P9-02-Parchamy

Spatial variation of the foil parameters from in situ calibration of the JT-60U imaging bolometer foil

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JAEA

NINS
自然科学研究機構

NFRC
핵융합연구센터
National Fusion Research Center

NIFS

16th International Toki Conference
Advanced Imaging and plasma Diagnostics
Ceratopia Toki, Gifu, JAPAN
December 5 – 8, 2006

Advanced Diagnostics
for Burning Plasmas

Motivation

- Radiation loss is an important measurement for fusion plasma experiments and fusion reactors will require diagnostics that can operate reliably in a high neutron flux environment
- Imaging bolometers provide a reactor relevant alternative to conventional resistive bolometers
- We present spatial variation of the foil parameters from in-situ calibration of the the JT-60U imaging bolometer foil

Radiation from Plasma to Infrared Camera

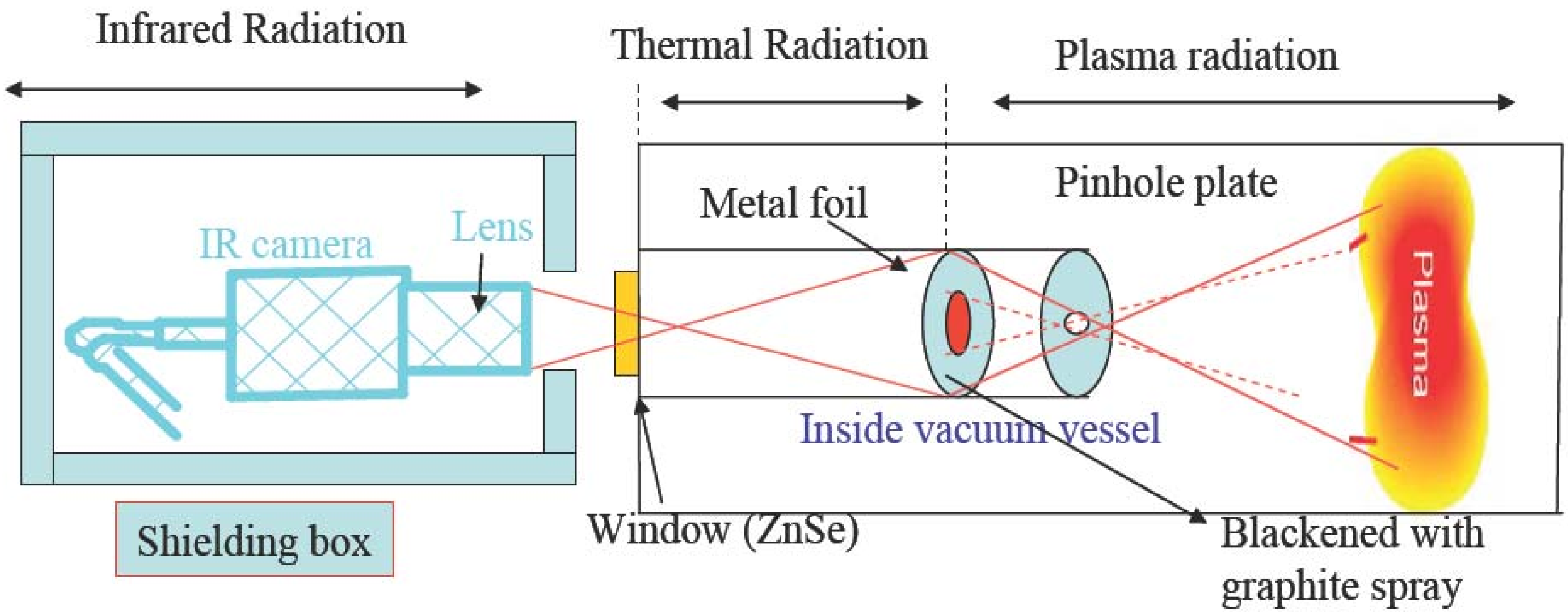
❖ ***Radiation from plasma***

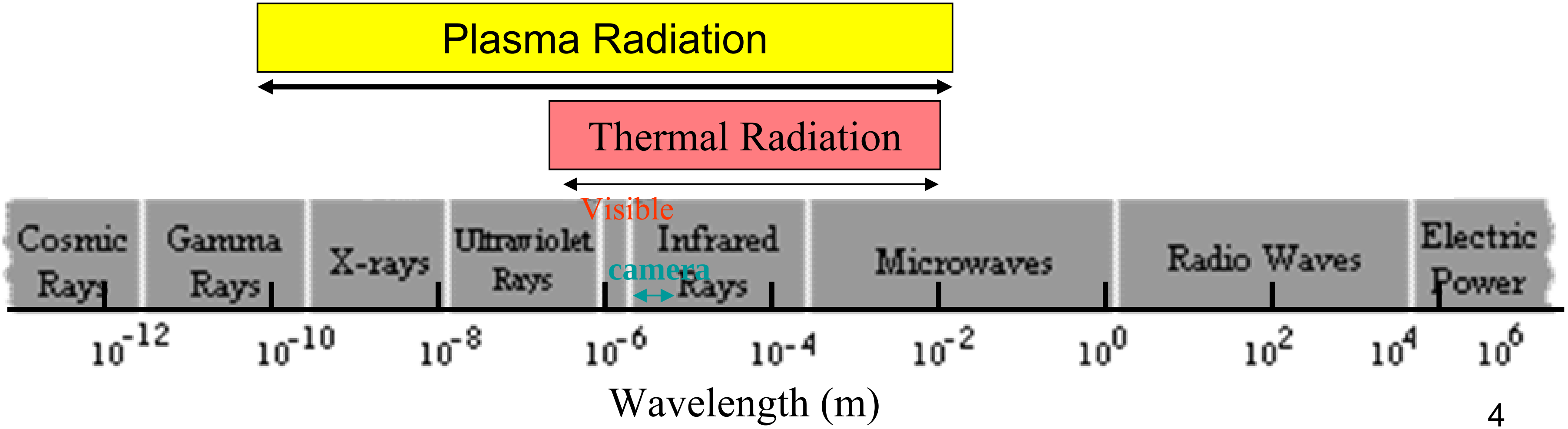
- Bremsstrahlung (the electrons accelerate by collisions)
- Synchrotron radiation (the electrons accelerate by cyclotron motion)
- Line radiation of impurities (major portion)

❖ ***IR imaging bolometer in JT-60U***

- The 2.5 µm × 7 cm × 9 cm gold foil (photon energy < 8 keV)
- The IR camera detector is a micro bolometer type (FLIR/Indigo micron/omega) and sensitive in the far Infrared wavelength range (7.5~13.5µm)
- The ZnSe window (Infrared range 3-12 µm)

Radiation from Plasma to Infrared Camera



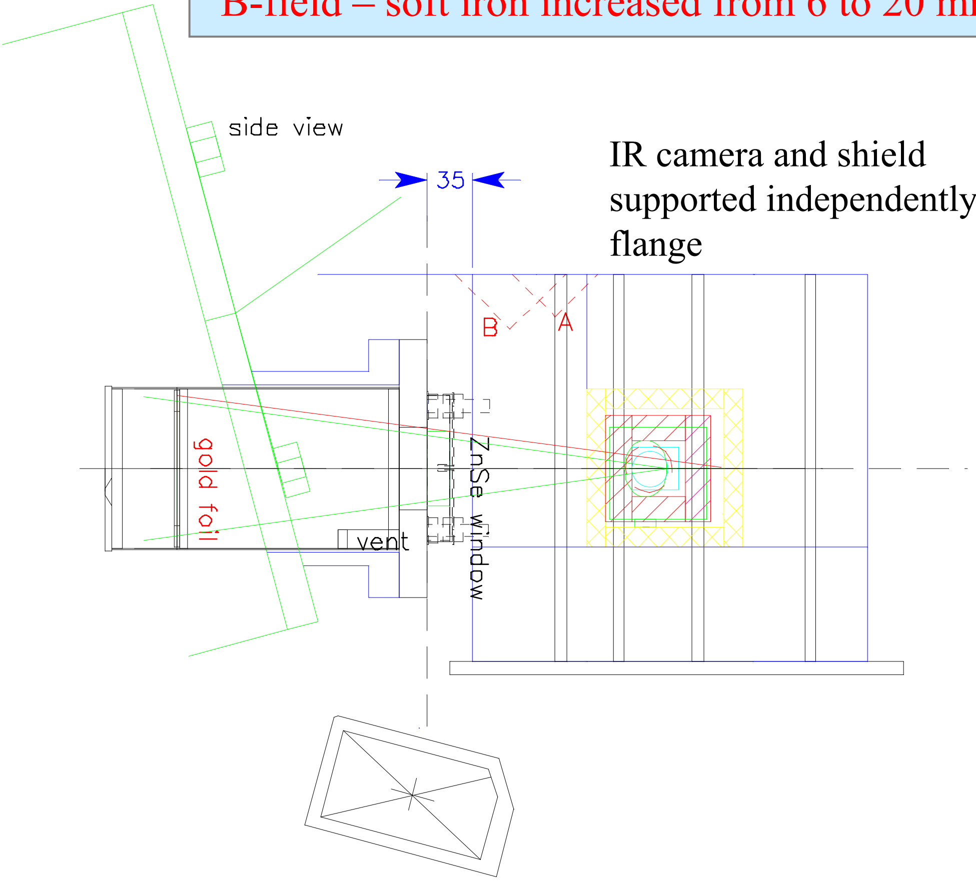


Shielding for IR camera (design for 2005 experiment)

Neutrons - polyethylene increased from 30 to 90 mm

Gammas - 15 mm lead added

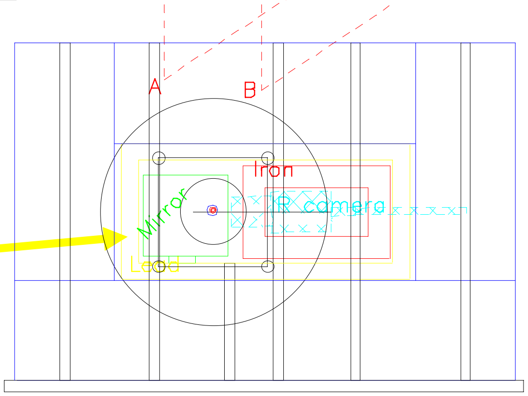
B-field – soft iron increased from 6 to 20 mm

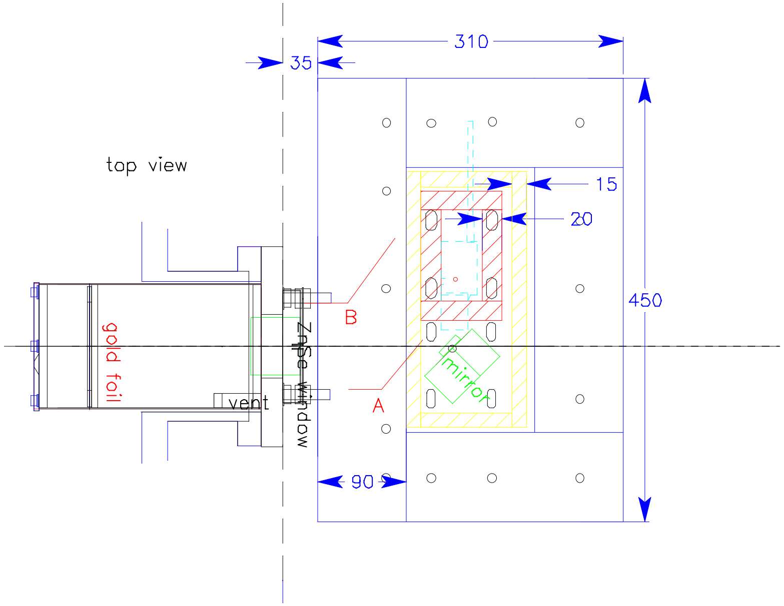


IR camera and shield supported independently of flange

Front view

Lead box

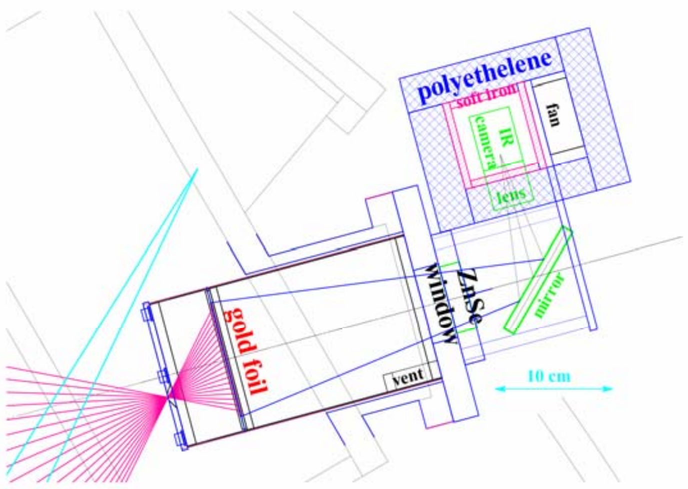


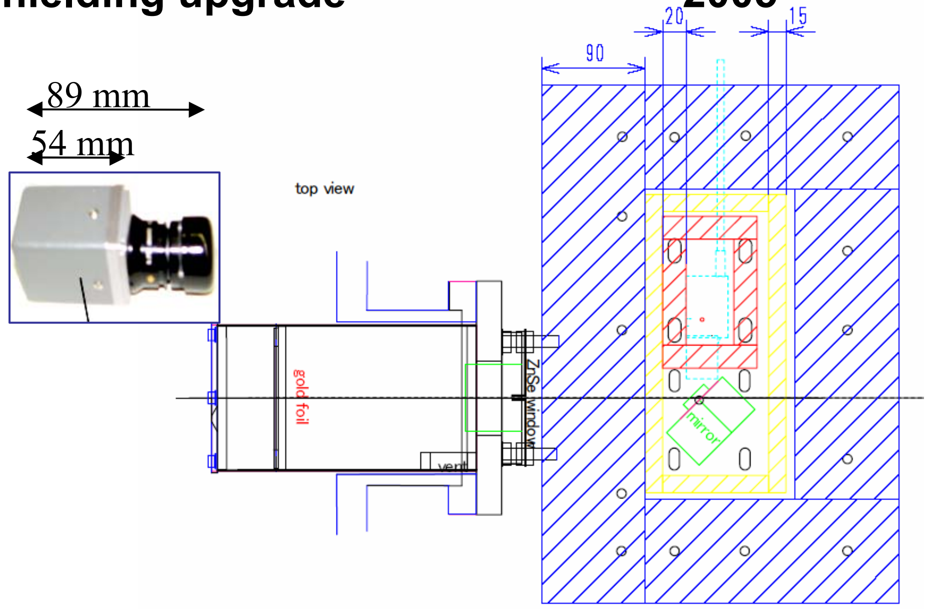


In current campaign we could measure with IR camera sometimes during Deuterium beams → additional shielding seems effective

