Laser Ablation Surface Preparation and Hazard Evaluation

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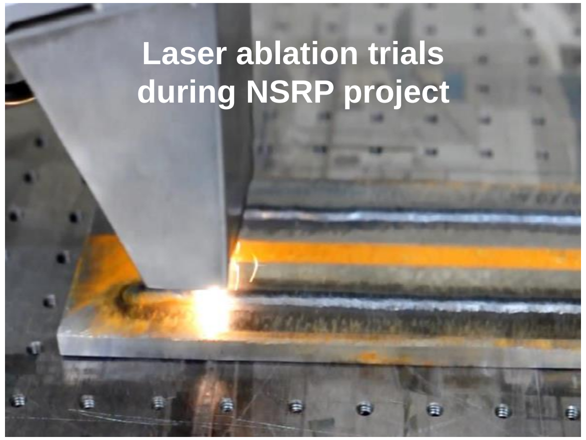
Today's Presentation

- Issue, Goal, & Objectives
- Project Approach
- Laboratory & Equipment
- Design of Experiment
- Multi-parameter Testing
- Challenges
- Challenges Addressed
- Next Steps
- Questions

Issue, Goal, and Objectives

Manual grinding removal of PCP

- The Institute for Manufacturing and Sustainment Technologies (iMAST) leveraged a National Shipbuilding Research Program Panel (NSRP) Project to address key safety concerns with using laser ablation in the shipyard.
  - iMAST: Laser Ablation of Pre-construction Primer on HSLA Steels
  - *NSRP: Identifying, Evaluating, and Mitigating Ocular Hazards in Laser Processing*
    - Issue
      - Must remove preconstruction primer (PCP) before welding in ship construction using needle guns, handheld or walk-behind grinders, and/or abrasive blast equipment
      - Methods are laborious, dangerous, often cause material erosion, and may produce excessive amounts of waste material
      - *Laser ablation is an option, but ocular hazards must be quantified, qualified and mitigated before being approved for use in shipyards.*
    - Goal:
      - Transition automated LA technology to shipyard Steel Fabrication and Assembly (SFA) for removing PCP from HSLA steels
      - *Measure and determine means to mitigate ocular hazards that are associated with LA surface preparation processes that will be used in areas where a controlled environment is not possible*
    - Objectives:
      - Reduce labor costs, substrate erosion, and consumables associated with PCP removal during naval ship construction.
      - *Measure laser beam reflections from HSLA steel when operating near IR laser to determine hazards to co-located personnel and design and develop a means to protect personnel from stray radiation.*



Laser ablation trials during NSRP project

Project Approach: iMAST & *NSRP*

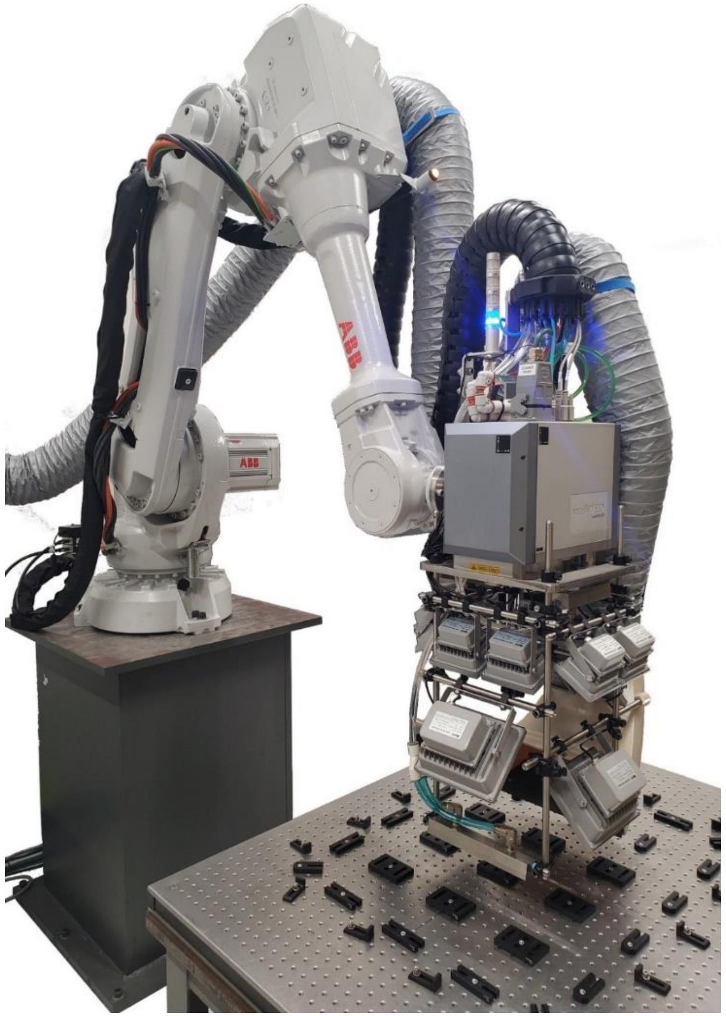
- Phase 1: Equipment Procurement, Process Evaluations & Testing
  - Evaluate SPF Flow vs. LA equipment capabilities — Completed Q2FY19
  - Socialize project ideas — Completed Q4FY20
  - Develop qualification test plan — Completed Q2FY21
  - Outline and initiate procurement plan — Completed Q2FY20
  - Install and debug LA system at PSU/ARL — Completed Q1FY21
  - Conduct process optimization / preliminary coupon testing — ECD Q1FY23
  - *Perform hazard analysis of ARL LA System* — *Completed Q1FY22*
  - *Design and develop ocular hazard mitigation means* — *Completed Q2FY22*

- Phase 2: Qualification Testing and Transition Planning
  - Conduct qualification testing — ECD Q1FY24
  - Report to TWHs and draft approval letter — ECD Q1FY24
  - Update business case — ECD Q1FY24
  - Conduct implementation planning — ECD Q1FY24

Laboratory and Equipment

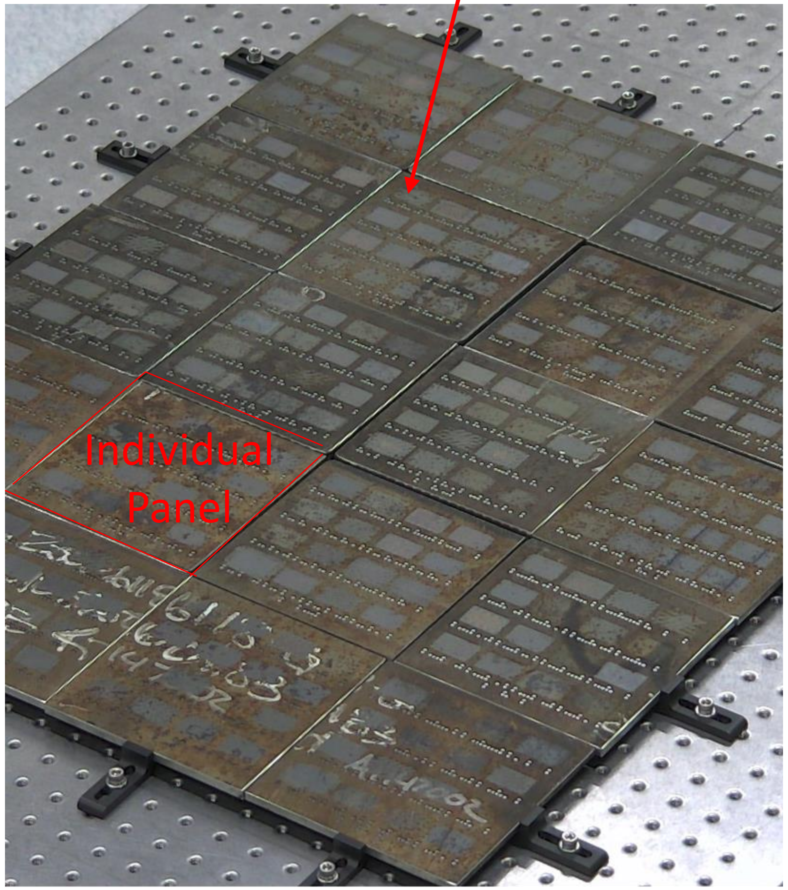
- Designed, built room and integrated LA system
- Completed programming to enable experimental and prototype processing
  - Allows ordered and non-ordered layouts, ID marking, etc. (Removes bias in “patch-based” experiments)
  - Allows user to programmatically vary process parameters
  - Allows generation of “Nominal Parameter Array” to quickly identify the applicable ranges of process variables
  - Allows multi-parameter processing

