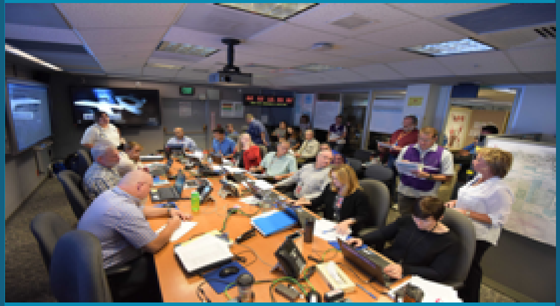
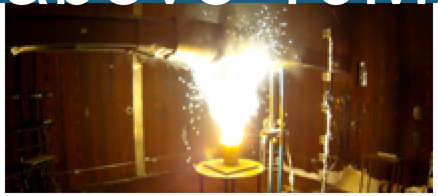
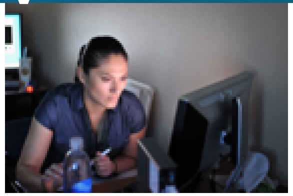
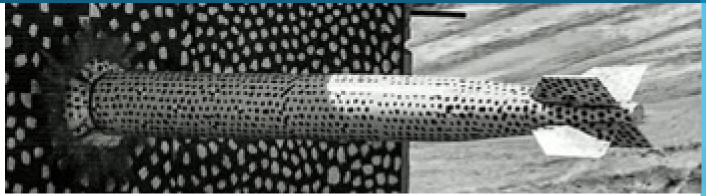
SAND2022-6784C

Secondary Ion Emission Modeling in a Planar Bremsstrahlung Diode operated above 10MV









Authors:

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- Planar Anode Diode
- Secondary Ions

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- 73cm Gap study

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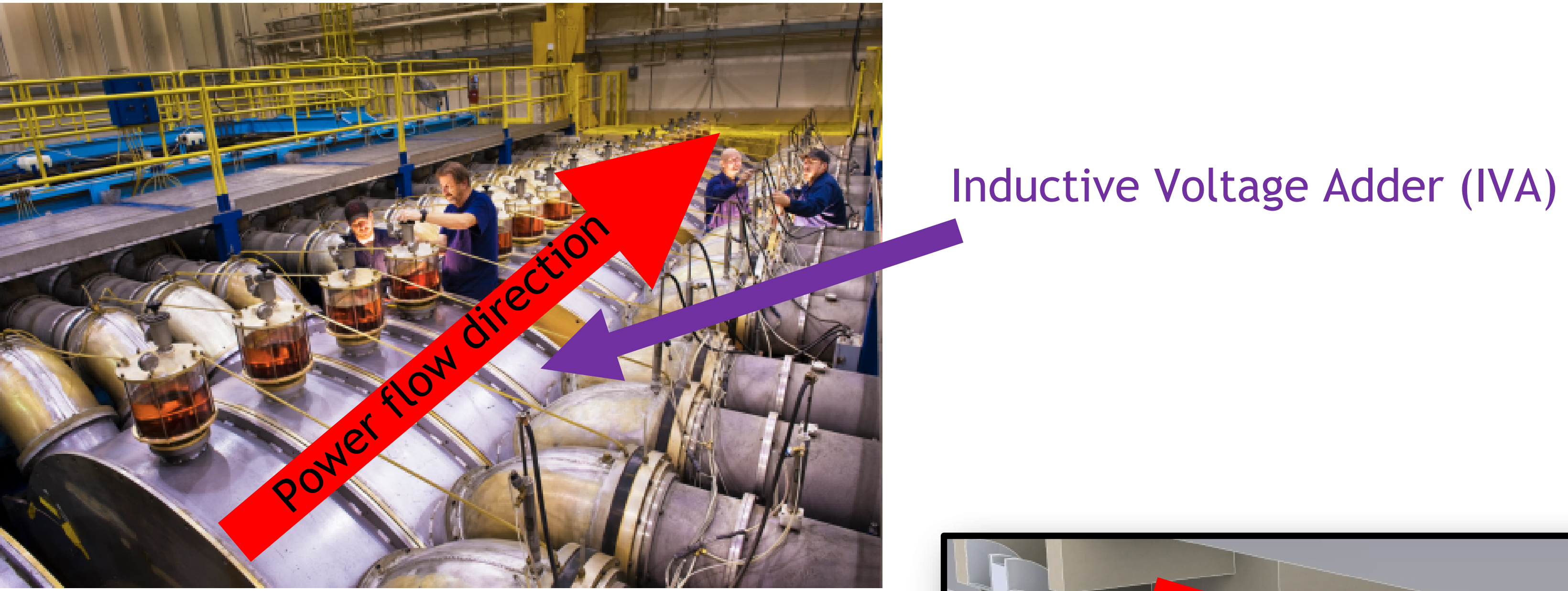
- 11027
- 11028

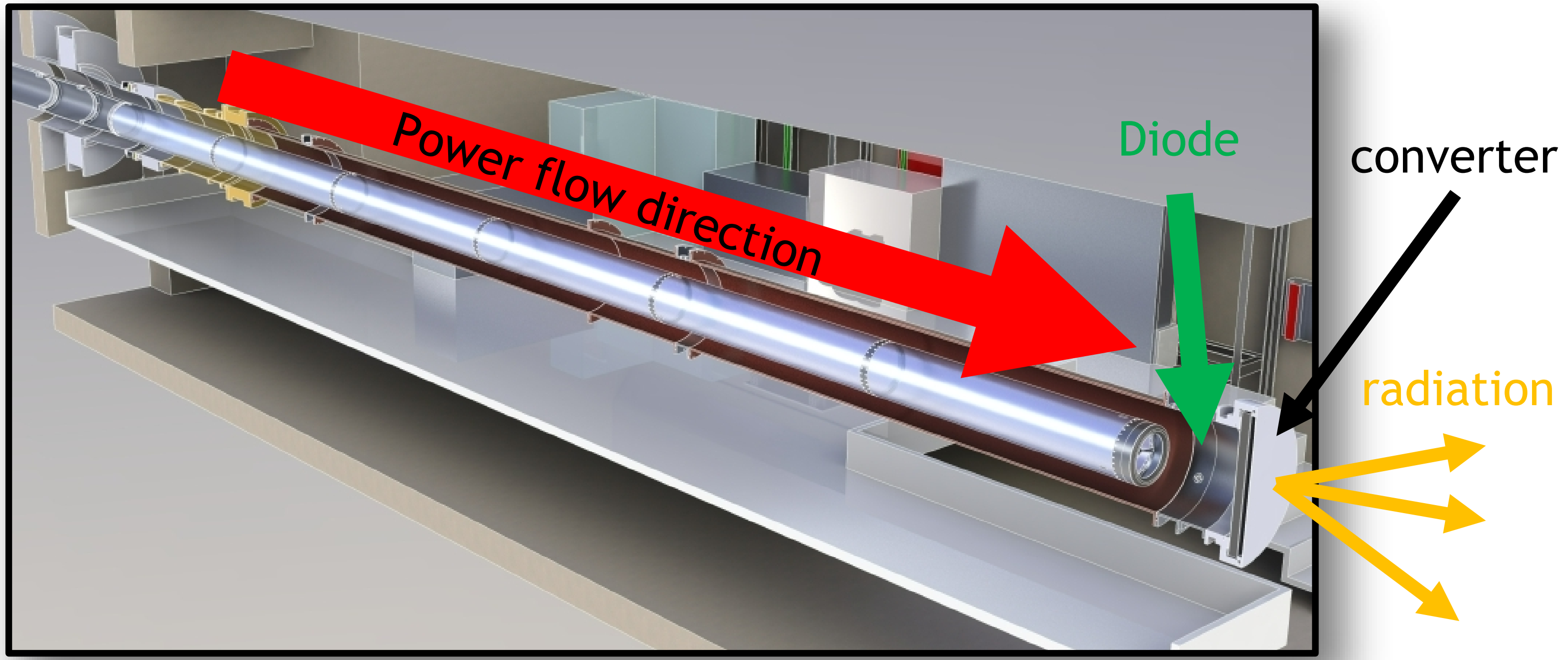
88cm gap study

Conclusions

Appendix

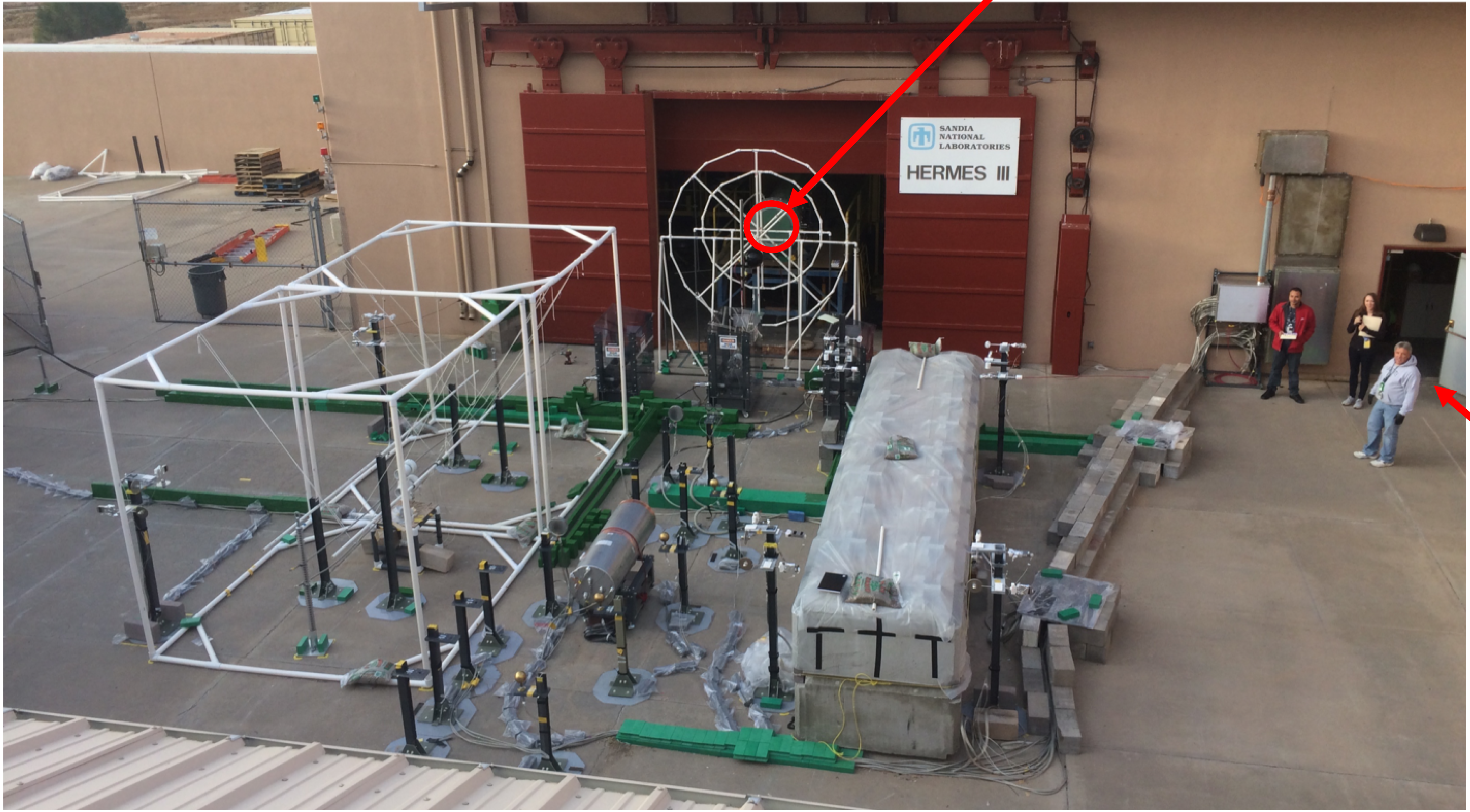
HERMES Power Flow





Application Space: HERMES-III Courtyard

converter



Tom
for scale

Bremsstrahlung Converters

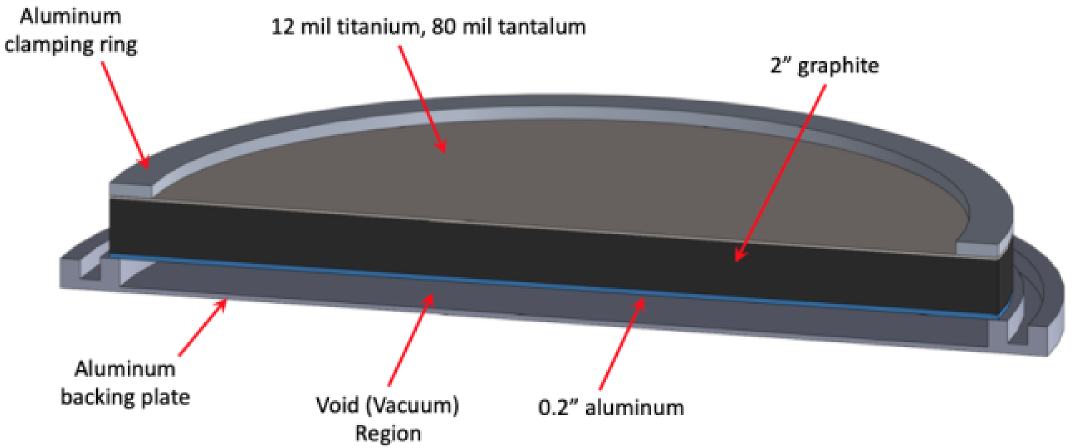
Convert electron beams into x-ray sources (γ-simulators)
- HERMES III (~18MV, 600kA)

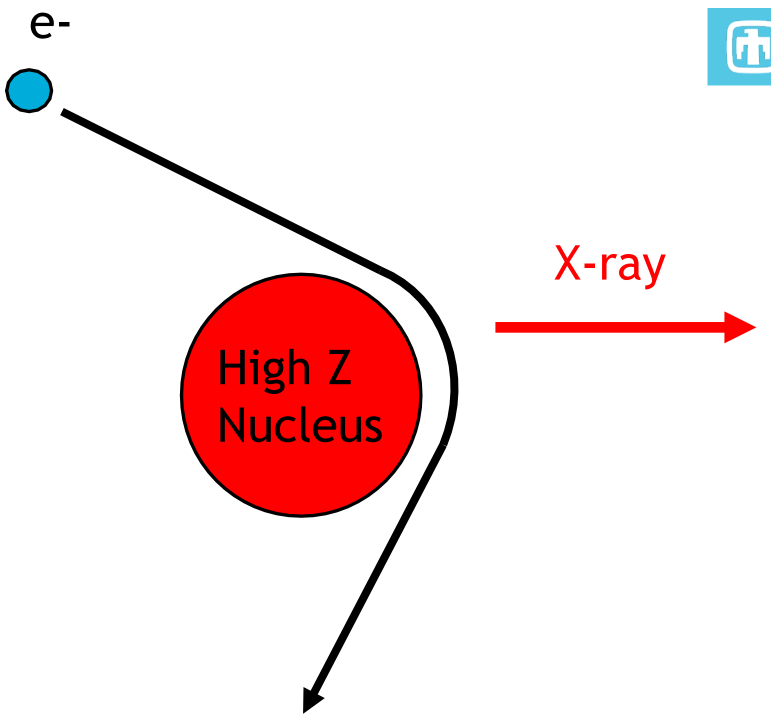
Tantalum converter (Z=73)

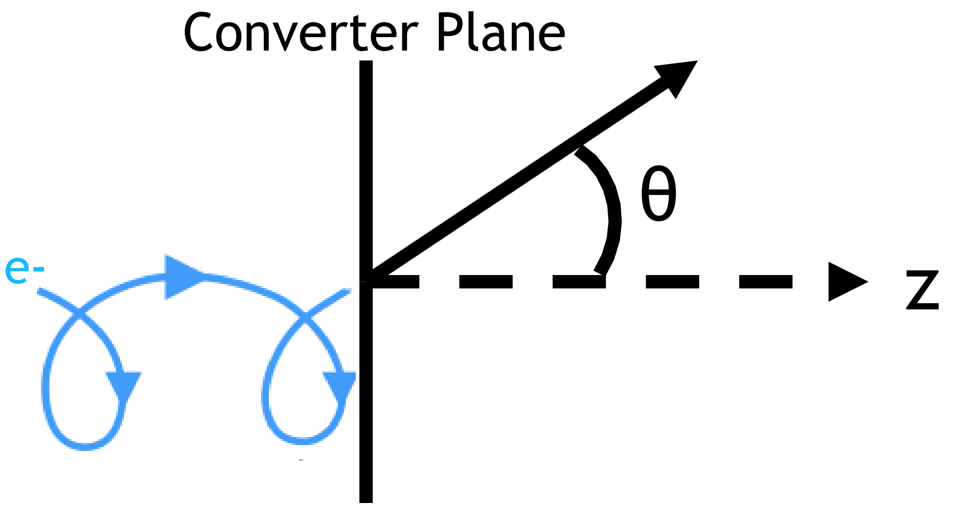
Interested in on-axis dose (D)

$D = cIV^x$; x = x(θ)~2 [1] $\frac{D}{Q} = (1.7 \times 10^3)V^{2.65}e^{-\theta V/2.1}$ [2]

