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HIGH-CURRENT BEAM TRANSPORT
IN THE FXR INJECTOR

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1.0 INTRODUCTION

The FXR injector is designed to generate a nominal 4-kA, 1.5-MeV electron beam which represents the central portion of a 15-20 kA beam emitted from the cold cathode [Ref. 1]. Because of difficulties in reaching the 4-kA level repeatably and with good beam quality during the early running-in experiments, it was decided at that time (Nov. 1981) to develop an accelerator tune based on a 2.5-kA injected beam that was better behaved. This beam adequately satisfied the overall design requirements for FXR, with 500 Roentgen of bremsstrahlung produced at 1 meter from the target, and with a radiographic spot size of 3-5 mm. More recently, we have begun to develop a 4-kA tune. During preliminary tests carried out in September and October, 1982, we found that in order to extract a 3.8-kA, 1.65-MeV injector beam, the earlier, axial-magnetic-field profile had to be modified and strengthened considerably, and the observed quality (pulse shape) of the emerging beam was not as good as before. This note will describe the modeling effort that was carried out to explain these results.

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2.0 INJECTOR GEOMETRY

The diode region of the FXR injector is shown in Fig. 1.

The electron source is a nearly planar, cold-cathode diode. The active cathode surface is an 88 mm diameter, slightly convex button that is formed by winding 0.03 mm thick, tantalum ribbon into a tight spiral of some 40 turns. The planar anode is formed by 24 line/cm, etched-tungsten mesh. Immediately behind the anode mesh is a graphite-faced, water-cooled, demountable collimator where the aperture limits the beam passage into the hollow anode stem.

During our measurements, a collimator aperture of 38 mm was used, identical to the diameter of the anode tunnel (drift tube). The anode-cathode (A-K) spacing was changed by moving the cathode stem axially, thus leaving the anode mesh at a constant reference position (4.75 cm in the code runs).

The free parameters for optimizing the beam transport through the diode region and the anode stem are the A-K spacing, the diode voltage, and the axial magnetic field profile. The latter is generated from a set of four solenoids (I15 - I17 in Fig. 1).

Fig. 1: The diode region of the FXR injector

3.0 CODE SIMULATION

The EBQ code follows high current beam particles in axially symmetric geometries, subject to external electric and magnetic fields. Unlike the code TRANSPORT, EBQ accommodates the high degree of cancellation between the self-magnetic and the space charge forces that occurs in very high current relativistic beams [Refs. 2, 3]. This is particularly important for modeling beam generation and transport in high current diode regions.

During the FXR injector design, EBQ had been put to intensive use primarily in modeling the diode region, with less emphasis placed on continuing the model into the anode tunnel and beyond. The purpose of the present modeling effort was twofold. First, for TRANSPORT code runs used in developing the overall machine tunes, we heretofore had to guess at the beam radius, the beam energy after space charge potential depression, and the beam emittance at the point of origin, somewhere beyond the anode mesh. An easily used model was therefore needed that could follow the beam into the anode tunnel to a waist point, and read out the radius, the potential, and the emittance as input to a TRANSPORT deck. Secondly, the initial attempts to experimentally produce higher current levels out of the injector had been more difficult than expected, and we had begun to suspect serious beam optics problems having to do with the higher emitted currents. The more complete code model now allows us to make a direct comparison between the beam optics at different current levels.

Considerable effort was spent in developing an input deck for EBQ that would transport the collimated beam for some distance beyond the anode mesh, without provoking code instabilities. EBQ models the self-magnetic force and the space charge force in alternate steps of the iterative calculation, and hence, for certain situations, this code is prone to instability, such as the beam collapsing to a very small waist and then blowing up. Several consultations with A. Paul, the author of the code, were invaluable in eliminating these problems. The input deck for an A-K spacing of 4.25 cm is reproduced in Appendix A. A typical runtime on a CDC7600 is 4-5 minutes.

4.0 CODE AND EXPERIMENTAL RESULTS

The approach used to increase the injector current was to raise the diode voltage, to decrease the A-K gap spacing, or to do both. Shot No. 7263, at A-K = 4.25 cm and V = 1.5 MV, serves as a reference example for good beam formation and transport. This shot produced 600 R of measured X ray dose one meter from the bremsstrahlung target, with 16.0 kA emitted, 2.8 kA collimated, and 2.1 kA current on target. Figures 2 and 3 show the pulse shapes for the injected and the on-target currents. Note that the currents quoted here are peak currents; the diode current reaches its maximum at the end of the applied, 90 ns long voltage pulse, in part because of progressive plasma closure of the diode gap.