    (Multiple LA processing steps are combined into a single “production” process occurring in one pass over substrate)



Design of Experiment

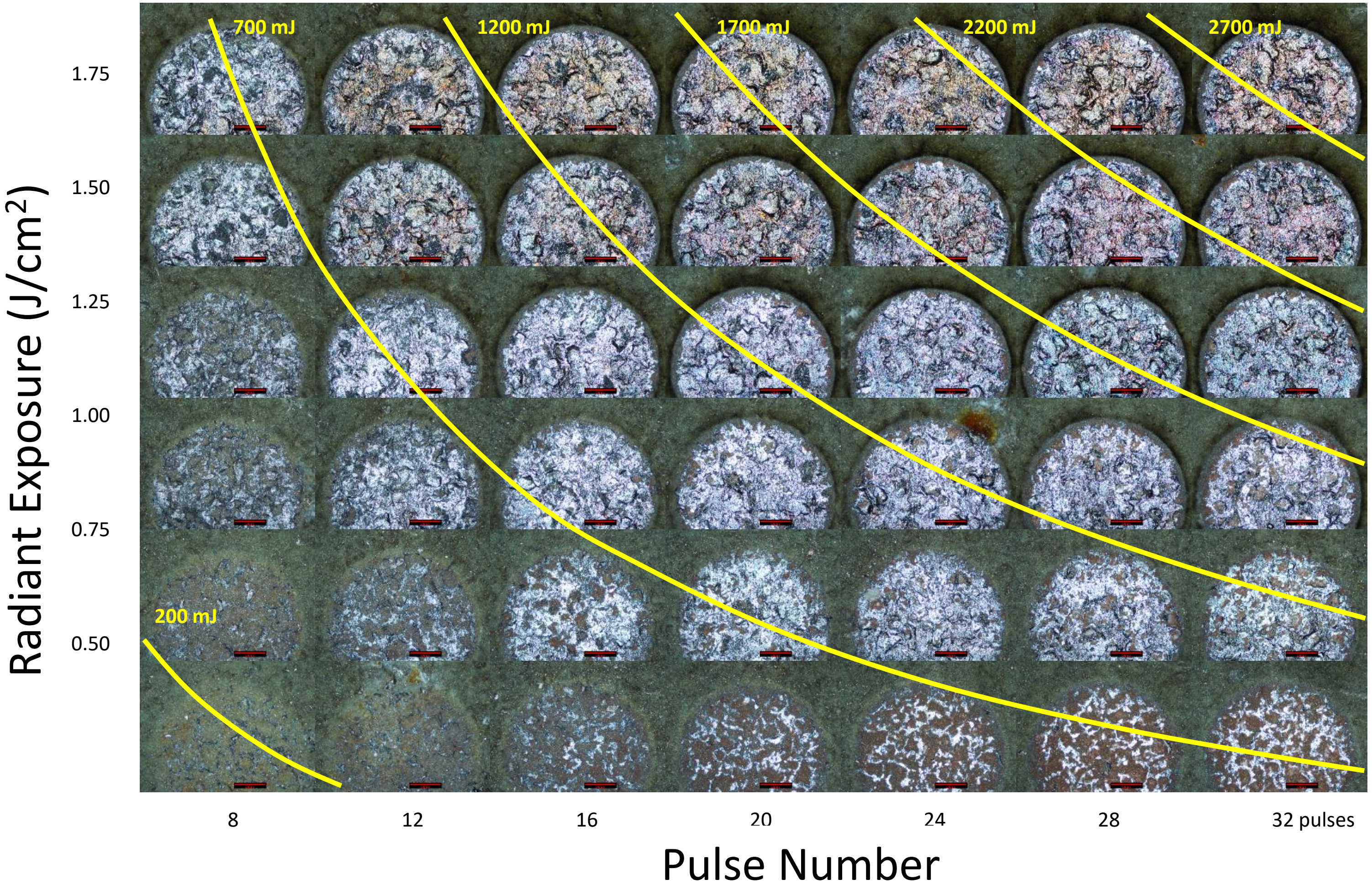
- Conducted 1000+ stripping trials to optimize removal of red and green primer on high strength, low alloy (HSLA) steels
  - Image at right: DOE 1 = 320 unique parameter sets on 640 test patches
  - Refined parameter development to a few variables, quickly assessed via a Nominal Parameter Array
    - Overlaid iso-energy (& process speed) contours enables quick reduction of processing variables
  - Improved system program to enable "clean up"
    - Removes shallow bluing (substrate oxidation)
  - Determined optimal parameters for weathered IOZ PCP
  - Learned unweathered primers and new primer colors would be encountered eventually



Rusted samples with test patches

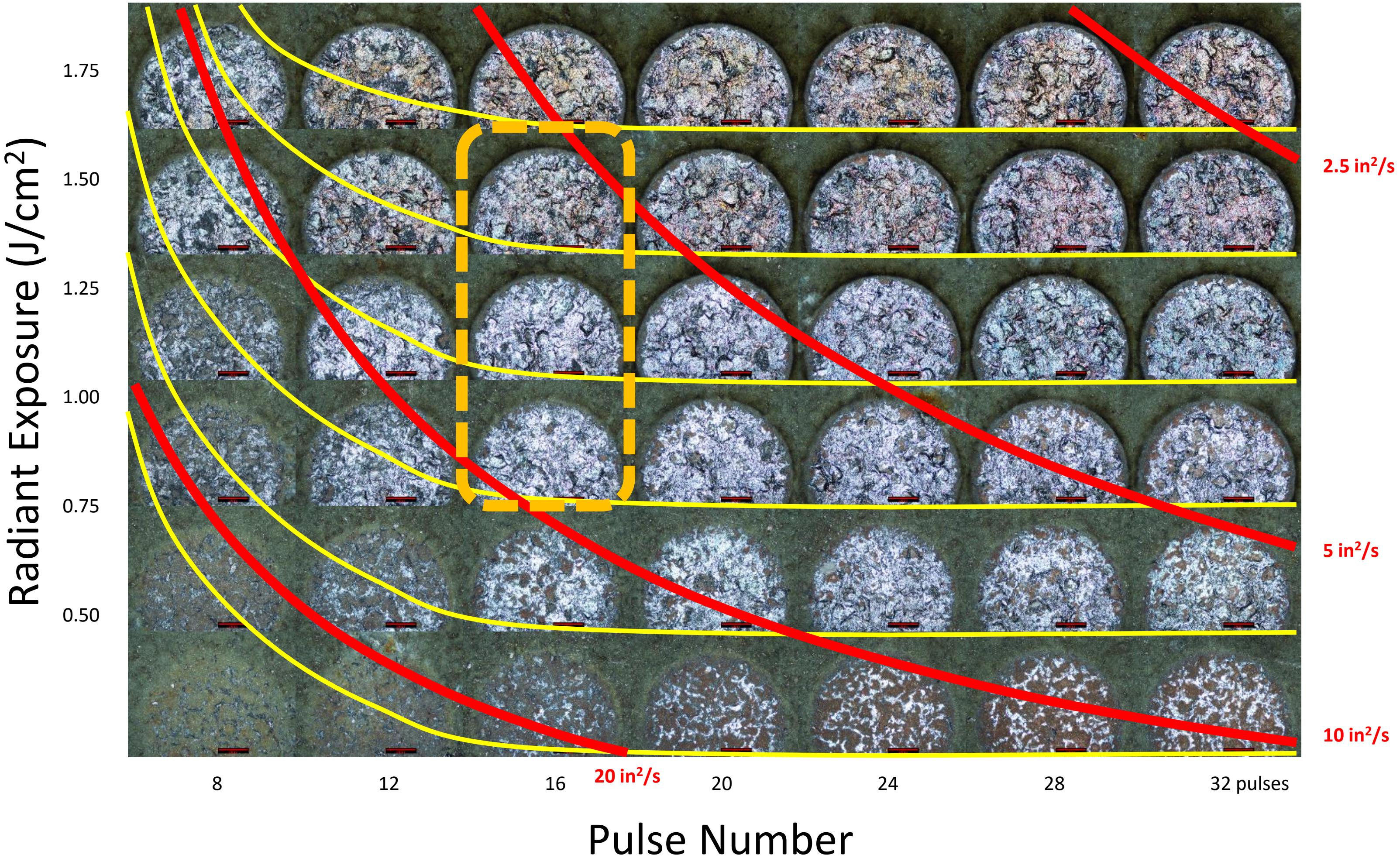
Multi-parameter Testing: Iso-energy Contours

