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COMPUTATIONAL SUPPORT FOR ITS, ECTOR, PIXY, AND PHERMEX

Annual Report

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Case 3: Shielding on bucking coil. Trim coil turned on.

Coil	kA-Turns	Iron Shielding
Bucking	-19.86	2 cm iron on 3 sides
Focus	39.28	none
Trim	-5.5	none

Beam trajectories and emittance are shown in Fig. 32. The downstream emittance is about 0.064 cm-rad. This is comparable to that obtainable from the air-core configuration,¹² and gives about a 30% reduction in the bucking-coil current.

Figure 32. Beam trajectories and emittance vs. z for Case 3 (iron shielding on bucking coil; trim coil on). Beam current and voltage are 2.9 kA and 1 MV.

Figure 31. Beam trajectories and emittance vs. z for Case 2 (iron shielding on bucking coil; trim coil turned off). Beam current and voltage are 2.9 kA and 1 MV.

Figure 30. Beam trajectories and emittance vs. z for Case 1 (iron shielding on bucking coil and focus coil; trim coil turned off). Beam current and voltage are 2.9 kA and 1 MV.

reduce these currents. The three cases described below show how putting shielding on the bucking coil and focus coil affects the current requirements. All cases had the same 4" diameter cathode with a 7.5 cm AK gap, producing 2.9 kA at 1 MV.

As a reference, we first give the air-core current requirements:

Reference case: No shielding

<u>Coil</u>	<u>kA-Turns</u>	<u>Iron Shielding</u>
Bucking	-33.0	none
Focus	46.8	none
Trim	-6.5	none

Case 1: Shielding on bucking coil and focus coil, no trim coil (lowest current requirement)

<u>Coil</u>	<u>kA-Turns</u>	<u>Iron Shielding</u>
Bucking	-12.0	1 cm iron on 3 sides
Focus	20.5	1 cm iron on 3 sides
Trim	0.	

The beam trajectories and emittance are shown in Fig. 30. The downstream emittance is about 0.1 cm-rad.

Case 2: Shielding on bucking coil, no trim coil

<u>Coil</u>	<u>kA-Turns</u>	<u>Iron Shielding</u>
Bucking	-16.2	2 cm iron on 3 sides
Focus	28.64	none
Trim	0.	

Beam trajectories and emittance are shown in Fig. 31. The downstream emittance is about 0.14 cm-rad.

about 7.65 cm.) The cathode inset causes a significant perturbation to the electric field at the edge of the cathode. The equipotentials are forced to bend around the edge. This reduces the axial electric field near the edge, thereby reducing the local current density, as shown in Fig. 29. It is difficult to get good resolution of the small step at the edge of the cathode using our present codes. To get Fig. 29, the cathode was inset by just one cell on the mesh.

Figure 29. Comparison of current densities at the cathode surface for (a) flush-mounted cathode and (b) 0.15 cm inset. Diode voltage is 400 kV.

In spite of these nonideal effects, the experimental perveance for the flat gun is still almost three times higher than for the old gun (see Fig. 28). A modified cathode which will mount flush with the surrounding electrode is in procurement.

3.2.3 Effect of Iron Shielding on Coil Currents

Because of the proximity of the bucking coil to the focus and trim coils in the flat-cathode design, the coil currents needed to provide sufficient field to extract a beam are quite large. We have looked at the use of iron shielding on the magnets as a way to

Figure 28. Current vs. voltage for new (flat) cathode and old (Pierce) cathode. Perveance of new diode is $2.7 \mu\text{perv}$ vs. $1.07 \mu\text{perv}$ for the old diode. The new cathode simulation results are for a cathode inset of 0.15 cm.

Figure 27. Experimental and numerical field calibrations for the PHERMEX flat-cathode magnets. Focus coil has 116 windings, bucking coil has 52 turns, and trim coil has 26 turns. Numerical results were obtained with POISSON. Calibrations are given in Table 7.

Figure 26. Transport of PHERMEX beam through iron-core focusing magnets. Beam envelope (a) is initialized from Fig. 23. Axial magnetic field is shown in (b). Magnet currents are both 5 A.

Figure 25. Transport of PHERMEX beam through two iron-core focusing magnets. Beam envelope (a) is initialized from Fig. 23. Axial magnetic field is shown in (b). Magnet currents are 4.5 A and 3 A, respectively. Poles are 58 cm and 114.5 cm from the cathode.

was transported through this field using an envelope code. Results are shown in Figs. 25 and 26.

3.2 Flat-Cathode Geometry

The flat cathode and its accompanying magnet coils have been assembled during the past year and initial tests are now in progress.

