ICANS-XIV
14th Meeting of the International Collaboration
on Advanced Neutron Sources
June 14-19, 1998
Starved Rock Lodge, Utica, Illinois, USA

Measurement of Pressure Wave in Mercury Target

M. Futakawa[1)], K. Kikuchi[1)], H. Conrad[2)], H.Stechemesser[2)],
and ASTE collaboration

1) Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan
2) Forschungszentrum Jülich GmbH,D-52425 Jülich Germany

ABSTRACT

The international ASTE (AGS Spallation Target Experiment) collaboration has performed a first series of measurements on a spallation neutron source target at the AGS (Alternating Gradient Synchrotron) in Brookhaven. The dynamic response of a liquid mercury target hit by high power proton pulses of about 40 ns duration has been measured by a laser Doppler technique and compared with finite elements calculations using the ABAQUS code. It is shown that the calculation can describe the experimental results for at least the time up to 100 μs after the pulse injection.

1. INTRODUCTION

Recently, worldwide efforts have done into planning and designing third generation spallation neutron sources. Mainly neutronics considerations have indicated that multi-MW sources may essentially benefit from using a liquid metal target and have led the ESS (European Spallation Source) project staff to propose mercury as the preferred target material. Both the US and the Japanese spallation source projects have come to the same conclusion and are pursuing the mercury target option, too.

On the other hand, one of the major problems with liquid targets is the pressure waves generated by the rapid energy deposition during the microsecond proton pulses. When the co investigate ntainer wall is struck, these waves may induce stresses over permissible limit. In order to investigate experimentally this phenomenon and also several other relevant topics under realistic conditions, an international collaboration has been established comprising institutions from Europe, Japan and the US (in alphabetic order). The collaboration has planned, installed and started to operate in 1997 with a scale mercury target at the AGS (Alternating Gradient Synchrotron) in Brookhaven. Being a versatile and powerful proton accelerator the AGS can be operated over a wide range of particle energies from 1.5 to 24 GeV.

The stress wave propagation on the container wall has been caught by measuring the time dependent strains employing two different methods, one of which (a Laser Doppler technique) is presented in this paper. The other (a fiber optic strain gauge method) will be published elsewhere. In this paper we report on the first stress and pressure measurements during the 1997 series of experiments of the ASTE collaboration and compare the experimental results with finite element calculations using the ABAQUS code[(1)].

2. EXPERIMENT

2.1 Stress wave measurement

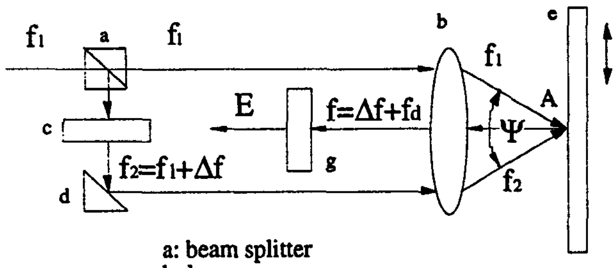
(1) Laser Doppler technique

The laser Doppler meters were made to measure the associated in-plane displacement to the preferable direction. A velocity at a point on the moving object is obtained by a frequency change of the echoed laser signal. A laser beam emitted from a laser beam source is split into two beams: one shots the particular point A on the moving object and the other beam also shots the same point but after passing through a frequency shifter that changes the frequency from f_1 to f_2 where $f_2=f_1+\Delta f$. When the moving object goes to the top direction, the frequency reflected from the point will be signed by the Doppler effect (Fig.1). The frequency of the reflected beam will be shifted by f_d defined by the next equation,

$$f_d = \frac{2V_A}{\Lambda}\sin\frac{\Psi}{2} \qquad \text{...1}$$

where V_A: the velocity of the moving object at the point A, Λ: a wave length of the laser beam, $\psi/2$: an angle of the beam against the moving object as shown in Fig.1. Finally the velocity V_A at the point A, proportional to the voltage converted from the frequency could be found by the next equation.

$$V_A = \frac{f_d \Lambda}{2\sin(\Psi/2)} \qquad \text{...2}$$



a: beam splitter
b: lens
c: frequency shifter
d: mirror
e: moving object
g: frequency voltage convertor

Fig. 1 A beam path in the laser probe.

