

# **Particle-in-Cell Modeling of Rf Breakdown in Accelerating Structures and Waveguides**

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7 October 03

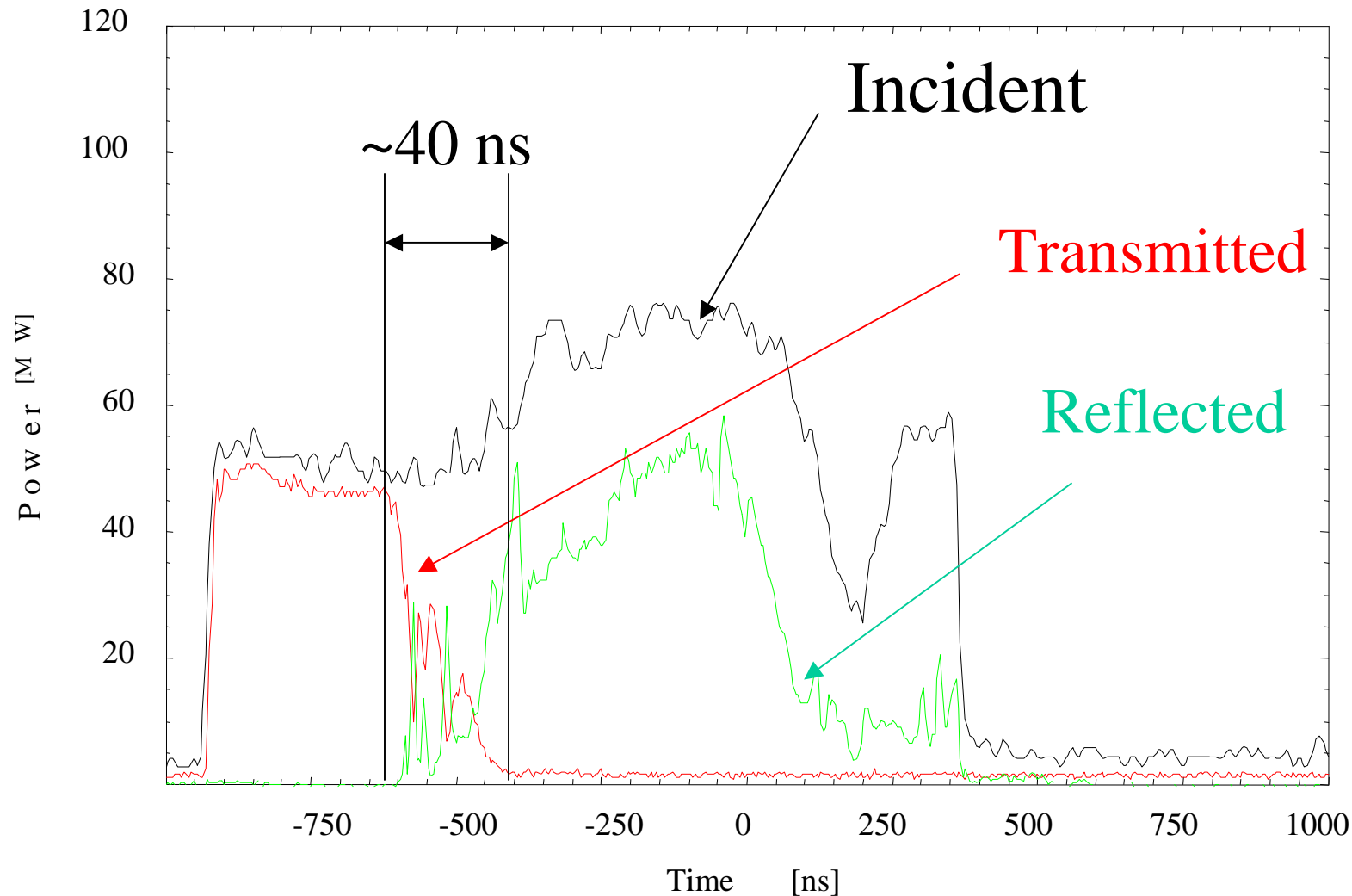
# Outline

- **Properties of rf breakdown** in waveguides and traveling wave (TW) accelerating structures
- **Particle In Cell (PIC) model, based on “cathode spot”**
- **Waveguides**
- **TW structures**
  - Ion current dependence
  - Spot size dependence
  - Coupler breakdown *vs.* cell breakdown
  - Beam pipe current mystery
  - Absorbed power

# **Properties of RF Breakdown**

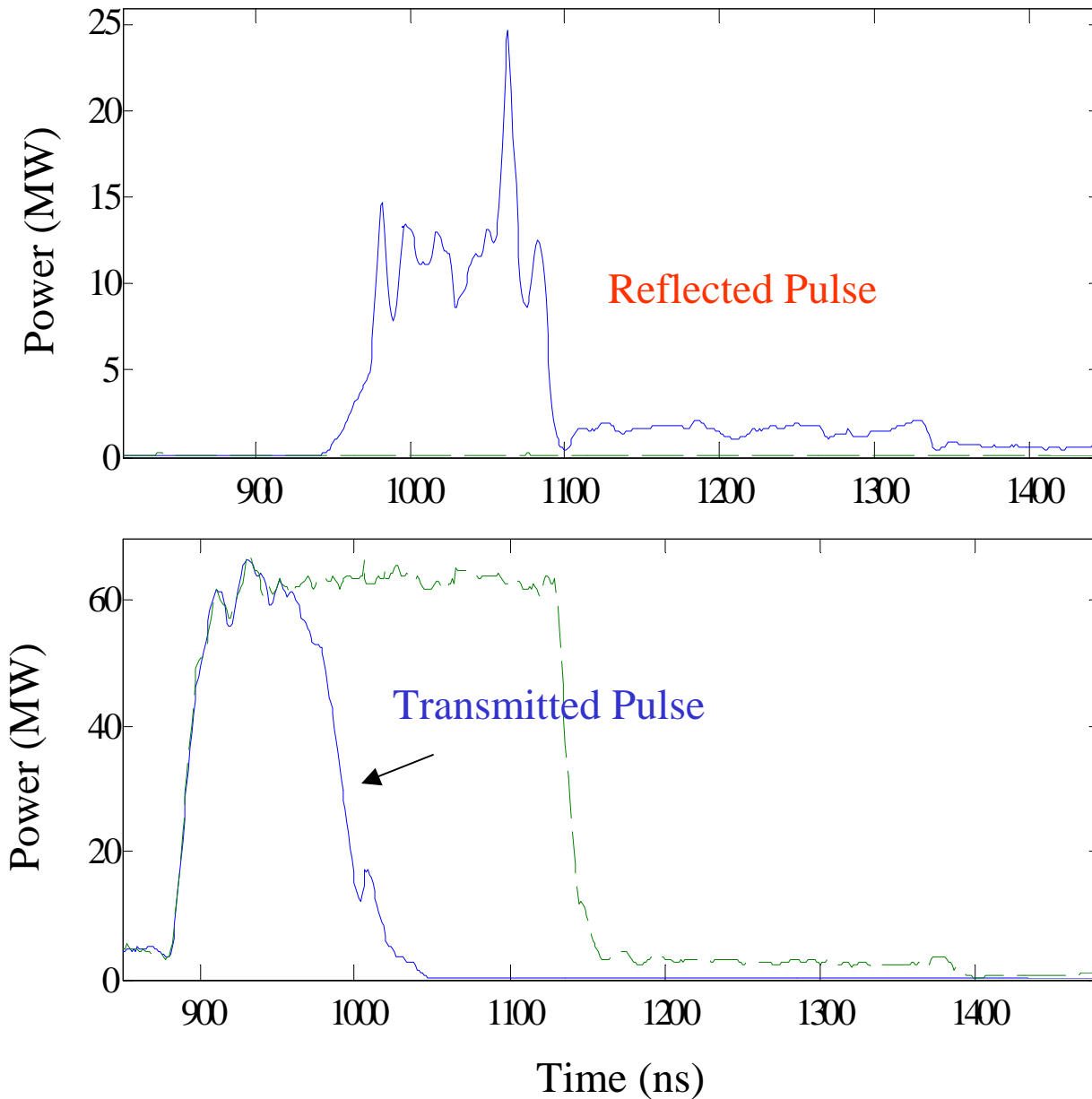
# RF signals of breakdown

34



Breakdown event in waveguide, absorbed 30%  
energy and up to 80% power

# RF breakdown in TW structure



Measurements of a Breakdown event in TW structure, up to 80% power absorbed

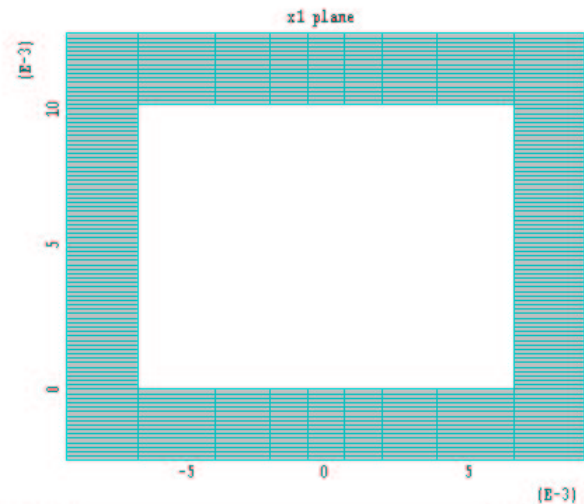
# Main Features of RF breakdown in TW structures and waveguides

- **Complete shut-off** of transmitted power
- Time constant of the power **shut-off** **20-200ns**
- Absorbed power **0-80%**
- Spectral lines of the light are mostly from **neutral copper** atoms (waveguide breakdown)

# **3D PIC simulation of breakdown in waveguide**

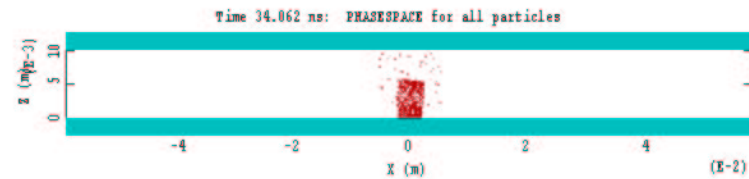
1. Geometry
2. Space charge limited emission of electrons only
3. Space charge limited emission of electrons and copper ion beam
4. Space charge limited emission of electrons, copper ion beam and neutral gas
5. Breakdown in magnetic fields

# 3D geometry of the waveguide as simulated in MAGIC3D



Remarks: Samis experiment	Device: near cutoff waveguid Run: File: wgd04.m3d Author: Valery A Dolgashev Organization: SLAC
MAGIC3D	Version: January 2001
Date: Mar 19, 2001	Time: 20:52
Page: 3	

$y$ - $z$  plane

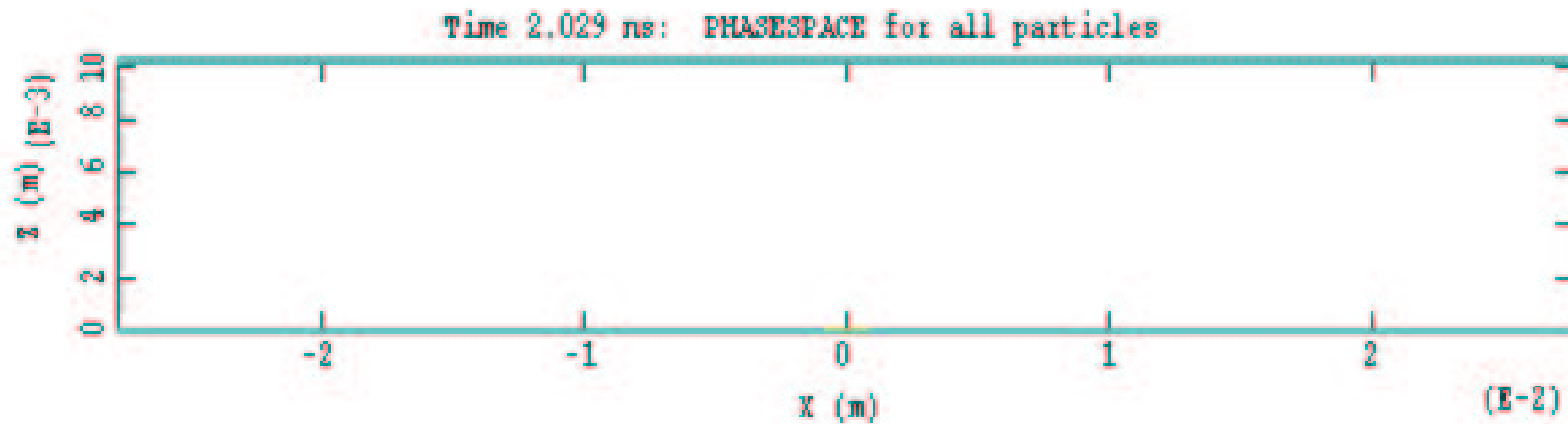


Remarks: Samis experiment	Device: near cutoff waveguid Run: File: wgd04.m3d Author: Valery A Dolgashev Organization: SLAC
MAGIC3D	Version: January 2001
Date: Mar 19, 2001	Time: 20:52
Page: 205	

