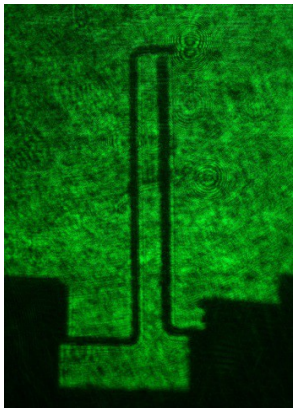
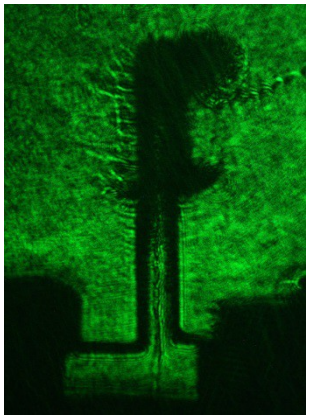
The inverse skin effect in Magnetically-insulated Transmission lines





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Cornell University

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SSAP Symposium 2016

Cornell University
Laboratory of
Plasma Studies

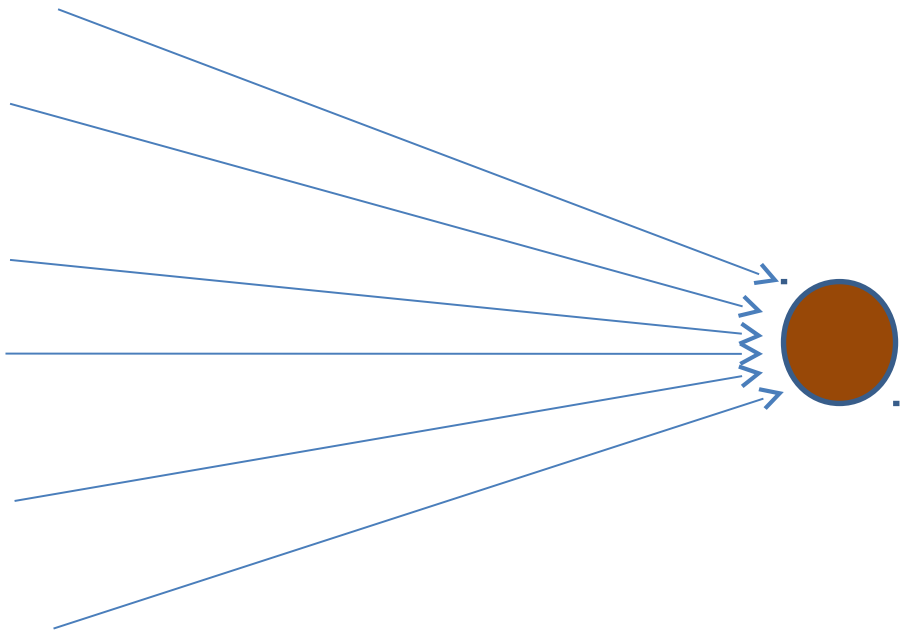
National Nuclear Security Administration

What physical processes determine ultimate limits to the concentration of electromagnetic power?

It’s always the interaction of EM fields with material surfaces: plasmas.

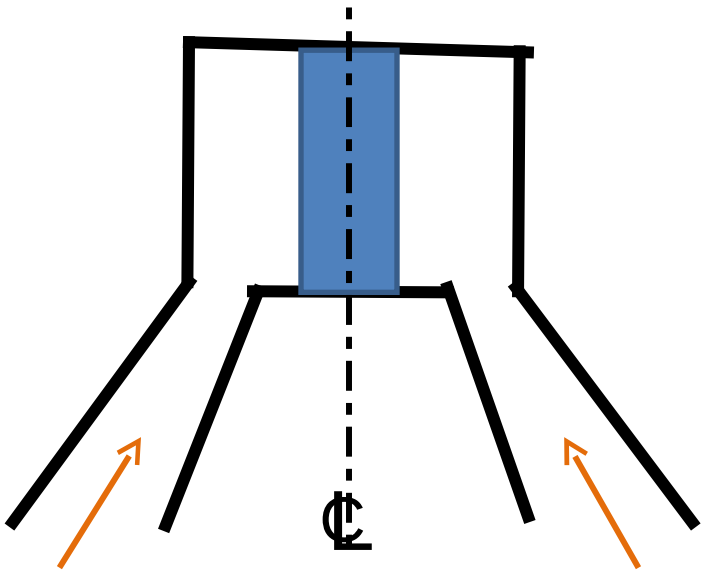
These processes limit the transmission and deposition of power to a target.

What physical processes determine ultimate limits to the concentration of electromagnetic power?



Lasers: λ << scale sizes except in interaction with target plasma.

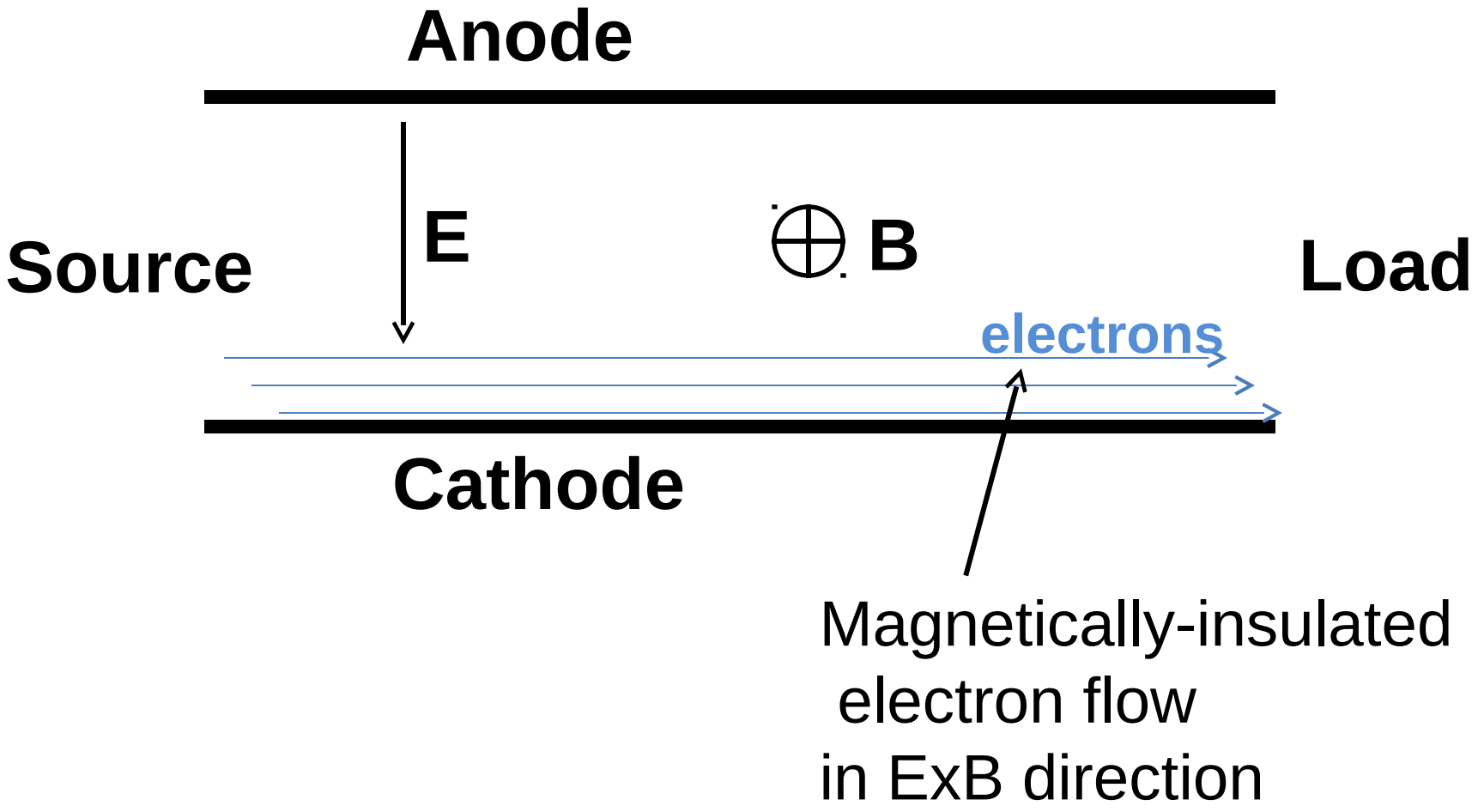
What physical processes determine ultimate limits to the concentration of electromagnetic power?



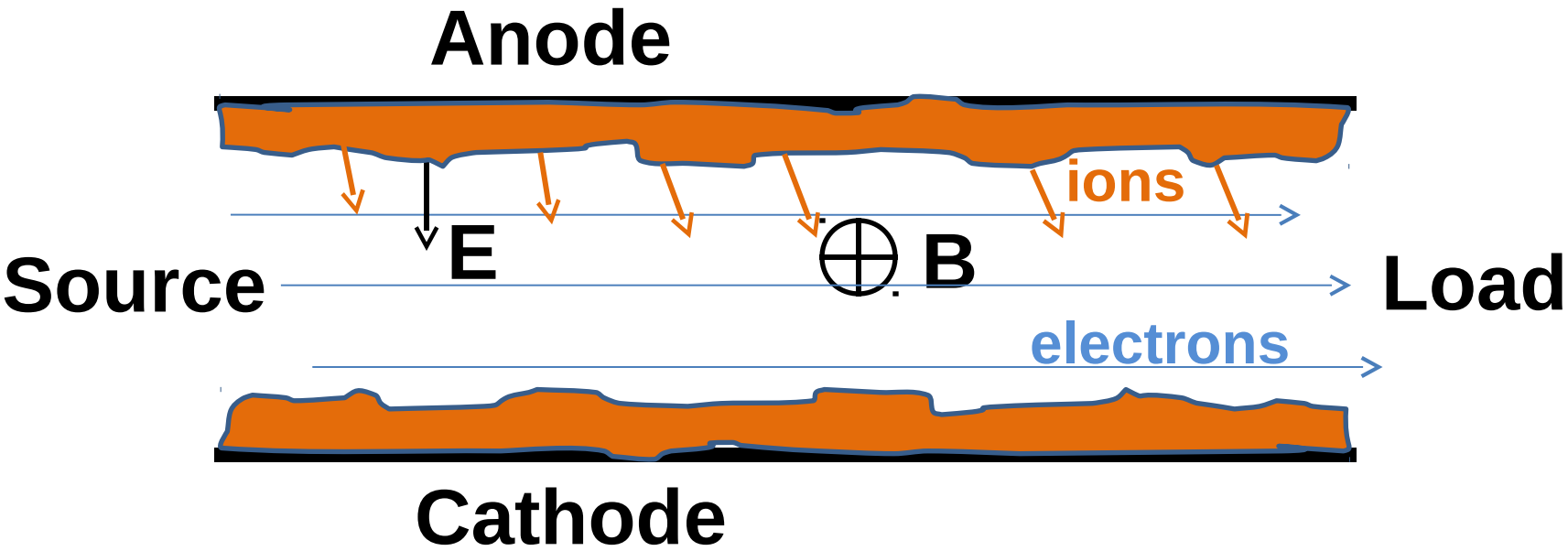
Pulsed power: λ >> scale sizes. EM power must be guided by electrodes: there are surfaces everywhere!

-- Large electric fields accelerate charged particles
-- Large current densities produce surface plasmas

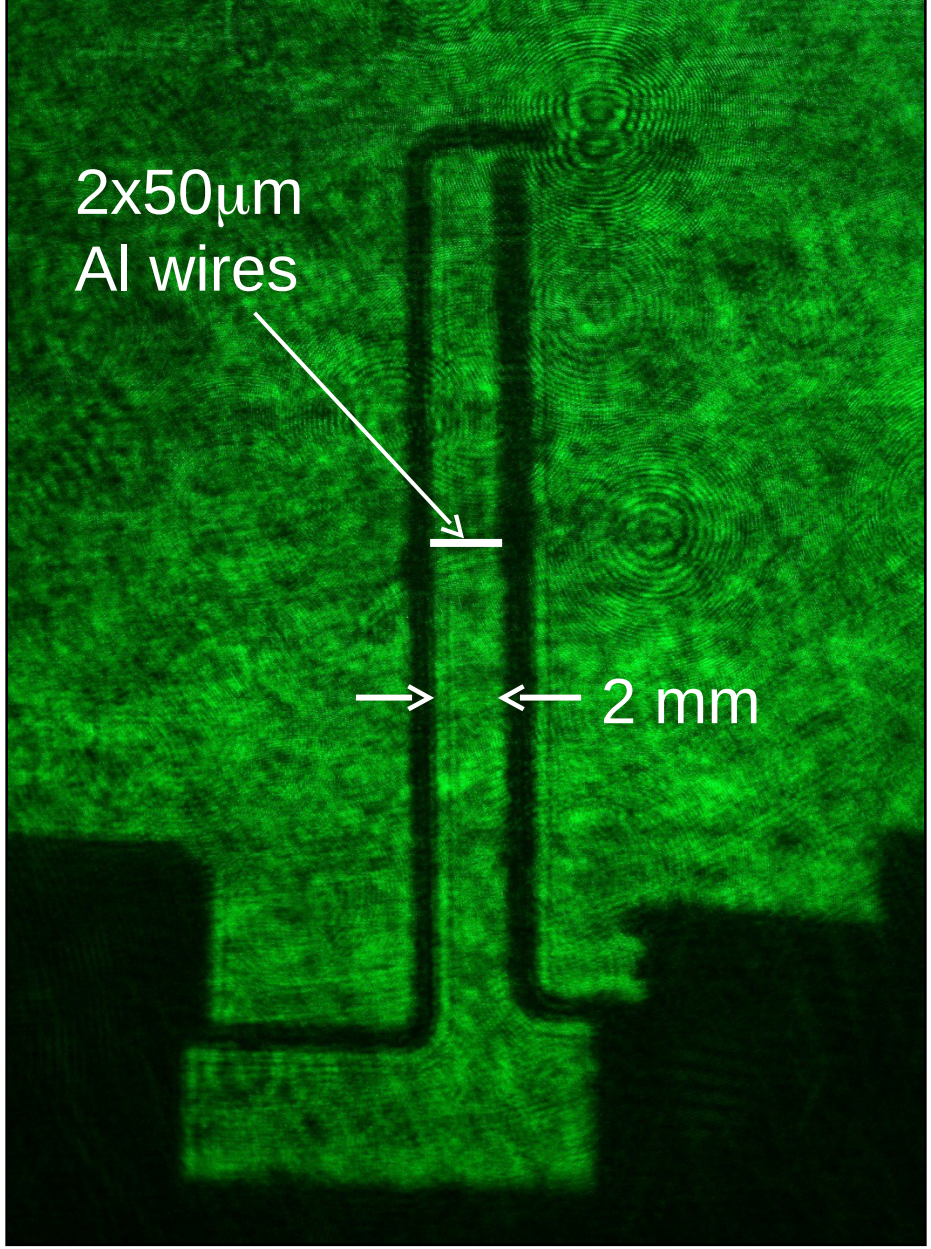
Vacuum self-magnetically-insulated transmission line (MITL)

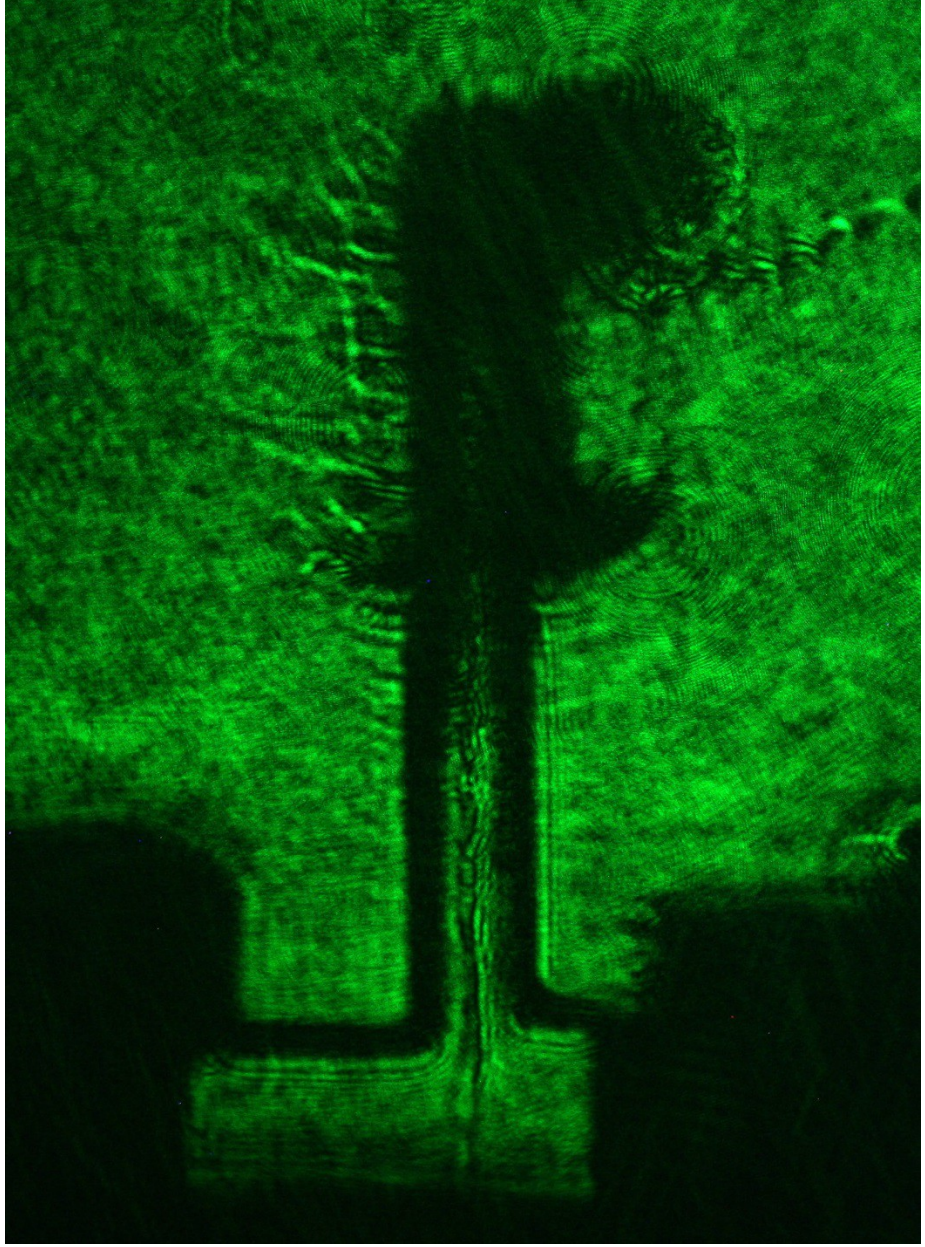


Vacuum self-magnetically-insulated transmission line (MITL)



With plasma on both electrodes, ions are emitted from the anode plasma.
The MITL becomes a magnetically-insulated ion diode, with nonlinear coupling between the space-charge populations.





