OTR STUDIES FOR THE HIGH CHARGE CTF3 BEAM

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Abstract

The CTF3 (CLIC Test Facility 3) will produce 1.56µs long intense electron pulses. The unbunched 5.4A beam of the injector will have a transverse beam size ~1mm. After the buncher the current is reduced to 3.5A and the transverse size varies between a few hundred micrometers and one millimetre along the length of the linac. Calculations indicate that these beam parameters will impose an unbearable thermal load for the intercepting screens currently in use (scintillators and aluminium OTR foils). Graphite and SiC have been investigated as possible alternative materials for the OTR radiators. The possibility of replacing scintillating screens with OTR targets at the low energies of the injector has also been considered. A possible limitation in the use of such high temperature radiators has been identified; ions released from the heated target could focus further the beam with the risk of damaging the target itself and/or blowing up the beam. This would also affect the emittance measurement and would hinder any effort to detect head-tail phenomena. This paper gives the results of the theoretical estimations, and of the beam-based experiments.

INTRODUCTION

During the last two decades the use of intense electron beams has been developed, especially for Free Electron Laser studies [1] and X-ray radiography [2]. With current densities of the order of tens of kA/cm^2 the beam impact destroys or damages any intercepting devices used for beam diagnostics or as Bremsstralhung X-ray sources. Moreover an instability caused by the interaction of the primary electrons beam with positive ions released by the target when heated up, has been observed [3]. This process has been identified as a time dependant effect that modifies the electron beam size at the location of the target within the beam pulse duration [4].

The CTF3 facility in the nominal phase will produce intense beams [5], 1.56µs long at a repetition rate of 50Hz. The injector delivers a 5.4A average current, which is then reduced to 3.5A after the buncher. Several beam-monitoring devices are foreseen, distributed along the accelerator at 140keV, 20MeV, 60MeV and 180MeV. With beam sizes varying from few millimetres to few hundred of micrometers, the current density can be as high as few kA/cm^2. The screens will suffer thermal related problems and the measurements will be potentially affected by this ions instability. Concerning beam diagnostics, our main concern is to provide a system, which is robust enough to stand the induced thermal load, and to allow quantitative measurements.

In this paper, thermal calculations are first presented with the aim of determining which material can be used for the CTF3 OTR radiators. Some simulations are performed with the LSP code, developed by Mission Research Corporation [6], in order to estimate the impact of the ion instability on the CTF3 beam. The third part is dedicated to OTR [7] and Black body photon intensities calculations to investigate the light yield of these two processes.

THERMAL ANALYSIS

Assuming an electron beam with a Gaussian spatial distribution, the time evolution of the target temperature can be calculated solving the following equation [8]

$$\frac{\Delta T(r,t)}{\Delta t} = \frac{1}{c_p \rho}\left[\frac{dE}{dx}\rho e^{-\frac{r^2}{2\sigma^2}} N(t) - k\nabla^2 T(r,t) - \frac{2\varepsilon\sigma_s}{\delta}\left(T(r,t)^4 - T_0^4\right)\right]$$

With σ the electron beam size and N(t) the particle flux. The target is characterized by the thickness δ, emissivity ε, specific heat c_p, density ρ and thermal conductivity k. T_0 is the room temperature and σ_s the Stefan-Boltzmann constant. The first term in brackets contains the stopping power, dE/dx, representing the electron energy deposition [9] and is responsible for the heating of the material. The target is cooled by thermal conduction (second term) and Black Body (BB) radiation emitted from the radiator surface (third term).

Electrons traversing matter loose energy by collision (ionization) and by radiation (Bremsstrahlung).]. If the target is sufficiently thin (~tens of microns), the Bremsstrahlung photons are not re-absorbed by the radiator and then do not contribute to the energy deposition process. For high energies particles, it represents a large fraction of the total energy loss [9]. The collision stopping power does not change sensibly from one material to the other (factor 2 between tungsten and graphite). For electron energies between 100keV and 360MeV, it only changes by a factor less than 2. In the following calculations, the target is supposed to be thin enough (10µm) to neglect the radiative stopping power and to reduce the collision energy deposition, which is much higher for low energies (<100keV). The key parameter for the heat of the screen is the specific heat of the material. An example of the temporal behaviour of the target temperature is displayed on figure 1, considering the interaction of a 140keV, 5.4A, 1mm beam size electron beam and a graphite target (ε = 0.7). This calculation assumes a cooled-radiator, which external temperature is kept at 20ºC.