The beam envelope was modeled for the above Shot No. 7263 and for two other shots, i.e., No. 7662 (A-K = 4.25 cm, V = 1.65 MV) and No. 8053 (A-K = 3.75 cm, V = 1.65 MV). The empirically, derived magnetic field settings for the four injector solenoids were duplicated in the modeling runs. As the EBQ code is limited to 6000 mesh points per run, the problem was segmented into four parts, beginning with the diode region and passing the beam from one segment to the next by using the ray and potential storage options offered by the code. In order to prevent potential errors due to the absence of space charge beyond the right-hand boundary of each run, the origin for the succeeding run was backstepped to a point well inside this boundary. (This precaution is not actually necessary at the anode mesh which is inherently a fixed, equipotential surface.) The ray trace plots for all three cases are shown in Figs. 4, 5, and 6, and the numerical results are summarized in Table I.

The anode mesh forces a constant potential across the beam and hence cancels locally the space charge force that would normally act to balance the self-magnetic (pinching) force and the external magnetic field force. As a result, the beam focuses down to a waist within a few inches from the anode mesh. The external magnetic field is dominated by solenoid II7, increasing to the right, and the minimum and maximum field values are listed on each graph. The external B field has very little effect on the beam trajectory near the anode mesh, however.

As can be seen from Table I, the calculated values of emitted and collimated current are generally 10-20% smaller than the peak measured values. In part, this can be explained by plasma closure of the A-K gap. Assuming a 2 cm/usec expansion velocity of the cathode flare [Ref. 3] during the 80 ns flat-topped portion of the applied, diode voltage pulse, one can account for an 8% increase in emitted current density, using the Child-Langmuir relation.

Only for Shot 8053 was the measured, collimated current lower than the calculated value, probably due to beam interception in the drift region beyond the anode mesh. This was investigated further, using the TRANSPORT code to model the beam. Computationally, it is convenient to use a waist point as the

origin from which to start a TRANSPORT code run, and this was done for Shots 7263 and 8053. The results were inconclusive, as in both cases there appeared to be a less than optimal match of the calculated beam phase space and the experimentally optimized, axial field profile, leading to a fair amount of scalloping. However, as it is straightforward to improve the simulated match by changing the field, the required direction and the amount of such changes serve as a useful guide in further experimental tuning operations.

In earlier work, [Ref. 1], we had determined the emittance of the injected beam to be 18 mr-cm at 1.6 kA and 70 mr-cm at 3.4 kA. The calculated values are much lower, probably because they do not include off-energy electrons, such as occur in a measurement that is integrated over the entire length of the applied diode voltage pulse. However, from Table I, it is seen that the calculated emittance increases threefold as the current is raised from 2.8 to 3.8 kA, indicating some beam degradation apparently due only to the current increase. (The perturbing effect of the finite anode mesh size is not modeled here.)

The similarity of the calculated beam trajectories in Figs. 4-6 indicates that there should be no adverse changes in the basic beam optics due to the associated increase in current level. Any difficulties in extracting the higher-current beam from the injector and in transporting it further down the beam line, therefore, should respond to refinements in the axial magnetic field tune.

Fig. 2. Total emitted current, Shot #7263, 1.88 kA/div. vertical, 20 ns/div. horizontal.

Fig. 3. Current on target, Shot #7263, four quadrants of the resistive beam monitor, 1.08 kA/div. vertical, 20 ns/div. horizontal, with baselines added. The beam centroid is 1-2 mm off axis.

Fig. 4. Simulation of Shot No. 7263, A-K = 4.25 cm, V = 1.5 MV. The anode mesh is at z = 4.75 cm. Calculated current levels are 13.0 kA emitted, 2.44 kA collimated and transported to 22 cm beyond the anode mesh. The waist occurs at z = 19.75 cm, with a beam radius of 0.41 cm, a beam edge potential of 1.27 MeV, and a nominal emittance of 5.0 mr-cm. The waist position roughly coincides with the peak of the magnetic focusing field, B = 1308 Gauss, plotted in Deck 4.

Fig. 5. Simulation of Shot No. 7662, A-K = 4.25 cm, V = 1.65 MV. The anode mesh is at z = 4.75 cm. Calculated current levels are 14.8 kA emitted, 3.10 kA collimated and transported to 22 cm beyond the anode mesh. The waist (not shown) occurs at Z = 21.55 cm, with a beam radius of 0.42 cm, a beam edge potential of 1.36 MeV, and a nominal emittance of 6.9 mr-cm.

