SAND2003-0310P

Z-Beamlet: Applications and Future Work

January 30, 2003

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy under contract DE-AC04-94AL85000.

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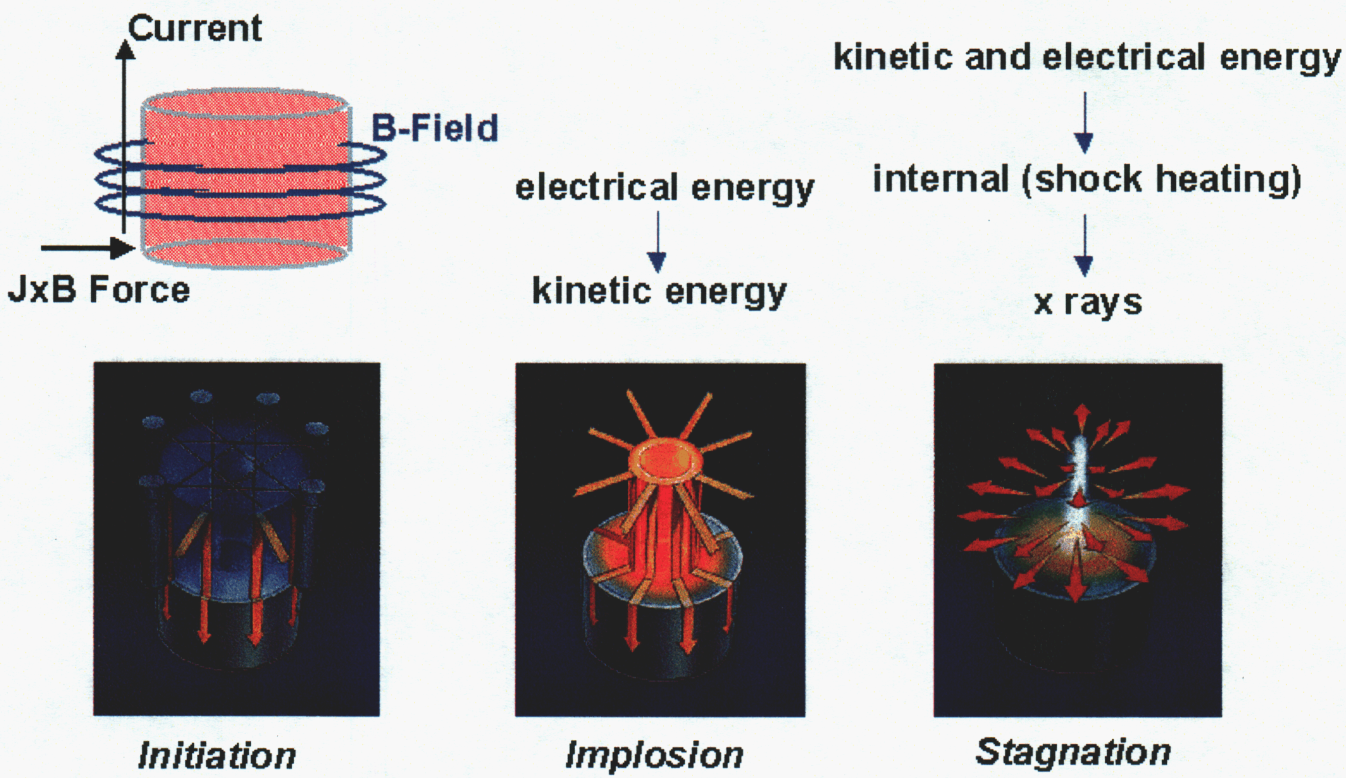
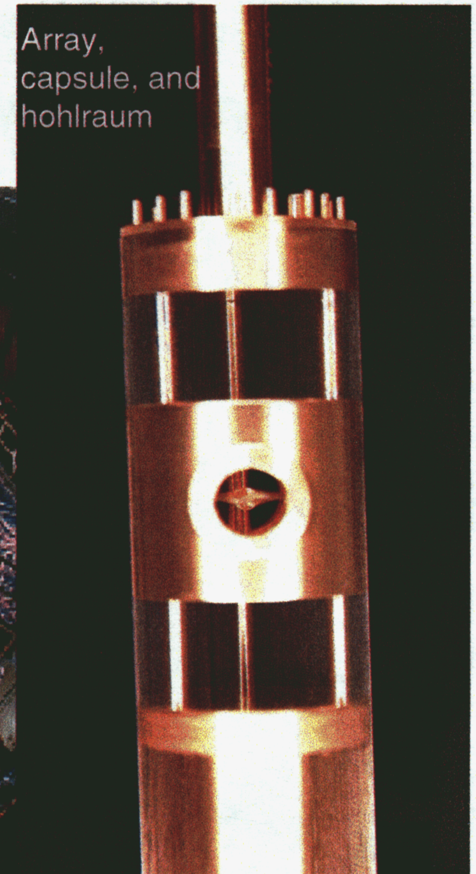
Z-Pinches



- Z-pinches use high electromagnetic fields (self-generated) to implode wire arrays.
- The wire array material is accelerated toward the axis of symmetry to form a hot dense plasma there.
- The plasma in turn emits x-rays over broad spectral (energy) range.

The Z-Machine



- Sandia's Z-machine uses large electrical impulses (currents of 20 MA and stored energies of 11 MJ) to implode wire arrays.

- The resulting plasmas provide high energy density physics (HEDP) conditions capable of producing up to 280 TW of x-rays (for 1.8 MJ total energy).

- One key application of the x-ray source to symmetrically drive capsules in inertial confinement fusion (ICF) research.

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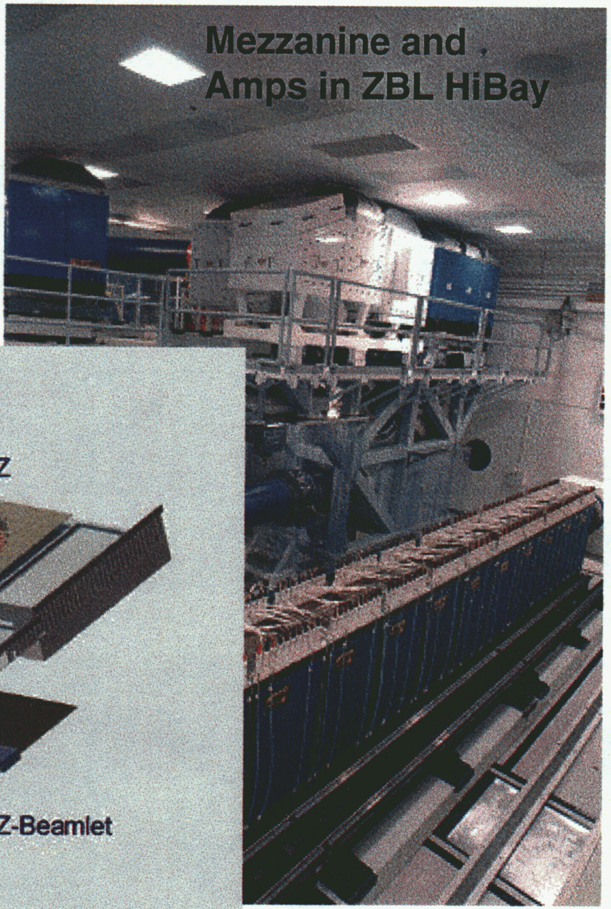
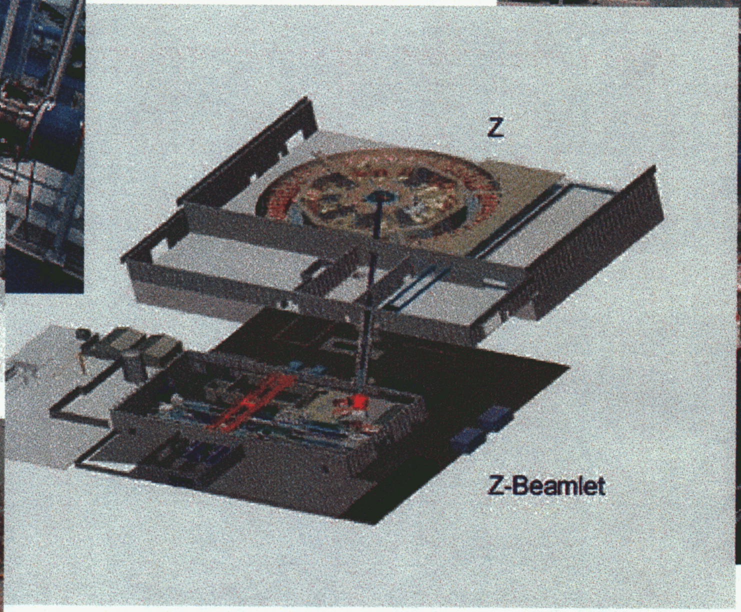
Z-Beamlet

- Sandia's Z-Beamlet (ZBL), a multi-kilojoule large-aperture (>30 cm) Nd:Glass laser developed as LLNL's National Ignition Facility prototype, creates x-rays for radiographic pictures of fast-moving high-energy density conditions on the Z-Accelerator.





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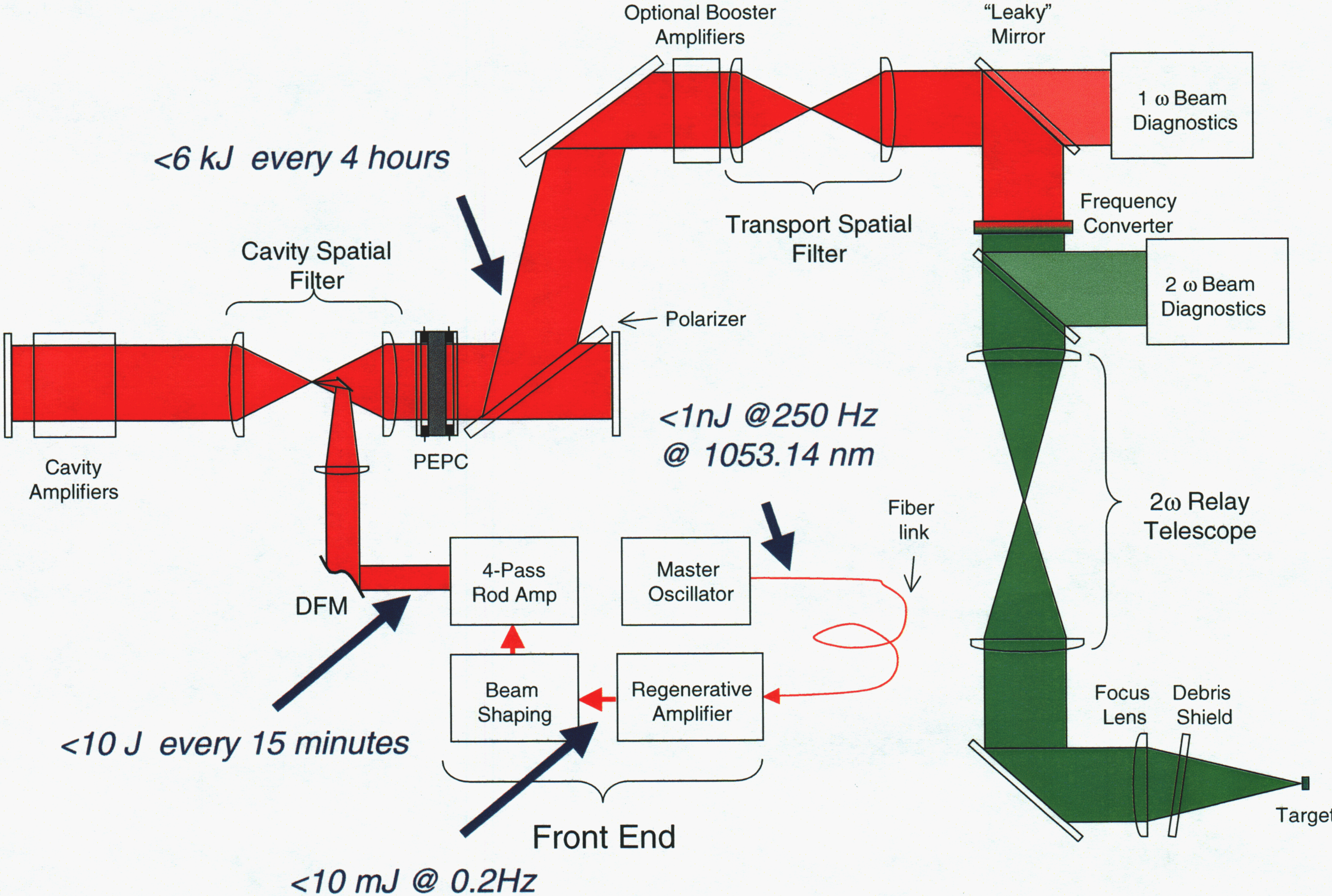
Z-Beamlet Schematic



