PROGRESS WITH TEVATRON ELECTRON LENSES*

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Abstract

The Tevatron Electron Lenses (TELs) were initially proposed for compensation of long-range and head-on beam-beam effects of the antiproton beam at 980 GeV. Recent advances in antiproton production and electron cooling led to a significant increase of antiproton beam brightness. It is now the proton beam that suffers most from the beam-beam effects. Discussed are the motivation for beam-beam compensation, the concept of Electron Lenses and commissioning of the second TEL in 2006. The latest experimental results obtained during studies with high energy proton beam are presented along with the LIFETRAC simulation results.

MOTIVATION

The luminosity of storage ring colliders is limited by the effects of electromagnetic (EM) interaction of one beam with another which leads to a blowup of beam sizes, a reduction of beam intensities and unacceptable background rates in HEP detectors. This beam-beam interaction is described by a beam-beam parameter $\xi \equiv r_0 N/4\pi\varepsilon$, where $r_0 = e^2/mc^2$ denotes the particle's classical radius, N is the number of particles in the opposing bunch and ε is its rms normalized emittance. This dimensionless parameter is equal to the tune shift of the core particles caused by beam-beam forces. While the core particles undergo a significant tune shift, halo particles with large oscillation amplitudes experience negligible tune shift. The EM forces drive nonlinear resonances which can result in instability of particle motion and loss. The beam-beam limit in modern hadron colliders is $\xi^{max} \cdot N_{IP} \approx 0.01 - 0.02$ (N_{IP} is the number of IPs), while it can exceed $\xi^{max} \cdot N_{IP} \approx 0.1$ in high energy electron-positron colliders [1].

Operation with a greater number of bunches allows a proportional increase of luminosity but requires careful spatial separation of two beams everywhere except at the main IPs. Long-range EM interaction of separated beams is also nonlinear and also limits the collider performance. These long-range effects usually vary from bunch to bunch, making their treatment even more difficult.

One of the most detrimental effects of the beam-beam interaction in the Tevatron is the significant loss rate of protons due to their interaction with the antiproton bunches in the main IPs (B0 and D0) and due to numerous long-range interactions [2]. The effect is especially large at the beginning of HEP stores when the positive proton tune shift due to focusing by antiprotons at the main IPs can reach $2\xi^p = 0.016$. Figure 1 shows a typical bunch-to-bunch distribution of proton loss rates at the beginning of an HEP store.

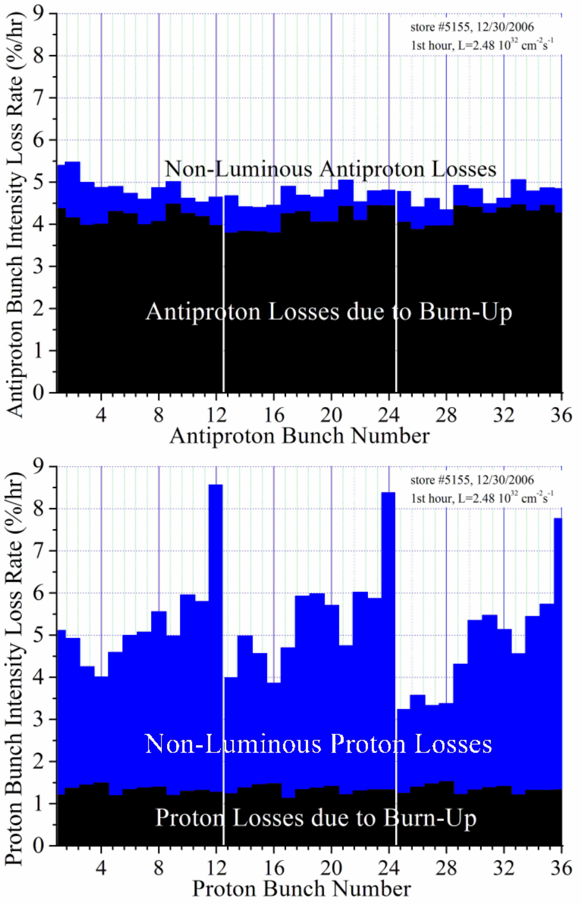

Figure 1: Proton bunch intensity loss rates at the beginning of store #5155.

