Implementing the FESAC Plan to Fusion Energy

General Atomics Perspective

by

Richard Buttery

Presented to

Fusion Power Associates

Washington, DC

December 16, 2020

General Atomics Enthusiastically Endorses the FESAC Plan

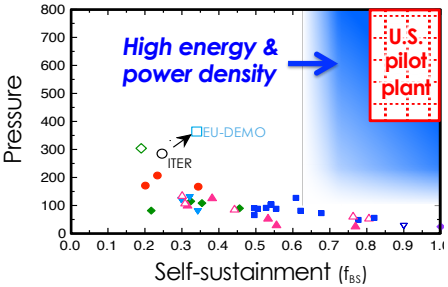
- Plan represents a bold and imaginative vision that takes the necessary steps to get to U.S. fusion energy
- Provides clear focus for the U.S. fusion community, appropriate to our skillset, and distinctive in the international context
- Strong basis for growth of the US fusion program, and for international leadership, that advances the path to fusion

This talk sets out some thoughts on how GA can help rapidly implement this plan

FESAC Plan Poses Challenges on Plasma and Technology Sides

- **Compact pilot plant path inherently higher energy and power density**
- **Key challenges**
  - **Better performance & power handling**
  - **Improved technologies & materials**

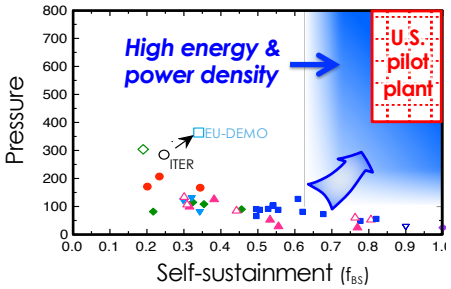
  } ***Marry together***
    - *Typically trade off against each other*

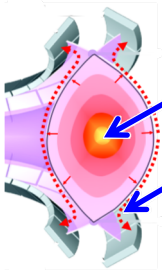


FESAC Plan Poses Challenges on Plasma and Technology Sides

- **Compact pilot plant path inherently higher energy and power density**
- **Key challenges**
  - **Better performance & power handling**
  - **Improved technologies & materials**

  } ***Marry together***
    - *Typically trade off against each other*



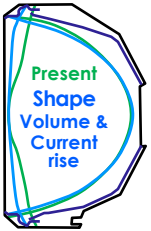


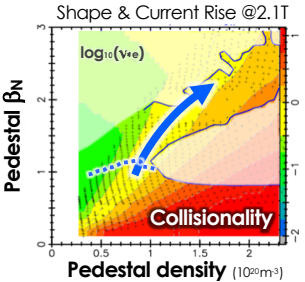
- **Tokamak research essential**
  - Resolve sustained high confinement scenario
  - Ensure compatibility with fusion technology

Develop & integrate solutions for fusion reactor

DIII-D Can Close Key Gaps to the Fusion Pilot Plant

- **Path identified to reactor physics regimes**
  - **Increase shaping**, **field** & **current drive** to raise energy and density

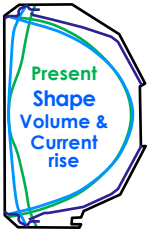


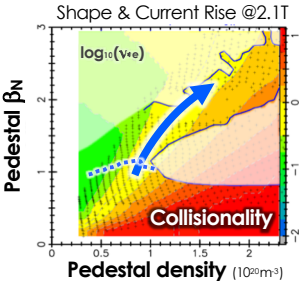


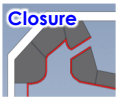
Flexibility & relevance to find core to edge physics solutions & project to reactor

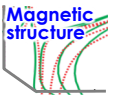
DIII-D Can Close Key Gaps to the Fusion Pilot Plant

- **Path identified to reactor physics regimes**
  - **Increase shaping**, **field** & **current drive** to raise energy and density
  - **Closed divertor for power handling** to raise local density and radiate heat





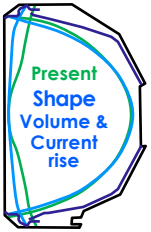


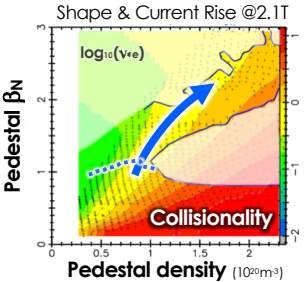


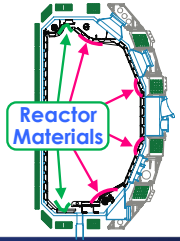
Flexibility & relevance to find core to edge physics solutions & project to reactor