Graphite beam stop
- Absorbs low energy electrons
- Hardens x-ray spectrum

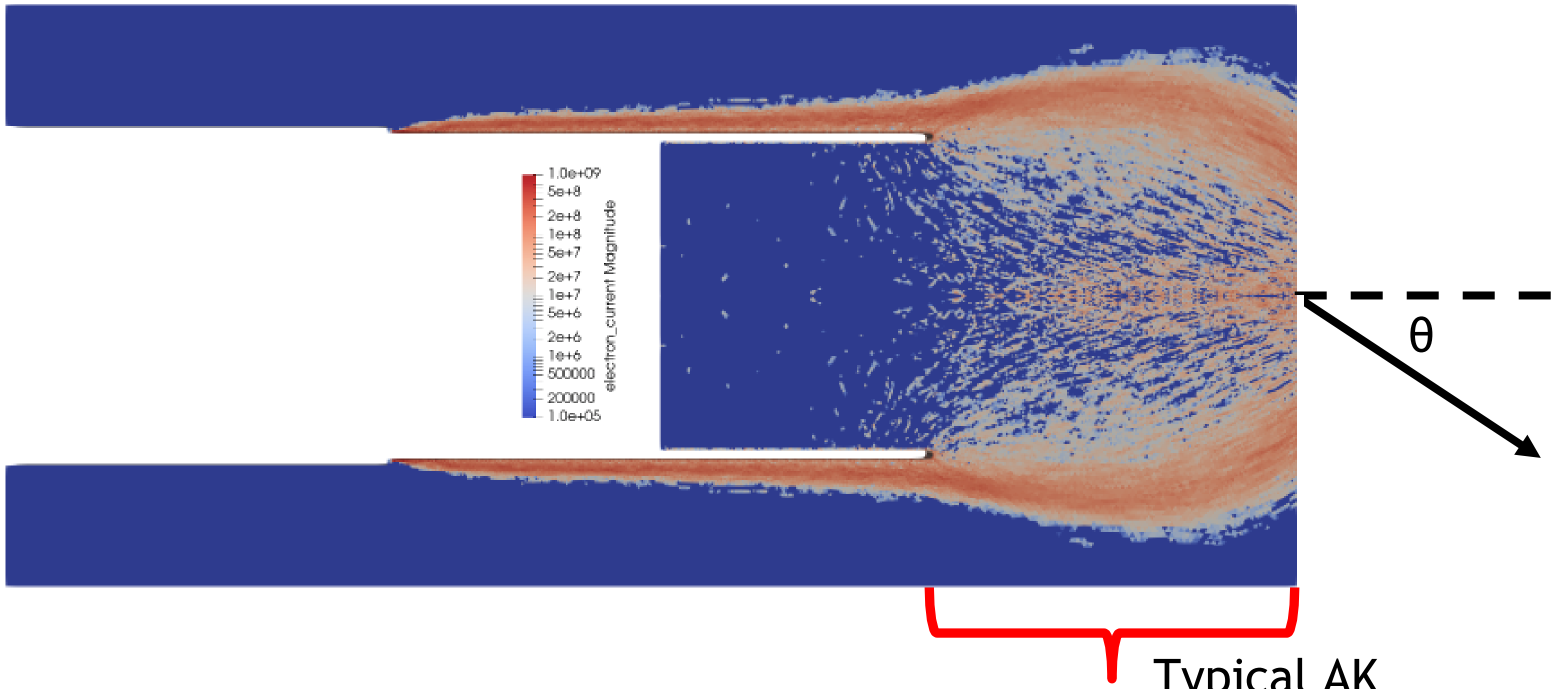


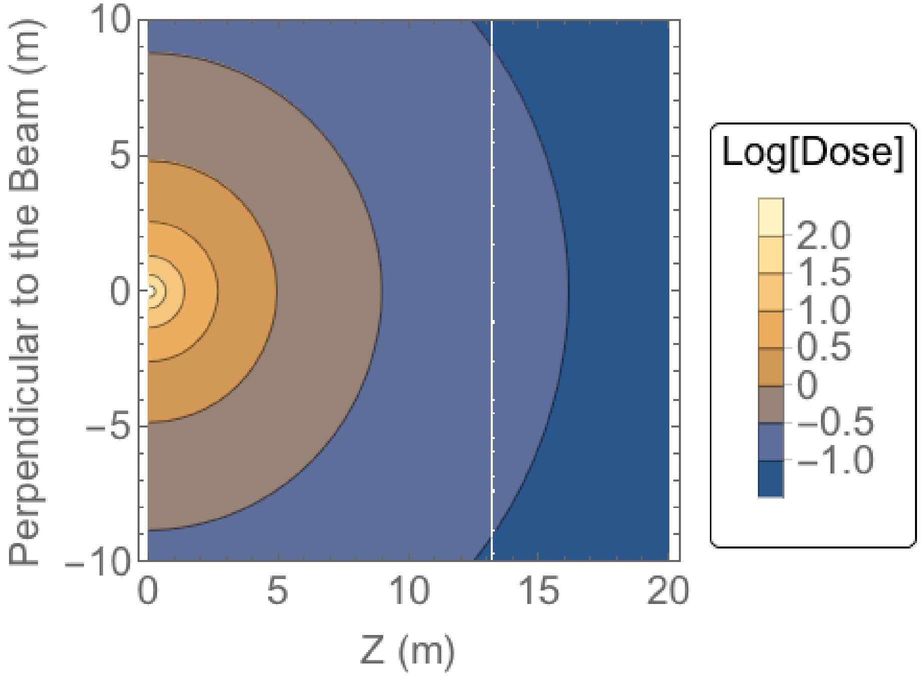




[1] – T. J. Renk, B. V. Weber, I. M. Rittersdorf, et al. Rev. Sci. Instrum. 90, 114709 (2019).
[2] - T.W.L. Sanford, D.E. Beutler, J.A. Halbleib, and D.P. Knott. "Experimental Verification of Bremsstrahlung Production and Dosimetry Predictions for 15.5 MeV Electrons". IEEE Transactions on Nuclear Science, 38(6):1160–1170, Dec 1991.

Dose From Bremsstrahlung Converters in High Current Diodes





Self-magnetic force causes e-beam pinching

Divergent x-ray beam causes poor downstream dose

Ideal performance is an x-ray “pencil beam”

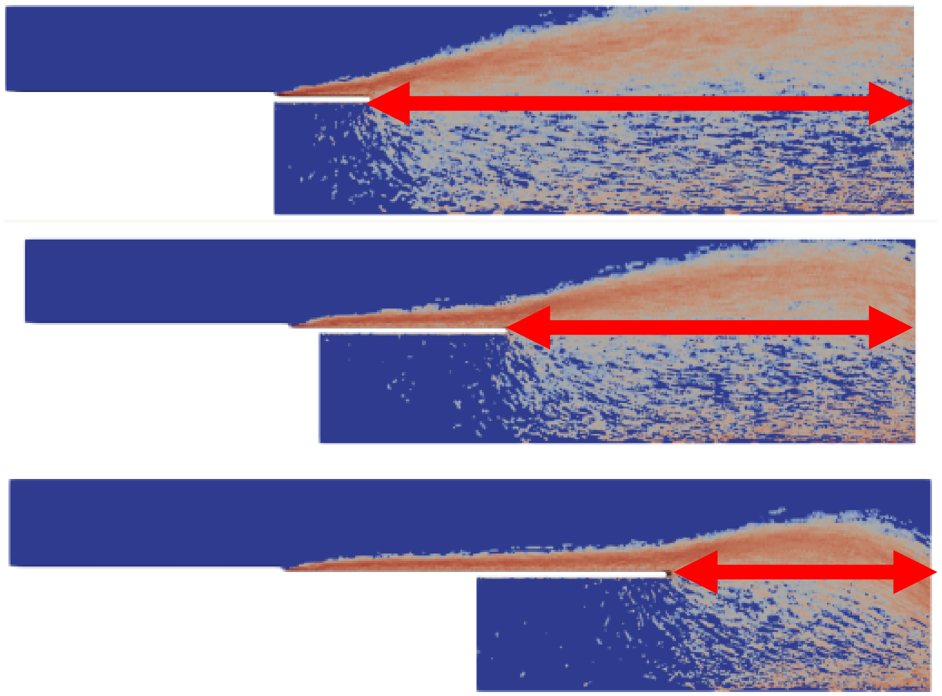
Planar Anode Geometry

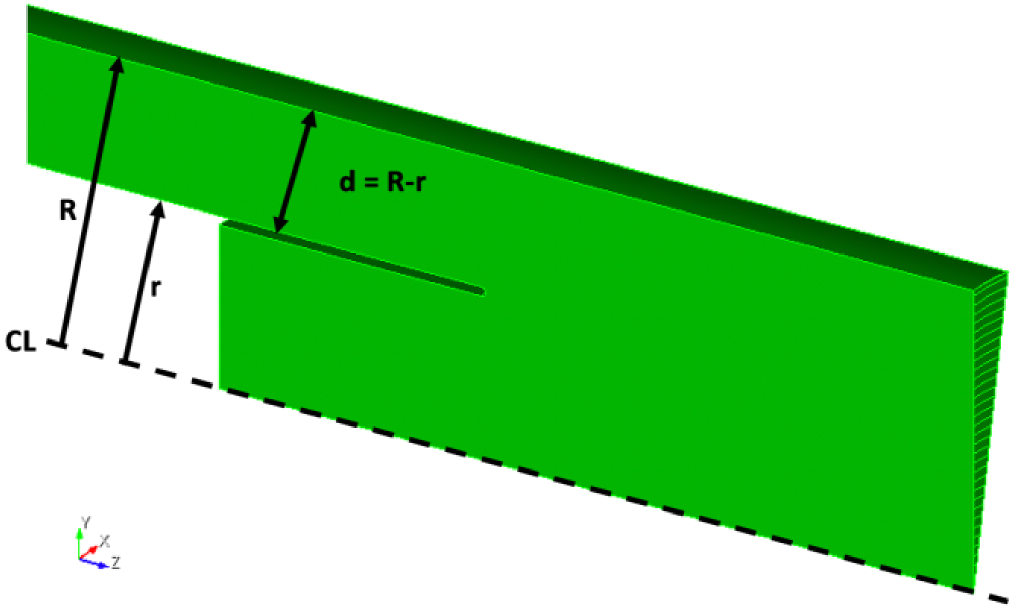
Planar diode:

- Line-dominated regime:
  - Diode impedance defaults to line impedance [3]
  - Current and AK gap determines pinch angles
- Load-dominated regime:
  - Operating impedance defaults to load impedance [3]
  - Low impedance (10Ω) yields high currents and high pinch angles
  - Low voltage yields low dose production (short-circuit reflections)

Coaxial Wedge in CUBIT:

- Annular cathode
- 1/50 sector
- Periodic Boundary Conditions
- Converter Radial Bins





[3] Sanford, et. al., Journal of Applied Physics, 63(3):681–688, 1988.

Secondary Ions

Electron bombardment the titanium anode surface liberates ions, generally in the form of H+[4]

Ions are emitted from converter surface with a selected yield fraction, f

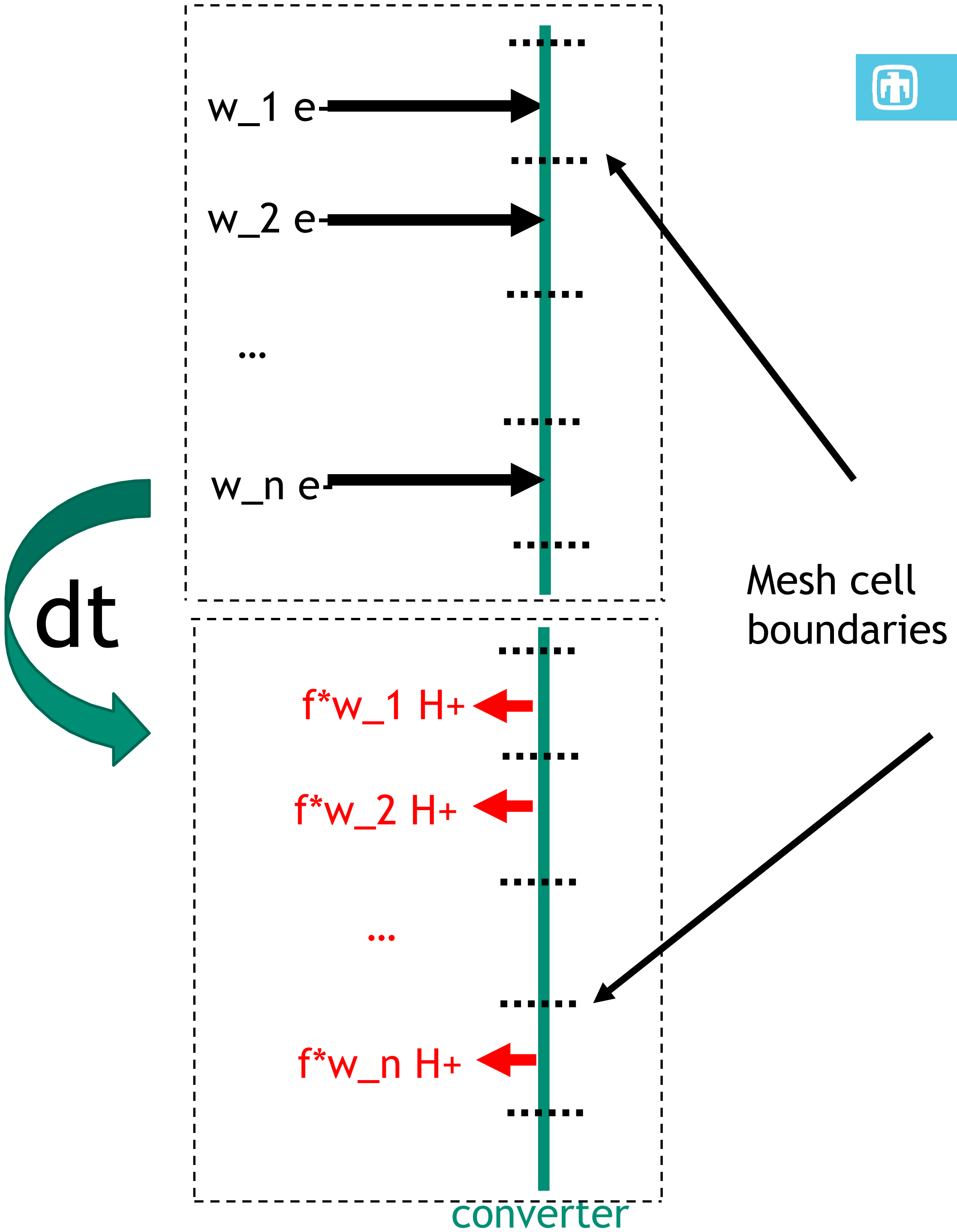
N_i = f * N_e

RHIC, CERN, and RITS see yields of roughly f = 0.02 – 0.05 [5-7]

Some reports give f ~ 10-15%, even as high as 31% [8]

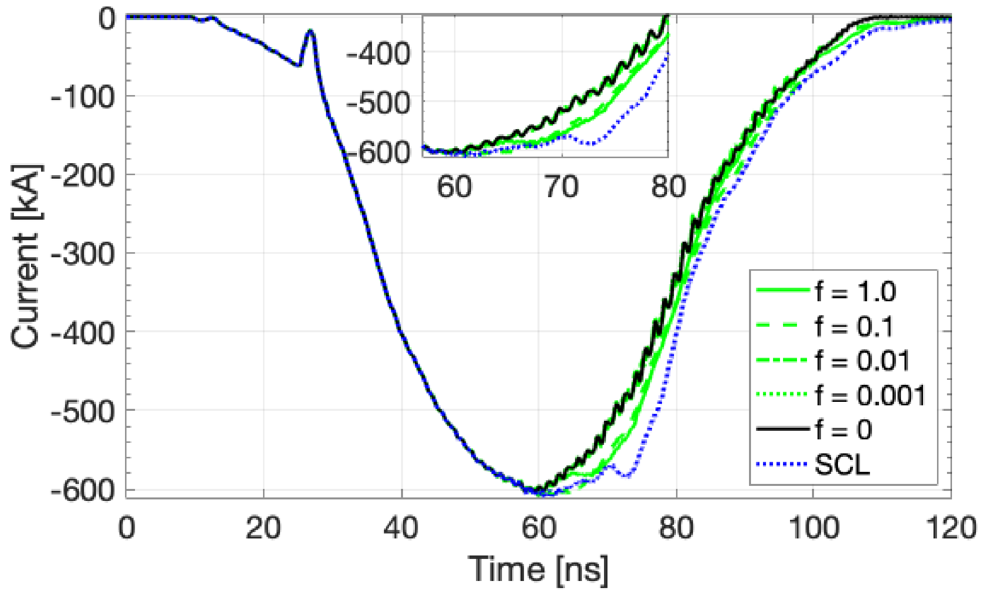
55cm gap runs: f = 0, 0.001, 0.01, 0.1, 1 and we include the upper bound of SCLe

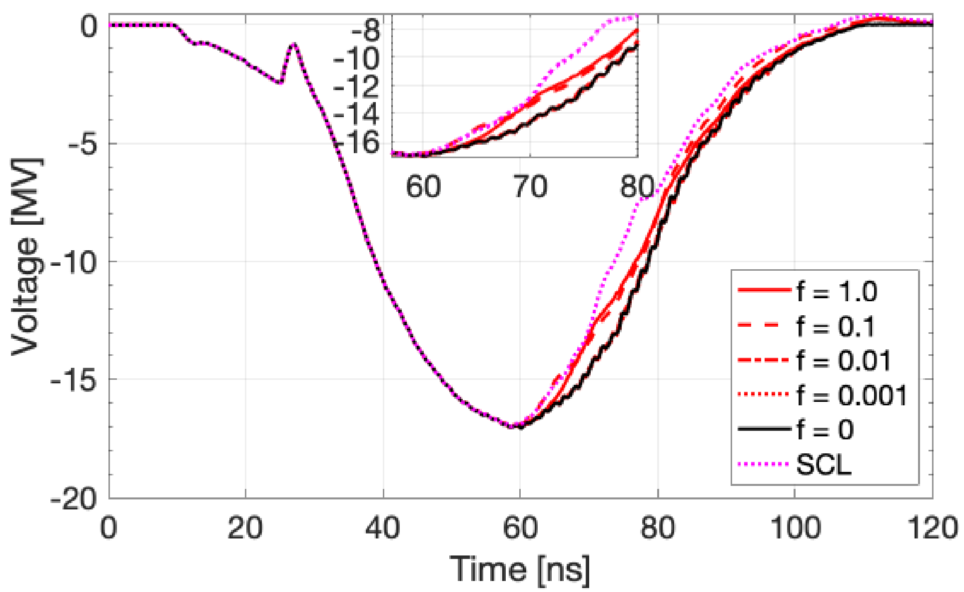
73+ AK gap runs: f = 0, 0.01, 0.02, 0.05, 0.1

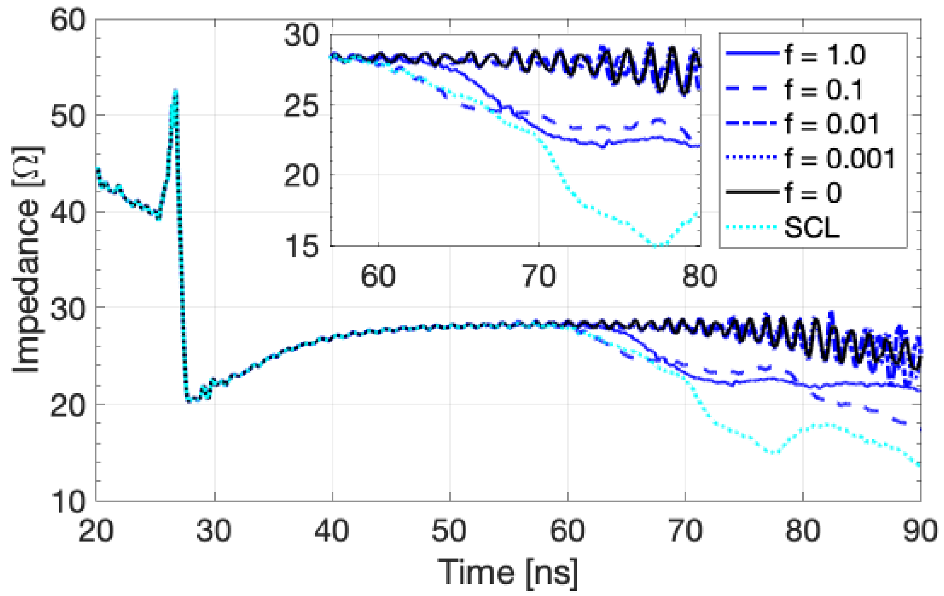


[4] Sanford, et. al., Journal of Applied Physics 66, 10 (1989);
[5] U. Iriso and M. Fischer, Phys. Rev. ST Accel. Beams 8, 113201 (2005).
[6] J. Gomez-Goni and A. Mathewson, J. Vac. Sci. Technol. A 15, 3093 (1997).
[7] Bruner, et. al., Phys. Rev. ST Accel. Beams **11**, 040401
[8] Mazarakis, Phys. Plasmas 25, 043508 (2018)

