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A REALISTIC ENDURANCE TEST OF THE TARGET WINDOW OF THE ENERGY AMPLIFIER (NICE[1])

C. Rubbia, S. Buono[2], F. Carminati, M. Embid[3], Y. Kadi, P. Mandrillon[4], and A. Negrini[5]

Abstract.

The spallation target window of the Energy Amplifier (EA) [1] is a critical element since it must endure both a high specific power dissipation (≥ 5 kWatt/cm^3) and a strong radiation damage due to the charged particle beam. This damage is very different than the one produced by neutrons since, while neutron collisions essentially displace nuclei, charged particles mostly interact electromagnetically. Therefore the beam window will experience a substantially different phenomenology, when compared for instance with the cladding of the nuclear fuel. Very little is known on the behaviour of materials under these conditions and an appropriate test bench is necessary, a specific R&D programme of considerable interest on its own.

Precursory to the general programme on a full scale (MWatt) Spallation Target, which needs a high current, high energy beam and large scale installations (Los Alamos, PSI), we propose a "table-top" experiment using a small Cyclotron and specifically addressed to the *high power phenomenology of the window*. High power densities — well above the one to be experienced in the EA and due to almost pure ionisation losses — will be produced by the well focused low energy (60 MeV, 50 µA) beam from the Lacassagne Laboratory located in Nice. A 1/10 scale mock-up of the Lead-cooled spallation target is proposed. We show that the thermodynamics and radiation exposure are very close to the ones in the final EA window, though the spallation process occurring in the subsequent Lead (fast growing function with proton energy) is effectively suppressed, and so is the bulk of the neutron induced activation. The tiny set-up will permit to explore systematically and realistically the complex phenomena in the window exposed *simultaneously to (1)the heat, (2) the radiation damage and (3) the (potentially corrosive) contact with hot molten Lead.*

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[1]Neutronless Ionization Confirmed Endurance

[2] CRS4 , Cagliari, Italy

[3]LAESA, Zaragoza, Spain (as of the 1/7/97)

[4] Centre Lacassagne, Nice, France

[5]ANSALDO, Genoa, Italy

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1.— Generalities. The realisation of the spallation target is one of the key elements for the Energy Amplifier (EA) [1]. Its realisation is not without challenges, because of the intense radiation damage produced by the beam in the window. In this paper we propose a practical scenario of experimentation toward the realisation of such an element in which the key features of the operation of the final window are reproduced with the help of experimental conditions which, though being realistic, are much simpler and cheaper to realise than the full target set-up. In particular the large power and the strong neutron flux which are usually associated with the Spallation target are replaced by a lower energy, low current beam. We propose to realise a scale 1/10 table-top mock-up of the final Spallation target, with essentially the same phenomenology and power densities in the window region and in the immediately subsequent molten Lead layer of the final target, but without the inconveniences of the subsequent spallation process and the associated large amount of power and of activation. The beam power is only about 3 kWatt and it can be dissipated with the help of a natural convection column of less than one meter.

Radiation damage due to a charged particle beam is conceptually very different than the more familiar one produced by neutrons and widely tested with Reactors. While charged particles interact essentially electromagnetically with electrons and nuclei of the medium, through the well known ionisation/excitation phenomenon and Coulomb scatterings, neutrons "see" primarily nuclei, which are significantly displaced by collisions. Neutrons produce also a significant amount of nuclear capture reactions, which may produce hydrogen and helium occlusions, of much less relative importance in the case of charged particle beams where one must overcome the strong Coulomb barrier of the high Z target nuclei to reach the nuclear core. Instead elastic or quasi-elastic Coulomb scatterings have a large cross section for small momentum transfers ($\propto 1/q^4$), though large enough to produce significant lattice displacements. Therefore the beam window will experience a substantially different phenomenology, when compared for instance with the cladding of the nuclear fuel, and which demands a specific research programme of considerable interest on its own.

In addition to radiation damage, the high energy density dissipated by ionisation ($\approx$ 5 kWatt/cm^3) is very localised and will produce all kind of thermal stresses and deformations in the window material and which have to be carefully studied and understood before embarking into the definition and construction of the final device for the EA-250 [2] and beyond [3]. Therefore a benchmark experiment in which all this complex phenomenology can be and studied systematically is of considerable importance in the way toward the ultimate realisation of a practical EA [2].

On the other side, by concentrating on the problem of the ionisation losses in the window and on their practical consequences greatly simplifies the experimental set-up and the measuring procedures, since the required ionisation density can be enhanced scaling down the target size and therefore the beam spot and using particles (protons) of lower energy and therefore higher specific ionisation. On the other hand the additional radiation damage due to neutrons which permeate the EA environment is expected to be much smaller than the one produced by the direct charged particle beam and it could eventually be studied separately or subsequently by irradiating our samples with the conventional sources of fast neutrons. Clearly these two different problems lead naturally to a factorisation and hence to separate experiments in which they may be specifically studied.

The beam for the full scale Spallation source for the EA has a typical current of 10 mA and a kinetic energy of 1 GeV. We propose to make use instead of the much more modest 60 MeV proton beam of Lacassagne Laboratory in Nice which has a continuous current of 50 μA and an (invariant) emittance of $1 \div 2\ \pi\ 10^{-6}$ m rad. The beam is injected in a scale ≈ 1/10 mock-up of the molten lead cooled spallation target for the EA-250: the required high power density conditions are generated in a correspondingly smaller beam spot size and therefore with a much smaller total power (50 μA × 60 MeV = 3 kWatt). Unlike the spallation process which has an intrinsic size determined by the dynamics of the nuclear cascade, the ionisation losses, being essentially a local phenomenon, can be strongly enhanced by concentrating the beam on a smaller spot.

An additional advantage of the low energy beam in creating high power densities (about a factor 5 with respect to 1 GeV) is associated with the higher specific ionisation of a lower energy beam. Fortunately the main features of ionisation loss phenomenon, due to distant interactions with the electrons of the medium, are hardly affected by the actual speed of the particle, the main consequence being a longer collision time due to the slower particle motion.

