Accurate Numerical Models of the Secondary Electron
Yield from Grazing-incidence Collisions
Final Report

Small Business Innovation Research Contract #DE-FG02-03ER83797
supported by the Office of Fusion Energy Sciences

Seth A. Veitzer, PI
Tech-X Corporation

October 21, 2008

Summary

This project had three main technical objectives, which we have successfully completed. The first objective was to provide models of secondary electron emission for grazing-angle collisions between ions and accelerator beam pipe walls with applications to high current accelerators. The second objective was to enable cross-platform simulations of ion/solid interactions for Heavy Ion Fusion (HIF) researchers, and the third objective was to provide the High Energy Density Physics (HEDP) community with accurate models of heavy ion energy deposition in Inertial Confinement Fusion (ICF) targets.

Benefit to Department of Energy

Collisions between halo beam ions and solid material walls can represent a significant obstacle to the development of high-current accelerators, because such collisions are sources of secondary electrons and sputtered neutral atoms. This effect is exacerbated by the grazing incidence of the collisions, which can increase the yields of unwanted particles by an order of magnitude. In the course of this project we developed and implemented numerical models describing both the deposition of energy of heavy ions in material targets, and also the dependence of those models on the angle of incidence. These models, and others relevant to collisions between heavy ions and solid materials, have been implemented into a numerical software library called TxPhysics, and have been made available to the DOE research community in a cross-platform, language-agnostic way. The TxPhysics library is currently linked to a number of DOE-funded simulation packages, including WARP and HYDRA, as well as to Tech-X codes such as OOPIC Pro and VORPAL. In addition, work on this project helped to develop a web interface to the TxPhysics library, in congruence with the SBIR project CMEE [1], allowing DOE researchers and others to quickly get answers to beam/solid questions without having to write extensive modeling codes.

Commercial Successes

The new physics capabilities developed under this SBIR project have helped to lead to increased commercial sales of the VORPAL and OOPIC codes. The availability of VORPAL to accurately simulate particle/surface processes has added to the overall strength of both VORPAL and OOPIC Pro, although it is difficult to estimate the commercial gain due to specific physics modules implemented as a part of this particular project. VORPAL licensing and consulting sales increased to over \$291,000 in the last nine months, and a significant number of existing OOPIC Pro customers purchased license upgrades since the additional physics modules were added. Tech-X is currently providing an evaluation of VORPAL's ability to simulate particle/surface dynamics in a sputter magnetron device for a global electronics manufacturer, that may lead to additional licensing and consulting contracts. The ability of VORPAL to accurately model sputtering depends in large part on the additional nuclear stopping and physical sputtering models added to TxPhysics as part of this SBIR project.

Selected Publications and Presentations

P. H. Stoltz et. al., *Energy loss, range, and electron yield comparisons of the CRANGE ion-material interaction code*, Nuc. Inst. Meth. Phys. Res. A, **544**, 1-2, doi:10.1016/j.nima.2005.03.011,

(2005).

S. A. Veitzer, P. H. Stoltz, J. J. Barnard, *Evolution of the energy distribution of ions moving in aluminum targets*, Nuc. Inst. Meth. Phys. Res. A, **577**, 1-2, doi:10.1016/j.nima.2007.02.089, (2007).

P. H. Stoltz, S. A. Veitzer, J. J. Barnard, *Effects of beam temperature on ion heating for high energy density physics experiments*, Innovative Confinement Concepts Workshop, (2007).

Introduction

Effects of stray electrons are a main factor limiting performance of many accelerators. Because heavy-ion fusion (HIF) accelerators will operate in regimes of higher current and with walls much closer to the beam than accelerators operating today, stray electrons might have a large, detrimental effect on the performance of an HIF accelerator. A primary source of stray electrons is electrons generated when halo ions strike the beam pipe walls. There is some research on these types of secondary electrons for the HIF community to draw upon, but this work is missing one crucial ingredient: the effect of grazing incidence. The overall goal of this project was to develop the numerical tools necessary to accurately model the effect of grazing incidence on the behavior of halo ions in a HIF accelerator, and further, to provide accurate models of heavy ion stopping powers with applications to ICF, WDM, and HEDP experiments.

