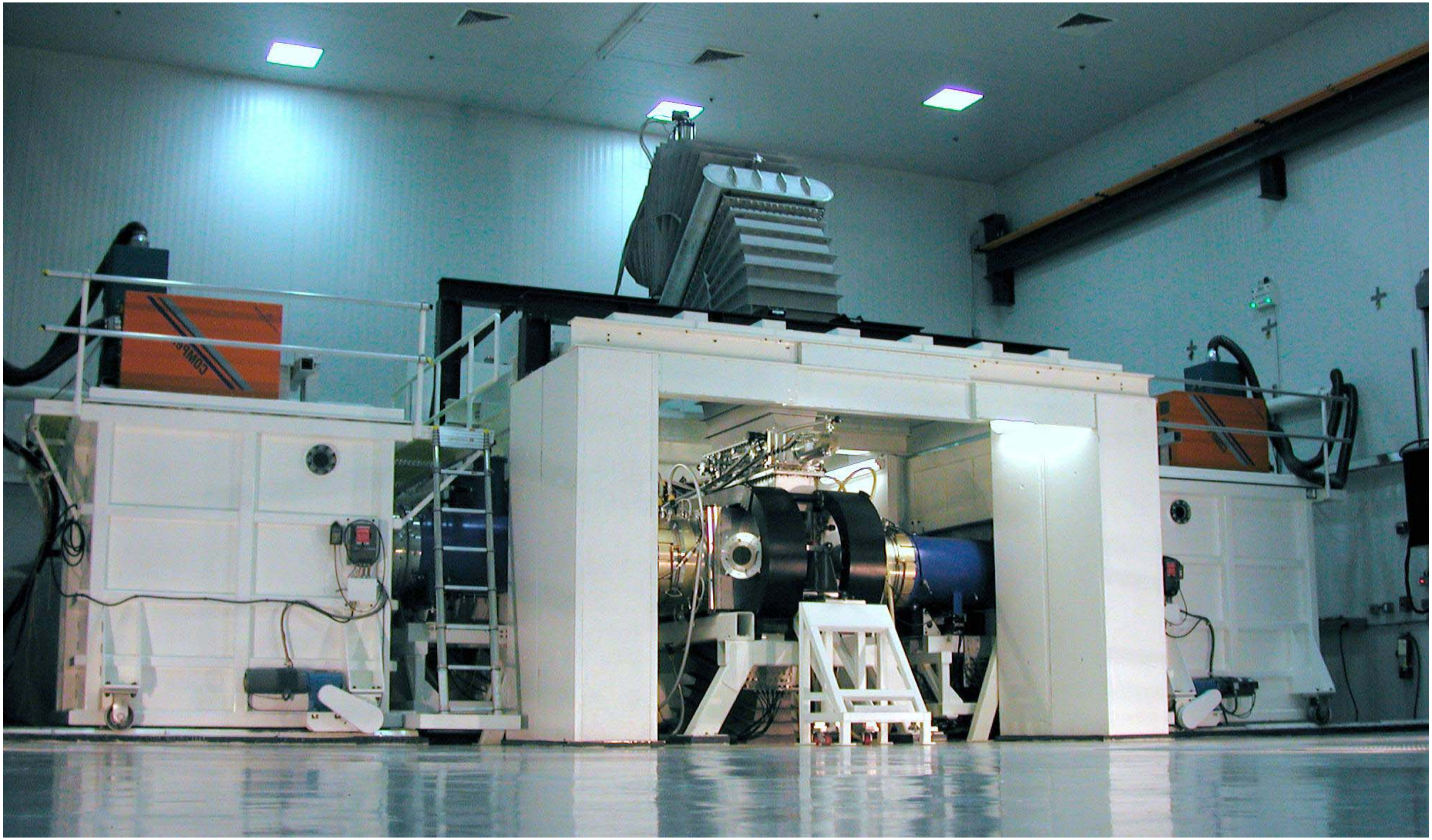
KrF Laser Development



Opening Remarks on KrF Laser Development

Many institutions have had programs in e-beam pumped KrF lasers

Los Alamos National Laboratory
Livermore National Laboratory
Avco Textron
Rutherford Appeleton Labs, UK
ETL, Ministry of Technology and Industry, Japan
Lebedev Institute, Russia

The Naval Research Laboratory is the first to develop routine, high energy, efficient, and repetitive KrF capability

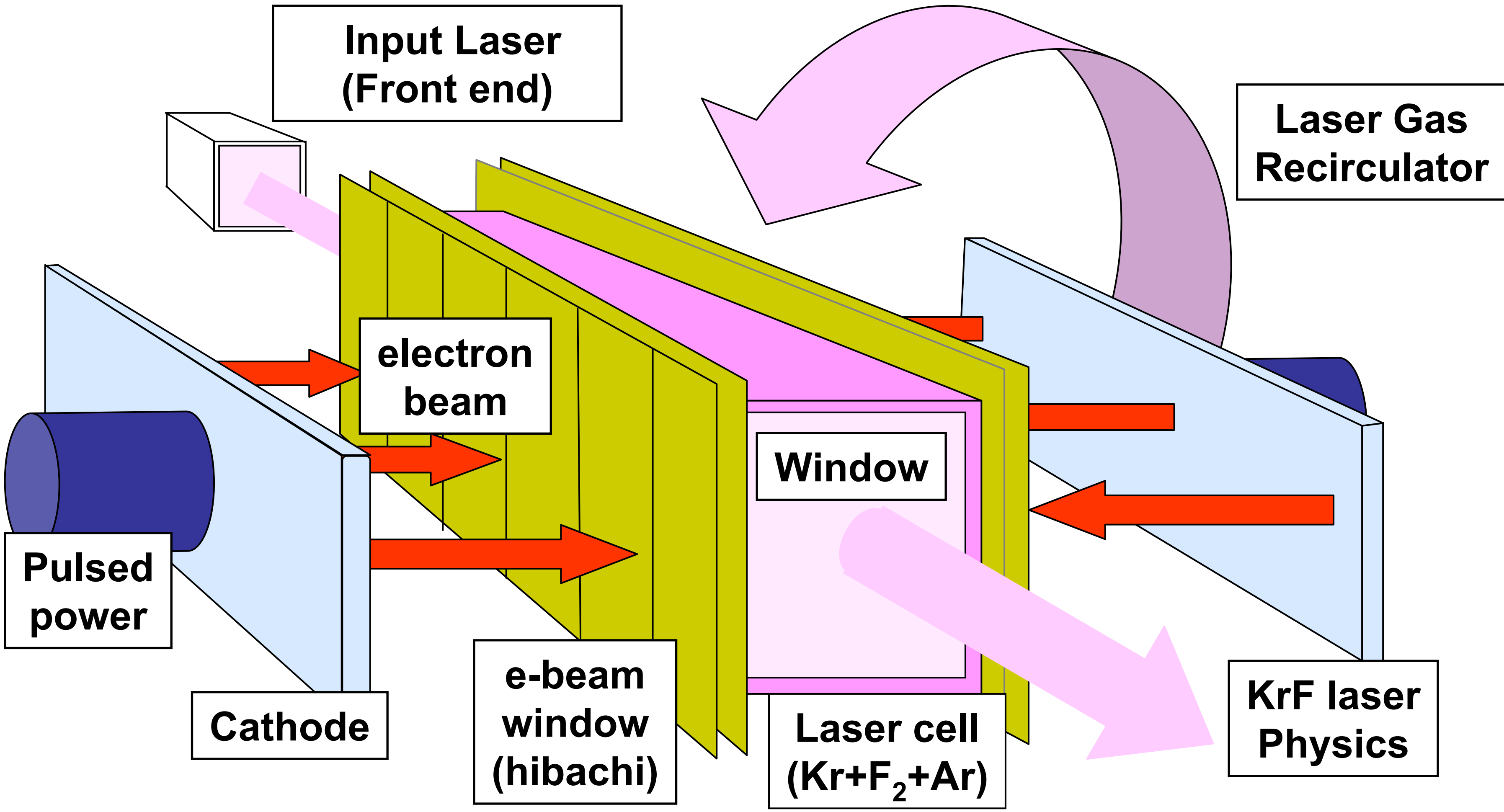
NRL Progress in KrF Laser Development

	2001	2010	IFE
Repetition rate (pulses/second)	.00056	2.5 to 5	5
Predicted Efficiency (%)	1.9	7.1	> 6.0
Durability (continuous shots)	200	90,000	300 M

Most all of these advances have been made through understanding and controlling the relevant physics

Elements of a Krypton Fluoride (KrF) electron beam pumped gas laser

Energy + (Kr+ F_2) $\Rightarrow$ (KrF)* + F $\Rightarrow$ Kr + F_2 + hν (λ = 248 nm)

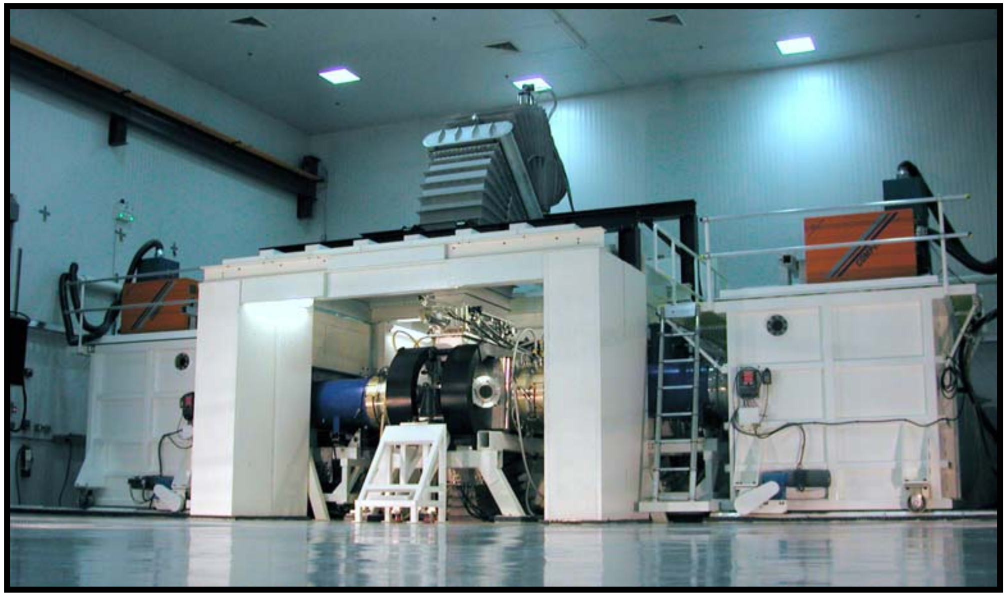


Typical e-beam: 500 -700 keV, 100 - 500 kA, 3000 – 12,000 cm^2

KrF developed with the NRL Electra and Nike Lasers

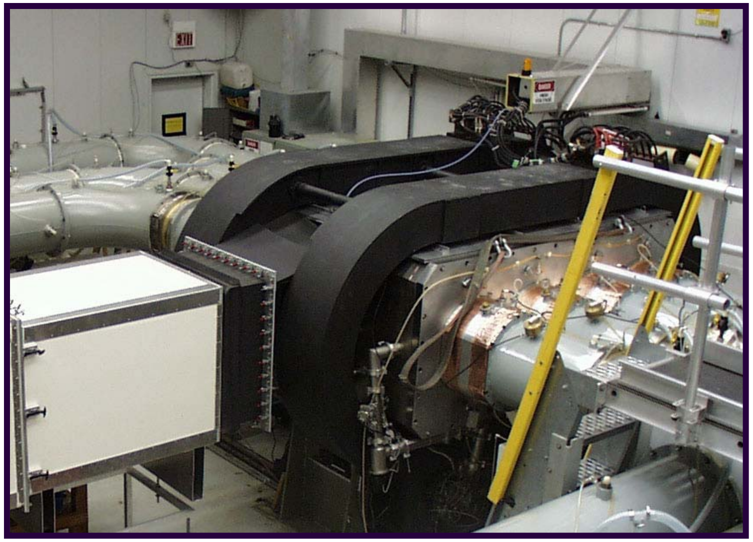
Electra: (5 Hz)
400-700 J laser light
500 keV/100 kA/100 nsec
30 cm x 100 cm e-beam