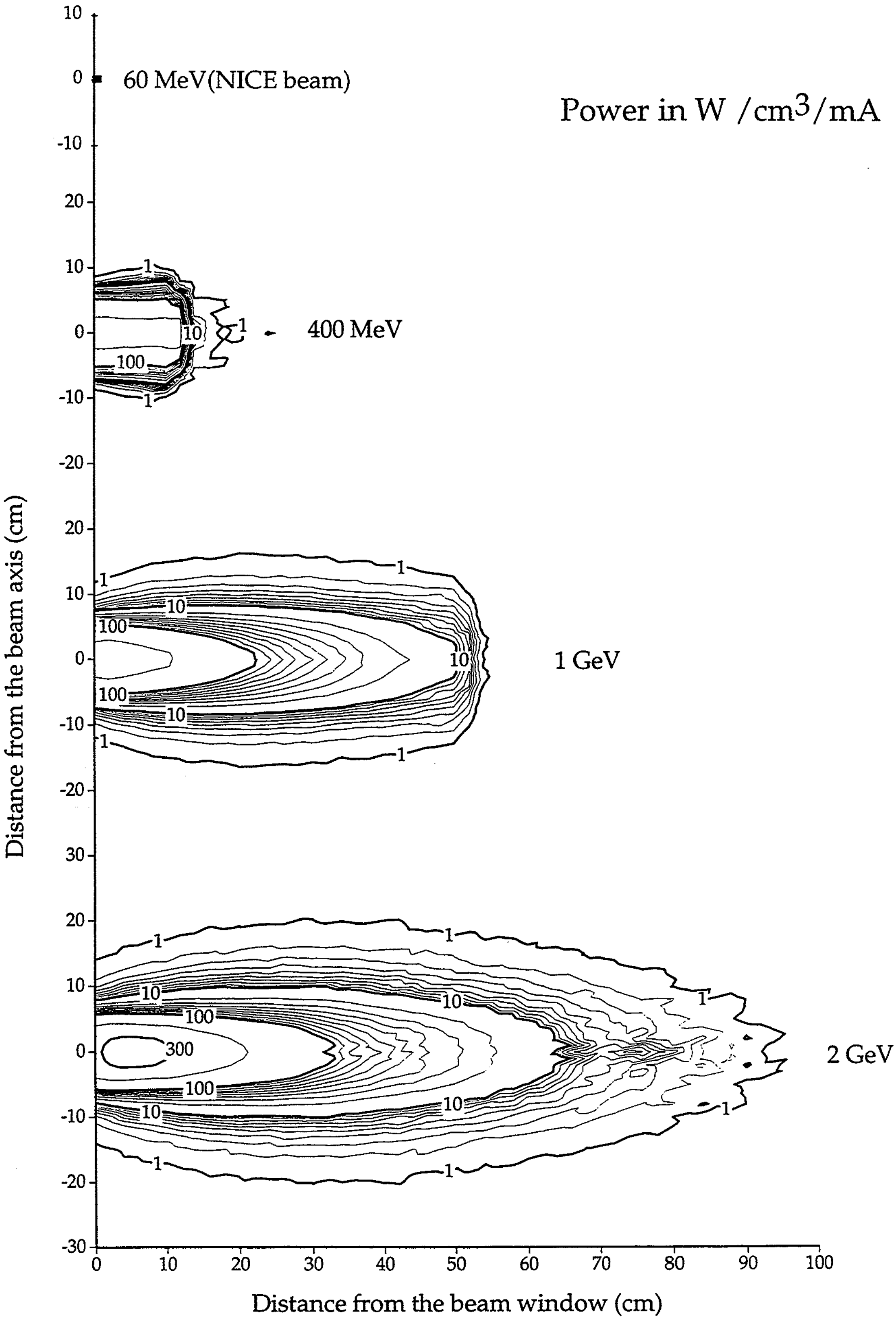

Figure 1. *Energy deposition iso-contours in the proton driven spallation cascade at different energies in molten Lead. In the Nice experiment the deposition volume is less than 1 cm*^{3}*, corresponding to power densities of the order of 60000 Watt/cm*^{3}*/mA*

One can easily describe the ionisation losses in the Weitzäcker-Williams approximation as the combined photo-effect and of the Fourier transformed electromagnetic field of the passing particle, as seen by the atoms and nuclei. The dominant contribution to the effect comes from relatively soft photons which are already asymptotic at moderately relativistic proton speeds. Therefore the actual proton speed is largely irrelevant to the features of the process, with the exception of the different rate of the energy loss.

Though the low energy beam has a similar ionisation losses on the target as the high energy beam, the spallation process is effectively suppressed. The nuclear interactions are significantly suppressed because of the difficulties of a low energy charged particle to overcome the coulomb barrier due to the high Z of the Window and the molten Lead. In addition since the beam current is small, the total activation and the neutron yield are even further reduced. The volumic extent of the energy deposition for a high energy beam is compared to the situation of the present experiment in Figure 1. One can see the minuscule energy deposition spot of this experiment (of ≤ 1 cm^3) when compared with the one of a full scale device. The power density in our case, as discussed further on is typically of the order of ≥ 60 kWatt/cm^3/mA, to be compared with the few hundred watts of the full scale spallation process (see Figure 1). This explains why with much smaller currents and powers we can achieve comparable energy deposition densities and a corresponding large radiation damage.

A Spallation target development is planned in Los Alamos [4]. In this programme a full intensity beam of high energy is hitting a rather complex and costly target geometry. As already pointed out, we believe that our programme, far more modest in scale and addressed to the main technological question — the endurance of the window exposed to high beam power and to the cooling of the molten Lead — can give a much higher flexibility because of the much reduced activation and the modesty of the dimensions and of the power involved (a few kWatts). In addition our method ensures that the problem of the window is factorised from the rest of the dynamics of the device. Both programmes are therefore complementary and directed toward the same goal of providing a credible design for the EA.

