Measurement of MTF Target Plasma Temperature Using Filtered Silicon Photodiodes

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Presented at the 40th Annual Meeting of the APS
Division of Plasma Physics

November 16-20, 1998
New Orleans, Louisiana

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Magnetized Target Fusion (MTF) is an approach to fusion where a preheated and magnetized plasma is adiabatically compressed to fusion conditions. Successful MTF requires a suitable initial target plasma with a magnetic field of at least 5 T in a closed-field-line topology, a density of roughly 10^{18} cm^{-3}, a temperature of at least 50 eV but preferably closer to 300 eV, and must be free of impurities which would raise radiation losses. Target plasma generation experiments are performed at Los Alamos National Laboratory using the Colt facility, a 0.25 MJ, ~2.5 μs rise-time capacitor bank. The goal of these experiments is to demonstrate plasma conditions meeting the requirements for an MTF initial target plasma. The plasma is produced by driving a *z*-directed current of 1-2 MA through either a static gas fill or a 200 μm diameter frozen gas fiber along the axis. The resulting plasma is contained in a 2 cm radius by 2 cm high cylindrical metal wall. The diagnostics include B-dot probes, a framing camera, a gated OMA visible spectrometer, a time-resolved monochromator, filtered silicon photodiodes, and a plasma-density interferometer. The data obtained from the array of seven filtered silicon photodiodes is used to estimate the plasma temperature as a function of time, for both gas and polyethylene fiber *z*-pinches. (Any results available from cryogenic deuterium fiber *z*-pinches will also be presented.) The filter material and thickness for each diode is chosen such that the transmission edge for each is at a successively higher energy and lower energies are absorbed, covering the range from a few eV to 5 keV. The analysis assumes a fully stripped plasma that is optically thin and radiates as a bremsstrahlung emitter. The amount of energy transmitted by a particular diode is obtained by combining its signal with that of an unfiltered diode.

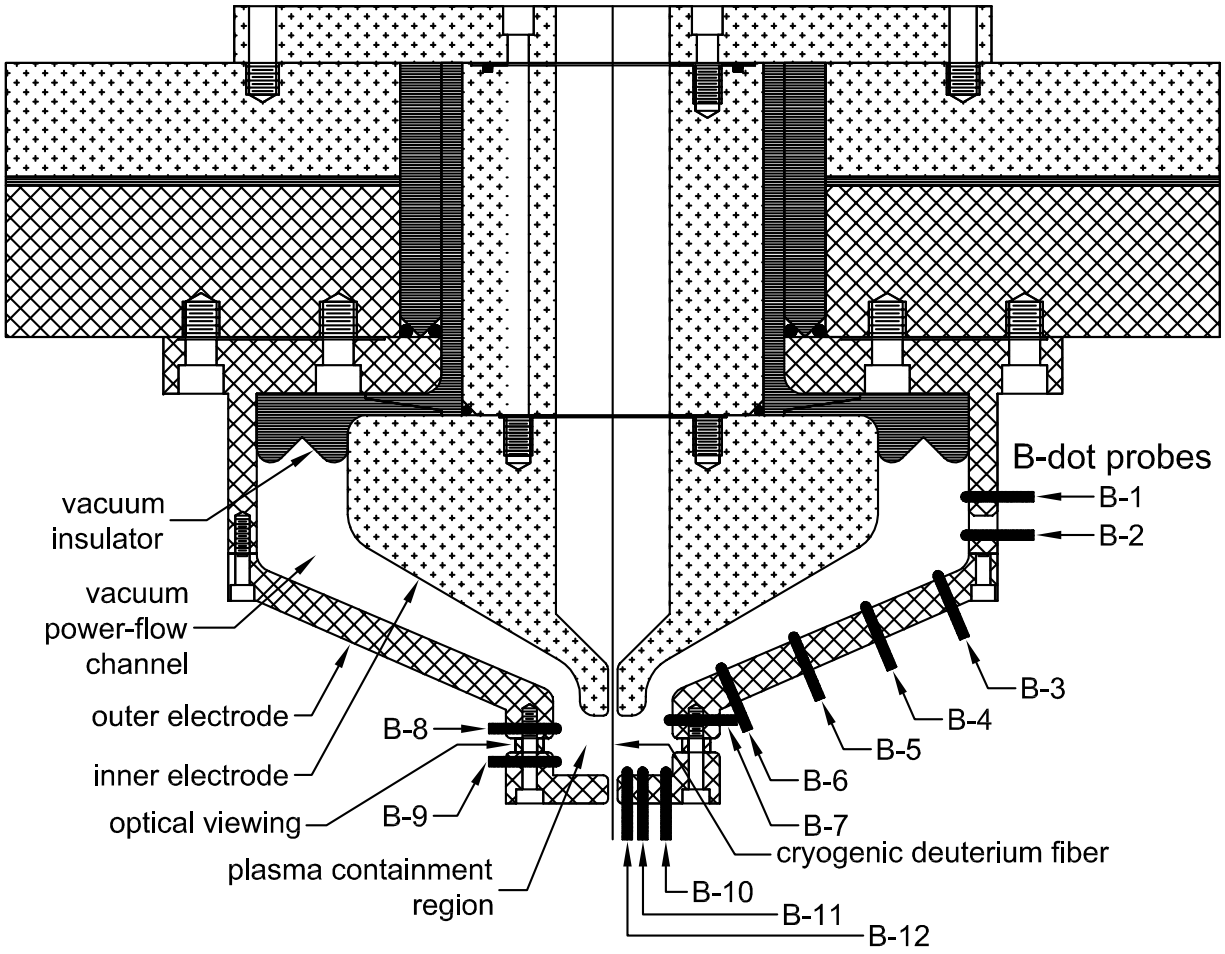
MTF: Magnetized Target Fusion

- Initial target plasma is *preheated* and *magnetized*
- Subsequent *adiabatic implosion* to fusion conditions

Our goal is to obtain a plasma with the conditions required for a successful MTF target:

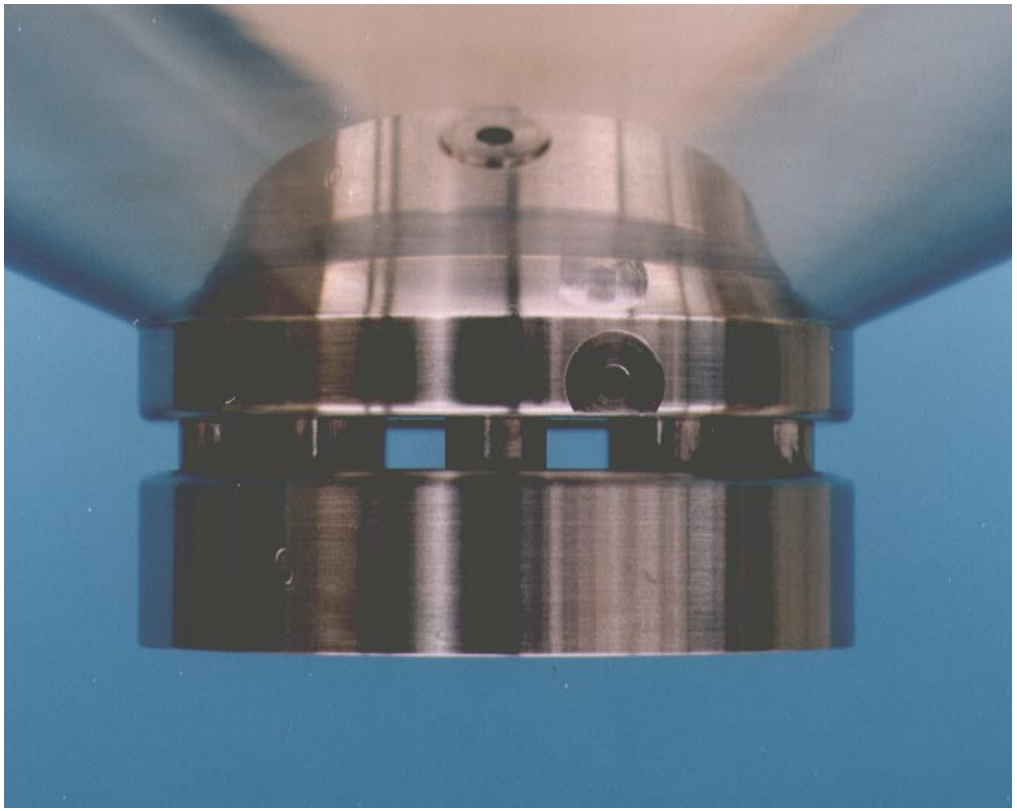
- magnetic field of at least 5 T in a closed-field line topology
- density of roughly 10^{18} cm^{-3}
- temperature of at least 50 eV (preferably closer to 300 eV)
- free of impurities which would raise radiation losses

Plasma-generation Region



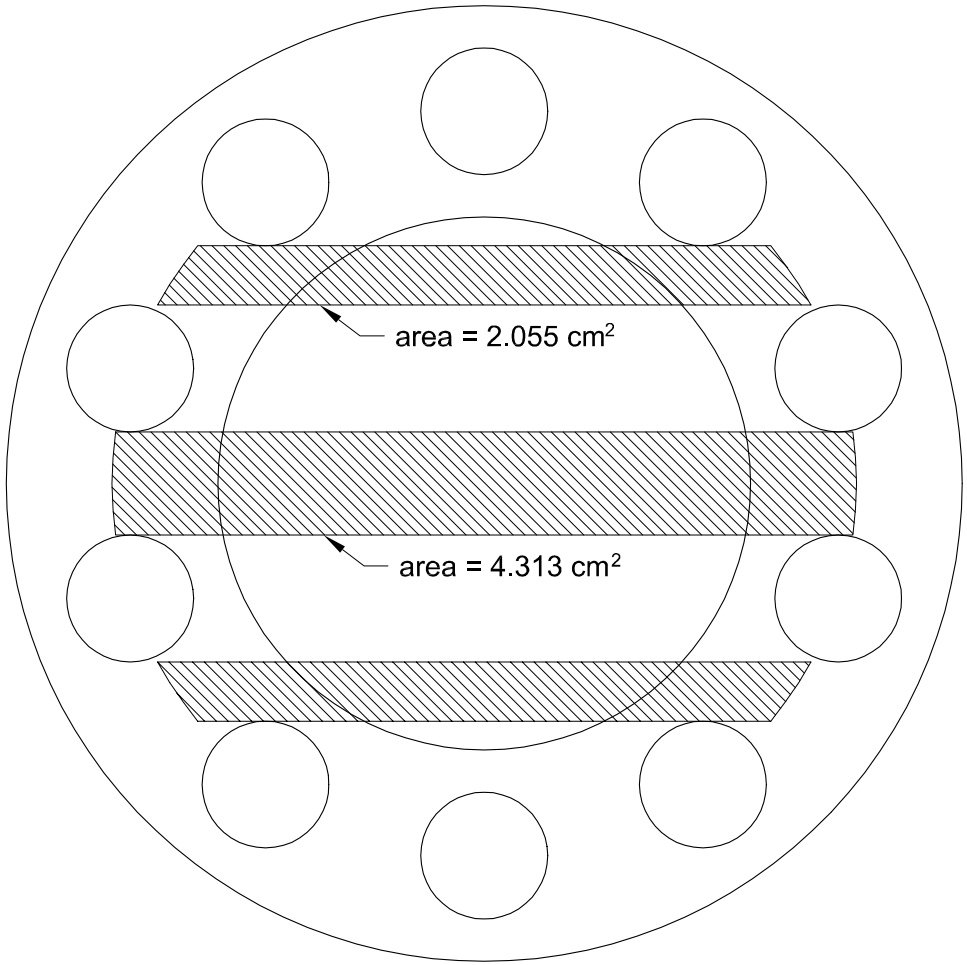
Cross-sectional view of the Los Alamos MTF target-plasma generator
(although shown with fiber in place, same configuration is used during gas-fill shots)

Plasma Containment Region

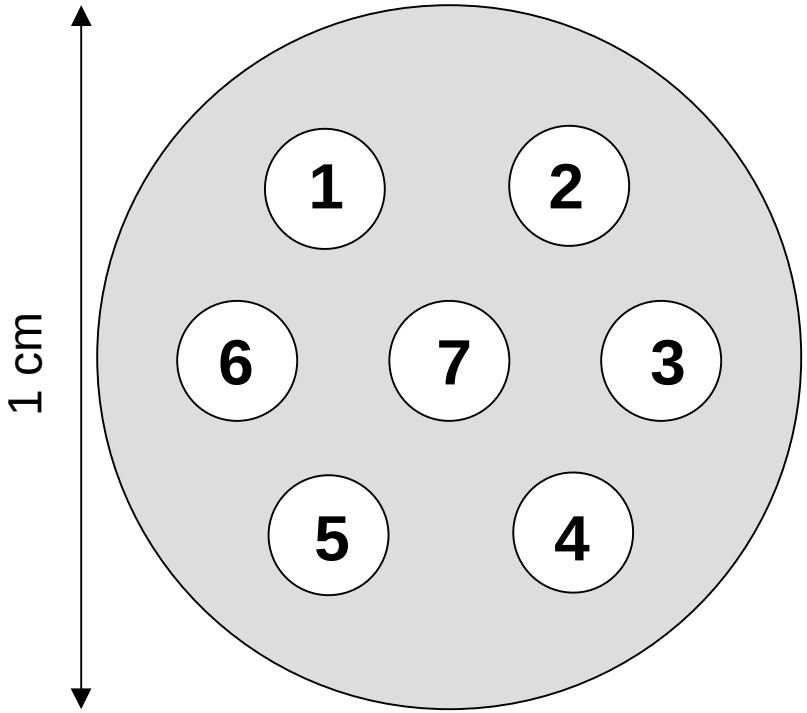


- 2 cm radius by 2 cm high cylindrical region (with viewports for diagnostic access)
- Diagnostics include:
  - B-dot probes
  - framing camera
  - gated OMA visible spectrometer
  - time-resolved monochromator
  - plasma-density interferometer
  - **filtered silicon photodiodes**
- Static gas-fill shots and polyethylene fiber shots (planned cryogenic deuterium fiber shots were not possible due to insufficient pumping speed in the region).
- Current of 1-2 MA along vertical axis
- Driven by Colt capacitor bank, at LANL, capable of 0.25 MJ, 2.5 μs current rise-time discharges

