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BEAMDUMP CALORIMETRY FOR NEUTRAL BEAMS

Real Time Systems Group

July 1982

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# Beamdump Calorimetry for Neutral Beams

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# A User's View of NBSTF Calorimetry Displays

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## 1. A Brief Foreword

The following is an informal discussion of the calorimetry displays at NBSTF. Details about the computer and the derivation of mathematical formulas or methods have been suppressed in order to give a quick and relatively non-technical view of some of the less obvious diagnostics and control procedures.

The purpose of the Calorimetry subsystem is to provide information about the detailed behavior (shape, intensity, energy, etc.) of the beam itself. In addition to the shot-to-shot behavior, the information derived from the data is used in establishing the beam perveance through "source tuning" and thus, ultimately, in source modeling and control.

## 2. Calorimetry

We discuss this topic in order of increasing complexity: first, the simple display of temperature data, then the creation of thermal contours and, finally, the use of a mathematical model of the beam itself.

### 2.1 Temperature Displays

The beamline at NBSTF is designed so that the beam is stopped by either the beam dump or the target dump. Both are instrumented with arrays of thermocouples (hence the name "calorimeter") whose signals are read into the computer, translated into temperatures and then displayed on request, with some rudimentary analysis (e.g., identify the hottest thermocouple). This particular display is requested by pressing 'TEMPERATURES' on the Dump Menu. See Figure 2.1a.

A separate document describes the temperature acquisiton process. At NBSTF, the display of temperatures on the dumps is simply one example of the general problem of temperature displays on any instrumented device. We have approached this problem by using "data-driven" displays. For example, Figure 2.1b is created by the same program that also created Figure

2.1a. All temperature displays (the number depends on the number of instrumented dumps, collimators, etc. and has no limit) are generated by the same task.

## 2.2 Thermal Contours

Since humans deal better with pictures than tables of data, a next step is to produce isothermal contours from the temperature data (see Figs. 2.2a,b). These are very much like the isobars one sees on weather maps in the newspapers. Each of the four curves displayed indicates a constant temperature at a fixed percentage of the maximum.

The contours give a fast visual indication of the beam's "heat print". On a good shot, the contours should close on themselves, be roughly elliptical and show a degree of regularity. On poor shots, with little or no heating, the contours are random, sometimes resembling an Indian rug pattern when viewed on the color screen.

Figures 2.2a and 2.2b also illustrate the usefulness of the Sensor On/Off touch panel display. "Removing" a thermocouple that has failed can produce a marked change in the contours and in other calorimetry diagnostics.

## 2.3 A Mathematical Model

One of the advantages of the contour display is that it makes no assumptions about the beam; the temperature data speaks for itself via a graphical display. On the other hand, just because no assumptions are made, it is difficult to assign quantitative results. For example, we need a means of measuring the spread ("divergence") of the beam -- ultimately, it has to get into a Tokamak-- and we'd like to know how much of the electrical power sent to the ion source is transformed into useful heat at the target.

In order to estimate these and a slew of other quantities, we assume that the beam has a shape that can be described mathematically. As with all models, physical or otherwise, this one will fall short of describing the real beam to some extent, but it seems possible to introduce assumptions about the beam's behavior that make the model quite plausible. Our current experience suggests that the model gives an adequate description for its intended purposes, which are: 1) as a diagnostic tool to monitor the beam's overall behavior; 2) as a source of data on power conversion efficiency; 3) as an aid in 'tuning' the source. This last point refers to the determination of the ratio of accelerator current to voltage which produces minimum beam divergence. This is important both for conditioning the source and in actual tokamak operation.

In the mathematical description of the beam, there are undetermined parameters (e.g., the center of the beam, its divergences, etc.). On each shot, the resulting temperatures on the calorimeter are fitted to the model to provide estimates of these parameters. The model contains corrections for the "vee" shape of our calorimeters, the distance to the dumps and, in the case of Doublet III type sources, the finite focal length.

The way in which the parameters are estimated is just a more sophisticated version of the process by which the slope and intercept of a "least-squares" line are determined when the line is fit to a scatter diagram. The chief difference here is in the nonlinearity of the functions. The derivation of the model and its explicit formulae appear in a separate document.

The different pieces of information produced by this analysis are numbered in Fig. 2.3 and explained briefly in the following.

### 2.3.1 Legend For Figure 2.3

(All temperatures are "deltas"; gains from pre-shot values.)

1. The shot number, date and time of shot are displayed, as well as the accelerator voltage and current.

2. DIV - divergence: a measure of the beam spread in the directions perpendicular (+) and parallel (ll) to the grids. Optimums are roughly 1 and .4 degrees, respectively. The numbers in parentheses are in millirads (i.e., normalized by the distance from source to calorimeter).

3. The center of the theoretical distribution of the beam, relative to the center of the plate.

4. The highest measured temperature (labelled 'H' on the righthand graph).

5. The estimated maximum temperature (at the center of the distribution).

6. The average temperature, computed by weighting the values by the area subtended by the particular thermocouple. In general, it does not agree with the arithmetic average displayed in Fig. 2.1.

7. The power density. This number is computed by converting the maximum temperature to joules and then to kilowatts, then normalizing it by the area of the

ion source.

