PMI-Driven Mission Risks, Status and Data Sources for the Next DT Device

Rob Goldston
ARIES Team Meeting
July 30, 2010

Mission Risks & Status - I

1. **Disruption heat loads to FW drive design to tritium breeding ratio < 1 ?**
   - A few unmitigated VDEs compromise FW survival in ITER.
2. **Disruption runaways to FW drive design to tritium breeding ratio < 1 ?**
   - Unmitigated runaways projected to be highly destructive.
3. **High steady heat loads to FW inconsistent with thick surfaces needed for disruption survival ?**
   - Up to 5 MW/m^2 projected in some areas in ITER.
4. **ELMs result in divertor melting, cracking, thermal instability ?**
   - Very low allowable fractional energy loss must be maintained for high duty factor.

Mission Risks & Status - II

5. **Steady heat and particle loads result in unacceptable power loads, divertor erosion and/or redeposition ?**
   - Projections problematic, *e.g.*, $1/I_p$ scaling of λ_{SOL}, H-mode performance at high f_{Rad} and n/n_{GW}.

6. **Fuel and/or impurity influx from metallic FW and divertor degrade core plasma performance unacceptably ?**
   - ASDEX-U results with cold W and C-MOD results with cold Mo problematic with ICRF, advanced regimes.

7. **Tritium inventory, throughput and/or permeation unacceptable ?**
   - No tokamak data with hot W or liquid lithium.

8. **Dust and/or liquid accumulation from PFCs unacceptable ?**
   - Little data for extrapolation, need real-time control.

Data Timetable

- **2016 ± 2**
  - C-MOD, DIII-D, NSTX, AUG, JET ILW, EAST, KSTAR.
    Enhanced technology development?
- **2022 ± 2**
  - ITER at full current and full auxiliary H&CD.
    JT-60SA starting up.
    New technology test stands?
    New plasma test stands?
    New Tokamak PMI facility?
- **2028 ± 2**
  - ITER Q = 10, 300 - 500 sec.
    JT-60SA in full operation.

Simplified PMI Parameters

	EAST, KSTAR, JT-60SA	JET ILW	ITER	FDF 2MW/m^2 NWL	ST-FNSF 2MW/m^2 NWL	Pilot Plant 2MW/m^2 NWL
W/S, MJ/m^2	0.06	0.13	0.63	0.71	0.81	0.81
e^(2*Ip), RA Avalanche	55, 400	3 10^3	10^13	5 10^5	3 10^10	10^7
P_tot/S, MW/m^2	0.5	0.29	0.24	0.8	1.4	0.77
W/R, MJ/m	1.6	6	64	33	43	45
P_heat/R, MW/m	13	13	20	29	57	37
Wall Temperature	~30C	~30C	~200C	~700C	~700C	~700C
Duty Factor	low	low	low	~0.3	~0.3	~0.3

Disruption heat loads to FW drive design to TBR < 1 at W/S ~ 0.75 MJ/m^2 ?

- **2016 ± 2**
  - Mitigation experiments on short-pulse tokamaks. JET ILW W/S ~ 0.13. First experience with moderate pulse length operation in EAST, KSTAR for frequency of unmitigated disruptions at W/S ~ 0.06. Initial technology development results.
- **2022 ± 2**
  - Full current and full auxiliary power results (~1/2 of Q=10 power) from ITER in 2024 at W/S ~ 0.38. Long pulse results from EAST, KSTAR, JT-60SA at W/S ~ 0.06. Technology development and testing results. High power, hot walls, high duty factor results with self-consistent power handling, liquid divertor targets, from PMI-f at W/S ~ 0.08.
- **2028 ± 2**
  - Full energy disruptions on ITER at W/S ~ 0.6. More data from KSTAR, EAST, JT-60SA, PMI-f at W/S ~ 0.07. More technology development and testing.

Disruption runaways to FW drive design to TBR < 1 at $e^{2Ip} > 10^6$?

