SAND2024-06802C

Sandia National Laboratories

Exceptional service in the national interest

E-field Measurements of HERMES III Electromagnetic Pulse (EMP) Environment

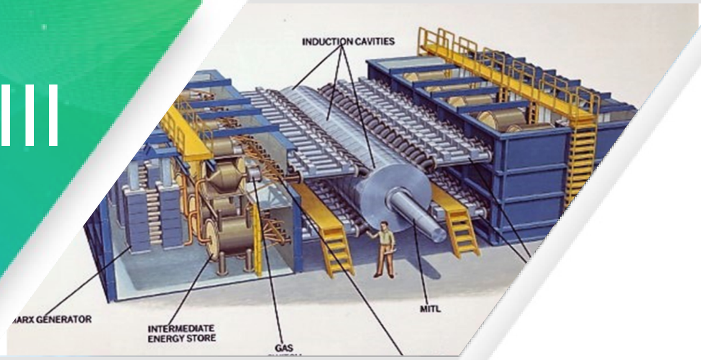
Mark Johnston and Chris Grabowski

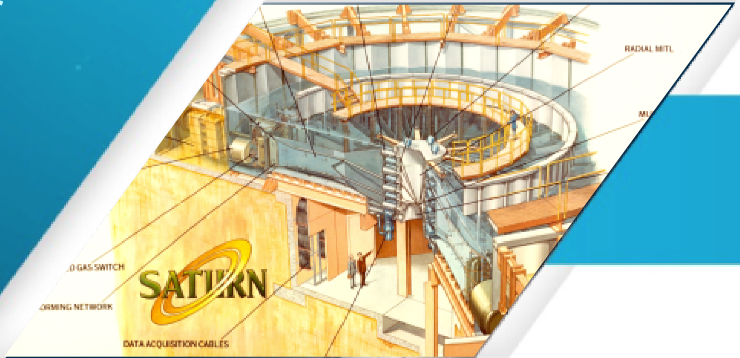
Sandia National Laboratories

Albuquerque, NM, USA

2024 International Power Modulator and High Voltage Conference

May 28 - June 1, 2024





Abstract

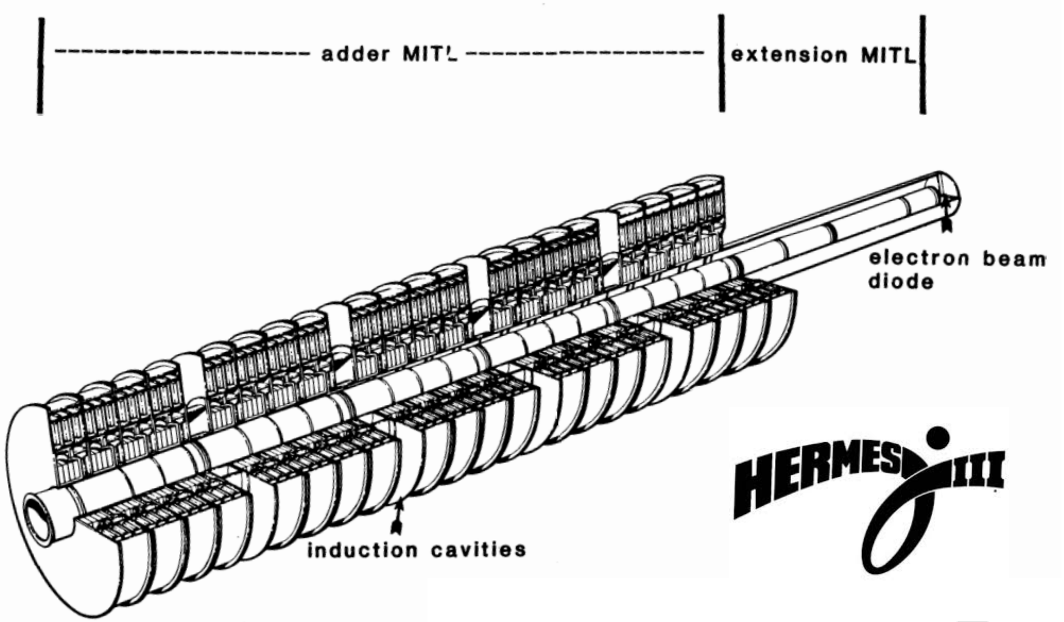
Experiments were conducted at the High-Energy Radiation Megavolt Electron Source (HERMES) III Facility to quantitatively determine the electric field environment around the pulsed-power side of the machine. HERMES III is a 20MV, 700kA, 25ns, Marx driven, 20-stage Inductive Voltage Adder (IVA), e-beam accelerator used for Radiation Effects Testing. The Marx banks, laser triggered gas switches and self-break water pulse forming line switches create significant electromagnetic energy releases that propagate throughout the vicinity of the machine. This EMP radiation can damage sensitive electrical equipment and components and interfere with electrical measurements. There is an effort underway to characterize the electromagnetic fields at HERMES to better understand their magnitudes at various locations around the accelerator. This is important for proper placement and shielding of sensitive electrical equipment at HERMES and similar machines.

The electric field measurements were conducted using D-dot capacitive probes positioned along three orthogonal axes. The D-dot probes measure the time rate of change of the electric field displacement vector (D). D-dot signals are then integrated to provide the magnitude of the electric field in time in units of V/m, which for HERMES are in the 10s to a few hundreds of kV/m. For HERMES, there are two distinct regions of EMP noise, separated by about one microsecond in time, corresponding to the sequence of high voltage spark gap switch breakdowns through the machine. The second region is the strongest in magnitude and occurs throughout the duration of the main gamma radiation pulse and is thus of primary concern. The frequencies of the EMP are between 1-100MHz and fall primarily within the high (HF) and very high (VHF) frequency radio bands.

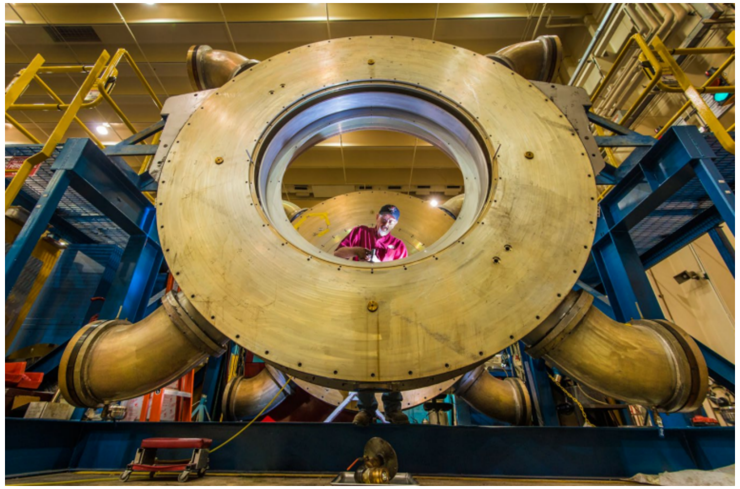
This presentation describes the measurement techniques employed, the methods of analysis, and interpretation of the data. Mitigation techniques and suggestions for proper electrical shielding and grounding will also be provided.

HERMES III Pulsed-Power Accelerator at SNL

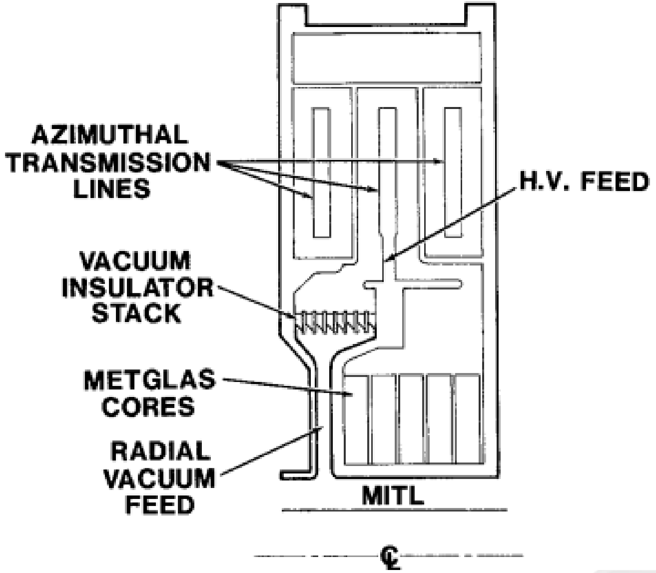
13 TW of Power



HERMES (High-Energy Radiation Megavolt Electron Source) III is a 20 MeV, 700kA, 25ns Marx driven twenty-stage Inductive Voltage Adder (IVA)[2]



HERMES III Induction Cavity



[1]J.J. Ramirez, Proc. Particle Accel. Conf., Chicago, IEEE Cat. No. 89CH2669-0, p. 1446 (1989).

