Science and Technology Issues and Opportunities for a Burning Plasma Science Experiment

Prepared and presented by:

John Wesley
General Atomics
San Diego, California

University Fusion Association
Burning Plasma Science Workshop II
1-3 May 2001
General Atomics
San Diego CA

Science and Technology Considerations for a BPSX*

- Foreseeable near-term BPSX's will be tokamaks
- Plasma performance ($nT\tau$) significantly above that achievable in present tokamaks is required
- Enhanced or new technologies are required
- This presentation examines several key generic BPSX requirements and the resulting 'BP' technology needs
- A BPSX can also provide a unique stimulus/opportunities to develop and test generic future MFE technologies

*generic Burning Plasma Science Experiment

Selected Topics and Organization

- High-field/long-pulse TF and PF magnets
- PFCs: power loading and pulse duration, T-retention and disruption resistance/tolerance (also Session 1)
- BP-compatible/enabling H/CD (also Session 2)
- AT-enabling H/CD, etc. (Session 2)
- BP- and AT-compatible diagnostics (Session 5)

Framework for Consideration:


Science → BP Technologies → BP Science Ops

BP Technologies → Fusion Tech Ops

Acknowledgements and Cautions

- The analyses presented here are supported by General Atomics internal funding: opinions expressed are those of the author alone

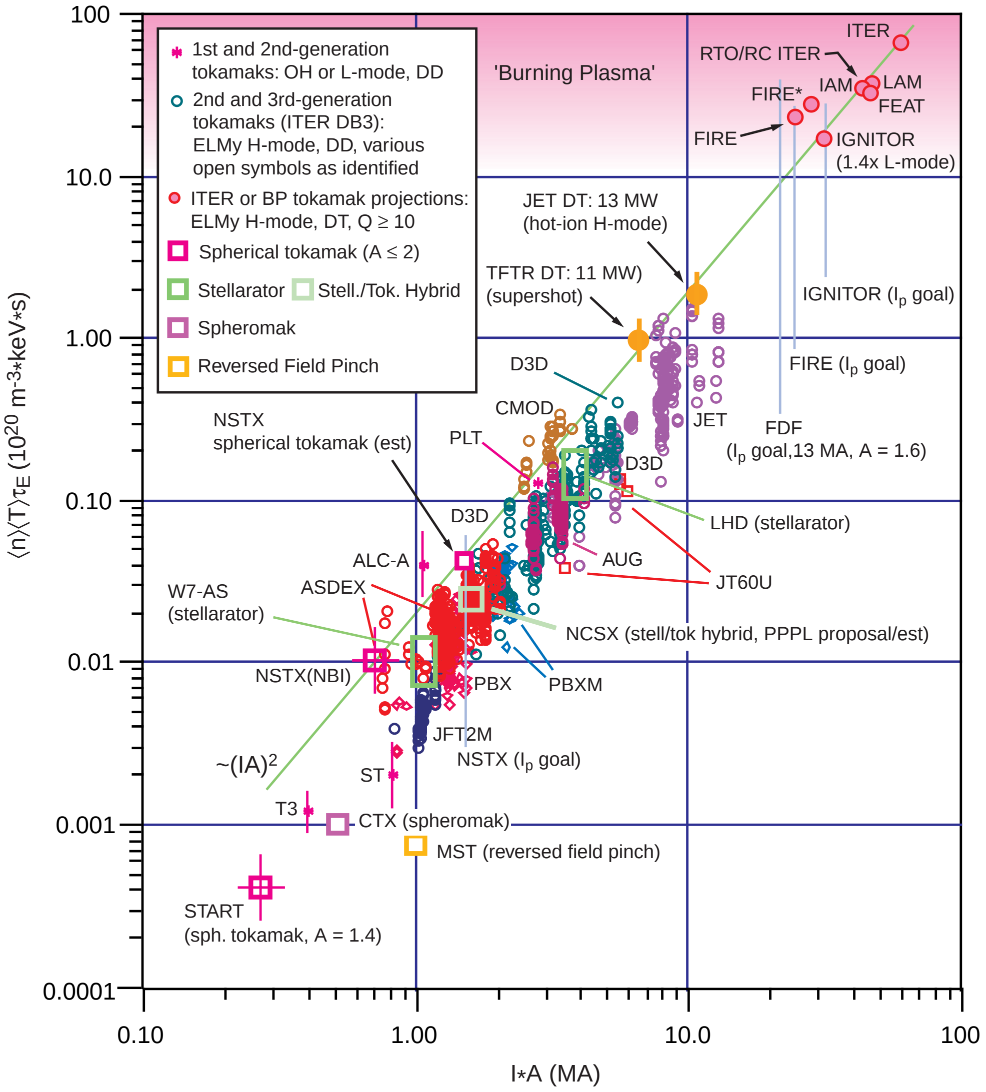
- Methodologies adopted derive from a long succession of [would-be] first-of-kind burning plasma experiments: INTOR, FED, ITER-CDA, ITER-EDA, CIT, BPX, ...

