SAND2017-13833C

# Electrical Sciences Experimental Capabilities

## ICF Diagnostics Working Meeting
## Sandia National Laboratories
## December 6, 2017


**Steve Glover**

**Sandia National Laboratories**
**Albuquerque, NM 87185**



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# System qualification/design support

| Environment | *EM / Electrical* 1350 | *Radiation* | *Thermal* ← 1500 | *Mechanical* → |
|---|---|---|---|---|
| Normal | EMR<br>ESD<br>Nearby Lightning<br>DeGauss | | Climate | Shock<br>Vibration<br>Acceleration<br>Aero |
| Hostile | EMP<br>*SREMP*<br>*SGEMP*<br>TREE | Neutrons<br>Gammas<br>X-rays | | Blast<br>Shock |
| Abnormal | Lightning<br>External Power | | Jet-fuel, propellant fire | Shock<br>Crush |

ELECTRICAL SCIENCES
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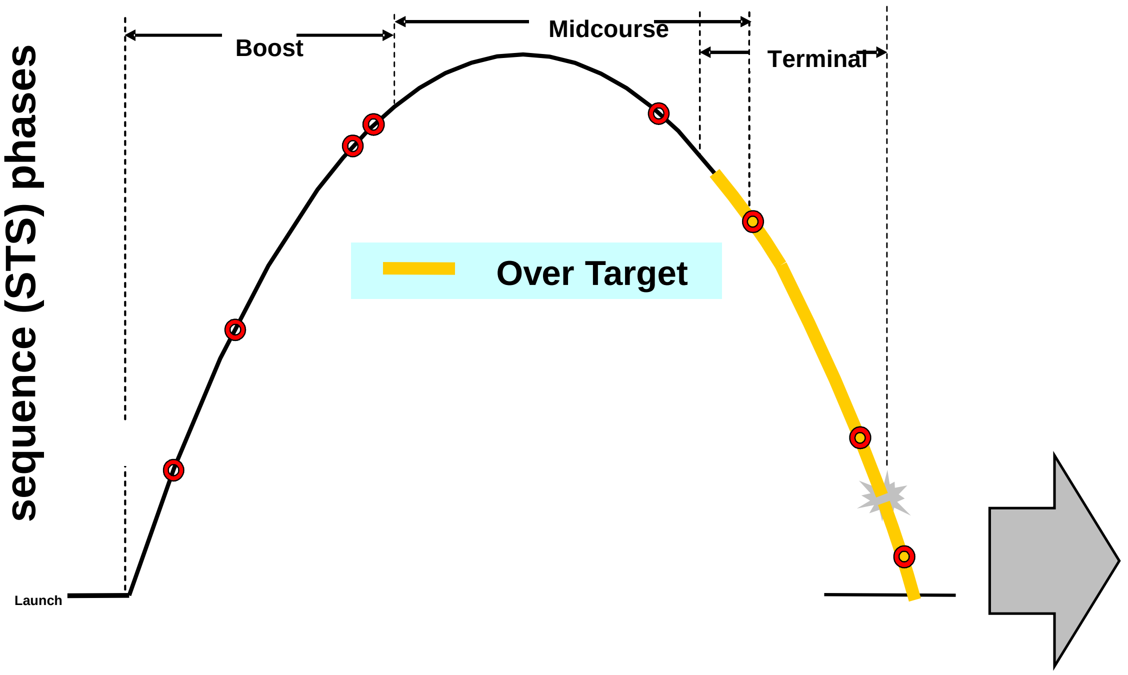
# Nuclear Weapons Stockpile Responsibilities Drive Deep Expertise in Grid-relevant Science and Engineering

**All stockpile-to-target-sequence (STS) phases**




**Physical Environments**

- **Weapon storage, transportation, maintenance, storage on delivery platform, launch and in-flight path**
- **Normal Environments** (EMR, ESD, nearby lightning, degaussing)
- **Abnormal Environments** (lightning, exposure to power sources)
- **Hostile Environments** (nuclear weapon effects, directed energy weapons, high power microwaves)

**Grid-relevant Science and Engineering at Sandia**

- Advanced power systems and AC/DC microgrids
- High voltage breakdown science & experiments
- Pulsed power components and systems development
- Electromagnetics Experiment / theory / code
- Systems engineering and integration
- Circuits and devices



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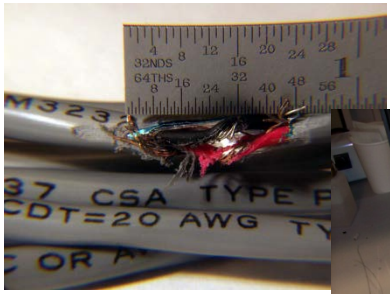
# Electrical and Radiation Sciences Support a Broad Range of Customers

**National security activities for and in collaboration with:**

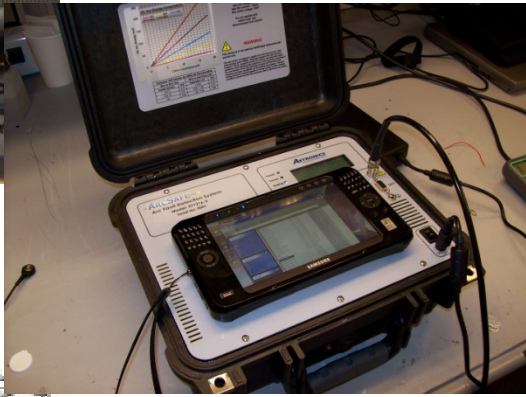
- **Department of Energy** (National Nuclear Security Administration, Office of Science, Office of Electricity)
- **Other federal agencies** (DOD-Army/USAF/NRL, DOT-Federal Aviation Administration, DOL – Mine Safety and Health Admin.)
- **Non-federal entities**
- **Industry** (Goodyear, FMC, Inc., Lockheed Martin Technology Research)
- **Universities**