Shielding for IR camera

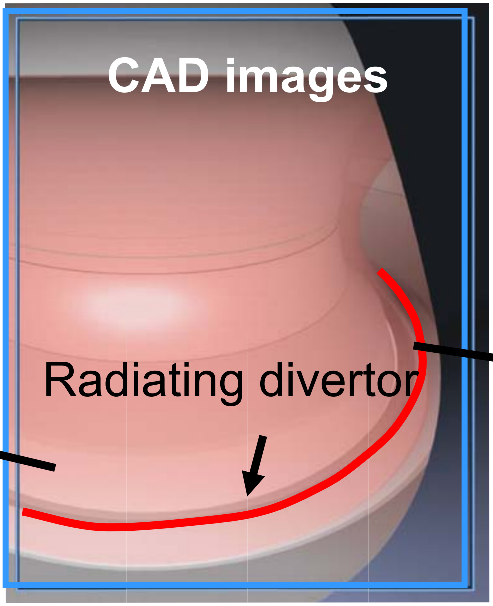
2004 **Shielding upgrade** **2005**





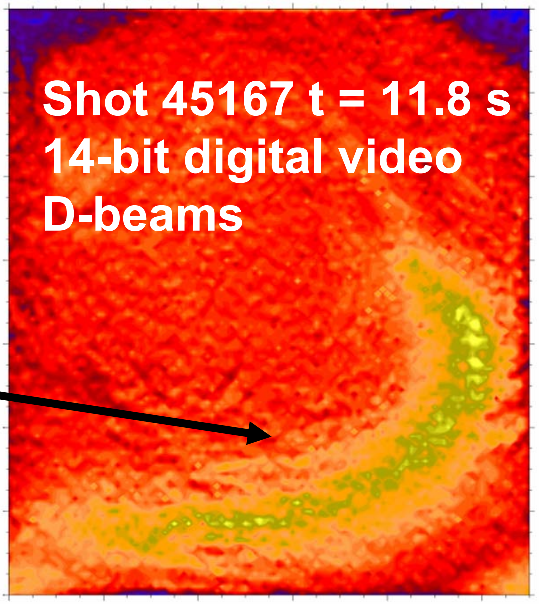
2004 Data acquisition upgrade 2005

Shot 44354 t = ~10.5 s
8-bit analog video
H-beams



CAD images

Radiating divertor



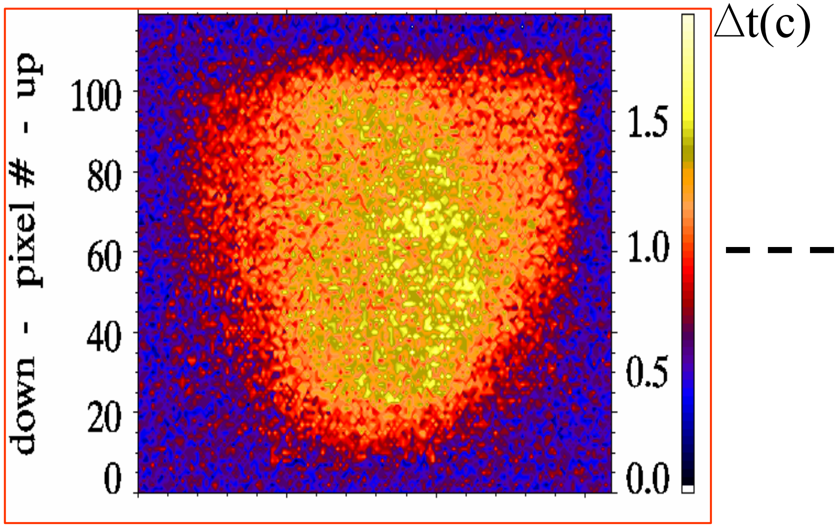
Shot 45167 t = 11.8 s
14-bit digital video
D-beams

The importance of calibration of the IRVB

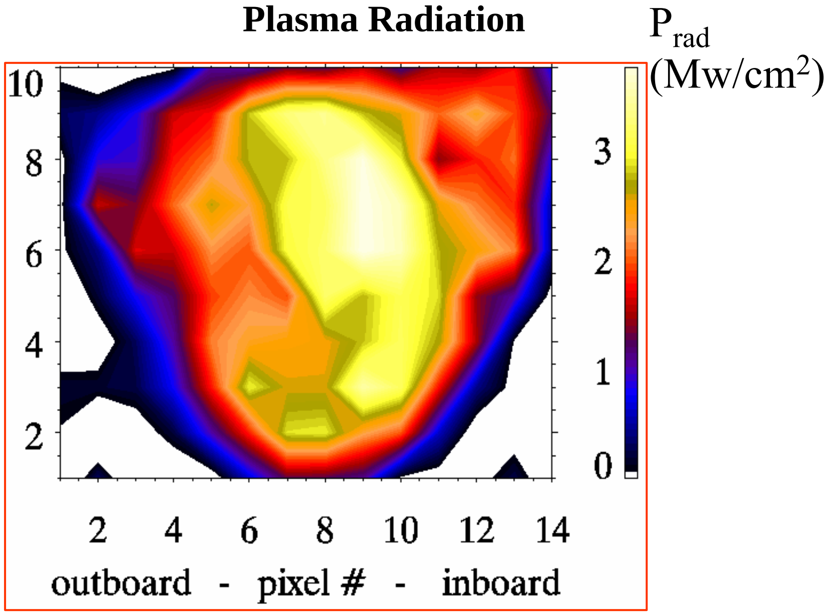
- The calibration of the infrared imaging video bolometer will compensate for non-uniformities in the foil.
- This technique gives confidence in the absolute levels of the measured values of radiation from divertor and core regions that is necessary for tomographic analyses.
- Calibration data is necessary to correctly convert from foil temperature data to plasma radiation data

IRVB Data (For LHD)[1)]

IR Camera data
120 x 160 pixels



Before calibration and analysis



After calibration and analysis

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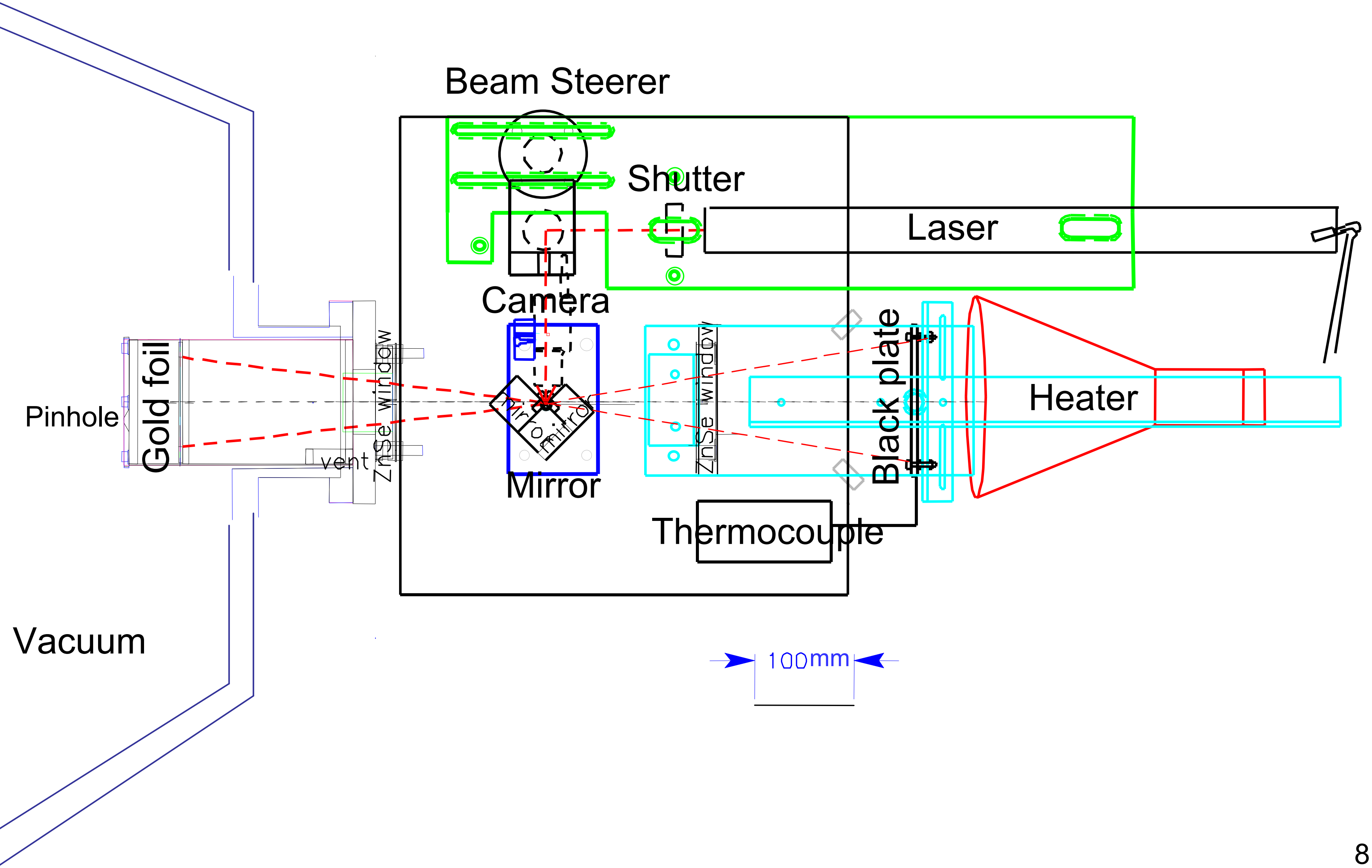
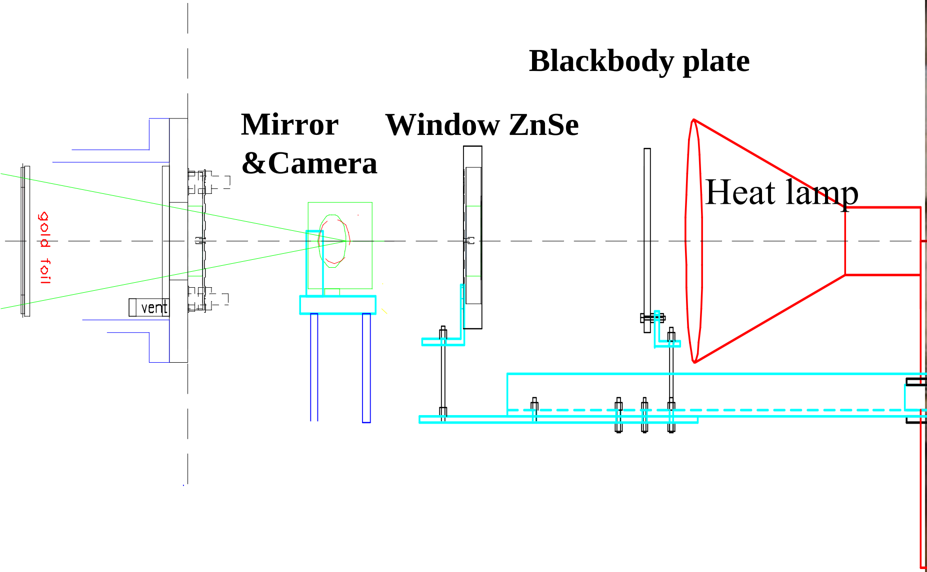
1)B.J. Peterson, N.Ashikawa, et al., IEEE Trans. Plasma Sci. **30** (2002) 52-53.

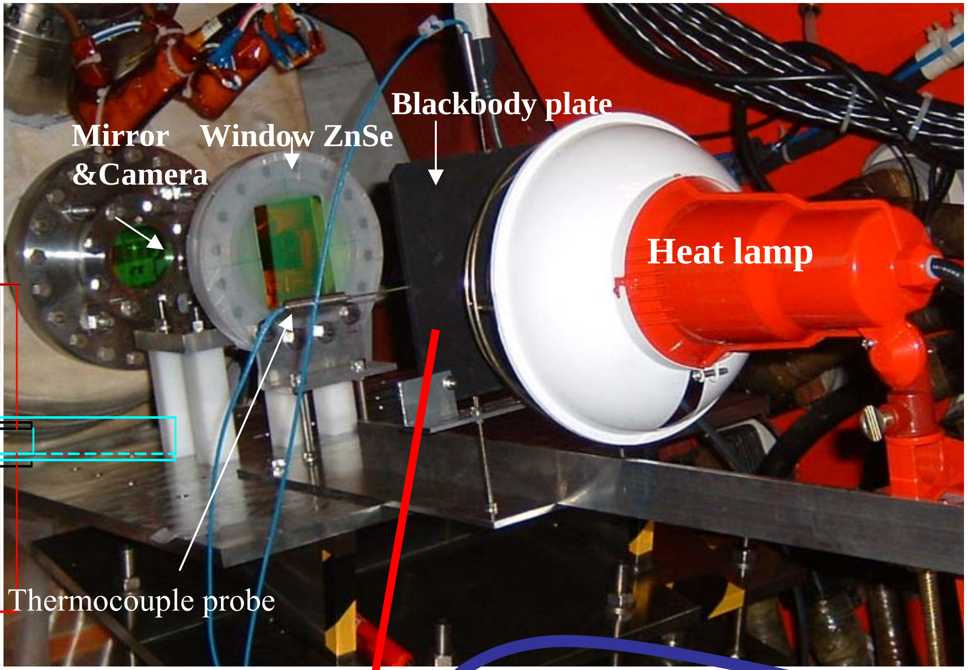
Infrared Imaging Video Bolometer Calibration setup for JT-60U



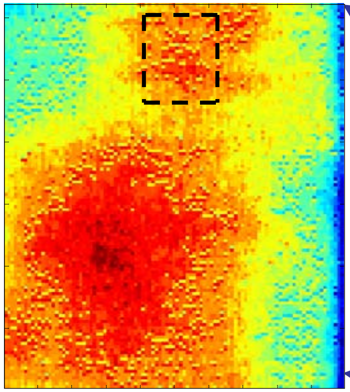
IR Camera Calibration

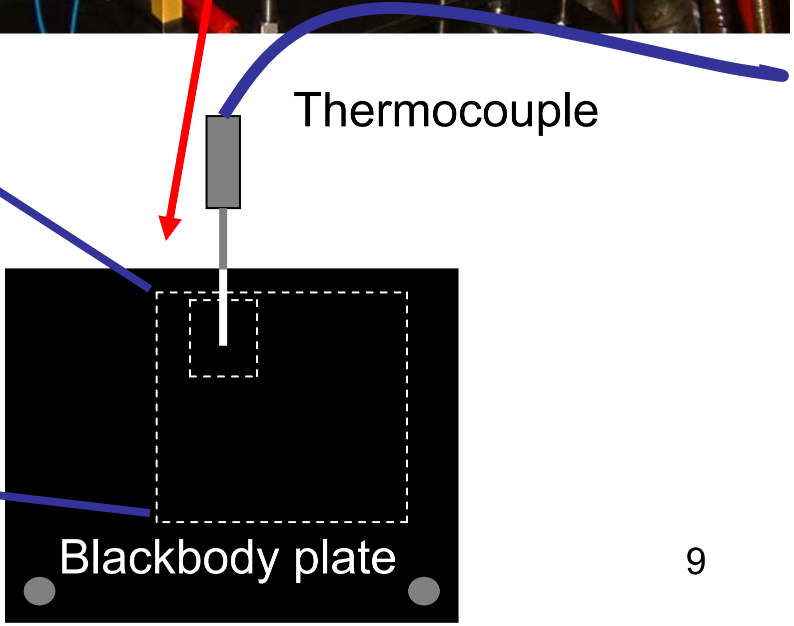
IR Camera calibration setup on JT-60U





FOV by IR camera





The black plate is heated up to a temperature of ~170 °C when the room temperature was 21.5 °C , then the lamp is turned off.

