EAGLE HARBOR TECHNOLOGIES

# High Voltage Pulse Generator for High-Energy Beam Kickers

**Dr. James Prager**

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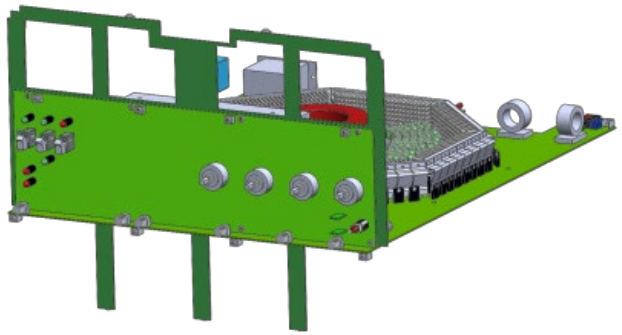
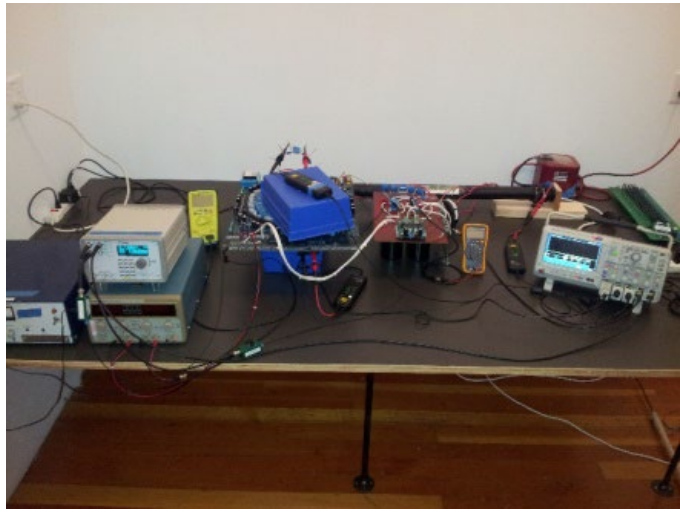
Sponsored by the Department of Energy Office of Science, Office of Nuclear Physics

# Eagle Harbor Technologies, Inc.

EHT develops innovative pulsed power solutions to enable new science and engineering capabilities for a wide range of plasma and electromagnetic applications.

We specialize in rapid prototyping and product development of solid-state, high-frequency, repetitive pulsed power.



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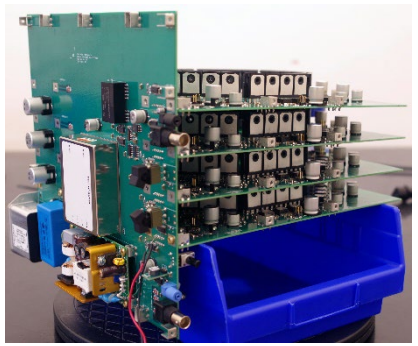
# Company Background

**Quick Facts**

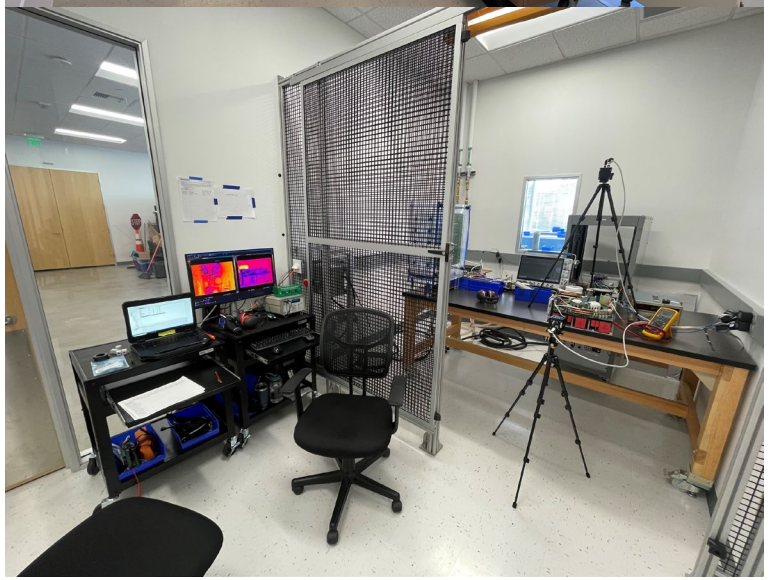
- Founded 2005
- Founders: background in plasma physics & power systems from University of Washington
- 40 employees
- Initial SBIRs - DOE, FES
- SBIRs to develop and commercialized IP
- Strong IP protection: >175 patents/applications

| R&D (20%) | Commercial (30%) | Semiconductor (50%) |
|---|---|---|
| • SBIR – DOD, NASA, DOE<br>• IR&D | • Custom systems<br>• Products | • Power systems<br>• Plasma processing |