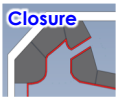
DIII-D Can Close Key Gaps to the Fusion Pilot Plant

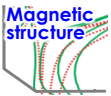
- **Path identified to reactor physics regimes**
  - **Increase shaping**, **field** & **current drive** to raise energy and density
  - **Closed divertor for power handling** to raise local density and radiate heat
  - **New wall materials** to reduce impurities & test compatibility of reactor solutions







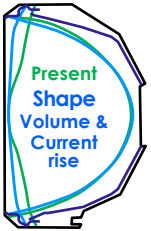


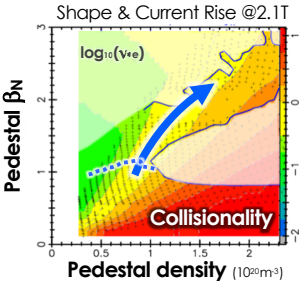


Flexibility & relevance to find core to edge physics solutions & project to reactor

DIII-D Can Close Key Gaps to the Fusion Pilot Plant

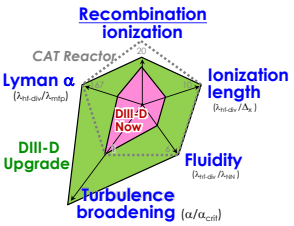
- **Path identified to reactor physics regimes**
  - **Increase shaping**, **field** & **current drive** to raise energy and density
  - **Closed divertor for power handling** to raise local density and radiate heat
  - **New wall materials** to reduce impurities & test compatibility of reactor solutions

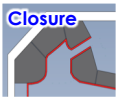


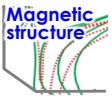


➔**Reactor-relevant core & edge simultaneously**
  - Project 3x pressure & density steady states
  - Find techniques and technologies that work

Flexibility & relevance to find core to edge physics solutions & project to reactor

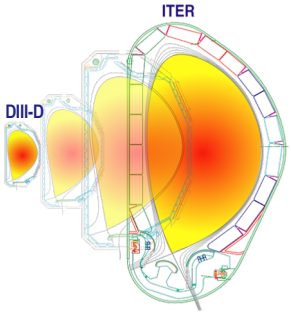






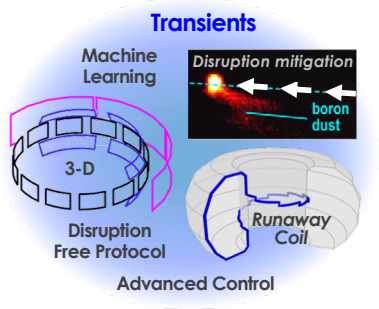
DIII-D Enables U.S. Success in ITER

DIII-D can



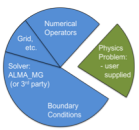
- **DIII-D is the U.S.'s ITER simulator**
  - Relevant parameter, shape, physics & control
- **Make ITER better**
  - Address transients & raise performance – *Q>10!*
- **Rapidly resolve ITER issues when running**
- **Validate techniques, theory & simulation**
  - Develop on DIII-D → test on ITER
  - Gain leadership. Develop tools for U.S. reactor

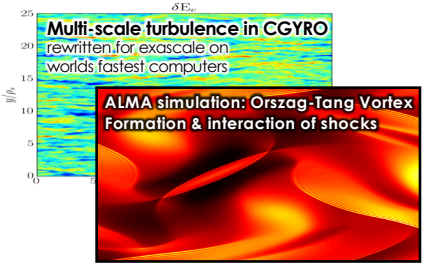
Develop techniques, codes & personnel
Bring learning back from ITER to U.S. program



Theory and Simulation Advances Critical to Fusion Goal

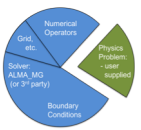
- **Multiscale nature & extension to boundary require more power & new algorithms**
  - CGYRO rewritten for exascale
  - ALMA decouples **solver** from **physics**
    - *Antisymmetric form conserves 1 in 10^{14}*