World class EM capabilities

EMP coupling into facilities

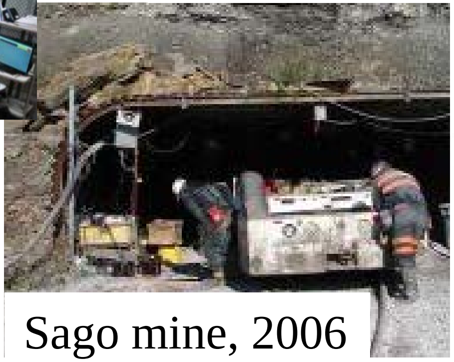



ASTRONICS CORPORATION

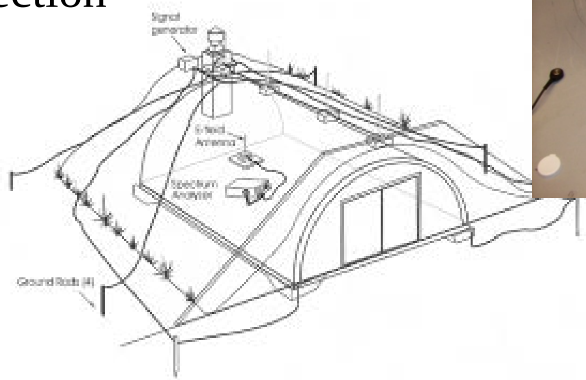


Power systems
All Electric Warship

Lightning protection



Sago mine, 2006



# Sandia has a long history in EMP effects and electromagnetic hardening

**Collaborations and contributions in EMP modeling, analysis and testing:**

- **1962 Starfish Burst - Honolulu Streetlight Incident Analysis (SAND Report 1989)**
- **Fault Tree Methodology used for Power Plants EMP Effects (1982)**
- **EMP/EM penetration into enclosures and through cable shielding (1994-present)**
- **Congressional EMP Commission - SCADA Equipment and Electrical Service-Entrance Testing, Long-line Coupling Analysis (2003-04)**
- **NRC Sponsored Watts Bar and Fermi-II Nuclear Power Plants EMP/HPM Studies (2008-10)**
- **North American Air Defense (NORAD) EMP Protected Shield-Room Installation (2009-2010)**
- **DOD Sponsored Urban EMP Infrastructure Response Modeling (2012-2016)**
- **Fast simulation tool suite for EMP coupling to above ground and buried cable systems for the DOE (2013-present)**
- **DOD-DOE Collaboration on EMP Grid Response Modeling Capabilities (2015-2017) (Weapons Effects Strategic Collaboration)**
- **In process of initiating three-year internal research program to study EMP effects on US power grids. (July, 2017 status)**

# Sandia is Investing Regularly on a Grand Challenge LDRD Scale

SSM SECURE SCALABLE MICROGRIDS
It's the end of the grid as we know it

**Creating solutions for high penetration of stochastic sources.**

- Hamiltonian based controls
- Energy storage
- Power electronics
- Cyber security
- Network of DC microgrid test beds

UWBG ULTRAWIDE BANDGAP

**Enabling ultra-wide bandgap power electronic devices.**

- Higher efficiency
- Wider temperature range
- Greater bandwidth
- Higher voltages
- SWaP advantages

MODULAR POWER BUS

**Increasing resiliency and agility for advanced power systems.**

- Advanced bus based power distribution architectures
- Increased reliability
- Increased robustness

SWaP = size, weight, and power

# Power Density, Safety, and Resilience is a Focus of Two New Sandia Grand Challenge LDRDs

**Enabling predictive breakdown/discharge tools including correct physics**

- Improved models
- Improved design
- Increased power density
- Increased safety

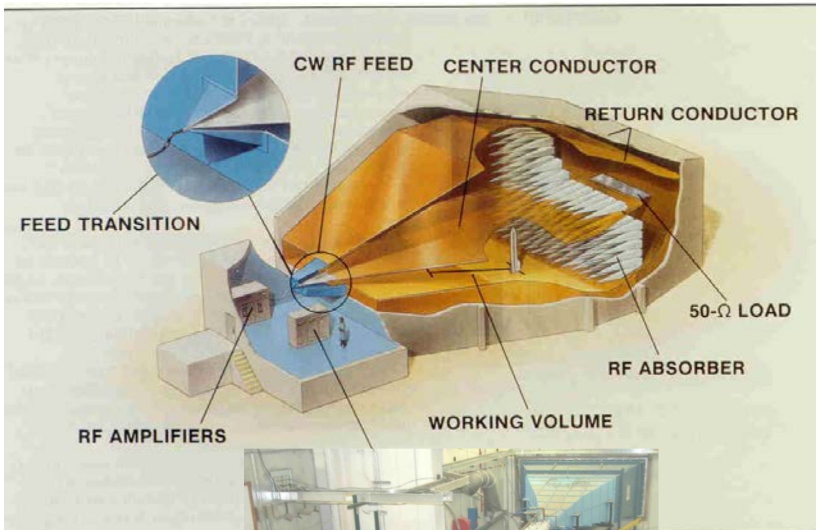
**Creating a grid scale understanding of EMP impact**

- Physics based understanding
- New protection techniques
- Strategy optimization

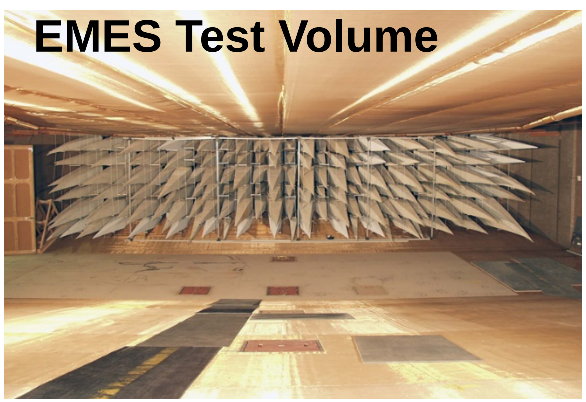
SWaP = size, weight, and power

# Experiment and Test Capabilities

# EMES Facility (10 kHz - 200 MHz)




EMP Pulser



EMES Test Volume


Test volume:
- 4x5x11 m (approx.)

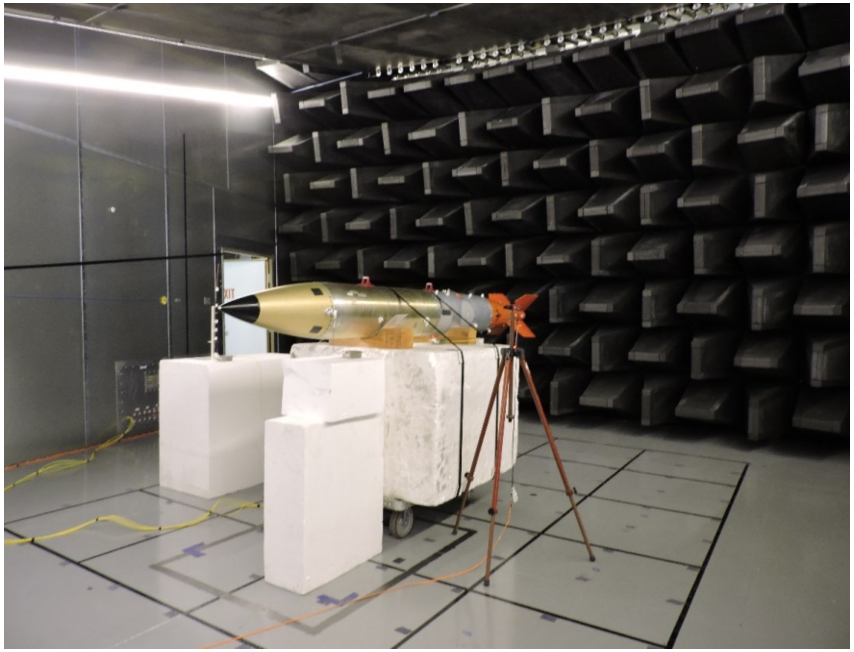
Environments:
- High altitude EMP:(1ns risetime) 30-250 kV/m
- Plane-wave RF (CW): 100 kHz – 100 MHz at 125 V/m
- Rolls off to 100 V/m at 250 MHz

