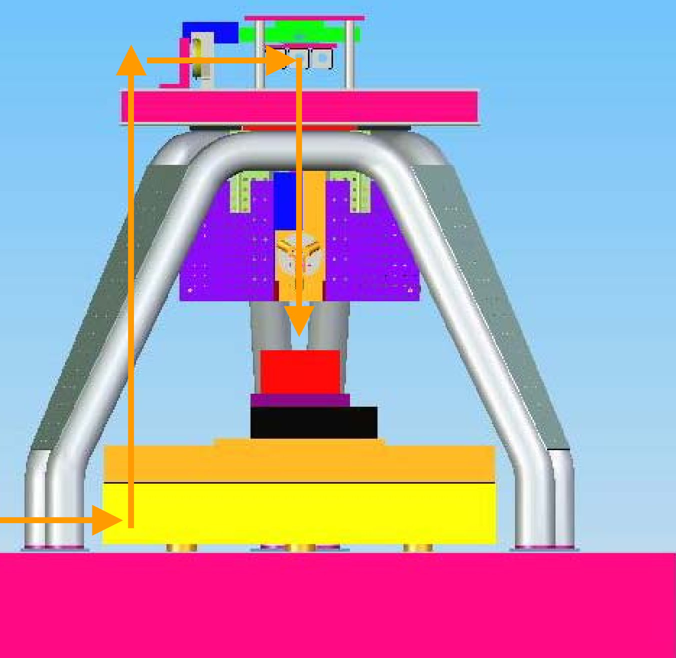
“The Laser Microengineering Experimental Station” at the Jefferson Laboratory Free Electron Laser Facility

Henry Helvajian
The Aerospace Corporation
Los Angeles, California

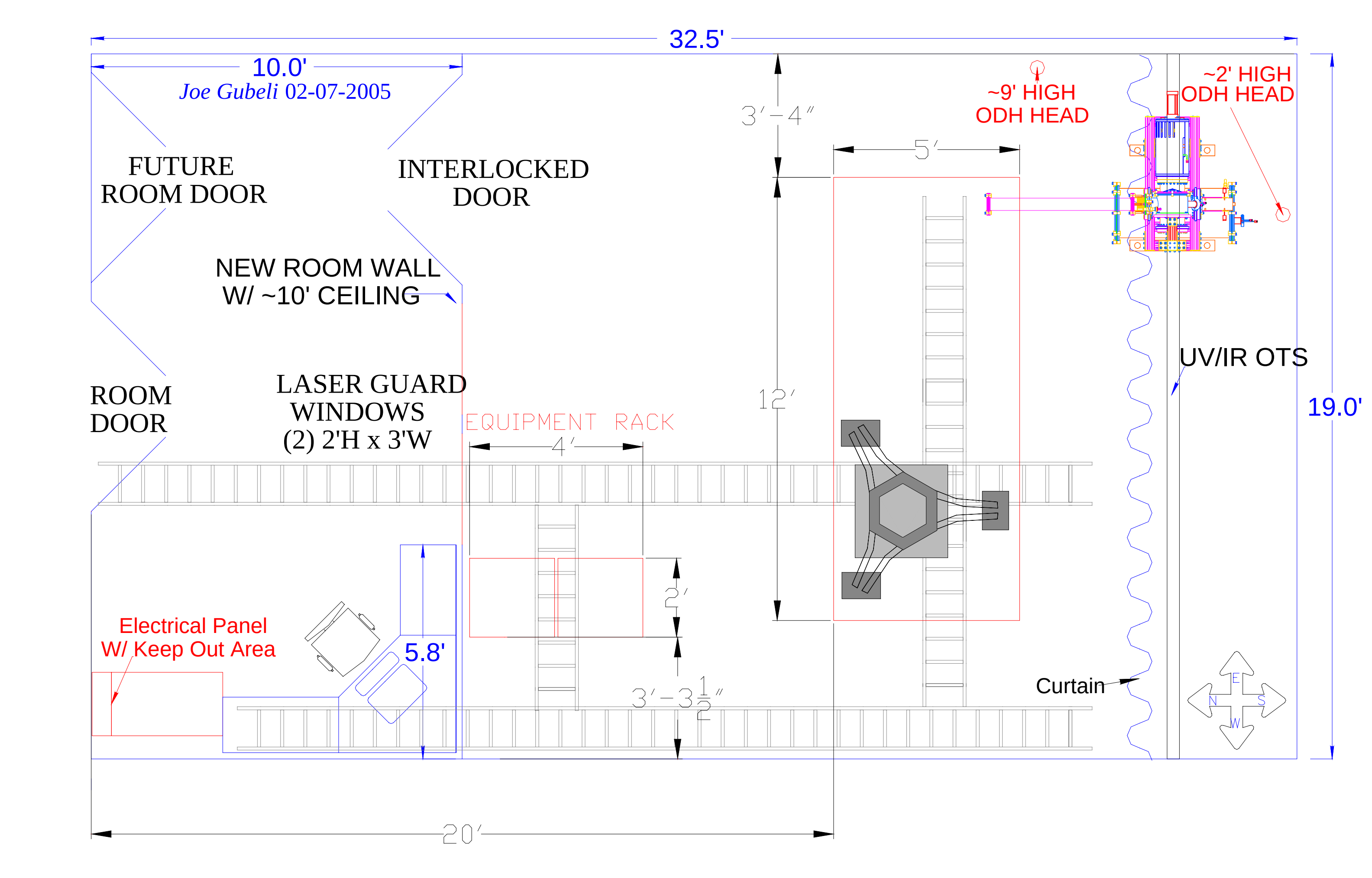


Henry.Helvajian@aero.org
Department of MicroNanotechnology

Proposed Effort

- **Establish a working facility that will enable user-friendly application of the unique FEL properties for investigations in laser microengineering science and laser material processing technology development.**
- **Effort delineated into two segments.**
  - Build
    - an engineering model and process development station at The Aerospace Corporation - called Aerospace-Engineering Model (A-EM)
    - a working model at the Jefferson FEL - called JLAB-working Model (JLAB-WM)
  - Operate
    - transition newly developed laser processes and techniques,
    - conducting fundamental investigations in laser material interaction phenomenon,
    - assisting/guiding new users.

The Laser Microengineering Laboratory at the Jefferson Laboratory FEL Facility



Henry.Helvajian@aero.org
Department of MicroNanotechnology

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Examples of laser microengineering applications

- Multi-color direct-write microfabrication
- Volumetric exposure, multi-photon exposure processing
- Percussion machining, ablative machining
- Polishing
- Chemical vapor deposition (with special cell)
- Crystallization
- Micro-fusing
- Surface texturing
- Investigations Laser Material Interaction Phenomena
- Mass & optical spectroscopy of desorption and ablation
- Mass removal rate measurement
- Pump-probe physics
- Multiple pulse - rep-pulse physics
- Small Scale Pulsed Laser Deposition (PLD)

System Attributes

- A laser beam delivery system for processing in the UV and IR.
- Automated sequencing of tool changes (e.g. color, objective).
- User selects from three focusing objectives.
- A coordinated three-axis motion system, XY motion range of >100mm.
- An optical table with integrated vibration isolation capability.
- An automated means for laser power and repetition rate control.
- A vision system for process control.
- A means for the User to measure the laser spot size & intensity distribution.
- CAD software for solid modeling of patterns.
- CAM software for generating 3 axes tool-path.
- Software for visual verification of the tool-path geometry.
- Software for converting the tool-path geometry into motion language.
- A generic scheme for mounting user supplied sample holders..
- Additional laser beam delivery lines & stations for other experiments.

NASTRAN analysis used in designing optical support superstructure

Solve for lowest weight with first resonant mode > 90 Hz

Henry.Helvajian@aero.org
Department of MicroNanotechnology

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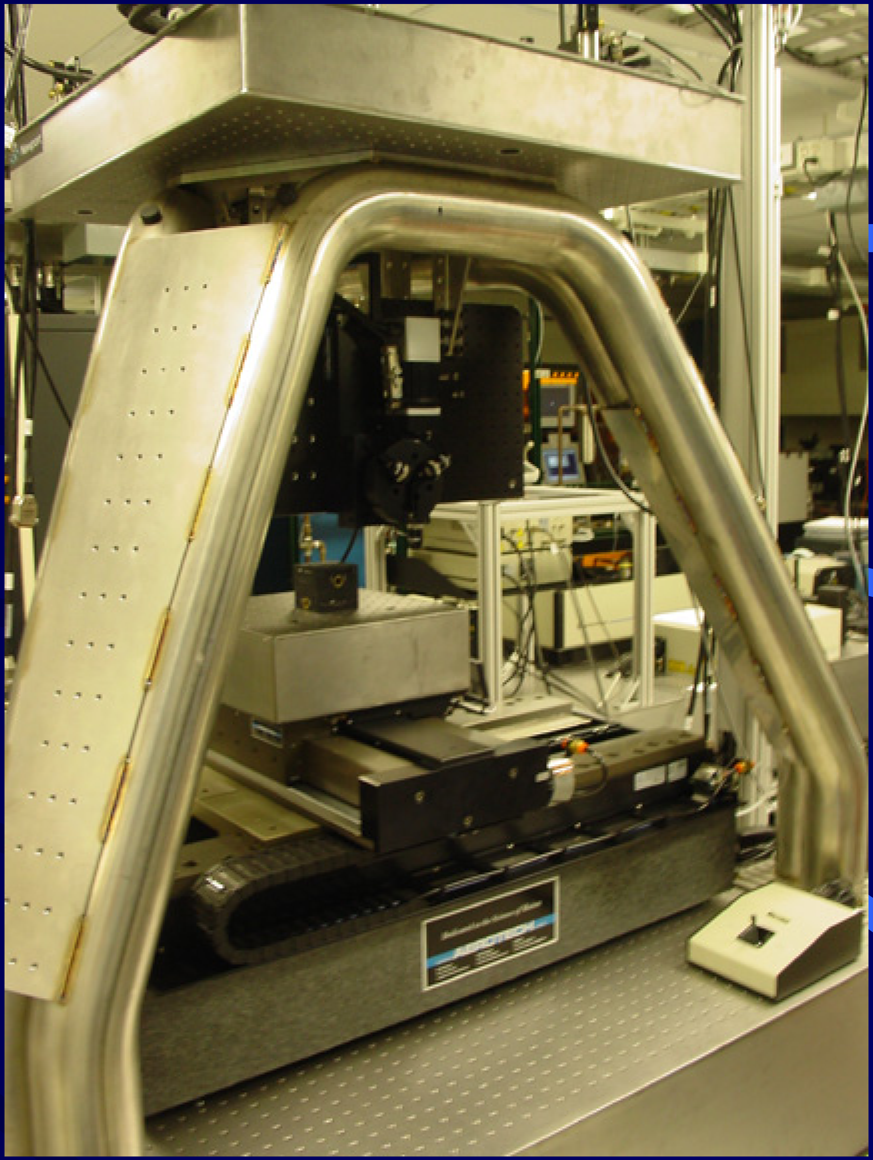
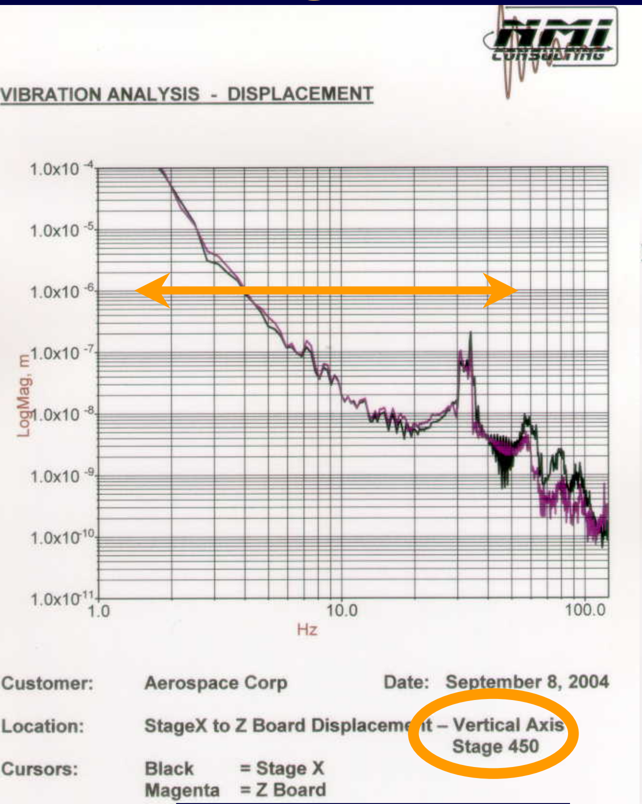
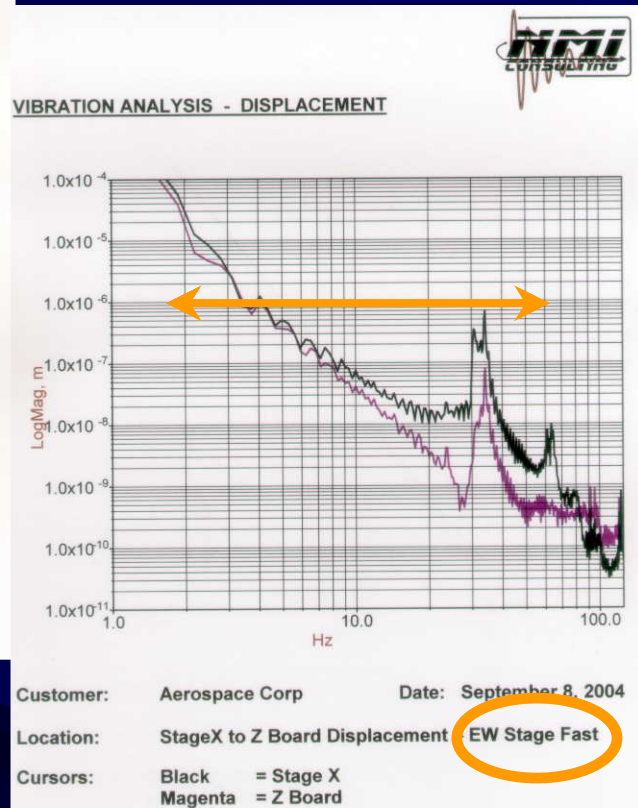
Engineering-Model Status in Overview

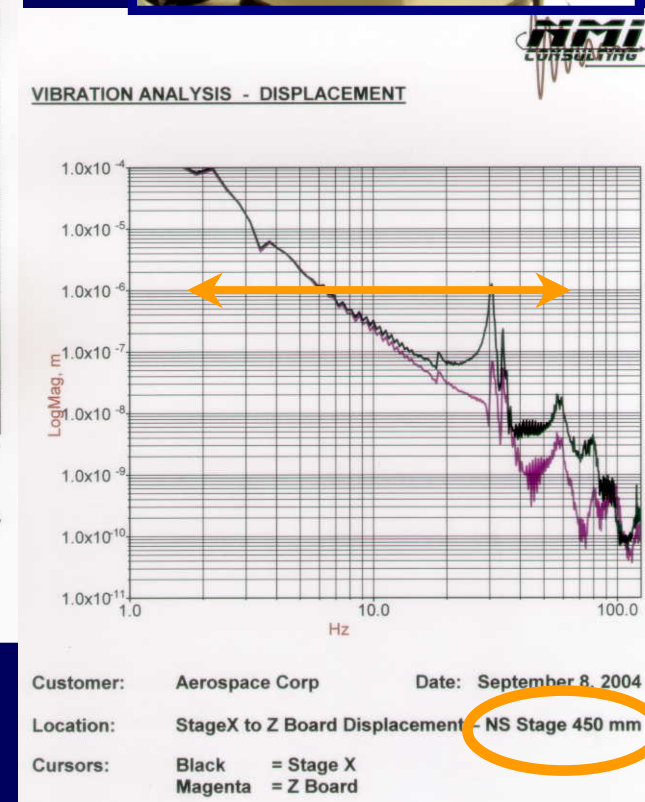
- Engineering model has been operated (have machined parts) on one line (400 nm).
- Velocity Compensation and power control has been demonstrated in laser machining operation.
- Superstructure design has met relative displacement specifications during high speed (>400 mm/sec) patterning.



Measured Displacement of Superstructure and XYZ Stages with Motion: Velocity of 450 mm/sec







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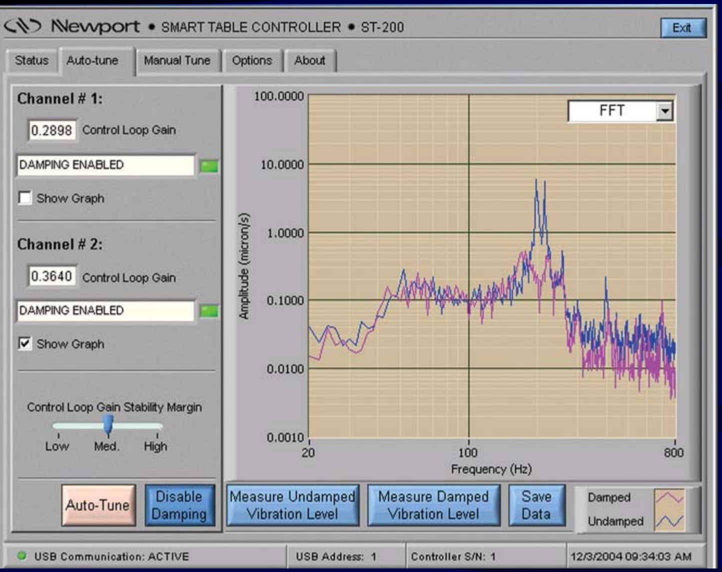
Department of MicroNanotechnology

Vibration Isolation

Optical tables are tuned for one mass distribution



In Micromachining you generate Vibration Noise here

Exploring the use of "embedded" voicecoils & accelerometers to dynamically tune the table > 100Hz.

