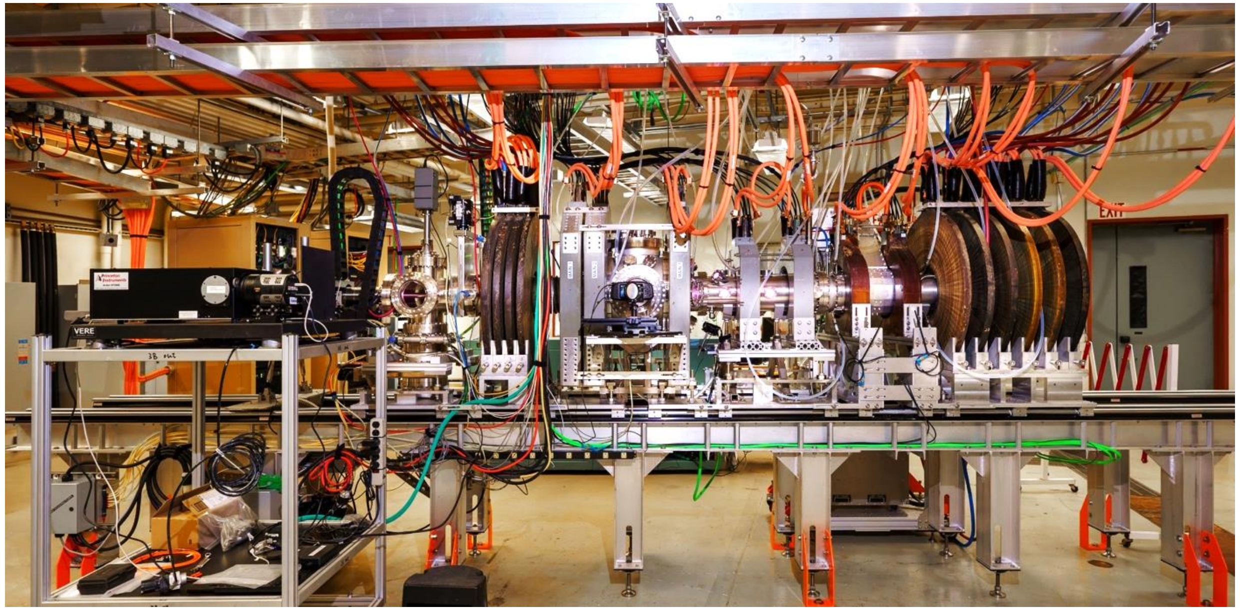
# Fusion Energy: Progress, Challenges and Promise at UC San Diego



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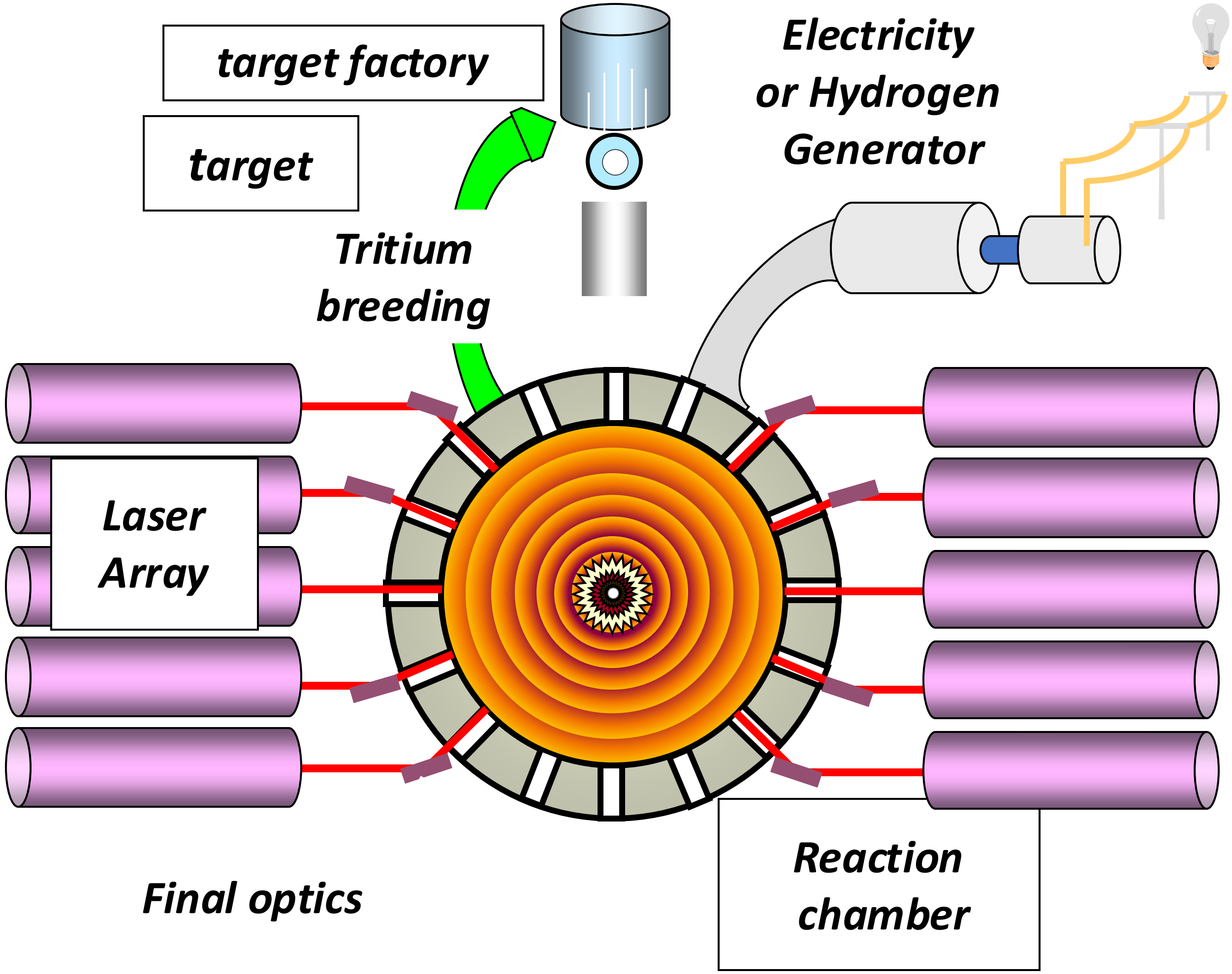
# IFE Progress and Opportunities

