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Energy Absorption in Pulsed Laser Welding
Effect of Joint Geometry

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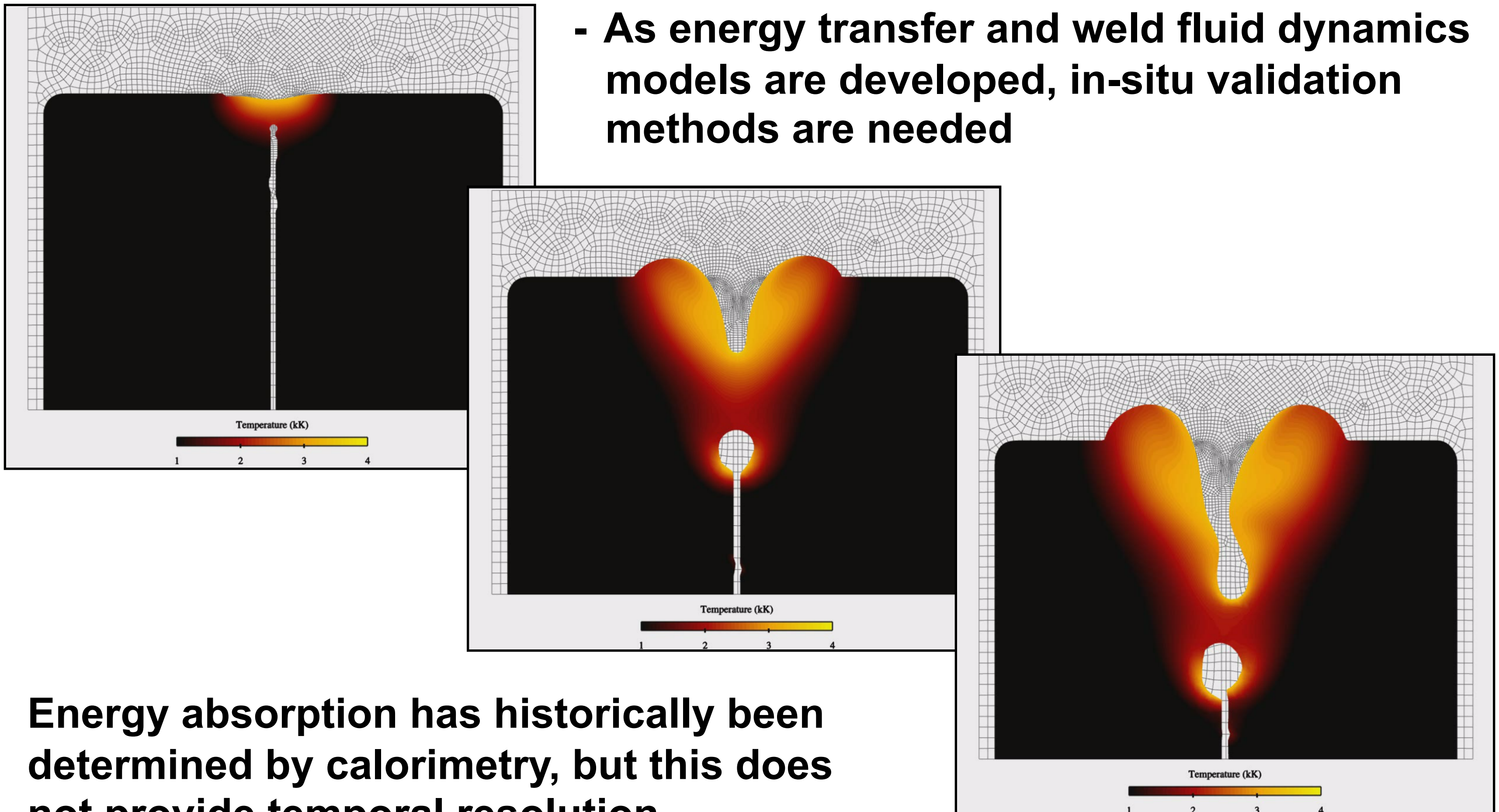
Motivation

- Understanding of energy transfer and melting efficiencies is critical for procedure optimization

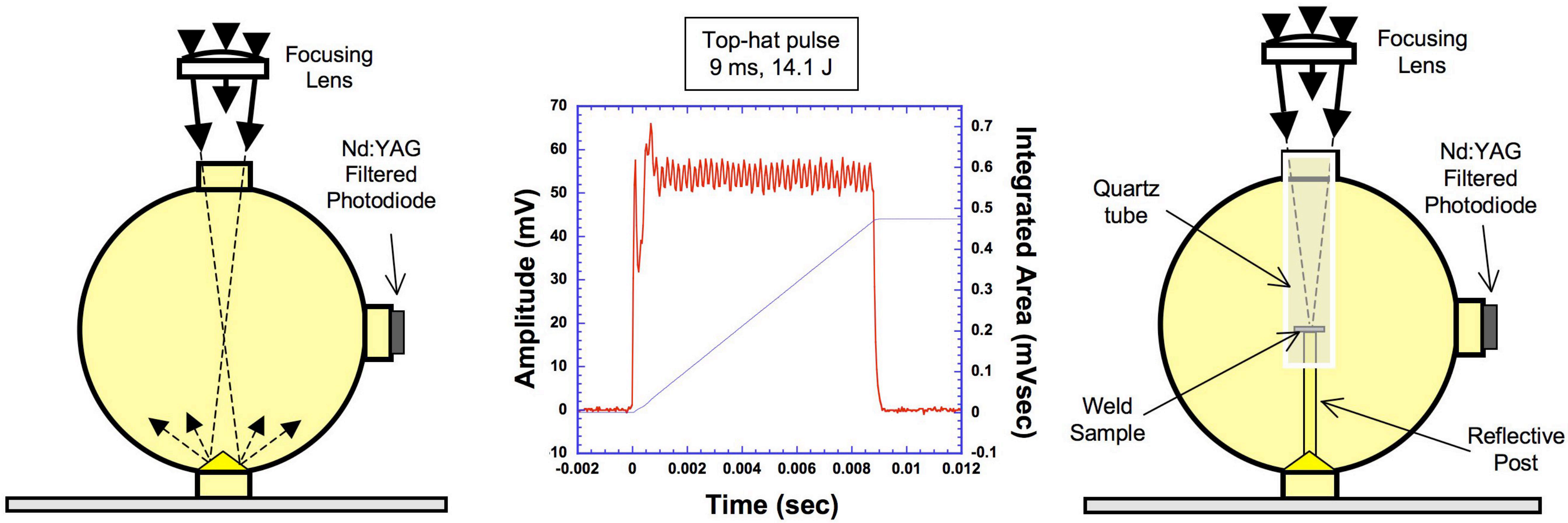
- As energy transfer and weld fluid dynamics models are developed, in-situ validation methods are needed



Energy absorption has historically been determined by calorimetry, but this does not provide temporal resolution

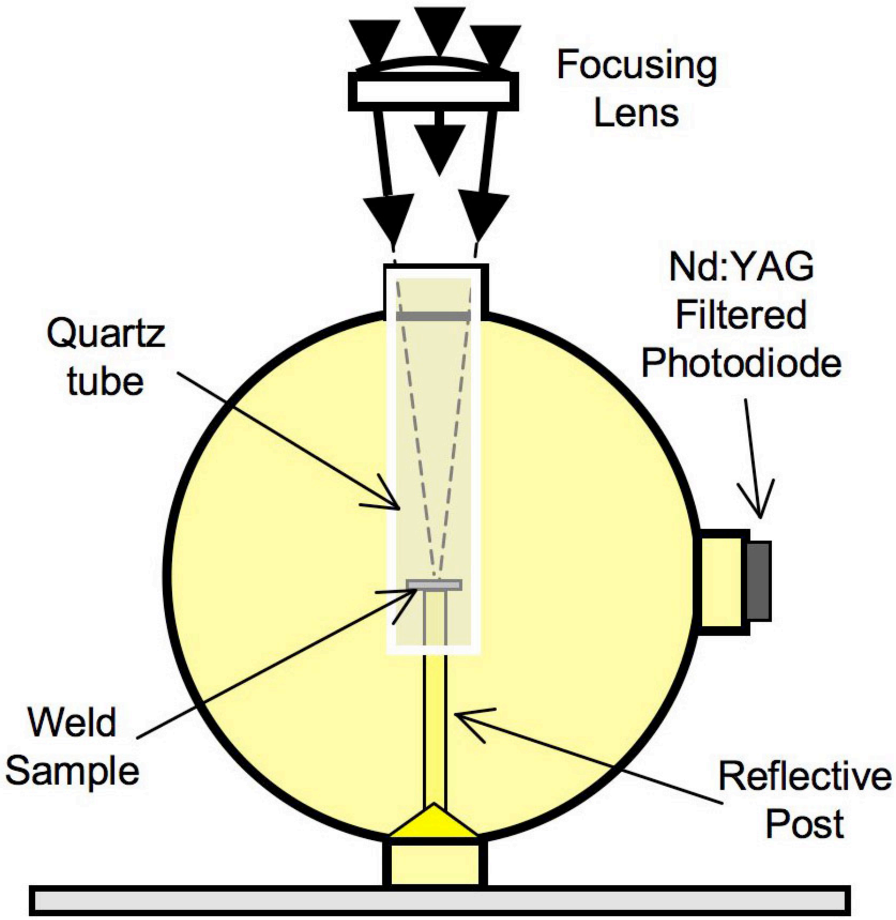
Basic Concept

Capture and measure the reflected light during pulsed welding by welding inside an integrating sphere