$x$ - $z$  plane

# Space charge limited emission of electrons only

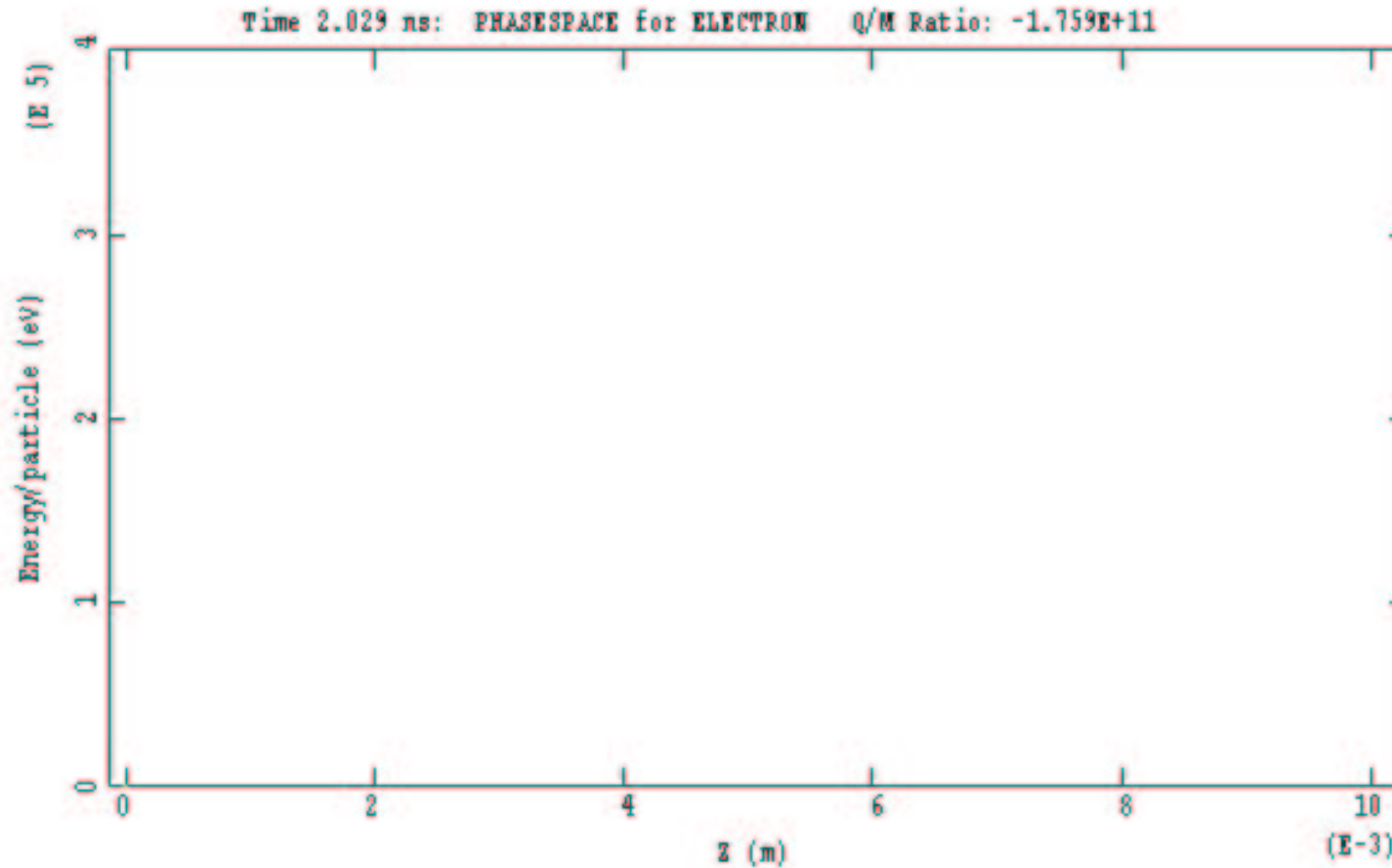
Spot size 1.6x1.6mm, space charge  
limited emission of electrons



Projection of phase space on the  $x$ - $z$  plane

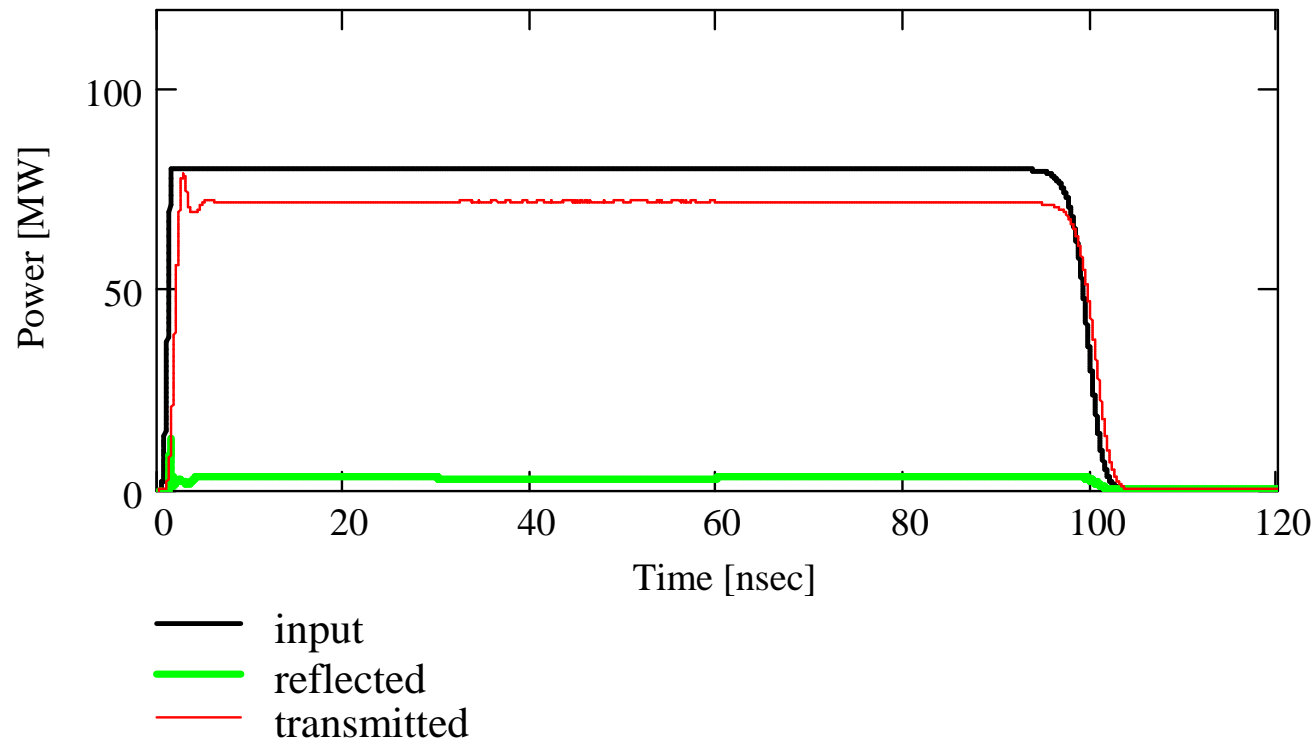
# Space charge limited emission of electrons only

Spot size 1.6x1.6mm, space charge  
limited emission of electrons,  
average current 40 A



Projection of phase space on the  $z$ - $\gamma$  plane

# Space charge limited emission of electrons only



Emission spot 4x4 mm, space charge limited emission of electrons, input power 80 MW, breakdown at 2 ns

## Result

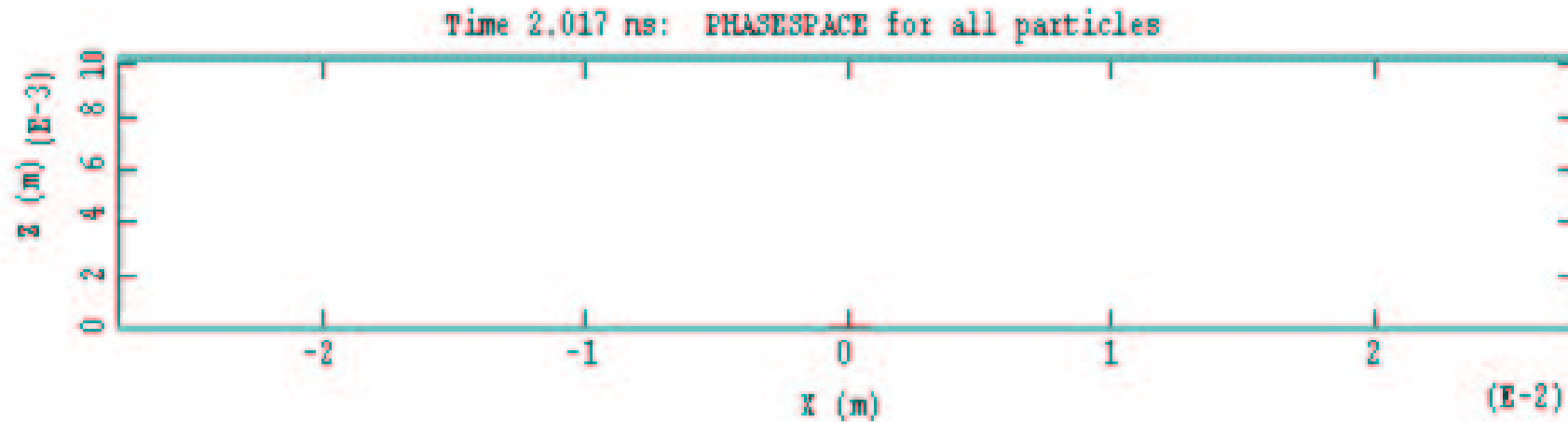
- In order to significantly disrupt RF power spot size should be  $> 2\text{cm}^2$
- Fast transient process  $\sim\text{ns}$
- $\sim 50\%$  of emitted current returns back to the emitting spot

# **Model based on properties of “plasma spot”**

- Space charge limited emission of electrons
- Copper ion beam with current needed to disrupt transmitted power**

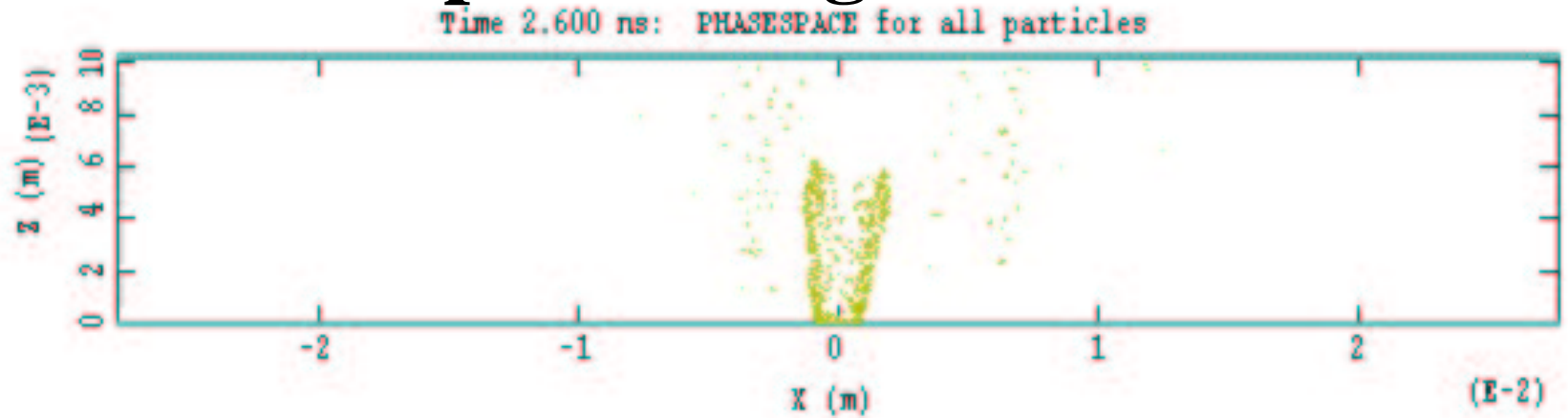
# Ions and space charge limited electrons

Spot size 1.6x1.6mm, copper ion  
current ~8A

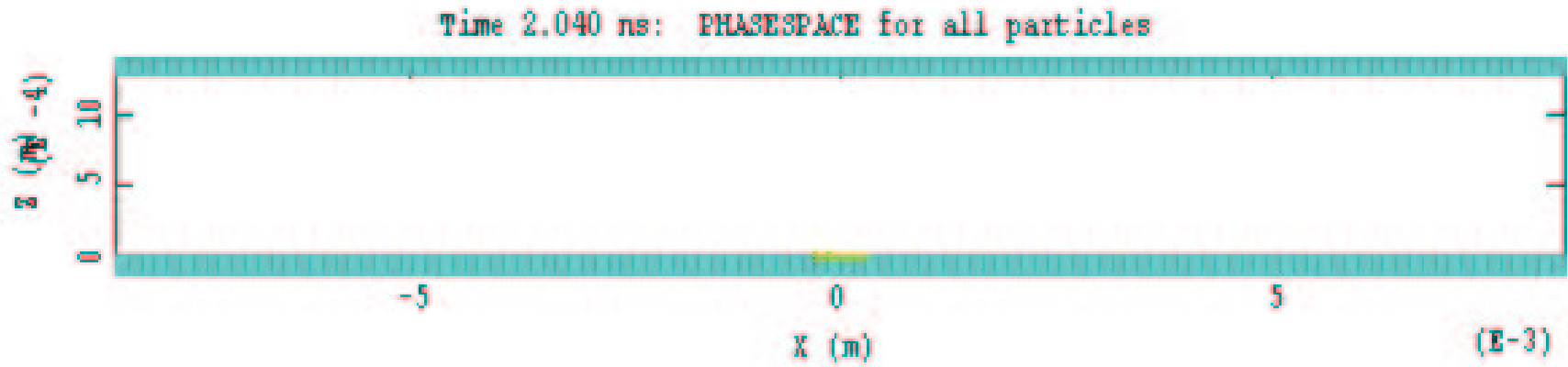


Fast electron motion, projection of phase space on the  $x$ - $z$  plane

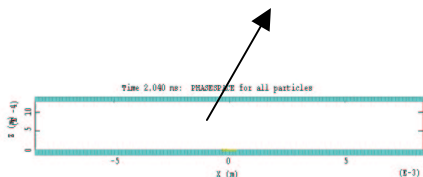
# Ions and space charge limited electrons



**Low magnetic field waveguide, spot size 1.6x1.6mm,  
copper ion current ~8A**



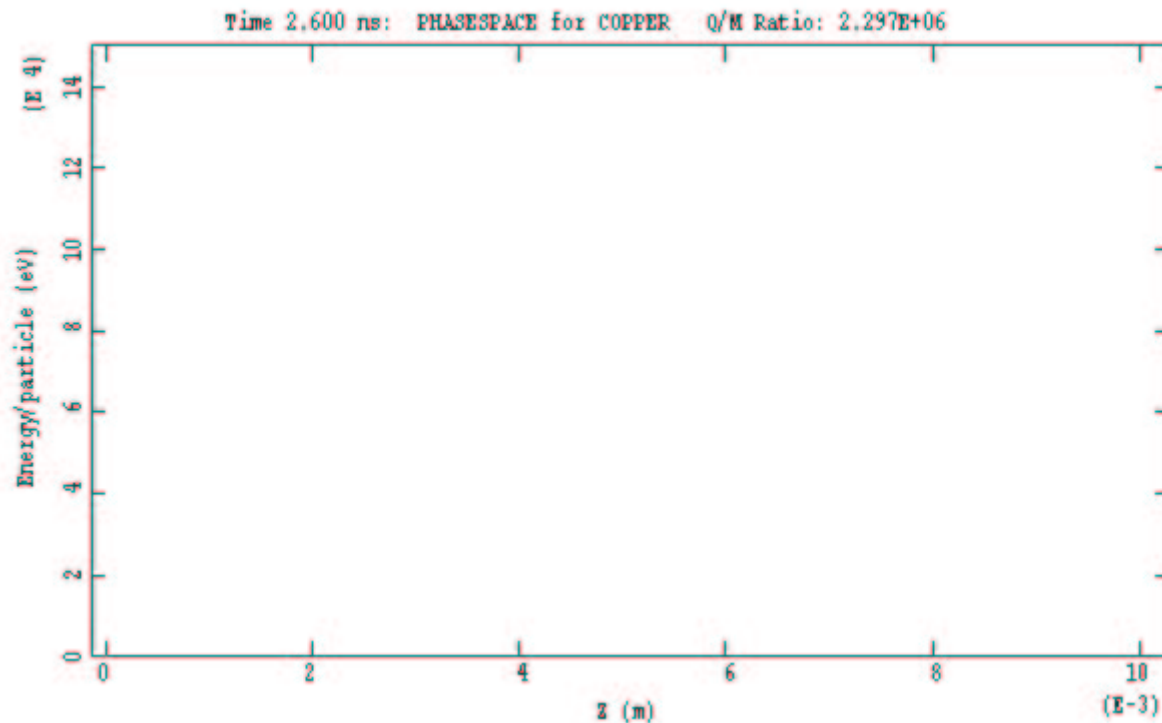
**High magnetic field waveguide, spot size  
0.6x0.6mm, copper ion current ~35A**



