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# Time-dependent, x-ray spectral unfolds and brightness temperatures for intense $Li^+$ ion beam-driven hohlraums.

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## ABSTRACT

X-ray-producing hohlraums are being studied as indirect drives for Inertial Confinement Fusion targets. In a 1994 target series on the PBFAII accelerator, cylindrical hohlraum targets were heated by an intense $Li^+$ ion beam and viewed by an array of 13 time-resolved, filtered x-ray detectors (XRDs). The UFO unfold code and its suite of auxiliary functions were used extensively in obtaining time-resolved x-ray spectra and radiation temperatures from this diagnostic. UFO was also used to obtain fitted response functions from calibration data, to simulate data from blackbody x-ray spectra of interest, to determine the suitability of various unfolding parameters (*e.g.*, energy domain, energy partition, smoothing conditions, and basis functions), to interpolate the XRD signal traces, and to unfold experimental data. The simulation capabilities of the code were useful in understanding an anomalous feature in the unfolded spectra at low photon energies ($\leq$ 100 eV). Uncertainties in the differential and energy-integrated unfolded spectra were estimated from uncertainties in the data. The time-history of the radiation temperature agreed well with independent calculations of the wall temperature in the hohlraum.

## I. Introduction

Cavity radiation is currently being studied as an indirect drive for Inertial Confinement Fusion (ICF). In this concept a fuel pellet resides in a chamber (hohlraum) which is heated externally by intense laser or particle beams. Given adequate time and a sufficiently high radiation temperature *T*, the fuel pellet is expected to implode more smoothly and uniformly than if driven directly by the external beams. The first step in realizing such an implosion process is measuring the typically soft, x-ray spectrum obtained in the cavity. X-ray measurements have been reported[1] for hohlraums heated by an intense $Li^+$ ion beam from the PBFAII pulsed-power accelerator. In more recent experiments (1994), a record temperature (61 eV) was obtained for this type of heating. This paper describes the spectral unfolding method applied to the latest spectrometer signals and reports results derived from it. Similar x-ray measurements (yielding temperatures up to 300 eV) have been reported for laser-driven hohlraums[2,3].

Although details of the 1994 PBFAII shot series will be reported elsewhere, some information about the experiments is necessary to understand the unfolded x-ray results. For this work, cylindrical hohlraum targets were fielded (Fig. 1). Each target (4 mm in diameter and 4 mm long) had thin, gold-lined, plastic walls. The interior was filled with a low-density, plastic foam. During a PBFAII shot, $Li^+$ ions deposited energy primarily in the foam, which then heated the gold radiation case. X rays were emitted through a diagnostic aperture at one end of the target. By convention, the emitted spectrum is assigned a "brightness" radiation temperature, defined as the characteristic temperature of a blackbody of equal radiance.

Several diagnostics witnessed the heating of cylindrical hohlraums. On set-up shots, a magnetic Rutherford-scattering spectrometer[4] measured the average kinetic energy of the $Li^+$ beam to be 9 MeV at peak power. For each target shot, the absolute intensity and spatial variations of the beam were derived from K-shell fluorescence (4.5 keV) as $Li^+$ ions interacted with several Ti wires, upstream of the target[5]. The spatially-averaged beam intensity for the shot series was $2.0 \pm 0.4$ TW/cm$^2$, but the unaveraged intensity could vary azimuthally by 300%. The interiors of the hohlraums were viewed through the diagnostic aperture by time-integrated and time-resolved x-ray spectrometers and imaging detectors. Of the spectroscopic data, only signals derived from arrays of planar, photoemissive x-ray detectors (XRDs)[6] have been studied in any detail and constitute the input data for the spectral unfolds reported here.

## II. Unfold Formulation with the UFO code

The XRD spectrometer is an array of 13 filtered XRD's. The response function $R_i(E)$ (*i.e.*, spectral sensitivity) of each channel *i* was varied by adjusting the type and thickness of the filter and the cathode material of the detector. Before the 1994 shot series, fielded filters and detectors were calibrated separately on a synchrotron x-ray source ($200 \leq E \leq 1500$ eV) at Brookhaven National Laboratory (BNL); the filters were also cross-calibrated on a steady-state, fluorescent x-ray source (180-5000 eV). The calibration data were fit to an empirical model[7]. Four of the 13 calibrated response functions are shown in Fig. 2.

The governing equations for the XRD spectrometer are derived as follows. Assume that the $i$-th spectral channel views the hohlraum x-ray source at off-normal angle $\beta_i$ through solid angle $\Omega_i$, that x rays emitted by the hohlraum are characterized by a differential spectrum $F(E,t)$ [W/(Sr-cm$^2$-eV)] with source aperture area $A_{source}$ (cm$^2$), and that the impedance of the recording system is Z (=50 ohms); then the detected voltage signal $V_i(t)$ (Volts) in each XRD channel due to x rays is given by

$$V_i(t) = \left[ \int_{E_1}^{E_2} F(E,t) R_i(E) dE \right] \alpha \cos(\beta_i) A_{source} \Omega_i Z \qquad (i=1,2,\ldots,M=13) \quad , \qquad (1)$$

