ANALYSIS OF BEAM DAMAGE TO FRIB DRIVER LINAC*

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Abstract

Damage caused by the particle beam is an important issue in a superconducting linac. The FRIB driver linac will deliver a beam on target about 1 mm in diameter, increasing beam power density significantly compared to other SRF linacs. Because the stopping power of a heavy ion beam is a few ten times larger than proton or electron beam, the situation is more severe: at full power, 400 kW, a uranium beam may cause component damage in less than 40 µs. A fast response machine protection system is necessary, in addition to special protection design, very careful linac beam tuning and operation. In this paper, the temperature rise of niobium and stainless steel at different beam incident angles are compared, and thermal stress analyzed for nominal FRIB beam at different energies. Some protection designs are also briefly discussed.

INTRODUCTION

The Facility for Rare Isotope Beam (FRIB) is currently under construction at Michigan State University (MSU), which also hosts the largest campus-based nuclear science facility in the U.S.A – The National Superconducting Cyclotron Laboratory. As a national user facility, FRIB is funded by Department of Energy (DOE). It will provide intense beams of rare isotopes for ions up to uranium for nuclear physics and nuclear astrophysics research. FRIB is based on a heavy ion superconducting driver linac which will deliver a minimum energy of 200 MeV/u for uranium at a beam power of 400 kW. The facility includes the driver linac, a production target, an in-flight fragment separator, gas-stopping stations, and a re-accelerator for fast, stopped and reaccelerated rare isotope beams [1].

As high beam power and SRF techniques are involved, component damage caused by particle beams is a concern. The issues not only include normal operations with excessive beam halo and loss in a limiting beam aperture, but also include any accelerator subsystem failure which redirects high power beams to a component other than the target. Both occasions are not expected to be rare in routine operations. In this paper, we analyze beam heating and thermal stress in stainless steel and niobium when hit directly by a nominal FRIB beam, and compare different machine protection system requirements.

BEAM HEATING

Beam heating is calculated by Monte-Carlo simulation of stopping power dE/dx in niobium and in stainless steel with the SRIM code [2] first, then we use a nominal beam size, rms radius 1 mm, and a nominal current to compute beam deposited power density in the materials. Finally, the data is entered into a finite-element code ANSYS [3] to compute temperature rise versus the beam heating time.

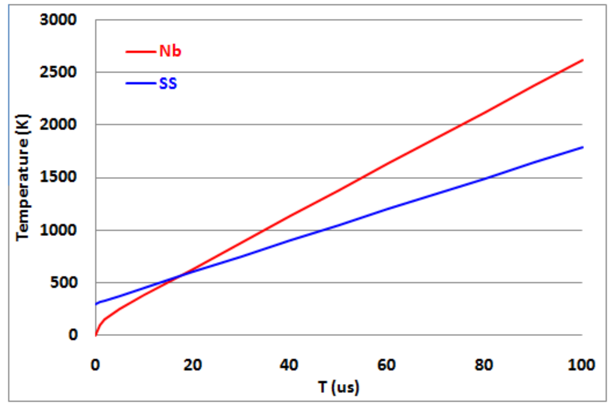

Fig. 1: Temperature vs. time of stainless steel (SS) from 300K, and niobium (Nb) from 2K, after hit by a uranium beam, 100 MeV/u, 200 kW, and beam rms radius 1 mm.

Figure 1 shows the temperature rise of stainless steel (SS, from 300K) and niobium (Nb, from 2K) after being hit by a uranium beam, 100 MeV/u and 200 kW, at 90° incident angle. In about 100 µs, both materials reach their melting points, which means component damage could happen in a shorter time. An argument is that it could be rare for a beam hit a surface at 90°, unless intentionally on a target, or accidently on a valve. However, if we ignore scattering and reflecting of particles when beam hits a surface at a large grazing angle, which is very close to the case for a heavy projectile at low energy, the relationship between incident angle and damage time is weak.

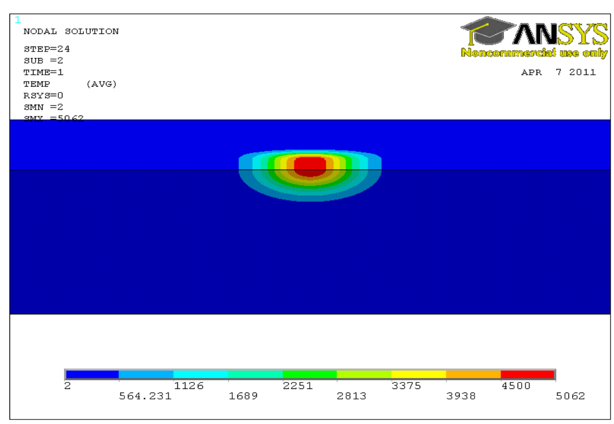

Fig. 2: Temperature of niobium, hit with a uranium beam at a 90° incident angle, after irradiation of 200 µs.

Figure 2 shows a temperature distribution of niobium after 200 µs irradiation with 100 MeV/u, 200 kW uranium beam at a 90° incident angle. Figure 3 shows that of a 15° incident angle. In reality, we could not heat niobium above its melting or boiling point, 2750 and 5017 K. Simulations are shown here only to demonstrate the

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effects of different incident angles: peak temperature merely differs about 6 percent.

