Table 1. Beam parameters at the location of slit in MEBT

Beam current	38 mA or less
Beam energy	2.5 MeV
RMS beam size	σ_x~1.47 mm, σ_y~1.38 mm
RMS power density	760 kW/cm^2 at I=38 mA

Objectives;

- a proper material for the MEBT slit with reasonable physical dimension
- allowable pulse length in connection with beam current
- allowable pulse repetition rate

Four different carbon types list below are investigated along with **TZM and tantalum**.

- Polycrystalline Graphite (POCO, ATJ)
- Graphitic foam (POCO Foam)
- Pyrolytic Graphite (MINTEQ, Advanced Ceramics)
- Carbon-carbon Composite
  (INTEQUE, HITCO, & Data from published journal)

The upper limit of temperature rise during the beam pulse,

at given beam power

- DT_{max} **µ** $1/(d\ C_p\ r)$

where d is the stopping distance, C_p is the specific heat and r is the density.

- Thermal diffusion during the beam pulse

(thermal diffusivity; k/rC_p where k is thermal conductivity)

- In this application, k in the longitudinal direction is more important, since thermal load is very shallow.

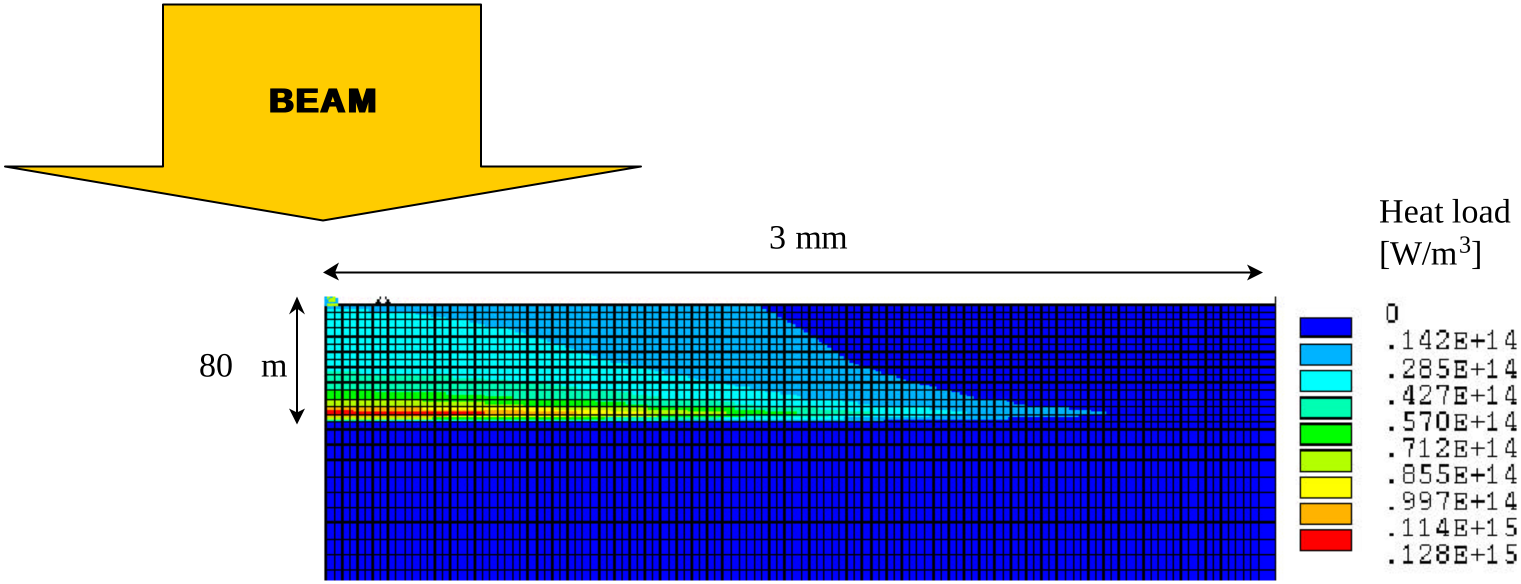
Thermal shock resistance from the very short thermal load

$$TSR = \frac{s_f (1 - n)}{aE}$$

where **TSR** is the thermal shock resistance, s_f is the fracture stress (or tensile),

ν is the Poisson's ratio, a is the thermal expansion coefficient,

νand E is the Young's modulus.