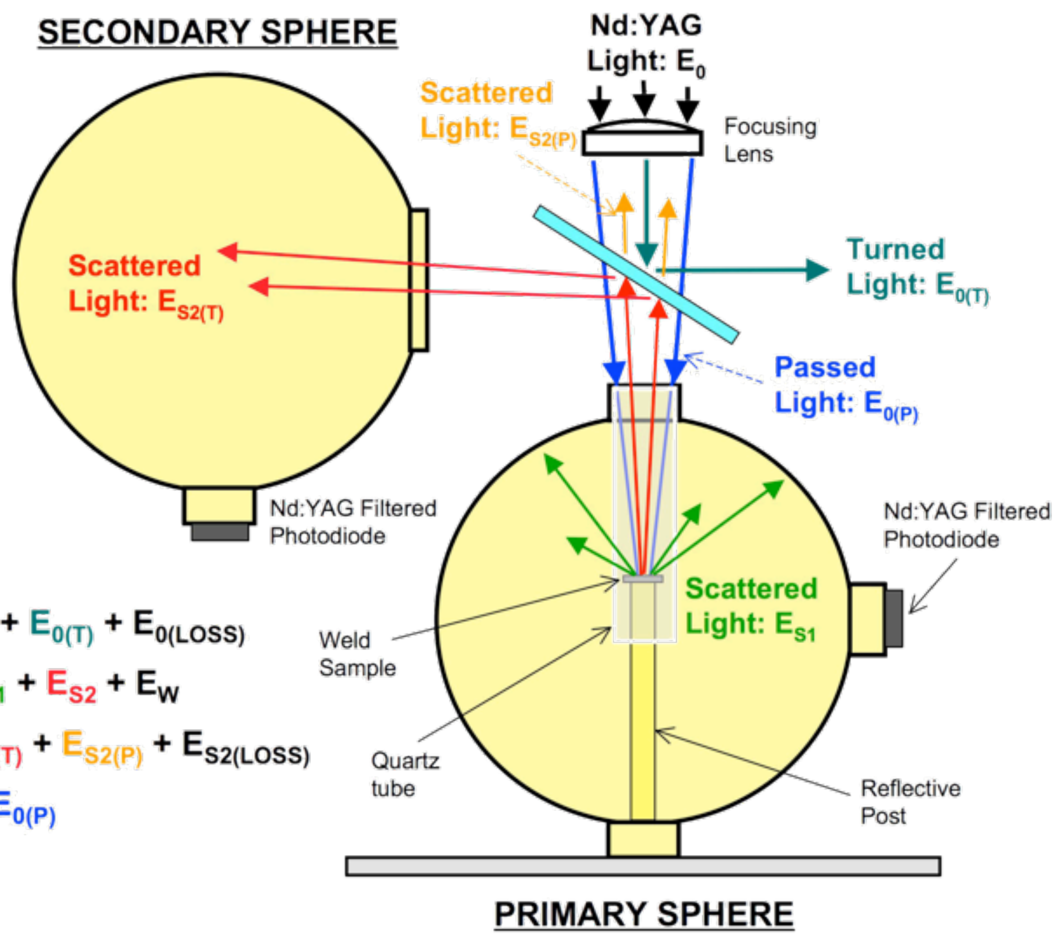
- **Absorption can be deduced by subtraction from the delivered energy**
- **Instantaneous and cumulative quantities can be determined**

Important Considerations

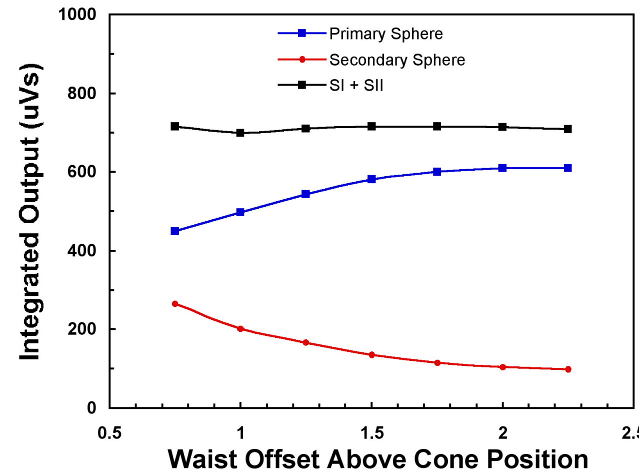


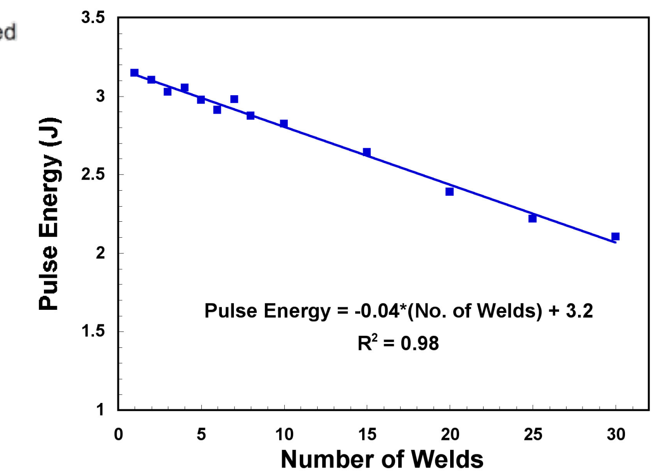
- ***Photodiode Calibrations***
- ***Quartz Tube*** – is Nd:YAG light absorbed by the tube?
- ***Metal Vapor Deposits*** – how much energy is absorbed by metal vapors deposited on quartz tubes?
- ***Post Height*** –Does post height (relative to sphere opening and diode position) alter voltage output?
- ***Scattered Light*** – how much is lost through sphere opening, and how does it vary in time and with weld mode?

Laser Spot Weld Absorption



$$E_0 = E_{0(P)} + E_{0(T)} + E_{0(LOSS)}$$
$$E_{0(P)} = E_{S1} + E_{S2} + E_W$$
$$E_{S2} = E_{S2(T)} + E_{S2(P)} + E_{S2(LOSS)}$$
$$\eta_t = E_W / E_{0(P)}$$





- Accurate determination of absorption requires characterization of numerous potential losses

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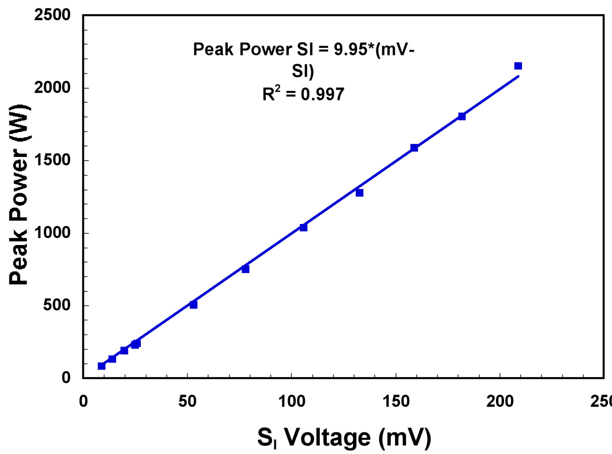
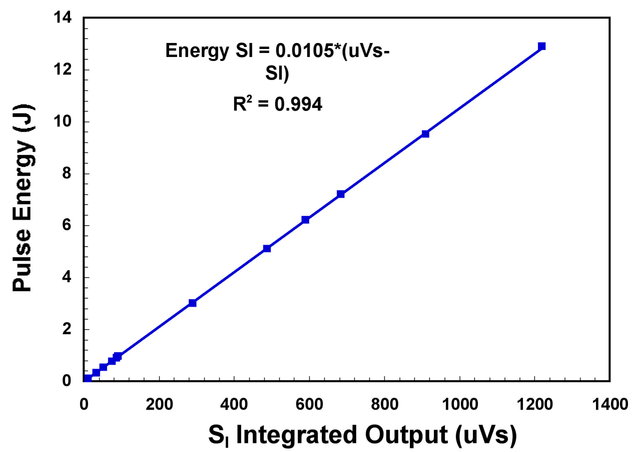
Photodiode Calibrations

