

Can we use graphene as a conversion surface for a neutral particle detector?

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An important technique of modern space plasma diagnostics is a detection and imaging of low energy (below 10 keV) energetic neutral atoms (ENA). Any space mission devoted to study of the planetary plasma environments, planetary magnetospheres and heliosphere boundaries, needs a low energy ENA imaging sensor in its payload list. A common approach to the ENA detection/imaging is to make energetic neutral atoms glance a high quality conductive surface and either produce a secondary electron, and/or produce a positive or negative reflection ion. In the first case we can collect and detect the yielded secondary electron and generate a start signal. The reflected neutral atom can be directed to another surface with a high secondary electron yield. Thus we can measure a time-of-flight of the reflected particle to get its velocity. In the second case we can analyze the reflected ion in an electrostatic analyzer to get the particle energy.

Many types of conversion surfaces have been investigated over last decades in order to optimize an ENA sensor properties. We investigated properties of a thin layer of graphene applied to a silicon wafer surface. The experimental setup consisted of a secondary electron detector, neutral/ions separator and a high resolution particle imager. We used an incident He beam with energy of 200 eV - 3000 eV. We obtained a secondary electron emission, particle reflection efficiency, scattering properties, and a positive ion production rate as a function of the incident beam energy and the grazing angle.

Any event or structure (like substorm, magnetic storm, reconnection, cusp, direct interaction of solar wind with ionosphere, etc) in a planetary space environment can produce energetic neutral atoms (ENA) due to charge exchange between the ions of the magnetospheric plasma and the exospheric neutral particles. Remote imaging of such ENAs allows us to get a distance and a global view of corresponding plasma processes. In ENA imaging it is not only the angular distribution that is measured, but also the energy and mass of ENAs originating from an ENA source region. By determining ENA flux angular distribution as well as ENA energies and masses it is possible to establish plasma ion composition and distribution function remotely. This makes it possible to probe inaccessible regions in space from afar, as well as to obtain instantaneous information about the object.

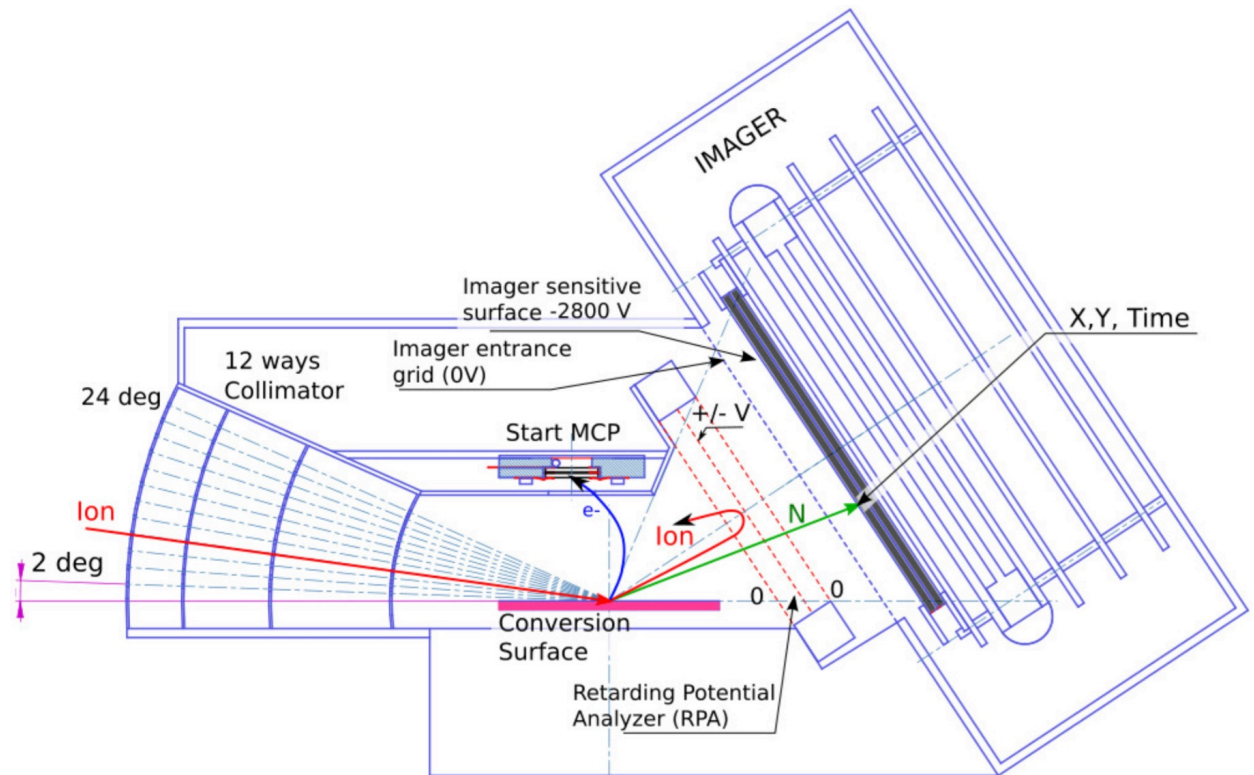
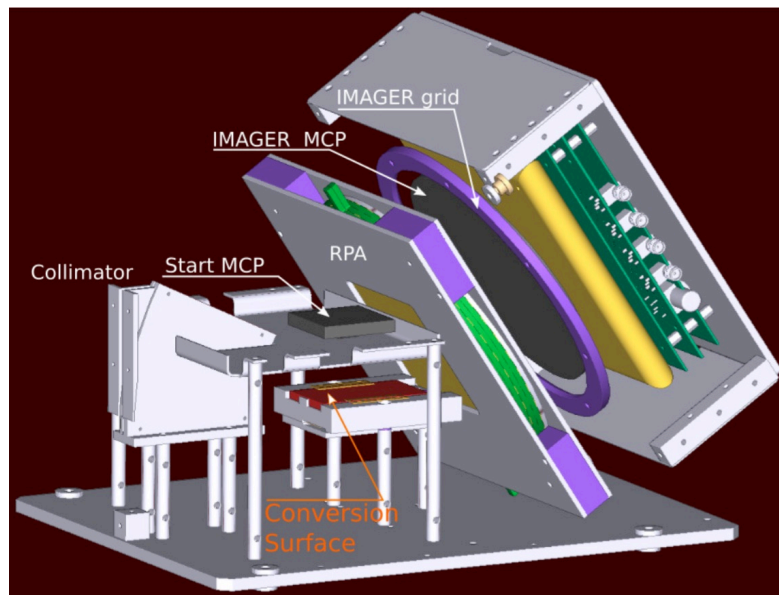
To cover most of the ENA sources of interest an ENA instrument shall be capable to detect ENA within 100 eV to 10 keV energy range, capable to shot the image of the neutral particles angular distribution with very high angular resolution (better than 1°), acceptable energy resolution and a large geometrical factor.