In the Tevatron, 36 bunches in each beam are arranged in 3 trains of 12 bunches separated by 2.6 µs long abort gaps. Proton bunches P12, P24, and P36 at the end of each bunch train typically lose about 9 % of their intensity per hour while other bunches lose only (4-6) %/hr. In the beginning of high luminosity stores these losses are a very significant part of the total luminosity decay rate of about 20 % per hour. The losses due to burn-up at the two main IPs are much smaller (1.1–1.5%/hr). Figure 1 shows large bunch-to-bunch variations in the beam-beam induced proton losses within each bunch train but similar rates for equivalent bunches in different trains, e.g. P12, P24, and P36. Figure 2 shows the vertical proton bunch-by-bunch tunes about six hours into a store. Proton bunches at the end of each train have the lowest vertical tune due to the missing long-range collisions in the proximity of the main IPs.

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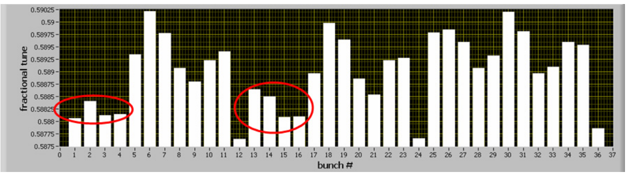

Figure 2: Vertical proton bunch-by-bunch tunes 6 hrs into store #5592 measured by the Digital Tune Monitor. Circled are the proton bunches affected by the four missing antiproton bunches. Full scale: 0.5875 – 0.59025.

This translates in the highest loss rates for this proton bunches (see Figure 1). Due to injection problems, the antiproton bunches A25-A28 were lost, so in store #5592 36 proton bunches collided with only 32 antiproton bunches. Proton bunches missing collisions (head-on and long-range) at one IP had lower tunes (circled red).

ELECTRON LENSES

Electron lenses were proposed for compensation of both long-range and head-on beam-beam effects in the Tevatron collider [3]. The lens employs a low energy $\beta_e = v/c << 1$ electron beam whose space charge forces act on the high-energy hadron beam. These forces are linear at distances smaller than the characteristic beam radius $r < a_e$ but scale as $1/r$ for $r > a_e$. Correspondingly, such a lens can be used for linear and nonlinear beam-beam compensation depending on the beam-size ratio a_e/σ and the current density distribution $j_e(r)$. Main advantages of beam-beam compensation by the electron lenses are: a) the electron beam acts on high-energy beams only through EM forces (no nuclear interaction), eliminating radiation issues; b) unused electrons interact with the high-energy particles each turn, leaving no possibility for coherent instabilities; c) the electron current profile can be optimized for different applications; d) the electron current can be adjusted for individual bunches, equalizing the bunch-to-bunch differences and optimizing the performance of all of the bunches in multi-bunch colliders.

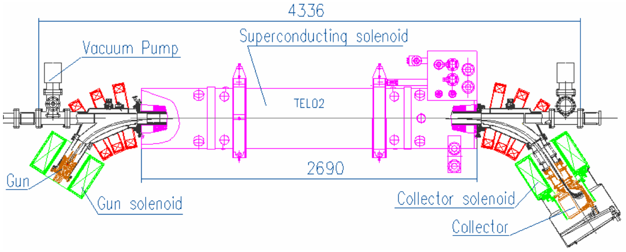

Figure 3: TEL2 layout.

Two Tevatron Electron Lenses (TELs) were built and installed at two locations of the Tevatron ring, A11 and F48. Figure 3 shows the layout of TEL2 [4]. Relevant parameters of the Tevatron and the TELs are given in Table 1.

In order to keep the electron beam straight and its distribution unaffected by its own space-charge and the EM fields of the circulating beam, the electron beam is immersed in a strong magnetic field. The conventional solenoids generate up to 4.5 kG in the electron gun and collector regions, while the superconducting (SC) one generates up to 65 kG in the interaction region. The deviations of the magnetic field lines from a straight line are less than ±100 µm over the entire length of the SC solenoid. Therefore the electron beam, following the field lines, does not deviate from the straight Tevatron beam trajectory by more than 20% of the Tevatron beam rms size $\sigma \approx 0.5$ mm at the TEL locations.