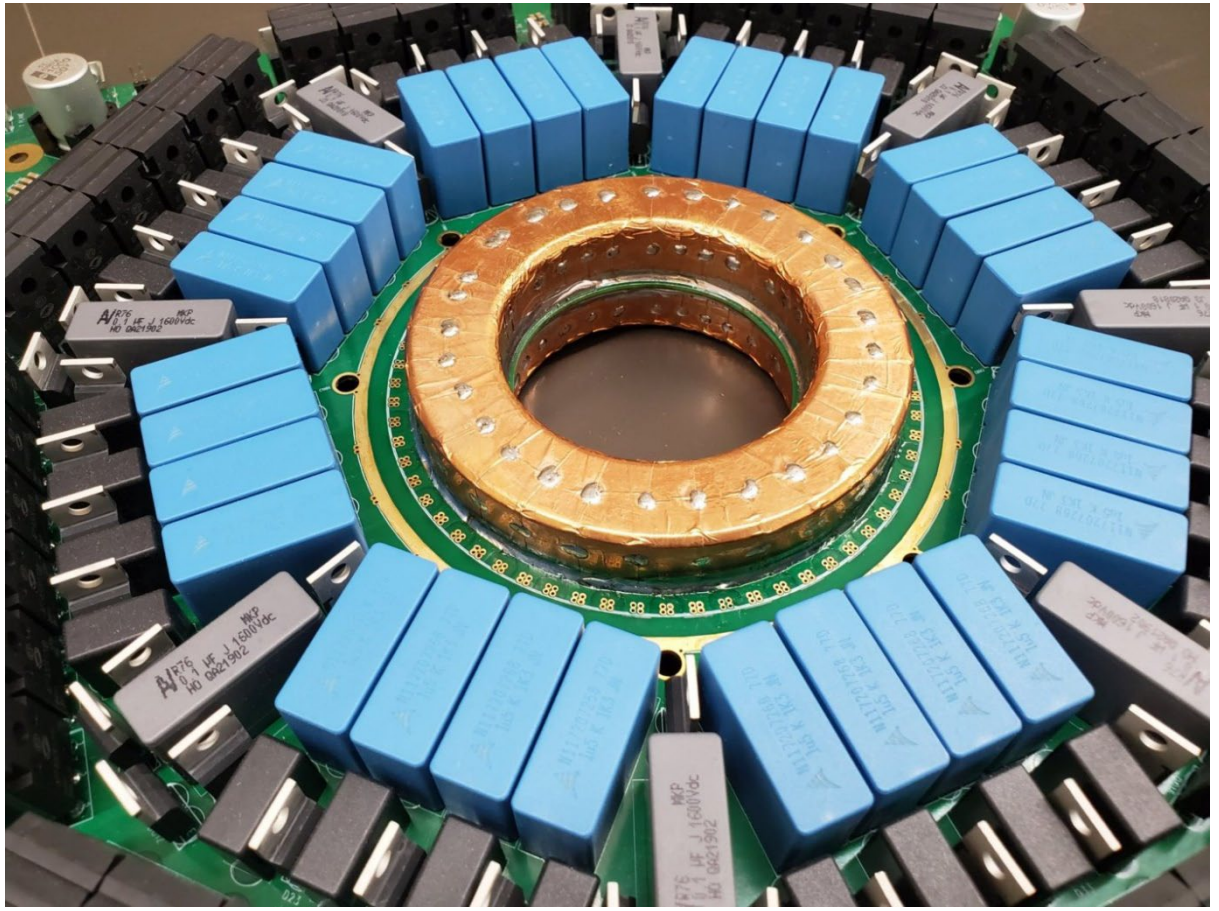
# New Facility (July 2023)

- 35,000 ft$^2$ facility in downtown Seattle
- Electronics fabrication
- High voltage testing rooms
  - GHz scale current & voltage probes, scopes
  - Water cooling for high average power
  - Thermal cameras
  - Fully gated and remote control for HV safety
- Vacuum systems
  - Capacitively coupled plasma for semiconductor research
  - Megawatt-class helicon/inductive plasma source
  - Small test chamber (e-beam, jets, etc.)
- Machine shop (metal, wood, 3D…)



# EHT Core Technologies

- Massive parallelization of discrete semiconductor components
  - Geometric layouts based on experience in pulsed power and informed by fundamental physics
  - Unique gate drive design allows for faster switching and improved efficiency
- PCB-integrated transformer
  - Unique design minimizes stray inductance and stray capacitance
  - Allows an adjustable step-up ratio to achieve high voltage output
- Core technology works with IGBTs, SiC MOSFETs, and GaN HEMTs



# EHT Solid-State Power Systems

**Output waveforms, power system, and load are intimately tied together. EHT designs systems to deliver the desired waveform to the user's load.**

- Designed for resistive, capacitive, inductive, & plasma loads
- Allows precision waveform control on fast timescales
  - Fast rise/fall times (nanoseconds)
  - Adjustable pulse width
  - Bipolar pulses with short dead time (< 20 ns)
  - High pulse repetition frequency (100s kHz)
- High voltage outputs (up to 10s kV)
- Wide range of output currents (mA to kA)
- Power: 0-50 kW (average); 10s MW (peak)
- Integrated control systems (FPGA, microcontroller, industrial protocols…)

# Where do EHT Power Systems Go?

## Manufacturing

- Additive manufacturing
- Advanced welding
- Insulation testing
- **Semiconductor processing**
- Surface prep/cleaning
- UV/EUV production

## Medical

- **CAR-T Cell Therapy (Cancer)**
- **Cardiac ablation**
- **Electroporation**
- **Soft-tissue ablation (Cancer)**
- Sterilization

## Energy & Science

- In-situ ammonia production
- **Fusion energy science**
- **Low-temperature plasma research**
- Particle accelerators
- Water decontamination

## Defense/Aerospace

- Combustion
- In-space propulsion
- Active flow control
- Radar systems
- **High-power microwaves**

# Motivation

A new short-pulse stripline kicker is required for the new 150 MeV energy recovery LINAC (ERL) being developed for the Electron Ion Collider, under construction at Brookhaven National Laboratory (BNL). The specifications for the ERL kickers are as follows:

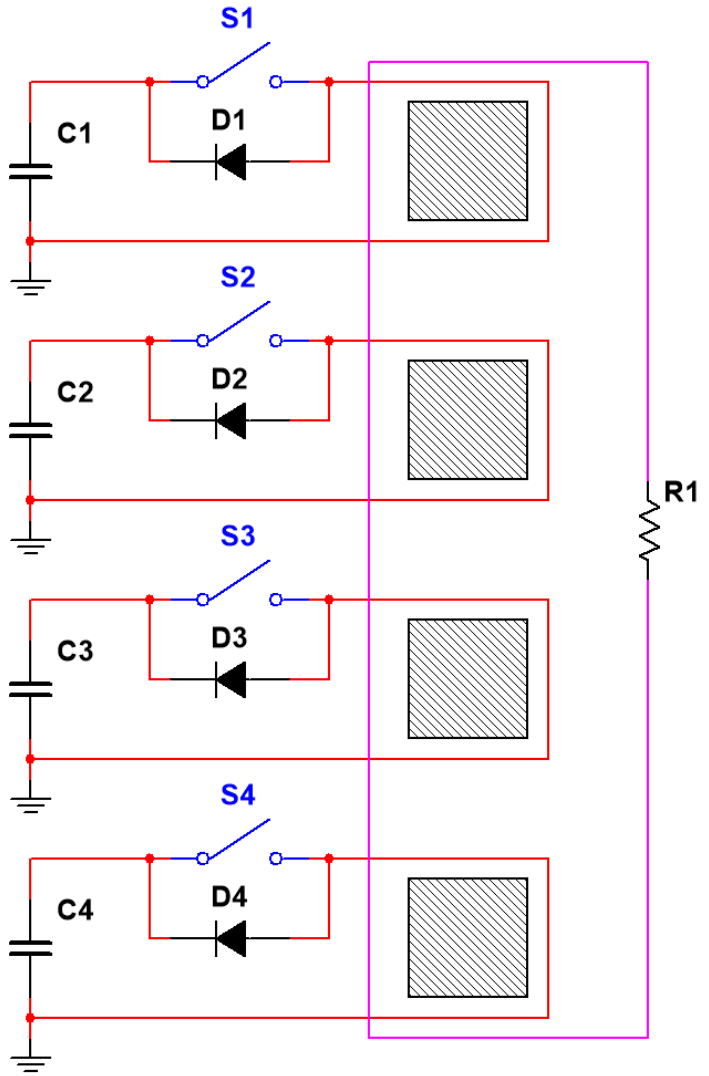
- Output voltage: ±50 kV ±2% for flattop
- Output current: 1 kA
- Load impedance: 50 Ω
- Pulse shape: 6 ns rise, 20 ns flattop, 12 ns fall (entire pulse must be < 38 ns with residual voltage < 1 kV)
- Pulse repetition frequency: 10 Hz (during operation) and 100 Hz (lifetime testing)
- Robust to faults (short/open/noise)
- High reliability: Operate 12 – 20 weeks out of the year (availability 99% or better)
- Jitter < 0.5 ns with respect to external clock

# Inductive (Voltage) Adder

- Each stage: energy storage, solid-state switch, and single-turn transformer primary (with core).
- Single-turn transformer secondary contains cores from all *N* stages.
- Resulting output voltage:

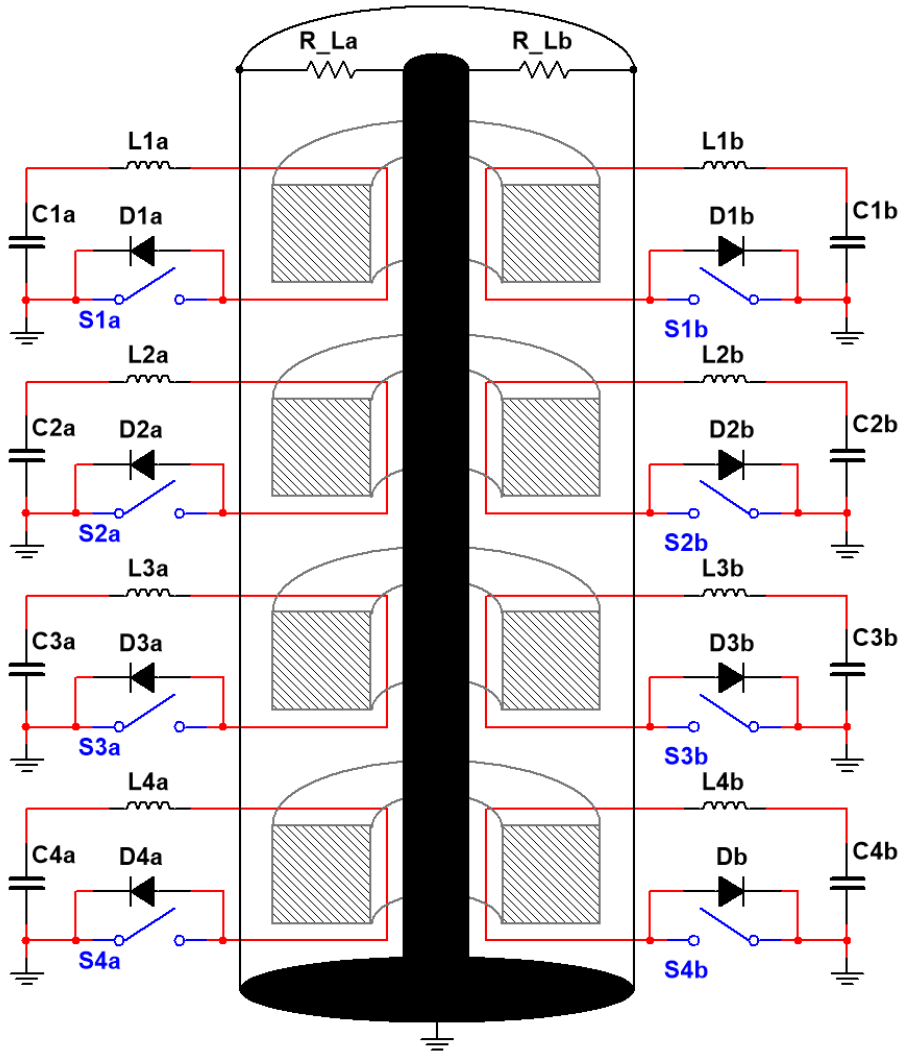
$$V_{out} = N\, V_{primary}$$

- Each stage switches a small fraction of the output voltage but must switch the full current.
- High current requires massively parallelized switching.



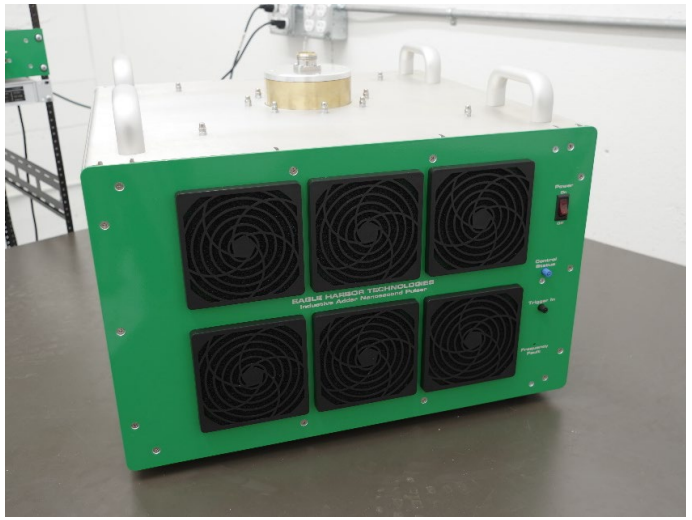
# Inductive Adder Advantages

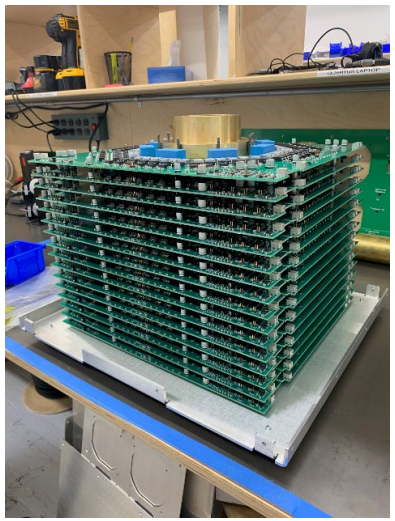
- High voltage is limited to transformer secondary. All circuit components are low voltage.
- Main switching components are ground referenced, which simplifies gate drive, increases robustness, and reduces jitter.
- MOSFETs, IGBTs, and GaN FETs allow for user-adjustable pulse widths.
- Off-the-shelf components are used, which reduces build times and lowers risk.
- Single stage failure does not fail the entire power system.
- System is robust to open loads and short circuit conditions.

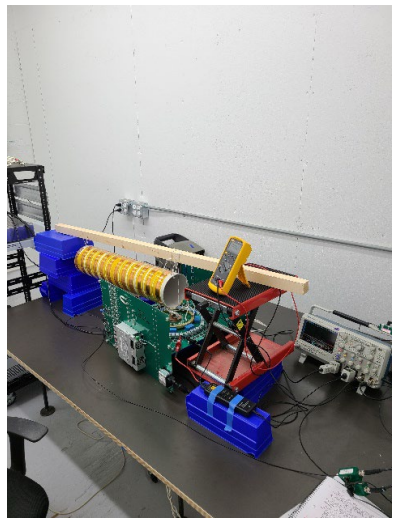


# EHT Inductive Adder Summary

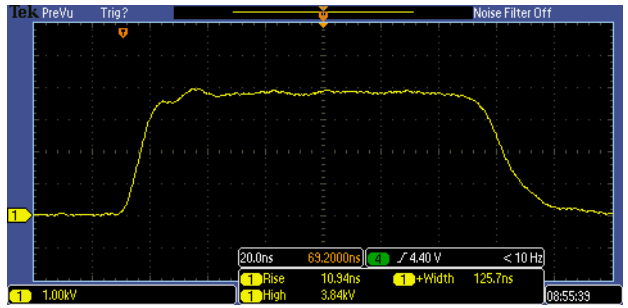
| Customer | Voltage [kV] | Min Load [Ω] | Current [A] | Rise Time [ns] | Min PW FWHM [ns] | PRF [kHz] | Peak Power Density [MW/ft$^3$] |
|---|---|---|---|---|---|---|---|
| **ONR** | 30 | 50 | 600 | 11 | 30 | 25 | 2.7 |
| **UMKC** | 12 | 50 | 240 | 8 | 30 | 11 | 1.2 |
| **Nat. Lab.** | 24 | 25 | 960 | 10 | 30 | 50 | 5.0 |
| **Purdue** | 24 | 25 | 960 | 10 | 30 | 1 | 5.4 |
| **Medical** | 15 | 50 | 300 | 50 | 100 | 1200 | 53.2 |
| **Multi-turn IA with NLTL** | 30 | 50 | 600 | <3 | 150 | - | 25.7 |

