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Requirements of a Proton Beam Accelerator for an Accelerator-Driven Reactor

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Introduction

When we first proposed an accelerator-driven reactor, the concept was opposed by physicists who had earlier used the accelerator for their physics experiments. This opposition arose because they had had nuisance experiences in that the accelerator was not reliable, and very often disrupted their work as the accelerator shut down due to electric tripping. It is still not infrequent to have tripping of the accelerator during physics experiments. While this might be tolerable in experimental work if it does not occur too frequently, for the industrial use of an accelerator, such as for power generation, the possibility of shutting off the accelerator by tripping must be eliminated; even a once-a-year stoppage is very destructive for supplying electricity energy. To prevent this, a multiple-channeled accelerator beam was suggested; however, this approach becomes uneconomical.

The operation of a storage ring for a synchrotron radiation facility is required to be a very stable beam-track operation; otherwise, precise measurements cannot be carried out with unstable photon beams. Stable beam operation is now successful even when it is not accelerating the particles.

Tripping of the Accelerator

Although very short trips of the proton beam do not affect power production due to the large heat capacity of the subcritical reactor, the lack of the beam for some short interval creates a loss of heat generation and causes thermal shock to the reactor elements.

One cause of tripping of the accelerator is the sparking of a cavity caused by the applied high electric field which generates flakes from the impurities, defects, or dust on the cavity's surface,

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resulting in electric avalanches. Table 1 shows experimental data on the X-ray doses and spark rates obtained at CERN and Fermi Laboratory during conditioning.

Near the Kilpatric electric field, the radiation dose rate from X-rays and electrical breakdown increases, respectively, with the electric field strength (E) of $E^{11+-3.9}$ power and $E^{19.5+-1.2}$ power[5]. A small reduction in the electric field drastically reduces these X-ray dose rates and sparking probabilities, while the length of an accelerating particle's track is inversely proportional to E. Thus, by slightly lowering the accelerating field and lengthening the accelerator beam's track, the occurrence of electrical breakdown in the cavity can be reduced without incurring a big economical penalty. To prevent electron avalanches, cleaning the cavity's surface by injecting clear water, eliminating impurity materials which make flakes, and conditioning are essential.

Another cause of tripping is the breakdown of the coupler between the wave-guide to the cavity, and the RF windows for its transmission. This cause also can be eliminated by reducing the high gradient in the electric field caused by sharp edges.

Spread of the Proton Beam and its Shape

To run a deep subcritical solid-fueled assembly, a high current proton beam is required; further, to reduce the need to frequently replace the beam windows damaged by radiation, the proton beam should have a wide, uniform transverse distribution, achievable by using quadrapole and octapole magnets [2]. According to our analysis, a long expansion length of 17 meters is required before injecting the 1.5 GeV proton beam with a spread of $15^{cm}x20^{cm}$ into the target assembly. A vertical injection of proton beam, like a Rubbia's Pb coolant reactor which has 30 meter depth reactor, can accommodate this length. However, when the beam power is much higher, then it requires a wider window, and horizontal injection is preferable to vertical injection for a deep subcritical reactor. Horizontal injection was adopted in our light-water fuel regenerator[3] and in Los Alamos National Laboratory's accelerator tritium producer [4].

The analysis shows that the beam spread has some peaking at its edge, but the uniformity of the beam spread is important to reduce the peaking factor of heat generation. Additional expansion length may be required to achieve uniformity. The old design of beam spreading using the

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rastering method which is used for TV beams, is not suitable for our heat generation system because a pulsed beam with a large time-interval generates a shock wave which is harmful to the integrity of the fuel and other component elements in a reactor.

Another caution in using the electric magnet for spreading the beam is the possibility of a cut off in the electricity for the magnet. When cutting off occurs, the spread of the beam is shrunken, and then a high intensity beam could instantaneously melt the windows' material, and make a hole. To prevent such an accident, some part of the expanding magnet should use a permanent magnet. The magnetic field created by a permanent magnet is of the order of 0.2 Tesla; thus, we can design the configuration such that the beam is still spread, even in this accidental situation. Also, the sharp edges created in tailoring the beam [2] should not contribute to radiation hazards in the target's design.

A liquid-fuel target without windows can alleviate many of the problems associated with radiation damage, and also mitigate the sharply peaked heat-generation from a localized spallation source.

Variable Beam Power

In some designs for the accelerator-driven reactor, the use of proton-beam power to control reactor power has been suggested.

This can be done easily for a small power change for a small reactivity change. But for a large reactivity change, like the burn up of fuel, a large change in accelerator power beam is required. This is uneconomical because the full capacity of an expensive accelerator facility then is not used, unless the beam is split to run the other subcritical reactor. Without a neutron absorber, such as control rods, the neutron economy can be increased. A reactor without control rods becomes a simple mechanical system and confers an economical benefit, but this benefit is not large enough to compensate for the economical penalty of the high cost of an accelerator facility. The use of control rods is much more economical.

When subcriticality is changed by a large amount, the spatial distribution of heat generation for the localized spallation neutron source will be changed; then, a simple change in the accelerator's power cannot accommodate it unless the subcritical reactor is a liquid-fueled reactor. The slow response time of the control rods can be sufficient to adjust to the slow change in power due to subcritical operation, and a fast change in power, which may be needed in an emergency, can be done with the accelerator.

A high-powered accelerator with a high current creates a high wake field besides an accelerating RF, and the temperature of the accelerating cavity will be affected by the power change. A large change in beam current is not desirable in terms of the beam's stability, and the beam halo created by phase mismatch increases the radiation level, an effect which should be avoided. The jittering of an unstable beam creates fluctuations of fission power in the reactor. This occurrence also should be avoided as much as possible so that the plant can have a long life, which is very important for its overall economy.

Conclusion

Accelerator technology has been impressively improved, and accelerators have been utilized in many fields. The maturity of the technology has been established by this extensive use. So far, accelerators have been used mostly for scientific research and the reliability was a secondary consideration to their high performance. But, for industrial use, especially in the sector of electric power production, reliability is the first priority and high performance is the secondary one. We have the ability to construct very reliable, economical accelerators.

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Table 1. **Experimental Data (during conditioning) of X-Ray Doses and Spark Rates**

CERN (for a 200 MHz cavity)
Dose rate 50 rad/hr @ $E_{s\,max}$, 12 MV/m Gradient: 1.32 MV/m
@ 60kW CW, 1m from the axis
0.45 rad/hr @ pulse operation with duty 0.009
(Data quoted or deduced from P.E. Fangesras et al. PAC-87.p.1719)

FERMI Laboratory (for prototype #1, 6 cells of the 805 MHZ cavity)

Dose rate/hr (at 3.6 meters) = $0.3*(E_{field}/E_{Kilpatric}=X)^{11.8+-3.9}$
Sparks/pulse (after $4*10^6$ RF pulse) = $0.7*10^{-6}X^{19.5+-1.2}$
where $E_{kilpatric}$ (800 MHz) = 26 MV/m