EMP capacity:
- 2 shots/day (Max voltage)
- 4 shots/day (nominal)

Typical experiments:
- Susceptibility measurements
- Transfer function measurements

**EMES = Electromagnetic Environment Simulator**

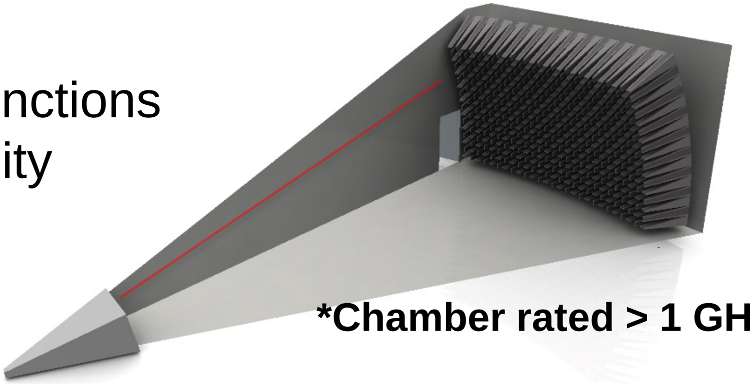
# GTEM Chamber (10 kHz – 1 GHz)



## GHz TEM environment:

- 4.5 (h) x 3.7 (w) at back absorbers
- λ at 200 MHz = 1.5 m
- Plane-wave, continuous wave
  RF amplifier system: 10 kHz-1 GHz, 125 V/m, 5kW max. input
- EMP (E1)
  ~1 ns risetime, ≤130 kV/m

- Transfer functions
- Susceptibility



*Chamber rated > 1 GHz

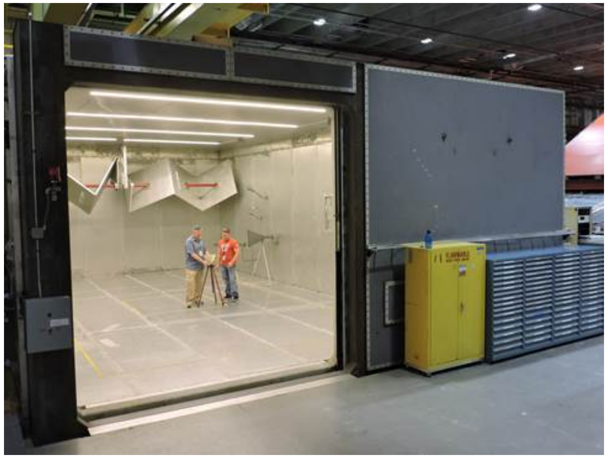
***GTEM reproduces STS plane wave environments – multiple device orientations are needed to capture maximum coupling***

# Mode-Stir Chamber (200 MHz - 40 GHz)

**MSC Environment**:

- 4 (h) x 7 x 11 Reverberant chamber
- $\lambda$ **=** 7.5 mm @ 40 GHz
- Q ~ 100,000 - 1,000,000 (low loss)
- RF amplifiers: 200 MHz - 40 GHz, 130-200 V/m average

- Transfer functions
- Susceptibility



***Multiple device orientations are not needed in the MSC – measurement data needs correction to capture plane wave response***



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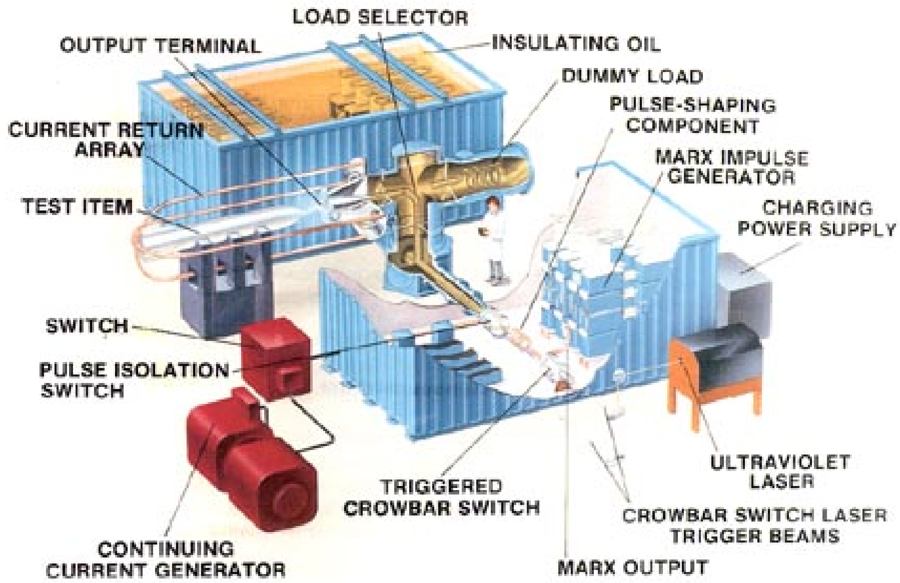
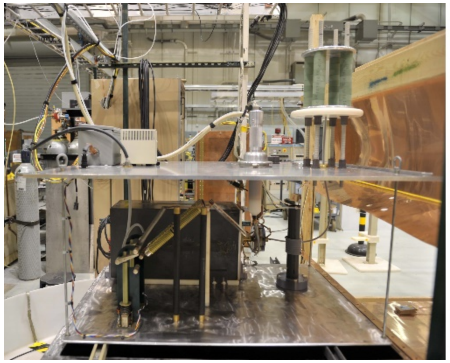
# Lightning Simulator Facility