3.2.1 Magnet Calibration

The flat-cathode design uses three air-core magnets: a focus coil, a bucking coil and a trim coil which controls the radial field profile. Results of experimental and numerical calibrations are shown in Fig. 27. The numerical results in Fig. 27 were obtained with POISSON. As a check, we also did the calculation with the BFIELD code (see Sec. 1.3). The results are compared in Table 7. Agreement is good except for the focus coil (see Fig. 27). The discrepancy is not understood at present.

TABLE 7. Magnet Calibration for PHERMEX Flat Cathode.

Magnet	Turns	Measured	BFIELD (gauss/Amp)	POISSON
Focus	116	3.04	3.236	3.204
Bucking	52	1.28	1.248	1.226
Trim	26	1.24	1.253	1.219

3.2.2 Flat Gun Perveance Measurements

The main motivation for going to a flat cathode geometry was to increase the current output at a given voltage, i.e., the gun perveance. Current as a function of voltage for a 4" cathode is shown in Fig. 28. The measured current is less than that originally predicted by SPEED for the nominal 7.5 cm AK gap design.¹² The discrepancy can be accounted for by the fact that the cathode is inset from the surrounding flat electrode by about 0.15 cm. (In addition, the distance from the electrode to the anode in the experiment is

Figure 24. Comparison of axial magnetic field obtained from POISSON (solid line) with experimental measurement (+).

3.0 PHERMEX CALCULATIONS

A test stand has been set up for PHERMEX gun development. Both the original Pierce geometry and the new flat geometry are being studied.

3.1 Original PHERMEX Gun

We carried out calculations for the Pierce geometry using the SPEED code.⁵ Previously we used the boundary-fitted version of ISIS to deal with the curved emitting surface,¹⁰ but the simulations were very time-consuming to set up. Figure 23 shows a SPEED simulation at 570 kV, which generates 462 A. This is in good agreement with the experimentally measured 461 A, and gives a perveance of $1.07 \mu\text{perv}$ (see also Fig. 28).

Figure 23. Simulation of the PHERMEX Pierce diode using SPEED. At 570 kV, obtain 462 A, giving a perveance of $1.07 \mu\text{perv}$.

The extracted beam was transported using two standard iron-clad PHERMEX magnets.¹¹ The magnetic field was calculated using POISSON (see Appendix C), and is compared with the experimental measurements in Fig. 24. The beam generated in SPEED

It would be desirable to verify the spot-size dynamics by obtaining time-resolved measurements on ECTOR or PIXY. If confirmed, this would significantly increase our understanding of these machines, and our ability to optimize them.

Figure 22. Instantaneous X-ray distribution vs. transverse spatial coordinate near minimum beam focus. (Courtesy of Mike George, M-4.)

Here, q_i is the charge carried by the particle and $\gamma_i mc^2$ is its energy. By binning the d_i by radius for all the particles in the table, a point spread function is obtained. This can be converted to a spot-size using standard M-4 radiographic algorithms. We obtain a value of 7.1 mm for the time-integrated spot-size, and 2.7 mm for the minimum spot-size, in reasonably good agreement with the MCNP results.

2.5 Implications of Gas Transport Results

The prediction that the instantaneous spot-size is considerably smaller than the time-integrated spot-size during the most energetic part of the pulse is potentially important. It means that one may be able to improve spot-size by using shaped targets to produce more dose when the beam is small.

produced. The time-integrated result is shown in Fig. 21. The distribution in this figure simulates that obtained using a lead brick.⁹ The effective spot-size obtained⁹ is 7.4 mm. Since the spot-size clearly varies a lot during the pulse (Fig. 18), the calculation was repeated using a segment of the beam near minimum focus. From the result in Fig. 22, a spot-size of 3.1 mm is obtained.

Figure 21. Cumulative X-ray energy distribution vs. transverse spatial coordinate obtained from MCNP for simulation in Fig. 18. (Courtesy of Mike George, M-4.)

The second method of computing an effective spot-size makes use of the same particle table, but, instead of using MCNP, we obtain the dose for the i^{th} particle from the expression

$$d_i \propto q_i (\gamma_i - 1)^{2.8}$$

For the cases in Figs. 18 and 19, the conductivity does not become large enough to freeze in the currents. The net current, which obeys a diffusion equation, continues to increase until the beam current falls below the net current as shown in Fig. 20. This explains why the beam focal length in Figs. 18 and 19 continues to shorten during the pulse, instead of lengthening again as the current and voltage drop.

Figure 20. Beam current (a) and net current (b) for the simulation in Fig. 18. (Run AE5).