Pneumatic Isolators work to isolate vibrations coming from the floor

Initial data shows that surface vibrations can be damped in under 200 ms

Henry.Helvajian@aero.org
Department of MicroNanotechnology

JLAB Microengineering User Sofware
The MUSe

Henry.Helvajian@aero.org
Department of MicroNanotechnology

User Interface Computer   Machining Computer

User Interface Computer

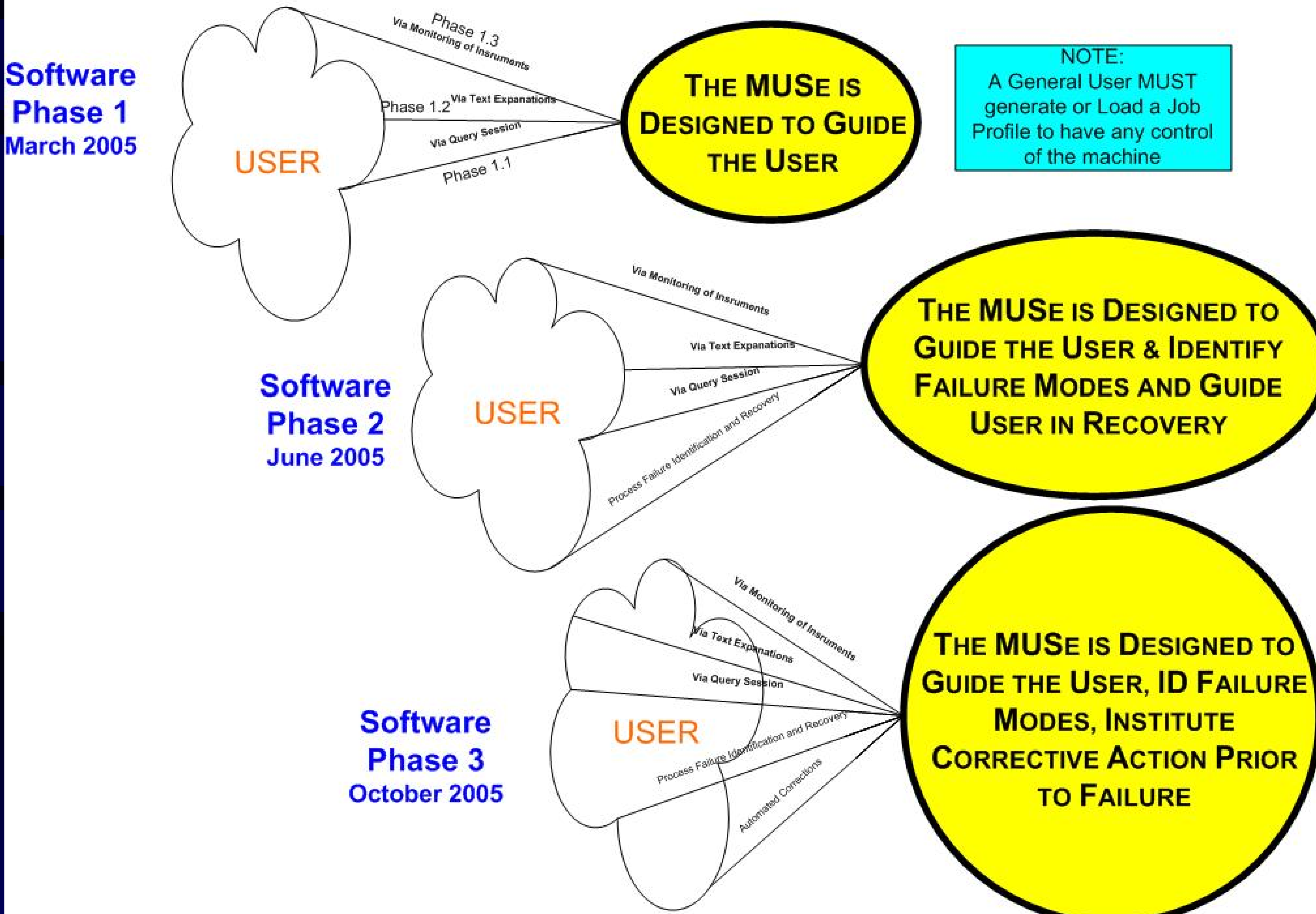
- Labview (MUSe)
- MasterCam (CAM)
- Solidworks (CAD)
- LBA-7 (Laser Beam Profiler)

Machining Computer

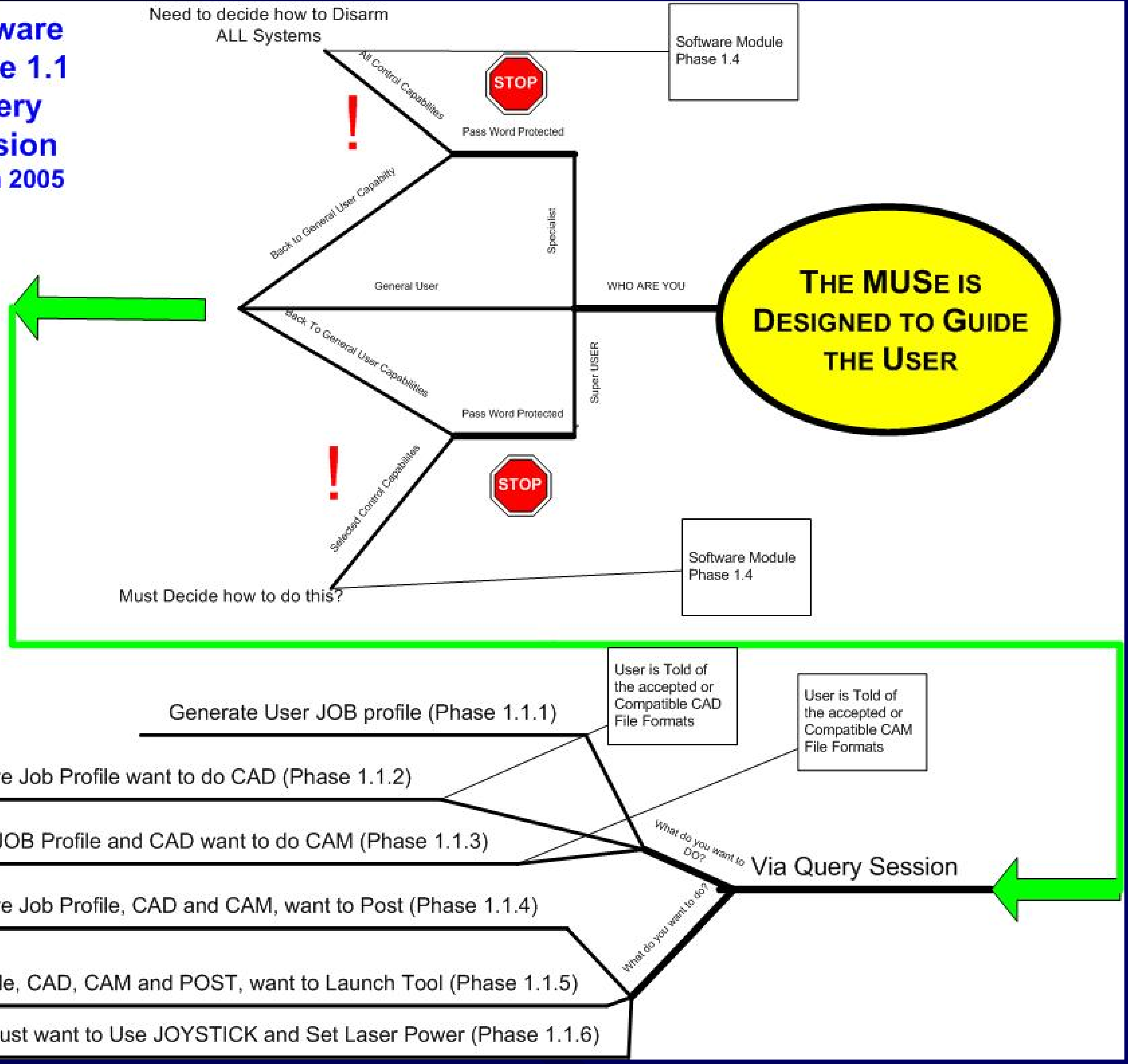
- Labview (MUSe)
- MasterCam (CAM)
- Aerotech 3200 (Motion Control)

Henry.Helvajian@aero.org
Department of MicroNanotechnology

JLAB Microengineering User Software
the JLAB MUSe
Overview



Software Phase 1.1 Query Session March 2005



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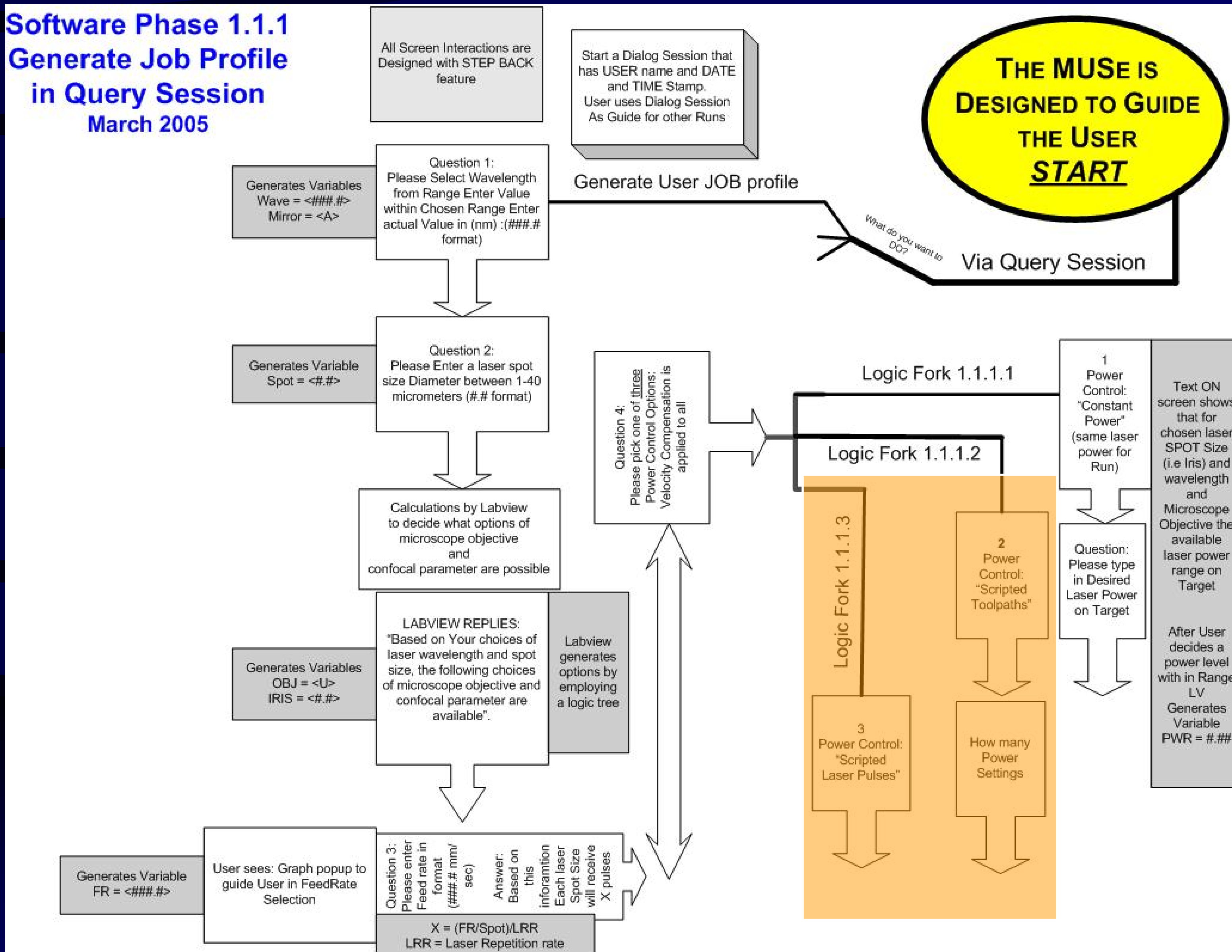
Department of MicroNanotechnology

Software Phase 1.1.1 Generate Job Profile in Query Session

March 2005



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Department of MicroNanotechnology

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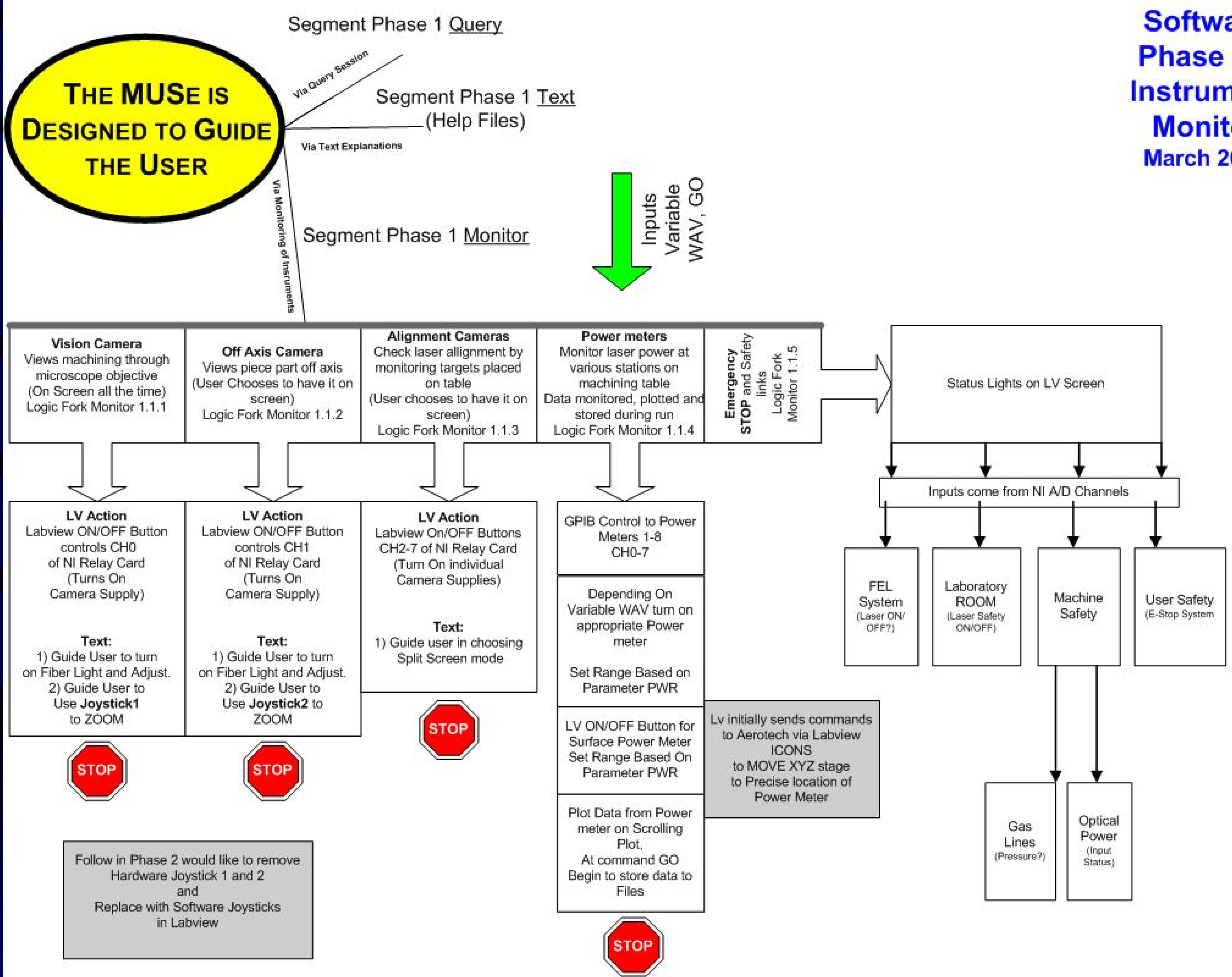
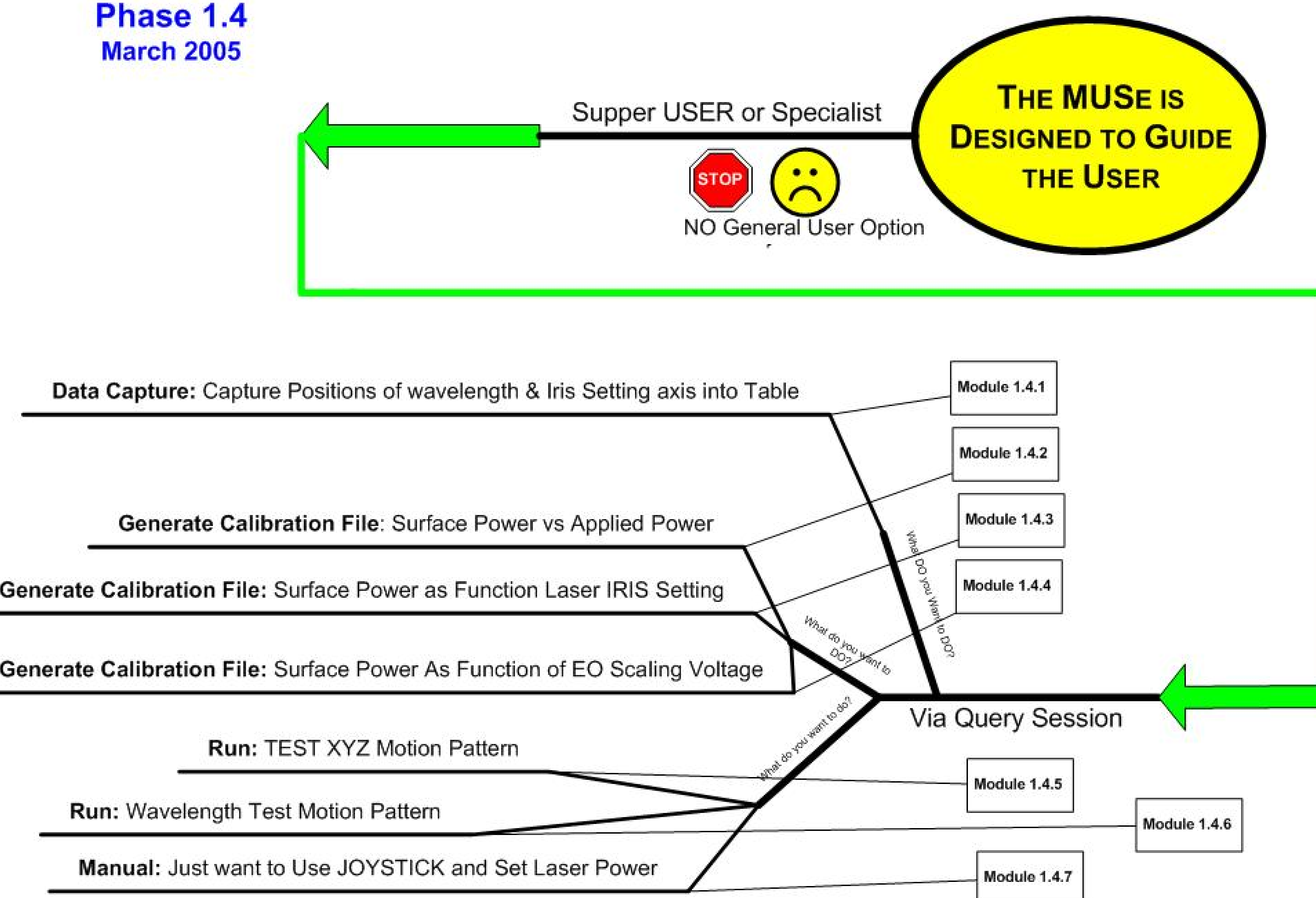
Software Phase 1.3 Instrument Monitor
March 2005



