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Cover Page:

Trapped Electron Plasmas for Space-Charge Compensation in High Intensity Circular Accelerators

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Contents

Project Summary/Abstract:

Trapped Electron Plasmas for Space-Charge Compensation in High Intensity Circular Accelerators

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The main goal of this project is to explore a novel scheme of space-charge compensation that could lead to a significant increase of the beam intensity for future accelerator-based high-energy physics experiments and other sciences. The scope of this proposal will be based on the resources and facilities readily available at Fermilab within the five year timeline. The scientific program will consist of both theoretical modeling of the beam-plasma system, and installation and operation of the proton injector system and electron column system for the newly proposed Integrable Optics Test Accelerator (IOTA) ring, which is now under construction at Fermilab with completion expected in FY 2014-2015 [1].

Through its past success in electron cooling [2], beam-beam compensation [3], and controlled halo removal [4], Fermilab has gained extensive experience and resources in manipulating high-energy particle beams by means of well-controlled electrons. As the mission of the US high energy physics program is pushing the Intensity Frontier, it is of great technical and scientific merit for the community if this remarkable tradition of Fermilab can be applied to overcome the beam intensity limit in the present accelerator technology. Hence, we propose to investigate a novel method of space-charge compensation to achieve very intense and stable beams in circular accelerators through trapping and controlling of electrons generated from beam-induced residual gas ionization. The main idea of this compensation method is based on the long-known fact that the negative effect of Coulomb repulsion can be mitigated if beams are made to pass through a plasma column of opposite charge. This idea has been successfully applied to transport high-current low-energy proton and H- beams into the RFQ in many linacs. In circular machines, partial neutralization by ionized electrons was attempted with notable improvements in beam intensity, namely one order of magnitude higher than the space-charge limit [5]. However, the beam-plasma system was subject to strong transverse electron-proton (e-p) instability. In principle, this difficulty can be overcome if protons and electrons are immersed in a strong enough longitudinal magnetic field [6]. Further, the nonlinear optics adopted in the IOTA ring are expected to suppress the e-p instability [7], and minimize the space-charge driven halo formation [8]. These synergistic mechanisms can be readily studied by injecting low-energy protons into the IOTA ring.

The proposed research has great potential to improve the performance of leading high-current proton accelerator facilities and experiments such as LBNE with Project-X intensities, Mu2e and g-2 after the intensity upgrades, and compressor and accumulation rings envisioned in the Neutrino Factory and Muon Collider projects. The research may also offer a transformational technology for the next generation high-intensity accelerators such as those needed for Accelerator Driven System and Heavy Ion Fusion.

Project Narrative:

We propose to investigate a novel method of space-charge compensation in high-intensity circular accelerators based on trapping and controlling of the electrons generated from beam-induced residual gas ionization. The nature of the proposed research encompasses aspects of both plasma and accelerator physics. The characteristics of the trapped electron plasmas need to be well understood, and at the same time, the circulating proton beam's tune shift and coherent instability should be well controlled. The PI had a strong education in plasma physics from graduate school, and also has had an excellent training in accelerator physics from Fermilab. The proposed research is a logical continuation and extension of PI's academic interest.

1 Overview

This proposal requests funding to install and operate a low-energy proton injector system and electron column system for the newly proposed Integrable Optics Test Accelerator (IOTA) ring, which is now under construction at Fermilab with completion expected in FY 2014-2015 [1]. The IOTA ring plans to use electron beams to study the single-particle motion stability in the nonlinear integrable system with negligible space-charge effects. Considering the importance of space-charge effects in many intensity-frontier accelerators, it is quite logical and timely to expand the scope of the IOTA program to include space-charge issues. Through the High Intensity Neutrino Source (HINS) program, Fermilab has established an ion source, LEBT, and an RFQ system working with a 2 MW, 325 MHz klystron [9]. As the HINS program was recently replaced by a CW Superconducting RF linac program, reuse of the HINS front-end is highly desirable. It turns out that the magnetic rigidity range of the IOTA ring matches perfectly with the 2.5 MeV proton beam from the HINS RFQ.

The combination of the IOTA ring and the HINS front-end will be a great asset to the advanced accelerator R&D community, in particular for the Intensity Frontier. This unique configuration will enable researchers to investigate novel methods of space-charge compensation in high-intensity circular accelerators, and their synergies with nonlinear integrable lattices, which might eventually lead to a *super-intense stable beam* that this community has dreamed of. Table 1 summarizes the uniqueness of the proposed experimental setup.

Also, the funding will enable theoretical modeling of the unique beam-plasma systems. Involvements of graduate students are highly anticipated in this activity. Electron generation and trapping processes, and the equilibrium and stability of the non-neutral electron plasmas will be modeled using 3D Particle-In-Cell (PIC) WARP code [10]. Beam dynamics of the circulating proton beams will be modeled including both the electron column and the nonlinear lattice. Previously, a 2D space-charge simulation with MAD code was performed to study the possibility of space-charge compensation in the Fermilab booster with multiple electron columns [11]. The PyORBIT tracking code has been used to simulate high-intensity proton beams in nonlinear lattice [8]. The coupled simulation of non-neutral plasmas and intense circulating beams is itself a rich research field academic wise, and will practically guide the beam measurements planned in this study.

Facility	Main beams	HEP Discovery Science		Applications
		Intensity Frontier	Energy Frontier	
ATF (BNL)	e-, CO_2 laser		PWFA, LPWA for e+e- LCs	FEL, γ's, medical laser-gas
A0 (Fermilab)	e-		e+e- LCs, PWFA	FEL
AWA (ANL)	e-		e+e- LCs, DWFA	
BELLA (LBNL)	Laser		e+e- LCs, LWFA	FEL, γ's, medical laser-gas
FACET (SLAC)	e-, e+		e+e- LCs, PWFA	
TTF (DESY)	e-		Initially – e+e- LC	FEL, SCRF technology
ASTA (Fermilab) with IOTA ring and HINS front-end	e-, p/ions, laser	Losses, beam dynamics, novel optics, space-charge compensation, collimation, diagnostics	e+e- LCs, e+ sources, LHC & upgrades, Muon Collider R&D	FEL, γ's, SCRF techn. dev. & test, material test

Table 1: Accelerator facilities and accelerator R&D thrusts [12].

2 Background

In the next decade the High-Energy Physics (HEP) community will explore the energy frontier by operating the Large Hadron Collider (LHC), designing its upgrades, and developing novel concepts and technologies necessary for the design of the next lepton collider. The community will also explore the intensity frontier by designing (and possibly operating) high intensity proton sources for neutrino physics and precision measurements in rare processes, and designing high intensity muon sources for neutrino physics, i.e., neutrino factories [13]. In both cases there is a need to understand the limiting factors and develop mitigation techniques in the design of high-intensity linear and circular accelerators. One of the most important physics processes affecting the high-intensity accelerators is beam space charge. The beam loss minimization by mitigating space-charge effects is essential for the successful operation of a high-intensity accelerator complex.

In general, the CW operation of a linac can reduce the space-charge effect by spreading the total beam charge over more RF buckets [14]. Also, the increase of the final linac energy can reduce beam loss and emittance dilution due to space-charge tune shifts in circular accelerators. The space-charge compensation method proposed in this research has great potential to overcome the tune-shift limit, improve the performance of the circular accelerators, and reduce the linac cost. Eventually, this method will benefit the leading intensity frontier experiments, such as the Long-Baseline Neutrino Experiment (LBNE) with Project-X intensities, Mu2e and g-2 after the intensity upgrades, and compressor and accumulation rings envisioned in the Neutrino Factory and Muon Collider projects. The method may also offer a transformational technology for the next-generation accelerator applications such as Accelerator Driven System (ADS) and Heavy Ion Fusion (HIF).

