intensity pulsed proton beams. This is especially interesting for pulsed spallation neutron sources. In a survey type study we looked at different options for the FFAG, varying injection and extraction energy, field index of the magnets, number of sectors, the maximum and minimum field of the sector magnets, and repetition rate, leaving the output power always at 5 MW. The different options are shown in Table 1.

In the following we concentrate on option b) in which protons are accelerated from 800 MeV to 2.5 GeV. We have studied this option in more detail, and we have optimized this version for minimum investment and operation cost.

2 Design Principles of FFAG Accelerators

Beam power at the extraction energy and repetition frequency are the main input parameters for the FFAG design. For a chosen FFAG the beam power can be doubled by doubling the repetition frequency. This is an advantage of the FFAG. It can be easily upgraded. Here we discuss the option with 5 MW beam power at the repetition frequency of 50 Hz. A higher extraction energy reduces the current, which simplifies the injector at low energies, but the larger magnetic rigidity causes additional costs for the extraction system. As the magnet gap is determined by the vertical beam size, which is proportional to $(\beta\gamma)^{-1/2}$, and the magnet power consumption is proportional to the gap squared, thus the power cost is proportional to γ^{-1}. The power of the particles lost at injection increases with the injection energy, favouring a lower injection energy.

Table 2: FFAG General Specifications (type B)

Beam Power	5	MW
Aver. Beam Current	2	mA
Inj. Energy	800	MeV
Extr. Energy	2500	MeV
Inj. Radius	36.31	m
Extr. Radius	38.00	m
Field index K	16.90	
Rep. Rate	50	Hz
Req. Part. Number	$2.5 \cdot 10^{14}$	ppp
$B\rho$ inj.	4.88	T·m
$B\rho$ extr.	11.03	T·m
Magnet Field at inj.	2.3	T
Magnet Field at extr.	5	T

The conversion efficiency of electrical into beam power is proportional to U_0^{-2} where U_0 is the rf voltage amplitude. This is much smaller in the FFAG than for any normal conducting linac. In this study we assumed U_0=20 kV. Because of the cost considerations one should not attempt to accelerate beyond a momentum range in one FFAG of $p_{inj}/p_{extr} \approx 1/3$. A system consisting of

Table 1: FFAG-options for 5MW beam power.

	a	b	c	d	e	
Max Energy	3200	2500	900	1600	800	MeV
Inj Energy	430	800	400	430	430	MeV
Inj Radius	41.57	36.31	40.99	24.3065	24.85	m
Ext Radius	45.00	38.00	45.00	26	26.00	m
Max +B field	4.00	5.00	4.00	4.00	3.50	T
Min +B field	1.04	2.31	2.86	1.81	2.59	T
Max –B field	–3.00	–1.70	–1.70	–2.0	–1.50	T
Min –B field	–0.78	–0.79	–1.22	–0.91	–1.26	T
Field Index k	16.66	17.41	3.58	11.8	7.5	
Repetition Rate	50	50	200	100	100	Hz
Number of Sectors	24	24	24	16	16	
Azimuthal Cell Length	11.78	9.95	23.56	10.21	10.21	m
Straight Section Length	7.94	7.11	20.84	7.447	8.20	m
Average Current	1.56	2.00	6.25	3.13	6.25	mA
β=v/c max	0.97	0.96	0.84	0.93	0.84	
β=v/c min	0.73	0.85	0.71	0.73	0.73	
$B\rho$ max	13.44	11.03	4.88	7.87	4.88	T·m
$B\rho$ min	3.32	4.88	3.18	3.32	3.32	T·m
radial width	3.426	1.69	4.01	1.694	1.151	m
Ions Number/Pulse	1.95	2.50	1.95	1.95	3.90	$*10^{14}$
(+) Plateau Width	6.75	3.03	2.54	4.53	2.32	%
(–) Plateau Width	2	2.73	3.18	1.5	0.0	%
Approx. Magnet Width	3.84	2.29	4.61	2.76	2.01	m
Vert. Beam Size (95%)	33.84	99	35.12		47.85	mm
Spiral Angle	4.86	0	0	0	0	deg
Q_x	4.75	4.78	2.71	4.26	3.317	
Q_y	3.75	3.29	2.76	3.26	5.308	
x: phase adv/cell	71.25	71.70	81.30	95.85	74.63	deg
y: phase adv/cell	56.25	49.35	82.80	73.35	119.43	deg
W_x for z=0	453000	740239	945410	83412	39725	π·mm·mr
W_x for z/R=0.001	28183	59301	131508	32219	10717	π·mm·mr
Harmonic Number	1	2	1	1	1	
Max Acc. Time	0.018	0.018	0.0045	0.01	0.009	sec
Energy Gain/turn	179.83	92.40	118.00	200.0	31.43	kV
Max RF Freq.	1.03	2.42	0.89	1.7052	1.54	MHz
Freq. Swing Ratio	1.27	1.09	1.08	1.1934	1.06	
Number of Cavities	11	6	7	10	2	