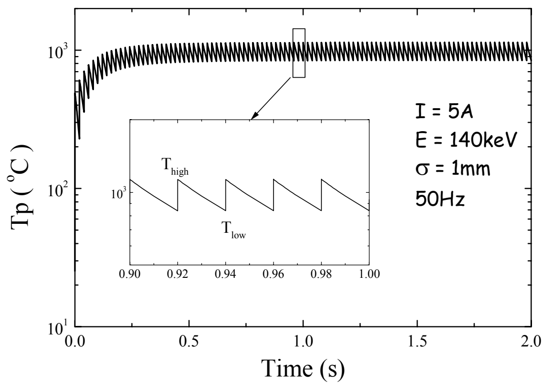

Figure 1: Graphite target temperature versus time

Due to the pulsed nature of the beam (50Hz,1.56μs) the temperature after a short transition period (~200ms) will cycle between two values here defined as T_{high} and T_{low}, corresponding to the temperatures attained just after and just before the electron pulses as shown in figure 1. In this example, the target is 10μm thick and its temperature oscillates between 778ºC and 1003ºC. By reducing the repetition rate to 10Hz, T_{high} and T_{low} become respectively, 440ºC and 106ºC.

The power evacuated via Black Body radiation is given by the Stefan-Boltzmann law:

$$P = 2\pi\sigma^2 \varepsilon \sigma_S T^4$$

and it represents only a small contribution to the total thermal balance of the target. In the case represented in figure 1, it amounts to only 65mW compared to the 2.88W deposited by the beam (50Hz). This effect makes the cooling between pulses faster but is almost irrelevant on the maximum temperature attained by the radiator. The cooling by BB radiation would have a more significant effect if using much thinner foils (<μm) in order to minimize the beam energy deposition.

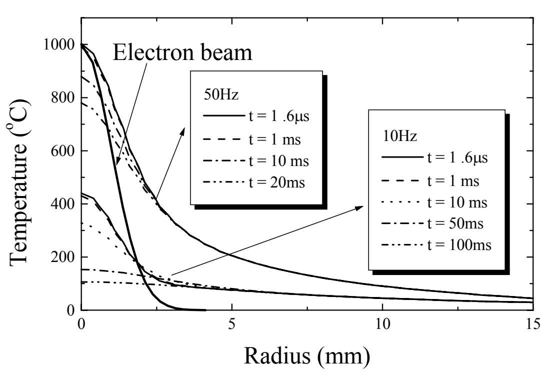

Figure 2: Temperature profile as a function of the radial position at different times in the cycle

On figure 2 the different curves illustrate the time evolution of the temperature profile of the target. Heat exchange is negligible within the pulse duration (μs). The cooling has just started 1ms after the beam pulse (considering graphite), and 10ms later the temperature in the centre has decreased by 15%. Choosing a high thermal conductivity material allows a faster radial cooling of the target.

Good candidates will have a high fusion temperature, a high specific heat and a high thermal conductivity. The characteristics of the material considered in this analysis are summarized in table 1. On CTF3, even if the beam is focused to a σ equal to 250μm, supposed to be the lower limit, a graphite target can stand the full thermal load reaching temperatures of the order of 2250ºC. Beryllium would be slightly better but its use is discouraged due to costs and difficulties of machining.

Table 1: Material characteristics

Material	c_p *(J/gK)*	*K (W/mK)*	T_{fusion} *(ºC)*
Be	**1.825**	**190**	**1287**
C	**0.7-2.8**	**140**	**3527**
Al	0.9	235	660
Si	0.7	150	1414
Ti	0.523	22	1668
Mo	0.25	139	2623
W	0.13	170	3422

ION INSTABILITY

The effect of target-emitted ions on the propagation of the electron beam is sketched on figure 3.

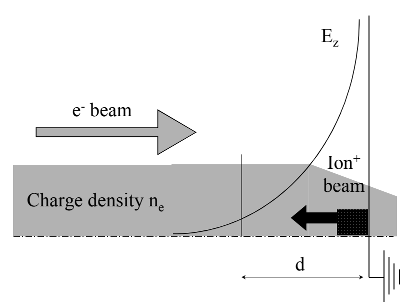

Figure 3: Effect of target emitted ions from the target

Molecules are released from the target by gas desorption of hydrocarbon surface contaminants or water when the material is heated. Ions are produced by direct electron impact ionization with a cross section of the order of 0.1Å^2, depending on the electron energy and the nature of the molecule. These ions are then accelerated by the beam space charge potential and propagate along the electrons in the opposite direction. The electric field can be as high as 10MeV/m. This positive ion column partially neutralizes the electron beam charge and modifies the propagation of the primary electrons left with their auto-focusing magnetic force.

Simulations with the code LSP [6] have been done to estimate how important this effect will be. The parameters of the simulation are adjusted, based on the results of recent studies [10]. Two kinds of ions are considered, H^+ 9% and OH^+ 91%. In the simulations, ions are emitted right at the beginning of the pulse. In reality it was shown that to fit the experimental data, ions should be released after the time needed to heat the target to 400ºC. An example of the time evolution of the beam size on the target in the case of the CTF3 injector is shown in figure 5.