HERMES III Energy Storage

Initial energy storage – 10 Marx generators

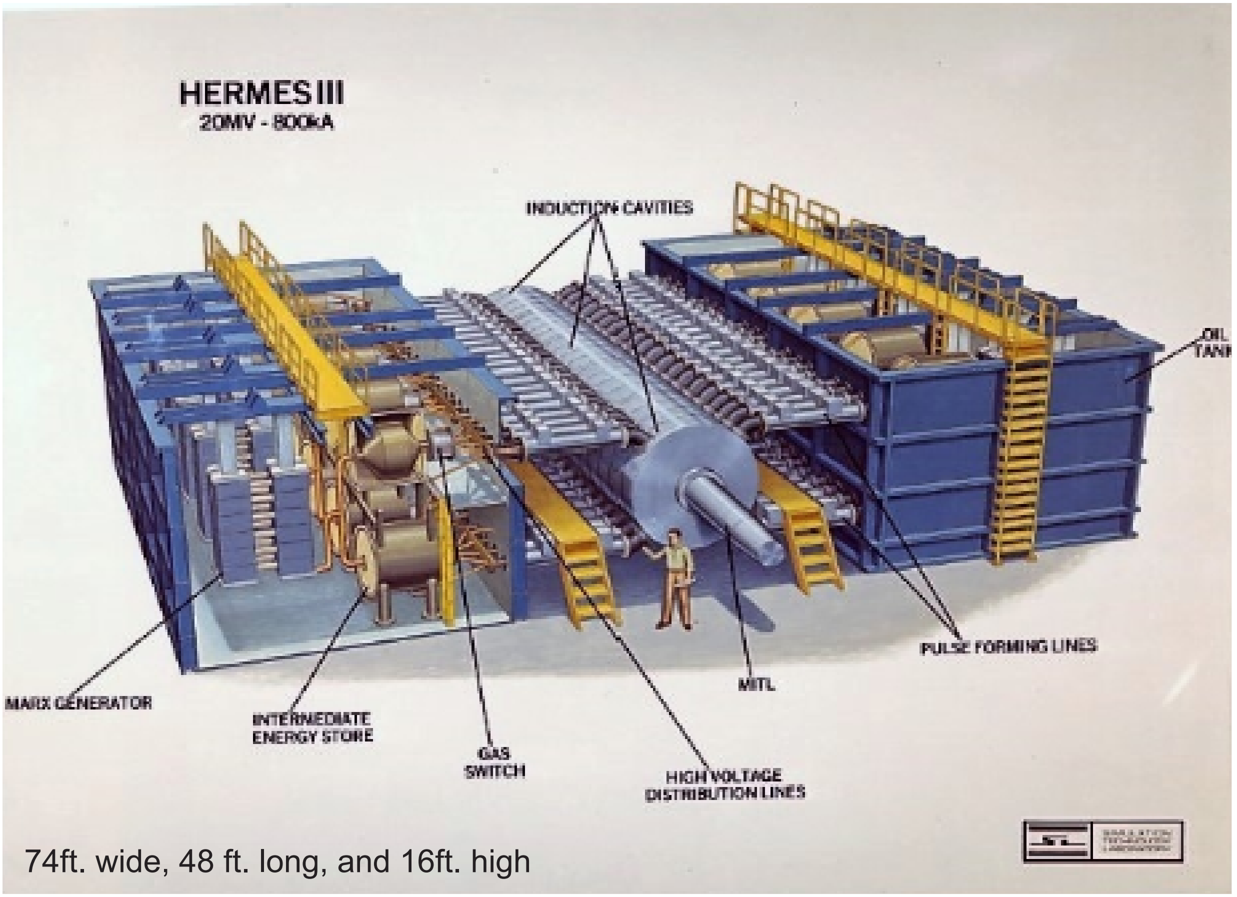


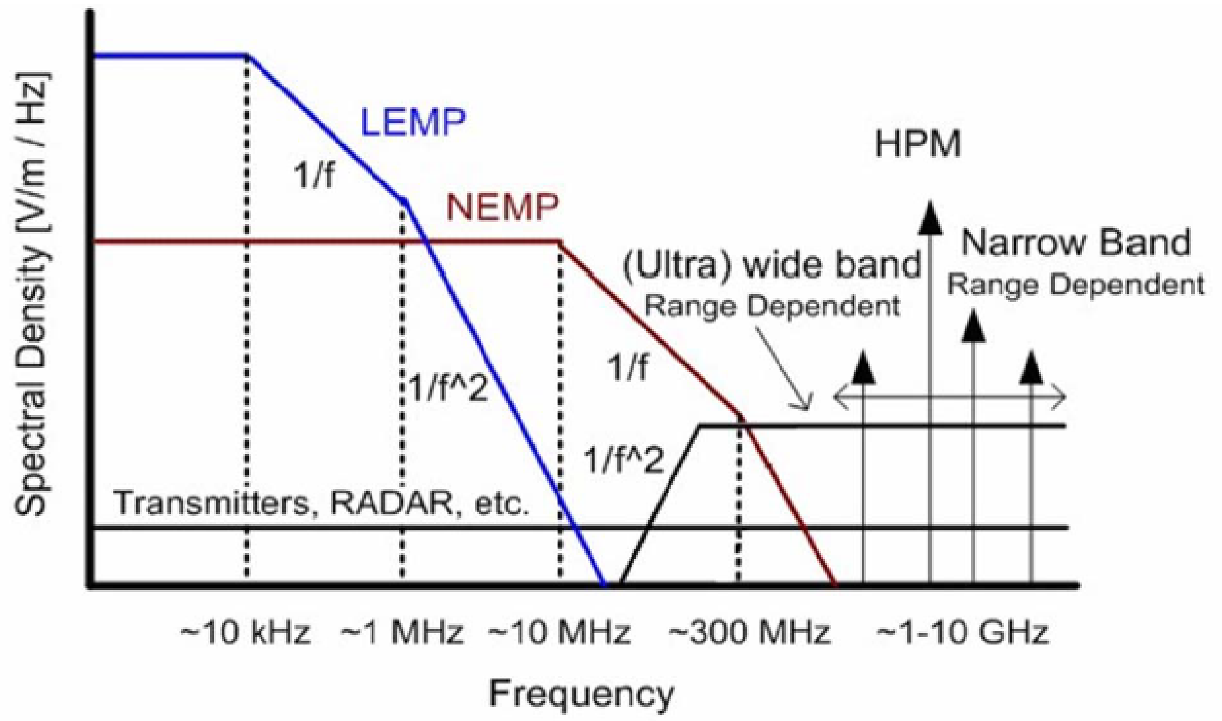
Table I. Equivalent Marx Generator Circuit Parameters

Output Capacitance	56 nF
Series Inductance	4.9 μH
Series Resistance	1 Ω
Parallel Resistance	480 Ω
Stages	24
Max Voltage	2.4 MV
Max Energy	156 kJ

[2]J. J. Ramirez, *et. al.*, "The HERMES III Program," *Digest of Technical Papers Sixth IEEE International Pulsed Power Conference*, pp. 294-299, 1987.

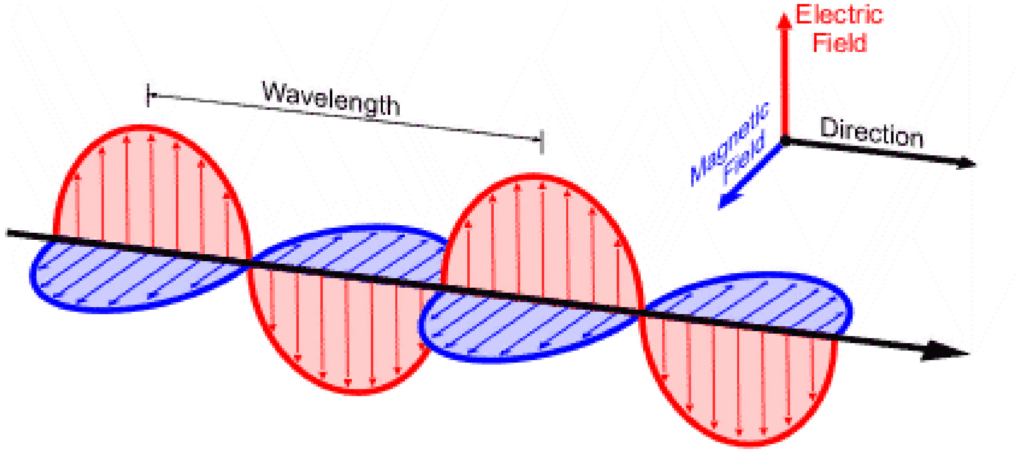
Motivations for Studying EMP on HERMES III

- Understand induced voltages/surges on conductors and cabling
- Necessary for proper system hardening and shielding
- Electrical or electronic system failures, damage, or lifetime issue (can be temporary or permanent).
- HERMES EMP falls in a unique range between LEMP and NEMP.
- Understand power and distance effects



[3]R. Przemycki and M. Wnuk, "Susceptibility of IT devices to HPM pulse," *International Journal of Safety and Security Engineering*, **8**(2), pp. 223-233, 2018.

D-dot Probe Orientation and Relationship to the Poynting Vector



$$S = E \times H = E \times B / \mu_o = D \times B / \mu_o \epsilon_o = c^2 D \times B \qquad (1)$$

where

- S = power density being transported in the direction of the vector, w/m^2
- E = electric field strength (vector), v/m
- ϵ_o = permittivity of free space, 8.85×10^{-12} farad/m or coul/v-m
- D = electric displacement (vector), coul/m^2, (= $\epsilon_o E$ in free space)
- H = magnetic field strength (vector), amp/m
- μ_o = permeability of free space, 1.26×10^{-6} h/m or weber/amp-m (1 weber = 1 v-sec and 1 weber/amp = 1 h), or, fundamentally, v-sec/amp-m
- B = magnetic induction (vector), weber/m^2 or v-sec/m^2 (= $\mu_o H$ in free space) (1 weber/m^2 = 1 Tesla = 10^4 Gauss)
- c = speed of light in free space, 3×10^8 m/sec