3 Effects of Beam Space Charge

Transverse space-charge effects have long been recognized as a fundamental intensity limitation in synchrotrons and storage rings [15]. They lead to beam losses and emittance growth that can not be tolerated. Space-charge forces in a beam result from mutual Coulomb repulsion. In a moving beam, they are partially mitigated by magnetic attraction. Coulomb forces are independent of beam velocity, whereas magnetic forces are proportional to $(-\beta_b^2)$, where $\beta_b = v_b/c$ is the ratio between the beam velocity and the speed of light in vacuum. The net force is therefore proportional to $(1-\beta_b^2) = 1/\gamma_b^2$. We note that the space-charge forces become negligible at high beam energies. So increasing the injection energy, either by making the linac longer or by adding a small booster, would be a straightforward solution, but very costly. In synchrotrons, fast acceleration would help the beam to cross resonances of order 3 and higher, but still there is enough time for lower order modes to develop [15, 16].

For a uniform beam with a circular cross section, the net space-charge force on a beam particle of charge q_b is $F_{sc} = q_b E_r(1-\beta_b^2) = q_b E_r/\gamma_b^2$ with

$$E_r(r) = \begin{cases} \frac{q_b \bar{n}_b}{2\epsilon_0} r, & 0 \le r \le r_b, \\ \frac{q_b \bar{n}_b}{2\epsilon_0} \frac{r_b^2}{r}, & r_b \le r \le r_w. \end{cases} \tag{1}$$

Here, r_b is the radius of the beam with constant density $\bar{n}_b$, and r_w is the radius of a perfectly conducting cylindrical wall. Inside the beam the space-charge force increases linearly with the distance from the beam center. It tends to counteract the linear focusing provided by the external fields, and thus the beam particles experience a reduction in the betatron oscillation frequency.

Incoherent tune shift: In circular accelerators, the usual figure of merit of the space-charge effect is the *incoherent tune shift*. It is defined as the frequency change of a single particle's betatron oscillations caused by the space charge of a stationary beam. For a *uniform beam* it is given by

$$\Delta\nu_u = -\frac{N_{tot} B_f r_c}{2\pi\beta_b^2\gamma_b^3\epsilon}, \tag{2}$$

where N_{tot} is the total number of beam particles in the ring, $r_c = 1.53 \times 10^{-18}$ m is the classical proton radius, and $\epsilon = 4\epsilon_{\rm rms}$ is the effective transverse emittance. The bunching factor $B_f = \hat{I}/\bar{I} \ge 1$ is the ratio of the peak current to the average current (Note that in some literature the bunching factor is defined inversely, i.e., $B_f = \bar{I}/\hat{I} \le 1$). As the RF voltage is turned on in the ring, the injected beam is gradually bunched and experiences the largest space-charge tune shift [17]. If the tune shift is larger than the free space between dangerous (lower order) resonances, then the beam suffers from coherent (e.g., quadrupole breathing modes of the beam envelope) and incoherent (e.g., parametric resonances in a single particle's motion) instabilities [15, 16].

Tune spread: For a non-uniform beam density profile there is a nonlinear dependence of the restoring force on the amplitude, which leads to anharmonic betatron oscillations [18]. Take, for example, a round Gaussian profile with rms size of $\sigma = \sigma_x = \sigma_y = r_b/2$ and the same total current as the uniform beam (i.e., $\hat{n}_b = 2\bar{n}_b$), that is,

$$n_G(r) = \hat{n}_b \exp\left(-\frac{r^2}{2\sigma^2}\right). \tag{3}$$

Then the space-charge tune shift becomes a function of betatron amplitude r [16], i.e.,

$$\Delta\nu(r) = \frac{(1-e^{-\alpha})}{\alpha} I_0(\alpha)\Delta\nu_G, \tag{4}$$

where $\alpha = (r/2\sigma)^2$, $I_0(x)$ is the modified Bessel function of order 0, and the peak tune shift of the Gaussian beam is

$$\Delta\nu_G = -\frac{N_{tot} B_f r_c}{4\pi \beta_b^2 \gamma_b^3 \epsilon_{\rm rms}}. \tag{5}$$

Note that for $r \to 0$, $\Delta\nu(0) = \Delta\nu_G$, and $\Delta\nu(r)$ has a minimum value around $r = 2\sigma = r_b$. It should be emphasized that the peak tune shift of the Gaussian beam $\Delta\nu_G$ is a factor of 2 larger than the tune shift of a uniform beam of the same current and the same rms transverse dimensions. The amplitude-dependent de-tuning for a non-uniform density distribution indeed features a *tune spread* rather than a shift. In many cases, the increase of the tune spread due to the nonlinear effects becomes a more serious problem.

Space-charge limit: There is some disparity in the accelerator community as to how large a tune shift is acceptable. Part of the reason is confusion between $\Delta\nu_u$ and $\Delta\nu_G$. Another reason is the fact that betatron resonances do not occur at the incoherent value of the tune, but rather at the frequencies of the appropriate collective modes [19]. In general, $|\Delta\nu_G|$ of beyond 0.5 can barely be tolerated without excessive particle loss. Therefore, for a given machine transverse acceptance (i.e., maximum emittance), there is a hard limit in beam intensity N_{tot}, the *space-charge limit*. For most of the existing and planned high-intensity circular accelerators, the tune shifts stays in the range of $|\Delta\nu_G| \leq 0.5$. Attempts to overcome the space-charge limit have been made in various ways. For example, in the AGS at Brookhaven National Laboratory, tune shifts as high as 0.7 have been achieved through many critical accelerator manipulations, such as resonance stopband corrections, second harmonic cavities, direct RF feedback, gamma-transition jumps, longitudinal phase space dilution, and transverse instability damping. For the Main Injector at Fermilab, the number of protons has to be increased by a factor of 3 to meet the Project-X specifications. If no measures are taken, losses soon become intolerable. Under the current plan, space-charge mitigation includes forming a uniform beam at injection with phase-space painting or increasing beam emittance [20].

4 Space-Charge Compensation

The main idea of the space-charge compensation is based on the long-known fact that the negative effect of Coulomb repulsion can be mitigated if beams are made to pass through a plasma column of the opposite charge [21]. This idea has been successfully applied to transport high-current low-energy proton and H- beams into the RFQ in many linacs (i.e., *gas focusing* [22]). In circular machines, partial neutralization by ionized electrons was attempted with remarkable improvements in proton beam intensity, namely one order of magnitude higher than the space-charge limit [5]. However, the beam-plasma system was subject to strong transverse electron-proton (e-p) instability. Therefore, necessary conditions for the effective space-charge compensation in rings will be [6, 16]

1. The impact of electrons is equal to the total impact of beam space charge over the ring.

2. The Transverse profile of the electron density $n_e(r)$ is the same as that of the proton beam.

3. The system of electrons and protons is dynamically stable.

Use of an external electron source like electron lenses was originally suggested to meet these conditions [16], but the method is technically challenging, particulary, it requires a large number of expensive lenses for high periodicity machines. In this project, we propose to investigate a variation of the same concept, the *electron column*. For the electron column, electrons are generated internally through beam-induced residual gas ionization without special electron sources and optics, hence it would be more effective and technically feasible.

