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Requirements of the proton beam accelerator for an accelerator-driven reactor

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The reliable operation of an accelerated beam is an essential requirement for using an accelerator in the nuclear industry[1]; this requirement is more stringent than that needed for a physics experiment.

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 quadruple and octuple magnets [2]. This configuration requires a long expansion length of 17 meters before injecting the beam with a spread of $15^{cm}x20^{cm}$ into the target assembly; 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]. If the magnets used for widening the beam malfunction, a high intensity beam can instantaneously make holes in the windows' material. To prevent such an accident, some part of the expanding magnet should use a permanent magnet with a magnetic field less than 0.5 Tesla; thus, the beam is still spread even in this accidental situation. Also, the sharp edges created in tailoring the beam [2] should not contribute 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.

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Tripping of the accelerator

The industrial use of an accelerator has more stringent requirements for operation than in a physics experiment. Especially when it is used for energy production, the possibility of shutting off the accelerator by tripping should be eliminated; even once-a-year stoppage is very destructive for the supply of electricity energy. To prevent this, a multiple-channeled accelerator beam was suggested; however, this approach become uneconomical.

One cause of tripping of the accelerator is the sparking of a cavity caused by applying a high electric field. The high electric field generates flakes from the impurities, defects, or dust on the cavity's surface, and causes electric avalanches. Table shows experimental data on the X-ray doses and spark rates obtained in CERN and Fermi Laboratory during conditioning.

Near the Kilpatric electric field, the radiation dose rate from X-rays and electrical breakdown increase, 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 probabilities, while the length of an accelerating particle's track is inversely proportional to E. Thus, by lowering the accelerating field slightly 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 surface by injecting clear water, eliminating impurity materials which make flakes, and the conditioning are essential.

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

Variable beam power.

Some designs for the accelerator-driven reactor are suggesting making a large change in proton-beam power to achieve constant reactor power, and also to eliminate the control rods that regulate the reactor's power. This requires a large change in accelerator power, and it is not economical because the capacity of an expensive accelerator facility is not fully used. A slow transient of the reactor power can be regulated with control rods, or with a liquid neutron-absorber. The latter approach can improve neutron economy because we have small absorber nuclei at operating temperature. When subcriticality is changed by a large amount, the density of heat generation for the localized spallation source will be changed; then, a simple change in the accelerator's power cannot accommodate this unless the subcritical reactor is a liquid-fueled reactor. The slow response time of the control rods can be sufficient to adjust the slow change in power due to subcritical operation, and the fast change in power which is needed for 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 for the beam's stability, and the beam halo created by phase mismatch increases the radiation level, which should be avoided. The jittering of beam due to unstable beam creates fluctuations of fission power in the reactor. This occurence should be avoided as much as possible so that the plant can have a long life, which is very important for its economy.

Reference

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(4) M. Cappiello, et. al., "ATP ^{3}He target/blanket topical report," Revision 1.0, Los Alamos Natinal Laboratory, LA-CP-94-2

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Table 1. **Experimental data (during conditioning) of X-Ray dose and Spark rate**

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