Fig. 6. Simulation of Shot 8053, A-K = 3.75 cm, V = 1.65 MV. The anode mesh is at 4.75 cm. Note the increased focusing field (400 less than B less than 2100 Gauss) in the drift tube region. Calculated current levels are 17.8 kA emitted, 4.27 kA collimated and transported to 22 cm beyond the anode mesh. The waist occurs at z = 16.75 cm, with a beam radius of 0.45 cm, a beam edge potential of 1.27 MeV, and a nominal emittance of 11.7 mr-cm.

Table 1. Predicted and measured results for three shots on the FXR injector

Shot No. and Date	A-K spacing	Diode voltage	B field excitation near diode	Emitted Current		Collimated Current		Calculated emittance at waist
				Calculated	Measured	Calculated	Measured	
7263 9 Sept. 82	4.25 cm	1.50 MV	-175 A	13.0 kA	16.0 kA	2.44 kA	2.81 kA	3.9 mr-cm
			240 A					
			190 A					
			200 A					
7662 5 Oct. 82	4.25 cm	1.65 MV	-175 A	14.8 kA	16.5 kA	3.10 kA	3.34 kA	6.9 mr-cm
			240 A					
			190 A					
			200 A					
8053 19 Oct. 82	3.75 cm	1.65 MV	-260 A	17.8 kA	18.8 kA	4.28 kA	3.76 kA*	11.7 mr-cm
			360 A					
			360 A					
			310 A					

*Suspect beam interception in anode tunnel.

5.0 CONCLUSION

Using the EBO code, a direct calculation was made of the beam envelopes corresponding to three different current levels in the FXR injector, using actual, experimental parameters. For collimated current levels between 2.4 and 4.3 kA, the calculated beam envelopes behave very similarly. The beam comes to a 8-9 mm diameter waist within a 12-15 cm distance from the anode mesh, and expands from there to a diameter that is controllable by the external magnetic field in that region. With the exception of the 4.3 kA case, the measured and calculated current values agree within 10-20%; for that latter case, some beam interception in the drift region probably is responsible for the abnormally low value of measured current (3.8 kA) at the injector output.

While the calculated emittance is small compared to values measured earlier, this emittance is observed to increase threefold as the current is raised from 2.4 to 4.3 kA, indicating some degradation of beam quality due solely to the higher current. However, the similarity of the calculated beam trajectories indicates that difficulties in extracting and transporting a higher-current beam should yield to simple refinements in the axial magnetic field tune.

