SPARC and the High Magnetic Field Path to Fusion Energy

Presented by Martin Green

LLNL HEDSC Seminar – March 25, 2023
Acknowledgements – The SPARC Team, Particularly

- Sean Ballinger
- Dan Brunner*
- Alex Creely*
- Chris Chrobak*
- Darren Garnier
- Bob Granetz
- Zach Hartwig
- Nathan Howard
- Jerry Hughes
- Adam Kuang
- Yijun Lin
- Earl Marmar
- Bob Mumgaard*
- Matt Reinke*
- Pablo Rodriguez
- Steve Scott*
- Brandon Sorbom*
- Ryan Sweeney
- Alex Tinguely
- Libby Tolman
- Dennis Whyte
- John Wright
- Steve Wukitch
- SPARC Team

*Commonwealth Fusion Systems

Collaborating Insitutions
- Aalto U.
- Chalmers
- Columbia U.
- Fiat Lux
- GA
- ORNL
- PPPL
- UCSD
- U. York

SPARC

Commonwealth Fusion Systems

PSFC

LLNL Seminar: 03/25/21
Outline

- Quick introduction to fusion energy and magnetic confinement
- High Temperature Superconductors – a game-changing technology
- Plans, projections and physics for the SPARC device
- The role of private industry

SPARC – planned as the first magnetic confinement which would make net energy
The World Needs Reliable, Safe, Clean, Carbon-Free Energy
The World Needs Reliable, Safe, Clean, Carbon-Free Energy

Can Fusion Contribute To The Solution?
The Technical Challenges Are Well Understood

1. Plasma physics
   - Create, confine and sustain hot plasmas that produce net energy

2. Taming the plasma material interface
   - Minimize heat and particle loads
   - Develop materials and strategies to handle what remains

3. Harnessing fusion energy
   - Fuel cycle – tritium breeding, inventory control
   - Structural materials – maintaining structural, thermal and electrical properties under intense neutron bombardment
   - Reliability, Availability, Maintainability, Inspectability
Hot Magnetically Confined Plasma
Self-heating sustains reaction energetically

\[ D + T \Rightarrow He + n \]

Deuterium
Lithium

He + T \Leftarrow Li + n

Energy Extraction
Breeding

Net reaction: \[ _1D^2 + _3Li^6 \Rightarrow _2He^4 + _2He^4 + \sim20 \]
Beyond the Fusion Core
Electricity Would Be Produced In Conventional Fashion

Electricity Would Be Produced In Conventional Fashion
Fusion is mediated by the strong nuclear force – with a range of $10^{-15}$ m. So we need significant wave function overlap at that range.

Nuclei are charged $\Rightarrow$ Fusion requires ion energies on the order of 100 keV.
The Physics Challenge:
Very High Kinetic Energies Are Needed To Overcome Electrostatics

- But, even at the optimum energy, the nuclei are much more likely to scatter elastically than to fuse
- Particles rapidly thermalize, equilibrate
- We need to confine hot plasmas for many collision times
- Fusion plasmas need to reach temperatures on the order of 20 keV ≈ 200,000,000 K
- Must be isolated and insulated from ordinary matter
Plasma Can Be Confined by the Gyration Of Charged Particles in a Magnetic Field.

Magnetic Confinement = Thermal Insulation Perpendicular To Field Lines

The quality of the magnetic insulation increases with the strength of the magnetic field.

At $B = 10^7 T$:
- $\rho_e = 0.1$ m
- $\rho_i = 1.0$ m

We need $\rho > 500 \sim 500 - 1000$ to:
- i.e. $10^6 - 10^7$
- (Bremsstrahlung requirement)

[Image of plasma confinement diagram with magnetic field lines and charged particles]
Magnetic fields confine charged particles in the perpendicular direction.

- At the temperatures involved, ions are moving at over 1,000 km/s.
- But, even at these temperatures, the average time for an ion to fuse is approximately 25 seconds.
- For a practical device, the end losses must be eliminated.

Voila! Eliminate the ends.

A torus is unique topologically. It is the only 3D shape where the magnetic vector field (B in our case) can be tangent to the surface.
The Tokamak is the Leading Concept in the Race for Practical Fusion Energy

Nature provides a well-founded and quantitative set of metrics for progress in fusion energy in the Lawson criteria (1955): $n\tau_E$ and $T_i$

(Density x confinement time and temperature)

We’ve achieved the required $n\tau_E$ and $T_i$ individually, but not both together - YET
Tokamaks Demonstrated Enormous Progress For 3 Decades, But...  