- 2D axisymmetry modeling
- beam shape; circle
  case1; σr=1.41 mm, case 2; σr=2.4 mm
- beam current; 50 mA
- pulse length; 50 μm
- Thermal load ; radial direction→ Gaussian distribution
  axial direction → Bragg's curve (see Fig.1)
  Figure shows thermal load input (magnified view)
- thermal and mechanical parameters ; see appendix.
- radiation cooling effects are neglected.

→ non-linear transient analysis

Table 2. Peak temperatures and von Mises stresses (from single pulse)

	σ_r (mm)	Peak Temp. (K)	Max. von Mises stress (MPa)[b]	Tensile strength at RT (MPa)	Melting. (K)
POCO	2.4	1050	(67)	20~60	~3900*
	1.4	2150	(170)		
ATJ	2.4	1050	25	>15	~3900*
	1.4	2150	(70)		
Pryolytic[a]	2.4	1900	22	20 (in-plain)	~3900*
	1.4	3800	50		
C/C[a]	2.4	1100	15	10-200 (in-plain)	~3900*
	1.4	2400	40		
TZM	2.4	1400	(2600)	500-1200	3885
	1.4	3100	(6700)		
Ta	2.4	1800	(2000)	240~480	3270
	1.4	(4100)	(5000)		

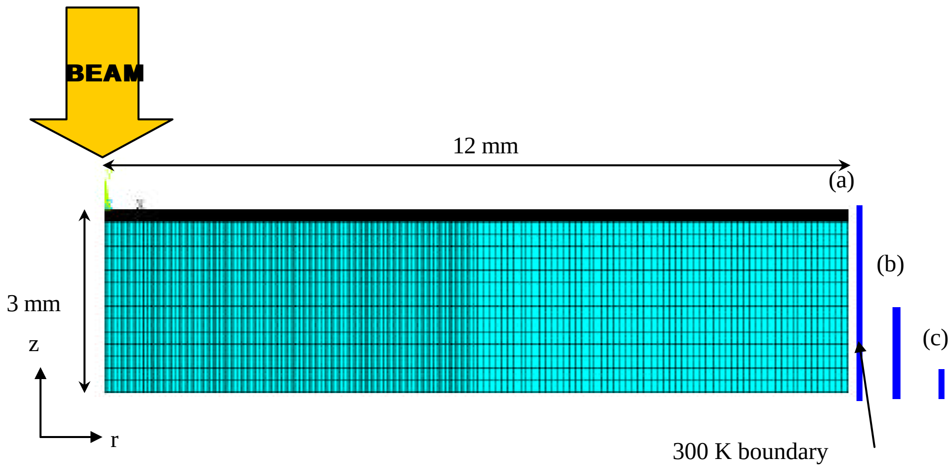
*at 1 atm, Carbon sublimation vapor pressure; 1900 K→ 10^{-7} Pa (~10^{-9} Torr), 2500 K → 10^{-2} Pa (~10^{-4} Torr).
** ( ); melting or fracture is expected
*** Poisson ratio ν of graphites and C/C composite is assumed 0.15.
The simulation indicates that 10 % increment of stress is expected with ν=0.3.
**** other material properties; see appendix.
a; anisotropic material. Young's modulus and Possion ratio
in the out-of-plain direction are assumed same with the in-plain value for conservative design.
b; under static assumption. (wave propagation effect in actual thermal shock is not included)