Power Calibration

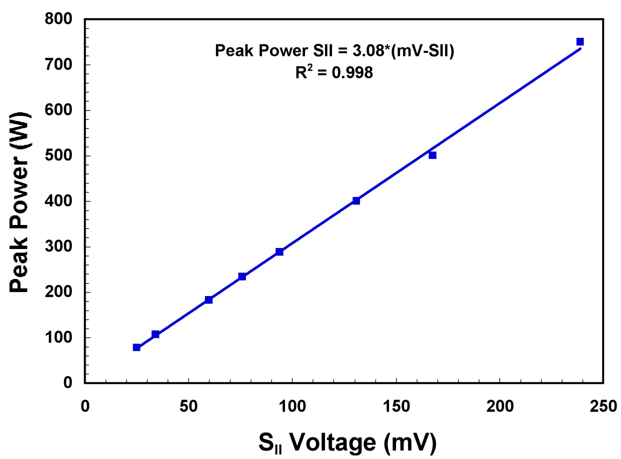
Energy Calibration

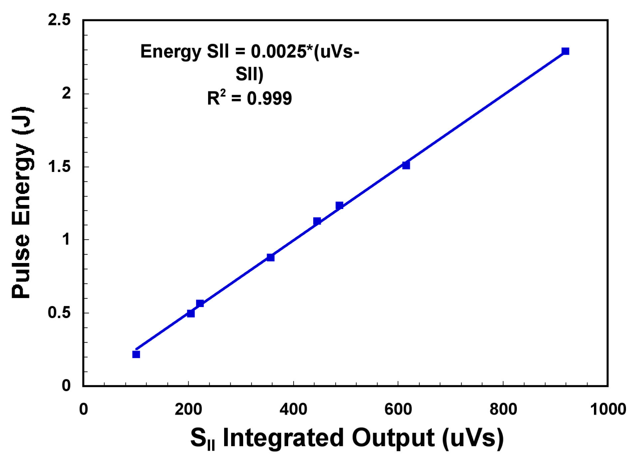
Primary Sphere

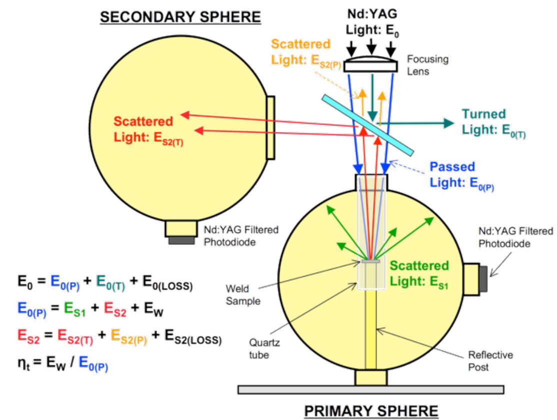




Secondary Sphere







- New photodiodes procured and calibration methods further improved
- Calibration of S1 at low values is important since it influences calibration of S2
- Calibration of both spheres is linear over useful power range

Experimental Matrix A

Matrix A

Time Series:

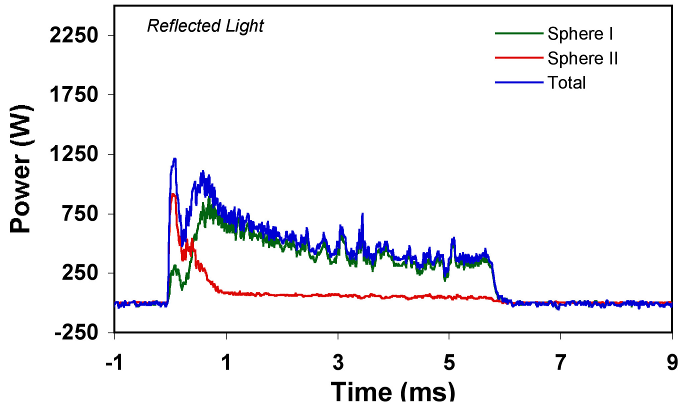
- 4 ms, 3 kW, 6.2 J, Ar
- 6 ms, 3 kW, 9.5 J, Ar
- 8 ms, 3 kW, 12.8 J, Ar

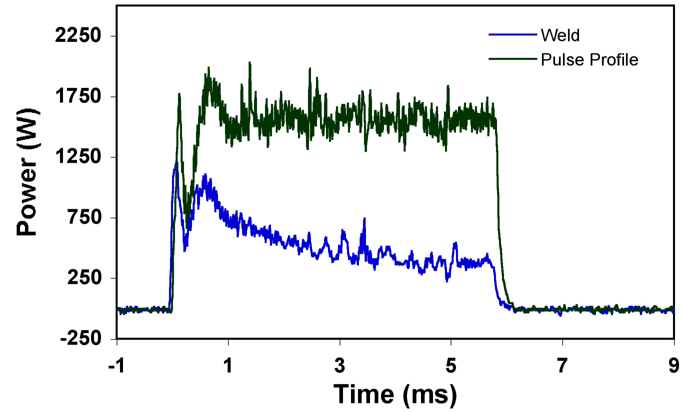
Power Series:

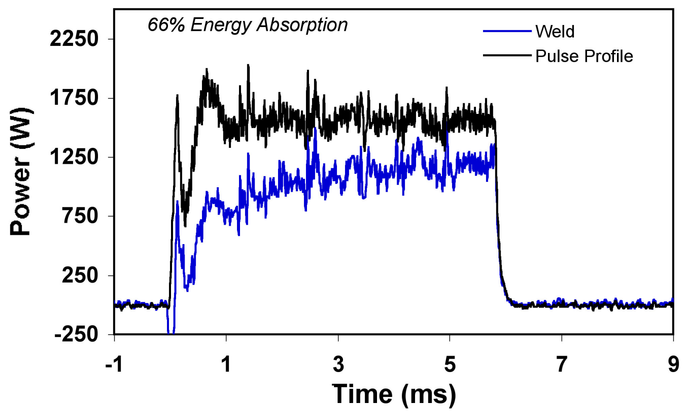
- 6 ms, 1 kW, 3.0 J, Ar
- 6 ms, 2 kW, 6.2 J, Ar
- 6 ms, 3 kW, 9.5 J, Ar

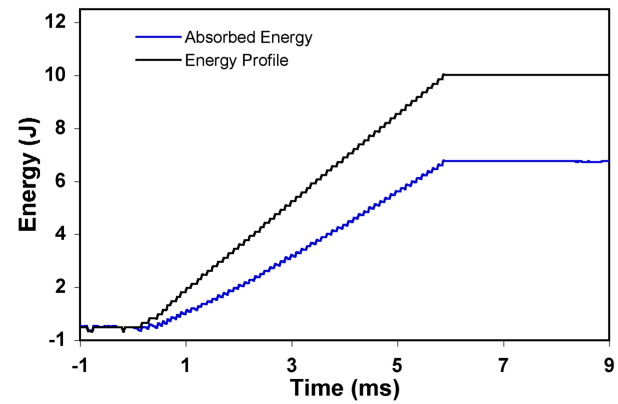
Shielding:

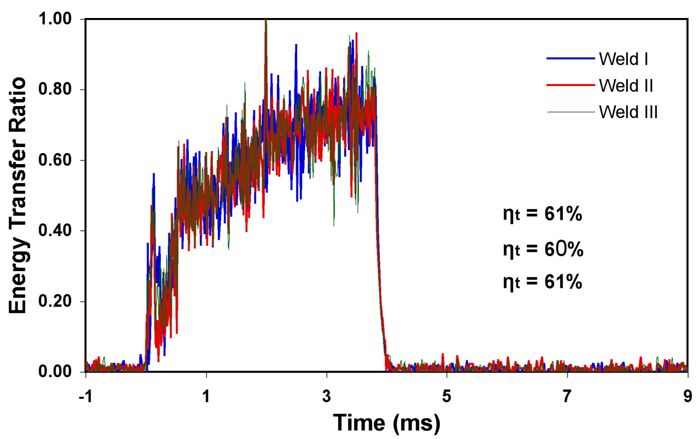
- 6 ms, 1 kW, 3.0 J, Ar
- 6 ms, 1 kW, 3 J, Air





