NIF: An Unexpected Journey and Lessons Learned to Secure “Projects of Scale”

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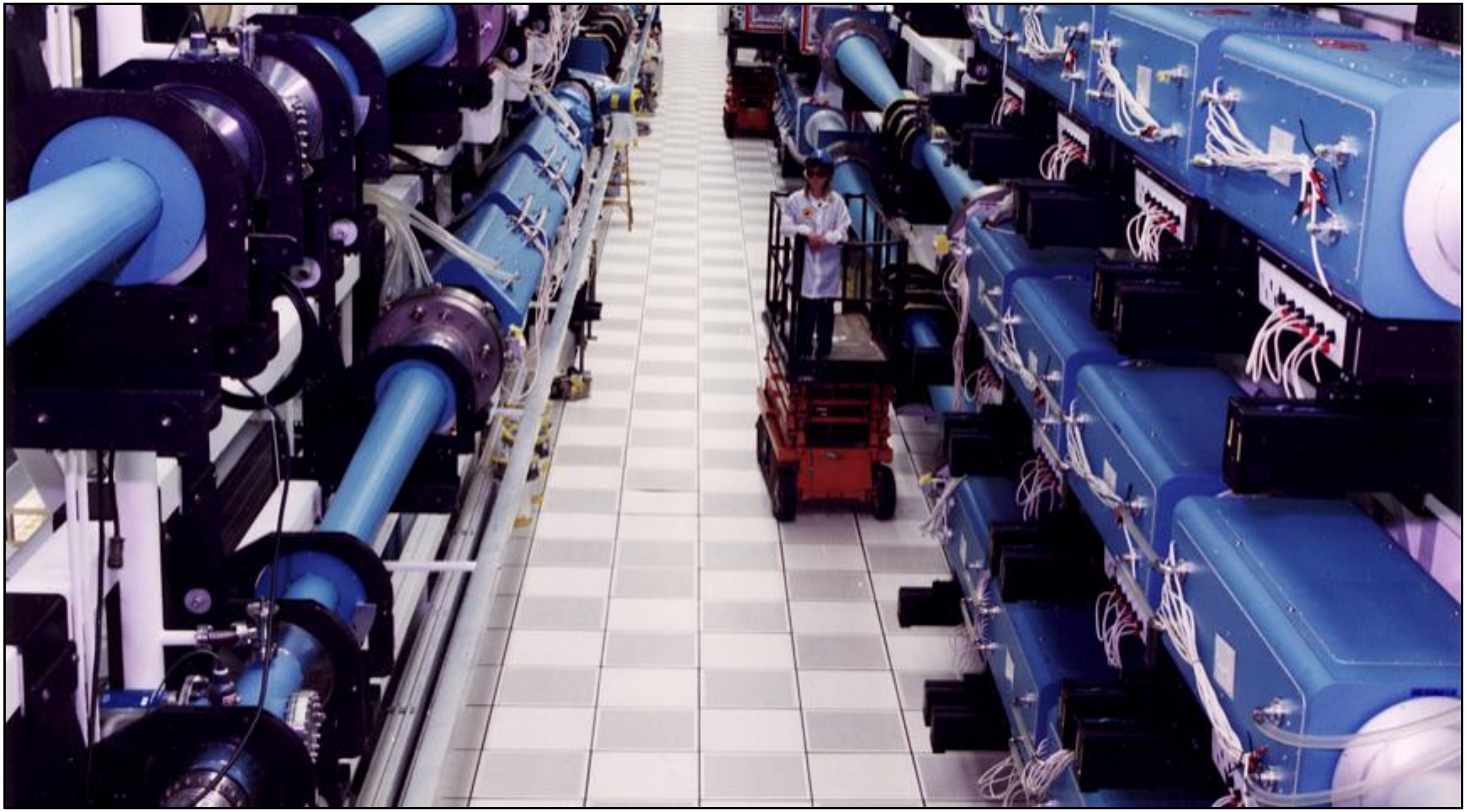
History is important: Look forward but learn from the past

- **LLNL ICF Program History**
  - “100× Campaign” (compressing DT to ~20 g/cm^3 as a focus)
- **Past research programs with lessons to be learned**
  - X-ray laser program (“Star Wars”)
- **National Ignition Facility**
  - background
  - technical approach
  - “political” approach
- **Lessons for future large-scale facilities**

LLNL ICF Program History*

Nova laser at LLNL



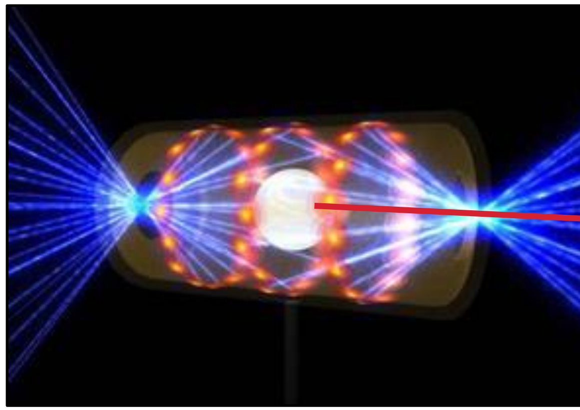
* Any inaccuracies are mine

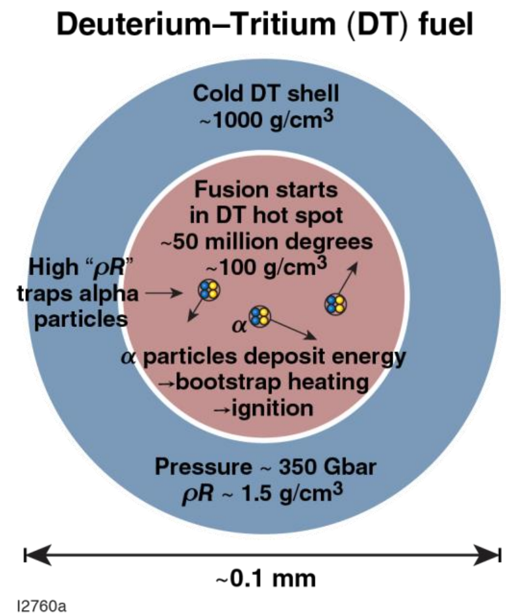
The 1970s was a decade of laser building at LLNL culminating in the planned construction of Nova

- **Janus** (two beams at ~100 J/beam)
  first LLNL neutrons! (KMS was first!)
- **Argus** (two beams ~1000 J/beam)
  ~*first modern laser architecture*
- **Shiva** (20 beams at 500 J/beam)
  radiation-driven ablative implosions to high density
- **Nova** (20 beams at 12 kJ/beam)
  ignition and gain

All lasers Nd:Glass with λ = 1 μm with “unconditioned” laser beams on target.

The LLNL (NIF) main fusion approach is laser-produced x-ray drive ("indirect drive")





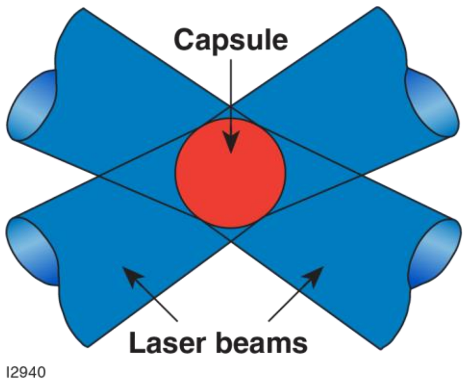
Target design and temporally tailored drive pulse produce an assembled fuel configuration

What was the motivation?

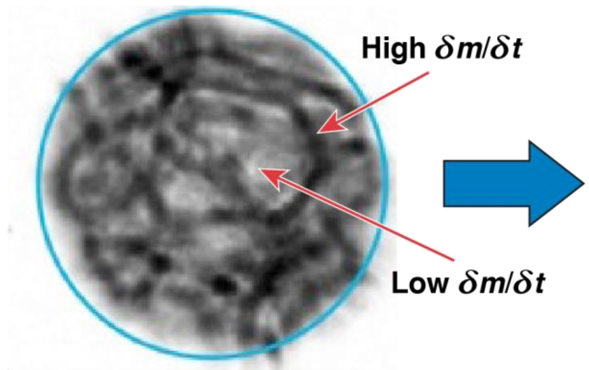
- $P_{ign} \sim (E_{fuel})^{-1/2}$
- **NIF has achieved ~350 Gbar**
- **Alpha heating of fuel demonstrated (~55 kJ)**

In the 1970s direct drive faced many scientific challenges

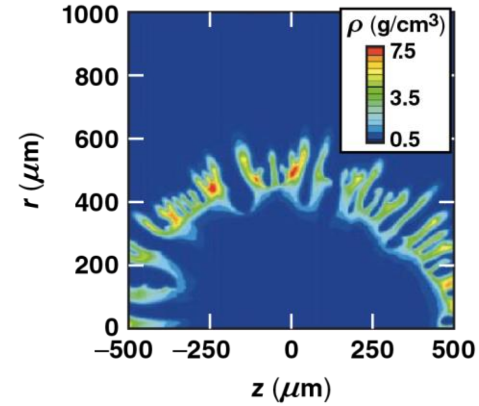
Direct-drive target



"Unsmoothed laser beam



Shell breakup with high ($R/\Delta R$)