COBRA 3875

Cu strip electrodes, 8 mm wide

Power feed losses:

losses are not generally significant in COBRA (1 MA),
but in Z (25 MA) they can be substantial.

Both the generator and the load apply electric field stress to the MITL.

Electric field across a 3 mm feed gap at peak current:

Cobra, with 1 MA, if L is increasing at 1 nH/10 ns,
I(dL/dt) = 100 kV or ~ 300 kV/cm

Z, with 25 MA, I(dL/dt) = 2.5 MV or ~8 MV/cm

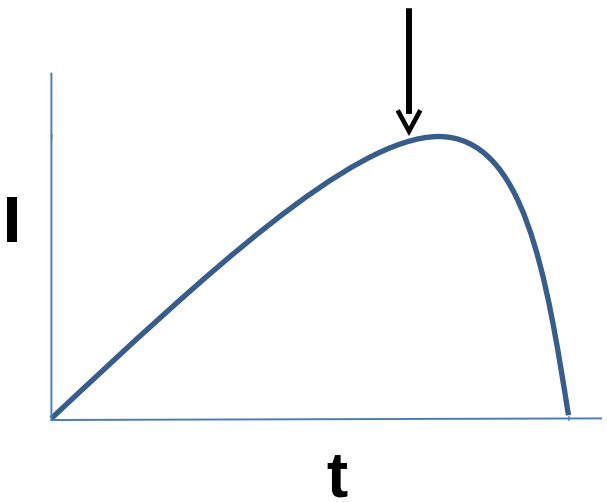
What about the “inverse skin effect”?

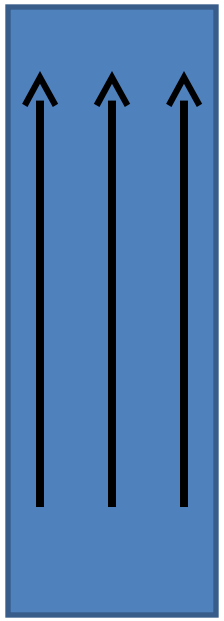
Both the driver and the load dynamics affect the stress on the MITL feed.

When dI/dt is driven negative, an **inverse skin effect** may result in rapid ejection of plasma from electrode plasma surfaces into the MITL gap, causing current loss or power feed closure.

Given a current carried by a bounded conductor, if you drive that current down by reversing the applied electric field at the boundary, on a time scale short compared with the resistive diffusion time, then a reversed current layer forms at the plasma boundary and diffuses into the conductor.

This also reverses the JxB force on that surface layer. In a solid conductor, no problem, but in a plasma that can move, the reversed JxB drives that surface layer outward, away from the body of the plasma (that still carries the original current).





Current initially ~ fully penetrated

Given a current carried by a bounded conductor, if you drive that current down by reversing the applied electric field at the boundary, on a time scale short compared with the resistive diffusion time, then a reversed current layer forms at the plasma boundary and diffuses into the conductor.

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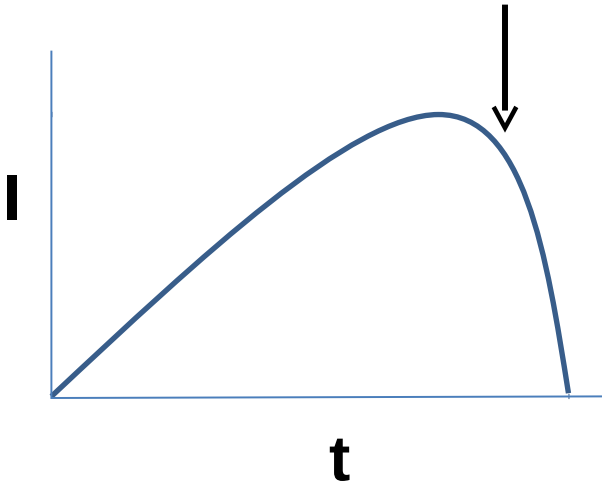
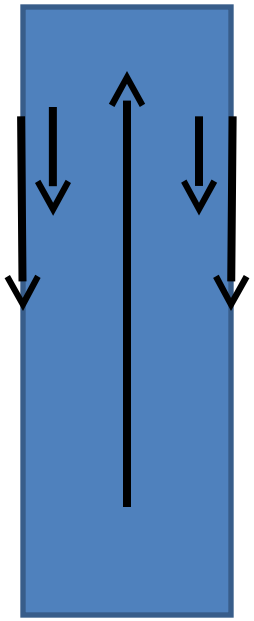
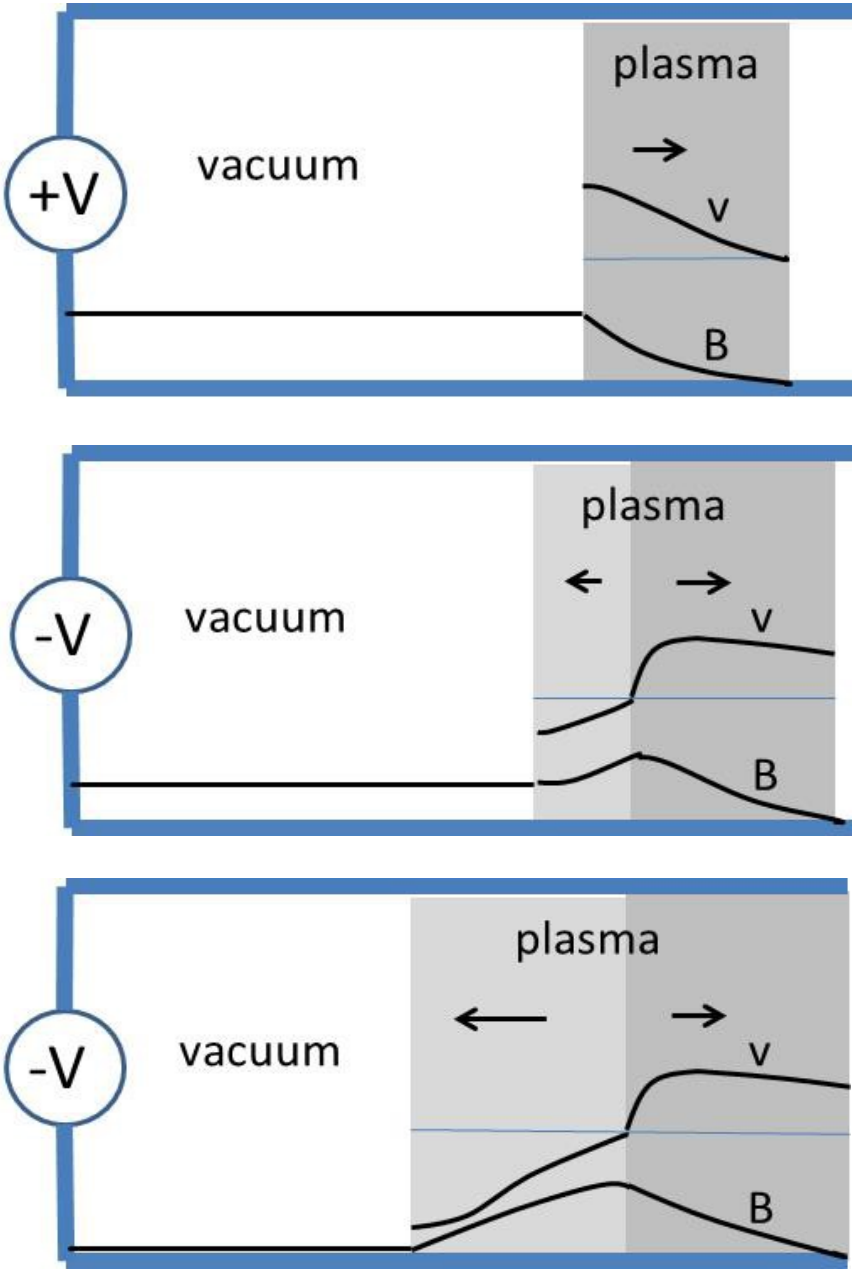




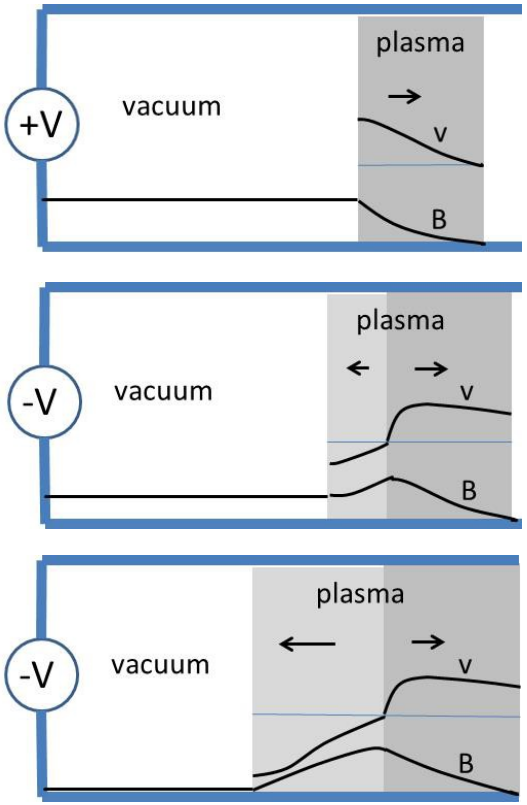
Internal current remains, surface current reverses and penetrates

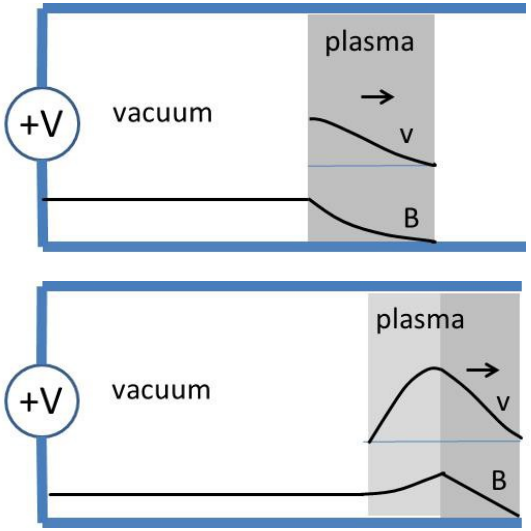


- Voltage reversal with a pulsed-power driver produces this electric field reversal.

- On time scale short compared with resistive penetration of plasma:

- An “inverse skin effect”

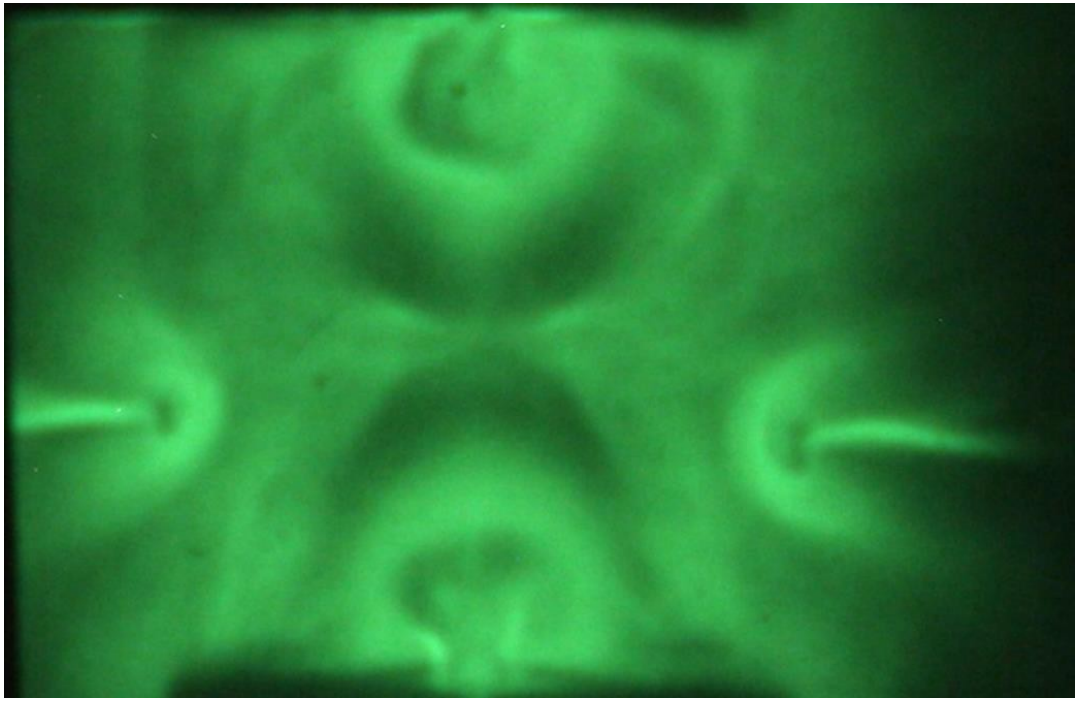




I dL/dt > V

–-> B must decrease

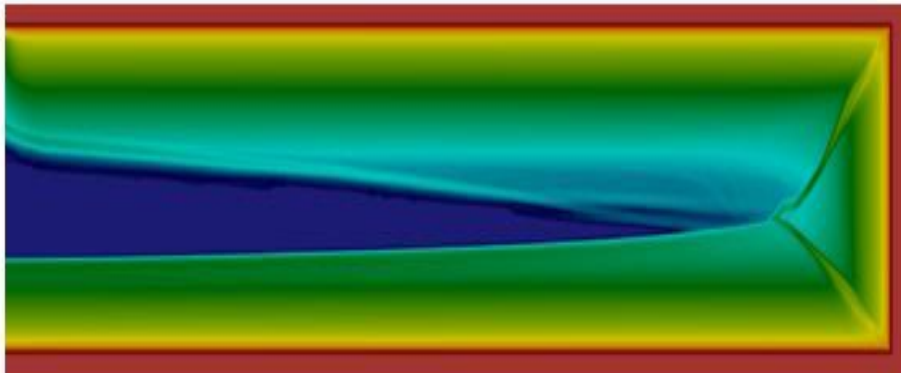
Important: load plasma motion and increasing inductance also produces inverse skin effect. Any dynamics or driving waveform that forces current down faster than field can diffuse out of plasma will do this.



We first began using the inverse skin effect to generate outflows from exploded wire plasmas to drive magnetic reconnection.

Supersonic and super-alfvenic flows are generated

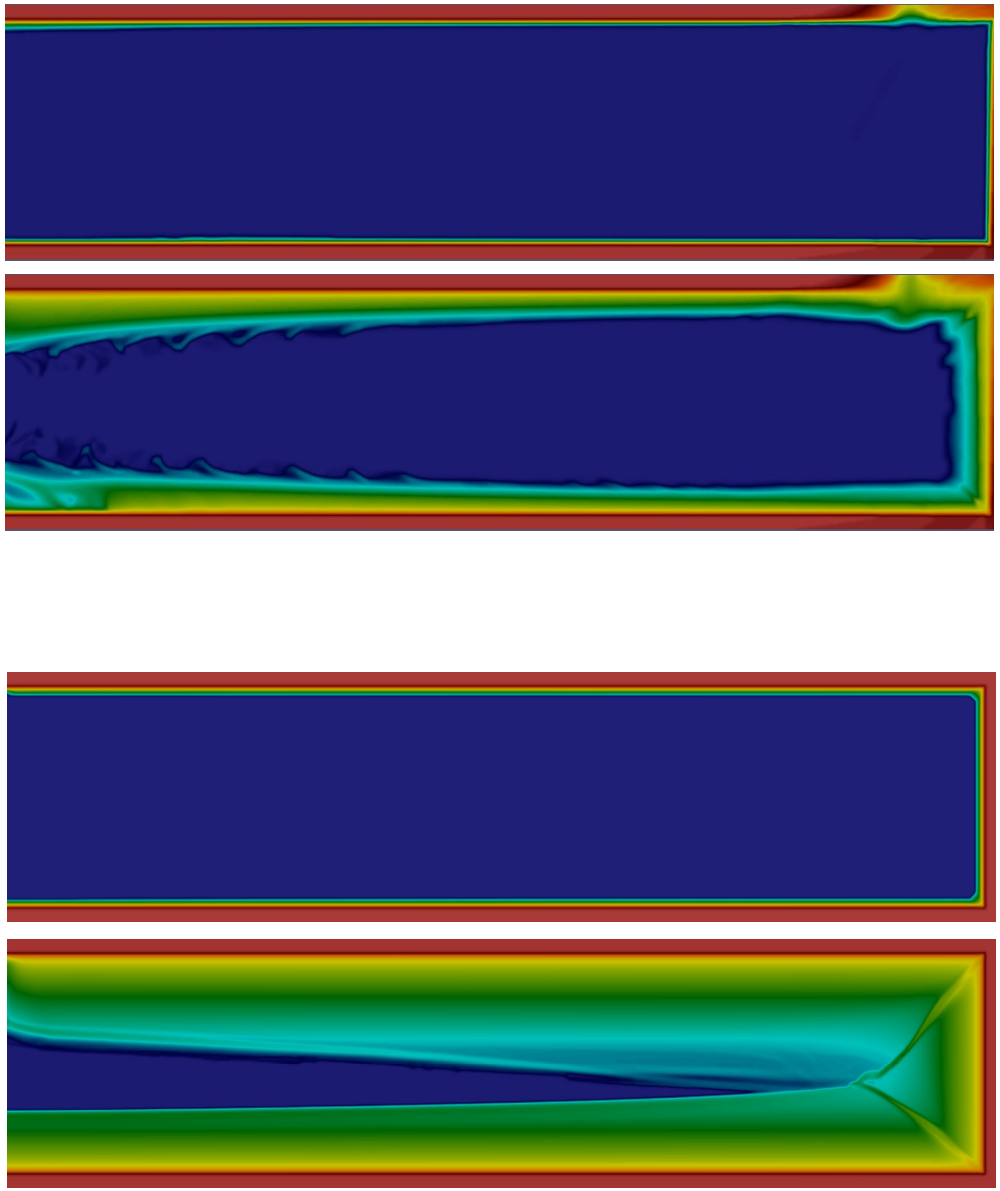
up to 200 km/s.



