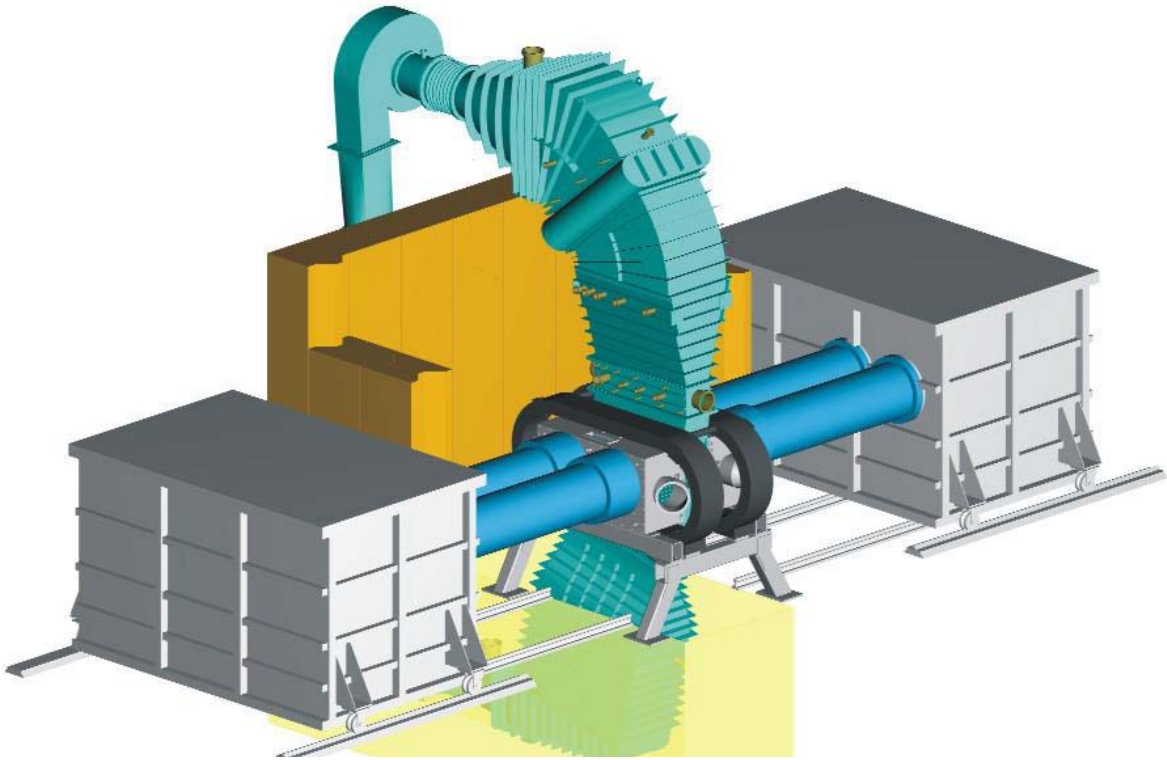
KrF Lasers for Fusion Energy



Presented by John Sethian
Naval Research Laboratory

Work proudly sponsored by DOE/NNSA/DP

NRL
M. Friedman
M. Myers
S. Obenschain
R. Lehmberg
J. Giuliani
P. Kepple

JAYCOR
S. Swanekamp

Commonwealth Tech
F. Hegeler

SAIC
M. Wolford
W. Yi
R. Smilgys

RSI
S. Searles

Titan PSD, Inc
D. Weidenheimer

MRC/Albuquerque
D. Rose
D. Welch

Georgia Tech
S. Abdel-Khalik

A three phase program to develop Laser Fusion Energy

Phase III
Engineering Test Facility (ETF)
start ~2014, operating 2020

- *2-3 MJ, 60 laser beam lines*
- Optimize high gain target implosions
- Optimize chamber materials & components.
- Generate ~ 300 MW electricity from fusion

?

Establish: Target physics, Full scale Laser technology, Power Plant design

Phase II
Integrated Research Experiment (IRE)
start ~2006

- *Laser facility* – 5 Hz full energy beam line, hits injected targets
- *Target facility*- inject Cryo pellets into chamber environment
- *Power Plant Design*

Target Physics-II
- 3D Modeling
- High Energy NIF experiments

?

Develop Viable: Target designs, scalable laser tech, target fab/ injection, final optics, chamber

Phase I:
Mission Oriented R&D
1999 - 2005

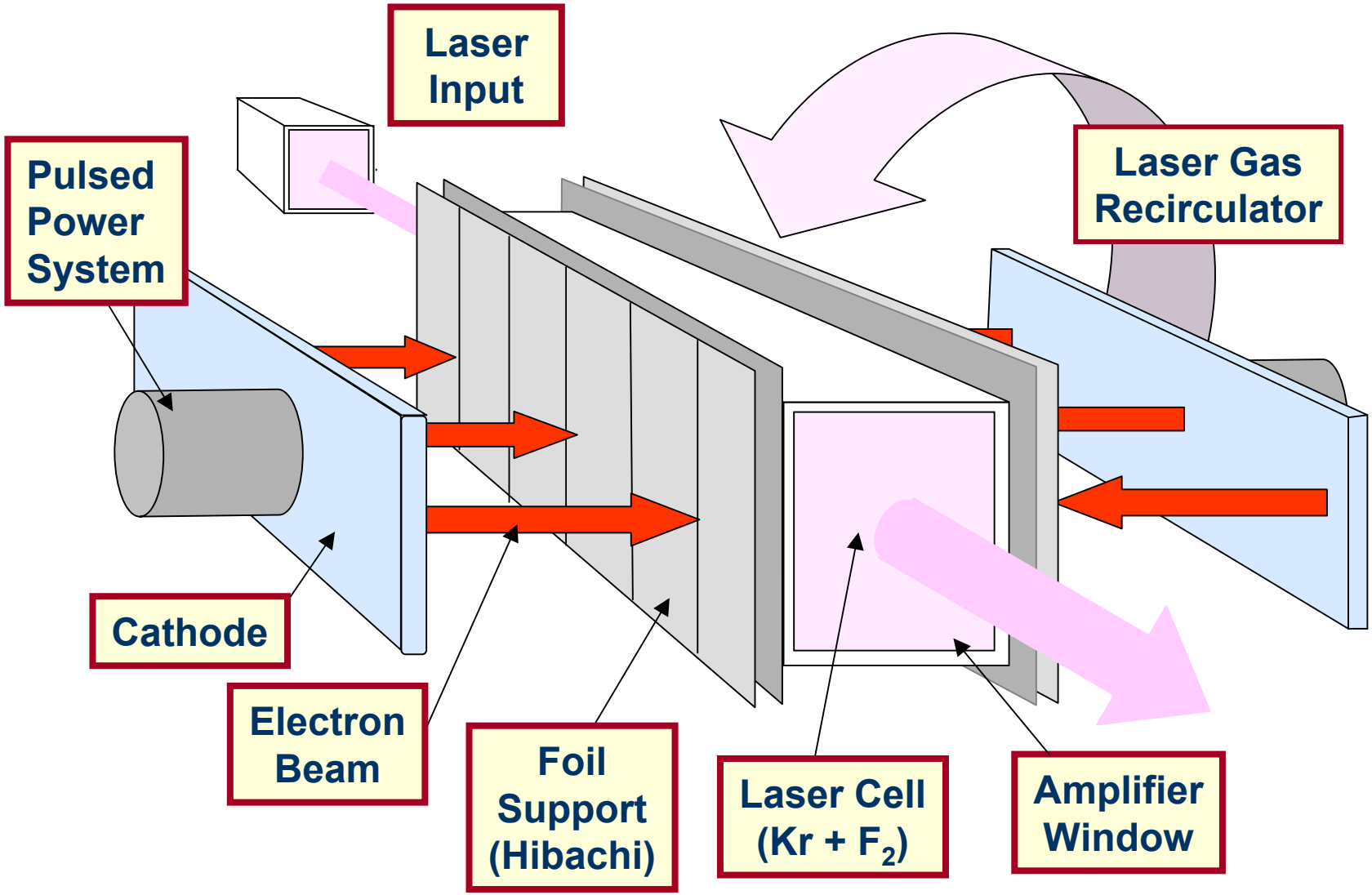
We are here

Lasers
- *Electra KrF*
- Mercury DPPSL

Other Components
- target fabrication
- target injection
- final optics
- chamber & materials

Target Physics-I
- 2D/3DModeling
- Laser/Target Expts @1-30 kJ (Nike & Omega)

The key components of a Krypton Fluoride (KrF) Laser



$$\text{ENERGY} + (Kr + F_2) \Rightarrow (KrF)^* + F \Rightarrow (Kr + F_2) + h\nu\ (248\ \text{nm})$$

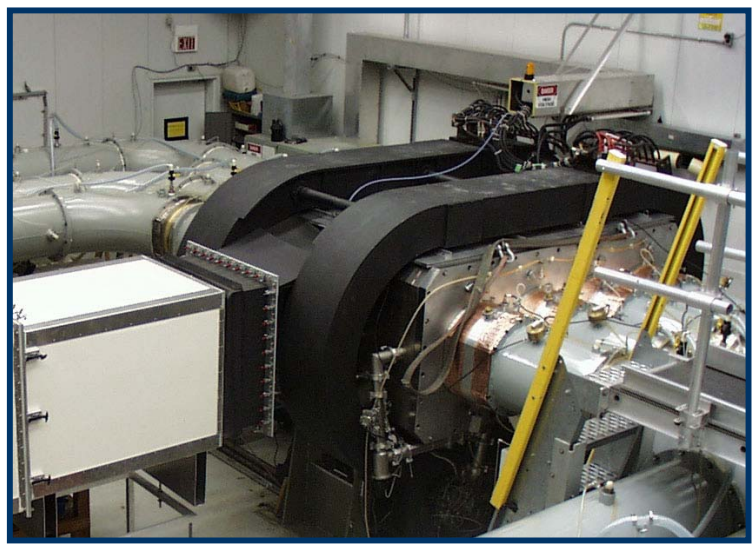
The key issues for KrF are being addressed with the Electra and Nike Lasers at NRL

Electra:
400-700 J,
5 Hz :

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

Nike:
2-3 kJ,
single shot

E-beam physics on full scale diode

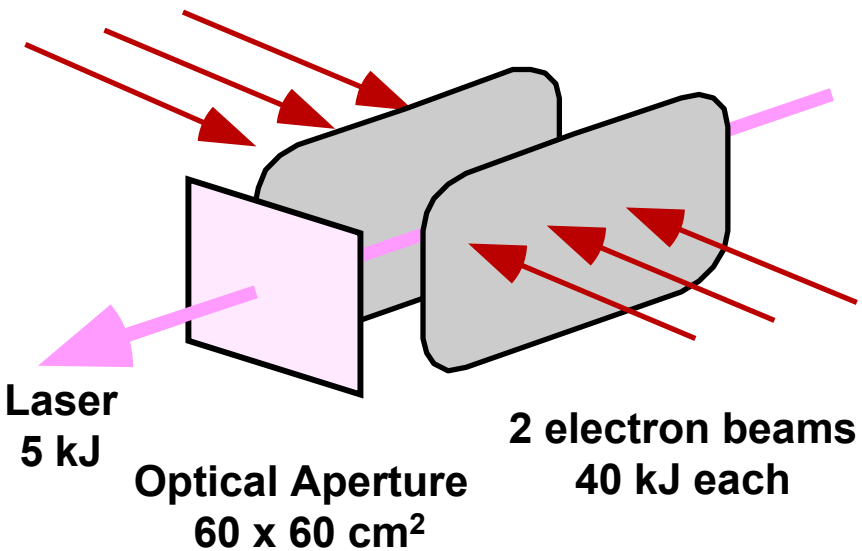


Program Philosophy: Technology Development + Predictive Capability

Large Amplifiers will be pumped with stacked pairs of diodes… each the same size as the Nike 60cm amplifier

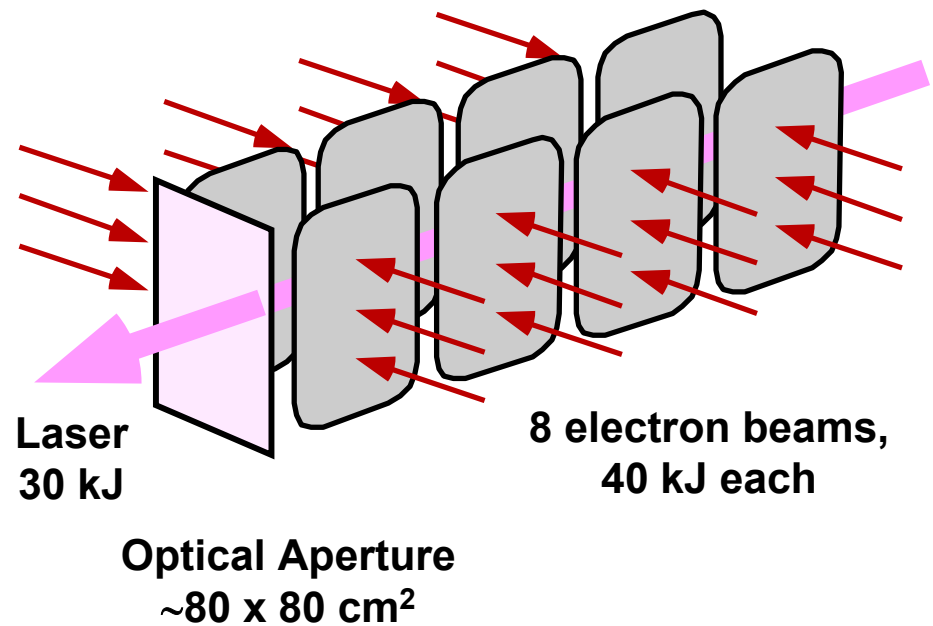
WHERE WE ARE…..

Nike 60cm Amplifier - 5 kJ output

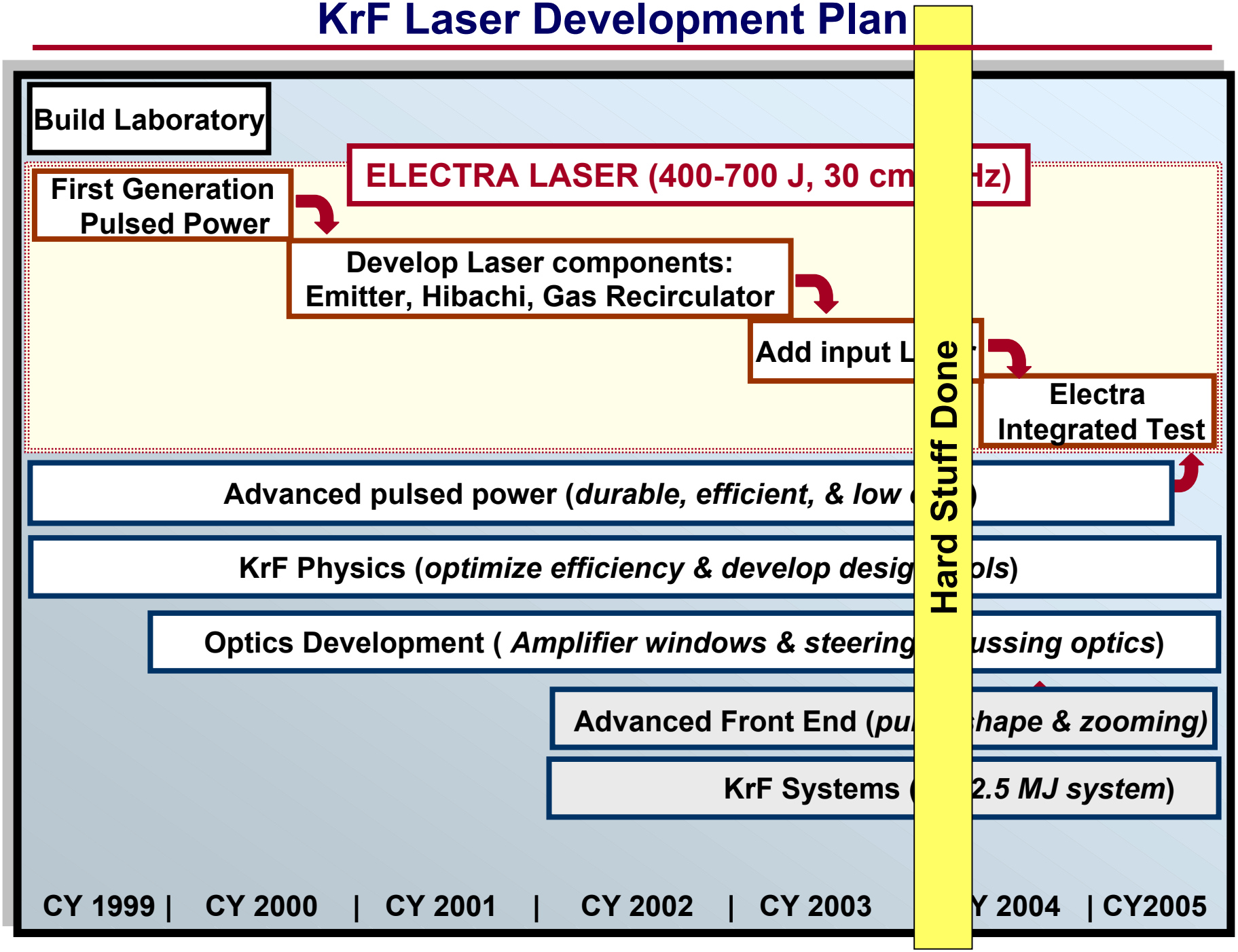


WHERE WE WANT TO BE….

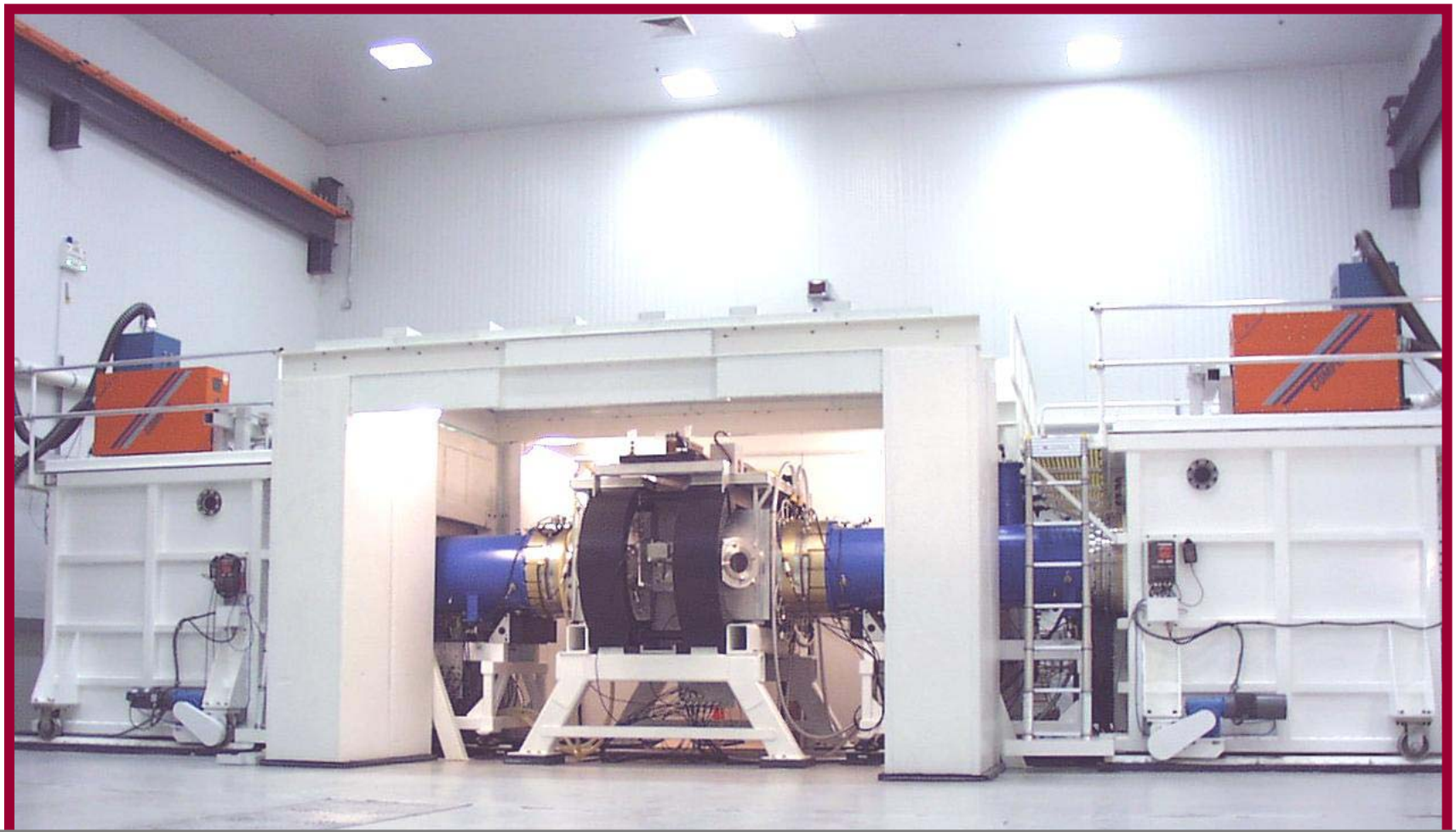
IFE-sized Amplifier- 30 kJ output
(Representation)