- **Direct-drive issues**
  - **hydrodynamic instabilities: $A(t) = A_0\, e^{\gamma t}$**
    - **A_0: "seeds" for Rayleigh–Taylor instabilities by nonuniform laser irradiation**
      - **$(\delta m/\delta t) \sim I^{1/3}$**
    - **γ: high growth rates resulting from inefficient (mass removal) electron-driven ablation**
      - **$\gamma = \alpha \cdot (kAg)^{1/2} - \beta \cdot k \cdot V_a$**
        - **$V_a \sim (\delta m/\delta t)/\rho$; A = Atwood # $(\Delta\rho/\Sigma\rho)$, $k = 2\pi/\lambda_{pert}$, g = acceleration**
  - **reduced preheat tolerance (laser interaction takes place "near" DT fuel)**
  - **lower rocket efficiency**
    - **high "exhaust velocity" ($\eta_{rocket} \sim$ 5% to 10%)**

Additional motivations for laser x-ray drive

- **Symmetry control via target design**
  - convergence of 30 to 40 requires $\Delta P/P \sim 1\%$
- **Requires lower-quality laser beams**
  - minimal/no impact of high spatial frequencies on capsule hydro
    - But laser-plasma instabilities depend on beam quality!
- **Improved hydrodynamic stability**
  - x-ray–driven ablation has high mass ablation rates and shallower density gradients
    - $P_{\mathrm{abl}} = (\delta m/\delta t)\, u_{\mathrm{exhaust}}$
- **Improved "rocket efficiency"**
  - "exhaust velocity" matched to implosion velocity
    - some compensation for "geometric losses"
      - $\mathrm{Area}_{\mathrm{cap}} < \mathrm{Area}_{\mathrm{hoh}}$
- **And…….**
  - "LLNL familiar with x rays"
  - energy (IFE) considerations
    - x-ray generation via efficient heavy ion drivers
    - target illumination does not require 4π illumination
      - "wet wall" chamber concepts

The 100× (ρ_{DT} = 20 g/cm^3) campaign was the first major x-ray drive experimental program

- **100× campaign (Shiva laser)**
  - **goal: radiation-driven ablative implosion to achieve fuel densities of 20 g/cm^3 (~100 liquid density of DT)**
- **Method: 1.064-μm irradiation of Au hohlraums**
  - ~200-eV radiation drive
  - high-pressure DT capsule (SiO_2 pusher and CH ablator)
- **Compression diagnostics were limited**
  - rad chem (neutron activation of compressed pusher(^{28}S (n,p)^{28}Al) was the main compression diagnostic
  - nTOF for yield but $\rho\Delta R$ too small for any compression information
- **Preliminary experiments on Argus**
  - **1.064-μm laser; two beams total 2 kJ; "unconditioned beams"**
  - **diagnostics were limited**
    - Dante filtered XRD spectrometer (~5 channels) (~0.1 keV < E_{cov} < 1.5 keV)
    - crystal spectrometer (Au M band (~2.5 keV); time integrated
    - neutron TOF

Harry Kornblum: "Mr. Dante"

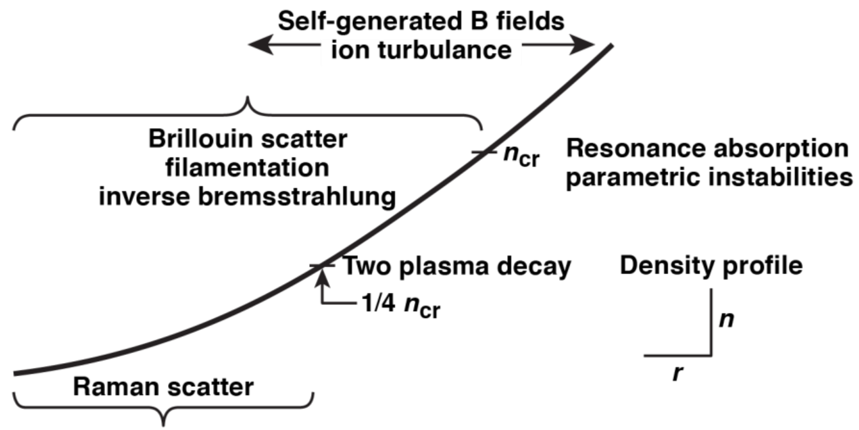
100× campaign discovered the "infrared" catastrophe*

- **Argus "100× preliminary" experiments summary**
  - fusion yields were ~10^{-4} of "expected"
    - $\rho \Delta R$ measurement required neutrons!!!
  - TOF neutron detectors showed evidence of ~100-keV electrons
    - no x-ray diagnostics above ~2.5 keV
    - no scattered-light measurements for laser–plasma instabilities (LPI)

John Hunt: laser scientist and father of present high-power laser architecture

* How to make a 1-μm laser act like a CO_2 laser

“Infrared catastrophe”—laser–plasma interaction physics in the long scale-length holhraum plasma



Many processes compete to determine the coupling.
The mix of these processes depends on the plasma conditions.
The plasma conditions depends on the mix of the processes.

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SRS threshold in inhomogeneous plasma (single beam)

$$I\left(\mathrm{W/cm^2}\right) > \frac{4\times 10^{17}}{L_{\mu\mathrm{m}}\lambda_{\mu\mathrm{m}}}$$

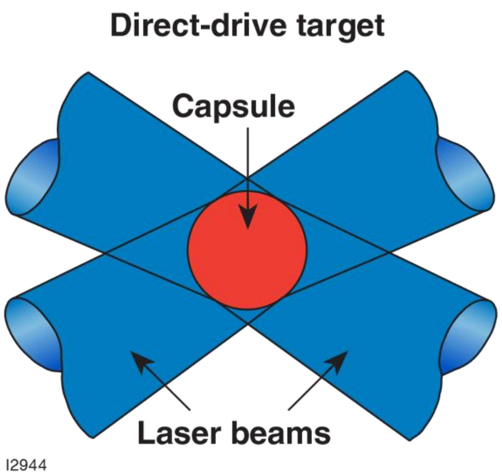
- $L_{\mu m}$: plasma density scalelength
- $\lambda_{\mu m}$: laser wavelength

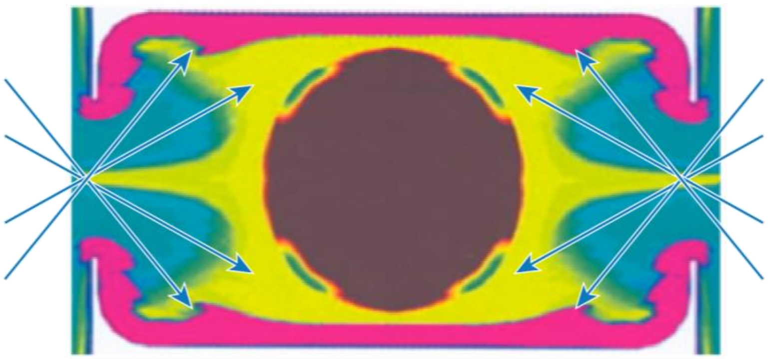
- Many possibilities even without dc magnetic fields
- Resonance absorptions (linear mode conversion at $n = n_{cr}$)
- Resonant coupling of laser light into two other waves
  - ion-acoustic decay instability $\omega_0 \rightarrow \omega_{pe} + \omega_i \; at \; n \cong n_{cr}$
  - Raman instability $\omega_0 \rightarrow \omega_{sc} + \omega_{pe} \; at \; n \lesssim \frac{1}{4} n_{cr}$
  - Brillouin instability $\omega_0 \rightarrow \omega_{sc} + \omega_i \; at \; n \lesssim n_{cr}$
  - 2 ω_{pe} instability $\omega_0 \rightarrow \omega_{pe} + \omega_{pe} \; at \; n \cong \frac{1}{4} n_{cr}$
- There are kinetic versions of these processes (Stimulated Compton Scattering)
- Filamentation

Bill Kruer

"Infrared catastrophe"—laser–plasma interaction physics in the long-scale-length holhraum plasma

SRS threshold: $I\left(\mathrm{W/cm^2}\right) > \frac{4 \times 10^{17}}{L_{\mu m}\lambda_{\mu m}}$ **Single laser beam**





- $L_{\mu m} \sim r_{\text{capsule}} \sim 100\ \mu m$
- $I_{\text{laser}} < 10^{15}$ W/cm^2
  - $I_{SRS} \sim 4 \times 10^{15}$ W/cm^2

- $L_{\mu m} \sim \text{length}/2_{\text{hohlraum}} \sim 1000\ \mu m$
- $I_{\text{laser}} > 10^{15}$ W/cm^2 (Argus was a single beam at each hohlraum aperture)
  - $I_{SRS} \sim 4 \times 10^{14}$ W/cm^2

Given the complexity in LPI, what can be done to mitigate it?