- Qualitative parameters are based on public-accessible machine concept data and do not necessarily constitute a fully accurate or equivalent comparison basis. Small distinctions among concepts in computed parameters are not necessarily meaningful

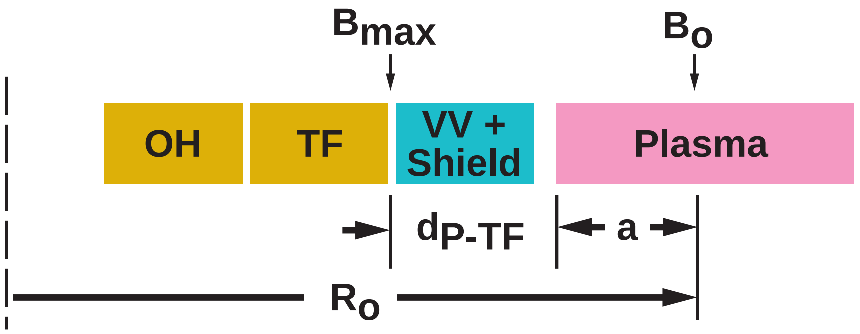
- Don't attempt BPSX comparisons like this at home, at least without taking adequate protective measures!

BP Regime Access Requirements

- **Maximum $\langle n\rangle\langle T\rangle\tau_E$ in tokamaks increases approximately as $(I^*A)^2$**
- **Stellarator and [sparse] ST data fall on the same scaling (and hence tend to confirm the A dependence of the tokamak scaling, which spans a range A = 2.5 - 5)**
- **There are factor-of-2 variations (±) among the tokamak data (profiles, other significant parameters, optimization, ...). IA is not the <u>only</u> performance predicting parameter**
- **BP regime (Q ~ 10) typically requires $\langle n\rangle\langle T\rangle\tau_E \geq$ 2-4 x 10^{21} m^{-3} keV·s (varies owing to assumptions about profiles, impurities, self-consistent He, ...)**
- **BP requires IA ≥ 30 MA (eg. ≥ 10 MA at A = 3; cf. JET-EFDA IA = ~12 MA)**
- **IA ≥ 40 MA provides modest margin; IA ≥ 60 MA yields 'ignition' (Q ≥ 25) and/or a 'reactor-prototype' device**