The electron beam's transverse alignment on the proton or antiproton bunches (within 0.2–0.5 mm all along the interaction length) is crucial for successful BBC. The electron beam steering is done by adjusting currents in the SC dipole correctors installed inside the main solenoid cryostat. It is also important that the transverse electron current distribution utilizes wide flat top and smooth radial edges.

The high-energy protons are focused by the TEL and experience a positive betatron tune shift given by [3]:

$$dQ_{x,y} = +\frac{\beta_{x,y} L_e r_p}{2\gamma e c} \cdot j_e \cdot \left(\frac{1-\beta_e}{\beta_e} \right) \qquad (1)$$

Table 1: Electron Lens and Tevatron collider parameters.

Parameter	Symbol	Value	Unit
Tevatron Electron Lens			
Electron energy (oper./max)	$U_{e,}$	5/10	kV
Peak electron current (oper./max)	J_e	0.6/3	A
Magnetic field in main/gun solenoid	B_{main} B_{gun}	30 3	kG
Radii: cathode/*e*-beam in main solenoid	a_c a_e	7.5 2.3	mm
e-pulse period/width, “0-to-0”	T_0 T_e	21 ≈0.6	µs
Interaction length	L_e	2.0	m
Tevatron Collider Parameters			
Circumference	C	6.28	km
Proton/antiproton beam energy	E	980	GeV
Proton bunch intensity	N_p	250	10^9
Antiproton bunch intensity	N_a	50-100	10^9
Emittance proton, antiprot. (norm., rms)	ε_p ε_a	≈2.8 ≈1.4	µm
Number of bunches, bunch spacing	N_B T_b	36 396	ns
Initial luminosity	L_0	1.5-2.9	10^{32} cm^{-2}s^{-1}
Beta functions, TEL2	β_y / β_x	150/68	m
Beta functions, TEL1	β_y / β_x	29/104	m
Proton/antiproton head-on tuneshift	ξ^p ξ^a	≈0.008 ≈0.011	max., per IP
Proton/antiproton long-range tuneshift	ΔQ^p ΔQ^a	≈0.003 ≈0.006	max.

Electron Gun

A charge density distribution required for tune shift compensation is generated by the electron gun utilizing a convex dispenser cathode and optimized electrode geometry [5]. The convex cathode shape allows for high perveance (≈ 4.2 μP) even at high electron currents.

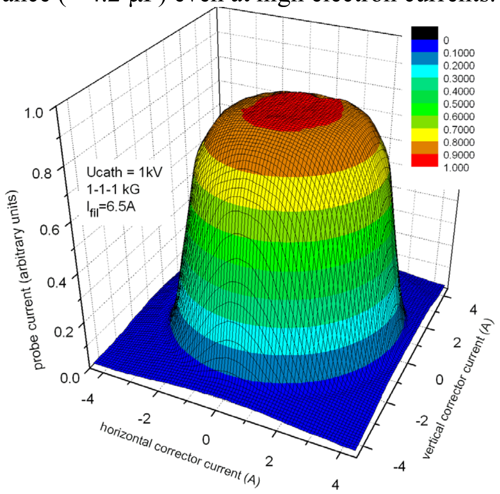

Figure 4: 2D charge density distribution generated by the SEFT (smooth edge flat top) electron gun.

The electron beam profile shown in Figure 4 was measured on the test bench by recording the electron current passing through a 0.2 mm hole while scanning the beam over the hole using the corrector coils [5]. The TEL magnetic system compresses the electron-beam cross-section area in the interaction region by the factor of $B_{main}/B_{gun} \approx 10$ (variable from 2 to 30), proportionally increasing the current density of the electron beam in the interaction region. Most recent experiments have not required more than 0.6 A of electron current, however tests with up to 3.0 A have been performed.

Electron Gun Drivers

To make compensation of individual bunches separated by 396 ns possible, the anode voltage, and consequently the electron beam current, are modulated with 500-600 ns pulses and a repetition rate equal to the Tevatron revolution frequency of $f_0 = 47.7$ kHz by using a newly developed Marx generator [6] or a HV RF tube based modulator [7].

