RELEASE OF H AND He FROM TiC, STAINLESS STEEL ANDGRAPHITE BY PULSED ELECTRON AND FURNACE HEATING*

S. T. Picraux and W. R. Wampler
 Sandia National Laboratories†
 Albuquerque, New Mexico 87185

MASTER**ABSTRACT**

DISCLAIMER
 This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The release of implanted D and ³He from TiC coatings, SS 304 and graphite by pulsed electron beam (e-beam) heating and furnace heating has been investigated. Low fluence implants of D or ³He and saturation fluence D implants have been studied for 0.5 - 1.5 keV D and 3 keV ³He. The retained D or ³He was monitored by ion beam analysis. The 50 ns e-beam pulsing resulted in the release of D in all materials and was compared with release during isochronal annealing in a furnace. A substantial enhancement in the fractional D release was found for D saturated TiC (0.25 D to host atom ratio) compared with low fluence implants. In contrast no enhancement of D release was observed for D saturated graphite and SS 304 compared with low fluence implants. Release of ³He from TiC was also obtained by e-beam pulsed heating and this release was not affected by the presence of saturation concentrations of D. Comparison to furnace anneals and the calculated time evolution of the temperature profiles suggests a simple model for the D release based on diffusion-limited release in the case of pulsed e-beam treatments and trap-limited release in the case of furnace bulk heating. These processes are closely related to hydrogen recycle in tokamaks and have implications for T inventory control and He ash removal.

*This work supported by the U.S. Department of Energy, DOE, under contract number DE-AC04-76-DP00789.

†A U.S. Department of Energy Facility.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *sp*

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

1. INTRODUCTION

Electron bombardment and other rapid local heating events at the interior surfaces of tokamaks frequently occur during plasma discharges (1,2). For example, runaway electrons most frequently occur in the energy range 50-200 keV with estimated current densities of $\sim 1.5 \text{ kA/cm}^2$ and times $\sim 0.01 - 1 \text{ } \mu\text{s}$. (2). Arcing is an even more intense process which may involve up to 10^3 kA/cm^2 with total duration times $\sim 50 \text{ } \mu\text{s}$ but with such rapid movement of the arc spot across the surface that for a given area the residence time may be only $\sim 0.1 \text{ } \mu\text{s}$ (1,3). Both of these processes can result in intense heating leading to melting, evaporation and material ejection. It may be that less intense electron energy depositions occur even more frequently within tokamaks.

Little is known about the influence of these brief, but intense, pulses on the release of hydrogen or helium. Previous results have been restricted to laser pulsed and long ($\sim 1\text{s}$) electron pulsed release (4-6). Measurements of such effects are important because they bear on the recycling of plasma and burn species from the wall materials and therefore on fueling, plasma density control, and He ash removal. Electron pulsed heating release of hydrogen and helium is also of interest as a possible means for the controlled release of gas from wall materials without bulk heating of components. Such applications, if feasible, could have important implications for T inventory control and He ash removal between burns and would be compatible with the high duty cycles needed for the reactor operation.

In this paper we report systematic studies of the release of implanted D and ^3He from TiC, a promising coating being developed for tokamak components (7), and for SS 304 and graphite, both common liner and interior component materials in tokamaks. Electron pulses of 50 nsec duration and energies of 30-60 keV are used. These penetrate to depths $\sim 1\text{-}10\ \mu\text{m}$ and are below the threshold for creating direct atomic displacements. Typical current densities are $1.5\ \text{kA/cm}^2$ and thus the electron beam pulses correspond closely to the conditions believed to occur for low energy runaway electrons.

