

INDUCTION FFAG FOR ACCELERATOR DRIVEN REACTOR

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Abstract

To operate a sub-critical reactor with a high-intensity proton accelerator, I propose using an induction fixed field alternating gradient (IFFAG) accelerator. This multi-orbit accelerator, which uses a static, fixed magnetic field for strong focusing, can readily accommodate a proton beam with a high space charge accelerated by an induction cell. Furthermore, it is free from a wake field and also from the electric field associated with electric breakdowns, which are a major concern in RF generation in an acceleration cavity. In these ways, the reliability of the acceleration can be improved. A tandem type of circular accelerator can be a compact one, and can be built for less cost than a linear accelerator.

1 ACCELERATOR DRIVEN REACTOR(ADR)

At BNL, we have been promoting the use of an accelerator-driven reactor with a slightly subcritical operation. After creating spallation neutrons by injecting medium-energy protons into a heavy metal target and using them as a neutron source for the sub-critical reactor, the operation becomes safer than under critical conditions[1]. A fast reactor with a hard neutron energy-spectrum has a high neutron economy and efficient fissile-fuel production; further, minor actinides are transmuted effectively. However, the delayed neutron portion is small and neutron lifetime is shortened, so that the operation of this reactor is no safer than that of a critical reactor without a hard neutron-energy spectrum.

The deep subcritical reactor is not necessarily safer than a slightly sub-critical reactor because of the high peaking factor in heat generation for the localized spallation- neutron source. A transmutor with highly concentrated minor actinides has a very small Doppler coefficient; it was suggested that it should be run in a deep-subcritical condition[2]. However, the Doppler coefficient can be increased by employing a fertile material, such as thorium. Thorium ensures a long burn-up of the fuel, and also produces fissile material that is more resistant to proliferation than is Pu - uranium fuel. A slightly subcritical reactor can be driven by a circular accelerator, such as a cyclotron or a fixed field alternating gradient accelerator, both of which are much more economical than is a linear accelerator. Although presently, the cyclotron has limited power so that several machines are required to drive a high-powered subcritical assembly, the use of

multiple cyclotrons can provide a steady supply of the power to the consumer.

2 FIXED FIELD ALTERNATING GRADIENT ACCELERATOR (FFAG)

Although the cyclotron can act as a CW machine, which is most suitable for driving a subcritical reactor without incurring a shock wave, the beam's current is somewhat limited, although it was suggested that a 10 MW beam power (1GeV* 10mA.) could be attained without difficulty. The higher energy can reduce the beam's current, but extracting a high beam becomes difficult in a cyclotron.

To get a high-intensity proton beam for a circular accelerator, the fixed field alternate gradient accelerator (FFAG)[3] has been proposed; a prototype of the FFAG was successfully operated by Mori and Machida[4] at KEK.

FFAG is pulsed-beam acceleration rather than CW, so that the thermal shock in subcritical operation becomes the problem, but, by increasing the high-frequency macro pulse, this drawback can be avoided. Further, due to the bunched-beam operation and the generation of a high-response magnetic field, a succession of beams can be injected before the proceeding beam exits. In this way, the beam current can be increased.

To inject a high-intensity proton beam, Ruggiero et al suggested using the linear induction accelerator instead of stripping the electrons from negatively charged[5]. Since the linear induction accelerator is 300 meters in length, to accelerate the initial E_{in} to E_{out} , requires a large area of real estate.

3 CIRCULAR INDUCTION ACCELERATOR (CIA)

Recently, Kishiro and Takayama [6] proposed having a circular induction accelerator that efficiently uses induction acceleration by repeatedly circulating the beam via an induction cell. Thus, the accelerator can be designed as a compact one.

The induction accelerator was studied with a view to accelerating a very high peak electron current for the free electron laser, and also to accelerate ultra-high intensity heavy ions for inertial fusion applications; the latter proposes inducing 50-100 turns to get more than KA. Induction acceleration for protons might be possible with a turn number of $2 \cdot 10^4$. To get a high-intensity beam, a beam bucket can be created using a

power supply (modulator) with a frequency of 100 KHz to 1 MHz.