Lightning Facility:
- Large volume for bombs, RV/RBs, structures

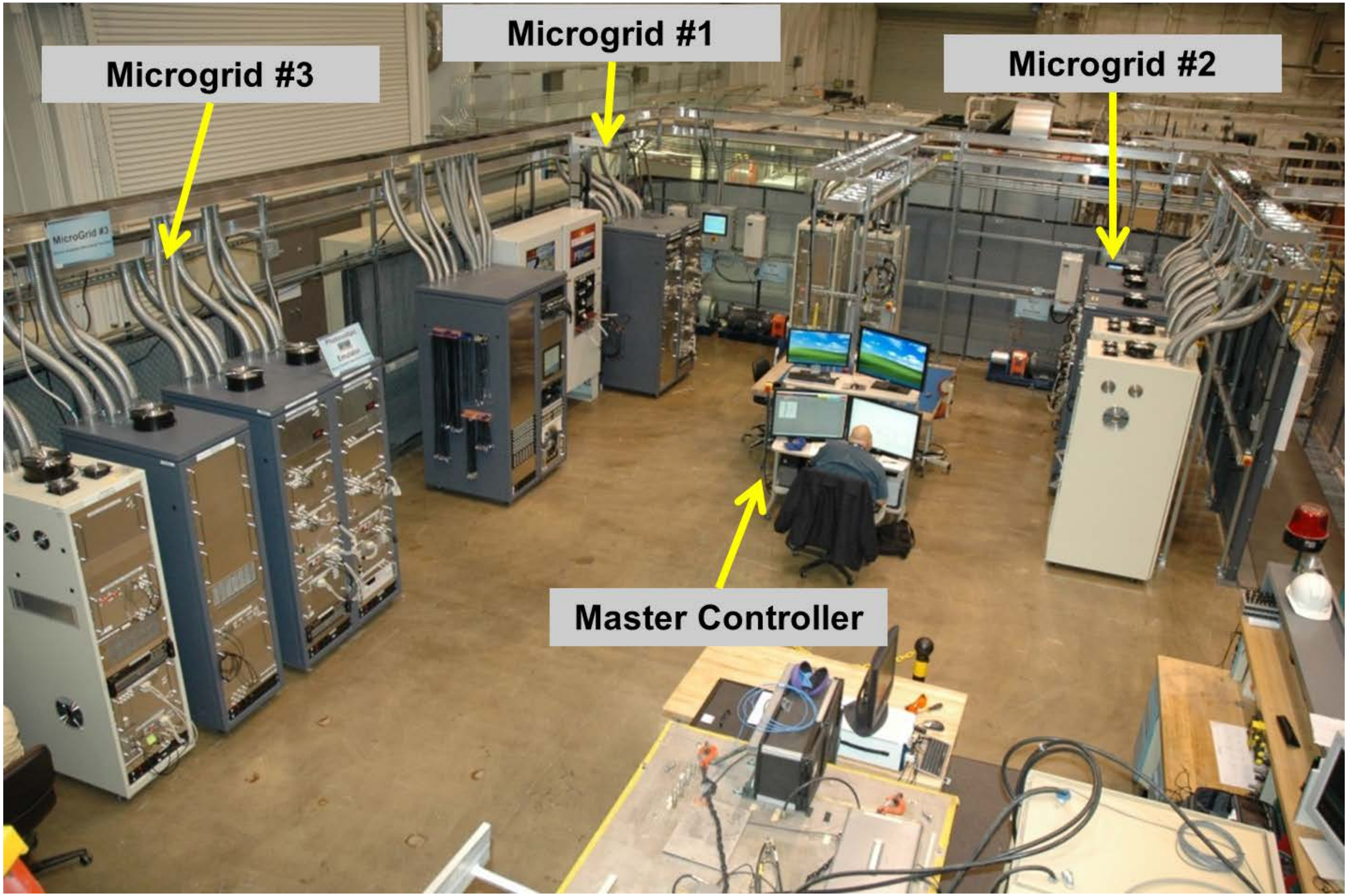
Environments:
- Full-threat lightning (direct-attach and nearby lightning)
- Dual-stroke, with or without continuing current

Specs:
- 1.6 MV
- Peak current – 200 kA (99$^{th}$ percentile)
- Min current – 30 kA
- Current rise time: 1 to 5 μsec
- Current rate of rise: 200 kA/μsec, max
- Pulse width (@50% level): 50 to 500 μsec (dependent on load impedance)
- Number of pulses: 1 or 2, variable interval
- Continuing current 100s A for up to 1 sec

Other:
- Small scale HV testbeds (100's kV)
- Complete Electrostatic Discharge (ESD) lab including testing at high temperatures

# Secure Scalable Microgrid Testbed

- Hardware Testbed includes components representing generation, loads, energy storage and transmission/transfer
- Component building blocks enable a variety of system configurations



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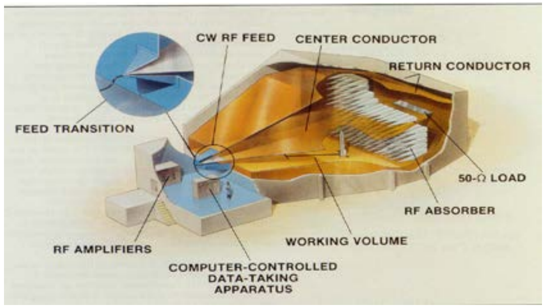
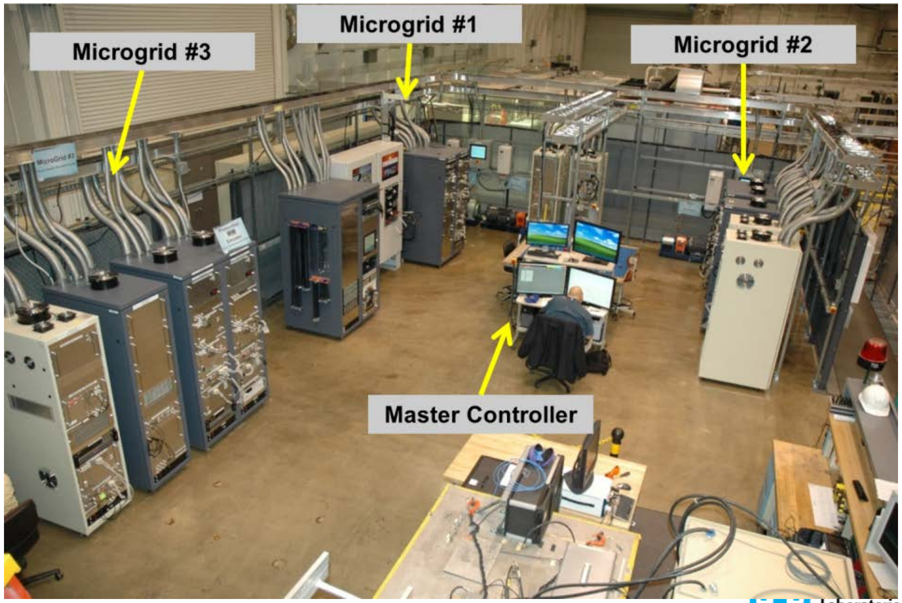
# Power Electronics and Controls Related Research is Addressing Key Challenges