Henry.Helvajian@aero.org
Department of MicroNanotechnology

Super USER or Specialist Control

Software Phase 1.4
March 2005



Henry.Helvajian@aero.org
Department of MicroNanotechnology
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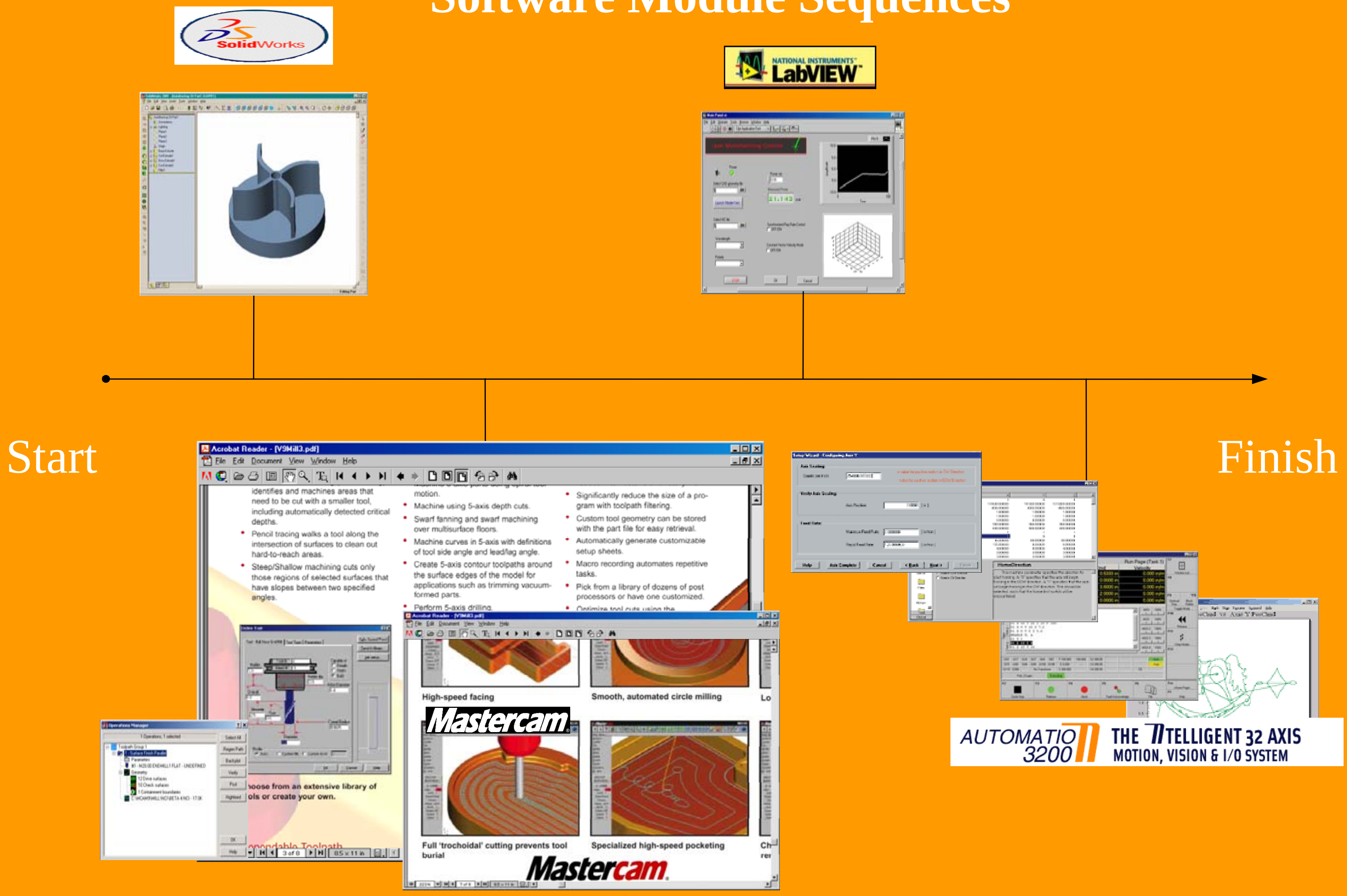
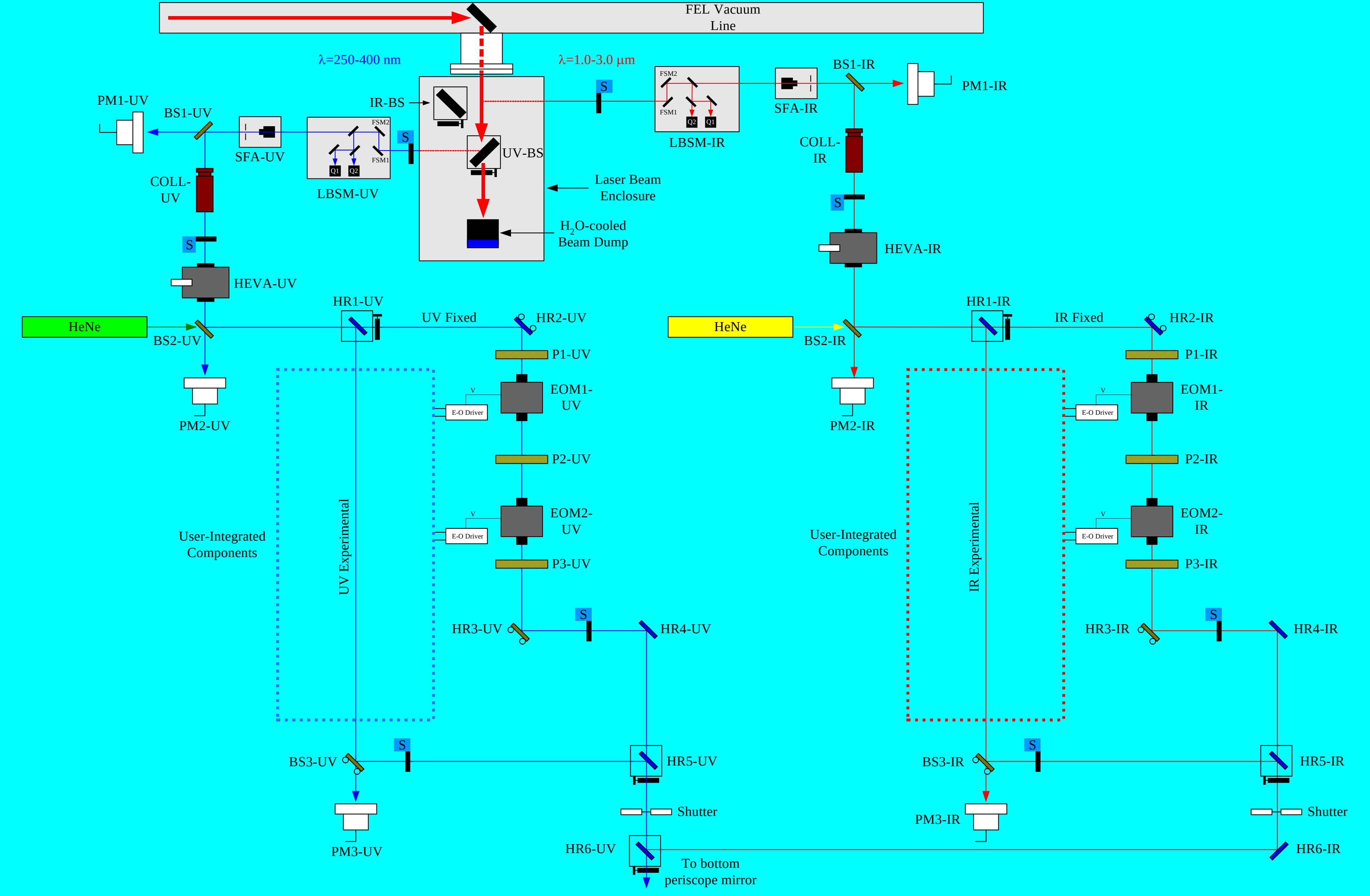
Software Module Sequences



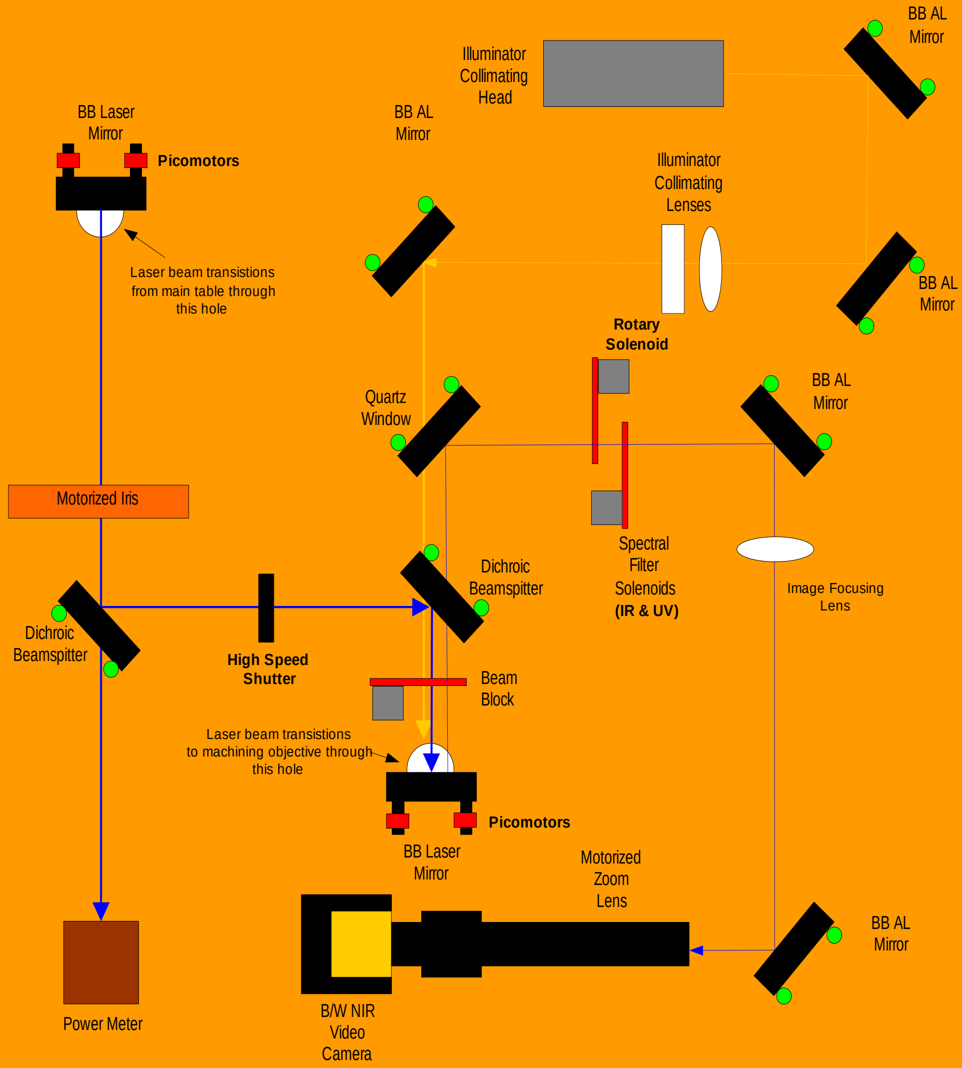
Henry.Helvajian@aero.org
Department of MicroNanotechnology

Optical Beam Path



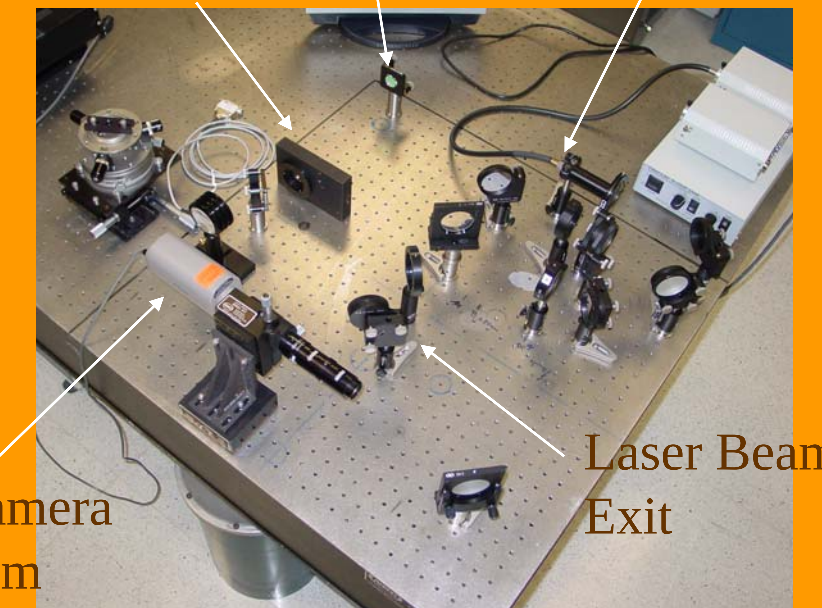
FEL-6 ; Optical Design
SRR 8/22/02

Upper Optical Table Vision System



Test Results: Horizontal FOV
Min = 50 µm
Max = 500 µm
Off axis camera for FOV >500 µm

In situ laser beam analyzer for on target laser spot size and intensity distribution measurements



Pulse Picking
Velocity Compensation
Dynamic Control of Laser Power

Henry.Helvajian@aero.org
Department of MicroNanotechnology

Major Weaknesses in Conventional Laser Material Processing

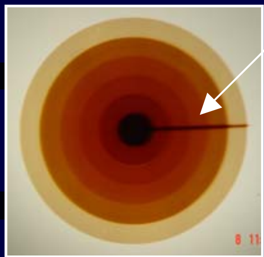
- Limited power/photon control during processing
- No compensation for variations in part motion velocity (velocity compensation)
- No provisions for laser pulse modulation (intra-pulse, inter-pulse, extraction, temporal)

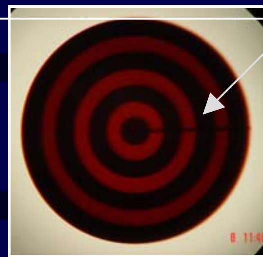
- Thermal energy transfer outside irradiated region
- Material removal from unexposed regions
- Thermal-induced effects
  - Defects, color centers, fractures, stress
- Difficult to investigate energy transfer from laser $\rightarrow$ electronic system $\rightarrow$ bulk lattice
- Restricted to homogeneous materials

