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Title: PHELIX

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14 January 2008

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Form 836 (7/06)

PHELIX

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D. M. Oro, F. E. Merrill, J. R. Griego,
R. E. Reinovsky

Sandia National Laboratory Seminar

14 January 2008

Abstract

The **Precision, High-Energy Density, Liner Implosion eXperiment** (PHELIX) pulsed power driver is currently under development at Los Alamos National Laboratory. When operational PHELIX will provide 0.5-1.0 MJ of capacitively stored energy into cm size liners which will reach implosion velocities of 1-4 km/s with approximately 10-20 microsecond implosion time. Peak load currents will be in the 5-10 megamp range. To do this the machine will utilize a reusable, multi-turn primary, single-turn secondary transformer to couple the 100-120 kV Marx capacitor system to the load. The transformer has been designed toward a coupling coefficient of 0.9.

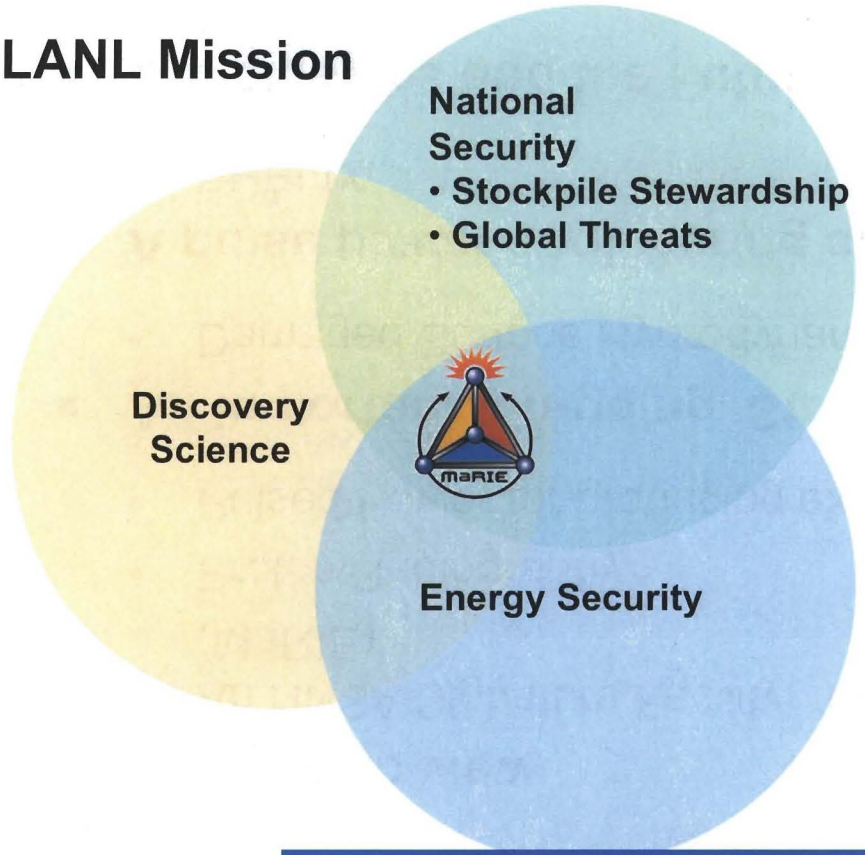
PHELIX is being designed to be portable with only an 8 x 25 ft^2 footprint. This will allow the machine to be taken to the experiment designer's diagnostic of choice. The first such diagnostic will the LANL proton-radiography facility. There the multi-frame, high-resolution, imaging capability will be used to study hydrodynamic and material phenomena

Outline

- **A strategic view**
  - An NNSA Signature Facility, "Matter-Radiation Interaction in Extremes" (MaRIE)
  - Proton Radiography
  - Pulsed Power for producing extreme environments
- **An important, on-going, Stockpile Stewardship experiment**
  - Damaged Surface Hydrodynamics Experiment (DSH)
- **A pulse power engineering challenge**
  - PHELIX
- **Conclusions and the Future**

MaRIE is a family of related facilities and capabilities to address science of critical importance to both national security science missions and research challenges of the future

LANL Mission



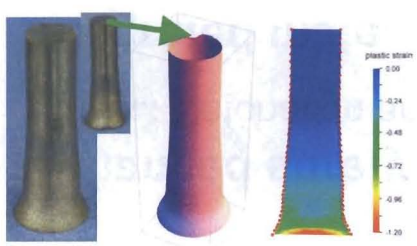
National Grand Challenges

- Transform the nuclear weapons enterprise: Stockpile Stewardship and Stockpile Manufacturing
- Close the 10 TW Gap between the energy we have and the energy we need: From fission & solar to fusion
- Ubiquitously detect global threats

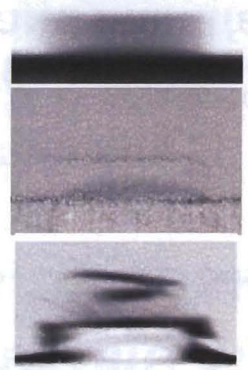
The transition from "observation & validation" to "prediction & control" is a central mission challenge

Grand Challenge for Stockpile Stewardship: Predicting materials performance, including failure, in extremes

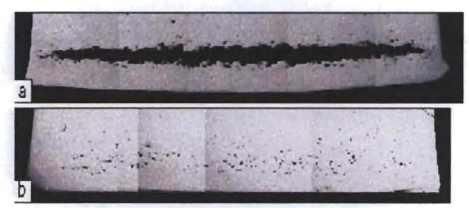
- **Multi-phase equation(s) of state and the influence of microstructure on performance**
  - Ex.: Understanding and controlling differences introduced by the manufacturing process (e.g., cast and wrought product; new production lines; etc.)
- **Predicting component/system lifetime**
  - Ex.: Unraveling the effects of aging on performance
- **Scale effects for high energy density physics, later time phenomena**
  - Ex.: Initial conditions for boost



Taylor Cylinder Test



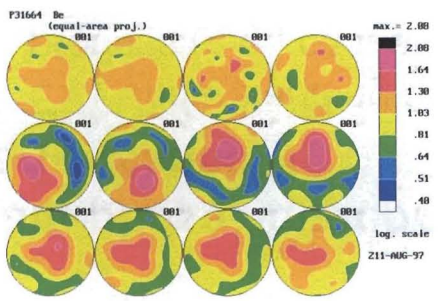
Dynamic Spall



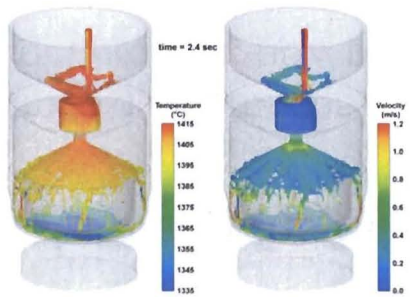
Spall Characterization

Grand Challenge for Stockpile Manufacturing: Process aware materials by design

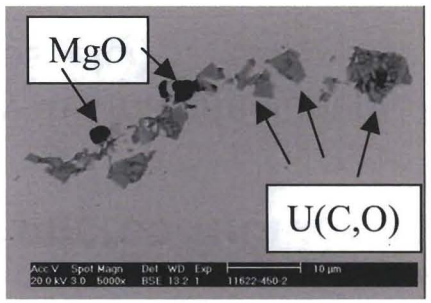
- **Enhanced surety and performance**
  - Ex.: Detonation and deflagration of energetic materials
- **Integrated materials design and manufacture**
  - Ex.: Variations in materials supply, materials compatibility and substitution challenges
- **Controlling surface reactions and irradiation damage**
  - Ex.: Corrosion and radiolytic effects



Beryllium Texture



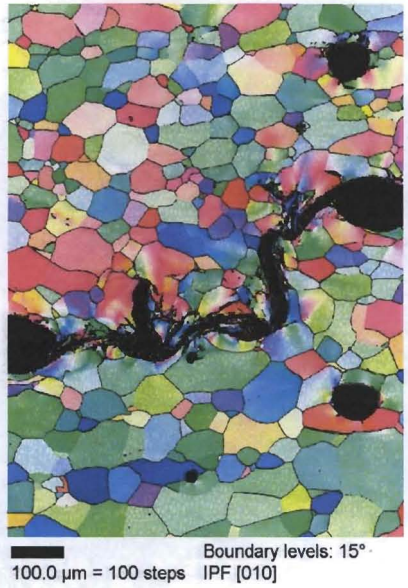
Casting Modeling – Test Works

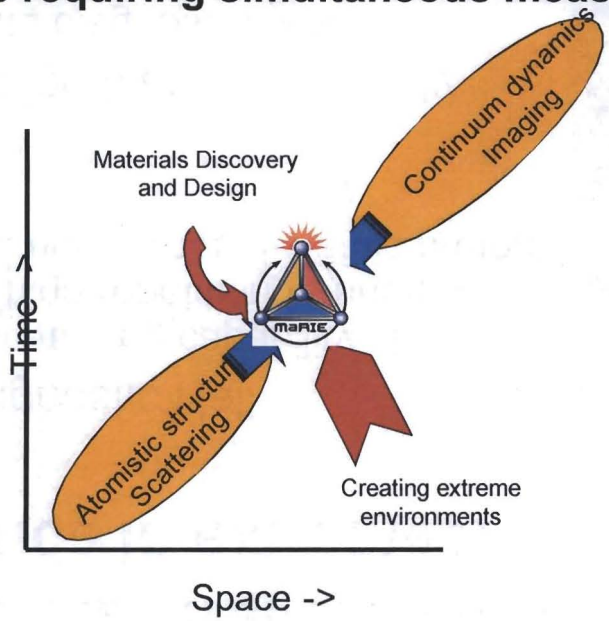


Weld Characterization

The "micron gap" is a scientific frontier that limits our ability to achieve the materials performance we need

- **~ 1 μm scale represents an experimental and theoretical frontier**
  - Crossover from continuum to atomic scale models
  - Interface between scattering & imaging
  - Nexus of discovery science & predictive validation
- **Explicit focus on dynamic (~ ns/ps), stochastic processes requiring simultaneous measurements**





~ 1 μm is the domain of defect consequences and microstructure interactions that drive materials strength, damage evolution, etc.

MaRIE provides the first comprehensive set of co-located tools to realize transformational advances in materials performance in extremes.