2. EXPERIMENTAL TECHNIQUE

Three types of materials were used: 1) chemical vapor deposited $\sim 10\ \mu\text{m}$ TiC coatings on POCO AXF5Q graphite formed at 1300°C with TiCl_4 and CH_4 (7); 2) stainless steel 304 of nuclear grade rolled to $\sim 0.5\ \text{mm}$ sheets and annealed; and 3) papyex graphite, a high purity graphitized paper which appears smooth by SEM on a $50\ \mu\text{m}$ scale with occasional cracks. Implantations of 1.5 keV D (and 0.5 keV in one case) were carried out using molecular D_2^+ at twice the energy and $\sim 15\ \mu\text{A/cm}^2$. D implantations were made to high fluences to achieve saturation trapped concentrations of $1.25 \times 10^{17}\ \text{D/cm}^2$ in TiC and $2.6 \times 10^{17}\ \text{D/cm}^2$ in graphite, and to below saturation fluences of $3 \times 10^{16}\ \text{D/cm}^2$ in TiC and $5.6 \times 10^{16}\ \text{D/cm}^2$ in graphite. High and low fluence implants in SS 304 of 2×10^{16} and $3 \times 10^{17}\ \text{D/cm}^2$ were used with ~ 10 to 30% of the D remaining trapped in the near surface layer ($\leq 4000\ \text{\AA}$). All ^3He implants were at 3 keV to a fluence $1 \times 10^{16}\ \text{cm}^2$. Analyses of the total near-surface D/cm^2 ($^3\text{He/cm}^2$) were carried out with

a 750 keV ^3He (400 keV D) beam by means of the $\text{D}(^3\text{He}, \text{p})^4\text{He}$ nuclear reaction.

Pulsed e-beam treatments were carried out using a cold cathode 50 ns pulsed system of our design. The voltage and current waveforms were recorded by fast electronics and the energy depositions were varied between 0.5 and 2.8 J/cm². For example, the 1.6 J/cm² pulse corresponded to an average electron energy of 55 keV and current density of 0.6 kA/cm² and the 2.8 J/cm² pulse to 35 keV and 1.6 kA/cm². These pulse conditions resulted in rapid heating of the near-surface (0 to 1-10 μm) to temperatures 500-2000°C for the materials studied with no significant heating of the bulk. All furnace anneals were done in vacuum at $\sim 10^{-6}$ torr for isochronal times of 6 s.

3. THEORETICAL ELECTRON PULSE TEMPERATURE PROFILES

During pulsed electron deposition only the near surface region of the material is heated appreciably, whereas during furnace annealing the entire sample is uniformly heated. Calculations of the heat flow under pulsed conditions have been carried out to obtain the time evolution of the temperature profiles. This required numerical solution of the one dimensional heat equation (8)

$$c\rho \frac{\delta T}{\delta t} = I(z, t) + \frac{\delta}{\delta z} \left(k \frac{\delta T}{\delta z} \right) \quad (1)$$

where c is the heat capacity, ρ the mass density, I the power density profile of the electron beam (9) and k is the thermal

conductivity. Surface radiation has been neglected and bulk values for c , ρ and k were used. In Fig. 1 results are shown for a 2.8 J/cm^2 pulse onto TiC along with the initial electron deposition profile.

4. RESULTS

4.1 D Release by Pulsed Electron Heating

In Fig. 2 the fractional D released for a single pulse is shown as a function of pulse energy density for low fluence D implants. Substantial amounts of D are released from SS 304 even at 1.6 J/cm^2 whereas the threshold for release from TiC and graphite is between 1.6 and 2.8 J/cm^2 .

The total amount of D which remains trapped as a function of number of electron pulses for both low and saturation D fluence implants is shown in Fig. 3 for TiC, and in Fig. 4 for SS 304 and graphite. In TiC saturation fluence implants result in an enhanced release of D on the first pulse. The open square in Fig. 3 corresponds to a low fluence re-implantation of the original saturation fluence sample after the 3 pulses removed 95% of the D originally present. In this sample the release behavior continues to correspond more closely to the high fluence implant than to virgin samples receiving low fluence implants. Also shown in Fig. 3 is the release rate for a low fluence implant which was implanted to a shallower depth corresponding to 0.5 keV D rather than the 1.5 keV D used for all the other implants. This corresponds to a drop in the projected range by a factor ~ 3 from the $183 \text{ \AA}$ calculated for

1.5 keV D. Except for the first pulse on saturation fluence implants, the percentage of the retained D that is lost per pulse in TiC is nearly constant at $\approx 25\%$ for the 1.5 keV D implant and $\approx 85\%$ for the 0.5 keV implant. The low fluence release behavior in TiC is qualitatively similar to that observed previously for laser pulsed release of implanted D in TiB_2 coatings (4).