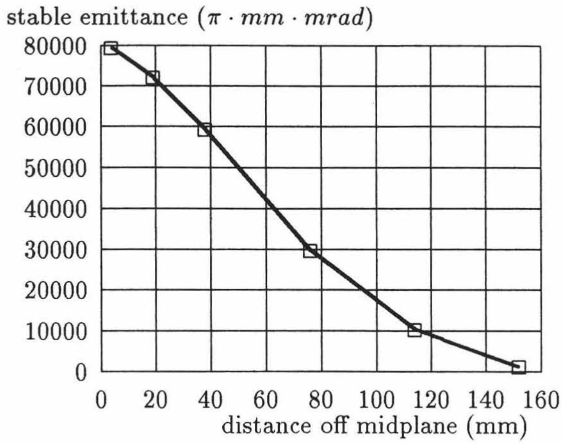

Figure 1: *FFAG (type B) Dynamic Aperture*

more than one FFAG may be a more economic solution.

The field index k in the FFAG is defined by $B/B_{extr} = (R/R_{extr})^k$ and is related to the transition energy by $k = \gamma_{tr}^2 - 1$. The maximum energy should be safely below transition energy. Following K. Johnson[1] this is $\gamma_{tr} = 2/\sqrt{3}\ \gamma_{extr}$. Operation above transition energy has been discussed by V. Dmitrievskii[2]. We choose to operate below transition: $\gamma_{tr} \approx Q_x$=4.78. The phase advance per period $\Delta\varphi_{cell}$=71.7° should be significantly below 90° [3]. Finally the number of periods $N_{sectors}$ is determined by the tune: $N_{sectors} = 2\pi Q_x/\Delta\varphi_{cell}$=24.

3 2.5 GeV FFAG Beam Dynamics

Detailed calculations of the optics described earlier[4] demonstrate the very large dynamic aperture. It has been defined for a stable phase over 1000 periods (Fig.1). This large aperture is a typical radial type FFAG attribute. The calculations have been done by means of the program ORBIT[5].

Injection is done by charge exchange of H^--ions coming from the linac. There are 443 injected turns if the linac delivers 100 mA peak current at 200 MHz. The closed orbit offset at the beginning of the injection is 110 mm and goes down to 0 mm during the injection time of 400 μs. The number of passages through the target has to be minimized in order to reduce the load on the stripper foil. The phase space distribution at the end of the injection process is shown on Fig.2. The total number of turns through the stripper is 5400. The average number of target passages during injection is 12. The average energy loss of H^- ions in a 0.5 mg/cm^2 thick carbon target is about 1 keV per passage at 800 MeV. The optimization of the injection process needs some additional investigation (target cooling, tune adjustment during injection).

The extraction of the beam at the 2.5 GeV is done by a fast kicker followed by a magnetic septum. The data are given in Table 4. A separation at the magnetic septum was specified as big as two times of the beam diameter, including dispersion.

Table 3: FFAG Lattice (type B)

Phase adv. cell x	71.70	degr.
Phase adv. cell y	49.35	degr.
Q_x	4.78	
Q_y	3.29	
β_{xmax}/R	0.9620	
β_{xmin}/R	0.8418	
β_{xmax}	36.6	m
β_{xmin}	32.0	m
β_{ymax}/R	0.95	
β_{ymin}/R	0.82	
β_{ymax}	36.1	m
β_{ymin}	31.16	m
ΔQ Laslett	0.5	
Emittance Inj.	78	π·mm·mrad
Emittance Norm.	122	π·mm·mrad
Cell Length	9.948	m
Beam Diameter	99	mm