where $\alpha = 10^{-6}$ MW/W converts the units in Fig. 2 to A/W. In Eqs. (1) the spectrum is assumed non-zero over the photon energy domain $[E_1 , E_2 ]$, and $A_{source}$ may be time-dependent due to plasma hole-closure. Moreover, since the response-time of the XRD's is $\sim 500$ ps, the time $t$ corresponds on both sides of the equation only for sampling rates $\leq \sim 1$ GHz. Finally, grouping several experimental variables together, one transforms the voltage signals into reduced data $D_i(t) = V_i(t)/(\alpha \Omega_i \cos\beta_i A_{source} Z)$ to obtain a set of coupled, Fredholm integral equations of the first kind [Eqs. (2), left]:

$$D_i(t) = \int_{E_1}^{E_2} F(E,t) R_i(E) dE + \epsilon_i \approx \sum_{j=1}^{N} R_{ij} F_j(t) + \epsilon_i \quad . \qquad (2)$$

Here the terms $\epsilon_i$ represent experimental uncertainties and perturbations to the data.

The inverse mathematical process of estimating the source x-ray spectrum from Eqs. (2) is called unfolding. A description of this process is given elsewhere in this proceedings[8]. One unfold method approximates the desired solution $F(E,t)$ with a series $\Sigma_j F_j(t) B_j(E)$ to obtain the matrix form on the right side of Eqs. (2), where the $B_j(E)$ are basis functions ($j=1,\ldots,N$), and $R_{ij} = \int R_i(E) B_j(E) dE$ over the interval $[E_1,E_2]$. Useful basis functions include B-splines (either histograms or piecewise-continuous functions) and prescribed blackbody functions $\Phi_{BB}(E,T)$. If the noise terms $\epsilon_i$ in Eq. (2) can be characterized as normally distributed, independent random variables with zero means and variances $\sigma_i^2$, the set of fit coefficients $F_j(t)$ can be obtained by minimizing the function $\chi^2(F_1, F_2, \ldots ,F_N) = \Sigma_i (D_i - \Sigma_j R_{ij} F_j)^2/\sigma_i^2$ at each time step $t$, where the sums run from $(i,j) = 1,2,\ldots, (M,N)$, respectively. The minimized value $\chi^2_{\min}$ ($M$ - $N$ degrees of freedom) is a goodness-of-fit parameter. Uncertainties in the $F_j(t)$'s and in functions of them [*e.g.*, $\int F(E,t)dE \approx \Sigma_j F_j(t) \int B_j(E)dE$] can be estimated from uncertainties in the data[8].

The UFO (UnFold Operator) code[9] is one of several numerical algorithms[8] developed to cope with Eqs. (2). UFO is a matrix manipulation code, performing a $\chi^2$ minimization with error matrix uncertainty estimates[8]. Additional *a priori* information about constraints, weighting, *etc.*., are added as needed to UFO to obtain a solution in a given problem. For example, theoretical predictions plus comparisons between experimental and simulated data (see below) indicated hohlraum temperatures $<80$ eV for the 1994 PBFAII experiments. Thus, in UFO the domain of the unfold spectrum for the XRD signals was set to $[E_1=0, E_2=1200$ eV$]$, and it was assumed that $F(0) = 0$. Also, the unfold spectrum was approximated by a set of $N = 9$ histograms (basis functions); some of the edges of these histograms coincided with x-ray edge features in the responses $R_i(E)$. Finally, two types of data uncertainty were included: (1) cable noise was estimated from baseline signals ($\leq \sim 5\%$ of peak signal); and (2) experimental uncertainties (*e.g.*, solid angles and response functions) were estimated to be 10 - 20%.

## III. Simulations

A useful feature of UFO is its simulation capability. For example, one can generate a sequence of differential blackbody spectra $\Phi_{BB}(E,T)$ as functions of photon energy $E$ and temperature $T$ and then simulate data $\Delta_i(T)$ for the x-ray spectrometer from the left side of Eq. (2). While such simulations do not constitute unfolds, they can provide useful information for subsequent unfold analysis. For example, Fig. 3 shows a set of such simulated XRD data curves, which correspond to blackbody spectra with temperatures 50 - 75 eV. Also shown as individual points are the (reduced) peak XRD data for shot #6517, which occurred 16 ns after the onset of the $Li^+$ beam. The trend in these data suggest that the experimental spectrum at this time was approximately Planckian with a temperature $T$ of 50-75 eV.

Simulations are also useful in testing the unfolding parameters (basis functions, constraints, smoothing, *etc.*) since all the unfold operations can be made on known functions. Fig. 4. shows the results for XRD data simulated from a 60 eV blackbody. The unfold solution $F(E)$ was approximated as a histogram. (See Sec. II.) The source spectrum $\Phi_{BB}(E,T=60$ eV$)$ is also shown for comparison. The numerically calculated radiances, $\int \Phi_{BB}(E,T=60 \text{ eV})\, dE$ and $\int F(E)dE$ ($E = 0 \rightarrow 1200$ eV), differ by no more than 3%. Contributions to $\int \Phi_{BB}(E,T=60 \text{ eV})\, dE$ for $E > 1200$ eV are negligible. Such simulations were constructed from blackbody spectra for $20 \leq T \leq 75$ eV. Unfolded radiances calculated over the *complete* energy domain [0,1200 eV] agreed with the corresponding blackbody radiances to better than 93% for $T \geq 50$ eV, but the agreement dropped to 66% for $T = 25$ eV. However, if the integrals were calculated over the *truncated* interval [98.1, 1200 eV], 93% agreement was obtained.