Area of Plasma Seen by Diode Array



Relative Position of Photodiodes

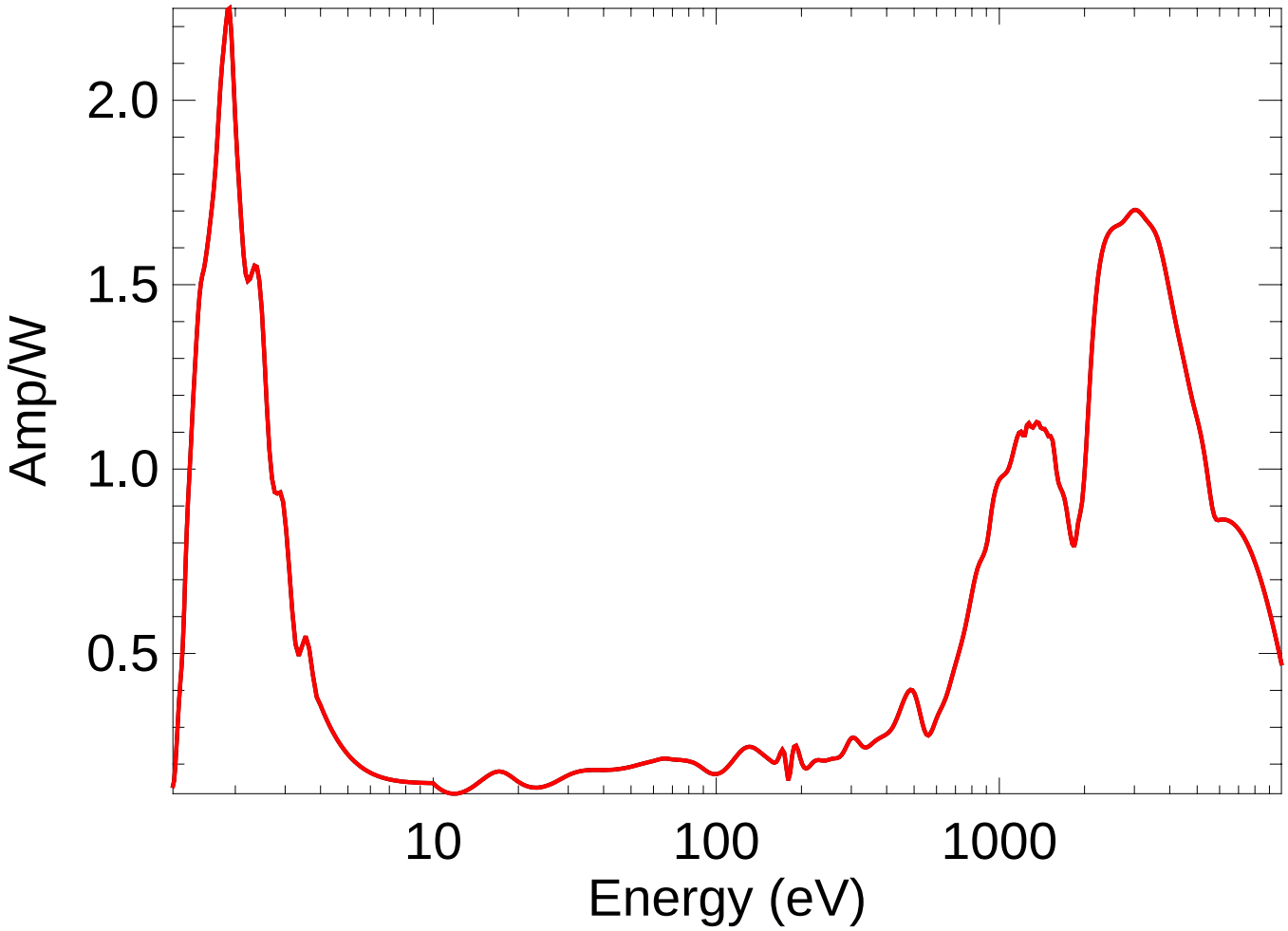


1. 66×10^3 μg/cm^2 polystyrene (C_8H_8)
2. 1.028×10^3 μg/cm^2 aluminum
3. 322 μg/cm^2 Parylene-n (C_8H_8) *
4. 323 μg/cm^2 Kimfol ($C_{16}H_{14}O_3$) with an aluminum flash
5. 452 μg/cm^2 nickel
6. 1.143×10^3 μg/cm^2 titanium
7. bare

* only survived one shot intact

- IRD (International Radiation Detectors) type HS-1 chips (same type of diode array (different filters) as those used in MAGO Russia / US collaborations)
- 0.05 mm^2 sensitive area on 1 mm^2 chip
- diodes located around 50 cm from plasma, protected from shock wave by fast-closing valve
- curves shown were obtained by calibration in the visible range (#1, 3 only) and theoretically (using scattering factors) for the remaining range

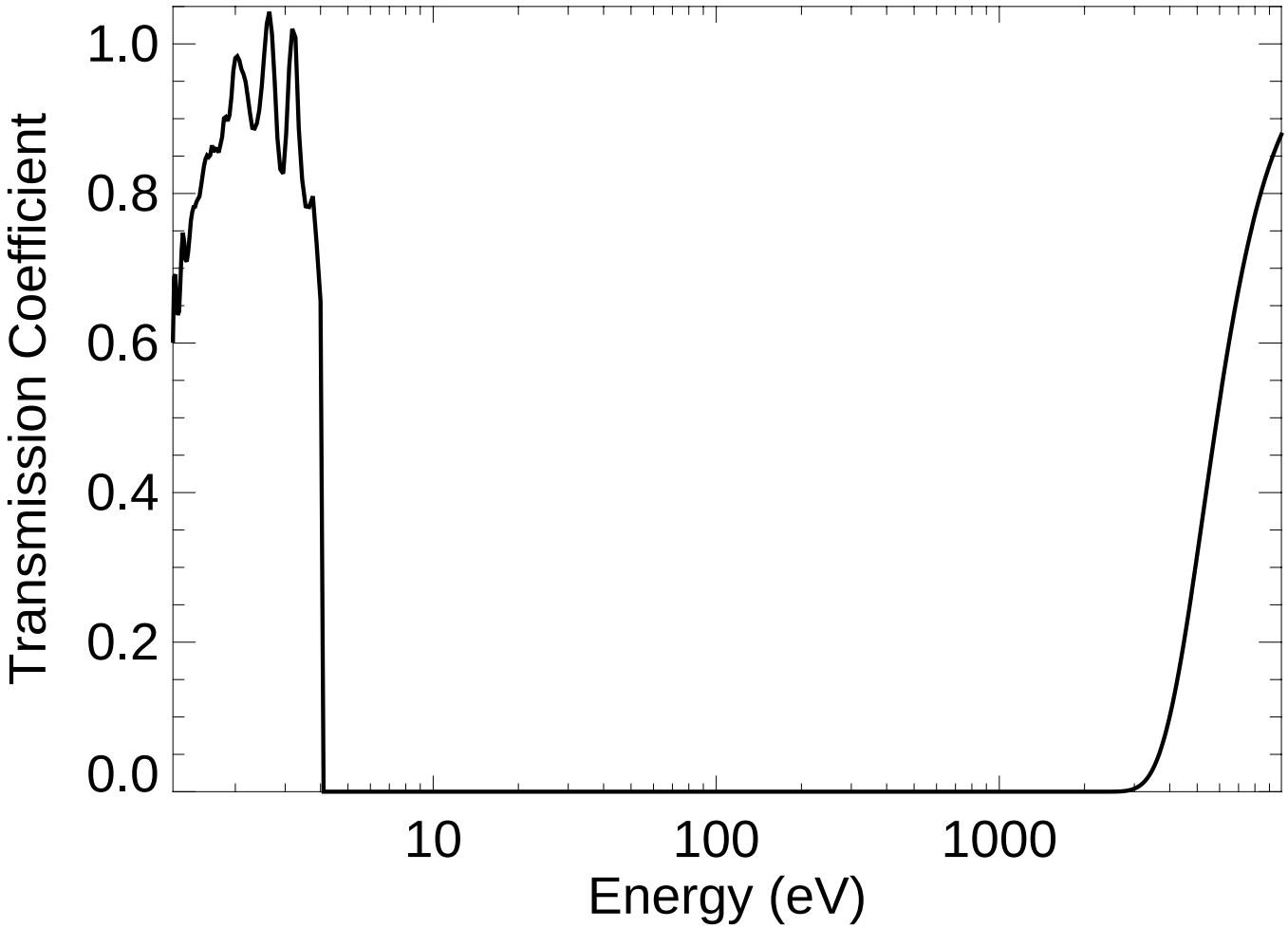
Photodiode Response Curve



Response amps for applied watts of power for a brand new diode (some regions are interpolated)

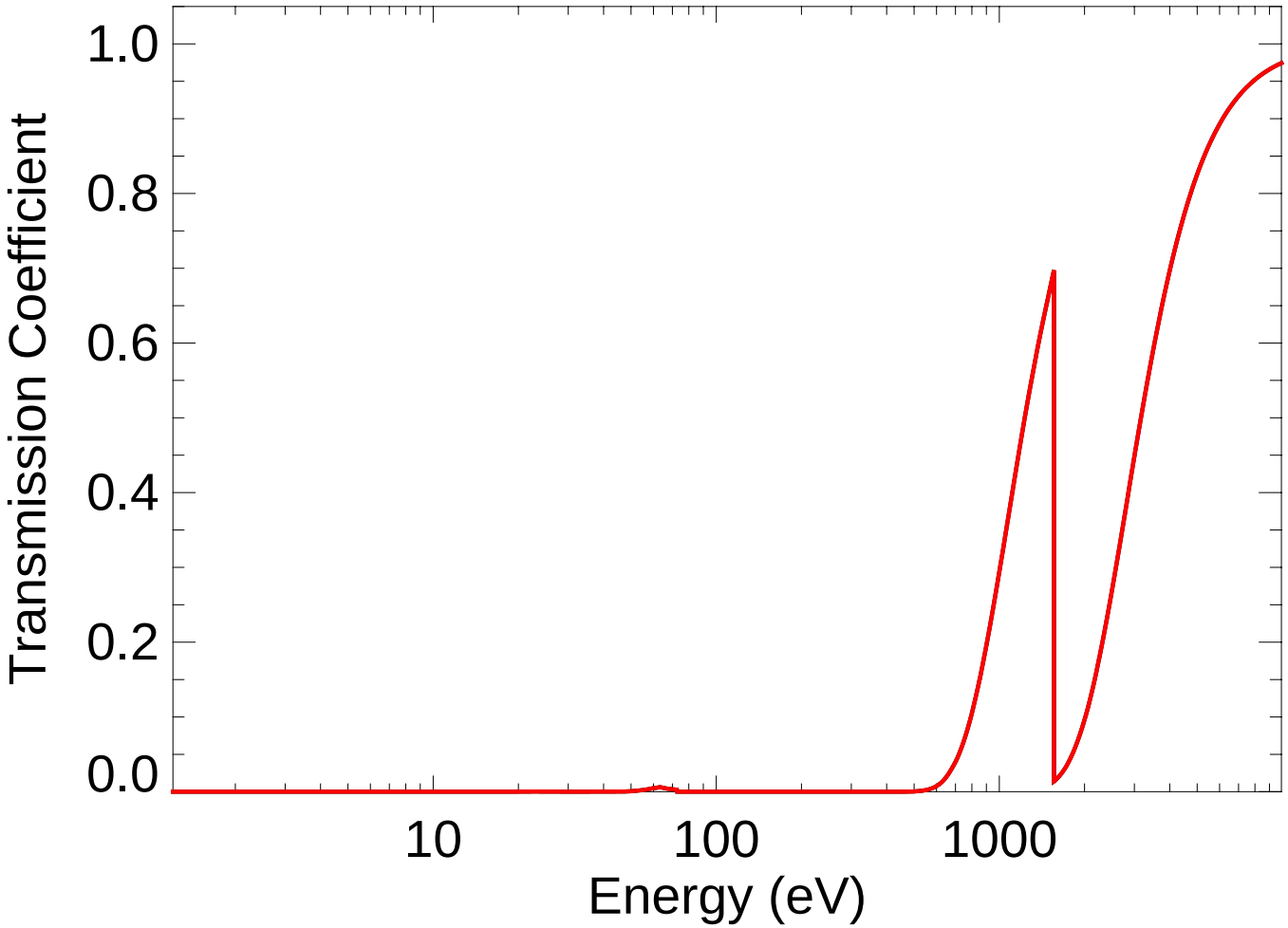
Filter #1 Transmission

(66×10^3 μg/cm^2 polystyrene)



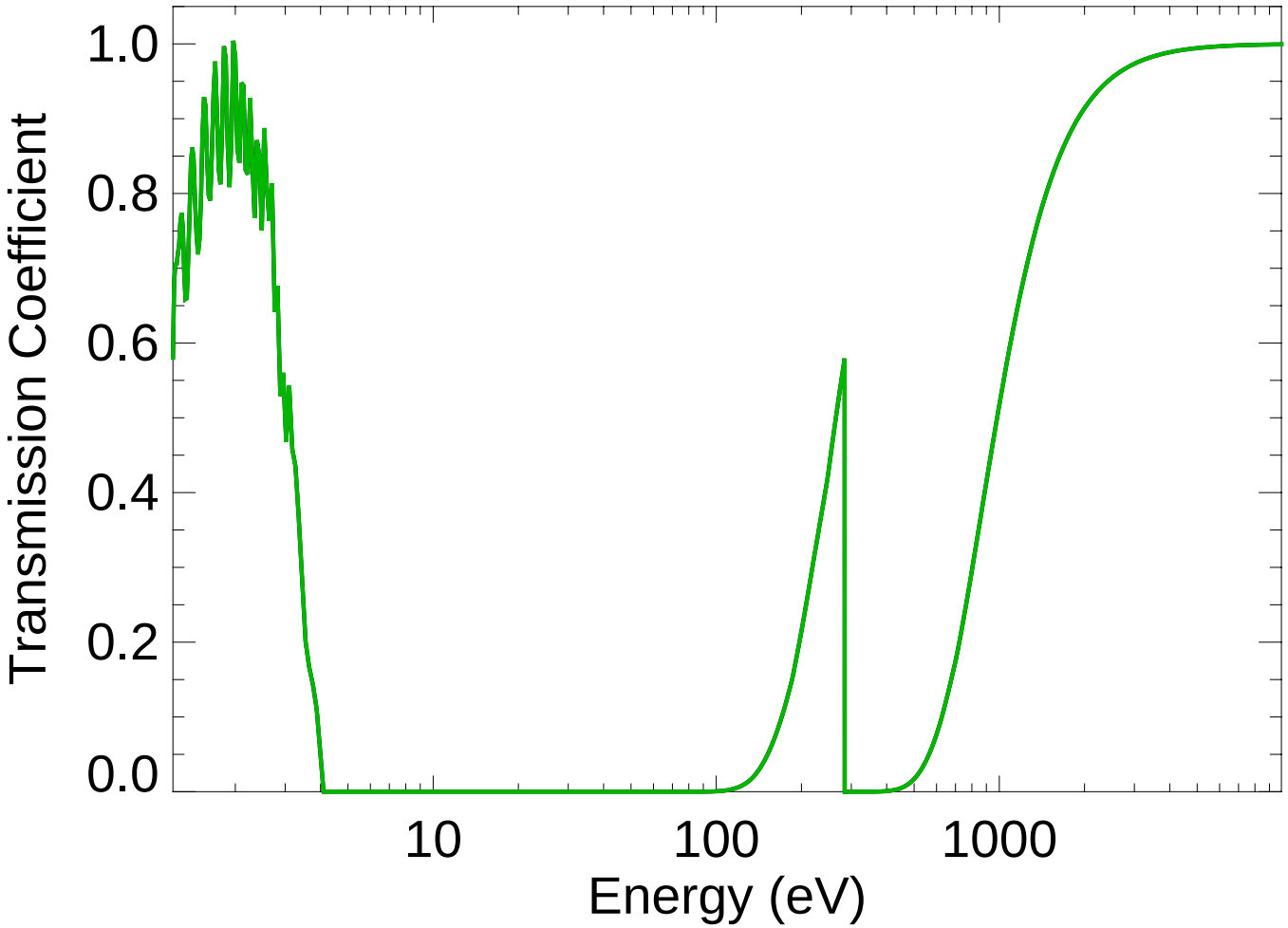
Filter #2 Transmission

(1.028×10^3 μg/cm^2 aluminum)