To find the calibration coefficients of IR camera

a = 6.86204e-008 ±1.19794e-010

b = 8152.25 ±2.62839

ΔT ±0.1

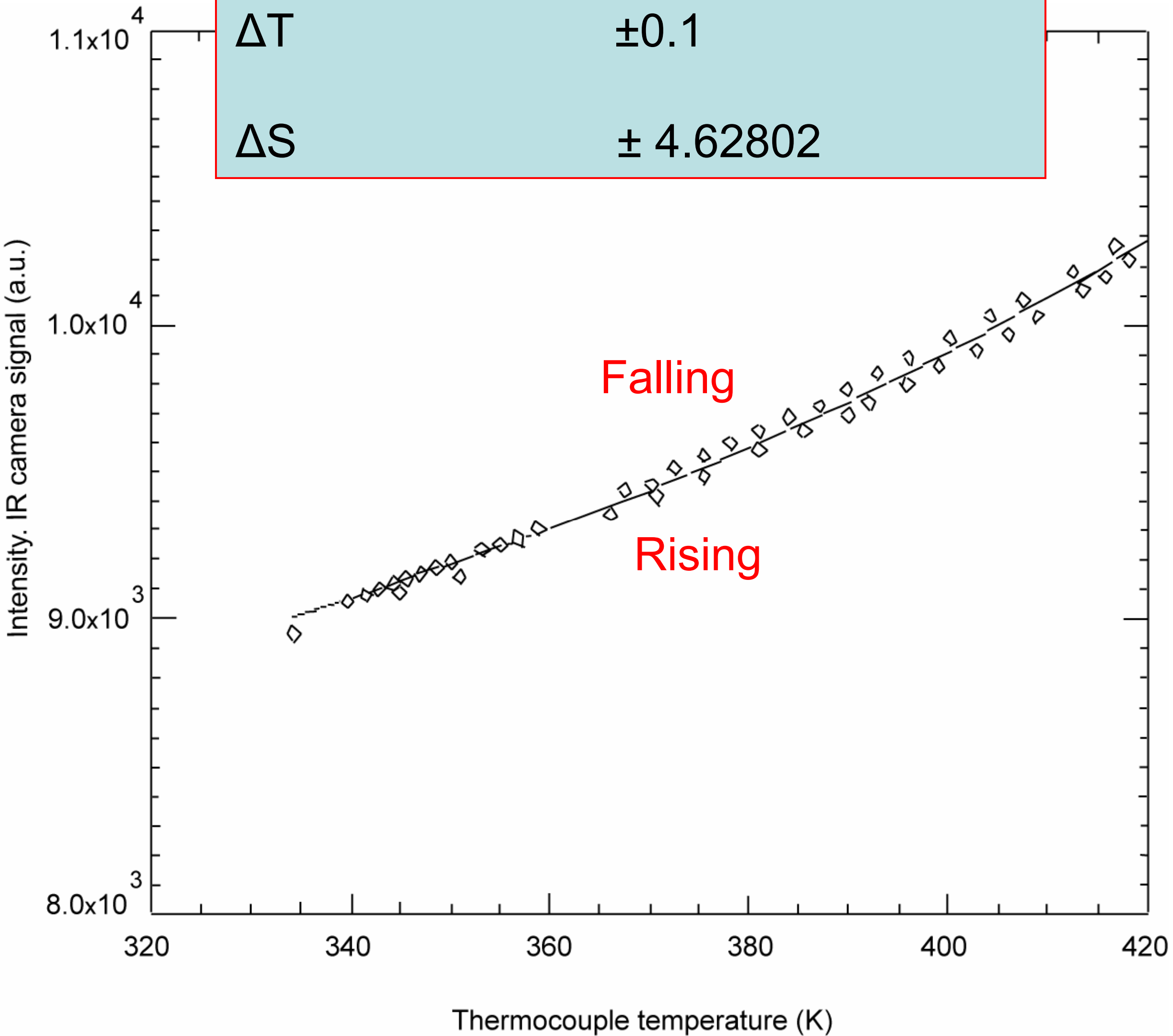
ΔS ± 4.62802

Stefan-Boltzman law

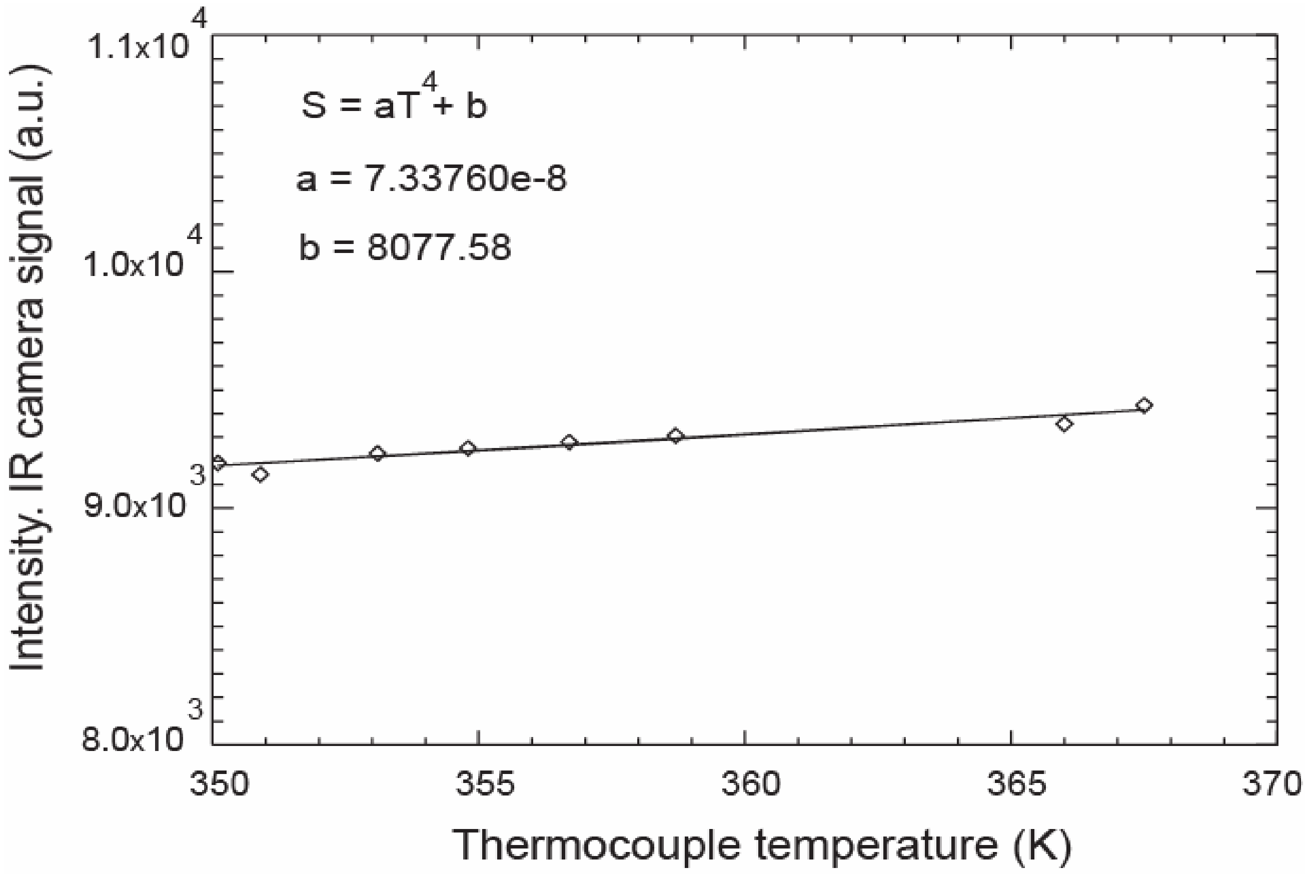
$$S = aT^4 + b$$

Method: By fitting camera signal level, *S*, and thermocouple data, *T*, to Stefan-Boltzmann law, determine calibration coefficients *a* and *b*.

The foil temperature is obtained by applying *a* and *b* as coefficients to the IR camera data.

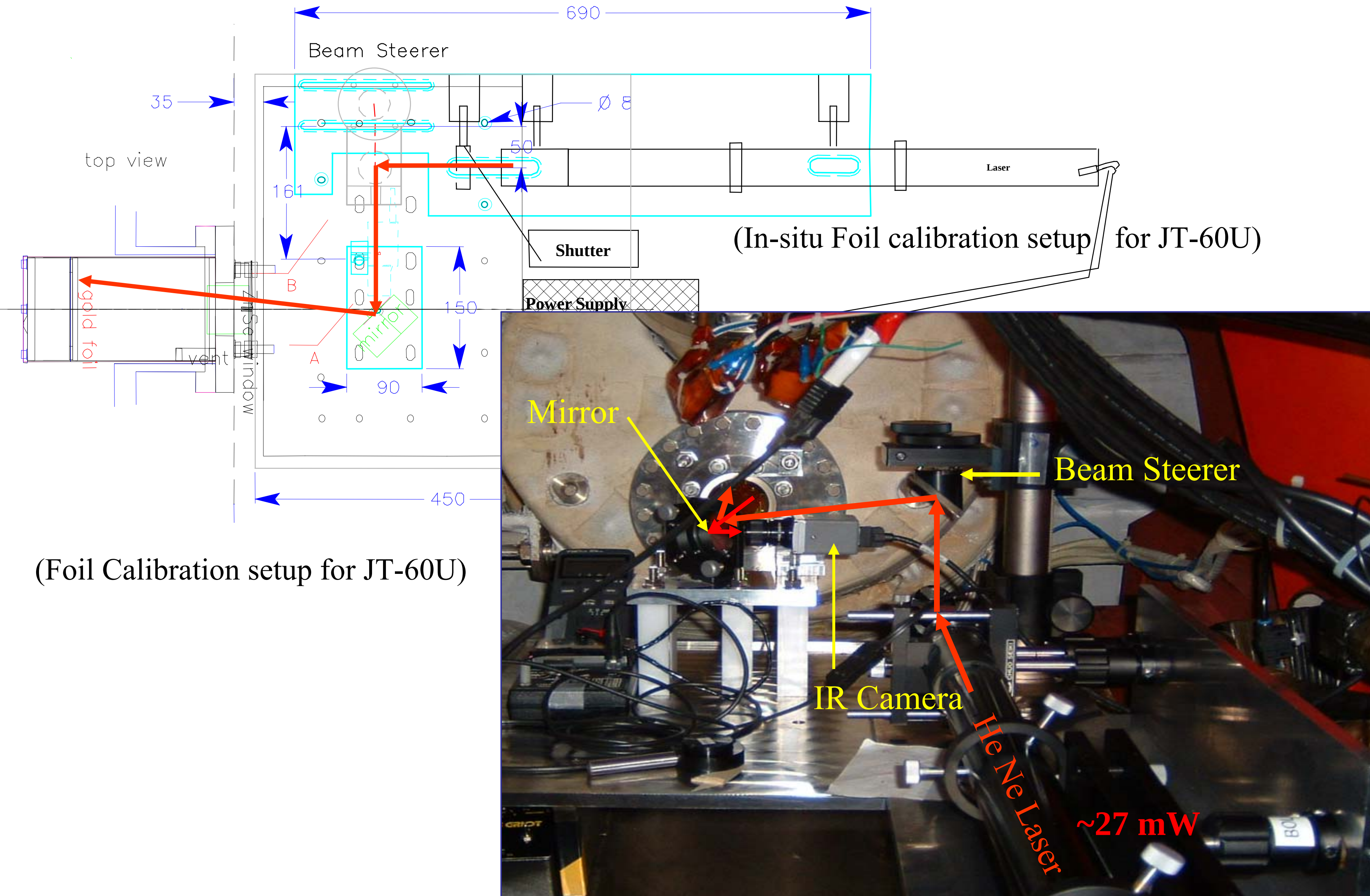


To find the calibration coefficients of IR camera (350-370 K)



The IR camera calibration coefficients *a* and *b* had a negligible temperature dependence in the range of temperature used in the measurement on the JT-60U in the previous investigation. The calibration factors are corrected to a = 7.34e-8 W/K^4 and b = 8077.58 in the range of experiment temperatures (350-370 K).

