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Controlling Feed Electron Flow in MITL-Driven Radiographic Diodes

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Abstract

The electrons flowing in a coaxial magnetically insulated transmission line (MITL), if allowed to flow uncontrolled into a radiographic electron diode load, can have an adverse impact on the performance of the system. Total radiation dose, impedance lifetime, and spot quality (size, shape, position, and stability) can be all affected [1]. One common approach to keeping such feed electrons out of the diode region involves greatly increasing the radius of the MITL's outer (anode) electrode near the diode and adding a large, rounded protuberance to the load end of the inner cathode conductor, forcing these electrons to be lost to the to the anode outside the diode itself [2]. While this approach can be quite successful, there is an inductance penalty that reduces the current that can be delivered to the load and requires a large volume in the vicinity of the load. For applications where this volume is not available, an alternate method of controlling the feed electrons is needed.

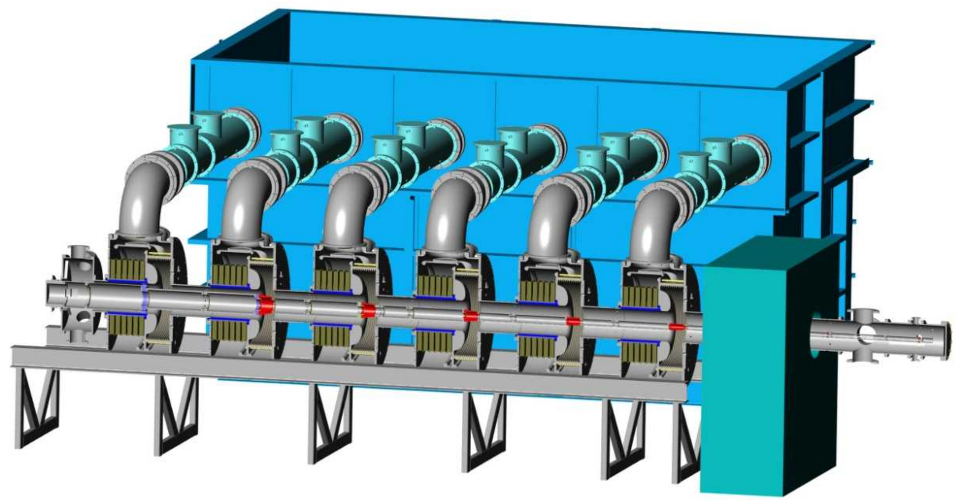
In this paper, we will investigate various ideas for dealing with this issue. For example, one could consider the effect of a solenoidal magnetic field at or near the end of the MITL on the electron flow. Such fields have been successfully used in other devices, such as ion diodes [3] and plasma opening switches [4], to control the flow of electrons. These fields could be produced using the MITL current directly by adding one or more field coils in series with the MITL circuit, or through coils that are pulsed using a separate power supply, possibly on a longer timescale.

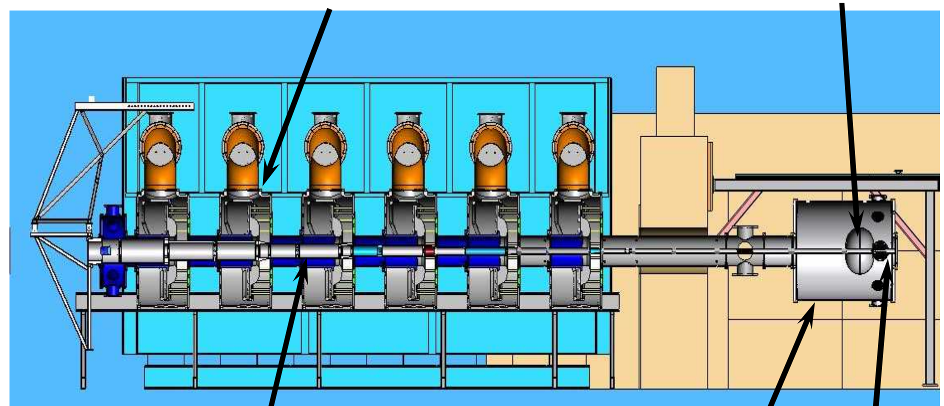
We will present results showing the properties of the various schemes investigated, and compare the relative merits of any that prove viable.

1. K. D. Hahn, et al., IEEE Trans. Plasma Sci. 38, 2652, 2010.
2. N. Bruner, et al., PRST Accel. Beams, 11, 040401, 2008.
3. S.A. Slutz, D.B. Seidel, and R.S. Coats, J. Appl. Phys., 61, 4970, 1987.
4. M.E. Savage, D.B. Seidel, and C.W. Mendel, Jr., IEEE Trans. Plasma Sci. 28, 1533, 2000.

RITS-6 Induction Voltage Adder Accelerator

- The Radiographic Integrated Test Stand is used for advanced X-ray radiography applications at Sandia
- 6 PFL feed 6 induction cavities which are joined in series by a 51 Ω MITL
  - Delivers 7 to 11 MV, 150 to 200 kA in a 75 ns pulse
- “Dustbin” and “Knob” configuration has been effective in preventing MITL feed current from entering the diode region
  - Disadvantage: requires large volume at accelerator front end
- Can lower-volume configurations be found that provide comparable feed electron control?
  - Geometric
  - Magnetic





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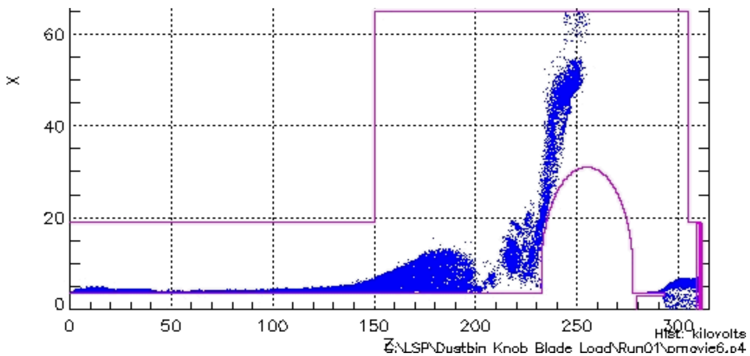
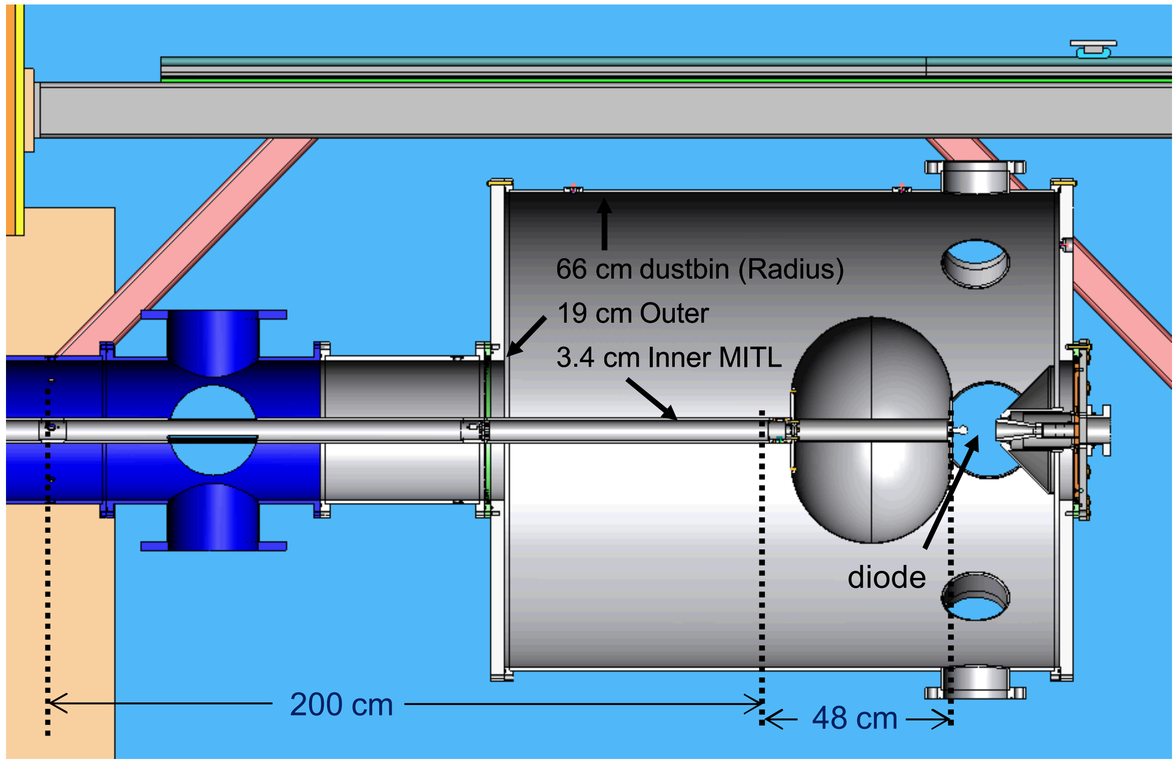
Knob and Dustbin Configuration

- This front end configuration has proven effective for keeping feed electrons out of the diode region
  - Relies on knob surface being non-emitting
  - Requires a larger-than-desirable volume
  - Increases system inductance
- EM-PIC Simulations have confirmed its operation

High Impedance (102 Ω) MITL



Lsp simulations by V. Bailey, L-3com



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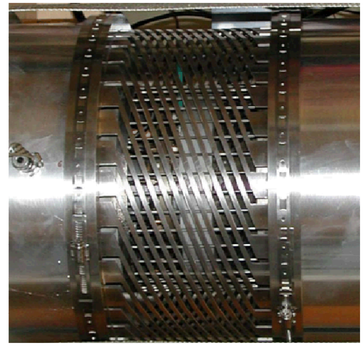
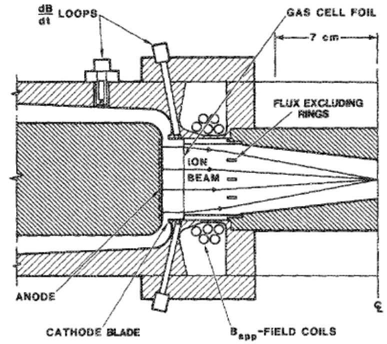
Using Magnetic field to control feed electrons

- Two methods of generating field:
  - Use accelerator current to drive coils placed in series with the MITL
  - Use pulsed external circuit to drive coils (on a longer time scale)

