Scientific Relationship Between ST and BPX Tokamak, and an ICC (ST) Development Path
A Discussion with PAC-12

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- **How does the vision for development of an ICC approach (such as ST) fit with an overall strategy which includes a near-term BP experiment (IGNITOR, FIRE, or ITER)?**
  - Tightly coupled to an overall vision for fusion science and energy development
  - Science-based program with an energy goal

- **Important to be consistent with recent planning for fusion energy science program**
  - FESAC FES Program Strategy
    - *Three components: Plasma Science, Innovation, International Fusion Energy Development Step (in U.S. or abroad)*
  - FESAC Opportunities Documents (Knoxville)
  - SEAB
  - NRC

ST Development Can Benefit Greatly From Tokamak BPX & Complete the ST-Tokamak Science Basis for Optimized Fusion

- **Roles of ST in FES Development**
- **ST synergy with Tokamak BP Experiment**
- **Role of ST in component testing**
- **Dimensionless parameters of ST & Tokamak scenarios**
- **“Magnetic Fusion Integration Test” (MFIT) Facility**
- **ST development path assuming a U.S. Tokamak BPX**
- **ST development path assuming international ITER**

Two Roles for the ST as an ICC Approach - I

1) Broaden fusion plasma science basis

- Explore extreme of tokamak-like behavior near toroidicity limit
  - *Verify predictive models for high temperature plasma behavior by testing them under a broader range of conditions*
    - Transport and confinement, MHD, energetic particles, noninductive sustainment, edge physics, coupling between BS-driven equilibrium, stability, & confinement
- Cover new topics
  - *Solenoid-free startup (similarly in ARIES-AT reactor concept), uniquely required*
  - *Discover new opportunities for fusion*
- Extend scientific basis from tokamak to RFP-spheromak-FRC
  - *ST occupies an intermediate parameter space in the self-organization continuum*

Two Roles for the ST as an ICC Approach - II

2) Investigate innovative concepts for effective fusion energy development and application

- Develop a credible path for the ST approach to fusion power production and applications
  - *Power production Physics and Technology: ST BPX, VNS*
  - *Demonstration of physics advantages*
    - Requires PoP and PE physics database
    - Combines ST-AT parameter space to enable DEMO physics optimization

Note: Either role is sufficient justification for aggressive ICC R&D

- Plasma Science and Innovation components of the U.S. FES Program must maintain capability and flexibility to integrate new developments into an eventual optimized reactor concept
  - *Choices get necessarily more constrained as capabilities grow in scale*
  - *Concept development is mandatory to maintain adequate flexibility*

ST Synergy with a Near-Term Burning Plasma Experiment - I

- *General*
  - As a close relation to the tokamak, especially the AT, a strong overlap of scientific issues and capabilities exists between ST and tokamak-based BP developments
  - This has enabled a more rapid progress of ST PoP research
- *What do ST's gain from a tokamak-based BP experiment?*
  - Paradigm development for a strongly coupled self-organizing plasma with self-heating in modest beta plasmas that leave the toroidal field relatively intact
    - *Both intellectual and experimental*
  - Demonstration of self-heating in a burning plasma brings confidence in achieving burning plasmas in broader ICC parameter space
  - Tests of predictive transport models in BP regime of modest beta and Alfvén number (v-flow/v-Alfvén)
  - Fast-particle/MHD interactions with high trans-Alfvénic fast-particle population
  - Fusion-environment diagnostic development for dielectric constant~1 plasmas
  - Physical and intellectual infrastructure supports rapid development of ST-BP demonstration
    - *A simpler ST BPX can plug into same site, power supplies, etc.*
    - *Tritium and remote handling experience can be shared*

ST Synergy with a Near-Term Burning Plasma Experiment - II

- **What do ST's add to a Tokamak-based BP experiment**
  - Test and develop a broadened scientific basis for tokamak and AT-related physics issues
    - *MHD control and understanding at much higher beta values (β_0~1) and stronger in-out asymmetry*
    - *Tests of predictive models for beta-related MHD issues, including RWM, NTM, etc. under extreme toroidicity and large fractional Alfvén number*
    - *Exploration of supra-Alfvénic fast-particle interactions with MHD*
    - *RWM and close-fitting wall requirements at high q_0 (~2-3) and q_{95} (~10)*
    - *Transport tests with enhanced electromagnetic short wavelength fluctuations and suppressed electrostatic longer wavelength fluctuations*
      - Energy and particle (especially alpha ash implications?)
    - *Strong coupling between transport, heating, and equilibrium/stability with high BS fraction with strongly hollow J and monotonic q profiles*
    - *Develop concept for practical alpha-channeling via CAE's (or magnetosonic waves at sub-, trans-, and high-harmonic numbers)?*
    - *Wave-plasma-energetic particle interactions in over-dense plasmas (dielectric constant >> 1)*
    - *Solenoid-free initiation and rampup of plasma current with current hole*
  - Plasma control techniques development
    - *e.g., pressure and current profile control with high bootstrap-drive fraction*
    - *Current drive techniques in over-dense plasmas*
    - *Fueling techniques in extreme in-out asymmetry plasmas with large magnetic well*