- Networked microgrid systems (DC, AC, and Hybrid)
  - Focused on reliability and resiliency
  - Solutions to highly stochastic sources and loads
- Power electronics
  - Advanced controls, performance, and interfaces
    - » (with sources, loads, and storage)
- High voltage sciences
  - Electrical breakdown and SWaP
- Power systems and Electromagnetic pulses
  - Focused on performance and reliability
- Controls
  - Centralized and distributed
  - Energy and exergy based
  - Model predictive and conventional
  - Energy management
  - Wide area controls




Electromagnetic Environment Simulator (EMES)

Electrical breakdown phenomena




Secure, Scalable, Microgrid (SSM) Test bed

SWaP = size, weight, and power



Laboratories

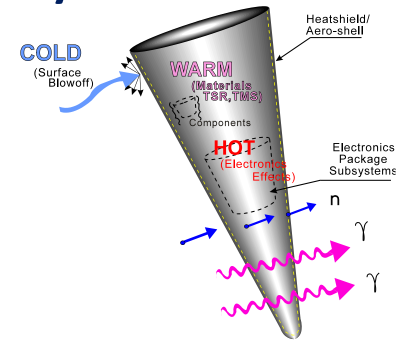
# Analysis & Modeling/Simulation

# Our Electromagnetics Code Suite was Developed and Validated to Address our Specific Needs

- Time domain (EMPHASIS & Quicksilver)
  - FEM & finite-difference
  - Full-wave, time-domain EM
  - Charged particle-in-cell/plasmas
  - Electrostatics
  - Non-linear eddy-current EM
- Frequency domain (EIGER)
  - Boundary elements
  - Full-wave, frequency-domain EM
  - Electrostatics
  - Magnetostatics
- High voltage breakdown (breakdown_$\alpha$)
  - Non-uniform geometry
  - Streamer and static breakdown modeling

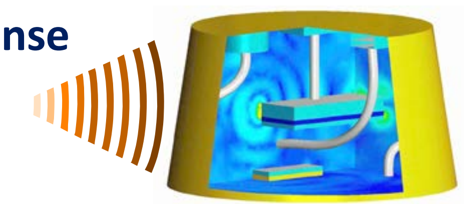
Code / Model development
Verification / Validation
Modeling / Analysis