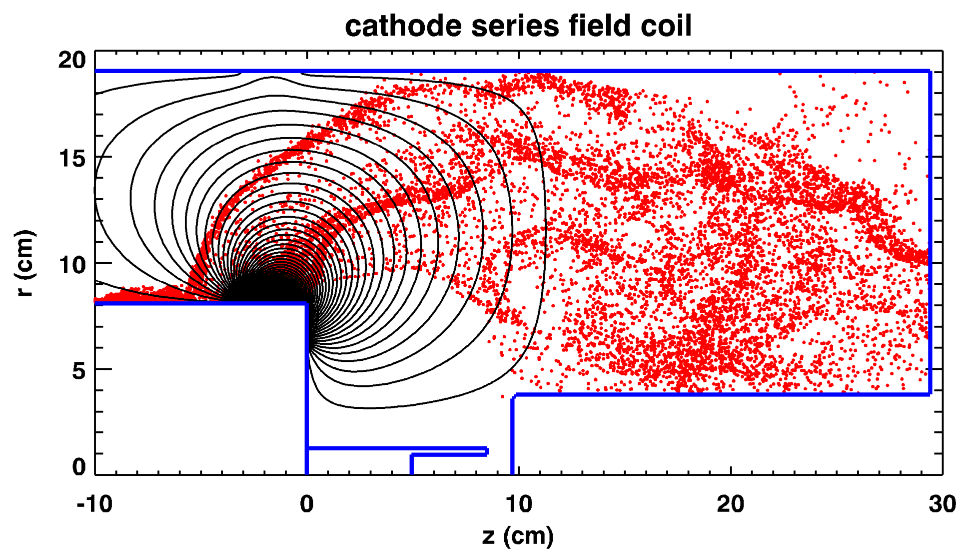


Triggered plasma opening switch (ref. 4)



Applied-B Ion Diode (ref. 3)

- Two effects on electron flow:
  - Field lines connecting feed electrodes can carry electrons to anode outside the diode region
  - Electrons crossing magnetic flux before striking anode are constrained outside some minimum radius



19 cm outer radius

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Minimum radius constraint due to crossed magnetic flux

- If energy and canonical angular momentum are conserved,

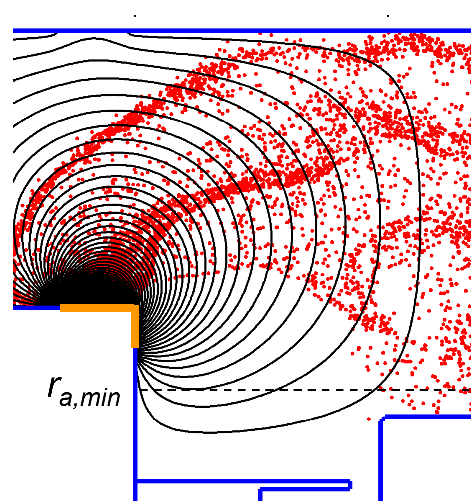
$$\left(\frac{\Delta\Psi}{r_a}\frac{e}{mc}\right)^2 = \left(\frac{e\phi}{mc^2}+1\right)^2 - 1 - \gamma\left(\beta_z^2+\beta_r^2\right),$$ where $\Psi(\mathbf{r}) = rA_\theta(\mathbf{r})$ is the magnetic stream function,

and $\Delta\Psi = \Psi(\mathbf{r}_c) - \Psi(\mathbf{r}_a)$. β is the the electron's normalized velocity v/c.

$\mathbf{r}_c$ and $\mathbf{r}_a$ are the electron's cathode emission and anode loss locations, respectively.

- Since the β terms are always positive, a minimum electron radius can be obtained

$$\left(\frac{\Delta\Psi}{r_a}\frac{e}{mc}\right)^2 \le \left(\frac{eV}{mc^2}+1\right)^2 - 1 \quad \Rightarrow \quad r_a \ge \frac{\frac{e}{mc}\Delta\Psi}{\left[\left(\frac{eV}{mc^2}+1\right)^2-1\right]^{1/2}}$$

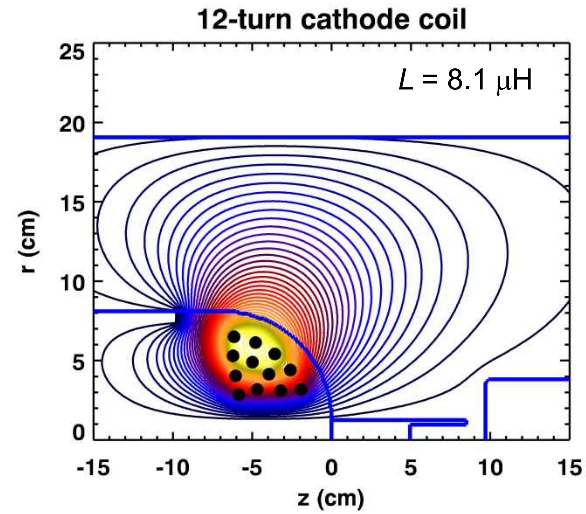


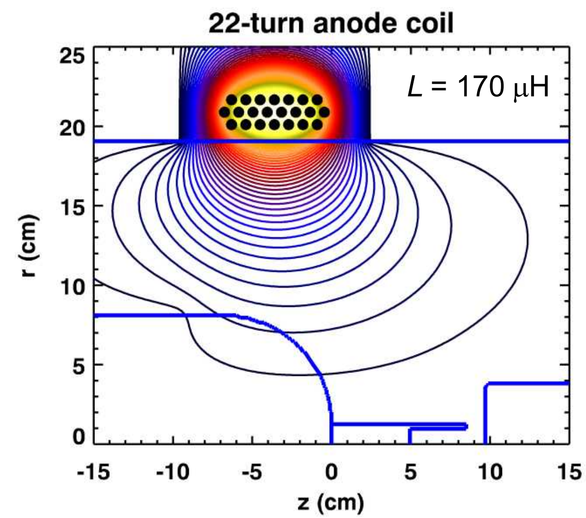
- For example at right, the magnetic field amplitude can be chosen such that electrons emitted over the orange portion of cathode cannot get into the diode region
  - For V = 6 MV, this series field coil configuration requires 120 kA-turns to obtain this field amplitude !

Current requirements for series coils make their use problematic

Use externally-driven applied field coils to provide magnetic field

- Advantages:
  - Longer time scales allow field to penetrate lossy conductors (stainless, titanium, etc.)
  - Conductors can be used to precisely shape the field
  - Mechanical issues with high-wrap field coils can be avoided
- Disadvantages:
  - Complication of separate drive circuitry
  - Activation issues for cathode coil housing materials
- Cathode coils are most effective for providing desirable field topologies, but
  - external circuit connection must go through cathode stalk
  - Coil housing presents activation issues
- Anode coil requires lossy or vaned cathode to allow flux penetration — it also adds volume
- Several Quicksilver simulations have been performed using the two field configurations shown at right





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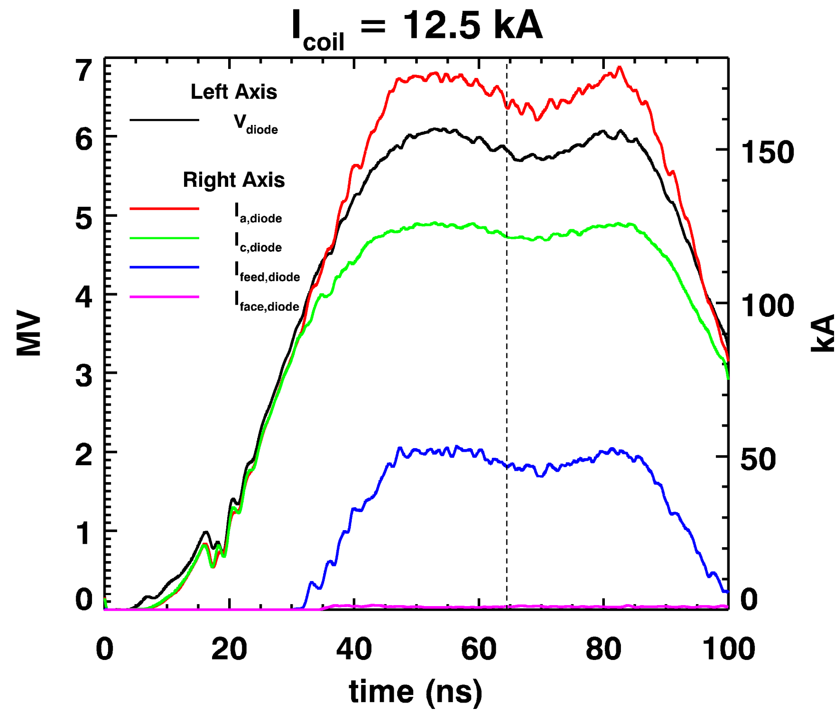
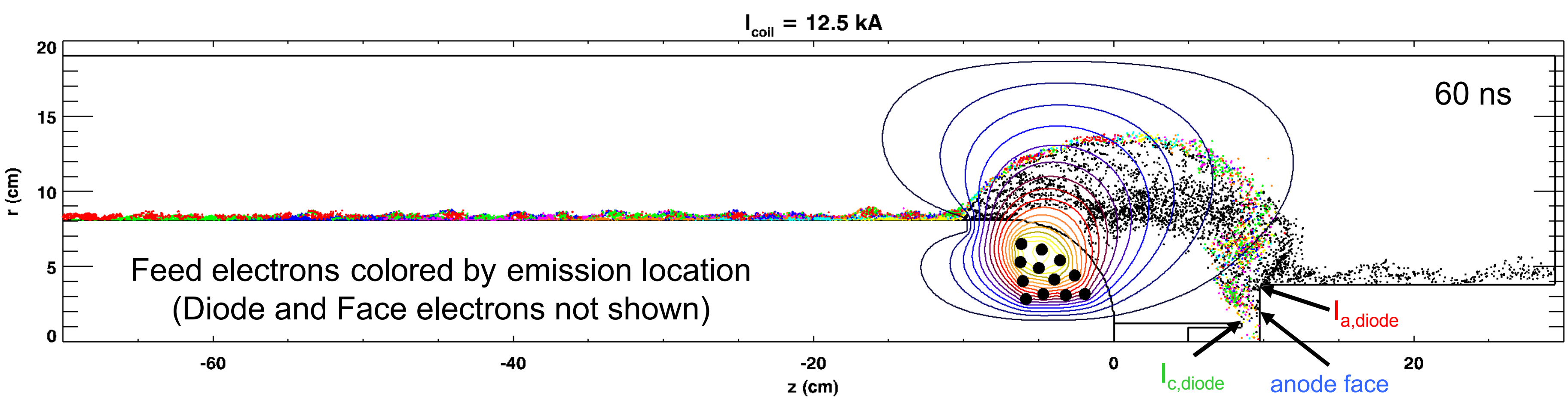
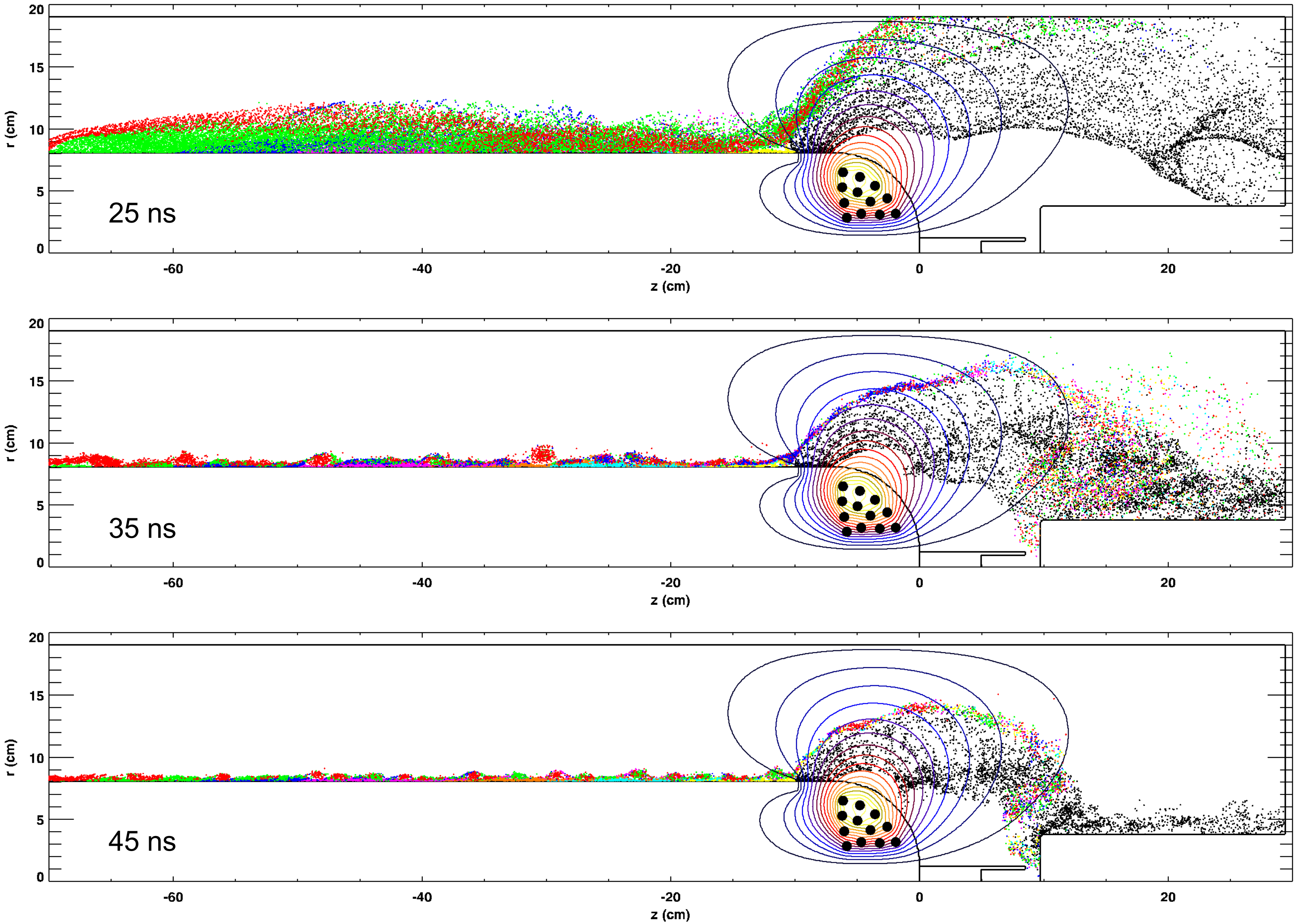
12-turn cathode coil with 12.5 kA drive current