55cm AK Gap





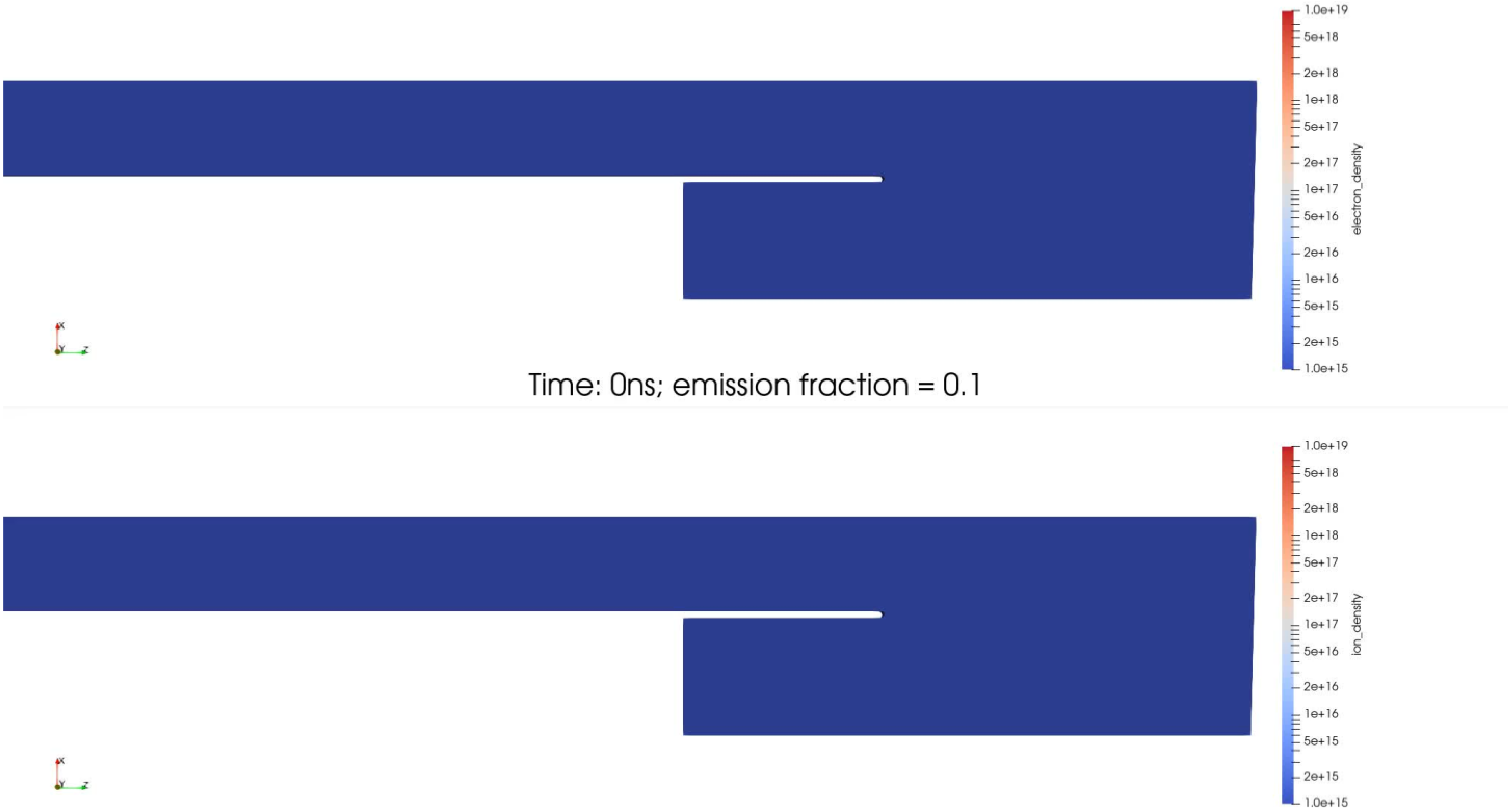


Impedance departs early for f = 0.1 and SCL.

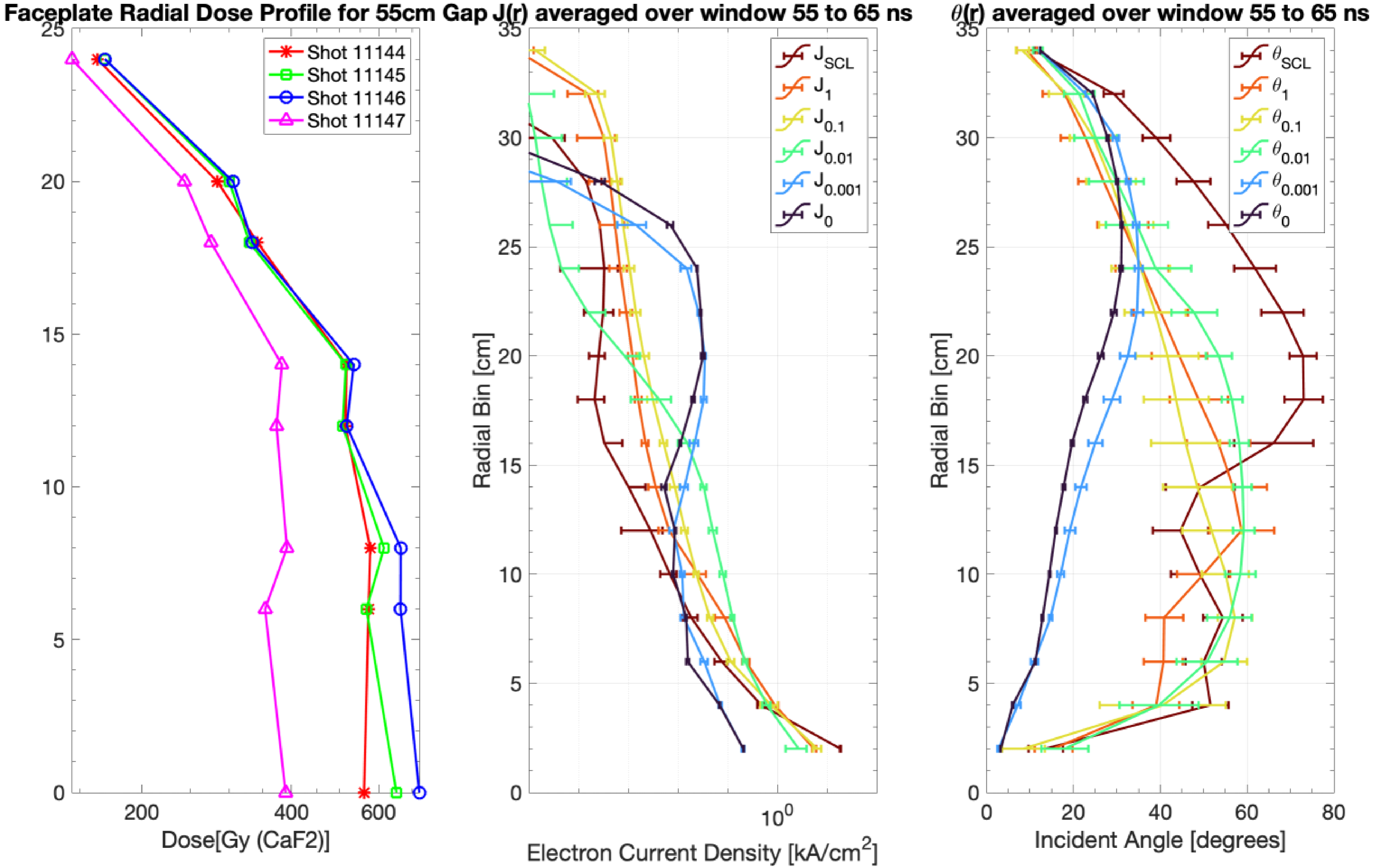
Later departure for f=1 case due to higher ion density than either SCL or f = 0.1 cases

Effects of ions in diodes occurs primarily after the peak x-ray pulse due to slow acceleration of ions.

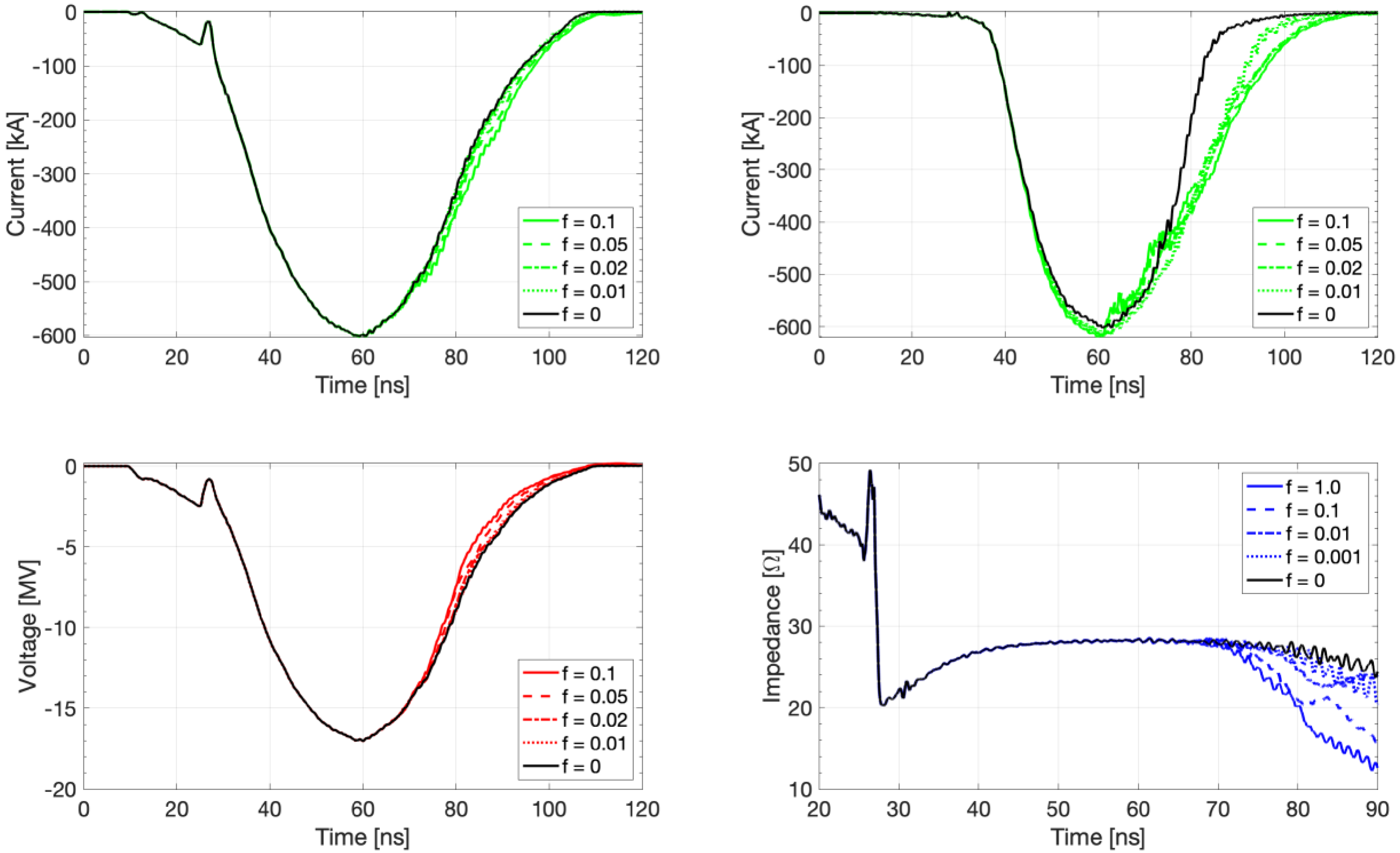
55cm AK Gap, f = 0.1



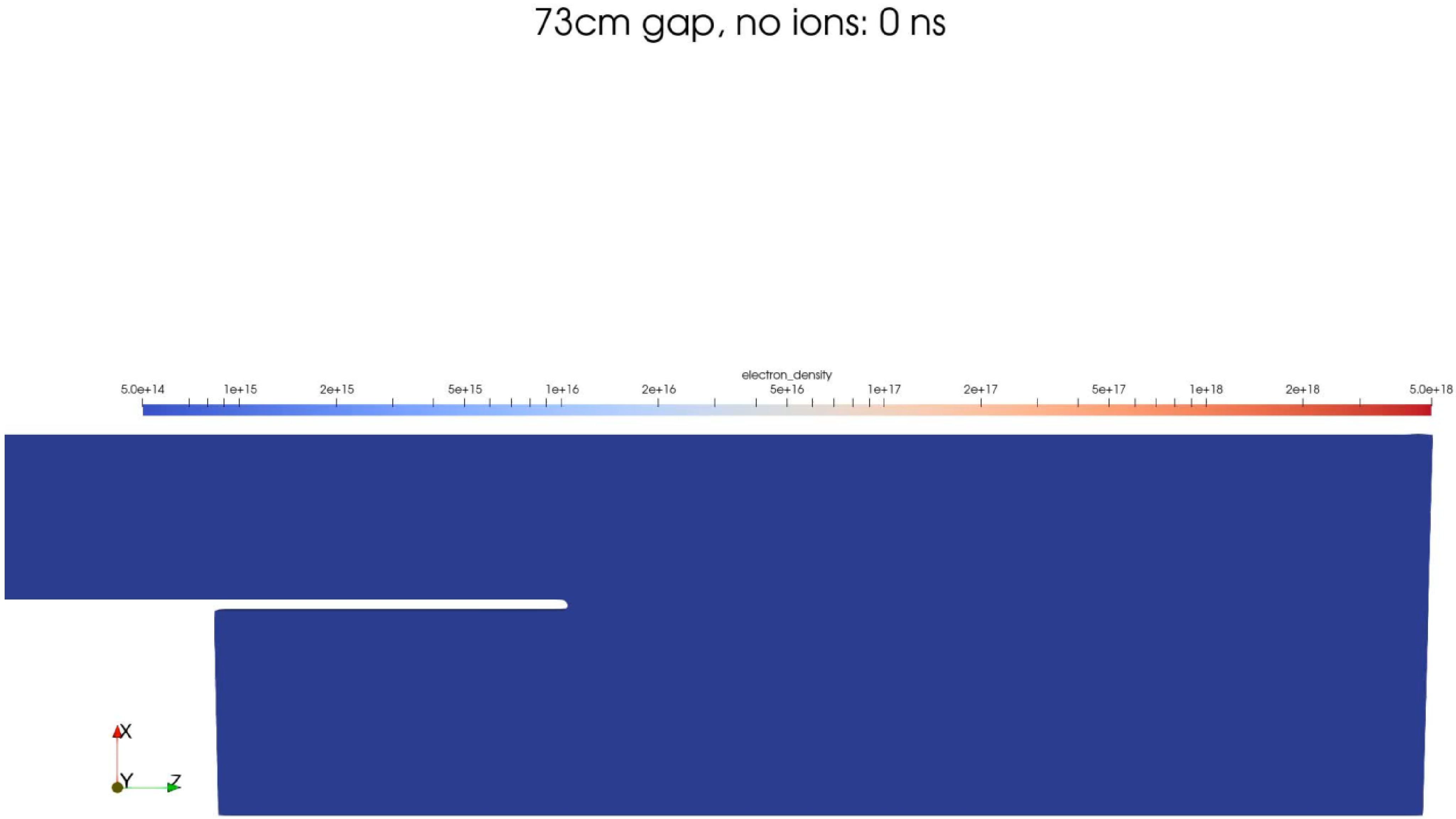
55cm AK Gap


Faceplate Radial Dose Profile for 55cm Gap
Shot 11144
Shot 11145
Shot 11146
Shot 11147
Dose[Gy (CaF2)]
J(r) averaged over window 55 to 65 ns
J_{SCL}
J_1
$J_{0.1}$
$J_{0.01}$
$J_{0.001}$
J_0
Radial Bin [cm]
Electron Current Density [kA/cm^2]
θ(r) averaged over window 55 to 65 ns
θ_{SCL}
θ_1
$\theta_{0.1}$
$\theta_{0.01}$
$\theta_{0.001}$
θ_0
Radial Bin [cm]
Incident Angle [degrees]

First attempt at modeling 73cm AK Gap with 18MV pulse



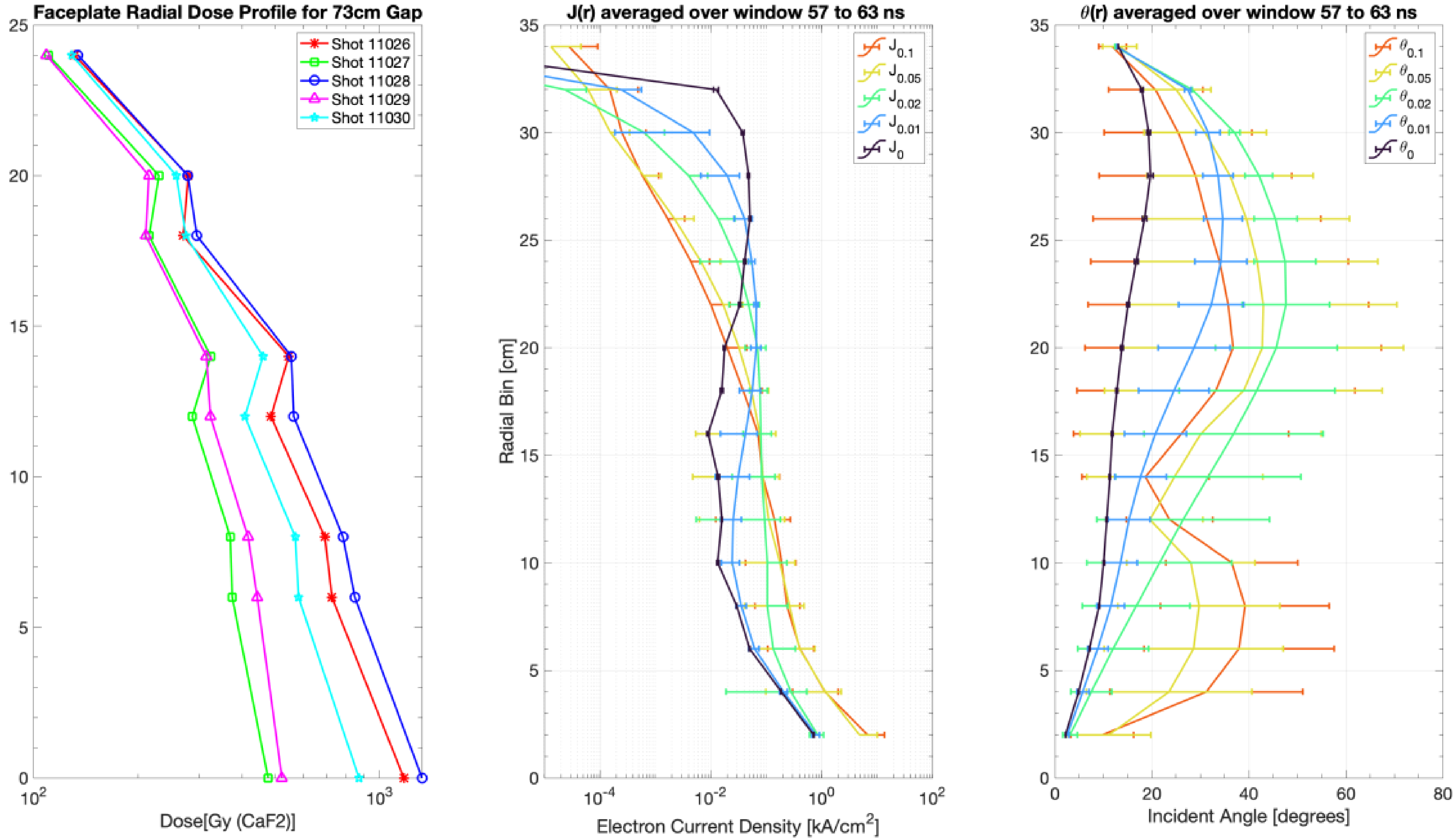
First attempt at modeling 73cm AK Gap with 18MV pulse