**X-ray Environments**

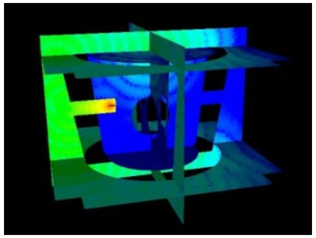



*Cable, Cavity, Box SGEMP, SREMP*

**System Response to EM Fields**



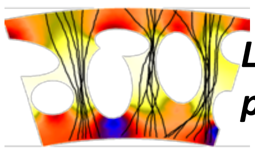
*EMR, EMP*



**Interactions**

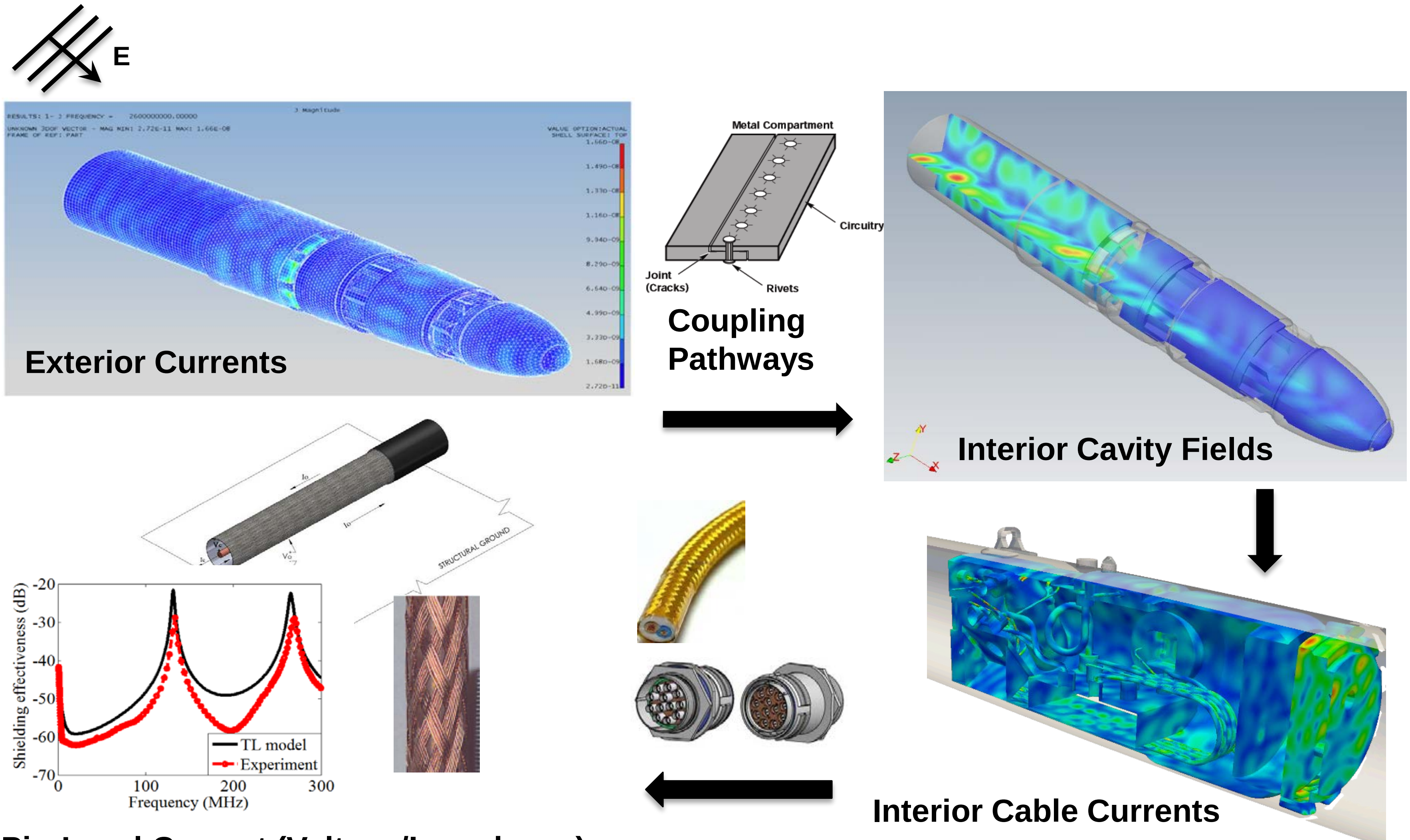
Radar coupling to system components

**Component Breakdown**



*LAC, connector performance*

# Modeling and Measurements Predicts the Effects on Interior components and Circuits of Systems




**Pin-Level Current (Voltage/Impedance)**

**Visualization of the interior fields can provide guidance for the testing configurations**



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# Summary

- **Sandia's primary mission is the design and qualification of NW systems and includes EMP environments.**
- **Sandia has extensive capabilities in electrical sciences**
  - **Electromagnetics**
    - » **Continuous and pulsed**
  - **High voltage sciences**
  - **Advanced power systems**
  - **And many other fields**
- **We support other aligned *National Security* mission space when:**
  - **A strategic partnership strengthens both entities**
  - **Special expertise is needed to enable new national capabilities**
  - **Performing as an honest broker serves the national interest**



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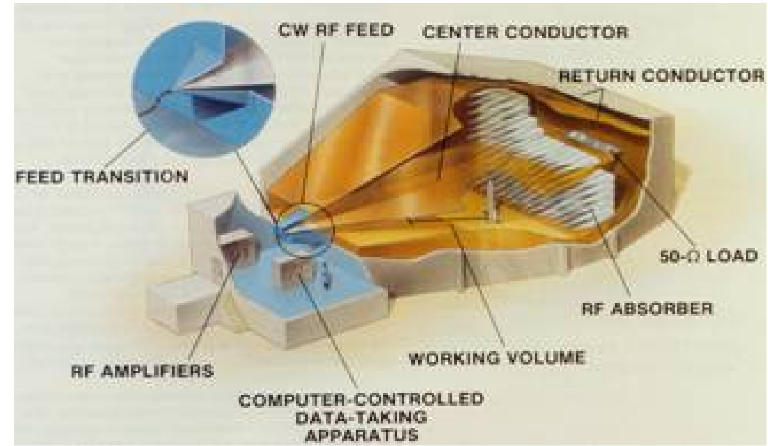
# BACKUP

# A Suite of EM Test/Experiment Capabilities are Required for Nuclear Weapon Design & Qualification

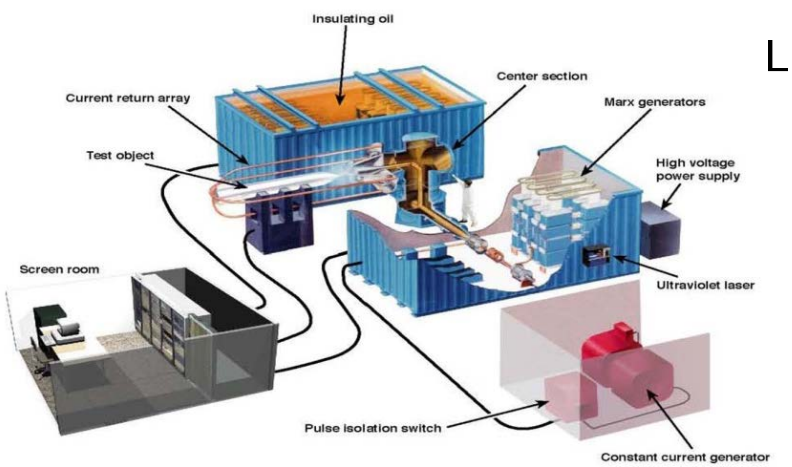
## Mode-Stir Chamber

- CW (220 MHz – 40 GHz)