- **Intensity as low as possible**
  - but intensity required for T_{Rad}, P_{abl}
- **Wavelength as short as possible**
  - LPI gain $\sim I * \lambda^2$
    (optics damage threshold decreases with decreasing wavelength)
- **Reduce laser coherence**
  - **spatial incoherence (beam smoothing)***
    - RPP/DPP (spatial smoothing)—mitigates filamentation which can lead to LPI
    - temporal smoothing (SSD, ISI)—further mitigates filamentation—time scale to move speckles faster than speckle sound-speed crossing time
- **Temporal incoherence (Bandwidth)**
  - bandwidth $\Delta\omega > \gamma$ (growth rate) suppresses instability growth
    - requires $\Delta v >$ ~10 THz
- **STUD pulses (B. Afeyan)**

All fusion lasers today operate at short wavelength and employ some level of "beam smoothing."

* Pioneered by Osaka University, LLE (U of Rochester), and NRL; 1993 Dawson Award

Argus hohlraum campaign implications

- **Shiva (10 kJ at 1.064 μm; 20 beams; indirect-drive illumination) would not easily achieve 100× milestone**
  - Shiva designed and *under construction*
  - hope that larger energy would improve physics!
    - "high-level" discussions on converting Shiva to 0.5 μm
      - decision not to pursue shorter wavelength
        - too costly
        - no time
        - Nova planning too advanced
        - infrastructure for large (20-cm-diam) nonlinear crystals not in place
- **Argus Laser Program: study laser–plasma interactions as a function of wavelength (1979)**
  - low (<100-J) energy at 1 μm, 0.5 μm, and 0.35 μm, "unconditioned" beam
    - limited by KDP crystal sizes
  - disk and hohlraum targets
  - laser–plasma interaction (LPI) physics of "large" scale (~mm's) plasmas
  - high-*Z* plasmas [i.e., x-ray conversion efficiency (Dante), hot electrons (FFLEX)]
  - scattered-light detectors and spectrometers
    - SRS: $3/2\lambda_0 < \lambda_{scat} < 2\,\lambda_0$ [$\lambda_0 = 1\ \mu$m (λ_{scat} ~1.5 μm to 2.0 μm)]
    - SBS; $\lambda_{scat} \sim \lambda_0$ (λ_0 ~ 1 μm)
    - 2 ω_{pe}: 2 λ ~$2/3\lambda_0$ [for λ_0 ~1 μm ~ 0.67 μm (3/2 harmonic or 2 μm)]

Shiva 100× campaign results led to the cancellation of Nova

- **Low yield required significant diagnostic and technique development (and time!)**
  - ultra-sensitive detector for compression measurements
    - neutron activation of Si [$^{28}Si(n,p)^{28}Al$]
    - fast rabbit system ($t_{1/2}$ ~ 2.24 minutes)
    - efficient collection of pusher debris (~25% of mass)
    - coincidence detector [NAI (γ ray) and plastic scintillator (β ray) with extremely low BKG]
- **General consensus that Nova would not achieve fusion ignition/gain**

DOE cancelled Nova—the end of ICF Program at LLNL !?

Lessons learned from 100× Campaign

- **Reliance on numerical simulations in "untested physics" regimes**
  - overconfidence in modeling/simulations
  - insufficient peer review
- **Leadership consisted of a facility/driver expert and computational/designer/theoretical physicist**
- **No experimental leadership role**
- **Inadequate diagnostics**

Establishing trust with DOE-HQ and staff is critical !

John Nuckolls "Father of ICF"

But….progress enabled LLNL leadership to restore (via Congress)

- **Argus experiments (<100 J) demonstrated the benefits of short wavelength**
  - Fabre group (Ecole Polytechique) presented short λ results at 1979 APS meeting in Boston (indirect drive classification limited discussion!)
- **Rad Chem demonstrated that the "100×" milestone was fulfilled with a large enough pusher (SiO_2) ρR**
  - yields were still <10^{-4} of calculated

But…..

The performance and mission of Nova were changed

- **Performance**
  - 240 kJ (20 beams) at 1 μm to 30 kJ to 40 kJ (10 beams) at 0.35 μm
    - largest 0.35 μm at time was Argus (~30 J!)—no change in cost (~$176M)

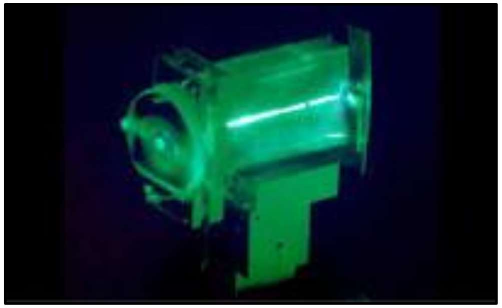
- **Mission**
  - explore physics of indirect-drive ICF and develop a "physics case" for a "high-gain" 10-MJ facility (i.e.; Zeus, LMF)
    - supporting weapons science was *not* a mission
      - nuclear testing was ongoing and was the focus of the weapons program

- **The Novette laser was funded as a "bridge between Shiva and Nova"**
  - demonstrate Nova technology
  - conduct multikilojoule experiments at 0.53 μm and 0.26 μm
  - operated while Nova was under construction
    - Novette two beams to be installed as last two beams for ten-beam Nova

Lessons both good and bad were learned on Novette

- **Positive lessons**
  - **short λ physics (LPI) continue to be positive at multi-kJ laser energies**
    - unconditioned beams
  - **first “weapons” research**
    - first (along with PPPL) laboratory demonstration of x-ray laser*
      - collisionally excited Se laser
      - 30-year anniversary, May 5, 2015!
      - first ICF/HEDP-based Dawson Award (1990)!
  - **laser physics**
    - large-aperture (~20-cm) KDP crystals for frequency conversion
    - demonstration of Nova laser chain performance and component supply chain

Novette Laser



“Soft” x-ray laser

*EUV lithography was derivative program

We Need Diversity

X-ray laser team—30 years later!!

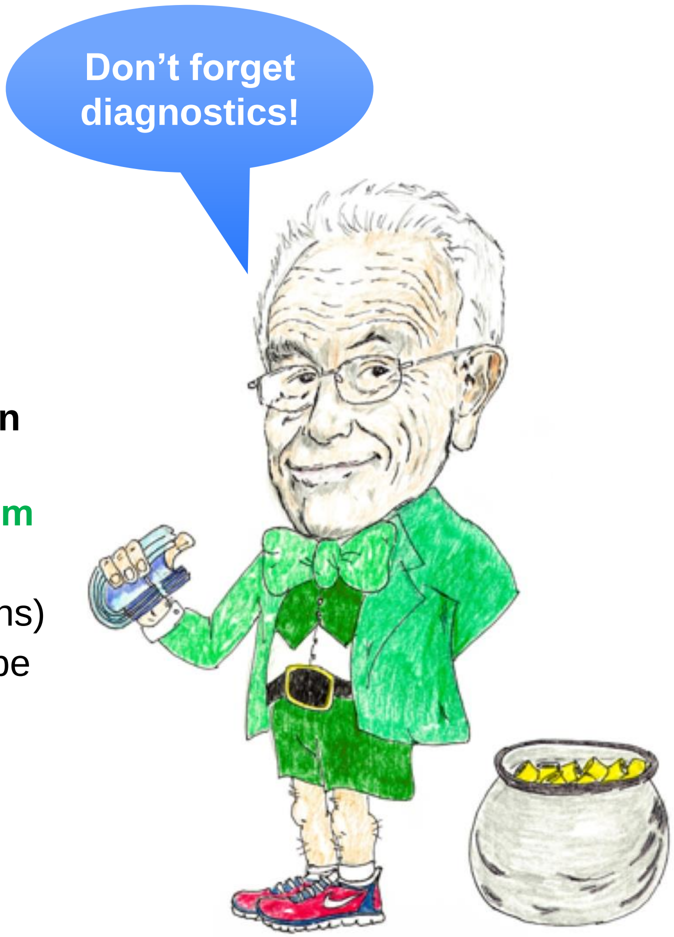
But…

Laser glass manufacturing was flawed and resulted in Pt damage that significantly limited laser energy/power

- discovered when Novette was dismantled to be placed at Nova
  - Novette beams were *last* to be installed at Nova
  - inadequate laser diagnostics!