A displacement X_A at the point A will be given by integrating the velocity as follows:

$$X_A = \int_0^t V_A dt \qquad \text{...3}$$

(2) Non-contact dynamic strain measuring system

A non-contact dynamic strain probe using the laser Doppler technique was developed by JAERI and ONOSOKKI Co. Ltd.. We used a He-Ne laser at 632.8nm of the wavelength. The performance of frequency response is up to 1MHz. The laser strain probe consists of two laser probe heading in the same direction as shown in Fig.2. The strain ε in defined by a relative displacement between two points and gauge length L.

$$\varepsilon = \frac{X_A - X_B}{L} \qquad \text{...4}$$

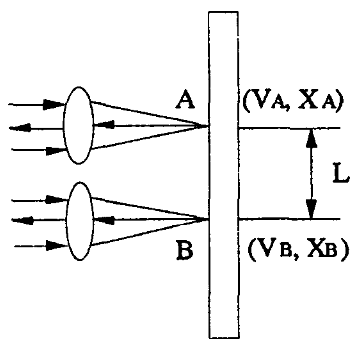


Fig.2 Laser strain probe.

Signals were transmitted to a wave memory, type AR4400 YOKOGAWA Co. Ltd., through a 50-meter optical fibre, FUJIKURA Co. Ltd., type GI, 50 μm in core diameter. The sampling rate is 1/μs for 4 channels. A piezo type accelerometer, Endevco Co. Ltd., type 7259A, was attached to the sensor box mounted to the rod for monitoring a swing induced by a vibration of the target container (Fig.3). All electric circuits were apart from the target container outside the U-line of the AGS and laser beams pass through an optical fibre in the area of proton field.

In this experiment, the intensity in one of two beams was not sufficient by an unsuitable alignment of the sensor head suffered from perturbation after final adjustment. We concentrated to get focusing of just one laser beam line. This means that only a velocity or a displacement at a point will be measured hopefully.

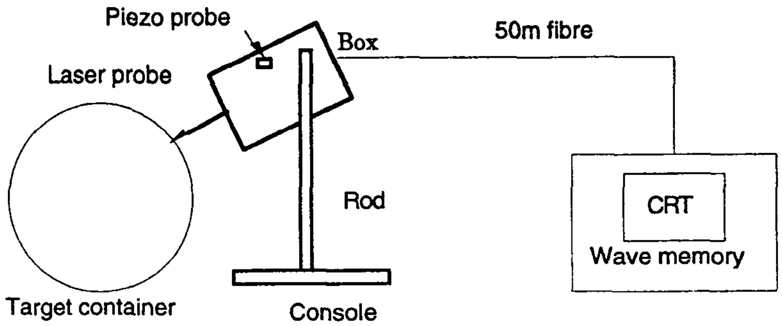


Fig.3 Measuring system.

2.2 Target container

A cylindrical target container with a hemispherical proton beam window has been manufactured at Forschungszentrum Juelich. The material used is the Chromium-Nickel steel X10CrNiMoTi18 10 (German norm DIN 1.4571). The proton beam window has been machined from a solid piece and welded to the cylindrical part, which both have a thickness of 2.5 mm. The hemispherical part including the welding has been polished and super-finished to yield the optimum surface quality. The downstream end of the 1.3 m long container with an inner diameter of 20 cm is closed by a 2.5 cm thick flange designed so as to withstand even a stationary internal pressure of 1.2 MPa without weakening the gas-tight seal.

