AN FFAG COMPRESSOR AND ACCELERATOR RING STUDIED FOR THE GERMAN SPALLATION NEUTRON SOURCE

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Introduction

For the German spallation neutron source (SNQ), a design of an 1100 MeV proton linac is in progress.[1] The goal of this linac will be a mean current of 5 mA, a repetition rate of 100 Hz and a pulse length of 250 µs. As an alternate to this approach, we are checking the feasibility of a circular machine that would be able to compress and to accelerate the beam. This ring (Fig. 1) would need an injection linac of 350 MeV. The final energy would be variable between 1100 MeV and 1500 MeV. As a design goal, this circular machine would deliver a mean current of 5 mA with a repetition rate of 100 Hz, and the length of the extracted pulse can be chosen between 200 ns and 500 ns. This ring would greatly improve the spectrum of applications of the spallation source, especially in the fields of neutrino-, muon- and epithermal-neutron research.

Choice of the Machine

The FFAG seems to be the only machine which fits all these design requirements. It has a dc magnetic field to guide the particle on its orbit. This field can be shimmed and trimmed as accurately as is needed to reduce any particle losses. The vacuum tank can be stainless steel as there exist no Eddy currents to alter the field distribution. Particles that are not trapped at injection or are lost from the bucket during acceleration are not swept out of the chamber thus causing activation. This is a very important argument for a high-current accelerator because it is possible to make the losses and consequent activation much smaller in this machine compared to a machine with a pulsed guiding field.

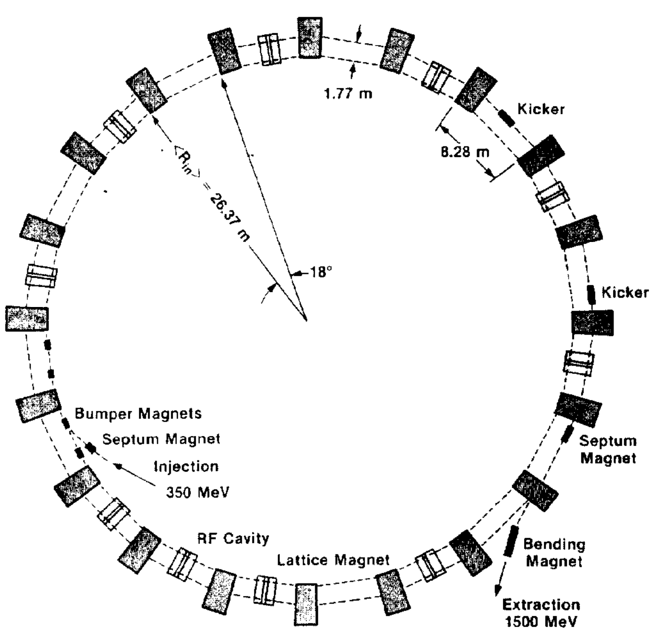

Fig. 1. General scheme of the radial FFAG ring.

The synchrotron-mode acceleration of the beam can be done in a way to minimize particle losses. There is no time-dependent magnetic field that defines the speed of acceleration. The acceleration scheme can be better adjusted to adiabatic requirements, especially during the capture of the beam.

There are two basic principles to design an FFAG, the spiral and the radial type. The spiral type is discussed in several papers.[2] The radial type was, up to now, not seriously considered as a driver of a spallation source because it uses the magnetic field less efficiently. However, by building it with superconducting magnets, it becomes a very promising machine.

Conceptual Design of a Radial FFAG Lattice

Applying the smooth approximation, a simple estimate of the main ring parameters is possible.[3] In this approximation, the tunes in a radial FFAG are given as[4]

$$Q_x^2 = k + 1 + k^2G^2$$

$$Q_y^2 = -k + k^2G^2 + F^2/2.$$

The magnetic field in the midplane is given as

$$B(R,\theta) = B_o(R/R_o)^k \sum_{n=o}^{\infty} (g_n \cos nN\theta + f_n \sin nN\theta),$$