Grazing-angle collisions introduce two effects to the generation of secondary electrons: (i) surface roughness effects and (ii) ion scattering effects. These change the angular dependence of the secondary electron yield (SEY) for grazing angles, and understanding how requires detailed modeling of the interactions of halo ions with the beam pipe wall. The main software tool for modeling ion-material interactions, SRIM [2], is limited because it operates only on the Windows platform and because the source code is written in BASIC, meaning one can not easily add custom modules or change the underlying computational algorithms. Therefore a main focus of this work was to develop an open-source code to model ion-material interactions, with support for multiple languages and the ability to build and link on many different computer platforms.

The process of ion-induced secondary electron emission depends critically on the details of energy deposition and stopping power. With the recent refocusing of effort of the HIF community to support research in ICF and Warm Dense Matter (WDM) physics, we also devoted a large amount of effort in developing accurate stopping power models in support of this program, and providing these alternative stopping power models to DOE researchers in order to better simulate ICF and WDM experiments.

Selected accomplishments by task

We describe below some of the major tasks that we completed in order to meet the overall goals of the Phase II project. While undertaking these tasks, we recognized new important areas in which we could make progress and support both the HIF accelerator community and also the beam-driven ICF community. We also describe successes in additional computational functionality to support these DOE researchers.

Create tables of data for ions, materials, energies and angles important to heavy-ion fusion and the routines to access that data

This is the major task of the Phase II project, and resulted in many new results and software technologies. We completed this task in two parts. The first part of this task was to develop detailed numerical models of stopping power models relevant to grazing incidence ion/material collisions, and to HEDP and ICF experiments. These models were implemented into the Tx-Physics numerical library, and routines and multi-language wrappers for accessing the models

were also implemented in order to make them easily accessible to a variety of simulation packages. The completion of this work is a major success of the overall project. Stopping power is a major aspect of many ion/material interactions. For instance, ion-induced secondary electron emission is proportional to the electronic stopping power; sputtering yields are proportional to nuclear stopping power; and the majority of the temperature dependence of ion/material interactions is contained in the free electron stopping. Thus developing accurate models of stopping powers in an accessible way was a key element of this project. Initially we focussed on developing the CRANGE (electronic) stopping power code, which is relevant for high-energy beams. We subsequently focused on developing alternative models of electronic and nuclear stopping powers that are needed at and below the Bragg peak.

For beam energies above 10 MeV/u our libraries compute bound electronic stopping power based on the CRANGE code, which we have modified and made easier to use by integrating it with other stopping power codes and providing Python language bindings. For energies below 10 MeV/u, we implemented an alternative model of bound electronic stopping power due to Brandt & Kitagawa [3]. This method uses semi-empirical scaling laws to compute heavy ion stopping from tables of protonic stopping, and is the same method used in SRIM. We use tables of protonic stopping powers from NIST in our calculations.

Figure 1 shows a comparison between our implementation and SRIM values for stopping of four ions in Aluminum. In the figure blue is stopping power derived from SRIM tables, and red is stopping power computed with our new code, based on the theory of Brandt & Kitagawa. Our code agrees with SRIM values up to about 10%. We use different empirical tables of protonic stopping which accounts for the differences. By providing platform-independent libraries we have made the alternative stopping power models available to a wide research and simulation community, as well as specifically helping LBNL researchers to model driving physical processes that are important for understanding heating of targets in the WDM regime.

For free electron stopping, which becomes increasingly important as the target temperature increases and target atoms ionize, we successfully implemented a model for free electron stopping into TxPhysics due to Peter and Meyer-ter-Vehn [4, 5]. We have also coupled the free electron stopping model with a model for computing the non-equilibrium effective charge state of the projectile in partially ionized materials [5]. This model uses the average ionization potentials calculated by Mehlhorn [6], and together these routines provide a temperature-dependent model to calculate stopping powers in WDM and ICF targets.

We have verified our implementation of the free electron stopping power models, and have made extensive comparisons of our total stopping power models with the classical energy deposition models as are currently implemented in HYDRA. We found that at intermediate to high beam energies, near and above the Bragg peak, the models differ to a small degree, but show essentially the same behavior in terms of energy deposition rates. At low beam energies, well below the Bragg peak, the models differ significantly. This is due to both differences in the electronic stopping power formulations and the addition of nuclear stopping.