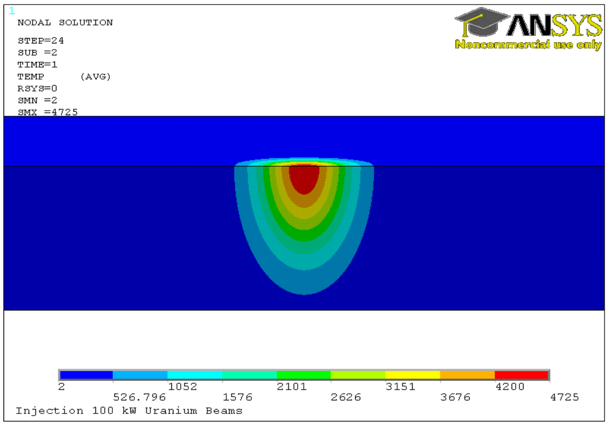

Fig. 3: Temperature of niobium, hit with a uranium beam at a 15° incident angle, after irradiation of 200 µs.

Though the cooling from thermal conduction and radiation varies with the beam incident angle, temperature rise in such a short time is mainly determined by beam deposited power density, and specific heat of the material. Incident angle is not so critical as the case of equilibrium temperature establishment. Actual component damage may happen even before the material melts, which is a consequence of thermal stress development.

THERMAL STRESS

Thermal stress can be computed with ANSYS, and after the simulation of beam heating with the same code, co-simulation of thermal stress in the materials is straight-forward. However, an analytical solution for this special case is even more convenient.

H. Takei and H. Kobayashi analyzed thermal shock damage of accelerator materials caused by a high power beam. In their analytic solutions, thermal conductivity and surface radiation are ignored, injection beam is assumed to follow a Gaussian distribution, the angle of incidence is 90°, and multiple scattering is neglected [4]. As we can see from the above simulations, these approximations are also valid to other incident angles, as long as multiple scattering of particle is not a concern.

Because beam heating, thermal expansion, and Mises equivalent stress are computed analytically, the allowable injection time limited by yield strength of the material can then be described as [4]:

$$t = \frac{4\pi}{\sqrt{3}} \cdot \frac{\sigma_x \sigma_y}{IR_{\max}} \cdot \frac{\rho c_v}{\alpha E} \cdot \sigma_m \qquad (1)$$

where, σ_x and σ_y are the horizontal and vertical rms beam radii, I is the peak current, R_{max} is the maximum stopping power of the Bragg curve, ρ is the density of the material, c_v is the specific heat, α is the coefficient of linear expansion, E is the Young's modulus, and σ_m, the yield strength.

From Eq. 1, the limiting heat density (J/g) of materials commonly found in particle accelerators are calculated, among them: copper and stainless steel 50, niobium 240, alumina 100, and titanium 80 [4]. The results are slightly less than those from numerical simulations.

In fact, beam may hit accelerator component surfaces at very large grazing angles in most of the failure modes, and scatterings in the materials and reflections from the surfaces could not be ignored completely. To address this issue, and to avoid overestimation of beam damage effects at FRIB, we use the average beam stopping power from SRIM, instead of the Bragg peak.

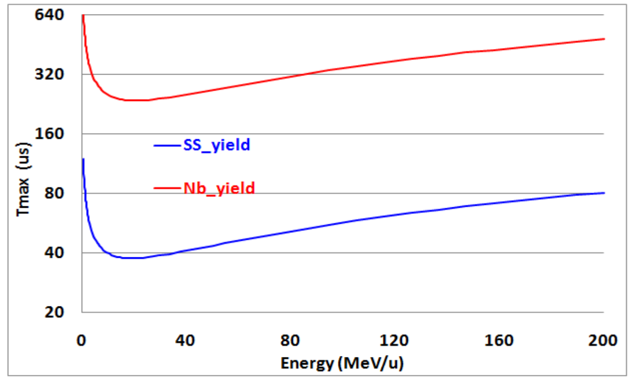

Fig. 4: Allowable beam injection time of different uranium beams at FRIB, calculated from yield strength with Eq. 1.

From yield strength as shown in Fig. 4, FRIB beam may damage stainless steel in less than 40 µs, which happens before melting. Niobium is the opposite: it melts in about 100 µs for a 100 MeV/u uranium beam, but needs more than 320 µs to reach yield stress. In reality, both melting point and yield stress should be included in beam damage, whichever happens first, as shown in Fig. 5.

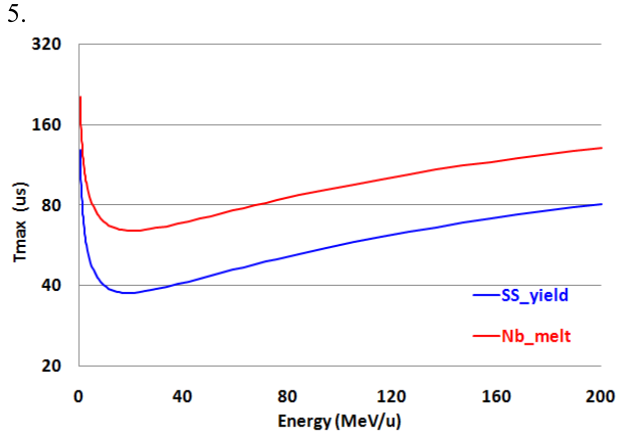

Fig. 5: Limit of injection time for uranium beams at FRIB on SS, and on Nb, from both yield strength and melting.