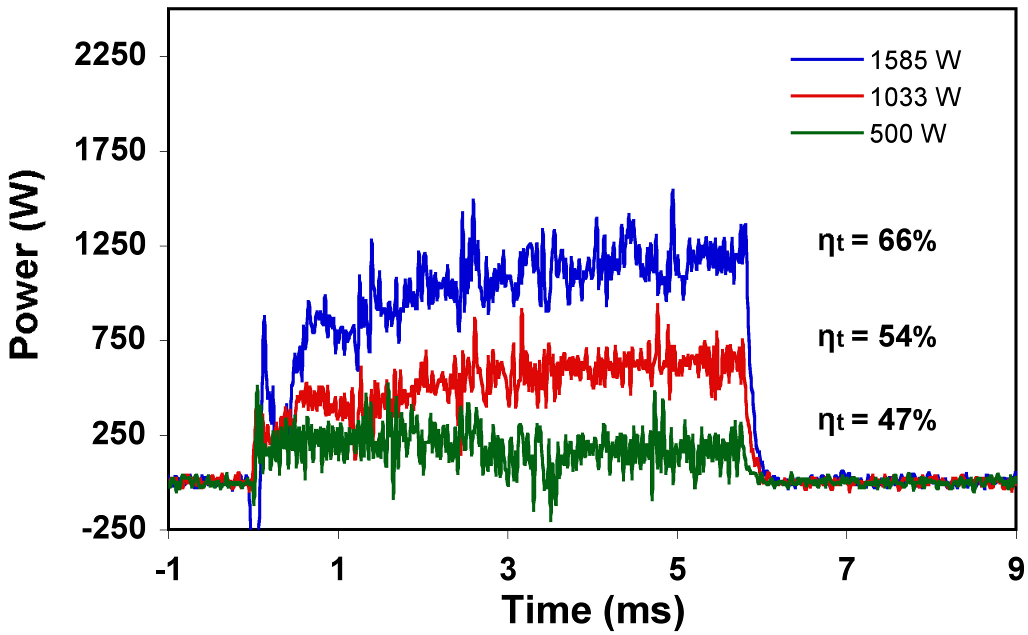




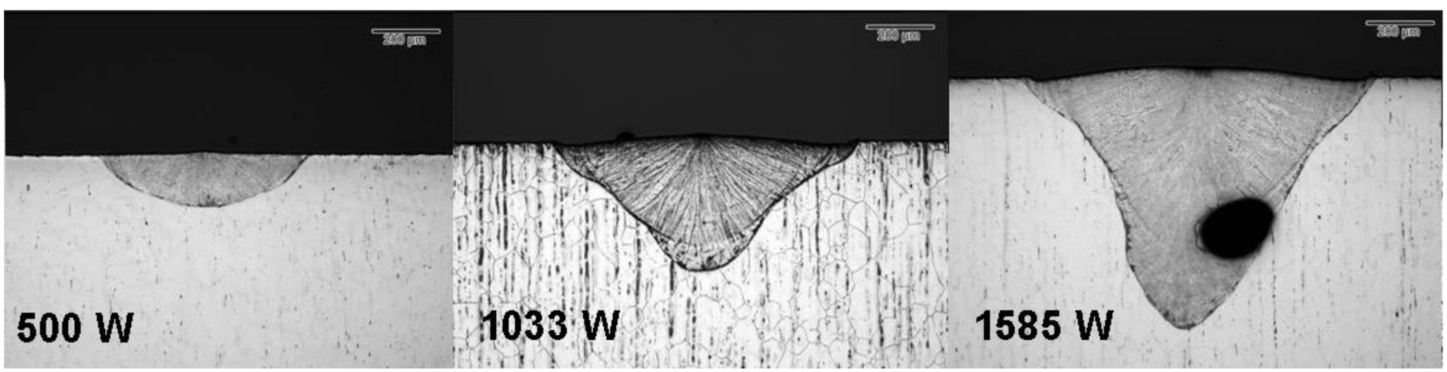


- **Measurements exhibit good repeatability**
- **Both power and absorbed energy profiles provide appropriate validation metrics**

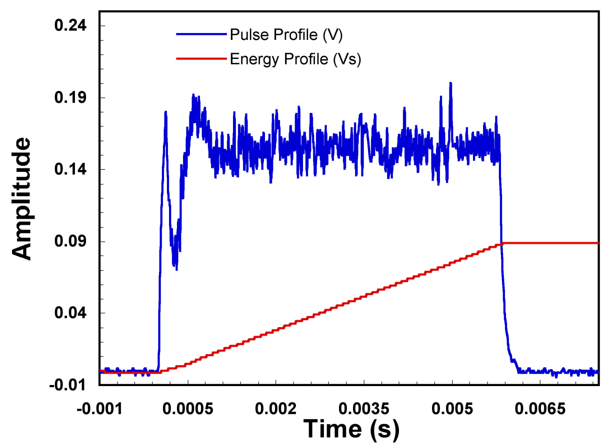
Experimental Matrix A - Power Series



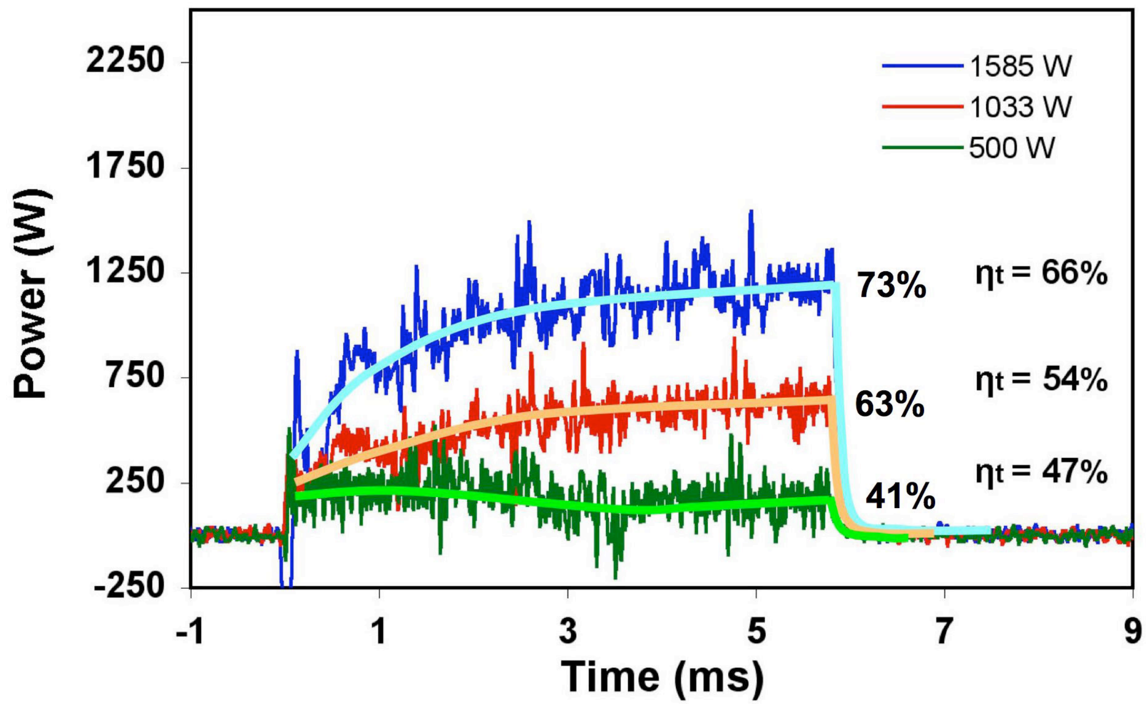
- For low power welds (i.e. insufficient recoil pressure to develop keyhole), transfer efficiency remains low throughout pulse
- Initial transfer efficiency about 50%, defines the mode transition and "coupling"



Initial Absorption

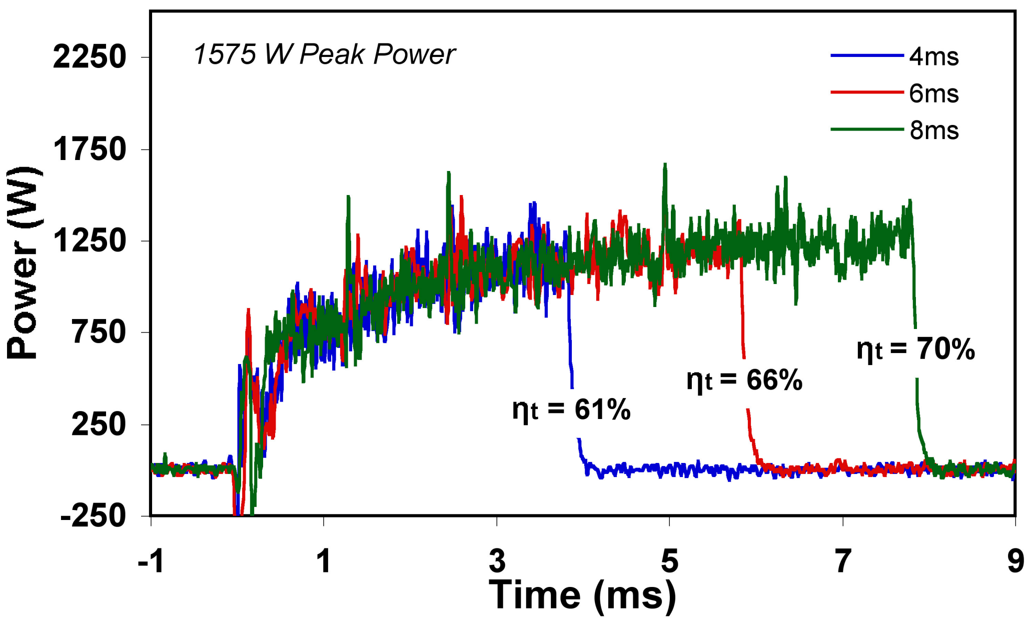


Weld pulse currently determined in separate experiment, can result in initial spiking

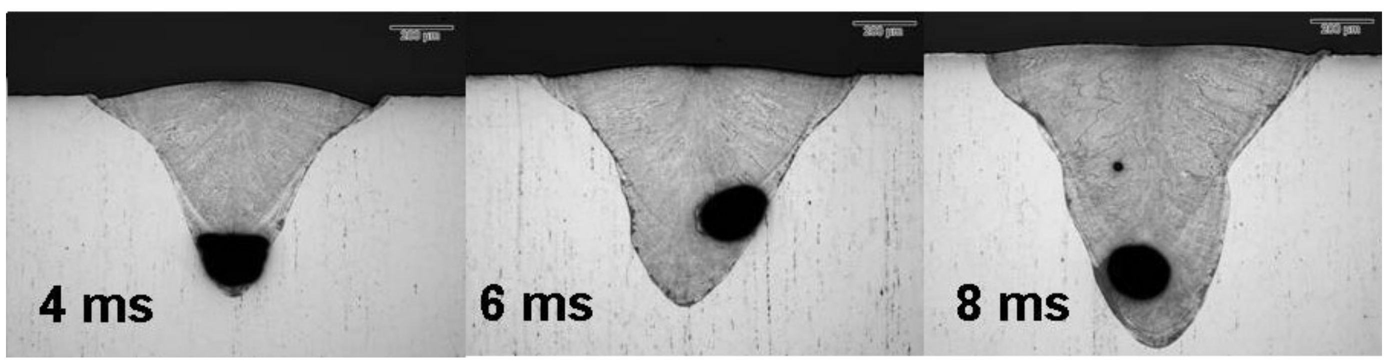


- **Absorption of both keyhole welds plateau at about the same time**
- **Relative to conduction mode weld, instantaneous absorption of 1033 W weld increases from ~40 to 63% and the 1585 W weld increases to 73%**