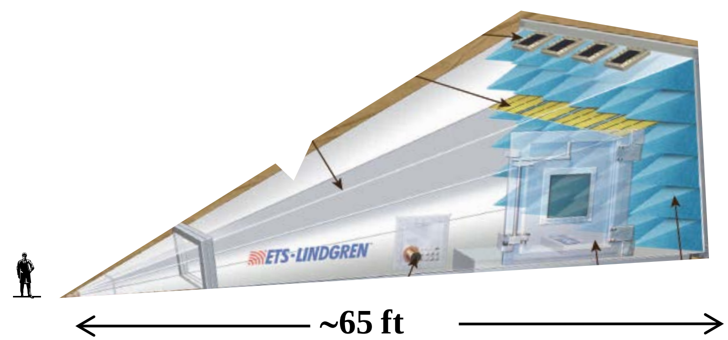

## Large Volume TEM Facility (EMES)

- CW (10 kHz – 220MHz) 125 V/m
- EMP (1 ns risetime) ≤250 kV/m




## Lightning Facility

- 1.6 MV
- 200 kA
- 500A continuing current
- 2 pulses

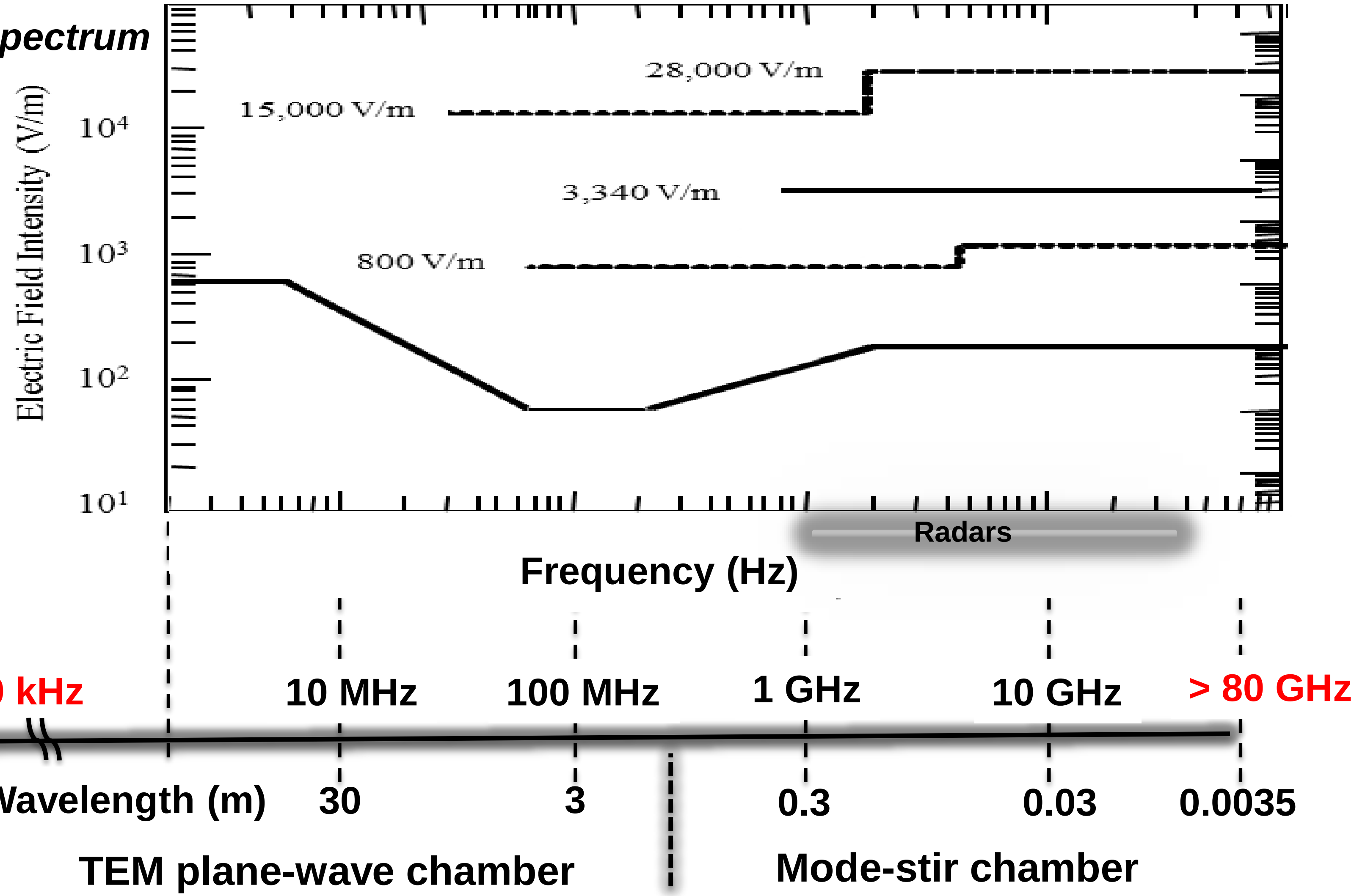



## GTEM (Feb. 2016)

- CW (DC– 1GHz) 125 V/m
- EMP (1 ns risetime) ≤130 kV/m

# EMR spectrum is currently covered in two separate types of test facilities

*Example spectrum*




***Device and chamber dimensions and wavelength establish test approach***



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# We Apply a Combination of Theoretical Analysis and Numerical Simulation Tools in our Mission

- Theoretical analysis is often used when
  - Detailed models, parameters are not available
  - Bounding calculation is desired (general application)
  - The approach offers time savings versus simulation

- <u>Numerical Simulation:</u>
- EIGER: Electromagnetic/Electrostatic
  - Integral Equation, Method-of-Moments
  - Frequency-Domain

- EMPHASIS: Electromagnetic with Particle-In-Cell
  - Finite-Element Method
  - Time-Domain

**In-house codes offer the advantages that**
- **Physics models are known and documented**
- **Models and capabilities have been tailored to our problems**
- **Models, algorithms can be easily accessed by the analyst**

# Summary of SNL EM Code Capabilities

| Code | Environments | Description | Usage |
|---|---|---|---|
| **EMPHASIS** | EMP, SREMP, SGEMP, Lightning | Full-wave EM, MPP → high rigor | NW Qualification, R&D |
| **EIGER** | EMR, EMP, Nearby Lightning | Full-wave EM, MPP → high rigor | NW Qualification, R&D |
| **ALEPH** | Electrical Breakdown | PIC+DSMC, MPP → high rigor | R&D |
| **Breakdown Alpha** | Electrical Breakdown | Reduced-Order Model → quick turnaround | Component Design, Significant Findings |
| **ATLOG** | EMP, SREMP, Nearby Lightning | Transmission Line Code → quick turnaround | Consequence Assessment to Grid Infrastructure |

**SREMP: Source-Region EMP**
**SGEMP: System-Generated EMP**
**PIC: Particle-In-Cell**
**MPP: Massively Parallel**
**DSMC: Direct Simulation Monte-Carlo**

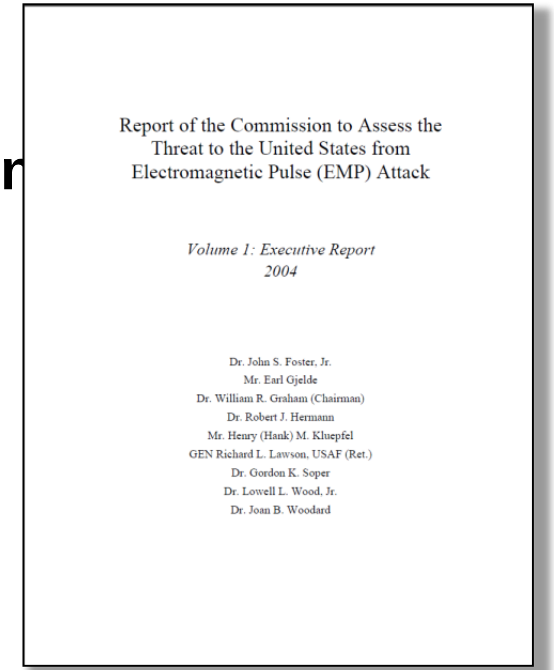
# Capabilities include nuclear EMP effects on large scale systems

- **Nuclear weapon source region characterization**
- **EMP, SGEMP, SREMP effects on systems**
- **Modeling and simulation**

| Code | Physics |
|---|---|
| ITS | $\gamma$ - $e^-$ transport |
| SCEPTRE | $\gamma$ - $e^-$ transport |
| EMPHASIS / | EM-Plasma |
| NuGET | N - $\gamma$ environment, fireball |