Henry.Helvajian@aero.org
Department of MicroNanotechnology

Need for Velocity Compensation During Processing

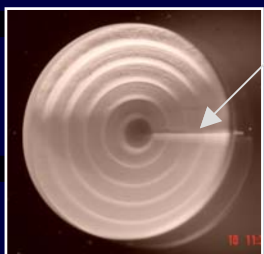
Permanent Images

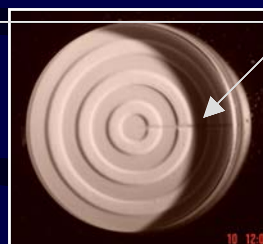




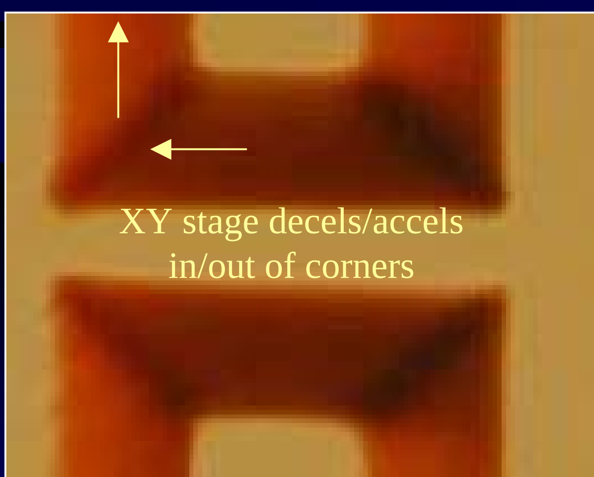
Over-exposure occurs at beginning and end of tool path segments

Etched Structures

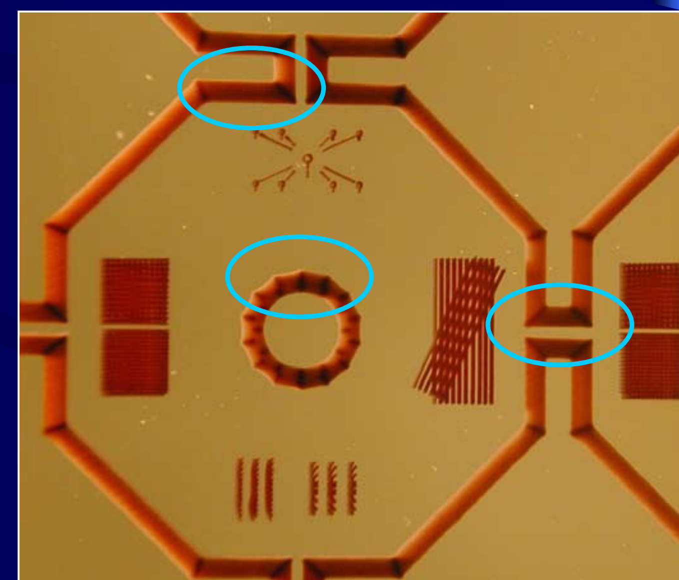




Over-etching occurs at regions of over-exposure



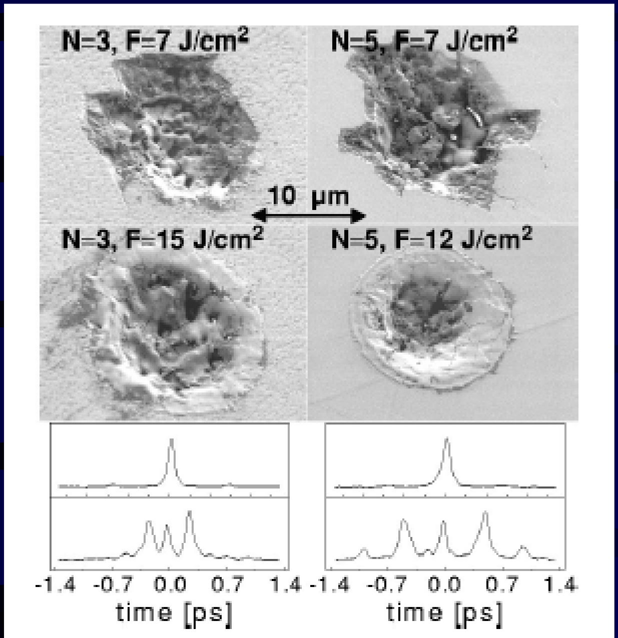
Over-exposure occurs at regions where velocity < avg. velocity



Henry.Helvajian@aero.org
Department of MicroNanotechnology

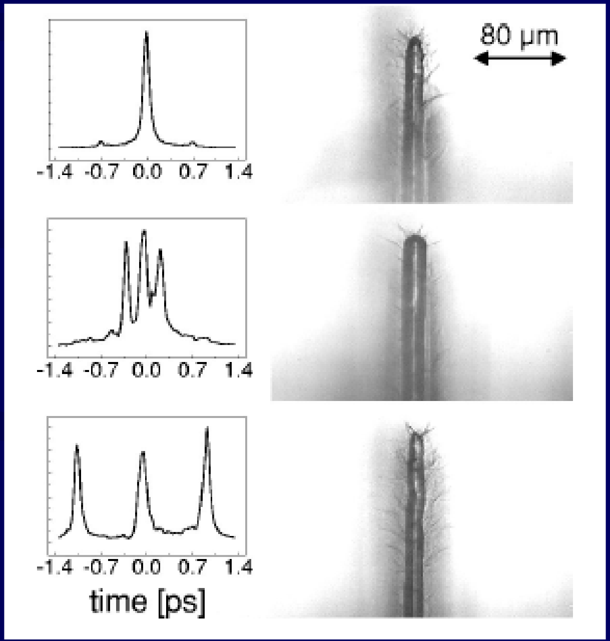
Laser Ablation of Dielectrics with Temporally Shaped Femtosecond Pulses

CaF_2 Ablation



- Multi-pulse sequences promote reduced exfoliation
- Controlled heating surface preparation

a-SiO_2 Drilling



- Improvement in structure when employing pulse trains
- Further increase in separation time worsens result due to enhanced thermal stress

R. Stoian, et al., *Appl. Phys. Lett.* **80**, 353 (2002).

Henry.Helvajian@aero.org
Department of MicroNanotechnology

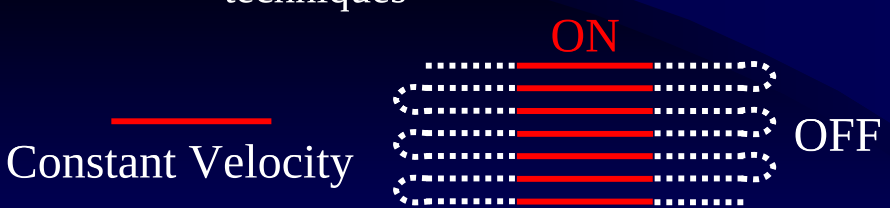
Key to Laser Processing

Apply laser controls that are required for the *specific* material under irradiation at the *OPTIMUM TIME*

Laser Wavelength/Power
Repetition Rate
Temporal/Spatial Intensity
Coherence/Polarization

Conventional Approach

- Fix laser power
- Minimize laser power fluctuations
- Employ “cut-in” and “cut-out” techniques



Processing Limitations

- No velocity compensation
- Adds appreciable overhead to machining code and processing time
- Limits types of motion sequences
- Cannot machine heterogeneous materials in a sequential motion process

Henry.Helvajian@aero.org
Department of MicroNanotechnology

Laser Pulse Modulation During Tool Path Motion

Advanced Laser Material Processing

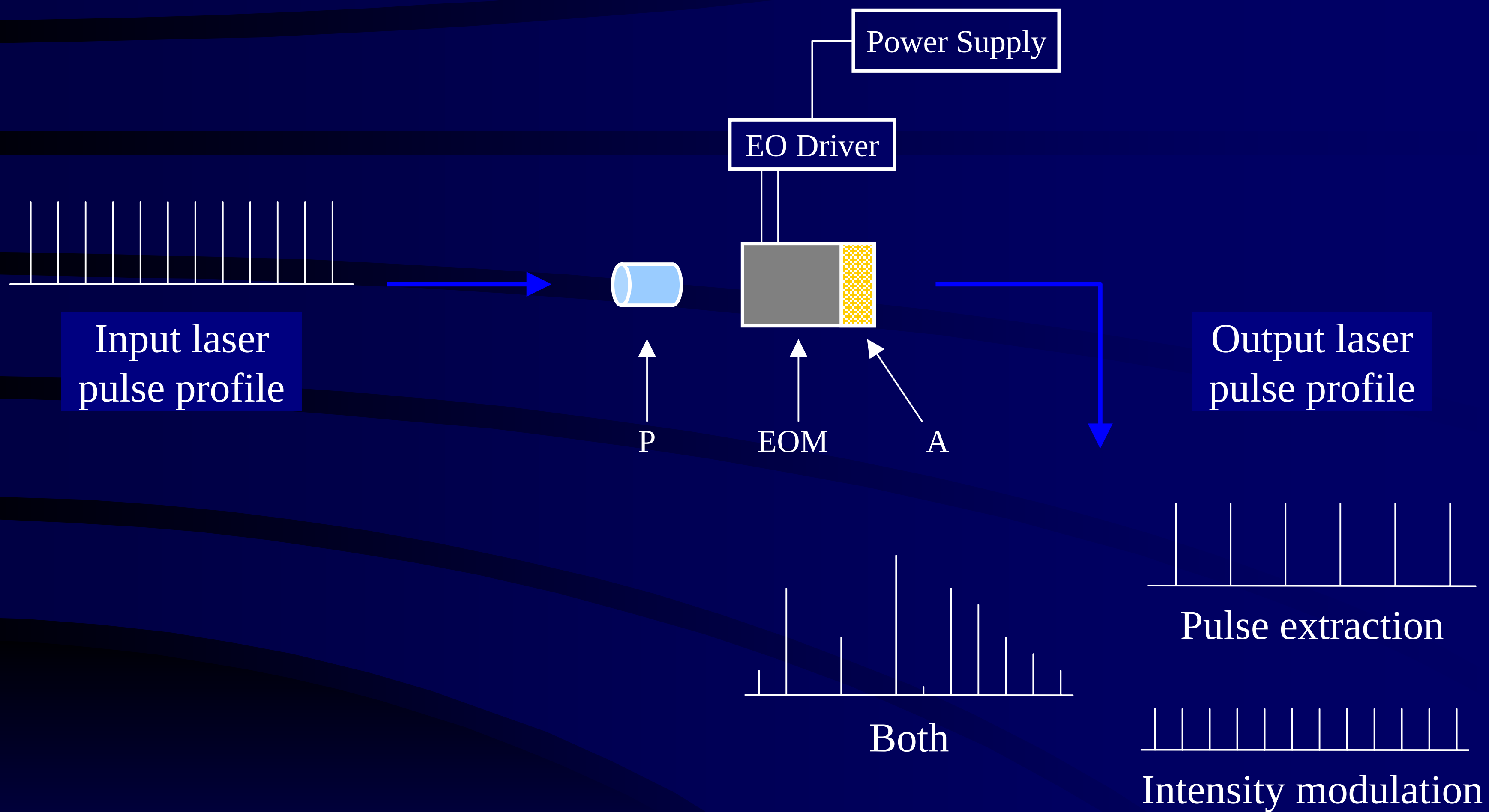
Unique Features

- Control photon flux and energy that is delivered to *each* laser spot
- Pulse sequence (number and intensity) is determined by *travel distance* and is related to the spot diameter
- Feed rate of XYZ stages can be adjusted or *"throttled"* on a per tool path segment basis

Advantages

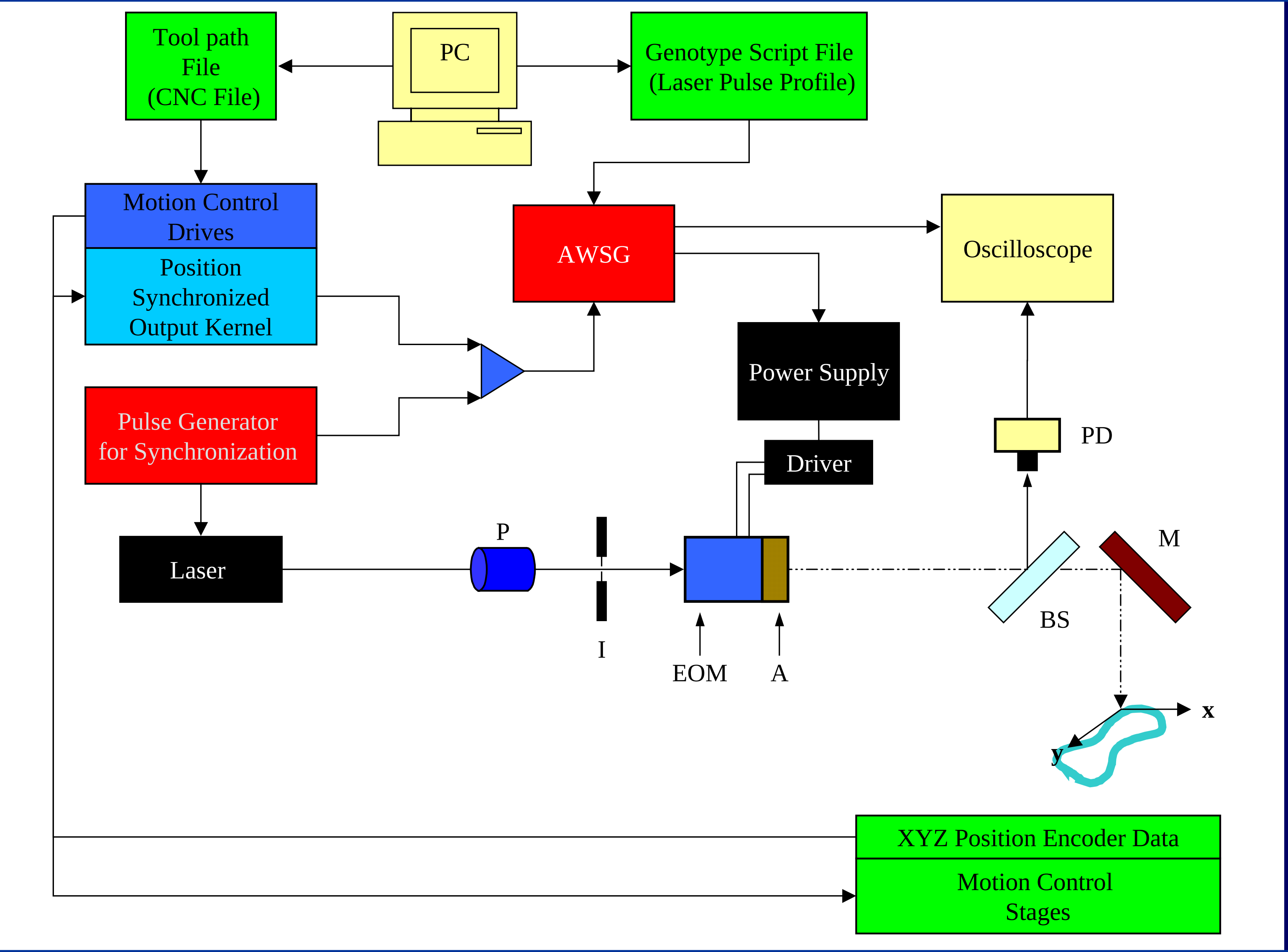
- Laser processing (exposure) is *velocity-independent*
- Each laser spot receives an equivalent photon dose
- Pulse profile can be tailored for a specific material
- Ideal for variegated or heterogeneous materials

Optical Power Control: Dynamic Attenuation



Henry.Helvajian@aero.org
Department of MicroNanotechnology

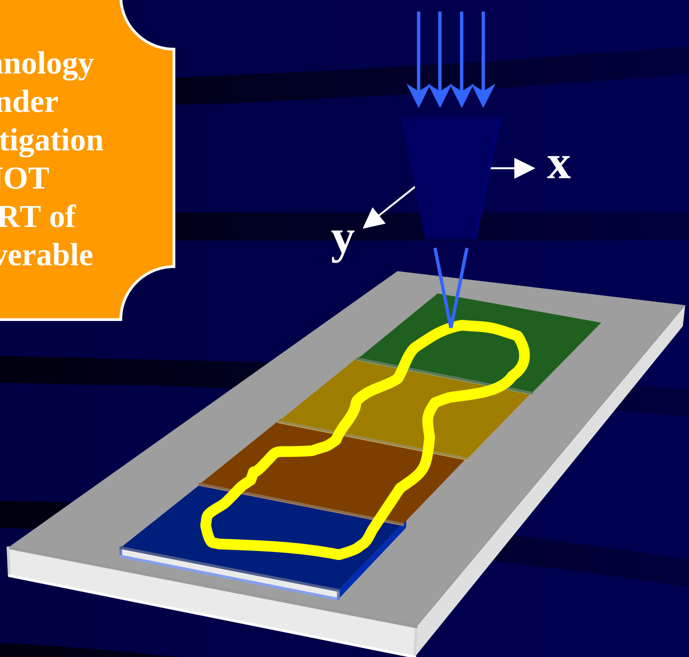
Laser Pulse Modulation Scheme: Design Concept and Experimental Setup



Henry.Helvajian@aero.org
Department of MicroNanotechnology
THE AEROSPACE CORPORATION

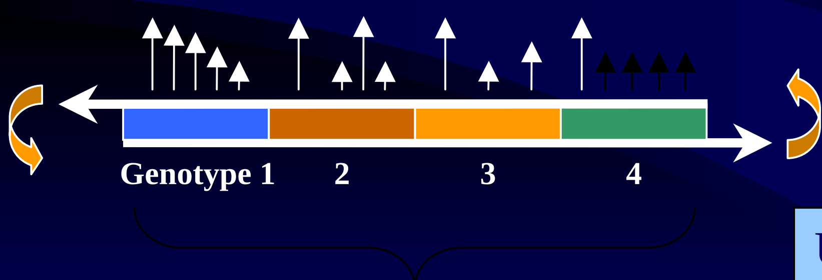
Use of Digitally-Scripted Genotype Pulse Patterns

Technology Under Investigation NOT PART of Deliverable



GENOME = Sequence of concatenated genotypes that define a “script”.
“Script” contains attributes that are to be expressed according to the specific sequencing.