Multi-probe Diagnostic Hall

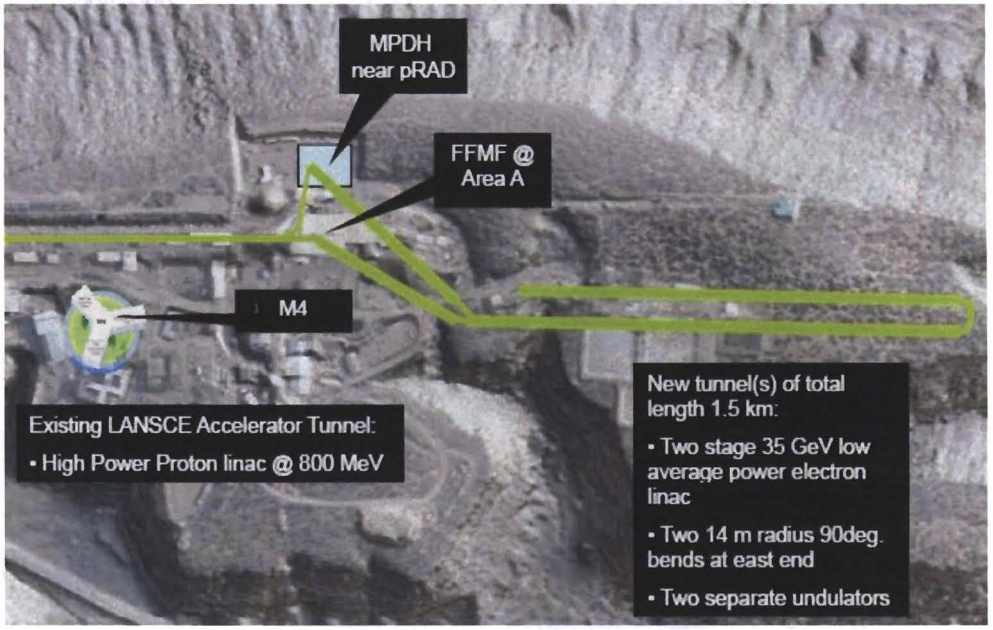
First x-ray scattering capability at high energy and high repetition frequency along with simultaneous dynamic proton imaging

Fission and Fusion Materials Facility

Unique in-situ diagnostics and irradiation environments beyond best planned facilities

Make, Measure, Model Materials (M-4)

Comprehensive, integrated resource for materials synthesis and control, with national security science infrastructure



MaRIE will provide unprecedented international user resources

Current MaRIE definition is pre- pre-conceptual

Pre-Pre Conceptual Baseline Facility includes:

- 800 MeV, 1 MW protons → 800 MeV, 1.8 MW with MaRIE
- 35 GeV XFEL w/ 2 undulators → 50-100 keV photons

- New Measurement Hall – MPDH (including dynamic drivers)
- Enhanced MTS → FFMF (in-situ/near in-situ/PIE measurement capability)
- M4 Complex: Gateway to MaRIE – office, labs, etc. (beyond conventional facilities)

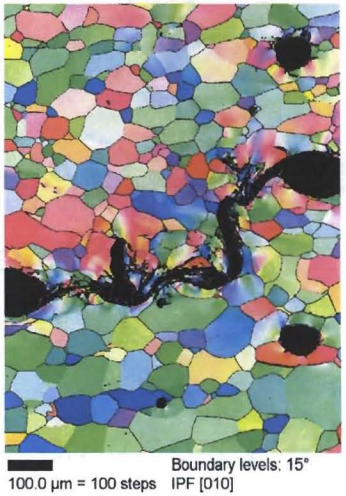
Potential evolutionary additions to the Baseline:

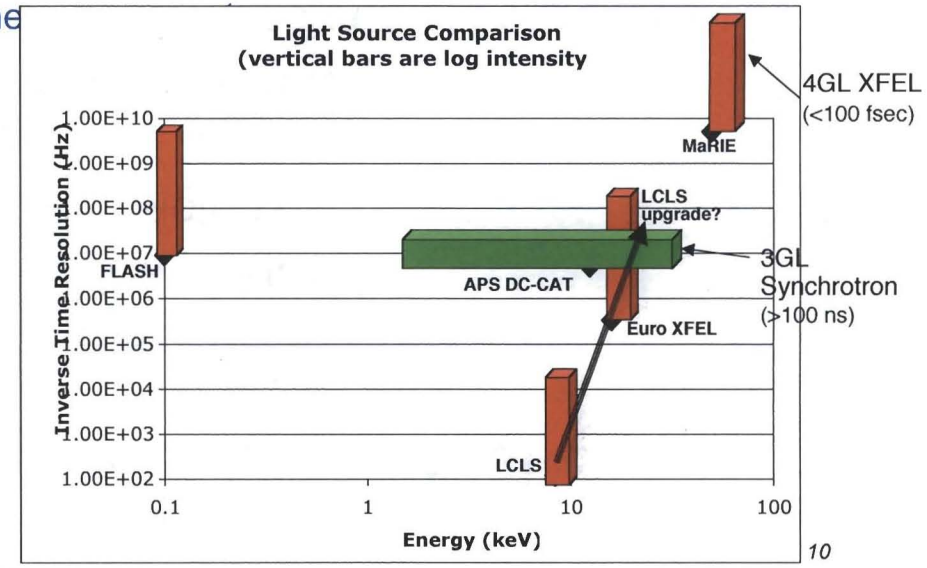
- Alternate scenarios for proton accelerator (SC linac: few GeV, few MW)
- Alternate electron accelerator approaches (laser-based; high gradient)
- Additional undulator to M4

Facility definition must be driven by community-identified performance gaps and functional requirements

Through Multi-Probe Diagnostic Hall, **MaRIE** provides unique scattering and imaging capabilities to bridge the micron gap in extreme environments

- **High-energy (50-115 keV) photon source (for multigranular sample penetration) with high intensity (to resolve transient effects) and high repetition rate (quantitative imaging of dynamic processes)**
  - Baseline plan is 4GL XFEL light source (low duty cycle to reduce cost)
  - Can provide 3-dimensional dynamic structure information
- **Proton microscopy to provide simultaneous measurements to constrain information at many scales**
  - Baseline plan is at 0.8 GeV, with higher current (better time resolution & FFMF drivers) and better optics (for better spatial resolution)
  - Examining possibilities for sufficient current of highe
- **Flexibility in creating material environments (pressure, strain, temperature, ...)**
  - Robust suite of dynamic loading and material heating techniques
- **Couple probes with *in-situ* irradiation and controlled synthesis**
  - ultra-fast/ultra-short *in-situ* microscopies
  - initial synthesis and post-mortem characterization





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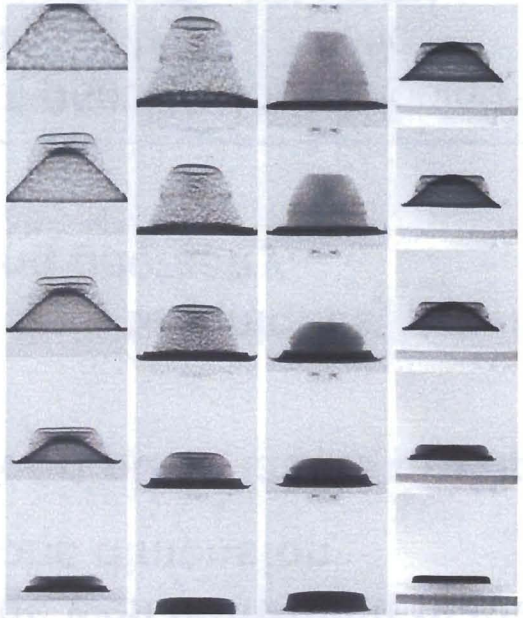
Proton Radiography is a Core LANL Capability for Materials Physics

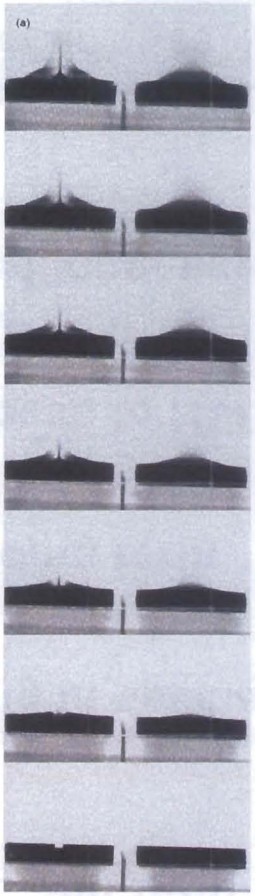
- **Up to 32 frames of Single Experiment**
- **PHELIX Pulsed Power Driver Would Complement the Existing HE Drive**

Planer Spall (D. Holtkamp LANL)

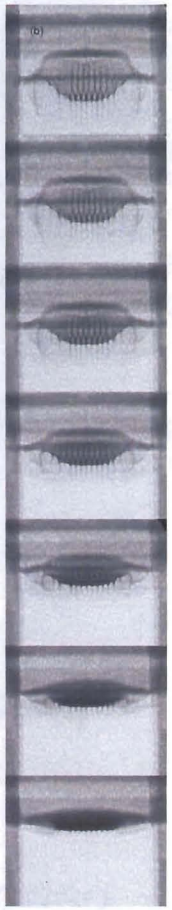


Time

Metal Jet Formation**



RM Instability Growth***



**K. Prestridge (LANL)

***W. Butler (LANL)

Area-C

A robust suite of carefully controlled, dynamic loading and material heating techniques at extreme conditions will be needed for the MPDH

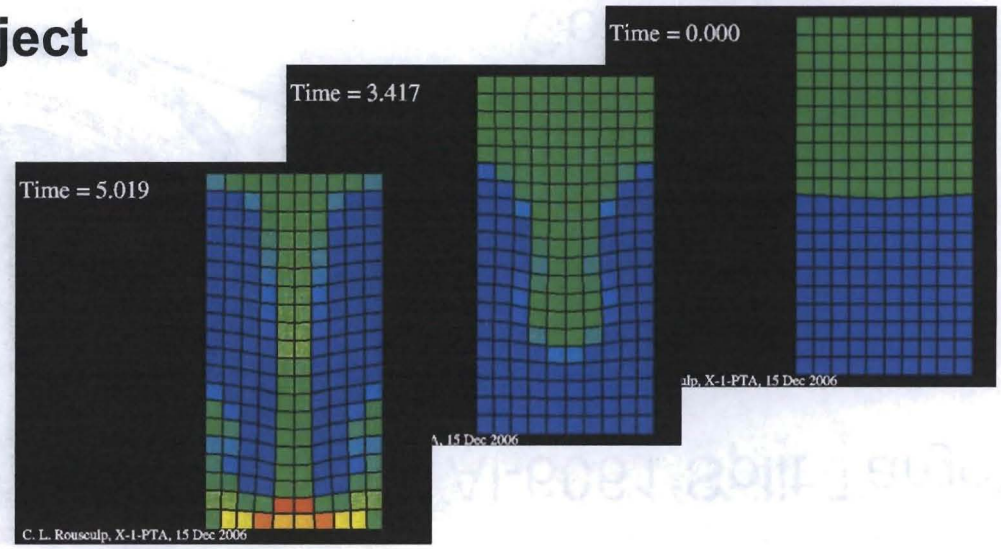
- **Contained High-explosive techniques provide loading in specialized geometries**
- **Gas/Powder guns provide well controlled planer loading form fundamental studies in one dimension**
- **High energy and ultra-short pulse lasers provide access to HEDP regimes**
- **Pulse power, especially liner techniques, provide multidimensional strain fields in converging geometry.**