Role of ST in Component Testing

- **Required development of materials and technology components for the DEMO reactor**
  - *Assume IFMIF relevance for material samples tests (for ≤ 2 MW/m^2 in ~0.5 liter testing volume)*
  - *Consider ST-VNS relevance for high-availability component tests (for ~ 6 MW-yr/m^2 over ~10 m^2 testing wall area)*

Dimensionless Parameters of ST & Tokamak Scenarios

	NSTX-MAST	PE Tokamaks	PE NSST	FED FIRE	FED ITER-FEAT	FED VNS	ARIES -AT	ARIES -ST
q_{95}	10	5	10	4	4	10	4	10
κ	2.5	2	2.5	2	2	3	2	>3
β_T	0.4	0.04	0.4	0.05	0.05	0.25	0.1	0.5
M_{Alfven}	0.3	0.05	0.3	0.01	0.01	0.3	0.01	0.3
a/ρ_i	35	200	100	400	1000	100	1000	140
B_p/B_t	1	0.1	1	0.1	0.1	1	0.1	1
V_{fast}/V_{Alfven}	4	1	4.4	1.6	1.6	5	1	5
$\omega_{pe}^2/\omega_{ce}^2$	100	1	100	1	1	100	1	100
M_{SOL}	≤ 4	≤ 1.5	≤ 3	≤ 1.5	≤ 1.5	≤ 4	≤ 1.5	≤ 4
f_{BS}	0.7	0.6	0.8	0.66	0.66	0.5	0.95	0.95

A U.S. Tokamak BP Experiment Could be Located in "Magnetic Fusion Integrated Test" (MFIT) Facility

- **Provide opportunity to ST (or other eligible ICC) to contribute to reactor realization**
  - Scale and cost of ICC BPX must contribute effectively to a flexible program plan
  - Broadens the scientific basis (parameter space) for optimized DEMO

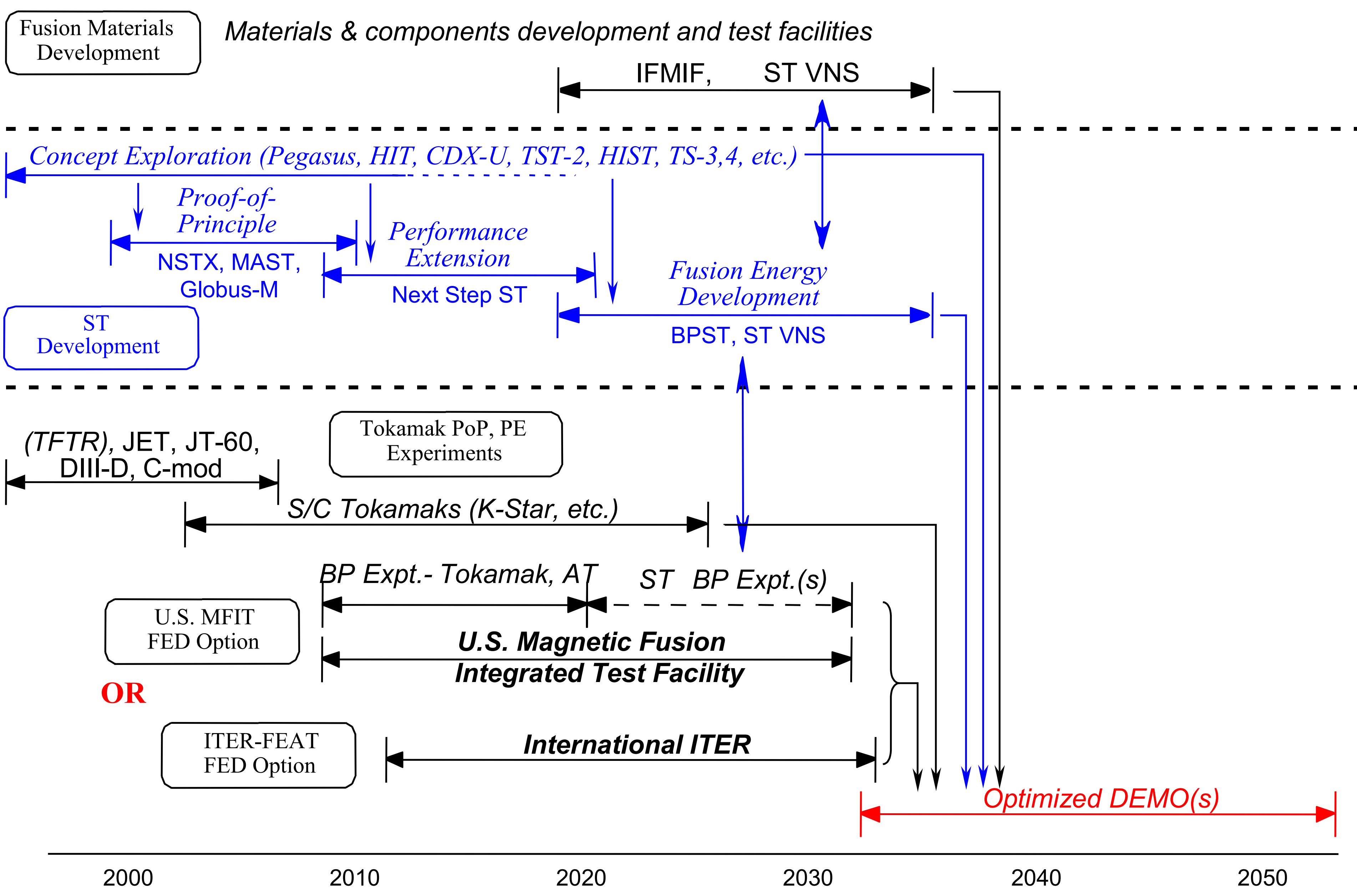
- **An attractive, flexible facility to allow ST plug-in**
  - Facilitates realization of low-cost ST path if supported by physics and engineering from PoP & PE tests
  - Assume ~70% of cost in base site development - facilities, power supplies, etc.
  - Install "low-cost" ST in facility for BP experiment following initial tokamak BP experiments