Electron - ion motion, projection of phase space on the  $x$ - $z$  plane

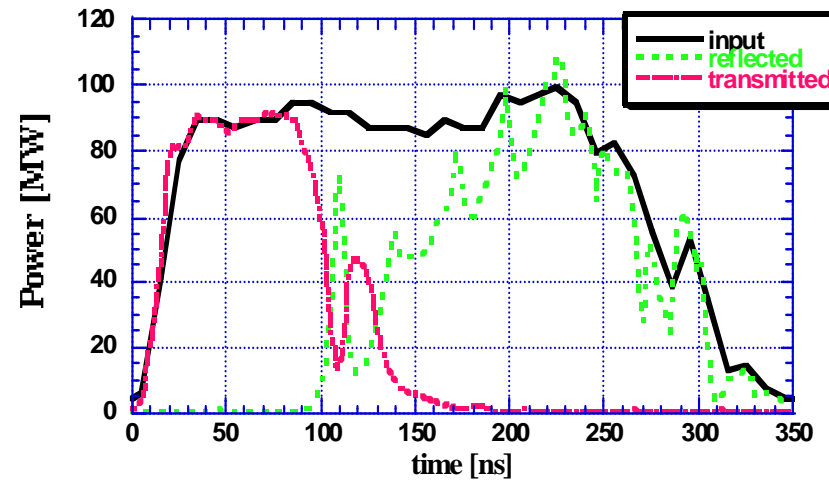
# Ions and space charge limited electrons

Spot size 1.6x1.6mm, copper ion  
current ~8A

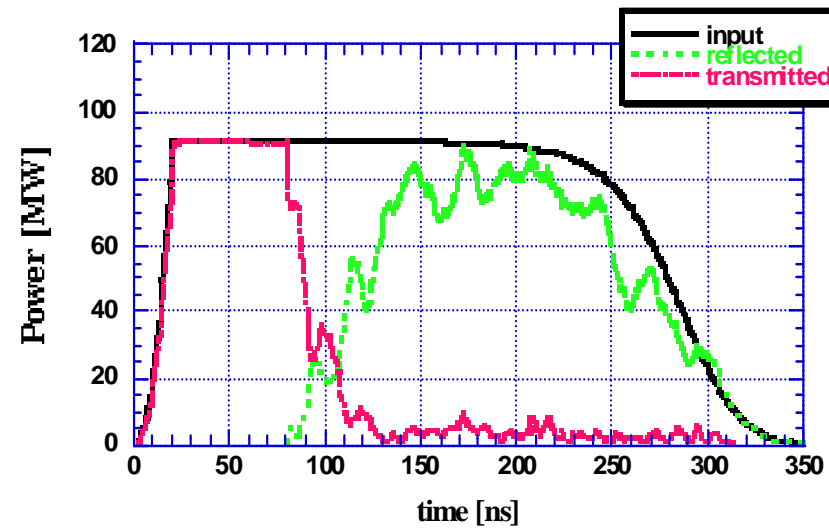


Slow ion motion, projection of phase space on the  $z$ - $\gamma$  plane

# Ions and space charge limited electrons

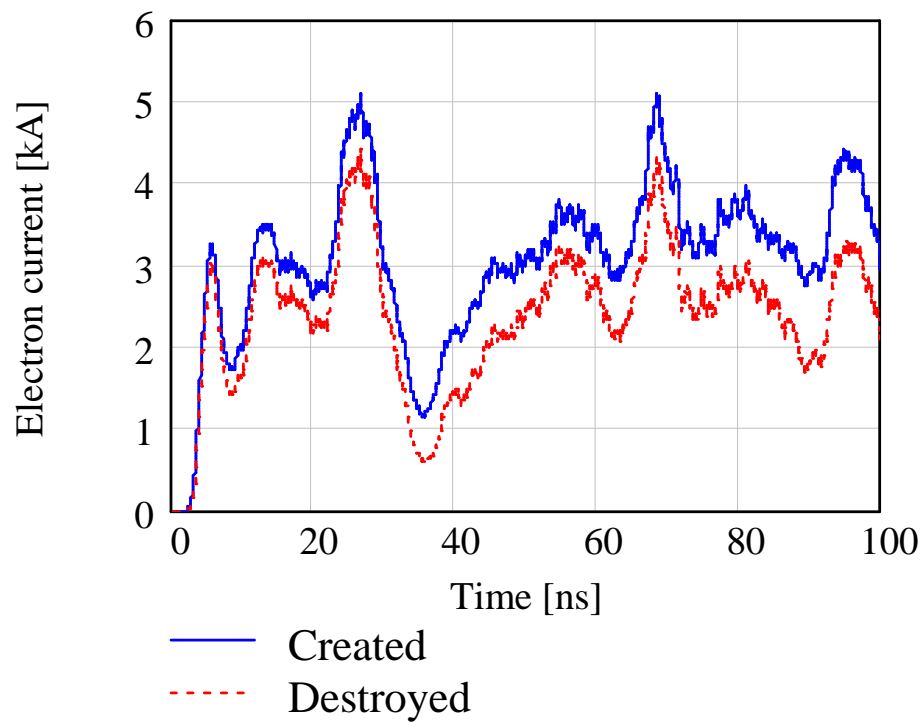


Measurements, 24 April 2001, 18:13:40, shot 45

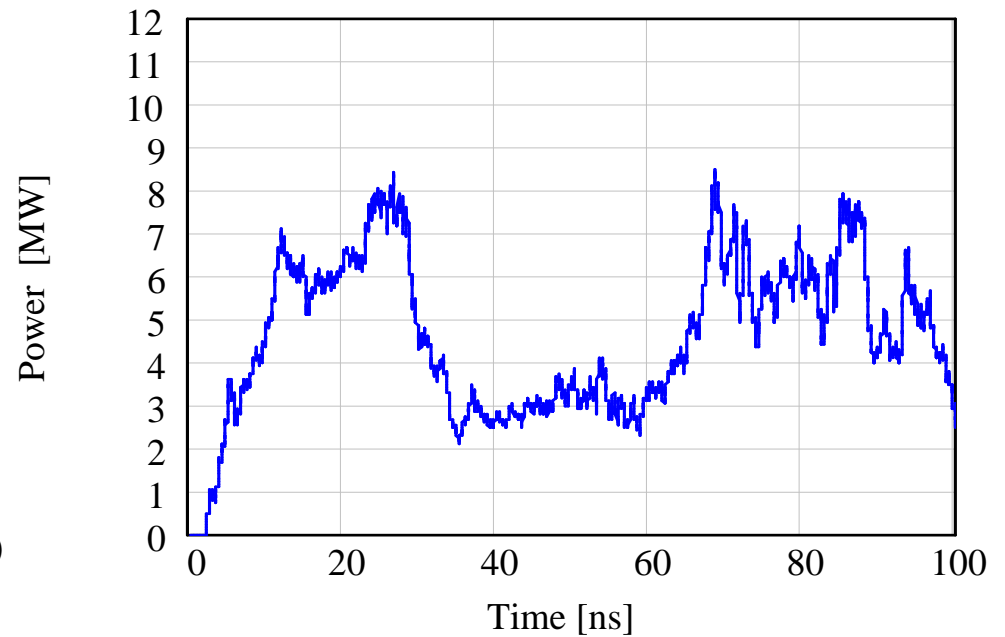


3D PIC simulations, 4x4 mm emitting spot,  
electron current 7kA, copper ion current 30A

# Electron **currents** and back **bombardment power** for waveguide breakdown, 12 A ion current, spot $\sim 16 \text{ mm}^2$



Electron currents



Back bombardment power

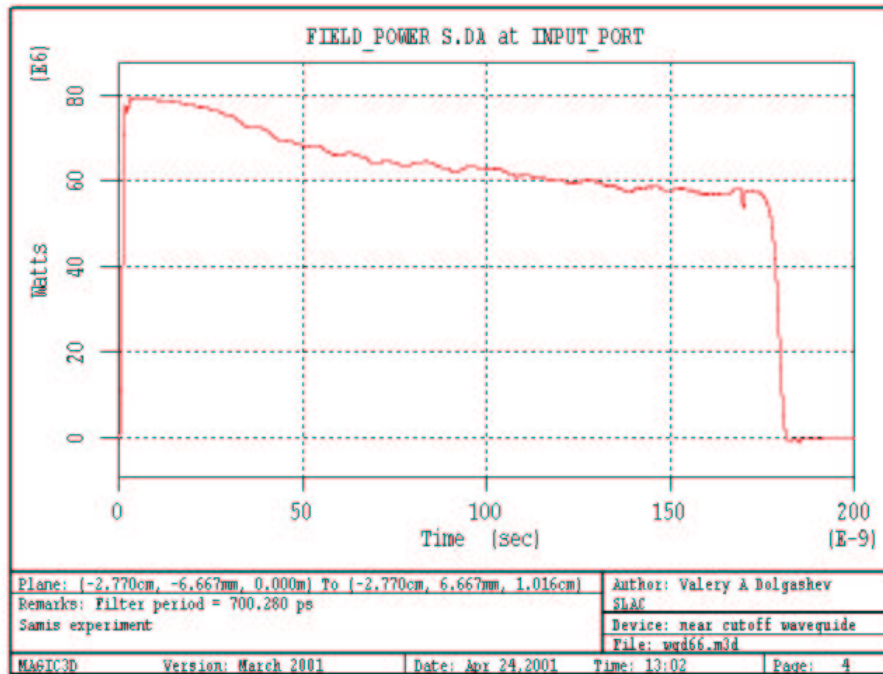
# Result

- Ion current determines electron current by compensating space charge of electrons
- Breakdown behavior strongly depends on ion current and weakly on size of emitting spot
- Ions cross low magnetic field waveguide (10 mm) the waveguide in  $\sim 30$  ns
- Ions cross high magnetic field waveguide (1.3mm) the waveguide in  $\sim 10$  ns
- Time constant of the power shut-off 10-20 ns
- $\sim 80\%$  of emitted current returns back to the emitting spot
- Maximum absorbed power 50%

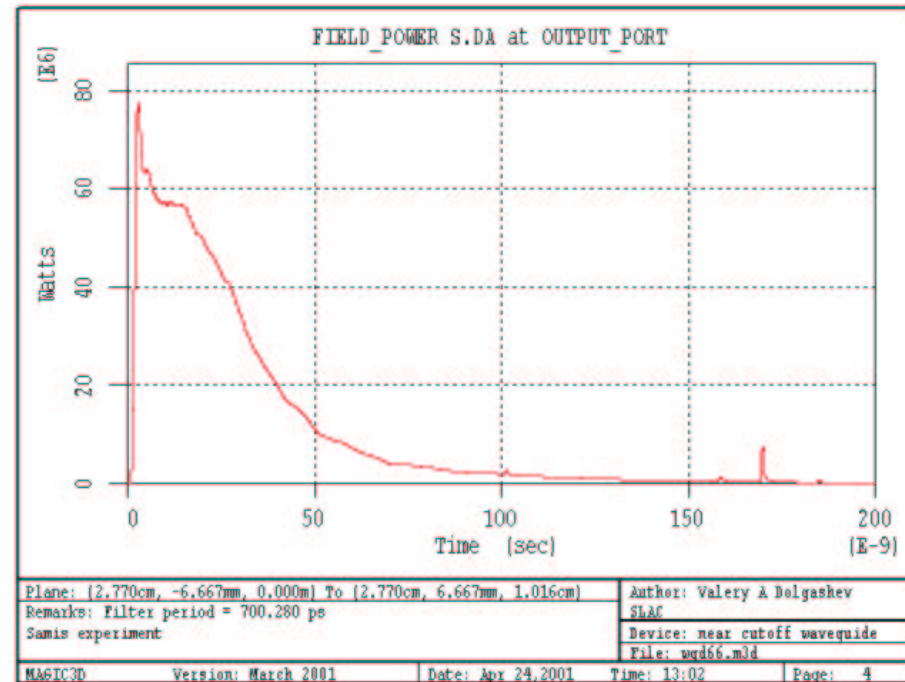
# Model

- Space charge limited emission of electrons
- Copper ion beam with current needed to disrupt transmitted power
- Drag associated with presence of neutral copper ions**