- With this field amplitude, all feed electrons stay outside the diode region below ~ 3.5 MV
- At higher voltage, upstream feed electrons are lost to the anode face
- Only a small fraction of electrons emitted from the cathode face (i.e., the rounded surface) are lost to the anode face
- Upstream electron flow capture would be improved if the magnetic flux penetrated the feed's anode





Time evolution of feed electron flow



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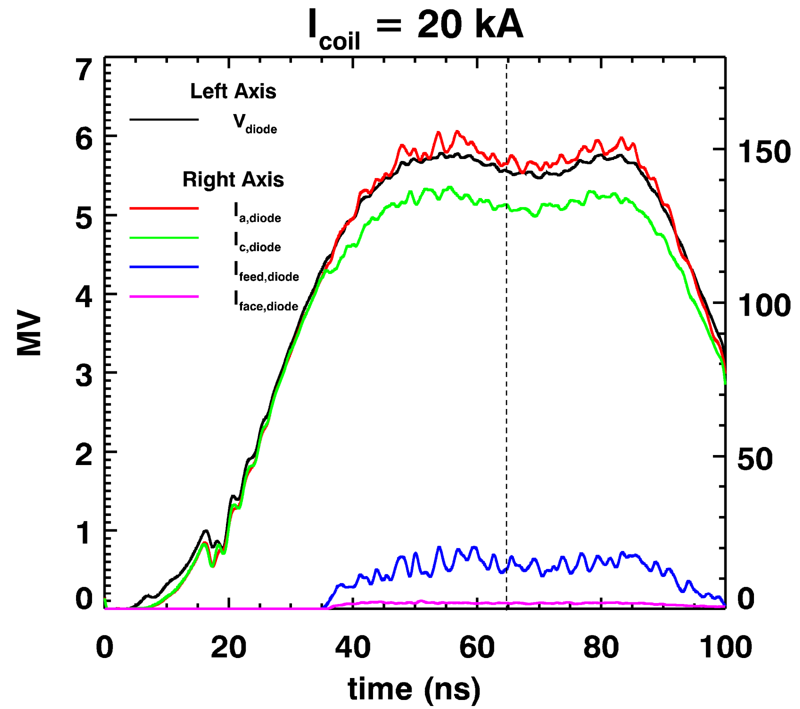
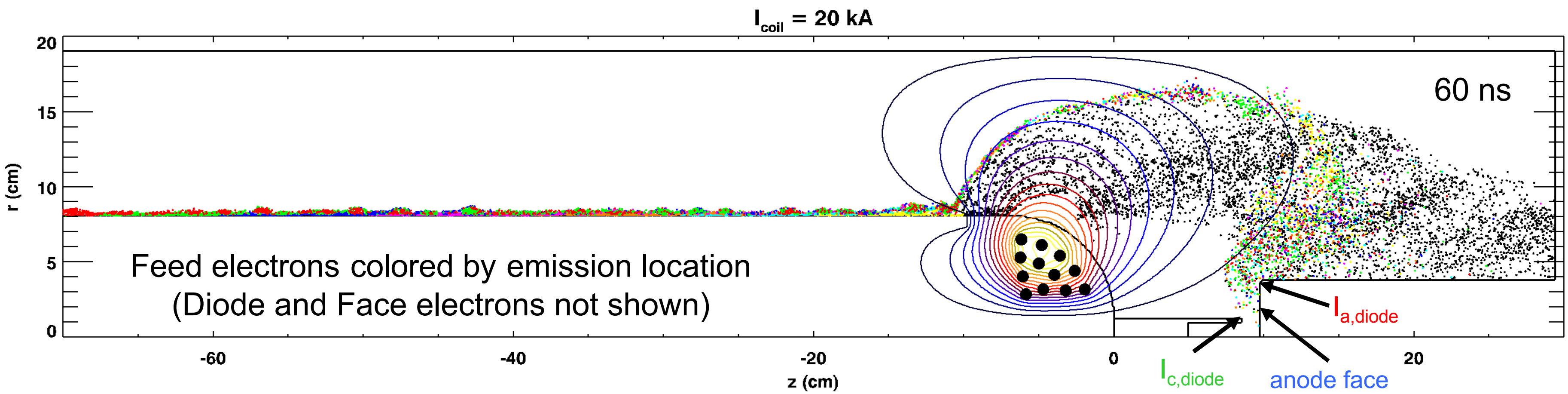
12-turn cathode coil with 20 kA drive current

- With this field amplitude, all feed electrons stay outside the diode region below ~ 5 MV
- Peak current from feed electrons lost to the anode face is down by a factor of 3
- Remaining portion is due almost entirely to electrons born on zero flux surfaces
- Current due to electrons emitted from the cathode face is up slightly, but still small
- Next try configuration in which the magnetic field penetrates the feed anode





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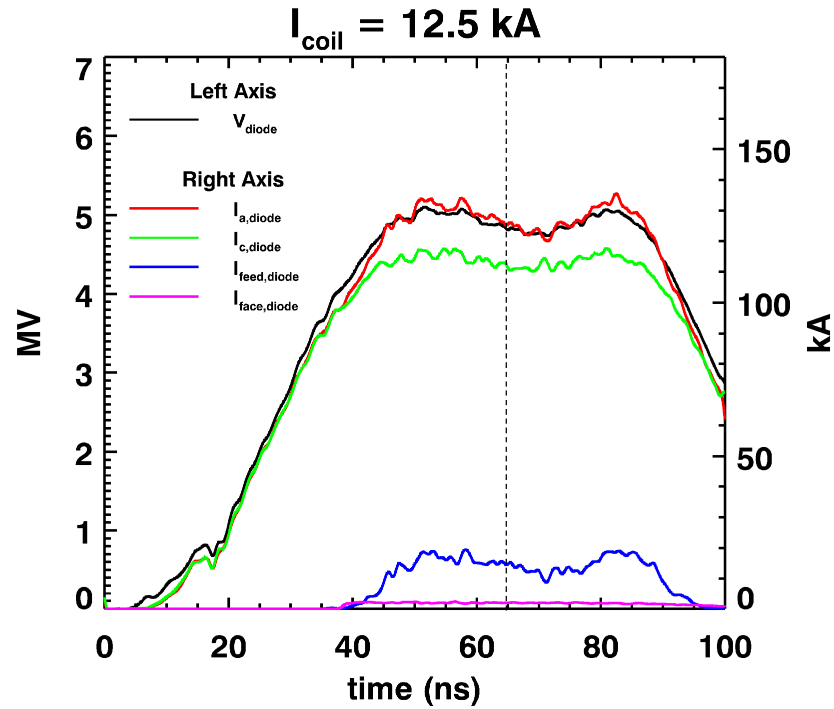
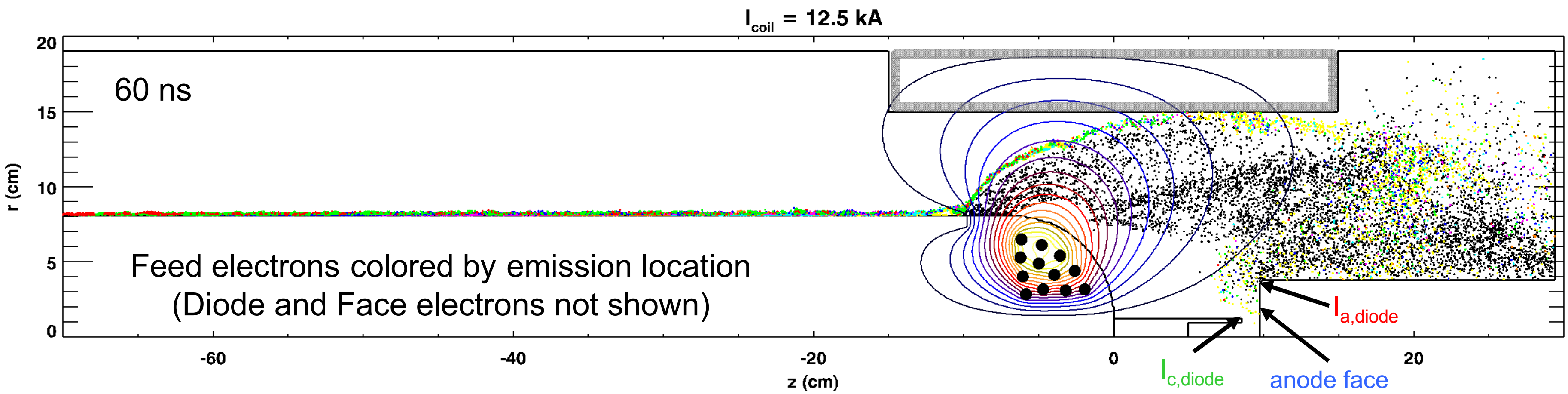
Add an “electron catcher” to intercept upstream flow electrons

