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Publication Date
1976-11-01

Presented at the IEEE 1977 Particle
Accelerator Conference, Chicago, IL,
March 16 - 18, 1977

LBL-5901
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November 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

THE DESIGN AND DEVELOPMENT OF MULTI-MEGAWATT BEAM DUMPS*

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Introduction

The next generation of U.S. fusion experiments which includes TFTR, MFTF, and Doublet III, will utilize neutral-beam injection for plasma heating. TFTR, for example, desires 20 MW of 120-keV deuterium atoms in pulses of 0.5-sec duration.

In order to meet these requirements, a 15-A, 120-keV, 0.5-sec pulse per minute module[1] is presently under test at the neutral-beam test facility[2] at the Lawrence Berkeley Laboratory. A 65-A, 120-keV, 0.5-sec module is under construction and is scheduled for assembly in April of this year. This paper discusses some of the features of a calorimeter/beam dump that is presently being used in the testing and evaluation of these neutral beam sources.

Background

The neutrally-charged particles that impinge upon the surface of the calorimeter/beam dump penetrate to a depth of only a few microns. The deposition of this energy may be considered to be strictly a surface phenomena of constant intensity during the short pulse. The temperature gradients in the plane of the plate are much less than the gradient through the thickness of the plate, and so the situation can be described by the one-dimensional transient conduction equation

$$\frac{\partial T}{\partial t} = \gamma \frac{\partial^2 T}{\partial z^2}$$

with the boundary conditions

$$T = T_0 \quad \text{at } t = 0,\ 0 \le d \le z$$

$$\frac{\partial T}{\partial z} = \frac{F_0}{k} \quad \text{at } d = z,\ 0 < t \le \tau$$

Constant heat flux over the front surface, and no flow of heat from the back surface.

The solution to this boundary value problem is

$$T = T_0 + 2\frac{F_0}{k}\sqrt{\gamma\tau}\sum_{n=0}^{\infty}\left\{\text{ierfc}\left[\frac{(2n+1)z-d}{2\sqrt{\gamma\tau}}\right] + \text{ierfc}\left[\frac{(2n+1)z+d}{2\sqrt{\gamma\tau}}\right]\right\}$$

Where

T = Temperature at any point, d, in the plate. . °C
T_0 = The original temperature in the plate, prior to the pulse . . . . °C
F_0 = The uniform surface heat flux $\frac{\text{gcal}}{\text{cm}^2\text{sec}} = \frac{\text{kW}}{\text{cm}^2}(239)$ . . . . gcal/sec/cm^2
γ = The thermal diffusivity of the plate $= \frac{k}{\rho c_p}$ . . . . cm^2/sec
k = The thermal conductivity . . . gcal·cm/sec·cm^2 °C
ρ = The plate density . . . . gm/cm^3
c_p = The specific heat of the plate . . . . . gcal/gm °C
τ = The length of the heating pulse . . . . sec
z = The thickness of the plate . . . . cm
d = The distance through the plate measured from the unheated surface. . . . . cm

The maximum temperature occurs at the front surface of the plate where d = z; there the temperature is given by

$$T = T_0 + \frac{F_0}{k}\sqrt{\gamma\tau}\sum_{n=0}^{\infty}\left\{2\text{ierfc}\left[\frac{nz}{\sqrt{\gamma\tau}}\right] + 2\text{ierfc}\left[\frac{(n+1)z}{\sqrt{\gamma\tau}}\right]\right\};$$

and for a thick plate, this expression reduces to

$$T = T_0 + 1.1284\ F_0\sqrt{\frac{\tau}{k\rho c_p}}\ .$$

A relative measure of a calorimeter's expected front surface temperature is given by the quantity $[k\rho c_p]^{-1/2}$. This quantity, along with other physical properties, is listed for four possible calorimeter materials in Table 1.

Material	Density ρ	Conductivity k	Specific Heat c_p	Diffusivity γ	$[k\rho c_p]^{-1/2}$	Approx. Melting Point C°
Copper	8.94	0.93	0.091	1.14	1.15	1084
Tungsten	19.4	0.40	0.034	0.61	1.95	3399
Molybdenum	10.2	0.31	0.064	0.48	2.22	2621
Tantalum	16.6	0.13	0.036	0.22	3.59	2982

Table 1

These values of $[k\rho c_p]^{-1/2}$ show that, for the same heat flux density and pulse length, the front surface temperature of a copper plate will be less than that of a tungsten, molybdenum, or tantalum plate. In addition to being less expensive, copper has the added advantage of being easily fabricated. In the testing of our 120-keV source modules, the maximum length of the heating pulse is fixed at 0.5 sec, and the power density is such that the beam could melt a copper calorimeter used at normal incidence. However, we can keep the maximum temperature of the copper calorimeter below the melting point by adjusting F_0, the heating flux; i.e., by tilting the plate to distribute the heat.

Computation shows that, in the case of the 15-A, 120-keV source, the beam can be focused under ideal conditions to an elliptically-shaped area with major axes of 9.5 cm and 33.9 cm respectively, at a distance of 8 meters; the expected maximum heat flux (ions plus neutrals) will be approximately 20.5 kW/cm^2. Although practical considerations may prevent our reaching this power density, we used this value in order to arrive at a conservative design.

In the design of the calorimeter, an effort was to be made to reduce this heat flux to a reasonable value; say, something less than 3 kW/cm^2. The geometry of the target chamber was such that we could install two plates forming a vee, with an included angle of approximately 15°. The resulting maximum heat flux density of 2.6 kW/cm^2, was acceptable, and the 570°C

*Work done under the auspices of the U.S. ERDA.

maximum front surface temperature of the copper plate was well below its melting point.

