Revolutionizing our Understanding of Particle Energization in Space Plasmas Using On-Board Wave-Particle Correlator Instrumentation

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Synopsis: A leap forward in our understanding of particle energization in plasmas throughout the heliosphere is essential to answer longstanding questions in heliophysics, including the heating of the solar corona, acceleration of the solar wind, and energization of particles that lead to observable phenomena, such as the Earth's aurora. The low densities and high temperatures of typical heliospheric environments lead to weakly collisional plasma conditions. Under these conditions, the energization of particles occurs primarily through collisionless interactions between the electromagnetic fields and the individual plasma particles with energies characteristic of a particular interaction. To understand how the plasma heating and particle acceleration impacts the macroscopic evolution of the heliosphere, impacting phenomena such as extreme space weather, it is critical to understand these collisionless wave-particle interactions on their characteristic ion and electron kinetic timescales. Such an understanding requires high-cadence measurements of both the electromagnetic fields and the three-dimensional particle velocity distributions. Although existing instrument technology enables these measurements, a major challenge to maximize the scientific return is the limited amount of data that can be transmitted to the ground due to telemetry constraints. A valuable, but underutilized, approach to overcome this limitation is to compute on-board correlations of the maximum-cadence field and particle measurements. Here we propose the development of on-board wave-particle correlator instrumentation for spacecraft missions using existing instrumental capabilities for particle velocity distribution measurements, potentially enabling an increase in the effective sampling time by several orders of magnitude. Such an advance would foster a transformation of our understanding of how the mechanisms of particle energization in heliospheric environments depend on the physical parameters of the system.

Introduction One of the key goals in heliophysics is to discover and characterize the processes controlling the flow of energy and the impact of that energy on the evolution of the space plasma environment. For example, although the source of energy in the heliosphere is nuclear fusion occurring at the heart of the Sun, the mechanisms which mediate the flow of some fraction of that energy into the solar corona—where it ultimately heats the coronal plasma to temperatures in excess of one million Kelvin—remain poorly understood. In particular, the fundamental plasma physics mechanisms of turbulence, magnetic reconnection, shocks, and instabilities (e.g., see Howes, 2017; Hesse and Cassak, 2020; Verscharen *et al.*, 2019; Wilson III *et al.*, 2021b,a, and references therein) play crucial roles in mediating the transport of energy in space and astrophysical plasmas.

Under the typically low-density and high-temperature conditions of turbulent plasmas in the heliosphere and planetary magnetospheres, the energization of particles occurs primarily through the collisionless interaction between the electromagnetic fields and the individual plasma particles (Howes, 2017; Wilson III *et al.*, 2018). To understand how the consequent plasma heating and particle acceleration impacts the macroscopic evolution of the heliosphere, driving phenomena such as extreme space weather, it is critical to understand these collisionless wave-particle interactions on their characteristic ion and electron kinetic timescales. Such understanding requires high-cadence measurements of both the electromagnetic fields and the three-dimensional particle velocity distributions. Although existing instrument technology enables these measurements, a major challenge to maximize the scientific return from these measurements is the limited amount of data that can be transmitted to the ground due to telemetry constraints. A valuable, but not widely used, approach to overcome this limitation is to compute on-board correlations of the maximum-cadence field and particle measurements. Here we propose a novel spacecraft mission concept focused on the coordinated operation of field and particle instruments that has the potential to achieve an improvement of both measurement cadence and total effective sampling time each by orders of magnitude, opening the door for transformative progress in our understanding of particle energization in the heliosphere.

Nonlinear plasma kinetic theory dictates that the collisionless interactions between the electromagnetic fields and charged particles in weakly collisional heliospheric plasmas necessarily lead to correlations between the fields and fluctuations in the particle velocity distributions. This fundamental insight lead to the recent development of the *field-particle correlation technique* (Klein and Howes, 2016; Howes *et al.*, 2017; Klein *et al.*, 2017), which employs *single-point* measurements of the electromagnetic fields and particle velocity distributions to determine not only the net energy transfer between the fields and particles, but also how that transferred energy is distributed in particle velocity space. A variation of this technique, denoted the Particle Arrival Time Correlation for Heliophysics (PATCH) method (Verniero *et al.*, 2021b), was devised specifically for implementation with on-board wave-particle correlator instrumentation. These developments provide a solid theoretical foundation for the pursuit of potential new missions based on novel wave-particle correlator instrumentation (Howes *et al.*, 2022).