HT-7 (CN)  
JT-60U (JP)  
KSTAR (KR)  
MAST-U (UK)  
NSTX-U (US)  
Tore Supra (FR)  
Alcator C-Mod (US)  
ASDEX-U (DE)  
COMPASS (CZ)  
DIII-D (US)  
EAST (CN)  
FTU (IT)  

+ 160 other tokamaks across 60 years  
Enormous technical and scientific base  

Progress Exceeded Moore’s Law  

fusion triple product \([10^{20} \text{ m}^3 \text{ keV s}]\)
Progress Slowed As The Devices Got Too Big, Too Expensive

JET
Now operating

JT-60SA
Commissioning, 2021

ITER
US-USSR Agreement 1985
Research 2030
D-T 2035-2040

FNSF/Pilot (US)
Construction Start 2040-2045?
Operation 2050?
Progress Slowed As The Devices Got Too Big, Too Expensive

- JET: Now operating
- JT-60SA: Under construction, 2019
- First Plant Online
- Deploy Ten Plants Per year
- FNSF/Pilot (US): Construction Start 2040-2045? Operation 2050?
What Can We Do About This?

- Tokamaks: Impressive and unparalleled fusion performance
- Stagnating due to size & cost, not saturation due to physics
- Can they be fielded in time to deal with global warming?
Private Companies Have Attracted $$$ On Small But Risky Concepts

- Small enough to carry out without government funding
- Can be built quickly
- Raise the profile of fusion
- Have been innovative and nimble
- But – are taking a big leap into unknown physics and engineering

(all figures to scale)
These Alternates Currently Fall Far Short of What’s Needed

fusion triple product [$10^{20} \text{ m}^{-3} \text{ keV s}$]

- breakeven (Q=1)
- tokamaks
- ITER (projected)

This was faster than Moore’s law!

slow/big/expensive

high-confidence physics

SPARC

LLNL Seminar: 03/25/21
Moreover Can We Follow a Development Path That Retires Risk?

What should the risk retirement and cost curves look like?

- Retire the largest portion of the risk at lowest expenditure
- If the risk is in the physics then the entire device must be built before that risk is retired
- But if the risk is in the enabling technology, that can be retired early leaving high confidence the device will operate as designed

- Innovate in the areas of highest return
- Avoid putting all innovation on unproven physics and instead innovate in engineering of new components to make proven physics work better
We Need To Consider Another Approach

- We’re looking for a path which builds on the progress and knowledge built by decades of research on the tokamak.
- Reduced in scale to learn fast.
- Focused on fusion power plants that are practical and economical.
We Think The Basis For Breakthrough Is Here – High Temperature Superconductivity

- Discovered more than 100 years ago – 1987
  - Nobel prize for Muller 1987
- High $T_c$ was a surprise to theory still incomplete
- Ceramic form – too brittle for practical applications
Some People Understood The Implications Right Away


Tokamak Reactor Concepts Using High Temperature High-Field Superconductors

D. R. Cohn, J. Schwartz, L. Bromberg, and J. E. C. Williams

Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 U.S.A.

Received April 4

The rest of us took a bit more time to appreciate the promise.
High Temperature Superconductors
Out of the Lab and into Industrial Production

- Deposited as a thin film on a steel substrate
- Over-coated with copper for stability
These New Superconducting Materials Are Ideal For Large-Voltage High-Field Fusion Magnets

- Much wider operating space in field, current density and temperature
- Higher current densities – more compact magnets
  - Strong structure - substrate is mainly steel
- Operation at higher temperatures
  - New cryogenic options
  - Better stability against quench
  - Higher heat capacity should enable magnets with demountable joints
- No reaction process as part of winding
Capabilities of HTS Magnets Are Rapidly Increasing, Costs Decreasing

- **Magnetic Field vs. Year**

  - Completed
  - Completed (with resistive outsert)
  - In progress
  - In Progress (with resistive outsert)

K. Kim (ASC-MagLab)

SPARC

LLNL Seminar: 03/25/21
Why Do We Care? At Higher Fields, Fusion Reactors Can Be Smaller

- The “size” of the plasma is properly measured in ion gyro-radii, \( R/\rho_i \propto BR \)