PHELIX provides proof of principle for imploding liner techniques using today's proton radiography diagnostic

Damaged Surface Hydrodynamics Experiments (DSH) are an ongoing series to address an issue essential to SSP

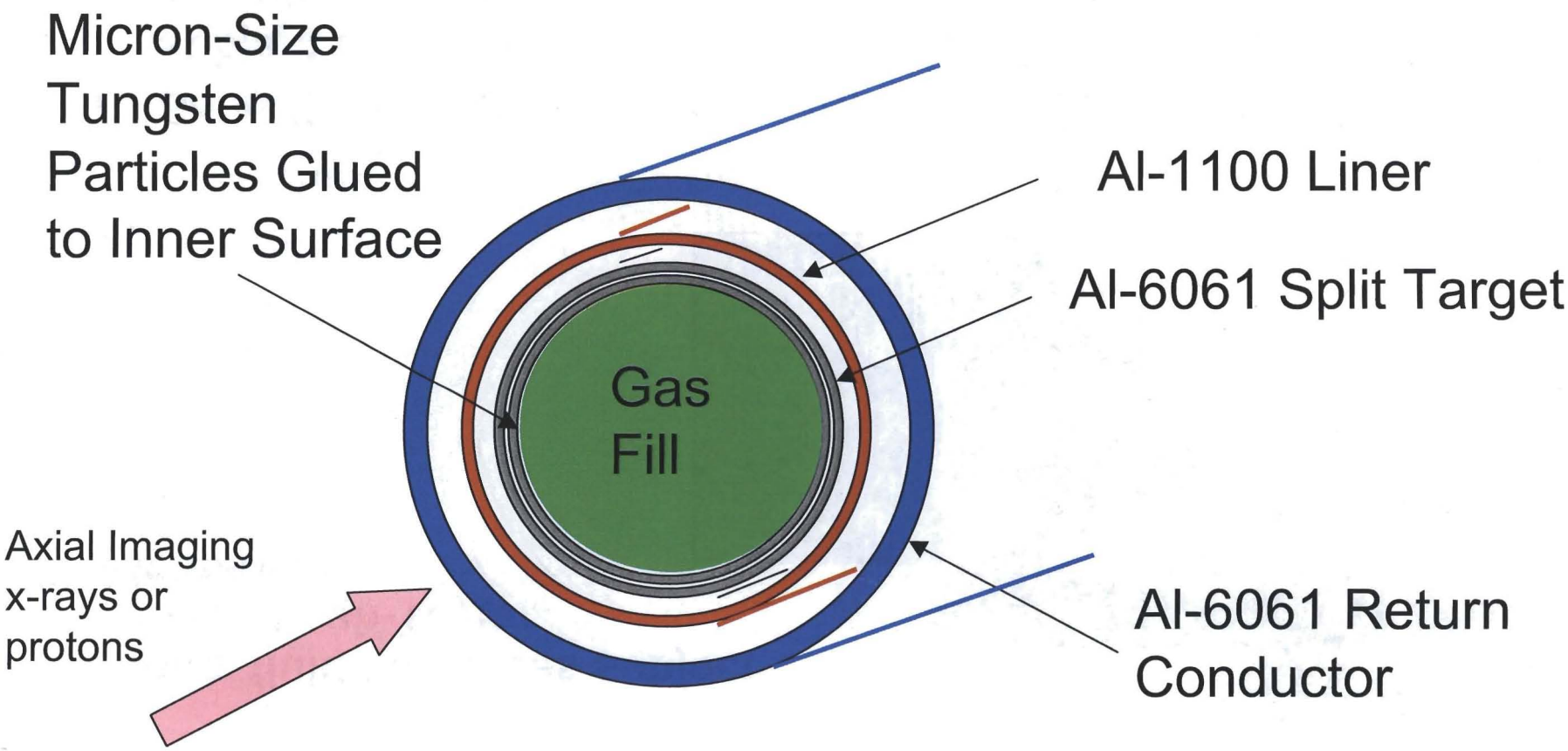
- **Ideal fluid interfaces subject to Rayleigh-Taylor instability**

RT Simulation with LANL ASC Shavano Project FLAG code



- **Solid-fluid interfaces can be non-ideal. They can be subject to damage via spall or ejecta. These lead to complex instability growth and material transport.**

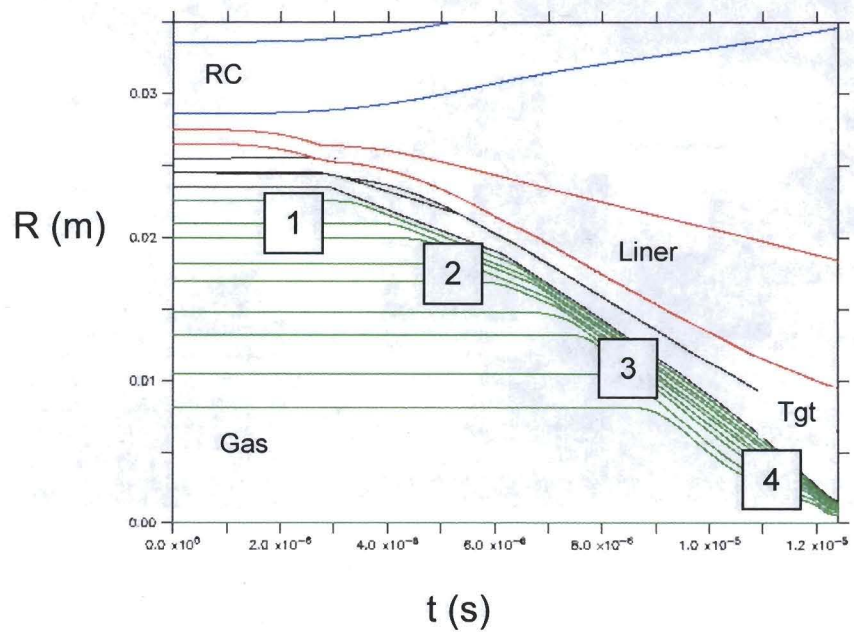
Conceptual DSH Experiment



- **Pre-formed damaged material eliminates the source question**

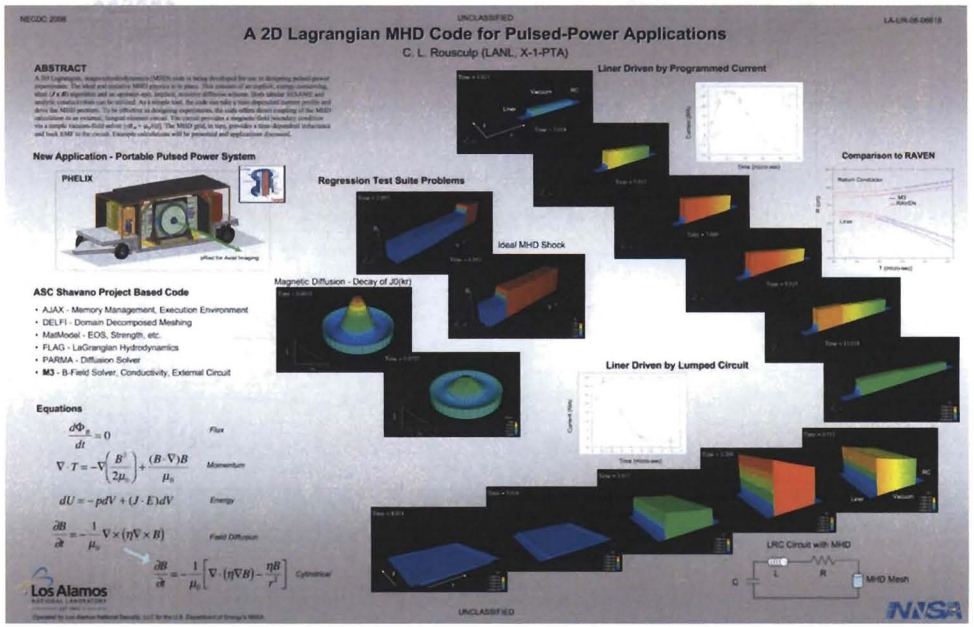
Four Design Criteria for DSH Experiment

1. **Shock impact of liner on target causes release of preformed material**
2. **Coasting of ballistic target**
3. **Recollection of released material**
4. **Stagnation and instability growth**