Magnet and shielding requirements set BPSX size



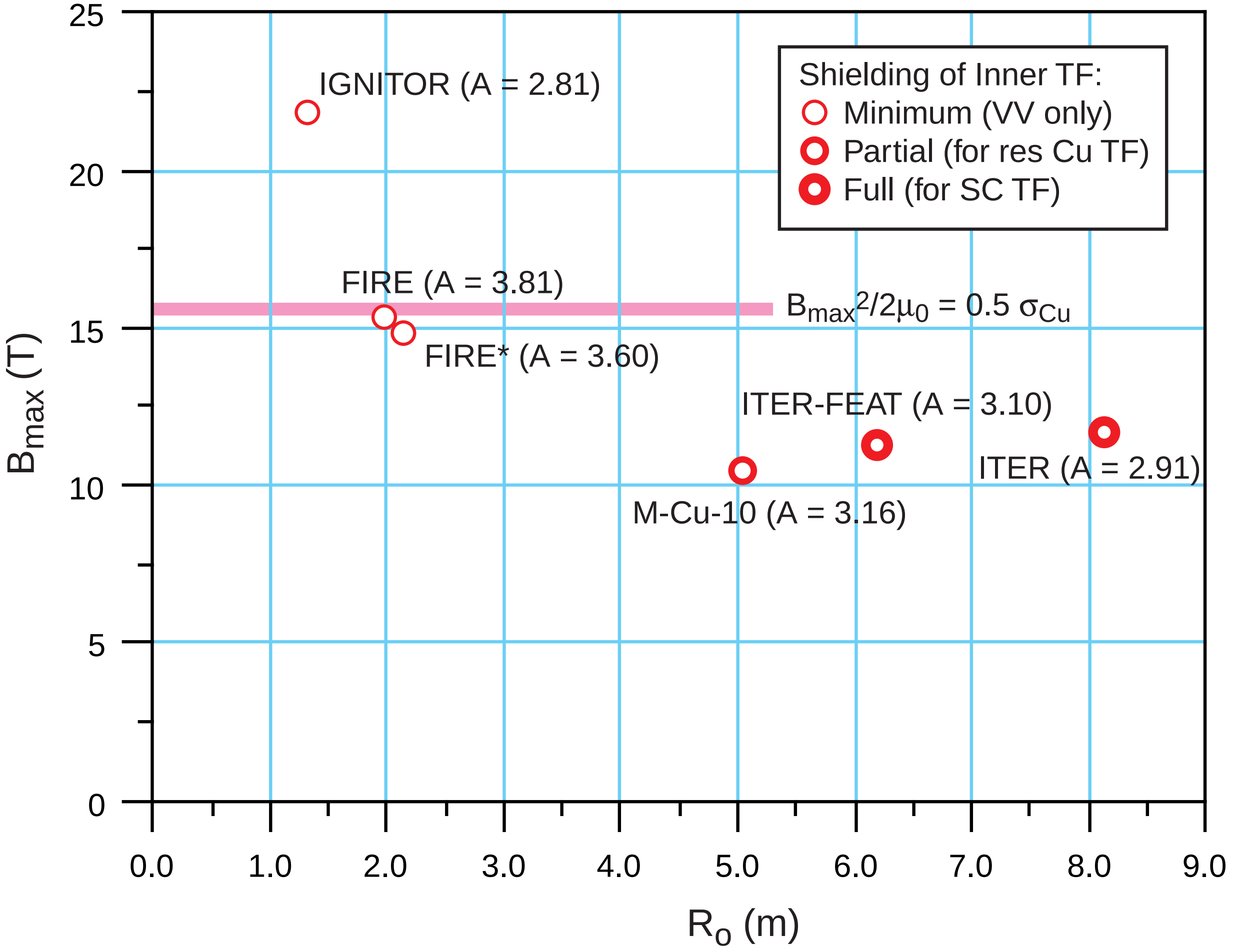
$$a = \frac{d_{P\text{-}TF} + \dfrac{q_{95}\, IA * A}{5\, B_{max}\, C(\kappa,\delta)\, C(A)}}{A-1}$$

$$R_o = A\, a$$

Device	ITER-FDR	ITER-FEAT	FIRE-10T	FIRE*-10T	IGNITOR	M-Cu-10
A	2.91	3.10	3.81	3.60	2.81	3.16
I(MA)	21.0	15.2	6.6	7.7	11.5	14.2
κ_{95}	1.60	1.70	1.80	1.80	1.83	1.77
δ_{95}	0.25	0.33	0.40	0.40	0.43	0.33
q_{95}	3.00	3.00	3.00	3.00	3.00	3.00
B_{max} (T)	11.7	11.3	15.3	14.8	21.8	10.5
$d_{P\text{-}TF}$ (m)	1.45	1.25	0.167	0.167	0.08	0.54
a (m)	2.80	2.00	0.521	0.597	0.47	1.61
R_o (m)	8.14	6.20	1.98	2.15	1.32	5.05
B_o (T)	5.61	5.38	10.0	9.6	12.7	6.1
IA (MA)	61	47	25	28	32	45