## IV. Results and discussion

Figure 5 shows the unfold solution $F_{6517}(E,t=16$ ns$)$ for shot #6517 at peak signal time. Also shown are unfold uncertainty estimates $[F_{6517}(E,t=16 \text{ ns}) \pm \sigma(E,t=16 \text{ ns})]$. The unfold uncertainties were propagated in UFO assuming 20% relative experimental uncertainties plus cable noise. The same unfolding parameters and basis functions were used as in the simulations. Other unfolding parameters (*e.g.*, an underdetermined set of histograms and a linear combination of fixed blackbody spectra) gave similar results.

Although the unfolded spectrum $F_{6517}(E,t=16$ ns) in Fig. 5 is qualitatively reasonable above 98.1 eV, a significant peak ("spike") is visible in bin $j = 2$ (71.1 - 98.1 eV). All the time-resolved unfolds show this feature, which was not detected by a time-integrated, grazing-incidence spectrograph. We believe these spikes are anomalies due to the lack of XRD and foil calibration data below 200 eV for two reasons. First, unfolding the data with different unfolding parameters did not remove the feature. Second, after the PBFAII target series was completed, several, unused[10], aluminum XRD's were calibrated both above 200 eV at BNL (as usual) and below 200 eV at the SURFII facility (National Institute of Standards and Technology, NIST). The BNL calibrations were fit, as noted above. Below 73 eV, the usual *extrapolation* of the BNL responses was found to be ~200% *lower* than the *measured* NIST responses. UFO simulations then showed that such discrepancies in response functions $R_1$ and $R_2$ (which have appreciable low energy sensitivity) can produce an anomalously high unfold value in bin 2 *without significantly affecting* the unfold at higher energies. Thus, the "spike" in bin $j = 2$ was considered spurious and not counted as part of the spectrum. The radiation brightness temperature $T_{br}$ was then defined by the integrals of the unfold and corresponding blackbody spectra over the truncated interval [98.1, 1200], a mapping shown above to be reliable for simulated data. For shot #6517 $T_{br}$ was 61 $\pm$ 1.5 eV.

Fig. 5 also compares the unfold $F_{6517}(E,t=16$ ns) to the blackbody sprectrum $\Phi_{BB}(E,T_k=60$ eV). While the unfold has a local maximum near the peak of $\Phi_{BB}(E,T_k=60$ eV), it also has a somewhat higher tail. Details of this comparison are still under study, but such features appear to be consistent with the spectrum predicted from a non-uniformly heated body[11]. In this model, the opacity of cooler material skews the emitted spectrum to higher energies, compared to a blackbody of uniform temperature. Beam intensity measurements on the PBFAII shots clearly support non-uniform heating.

Unfolds of the XRD signals on shot #6517 were performed with UFO at 2-ns intervals from times 6 ns to 38 ns (relative to the onset of the $Li^+$ beam). An automated procedure was written to reduce and unfold the sampled data at each time step. The unfolding specifications (*e.g.*, bin sizes, unfolding constraints, *etc.*) were kept constant, and reasonable $\chi^2$ "goodness of fit" probabilities (5 - 95%) were obtained at all but the earliest and latest sample times. The brightness temperatures are shown in Fig. 6 with uncertainty estimates. Temperature estimates below ~25 eV were avoided because of poor signal-to-noise ratios and non-optimal unfold parameters. Also shown in Fig. 6 is an independent calculation of the inner wall temperature, made with the LASNEX code[12]. The spatially-averaged, peak intensity of the $Li^+$- beam, derived from the Ti-K fluorescence diagnostic, was included as an input parameter. The time axis has been arbitrarily shifted 2 ns in this comparison. At early times, departures between the measurements and calculations may be due to inaccuracies in the unfolds, while at late times a more significant disagreement may be due, in part, to plasma closure of the diagnostic aperture in the hohlraum.

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Figure Captions:

1. Cut-away view of the (1994) PBFAII experiments with cylindrical hohlraum targets. The target (placed at the center of the two, vertical, conical target holders) has a gold-coated, plastic wall (3-$\mu$m thick Parylene-D, 1.5-$\mu$m thick gold inner lining) and is filled with TPX foam (5 mg/cm$^3$). $Li^+$ ions are incident azimuthally at midplane. As the $Li^+$ beam converges on the target, some ions interact with small Ti wires which are visible to diagnostics below. Characteristic K-shell radiation emitted by these wires is a measure of the beam intensity. The interior of the hohlraum was visible to a set of x-ray diagnostics, located above the target, through a 1.5- or 3-mm diameter aperture.

2. Four samples of the 13 response functions for the XRD spectrometer (channels #1, 6, 12, and 13). These functions are curve fits to x-ray calibration data (not shown). Since the x-ray calibration measurements only extended down to ~200 eV, the response at lower energies is an extrapolation.