# Fusion energy requires $\eta G^1 > \sim 10$ for acceptable levels of recirculating power to the plant

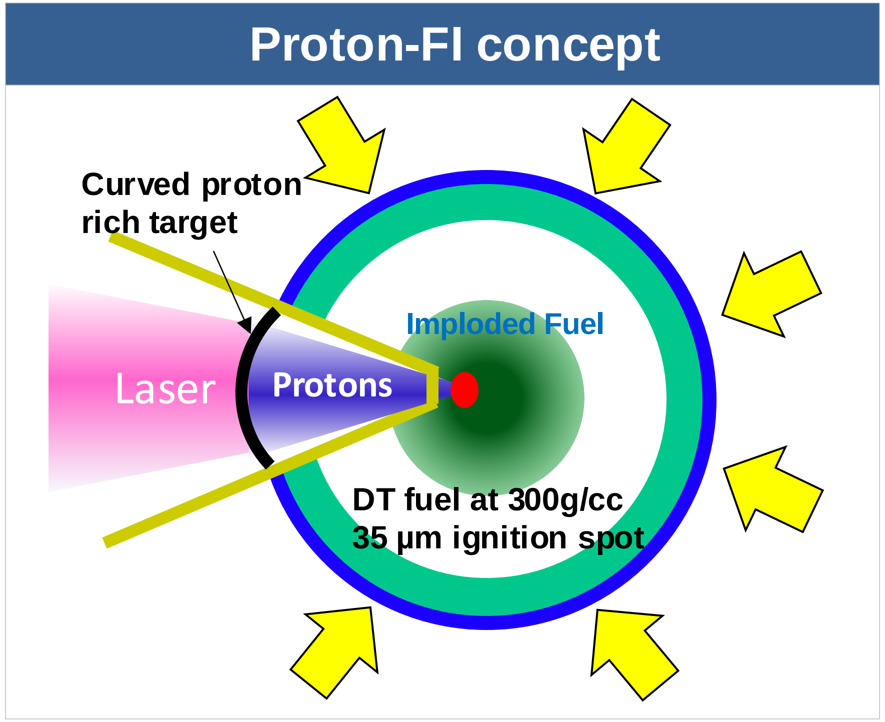


The metric is not G ($E_{driver}$) but $\eta$G ($E_{driver}$)

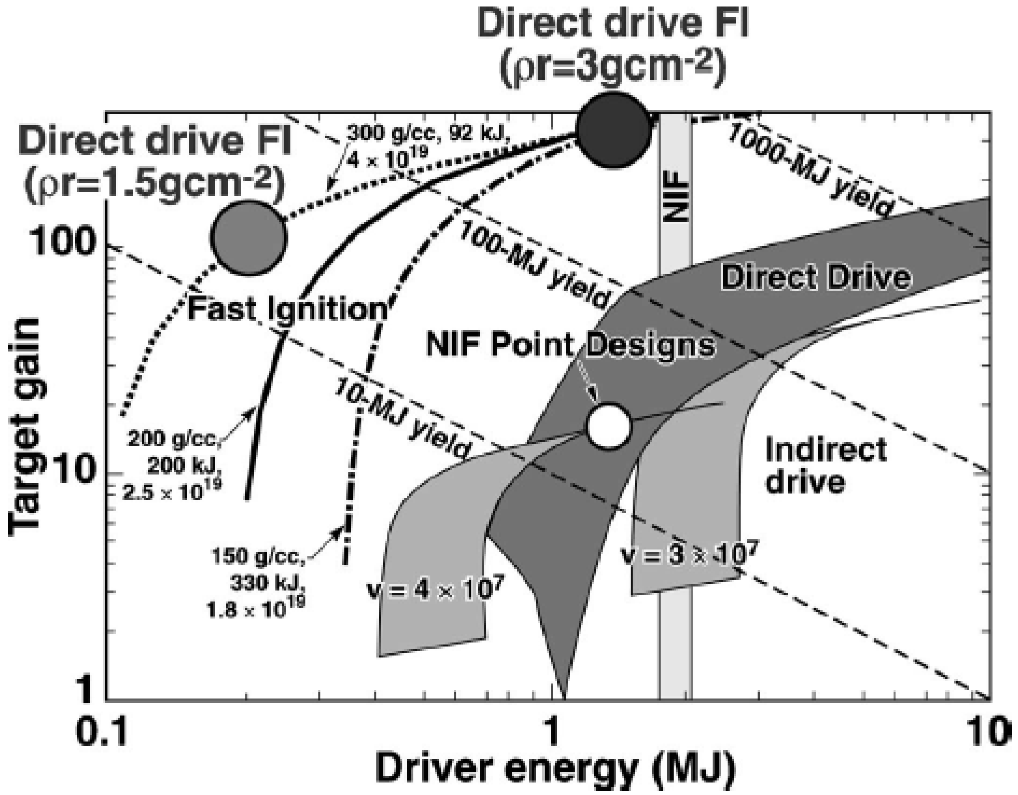
[1] Driver efficiency, η; Target gain, G

