The Electra KrF Laser Program: A Viable Path Towards an Efficient and Durable IFE Driver

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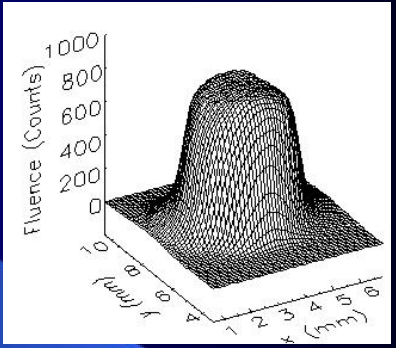
24th Symposium on Fusion Engineering
Chicago, IL, June 30, 2011

Work was supported by *DOE/NNSA/DP*

Why KrF Lasers for IFE?

Short wavelength (248 nm) maximizes target gain and stability



Demonstrated outstanding spatial uniformity
and large bandwidth (2 THz) on NIKE laser

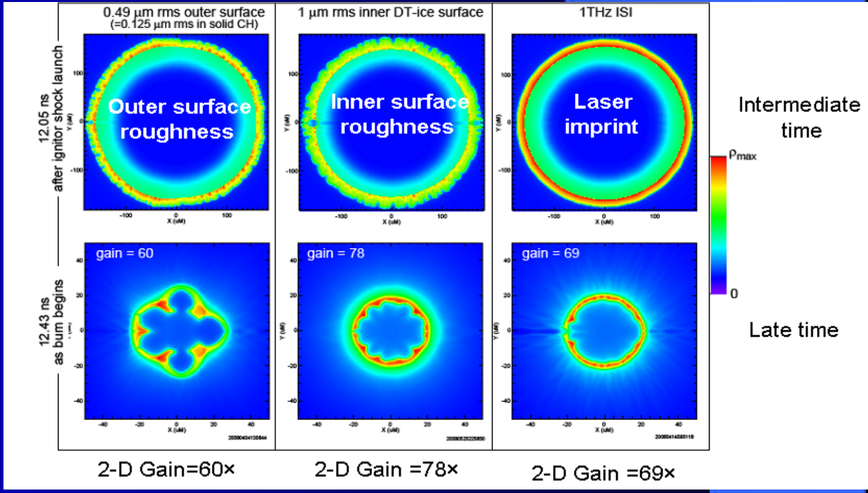
Straightforward zooming

High laser system efficiency (estimated wall plug: 6-7%)

2D simulations show power plant gains with KrF-driven targets

Gains >150 @ 500 kJ (shock ignition)

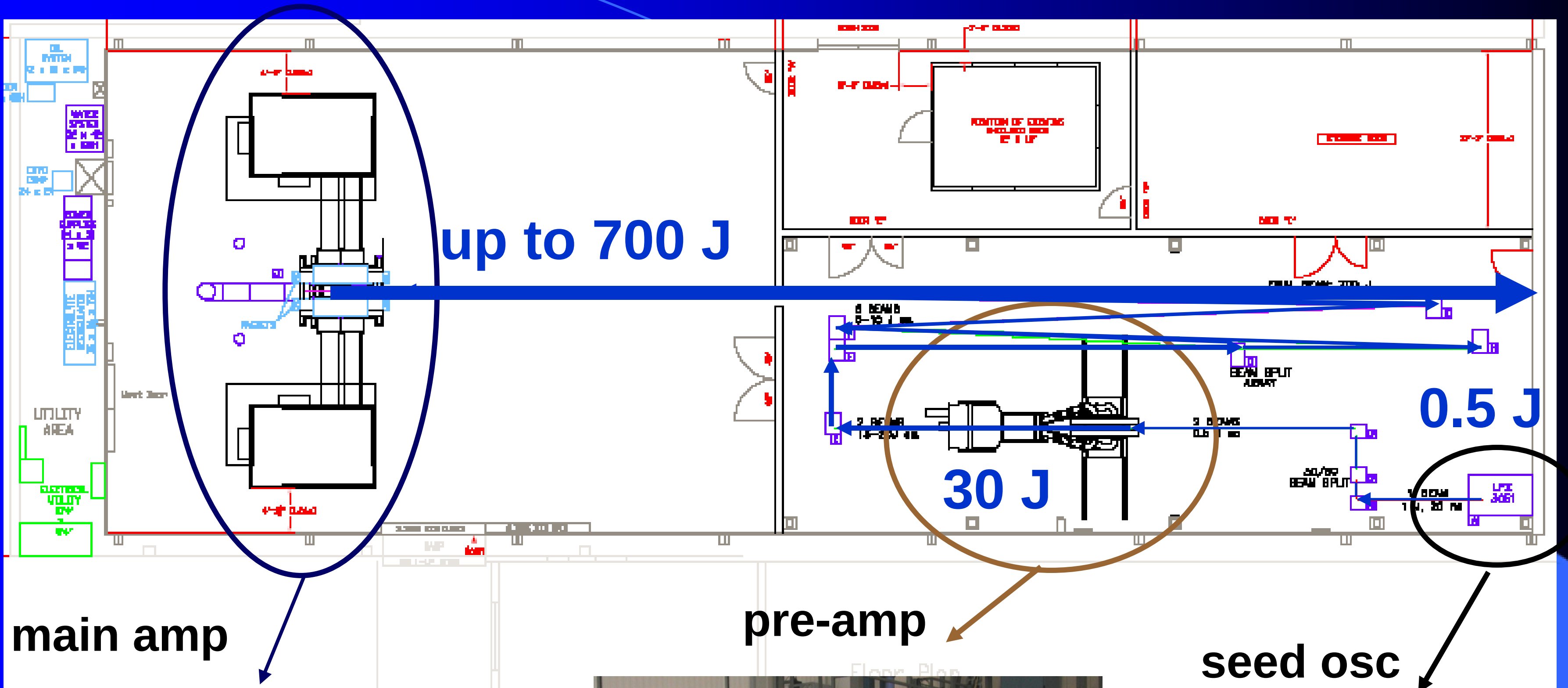
Gains >140 @ 1 MJ (conventional direct drive)

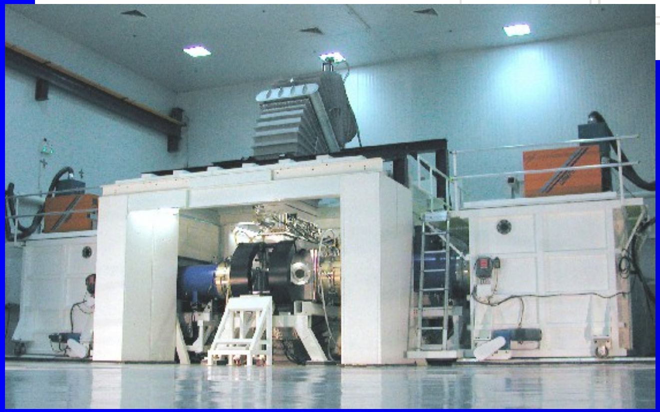


Shock Ignition Concept
Betti et al, Phys. Rev. Lett. 98, 155001 (2007)
(LLE, University of Rochester)