For SS 304 the D release was observed to be similar for both 1.6 and 2.8 J/cm^2 pulse energies with the fraction lost per pulse decreasing slowly with increasing number of pulses (Fig. 4a). High fluence implants consistently required 2 pulses before substantial D release occurred. For the graphite the low fluence and saturation D fluence implants gave similar release curves with a loss of about 10% of the D per pulse. This behavior contrasts markedly with that for TiC in which a large release occurs on the first pulse for the sample implanted to saturation.

No degradation of the TiC or SS 304 surfaces was observed under repeated electron beam pulsing, whereas the graphite surface exhibited increasing amounts of flaking and other degradation after typically 3 to 5 pulses at the higher pulse energies. This loss of graphite surface accounts for the somewhat poorer reproducibility which was observed for graphite only (see Fig. 2).

4.2 D Release by Furnace Heating

In Fig. 5 the release of D during isochronal annealing in a vacuum furnace is shown for TiC implanted to both low and saturation D fluences. D release is seen to occur at substantially

lower temperatures for saturation fluence implants with initial release occurring $\sim 150^\circ\text{C}$ lower and 50% release occurring $\sim 257^\circ$ lower. Isochronal release curves are shown in Fig. 6 for a low fluence implant in SS 304. Also shown is the D release curve for graphite from previous measurements by Langley et. al. (10). In contrast to TiC, the graphite isochronal release curves were found to be the same for both saturation and low fluence D implants.

4.3 He and D Release

Selected release studies were also carried out on samples implanted with ^3He only and with ^3He after prior saturation fluence implants of D. E-beam pulsed release results are shown in Fig. 7 for SS 304 and TiC for ^3He only, and for TiC with combined $^3\text{He} + \text{D}$ implants. For TiC the ^3He release is relatively unaffected by the presence of the D and the D release is similar to that previously observed in the absence of ^3He . Also, ^3He releases much more efficiently from SS 304 than from TiC. Furnace annealing of TiC with saturation D + ^3He (not shown) resulted in D release identical to that for saturation D only (Fig. 5). In this sample ^3He release occurred much more slowly than the D release, with only $\approx 20\%$ of the ^3He released by 600°C .

5. DISCUSSION

Intense energy depositions by electrons and other particles occur in tokamaks both during stationary and nonstationary phases of discharges. In addition to being a source of impurities, similar pulsed events are shown in the present experiments to be able to rapidly recycle appreciable fractions of trapped gas even

for conditions which do not give rise to surface melting or bulk heating. Since trapped hydrogen levels can be $\sim 10^{17}/\text{cm}^2$ in many wall materials and plasma densities are only $\sim 10^{13} - 10^{14}/\text{cm}^2$, significant local density increases in the working gas are to be anticipated during pulsed energy depositions. In addition, intentional pulsed heating of the surface offers the possibility of controlled gas release from the surface of materials without appreciable heating of bulk components for such purposes as reduction of T inventory or He ash removal. However, until now no fundamental investigations of the gas release under intense electron pulse heating have been carried out. In what follows we develop a model for the release of D from TiC, a promising candidate material for coating interior tokamak components, and also show how it applies to the bulk materials SS 304 and graphite.

5.1 Model of D Release in TiC

5.1.1 Low Fluence D Release

TiC represents a class of coating materials which include TiC, TiB₂, VB₂, B₄C, and B where hydrogen may be relatively mobile in the perfect lattice as an interstitial, but is found to be strongly trapped at room temperature when introduced by implantation. Thus for our low fluence implants where the D concentration is approximately a factor of 5 below the trap concentration at saturation, one may anticipate a large number of unoccupied traps. Under an intense pulse of electrons the lattice is rapidly heated to temperatures well above that for

which the hydrogen undergoes rapid diffusion in a field of traps with the sample surface as a sink for the release of hydrogen. Once the surface region again cools to temperatures where the hydrogen can no longer be released from traps diffusional spreading and release ceases.