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2. A. C. Paul, EBQ Code: Transport of space charge beams in axially symmetric devices, UCID-8005, University of California, Nov. 1978.
3. A. C. Paul, TRANSPORT, An Ion Optic Program, LBL Version, LBL-2697, University of California, (1975).
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Appendix A. Typical EBQ input deck (Shot 7263 simulation)

```

1 FXR INJECTOR AK=42.5MM SETPOT L17,58,59 SETB 3PL SETJULIM L42
2 TITLE :INJ425
3 MAP OFF
4 BOUNDARY
5 64 93 0 15.75 -2.65 6.55 $ .25 X .10 CM MESH SIZE 5952 CELLS
6 1 7.-2.65 1 7. -2.5 1 6.85 -1.9 1 6.5 -1.35
7 1 6. -.95 1 5.5 -.8 1 4.75 -.8 $---BF ELECTR
8 2 4.4 -.8 2 4. -.7 2 3.5 -.4 2 3. -.15 2 2.5 .05
9 2 2.0 .22 2 1.5 .34 2 1.0 .43 2 0.5 .48 2 0. 0.5 S $---CATHODE
10
11 STOP PLOT 3 1.9 4.75 3 4.3 4.75 3 5.05 5.05
12 3 5.5 5.35 3 5.82 5.8 3 5.82 5.85 3 5.82 6.55 S $---ANODE
13 4 0. 4.75 4 1.9 4.75 S $---ANODE MESH
14 5 1.9 4.75 5 1.9 6.55 S $---BEAM TUNNEL
15 6 15.75 -2.65 6 15 75 6.55 S $--- OUTER WALL
16 S
17 POT 0R2 1.5E6R3 1.0E6 S $---LIST POTENTIALS KEYED TO BOUND INDICES
18 COILGEN 2 0R2 2.0 $---CALC B FIELD TO 5.0 CM RADIUS
19 -2.65 6.55 0.2R2 $---0.2X0.2CM MESH
20 -175 240 190 200 S $---I15,16,17,18 EXCIT AMPS
21 $---LIST CURRENT LOOPS RMIN RMAX OR ZMIN ZMAX DZ
22 20.8 29.8 1. -6.8 -3.8 1. $---I15
23 10.5 19.5 1. 16 25 1. $---I16
24 8.2 9.2 1. 16 56 1. $---I17
25 13. 14. 1. 52.9 61.9 1. $---I18
26 CONST
27 *3 0 $---OMIT FIRST CYCLE GAUSS LAW CONTRIB TO FIELD
28 *14 0 $---SUPPRESS PRINTED BEAMLINE PLOTS
29 *16 10 $---DELTA V MIN ON POISS POT MESH
30 *17 300 $---MAX NO POISS CYCLES
31 *18 50 $GEN OUTPUT EVERY 50 POISS CYCLES
32 *22 5E-5 $---IAMP CHILDS LAW CONVERGENCE
33 *35 6.2 3.622 $---PLOT SCALES 0.394 IN PER CM
34 *37 10 $---PLOT PHASE SPACE DIAG
35 *44 01 $--- PLOT OF CUR DEN
36 *17 30 $---CURRENT RAYS + 30 EQUIPOT LINES
37 *2 10 $---10 ITERATIONS TO FIND EQUIP LINE
38 *71 0 $---NO ENVELOPE PLOT
39 S
40 LAPLACE
41 PLOT EQUIP S
42 RAYGEN 3 50 2 0.70 2.5E4 0 240 4.4
43 MOMENT 4.75 S $---SHOW EMITTANCE BEYOND ANODE MESH
44 PUNCHB 4.75 S $---STORE RAYS AT Z=4.75CM FILE1
45 PLOT TRAJ S $---PLOT ALL RAYS
46 TRACK X 9
47 ENDTRACK

```

```

48 PRINT DENSITY
49 END
50 $-----
51 TRANSPORT THROUGH DRIFT TUBE---DECK2
52 MAP OFF
53 BOUNDARY
54 96 26 0. 1.9 4.75 14.75 $---0.02X0.4CM MESH 2500CELLS
55 4 0. 4.75 4 1.9 4.75 S $---ANODE MESH
56 STOP PLOT 5 1.9 4.75 5 1.9 14.75 S $---BEAM TUNNEL
57 S $---END OF BOUNDARY DATA
58 POT 0R2 1.5E6R3 1.0E6 S $---LIST POTENTIALS KEYED TO BOUND INDICES
59 COILGEN 2 0R2 2.0 $---CALC B FIELD IO 5.0 CM RADIUS
60 4.75 14.75 0.2 0.4 $---0.2X0.4CM MESH ON BFIELD
61 -175 240 190 200 S $---I15,I6,I7,I8 EXCIT AMPS
62 $---LIST CURRENT LOOPS RMIN RMAX DR ZMIN ZMAX DZ
63 20.8 29.8 1. -6.8 -3.8 1. $---I15
64 10.5 19.5 1. 16 25 1. $---I16
65 8.2 9.2 1. 16 56 1. $---I17
66 13 16. 1. 52.9 61.9 1. $---I18
67 CONST
68 *22 0.001 $---LIM RADIUS ON POISSON ITER AT ZMAX
69 *30 1.5E6 $---INITIALIZE POT ARRAY IN FARADAY CAGE
70 *33 2 $---USE FILE2 FOR RAYSTORE
71 *35 0.748 3.937 $---PLOT SCALE 0.394 IN PER CM
72 *47 15 $---CURRENT RAYS + 15 EQUIPOT LINES
73 S
74 LAPLACE
75 PLOT EQUIP S
76 PRINT R FIELDS 10.75 0. 1.9 0.1
77 RAYS 8 1 $---READ FILE1 FOR RAY INPUT
78 DENSITY OFF $---SWITCH TO STD DEPOSITION
79 MOMENT 10.75 S $---ADDL. EMITTANCE READOUTS
80 PUNCHB 10.75 S ---STORE RAYS ON FILE2, AT Z=10.75CM
81 PLOT TRAJ S $---PLOT ALL RAYS
82 TRACK X 7
83 ENDTRACK
84 PRINT R FIELDS 10.75 0. 1.9 0.1
85 PRINT R FIELDS 14.75 0. 1.9 0.1
86 POT STORE R 10 105 10.75 0. 1.9 0.02 $---0.02CM STEPS
87 END
88 $-----
89 CONTINUE TRANSPORT THROUGH DRIFT TUBE---DECK 3
90 BOUNDARY
91 96 26 0. 1.9 10.75 20.75 $---0.02X0.4CM MESH 2496CELLS
92 STOP PLOT 5 1.9 10.75 5 1.9 20.75 S $---DRIFT TUBE
93 INCREMENT 10 105 $---CALL POT ARRAY
94 I 0. 10.75 105 1.9 10.75 S $---USE POT ARRAY
95 S $---END OF BOUNDARY DATA