- Laser-processing programmer develops a pulse “script”
- “Script” is synchronously matched with the laser tool path
- “Script” can be altered on a per laser spot basis
- Feed rate can be “throttled” to control speed, exposure and resolution



Laser Pulse “Script”

Ultrafast and high repetition rate lasers are ideally suited for digitally-scripted laser processing

Henry.Helvajian@aero.org
Department of MicroNanotechnology

Laser Material Processing Using Modulated Pulse Sequences

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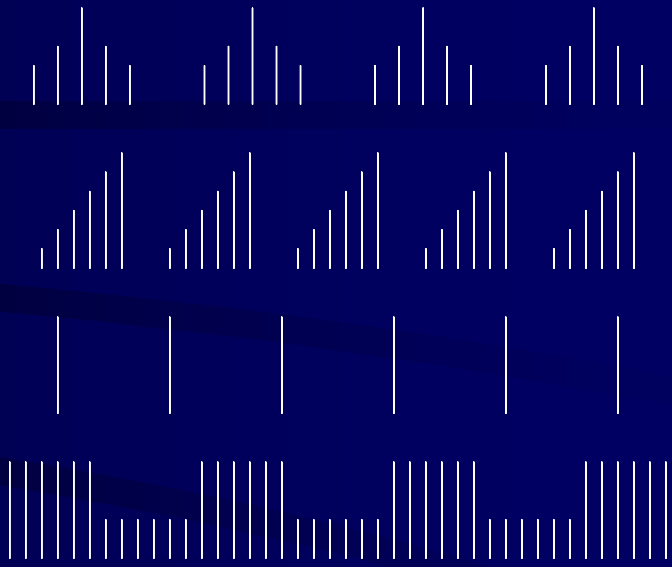
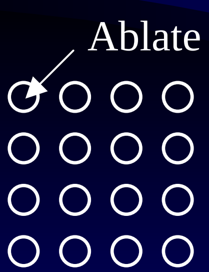
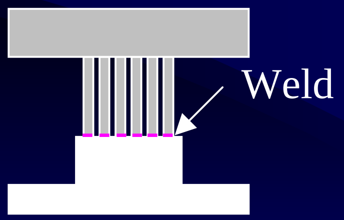
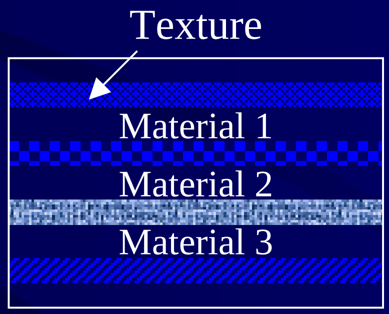
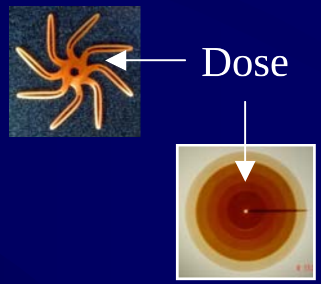
Process	Laser Pulse Structure
a] Ablation	
b] Welding	
c] Texturing	
d] Dosing	











Henry.Helvajian@aero.org
Department of MicroNanotechnology

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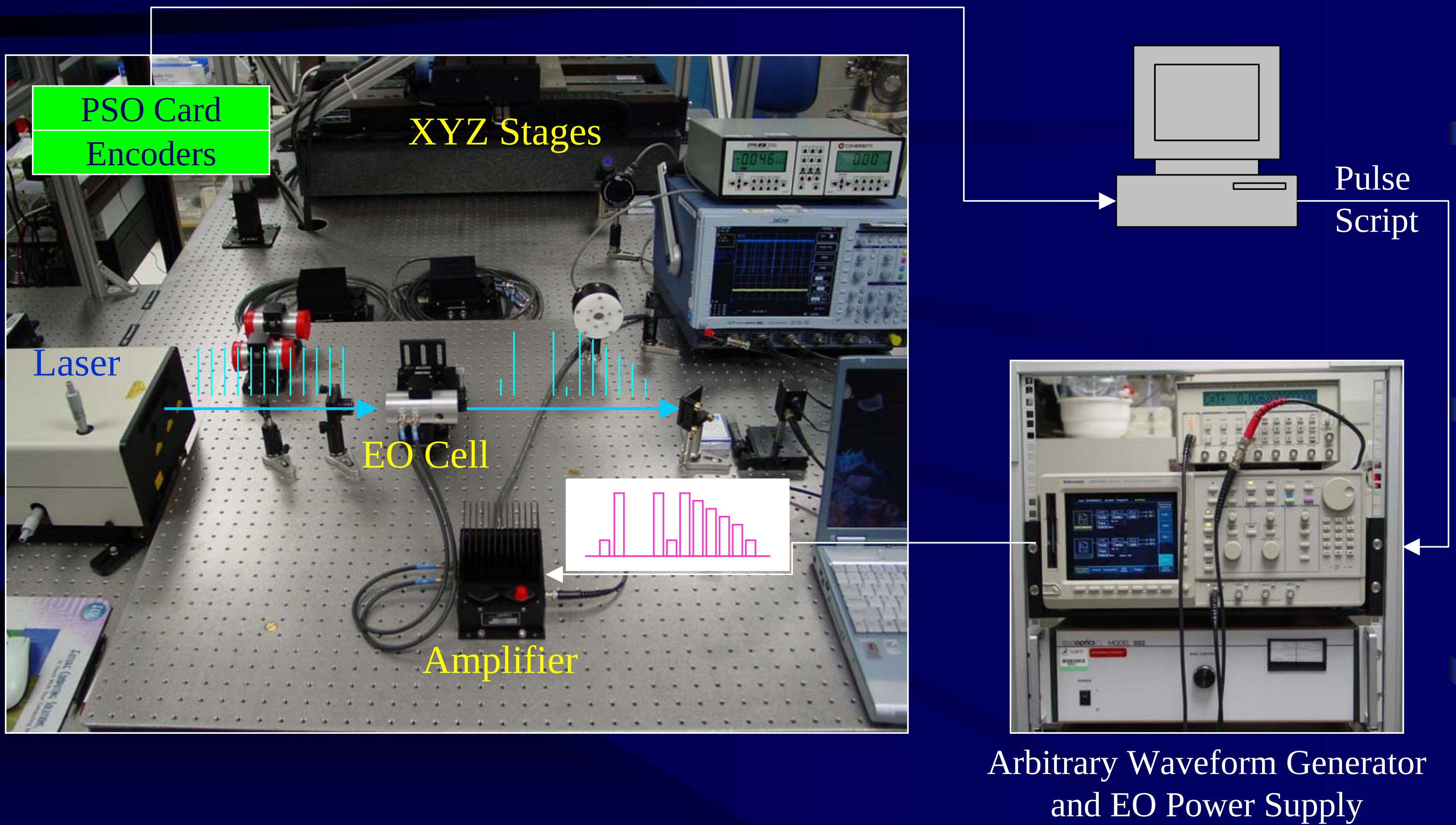
Experimental Setup for Synchronized Pulse Modulation



Henry.Helvajian@aero.org
Department of MicroNanotechnology
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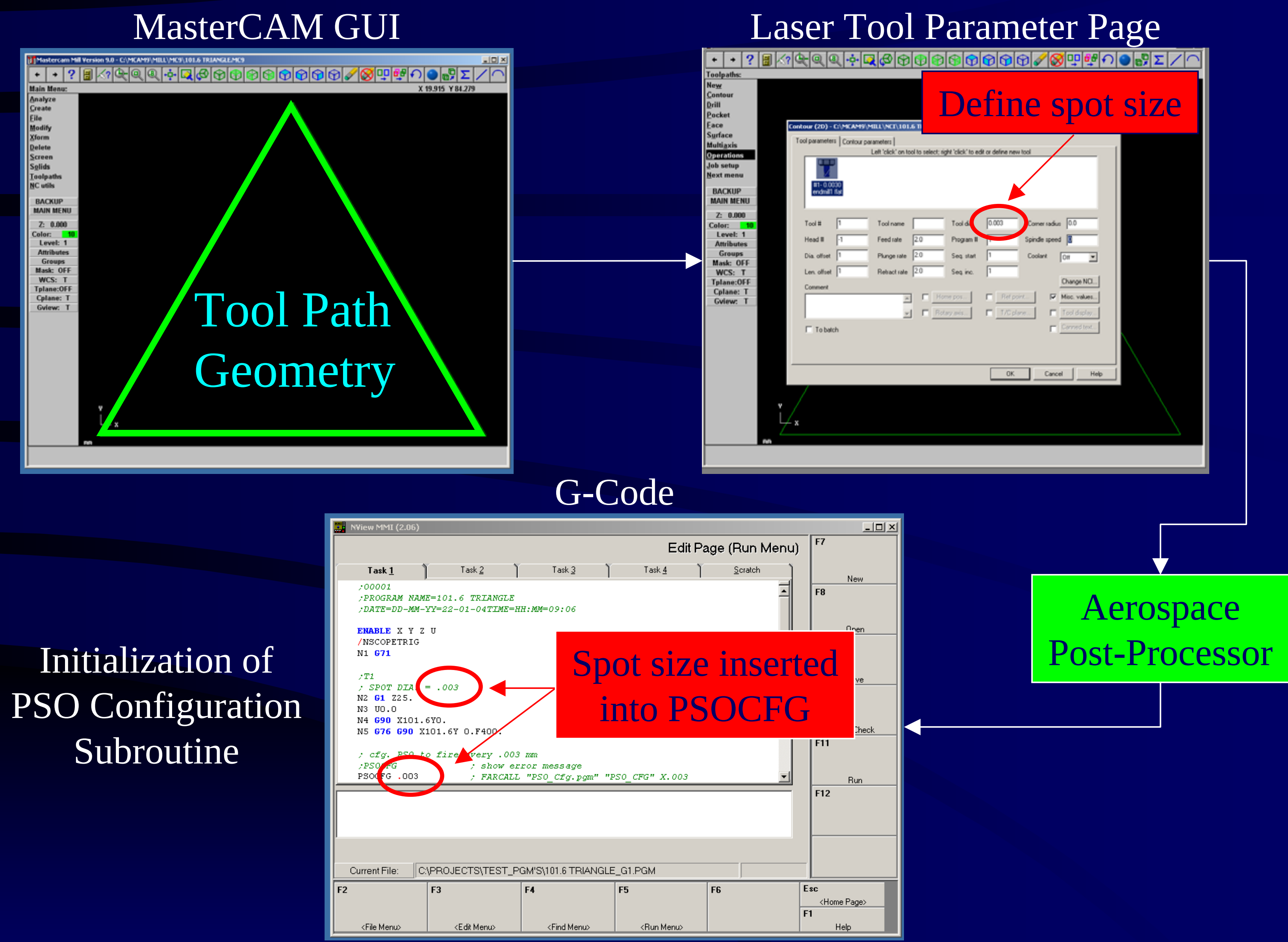
Information Process Flow



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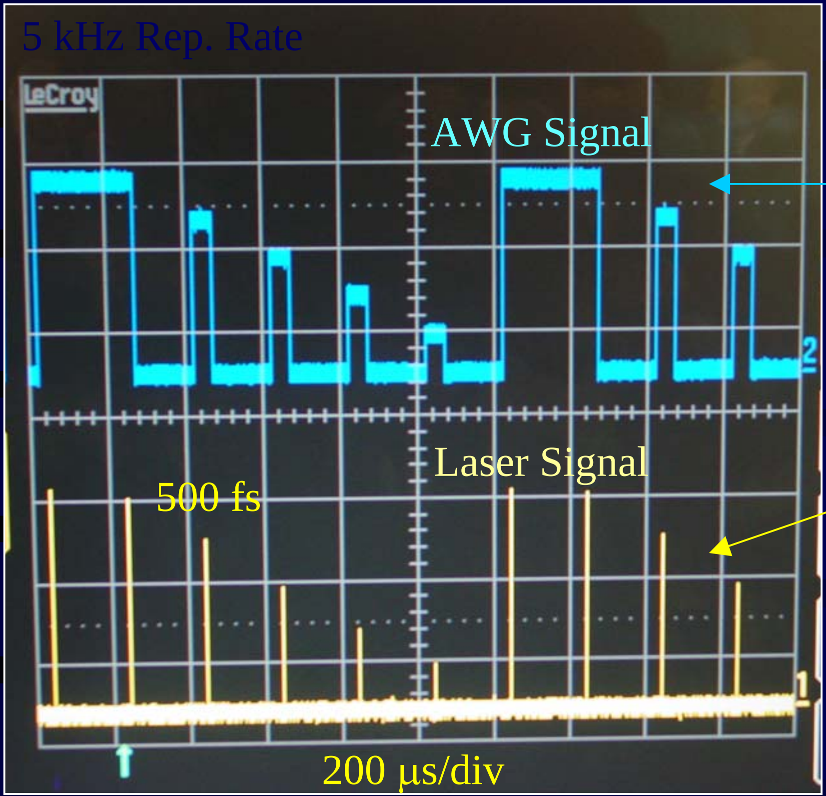
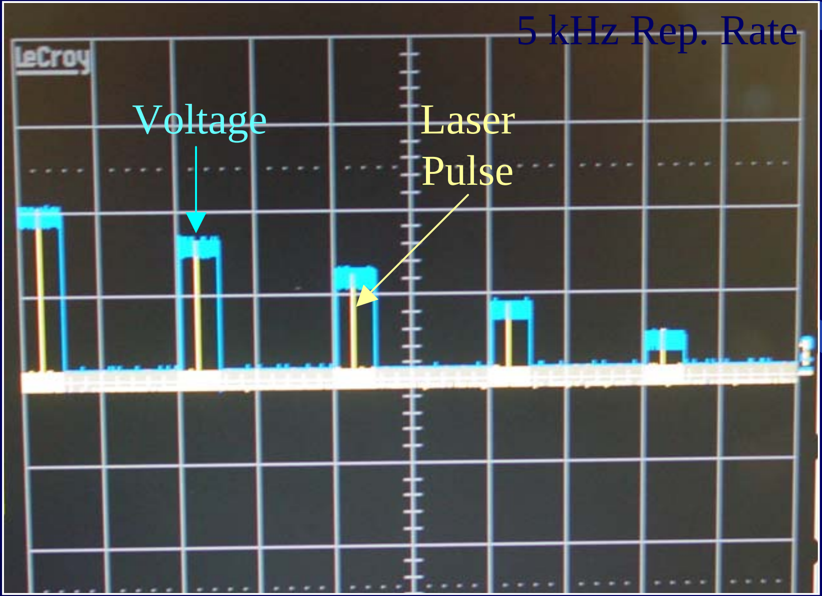
Laser Pulse *Intensity Modulation*