Courtesy of Mike Campbell

# Why Proton Fast Ignition and why now?



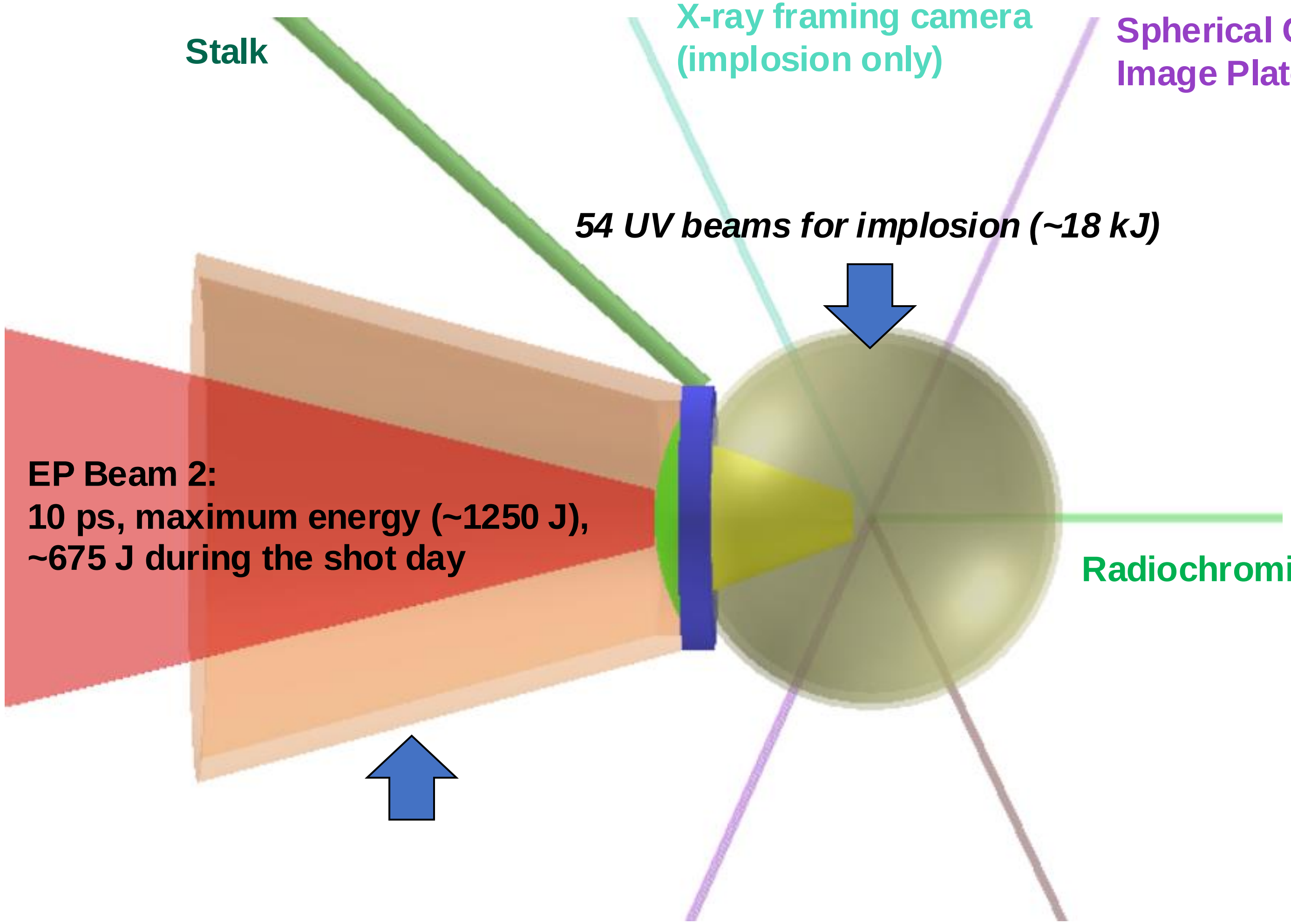
Proton-FI concept



- Higher gain and lower ignition threshold
- Less stringent symmetry requirement
- Stand off distance is challenging

M. Key *et al*., Physics of Plasmas**14**, 055502 (2007)
https://www.laserfocusworld.com/lasers-sources/article/14208866/llnls-national-ignition-facility-achieves-13-mj-fusion-ignition

# First Integrated Proton Fast Ignition Experiment on Omega Facility



Stalk

X-ray framing camera
(implosion only)

Spherical Crystal Imager
Image Plate detector

***54 UV beams for implosion (~18 kJ)***

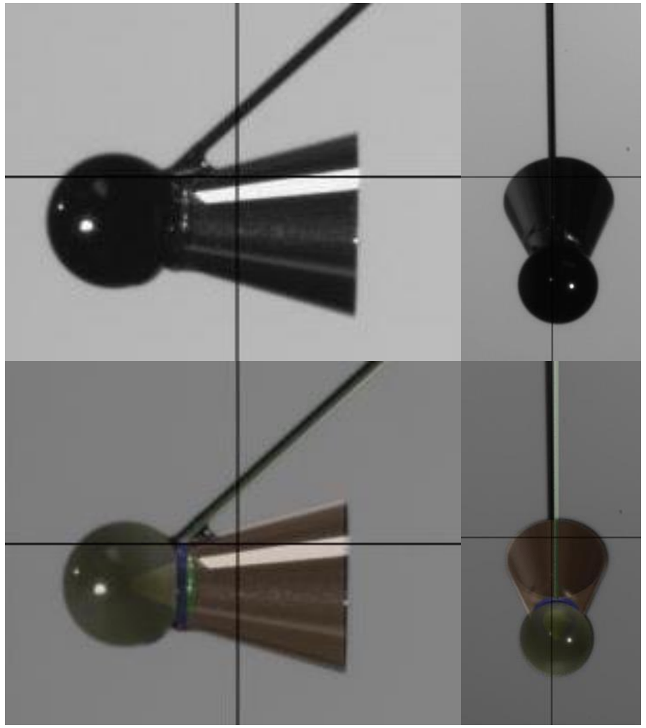
**EP Beam 2:**
**10 ps, maximum energy (~1250 J),**
**~675 J during the shot day**