8. This is the power deposited on the beam dump, calculated first by using the average temperature (6.) converted to megawatts and then using the same idea with the fitted temperatures. They tend to be close almost all the time, as one might expect.

9. This graph and #10 give three different cross section views of the temperature distribution. The wider curve corresponds to the distribution along the column of thermocouples closest to the center of the pattern. The points marked 'x' show the temperature at each thermocouple in that column. The narrow curve and points marked 'o' do the same thing for the row of thermocouples closest to the center.

10. This graph shows a cross section of the fitted surface normal to the two in #9, drawn at one-half the maximum measured temperature. Again, 'x' marks a point where the measured temperature is the same as on the curve.

    Thermocouples may be 'suspect' (?) as determined by the program, or 'bad' (*), as determined by the program or by the operator. (See "Sensor on/off" button on the beam dump menu). In the latter case, their values are ignored in all calculations.

11. Chi-Square is a goodness-of-fit value. It should be about 1. for a good fit on the beam dump. (For minor technical reasons, it currently reads lower for the target dump).

12. Rotation measures the departure from the vertical in #10. Notice that the graph does appear to be slightly tilted. The physical reasons for this are unclear.

13. FWHM means "full width, half maximum". It refers to the lengths of the major and minor axes of the ellipse in #10.

14. Beam on: - as contrasted to beam request. This number is reported in whatever units are appropriate at the time; here, milliseconds.

SHOT 75592 TARGET DUMP 03/03/82 08:46

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -0.3<br>0.0 | 0.5<br>-4.2 | -2.5<br>-3.8 | 2.6<br>-3.8 | 4.3<br>-3.8 | 5*7<br>84*0 | 5.8<br>-4.6 | 3.4<br>-4.6 | -0.4<br>-3.8 | 0*1<br>63*1 | 0*9<br>0*0 | -1*5<br>0*0 |
| -0.2<br>-3.8 | 1.2<br>-4.2 | 1.3<br>-3.8 | 1.5<br>-3.3 | 9.6<br>-3.8 | 11.3<br>-3.8 | 9.0<br>-5.0 | 5.5<br>-5.0 | 1.5<br>-3.8 | 1*7<br>82*2 | -0*2<br>0*0 | 2*1<br>0*0 |
| 1.0<br>-4.2 | -1.5<br>-4.2 | 4.0<br>-3.8 | 4.8<br>-3.8 | 14.1<br>-3.3 | 23.5<br>-3.8 | 19*3<br>-4*6 | 5.5<br>-4.6 | 1.7<br>-3.8 | 0.5<br>-3.3 | -1*0<br>0*0 | -4*4<br>0*0 |
| 0.4<br>-4.2 | -0.1<br>-4.2 | -1.8<br>-3.8 | 6.4<br>-3.8 | 16.7<br>-3.8 | 27.8<br>-3.8 | 24.7<br>-4.6 | 10.6<br>-4.6 | 1*8<br>-3*8 | 0.2<br>-3.8 | 1*4<br>0*0 | -1*5<br>0*0 |
| -0.6<br>-3.8 | 1.9<br>-4.2 | 1.6<br>-3.8 | 4.3<br>-3.8 | 18.0<br>-3.8 | 28.5<br>-3.8 | 20.5<br>-4.6 | 9.8<br>-4.6 | 3.2<br>-3.8 | 2.6<br>-3.8 | -0*5<br>0*0 | 2*1<br>0*0 |
| 2.4<br>-3.8 | -2.2<br>-4.2 | 2.8<br>-3.8 | 4.5<br>-3.8 | 12.9<br>-3.8 | 21.8<br>-3.8 | 19.0<br>-4.6 | 6.1<br>-4.6 | 1.8<br>-3.8 | 0*6<br>0*0 | -1*3<br>0*0 | -2*0<br>0*0 |
| 0.8<br>-3.8 | 0.7<br>3.3 | -1.8<br>-3.8 | 2.4<br>-3.8 | 5.7<br>-3.8 | 10.7<br>-3.8 | 14.7<br>-5.0 | 5.5<br>-4.6 | 1.9<br>-3.8 | 0.0<br>-3.8 | 1*8<br>0*0 | -1*3<br>0*0 |
| -1.0<br>-3.8 | 2.9<br>3.7 | 0.7<br>-3.8 | 0.3<br>-3.8 | 3.1<br>-3.8 | 6.0<br>-3.8 | 2.4<br>-4.6 | 2.2<br>-4.6 | 1.4<br>-3.8 | -0.5<br>-3.8 | -1*5<br>0*0 | 1*8<br>0*0 |