# Higher power absorption



Input - reflected power



Transmitted power

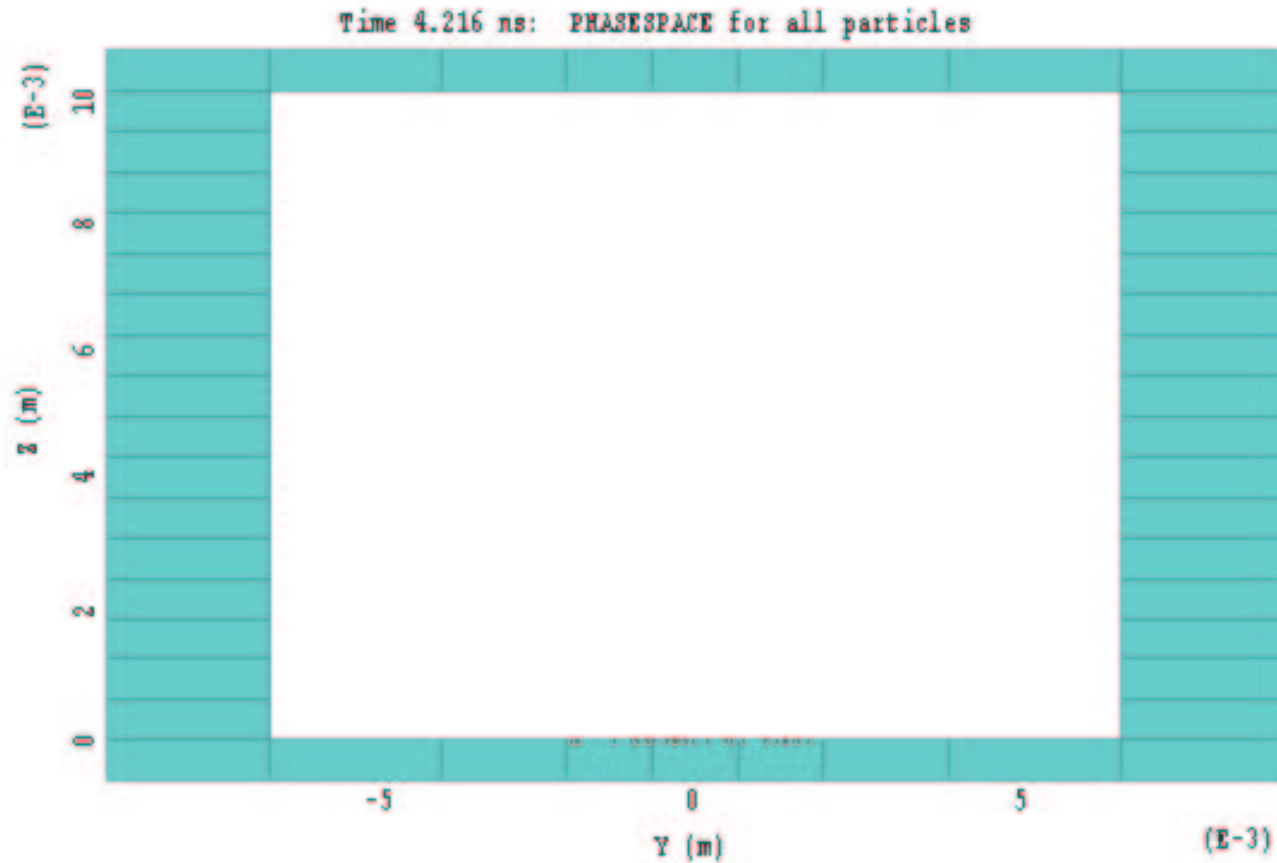
## Result

- Maximum absorbed power up to 75%
- Ion-electron oscillation damped

# **Breakdown dynamics in DC magnetic fields**

Electron currents and back bombardment power for waveguide breakdown, 12 A ion current, spot  $\sim 16 \text{ mm}^2$

External magnetic field 3000 Gauss

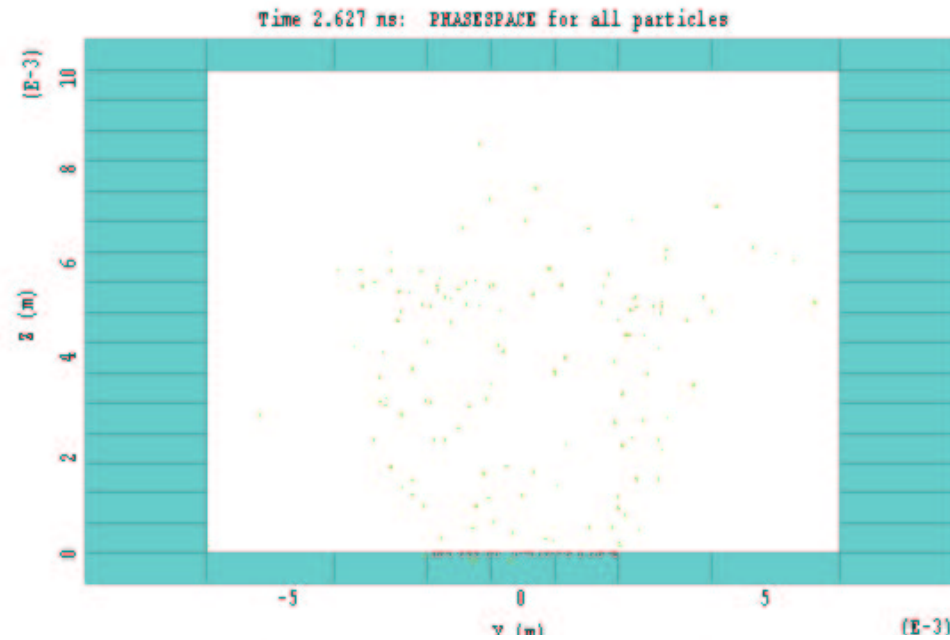


$H_x$

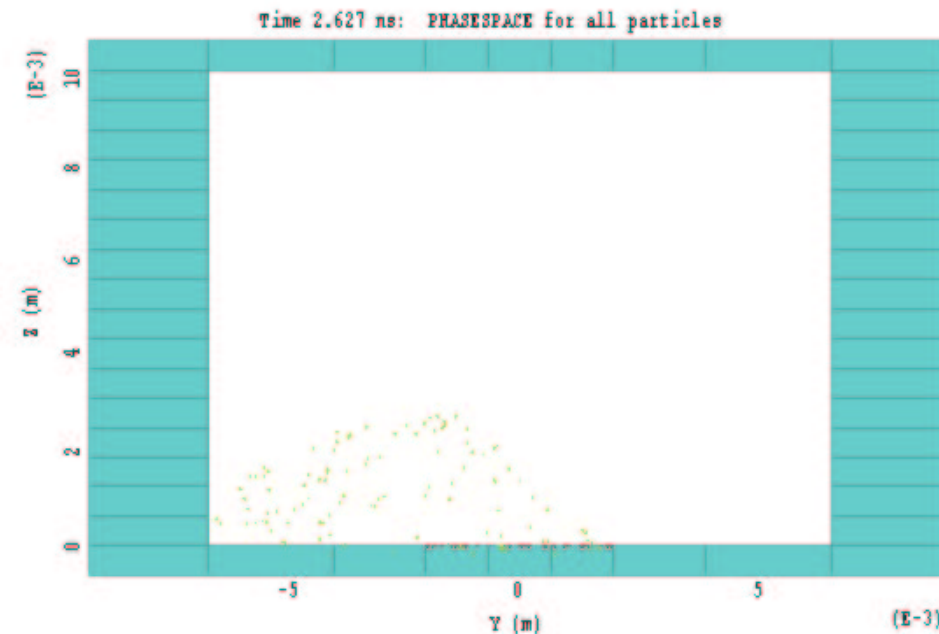


Electron currents and back bombardment power for waveguide  
breakdown, 12 A ion current, spot  $\sim 16 \text{ mm}^2$

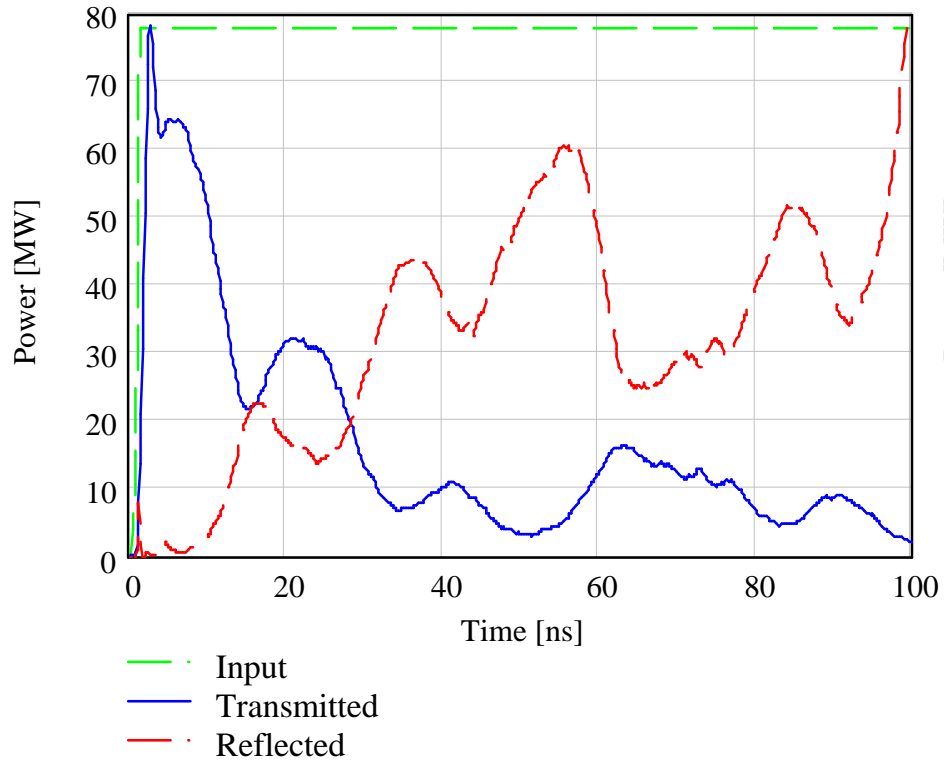
No external magnetic  
fields



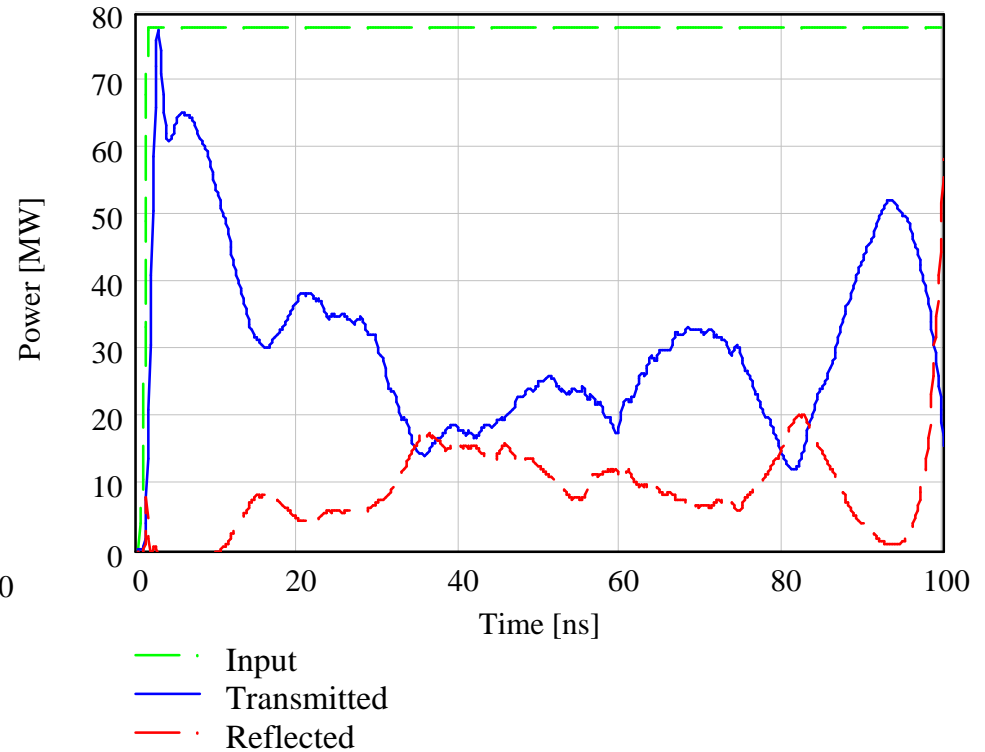
External magnetic  
field 3000 Gauss



# Rf signals for waveguide breakdown, 12 A ion current, spot $\sim 16 \text{ mm}^2$



No magnetic fields



Magnetic field  $H_x = 3 \text{ kG}$

# Result

- Breakdown dynamics determined by ion movement is weakly effected by  $\sim$ kGs DC magnetic field

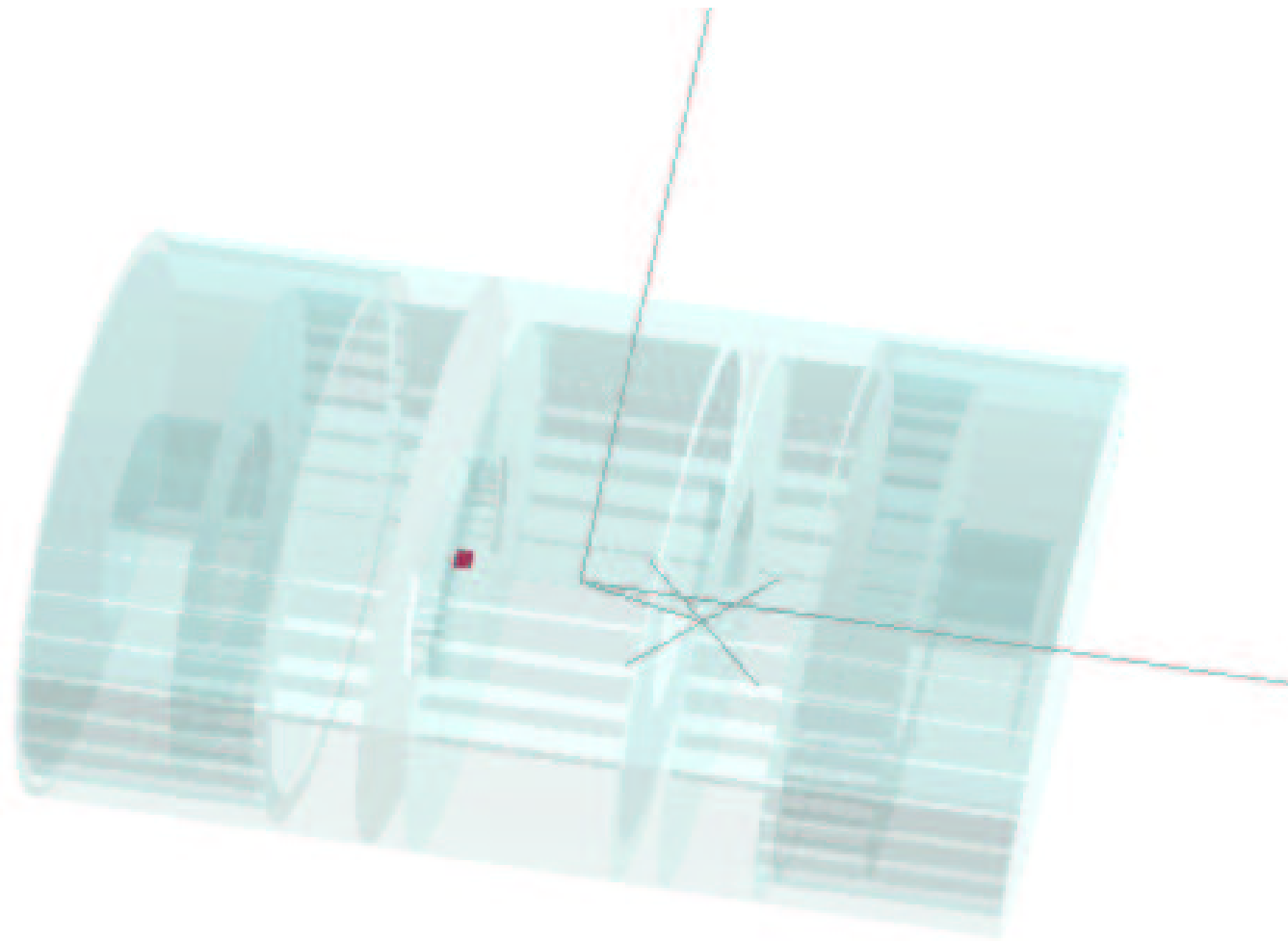
# **Traveling wave accelerating structures**

