Simulation of Heat Transfer and Dissipation in targets used in Real Nuclear Astrophysics Experiments

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Introduction

In Nuclear Astrophysics(NA) experiments low fusion or capture cross-section make the measurements with appreciable accuracy difficult. In order to improve the statistical accuracy in a reasonable time of the *beam time*, a high current is desirable.
The purpose of this simulation will be to develop an idea about the amount of heating generated in the target, its temperature profile and how the temperature can be controlled by heat dissipation and the different factors on which it depends.The simulation will mostly be based on the physical concepts and more realistic aspects that will lead to the design of a cooling setup which will be developed based on the present basic study.
To perform such an experiment in laboratory there is a strong need to increase the number of projectile to hit the target. To do so projectile current become very high (μA, may be in some cases it can go upto mA). By increasing current we can increase the *reaction cross-section* but to do so we are striking a large number of projectile into the target which leads to a large amount of heat generation inside the target material. Now if the heat generation inside the target is higher than the melting point of that material then it will melt and nuclear reaction experiment will fail, apart from that it can cause damage to the scattering chamber and attached detectors. Although melting is not the only issue for the *survival* of the target, sputtering, stress due to radiation damage, recrystallization etc. play destructive roles.

Cooling processes

To cool down any system there are three basic processes involved. But since most of the experiments are performed under vacuum, so cooling by convection is ruled out. So radiation (for material with high emissivity) and conduction (material with high conductivity) will play main role.

Heat generation in high current experiments

Calculation of heating in these targets will give a guideline to the safe maximum beam current they may be exposed before melting. The equation need to be satisfied to reach a *steady state* is *Heat in= Heat out*. Heat is brought into account inside the target by the energy loss of the beam inside the foil(target). This may be calculated by using a *stopping power* model such as SRIM[1]. The heat in the target gradually decreases over time by *conduction* through the target away from the beam spot and *Radiation*,which is given by *Stefan-Boltzmann law*, $E = \epsilon\sigma S(T^4 - T_0^4)$, where E is the *radiant heat energy* emitted per unit time; ϵ, *emissivity* of the target material; σ, *Stefan-Boltzmann* constant ($\sim 5.67 \times 10^{-8} watt/m^2.K^4$); S is the surface area irradiated by the *Gaussian shaped beam* and T_0 is the *ambient temperature* of the target surrounding.
Now to have an idea about *steady state temperature* one need to solve this equation[2]:

$$WI = mC_v\frac{dT}{dt} + (T-T_0)\frac{\lambda S}{D/\rho} + 2\epsilon\sigma S(T^4-T_0^4) \quad (1)$$

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where left hand side is the amount of heat generated by the incident beam in the target and right hand side is the different processes to dissipate that energy. Here *temperature, T* is a function of *x,y,z*. W equals to the energy loss in the target by each projectile, I is the number of projectile coming per unit time(*particle current*), m and C_v are mass and the specific heat of target, λ is the *thermal conductivity* of the target, ρ is the density of target material, D is the *areal thickness.*

These kind of calculation is done by the simulation package **ANSYS**. Which numerically solve the equation by creating *mesh* on the body of target sample.

Simulation Results from ANSYS

All simulations have been done by considering foil size of **25mm** $\times$ **25mm** cross sectional area. And *diameter* of beam spot is taken as **6mm.** Ambient Temperature taken 16^0C.

A. STUDY 1: $^{27}Al(p, p_0)$ reaction:

To study $^{27}Al(p, p_0)$ we used 39 μg/cm^2 thick Al target. Stopping power of 1.1 MeV proton is 0.1654 MeV/(mg/cm^2). Range of p at this energy inside Aluminium is 16.54 μm. Proton beam used in this experiment was 50-150 nA [3]. Here we tried to find the maximum current we can use for that target thickness after applying two side 4^0C cooling. Melting point of Al is around 660^0C. But we have taken our cut-off temperature around 600^oC.

Simulation result shows that $\mathbf{16\mu A}$ current is permissible before melting.

B. STUDY 2: $^{12}C(^{12}C, x)$ reaction:

To study $^{12}C(^{12}C, x)$ we used 1mm ($\sim$ $225.3mg/cm^2$) thick *graphite* target. Proton current taken 40 μA(4.2-9.5 MeV) [4]. Range and stopping power in C at that energy are respectively 3.43 μm and 7.346 MeV/(mg/cm^2).

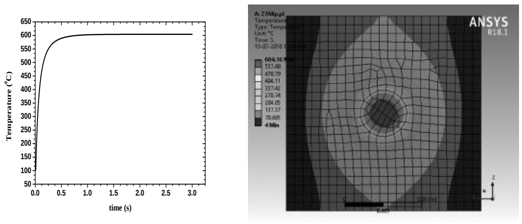

FIG. 1: Steady state temperature and temperature profile for $^{27}Al(p, p_0)$ reaction.

Charge state of carbon beam is 2+. Melting point temperature of Graphite is around $\sim 3900^0$C.

Simulation has been done to have an idea about the maximum allowed current applying cooling in two sides of the target by 4^0C. Applying cooling on two sides we found that the maximum current which can be used is around 200μA.

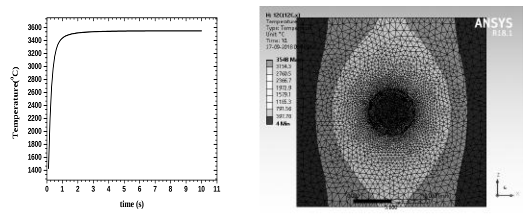

FIG. 2: Steady state temperature and temperature profile for $^{12}C(^{12}C, x)$ reaction.

References

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