Radiochromic film stack

Spherical Crystal Imager

X-ray spectrometer

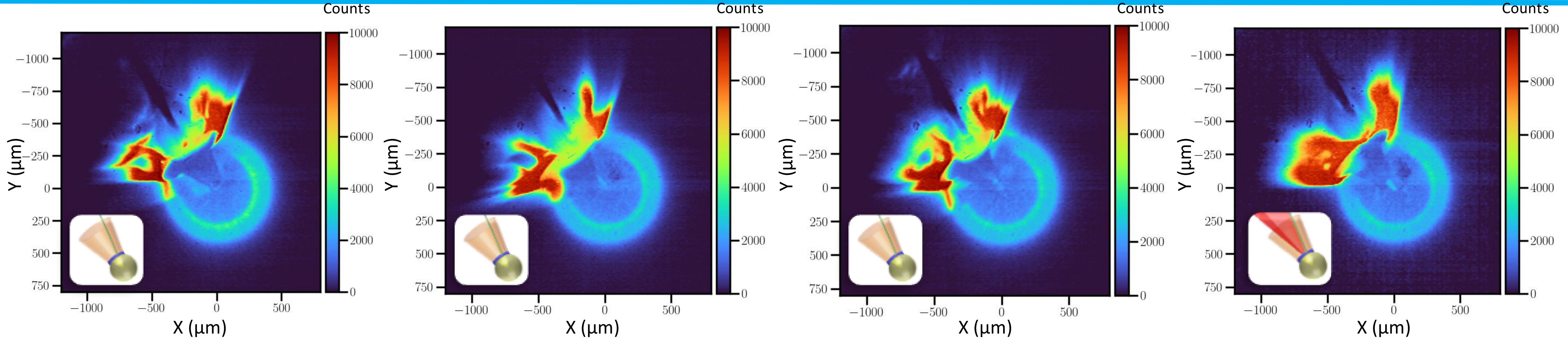
*Target pictures*



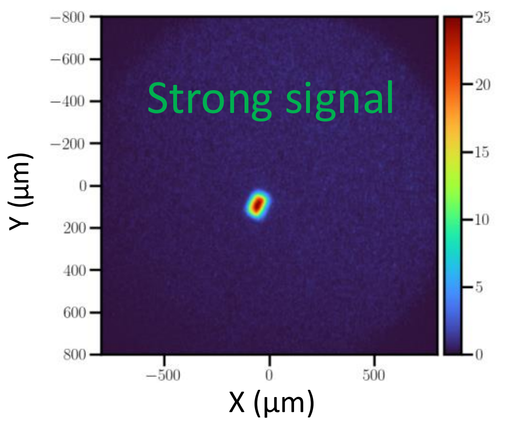
- The capsule and drive designs are based on previous electron-FI experiments on OMEGA[1]

C. Jarrott *et al.*, Nature Physics **12**, 499 (2016)

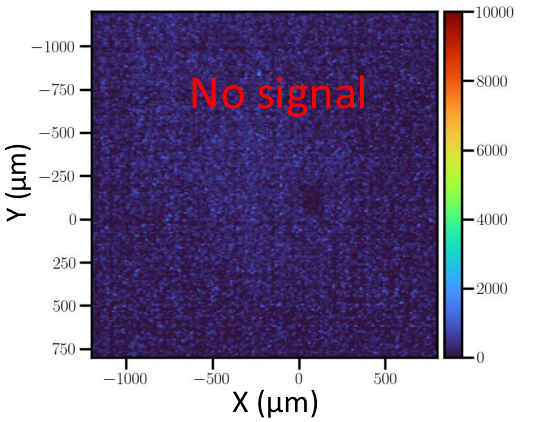
# Results are encouraging



EP-only with a Cu block
(8 keV only – SCI)



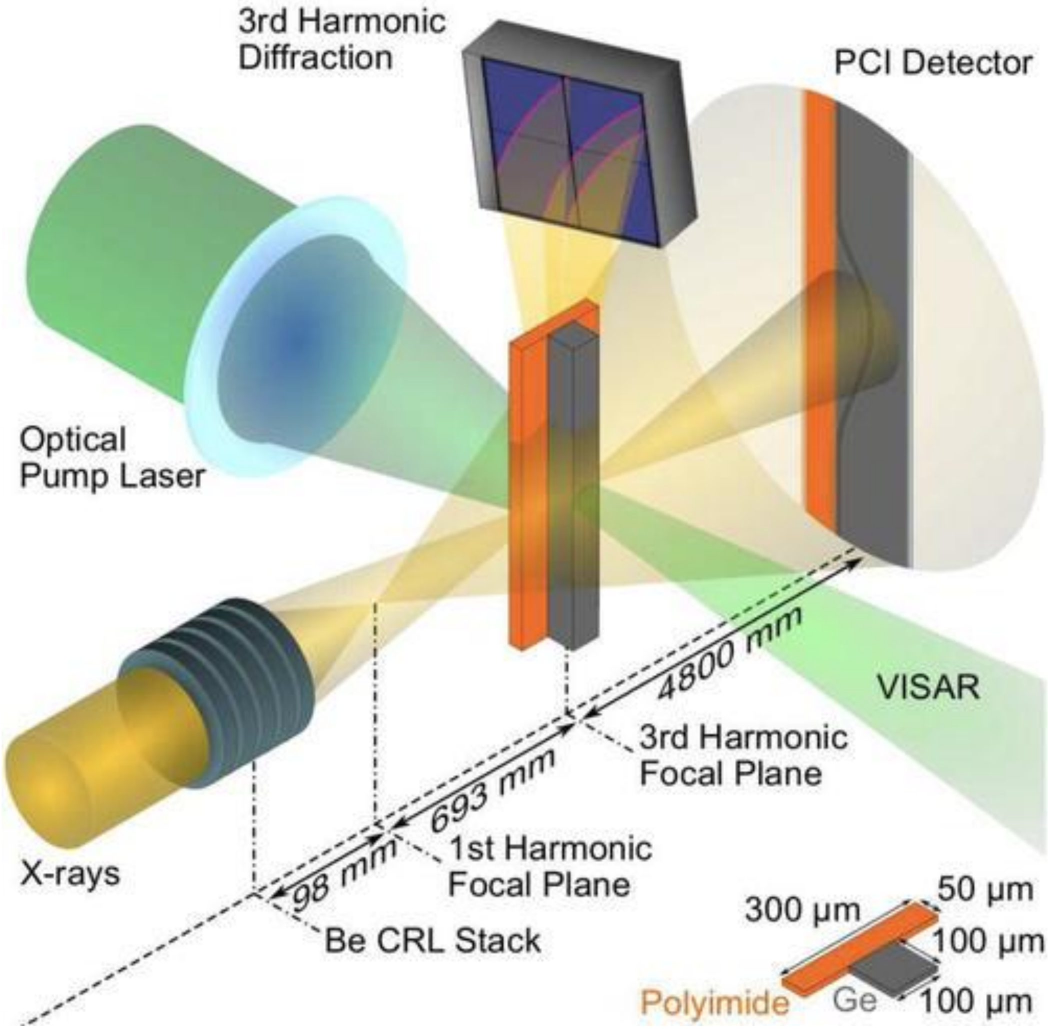
EP-only with a Cu block
(broadband – XRPHC)



- Along the least polluted line-of-sight, a brighter core appears on the joint shot.
- This stronger emission cannot be attributed to additional Cu Kα fluorescence from hot electrons.
- Is this heating due to protons?