In order to detect ENAs and obtain a sufficiently good signal-to-noise ratio, an ENA sensor has to be able to perform the following functions:

- detection of incoming ENAs with angular, energy and mass resolution
- rejection of charged particles
- suppression of EUV/UV photon background

Detection of the ENA of low and medium energy range is usually performed by ionization of neutral particles by means of interaction with foils or conversion surfaces, followed by detection of ionized components. Detectors of ENA of energy >600 eV can use thin/ultra-thin foils in order to convert an incoming ENA to an ion in a foil passage. ENAs with lower energy (<600 eV) are not able to effectively penetrate through an ultra-thin foil without significant scattering. In this case an approach is to let a particle interact with a conversion surface upon scattering to initiate detection.

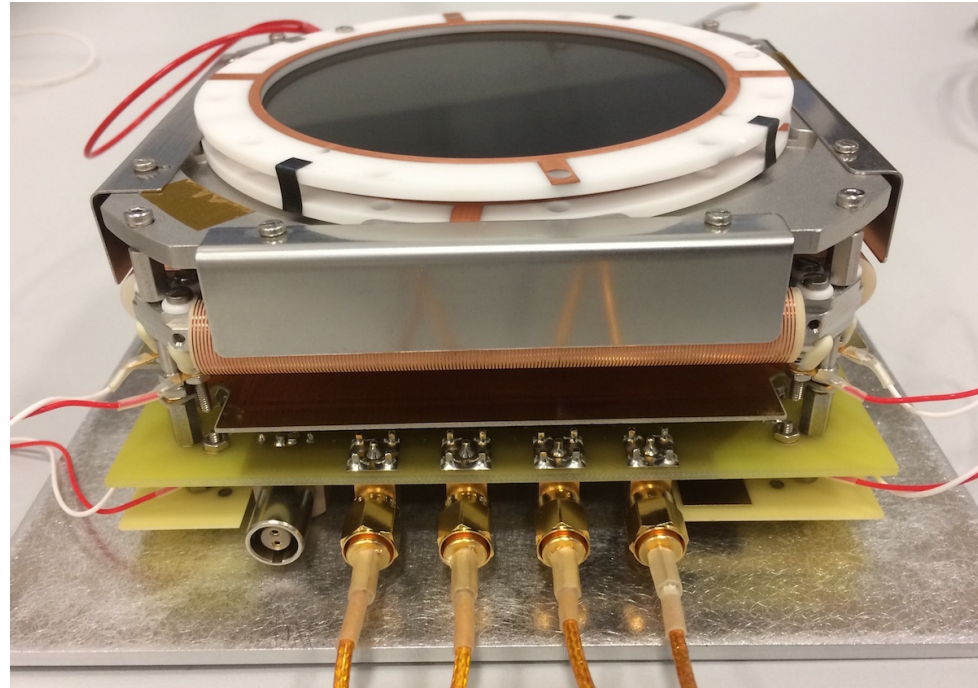
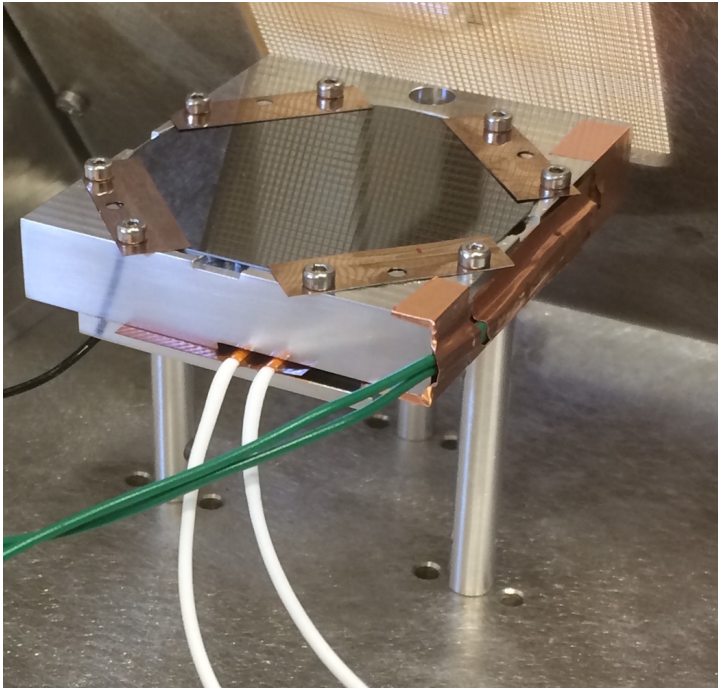
The goal of this work is to find a conversion surface with a high secondary electron yield for low energy incident atoms and low reflecting atoms dispersion in angular and energy range. To find the way to detect reflecting atoms of as low energy as possible with estimation of their energy.