First attempt at modeling 73cm AK Gap with 18MV pulse

73cm AK Gap; f = 0.1; 0.0 ns

First attempt at modeling 73cm AK Gap with 18MV pulse



Replicating HERMES-III Shots in EMPIRE

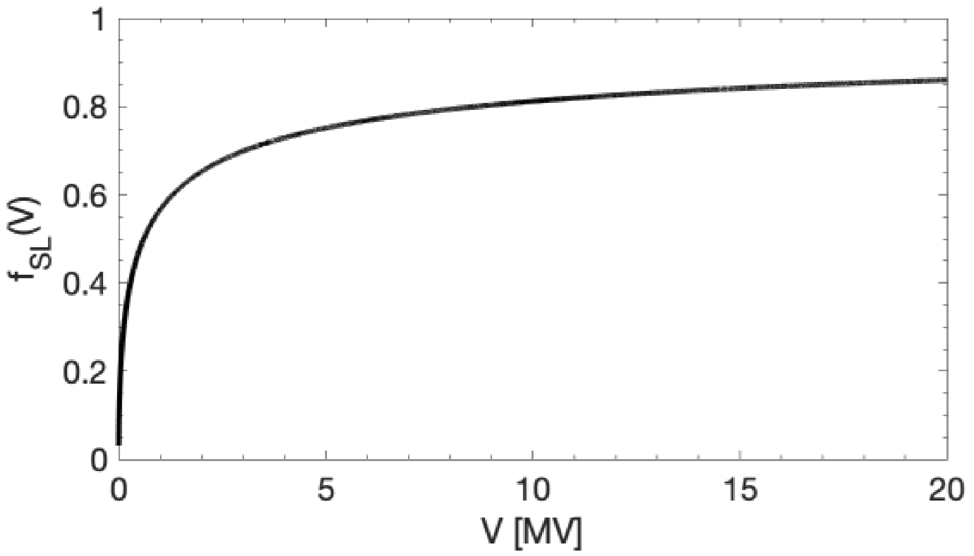
MITL operates in a self-limited moc $V = f_{SL}(V) Z I_a$

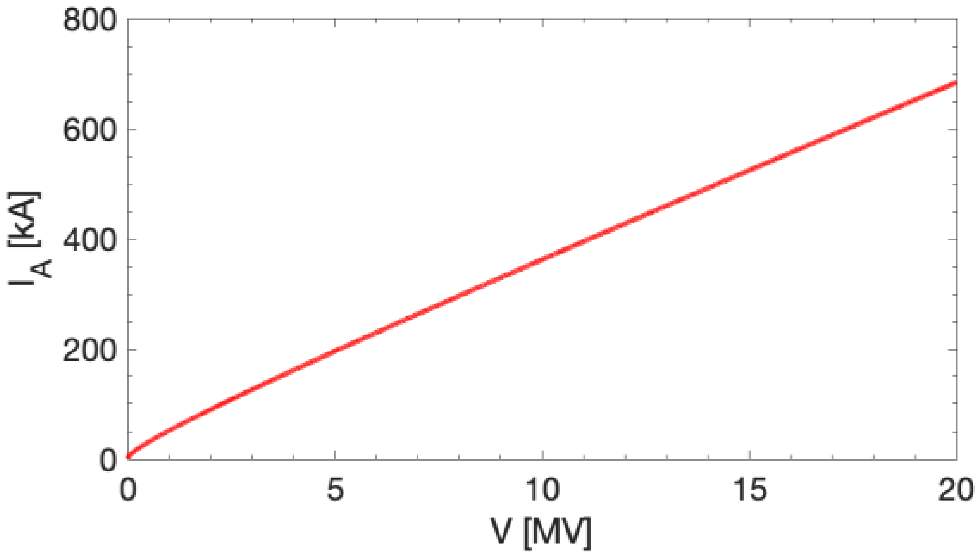
Numerically solve Mendel's voltage model [ref] for the self limited function

Use Thevenin source open-circuit voltage to drive simulation

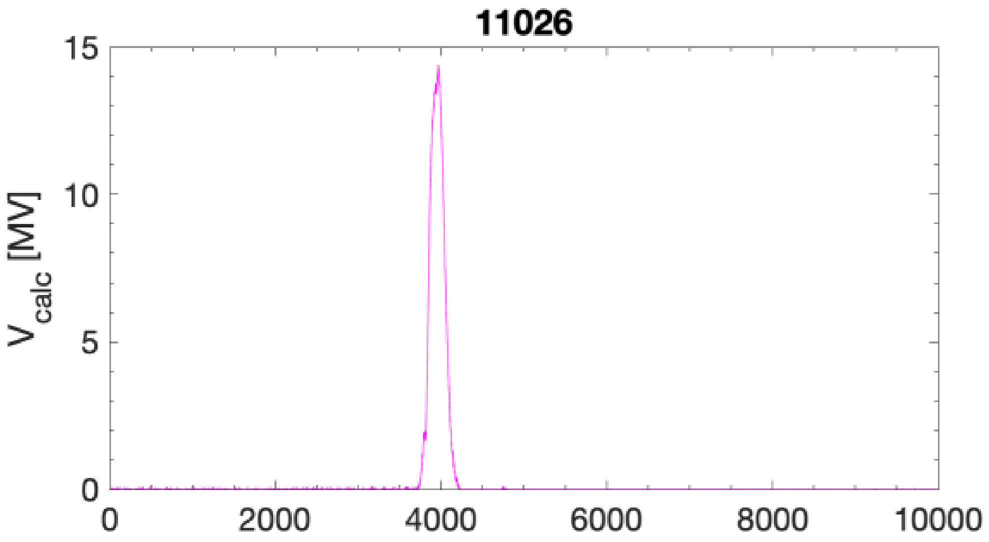
$$V = Z_0 \sqrt{I_A^2 - I_K^2} - \frac{mc^2}{2e} \frac{I_A^2 - I_K^2}{I_K^2}$$

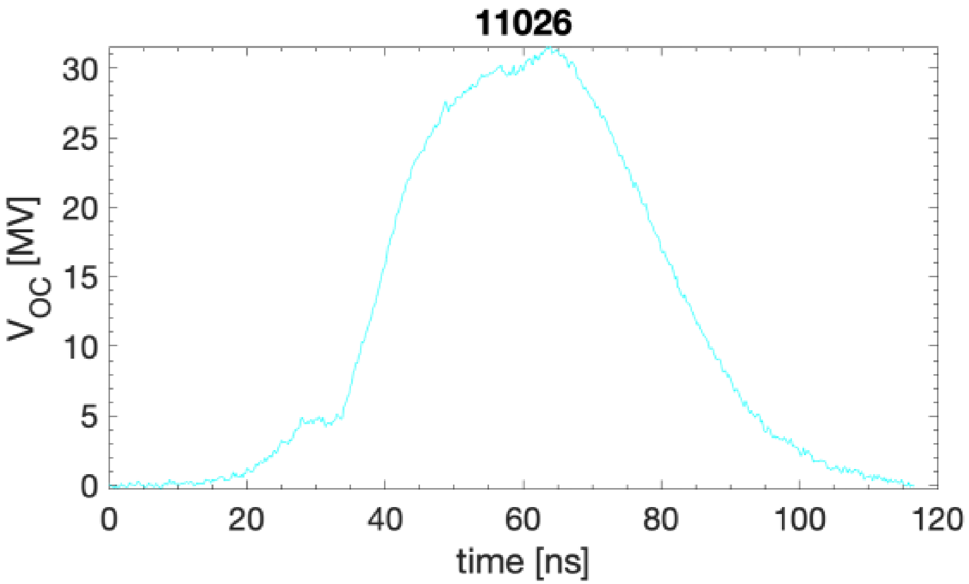
$$V_{OC}(t) = V(t) + Z_{src} I_a(t)$$

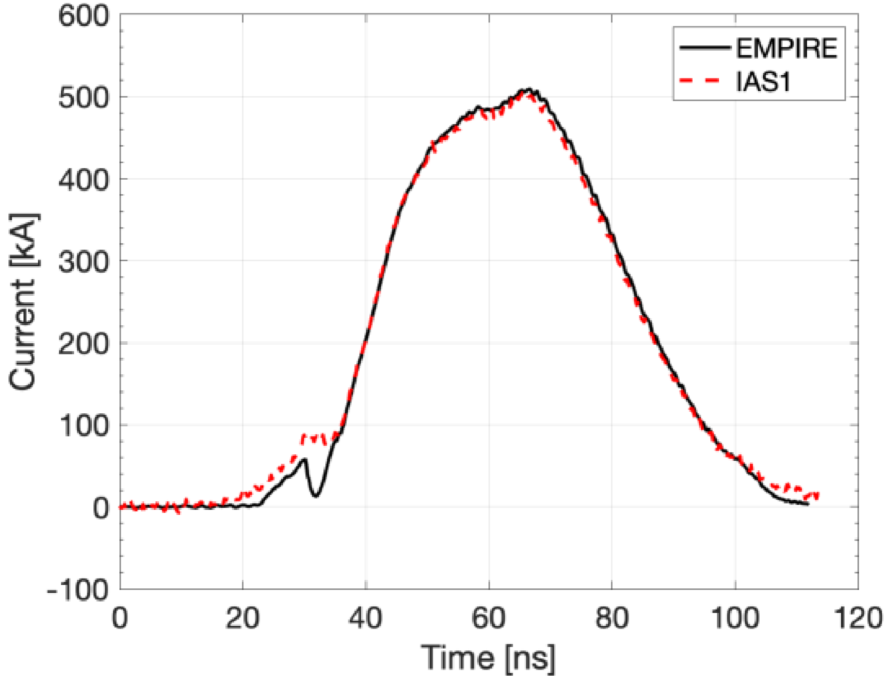




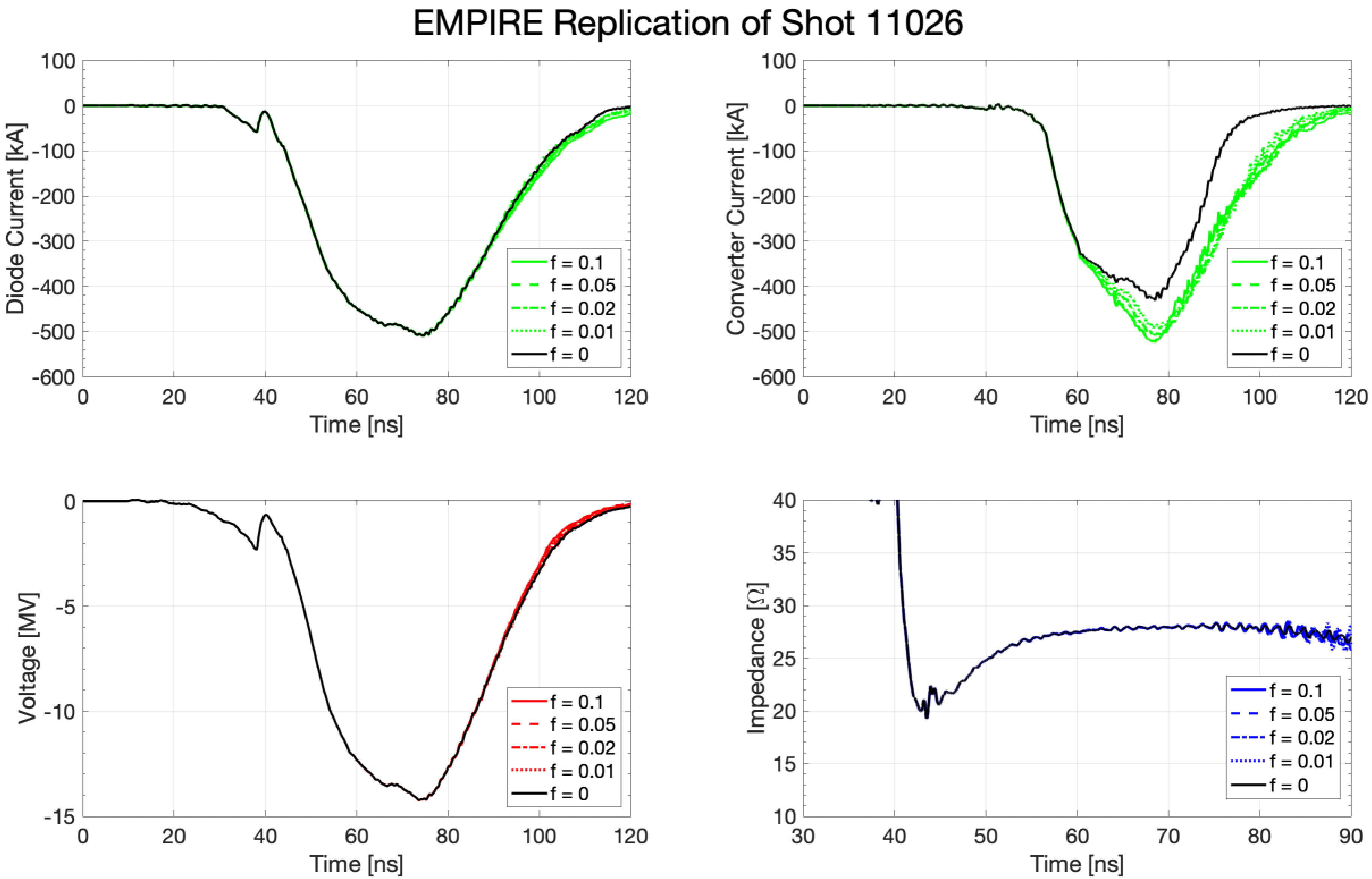
Replicating 11026



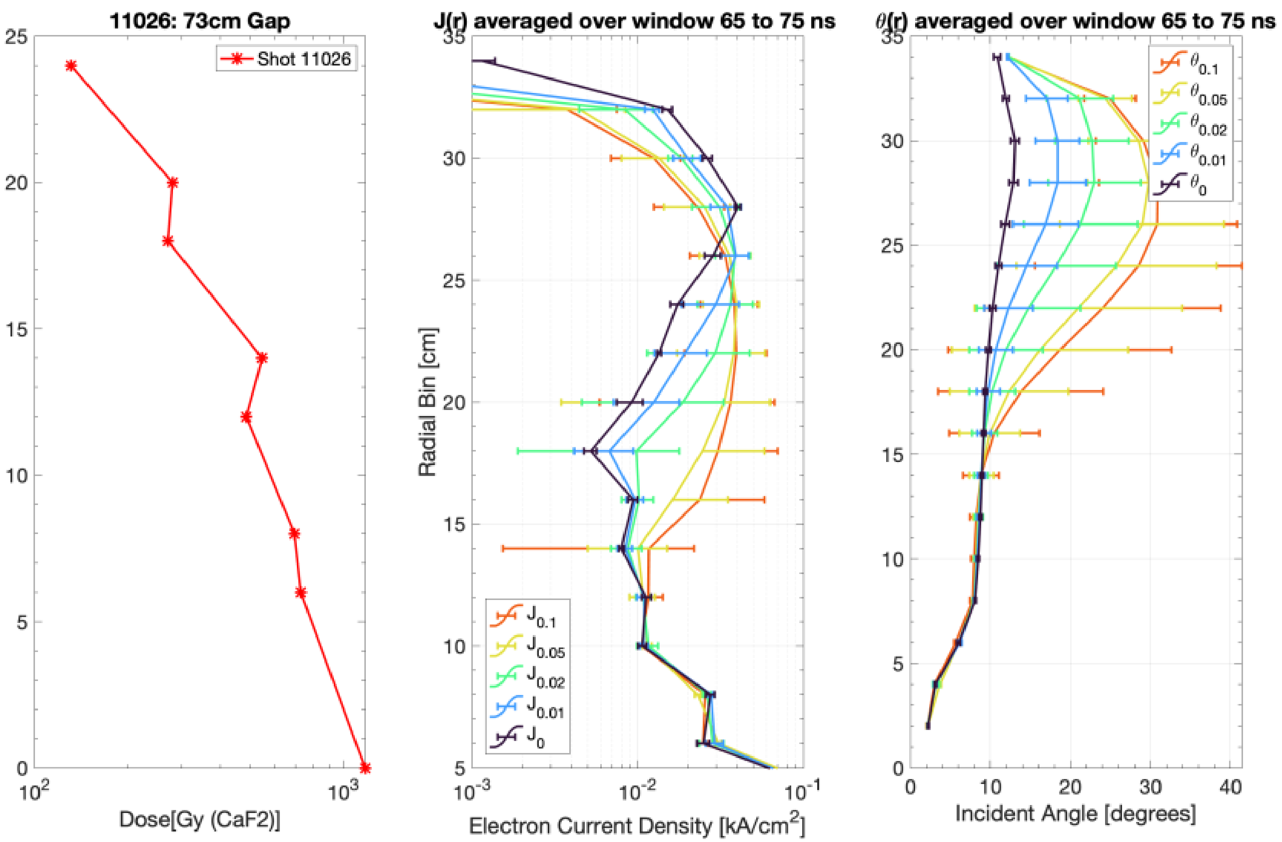


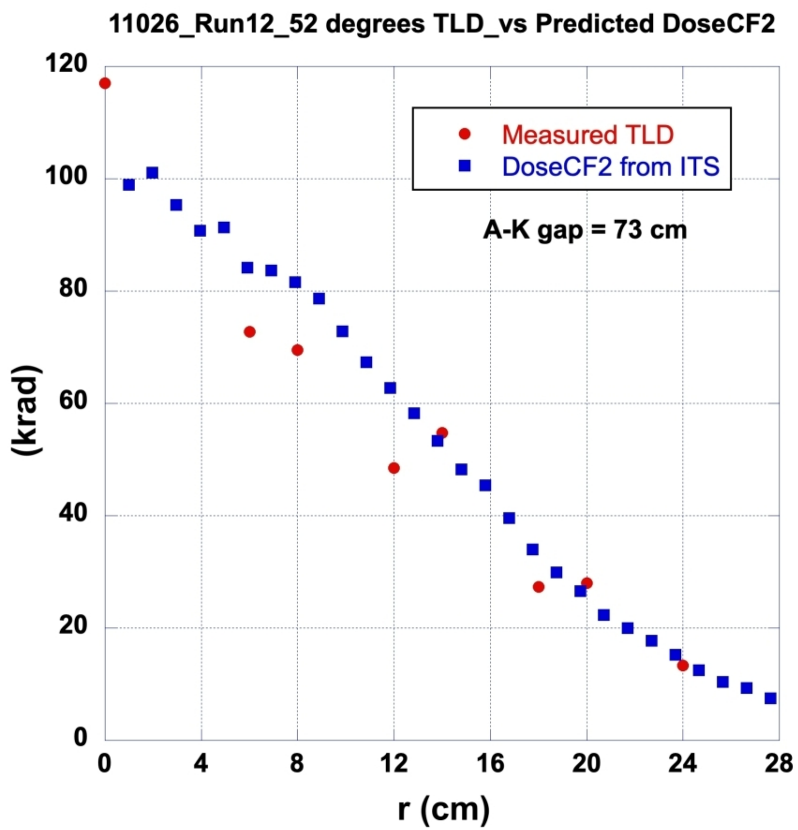


11026

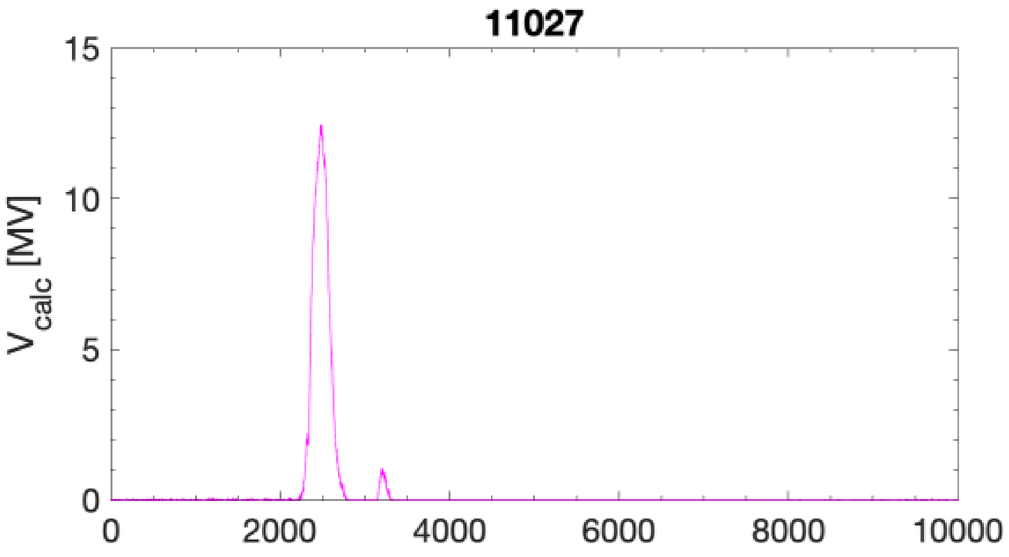

EMPIRE Replication of Shot 11026
Diode Current [kA]
Time [ns]
Converter Current [kA]
Voltage [MV]
Impedance [Ω]
f = 0.1
f = 0.05
f = 0.02
f = 0.01
f = 0