2.4 Comparison of Spot-Size Measurements with MCNP

For the ECTOR simulation in Fig. 18, we carried out a detailed analysis of the time-integrated spot-size using two methods. The position, charge and momentum of particles striking the target were written out to a table. In the first method, this data was input to the transport code MCNP,⁸ which then calculated the X-ray distribution

$$\alpha = \frac{3.49 \times 10^{15} (E/p)^6}{1 + 26.67 (E/p)^2 + 2242 (E/p)^4 + 691.6 (E/p)^6} \text{ s}^{-1} \quad (2)$$

where E is in units of 0.511 MV/cm, and p is in atmospheres. The inductive electric field on the beam axis is given by

$$E = \frac{1}{c} \frac{d\nu_n}{dt} \left(1 + 2 \ln \frac{r_{\text{wall}}}{r_b} \right) \quad (3)$$

where ν_n is Budker's parameter for the net beam current (I_{net} (kA)/17), r_{wall} is the wall radius, and r_b is the beam radius. For a beam with a linear rise in current, we find from the first term in Eq. (1) that the density of background electrons produced rises quadratically in time, and is equal to the beam density at

$$t \approx 2/\kappa pc$$

At 1.2 torr, this gives 0.44 ns. The number of background electrons continues to increase through direct impact and avalanching. The transport of these electrons is dominated by collisions with neutrals and ions, so that their behavior can be described by a conductivity σ . For $\nu_m \gg \omega_c$ where ν_m is the momentum-transfer (or 'collision') frequency and ω_c is the cyclotron frequency,

$$\sigma = \frac{n_e e^2}{m_e \nu_m} \text{ s}^{-1} \quad (4)$$

The beam electrons generate radial and axial electric fields which drive radial and axial currents given by σE_r and σE_z , respectively. One can show⁷ that when σ increases to the point where

$$4\pi\sigma r_b/c > 1, \quad (5)$$

then the axial (return) current dominates. When avalanching is important, the conductivity, and consequently the magnetic decay time, $\tau_m = \pi\sigma r_b^2/c^2$, increase exponentially. For sufficiently large conductivity, the magnetic field becomes 'frozen in', i.e., the net current (beam current - return current) becomes fixed on the time-scale of the beam pulse. This causes the induced field (Eq. (3)) to drop to zero, and the avalanching shuts off.

Figure 19. Beam RMS radius vs. z at successive intervals of 8.3 ns in 1.2 Torr gas cell, for 1/2" ECTOR ball and 1.5 cm AK. Injected beam current is 23.5 kA at 3.5 MV. (Run AE14).

understand the time-variation of the beam radius, we need to look at how the neutral gas breaks down. This is discussed in the next subsection.

2.3 Gas Breakdown Model

Neglecting recombination, the density of electrons, n_e , produced by the beam is given by

$$\frac{dn_e}{dt} = \kappa p n_b c + \alpha(E/p) n_e \quad (1)$$

where κ is the direct-impact ionization coefficient, p is the gas pressure in atmospheres, n_b is the beam density, α is the avalanche ionization coefficient, and E is the electric field. Avalanche ionization results from acceleration of background electrons by the electric field, leading to a cascade of further ionizations. We use values for κ and α from the LLNL PHOENIX model:⁶

$$\kappa = 96.5 \text{ cm}^{-1} \text{ atm}^{-1}$$

Figure 17. ECTOR simulation at 3.5 MV with 1/2" ball diameter, 1.3 cm AK gap. Obtain 27.2 kA. (Run AE5).

Figure 18. Beam RMS radius vs. z at successive intervals of 8.3 ns in 1.2 Torr gas cell. Initial conditions are obtained from simulation in Fig. 17. (Run AE5).

conditions at the anode foil. For an AK gap of 1.3 cm, the gas cell results obtained from the IPROP simulation code are summarized in Table 6. The "Focus" column in the table is a qualitative characterization of where the beam focus is during the peak of the beam pulse.

TABLE 6. Gas-Cell Propagation Results for ECTOR and PIXY.

Machine	Ball	Emission Region	Current (kA)	Voltage (MV)	Focus
ECTOR	3/8"	front half	28	3.5	Near target (AE3)
ECTOR	1/2"	front 90%	27	3.5	Near target (AE5)
PIXY	3/8"	front half	36.8	3.5	Near target (AF1)
	1/2"	front half	44	3.5	Before target (AD3)
	1/2"	front half*	50.7	4.0	Before target (AJ3)

*shank shortened from 4.5 to 2 cm.

As noted in Ref. 1, the position of the beam focus is strongly affected by the 'initial conditions' at the anode foil. To make the beam more divergent at the foil than the cases looked at in Ref. 1, and thus move the focus downstream, one can

- a. lower the beam voltage,
- b. increase the AK gap,
- c. use a smaller ball diameter, or
- d. restrict emission to a smaller area of the ball.