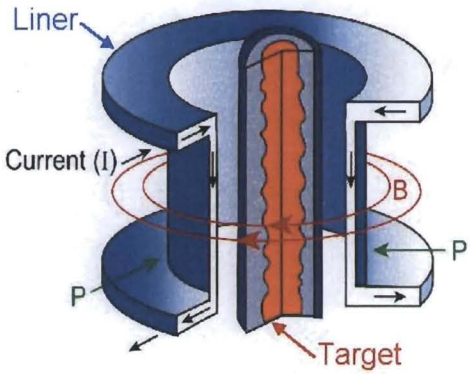
Current Work on DSH is Proceeding

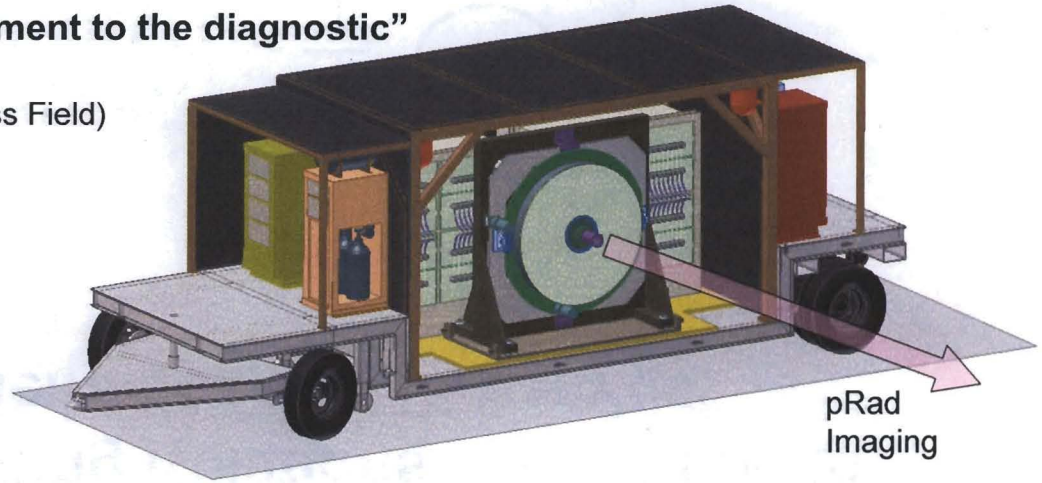
- **Re-Analysis of DSH on ATLAS-NTS from 2006**
- **New Calculations for Comparison to Data**
  - New Ejecta Transport Models (J. Fung et al. at NECDC 2008)
  - MHD Capability (C. L. Rousculp, NECDC 2008) in LANL ASC Shavano Project M3 code in calculations for comparison to data
- **Design of DSH Experiment for PHELIX**



PHELIX - Precision High Energy-density Liner Implosion eXperiments

- **Magnetic Drive Features**
  - Dial-able and Reproducible
  - Fundamentally cylindrical (converging geometry)
  - Liner implosion experiments have high azimuthal precision (< 50 micron / 1 cm)
- **Better diagnostic (pRad) resolution permits smaller drivers and lower energies.**
  - pRad offers possibility of resolving 70 micron features on cm-scale implosions with multi-frame imaging
  - Lower energies implies cheaper source and less collateral damage
  - Cheaper source implies higher data rate - 5-10 shots / year maps a 2-D parameter space in 1-2 years
- **PHELIX is portable - "Take the experiment to the diagnostic"**
  - 0.5 - 1.0 MJ stored energy
  - ~ 10 MAmps peak current (0.1-1.0 MGauss Field)
  - ~ 5 μs rise-time
  - 8 ft x 25 ft footprint fits in Area-C
  - ~ 1- 4 km/s liner velocities

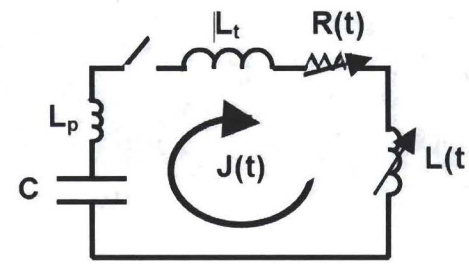




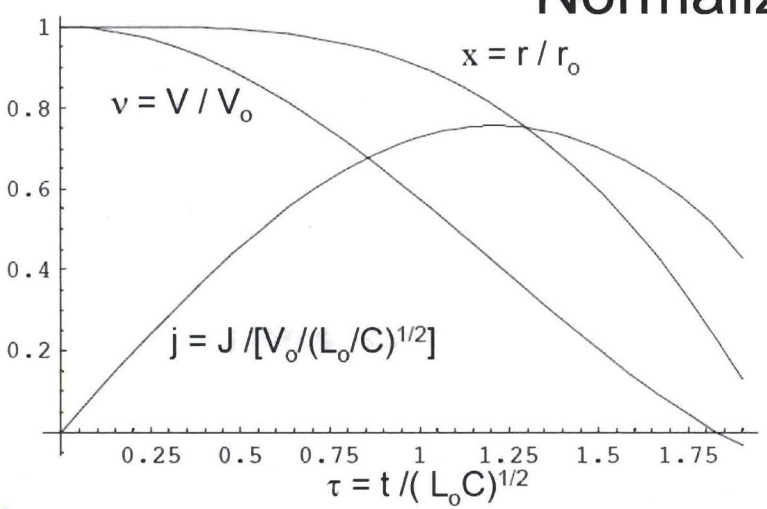
E&M Circuits Provide Scaling Relations that couple to Fluid Scaling through Kinematics and Dynamics*

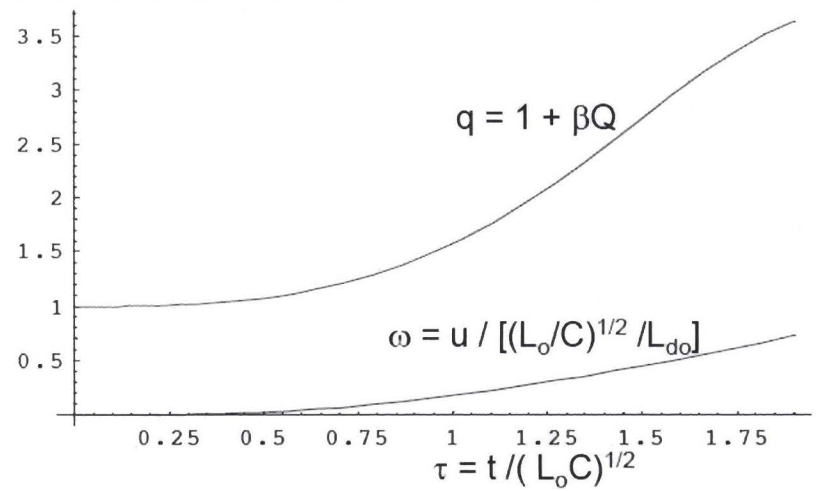
- **5 ODEs**
- **5 - Dimensionless Parameters**
  - Dynamic
  - Inductance
  - Liner Resistance
  - Circuit Resistance
  - Liner Heating

LRC (Z, Shiva-Star, Atlas)



Normalized Solutions



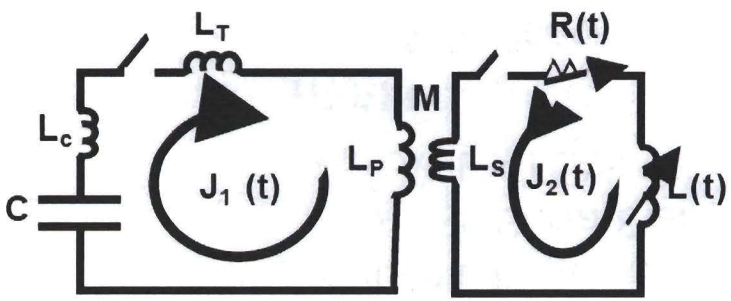


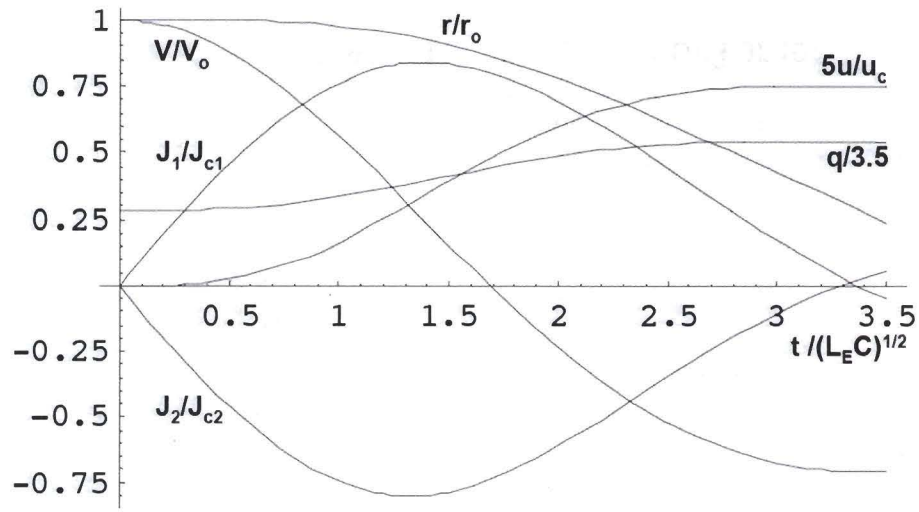
* P. J. Turchi, IEEE Trans. Plasma Sci., Oct 2006

Normalized Solutions for Current Step-Up Transformer

- **Use of transformer-coupling allows increased budget for parasitic inductance on the primary side and reduces the stored energy to < 700 kJ**

Transformer (PHELIX)



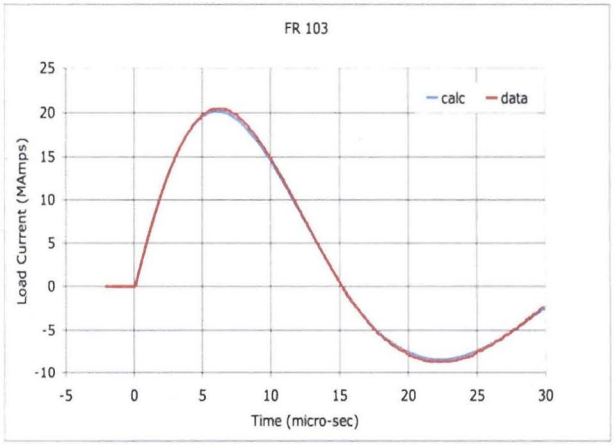


Normalized solutions for transformer-drive vs normalized time. Half-radius is reached at t = 2.9 (t = 7.7 ms) at which point the liner speed is 3.9 km/s.