Develop technologies for:
Rep-Rate,
Durability,
Efficiency,
Cost

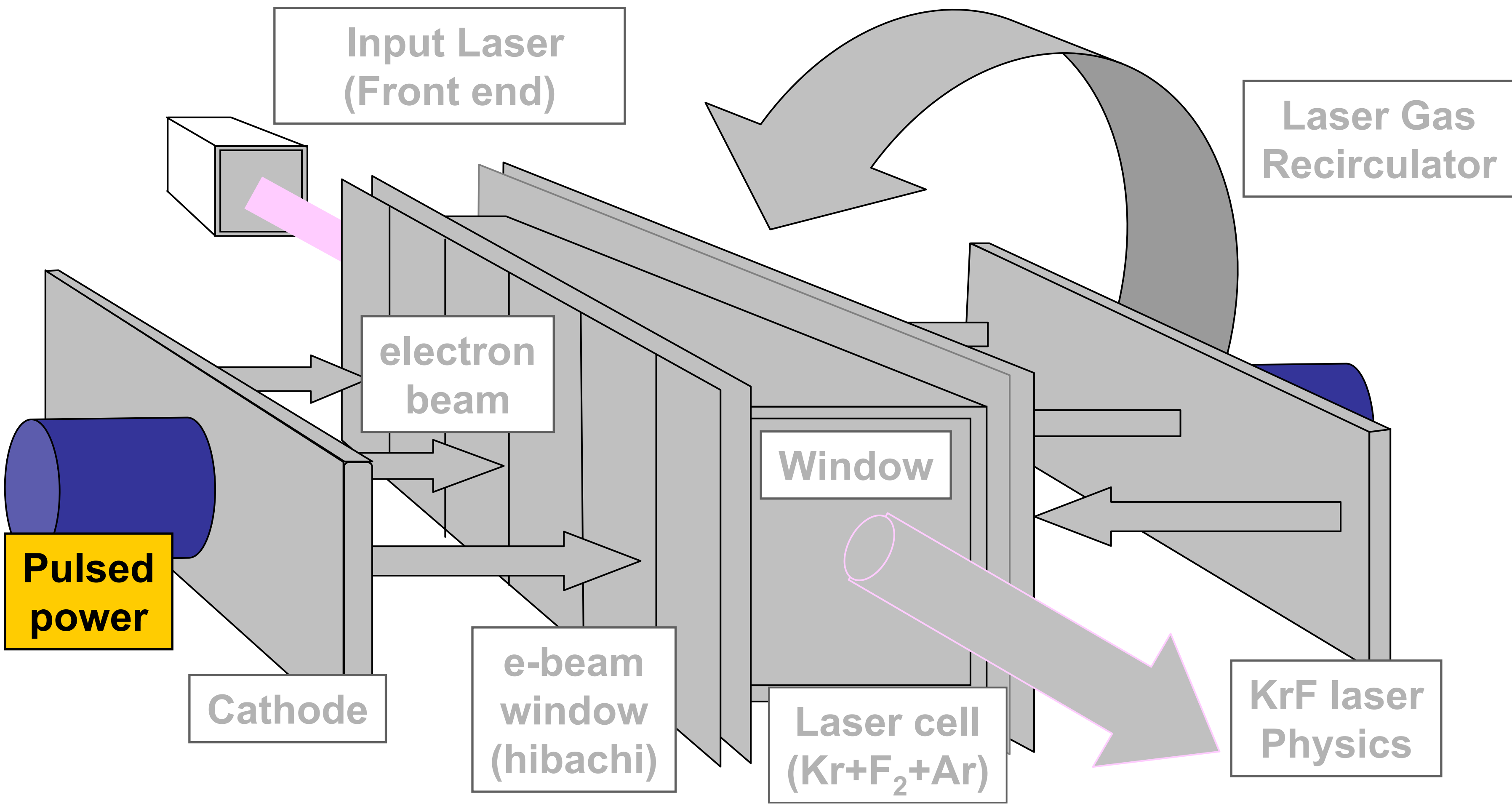


Nike: (Single Shot)
3-5 kJ laser light
750 keV, 500 kA, 240 nsec
60 cm x 200 cm e-beam

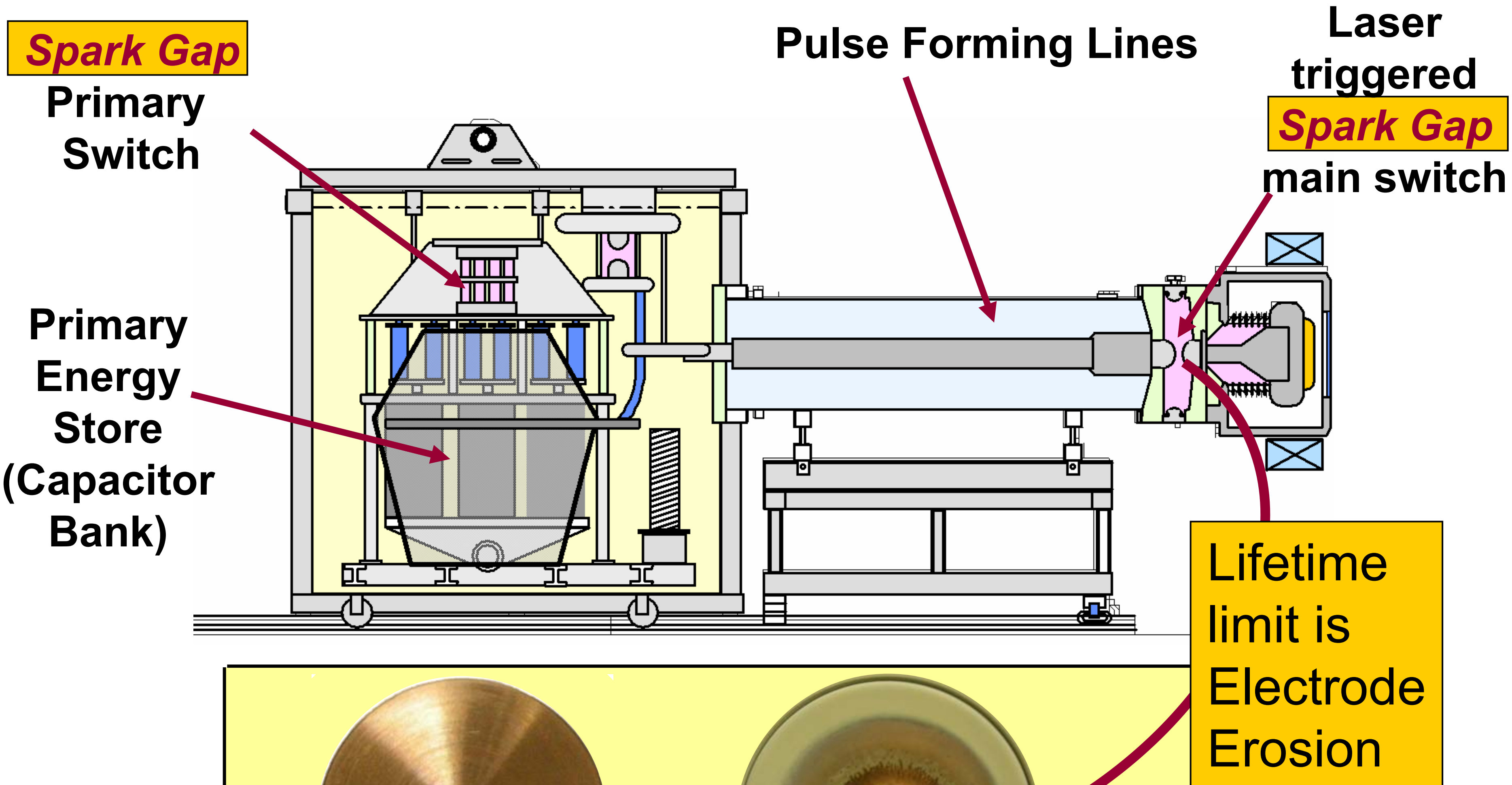
E-beam physics on full scale diode
Laser-target physics

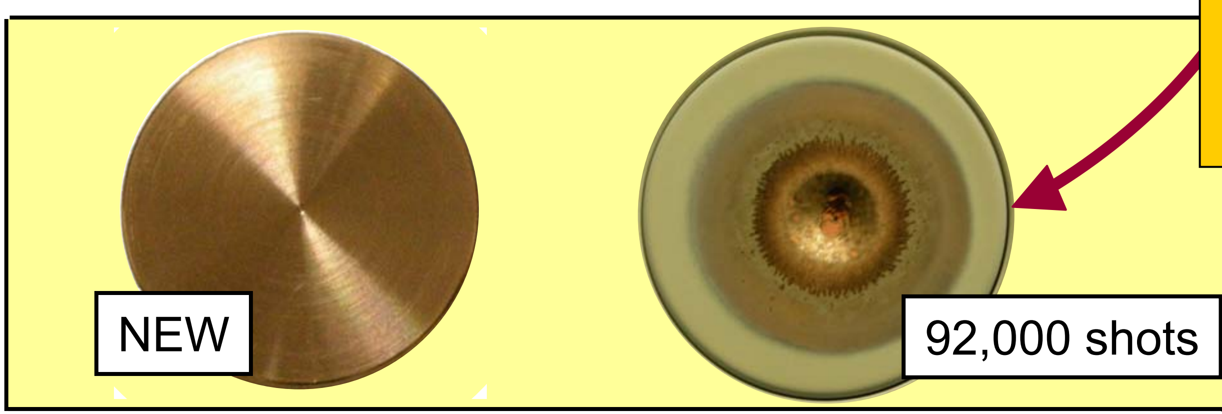


Pulsed Power



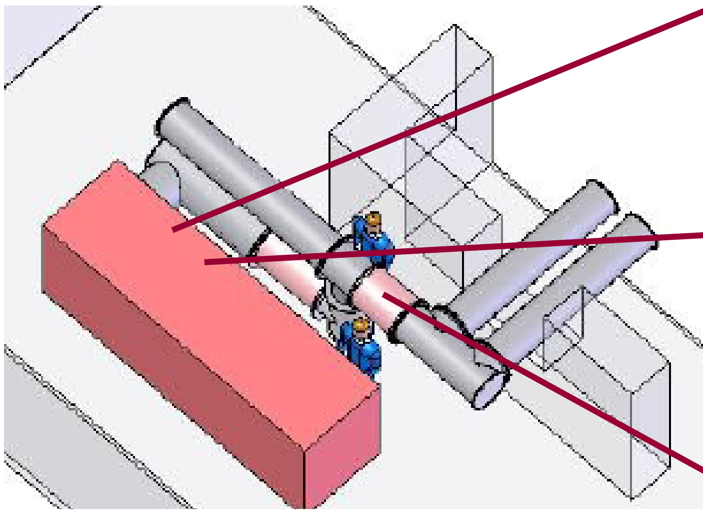
Existing "spark gap based" pulsed power system: Limited to 50,000 – 100,000 shots continuous





Solid State system should be durable and efficient

- Concept for Electra, scalable to IFE size system
- Basic elements tested to > 300 M shots



Primary Energy Store

Fast Marx

Long Life capacitors

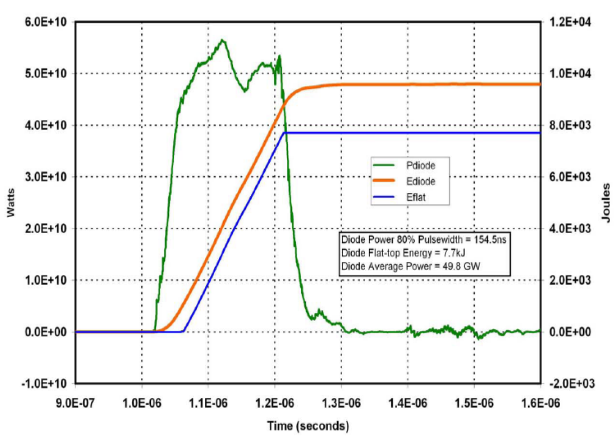
Primary Switches

New fast thyristors

(Modified commercial units)