For the ECTOR 1/2" ball with an AK gap of 1.3 cm, for example, it was necessary to restrict emission to the silver-painted region which covers about 90% of the front surface, in order to put the focus on the target. At present, we do not know whether this is a valid assumption for the actual device. The diode simulation is shown in Fig. 17, and the time-variation of the beam radius in the gas cell is shown in Fig. 18. When the AK gap is increased to 1.5 cm, the focus occurs on target later in the pulse, as shown in Fig. 19. To

Figure 16. Redesigned PIXY beam stopper to approximate the ECTOR geometry. Mogul-D geometry is shown dotted.

2.2 Gas Cell Propagation

In ECTOR and PIXY, a low-pressure (≈ 1 Torr) gas cell is used to focus the electron beam onto the X-ray conversion target. Some results for the ECTOR beam were reported last year in Ref. 1. In those calculations, the diode was simulated with ISIS and the cathode balls were allowed to emit over their entire surface. In all cases examined, the beam focused before the target, resulting in spot-sizes which are too large to agree with experiment. Since then, we have attempted to obtain better agreement. We have used the SPEED code,⁵ which handles the curved emitting surface much better than the stair-stepped approximation used in the ISIS simulations, to obtain more accurate beam

Figure 15. PIXY with shortened shank on the 1/2" emitting ball. Obtain 36.5 kA at 3.5 MV, close to the ECTOR result in Fig. 14.

Figure 14. Fine-grid simulation of ECTOR. Ball is $1/2''$ in diameter; AK gap is 1.3 cm. Obtain 33.8 kA at 3.5 MV. (Run AE2).

Figure 13. Fine-grid simulation of PIXY using fields from the simulation in Fig. 12. Ball is $1/2''$ in diameter; AK gap is 1.3 cm. Obtain 44.2 kA at 3.5 MV. (Run AD3).

Figure 12. Coarse-grid simulation of PIXY to obtain fields near the AK gap.

TABLE 5. Beam Emission Results for PIXY (Original Design) and ECTOR. Front Half of Ball Allowed to Emit. AK gap is 1.3 cm.

Ball Diameter	Beam Voltage (MV)	Beam Current (kA)	
		ECTOR	PIXY
1/2"	3.5	33.8	44.2
3/8"	3.5	28	36.8
1/2"	4.0	39.4	51.5
3/8"	4.0	32.8	49.0

Figure 11. Beam stopper and AK gap in ECTOR.

Figure 10. Beam stopper and AK gap in original PIXY design.

2.0 ECTOR AND PIXY CALCULATIONS

2.1 Effects of Geometric Differences in the ECTOR and PIXY Diodes

In designing the PIXY machine, emphasis was placed on suppressing beam emission from the front of the beam stopper (Fig. 10). The goal was to reduce the field stress on the beam stopper below 700 kV/cm at 8 MV. The design in Fig. 10 gives a peak stress of about 650 kV/cm on the beam stopper. This design differs from the ECTOR beam stopper which has a flat front surface (Fig. 11). The anodes on the two machines also differ substantially. Since radiographic measurements on PIXY gave larger spot-sizes than on ECTOR at comparable voltages, we carried out a series of calculations to determine the effect of these geometry differences.

Both PIXY and ECTOR have large vacuum regions and small AK gaps, so we carry out the diode simulations in two steps. First, a coarse-grid simulation is used to get fields in the neighborhood of the AK gap (see Fig. 12). These fields are then used to set the boundary conditions on a fine-scale simulation of the AK gap (see Fig. 13). Figures 13 and 14 show fine-scale simulations of PIXY and ECTOR for 1/2" diameter emission balls, and 1.3 cm AK gaps. Emission was restricted to the front half of the ball in each case. The main difference in the results is that PIXY emits more current than ECTOR because of the greater field stress at the edge of the ball. This is due to the long shank on the ball, and the sloping face of the beam stopper, which allow the equipotentials to stay closer to the ball surface than on ECTOR. For 3/8" diameter balls, the results are qualitatively similar. At the anode foil, the beam is less convergent for the 3/8" than for the 1/2" balls. Emission results are summarized in Table 5.

In order to make PIXY behave more like ECTOR, we found that it was necessary either to greatly shorten the shank on the emitting ball as shown in Fig. 15, or to make the beam stopper and anode more like those on ECTOR. With a redesigned beam stopper like that in Fig. 16, and a 1" protrusion from the anode with the same diameter as the ECTOR anode, the beam behavior in the AK gap in PIXY is almost identical to that in ECTOR.