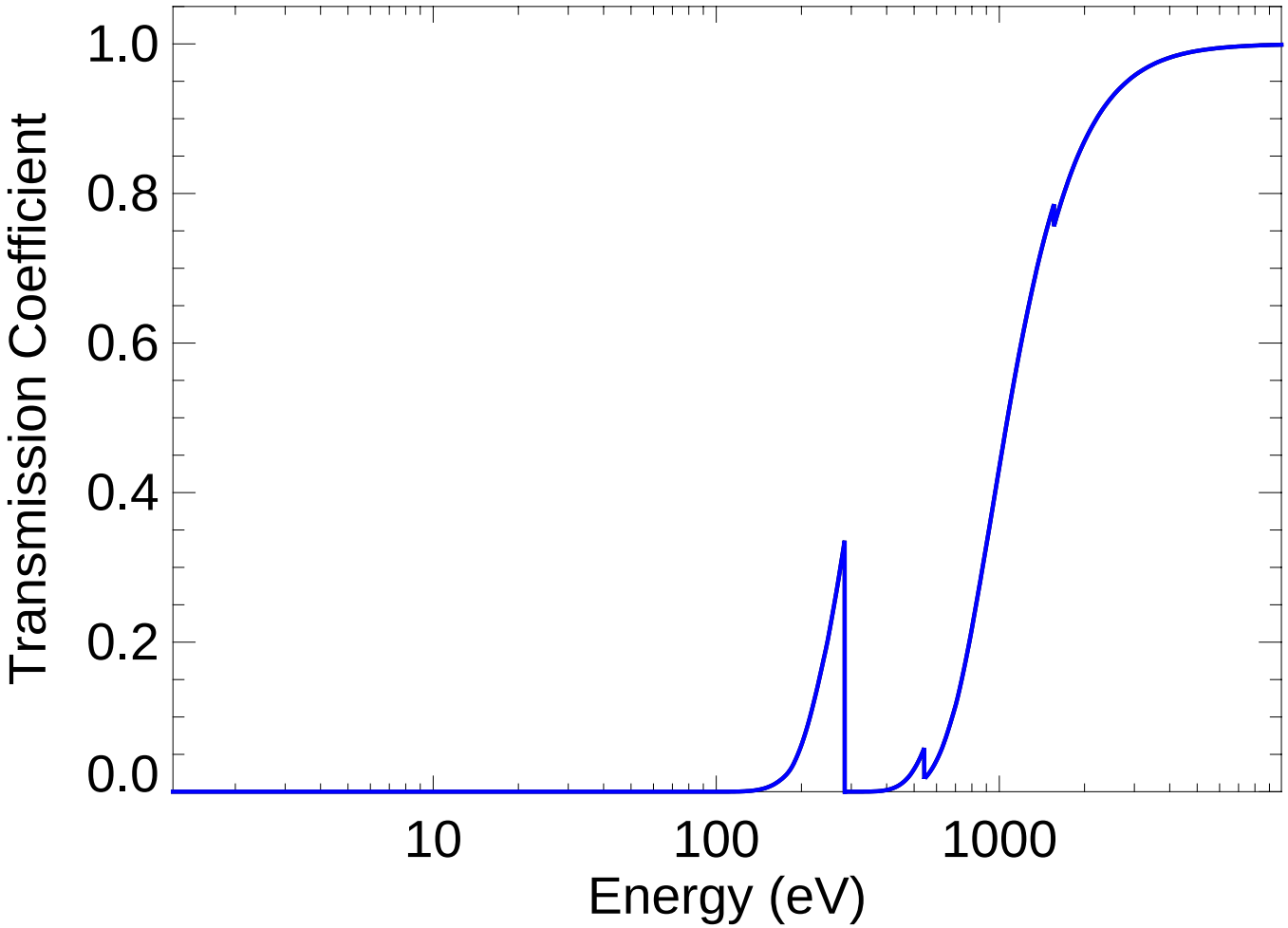
Filter #3 Transmission

(322 μg/cm^2 parylene-n)



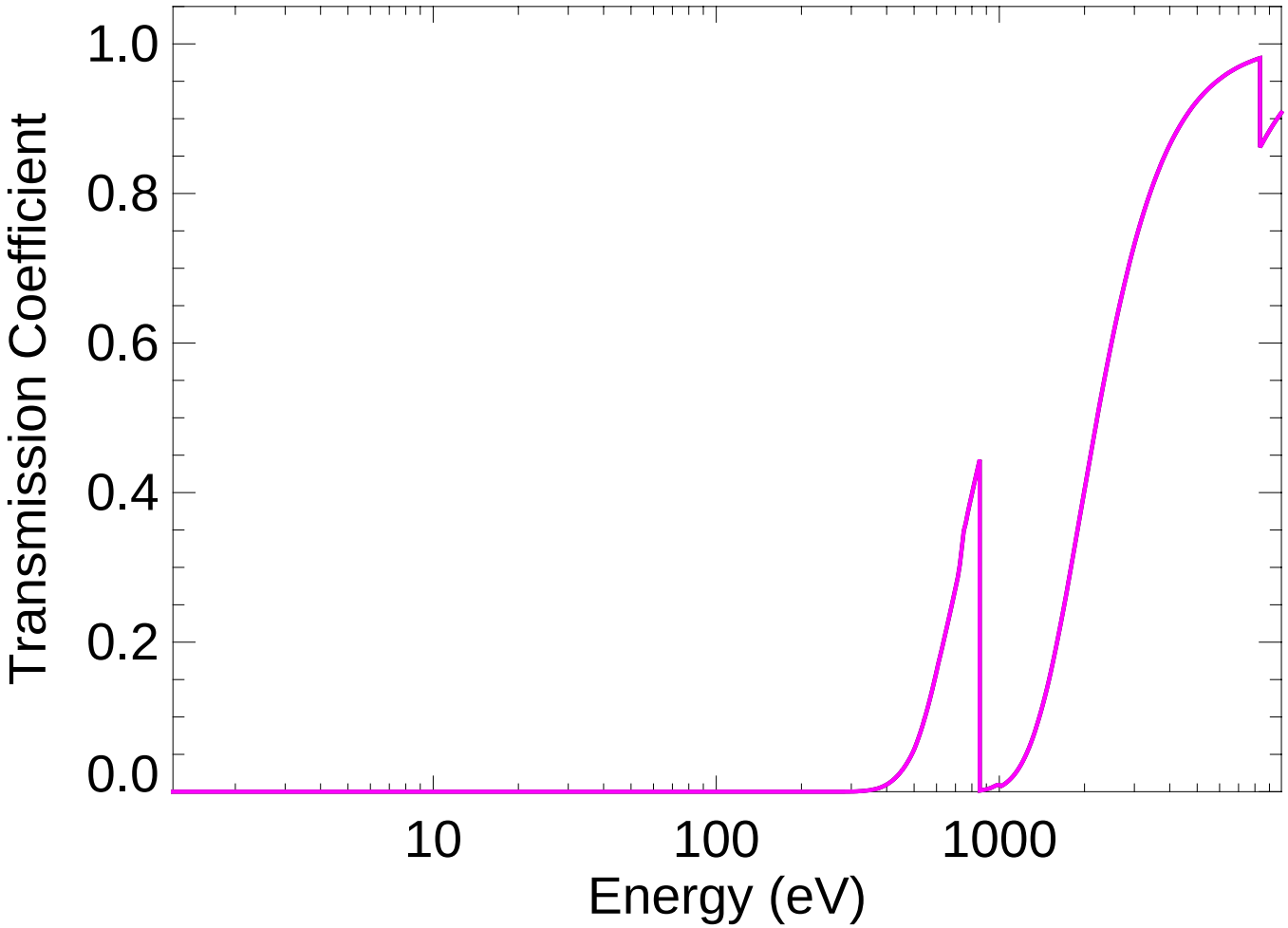
Filter #4 Transmission

(323 μg/cm^2 Kimfol)



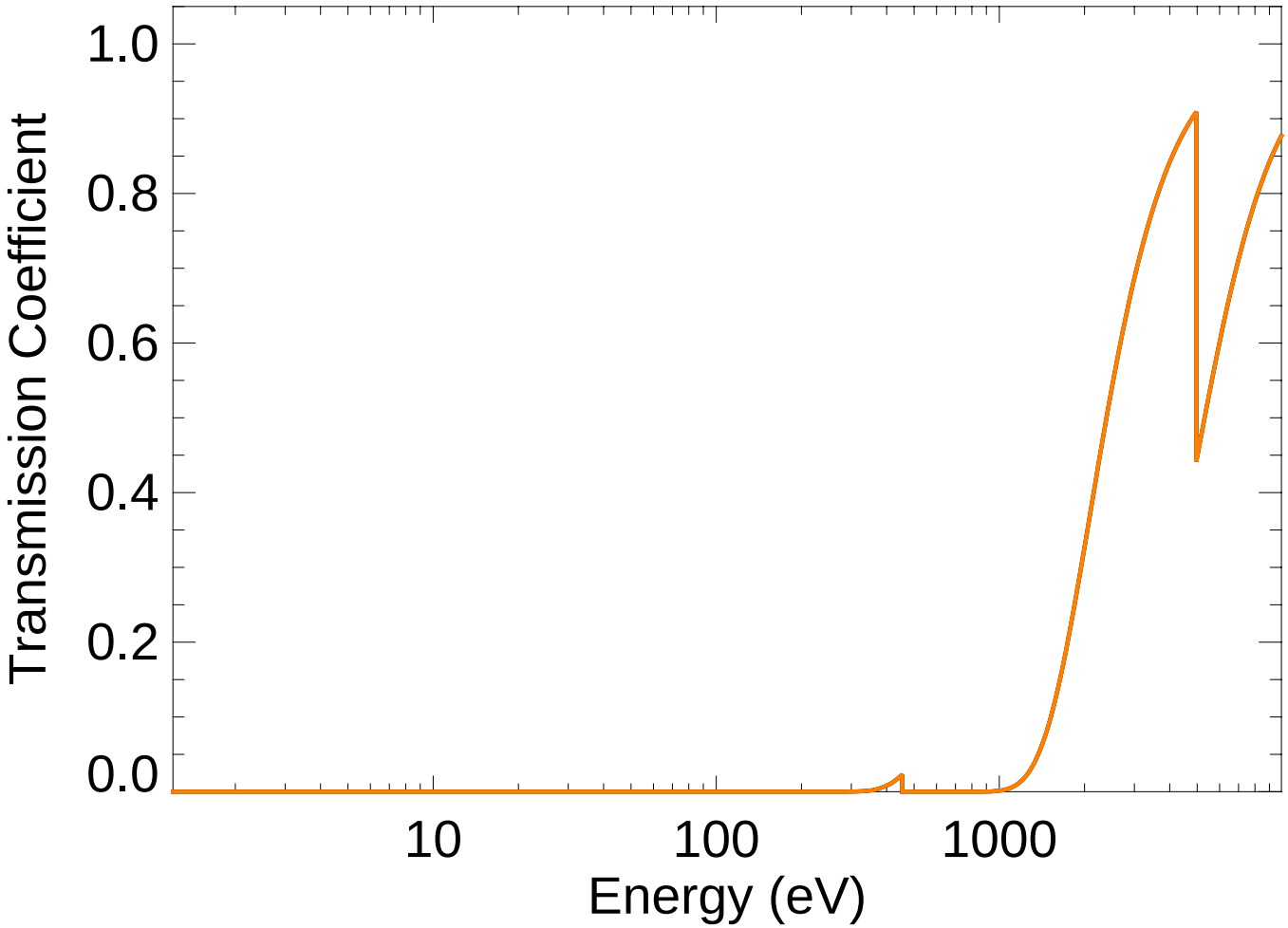
Filter #5 Transmission

(452 μg/cm^2 nickel)



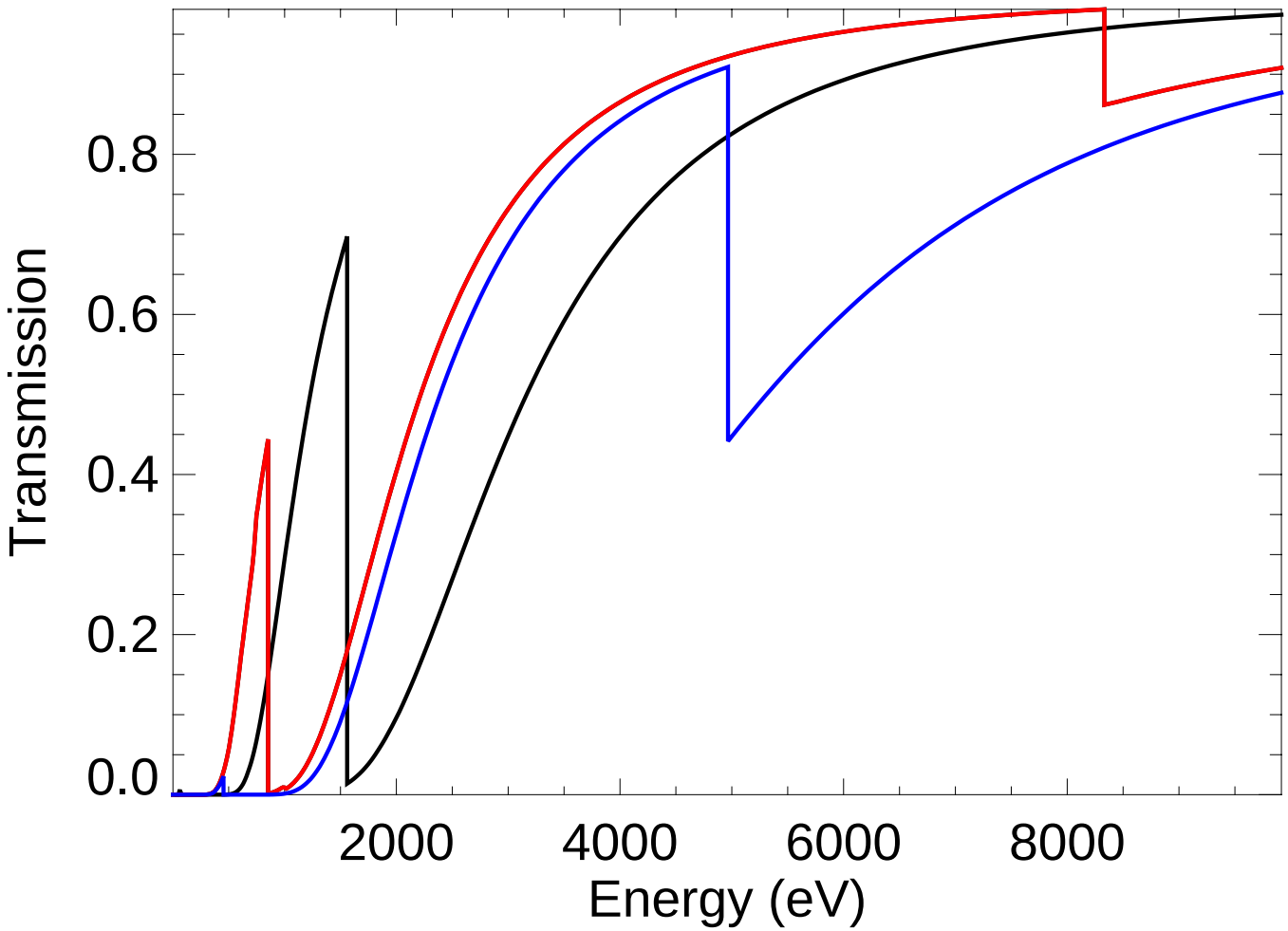
Filter #6 Transmission

(1.143×10^3 μg/cm^2 titanium)



Overlap of Higher-Energy Transmission Filters

(black=aluminum, red=nickel, blue=titanium)



Photodiode Signal Fitting Routine

Diode signals are composed of the plasma spectral shape [$P_{spectrum}$, W/(eV cm^3 steradian)], the filter transmission coefficient [T_{filter}, dimensionless], and the photodiode response [R_{diode}, A/W], integrated over the energy range, diode area, and plasma volume.

$$S_{diode}^{1\ldots n} = \int_{plasma} \int_{area}^{diode} \int_{E=1\mathrm{eV}}^{10\mathrm{keV}} R_{diode}(E) T_{filter}(E) P_{spectrum}(E, \vec{x}) dE d\Omega(A_{diode}, \vec{x}) dV(\vec{x})$$

Given a diode photodiode response and filter transmission, a spectral model is selected (blackbody, bremsstrahlung, or 'gaussian'), and the parameters of this spectral model which best fit the *n* data points (at each time *t*) are found.
(note: not all diodes gave useful data for every shot)

Assumptions made for the fit are:

- uniform plasma inside containment region (not quite correct)
- volume of plasma seen by diodes is height of ports times three slices through plasma within inner diameter of bushings
  (approximately 4.0 cm^3) -- see figure below
- uniform radiation over area of diode array (safe to assume), which is 53 cm away from plasma.