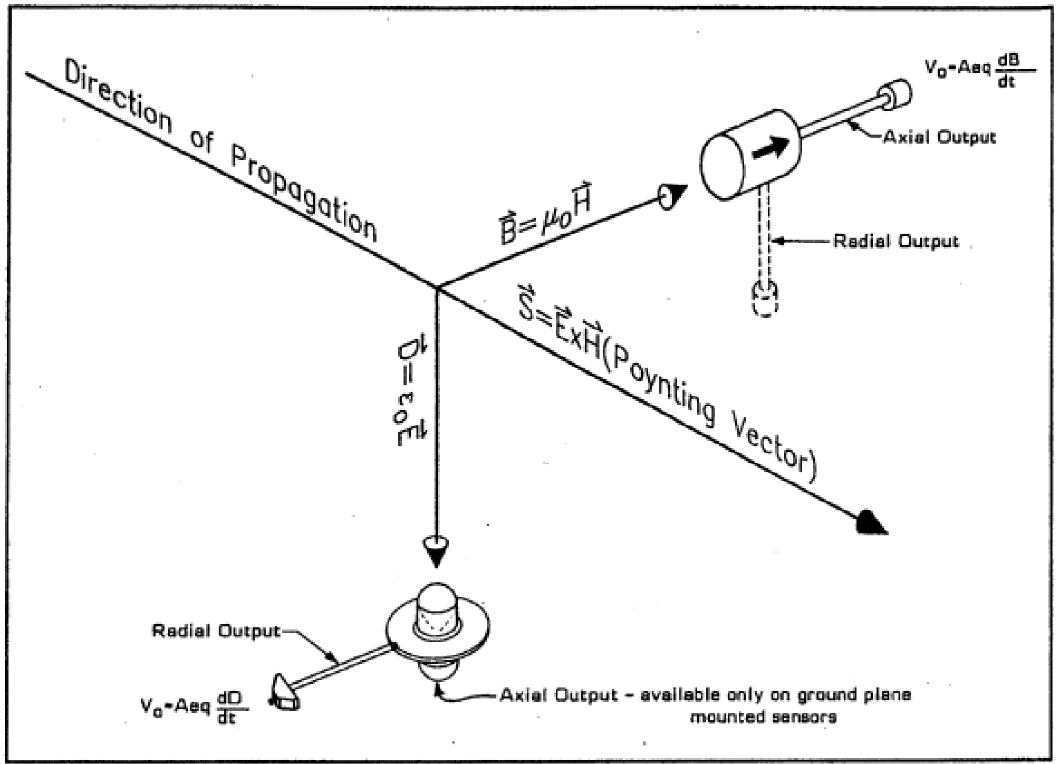
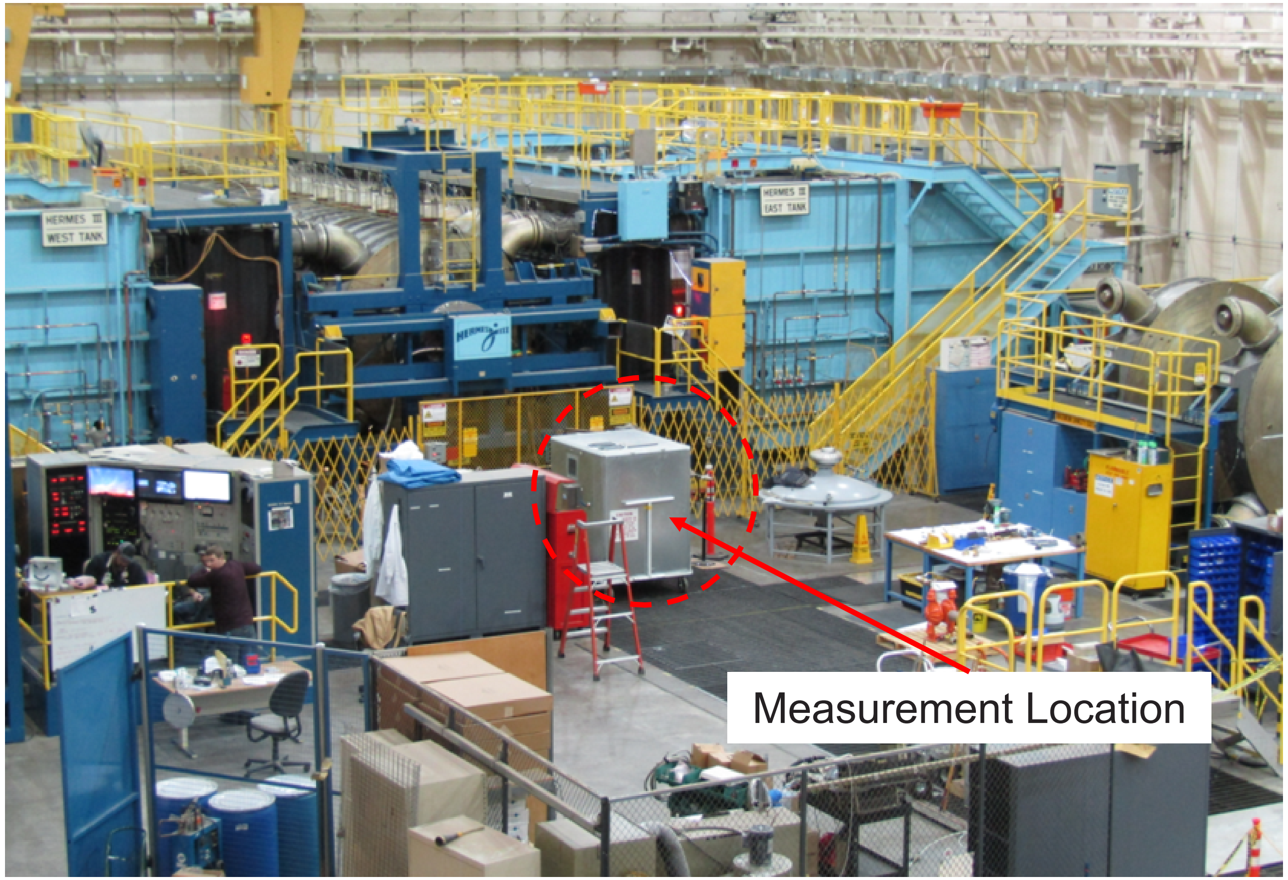
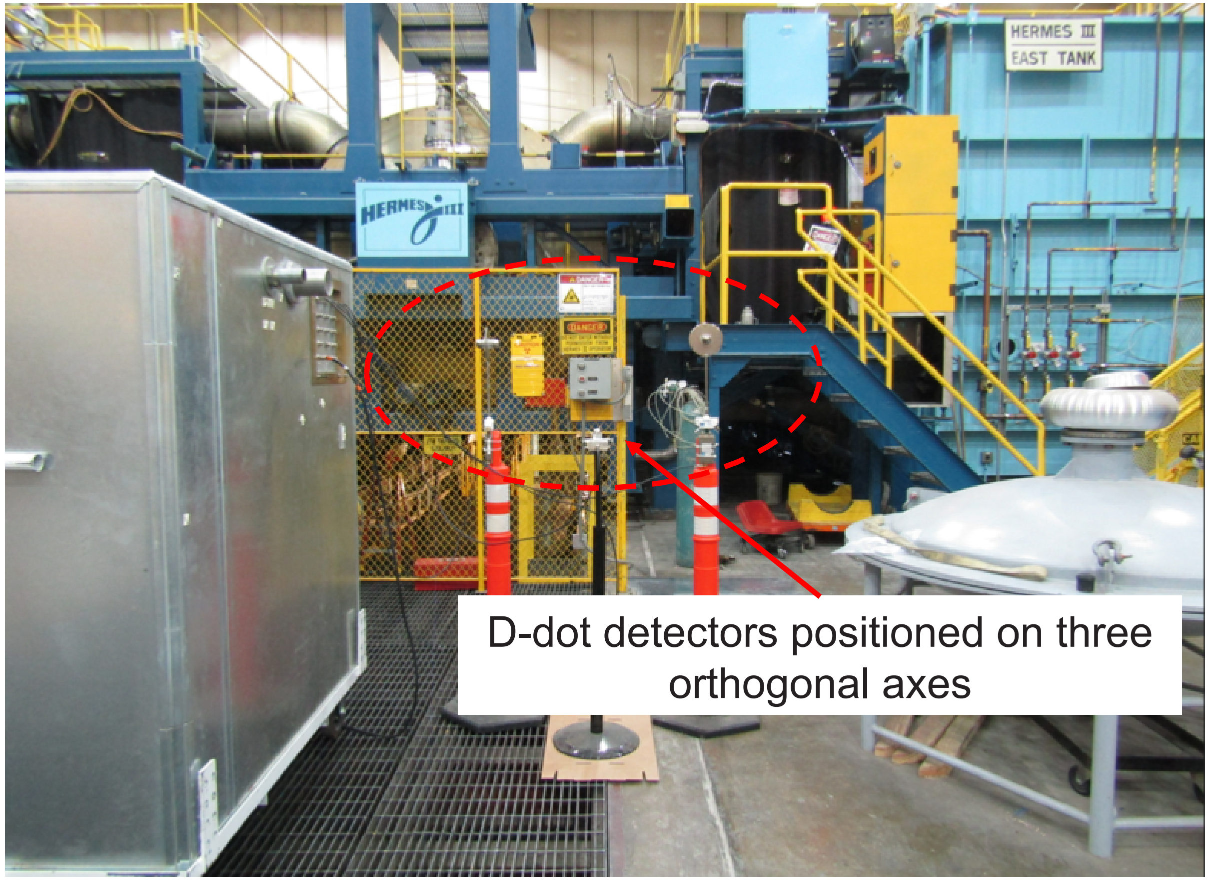


Figure 2. Electric and magnetic fields being measured with D-dot and B-dot sensors.

[4] W. Reed Edgel, "Primer on Electromagnetic Field Measurements," PAN 895, Prodyn Technologies.

Location of Electric Field Measurements on HERMES III





Probes positioned 6ft. back from HERMES gate

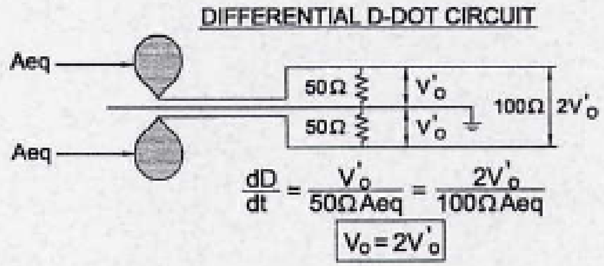
D-dot Probe Experimental Setup

The equation pertinent to this device is:

$$V_o = R\, A_{eq} \frac{dD}{dt}$$

Where:

- V_o = sensor output (volts)
- R = sensor characteristic load impedance (100 ohms)
- A_{eq} = sensor equivalent area (m²)
- D = magnitude of electric displacement vector ($\vec{D} = \varepsilon_o \vec{E}$ in Coul/m²)