To test this we calculate by Eq. 1 the time during which the first 0.25 μm surface layer of TiC is heated to a temperature where the D is detrapped (as determined from the furnace release data). Results are shown in Fig. 8 for two pulse energy depositions in TiC. We see for 1.6 J/cm^2 the temperature never exceeds $\approx 500^\circ\text{C}$ whereas for the higher pulse energy the temperatures reaches approximately 1400°C . From the furnace annealing curves (Fig. 5) we know that the D is 50% released for the low fluence implants in TiC by approximately 550°C . Taking this level (dashed line in Fig. 8) as a measure of the approximate temperature during a pulsed heating event above which the majority of the D is free to migrate and below which the D will be retrapped we predict a threshold for pulsed release slightly above 1.6 J/cm^2 . This is consistent with the experimental results shown in Fig. 2. Also for the 2.8 J/cm^2 pulse the time during which the D would be expected to be detrapped is approximately 3 μs . This allows an estimate of the D diffusivity of $\sim 1 \times 10^{-6} \text{ cm}^2/\text{s}$ if we assume a diffusion length the order of the projected range ($\approx 180 \text{ \AA}$) for substantial release. This is quite a reasonable

value for hydrogen diffusion in a field of traps at these temperatures. Thus both the threshold for D release and the observed magnitude of energy deposition necessary for substantial release are consistent with this model of diffusion-limited release during pulsed heating.

In contrast, the hydrogen release observed during furnace heating corresponds to long times and since the untrapped diffusivities are indicated by the pulsed release to be high, the release is determined primarily by the detrapping rather than by the time required to migrate from the sample. Thus we refer to the furnace heat treatments as trap-limited release.

As a further check on this model of diffusion-limited release for the pulsed electron heating one low fluence D implant was done at a factor of 3 lower energy of 0.5 keV per D. Since the D range is approximately linearly proportional to energy here the D peak is only $\sim 1/3$ as deep. Thus if one has a free diffusion of the D during the pulse with the surface a sink then one would expect a substantial enhancement in the fraction released per pulse for the shallower implant. This predicted difference was found, as shown in Fig. 3 where the additional D release per pulse is seen to increase from 25% to approximately 85% for the shallow implant.

5.1.2 Saturation Level D Release

At sufficiently high implantation fluences the amount of trapped D is known to saturate to a concentration corresponding

to approximately one D atom for every four host atoms in TiC (11). At this saturated concentration we have observed a new phenomena whereby the D release is significantly enhanced over that for low fluence implants in TiC. This is seen in Fig. 3 to result in even lower absolute concentrations of trapped D after a single pulse than for the low fluence implants, even though a factor of ~ 5 more D is present initially. This behavior is qualitatively consistent with the furnace anneal results shown in Fig. 5 where at saturation fluences the D release begins at substantially lower temperatures ($\approx 150^\circ\text{C}$) and the 50% release point is reduced from $\approx 550^\circ$ to $\approx 270^\circ\text{C}$. From Fig. 8, this relatively small decrease in release temperature results in substantially longer times (20 vs. 3 μs) for which diffusive release is possible under pulsed heating conditions. Thus a substantial increase in the D release is expected for diffusion-limited (pulsed) conditions, as is observed.

The reason for this enhancement in the release for saturation D implants in TiC is not presently known, and this behavior contrasts markedly with graphite where no such enhancement is observed (10). One possible explanation is that a microstructural change occurs in the TiC lattice at the high D concentrations such that the D trap configuration is altered or that the subsequent D release occurs through some type of interconnected network of microcracks. Microstructural modifications of other materials under high fluence bombardment by deuterium or helium have been reported (12) and in the case of He similar enhancements of

release at lower temperature have been observed at critical He concentrations (13). To check for such microstructural changes one saturation D implanted TiC sample was pulsed to release the D and then re-implanted to a low fluence with D and pulsed twice (open square in Fig. 3). If a permanent microstructural change takes place during saturation D fluence implantation then one may anticipate some enhancement over the release observed for low fluence implants into virgin material. This is seen to occur (Fig. 3) with the fractional release being clearly greater than that for the corresponding virgin low fluence implants and approaching that observed for the original high fluence implant.

