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NSRP | National Shipbuilding Research Program

# Laser Ablation Surface Preparation and Hazard Evaluation

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NATIONAL SHIPBUILDING RESEARCH PROGRAM™
Taking Shipbuilding and Repair to the Next Level



PennState
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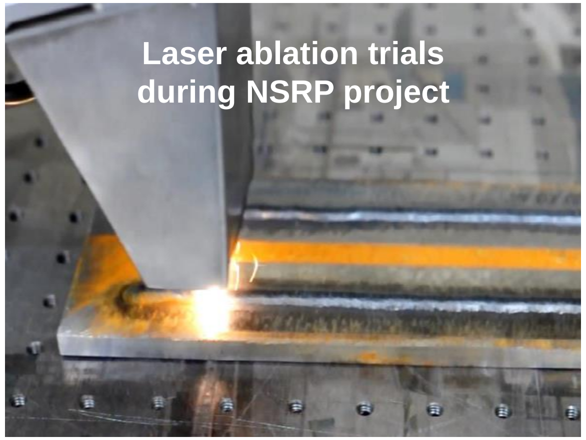
# Today's Presentation

- 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.*

# Project Approach: iMAST & *NSRP*

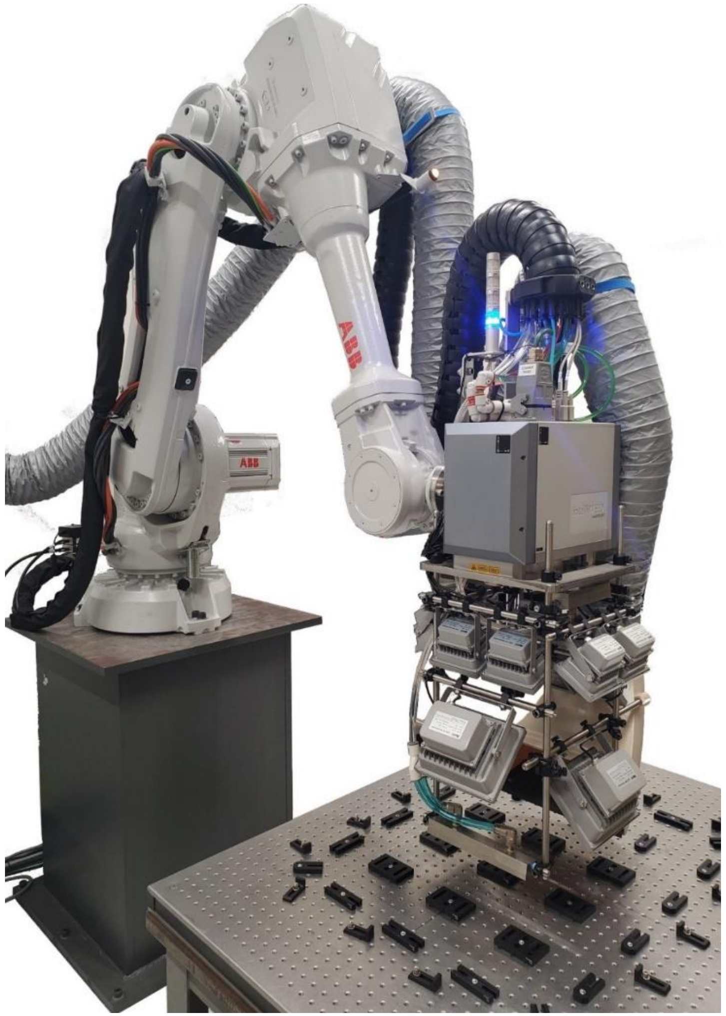
- Phase 1: Equipment Procurement, Process Evaluations & Testing
  - Evaluate SPF Flow vs. LA equipment capabilities — Completed Q2FY19
  - Socialize project ideas — Completed Q4FY20
  - Develop qualification test plan — Completed Q2FY21
  - Outline and initiate procurement plan — Completed Q2FY20
  - 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

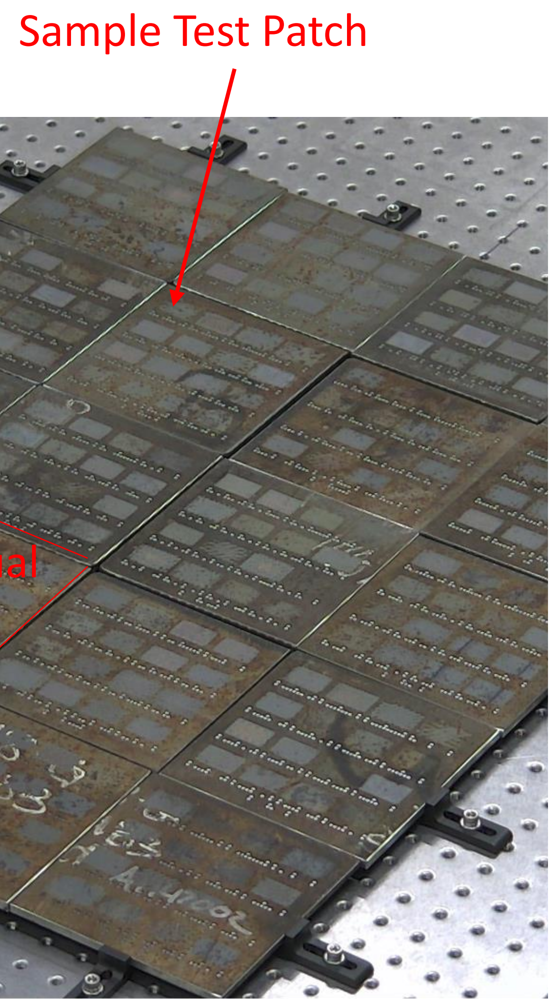
- Designed, built room and integrated LA system
- Completed programming to enable experimental and prototype processing
  - Allows ordered and non-ordered layouts, ID marking, etc. (Removes bias in "patch-based" experiments)
  - Allows user to programmatically vary process parameters
  - Allows generation 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