Experimental setup sketch (right panel) and 3D view of the setup implementation (left panel)

The instrument comprises a **Collimator** which forms a collimated ion beam and allows the particles to strike the Conversion surface under a chosen shallow angle, a **Conversion surface** followed by a **Retarding Potential Analyzer (RPA)** or a **Deflector**, which allows separation of charged particles from neutral ones, a **Start MCP** to collect secondary electrons yielded from the conversion surface, a **Stop MCP** to detect the particles and the **FEE** to register Start and Stop events to perform Time-of-flight analysis as well as a calculation of a detected particle position.

- The Collimator has 12 channels of $1 \times 1\text{mm}$ of aperture and 1° each . The channels create 12 separated angular entrances with 2° step. Each channel radiates a very small part of the conversion surface, the same for all channels.
 - Above the conversion surface there is a start MCP. The sensitive surface of the MCP is polarized to positive voltage between +100 and +400 V. Thus all secondary electrons created on the Conversion Surface are collected by the Start MCP which generates a Start signal for the acquisition system.
 - The setup is bombarded by positively charged ions of selected species and selected energy. The incident ion beam flux is known.
 - The incident ions strike the conversion surface and convert to neutral atom, positive and negative ions. At the moment we cannot measure the negative ions because of the IMAGER entrance polarization.
 - The ions are separated from the neutral atoms by a Retarding Potential Analyzer (RPA).
 - A deflector with a vertical slit is used in the modified setup instead of the RPA.
 - The instrument EGSE allows to measure the time interval between a Start signal and an impact (Stop) time. The precision is 25 ps. This time interval can be easily converted to the particle Time-Of-Flight (TOF) and to the incident particle velocity.
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The graphene conversion surface (left panel) is a polished Si wafer coated with single layer of graphene. Producer LUXEL, Seattle, USA.

The conversion surface is replaceable. A small heater is installed under the conversion surface in order to remove the contamination layer from the surface. Attached temperature sensor allows to control the conversion surface temperature.