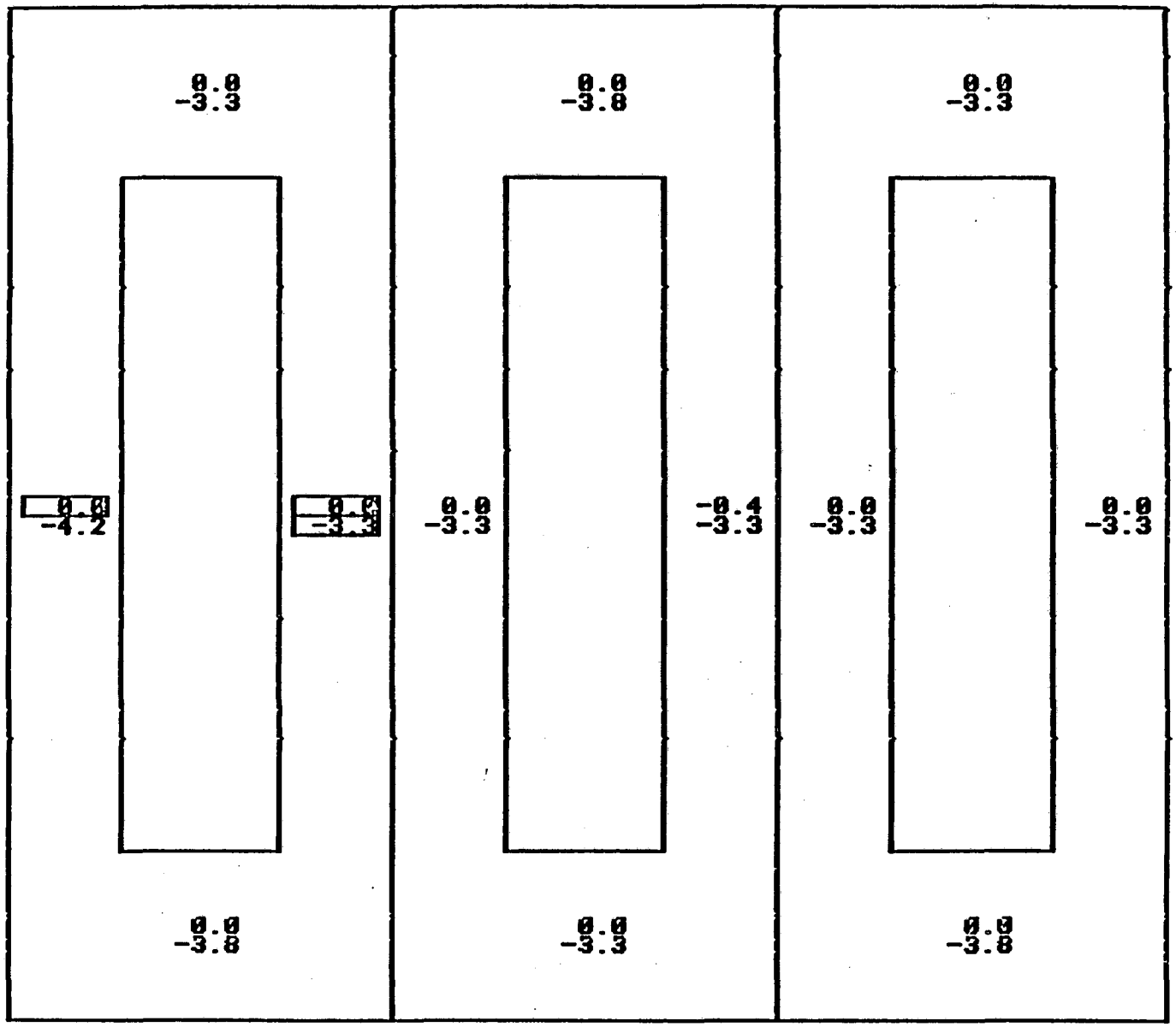
| | | AVG | PEAK |
|---|---|---|---|
| DELTA T | DEL | 5.5 | 28.5 |
| REF TEMP | REF | -3.7 | 3.7 |
| | FIN | 1.8 | 24.7 |

All temps in degrees C
viewed from source

* 22 BAD SENSORS

Fig. 2.1a

SHOT 75592 CALORIMETER SCRAPERS 03/03/82 08:46




| | | AVG | PEAK |
|---|---|---|---|
| DELTA T | DEL | -0.0 | 0.6 |
| REF TEMP | REF | -3.5 | -3.3 |
| | FIN | -3.5 | -3.3 |