KrF Laser Development Plan



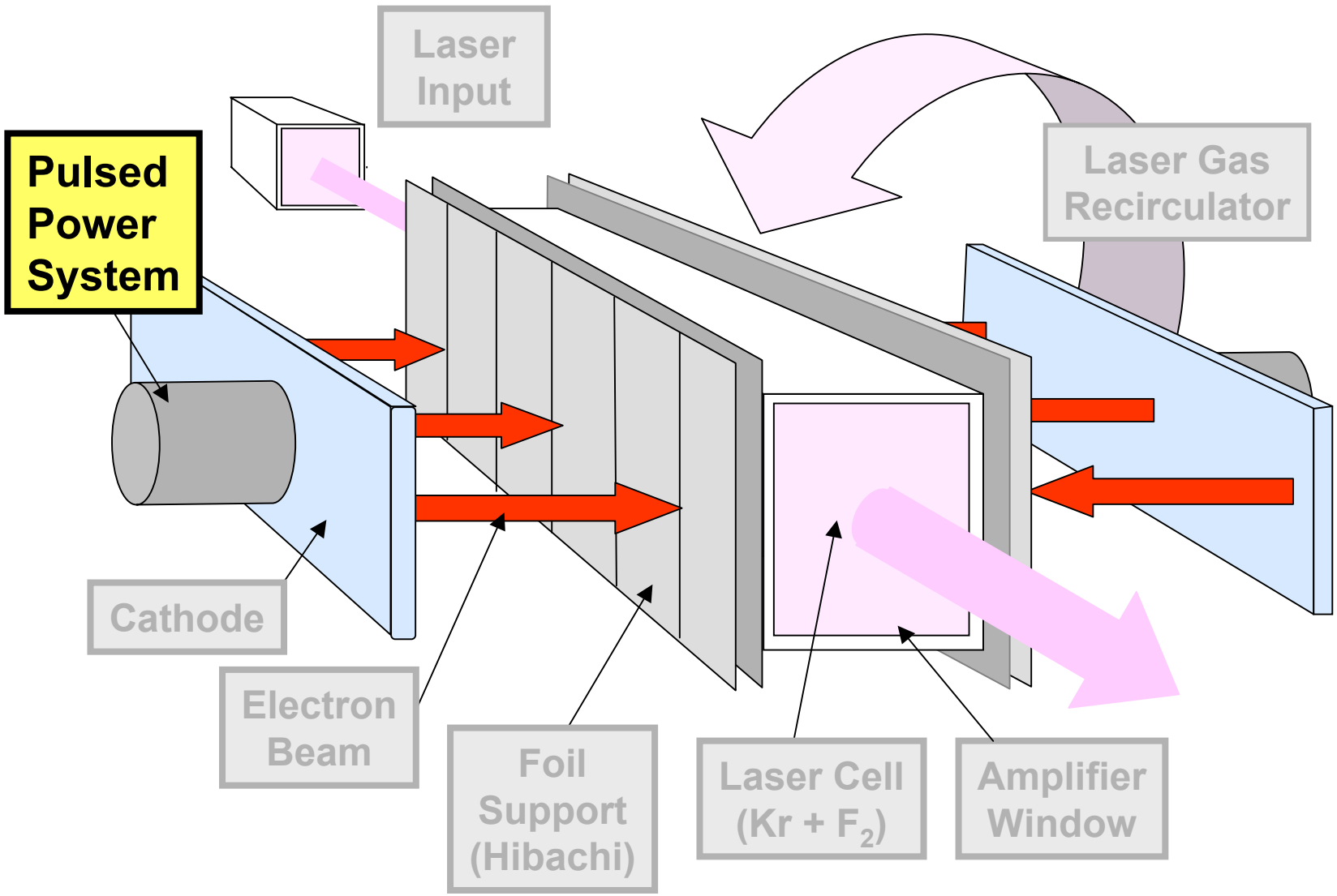
First Generation system can run at 5 Hz for 5 hours. Excellent test bed for developing laser components



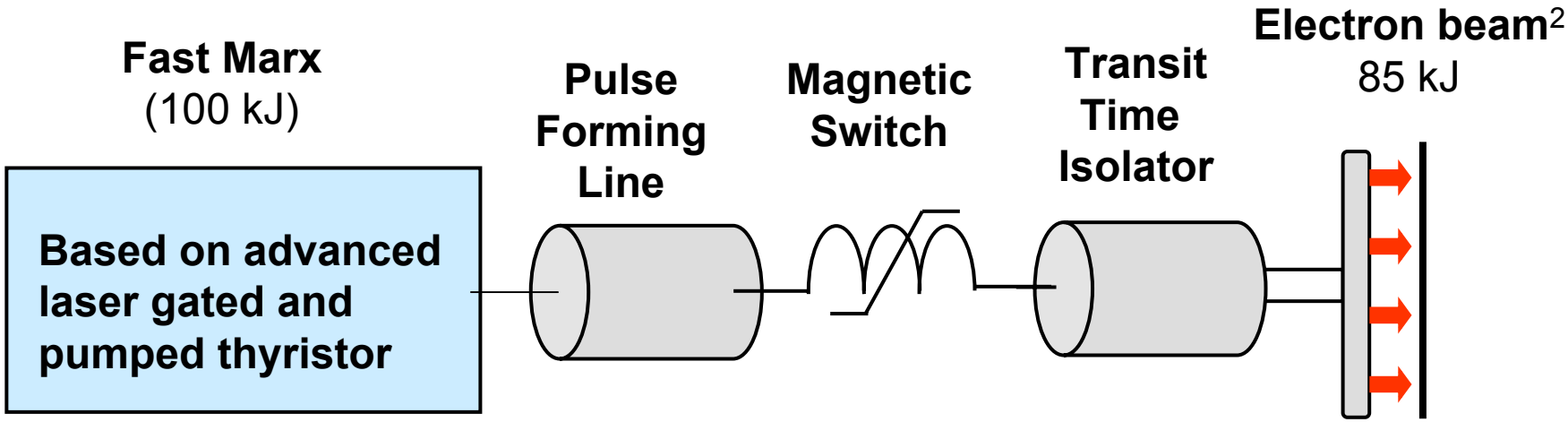
The Electra Laser Facility

Two beams: 30 cm x 100 cm, 500 keV, 100 kA, 100 nsec @ 5 Hz (50 kW total)

Pulsed Power Development



We have identified an Advanced Pulsed Power System that can meet the IFE requirements



	PROJECTED	IFE Req
Rep rate:	5-10 Hz	(5 Hz)
Efficiency:	85%	(80%)
Durability:	3×10^8 shots	(3×10^8)
Cost:	\$7.25/J[1]	(< \$10/J)

1. For 100 kJ systems in quantities
2. 800 kV/600 nsec/175 kA

NRL

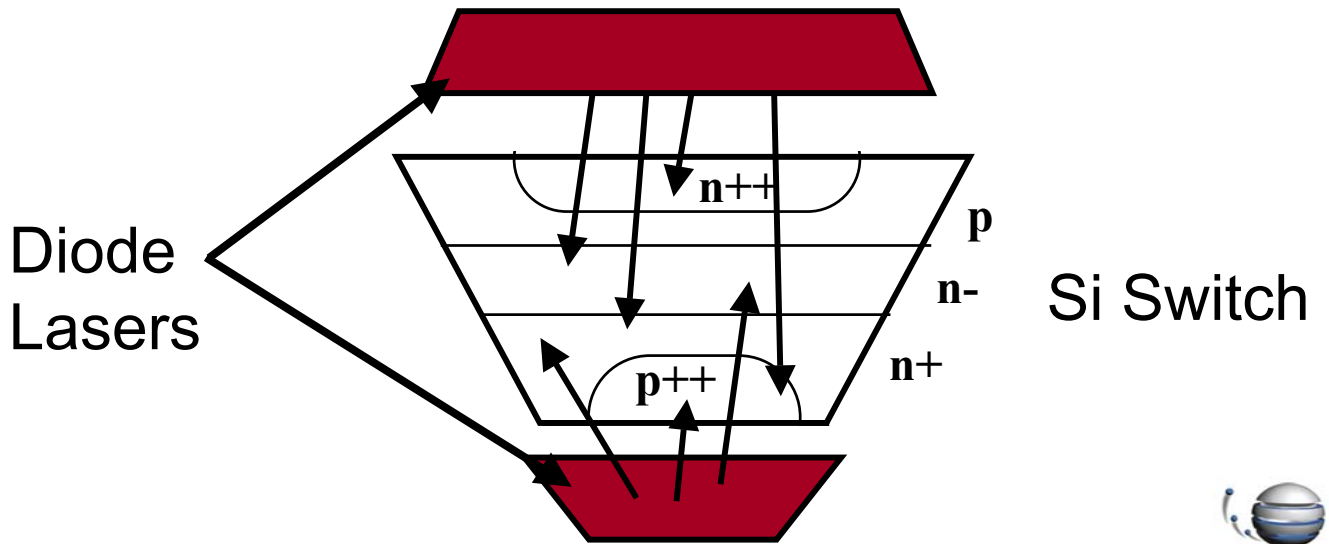
TITAN
Pulse Sciences Division

Concept of advanced Laser Gated and Pumped Thyristor

Flood entire switch volume & junction with photons….
gives fast (~ 100 nsec) switching times
> *Reduces number of compression stages*

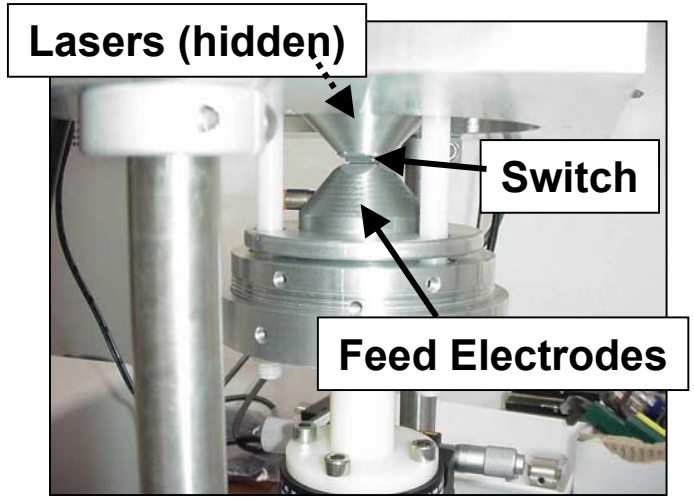
Continuous laser pumping reduces losses
> *efficient*

Four junction device
> *enables ~20 kV working devices*



TITAN
Pulse Sciences Division

The Advanced Switch concept has been demonstrated



FIRST GENERATION (DEMO):

Voltage	3.2 kV	20% IFE Req
Lifetime	10^5	N/F
Rep Rate	5 Hz	IFE Req[1]
Current:	2.7 kA/cm^2	121% IFE Req
dI/dt	1.36 x 10^{10} A/sec/cm^2	154% IFE Req
Q/A/pulse	1.7 mCb/cm^2	152% IFE Req

SECOND GENERATION (ADV CONST):

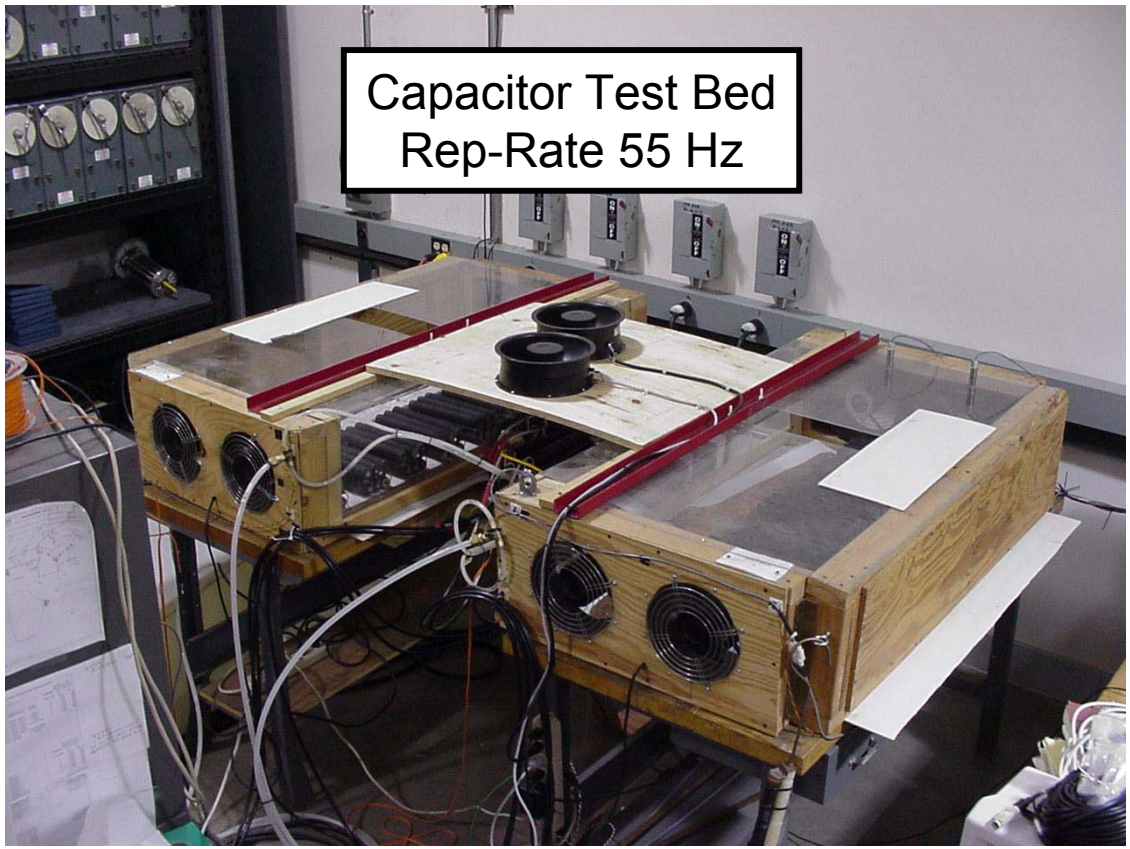
Voltage:	15.2 kV (switched)	91% IFE Req
	24 kV (charged)	144% IFE Req

1. Limit 250 Hz

TITAN
Pulse Sciences Division

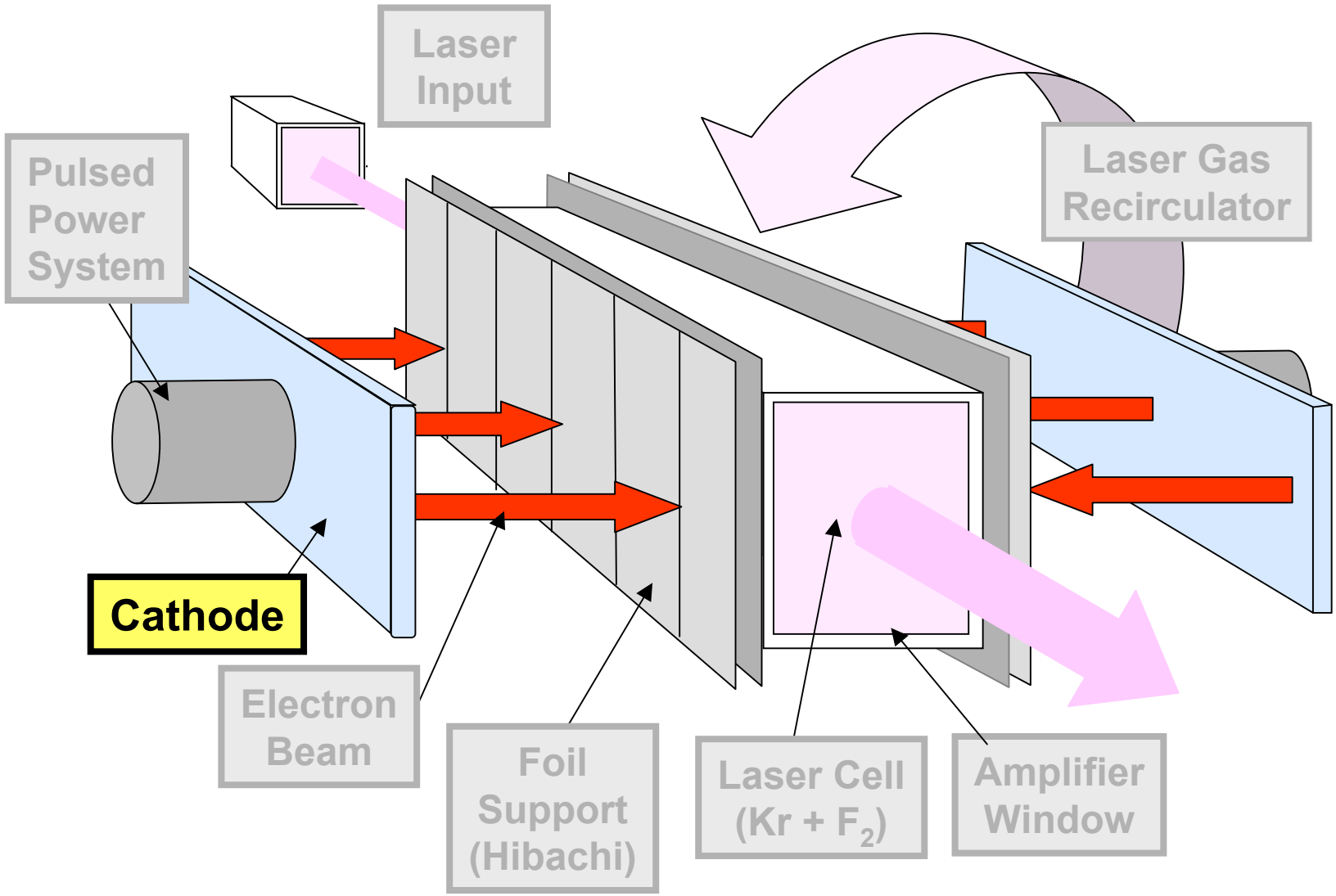
FE

Selected capacitor design has demonstrated IFE lifetime requirements….(> 3 x 10^8 shots)



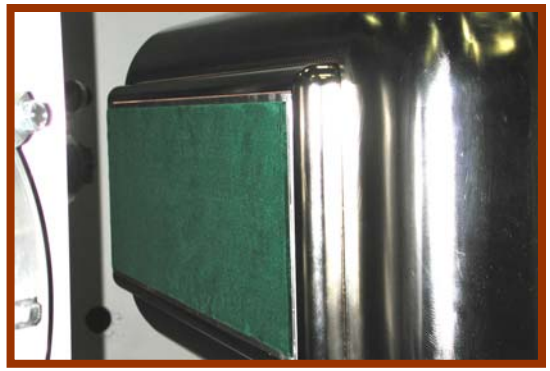
- **3.0 x 10^8 shots** on CSI capacitors (~0.03 J/cm^3)
- **2.0 x 10^8 shots** on GA capacitors (~0.015 J/cm^3)

Cathode development

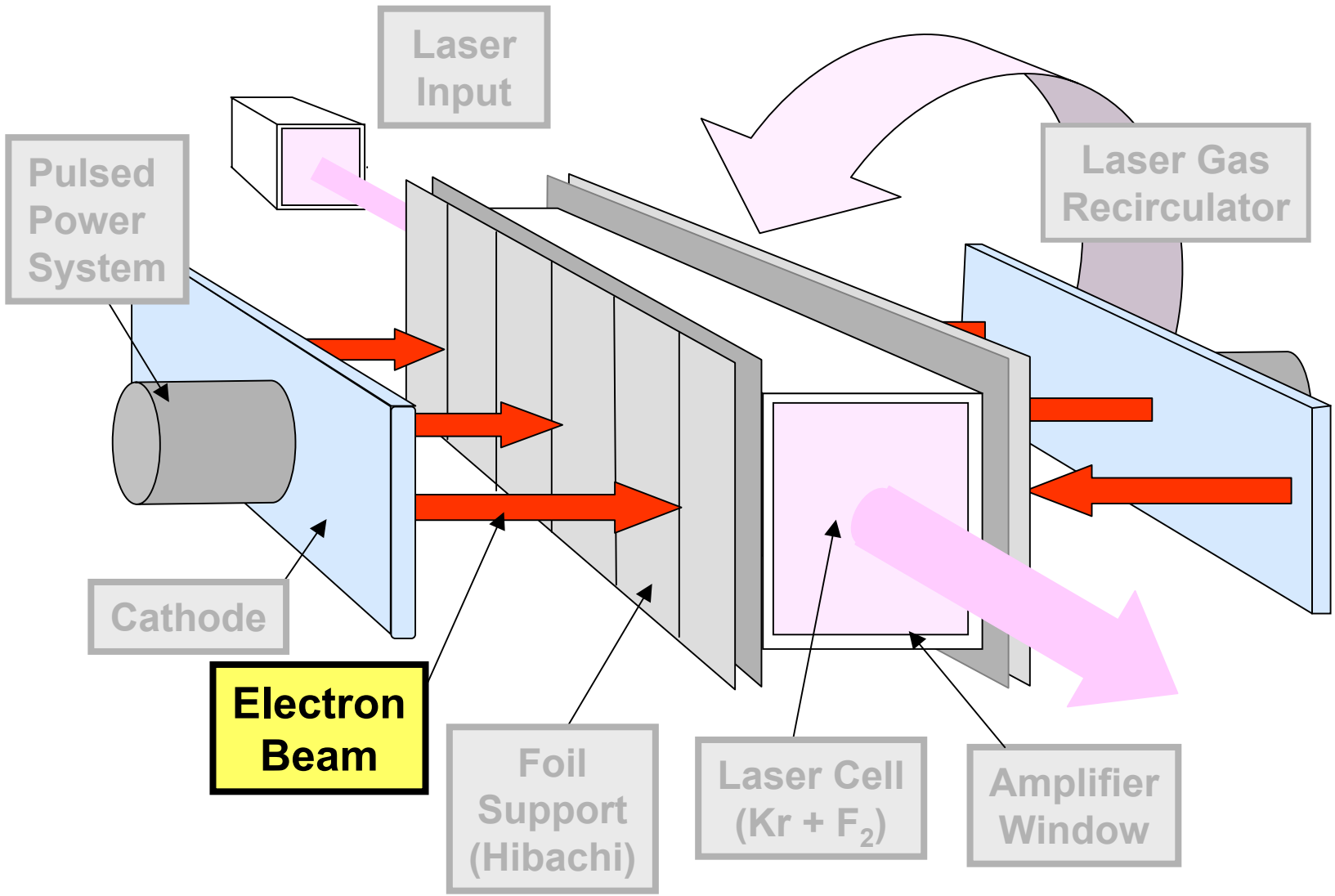


We have evaluated a wide range of cold cathode materials for: *Uniformity, Turn on, Gap Closure, Durability*