This circular induction accelerator uses a single track, but, by employing a multi-track orbit trajectory in the FFAG's magnetic field, the space-charge limitation can be extended further. In regular FFAG acceleration, particles are accelerated and modulated by RF. Induction acceleration, which can generate a higher acceleration field than can RF acceleration, might be more efficient than a FFAG with RF acceleration.

Since the induction-accelerator system does not have an associated wake-field in the RF cavity, the beam's track is not disturbed and each train of the beam is independent. Because induction acceleration, does not involve the breakdown of the electric fields in the cavity, its reliability might be increased more than in RF acceleration, although each beam's track must be stabilized. The beam's current in the proton accelerator is much smaller than in the electron machine. But in CW operation, using a super-conduction cavity entails a wake field having a longer lifetime; the beam then might be disturbed by this wake field.

Space charge can be reduced by spreading the beam's length using the beam bucket's potential barrier created by induction. Also, the beam can be accelerated by this induction mechanism.

4 INDUCTION FFAG (IFFAG)

In this paper, I discuss on the possibility of combining the FFAG and CIA so that the proton beam can be spread both longitudinally and transversely to reduce its space charge effects. In our Induction Fixed Field Alternating Gradient (IFFAG) accelerator[7], a modulator regulates those changes in acceleration that are carried out by RF in the regular FFAG by the induction cell.

When RF is used to accelerate a beam, the RF phase has to be matched to that of beam circulation, so that a limited portion of RF can be used. Such isochronous acceleration is mandated. When in induction acceleration the high E field is created by DB/Dt , the iso-chronous motion of the beam is not necessary.

If the FFAG incorporates a bending magnetic field, the magnet itself must be a large one to spread the beam transversely; hence it is costly. However, by focusing and de-focusing the magnetic field skillfully, a smaller bending magnet might suffice. Since the acceleration E field depends upon the intensity of the time derivative of B, the transverse dimension in accelerator section should be small to get a high B field using a small induction cell, thereby lowering the cost.

RF can be created in the high frequency range so that the beam can be maneuvered rapidly without difficulty, although phase matching, such as an iso-synchronous

beam is required. But the magnetic field cannot be generated as fast as the RF frequency.

To reduce the circumference of the IFFAG, the beam particles must be accelerated at many places, and the capacity bank discharged using a fast switching device that was recently developed. For a medium-energy accelerator, such as 1-3 GeV energy, the length of the acceleration section might be limited, so that the beam cannot be accelerated at every turn, but rather, at every few turns. For a high-energy accelerator, there is enough room to maneuver the beam in the long section, as Trojevic discussed in the FFAG for 50 GeV hadron accelerator machine[8].

The FFAG and IFFAG are not CW machines like the cyclotron. A shock wave will be created in the subcritical assembly by pulsed operation. Its magnitude can be reduced by pulsing it at a high repetition rate of more than a kilohertz, in contrast to the conventional synchrotron, and also by elongating the pulse length.

5 FURTHER STUDY ITEMS

Induction acceleration using a magnetic field is not suited for high frequency acceleration. To induce a high field, the capacitance must be charged fully before discharge to obtain a high current. There is no suitable material wherewith we can skip the beam without acceleration, and it takes a long time to reach acceleration. Alternatively, to reach high acceleration rapidly, a large capacitance is charged up, and by quickly switching it on and off, the passing beam can be accelerated without delay. The technology of high switching should be explored.

This IFFAG has a wider beam-spread than the single beam track in CIA, as discussed in Takayama's paper. To simulate and analyze these beam tracks, the computer code developed by Luccio et al., will be dispensable. We will use it to optimize the IFFAG design.

6 CONCLUSION

Although a linear accelerator can act as a high-powered accelerator due to its excellent technology and development, the cost of constructing it is high due to the need for a long acceleration building and the expense of real estate in populated area. Costs could be reduced by constructing it deep under-ground, a concept which I strongly support[9].

The circular accelerator is cost-effective and lacking the penalty of high cost, it can satisfy the demands for industrial use. The cyclotron that also is cost-effective is limited in its beam current. Using the technology of the FFAG and induction acceleration might be a helpful way to get an economical accelerator, although the analytical tools for its design are not yet established. New computer technology might provide

a design tool for unraveling its complicated beam dynamics.

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