- Minimum size and A are also constrained by OH solenoid requirement

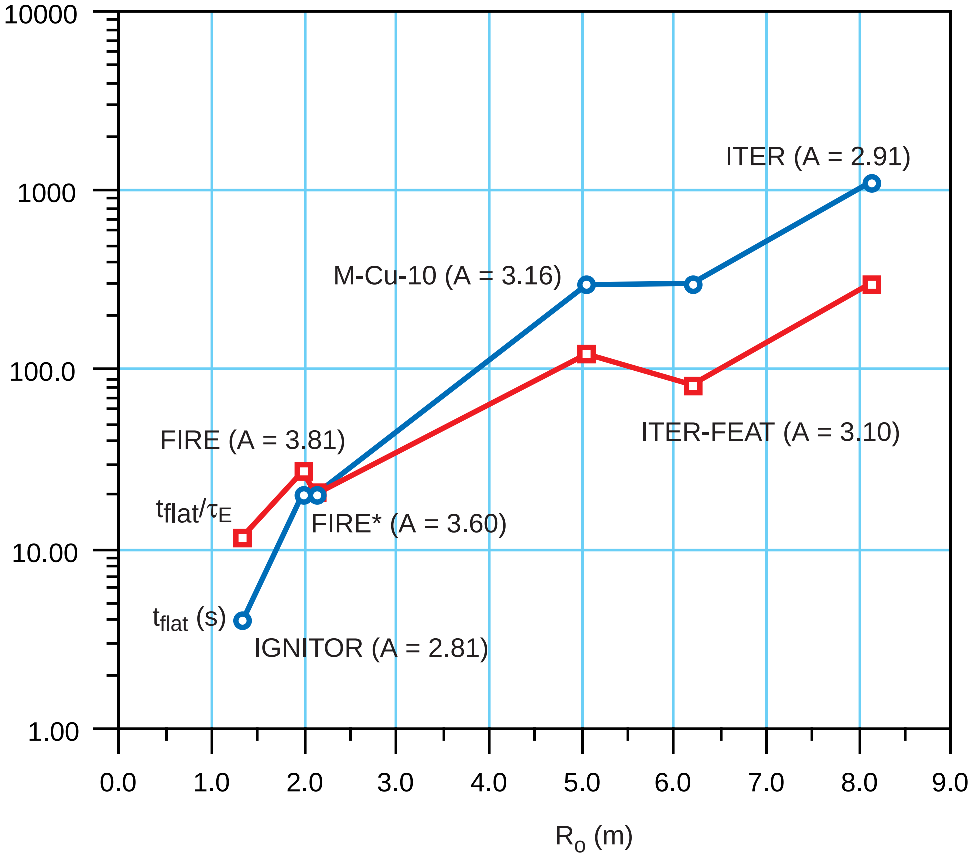
High B_{max}, Low A and No Shielding Yield Smallest R_o



- $B_{max} \geq \sim 16$ T pushes to (or above) ‘pure-Cu’ stress limit

Pulse Duration (with inductive/OH current drive)

- **Compact inertially-cooled designs are thermal and OH-limited**
- **Larger designs with steady-state TF are OH-limited (OH V-s swing)**
- **Absolute pulse duration increases strongly with R_o, but confinement-normalized duration increase is ~ 10-x weaker:**



BPSX Magnet Technology Summary

- A variety of resistive (copper) and superconducting (SC) magnet technologies to support $Q \geq 10$ BPSX's have been identified
- Concepts separate into two categories based on TF magnet cooling (inertial or steady-state) and at-magnet peak field:
  1) cryo-precooled copper (typically with some alloying), inertially cooled, with 15-22 T peak fields, or
  2) steady-state resistive pure copper or SC, with peak fields 10-12 T
- Machine size (R_o) decreases strongly with higher B_{TF} and/or weakly with lower A. But OH requirement sets a limit on minimum A
- TF structural limitations apply to all concepts and are important configuration drivers, especially for compact designs
- For both inertial and steady-state concepts, OH solenoid flux swing sets an V-s limited plasma current/burn duration
- For compact inertial-Cu designs, TF thermal and OH duration limits are similar; for steady-state TF designs, OH duration limit sets burn duration
- Reliable magnet operation will be critical: all BPSX designs will require essentially full-field, full-current operation (for ??? pulses)

BPSX Plasma Facing Component Requirements

- **A BPSX will require a larger scale (size and/or field strength) and higher power (aux + alpha) device than the largest present tokamaks. PFCs, VVs, etc. will also be exposed to significant volumetric neutron heating**
- **Increase in 'scale' and plasma power (plus neutron heating) results in an increase in the effective plasma wall loading — P_{th}/A_{FW} and also in the plasma specific energy — W_{th}/A_{FW}**
- **These increases plus the effects of neutron irradiation on material and structure properties and PFC maintenance impact BPSX PFC selection, design and operation planning**
- **In addition, BPSX PFC's *must* be selected to minimize T retention (in co-deposited layers). Use of carbon may be constrained or prohibited**
- **Finally, in almost all cases, BPSX primary PFCs will operate in thermal steady state and require active cooling. Provision will also be needed to replace eroded or damaged PFCs on a regular basis**