Outstanding Science Questions The transfer of energy between the electromagnetic fields and the plasma particles underlies most of the key science questions at the forefront of investigations in heliophysics. Particular theoretical challenges focus on how the fundamental processes of turbulence, magnetic reconnection, shocks, and instabilities govern plasma heating and particle acceleration in heliospheric plasmas.

In plasma turbulence, we want to identify the physical mechanisms that dissipate the turbulence and consequently heat the plasma species and accelerate particles. Large statistical studies using spacecraft observations are critical to develop a predictive capability of the particle energization as a function of the plasma parameters (*e.g.*, plasma beta and ion-to-electron temperature ratio) and turbulence parameters (*e.g.*, scale, amplitude, and possible anisotropy of the turbulent driving). A mission centered on a wave-particle correlator instrument would enable both high cadence measurements and a large effective sampling time essential for such statistical studies, laying the foundation for the development of predictive theories of plasma turbulent heating. Such a capability would enable us to answer long-standing science questions, such as how the solar corona is heated and the solar wind accelerated—two of the primary science questions motivating both the *Parker Solar Probe* and *Solar Orbiter* missions.

In magnetic reconnection, correlations between the fields and particle distributions provide a novel means for identifying the signatures of electron energization in the reconnection exhaust region (McCubbin *et al.*, 2022). Furthermore, these correlations can be used to characterize the different physical mechanisms that play a role in particle heating and acceleration, such as direct acceleration by the parallel elecric field (Egedal *et al.*, 2012) or Fermi acceleration by the curvature drift (Dahlin *et al.*, 2014, 2015; Dahlin *et al.*, 2016). The large samples enabled by on-board wave-particle correlator instrumentation provide a viable means to determine the statistical occurence of different energization mechanisms and to establish how energization is partitioned between plasma species, shedding light on key science questions, such as how reconnection in solar flares leads to the acceleration of particles to relativistic energies.

In the collisonless shocks that play a crucial role in thermalizing supersonic plasma flows at planetary magnetospheres and in potentially accelerating particles to high energies, high-cadence correlations between electric field and particle velocity distributions enable the identification of different proposed acceleration mechanisms (Juno *et al.*, 2021), such as shock-drift acceleration (Paschmann *et al.*, 1982; Sckopke *et al.*, 1983; Ball and Melrose, 2001; Park *et al.*, 2013), shock surfing acceleration (Sagdeev, 1966; Lever *et al.*, 2001), and diffusive shock acceleration (Fermi, 1949; Blandford and Ostriker, 1978; Ellison, 1983; Decker, 1988; Malkov and Drury, 2001; Caprioli *et al.*, 2010). Furthermore, how the kinetic instabilities that arise in sufficiently high Mach number shocks affect the particle dynamics and modify particle energization currently remains an open question in shock studies. On-board wave-particle correlation instrumentation, in concert with the field-particle correlation analysis of kinetic simulations of such shocks, potentially provides a new avenue to assess the impact of non-stationary fluctuations on the particle energization. Ultimately, large-scale statistical studies provide the means to predict the fundamental kinetic mechanisms governing the energization of particles at heliospheric shocks as a function of the key shock parameters, *e.g.*, Mach number and shock-normal angle. These capabilities could enable us to answer questions about how particles are accelerated to high energies, such as solar energetic particles, anomalous cosmic rays, and galactic cosmic rays.

Finally, in the kinetic instabilities that regulate the thermodynamic state of the expanding solar wind—*e.g.*, converting free energy in from temperature anisotropies driven by spherical expansion into unstable electromagnetic waves (Bale *et al.*, 2009)—correlations between the unstable particle velocity distributions and the electromagnetic fluctuations driven by these instabilities will enable a more complete understanding of how such instabilities impact the evolution of the plasmas in heliospheric environments of interest, such as the solar corona, solar wind, and planetary magnetospheres.

Background and Current State of the Field Several previous rocket and spacecraft missions have indeed sought to perform on-board mathematical correlations between field measurements and particle measurements at the same point in space, thereby preserving the valuable phase information needed to establish definitively an interaction between the fields and particles. The earliest attempts to identify wave-particle interactions in space plasmas sought to measure the phase bunching of resonant electrons predicted to occur in the presence of sufficiently large-amplitude Langmuir wave fluctuations (Melrose, 1986). On-board particle auto-correlator instruments were developed to detect electron phase bunching at $f \sim 10^6$ Hz frequencies in the auroral ionosphere, even when electron count rates were $\nu \lesssim 10^5$ Hz (Spiger *et al.*, 1974, 1976; Gough, 1980; Gough *et al.*, 1980), providing a critical foundation for later development of wave-particle correlators.