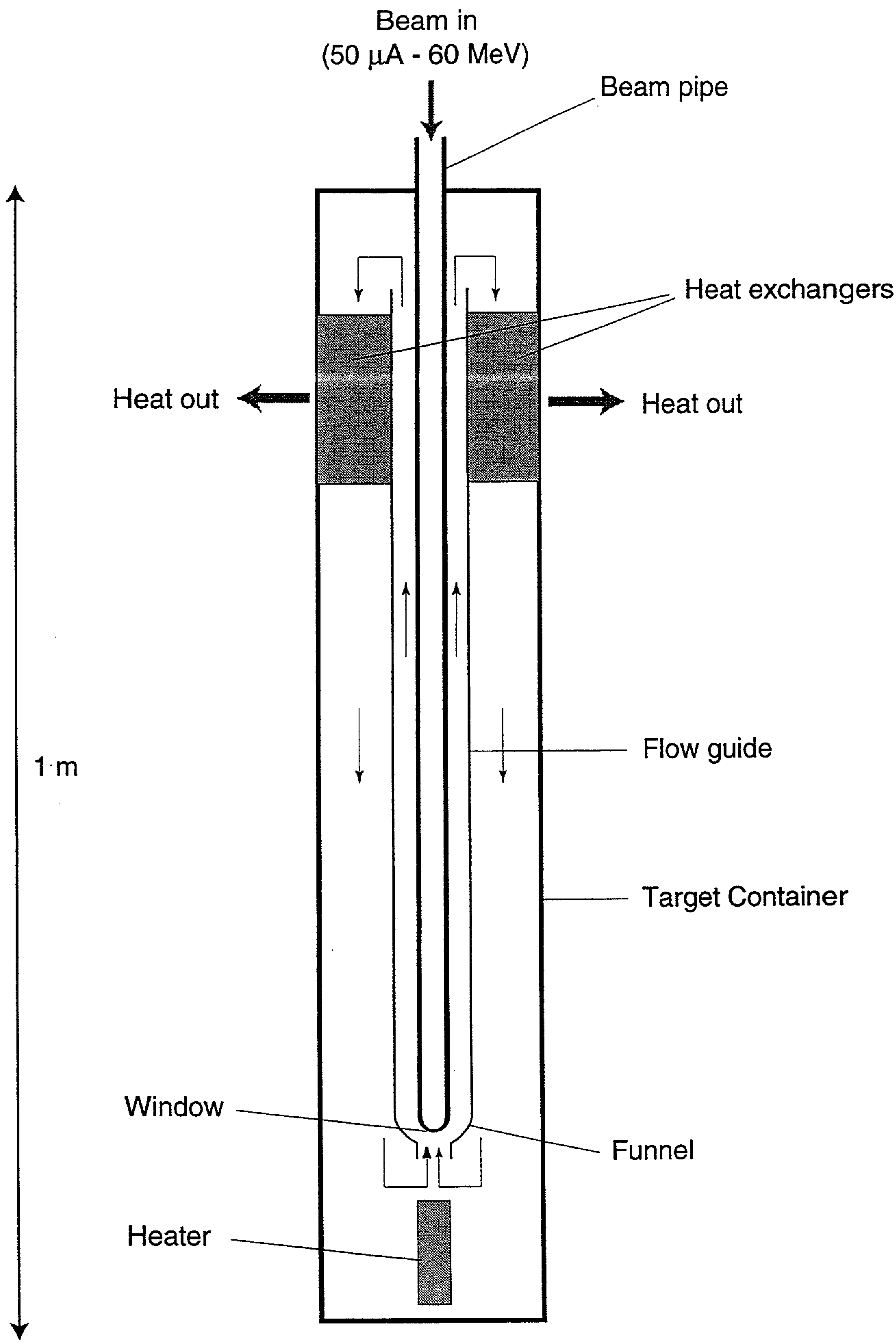

Figure 2. Schematic lay-out of the experimental set-up.

2.— *Experimental set-up.* The experimental set-up is schematically shown in Figure 2. It consists in a cylindrical vessel about 1 m tall and some 20 cm diameter which can withstand without corrosion the molten Lead, for instance made of HT-9 steel, eventually with a Tungsten lining. The top of the vessel is closed with a flange through which most of the instrumentation wiring is extracted. The beam is entering in the molten lead through the beam pipe of about 2 cm inner diameter made also of HT-9 and which has at the bottom end the beam window under test.

Appropriate mechanics should permit the easy substitution of the Beam Window after extraction of the full beam tube. Evidently a variety of beam windows must be tested. Note that the power density which can be produced with the present set-up is up to an order of magnitude greater than the one in the final Energy Amplifier. Therefore an accelerated ageing/radiation damage is possible. The power and the power density in the Target are selected by tuning the beam current and the beam spot size with the variable optics. In same cases, the beam energy may be varied as well.

Below the Beam Window, at some 10 cm distance to ensure the complete absorption of the beam and of its secondaries, an electric heater is installed of the approximate power (a few kWatt), in order to initiate the convective flow and inhibit solidification of the Lead. On the top part of the vessel, a heat exchanger is installed, designed in order to extract the heat produced by the beam (≈ 3 kWatt) and the extra heaters (≈ 5 kWatt). The temperature of the top of the Lead (exit of the heat exchanger) is stabilised with the help of such a heat exchanger to the appropriate value, which we assume inductively to be 400 °C. Note that either pure Lead or Lead-Bismuth eutectic mixtures can be used at this stage. The container is normally sealed and filled with inert gas at room pressure. We have estimated the main volatiles produced by the beam interactions and found that the main contaminants are short-lived. Therefore there should be no specific radio-nuclide problem though standard precautions should be taken in view of the presence of the beam. In particular about 10^{13} neutrons/s are emitted from the Target and standard shielding precaution should be taken, but not significantly different than the ones already in operation for such a beam. The accidental collapse of the Beam Window will have no significant consequences, in view of the low vapour pressure of the Lead. The molten Lead will rise of about 1 metre in the beam tube, because of the differential in pressure. Since the proton beam enters vertically from the top, enough space could be provided to make such an eventuality harmless. Spilling of the molten Lead should be avoided, since it is generally radioactive, though these contaminants are mostly dissolved in the molten metal. A cold trap and a fast shutting valve could eventually protect the vacuum of the Accelerator against some more extended mechanical accident.

At the end of the exposure, the target tip should be removed with the beam tube and then separated out to perform on it standard metallurgical tests and other inspections. The observation during operation is an important part of the programme. We propose to use the following methods:

(1) temperatures are mapped with the help of Pt-Rhodium(10%) thermocouples, which should exhibit no corrosion problem. Both the window and the molten Lead can be accurately monitored in this way since the standard sensitivity of the devices is about 11 μV/°C around 800 °C.

(2) liquid movement (speed) is probably measured best using the electromotive force produced by the motion in the presence of a magnetic field. To this purpose a set of three Helmoltz coils are used to produce a field of the order of 1 kGauss in the three orthogonal directions[6]. Evidently one coil is energised at the time. At the speed v, the electromotive force ΔV produced over the distance Δx, for simplicity orthogonal both to the field B and the speed is given by $\Delta V = -B \;\; \Delta x \;\; v$. More generally, in a vector notation $\Delta V = (\vec{v} \times \vec{B}) \cdot \Delta \vec{x}$. Setting for instance B = 0.1 Tesla, Δx = 10^{-2} m (1 cm) and v = 0.1 m/s, we find ΔV = 100 μV, which is a perfectly measurable voltage, comparable to the one of the thermocouples. The signal has potentially a relatively large bandwidth and therefore the presence of instabilities, due to turbulence, vortexes etc. can be sensed directly. The same wires, insulated with the exception of the tip end, can be used both as thermocouples and as voltage sensors.