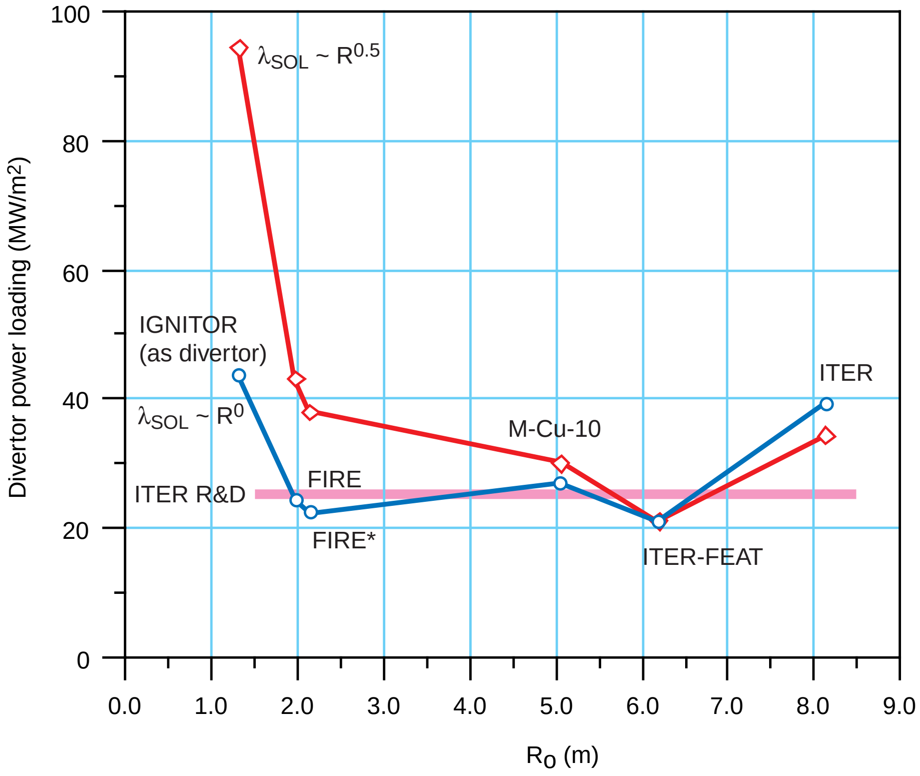
BPSX PFC Parameters (Estimated)

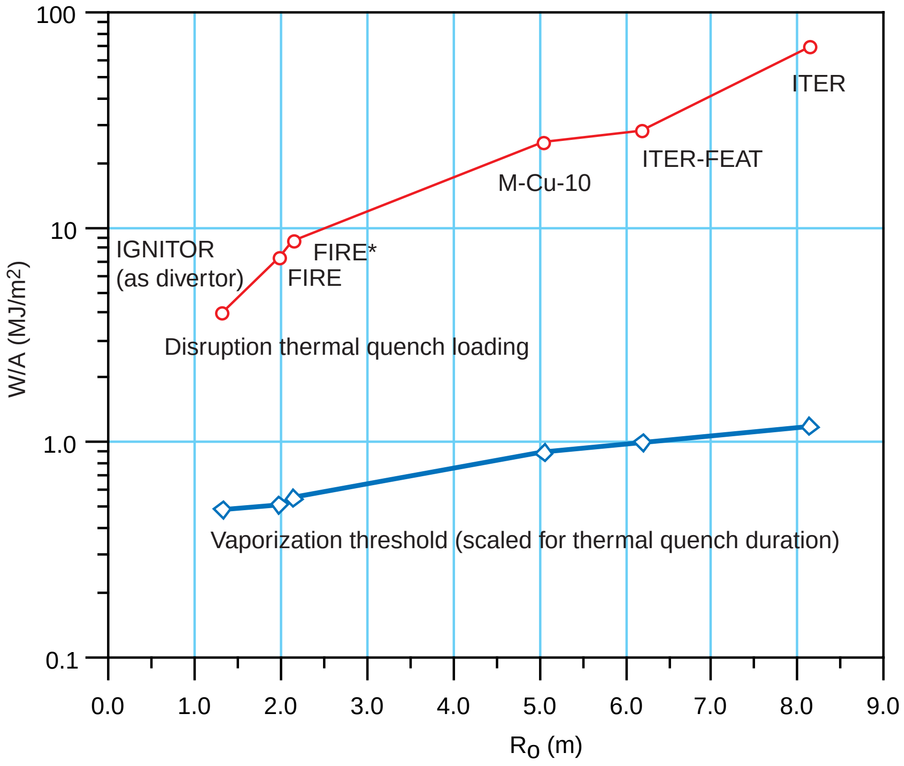
- A BPSX requires a larger scale (size and/or field strength) and higher (aux + alpha) power device than the largest present tokamaks
- PFC 'steady-state' power/area (MW/m^2) and disruption energy (MJ/m^2) are appreciably higher than in present 'long-pulse' (~10 s) tokamaks:

Device	ITER-FDR	ITER-FEAT	FIRE-10T	FIRE*-10T	IGNITOR	M-Cu-10
A	2.91	3.10	3.81	3.60	2.81	3.16
I (MA)	21.0	15.2	6.6	7.7	11.5	15.0
R_o (m)	8.14	6.20	1.98	2.15	1.32	5.00
P_{fus} (MW)	1500	410	150	150	180	325
P_α (MW)	300	82	30	30	37	65
P_{aux} (MW)	0	40	15	15	18	33
P_{tot}/A_{wall} (MW/m^2)	1.19(a)	0.61	2.4	1.9	5.0	0.94
P/A_{div}	39(b)	21	24	22	44(c)	27
W_{th} (MJ)	1100	325	27	35	~10	235
W_{th}/A_{div} (MJ/m^2)	70	28	7.2	8.5	4.0	25

(a) Basis: total power = neutron + alpha + auxiliary, uniformly spread over first wall
(b) Basis: 0.67*(alpha + aux) power to divertor; 10-x SOL expansion; SOL = 0.01 m (R ind.)
(c) Basis: same divertor geometry and SOL as others: design is with a limited plasma

BPSX Divertor Thermal and Disruption Loadings

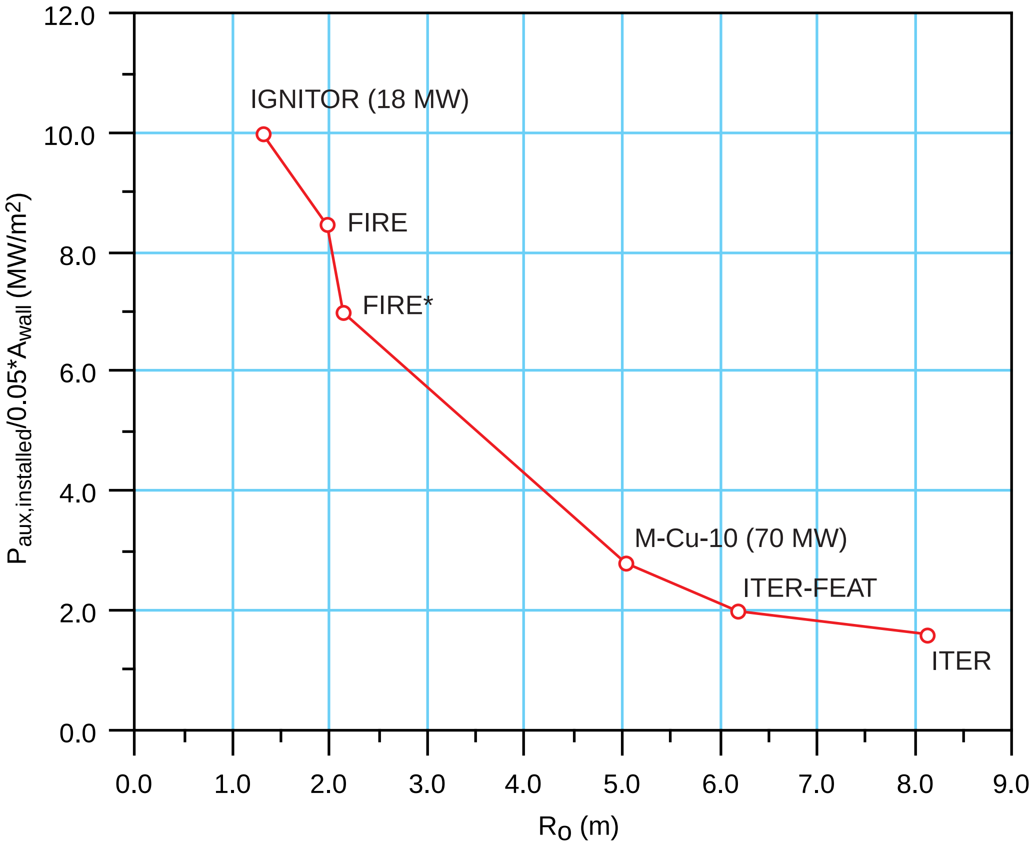




- **Thermal loading: present BPSX's except IGNITOR(div)] have 'raw' (without radiative mitigation) power loadings ~25 MW/m^2 (ITER-EDA R&D goal/achievement)**
- **All BPSX's will need radiative PFC power mitigation for 'routine' operation ($P_{div} \leq 10$ MW/m^2)**
- **Disruption loading: all BPSX's have 'raw' (without plasma shielding) divertor loadings ≥ 10-x PFC surface vaporization threshold. Disruption-affected PFC's will be consumable components. Disruption avoidance (frequency reduction) is needed; will pay off!**

BPSX Auxiliary Heating and Current Drive

- All BPSX's will require, provide substantial auxiliary heating/CD
- Port power density ($A_{port} \leq 0.05\ A_{wall}$) increases with decreasing R_o



GENERAL ATOMICS

BPSX Auxiliary Heating and/or Current Drive

- H/CD selection and installed power mix (or possibly installable mixes) varies among BPSX candidates; constrained by H/CD technologies, plasma access and parameters and H/CD cost(s)

Device	ITER-FDR	ITER-FEAT	FIRE-10T	FIRE*-10T	IGNITOR	M-Cu-10
R_o (m)	8.14	6.20	1.98	2.15	1.32	5.00
P_{aux} ($Q = 10$) (MW)	NA	40	15	15	10-20	40 (~FEAT)
Install'd $P_{H/CD}$ (MW)	100	70 (100)	45?	55	10-20?	70 (?, ~FEAT)
NI-NBI (tang) (MW)	50	33	???	???	NA	40 (~FEAT)
PI-NBI ($\perp$)	---	---	---	---	---	???
ICRF	50(a)	20(b)	30	30	10-20	~FEAT
LHRF (MW/m^2)	50(a)	0(b) (20)	15?	25	?	~FEAT
ECRF	50(a)	20(b)	NA	NA	NA	~FEAT

(a) maximum option; final mix in addition to NBI TBD
(b) initial selection; other options added later