The first conclusive wave-particle correlator, that performed a direct correlation of the arrival times of electrons with the phase of the high-frequency wave field, flew on a sounding rocket in the auroral zone (Ergun *et al.*, 1991a,b). This experiment indeed detected electron phase bunching during periods of intense Langmuir waves, driving subsequent theoretical work to develop refined theoretical predictions for finite-size Langmuir wavepackets (Muschietti *et al.*, 1994). A wave-particle correlator was attempted on the *Wind* spacecraft (Wilson III *et al.*, 2021a) between the WAVES and 3DP instruments, but it did not correctly trigger. Another wave-particle correlator was flown on the NASA *Combined Release and Radiation Effects Satellite* (*CRRES*), computing correlations onboard between the Low Energy Plasma Analyzer and the electric field/Langmuir probe instrument (Watkins *et al.*, 1996), and later a refined wave-particle correlator was implemented as a component of the Fields instrument on the *FAST* spacecraft (Ergun *et al.*, 1998, 2001). Subsequent development lead to an improved wave-particle correlator design with higher phase resolution than previous instruments, flown on an auroral sounding rocket, which measured the reactive component of the electron phase bunching in a Langmuir wave (Kletzing *et al.*, 2005; Kletzing and Muschietti, 2006). Further developments in wave-particle correlator instrumentation have continued (Fukuhara *et al.*, 2009), with the latest implementation of a Software-type Wave-Particle Interaction Analyzer (S-WPIA) on-board the Japanese *Arase* spacecraft (Miyoshi *et al.*, 2018) to study the energy transfer process between energetic electrons and whistler-mode chorus emissions in the Earth's inner magnetosphere (Katoh *et al.*, 2013; Katoh *et al.*, 2018).

All of these previous wave-particle correlator instruments were specially designed to explore the energy transfer to particles from waves that have frequencies f at or above the particle detector counting rate, $f \gtrsim \nu$, for example studying the interaction of electrons with whistler waves or Langmuir waves in the Earth's magnetosphere. But the Alfvénic turbulent fluctuations in the magnetosheath, solar wind, and solar corona have a much lower frequency than the whistler and Langmuir wave fluctuations of interest in the magnetosphere. Furthermore, current spacecraft missions—such as the *Magnetospheric Multiscale* (*MMS*) (Burch *et al.*, 2016), *Parker Solar Probe* (Fox *et al.*, 2016; Bale *et al.*, 2016; Kasper *et al.*, 2016; Whittlesey *et al.*, 2020; Livi *et al.*, 2021), and *Solar Orbiter* (Müller *et al.*, 2013) missions—boast fast, three-dimensional particle velocity measurements at a sampling rate approaching or surpassing the frequency of the fluctuations involved in the collisionless transfer of energy between fields and particles, $f \lesssim \nu$. These unprecedented measurement capabilities, coupled with recent advances in plasma kinetic theory for determining particle energization from single-point measurements of electromagnetic field and particle velocity distribution measurements (Klein and Howes, 2016; Howes *et al.*, 2017; Klein *et al.*, 2017), make possible an *entirely new approach* to understanding particle energization using an on-board field-particle correlator, providing a strong motivation for a new mission concepts.

Expected Impact The application of the field-particle correlation technique, recently developed in 2016 (Klein and Howes, 2016), has already lead to a number of significant achievements. The technique has established that ion Landau damping is effective as a turbulent dissipation mechanisms in weakly collisonal plasma turbulence (Klein *et al.*, 2017) such as that found in the solar wind, has shown that current sheets that naturally develop in Alfvénic plasma turbulence experience Landau resonant dissipation (Howes *et al.*, 2018), has first identified electron Landau damping in *MMS* observations of Earth's turbulent magnetosheath (Chen *et al.*, 2019) and found this mechanism to be a dominant turbulent dissipation mechanism in one third of 20 sampled intervals (Afshari *et al.*, 2021), and has been instrumental in a laboratory investigation demonstrating the acceleration of electrons by Alfvén waves under conditions relevant to Earth's aurora (Schroeder *et al.*, 2021). With the large effective sampling times enabled by a wave-particle correlator instrument, and the recent development of the theoretical basis for such instrumentation in the Particle Arrival Time Correlation for Heliophysics (PATCH) method (Verniero *et al.*, 2021b), we can expect significant progress on important scientific questions dependent on the physics of plasma heating and particle acceleration in the heliosphere.