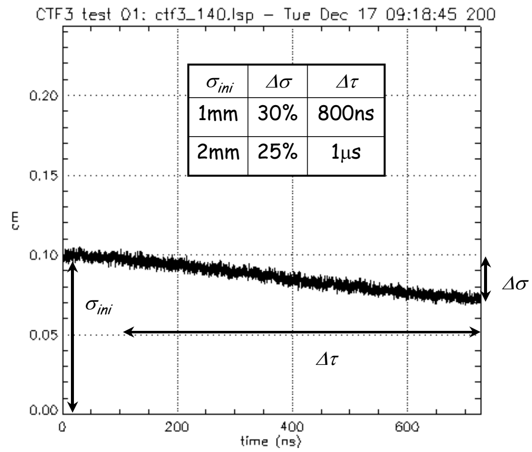

Figure 5: Time evolution of the R.M.S beam size

At 140keV, the beam is continuously focused during the pulse duration. A diminution $\Delta\sigma$ of 30% is expected within 800ns considering nominal conditions. The results summarizes in the table in figure 5 indicate that the smaller the initial beam size (σ_{ini}), the stronger and the sooner the focusing takes place. At 20 MeV, $\Delta\sigma$ is small (< 5% over 1µs) and for electrons of higher energies the effect becomes negligible.

OTR VERSUS BLACK-BODY RADIATION

The CTF3 beam profile monitors are based on the backward OTR emission from a graphite screen. The number of OTR photons emitted by an electron in the wavelength range [λ_a, λ_b] is given by [7]:

$$N_{OTR} = \frac{2\alpha}{\pi}\left[\left(\beta + \frac{1}{\beta}\right)\cdot \ln\left(\frac{1+\beta}{1-\beta}\right) - 2\right]\ln\left(\frac{\lambda_b}{\lambda_a}\right)$$

N_{OTR} increases with the beam energy. For non relativistic particles, it is roughly proportional to β^2, and for high energy particles it behaves like ln(2γ). Moreover the OTR angular distribution [7] can be represented by a cone with a 1/γ aperture with γ the relativistic factor of the electrons. In consequence, taking into account that the optical system has a finite collection angle (~ 1.2610^{-3} Sr), only a small part of the OTR light cone would be collected for low energy particles. This calculation must also consider that thermal resistant radiators, like graphite, have low reflectivity (27%) compared to perfect (mirror-like) OTR screens, limiting by the same amount the light intensity produced in the backward OTR.

The number of Black body photons emitted per second in the wavelength range [λ_a, λ_b] and in 2π sr is given by:

$$N_{BB} = \int_{\lambda_a}^{\lambda_b} \frac{2\pi c}{\lambda^4} \frac{2\pi\sigma^2\varepsilon}{e^{\frac{hc}{kT\lambda}} - 1} d\lambda$$

with k the Boltzmann constant, h the Planck constant, and c the speed of light. Thermal calculations have shown that within 10ms the temperature has decreased by 15%. At the same time N_{BB} emitted in the visible range [300, 900] nm has drop by at least one order of magnitude, so that we have considered that the BB photons are emitted only during the first 10ms.

At 140keV, with a typical beam size of 1mm, the maximum temperature is 1003ºC. In these conditions 5.3 10^8 N_{BB} photons are collected by our optical system. This value has to be compared with the 1.7 10^8 OTR photons expected in the same conditions.

At 20MeV and for higher energies along the linac, the beam size could be as small as 250µm. The temperature increases up to 2250ºC, emitting 6.8 10^{11} BB photons. The number of OTR photons sent onto the camera will increase significantly with the beam energy. N_{OTR} would be 8.4 10^{10} at 20MeV, 2.6 10^{12} at 60MeV and 2.1 10^{13} at 180MeV.

CONCLUSIONS

The thermal analysis presented in this paper shows that thin foil of graphite must be used as OTR radiator for the CTF3 beam profile monitor.

Simulations with LSP indicate that the ion instability has only a significant effect on 140keV electrons. Even if the beam is over-focused by 30%, there is no risk of damaging the graphite target. Possible cures of this effect are envisaged by direct beam conditioning or laser surface cleaning. Targets will be prepared using a high temperature treatment for outgasing.

At low energy BB radiation is a source of light as intense as OTR. The light spectrum is however quite different. Most of the BB photons are emitted in the red part of the visible range and can be easily suppressed using a blue filter or by gating the camera.

By lowering the repetition rate of the machine to 10Hz, the temperature of the screen can be effectively reduced, eliminating the ion instability and reducing the BB radiation by at least three orders of magnitude depending on the beam parameters.

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