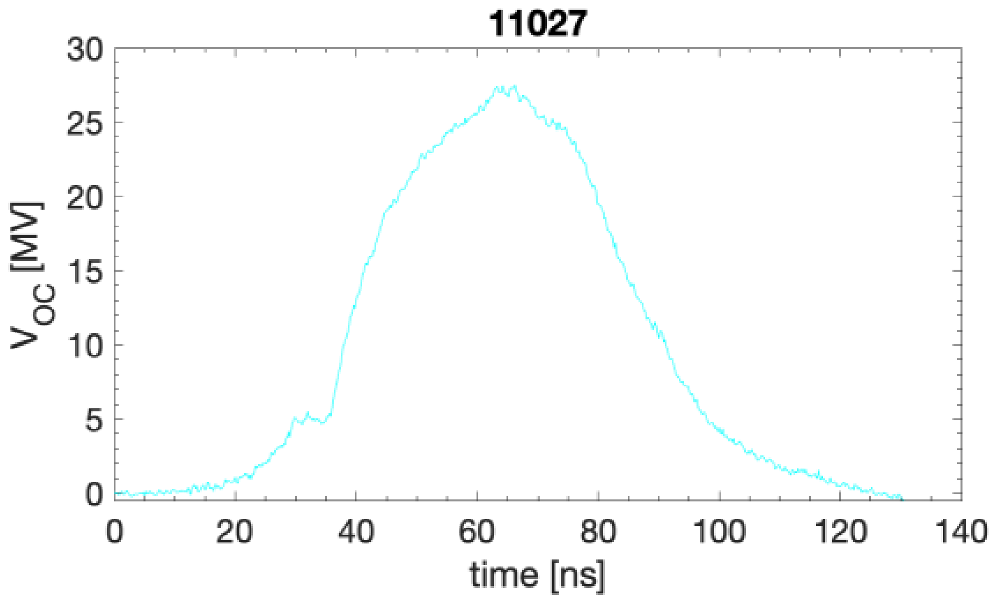
11026

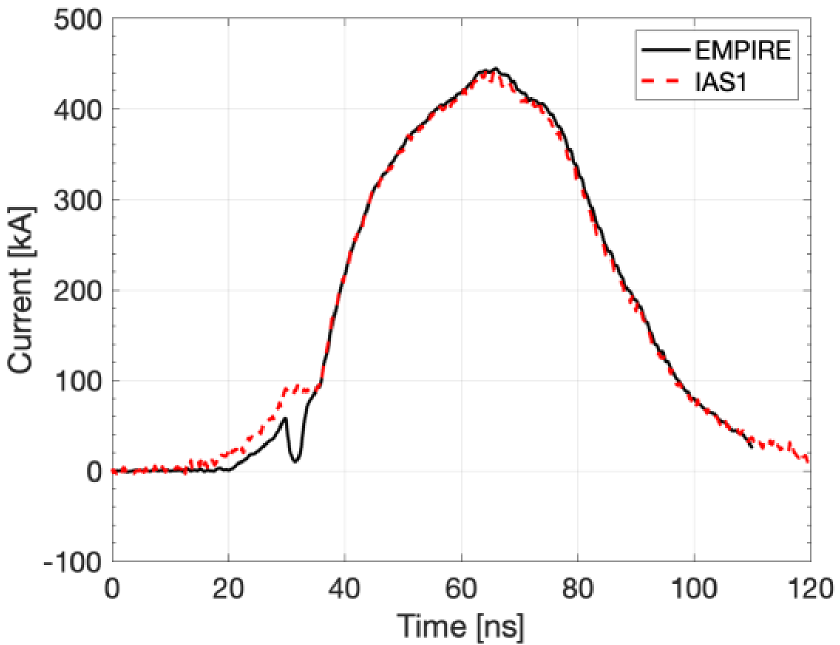

11026: 73cm Gap
Shot 11026
Dose[Gy (CaF2)]
J(r) averaged over window 65 to 75 ns
Radial Bin [cm]
Electron Current Density [kA/cm^2]
θ(r) averaged over window 65 to 75 ns
Incident Angle [degrees]


11026_Run12_52 degrees TLD_vs Predicted DoseCF2
Measured TLD
DoseCF2 from ITS
A-K gap = 73 cm
(krad)
r (cm)

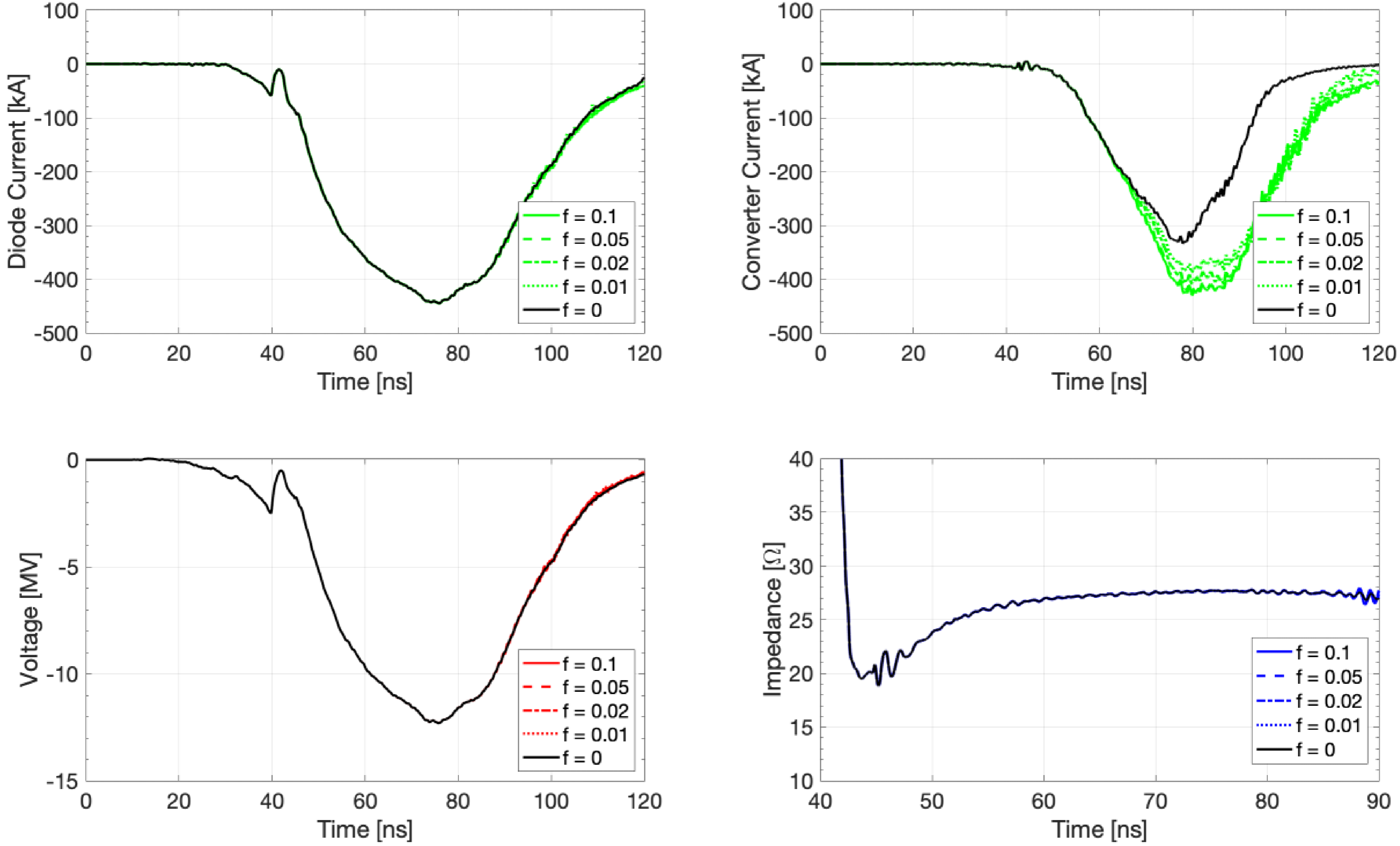
11027


11027
15
10
5
0
0
2000
4000
6000
8000
10000
V_{calc} [MV]

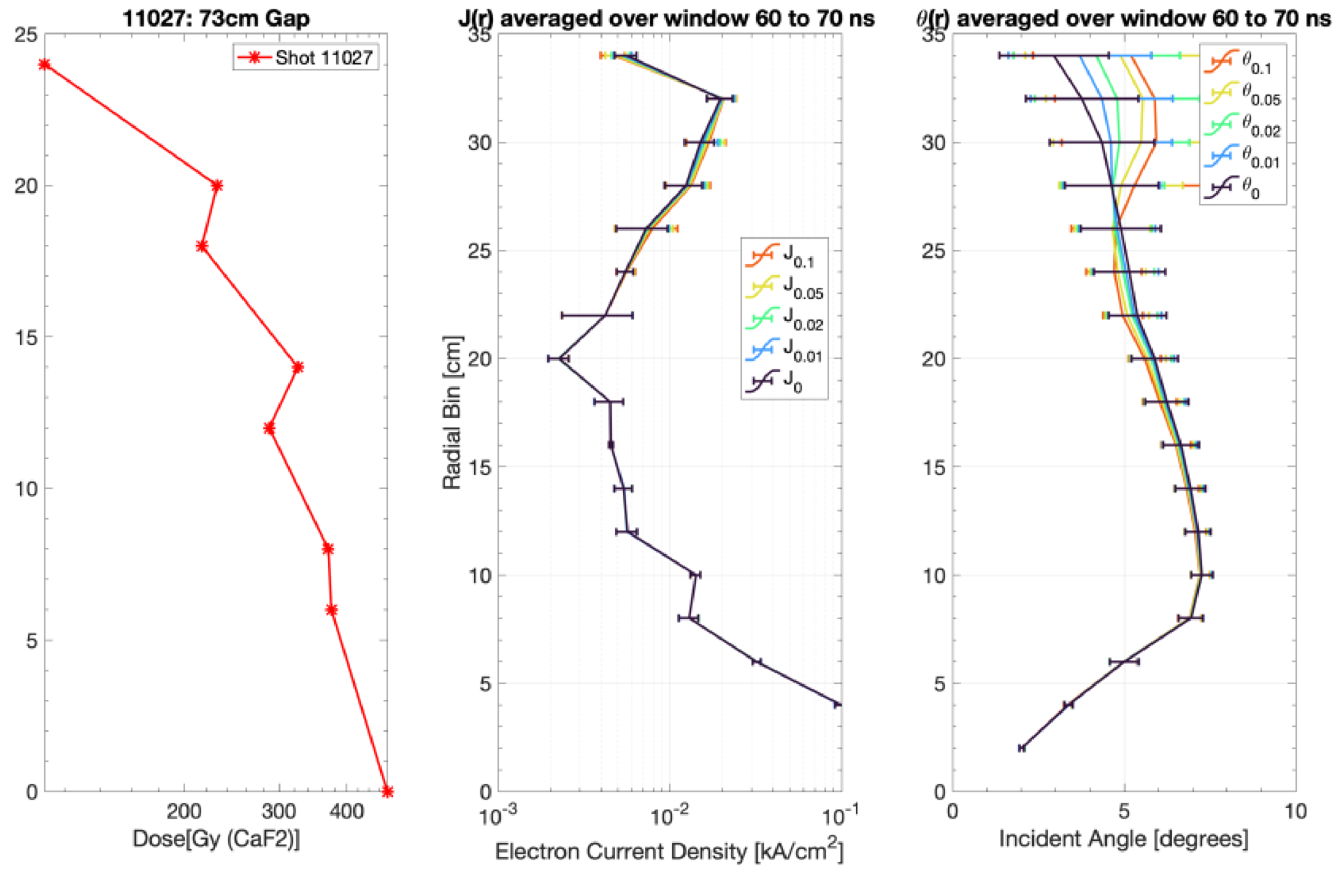

11027
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
time [ns]
V_{OC} [MV]


EMPIRE
IAS1
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
Time [ns]
Current [kA]

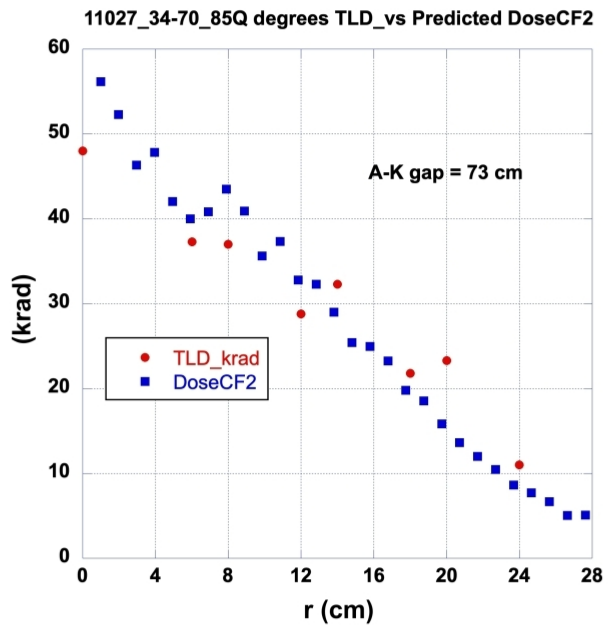
EMPIRE Replication of Shot 11027



11027

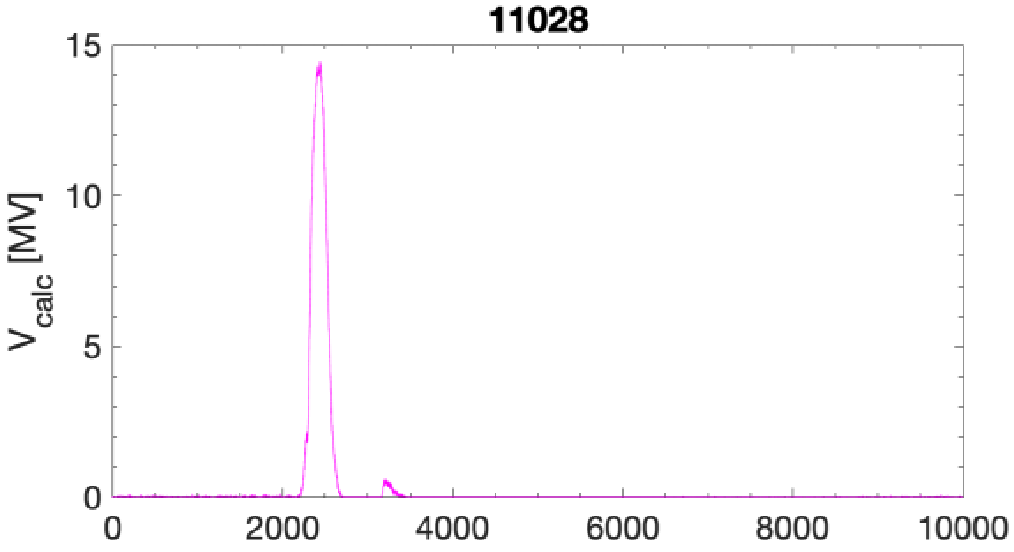


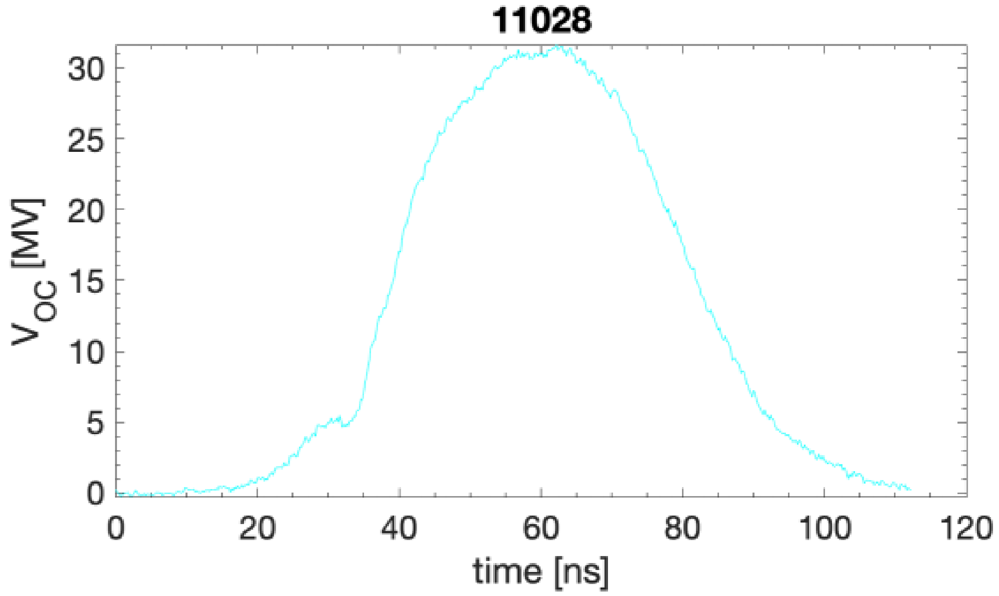
11027: 73cm Gap
Shot 11027
Dose[Gy (CaF2)]
J(r) averaged over window 60 to 70 ns
Radial Bin [cm]
Electron Current Density [kA/cm^2]
$J_{0.1}$
$J_{0.05}$
$J_{0.02}$
$J_{0.01}$
J_0
θ(r) averaged over window 60 to 70 ns
Incident Angle [degrees]
$\theta_{0.1}$
$\theta_{0.05}$
$\theta_{0.02}$
$\theta_{0.01}$
θ_0

