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Diagnostics for the NBETF Actively Cooled Beamdump

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Lawrence Berkeley Laboratory's Neutral Beam Engineering Test Facility is currently testing multi-megawatt beams with pulse durations of up to 30 seconds. For this purpose, an actively cooled beam dump composed of heat-absorbing panels that dissipate the beam energy via high speed water flow has been installed and tested. The panels are mounted in a complex assembly necessary to accommodate the variety of ion sources to be tested.

The beam dump required new diagnostics of two kinds: beam diagnostics that provide graphic and quantitative information about the beam, as inferred from energy transferred to the water, and panel diagnostics that provide graphic and quantitative information about the beam dump itself.

In this paper we describe our response to these requirements, including new algorithms for beam profiles, and we compare this work to our earlier results for inertial beam dumps. Principal differences are that the power densities on the water-cooled panels can be only indirectly inferred from measurements of the transferred beam energy, and that the acquisition and preparation of 'raw' data is much more complex.

Background

NBETF provides a common facility for testing a variety of long pulse neutral beam sources. It accommodates as much as 8MW of beam for up to 30 seconds. (The MFTF-B experiment will require 30 second 3.2MW beams, while TFTR plans to use 2 to 5 second 8MW beams).

A major component of NBETF is its actively cooled, long pulse beam dump (called the "active dump" hereafter). The dump, described in [1], consists of 40 Amzirc copper panels with interior cooling channels. The 21.5 by 20 cm. panels are arranged in eight sub-assemblies of five each. The sub-assemblies are mounted on a support structure inside a target tank. Figures 1 and 2 show overhead views of the beamline and the dump.

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As suggested in fig. 2, the dump can be repositioned under computer control. Each subassembly can be moved individually with three degrees of freedom, including rotating the panel to change the angle of beam incidence. The panels were designed to withstand power densities of 2KW/cm² with internal water flows as high as 3.8 liters/sec. per panel. By moving the panels appropriately, power constraints can be met while accommodating a variety of different beam footprints.

Goals for the Diagnostic Subsystem

Water flow calorimetry is normally used to determine the total energy deposited on some device. However, we were interested in providing a more detailed picture of the beam. Our earlier work with inertial beam dumps (see [2]) permitted shot-to-shot estimates of beam divergence and centering derived from thermocouple measurements of the beam power density distribution. For the NBETF active dump, however, the measured values reflect the power distribution.

Our goal was to provide much the same diagnostic information as existed for inertial dumps: model-free power density contours together with estimates of divergence, center, and peak power density derived from a model of the beam’s power distribution. These had to be consistent with diagnostics for the inertial dump, of course. Further, the protection of the active dump was of great importance, so a diagnostic that monitored peak power densities for individual panels was required.

Data Acquisition: Methods and Problems

Two numbers are associated with each of the 40 panels: water flow and water temperature rise. The temperature rise is measured by thermocouple in/out pairs attached to the inlet and outlet bellows of each panel. The thermocouples are wired to produce a single voltage which is the difference of their output signals. The flows are derived indirectly. The measured values are actually waveforms from pressure transducers on eight inlet and outlet manifolds, one for each subassembly. During installation, each panel was calibrated: first, to relate its water flow to the pressure drop across the panel, and second, to relate that pressure drop to the pressure drop of the manifold servicing that assembly. Thus, the flows are derived from the pressure transducer waveforms by the transformations:

\[
M_{\text{in}} = c_1 + c_2 D_{\text{in}} + c_3 D_{\text{in}}^2 \\
M_{\text{out}} = c_4 + c_5 D_{\text{out}} + c_6 D_{\text{out}}^2 \\
\Delta P_{\text{panel}} = c_7 + c_8 (M_{\text{in}} - M_{\text{out}}) \\
F_{\text{panel}} = c_9 + c_{10} \sqrt{\Delta P_{\text{panel}}}
\]

where \(D_{\text{in,out}}\) are the averaged waveform digitizer readings, \(M_{\text{in,out}}\) are the manifold pressures, \(\Delta P_{\text{panel}}\) is the pressure drop across a particular panel, \(F_{\text{panel}}\) is the water flow through that panel and the \(c_i\)'s are the panel's calibration coefficients. Each panel carries its own set of 10 calibration.
coefficients as part of an overall database. Thanks to careful calibration of each manifold and panel by the mechanical engineering crew, this indirect way of obtaining flows has consistently worked well.

The acquisition and use of the $\Delta T$ waveforms, while conceptually simpler, created problems which persisted during the early months of NBETF. The waveforms tended to be noisy and unreliable, due to thermocouple problems associated with the presence of the beam. (A detailed explanation of these problems and their solution is given in [3].)