2-D simulations by A. Schmitt, NRL

The Electra KrF Laser System



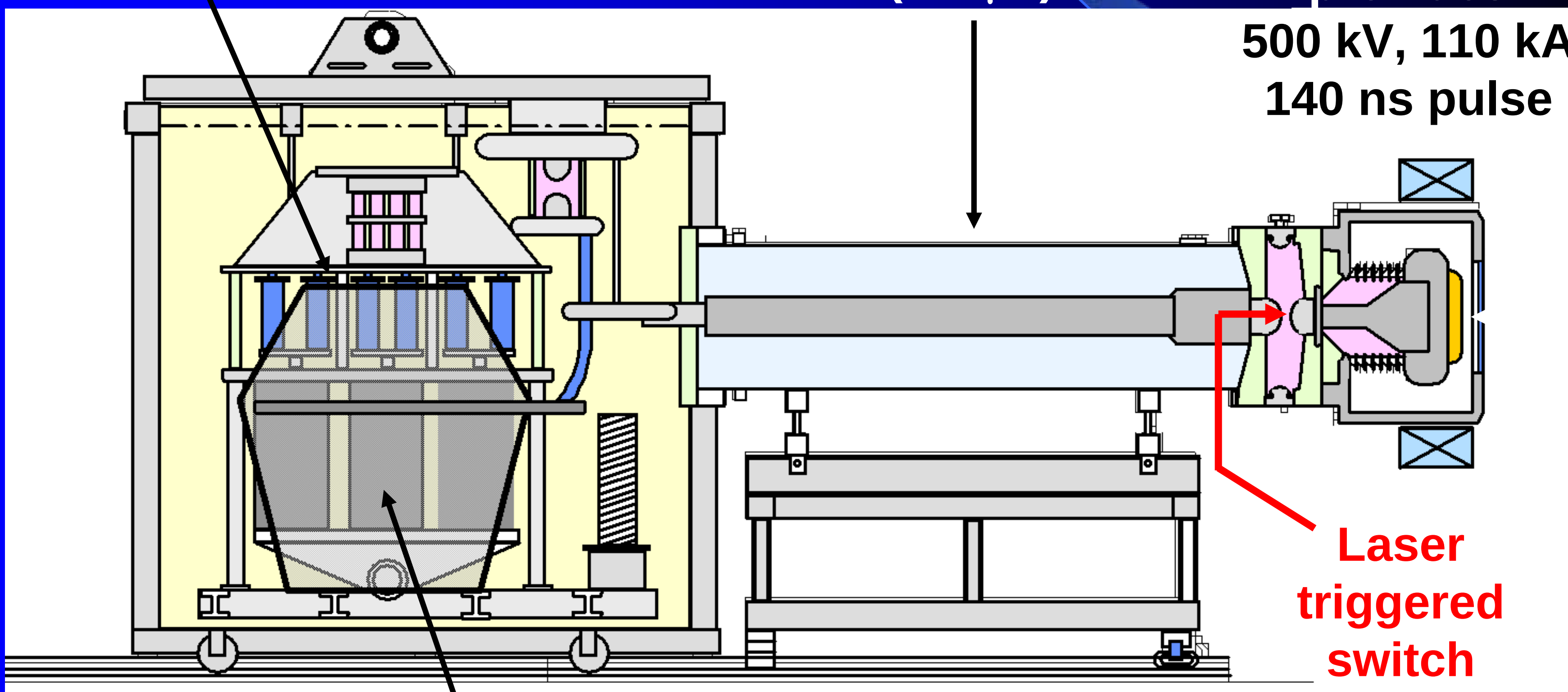


NRL Progress in KrF Laser Development

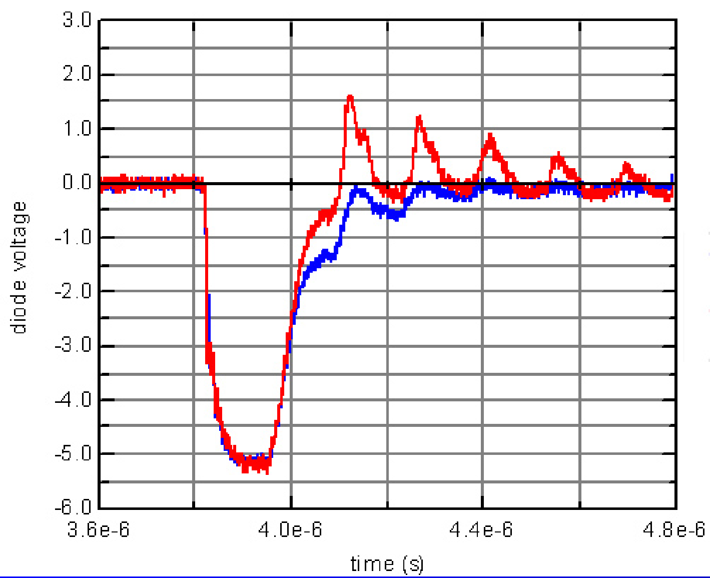
	2001	2011	IFE
Repetition rate (pulses/second)	.00056	2.5 to 5	5
System efficiency based on experiments on main components (%)	1.9	6 to 7%	> 6.0
Durability (continuous shots)	200	90,000	300 M
Shots in eight days	50	350,000	4,000,000

These advances have been made through understanding and controlling the relevant physics

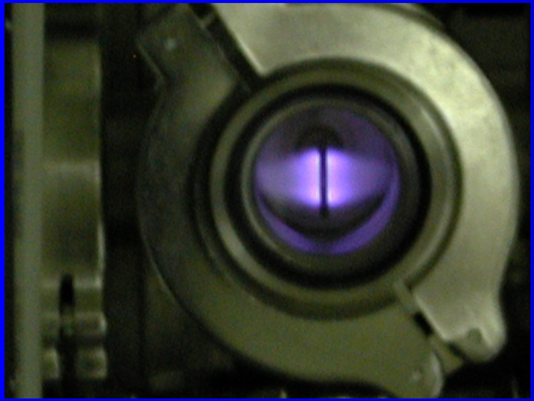
Electra's Main Oscillator Uses a First Generation Pulsed Power System Utilizing a High Voltage Transformer and Gas Switches



Better Understanding of Electron Beam Diode was Key to Increase Durability by a Factor of 10



Voltage reflection leads to cathode spots on foil and cause failures



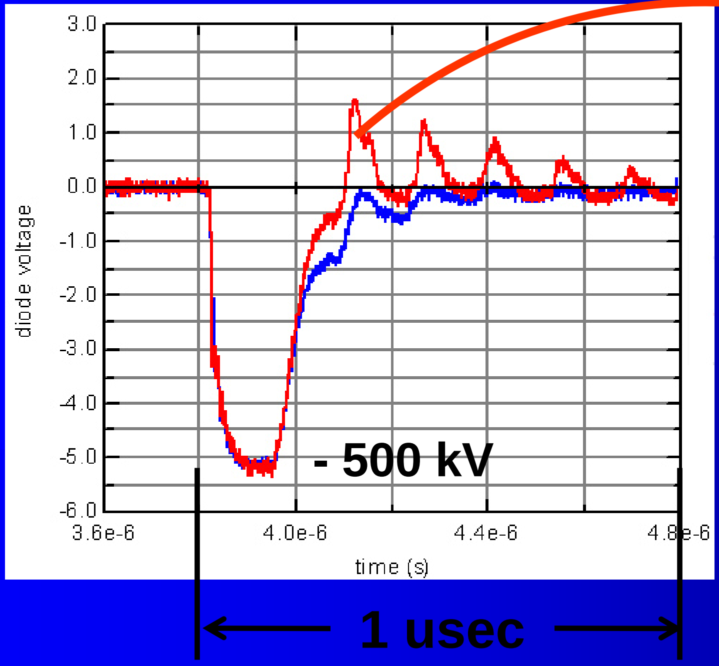
Pinhole detection system prevented catastrophic foil failures

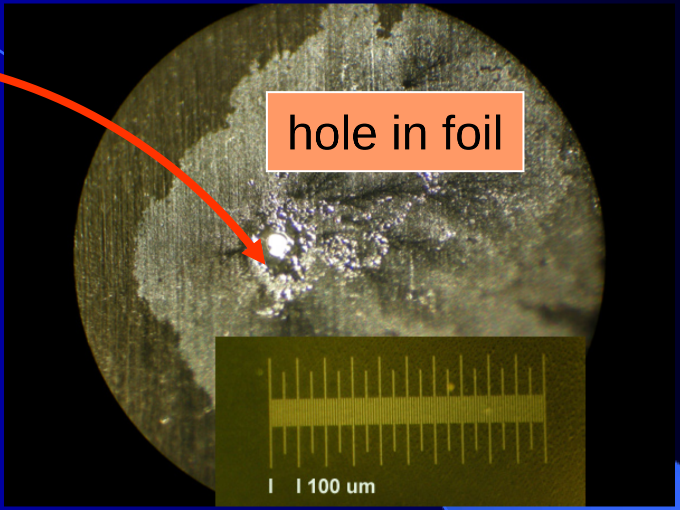
Carbon fiber cathode with >500,000 shots

ESLI

One Key to KrF Durability (aka long foil lifetime): Minimize Residual Current in the E-Beam Diode

Diode Voltage

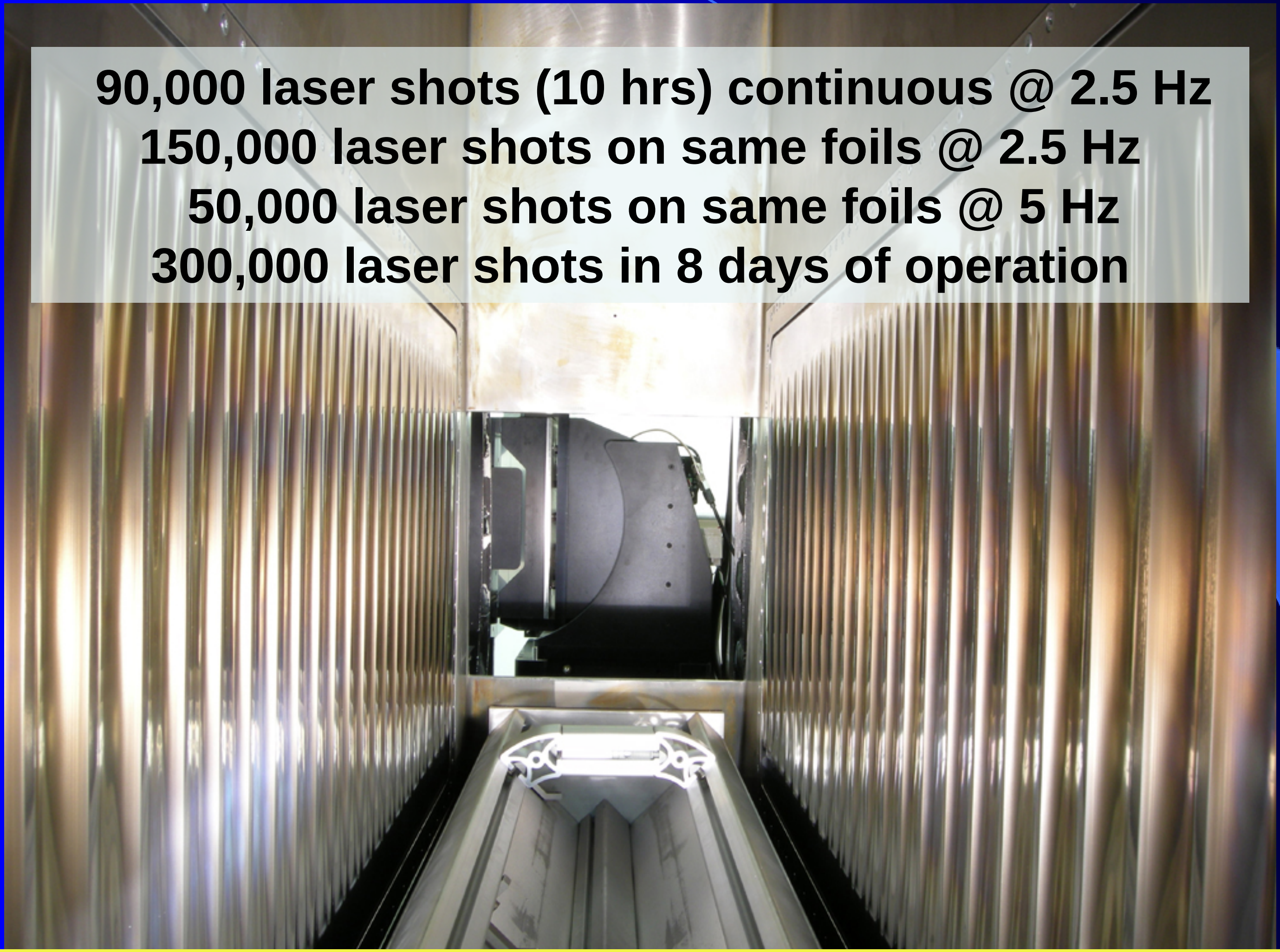




Voltage reflections allow the electrically grounded 25 μm thick pressure foil to explosively emit electrons, which leads to cathode spots on foil and cause failures.