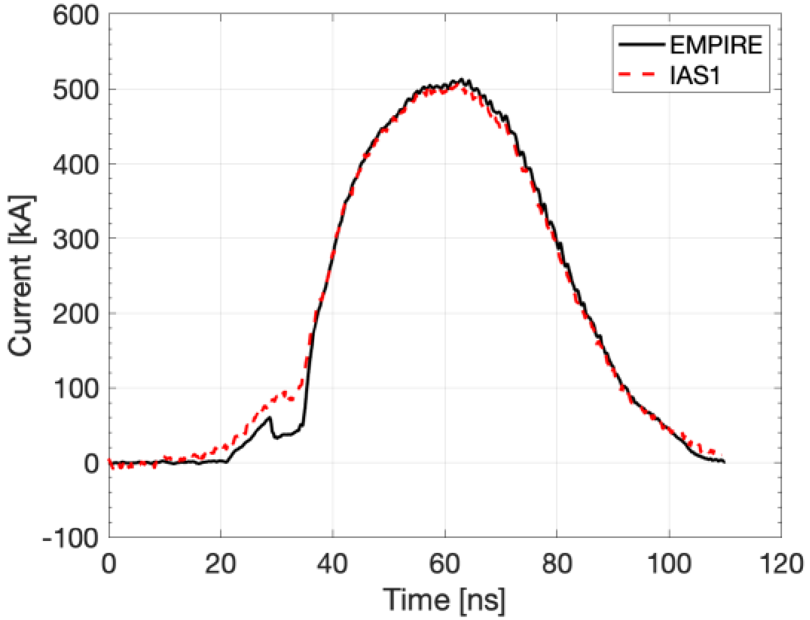


11027_34-70_85Q degrees TLD_vs Predicted DoseCF2
A-K gap = 73 cm
(krad)
TLD_krad
DoseCF2
r (cm)

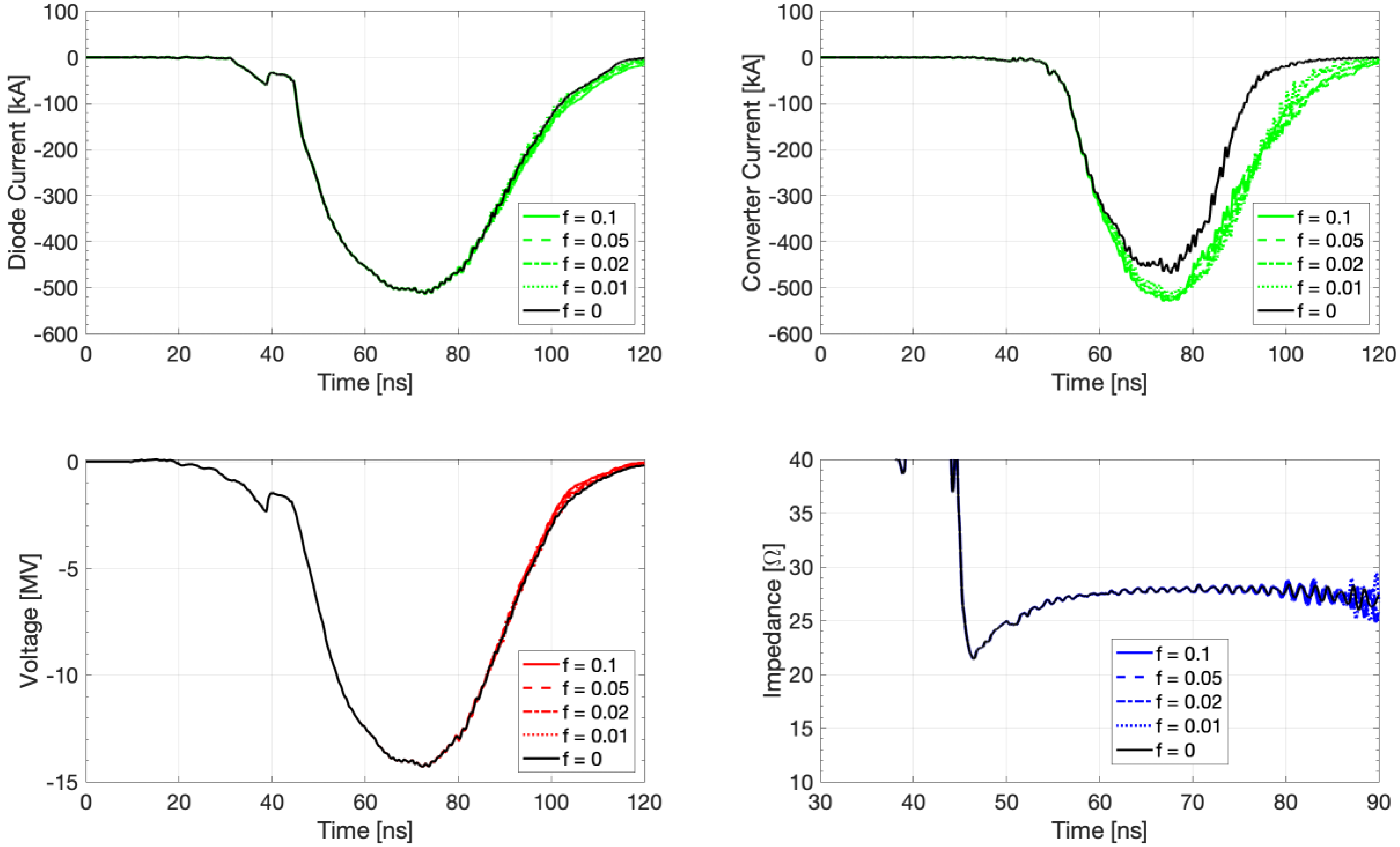
11028


11028
V_{calc} [MV]
15
10
5
0
0
2000
4000
6000
8000
10000

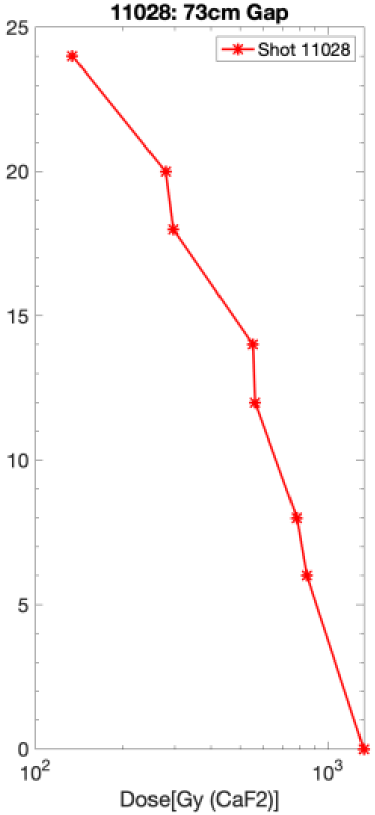

11028
V_{OC} [MV]
30
25
20
15
10
5
0
0
20
40
60
80
100
120
time [ns]

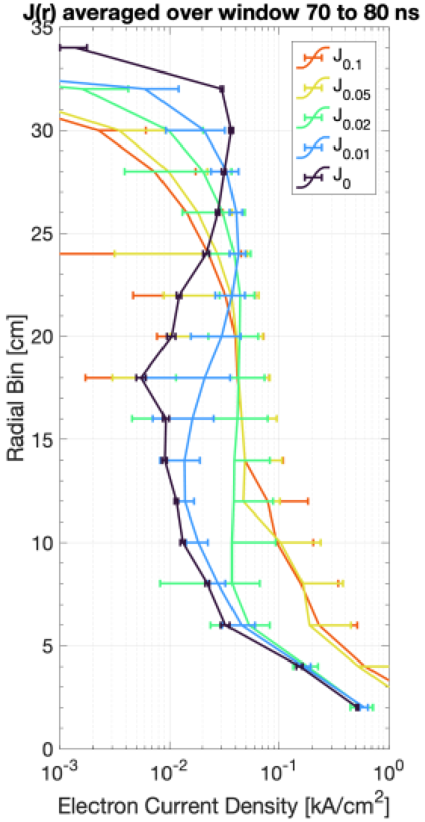

EMPIRE
IAS1
Current [kA]
600
500
400
300
200
100
0
-100
0
20
40
60
80
100
120
Time [ns]

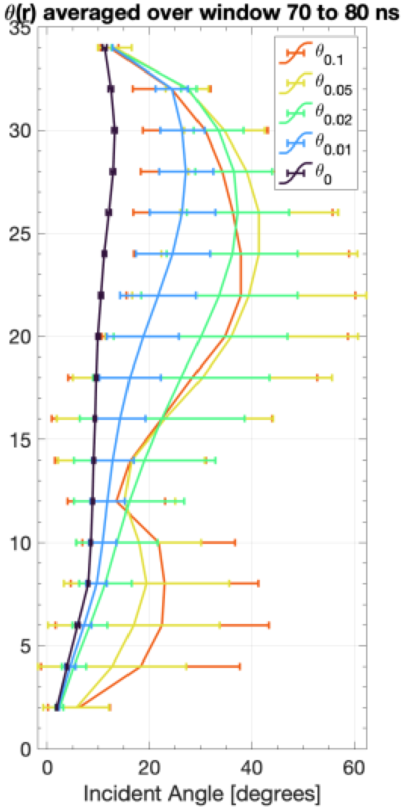
EMPIRE Replication of Shot 11028

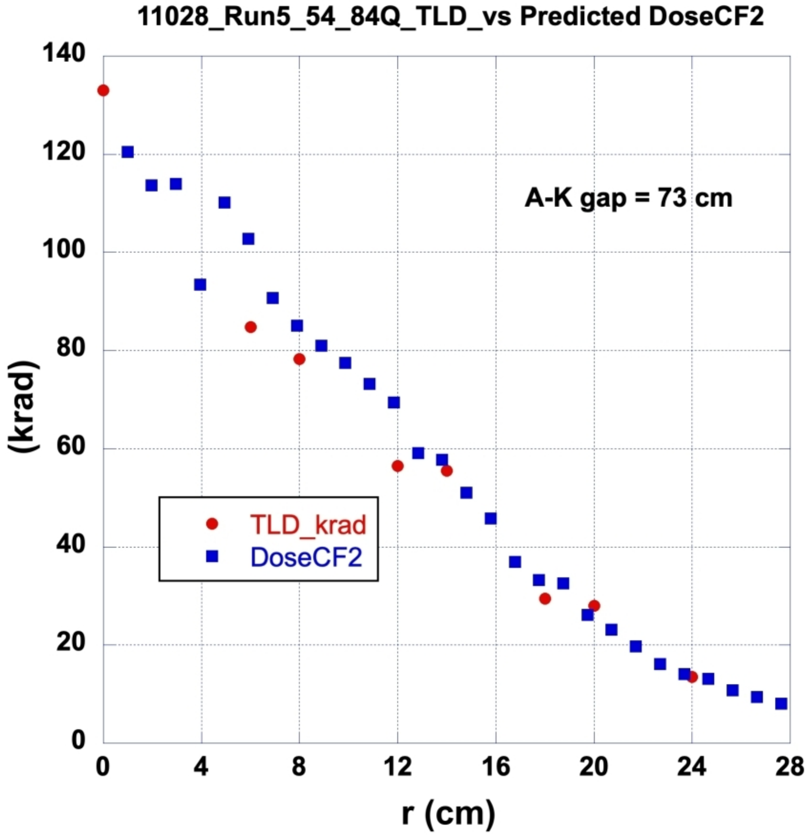


11028

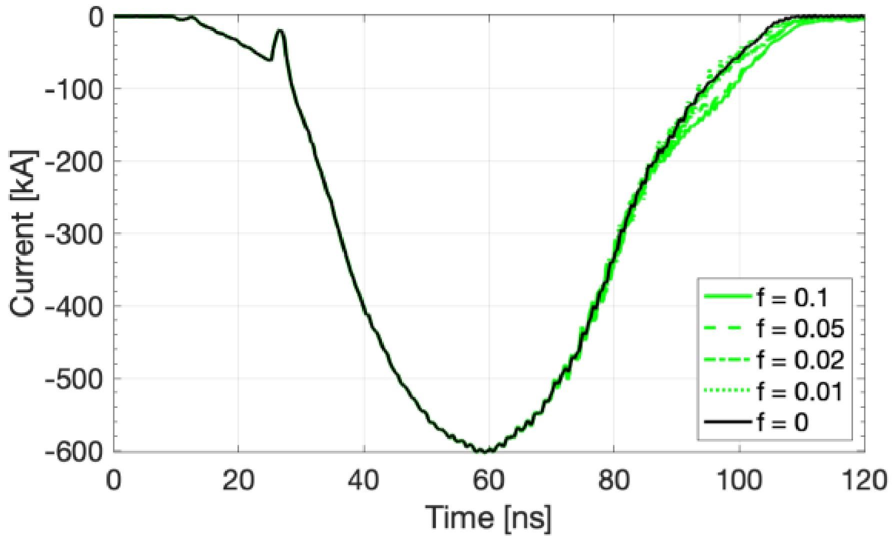

11028: 73cm Gap
Shot 11028
0
5
10
15
20
25
10^2
10^3
Dose[Gy (CaF2)]

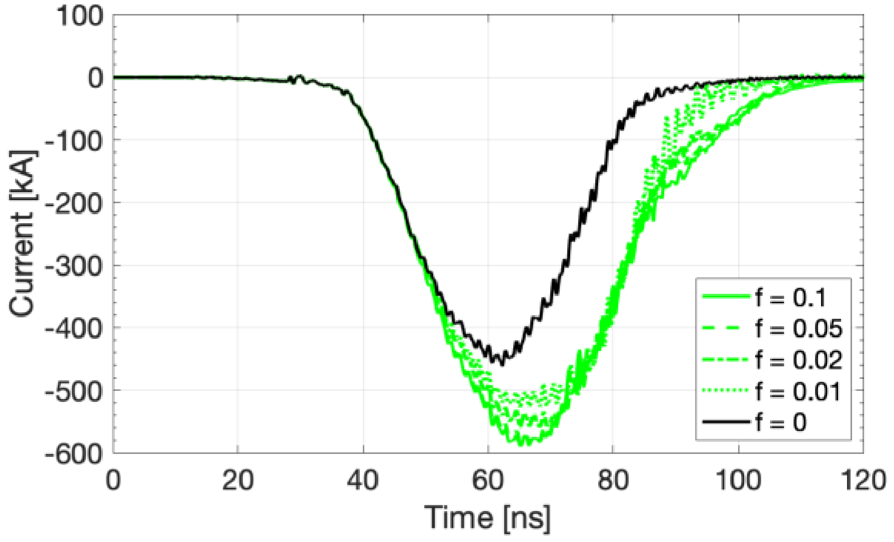

J(r) averaged over window 70 to 80 ns
$J_{0.1}$
$J_{0.05}$
$J_{0.02}$
$J_{0.01}$
J_0
Radial Bin [cm]
0
5
10
15
20
25
30
35
10^{-3}
10^{-2}
10^{-1}
10^0
Electron Current Density [kA/cm^2]

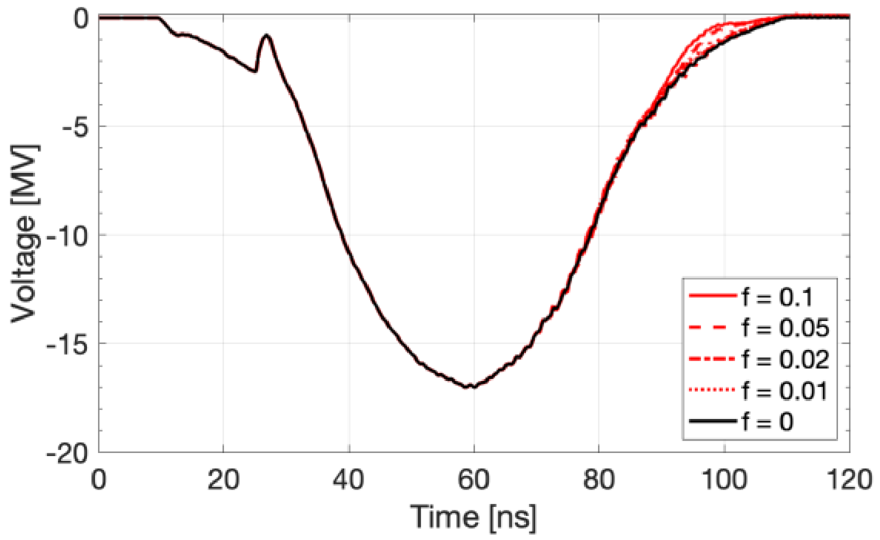

θ(r) averaged over window 70 to 80 ns
$\theta_{0.1}$
$\theta_{0.05}$
$\theta_{0.02}$
$\theta_{0.01}$
θ_0
0
5
10
15
20
25
30
35
0
20
40
60
Incident Angle [degrees]

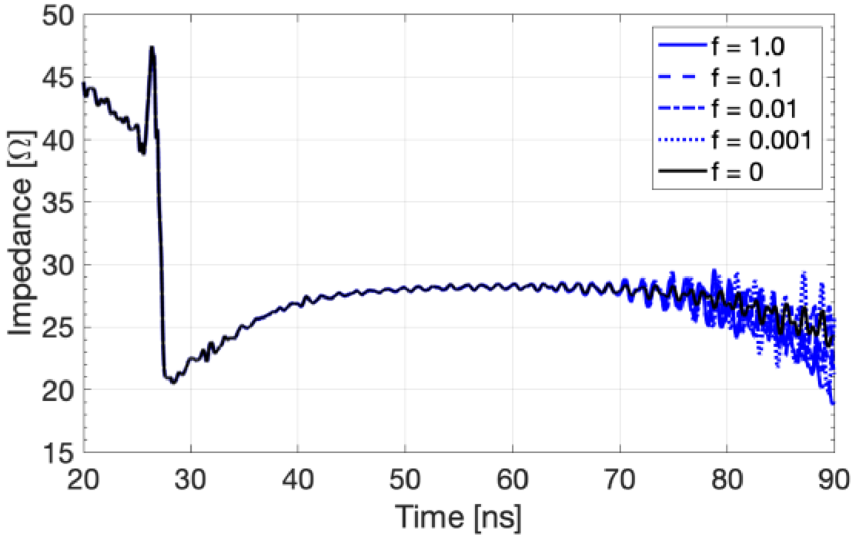

11028_Run5_54_84Q_TLD_vs Predicted DoseCF2
A-K gap = 73 cm
TLD_krad
DoseCF2
(krad)
0
20
40
60
80
100
120
140
0
4
8
12
16
20
24
28
r (cm)