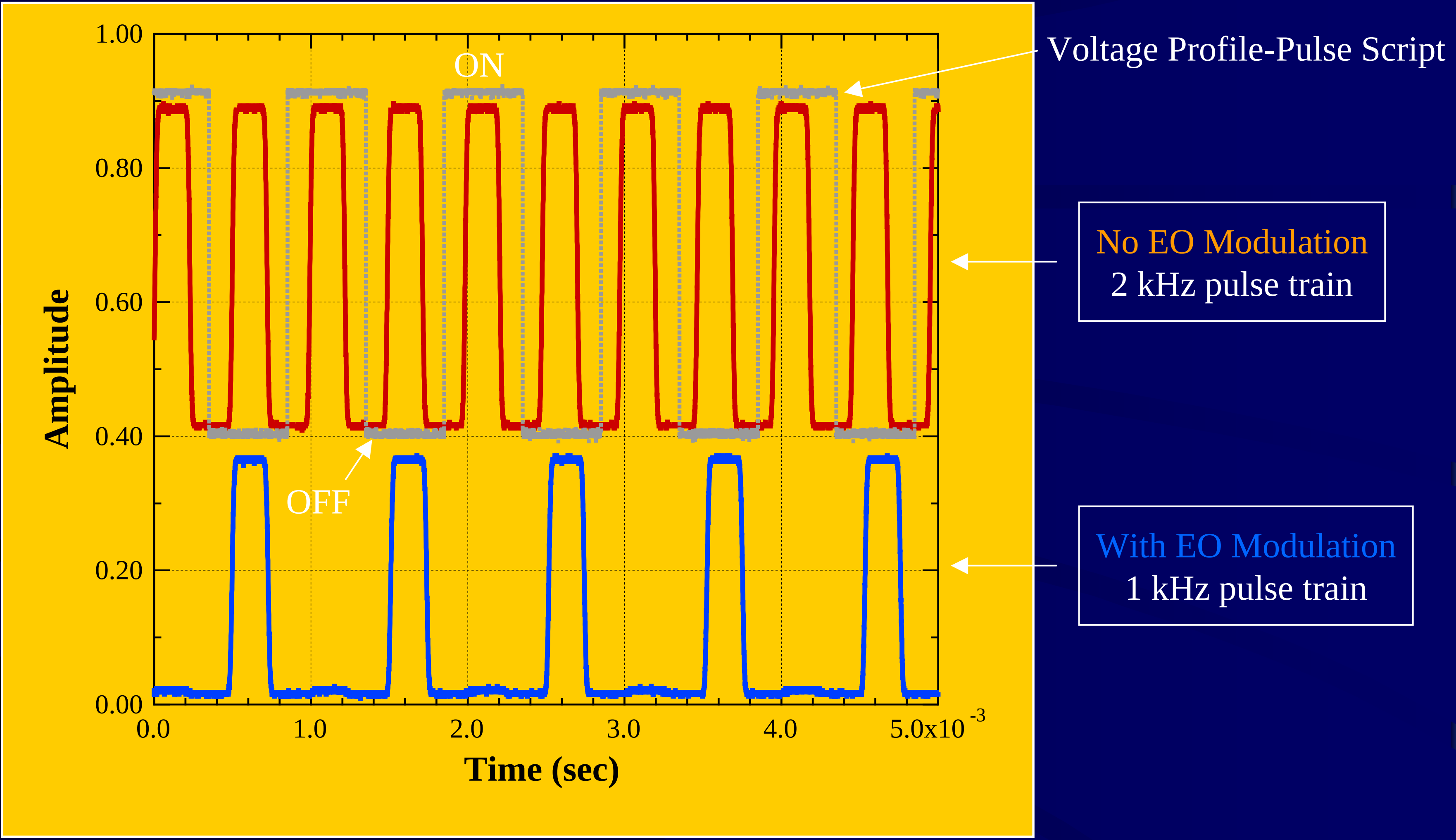
Voltage Profile-Pulse Script

Modulated Laser Pulse Sequence

- Can precisely modulate *intensity* of *each* laser pulse

Henry.Helvajian@aero.org
Department of MicroNanotechnology

Laser Pulse *Selection (Extraction)*

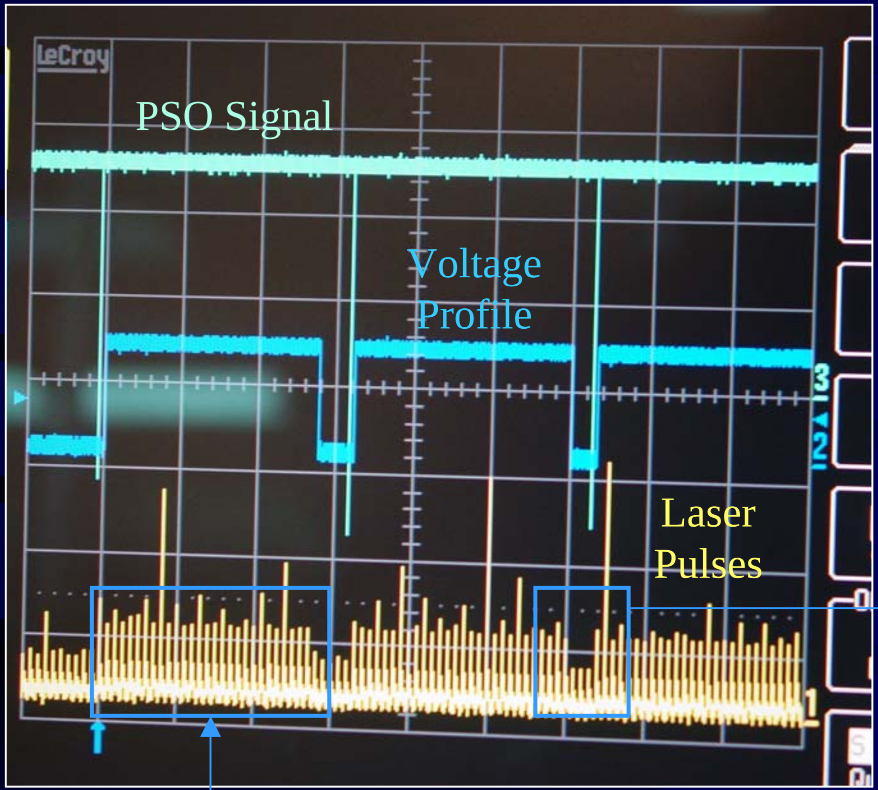


- Can precisely control laser pulse frequency via individual pulse extraction

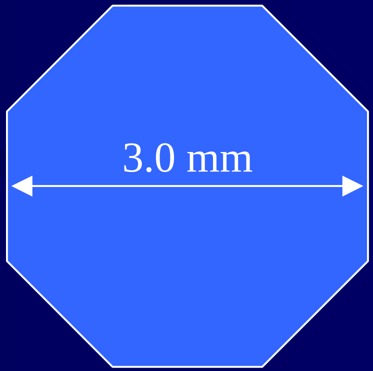
Henry.Helvajian@aero.org
Department of MicroNanotechnology

Synchronized Motion and Laser Pulse Delivery

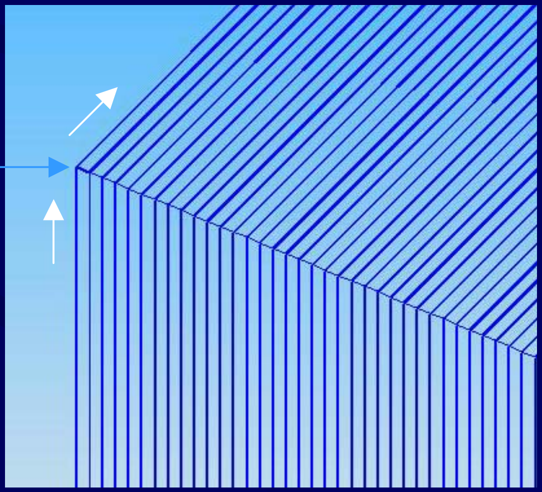
Feedrate: 500 µm/s
PSO Distance: 3.0 µm
Repetition Rate: 5.0 kHz



30 laser pulses delivered to each spot diameter

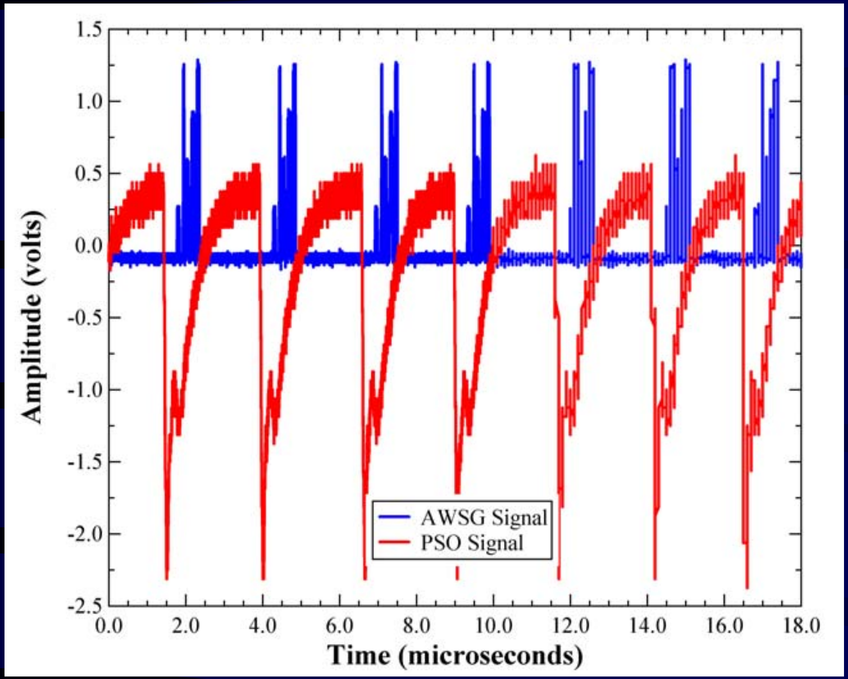


Acceleration/deceleration through corners and "stepover"

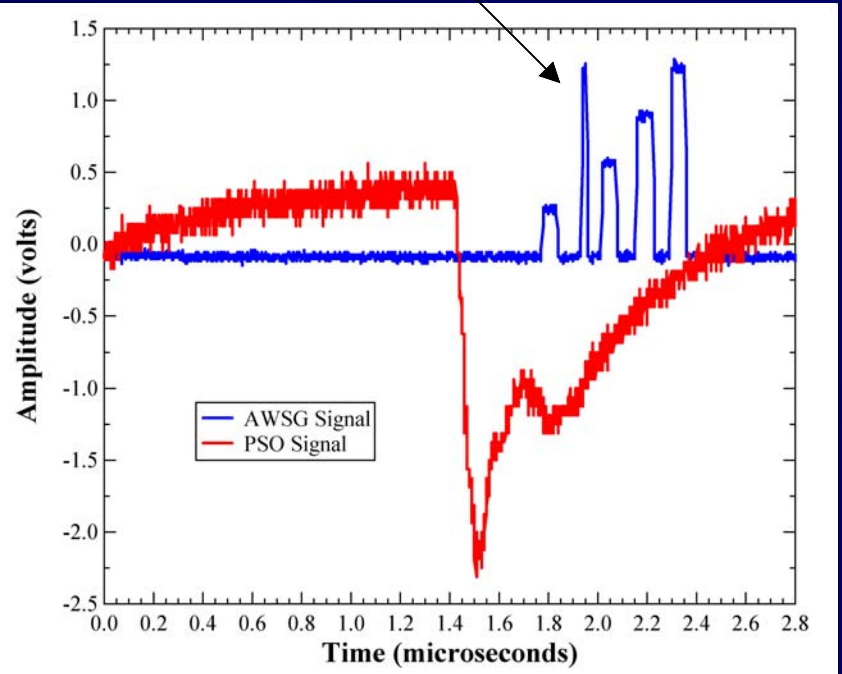


Henry.Helvajian@aero.org
Department of MicroNanotechnology

PSO-AWSG Application Example



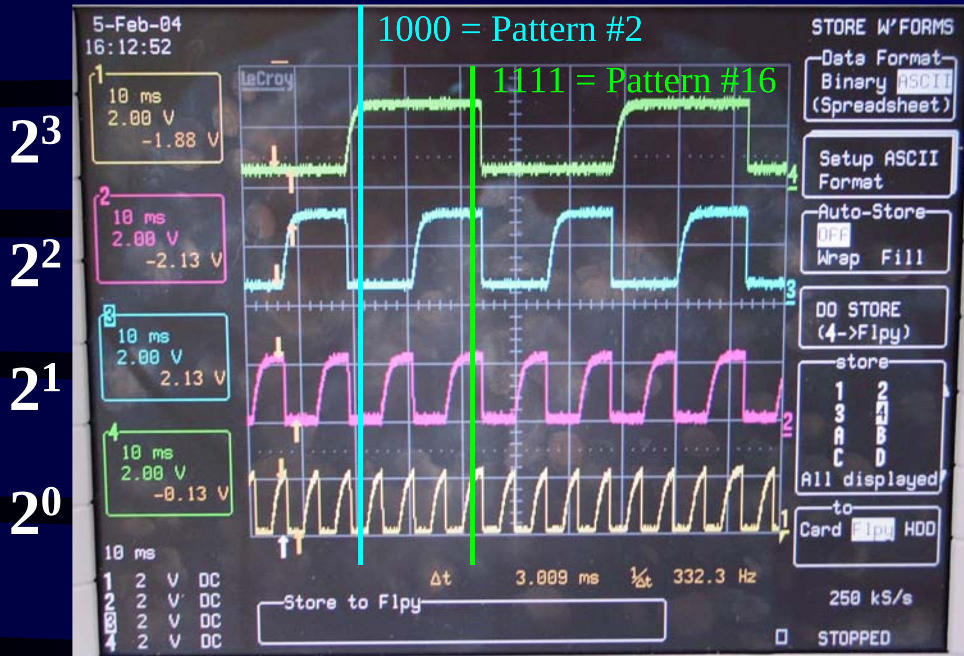
Pre-programmed laser pulse script



- PSO firing frequency of 400 kHz corresponds to a pattern velocity of 400 mm/s and a laser spot size of 1.0 µm
- PSO and AWSG signals are synchronized with tool path motion

Henry.Helvajian@aero.org
Department of MicroNanotechnology

Heterogeneous (Multi-Material) Laser Processing



- 4-bit signals (M-codes) sent from PSO card to AWSG
- M-codes embedded (M6000-M6015) in tool path motion code
- Each M-code is assigned to a specific, resident pulse pattern on the AWSG (2 channel, 32 patterns total)
- Laser pulse profile (genotype) can be altered for each laser spot

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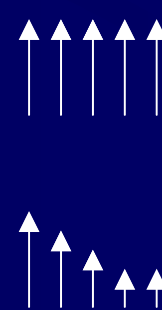
If 1000:

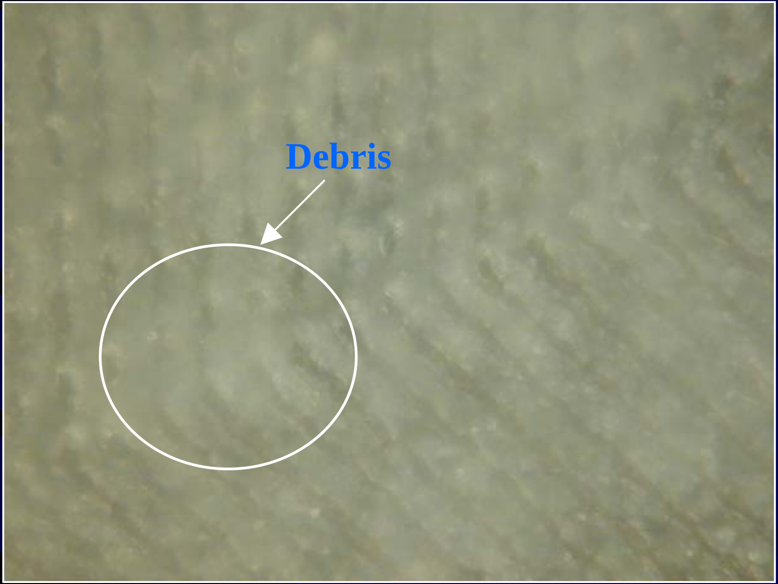
If 1111:



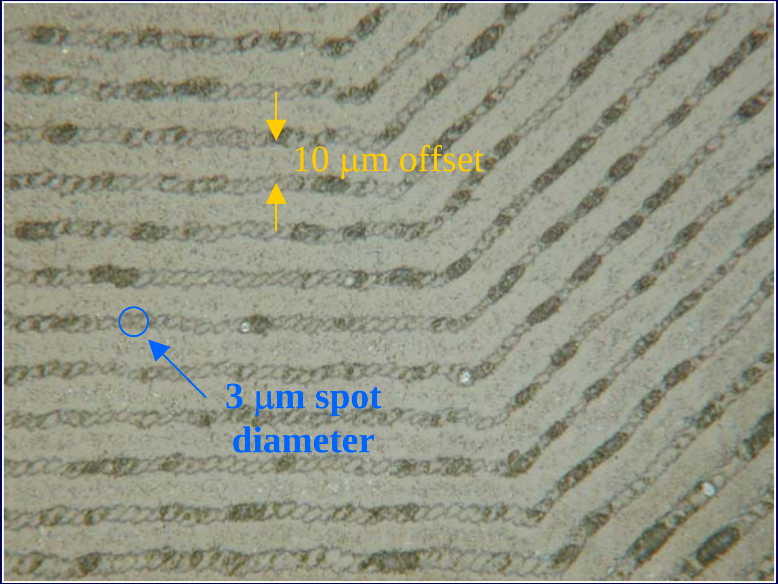
Henry.Helvajian@aero.org
Department of MicroNanotechnology