Output Switch

Saturable Magnetic Inductor



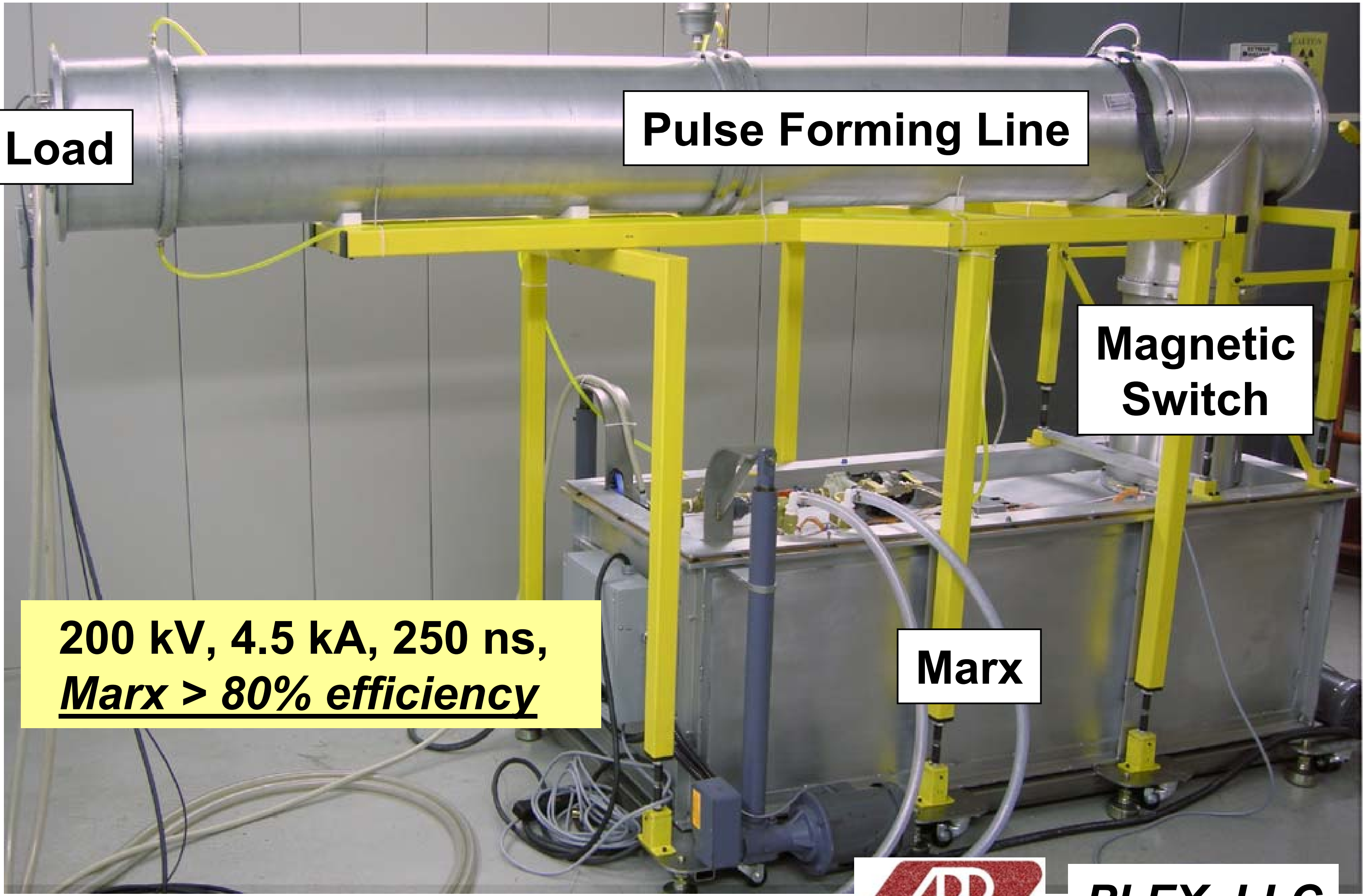
Modeled system for Electra:

Predict Efficiency > 82%

(Wall plug to flat top pulsed power)

PLEX, LLC

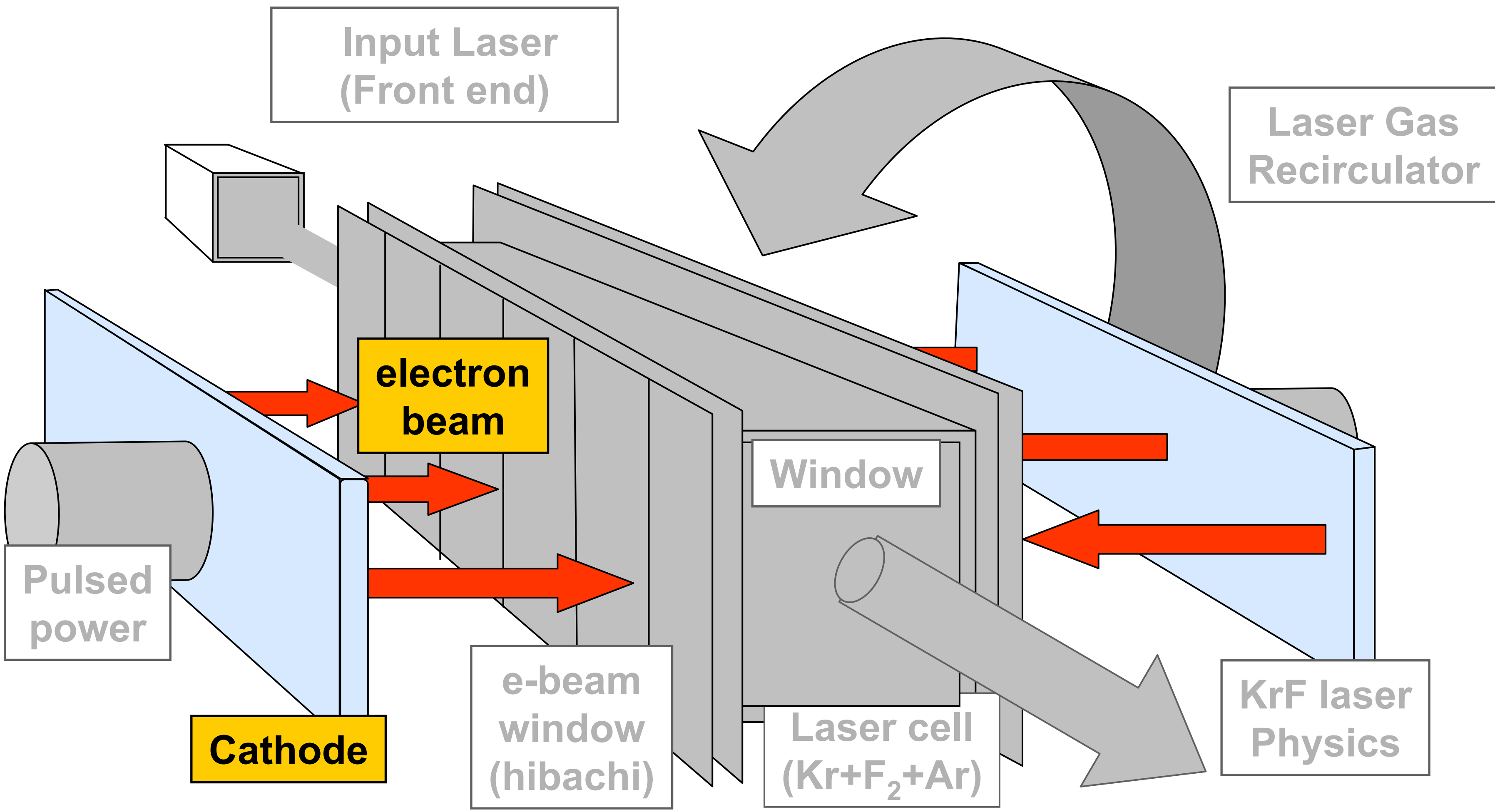
All Solid State Pulsed Power demonstrator
Continuous run: 11.5 M shots @ 10 Hz (319 hrs)



200 kV, 4.5 kA, 250 ns,
<u>Marx > 80% efficiency</u>

APP ***PLEX, LLC***

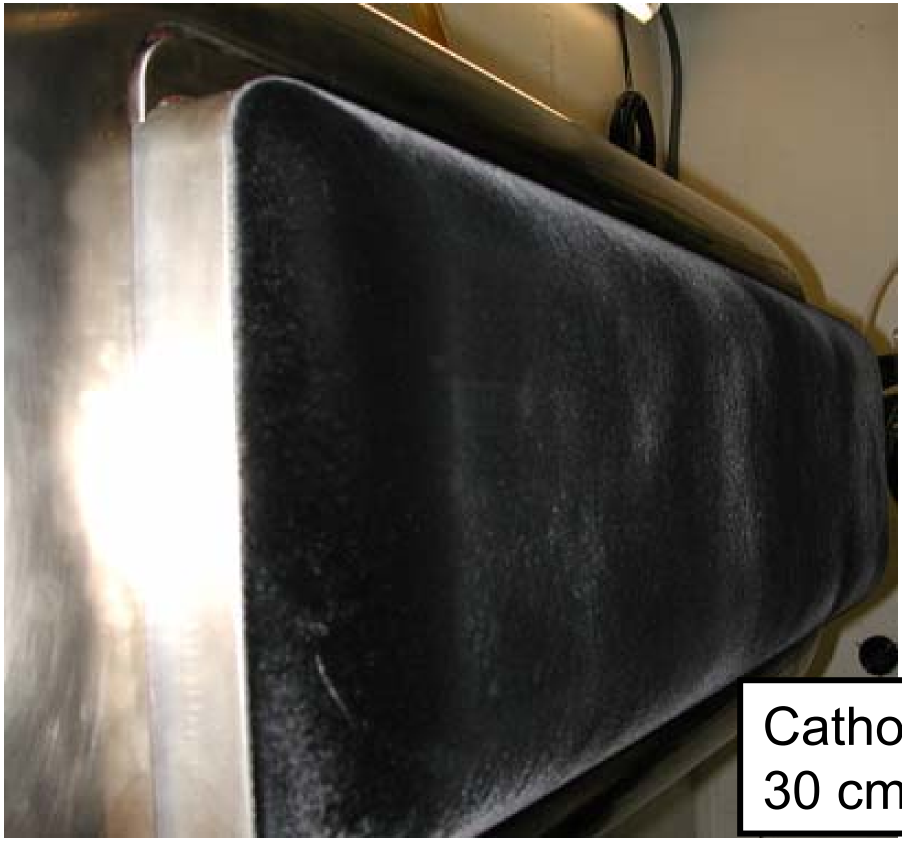
Electron Beam -- Generation and Transport



ELECTRON BEAM GENERATION

Need cold cathodes: simplicity, efficiency, durability

Best so far: Carbon Fibers pyrolized to aluminum



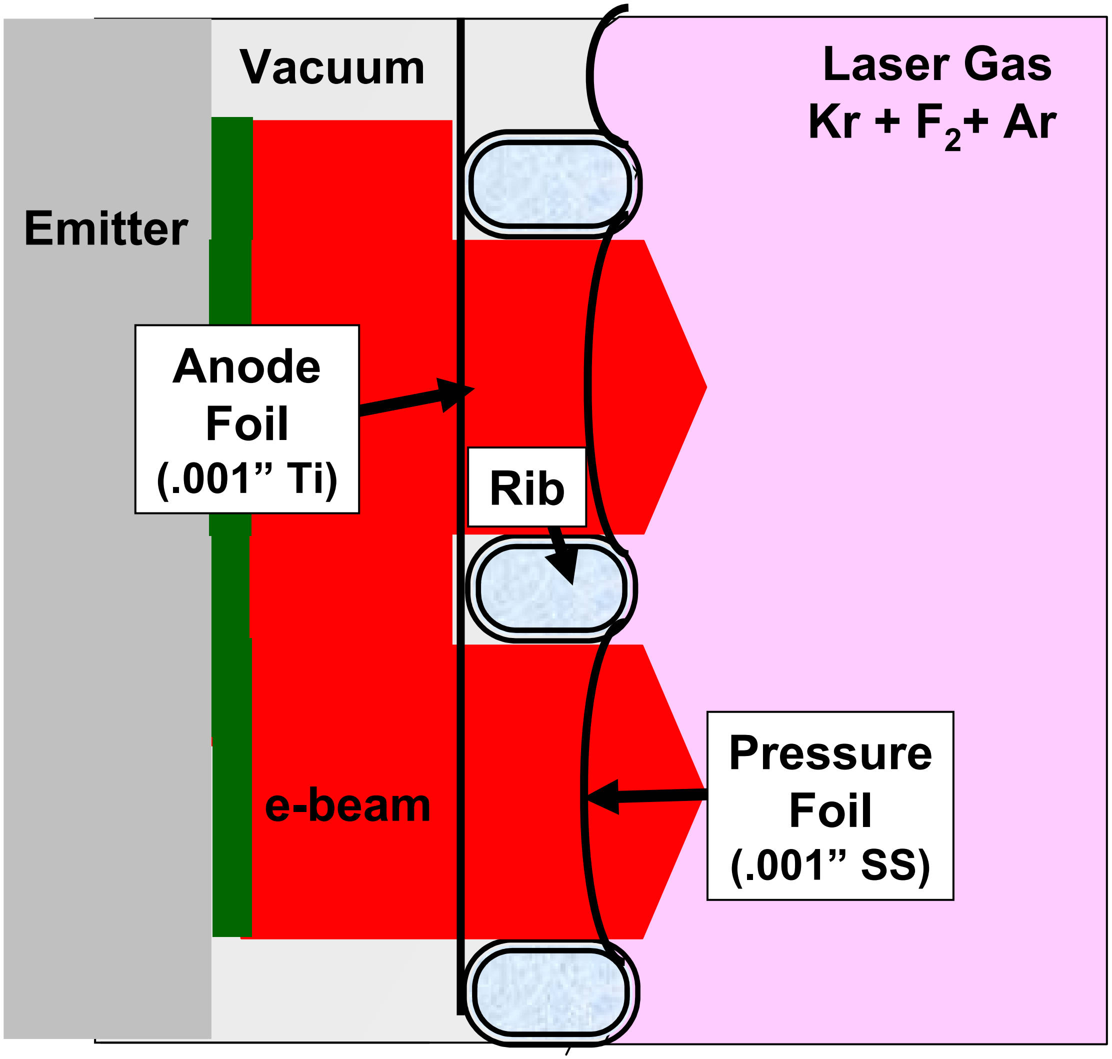
- Robust (> 250,000 shots)
- Low cost ($15 k Electra)
- Easy to make to patterned cathodes