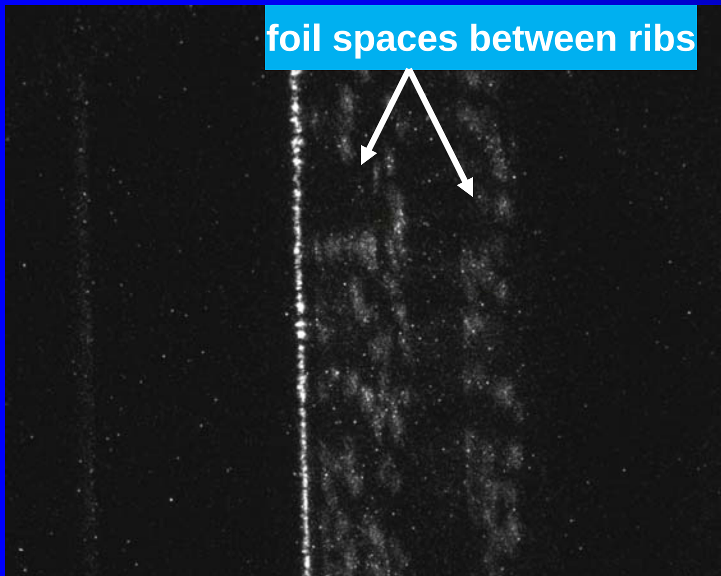
Increasing the e-beam diode impedance removed these voltage reflections and improved the foil durability by a factor of 10.

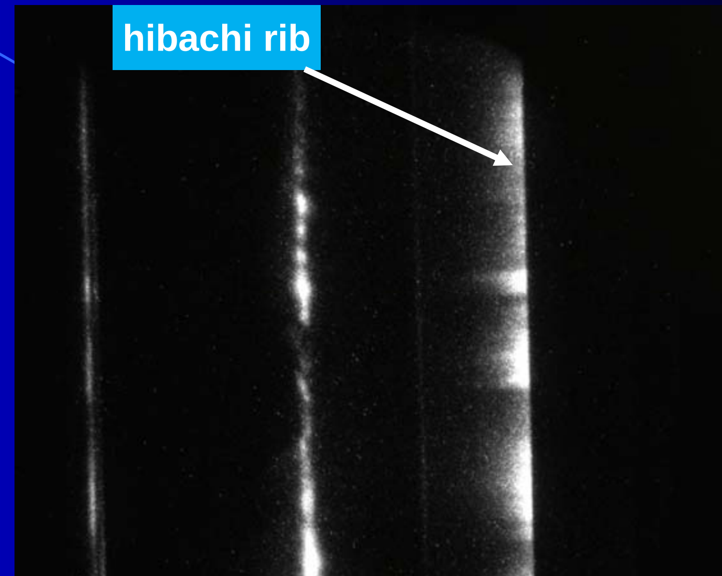
Cathode Spots on Foil Eliminated and Diode Durability Greatly Extended By Suppressing Reversals

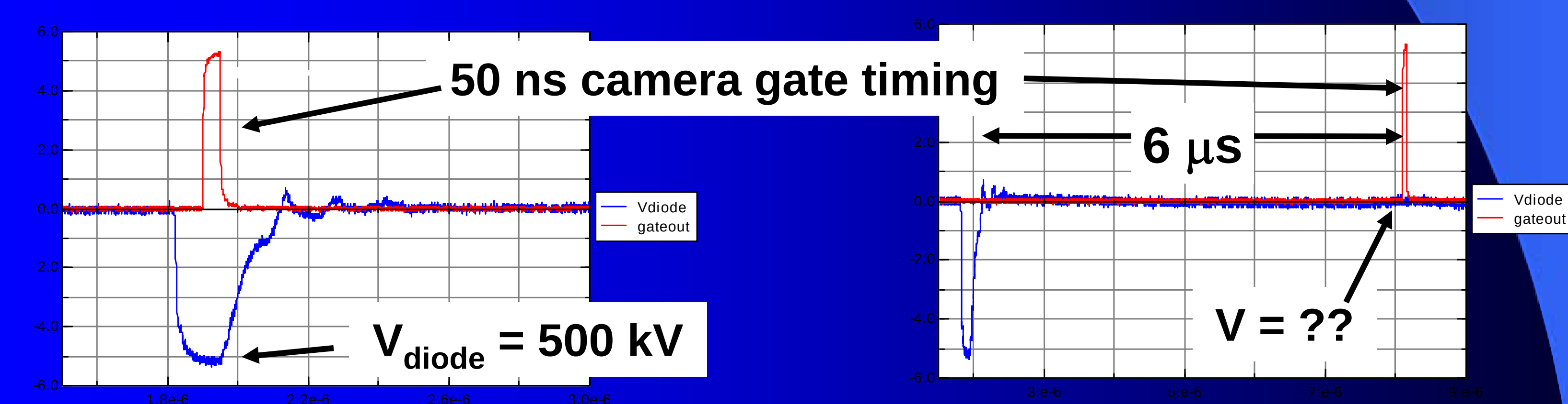


Electra cell after 30,000 shot, 2.5 Hz continuous laser run

Rib Emission Captured by Gated Camera 6 μs After Main Pulse







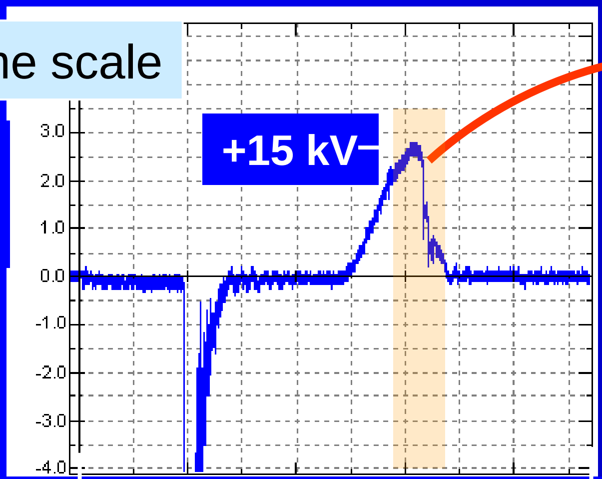
50 ns gate in middle of voltage pulse

50 ns gate ~ 6 μs after voltage pulse

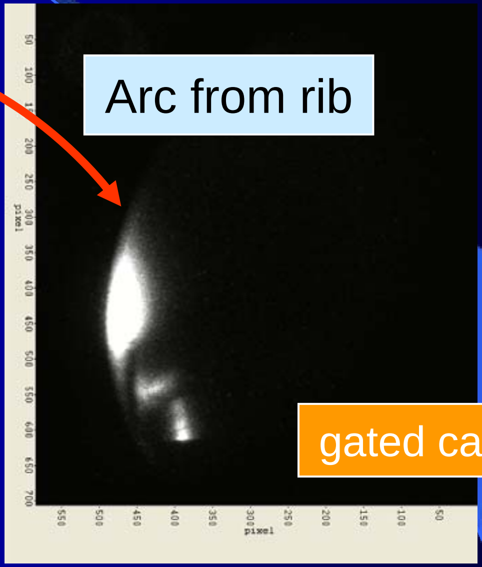
The First Generation Pulsed Power System Also Shows a Voltage Reversal About 6 μs After the Main Pulse