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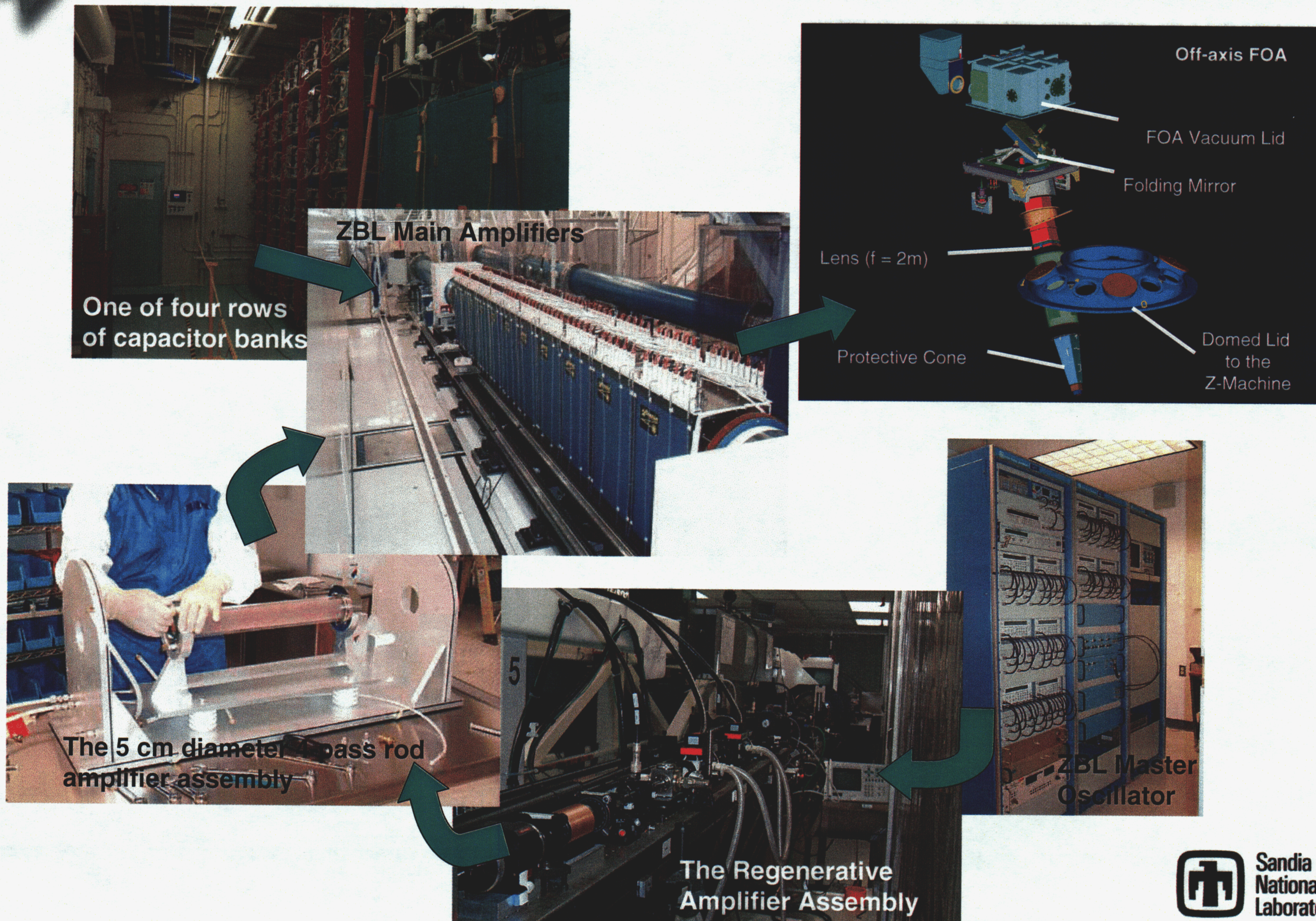
Z-Beamlet Schematic: Photographic Views



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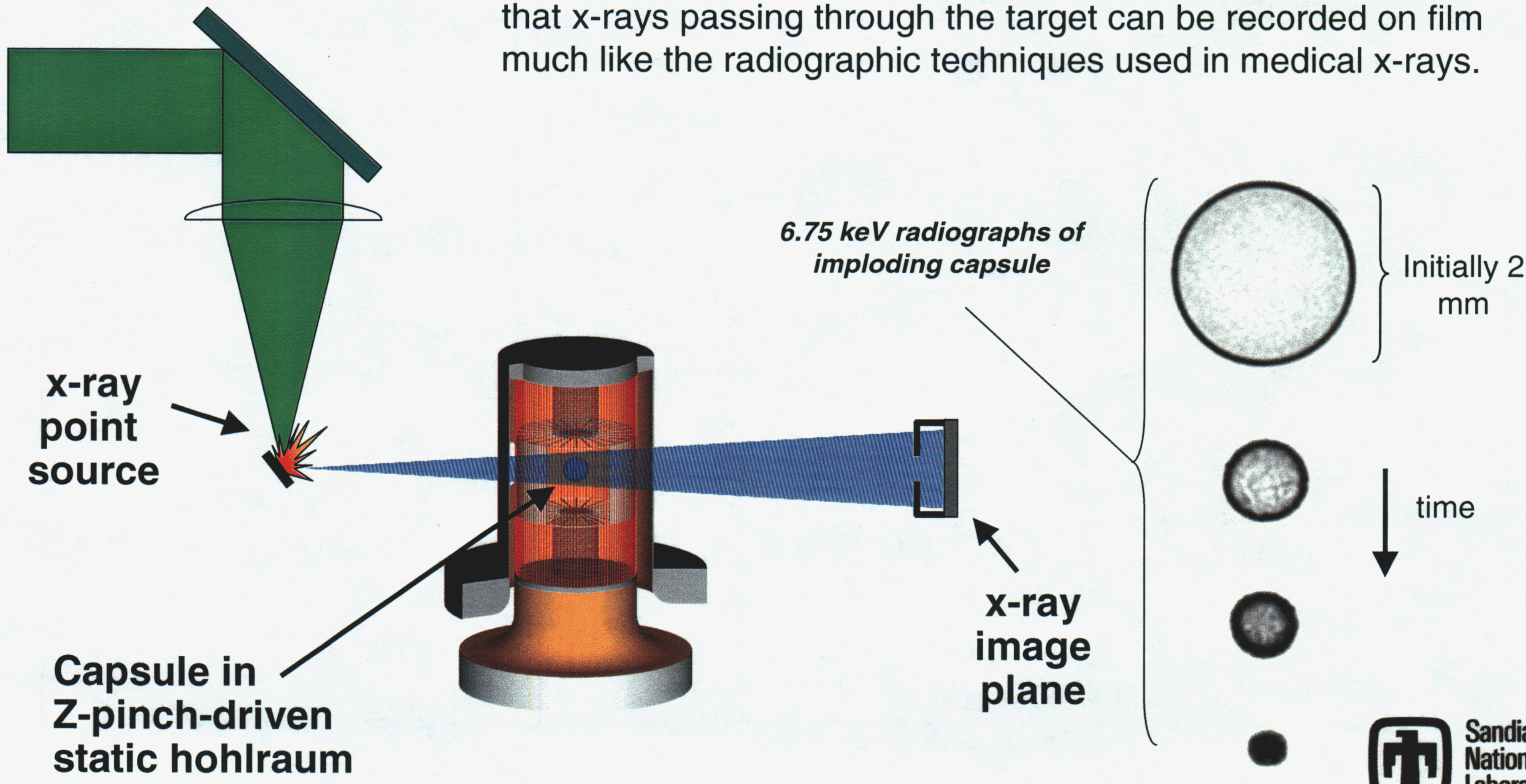
Z-Beamlet Mission

- To enhance studies on the Z-machine, Sandia requires a “backlighter”.
- The concept is to generate additional x-rays by illuminating a thin foil with an intense laser pulse. A nanosecond scale pulse optimizes laser to x-ray conversion while shorter pulses prevent motional blurring.
- This new x-ray source is located off-center from the target such that x-rays passing through the target can be recorded on film much like the radiographic techniques used in medical x-rays.