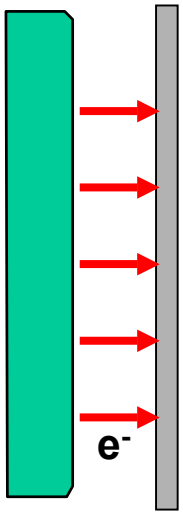
- Velvet
- Carbon fiber
- Carbon flock
- Metal/Dielectric
- Silicon Carbide foam
- CsI treatments
- Capillary Discharge

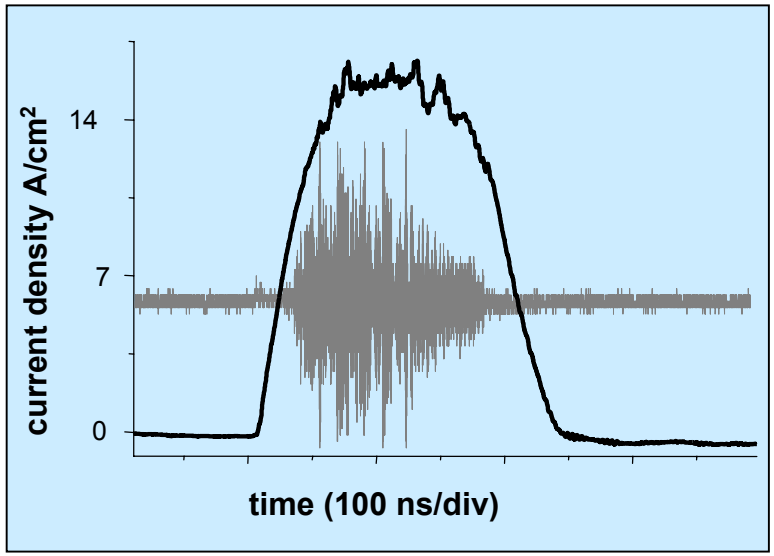


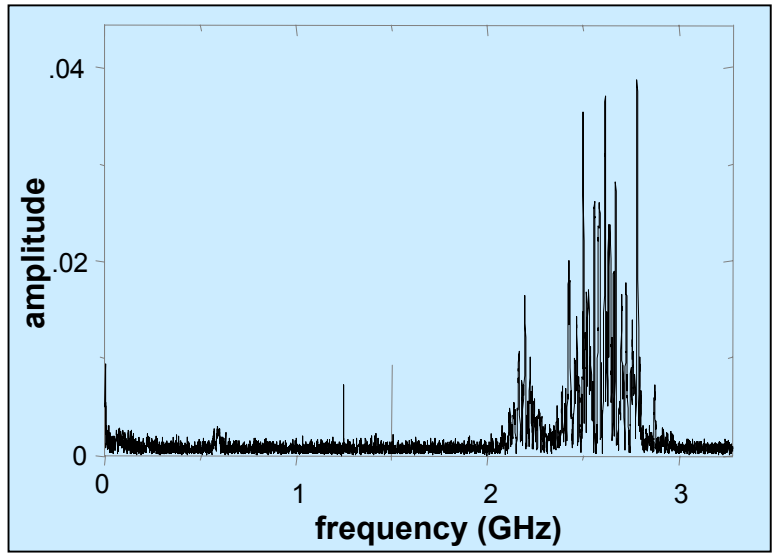
Electron Beam Physics

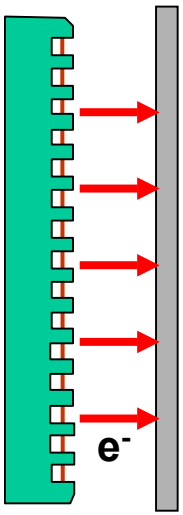


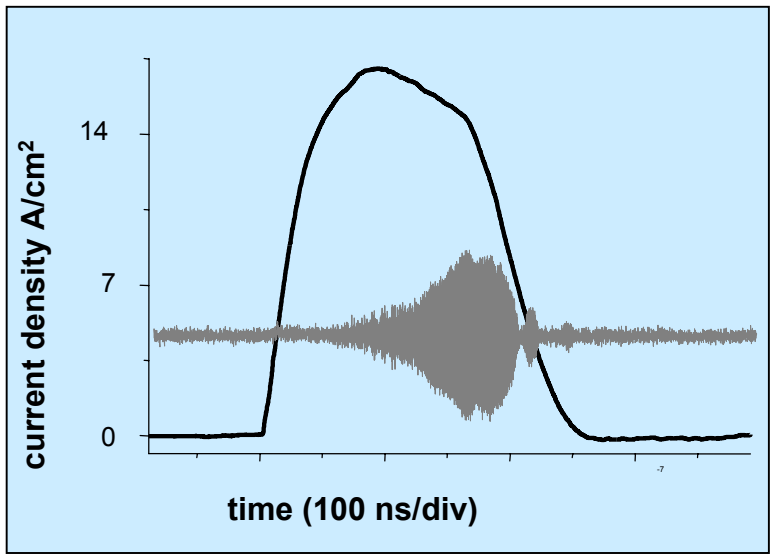
The slotted cathode suppresses the transit-time instability on NIKE 60 cm Amplifier

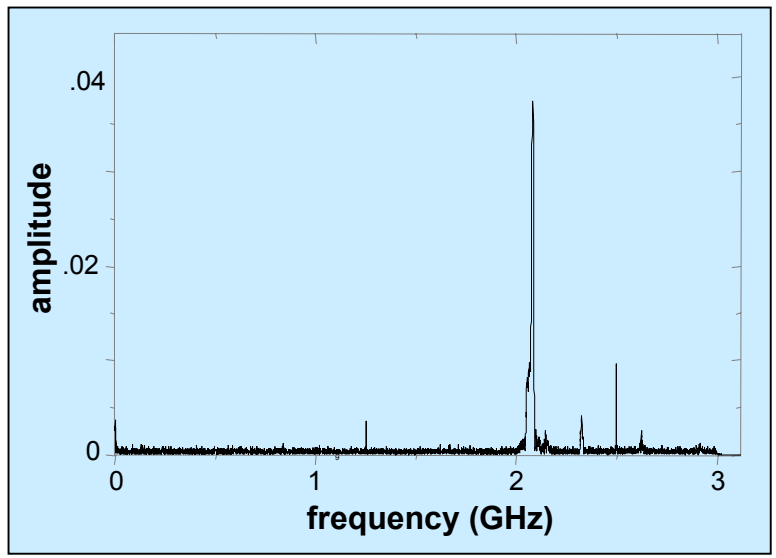






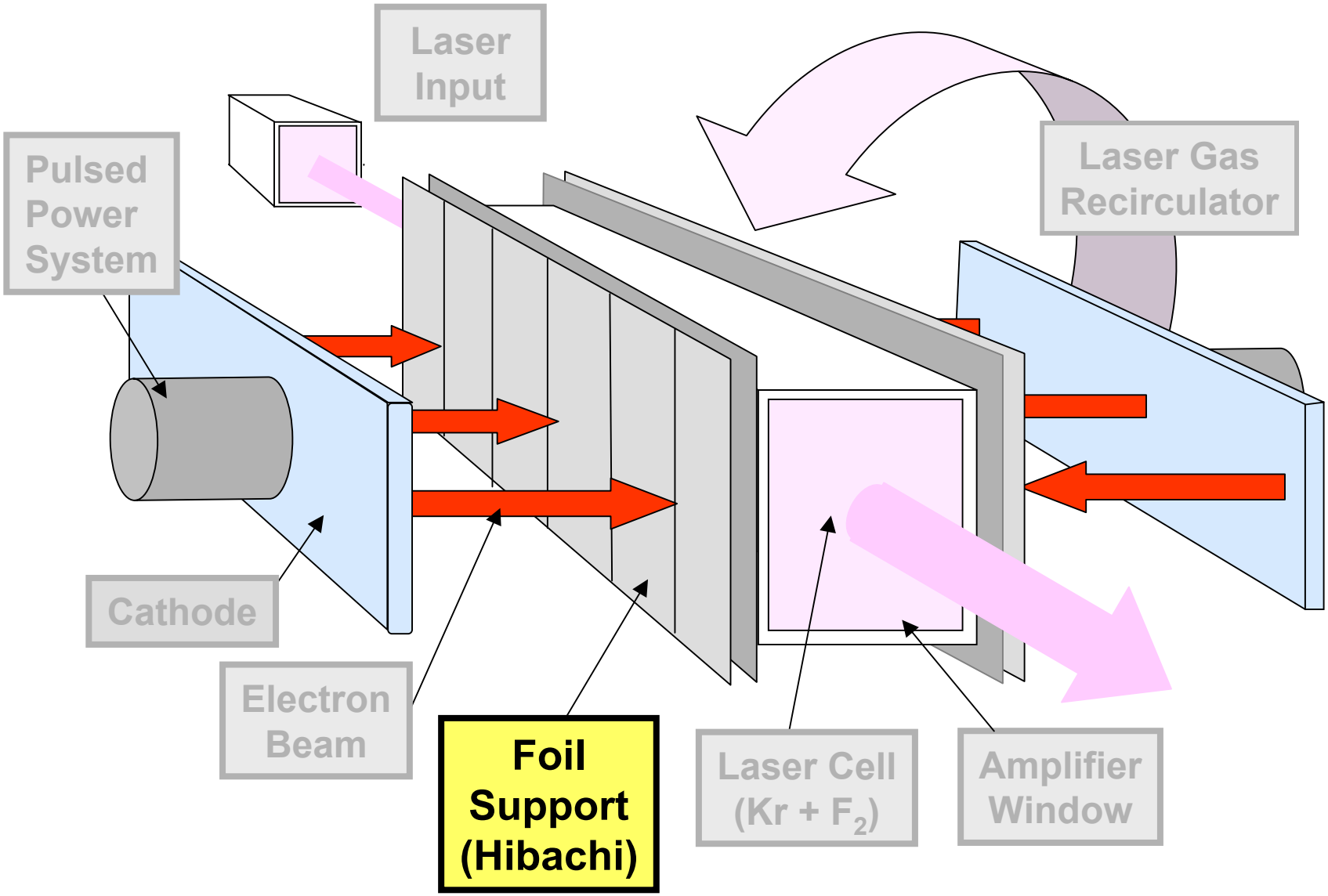






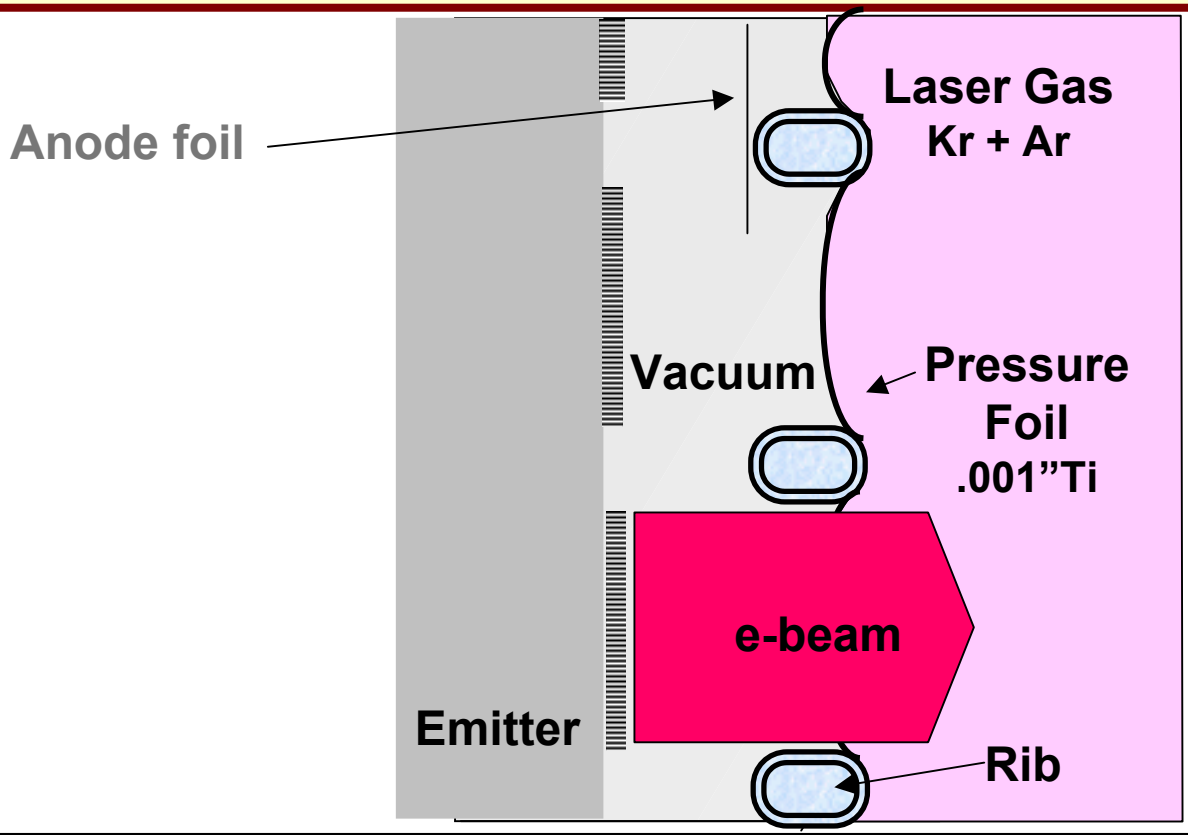
Adding Resistors or Slotting cathode in other direction is expected to eliminate instability

Hibachi development



Two innovations have allowed high hibachi transmission:

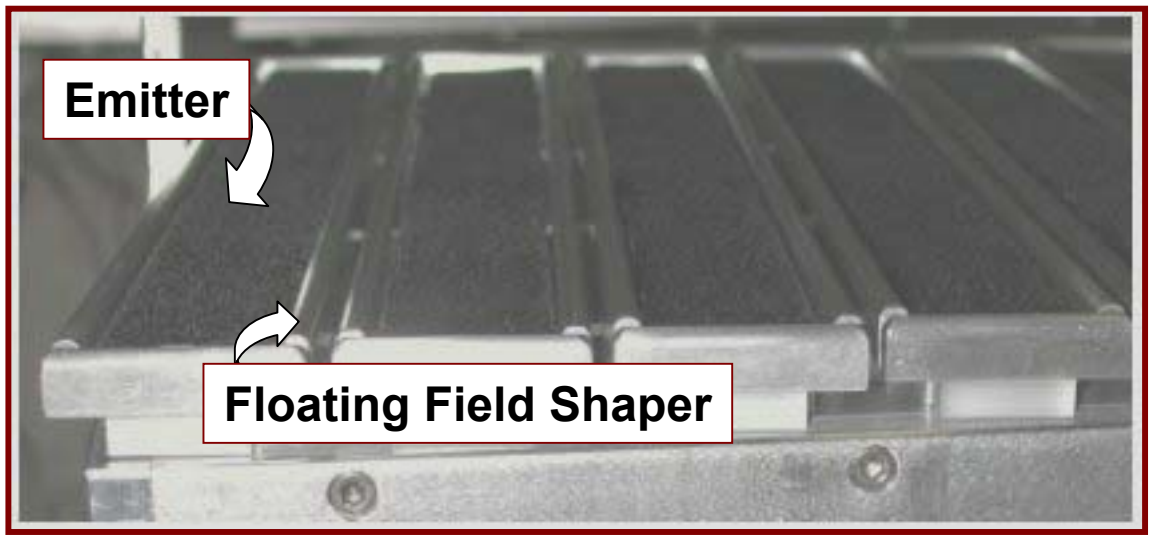
1. **Eliminate the anode foil**
2. **Pattern the electron beam to "miss" the hibachi ribs**

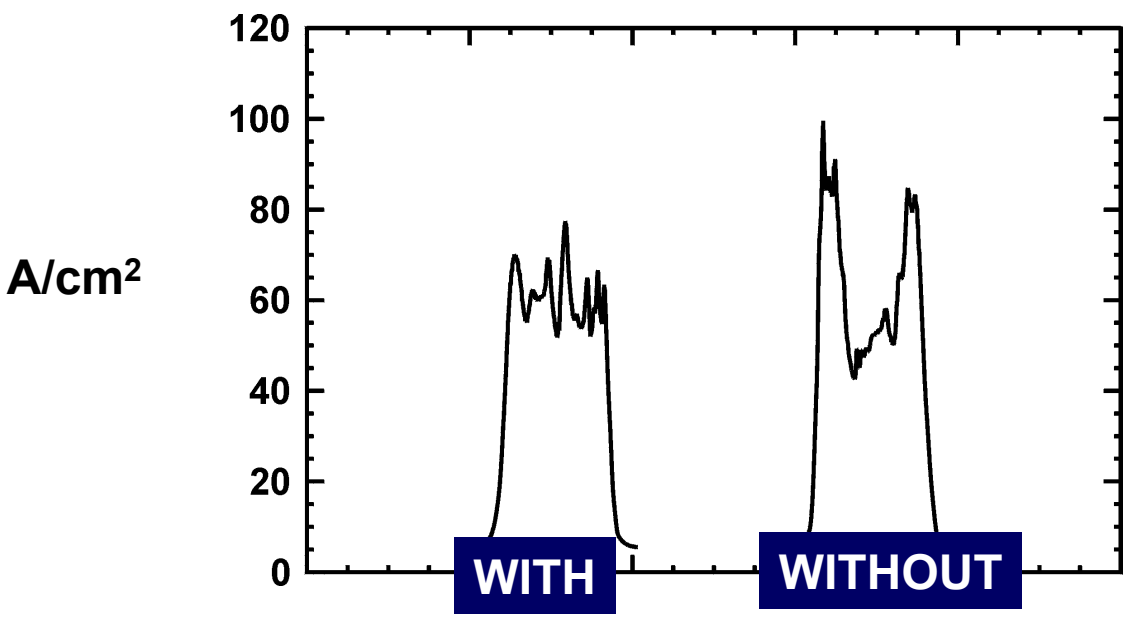


Issues

1. High Current "edge" from each strip
2. Non-uniform electric field at anode causes beam spreading
3. Beam rotates and skews between cathode and anode

Floating "Field Shapers" on perimeter of cathode strips eliminates enhanced edge emission