1 μsec time scale

Diode Voltage



20 usec

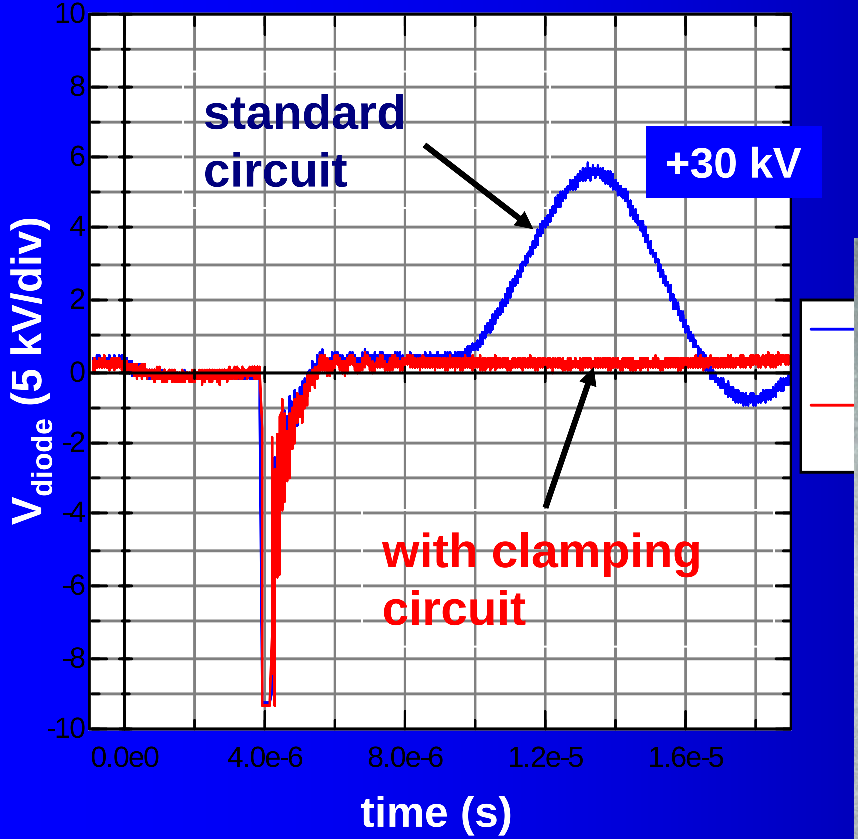


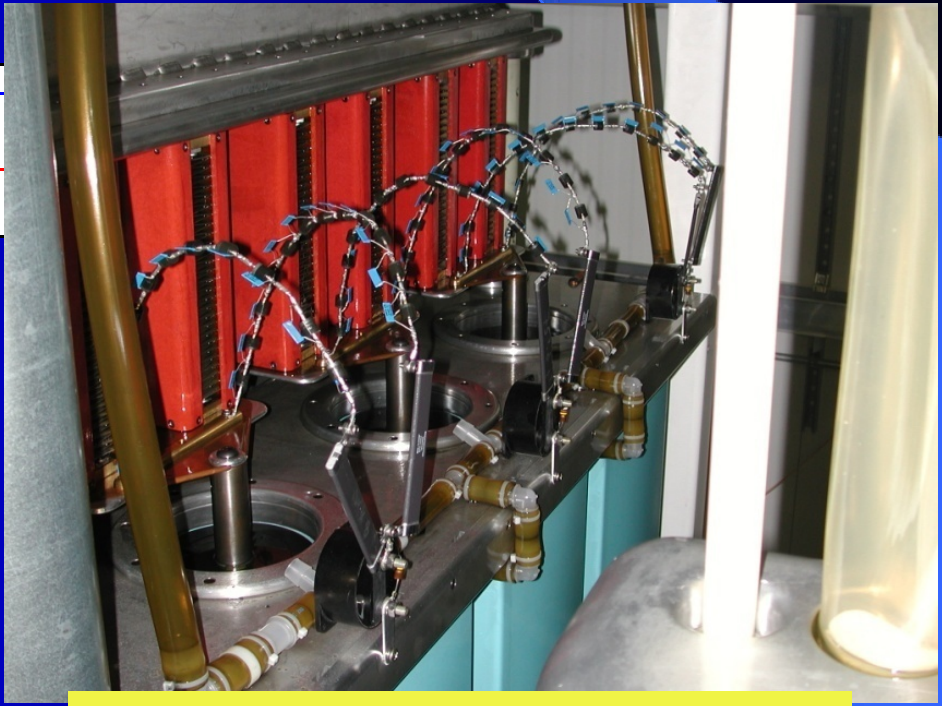
- 500 kV

Breakdown does not occur on most shots

This secondary voltage reversal correspond to ~ 0.1% of the main pulse energy

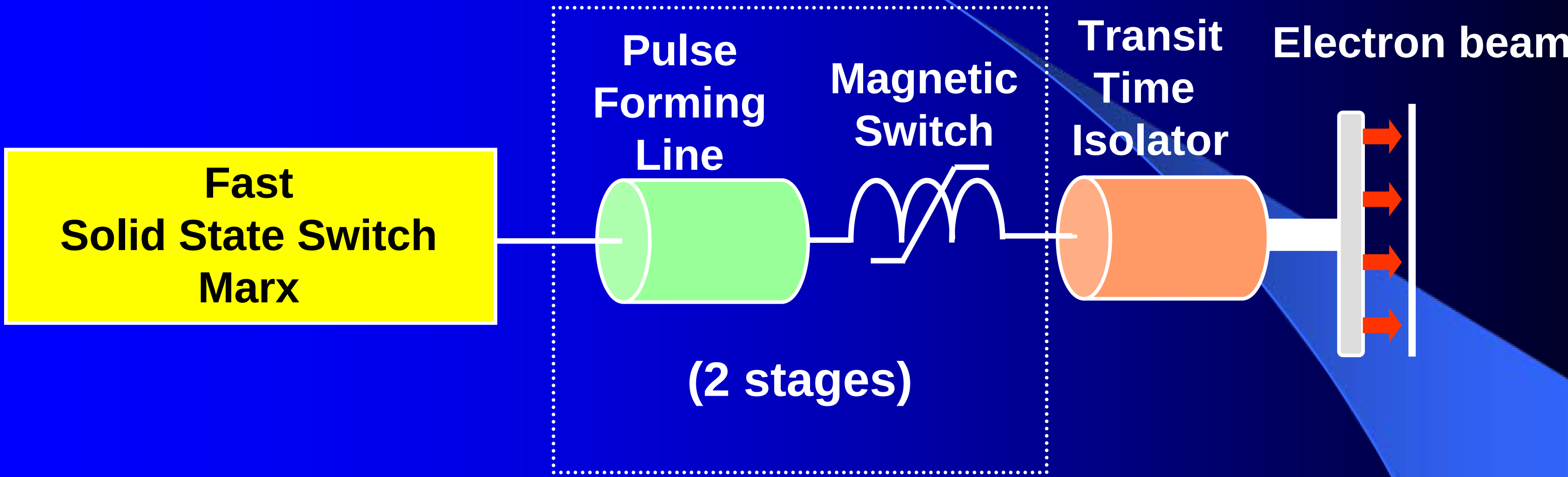
Imperfect Coupling Across HV Transformer Generates the Late Time Voltage Reversals, Which are Removed with Diode Clamping Circuits





Diode array on prime power caps

Efficient and Durable Pulsed Power System for IFE Requires Solid State Switches



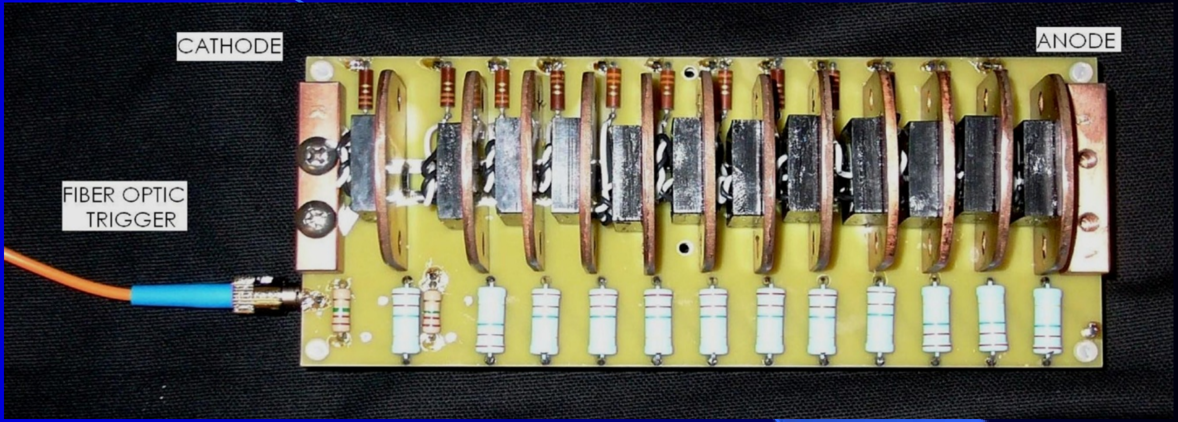
Advantages:

- Flat-top pulsed power efficiency is 80-85% compared to < 40% of first generation pulsed power system
- Misfire (pre- or late fire) rate of gas based switches is eliminated with solid state switches

Solid State System is Constructed with 48 kV, 7 kA Thyristor Switches

Each switch has 12 x 4 kV Thyristors

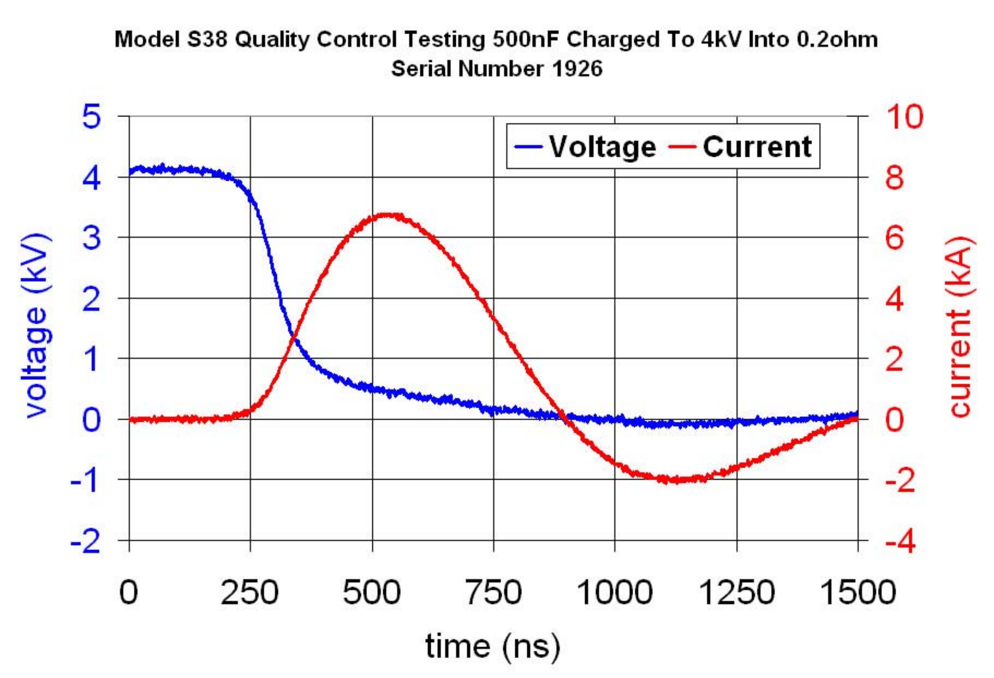
Only the first two Thyristor stages are command triggered, the remaining stages are auto-triggered.