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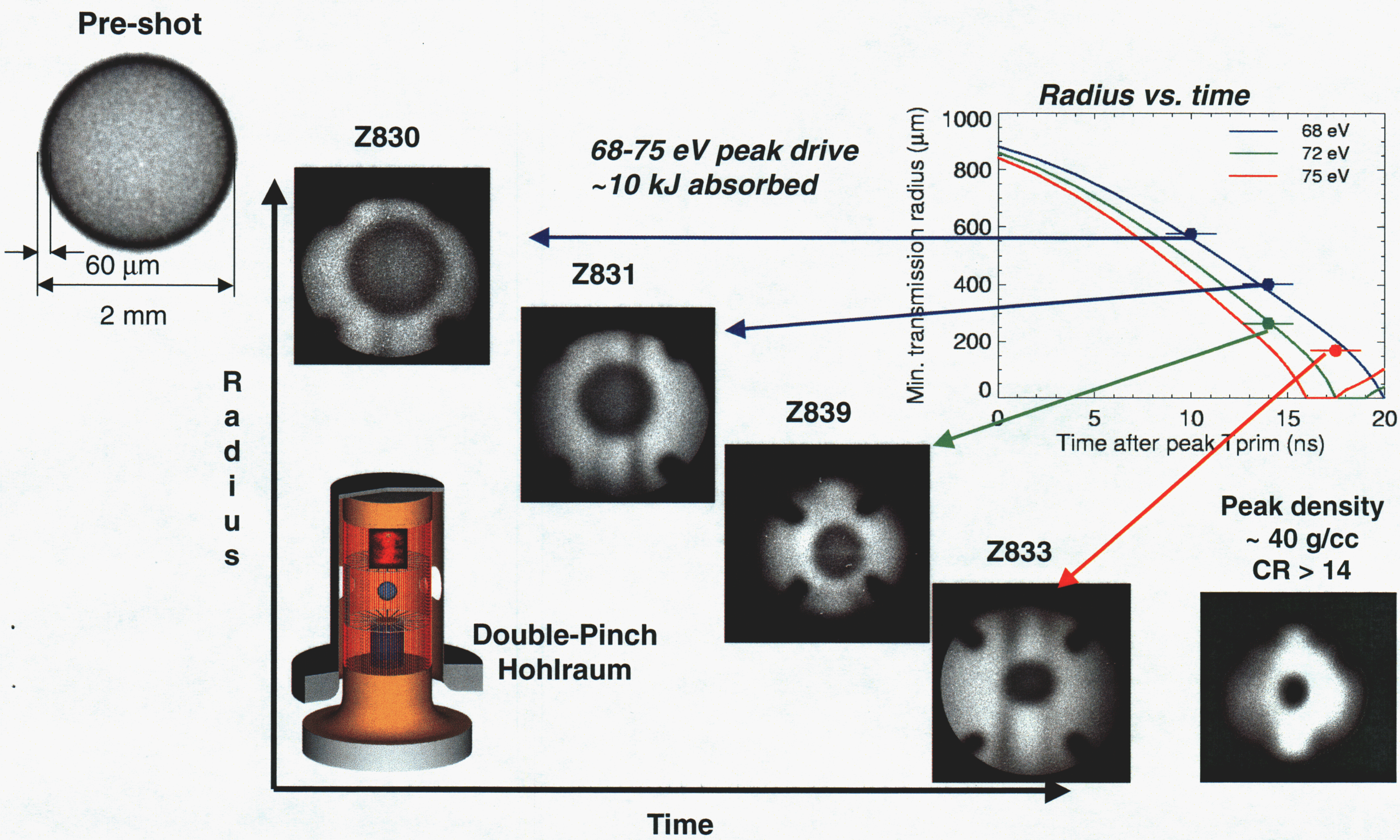
Imploding Capsules



Data from November 2001 (Fe foil @ 6.7 keV)

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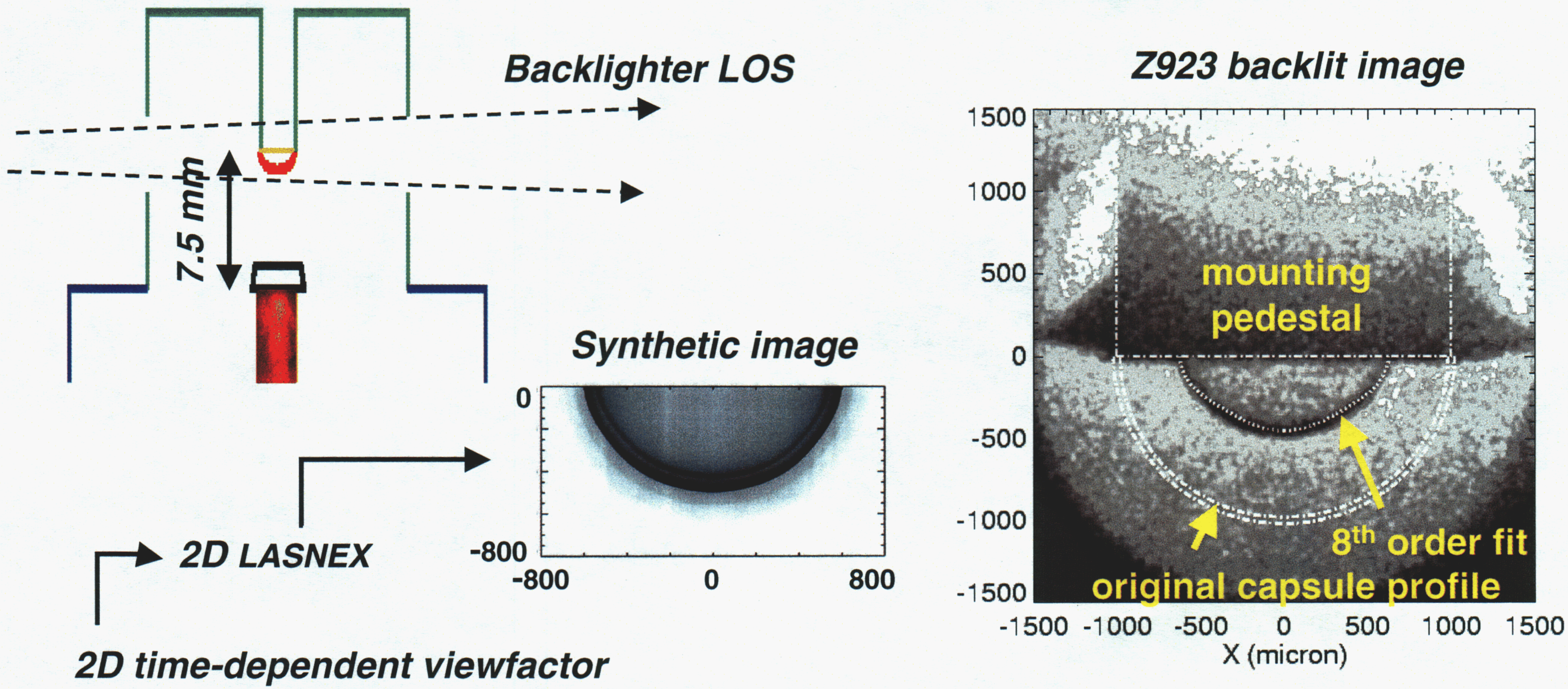
Fast Ignitor Geometries



- Preliminary image analysis agrees qualitatively with piecewise simulations
- 2D simulations give polar-averaged peak ρ = 60 g/cc, ρ r = 0.3 g/cm^2 for this case

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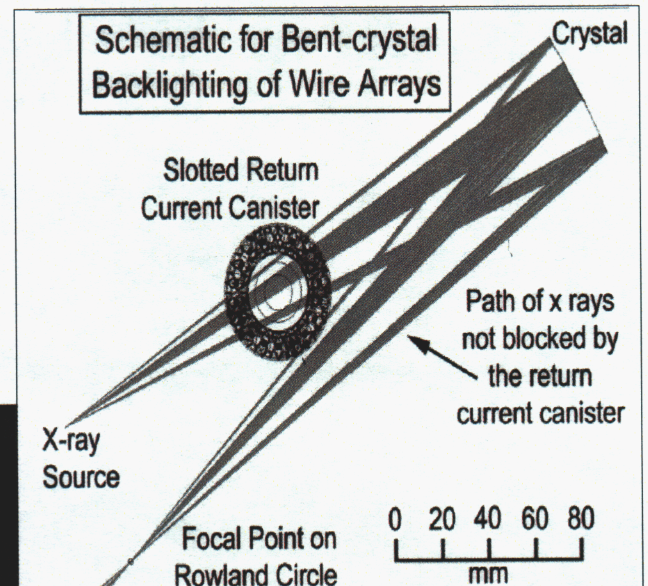
Monochromatic Crystal Imaging

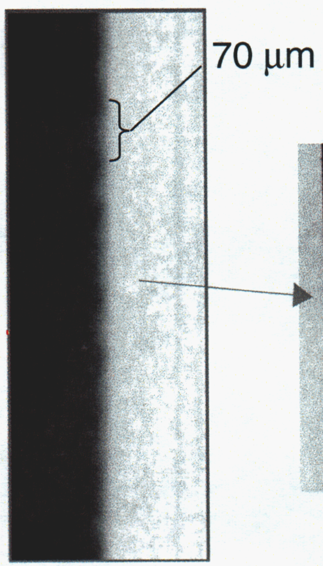
- A bent/ curved crystal can be used for x-ray imaging if the x-ray wavelength matches the lattice spacing.

- The approach works with a few selected x-ray energies (such as 1.865 keV from Si backlighting) although work is underway to extend the capability to higher x-ray energies.

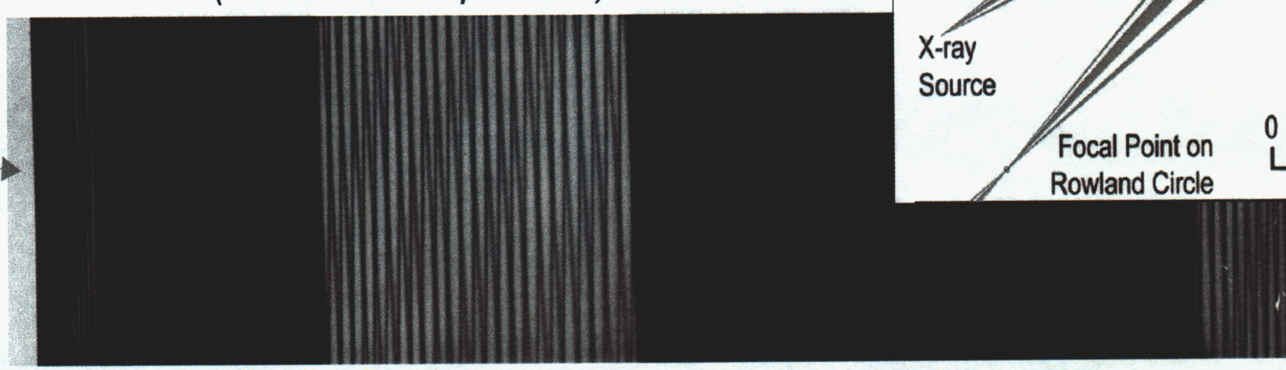
- The method allows spatial resolutions of 10 μm and has the added benefit of being insensitive to x-ray spotsize.

- The technique allows imaging of the wires during a z-pinch, allowing better studies on z-pinch physics.





Wire array during early stages of a z-pinch (~33%into implosion)



Z-Beamlet Petawatt Motivation

What is the motivation for a ***Petawatt*** capability at Sandia on a modified ZBL?

- New radiography options for the HEDP conditions generated with a z-pinch:
  - ➢X-rays up to MeV range (instead of the <10 keV range extant at ZBL) allow radiography of more opaque materials
  - ➢Potentially proton radiography (with possible E-field mapping)
  - ➢Sub-picosecond time-resolved radiography (for fast events)

  Radiography options can use and expand upon 0.5-1.0 ps petawatt technologies proven elsewhere.

- Fast Ignitor fusion research on the Z-machine:
  - ➢ Electrons and/or proton beams for ignition

  Fast ignitor options motivate an improvement to higher energy petawatt lasers (multi-kilojoule) in the 5-10 ps regime.