(3) Standard instrumentation can be used to observe the beam spot-size, the current etc. In particular the beam current can be easily and accurately measured with Beam Transformers. The beam spot inside the target tube near the window can also be monitored with appropriate devices

[6] Vertical and two orthogonal horizontal directions. The effects on the beam are very small.

(secondary emission chamber hodoscopes) and for instance a fluorescent screen, visible through the beam pipe by a camera located after the vertical bend.

A secondary container for the (radioactive) Lead should be provided. A secondary heater is used to melt the Lead prior to injection inside the Target. Purity and monitoring devices are probably also needed, not discussed here, though the amount of Lead used is small and the Target walls can be made such as to withstand confortably corrosion. The transfer of the liquid can be performed with the help of a modest pressurisation. It must be possible, whenever necessary to evacuate vessels and pipes.

3.— *Beam Design* . In order to scale down the size of the mock-up of the target to smaller dimensions and therefore to a modest cost, the beam size must be correspondingly reduced. The beam extracted from the Cyclotron complex has a typical transverse invariant emittance of $\varepsilon_{inv} = 2\ \pi\ 10^{-6}$ rad m[7] (the true emittance is $\varepsilon = \varepsilon_{inv} / \beta\gamma$ where $\beta\gamma$ is the usual relativistic factor), and a momentum spread of the order of a few 10^{-4}. The current density is roughly uniform in the transverse phase-space, leading to an approximately parabolic current density in a focal point. The momentum of a 60 MeV kinetic energy protons is 340.9 MeV/c, corresponding to a magnetic curvature radius[8] of 75.7 cm in a field of 1.5 Tesla and to $\beta\gamma = 0.3415$. As a comparison the 1 GeV beam of the full scale EA has the significantly larger value $\beta\gamma = 1.807$. The actual emittance is therefore $\varepsilon = \varepsilon_{inv} / \beta\gamma = 5.857 \times 10^{-6}\pi$ rad m. As is well known, the beam transverse radial dimensions in each plane are determined by the so-called betatron function $\Delta x(z) = \sqrt{\beta(z)\varepsilon / \pi}$. Over the beam transport channel, typically $\beta(z) \approx 10$ m and the beam radius is $\Delta x \approx 7.65$ mm. Assume we want at the EA beam window $\Delta x \approx 5.0$ mm and therefore $\beta(z) \approx 4.268$ m. There is no problem in designing an appropriate beam transport to satisfy such a requirement. The smallest β value which could be realistically achieved, though with a more complicated optics, is of the order of $\beta = 0.1$ m, corresponding to $\Delta x \approx 0.75$ mm. However such a sharp

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[7] The emittance is usually defined such as to contain about 95 % of the beam current

[8] The beam in the Lacassagne experimental area is already oriented downwards

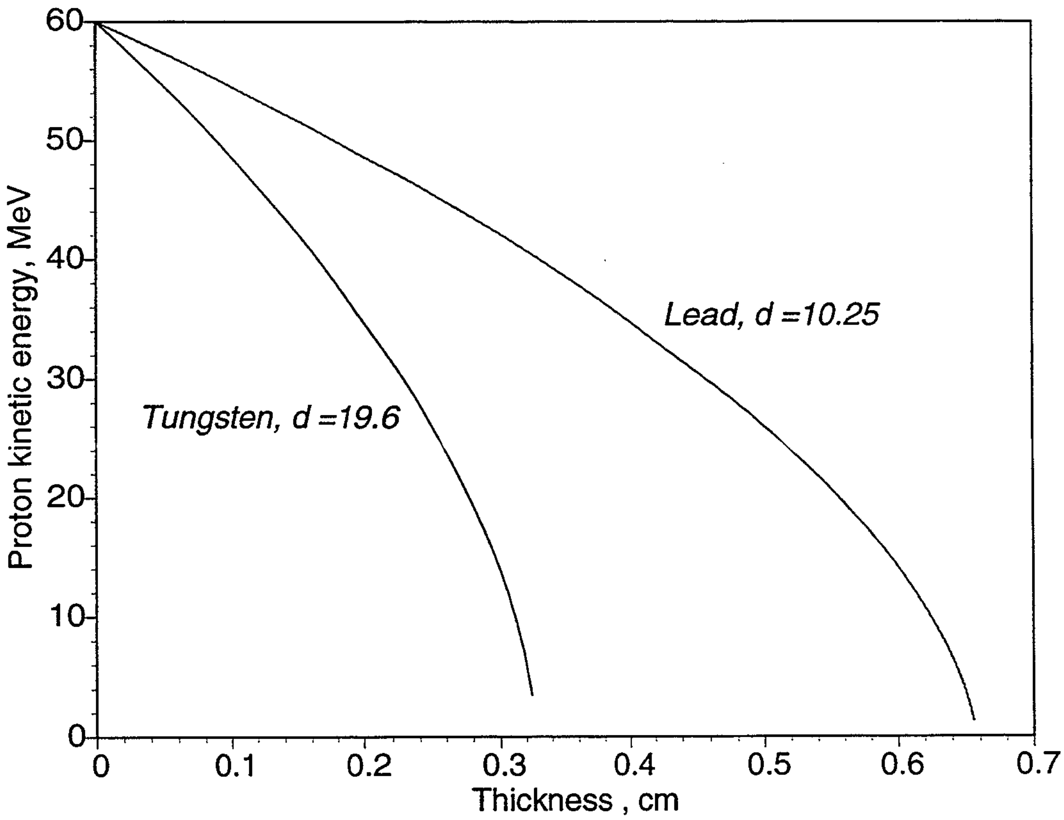

Figure 3. *Energy vs. thickness in cm for 60 MeV protons in Tungsten and Lead.*

focusing will imply a correspondingly larger angular divergence. The angular divergence of the beam given by $\Delta\theta(z)=\sqrt{\varepsilon/\beta(z)\pi}$, which is respectively $\Delta\theta = 7.63$ mrad at $\beta = 0.1$ m and $\Delta\theta = 1.17$ mrad at $\beta = 4.268$ m.