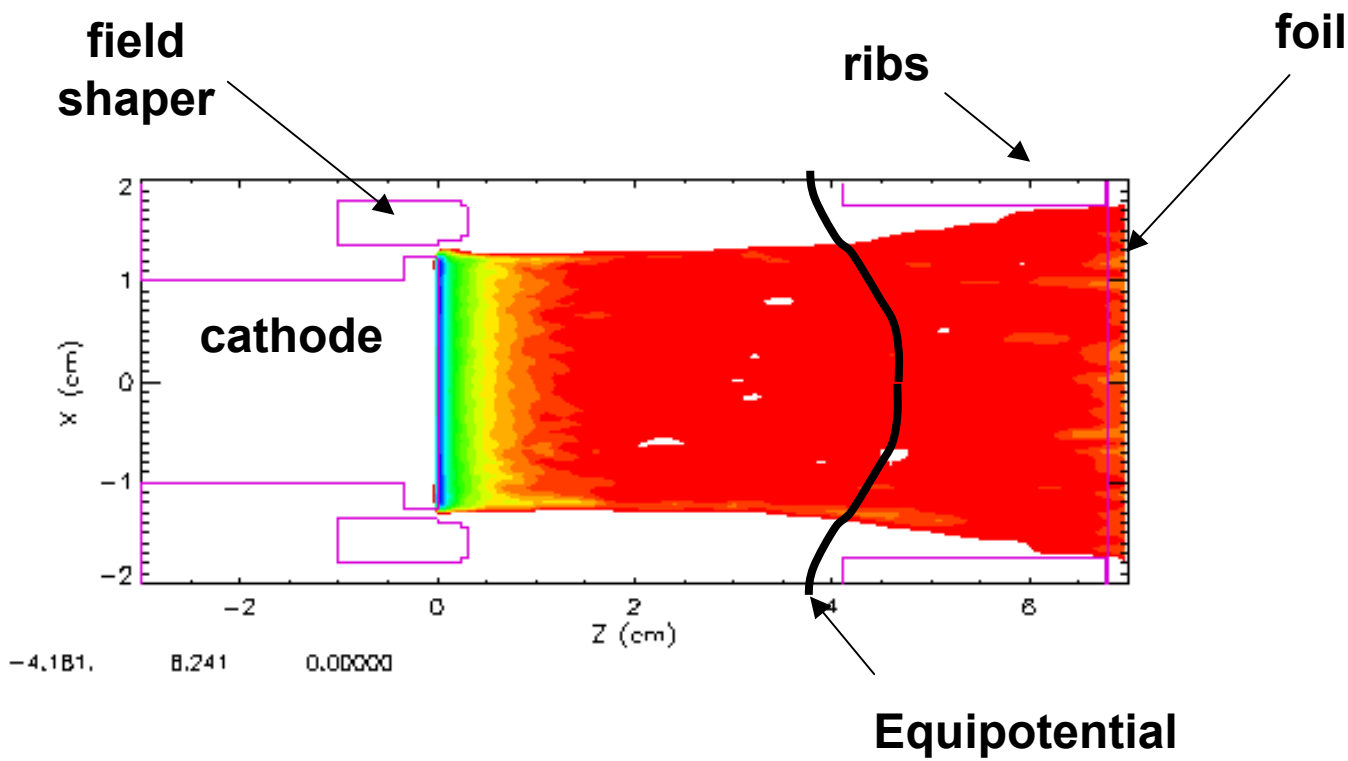




Line out of Radiachromic film image of beam at anode

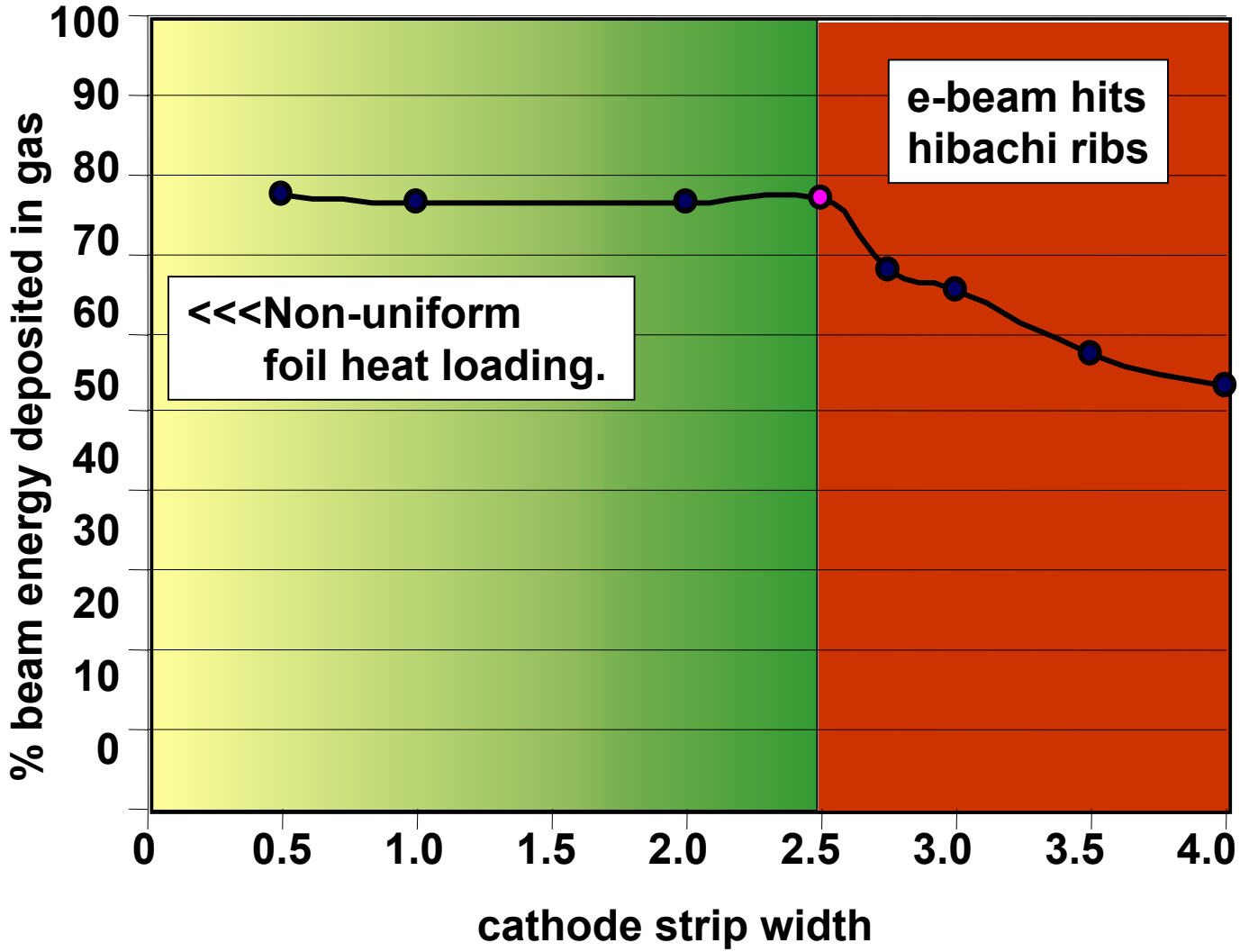
F. Hegeler,
Phys Plasmas

LSP modeling prescribes cathode width needed to accommodate beam spreading-1



Simulations by D. Rose & D. Welch, MRC Albuquerque

LSP modeling prescribes cathode width needed to accommodate beam spreading-2



Simulations by D. Rose & D. Welch, MRC Albuquerque

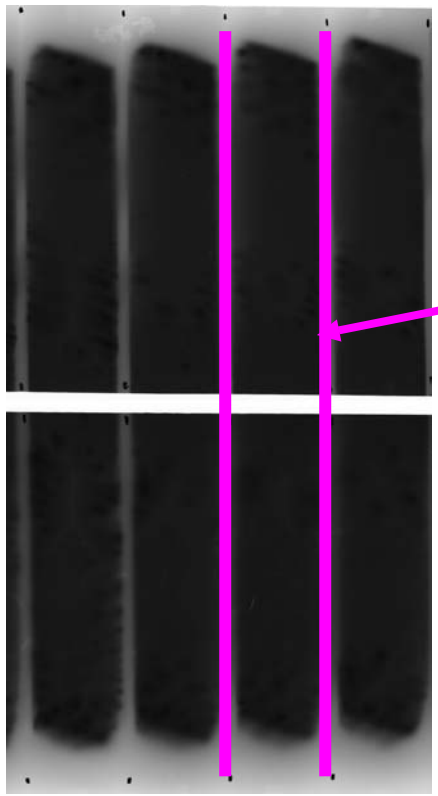
We can counter-rotate the emitter strips so beam goes straight through the hibachi ribs

Cathode strips rotated 6 degrees

30 cm

100 cm

Radiachromic Film:
Time integrated current profile at the pressure foil

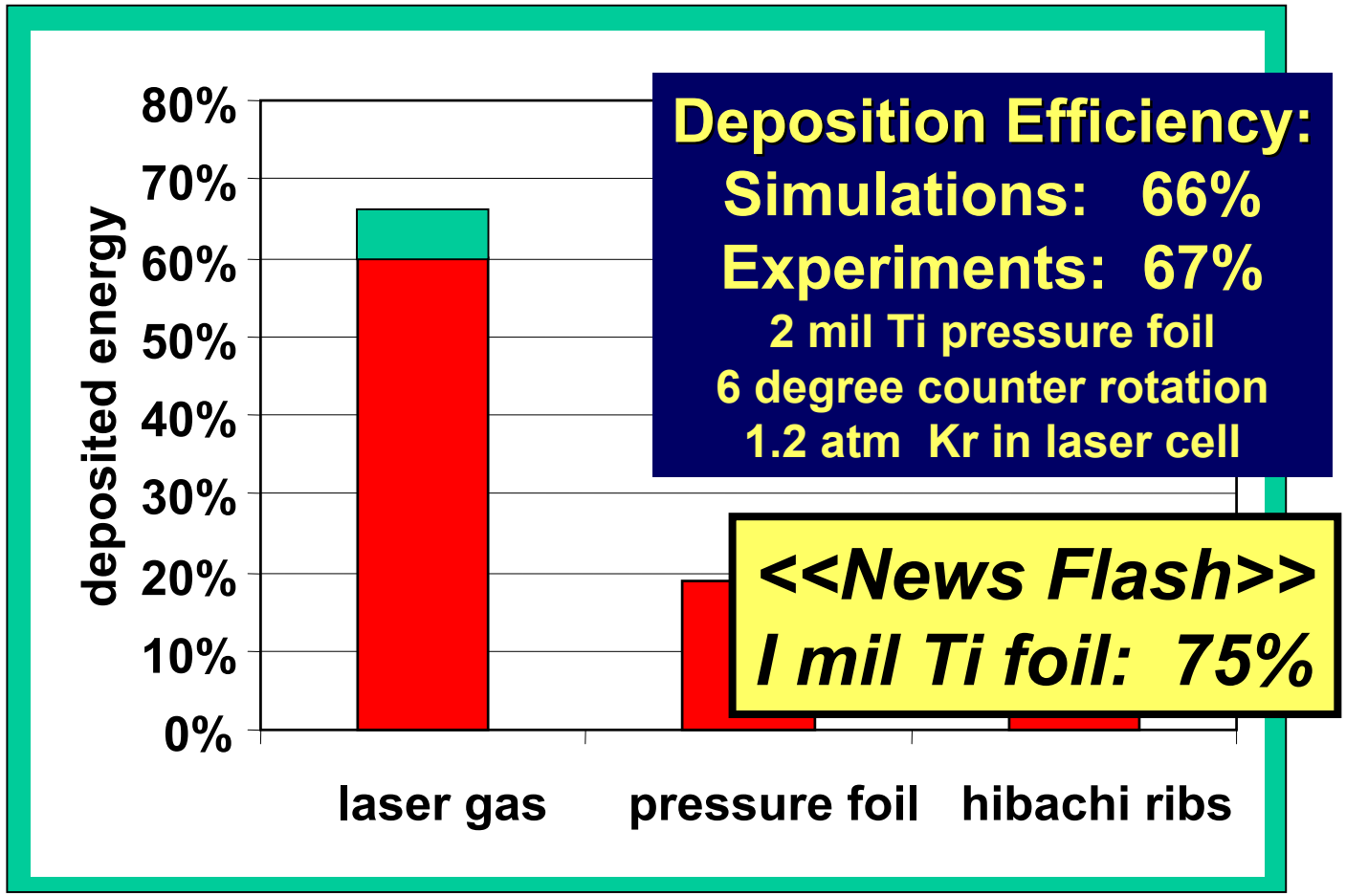


Position of the hibachi ribs

3-D LSP Simulations (MRC/Albuquerque)

Prescribe the cathode rotation

Predict observed electron beam deposition into the gas



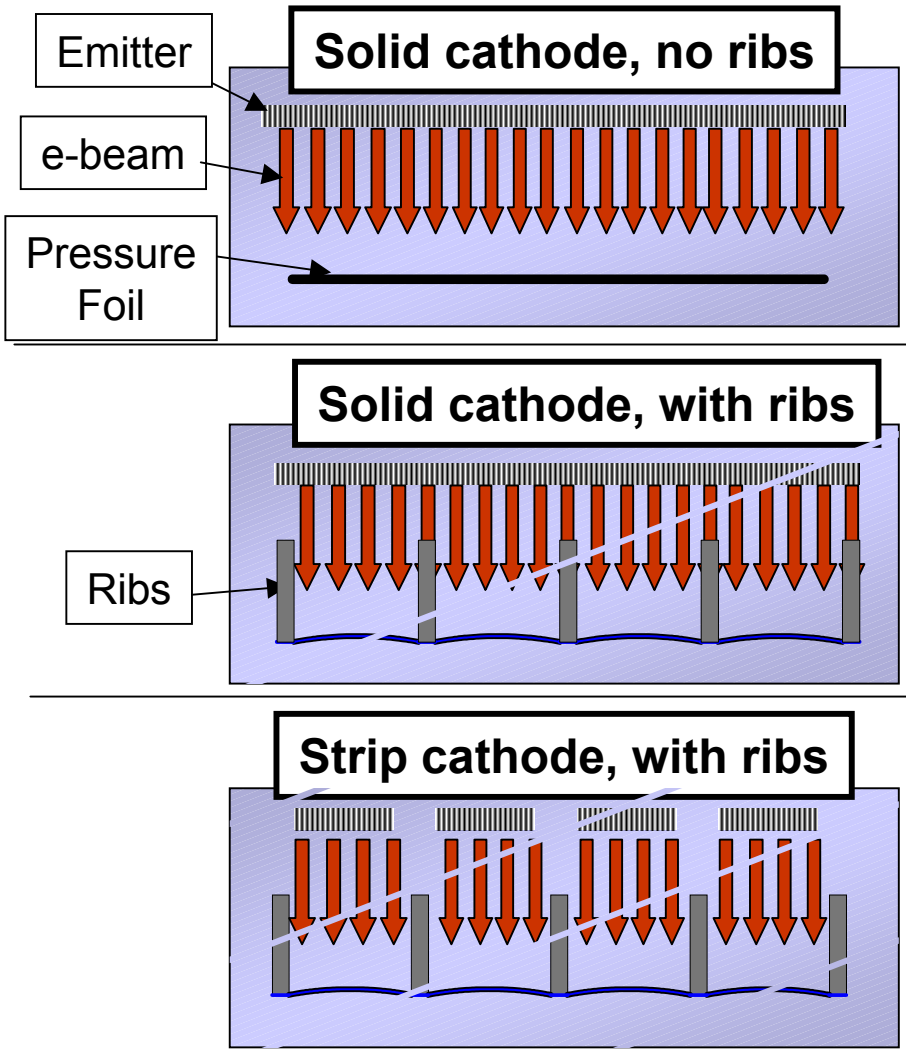
Efficiency ≡ Energy deposited in laser gas/energy in diode (for flat top portion of beam)

Comp
Iter

Simulations by D. Rose & D. Welch, MRC Albuquerque

Patterning beam:

1. Increases energy deposition by 26% over monolithic cathode
2. Gives performance close to “rib-less” hibachi



Simulation (1-D Tiger) **72%**

74% of max

Experiment **53%**

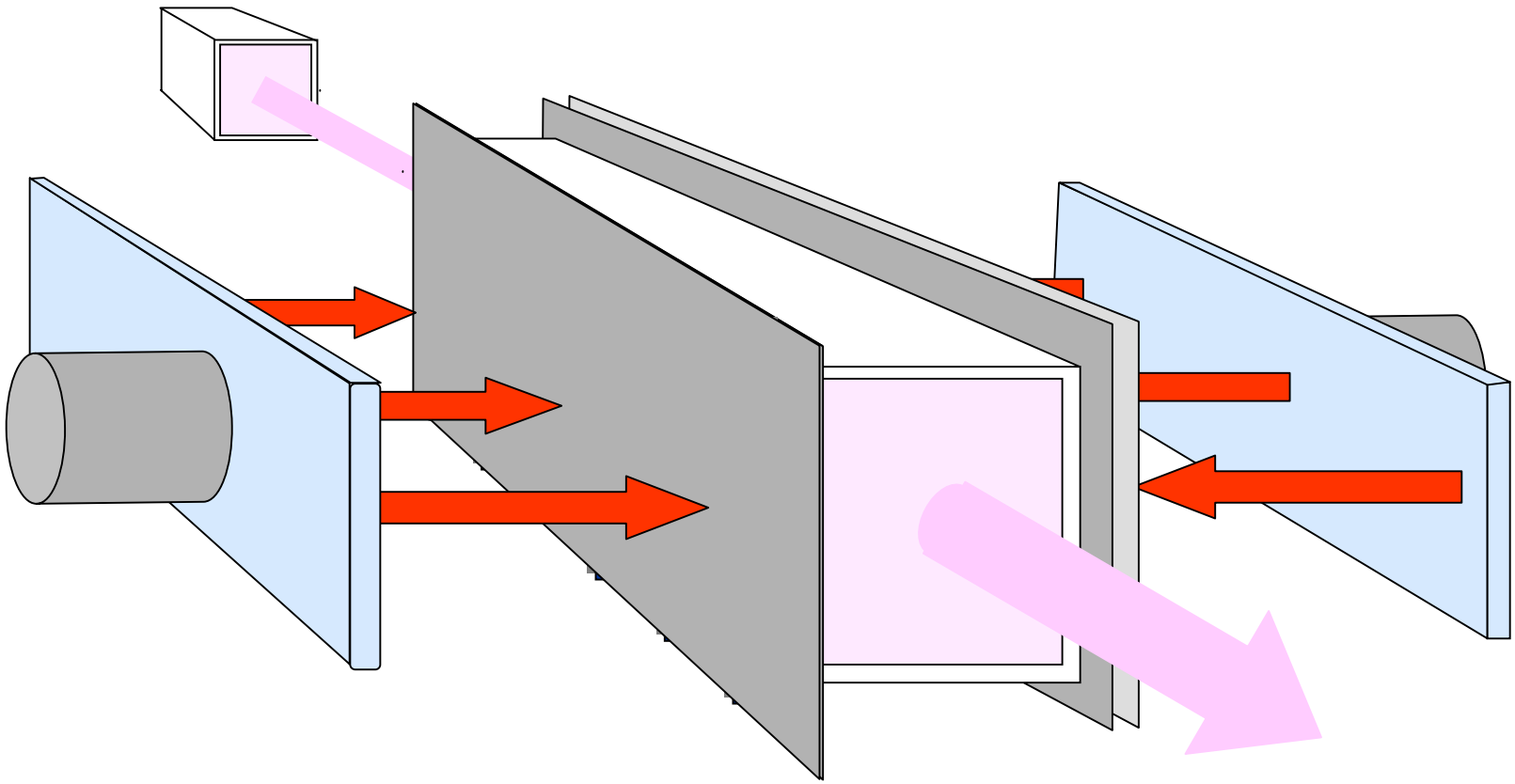
93% of max

Experiment **67%**

(most of this loss is beam grazing ribs)

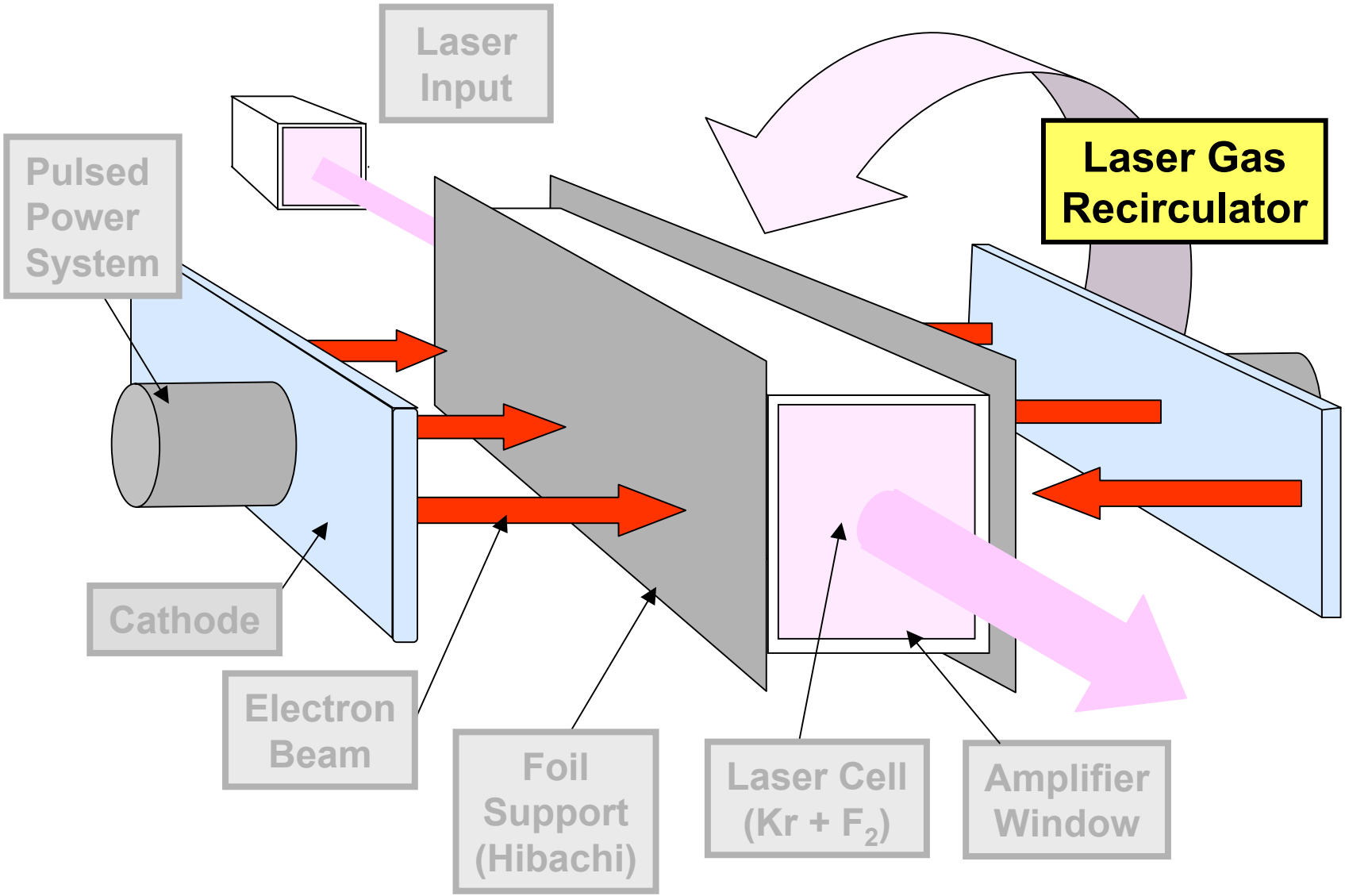
* All measurements corrected for flat portion of e-beam pulse

The Bottom Line

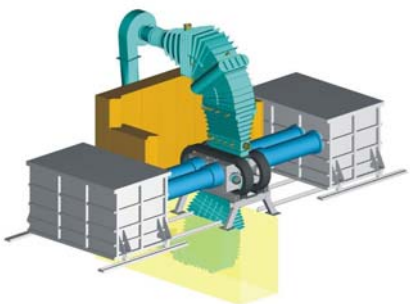


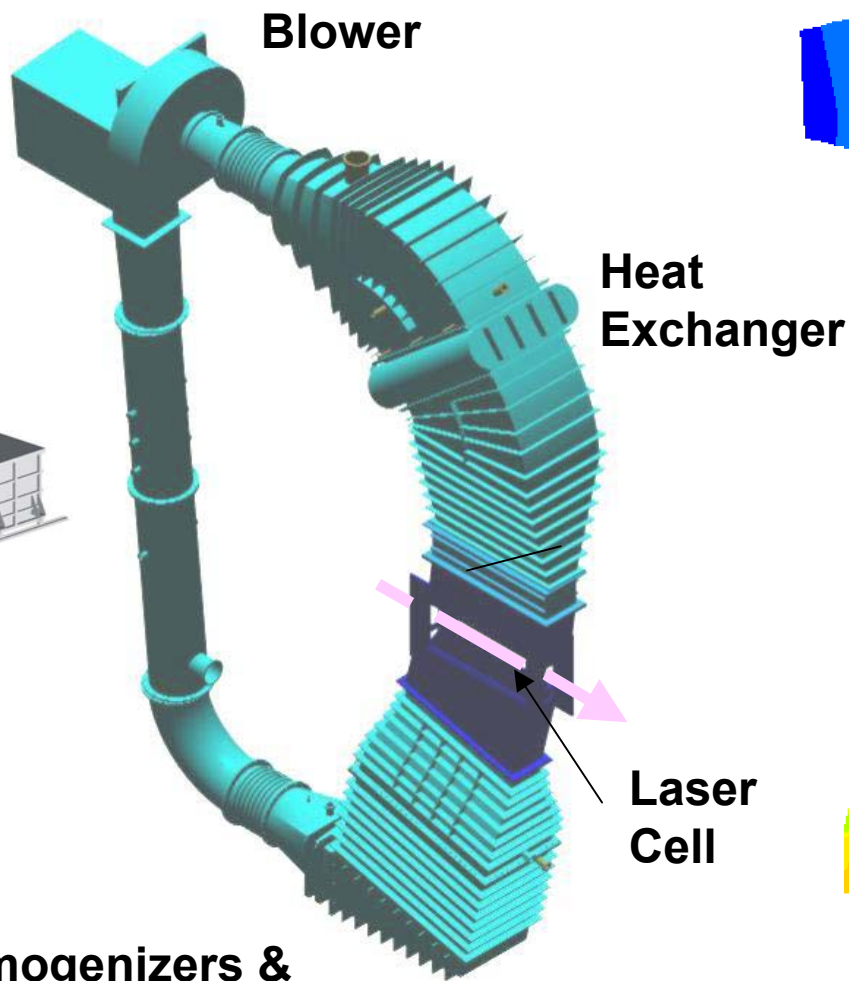
Tiger 1-D modeling shows efficiency of 81% @ 750 keV (full scale system, or Nike)