The acquisition and data preparation by the computer proceeds as follows:

1. Acquire the 40 $\Delta T$ waveforms via CAMAC. Convert them from digitizer units to temperature.
2. Compute and save the waveform integrals, $\sum \Delta T$.
3. Acquire the 16 pressure transducer waveforms. Compute the waveform averages and convert these to flow as described above. Save average inlet and outlet pressures and flows.
4. For each of the 40 panels, compute the power by

$$P_{wr} = \frac{C_p(T) \times \sum \Delta T \times \text{flow}}{\text{ontime}}$$

where $C_p(T)$ is the specific heat of water at temperature $T$.

In all, 56 digitized waveforms of 1000 samples each are acquired and processed in order to prepare the 40 power numbers. The result of this sequence of steps for a typical shot is seen in fig. 3. The lower number in each box is the power on that panel in kilowatts. The upper number is an average power density for that panel, obtained by simply dividing the power by the exposed area. This latter value, however, is too coarse an estimate of power density to be useful for the more detailed analyses described below.

**Power Density Contouring**

We generate power density contours without a reference "model" in order to derive graphical information about the beam with as few preconceived notions about its shape as possible. Only panel positions and their measured power values enter into the analysis.

The goal is to produce estimates of power density at any point on the panels and then to create iso-density contours. To accomplish this, the power values are first transformed into a cumulative distribution whose value for the panel in column $i$ and row $j$ is:

$$C_{i,j} = \sum_{k \leq i} \sum_{l \leq j} P_{wr_{k,l}}$$

The use of this cumulative distribution is analogous to using a statistical cumulative distribution to determine a probability density function. The analogue of the latter here is the mixed spatial derivative of the cumulative power function, i.e., the power density.
Once the cumulative distribution is formed, an interpolating bicubic spline is computed. The spline models the power distribution on each panel as a bicubic polynomial with coefficients chosen to join smoothly at adjacent panel boundaries. It is relatively simple to compute the mixed partial derivatives of the spline and, using these, to approximate the power density at points on a mesh considerably finer than that of the 5 x 8 panel arrangement. These points are then used to generate the contours, using a standard contouring algorithm.

Figure 4 shows a typical result. Two sets of contours are displayed. On the left, the power densities have been corrected for the beam incidence angle, to present a picture of the beam profile. On the right, the contours are shown with the angles “left in”, to present a picture of the panel power loading. The operator has the option of removing panels with bad signals and the analysis will fill in the resulting gaps in a reasonable way. In the figure, 9 panels have been deleted.

A Model for the Power Distribution

Temperature measurements from inertial dump calorimetry have been used for some time to determine beam parameters by fitting the data to a model of the beam profile [2]. If \((x, y)\) is a point at a distance \(z\) from the accelerator grids, then the power density \(PD\) is approximately

\[
PD(x, y) = A \left[ \text{erf} \left( \frac{x + aF_x}{\sigma_x} \right) - \text{erf} \left( \frac{x - aF_x}{\sigma_x} \right) \right] \times \left[ \text{erf} \left( \frac{y + bF_y}{\sigma_y} \right) - \text{erf} \left( \frac{y - bF_y}{\sigma_y} \right) \right]
\]

where \(A\) is an ‘amplitude’ that incorporates source geometry and power density; \(F_x = (R_z - z)/R_z\) accounts for focusing \((R_z\) is the focal length in the \(x\) direction); \(\sigma_z = z \tan \theta_z\) (\(\theta_z\) is the 1/e half width divergence angle); and \(a\) is the source half-width.

\(F_y, \sigma_y\) and \(b\) are defined similarly. Details on the derivation of (1) are given in [2].

This model must be extended to the situation where power \(P\) on a surface \(S\) is the input data. In general,

\[
P(S) = \iint PD(x, y, z) dS.
\]

More specifically,

\[
P(\text{panel}) = A \int \text{erf} \left( \frac{x + aF_x}{\sigma_x} \right) - \text{erf} \left( \frac{x - aF_x}{\sigma_x} \right) dx \int \text{erf} \left( \frac{y + bF_y}{\sigma_y} \right) - \text{erf} \left( \frac{y - bF_y}{\sigma_y} \right) dy
\]

where the integrations are carried out over the length and width of that section of the panel exposed to beam.

For this development it is sufficient by symmetry to manipulate just the \(x\) integral, which we denote by \(P_z\). A general formula is

\[
\int_{\alpha}^{\beta} \text{erf}(x) dx = \beta \text{erf}(\beta) - \alpha \text{erf}(\alpha) + \frac{1}{\sqrt{\pi}} \left[ e^{-\beta^2} - e^{-\alpha^2} \right]
\]

obtained by integrating by parts. This result is substituted in \(P_z\) to obtain, after some algebraic manipulation,
A corresponding expression holds for $P_{y}$, of course.