Electron column concept

The condition 1 for full compensation *on average* can be written in terms of tune shifts:

$$\Delta\nu_e = +\frac{N_e r_c}{4\pi\beta_b^2\gamma_b\epsilon_{\rm rms}} = -\Delta\nu_G. \tag{6}$$

Because the electrons are stationary in the laboratory frame, there is no relativistic cancellation term. For the discrete distribution of electron columns around the ring, Eq. (6) can be rewritten as

$$\frac{N_e}{N_{tot}B_f} = \frac{1}{\gamma_b^2} = \frac{\lambda_e N_{ec} L_{ec}}{\lambda_b B_f C} = \eta_0\frac{N_{ec}L_{ec}}{C}, \tag{7}$$

where, N_{ec} is the number of electron columns, L_{ec} is the length of the one column, λ_e is the average line charge density of the electrons over L_{ec}, λ_b is the average line charge density of the beam particles over the ring circumference C, and $\eta_0 = \lambda_e/(\lambda_b B_f) = C/(\gamma_b^2 N_{ec}L_{ec})$ is the degree of local space-charge compensation required. The full compensation can be achieved in several ways: a) electrons are distributed along the whole ring, $N_{ec}L_{ec}/C = 1$, and $\eta_0 = 1/\gamma_b^2$; b) dense electron columns occupy only a fraction of the ring, $N_{ec}L_{ec}/C < 1$, and $\eta_0 > 1/\gamma_b^2$, which corresponds to Budker condition of self focusing [22].

In the electron column concept, conditions 2 and 3 can be achieved if protons and electrons are immersed in a longitudinal magnetic field which is a) strong enough to freeze the electron density distribution; b) strong enough to suppress the e-p instability; c) weak enough to allow positive ions to escape transversely, in addition to longitudinal draining; and d) well matched to the ring optics to avoid beta-beat excitations.

Schematically, the electron column may look like what is shown in Fig. 1. The electron column consists of a solenoidal magnet, a pair (or many pairs) of cylindrical electrodes to control the electron accumulation, a controlled leak to vary vacuum conditions locally in the electron column, and electron collectors and vacuum ports for possible differential pumping [6]. Note that the configuration is quite similar to the Malemberg-Penning trap for nonneutral plasma physics [23]. Remarkable improvements have been made in the physics of non-neutral plasmas and on the stability of beam-plasma systems in the plasma physics community over the past decade, some of which could be readily adopted for the present project.

Electron generation: As mentioned, electron-ion pairs are generated by beam-induced residual gas ionization. The production rate depends on the ionization cross section σ_i, beam velocity, and gas pressure p (or gas density n_g). The time needed to generate enough electron-ion pairs for full space-charge compensation is called the charge-neutralization time τ_n [22]:

$$\tau_n = \frac{n_{ei}}{dn_{ei}/dt} = \frac{\eta_0}{\sigma_i\beta_b c n_g}. \tag{8}$$

For example, to compensate a 2.5 MeV proton beam with an electron column of $L_{ec} = 1$ m in a ring of $C = 38.7$ m, we require $\tau_N = 3.3\times10^{-8}/p$[Torr] for an H_2 dominated vacuum. If we want to achieve space-charge compensation within about 1 ms (the typical ring cycle time to avoid many

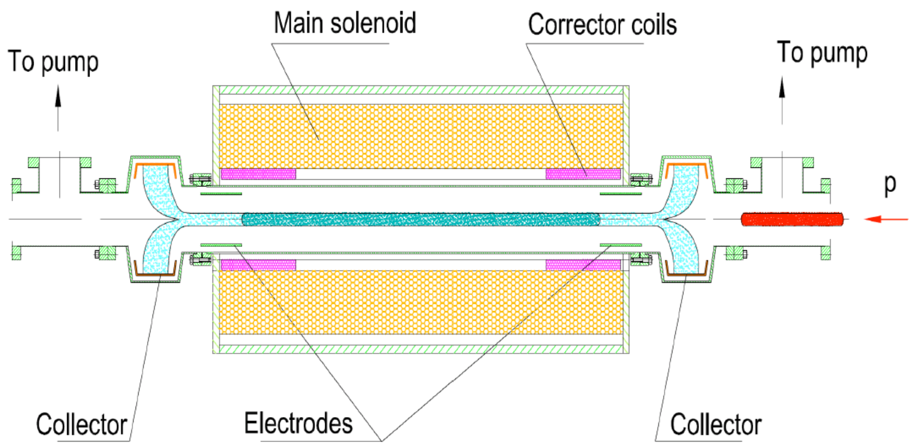


Figure 1: A conceptual layout of electron-column apparatus for space-charge compensation.

types of instabilities from fully developing), the local vacuum pressure in the electron column should be as high as 3.3×10^{-5} Torr. At this pressure, radial plasma expansion due to collisions could be an issue. Another option is to accumulate electrons over many ring cycles in the UHV condition which increases the plasma lifetime, and then do the compensation experiments. Of course, there are many other processes that need to be investigated such as ion accumulation/draining, secondary electron generation, electron diffusion/losses, and plasma heating by the beam, to mention a few.

Electron energy: During beam-induced ionization, the ejected electrons can have a kinetic energy up to the maximum allowed $T_{max} \approx 2m_e c^2 \beta_b^2 \gamma_b^2 = 5.45$ keV for a 2.5 MeV proton beam. The angle of emission is $\cos\theta = (T/T_{max})^{1/2}$. An expression for the number of electrons ejected at a kinetic energy larger than or equal to T_0 is given by [24]

$$N(T \geq T_0) = W \left(\frac{1}{T_0} - \frac{1}{T_{max}} \right), \tag{9}$$

for $I \ll T \leq T_{max}$. Here, W is a constant determined by properties of incident and target particles, and $I = 19.2$ eV is the mean excitation energy for H_2. The fraction of electrons with energy exceeding 200 eV is approximated as $N(T \geq 200 \text{ eV})/N(T \geq I) \approx 10\%$. Some ionized electrons have enough energy ($T > E_i = 15.42$ eV) to produce secondary electron-ion pairs.

Longitudinal trapping: Since most ionized electrons have initial energies less than 200 eV, it seems the trapping electrode voltage $-\hat{V}$ could be set as low as 200 V. However, as electrons are accumulated more and more, the longitudinal space-charge force becomes significant. The actual electrode voltage to trap the required number of electrons N_e for full space-charge compensation is estimated as [22]

$$|\hat{V}| = \left(\frac{1}{4\pi\epsilon_0}\right)\frac{eN_e}{L_{ec}}\left[1 + 2\ln\left(\frac{r_w}{r_e}\right)\right]. \quad (10)$$

Here, r_e is the radius of the cylindrically uniform plasma column ($r_e \approx r_b$). For a single-turn injection of a 2.5 MeV proton beam with $\bar{I} = 8$ mA and $B_f \approx 5$, we would require $N_e \approx 4.6 \times 10^{11}$ for $L_{ec} = 1$ m. In this case, the electrode voltage should be $|\hat{V}| \approx 3.7$ kV for $r_w/r_e \approx 10$. In this voltage range, the 2.5 MeV proton motion would not be altered too much (or could be compensated by a ~ 75 kV RF cavity) and any vacuum DC breakdown is very unlikely. For a cylinder-shaped electrode with radius r_w, the axial voltage distribution inside the column, $-L_{ec}/2 < z < L_{ec}/2$, is $V(z) \approx \hat{V}/2[1 - \tanh\{1.318(L_{ec}/2 - |z|)/r_w\}]$.

