Abstract. Intense beams of energetic heavy ions from SIS-18 at GSI can heat extended volumes of condensed matter to a temperature of several eV. The matter at about solid density and a temperature near or above the Fermi temperature is referred to as “Warm Dense Matter” (WDM). The knowledge of radiative properties and the equation of state of WDM is particularly limited because standard perturbative theoretical approaches are not applicable in this regime. The kilojoule PHELIX laser at GSI can be used to produce X-rays of several keV energy for scattering diagnostics of ion beam heated matter. In this paper special target configurations for compression and isochoric heating of matter with heavy ions are presented. The possibilities of X-ray scattering diagnostics of such targets are discussed. The target parameters achievable with the new FAIR facility are calculated.

1. Introduction
With increasing of available intensities, heating of condensed matter with beams of energetic heavy ions becomes a promising way for production of Warm Dense Matter [1] in the laboratory. The ions with energies of several 100 MeV/u deposit their energy quite homogeneously over a distance $\gtrsim 1$ mm as long as the Bragg peak stays outside the sample. The total specific energy deposited by the ion beam in the target can be determined with good accuracy, if the ion beam characteristics are measured. The stopping power of a single ion is well known for most materials. For targets near solid density and temperatures of several eV stopping data the cold material can be used.

Intense energetic heavy ion beams are able to heat extended volumes of condensed matter to temperatures corresponding to the WDM regime. To perform accurate measurements of the material properties, a special target design is needed. If the target is heated isochorically, and the deposited energy is known, every measured physical quantity is defined as a function of density and internal energy. This means, that one has to measure only one thermodynamic quantity, for example temperature, to obtain equation of state data. The ion pulse length for the isochoric heating is limited by the deposited energy and the focal spot size of the beam. The ion pulses at GSI and FAIR are too long to heat a bare sample of matter isochorically to
interesting temperatures and a special confinement scheme has to be applied. The region of the phase diagram which can be investigated with heavy ion beams can be extended to compressed matter. A crucial point in the target configuration for the compression experiments, as well as for the isochoric heating, is the possibility of the diagnostic access to the target interior.

The WDM-collaboration was formed to investigate radiative properties of warm dense matter created with heavy ion beams at GSI and FAIR [2, 3, 4]. The collaboration currently involves more than 20 laboratories from Germany, USA, Japan, France, UK and Russia. The WDM-collaboration proposes to use X-ray scattering diagnostics driven by the PHELIX laser at GSI to perform atomic and radiation physics research in warm dense matter created with the ion beams. X-ray scattering was demonstrated as a diagnostic for warm dense matter by different authors in recent years [5, 6]. The use of this diagnostic requires a homogeneous target volume and excludes high-Z target materials due to the high absorption. In this paper we present target configurations suitable for WDM research at GSI and FAIR fulfilling these requirements.

2. Target configurations for the SIS-18 ion beam

Isochoric heating of a bare sample can be realized if the ion beam pulse is shorter than the target expansion time. The SIS-18 machine at GSI will be able to deliver up to $1.5 \times 10^{11}$ $U^{28+}$ ions of 200 MeV/u in a 100 ns pulse [7]. Focused down to $r_b = 350 \mu m$ (spot radius) this beam will deposit – for example in solid hydrogen – $P_b = 4.5$ TW/g of specific power. To describe hydrodynamic response of the ion beam heated matter an analytical equation of state can be written as

$$p = p(\rho, \epsilon) = c_0^2 (\rho - \rho_0) + \Gamma \rho \epsilon,$$  

(1)

where $c_0$ is the initial sound speed, $\rho_0$ is the initial density, and $\Gamma$ is the Grüneisen parameter of the material. Using $(\partial \epsilon/\partial \rho)_S = P/\rho^2$ the sound speed at $\rho = \rho_0$ becomes

$$c = (c_0^2 + \Gamma (\Gamma + 1) \epsilon) \epsilon^{1/2}.$$  

(2)

Consider a cylindrical target of radius $R_0 = r_b$, heated with an ion beam with a rectangular radial profile. The specific internal energy will initially rise with time as $\epsilon = P_b t$. A rarefaction wave, propagating with the sound speed into the heated volume, arrives at the center of the target at time $t_H$. From

$$R_0 = \int_0^{t_H} (c_0^2 + \Gamma (\Gamma + 1) P_b t)^{1/2} dt$$  

(3)

one obtains the effective heating time $t_H$. For solid hydrogen irradiated with the SIS-18 beam parameters as mentioned above the effective heating time is $t_H = 39$ ns, which is less that the ion pulse duration ($c_0 = 2.1 \cdot 10^5$ cm/sec, $\Gamma = 2/3$). Assuming $c_0^2 \ll \Gamma (\Gamma + 1) \epsilon$ and $\Gamma (\Gamma + 1) = 1$, one gets a simplified estimation $t_H = (9R_0^2/4P_b)^{1/3}$, as obtained in [8].

The calculation of the effective heating has shown that the isochoric heating of a bare sample with the SIS-18 ion beam is not possible for a small focal spot considered above. In the reference [9] the authors proposed a target configuration called “dynamic confinement” which allows us to maintain a cylindrical sample of constant density without using high-Z shells. The calculations presented in this paper were performed for the SIS-18 ion beam parameters which will be available for the experiments. Quasi-isochoric heating is provided by a thin low-Z tamper heated by the wings of the Gaussian ion beam to produce confining pressure on the core target material. Using spherical geometry can improve the dynamic confinement scheme significantly [10]. The spherical targets provide better temperature homogeneity in the target core, larger mass of confined material, and a low linear density of the tamper after irradiation. The spherical target can be used for a wider range of ion energies compared to the cylindrical case.
The dynamically confined targets are well suited for X-ray scattering diagnostics. In reference [10], scattering spectra of the integrated target have been calculated. It was shown, that the problem of overlapping peaks originating from photons scattered in the shell and the target core can be circumvented by a spacial resolution of the spectrometer and spectral discrimination by variation of the scatter angle.