88cm AK Gap

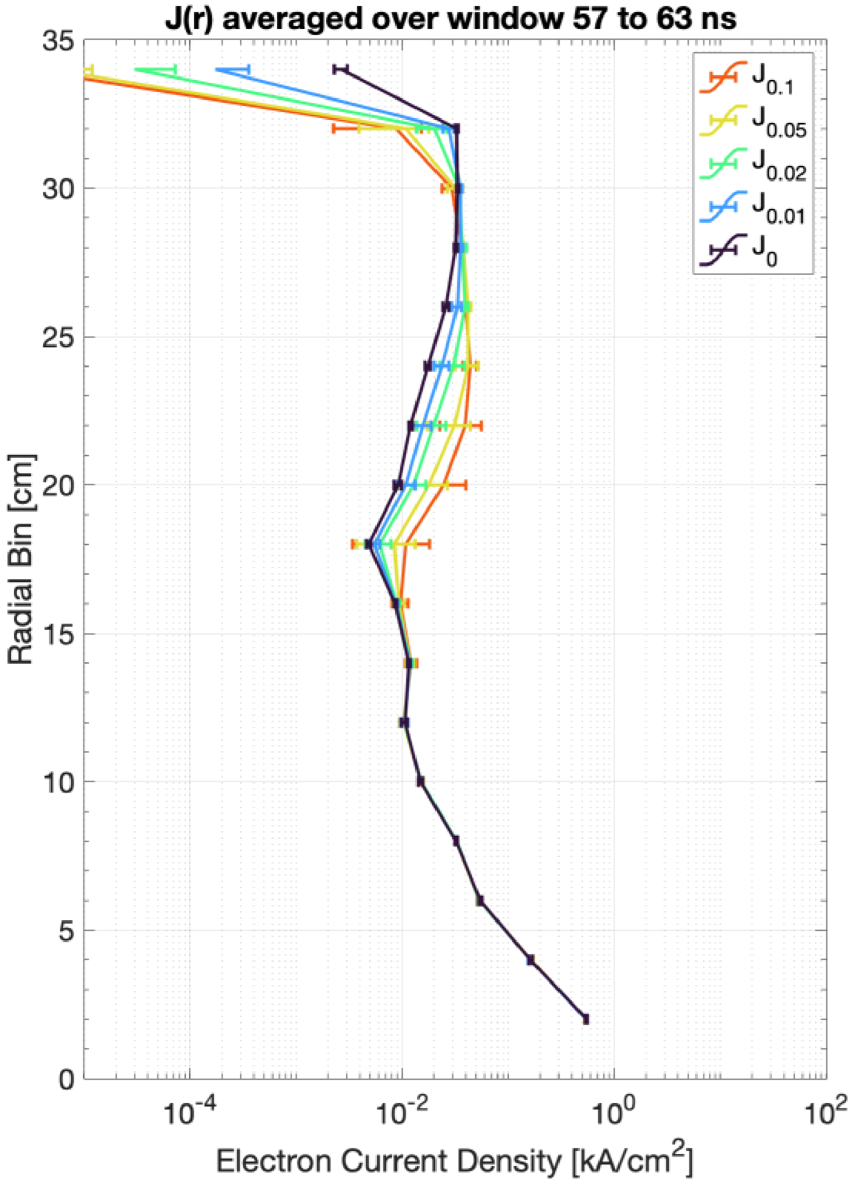

Current [kA]
Time [ns]
f = 0.1
f = 0.05
f = 0.02
f = 0.01
f = 0

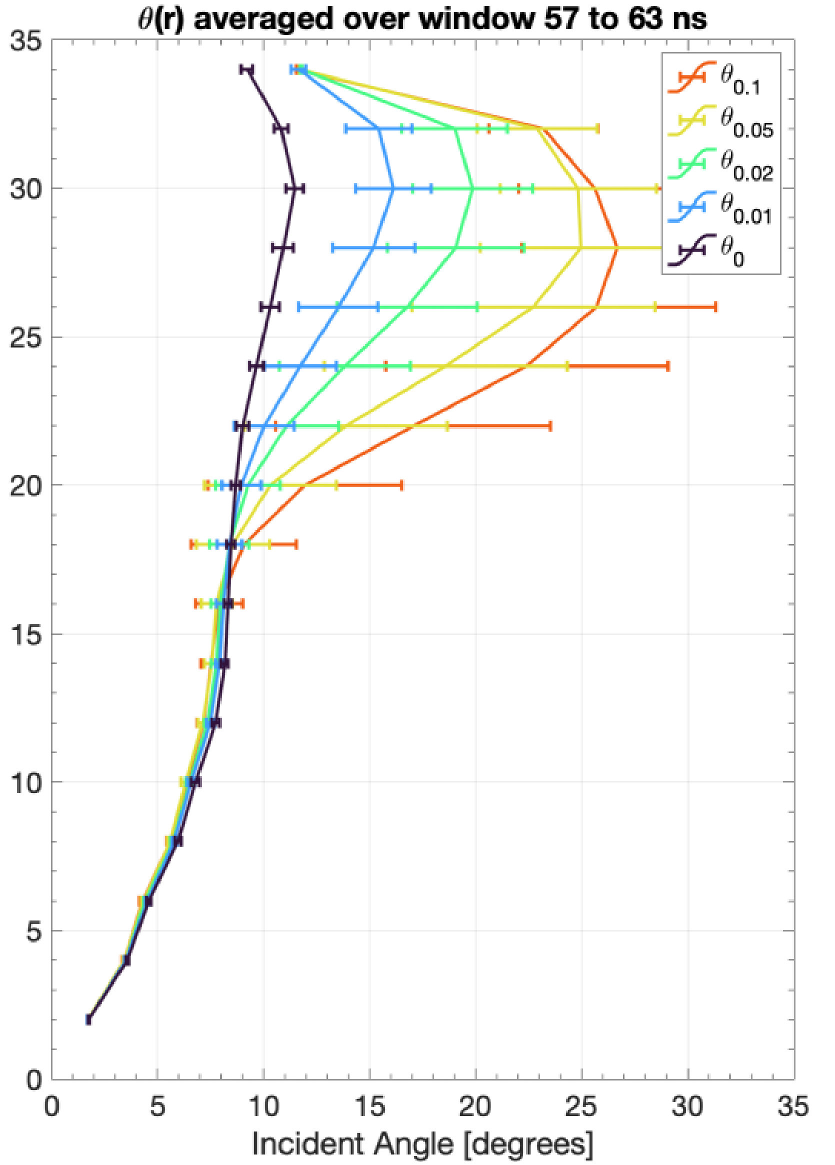

Current [kA]
Time [ns]
f = 0.1
f = 0.05
f = 0.02
f = 0.01
f = 0


Voltage [MV]
Time [ns]
f = 0.1
f = 0.05
f = 0.02
f = 0.01
f = 0


Impedance [Ω]
Time [ns]
f = 1.0
f = 0.1
f = 0.01
f = 0.001
f = 0

88cm AK Gap

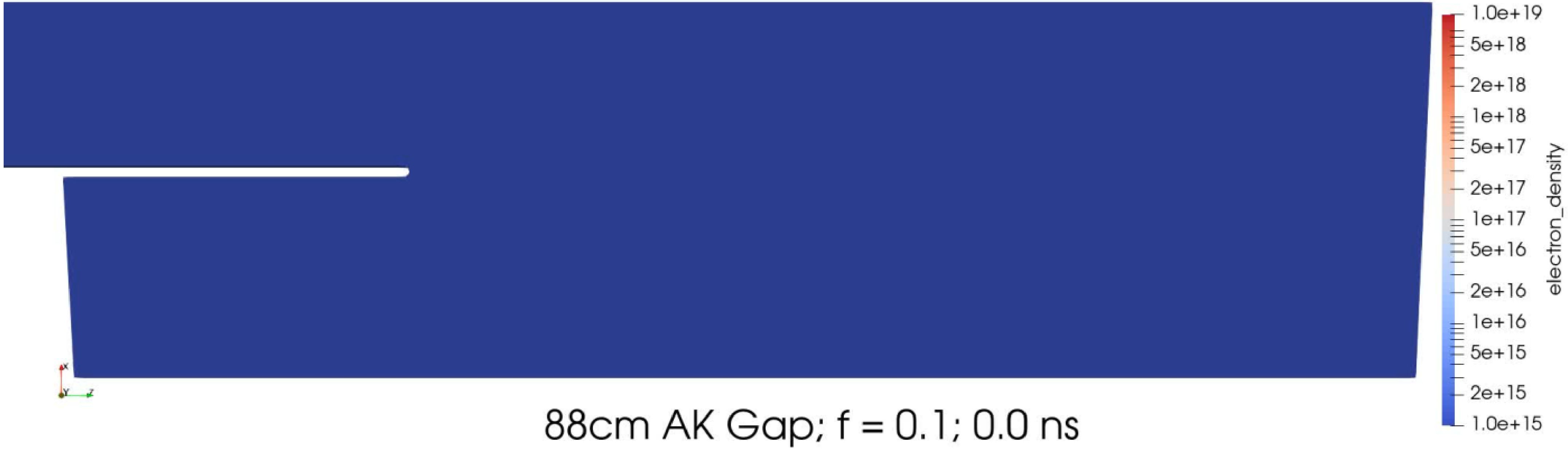

J(r) averaged over window 57 to 63 ns
Radial Bin [cm]
Electron Current Density [kA/cm^2]
$J_{0.1}$
$J_{0.05}$
$J_{0.02}$
$J_{0.01}$
J_0
35
30
25
20
15
10
5
0
10^{-4}
10^{-2}
10^{0}
10^{2}


θ(r) averaged over window 57 to 63 ns
Incident Angle [degrees]
$\theta_{0.1}$
$\theta_{0.05}$
$\theta_{0.02}$
$\theta_{0.01}$
θ_0
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35

88cm AK Gap


88cm Gap, ions off 0.0 ns
1.0e+18
5e+17
2e+17
1e+17
5e+16
2e+16
1e+16
5e+15
2e+15
1.0e+15
electron_density
X
Y
Z

88cm AK Gap


1.0e+19
5e+18
2e+18
1e+18
5e+17
2e+17
1e+17
5e+16
2e+16
1e+16
5e+15
2e+15
1.0e+15
electron_density
88cm AK Gap; f = 0.1; 0.0 ns


1.0e+19
5e+18
2e+18
1e+18
5e+17
2e+17
1e+17
5e+16
2e+16
1e+16
5e+15
2e+15
1.0e+15
ion_density

Conclusions and Future Work

Secondary ions play a large role in pinching the HERMES electron beam

Pulse replication works nicely in EMPIRE
- FN emission should help leading edge of pulse

Voltage and current play a large role in maintaining magnetic insulation in extended AK gaps

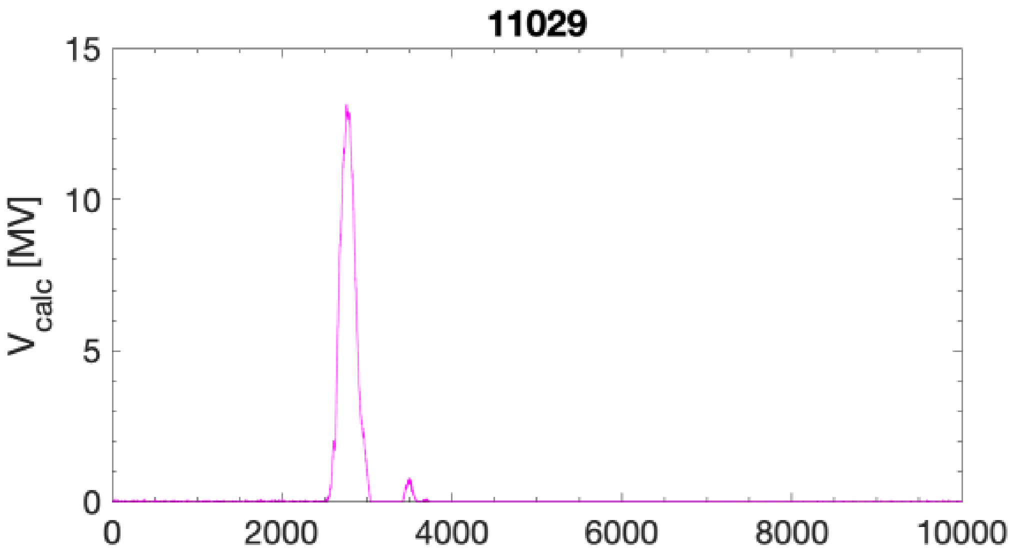
Secondary ions are a likely suspect for the increased dose (lower incident angles)

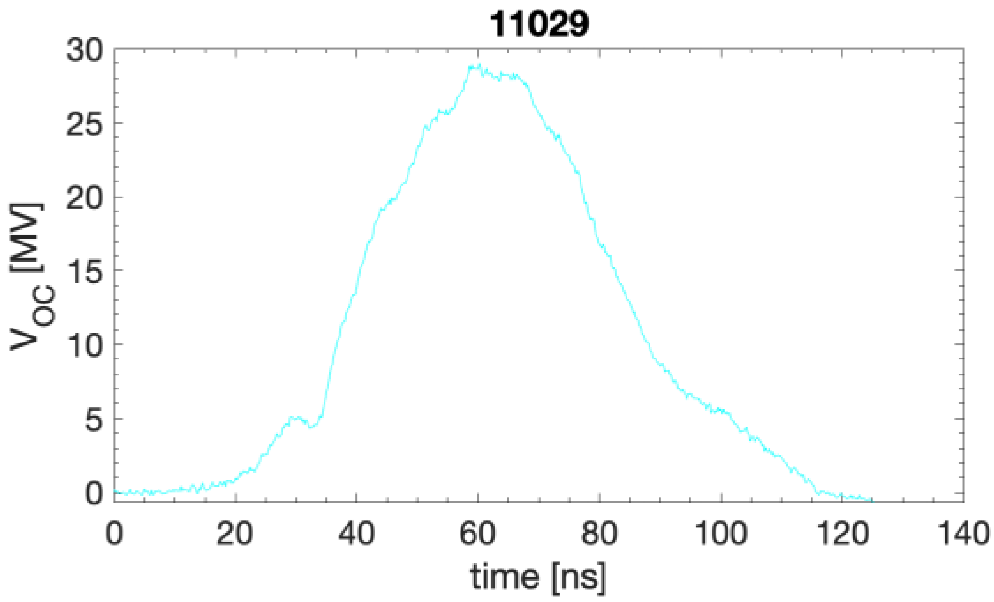
Cannot accurately predict dose with EMPIRE just yet
- EMPIRE-ITS capability nearly ready
- Need to model graphite plug in diode

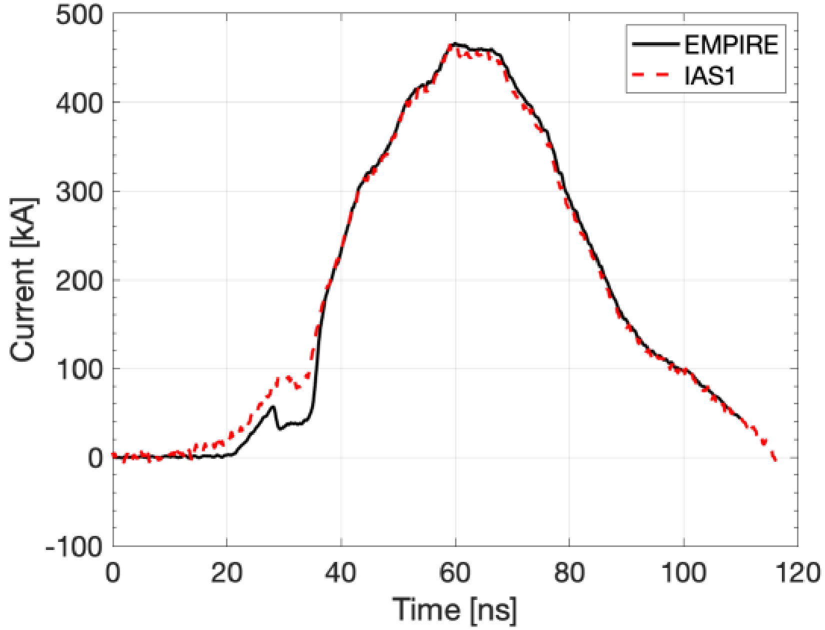
Appendix

Extra content for nerds

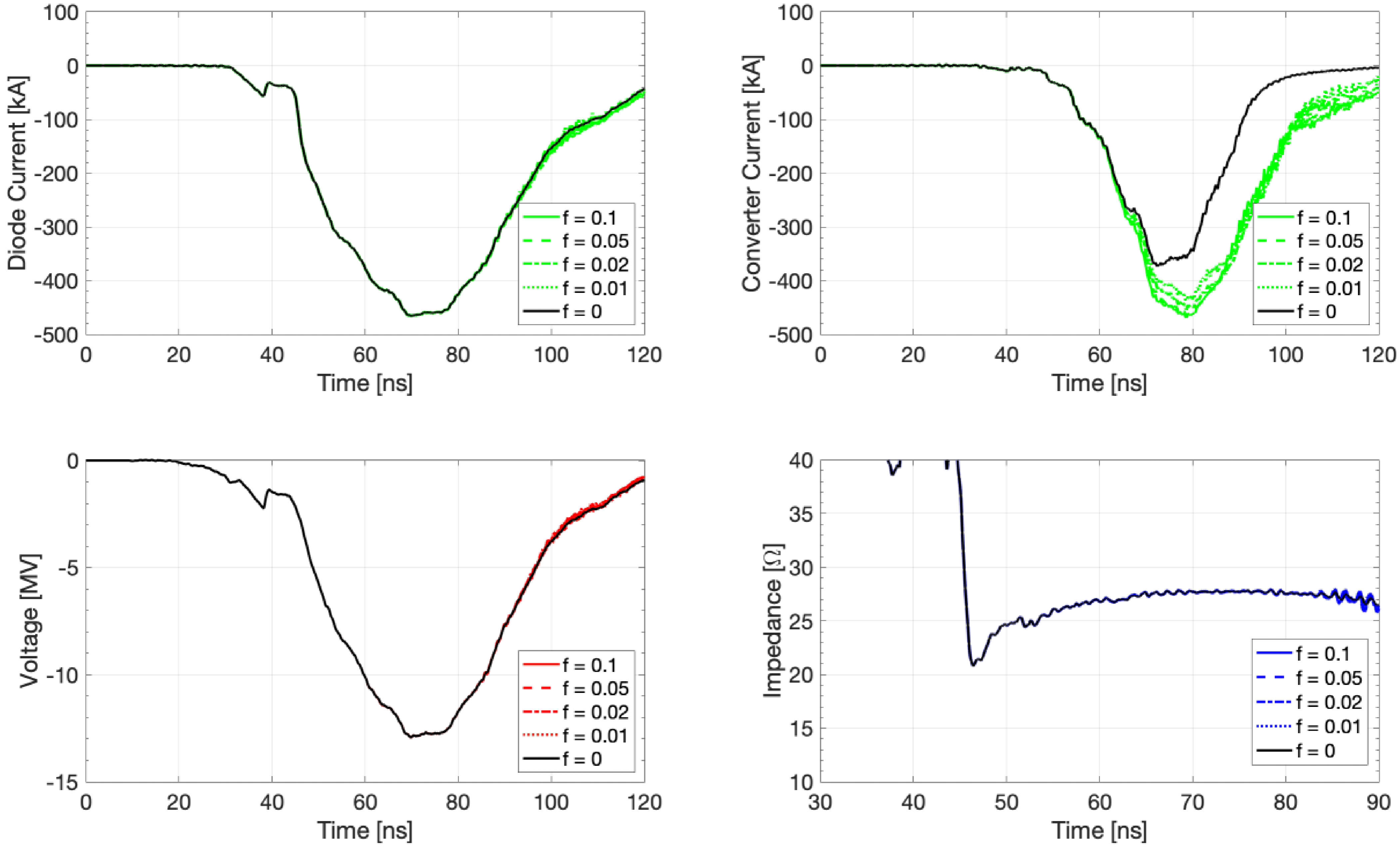
11029


11029
15
10
5
0
V_{calc} [MV]
0
2000
4000
6000
8000
10000

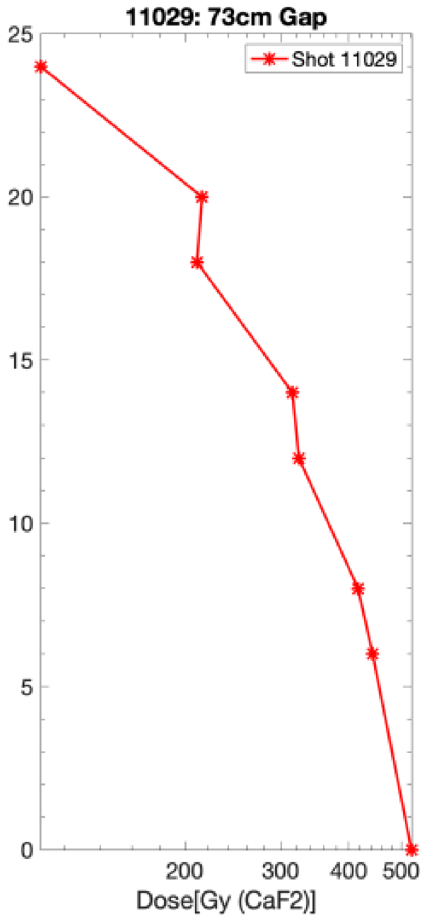

11029
30
25
20
15
10
5
0
V_{OC} [MV]
0
20
40
60
80
100
120
140
time [ns]