- Nominal Parameter Array overlaid with iso-energy contours
  - Plotting Radiant Exposure (Pulse Energy divided by Spot Size) vs. Number of Pulses
    - Overlaid (yellow) contours show increasing levels of average energy input
  - *Radiant Exposure affects potential for ablation*
  - *Pulse Number affects thoroughness of ablation*
  - *Total energy affects onset of melting*

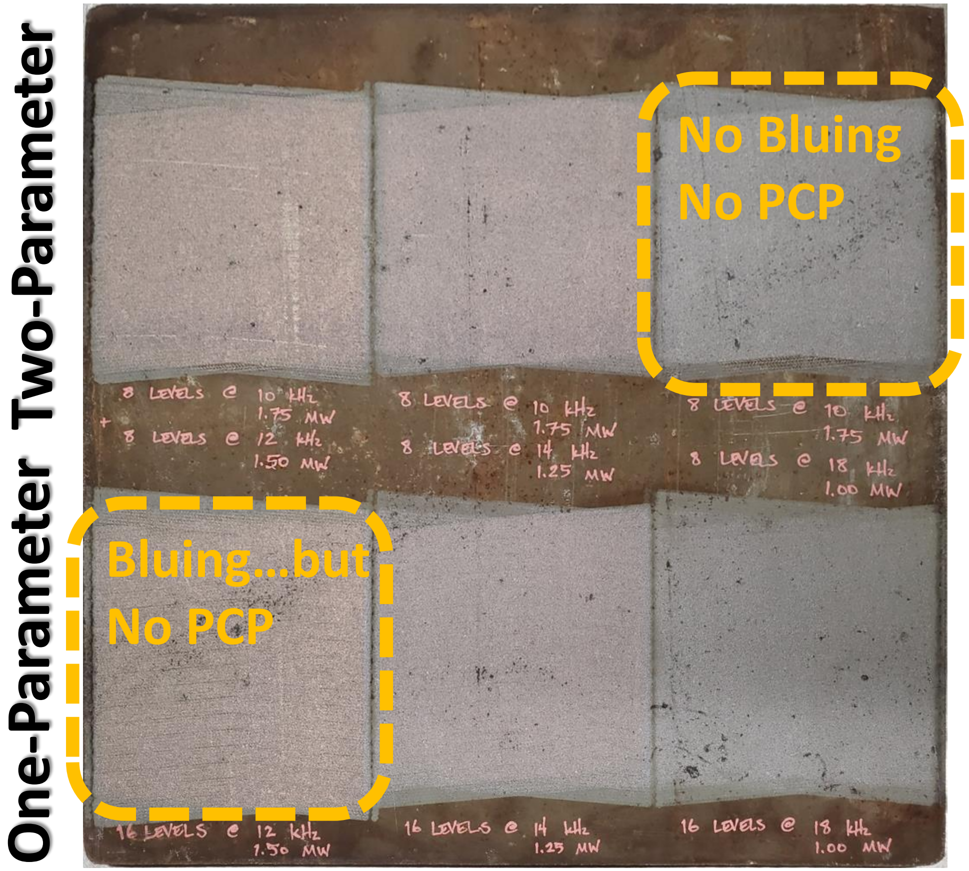


Multiparameter Testing: Iso-LA & Iso-speed Contours

- Developed iso-LA and iso-speed contours
  - Red lines = maximum, theoretic processing speed (in^2/s)
    - Baseline blast speed is 2.5 in^2/s
  - Yellow lines show LA PCP removal reaches steady-state after ~ 20 pulses, followed by melting thereafter
  - Orange dotted box = best processing window
    - Higher Radiant Exposure rows show onset of bluing
    - Lowest Radiant Exposure row shows steady-state of primer removal after 20 pulses (similar in other rows).



Multi-parameter Testing: LA and Clean Up

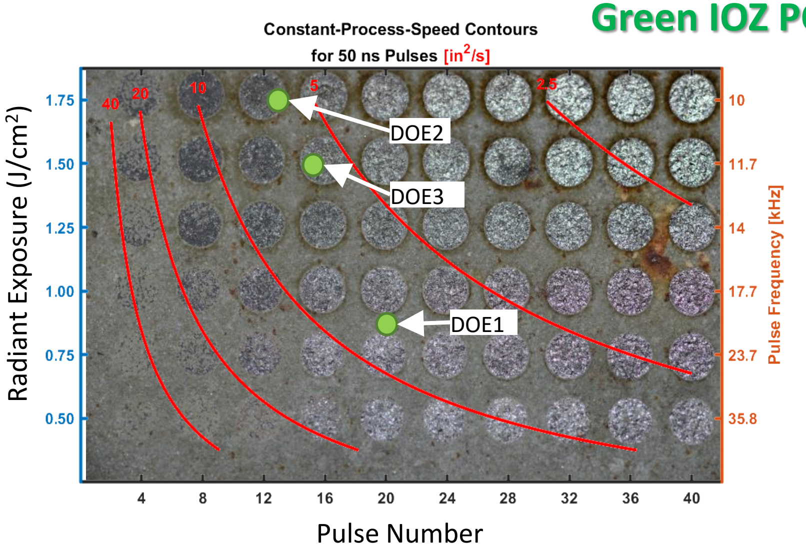


- Best single-parameter set removed primer, but slightly blued the substrate
- Multi-parameter approach removed the primer and the shallow bluing of the substrate
  - Multi-parameter approach initially "hit harder", but fewer times; followed with softer hits

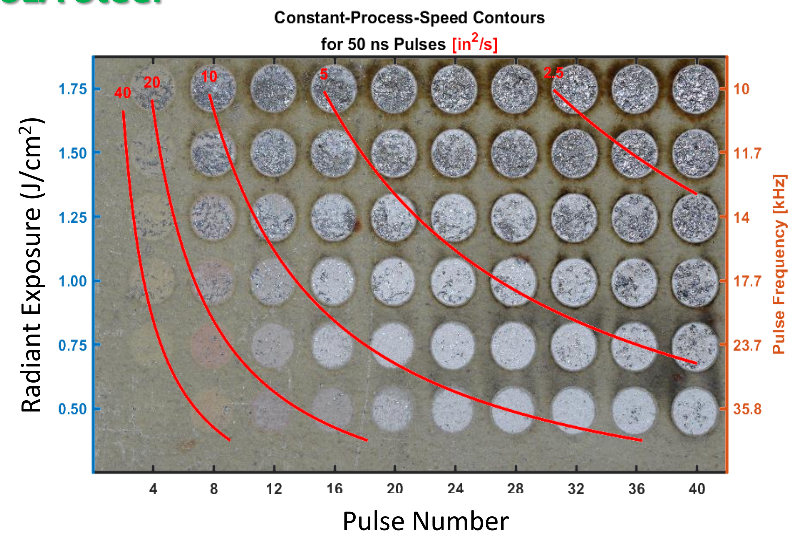
Challenges: Weathered vs. Unweathered Paint