Transverse confinement: For nonrelativistic electrons, the Larmor radius r_L is proportional to the square root of the perpendicular kinetic energy $T_\perp = T\sin\theta$, and inversely proportional to the magnetic field B_0:

$$r_L = (3.37\mu\text{m})\frac{\sqrt{T_\perp/(1\text{ eV})}}{B_0/(1\text{ T})}. \quad (11)$$

In a 0.5 T solenoid considered in this study, the initially ionized electrons are safely confined along the magnetic field lines as their Larmor radii are $r_L < 0.1$ mm for $T_\perp < 200$ eV. Even when the trapped electrons pick up some transverse kinetic energy from the space-charge potential, say $T_\perp \approx e|\hat{V}| \approx 3.7$ keV, their Larmor radii are still $r_L \approx 0.4$ mm, which is smaller than the typical rms beam size expected in this study ($\sim$ few mm). Indeed, the exact matching of the transverse profiles of the trapped electrons and proton beams may not be necessary at all if the major intensity limitation comes not from incoherent (single-particle) motion but from coherent modes [16]. We also need to make sure the macroscopic force balance. The equilibrium condition between the outward centrifugal and electric forces [see Eq. (1)], and the inward magnetic force requires a rigid azimuthal rotation of the plasma column with frequencies [23]

$$\omega_{re}^{\pm} = \frac{1}{2}\omega_{ce}\left[1 \pm \left\{1 - \frac{2\omega_{pe}^2}{\omega_{ce}^2}(1 - f_i)\right\}^{1/2}\right], \quad (12)$$

where $\omega_{re}^-(\omega_{re}^+)$ corresponds to a slow(fast) rotation of the plasma column, $\omega_{ce} = eB_0/m_e$ is the electron cyclotron frequency, $\omega_{pe}^2 = \bar{n}_e e^2/\epsilon_0 m_e$ is the electron plasma frequency, and f_i is the fractional charge neutralization provided by a proton beam and residual ions. For full compensation without residual ions, $f_i = 1/\eta_0$. In general, whether the plasma column is rotating with either slow or fast rotation velocity, depends on the way in which the non-neutral plasma is formed [23]. From the condition, $2\omega_{pe}^2/\omega_{ce}^2 = 2\bar{n}_e m_e/\epsilon_0 B_0^2 \leq 1$, we require $B_0 \geq 0.07$ T for the expected electron column parameters, which can be easily realized with the 0.5 T solenoid. Also, to minimize the plasma cross section change due to the rotation ($2\pi/\omega_{re}^- \approx 15$ ns for $B_0 = 5$ T and $f_i = 0$), the electron column should be placed in a region where the Twiss parameters β_x and β_y are equal.

Stability : Stability of the beam-plasma system has two aspects; stability of the non-neutral plasma itself and interactions between electrons and the proton beam. In equilibrium, the trapped electron plasma rotates rigidly with frequency $\omega_{re}^{\pm}$. If the plasma is moved off center, it undergoes additional $\mathbf{E} \times \mathbf{B}$ drift from its image electric field. This motion, with the fundamental mode frequency $\omega = \omega_D(r_e/r_w)^2$, is called the diocotron mode and is known to be very stable [23]. Here, $\omega_D = \omega_{pe}^2(1 - f_i)/2\omega_{ce}$. In practice, small static field errors and background neutral gas exert a drag on the rotating plasma and cause a shear in the angular flow velocity. Radial plasma expansion or growth of unstable diocotron modes (plasma filamentation and vortex formation) are unavoidable.

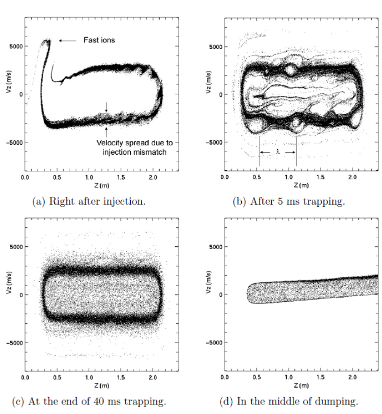
A “rotation wall” technique (providing a radial rotating electric field by azimuthally segmented electrodes), developed in the plasma physics community, could be a remedy [25].

The interaction between the trapped electrons and circulating proton beams is two-stream in nature. It will degrade the quality of both the electron column and the main beam. It is well-known that the increase of the confining solenoidal field and Landau damping through momentum spread can suppress the instability [26]. In addition, there are two unique instability suppression possibilities in the proposed experimental setup. One is self-stabilization of the e-p instability by the accumulation of secondary ions. It is observed [5] and also theoretically confirmed [27] that if there are not only electrons but also some residual ions in the cloud, the ions tend to short-out the electrostatic perturbations whose wavelengths are less than the transverse beam size r_b. The residual ion formation could be controlled by the proper choice of working pressure, solenoidal field, and electrode voltage. The full space-charge compensation condition in this case becomes $N_e - N_i = N_{tot} B_f / \gamma_b^2$. The other is the increased Landau damping by a broad tune spread enabled by a special nonlinear lattice. This nonlinear lattice is designed to be integrable, and thus can create a large tune spread and zero resonance strength [1]. Usual nonlinearities in the conventional circular accelerators, of course, lead to resonances and limit the dynamic aperture.

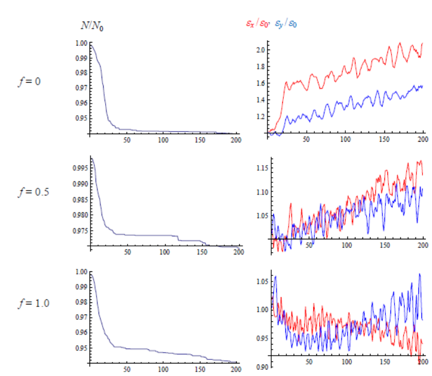
5 Relevant Simulation and Experimental Efforts

Here, we summarize several previous simulation and experimental efforts directly related to the proposed subject, which were performed by the PI and collaborators.

Simulations: In PI’s thesis work [28], trapping of non-neutral ion plasmas in a linear Pual trap was simulated using 3D WARP code [Fig. 2(a)]. Longitudinal temperature increase due to the two-stream interactions has been clearly observed. Y. Alexahin et al. at Fermilab performed space-charge simulation with MAD code [11], showing that placing electron columns in each 24 Booster periods reduces emittance blowup and beta-beat excitation [Fig. 2(b)].



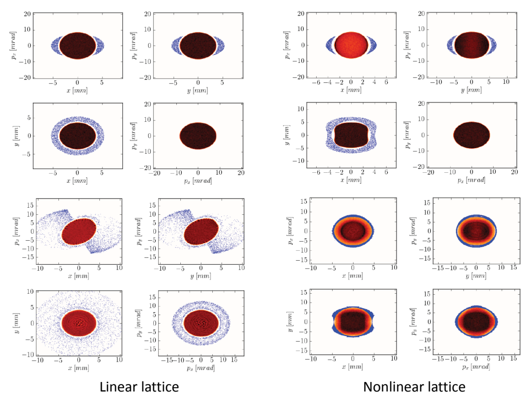
(a) Plots of axial phase space obtained from 3D WARP simulation of ion trapping process [28].



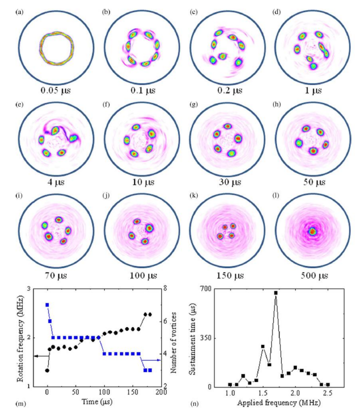
(b) Normalized beam intensity and emittances versus turn number with $N_{ec} = 24$ [11].

Figure 2:

In Fig. 3(a), S. Webb et al. at Tech-X and S. Nagaitsev et al. at Fermilab demonstrated, using the PyORBIT tracking code, that the nonlinear decoherence of the integrable lattice prevents the formation of beam halo [8]. In Fig. 3(b), the PI and collaborators at Pusan National University in Korea have shown, using 2D PIC code, that the evolution of diocotron instabilities can be controlled by applying "rotating wall" electric fields [29].