- **Large-scale EMP and radiation simulators**
  - **EMES, GTEM, Hermes III**

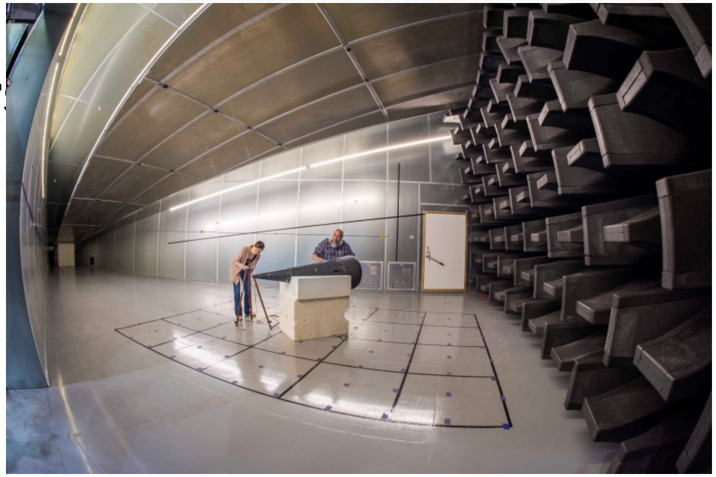
- **Utility scale power systems effects**
  - **EMP line coupling, propagation**
  - **Coupling into facilities**
  - **Utility equipment response**



Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack

*Volume 1: Executive Report*
*2004*

Dr. John S. Foster, Jr.
Mr. Earl Gjelde
Dr. William R. Graham (Chairman)
Dr. Robert J. Hermann
Mr. Henry (Hank) M. Kluepfel
GEN Richard L. Lawson, USAF (Ret.)
Dr. Gordon K. Soper
Dr. Lowell L. Wood, Jr.
Dr. Joan B. Woodard





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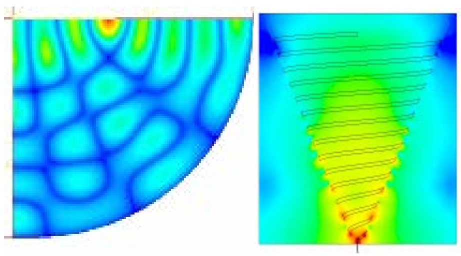
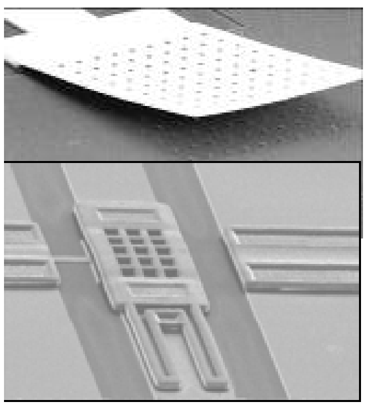
# Our Electromagnetics Codes Support Many Applications and Customers

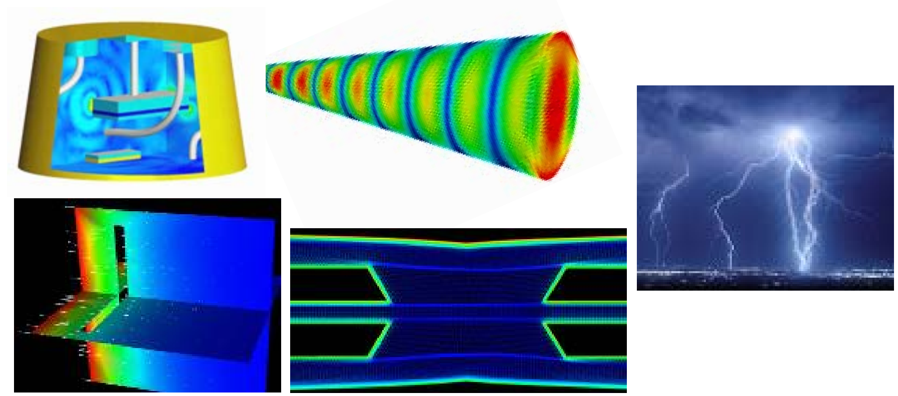
**New EM environments & devices**



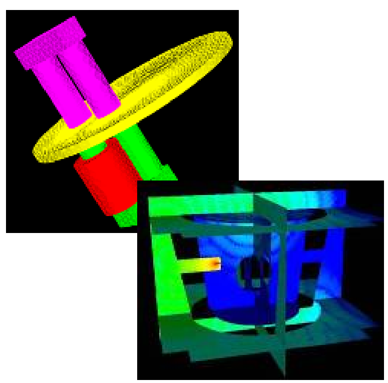


***High-Frequency Cavity/Aperture Response, Advanced Antennas, RF-MEMS devices***

**System Response to EM, lightning, high voltage & SGEMP Environments**

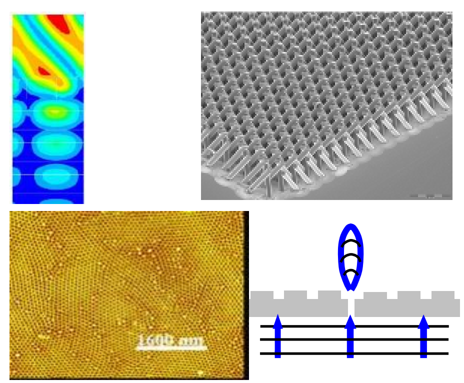


**Components**



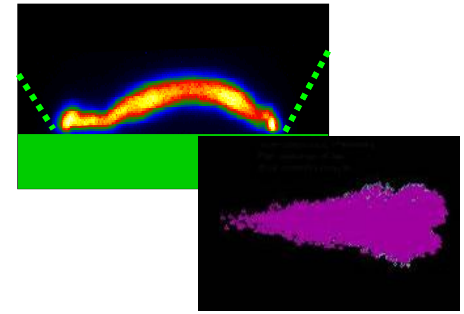
***Stronglinks, Radar, Firesets, Neutron Tubes***

**EM Materials**



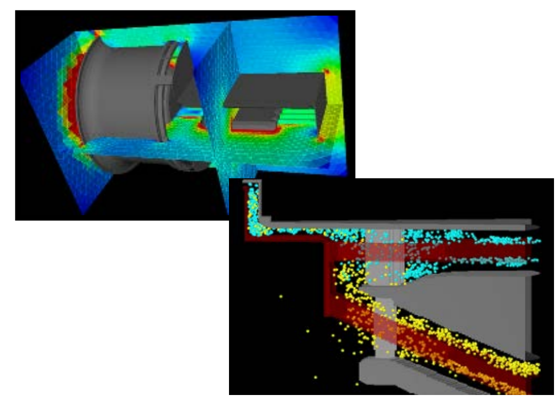
***Photonic Band-gap Devices; Plasmon Structures; Metamaterials***

**High Voltage Sciences**



***HV Standoff, Arcing, Leakage Currents, Electrostatic Discharge***

**Fast Pulsed Power**



***Z-pinch apps for NW, Mat'l Dynamics, Fusion Energy***



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