Table 3. Comments

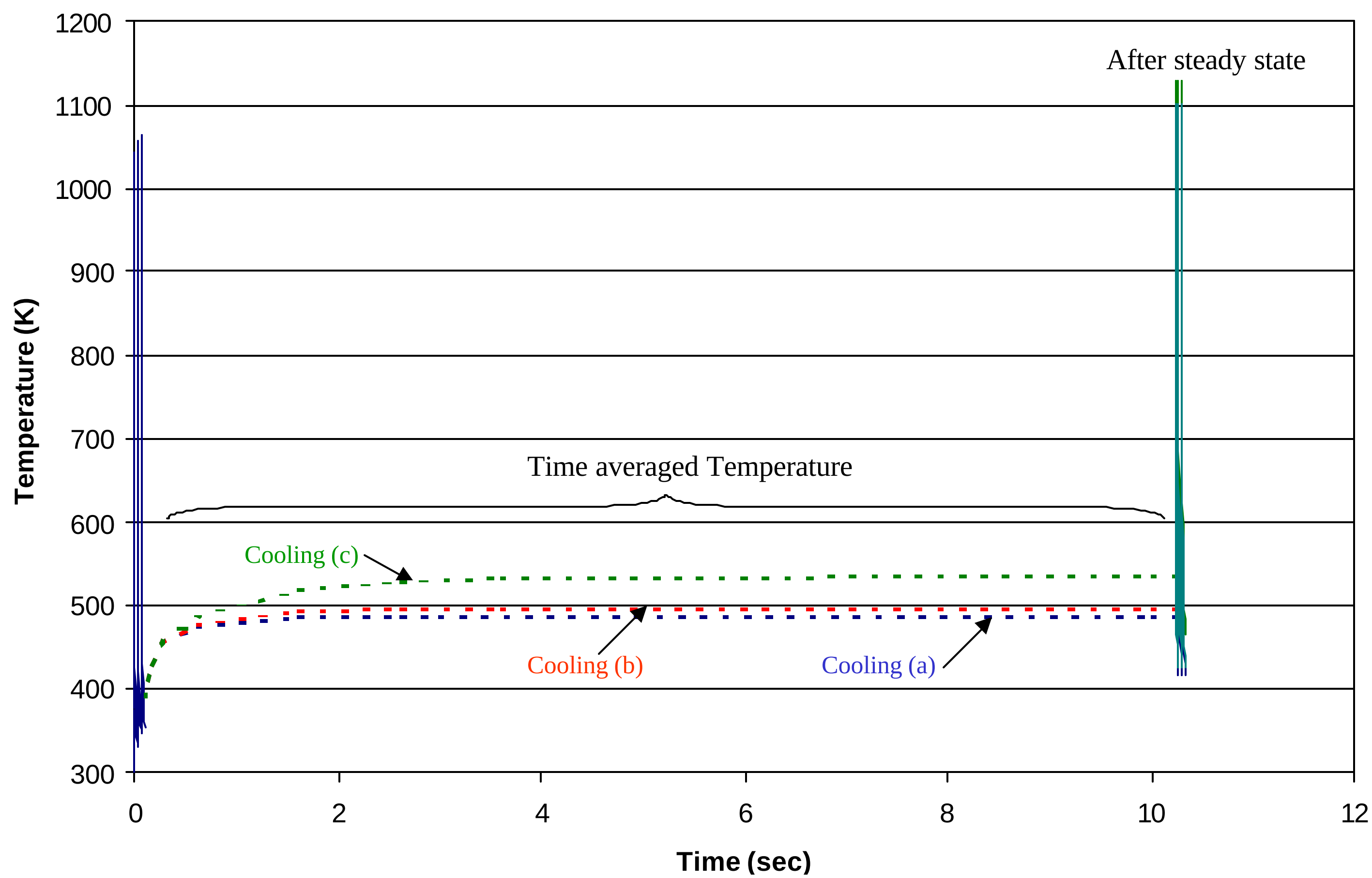
Material	Comment
POCO graphite	High thermal expansion; [not adequate]
ATJ Graphite	Moderate thermal expansion; [marginally usable] not for the high power density..(1 sigma beam)
POCO Foam	Lack of data, large pore size (~0.35 mm), low tensile strength; [lack of data]
Pyrolytic Graphite	Strong orthotrophic property (in-plane thermal property; best, but vertical property; ceramic-like behavior), no thermal diffusion in axial direction, could reach the sublimation temperature from multi-pulses thermal load, inter-laminar fracture could happen ; [not adequate]
C/C composite	Othotropic property, Moderate modulus, high strength, low thermal expansion, very wide range of material property, Checking points; inter-laminar mechanical property, thermal expansion coeffs., Young's modulus, tensile strength, etc. [usable]

* metals are not adequate mainly due to high Young's modulus and low specific heat.