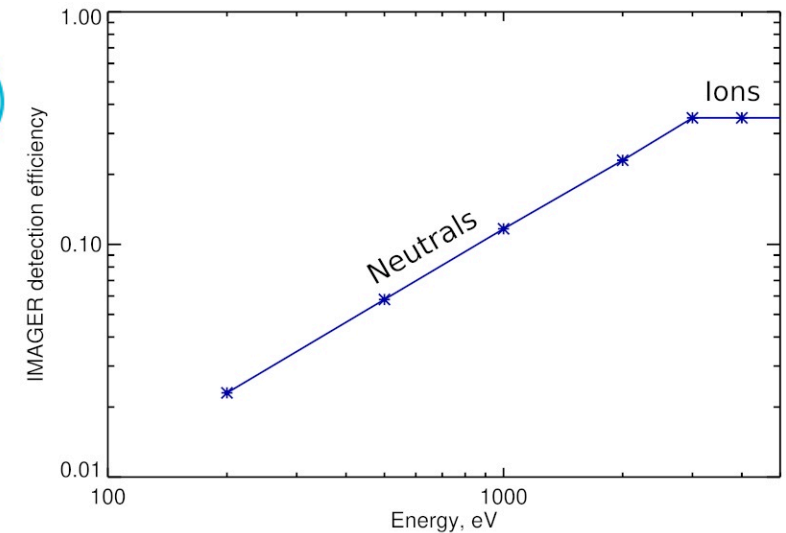
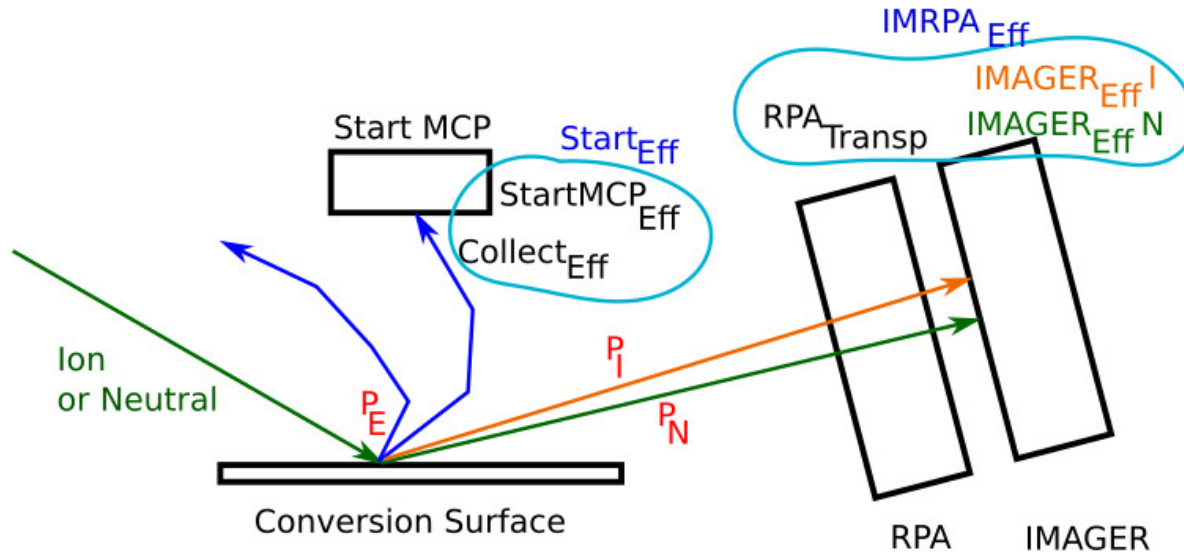
The MCP + delay line FEE (right panel) allows to measure an exact (with 0.1 mm precision) position of the incident particle.

The incoming He⁺ ion beam of known intensity is being collimated by the collimator, which also defines an elevation angle of the incidence, then strikes the conversion surface under a chosen shallow angle and is being scattered towards the Stop MCP. During the interaction of the ion beam with the conversion surface secondary electrons are yielded and collected by the Start MCP. During the scattering process the incoming particles can be converted to neutral atoms, positive or negative ions. The ions can be separated from the neutral atoms by a RPA or a Deflector. Then the particles are being detected upon hitting the Stop MCP detector. The EGSE allows to count the Start and the Stop events, calculate detected particles positions, perform Time-of-flight analysis as well as to remotely control all necessary high voltage power supplies.

The experiment goal is to characterize the conversion surface by means of an incident He ion beam which energy changes from 200 eV up to 3000 eV for two inclination angles of 4 deg and 16 deg.

During the characterization process a following set of parameters as a function of the incident beam energy and the grazing angle is to be obtained:

- a secondary electron emission,
 - particle reflection efficiency,
 - a positive ion production rate
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Term	What is it	Comments
P_E	Secondary electron efficiency	Goal. Probability to generate secondary e- = 0.66 for any cases
$Collect_{Eff}$	Probability of sec. e- reach Start MCP	
MCP_{Eff}	Probability to get event at Start MCP	estimated as 0.8 (no way to measure)
$Start_{Eff}$	$Collect_{Eff} \cdot MCP_{Eff}$	= 0.53 Probability to register secondary e-
P_I and P_N	Probability to reflect Ion+ (I) or neutral (N)	Goal. Probability for atom to reflect = 0.66 in normal incident
RPA_{Transp}	Transparency of the RPA	= 0.351 (for 3KeV) <u>measured</u>
$IMAGER_{Eff}^I$	Probability to get event at IMAGER for Ions	
$IMAGER_{Eff}^N$	Probability to get event at IMAGER for neutrals	
$IMRPA_{Eff}$	$RPA_{Transp} \cdot IMAGER_{Eff}$	Probability to detecte reflected particles

The goal is to define the P_E , P_N , and P_I .