Scattering of beam ions off of target nuclei is an important process that is relevant to both grazing incidence collisions and to target heating in WDM and ICF experiments. We addressed this issue by implementing a model of nuclear stopping based on a semi-empirical universal scaling relationship into the TxPhysics library. This model has been used in a variety of simulation packages as is described below. The nuclear stopping model is based on the algorithms described in Ziegler et. al. [7], and is the same algorithm used in SRIM to compute nuclear stopping. The

Figure 1: Stopping powers of protons, Li, Na, and K ions in Aluminum as computed using SRIM (blue) and TxPhysics (red). Green lines indicate beam ion energies of 400 keV and 1.6 MeV.

basic model reduces nuclear screening potentials calculated using Thomas-Fermi atoms to a universal parameterization, describing all classical ion-target collisions. A parameterized fit is then generated that describes the nuclear stopping. Comparisons between our implementation and SRIM show very good agreement. As with our implementation of electronic stopping powers, the nuclear stopping routines are cross-platform and cross-language, so they are callable from other simulation codes such as WARP and HYDRA.

In the second part of this task we succeeded in parameterizing statistical distributions describing grazing incidence collisions between ions and solid material surfaces based on Monte Carlo simulations of ensembles of such collisions for different incident energies and angles. This process is based on performing a large number of simulated collisions between beam ions of a given energy and material surfaces with different angles of incidence. For a given incident energy and angle to the surface normal, the probability density functions (pdfs) for reflected energy and reflected angle are determined. The pdfs are fitted with a 4th-order polynomial, which is sufficient to reconstruct the probability distributions for lookup in future simulations.

An example of this is shown in the left plot of figure (2). Here, we show the first four moments describing the reflected energies of 2.0 MeV potassium incident on stainless steel as a function of incident angle. The red curve shows the reconstructed moment curves derived from the estimated polynomial coefficients, and the blue does show values measured from the Monte Carlo simulations, using TRIM. Similarly, the distributions of velocity components for reflected ions may also be estimated by reducing Monte Carlo simulation results to polynomial coefficients. Figure (2) (right plot) shows the first four moments of the pdfs for reflected velocity normal to the target surface as a function of incident angle. The pdfs reconstructed from estimated coefficients

Figure 2: First four moments describing the reflected energies (left) and normal projection of reflected velocities of 2.0 MeV potassium incident on stainless steel as a function of incident angle. Red lines are reconstructed moment curves, and blue dots are Monte Carlo estimates based on ensembles of 10,000 events.

(red lines) provide a good estimate as verified by the Monte Carlo simulations (blue symbols).

In circumstances where the incident beam ion has an energy for which the pdfs have not been estimated, we linearly interpolate the polynomial coefficients between the two nearest incident energies. A priori, it is not fundamentally clear that the assumption that the statistical distributions would smoothly vary with incident energy. However, we have verified that this is the case for a number of different simulation parameters. Figure (3) shows an example of coefficient interpolation. In this figure we show (in blue) distributions of reflected ion energy for 1.6 MeV and 1.7 MeV potassium on stainless steel at an incident angle of 89.0 degrees from the surface normal. The red histogram is the estimated distribution for 1.65 MeV ions from TRIM Monte Carlo simulations.

Model ion scattering to better model grazing collisions

We completed this task by developing simulations that compute the stochastic effects of nuclear scattering on beam evolution using the Monte Carlo code TRIM. We measured the amount of energy spread (also called longitudinal straggling) induced in initially mono-energetic beams due to random nuclear scattering collisions, as well as the amount of beam spreading (lateral straggling). Models were developed for two beams; 2.8 MeV lithium and 400 keV potassium, both moving in solid density aluminum targets. These parameters were chosen to represent the potential effects in experiments at the NDCX and (proposed) NDCX II WDM experiments. We found that nuclear scattering could induce nearly a 100% energy spread in the potassium beam over a $3.4 \mu m$ foil, while a roughly 10% energy spread would be found for lithium over the same range. This is due to the increased role of nuclear stopping for the potassium beam, which is well below the Bragg peak at this energy. This is shown in figure 4, where the estimated distributions of beam ion energies are plotted for both beams (moving from right to left).

These results were presented to Heavy Ion Fusion Virtual National Laboratory (HIF VNL) researchers and at the HIF Symposium in July, 2006. Subsequently, these results were published for publication in Nuclear Instruments and Methods in Physics Research Section A, (NIMA), and

Figure 3: Estimate of the distribution of reflected energies for 1.65 MeV potassium ions incident on stainless steel at 89 degrees from normal. The red line is an estimate based on TRIM Monte Carlo simulations, and blue lines are generated from 4th-order polynomial fits to simulations at 1.6 and 1.7 MeV simulations.

have also been presented by Tech-X researchers at the 2007 Innovative Confinement Concepts (ICC) workshop.