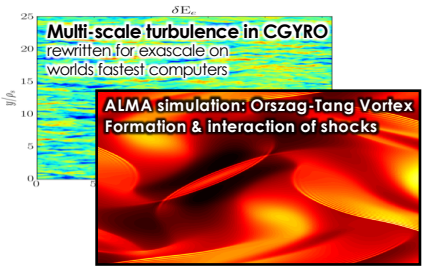


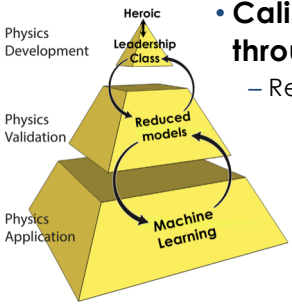


Theory and Simulation Advances Critical to Fusion Goal

- **Multiscale nature & extension to boundary require more power & new algorithms**
  - CGYRO rewritten for exascale
  - ALMA decouples **solver** from **physics**
    - *Antisymmetric form conserves 1 in 10^{14}*

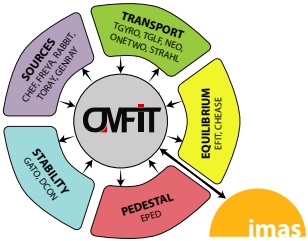






- **Calibrate & validate through fidelity hierarchy**
  - Reduced models & ML increase speed
- **Integration frameworks key**
  - Test and validate on DIII-D… *& ITER*
  - Predict and discover new solutions

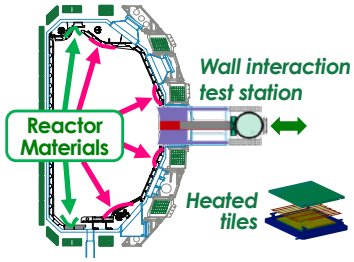
Robust basis for reactor design

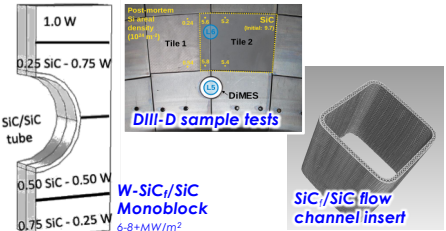


Critical to Qualify Reactor Materials for Tokamak Environment

- **Tokamak tests needed for prototyping**
  - Evaluate new materials with reactor-relevant exposure
  - Assess PMI and migration with high-temperature walls and on larger scale (reconstituted surfaces, integrity)
    - *Real-time composition studies (eAIMS e^- beam)*
- **Silicon Carbide: potential disruptive technology**
  - High-temperature, strong, tritium barrier, low activation
- **Advanced materials in structural components for strength, heat flux & neutron hardness**
  - W-SiC_f/SiC promising in simulations & coupon tests
    - *Engineered SiC-W RF Waveguides*
  - SiC_f/SiC inserts in blanket designs

Key opportunities to advance material research

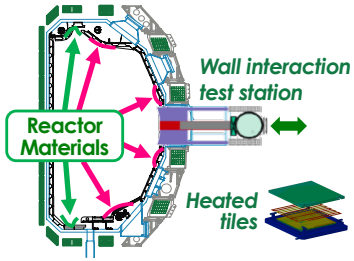




Critical to Qualify Reactor Materials for Tokamak Environment

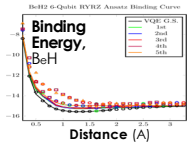
- **Tokamak tests needed for prototyping**
  - Evaluate new materials with reactor-relevant exposure
  - Assess PMI and migration with high-temperature walls and on larger scale (reconstituted surfaces, integrity)
    - *Real-time composition studies (eAIMS e^- beam)*
- **Silicon Carbide: potential disruptive technology**
  - High-temperature, strong, tritium barrier, low activation
- **Advanced materials in structural components for strength, heat flux & neutron hardness**
  - W-SiC_f/SiC promising in simulations & coupon tests
    - *Engineered SiC-W RF Waveguides*
  - SiC_f/SiC inserts in blanket designs

Key opportunities to advance material research



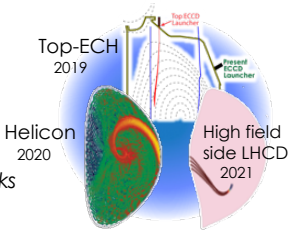
- **Simulation plays key role**
  - Quantum computing for most challenging issues
  - Better QCs needed

Novel QC algorithms capture surface chemistry on NISC



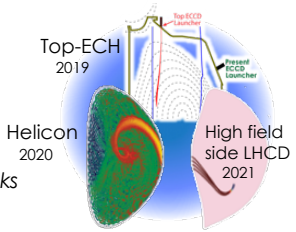
Improved Magnets & RF Crucial for Pilot Plant Path