H_2 absorption from the plasma containment region to the photodiode array location is included for static gas-fill shots

Polyethylene Fiber Signals

Four phases in time can be distinguished in all polyethylene fiber shots:

I. initial axisymmetric ‘sausage’ instability (2-8 energetic narrow x-ray pulses)

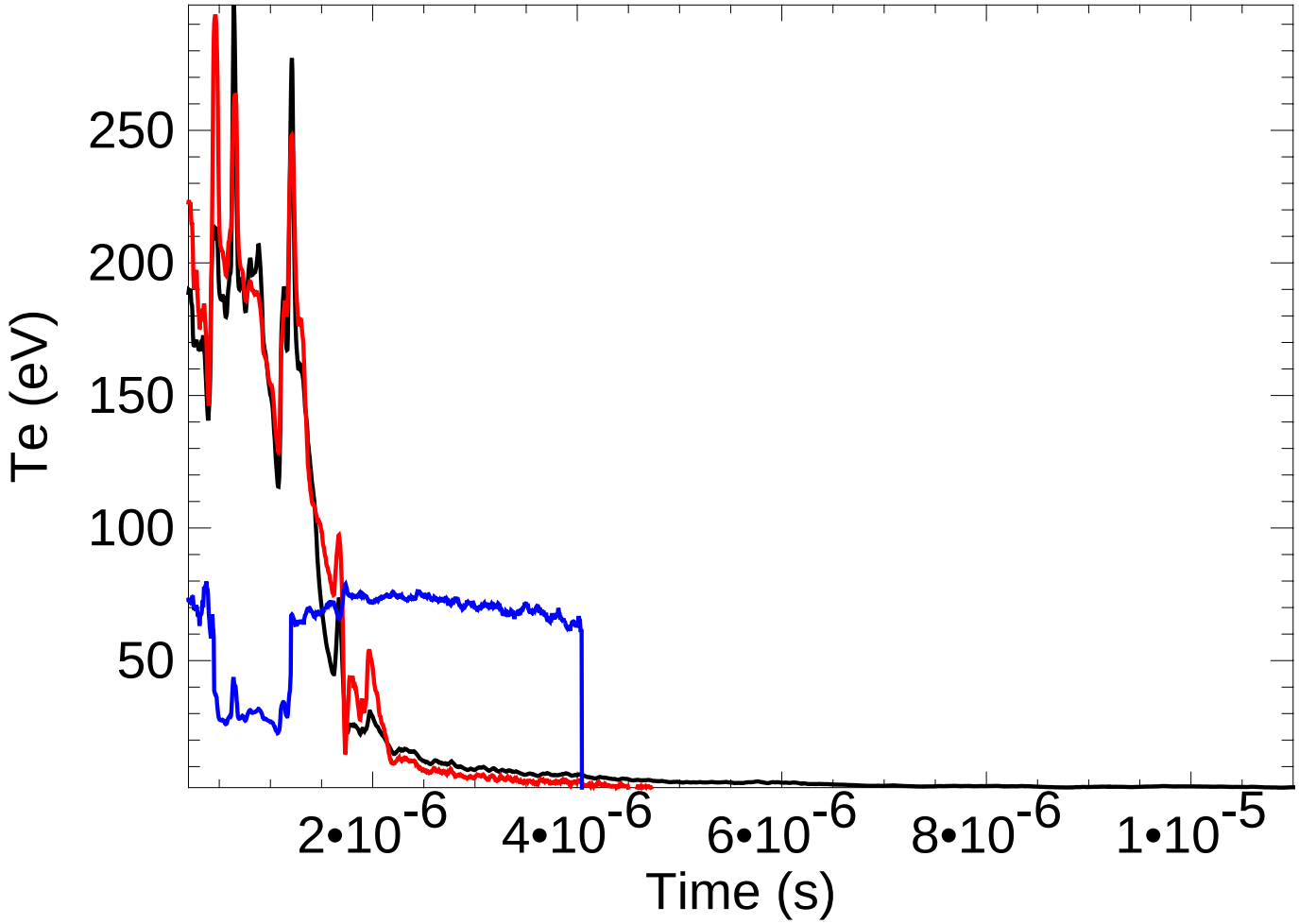
II. evolution to an asymmetric ‘kink’-like instability

III. subsequent axisymmetric re-pinching of plasma column (1-2 wider pulses, including a measurable increase in inductance)

IV. final uniform visible light emission (‘afterglow’) and quiescent B-dot signals

Electron Temperature for Different Spectra

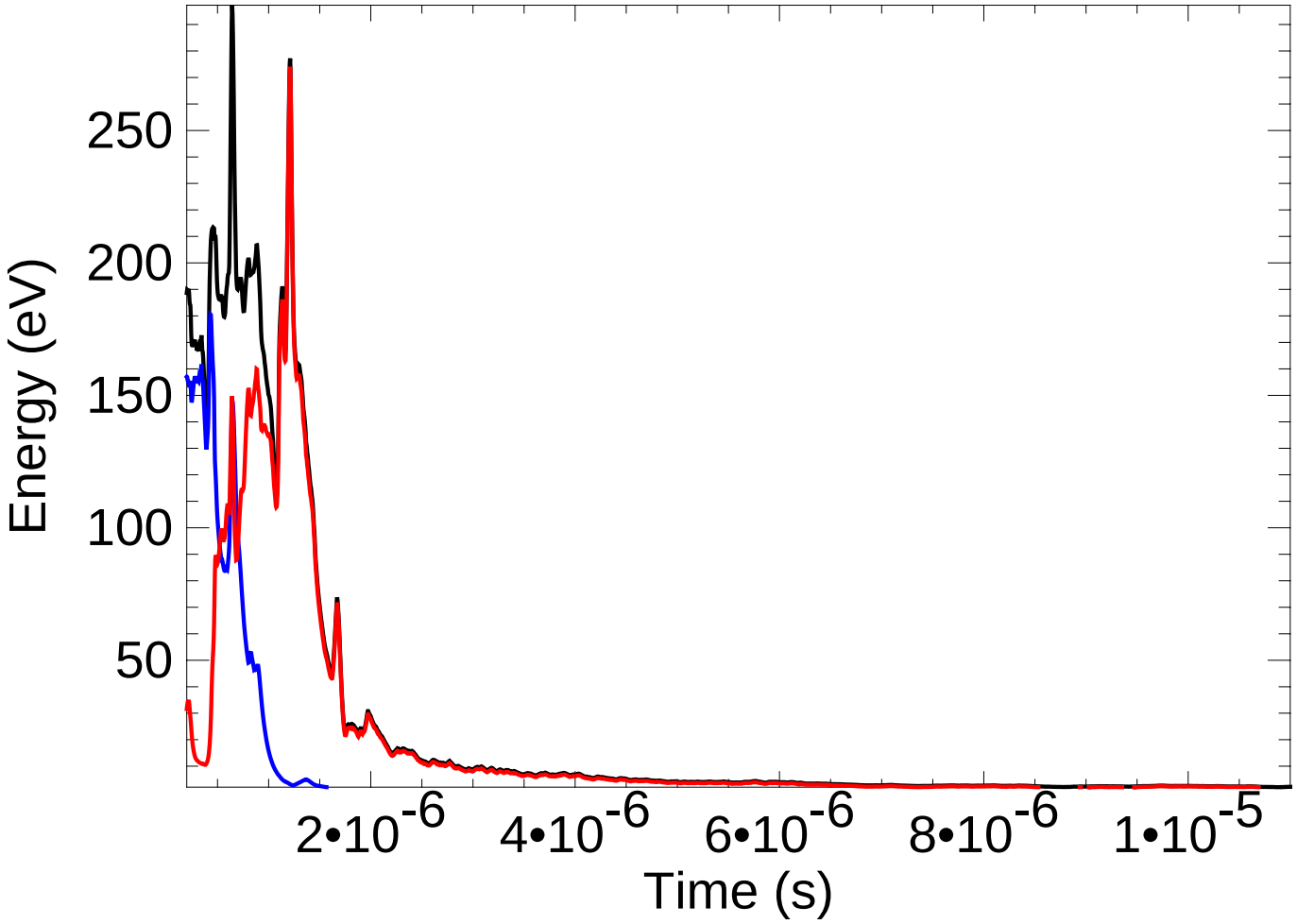
(polyethylene fiber shot)



black: gaussian
blue: blackbody
red: bremsstrahlung

Temporal Evolution of Emission Spectrum

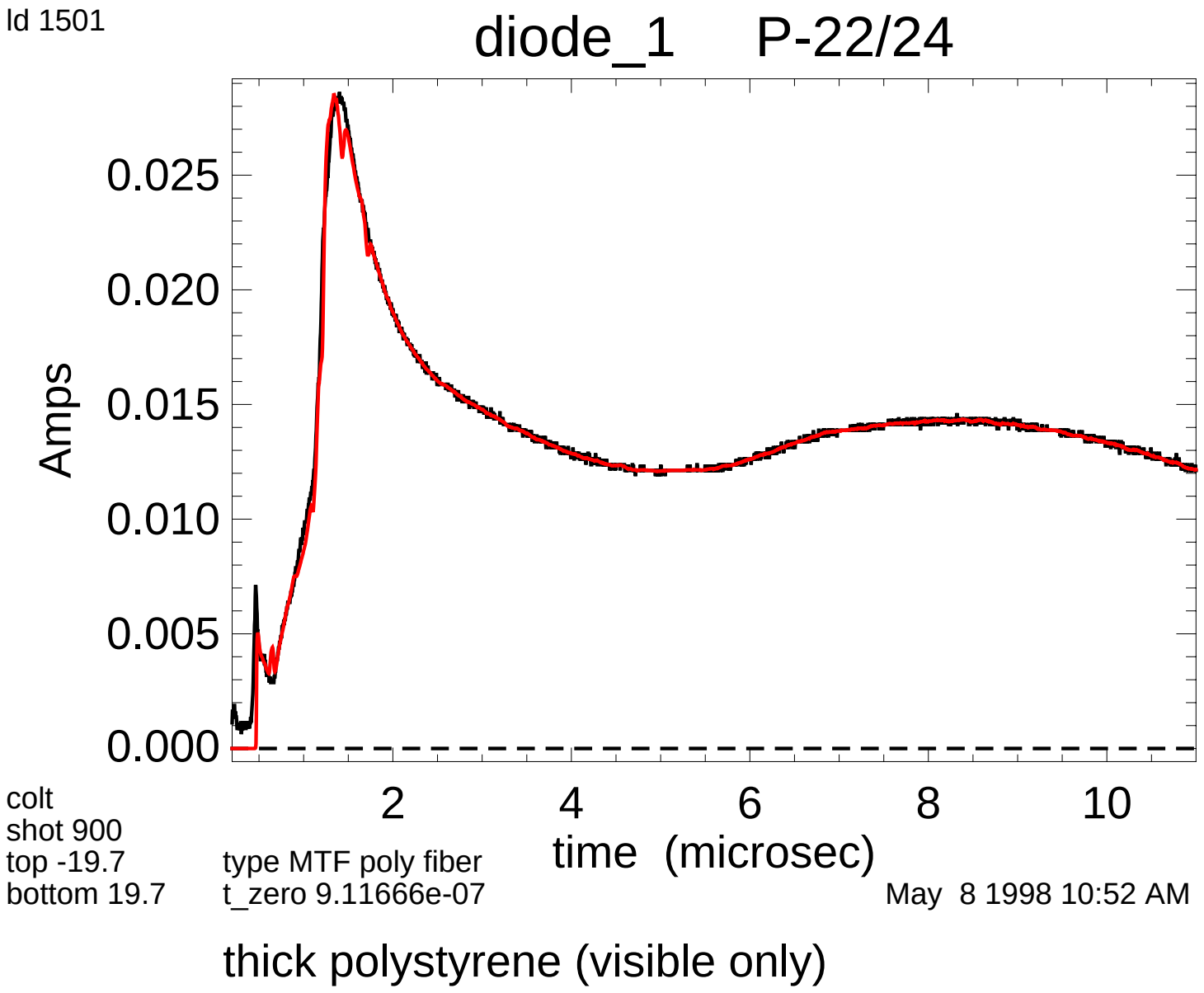
(gaussian spectrum fit of polyethylene fiber shot)