- **2016 ± 2**
  - Mitigation experiments on short-pulse tokamaks. JET ILW at $e^{2Ip} \sim 3000$. First experience with moderate pulse length operation in EAST, KSTAR for frequency of unmitigated disruptions at $e^{2Ip} \sim 55$. Initial technology development results.

- **2022 ± 2**
  - Full current and full auxiliary power results (~1/2 of Q=10 power) from ITER in 2024 at $e^{2Ip} \sim 10^{13}$. Long pulse results from EAST, KSTAR at $e^{2Ip} \sim 55$, JT-60SA at 400. Technology development and testing results. High power, hot walls, high duty factor results from PMI-f at $e^{2Ip} \sim 1000$.

- **2028 ± 2**
  - Full energy disruptions on ITER at $e^{2Ip} \sim 10^{13}$. More data from KSTAR, EAST, PMI-f at $e^{2Ip} \sim 55 - 1000$, JT-60SA at $e^{2Ip} \sim 3000$. More technology development and testing.

High steady heat loads to FW inconsistent with thick surfaces needed for disruption survival at $P_{tot}/S \sim 0.8$ MW/m^2 ?

- **2016 ± 2**
  - IR measurements in short- and moderate-pulse tokamaks at $P_{tot}/S \sim 0.3 - 0.5$. Initial technology development results.
- **2022 ± 2**
  - Full current and full auxiliary power results (~1/2 of Q=10 power) from ITER at $P_{tot}/S \sim 0.11$. Long pulse results from EAST, KSTAR at $P_{tot}/S \sim 0.5$. Technology development and testing results. High power, hot walls, high duty factor results from PMI-f at $P_{tot}/S \sim 1$, in self-consistent heat dissipation scenario.
- **2028 ± 2**
  - Full current and full power results from ITER at $P_{tot}/S \sim 0.24$. First results on lost fast ions heating FW. More long pulse results from EAST, KSTAR, JT-60SA at $P_{tot}/S \sim 0.5$. More technology development and testing. More high power, hot walls, high duty factor results from PMI-f at $P_{tot}/S \sim 1$, multiple self-consistent heat dissipation scenarios tested.

ELMs result in divertor melting, cracking, thermal instability at W/R ~ 35 MJ/m, DF ~ 0.3

- **2016 ± 2**
  - Further studies on ELM mitigation on all tokamaks. First experience with moderate pulse length operation in EAST, KSTAR for reliability of ELM control at W/R ~ 1.6. W/R in JET ILW ~ 6. Initial technology development results.
- **2022 ± 2**
  - ELMs and ELM control in ITER He plasmas, with W/R ~ 39. Long pulse operation of EAST, KSTAR with W/R ~ 1.6. Technology development and testing results. High power, hot walls, high duty factor results with self-consistent power handling, liquid divertor targets, from PMI-f at W/R ~ 4.
- **2028 ± 2**
  - ELMs and ELM control in ITER Q=10 plasmas, with W/R ~ 64. More long pulse operation of EAST, KSTAR and JT-60SU with W/R ~ 1.6. More technology development and testing. More high power, hot walls, high duty factor results from PMI-f at W/R ~ 4, multiple divertor scenarios tested.

Steady heat and particle loads result in unacceptable power loads, divertor erosion and/or redeposition at $P_{heat}/R \sim 40MW/m$, DF ~ 0.3 ?

$P_{heat} = P_{tot} - P_{brems}$

- **2016 ± 2**
  - Cold W divertors in JET and AUG. Hot W divertor in C-Mod. Lithium in NSTX. Moderate pulse length in EAST, KSTAR: $P_{heat}/R \sim 13$, low DF. Initial technology development results.

- **2022 ± 2**
  - ITER operation at full auxiliary power, $P_{heat}/R \sim 11$, He H-mode, C divertor targets. Long pulse operation of EAST, KSTAR, JT-60SA with $P_{heat}/R \sim 13$.Technology development and testing results. Plasma test stand studies of erosion and redeposition. High power, hot walls, high duty factor results from PMI-f at $P_{heat}/R \sim 40$, self-consistent divertor scenario, variable magnetic geometry, liquid divertor targets, extrinsic impurities that sputter W.