Ablation of Glass Using Modulated fs Laser Pulses at 400 nm

Velocity Comp. OFF



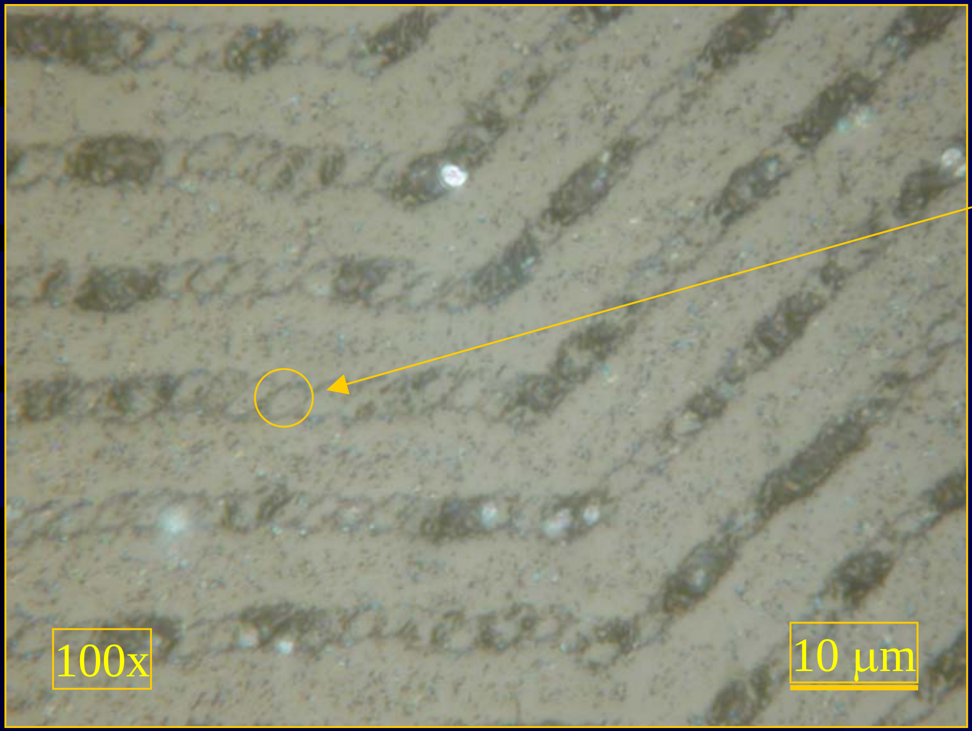
Velocity Comp. ON

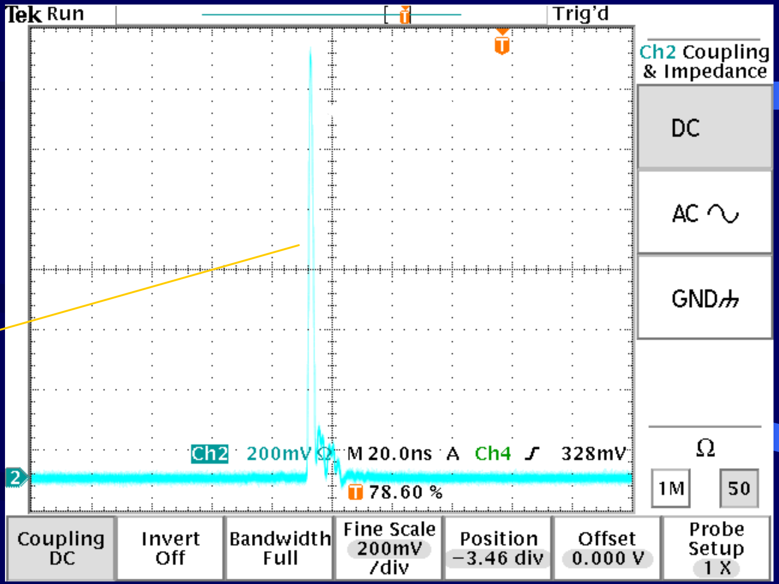


- Spallation and debris formation
- Fractures and thermal-induced stress

- Localized material removal
- Patterns are clean and well defined

Single Pulse Ablation of Glass Using Modulated fs Laser Pulses at 400 nm

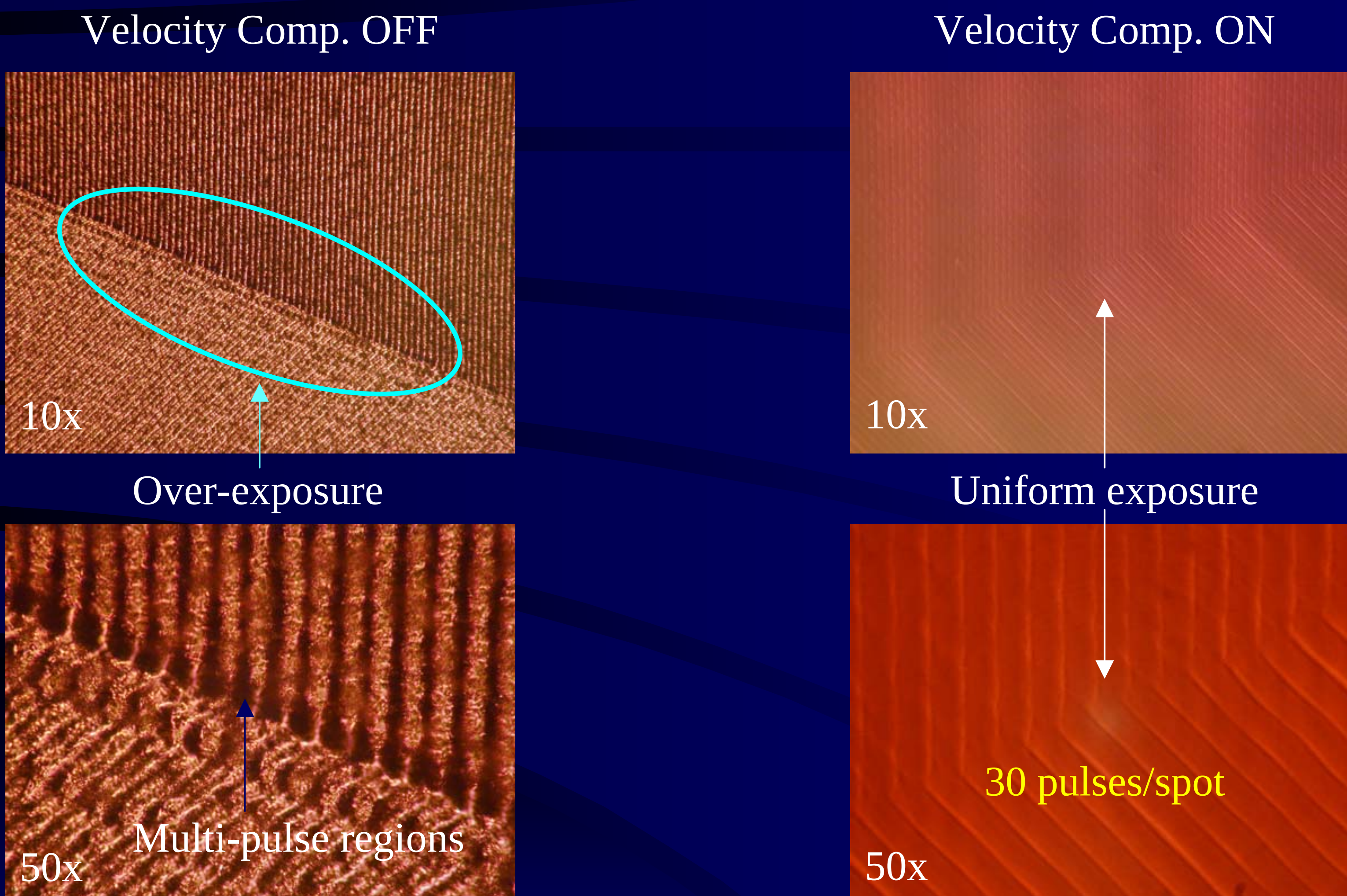




- Single 500 fs laser pulse delivered to each spot
- Overexposure or multiple-pulse behavior not observed

Henry.Helvajian@aero.org
Department of MicroNanotechnology

Exposure of Photosensitive Glass Using Modulated fs Laser Pulses at 400 nm



Henry.Helvajian@aero.org
Department of MicroNanotechnology

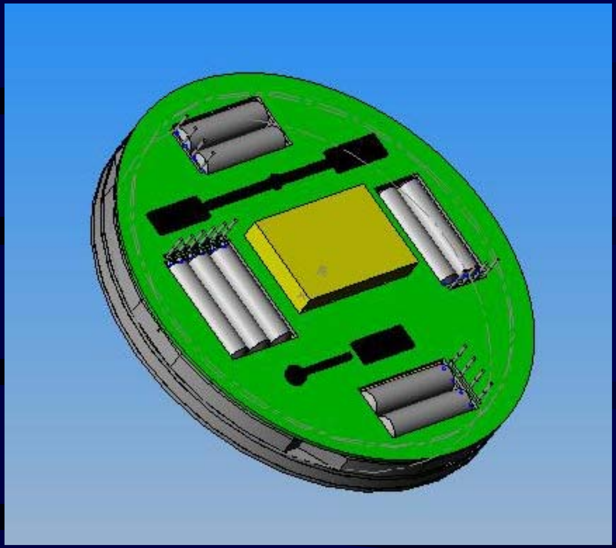
Summary

- Permits the precise control of photon flux during laser processing
  - Intensity modulation
  - Pulse selection
  - Temporal modulation
  - Velocity independent
  - Heterogeneous (multi-material) processing
- Takes into account all primary experimental parameters
  - Material type
  - Surface finish
  - Photon dose history
  - Type of material processing

The Co-Orbiting Satellite Assistant (COSA) Project
and
Manufacturing Performance Metrics for Fabrication with KW UV FEL

Henry.Helvajian@aero.org
Department of MicroNanotechnology

COSA Prototype Propulsion Module (Circa 2004)



Attributes of a Glass Ceramic Mass Producible Satellite

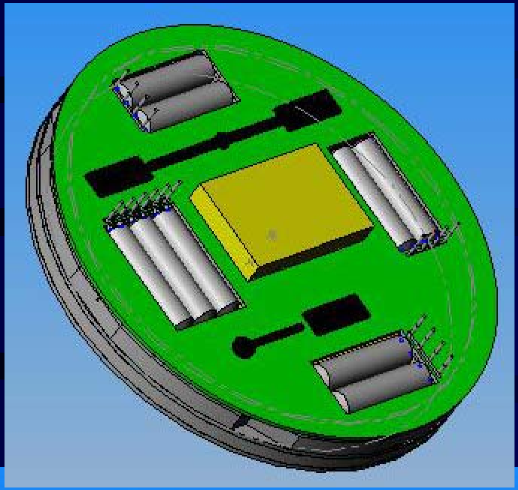
- Designed for mass production
- Multi-functional glass ceramic material
- Reduced number of piece-parts
- Satellite can be pre-shaped/molded into complex shapes
- Microstructured elements in macroscopic material
- RF transparent; low radar cross section
- Integrated structure and optical bus
- Local control of material transparency and strength
- Wide operational temperature range
- Radiation shield for gammas, X-rays
- Low thermal conductance
- 30 m/s ΔV capability (2 modules and 1kg satellite)

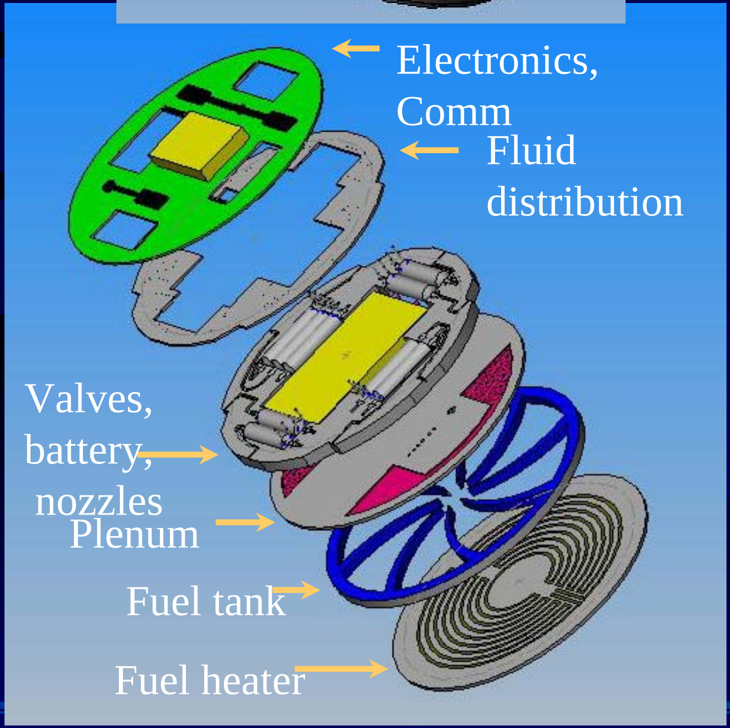
Prototype Propulsion Module

- Size: 100 mm x 21 mm, Weight: 330 g (wet)
- Integral attitude control capability with wireless telemetry
- Integral thrust nozzles (8) and fuel tank
- 15 m/s ΔV capability
- Designed for 2-week duration observation mission
- Optional balloon de-orbit capability

Henry.Helvajian@aero.org
Department of MicroNanotechnology

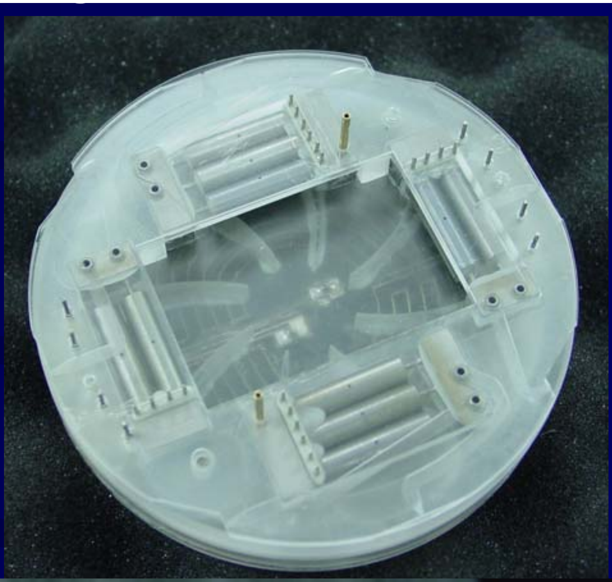
A Propulsion System with GNC in PSGC Material

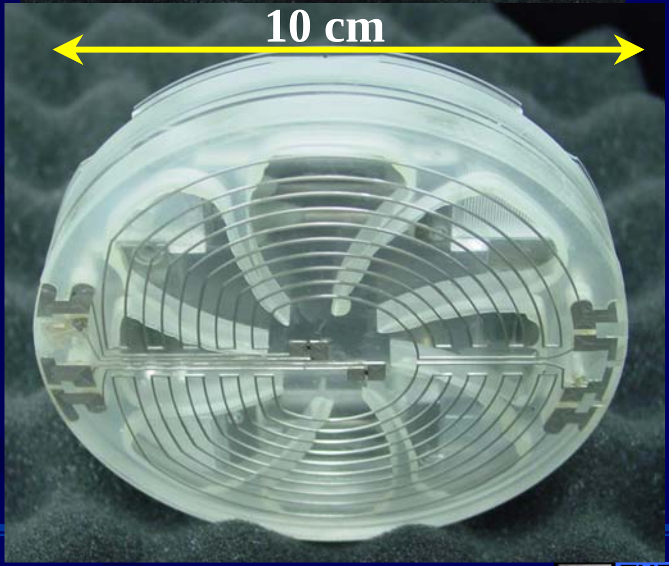




The Aerospace Corporation Co-Orbiting Satellite Assistant (COSA)