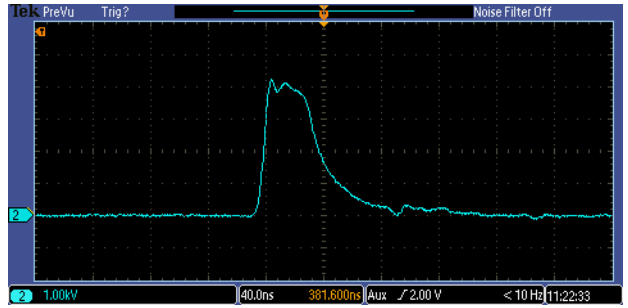




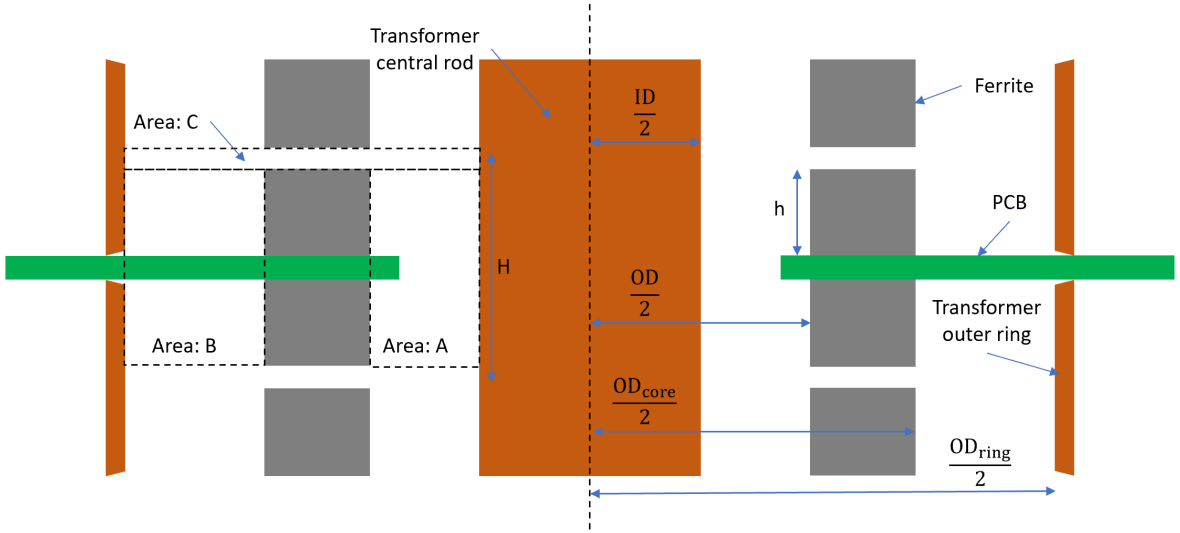


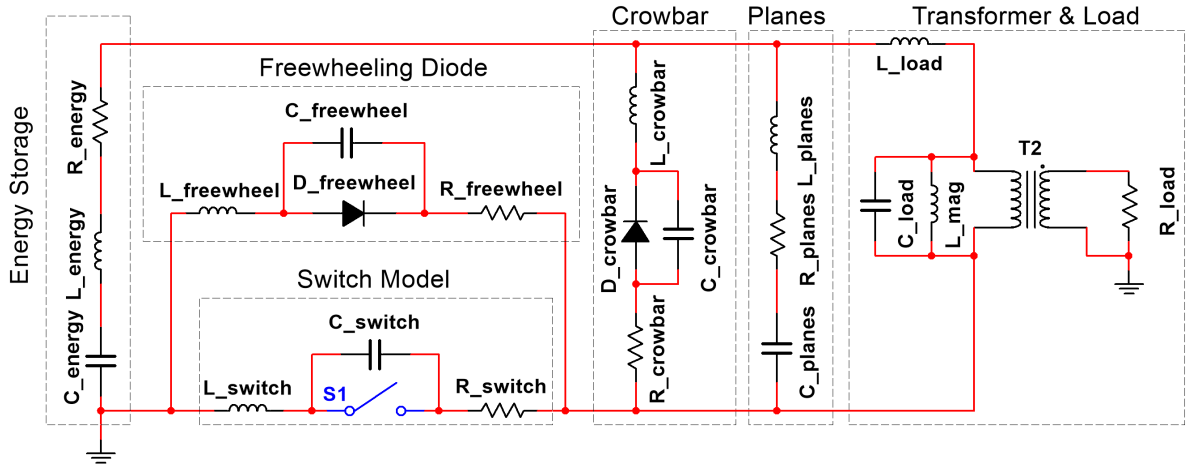
Images (left to right): Purdue IA boxed, Purdue IA unboxed, IA during single-board testing, output voltage (yellow): 30 kV, 100 ns, into 50 Ω output voltage (blue): 24 kV, 40 ns, into 50 Ω.