3. Reduced simulated and real XRD data. The simulated data $\Delta_i(T) = \int R_i(E)\Phi_{BB}(E,T)dE$ are plotted as solid lines versus channel $i$ for blackbody spectra with characteristic temperatures $T = 50$, 65, and 75 eV. The solid points are the reduced data from Shot #6517.

4. Comparison of a known spectrum $\Phi_{BB}(E,T=60$ eV) with the UFO unfold $F(E)$ of data simulated from $\Phi_{BB}(E,T=60$ eV).

5. Unfold $F_{6517}(E,t = 16$ ns) of the 13 XRD signals in PBFAII shot #6517 at peak time (solid histogram). Error bounds ($\pm$1-$\sigma$) for the unfold are shown as dotted lines. The "spike" in bin $j = 2$ was not counted in the estimate of the radiance $\int F_{6517}(E,t)dE$ . In this shot, the spectrally truncated radiance corresponded to a 61 eV blackbody. Shown for comparison is a 60 eV blackbody spectrum [dashed line].

6. Comparison of the measured, time-dependent, brightness temperature of a $Li^+$-heated hohlraum (PBFAII shot #6517) and a LASNEX calculation of its inner wall temperature, based on spatially averaged beam-intensity measurements. No plasma closure of the diagnostic aperture was assumed in the measurements.

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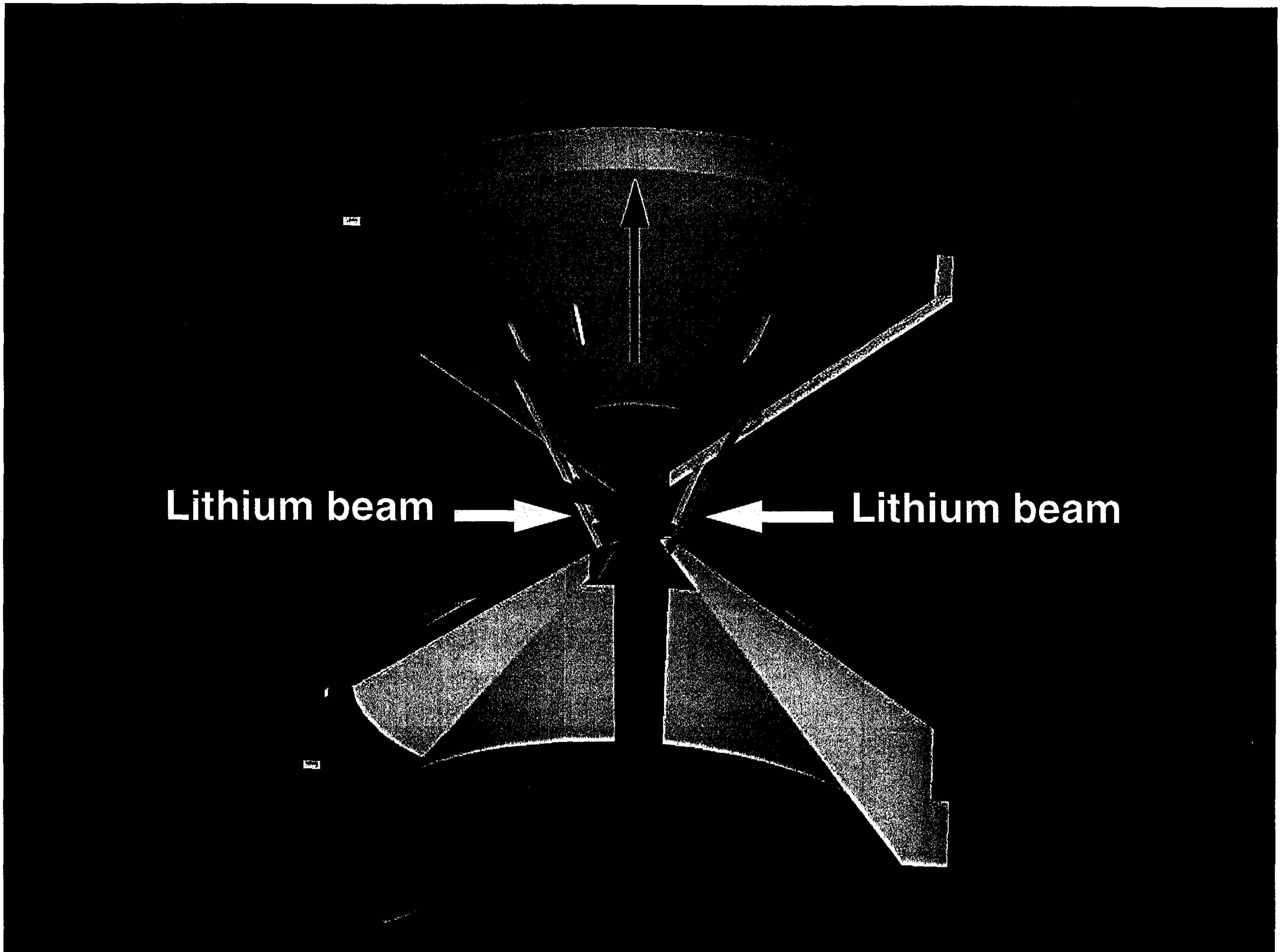