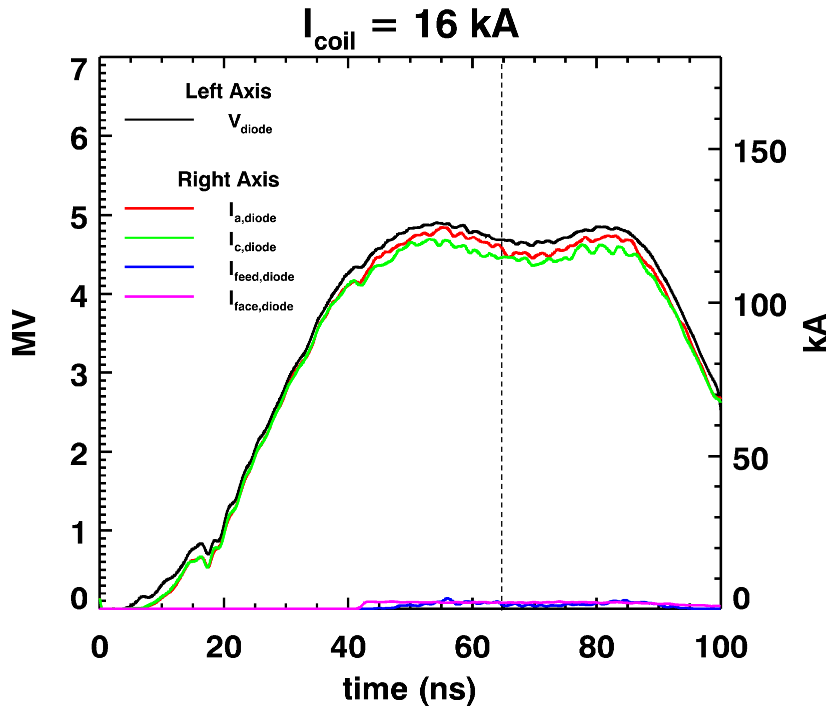
- Electron catcher is a thin shell made of stainless steel or alternate lossy conductor
  - Activation not an issue for anode
- The one simulated is 30 cm long with an inner radius of 15 cm
- Provides comparable performance to 20 kA configuration (w/o catcher) with only 12.5 kA coil drive current.
- Increased electron loss current has loaded down the voltage — catcher AK gap determines MITL operating impedance

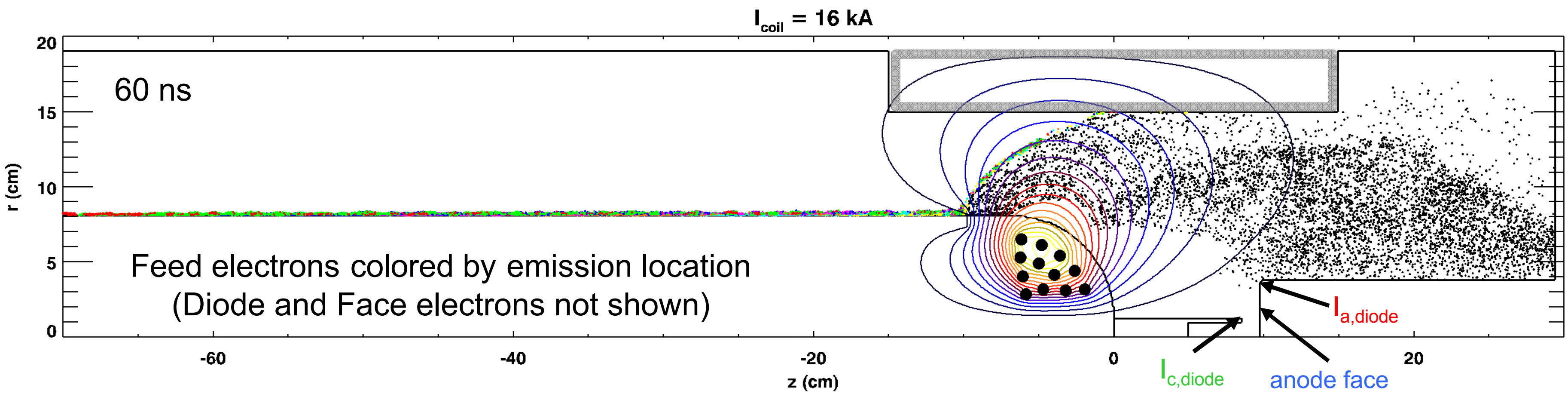




Modest increase in coil current eliminates all feed electrons from the diode region

- By increasing coil current to 16 kA, virtually all feed electrons are captured outside of the diode region.
  - Electrons emitted upstream of coil are driven to the catcher.
  - Electrons emitted from coil region are constrained by their non-zero canonical angular momentum.
- External circuit requirements (neglecting losses):
  - $L = 8.1\ \mu\text{H},\ \tau_{peak} = 60\ \mu\text{s},\ C \approx 200\ \mu\text{F}$
  - $I_{peak} = 16$ kA, $V_{chrg} \approx 4$ kV, E ≈ 1.6 kJ





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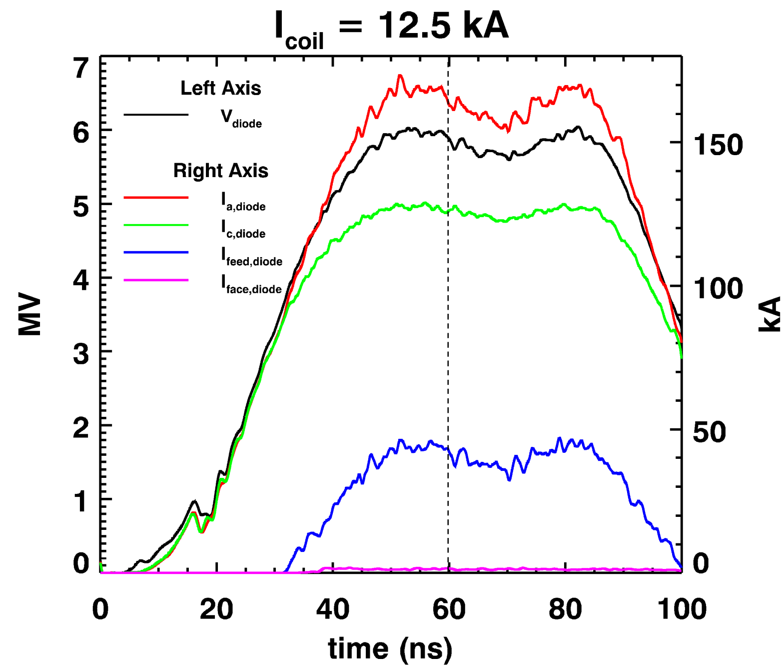
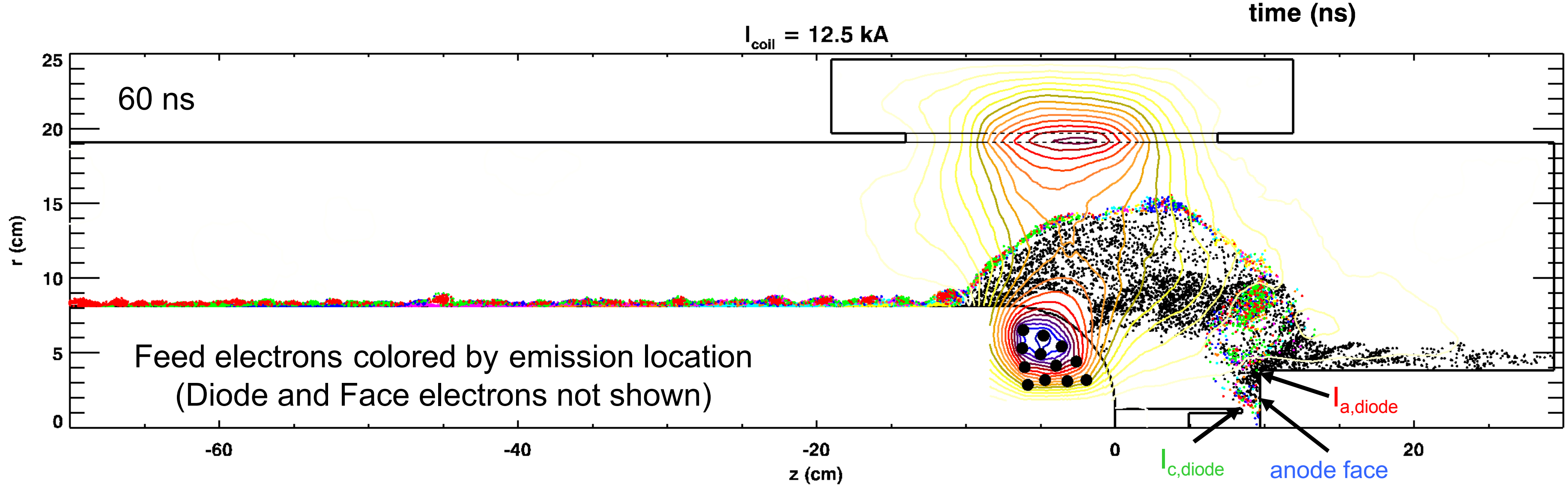
Add an anode series field coil for anode flux penetration

- A modest series field coil was placed in feed's anode
  - Δz = ~10 cm, pitch = 2 → ~1 radian wrap
  - ~5 cm radial coil vanes at each end
- 12.5 kA drive for external cathode coil
- Provides only a slight improvement over original configuration with same external coil drive current





