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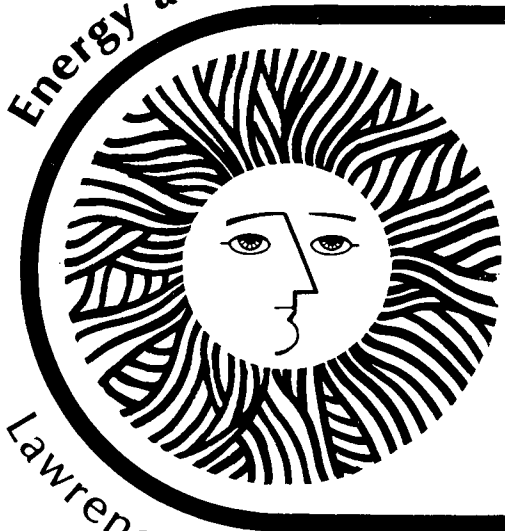
Calorimetric and Optical Beam Diagnostics
on the LBL 120-keV Neutral Beam
Test Facility

C. F. Burrell, W. S. Cooper,
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CALORIMETRIC AND OPTICAL BEAM DIAGNOSTICS ON THE LBL 120-keV NEUTRAL BEAM TEST FACILITY*

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The 120-keV Neutral Beam Test Facility at LBL is fitted with several types of instrumentation to determine the properties of the 10- to 15-A hydrogen and deuterium beams produced in this facility. These include a neutral particle dump for measuring the temperature profile generated by the beam, and a fixed and a moveable ion dump to measure the temperature profiles generated by the various ion components after they have been swept out of the neutral beam by a bending magnet. These several dumps provide enough information to determine the power density profiles and divergences of the neutral beam and the various ion beams for comparison with theoretical calculations, the beam composition, and the neutralization efficiency. The optical beam diagnostic consists of a high-resolution spectrometer coupled with a commercial optical multichannel analyzer. These instruments analyze Doppler-shifted optical radiation from the moving neutral atoms in the beam. Analysis of data so obtained provides the aiming directions and divergences of the various energy components in the neutral beam, as well as the beam composition. All of the above instrumentation is monitored and controlled by a computer-based diagnostic and control system described elsewhere in this symposium.

The arrangement of diagnostics is shown schematically in Fig. 1. There are three calorimeters with thermistors located approximately halfway through 1.91-cm thick copper plates.[1] The location of the thermistors optimizes the calorimeter time response. A computer program monitors the beam dump calorimeter on every shot and is very useful in tuning the neutral beam source for optimum beam divergence.
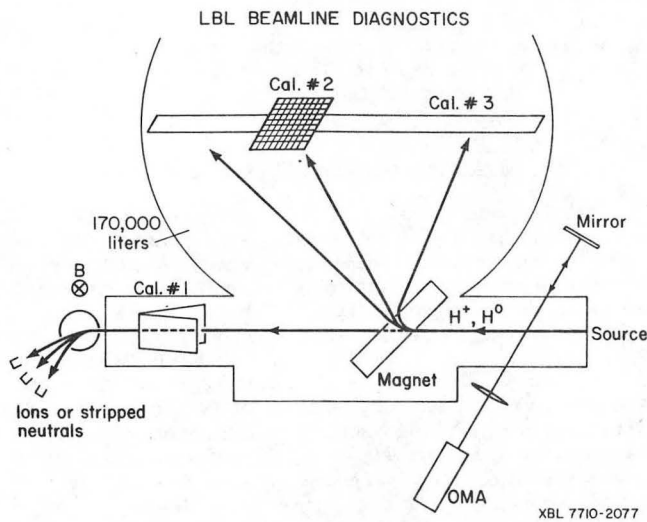
LBL BEAMLINE DIAGNOSTICS

XBL 7710-2077

Figure 1. Schematic representation of neutral beam line diagnostics to measure beam divergence and composition including optical diagnostics in the neutralizer, an in-line calorimeter and mass spectrometer for neutrals, and a sweep magnet with linear and rectangular calorimeters for ions.

In Line Beam Calorimeter

The Calorimeter No. 1 at the end of the neutral beam line serves as a beam power density profile and beam current monitor as well as a beam dump. It is constructed in the shape of a "V" with the axis parallel to and the apex in the beam direction so as to minimize the power density on the calorimeter surface. The calorimeter has been used to gather data both for neutral beams (ion sweep magnet active) and for beams containing unneutralized ions.

Data is acquired as follows. Prior to each shot, the calorimeter cooling water flow is shut off. At this point the thermistor temperature reference values are recorded. Following a preset delay after termination of the shot, final thermistor temperatures are recorded. The pointwise difference of these two sets of values is taken to represent the temperature rise due to beam energy deposition on the calorimeter plate at the thermistor locations.