Repetition rate & cooling



(a) Whole outside area cooling



Summary

- Material;

C/C composite shows best performance for the beam at MEBT.
50 ms, 50 mA, 30 Hz (with cooling) beam is allowable.
Here it is assumed that the media is continuous and the dynamic mechanical response is not included.
Remark; C/C composite physical properties can be **highly tailored.
Precise discussion with venders or suppliers is required to confirm the **material properties**.

- Repetition rate;

No significant thermal accumulation is expected when repetition is less than **30 Hz** with cooling.
Brazing is not required between C/C composite and cooling channel.
1 Hz operation seems possible **without cooling**.

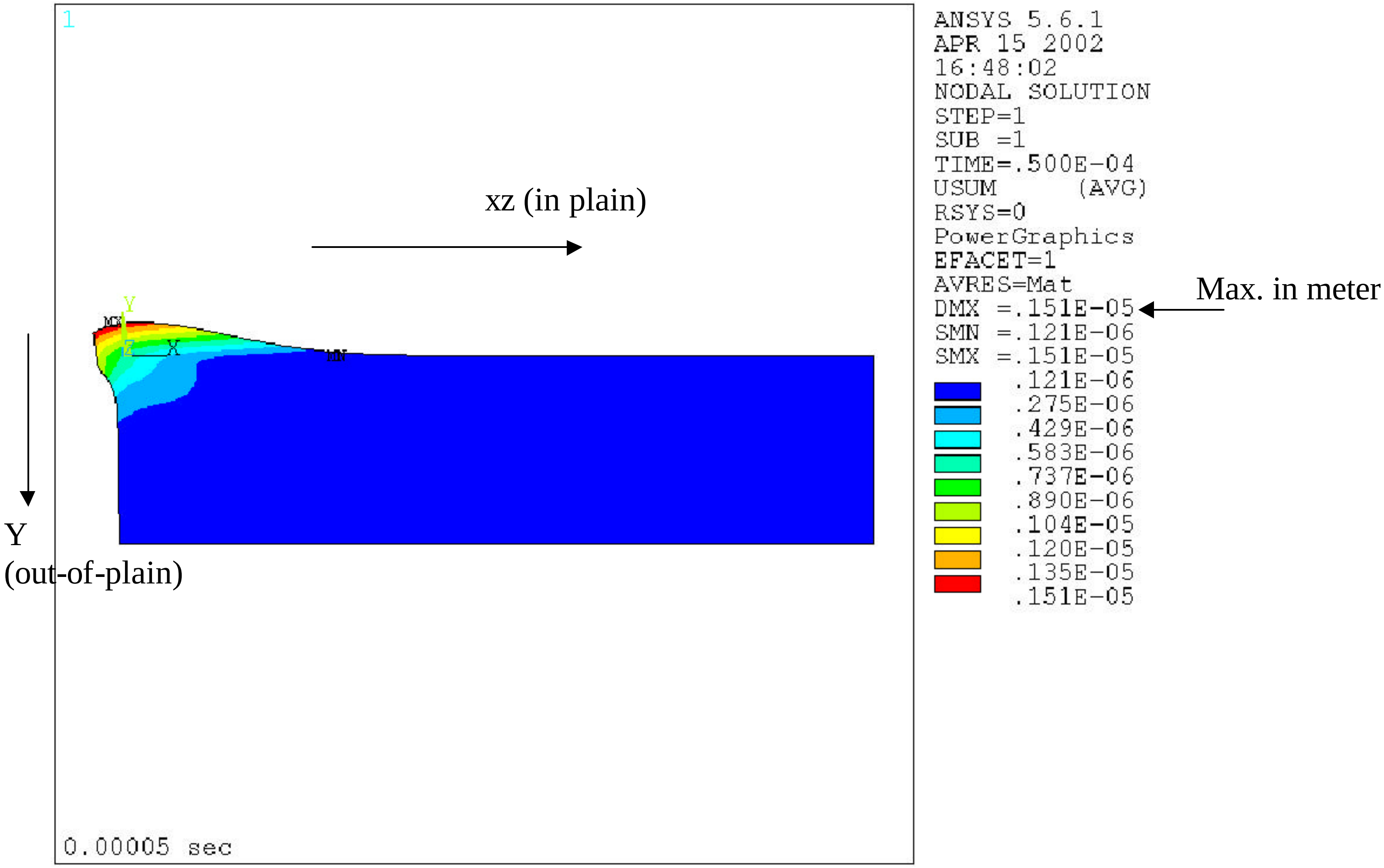
- Beam size reduction (Power density) at slit

