White paper submission to the

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TITLE:

"IOTA: An engine to advance plasma science of intense charged particle beams"

Primary panel: Interaction of plasma waves and particles

Secondary panels: Plasma self-organization and Plasma statistical mechanics

RESEARCH FRONTIER and IMPACT on SCIENTIFIC CHALLENGE:

Relativistic and nonrelativistic charged particle beams in accelerators are essentially plasmas but with three special attributes: (i) charged particle beams are essentially non-neutral plasmas; (ii) particle beams have an average non-thermal directed momentum/velocity and associated acceleration/deceleration superposed on otherwise kinetic/thermal distribution in phase-space; (iii) beams evolve self-consistently under inter-particle forces beyond just internal Coulomb self-forces, but includes electromagnetic interaction with its surrounding environment described by a 'complex' impedance function, which includes dissipation, self-feedback and synchrotron radiation. Often the interaction within a beam of charged particles is intrinsically non-hermitian.

One of the major research frontiers in charged particle beam physics is the collective behavior and stability of an 'intense' particle beam undergoing coherent instabilities under the interaction of intrinsically nonlinear dynamics of a collection of self-interacting charged particles moving under complex externally imposed nonlinear electromagnetic fields. The interplay of externally imposed dynamical nonlinearities of beam phase-space and its nonlinear Coulomb self-fields or 'space-charge' forces end up being dissipative and non-local and often limit the highest intensities supported by the external confining electromagnetic fields as a storage ring or 'trap' for these particles. Since 'precision' physics using beams is data-hungry, intense beams are essential to probing fundamental physics of symmetries and forces in nature. Coherent plasma instabilities, nonlinear diffusion, electronically induced self-feedback and various damping mechanisms including synchrotron radiation damping, Landau-damping and direct external electronic feedback via microwaves or optical amplifiers, all operate at the limits of thresholds exhibiting critical characteristics distinctly different from classical plasmas: plasma mode turbulence overlapping with single particle nonlinear dynamical chaos, further complicated by the quantum fluctuational effects of photon emission in light mass charged particles.

A dedicated investigation and analysis of the various effects and regimes requires on the one hand a carefully designed and appropriately "scaled" compact test facility as a storage ring for intense beams where the interplay of various nonlinear and collective, incoherent and coherent effects, of a strongly coupled nonlinear, dissipative many-body system of relativistic charged particle beams can be studied and on the other hand modeling and simulation of sophisticated self-consistent Markovian and non-Markovian Fokker-Planck equation and higher order transport processes leading to unconventional "fluctuation-dissipation" relationships characteristics of charged particle beams. Such transformative understanding with discovery potential has only been glimpsed at in the past, in the limited context of cooling "anti-proton" beams stochastically in the 1980s via microwave "stochastic cooling", leading to Nobel Prize winning research in 1980s. The future of this research now lie in unveiling new regimes of dissipative nonlinear self-consistent dynamical systems of charged particles. The resulting knowledge is also very relevant to the studies of the early evolution of universe, and fluctuations in the "dark" sector fields of the quantum vacuum.

APPROACH:

The Integrable Optics Test Accelerator (IOTA), under construction at Fermi national Accelerator Laboratory and to be completed in 2016, provides an ideal test facility to study the above frontier of knowledge in collective phenomena in many body systems exhibiting unconventional behavior. The 10 meter circumference charged particle storage ring can be envisioned as a giant trap for both precision studies of a single particle under extreme nonlinear forces and distorted topological phase-space in the Poincare sense as well as for studying ultra-intense beams at low nonrelativistic regimes exhibiting new collective and coherent phenomena, whose mitigation measures can be systematically studied. The electromagnetic lattice of IOTA is flexible by "design" allowing for frequent reconfiguration as needed for installing novel and exotic nonlinear elements in it, including electron and plasma lenses and optical elements such as precision lasers to monitor and probe the beam. A precise pencil-like electron beam will be available to map out the Poincare nonlinear phase-space stability portrait of the storage ring trap from the perspective of single particle dynamics, while a Coulomb self-force dominated low energy ion beam will be available to investigate in detail the intensity dependent collective effects under effects of various nonlinearities and externally controllable 'non-hermitian' interactive elements, leading to exotic behavior of particle motion. The discovery potential is notable: generation of 'solitons' with unusual properties; unconventional transport processes including radiation and self-dissipative interactions; unique "fluctuation-dissipation" relations; understanding for the first time the real motion of a quantum oscillator in a time-varying anaharmonic nonlinear potential well interacting within a bath of its own self-radiation and coupled to other similar oscillators electronically and Coulomb-wise.

Outside of small experimental tokomaks around the world operating in regimes far from the regime of a charged particle beams described above and laboratory-scale "Paul traps" operating in a single- or few-atom or molecular level for 'cold' sources, there is no dedicated test facility or beam 'trap' available in the world for these unique studies. The IOTA at Fermilab will be a unique facility and it is opportune time for plasma physicists to recognize this unique resource and develop a research plan and its funding to exploit this facility for academic research of the unusual plasma physics of intense charged particle beams.

IMPACT:

The impact of successful research on such a facility can hardly be overestimated. It may lead the way to alternate and economically feasible “smart” storage and acceleration of charged particles offering an attractive alternative to the expensive microwave superconducting accelerator technologies and making precision physics of rare particles a reality. The facility can provide insight in a laboratory setting in astro-physical plasmas but by using charged particle beams. The facility will enable understanding quantum mechanical wave-function of a single charge in the regime of strong coupling to nonlinear external and intrinsic radiative forces of a collection of other charged particles, including the age-old problem of radiation-reaction. Compact and “smart” charged particle boosters of protons and other ions have the potential of being relevant to health care in society, offering possible alternatives to particle beam cancer therapy.