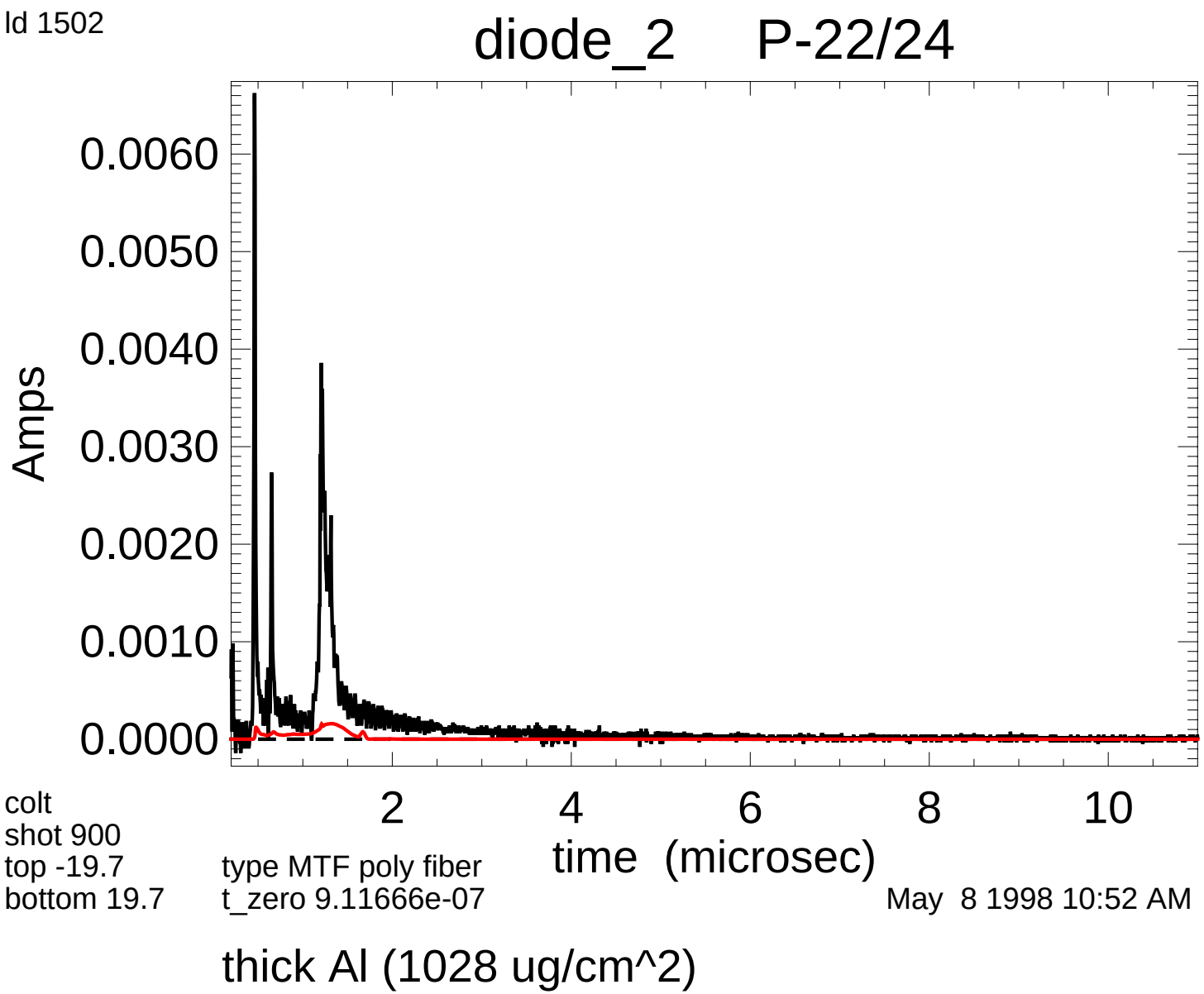


black: center + width of gaussian peak

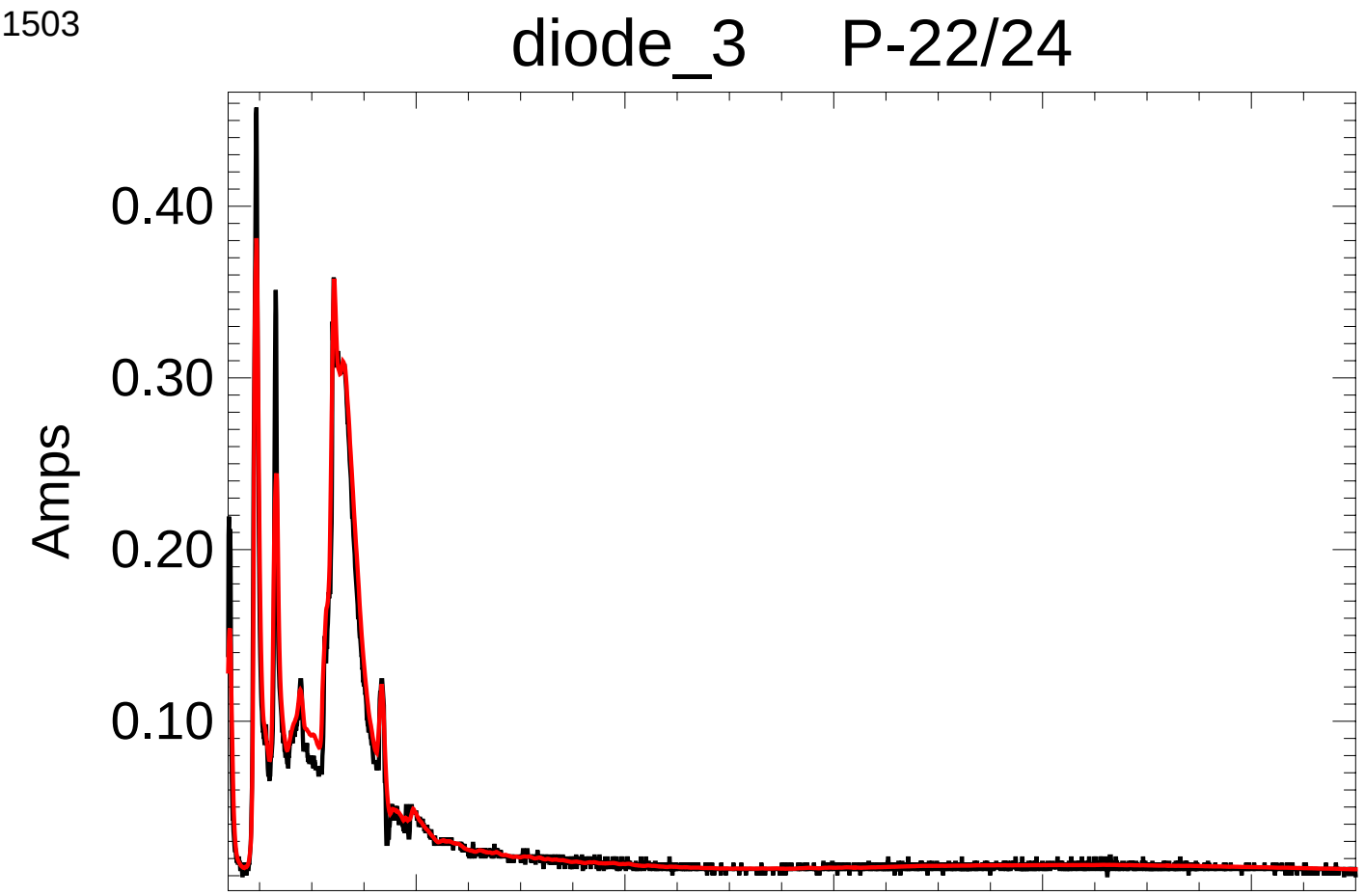
blue: center

red: width


ld 1501
diode_1 P-22/24
0.025
0.020
0.015
0.010
0.005
0.000
Amps
2
4
6
8
10
time (microsec)
colt
shot 900
top -19.7
bottom 19.7
type MTF poly fiber
t_zero 9.11666e-07
May 8 1998 10:52 AM
thick polystyrene (visible only)


ld 1502
diode_2 P-22/24
0.0060
0.0050
0.0040
0.0030
0.0020
0.0010
0.0000
Amps
2
4
6
8
10
time (microsec)
colt
shot 900
top -19.7
bottom 19.7
type MTF poly fiber
t_zero 9.11666e-07
May 8 1998 10:52 AM
thick Al (1028 ug/cm^2)