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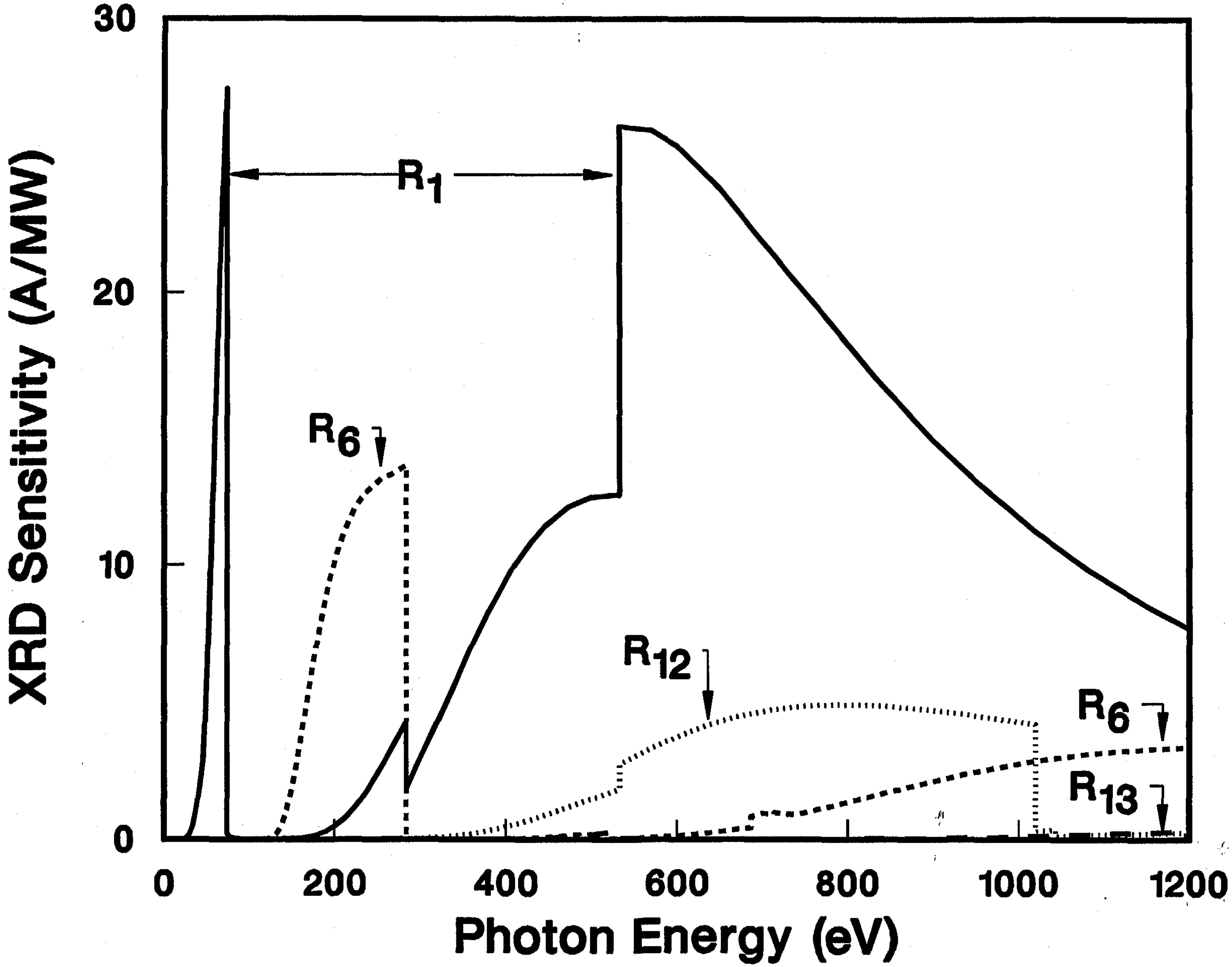
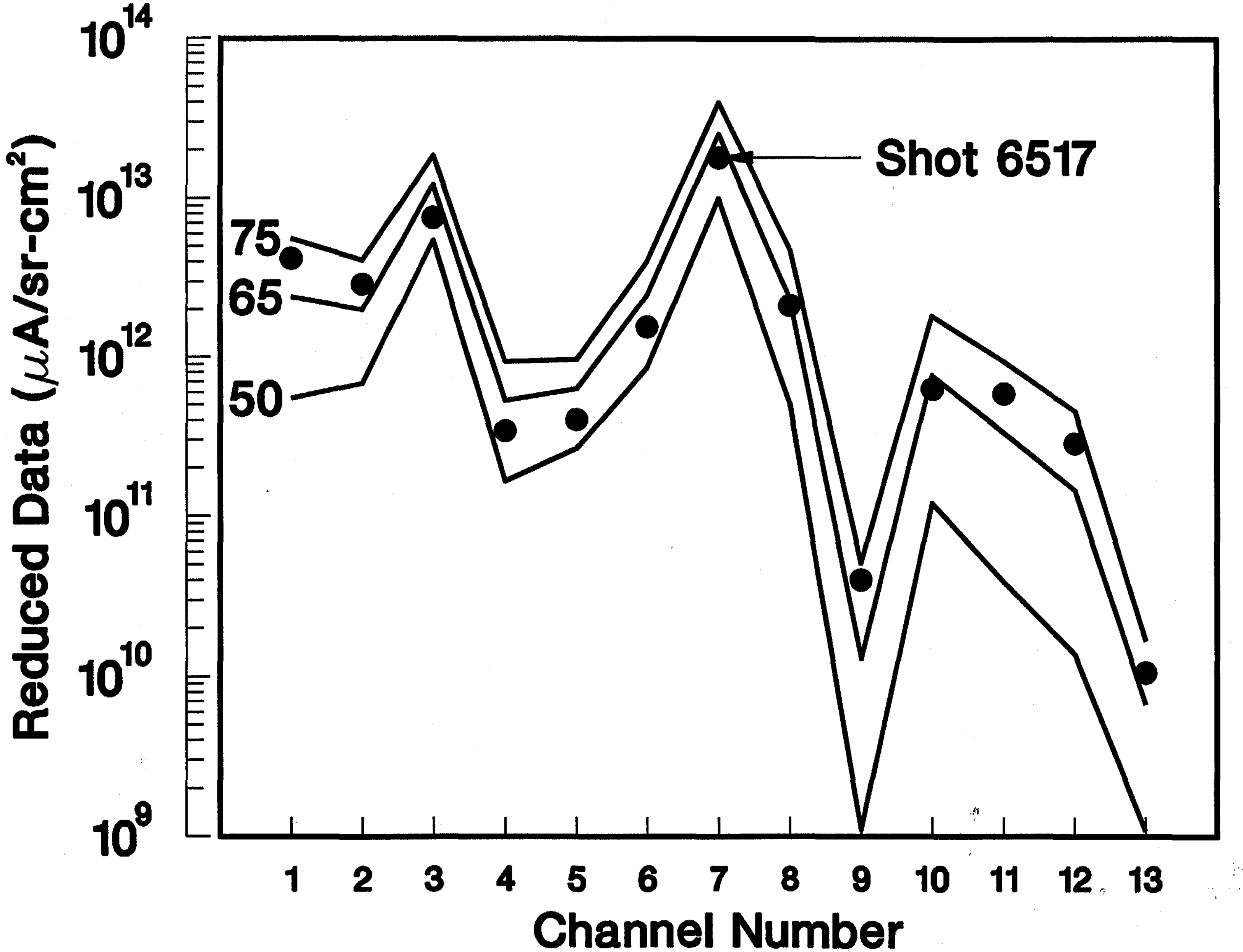
Fig 1