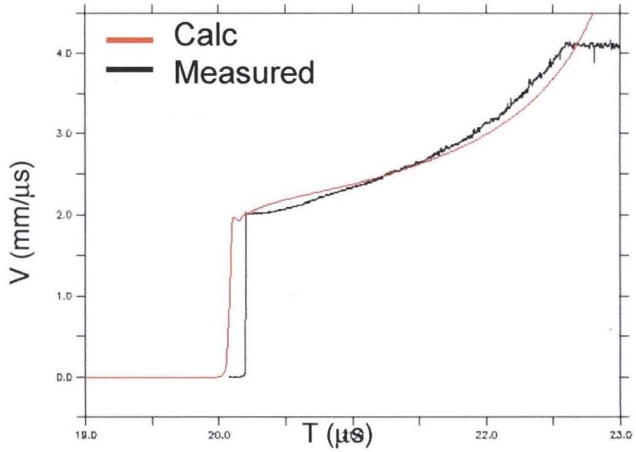
RAVEN Has Been Used Successfully to Model Capacitor and HE Pulsed Power Systems

- **Capactively Driven**
  - LANL Pegasus
  - AFRL Shiva-Star
  - LANL ATLAS
- **HEPP**
  - LANL Ranchero
  - RHSR
  - R-Damage
- **Transformer**
  - PHELIX

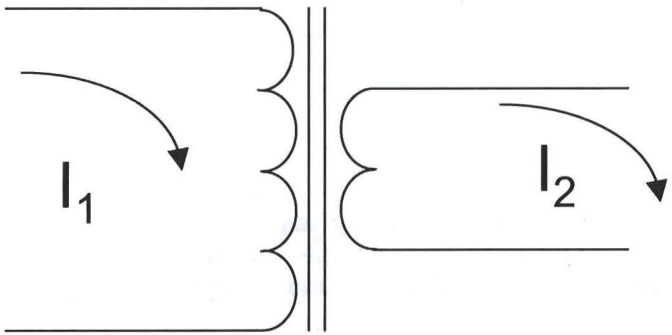
ATLAS FR 103 - Faraday



VISAR of Free Surface of Target



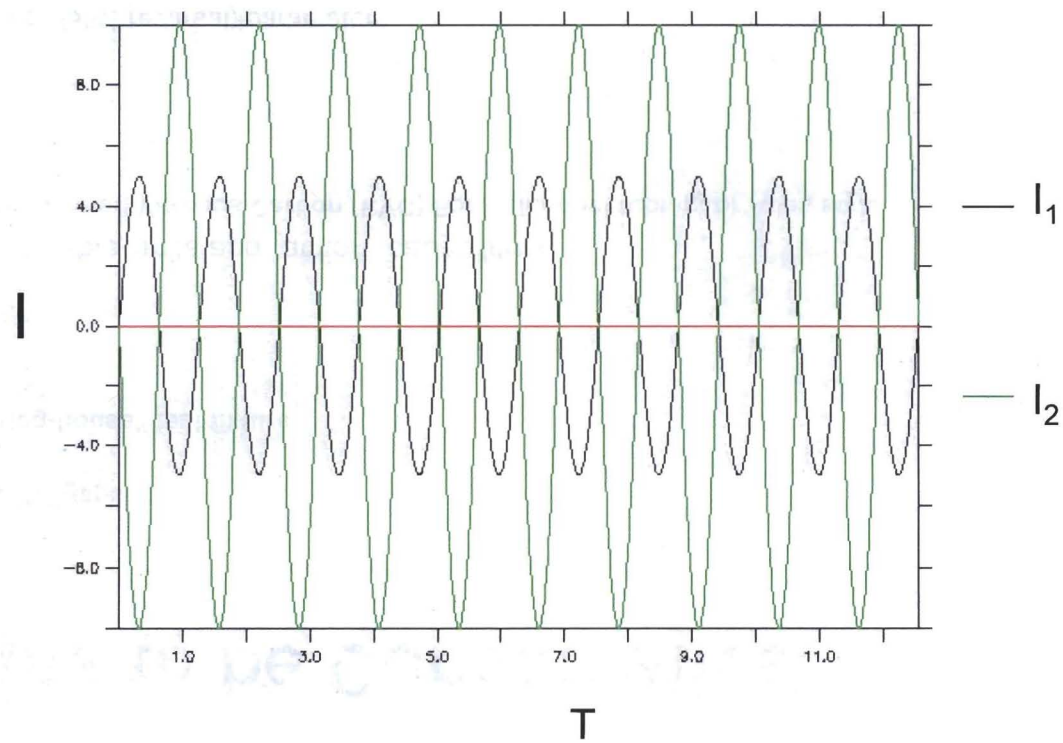
RAVEN Transformer Model Verification



$$\frac{N_1}{N_2} = \frac{2}{1}$$

$$k = 1$$

$$\boxed{\frac{I_1}{I_2} = \frac{5}{10} = \frac{N_2}{N_1}}$$

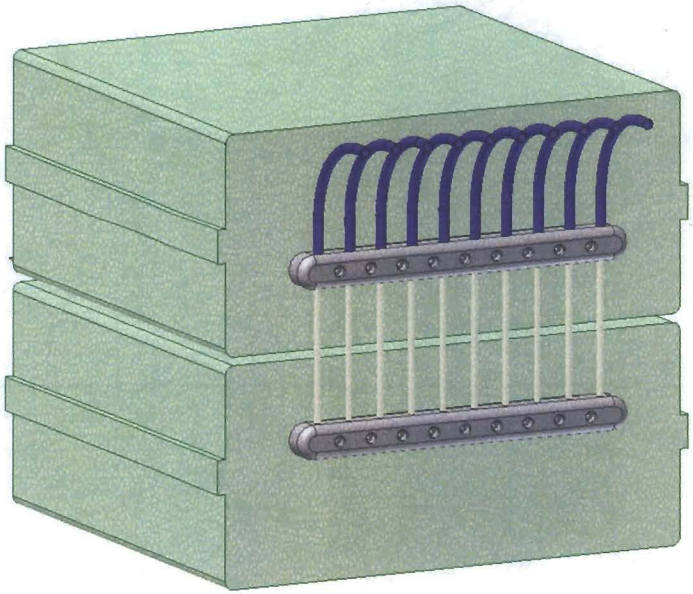


Pulse Power Designs to be Conservative

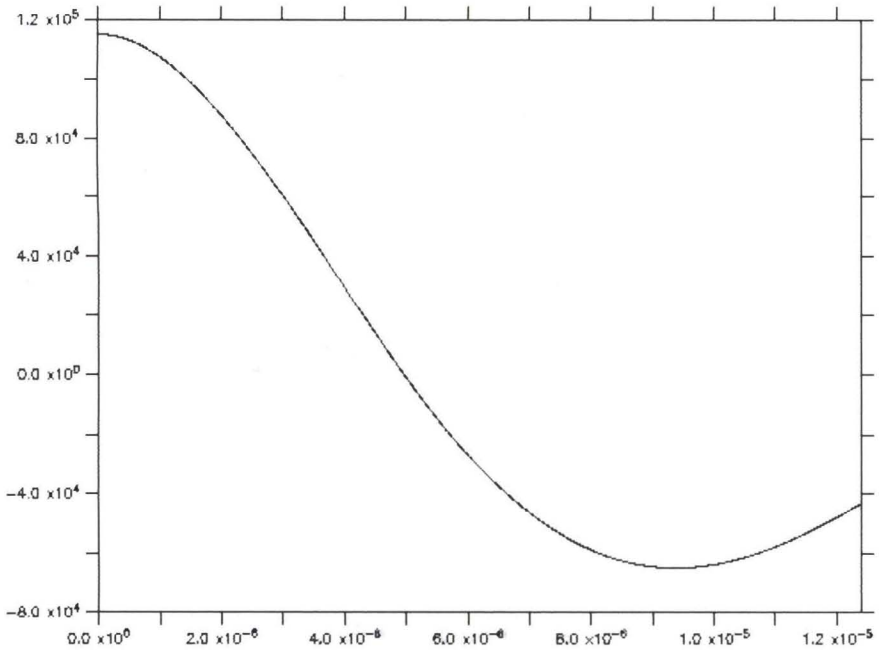
- **System to use proven Atlas Capacitors and Railgaps**
  - Resistive damping to limit fault currents
- **120 kV operation in air as proven in Atlas "dog-house" test fixture**
  - Many thousands (50,000) of successful shots
- **System to interconnect with RG-217 cable**
  - Proven performance at 130 kV test voltage
  - All experts agree cable can handle current
    - Building test fixture to evaluate cable limits and "action" capabilities
- **Bank damping resistance (6 mΩ) can use Reticulated Vitreous Carbon (RVC) Foam, Inconel tubing, or Atlas style "wrinkle" resistors.**
- **RVC tested during ATLAS program**
  - 850 kA, 17 kA / cm2
  - 120 kV, 130 J/cc
- **Capacitor Lifetime ~500 Shots with "8 module" (55% reversal) parameters**
  - Determined by capacitor vendor using Atlas data
  - Initial Atlas Design was 1000 shots

Charging

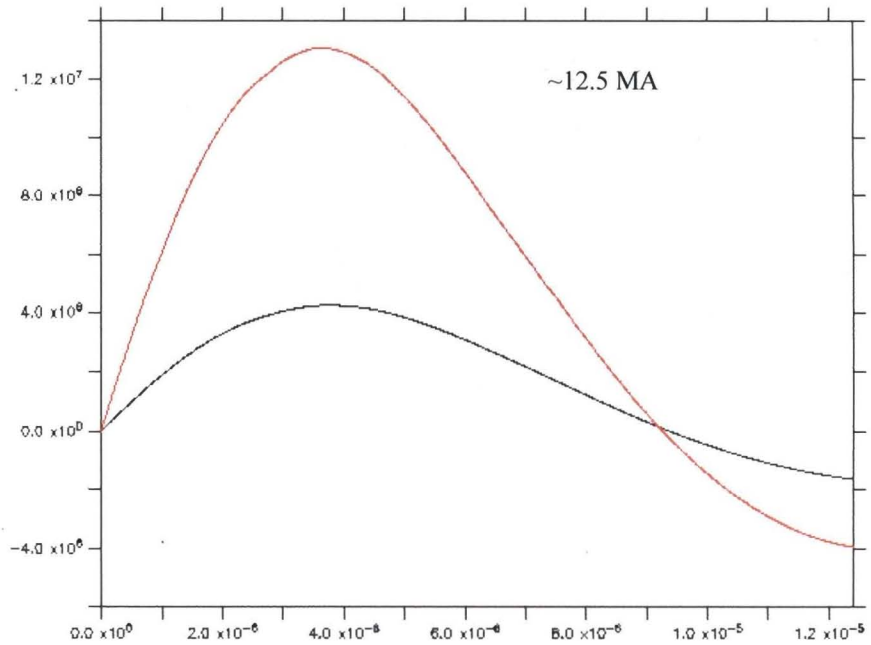
- **Commercial 65kV, 12 kJ/s charging supplies**
  - Individual supply for "+" and "-" capacitors
  - Charge time ~30 Seconds
- **RFI/EMI line filters on 480V, 3Φ power feeds**
- **Fiber optic interfaces**
- **Control via remote control rack**