# Model

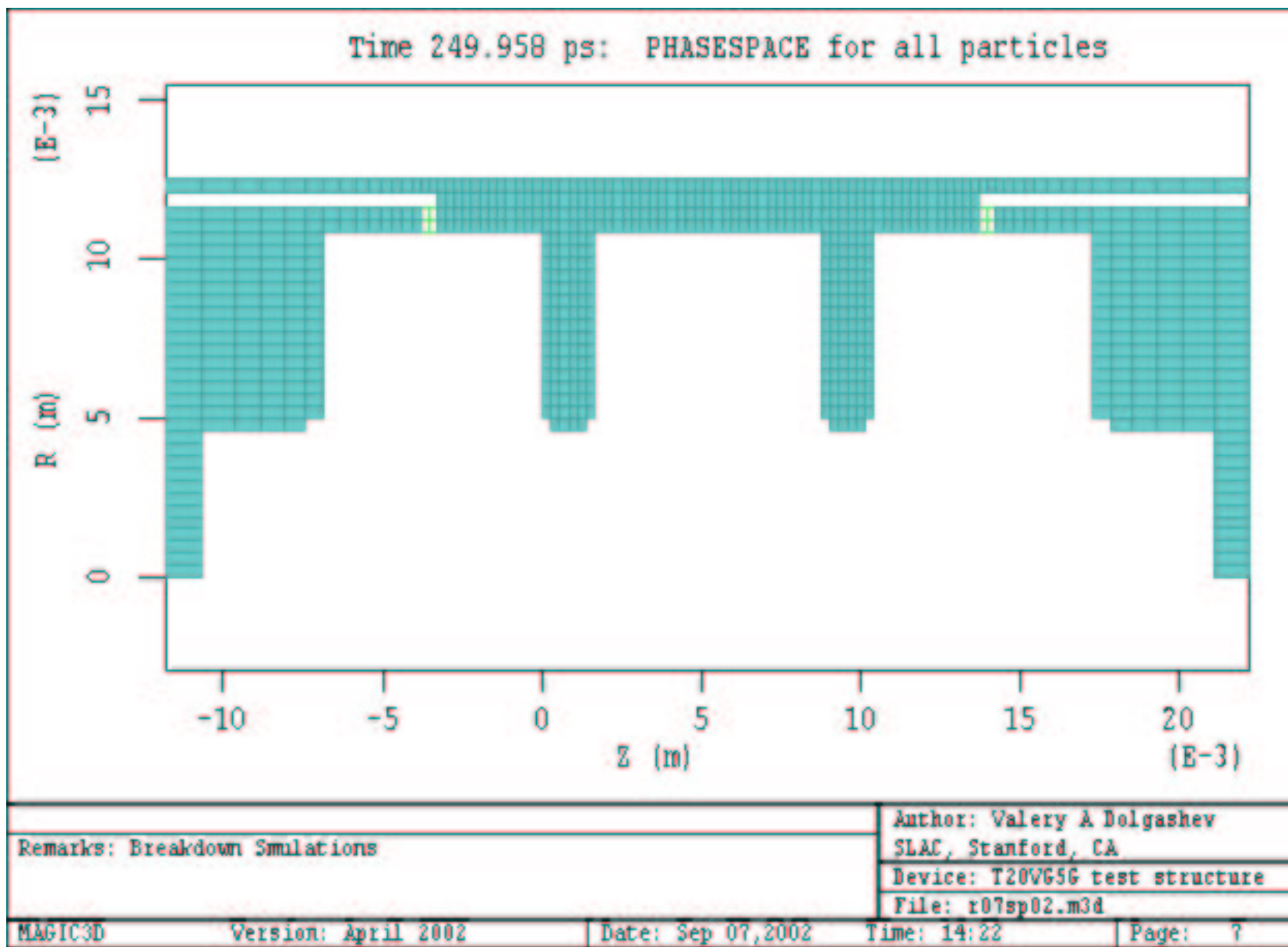
- Matched traveling wave structure with coaxial couplers
- Emission of ion beam with predetermined current from small spot on iris
- Space charge limited electron current from the same iris spot

Spot size  
dependence

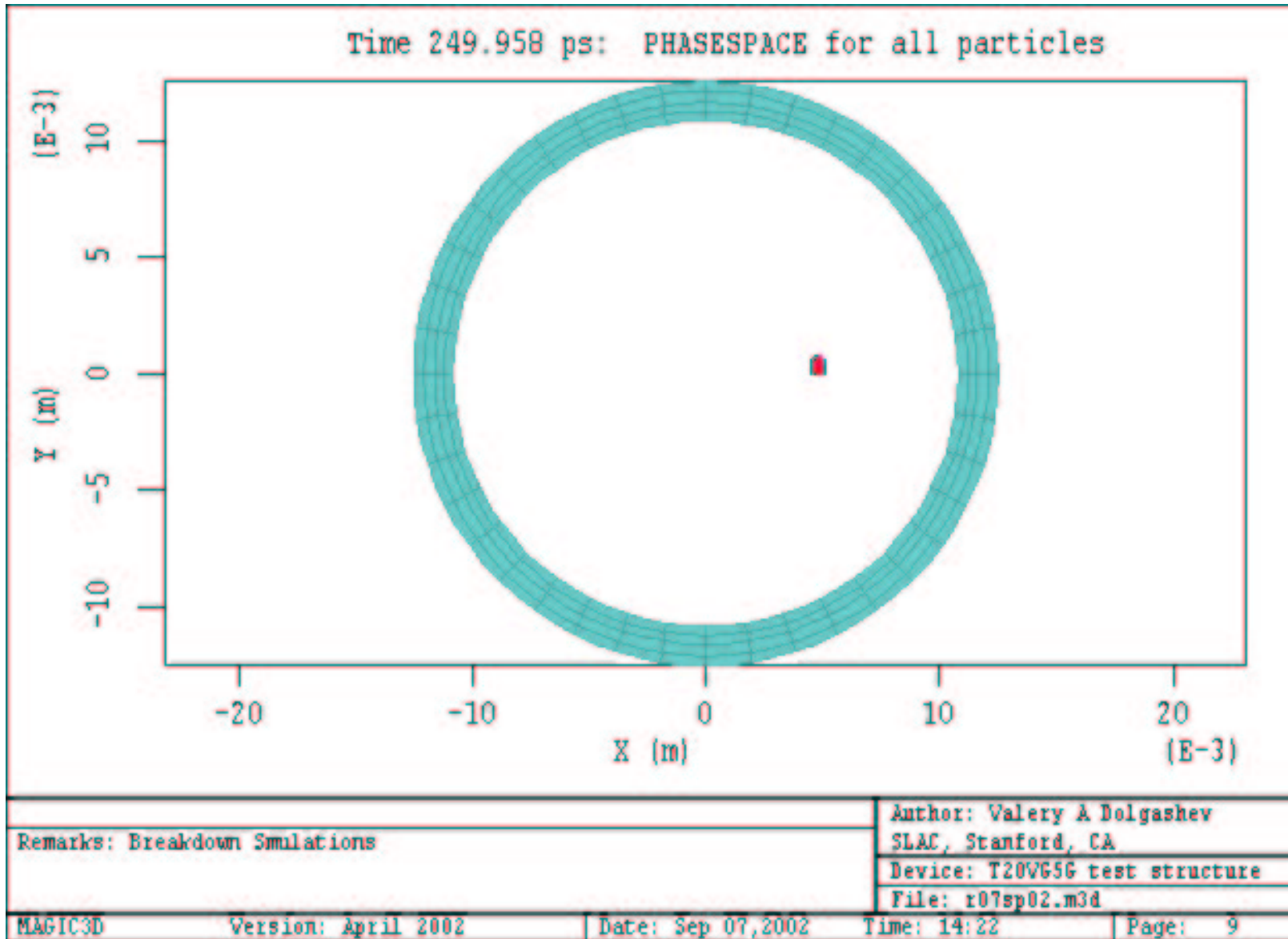
3D PIC simulations, coupler breakdown, T20VG5, spot  $\sim 1\text{mm}^2$



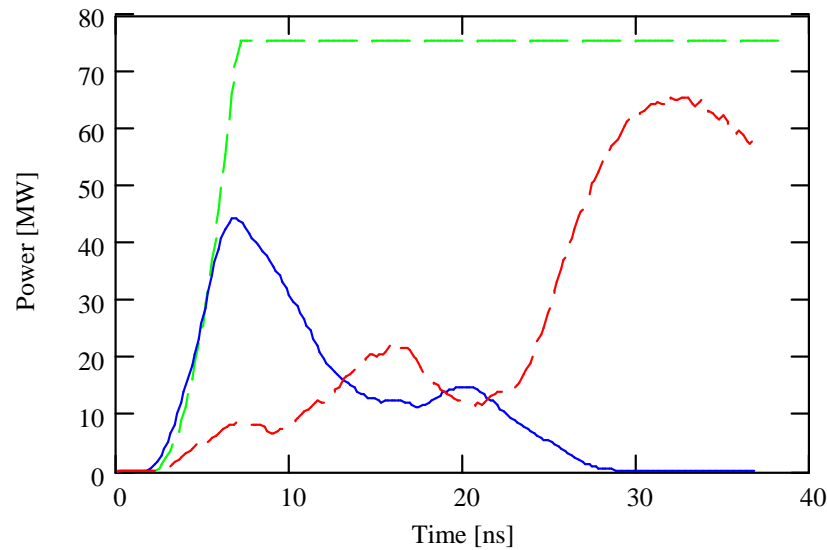
# 3D PIC simulations, T20VG5, coupler breakdown, spot $\sim 1\text{mm}^2$