ld 1503

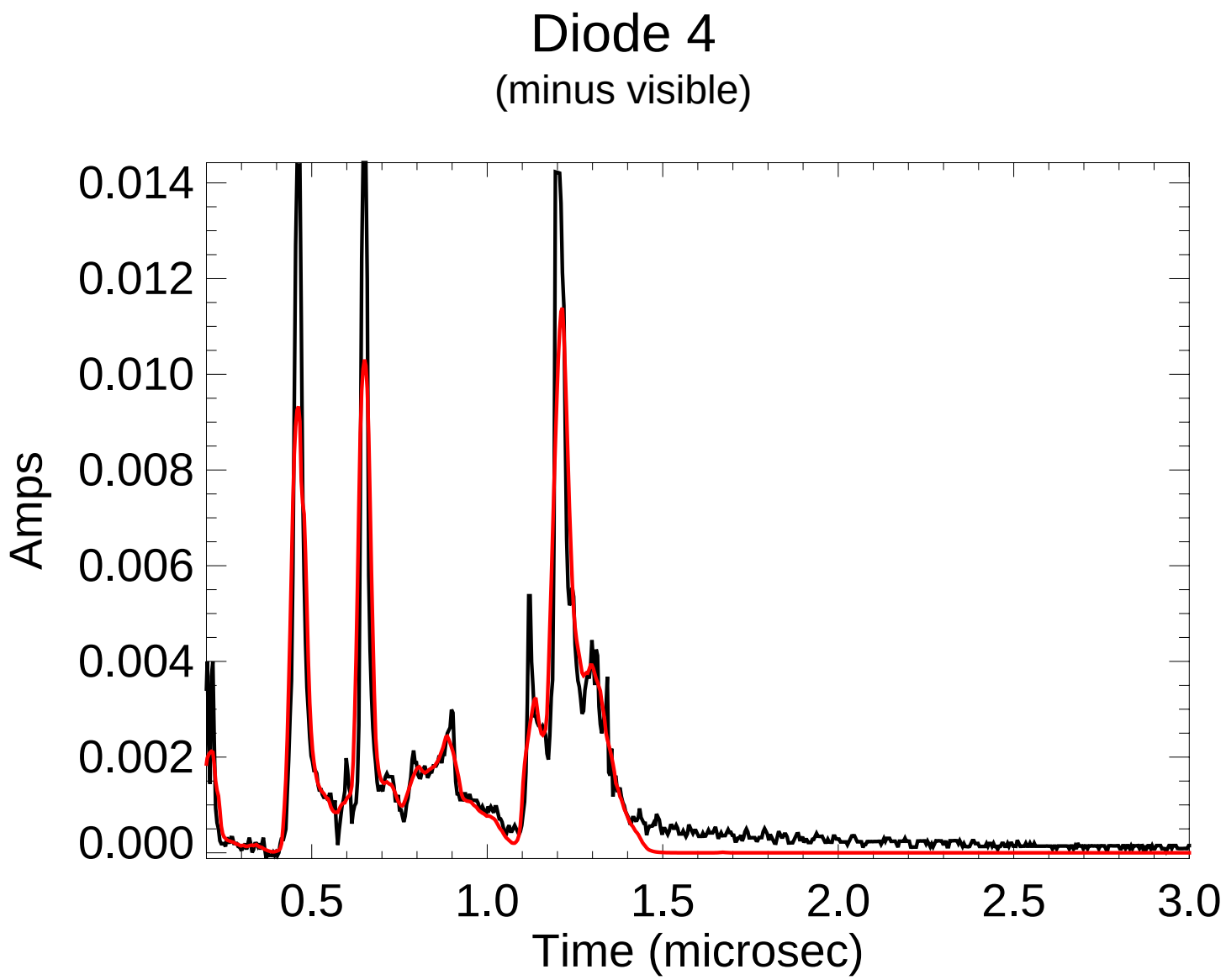


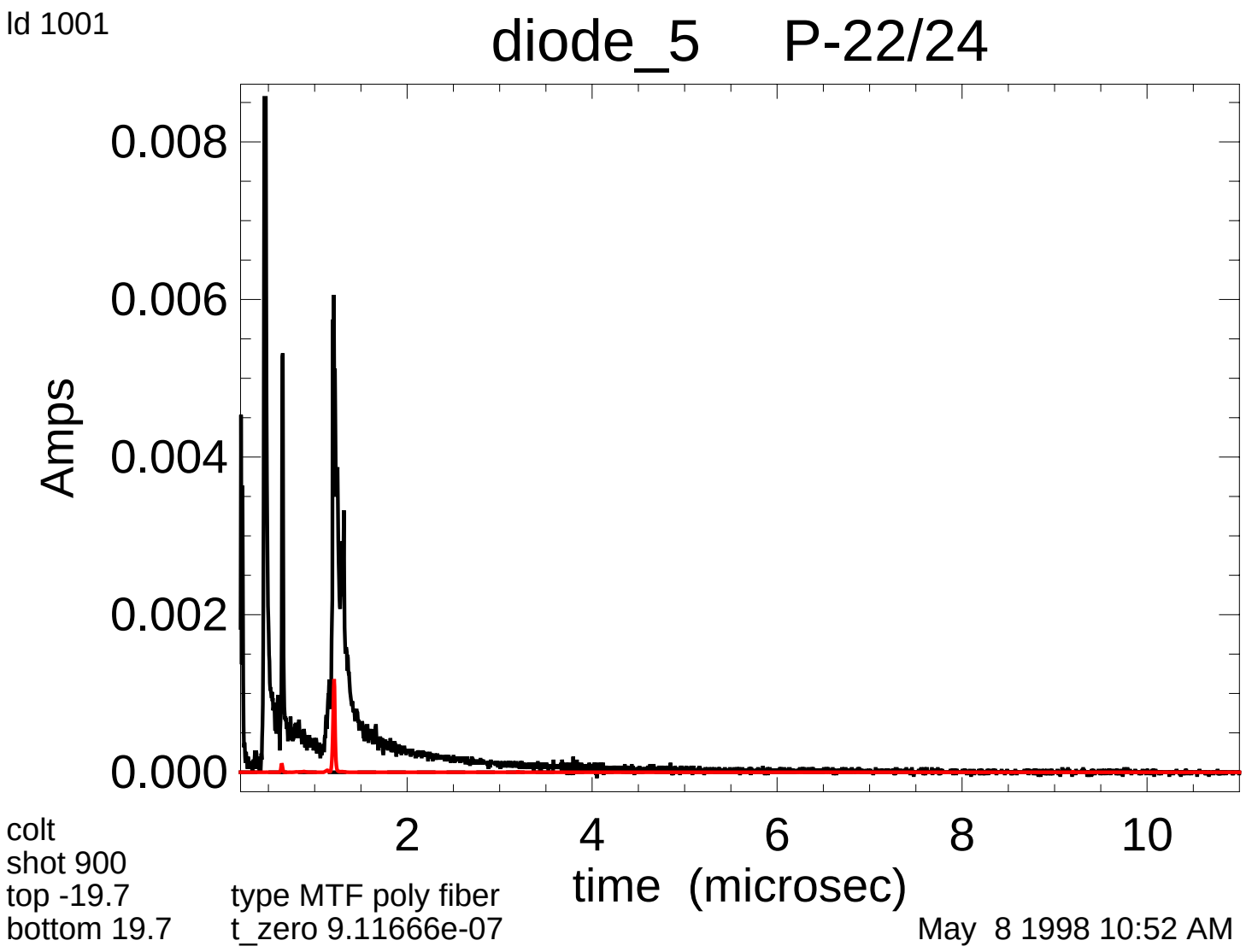
colt
shot 900
top -19.7
bottom 19.7

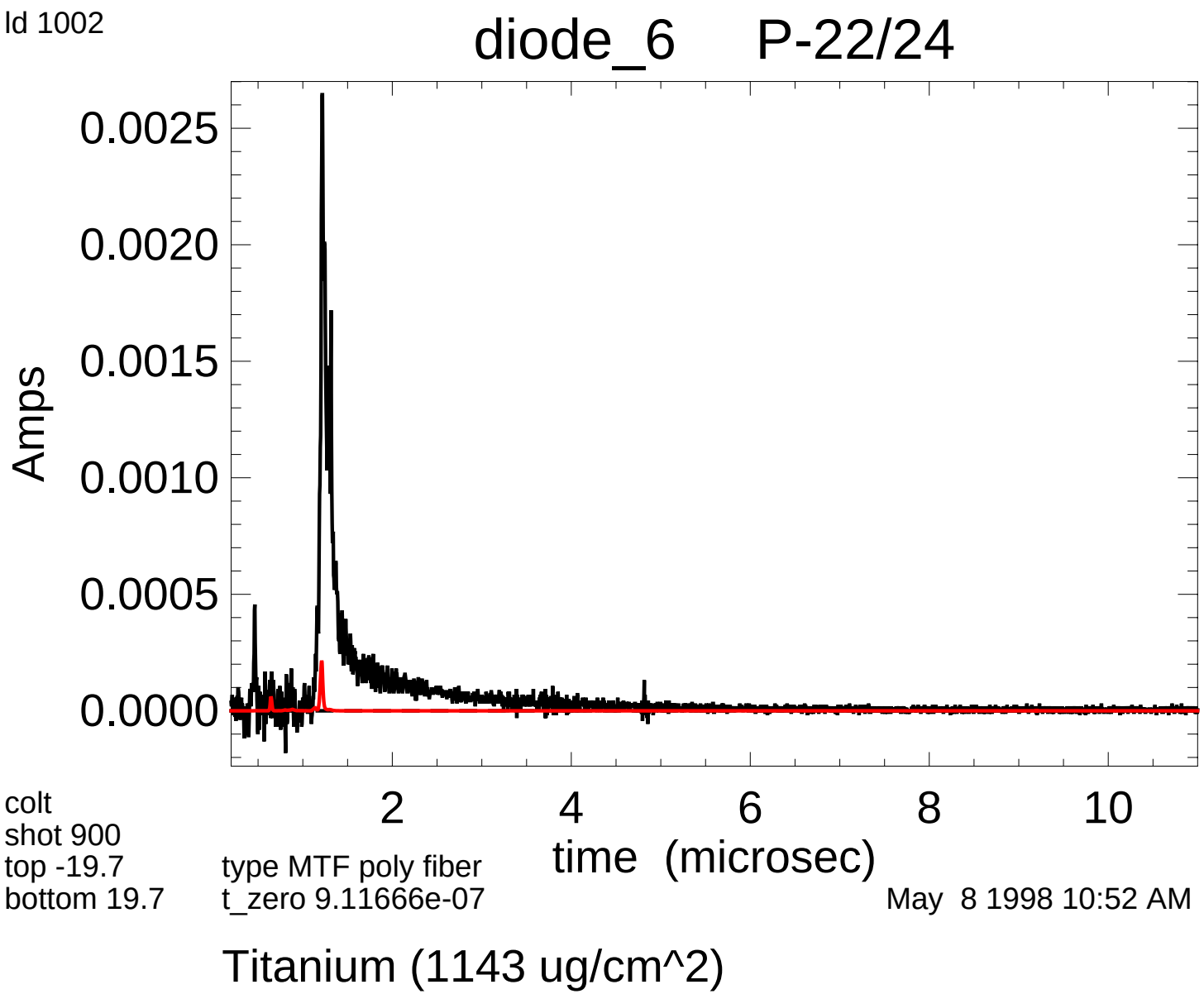
type MTF poly fiber
t_zero 9.11666e-07

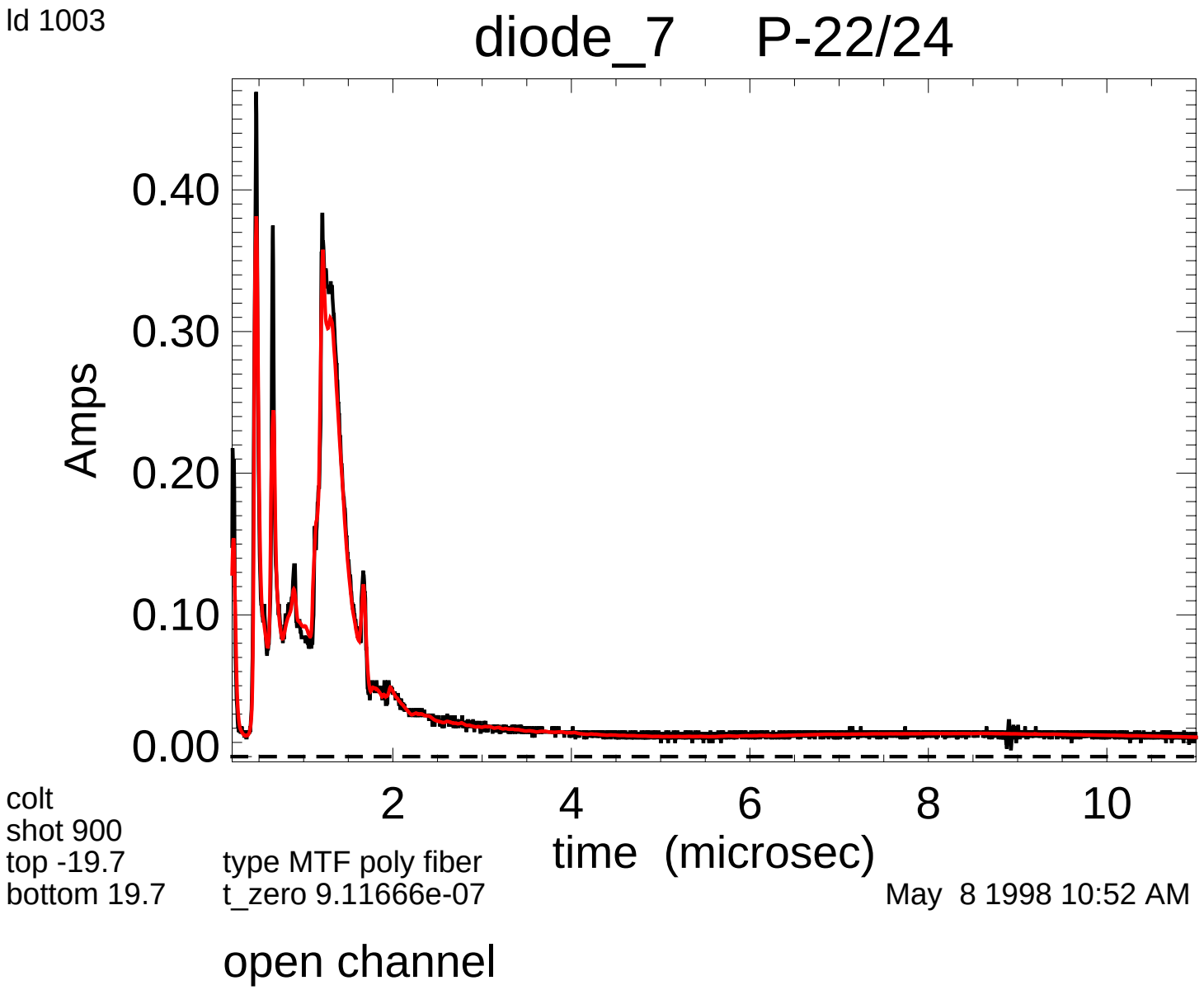
May 8 1998 10:52 AM

thin parylene-n (322 ug/cm^2)


Diode 4
(minus visible)
Amps
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0.5
1.0
1.5
2.0
2.5
3.0
Time (microsec)


ld 1001
diode_5 P-22/24
0.008
0.006
0.004
0.002
0.000
Amps
2
4
6
8
10
time (microsec)
colt
shot 900
top -19.7
bottom 19.7
type MTF poly fiber
t_zero 9.11666e-07
May 8 1998 10:52 AM
Nickel (452 ug/cm^2)


ld 1002
diode_6 P-22/24
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
Amps
2
4
6
8
10
time (microsec)
colt
shot 900
top -19.7
bottom 19.7
type MTF poly fiber
t_zero 9.11666e-07
May 8 1998 10:52 AM
Titanium (1143 ug/cm^2)


ld 1003
diode_7 P-22/24
0.40
0.30
0.20
0.10
0.00
Amps
2
4
6
8
10
time (microsec)
colt
shot 900
top -19.7
bottom 19.7
type MTF poly fiber
t_zero 9.11666e-07
May 8 1998 10:52 AM
open channel

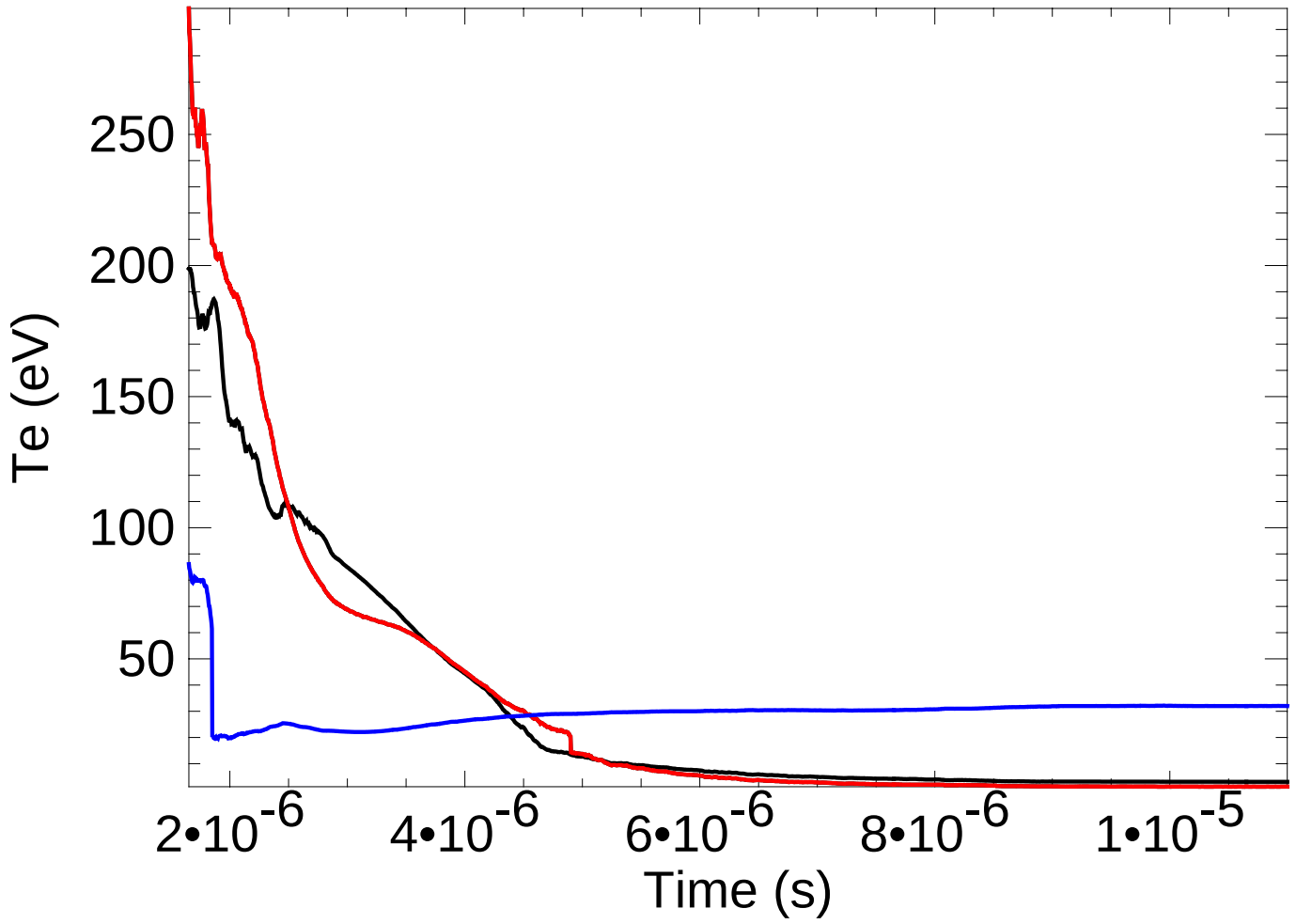
Static Gas Fill Signals

In contrast to polyethylene fiber pinches:

- signal appears after about 1.6 μs due to time it takes plasma to run down power-flow channel
- single wide x-ray pulse (often with ‘steps’), with peak at about 2.5 μs
- absence of narrow x-ray pulses
- similar final uniform visible light emission (‘afterglow’) and quiescent B-dot signals

Electron Temperature for Different Spectra

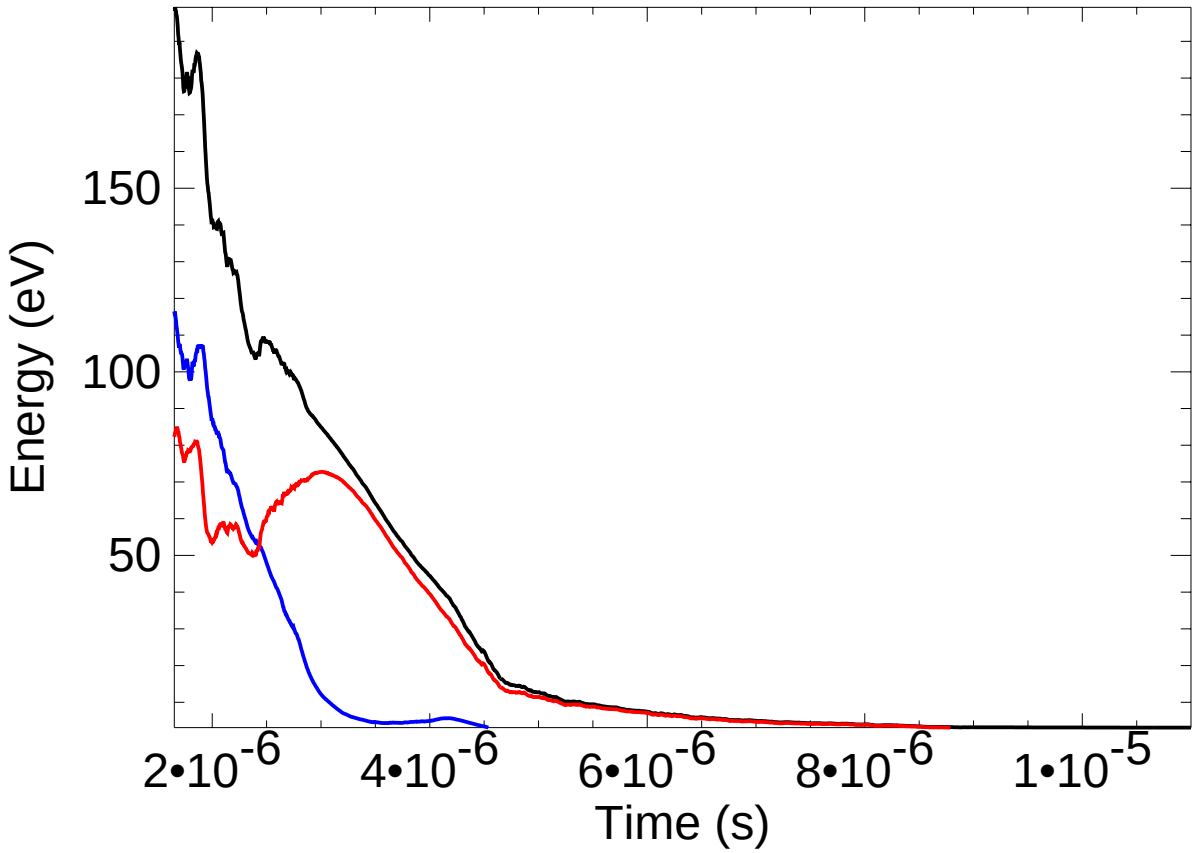
(static gas-fill shot)



black: gaussian
blue: blackbody
red: bremsstrahlung

Temporal Evolution of Emission Spectrum

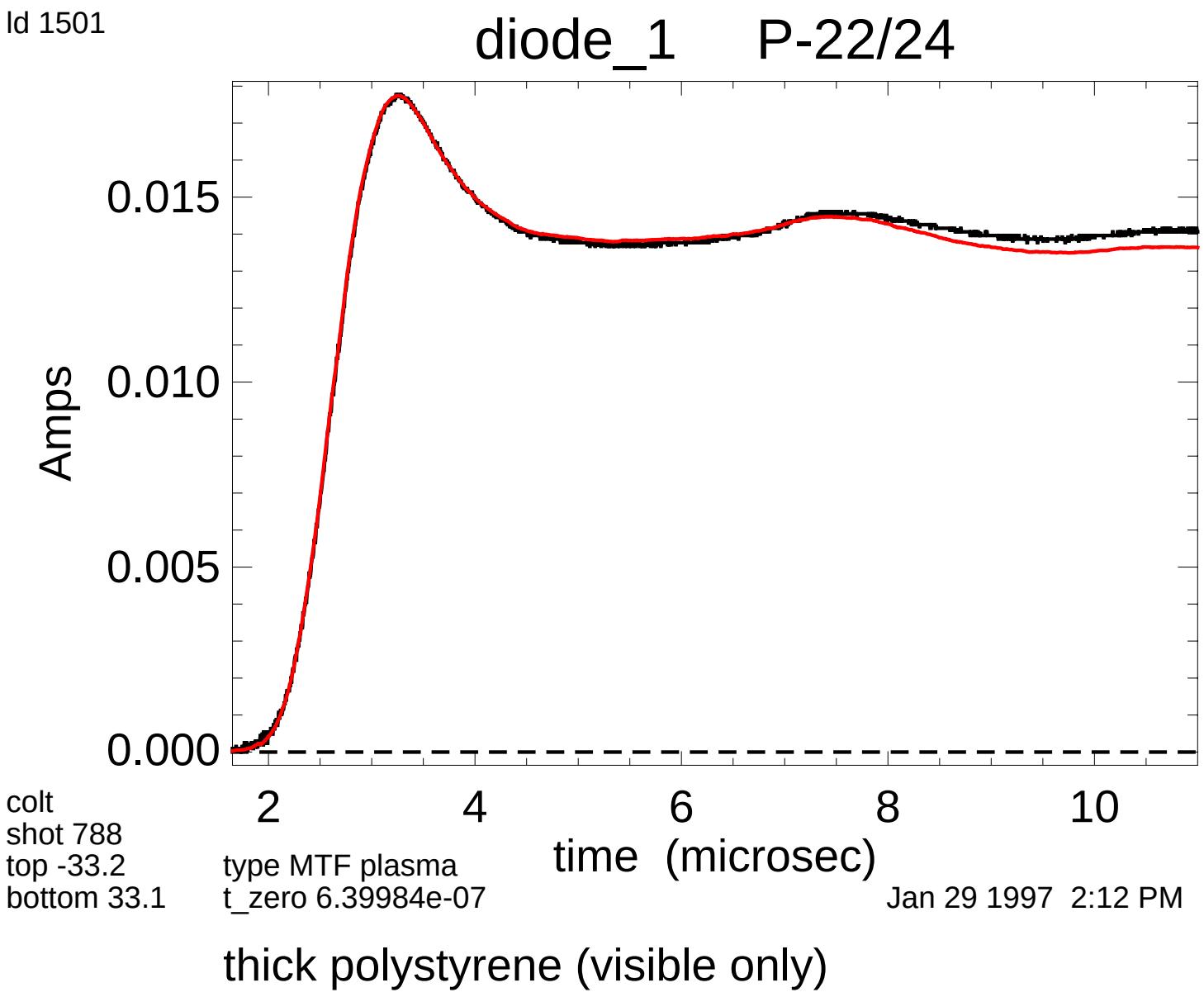
(gaussian spectrum fit of static gas-fill shot)