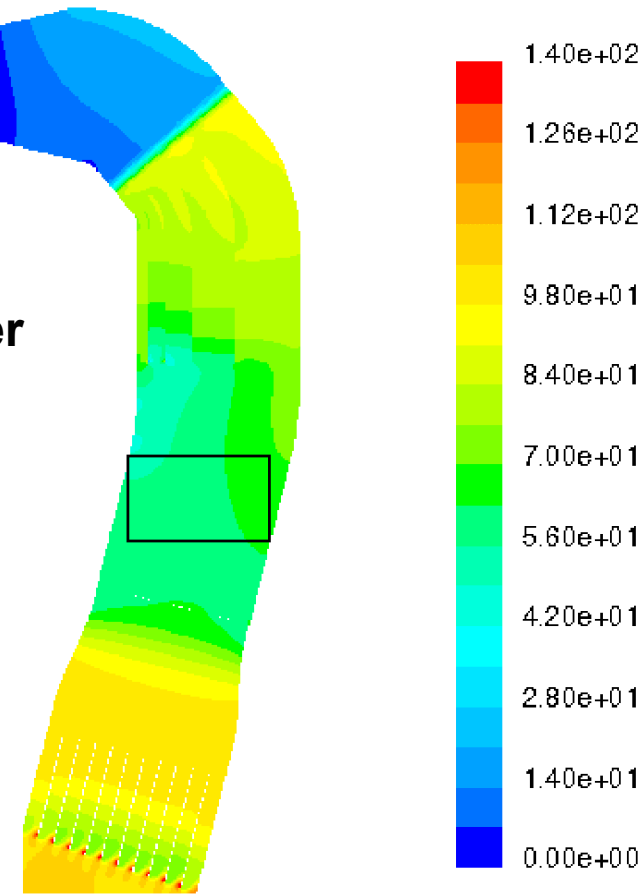
Gas Recirculator development



The Recirculator to cool and quiet laser gas has been designed. Construction has begun.

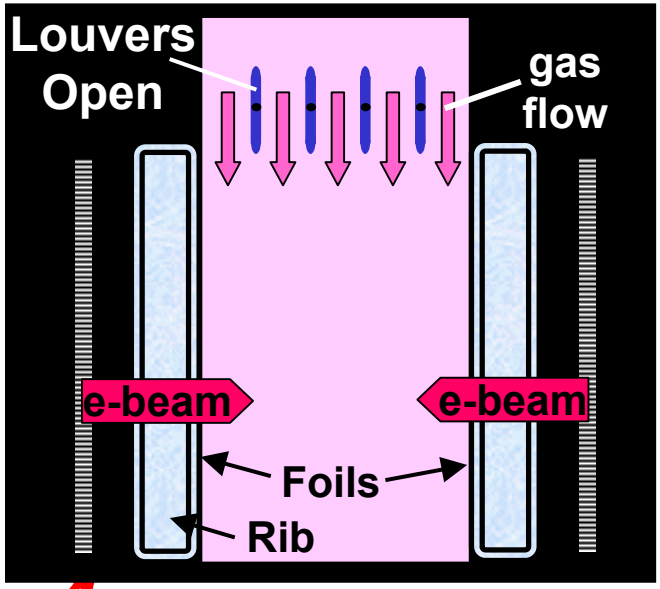


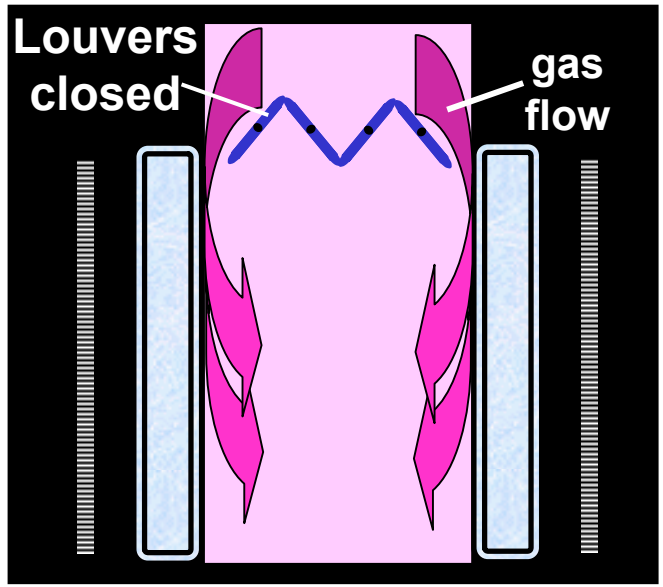




Static Pressure Contours varies by 14 Pa ($\Delta\rho/\rho = 10^{-4}$) over laser cell

The recirculating laser gas can be used to cool the Hibachi



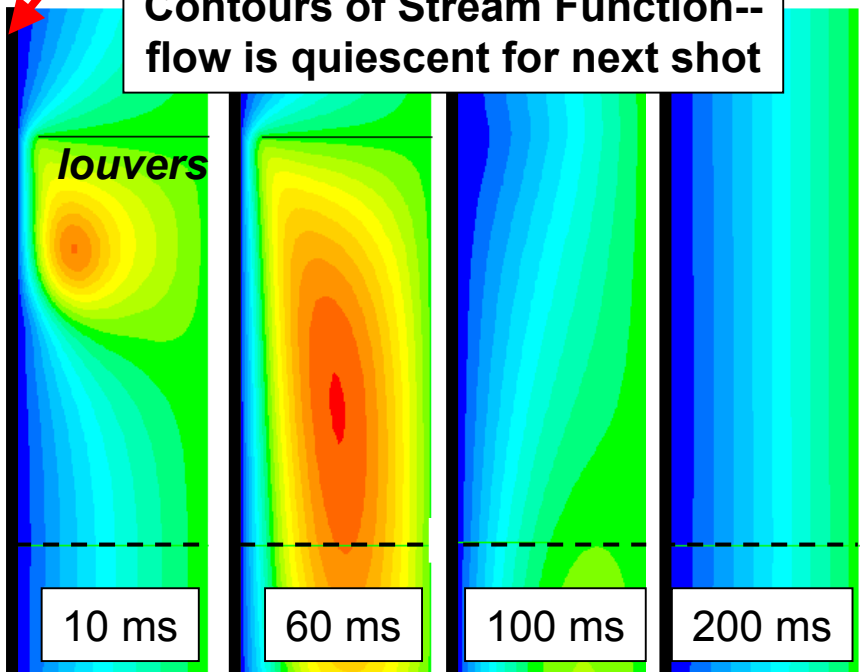


Contours of Stream Function--
flow is quiescent for next shot

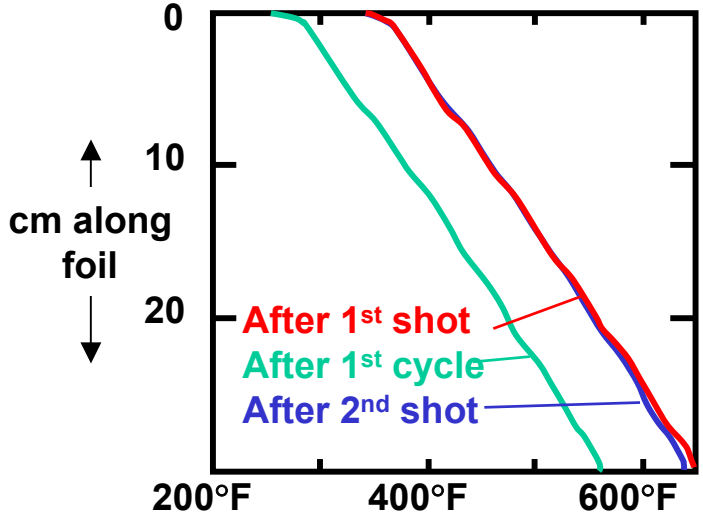
Cell
Entrance

gas
flow

Cell Exit

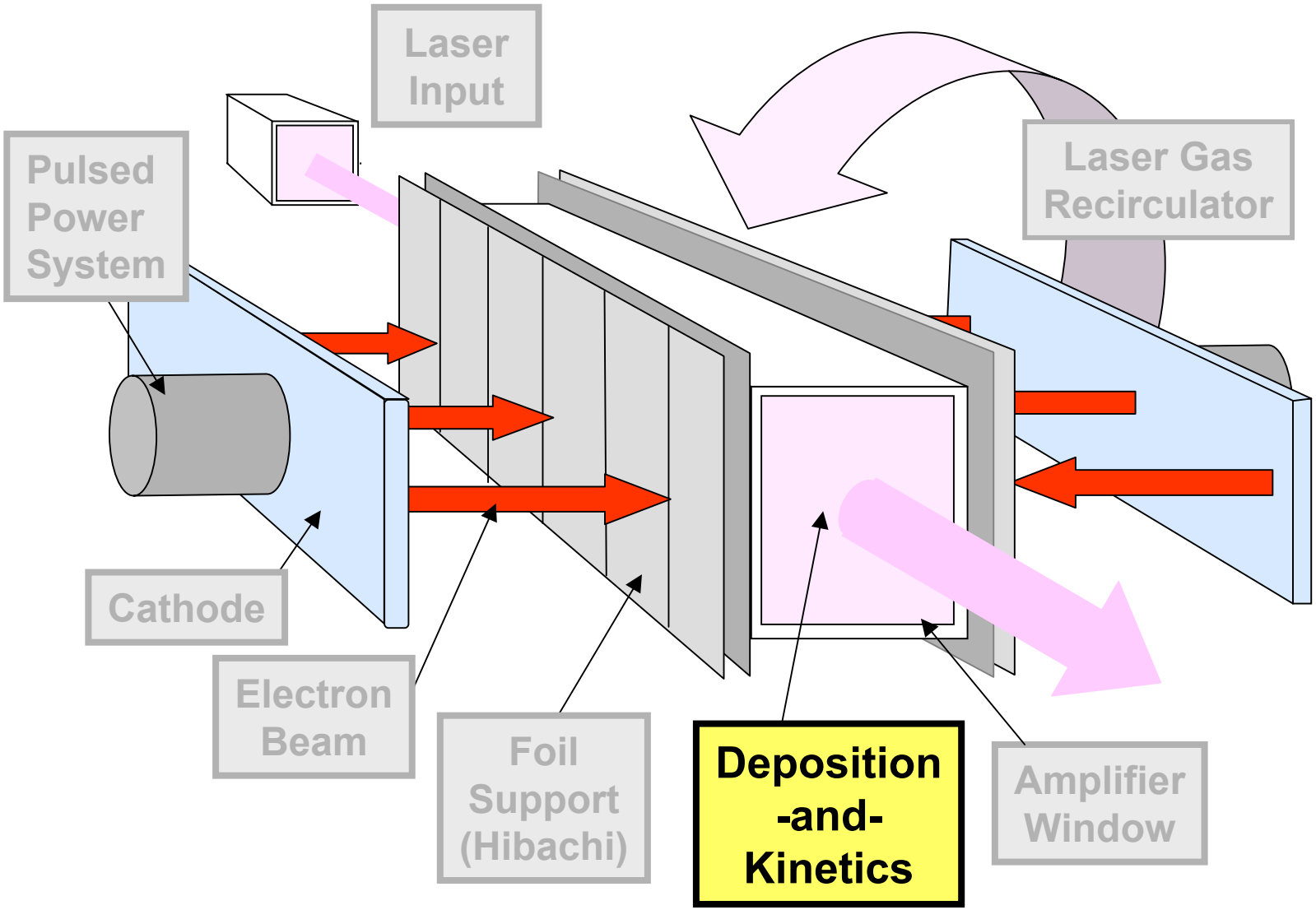


Foil Temperature below required 650°F

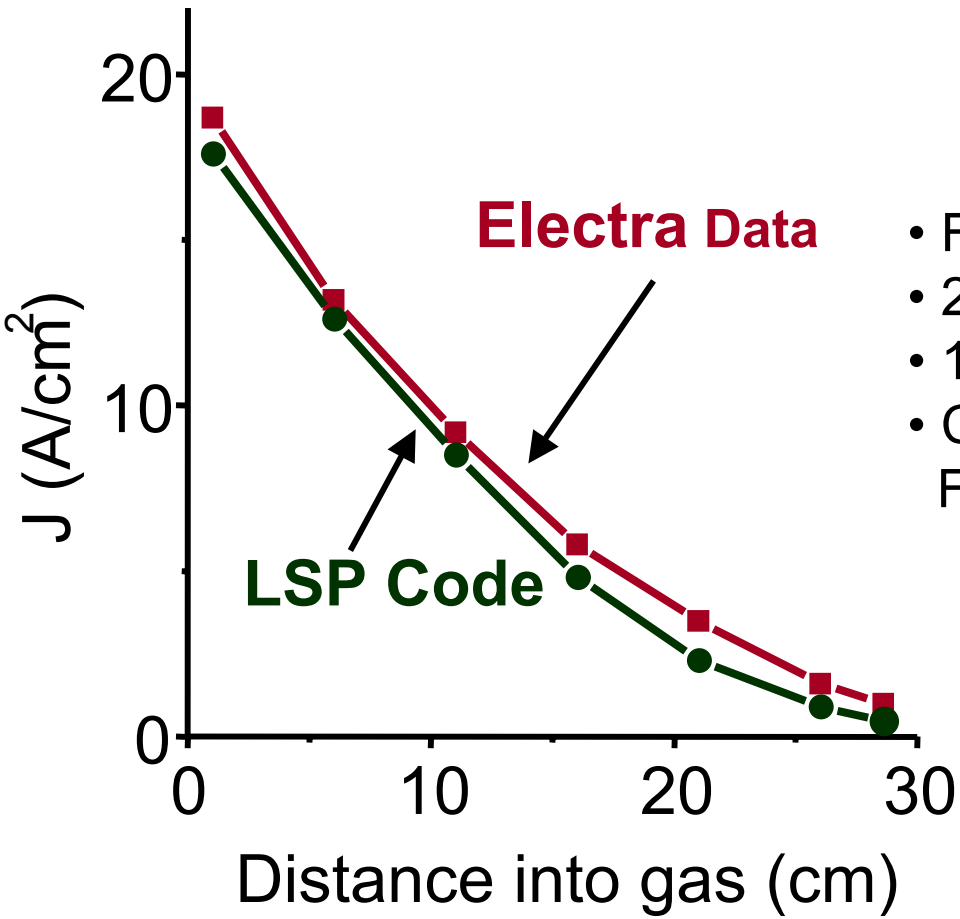


Concept & Modeling:
A.Banka & J.Mansfield, Airflow Sciences, Inc

KrF Physics


Laser Input
Pulsed Power System
Laser Gas Recirculator
Cathode
Electron Beam
Foil Support (Hibachi)
Deposition -and- Kinetics
Amplifier Window

We can accurately predict measured e-beam deposition in laser gas



- Flat Cathode w/Mark I hibachi
- 2-mil Ti Pressure Foil
- 1.2 atm Kr
- Current density measured with Faraday cups filtered w/1-mil Ti foil

Calculations by D.V. Rose, MRC Albuquerque

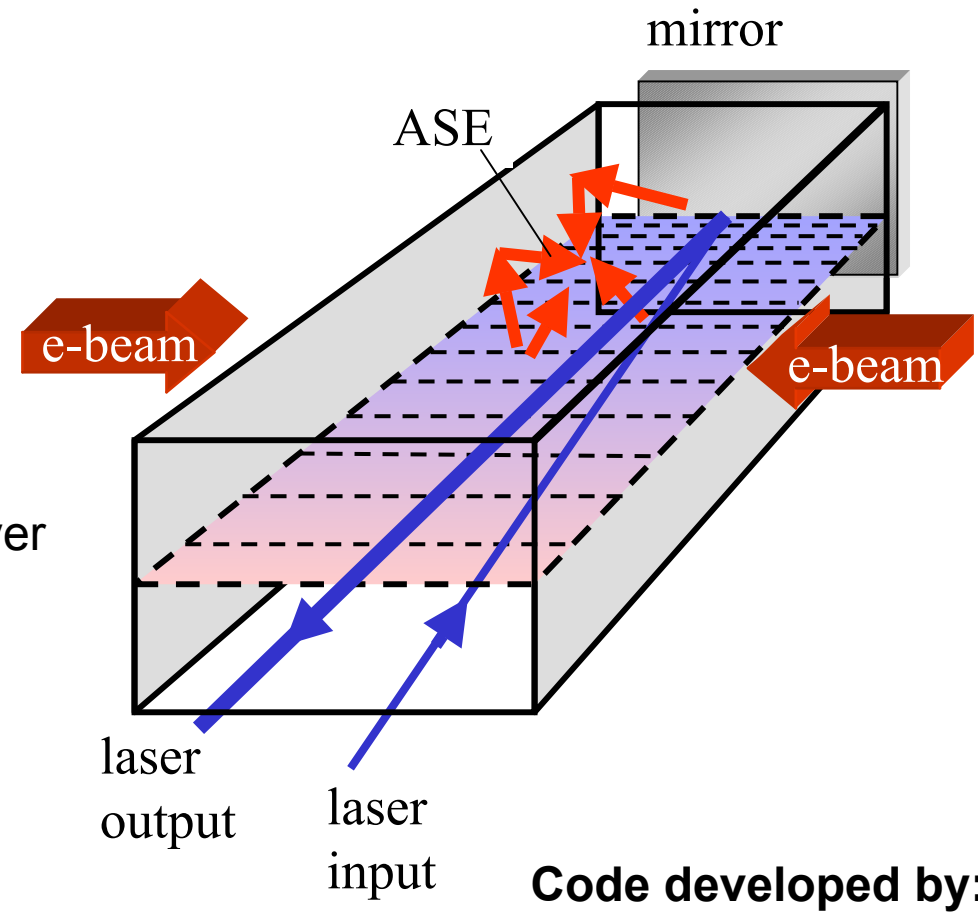
"Orestes" Laser Amplifier Physics code: Kinetics coupled to 3D, time dependent, radiative transport of the ASE

Deposition: presently uniform
Can be 2D, or 3D

Plasma: 1 -D axially resolved grid
T_e and T_g energy eqns

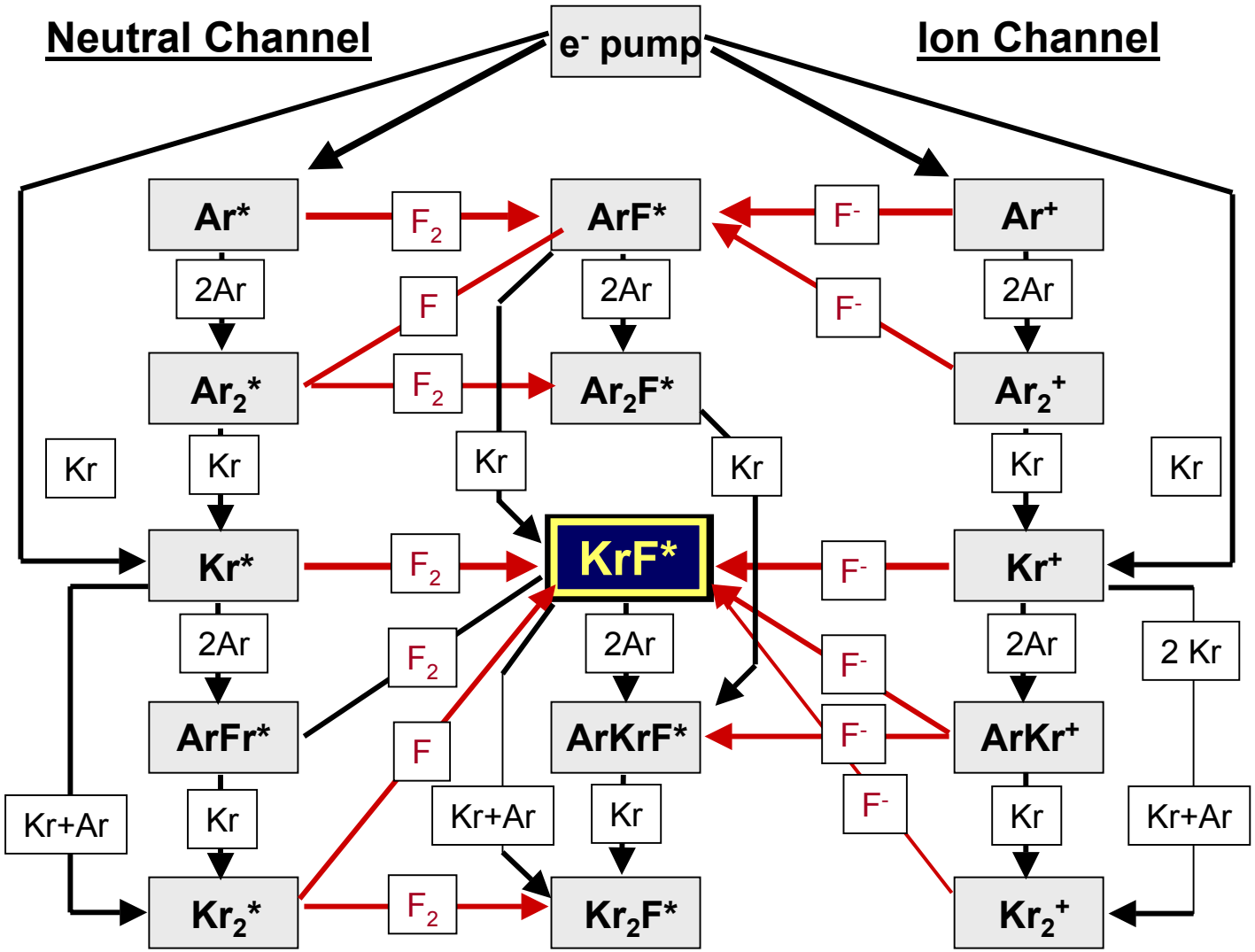
Kinetics Automated chemistry solver
25 species
20 KrF vib levels
429 reactions,

