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FFAG - OPTIONS FOR SPALLATION NEUTRON SOURCES

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ABSTRACT

The architecture of facilities needed to produce intense pulsed proton beams to obtain a high power pulsed neutron flux is described. We elaborate on one architecture and give reasons, why we think this combination is particularly suitable for a spallation neutron source. The ring accelerator we favour is an FFAG (Fixed Field Alternating Gradient) machine, known since the late fifties from studies at MURA. We describe several options for the FFAG machines, all producing a beam power of 5 MW. In conclusion an outlook on 'new' ideas concerning nonscaling FFAG's including nondispersive straight sections and their advantages is given.

1. Introduction

For the design of a pulsed spallation neutron source two architectures are feasible: a) a linear accelerator followed by a ring machine, with an orbit period of a little more than the required length of the proton pulse (~1 μs), or: b) an induction linac, which can produce the desired pulse length directly. As induction linacs for high power proton beams have never been built and operated and their estimated price appears high[1] compared to architecture option a), so far only this option has been investigated in more detail[2–5]. One of the major design criteria for high power accelerator facilities is the requirement of extremely low beam losses ($<10^{-5}$), in order to allow 'hands on' maintenance and repair, and to have remote handling facilities only at areas beforehand determined where the beam is disposed of in emergency or in a test period. Beam losses are the main reasons limiting the performance of the existing spallation sources at Rutherford Appleton Laboratories in England and Los Alamos Laboratories in the USA. In the linac-ring scenario there are unavoidable losses at injection into the ring, because the 'stripping injection method' used to modify the phase space density of the incoming beam through the non liouvillean stripping process. The stripping of the incoming H^- beam produces a charge

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state distribution of H^-, H^0 (in excited Rhydberg states), and of the desired protons, with the relative abundance of the charge states depending on thickness of the foil and energy of the incoming beam. The amount of the undesired H^- and the excited H^0 beam is of the order of one to two percent. We think therefore, that it is best to inject at an energy as low as possible, to minimize the damage produced by the particles lost during injection, because this damage is proportional to the power contained in the lost beam. Therefore the major part of the beam power should be rather gained in the ring accelerator, than in the injector linac.

2. The Fixed Field Alternating Gradient Accelerator

The ring accelerator we have looked at is a Fixed Field Alternating Gradient (FFAG)[6] machine, and we have studied three versions, all producing a beam power of 5 MW. The FFAG machine is a circular machine which has properties of a synchrocyclotron and of a synchrotron. It uses DC magnets but the frequency has to be modulated, just as in synchrocyclotrons, however for the FFAG generally only by 10–20% compared to the 40–50% for synchrocyclotrons. The working point in the tune diagram for a FFAG is fixed as in synchrotrons. The beam is injected into the FFAG at an inner radius, the injection radius, and then accelerated and spiraling out to the extraction radius, somewhere between 1 m to 4 m larger than the injection radius. This requires relatively large magnets, the price one has to pay for using DC-magnets. Inherently the FFAG is a pulsed machine, like the synchrocyclotron, and therefore well suited for the production of pulsed proton beams. At the extraction radius the beam is kicked out of the machine using a fast kicker, and then transported to the target. The beam quality of the FFAG, like in synchrocyclotrons, is not extremely high, but that is exactly what one wants for high power beams, because one needs large size beams at the target, in order not to destroy the targetwindow or the target. We will now describe several FFAG-options, all laid out for a beam power of 5 MW. The obvious advantage of an FFAG over a linac–storage ring option or a linac–synchrotron version is the possibility of using a higher repetition rate. Frequencies of 200 to 250 Hz are quite feasible, opening up the possibility to use multiple targets with repetition rates of e.g. 200Hz, 50Hz, and 10 Hz respectively. The FFAG options discussed below range in the repetition rate from 50 Hz to 200 Hz, with the higher repetition rate demanding more RF power in the FFAG and also a higher repetition rate for the linac injector.