For each energy we do as follows:

1. Measure and calculate the incident partricle rate from the Beam Monitor (CEM) count rate:

$$C_{Inc} = C_{CEM} \cdot 2$$

2. If the count of Start MCP is C_{Start} , the real Conversion Surface secondary electron production probablility is:

$$P_E = (C_{Start}/Start_{Eff})/C_{Inc}$$

3. The insidend atom can reflect from the the surface in form of neutral atom or a positive charged atom (we cannot detect negative charged atoms in this setup). The reflection probablilities P_I and P_N are calculated from the corrected counts C_{Stop}^{ALL} and C_{Stop}^N of the IMAGER for the corresponding +13V RPA and +Energy+50V on the RPA . We calculates P_I and P_N as follows:

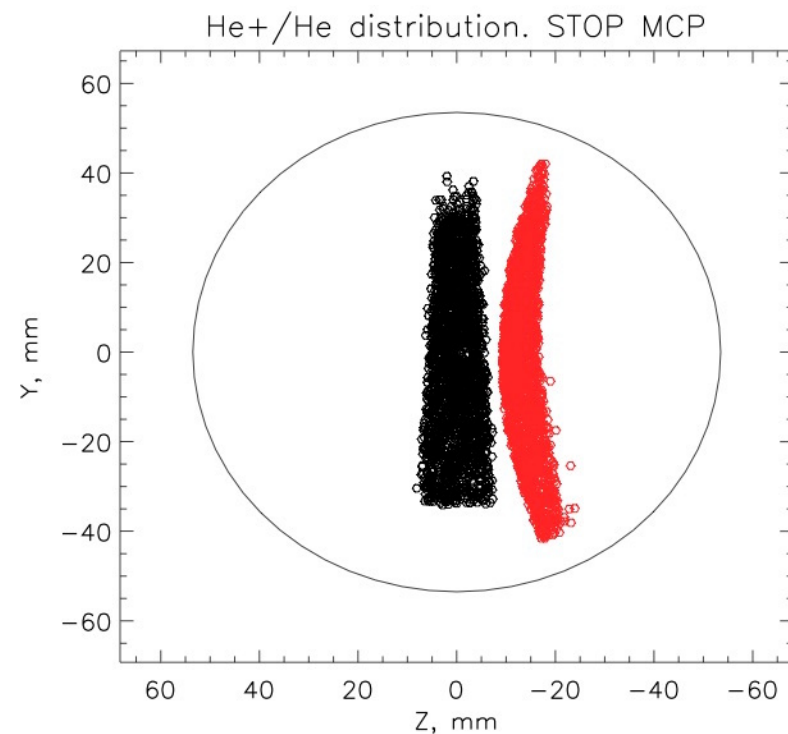
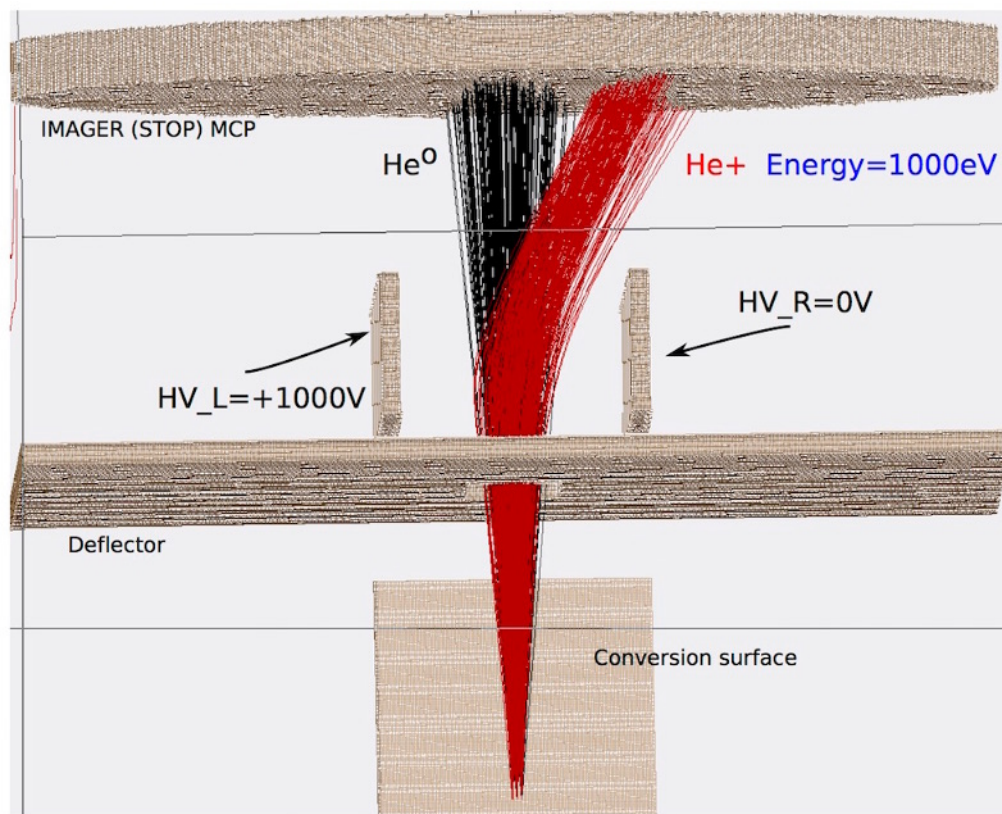
$$C_{Stop}^N/C_{Inc} = P_N \cdot IMAGER_{Eff}N$$