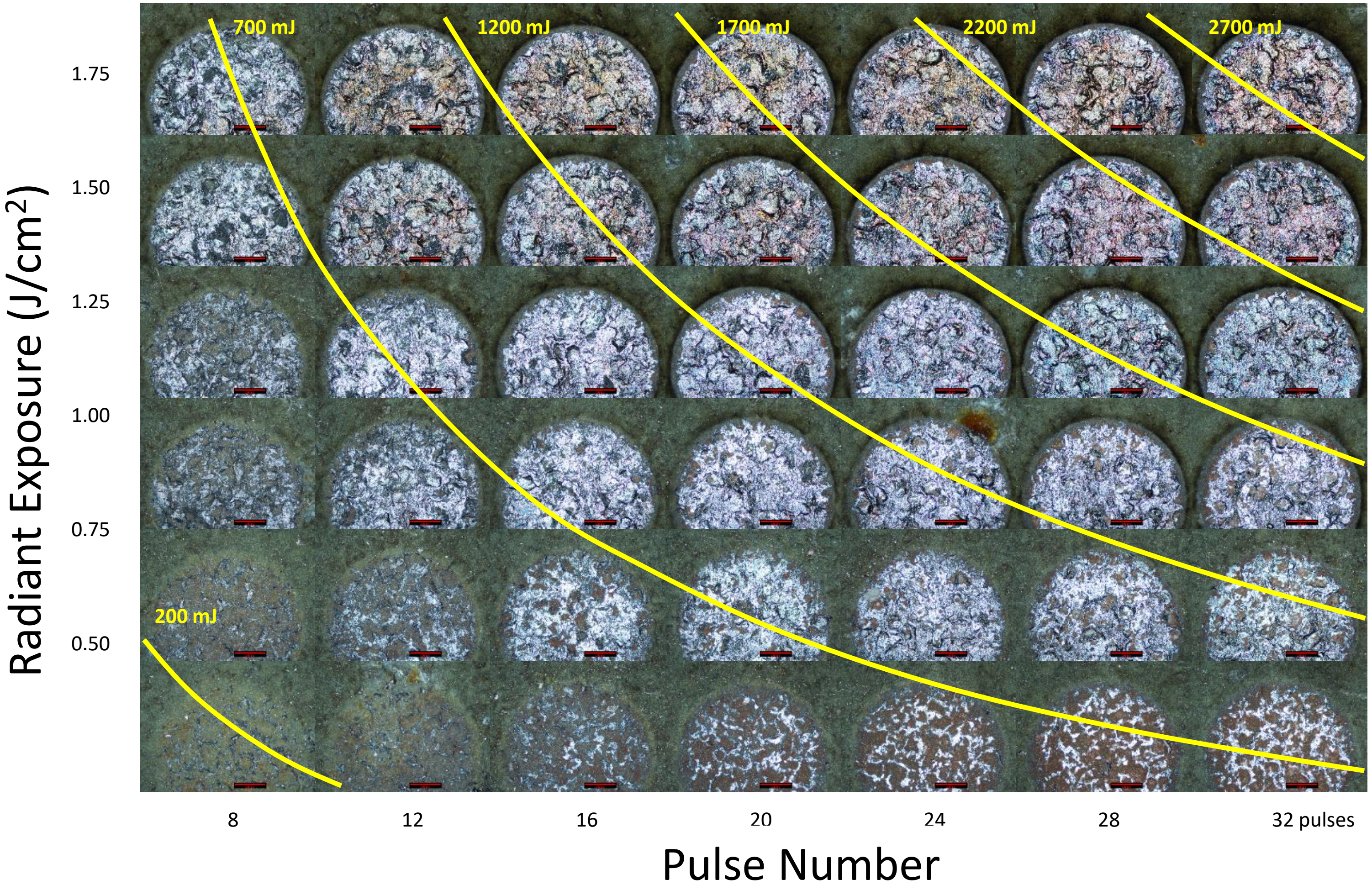
- Conducted 1000+ stripping trials to optimize removal of red and green primer on high strength, low alloy (HSLA) steels
  - Image at right:  DOE 1 = 320 unique parameter sets on 640 test patches
  - Refined parameter development to a few variables, quickly assessed via a Nominal Parameter Array
    - 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

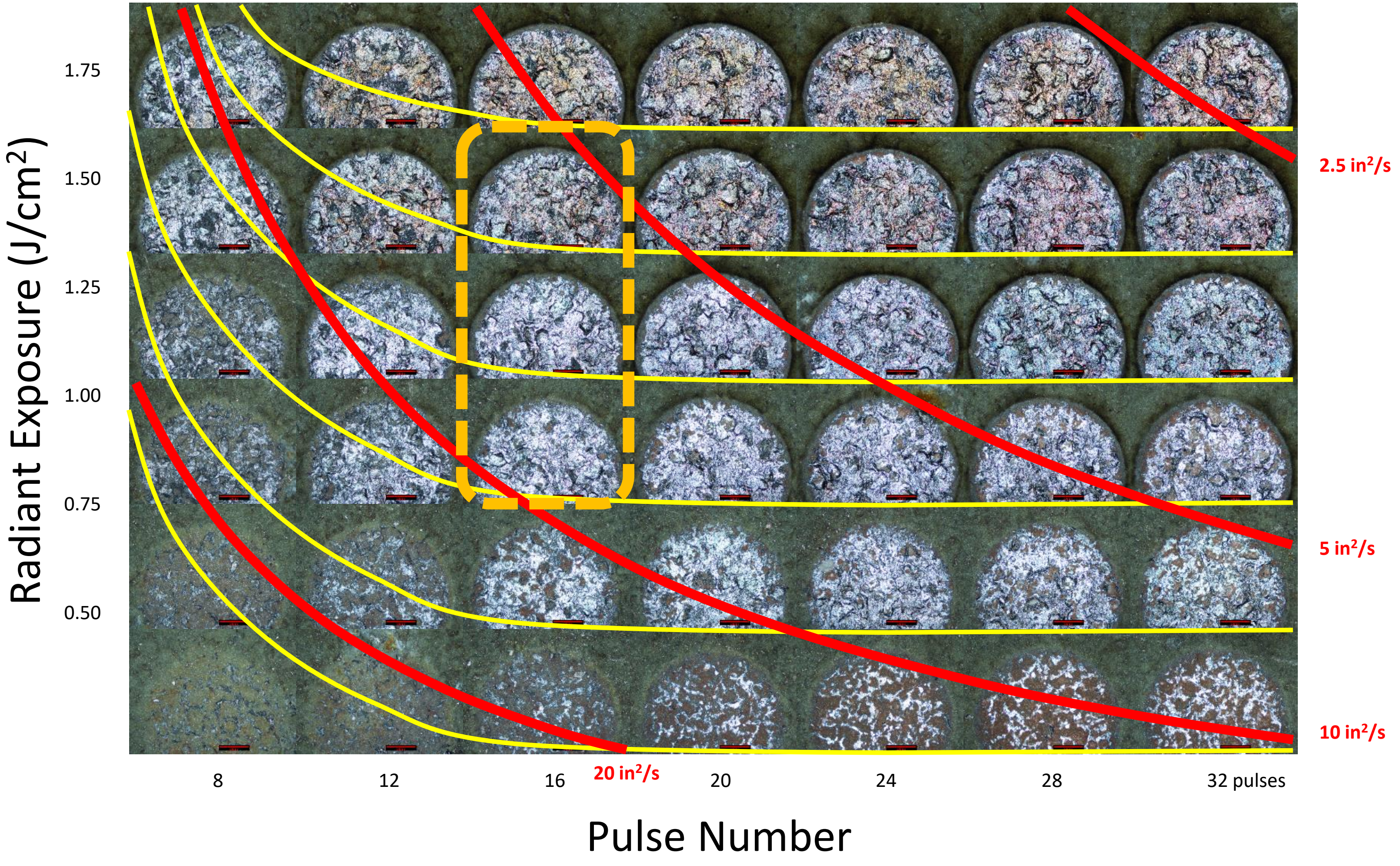
# Multi-parameter Testing: Iso-energy Contours