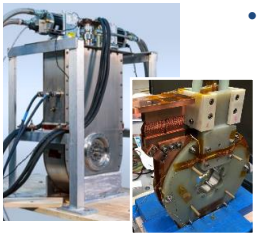
- **RF technology key to reactor economics & sustainment**
  - Challenges: efficiency, coupling, survivability
    - *Explore innovative RF schemes and coupling on DIII-D*
      - → *Top launch doubled EC efficiency* ✓
  - Make DOE resources available for RF testing – *sockets, power, tokamaks*



Improved Magnets & RF Crucial for Pilot Plant Path

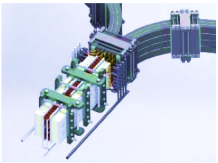
- **RF technology key to reactor economics & sustainment**
  - Challenges: efficiency, coupling, survivability
    - *Explore innovative RF schemes and coupling on DIII-D*
      - → *Top launch doubled EC efficiency* ✓
  - Make DOE resources available for RF testing – *sockets, power, tokamaks*





6T HTS magnet (700A)

- **GA proceeding with HTS development**
  - ← First cryogen-free conductively-cooled REBCO magnet operated for 104 hours at GA
  - → Pursuing jointed HTS for demountable magnet
    - *With LBNL & BNL*



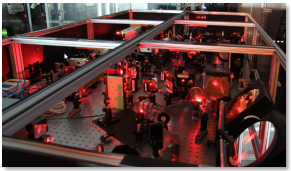
Jointed HTS design

Areas ripe for development offering advantages in field, shaping, performance & maintainability

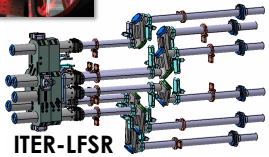
GA is Developing the Next Generation of Diagnostics In Support of a Broad Portfolio of Experiments

- **Critical, but unmet measurement needs**
- **Challenges in future fusion devices**
  - Harsh environment (ITER, NIF, CFETR, Z…)
  - Reduced or tight/compact access
  - Long pulse reliability
- **Approaches:**
  - Imaging, laser-based diagnostics, and remote sensing
  - Advanced RF/microwave-based diagnostics
  - Energetic particles (neutrons, gammas, protons, electrons)

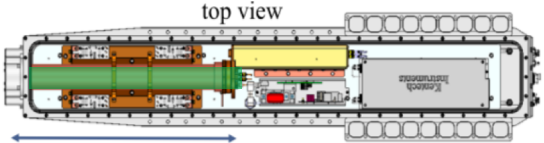
Broad range of applications in MFE, ICF and non-fusion areas



ITER-TIP
Two color
Interferometry
Polarimetry



ITER-LFSR
Low field side reflectometry



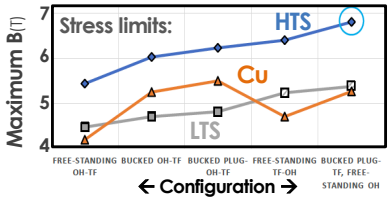
Single line of sight: Time dilation technology

GA is Developing Concept for a Flexible EXCITE Facility to Meet the Core-Edge Challenge

- **Full physics simulations project a compact device can reach reactor heat fluxes and high performance AT core**
  - Manned access short pulse D-D for core-edge integration
  - Reduces extrapolation gap to pilot plant
- **Engineering studies show manned access facility possible**
  - Stresses: HTS enables highest fields, bucked off central plug
    - *PF inside TF enables more shaping & higher performance*
  - Neutronics: 20cm inner blanket addresses pit & site boundary radiation
  - Off axis current: 476MHz helicon, 4.6GHz LH, 93kV NB, 220GHz EC
  - Core heating: 476MHz helicon, 2nd harm ICRH, 220GHz EC
- **Cost ~$1Bn, possibly alleviated with site credits**

Validate and optimize core-edge solutions reducing need for divertor testing in the pilot

Parameter	Range
Radius	1.25 m
R/a	2.5
TF	4 – 7 T
I_P	2 – 4 MA
$P_{H\&CD}$	30-60 MW
q_{95}	6.5 – 11
β_N	to 3.8
$f_e{}^{ped}{}_{GW}$	50-100%
P	to 300 kPA
PB/R	200 – 400
τ_R	2 – 3s
ν^*	~0.2
f_{BS}	50-100%
H_{98}	1.25 – 1.6



General Atomics Eager to Engage with Fusion Community to Advance this Exciting Vision

- **FESAC plan represents an inspiring path with needed elements to get to Fusion Energy**
- **Builds on strengths in the U.S. program**
  - **Continued tokamak work vital to develop integrated solutions necessary for ITER and fusion pilot plant**
  - **Alongside many opportunities to advance technology vision**

Many things can be started immediately
We are ready to go!