Comment on "Radiation-Belt Remediation Using Space-Based Antennas and Electron Beams" by Carlsten *et al.*

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***Abstract*— In a recent article, Carlsten *et al.* state "VLF modes in the ionosphere can be driven either by an antenna or by an electron beam" and dismiss the U.S. Naval Research Laboratory (NRL) concept of producing the very low frequency (VLF) waves by high-speed neutral atom injection perpendicular to the magnetic field as "impractical." In this comment, we highlight that the scientific basis used to make this conclusion is dubious and point to published literature that refutes this conclusion that was not cited in their article.**

***Index Terms*— Accelerators, ionosphere, radiation belts.**

I. Comment

In A recent article, Carlsten *et al.* [1] state "VLF modes in the ionosphere can be driven either by an antenna or by an electron beam" and dismiss the U.S. Naval Research Laboratory (NRL) concept of producing the very low frequency (VLF) waves by high-speed neutral atom injection perpendicular to the magnetic field as "impractical." In this comment, we highlight that the scientific basis used to make this conclusion is dubious and point to published literature that refutes this conclusion that was not cited in [1].

We would like to point out that Mithaiwala *et al.* [6] (see [1, Ref. 10]) is cited as the entirety of the NRL concept, although that article is only a linear electrostatic stability analysis of a heavy-ion ring beam in the ionospheric plasma condition with no discussion of the electromagnetic VLF wave generation. The NRL concept is discussed in detail in [2] and [3] and has the ability to supply the necessary energy for rapid remediation in minutes that other remediation concepts promoted in [1] cannot. Another major advantage of the NRL method is that it does not require stationing large numbers of wave-emitting satellites that must function flawlessly in the hazardous radiation-enhanced environment for days to achieve remediation within a week before the satellites are damaged. Other related NRL publications establish that the laboratory-validated-induced scattering rate [4] is higher in the low beta ionosphere for broadband turbulence than decay or coalescence processes [5], [6]. This makes induced scattering the dominant nonlinear process for conversion of electrostatic lower hybrid (LH) waves into whistler emissions in the ionosphere. The whistlers can then propagate into the radiation belt [7] and form a resonant cavity in which they can amplify through multi-pass gain [8] for a significant boost to the efficiency of the remediation process.

The heart of the authors' claim of impracticality is expressed in the following sentence: "detailed numerical [11] and laboratory experiments [12] have more recently shown that the conversion efficiency of ion ring energy to whistler mode energy is about 10^{-5}, ..." The quoted conversion efficiency is presumably to be found in the references cited, however, neither reference assessed this efficiency in a realistic ionospheric plasma condition. This quoted efficiency can only happen in a highly dissipative medium, which the upper ionosphere is not. The threshold of induced scattering is given by $\gamma_{\mathrm{NL}} \geq \gamma_{\mathrm{L}}$, where γ_{NL} and γ_{L} are the nonlinear-induced scattering and linear dissipation rates. Induced scattering by particles conserves the plasmon number density N, which implies that $N = W_W/\omega_W = W_{\mathrm{LH}}/\omega_{\mathrm{LH}}$, where $W_{W,\mathrm{LH}}$ and $\omega_{W,\mathrm{LH}}$ are the energy densities and frequencies of the LH (pump) and whistler (w, scattered) waves. In homogeneous plasma with negligible linear dissipation, as in the upper ionosphere, the fractional efficiency of scattering, given by $W_W/W_{\mathrm{LH}} = \omega_W/\omega_{\mathrm{LH}}$, will be large since $\Delta\omega/\omega \ll 1$, where $\Delta\omega = \omega_{\mathrm{LH}} - \omega_W$. The numerical simulation cited (see [1, Ref. 11]) is arguably a major step forward in simulation of 3-D LH turbulence, but as explained by Ganguli *et al.* [3] and Rudakov *et al.* [9], it is still far from reality, especially for estimating the efficiency of nonlinear conversion. The simulation uses beta = 0.003, which is much larger than typical in the ionosphere ($\sim 10^{-5}$) and results in an unrealistically high decay rate compared to induced scattering rate. Since the decay process does not conserve the plasmon number density, it will affect the LH-to-W conversion efficiency. In addition, the simulation assumes a homogeneous periodic box with all of the kinetic energy of the heavy ions dumped into the system at time $t = 0$, where in a realistic system, as explained in [3], the kinetic energy will be introduced over a long period of time (30 s) and the propagation of electromagnetic waves out of the generation region (i.e., the simulation box) will allow for more efficient conversion of kinetic energy to electromagnetic energy. In fact, the laboratory experiment cited (see [1, Ref. 12]) contradicts the simulation as it reports a large fractional efficiency of $W_W/W_{\mathrm{LH}} \approx 0.75$, which is a far cry from 10^{-5}. Carlsten *et al.* [1] provide no explanation

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of how this reference (and [11a], which has nothing to do with nonlinear processes) is to be used as evidence of low nonlinear conversion efficiency. Interestingly though, the efficiency reported in [1, Ref. 12] is similar to that found in the NRL experiment [10], which is consistent with theory. Reference [10, Fig. 8] provides a scaling of the conversion efficiency as a function of dissipation in the device to show increasing efficiency with decreasing linear dissipation rate as expected. In conclusion, for the ionospheric parameters under realistic injection conditions with low dissipation and beta $\sim 10^{-5}$, the nonlinear conversion efficiency will be much higher than the quoted 10^{-5}.

The details of the NRL concept were discussed in the Workshop, “Active Experiments in Space: Past, Present and Future,” Santa Fe, NM, USA, September 11–14, 2017, sponsored by the Los Alamos National Laboratory, which was attended by many (if not all) of the authors of Carlsten *et al.* [1]. The authors should have been aware of the physical basis of the NRL concept, which has been explained in several publications. Unfortunately, we are forced to write this comment in an effort to prevent the mischaracterization of our work to an uninitiated reader. We hope that the readers of [1] will also take note of our contributions to judge the merits of the available options for radiation-belt remediation.

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