The laser probe was mounted on the console plate attached on the secondary container using by M6 screw holes on a 40 x 80mm pitch. The plate was set over distance of 400 mm starting from the apex of the hemispherical cap. Although the probe was scheduled to shot some of hemispherical surface, a measuring point was changed to the cylindrical part on the target because there was not enough space for adjusting a focus of the beam. A suitable position for the strain measurement was found 300 mm behind the apex at an angel of 30 degree from the top, 200 mm downstream from a transition part of hemispherical part, after sharing a position with neutron sampling rod (Fig.4).

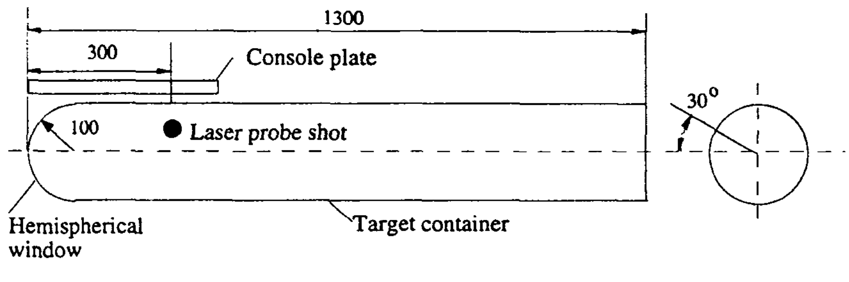


Fig. 4 Top view of the target container: all unit: mm.

3. Calculation for pressure and stress waves propagation in the container

3.1 Calculation model

Number of protons delivered from the AGS accelerator enter into the mercury target. In the target the particles produced in the course of spallation reaction generate an intense nuclear heat that causes pressure waves in the target material and stress waves in the target container.

The equation of motion for an elastic body is described by Eqs.5 and 6 in the polar system if the body force doesn't work

$$\frac{\partial^2 \bar{u}}{\partial t^2} = \frac{\eta + 2G}{\rho} \nabla^2 \bar{u} \qquad \text{...5}$$

$$\nabla = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} \qquad \text{...6}$$

where $\bar{u}$: displacement vector, η: elastic constant(=G(2G-E)/(E-3G)), G: modulus of rigidity, ρ: density, (r, θ): polar coordinates. The stress will propagate at the speed of sound in the material as follows:

$$\left(\frac{\lambda + 2G}{\rho}\right)^{1/2} = \left(\frac{3K + 4G}{3\rho}\right)^{1/2} \qquad \text{...7}$$

where K: the bulk modulus, λ: a material constant.

There are two driving forces for the stress occurred in the container: one is the instantaneous thermal expansion of the target material and the other is the pressure wave of the target material that expands the container. The target material is modeled by using CAX4R, axi-symmetric 4-point solid element, from the element library of ABAQUS(1) in the computer simulation. That is, the liquid behavior of mercury is represented by the solid element which has an apparent Young's modulus E to be coincident with the bulk modulus K of the target materials described by K=E/3(1-2ν) and G=E/2(1+ν). Poisson's ratio ν is nearly 0.5, meaning that a shear force might be negligible(2). Consequently the equation of motion is given by the pressure of mercury p for the target coolant material,

$$\frac{\partial^2 p}{\partial t^2} = \frac{K}{\rho}\nabla^2 p. \qquad \text{...8}$$

The container is modeled by using SAX1, axi-symmetric shell element. In the axi-symmetric shell structure both bending and membrane forces will occur. The basic equations of motion are given by the displacement u, for example,

$$\frac{\partial^2 \bar{u}}{\partial t^2} = \frac{E}{\rho}\nabla^2 \bar{u} \qquad \text{...9}$$

The contacting boundary condition between the mercury and the container wall is allowed the force to convey discountinuously between them.

