Intense Electron-Beam Transport in the Ion-Focused Regime
Through the Collision-Dominated Regime

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Abstract

This paper reviews the transport of the 19-MeV, 700-kA, 25-ns Hermes-III electron beam in long gas cells filled with N2 gas spanning six decades in pressure from 10^{-3} to ~10^3 Torr. We show through measurements and theoretical analyses that the beam has two windows of stable transport: a low-pressure window (between ~1 and ~100 mTorr) that is dominated by propagation in the semi-collisionless IFR (ion-focused regime), and a high-pressure window (between ~1 and ~100 Torr) that is dominated by propagation in the resistive CDR (collision-dominated regime). In the CDR, 79±1.5% of the beam energy is transported over 11 m at 20 Torr. In the IFR, we show that intense radiation fields with controllable rise times and pulse widths can be generated on axis at a bremsstrahlung target. In summary, the measurements and analyses presented here provide a quantitative description of the Hermes-III beam transport over six decades in pressure.

Measurements and analyses\textsuperscript{1,2,3} show that the 13-TW Hermes-III\textsuperscript{4} electron beam has two windows of stable transport in long drift cells filled with N2 gas terminated by a bremsstrahlung producing target: a low-pressure window (between ~1 and ~100 mTorr) that is dominated by propagation in the ion-focused regime (IFR)\textsuperscript{5} and a high-pressure window (between ~1 and ~100 Torr) that is dominated by propagation in the resistive collision-dominated regime (CDR). In the transition region between the two windows, beam plasma-electron instabilities significantly disrupt propagation.

Propagation in both regimes (the IFR at early time and the CDR at later time) is observed from ~5 to ~100 mTorr, which produces two distinct bremsstrahlung pulses from the single injected beam pulse. As the pressure increases, two-stream instabilities terminate IFR propagation and the associated bremsstrahlung pulse earlier and earlier in time. Above 5 mTorr, this instability is sufficiently quenched by gas collisions that CDR propagation in the beam body can occur, leading to a second bremsstrahlung pulse.

Above 200 mTorr, the gas breaks down too rapidly for a significant IFR pulse to form, and for higher pressures only a single pulse in the CDR is propagated. Between ~200 mTorr and ~1 Torr the hollowing instability and lack of magnetic confinement limit CDR propagation. Only for pressures above ~1 Torr is stability achieved in the CDR. Above ~100 Torr, however, the resistive hose instability degrades propagation. Within this high pressure window, maximum energy transport occurs at ~20 Torr. The optimum results from a combination of two effects: (1) improved beam confinement from the magnetic pinching force generated by the residual net current (sum of beam and plasma return current) as the pressure is increased, and (2) reduced energy loss from the inductive

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fields and inelastic collisions as the pressure is decreased.

The experimental arrangement is similar to that described in Ref. 1 (Fig. 1). Current shunts IA1, IA2,..., IA5 in the anode and IC1 in the cathode monitor the current flow. The voltage across the diode at IA1 is obtained from parapotential flow theory using the measured total current from IA1 and boundary current from IC1. The net current flowing 20 cm upstream of the target at the end of the drift cell is obtained from IA4 and IA5. For the data presented here, the peak voltage and current at IA1 are measured to be 19.0±0.5 MV and 655±14 kA, respectively. The full-width half-maximum (FWHM) of the voltage pulse is 33.5±1.4 ns (25 ns FWHM power pulse). The uncertainties, as those elsewhere in the paper, refer to RMS shot-to-shot variation.

The compound-lens diode6 is used to inject the Hermes-III annular electron beam at near paraxial angles and at 12-20 cm radii into the gas cell. This diode, shown in Fig. 1b, allows separate control of beam radius (by varying AK gap) and injection angle (by varying lens current IL).

At the drift cell exit are placed a variety of diagnostics, including a calorimeter (Fig. 1c), a thermoluminescent dosimeter (TLD) array (Fig. 1d), and Compton diodes (CDs) (Fig. 1e). A microwave detector (MW) is placed near IA4 to detect plasma electron oscillations such as from a two-stream instability. TLDs are mounted every 25 cm along the top and bottom exterior to the 11-m drift cell. These measure localized beam loss and, thus, are sensitive to the presence of betatron oscillations, resistive hose and hollowing instabilities, and give some measure of θ-asymmetry.