All temps in degrees C
viewed from source

Fig. 2.1b

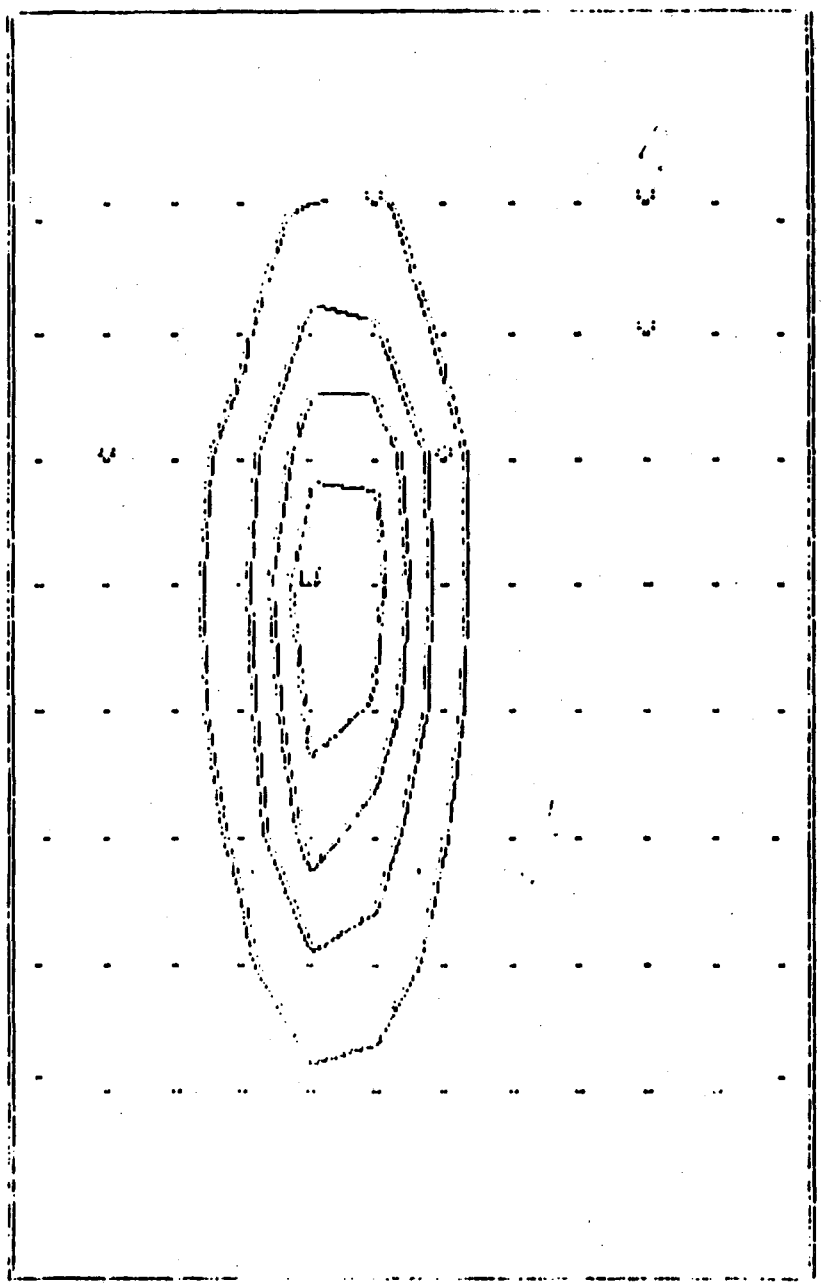
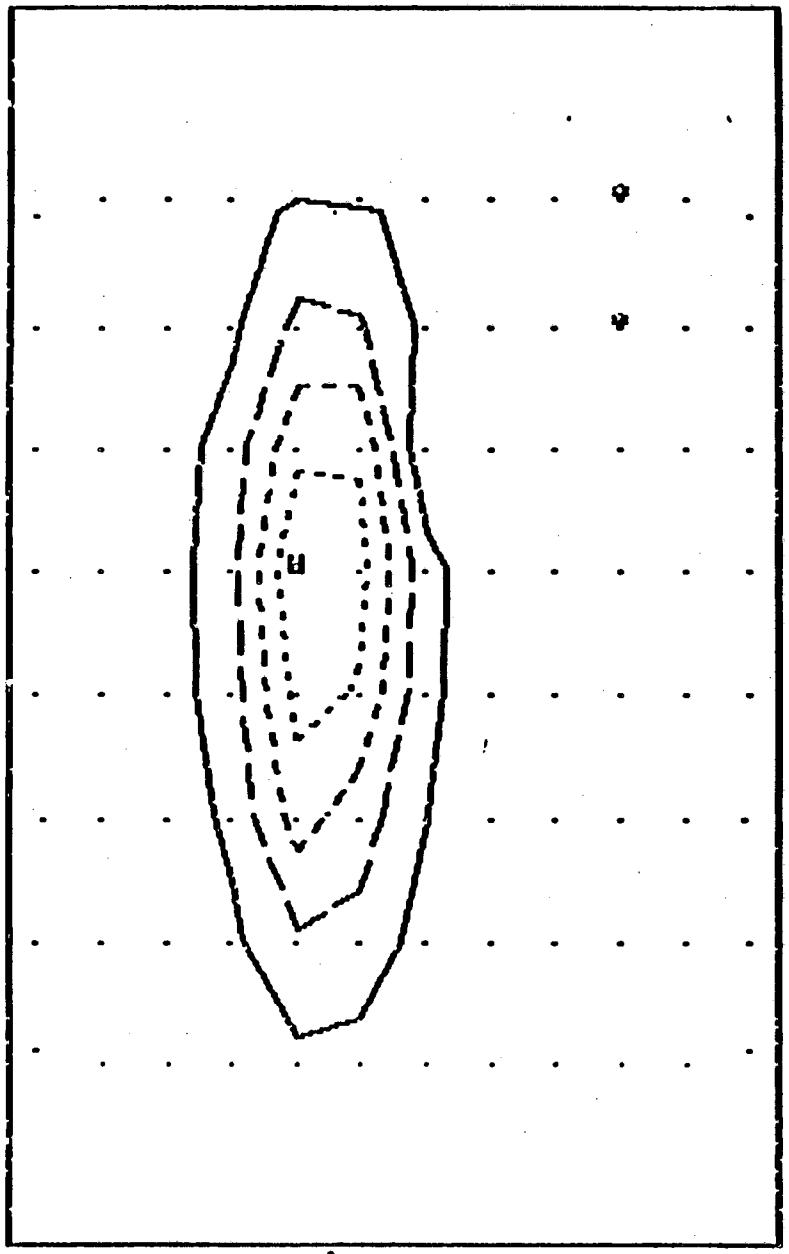


Fig. 2.19

TARGET DUMP

SHOT 35069 02/11/81 21:23

THERMAL CONTOURS



Beam on 0.241 secs.