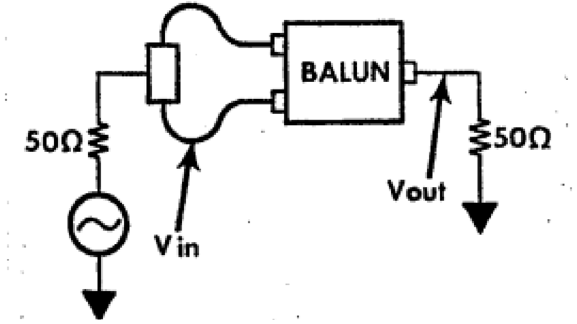
SPECIFICATIONS

	AD-20(R)	AD-80(R)	AD-70(R)	AD-55(R)	AD-40(R)	AD-100(R)
Electrical						
Equiv. Area (A_{eq})	1×10^{-4} m²	3×10^{-4} m²	1×10^{-3} m²	3×10^{-3} m²	1×10^{-2} m²	1×10^{-1} m²
Freq. Resp. (3db pt.)	>10 GH$_z$	>5.5 GH$_z$	>3.5 GH$_z$	>2 GH$_z$	>1 GH$_z$	>350 MH$_z$
Risetime (t_r 10-90)	<.029 ns	<.064 ns	<.11 ns	<.17 ns	<.29 ns	<1.1 ns
Capitance (F)	1.40×10^{-13}	2.91×10^{-13}	4.49×10^{-13}	7.80×10^{-13}	1.43×10^{-12}	4.58×10^{-12}
Max Output (peak)	±150 V	± 1 kV	± 1 kV	±1.5 kV	± 4 kV	± 5 kV
Output Connector (s)	SMA (male)*	SMA (male)*	SMA (male)*	SMA (male)*	GR-TCC**	GR-TCC**
Physical						
Mass	40g	260g	340g	448g	782g	2.8 kg
Dimensions A	39.40	17.78	38.58	36.35	47.50	61.60
(cm) B	2.54	5.08	7.60	10.16	14.00	28.26
C	1.09	1.95	3.31	5.66	10.00	31.12
D	0.16	0.32	0.32	0.48	0.51	0.64

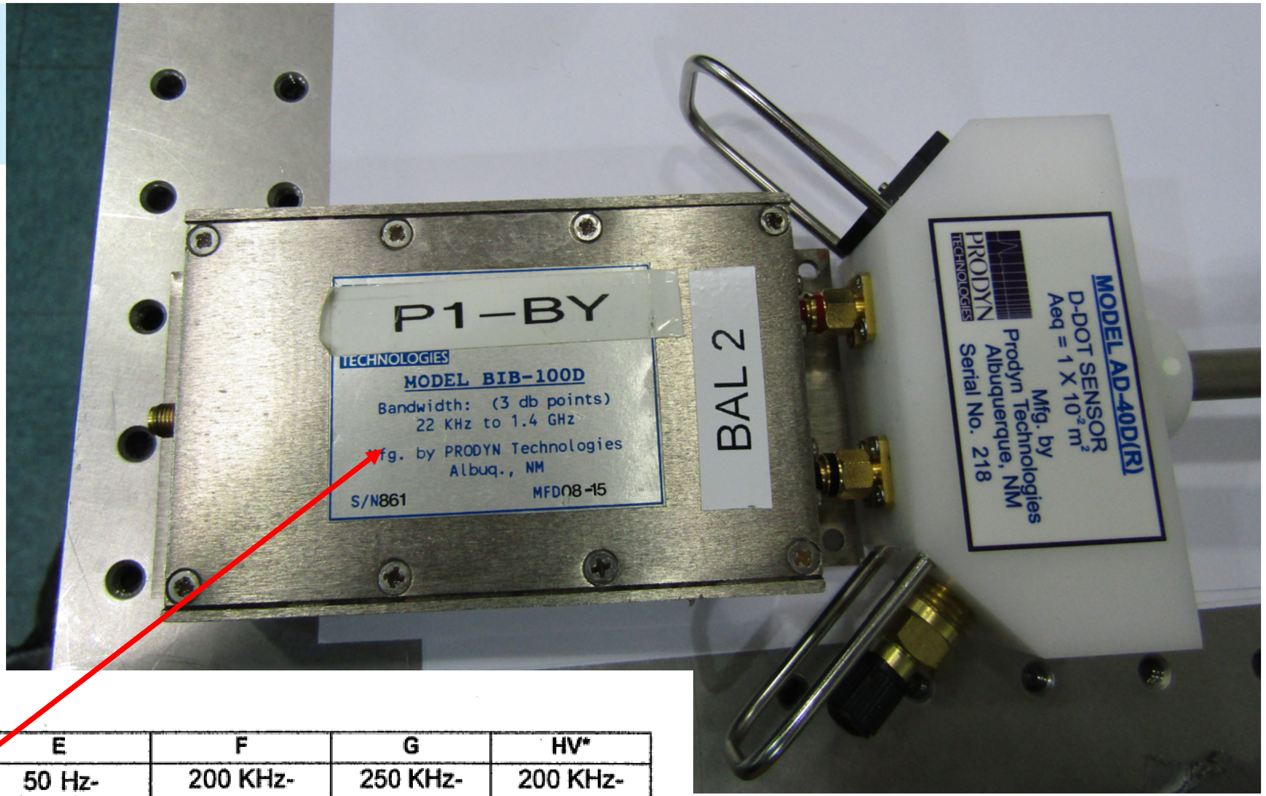
[5]Data Sheet, "Electric Field Sensors, D-Dot Free Field-Radial Output (R)," Prodyn Technologies, Albuquerque, NM 87107.

BALUN (BALanced-to-UNbalanced)

$$CMRR = 20 \ Log \frac{V\,out}{V\,in}$$



Insertion loss: 6dB



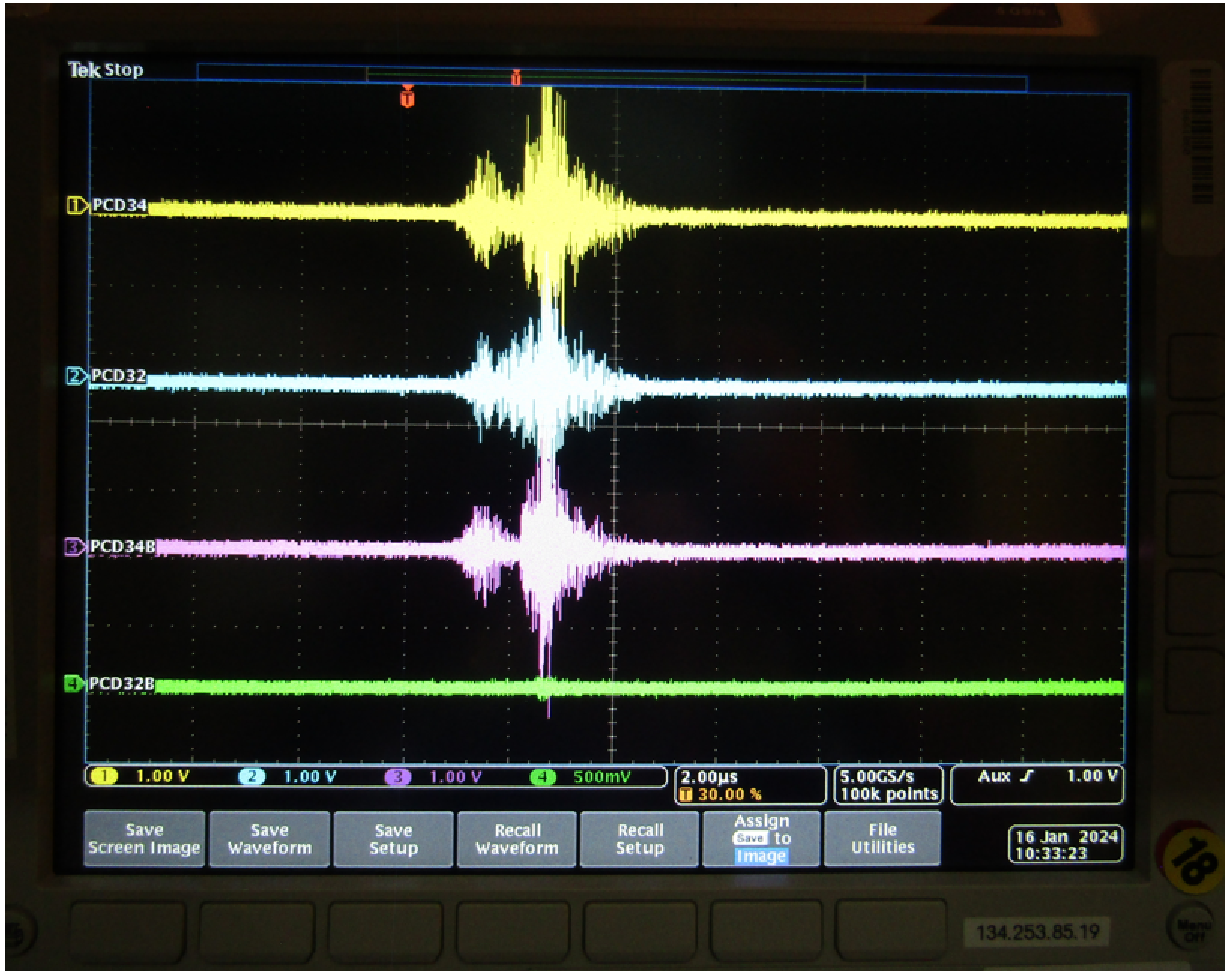
ELECTRICAL SPECIFICATIONS

	TYPE A	B	C	D	E	F	G	HV*
Bandwidth (3db)	10 KHz-250 MHz	15 KHz-400 MHz	20 KHz-600 MHz	22 KHz-1.4 GHz	50 Hz-150 MHz	200 KHz-3.5 GHz	250 KHz-10 GHz	200 KHz-3 GHz
Risetime (10-90%)	Pulse risetime approximates specified CW bandwidth							
Insertion Loss (Nominal) ± 3db	6 db	6 db	6db	6 db	6 db	8 db	8 db	8 db
Propagation Delay ns (Nominal)	3.2	2.2	1.9	1.4	5.3	.6	.6	.6
Max Input Voltage (50 ns Duration)	1000 V	1000 V	1000 V	1000 V	1000 V	1000 V	1000 V	5000 V
Common Mode Rejection Ratio (db) See Graph Below	≥32	≥32	≥30	≥30	≥36	≥28	≥20	≥28
Port Impedance (3 ports)	50	50	50	50	50	50	50	50

** This balun is equipped with type 'HN' connectors only, to accommodate high voltage.*

[6]Data Sheet, "Prodyn Baluns," Prodyn Technologies, Albuquerque, NM 87107.