Experimental Matrix A - Time Series

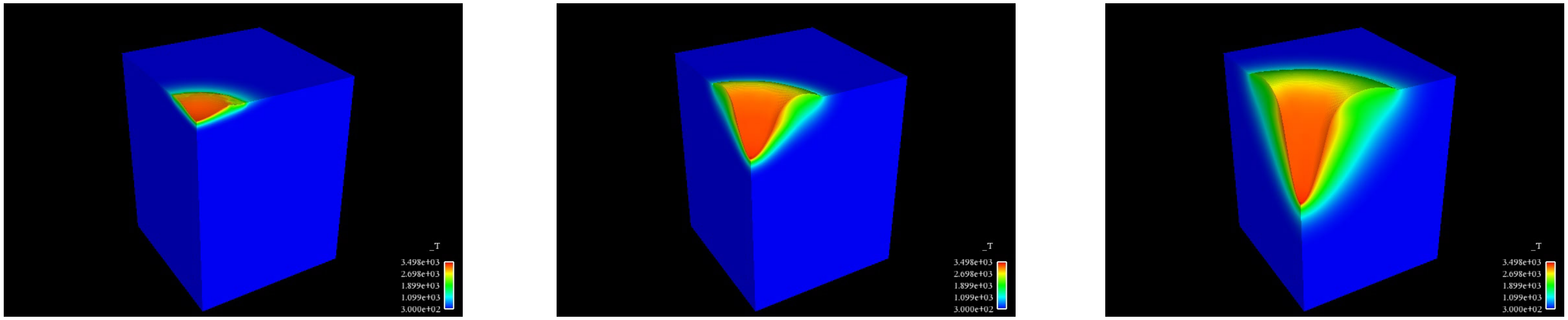


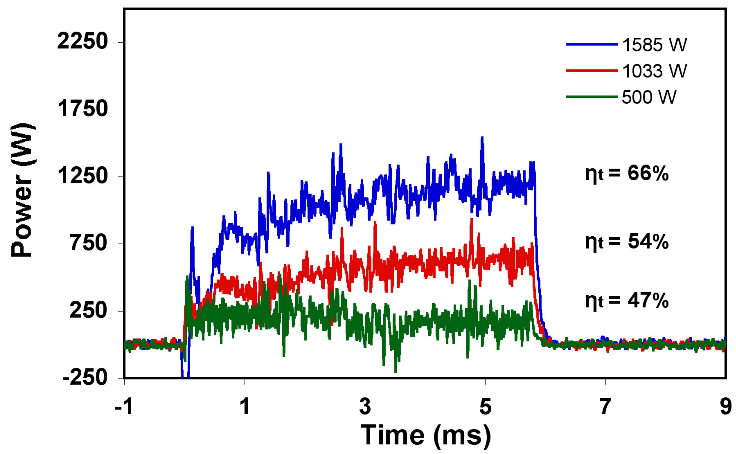
- For high powers, absorption evolves uniformly in time toward a steady value, instantaneous transfer efficiency approaches 80%
- Keyhole develops at same rate
- Increasing time in the high absorption regime increases average transfer efficiency
- Average efficiency measurements in agreement with calorimetry

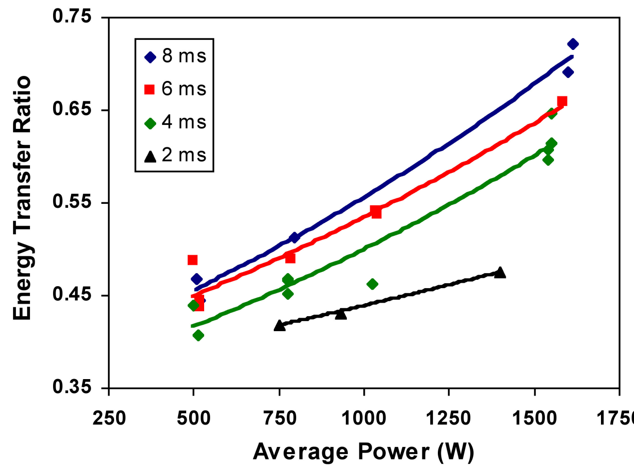


Absorption Phenomenology

Time

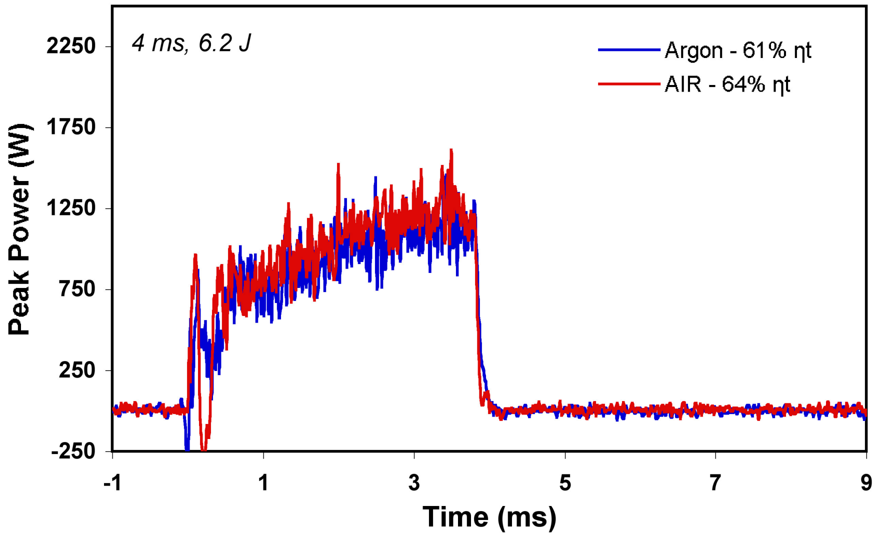






- Evolution of the keyhole geometry controls the absorption (number of reflections) and weld geometry
- The absorption measurements provide a quantitative description of this evolution

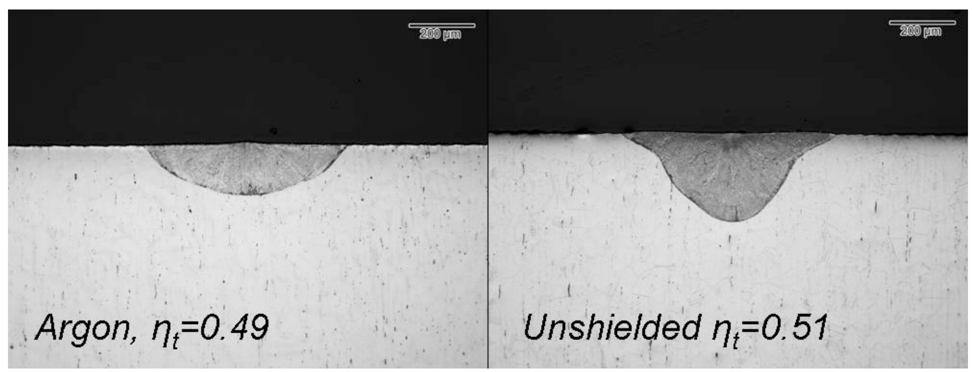
Effect of Shielding Gas



- Evaluation of effect of shielding gas (surface tension) implies small but measurable increase in absorption for reactive atmosphere
- Weld cross sections are strongly affected, presumably by flow reversal

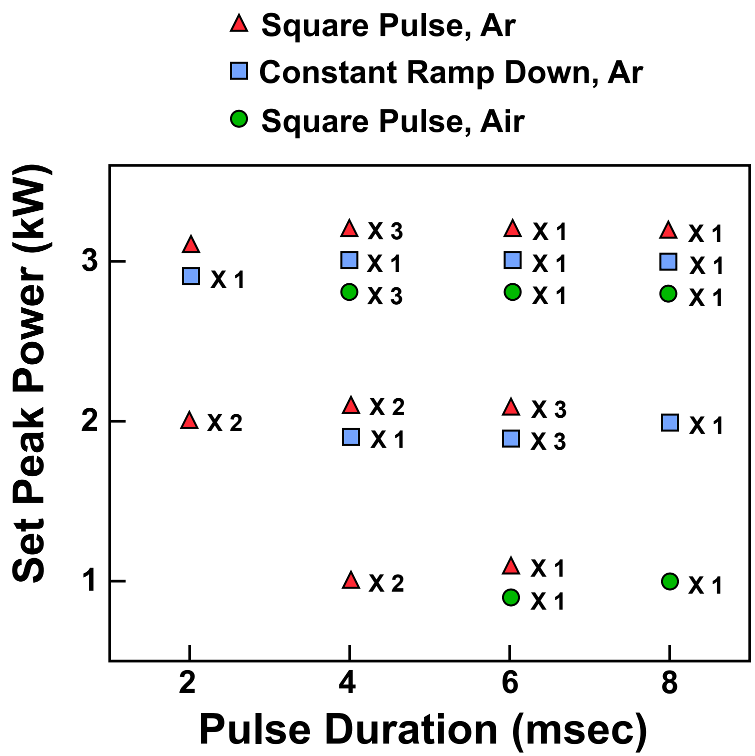
TRANSFER EFFICIENCY

Condition	Ar Shielding	Unshielded
8 ms, 3 kW, 12.8 J	69%	72%
6 Ms, 3 kW, 9.5 J	66%	70%
4 ms, 3 kW, 9.5 J	61, 60, 61%	64%
6 ms, 1 kW, 3.0 J	49%	51%