Add rough surface models to CRANGE to better model grazing collisions

We completed this task by developing new implementations of physical sputtering; a process in which ion collisions with rough surfaces physically dislodged neutral atoms of the wall material. The detailed interaction between incident ions and targets which produce sputtering depend on the incident ion energy, the projectile-target material combination, and the angle of incidence. Physical sputtering is often utilized in plasma processing to enhance plasma-assisted chemical vapor deposition and etching, and can be an important source of impurities in magnetic confinement fusion devices. For this task, the importance of angle of incidence is the main factor, because roughend beam pipes will present on average a smaller angle of incidence to beam ions.

We have implemented numerical routines to calculate yields of sputtered neutral atoms generated by impinging ions into the TxPhysics library. We have also written interfaces to these routines and incorporated them into the VORPAL plasma simulation code. The primary dependence of the sputtering yield is on the nuclear stopping power, and we have used the algorithms for computing the nuclear stopping power described above as the basis for implementing the sputtering algorithms.

We have implemented a model of sputtering proposed by Yamamura [8] that is an extension of the semi-empirical model of Sigmund [9]. In these models, a Boltzmann transport equation is derived which describes the transport of target atoms to the surface of the material when they

Figure 4: Evolution of beam ion energy distributions as a function of depth in an underdense aluminum foam. The left-hand plot shows 400 keV potassium, which gains a very large spread in energies due to enhanced nuclear scattering, while the right-hand plot shows 2.8 MeV lithium, which has less longitudinal straggling.

undergo collisions with impinging ions. Recoiling atoms which reach the target surface with energy sufficient to overcome the surface binding energy are ejected from the target as sputtered neutrals. The simplest model derived in [8] for the sputtering yield at normal incidence describes the yield as proportional to the nuclear stopping power and inversely proportional to the surface binding energy.

The Sigmund model has been found to be valid at large values of the incident ion energy, however below a threshold energy the sputtering yield drops off sharply to zero. The threshold energy depends on the masses of the ion/target atoms and the surface binding energy. The Yamamura model is a three-parameter fit model that extends the Sigmund model to include the low energy threshold effect. The fit parameters depend on the ion and target species and are tabulated in [9] for many ion/target combinations. We have tested the implementation of this sputtering model to experimental data and SRIM calculations and find good agreement for a large variety of ion/target combinations. We show in Figure 5 a comparison between the normal incidence sputtering yield for a variety of incident ions on nickel targets as predicted by SRIM and calculated by TxPhysics.

The sputtering yield depends on the angle of incidence at which ions strike the target surface. Sigmund showed that the ratio of the oblique incidence yield to normal incidence yield could be expressed as $Y(\theta)/Y(0) = \cos^{-f}(\theta)$ where $f = 5/3$, for a large number of ion/target combinations. θ is the incident angle measured from the surface normal. However, experiments show deviations from this behavior for $\theta > 60^\circ$. There is also a sharp turnover to in the sputter yield at very grazing incidence. To account for this, Yamamura introduced a two-parameter

Figure 5: Comparison of sputtering yields for Yamamura model (in TxPhysics) and that predicted by SRIM for normal incidence collisions on nickel targets.

model

$$\frac{Y(\theta)}{Y(0)} = \cos(\theta)^{-f} \exp [f \cos(\theta_{\text{opt}})(1 - \cos(\theta)^{-1})]$$

where f is similar to the single parameter for the Sigmund model, and θ_{opt} describes the angle at which the peak in $Y(\theta)/Y(0)$ occurs. A comparison of the simple angular dependence model from Sigmund and the Yamamura two-parameter model that is implemented in TxPhysics is shown in Figure 6. We also show experimental data for Ar ions impinging on an iron target. Throughout the literature, the values of f , and θ_{opt} vary with not only specific projectile/target combinations, but also the incident ion energy. Our implementation of the Yamamura sputtering model in TxPhysics uses default values of f , and θ_{opt} based on the available experimental data, but can also be specified by users of the code for researchers with known parameter values specific to a system of interest.

Add autotools and Python steering to ensure users on all platforms can take advantage of this package

The majority of newly developed and implemented models for this project were placed in the TxPhysics numerical library. TxPhysics is specifically designed to be cross-platform through the use of autotools, and contains Python wrappers for library routines for improved accessibility. TxPhysics was originally developed as part of the CMEE SBIR project at Tech-X. In this project, we added new physics modules; specifically models of stopping power and sputtering, as well as helping to streamline the build system and Python language bindings. Python bindings were also developed so that researchers can access these new modules from within their own simulation codes. In addition, these Python bindings are also used in the web interface to TxPhysics.