3.2 Deposited energy

The magnitude of stress and pressure waves generated in the container is very strongly dependent on the total deposited energy into the mercury target and its distribution. There is, however, not an exact information of the beam profile measured by the imaging plate(IP) at 24GeV run when the pressure wave was successfully measured but the beam profile for integrated multi-shots(3). In fact the maximum intensity of the proton projection normal to the beam line located 1 cm apart from the centre of the target window. It is announced that two bunches were delivered at 24GeV and the number of protons for two bunch was about 8×10^{12}. The total energy deposition in the mercury target is found to be 18.7 kJ for two bunches, as a result of the temperature measurement(PSI)(5). There are two ways to know the energy deposition over the target space. The direct ways to describe the energy deposition in the target is produced by the temperature measurement(PSI)(5). The distributed function shapes an ellipse,

$$q(r,z) = \eta\left[1-\exp\left(-\frac{z+1.2}{8.5}\right)\right]\exp\left(-\frac{z}{18}\right)\left[1-\sqrt{\left(\frac{x-x_o}{A(z)}\right)^2+\left(\frac{y-y_o}{B(z)}\right)^2}\right] \quad ...10$$

where $A(z)=8.3583+0.002125z^2$, $B(z)=5.9+0.0015z^2$, x_o=-0.5 (cm), y_o=-1.0 cm. This is modified to circle for easy calculation under the condition of the same deposition energy.

The indirect ways is to use the IP profile measured by JAERI with a help of the HERMES(4) code calculation. Equation 11 shows a distribution function of the energy deposition in the mercury target in this way,

$$q(r,z) = \xi\left[1-\exp\left(-\frac{z+3.09}{13.7}\right)\right]\exp\left(-\frac{z}{13.7}\right)\exp\left[-\frac{r^2}{2(2.88+0.00476z^2)}\right] \quad ...11$$

where z: a distance along the centre axis from the top of the mercury target, r: a radial distance.: A fitting parameter ξ to the total energy deposition is decided by integrating the temperature distribution measured by PSI.

Figure 6 shows the distribution of energy deposition in the target to z direction(left) and to radial direction(right).

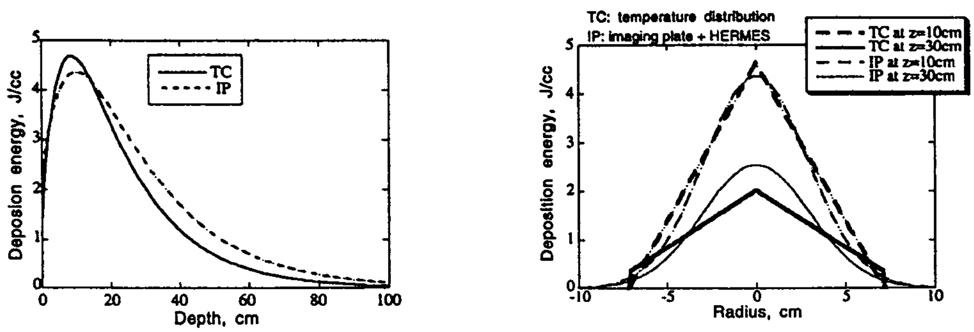


Fig.6 Energy deposition in the target.
q(r,z)=11.0*(1-Exp[-(z+1.2)/8.5])*Exp[-z/18.0]*(1-r/(7.0+0.00181*z^2))*
(1/(1+(r/(7.0+0.00181*r^2))^1000)) for TC equation.

4. Results

4.1 Signals obtained from the laser strain prove

A stress wave propagation on the container wall was successfully measured at 24 GeV with the highest proton intensity about 4×10^{12}, AGS announced. In the other energy levels as 1.5 and 7 GeV, no signal was observed by the laser Doppler probe. Next two CRT images copied in the AGS site showed signs of pressure waves at the first and the second bunches at 24GeV energy.