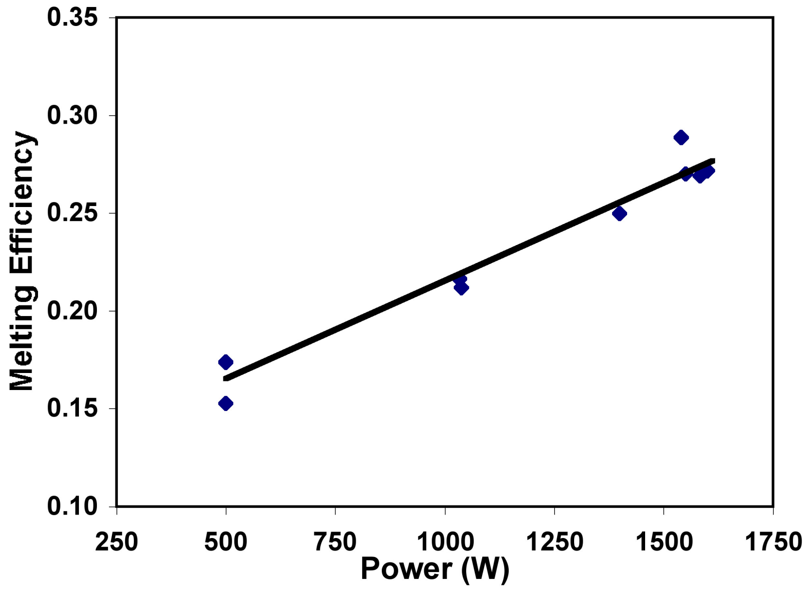
Experimental Matrix B

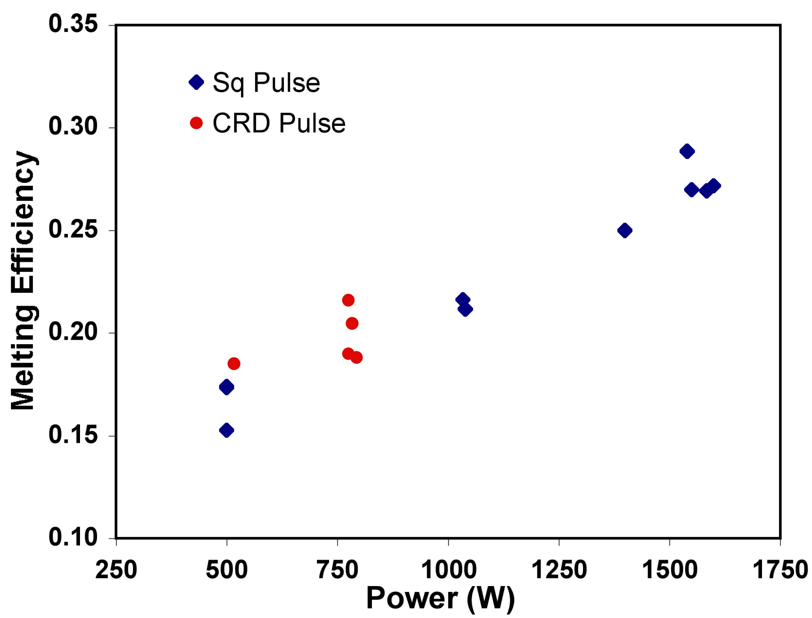
- Experiments for Matrix B have been completed and partially analyzed



- Weld matrix based around typical production procedures
- Includes variation in pulse shape (square and linear ramp-down) as well as shielding gas

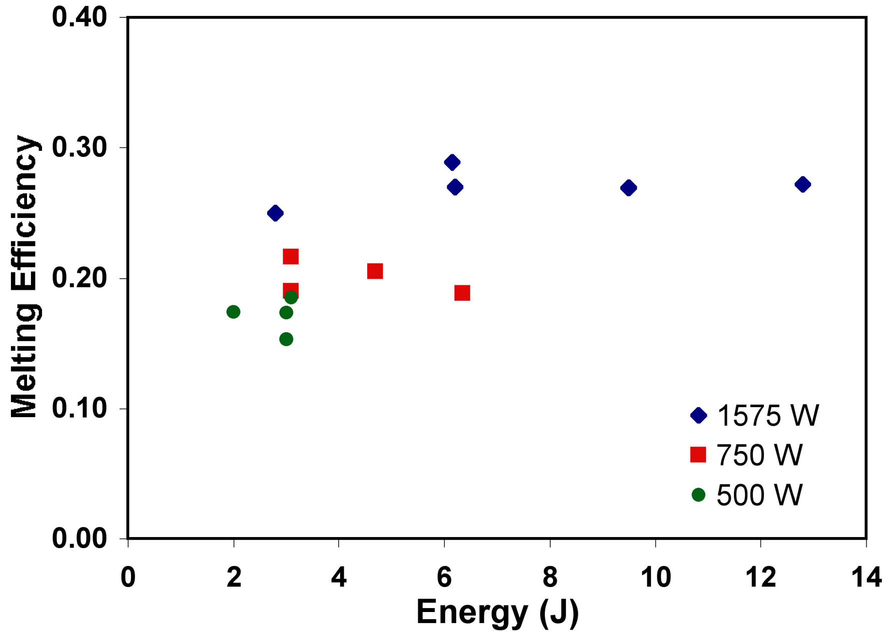
Melting Efficiency - Power



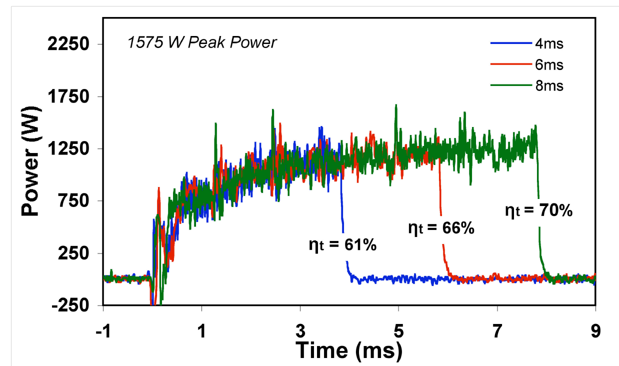


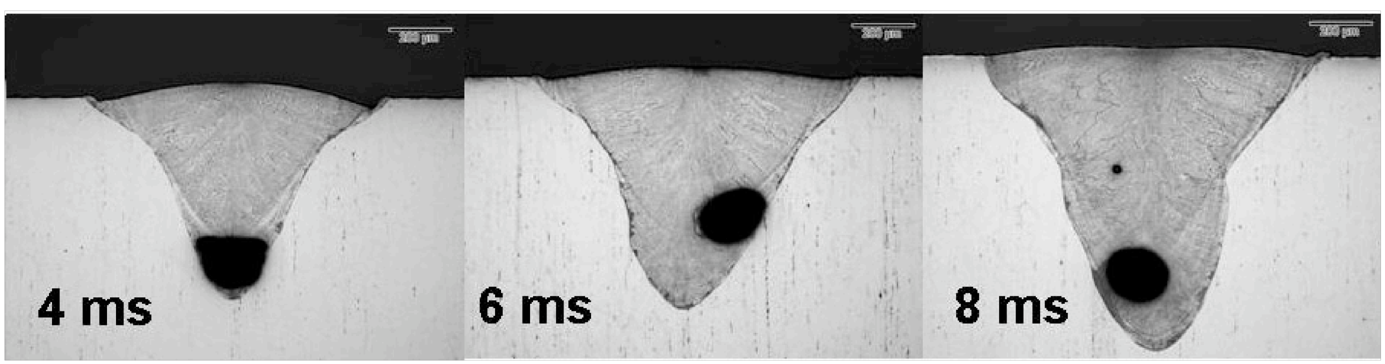
- Melting efficiency determined from weld volume measurements
- Correlation appears to hold for both square and ramped pulses if average power is considered