An example of the how the field-particle correlation technique and the PATCH algorithm can identify the physical mechanism of dissipation in plasma turbulence is shown in Figure 1. In panel (a), the alternative parallel electric field correlation $C'_{E_\parallel}(v_\parallel, v_\perp)$ on gyrotropic velocity space shows the characteristic blue-red (bipolar) signature of ion Landau damping at $v_\parallel/v_{ti} = +1$, corresponding to flattening of the distribution function at the resonant parallel phase velocity. The PATCH algorithm, with a modest particle count of $N = 25$ particles in the peak phase-space bin, reproduces this distinguishing signature, identifying ion Landau damping, and recovering the energy transfer rate to within 6% (Verniero *et al.*, 2021a).

The energy transfer governed by the physics of particle energization in space plasmas—whether through the dissipation of plasma turbulence, through the release of magnetic energy via magnetic reconnection, or through the compression of the plasma and the acceleration of particles at plasma shocks—generally occurs on the characteristic kinetic timescales. Although a recent analysis has shown clearly that, with a sufficiently long correlation interval, the field-particle correlation technique can indeed recover the physics of particle energization occuring on frequencies above the Nyquist frequency of the sampling (Horvath *et al.*, 2022), to resolve fully the details of the particle energization, one must generally sample the plasma at a faster cadence than the timescale of the process. For example, at a heliocentric distance of 1 AU in the solar wind, the frequency associated with fluctuations at ion length scales convected past a spacecraft at the solar wind velocity is typically $f_i \sim 1$ Hz. For the frequency of the convected ion gyroradius, for example, this frequency scales as $f_i \propto V_{sw} B / T_i^{1/2}$. Estimates of the changes in solar wind flow velocity, magnetic field, and ion temperature enable predictions of these characteristic frequencies at different heliocentric distances (Bale *et al.*, 2016). For example, at the heliocentric distance of the first perihelion of *Parker Solar Probe* at $r \simeq 36 R_\odot$, this frequency rises to $f_i \gtrsim 5$ Hz; near the predicted Alfvén radius of the sun at $r \simeq 10 R_\odot$, the frequency may rise to $f_i \gtrsim 30$ Hz. Additional mechanisms of collisionless energy transfer with electrons occurs at yet higher frequencies.

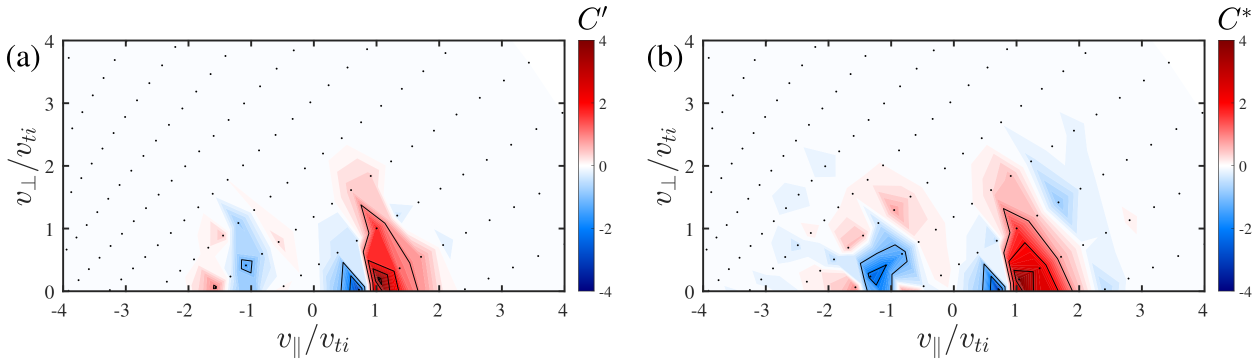

Figure 1: (a) Example of the alternative parallel electric field correlation $C'_{E_\parallel}(v_\parallel, v_\perp)$ computed at a single spatial point in a gyrokinetic simulation of plasma turbulence and downsampled to the phase-space resolution of the SPAN-I instrument on *Parker Solar Probe* (Verniero *et al.*, 2021a), compared to (b) the signature determined from applying the PATCH algorithm $C^*_\tau(v_\parallel, v_\perp)$, computed using $N = 25$ counts in the maximum density phase-space bin at the same phase-space resolution. The blue to red transition at $v_\parallel/v_{ti} \simeq 1$ is the distinctive velocity-space signature of ion Landau damping at the resonant parallel phase velocity. From Verniero *et al.* (2021b).

The most significant obstacles to investigating the particle energization in space plasmas are (i) the limited cadence of particle instrumentation, such as electrostatic analyzers and (ii) telemetry limitations that constrain the amount of measured data that can be transmitted back to the Earth for analysis. An on-board wave-particle correlator, such as the Integrated Field-Particle Correlator (IFPC) described in Howes *et al.* (2022), is a potential approach to overcome both of these obstacles. Here we estimate the capabilities of an IFPC incorporating electromagnetic field and plasma instruments equivalent to those on the *Parker Solar Probe* (*PSP*) mission.