ASE: 3-D, time dependent



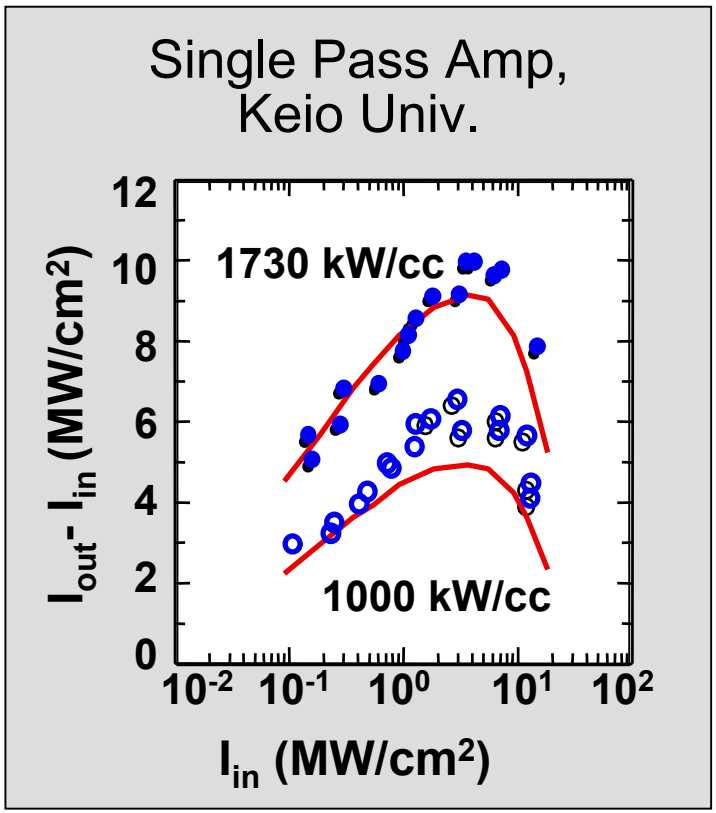
Code developed by:
John Giuliani
Paul Kepple
George Petrov
(NRL Code 6720)

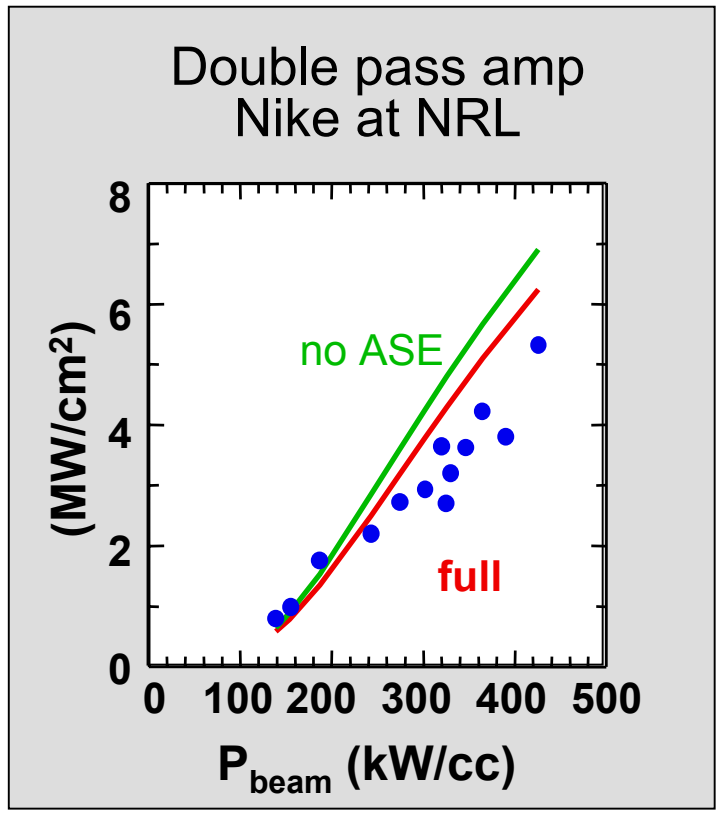
KrF Kinetics is a multi species process



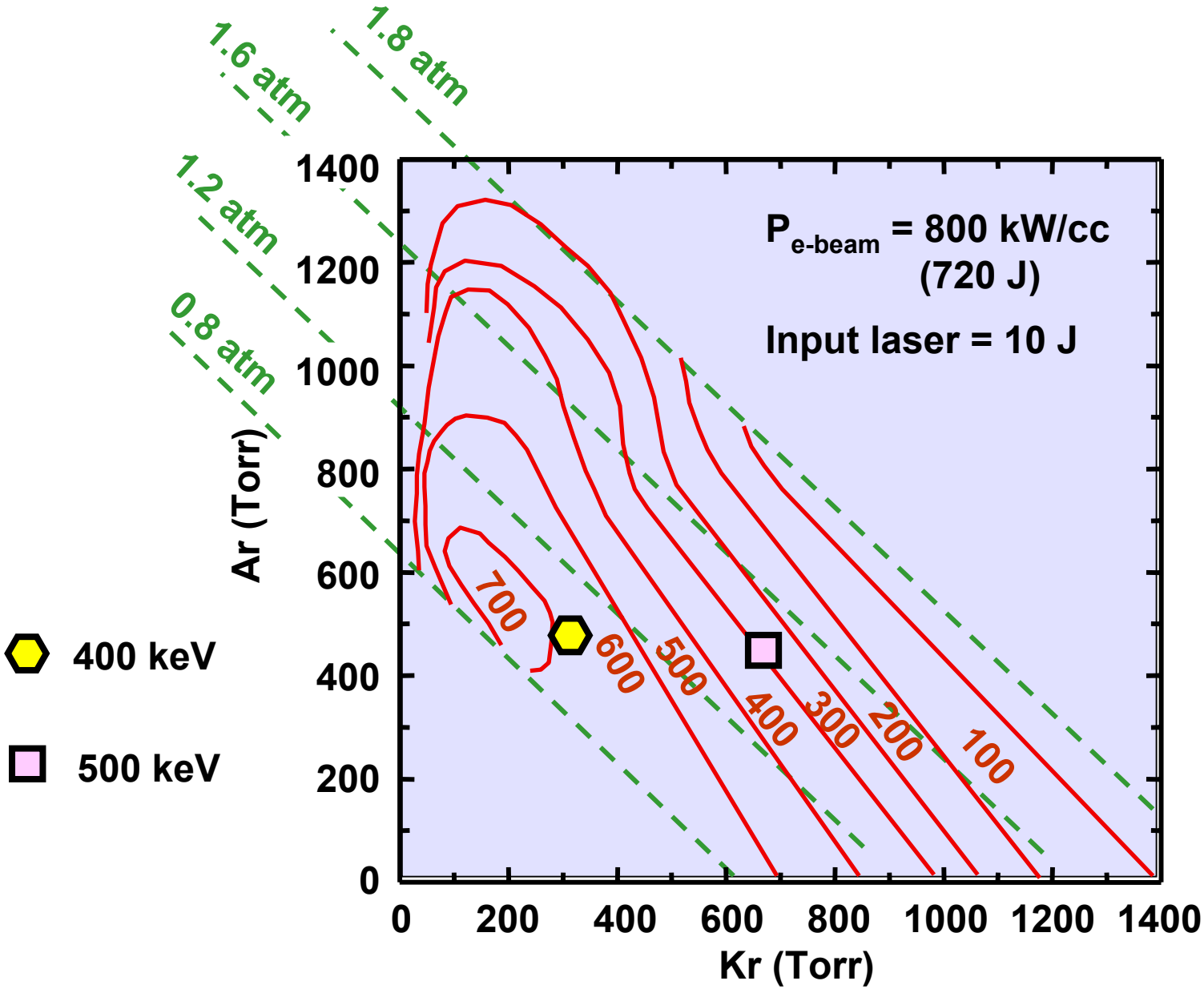
Adopted from Johnson & Hunter, J. Appl. Phys,. 31 p 2046 (1980)

Orestes predicts KrF Laser yields under a wide range of operating conditions

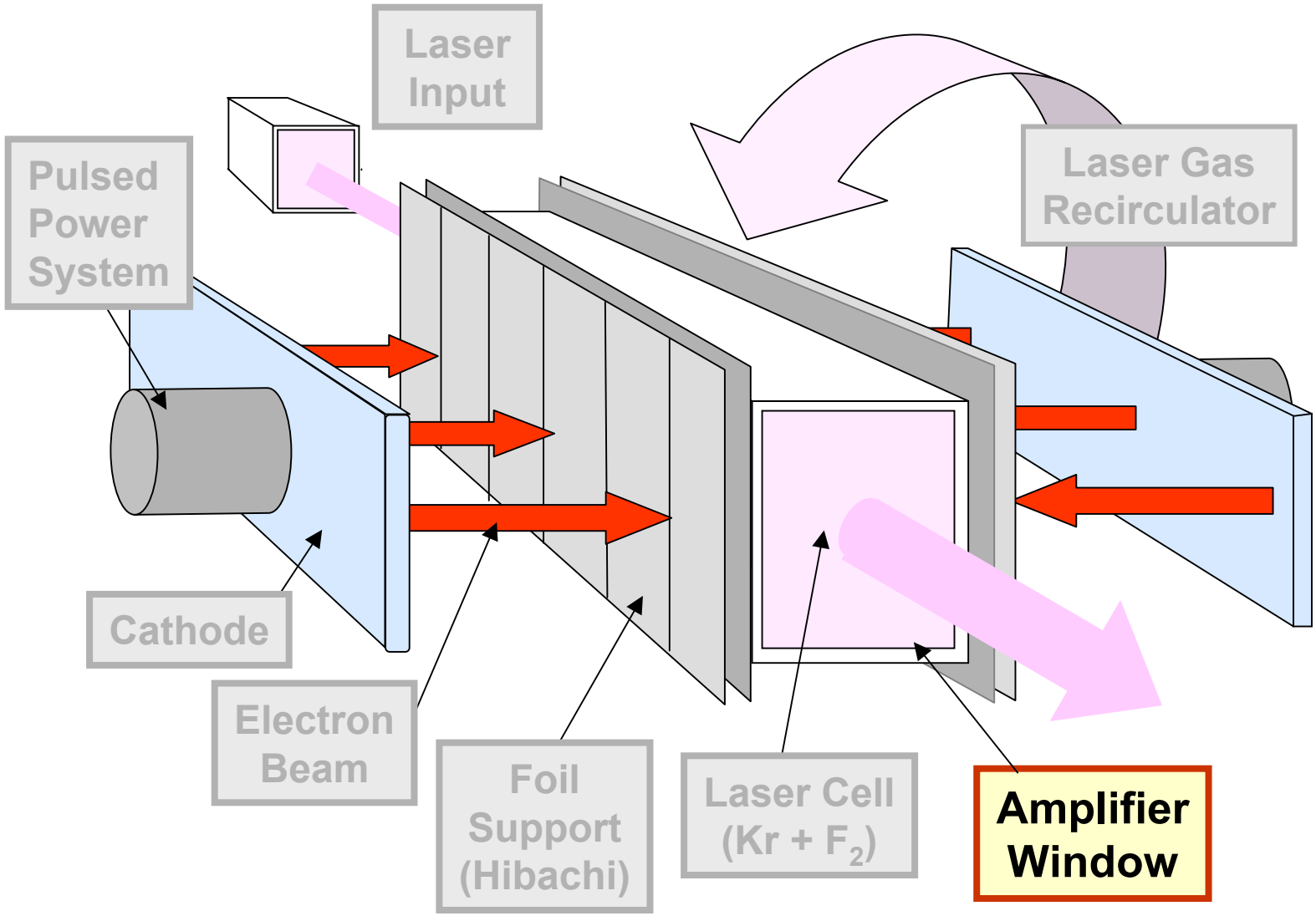




ORESTES prediction of Electra performance

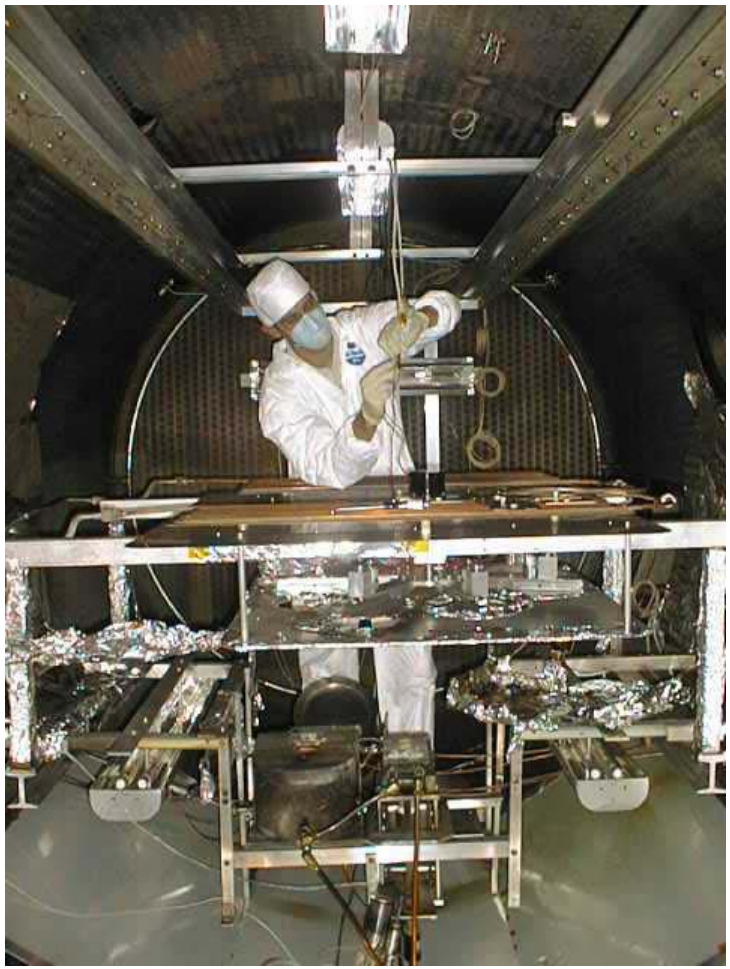


Amplifier Window development

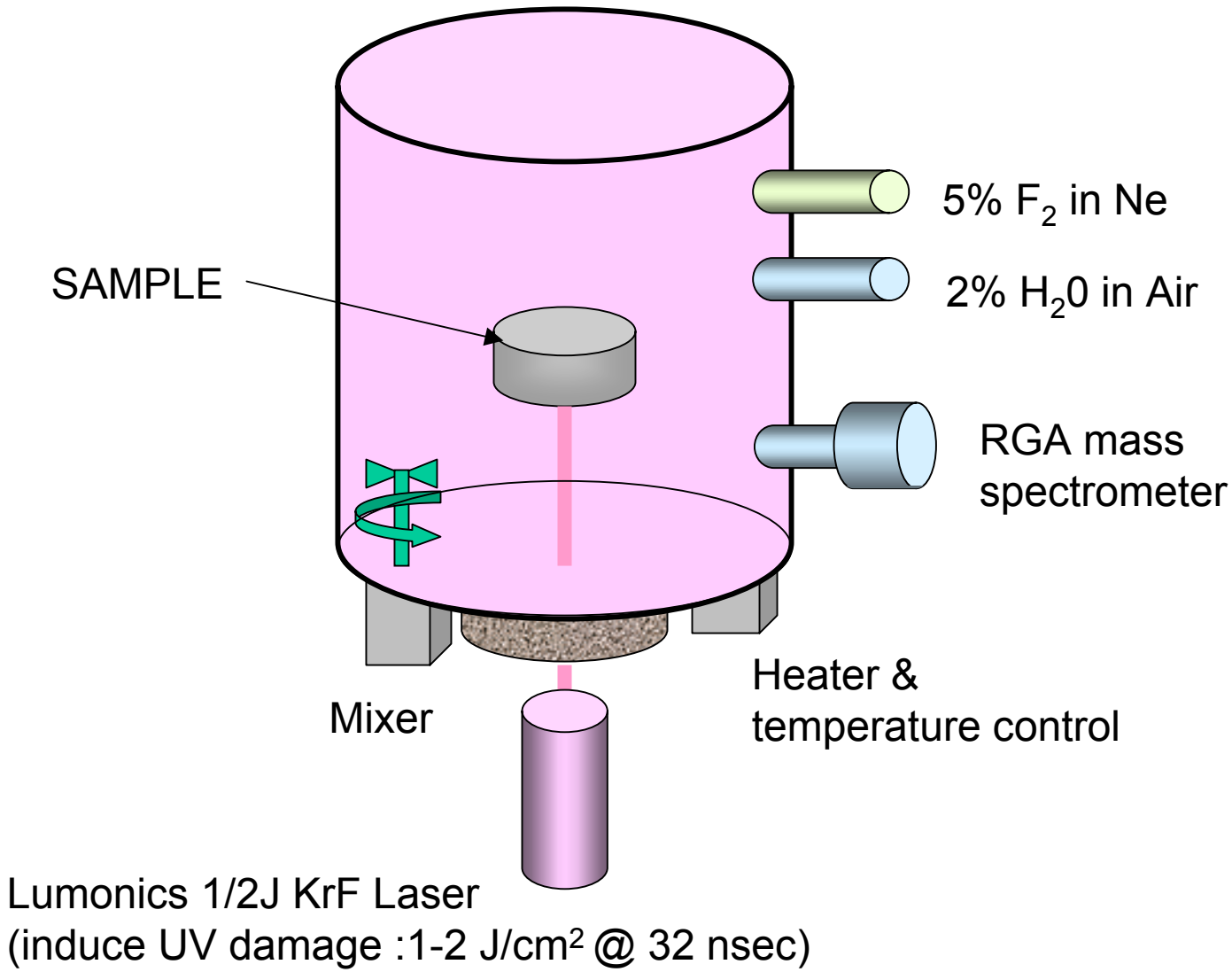


We can make our own optical coatings with "in-house" facility at SAIC

Chamber for E-beam evaporation
with ion beam assist

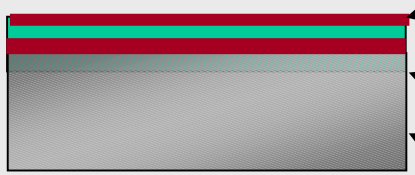


We have built a test cell to evaluate optical coating resistance to HF, F_2, and UV (@ 248 nm)



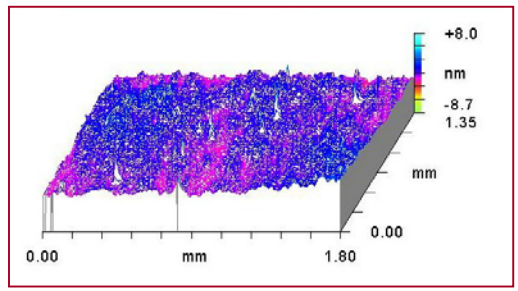
We have produced an optical coating with: good transmission, high laser damage threshold, and good HF resistance.

Sample # 20Mar02P1:



- 45 nm MgF_2
- 30nm Alumina
- 70 nm MgF_2
- quartz

Transmission loss: < 0.8% @ 248 nm



Surface Map

Exposure tests:

Start:		**RMS = .789 nm**
Laser:	5 Hz, 10 sec @ 1.4 J/cm^2 = 2.5 J/cm^2 @ 100 nsec = 6 J/cm^2 @ 600 nsec	**RMS = .743 nm**
F_2 + HF	6 hrs @ 5% F_2 + 1200 ppm HF	**RMS = .773 nm**

Goals for Phase I

Scaling: All technologies must scale to power plant size

Illumination: Uniformity as required by high gain target designs. (*presently < 0.4% low mode, < 2% high mode*)

Pulse Shaping: As required by high gain target designs.