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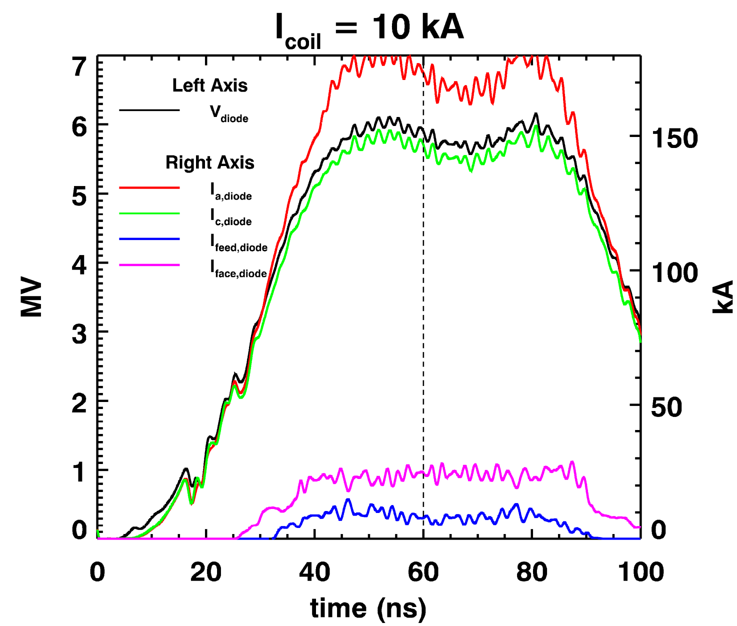
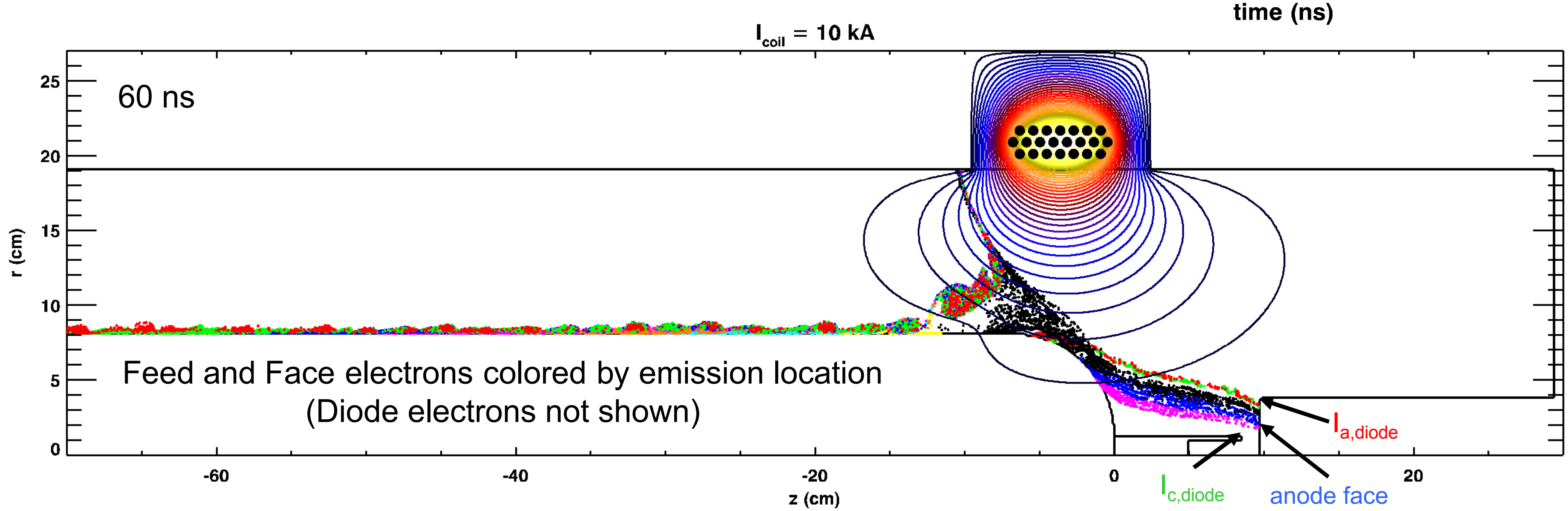
Anode coil driven with an external circuit

- Requires lossy or vaned cathode to allow flux to penetrate cathode
- Almost all feed electrons diverted to outer anode
- Only a small fraction of face electrons are excluded from the diode region
- Energy requirements for external coil driver are ~10 times higher than best cathode coil configuration





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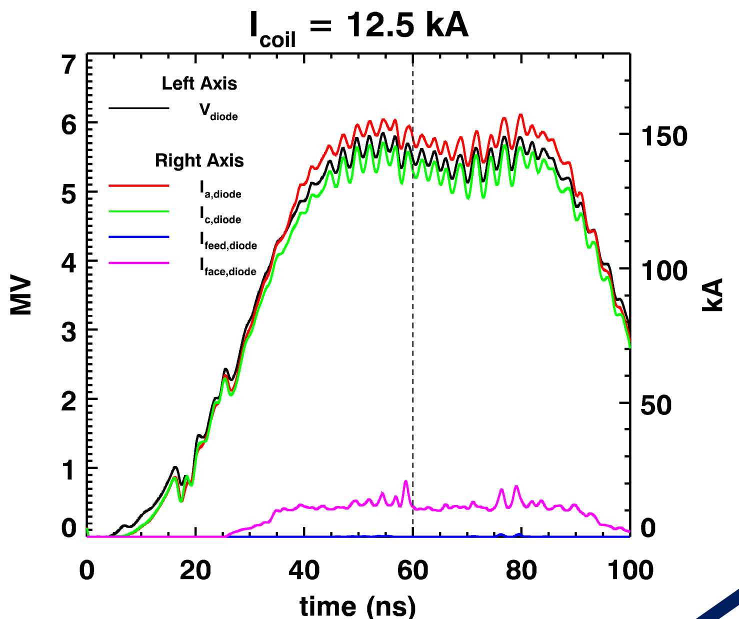
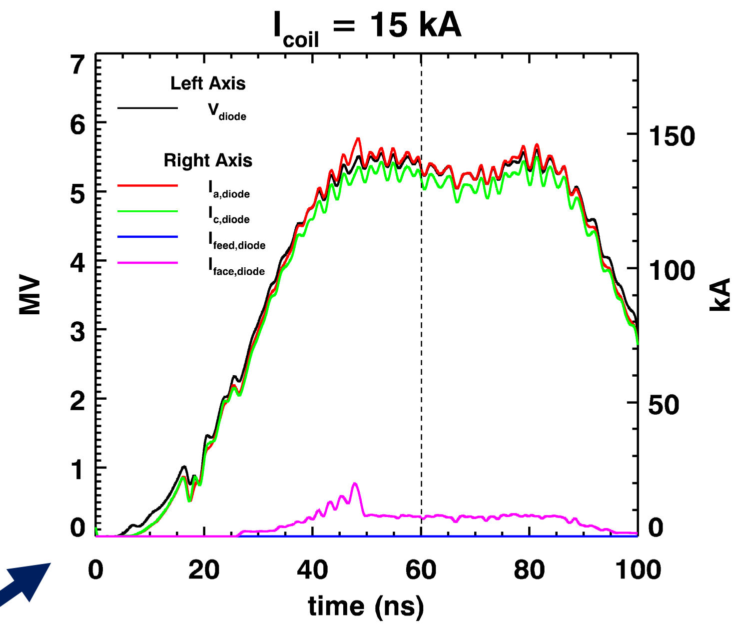
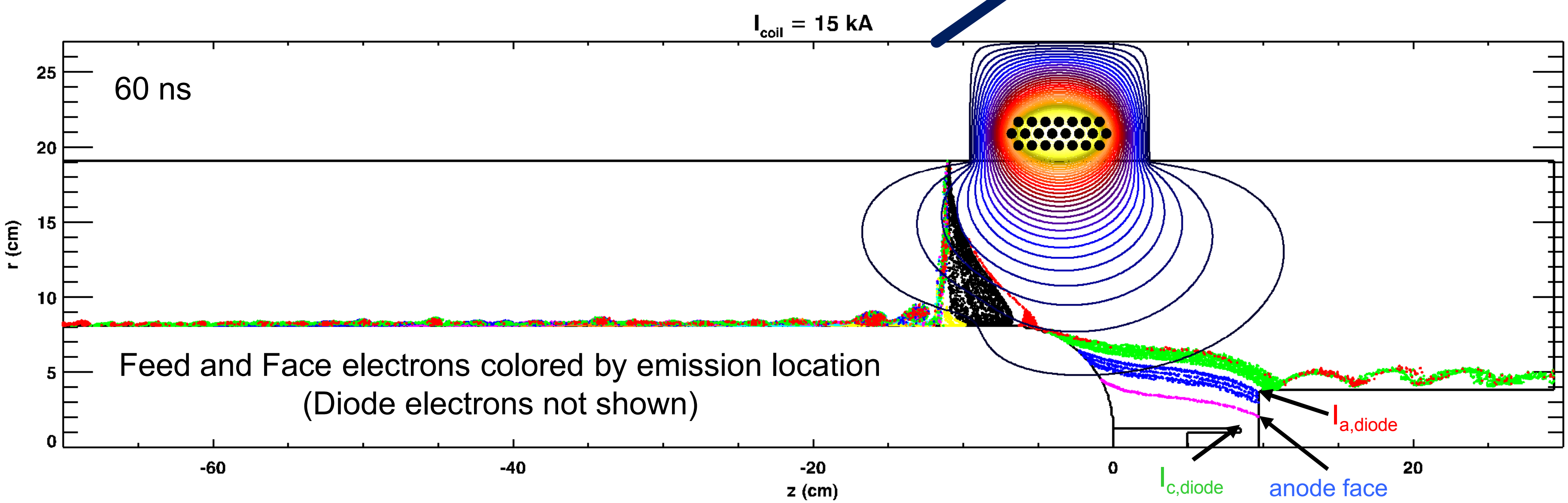
Increasing coil drive current reduces unwanted electron flow to anode face

- Reduction due to increased flux for face electrons to cross
- Reduction comes at expense of reduced voltage and diode current