- 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*

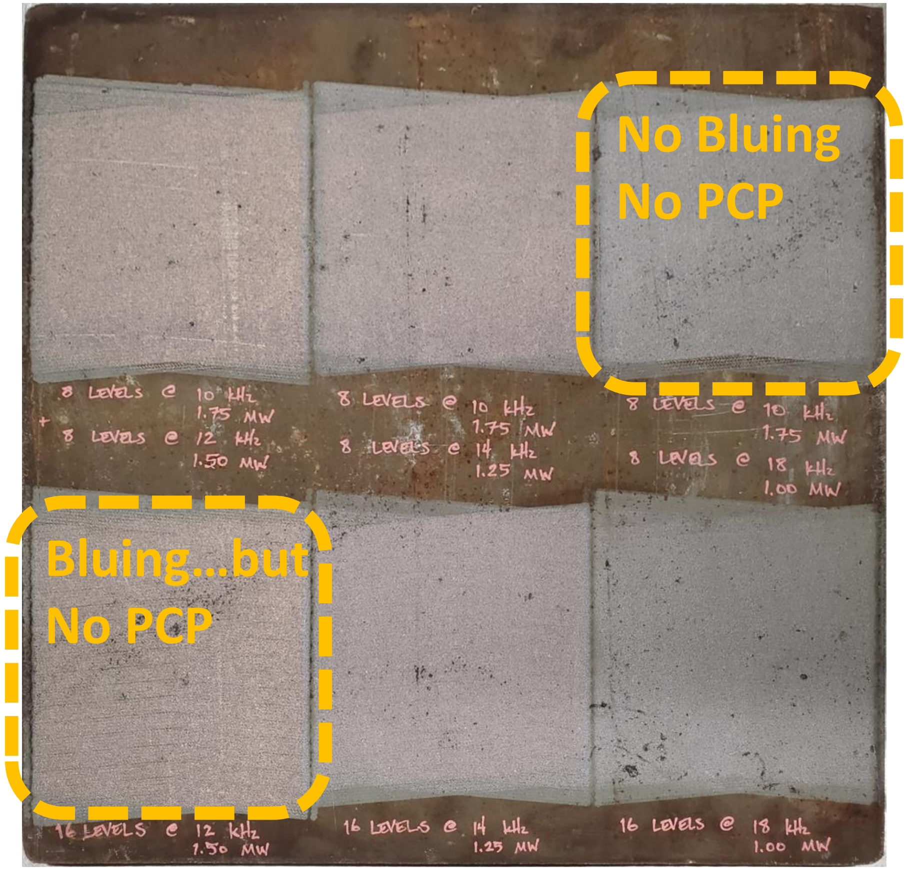


# Multiparameter Testing: Iso-LA & Iso-speed Contours

- 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).



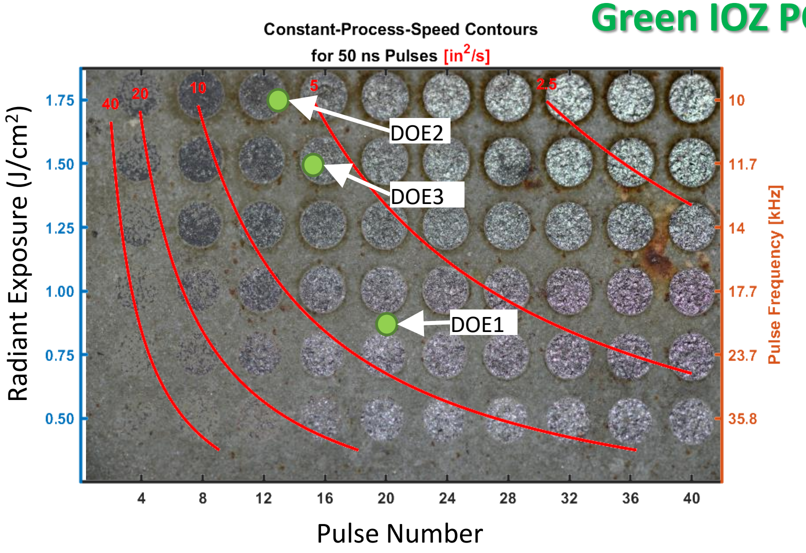
# Multi-parameter Testing: LA and Clean Up



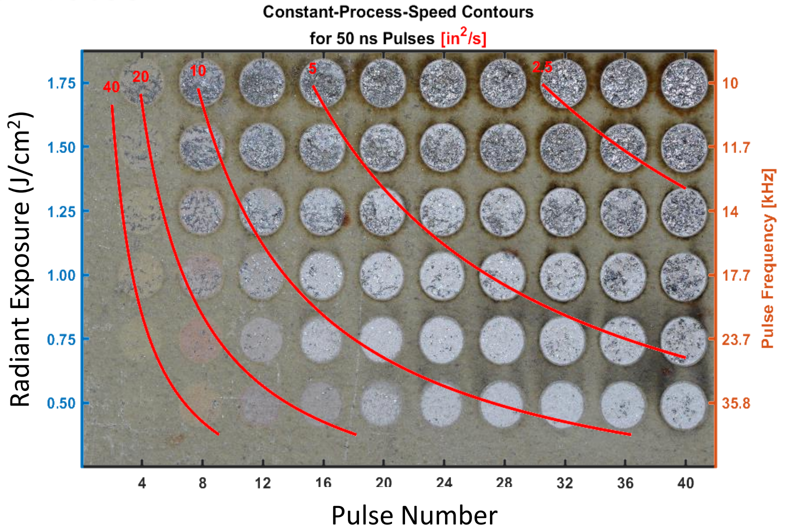

- Best single-parameter set removed primer, but slightly blued the substrate
- Multi-parameter approach removed the primer and the shallow bluing of the substrate
    - Multi-parameter approach initially “hit harder”, but fewer times; followed with softer hits

