FFAG STUDIES FOR A 5 MW NEUTRON SOURCE

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Abstract

Based on the requirements for a future European Spallation Neutron Source: 5 MW of beam power, a pulse repetition rate of 50 Hz, and a pulse length of less than 3 µs, we looked into the possibility of using different FFAG options for this source. Starting with an H^--linac, the beam will be accelerated to an energy between 400 MeV and 500 MeV and then transferred into an FFAG using stripping injection. We have looked at FFAG options giving final energies between 3.2 GeV and 1.6 GeV.

1. Introduction

The FFAG (Fixed Field Alternating Gradient)-Accelerator was invented in the fifties by the MURA group[1]. This group built a working electron model accelerator and performed a lot of beam studies with this machine, including beam stacking experiments. Unfortunately however a proton version was never built, because of the successful operation of the proton synchrotrons. We feel however, that it is necessary to look if an FFAG could be an option for a high intensity accelerator needed for a high power spallation neutron source. The FFAG can be considered as a ring synchrocyclotron (in the Russian literature: ring phasotron[2]) which like the synchrotron has a fixed working point in the resonance diagram. In the following we want to explain the general features of FFAG accelerators and give reasons why we think it worthwhile to investigate the possible usefulness of such an accelerator for a spallation neutron source.

2. General Features of FFAG Accelerators

We will first list what we consider advantages of the FFAG and then look at the points which can be made against using such a machine for a spallation neutron source facility.

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-The more powerful existing spallation sources are limited by the beam losses encountered during operation. Therefore the limitation of beam losses must be an essential design criterion for a new facility. Because of the required pulse structure, and the short beam bursts demanded, a linear RF-accelerator alone cannot fulfill these specifications. Therefore a storage ring or a ring accelerator must be added to provide the time structure. An induction linear accelerator recently discussed[3] as an option which would eliminate the need for a ring, seems not to be competitive for cost reasons. Experience has shown, that in the stripping injection process of the H^--ions into the ring accelerator about 2% of the beam is lost. Because the neutron production and therefore the activation of accelerator parts is proportional to the beam power, it is advantageous, to inject into the ring at the lowest possible energy acceptable by space charge considerations, and to gain the major part of the beam power during acceleration in the circular machine as it is done in an FFAG.

- The magnetic field of the FFAG is constant in time and therefore only the RF-frequency needs to be varied and losses due to incomplete tracking of magnetic field and RF-frequency do not occur. It is a generally accepted assumption, that in the FFAG there will be essentially no losses during acceleration.

- Assuming we will inject the linac beam into the FFAG with the RF-voltage turned of and then adiabatically trap the beam, the time structure for the injector linac is quite relaxed because no chopping will be needed. Preliminary studies indicate trapping losses at about the 1% level[4], and furthermore these losses are again at low power and they can be dumped into a specifically designed beam stop.

-Accelerating in the circular machine to a higher energy means one can for the equivalent power accelerate less current and therefore intensity dependend critical effects will be reduced.

-The radial aperture of an FFAG is large and so is the momentum acceptance.

-Stability conditions are good, because the beam does not see the extraction kicker ferrites except for the last few turns. Coherent instability problems are therefore relaxed.

-The FFAG can easily be upgraded to a higher repetition rate thus possibly serving additional targets simply by adding RF-cavities.

-Another option for the future is the possibility of beam stacking for intensity upgrading and reduction of the repetition rate. The option of stacking however hinges very much on the control of beam losses, and therefore again these questions need to be addressed seriously.

We think that all these properties of the FFAG clearly indicate, that a carefull evaluation of this type of accelerator needs to be made, before one can rightfully say that the FFAG is not an option for the spallation source.

The main argument against the FFAG is, that it has never been built, and therefore lacks the the experience of over 30 years of engineering and developments which synchrotrons have received. The design and development of synchrotrons and storage rings is well understood, while designing and building an FFAG means we are entering into a field where some unknown difficulties might be expected. Even so all the individual components are well understood the combination of all of them into one machine, and the need for all of them to work simultaneously to make the FFAG perform, is a scary thought for many, especially when a facility has to be built, which should have a very high reliability.

-Any evaluation of reliability and performance can therefore not be based on the experience of an existing machine but rather needs special discussion.

-The FFAG magnets are very large, superconducting, with a high flux of up to 4 Tesla. The radial type magnets are not complicated, but so far no prototypes have been built and studied.