# Important questions pertinent to IFE can be addressed using small scale rep. rate facility

- Understand laser foam interactions using varying density foams
- Compare mitigation of laser plasma instabilities with metal and diamond targets
- Target injection and tracking
- Target survivability in extreme environment
- Image foam targets with x-ray or proton radiography.
- Investigate laser-plasma interaction in magnetized plasma.



# New Laser Laboratory for Small Scale IFE Experiments

## Lasers

1. **Elite 15:** 40 J (1064 nm), 20 J (532 nm), 5 ns, 0.1 Hz
2. **Continuum:** 9.5 J (1064 nm), 4.5 J (532 nm), 6 ns, 2 Hz
3. **Quanta Ray:** 1 J (1064 nm), 8 ns, 10 Hz
4. **Arco X25:** 780 – 820 nm, 40 mJ, 35 fs, 100 Hz

## Diagnostics

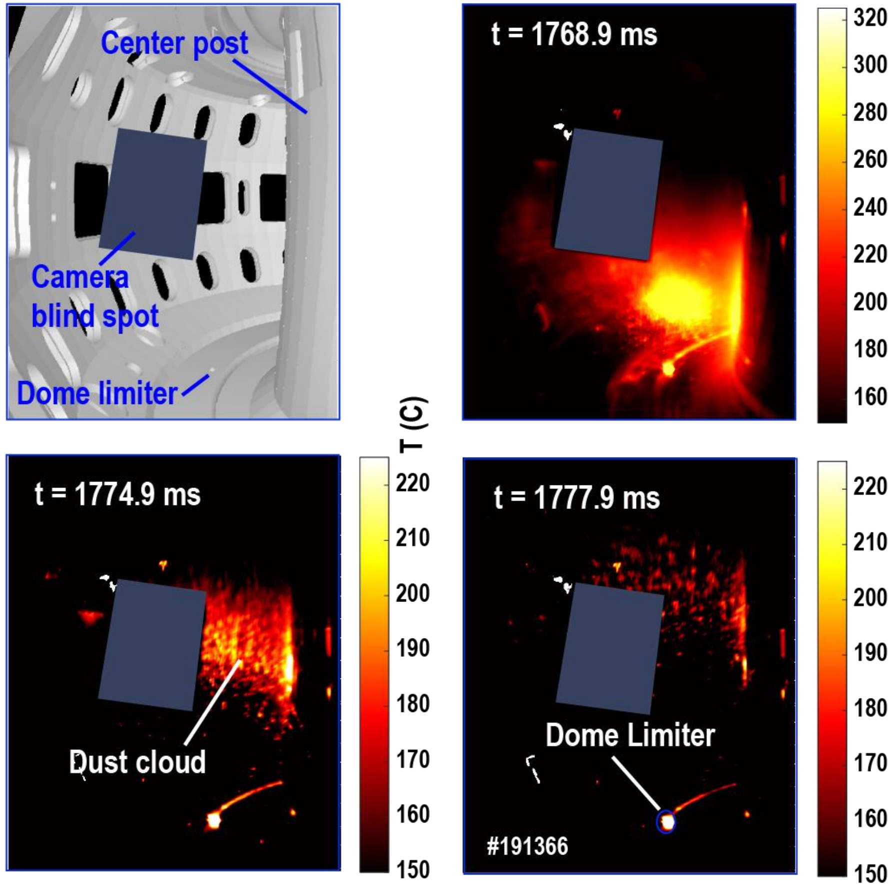
- ➢X-ray spectroscopy (spectral range ~ 0.1 - 80 nm)
- ➢Streaked Optical Pyrometry (SOP)
- ➢Optical Thomson Scattering (TS)
- ➢Interferometry/shadowgraphy

# MFE Progress and Opportunities

# Tokamak runaway electron studies

- Post-disruption runaway electron (RE) formation and wall impact is critical issue for future tokamak reactors.
- Can cause intense localized damage including dust explosion, melt flow, and wall puncture.
- UCSD (PI: Eric Hollman) is leading research on post-disruption RE wall damage studies at the DIII-D tokamak, including:
  - Novel diagnostic development (HXR scintillator arrays, IR time decay analysis, Synchrotron emission imaging, Ar line polarimetry).
  - Development of sacrificial limiter experiments to study details of plasma-materials interactions during RE-wall strikes.
  - Custom code development (RE background plasma simulation code development).

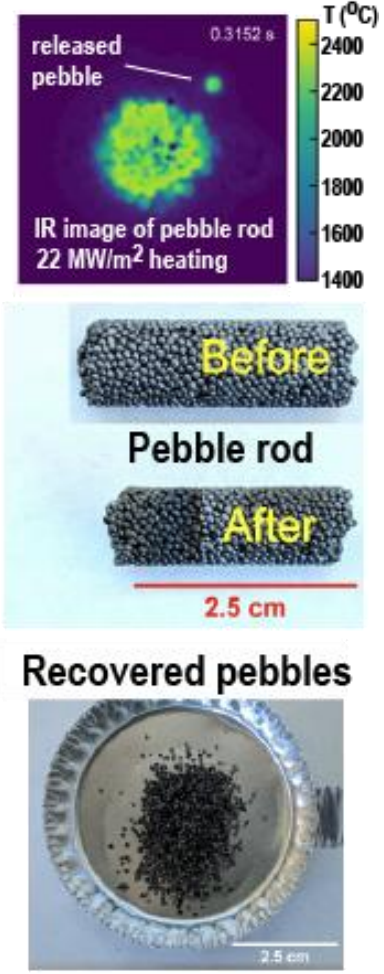
**RE impact on sacrificial dome limiter in DIII-D**



# Novel magnetic fusion energy device sacrificial wall development

- Designing first wall for magnetic fusion energy (MFE) reactors (tokamaks and stellarators) is extremely challenging.
  - Huge steady heat loads (>20 MW/m$^2$), huge transient heat loads (> GW/m$^2$), huge neutron damage (>10 dpa/year), huge slag buildup (tons/year) and associated tritium retention.
- No wall material presently exists that can handle all these issues, requiring novel solutions.
- UCSD is developing extruded pebble rods as a possible way to increase wall performance in critical regions of high steady heat loads, high transient heat loads, and high slag buildup.
  - Consist of pebble loosely bound with inter-pebble matrix
  - Formed rapidly (< 5 min) by baking liquid slurry mixed with pebbles
  - Decompose by thermal shock into constituent pebbles upon experiencing high heat loads.
  - Pebbles (~ 1 mm diameter) fall along wall, carrying away tritium and heat.
  - Technology can be applied to almost any material (carbon, boron, SiC, W pebble rods produced to-date).