2.1 The high energy 50 Hz FFAG-option

When the ESS study was initiated in 1991 in Simonskall one of the options considered, was a 430 MeV linac injecting into a 3.2 GeV FFAG at 50 Hz. We studied quite a range of machines for this option, varying magnetic field, number of sectors, field index k, as well as the radial and vertical tunes. Finally we looked into the feasibility of producing the required magnetic field, building the magnets, designing the RF-system, and looking at the dynamic aperture of the machines we considered. We had set the extraction radius to 45 m, and depending on the magnetic field data the injection radius varied between about 41.5 m and 42.3 m, giving a radial extent from 2.7 m to 3.5 m, obviously rather large magnets. Furthermore it became clear, that for a machine with such a high field index k, which we needed to avoid crossing γ_{tr} and to reduce the radial width, the dynamic aperture decreased dramatically with increasing vertical betatron amplitudes. Also an energy gain factor of about 7.5 seems rather large for a convenient FFAG machine, leading always to a rather large radial extent. When we looked into the cost of such a machine we concluded, that it would be a rather costly option for a 5 MW 50 Hz spallation source. In that case it would be less expensive to built a 50 Hz rapid cycling synchrotron, going from 430 MeV to 3.2 GeV, provided the multiturn injection and capture problem can be solved, as is indicated by the Argonne study[7]. The parameters of one version of a 430 MeV–3.2 GeV at 50 Hz are shown in Table 1, column 1.

2.2 A 50 Hz 800 MeV to 2.5 GeV FFAG-option

The study of this version was proposed at a meeting in Müden in December of 1993 by G. Bauer. It was to be compared with the 800 MeV – 3 compressor ring option proposed by our colleagues from RAL. We set the extraction radius of this machine to 38 m, and again varied the different field parameters to optimize radial width, mechanical dimensions, and dynamic aperture for the FFAG. We also had studied the magnetic field data and had come to the conclusion, that a maximum field of 5 T is quite feasible. The radial extend of this machine is 1.7 m, it has 24 sectors, and radial and vertical tunes of 4.78 and 3.29 respectively. This machine unfortunately does not use a low energy injection and it needs quite a detailed study to ensure the low losses required for the incoming 1.6 MW beam. The parameters for this machine are shown in table 1 column 2. A cost estimate of this machine has been given elsewhere[8] , and the investment cost for the FFAG including shielding and tunnel is 207 MDM. The cost per MW of beam power gained in the FFAG is approximately 66 MDM.

2.3 A 100 Hz 430 MeV to 1.6 GeV FFAG-option

This FFAG option was considered, when it appeared that the high energy version with an extraction energy of 3.2 GeV would not be competitive from cost considerations. We then set out to find the optimum parameters for a 5 MW machine. We set the extraction radius to 26 m with a maximum magnetic field of 4 T. The radial extent of this machine is 1.7 m and the field index k = 11.8. There are 16 sector magnets. The radial and vertical tunes are 4.26 and 3.26 respectively. There are 10 RF-cavities needed to produce the required energy gain per turn of 200 kV, each capable of delivering 26 kV. The RF-frequency modulation is 19%. The beam dynamics of this machine also are quite comfortable, giving a value of more than 83000 π·mm·mrad at zero vertical amplitude and 32000 at an amplitude of 5 cm. The technical requirements for this machine are quite conservative and can certainly be obtained. The parameters of this FFAG are given in table 1 column 3. We have studied the cost for this machine in more detail and conclude that the total cost for such an FFAG including shielding and tunnel, is estimated to be 180 MDM. The cost per MW of beam power gained in this FFAG is about 49 MDM. A cost breakdown is given in Table 2.

3. Cost Estimation Procedure

In order to get an idea of the relative cost of the different FFAG options we have looked at, we have set up a table calculation program, which gives us the estimated cost for the machine components. For instance to get the cost for a magnet, we calculate the total amount of steel needed for yoke and pole, and then use the cost for steel (3 DM/kG) and machining (3 DM/kG). For the vacuum chambers we estimated 300 TDM per magnet and for support and alignment 150 TDM per magnet. The cryogenic coils are estimated to 1.08 MDM per magnet. Clearly this estimates are based on a mixture of educated guesses and solid information. For comparisons of different FFAG-options as far as their price is concerned however it is quite reliable. Of course to estimate the cost of a linac–FFAG facility the varation of cost for the linac with linac energy and required beam current have to be looked at.