- Higher power density
  - \( R_{\text{Fusion}} \propto n^2T^2 \propto p^2 \propto B^4 \)
  - Fusion gain: \( n\tau_E T \propto B^3 \)

- Using “Standard” physics assumptions we can map out fusion performance and see the quantitative trade-off between field and size
  - \( H_{98} \sim 1 \)
  - \( q \sim 3 \)
  - \( A \sim 3 \)
  - \( D/(D+T) \sim 0.5 \)
  - \( \kappa \sim 1.8 \)
But - With Conventional Superconductors, Machines Have To

- Practical fusion needs superconducting magnets
- “Best” LTS (Low Temperature Superconductors) is Nb₃Sn
- Large-volume fusion magnets can’t have much more than 5-6 T on axis
- That set the size for ITER
- Requires the combined resources of the entire industrialized world to build
  - ~50 years from Reykjavik summit (1985) to DT operation (2035)
The New HTS Magnet Technology Relaxes That Constraint
At Higher Fields, We Can Go Smaller

- Doubling the field allows the size to drop in half
- The volume, weight decrease by a factor of 8
- Enables a new class of devices

$P_{\text{FUSION}}$
500 MW

ARC: Pilot Plant Concept
Sorbom et al., Fusion Engineering and Design 2015

Fusion Gain $Q$

Fusion Plant Concept

ITER

Magnetic field [T]

Size [m]
ARC: Concept for Class of Modular Fusion Pilot Plants

- Originated in a Graduate design class
- **Not** an engineering design (yet)
  - Though sufficient mechanical, hydraulic, and electrical calculations were performed to demonstrate engineering plausibility for this class of devices.

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>R [m]</td>
<td>6.2</td>
</tr>
<tr>
<td>Magnet LTS</td>
<td></td>
</tr>
<tr>
<td>B [T]</td>
<td>5.3</td>
</tr>
<tr>
<td>$P_{\text{fusion}}$ [MW]</td>
<td>500</td>
</tr>
<tr>
<td>$P_{\text{electric}}$ [MW]</td>
<td>0</td>
</tr>
</tbody>
</table>
We’re Not Ready To Build A Machine in the ARC Class

SPARC: An Intermediate Step From Today’s High-Field Experiments

- Burn DT to demonstrate $Q_{\text{FUS}}$ robustly above 1 and with significant fusion power
- Same $B_{\text{COIL}}$ as ARC – same technology
- Think of as a 12T, HTS version of AUG or DIII-D (currently operating expts.)
  - About 1/64 volume, weight, cost of ITER
  - Small enough to be built by a university/industry team
SPARC Mission

• Make a plasma with (robustly) break-even fusion energy gain, $Q > 2$
  – At long last, the Kitty Hawk moment for fusion
  – Our hypothesis – this would be a sufficient demonstration to put fusion firmly in national energy plans and to attract investments for the next step

• Demonstrate fusion-relevant HTS magnets at scale
  – Integrated with high-performance tokamak operation

• Provide the physics basis for high-field pathway
  – Demonstrate high-field, burning fusion plasma scenarios
That Is the Aspiration: What is the Plan? The SPARC Project

- Privately funded – official start March 2018
  - Bolster fusion research and education at MIT while building a strong industrial (Commonwealth Fusion Systems - CFS) that aims to commercialize fusion energy
  - Combined team now ~ 240 people, capital raised so far $215M
  - Go fast, accept risks, learn from mistakes
- Phase I
  - R&D & Demonstration of HTS fusion magnets at scale
  - Development of physics & engineering design for SPARC tokamak
- Phase II
  - Construction & Operation of SPARC
- (Phase III: CFS Builds the world’s first fusion pilot plant – an ARC-class device)
Audacious? Yes, But Consider Some History...

ATC, 2T

July 1974:
Tokamak physics mature enough to try DT

SPARC V2, 12T

2018:
HTS mature enough to build a tokamak

TFTR, 6T
Construction approved 1976; 1st plasma 1983
A Huge Step From Where We Were in 1974

Extrapolation factors from operating tokamaks

- Plasma current: 10
- Toroidal field: 2
- Magnetic energy: $10^2$
- Pulse length: $10^3$
- Auxiliary heating: $10^2$
- Ion temperature: 10
- $nT\tau$: $10^3$
- Fuel: DT
- Fusion power: $10^8$
- $Q$: $10^8$

Today, SPARC is a huge step compared to our decision to build.