Rising current: dI/dt >0

10 ns after voltage reversal, dI/dt <0

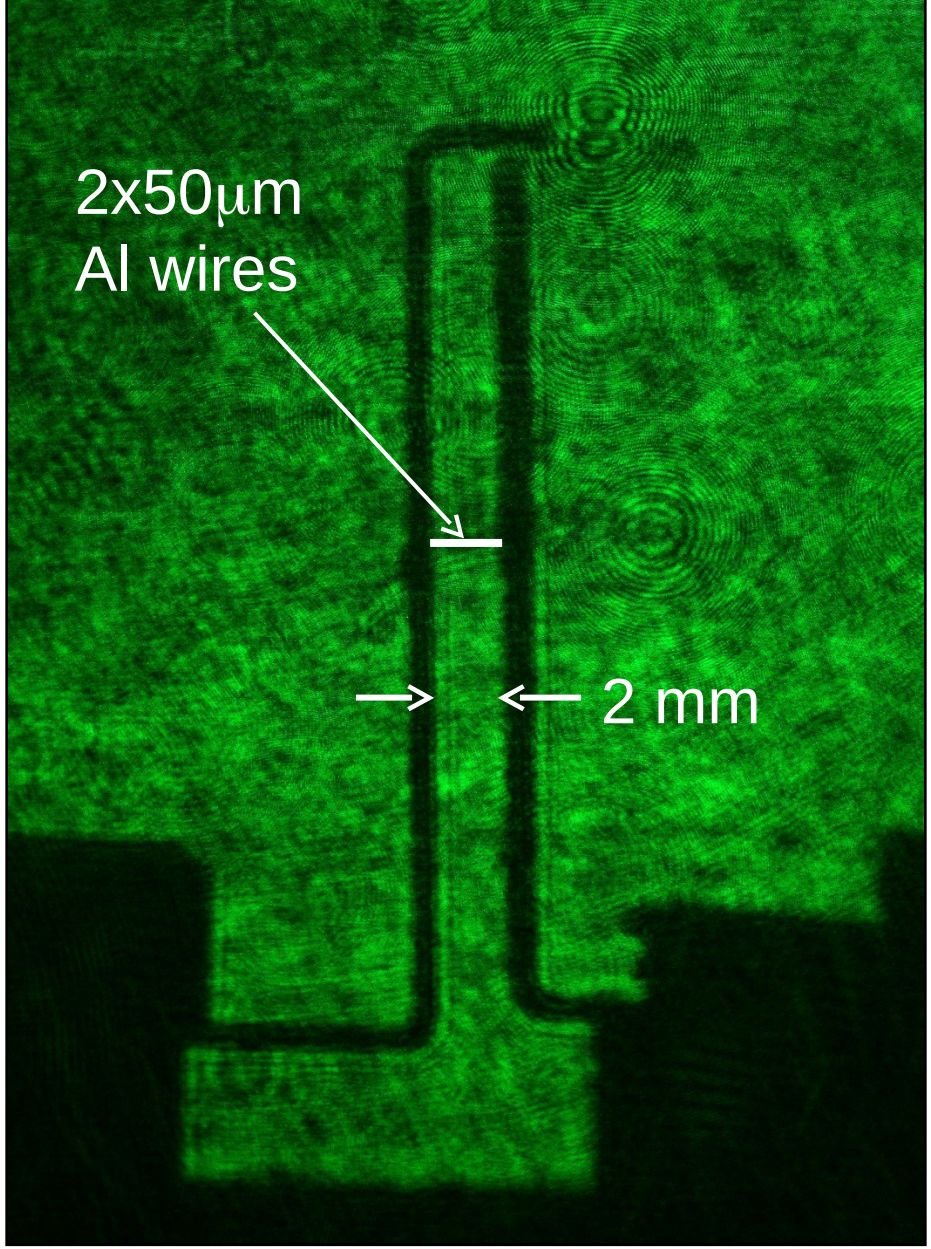
PERSEUS simulation of a MITL with dense electrode plasma.
During current rise, plasma is confined near the electrodes,
But within 10 ns after voltage reversal there is rapid acceleration of the surface of the plasma across the electrode gap.

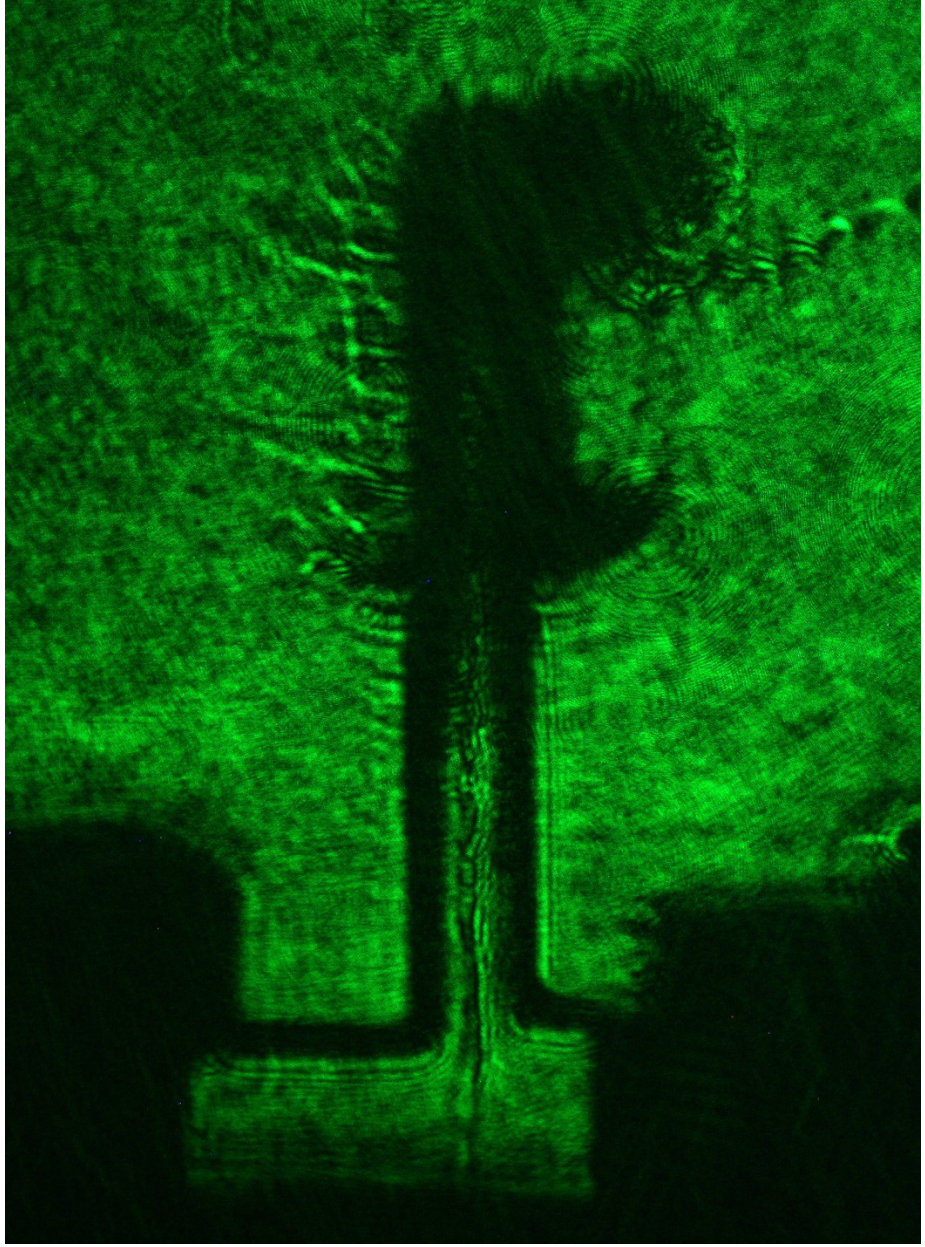


PERSEUS simulations of
MITL surface plasma.
Top pair MHD, bottom pair XMHD (Hall).
Poynting flux entering (leaving) from the left before (after) reversal.

These are density maps.

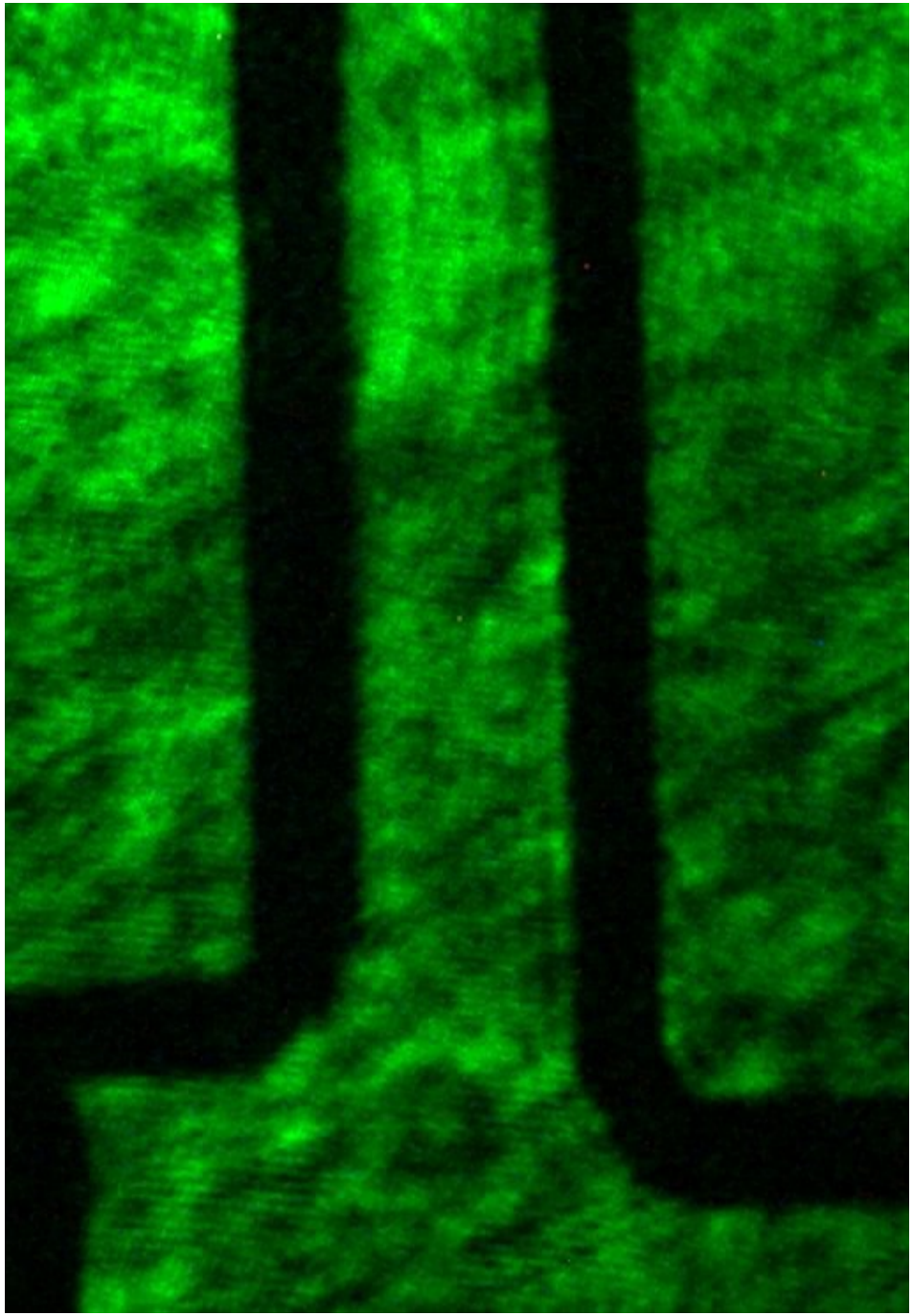
The first of each pair is before voltage reversal, second is after reversal.