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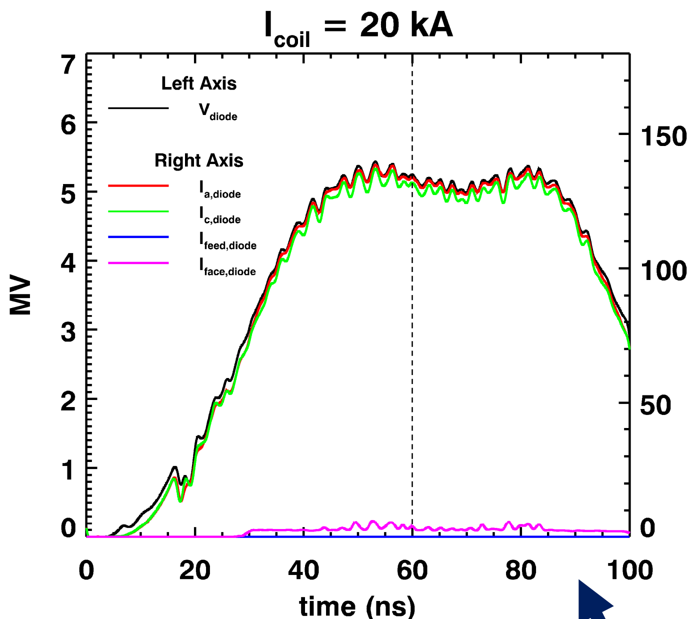
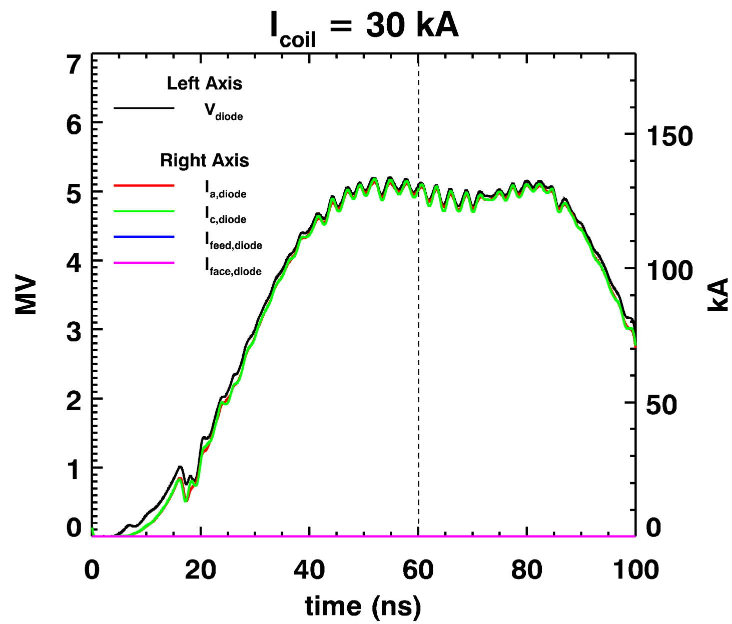
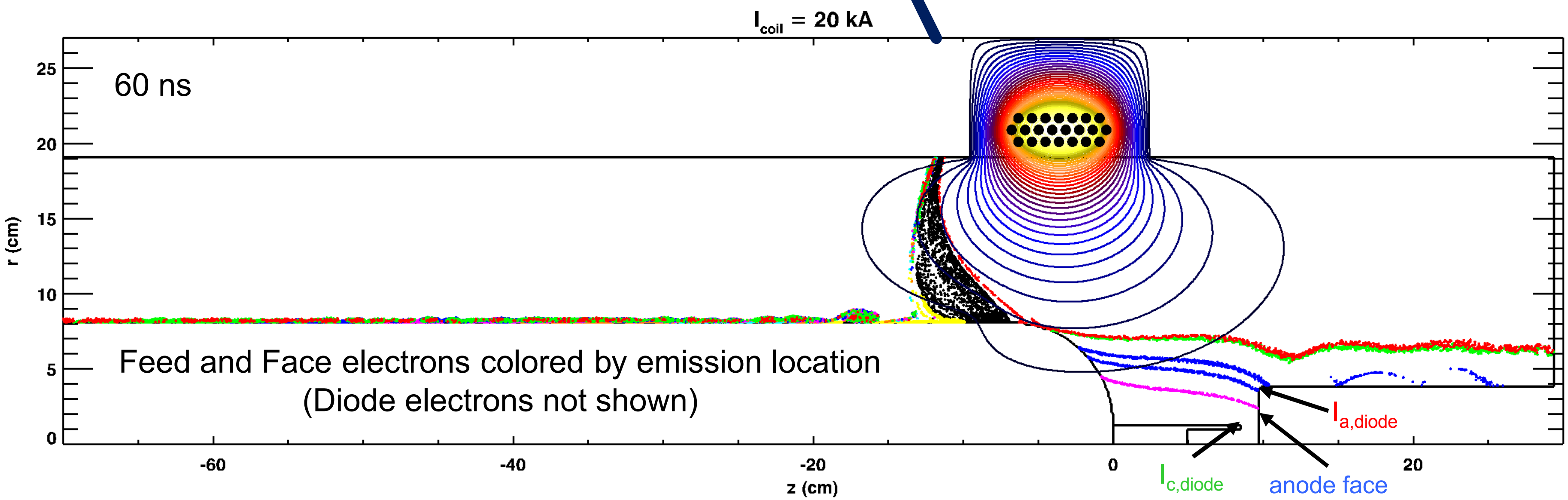
30 kA coil drive current eliminates unwanted flow

- Voltage and diode current continue to decrease
- At 30kA, the required coil circuit bank energy approaching 100 kJ.







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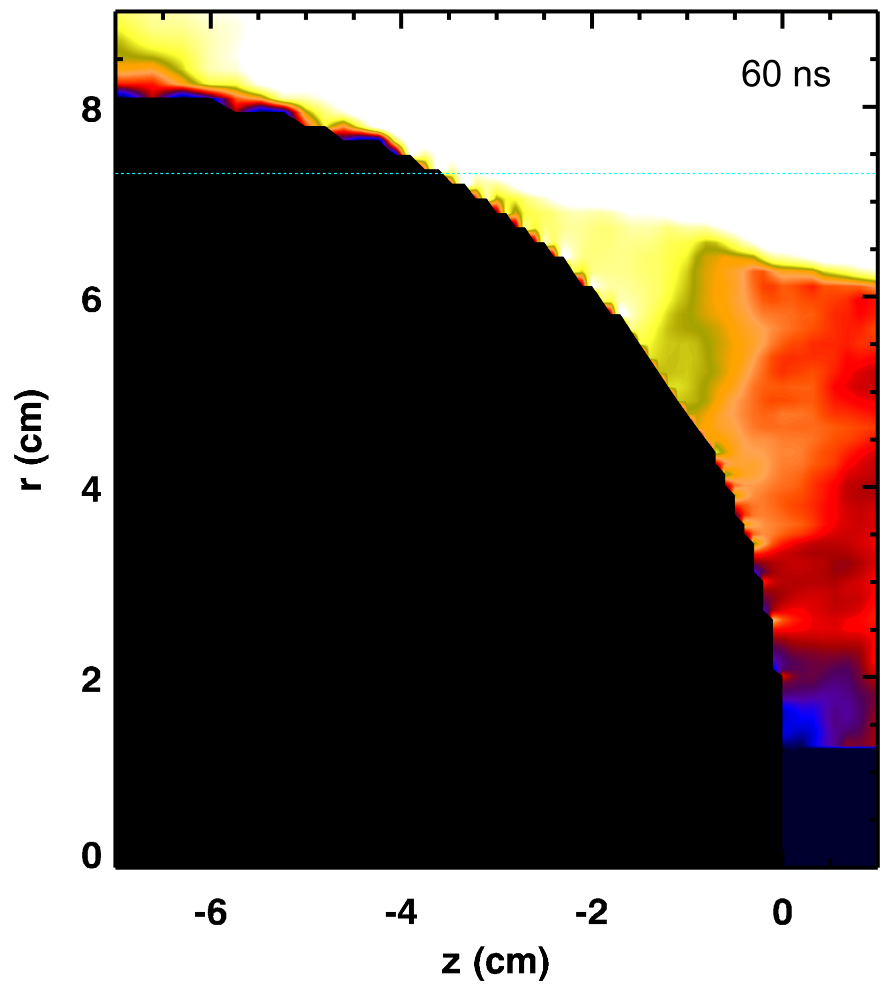
Electron emission from the cathode face is exaggerated by its stair-step surface

- With proper surface preparation, the knob of the existing RITS MITL electric field breakdown threshold has been demonstrated to exceed 550 kV/cm
- Simulation surface uses cell diagonals to avoid 90° corners
- Remaining corners still produce unphysical enhancement to electric field
- As shown at right, simulation E-field only exceeds this breakdown threshold at artificially-enhanced corners of surface
  - For this simulation, cathode emission was inhibited below 7.3 cm
  - Time shown is representative of peak field on this surface at any time in simulation
- It is reasonable to assume that limiting emission on this portion of the cathode is justified