# 3D PIC simulations, T20VG5, coupler breakdown, spot $\sim 1\text{mm}^2$

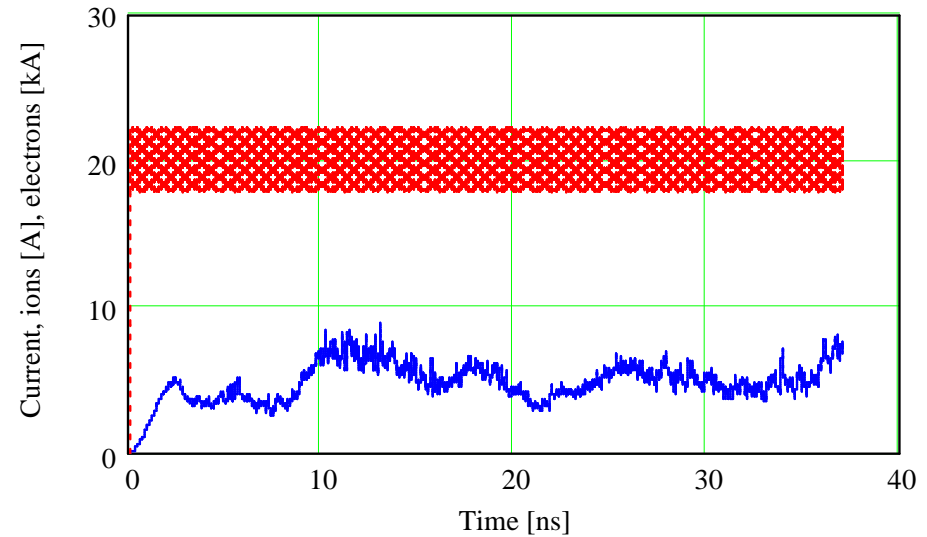


# 3D PIC simulations, T20VG5, coupler breakdown, spot $\sim 1\text{mm}^2$



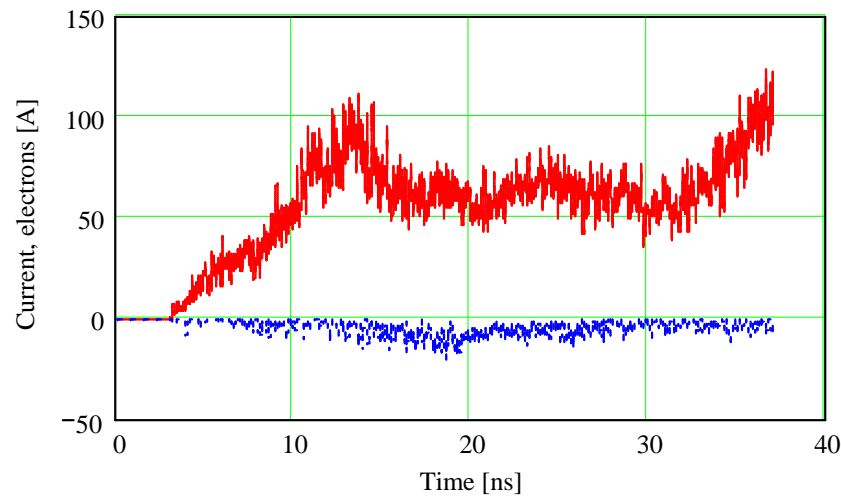
— Input  
— Transmitted  
- - Reflected

rf



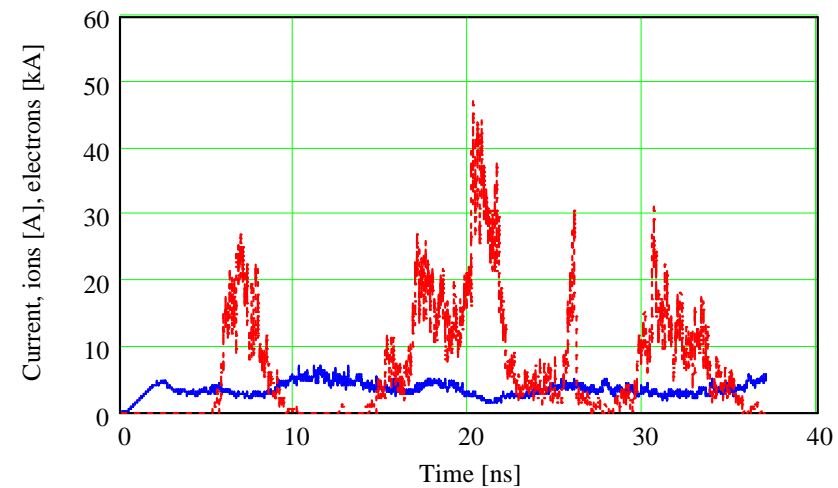
— Electrons  
- - Ions

Emitted currents



— Input  
- - Output

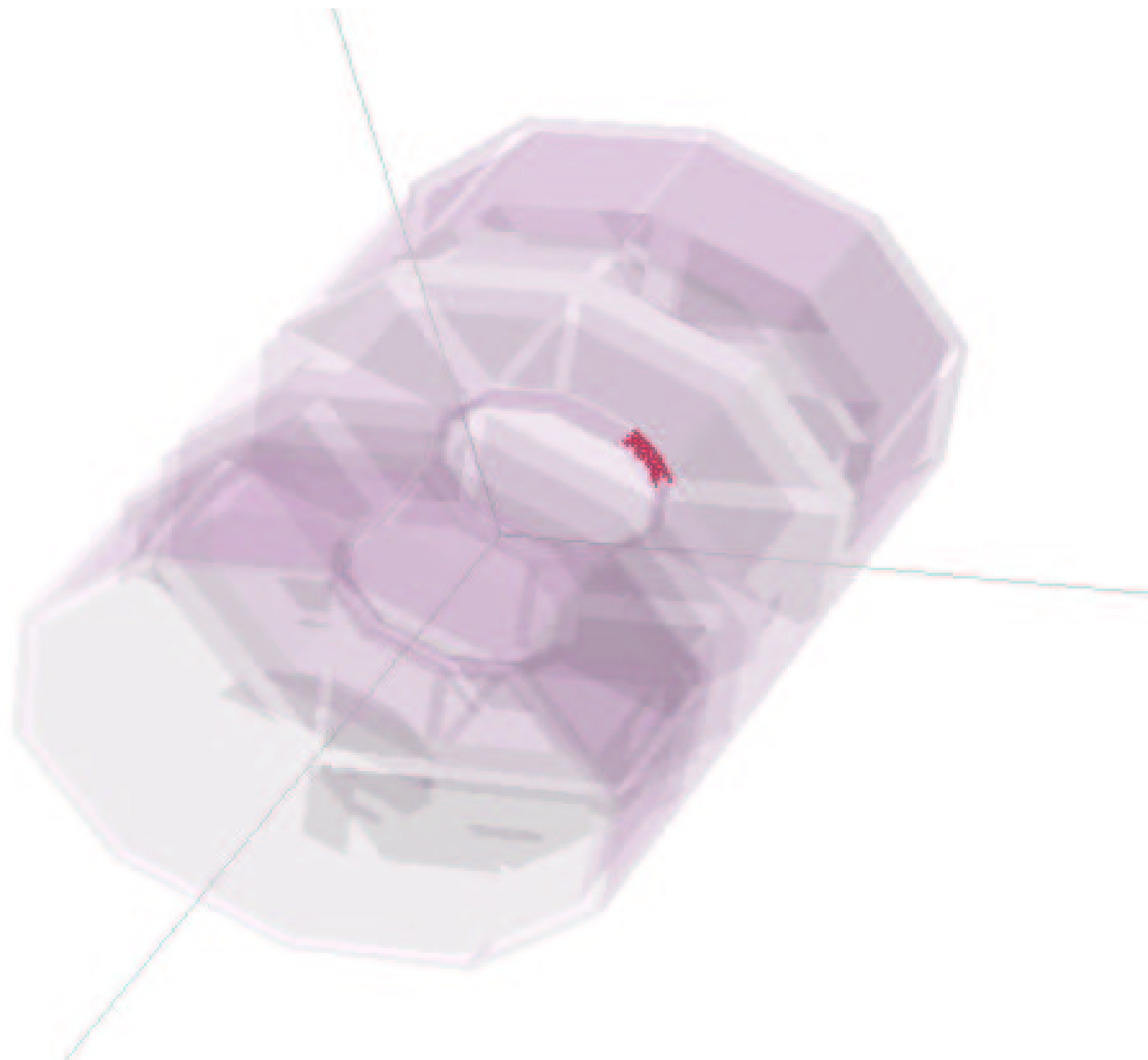
Beam pipe currents



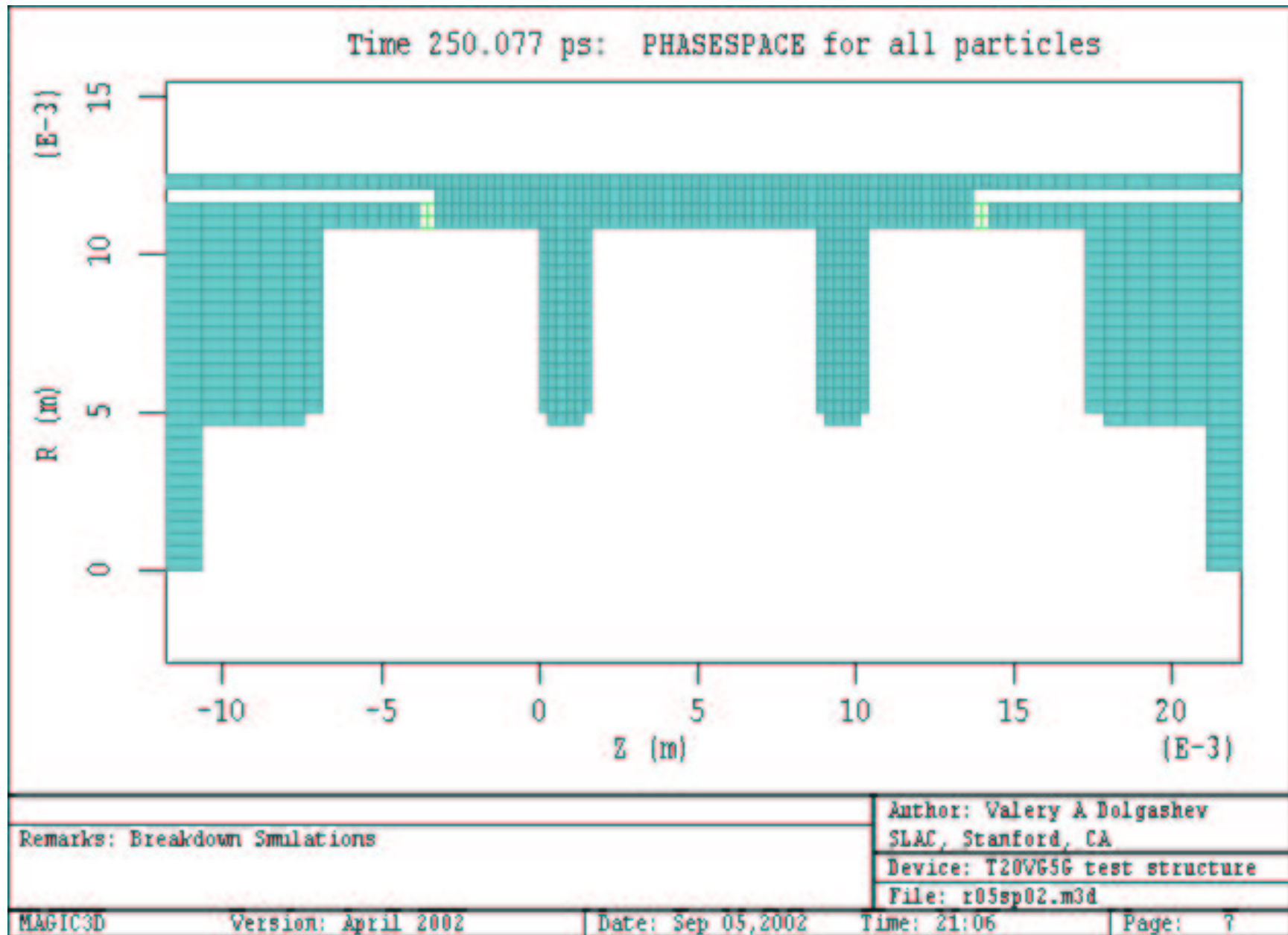
— Electrons  
- - Ions

Back-bombardment currents

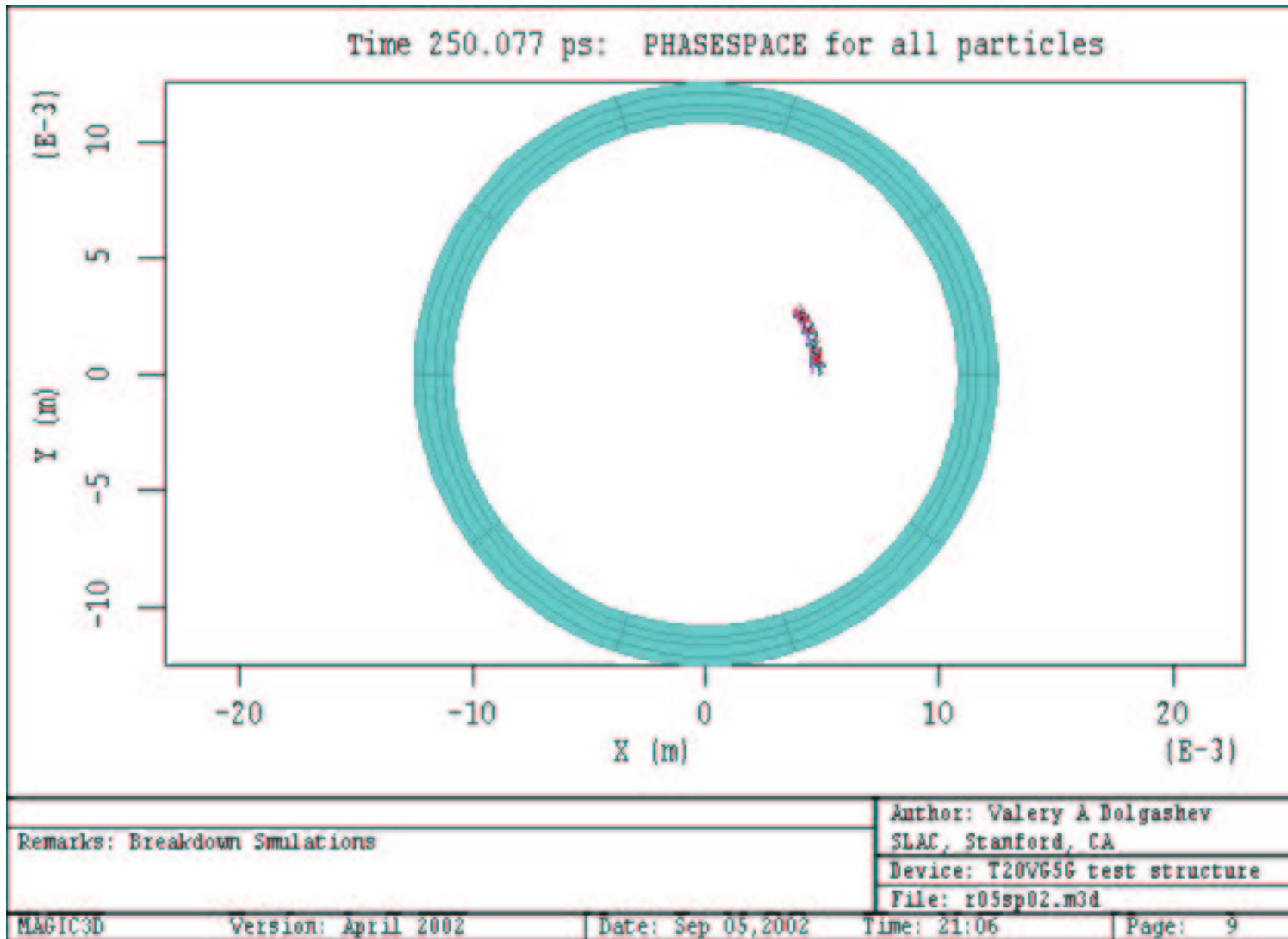
# 3D PIC simulations, T20VG5, coupler breakdown, spot $\sim 4\text{mm}^2$



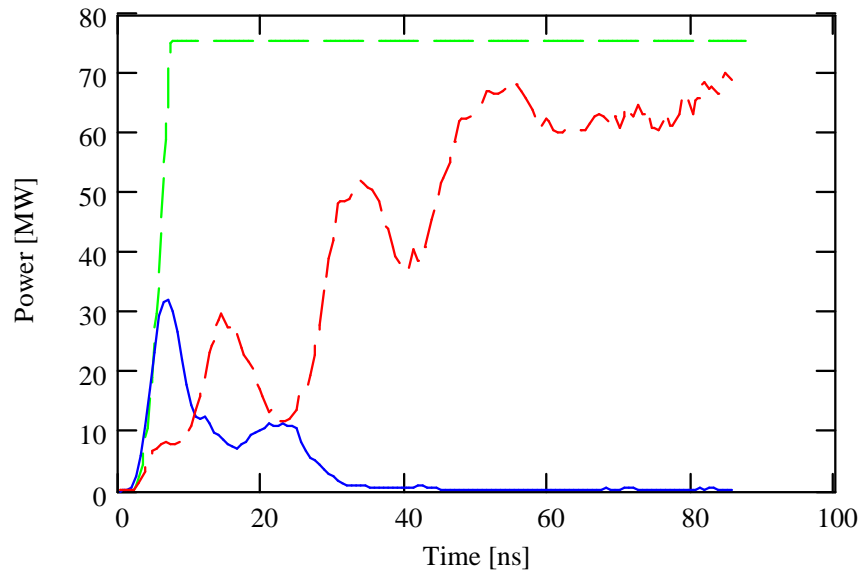
# 3D PIC simulations, T20VG5, coupler breakdown, spot $\sim 4\text{mm}^2$