The basic result of experiment, theory, and modeling with the 2D MAGIC7 and 3D PIC code IPROP8 is shown in Fig. 2. At low N2 pressure (1-100 mTorr), the beam propagates with up to 30% efficiency in the IFR mode, where plasma electrons are blown out and the beam is focused by the residual ions. The plasma itself is produced from the initially neutral gas by impact ionization and ion avalanche. Late in the pulse, the charge neutralization fraction reaches unity and the plasma electrons are no longer ejected, leading to growth of the two-stream instability which disrupts propagation. At intermediate pressure (p = 0.1-1.0 Torr in Fig. 2), charge neutralization occurs rapidly, but current neutralization is weak. Strong magnetic fields pinch the beam, and a hollowing instability is excited sending much of the beam to the outer wall. Above a few Torr, the current neutralization is adequate to restrain the hollowing instability. For these pressures, the beam propagates in the CDR, with a maximum efficiency of 79±1.5% at 20 Torr. At pressures above ~100 Torr, the hose instability sets in and quenches propagation.

The qualitative physics at low to moderate pressures (or at early time and higher pressure) are summarized in Fig. 3. We can think of the four phases (virtual cathode, IFR, two-stream, and collisional propagation) as representing time development, increasing pressure, or increasing charge neutralization (up to unity in phases c and d). This picture is in agreement with the measurements in Fig. 2 and is also supported by the measurements of the TLDs mounted along the 11-m drift cell, the CD measurements, and the MW measurements.

Several other results of interest, seen in both code/analyses and measurement, are: (1) the radial beam profile at the target (Fig. 4) is strongly peaked on axis in the IFR (the foil-pinch effect when space-charge neutralization is incomplete), which leads to an intense on-axis radiation pulse, but relatively flat in the CDR; (2) over the range 5 to 50 mTorr the rise time and width of the associated radiation pulse in the IFR can be controlled by adjusting the pressure; (3) a double radiation pulse is dramatically seen at ~0.1 Torr—the IFR pulse arrives first and the CDR pulse later (Fig. 5); and (4) current neutralization is maximum near 1.0 Torr as shown in Fig. 6.

In summary, we have measured, calculated, and understood the propagation of very high current electron beams over the wide pressure variation 10⁻³ to 10³ Torr.

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References


Fig. 1 (a) Schematic of experimental arrangement showing placement of the magnetically insulated transmission line (MITL), the compound-lens diode (LENS), the drift cell of length \( \ell \), and the bremsstrahlung target. (b) Detail of the compound-lens diode showing flow of the external current \( I_E \) and the average beam trajectory when the AK gap equals 20 cm. (c) Detail of upstream surface of the graphite calorimeter. (d) Detail of the TLD array showing TLD placement. (e) Detail of a shielded Compton diode.

Fig. 2 Energy transport efficiency measured in the calorimeter [Fig. 1(c)] as a function of drift cell pressure, for \( \ell = 11 \) m. Also shown is the two-dimensional IPROP model of Ref. 1 run with \( \theta \)-symmetry for the CDR and the simple analytic model of Ref. 2 for the IFR.
Fig. 3 Four temporal phases of beam propagation in the drift cell at low pressure: (a) virtual cathode formation, (b) IFR propagation, (c) two-stream instability formation, and (d) CDR propagation.

Fig. 4 Radial surface dose measured with the graphite calorimeter (Fig. 1c) for a pressure of 40 mTorr and for $\ell = 11$ m.

Fig. 5 Relative comparison of the on-axis radiation pulse measured at the target with the current pulse I measured upstream of injection (translated in time to the target) for a pressure of 100 mTorr and for $\ell = 11$ m.

Fig. 6 The peak net current measured at the target as a percentage of the peak injected current versus the drift cell pressure. Also shown is the 2D IPROP model prediction for the collisional regime. Here $\ell = 11$ m.