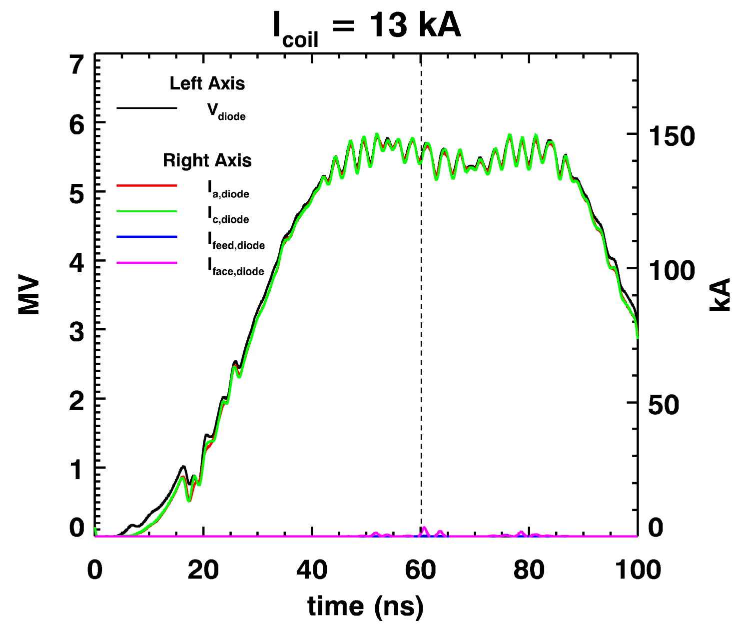
|E| on cathode face

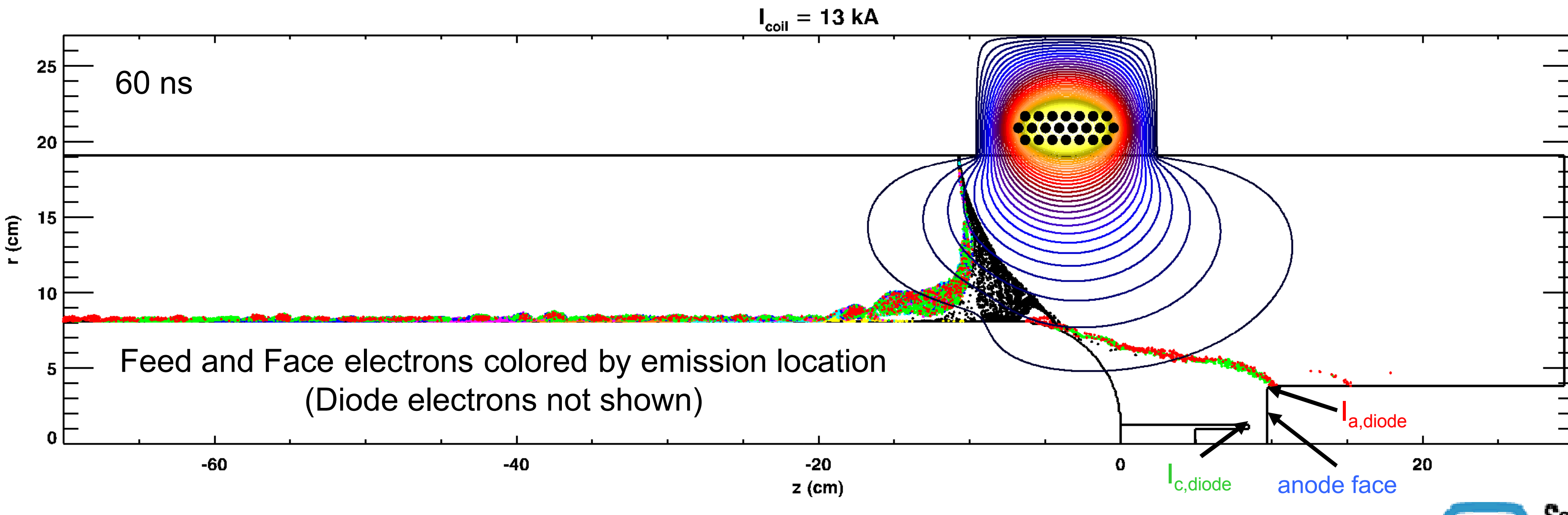


Cathode emission allowed for $r > 7.3$ cm
White indicates |E| > 550 kV/cm

Example of limiting electron emission on cathode face

- External circuit requirements (neglecting losses):
  - L = 170.1 μH, I_{peak} = 13 kA, E ≈ 16 kJ
  - Longer time scales required to avoid very high charge voltage. Some possible options are:
    - $V_{chrg} \approx 20$ kV → $\tau_{peak} \approx 175$ μs, $C \approx 72$ μF
    - $V_{chrg} \approx 25$ kV → $\tau_{peak} \approx 140$ μs, $C \approx 50$ μF
    - $V_{chrg} \approx 30$ kV → $\tau_{peak} \approx 115$ μs, $C \approx 32$ μF
- Note that although the external circuit requires ~10 times the energy as the 16 kA cathode coil, the voltage reduction due to loading down the accelerator is not as severe





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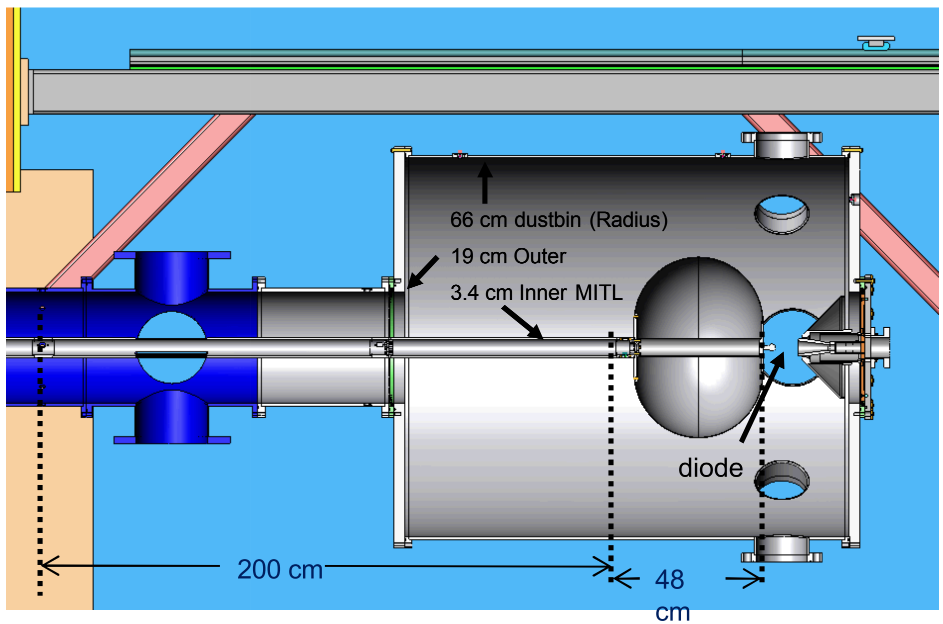
Using MITL geometry to control feed electrons

- We've just begun looking at using passive, geometry-only solutions to controlling feed electrons
- Since the dustbin/knob configuration has proven effective for this task, we've tried to use variations of that idea, but in smaller volumes
- So far, we've tried two variations:
  - A knob configuration confined to a 20-cm radius (comparable to our magnetic configurations)
  - A dustbin/knob scaled to fit within a 30-cm radius (original dustbin has 66-cm radius)

Original dustbin/knob system



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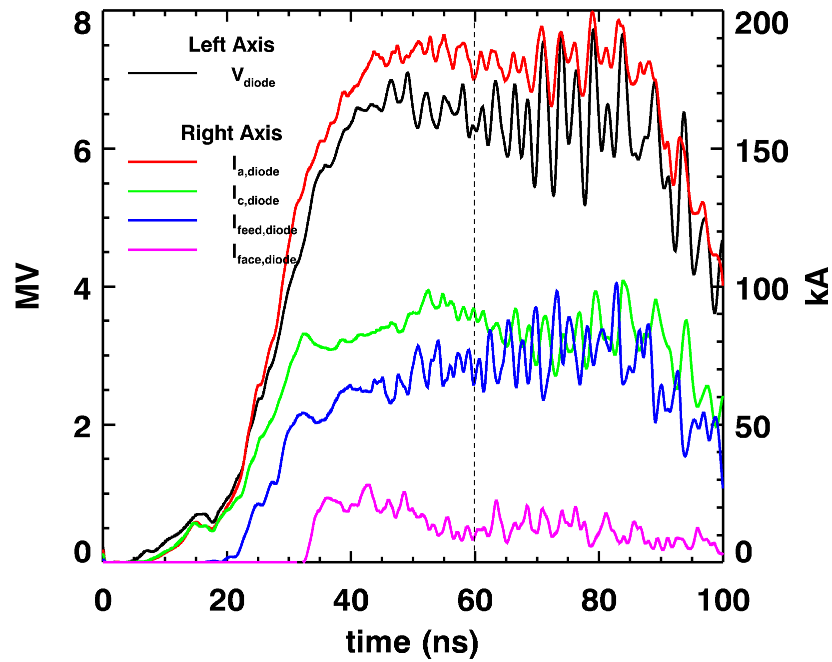
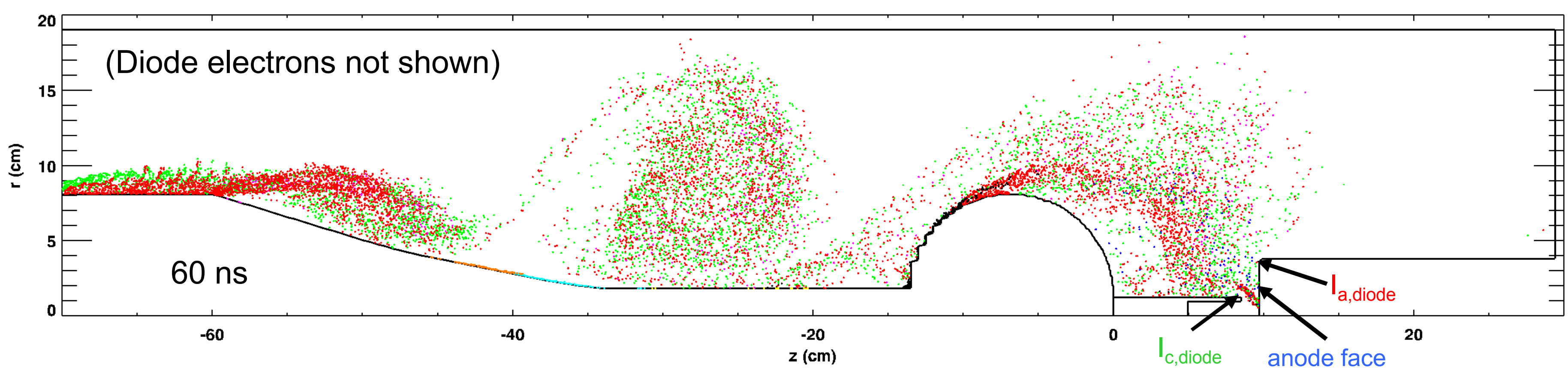
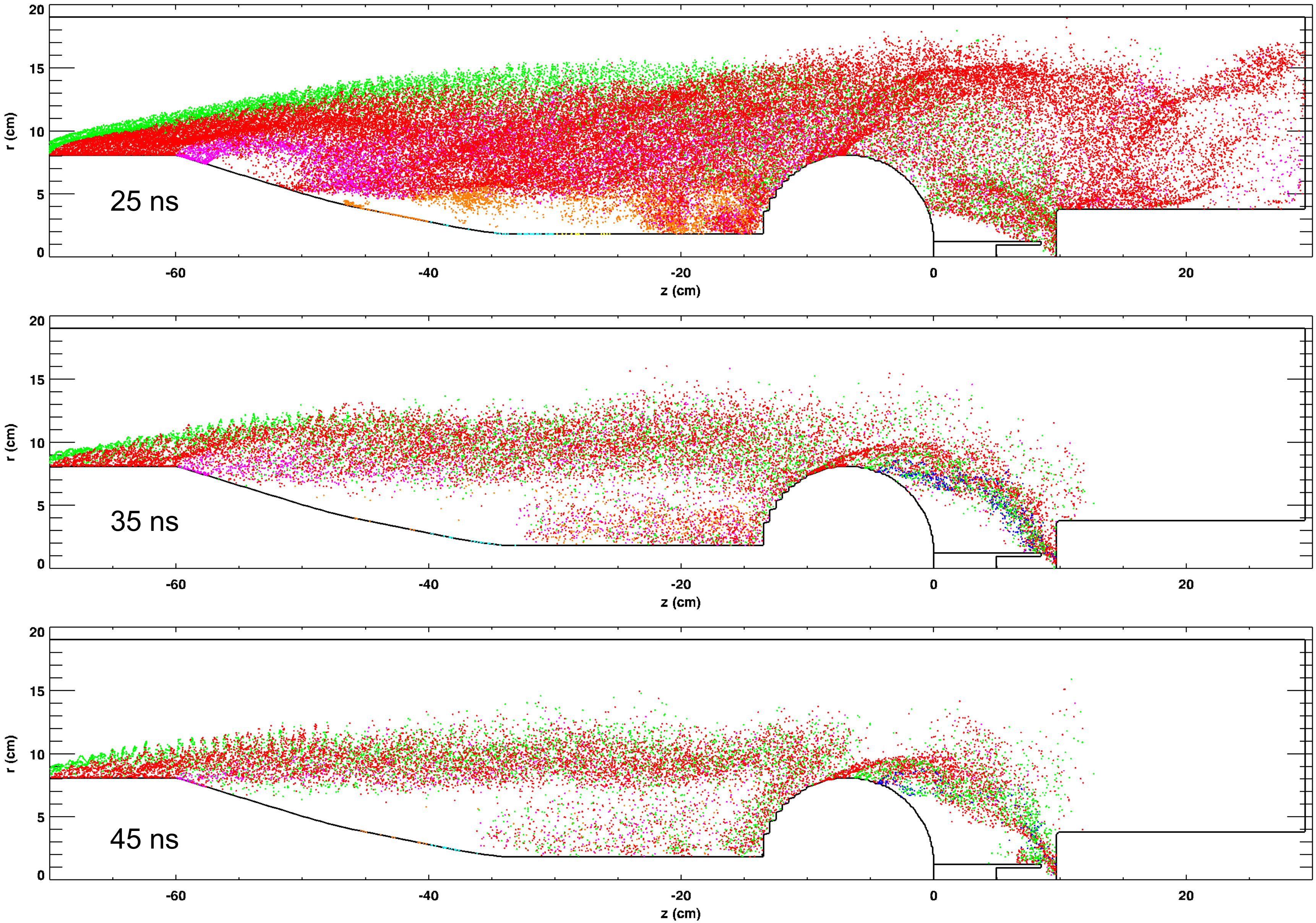
20-cm radius system with cathode knob