XRD Sensitivity (A/MW)
30
20
10
0
200
400
600
800
1000
1200
Photon Energy (eV)
R1
R6
R12
R6
R13


Fig 2



Reduced Data (μA/sr-cm²)
10¹⁴
10¹³
10¹²
10¹¹
10¹⁰
10⁹
75
65
50
Shot 6517
1
2
3
4
5
6
7
8
9
10
11
12
13
Channel Number


Fig 3

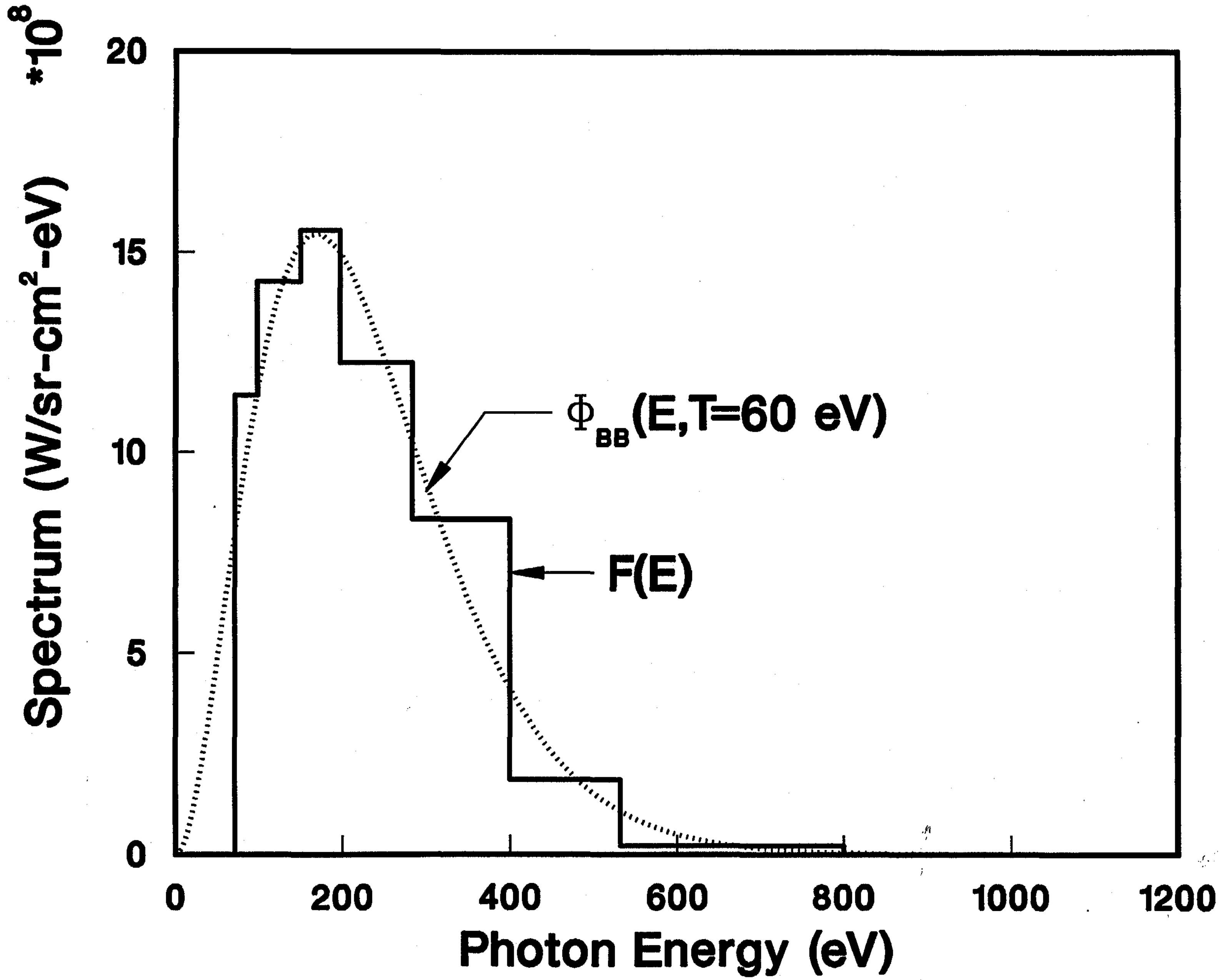

*10^8
Spectrum (W/sr-cm²-eV)
20
15
10
5
0
$\Phi_{BB}$(E,T=60 eV)
F(E)
0
200
400
600
800
1000
1200
Photon Energy (eV)