D-dot Scope Traces (X,Y, and Z axes)



Raw Signals on Oscilloscope

Tektronix DPO-4104B Oscilloscope (1GHz, 5GS/sec)

10x Attenuators on Scope Signals

RG223 Cables (6ft. in length)

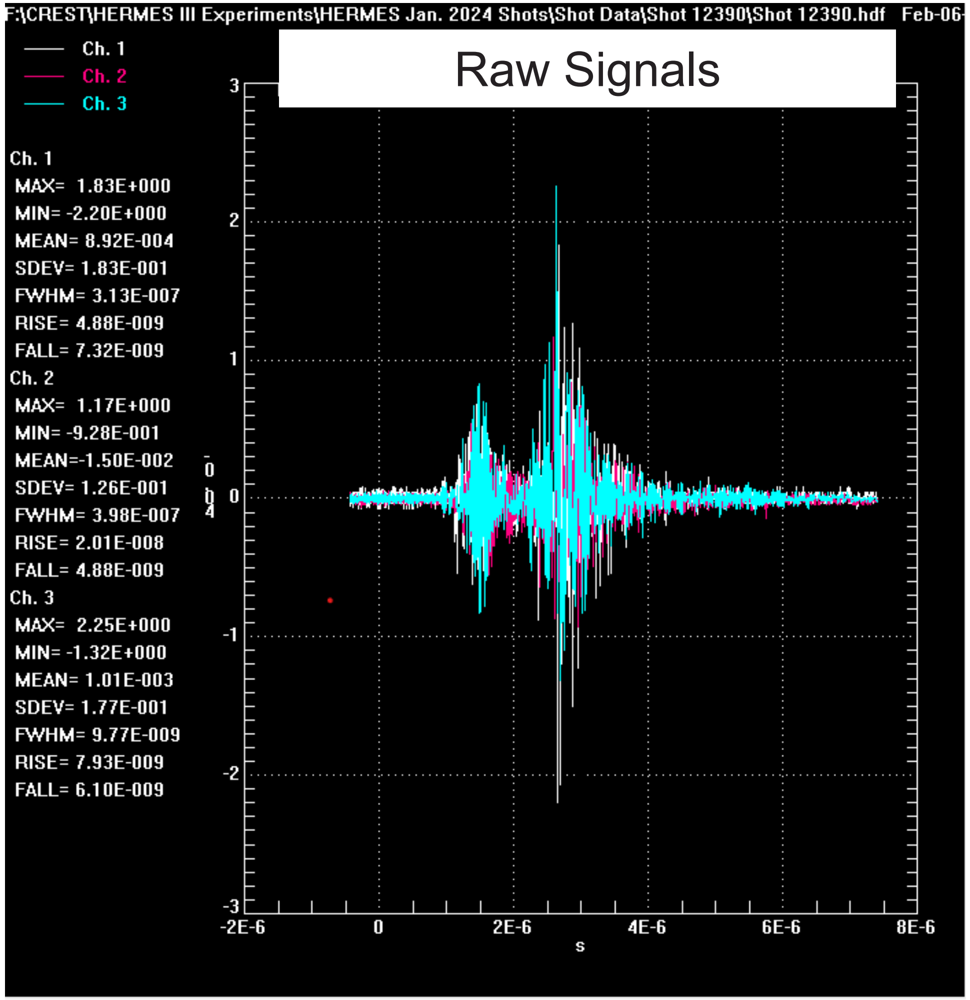
1 MΩ scope settings

Balun BIB-100D model (2x attenuation (3dB))

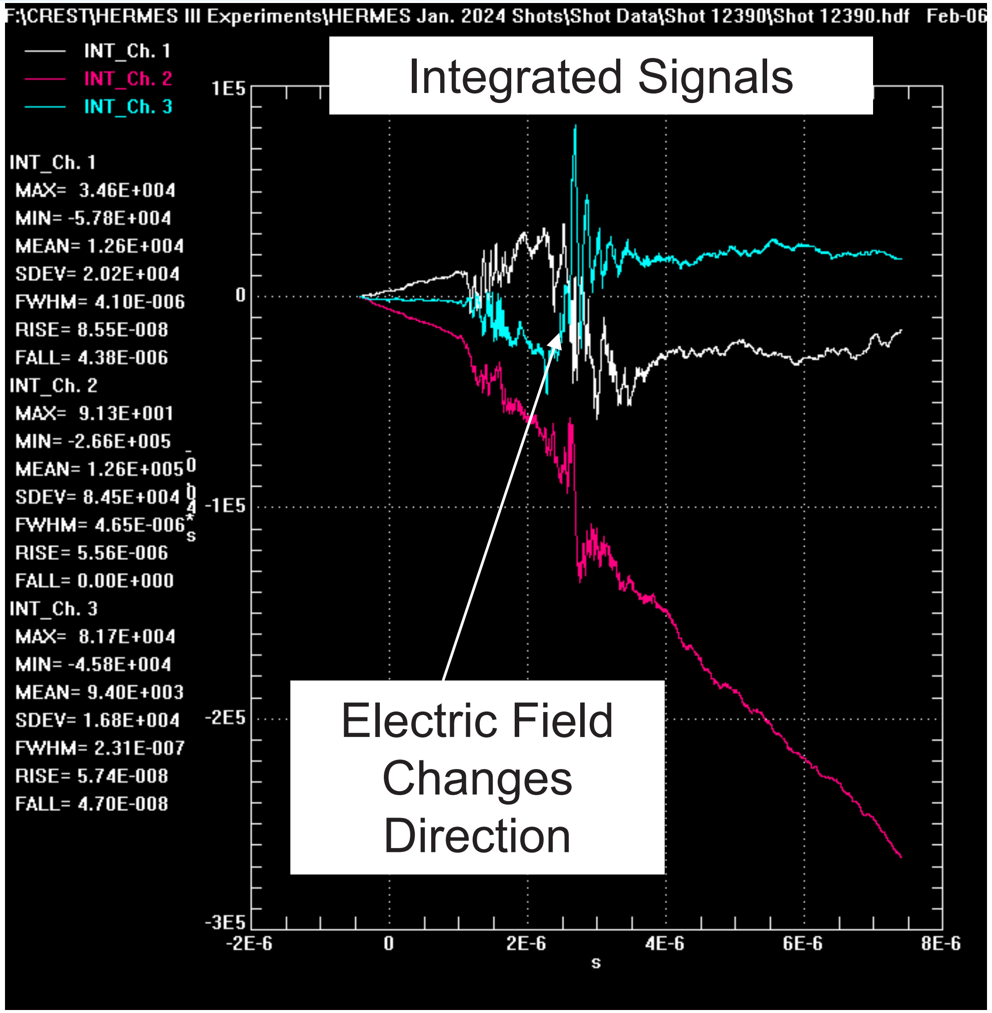
There are two main regions of EMP: MARXs (10 banks) and Intermediate Stores (20) + PFL water switches (160)[7]

[7]B.A. Lewis, N.R. Joseph, and J.D. Salazar, "Correlation of Noise Signature to Pulsed Power Events at the HERMES III Accelerator," SAND Report SAND2016-, 2016.