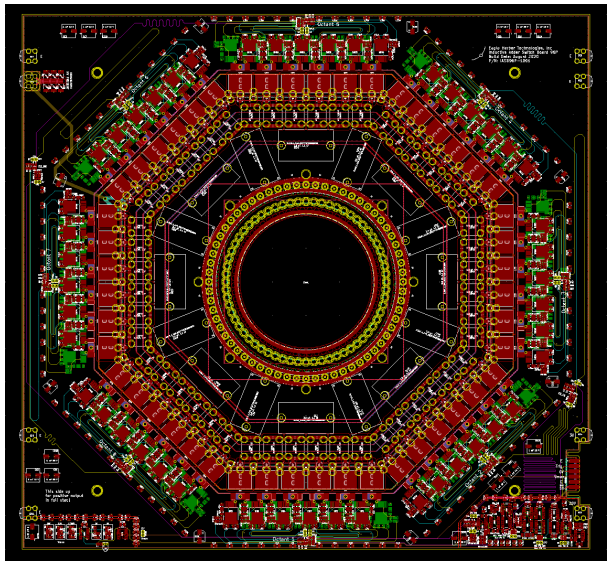


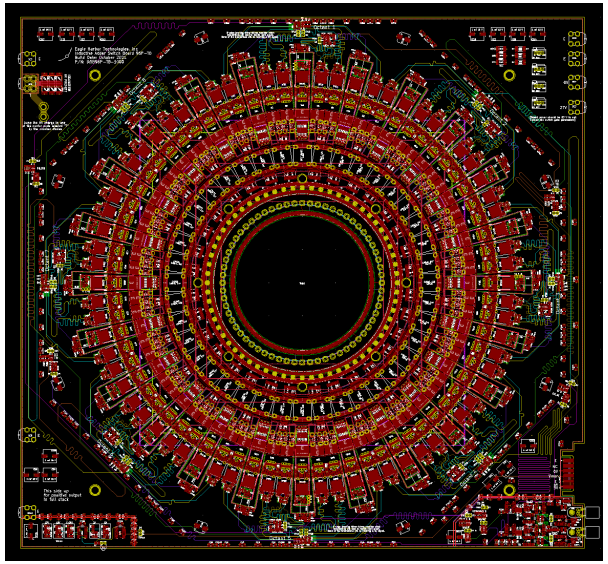
# Inductive Adder Design



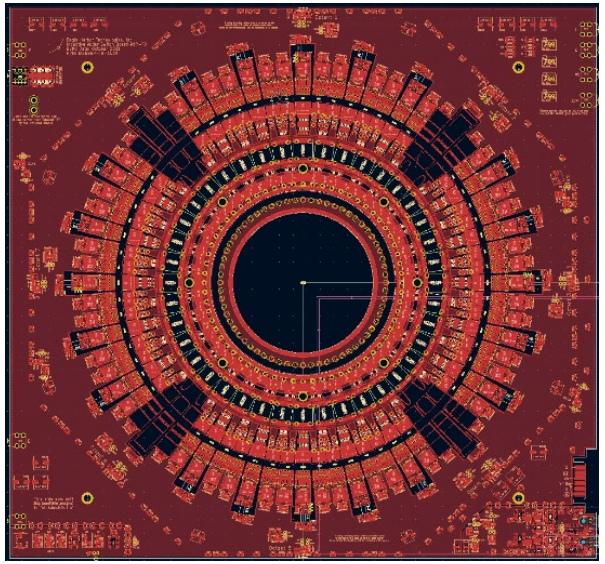



Phase I

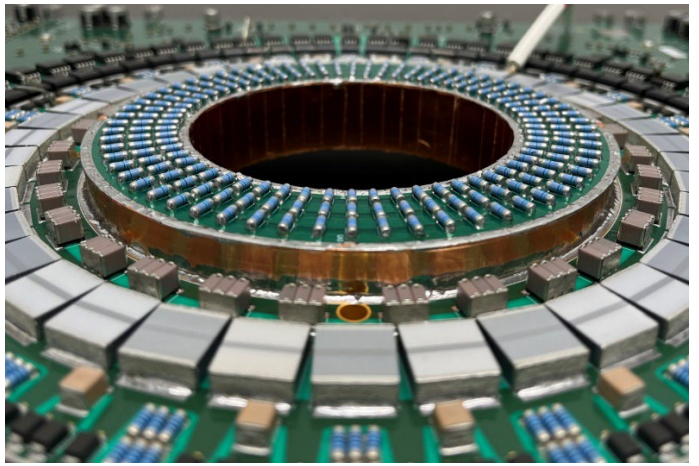


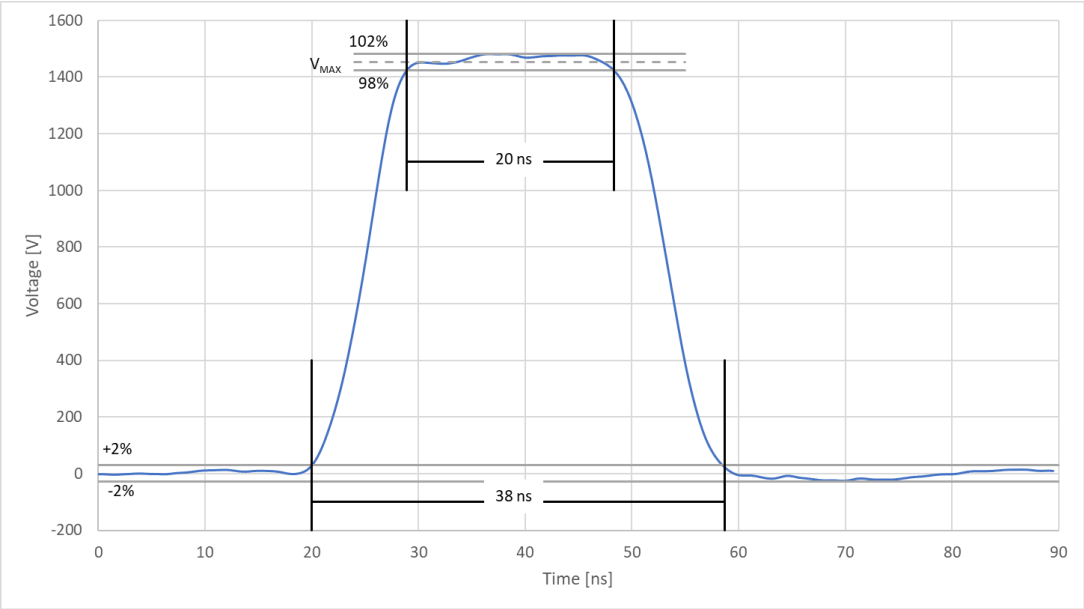
Phase II

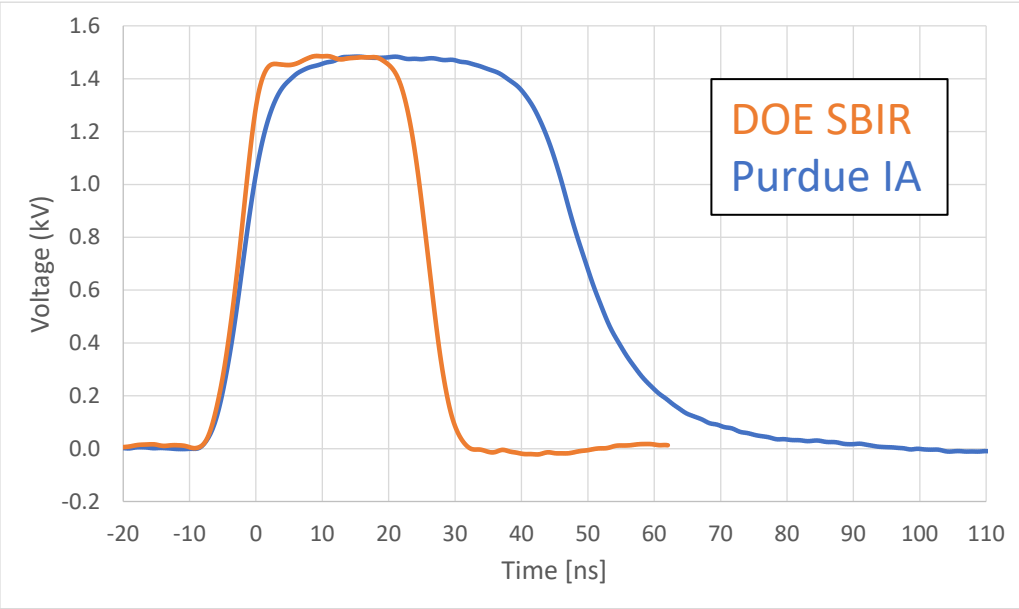


# Single Stage Testing

- Tested into scaled resistive load