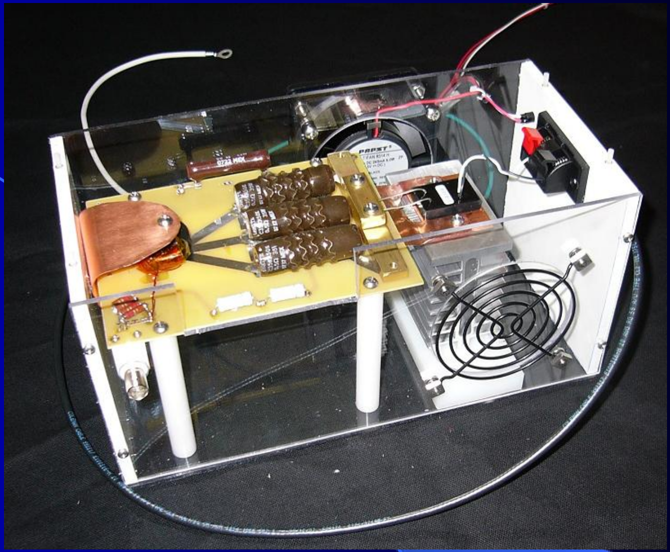


Switch parameters:

Hold-off voltage: 48 kV
Switch current: 7 kA
Max. fault current: 14 kA
Rated current rise: 30 kA/μs
Max. current reversal: 80%

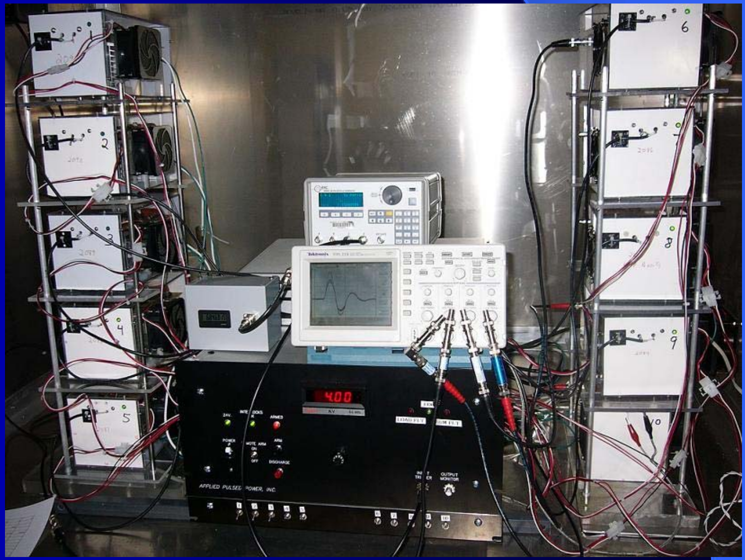
Lifetime exceeds 300 M shots for 4kV Thyristors





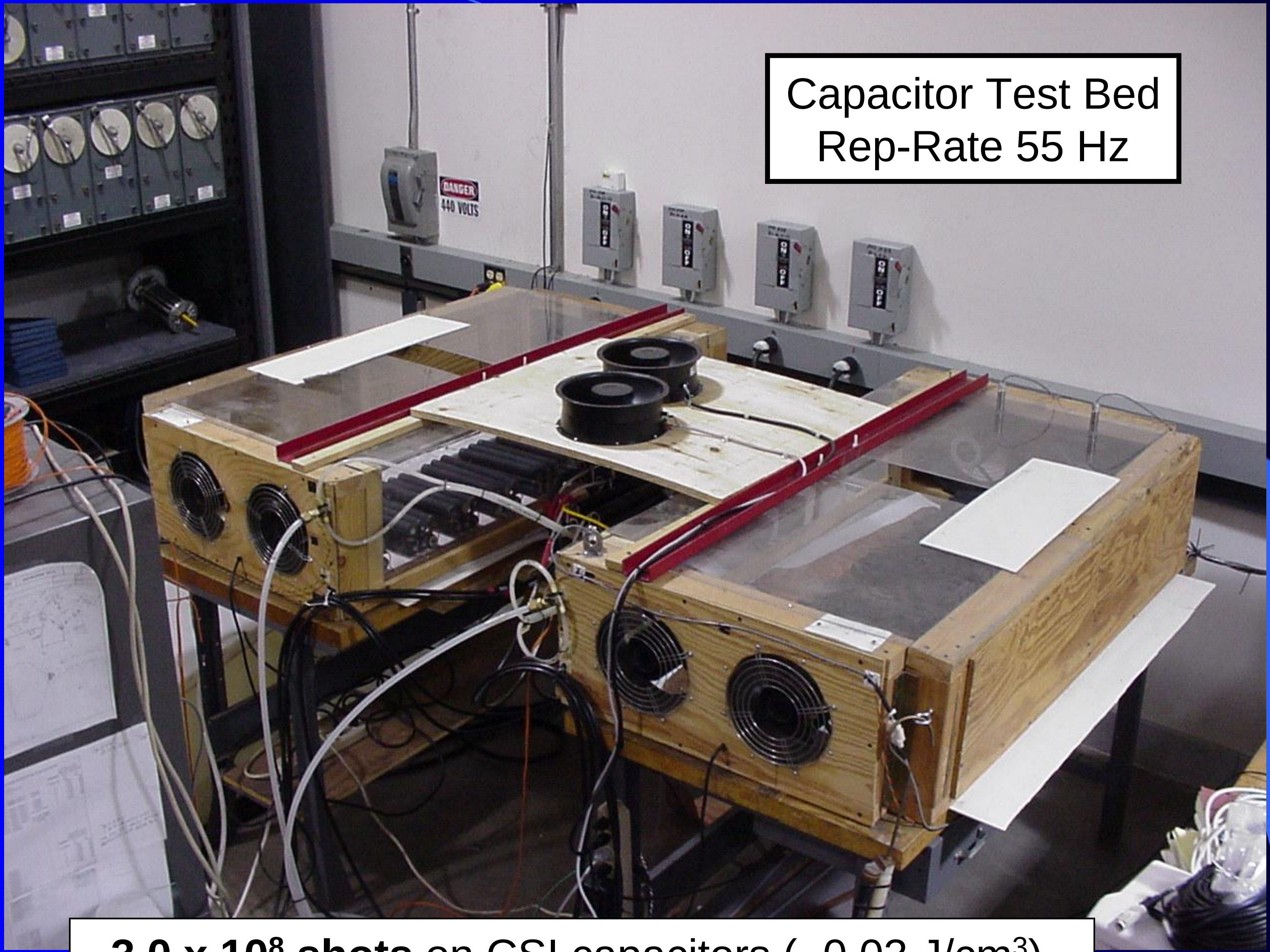
Single test stand

Tested @ 20 Hz:
Hold-off voltage: 4.1 kV
Switch current: 6.8 kA
Peak current rise: 36 kA/μs
Thyristors operated for 200-300 M shots
No failure