1.5 Upgrade of LAMDA Transport Code

The following significant changes were made to the LAMDA beam transport code (in addition to many minor ones). A complete description of the new algorithms is given in a revised edition of the user's manual.³

1.5.1 Improved Accelerating Gap Model

The improved model is an extension to higher order of the treatment used by Chen and Reiser⁴ to calculate the transfer matrix of a short accelerating gap. The resulting matrix agrees well with a numerical integration. The matrix is applied to both the beam centroid and beam envelope. Both the Transfer-Matrix and Runge-Kutta schemes in LAMDA use the new model. During this work, we discovered several numerical errors in Ref. 4.

1.5.2 Treatment of Non-Relativistic Beams and Space-Charge in Transfer-Matrix Algorithm

The transfer-matrix option for advancing the beam in LAMDA was originally written to carry out approximate calculations, and therefore assumed $\beta = v/c \approx 1$.³ However, it has come to be used as the primary algorithm for simulating ITS experiments. The assumption $\beta = 1$ is not accurate enough for this, and so we have removed this restriction. Since space-charge depression is non-negligible in the ITS and DARHT, β can vary within an element as a result of changes in beam radius. As a result we have replaced the usual σ -matrix approach³ (used in E-TRACE, for example), since it does not allow for varying β .

TABLE 4. ITS Diode Output for 3.5" and 4" Diameter Cathodes.

Cathode Diameter (inches)	Voltage (MV)	Emitted Current (kA)	Downstream Current (kA)
3.5	3.48	3.7	3.4
	3.95	4.4	4.3
4.0	3.52	4.7	3.9
	3.97	5.5	4.9

Figure 9. Diode simulation of 4" diameter cathode at 4 MV. Cathode emits 5.5 kA, of which 4.9 kA remains after beam-scraping at the anode.

Figure 8. POISSON calculation of magnetic field of ITS cell magnet. Ferrite of neighboring magnet is included. Mirror symmetry is assumed on the right.

The calibration differences have a non-negligible effect on beam envelope calculations (cf. Fig. 3) and it would be desirable to clear them up.

1.4 Diode Simulations for Higher Current

For beam breakup instability experiments, it is desirable to have as large a beam current as possible. For the standard 20 cm gap and 3" diameter cathode, ISIS gives 3 kA at 3.4 MV.¹ To obtain larger currents, calculations were carried out for 3.5" and 4" cathodes at nominal voltages of 3.5 and 4 MV. Results are summarized in Table 4. In all cases, the beam scrapes the wall at the anode, as shown in Fig. 9.

Figure 7. Axial magnetic field profiles of ITS final-focus magnet from experiment and from BFIELD code.

which are used to reduce winding errors, since BFIELD cannot treat them. Both codes give a calibration of 3.03 gauss/Amp. In Fig. 6, we show POISSON results with and without the rings. This calculation is done in a smaller region than those in Fig. 5 in order to resolve the rings (POISSON input is given in Appendix A). As a result of boundary effects, the peak on-axis field is reduced. We see that the rings produce a small (0.2%) drop in the field. We conclude that the 3.03 gauss/Amp result in Fig. 5 is an accurate free-space value for the assumed geometry. In Fig. 7 we overplot the experimental result on the BFIELD result.

The cell magnets are identical to the final focus magnet, but the effect of the ferrite induction cores must be included in the field calculations. Using POISSON, we calculated the field using both a fixed permeability of $\mu = 500$, and POISSON's internal soft-iron table. Both methods give a value of 3.36 gauss/Amp. Next, we added the ferrite of a neighboring solenoid to the calculation, using the standard center-to-center spacing of 43.18 cm (see Fig. 8). This has a negligible effect on the calibration.

Figure 5. Axial magnetic field profiles of ITS final-focus magnet obtained from POISSON and BFIELD codes.

Figure 6. Axial magnetic field profiles of ITS final-focus magnet with and without soft-iron rings.

the simulation values out the end of the simulation at 250 cm. The results, converted to effective edge values, are in Table 2.

TABLE 2. Beam Envelope at 111 cm from Cathode for Milestone 5.

Magnet Excitation (Amps)	Beam Edge Radius a (cm)	da/dz (radians)
170	5.35	-0.034
175	4.95	-0.043

1.3 ITS Magnet Calibrations

There are discrepancies between the experimental and numerical calibrations in gauss/Amp for the peak magnetic field values in the anode, cell and final focus ITS magnets. The differences are shown in Table 3.

TABLE 3. Numerical vs. Experimental Calibrations for ITS Magnets.

Magnet	Turns	Numerical (gauss/Amp)	Experimental (gauss/Amp)	Difference
Anode	141	3.33	3.42	2.7%
Cell ($\mu = 500$)	93	3.36	3.52	4.8%
Final	93	3.03	3.19	5.2%

Figures 5-7 show results for the final-focus magnet. The geometry for this magnet is given in Appendix A. Figure 5 compares the two codes, POISSON and BFIELD. These codes use entirely different ways to compute the field, viz., POISSON solves Laplace's equation on a mesh in a bounded region while BFIELD sums up the analytic Biot-Savart results for free-space current loops. The calculations in Fig. 5 do not include the 6 soft-iron rings

Figure 4. Particle positions and $B_z(z)$ in diode region for Milestone 5 parameters. At 3.1 MV, obtain 3.55 kA off cathode and 3.3 kA downstream. Magnet excitation is 170 A.