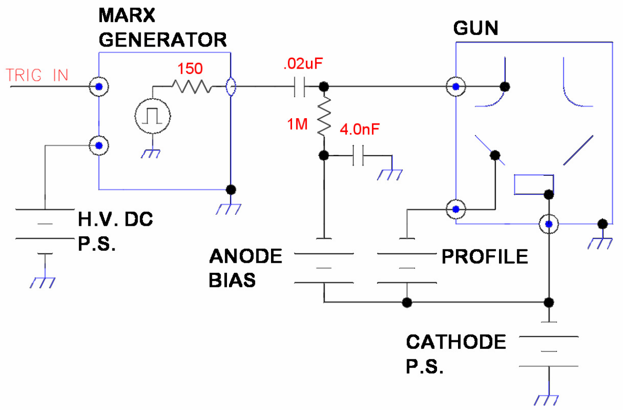

Figure 5: A schematic representation of the electron gun driving circuit.

Figure 5 shows the electron gun driving circuitry. In order to insure the shortest possible pulse rise and fall times the driver was installed in the Tevatron tunnel close to the electron gun [8]. All the dc power supplies, however are located outside the tunnel.

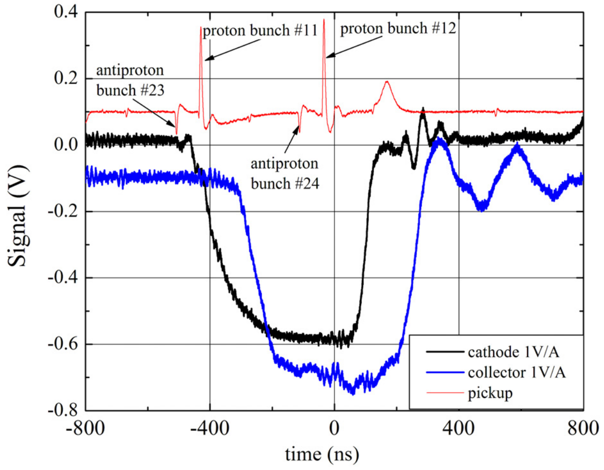

Figure 6: TEL2 timing for P12 compensation.

Figure 6 shows how the TEL2 timing is set up for single bunch compensation. Plotted are electron current leaving the cathode and the one arriving at the collector, measured by the current transformers, and a pickup signal. The capacitive pickup reports proton, antiproton and electron signals. Only proton bunch P12 was affected by the TEL during this experiment. The electron pulse timing jitter is less than 1 ns and the peak current is stable to better than 1%, so, the TEL operation does not cause any measureable emittance growth.

An improved Marx generator capable of driving the electron gun at repetition rates up to 150 kHz and a high voltage modulator utilizing a summed pulse transformer scheme [9] are being built. The latter is designed to add all-bunch compensation capabilities to the TELs.

EXPERIMENTAL RESULTS

Preliminary alignment of the electron beam was done by relying on the TEL beam position measurement system. However, additional fine tuning was necessary to achieve best possible compensation. Measurements of the proton loss rate versus electron beam position at increased electron current were performed at the very end of a store, when no beam-beam related losses occur. This approach allowed to determine the optimal electron beam position. Since the Tevatron orbit is kept stable by the orbit feedback system within 100 μm the end-of-store values can be used throughout other stores, unless an optics change is introduced.

The tune shift is about the same for most protons in the bunch since $a_e \approx 3\sigma$. Figure 7 shows the results of the vertical tune shift measurement of 980 GeV protons versus TEL2 electron current which are in good agreement with Equation 1 for the parameters summarized in Table 1– see solid line.

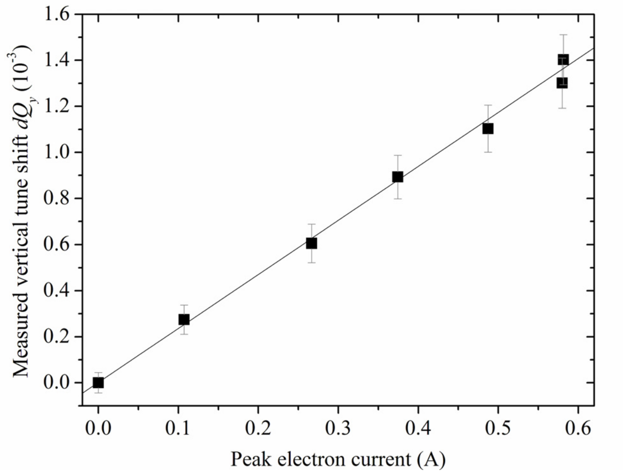

Figure 7: Vertical tune shift vs TEL2 electron current.