LESSON LEARNED

- **The experimental program focused on Novette and not in bringing Nova up as an experimental facility**
  - **created a need for the "Precision Nova (PN)" program**
    - full 1.05-μm performance (120 kJ at ~1 ns)
    - enhanced 0.35-μm performance (30 to 40 kJ at ~1 ns)
      - baseline Nova frequency conversion (type 1/type 2) was not efficient—polarization sensitivity!
    - power and energy balance to $\pm$5%
      - first temporal pulse shaping*
    - pointing accuracy (~10 μrad)



* micro-impulse radar (UWB) was derived from PN diagnostic development

Outline

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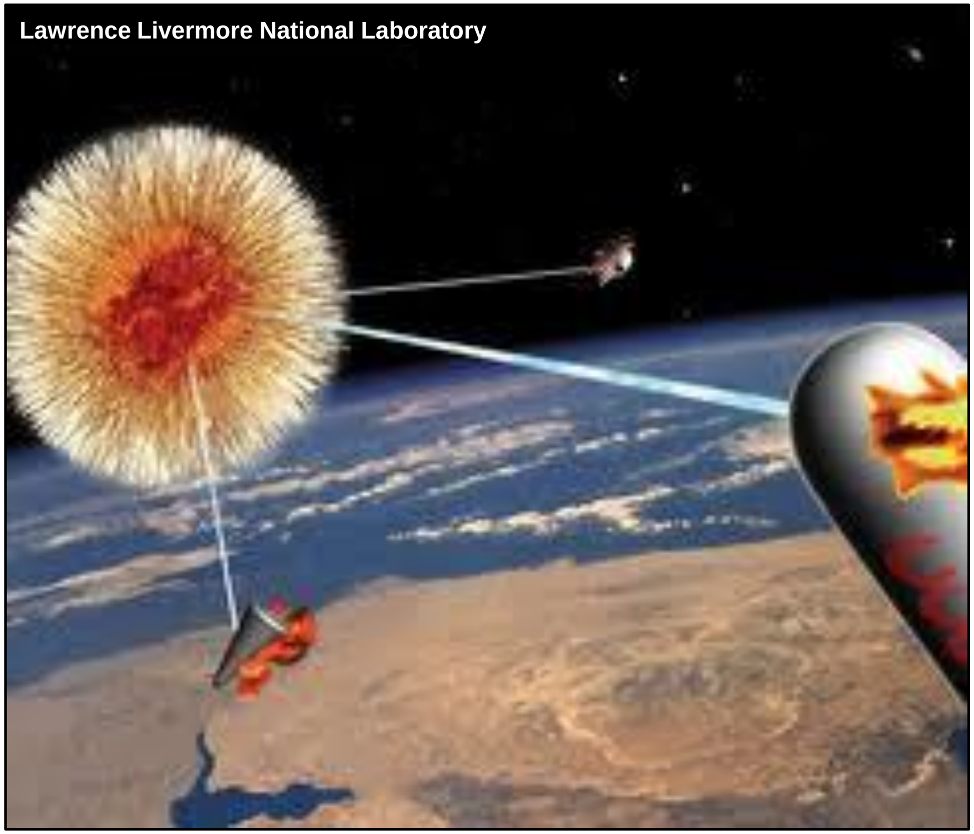
- **LLNL ICF Program History**
  - "100× Campaign" (compressing DT to ~20 g/cm^3 as a focus)
- **Past research programs with lessons to be learned**
  - X-ray laser program ("Star Wars")
- **National Ignition Facility**
  - background
  - technical approach
  - "political" approach
- **Lessons for future large-scale facilities**
- **Future of ICF**

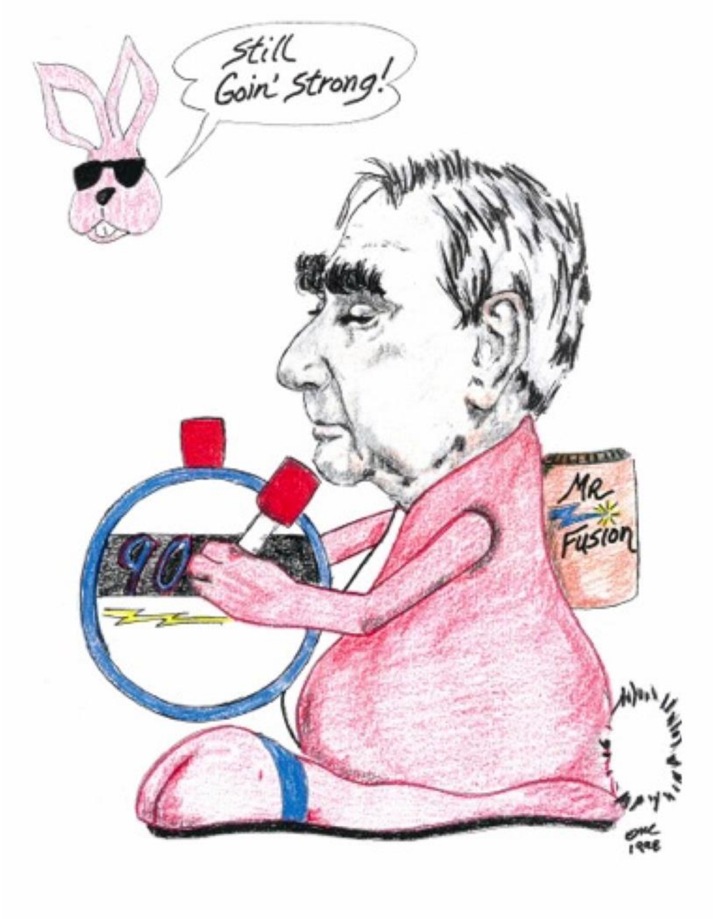
SDI, also known as “Star Wars”



Hank Shay: Early Program leader and former ICF and weapons designer.

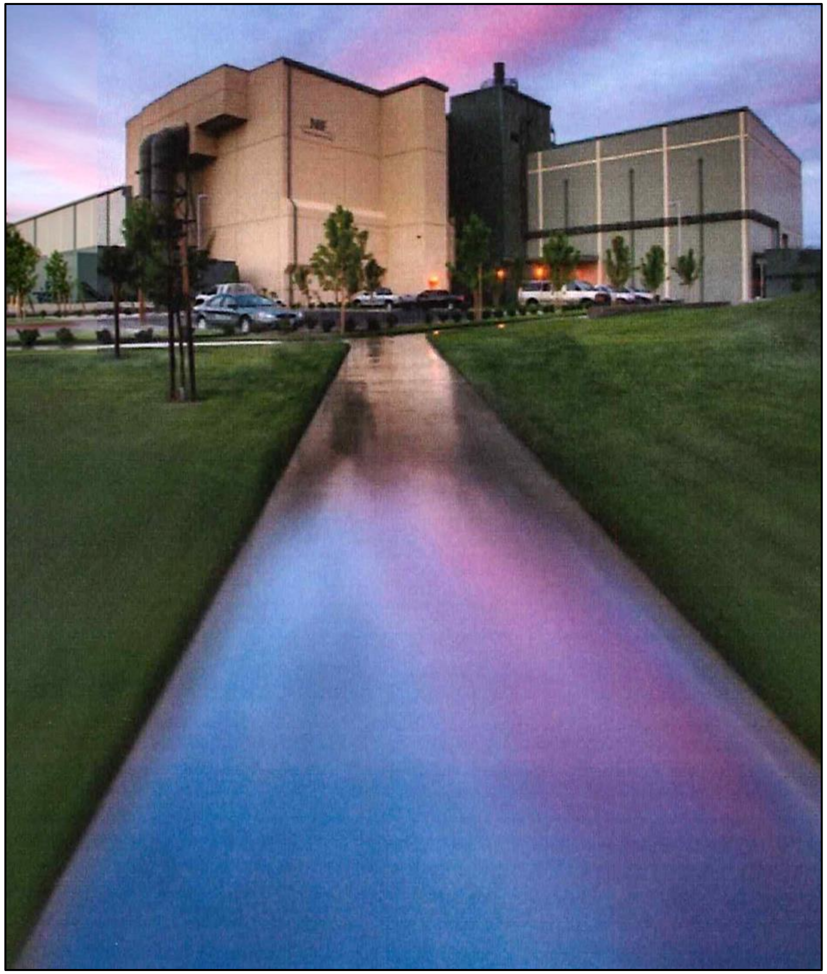
"Star Wars" X-Ray Laser Program shared identical features with 100× Campaign

- **Reliance on numerical simulations in "untested" physics regimes**
  - overconfidence
  - lack of internal/external peer review and culture adverse to self-criticism
- **Leadership consisted of design/ theoretical/computational physicists**
- **No experimental leadership role**
- **Inadequate diagnostics***



*Significant improvements in diagnostics were later made, led by Dick Fortner (Rick Stewart, Mark Eckart)

Modeling, theory, *and experimental expertise* are essential components of a successful program



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- **Lessons for future large-scale facilities**

NIF—Background

The journey to the NIF—the 1980s and early 1990s

- **With the reality of data, the LLNL long term strategy developed in the 1980's focused on the Laboratory Microfusion Facility**
  - 10 MJ, 0.35 μm (target cost ~$250 M)
  - target gain ~100; radiation drive at ~200 eV to 250 eV
- **Nova developed into a physics and user facility**
  - the Pt glass problem was fixed and glass replaced (J. Campbell)
    - full 1.06-μm performance (120 kJ at 3 ns)
    - 3ω frequency conversion was "fixed"
  - a second target chamber added (Novette Target chamber)
- **Progress in direct drive at LLE and NRL**
  - "beam smoothing"
    - ISI and SSD
    - beam smoothing valuable to ALL the laser community
      - Nova was the LAST large laser to adopt!
  - KrF (0.26 μm) at NRL and tripled Nd:glass (0.35 μm) at LLE
- **LANL abandons CO_2 and initiates KrF (Aurora) laser**
  - Aurora designed as a KrF laser at ~ Nova-scale energy

Strong and effective leadership at DOE-ICF was critical

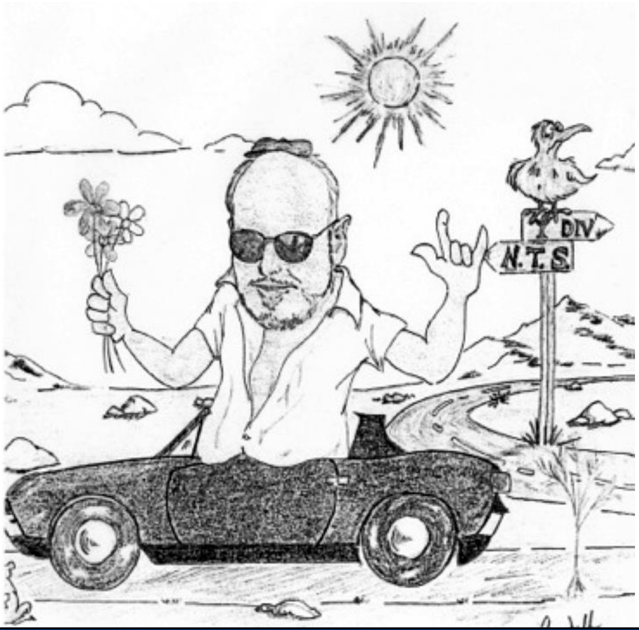
Antares CO_2 Amplifier

AND…….

