Physics Limitations And Their Impact On Engineering Design Of DEMO

A.D. Turnbull, General Atomics

With input from

P. Parks, A. Hyatt, E. Strait, and J. Wesley

P. Snyder, M. Schaffer, T. Evans, M. Fenstermacher, and A. Leonard

ARIES Team Meeting

Idaho Falls, ID

September 6-7 2007

ARIES TNS Project Requires Interaction And Balance Of Physics And Engineering Constraints

- **Engineering design requires guidance on key issues limiting physics parameter ranges for optimization:**
  - Specifically this includes:
    - o **Disruption limits**
    - o **Power Handling and ELM/Sawtooth suppression**
    - o **Discharge shape, profile control, and operations**
    - o **Advanced Operation**

- **In FY08/09: Propose to focus on first two issues**
- **In FY10+: Propose To Focus On Remaining Issues of Shape And Profile Control And Advanced Operation:**
  - The key specific questions will be determined at that time

Formulation Of The Right Questions Is A Key

- **Identify the key physics issues:**
  - That will have an impact on a next step demonstration reactor
  - The consequent limitations imposed by physics constraints across all areas of power plant operation
- **Attempt to formulate all questions as follows:**
  - Formulate the engineering question
  - Reformulate this as a physics question
  - Plus the link between the physics and engineering
- **This will require formulating each issue as a set of specific physics questions that will need to be answered:**
  - Propose to summarize each issue and question specifying the:
    - 'Current knowledge'
    - 'Knowledge expected to be obtained from ITER'
  - Identify consequent R&D needs for design of "next-step" machine

Avoiding 'Off-Normal Events' Is Identified By FESAC Planning Panel As A Key Requirement For DEMO

Require demonstration that events which

can cause catastrophic failure of internal components

would be essentially non-existent for DEMO:

This does not mean 'No Disruptions' !

Disruption Limits: Key Specific Issues Phrased As Physics Questions

- **Engineering Question:**
  What are the chances of disruption during the discharge duration

- **Physics Questions:**
  - What are the disruptions limits
  - How do we translate the physics limits into design guidelines
  - Where is the design point relative to the limits
    - Multidimensional parameter space
    - Likely to be challenging
  - Are disruptions deterministic
    - Can the likelihood of disruptions be quantified in a deterministic versus statistical sense
  - How much confidence is there that the design point will be disruption free over the length of the pulse or through steady state
    - What other time scales are important:
    - Wall saturation time scales and Chemistry interactions
  - What level of control over the discharge is required to maintain the requisite level of confidence in disruption avoidance
  - Are disruptions during startup and rampdown a problem

Disruption Limits: Key Specific Issues Phrased As Physics Questions

- **Engineering Question:**

  What are the physics manifestations of a disruption and what are the physical consequences

- **Physics Questions:**
  - What categories of disruptions need to be treated separately:
    - o Vertical Displacement Events (VDEs)
    - o β limit and current limit disruptions
    - o Hardware failures versus plasma operation
  - How is the energy dumped:
    - o Current quench
    - o Thermal quench, heat flash, radiation
    - o Runaway electrons

Disruption Limits: Key Specific Issues Phrased As Physics Questions

- **Engineering Question:**

  What can be done to avoid disruptions

▽ **Physics Questions:**
  - Can we avoid all disruptions with sufficient control
  - Which disruptions are unavoidable

- **Engineering Question:**

  What can be done to mitigate unavoidable disruptions

▽ **Physics Questions:**
  - Can disruptions be mitigated pre-emptively in time
  - Is after-onset mitigation effective
  - Can runaway electrons be controlled
  - Can currents in external conducting structures be managed
  - What are consequences to walls, divertors, and hardware (e.g. antennas)
  - What design and engineering requirements are needed for mitigation

Disruption Limits: Key Specific Issues Phrased As Physics Questions

- **Engineering Question:**

  What are consequences for recovery of mitigated disruptions

▽ **Physics Questions:**

- What are consequences of dumping large power from a huge volume:
  - To walls, divertors and nearby hardware such as antennas
  - How can approximately Terawatts of power expected during a 1 to 10 msec mitigated disruption be removed from the system
  - Can mitigation techniques work over large volumes in ITER and DEMO
- What is the distribution of the energy dump:
  - Heat, Radiation and Runaway high energy particles
  - Toroidal and Poloidal distribution
  - Is it highly localized or spread over an area
- What are the after-effects:
  - Dust showers
  - Erosion and other damage to structures

Disruption Limits: Key Specific Issues Phrased As Physics Questions

- **Engineering Question:**
  What are consequences for recovery from unmitigated disruptions