$$C_{Stop}^{ALL}/C_{Inc} = P_N \cdot IMAGER_{Eff}N + P_I \cdot IMAGER_{Eff}I$$

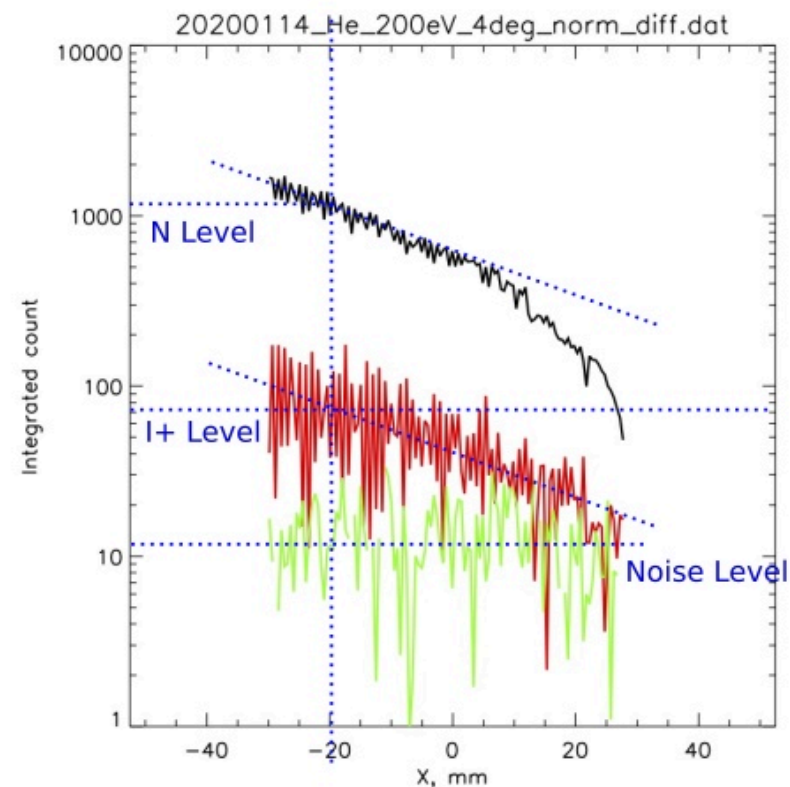
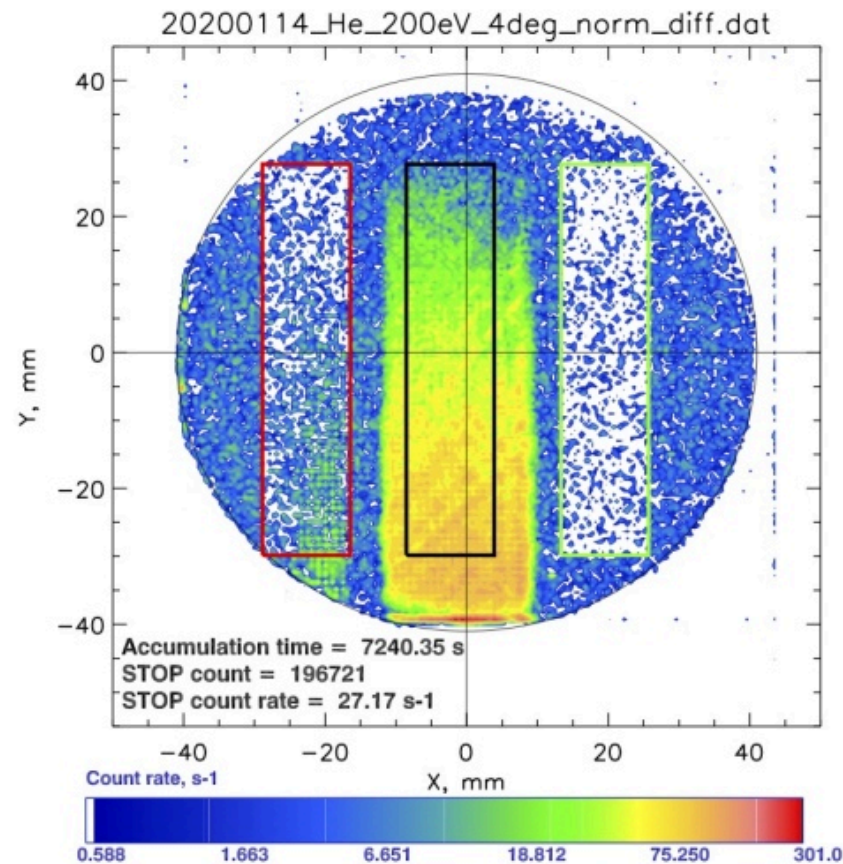
thus

$$P_I = (C_{Stop}^{ALL}/C_{Inc} - C_{Stop}^N/C_{Inc})/IMAGER_{Eff}I$$

$$P_N = (C_{Stop}^N/C_{Inc})/IMAGER_{Eff}N$$



To separate neutral atoms and positive ions charged on the conversion surface, we replaced the retarding potential analyzer with a deflector with a vertical rectangle aperture. The neutral particles give the black image (the right panel) and the positive ions give the red image. Thus we can calculate their ratio using the Imager detection efficiency function shown in the previous slide.