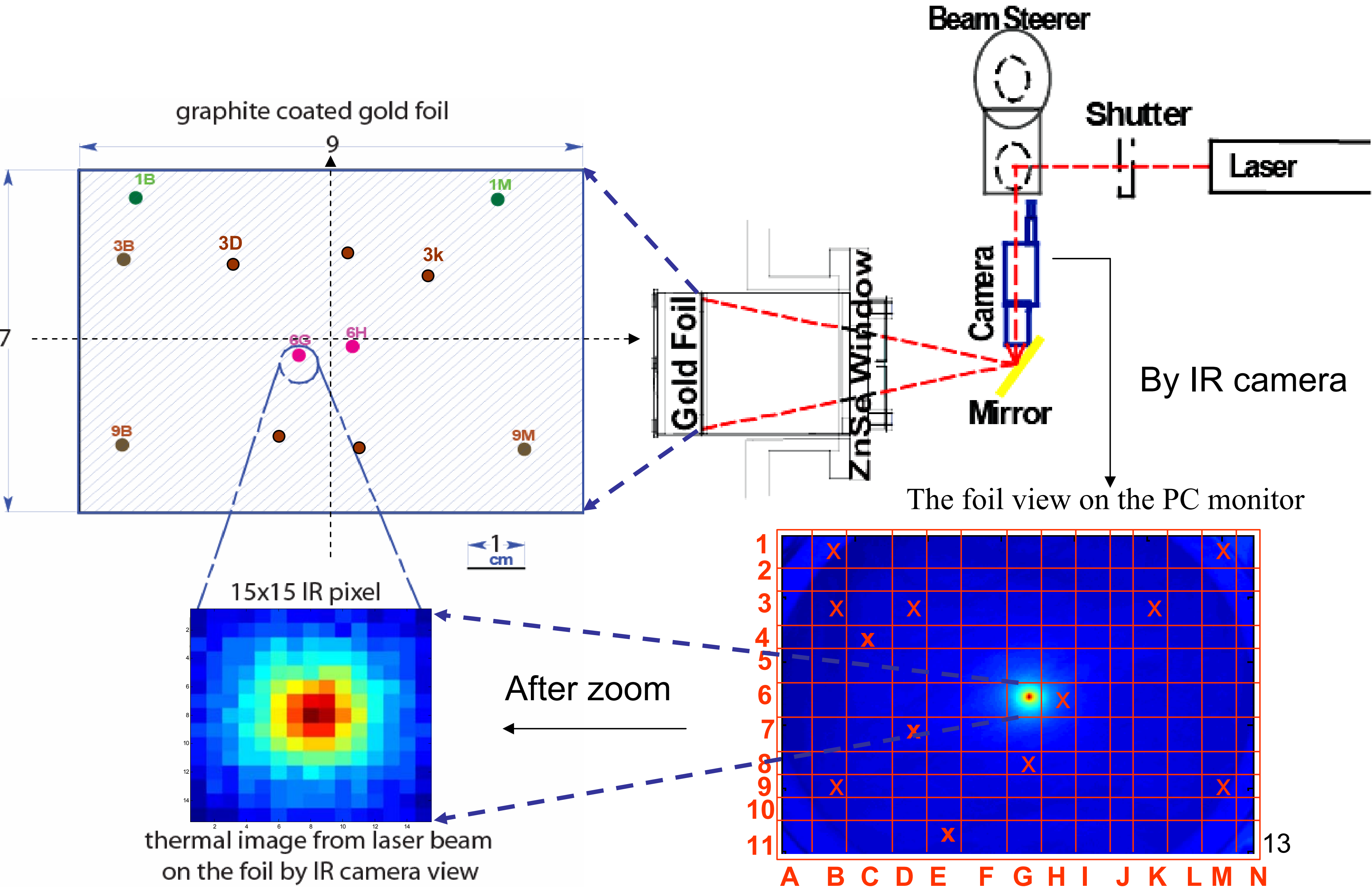
In-situ laser calibration setup of the foil



(In-situ Foil calibration setup for JT-60U)

(Foil Calibration setup for JT-60U)

In situ laser calibration of the single graphite-coated gold foil (IRVB of JT-60U) on difference position



By IR camera

The foil view on the PC monitor

After zoom

thermal image from laser beam on the foil by IR camera view

IR Imaging video Bolometer (analysis method)

- The incident radiation power distribution on the foil can be determined numerically by solving the two-dimensional heat diffusion equation.

$$\nabla \cdot (\nabla T) = \frac{1}{\kappa}\frac{\partial T}{\partial t} + \Omega_{bb} - \Omega_{rad}$$

Black body radiation from the foil

the incident radiation power to the foil

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\kappa}\frac{\partial T}{\partial t} + \Omega_{bb} - \Omega_{rad}$$

Parameters to be determined locally on the foil through calibration experiments

temperature on the foil

foil thermal diffusivity

Detected radiation power by solving heat diffusion equation

Blackbody thermal emissivity

$$\Omega_{bb} = \frac{\varepsilon \sigma_{S-B}(T^4 - T_0^4)}{k \cdot t_f}$$

$$\Omega_{rad} = \frac{P_{rad}}{k \cdot t_f \cdot l^2}$$

Bolometer pixel area

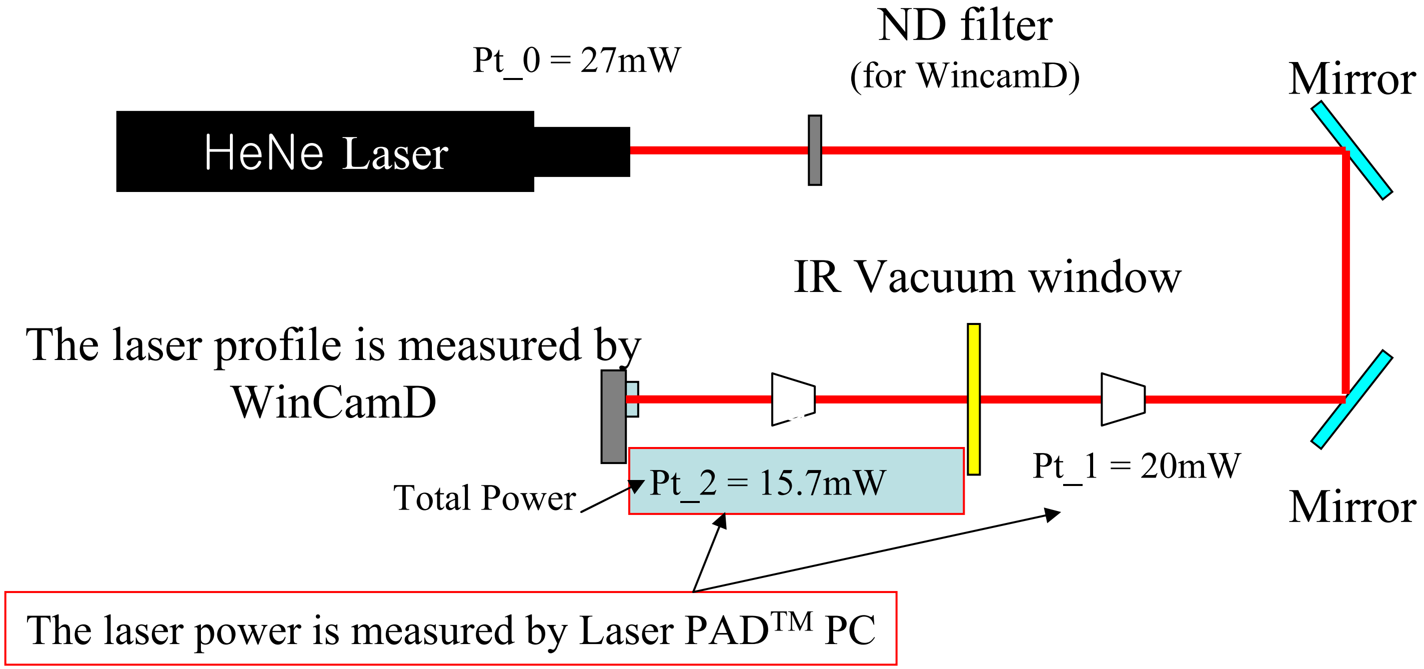
Foil thermal conductivity

Foil thickness

B.J.Peterson, N.Ashikawa, et.al., Rev. Sci. Instrum. 74 (2003)2040

The laser transmission power

The He-Ne laser (~27 mW) as a known radiation source to heat the foil



Pt_0 = 27mW

ND filter
(for WincamD)

Mirror

HeNe Laser

IR Vacuum window

The laser profile is measured by WinCamD

Total Power

Pt_2 = 15.7mW

Pt_1 = 20mW

Mirror

The laser power is measured by Laser PAD™ PC

Window's transmittance
(T) = Pt_2 / Pt_1

The laser transmission power to foil decreased after passing through the IR windows.
The laser power arriving at the foil is 58%.
42% remaining is absorbed and reflected by the ZnSe window and mirrors

Laser PAD^{TM} PC Description

The Laser PAD^{TM} (Power Analysis Display) application package is designed to be a complete menu driven power measurement system for use with a Pocket PC handheld PDA to provide optimum data processing, results display and data file storage.

Cross calibration handheld laser power meter with computer power meter

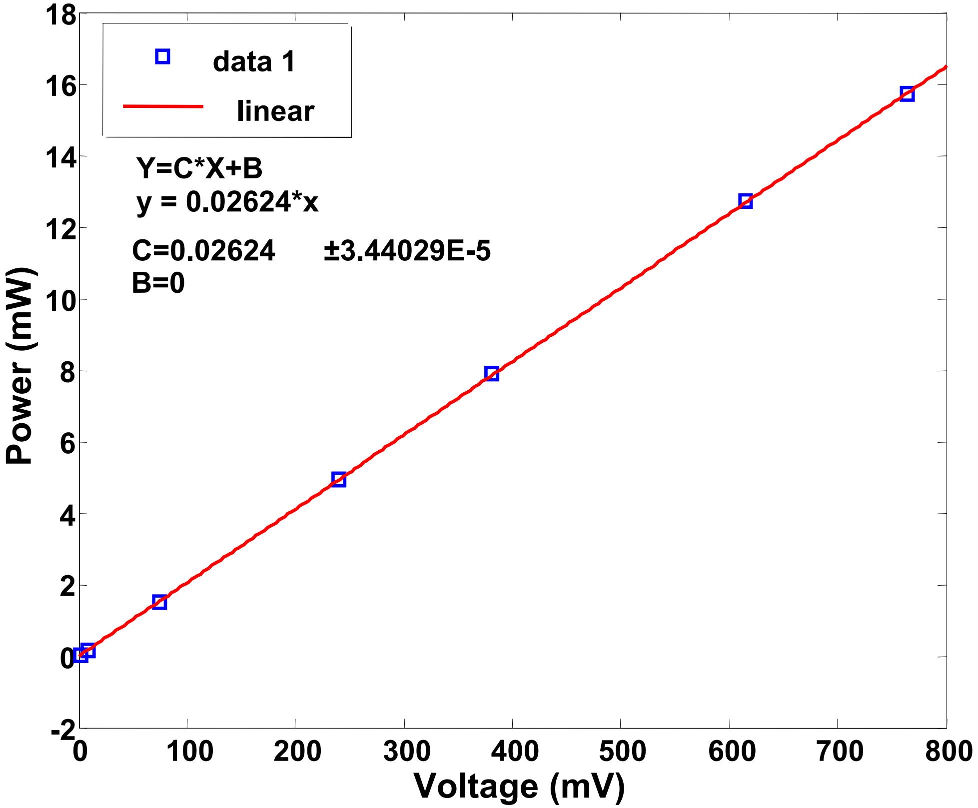
$$P_{laser} = TcV_{JT-60U}$$

P_{laser} is power of laser on the foil by cross calibration to handheld power meter

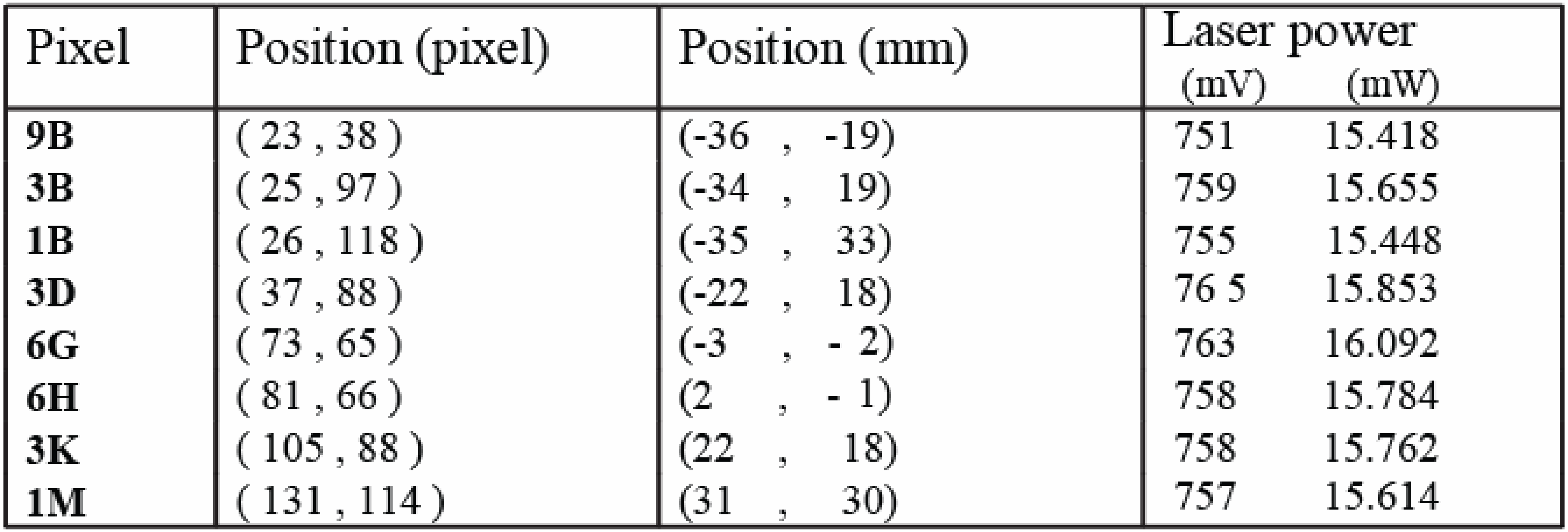
T is measured by comparing the power before and after the window

C is conversion factor of the laser power that measured by Laser PAD^{TM} PC to that the voltage of the handheld power meter

$V_{JT\text{-}60U}$ is voltage output of the handheld laser power meter that is measured by voltmeter



