A new collimator design for energetic neutral atom instruments

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A new type of collimator design is described for energetic neutral atom instruments for space research applications. The collimator consists of annular entrance and exit slits with charged particle deflection plates between them. This configuration allows one to meet three seemingly contradicting requirements of compact design, efficient rejection of the incoming ions, and a large field of view.

Hot plasmas in space emit energetic neutral atoms (ENAs) born in charge exchange between energetic (0.1–100 keV) ions and background neutral atoms. The measurement of ENA fluxes is recognized as a powerful tool in the study of both the planetary magnetospheres[1] and the heliosphere.[2–5] The low intensity ENA flux reaching an ENA sensor must be sorted out from the usually more intense ion fluxes and background EUV and UV radiation. An instrument for ENA detection usually consists of a mechanical collimator followed by a sensor performing detection and characterization (mass, energy, direction) of the particle.[5–7] Three major requirements to the collimator design must be typically satisfied: efficient prevention of background charged particles—ions and electrons—from entering the instrument, large geometrical throughput, and compact design.

In many space applications the expected ENA fluxes are very weak, and a compact instrument for ENA measurement requires a fairly large field of view (FOV) since increasing the FOV is a way to achieve a large geometrical throughput and consequently the sensitivity. In many cases, for example, global heliosphere imaging, the expected angular distributions of ENA fluxes allows the use of FOV as large as 30°. Such a large FOV often contradicts, however, the requirement of efficient ion deflection.

The use of electrostatic field is preferred to prevent ions from entering the instrument and the simplest arrangement of an electrostatic deflector is a pair of parallel plates of length L, separation d, and having a voltage V, between them. Ignoring the fringing fields, a simple trajectory under constant force allows one to approximate the maximum energy $E_{\max}$ of ions of charge q that such a collimator can reject, $E_{\max}=(qV/4)(L/d)^2$. For a given voltage source, maximizing the L/d ratio obviously maximizes $E_{\max}$. The requirement of maximum L/d ratio results in a selection of collimators with slit-like FOVs[6–7] and limits geometrical throughput of the instrument which must be maximized for the detection of low-intensity ENA fluxes. Such a FOV does not allow the efficient use of the full sensitive area of a particle detector, and the sensor has a narrow FOV in one dimension.

A strong emphasis on small, compact, light-weight (<1 kg), and low-power-consuming (<1 W) instruments for future deep space missions prohibits the use of large-size collimators and limits possible values of the deflecting voltage V. The goal of this work is to suggest a new design of the collimator for ENA instruments which accommodates the seemingly conflicting requirements of a high geometrical throughput, efficient ion rejection, and small size.

A wide FOV combined with a small distance between deflecting plates can be achieved by maintaining the slit-like structure of the collimator while bending it to form a full circle, i.e., by the annular configuration of the collimator. Depending on the application, the entrance S_{en} and exit S_{ex} annuli could be of different diameters and widths; here for simplicity we will consider equal size annuli only (Fig. 1). Deflecting plates between the entrance and exit plates prevent the entrance of the charged particles.

The collimator characteristic of interest is the effective sensitive area $S_a(\alpha)$, i.e., the area which allows the unobstructed passage of ENAs coming from the off-axis angle α. The subscript a here stands for "annular collimator." This dependence, $S_a(\alpha)$, can be easily determined by considering the "shadow" cast by the entrance annular slit on the plane of the exit slit. This shadow would be the annulus S_{sh} shifted from the axis by the distance $l=L_a tg(\alpha)$, where L_a is the distance between the entrance and exit annular slits (Fig. 2). Then the overlapping area of these two annuli (hatched area on Fig. 2) would be an effective area of the collimator in the absence of the inner deflection plate. The presence of the inner deflection plate (diameter d_s; Fig. 1) can be easily taken into account.

A typical slit-like collimator has a narrow FOV in one direction and a wide FOV in another direction. An annular collimator can be considered as a combination of the linear slit collimators with various orientation. Particles coming from a certain direction would enter the annular slit at angles (relative to the local slit orientation) varying from 0 to 90° depending on the exact position on the annulus (Fig. 2). As a result, a wide axis-symmetric FOV can be obtained using annular collimator while maintaining the minimal distance between ion deflection plates.

The collimator total geometrical throughput Γ_a,

$$\Gamma_a=\int_0^{\pi/2} 2\pi S_s(\alpha)\sin(\alpha)d\alpha. \tag{1}$$

As an example we will consider the collimator with the identical entrance and exit annular slits: $d_{11}=d_{21}=1.7$ cm; $d_{12}=d_{22}=2.5$ cm; and $L_a=2.5$ cm (Fig. 1). The diameter of the inner deflector plate is equal to that of the inner slit,