# 3D PIC simulations, T20VG5, coupler breakdown, spot $\sim 4\text{mm}^2$

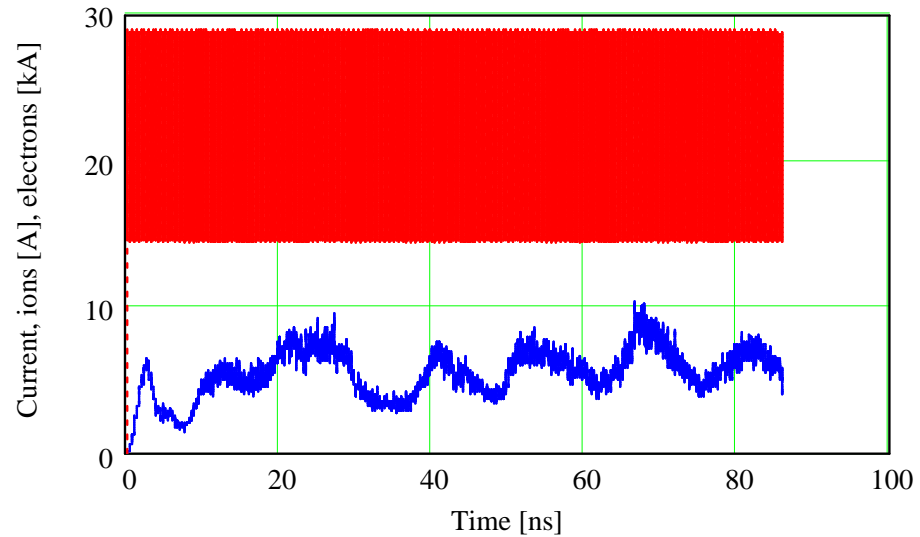


# 3D PIC simulations, T20VG5, coupler breakdown, spot ~4mm<sup>2</sup>



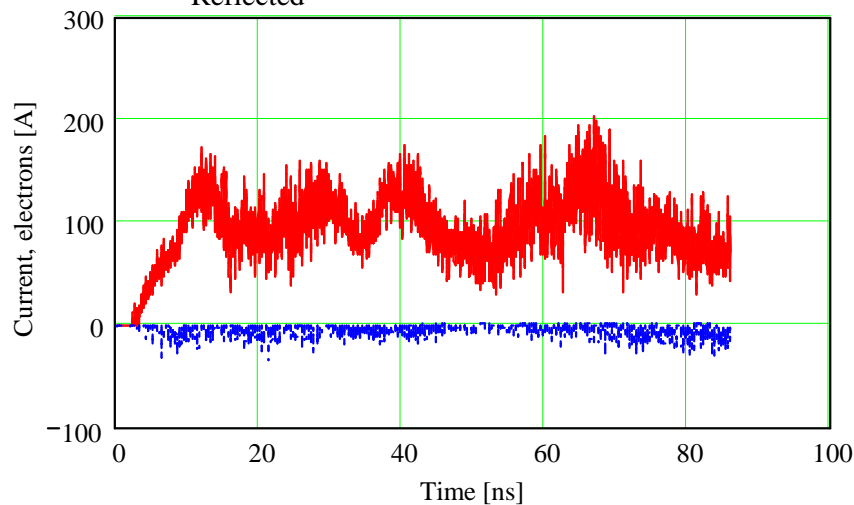
— Input  
— Transmitted  
- - Reflected

rf



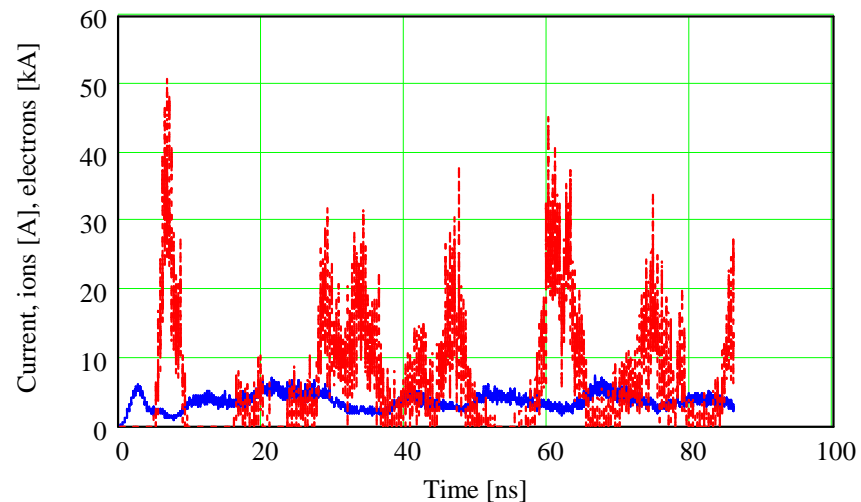
— Electrons  
- - Ions

Emitted currents



— Input  
- - Output

Beam pipe currents

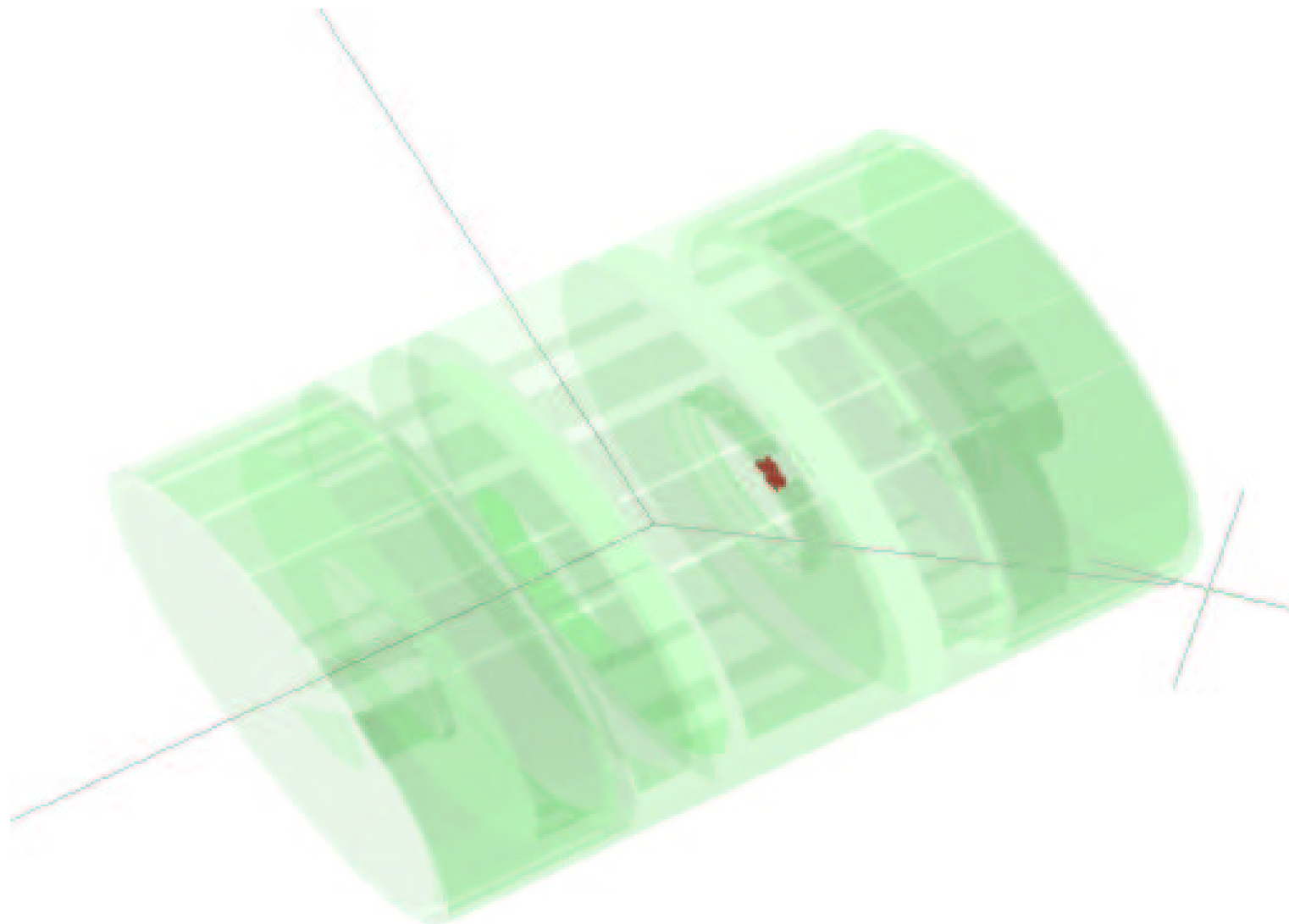


— Electrons  
- - Ions

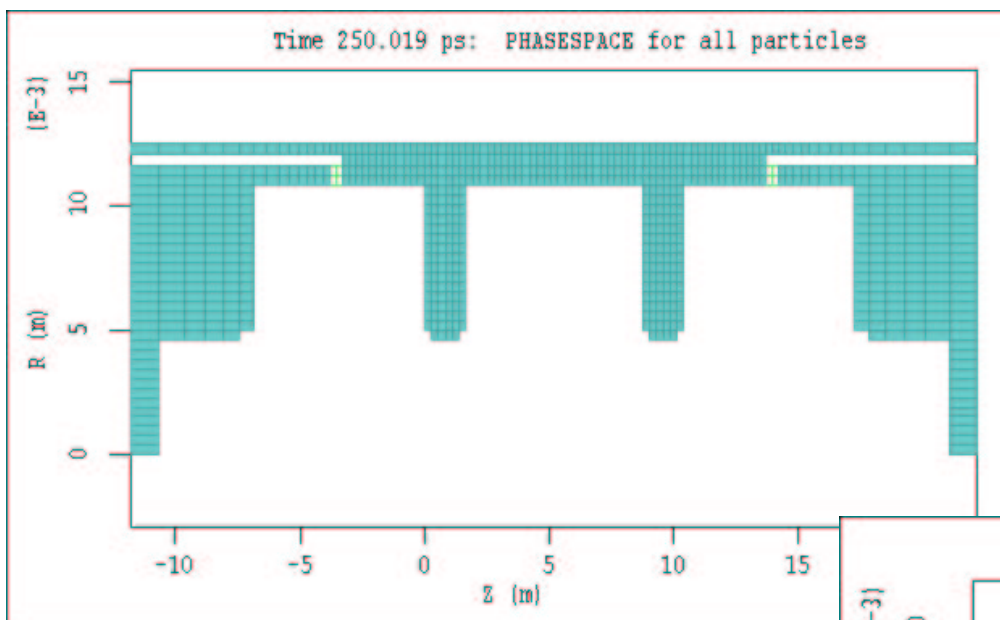
Back-bombardment currents

# Cell breakdown

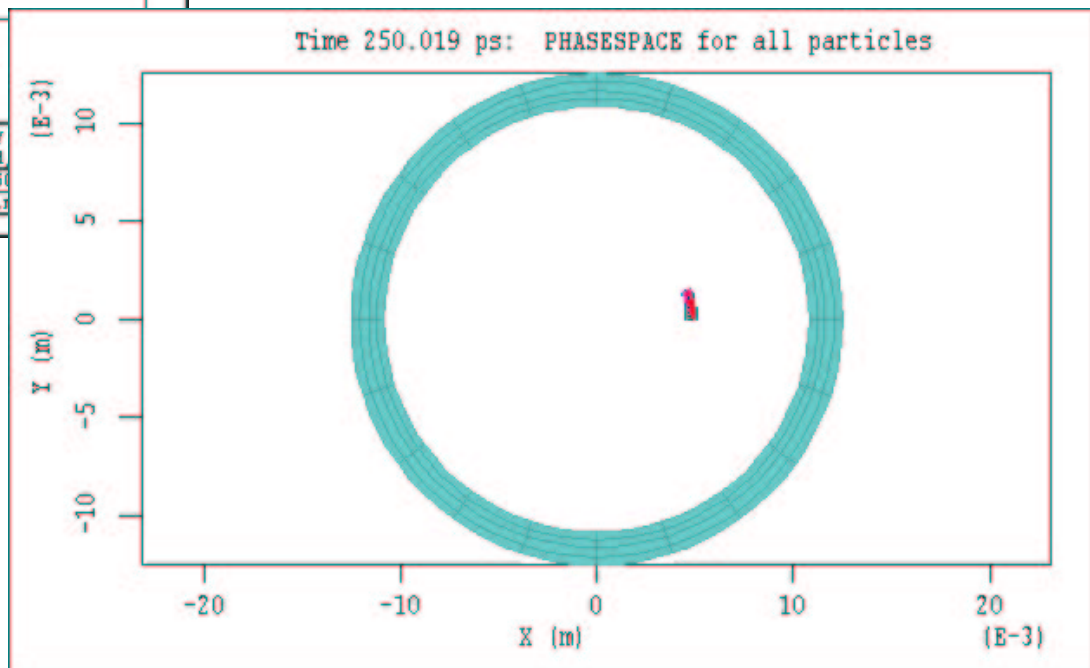
# 3D PIC simulations, T20VG5, cell breakdown, spot $\sim 2\text{mm}^2$



# 3D PIC simulations, cell breakdown, T20VG5, spot

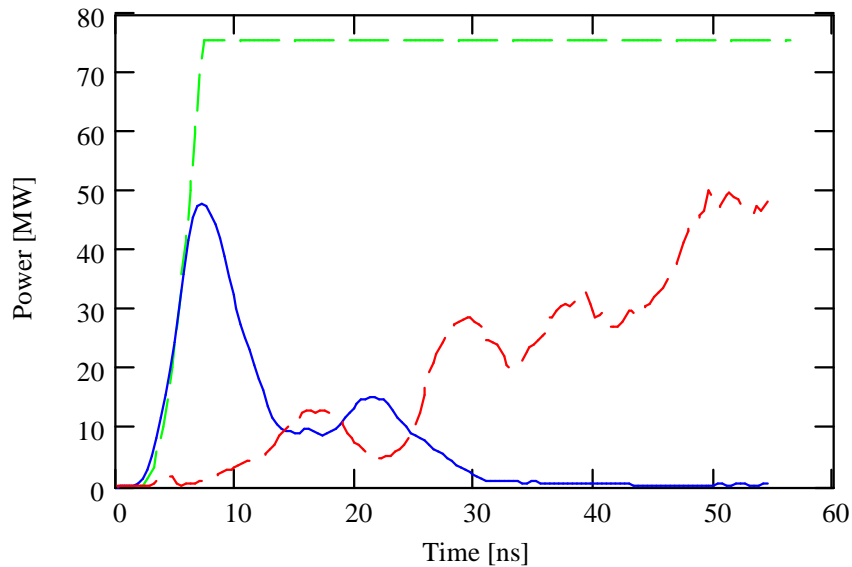


Remarks: Breakdown Simulations		Author: Valery SLAC, Stanford
		Device: T20VG56
		File: r10sp02.m3d
MAGIC3D	Version: April 2002	Date: Sep 10, 2002 Time: 21:24



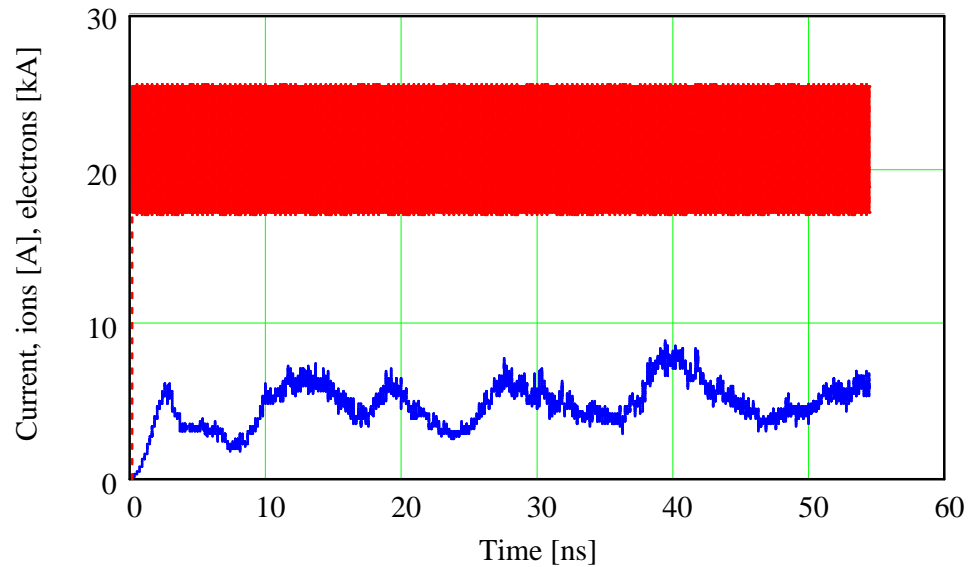
Remarks: Breakdown Simulations		Author: Valery A Dolgashev SLAC, Stanford, CA
		Device: T20VG56 test structure
		File: r10sp02.m3d
MAGIC3D	Version: April 2002	Date: Sep 10, 2002 Time: 21:24 Page: 9