The laser transmission power (~27 mW) on various positions of the foil



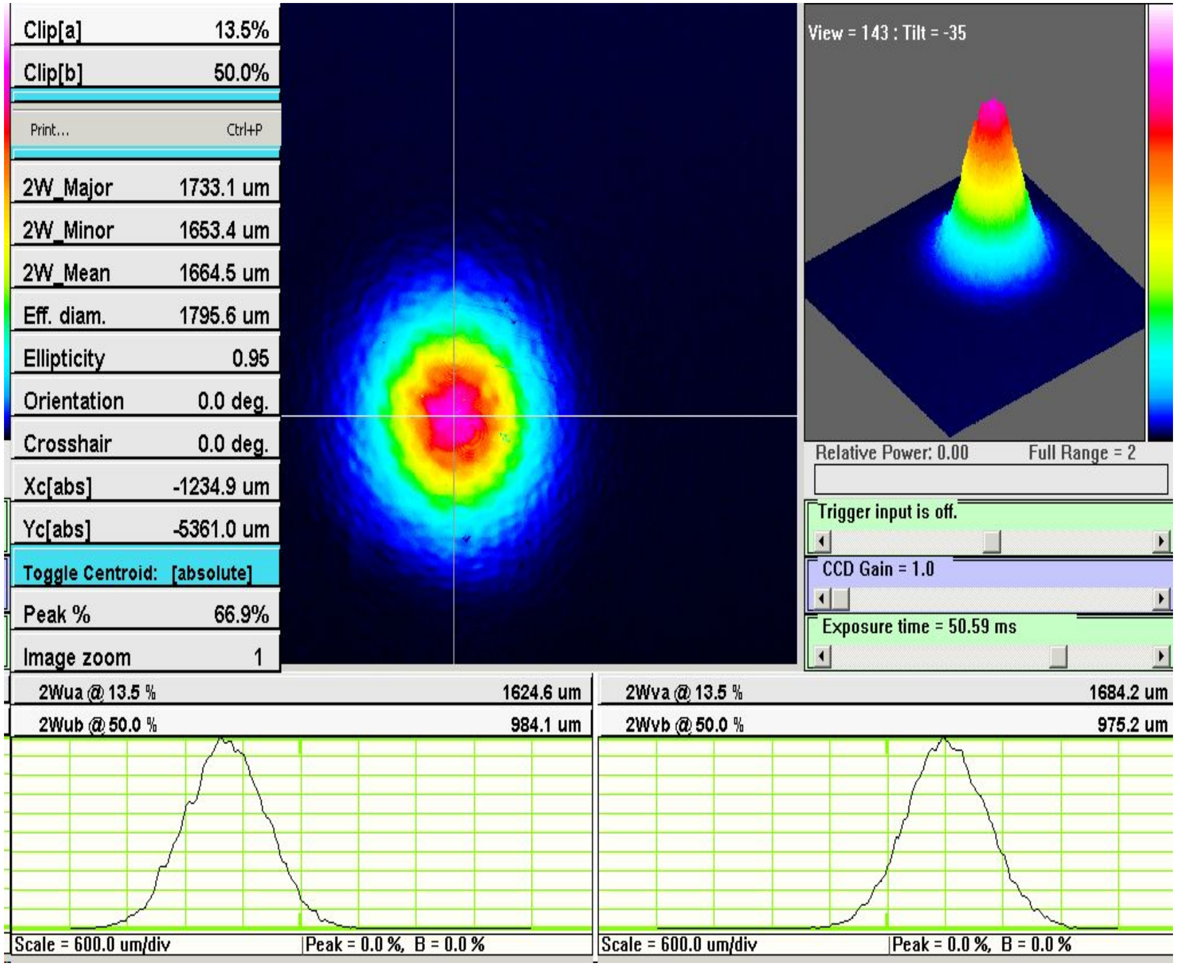
Pixel	Position (pixel)	Position (mm)	Laser power	
			(mV)	(mW)
9B	(23 , 38)	(-36 , -19)	751	15.418
3B	(25 , 97)	(-34 , 19)	759	15.655
1B	(26 , 118)	(-35 , 33)	755	15.448
3D	(37 , 88)	(-22 , 18)	76 5	15.853
6G	(73 , 65)	(-3 , - 2)	763	16.092
6H	(81 , 66)	(2 , - 1)	758	15.784
3K	(105 , 88)	(22 , 18)	758	15.762
1M	(131 , 114)	(31 , 30)	757	15.614

The laser power decreased after passing through the IR windows. The handheld laser power meter is calibrated using LASERPAD^{TM} PC. The experimental configuration details for eight points on the foil are shown in above table.

WinCamD Description

7.5 mm Chip surface-Default

WinCamD is used a high resolution progressive scan CCD chip with 1369 (H) × 1024(V) 4.65 µm square active pixels. The chip is driven by an 8 MPixel/s readout clock (16 MHz master clock).



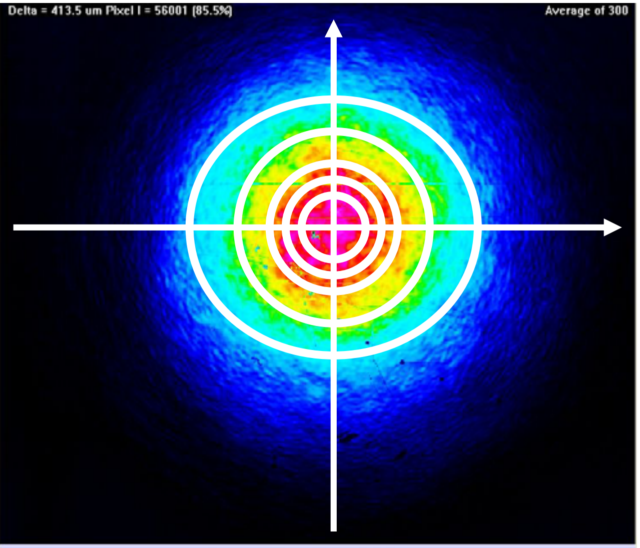
Clip[a] 13.5%
Clip[b] 50.0%
2W_Major 1733.1 um
2W_Minor 1653.4 um
2W_Mean 1664.5 um
Eff. diam. 1795.6 um
Ellipticity 0.95
Orientation 0.0 deg.
Crosshair 0.0 deg.
Xc[abs] -1234.9 um
Yc[abs] -5361.0 um
Toggle Centroid: [absolute]
Peak % 66.9%
Image zoom 1

View = 143 : Tilt = -35
Relative Power: 0.00 Full Range = 2
Trigger input is off.
CCD Gain = 1.0
Exposure time = 50.59 ms

2Wua @ 13.5 % 1624.6 um
2Wub @ 50.0 % 984.1 um
Scale = 600.0 um/div Peak = 0.0 %, B = 0.0 %

2Wva @ 13.5 % 1684.2 um
2Wvb @ 50.0 % 975.2 um
Scale = 600.0 um/div Peak = 0.0 %, B = 0.0 %

Measure laser beam profile and fit laser power profile to 2-DGaussian with two parameters



Irradiance (Power Density)

$$I_0 = (2 \times P)/(\pi \times w^2) = 2.55P/(2w)^2$$

$$r^2 = x^2 + y^2$$

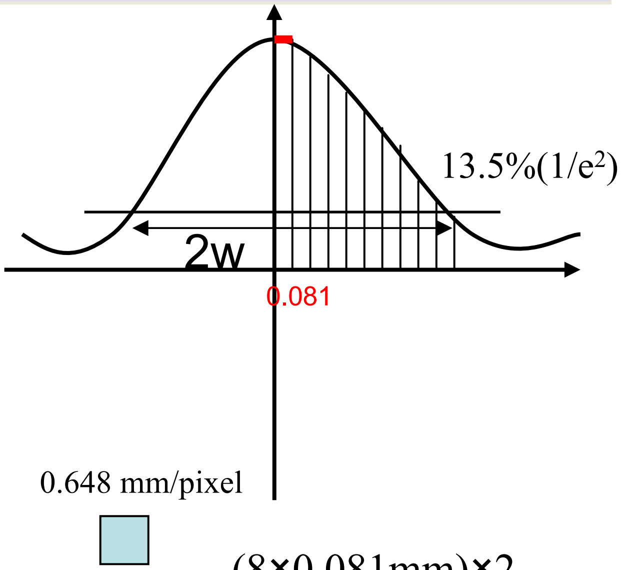
P : total beam power
w : the radius at the point at which the intensity has fallen to 13.5%(1/e²) of the peak value for Gaussian beam

$$I(r) = I_0 e^{-2r^2/w^2} = \frac{2P}{\pi w^2} e^{-2r^2/w^2}$$

(Ref: WinCamD User Manual 5-1, Appendix)

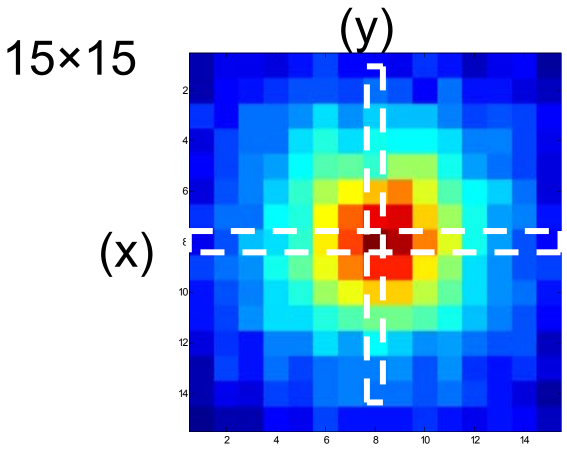
Measured Value(mV)	coefficient	transmittance	Total Power(mW)
751	0.02624	0.78403	15.45

Pattern 1			∠ =3mm	Average	
Area No	Radius(IN)mm	Radius(OUT)mm	Area (mm2)	W/mm2	Watts
1	0	0.081	0.020611989	0.00591284	0.000121875
2	0.081	0.162	0.061835968	0.00581849	0.000359792
3	0.162	0.243	0.103059947	0.00563469	0.000580711
4	0.243	0.324	0.144283926	0.00537389	0.000775366
5	0.324	0.405	0.185507905	5.04E-03	0.000935854
6	0.405	0.486	0.226731883	4.66E-03	0.001056949
7	0.486	0.567	0.267955862	4.24E-03	0.001136162
8	0.567	0.648	0.309179841	3.80E-03	0.001173718
9	0.648	0.81	0.742031618	3.12E-03	0.00231801
10	0.81	0.972	0.906927534	2.28E-03	0.002068194
11	0.972	1.134	1.071823449	1.56E-03	0.001675453
12	1.134	1.296	1.236719364	1.01E-03	0.001244325
13	1.296	1.62	2.968126474	4.77E-04	0.001414689
14	1.62	1.944	3.627710134	1.38E-04	0.00050053
15	1.944	2.268	4.287293795	3.12E-05	0.000133589
16	2.268	2.592	4.946877456	5.49E-06	2.7153E-05
17	2.592	3.24	11.87250589	4.17E-07	4.95633E-06
18	3.24	3.888	14.51084054	3.59E-09	5.21287E-08
19	3.888	4.536	17.14917518	1.16E-11	1.98464E-10
20	4.536	5.184	19.78750982	1.39E-14	2.74289E-13
					0.015527379



(8×0.081mm)×2

Fitting 2-D Gaussian to temperature profile with four parameters



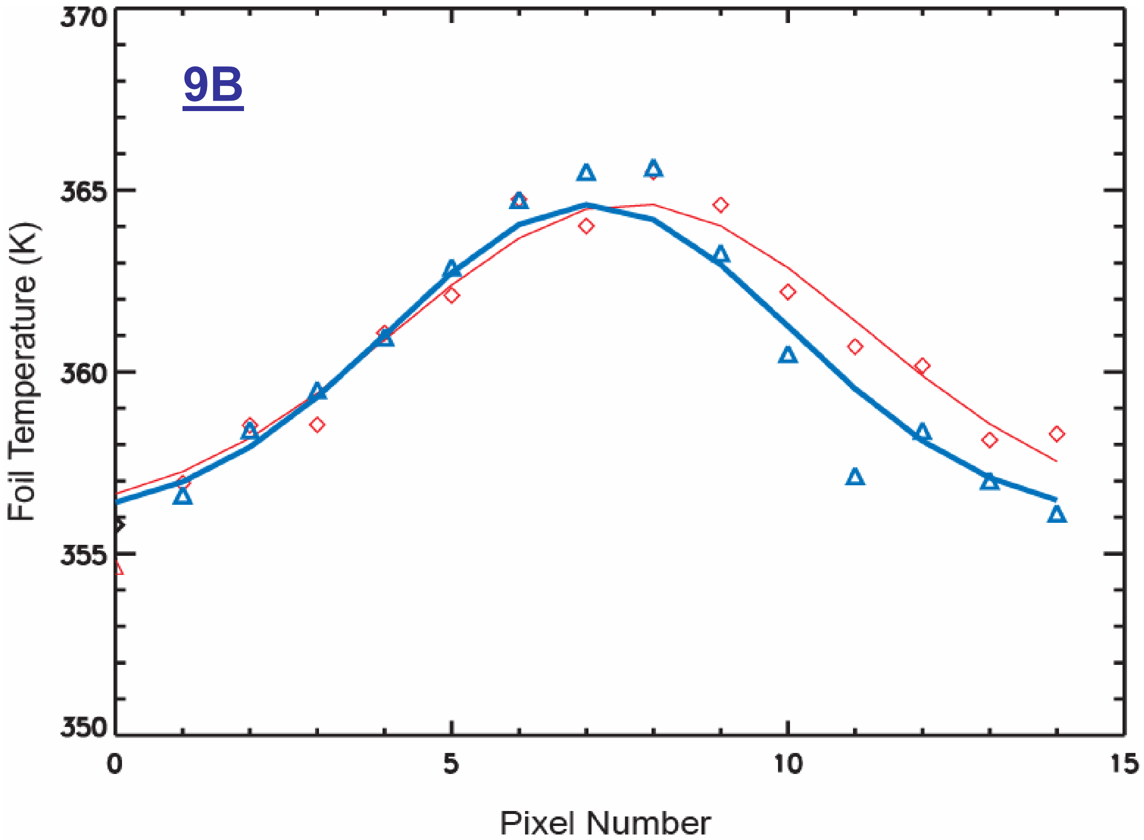
Thin line & diamonds symbol (y direction) and Thick line & triangle horizontal symbol (x direction) is found by using IDL program when the temperature profile of IR camera data fit with 2-D Gaussian

A_0=355.888 K
A_1=8.75258 K
A_2=2.97735 pixels
A_3=3.46312 pixels
A_4=7.07093 pixels
A_5=7.67089 pixels