Green IOZ PCP (0.8 – 1.2 mil) on HSLA Steel

Weathered Green: Consistent Ablation

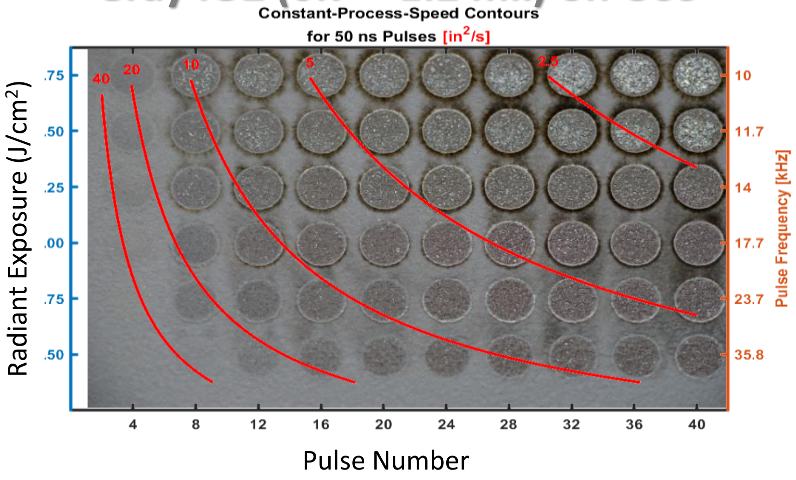


Newly applied green: Inconsistent / Patchy Ablation

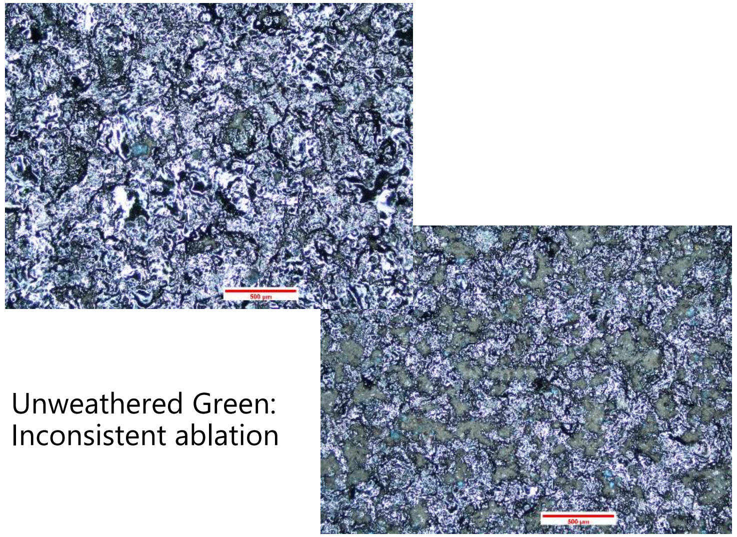


Gray IOZ (0.7 – 1.2 mil) on OSS

Newly applied gray: Incomplete ablation at uppermost energy density



Weathered Green: Consistent ablation



Unweathered Green: Inconsistent ablation

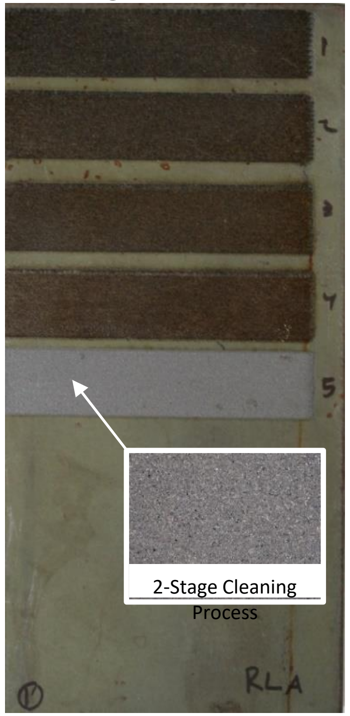
Coating Removal Successes and Challenges

- **Developed and Optimized LA parameters through successive DOEs:**
  - Distilled large LA parameter set into a few key variables
  - Optimized parameters for weathered materials (red and green IOZ PCP)
  - Found “multi-parameter” ablation aggressively strips coating (within a parameter range), followed by cleaning the surface of “blued” material
  - Unweathered and new primer coatings were more difficult to remove with existing energy density limitations of current system*
    - * Indicates nominal coating thickness, at varying (though unknown/uncontrolled) ages/conditions
- **Addressing higher energy density need for qualification specimens**
  - Increased energy density with decreased spot size or increased laser power (e.g., 3 kW now available)
  - Conducted testing at IPG with 2 kW pulsed laser and reduced spot size to enable greater energy density range
    - Easily tweaked large-spot-optimized LA variables to strip newly applied coatings and new colored coating systems
    - “Multi-parameter” ablation successfully removed more-difficult coating systems without bluing
  - Ordered/received/installed new lens at ARL to increase (~double) system energy density

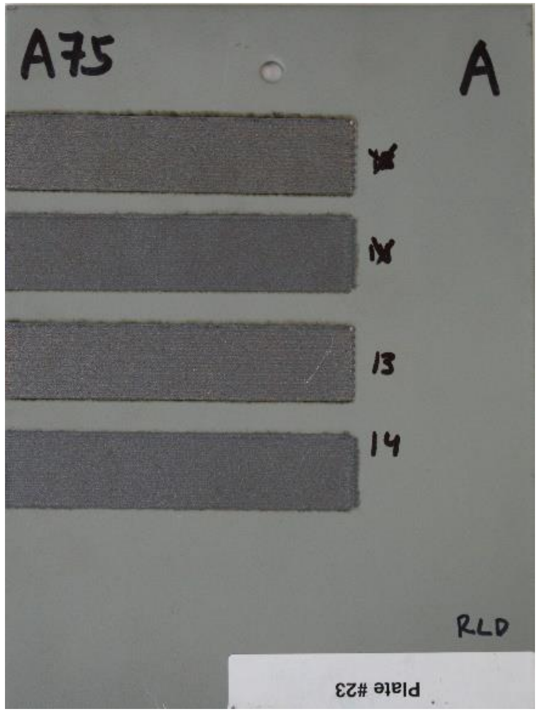
Challenges Addressed: Experiments at IPG

- Conducted LA at IPG Photonics
  - Used 2 kW laser with 1.66 mm spot size
  - Easily stripped coatings using project parameters on iso-energy curve
    - Used two LA passes at 872W
    - LA pulse-to-pulse [x] and hatch [y] overlap was 85% / 35%
    - Used one clean up pass (50% / 50% overlap)