Figure 3. Spot-size vs. final-focus magnet current at 50 cm from center of final-focus magnet. Curve (a) uses the experimental magnet calibration and (b) uses the numerical calibration.

Figure 2. Beam envelope calculation for Milestone 4. The axial magnetic field profile is overlain.

As shown in Fig. 2, the beam is allowed to expand to the drift-tube radius (≈ 7.5 cm) and is then focused onto a scintillator which is viewed by a streak camera. Figure 3 shows predicted and measured spot-sizes as functions of current in the final-focus solenoid. The experimental values are estimates of the beam edge radius from streak photographs. The two predicted curves arise from the fact that there are discrepancies between the experimental and calculated magnet calibrations (see Sec. 1.3). In any case, there is reasonably good agreement between theory and experiment. We have assumed a normalized Lapostolle emittance of 0.12 cm-rad in the envelope code.²

1.2 Diode Simulations for Milestone 5

In order to obtain linac entrance conditions for Milestone 5, we carried out diode simulations using IVORY. The standard 3" cathode was used with an AK gap of 15 cm. The experimental field calibration of 3.43 gauss/A was used to obtain the magnetic field strength. The result for an anode magnet excitation of 170 A is shown in Fig. 4. At 3.1 MV, we obtain 3.55 kA off the cathode surface, and 3.3 kA downstream of the anode scraping. Experimentally, 3 kA is measured downstream. To obtain the linac entrance conditions, we computed the beam rms radius at 111 cm from the cathode, which is in a low-field region downstream of the anode magnet. We then initialized an envelope code with this number, and adjusted the convergence angle so that the beam envelope matched

Figure 1. Schematic of ITS configuration showing injector, transport solenoids and final-focus magnet. The beam position monitors (BPM's) are labeled 1 to 5. For Milestones 4 and 5, the final-focus magnet was located further downstream than shown here.

1.0 ITS CALCULATIONS

1.1 Beam Transport for Milestone 4

The primary figure-of-merit for the ITS beam is the spot-size obtained in a 50 cm final-focusing distance. For Milestone 4 experiments in April 1992, the beam was transported through the first cell block without acceleration and brought to a focus at 730.3 cm from the cathode surface. A schematic is shown in Fig. 1. To model this configuration, we used ISIS to simulate the diode, and an envelope code to continue the beam transport to the final focus (see Ref. 1, p. 16). A sample envelope result is shown in Fig. 2. The key parameters are given in Table 1.

TABLE 1. Parameters for Beam Transport in Fig. 2.

AK gap	20 cm
Beam Current	3.35 kA
Beam Voltage	3.67 MV
Magnets currents:	
Anode magnet	180 A
Cell magnets 1-5	75 A
Cell magnets 6-8	0 A
Final focus magnet	280 A
Magnet positions:	
	Center (cm)
Bucking coil	-15.5
Anode magnet	55.85
Cell magnet 1	265
2	308.18
3	350.96
4	394.54
5	449.15
6	492.33
7	535.51
8	578.69
Final magnet	680.30

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Mike George carried out the MCNP calculations in Section 2.4.

DISCLAIMER

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SUMMARY

This report describes calculations carried out in the past year to assist in the design and understanding of experiments on the ITS, ECTOR, PIXY and PHERMEX machines at LANL. The main results are summarized as follows.

ITS: Transport calculations were carried out for Milestone 4, modeling the beam all the way from the cathode surface to the target, and gave good agreement with measurements. The LAMDA transport code was upgraded to compute the focusing effect of the accelerating gaps more accurately, and to remove some approximations in the treatment of space-charge. The code is currently being used in the analysis of the Milestone 5 BBU experiments.

ECTOR and PIXY: Beam focusing in the gas cell was studied in detail. The focal length was found to progressively shorten during the pulse. As a result, the minimum spot-size was significantly smaller than the time-averaged value. One may be able to exploit this using shaped converters. The beam distribution at the converter was used as input for the MCNP radiation transport code to obtain a radiographic spot-size. The result agrees reasonably well with experimental data from ECTOR.

PHERMEX: The new diode using a flat cathode has almost triple the perveance (current/voltage^{3/2}) of the old Pierce diode. The current is somewhat lower than that originally predicted by simulation because the cathode has a small inset from the surrounding electrode. When this effect is included, the calculated current agrees quite well with the experiment.