Integrated D-dot Signals give Electric Field in V/m

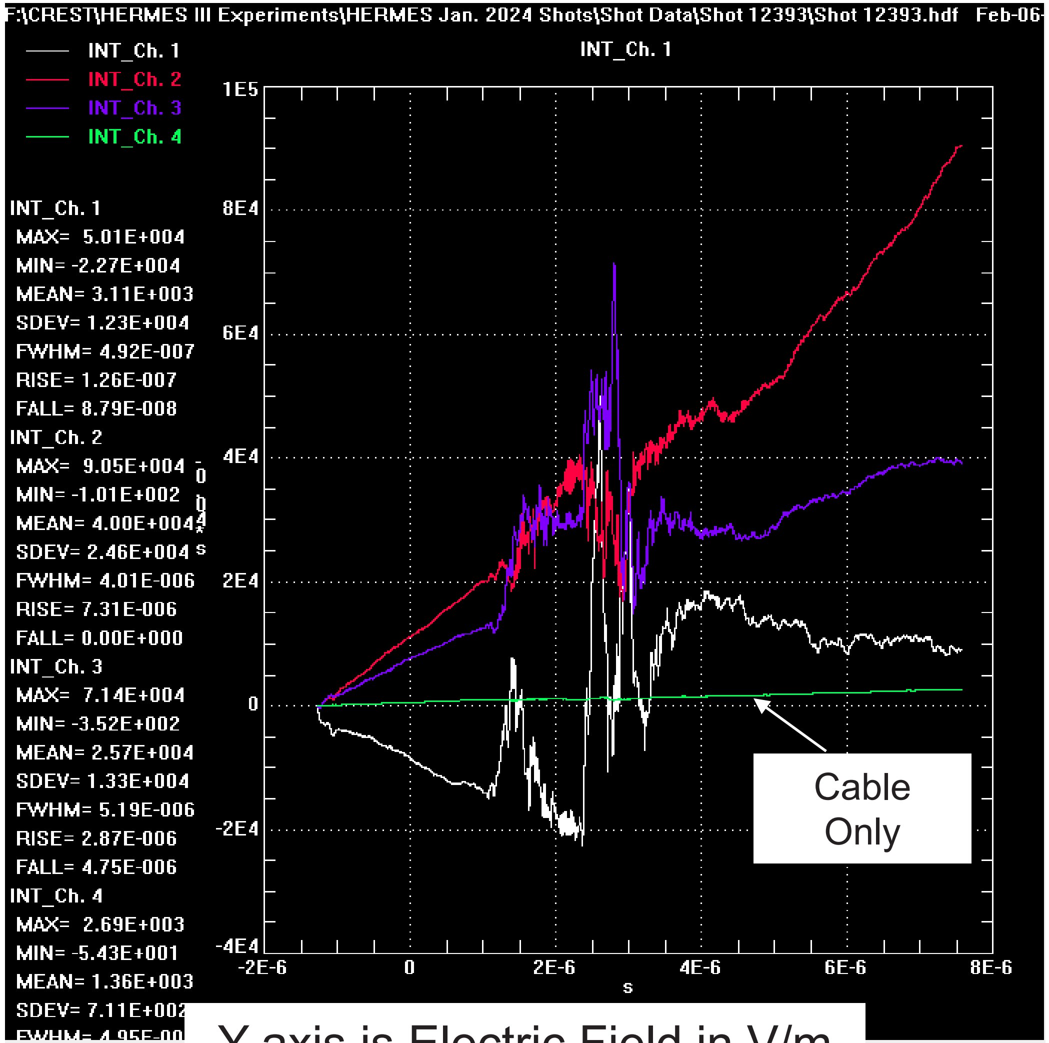


Multiplied by 20x and divided by ε_o = 8.85E-12 F/m

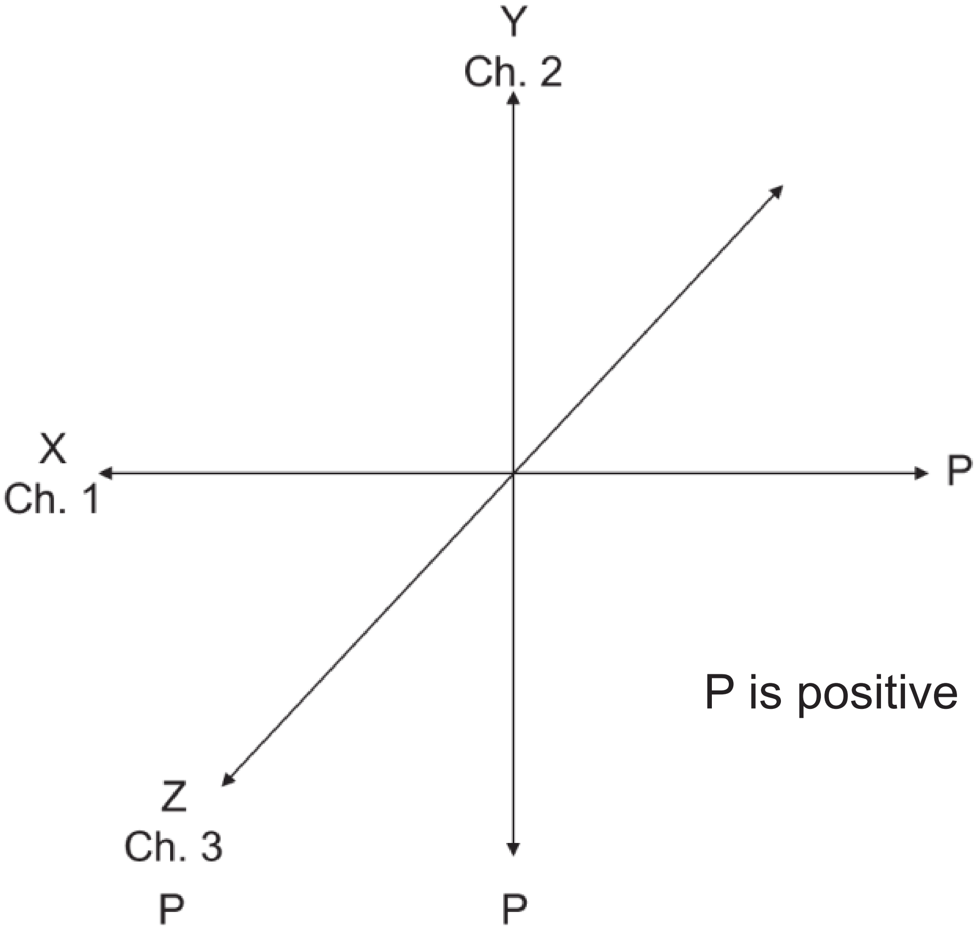


Temporal evolution of the electric field

Electric Field Orientation



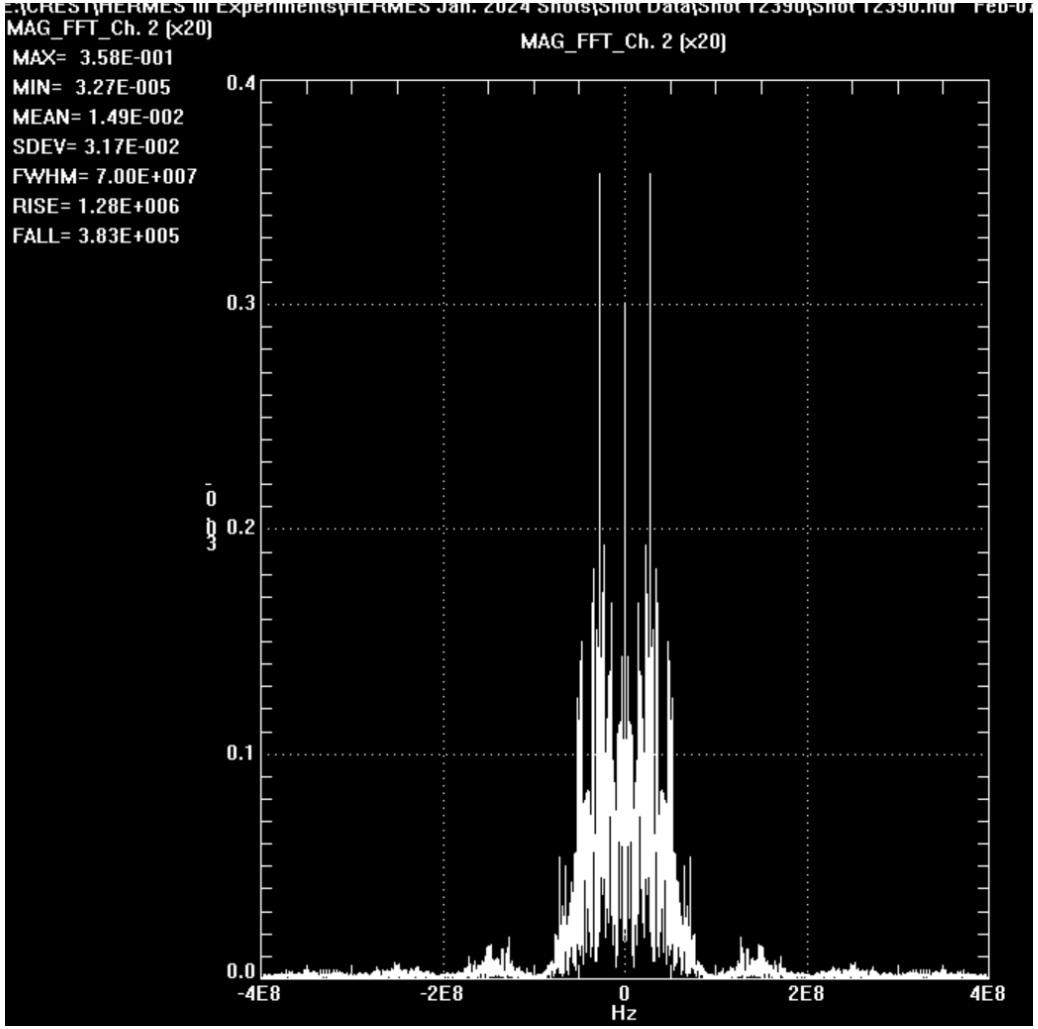
Y-axis is Electric Field in V/m

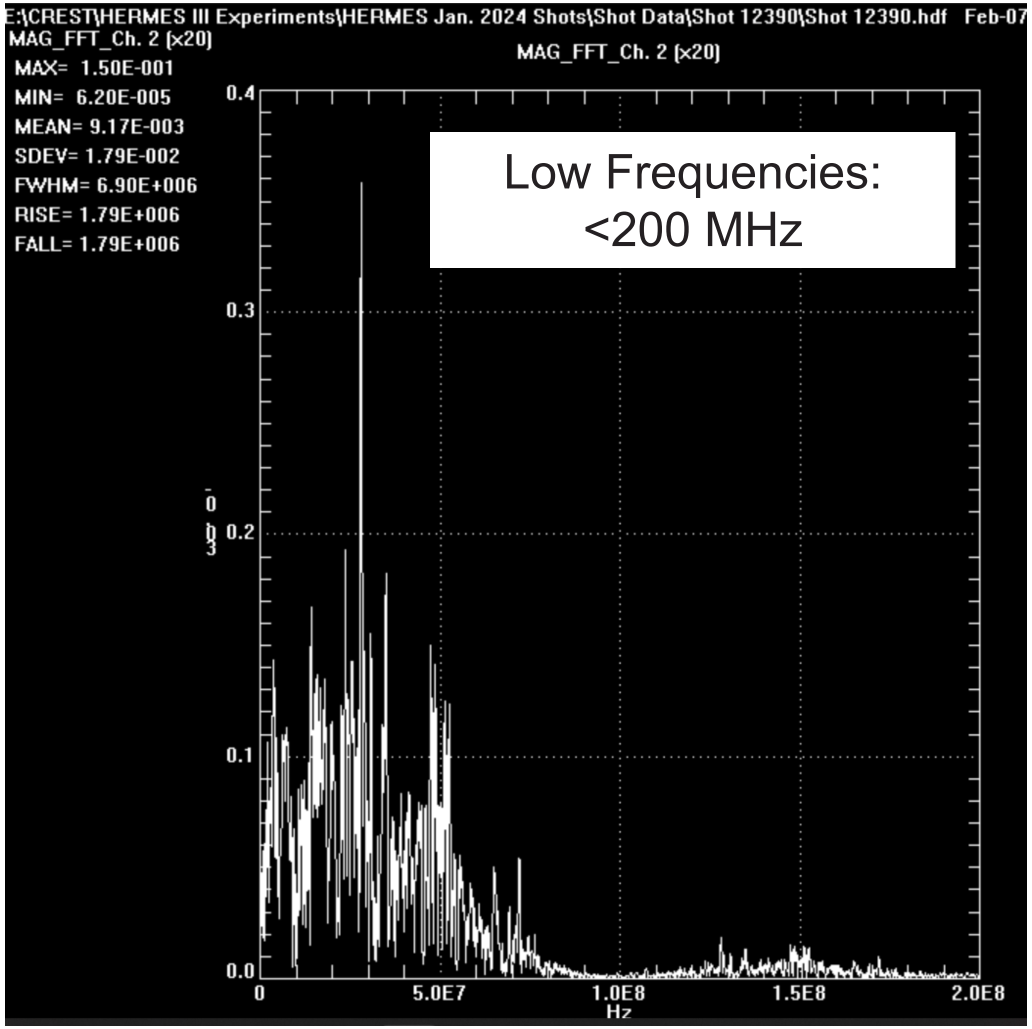


D-dot Orientation at HERMES
(viewed as looking at the machine)