4. Conclusion and outlook

We have looked at the possibility of using an FFAG as ring accelerator for a high power pulsed spallation source. In most cases we limited ourselves to investigate so called 'scaling' machines, where the orbit are simple photographic images of each other at all energies. This means, that if one has found a solution for one energy, all other energies are outomatically stable also. This procedure is necessary when one wants to scan a large variation in the parameter

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

	a	b	c	
Max Energy	3200	2500	1600	MeV
Inj Energy	430	800	430	MeV
Inj Radius	41.57	36.31	24.3065	m
Ext Radius	45.00	38.00	26	m
Max +B field	4.00	5.00	4.00	T
Min +B field	1.04	2.31	1.81	T
Max –B field	–3.00	–1.70	–2.0	T
Min –B field	–0.78	–0.79	–0.91	T
Field Index k	16.66	17.41	11.8	
Repetition Rate	50	50	100	Hz
Number of Sectors	24	24	16	
Azimuthal Cell Length	11.78	9.95	10.21	m
Straight Section Length	7.94	7.11	7.447	m
Average Current	1.56	2.00	3.13	mA
β=v/c max	0.97	0.96	0.93	
β=v/c min	0.73	0.85	0.73	
$B\rho$ max	13.44	11.03	7.87	T·m
$B\rho$ min	3.32	4.88	3.32	T·m
radial width	3.426	1.69	1.694	m
Ions Number/Pulse	1.95	2.50	1.95	$*10^{14}$
(+) Plateau Width	6.75	3.03	4.53	%
(–) Plateau Width	2	2.73	1.5	%
Approx. Magnet Width	3.84	2.29	2.76	m
Vert. Beam Size (95%)	33.84	99		mm
Spiral Angle	4.86	0	0	deg
Q_x	4.75	4.78	4.26	
Q_y	3.75	3.29	3.26	
x: phase adv/cell	71.25	71.70	95.85	deg
y: phase adv/cell	56.25	49.35	73.35	deg
W_x for z=0	453000	740239	83412	π·mm·mr
W_x for z/R=0.001	28183	59301	32219	π·mm·mr
Harmonic Number	1	2	1	
Max Acc. Time	0.018	0.018	0.009	sec
Energy Gain/turn	179.83	92.40	200.0	kV
Max RF Freq.	1.03	2.42	1.7052	MHz
Freq. Swing Ratio	1.27	1.09	1.1934	
Number of Cavities	11	6	10	

Table 2: FFAG Cost (type c)

All Magnets Cost	45	MDM	Total Shielding Cost	7	MDM
Total RF Cost	53	MDM	Total Diagnostic Cost	18	MDM
Instrumentation Cost	41	MDM	Tunnel Cost	15	MDM
			Investment Cost	179	MDM

space in order to find an optimum. However this also means, that there are further steps of optimization possible if one uses nonscaling machines with special insertions like non dispersive straight sections[9]. In that case however the machine has to be checked at each energy, as far as stability and dynamic aperture is concerned. The advantage of such nondispersive straight section is, that the beam goes through this section along the same orbit at all energies so relatively small RF cavities with accordingly high RF amplitudes can be used for the acceleration. It even appears to be possible to design the non scaling FFAG in such a way, that the necessary frequency modulation is so small, that even a constant frequency could be used with rather high RF amplitudes of several 100 kV, like for instance in the cavities of the PSI ring cyclotron[10], in which case the beam would be accelerated with a rather large energy gain and relatively few turns to the extraction radius and the question of getting close to resonances or even passing through a resonance will be quite alleviated. Further studies need to be made to investigate these questions, and we hope to report on the results shortly.

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