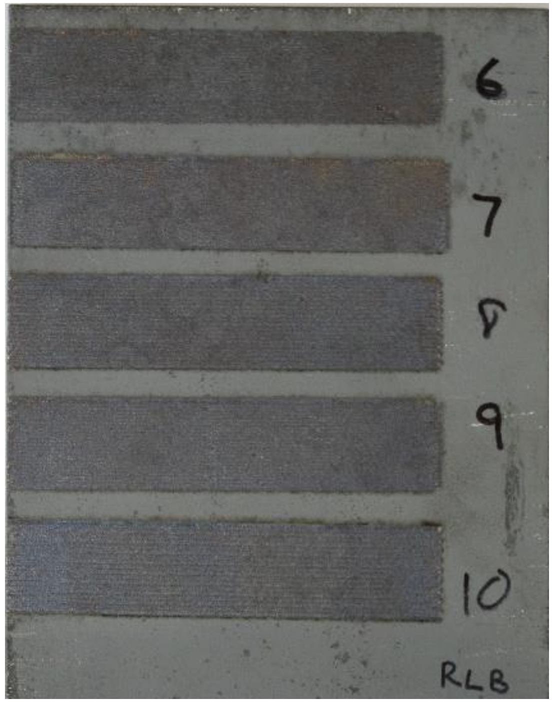
HSLA steel w/ Aged IOZ Primer



Ordinary Strength Steel (OSS) w/ Gray IOZ PCP



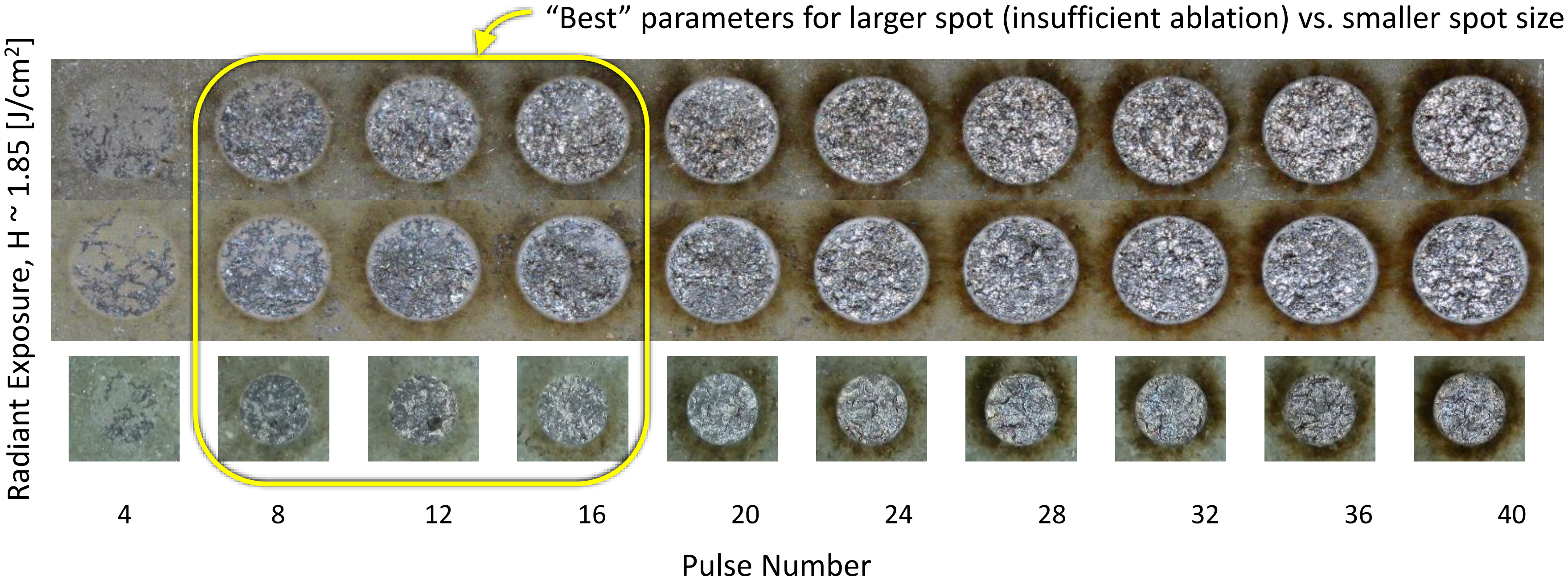
HSLA steel w/ Gray IOZ PCP



Optimal Conditions	Setting	Pulse to Pulse Overlap	Hatch Overlap	# of Passes	Zinc Remaining
All Primers & Steel Types	872W	85	30%	2	
	600W	75	75%	1	0%

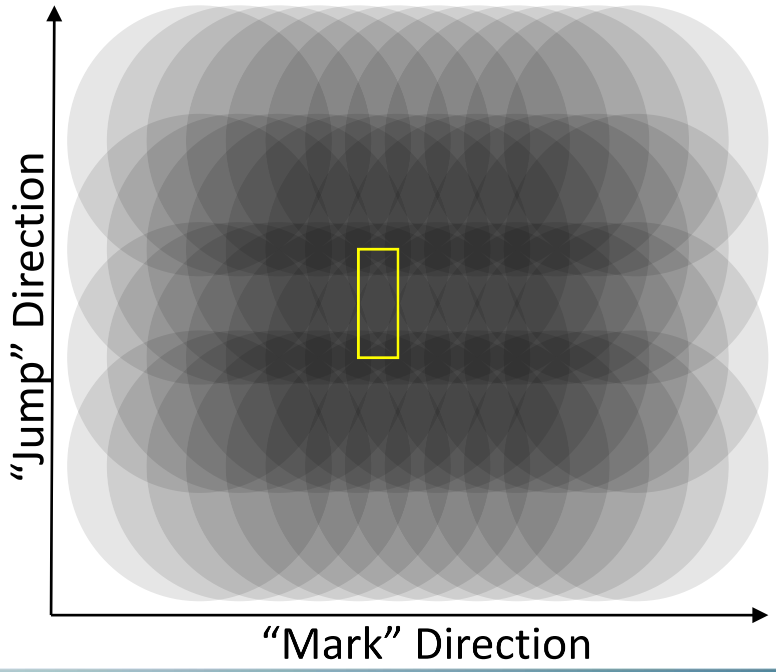
Challenges Addressed: A New Optic

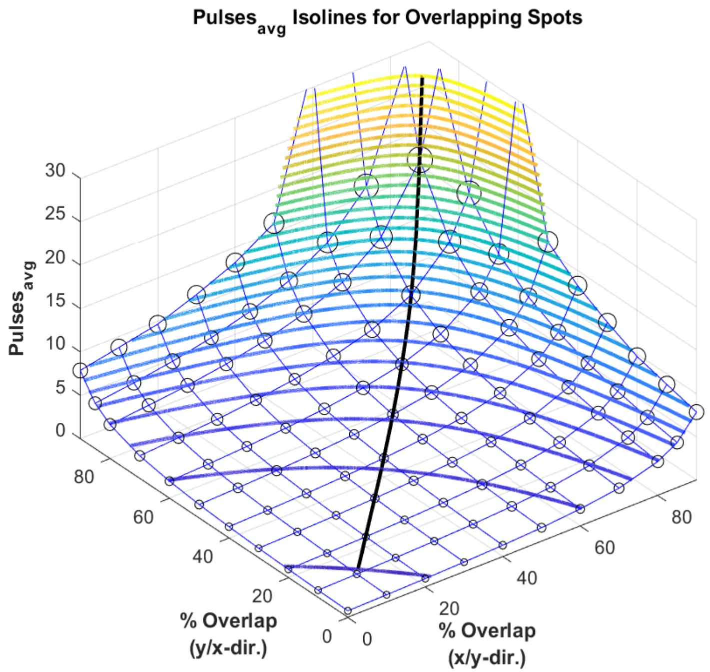
- Achieved smaller spot size (thus increased energy density) with new optic
  - Conducted trials at a fixed radiant exposure (H) vs. pulse number (P) at a fixed pulse duration (τ = 50 ns), and spot size (D = 1.6 mm)
  - Degree of remaining trace PCP appeared to be equivalent, and independent of spot size
- Created nominal LA parameter array (individual, ablated spots), where radiant exposure, avg. # pulses, and pulse duration were key ablation parameters for relatively uniform (i.e., top hat) beam
  - Radiant Exposure | Fluence — H — [J/cm^2]
  - Number of Pulses — P — [#]
  - Pulse Duration — τ — [ns]