Durability: Demonstrate 10^5 shots continuous with technologies that can be credibly extrapolated to > 10^8 shots. *(can also do 10^6 shots in ten five hour runs*)

Cost: Cost credibly extrapolated to power plant needs *(presently this number is $280/laser Joule)*

Efficiency: Sufficient for fusion power plant, as determined by high gain target designs & systems studies (*presently this number is ~ 6%)*

A total system efficiency of 6-7% should be achievable

Efficiency allocation:		Phase I Confirmation
Pulsed power	85%	Integrated System + Adv Switch
Hibachi	81%	Experimental Demonstration
Intrinsic[1]	10-12%	Exp validation Orestes code[2]
Ancillaries	95%	Electra + Systems Studies
Optical Train	95%	Electra + Systems Studies
Total:	6.2 – 7.5%	

1. $\eta_{intrinsic} = \eta_{formation}$ (25-28%) x $\eta_{extraction;}$ (40-50%) = (10-14%). Also includes amp window losses
2. 12% demo on other systems:
   "KrF Laser Studies at High Krypton Density" A.E. Mandl et al, Fusion Technology 11, 542 (1987). also
   "Characteristics of an electron beam pumped KrF amplifier with atmospheric pressure Kr-rich mixture in strongly saturated region", A. Suda et al, Appl. Phys. Lett, 218 (1987)

The Next Step in the development of Laser Fusion Energy is the IRE:

1. **A Full Energy Laser Beam Line.**
   Demonstrates all fusion energy requirements:
   Efficiency, Rep-rate, Durability, Cost basis

3. **Hit targets injected into chamber**

4. **Be a repetitive high energy laser facility to:**
   Investigate chamber dynamics
   Study candidate wall and/or optics material behavior
   High energy, repetitive laser facility for DOE/DP

Note: The KrF IRE is one part of the integrated program™ to develop Laser Fusion Energy

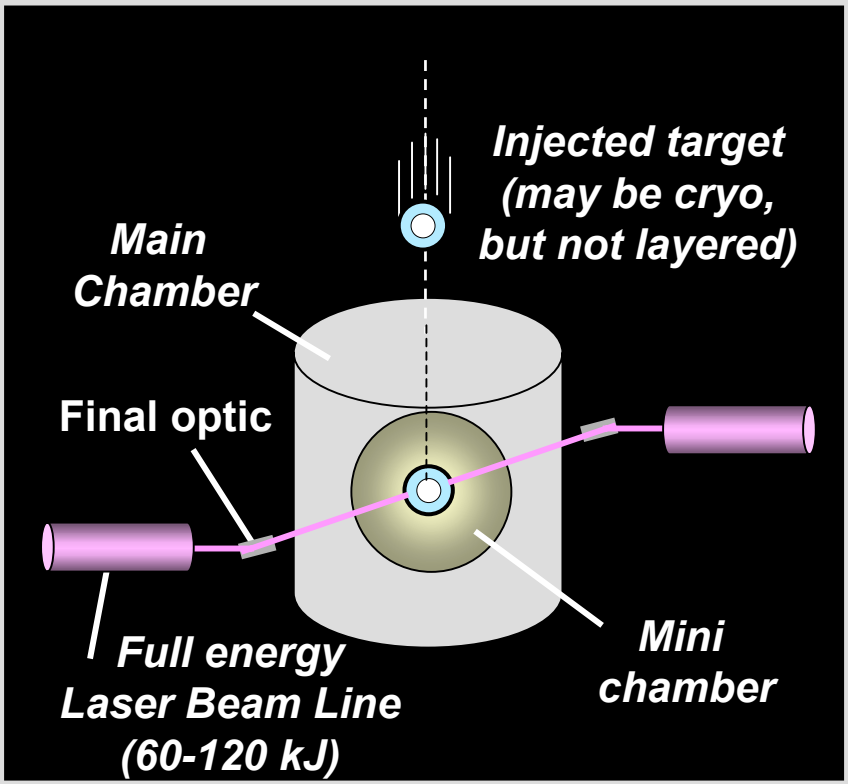
The IRE will be composed of two separate facilities, plus power plant design

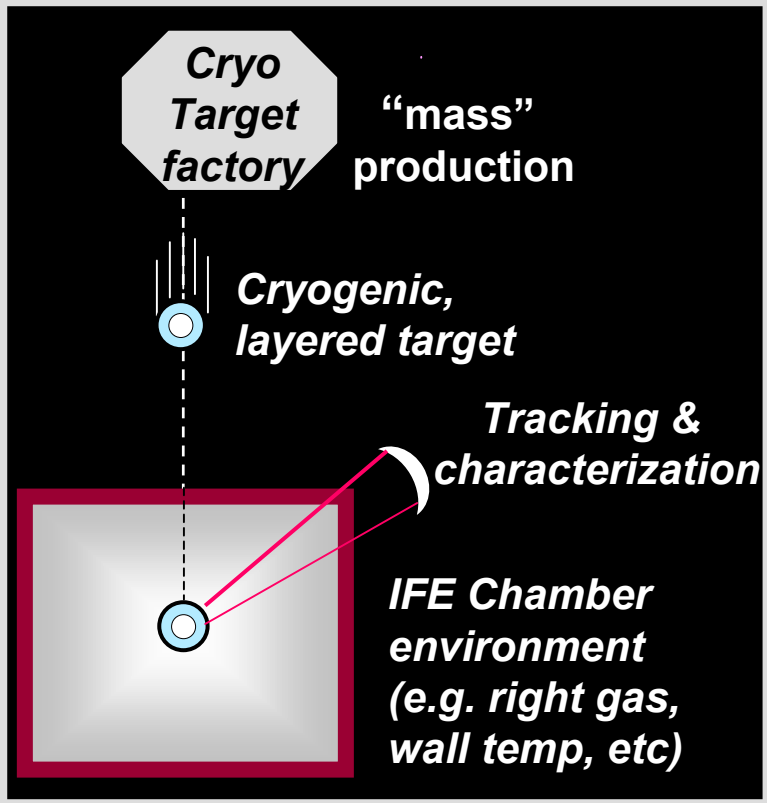
1. Laser Facility:

Full energy laser beam line
Steer beam to hit injected target
Test materials in "mini' chamber
Evaluate chamber dynamic models
Test final optics

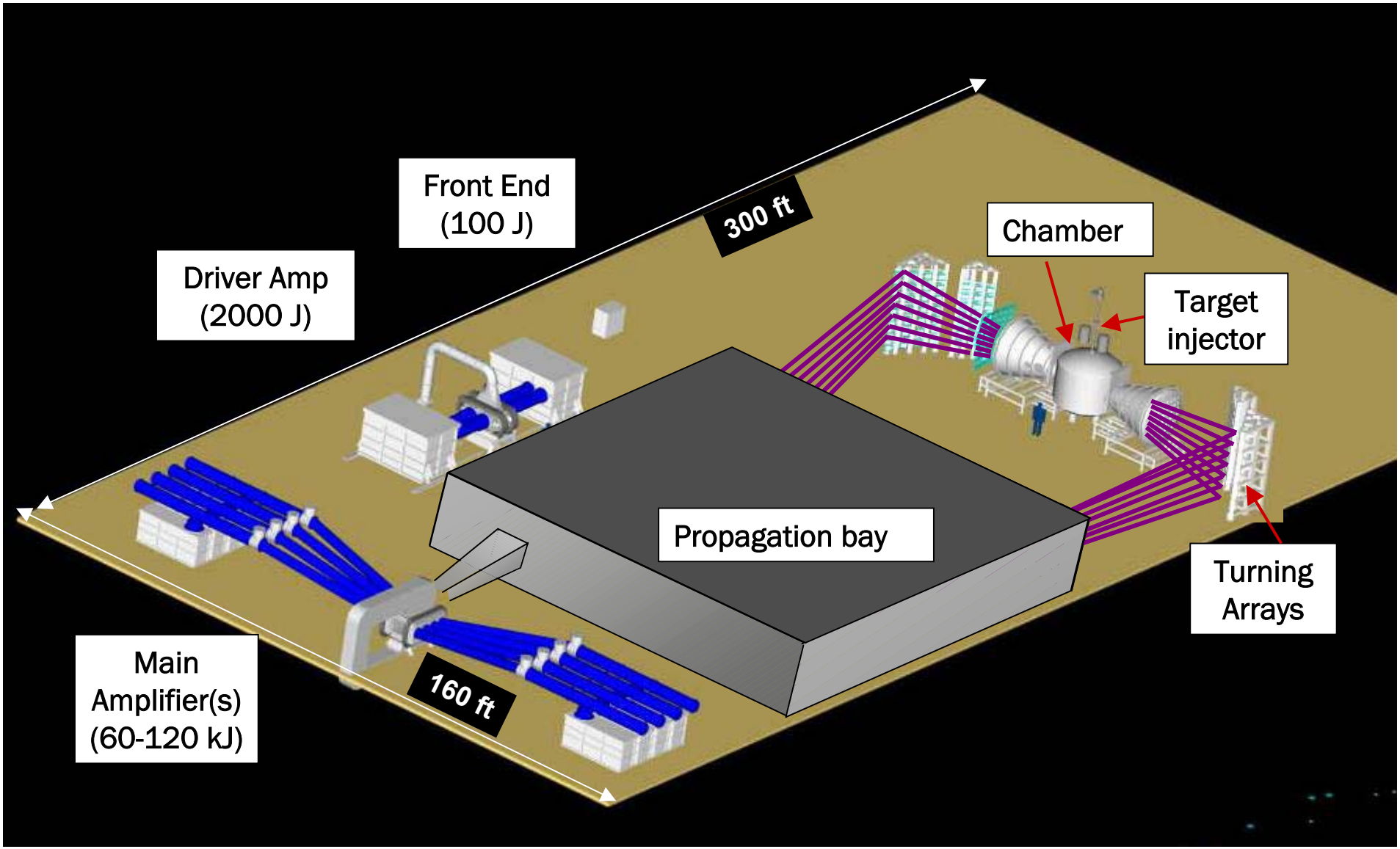
2. Target Facility:

demonstrate target injection and tracking in an IFE chamber environment

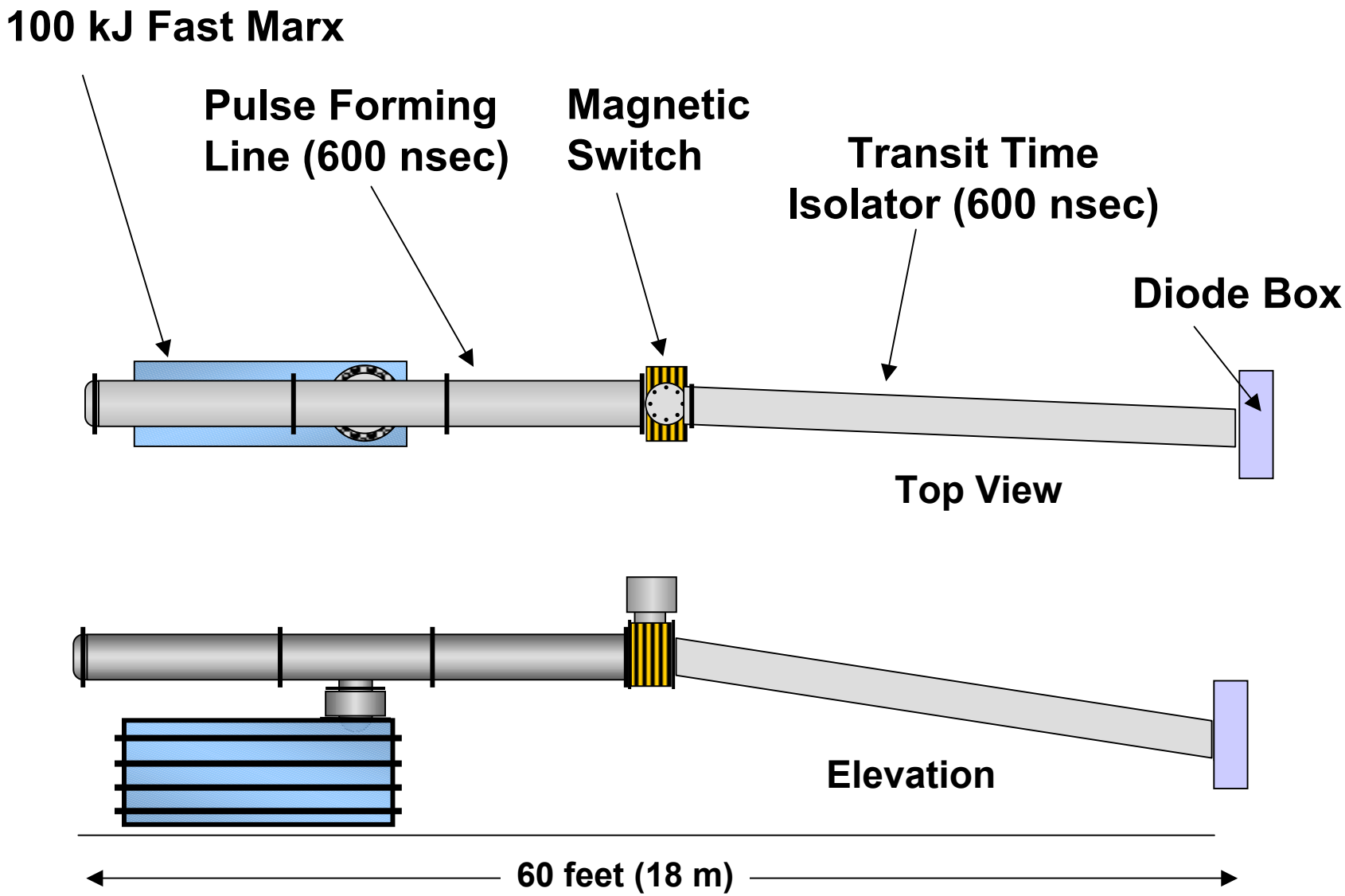




The Laser Integrated Research Experiment (KrF)

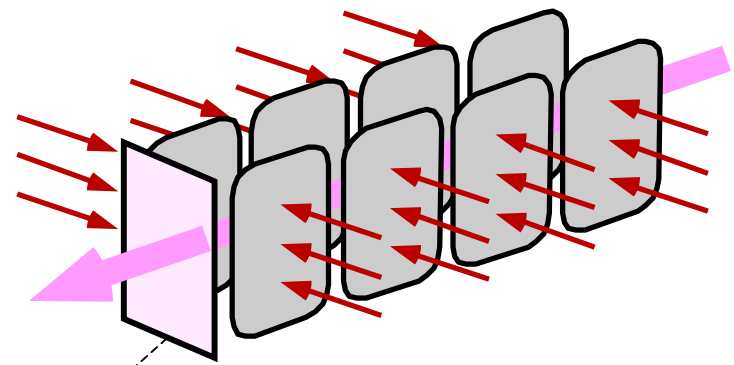


The Fundamental Building block of the Main Amp is the 100 kJ Pulsed Power Module

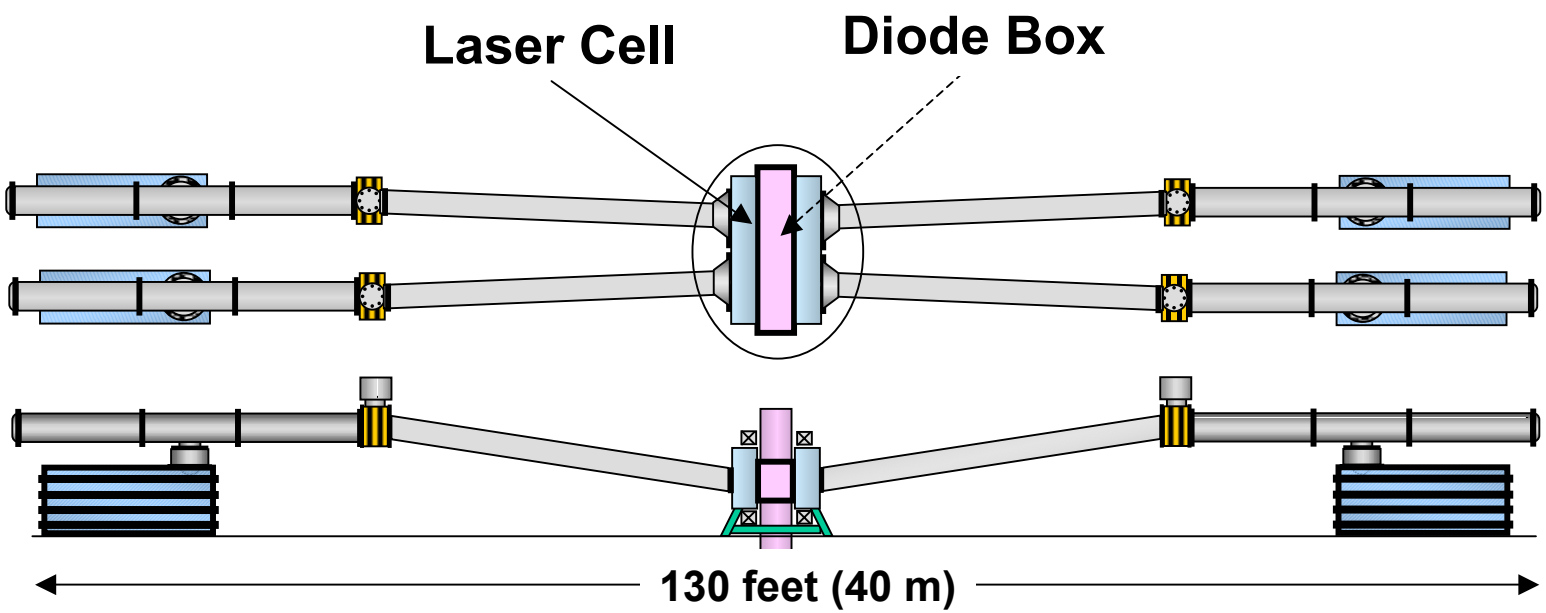


30 kJ IRE Amplifier

E_{stored}	100 kJ x 4 = 400 kJ
V	800 keV
I	85 kA x 8
T	600 nsec
E_{laser}	30 kJ



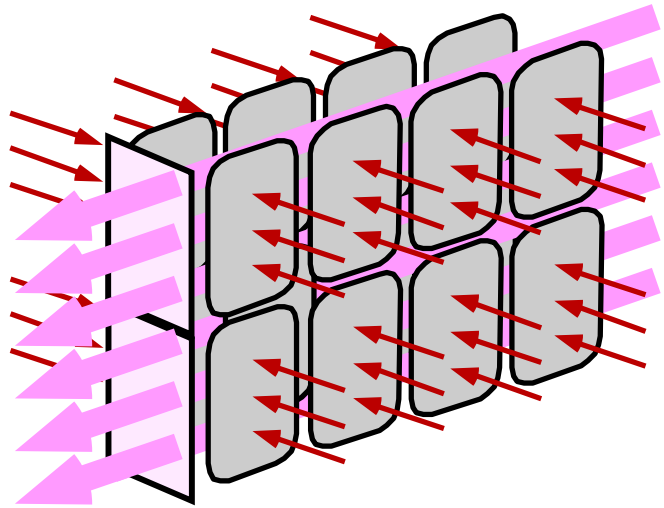
Each 100 kJ pulse line powers two diodes



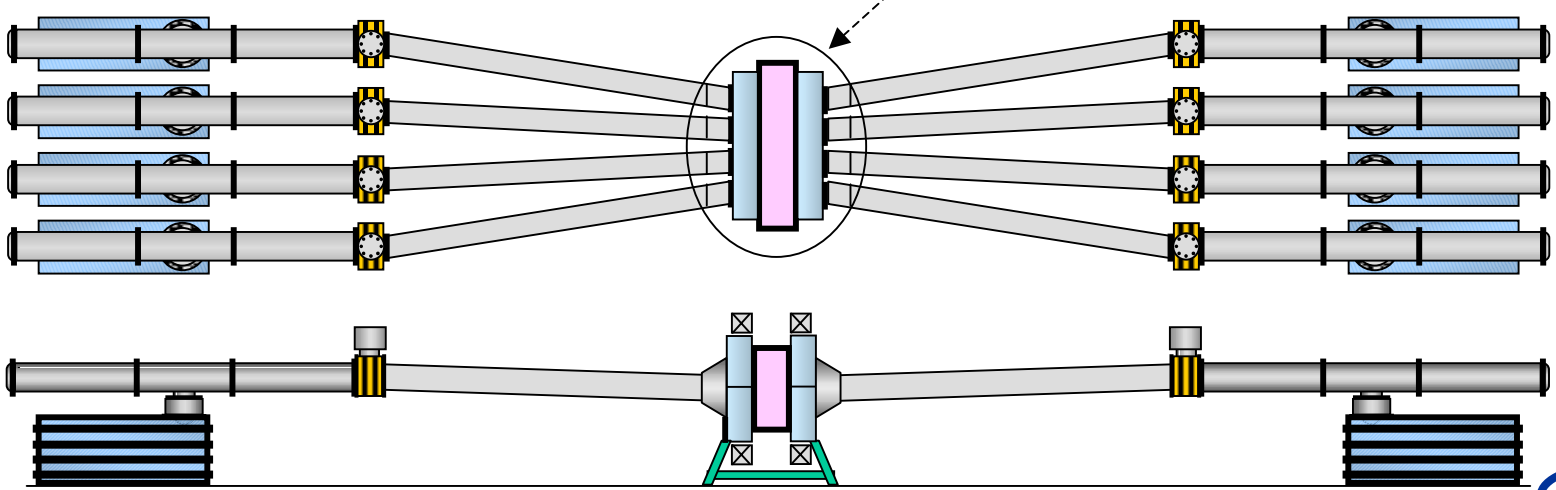
400 kJ x 80% (e-beam flat top energy/stored energy) x 80% (hibachi transmission) x 12% KrF efficiency = 31 kJ

60 kJ IRE Amplifier

E_{stored}	100 kJ x 8 = 800 kJ
V	800 keV
I	85 kA x 16
T	600 nsec
E_{laser}	60 kJ



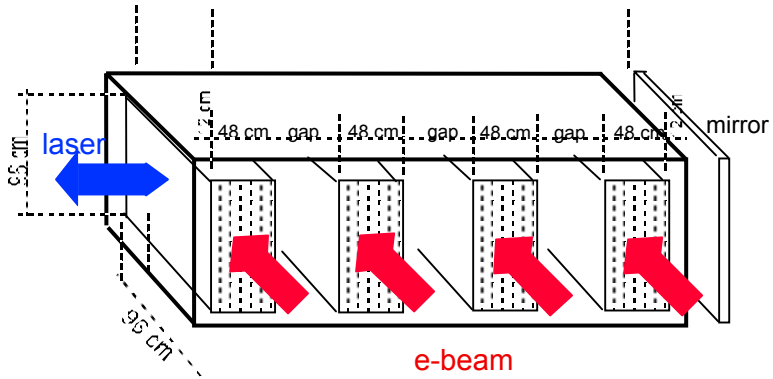
Each 100 kJ pulse line powers one vertical pair of diodes