Compressed matter in the WDM regime can be prepared using energetic SIS-18 ion beams in a way suitable for the X-ray scattering. The spherical target geometry can be optimized to achieve compression of the core target material. To show the capabilities of the SIS-18 beam, we considered a solid hydrogen core surrounded by a carbon shell with a density of 2.25 g/cm$^3$. The ion beam consists of $10^{11}$ ions of U$^{28+}$ with 200 MeV/u focused down to 1 mm spot (FWHM). A parabolic temporal profile of 100 ns length is assumed. The initial radius of hydrogen is $r_0 = 350 \mu$m, the tamper has a thickness of 150 $\mu$m.

Figure 1 shows the distributions of the normalized density of the core, $\rho/\rho_0$ in length-radius plane for different times; $\rho_0$ is the initial density of hydrogen. During the heating time the pressure in the carbon shell exceeds the pressure in the hydrogen core and the H/C interface moves inwards. This pressure gradient launches a weak shock propagating towards the center of the core ($t = 50$ ns). Later, at $t = 80$ ns the reflected shock moves back. It arrives at the H/C interface at the end of the ion beam pulse, so that at $t = 100$ ns the compressed core is very homogeneous as it can be seen from the $\rho/\rho_0$ profiles. The hydrogen is compressed by a factor of 1.8 and has according to the calculations an almost uniform temperature of 0.6 eV. The expanded low-Z tamper allows X-ray scattering diagnostics. The proposed compression scheme utilizes a Gaussian ion beam profile without the need for special beam shaping techniques.
3. Target configurations for the FAIR facility

A new accelerator FAIR (Facility for Antiproton and Ion Research) is currently under construction at GSI. For plasma physics experiments up to $5 \times 10^{11}$ ions of $U^{28+}$ accelerated to 400 MeV/u will be delivered in a 70 ns pulse [11]. A focal spot radius $r_b = 350 \mu m$ is assumed for the calculations. Estimation of the effective heating time results in $t_H = 26$ ns, which is shorter than the designed pulse length for the machine. This means that to heat matter isochorically with the FAIR-beam target configuration similar to the dynamic confinement proposed for the SIS-18 beam parameters should be used. In table 1 the target parameters which can be achieved with FAIR and SIS-18 beam are compared assuming isochoric heating of solid hydrogen. The temperature is calculated using the SESAME table.

|                  | SIS-18 | FAIR |
|------------------|--------|------|
| Energy, MeV/u    | 200    | 400  |
| Number of ions   | $1.5 \times 10^{11}$ | $5 \times 10^{11}$ |
| Specific energy, kJ/g | 450    | 1050 |
| Temperature, eV   | 2      | 4.2  |

4. Conclusion

Intense energetic heavy ions at GSI and FAIR can be used to create extended volumes of matter in the WDM regime. However, GSI and FAIR ion pulses are too long compared to the hydrodynamic time scale of the target response and can not provide isochoric heating of bare samples of condensed matter for a small focal spot. The use of a low-Z shell allows to heat matter isochorically or to compress target samples in a way suitable for X-ray scattering diagnostics. Intensity growth at the new FAIR machine will lead to a temperature increase by about factor of 2 compared to GSI.

References

[1] Lee R W, Moon S J, Chung H, Rozmus W, Baldis H A, Gregori G, Cauble R C, Landen O L, Wark J S, Ng A, Rose S J, Lewis C L, Riley D, Gauthier J, Audebert P 2003 J. Opt. Soc. Am. B 20 770
[2] http://www.gsi.de/phelix/Experiments/FAIR/WDM
[3] FAIR Newsletter, No. 2 (April 2006), p. 14, http://www-win.gsi.de/Fair-Newsletter/
[4] FAIR Baseline Technical Report 2006, vol. 5, paragraph 5.3 "WDM-Radiative Properties of Warm Dense Matter Produced by Intense Heavy Ion Beams", http://www.gsi.de/fair/reports/btr.html
[5] Riley D, Woolsey N C, McSherry D, Weaver I, Djaoui A, and Nardi E 2000 Phys. Rev. Lett. 84 1704
[6] Glenzer S H, Gregori G, Lee R W, Rogers F J, Pollaine S W, and Landen O L 2003 Phys. Rev. Lett. 90 175002
[7] Spiller P J, Barth W, Dahl L A, Eickhoff H, Hollinger R, Spaedtke P S 2006 EPAC 2006 Proceedings Edinburgh, Scotland 26 30 Juni, p. 24
[8] Arnold R C and Meyer-ter-Vehn J 1988 Atoms, Molecules and Clusters 9 65
[9] Kozyrev A, Basko M, Rosmej F, Schlegel T, Tauschwitz A, and Hoffmann D H H 2003 Phys. Rev. E 68 056406
[10] Tauschwitz An, Maruhn J A, Riley D, Shabbir Naz G, Rosmej F B, Borneis S, Tauschwitz A 2007 High Energy Density Physics (in print)
[11] Boine-Frankenheim O, Lehrach A, Spiller P, Steck M 2007 Beam Parameters of the International Facility for Antiproton and Ion Research FAIR (GSI internal report)