500
400
300
200
100
0
-100
Current [kA]
0
20
40
60
80
100
120
Time [ns]
EMPIRE
IAS1

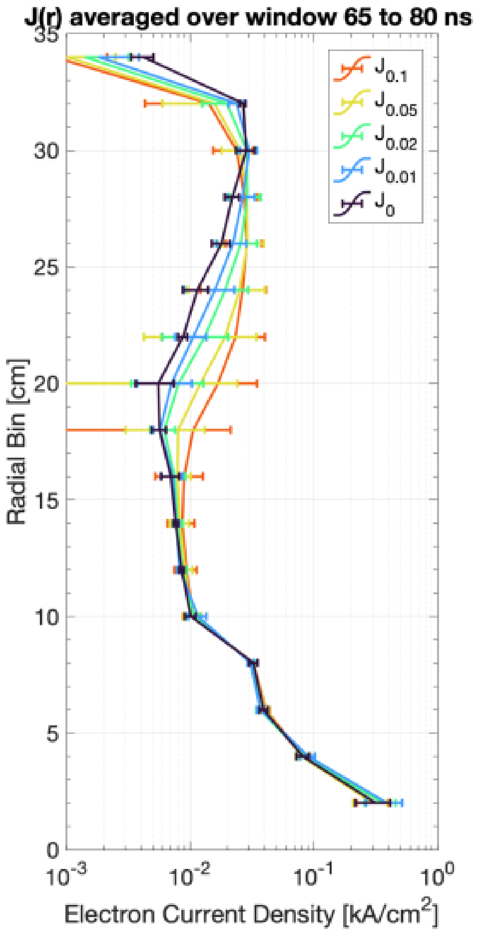
EMPIRE Replication of Shot 11029



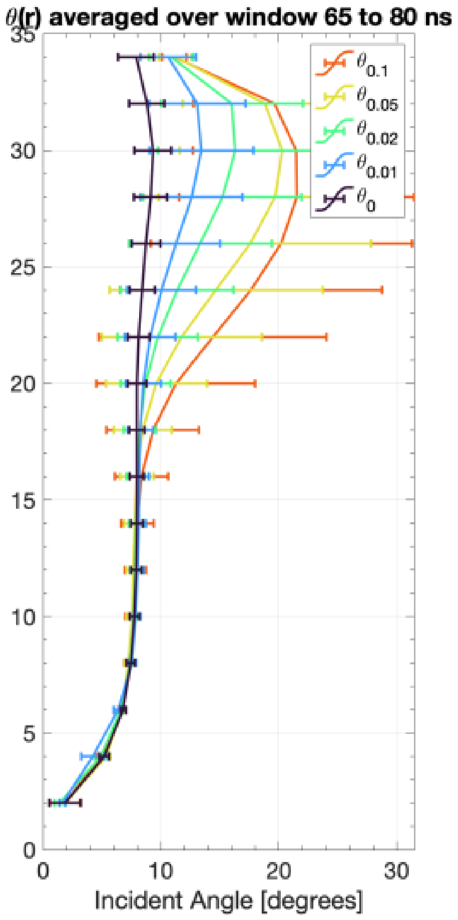
11029



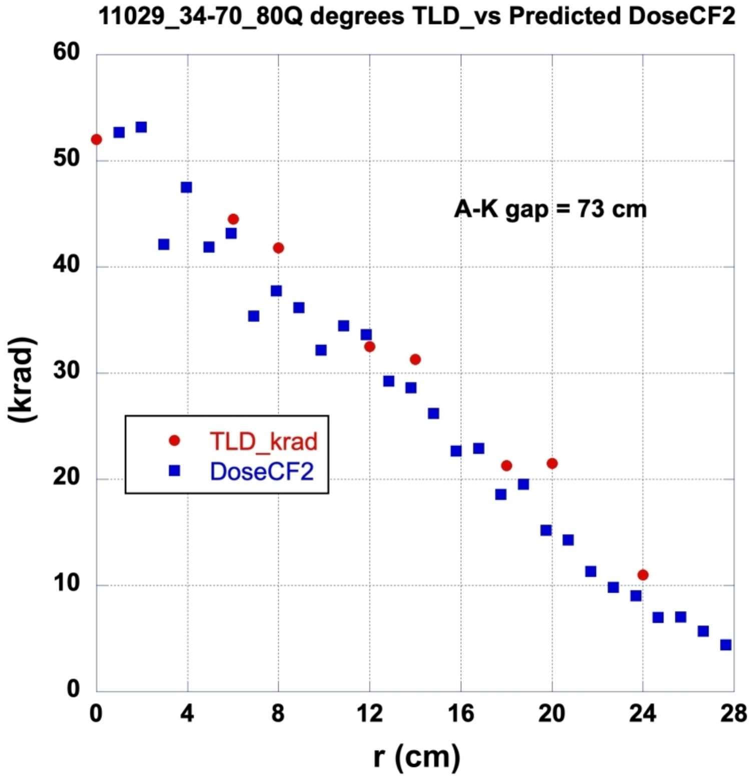
11029: 73cm Gap
Shot 11029
Dose[Gy (CaF2)]



J(r) averaged over window 65 to 80 ns
Radial Bin [cm]
Electron Current Density [kA/cm2]

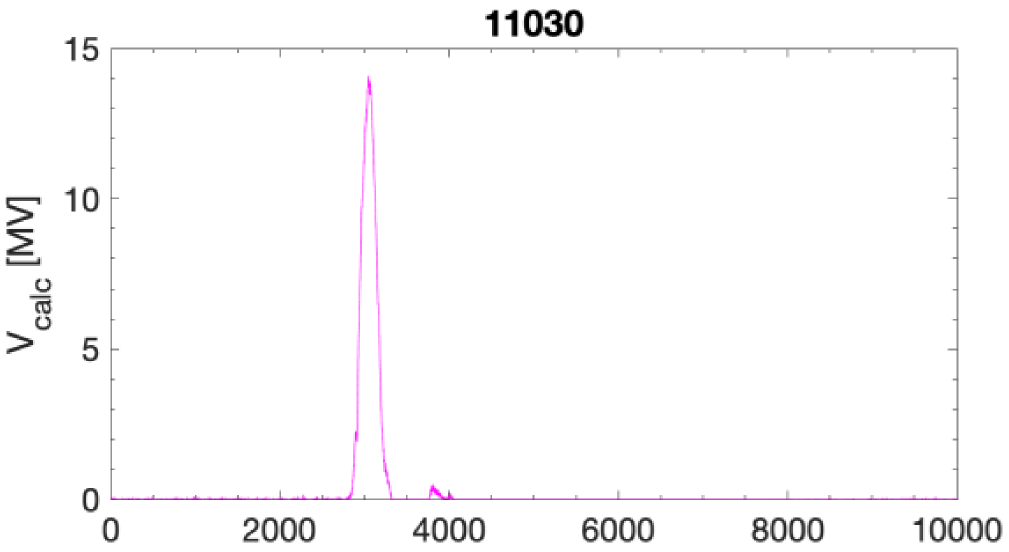


θ(r) averaged over window 65 to 80 ns
Incident Angle [degrees]

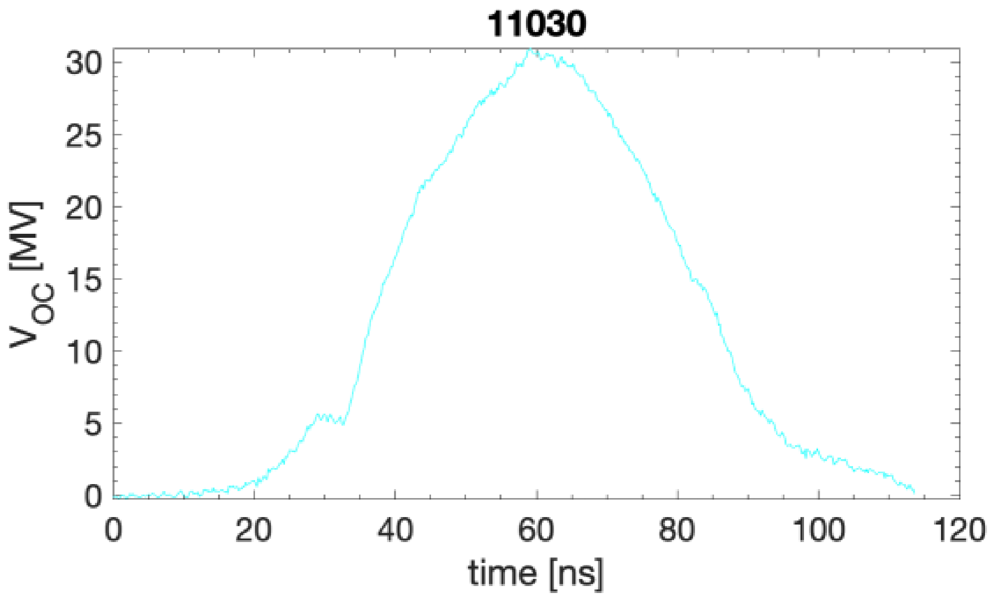


11029_34-70_80Q degrees TLD_vs Predicted DoseCF2
A-K gap = 73 cm
TLD_krad
DoseCF2
(krad)
r (cm)

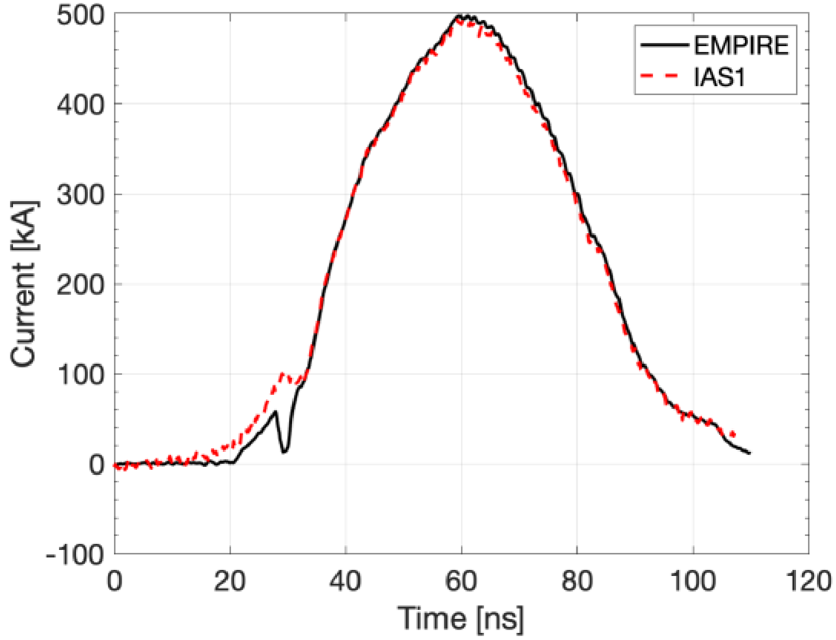
11030



11030
15
10
5
0
V_{calc} [MV]
0
2000
4000
6000
8000
10000

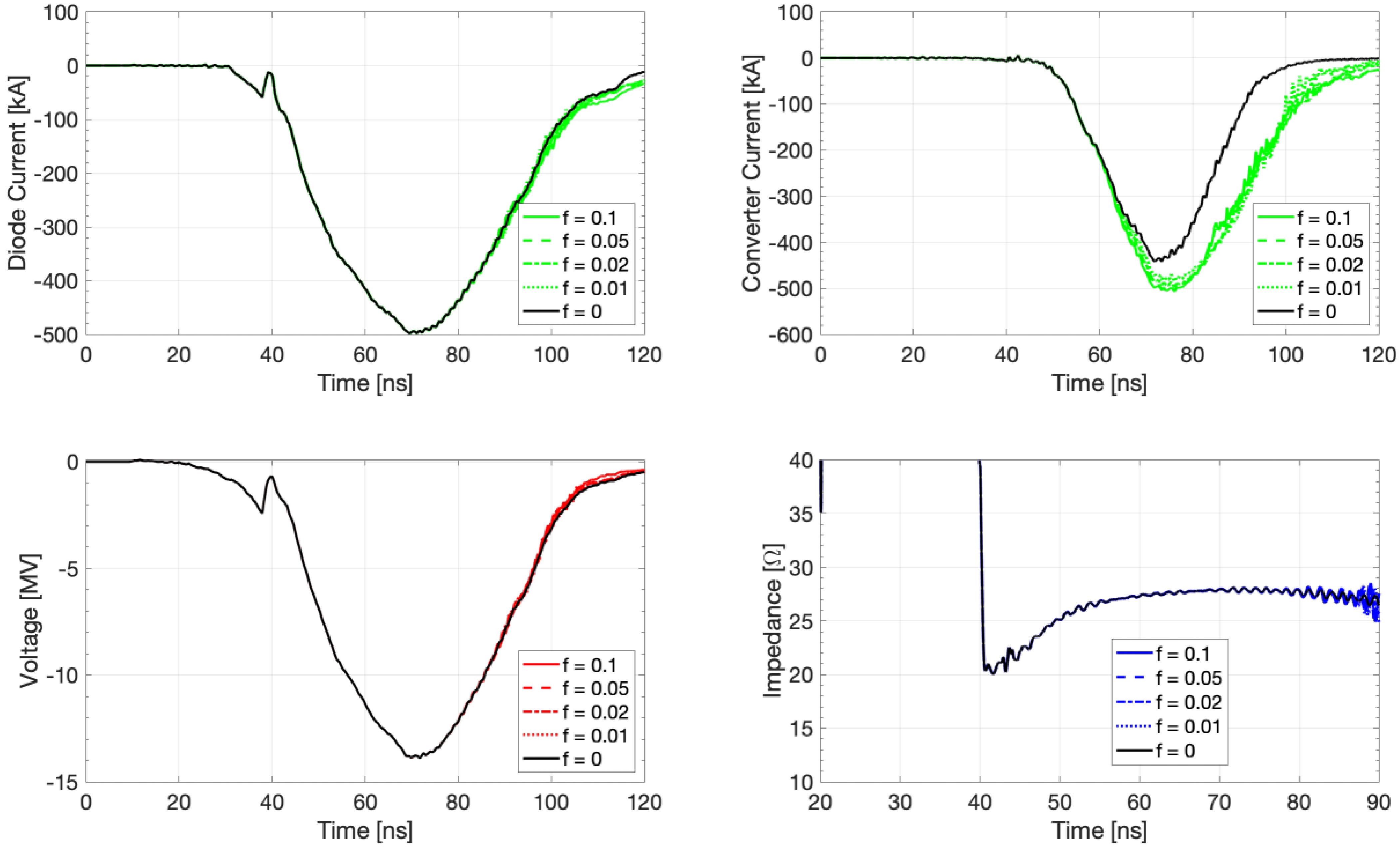


11030
30
25
20
15
10
5
0
V_{OC} [MV]
0
20
40
60
80
100
120
time [ns]

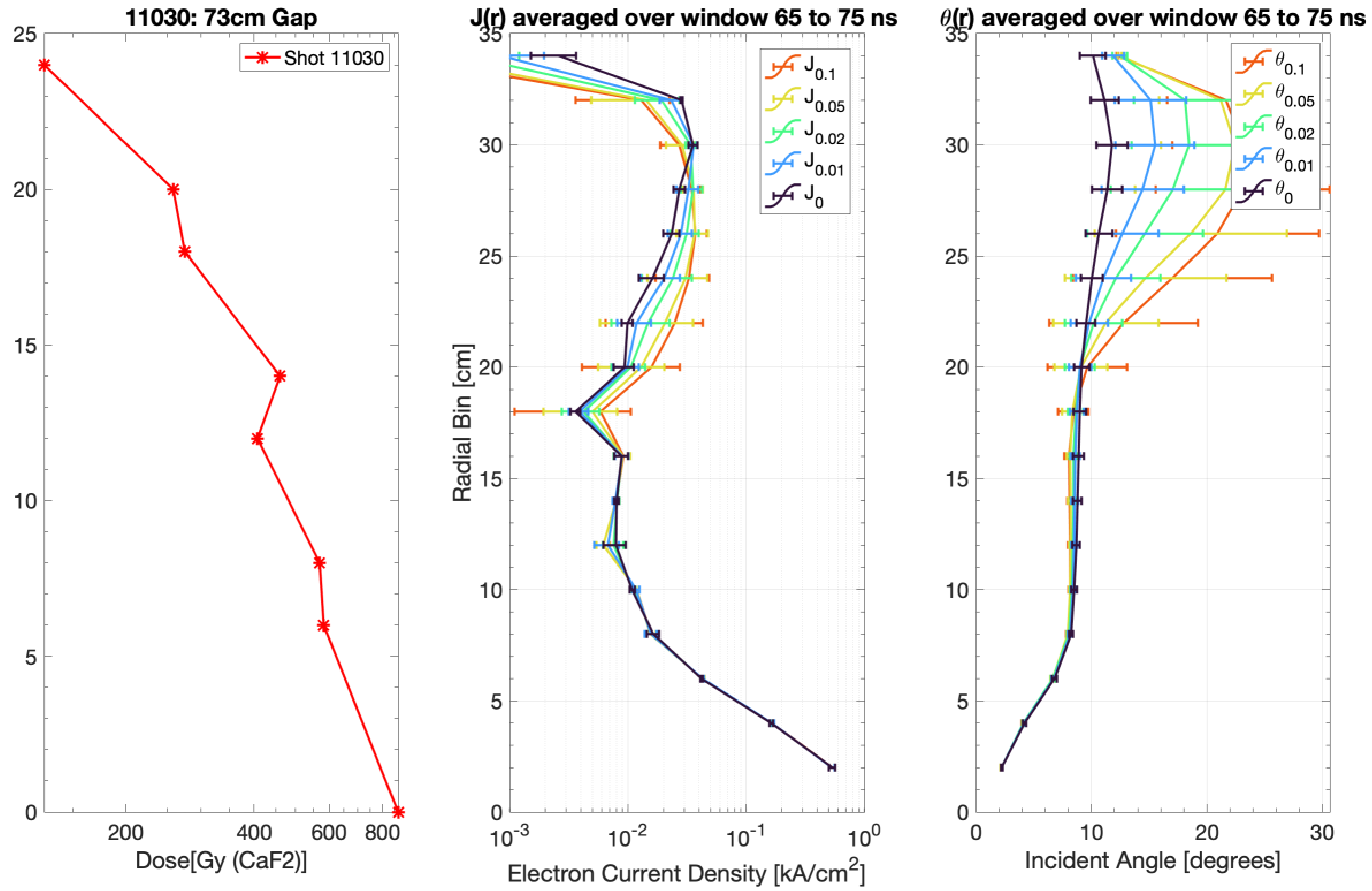


EMPIRE
IAS1
500
400
300
200
100
0
-100
Current [kA]
0
20
40
60
80
100
120
Time [ns]

EMPIRE Replication of Shot 11030



11030



11030: 73cm Gap
Shot 11030
Dose[Gy (CaF2)]
J(r) averaged over window 65 to 75 ns
Radial Bin [cm]
Electron Current Density [kA/cm2]
$J_{0.1}$
$J_{0.05}$
$J_{0.02}$
$J_{0.01}$
J_0
θ(r) averaged over window 65 to 75 ns
$\theta_{0.1}$
$\theta_{0.05}$
$\theta_{0.02}$
$\theta_{0.01}$
θ_0
Incident Angle [degrees]