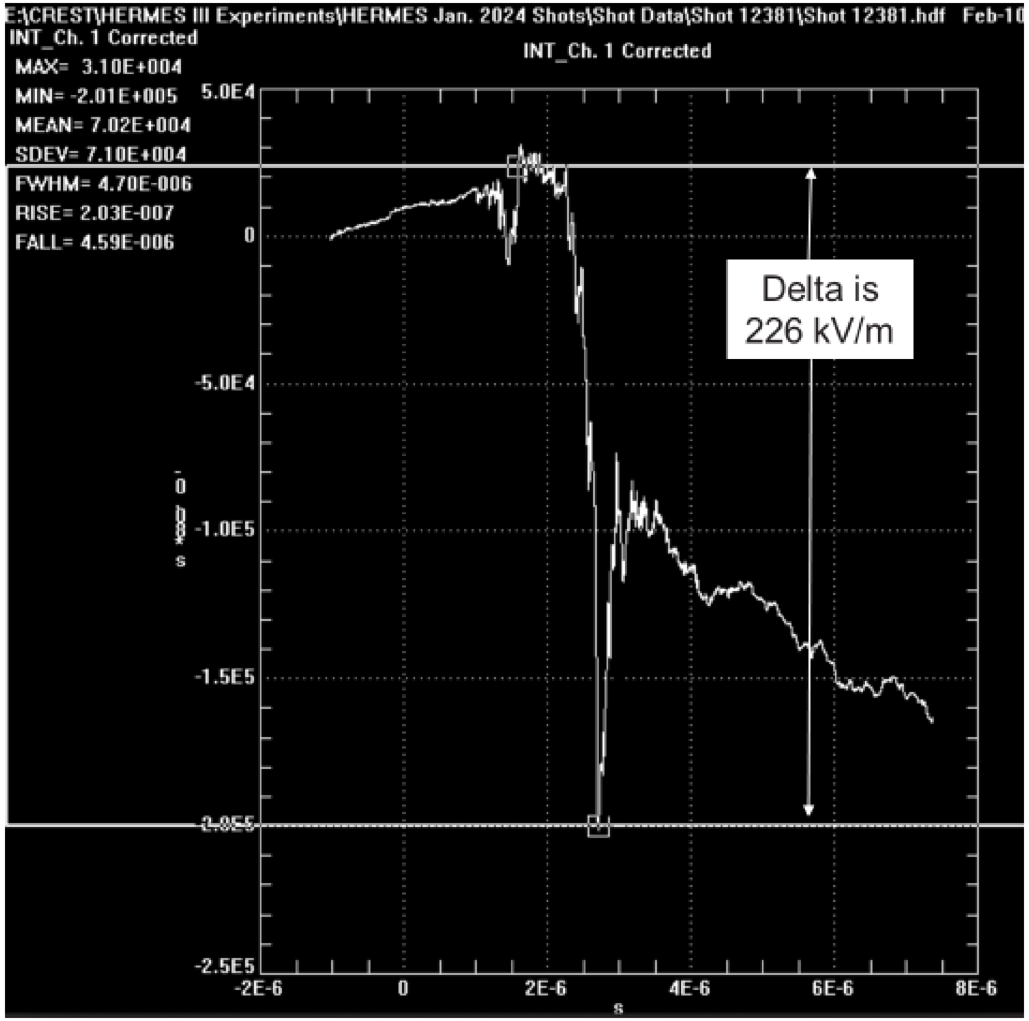
Electromagnetic Pulse Frequencies

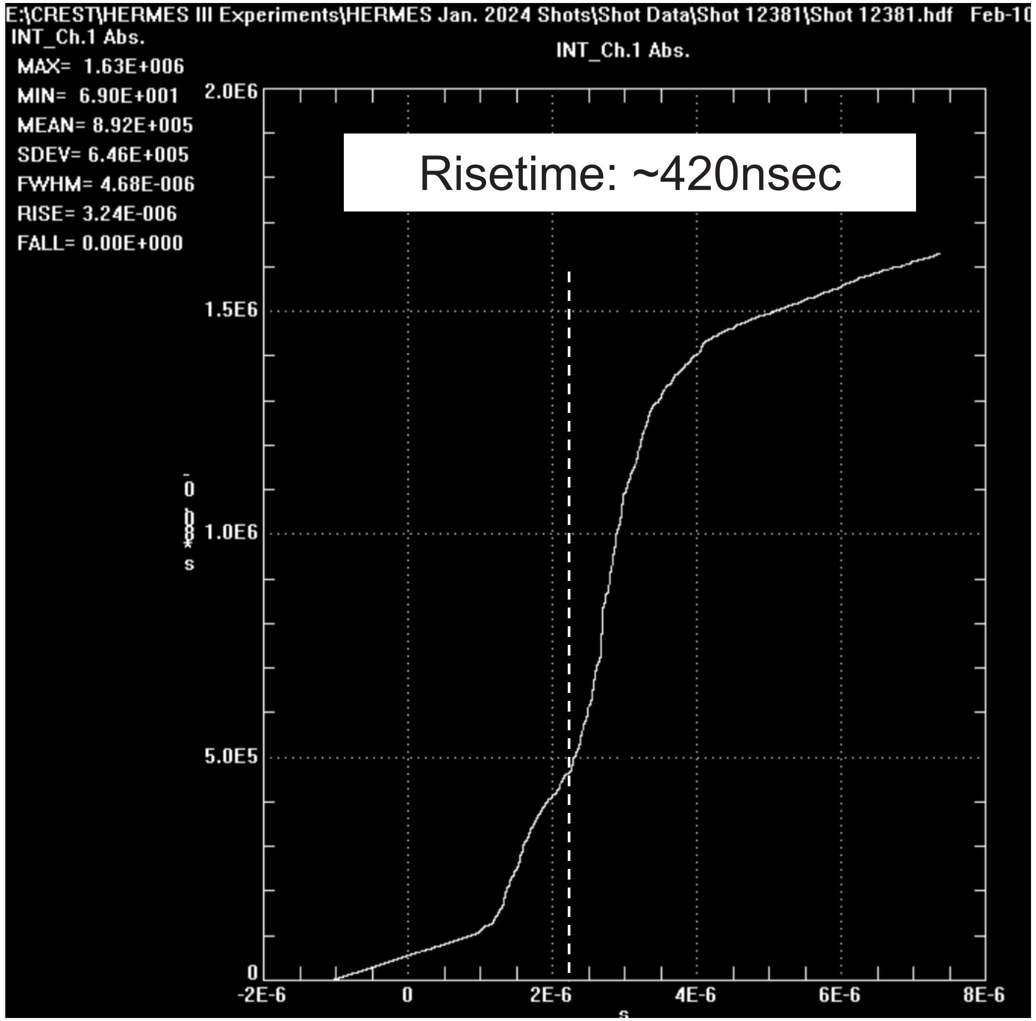
Fast Fourier Transform (FFT)