Left panel shows the neutral He atoms distribution (center rectangle) and He⁺ distribution (left rectangle). We can see a significant difference between two distributions. Right empty rectangle shows the noise level. The right panel shows the corresponding distributions integrated over the horizontal axis of each rectangle. Both, ions and neutrals distributions have identical profiles along vertical axis. Thus we can compare them removing the Imager noise level.

$$StopCountRate \cdot IMAGE_T = Nrate \cdot IMAGR_{eff}N + Irate \cdot IMAGR_{eff}I$$

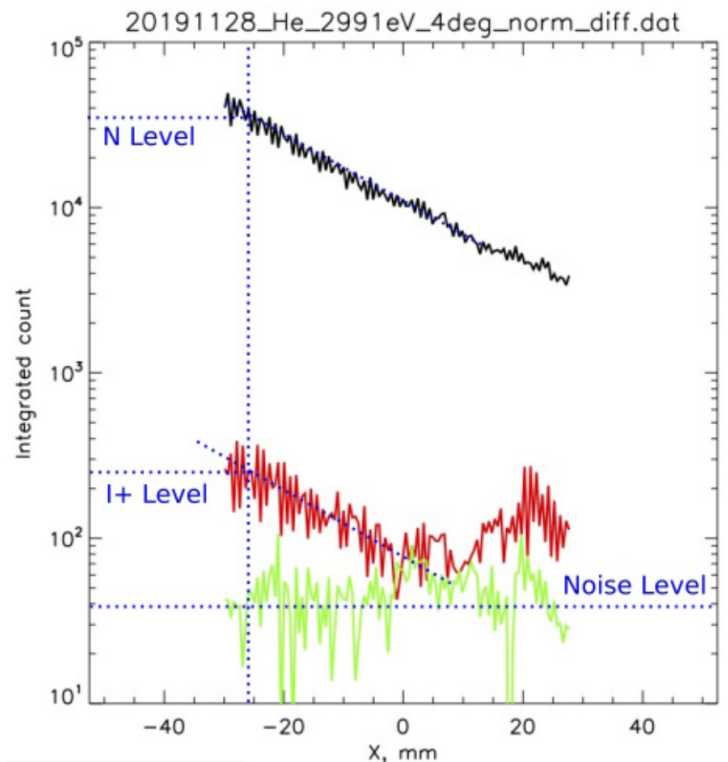
$$I/N = ((Ilevel - NoiseLevel)/IMAGR_{eff}I)/((Nlevel - NoiseLevel)/MAGR_{eff}N) \quad (1)$$

$$Nrate = \frac{StopCountRate \cdot IMAGE_T}{IMAGR_{eff}N + I/N \cdot IMAGR_{eff}I} \quad (2)$$