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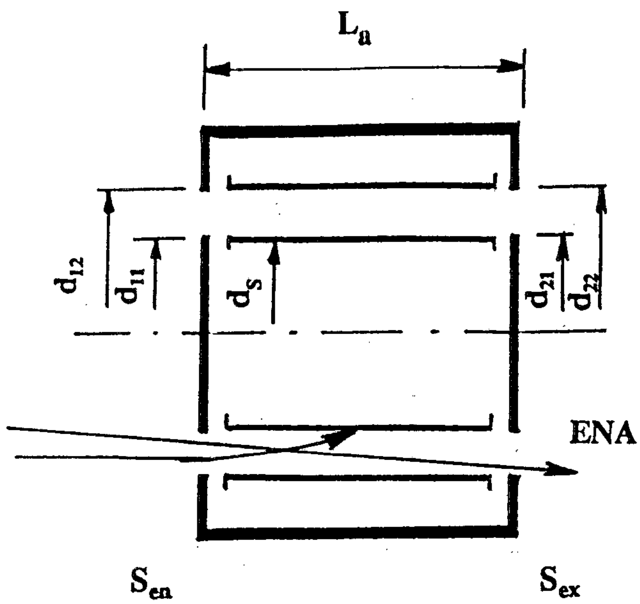

FIG. 1. Axis-symmetric annular collimator with the identical entrance and exit slits; S_{en} is the entrance slit and S_{ex} is the exit slit. The trajectories of ENA (straight line) and ion (curved line hitting the deflector plate) are shown.

$d_s=d_{11}$. The calculated dependence $S_a(\alpha)$ is shown in Fig. 3; the total geometrical throughput for such a collimator is $\Gamma_a \approx 0.36\ \text{cm}^2$ sr. The relatively large value of the geometrical throughput is achieved due to large wings of the angular dependence $S_a(\alpha)$ which efficiently contribute to the integral (1).

It is useful to compare characteristics of this collimator with those of a "standard" collimator consisting of two circular openings of equal diameter d_0 separated by the distance L_s. The subscript "s" stands for "standard collimator." The standard collimator with the same area of opening, i.e., $\pi d_0^2/4=\pi(d_{11}^2-d_{12}^2)/4$, has the aperture diameter $d_0=1.83$ cm. The same geometrical throughput of the standard collimator Γ_s is obtained for the distance between the two apertures $L_s=5.84$ cm.

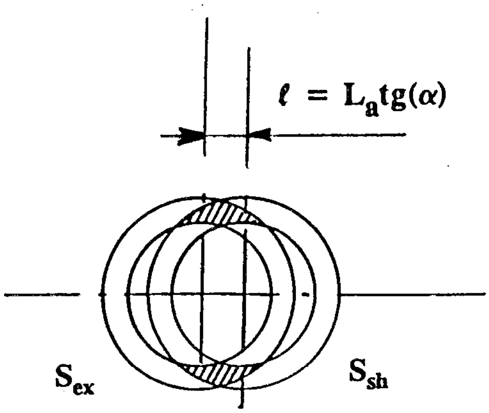

FIG. 2. "Shadow" cast by the entrance annular slit on the plate of the exit slit; S_{ex} is the exit slit and S_{sh} is the shadow of the entrance slit. The hatched area corresponds to the effective area (in the absence of the deflecting plates) of the collimator transmitting ENAs coming from the off-axis angle α.

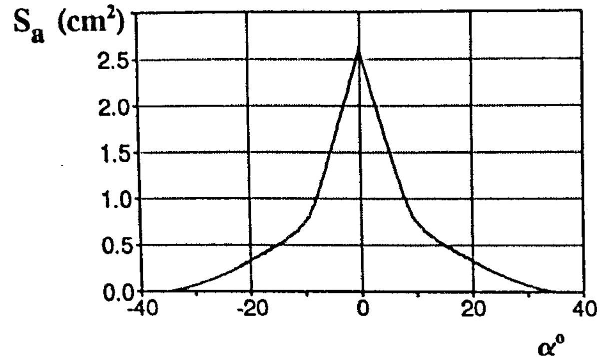

FIG. 3. Angular dependence of the annular collimator effective area.

Possible minimal distances between the deflecting plates are $\Delta_a=(d_{11}-d_{12})=0.4$ cm and $\Delta_s=d_0=1.83$ cm for the annular and standard collimators correspondingly. The deflecting electric field in the annular collimator is inversely proportional to the distance from the axis R. We can, however, assume for our estimates that the field is uniform since the distance between the cylinders, Δ_a, is much smaller than the cylinder diameter. Indeed, the electric field between cylinders is given by[8] $V/[R \ln(d_{12}/d_{11})]$ and its value varies within $\pm 20\%$ from the average electric field, V/Δ_a, in our case.

If we apply the same voltage between the plates, then the ratio of maximum ion energies that are deflected by the annular and standard collimators would be $(L_a/\Delta_a)^2/(L_s/\Delta_s)^2 \approx 3.8$. Not only is the length of the annular collimator less than half of the standard collimator, but the same voltage would provide deflection of ions with almost four times the energy than in the case of the standard collimator. The lateral size of the annular collimator is only slightly larger than the size of standard collimator, 2.5 cm as compared to 1.83 cm.

The annular collimator described here offers a substantial advantage over the standard collimator design and it would allow the building of compact, wide FOV ENA instruments with efficient ion rejection.

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