where R is the radial distance from the center of the machine, B_o is a reference field at the distance R_o, k is defined by (R/B)(dB/dR), θ is the azimuthal variable, g_n and f_n are the Fourier harmonics of the field and, for a scaling machine, are independent of the radius, N is the number of periodic lattice cells along the beam orbit. F^2 and G^2 are defined as

$$F^2g_o^2 = \sum_{n=1}^{\infty} (g_n^2 + f_n^2)$$

$$2G^2g_o^2N^2 = \sum_{n=1}^{\infty} (g_n^2 + f_n^2)/n^2.$$

For a lattice consisting of one positive and one negative step function bending magnet (inset, Fig. 2), we can calculate F^2 and G^2 analytically and find

$$F^2 = 2\left(\frac{2\pi}{N}\frac{P+M}{(P-M)^2} - 1\right)$$

$$G^2 = \frac{1}{3}L^2 + \frac{1}{3}\frac{PM}{(P-M)^2}\left[3L^2 + 2L(P+M) + PM\right].$$

The magnetic rigidity Bρ of the particles in this notation is given as $B\rho = B_o R\,N(P-M)/2\pi$, where the field in the magnet is given by B_o. With these relations, a coherent set of parameters can be easily generated. Interesting solutions will also exist for M=0 (positive magnetic fields only) and, what is not considered here, solutions with additional small spiral angles.

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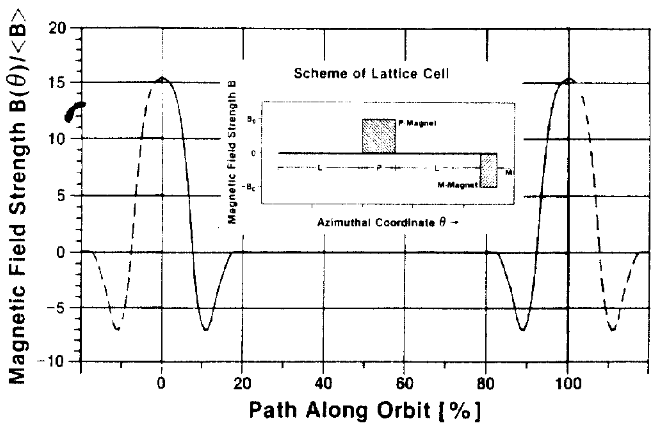

Fig. 2. The azimuthal profile of the magnetic field along one lattice cell. The calculations of the orbit dynamic is based on this field. The inset shows the azimuthal field profile which is used for the smooth approximation.

In most cases, k^2G^2 is small compared to k or $F^2/2$. Taking the equation for the tunes and ignoring for the moment the term k^2G^2, we find

$$(Q_x^2 + Q_y^2)(B\rho/B_oR)^2 = N(P+M)/2\pi.$$

As a very important result, we see that the total length of all necessary magnets, N(P+M), is inversely proportional to the square of the applied magnetic field B_o. By using superconducting magnets instead of normal conducting magnets, one can easily reduce the total length of all magnets by one order of magnitude and gain a lot of available space between the magnets.

The result of the smooth approximation is very useful to get a first set of design parameters. We got k = 14.2, P = 0.74 m and M = 0.15 m (only those parameters which differ from Table I). A refined calculation was done with the program "ORBIT".[5] With a magnetic field, as shown in Fig. 2, we got the parameters of Table I. This magnetic field was derived with a set of 4 infinitely long conductors.

Table I
Lattice Parameters

Radial Tune Q_x	4.25
Vertical Tune Q_y	3.25
Lattice Cell Length	8.84 m
Max. Field	4 T
Number of Sectors N	20
Field Index k	13.4

The field outside the coils was artificially damped to zero.

At this stage of design, the magnet is not at all optimized. However, a first two-dimensional calculation[6] with "TRIM" reproduces easily the required azimuthal field distribution by using a combination of one plus and two minus magnets consisting of a warm iron core and superconducting coils.

Table II shows a set of the main ring parameters.