# Challenges: Weathered vs. Unweathered Paint

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

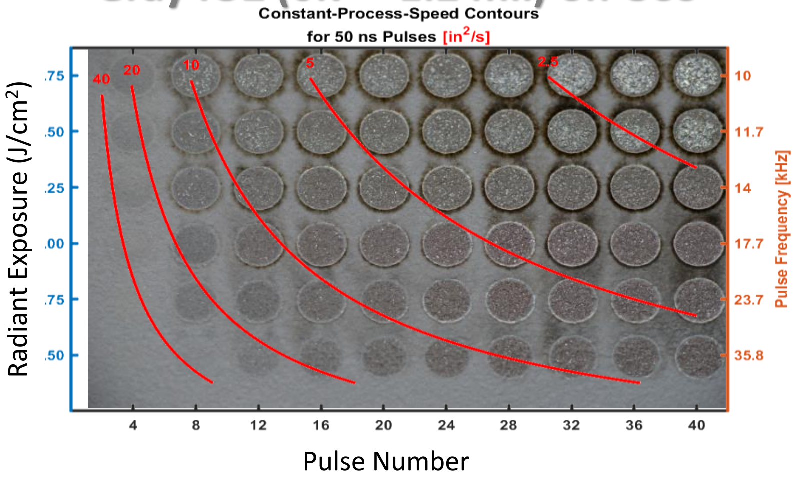



Weathered Green: Consistent Ablation



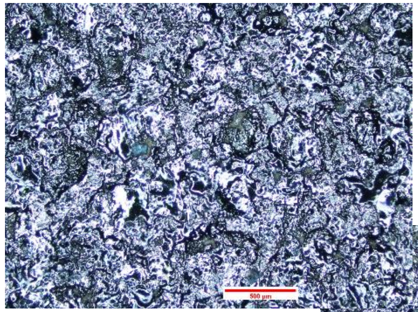

Newly applied green: Inconsistent / Patchy Ablation

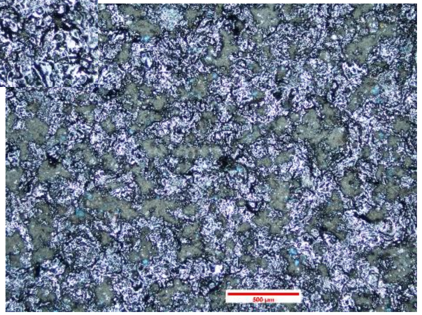
## Gray IOZ (0.7 – 1.2 mil) on OSS




Newly applied gray: Incomplete ablation at uppermost energy density

Weathered Green: Consistent ablation





Unweathered Green: Inconsistent ablation

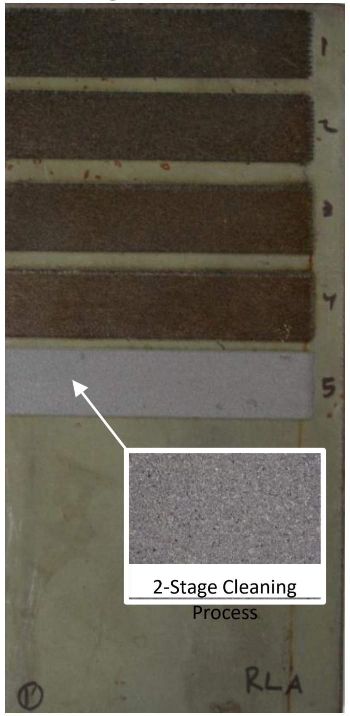
# Coating Removal Successes and Challenges

- **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

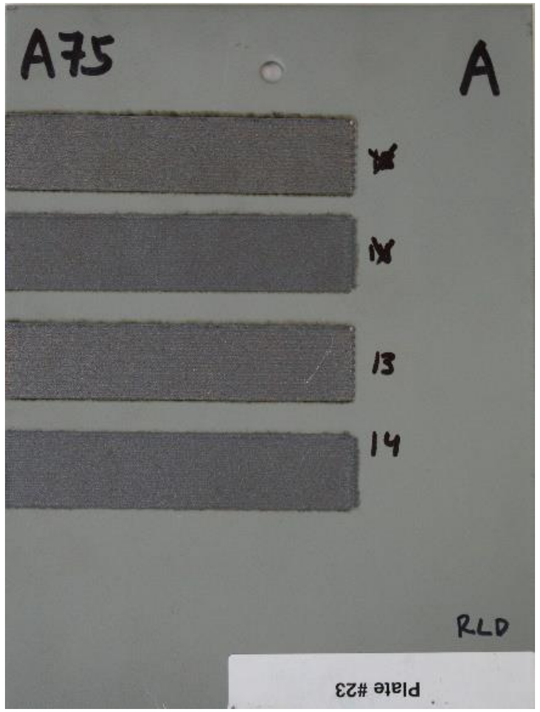
# Challenges Addressed: Experiments at IPG

- 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)