Petawatt Implementation Plan:

•Phase I:	450 J in 450 fs	(FY05 goal)
•Phase II:	2kJ in 2 to 5 ps	(FY06 goal)
•Phase III:	4kJ in 5 ps	(FY07 goal)

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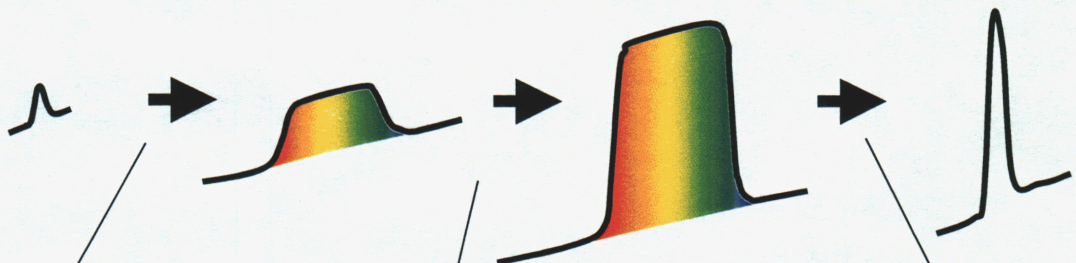
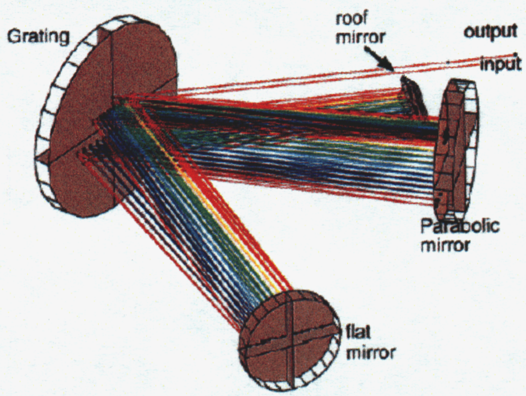
The Petawatt Modification: Phase I Goals

Chirped Pulse Amplification (CPA)

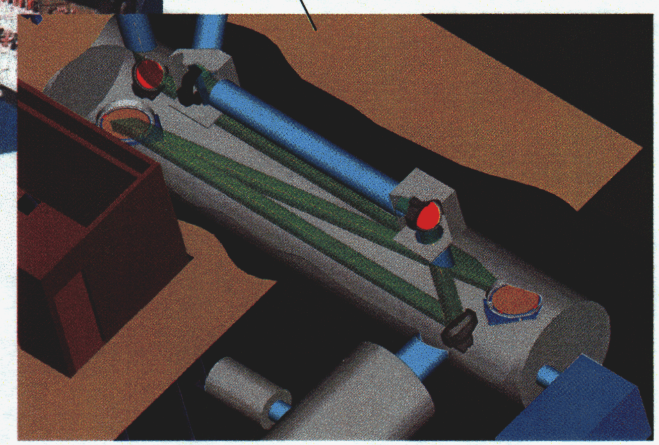
Seed pulse	Stretched pulse	Amplified pulse	Re-Compressed pulse
0.1 ps, 10 nJ (100 kW)	3 ns, <10 nJ	3 ns, 700 J	0.5 ps, 500 J (1 PW)





Grating Stretcher

ZBL Pre-amps and Main Amplifiers



Petawatt Grating Compressor

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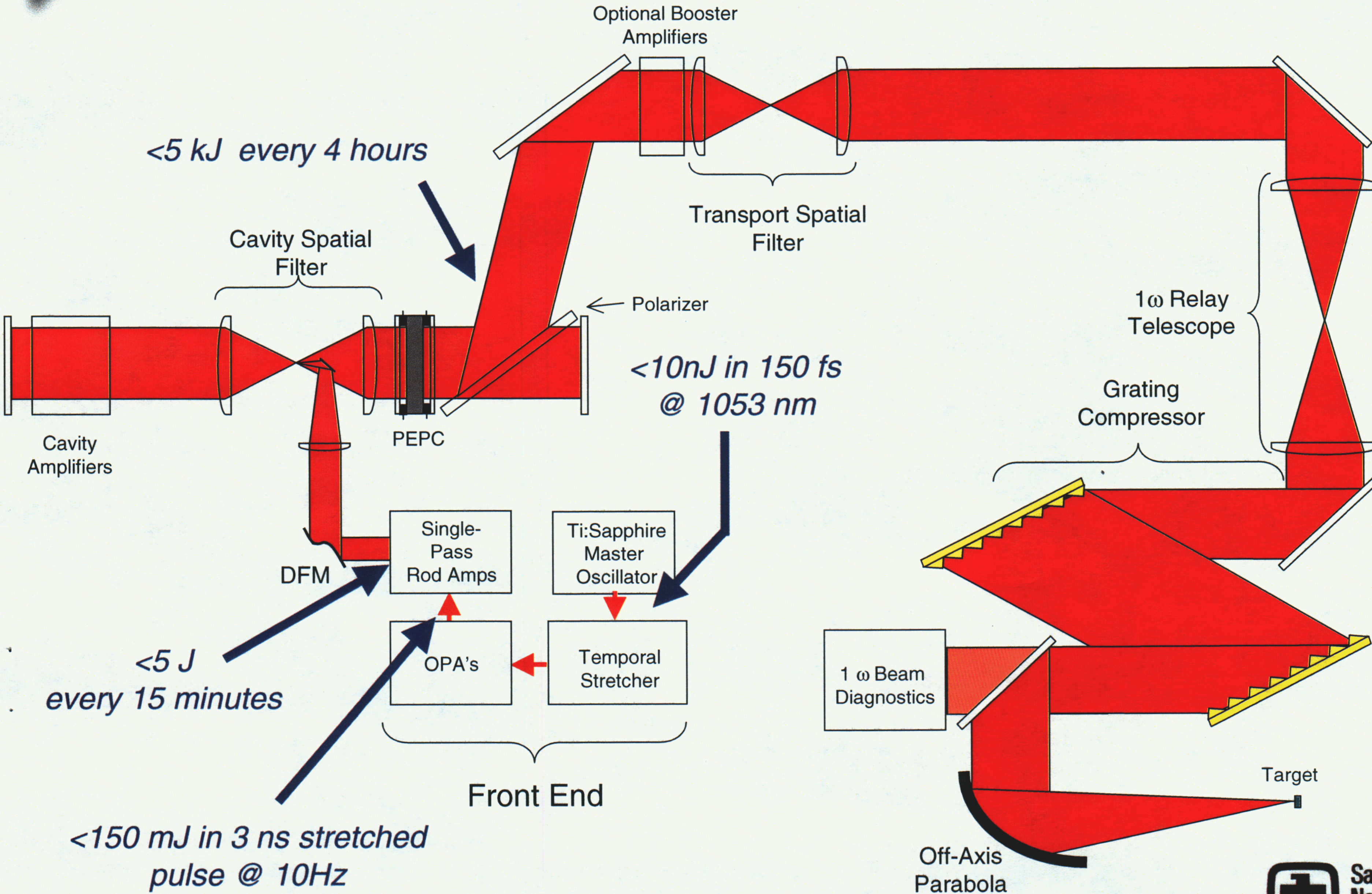
Z-Beamlet Modified Schematic for CPA



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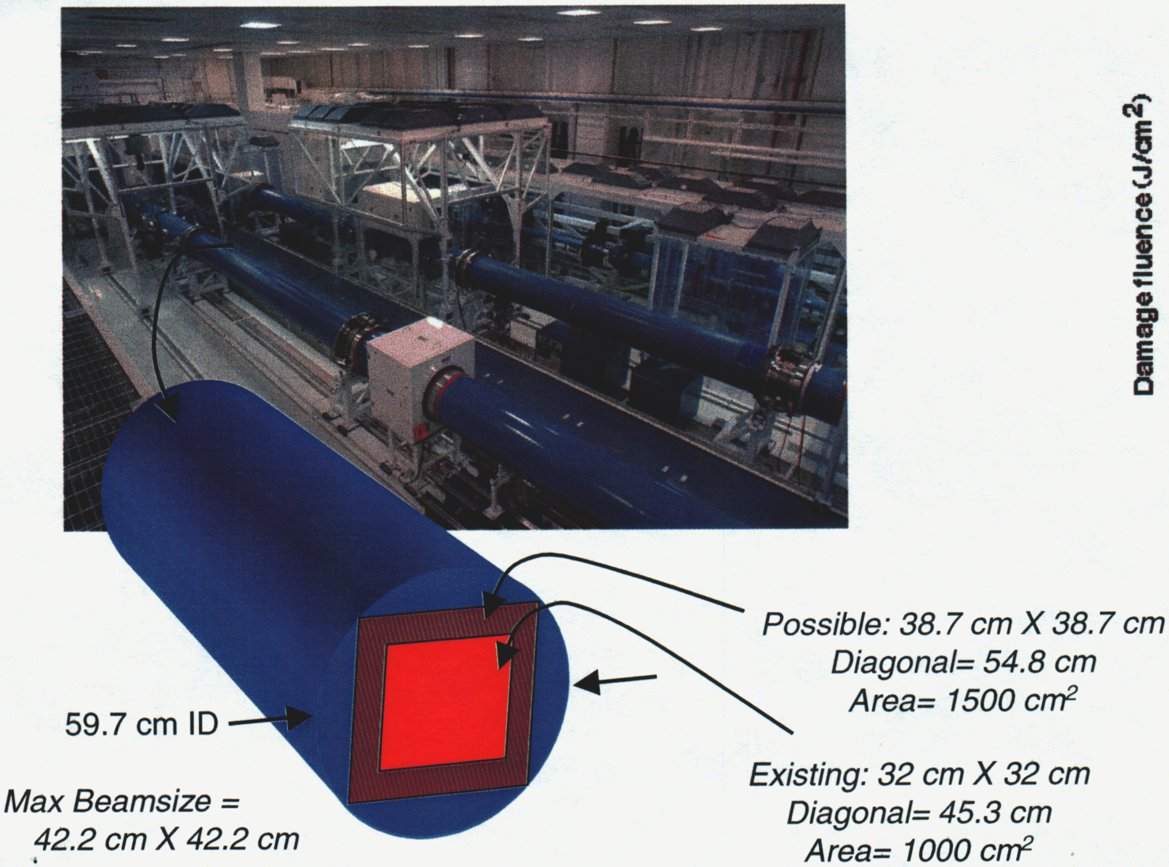
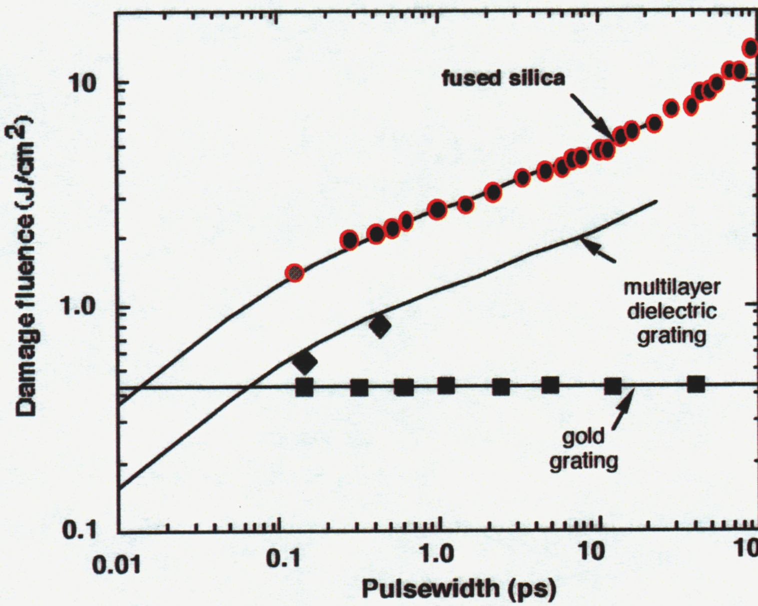
Achievable ZBL-PW Parameters





Required Grating Size:

32 cm X 32 cm input beam
- → 54 cm X 32 cm beam (at second grating)
- → 63 cm diag.

39 cm X 39 cm input beam
- → 62 cm X 39 cm beam (at second grating)
- → 73 cm diag.