Fig 4

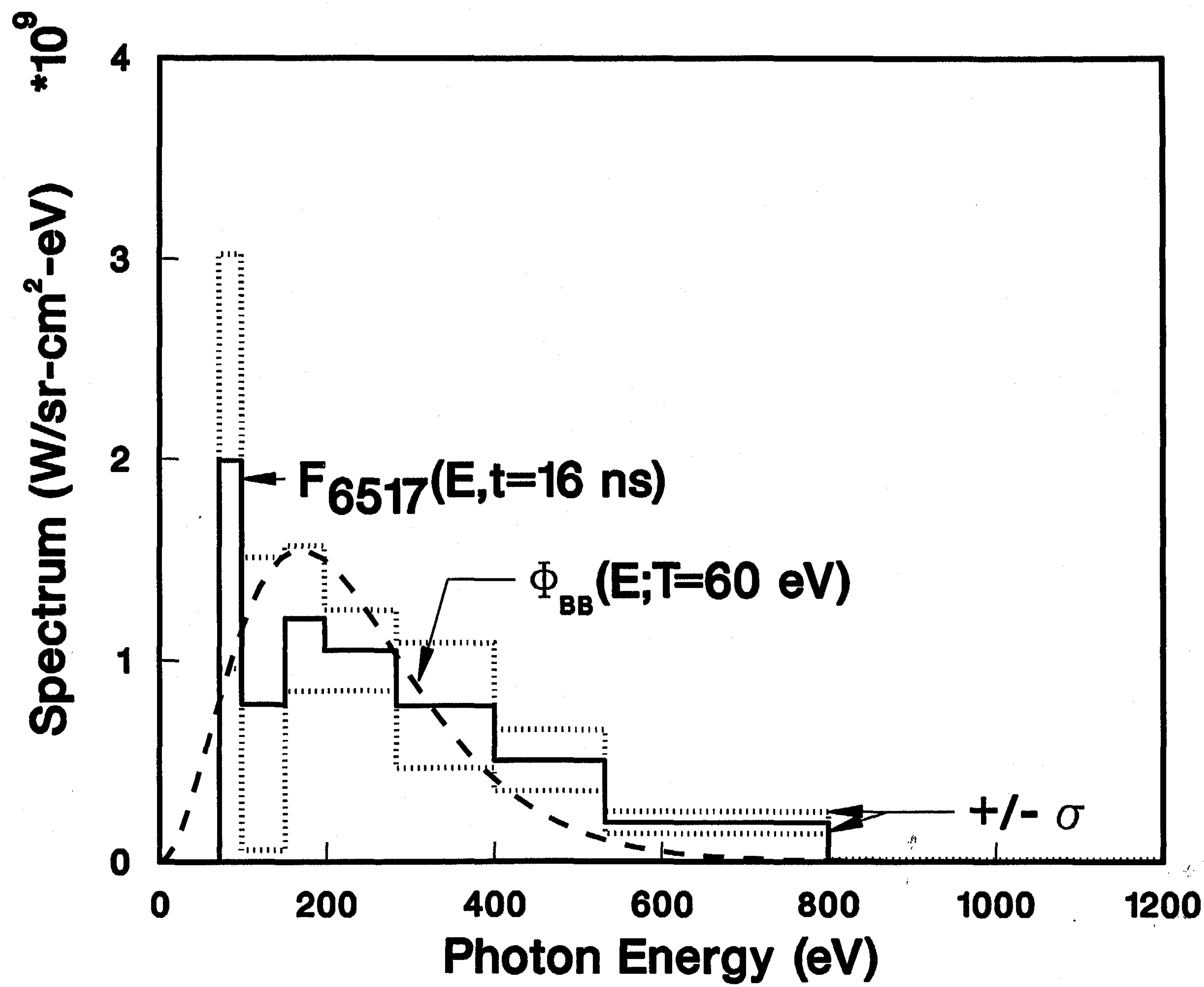

*10^9
Spectrum (W/sr-cm²-eV)
4
3
2
1
0
0
200
400
600
800
1000
1200
Photon Energy (eV)