Figure 6: Sputtering yield as a function of incident angle for argon on iron targets. Comparison is between models of Yamamura, Sigmund, and experimental data.

Add GUI capability to make physics modules user-friendly

Accessibility to new physics models developed here and the ability to include those models in many different simulation codes was a major objective of this project. We achieved that goal by both providing ease of use for building the TxPhysics library and through support for multiple steering languages. In addition, we completed this task by providing a web-based GUI for researchers to be able to access stopping power routines without having to write any code at all. The TxPhysics web site, <http://txphysics.txcorp.com> allows users to plot and compare different components of stopping power for many different beam/target combinations, different target temperatures, and over a large range of incident beam energies. Different TxPhysics stopping power models are available, including bound electronic, free electron, nuclear, and the classical Bethe-Bloch models. In addition, the data underlying the plots may be viewed and downloaded, and the calculations may be saved and published to colleagues from the web site. Figure 7 shows a screen shot of the web interface to TxPhysics. The plots are of stopping power components for lithium and sodium incident on copper targets with a temperature of 10 eV.

In addition to providing libraries which calculate stopping powers and sputtering yields in TxPhysics, we have succeeded in providing routines which calculate other quantities important to HEDP, such as fractional ionization and effective charge. These quantities are computed as part of the electronic stopping power calculations, but are also important quantities in terms of calculating beam dynamics and target evolution in WDM and HEDP configurations. Figure 8 shows computed values for fractional ionization and effective charge for various ions moving in Aluminum. The variation of these quantities can directly affect target heating as the ions lose energy to the target electrons.

Figure 7: The web interface to TxPhysics numerical library provides quick access to stopping power calculations without the need to write complicated test codes.

Additional achievements

In addition to achieving the goals set out in the Phase II proposal, we additionally succeeded in a number of other areas related to WDM and HEDP modeling, as the focus of the HIF program changed to supporting ICF experiments. We worked with researchers at the HIF-VNL and at LLNL to interface the HYDRA rad/hydro simulation code to new stopping power algorithms implemented in TxPhysics, and to design and carry out simulations relevant to ICF experimental programs.

Sophisticated hydrodynamics codes such as HYDRA depend on accurate stopping power algorithms in order to compute energy deposition when simulating ion-beam driven HEDP and WDM experiments. Our alternative stopping power models are more accurate at low beam energies than the classical energy deposition algorithms, primarily due to the inclusion of nuclear stopping, but also in part to differences in electronic stopping at low beam energies.

Figure 9 shows a comparison between the stopping power algorithms implemented here in TxPhysics and the classical energy deposition algorithms as implemented in HYDRA. The left plot is for 360 keV potassium in aluminum corresponding to NDCX I parameters, while the right plot is for 2.75 MeV lithium in aluminum, corresponding to the proposed NDCX II experiment. Components of stopping power for HYDRA are in red, while for TxPhysics are in yellow. The solid line is the total stopping power, dot-dashed is stopping due to bound electrons in the target, dashed is free electron stopping, and dotted is nuclear stopping. The overall lower total stopping implies deposition over a larger volume of the target.

Figure 8: Fractional ionization (red) and effective charge of primary ions as a function of incident energy for protons, Li, Na, and K ions.

Figure 9: Comparison between TxPhysics and HYDRA stopping powers relevant to the NDCX I and NDCX II WDM experiments. TxPhysics stopping power components are plotted in yellow, while HYDRA is in red.

Test simulations measured differences in target density and velocity evolution due to alternative stopping power models. For beams with energies much below the Bragg peak, nuclear stopping plays a significant role in energy deposition, which can affect the evolution and heating of WDM targets. In the simulations two 1 ns pulses at different energies, and separated by 1 ns, impact a 30 μm aluminum target that is 50% solid density. Significant differences in the target density and velocity evolution were observed between the two energy deposition models, even in cases where the second beam was above the Bragg peak. Figure 10 shows an example of

differences in the evolution of an aluminum foam target between the two stopping power models. In the simulation on the left plots, the first beam energy is well below the Bragg peak, while the second beam is just above the Bragg peak. On the right hand plots, the ratio between first and second beam energies is about the same, but the overall energies are much larger.

Figure 10: Dual pulse simulations of lithium incident on a 30 μm 50% solid density aluminum foam. Significant differences can be seen in the density and target material velocity due to the different energy deposition models.