APPENDIX A GEOMETRY OF ITS FINAL FOCUS MAGNET

Windings (93 turns):

Inner radius	9.47 cm
Outer radius	10.82 cm
Length	32.77 cm

Iron rings (6 equally spaced):

Inner radius	9.11 cm
Outer radius	9.74 cm
Length	0.635 cm

POISSON input for final focus magnet without iron rings. (Large region (160 cm axial by 130 cm radial) used to approximate free space.)

```
cell magnet without iron (double size)
$reg nreg=2,dx=0.5,xmin=0.,xmax=80.,ymax=130.,ymin=0.,npoint=5,
$
$po x=0.,y=0.$
$po x=0.,y=130.0$
$po x=80.,y=130.0$
$po x=80.,y=0.$
$po x=0.,y=0.$
$reg mat=1,cur=7000.0,npoint=5$
$po x= 9.471 ,y= 0 $
$po x= 10.817 ,y= 0 $
$po x= 10.817 ,y= 16.383 $
$po x= 9.471 ,y= 16.383 $
$po x= 9.471 ,y= 0 $
```

POISSON input deck for final focus magnet with iron rings. (Region size reduced to 80 cm (axial) by 65 cm (radial) in order to resolve rings.)

```
cell magnet with iron
$reg nreg=6,dx=0.175,xmin=0.,xmax=40.,ymax=65.,ymin=0.,npoint=5,
yreg1=50.,lreg1=250,
lmax=325,xreg1=12.0$
$po x=0.,y=0.$
```

```

$po x=0.,y=65.0$
$po x=40.,y=65.0$
$po x=40.,y=0.$
$po x=0.,y=0.$
$reg mat=1,cur=7000.0,npoint=5$
$po x= 9.471 .y= 0 $
$po x= 10.817 .y= 0 $
$po x= 10.817 .y= 16.383 $
$po x= 9.471 .y= 16.383 $
$po x= 9.471 .y= 0 $
$reg mat=1,itr=1,npoint=5$
$po x=0.,y=16.383$
$po x=0.,y=65.0$
$po x=40.,y=65.0$
$po x=40.,y=16.383$
$po x=0.,y=16.383$
$reg mat=2,npoint=5$
$po x= 8.476 .y= 2.9211 $
$po x= 9.111 .y= 2.9211 $
$po x= 9.111 .y= 3.5561 $
$po x= 8.476 .y= 3.5561 $
$po x= 8.476 .y= 2.9211 $
$reg mat=2,npoint=5$
$po x= 8.476 .y= 9.3983 $
$po x= 9.111 .y= 9.3983 $
$po x= 9.111 .y= 10.0333 $
$po x= 8.476 .y= 10.0333 $
$po x= 8.476 .y= 9.3983 $
$reg mat=2,npoint=5$
$po x= 8.476 .y= 15.8755 $
$po x= 9.111 .y= 15.8755 $
$po x= 9.111 .y= 16.5105 $
$po x= 8.476 .y= 16.5105 $
$po x= 8.476 .y= 15.8755 $

```

(Note: above files are on CFS at /rex/poisson/maglib)

APPENDIX B POISSON INPUT FOR ITS CELL MAGNET WITH FERRITE CORES

The eighth region here is the ferrite of the neighboring magnet in a cell block.

(Note: this file is on CFS at /rex/poisson/modellib)

```

cell magnet with iron rings and ferrite (93 turns)
$reg nreg=8,dx=0.175,xmin=0.,xmax=40.,ymax=65.,ymin=0.,npoint=5,
yreg1=50.,lreg1=250,
lmax=325,xreg1=12.0$
$po x=0.,y=0.$
$po x=0.,y=65.0$
$po x=40.,y=65.0$
$po x=40.,y=0.$
$po x=0.,y=0.$
$reg mat=1,cur=7000.0,npoint=5$
$po x= 9.471 ,y= 0 $
$po x= 10.817 ,y= 0 $
$po x= 10.817 ,y= 16.383 $
$po x= 9.471 ,y= 16.383 $
$po x= 9.471 ,y= 0 $
$reg mat=1,itri=1,npoint=5$
$po x=0.,y=16.383$
$po x=0.,y=65.0$
$po x=40.,y=65.0$
$po x=40.,y=16.383$
$po x=0.,y=16.383$
$reg mat=2,npoint=5$
$po x= 8.476 ,y= 2.9211 $
$po x= 9.111 ,y= 2.9211 $
$po x= 9.111 ,y= 3.5561 $
$po x= 8.476 ,y= 3.5561 $
$po x= 8.476 ,y= 2.9211 $
$reg mat=2,npoint=5$
$po x= 8.476 ,y= 9.3983 $
$po x= 9.111 ,y= 9.3983 $
$po x= 9.111 ,y= 10.0333 $
$po x= 8.476 ,y= 10.0333 $
$po x= 8.476 ,y= 9.3983 $
$reg mat=2,npoint=5$
$po x= 8.476 ,y= 15.8755 $