<table>
<thead>
<tr>
<th>SPARC extrapolation from operating tokamaks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma current</td>
</tr>
<tr>
<td>Toroidal field</td>
</tr>
<tr>
<td>Magnetic energy</td>
</tr>
<tr>
<td>Pulse length</td>
</tr>
<tr>
<td>Auxiliary heating</td>
</tr>
<tr>
<td>Ion temperature</td>
</tr>
<tr>
<td>$nT\tau$</td>
</tr>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td>Fusion power</td>
</tr>
<tr>
<td>$Q$</td>
</tr>
</tbody>
</table>
SPARC V2: Starting Point for Detailed Engineering Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_0$</td>
<td>12.1 T</td>
</tr>
<tr>
<td>$I_p$</td>
<td>8.7 MA</td>
</tr>
<tr>
<td>$R_o$</td>
<td>1.85 m</td>
</tr>
<tr>
<td>$a$</td>
<td>0.57 m</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>0.31</td>
</tr>
<tr>
<td>$\kappa$ (area)</td>
<td>1.75</td>
</tr>
<tr>
<td>$P_{fus}$</td>
<td>50-140 MW</td>
</tr>
<tr>
<td>$P_{ext}$</td>
<td>25 MW</td>
</tr>
</tbody>
</table>

SPARC V0 technical requirements:
- Burn D-T fuel
- Fusion Gain: $Q > 2$
- $P_{fusion} > 50$ MW up to 140 MW
- Pulsed with 10s flattop pulse

Desired schedule:
- R&D: 3yrs (mainly HTS improvements)
- Construct: 4 yrs
- Operate: 5 yrs
- Decommission: 4 yrs

Desired construction cost:
SPARC – Similar In Size To Machines We’ve Built

DIII-D, General Atomics:
- 1.66m, 2.1T, <2.0MA
- Water cooled Cu

SPARC V0, MIT:
- 1.85m, 12T, 8.7 MA
- Cryogenic HTS
- To scale

ASDEX-Upgrade, IPP Garching:
- 1.65m, 3.1T, 1.6MA
- Water cooled Cu

There are many others at this size:
- KSTAR, EAST, WEST, TEXTOR, PDX, PLT
- (and several bigger – TFTR, JET, JT60, JT60-SA, Tore-Supra)
What Are The Principles Behind The SPARC Design Points

- Use the ITER plasma physics basis
  - As far as possible, stay close to regimes and parameters where we have data
  - Be less of an extrapolation from existing experiments than ITER
- Use proven heating & control techniques
- Ensure robust operating windows
  - Stay away from known operational limits ($\beta$, $n/n_G$)
  - Operate away regimes requiring complicated or expensive control systems
- Keep pulse short to avoid other engineering complications (current drive, heat removal) for the mission
  - But long enough for the plasma to reach steady state
- Keep nuclear envelope within fusion precedence (TFTR, JET) – no blanket
Leverage As Much Mature Technology As Possible

Mature knowledge utilized for SPARC

Plasma Physics:
From 170+ tokamaks over the last 50+ years

PF/CS design:
From FIRE, BPX, CIT

Power supply design:
From C-Mod,
Smaller than DIII-D, AUG

Plasma heating design:
From TFTR, JET, FIRE, C-Mod

Licensing:
From accelerators, TFTR, JET

Heat exhaust:
From C-Mod

Cryo systems:
From rocket industry

Site size:
From TFTR/JET/FIRE

Cell size:
From AUG

Shielding:
From accelerators, TFTR, JET
fission reactors

Tritium handling, processing:
From TFTR, JET, LANL, Sandia, Bates

Decommissioning:
TFTR, accelerators

SPARC
One Key Innovation
High Field Mode
New HTS Tech

The SPARC HTS Magnet
(12 T on axis; 8.5 T on axis)
SPARC: How Do We Estimate Fusion Performance?