Results related to the implementation of new stopping power formulations and comparisons with the HYDRA algorithms have been reported to the HEDP and WDM research community as posters at the 2007 Particle Accelerator Conference (PAC07), and at the 2007 APS Division of Plasma Physics (DPP) Meeting.

Plasma Sheath Simulations

We also did extensive numerical experiments to model the effect of particle/solid material interactions on sheath formation. Plasma sheaths play an important role in ion/material interactions for many plasma systems. The non-neutrality of the sheath region can significantly affect ion trajectories close to conducting surfaces, the distribution of ion energies upon wall impact, and even the degree of ionization in the plasma. Sheath physics can further affect physical sputtering of wall material, which is a significant source of energy loss due to impurity radiation in magnetized fusion and magnetic confinement fusion reactors.

We made significant progress on high-resolution simulations of sheath physics incorporating physics routines from TxPhysics such as impact ionization, secondary electron production, and physical sputtering. More specifically we modeled single and dual frequency capacitive plasma discharges using VORPAL [10]. These discharges are used for etching, sputtering and other

surface treatments of materials, and these simulations will have a positive impact on researcher's ability to model accelerating cavities in which beam ions impact beam pipe walls.

We performed extensive simulations in which a radio frequency biased electrode heats plasma electrons stochastically. This results in enough electron impact ionization to sustain the discharge. Results have been compared to the existing literature and show reasonable agreement.

Figure 11: The number of peaks in the ion energy distribution function varies with the ion transit time in a single-frequency capacitive discharge

Theory predicts that the number of peaks in the statistical distribution of ion energy at the electrode varies with the ion transit time over one RF period. Our simulations show that the number of peaks in the ion energy distribution function (IEDF) scales roughly as the square root of the ion mass. Figure 11 shows the distribution of ion energies at the wall for a hydrogen plasma in a single-frequency capacitive discharge. This is for comparison with the experimental study for an Argon plasma reported in [11]

We also performed high-resolution simulations of multiple-species plasmas. Bohm's criterion for a single species plasma states that the ions must have a velocity of at least their sound speed at the sheath entrance. In a multiple species plasma many solutions are mathematically possible, allowing for the possibility that some species may arrive with a Mach number less than unity. However, studies performed using VORPAL so far demonstrate that the slowest of the ion species still arrives at the Debye sheath entrance at its sound speed. Results for our sheath simulations were presented at the 2007 Gaseous Electronics Conference.

References

- [1] *Computational Modules for Electron Effects*, Small Business Innovation Research Grant #DE-FG02-03ER83840, Principal Investigator: Peter Stoltz, Tech-X Corporation.
- [2] [4] <http://www.srim.org/> .
- [3] W. Brandt and M. Kitagawa, *Effective stopping-power charges of swift ions in condensed matter*, Phys. Rev. B **25**, 5631 (1982).
- [4] T. Peter, J. Meyer-ter-Vehn, *Energy loss of heavy ions in dense plasma. I. Linear and non-linear Vlasov theory for the stopping power*, Phys. Rev. A, **43**, 1998, (1991).
- [5] T. Peter, J. Meyer-ter-Vehn, *Energy loss of heavy ions in dense plasma. II. Nonequilibrium charge states and stopping powers*, Phys. Rev. A, **43**, 2015, (1991).
- [6] T. Mehlhorn, *A finite material temperature model for ion energy deposition in ion-driven inertial confinement fusion targets*, J. Appl. Phys., **52**(11), (1981).
- [7] J. F. Ziegler, J. P. Biersack, U. Littmark, "The stopping and range of ions in solids," Pergamon Press, New York, (1984).
- [8] Y. Yamamura, H. Tawara, *Energy dependence of ion-induced sputtering yields from monatomic solids at normal incidence*, Atomic Data and Nuclear Data Tables, **62**, p. 149-253, (1996).
- [9] P. Sigmund, *Theory of sputtering. I. Sputtering yield of amorphous and polycrystalline targets*, Phys. Rev., **184**(2), p. 383, (1969).
- [10] C. Nieter and J.R. Cary, *VORPAL: A versatile plasma simulation code*, J. Comput. Phys., **196**, pp. 448-473, (2004).
- [11] J.K. Lee and O. V. Manuilenko and N. Yu. Babaeva and H. C. Kim and J. W. Shon *Ion energy distribution control in single and dual frequency capacitive plasma sources*, Plasma Sources Sci. Technol., **14**, (2005).