BEAM SCRAPING PROBLEMS IN STORAGE RINGS; THE BLACK CLOUD

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1. INTRODUCTION

The heavy ion, multi-GeV drivers for inertial confinement fusion are being designed to produce beams of an energy, power, and specific ionization sufficient to raise matter to thermonuclear temperatures. The magnitude of these parameters is so far beyond current experience that some problems raised warrant careful scrutiny. In particular, the consequence of some fraction of the beam lost on storage ring inflection septa, extraction channels, and beam-defining collimators seems potentially very serious. Unless carefully contained, a beam halo can easily vaporize the best refractory materials, and the resulting vapor cloud will interact destructively within microseconds with the following beam. The limits on beam flux which may be so lost for particular examples are orders of magnitude below current experience.

2. BEAM AND SEPTUM PROPERTIES

As examples of the problems in this area, consider the parameters of a 10 GeV, 3-MJ $^{238}U^{+1}$ linac-storage ring driver(1). The critical quantities, referenced to the linac output, are:

T = 10 GeV
I_{inj} = 0.30 Amperes from linac injector
P_{inj} = 3.0 GW
E = 3MJ total beam energy
$N = 1.875 \times 10^{15}$ U^{+1} ions finally accumulated
$\frac{\epsilon_{inj}}{\pi} = 1.5 \times 10^{-6}/\beta\gamma$ m linac injector emittance
$\frac{\epsilon_{SR}}{\pi} = 60 \times 10^{-6}$ m storage ring emittance
τ = 5.9 μsec period of revolution in S.R.
n_t = 64 injected turns into each of 3 S.R.
t = 380 μsec total time of injection into each S.R.

(1) N.M. King. These Proceedings.

We will assume that, where lost, the beam strikes a tungsten surface. The relevant properties of tungsten are:

density	$\rho \simeq 20$ g/cm^2
atomic mass number	$A = 184$
specific heat	$c \cong 0.145$ J/g
thermal conductivity	$1.50 \frac{W}{cm^\circ K}$
melting temperature	$T = 3653^\circ$K
latent heat of fusion	$\ell = 190$ J/g

From this may be derived several quantities of interest assuming that the boiling point is close to the melting point and the latent heat is small compared to the sensible heat.

Range of 10 GeV U^{+1} in W: $\delta x = 0.2$ g/cm^2 = 0.01 cm

Energy to melt W: $u = c\Delta T + \ell = 680$ J/g
$u\delta x = 140$ J/cm^2

Black body radiation of W at 4000°K $\quad p = \sigma T^4 = 1450$ W/cm^2

Thermal conductivity of W over $\Delta T = 3000$°K, $\Delta x = 0.1$ cm $\quad p = k\frac{dT}{dx} = 45$ kW/cm^2

The handbook vaporization temperature and latent heat for tungsten are given at atmospheric pressure: it is my understanding that the vaporization temperature in vacuum is close to the melting temperature, and that the latent heat there is small. In what follows we will assume a vaporization temperature of 4000° K and a total heat required to raise room-temperature tungsten to vapor (in vacuum) at 4000°K as 750 J/g = 150 J/cm^2.

3. ILLUSTRATION OF THE PROBLEM

The scope of the problem is recognized when these values are combined with the beam parameters. Thus, if all of the beam were dumped into tungsten the 3MJ is sufficient to vaporize 4 kg of W; the full beam rate would vaporize tungsten at a rate of 4 metric tons per second. In order to dissipate this energy by radiation, the full beam energy would need to be spread (uniformly) over an area of tungsten of 165 m^2. Since the beam is absorbed in a thin surface skin of thickness 100 sinθ microns (θ is the angle between the beam and the normal to the the surface), it seems improbable that this energy can be removed by conduction, e.g. by water cooling of septa or slits. The effect of thermal conductivity will be to increase the effective depth over which the ionization energy is deposited beyond the 0.01 cm nominal range. However the linac beam power is so high (3 GW) that thermal conductivity cannot dissipate the temperature build-up from even a small fraction of the beam. Thus the means for dissipating any beam energy lost are assumed to be: (a) the sensible heat to raise W to the boiling point (it could be cooled between pulses), (b) radiation from the hot tungsten, and (c) ablation or vaporization from the surface. In the case of this device, this ablation can cause immediate destruction of the beam. The following argument illustrates this concern.