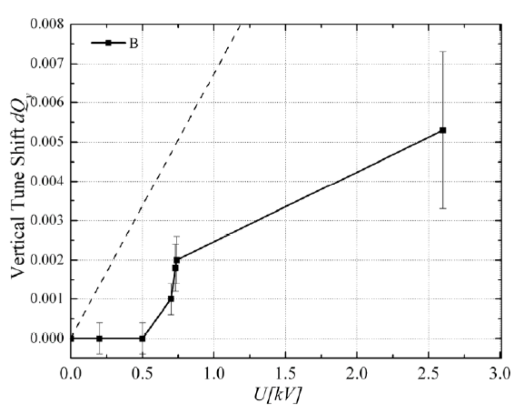
(a) PyORBIT simulations of halo formation in nonlinear integrable lattice [8].



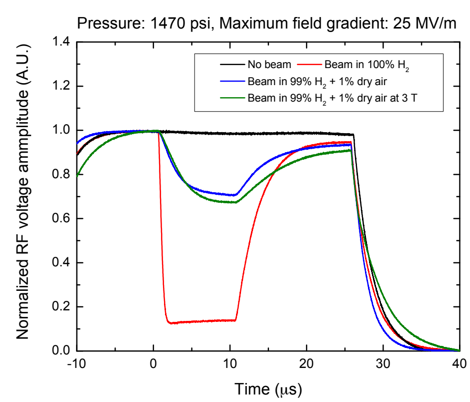
(b) 2D PIC simulations of control of diocotron instability using rotating wall [29].

Figure 3:

Experiments: Preliminary experiments were conducted at the Tevatron with 150-GeV protons [30]. The studies have revealed that a positive tune shift can be observed, which is consistent with accumulation of electrons by applying electrode voltages, but the shift is less than half of what is expected [Fig. 4(a)]. Through the beam tests of a gas-filled RF cavity performed by the PI and collaborators [31, 32], beam-induced gas ionization processes and many molecular processes have been studied through pick-up voltage measurements [Fig. 4(b)].



(a) Test results at Tevatron, dashed line representing the prediction [30].



(b) RF voltage changes due to beam-gas interactions [31, 32].

Figure 4:

6 Experimental Goal and Plan

The main experimental goal is to inject protons into the Integrable Optics Test Accelerator (IOTA) ring and to investigate space-charge compensation methods using the electron column and nonlinear lattice. First, we need to make sure: a) the 2.5 MeV proton beam from the HINS RFQ can be accepted in the IOTA ring with minimal changes in the beam and machine parameters, and b) the injected proton beam intensity is high enough to cause noticeable space-charge effects and thus enables the test of space-charge compensation schemes. The magnetic rigidity of the IOTA ring is designed to be

$$B\rho = p/q = 0.135 \sim 0.6 \text{ Tm}, \tag{13}$$

which is a perfect fit to a 2.5 MeV proton beam ($B\rho = p/q = 0.23$ Tm). There are several injection options; single-turn or multi-turn injection of th proton beam, or charge-exchange injection of the H- beam. Since the single-turn injection is relatively straightforward and easy to implement using the existing kicker system in the IOTA ring (orbit dump + magnetic septum + strip-line kicker), we first estimate the total number of protons for the case of the single-turn injection. The maximum allowed number of protons for the single-turn injection with 8 mA HINS operation is $N_{max} \approx 8.8 \times 10^{10}$. The kicker rise/fall time determines the size of the gap in the ring. Here, we assume the gap to be about 300 ns. Then the total number of protons will be $N_{tot} \approx 7.3 \times 10^{10}$. Because there is no damping via synchrotron radiation for the protons, the emittance growth due to injection mismatch is unavoidable. In general, the final emittance can be estimated from the rough formula, $\epsilon_f \geq 1.5 N_t \epsilon_i$ over N_t turns [33]. For a single-turn, 50 % emittance growth is expected. Considering the finite gap width and emittance growth, the space-charge tune shift with the nominal IOTA and HINS operation parameters can be estimated as

$$\Delta\nu_G \approx -0.56 B_f. \tag{14}$$

Therefore, even with the minimum bunching factor ($B_f = 1$, no bunching at all), the proton beam is above the space-charge limit (see Sec. 3). If there is more than 50 % emittance growth, then we may increase the bunching factor ($1 \leq B_f \lesssim 5$) using nominal RF voltage manipulation to reach above the space-charge limit. The multi-turn injection could increase the total number of particles, but at the same time increases the emittance accordingly, so there is no significant merit in terms of obtaining higher tune shift. Fine tuning of the HINS ion source and low repetition-rate operation of the RFQ could lead to higher beam currents (> 8 mA) and space-charge tune shift in the ring. On the other hand, while an H- source is readily available for the HINS, the charge-exchange injection is currently not considered in the project. That should be the top priority in the next phase once the feasibility of the electron-column concept is demonstrated. So far, we see no technical show-stopper to inject a 2.5 MeV proton beam into the IOTA ring to investigate space-charge physics. The main parameters of the IOTA ring and HINS RFQ are summarized in Tables 2 and 3, respectively. An example of beta-functions matched to a solenoid (0.5 T) in the IOTA ring is shown in Fig. 5.

The project is organized as follows:

Infrastructure establishment:
We'd like to emphasize again that the scope of this proposal is based on the resources and facilities readily available at Fermilab within the five year time-line. No major procurement or construction is required. The Fermilab accelerator division (AD) RF and mechanical engineers will lead the following tasks.

1. Relocation of HINS RF system and front-end: The cost for relocation and reconfiguration of

Parameter	Value	Unit
Nominal electron beam energy	150	MeV
Nominal electron momentum	150.5	MeV/c
Nominal beta (β)	1	-
Nominal gamma (γ)	294.6	-
Nominal magnetic rigidity	0.5	Tm
Range of electron beam energy	40 $\sim$ 180	MeV
Range of electron momentum	40.5 $\sim$ 180.5	MeV/c
Range of magnetic rigidity	0.135 $\sim$ 0.6	Tm
Bending field	0.7	T
Beam pipe aperture (diameter)	50	mm
Maximum beta function	3 $\sim$ 9	m
Betatron tune	3.5 $\sim$ 7.2	-
RF voltage and frequency	75 / 162.5	kV / MHZ
Momentum compaction	0.015 $\sim$ 0.1	-
Natural chromaticity	-5 $\sim$ -15	-

Table 2: Summary of the main parameters of IOTA.

HINS RF system and front-end is not specifically included in this proposal, because it obviously would not fit within the $ 500 k/year cost envelope. Currently, Fermilab is preparing a proposal for an Accelerator R&D User Facility at the Advanced Superconducting Test Accelerator (ASTA). We anticipate Fermilab being able to provide costs and manpower associated with the relocation and reconfiguration of HINS.

2. Design and installation of beamline and proton injection system: The HINS beamline and beam diagnostic system will be modified to facilitate injection of protons into the IOTA ring. Single-turn injection using a septum and a kicker of the IOTA ring will be used.

3. Design and installation of electron column system: The Tevatron Electron Lens (TEL) system will be modified. To minimize technical complexity associated with superconducting magnets, a modified version with a 0.5 T, 1-m long normal conducting solenoid is planned to be used.

Beam measurements: The PI will lead the beam measurements with strong involvement of graduate students and outside collaborators.