All Digital Direct Manufacturing

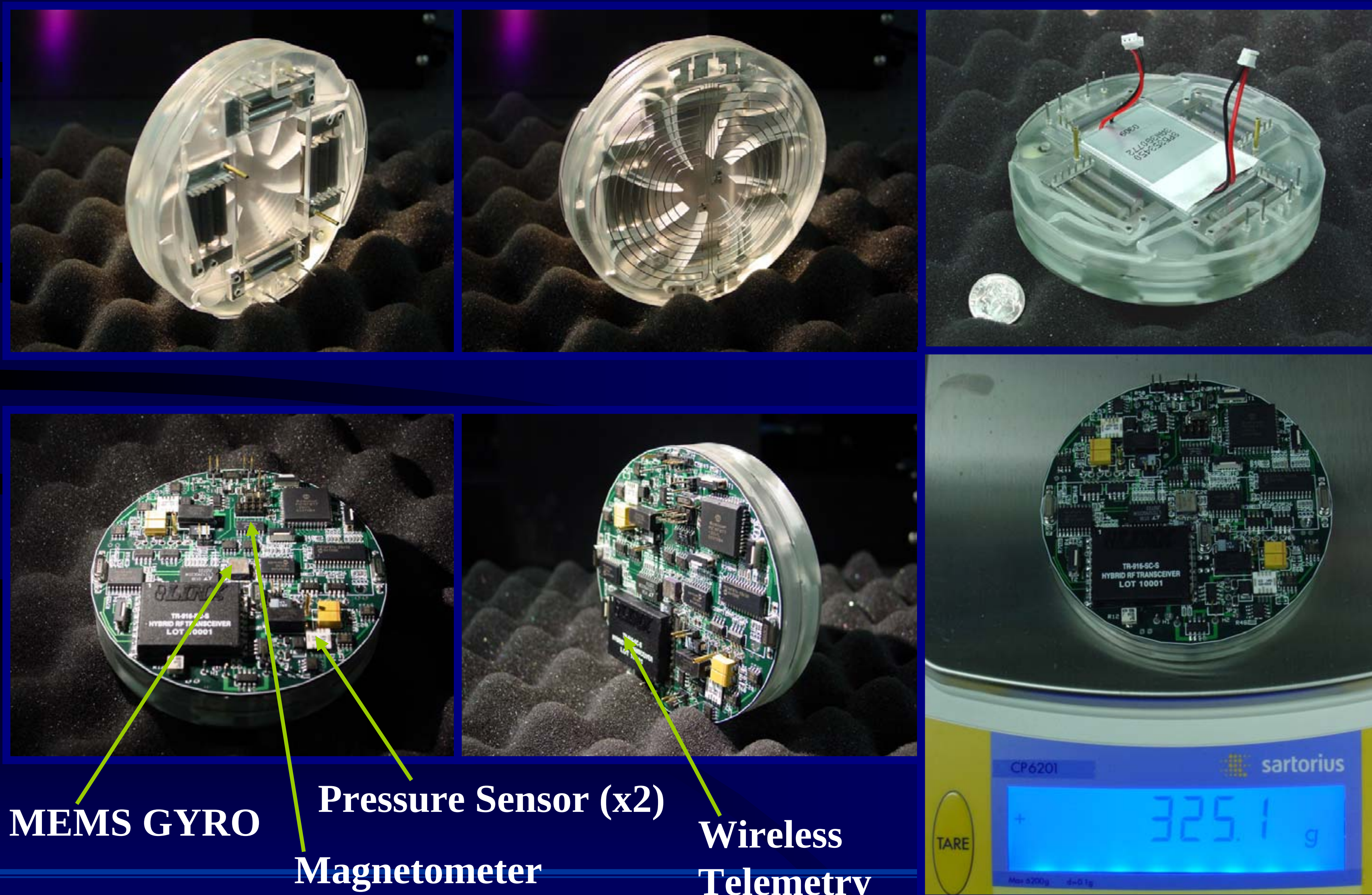




Henry.Helvajian@aero.org
Department of MicroNanotechnology

THE AEROSPACE CORPORATION

The Prototype Propulsion Module Circa 2005

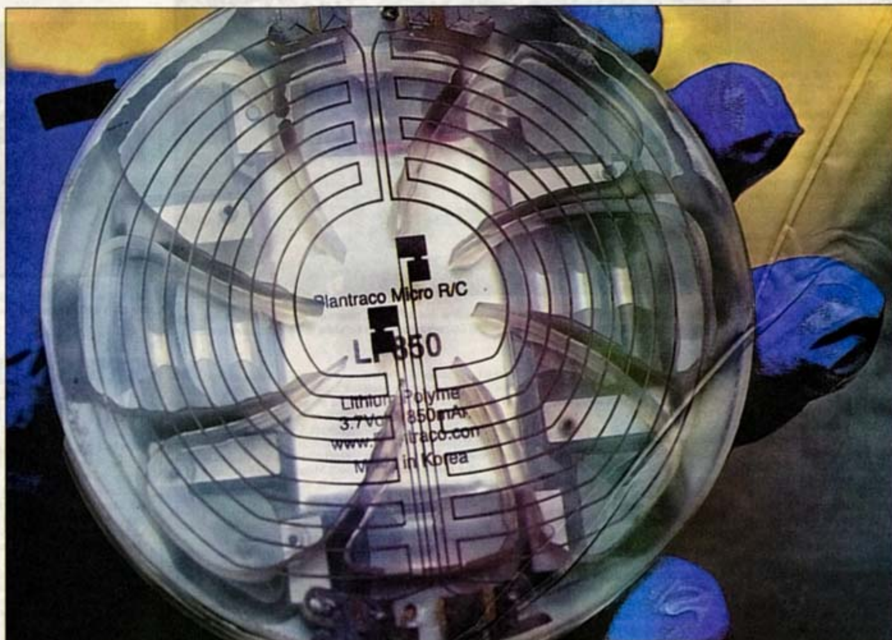


Henry.Helvajian@aero.org
Department of MicroNanotechnology

Daily Breeze
SUNDAY
February 27, 2005

BUSINESS

Section C



BRUCE HAZELTON/DAILY BREEZE

This prototype of a satellite propulsion module built by The Aerospace Corp. uses glass and ceramic components to make a significantly lighter and smaller satellite.

Swarms to alter Space Age

AEROSPACE: New use for old materials — glass and ceramics — can cut the costs of putting satellites into orbit.

By Muhammed El-Hasan
DAILY BREEZE

Sometimes at work, between refining a fabrication method and keeping up with scientific theory about tiny electronic parts, Henry Helvajian floats a disk filled with circuitry on a makeshift air hockey table.

Some day, a similar disk may float over the Earth's atmosphere.

The disk is a satellite propulsion system that Helvajian, a senior scientist at The Aerospace Corp. in El Segundo, made out of glass-ceramic. The process used to make the disk could one day lead to the deployment of thousands of tiny glass-ceramic satellites circling the globe.

Siegfried Janson and Henry Helvajian of the nanotechnology department of The Aerospace Corp. in El Segundo display a prototype of a nanosatellite part.

This project, led by Helvajian and his colleague, senior scientist Siegfried Janson, is significant in part because of the novelty in using glass-ceramic material to manufacture the structure of satellites, which traditionally are made from metal.

Their work is also important because glass-ceramic is relatively light, and could help lower launch costs.

"Nobody in their right mind would make a glass satellite," Helvajian said dryly about conventional wisdom. "They would argue that by the time it got into orbit, the satellite will crack or break from the shaking. *Not true.* Glass doesn't bend. *Not true.*"

The satellites Helvajian and Janson envision would weigh about 1 kg, or 2.2 pounds. Being about 100 times smaller than a conventional model, these tiny satellites — known as nanosatellites — could be held in one hand.

In 1993, Janson coined the term nanosatellites, referring to satel-

SWARMS/C2

Glass-ceramic nanosatellites

- A glass-ceramic satellite could weigh 1 kg, or 2.2 pounds. Such satellites could be heavier.
- Glass-ceramic satellites are called nanosatellites because of their small size. They can be one one-hundredth the size of a conventional satellite.
- Because of their transparent structure, they can use light, or photonics, to transfer information between different parts of the satellite.
- Glass-ceramic satellites can be used as "assistants" that pop out of a large conventional satellite to photograph the exterior of that large satellite.
- Nanosatellites also may be used in swarms that could number in the thousands to perform the functions of one large satellite.

SWARMS: New use for old materials can cut into launch costs

FROM PAGE C1

lites that weigh about 1 kg to 10 kg.

Conventional satellites are made with aluminum, carbon composite material, beryllium or other metals, Janson said. The glass-ceramic is lighter than these metals.

"It's about $5,000 a pound to put something in orbit," Janson said. "You save money."

The tiny satellites could be sent into orbit inside a larger satellite or separately sent up in clusters on a rocket.

In addition, because the glass-ceramic is transparent, information can move within the satellite using light, or photonics, reducing the encumbrance of cables and wires.

Further simplifying the structure, a cavity formed within the glass-ceramic satellite can be used as a fuel tank, while channels can serve as the satellite's "plumbing" that sends fuel to the thrusters.

The aerospace industry has been trying to reduce launch weight and cost for years, said defense analyst Paul Nisbet, of JSA Research Inc. in Newport, R.I.

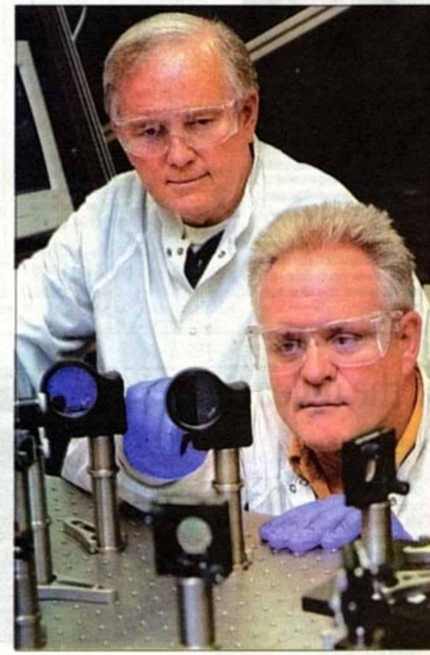
But nanosatellites are "limited compared to the large guys as to what all they can do," Nisbet said.

Satellites used for weather observation, communications and spying can weigh thousands of pounds because of the intricate electronics on board and the platform and power system that must keep the device working for years.

A nanosatellite alone can't replace such a conventional satellite. But a swarm of dozens, hundreds or even thousands of the tiny satellites might be deployed together to replace a single big satellite, Janson said.

"There are a number of benefits like graceful degrading," Janson said. "If you lose 10 percent of the satellites, the performance will still be good. With the big satellites, if it loses 10 percent of its components, it probably wouldn't be any good."

In addition, the smaller satellites could be mass-produced. That would allow companies or the government to put technology into orbit sooner, before it becomes obsolete, Janson said.



BRUCE HAZELTON/DAILY BREEZE

Micro/nanotechnology department senior research associates William Hansen, left, and Lee Steffency make adjustments at the micro-laser engineering station.

Nanosatellites also could be used as "satellite assistants," a role Janson is working on. Many tiny satellites could be housed inside a large satellite. The small satellites could exit the larger model and circle it, using cameras to send to Earth images of damage or other problems with the mother ship.

Once a glass-ceramic satellite has served its function, the device may blow up a balloon that drags against the Earth's outer atmosphere to slow down. The small satellite then descends into a lower orbit and burns up.

"These glass satellites are disposable satellites," Helvajian said. "This is not space garbage."

It's possible to build nanosatellites out of conventional metals.

"But historically, if you take one big satellite and split it up into hundreds of different satellites, it will cost more using conventional manufacturing," Janson said. "That's why we're developing this new manufacturing technique."

That technique, known as digital direct manufacturing, creates a material Helvajian describes as a cousin of Corning Ware.

The three-step process starts with instructions given to a computer, which directs a robot to expose ultraviolet laser to a certain type of glass, sketching a design that determines the material's shape. The glass is then baked in an oven.

The last step involves dipping the glass in acid. The process can turn the glass into various shapes depending on the function, such as the shape of an antenna.

Depending on how long the material is treated in different stages of the process determines whether it ends up as flexible, transparent glass or opaque, stiff ceramic.

Glass and ceramic each can have different uses on a satellite. For example, ceramic might be appropriate for areas where thrusters are located. Glass might be used where light messages must travel through a transparent surface.

Some of the material created from this process sits on an exterior panel of the international space station. The glass and ceramic pieces are being tested for their ability to hold up in low-Earth orbit.

The Aerospace Corp. has patented the fabrication process, and licensed it to Invenios, a Santa Barbara firm that machines and fabricates metal, glass and ceramic products.

Janson, Helvajian and another scientist co-wrote a paper on nanosatellites in 1993.

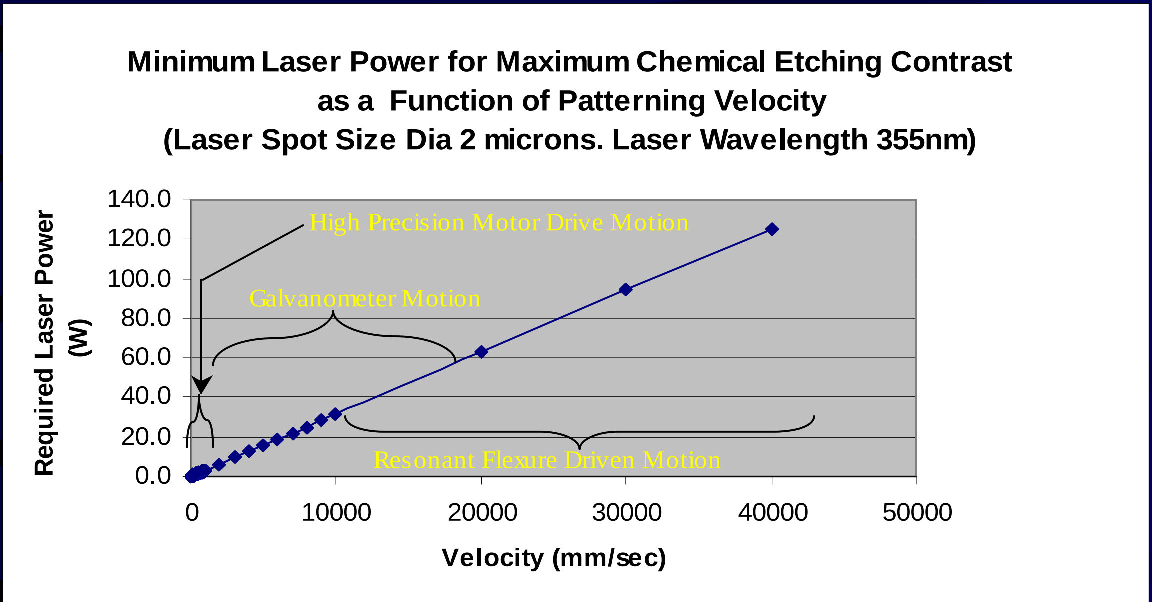
But it wasn't until two years ago that the Defense Advanced Research Projects Agency, the Defense Department's main research and development organization, began funding their project.

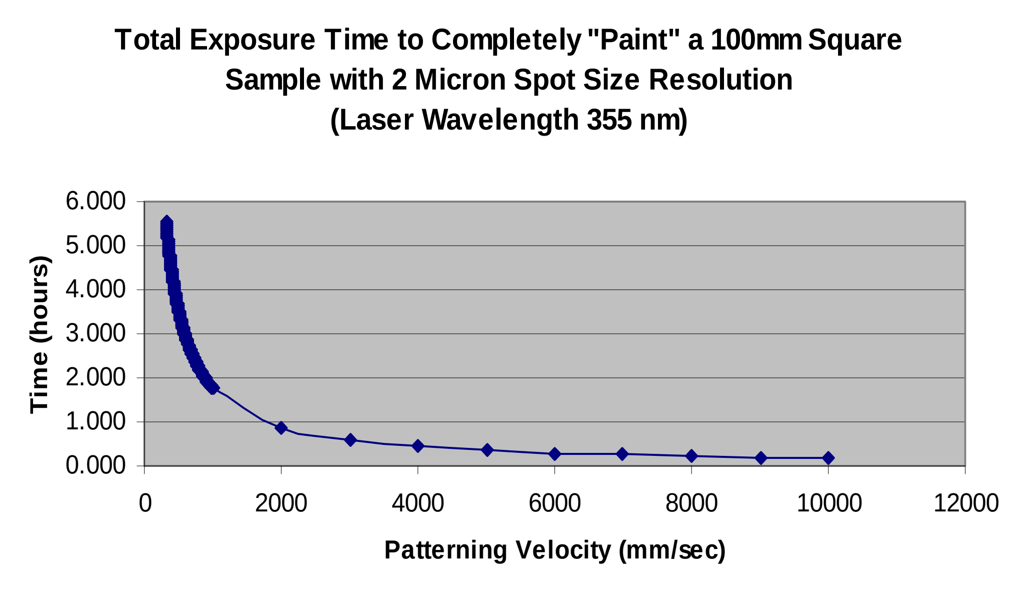
It's unclear when the first glass-ceramic satellite will be deployed, Janson said. The timing depends on further funding.

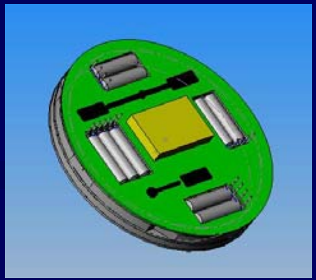
"We're trying to get additional funding," Janson said. "There's no timetable. We could make the first operational satellite in three years if we get the funding."

Henry.Helvajian@aero.org
Department of MicroNanotechnology

Fabrication Performance Metrics: Based on Data from Existing PSGC Material Formulation



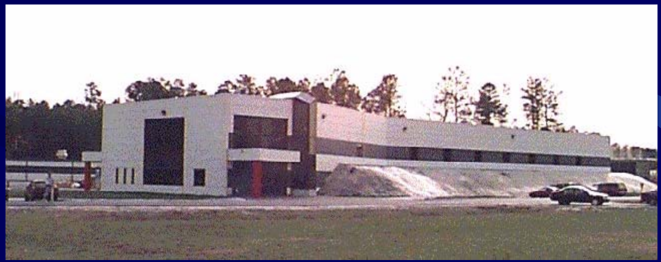




COSA Vehicle

High Throughput Manufacturing at Patterning Resolution Sufficient for COSA and Nanosatellites.

– With 600 W of UV pulsed laser light, a processing speed of 10 meters/sec with a spot size (resolution) of 11 microns, a 100 mm square surface is completely processed or "painted" in under 2 minutes.



DOE – Jefferson Laboratory Free Electron Laser Processing Facility

1KW UV pulsed laser light in 2006.

THE AEROSPACE CORPORATION

High Throughput
Glass Ceramic Nanosatellite/COSA Manufacturing

- All digital direct manufacturing
- Design alterations are done on the digital model of the vehicle and reflected in the processed part.
- A complete set of COSA vehicle wafers can be patterned in less than 15 minutes.
- Multiple COSA vehicles can be assembled in batch mode in less than 15 hours.
- No processing limitation in area size and shape.
- Do not see physical limitation to satellite size and weight.

Conclusion

- JLAB equipment procurement on schedule.
- Software control program on schedule.
- Aerospace on schedule to deliver & install the JLAB module in July, 2005.
- Aerospace will begin Commissioning phase in August 2005.
- Aerospace expects full operation system by July 2006

LPM 2005 The 6th International Symposium on Laser Precision Microfabrication
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Frank Livingston, Bill Hansen,
Lee Steffeney, Katherine Venturini

Thank YOU

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