130 feet (40 m)

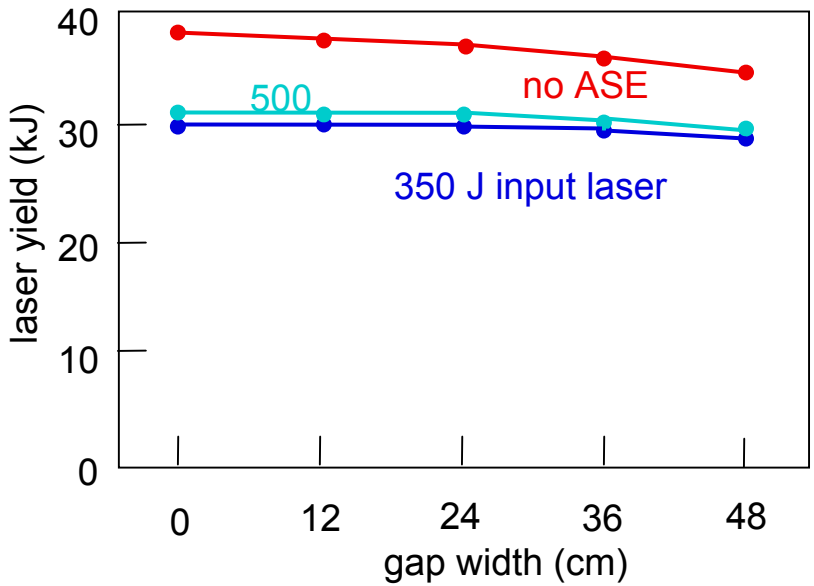
800 kJ x 80% (e-beam flat top energy/stored energy) x 80% (hibachi transmission) x 12% (KrF efficiency) = 62 kJ

Preliminary modeling shows segmented e-beam diodes should not effect laser performance



30%Kr
0.6%F2
800 kW/cc
t_{FWHM}(beam)= 300 ns
t_{FWHM}(input laser)=250 ns

Light is absorbed by F_2 in gaps…
…but loss is offset by:
no ASE amplification in gaps
and
destruction of F_2 by ASE absorption

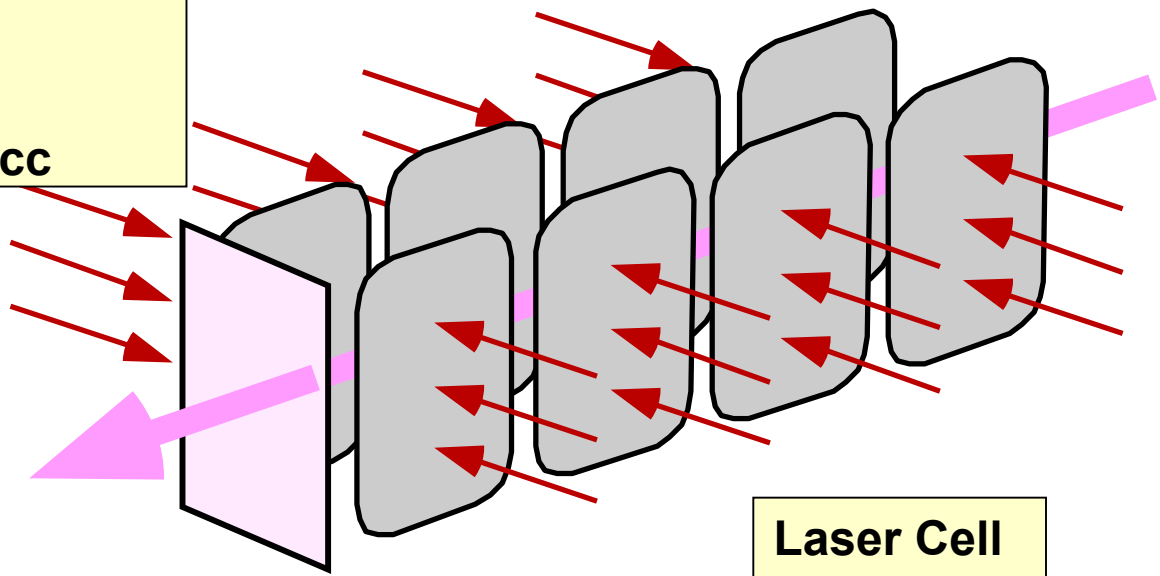


M.W. McGeoch et al, "Conceptual Design of a 2 MJ KrF laser Fusion Facility" Fusion Technology, **32**, 610, (1997)

Orestes Modeling of 30 kJ IRE amp

Pump:	8 e-beams
Voltage	800 kV
Current	87.5 kA x 8
Pulse (flat top)	600 nsec
Cathode	50 x 80 cm
E-beam energy	42 x 8 = 336 kJ
Deposited Energy:	**272 kJ**
Pump Power:	350 kW/cc

Input Laser: 2 kJ



Laser Cell
45% Kr
54.2% Ar
0.80% F_2

Optical Aperture
80 x 80 cm^2

Laser output:
28.9 kJ
η= 10.6%

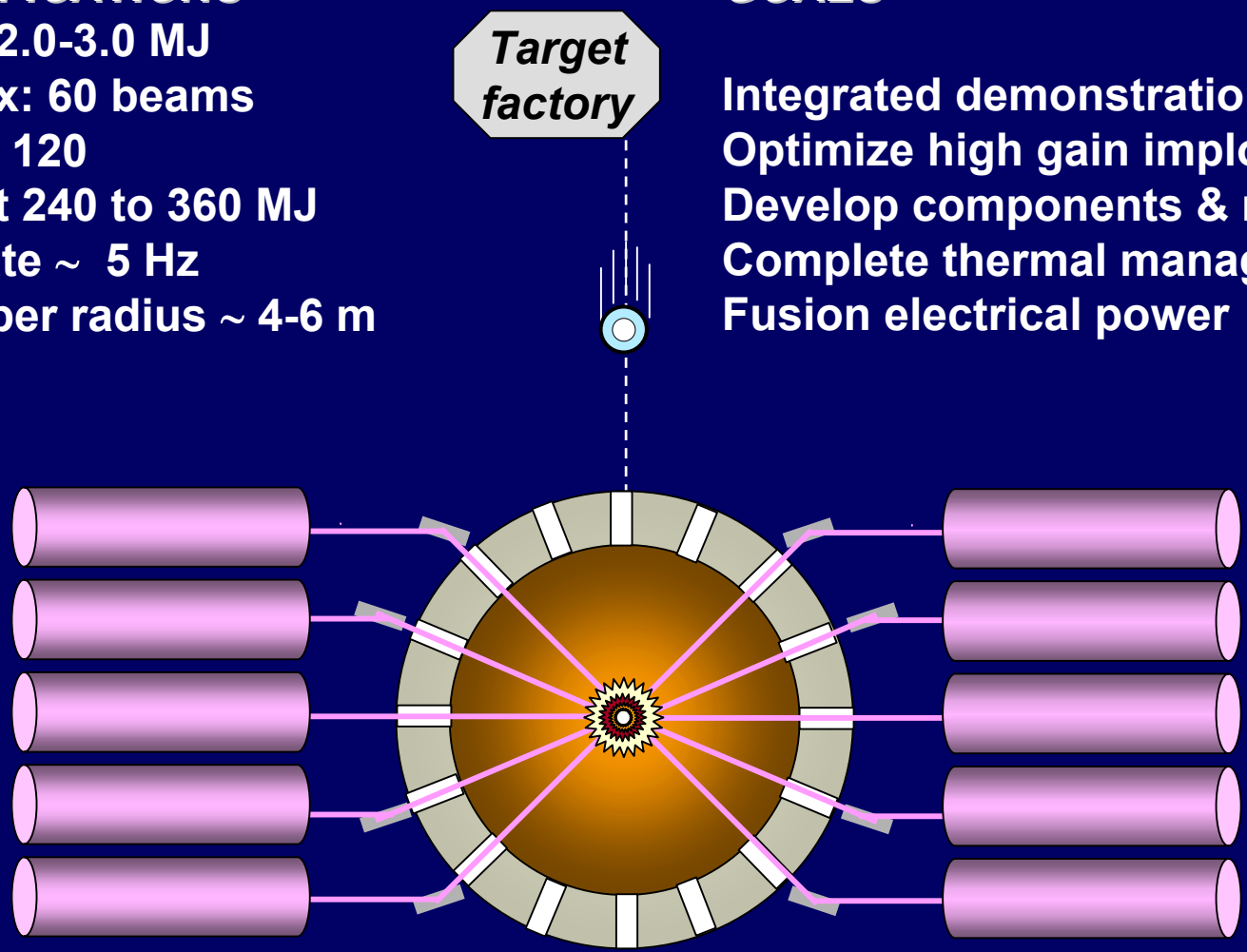
The ETF will be a full scale laser facility and the first demonstration of repetitive high fusion yield

SPECIFICATIONS

Laser 2.0-3.0 MJ
Approx: 60 beams
Gain ~ 120
Output 240 to 360 MJ
Rep rate ~ 5 Hz
Chamber radius ~ 4-6 m

GOALS

Integrated demonstration
Optimize high gain implosions
Develop components & materials
Complete thermal management
Fusion electrical power (300 MW)



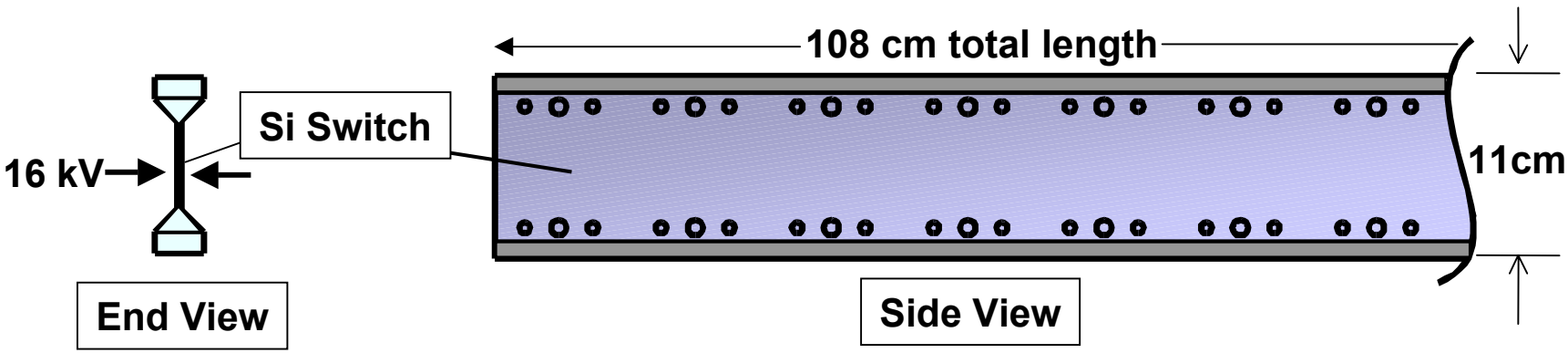
Up
R.W

Fast Marx based on Advanced Switch

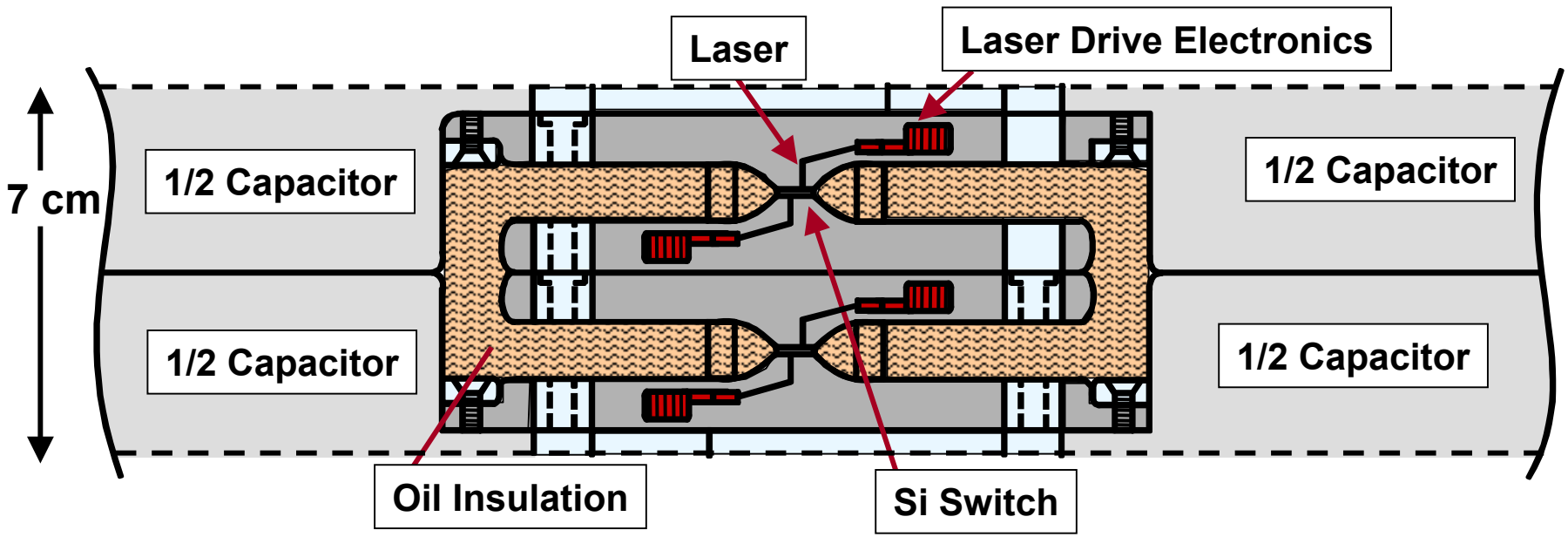
TITAN
Pulse Sciences Division

FINAL CONFIGURATION **Rail Gap Geometry**

Full-Stage Switch Assembly (16.4 kV)

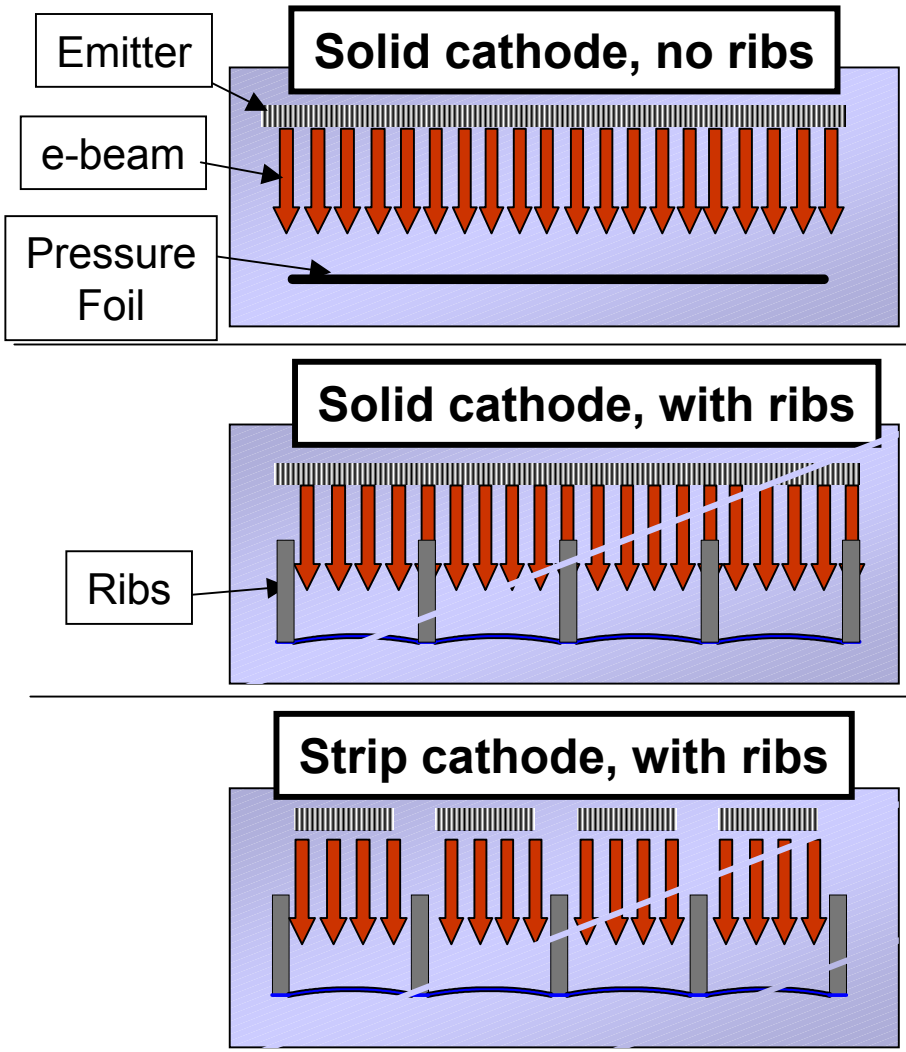


Application- Ultra Fast Marx (+/- 16.4 kV stage)



Patterning beam:

1. Increases energy deposition by 26% over monolithic cathode
2. Performance close to "rib-less" hibachi



Simulation (1-D Tiger) **72%**

Experiment **53%**

Experiment **67%**

26% Increase

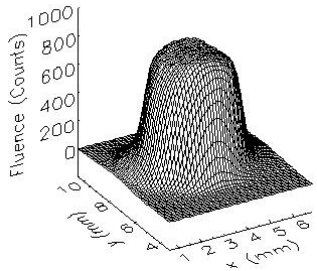
93% of max*

(most of this loss is beam grazing ribs)

* All measurements corrected for flat portion of e-beam pulse

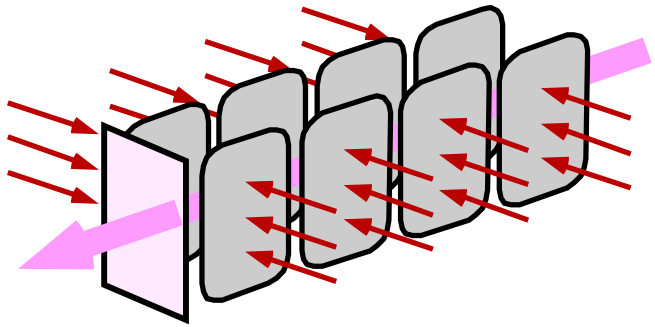
Why we like KrF lasers

1. Demonstrated outstanding spatial uniformity minimizes hydrodynamic instabilities



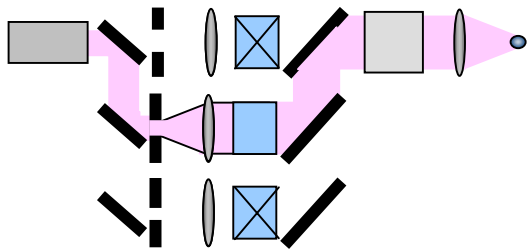
2. Shortest wavelength (1/4 μm) maximizes absorption and rocket efficiencies, minimizes risk from laser plasma instabilities

3. Electron beam pumped architecture scalable to large systems



4. Low cost (pulsed power is cheap!)

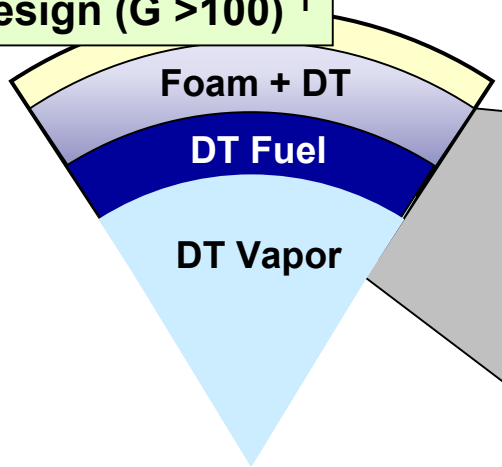
5. Pulse shaping & zooming achieved at low energy in front end "seed" amplifier



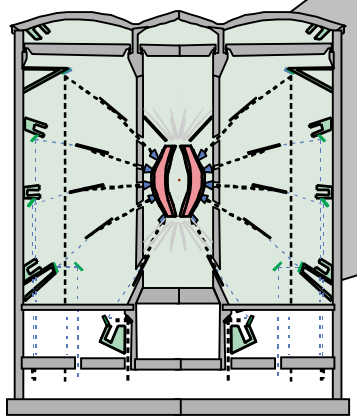
6. Modular nature lowers development costs

Target gain, power plant studies define laser requirements.

High Gain Target Design (G >100) [1]



Power Plant Study [2]



Laser IFE Requirements

	IFE	NIKE
Beam quality (high mode)	0.2%	0.2%
Beam quality (low mode)	2%	N/A(4)
Optical bandwidth	1-3 THz	3 THz
Beam Power Balance	2%	N/A(4)
Rep-Rate	5 Hz	.0005
Laser Energy (amplifier)	30-150 kJ	5 kJ
Cost of pulsed power(1)	$5-10/J(e-beam)	N/A3
Cost of entire laser(1)	$280/J(laser)	$3600/J
System efficiency	6-7%	1.4%
Durability (shots) (2)	3×10^8	20
Lifetime (shots)	10^{10}	10^4

Easy

Hard

1. 2002 $. Sombrero (1992) gave $180/J and $4.00/J
2. Shots between major maintenance (2.0 years)
3. Not Applicable: Different technology
4. Not Applicable: Nike shoots planar targets

1. 1-D gain. S.E. Bodner, D. G. Colombant, A.J. Schmitt, and M. Klapisch, Phys of Plasmas 7, 2298,-2301 (2000).
2. 2. Sombrero: 1000 MWe, 3.4 MJ Laser, Gain 110; Cost of Electricity: $0.04-$0.08/kWh; Fusion Technology, **21**,1470, (1992)