Table II
Main Ring Parameters

Injection/Extraction Energy	350/1500 MeV
Injection/Extraction Radius	26.37/28.14 m
Injection/Extraction RF Frequency	1.241/1.566 MHz
Space Charge Limit	$3.12 \cdot 10^{14}$
Radial/Vertical Beam Emittance	950/750 $\pi \cdot 10^{-6}$ rad m
Maximum RF Voltage per Turn	200 kV
Harmonic Number	1
Average Current	5 mA
Repetition Rate	100 Hz

Orbit Dynamics

Some basic orbit properties of the lattice shown in Fig. 2 are calculated by using the program "ORBIT". Some results of this integration code are reproduced in Figs. 3 to 5.

Compared to the previously studied spiral type FFAG, the radial type FFAG with a 4-T magnetic field has several important advantages.

There is more space between the magnets for a fixed length of the lattice cell. This will simplify the design of the rf cavities, and there will still be sufficient space for beam diagnostics, stabilization systems, injection and extraction devices. The stable areas of the vertical and radial phase spaces for the beam is much larger. This will make the machine less sensitive to field errors and misalignments. The vertical tuning of the machine will be much easier. By changing the strength of the plus and minus bending magnets, but keeping the integrated deflection of the beam per lattice cell constant, one can easily adjust the vertical focusing of the beam. The required k-value, which mainly defines the radial tune, can be adjusted by a set of pole-face windings, as in the spiral machine.

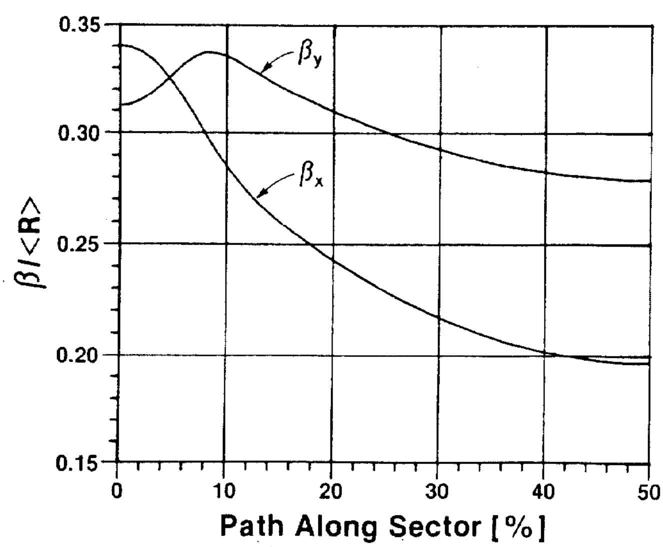

Fig. 3. The Courant-Snyder β-functions for half of the sector.

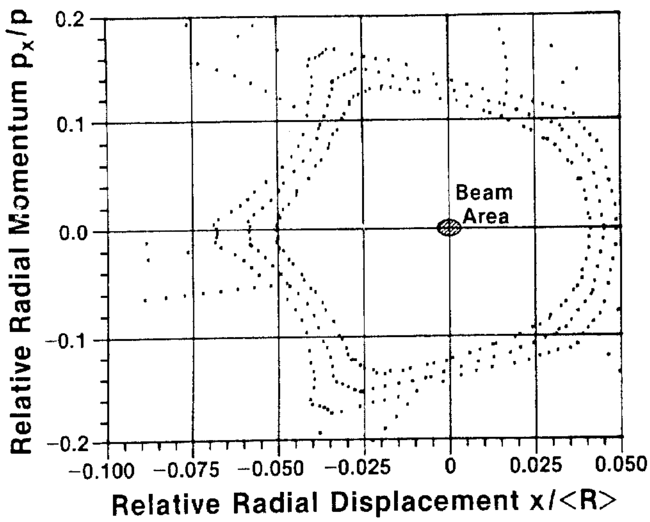

Fig. 4. Radial phase space plot near the stability limit. The dashed area corresponds to a radial beam emittance of $650\cdot10^{-6}\pi$ [mrad].