DAMAGE AND MACHINE PROTECTION

Thermal shock damage from both stress and melting of materials can be calculated numerically and analytically. Even though, the actual consequence in a linac is still not fully understood, particularly what happens immediately when a high power beam hits a cavity surfaces. Since at cryogenic temperature, the specific heat of niobium is 2 to 3 orders of magnitude less than that at room temperature, thermal stress develops much faster than Eq.1; and it is not a necessary to melt niobium to damage a SC cavity when it operating at a high acceleration gradient.

None of the existing heavy ion SRF linac delivers a beam power equal to the level of FRIB, 400 kW. We need to investigate existing ones either with low power, or for different species. ATLAS at ANL observed heavy ion beams causes cavity quenches, but after bringing RF back on, no performance degradation was noticed [5]. ALPI at LNL recorded multipacting re-appearing when cavities were hit by heavy ion beams, and after rf conditioning, performance resumed [6]. However, both ATLAS and ALPI are low power ones. Only the SNS linac delivers a power of 1 MW, which equals to the FRIB power, but it is a pulsed proton beam. SNS has reported SC cavity performance degradations after being hit by high power beams: gradients of two cavities significantly decreased even after rigorous conditioning.

In order to protect SC cavities and other accelerator components from beam caused damages a fast response machine protection system (MPS) is required. Response time of the MPS system should be adequate to effectively prevent excessive radiation and component damage from any abnormal beam loss, while at the same time not inhibiting routine operation with too many false alarms. At FRIB, avoiding component damage is the major task because beam line component activation is much lower from heavy ions, and the beam stopping power is a few ten times that of proton or electron beam.

Because of heavy ions, relatively lower energy, and shielding effects of cryomodules, detectors other than beam loss monitors (BLM) should also be included in the MPS, such as the beam current monitor (BCM) developed at JLAB, which has been in operation for years [7, 8].

Table 1: MPS response time and critical device

	beam	mode	t (µs)	device
TTF	e	pulse	50	BCM, BLM
CEBAF	e	CW	40	BCM, BLM
SNS	p	pulse	20	RF, BLM
FRIB	ion	CW	20~40	RF,BCM,BLM

Table 1 lists beam mode and MPS response time (t) of selected high power SRF linacs. Among them are two pulsed accelerators, TTF [9] and SNS [10], for electron beam and proton beam, respectively; and two CW machines, CEBAF and FRIB, one for electron and one for heavy ion beam. For these high power linacs, MPS response time varies from 20 to 50 µs, and critical devices include BCM, BLM, and RF cavity.

At FRIB, the nominal beam size is 1 mm rms radius in most linac segments, but there are a few locations that require a smaller beam, e.g, at the stripper and target. Especially the target needs 90% of the beam in 1 mm diameter. From a simple scaling, one can determine that component damage may happen in less than 10 µs if irradiated directly with such a beam. This is beyond the capability of MPS, and other special protection techniques should be adopted in the linac design, e.g, use graphite in front of the target and the stripper. However, use of graphite inside beam pipes at other linac segments should be strictly limited because excessive degassing may jeopardize SRF cavities.

Beam loss from halo formation in the linac is a concern too, which is different from abrupt beam loss for a beam device failure, and may not cause immediate damage. However, without proper diagnostics and protections, it may also cause problems, e.g., frequent cavity trips.

In the design, the most limiting beam apertures at FRIB are cryomodules and SC cavities. Increasing the aperture of either HWR or QWR cavity is expensive, and in an SC cavity, beam size is generally at a minimum. Beam halo may not follow exactly the same pattern as that of the core, so it may become an issue for operation at high power. Nevertheless, reduce aperture of magnets and other beam transport systems could be more problematic, as there is very little margin already. Because it is difficult to predict beam halo and loss down to a level as low as 10^{-4} to 10^{-5}, such kind of beam loss, if persistent in the future, could be solved with dismountable scrappers made of refractory metal in front of the cryomodule.

As we have mentioned: heavy ions, lower energy beam, and strong shielding from the cryomodule itself, may not yield sufficient information in some cases from BLMs outside of the cryomodule. Monitoring temperature on the beam pipes of SRF cavities could help. In addition to cryogenic temperature sensors that provide essential diagnostics to cavity and rf coupler, two more sensors, on two beam pipes of a cavity, could be very useful for high power operation.

CONCLUSIONS

Abrupt beam loss from a beam element failure at the FRIB driver linac may cause accelerator component damage in a very short time. A fast response MPS as well as other protection designs are important for routine operation. In addition, excessive beam loss from halo formation in the linac under normal operation conditions should also be properly monitored, and flexible mitigation techniques are considered for high power beam.

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