1. Beam injection commissioning and basic beam studies without electron column or nonlinear lattice.

2. Beam studies of space-charge compensation using an electron column.

3. Beam studies of space-charge effects in a nonlinear lattice: For example, we will test whether the nonlinear integrable optics is working as desired with space-charge effects. Also, we can measure the beam halo mitigation using novel halo diagnostics, such as a vibrating wire monitor.

4. Beam studies of e-p instability suppression with both the electron column and nonlinear lattice.

Parameter	Value	Unit
Nominal proton beam energy	2.5	MeV
Nominal proton momentum	68.5	MeV/c
Nominal beta (β)	0.073	-
Nominal gamma (γ)	1.003	-
Nominal magnetic rigidity	0.23	Tm
RF structure	325	MHz
Average beam current	≤ 8	mA
RMS emittance	~ 2	mm-mrad
Estimated momentum spread $(\Delta p/p)_{rms}$	0.37	%
Bunch spacing	3.1	ns
Bunch width (1σ)	0.3	ns
Pulse rate	0.2 / 1	Hz
Pulse width	1 @ 0.2 Hz / 0.1 @ 1 Hz	ms
Revolution time in IOTA ring	1.77	μs
Maximum number of protons for single-turn injection	8.8×10^{10}	-
Space-charge tune shift ($\Delta\nu_G$) for single-turn injection	$-0.56 \times B_f$	-

Table 3: Summary of the main parameters of HINS.

For the diagnostics of the beam-plasma system, collaborations are being setup with Dr. Erik Gilson and his team at Princeton Plasma Physics Laboratory (PPPL) and with Dr. Oliver Meusel of Goethe University in Germany.

Theory and simulations: The PI will lead the theory and simulations with strong involvement of graduate students and outside collaborators.

1. Simulation of plasma formation and trapping using WARP 3D code.
2. Beam dynamics simulation in the presence of both the electron column and nonlinear lattice (MAD or PyORBIT).
3. Theory of e-p instability suppression.

For the numerical simulation of the beam-plasma system, collaborations are being setup with Prof. Ron Davidson and his team at Princeton Plasma Physics Laboratory (PPPL) and with Prof. Hae-June Lee and his team of Pusan National University in Korea.

The schedule and overall structure of the proposed research are summarized in Table 4.

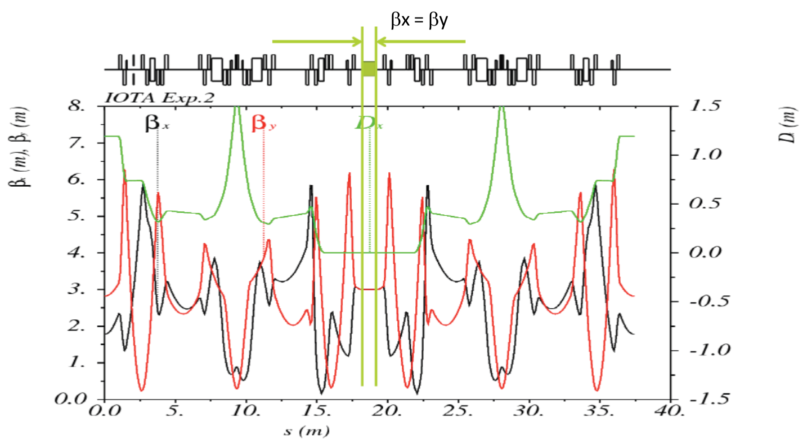


Figure 5: An example of Twiss parameters of IOTA ring with a solenoid inserted.

Period	1	2	3	4	5
FY	13 -14	14 -15	15 -16	16 -17	17 -18
ASTA Project	**Note 1: IOTA ring construction is expected to be complete in FY2014-2015** **Note 2: HINS relocation project will be supported by Fermilab**				
HINS RF system Relocation					
HINS front end Relocation					
HINS Beam-line Reconfiguration/Commission					
Budget (M&S / SWF)	200 k 1 FTE	200 k 1.5 FTE	60 k 1 FTE		
Early Career Project	**Note 1: Single-turn injection of proton using IOTA kicker is considered** **Note 2: Electron lens of IOTA will be modified to trap electrons**				
Theory and Simulations					
Proton Injection System					
Electron Column System					
Bema Measurements and Data Analysis					
Budget (M&S / SWF)	110 k 2.25 FTE	90 k 2.5 FTE	90 k 2.5 FTE	90 k 2.5 FTE	50 k 2.25 FTE

Table 4: Schedule and organization of the proposed research.

Appendices

A Biographical Sketch

A.1 Education and Training

- **Princeton University** (Princeton, NJ), Ph.D in Plasma Physics, September, 2008. "Studies of Charged Particle Beam Dynamics on the Paul Trap Simulator Experiment Pure Ion Plasmas", Advisor: Prof. Ron Davidson.
- **Seoul National University** (Seoul, Korea), MS in Nuclear Engineering (Nuclear Fusion Major), February, 1996. "Full Wave Modeling for Fast Wave Current Drive Simulation in Tokamak Plasmas", Advisor: Prof. Sang-Hee Hong.
- **Seoul National University** (Seoul, Korea), BS in Nuclear Engineering (Cum Laude), February, 1994.

A.2 Research and Professional Experience

- **Peoples Fellow** (Fermi National Accelerator Laboratory, Batavia, IL):
  February, 2012 - Present
  - Successful beam test of gas-filled RF cavity
  - Measurement of beam halo using vibrating wire monitor at HINS front-end
  - Studies of beam-gas and beam-plasma interactions for advanced accelerator control
- **Assistant Professor** (Handong Global University, Pohang, Korea):
  September, 2010 - January, 2012
  - Principal investigator of high-energy density plasma program
  - Studies of diocotron instability in hollow beam
- **Postdoctoral Research Associate** (Fermi National Accelerator Laboratory, Batavia, IL):
  July, 2008 - July, 2010
  - Experimental studies of beakdown in gas-filled RF cavity
  - Theoretical estimation of beam-induced plasma loading effects in gas-filled RF cavity
  - Design and installation of various beam instrumentations for the beam test
  - New formulation of coupled transverse beam dynamics
- **Research Assistant** (Princeton Plasma Physics Laboratory, Princeton, NJ):
  August, 2001 - June, 2008
  - Beam physics studies at Paul Trap Simulator Experiment (PTSX)
  - Development of laser-induced fluorescence diagnostic system

A.3 Publications (up to 10 most closely related to the proposed project)

1. Seung Il Chung, Hyun Jin Yun, Seung Bo Shim, Moses Chung, and Hae June Lee, "Control of Vortex Merging Induced from Diocotron Instability Using Rotating Wall Electric Fields", IEEE Transactions on Plasma Science **17**, 2496 (2011).

2. M. Chung, H. Qin, and R. C. Davidson, "Twiss Parameters and Beam Matrix Formulation of Generalized Courant-Snyder Theory for Coupled Transverse Beam Dynamics", Physics of Plasmas **17**, 084502 (2010).

3. M. Chung, A. Jansson, A. Moretti, A. Tollestrup, K. Yonehara and A. Kurup, "Beam Test of a High Pressure Cavity for a Muon Collider", Proceedings of the 2010 Particle Accelerator Conference, 3494 (2010).

4. M. Chung, A. Tollestrup, A. Jansson, K. Yonehara, and Z. Insepov, "Beam-induced Electron Loading Effects in High Pressure Cavities for a Muon Collider", Proceedings of the 2010 Particle Accelerator Conference 3497 (2010).

5. H. Qin, M. Chung, and R. C. Davidson, "Generalized Kapchinskij-Vladimirskij Distribution and Envelope Equation for High-Intensity Beams in a Coupled Transverse Focusing Lattice", Physical Review Letters **103**, 224802 (2009).