CONTOUR LEVELS
DELTA T DEG C

29.2 --------
21.9 ------
14.6 ——— —
7.3 ———

(H) MAX DT = 36.5 DEG C

MIN DT = 0.0 DEG C

AVG REF = 4.1 DEG C

(*) 2 BAD SENSORS

I-accel = 57.73 A.
V-accel = 109.03 KV.

Fig 2.2b

TARGET DUMP

SHOT 33214 I-accel 63.5 A. V-accel 119.9 KV. 01/21/81 13:35

Beam on 113mS (14)

(2) DIV (+) 1.15 degs( 20.1 mrads) 48.6 cm FHHM
DIV (||) 0.43 degs( 7.6 mrads) 15.7 cm FHHM (13)

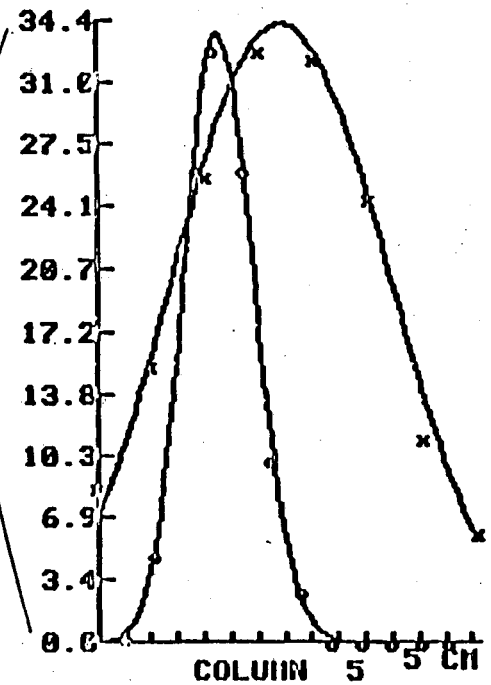
(3) Y-cnt -1.3 cm ( -1.2 mrads)
X-cnt -6.7 cm ( -6.1 mrads)

ROTATION 2.4 degs (12)
CHI-SQUARE 0.3 (11)

(4) dT max = 33.0 C
(5) dT max = 34.4 C (from fit)
(6) dT avg = 5.7 C

(7) dP/dA max = 6.14 KW/sqcm 32.3% Accel pwr
(8) P (t.dump) = 4.77 MW 62.6% Accel pwr
P (t.dump) = 4.8 MW (from fit)

(9)

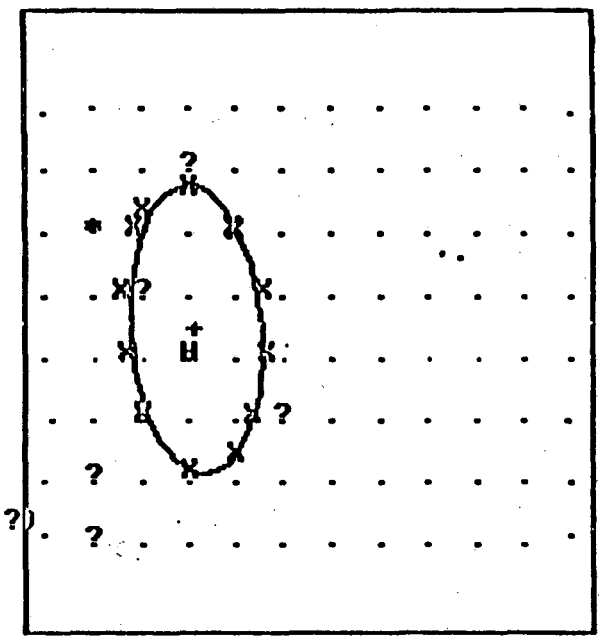



ROW 6

95 SENSORS
USED IN FIT

5 SUSPECT (?)

1 BAD (*)



(10)

-6-

367

Fig. 3

# Bi-gaussian Temperature Model for Beamdump Calorimetry

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## 1. Introduction

This note presents a heuristic derivation of the models used at LBL to derive beam parameters with the so-called "calorimeter fit program." The derivation refers to both unfocused sources and focused sources of the Doublet III type. The person principally responsible for this model at LBL is Bill Cooper. Richard Smith also contributed and, independently, Kim and Whealton (ORNL) proposed a similar model (Nucl. Inst. Meth.,v.141,187, 1977).

Also included is a list of the required inputs to the fit program and a list of its outputs

## 2. Notation and Preliminaries

Let x and y denote coordinate axes on a calorimeter in directions parallel and perpendicular to the accelerator grids. (If the face of the calorimeter is not normal to the beam, we assume that the coordinates have been projected onto a normal plane at the back of the calorimeter). Let z be the minimum distance from the point (x,y) on the calorimeter to the exit plane of the accelerator (see Figure 1). Because there is no preferred orientation for the source, we give full details for just one direction (arbitrarily , "x").