- **Hierarchy of models** – No closed-form solutions for turbulent transport
  - **Empirical Scaling: 0D** – Transport is characterized by $\tau_E = \text{energy confinement time}$
    - For ITER design, a large data set was assembled
    - Regress $\tau_E$ against “engineering” parameters (plasma size, input power, magnetic field, ...)
  - **Dimensionless identity:**
    - Plasma physics equations can be cast in dimensionless form
    - With identical dimensionless parameters, plasma physics should be identical

- **Time-dependent simulation** – quasi-linear transport model
  - Quasilinear = calculate linear growth rates at all wavenumbers and normalize transport to saturation “rule” calibrated to nonlinear GK simulations

- **Nonlinear gyro-kinetic simulations**
  - GK = Boltzmann equation averaged over gyro-motion (equation of motion in 5D phase space)
0D Analysis From Empirical Scaling Laws

- **Use ITER Performance Rules**
  - Energy Confinement: \( H_{98} = 1 \)
  - Profile peaking factors
  - Fuel mix
  - Fuel dilution

- **Operating Space Defined by**
  - \( Q_{\text{FUSION}} > 2 \)
  - \( P_{\text{LOSS}} > P_{\text{L-H}} \) (Threshold)
  - \( P_{\text{HEATING}} < 30 \text{ MW} \)
  - \( P_{\text{FUSION}} < 100 \text{ MW} \)

**Calculation Proceeds in the \( \langle n \rangle, \langle T \rangle \)**

1. Compute fusion power using \( n, T \), fuel dilution, profile peaking factors
2. Compute radiated power (Bremms, Larmor radiation, synchrotron) using \( Z_{\text{EFF}}, \text{plasma B}_T \), profile factors
3. Compute total input power required from confinement law (from empirical scaling)
4. Compute aux power required from power balance \( P_{\text{AUX}} + P_\alpha + P_{\text{OH}} = P_{\text{Loss}} + P_{\text{RA}} \)
5. Compute operational limits \( (\beta, n/n_G) \)
SPARC: Nominal Operating Space; $Q_{\text{FUS}}$ up to 11

- Use ITER Performance Rules
  - Energy Confinement: $H_{98} = 1$
  - Profile peaking factors
  - Fuel mix
  - Fuel dilution
- Operating Space Defined by
  - $Q_{\text{FUSION}} > 2$
  - $P_{\text{LOSS}} > P_{\text{L-H}}$ (Threshold)
  - $P_{\text{HEATING}} < 25$ MW
  - $P_{\text{FUSION}} < 140$ MW

$Q_{\text{MAX}} = 17$

- $P_{\text{FUS}} = 134$ MW
- $P_{\alpha} = 26.9$ MW
- $P_{\text{AUX}} = 10.2$ MW
- $P_{\text{OHM}} = 1.8$ MW
- $P_{\text{RAD}} = 9.8$ MW
- $P_{\text{LH}} = 29.0$ MW
- $\langle T_i \rangle = 7.9$ keV
- $\langle n_e 20 \rangle = 2.9$
- $n_g = 0.34$
- $q^* = 2.49$
- $\tau_e = 0.74$ s
- $W = 21.53$ MJ
- $\beta_T = 1.17\%$
- $\beta_N = 0.93$
- $\delta = 0.0019$
- $\nu^* = 0.0122$
As Planned, SPARC Has Performance Margin

- Limited by auxiliary power at low confinement
- Engineering limits on fusion power output at high confinement
- Exceeds Q=2 at $H \approx 0.7$
- Provides margin against confinement uncertainty or
- Reduced pedestal height
  - i.e. margin against peeling-ballooning (ELM suppression)
In Dimensionless Variables, the SPARC Operating Point Is Generally Closer to the Mean of the H-mode Confinement Database than...
We Can Find Discharges That Are Very Close To Matching All SPARC Dimensionless Plasma Parameters \((\beta_N, \nu^*, \rho^*, q_{95}, n_G, \varepsilon, \kappa, \delta_L)\) Simultaneously.

The same 20 (JET) discharges are shown in red:
- \(B_T = 3.0 - 4.2\)
- \(I_p = 3.0 - 4.2\)
- \(P = 8.2 - 15.2\)
- \(H_{98} = 0.82 - 1.00\)
We Can Find Discharges That Are *Very Close* To Matching All SPARC Dimensionless Plasma Parameters \( (\beta_N, \nu^*, \rho^*, q_{95}, n_G, \varepsilon, \kappa, \delta_L) \) Simultaneously.

Thus: Much of the Core Plasma Physics Has Been Already Created.