Cathode dimensions:
30 cm x 100 cm

ELECTRON BEAM TRANSPORT

Two innovations gave high hibachi transmission:

1. Eliminate anode foil
2. Pattern the beam to "miss" the ribs

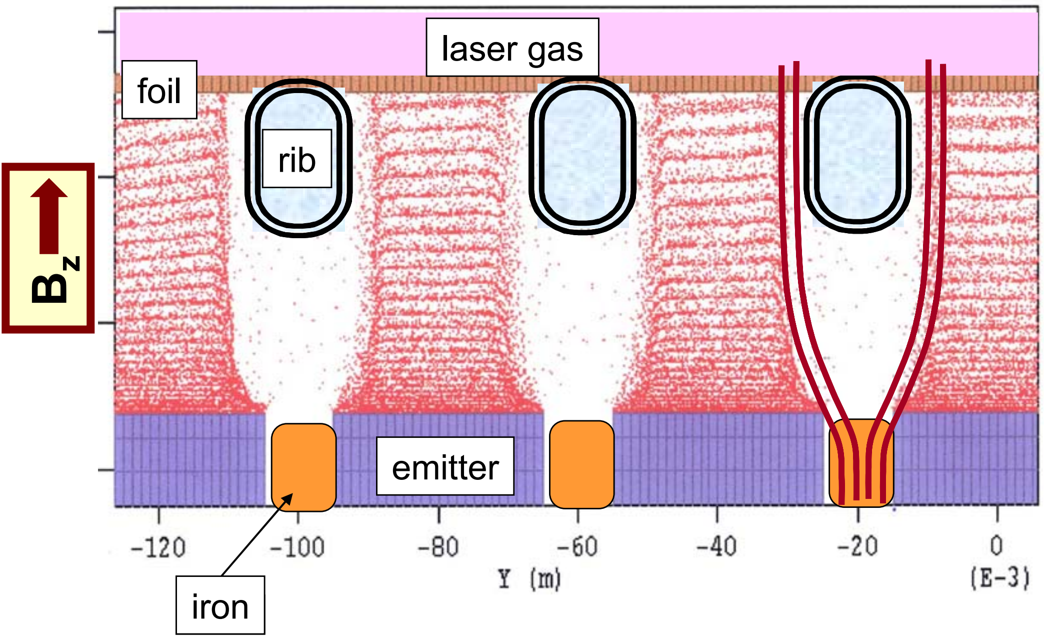


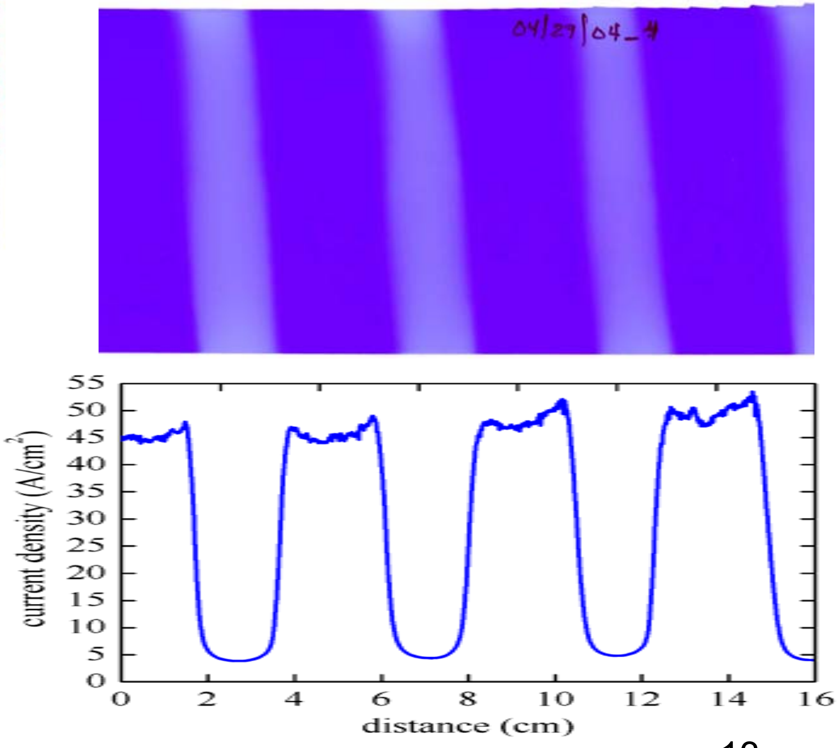
Energy Deposited in gas

Before: ~ 35%

After: ~ 76 - 81%

Simulations and experiments show iron bars can efficiently guide electron beam past the hibachi ribs





3-D LSP Simulations (Voss Scientific/Albuquerque)

- Prescribe the emitter topology
- Predict observed electron beam deposition into the gas

Efficiency ≡ Energy deposited in laser gas/energy flat portion of e- beam

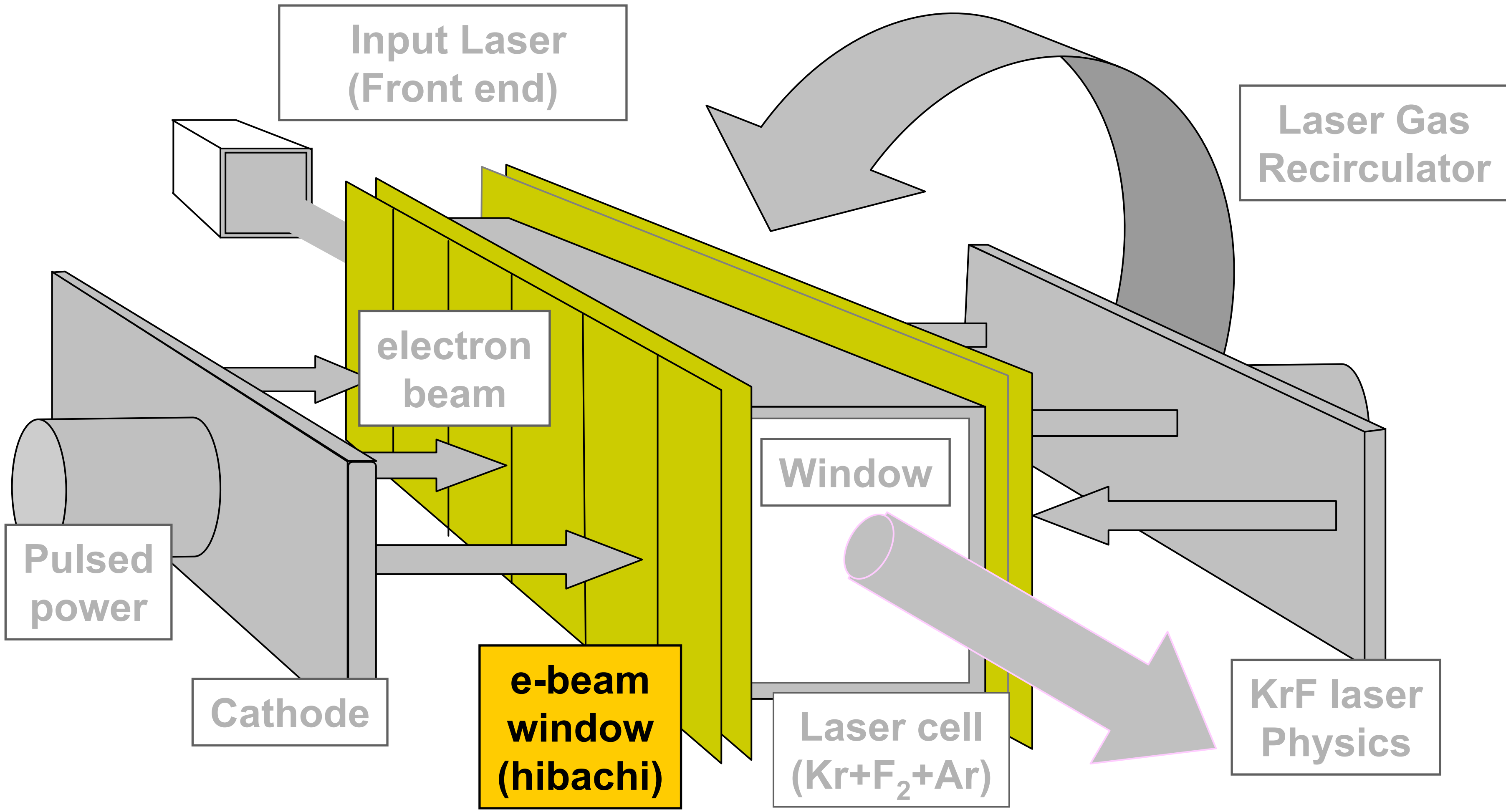
Deposition Efficiency

Efficiency ≡ Energy deposited in laser gas/energy flat top portion of beam)

E-beam Voltage	500 keV	500 keV	800 keV
Pressure Foil	2 mil (Ti)	1 mil (Ti)	1 mil (SS)
Experiments	67%	75%	N/A
Simulation	66%	76%	> 81%*

*1-D modeling for 800 keV full size IFE system

Hibachi Foil: Cooling and Durability



FOIL COOLING

Needed to avoid metal fatigue (470 °C for SS 304) and minimize unwanted chemistry

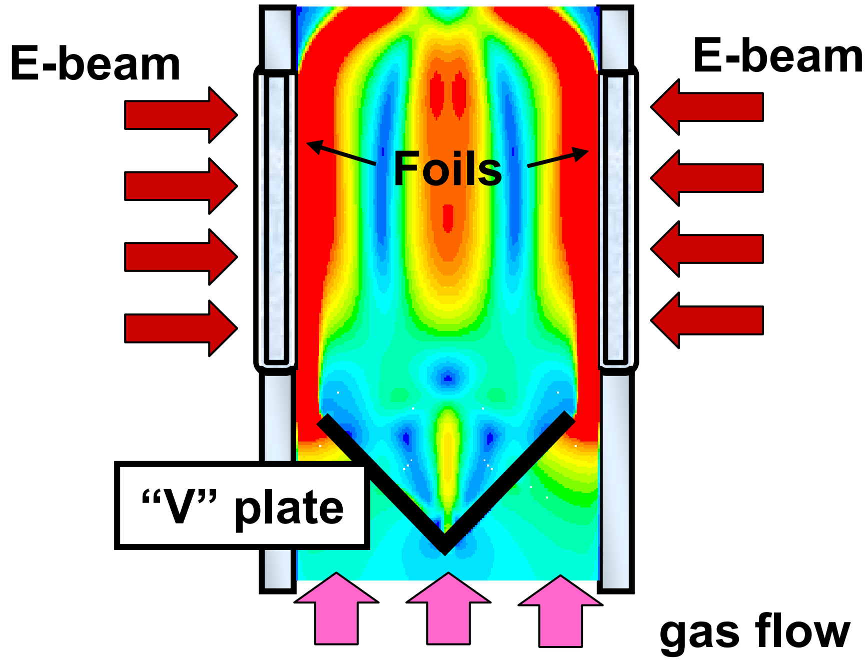
Two previous concepts we evaluated:

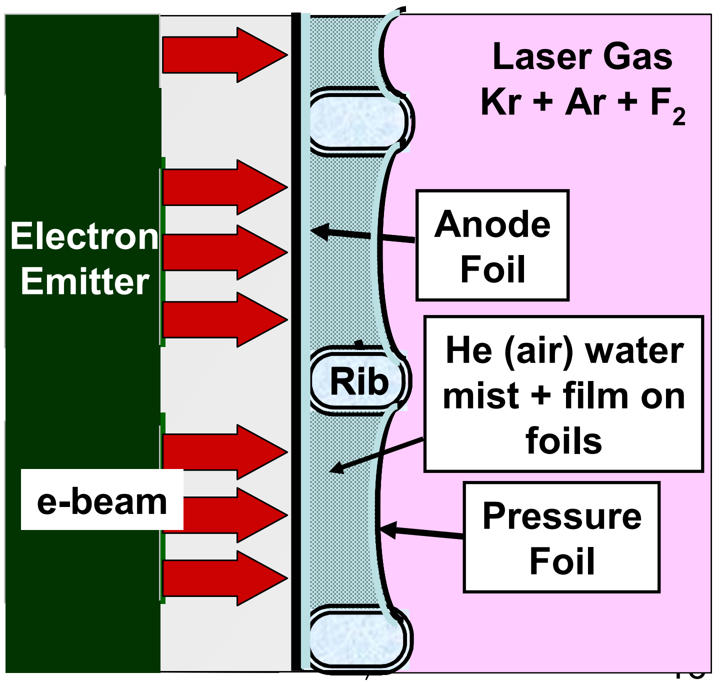
"V" plate

Foil Temp = 220 °C @ 2.5 Hz
Predict 440 °C @ 5 Hz. (A bit warm)

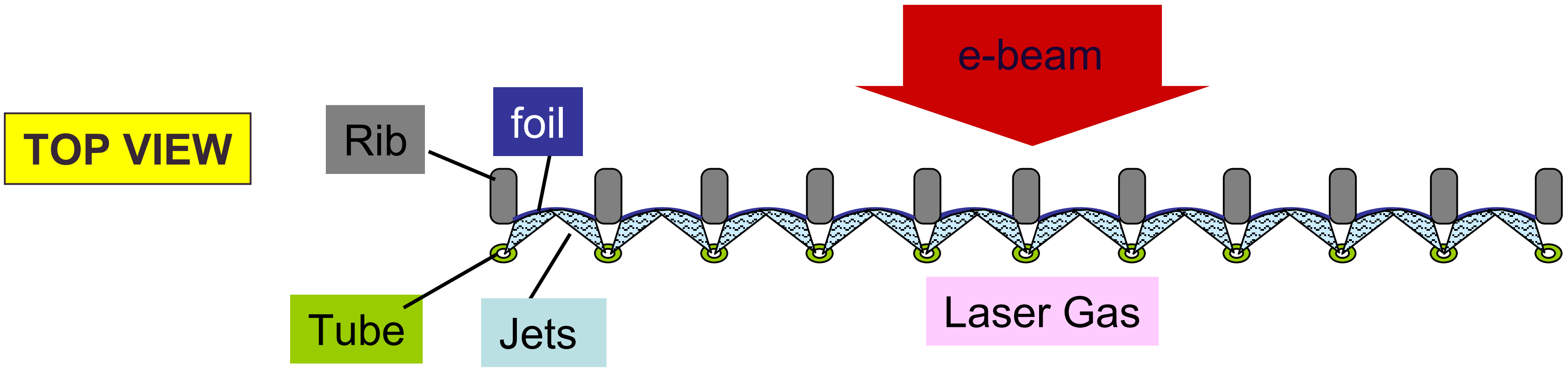
"Mist Cooling"

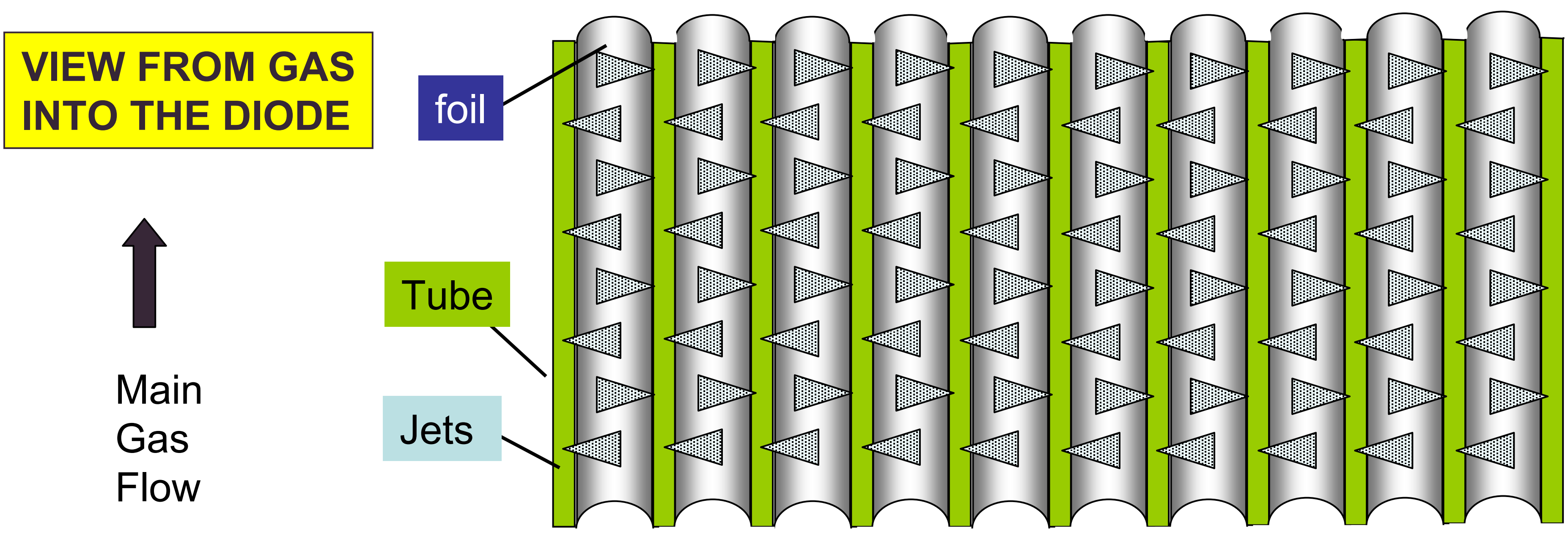
Foil Temp < 140 °C @ 5Hz



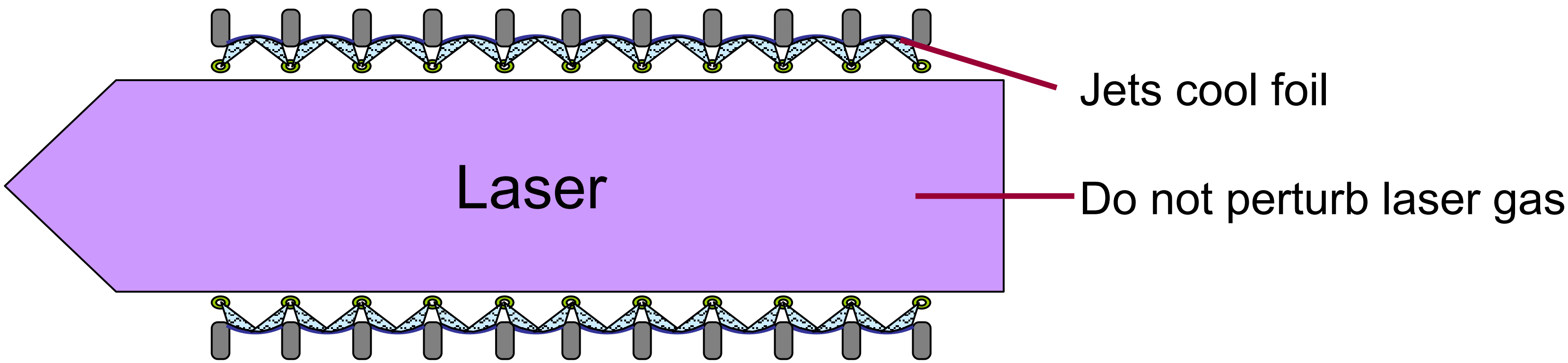


"Jet" cooling technique developed by Georgia Tech: Effective, efficient, and scalable to large apertures

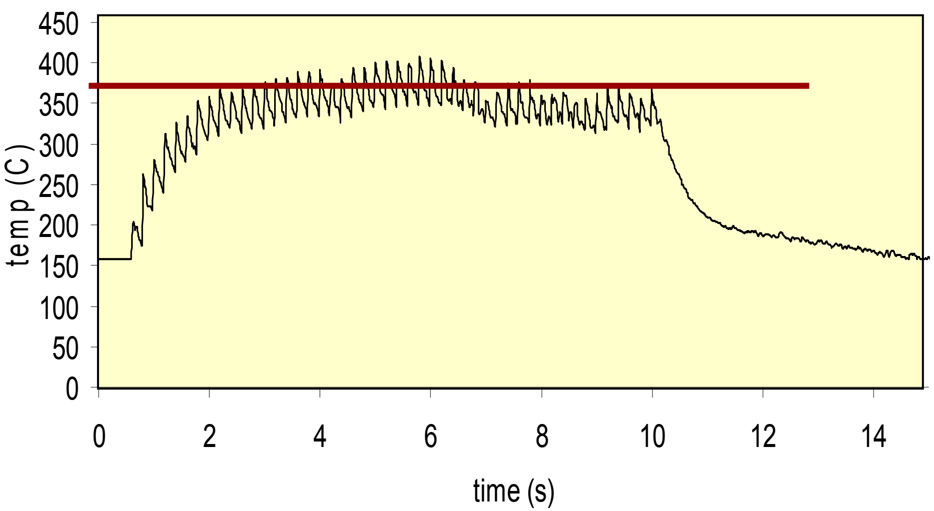




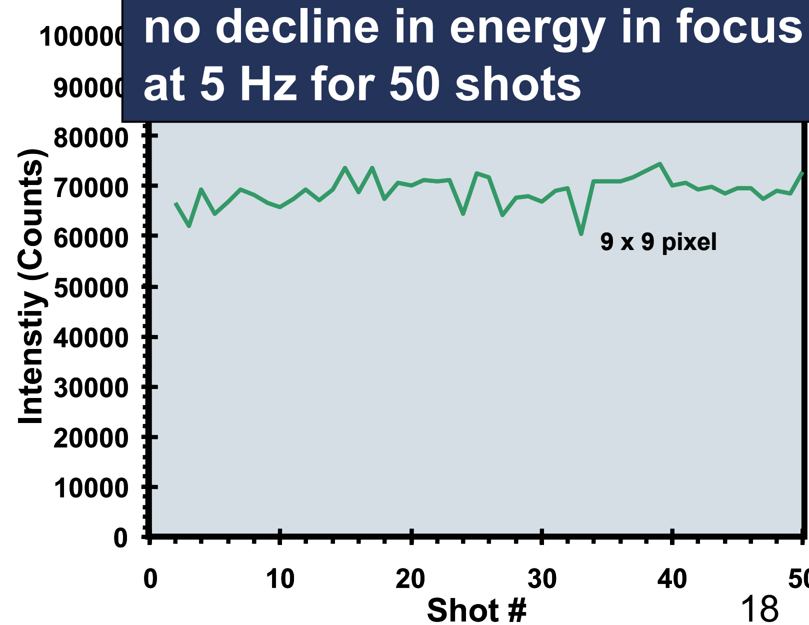
Jets cool foil while maintaining laser quality with minimal power consumption