**Carbon-based pebble rod images**

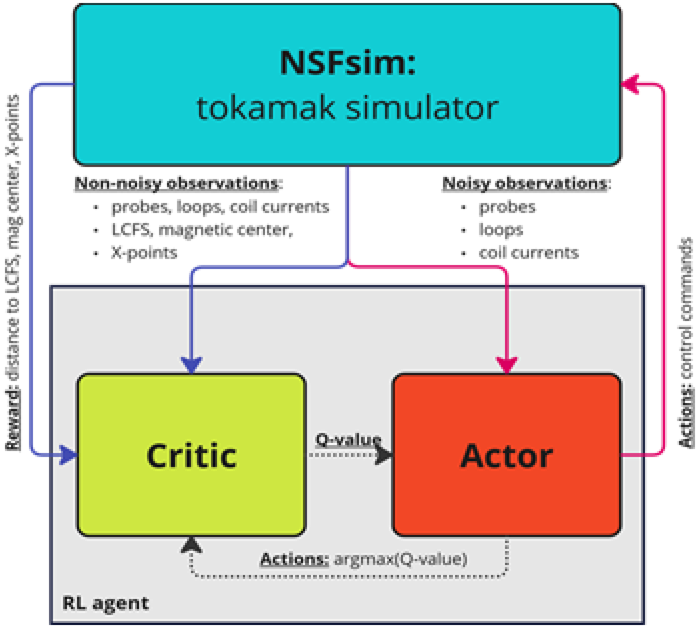


**PI: Eric Hollman**

# Reconstruction-free magnetic control of DIII-D plasma using reinforcement learning

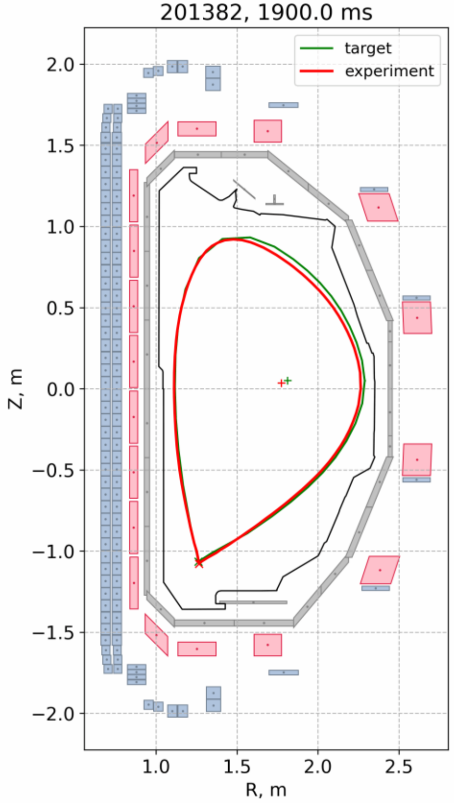
- Magnetic control on DIII-D is a public-private collaboration between Orlov’s Group and Next Step Fusion
- The goal is <u>Machine-Agnostic Plasma State control (MAPSc)</u>: Integrating conventional controllers, advanced Plasma Control Systems, and ML-based technologies for FPP control

- Non-linear MIMO controller for plasma shape and position is trained using Reinforcement Learning (RL)
- Bypassing equilibrium reconstruction
- 4 kHz control frequency - still vertically stable
- Fast evaluation <40 us/cycle
- Successfully tested in H-, L-modes and H-L transition
- Scan over power PNBI = 1.8-7.5 MW



**Control errors are quite small:**

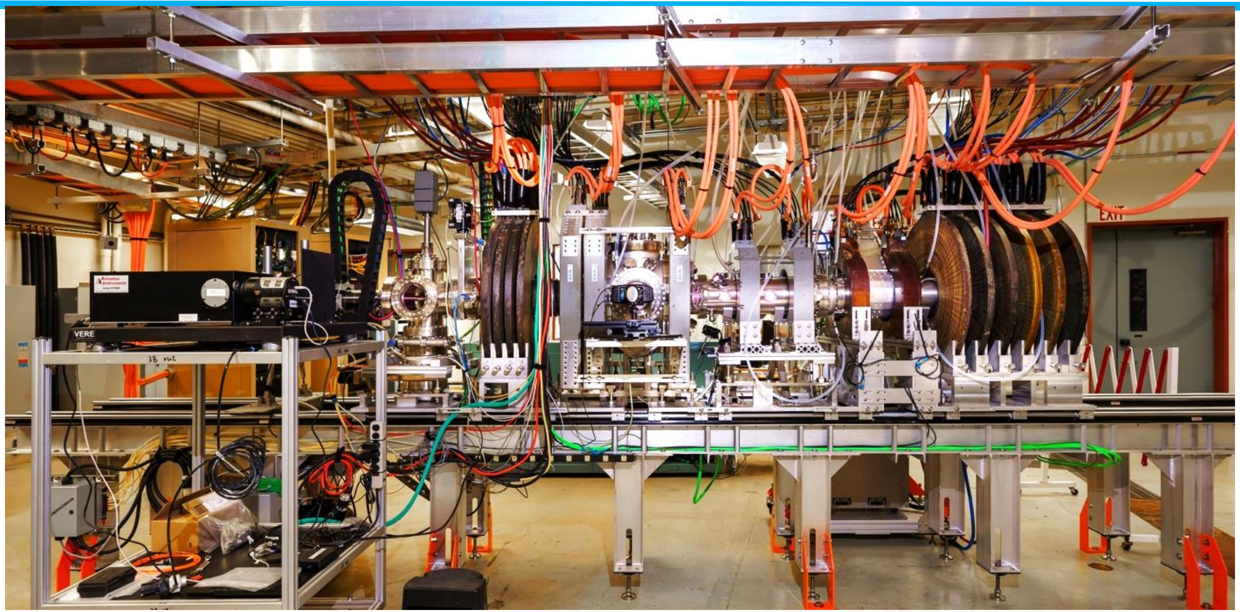
- **Shape: (1-5)·$10^{-3}$ m**
- **Axis: (1.3-5)·$10^{-2}$ m**
- **X-point: (4-6)·10-2 m**