Pulsewidth:	*0.5 or 5.0 ps*	*0.5 ps*	*5.0 ps*
Damage Threshold:	*Gold: 0.4 J/cm²*	*MLD: 1.5 J/cm²*	*MLD:3.0 J/cm²*
Area: 1000 cm²	0.4 kJ (0.8 PW, 0.08 PW)	1.5 kJ (3.0 PW)	3.0 kJ (0.6 PW)
1500 cm²	0.6 kJ (1.2 PW, 0.12 PW)	2.25 kJ (4.5 PW)	4.5 kJ (0.9 PW)
Limitation:		*Grating damage*	*B-Integral*

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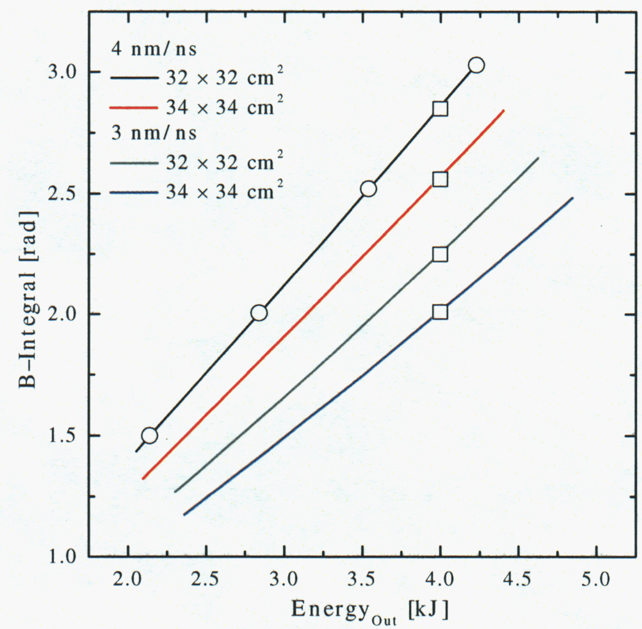
Limitations to Achievable ZBL-PW Parameters

Grating damage

- Multi-layer dielectric (MLD) gratings were fabricated at 2" diameter by General Atomics.
- Efficiency was ~97% at Littrow for 1550 lines/mm.
- Preliminary laser damage threshold was measured at 1.7 J/cm^2 in the projected area on the grating surface (2.6 J/cm^2 in the incident beam) for 300 fsec pulses.
- Accounting for a 1.3:1 Peak-to-average beam modulation and an additional 20% safety margin, the usable beam fluence (measured normal to the beam) is de-rated to 57% of 2.6 J/cm^2 or 1.5 J/cm^2.
- At 1.5 $J.cm^2$ for 1500 cm^2, 2.25 kJ (4.5 PW) is allowed for 500 fs pulses (conservative answer).
- At 2.6 $J.cm^2$ for 1500 cm^2, 3.9 kJ (7.8 PW) is allowed for 500 fs pulses (risky answer).

B-Integral Limit

- Simulations indicate that the energy should run between 3.25kJ and 4.5 kJ (depending on area and stretched pulsewidth) to stay below B=2.5.



B-Integral vs output energy

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Reasons to Demonstrate an Integrated Test-Bed

As part of the implementation of a PW, certain laser physics questions need answered. *How?*

Plan: **Use spare ZBL parts and sub-apertured beam to economically construct an integrated test-bed (Phase 0.5).**

Justification: Mitigation of development impact on primary ZBL operations.

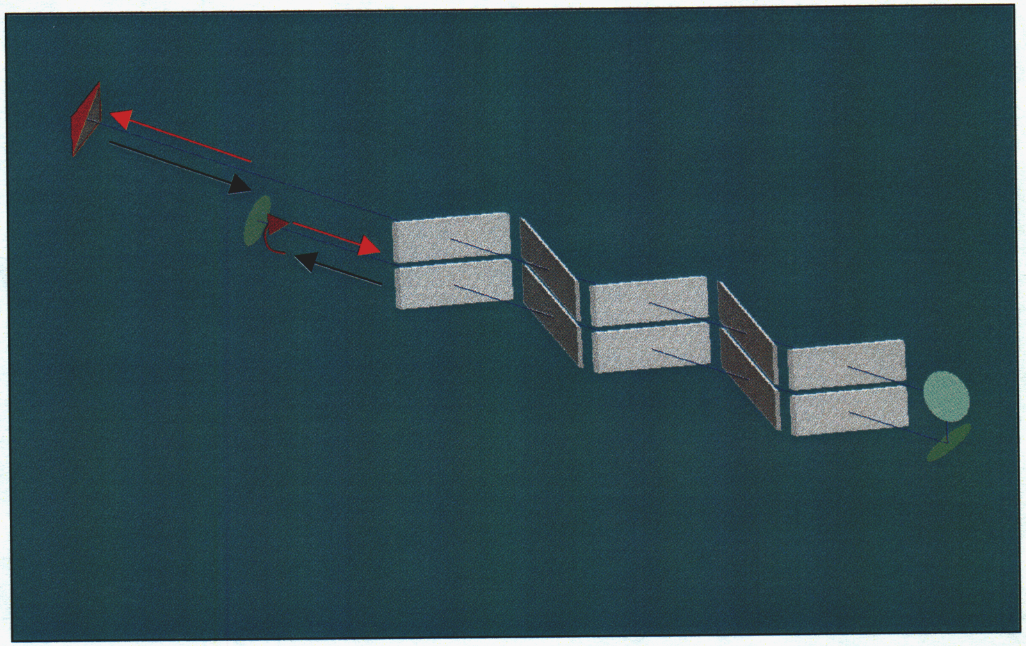
- *Down time:* The main backlighter mission is uncompromised by long periods of down time.
- *Hardware:* Development issues which might possibly be damaging will not affect ZBL.

Issues in question:

- Bandwidth concerns:
  - Effect of spectral bandpass of system optics;
  - Gain narrowing in a multipass system
- Multipass design options:
  - Effect of gain narrowing in a large-aperture multi-pass system;
  - Effects of multipass designs on wavefront distortions in a PW-class system;
  - Two versus four-pass configurations
- Ability to achieve best focus:
  - Spot optimization and investigation of appropriate PW adaptive optics approach
  - Effects of debris shields upon spot size (as studied with a focusing vessel)
- Synchronization
- Appropriate measures for machine safety

The Basics of a Compact Test-Bed Design

Use (in double-pass configuration) the 5 boosters with both segments of the 2x1 unit populated with amplifier glass.



Benefits:

- The design tests the close-packed 2x1 amplifier layout.
- Modest sizing for a 16 cm diameter beam will require normal incidence optics of 8" diameter (200 mm) and 45 degree incidence optics of 12" (300 mm)
- The design more efficiently uses space at ZBL.
- The folded option only requires the pulsed power for 5 amplifier units.
- A PEPC is not necessary for operation since the folded-5 layout is intended as a two-pass layout. Having said this, a modification could allow 4-pass U-turn/L-turn designs.

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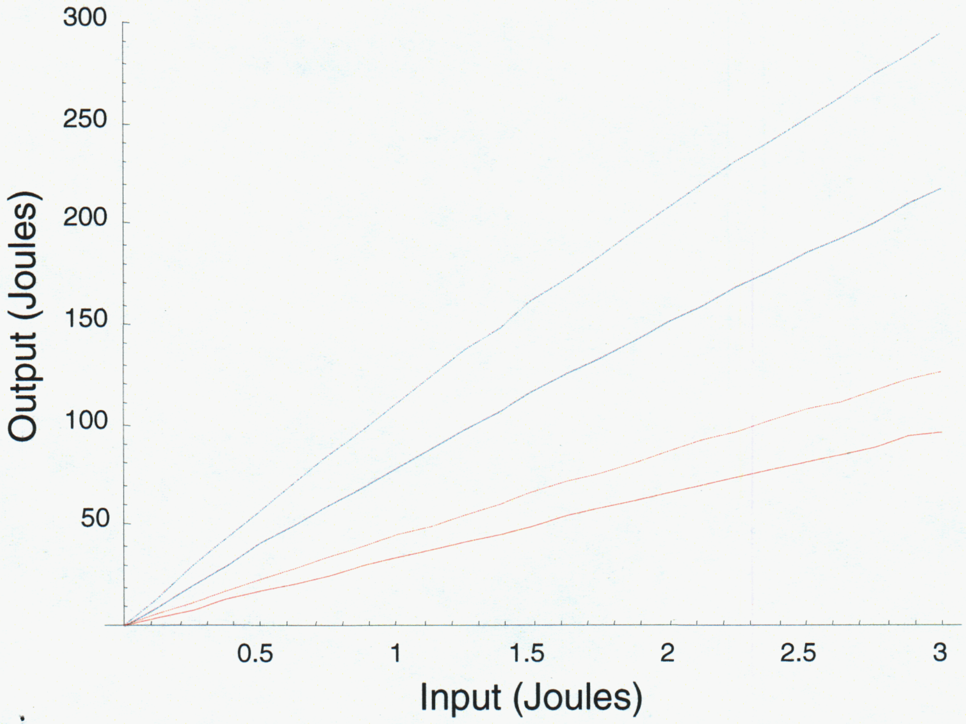
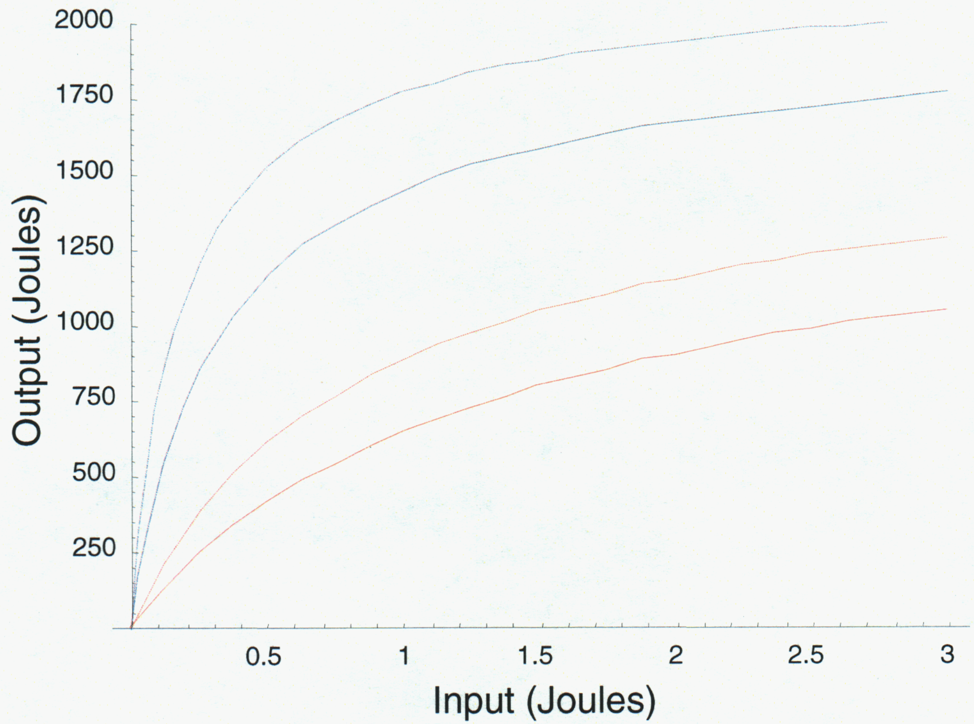
Gain Considerations
(Including Saturation Effects)