Similarly, let (x',y',0) denote points on the exit plane of the accelerator. If the beam is focused, as discussed in Section 6, the exit "plane" is really a curved surface, and then there is a z' > 0 in general, which denotes the distance from the point (x',y',z') on the surface to (x',y',0).

It is heuristically convenient to imagine that the beam is composed of a great many "beamlets".

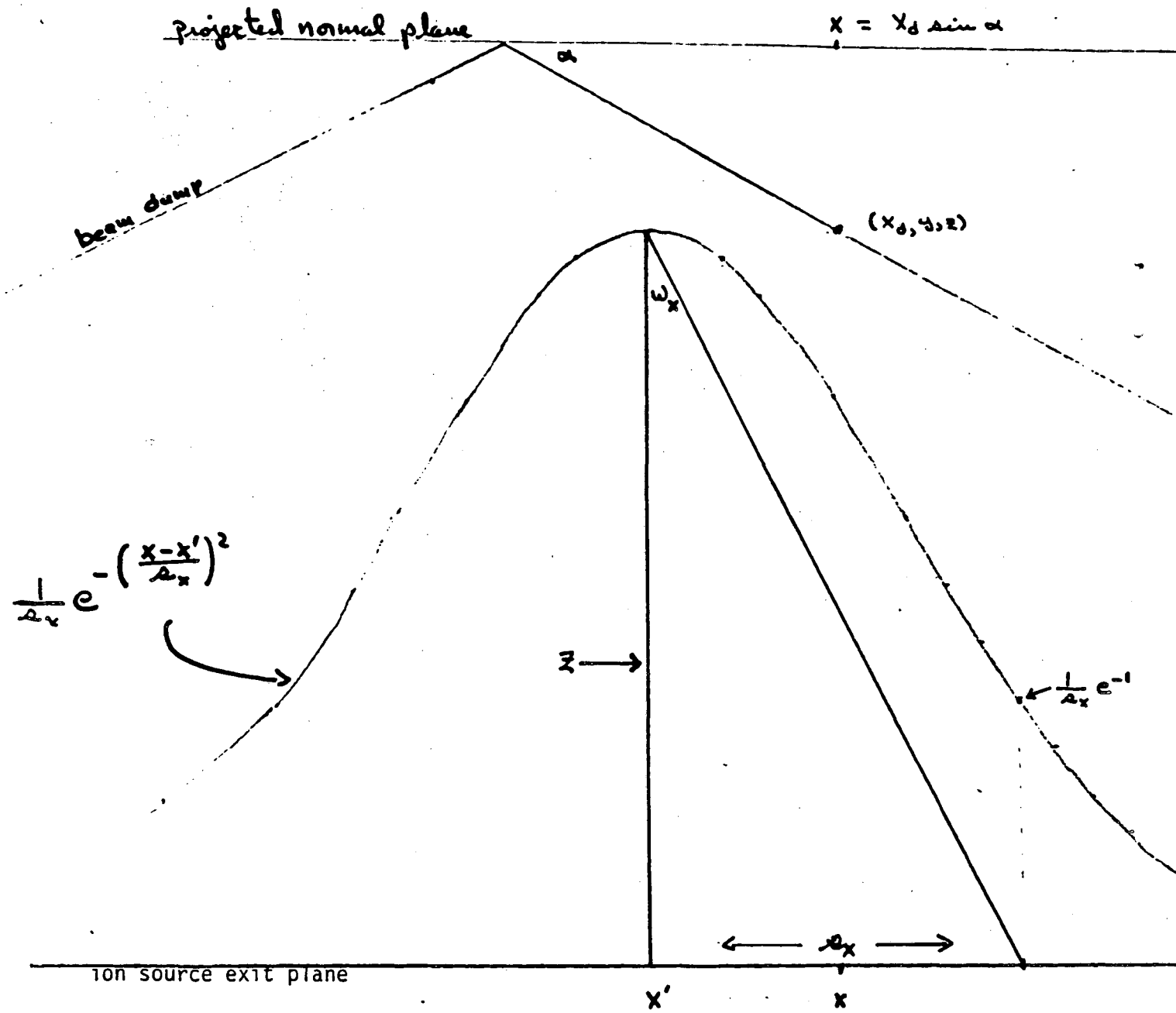


Figure 1

View of a beamlet in the x-z plane

## Basic Assumption

The temperature density contribution at x on the calorimeter from the beamlet at x' at the source is proportional to a gaussian function

$$(1/s_x)\exp[(x-x')/s_x]^2$$

where $s_x$ is the standard deviation of the function.

(N.B. It has been found empirically that this assumption leads to a model which provides good data fits. See section 7).

Of course it is more meaningful to speak of temperature density in units of deg/cm². Since the two directions are entirely similar, with independent distributions assumed, we can write the density D as

$$D(x,y,z) = C*1/(s_x s_y)*\exp[(x-x')/s_x]^2\exp[(y-y')/s_y]^2 \quad (1)$$

(C is a constant of proportionality).

## 3. The Divergence Angles

It is customary to characterize neutral beams in terms of their divergence angles. The divergence angle $w_x$ is defined by

$$s_x = z\tan(w_x) \quad (2)$$

## Assumption 2

The divergence angles of all the beamlets are equal and constant in time and space.