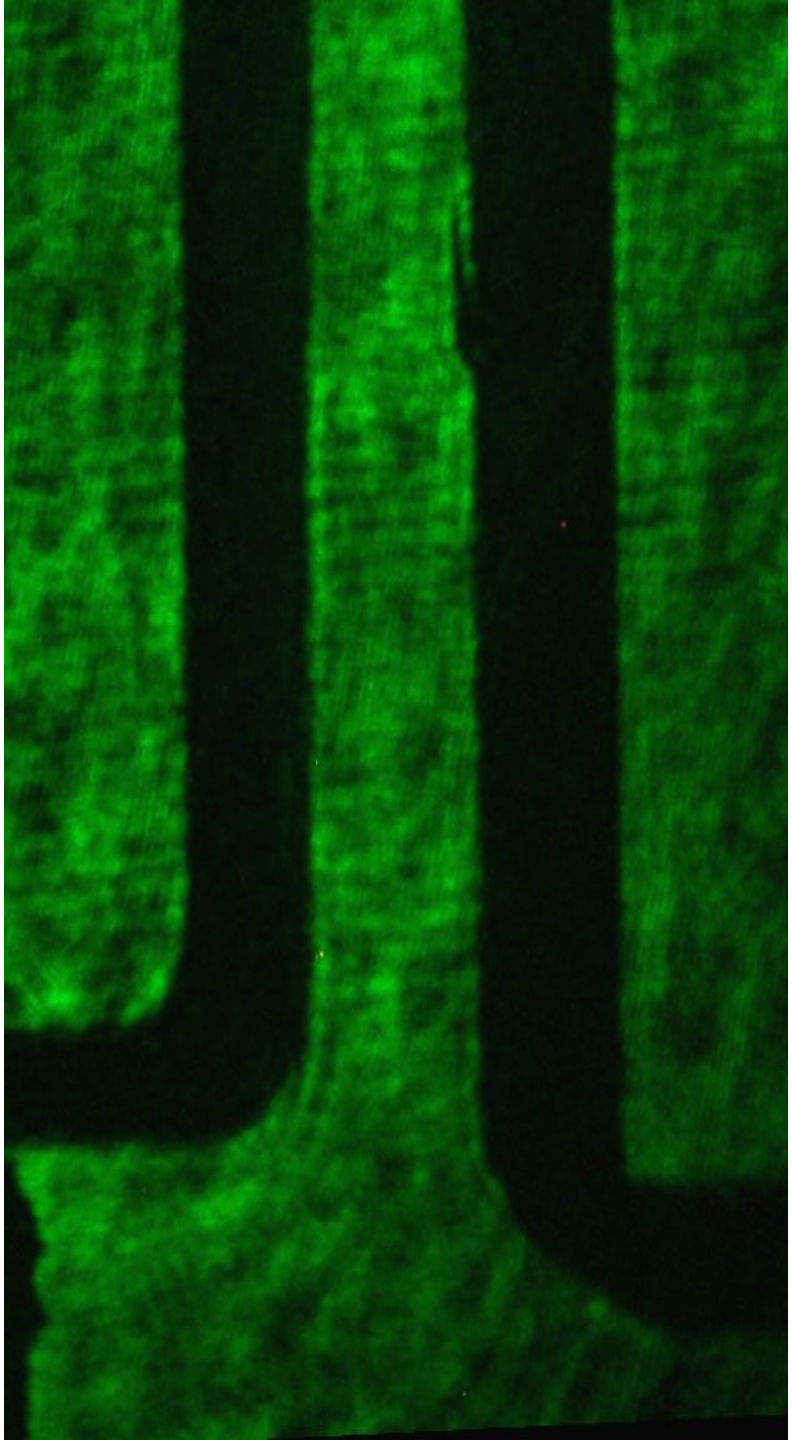


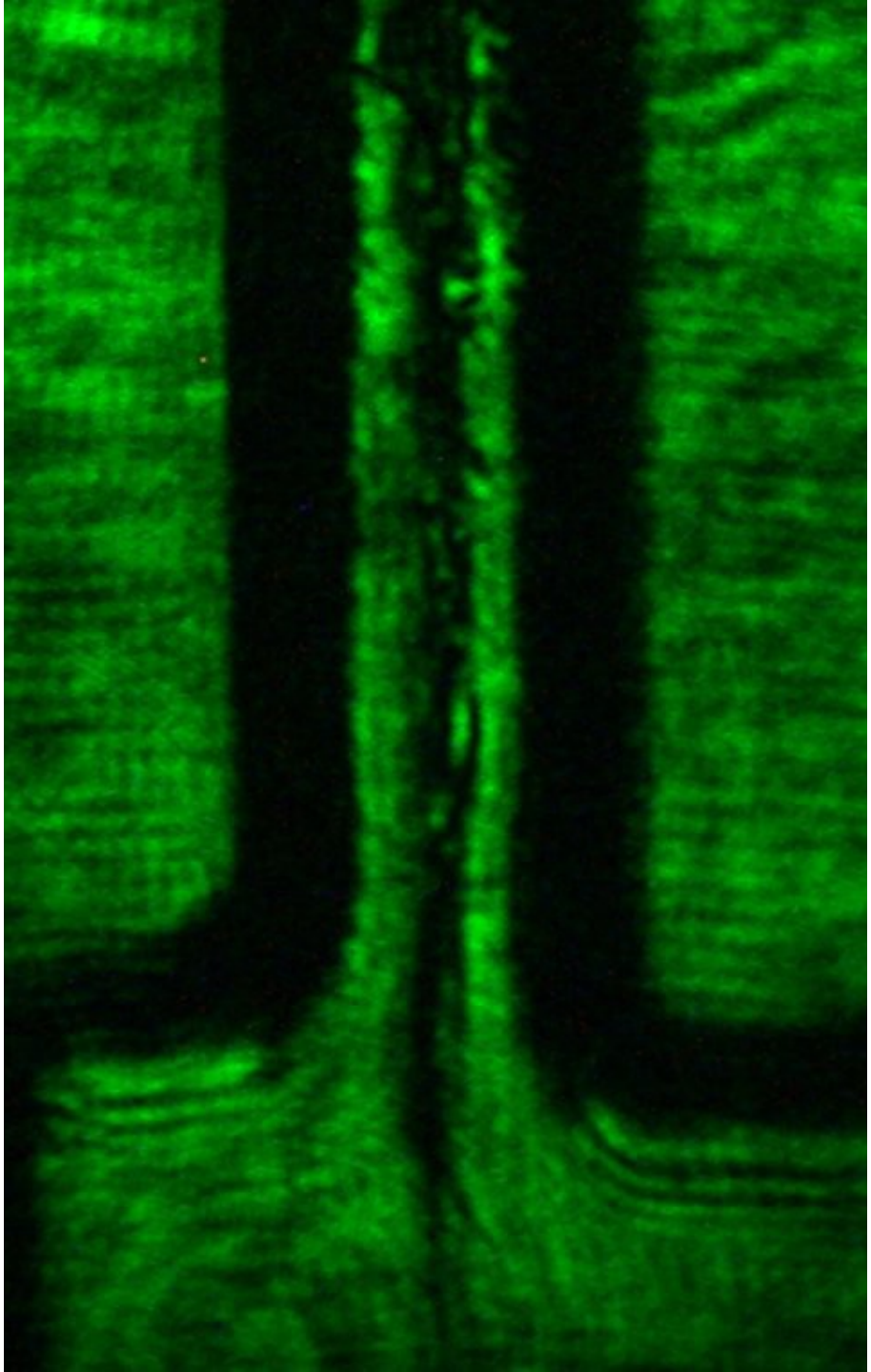


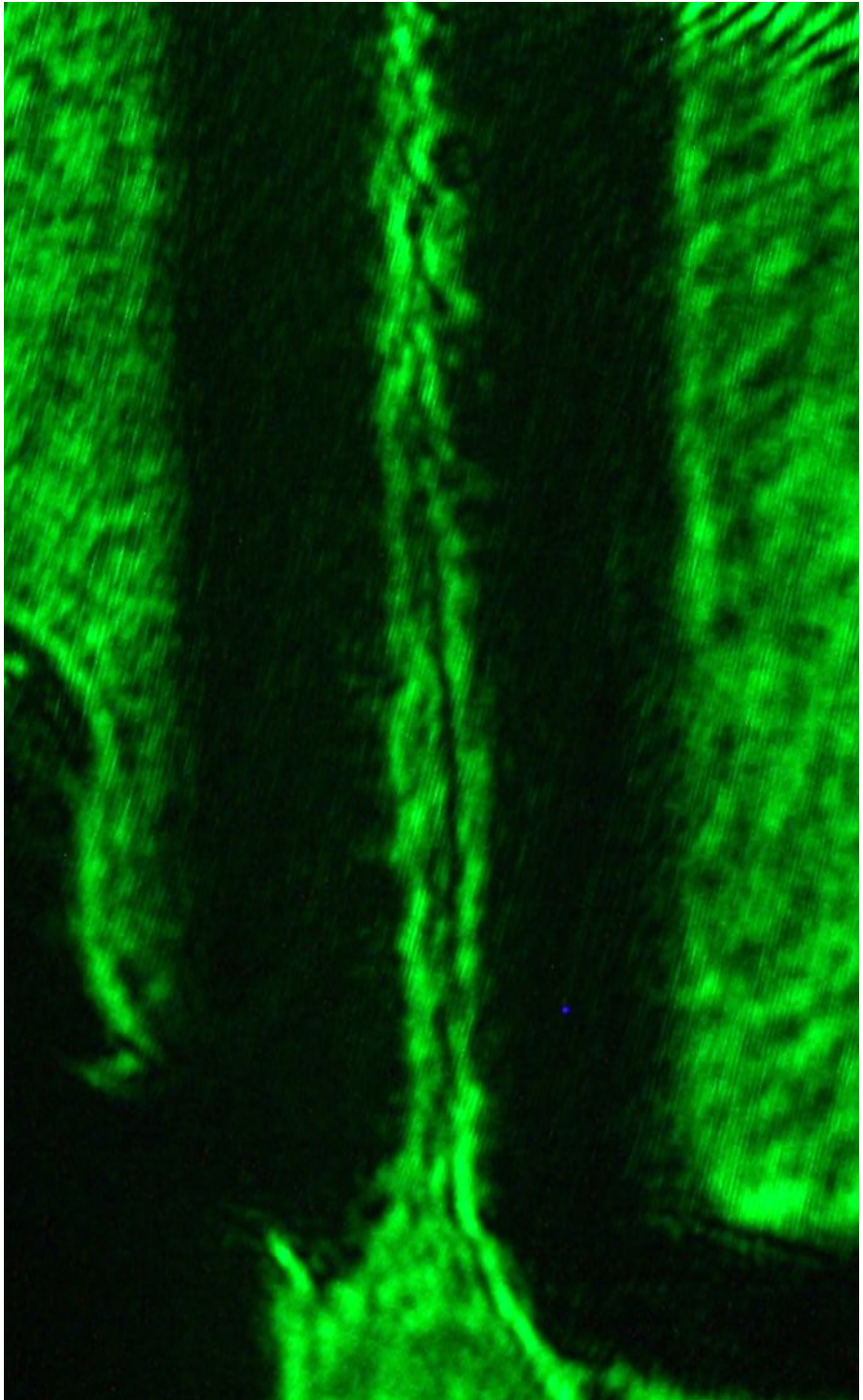
COBRA 3875

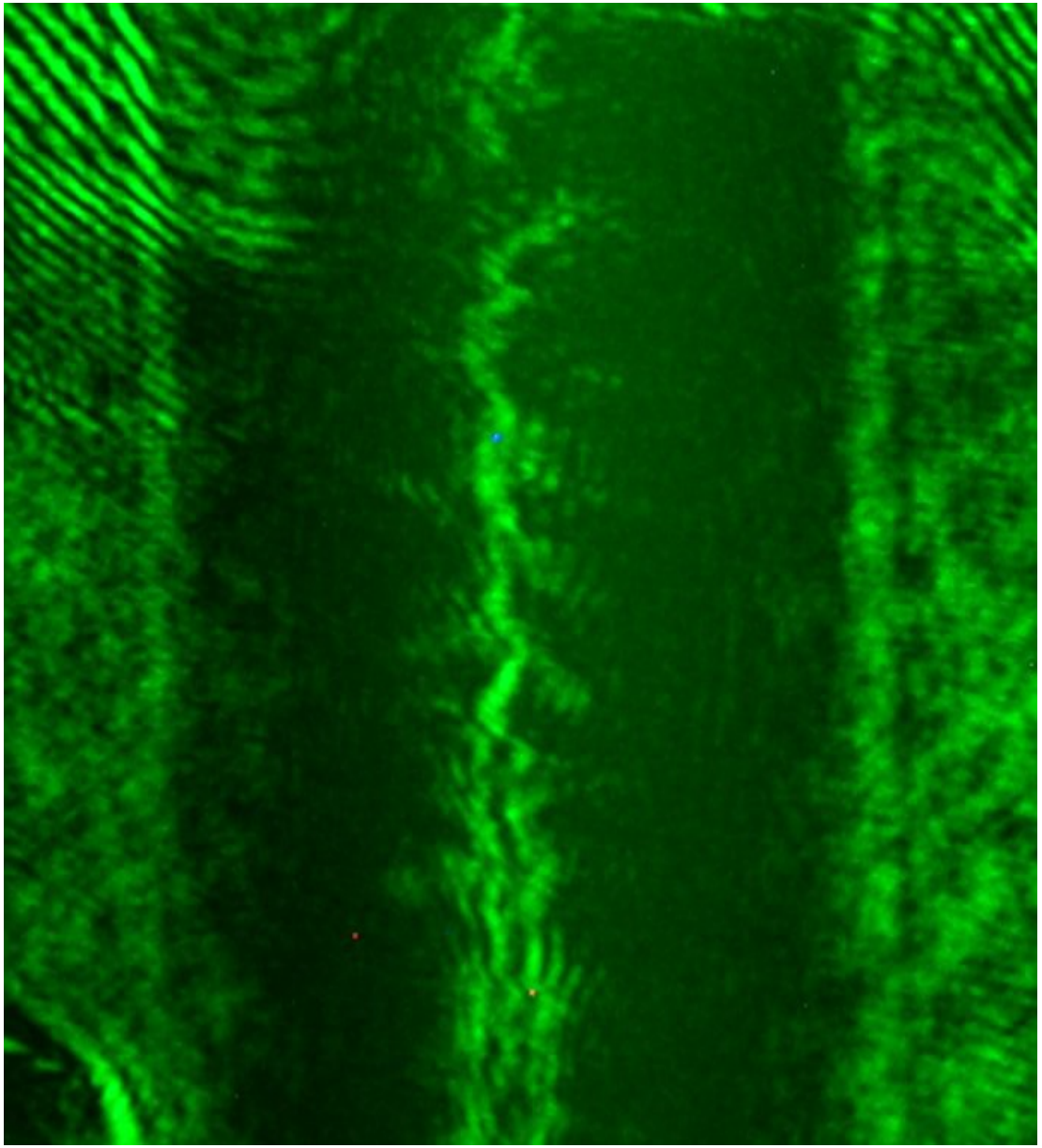
Cu strip electrodes, 8 mm wide

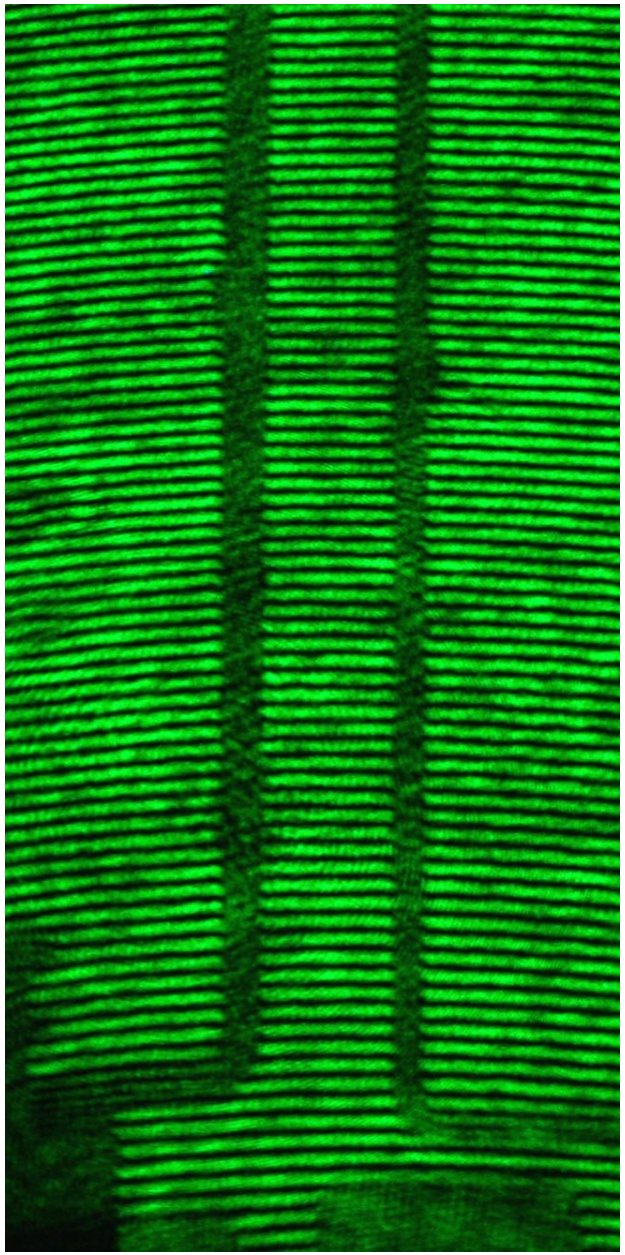


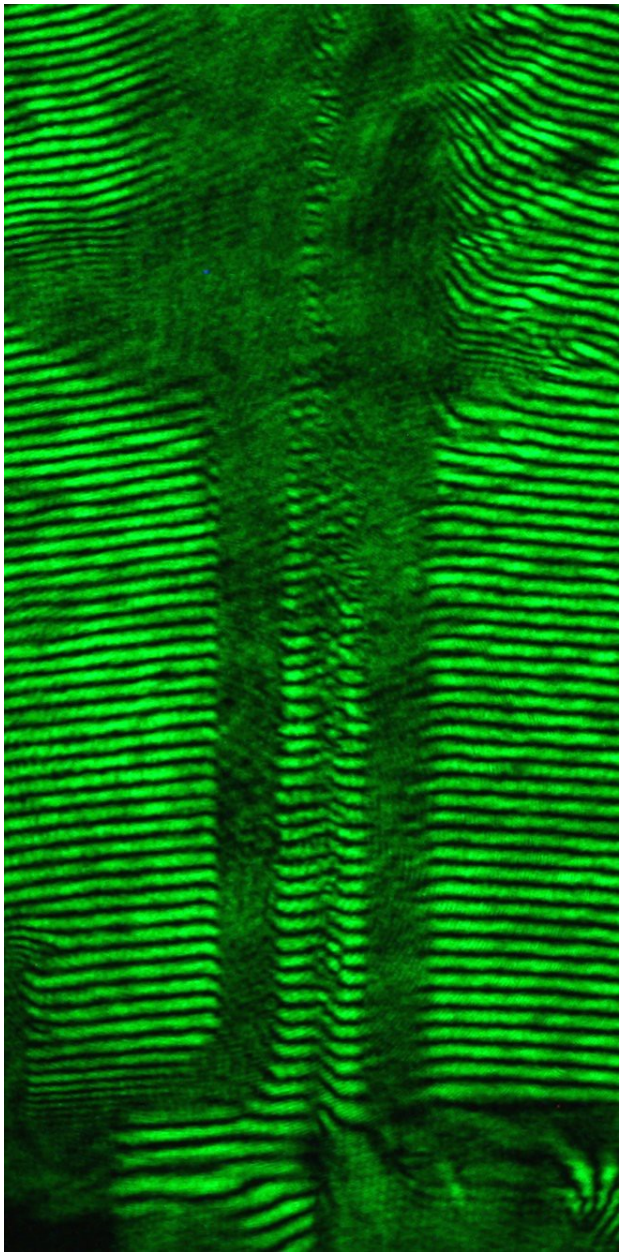






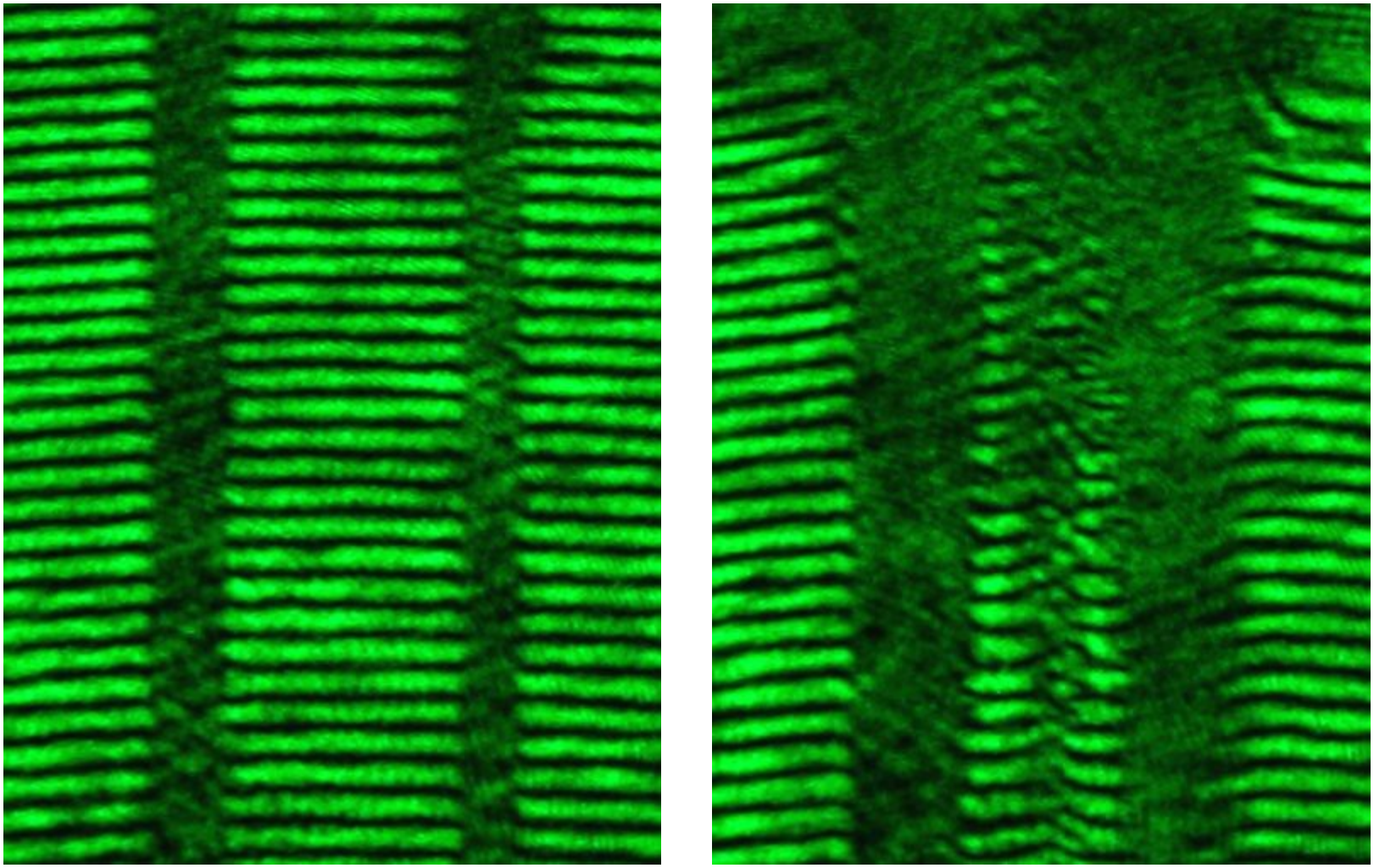