NEXT STEP FUSION

# A NEW PMI science program with ***simultaneous plasma + displacement damage*** to emulate PMI in burning plasmas

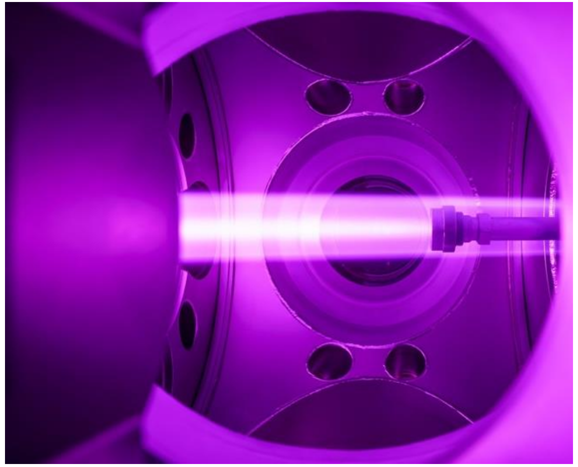
**2024** – PISCES-RF upgrade with new chamber allowing better optical /diagnostic access & incoming high energy beam delivery to target.



**2025** – Ion beam coupling

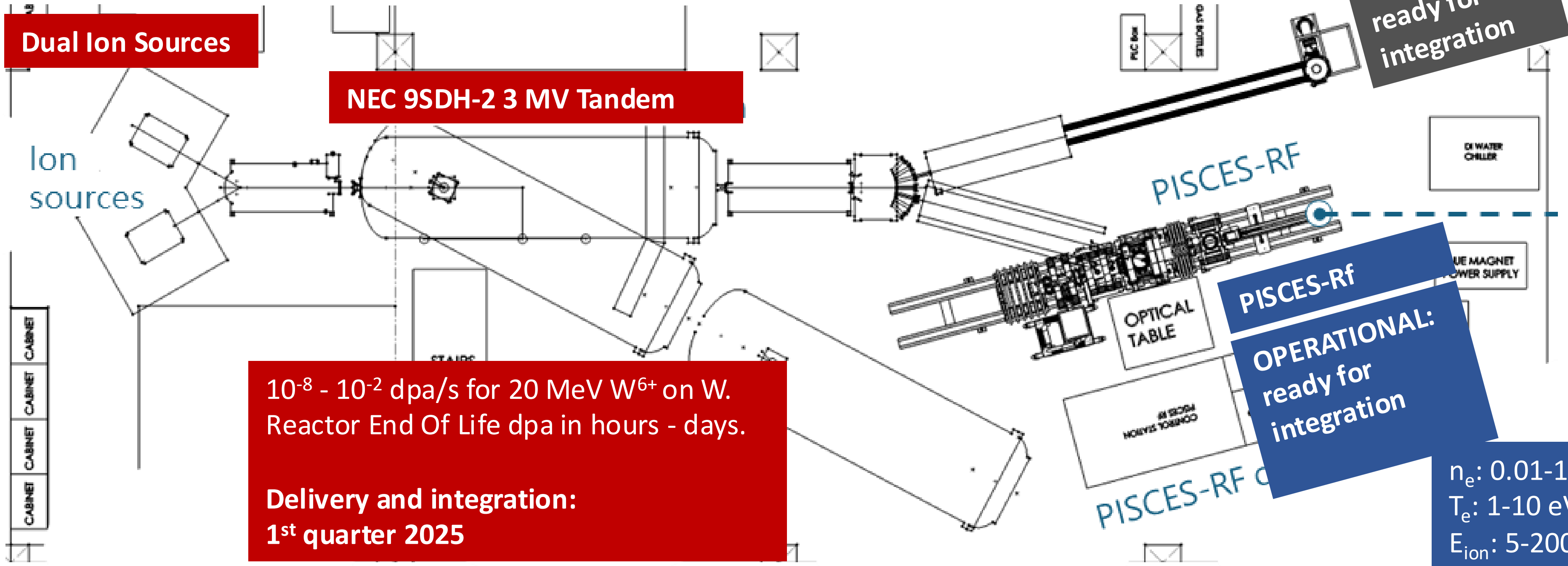
**Professor George Tynan**

UC San Diego
CENTER FOR ENERGY RESEARCH
POSEIDON



# A NEW PMI science program with *simultaneous plasma + displacement damage* to emulate PMI in burning plasmas

POSEIDON Laboratory



**Dual Ion Sources**

**NEC 9SDH-2 3 MV Tandem**

**Ion-beam analysis**

**COMPLETE: ready for integration**

**PISCES-Rf**

**OPERATIONAL: ready for integration**

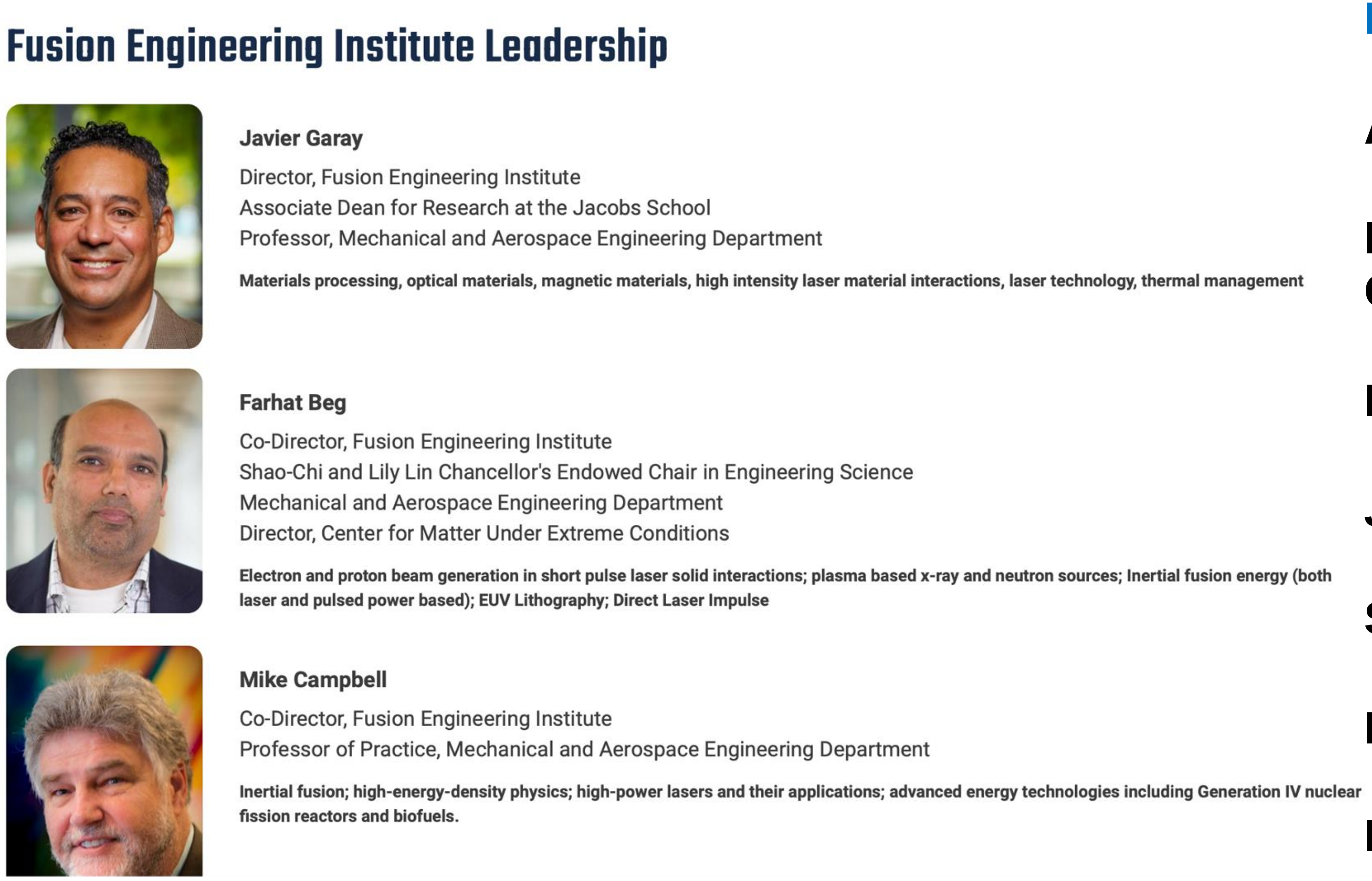
$10^{-8}$ - $10^{-2}$ dpa/s for 20 MeV $W^{6+}$ on W.
Reactor End Of Life dpa in hours - days.

**Delivery and integration:**
**1st quarter 2025**

$n_e$: 0.01-$10^{19}$ $m^{-3}$
$T_e$: 1-10 eV
$E_{ion}$: 5-200 eV
$\Gamma_{ion}$: up to $10^{23}$ $m^{-2}s^{-1}$
$\Phi_{ion}$: up to $10^{28}$ $m^{-2}s^{-1}$
$T_{targ}$: 320 - 1100 K
Gases: $D_2$, He, $D_2$-He
PMI: Metals, HEA's, UHTC's

**PMI science with simultaneous displacement damage to *simulate* fusion material aging in burning plasma.**

# Fusion Engineering Institute will address IFE and MFE relevant questions



## Fusion Engineering Institute Leadership

**Javier Garay**

Director, Fusion Engineering Institute
Associate Dean for Research at the Jacobs School
Professor, Mechanical and Aerospace Engineering Department

**Materials processing, optical materials, magnetic materials, high intensity laser material interactions, laser technology, thermal management**

**Farhat Beg**

Co-Director, Fusion Engineering Institute
Shao-Chi and Lily Lin Chancellor's Endowed Chair in Engineering Science