Lifetime station with 10 stands

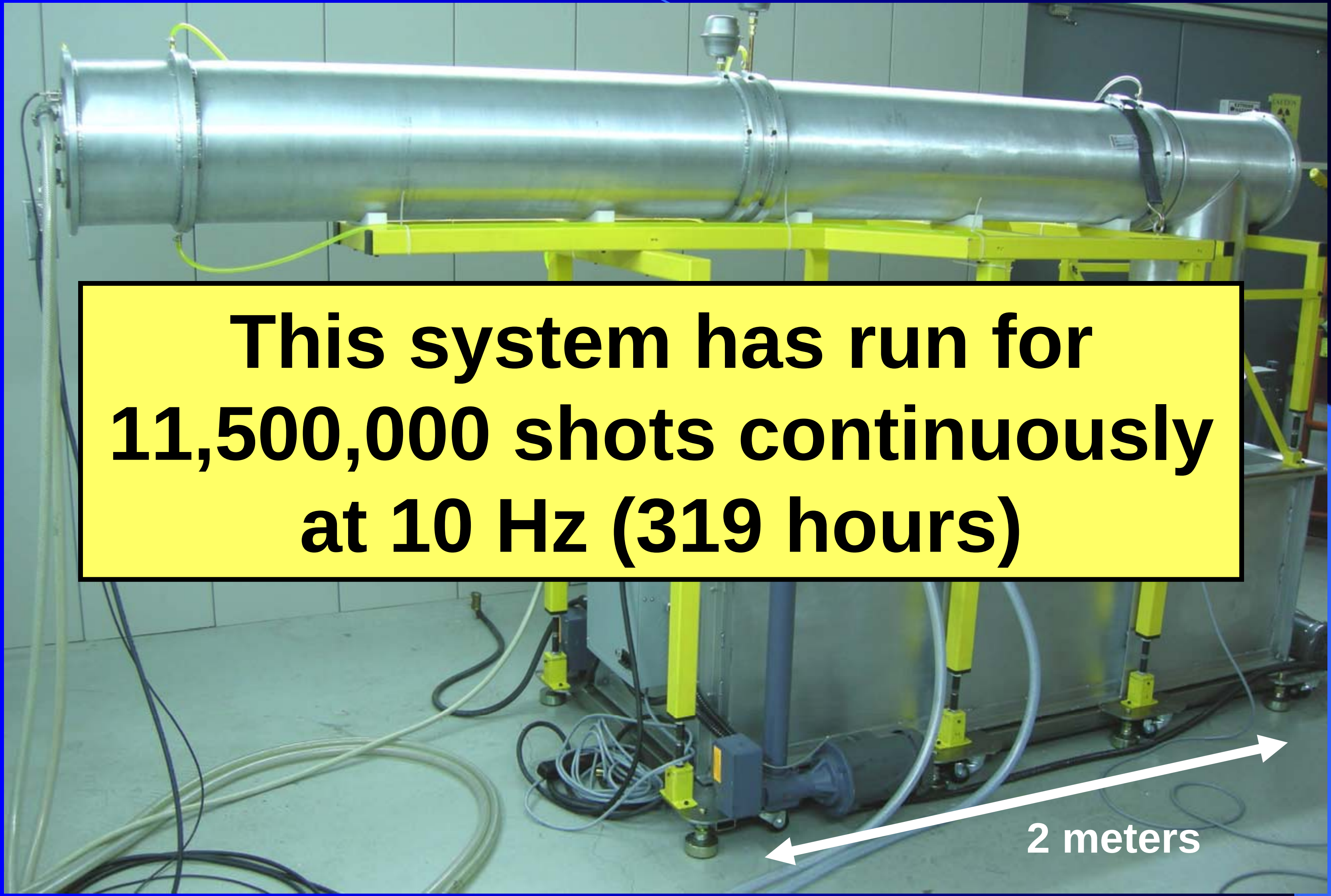
Lifetime of Capacitors exceeds 300 M shots



- **3.0 x 10^8 shots** on CSI capacitors (~0.03 J/cm^3)
- **2.0 x 10^8 shots** on GA capacitors (~0.015 J/cm^3)

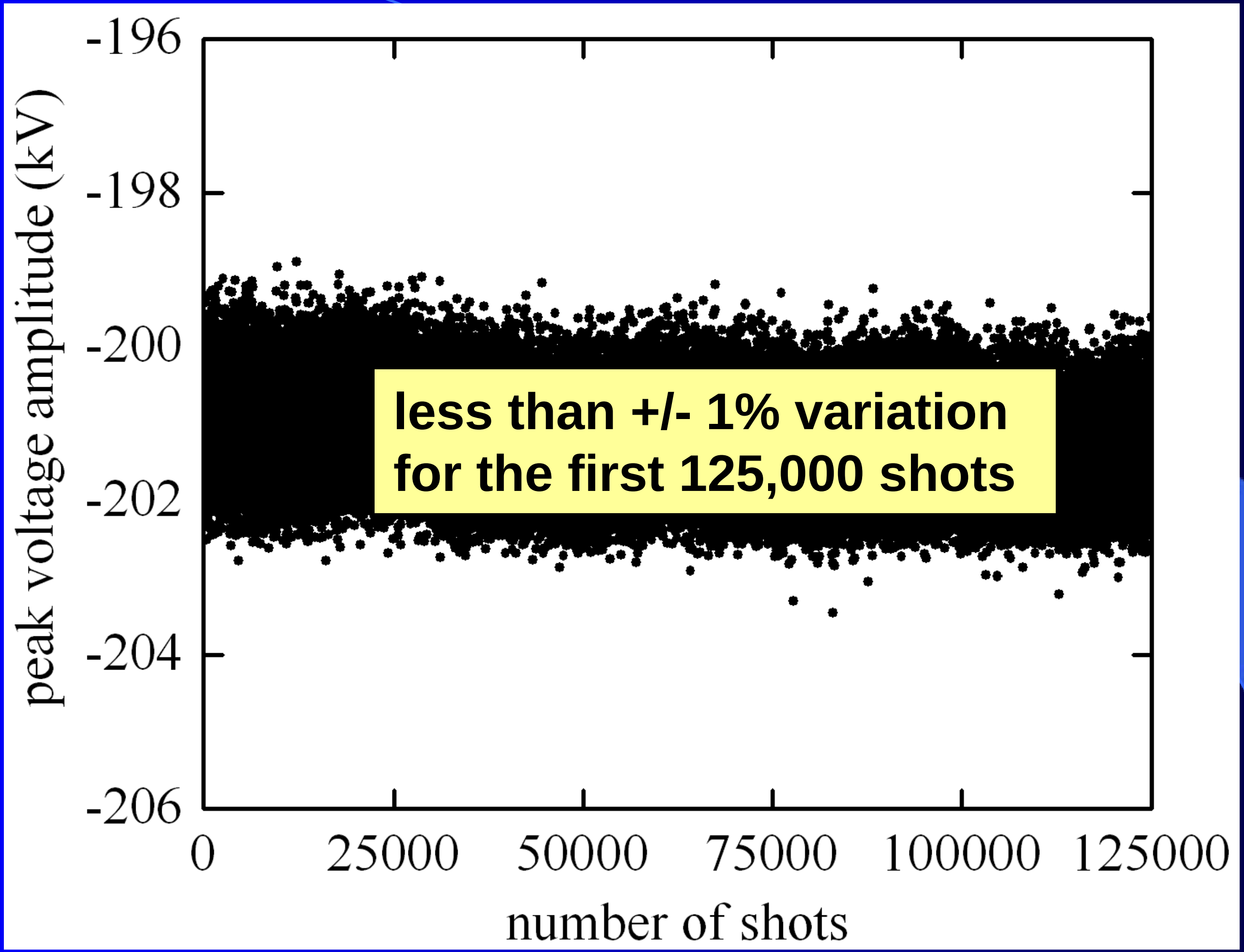
L3 communications
Applied Technologies
Pulse Sciences

Compact 200 kV, 4.5 kA Solid State Pulse Generator
Integrated Test of Components



This system has run for 11,500,000 shots continuously at 10 Hz (319 hours)

The Solid State Generator has a Stable Performance



The voltage amplitude shows a variation of less than ± 1% (a single digital step of the scope corresponded 1% of the signal amplitude).

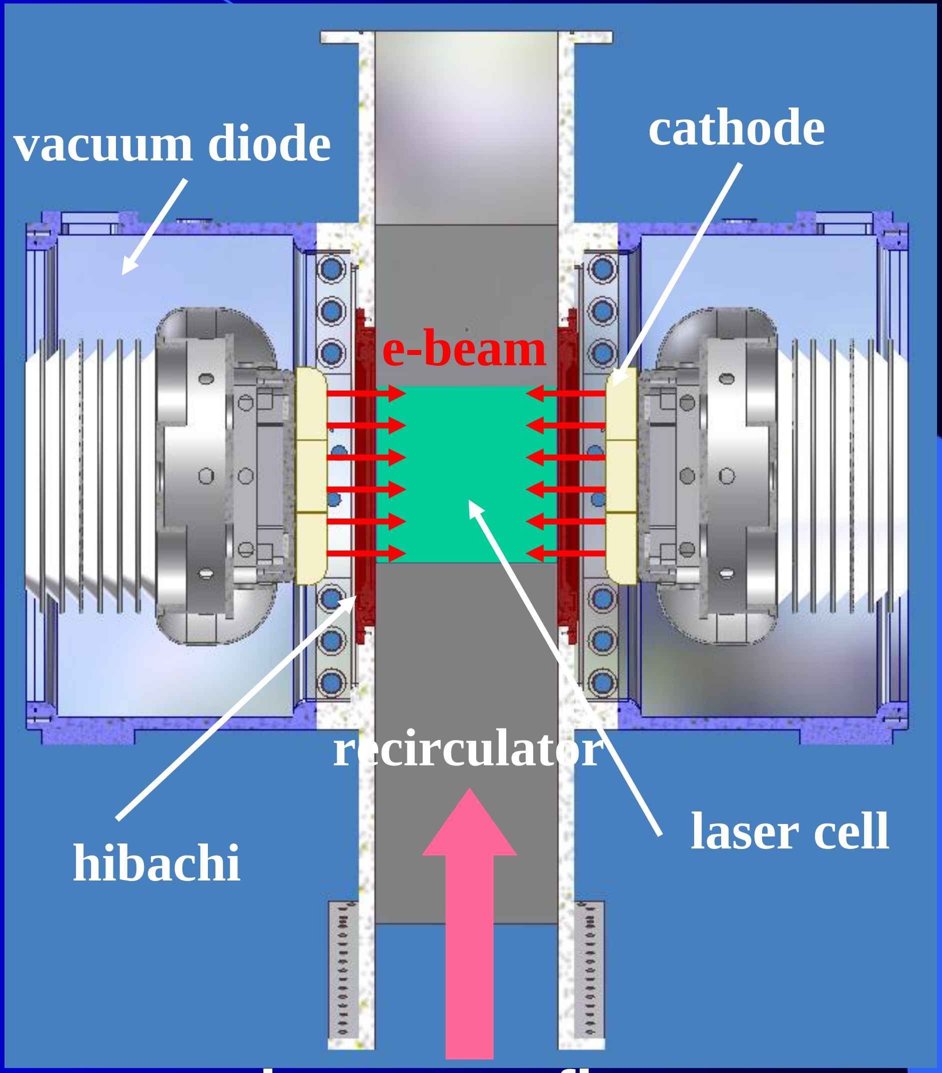
The time jitter for the initial 125k shots is ± 0.4 ns, ± 0.9 ns, and ± 1.4 ns at 1σ, 2σ, and 3σ standard deviation

Three Foil Cooling Techniques are Evaluated: Bulk Flow, Forced Convective Cooling with Airfoils, and Jet Cooling

Cooling by bulk flow:

Laser gas flows along the hibachi foils with velocities of ~ 9 m/s.