Halite/Centurion

- **Innovative use of nuclear explosives to explore the implosion physics relevant to ICF**
  - conducted by LANL/LLNL
  - remains classified
    - Steve Haan, Max Tabak and others made major contributions

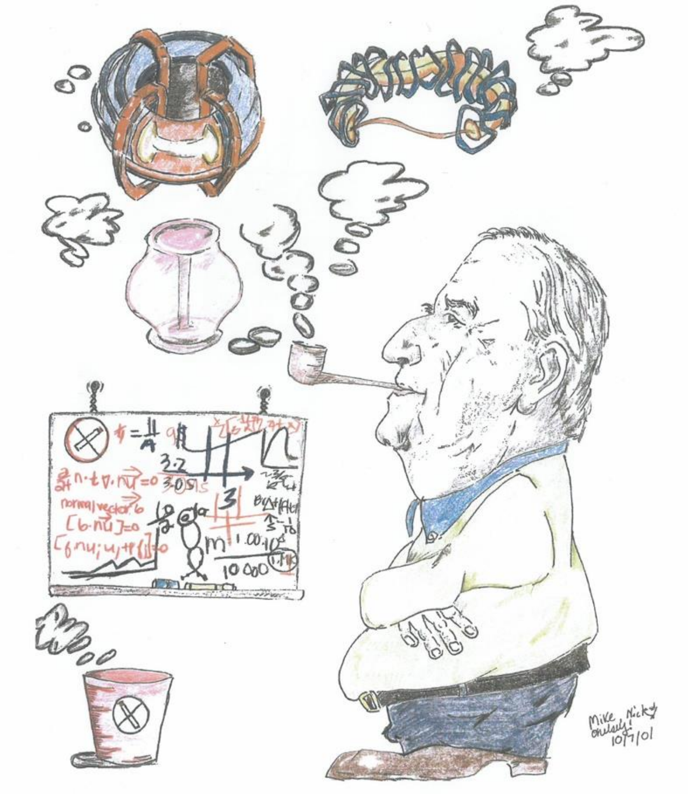
- **Success resulted in Congressional demand for NAS review of Program**
  - chaired by Steve Koonin
  - from 1989–1990



Hal Alhstrom: leader of ICF experiments/diagnostics moved to LLNL experimental leadership of H/C; E. Storm also made major contributions

The Journey to NIF—the 1990s

- **Koonin's NAS review was pivotal**
  - **LLNL proposed LMF as the next step**
    - LMF: 10-MJ laser with target yield of 1-GJ (gain 100)
    - NAS rejected as too ambitious
  - **Preliminary report suggested "competition between Nova and Aurora"**
    - Nova was an operating facility!
    - Aurora was NOT even built let alone an operating facility!



Marshall Rosenbluth "the Pope of Plasma Physics" and key member of Koonin NAS

NIF—Technical Approach

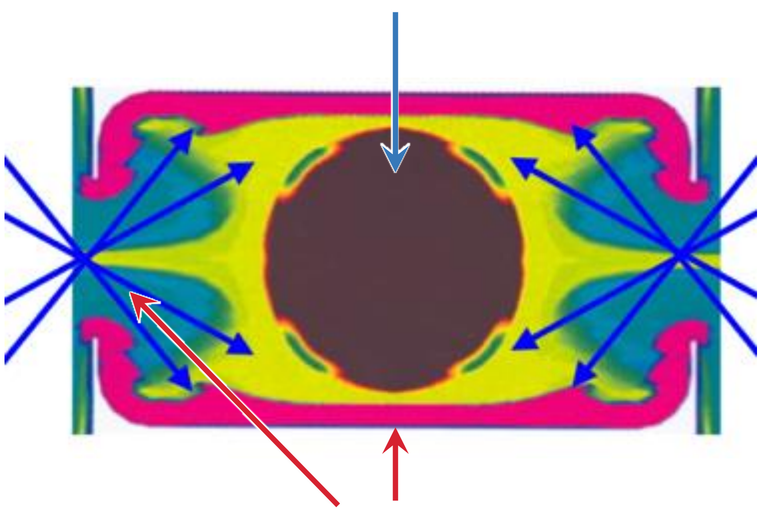
Early encounters with the NAS committee and its Preliminary Report altered LLNL Strategy

- **The *Nova Upgrade* became the focus with indirect (x-ray) drive**
  - ~1 MJ at 0.35 μm in the Nova/Shiva building
    - **required a hohlraum peak T_{rad} ~ 300 eV—*demonstrated on Nova***
    - ignition and modest gain (~10)
- **Needed to better inform the committee and stakeholders of technical progress (and history)**
  - NAS recommended a standing independent review committee (ICFAC)
  - recognized of the need for a "Technical Contract"
    - program plan that guided ICF research on Nova and would be accepted/endorsed by the community
    - established milestones
      - ICFAC and other stakeholders could follow progress/setbacks
  - need to improve Nova performance
    - precision Nova
- **Direct drive was too immature as a baseline and NO pulsed-power approaches showed promise**
- **Developed Nova into a user facility with increased emphasis on the <u>Weapons Program</u>**
  - limited basic science programs were also initiated for outside users
    - the first laboratory astrophysics conference was held in 1996 (sponsored by the LLNL ICF Program)

The final NAS report endorsed the LLNL strategy and recognized Nova as a premier ICF facility.

The Nova Technical Contract (NTC) became the ICF Program plan for indirect drive

- **Nova Technical Contract**
  - <u>required a point design</u> that specified hohlraum and capsule requirements
  - specified 12 physics goals (limited implosion experiments because of “limited symmetry” available on Nova)
    - hydrodynamic stability
      - RT growth factors (single mode, multimode)
    - symmetry control
      - implosion symmetry control via laser placement in the hohlraum
    - laser–plasma interaction physics
      - absorption [stimulated Brillouin scattering (SBS)]
      - hot electrons [stimulated Raman scattering (SRS), and fillamentation]
      - **LPI scaling was controversial**
- **NTC was endorsed by the ICF community, ICFAC, and DOE**



Hohlraum physics

- **LPI**
  - **hot electrons**
  - **absorption**
- **Symmetry control**

<u>NTC did not eliminate risk</u> but addressed the physics issues that Nova could explore—there were no cryogenic implosion milestones!

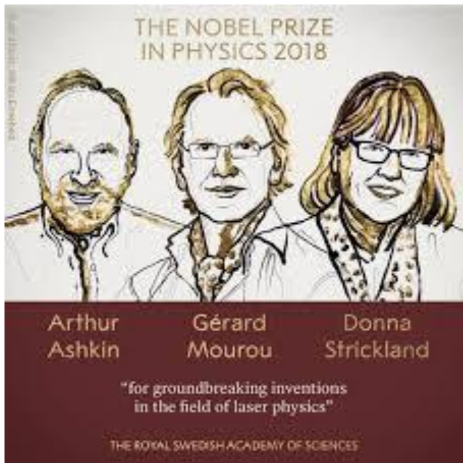
The Nova Technical Contract (NTC) became the ICF Program plan for Indirect drive

- **Precision Nova was successful**
  - first to emphasize power balance, temporally shaped pulses, and develop needed diagnostics
  - exceeded power/energy and pointing specifications
  - added beam smoothing (LLE help!)
- **Nova became an effective user facility**
  - **~1500 experiments per year**
    - two target chambers were essential
  - **the Weapons Program conducted over 50% of experiments with ~50% by primary division**
  - **the ICF Program completed the "technical contract"**
    - **LANL and SNL played a significant role**
  - **extensive diagnostic development**
    - framing cameras, neutron spectroscopy, etc.
  - **limited but innovative Science Campaigns**
    - laboratory astrophysics
    - equation of state (EOS)
    - high-field physics
      - first PW demonstrated
  - **Numerous awards**
    - three Dawson Awards
    - five excellence in Weapons Physics Awards
    - two Best of the Best Popular Science Awards
      - petawatt laser
      - micro-impulse radar (UWB)
    - >20 Research and Development 100 awards

DOE-Defense Programs became an advocate!