- \( B_T = 3.0 - 4.2 \)
- \( I_p = 3.0 - 4.2 \)
- \( P = 8.2 - 15 \)
- \( H_{98} = 0.82 - 1.0 \)
We Can Find Discharges That Are Very Close To Matching All SPARC Dimensionless Plasma Parameters ($\beta_N$, $\nu^*$, $\rho^*$, $q_{95}$, $n_G$, $\varepsilon$, $\kappa$, $\delta_L$) Simultaneously.

Why didn’t those JET discharges generate 100 MW of fusion?

Fusion is nuclear physics – Doesn’t scale with dimensionless plasma parameters.

It cares about $T/E_{\text{Nuclear}}$

• In fact, we’re eagerly looking forward to experiments in the regime where plasma physics and nuclear physics are coupled – this will be new

$P = 8.2 - 15$

$H_{98} = 0.82 - 1$
Ensuring Performance: Time-dependent Plasma Simulations

- Compared to empirical scaling which is **ALL DATA** and minimal physics

- These simulations are **ALL PHYSICS (reduced models where necessary)** and minimal data
  - 2D MHD equilibrium, (1D radial profiles = 1.5D)
  - Plasma Profiles - Quasi-linear transport to calculate
  - Heating - RF wave propagation & damping
  - Heating – Fusion reaction rate and alpha power deposition
  - + lots more...
Remarkable Agreement Between 0D and 1.5 D Time-dependent

- For this calculation, the energy confinement time, H factor, temperatures, fusion power, Q are all outputs
- Methods are entirely independent
- However, results are remarkably close

<table>
<thead>
<tr>
<th></th>
<th>TRANSP</th>
<th>Empirical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{98}$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$&lt;T_i&gt;$</td>
<td>7.8 keV</td>
<td>7.9 keV</td>
</tr>
<tr>
<td>$T_i(0)/&lt;T_i&gt;$</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$P_{RAD}$</td>
<td>13.2 MW</td>
<td>10.4 MW</td>
</tr>
<tr>
<td>$P_{FUS}$</td>
<td>105 MW</td>
<td>140 MW</td>
</tr>
<tr>
<td>Q</td>
<td>9</td>
<td>11</td>
</tr>
</tbody>
</table>
1.5 D Predictions of Plasma Profiles For SPARC
Next Steps - Nonlinear Simulation of Gyrokinetic Turbulence

- Quasi-linear model has been benchmarked against experiments and gyrokinetic codes
- We’ve sampled the profile at a few points and looked at the expected turbulence
  - No surprises – SPARC should be in turbulence regimes similar to other devices
- Still, we want to take the next step
- We’re in the process of launching a fully nonlinear gk prediction of profiles – a “heroic” simulation
  - Constrain gradients at each radii with nonlinear GK
Getting Power In: Plasma Heating - 25 MW ICRF

- Simplicity: Utilize a single type of heating
  - Proven to work on C-Mod (at required plasma density) and on DT devices (TFTR & JET)

- Heating scenarios at 120 MHz look promising
  - Options for DD (H minority at 8T)
  - DT (He\(^3\) minority at 12T) operation (+ perhaps 2\(^{nd}\) harmonic T)
  - Good single pass absorption predicted

- Optimum antenna spectrum is a balance between coupling and absorption
ICRF Heating Is Well Localized In Plasma Core
Most ICRF Power into Ions, Alpha power to electrons
Getting Power Out: Divertor Loading – A Challenge At High Performance

We need to manage the interface between hot plasma and ordinary matter

- For “attached” divertor, the heat flux scales like $1/B$
- Detachment scales like $PB/Rn_{SEP}^2$

New C-Mod data

Eich, et al., JNM 2011
Brunner, 2017

(Though recent results for ITER suggest this may not be beneficial, further work is needed to account this)
Boundary power exhaust challenging but not a show-stopper for SPARC
Simulations show that heat flux can be handled with aggressive strike point

• With standard (C-Mod, ITER) vertical target divertor, 10 sec pulse
  – At typical and acceptable radiation fraction (50%), target materials survive full power pulse. (assumes fully attached, single null)
  – Radiation fractions of > 90% have been demonstrated on C-Mod, AUG, JET while maintaining good core confinement
Disruptions: A Challenge For All High-Performance Tokamaks
Compact, High-Field Has Some Advantages

- Operating away from limits
  - Staying further away from limits (especially pressure, density) should reduce disruptions

- Disruption forces are not obviously more difficult for compact, high-field
  - IxB and stresses about the same
  - Distances can be smaller for mitigation actuators (gas, pellets)
  - But, quench times faster for compact devices