6. E. P. Gilson, M. Chung, R. C. Davidson, M. Dorf, P. C. Efthimion, A. B. Godbehere, and R. Majeski, "Recent Advances in the Physics of Collective Excitations in the Paul Trap Simulator Experiment", Nuclear Instruments and Methods in Physics Research A **606**, 48 (2009).

7. M. Chung, E. P. Gilson, R. C. Davidson, P. C. Efthimion, and R. Majeski, "Use of a Linear Paul Trap to Study Random-Noise Induced Beam Degradation in High-Intensity Accelerators", Physical Review Letters **102**, 145003 (2009).

8. M. Chung, E. P. Gilson, M. Dorf, R. C. Davidson, P. C. Efthimion, and R. Majeski, "Experiments on Transverse Compression of a Long Charge Bunch in a Linear Paul Trap", Physical Review Special Topics on Accelerators and Beams **10**, 064202 (2007).

9. M. Chung, E. P. Gilson, M. Dorf, R. C. Davidson, P. C. Efthimion, and R. Majeski, "Ion Injection Optimization for a Linear Paul Trap to Study Intense Beam Propagation", Physical Review Special Topics on Accelerators and Beams **10**, 014202 (2007).

10. M. Chung, E. P. Gilson, R. C. Davidson, P. C. Efthimion, R. Majeski, and E. A. Startsev, "Laser-Induced Fluorescence Diagnostic of Barium Ion Plasmas in the Paul Trap Simulator Experiment", Nuclear Instruments and Methods in Physics Research **A 544**, 514 (2005).

A.4 Synergistic Activities

- Accelerator R&D coordinator of Korea-US Collaboration Center (KUCC), promoting collaboration between Rare Isotope Science Project (RISP) in Korea and US laboratories
- Invited talk at Heavy Ion Fusion Symposium 2012
- Member of the scientific program committee for PAC'11 (Beam Dynamics and EM Fields section)
- Peoples Fellowship (2012-2014) from Fermi National Accelerator Laboratory

A.5 Collaborators and Co-editors

Yuri Alexahin ((Fermi National Accelerator Laboratory)
Ronald C. Davidson (Princeton University)
Mikhail Dorf (Lawrence Livermore National Laboratory)
Philip Efthimion (Princeton Plasma Physics Laboratory)
Erik Gilson (Princeton Plasma Physics Laboratory)
Andreas Jansson (European Spallation Source)
Igor Kaganovich (Princeton Plasma Physics Laboratory)
Sun-Kee Kim (Rare Isotope Science Project, Korea)
Bong-Ju Lee (Handong Global University, Korea)
Hae-June Lee (Pusan National University, Korea)
Richard Majeski (Princeton Plasma Physics Laboratory)
Oliver Meusel (Goethe University, Germany)
Sergei Nagaitsev (Fermi National Accelerator Laboratory)
Hong Qin (Princeton Plasma Physics Laboratory)
Victor Scarpine (Fermi National Accelerator Laboratory)
Vladimir Shiltsev (Fermi National Accelerator Laboratory)
Giulio Stancari (Fermi National Accelerator Laboratory)
Edward Startsev (Princeton Plasma Physics Laboratory)
Alvin Tollestrup (Fermi National Accelerator Laboratory)
Yagmur Torun (Illinois Institute of Technology)
Alexander Valishev (Fermi National Accelerator Laboratory)
Katsuya Yonehara (Fermi National Accelerator Laboratory)

A.6 Graduate and Postdoctoral Advisors and Advisees

Ronald C. Davidson (Ph.D Advisor, Princeton University)
Sang-Hee Hong (MS Advisor, Seoul National University, Korea)
Andreas Jansson (Postdoctoral Advisor, European Spallation Source)

B Current and Pending Support

None.

C Bibliography and References Cited

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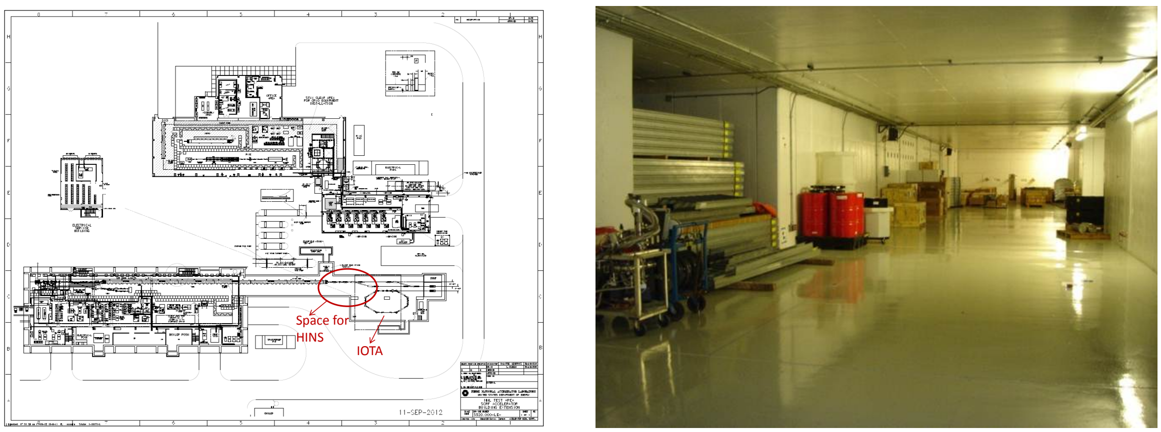
D Facilities and Other Resources

The scope of this proposal will be based on the resources and facilities readily available at Fermilab within the five year time-line. No major procurement and constructions are required in this proposal.

- **ASTA Facility:** The proposed project will be a part of Advanced Accelerator R&D (AARD) program in the newly established Advanced Superconducting Test Accelerator (ASTA) facility. The ASTA facility has complete infrastructure for AARD program, and has enough space to accommodate both injector and ring.



(a) Floor plan of ASTA facility.

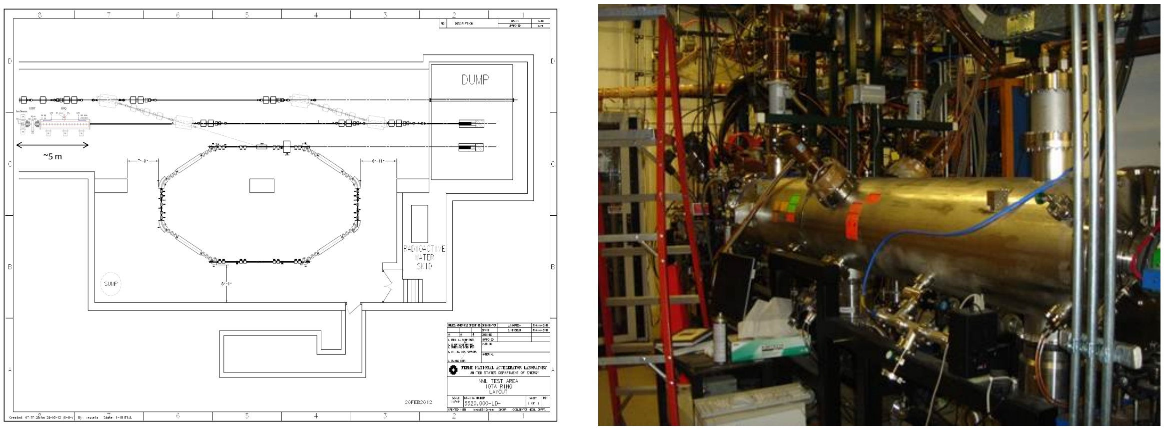
(b) Space for HINS front end and IOTA ring.