In general, the values of β in the two transverse planes are not equal, especially for low values and one might expect to obtain an elliptically shaped beam. The area is then

$$A = \pi\Delta x\Delta y = \varepsilon\sqrt{\beta_x\beta_y} = 5.857\sqrt{\beta_x(m)\beta_y(m)} \quad [mm^2]$$

where the beta functions values at the target location (focus) are given in meters. Note that the emittance is normally defined as 95% point and therefore the r.m.s. size is about a factor 2 smaller. The general conclusion is that beam area of a fraction of cm^2 is easily obtained with the characteristics of the beam at Lacassagne.

A first estimate ionisation losses of the beam are easily calculated with the Bethe formula. More precise calculations are given in the next Paragraph, using the full FLUKA simulation. The ionisation losses as a function of the Tungsten target and molten Lead depths is shown in Figure 3. Assume the nominal window thickness [2] of 1.5 mm W -Re. The energy lost is $\Delta T = 17.96$ MeV, i.e. 30% of the incoming beam energy. The remaining 70% is deposited in the subsequent Lead over a small thickness of 3.6 mm. Assuming the beam area A (in cm^2), the power densities in the window is then $P_W = 898/A$ $Watt/cm^2$, which compares with the parameters of the final window for $A \approx 1$ cm^2. The volumic power in the Lead is correspondingly larger, $P_v = 5820./A$ $Watt/cm^3$. Proton range is a little more than 3 mm of Tungsten or 6.5 mm of molten Lead.

The neutron spallation yield from both the W and the Lead is of the order of 10^{13} n/s and the corresponding activation very modest. About 10% of the protons interact elastically or inelastically before the end of the range.

Therefore our conditions are very close to the ones of the actual full scale window, while the spallation process, with consequent neutron emission and activation problems is effectively suppressed. These are ideal conditions for a factorized analysis of the phenomenology of the target. The high power density is also sufficient to develop a number of different configurations in realistic conditions.

4.— Cascade simulations . The nuclear cascade in the Window and in the Lead, initiated by the 60 MeV protons can be easily simulated with FLUKA [5]. The geometry of the Window, somewhat arbitrarily has been taken as 1.5 mm thick at the centre of the dome and tapered to 3 mm at the edges, closely resembling to the thickness ands shape to be used for the EA-250 demonstration prototype. The types of energy deposited per beam particle is listed in Table 1. As one can see the ionisation losses are vastly predominant.

Table 1 - Energy depositions.

Type of event	*MeV/proton*	*% of proton k.E.*
Ionisation losses	58.63	97.7
E.M. Cascades	0.42	0.7
Nuclear recoils & heavy fragments	9.35 E-3	
Escaping the system	0.181	0.3
Invisible	0.747	1.2

Table 2. Main secondary products of proton interactions in Window. Data are normalised to 1 Coulomb of proton charge (2×10^4 sec @ 50 μA)

Element	*Lifetime*	*Atom/prot*	*Gram/Coul*	*Cie/Coul*
HF-179	stable	0.950E-05	0.176E-07	—
TA-181	stable	0.200E-04	0.375E-07	—
TA-182	114.4 d	0.200E-04	0.378E-07	0.000
TA-183	5.100 d	0.200E-04	0.380E-07	0.008
W-177	2.250 h	0.200E-04	0.367E-07	0.417
W-178	21.60 d	0.220E-03	0.406E-06	0.020
W-179	37.50 m	0.360E-03	0.668E-06	27.027
W-180	stable	0.700E-03	0.131E-05	—
W-181	121.2 d	0.930E-03	0.175E-05	0.015
W-182	stable	0.170E-02	0.321E-05	—
W-183	0.11E+18 y	0.120E-02	0.228E-05	0.000
W-184	0.30E+18 y	0.180E-02	0.344E-05	0.000
W-185	75.10 d	0.390E-03	0.748E-06	0.010
W-186	stable	0.100E-02	0.193E-05	—
W-187	23.72 h	0.700E-05	0.136E-07	0.014
RE-176	5.300 m	0.200E-04	0.365E-07	10.624
RE-177	14.00 m	0.240E-03	0.441E-06	48.263
RE-178	13.20 m	0.130E-02	0.240E-05	277.266
RE-179	19.50 m	0.210E-02	0.390E-05	303.188
RE-180	2.440 m	0.170E-02	0.317E-05	1961.490
RE-181	19.90 h	0.220E-02	0.413E-05	5.187
RE-182	2.667 d	0.130E-02	0.245E-05	0.953
RE-183	70.00 d	0.940E-03	0.178E-05	0.026
RE-184	38.00 d	0.590E-03	0.113E-05	0.030
RE-185	stable	0.100E-02	0.192E-05	—
RE-186	3.777 d	0.290E-03	0.559E-06	0.150
RE-187	0.43E+11 y	0.940E-03	0.182E-05	0.000
RE-188	16.98 h	0.360E-04	0.702E-07	0.099
OS-179	6.500 m	0.200E-04	0.371E-07	8.663
OS-180	21.50 m	0.260E-03	0.485E-06	34.046
OS-181	1.750 h	0.660E-03	0.124E-05	17.696
OS-182	22.10 h	0.920E-03	0.174E-05	1.953
OS-183	13.00 h	0.900E-03	0.171E-05	3.248
OS-184	0.56E+14 y	0.920E-03	0.176E-05	0.000
OS-185	93.60 d	0.120E-03	0.230E-06	0.003
OS-186	0.21E+16 y	0.120E-03	0.232E-06	0.000
OS-187	stable	0.400E-04	0.776E-07	—

Table 3. Main secondary products of proton interactions in Lead. Data are normalised to 1 Coulomb of proton charge (2×10^4 sec @ 50 μA)

Element	*Lifetime*	*Atom/prot*	*Gram/Coul*	*Cie/Coul*
HG-205	5.200 m	0.920E-05	0.196E-07	4.981
TL-206	4.199 m	0.400E-04	0.855E-07	26.819
TL-207	4.770 m	0.290E-04	0.623E-07	17.116
PB-202	0.527E+05 y	0.800E-04	0.168E-06	0.000
PB-203	2.161 d	0.210E-03	0.442E-06	0.190
PB-204	0.147E+18 y	0.110E-02	0.233E-05	0.000
PB-205	0.157E+08 y	0.130E-02	0.276E-05	0.000
PB-206	stable	0.130E-01	0.278E-04	—
PB-207	stable	0.130E-01	0.279E-04	—
PB-208	stable	0.620E-02	0.134E-04	—
PB-209	3.253 h	0.510E-04	0.111E-06	0.736
BI-202	1.720 h	0.800E-04	0.168E-06	2.182
BI-203	11.76 h	0.540E-03	0.114E-05	2.155
BI-204	11.22 h	0.180E-02	0.381E-05	7.528
BI-205	15.31 d	0.330E-02	0.702E-05	0.421
BI-206	6.243 d	0.360E-02	0.769E-05	1.127
BI-207	31.55 y	0.210E-02	0.451E-05	0.000
BI-208	0.37E+06 y	0.200E-03	0.432E-06	0.000