-The operation of superconducting coils close to a high intensity beam requires again special attention to particle losses, and their effect on the superconducting coils.

-The working point of the FFAG is determined by the hardware of the magnets, and special systems like e.g. pole face windings need to be built for fine tuning.

-The ferrite tuned-cavities require large ceramic windows for the acceleration gap. Other concepts for tuning of the cavities need to be looked into and require additional studies.

-The high beam intensity requires special studies of beam loading effects.

-The shielding for the higher beam energy is more costly.

-Operational costs for an FFAG cannot be based on experience, but again require special discussion and study.

3. Discussion of FFAG Options

In the range between 1 GeV and 3 GeV, the required proton beam power for a given thermal neutron flux is approximately independent of the proton energy. We have therefore concentrated on this range of energies with a preference toward the higher energy because this requires lower beam intensities. The repetition rate of 50 Hz is specified by the user community. For the RF harmonic we select the first or second in order to avoid the coupled bunch instabilities. So far we have concentrated on scaling FFAG options, where the average magnetic field increases with average radius as $\langle R\rangle^k$. Gamma transition is given by $\gamma_{tr} = \sqrt{(k+1)}$. We choose the FFAG ring parameters such to prevent the crossing of γ_{tr} in order to avoid the excitation of strong longitudinal beam oscillations, possible beam blow-up, and, in the worst case, particle losses. If we assume 2×10^{14} accelerated particles - a number achieved in the CERN synchrotrons - the final energy at 50 Hz repetition rate must be 3.12 GeV. For a Laslett tune shift of 0.2 we get with 2×10^{14} protons an injection energy of 430 MeV. Using these data we have looked into the possible FFAG options, which we will describe in the following.

3.1 The 3.2 GeV FFAG

The relativistic γ at 3.2 GeV is about 4.4, consequently we want the field index k to be not

Inj. Energy	430 MeV	Q_x	5.75
Max. Radius	45 m	Q_y	2.75
Radial Width	2.8 m	Max. RF-Frequency	1.03 MHz
Field Index	21	Frequency Swing	25 %
Nr. of Sectors	20	Min. Orbit Period	968 ns
Max. B_+-Field	4 T	Cavity Voltage	20 kV
Max. B_--Field	2 T	Min. Nr. of Cavities	10
Spiral Angle	17 °	Repetition Rate	50 Hz

Table 1. Parameters for a 3.2 GeV FFAG

smooth beam envelope), we will need about 20 sectors. The radius should be larger than 40 m in order to provide adequate space for the RF cavities, the injection and the extraction systems. The radial width of the magnets is determined by the field index, k, and the injection and extraction energies. The parameters of a version of a 3.2 GeV FFAG are shown in table 1. Further details of this machine have been given earlier[5] A closer look at a machine with these parameters convinced us, that it would be to much of a challenge to try to build this accelerator. The magnets with a 2.8 m radial extent of the usefull field were calculated and the required field seemed to be achievable. However a rough estimate of the magnet cost resulted in a price of about 10 million DM. Also the amount of ferrite needed for the 10 cavities came to over 24 m^3. Calculations of the dynamical aperture of this machine also indicated a rather large reduction in the aperture as soon as we introduced sizeable vertical oscillations. We attributed this to the rather strong nonlinearities due to the large field index and the spiral angle. Therefore we looked into another option, namely a FFAG with a maximum energy of 1.6 GeV.

3.2 The 1.6 GeV FFAG

The reduction of the maximum energy to 1.6 GeV at the same injection energy of 430 MeV and the same repetition rate results in a beam power of 2.5 MW. We therefore considered to design the FFAG for a repetition rate of 100 Hz, with the possibility to start with 50 Hz at 2.5 MW and then try to investigate the option of beam stacking at an intermediate energy. With a two to one stacking we could then again deliver 5 MW at 50 Hz, provided the losses in the stacking process can be kept small and under control. The following table shows the parameters of the 1.6 GeV FFAG. Further information on this option has been presented elsewhere[6]

Inj. Energy	430 MeV	Q_x	4.26
Max. Radius	26 m	Q_y	3.26
Radial Width	1.8 m	Max. RF-Frequency	1.72 MHz
Field Index k	11.8	Frequency Swing	19 %
Nr. of Sectors	16	Min. Orbit Period	586 ns
Max. B_+-Field	4 T	Cavity Voltage	20 kV
Max. B_--Field	2 T	Min. Nr. of Cavities	10
Spiral Angle	0 °	Repetition Rate	100/50 Hz