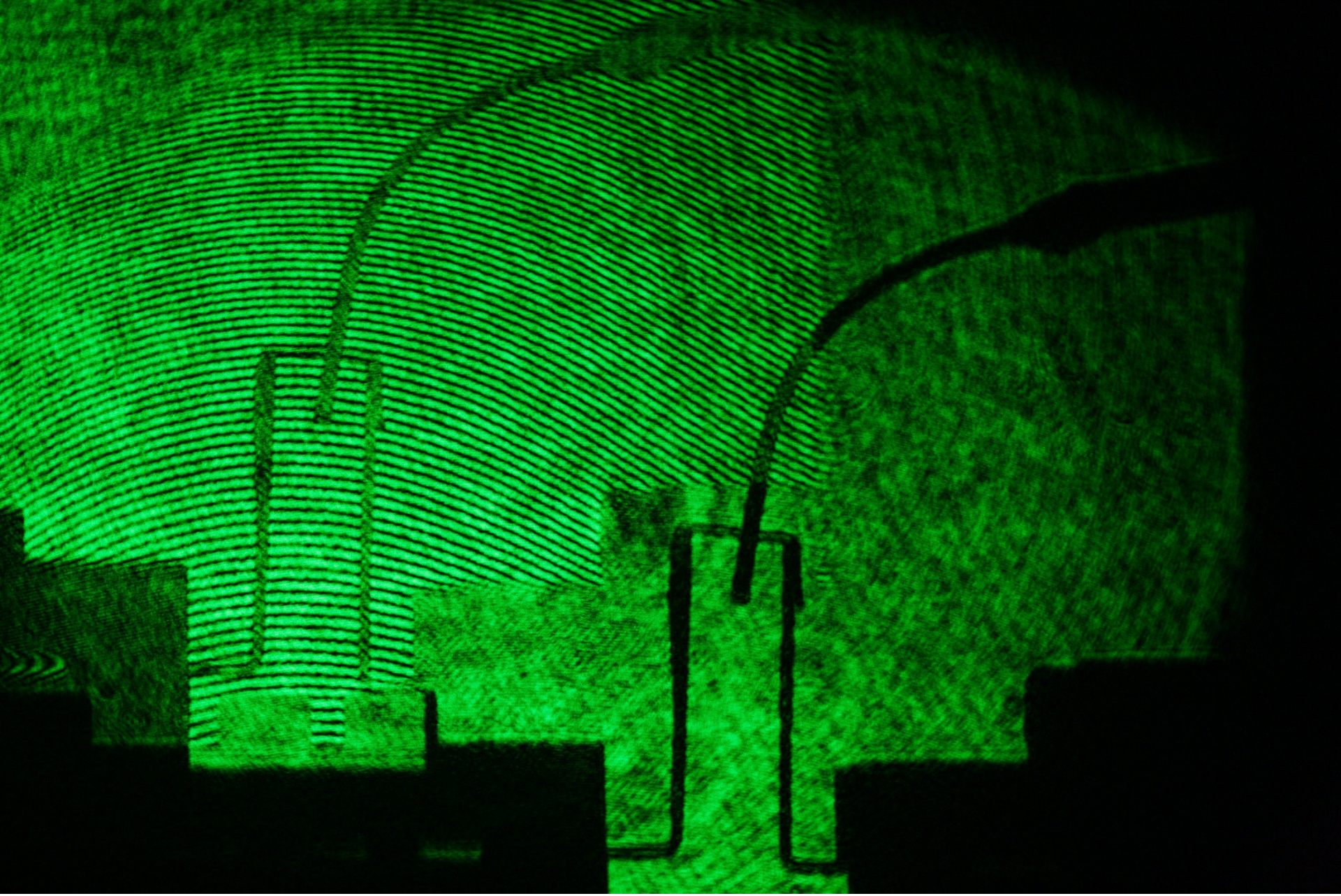


3875

Laser interferometry

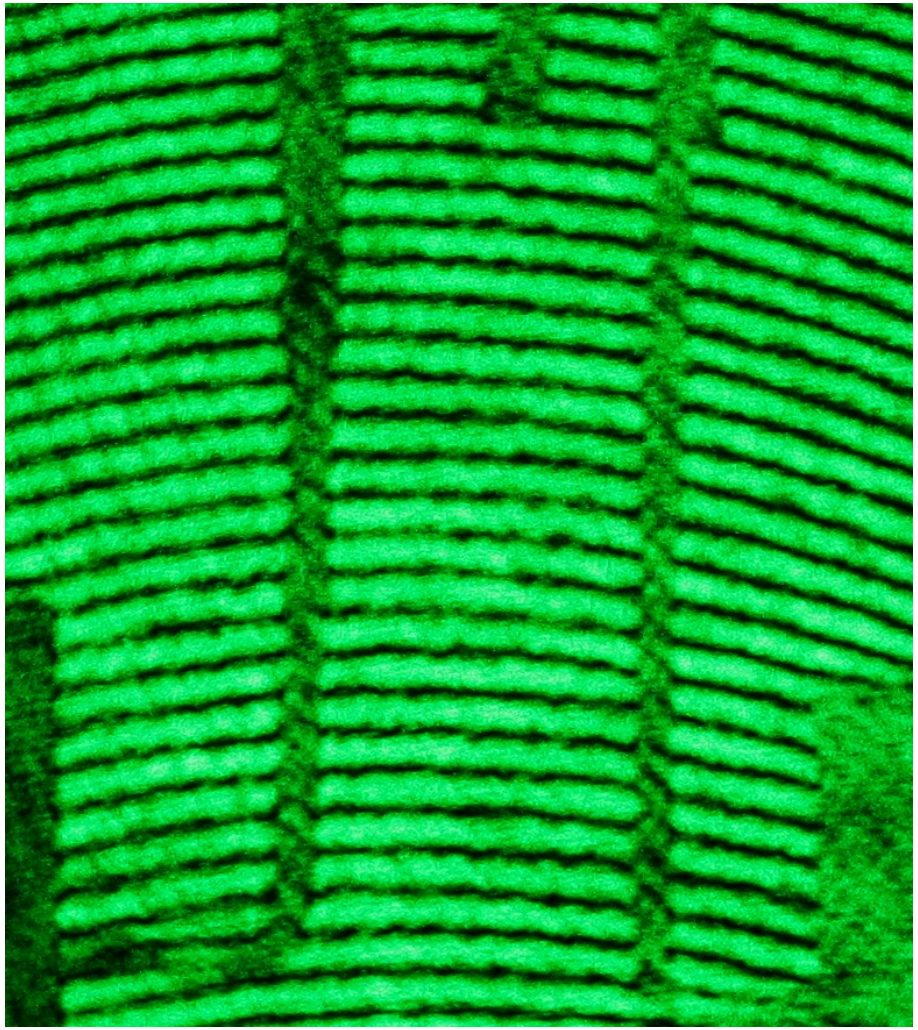


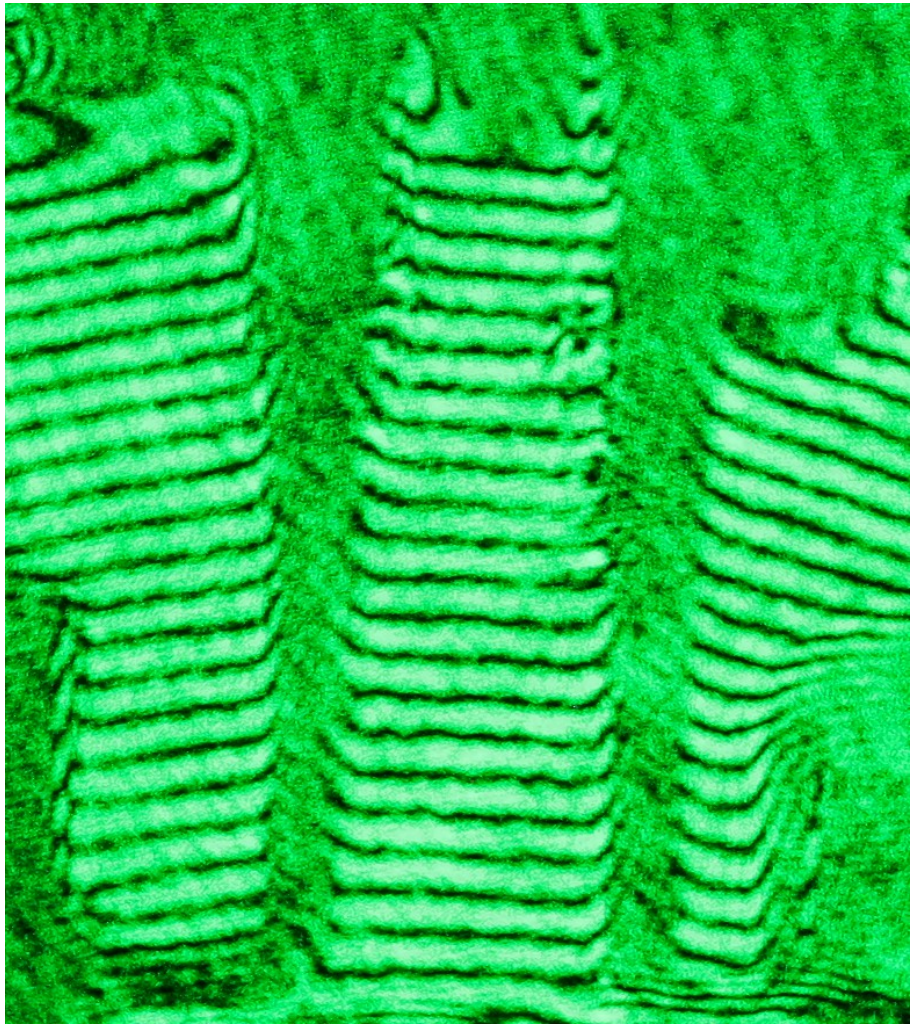
Interferogram closeup: 1 fringe shift ~ 5×10^{17} /cm^3



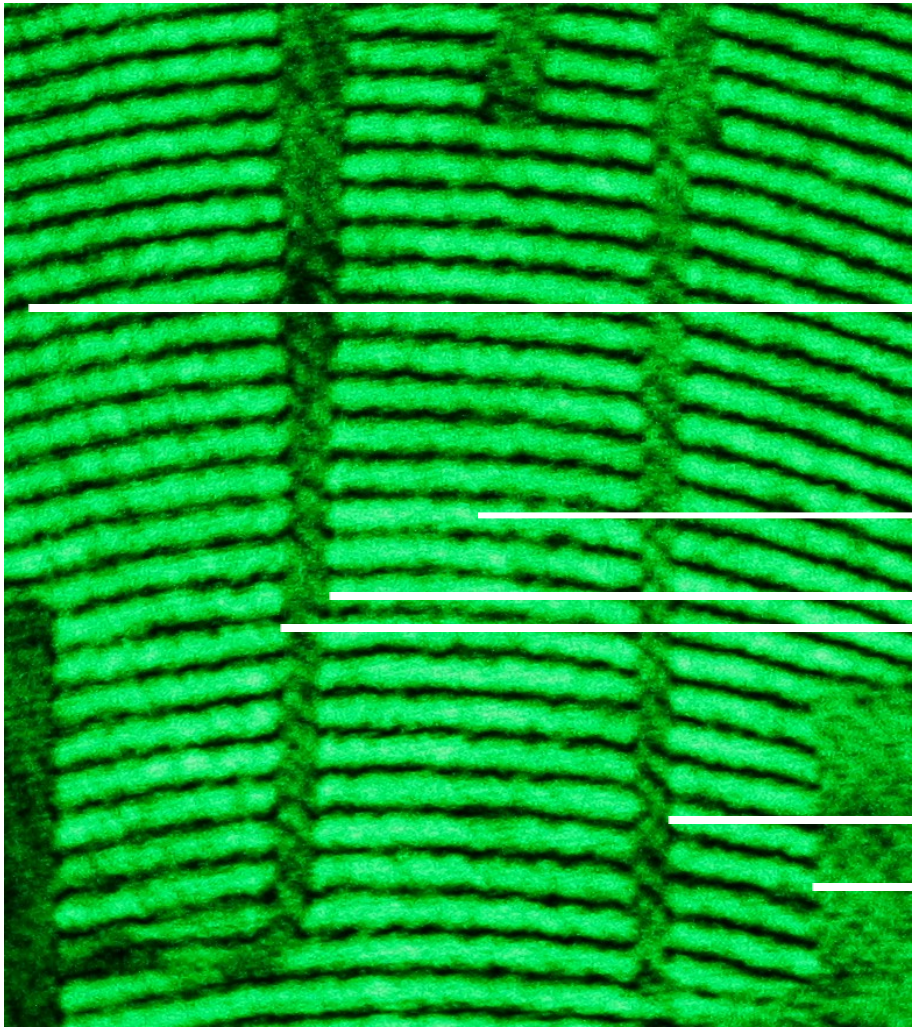
COBRA 3712: plates 7mm wide, 12 mm tall, 4mm gap, 2x 254 m A