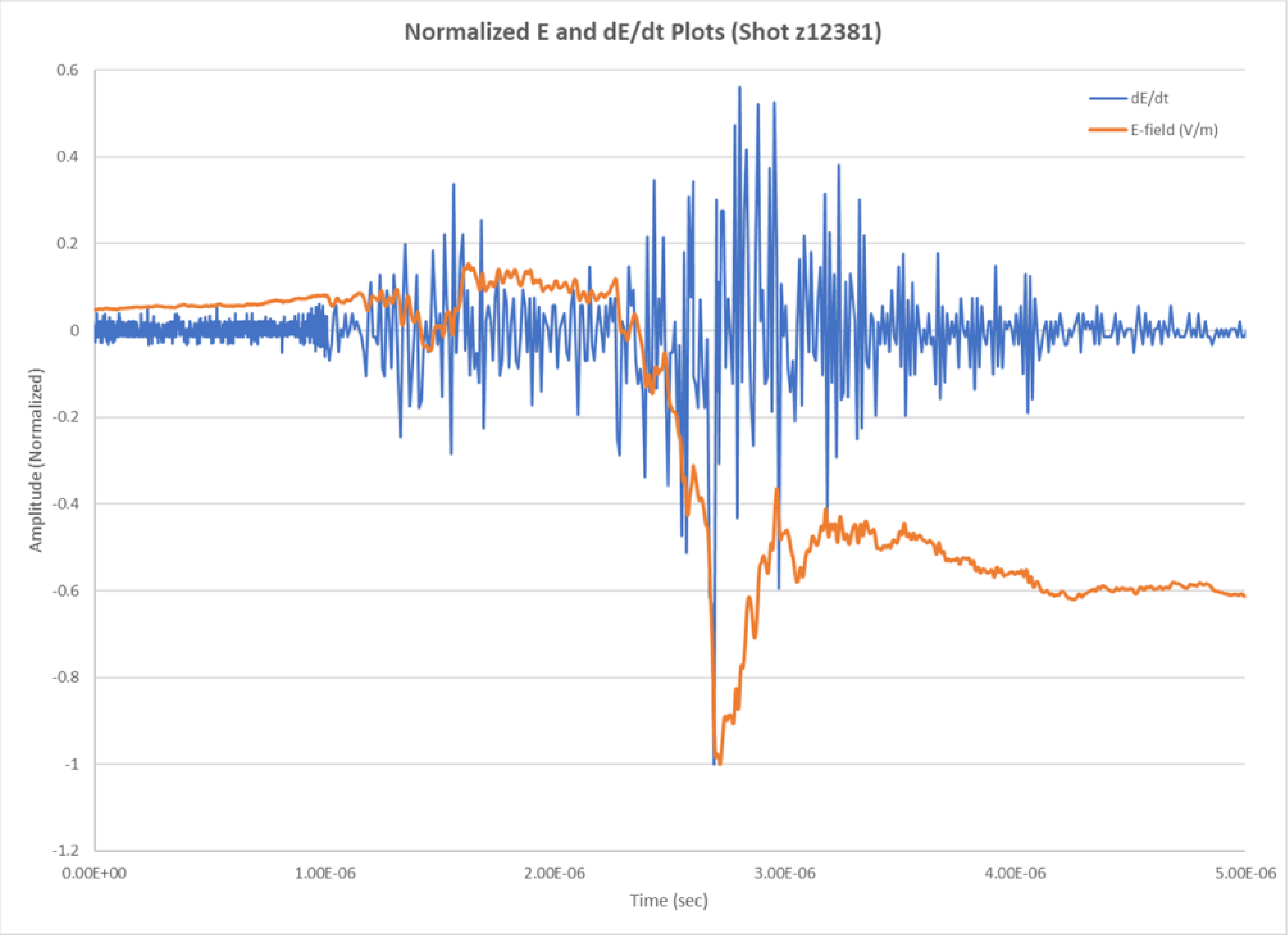
Electric Field Magnitude



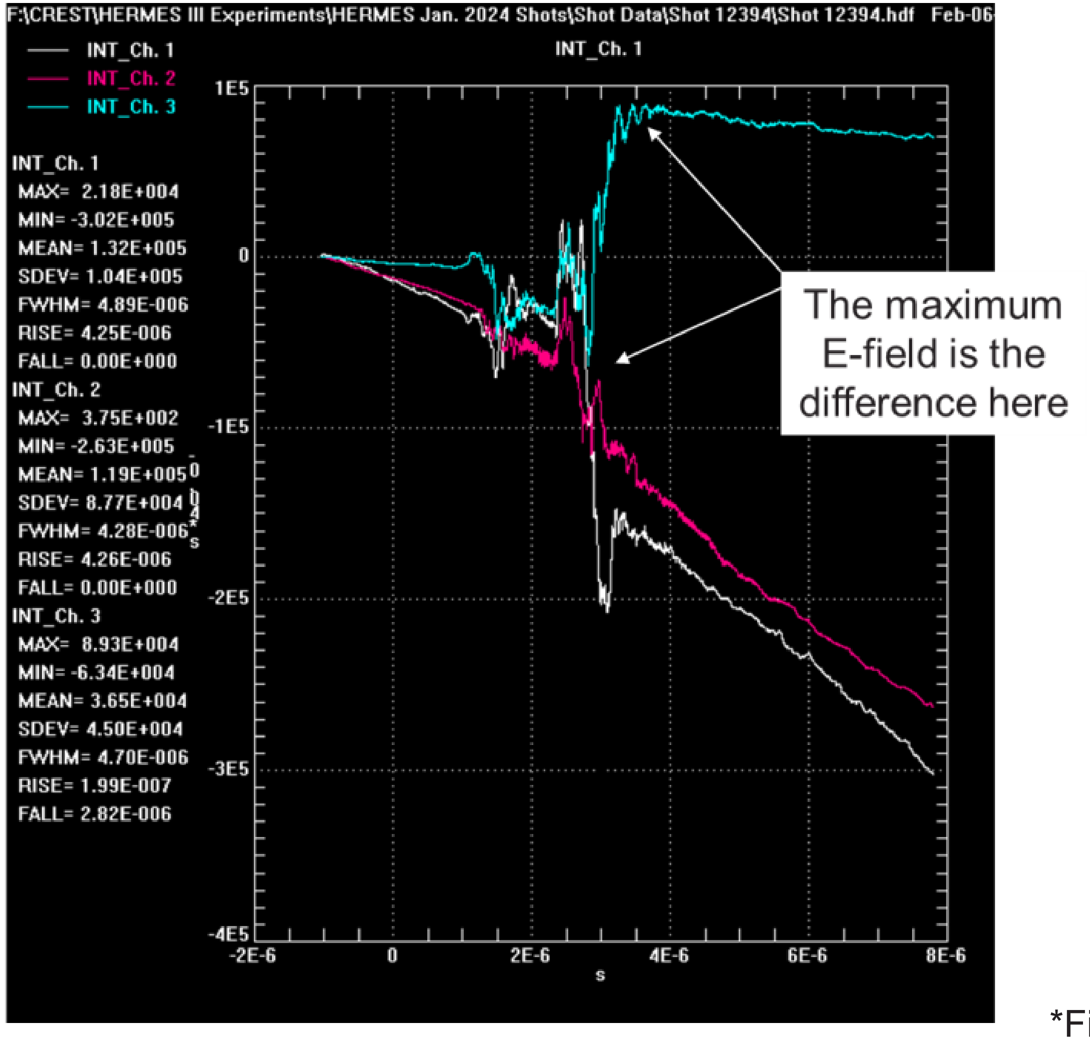


Normalized E and dE/dt

- Higher frequencies and faster risetimes have larger detrimental effects on electrical equipment
- HERMES EMP risetimes are on the order of 420nsec
- Electrical field strength decays with distance from source
- Induced cable voltages (SGEMP) are affected by risetime, length of cable, impedance, and shielding



Electric Field Measurements in Each Direction



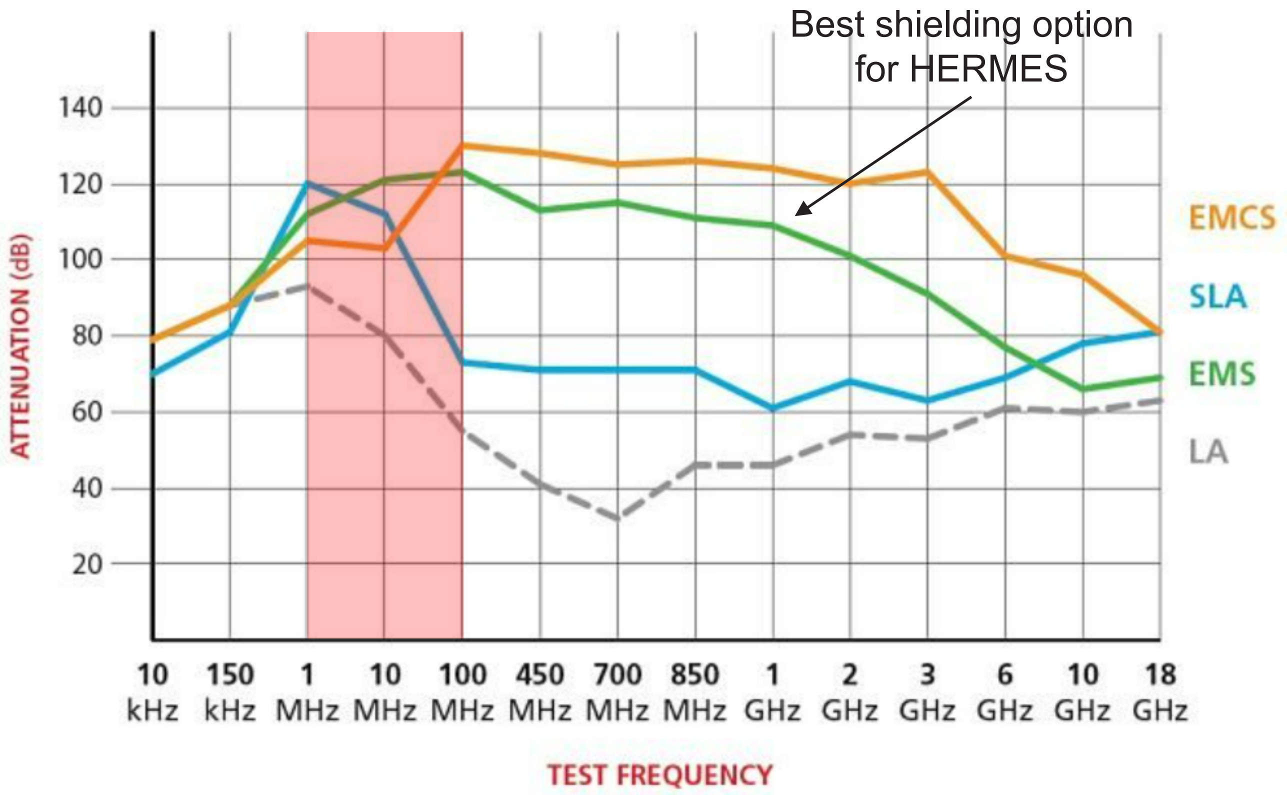
Shot	X (kV/m)	Y (kV/m)	Z (kV/m)
12379	-451	2990	1310
12380	-490	-484	-219
12381	-201	183	192
12382	87.7	174	52
12383	-85.5	-245	-229
12384	94.1	-172	58.4
12385	-53.2	140	-67.4
12386	-50.3	-190	-185
12387	-120	191	96.4
12388	-135	172	167
12389	99.4	-211	116
12390	-57.8	-266	81.7
12391	204	190	-114
12392	64.8	164	122
12393	100	181	143
12394	-302	-263	89.3
Average	**118**	**196**	**122**

*First and second shots have poor S/N, not included in average

Shielding Options for HERMES III Environment

Conduit Shielding

- Double-walled screen room for diagnostic measurements
- Electrically isolated conduit
- Filtered feedthroughs into screenbox
- Cable feedthroughs into screenbox
- Waveguides for non-electrical cabling (fiber optics or optical access)



[8]Liquatite Shield-Flex Data Sheet, Electri-Flex Company, Roselle, IL 60172.

Conclusions

- Intense electromagnetic radiation (EMP) is produced when HERMES III fires
- This EMP is in the 10s of MHz range and lasts for several microseconds throughout the duration of the main HERMES gamma pulse
- This radiation is strong enough to cause damage to electronic equipment and interfere with sensitive electrical signals
- Characterization of the EMP environment is important to ensure proper equipment operation (radiation hardening) and electromagnetic compatibility
- D-dot probes are sensitive to the time-derivate of the electric field
- D-dot (conductive) probes are affected by charged particles, ultraviolet radiation, x-rays/γ-rays, and the photoelectric effect, so they are challenging to field in the HERMES III environment
- Measurements assume a plane wave approximation, accuracies to be determined
- Higher energy, voltages, and/or currents on switches planned for future machines will results in greater EMP noise

Future Work

Relationship between Cross-Sectional Area and Power Density

- Measurements of the Magnetic Fields (B-dot probes).
- Measurements at multiple locations (3D mapping).
- The cross product of the Electric and Magnetic fields gives the Power Density (Poynting Vector).

$$P = \frac{E^2 A}{Z_o}$$

$$\sqrt{\frac{\mu_0}{\epsilon_0}} = Z_o \approx 377\Omega$$

- For an Electric Field of 100kV/m, the Power is 2.7x10^5 Watts