The SPAN-E electrostatic analyzer instrument for electrons on *PSP* (Whittlesey *et al.*, 2020) is capable of performing a full energy sweep of 32 steps in energy E and 8 steps in deflector angle θ over a sampling interval of $\Delta t = 0.218$ s. All 16 anodes covering the azimuthal angles ϕ are measured simultaneously, for a total of 4096 (E, θ, ϕ) phase-space bins sampled in that interval. Each phase-bin is therefore measured in a time $\delta t = \Delta t/(32 \times 8) = 0.85$ ms, equivalent to a sampling frequency greater than 1 kHz. The electric field components necessary to determine the rate of particle energization are measured by the FIELDS instrument at sampling frequency of 2 MHz (Bale *et al.*, 2016). By combining the electric field and particle counts on-board using the PATCH algorithm, the effective sampling time is reduced from $\Delta t = 0.218$ s to $\delta t = 0.85$ ms, an improvement by a factor of 256, with a corresponding Nyquist frequency of the measurements of $f \simeq 587$ Hz.

One significant caveat is that each individual phase-bin is only sampled once over an interval $\delta t = 0.85$ ms every $\Delta t = 0.218$ s. Therefore, one must interpret the correlated measurements carefully. For example, for the PATCH correlation of the parallel electric field $C^*_{E_\parallel}(v_\parallel, v_\perp)$ over the full velocity-space sweep interval of $\Delta t = 0.218$ s, which would appear similar to the right panel of Figure 1, each individual phase bin measurement over $\delta t = 0.85$ ms would be measured at a different time during the sweep. So, a plot of a single entire velocity-space sweep combines these measurements at different times, but the electric field and particle measurements in each of the phase bins would use a time accurate to at least 0.85 ms. Significant modeling efforts would be needed to ensure that the results returned by the implementation of the PATCH algorithm can be interpreted accurately to reflect the underlying kinetic physics of particle energization. This factor of 256 improvement in samping cadence opens up new avenues to explore the kinetic physics of both ion and electron energization in space plasmas.

In addition to new science targets enabled by the development and implementation of an IFPC instrument on an upcoming spacecraft mission, the on-board correlations can improve the statistics of sampling by orders of magnitude. For example, the *MMS* S-band downlink of 4 Gb/day allows only about 20 min of full-cadence, burst-mode data to be transmitted to the ground for analysis per day, even though the instruments are always sampling at burst-mode cadence. This leads to an effective duty cycle of 1.4%. In principle, on-board correlations could utilize the full 24 hours of burst-mode measurements per day in computing correlations, leading to a factor of 72 improvement in total sampling time. For more distant spacecraft that are limited to lower downlink rates, such as *Parker Solar Probe* and *Solar Orbiter*, the improvement factor can be even larger. With the potential for the velocity-space signatures generated by the PATCH algorithm to be used to identify different physical mechanisms of particle energization and to quantify the rate of energization, this major improvement in sampling time would enable statistical studies of the occurence of kinetic particle energization via different mechanisms, a long term goal of the heliophysics community.

Another potential capability of an IFPC is to enable alternative operating modes that are designed to sweep over a reduced region of 3V velocity-space on a much faster cadence. For example, one could select a single deflector angle θ and perform a sweep over all 32 energies with a sampling interval of $\Delta t = 0.0273$ s, improving time resolution by a factor of 8 by eliminating the deflector angle sweep; alternatively, one could select a single energy and sweep over only deflector angles with a sampling interval of $\Delta t = 0.0068$ s, improving time resolution by a factor of 32 by eliminating the energy sweep. This is not dissimilar from the existing alternating full and targeted sweeps that are already used by the SPAN-E electrostatic analyzer instrument. With scientific insight guiding the selection of a reduced sampling region in 3V velocity-space, one would potentially be able to tailor different operating modes to tackle different science questions.

Conclusions In conclusion, the development of wave-particle correlator instrumentation (Howes *et al.*, 2022) holds the promise of transforming our understanding of plasma heating and particle acceleration through higher cadence measurements and a much longer total effective sampling time. Such improvements will enable the identification of specific mechanisms of particle energization and the quantification of the consequent plasma species heating and particle acceleration rates, making it possible to answer long-standing questions in heliophysics, such as the heating of the solar corona and acceleration of high-energy particles at collisionless shocks.

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