From the measured temperature rises ΔT_i, beam energy V and beam on time t, the effective beam current is given by:

$$I = \frac{K}{Vt} \sum \Delta T_i$$

The current measured for the neutral fraction of a hydrogen beam is typically 30% of the current of the total beam (ions and neutrals). The ΔT array may be used to deduce contours of equal temperature rise. Figure 2 is such a contour plot. A fitting procedure is used to extract from the data a measure of the beam divergences parallel and perpendicular to the accelerator slots. The beam power density is assumed to be of the form

$$P(x,y) = A\, e^{-x^2/w_x}\, e^{-y^2/w_y}$$

where x and y are coordinates measured perpendicular and parallel respectively to the accelerator slots with origin at the beam center. The parameters w_x and w_y are adjusted so as to minimize

$$\chi^2 = \sum_{i,j} [\Delta T_{ij} - P(x_i, y_j)]^2$$

where (x_i, y_j) are the coordinates of the (i,j) thermistor. The resulting function P is taken to represent the beam power density profile. The parameters w_x and w_y measure the beam divergences.

Beam divergences measured this way are typically $1.3°$ perpendicular and $.7°$ parallel to the slots for beams which include the ions, while for neutral beams they are slightly smaller, by about $.1°$. These divergence values pertain to a flat (i.e., unfocused) source; no correction has been made for the finite size of the source.
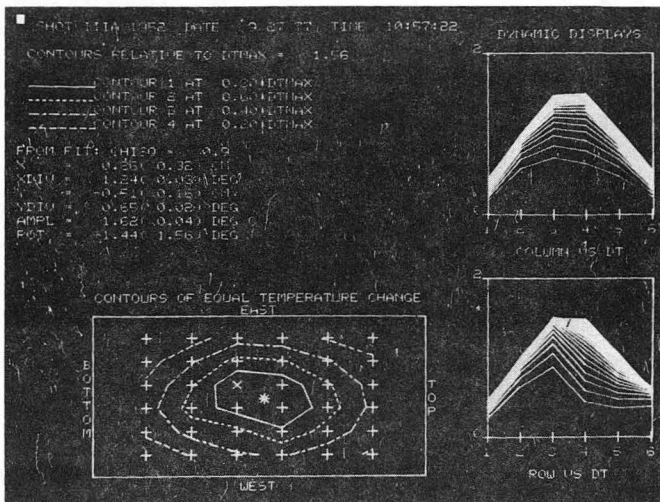
Figure 2. Computer generated display of calorimeter data including a plot of equal temperature rise contours.

Ion Dump Calorimeter

The ion dump calorimeter is located at a height 264 cm above the beam center line (see Fig. 1). There are two separate arrays of thirty-six thermistors each. The first array is linear with 14 cm thermistor spacing (Calorimeter No. 3). The second is a six by six square array, with 7.6 cm spacing (Calorimeter No. 2). Calorimeter No. 2 is suspended slightly below Calorimeter No. 3 and can be moved to different locations along Calorimeter No. 3. In one shot, we can obtain data on the two dimensional spatial distribution of one ion species and also a measurement of the power in several of the major ion species.

Calorimeter No. 2 has been used to investigate the possibility of beam blowup due to lack of complete space-charge neutralization of the ion beam between the poles of the bending magnet. The component of the unneutralized beam with the highest power, 120-keV H^+ ions, was deflected by 60°. Temperature profiles in two perpendicular planes were measured and compared with the predictions of a single particle trajectory code. The power distribution was measured on Calorimeter No. 2 in directions parallel and perpendicular to the original beam direction. Space charge was not considered in the trajectory code. After determining the central ray, a linear approximation was computed in order to transform the given spatial distribution of source emission and divergence to any plane along the central ray. The agreement between measured and calculated spatial power distributions was within the experimental error of 10%.

As shown in Fig. 3, we can observe the 60-keV H^+, 120-keV H^+, 120-keV H_2^+, and 120-keV H_3^+ components simultaneously. The various species track as expected when the magnetic field is varied. A correction for the variation in the focus transverse to the plane of bend has been made by moving one component along the length of calorimeter No. 3 and also by using the single particle trajectory code. Assuming that a particular specie has the same power at each region where it can be directed onto Calorimeter No. 3, the distribution of heat in the plane of bending, i.e. in the long direction of Calorimeter No. 3, can be used to infer the distribution of heat transverse to the plane of bending. The distribution of beam between the 120-keV H_2^+ and 60-keV H^+ components was used to compute the neutralizer thickness. In combination with the measured power of other ion components