Note: Assumption 2 implies that the beamlet propagates down the beamline with an expanding profile, since $s_x$ controls the "spread" of the function.

Now adding all the contributions from all the beamlets (and assuming no interaction between beamlets) and substituting (2) in (1), the temperature at a point (x,y,z) on the calorimeter is given by

$$T(x,y,z) = C\int_{-a}^{a}dx'\int_{-b}^{b}dy'\,\frac{\exp\left[-\frac{(x-x')}{z\tan w_x}\right]^2\cdot\exp\left[\frac{-(y-y')}{z\tan w_y}\right]^2}{(z\tan w_x)(z\tan w_y)} \quad (3)$$

where a and b are the half widths of the ion source in the x' and y' directions, respectively.

## 4. Rotation and Translation

Up to this point, it's been assumed that there is no offset in the beam - that is, (0,0) on the source corresponds to (0,0) on the calorimeter. To compensate for the possibility that the beam hits off-center (in fact, it virtually always hits off-center) and for the less obvious possibility that the beam is somehow rotated in transmission, we postulate that

$$\begin{aligned} x' &= (x-u)\cos(r) + (y-v)\sin(r) \\ y' &= -(x-u)\sin(r) + (y-v)\cos(r) \end{aligned} \qquad (4)$$

These are the usual equations of translation followed by rotation and permit the beam from (0,0) on the source to hit (u,v) on the calorimeter.

## 5. Error Function Formulation

Finally, let us put equation (3) into a form more congenial for computation. Let

$$v(x') = (x-x')/s_x \qquad (5)$$

so

$$dv = -dx'/s_x$$

From (3):

$$1/s_x \int_{-a}^{a} \exp[-(x-x'/s_x]^2 dx' = -\int_{(x+a)/s_x}^{(x-a)/s_x} \exp[-v]^2 dv \qquad (6)$$

Observing that the error function is defined by

$$\mathrm{erf}(x) = -\mathrm{erf}(-x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp[-v]^2 dv ,$$

(6) may be written as

$$\frac{\sqrt{\pi}}{2}\Big(\mathrm{erf}[(x+a)/s_x] - \mathrm{erf}[(x-a)/s_x]\Big)$$

The same kind of expression must hold for the y' integral, so (3) becomes

$$T(x,y,z) = C*(\mathrm{erf}[(x+a)/s_x] - \mathrm{erf}[(x-a)/s_x]) * (\mathrm{erf}[(y+b)/s_y] - \mathrm{erf}[(y-b)/s_y]). \qquad (7)$$

Fast numerical approximations for the error function erf are available, so this is a convenient form in which to express the model.

## 6. Generalization for Curved Grids (a "Focused" Source)

When the exit surface is curved, Figure 2 applies. $R_x$ and $R_y$ denote the radii of curvature in the x and y directions, respectively. Only $R_x$ is shown in the view of Figure 2. If both $R_x$ and $R_y$ are infinite, the surface is flat and we are in the unfocused case. Now we may imagine that, due to the curvature, the beamlet has been rotated through the angle p from its nominal path for a flat surface. The rotation equations this time are:

$$x_p = x'\cos(p) - z\sin(p)$$

$$z_p = -x'\sin(p) + z\cos(p)$$

(y is not rotated in the x-z plane).

For ease of notation, we will temporarily drop the subscript x on $R_x$.

From Figure 2,

$$\cos(p) = (R-z')/\sqrt{(R-z')^2 + x'^2}$$

and

$$\sin(p) = x'/\sqrt{(R-z')^2 + x'^2} \ ,$$

but assuming (as is the case for Doublet III) that R >> z' and x'/R is small, <.1, say, then