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



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

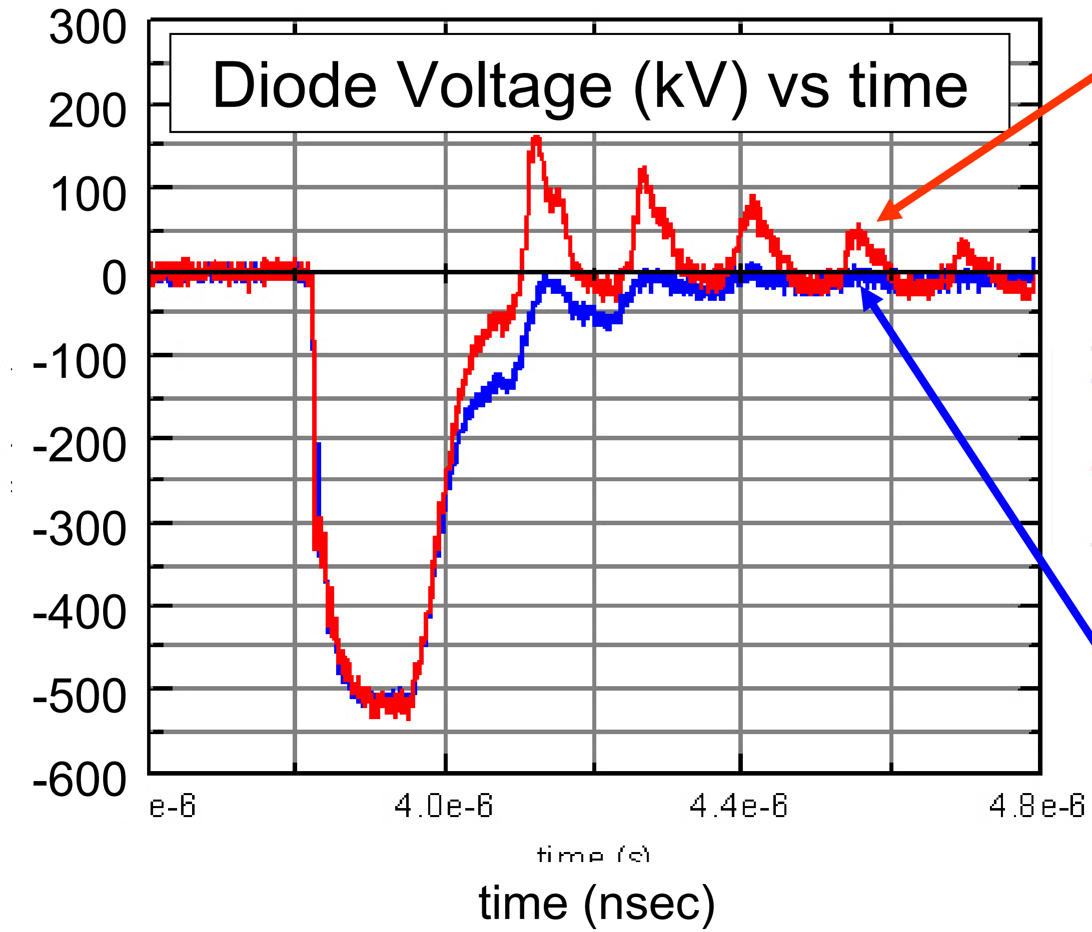


Georgia Institute of Technology & Matt Wolford

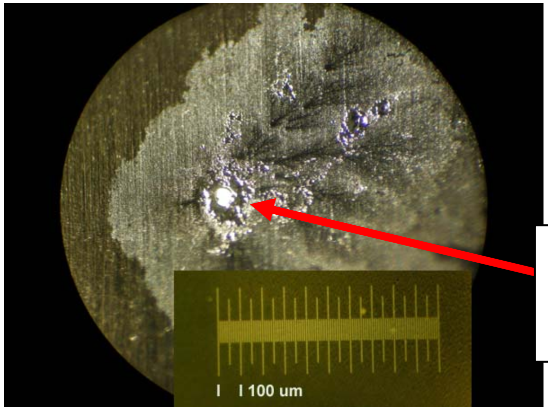
FOIL DURABILITY

One key: Control late time *voltage* in e - beam diode.

Increasing diode impedance 10%, lowering charge voltage 15%:
Eliminates voltage reversal, and hence damaging foil emission



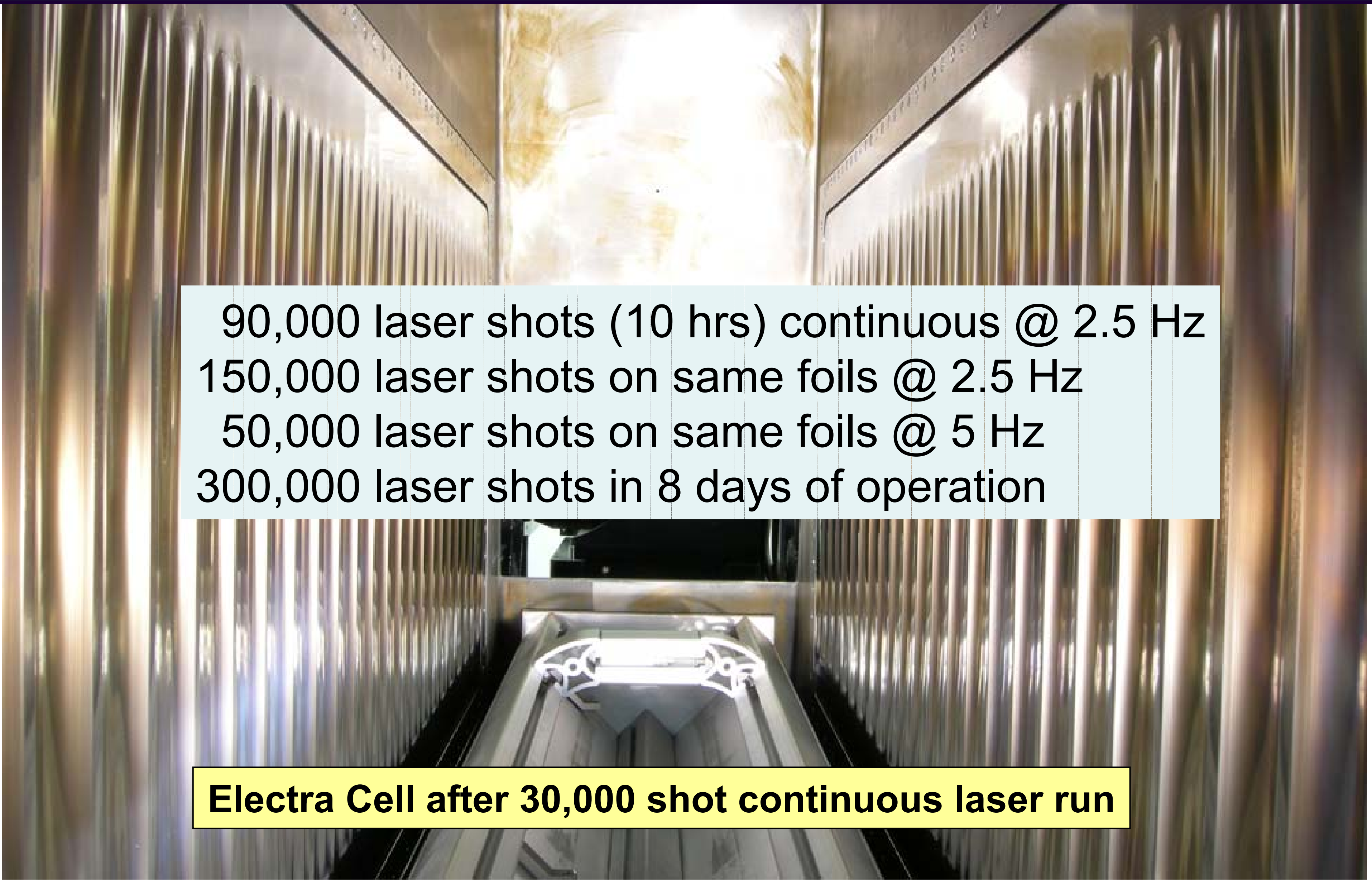
Voltage reverses
< 10,000 shot runs
Foil fails due to pinhole.
("Cathode spots")