  - Same capacitance and inductance per stage
  - Stage is switching the full current
- Single stage boards meet the BNL timing specs will switching the full current (1 kA)
- Significant improvements over Purdue IA



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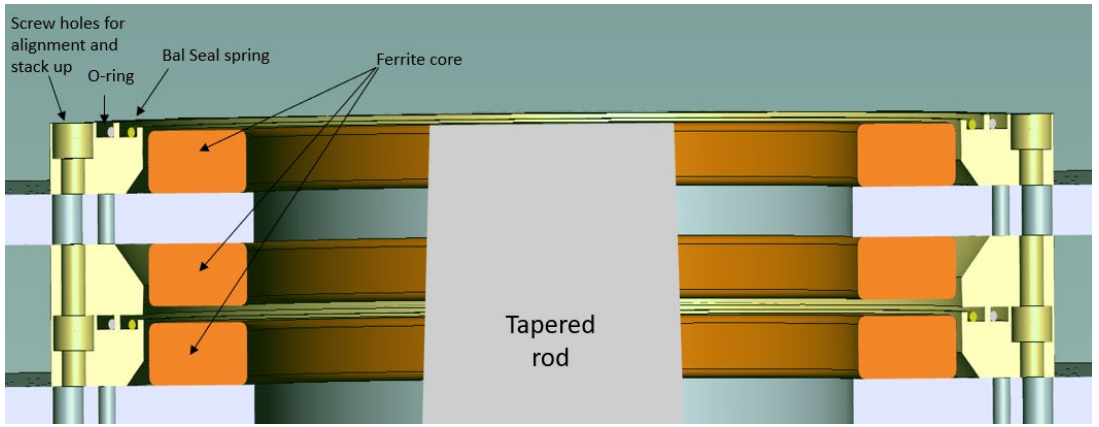
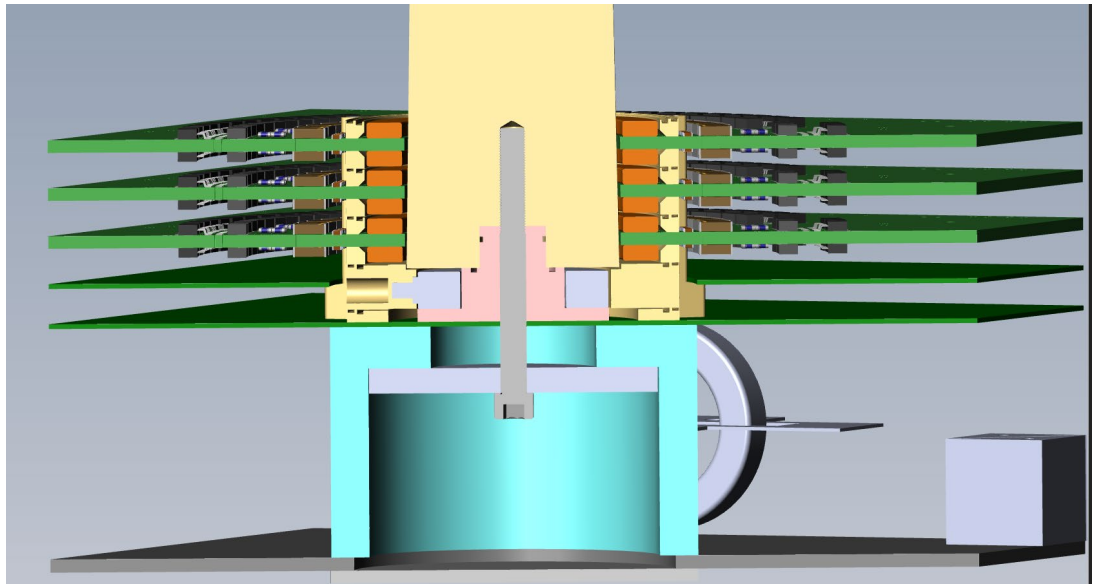
# Major Tasks in Phase II