Thus we propose that the enhanced release of D from TiC both by pulsed and furnace heat treatments may be associated with a microstructural change in the lattice which occurs at saturation fluence implants. Such a phenomenon could prove quite beneficial in tokamak reactors where it may be desirable to minimize hydrogen isotope inventories in first wall components.

5.2 D Release From SS 304 and Graphite

D release from SS 304 is seen to occur quite readily even at pulse energies of 1.6 J/cm^2 where no release is observed for TiC or graphite (Fig. 2). This is consistent with the furnace anneal release data of Fig. 6 where it is seen that 50% of the D is released at only 70°C whereas the calculated surface temperature reaches $\approx 900^\circ\text{C}$ for the 1.6 J/cm^2 pulse. For the 2.8 J/cm^2 pulse the stainless steel surface melts, reaching

$\approx 2800^{\circ}\text{C}$. This is in contrast to the case for TiC and graphite where the surface remains solid for all pulse energies used. However, no qualitative changes are seen in the D release (Fig. 4a).

The quantitative description of D release in stainless steel is somewhat complicated by the fact that the D is only weakly trapped at room temperature and slowly releases over a period of days at ambient temperatures(14). In addition to D trapping at defects within the bulk of stainless steel some trapping may also occur at the surface oxide. One particularly interesting feature of the pulsed release results is (Fig. 4a) that at the higher D fluences, where an approximate saturation in the amount of D trapped was achieved, little release occurred for the first pulse, whereas substantial release occurred after the second pulse. The reason for the requirement of an initial pulse to condition the sample prior to D release for high fluence implants is not known, but may be related to surface alterations which take place during the first pulse. For example, blow-off of the initial surface oxide layer or annealing of traps within the implanted region may occur.

For graphite no difference in the D release with implant fluence is observed for pulsed or furnace heating (Fig. 4b and 6). Also the lower fractional release rate of $\approx 10\%$ per pulse is consistent with the much higher furnace temperatures required to release D in graphite.

5.3 He Release

Substantial ^3He was released on the first pulse in SS 304 and to a lesser extent also in TiC (Fig. 7) and subsequent pulses

removed proportionally less ^3He . Mixed $^3\text{He} + \text{D}$ implants were studied in TiC by both pulsed and thermal release. The D was first implanted to saturation and then the ^3He implanted to lower concentrations in the region containing D. This was chosen to simulate fusion reactor conditions of a high fluence of working hydrogen gas and lower fluence of the helium ash. Both the D and ^3He release upon pulsed annealing were similar to that observed when either D or He alone were implanted. This suggests that the nature of the traps for D and He may be different, so that a saturation concentration of trapped D does not appreciably influence He release below saturation.

6. CONCLUSIONS

It has been demonstrated that heating by intense 50 ns pulses of electrons can release substantial fractions of trapped D and ^3He in the near surface region of TiC coatings and SS 304 and a model for the release process is developed and shown to be qualitatively consistent with experiment. Such intense energy deposition events in tokamaks, even on the shortest time scale known for these events, would thus be expected to release substantial amounts of hydrogen from the first wall of tokamaks. This will give rise to large local density fluctuations in the working gas which may lead to plasma instabilities or disruptions. Alternatively this may act like local gas puffing to help damp out local instabilities. Also such high intensity electron pulses could be used for the controlled release of H or He isotopes from selected components without significantly heating the bulk material. Due to different release behavior it also may be possible to

selectively release T and He separately.

In addition, three specific conclusions concerning TiC coatings may be inferred from this study: 1) The mechanism of release during fast electron beam pulsed heating of TiC is diffusion-limited, whereas slow furnace heating involves a trap-limited release process. 2) In TiC the release of implanted D is substantially enhanced once saturation D concentrations are reached and the evidence indicates that this enhancement is due to microstructural changes. 3) Mixed ³He + saturation D implants in TiC reveal no correlation in the release over that found for separate implants of D or He, suggesting different trap sites for these two gas species.