Description

The completed calorimeter is shown in Figures 1 and 2. It consists of two 1.9-cm copper plates, tightly clamped at their rear edge, forming an opening angle of 15°. Copper cooling tubes are furnace brazed in a parallel array to the backside of each plate, and an external valving arrangement allows the circuitry to be drained of cooling water just prior to each beam pulse. Not shown in the photographs is

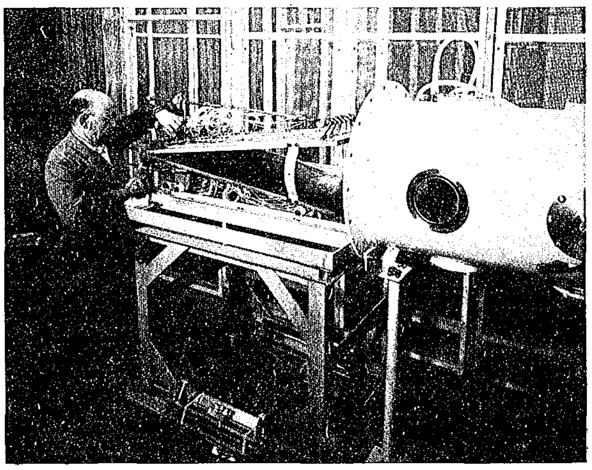

Figure 1. Multi-Megawatt Calorimeter/Beam Dump.

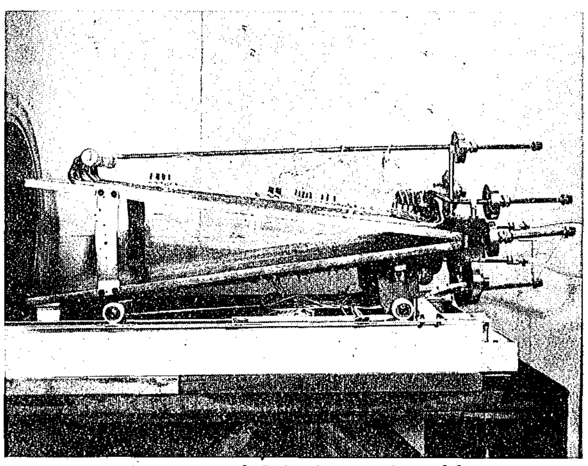

Figure 2. Close-up of Calorimeter Assembly.

another 1.9-cm thick cooled-copper plate that acts as a collimator and limits the beam to the 15° opening. The assembly is mounted on wheels for ease in installation and inspection. The cooling tubes and electrical connections emerge thru vacuum tight fittings in the rear cover plate. Shuttered 6-in diam viewports provide for inspection during operation.

Operation

Since the beam pulse length is short (0.5 sec) compared with any thermal time constants associated with the copper plates, we can make point-by-point measurements of the temperature differences on the calorimeter caused by a beam shot, and can deduce from them the required beam diagnostic information. The system we use to make these measurements consists of a set of thermistor bridge circuits and a computer data acquisition and analysis system based on a MODCOMP II computer.

Precision thermistors are cemented with thermally-conducting cement into holes partially drilled into the rear surface of each copper plate. Arranged in an array of 36, with six thermistors on a side, they were calibrated prior to initial use of the calorimeter. The bridge outputs cover a voltage range of ± 10 V, which corresponds to a temperature range of $\overline{0}$ to 150 deg C. The bridge outputs are nonlinear, but this is no disadvantage, as the computer is available for data analysis.

Just before a beam shot we begin reading the temperature distribution of the plate every 0.25 sec. The temperature distribution along a vertical and horizontal "slice" through the center of the thermistor array is plotted in real time during and after the shot on a video display every 0.5 sec, allowing us to monitor the performance of the most critical bridges visually, and to observe very conveniently and directly the thermal time constants of the system. At a specific time after the shot, when the temperature at each thermistor location has reached an equilibrium through the plate but before significant thermal diffusion in the transverse directions can occur, we read and store a set of temperatures as the "final" values and calculate the temperature rise at each thermistor location.

The computer then calculates and displays four selected ΔT contours, which give a quick visual indication of beam quality. The data analysis program performs a least-squares fit of a bi-gaussian distribution to the data and displays the values of the 1/e half-widths in the horizontal and vertical directions, as well as the coordinates of the center of the distribution.

Every 2 msec, the computer also samples a signal from a resistive divider between the ion source and ground and calculates from this information and the calorimetric data the mean beam voltage, the pulse length, and the average beam current to the beam dump.

This diagnostic system is useful for temperature rises on the beam dump of as little as 1 deg C; for such temperature rises, the 1/e half-widths of the best-fit gaussians can be determined to a accuracy of about ± 0.1 deg (in angle), and the center of the distribution to about ± 1.0 cm.

Status

The calorimeter shown in Figures 1 and 2 has been in use since the testing of a 15-A, 120-keV, ion source module began in August of 1976. At present, the operating level of the power supply is 100 kilovolts with 10 amperes accel current, limiting the beam to a 100 msec pulse of 3 kW/cm^2 peak power density. Reconnections to the power supply are being made at this time to allow operation at the 120-kV level.

Another calorimeter/beam dump has been constructed and is awaiting installation on the second beam line of the test facility. Constructed with its copper plates in vertical planes, it is intended for use in the testing of the 65-A, 120-keV, 0.5-sec source modules suitable for use on TFTR.

References

1. J. M. Haughian et al., "Update on the Development of 120-keV Multi-Megawatt Neutral Beam Source," presented at this conference.

2. J. M. Haughian et al., "Test Facility for the Development of 150-keV, Multi-Megawatt Neutral Beam Systems," in Proceedings of the Sixth Symposium on Engineering Problems of Fusion Research, San Diego, Ca. (1975); LBL-4427.