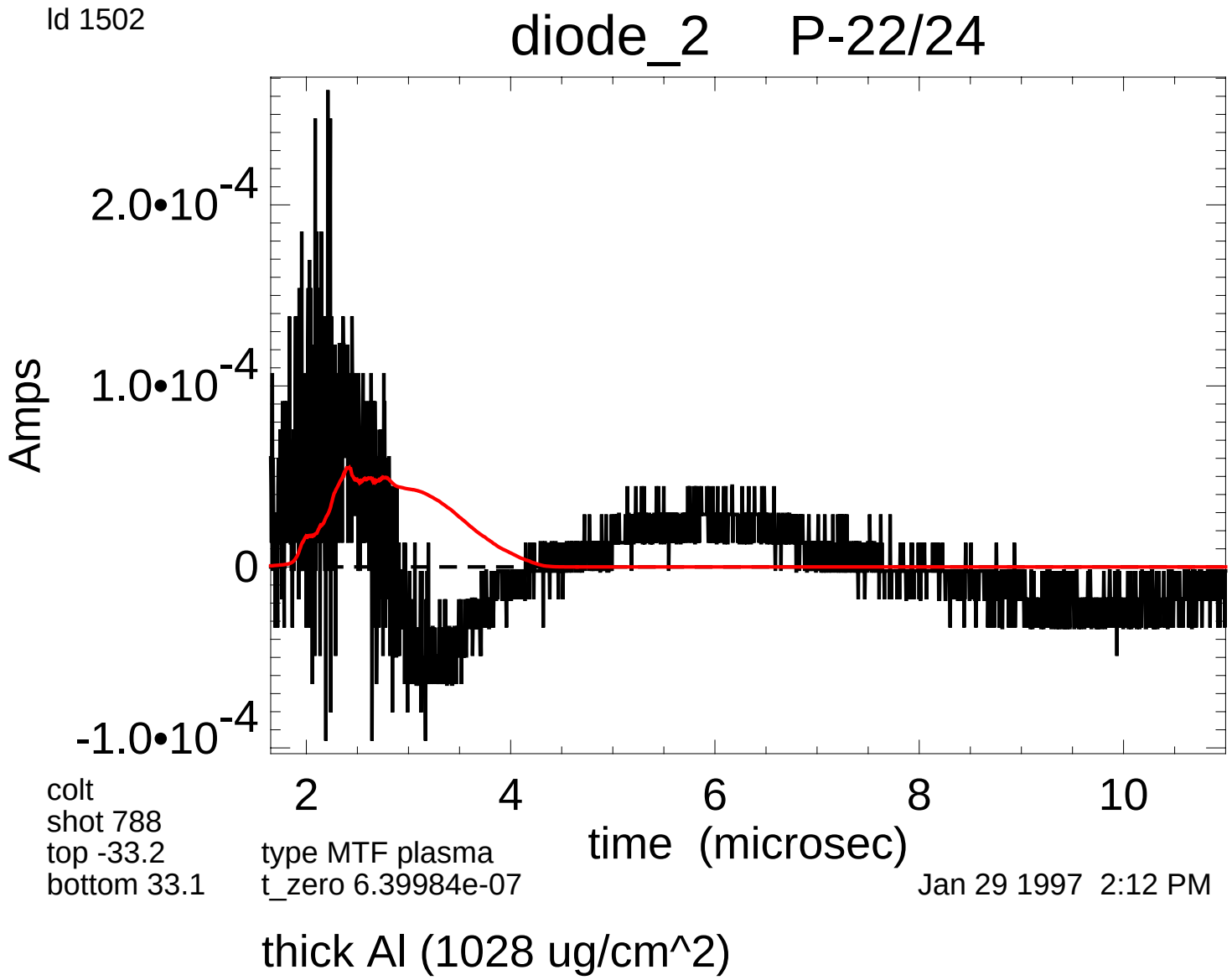


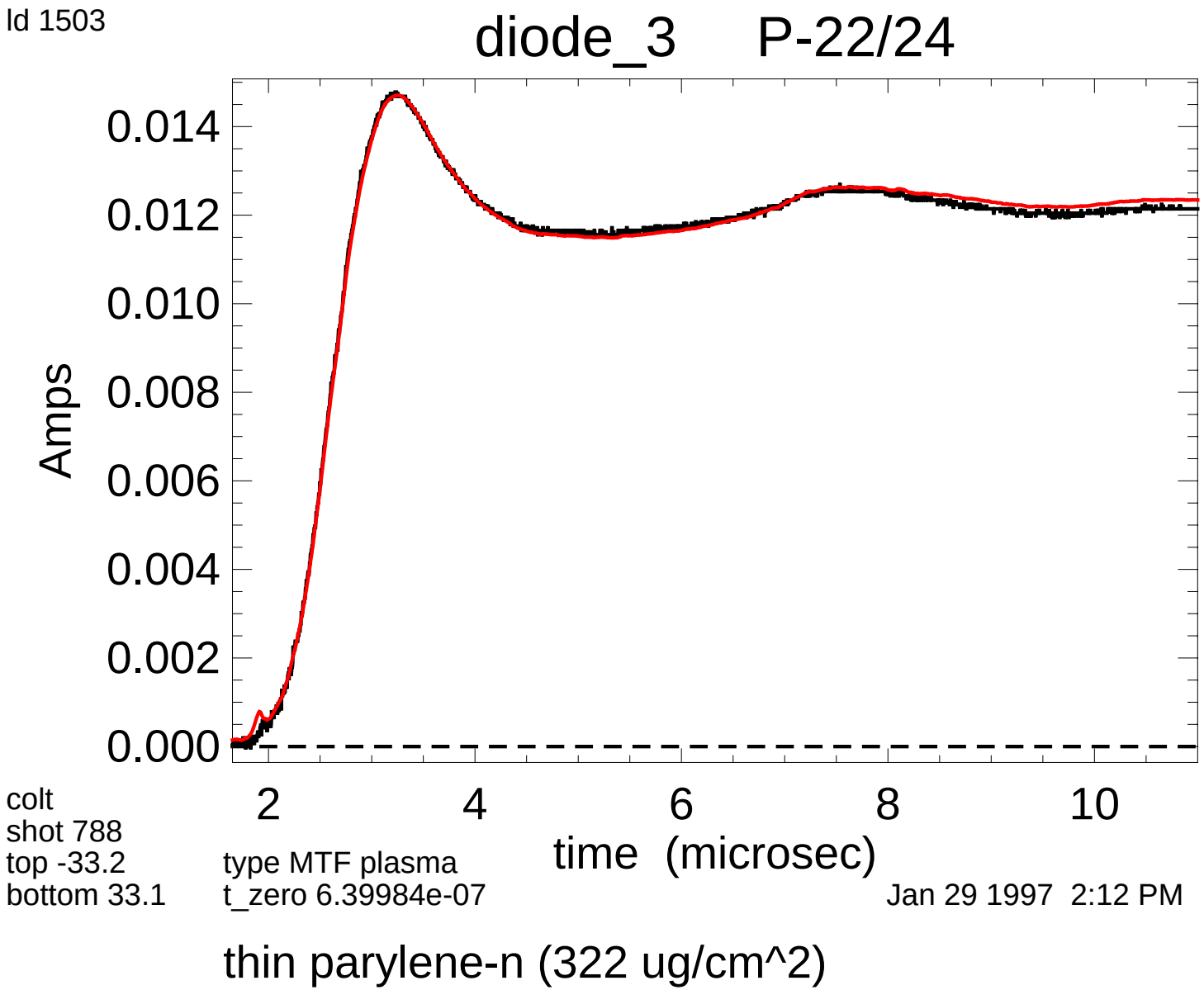
black: center + width of gaussian peak

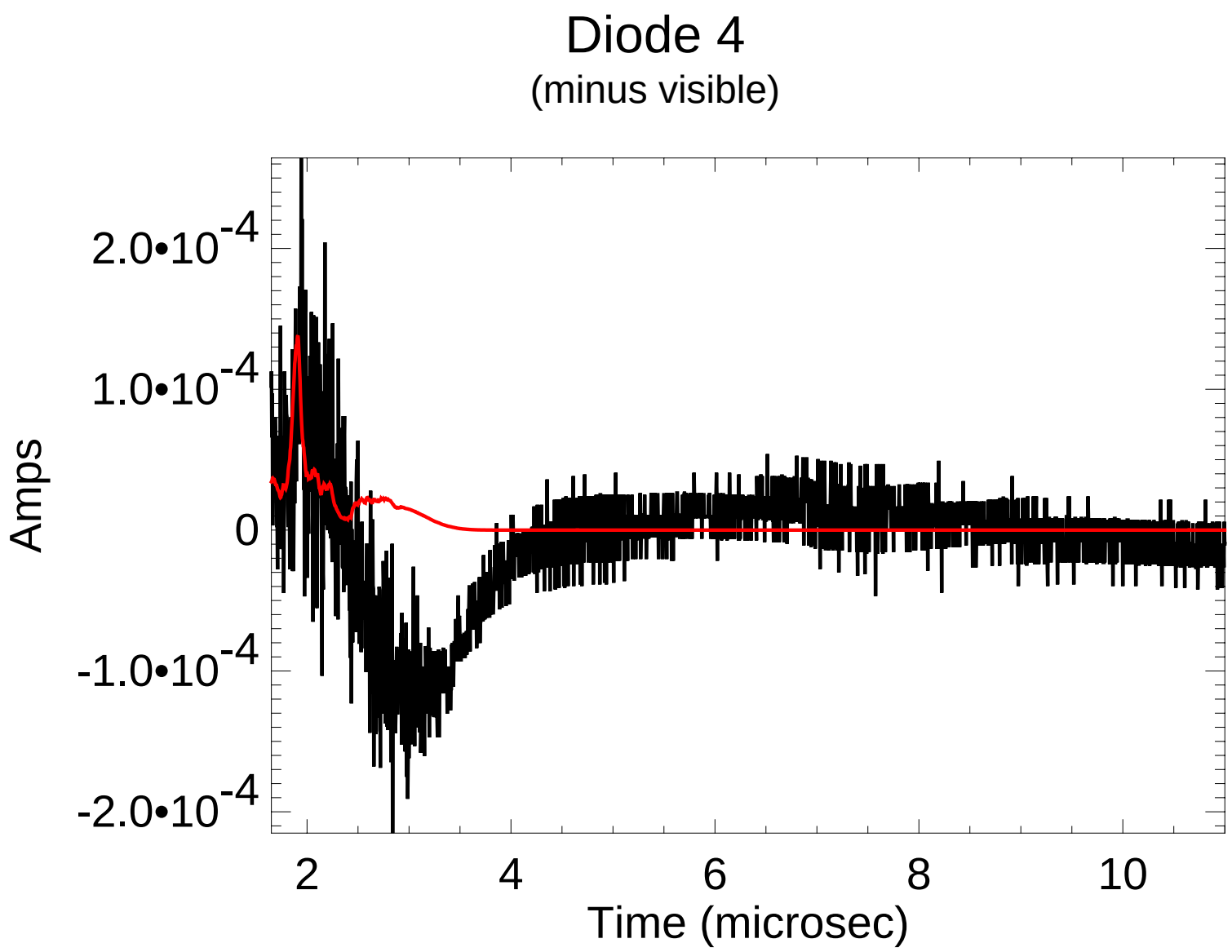
blue: center

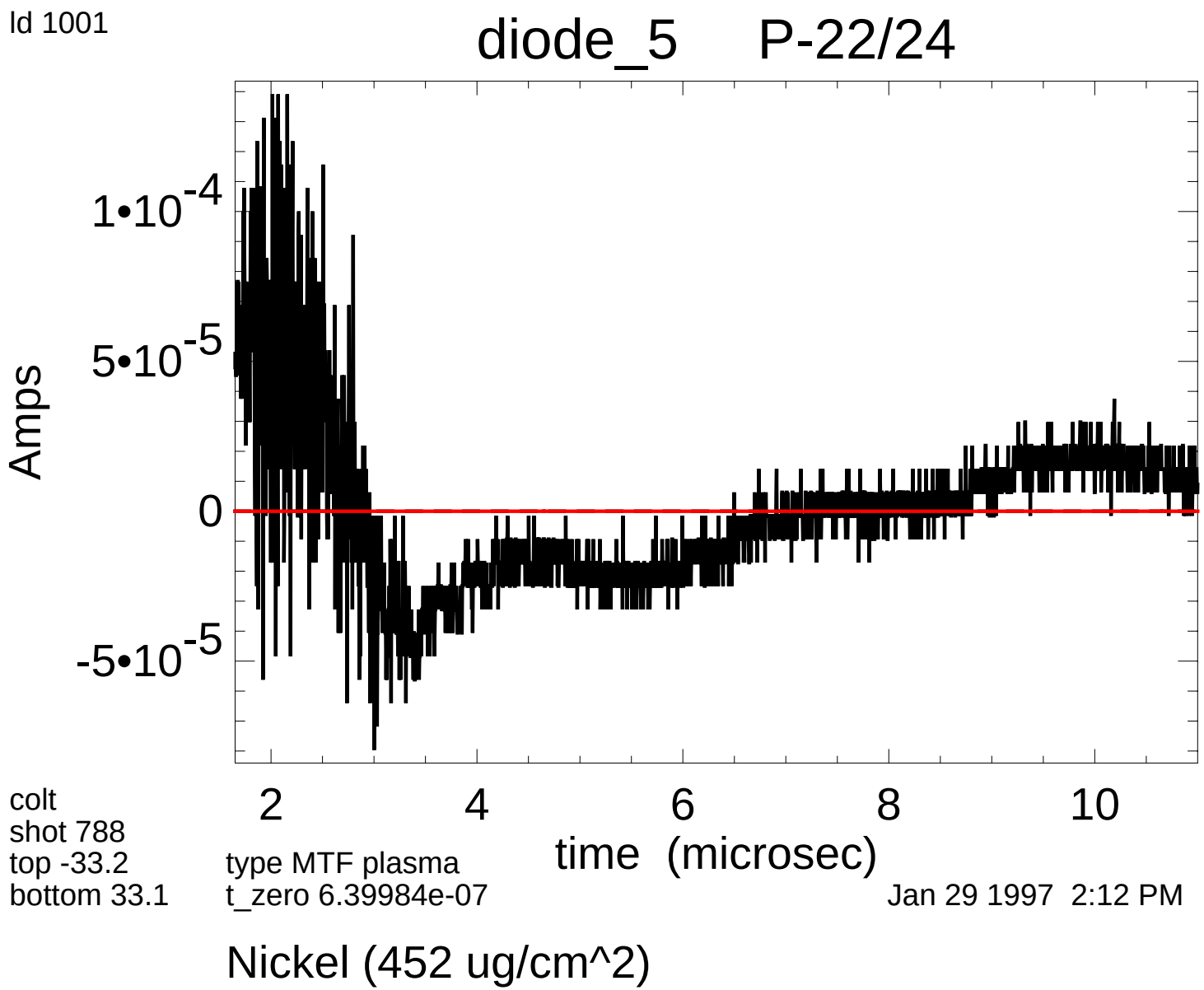
red: width


ld 1501
diode_1 P-22/24
0.015
0.010
0.005
0.000
Amps
2
4
6
8
10
time (microsec)
colt
shot 788
top -33.2
bottom 33.1
type MTF plasma
t_zero 6.39984e-07
Jan 29 1997 2:12 PM
thick polystyrene (visible only)