8 Module Model Results Indicated Physics Results Achieved with Adequate Damping



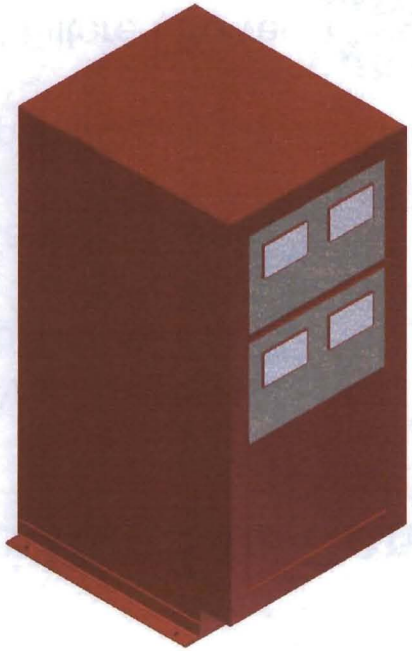
Bank Voltage (~55% reversal)



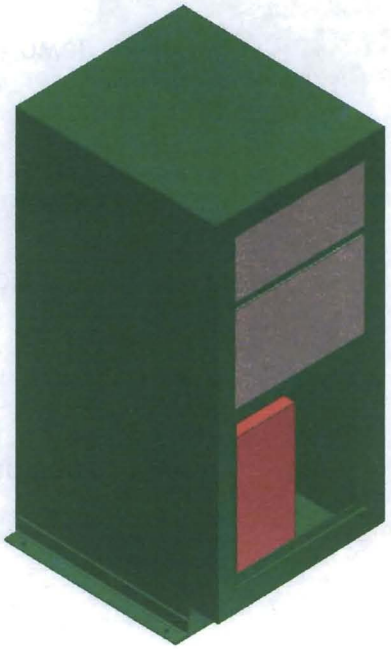
Primary and Secondary Current (MA)
500 kA module current, 50 kA cable

Charging and Trigger Racks

- Commercial Cap Chargers
- <60 Second Charge Time
- Fiber Optic I/O
- Protect Networks in Rack
- Additional EMI/RFI Filtering

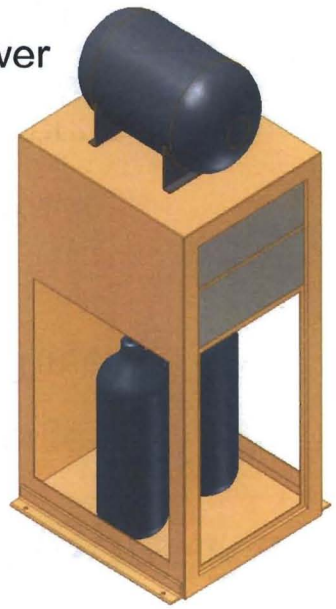


- Trigger units available
- Spare parts are available
- Fiber Optic I/O
  - triggers
  - "ready"
- FFI/EMI Filtered and Isolated Power

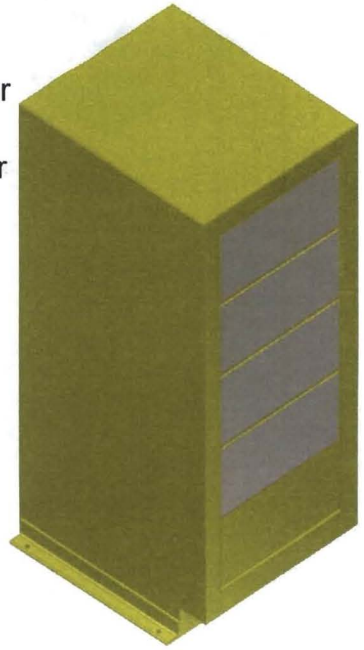


Gas and Remote-Control Rack

- Poppet Valves for Fast Response Time
- Surge Tank for Purge
- Fiber Optic I/O
- EMI/RFI Filtered Power

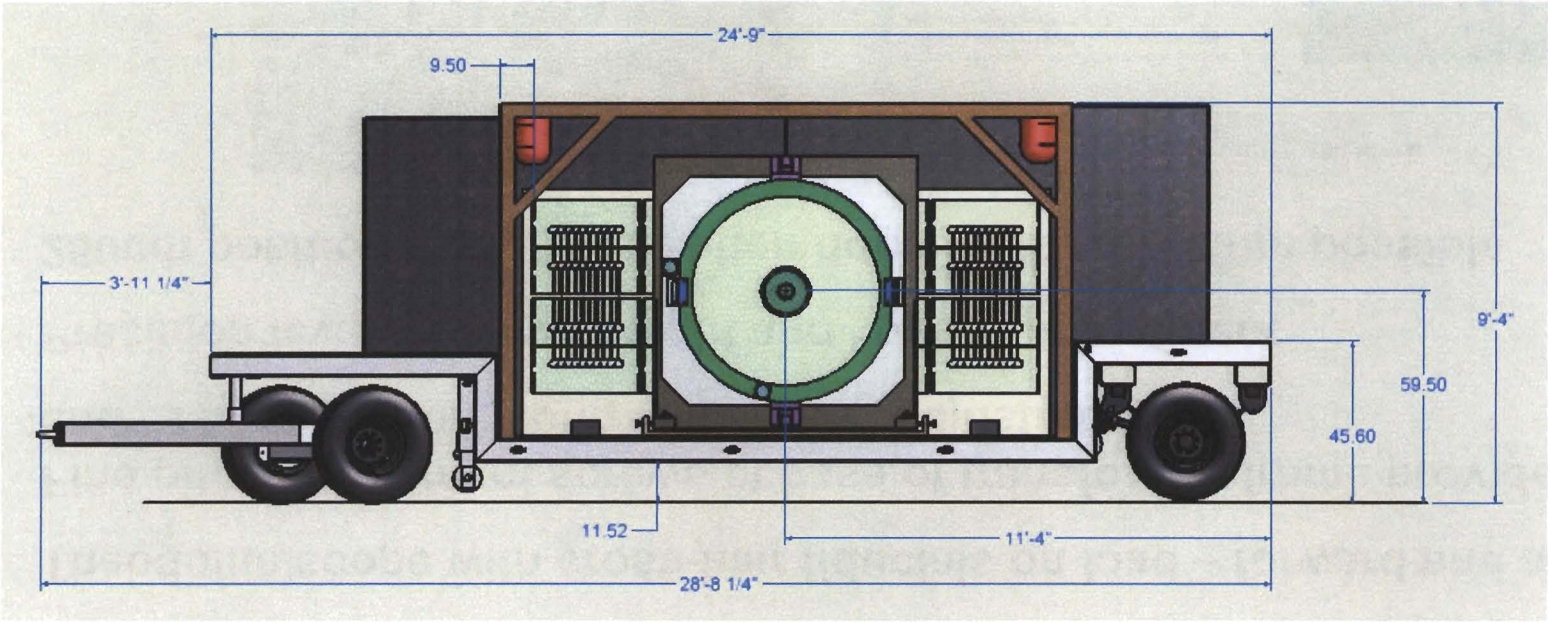


- Located with an additional Partition
  - "double shielded"
- All I/O for Timing
- All I/O for Handshake Protocols
- I/O for Personnel Protection Interlocks
- I/O for Equipment Interlocks
- Filtered and Isolated Control Power
- Additional Rack Space Available for Other Dedicated Systems



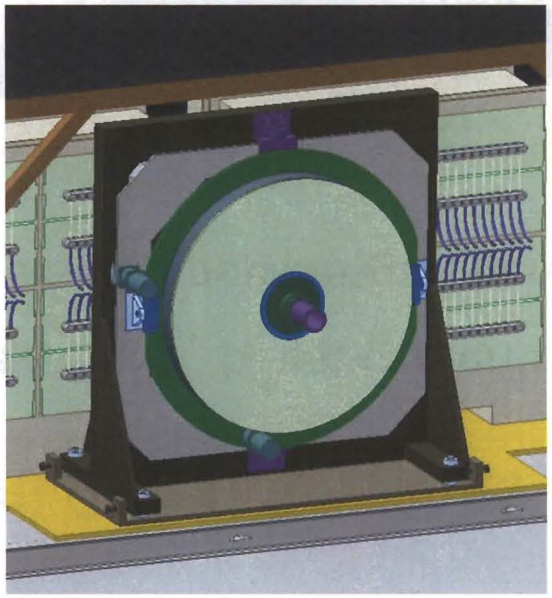
Mechanical Considerations

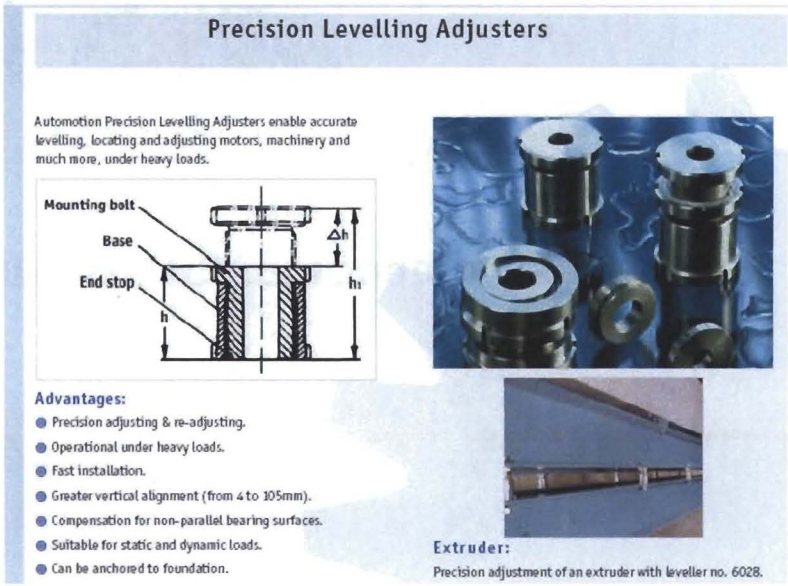
- **Maintained 59.50" beam centerline**
- **Need to relocate powder gun hardware to accommodate trailer length**