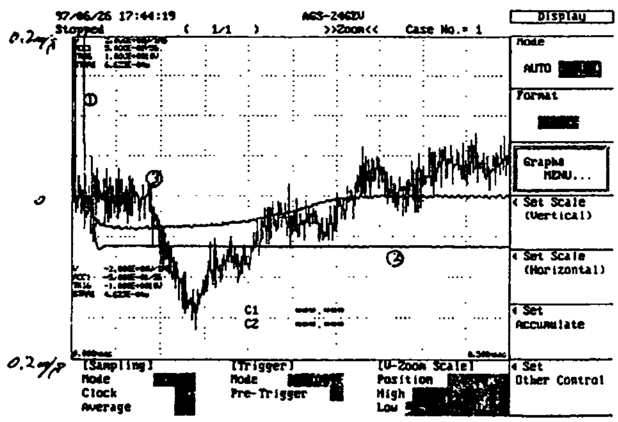


Fig.7 CRT image of the first bunch.

2nd bunch, ΔT/

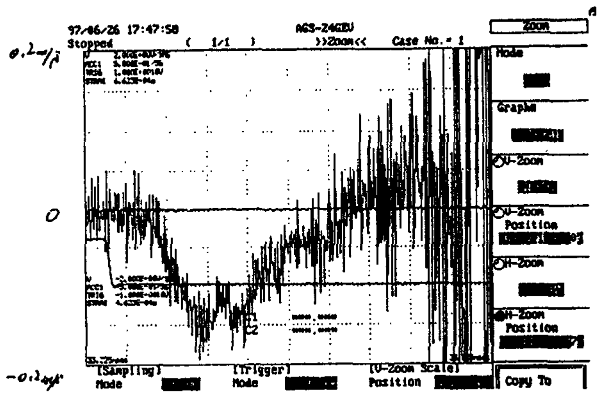


Fig.8 CRT image of the second bunch.

The accelerometer signal, signal “2” in Fig.7, dropped immediately just after a proton beam was injected into a target because over currency was caused by the injected protons. The drop was decided to the time when protons injected into the target. Signal “3” indicates a velocity of the deformation for the target. Signal "1" is a trigger from AGS. It must be stressed on the reproducible for pressure wave in the first and the second bunches (Fig.8).

Figure 9 shows whole history of pressure wave stored in the wave memory for the first bunch. Around 15 ms after the proton injection the vibration of about 5 ms period was observed. It seems to be caused by the natural vibration of the sensor rod, ϕ 30 mm x L300 mm(see Fig.4).

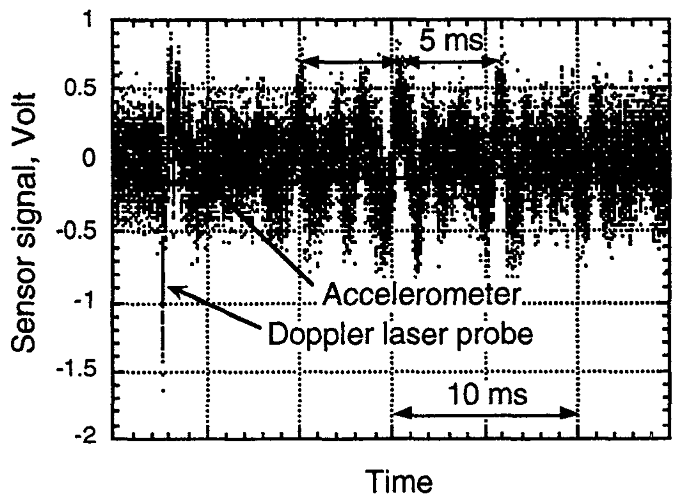


Fig.9 Time response of velocity during 25 ms after first bunch of proton.

4.2 Comparison between experiment and calculated results

Figure 10 shows a comparison between the experimental result for the first bunch and the calculation results. Fig.11 is a replotting of Fig.10 on the short range mat. The target container started to response against the pressure wave at a time of 60 μs and showed the maximum velocity after a couple of tens micron seconds. Calculations followed the decent of velocity before a change of movement. Two calculation results were shown by the different deposition energy distribution in the target. The energy deposition function affected the level of peak values but not the frequency composition of stress waves. Large pressure waves at a period of 500 μs resulted in a superimpose with reflected waves from a bottom of the target container. This phenomena is also plotted by the calculations.