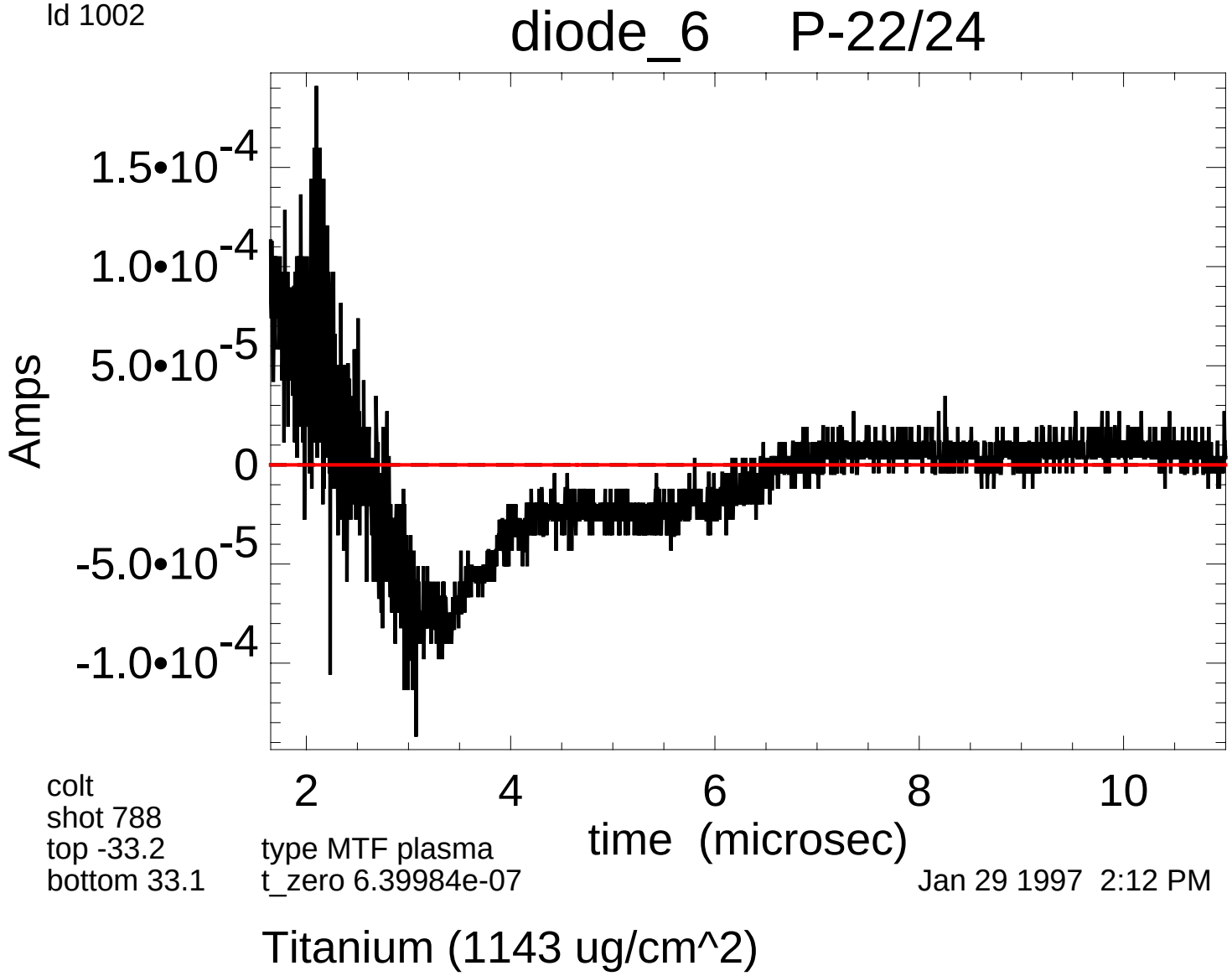

ld 1502
diode_2 P-22/24
2.0•10-4
1.0•10-4
0
-1.0•10-4
Amps
2
4
6
8
10
time (microsec)
colt
shot 788
top -33.2
bottom 33.1
type MTF plasma
t_zero 6.39984e-07
Jan 29 1997 2:12 PM
thick Al (1028 ug/cm^2)


ld 1503
diode_3 P-22/24
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Amps
2
4
6
8
10
time (microsec)
colt
shot 788
top -33.2
bottom 33.1
type MTF plasma
t_zero 6.39984e-07
Jan 29 1997 2:12 PM
thin parylene-n (322 ug/cm^2)

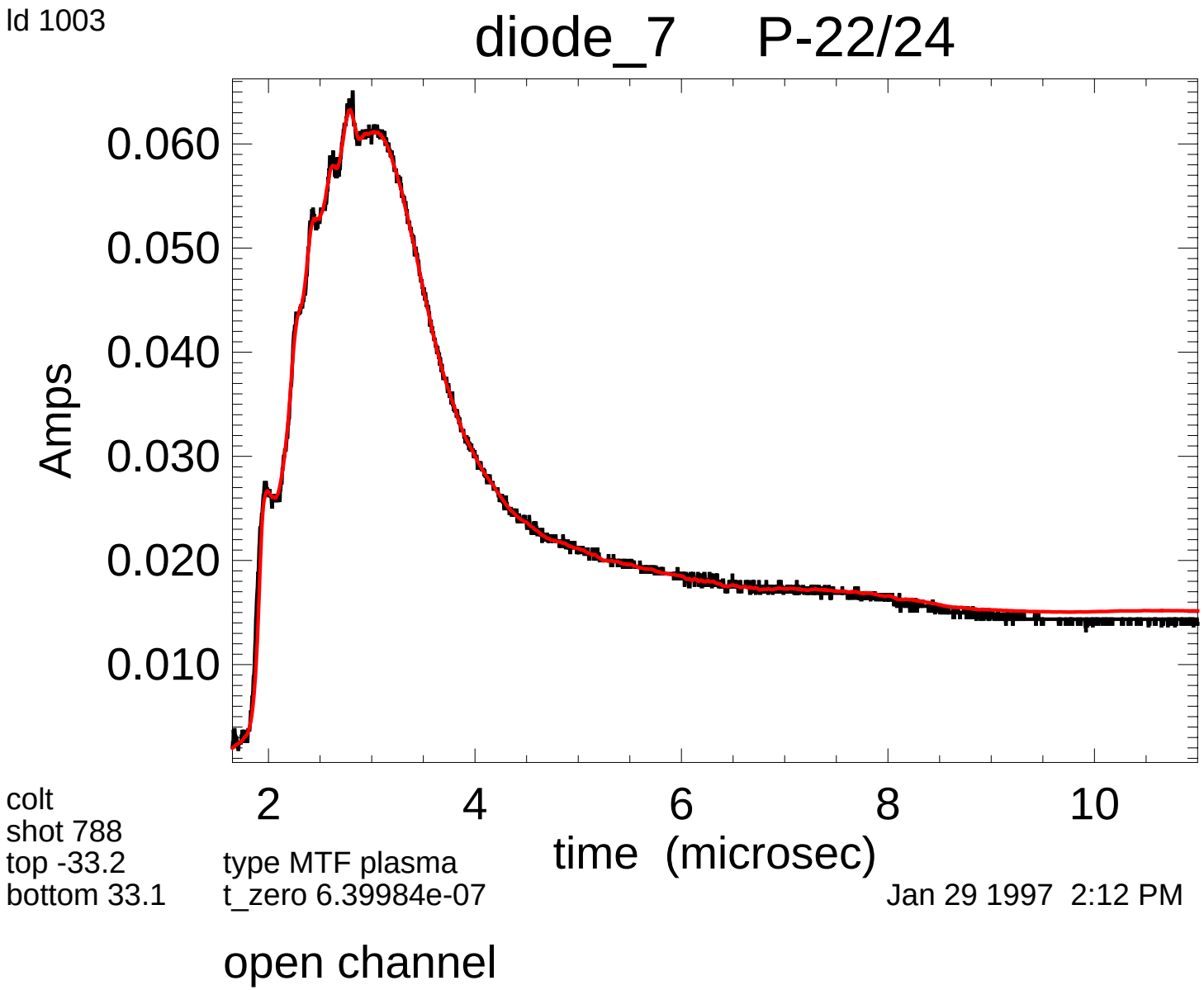

Diode 4
(minus visible)
Amps
2.0•10-4
1.0•10-4
0
-1.0•10-4
-2.0•10-4
2
4
6
8
10
Time (microsec)


ld 1001
diode_5 P-22/24
1•10-4
5•10-5
0
-5•10-5
Amps
2
4
6
8
10
time (microsec)
colt
shot 788
top -33.2
bottom 33.1
type MTF plasma
t_zero 6.39984e-07
Jan 29 1997 2:12 PM
Nickel (452 ug/cm^2)

ld 1002

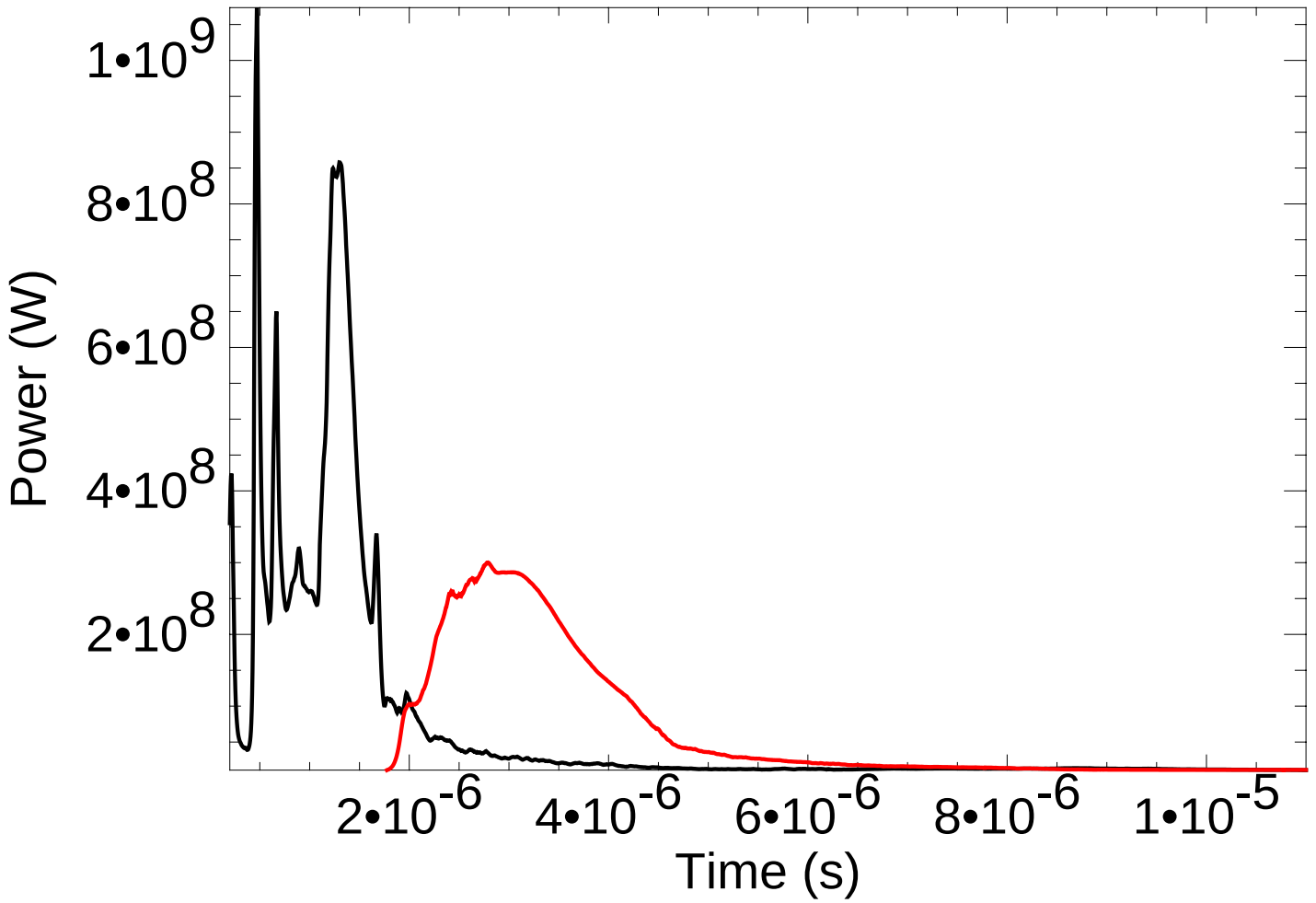


Titanium (1143 ug/cm^2)


ld 1003
diode_7 P-22/24
0.060
0.050
0.040
0.030
0.020
0.010
Amps
2
4
6
8
10
time (microsec)
colt
shot 788
top -33.2
bottom 33.1
type MTF plasma
t_zero 6.39984e-07
Jan 29 1997 2:12 PM
open channel

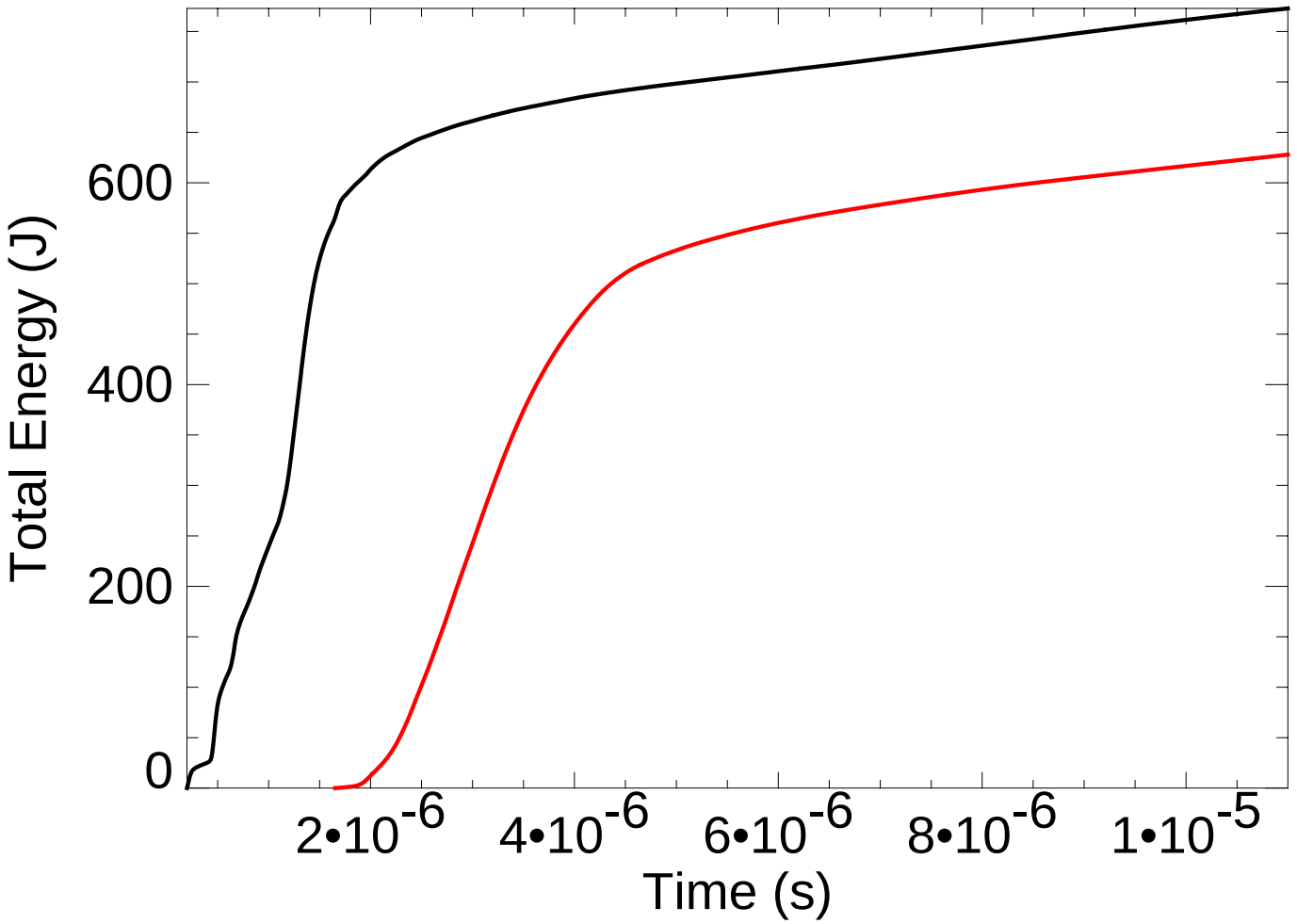
Comparison of Emitted Power

(black=fiber, at 40kV, red=gas-fill, at 66kV - both fit by a gaussian)



Comparison of Total Emitted Energy

(black=fiber, at 40kV, red=gas-fill, at 66kV - both fit by a gaussian)



Summary/Future Directions

- deploy a second array of photodiodes with different filters (simultaneously with first) to obtain better ‘resolution’ and improve fitting capabilities
- add a transmission grating spectrograph to obtain better spectral resolution of plasma radiation (including identification of any contaminants present)
- use photodiode array temperature measurement method on the FRC (field-reversed configuration) to be developed at LANL for future MTF studies (as a complement to Thomson scattering)