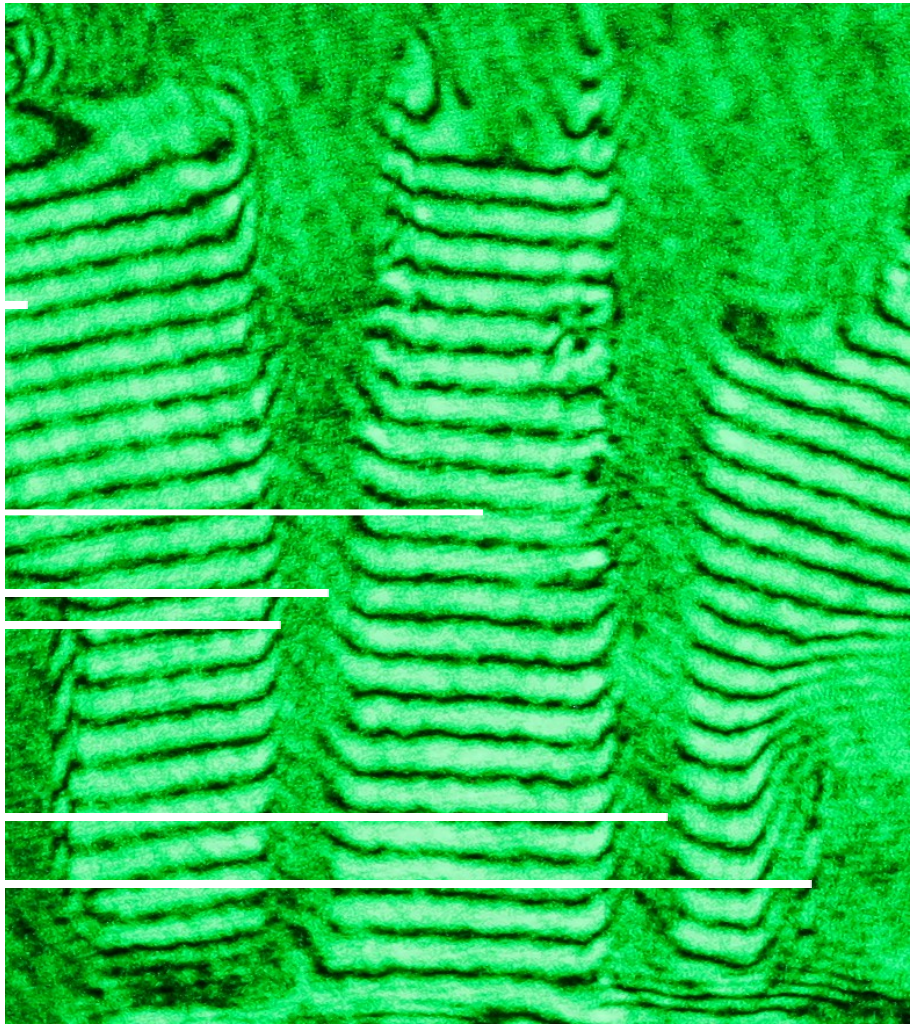
COBRA 3712



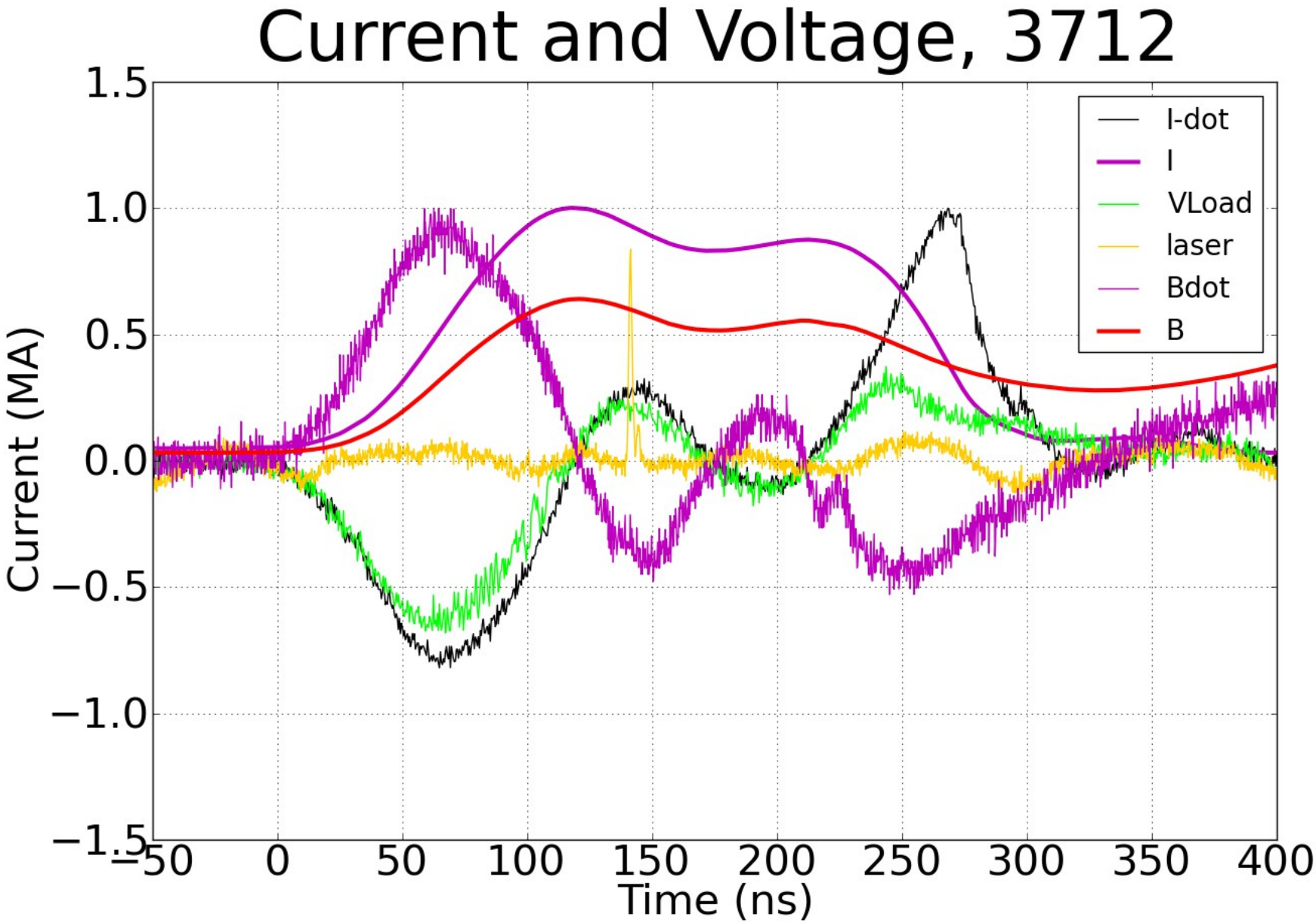


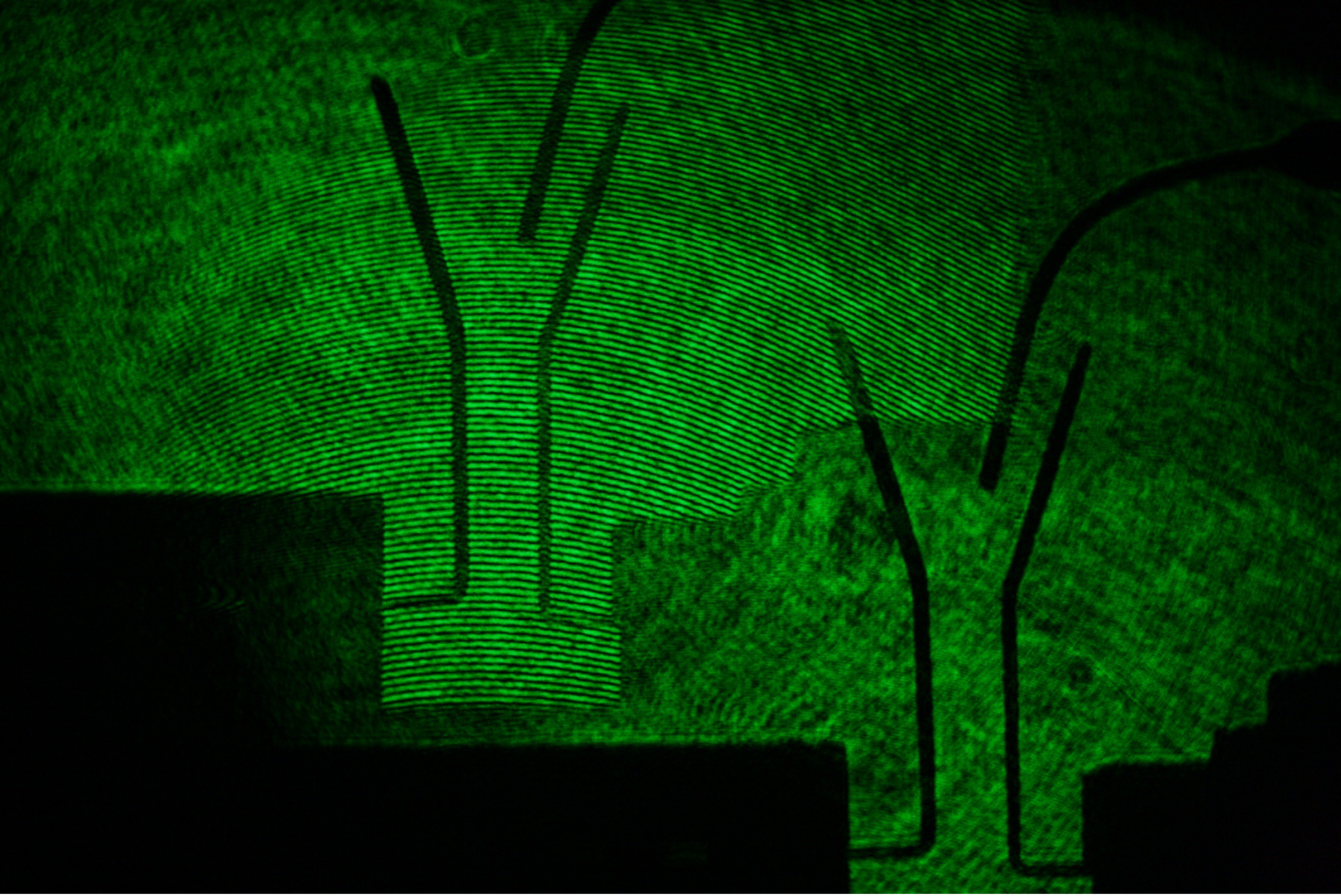
COBRA 3712



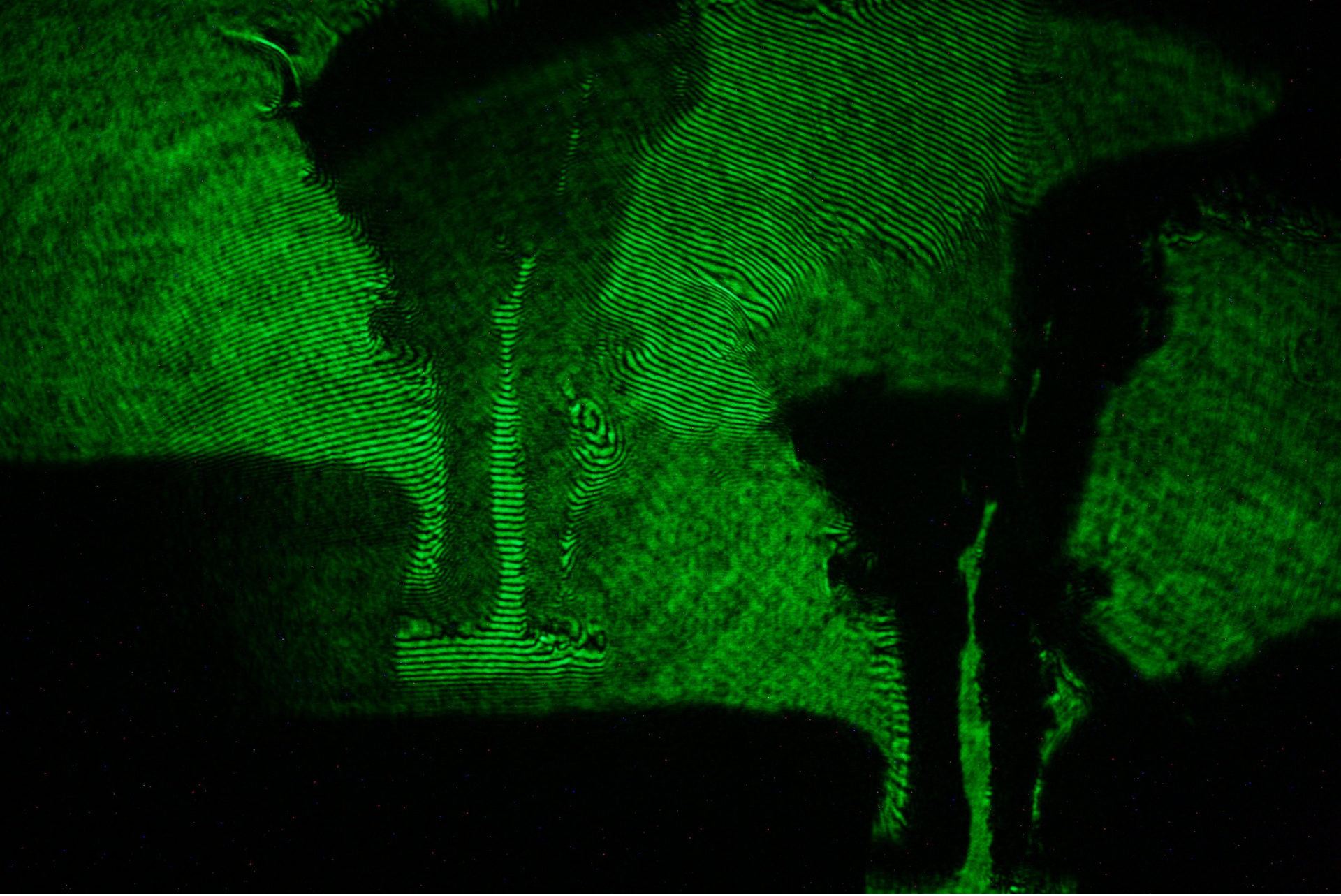


COBRA 3712

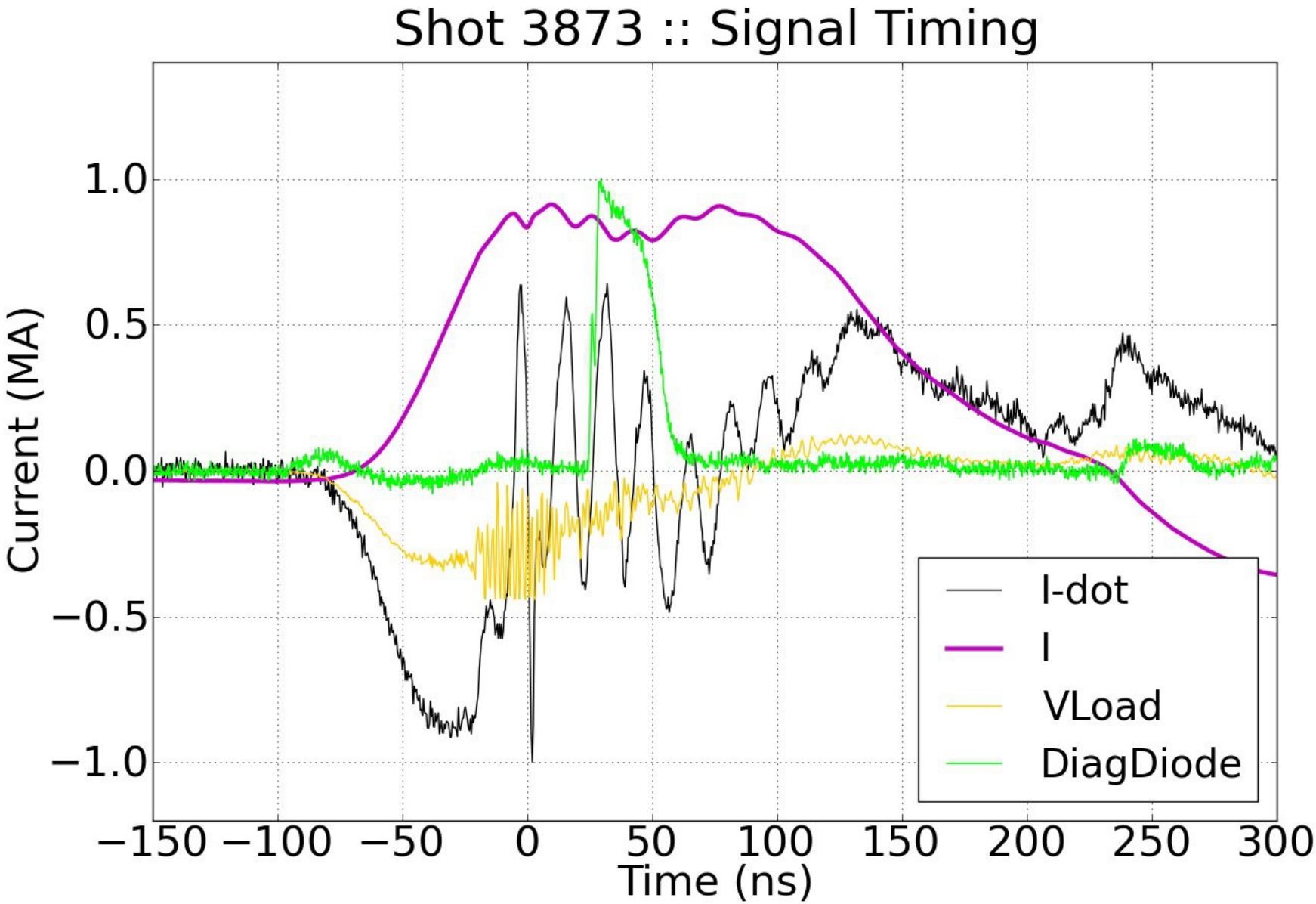

Current and Voltage, 3712
I-dot
I
VLoad
laser
Bdot
B
Current (MA)
Time (ns)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−50
0
50
100
150
200
250
300
350
400



3714: 8mm wide, 12mm tall, 3mm gap, 2x 25 micron Al, diverging



3714

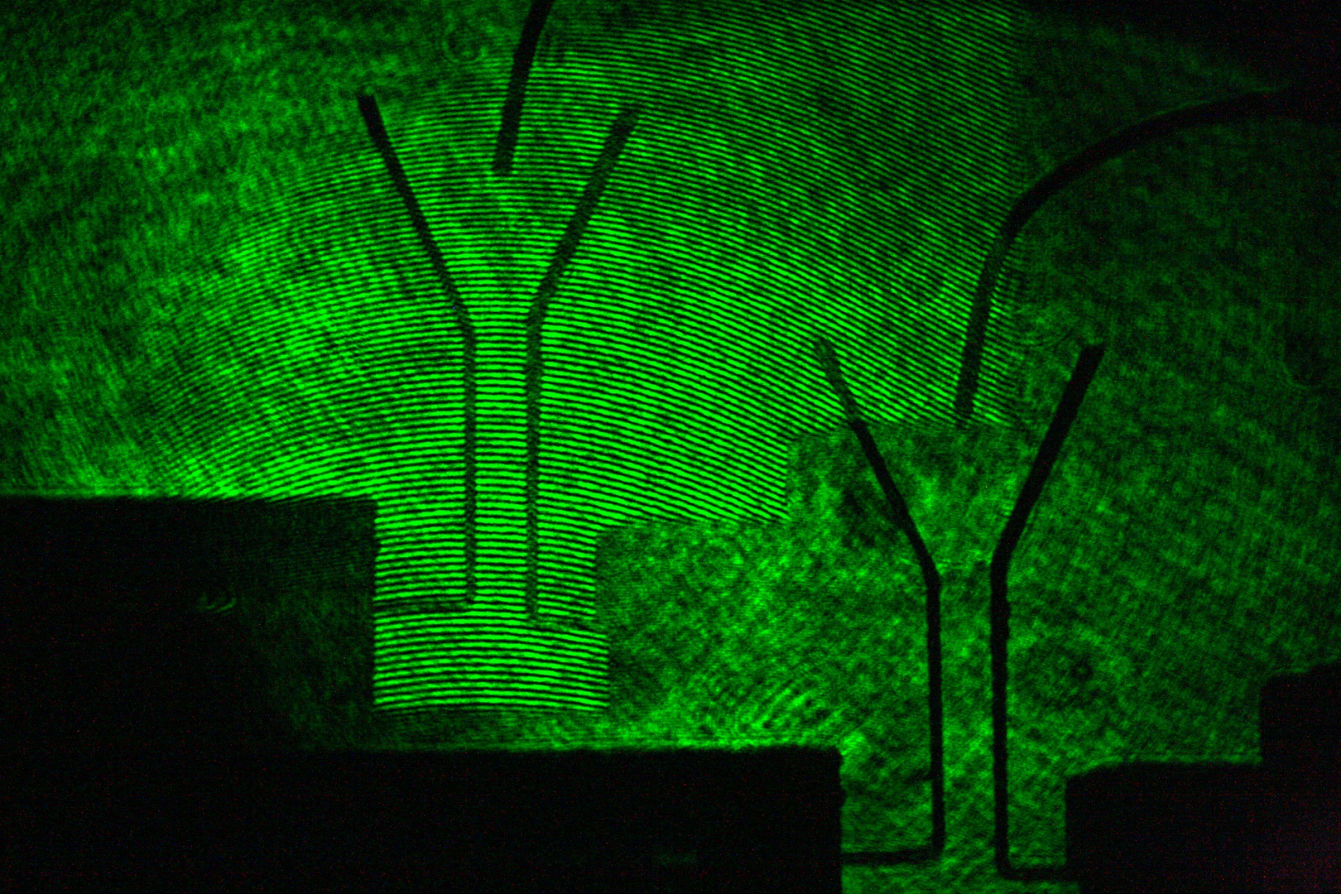

Shot 3873 :: Signal Timing
Current (MA)
1.0
0.5
0.0
−0.5
−1.0
−150
−100
−50
0
50
100
150
200
250
300
Time (ns)
I-dot
I
VLoad
DiagDiode

3718

Hannes Alfven discussed inverse skin effects in The Book [1], making the point that these effects are simple in a solid conductor but become quite complex in a movable, fluid conductor like plasma. He wrote:
"A careful analysis of the problem would be very desirable."
(Cosmical Electrodynamics, p.71)

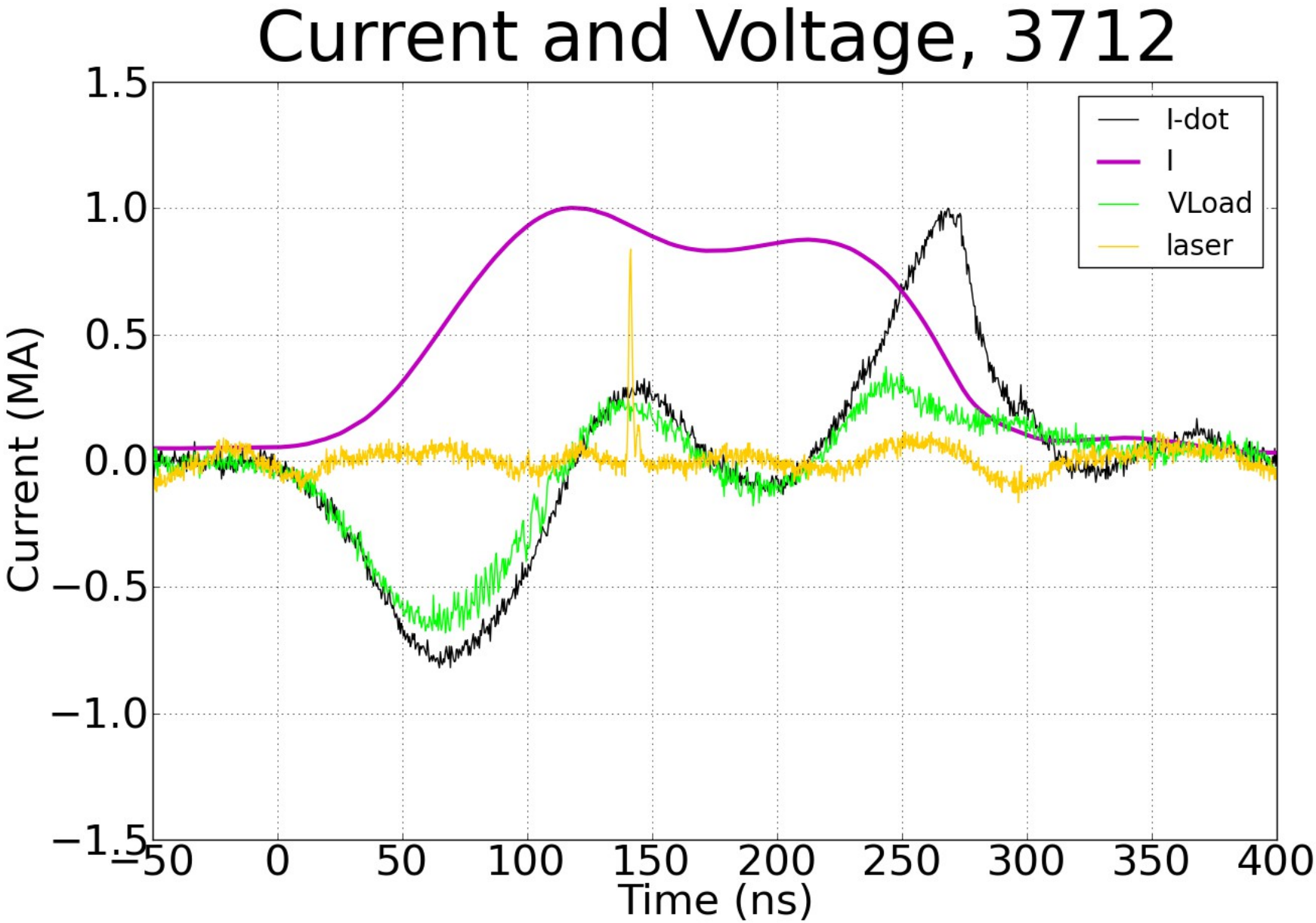
Malcolm Haines found a simple set of conditions for which he found an analytic solution [2] in 1959.

1. H. Alfvén, *Cosmical Electrodynamics* (Oxford: Clarendon) pp.67-71 (1950).
2. M. G. Haines, Proc. Phys. Soc. 74, Part 5, 479 (1959).