The beam-beam compensation studies were performed in the beginning of stores. As soon as TEL2 electron current was turned on (affecting P12 only) a significant change of slope of P12 intensity decay was observed (see Figure 8). This change corresponds to a lifetime improvement of about 100%. This result has been confirmed in several beam studies.

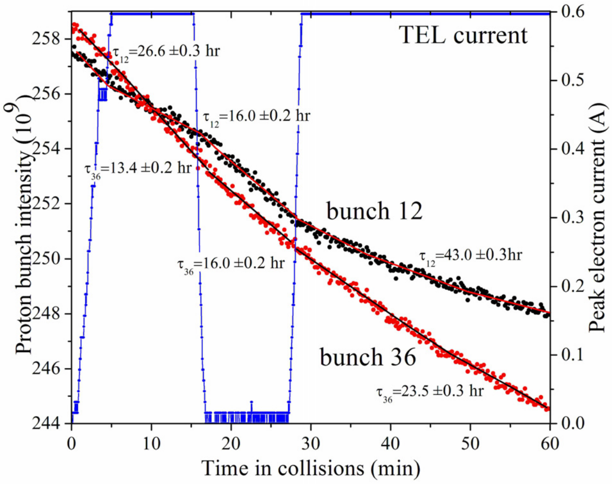

Figure 8: Dependence of the proton intensity decay rate on TEL2 peak electron current.

Another way to look at the same phenomena is to measure the effect of the TEL on the proton loss rate. Both HEP experiments D0 and CDF routinely measure loss rates (halos) around their detectors on a bunch-by-bunch basis. Figure 9 shows the dependence of D0 proton loss rate on TEL1 electron current. In this experiment TEL1, being a horizontal beam-beam compensation device, was acting on P13 which has the lowest horizontal tune. P14 was chosen as a reference bunch because its behavior in terms of halo and lifetime was very similar to P13. The loss rate of P13 dropped by about 35% once the electron current was turned on, while P14 loss rate stayed unaffected (TEL1 is not acting on P14). The P13 loss rate actually became smaller before the final e-current value (0.6 A peak, 19mA AVG) was reached. After about 12 min the e-current was turned off which made P13 loss rate return to the reference level. This result has been confirmed in several beam studies.

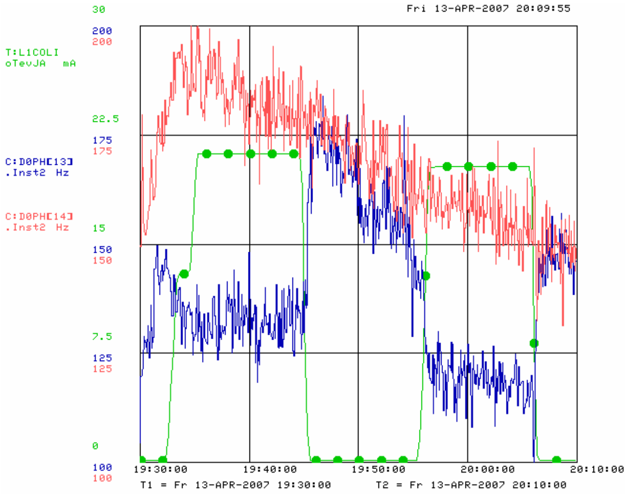

Figure 9: Dependence of proton loss rate of P13 (C:D0PH[13]) and P14 (C:D0PH[13]) on TEL1 average electron current (T:L1COLI).

The effect of the TEL2 and TEL1 improving the proton intensity lifetime, can be explained by a positive tune shift introduced by the TEL (see Figure 7) pushing the tune away from the 12th order resonance. However, it is not yet clear whether it is the only mechanism responsible for the significant lifetime improvement.

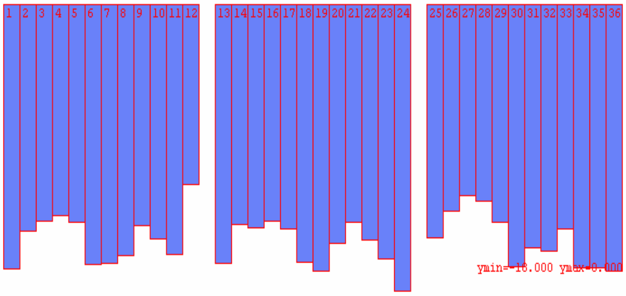

Figure 10: Lost bunch intensity as reported by T:SBDPIS for the first 1.5 hours of a store. TEL2 was acting on P12, J_e = 0.3 A. Scale:-18·10^9 – 0 protons.