The five parameters to be estimated using (2) and (3) are then: $A$, the "amplitude" of the power distribution; $\theta_x, \theta_y$, the divergence angles of the beam; and $(x_0, y_0)$, the center of the distribution on the dump. These are the same five parameters that result from fitting model (1) to the inertial dump temperatures.

The input data are the 40 panel power values calculated during the shot data acquisition phase, together with geometric information about the source and current dump configuration. The result of the fitting process (which involves the nontrivial calculation of the five partial derivatives of (3) for each panel) is shown in fig. 5.

### Panel Diagnostics

In addition to beam information, we wished to monitor the panel power distribution. In particular, it was important for operators to know the peak power density on each subassembly of five panels and the peak integrated power along individual water channels inside a panel.

Using the beam model described above, one can estimate the power density at any point and the power in any region. Our data suggest that the model describes the beam well near the center of the distribution, with most of the error occurring in regions of lower power density. (I.e., "the tails of the beamlets are not gaussian"). Thus, estimates of peak power density – where the panels might be endangered – had a relatively high degree of confidence. Figure 6 shows the result of these estimates. The two rows of graphs show the power density across each subassembly along the horizontal slice through the peak power density point. The lower half of the display is an ordered list of the ten panels whose ‘power per channel’ is closest to exceeding its allowable limit (which depends on the flow rate through that panel). The leftmost column is an estimate of the possible error in the prior number, made by comparing measured vs. fitted power for that panel.

### Conclusions

Our operational experience during 1983-84 has brought forth the following points.

- Results from actively cooled dump calorimetry were quite consistent with diagnostic results from the inertial dump. The horizontal divergence estimates on the former tended to be about 12% larger than on the latter (0.4° vs. 0.35), possibly due to the poorer spatial resolution of the active dump (40 points vs. 117).
• Estimates of peak power densities derived by the two methods described here (spline interpolation and model fitting) were consistent. The fact that a model-free estimate agrees generally to 5–15% with our “error function” model is gratifying and gives us additional confidence in the results.

• Analysis of residuals from the fitting process suggests that the peak and shoulders of the distribution are described quite well by the model, with the error carried mostly in the tails. This is consistent with results obtained with inertial calorimetry at LBL and Oak Ridge National Laboratory [4].

• The design of the active dump was intended to be conservative, and our results support that claim. The principal beam parameters, divergence and delivered power, were assumed to be about 15% more stringent in the design than actually appeared in practice. This translated to peak power densities of only 60–70% of the critical limits.

• Measured beam power on the panels accounts for 80–85% of the beam. An additional 5–10% is measured by calorimetry on scrapers in the target area and elsewhere in the beam line, so total power accountability is 90–95% of electrical power at the source.

• The existence of detailed diagnostics, together with raw data, on a timely, shot-to-shot basis contributes to overall efficiency of operation. For example, without active dump diagnostics, the operator would need to frequently switch back to the inertial dump for beam parameters or to do a perveance sweep. Further, in the absence of other diagnostics, it would be an open question as to whether the beam parameters changed significantly on longer pulses (we found they did not). Finally, the ability to continually monitor the safety of the long pulse dump was an important factor in assaying the integrity of the overall NBETF beamline design.

References


Fig. 1

WBETF
NEUTRAL BEAM ENGINEERING TEST FACILITY

Fig. 2

CBB 839-8010
Fig. 3

Fig. 4
ACTIVE COOLED TARGET DUMP
SHOT 185806 1-acc 40.9 A V-acc 89.5 KV 08/08/88 08:00

RISIO 22.95

RIV (1) 6.9 deg (16.6 mrad)
RIV (11) 6.43 deg (7.4 mrad)

T-cut -2.8 cm (-1.6 mrad)
X-cut 1.8 cm (0.8 mrad)

Max avg dp/dt = 565 W/sq.cm

ROTATION 9.9 deg

CHI-SQUARE 9.9

dP/dt avg = 0.56 KW/sq cm

Pwr = 2.05 MW (measured)

Pwr = 2.25 MW (from fit)

Fig. 5

SUBPWR CHNL PWR (KW) % OF CRIT. EST. ERROR (%) 1R 2R 3R 4R
2L 2.2 26.2 10.9
1L 2.2 26.2 10.9
1L 6.3 27.4 3.3
2L 6.3 27.1 3.4
3R 6.3 26.2 10.9
2R 6.3 27.4 3.3
3R 6.3 27.1 3.4
1R 6.1 26.2 10.9

Fig. 6
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