4. EFFECTS OF SEPTUM VAPORIZATION

Consider that the full beam falls on a septum of vertical height y, and vaporizes tungsten at a rate of 4 x 10^6 g/sec. At T = 4000°K, the rms x-component of velocity of the tungsten ions will be 425 m/sec; the density of tungsten vapor atoms close to this septum will be

$$\rho = \frac{4 \times 10^6\, n_a/A}{(2)y\langle v_x\rangle} = \frac{3.1 \times 10^{23}}{(2)y}\ \frac{\text{atoms}}{\text{cm}^2},$$

where y is the vertical height of the septum, n_a is Avogadro's number, A = 184 for W, and the factor of two is appropriate if the vapor can fly off to ± x, rather than in one direction only. The limited data available on charge exchange cross sections indicate $\sigma \sim 4 \times 10^{-16}$ cm^2 for $Cs^{+1} + Cs^{+1}$: singly charged ions of U, etc. probably have charge-changing cross sections on neutral, heavy atoms at high energy of at least 10^{-16} cm^2. This suggests that, for a 1 cm septum which may vaporize to both sides, the fraction of the incident beam which, when lost on a septum, will develop a vapor cloud equal to an ion interaction mean free path is:

$$f = \frac{2}{3.1 \times 10^{23} \times 10^{-16}} = 6.5 \times 10^{-8}$$

This vapor would propagate across the vacuum chamber at a rate $\langle v_x\rangle$, or 0.4 mm/μsec. In the time it takes to fill the storage ring (380 μsec) this cloud would propagate 16 cm. Of course the high-energy tail of the thermal distribution would propagate correspondingly faster. The conclusion I draw from this simple calculation is that one must so engineer the beam and the various septa so that any beam lost is absorbed by the heat capacity of the loss target and/or radiated as black body radiation. Even in the linac or transfer line, a vapor cloud will develop fast enough to destroy following beam in a 1 cm^2 aperture in several microseconds if $\gtrsim 10^{-6}$ of the beam scrapes and leads to ablation. If the loss results in sputtering of metal at epithermal velocities, the vapor density is correspondingly reduced. If a lighter element is considered (beryllium or titanium) the heat capacity per gram is greater, but the number of atoms vaporized per unit energy may also be greater. As $\langle v_x\rangle$ will also be greater the problem is qualitatively similar.

5. TOLERABLE BEAM LOSS

The problem of accommodating the energy of the scraped beam on a storage ring inflection septum may be restated as follows (for the numerical case under discussion). The heat capacity of the tungsten surface area normal to the beam of 150 J/cm^2 while the total beam energy is 3 x 10^{6}J. There may be n_{sr} storage rings. The fraction of beam which may be lost in each ring, f, on a septum of projected area A cm^2 is given by

$$f \lesssim \frac{150 n_{sr}}{3 \times 10^6} A \cong 5 \times 10^{-5}\, n_{sr}\, A.$$

If there are 3 storage rings, and if the septum area is 1 cm x 1 mm, the maximum loss f = 1.6 x 10^{-5}.

It may be noted that this beam would fall onto the septum with a power of 50 kW; even with the septum inclined at 5° (so that the energy is spread over 1 cm^2) the beam power is still 30 times that which could be removed by radiation.

The energy per unit area on the septum may be related to the emittance of the linac and the betatron wavelength (or, more explicitly, β_x and β_y). For our example, the linac emittance at 10 GeV is 0.5 cm rad, so that the beam area would be 5 cm^2 for $\beta_x = \beta_y = 33$ m. Thus the beam energy density, for three storage rings, is 200 kJ/cm^2. As the septum can only tolerate $\lesssim$ 150 J/cm^2, the beam halo at the septum must be less dense than the central beam by a factor of 1330. This is a less frightening factor than 10^5 (cited above). The problem may be made to appear even less severe if a larger number of storage rings and larger β values are considered. Thus, if there are 10 storage rings and β = 50 m, the beam energy density in each ring is only 38 kJ/cm^2, so that the halo density need only be less than the central beam density by a factor of 250.

In conclusion, we believe that this problem merits serious study. This limitation will affect the choice of storage ring parameters and perhaps the number of storage rings.

The diffusion equation for the temperature vs. time and depth for the one dimensional problem should be explored with the proper parameters for tungsten and other candidate materials (Ta, Mo, Ti, Be) considering heat capacity, conduction, and radiation.

The targets of high-power klystrons and x-ray tubes surely are limited by these same considerations, and there is a body of engineering experience in this connection which would be instructive.