Mechanical and Aerospace Engineering Department
Director, Center for Matter Under Extreme Conditions

**Electron and proton beam generation in short pulse laser solid interactions; plasma based x-ray and neutron sources; Inertial fusion energy (both laser and pulsed power based); EUV Lithography; Direct Laser Impulse**

**Mike Campbell**

Co-Director, Fusion Engineering Institute
Professor of Practice, Mechanical and Aerospace Engineering Department

**Inertial fusion; high-energy-density physics; high-power lasers and their applications; advanced energy technologies including Generation IV nuclear fission reactors and biofuels.**

https://fei.ucsd.edu/

## Members

**Alexey Arefiev**

**Mathieu Bailly-Grandvaux**

**Matthew Baldwin**

**Jose Boedo**

**Simon Bott-Suzuki**

**Renkun Chen**

**Patrick Diamond**

**Chris Holland**

**Eric Hollmann**

**Sergei Krasheninnikov**

**Amit Majumdar**

**Alessandro Marinoni**

**Dmitri Orlov**

**George Tynan**

**Kenneth Vecchio**

**Frank Würthwein**

**Rose Yu**

# Summary

- **First Integrated Proton Fast Ignition experiments**
- **New laboratory to test target injection in extreme conditions with 10 Hz rep. rate**
- **Investigation of post-disruption RE wall damage at the DIII-D tokamak**
- **Development of extruded pebble rods to increase wall performance.**
- **Integration of conventional controllers, advanced Plasma Control Systems, and ML-based technologies for FPP control**
- **New 3 MV dual-source tandem ion accelerator with PISCES-RF plasma**
- **Installation of optical spectroscopic & laser-based diagnostics on the newly rebuilt linear plasma device (TGS, HSI, OES).**
- ***First burning plasma materials interaction (B-PMI) experiments on POSEIDON.***
- **Testing of new advanced materials (CCAs, UHTCs, AM+ W/steel alloys, etc) on POSEIDON in support of ARPA-E CHADWICK initiative.**