Table 2. Parameters for a 1.6 GeV FFAG

Another option could be not to try to gain the total energy in one ring, but rather to use two rings instead. By operating the first ring on the first harmonic of the RF frequency and the second ring then on the second harmonic, one again could get a two to one reduction of the repetition rate. The extraction energy of the first and thus the injection energy of the second ring would need to be optimised, for either a phased construction or the cost. This aproach is considered by the Argonne people. The parameters for the 1.6 GeV FFAG appear quite acceptable, as far as building such a machine is concerned. With the considerably lower field index k and the absence of any spiral angle the dynamic aperture is not as sensitive to vertical oscillations and reasonably large.

4. Conclusions

The next steps we need to take are to settle on the best option for a 5 MW source, and then to investigate in detail all the questions which have not been addressed so far. We have convinced ourselves, that the construction of all the hardware is possible, with all the required properties given by the parameters shown. The magnets with the required fields are possible (see Fig. 1), the RF-systems with the necessary frequency swing can be built (see Fig. 2) and it is possible to inject the beam into and extract it from the accelerators. However none of the details has been worked out yet. An optimised injection scheme can only be calculated, when the ring parameters are settled, and the same is true for the extraction scheme. It might be necessary to even deviate from the circular shape of the FFAG and include dispersion-free long straight sections, as described earlier[7]. This might be quite helpful for the design of an optimised injection system.

Clearly there are a host of details which need to be looked at, and it appears to us it would be an act of negligeance if one would not study these questions and then decide for or against the FFAG after a reasonable basis for this decision has been found.

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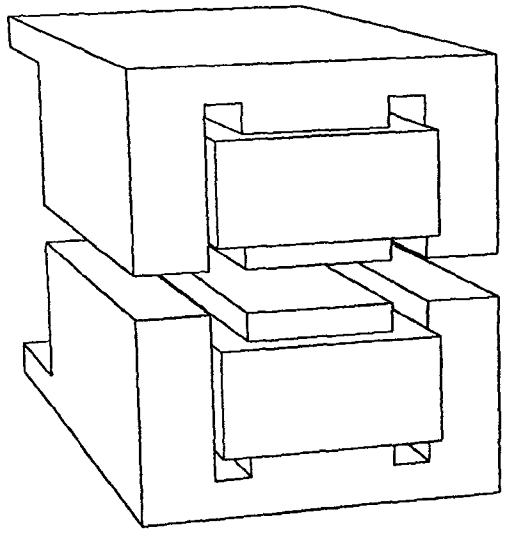

Fig. 1 FFAG magnet scheme with 4 T peak field and reverse "gulley" fields to -2 T.

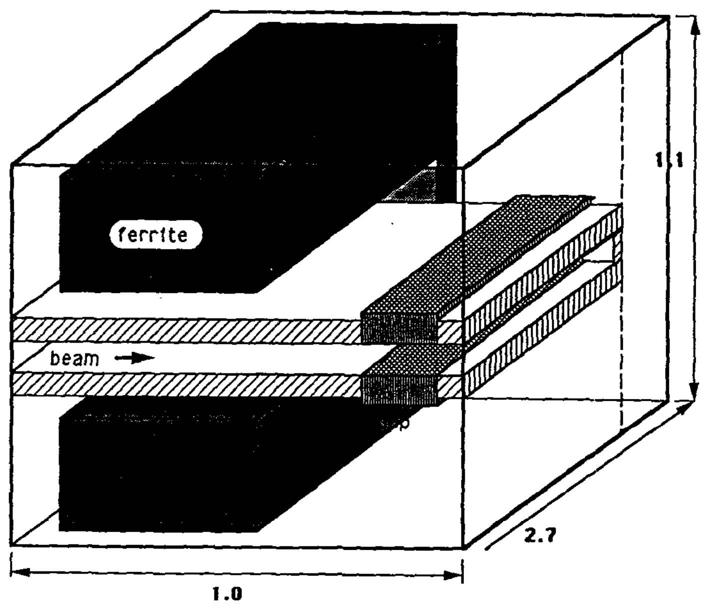

Fig. 2 Geometry of a possible FFAG cavity.