Challenges Addressed: Image Analysis

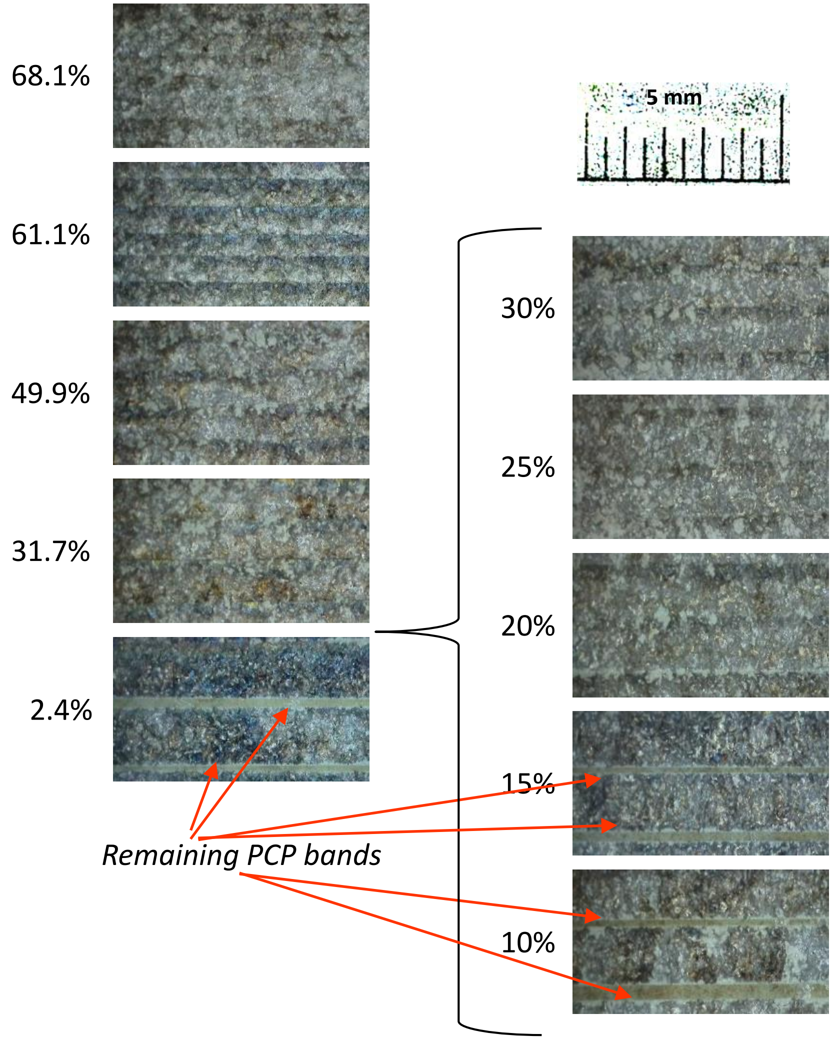
- Used image analysis to estimate average number of pulses
- Average Pulse Number drives strip rate
  - Image processing (below) for $P_{avg} = 0$ to 30 is sufficient for ablation of PCP on HSLA
  - $P_{avg} > 30$ is overly sensitive to changes in % Overlap.
- Changes in jump direction affect LA rate more than mark direction
  - Maximizing jump direction distance maximizes processing rate
  - Avoid extremes to avoid non-ideal beam behavior (e.g., non-top hat energy profiles)
  - More data scatter occurs as the images get darker
    - Process sensitivity increases with the number of layers





Challenges Addressed: Pulse Overlap

- Conducted experiments to determine limitations of non-symmetric pulse overlap
  - Fixed Avg. Power and Frequency
  - Radiant Exposure, $Pulse_{avg}$, and Pulse Duration to intentionally retain a slight haze of PCP
  - Varied % Overlap in jump and marking directions
- Findings:
  - % Jump Overlap >20% resulted in equivalent ablation
    - Equivalent ablation = constant % remaining PCP (minor discoloration differences are ignored as will be removed with "clean-up" pass)
  - % Jump Overlap <20% resulted in unequivalent ablation
  - Non ideal top hat spots are produced. Must be considered during process optimization.
  - Decreasing % Jump Overlap correlates with increasing carriage velocity and more-time-sensitive scanning (hence the non-uniform jump distances)
- Recommendation: Avoid % Jump Overlap < 20%



% Jump Overlap Images

Challenges Addressed: Developing LA Parameters

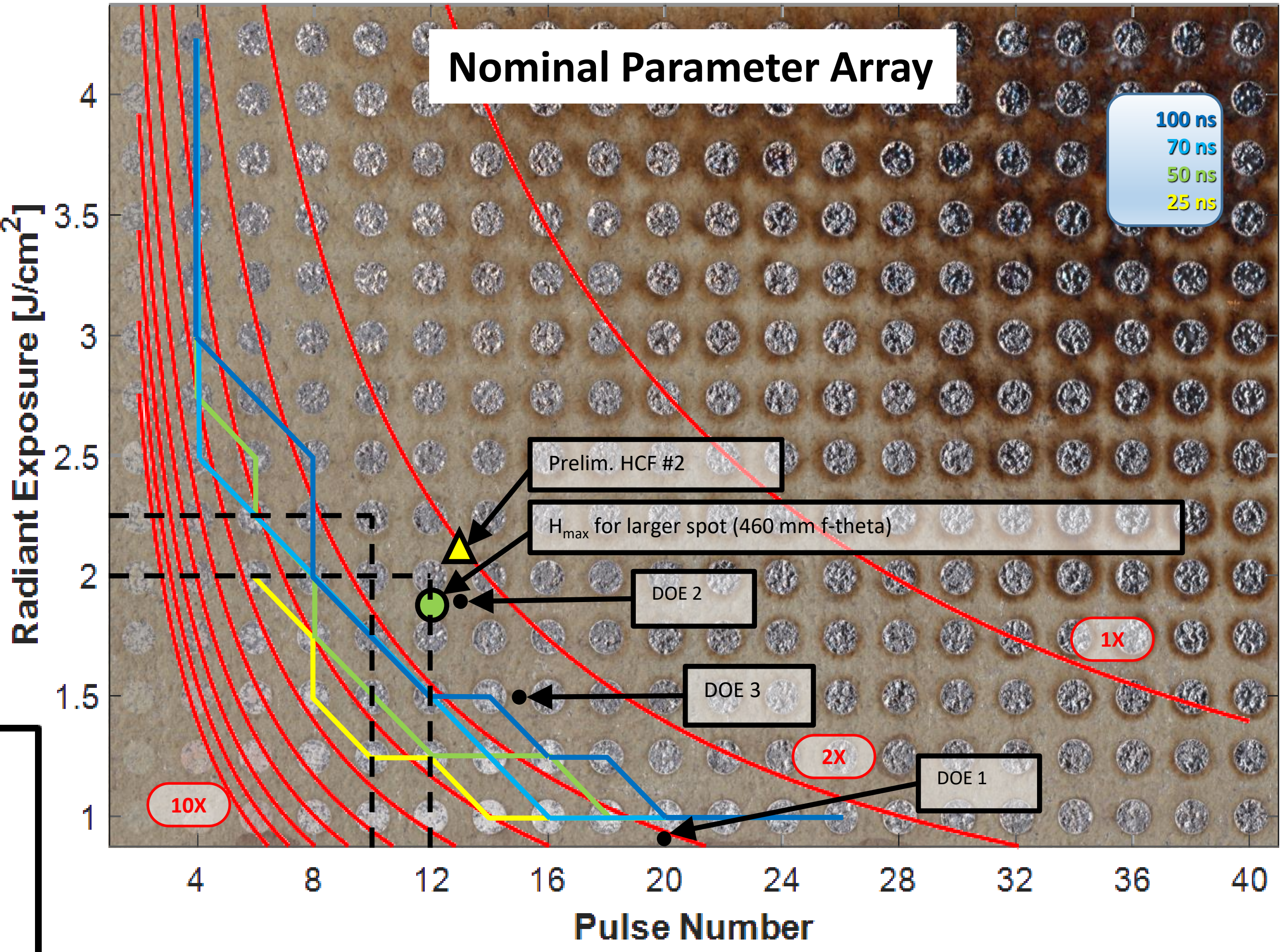
- Continued experimentation to develop optimal processing rate for LA with new lens
  - Trialed 25, 50, 70 and 100 ns (sample experiment image below [100 ns] with findings of DOEs 1-3 overlaid)
  - Red curves indicate maximum possible processing rates compared to estimated baseline grit blast rate (2.5 in^2/s)
  - Nominal Parameter Array led to these recommended parameters for further optimization

Recommended Parameters:

H	**=**	**2.0**	**± 0.1**	**[J/cm^2]**
P	**=**	**12**	**± 2**	**[#]**
τ	**=**	**50**	**± 25**	**[ns]**

Or, if higher energy is req'd:

H	=	2.25	± 0.1	[J/cm^2]
P	=	10	± 2	[#]
τ	=	50	± 25	[ns]