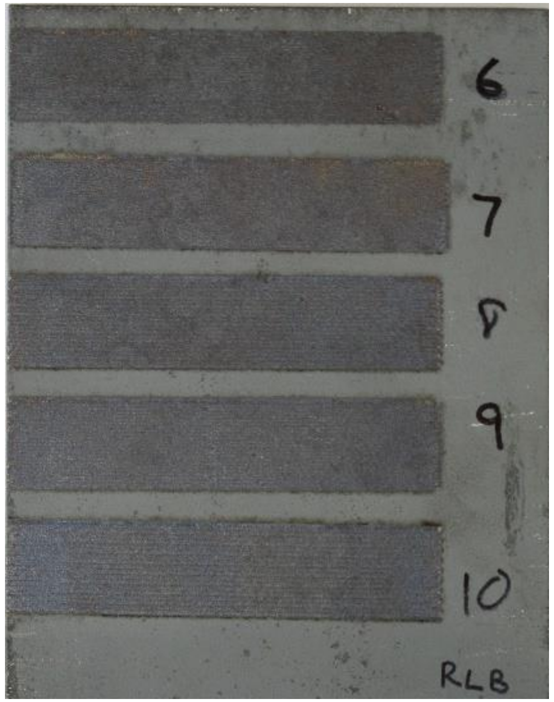
HSLA steel w/ Aged IOZ Primer




Ordinary Strength Steel (OSS) w/ Gray IOZ PCP




HSLA steel w/ Gray IOZ PCP

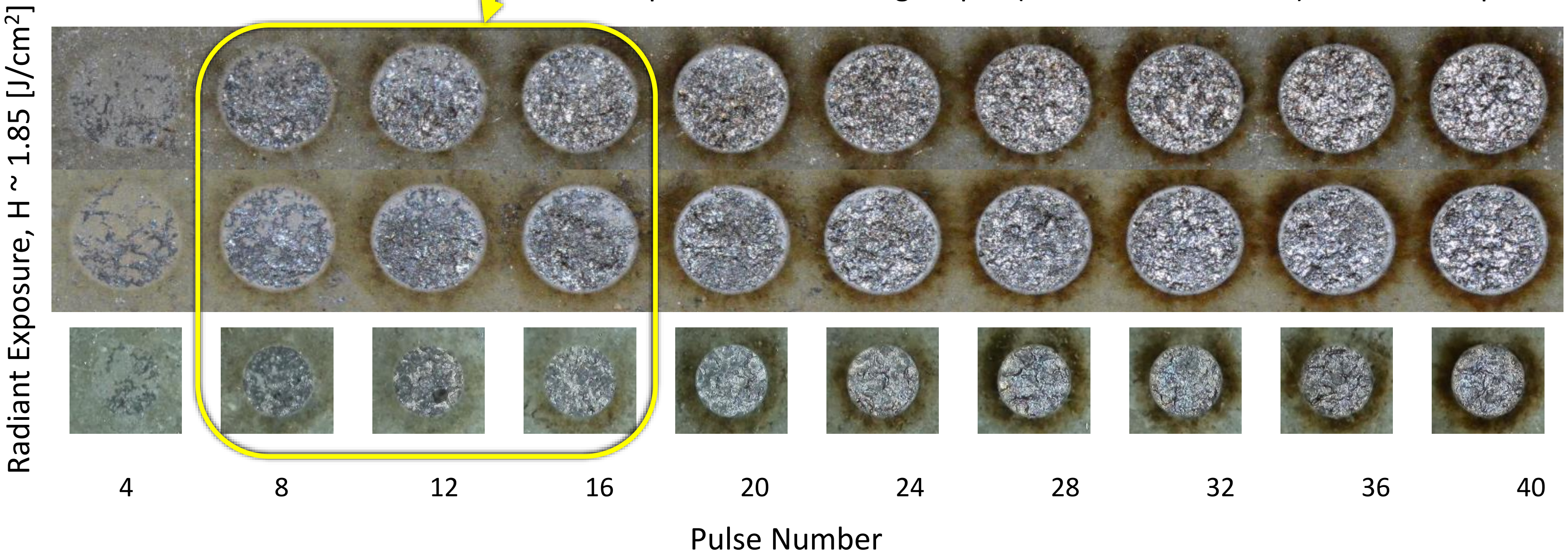



| Optimal Conditions | Setting | Pulse to Pulse Overlap | Hatch Overlap | # of Passes | Zinc Remaining |
|---|---|---|---|---|---|
| All Primers & Steel Types | 872W | 85 | 30% | 2 | |
| | 600W | 75 | 75% | 1 | 0% |

# Challenges Addressed: A New Optic

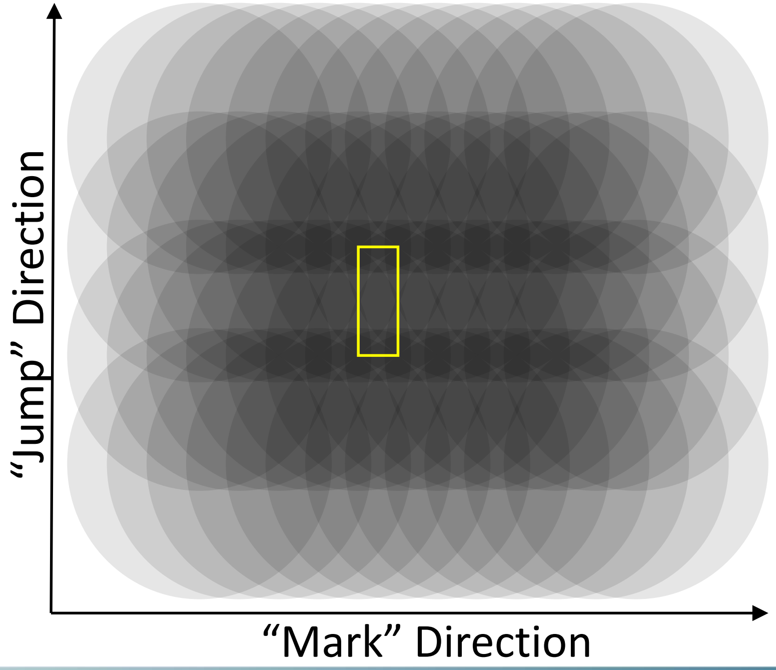
- Achieved smaller spot size (thus increased energy density) with new optic
  - Conducted trials at a fixed radiant exposure (H) vs. pulse number (P) at a fixed pulse duration (τ = 50 ns), and spot size (D = 1.6 mm)
  - Degree of remaining trace PCP appeared to be equivalent, and independent of spot 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]

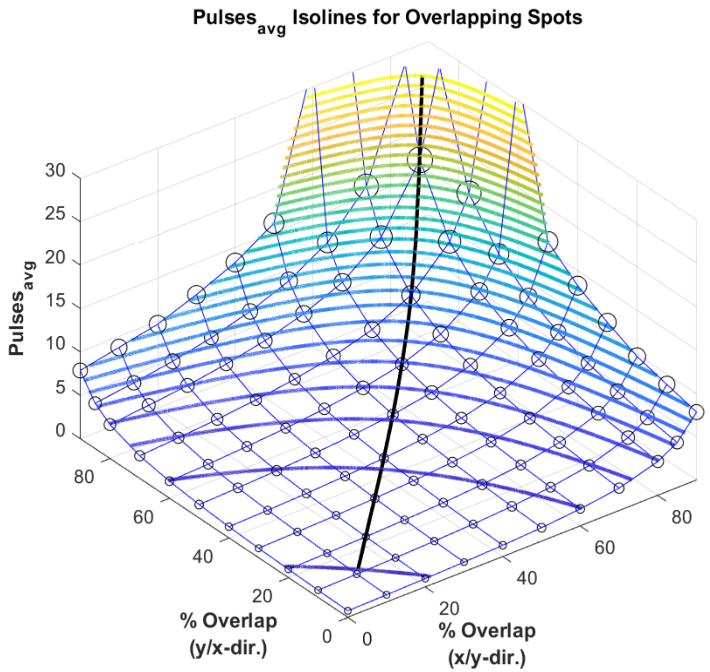
“Best” parameters for larger spot (insufficient ablation) vs. smaller spot size