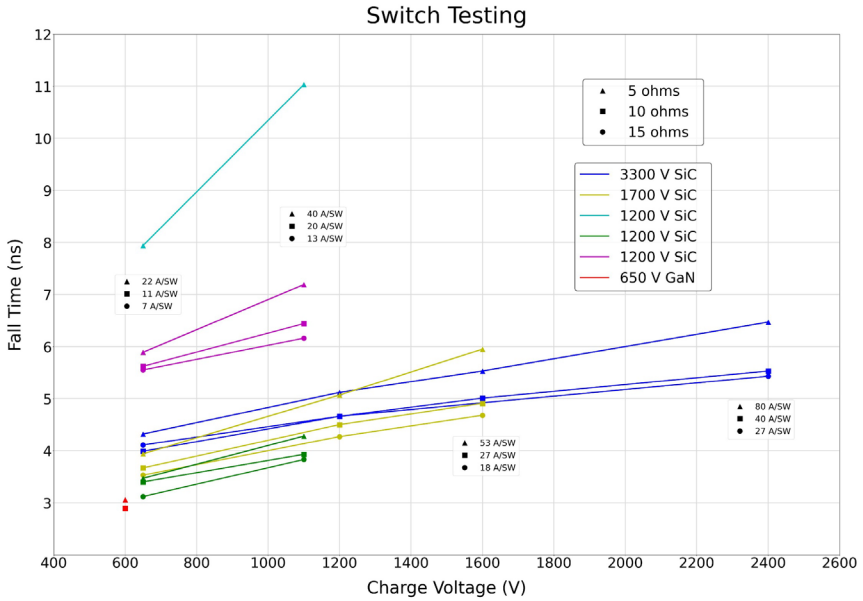
- Design IA Subsystems
  - Mechanical structure
  - Control voltage power
  - Trigger fan out
  - Central transformer
- Load/diagnostics
  - 60’ hardline
  - Current probes
  - 50 Ω low-inductance/low-capacitance load that can withstand 50 kV
- 50 kV IA Test

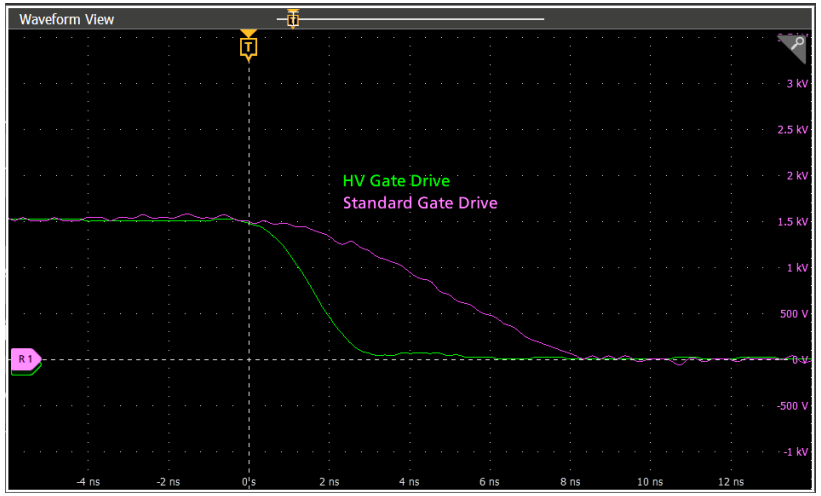


# Future Work (beyond Phase II)

- Improved solid-state switches
  - Higher current per switch
  - Lower capacitance
  - Lower price
  - Faster switch transition times
  - Higher voltage switches
- High voltage gate drive
  - Standard gate drive: 4.5 ns transition
  - HV gate drive: 1.5 ns transition
- Cost reduction
  - Higher voltage switches combined with HV gate drive
  - Significantly reduce the number of stages



# Conclusions

- EHT solid-state pulsed power capabilities
  - Understand underlying physics to design successful solutions
  - High voltage (10s kV) and high currents (10s kA)
  - Fast rise times (< 10 ns)
  - High pulse repetition frequency (> 500 kHz)
- BNL Stripline Kicker Power System
  - Inductive adder topology has advantages
  - Single stage can meet the challenging pulse timing requirements: 6 ns rise, 20 ns flat top (±2%), and 12 ns fall while switching full current
  - Inductive adder subsystem designs are underway
  - Designs can be leveraged for other high-voltage, fast pulse generators
- Future Work (beyond Phase II)
  - High voltage gate drive combined with higher voltage switches
  - Significant system cost reduction
- EHT Ventures LLC (spinout for future R&D and commercial )