3715: 8mm wide, 13 mm tall, 2.2 mm gap, 2x50 micron Al, diverg

3715


Current and Voltage, 3712
I-dot
I
VLoad
laser
Current (MA)
Time (ns)
1.5
1.0
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−0.5
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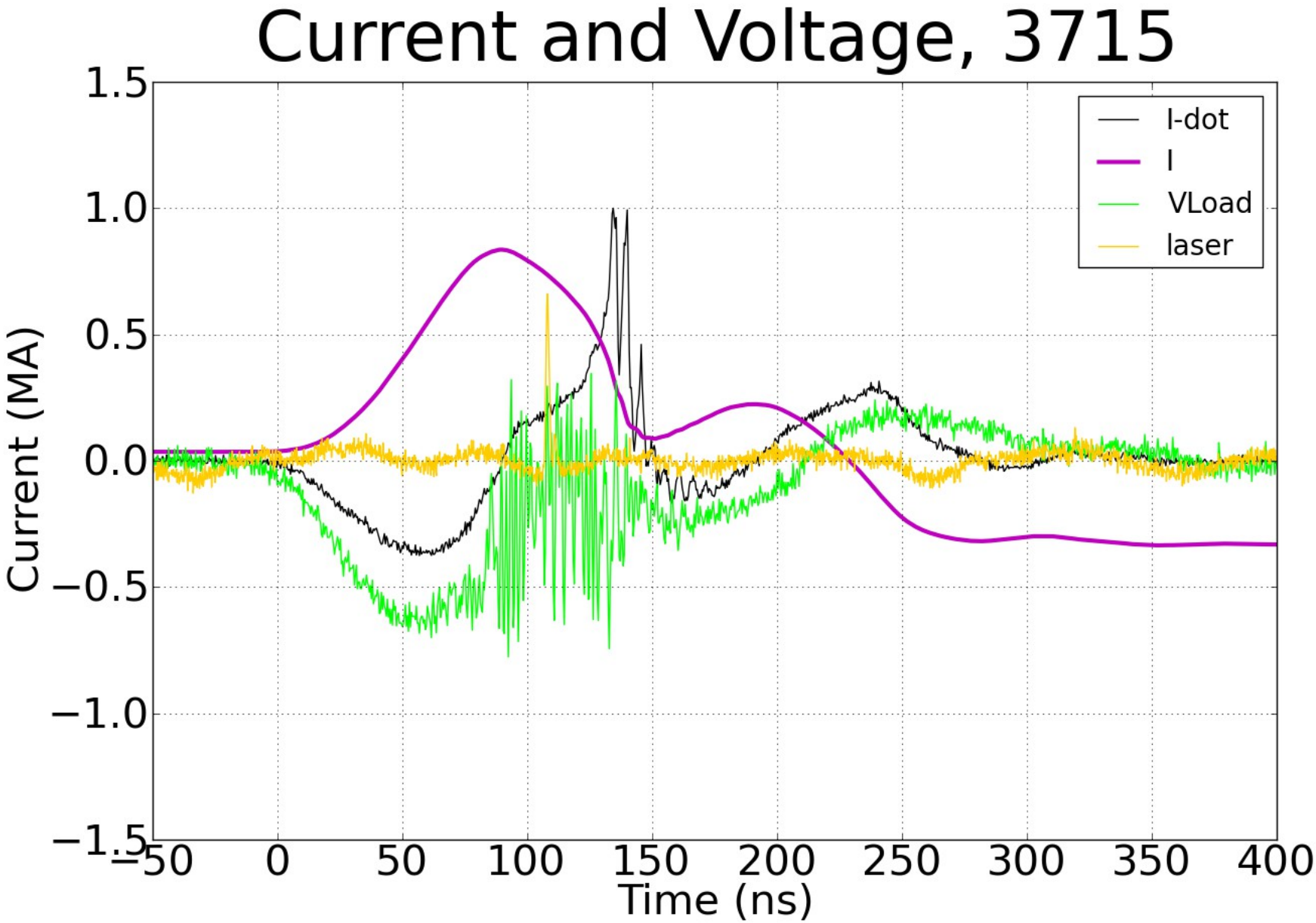
−1.5
−50
0
50
100
150
200
250
300
350
400


Current and Voltage, 3715
I-dot
I
VLoad
laser
Current (MA)
Time (ns)
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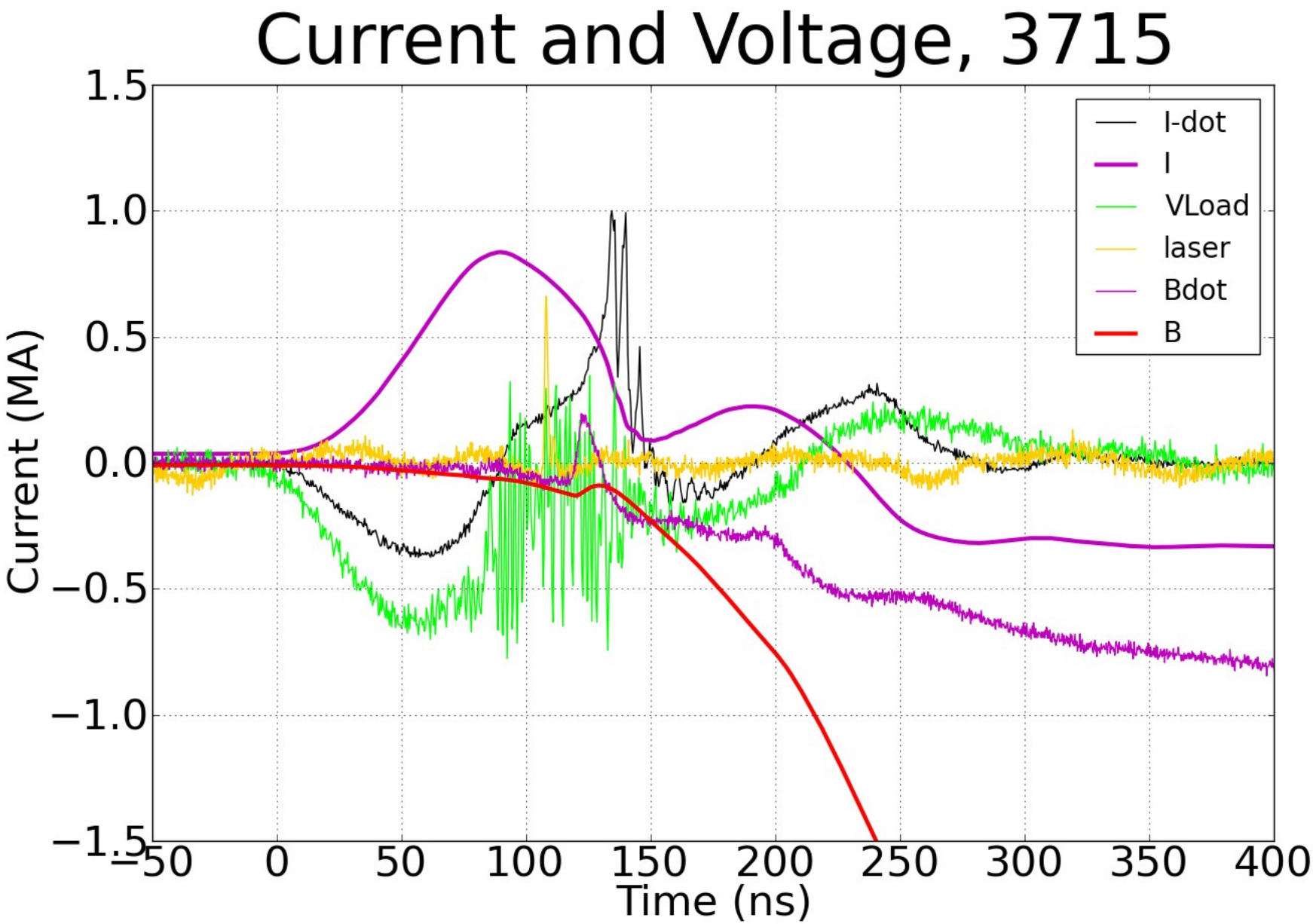
Current and Voltage, 3715
I-dot
I
VLoad
laser
Bdot
B
Current (MA)
Time (ns)
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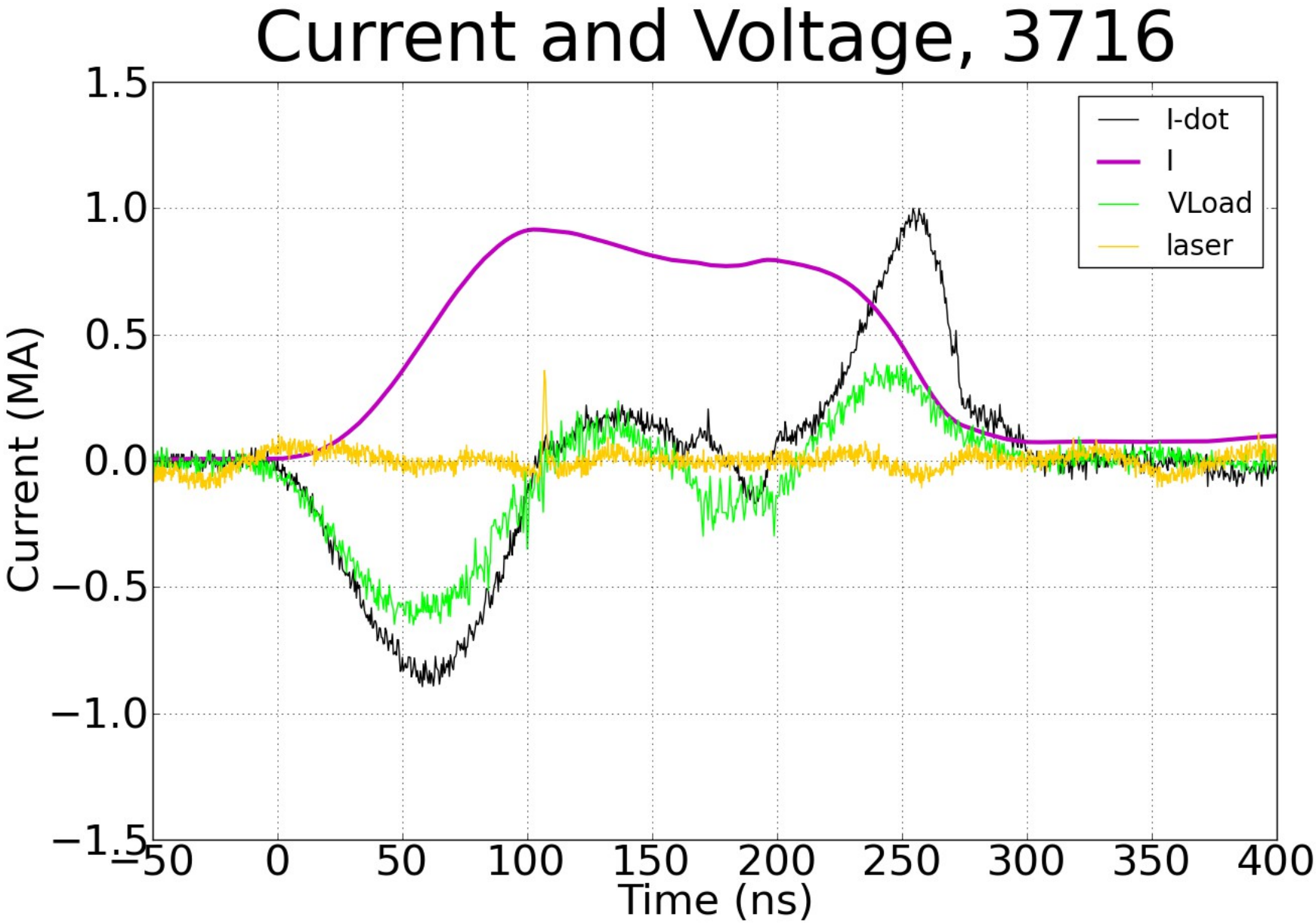
1.0
0.5
0.0
−0.5
−1.0
−1.5
−50
0
50
100
150
200
250
300
350
400

3716: 8mm wide, 13 mm tall, 3mm gap, 2x 50 micron Al, non-diver

3716


Current and Voltage, 3716
I-dot
I
VLoad
laser
Current (MA)
Time (ns)
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1.0
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−0.5
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50
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350
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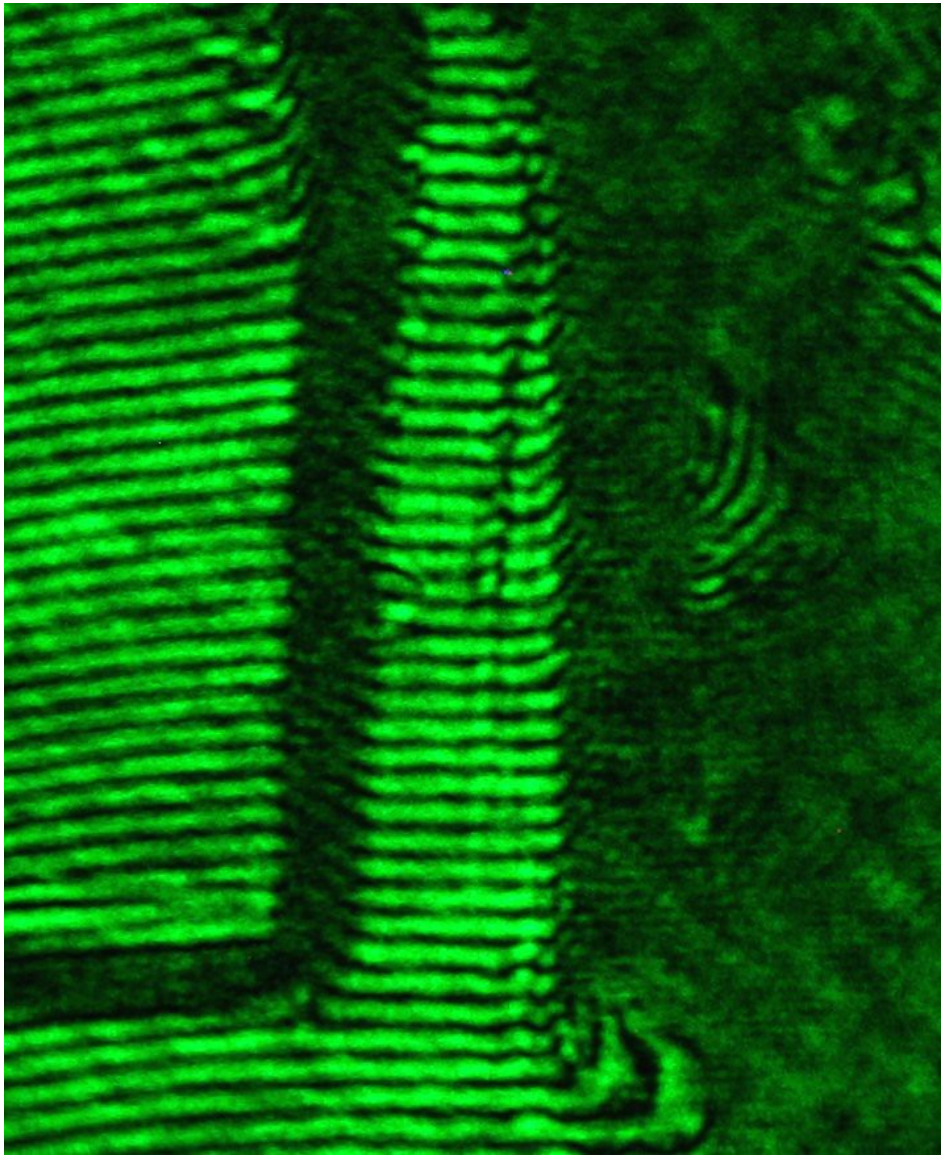
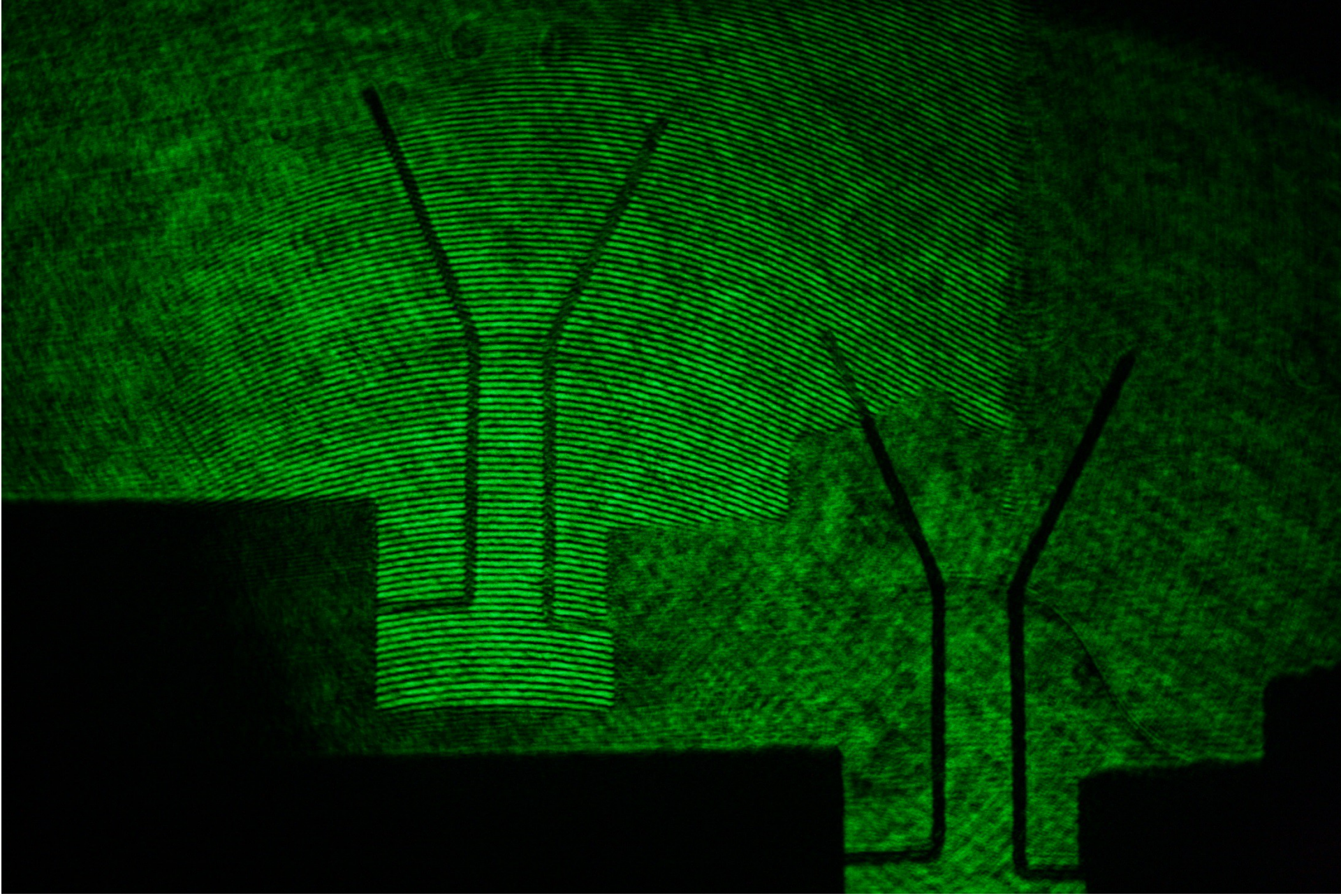
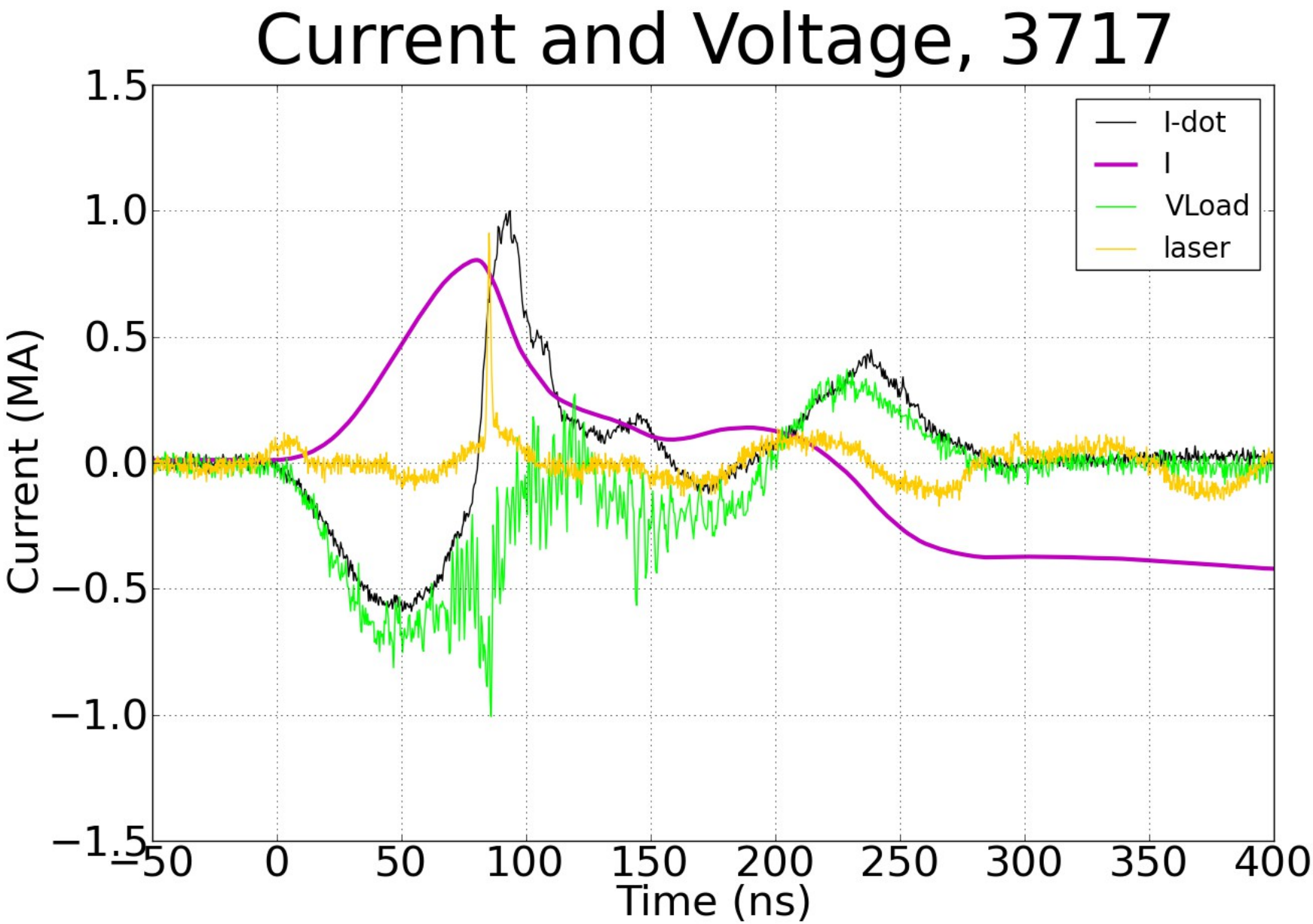