Alignment – coarse positional

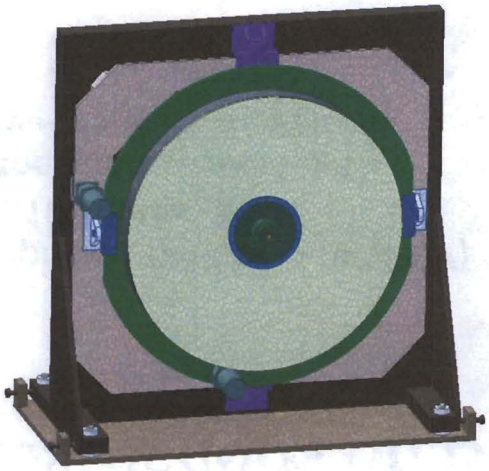
- Theodolite/scope with cross-hair fiducials on load – forward and aft
- Fine pitch adjustment screws at base of transformer frame provide "X" and "Y" translation along with "yaw" adjustment
- Precision levelers allow height and "pitch" adjustment
- 250um positional alignment often done at P-rad, 125um possible

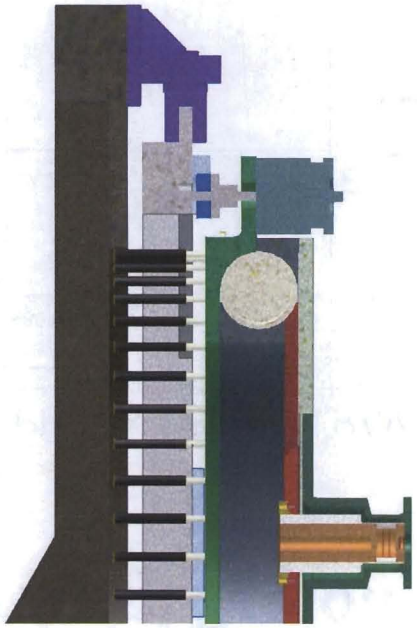




Alignment – precision axial

- Transformer supported on gimbal – two axis independent pivots
- Pivot points – spring loaded with precision bearings
- Push-Pull adjusters - 50:1 zero back lash gear box and precision ball lead screw
- Can be manual or stepper motor driven
- Stepper motors allow remote adjustment



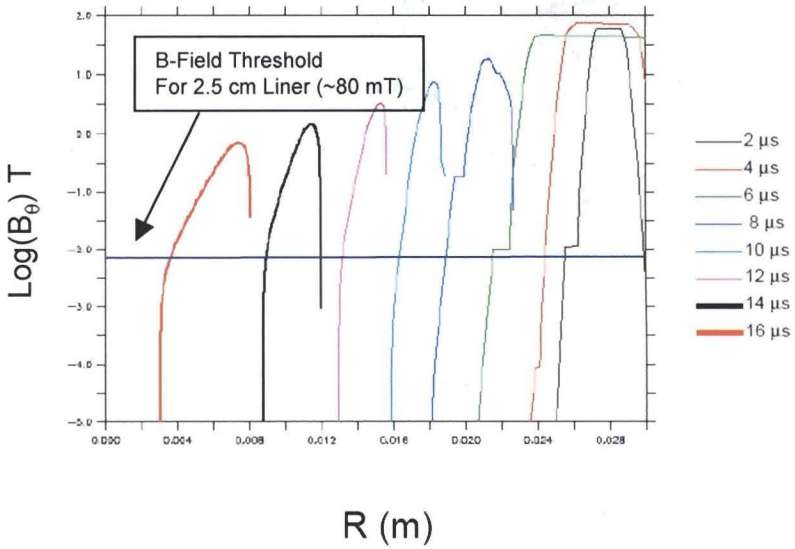


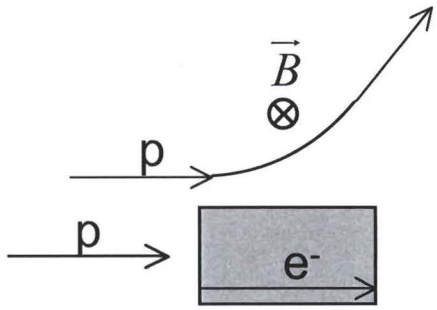
There are 2 Restrictions on B-Fields and Axial Proton Radiography

- **B-Field within the proton field of view (FOV) must be less than 10^{-4} meter-Tesla, integrated along the proton beam path. Calculations show ~ 1 cm diam. FOV for PHELIX-DSH.**

- **Electron flow within the liner/target must be the same direction as the proton beam direction. This ensures that peripheral protons will be deflected outside of the FOV.**

B-Field Profiles for PHELIX-DSH from RAVEN





Cylinder

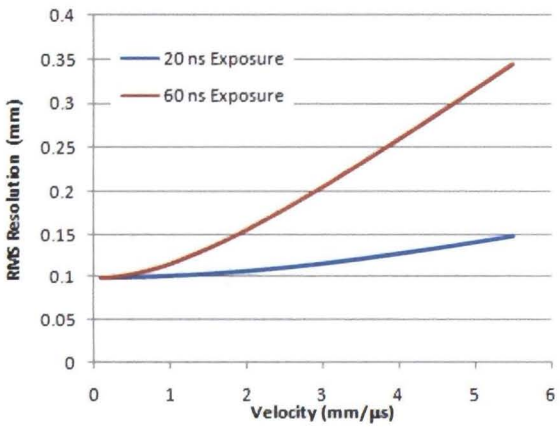
Proton Radiographic Sensitivity

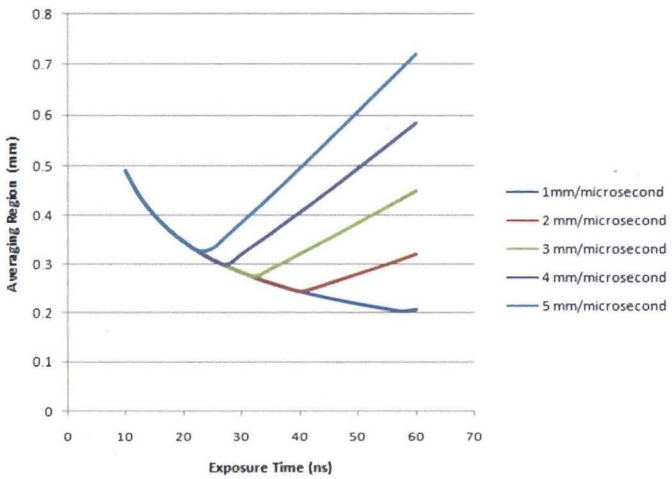
- **Material Assumptions**
  - 2 x 1/4" Al Target Windows
  - 2 x 1/8" Al Containment Windows
  - 2 x 1/8" Glass Containment Windows
  - 2 x 1/8" Plexiglass Surrounding Cylinder
  - 2 cm long target of Tungsten
- **Beam/Detector Assumptions**
  - 7.5 mRad Collimator
  - 2 cm x 2 cm FOV
  - 0.2 mm "pixel" size
  - DQE 30% (conservative)
  - S/N = 4

Sensitivity for a Given Exposure

Exposure Time (ns)	Protons (No. x 10^9)	ρ (mg/cm^3)	Area Density (mg/cm2)
20	1.2	75	150
60	3	45	90

Spatial-Temporal Resolution and Motion Blur





- **Competing Effects**
  - Motion blur will result in an effective spatial average
  - Reduced exposure will require an average over a larger spatial region to be sensitive to 100 mg/cm^2
  - Optimize exposure time to minimize the spatial region averaged over at the most interesting velocity
- **This needs to be optimized to meet the goals of each experiment, but is most likely between 20 ns and 60 ns exposure times**

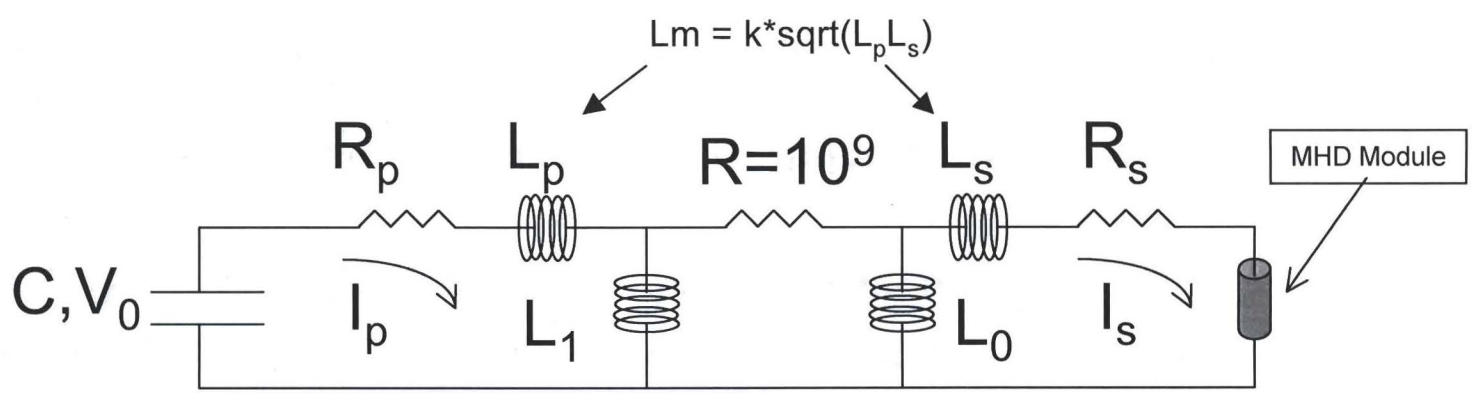
C1 FY09 - Conduct one PHELIX full-system experiment outside of pRad utilizing a fabricated load

- Complete engineering design, fabrication and testing of the pulsed power system including mechanical systems, Marx assemblies, charging system, trigger systems, gas-handling system, control system, and safety/shielding system.
- Complete detailed conceptual design, engineering design, and fabrication of PHELIX transformer assembly. Integrate the transformer with the pulsed power system.
- Design and fabricate assembly for static or dynamic load.
- Provide rudimentary PHELIX machine and load current diagnostics
- Design and fabricate assembly for static or dynamic load.
- Provide 1D computational model and calculations of the pulsed power and test-load to compare with system test.