```



```

96 PRINT R FIELDS 10.75 0. 1.9 0.1
97 LAPLACE
98 PLOT EQUIP S
99 COILGEN 2 0R2 2.0 $---CALC B FIELD TO 5.0 CM RADIUS
100 10.75 20.75 0.2 0.4 $---0.2X0.4CM MESH ON B FIELD
101 -175 240 190 200 S $---I15,16,17,18 EXCIT AMPS
102 $---LIST CURRENT LOOPS RMIN RMAX DR ZMIN ZMAX DZ
103 20.8 29.8 1. -6.8 -3.8 1. $---I15
104 10.5 19.5 1. 16 25 1. $---I16
105 8.2 9.2 1. 16 56 1. $---I17
106 13 16. 1. 52.9 61.9 1. $---I18
107 CONST
108 *3 1 $---RESTORE GAUSS LAW CONTRIB 1STCYCLE
109 *33 3 $---USE FILE3 FOR RAYSTORE
110 *50 0.5 $---ANTIPINCH
111 S
112 RAYS 8 2 $---READ FILE2 FOR RAY INPUT
113 PUNCHB 16.75 S $---STORE RAYS TAPE9 FILE3
114 MOMENT 12.75 14.75 16.75 18.75 S $---EMITTANCE READOUTS
115 PLOT TRAJ S
116 TRACK X 7
117 ENDTRACK
118 PRINT DENSITY
119 PRINT R FIELDS 12.75 0. 1.9 0.1
120 PRINT R FIELDS 14.75 0. 1.9 0.1
121 PRINT R FIELDS 16.75 0. 1.9 0.1
122 POT STORE R 110 205 16.75 0. 1.9 0.02 $---0.02CM STEPS
123 END
124 $-----
125 CONTINUE TRANSPORT THROUGH DRIFT TUBE---DECK4
126 BOUNDARY
127 96 26 0. 1.9 16.75 26.75 $---0.02X0.4CM MESH 2496CELLS
128 STOP PLOT 5 1.9 16.75 5 1.9 26.75 S $---DRIFT TUBE
129 INCREMENT 110 205 $---CALL POT ARRAY
130 1 0. 16.75 205 1.9 16.75 S $---USE POT ARRAY
131 S $---END OF BOUNDARY DATA
132 PRINT R FIELDS 16.75 0. 1.9 0.1
133 LAPLACE
134 PLOT EQUIP S
135 COILGEN 2 0R2 2.0 $---CALC B FIELD TO 5.0 CM RADIUS
136 16.75 26.75 0.2 0.4 $---0.2X0.4CM MESH ON B FIELD
137 -175 240 190 200 S $---I15,16,17,18 EXCIT AMPS
138 $---LIST CURRENT LOOPS RMIN RMAX DR ZMIN ZMAX DZ
139 20.8 29.8 1. -6.8 -3.8 1. $---I15
140 10.5 19.5 1. 16 25 1. $---I16
141 8.2 9.2 1. 16 56 1. $---I17
142 13 16. 1. 52.9 61.9 1. $---I18
143 CONST *50 1. S $---ANTIPINCH

```

144 RAYS 8 3 \$---READ FILE3 FOR RAY INPUT
145 MOMENT 18.75 20.75 22.75 24.75 S \$---EMITTANCE READOUTS
146 PLOT TRAJ S
147 TRACK X 7
148 ENDTRACK
149 PRINT DENSITY
150 PRINT R FIELDS 18.75 0. 1.9 0.1
151 PRINT R FIELDS 20.75 0. 1.9 0.1
152 PRINT R FIELDS 22.75 0. 1.9 0.1
153 END
154 END