Furthermore, another beam study with TEL2 at J_e = 0.3 A on P12 showed that this bunch experienced the smallest intensity loss as compared to any other proton bunch (see Figure 10). The tune shift caused by such a moderate electron current is not sufficient for P12 to reach the average tune value. Nevertheless, P12 had the best lifetime among all proton bunches. This single result is not fully understood yet.

LIFETRAC SIMULATION

To simulate the effect of the TEL on dynamics of the proton beam we used the weak-strong code LIFETRAC [10] which has been extensively used to study beam-beam effects in the Tevatron [11]. This is a multi-particle simulation code where a single bunch of particles is tracked through a sequence of maps and points of beam-beam interaction reproducing the real pattern of collisions in the machine. The code takes full advantage of the current knowledge of the Tevatron optics by using the measured beta-functions and helical orbits in order to compute the transfer maps for tracking particles between the IPs and to calculate the beam-beam kick.

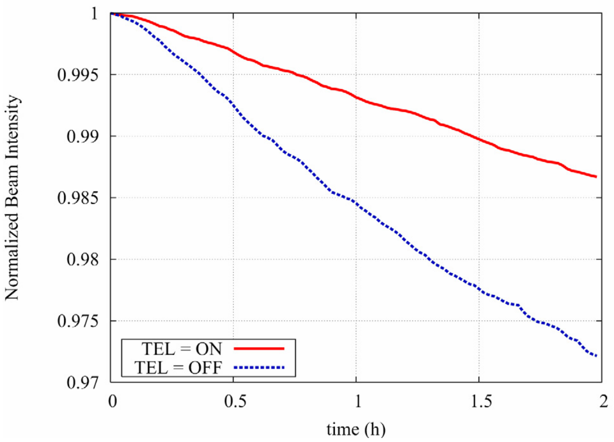

Figure 11: Normalized proton beam intensity, first two hours of an HEP store, simulated with LIFETRAC code.

In the simulation, the TEL was represented by a thin kick generated by the electron beam with the transverse density distribution described by the formula

$$\rho(r) = \rho_0\left(1 + (r/r_0)^8\right)^{-1} \tag{2}$$

Particle diffusion in the Tevatron is dominated by the intrabeam scattering which however may be enhanced significantly by the beam-beam effects, especially when the betatron tune is close to strong resonances. Still, the strength of the random noise can be used to set the time scale for tracking simulations. With the present computing capacity it is possible to track a bunch of 10,000 macro particles for up to 10^6 turns. With the real Tevatron revolution frequency this corresponds to roughly 2 minutes. By artificially increasing the IBS diffusion rate we are stretching this time to about 2 hours. Hence, calculating the number of particles lost from the beam during the time of simulation can be used to estimate the non-luminous beam lifetime. Although this method does not give a very accurate absolute result it is quite effective for relative comparison of various conditions. This approach has been applied to the beam-beam compensation with the TELs. Figure 11 shows the evolution of intensity of a single proton bunch with and without the TELs acting on it.

The simulation shows that the TELs improve non-luminous proton lifetime by about a factor of 2. The TELs push the betatron tunes away from the 12th order resonance thus improving the beam lifetime.

SUMMARY

The Tevatron Electron Lenses equipped with SEFT electron guns were operated in pulsed mode to perform single bunch beam-beam compensation. Significant proton intensity lifetime improvement achieved in numerous beam studies is consistent with computer simulations carried out using weak-strong code LIFETRAC. However, a single result indicating that TEL2 made the lifetime of a proton bunch it was acting on better than the lifetime of any other proton bunch is not fully understood yet. BBC with dc electron beam using TEL2 has been performed as well with positive results, however they were not treated in this paper. The high voltage pulse generators being built are expected to add multi-bunch compensation capabilities to the TELs. Preparations for the beam studies using the electron gun with Gaussian charge density distribution are underway.

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