```

```

$po x= 9.111 .y= 15.8755 $
$po x= 9.111 .y= 16.5105 $
$po x= 8.476 .y= 16.5105 $
$po x= 8.476 .y= 15.8755 $
$reg mat=2,npoint=5$
$po x= 11.59 .y= 0.0 $
$po x= 25.22 .y= 0.0 $
$po x= 25.22 .y= 14.85 $
$po x= 11.59 .y= 14.85 $
$po x= 11.59 .y= 0.0 $
$reg mat=2,npoint=5$
$po x= 11.59 .y= 28.33 $
$po x= 25.22 .y= 28.33 $
$po x= 25.22 .y= 58.03 $
$po x= 11.59 .y= 58.03 $
$po x= 11.59 .y= 28.33 $

```


APPENDIX C

PHERMEX IRON-CORE MAGNETS

The PHERMEX iron-core magnets have 6 coils, with 900 turns each, driven in parallel.¹¹

POISSON input for centered magnet:

centered phermex magnet

\$reg nreg=3,dx=0.5,xmin=0.,xmax=100.,ymax=117.04,ymin=0.,npoint=5,
yreg1=40.4,yreg2=72.67,lreg1=40,lreg2=104,lmax=130,

xreg1=22.6\$

\$po x=0.,y=0.0\$

\$po x=0.,y=117.04\$

\$po x=100.,y=117.04\$

\$po x=100.,y=0.0\$

\$po x=0.,y=0.0\$

\$reg mat=1,cur=20000.,npoint=5\$

\$po x=12.9,y=46.47\$

\$po x=12.9,y=70.57\$

\$po x=21.4,y=70.57\$

\$po x=21.4,y=46.47\$

\$po x=12.9,y=46.47\$

\$reg mat=2,npoint=21\$

\$po x=11.1,y=44.4\$

\$po x= 11.1,y=55.52\$

\$po x= 10.1,y=56.52\$

\$po x= 10.1,y=57.32\$

\$po x= 11.767,y=57.32\$

\$po x= 12.086,y=57.\$

\$po x= 12.7,y=57.0\$

\$po x= 12.7,y=46.47\$

\$po x= 21.4,y=46.47\$

\$po x= 21.4,y=70.57\$

\$po x= 12.7,y=70.57\$

\$po x= 12.7,y=60.04\$

\$po x= 12.086,y=60.04\$

\$po x= 11.767,y=59.72\$

\$po x= 10.1,y=59.72\$

\$po x= 10.1,y=60.52\$

\$po x= 11.1,y=61.52\$

\$po x= 11.1,y=72.67\$

\$po x= 22.6,y=72.67\$

\$po x= 22.6,y=44.4\$

\$po x= 11.1,y=44.4\$

POISSON input for off-centered pole:

off-center phermex magnet

\$reg nreg=3,dx=0.5,xmax=100.,ymax=148.,ymin=45.,npoint=5,

yreg1=90.63,yreg2=118.9,lreg1=45,lreg2=102,lmax=169,

xreg1=22.5\$

\$po x=0.,y=45.\$

\$po x=100.,y=45.\$

\$po x=100.,y=148.\$

\$po x=0.,y=148.\$

\$po x=0.,y=45.\$

\$reg mat=1,cur=20000.,npoint=5\$

\$po x=12.9,y=116.8\$

\$po x=21.3,y=116.8\$

\$po x=21.3,y=92.7\$

\$po x=12.9,y=92.7\$

\$po x=12.9,y=116.8\$

\$reg mat=2,npoint=21\$

\$po x=10.,y=97.7\$

\$po x=10.,y=98.5\$

\$po x=11.,y=99.5\$

\$po x=11.,y=118.9\$

\$po x=22.5,y=118.9\$

\$po x=22.5,y=90.63\$

\$po x=11.,y=90.63\$

\$po x=11.,y=93.5\$

\$po x=10.,y=94.5\$

\$po x=10.,y=95.3\$

\$po x=11.667,y=95.3\$

\$po x=11.986,y=94.98\$

\$po x=12.6,y=94.98\$

\$po x=12.6,y=92.7\$

\$po x=21.3,y=92.7\$

\$po x=21.3,y=116.8\$

\$po x=12.6,y=116.8\$

\$po x=12.6,y=98.02\$

\$po x=11.986,y=98.02\$

\$po x=11.667,y=97.7\$

\$po x=10.,y=97.7\$

(Note: above files are on CFS at /phermex/at)