2-Pass Gain Analysis



4-Pass Gain Analysis



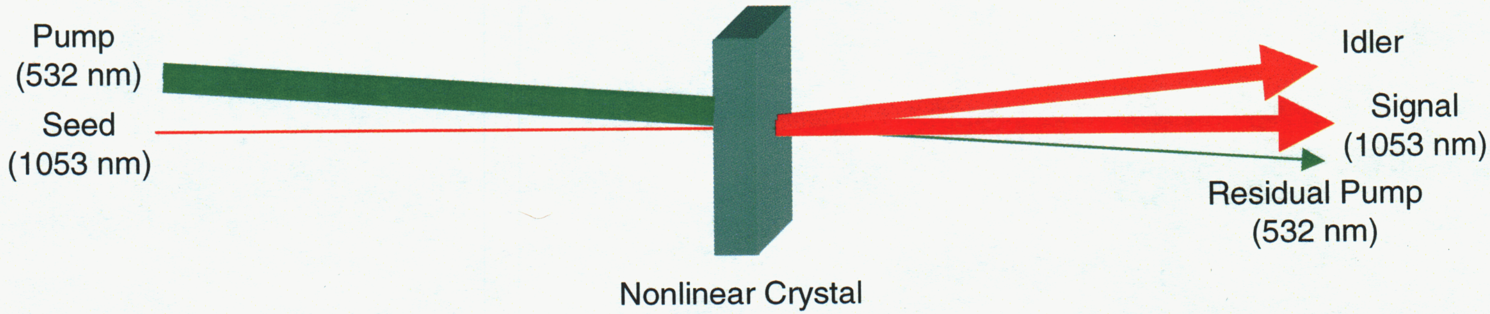
- - - - - - 20.1 kV (0.25 explosion fraction) and 10 amplifiers
——— 18.0 kV (0.20 explosion fraction) and 10 amplifiers
- - - - - - 20.1 kV (0.25 explosion fraction) and 8 amplifiers
——— 18.0 kV (0.20 explosion fraction) and 8 amplifiers

Note: A 16 cm diameter beam (A=201 cm^2) is assumed in a ZBL narrowband configuration. This size allows for use of 40 cm MLD gratings which can be fabricated with available resources.

The Seed: OPCPA

The typical amplifier choice is regenerative or multipass amplification in a solid state material such as Ti:Sapphire or Nd:Glass.

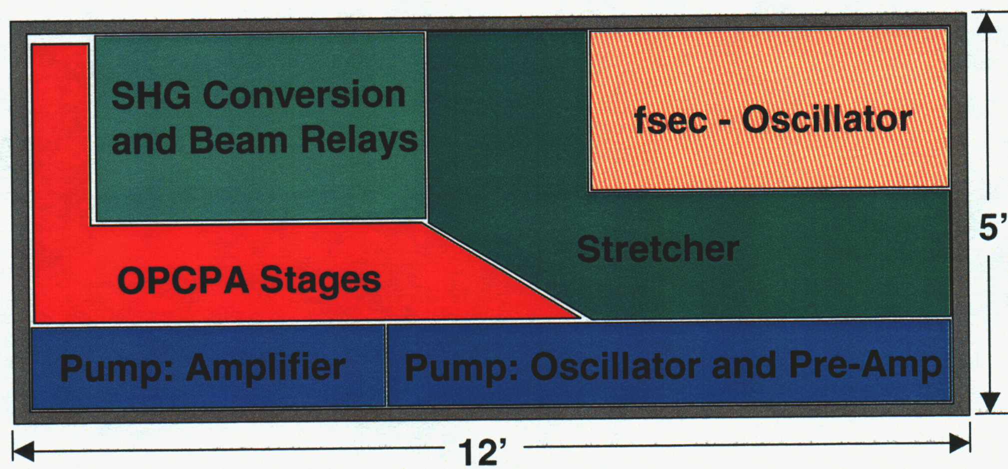
Optical parametric amplification (OPCPA) is another option.



The approach offers some interesting benefits for a front end:

- Broad bandwidths allowed near degeneracy.
- Efficient (on the order of 15-30%) pump conversion allows single passes, which also reduces material dispersion.
- Pump can act as a temporal gate due the OPA process, eliminating pre- and post-pulses.
- Thermal loading of the amplifiers is minimal, resulting is better beam quality.

OPCPA table layout



A 3-stage OPCPA designed and constructed by General Atomics will act as a pre-amplifier, boosting the stretched pulse to the 100 mJ level at 10 Hz with a retained 12 nm bandwidth in the 3 ns stretched pulse.

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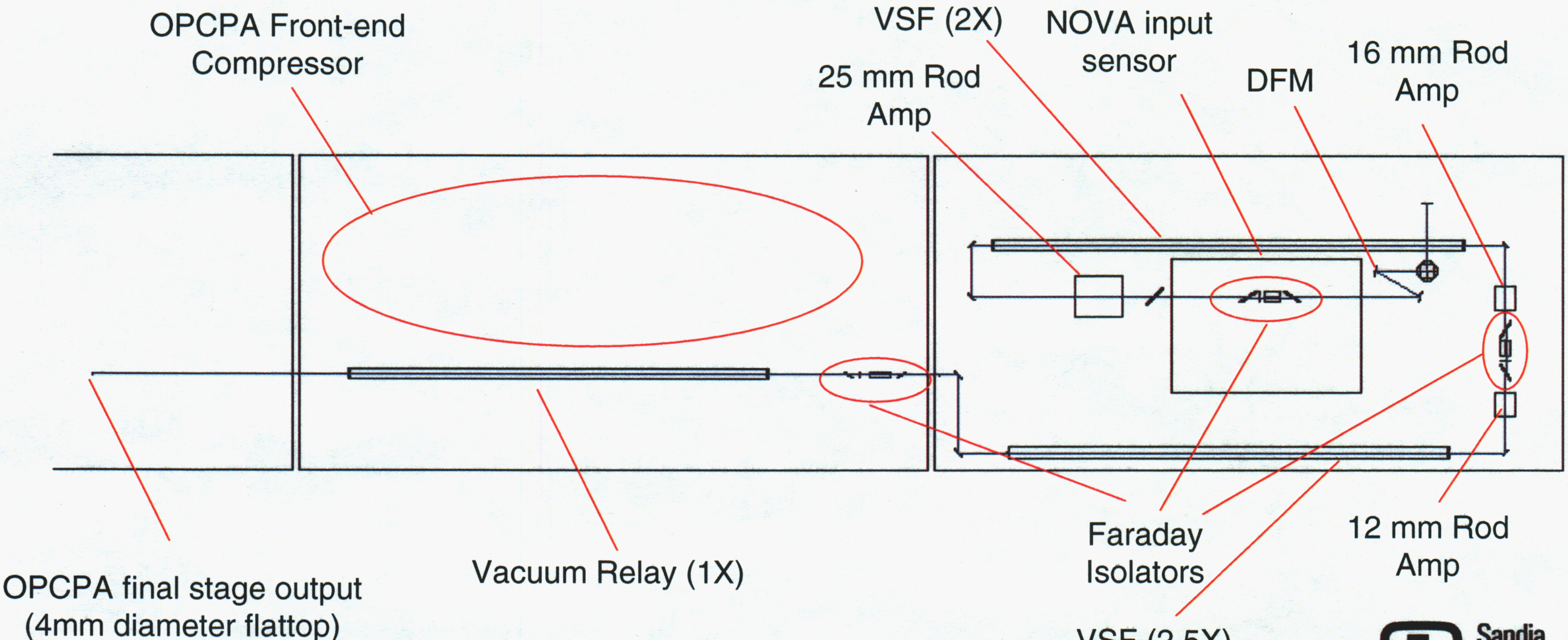
A Power Amplifier for the OPCPA

- As seen in the gain analysis, the OPCPA output of 0.1 J cannot adequately seed the integrated test-bed. A power amplifier is needed to reach the 3 J seed level for 200 J outputs (and at least 0.5 J seed level to reach 40 J outputs).

- We will use a simple single-pass amplifier design with the spare 12, 16, and 25 mm amplifier heads and power supplies.

- For an estimated 4 times gain per head, 3 heads will yield 64 times net gain, easily boosting the OPCPA seed to the multi-Joule level (6.4 J for 0.1 J input).



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Design Parameters Accounted For

We have accounted for a variety of issues in the optical design, including:

- Rod doping levels → Beam uniformity
- Beam Magnification → Saturation and damage fluence issues
- Fill Factors → Clipping/ diffraction issues
- Relay Imaging → Damage issues and beam quality
- Spatial Filter Pinhole Selection → Beam quality
- Pressure Safety → Vacuum implosion hazard
- Front-end Diagnostics → Beam parameters
- Ghost Reflections → Damage hazard
- Pencil Beams → Damage hazard
- B-Integral → Beam/pulse quality

These issues are largely intertwined, preventing one parameter from being adjusted without affecting another.

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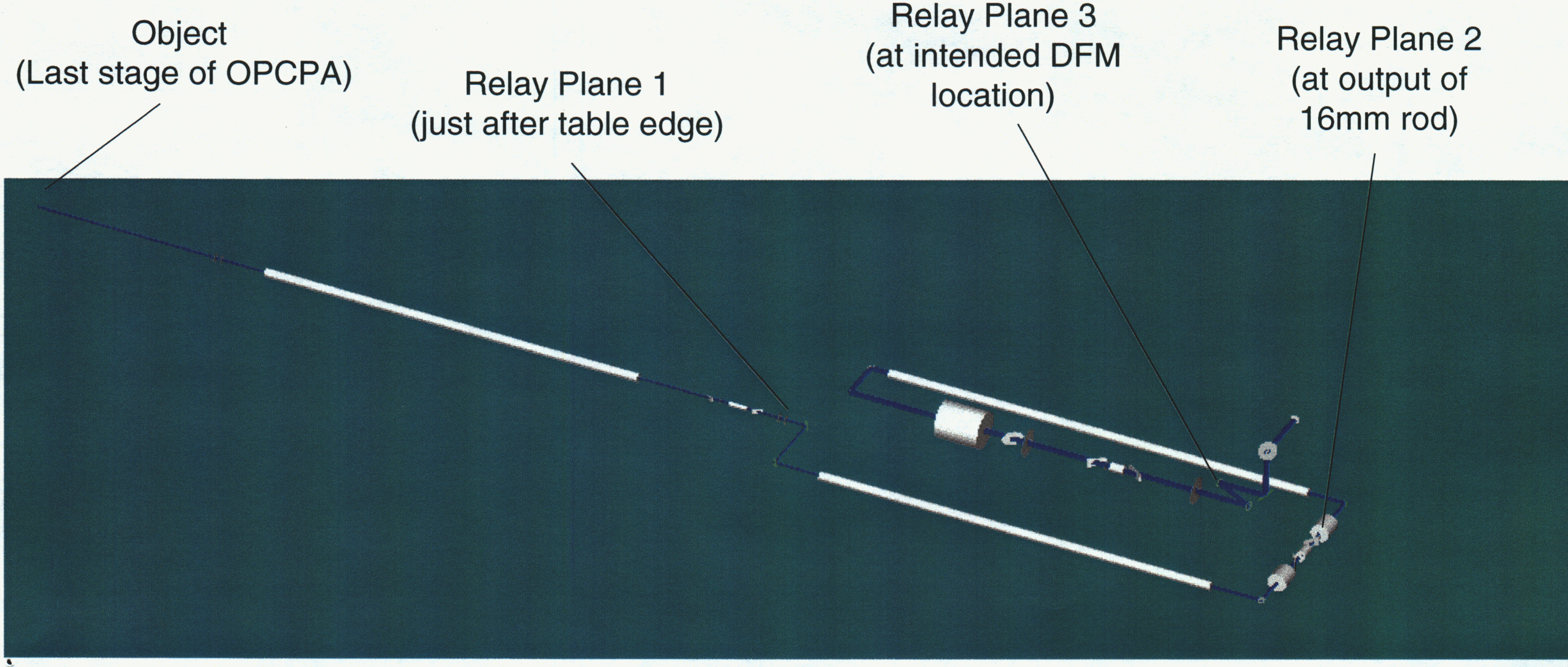
Optical Layout (Front-End)