# Challenges Addressed: Image Analysis

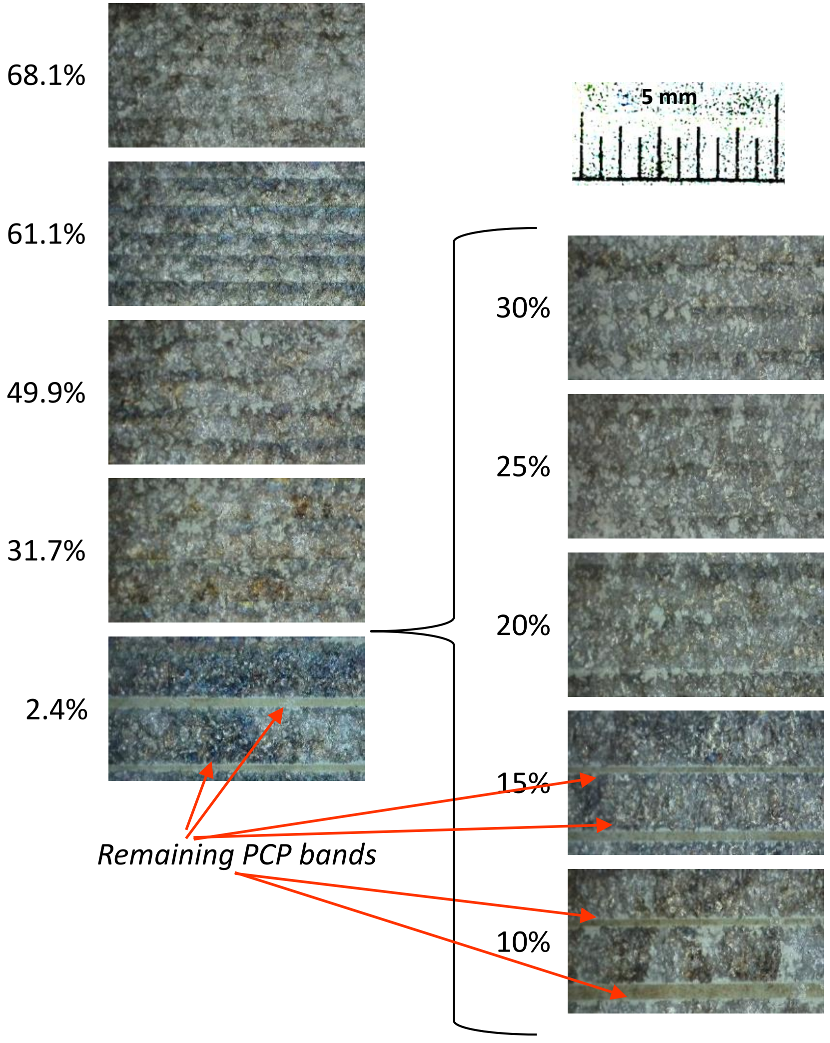
- Used image analysis to estimate average number of pulses
- Average Pulse Number drives strip rate
  - Image processing (below) for $P_{avg} = 0$ to 30 is sufficient for ablation of PCP on HSLA
  - $P_{avg} > 30$ is overly sensitive to changes in % Overlap.
- Changes in jump direction affect LA rate 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

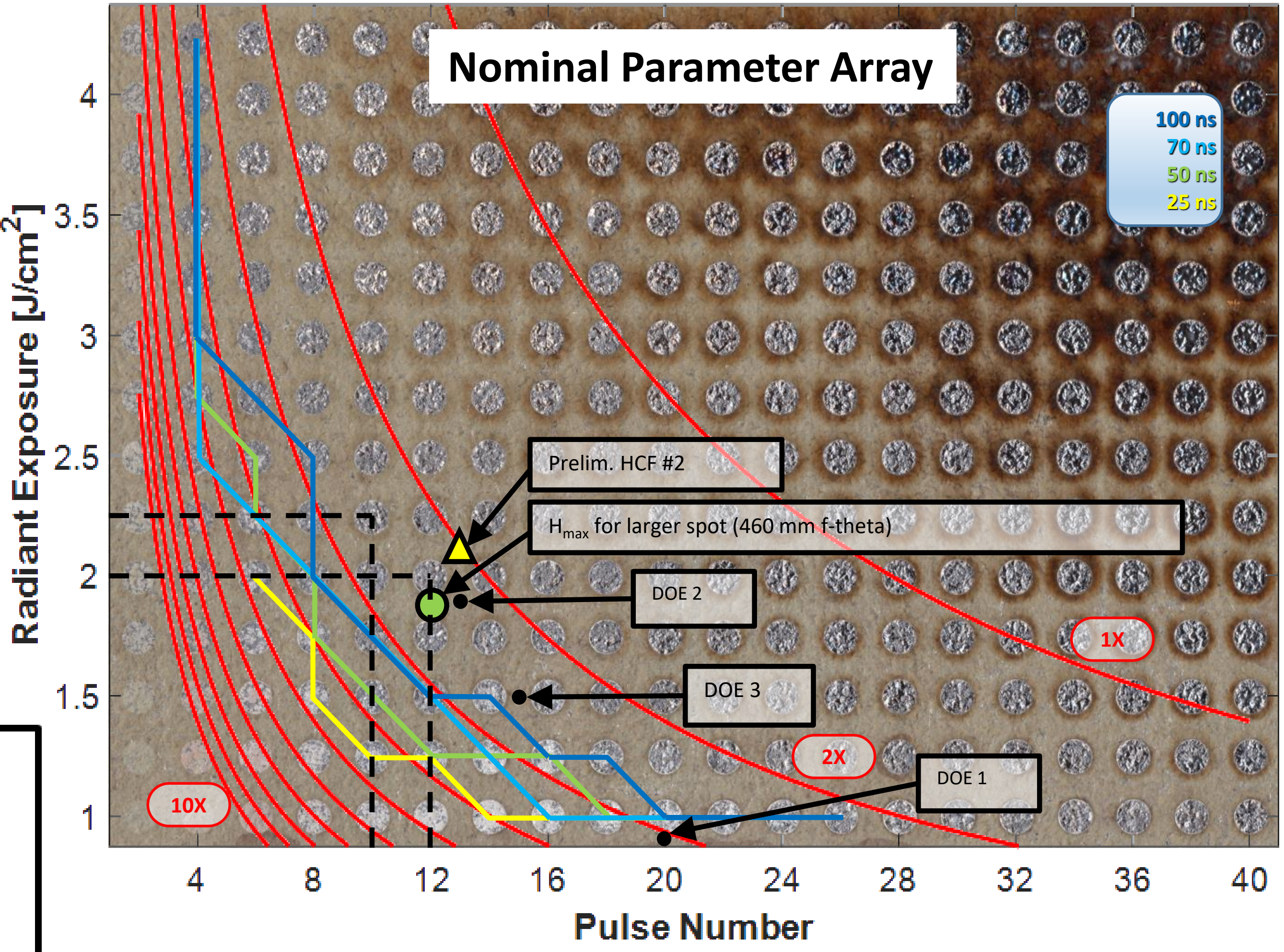
- Continued experimentation to develop optimal processing rate for LA with new lens
  - Trialed 25, 50, 70 and 100 ns (sample experiment image below [100 ns] with findings of DOEs 1-3 overlaid)
  - Red curves indicate maximum possible processing rates compared to estimated baseline grit blast rate (2.5 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] |