It does not provide adequate foil cooling at 5 Hz high efficiency operation.



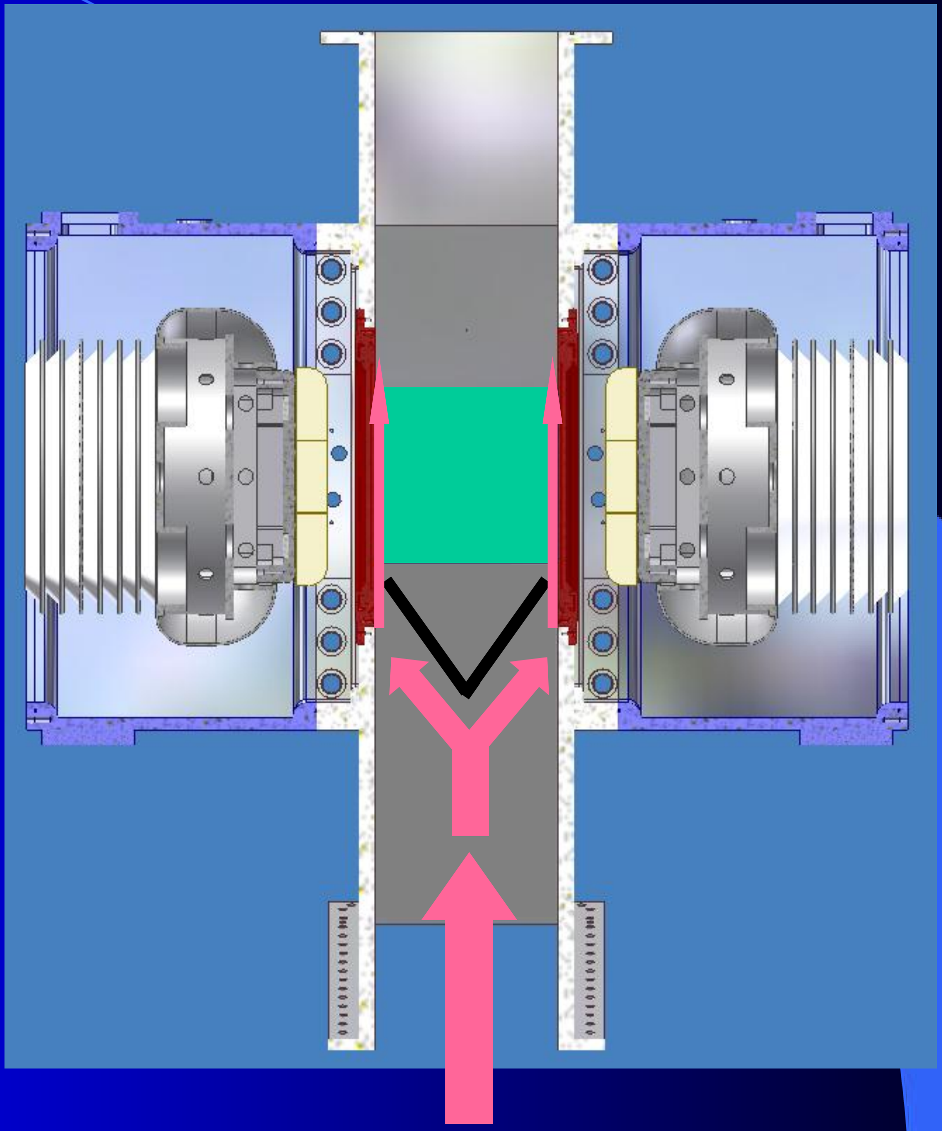
laser gas flow

Forced Convection With Airfoils Cools the Foils But Causes Focal Profile Perturbations

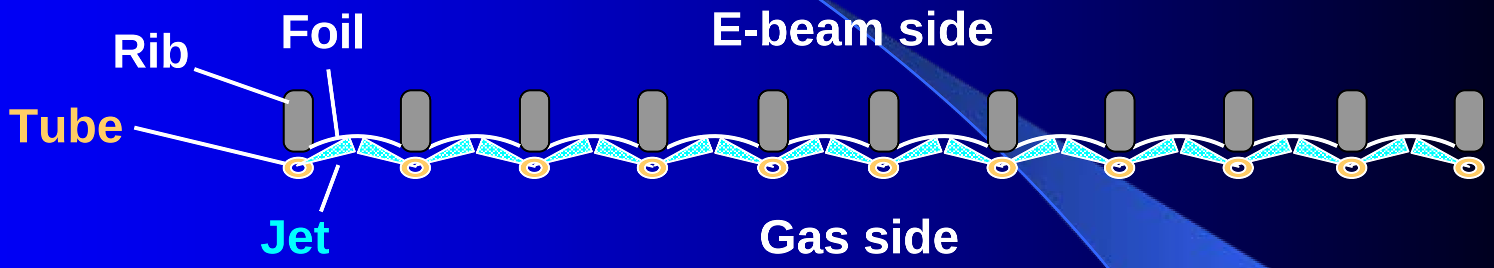
Cooling with Airfoils:

Laser gas flows along the hibachi foils with velocities of 20-30 m/s.

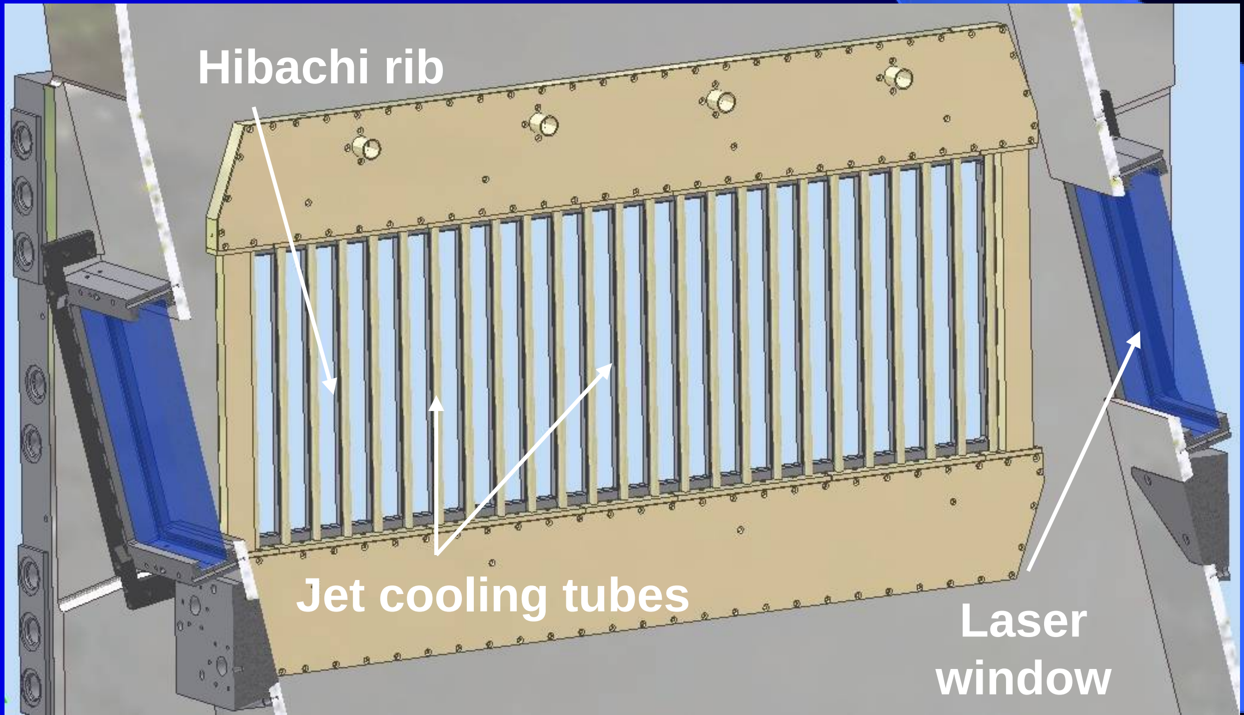
**It provides adequate foil cooling at 5 Hz operation (T~400 C),
but will not produce a smooth wavefront.**