Power density is most sensitive parameter that determines peak temperature and maximum stress.
About **>2.5 times power density reduction (<25 degree slit angle) is recommended** especially at around **slit aperture**.

- Pulse length vs beam current at a fixed beam size

When the pulse length is very short comparing with the thermal diffusion time,
effects of beam current and beam pulse length are almost same.

Displacement; max□ 1.5 m (usum), -1.2 m (in x-direction)



Maximum temperature ~2400 K (corresponds to vertical hitting)

In rectangular model

From single pulse

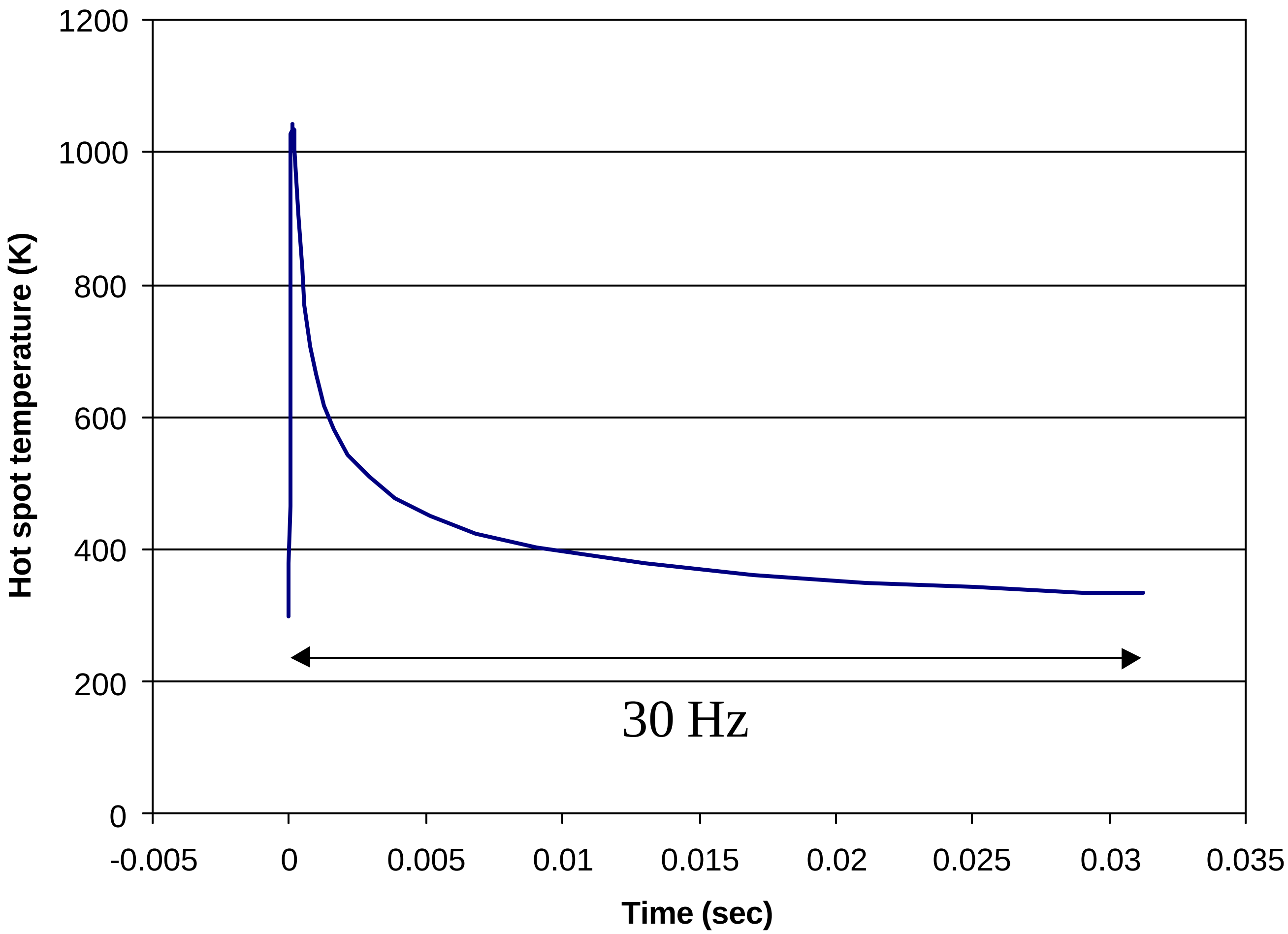
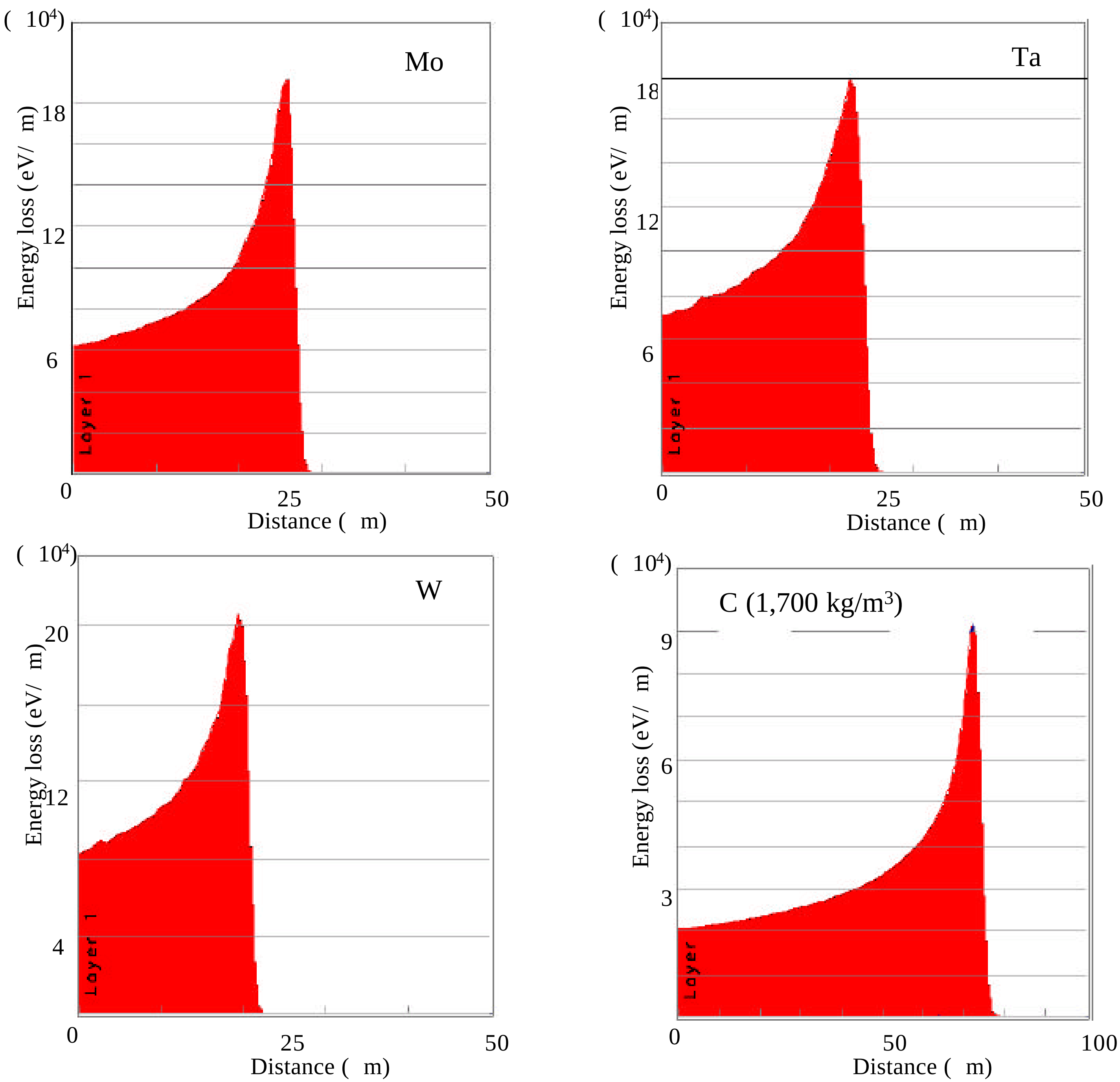
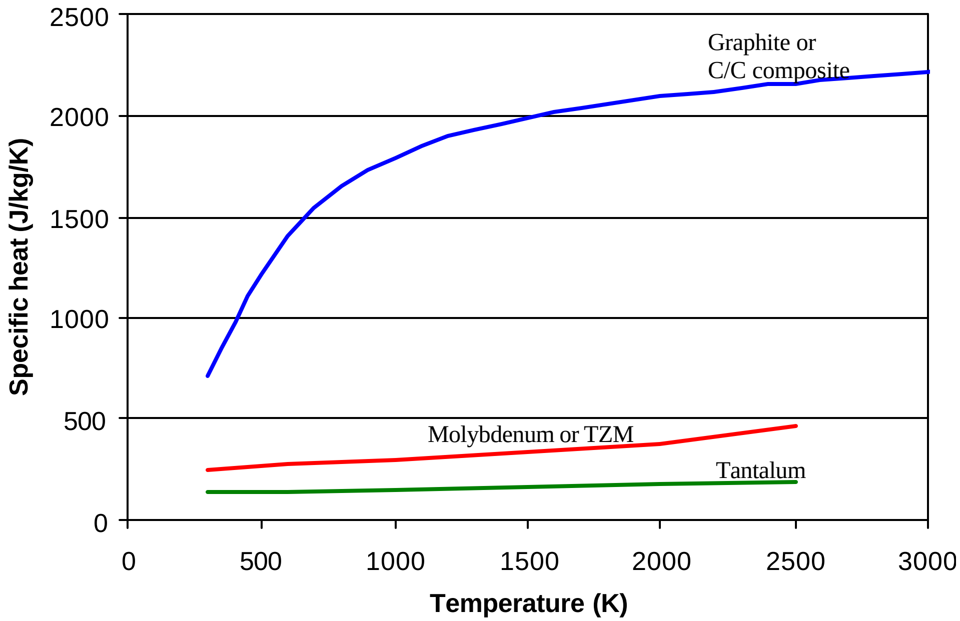
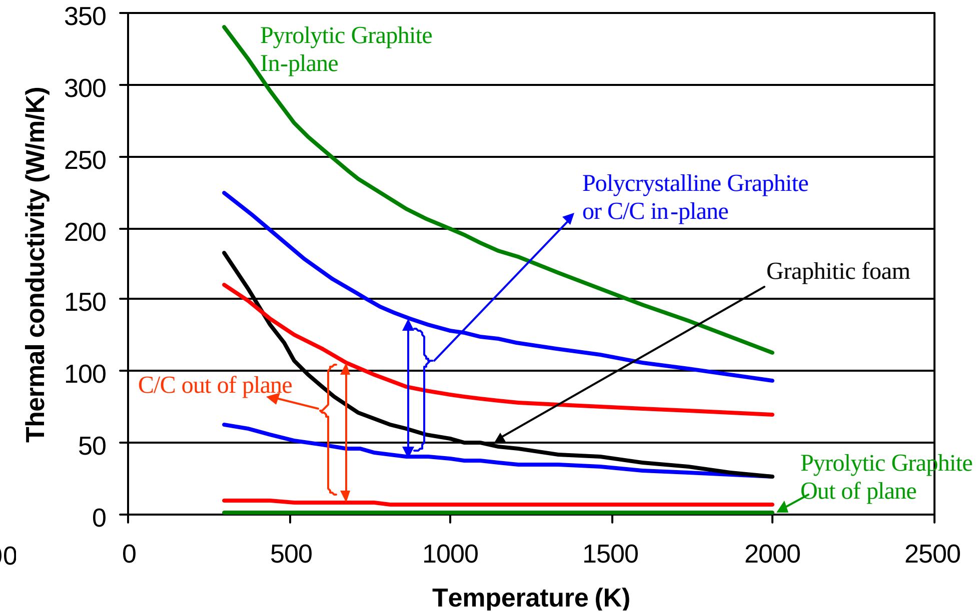