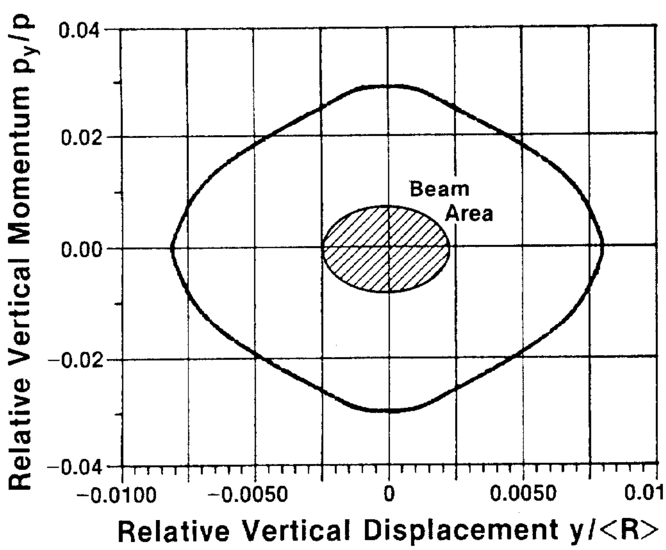

Fig. 5. Vertical phase space plot near the stability limit. The dashed area corresponds to a vertical beam emittance of $500\cdot10^{-6}\pi$ [mrad].

Injection, Acceleration and Extraction

A pulse of $3.12 \cdot 10^{14}$ negative hydrogen ions, accelerated by the linac injector to an energy of 350 MeV, will be injected in 250 μs via a multiturn charge-exchange method. The coasting beam will be carefully captured by slowly turning on the rf voltage. The time required for an adiabatic capture, one half synchrotron oscillation period or longer, can be accommodated without any problems in an FFAG synchrotron. The acceleration will be done on the first harmonic by 20 single-ended cavities which will deliver 200 kV per turn. A fast feedback, cathode follower system compensates beam loading and controls the Robinson instability. A feasibility study of the rf system has been done by W. Wilhelm.[7] At the end of the acceleration, the bunch will be shaped to the desired length (between 200 ns and 500 ns), extracted by a fast kicker system and transported to the target. The kicker, septa, and bending magnets can be moved to allow extraction at any energy between 1100 MeV and 1500 MeV.

Discussion

This is not at all a complete design of an FFAG accelerator. Several topics are similar to the more familiar (pulsed) synchrotron, injection, extraction and acceleration schemes and all kinds of coherent instabilities (and therefore better known). Typical problems unique to the FFAG, and therefore not so well known, are orbit dynamics and magnet design. The program "ORBIT", a special FFAG orbit integration code, is discussed in these proceedings.[5] The design of the magnets, which is now very preliminary, is one of the most important future topics. Up to now, there seem to be no special problems or technical risks. A radial magnet type might be more easily built than a spiral type. The first results in studying this machine are very encouraging.

Future developments to improve the properties of the machine are still possible. Especially, stacking of the beam at a high energy orbit, which will reduce the repetition rate by about a factor of 3 but will keep the mean current constant is of high interest for the users. One also can easily double the rf voltage per turn; there will be sufficient space available. In this way, the mean current can be doubled, and one can supply a second spallation target.

Acknowledgment

This work was done in a very close and friendly cooperation with the ASPUN[2] design team of Argonne National Laboratory. We gratefully acknowledge their support and hospitality.

References

1 C. Zettler, "The Linear Accelerator and Pulse Compressor of the SNQ Project," Proceedings of the 1984 Linac Conference, GSI-84-11, p. 480.

2 R. L. Kustom, T. K. Khoe, E. A. Crosbie, "A 1500-MeV Fixed-Field Alternating-Gradient Synchrotron for a Pulsed Spallation Neutron Source," these proceedings (1985).

3 G. Wüstefeld, "Conceptual design of a radial FFAG Type Lattice," Argonne National Laboratory Internal Report No. ASPUN-10 (4/18/85).

4 F. T. Cole, "Typical Designs of High Energy FFAG Accelerators," International Conference on High-Energy Accelerators and Instrumentation, CERN 1959, p. 82.

5 P.F. Meads, Jr., "A New FFAG Orbit Code," these proceedings (1985).

6 R. J. Lari, ANL, private communication 1985.

7 W. Wilhelm, "Studie über das HF-Beschleunigungs system für den an der SNQ vorgeschlagenen FFAG-Ring-Beschleuniger," to be published as an internal SNQ note (ABT-NOTE), KFA 1985.