F6517(E,t=16 ns)
ΦBB(E;T=60 eV)
+/- σ

Fig 5

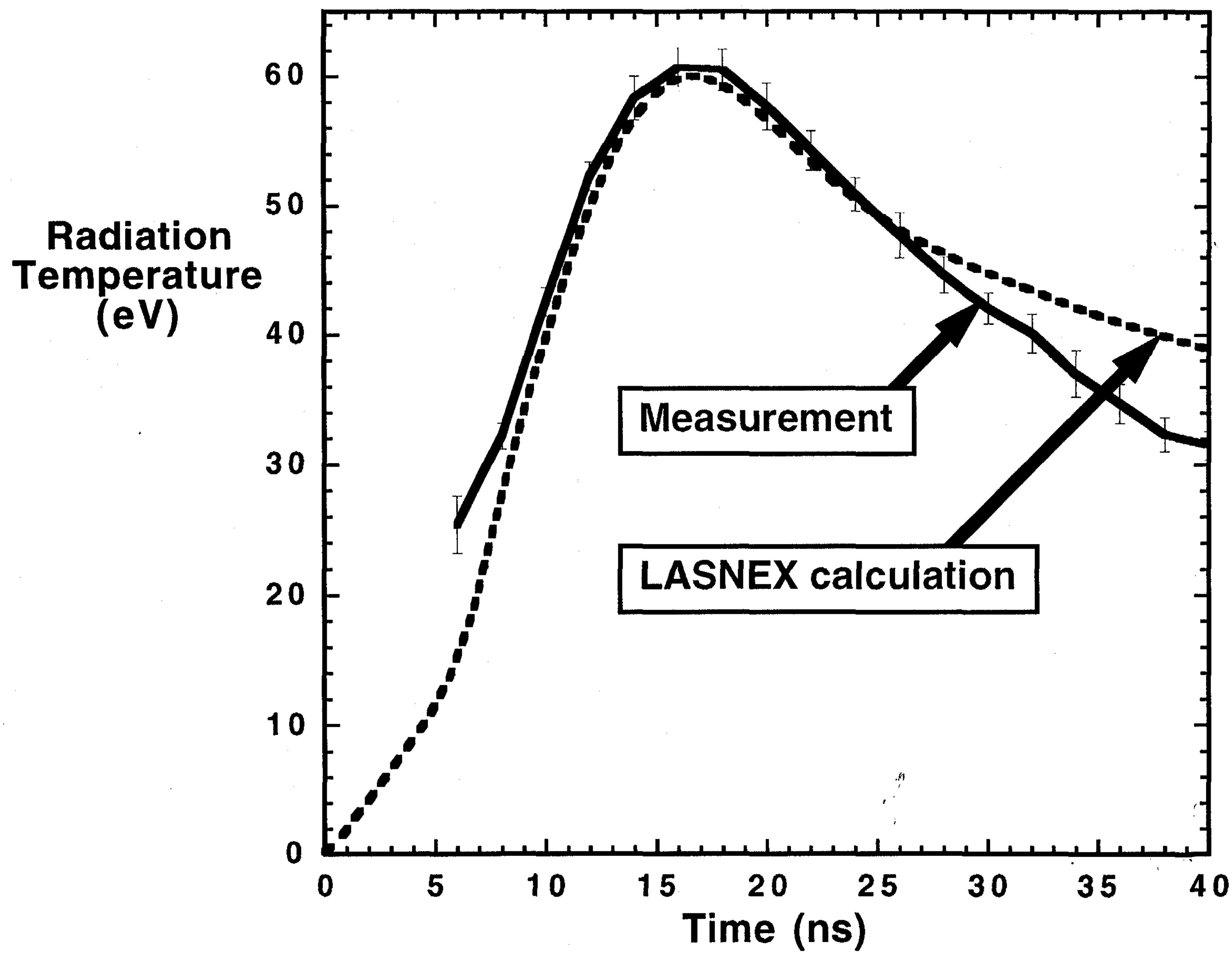



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Fig 6