FEEL

The absorption of the radiation by PbF2 blocks cause them to loose transmission and ultimately to loose energy resolution. The transmission properties can be restored by either heating the blocks (thermal curing) of exposing them to near UV light (optical curing). Because installing a oven around the DVCS calorimeter is unpractical, the solution under study is to use the optical curing method.

Our group is thinking about using the electron beam of the FEEL to submit the blocks to a series of irradiation and optical curing in order to test the effectiveness of the optical curring especially after over 10 cycles. One of the issue is to limit the electron beam power such that the beam doesn't create is own curring mechanism by heating the block.

1. **Derivation**

   The energy transfer equation[1] that describes the temperature distribution with a volume, can be written for a uniform value of k as

   $$k\nabla^2 T + S = \rho c \frac{\partial T}{\partial t} \tag{1}$$

   where :

   k is the thermal conductivity [W/(m K)]
   T is the temperature [K]
   S is the heating source power density [W/m^3]
   ρ is the density of the material [g/m^3]
   t is time [s]
   c is the specific heat of the material [J/(gK)]

   I also defined the total power given to the system as $P = SV$ where V is the volume and L the length of the block.

   In steady state condition $\partial T/\partial t = 0$. Moreover, in a cylindrical coordinates system, the integrated solution of equation 1 is:

   $$T = -\frac{Sr^2}{4k} + C_1 \ln r + C_2 \tag{2}$$

   With the boundary conditions:

   (a) When $r = 0$, $dT/dr = 0$ because of symmetry,
   (b) When $r = r_s$, $T = T_s$ at the surface of the cylinder.

   Therefore, the temperature distribution in the element can then be expressed as:

   $$T - T_s = \frac{S}{4k}\left(r_s^2 - r^2\right) = \frac{P}{16\pi k L} \tag{3}$$

   In this equation, the increase of temperature at the center of the system doesn't depend on the transverse size of the block assembly, but P is the total power dumped

[1] A. Foster and R. Wright Jr, "Basic nuclear engineering", ISBN 0-205-03653-8

in the system. This mean that if the system is of $n \times n$ block instead of 1 block, the power P_1received by 1 block is P/n^2.

The beam intensity I creating a power deposition P in the blocks depends on the energy E of the electrons and the electron charge e:

$$P = E\frac{I}{e} \tag{4}$$

where P is in Watt and E is in Joule and I is in A. Bringing this formula to more familiar units, one need to remembers that 1 MeV=$e \times 10^6$J and 1μA=10^{-6}A such that

$$I = \frac{P}{E} \tag{5}$$

where I is in μA, P in Watt and E in MeV.

Finally, the radiation dose D received by the system of mass M is

$$D = \frac{P\Delta T}{M} \tag{6}$$

where P is in Watt, T is the duration of exposure in second, D is the dose in Gray received by the system. If one supposes that the system is made of a compact assembly of $n \times n$ blocks, then both the power and the mass of the system are divided by n^2 such that the dose D_1 received by one block of this system is:

$$D_1 = D \tag{7}$$

2. **Numerical applications**
   For this exercise, I approximate a system of $n \times n$ blocks of the DVCS calorimeter arranged in a compact tower. Each block is a parallepipede of size 3×3×20 cm^3. I also consider they are made of glass with a thermal conductivity k=0.8 W/(m K) according to Wikipedia[2].
   I limit the maximum temperature elevation within the system to 10^0K. According to equation 3, the maximum power that can be dumped in the system is: 80 W. This calculation holds for a system in good thermal contact with the surrounding air.
   With a 110 MeV beam energy of the FEEL, 80W corresponds to a beam intensity of 0.73 μA.
   According to my calculations [3] , the radiation dose that was received by each blocks at the smallest angle during E00-100 and E03-106 was 750 kGy. The mass of each block is 1 kg.

# blocks	1×1	2×2	3×3
P_1 (W)	80	40	9
T (h)	2.6	5.2	23

[2]http://en.wikipedia.org/wiki/Thermal_conductivity quotes the thermal conductivity of glass to range between 0.8 to 0.93 W/(mK)

[3]DVCS elog entry #59 of the 12 GeV section: http://clrlpc:8080/12+GeV/59

3. **Discussion**

(a) Why ten degrees K as maximum temperature elevation?
I don't have a justification for choosing this number yet...

(b) How to stack the blocks?
The way the allowable power in the blocks seems to be independent of the transverse block size (see equation 3), which is of course troubling. But one should be careful: under this form the power P is the total power dumped into the assembly. This means that if ones dumps 85W for 2:30 h in an assembly of for example 3×3 blocks, the center part will undergo a 10 degrees elevation. But each blocks will only receive a does of 750kGy/9=83 kGy which is not enough for the radiation test. Therefore I suggest, we choose not to stack the blocks in a compact assembly but we separate them such that we can force air between them to insure good cooling. Therefore we can ask for more beam current: for nine blocks we could ask for 9×770 nA$\sim$ 7 μA. The question is then to make sure that we have a raster system that allow to cover all the blocks.

(c) How does that compare to the past experiences?
E00-110 and E03-106, the closest block received a dose of 750 kGy in roughly 1000h, which correspond to a power of 0.2 W. The electrons where 5.75 GeV for an average current of 3 μA: the beam power was 17 kW. So 1% of the beam power was dumped in the closest blocks. If for the FEEL test we are running with 85 W of power, we will rougthly need (0.2×1000/85=2:30 h).
Now suppose that all the power deposited in the calorimeter block is only transformed in heat; that is none of the energy is loss through thermal conductivity. In that case, the energy deposited heats the blocks at a rate defined by the specific heat of glass. Using equation 1 as a starting point, the formulation becomes

$$\begin{aligned} S \times V &= \rho V c \frac{\partial T}{\partial t} \\ \Delta T &= \frac{P \Delta t}{M c} \end{aligned} \qquad (8)$$

For glass, the heat capacity[4] is $c = 0.64$ J/gK. Such that neglecting the thermal conductivity with air, the temperature inside the calorimeter blocks of E00-110 and E03-106 would have been 1125 K above the ambient temperature. This is purely academical and of course doesn't happen in real life.

[4]Reference: http://en.wikipedia.org/wiki/Specific_heat_capacity, the value quoted is the average of the heat capacity of crown glass, flint glass and Pyrex.