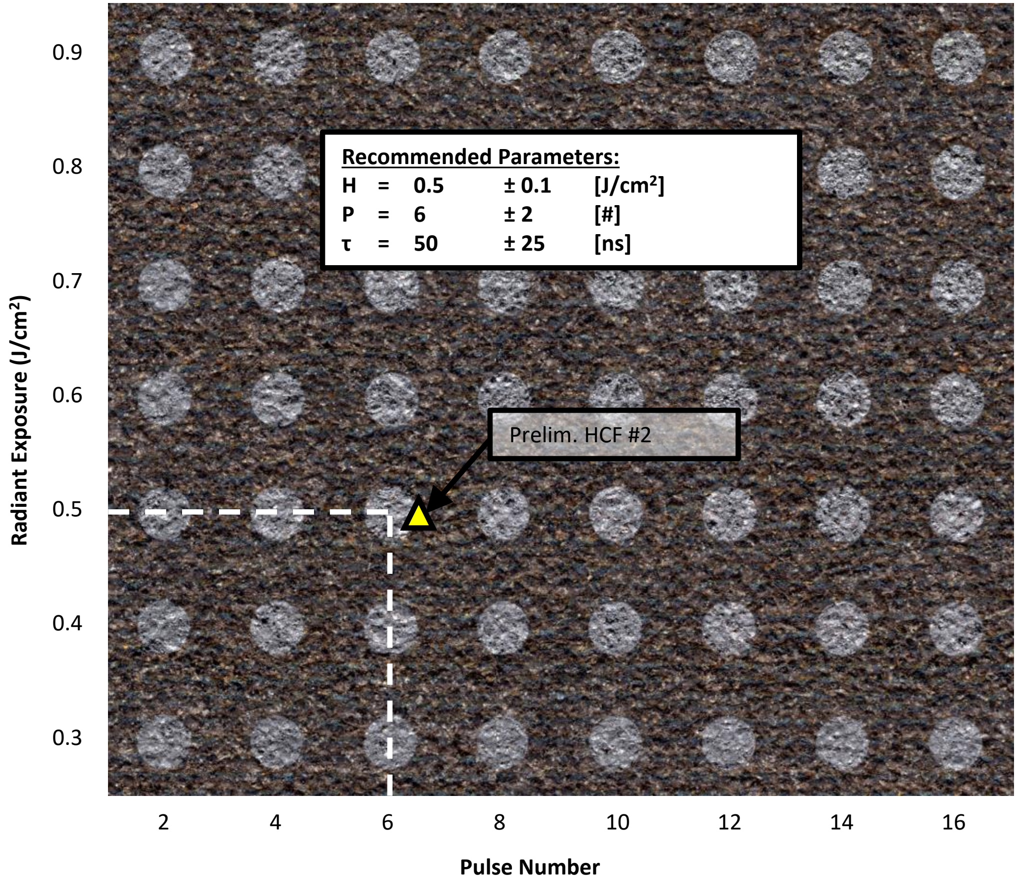


# Challenges Addressed: Clean-Up

- 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



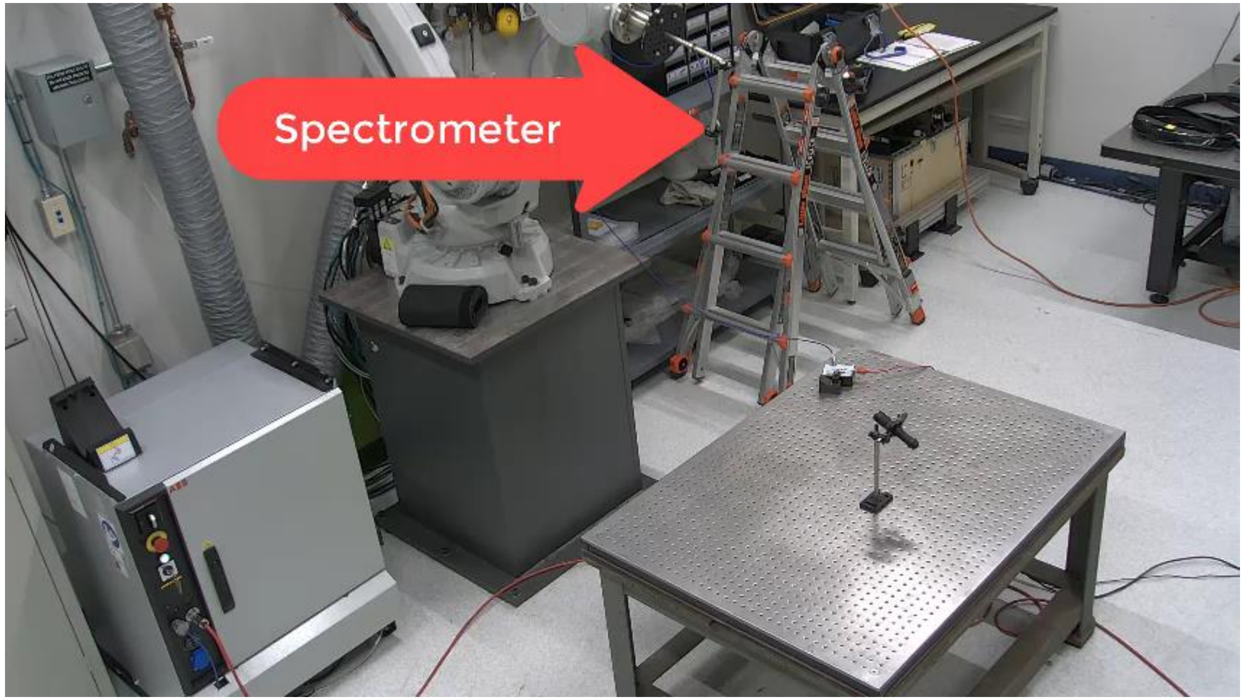

**Sample "Clean-up" passes *on* H2, P12, τ50**

# 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)*

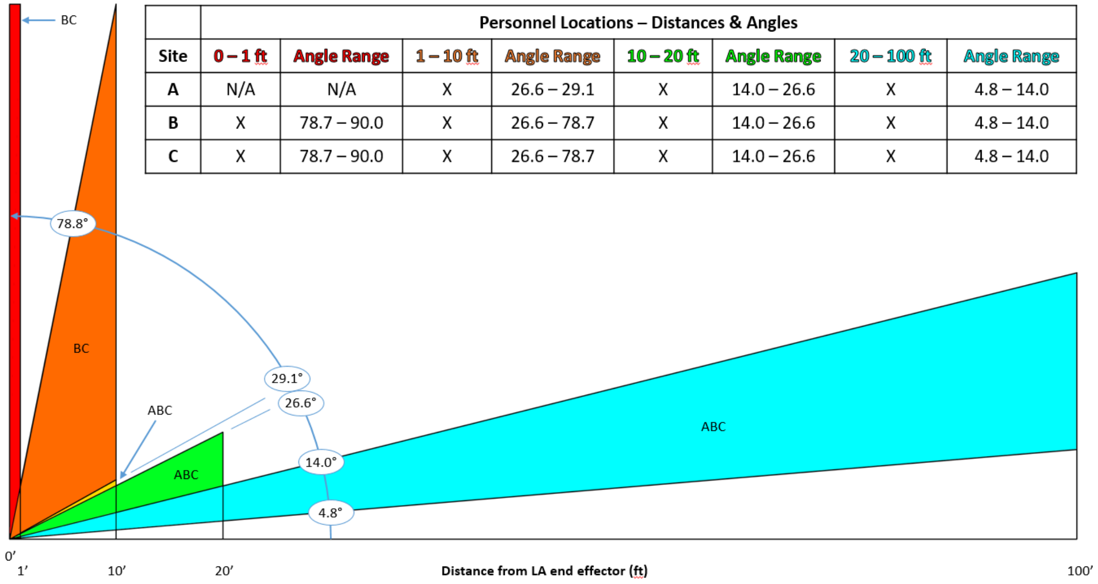
# Challenge Addressed: Safety Analysis

- 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

| Personnel Locations – Distances & Angles | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Site | 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 |

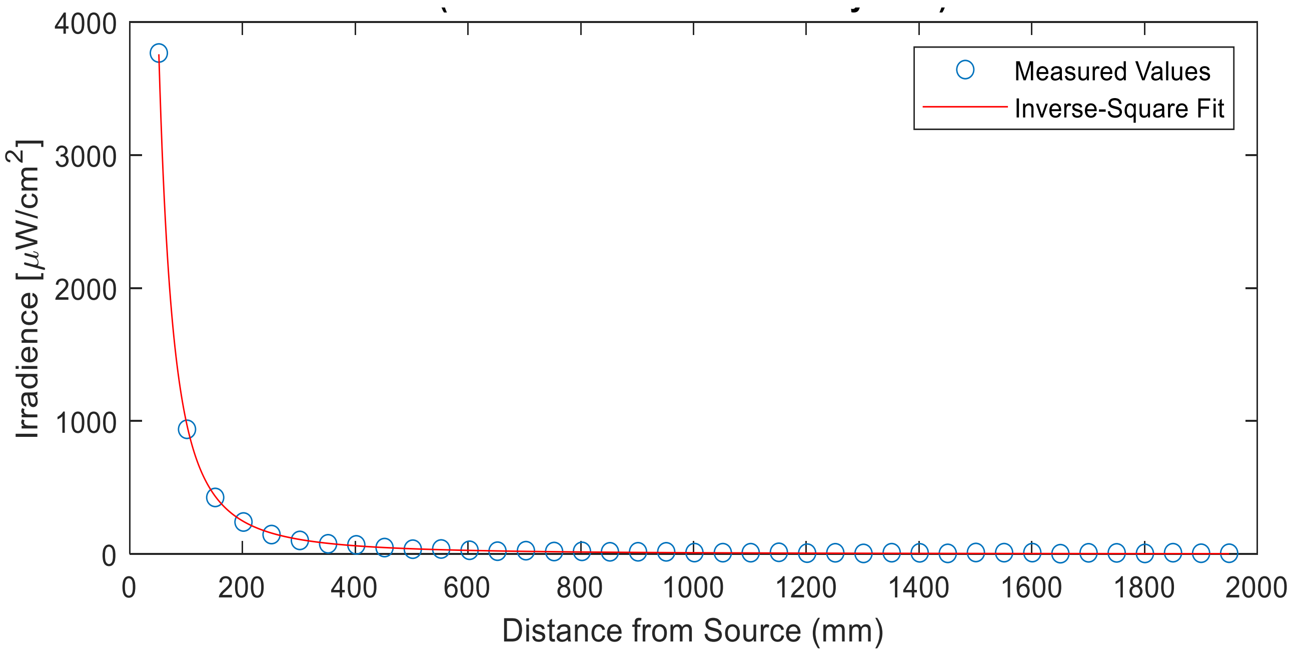