Dave Crandall became head of the ICF Program at DOE (moved from OFES)

High-intensity/high-field research was inspired by the Nova Petawatt*



First Petawatt at LLNL

Figure 1. With the Petawatt laser in the background, Livermore's Michael Perry (left) shows how far the technology has come to UC Berkeley Professor Charles Townes, who co-invented the laser.

UNIVERSITY of ROCHESTER

* 3 of the 4 high-power DEW approaches were made possible, inspired or invented by ICF

A "technical contract" was also developed for the next-generation laser: Beamlet

- New laser architecture and manufacturing would be required for a "sellable [what will the market (DOE, Congress) accept] program"
  - Nova was ~\$12,000/$J_{0.35\ \mu m}$ in FT2000 dollars
  - a MJ class, 0.35-μm laser would be >\$10B (with additional funds for a "nuclear target area")

The 1.8-MJ NIF would cost ~\$22B + target area.

Cost-effective, MJ-class fusion lasers required several "miracles"

- **Laser glass manufacturing**
  - "batch" to continuous processing (J. Campbell)
- **Major reduction in number of amplifier stages** (J. Trenholme, J. Hunt,…)
  - Nova: all amplifiers were used in a single pass NIF: all amplifiers were multi-pass
    - regenerative amplifier (regen)
    - four-pass angular multiplexed main amplifier
      - large-aperture plasma electrode Pockels cell (M. Rhodes)
      - "multi-nanosecond" spatial filter
- **Precision and flexible pulse shaping**
  - programmable pulse shaping (R. Wilcox)
    - adapted from telecom industry
    - fiber optic oscillator and transport to pre-amp (regen)
- **Large-aperture KDP crystals for harmonic conversion and Pockels cell**
  - adapted from Russian research (N. Zatzavia, H. Robey)
- **Beam conditioning**
  - adaptive optics (deformable mirrors)

Beamlet demonstrated architecture and advanced technologies needed for the NIF.

The beamlet laser was a major advance in ICF Lasers

(a) (b)

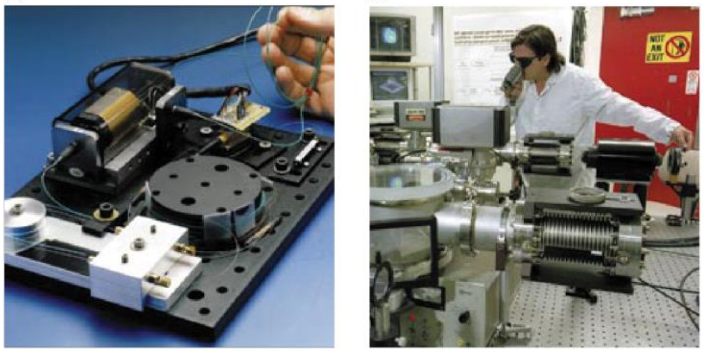


Figure 2 .(a) NIF's low-power pulse is first amplified by these ytterbium-doped optical fibers(seen glowing blue at lower left). (b) The pulse is then amplified to 22 joules by four-passamplifiers (here tested in the laboratory by technician Mike Martinez), which are part of thepreamplifier module (PAM).

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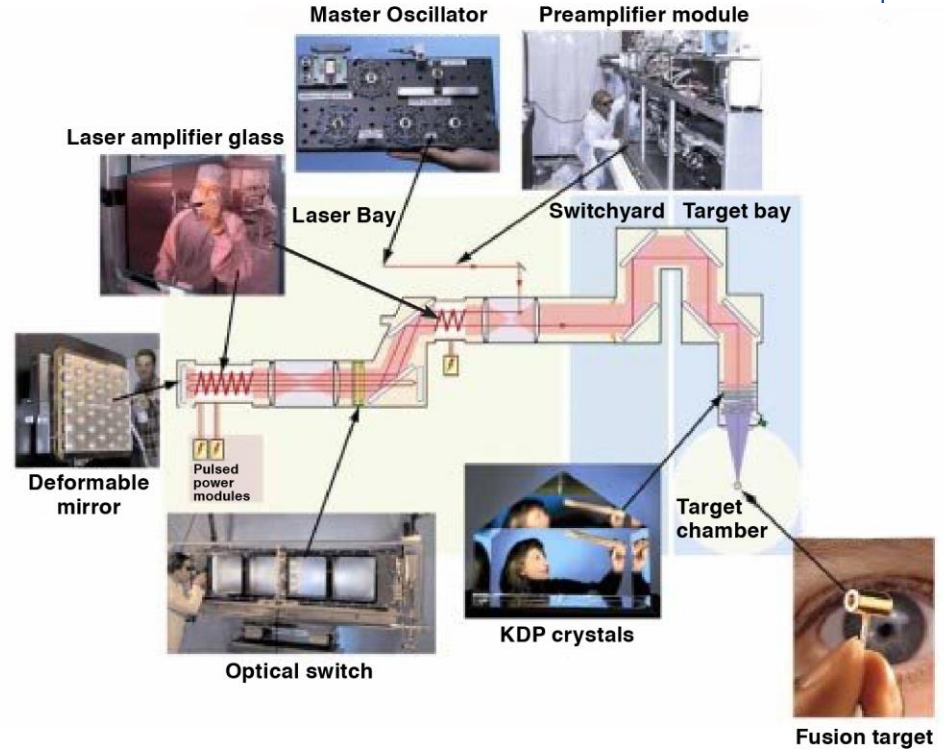


Beamlet energy output (one beam) at 1.05 μm exceeded the 20-beam Shiva laser

Beamlet is now at Sandia!

NIF—“Political Approach”

What happened to the "Nova upgrade"?

- CD0 (Mission Need) was proposed shortly after the final NAS report
- The Nova upgrade cost estimated at $350M
  - Nova/Shiva building to be used to "save cost"
- CD0 was rejected without "prejudice" but commented "*….cost inconsistent with value to DOE and the Nation.*"
- Nuclear testing was still ongoing

Lesson Learned: The NAS report was not enough and broader support and technical progress were required before moving forward with the next facility.

1992 to 1993 were pivotal years for the NIF

- **U.S. ceased nuclear testing**
  - 1032 tests had been conducted
  - nuclear testing was the "organizing principle" for the Nuclear Weapons Program
- **Admiral Watkins (DOE Secretary) signed CD0 (mission need) for the NIF**
  - **last action as Secretary !!!**
  - **Will Happer** (Director of Office of Science and Watkins Science advisor) was a key supporter
  - the mission need emphasized "Nuclear Weapons Effect Testing (NWET)"
  - progress in technical contract was essential
    - ICFAC recommended going forward
  - **increasing use of Nova by Weapons Program**
- **New Democratic Administration**
  - President Clinton, Secretary of Energy O'Leary, and Assistant Secretary for Defense Programs, Vic Reis

The end of testing

- **Labs were generally unprepared for the cessation of nuclear testing**
  – a political decision at the time [warming relations with former Soviet Union (USSR dissolved in December 1991)]—Cold War is over!
  – what to do?
  – CRADA era?
- **DOE-Defense Programs held a series of workshops (1992 to mid 1990s) to discuss the future of the Weapons Complex**
  – a key meeting was held at SNL
    – **Arthur Kerman (MIT)** presented the case for the NIF
    – LLE (McCrory) was a key partner

Stockpile Stewardship was the answer

- **Maintain a safe, secure, and reliable nuclear deterrent in the absence of testing**
  - science based
    - new facilities (NIF)
    - high performance computing (ASCI)
- **1994 Defense Authorization Act establishes SSP**
- **Russia, China, France, UK eventually agreed**

Vic Reis:
Assistant Secretary of Defense Programs and "Father of SSP"

NIF faced many challenges

- **End of the Cold War**
  - spend money on
    Nuclear Weapons Activities?
    - Galvin Committee (consolidate Weapons activities?)
- **Fear of “Big Science Projects”**
  - SSC recently cancelled
- **Democratic Administration with non-technical Secretary (Hazel O’Leary)**
- **Senate Energy & Water and Armed Services Committees chaired by “Saint” Pete Dominici (R-NM)**
- **Strong NGO opposition**
  (“NIF kept LLNL in Weapons”)
  - Tri-Valley Care
  - NRDC
  - Tax Payers against
    Government Waste
  - Rick Spielman

Craig Olsen:
Scientist, dancer, and Pulsed-Power IFE advocate from SNL

Technical, Mission, and Political Strategy was required

- **Technical**
  - point design (agreed to by LLNL and LANL)
  - successful Nova Program
    - Inclusive (SNL,LANL)
    - ICFAC monitored and endorsed progress
      - transparency
  - successful Beamlet Project
  - AWE and CEA support
    - CEA contributed ~$100 M for technology development
    - active users on Nova
- **Mission**
  - ~50% use of Nova experiments by Weapons Program
    - 50% by Primary Division
    - no HEDP for SSP alternative to lasers
      - Z-pinch experiments not yet done

Tony Tether: Former head of DARPA

- **Political**
  - broad political support
    - **<u>all members of CA delegation</u>** signed a letter to the DOE Secretary
      - Critical to get NIF 1st yr Funding
    - strong NY delegation support
      - LLE support
    - open letter by Hans Bethe (Nobel Prize for fusion), Henry Kendell (Nobel prize and founder of Union of Concerned Scientists), Herb York (first director of LLNL, ARPA, Arms Control negotiator)
    - Harold Agnew (LANL director)
    - strong industrial participation
      - e.g., Hoya glass established facility in Hayward CA to produce NIF glass
  - strong local community support
  - standing NIF Committee
    - broad participation (DOD, Science Community, Weapons Laboratories)

Resulting in…….