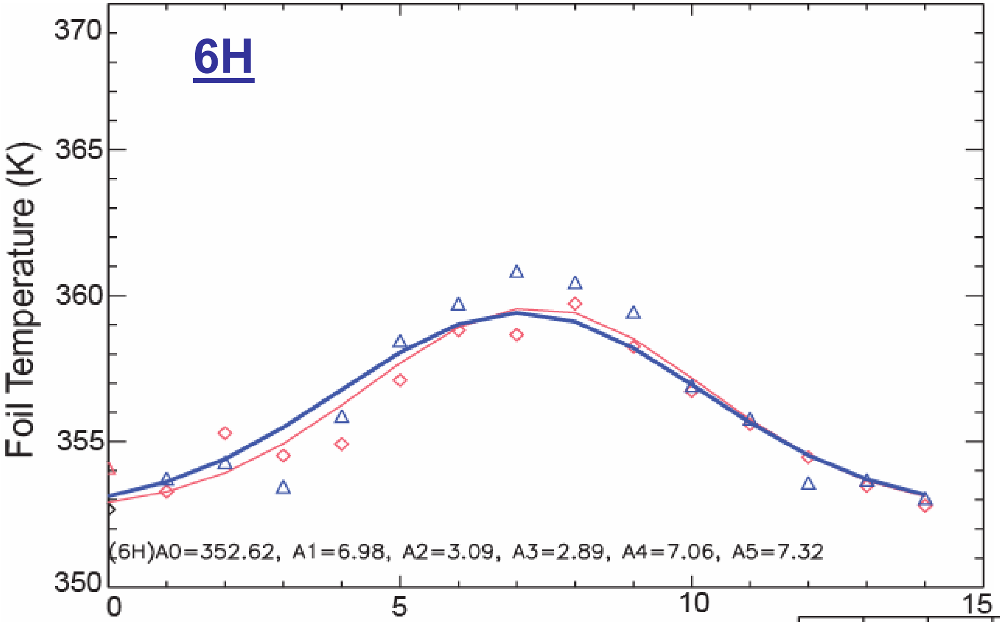
The calibration coefficient is found by fitting experimental data to 2-D Gaussian

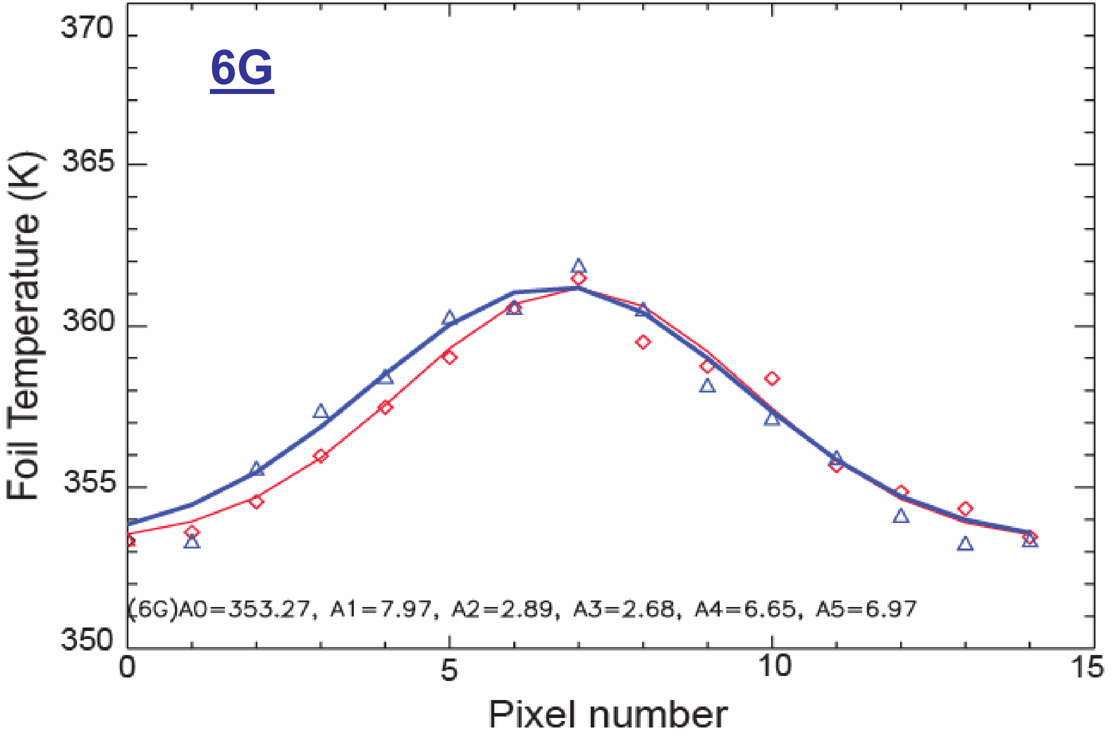
$$S = A_0 + A_1 e^{-\frac{1}{2}\left(\left(\frac{x-A_4}{A_2}\right)^2+\left(\frac{y-A_5}{A_3}\right)^2\right)}$$

- Average steady state data over 200 frames
- The foil temperature is obtained by applying a and b as coefficient of Stefan-Boltzman to the IR camera data

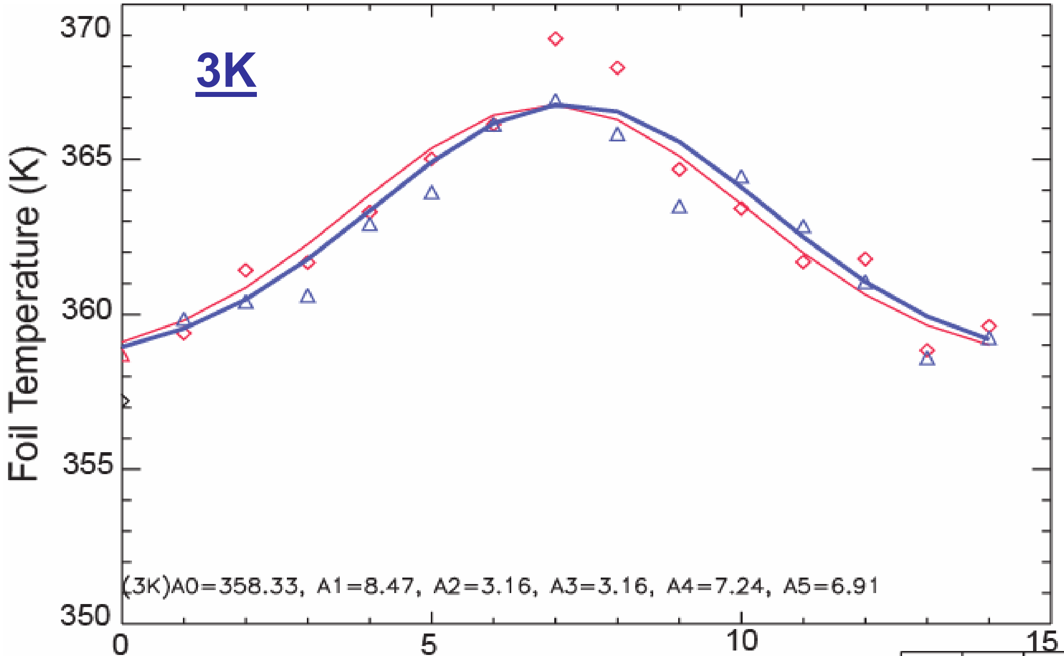


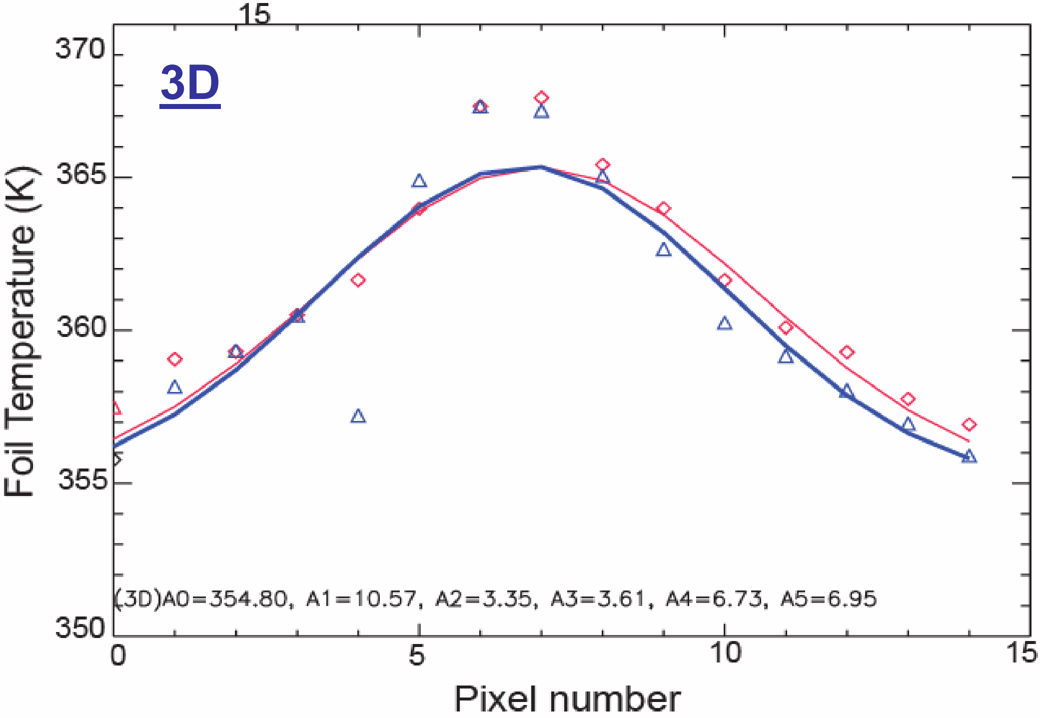
Some sample of fitting 2-D Gaussian to temperature profile due to local heating by laser



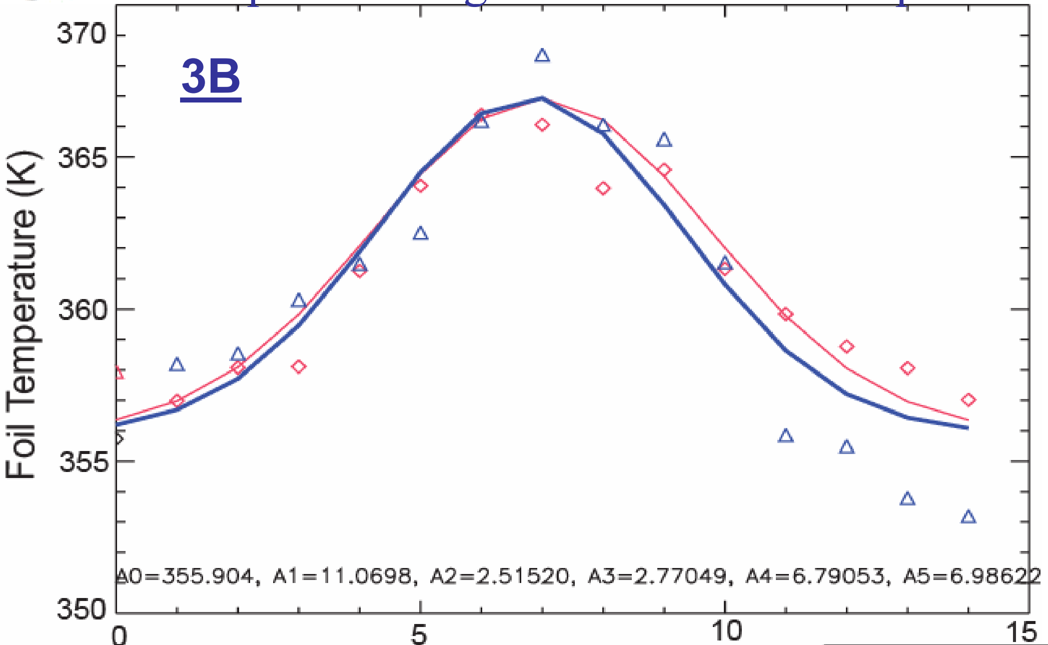


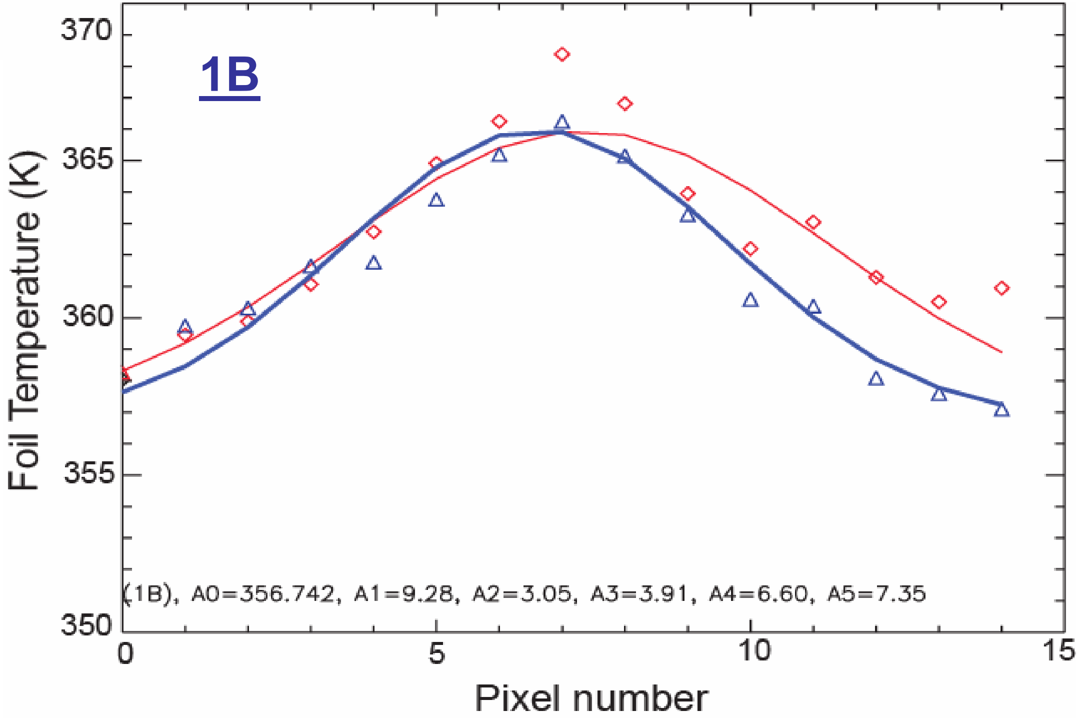
Some sample of fitting 2-D Gaussian to temperature profile due to local heating by laser