**Possible Distances and Angles of Personnel Locations**

- 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

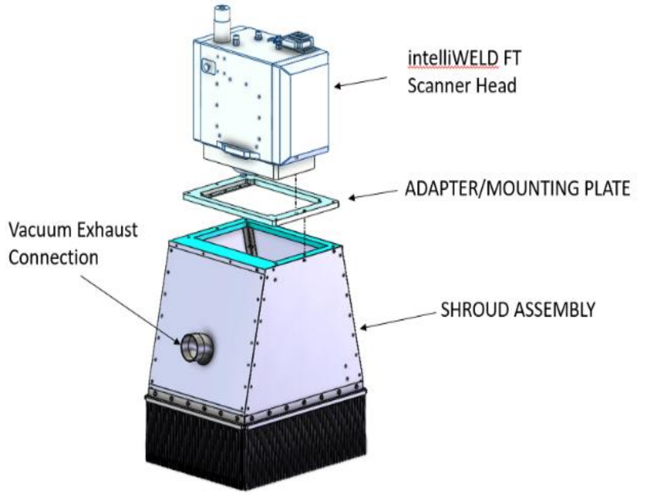
- Found maximum expected personnel exposure levels to be well below danger threshold (~5 mW/cm$^2$), even at distances near the LA process
  - Exposure levels decrease by a factor of 4 when doubling the observation distance
- Only region deemed to be hazardous for personnel is effectively within the 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).



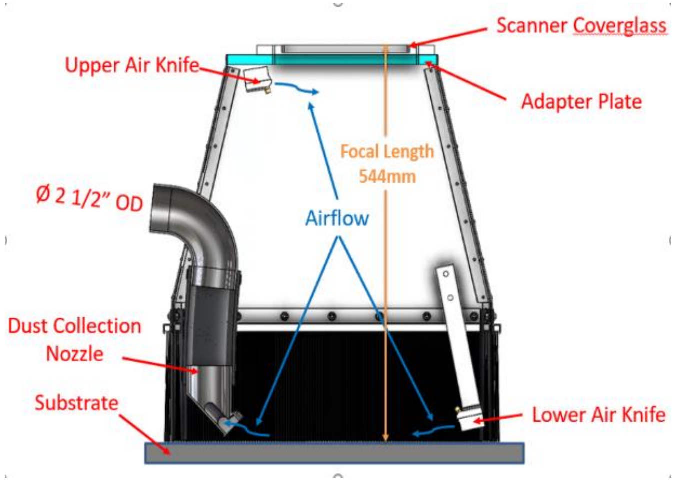

**Spectral Response over Distance at 45°° Elevation above Y-axis**

# 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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