Stopping power: Wrong terminology.  
Author’s response

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In a recent note [1] the author questioned the validity of the term ‘stopping power’ to denote the mean energy loss per path length of a charged particle and suggested to replace it by ‘stopping force’. In response to this note the ICRU received letters from three colleagues or groups of colleagues [2, 3, 4] which were transmitted to me by the commission and/or the authors. The present note serves to comment on what I believe are the main points expressed by these authors.

Linguistics: All authors point out that the term ‘power’ has a much wider range of applicability than energy transfer per time. Several examples are mentioned, some of them even within standard physical terminology. This, of course, is entirely correct. Indeed, stopping power appears to be a valid translation of the corresponding terms in German, French and Danish which I mentioned in [1]. One could argue, therefore, that a more consistent solution to the problem would be to replace ‘power’ in physics and technology by another term. While the English language unquestionably could provide a valid alternative, I have doubts as to whether this is a more feasible solution than to agree on an alternative to ‘stopping power’.

However, the fact that the term is linguistically correct does not deny the existence of a clash. I agree that there is no obvious way to mix up the resolving power of an optical instrument with the power of an engine. But what about this one? Consider a foil, thickness $\Delta x$, penetrated by a beam with a current $J$ [particles/second] (see first figure). Here,

$$\text{Power} = J \cdot \Delta x \cdot \text{(Stopping Power)},$$

where the factor $J \cdot \Delta x$ has the dimension of a velocity. Now, the beam power deposited in a foil is an important experimental parameter which determines its temperature and perhaps its lifetime. It has even been utilized to determine the stopping force in a series of precision measurements [5]. I have difficulties in trying to explain to my students how physicists can live with such a clash in terminology for almost a hundred years.

Stopping power and force  All authors comment on the use of the force concept, and various points are brought forward to question the validity of the term in the present context. These objections come to me as a complete surprise. I did not anticipate that the very fact that the stopping power is a force could be questioned, and therefore just briefly mentioned the dimension as well as Aage Bohr’s argument [6] which has been taken over by Lindhard [7], whose formalism has become common standard for computing stopping forces on swift ions.
Let me first note that the force exerted by an ion beam on a penetrated foil can be used to measure the stopping force (see second figure). The relation reads

\[ \text{Stopping force} = \text{Force} \cdot \frac{v}{J \Delta x}, \tag{2} \]

where \( v \) is the beam velocity\(^1\). Unlike (1), eq. (2) does not lead to a dimensional clash since the factor \( v / J \Delta x \) is dimensionless. Beware, corrections for secondary emitted particles would have to be made if this were going to be established as a precision technique, but that is not the issue here and now.

In ref. [2] the point is made that a force is a vector while the stopping power should be a scalar. Well, if this were true, then the Stokes friction force would also be a scalar. In either case the force is directed opposite to the velocity, at least in an isotropic medium, and hence the relevant directional information is the sign of the force. Certainly the stopping force is not a scalar: Directionally-dependent stopping is known e.g. in channeling and in magnetized plasmas.

In ref. [3] the point is made that usage of ‘stopping force’ would lead to associations with the continuous-slowing-down approximation. This objection disregards the fact that the stopping force represents an average over a large number of trajectories. In fact, precision measurements of the stopping force are performed on thin foils where the effects of slowing-down are kept small. Nevertheless, the stopping force is well defined experimentally even in the presence of large fluctuations (straggling).

Ref. [4] makes the point that the force concept is generally avoided in quantum mechanics. While this is true, the point does not pertain to the stopping force which is a macroscopic parameter that can be determined by macroscopic measurements such as the ones shown in the two figures. Stopping measurements involve an enormous number of particles. Hence, Ehrenfest’s theorem is the relevant issue, not Heisenberg’s uncertainty principle.

**Changing identity:** I brought up the point of particles changing identity during slowing-down since it is an issue that causes problems in certain experiments. The point was taken up in ref. [4], where the validity of the solution which I offered is questioned, i.e., making recourse to Bohr’s original concept of the velocity change per path length. Now, the very existence of a problem here is independent of whether we talk about stopping force, stopping power, momentum or velocity change. However, I agree with the authors that in that particular case the most relevant definition of stopping power goes over the average energy deposited per pathlength, mainly because it is the main application area in this case. However, I would vote against deposited energy as the basis for the definition of the stopping power in general: The average energy loss can be measured directly on the penetrating beam, while the energy deposited in the target goes into several channels, not all of which are readily accessible to measurement and some of which may not even be known.

**General issues:** All authors make general comments which are likely to be made – and unquestionably should be made – in connection with any change in terminology whatsoever. Ref. [2] asks for caution with regard to changing a nomenclature established by a great mind like N. Bohr (or whoever was the true originator). Well, Helmholtz wrote about the conservation of force. I am sure he knew well what he was talking about. Nevertheless the scientific community decided on energy as the pertinent terminology.

In ref. [4] the point is made that stopping power is the pertinent keyword in numerous literature databases. This is a serious point indeed, but taken literally it would imply that henceforth any change in terminology in any established area would be impossible. Finding the right balance here is a good reason for letting decisions about an issue like the present one be decided by a commission with a long lifetime and a long-lasting memory.

\(^1\)For simplicity I keep to the nonrelativistic limit here but note, for completeness, that the identity of stopping power and force on the projectile extends into the relativistic regime. This simply stems from the fact that a particle losing energy does work against the stopping force.
References