- *Relay imaging is used to maintain the best beam quality upon sensitive optics in order to mitigate damage.*

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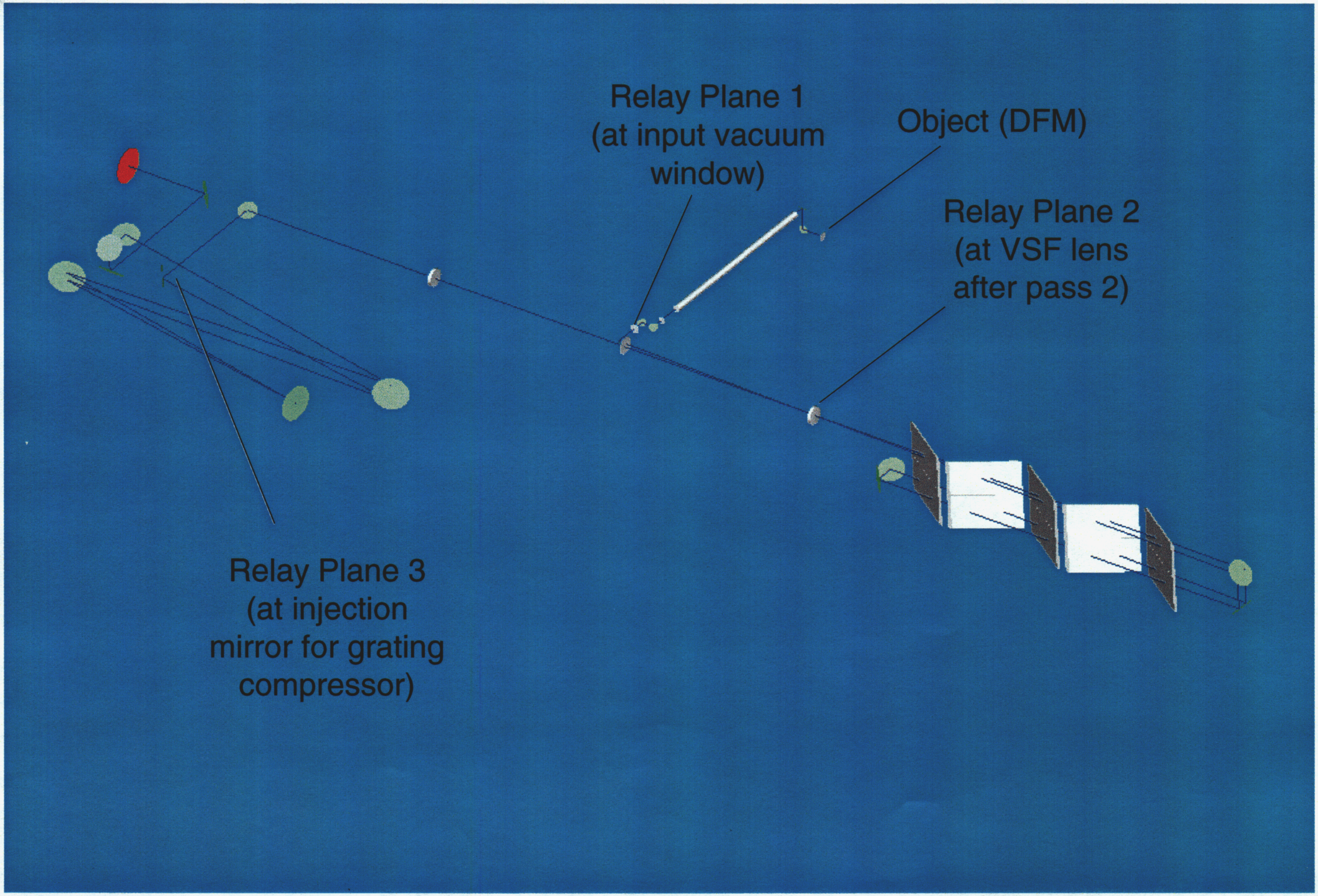
Optical Layout (Main System)



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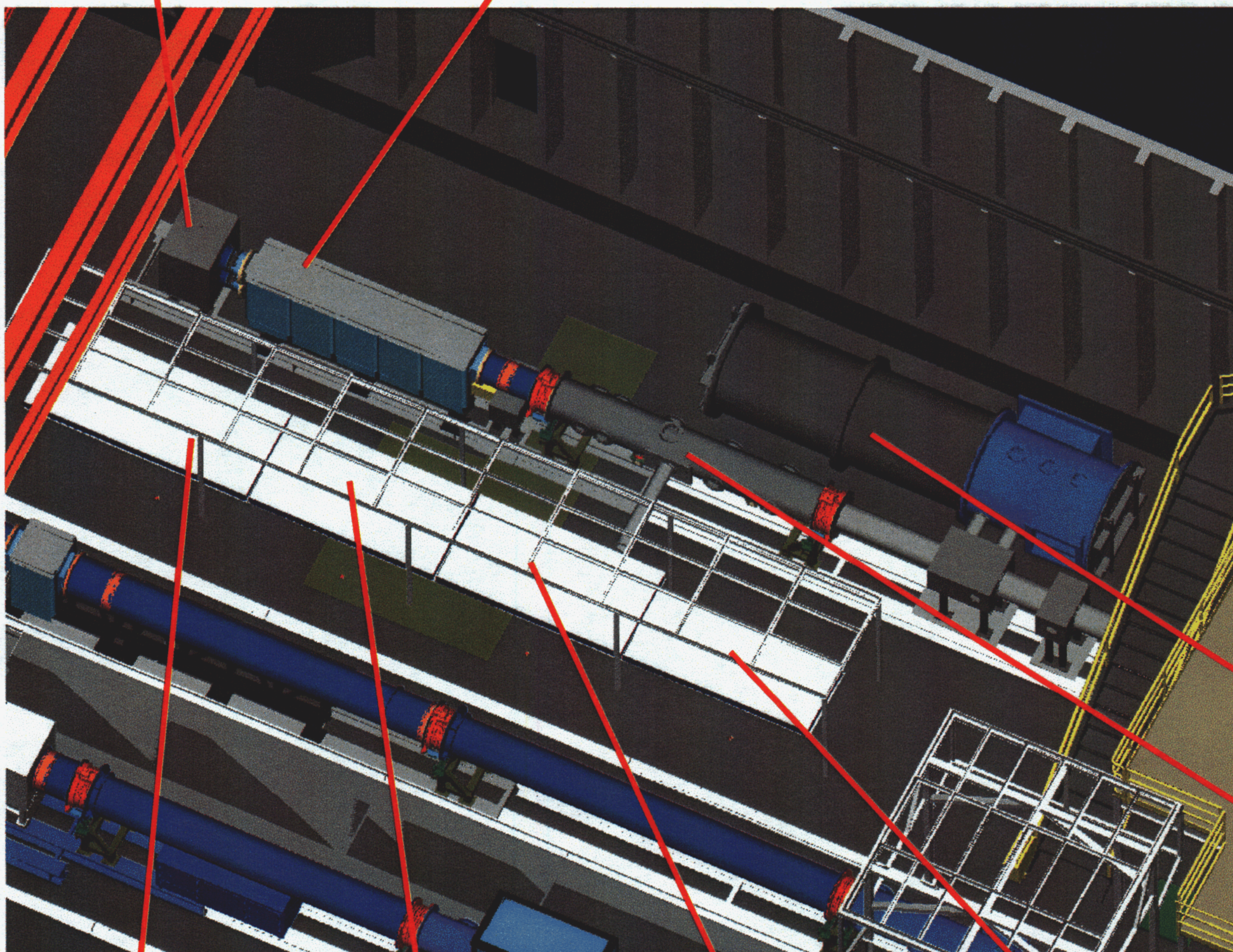
Integrated Test-bed CAD Layout



DESIGN PARAMETERS:

Supported bandwidth:	*>4 nm*
Pulsewidth:	*~400 fs*
Beam Size:	*ϕ = 16 cm*
Beam Area:	*200 cm^2*
Laser Energy :	*~ 200 J*
Fluence:	*1.0 J/cm^2*
Maximum Peak Power:	*0.5 PW*

NOTE: 1 J/cm^2 compares favorably with grating damage threshold. If the grating damage thresholds reach 2 J/cm^2, then 400 J/400 fs = 1 PW is possible.

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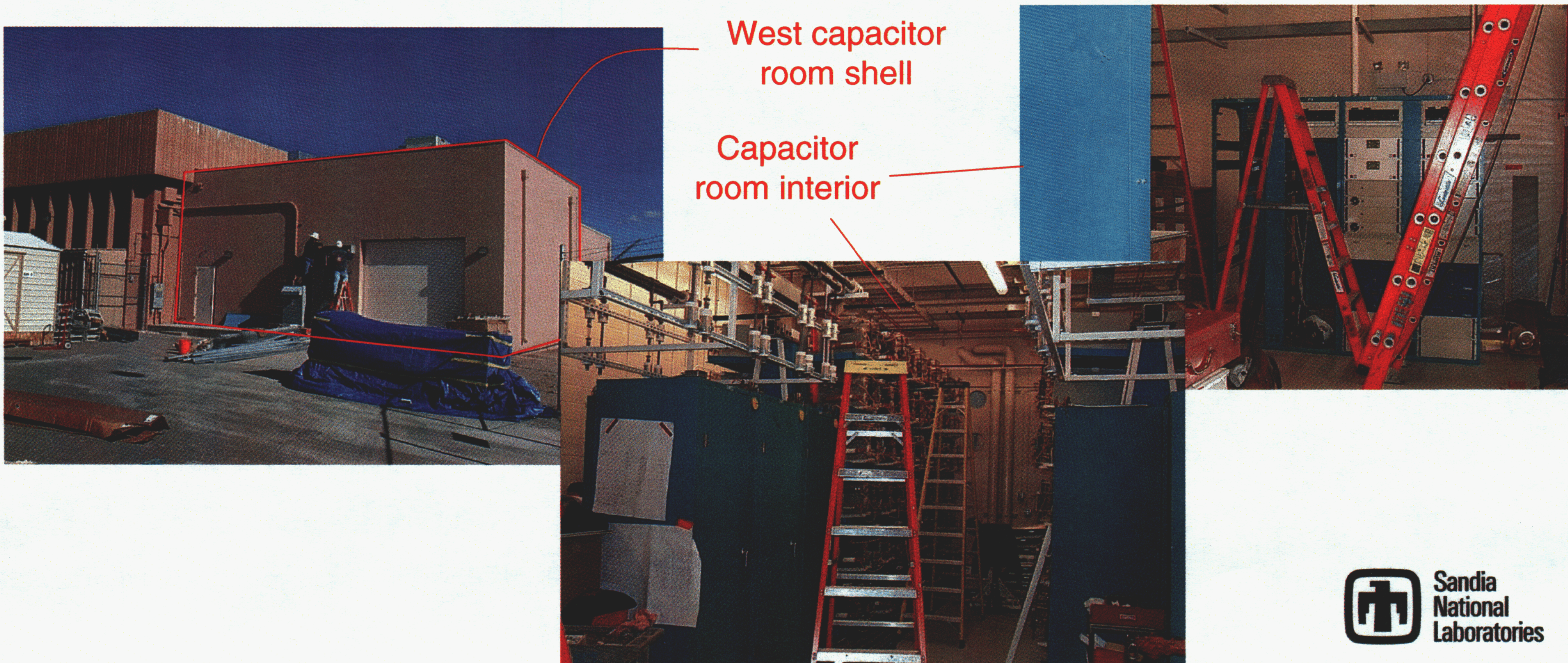
Current Status: Pulsed Power

- The basic shell to the west capacitor room was finished over the summer of 2002.
- Much of the key hardware (capacitor bank, power supply racks, and ignitron racks) has been placed in the room. Several racks remain to be placed.
- Infrastructure issues such as pressurized air lines, water supply lines, and electricity are being completed prior to activation.
- Access control and interlock issues are currently being addressed.



