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Author

Ni, P.A.

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by

P.A. Ni, F.M. Bieniosek, S.M. Lidia, J. Welch

from

Lawrence Berkeley National Laboratory (on behalf of U.S. HIFV-VNL)
1 Cyclotron Road, Berkeley, CA 94720
Accelerator Fusion Research Division
University of California
Berkeley, California 94720

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ABSOLUTE BEAM FLUX MEASUREMENT AT NDCX-I USING GOLD-MELTING-CALORIMETRY TECHNIQUE*

P.A. Ni, F.M. Bieniosek, S.M. Lidia and J. Welch
Lawrence Berkeley National Laboratory, University of California, Berkeley, CA, USA

Abstract

We report on an alternative way to measure the absolute beam flux at the NDCX-I, LBNL linear accelerator. Up to date, the beam flux is determined from the analysis of the beam-induced optical emission from a ceramic scintillator (Al-Si). The new approach is based on calorimetric technique, where energy flux is deduced from the melting dynamics of a gold foil. We estimate an average 260 kW/cm² beam flux over 5μs, which is consistent with values provided by the other methods. Described technique can be applied to various ion species and energies.

INTRODUCTION

The neutralized drift compression experiment-I (NDCX-I) linear accelerator at the Lawrence Berkeley National Laboratory (LBNL), can produce high current (~25-30 mA) ~300 keV, K⁺ ion beams. When a several microsecond duration beam pulse is focused to a few millimeter spot it has sufficient power to melt and evaporate a thin (≤200 nm) metal foil. For instance, a 300 keV K⁺ ion is stopped completely within a 150 nm thick gold sample, with a homogeneous energy deposition along the deceleration trajectory. High intensity and even volumetric heating make the NDCX-I beam a suitable driver for warm-dense-matter (WDM) experiments [1].

The knowledge of beam flux at the focal point is critical for beam tuning and characterization, as well as for numeric modeling of WDM physics. Presently, a 100 μm thick ceramic Al-Si scintillator is used for the determination of beam transverse density distribution at NDCX-I and the beam current is measured with a fast Faraday cup [2]. Beam-induced optical scintillation is measured with a fast gated camera and image counts are related linearly to the beam flux.

High beam intensities at the focal spot limit the applicability of the Al-Si scintillator. For instance, the beam induced emission becomes saturated at high currents, requiring some adjustment for the non-linear response. Moreover, the Al-Si is heated by the beam can be damaged after multiple high-intensity shots.

CALORIMETRY FOR BEAM FLUX MEASUREMENTS

The temporal intensity profile of an uncompressed NDCX-I beam is close to a flat-top shape with a sharp rise and fall (see figure 1). The goal of the performed

experiments was the determination of the flat-top value of the beam flux F [W/cm²].

Total energy, Q_1 , required to heat material from room temperature T_0 to melting temperature T_m , contained in a focal spot of radius r , is

$$Q_1 \approx mc(T_m - T_0) = \rho \cdot \pi r^2 \cdot d \cdot c(T_m - T_0),$$

Here c - specific heat capacity, m - mass of heated volume, d - sample thickness and ρ is density. Thermal losses, i.e. radiation and heat conduction, can be neglected at the microsecond time-scale.

Under the steady incident beam flux the temperature grows linearly with time until it reaches a melting plateau, which is for most metals, is around 1000 K. The time t_1 , it takes to reach this plateau is

$$t_1 = Q_1 / F.$$

Thus, by monitoring the sample temperature and determining the time it reaches the melting point, it is possible to make an estimate of an average beam flux, F . This estimate is applicable only if a foil is chosen so that an entire beam is stopped in a sample and the penetration range matches foil thickness. Also, beam flux should be constant in time during the heating processes.

Temperature of a sample can be measured optically with a pyrometer, which relates the absolute surface brightness to the temperature via the well-known Planck formula [3]. Generally, a pyrometer requires a time-consuming absolute calibration of a photo-detector. However, for the described calorimeter measurements, monitoring of surface brightness in arbitrary units is enough, since only a temporal profile of emission is necessary for the analysis.

EXPERIMENTAL DATA

Thermal emission of the sample was collected by a set of lenses and focused on a crystal of an amplified pin photodiode. The detector has a 2.5 ns response time with sensitivity in the near-infrared part of the spectrum. Figure 1 shows a typical voltage record obtained in experiment with a 150 nm gold (Au) foil. We used the gold because it has a relatively low temperature and the ion beam range matches the thickness of commercially

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available 150 nm thick foil. The beam duration in this experiment was 5 μ s and the focal spot size was 1 mm (FWHM).

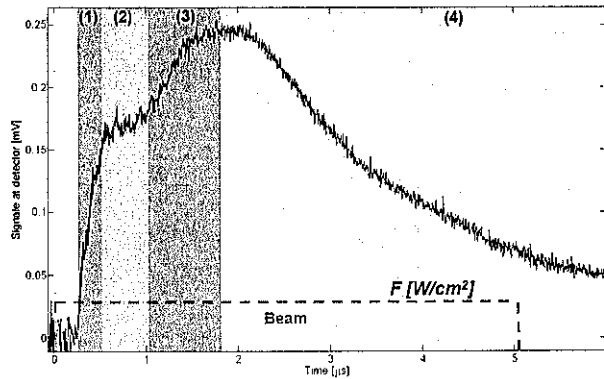


Figure 1: Thermal emission of Au foil heated with a potassium ion beam. The record includes emission integrated over 900 nm- 1500 nm range. The beam start heating a foil $t=0 \mu$ s, the signal appear from noise at later time due to the finite sensitivity of the detector.

The experimental record can be divided into four stages. In the stage (1), the sample is in a solid state and temperature increases linearly. The slope of the incline is determined by the Au heat capacity. During stage (2) the foil melts at 1377 K and starts breaking into micrometer-size droplets. The fact of foil disassembly into the droplets has been confirmed earlier by multiple techniques [4]. In stage (3) the foil is completely disassembled and the beam energy is spent on heating a cloud of liquid droplets. Eventually, in stage (4), the droplet cloud experiences significant expansion resulting in the decline of emission.

From the figure 1 it can be measured that the melting point is reached in $t_1=600$ ns. Having used the tabular data for gold density and heat capacity it can be estimated that absolute beam flux is 260 kW/cm^2 . A several per cent shot-to-shot repeatability has been observed in over twenty shots thus determining the several per-cent overall measurement uncertainty of F . This number is in a close agreement in values obtained with different techniques [2].

DISCUSSION

In principle, duration of the melting shelf at stage (2) can be also used for the determination of the beam flux. The time t_2 it takes to melt the entire sample is

$$t_2 \approx \frac{mL}{F},$$

where L is the specific latent heat.

Considering the earlier estimated 260 kW/cm^2 value, the NDCX-I beam should melt the Au sample in 50 ns. Meanwhile the data in figure 1 indicates that melting lasted for 400 ns. In order to understand this large discrepancy, one should consider the disassembly of the foil into droplets during the melting processes. As the foil bulges into droplets the area exposed to the beam heating shrinks, thus reducing the effective beam flux. This “geometrical factor” reduction of the heating rate explains the longer lasting melting plateau.

In principle, it is possible to use the duration of the melting shelf for the beam flux measurement, if a sample maintains its structural integrity. For instance, this can be achieved with thicker samples, i.e more energetic ions.

SUMMARY

A new approach to the beam flux measurement at NDCX-I had been investigated and good agreement with alternative techniques was found. The described principle can be applied to various beams and materials as long as detector has enough sensitivity around melting temperature and a sample maintains its mechanical integrity during the measurement.

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