- **2028 ± 2**
  - ITER operation at full power, $P_{heat}/R \sim 20$, DT H-mode. More long pulse operation of EAST, KSTAR, JT-60SA with $P_{heat}/R \sim 13$. More technology development and testing. More plasma test stand studies of erosion and redeposition. More high power, hot walls, high duty factor results from PMI-f at $P_{heat}/R \sim 40$, multiple divertor configurations tested.

Fuel and/or impurity influx from metallic FW and divertor degrade core plasma performance unacceptably at $P_{heat}/R \sim 50$ MW/m, DF ~ 0.3 ?

- **2016 ± 2**
  - Further results from ASDEX-U, JET ILW, C-MOD, NSTX, EAST and KSTAR. $P_{heat}/R \sim 13$, cool walls, but enhanced experience with W and Li.
- **2022 ± 2**
  - ITER operation at full auxiliary power, $P_{heat}/R \sim 11$, He H-mode, C divertor targets. Long-pulse results from KSTAR, EAST, JT-60SA at $P_{heat}/R \sim 13$. Technology development and testing. Plasma test stand studies of erosion and redeposition. High power, hot walls, high duty factor results from PMI-f at $P_{heat}/R \sim 40$, self-consistent divertor scenario, variable magnetic geometry, solid and liquid divertor targets, extrinsic impurities that sputter W.
- **2028 ± 2**
  - ITER operation at full power, $P_{heat}/R \sim 16$, DT H-mode. More long pulse operation of EAST, KSTAR, JT-60SA with $P_{heat}/R \sim 13$. More technology development and testing. More plasma test stand studies of erosion and redeposition. More high power, hot walls, high duty factor results from PMI-f at $P_{heat}/R \sim 40$, multiple divertor configurations tested.

Tritium inventory, throughput and/or permeation unacceptable at T_w ~ 700C, DF ~ 0.3 ?

- **2016 ± 2**
  - D inventory studies in all tokamaks at short to moderate pulse length. Hot W divertor in C-Mod, Li in NSTX. Initial technology development results.
- **2022 ± 2**
  - Technology development and testing results. Plasma test stand studies of retention and permeation. High power, hot walls, high duty factor results from PMI-f with self-consistent heat dissipation scenario, solid and liquid divertor targets.
- **2028 ± 2**
  - T retention studies in ITER with cold W divertor, Be walls. More technology development and testing. More plasma test stand studies of retention and permeation. More high power, hot walls, high duty factor results from PMI-f in multiple heat dissipation scenarios.

Dust and/or liquid accumulation from PFCs unacceptable at DF ~ 0.3 ?

- **2016 ± 2**
  - Dust studies in all tokamaks. JET ILW at low DF. Low DF moderate pulse operation on EAST, KSTAR. Initial technology development results.
- **2022 ± 2**
  - Initial dust production studies on ITER with C divertor targets. Technology development and testing results. Plasma test stand studies of dust production. High power, hot walls, high duty factor results from PMI-f with self-consistent dust, liquid metal removal.
- **2028 ± 2**
  - Full power dust production studies on ITER with cold W divertor targets. More technology development and testing. More high power, hot walls, high duty factor results from PMI-f with self-consistent dust, liquid metal removal tests in multiple configurations.

Conclusions

- **There are significant PMI-driven Mission Risks for the next DT device.**
  - Presented here is a *draft* list; this analysis could certainly be improved and deepened.
  - Attempt to quantify probabilities, consequences?
- **Mission Risks, Status and Data Source analyses should be performed for other risk areas as well**
  - One other PMI-related issue, early failure of divertors due to neutron embrittlement of W, might be among the neutron-interactions-driven Mission Risks.
- **One will have to choose thoughtfully the timing of the next DT device and the design of the R&D program to support it. Risk analysis is one useful tool.**
  - What level of Mission Risk should we accept?
  - What level of Mission Risk will we be allowed?

Post Script

If we undertake the international R&D program described here, we will have a pretty exciting attack on these problems, with a decent chance of success and a good chance of not missing a solution if there is one.