Melting Efficiency - Pulse Energy

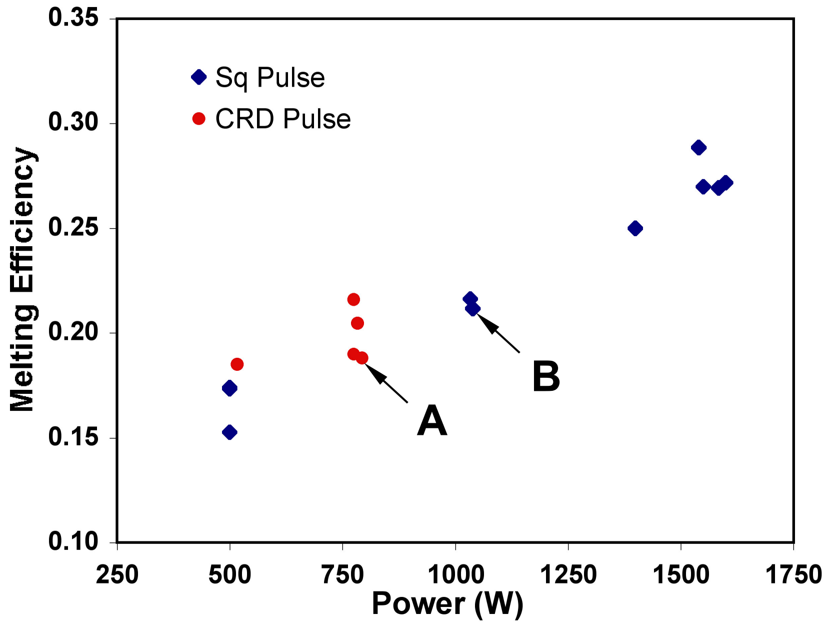


- Metallography not yet complete, but
- For 1575W square wave pulses, melting efficiency is independent of pulse energy

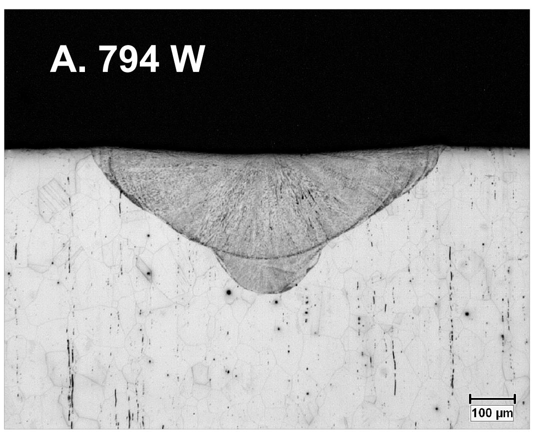


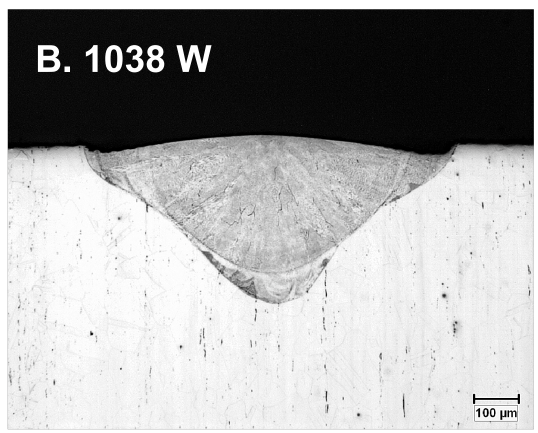


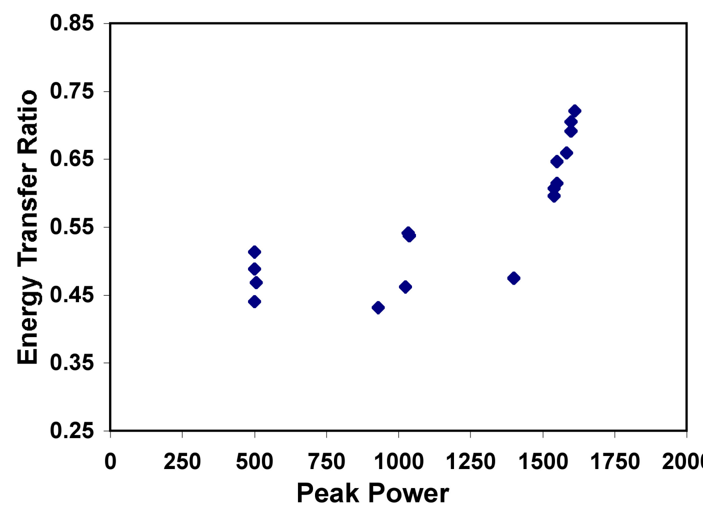
Weld Penetration



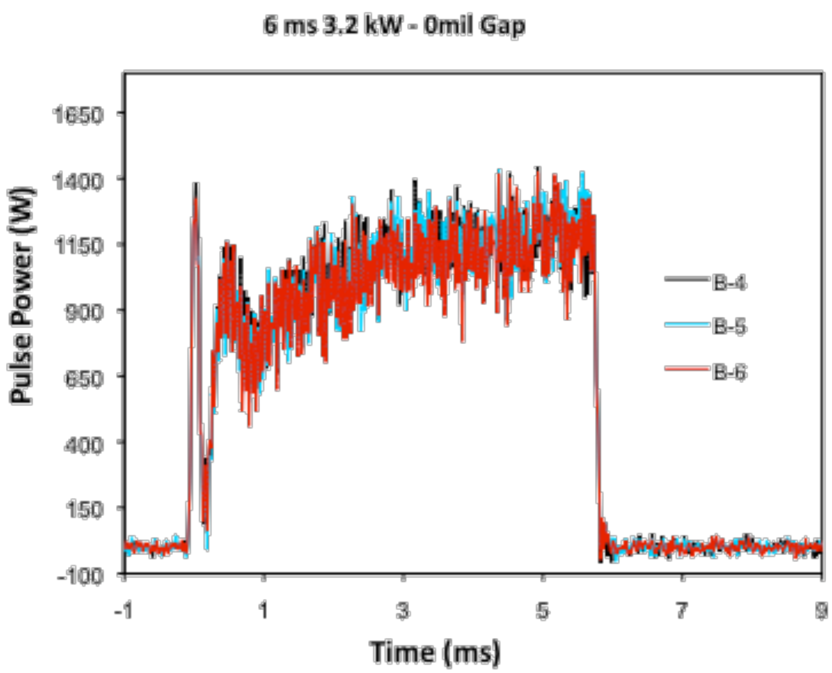
- Similar penetration can be achieved with suitable design of the pulse shape
- For weld A, penetration is similar that of B even though the average power and melting efficiency is lower
- This results from the variable balance of transfer and melting efficiencies