we infer the species composition at the exit of the source accelerator structure. On one particular non-optimum run, the data from the ion dump, consisting of temperature rises, gave 49.6% H^+, while the data from an analyzing magnet, which measures ion currents passing through a small hole in the beam dump calorimeter (not necessarily representative of the entire beam), gave 50.2% H^+.
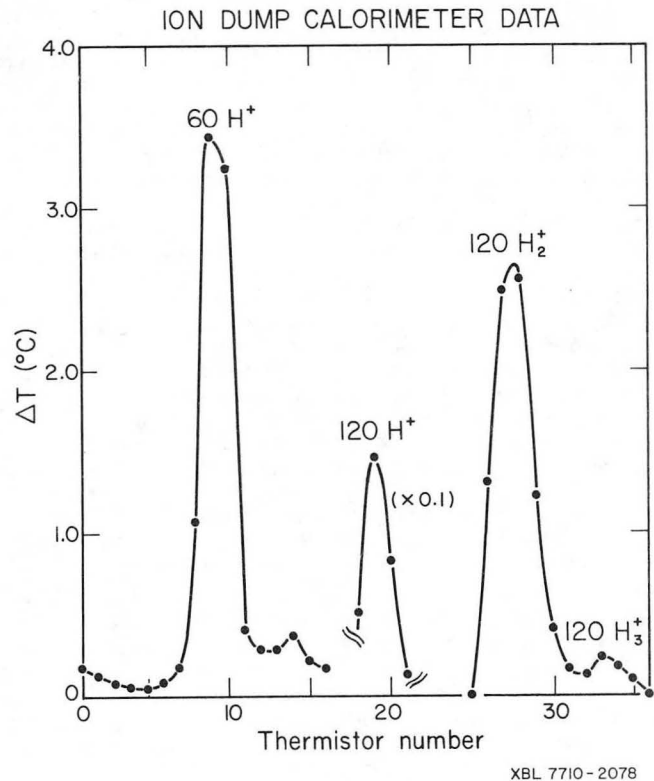

XBL 7710-2078

Figure 3. A typical distribution of the temperature rise along the 36 thermistor linear array showing four ion species.

Spectroscopic Beam Diagnostics

As the power of neutral beams increases it becomes increasingly difficult to measure the parameters of the beam with conventional calorimetric techniques. We have developed a spectroscopic technique which is capable of measuring the divergence, aiming direction and the species mix of the neutral beam. The spectrum of the H_β light emitted by fast hydrogen (or deuterium) neutrals is observed along an optic axis making an angle of 60° with the neutral beam axis. The light is Doppler shifted sufficiently to resolve the three energy components of the beam, caused by the breakup of molecular ions, and permits a measurement of the divergence and relative beam current of each component. If the optic axis makes an angle θ with a neutral particle trajectory then the emitted light is Doppler shifted from a wavelength λ_o in the rest frame, to a wavelength λ:

$$\lambda = \frac{(1 - \beta\cos\theta)}{\sqrt{1 - \beta^2}} \lambda_o, \quad \beta = v/c$$

The beam divergence of each component determines the width of its spectral line profile through the $\cos\theta$ term.
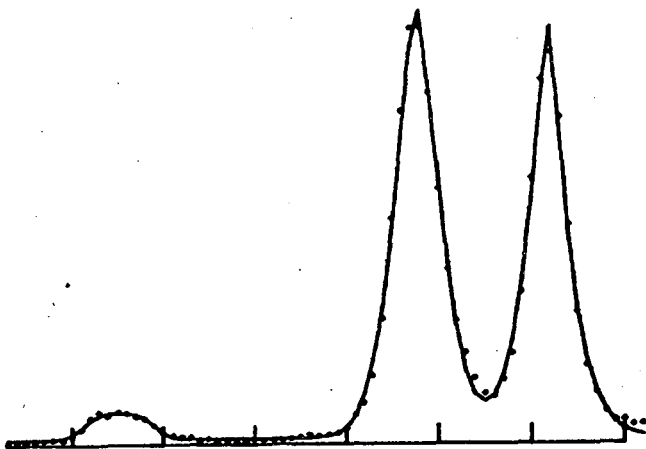
The Doppler-shifted H_β light is observed with a 500-channel polychromator. The system is based on a commercially available optical multi-channel analyzer (OMA; PAR Model 1205 A). The Silicon Intensified Target (SIT) detector head (Model 1205D) is mounted on a .3 m monochromator which has a 2360 lines/mm grating to give a dispersion of .33°A/channel. The 25 µm entrance slit of the monochromator is located in the focal plane of a f = 25 cm lens; thus the acceptance angle in the plane of the neutral beam and the optic axis is < .01° and has a negligible effect on the observed beam divergence. Time resolution is limited by the 32 msec scan time of the OMA. More commonly, all scans coincident with the neutral beam pulse duration are accumulated in the OMA memory. Data transfer to a Modcomp IV computer is accomplished via a serial converter card and is completed in 16 sec.