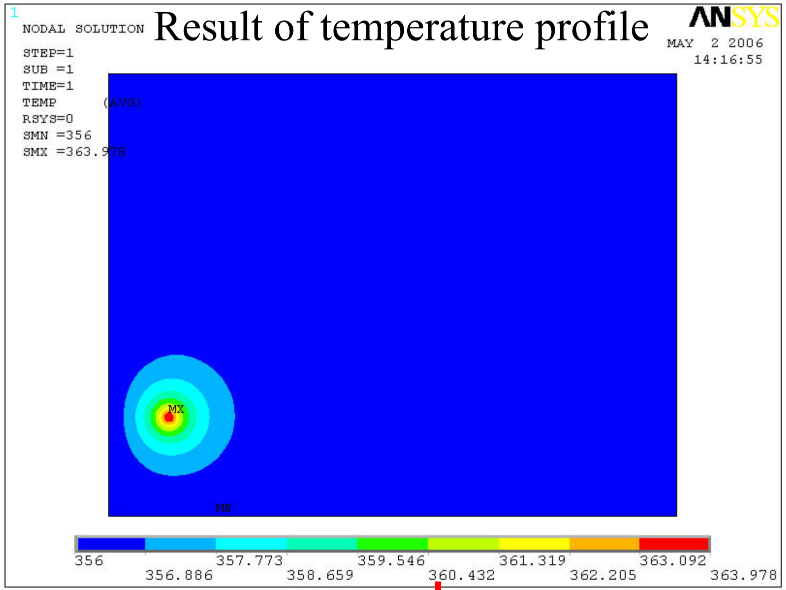


Some sample of fitting 2-D Gaussian to temperature profile due to local heating by laser



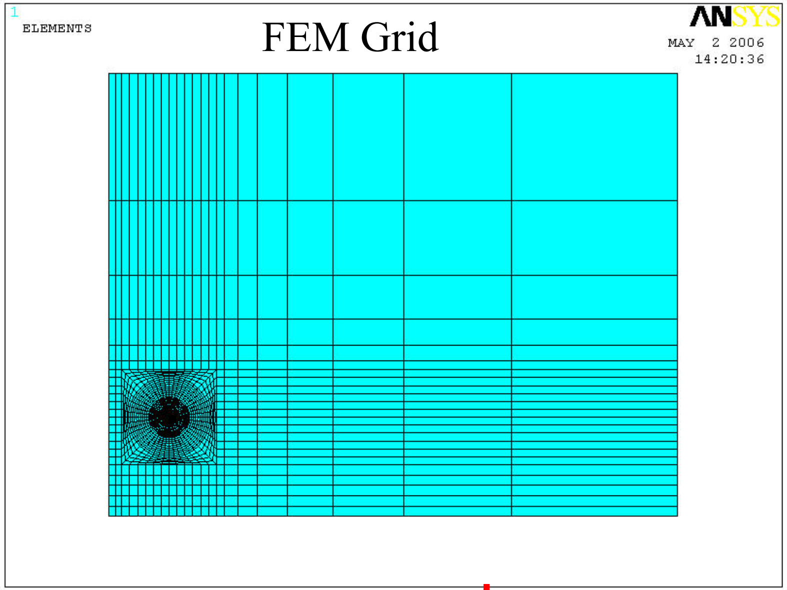


Finite Element Model



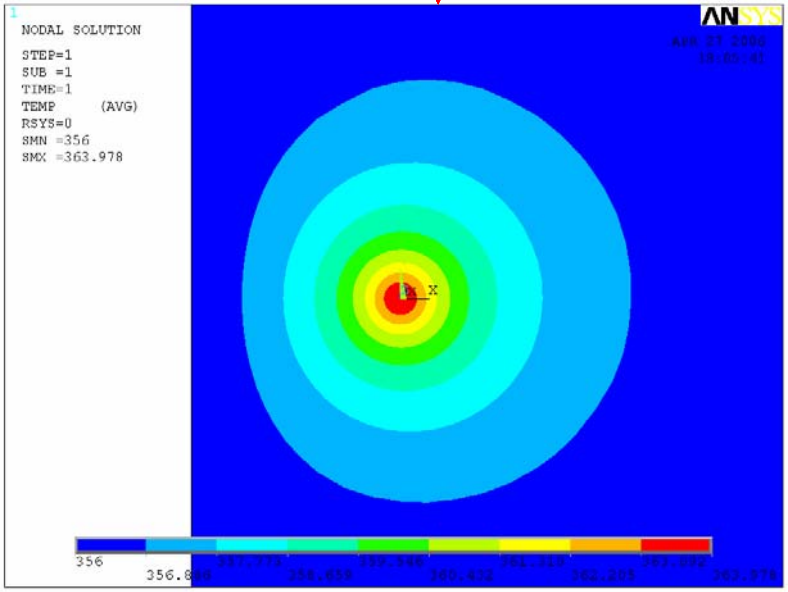
Result of temperature profile

```
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP       (AVG)
RSYS=0
SMN =356
SMX =363.978
```



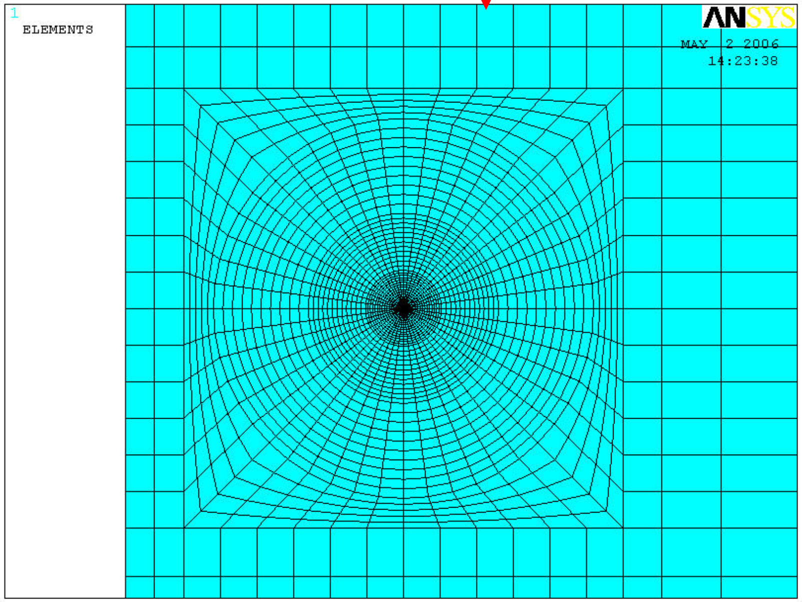
FEM Grid

Focused on the beam area



```
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP       (AVG)
RSYS=0
SMN =356
SMX =363.978
```

Focused on the beam area



Calculate of thermal conductivity and foil thickness (kt_f)

Method: By comparing temperature profile from steady state laser having known (measured) profile with that of FEM we can determine local value of product of thermal conductivity and foil thickness

For steady state

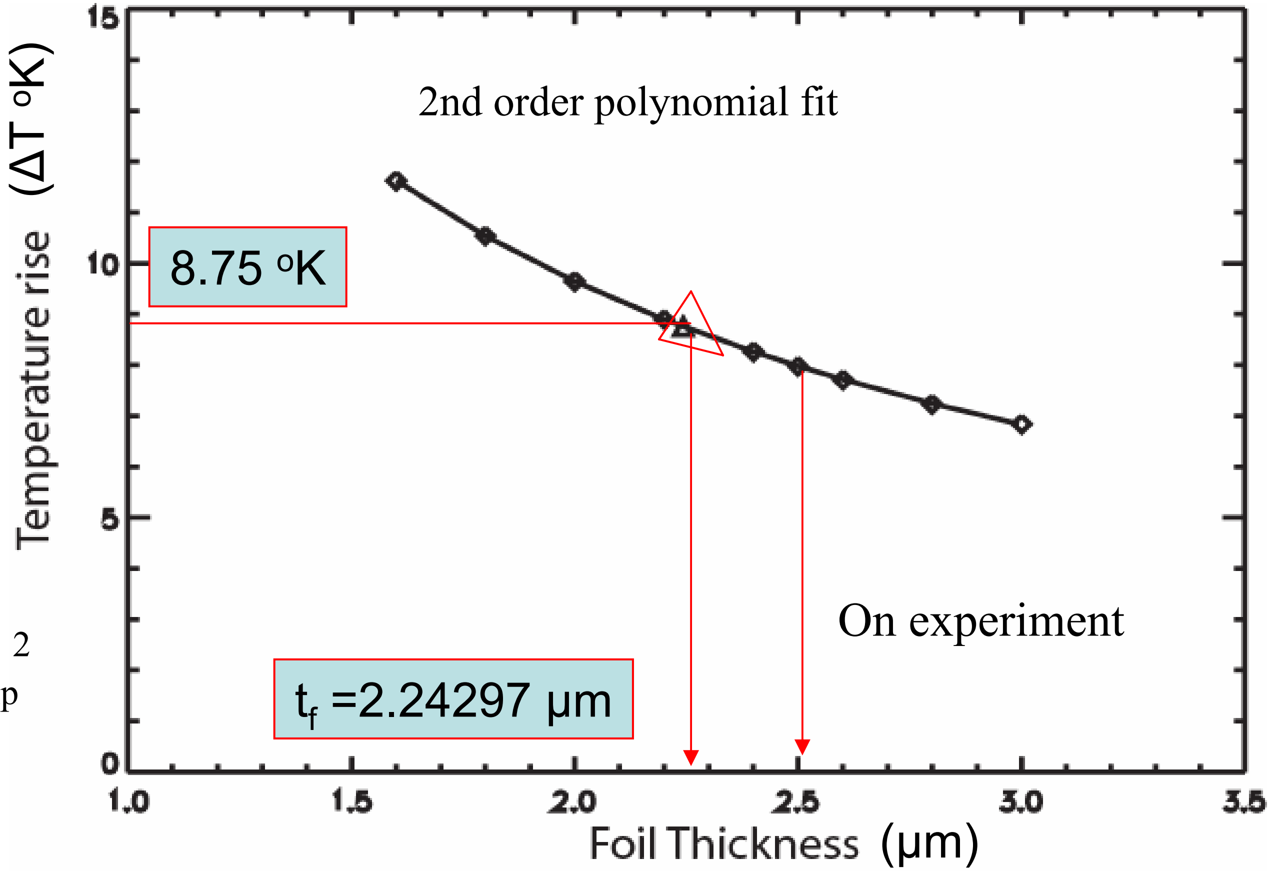
$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=\cancelto{0}{\frac{1}{\kappa}\frac{\partial T}{\partial t}}+\Omega_{bb}-\Omega_{rad}$$