3717: 8mm wide, 13 mm tall, 3mm gap, 2x50 Al, diverging

3717

3716


Current and Voltage, 3717
I-dot
I
VLoad
laser
Current (MA)
Time (ns)
1.5
1.0
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−0.5
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−1.5
−50
0
50
100
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200
250
300
350
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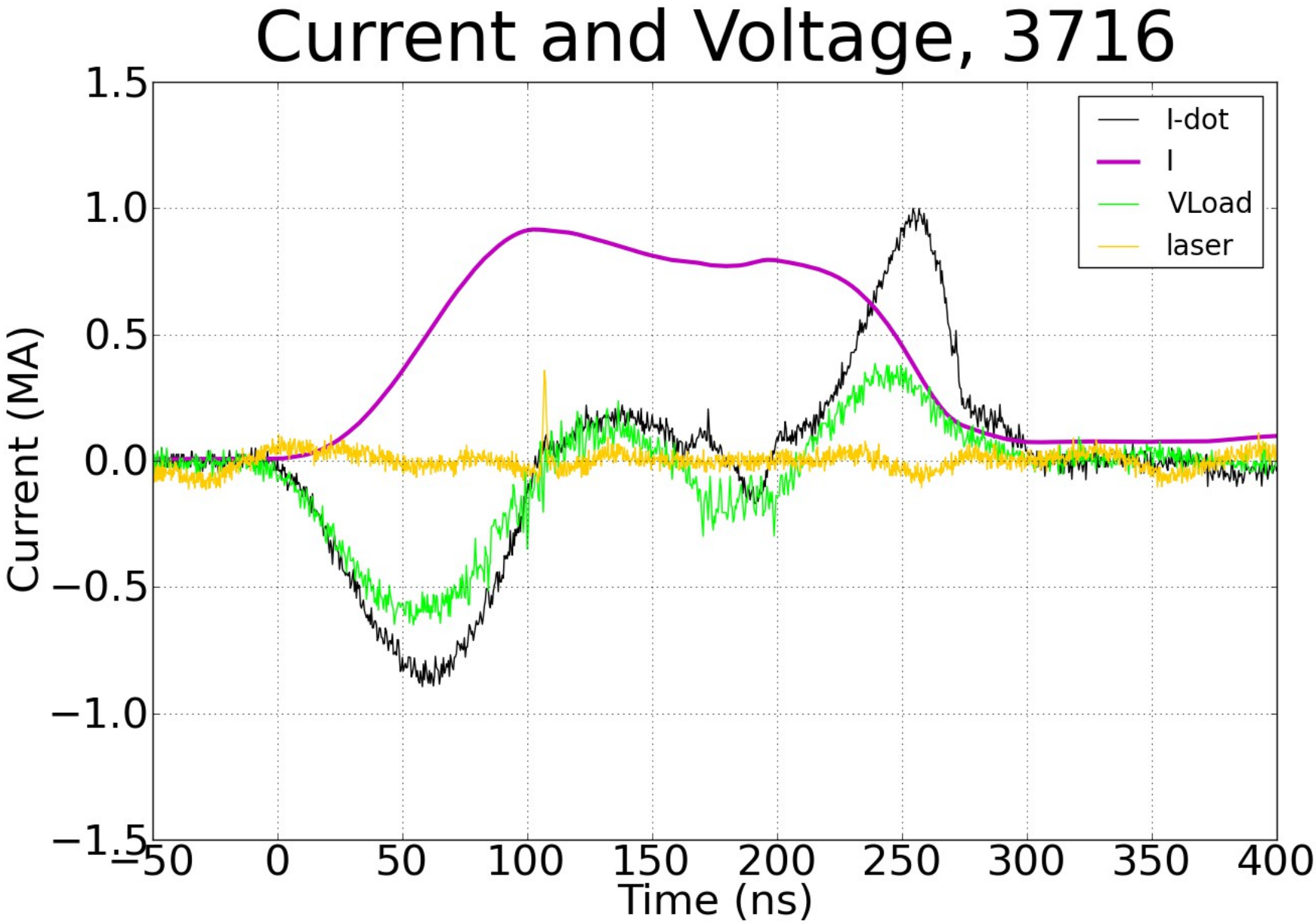
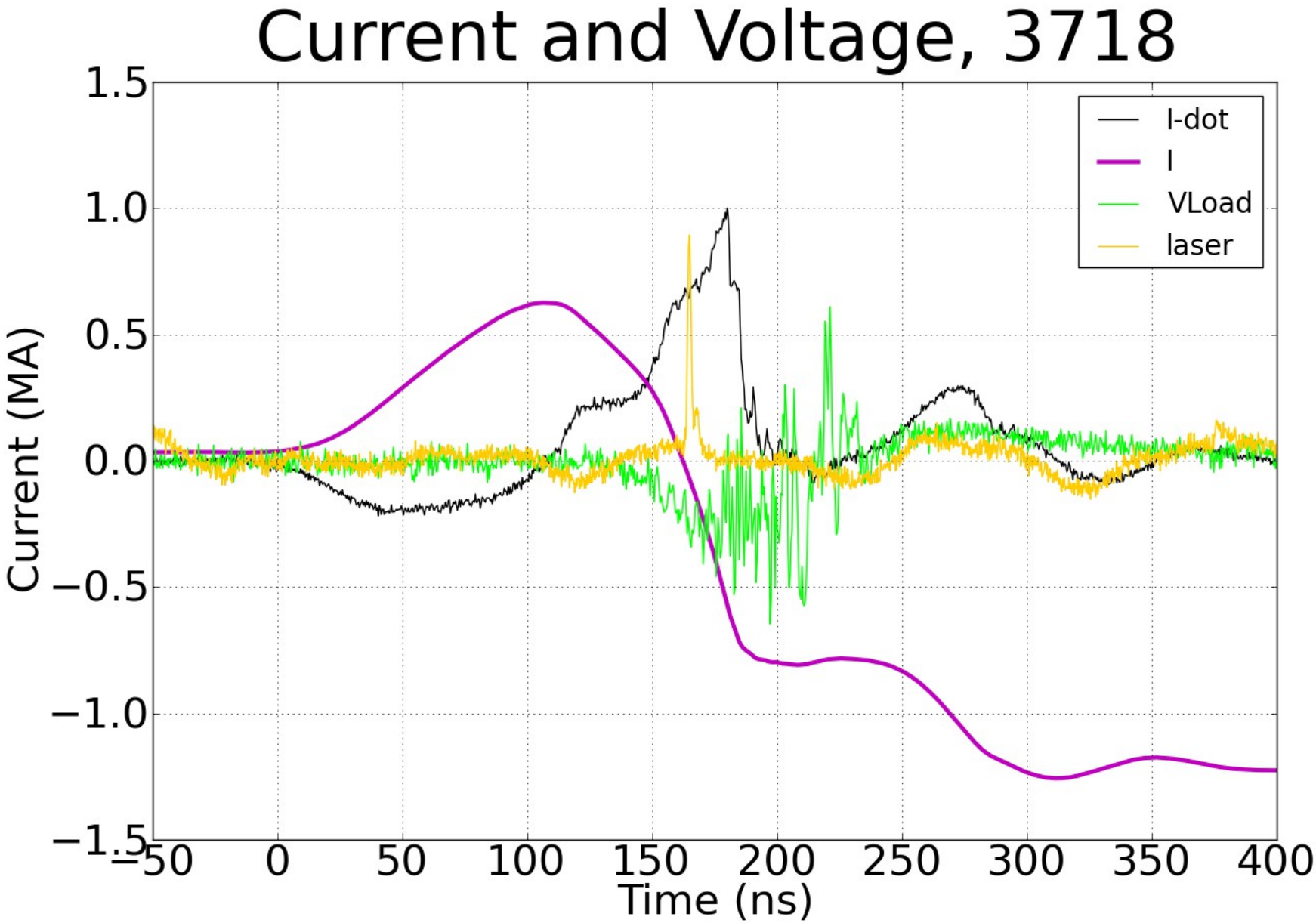
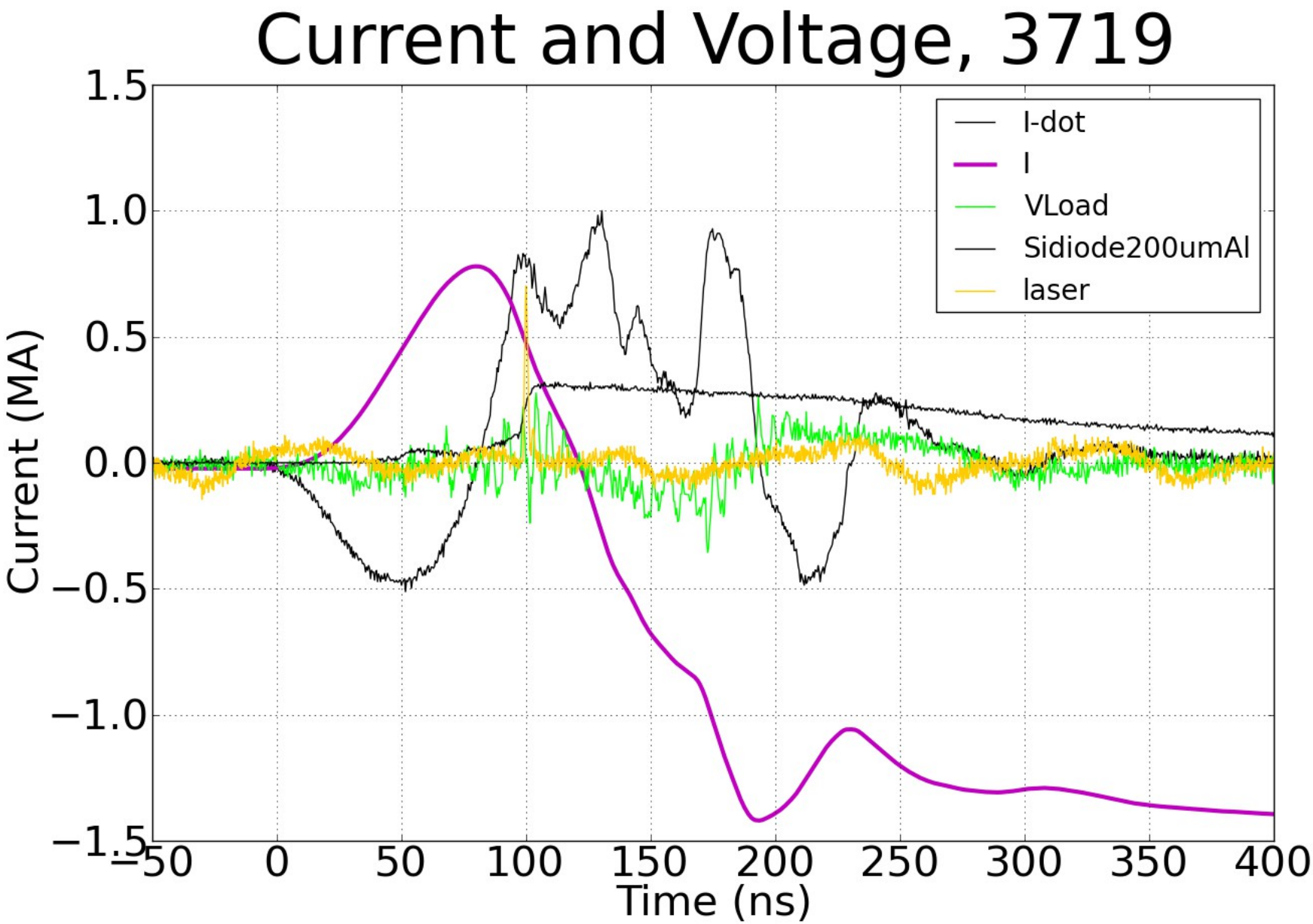

Current and Voltage, 3716
I-dot
I
VLoad
laser
Current (MA)
Time (ns)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−50
0
50
100
150
200
250
300
350
400

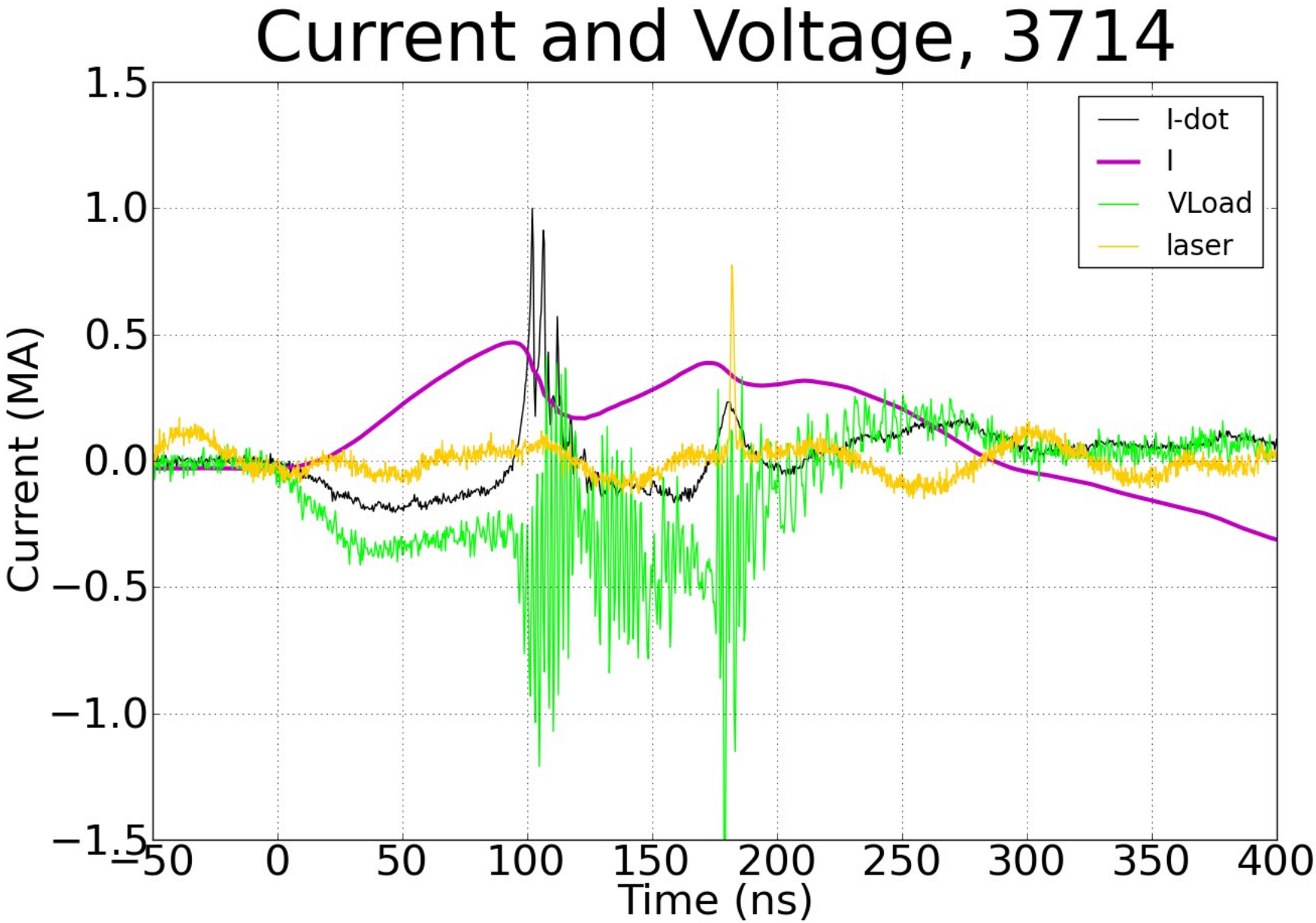
3718: same as 3717, but wider diverging


Current and Voltage, 3718
I-dot
I
VLoad
laser
Current (MA)
Time (ns)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−50
0
50
100
150
200
250
300
350
400

3719: same as 3718

3719


Current and Voltage, 3719
I-dot
I
VLoad
Sidiode200umAl
laser
Current (MA)
Time (ns)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−50
0
50
100
150
200
250
300
350
400


Current and Voltage, 3714
I-dot
I
VLoad
laser
Current (MA)
Time (ns)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−50
0
50
100
150
200
250
300
350
400