- Runaway electron growth rate reduced, damping enhanced
  - Runaways more strongly damped by collisions and synchrotron radiation
  - Growth (Coulomb Avalanche) exponential with plasma current \( \left( \frac{I_{\text{runaway}}}{I_{\text{seed}}} \right) \propto e^{2} \)
To Mitigate Disruption Runaways, We Will Try Out A Novel 3D System

- From an original idea by A. Boozer
- Current driven inductively by $dI_P/dt$ of disruption
- Non-axisymmetric coil creates 3D fields which break up flux surface, leading to rapid loss of “seed” electrons
- Analysis of plasma response by V. Izzo – with NIMROD – extended MHD code
- Looks very promising
- Offers possibility of passive safety wrt runaways!
Loss of Fast Alphas from Ripple Transport Should Be Minimized

- Ripple loss 0.25 %
- Neoclassical loss 2.8%

- Ripple loss 1 % (all from...
How About Transport of Fast Alphas by MHD?

• Perhaps the most important new physics that the SPARC experiment will address

• The fully self-consistent, nonlinear interaction of fast particle distributions and MHD in a burning plasma is a cutting edge research problem – need a burning plasma experiment to validate

• We’ve done some linear analysis (Tolman, et al., Nucl. Fusion 59, 046020, 2019.)
  – \( n_\alpha/n_e \propto T^{3.5} \)
  – Drive to damping ratio for Alfvénic modes \( \propto \beta_\alpha/\beta_e \propto T^{2.5} \)
  – Bottom line – with similar temperatures, alpha physics in SPARC will be similar to what expected on ITER - good for baseline H-mode operation
  – Higher field will push the spectrum of AE modes to higher n, m

• Diagnostics are planned to look at fusion rate, confined alpha distributions and fast MHD
  – Neutron detectors and neutron spectrometers look like promising tools


What’s Next?
Device Optimization, Physics Validation, Engineering Review

- Detailed engineering underway
- Deeper dive into physics validation
- Project reviewed by late spring 2021
- Leading to “ready for construction” milestone by June 2021
- Site selected - to be acquired in a few weeks, permitting process well underway
- Tritium supply secured, HTS supply secure
SPARC Is Privately Funded
The Role of Private Industry In Fusion Development
Bridging the Valley of Death for Fusion

- Government Labs & Universities are reluctant to sponsor basic research
- Outside of defense applications, the private sector is reluctant to sponsor research as it is not an immediate application
- Private companies are reluctant to sponsor fusion research if the time scale is long and financial returns are too low
- This is a particular problem for “Hard Target” research.
- MIT spun out a new fusion start-up (Commonwealth Fusion Systems)
  - We’re partnering to bridge the gap
  - The university “holds on” to the research longer, private industry picks it up
CFS, an MIT spinout, is part of a nascent fusion industry.

- There are many companies, the list is growing.
- They serve as indicators of the fusion value proposition.
- Most are pursuing more speculative approaches - optimizing economics, maintainability.
- Private industry/investors have a greater tolerance for risk than the USG.
We think this is a good thing

- Our basic research is being used! It is important and valued!
  - We’re attracting new stakeholders
  - Energizing the public and adjacents
  - Building momentum, building the ecosystem
- Having more players is good
  - Diversity of physics approaches — fusion is too important for one architecture — not everything has to work
  - Diversity of organizational approaches — fusion is too important for one team
  - Diversity of tolerance to risk
This is how new technology gets to market

- Fusion is following a well-worn tech-development arc
  - Drugs, Aerospace, Computers, AI, Robotics, Rockets, etc

- This is how fusion is going to get on the grid
  - The US government doesn’t build reactors, pilot plants, etc – it does basic research
  - Look to fission, fossil, ARPA-E, EERE

- How does the government program fill its role?
  - The mandate is basic research
  - To support a fusion industry
Summary

- Success from our research on HTS magnets and SPARC will open up a compelling case for smaller, faster, cheaper fusion development
  - We should have answers on the magnet technology in less than 6 months
  - Aim to demonstrate the first (controlled) net-energy fusion experiment 4 - 6 years
  - These steps will be funded by private investment

- As a private initiative, it provides opportunities that the US program can leverage
  - Builds on the solid foundations of decades of publicly funded research
  - Validates the goals and value of fusion research
  - Builds an industry and ecosystem which helps focus the publically funded program