Conceptual ST Development Roadmap Assuming a U.S. MFIT Facility

- **Consider spherical torus as contributor to optimized DEMO via PE followed by FED (BP ST and/or VNS high availability components test facility)**
- **Need cost-effective ST (as all ICC) PE and FED steps**
- **ST path can contribute to multi-use Magnetic Fusion Integrated Test (MFIT) Facility (2010-2035) preceding DEMO ~2035**
  - Start with tokamak/AT BPX (2010-2025)
  - In later stage, install an ST core in facility (2020-2035)
  - Multi-use facility allows accelerated development of new concepts at FED stage

Note: suggested timeline could readily be accelerated if funding available

ST Contributions to Fusion Energy Sciences Development



Conceptual ST Development Roadmap Assuming ITER-FEAT

- **Consider spherical torus as contributor to optimized DEMO via PE experiment followed by VNS high availability components test facility**
- **Need cost-effective ST (as all ICC) PE and FED steps**
- **ST path can complement ITER-FEAT operation for 2015-2035 and start of DEMO ~2035**
  - PE Next Step ST (NSST, up to 10 MA level) at a low cost site (2010-2020)
  - FED step via a VNS at a nuclear site (2020-2035)
  - PE NSST + ITER-FEAT ⇒ basis for physics optimization of DEMO
  - VNS + IFMIF + ITER-FEAT-U ⇒ basis for technology optimization of DEMO
  - Multiple fusion sites assuming broad international stakeholders

- **ITER-FEAT could be upgraded to an integrated test facility**

(for ~ 0.1 ⇒ 1 MW-yr/m^2 over ~20 m^2 testing wall area)

ST Development Can Benefit Greatly From Tokamak BPX & Complete the ST-Tokamak Science Basis for Optimized Fusion

- **ST (ICC) has two roles**
  - Broaden fusion plasma science basis
  - Develop innovation for effective fusion energy development
- **Strong synergy with Tokamak BPX**
  - Benefits from Tokamak science and a Tokamak BPX
  - Expands the ST-Tokamak parameter space, add strongly to BP physics
  - Can fit into a U.S. MFIT Facility
  - Can provide high-availability VNS
- **ST development can fit either ITER-FEAT (international), FIRE (US), or IGNITOR (Italy)**
  - Requires cost-effective ST PE and FED steps
  - PE NSST + ITER-FEAT ⇒ basis for physics optimization of DEMO
  - VNS + IFMIF + ITER-FEAT ⇒ basis for technology optimization of DEMO

Helps define the long-term goals of ST research