The probability of an inelastic interaction (star) is 3.6 %, out of which 94.5 % are due to the (primary) protons, the rest (5.5 %) is due to secondary interactions of spallation neutrons. The average number of secondaries per beam particle is 0.252, out of which 45.8 % are neutrons, 50.6% are gamma's and 3.6 % are protons.

The neutron multiplicity is therefore 0.114, i.e. the 50 μA protons (3.12 10^{14} p/s) produce over the full solid angle 3.57 10^{13} neutrons/s. The energy deposited is 1855 Watt in the Lead and 1095 Watt in the Window, normalised to a 50 μA current and a parabolic beam profile with a total width of 1.0 cm. These values are slightly different than the ones given in paragraph 2 since they take into account of the tapering of the window and of the actual beam profile.

Secondary products due to the beam interactions have also been examined. As expected, the spallation process is strongly suppressed and only a few nuclear species are produced, close to elements of the materials. In the case of the Window (see Table 2) the produced elements are Hf, Ta, W , Re and Os. In the case of Lead (see Table 3) we find Hg, Tl, Pb and Bi. The volatile Hg and Tl have a very short lifetime of the order of 5 minutes and therefore constitute no serious problem for a sealed target. The over-all decay of activity has been evolved over a reasonable period of time, including secondaries etc. and it is shown in Figure 4. The activity decays smoothly to a level of the order of 100 mCie/Coulomb after a cool down of about 1000 hours. Therefore metallurgical tests could be performed on irradiated materials without extravagant procedures.

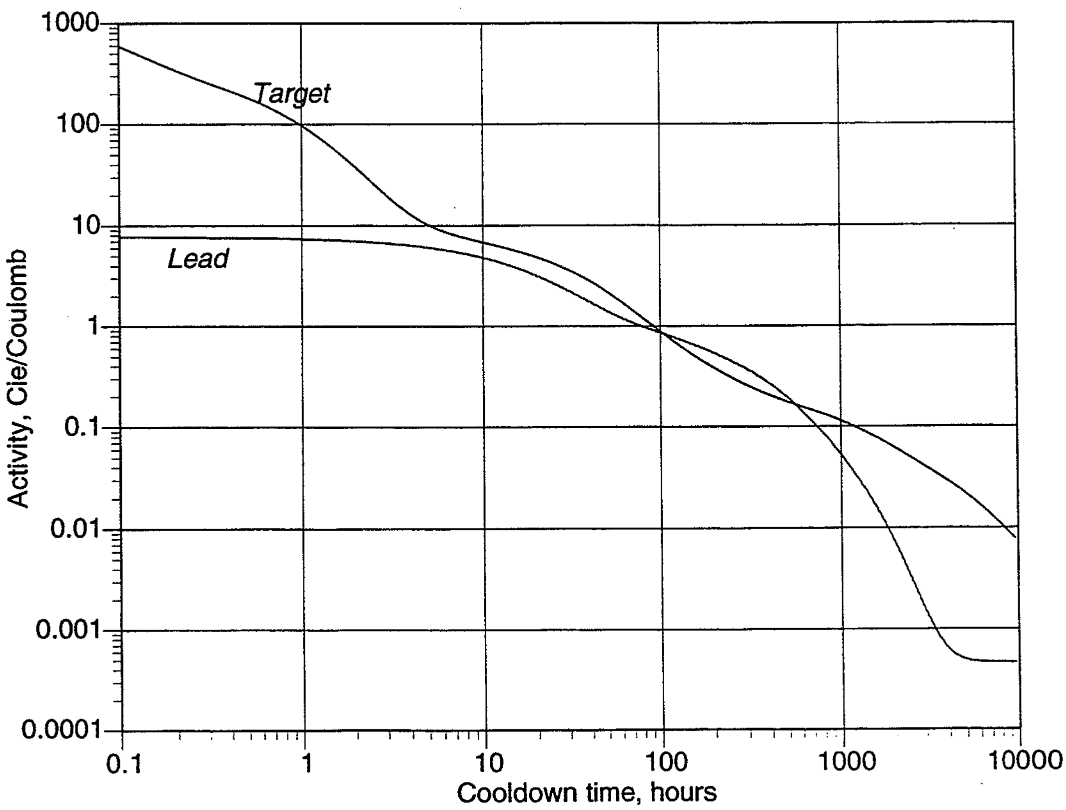

Figure 4. Time dependence of the activity produced by 1 Coulomb of beam charge (2 × 10^4 sec @ 50 μA) in the Target and in the Lead.

Activation of the HT-9 steel beam tube and of the steel outer container of 20 cm diameter is extremely small, as expected because of the modest neutron yield. In the Beam Tube we find 2.82 μCie/Coulomb of ^{51}Cr (27.7 d), 23.5 μCie/Coulomb of ^{55}Fe (2.73 y) and 1.58 μCie/Coulomb of ^{59}Fe (44.5 d). In the case of the outer container we find 14.1 μCie/Coulomb of ^{51}Cr (27.7 d), 64.4 mCie/Coulomb of ^{55}Cr (3.50 m), 23.5 μCie/Coulomb of ^{55}Fe (2.73 y) and 1.1 μCie/Coulomb of ^{59}Fe (44.5 d). These results are based on small statistics and should be taken as indicative.

Within the statistics of the Montecarlo calculation (50000 protons) we find no production of light gases, like He or H. Therefore the gas production is expected to be small. More detailed calculations are in progress.