80 μm pinhole

No Voltage reversal
~ 100,000 shot runs

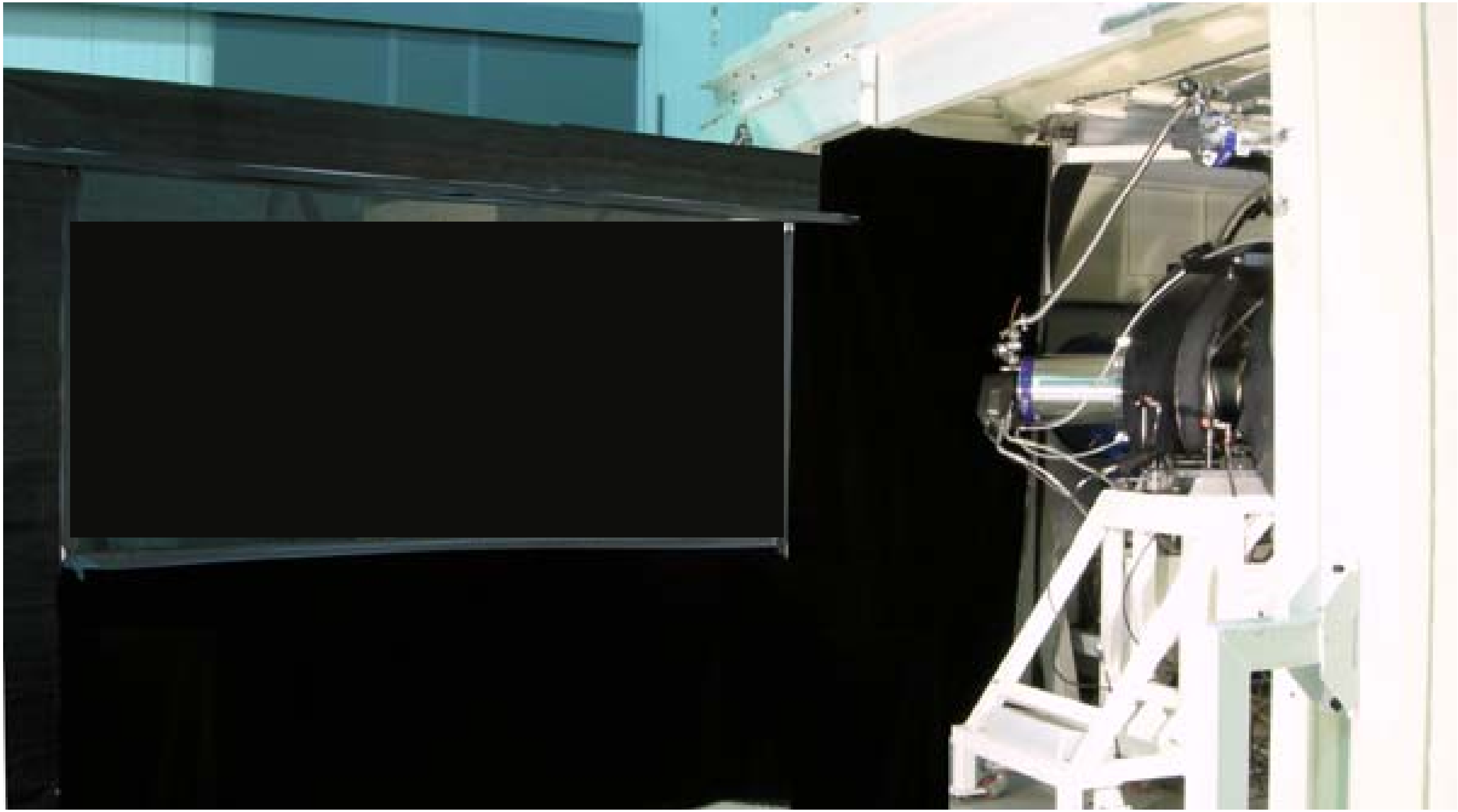
Electra now capable of ~100 k shot runs



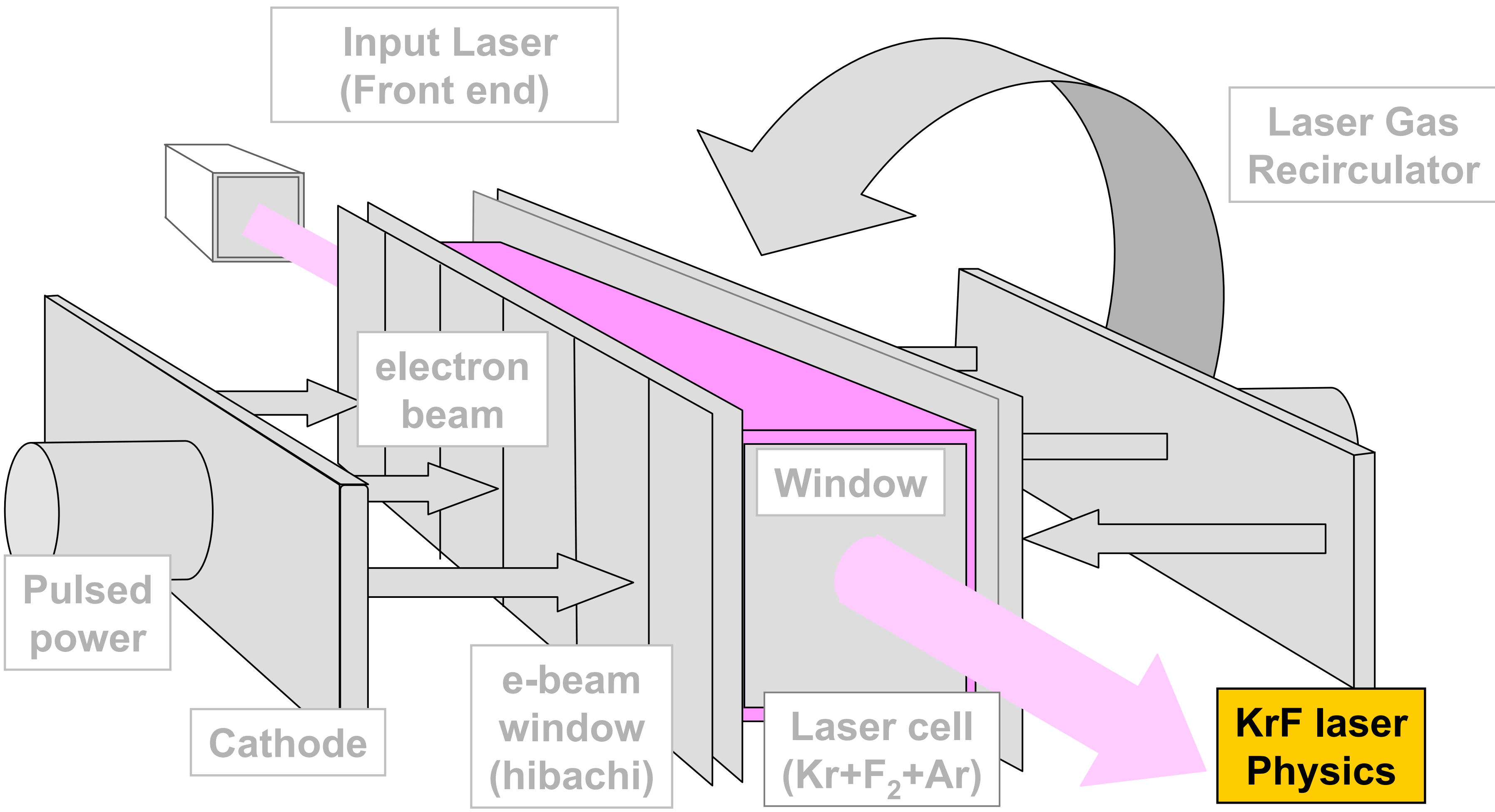
90,000 laser shots (10 hrs) continuous @ 2.5 Hz
150,000 laser shots on same foils @ 2.5 Hz
50,000 laser shots on same foils @ 5 Hz
300,000 laser shots in 8 days of operation

Electra Cell after 30,000 shot continuous laser run

A video starring Electra



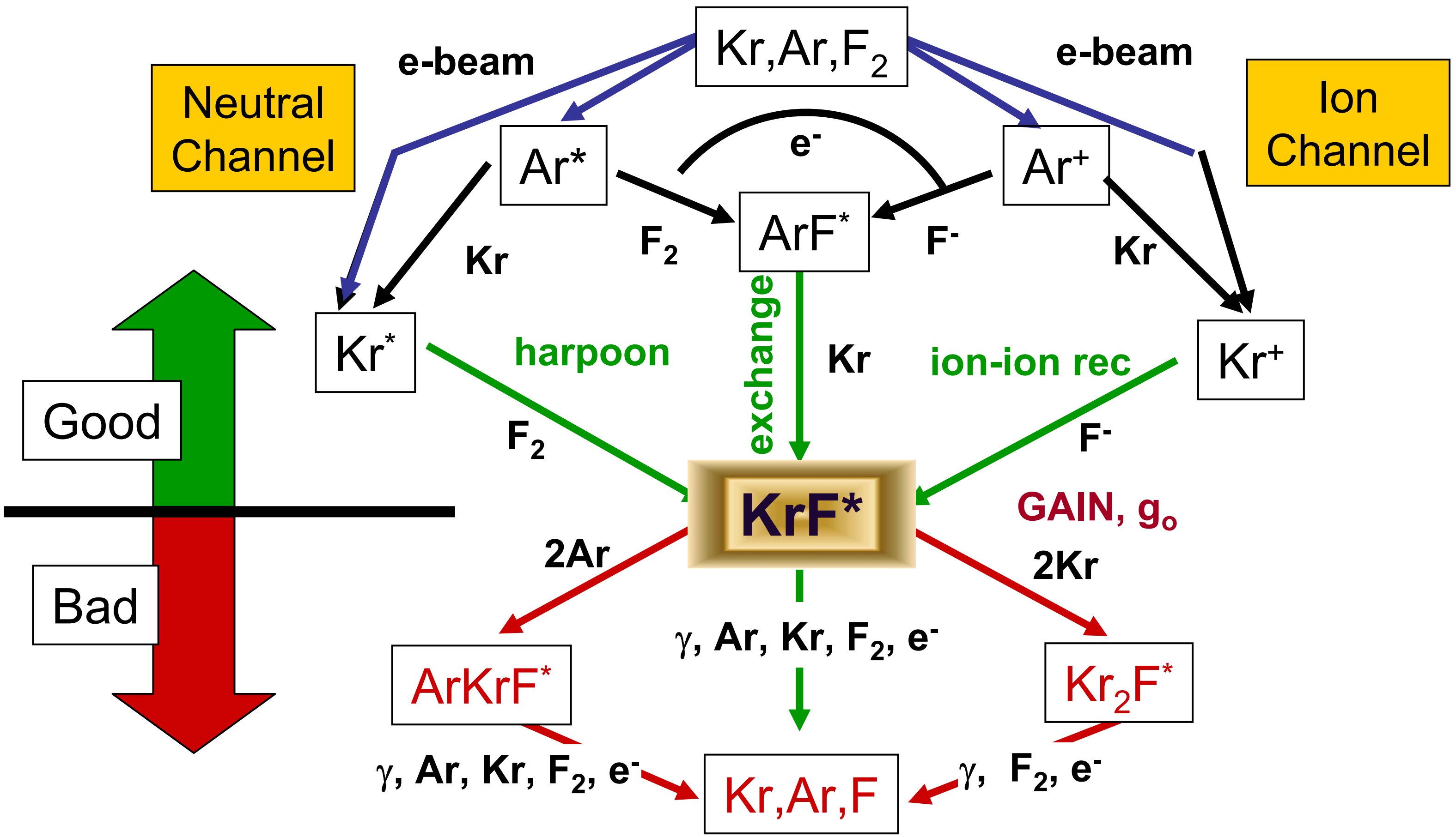
KrF Physics: Simulations and Modeling



KrF PHYSICS

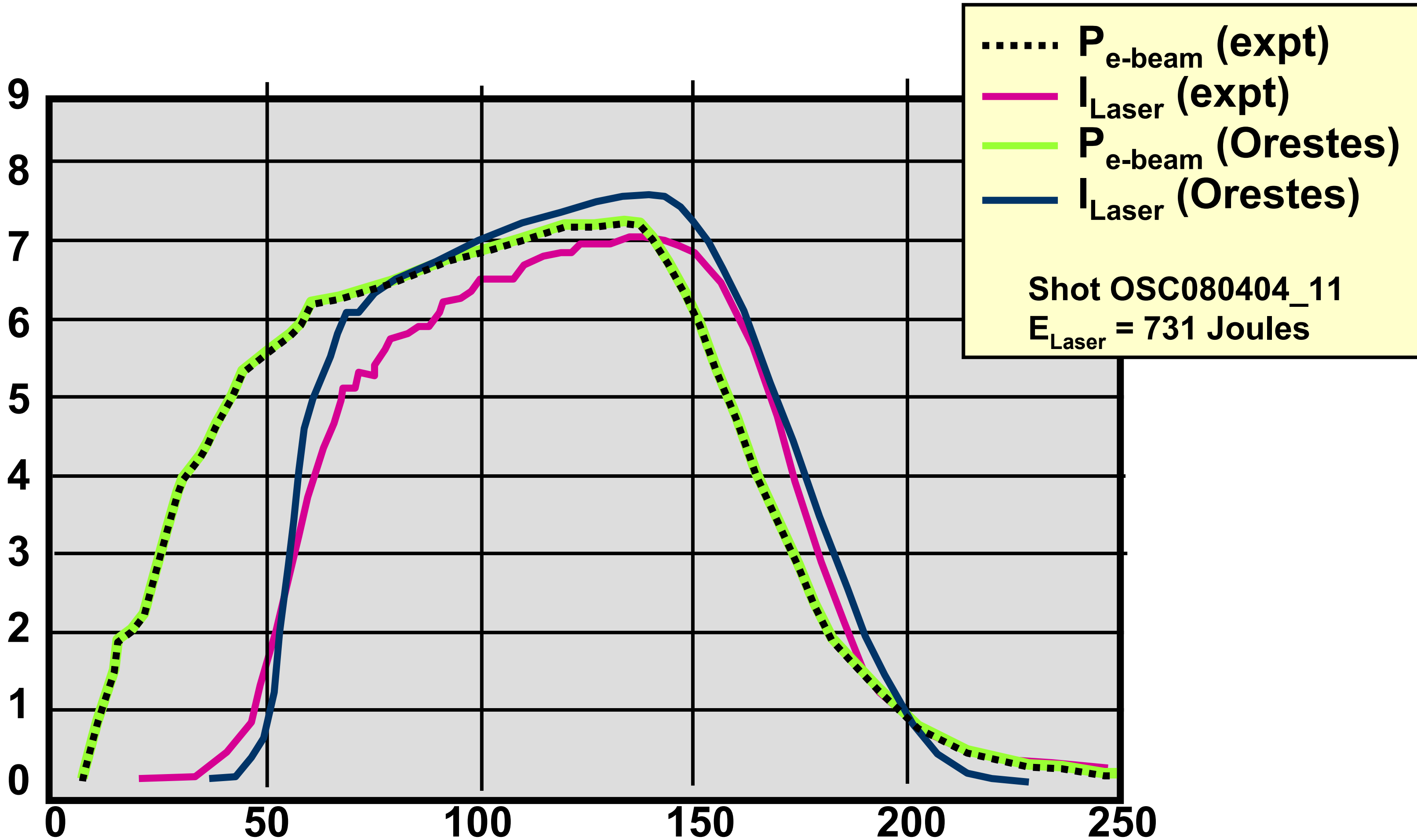
"Orestes" Code includes all relevant phenomena

1-D & 2-D Electron Deposition | *Plasma Chemistry*
3-D Laser Transport | *3-D Amplified Spontaneous Emission*
24 species, 146 reactions, 53 vibrational states



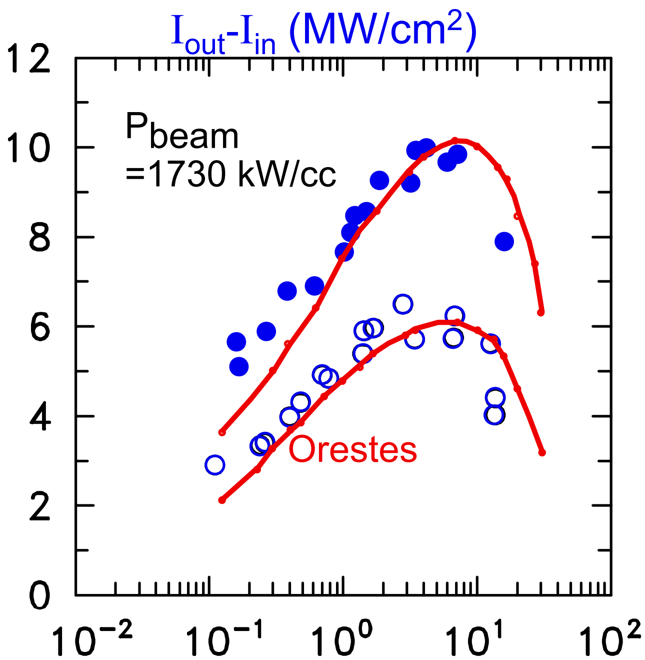
absorption, $\sigma = \sigma_{F2}\eta_{F2} + \sigma_{F-}\eta_{F-} + \sigma_{KrF2}\,\eta_{KrF2} + \sigma_{ArF2}\,\eta_{ArF2}$