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Current Status:
Main Amplifier Section Optics

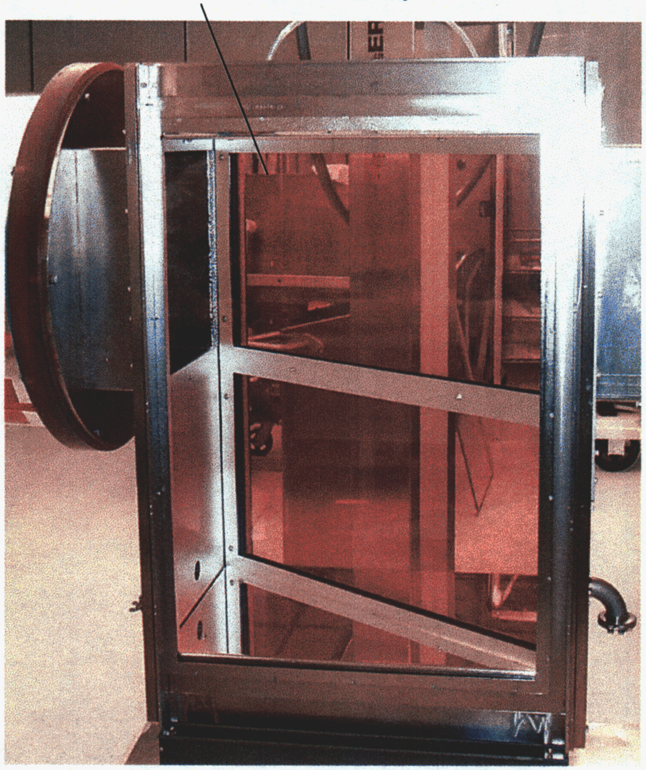
- Five amplifier casings and corresponding flashlamp arrays have been constructed. Refurbished laser glass (received in late December 2003 from Zygo) will be installed.

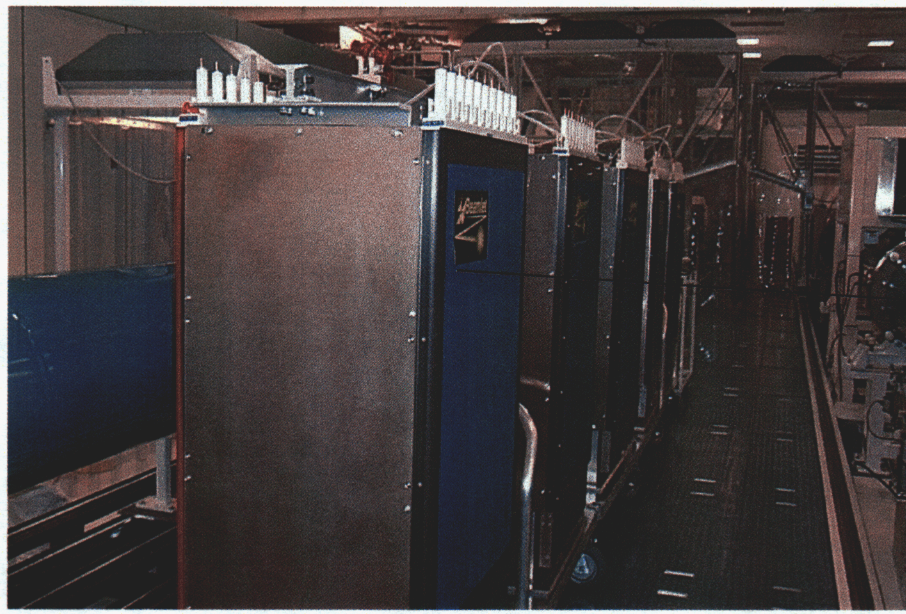
- The first double-amplifier has been constructed using the un-activated ZBL booster.

- 12” mirrors have been spec’ed and are ready for bid.

- The non-vacuum 12” mirror mounts have been ordered.

The first ZBL double-amplifier





Five amplifier casings under nitrogen purge while awaiting laser glass

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January 2003 Status: Laser Summary

Front-end Infrastructure
Tables: Available;
Spaceframe: In Fab;
HEPA's: In Fab
Desired Completion: < Feb '03

OPCPA
OPCPA Front-end: Constructing at GA
Desired Completion: < May '03

Rod Amplifiers
Design: Check
Rods/Spatial Filters/ Lenses: Quoted;
Faraday Rotators: Available/ordered;
Amplifier Cases/ Power: Available
Desired Completion: < Apr '03

Diagnostics
Design: Complete;
Optics: Avaliable
Desired Completion: < Apr '03

Main Cavity Infrastructure
Design: Partial;
Rails: In Design;
Facility Work: In Construction
Desired Completion: < Feb '03

Cavity Vacuum Spatial Filter
Design: Partial;
Center VSF Tube & Frame: Bid phase;
Lenses/Bezels: In Design/ Check
Desired Completion: < Mar '03

Main Amplifiers
Design: Complete
Amplifier Hardware: Complete
Refurbed Amplifier Slabs: Arrived;
Amp's Complete: 1
Desired Completion: < May '03

Amplifier Steering Mirrors
Mirror Design: Complete;
Mirror Mounts: Bid phase
Desired Completion: < May '03

Pulsed Power
Design: Complete;
Building: Complete;
Facility Work: In Construction;
Hardware: Mostly in Place
Desired Completion: < Mar '03

Grating Compressor
Design: In Progress at GA
Desired Completion: < Nov '03

Operational Laser

Design-phase
Procurement-phase
Construction-phase

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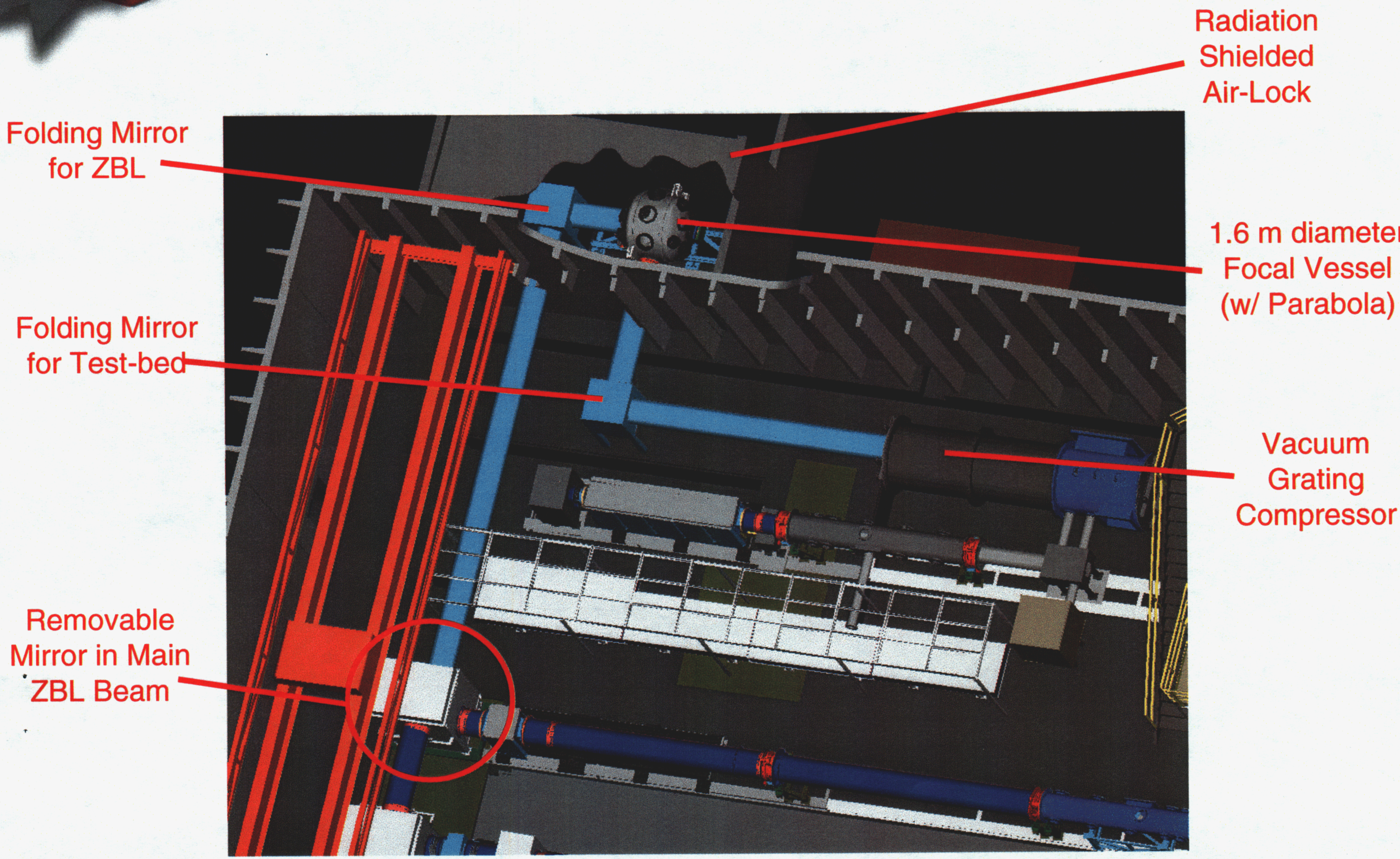
Experimental Testing Area



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Conclusions

- Sandia's motivations for a petawatt laser are advanced radiography and fast ignitor studies with the Z-accelerator facility.

- Grating damage thresholds will limit the output to less than 2.25 kJ for 500 fs radiography-based pulses and to less than 4.5 kJ for 5 ps fast ignitor-based pulses.

- Additionally B-integral limits will keep the energy less than roughly 4 kJ, regardless of pulse duration.

- An initial step will be to build a laser test-bed using spare parts at a sub-apertured beamsize.

- Such a test-bed system will nominally achieve 0.5 PW operation and will allow all development work to proceed without impacting ZBL.