- High-field/compact candidates: ICRF with LHRF option/addition; NBI or EC likely 'not applicable'; port power densities higher for all
- Low-field: NBI with ICRF/LHRF/ECRF options/additions; lower port power densities and/or more available ports/mix options

Summary (Objective)

- BPSX feasibility and cost-effectiveness depends on three key technologies: HP-magnets, HP-PFCs, and magnet/concept-compatible H/CD
- Magnet technology is the concept driver. Options has been identified and design concepts have been correspondingly optimized to address various embodiments of the basic Q = 10 'BPS mission'. All proposed magnet technologies have been or likely can be shown to be 'feasible'
- There is a correlation among TF cooling (inertial or steady-state) and peak field (10 -22 T), device major radius and energy-confinement-normalized fusion burn duration. Smaller (larger) designs trade compactness (cost) for increasingly longer normalized burn duration. In the large device category, both SC and steady-state resistive Cu options with similar OH-limited burn duration are feasible.
- Divertor PFC power loadings and vaporization-energy normalized disruption loadings are similar and equally challenging across the whole spectrum of BPSX's. T-retention will constrain material choices
- Choice of peak/plasma TF field determines H/CD options/mix. Compact high-B options focus on IC and LH; larger low-B options can also accommodate NI-NBI and ECRF and typically also allow a 'cafeteria' mix of the four possible H/CD candidates. Long-pulse/ss 'sources' are needed

Conclusions and Opinions

- Fusion science needs fusion technology (and vice-versa)
- Fusion technology is [close to being] ready for a BPSX
- But the challenges are great, and we must not lose sight of the fact that the scientific success of a BPSX will hinge critically on the achievement of adequate performance of *all* of its enabling technologies
- Conversely, given success with these enabling technologies, and then success with the ensuing plasma science, fusion will, for the first time, have a means to achieve routine production of copious amounts of fusion power, and to begin exploring the *real* challenges of fusion energy

"It is far better to light just one small
BPSX than to curse the darkness."