Figure 3. time history of maximum temperature from single pulse.

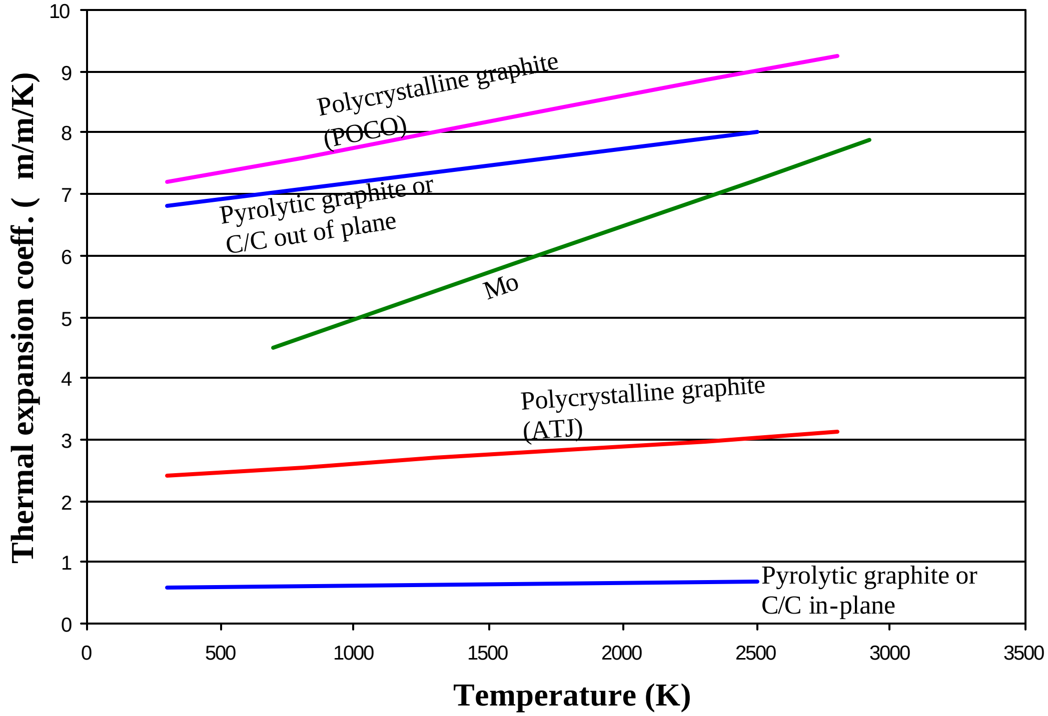


Mo
(10^4)
Energy loss (eV/ m)
18
12
6
Layer 1
0
25
50
Distance (m)
Ta
(10^4)
Energy loss (eV/ m)
18
12
6
Layer 1
0
25
50
Distance (m)
W
(10^4)
Energy loss (eV/ m)
20
12
4
Layer 1
0
25
50
Distance (m)
C (1,700 kg/m^3)
(10^4)
Energy loss (eV/ m)
9
6
3
Layer
0
50
100
Distance (m)





C/C composites have broad range of thermal conductivities and mechanical properties
→ Can be highly tailored (in-plain k can be higher than 1000 W/m/K)



Typical values are plotted

Table A-1. Mechanical properties at room temperature

Material		Young's modulus [GPa]	Tensile [MPa]
Molybdenum		320	500~1200
Polycrystalline Graphite		5-20	10~60
Pyrolytic Graphite**	In-plane	~20	~100
	Out of plane	<10	
C/C**	In-plane	10~200	20~600
	Out of plane	<10	

* temperature effect on Young's modulus is less than 15 %.

** inter-laminar (out of plain) fracture should be checked separately