Secretary O'Leary announced NIF in late 1994

The “greenfield site” for the NIF

NIF Groundbreaking: May 1997

Jeff Paisner

AND…….

NIF today (2020)

- **1.8 MJ, 500 TW at 0.35µm**
  - **2.1 MJ in 2018**
- **~400 experiments/yr**
- **First laboratory plasma with significant plasma “self-heating”**
  - **~56 kJ of fusion**
    - **Onset of alpha heating**

AND…….

The "set" for a 23rd Century Movie!!

Laser Bay

Target Bay

But not powered by Fusion!!!!

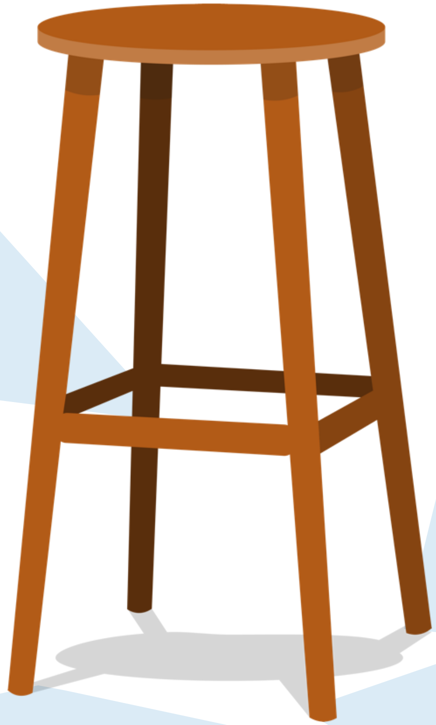
History is important: Look forward but learn from the past

UR LLE

- **LLNL ICF Program History**
  - "100× Campaign" (compressing DT to ~20 g/cm^3 as a focus)
- **Past research programs with lessons to be learned**
  - X-ray laser program ("Star Wars")
  - National Ignition Campaign (NIC)
- **National Ignition Facility**
  - background
  - technical approach
  - "political" approach
- **Lessons for future large-scale facilities**

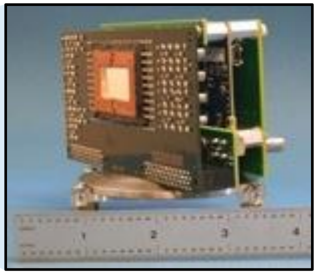
The necessary elements of a successful program

Facilities



Computers

People



Diagnostics

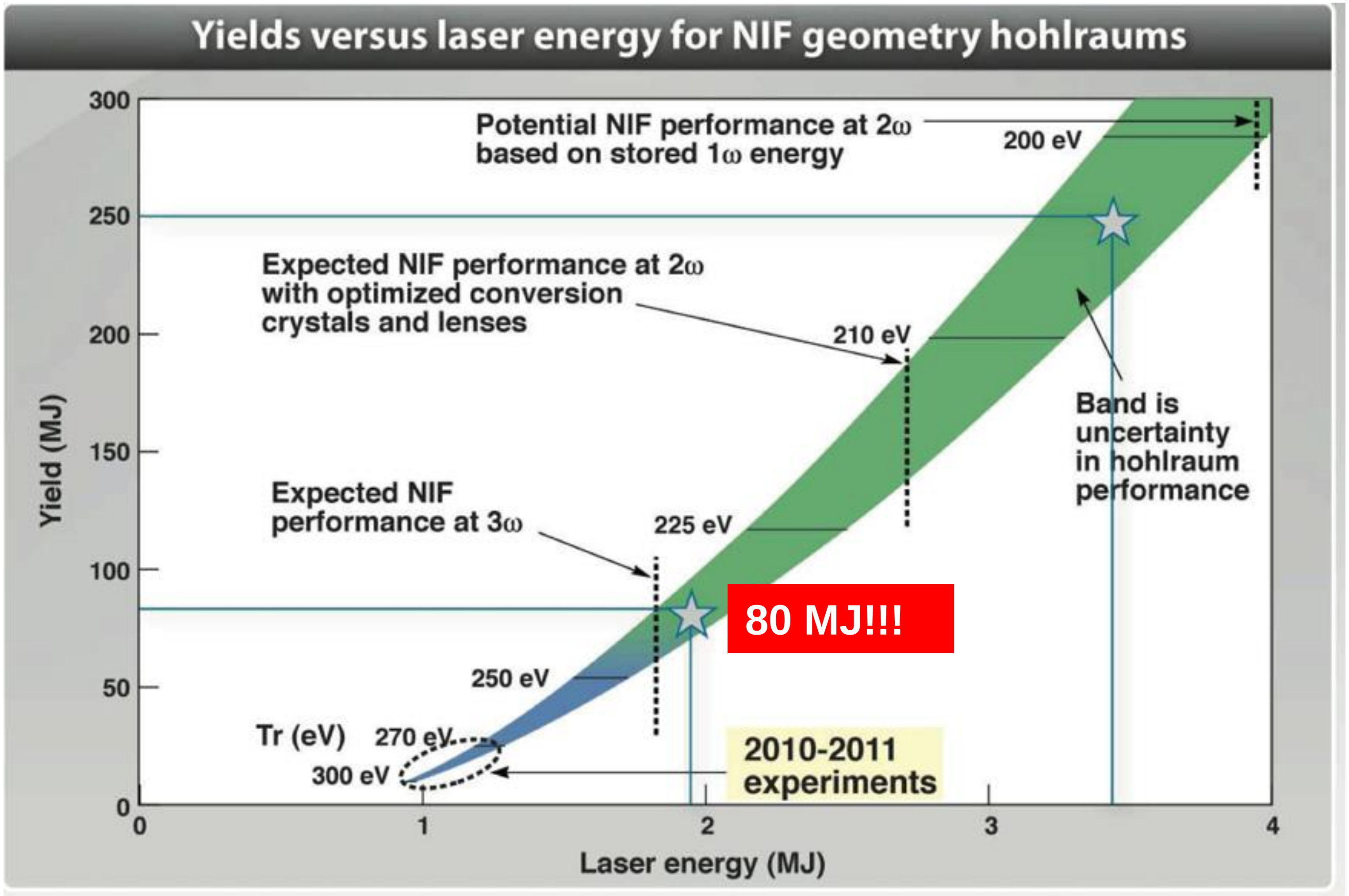
A successful physics strategy for any new facility must be broad and inclusive

- **Program leadership must be inclusive (experimental, theory, computational, driver, target fab)**
  - welcome and encourage criticism
- **Diagnostics must be able to validate, improve modeling**
- **Modeling/simulations must be state of the art and “independently verified”**
- **Research program (“technical contract”) must address physics and test/develop codes in relevant regimes and demonstrate driver technologies**
  - point designs to establish Facility requirements, identify physics and establish “metrics”
  - NIC failure has “raised” the bar
  - **point design will evolve with learning**
    - **encourage innovation and “backup strategy”**
  - utilize all facilities
- **Involve and communicate with broader community and stakeholders**
- **New technologies (drivers) must be demonstrated and “component” supply chain developed**

And…. don’t forget target fabrication!

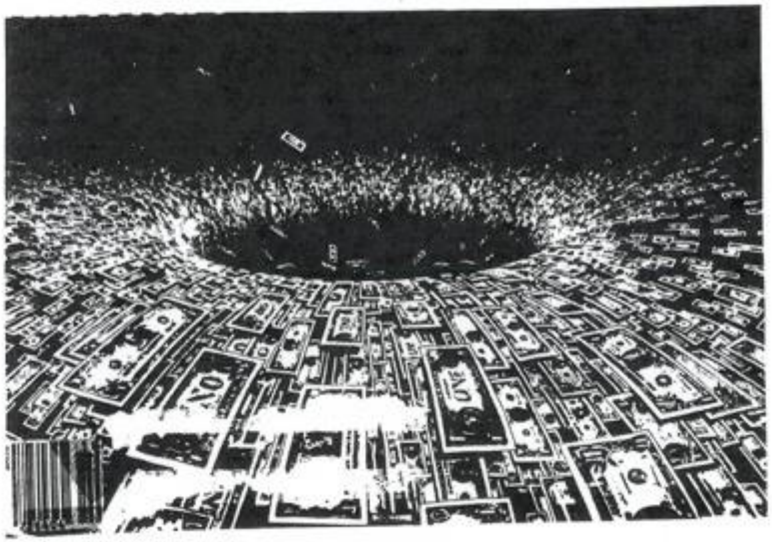
Programs and projects of scale require partnerships and collaborations

Don’t oversell and avoid the HYPE:
e.g., NIF target performance projected in ~2009*



Project/construction leaders for large facilities must be aggressive in cost control