Figure 6: Layout of ASTA facility.

- **IOTA Ring:** The newly proposed Integrable Optics Test Accelerator (IOTA) ring, which is now under construction at Fermilab, will be used to accumulate protons. Components of beam instrumentation and vacuum system have already been procured, and the rest of the construction is fully supported by Fermilab independently from this proposal. The ring assembly will take place during 2013, and beam commissioning will start in 2014. Currently, the ring is designed to accept a 150 MeV electron beam, but the magnetic rigidity of the ring is adequate to accept a 2.5 MeV proton beam as well.
- **HINS Front-End:** The existing ion source (proton and H-), LEBT system, and RFQ of the High Intensity Neutrino Source (HINS) program will be reused as an injector for the ring with currents up to 20 mA and an energy of 2.5 MeV. The beamline and beam diagnostic system will be modified to facilitate injection of protons into the IOTA ring.

In addition, the proposed project will benefit significantly from Fermilab's exceptional expertise and experience in accelerator development and operation.

- **Accelerator Division (AD) RF Department:** The AD RF department will provide technical support in relocating the HINS RF system and installing the HINS RFQ at the ASTA facility.



(a) Layout of IOTA ring. (b) HINS front end.

Figure 7: Layout of IOTA ring with possible injection beamline and picture of HINS ion source, LEBT, and RFQ.

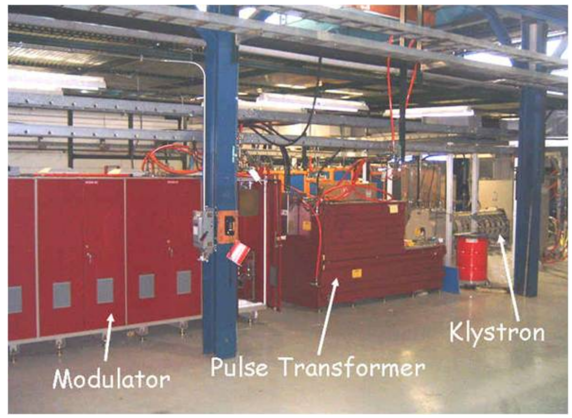
- **Accelerator Division (AD) Instrumentation Department:** The AD instrumentation department will provide technical support in reconfiguration of HINS beam instrumentation and installation of new diagnostic systems.
- **Accelerator Division (AD) External Beamlines Department:** The AD external beamlines department will provide technical support in installing a new beamline between the HINS front-end and IOTA ring.

E Equipment

Most of common laboratory equipment is readily accessible through the Accelerator Physics Center (APC) and Accelerator Division (AD) of Fermilab. Here, we only list equipment that needs relocation and some reconfiguration.

- **HINS RF system:** To drive a 2 MW, 325 MHz Toshiba klystron, a charing supply, modulator, and pulse transformer have been procured and installed for the HINS program. These equipment will be moved to ASTA facility with minor reconfiguration.

(a) HINS charging supply.



(b) HINS modulator, pulse transformer, and klystron.

Figure 8: RF systems for HINS front-end.

- **TEL system:** The Tevatron Electron Lens (TEL) system, a nonlinear element to be installed in the IOTA ring, will be used to trap electrons for the initial experiments. To minimize technical complexity associated with superconducting magnets, a modified version with a 0.5 T, 1-m long normal conducting solenoid is planned to be used.

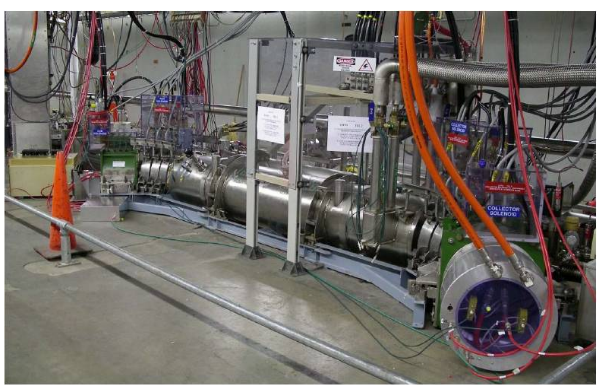


Figure 9: Tevatron Electron Lens (TEL) in the tunnel.

- **Vibrating Wire Monitor:** One of important figure of merits for the effectiveness of space-charge compensation is the degree of beam halo generation. Beam halo detection is very challenging and needs a wide dynamic range. A vibrating wire monitor system, which is installed and tested in the HINS beamline, will be installed in IOTA with some modification.

For the miscellaneous components needed for mechanical reconfiguration and beam instrumentation, the Fermilab machine shop and electronics shop will be heavily used.

F Other Attachments

PRINCETON PLASMA PHYSICS LABORATORY

Plasma Physics Laboratory
Princeton University
P.O. Box 451
Princeton, New Jersey 08543

Dr. Moses Chung
Peoples Fellow
Accelerator Physics Center
Fermi National Accelerator Laboratory
Batavia, IL 60510

November 20, 2012

Re: Proposal to US Department of Energy: *Trapped Electron Plasmas for Space-Charge Compensation in High Intensity Circular Accelerators*

Dear Dr. Chung:
If your proposal entitled, "Trapped Electron Plasmas for Space-Charge Compensation in High Intensity Circular Accelerators," is selected for funding under the DOE Office of Science Early Career Research Program, the PPPL Non-neutral Plasmas and Beam Dynamics Group would be pleased to collaborate with you as you carry out your research program.

We share a common interest in studying the neutralization of intense charged particle beams. Our research group has significant experience in the theory and modeling of intense charged particle beams and beam neutralization by background plasma. Our group also plays a key role in developing plasma sources that provide neutralizing electrons for lithium ion beams on the Neutralized Drift Compression Experiment at Lawrence Berkeley Laboratory. Further, our group has developed strong experimental expertise in relevant areas using Paul traps to simulate intense beam propagation, and also using Penning traps to study magnetized pure-electron plasmas.

Our collaboration will include theory, modeling and simulation support, and also participation in your experiments. Thanks very much for the opportunity to participate.

Sincerely

Ron Davidson

Ronald C. Davidson
Professor

Erik P. Gilson

Erik P. Gilson
Research Physicist

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Dr. Moses Chung

Accelerator Physics Center
Fermi National Accelerator Laboratory

Batavia, Illinois 60510

Date: 16 Nov 2012

Re: Proposal to US Department of Energy: Trapped Electron Plasmas for Space-Charge Compensation in High Intensity Circular Accelerators

Dear Dr. Chung,

the scientific program planned at Accelerator Physics Center will provide the opportunity to improve the understanding of the behavior of intense particle beams in accelerators. In recent times, the focus on high energy particle beams has shifted towards increased luminosity, enabling studies of rare reactions that have previously been unmeasurable.

However, accelerating high intensity beams is challenging, so emerging facilities depend on a good theoretical and experimental foundation to understand the collective behavior of the beam.

During the last decade our work group investigated effects like space charge compensation, emittance growth and stably confined electron clouds inside space charge lenses (Gabor lenses) and their application as a focusing device for ion beams. Non-interceptive diagnostics have been developed to study the interaction of beams with non-neutral plasma columns. The observed phenomena show good agreement with numerical models and theoretical predictions.

We are strongly interested to participate in your proposed research on space charge compensation in high intensity circular accelerators. It will be a pleasure for my research team and me to work closely with you to extend our experiments in an accelerator environment of Fermi National Accelerator Laboratory as an internationally renowned institution.

Sincerely,

Dr. Oliver Meusel

Campus Riedberg • Max-von-Laue-Straße 1 • 60438 Frankfurt am Main