# 3D PIC simulations, T20VG5, cell breakdown, spot $\sim 2\text{mm}^2$ , ion current $\sim 20\text{ A}$



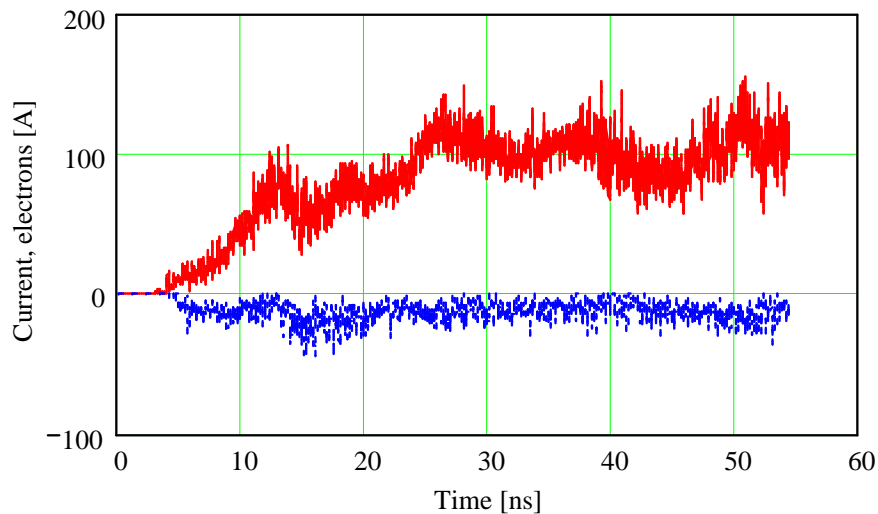
— Input  
— Transmitted  
- - Reflected

rf



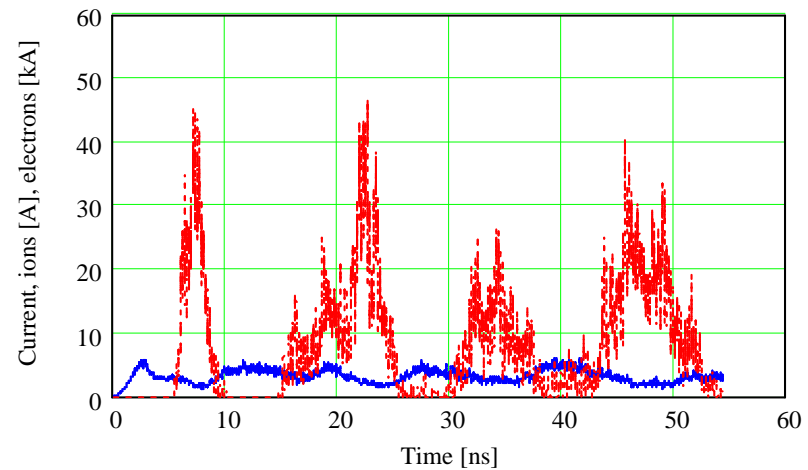
— Electrons  
- - Ions

Emitted currents



— Input  
- - Output

Beam pipe currents



— Electrons  
- - Ions

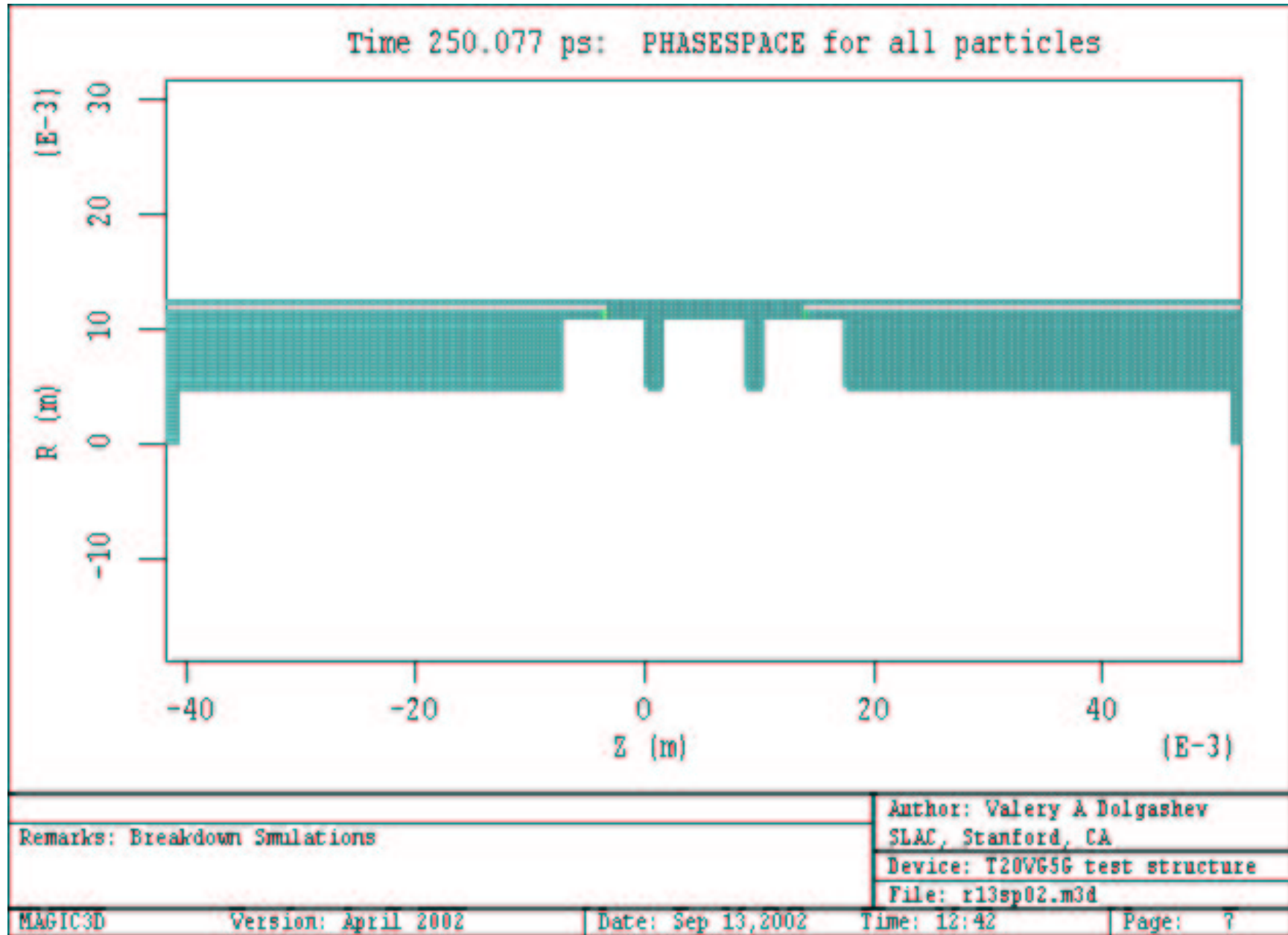
Back-bombardment currents

# **Mystery of small beam pipe currents:**

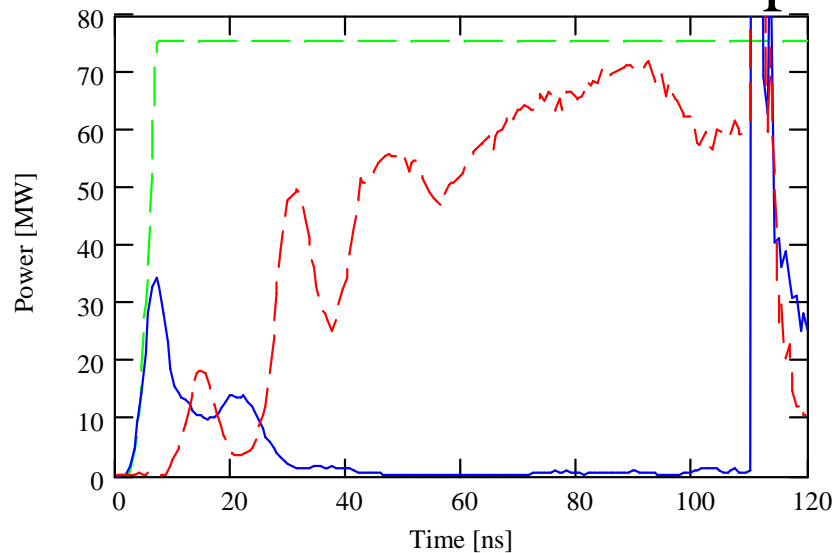
Beam currents through output pipes during breakdown are small  $\sim 100$  mA, while currents in the cell are  $\sim 10$  kA.

Why output current are only  $\sim 0.001\%$  of cell currents?

# 3D PIC simulations, T20VG5, coupler breakdown, spot $\sim 4\text{mm}^2$

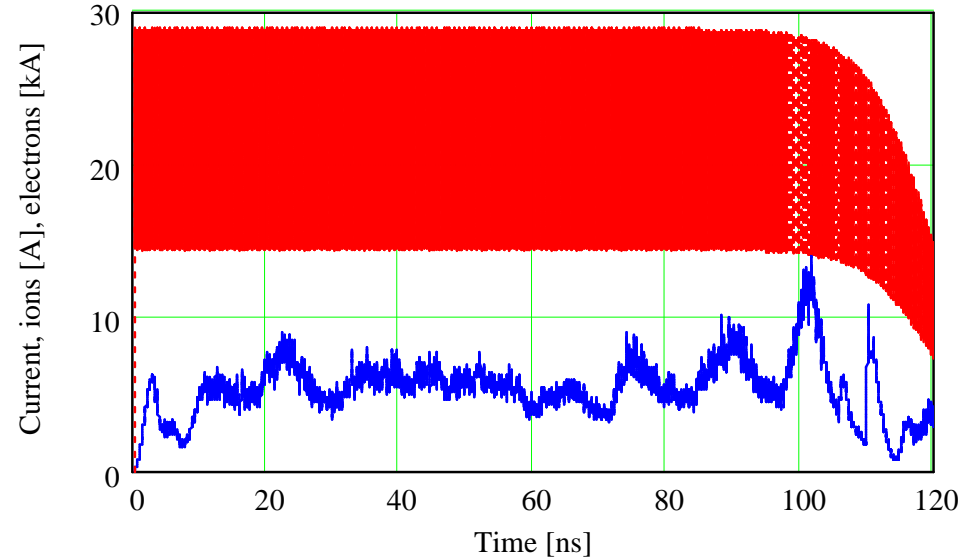


# 3D PIC simulations, T20VG5, coupler breakdown, spot $\sim 4\text{mm}^2$



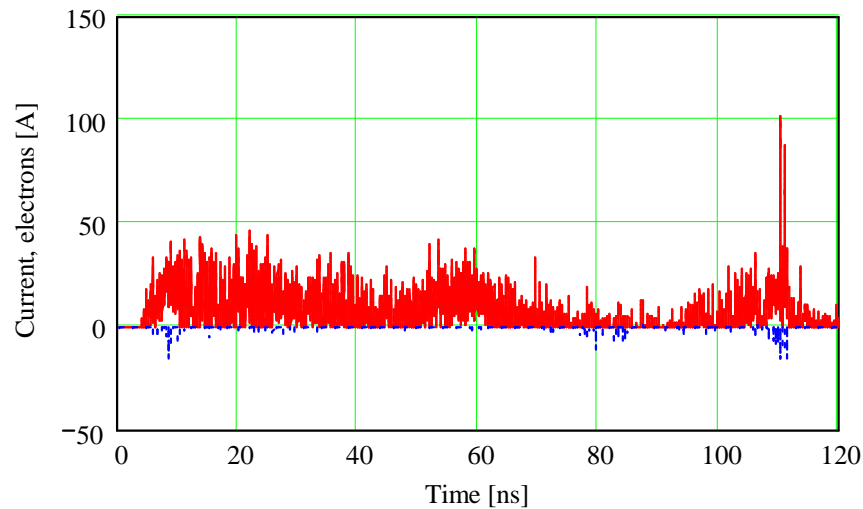
- Input
- Transmitted
- - - Reflected

rf



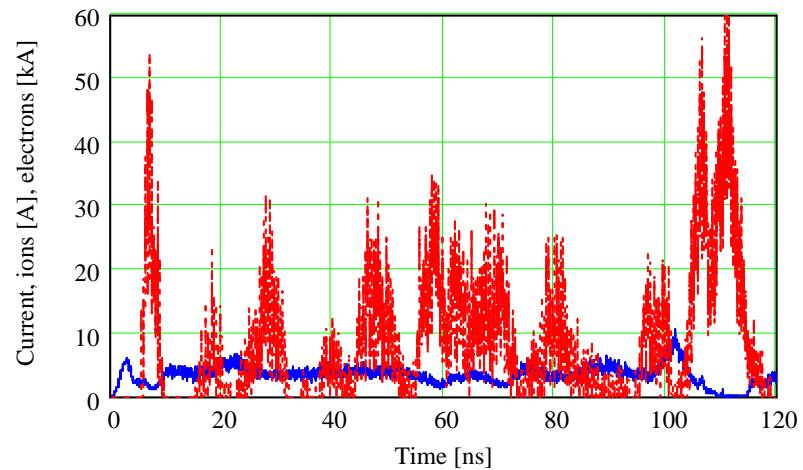
- Electrons
- - - Ions

Emitted currents



- Input
- - - Output

Beam pipe currents



- Electrons
- - - Ions

Back-bombardment currents

# Result

- Model of “*plasma spot*” with ion current of  $\sim 20$  A **reproduces** rf breakdown signals for “**soft event**” ( $\sim 25\%$  of input power absorbed in steady-state breakdown) in traveling wave structure
- Sensitivity of breakdown rf signal to emission spot size ( $1\text{-}4\text{mm}^2$ ) is **weak** (for the **same ion current**)
- **No obvious difference** of rf signals between **coupler** and **first cell** breakdowns
- To explain absorption of more than 25% of input power and extremely small beam pipe currents model need additional assumptions: for example *drag and scattering* for electrons on neutral copper gas or expansion of the emission spot