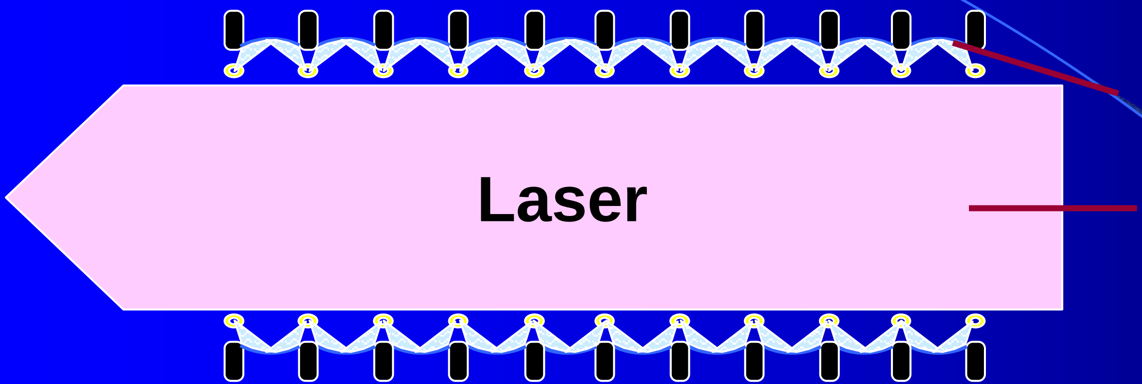
Jet Cooling Technique Developed by Georgia Tech Adequately Cools Foil and Minimizes Focal Profile Perturbations



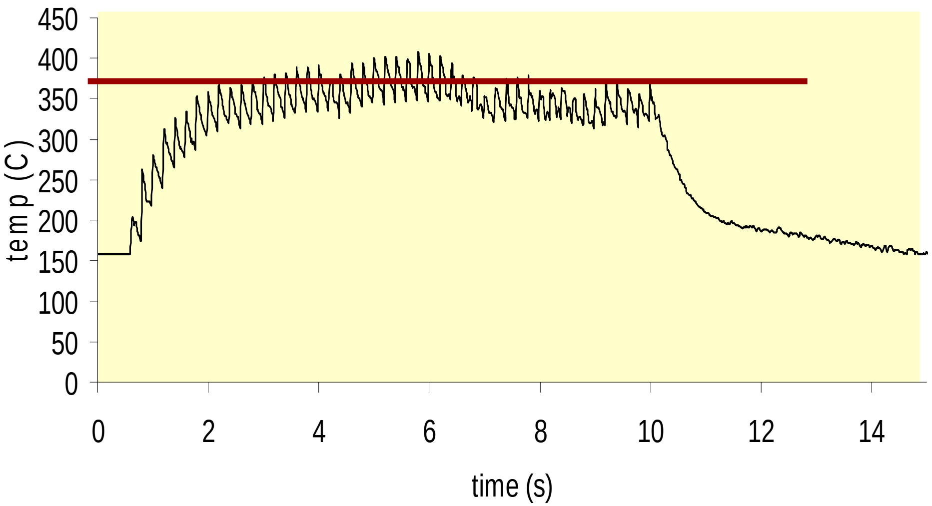
It provides adequate foil cooling at 5 Hz operation (T~370 C).



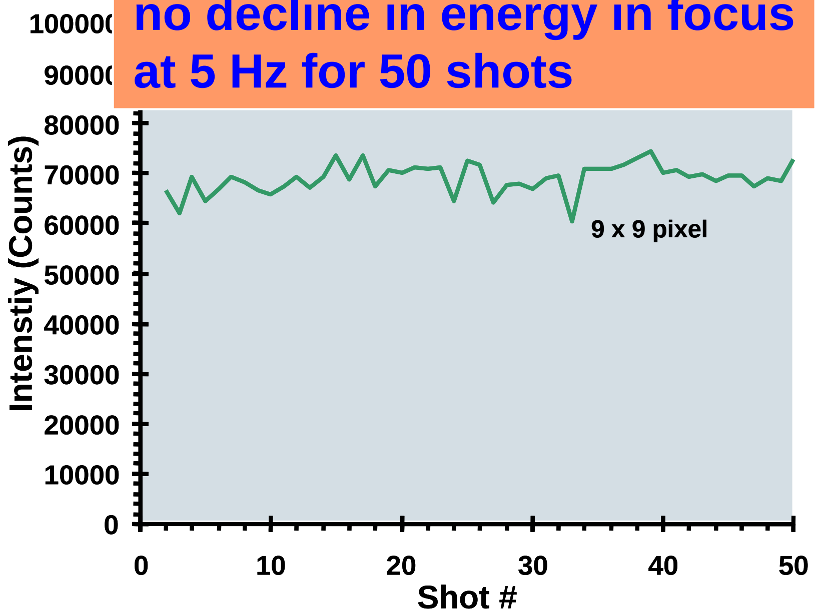
Jets Cool Foil with Minimal Power Consumption While Maintaining Laser Quality



average foil temperature < 370° C (Fatigue limit ~480 ° C)



no decline in energy in focus at 5 Hz for 50 shots



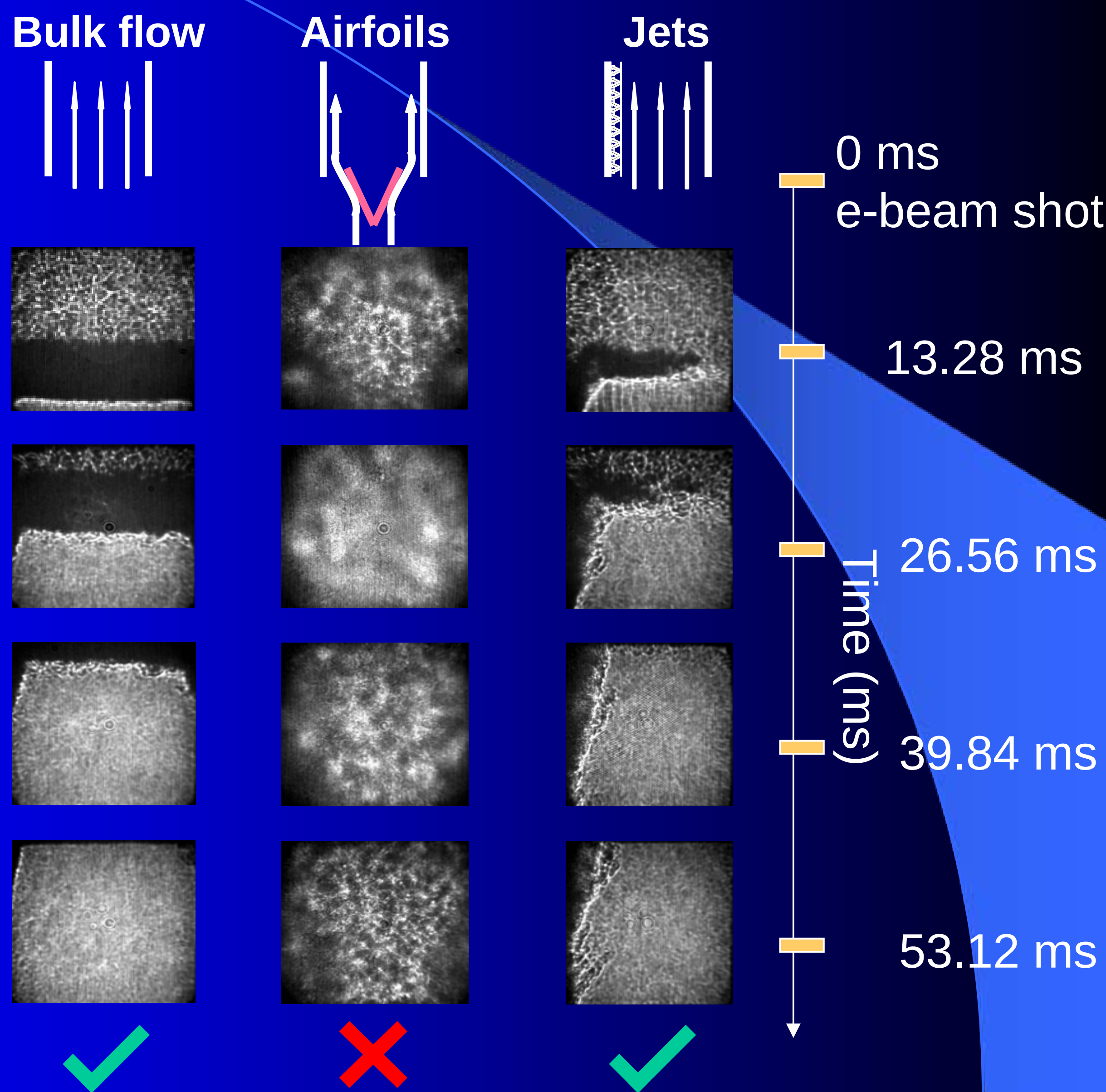
Georgia Institute of Technology & Matt Wolford

Interferometry Data Shows that Jet Cooling Provides Recovery of Wavefront

Heated gas by e-beam with nonuniform density distribution

Interferogram signal lost (HeNe laser is deflected)
Expect high gas temp gradients

Cool "new" gas with more uniform density distribution



Recovered after 200 ms:

KrF Development Goals for the Next Few Years

- Million Shot class operation
  - Improve the durability of first generation pulsed power system
  - High performance cathode
  - Jet cooling
- Design an all solid state pulsed power system for Electra (500 kV, 100 kA, 150 ns)
- Full size e-beam components on Nike

- Companion target physics program on Nike:
  - Develop science and technology underpinnings for high gain direct drive fusion target concepts