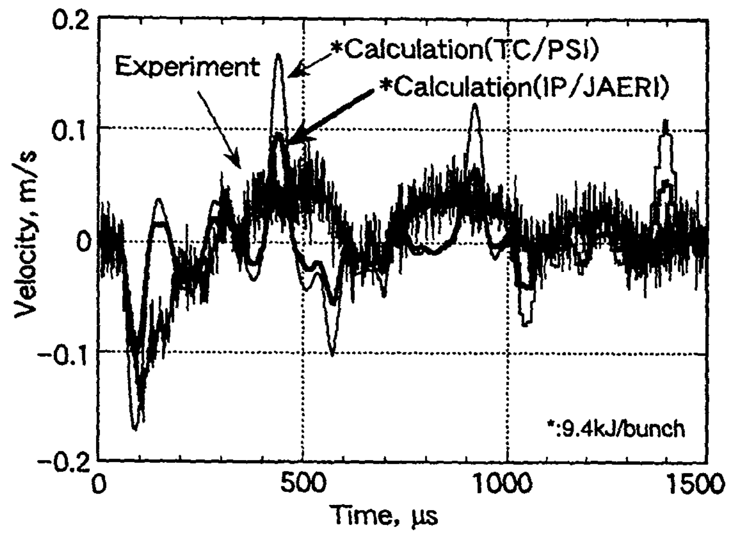


Fig.10 Comparison between experiment and calculation results

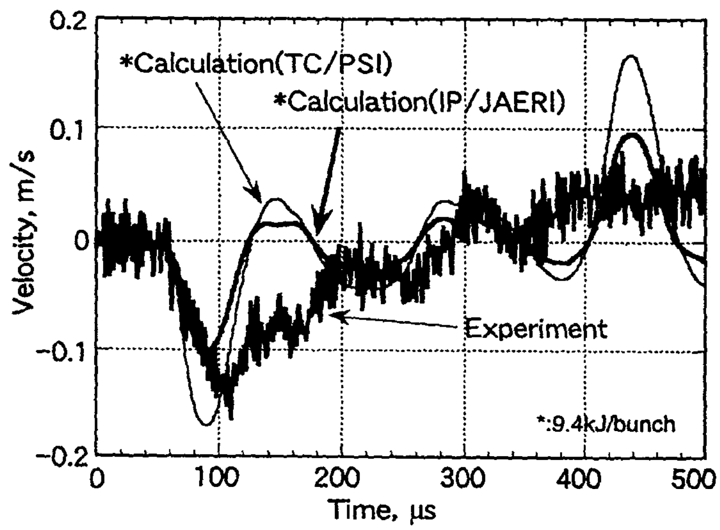


Fig.11 Comparison between experiment and calculation results in the short range of Fig.10.

5. Conclusion

Although the dynamic response of the liquid mercury target container was successfully caught by the non-contact dynamic strain prove using the laser Doppler technique under the present harsh radiation conditions, we don't have a good coincidence on velocity waves between experiment and calculation except for the first 100 μs. For the pressure wave measurement an exact temperature distribution in the target will be necessary for the calculation works of the first response in the target container. A success of the measurement on mercury pressure in the container scheduled in the 1998 test run will decide the state of the mercury, fluid or cavity ?, and the interactive motion between the solid container and the mercury target.

References

(1) Hibbitt, Karlsson & Sorensen, ABAQUS/Explicit Version 5-6.
(2) S Ishikura, K Kikuchi, M Futakawa, R Hino, Transient Stress Wave in a Heavy Liquid-Metal System at High Intensity Proton-Accelerator, ICM&M'97, pp.89-94,(1997).
(3) H Nakashima, et al., Beam profile measurement in AGS experiment.
(4) P Cloth, D Filges, R D Neef, G Sterzenbach, Ch Reul, T W Armstrong, B L Colborn, B Anders and H Bruckmann, KFA Jul-2203, (1988).
(5) G S Bauer, et al., Temperature measurement in AGS experiment.