5.— *Hydrodynamic considerations and modelling* .The full hydrodynamics of the test set-up has been studied with the STAR-CD programme. The beam current has been set to 50 μA and the energy is the nominal 60 MeV. The energy depositions have been extracted from the FLUKA simulation (see above). The beam size has been taken as a parabola with a width of 1 cm at the base. The heat exchanger sets the outlet temperature to 400 °C. In Table 4 we summarise the results of the calculations, which are compared with the EA-250 demonstration plant. Though the beam power is only 7.31 10^{-4} of the one of the full scale device, most of the features around the target are well reproduced. This factor is recovered with the help of the much smaller beam cross section and the power surface density of the beam is about 1/6 of the one of the EA-250. The energy density in the target which has the same thickness in both cases is in the model about 2.77 times larger,once the higher ionisation density of the beam has been taken into account. The power density is directly dependent on the beam radius and it can be varied over a large interval. It is therefore possible to explore power densities well in excess to the ones foreseen for the full scale machine. Such higher power densities are useful for an accelerated aging of the Window.

The Lead flow is smooth and quite comparable to the one of the full scale machine, except that the maximum Lead speed is now only about 0.2 m/s. The maximum temperature in the Window and in the Lead immediately below it are quite comparable in the model and in the full scale machine.

The effects of the local heater to the general flow has been also investigated. A power of 5 kWatt has been injected, right below the window.

Table 4. Comparative list of parameters between the test set-up and the full scale EA-250 demonstration prototype. Parameters with and without an auxiliary 5 kWatt heater are shown.

Target: preliminary parameters	*EA 250*	*NICE*	
Beam kinetic energy	350	60	MeV
Nominal beam current	11.7	0.05	mA
Nominal beam power	4.1	0.003	MW
Beam radius at spallation target	7.5	0.5	cm
Beam area	176	0.78	cm^2
Beam power density	23.3	3.84	kW/cm^2
Beam pipe material	HT-9	HT-9	
Beam pipe shape	cylind.	cylindrical	
Beam pipe length	≈ 10	≈ 1	m
Beam pipe external diameter	20	0.2	cm
Spallation target and cooling material	Lead	Liq. Lead	
Pumping method	N.Conv	Nat. Conv.	
Separated spallation source	yes	yes	
Container material	HT-9	HT-9	
Container shape	cylind.	cylindrical	
Container radius	22.5	10	cm
Beam window material	W-Re (26)	W-Re (26)	
Beam window thickness (edge, centre)	3.0, 1.5	3.0, 1.5	mm

	EA 250	*no heater*	*5 kW heater*	
Maximum heat flux in window	807	2239	2239	W/cm^2
Maximum temperature in window	867	1074	1064	°C
Heat deposition in the window	89	1.1	1.1	kW
Lead maximum speed in funnel	1.52	0.2	0.32	m/s
Lead average speed in ascending column	0.465	0.035	0.052	m/s
Lead coolant mass flow	169	0.56	0.82	Kg/s
Heat deposition in the lead	3150	1.86	1.86	kW
Maximum Lead temperature	693	914	894	°C
Average Lead temp @ inlet Heat Exch.	526	418	436	°C

There is a small increase of Lead speed and a better uniformization of the flow. The heater action will be replaced in the full scale device by the spallation region.

The predicted flow pattern is shown in Figure 5. There is little difference with or without auxiliary heater. In Figure 6 the corresponding temperature distribution is given, evidencing the rather sharp temperature rise in the narrow region in which the proton beam is active. The temperature diagram in the Window is shown in Figure 7. We remark the over-all similarity between the test device and the full scale unit, in spite of the very large differences in power.

6.— *Conclusions* . In spite of the relatively modest power and energy, the Lacassagne Cyclotron permits to create conditions of specific power density and of activation for the Target Window which are well within the range of values relevant to a full scale EA. *The Window will be exposed simultaneously to the (1)heat, (2) radiation damage and (3) the (potentially corrosive) contact with hot molten Lead.* In view of the remarkable similarity of the general conditions of the window environment, the small scale model would permit to study the main features of the final Target Window, the presence of Lead convection, etc., but in conditions of table-top dimensions and easy experimentation. In addition, the absence of the large neutron yield due to spallation reduces considerably the activation of the device and permits an easy access to the various parts of the set-up. The small size of the device minimises risks in the eventuality of accidents, which are likely to occur during the early phase of testing of such a novel technology.

A variety of different technical solutions could be realistically tested at low cost and their performances directly compared. Results can be continuously related to computer calculations, since most of the thermodynamical features, f.i. temperatures and liquid motions can be accurately measured. We believe that an ultimate smooth operation of the Nice Model would greatly simplify the design and the operation of the final target.

In our view, this programme should be started at once.