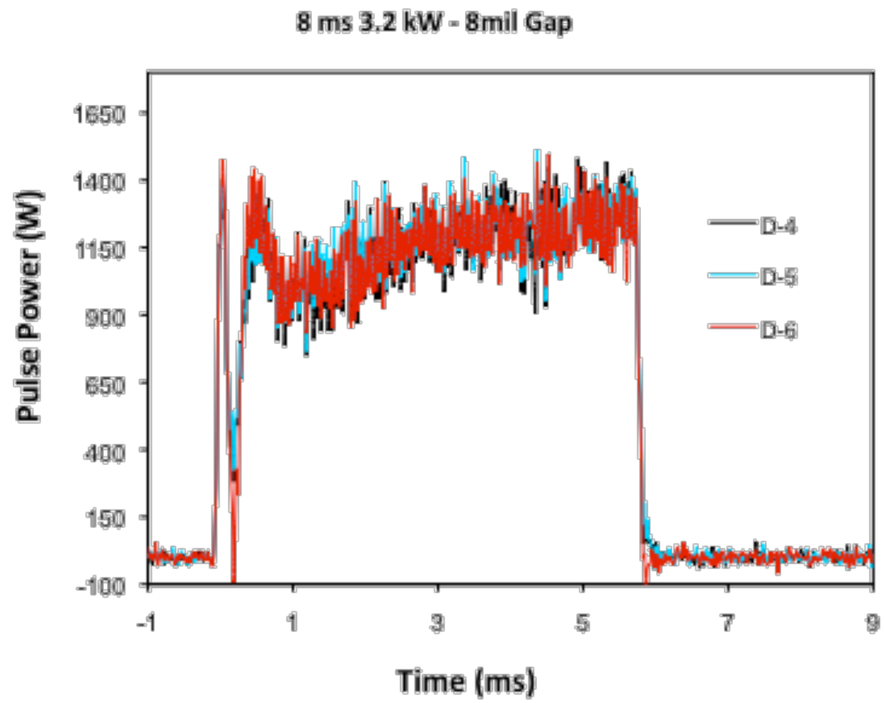






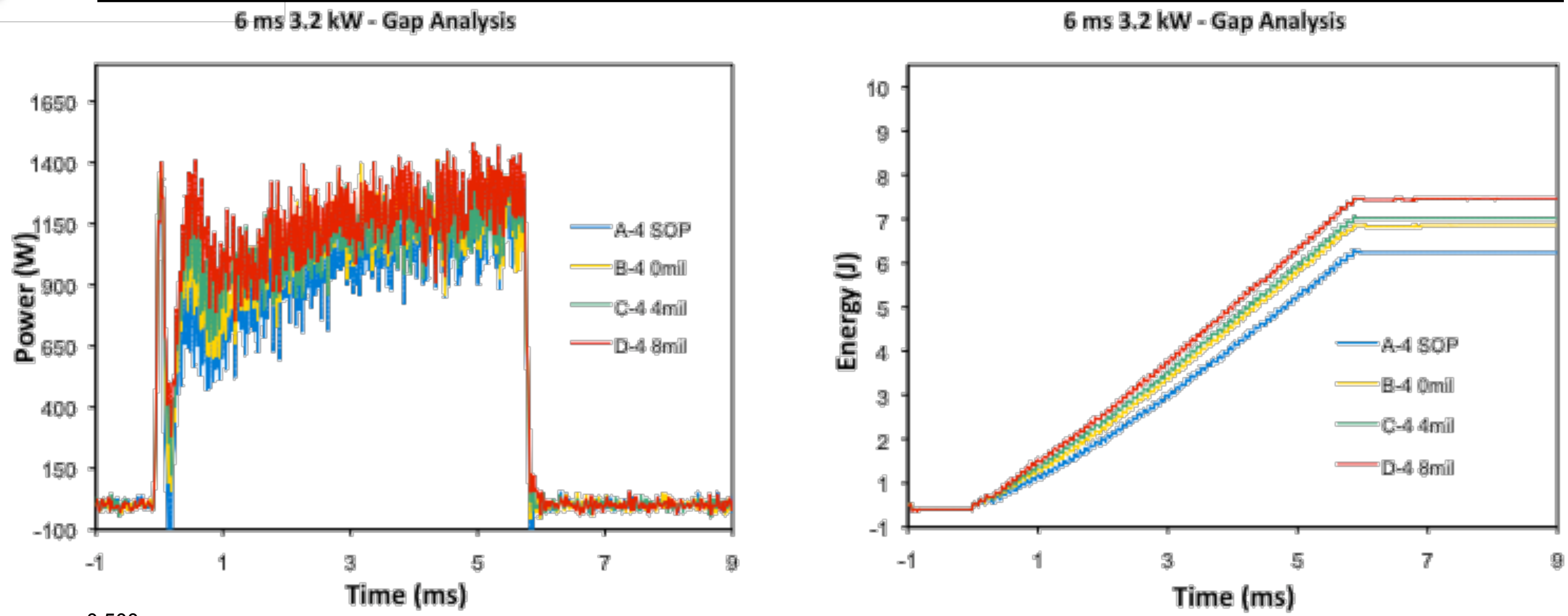
Effect of Joint Gap

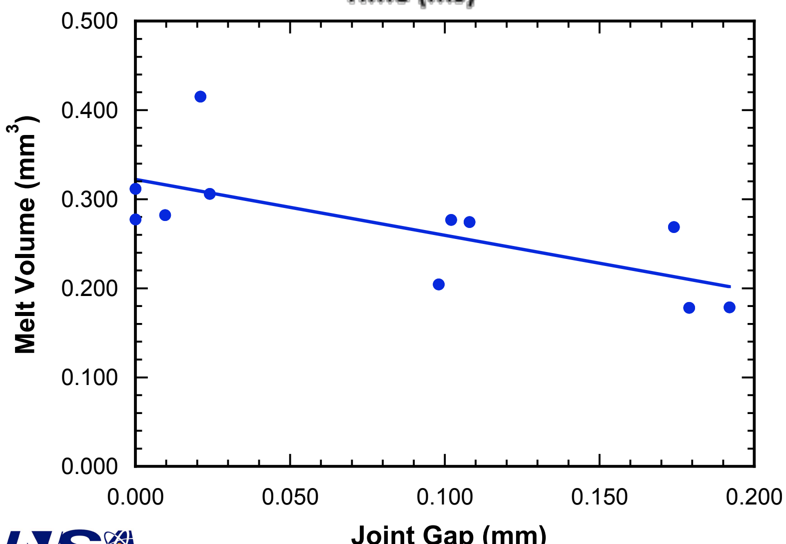




- Good measurement repeatability was observed across a range of joint gaps and welding conditions

Effect of Joint Gap





- For constant laser conditions, increasing gap increases instantaneous transfer during early stages of pulse
- For the measurement conditions the increased absorbed energy does not contribute to additional melting
- Though scattered, the extent of melting appears to decrease

Effect of Measurement Pedestal

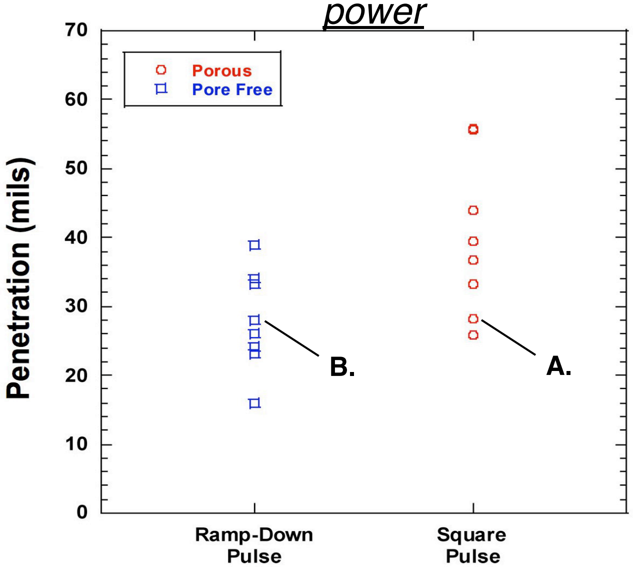
Initial Configuration

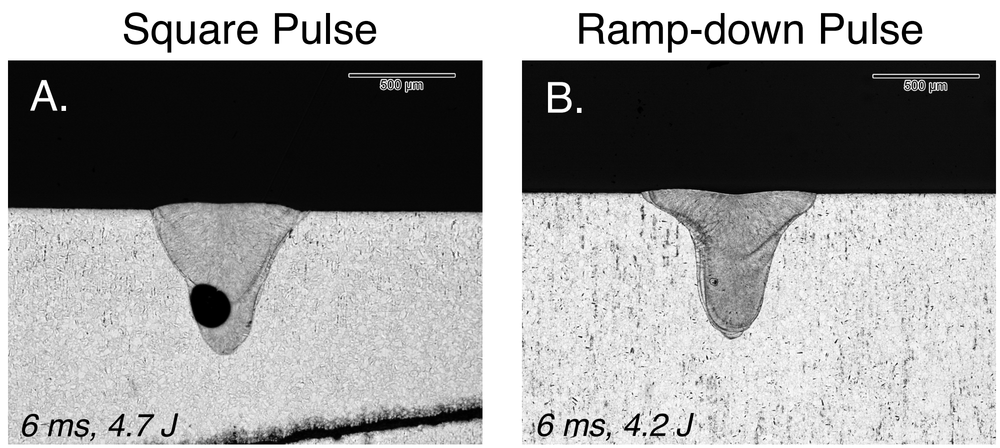
Initial Configuration

- Transmitting stage and pedestal provides a more direct measurement of absorbed power that contributes to melting
- Initial configuration serves as light trap and is probably much light many real joint designs
- Actual heat input assessments must consider both

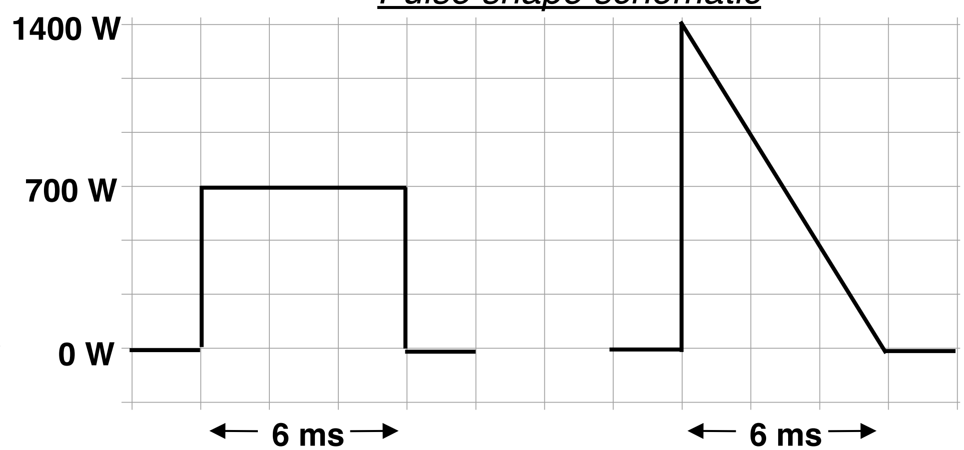
Implications and Continuing Work

100 mm lens, 3-9 ms, 1–14 J/ pulse, 800 – 2000 W peak power





Pulse shape schematic



- Pulse shaping allows for gradual collapse of the keyhole, reducing porosity
- Absorption measurements provide a basis to optimize pulse shape with respect to penetration, porosity and other thermal constraints

Summary

- A method for determining time resolved energy absorption in laser beam spot welds (LBSWs) has been developed ad provides quantitative insight into spot welding efficiencies and keyhole phenomena
- Keyhole welds separate into three regions of energy transfer: <50% during initial melting, 50-70% during keyhole formation, and >75% for a mature keyhole
- For low power (conduction mode) welds, transfer efficiency is low, <50%, and remains low throughout pulse
- The effect of gap is complex, but its influence occurs primarily during the early stages of the pulse prior to coalescence
- Actual joint designs have an appreciable effect on both energy transfer and melting efficiency, and gap (in many real joint configurations) can increase absorption while decreasing melting efficiency
- Melting efficiency in spot on plate welds correlates linearly with average power, irrespective of pulse shape, but appears independent of pulse energy for a given power
- The balance of transfer and melting efficiencies can be manipulated with pulse shape, thereby providing a basis for optimization of penetration, defect mitigation, and weld thermal characteristics