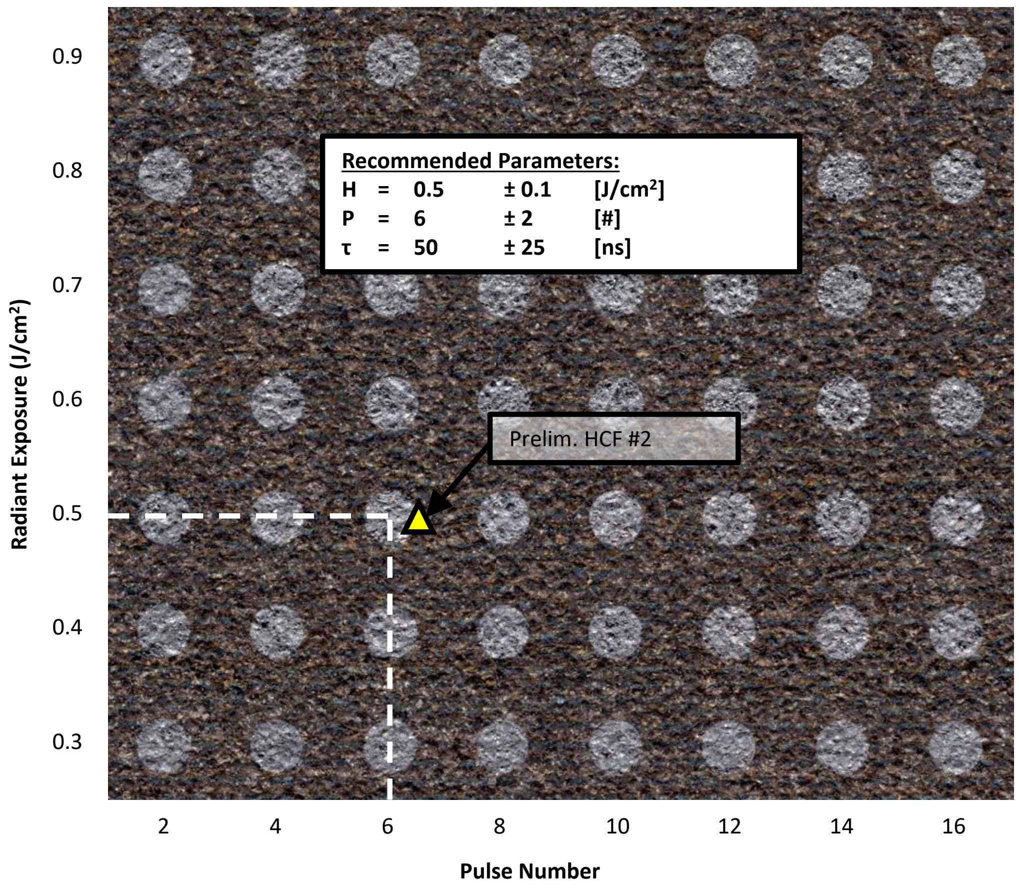


Challenges Addressed: Clean-Up

- Optimizing "clean-up" passes
  - All ranges (right) resulted in fairly good clean-up
    - Surface was slightly less "bright/shiny" using P < 4, and H < 0.4 J/cm^2
    - Surface was possibly less "bright/shiny" using P > 16, and H > 0.9 J/cm^2
  - LA Rate "isolines" are not uniform (not displayed) in clean up, compared to Nominal Parameter Arrays of prior slides
    - Recommended Parameters (as-noted) were ~10X the baseline rate

Qualification Testing Material

Green IOZ PCP (0.8 – 1.2 mil) on HSLA steel



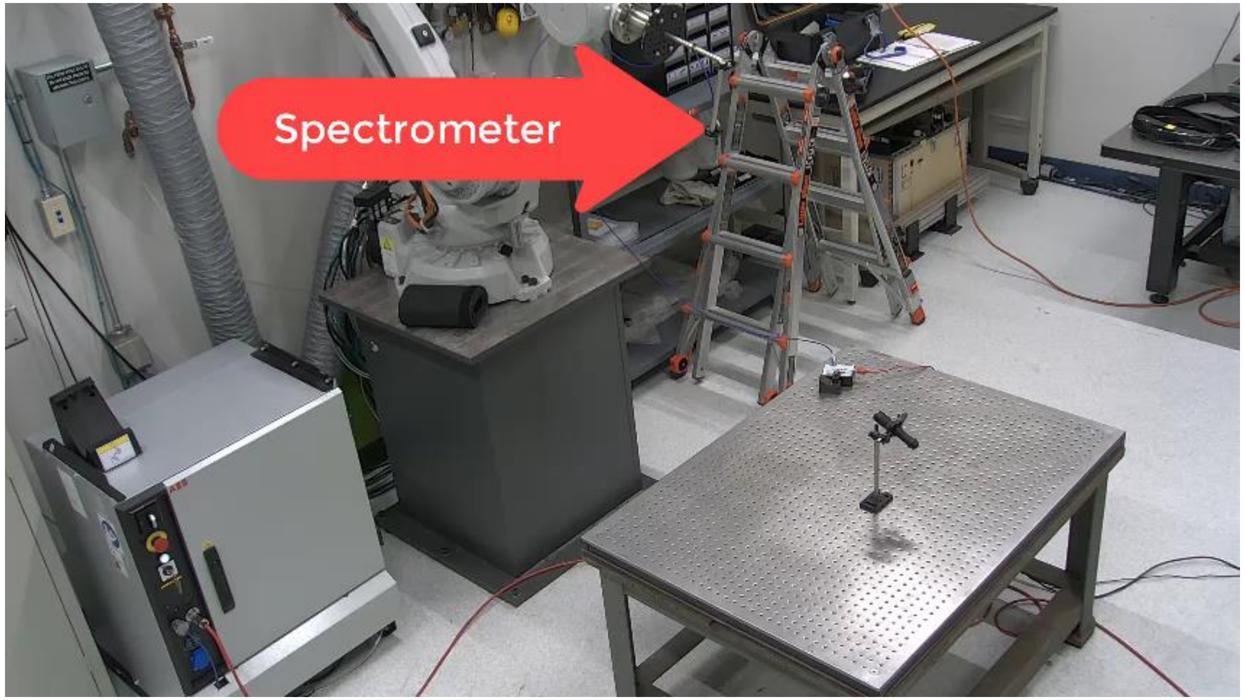
Sample "Clean-up" passes *on* H2, P12, τ50

Challenges: Testing and CBA

- Conducted preliminary fatigue testing on unwelded, weathered specimens
  - Found optimal load (62 ksi) to discern between different treatments (e.g., “Grit Blasted”, “Laser Ablated”, and “Laser Ablated + Grit Blasted”)
    - Note: Experienced gripline and edge failures, prompting media blasting of grip areas and larger radiusing of reduced-section edges
  - New HSLA specimens being run at 62 ksi and R= -1.0 to test worst case scenario of over-ablation
    - “Grit Blasted” vs. “Laser Ablated + Grit Blasted (only)” are being tested.
- Qualification panels were prepared for stripping and welding
  - Stripping qualification specimens using “refined processing parameters” for unweathered coatings
- Gathering updated cost information for updating project ROI
  - Updating materials and labor costs as well as usage rates.
- *Ocular hazards were initially concerning, but addressed in NSRP Panel Project (see following slides)*

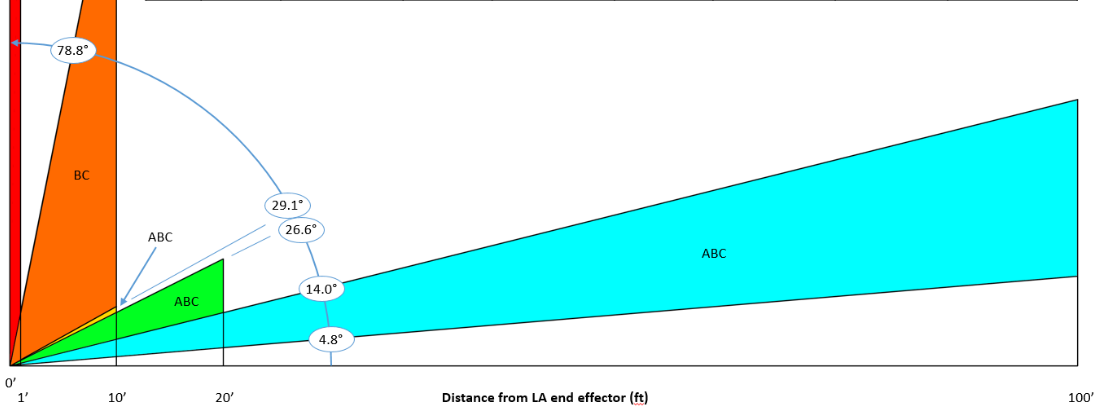
Challenge Addressed: Safety Analysis

- NSRP project addressed ocular hazards of PSU/ARL LA system
- Identified distances and angles of incidence of concern (see right) to co-located personnel
  - Based on planned insertion points for LA at shipyard.