-- Move PHELIX to pRad in FY10 --

PHELIX-I Circuit Model - Summary

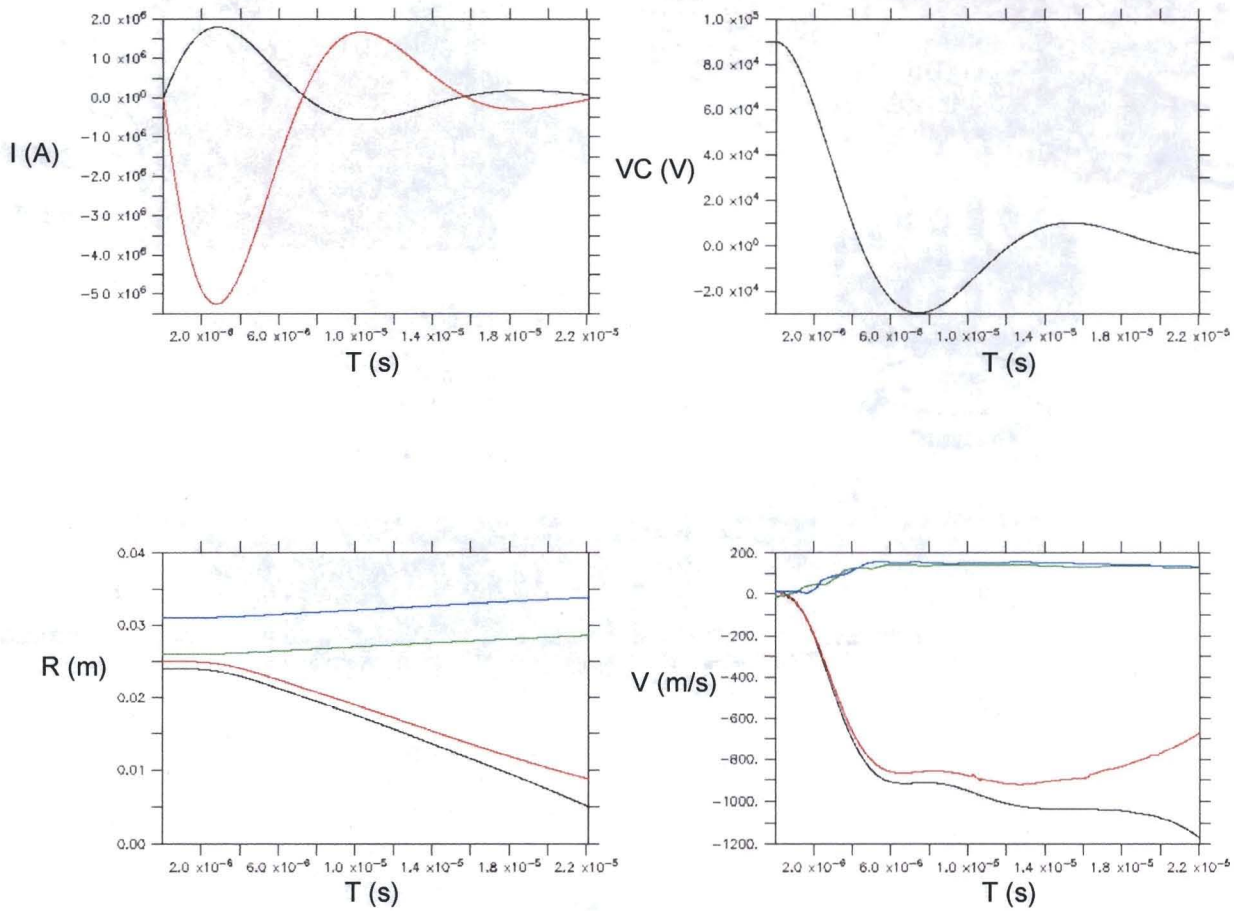
	4 Modules	Comments
V0 (kV)	50-100	
C (μF)	68.0	
Rp (mΩ)	0.12	
Lp (nH)	129.6	
L1 (nH)	33.25	Bank + 40 Cables
L0 (nH)	1.02	Plate + Standoff
Ls (nH)	8.97	
Lm (nH)	30.7	
Rs (mΩ)	0.10	



PHELIX-I Dynamic Load Calculation

	4 Modules
V0 (kV)	90
C (μF)	68.0
Rp (mΩ)	20.0
Lp (nH)	129.6
L1 (nH)	33.25
L0 (nH)	1.02
Ls (nH)	8.97
Lm (nH)	30.7
Rs (mΩ)	0.10

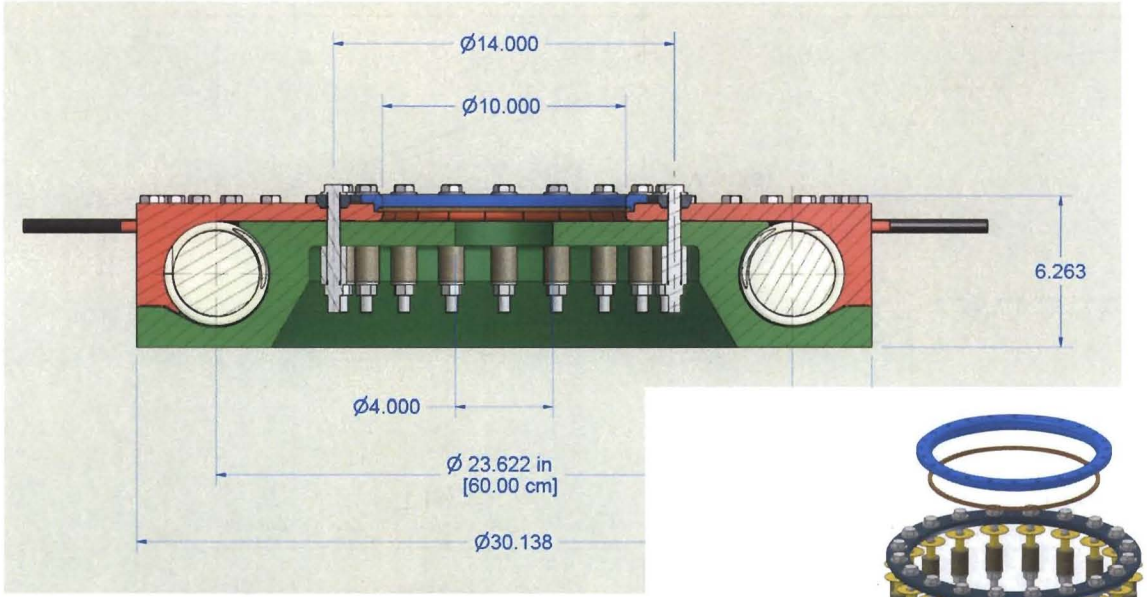
Length (cm)	2.0
R0 (cm)	2.5
Liner thick (cm)	0.1
Gap thick (cm)	0.1
RC thick (cm)	0.5

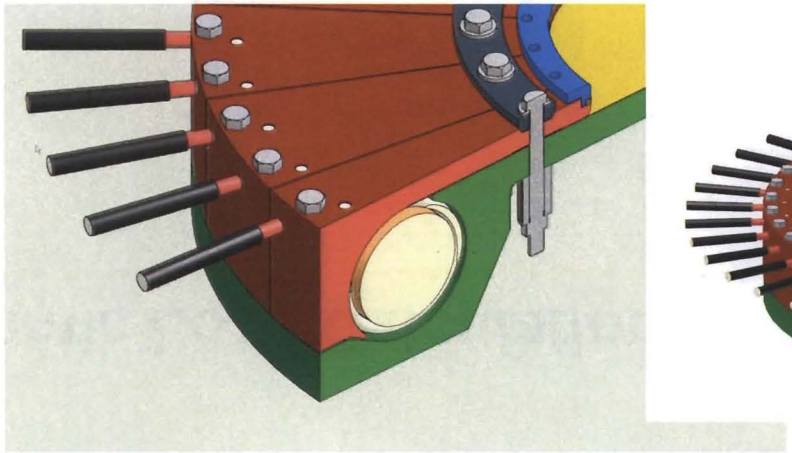


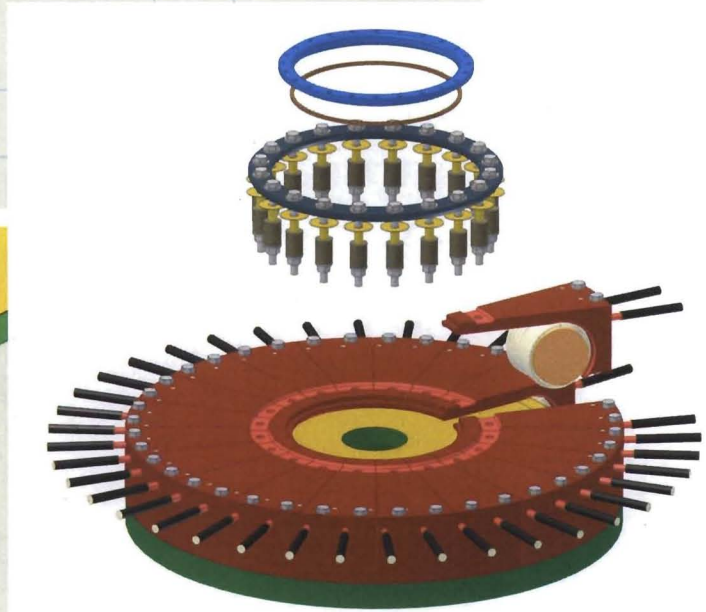
* Liner maintained 90% integrity throughout trajectory

PHELIX-I Toroidal Transformer Design

- Coupling Coefficient K ~ 0.9
- 20 Modular Sections for ease of construction
- R_{maj} = 30 cm
- R_{min} = 10 cm
- Winding Ratio - 4:1
- Primary - 40 - RG-217 coax
- Secondary - Solid Al 6061-T6







Conclusions

- **PHELIX is a portable, multi-Mamp, pulsed-power machine being developed at LANL to be used with proton radiography**
- **The transformer coupling reduces parasitic inductance and allows for scaled hydrodynamics experiments for high-resolution diagnostics**
- **The Damaged Surface Hydrodynamics (DSH) series of experiments are continuing to be studied and will be the first to utilize PHELIX with pRad**
- **PHELIX is well aligned with goals of the proposed LANL signature facility MaRIE**
  - Bridge the micron gap
  - The transition from "observation & validation" to "prediction & control" is a central mission challenge

Future - Possible LANL/SNL Collaborations

- **Near Term**
  - Membership on PHELIX design review committees
  - Monthly consultation at PHELIX design team meetings
  - Electro-mechanical FEA of the PHELIX transformer (e.g FLUX3D)
  - Theory and modeling of DSH on PHELIX
  - Intelligent interface of PHELIX with pRad
- **Far Term**
  - Design and construction of PHELIX-II (at pRad and MaRIE)
  - Enhancement of supporting diagnostics (high-resolution xray radiography)
  - Design of new diagnostics (Bridge the micron gap)
  - Design, construction, execution of experiments for PHELIX (Explore Transformational Materials)