AVLIS–TOONS



© Time Magazine March 84

Demo 85 master procurement plan

Cartoon describing AVLIS "Demo 85"

Successful projects (examples)

- OMEGA and OMEGA EP
- Spallation Source (ORNL)
- ZR
- Redefined Nova
- MESA

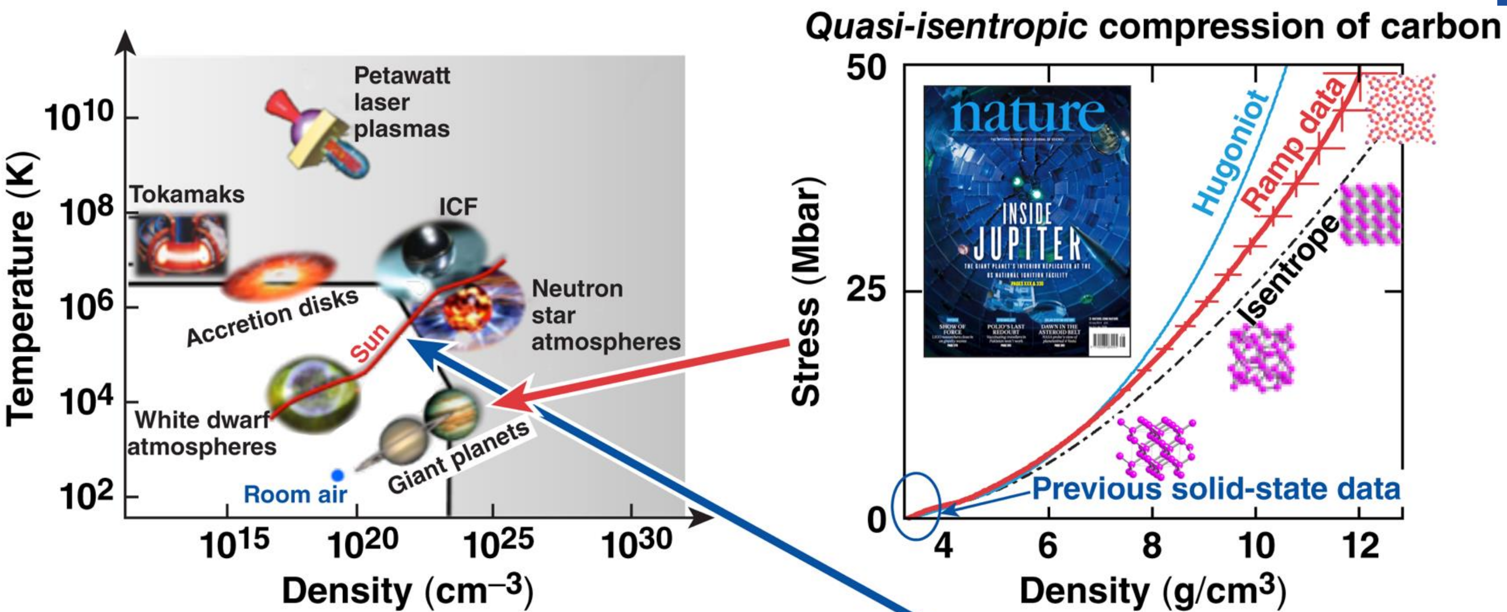
Unsuccessful "fiscal control" Projects (examples)

- NIF*
- ITER
- DARHT*
- ~~SSC~~
- Webb Telescope
- ~~PPPL Stellarator~~

Engineers must ultimately report to physicists— the users who are best able to make trade-offs when issues arise*

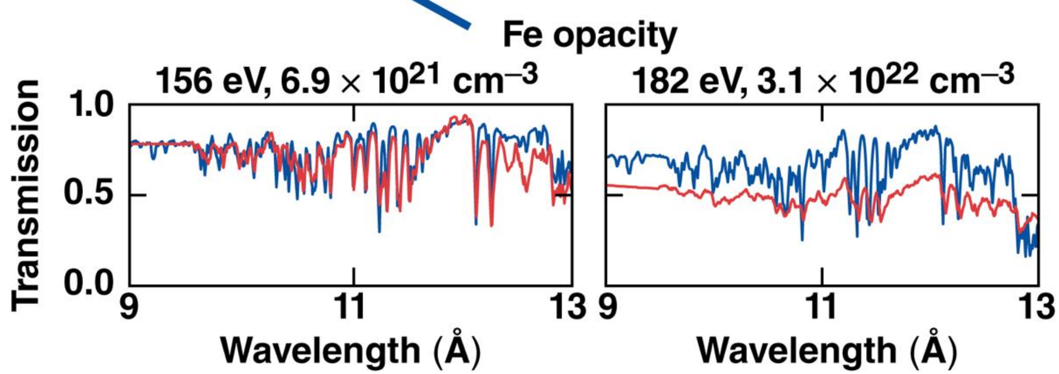
* Tunnel Visions: the rise and fall of the SSC

Expand and broaden the constituency and advocacy (HEDP)



***NATURE* Editorial (2013)**

“Laboratory-based experiments are sorely needed to complement the rapidly proliferating spectral data originating from the latest space telescopes”



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The sponsor must be viewed as a partner

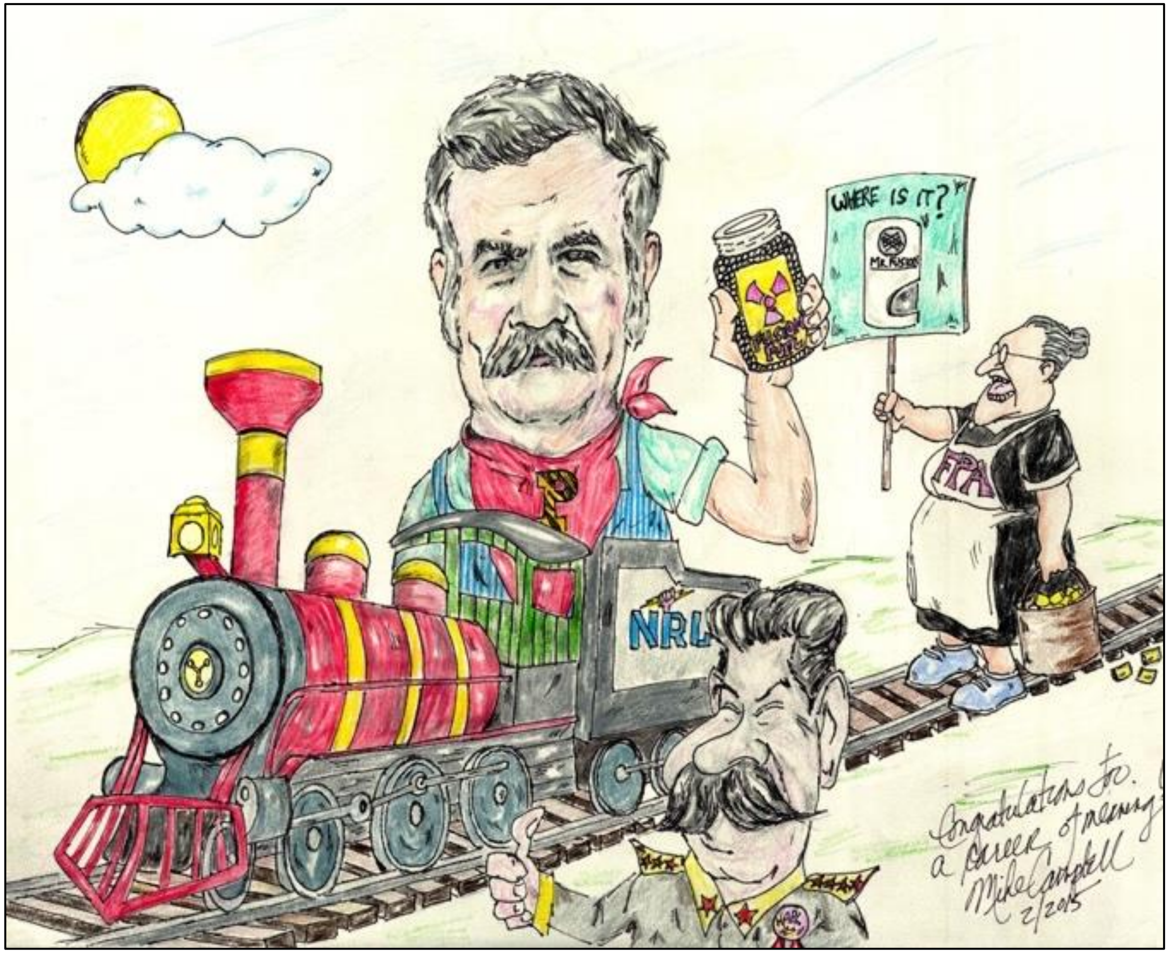
Fusion ignition is analogous to the Wright Flyer; could the Wright Brothers have imagined the 787?

The program must continue to develop technology for the future!

Fusion will require careers and dedication

John Sethian

- Retired NRL
- Fusion researcher >35 years!



Finally….. HAVE FUN in the process!!

A. Young? with Magic Sam and his band

Winner's circle at the Master's or Bob McCrory and friends