$$P_N = Nrate/IncidentRate \quad (3)$$

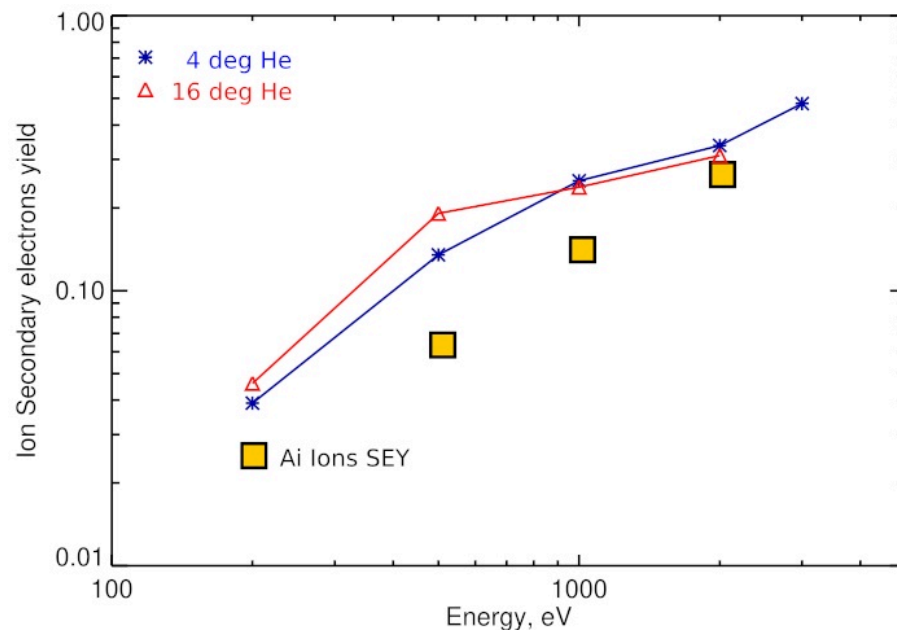
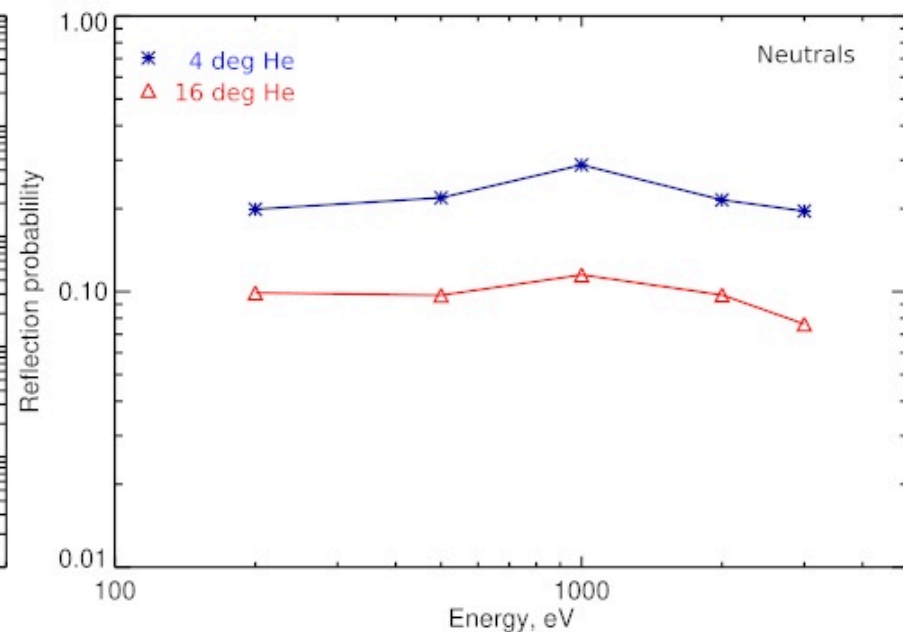
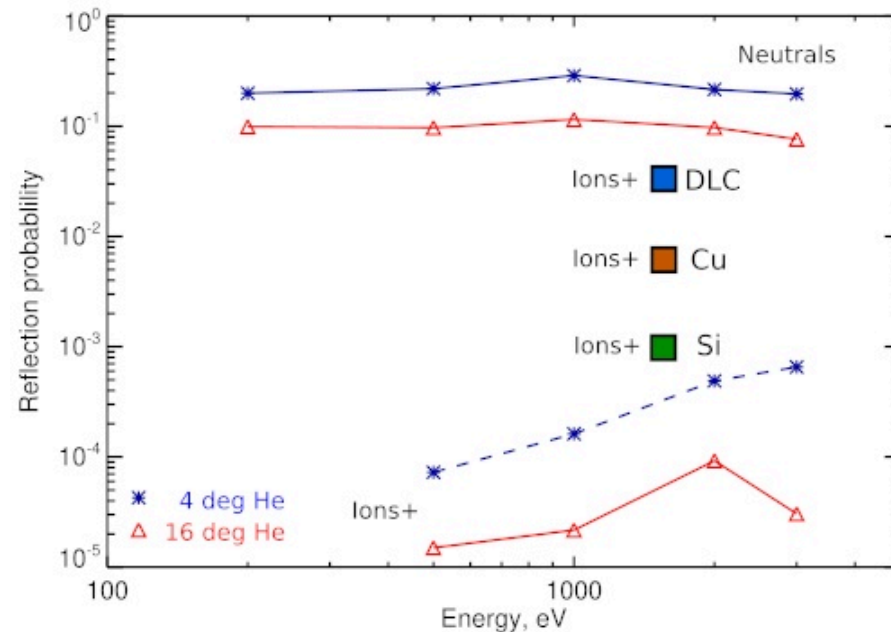
$$P_I = P_N \cdot (I/N) \quad (4)$$

We have to adapt the formulas shown in slide # 10 for the deflector. See below the image and the corresponding calculations



Item	w/o coinc	
CEM count rate, s <aver>	6300.0	Measured
Incident He+ rate, s-1 <aver>	12600.0	
Count rate stop, s-1 Defl OFF <normal>	554.50	Measured
Neutral eff OFF	0.1504	
Count rate stop, s-1 Defl ON <normal>	723.50	Measured
Noise Level	4.00E+01	Measured
I+ Level	2.40E+02	Measured
N Level	6.00E+04	Measured
Ion+/Neutral	3.336E-03	GOAL
Neutral Rate ON	2.472E+03	
Creation efficiency, N (P_N)	1.96E-01	GOAL
Creation efficiency, I+ (P_I)	6.54E-04	GOAL
Full reflection efficiency	1.97E-01	GOAL

Conversion surface Graphene Results



Top left panel shows graphene reflection probabilities for neutral He and ions He+. The squares show the data for positive ion generations on Si, Cu and Diamond-like Carbon surfaces. Our data are close to Si surface reflection. Right panel shows the same for neutrals only. Left bottom panel shows the secondary electron yield from the ions impact. The yellow squares show the gold surface properties.

1. Ion impact secondary electron yield (SEY) from graphene conversion surface is low and similar to the gold SEY. Thus this SEY is too small to be applied in a mass spectrometer.
 2. Efficiency of neutral atoms reflection at graphene conversion surface is constant and close to 20% (20% total reflection).
 3. Ion production is very small. Thus such graphene conversion surface cannot be applied to an ion spectrometer based on ion optics.
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