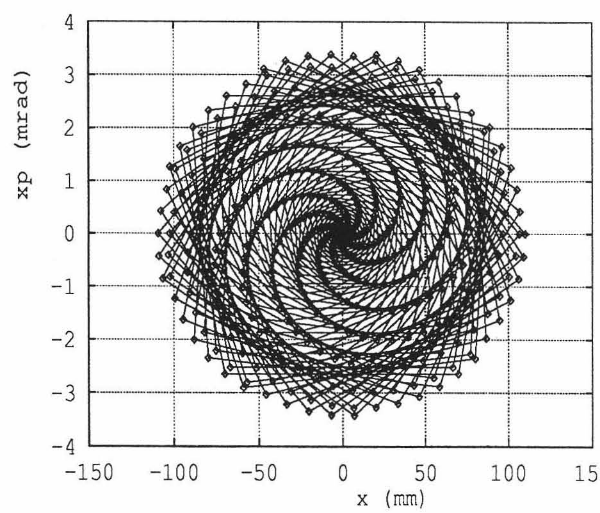

Figure 2: *Phase Space Distribution at the End of Injection*

4 2.5 GeV FFAG Magnet System

The parameters of a magnet consisting of a 30° bending angle main pole (1.4m azimuthal and 2.3 m radial lengths) and two gully field magnets (outward bending of 7.5° each) carrying the return flux of the main field are presented in Table 5). The magnet design has been discussed earlier[6]. Two more magnet designs have been considered as the possible FFAG magnet configuration — the air coil magnet[7] and the C-type magnet with so called S-coils[8,9].

Table 4: FFAG Extraction (type B)

Beam Displ. at Septum	214	mm
β kicker	32	m
β septum	32	m
Kick Angle	7.1	mrad
B*L	0.077	T·m
Kicker Field	0.05	T
Kicker Length	1.55	m

Table 5: FFAG Magnets (type B)

Number of Magnets	24	
Bend Angle per Magnet	15	degr.
Positive Bend Angle	26.12	degr.
Negative Bend Angle	2*5.56	degr.
Vac. Chamber Height	164	mm
Magnet Gap max.	224	mm
Extr. Field	5	T
Inj. Field	2.31	T
Max. Ampere Turns	1.7	MA
Supercond. Coils	6	per Magnet
Iron Weight	93	t/Magnet
Max. Termal Losses	20	W/Magnet

5 Cost Estimate

The cost estimation is done based on cost factors for steel (3 DM/kg material and 3 DM/kg machining), for the vacuum chambers (300 TDM per magnet), for the support and alignment (150 TDM per magnet). The cryogenic coils are estimated with 1.08 MDM per magnet. The investment per magnet is estimated to be 3.8 MDM. The factor for the conversion of thermal to electric power has been taken to 1:700. The cryogenic losses are proportional to the cryogenic volume and the number of feedthroughs. Each magnet will have less than 20 W of thermal losses. With a cost factor of 0.25DM/VAh for electricity, and a factor of 3 DM/m^3 water the yearly electric power adds up to 26 MDM and water cost goes to 12 MDM. The cost factor for shielding concrete is 500 DM/m^3. The thickness of the shielding is 6 m around the accelerator (inside, outside, top, and bottom). The total amount of concrete is 50000 m^3 which adds 25 MDM to the investment. The building is a hall with an area of 13000 m^2 and 13.5 m high, which is estimated to be 53 MDM. Placing the ring into a tunnel will reduce the building cost by about 15%. The overall investment cost factor per beam power gained in the FFAG is approximately 61 MDM per MW of beam power.

6 Summary

A number of 5 different FFAG designs have been described in table 1. The 800 to 2500 MeV type B version has been presented in more detail. A cost estimation has been discussed. Some additional R&D work should be done on the injection problem. The design of the superconducting magnets should be further optimised in terms of feasibility, reliability and costs.

Table 6: FFAG Cost (Type B)

All Magnets Cost	40	MDM
Total Shielding Cost	18	MDM
Total RF Cost	53	MDM
Total Diagnostic Cost	21	MDM
Instrumentation Cost	41	MDM
Tunnel Cost	34	MDM
Investment Cost	207	MDM
Annual Operation Cost	38	MDM
Electric/Year Cost	26	MDM
Water/Year Cost	12	MDM

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