ACKNOWLEDGEMENTS

Skilled experimental assistance by D. Buller and R. Burchard is greatly acknowledged. The e-beam pulser was developed with the design and development assistance of K. Prestwich, R. Clark, D. Buller, J. Knapp, and G. Peterson.

REFERENCES

1. G. M. McCracken and P. E. Stott, Nuclear Fusion 19 (1979) 889;
R. Behrisch, J. Nucl. Mat. 85 and 86, (1979) 1047.
2. P. Staib and G. Staudenmaier, J. Nucl. Mat. 76 and 77 (1978)
78.
3. P. Mioduszewski, R. E. Clausing, and L. Heatherly, J. Nucl.
Mat. 85 and 86 (1979) 963.
4. B. L. Doyle and F. L. Vook, J. Nucl. Mat. 85 and 86 (1979) 1019.
5. W. R. Wampler, S. T. Picraux, S. A. Cohen, H. F. Dylla, G. M.
McCracken, S. M. Rossnagel, and C. W. Magee, J. Nucl. Mat.
85 and 86 (1979) 983.
6. J. Lelegard and A. Schram, J. Nucl. Mat. 76 and 77 (1978) 637.
7. A. W. Mulendore, J. B. Whitley and D. M. Mattox (these
proceedings).
8. P. Baeri, S. U. Campisano, G. Foti, and E. Rimini, J. Appl.
Phys. 50 (1979) 788.
9. L. V. Spencer, U. S. National Bureau of Standards Monograph
No. 1 (1959).
10. R. A. Langley, R. S. Blewer, J. Roth, J. Nucl. Mat. 76 and 77
(1978) 313.
11. B. L. Doyle, W. R. Wampler, D. K. Brice, and S. T. Picraux
(these proceedings).
12. G. J. Thomas and K. L. Wilson, ANS Trans. 27 (1977) 273
13. G. J. Thomas and W. Bauer, Radiation Effects 17 (1973) 221.
14. K. L. Wilson and A. E. Ponteau, J. Nucl. Mat. 85 and 86
(1979) 989.

FIGURE CAPTIONS

Fig. 1

Initial heat deposition and calculated temperature profiles in TiC for a 50 ns, 2.8 J/cm^2 pulse of 35 keV electrons.

Fig. 2

Fraction of trapped D released for one pulse vs. energy density for low fluence, 1.5 keV D implants in SS 304, TiC, and graphite.

Fig. 3

Total trapped D/cm^2 remaining as a function of number of 2.8 J/cm^2 e-beam pulses on TiC. All implant D energies are 1.5 keV except for the shallow implant which was 0.5 keV. The open square corresponds to the saturation D fluence implant which after the third pulse was re-implanted to the low fluence implant level and subsequently pulsed twice.

Fig. 4

Total trapped D/cm^2 remaining as a function of number of pulses in a) SS 304 and b) graphite for both low and high fluence D implants. Results are for 1.6 and 2.8 J/cm^2 pulses for SS 304 and for 2.8 J/cm^2 pulses for graphite.

Fig. 5

Trapped D/cm^2 in TiC vs isochronal anneal temperatures.

Fig. 6

Trapped D/cm^2 in SS 304 and graphite vs isochronal anneal temperature. Graphite data from ref. 10 are for saturation fluence 8 keV D implants. Isochronal anneal times were $6 \times 10^2 \text{ s}$ for the SS 304 and $1.8 \times 10^3 \text{ s}$ for the graphite.

Fig. 7

Trapped D or ^3He vs number of 2.8 J/cm^2 e-beam pulses. All He implants are 3 keV to a fluence of $1 \times 10^{16}/\text{cm}^2$ and the mixed D plus ^3He implant in TiC corresponds to saturation D fluence, followed by the same He implant as for the other samples.

Fig. 8

Calculated temperature versus time within the first $0.25 \mu\text{m}$ of the surface of a TiC sample after a 50 ns e-beam pulse of 1.6 J/cm^2 at 55 keV and of 2.8 J/cm^2 at 35 keV.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 9