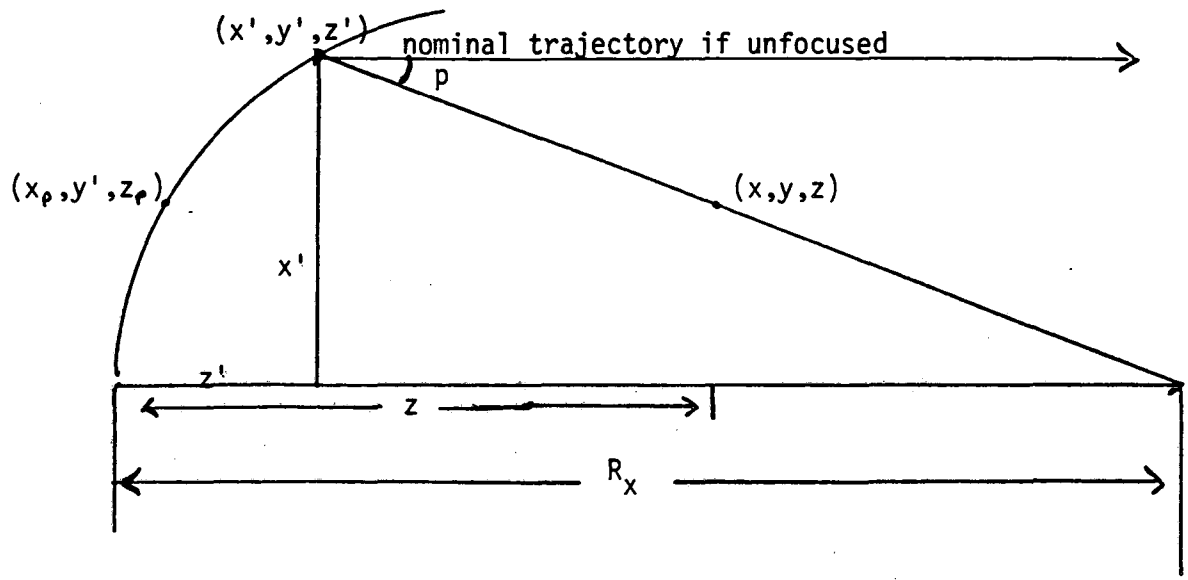


Figure 2

Side view of the x-z plane for a focused Source

$$\cos(p) \sim 1$$

$$\sin(p) \sim x'/R$$

and

$$x_p \sim x' - zx'/R = x'(1-z/R) = (x'/R)(R-z)$$

$$z_p \sim -x'(x'/R) + z \sim z - .1x' \sim z \qquad (8)$$

Figure 2 shows that the contribution of the beamlet from $(x',y',z')$ on a curved source should be the same as from $(x_p, y', z_p)$ on a flat source. Therefore, using (8), the $x'$ integral in eq. (3) becomes

$$1/s_x \int \exp[-(x-x_p)/s_x]^2 dx' = 1/s_x \int \exp\left[-\frac{\left(x - \frac{x'}{R}(R-z)\right)}{z\tan\omega_x}\right] dx'$$

Now let $u_x = \frac{a}{\tan\omega_x} \cdot \frac{R-z}{Rz}$ . Then the r.h. integral becomes

$$1/s \int_{-a}^{a} dx' \exp\left[-\left(\frac{x}{z\tan\omega_x} - \frac{x'u_x}{a}\right)\right]^2$$

$$= -\int_{\frac{x}{z\tan\omega_x}+u_x}^{\frac{x}{z\tan\omega_x}-u_x} (a/u_x)\exp[-v^2]dv$$

(The last integral is obtained by letting v = the exponent of e in the l.h. integrand. The r.h. integral is then

$$(a/u_x)(1/s_x)(\sqrt{\pi}/2)[\mathrm{erf}(u_x+x/(z\tan w_x)) - \mathrm{erf}(x/(z\tan w_x) - u_x)]$$

But $s_x = z\tan w_x$ , so $(a/u_x)s_x = R_x z/(R_x - z)$. Again, a corresponding expression holds for $y'$. Therefore, the final expression for T is

$$T(x,y,z) = C*ab(R_x/R_x-z)(R_y/R_y-z)[\mathrm{erf}(x/z\tan w_x + u_x) - \mathrm{erf}(x/z\tan w_x - u_x)] *[\mathrm{erf}(y/z\tan w_y + u_y) - \mathrm{erf}(y/z\tan w_y - u_y)] \qquad (9)$$

## 7. Data Needed as Input to the Fit Program

(1) Thermocouple "delta-t" temperatures (i.e., after shot reading - before shot reading)

(2) Thermocouple positions on the beamdump (projected onto a normal plane, as shown in Figure 1).

(3) The size of the "vee" angle of the calorimeter, in degrees (180 degrees is permitted, if there is no vee).

(4) The status ("deleted" or "good") of each thermocouple (so that the program can ignore bad data which could distort the fit).

(5) The source's radii of curvature (0,0 for TFTR sources).

(6) The half-width and half-height of the ion source (see eq. (9)).

(7) The distance from the center of the source to the apex of the beam dump.

## 8. Derived Data Output by the Fit Program

Taking equations (3) and (4) together, we see that there are six unknowns in the model to be determined by data fitting:

(1) u - the x-coordinate of the beam's center

(2) v - the y-coordinate of the beam's center

(3) w - the divergence angle in the x-direction

(4) w - the divergence angle in the y-direction

(5) C - a proportionality constant which scales with temperature

(6) r - a rotation angle

In addition, the program saves the temperature of the hottest sensor, its index or locator number, and a chi-square value indicating goodness of fit.

## 9. Remarks

9.1 The calculation of z depends on the geometry of the beamline and the beamdump. A subroutine general enough to work with vee shaped or flat dumps of either the TFTR or Doublet III varieties is used in the current calorimeter fit program.

9.2 We know, from rather extensive empirical investigations, that the model gives a fairly good overall fit to the data, but may not fit any particular row or column of sensors very well. Perhaps the most unrealistic assumption is that of uniform divergence angles. Several factors, such as plasma

inhomogeneity or damaged or poorly conditioned grids could cause the angles to vary. Richrd Smith (LBL) has done some numerical studies which suggested that indeed inhomogeneity may occur. However, the purposes for which the current model is used seem to have been sufficiently well served with the more restrictive hypothesis. The model seems to match the data better as the distance from source to target increases. At the TFTR source to reactor vessel distance, the fit is very good for a conditioned source.

9.3 It is comforting to observe that, as $R_x$ and $R_y$ tend to infinity, $u_x$ tends to $a/s_x$ , $u_y$ tends to $b/s_y$ and (9) reduces to (7), (with a different C).

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