The input data is corrected for the sensitivity of each channel and the wavelength of each channel is computed. We find that the wavelength calibration is significantly non-linear, presumably due to distortion at the image intensification stage. However, the data are fit well by a cubic: $\lambda = a_o + a_1 m + a_2 m^2 + a_3 m^3$ where m is the channel number.

A curve fitting routine simultaneously fits the three Doppler-shifted peaks to the function

$$f(x) = \sum_{i=1}^{3} a_i\, e^{-[(x-bi)/c_i]^{2 d_i}} + C$$

where x is the wavelength corresponding to a data channel. From the center wavelength of an intensity peak and from the width the program computes the aiming direction and the angular divergence of the neutral beam component. In Fig. 4 a typical computer fit to the OMA data is shown.

Figure 5 shows a comparison of the spectroscopic measurement of beam divergence with calorimetric data. The angular divergence normal to the accelerator slots is plotted against the gradient grid voltage. The full energy component has a divergence .3° to .4° smaller than the half and third energy components. It does not appear that the dissociation energy of the molecular species is sufficient to explain the difference.

The relative light intensities of the half- and third-energy components were observed to change as the gas flow into the source was increased from 4.5 to 10.5 Torr-ℓ/sec. The light from the third energy H^o neutrals increased from 35% to 58% while the half-energy component decreased from 60% to 39% as the gas flow increased. These results are consistent with the reaction $H_2^+ + H_2 \rightarrow H_3^+ + H$ for production of H_3^+ in the ion source. Further work is required to calibrate the spectroscopic measurement of species fraction.

NEUTRAL BEAM DIVERGENCE VS GRADIENT GRID VOLTAGE

ACCEL VOLTAGE 115 KEV
τ = 150 MSEC

● FULL ENERGY
▲ HALF ENERGY
■ THIRD ENERGY
x CALORIMETRY
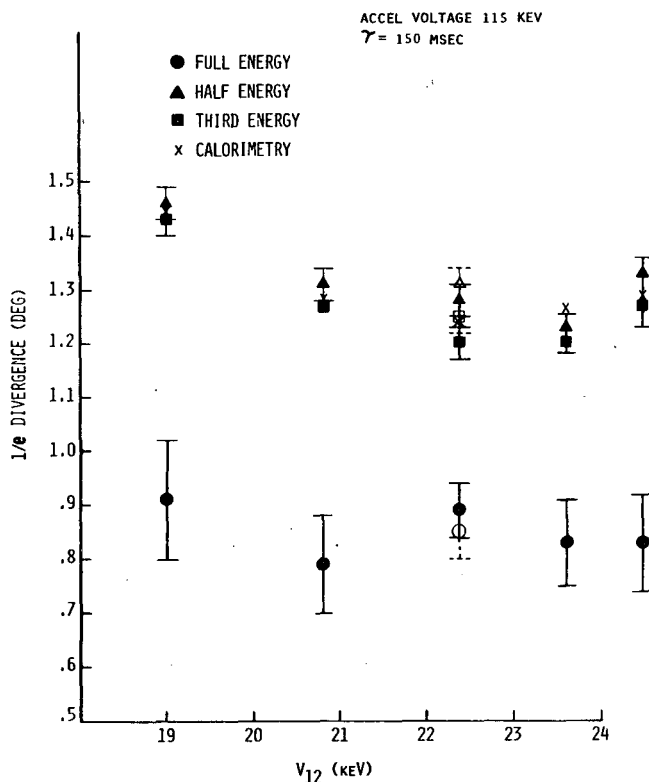
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Figure 5. Neutral beam divergence measured spectroscopically and calorimetrically as a function of gradient grid voltage.

SHOT # 343

E	LIGHT (%)	ANGLE (DEG.)	DIVERGENCE (DEG.)
1	4.1 (0.2)	0.09 (.16)	1.21 (.24)
2	52.1 (0.3)	0.07 (.10)	1.30 (.22)
3	43.7 (0.4)	-.15 (.13)	1.27 (.33)

Figure 4. A typical computer fit of the full-, half- and third-energy components and the computed light intensities, beam aiming direction, and divergences.

References

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2. K. H. Berkner, R. V. Pyle, J. W. Stearns, "Intense, Mixed-Energy Hydrogen Beams for CTR Injection," Nucl. Fusion 15, 249 (1975).