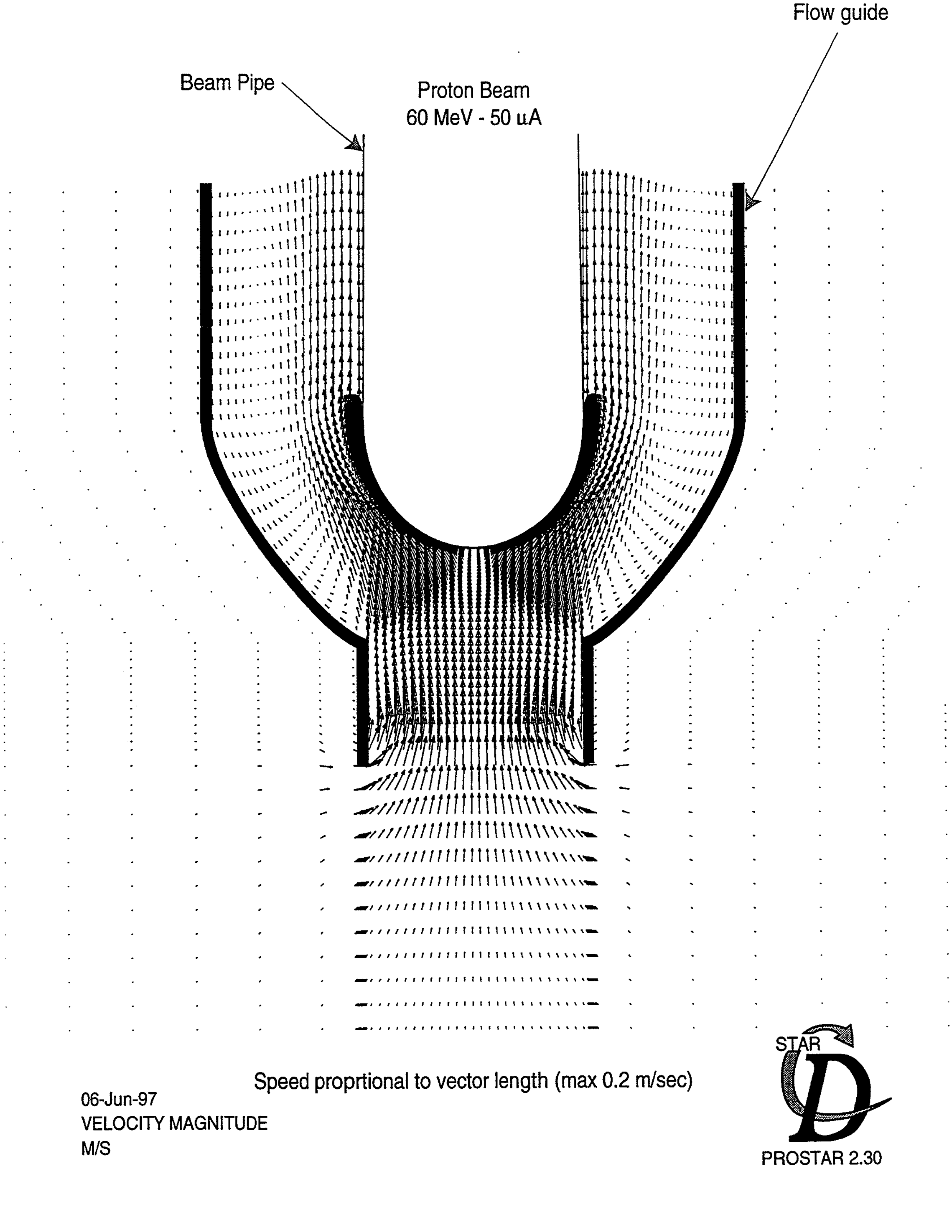

Figure 5. Predicted flow diagram for the test set-up and no auxiliary heater. The speed is proportional to the vector length.

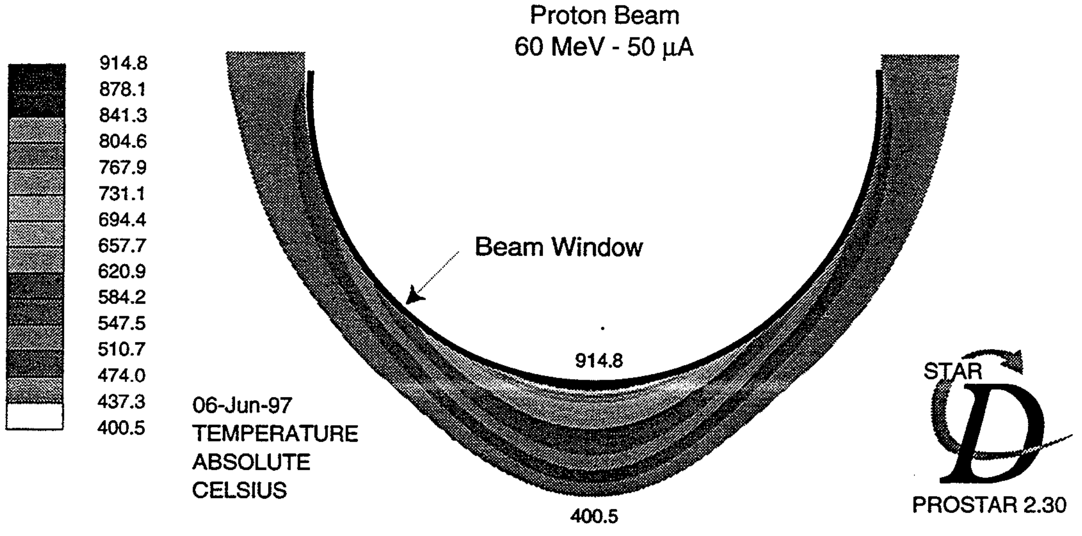

Figure 6. Temperature distribution in the immediate vicinity of the beam window. One notices the sharp temperature rise in correspondence to the region heated by the beam.

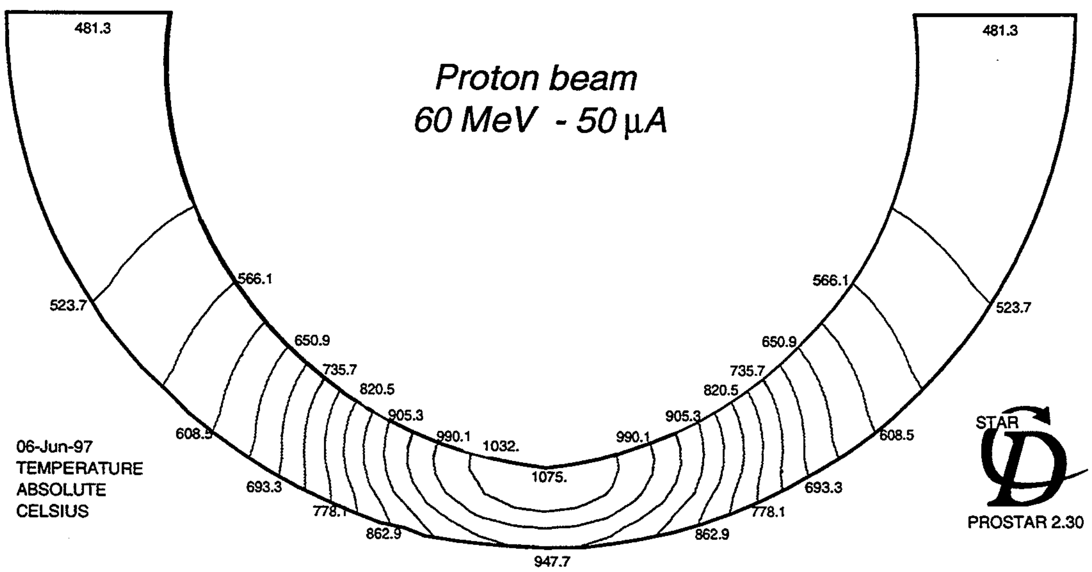

Figure 7. Temperature distribution inside the beam window. One notices the sharp temperature rise in correspondence to the region heated by the beam.

REFERENCES.

[1] C. Rubbia et al, "Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier", CERN/AT/95-44 (ET), 29th September 1995.

[2] Paper in preparation.

[3] The final machine has power of the order of 1 GWatt thermal and it is intended as an on-line incinerator for the Waste of a single LWR's

[4] F. Venneri and V. Gudowsky, private communications

[5] FLUKA has been written by A. Ferrari (Milano)