- Feed electron detach from cathode early in time and flow directly over the knob and into the diode region
- Eventually the flow becomes turbulent upstream of the knob, forming large vortices
- Almost all the feed and face electrons find their way to the anode face





Electron flow at earlier times



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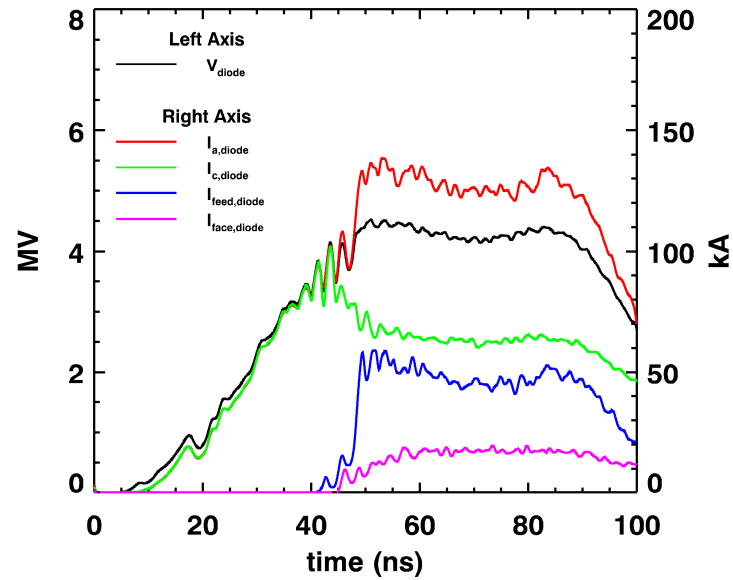
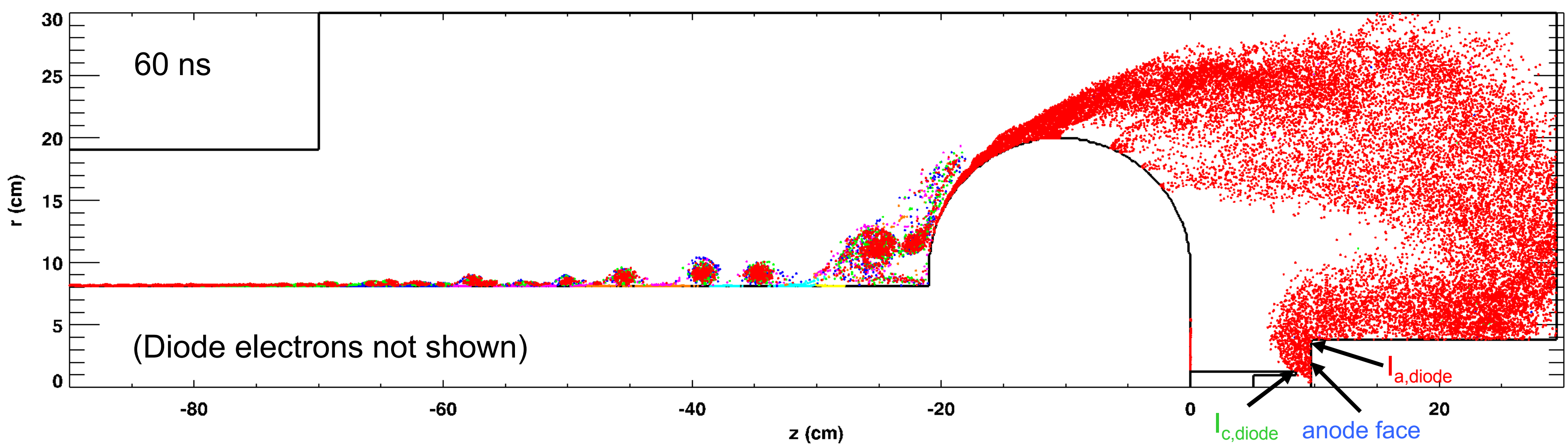
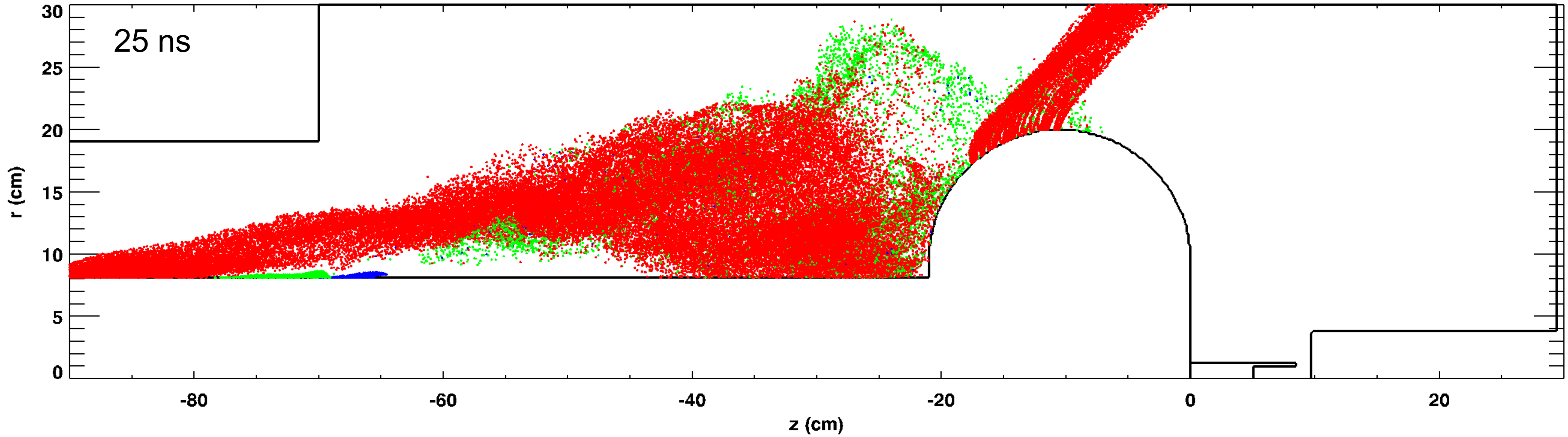
30-cm radius system with dustbin and knob

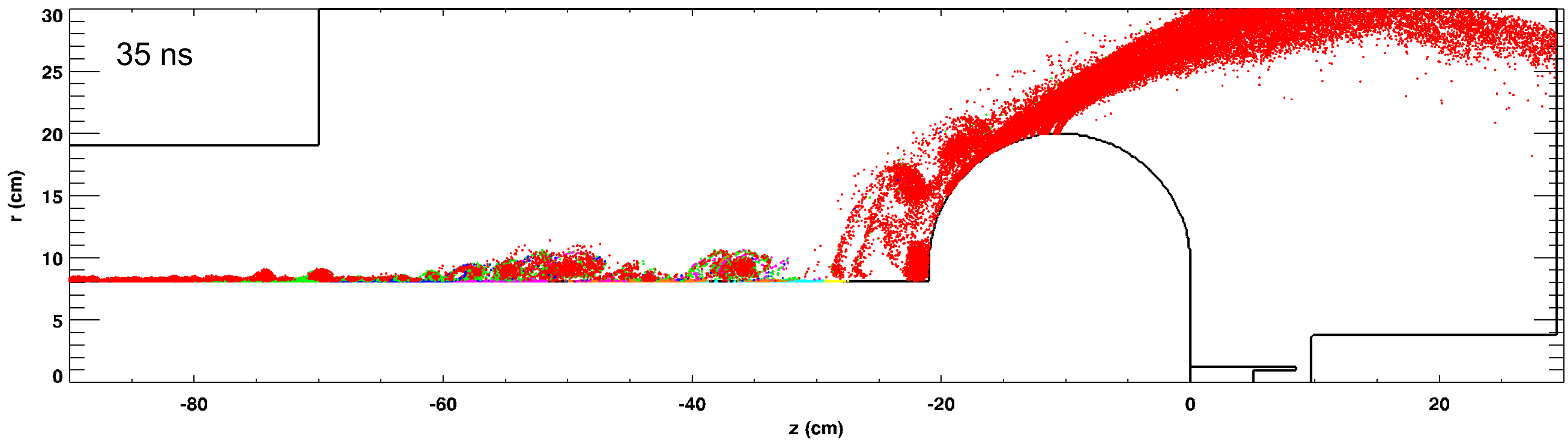
- Flow electrons stay out of diode until about 40 ns
  - after that over 50 kA are lost to anode face
- There is a large loss current in the feed itself, loading the voltage down to ~4 MV
- This is probably due to the impedance of the AK gap at the knob's tip being too small, limiting the MITL's operating voltage
- There are clearly several perturbations of this geometry that need to be tried





Electron flow at earlier times





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Summary

We have tested several ideas for feed electron control in low-volume front ends for RITS, using two basic approaches:

- Magnetic field control
  - Flux requirements at the voltages of interest are probably too high to use field coils in series with the MITL
  - Fields applied externally on a longer time scale can be effective solutions
  - Although cathode coil systems require substantially less energy to drive than anode coil systems, they present other difficulties, including more complicated drive circuitry and proton activation issues
  - Activation problems might be mitigated with judicious selection of coil housing materials
  - A more complete analysis of the coil systems, including proper treatment of losses would be needed to come up with an engineering design
- Geometric control
  - We've just started looking at this approach — only two configurations, both adaptations of the current RITS dustbin/knob system, have been examined so far
  - Both configurations we have looked at performed poorly
  - There is an arbitrarily large set of geometric controls we can try, and we will continue to look for something that works to control electron flow in a desirable fashion

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