Execution of Kinematic Model

Site	Personnel Locations – Distances & Angles							
	0 – 1 ft	Angle Range	1 – 10 ft	Angle Range	10 – 20 ft	Angle Range	20 – 100 ft	Angle Range
A	N/A	N/A	X	26.6 – 29.1	X	14.0 – 26.6	X	4.8 – 14.0
B	X	78.7 – 90.0	X	26.6 – 78.7	X	14.0 – 26.6	X	4.8 – 14.0
C	X	78.7 – 90.0	X	26.6 – 78.7	X	14.0 – 26.6	X	4.8 – 14.0

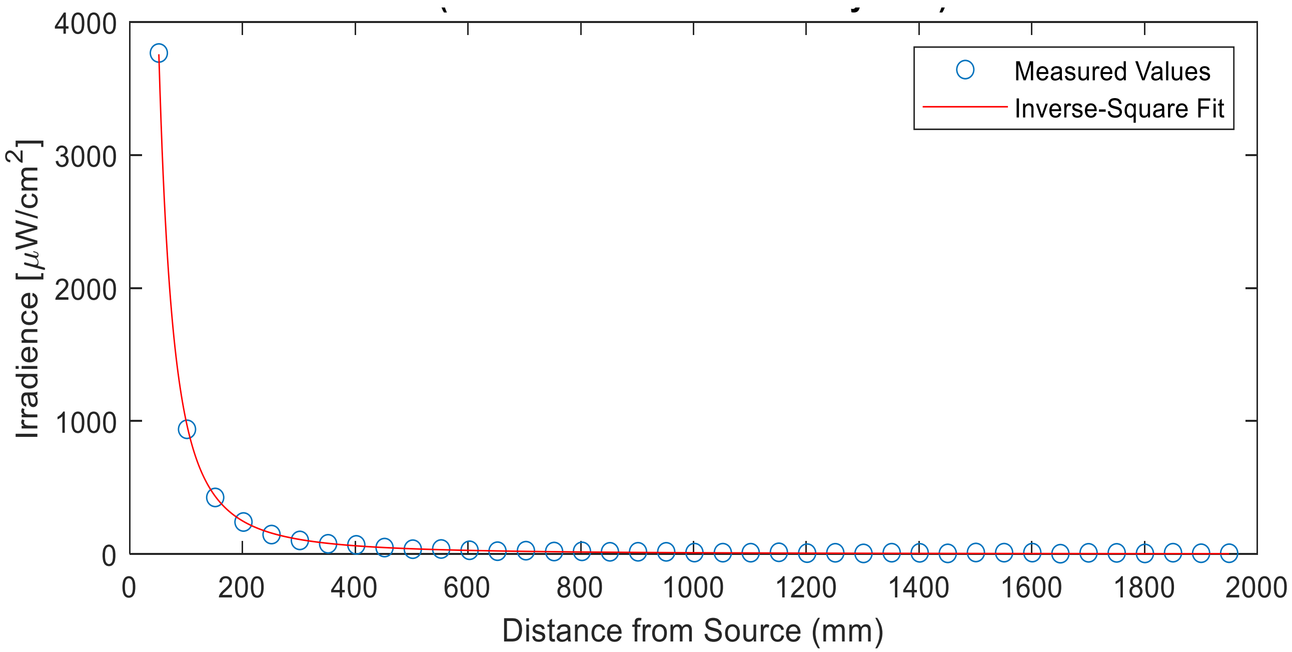


Possible Distances and Angles of Personnel Locations

- Distances/angles of concern (cont'd)
  - Orange triangle = Operator travel to blast area to assess conventional removal operations cleanliness
  - Other triangles = normal operator position or passers-by at those stations.
- Used MasterCam and Robotmaster to program robotics to measure stray radiation at ~all angles/distances (video)

Challenge Addressed: Safety Analysis

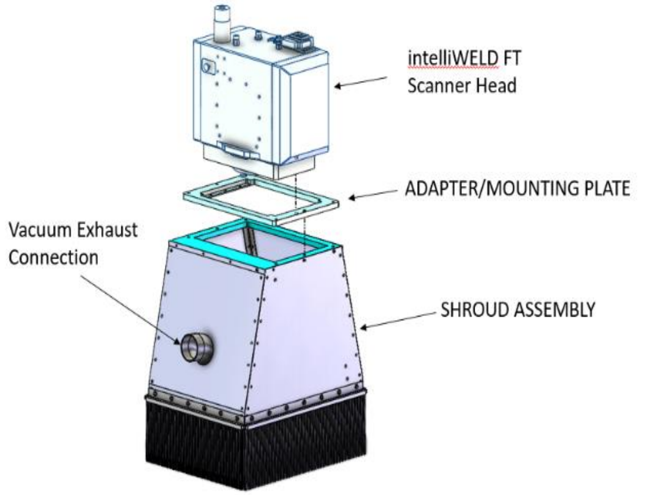
- Found maximum expected personnel exposure levels to be well below danger threshold (~5 mW/cm^2), even at distances near the LA process
  - Exposure levels decrease by a factor of 4 when doubling the observation distance
- Only region deemed to be hazardous for personnel is effectively within the bounds of the LA system (200 mm or less), where processing occurs
  - Includes the space below the scanner body and above the substrate being processed
    - Open beam could burn one's skin
    - Direct viewing into the scanner optics or the LA process itself could injure one's eyes (e.g., cause blindness if receiving levels exceeding the MPE threshold).



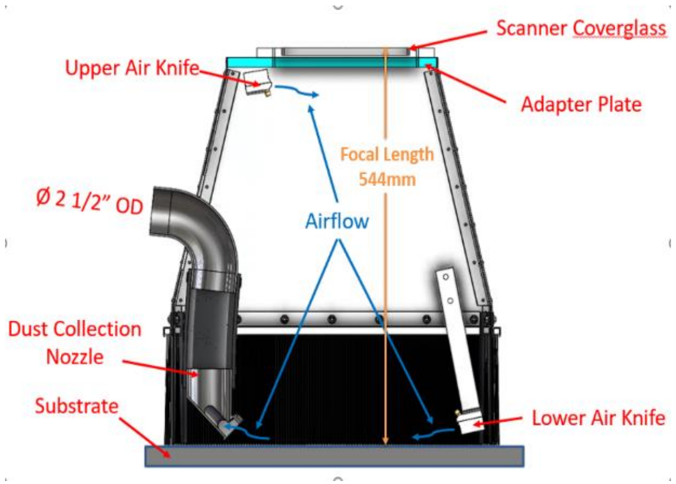
Spectral Response over Distance at 45°° Elevation above Y-axis

Challenge Addressed: Safety Analysis

- Completed NSRP project focused on mitigating ocular hazards of PSU/ARL system
    - Very low levels of radiation were present in all personnel locations (on HSLA steel)
    - Concerns still existed with:
        - More reflective substrates
        - Maintenance activities requiring close proximity (<200 mm) to beam impingement area
    - Designed, built, installed conceptual shroud for additional protection for more reflective surfaces.
        - Measurements outside the brushes showed an 8-fold reduction in radiation by the double layer bristles and laser blocking fabric.



Shroud Concept



Auxiliary Components

Shroud Integrated with Laser Scanner/Robotics

Next Steps

- Near-Term Milestones to be Addressed
  - Complete preliminary testing and analysis
  - Process and test qualification specimens
  - Conduct Cost Benefit Analysis
- Technical Progress to be Accomplished
  - Evaluate preliminary fatigue testing and finalize process parameters for qualification
  - Gather current material and process data at shipyard to develop more current return on investment
- Risk Reduction Items to be Addressed
  - Continue communication with fatigue vendor
  - Continue early investigation of best means to implement in the facility (e.g., equipment logistics)

Acknowledgements

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