Orestes accurately predicts Electra Main Amplifier Laser Pulse



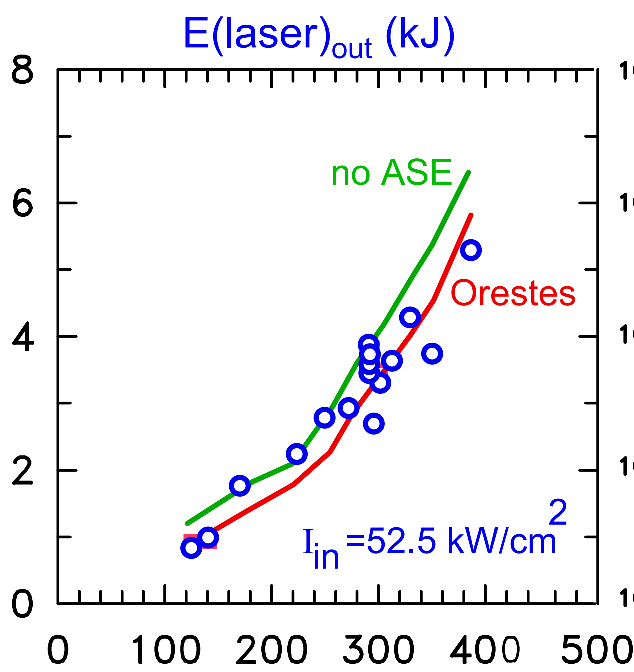
Orestes predicts performance of many KrF Lasers operating over a wide range of parameters

(a) Keio Univ.'s single pass amp



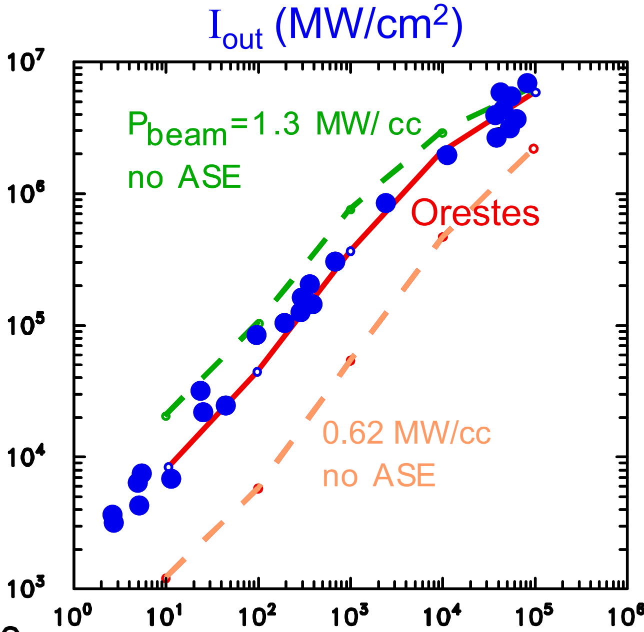
[Suda, et.al., Appl.Phys. Lett., **51**, 218 (1987)].

(b) NRL's NIKE double pass amp



[McGeoch, et.al., Fusion Tech., **32**, 610 (1997)].

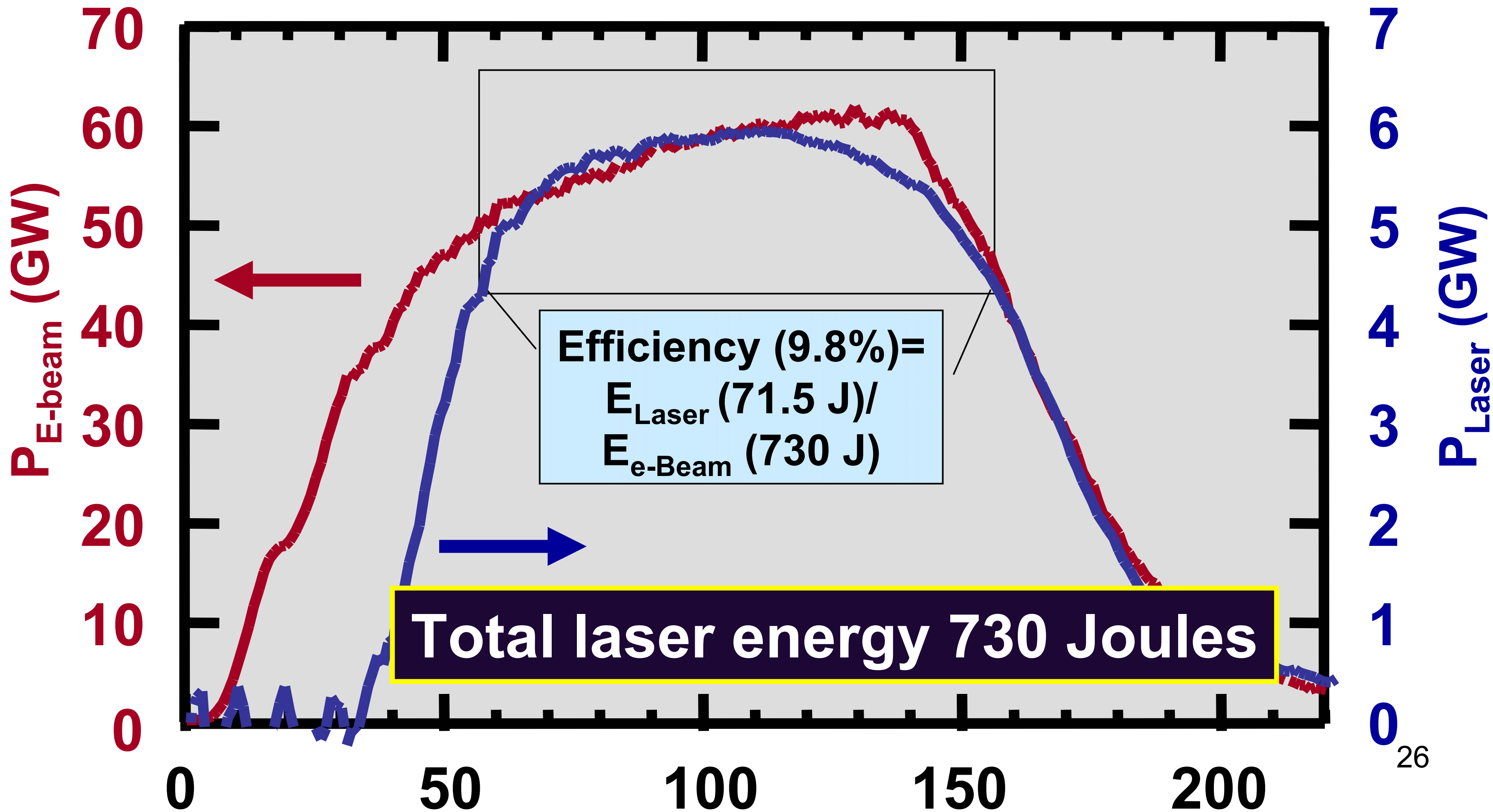
(c) Lebedev's Garpun single pass amp



[Zvorykin, et.al., Final Report, Lebedev Institute (2002)].

Electra: ~ 10% intrinsic efficiency as oscillator expect ~ 12 % as an amplifier

$$\text{Intrinsic Efficiency} \equiv \frac{\text{Laser energy}}{\text{e-beam energy}} \text{ (in flat part of pulse)}$$

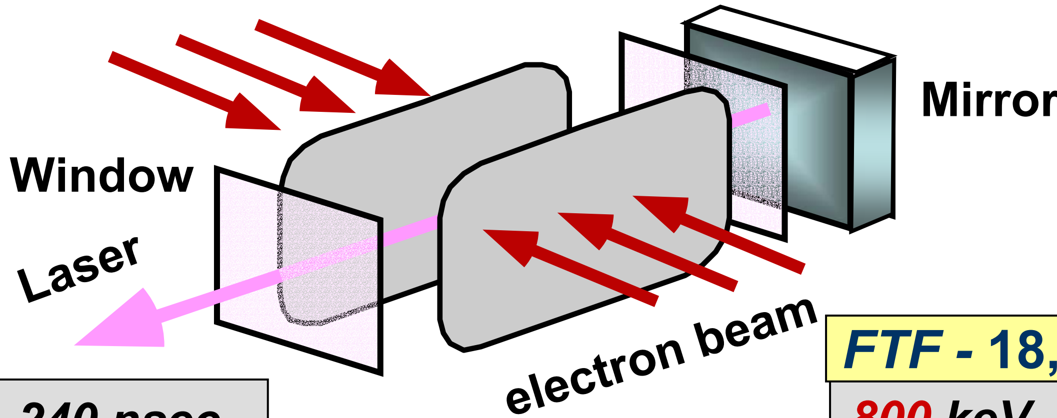


Based on our research, an IFE-sized KrF system should have a wall plug efficiency > 7%

Pulsed Power (wall plug- flat top e-beam)	**All solid state**	**82%**
Hibachi (e-beam in diode into gas)	**No Anode, Pattern Beam**	**81%**
KrF (e-beam to laser)	**Electra Experiments (literature ~ 14%)**	**12%**
Optics to target	**Estimate**	**95%**
Ancillaries	**Pumps, recirculator**	**95%**
Total		**7.1%**

For fusion energy want $\eta G > 10$.
with KrF and advanced targets: $\eta G = 7.1\% \times 300 \sim 21$

18 kJ, 5 Hz, KrF laser amplifier: Extrapolate Nike, using Electra Technologies

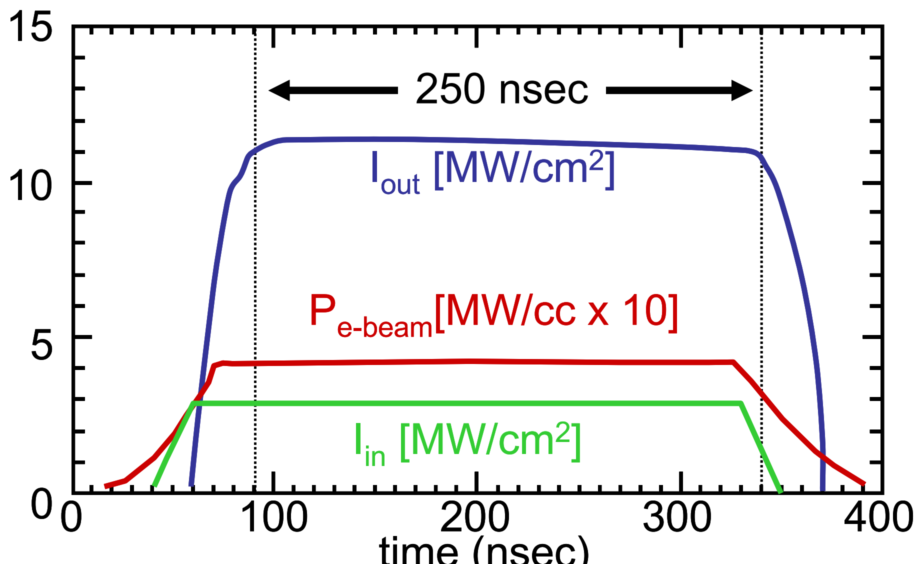


Nike - 5000 J

650 keV, 500 kA, 240 nsec
60 cm x 60 cm window
60 cm x 200 cm each beam
Monolithic Cathode

FTF - 18,000 J

800 keV, 500 kA, 250 nsec
60 cm x 100 cm window
60 cm x 250 cm each beam
Strip cathode



efficiency ~ 12%

Summary of Achievements.

- Durable, efficient, all solid state pulsed power
- Generation, transport, efficient deposition of electron beam
- Jet foil cooling
- Should meet efficiency, based on experiments
- Meets pulse shaping, zooming, uniformity requirements
- Orestes KrF physics code to design future systems

Main outstanding issue: >> 1M shot durability

SHORT TERM

- Windows (now quartz):
  - Exploring degradation mechanisms
  - Can use Calcium Fluoride, as in commercial units

- Foils:
  - Improve pulsed power durability
  - Mitigate all late time voltage

LONG TERM

- Long term integrated demonstration at IFE class size