$$\Omega_{bb}=\frac{\varepsilon\sigma_{S-B}(T^4-T_0^4)}{k\cdot t_f}$$

$$\Omega_{rad}=\frac{S_{laser}}{k\cdot t_f}$$

$$\frac{1}{t_f}=A_0+A_1\Delta T+A_2\Delta T^2$$

$$\frac{1}{t_{f\exp}}=A_0+A_1\Delta T_{\exp}+A_2\Delta T_{\exp}{}^2$$



2nd order polynomial fit

$8.75\ {}^{o}K$

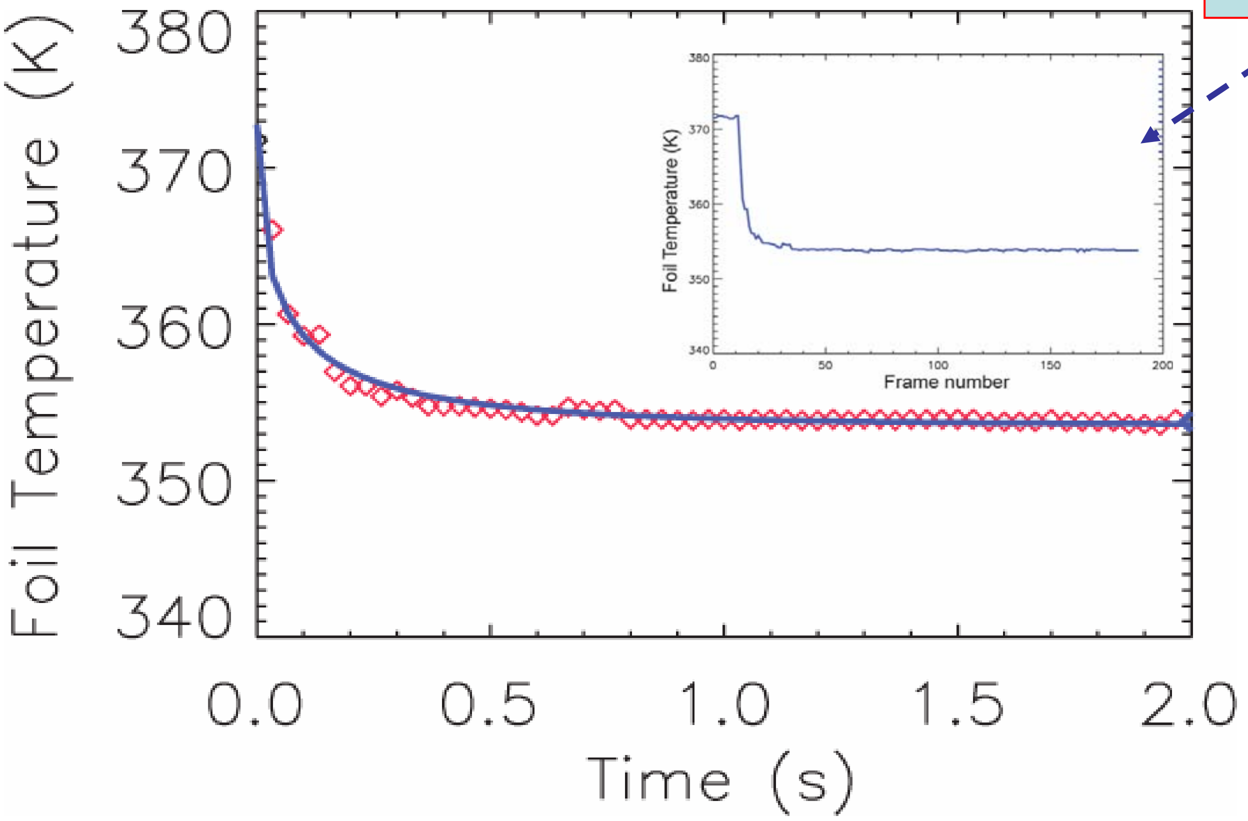
On experiment

$t_f = 2.24297\ \mu m$

Find decay time

$$T = \Delta T\left(e^{-\sqrt{t}/\tau}\right) + T_0$$

the IR thermal data are averaged to get the decay data over 200 time frames



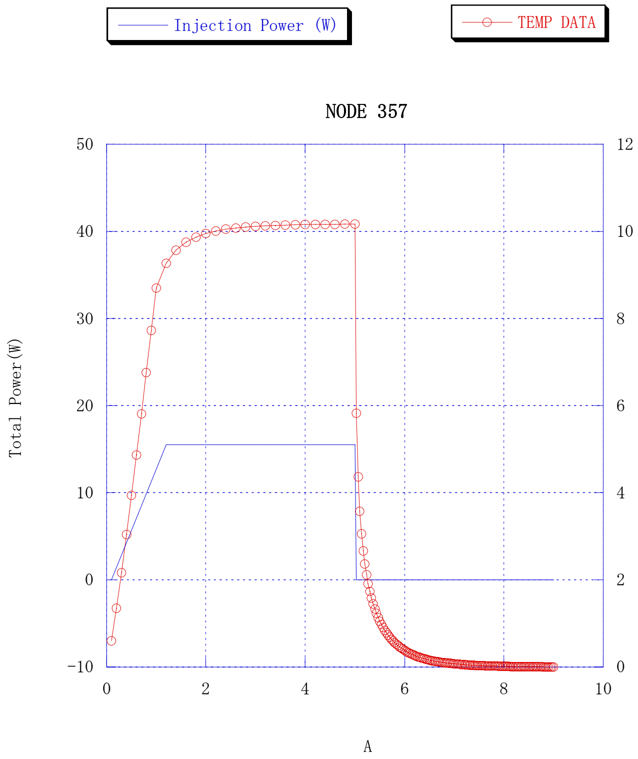
Example: 3D point

ΔT=6.5 ^{o}K

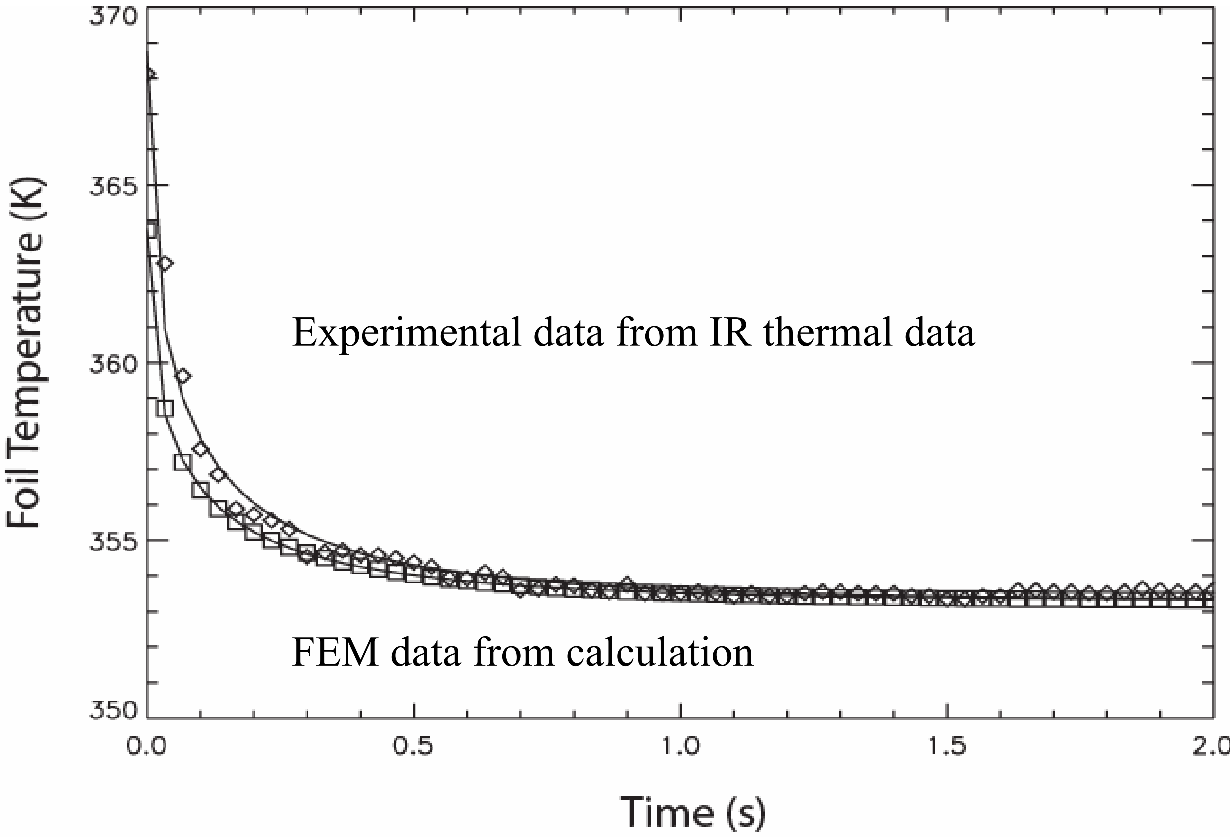
τ =0.38 S

T_0 =353.5 ^{o}K

Finite Element Model Results decay fit to the experimental data decay

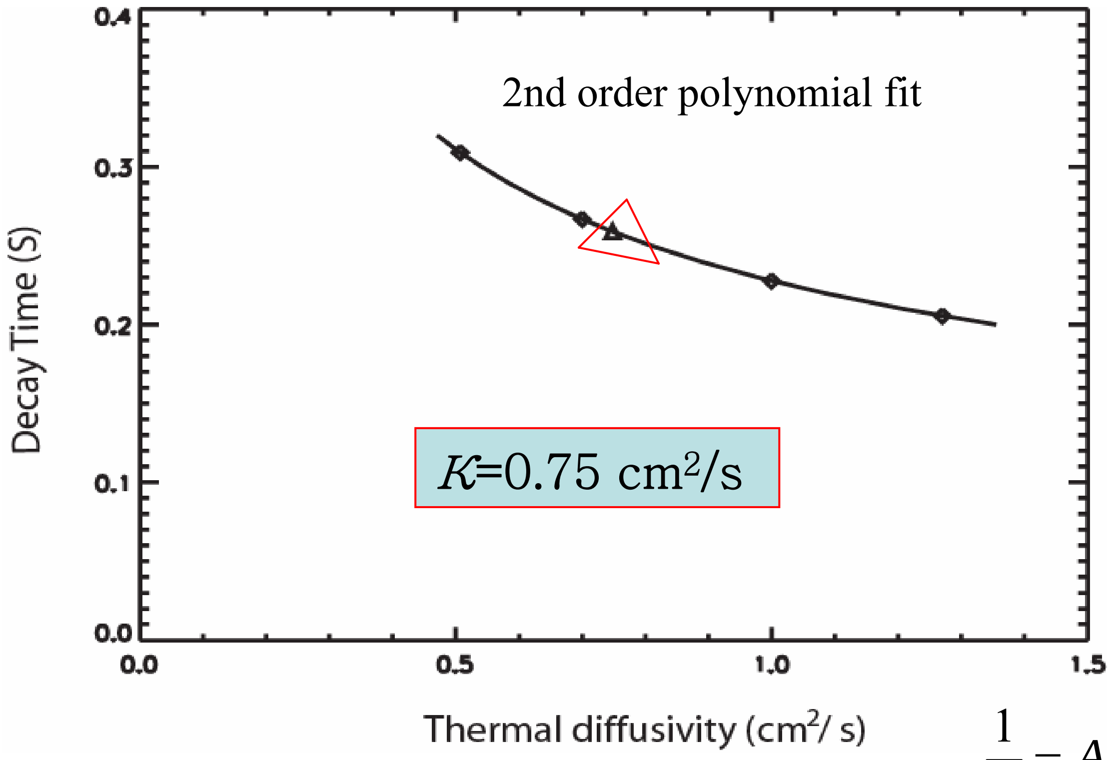


Experimental data fit to FEM data



the experimental foil temperature data during the decay to the modified exponential equation, fitting the FEM calculation numerical data decay of the foil temperature

Calibration to determine local thermal diffusivity κ



2nd order polynomial fit

$\kappa = 0.75$ cm²/s

$$\frac{1}{\kappa} = A_0 + A_1 \Delta T + A_2 \Delta T^2$$

$$\frac{1}{\kappa_{\exp}} = A_0 + A_1 \Delta T_{\exp} + A_2 \Delta T_{\exp}^2$$

For decay time

$$\boxed{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\kappa}\frac{\partial T}{\partial t} + \Omega_{bb} - \cancelto{0}{\Omega_{rad}}}$$

$$\boxed{\Omega_{bb} = \frac{\varepsilon \sigma_{S-B}(T^4 - T_0^4)}{k.th_f}}$$

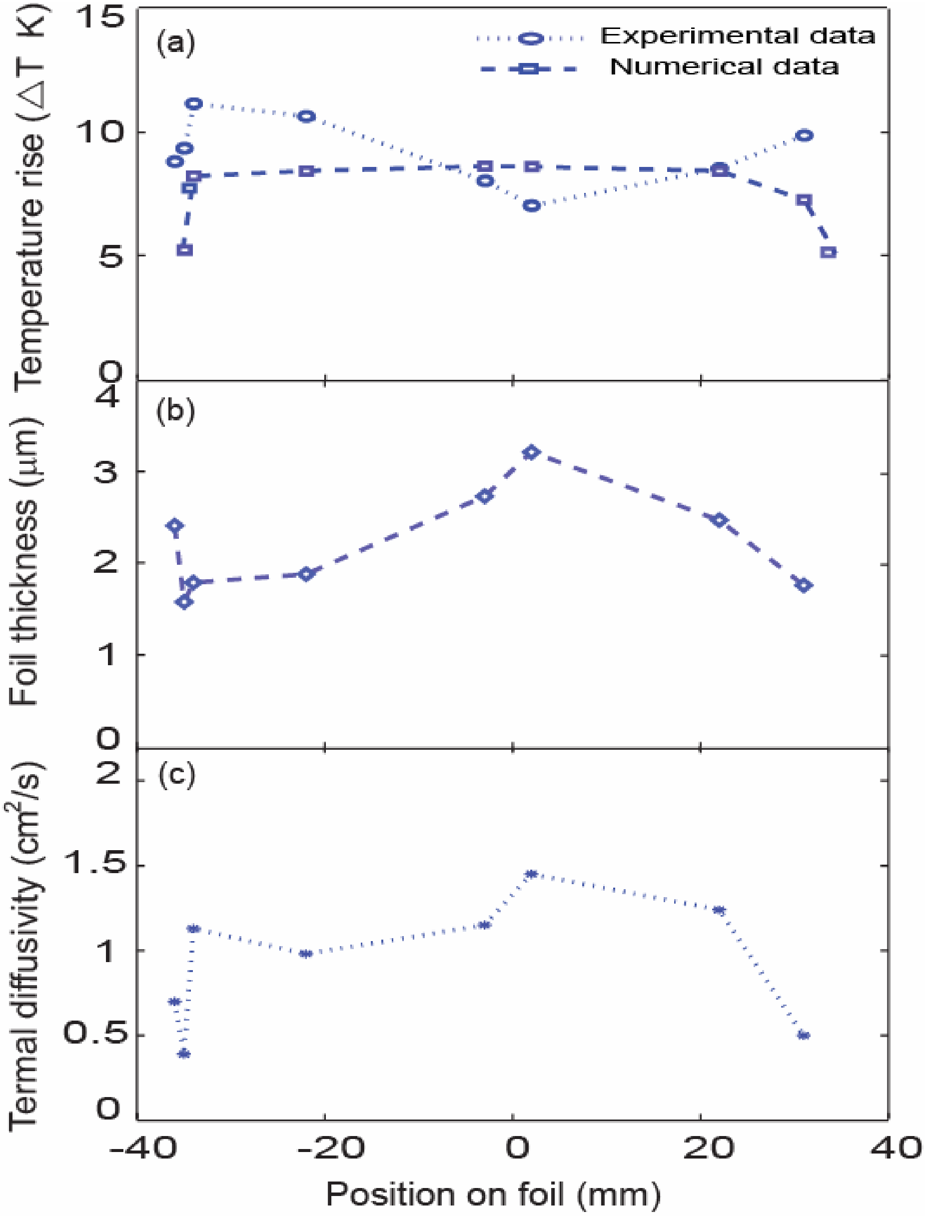
Method: By comparing temperature decay time from chopped laser with that of FEM we can determine local value of thermal diffusivity

Spatial variation of the foil parameters

Table of the some parameters on different positions on the foil of the JT-60U imaging bolometer

Pixel	Position (Camera pixel)	Position (mm)	Laser power (mW)	ΔT (^{O}K)	t_f (μm)	$\mathcal{K}$ (cm^2/s)
9B	(23,38)	(-36,-19)	15.42	8.8	2.4	0.7
1B	(26,118)	(-35,33)	15.5	9.3	1.6	0.39
3B	(25,97)	(-34,19)	15.7	11.07	1.8	1.13
3D	(37,88)	(-22,18)	15.9	10.6	1.9	0.98
6G	(73,65)	(-3,-2)	16.1	7.97	2.7	1.15
6H	(81,66)	(2,-1)	15.8	6.98	3.2	1.45
3K	(105,88)	(22,18)	15.8	8.5	2.5	1.24
1M	(131,114)	(31,30)	15.6	9.8	1.76	0.5

Spatial variation of the foil parameters



From steady state experimental data

By polynominal fit to FEM data and experimental steady state data for finding the thickness (t_f).

By polynominal fit to FEM data and experimental decay data for finding the thermal diffusivity (κ)

❖Improvement since last campaign

- Enable triggering of IR image data acquisition
- Data acquisition upgraded from Firewire to digital data link (8-bit video data →14-bit digital data)
- Magnetic shield 6mm →20mm, Added 15mm lead shield for gammas, Polyethylene shield 30mm →90mm for neutrons
- Detailed in-situ calibration with laser
- We obtain the local foil properties of the JT-60U imaging bolometer foil, by the calibrating of some part of the foil.
- Significant variation in the local temperature rise of the foil due to local heating by the laser beam indicates a possible spatial variation of the foil parameters κ, k and t_f.

❖Planned improvements

- Find the problem and a logical explanation for spatial variations of the calibration parameters.
- Improve detailed in-situ calibration by using new IR camera and close up lens in calibration laboratory (low noise).