∇ **Physics Questions:**

- What are consequences of dumping large power from a huge volume:
  - To walls, divertors and nearby hardware such as antennas
  - Over short period of a msec
- What is the distribution of the energy dump:
  - Heat, Radiation and Runaway high energy particles
  - Toroidal and Poloidal distribution
  - Is it highly localized or spread over an area
- What are the after-effects:
  - Dust showers
  - Erosion and other damage to structures
- Can sensitive structures be protected
- What are the consequences of designing a disruption tolerant blanket structure on maintenance schemes
- What additional design features are needed for recovery

Disruption Limits: Key Specific Issues Phrased As Physics Questions

- **Specific Engineering Question on Runaway Electrons:**

  What are the consequences of focused highly energetic particle beams

▽ **Specific Physics Questions on Runaway Electrons:**

- How are runaways generated
- Where do runaways go
- How do runaways interact with the walls
- What are the effects of the heat flash versus radiation:
  - Are there multiflashes from runaways
  - These questions are likely to be answered by ITER
- Does the runaway population filament or remain an intact localized beam
- How does the amplification factor scale between DIII-D (~3 to 10), JET (~20), ITER (expected ~ 50) and DEMO

ITER may fail because of this issue

Power Handling: Key Specific Issues Phrased As Physics Questions

- **Engineering Question:**

  Can steady state power fluxes to material surfaces be handled

∇ **Physics Questions:**

- What are the total steady state power levels
- What is the distribution of the flux to the walls versus divertor and other
- What is the toroidal and poloidal distribution
- How can the energy be extracted

- **Engineering Question:**

  What level of fluctuations in power fluxes to material surfaces can be expected

∇ **Physics Questions:**

- What fluctuations cause significant power flux variations:
  - o ELMs
  - o MARFES
  - o Sawteeth

Power Handling: Key Specific Issues Phrased As Physics Questions

- **Engineering Question:**

  Can peak power fluxes to material surfaces be handled

- **Physics Questions:**
  - Can the fluctuations be predicted:
    - What are the onset conditions
    - What amplitude levels are the fluctuations (power and peak energy)
    - What frequency do they occur
  - What are the predictions for the fluctuations in the design points
  - What are consequences on divertor and wall loads
  - Are divertor and wall modifications required in the design points
  - What options exist for reduced fluctuations:
    - Can the fluctuations be controlled by discharge control
    - Can the fluctuations be controlled by shaping or seeding
  - What options exist for eliminating fluctuations
  - How much performance is lost by reducing or eliminating fluctuations

Power Handling: Key Specific Issues Phrased As Physics Questions

- **Engineering Question:**

  What are the consequences of large amplitude fluctuations

- **Physics Questions:**
  - What is the distribution to the walls versus divertor or other surfaces:
    - Can this be controlled
  - What is distribution between radiation and heat and high energy particles
    - Can this be controlled

Power Handling: Key Specific Issues Phrased As Physics Questions

- **Engineering Question:**

  What design features are needed for handling fluctuations

- **Physics Questions:**
  - Will DEMO require the whole menu of a radiative divertor with both core and mantle radiation to even out the heat fluxes:
    - Need to avoid radiative divertor detachment
    - Window of attachment gets small to nonexistent for ITER/DEMO
  - What volume will the radiative divertor region need to be
    - Will the volume be so large as to destroy the core performance
  - Is a double null divertor better:
    - In terms of plasma performance
    - Reduced loads on each divertor
  - What additional maintenance issues arise as a result of divertor loads:
    - Replacement rates for various modules
    - How localized is the erosion on divertor plates
  - How can the energy be extracted from the divertor

Power Handling: Key Specific Issues Phrased As Physics Questions

- **Specific Engineering Question for ELMs:**

  Can peak power fluxes to material surfaces due to ELMs be handled

∇ **Specific physics questions for ELMs:**

- Can recently identified options for reducing ELM size or ELM-free operation be applied in DEMO:
  - Will internal coils work to control ELMs
    - Will this be demonstrated by ITER
    - If they are necessary or desirable, are they practical
    - What design features should such coils have
      - How close will they need to be
      - Will they need to be inside first wall or will outside TF coils suffice
    - Can we extrapolate from current experiments
  - Will other ELM-free operational regimes be possible:
    - L Mode operation
    - QH-Mode or EDA
    - How much is performance degraded by these options

Propose to summarize each question specifying 'current knowledge' and 'knowledge expected from ITER'

Issue	Current Knowledge	Expected from ITER	R&D needs
What are disruptions limits	?	?	?
Where is design point relative to limits	?	?	?
Can likelihood of disruptions be quantified (deterministic vs statistical)	?	?	?
Confidence that design point will be disruption free over length of pulse	?	?	?
Level of control over discharge required to maintain confidence in disruption avoidance	?	?	?
Can unavoidable hardware induced disruptions be mitigated	?	?	?
Disruptions during startup and rampdown	?	?	?

Propose to summarize each question specifying 'current knowledge' and 'knowledge expected from ITER'

Issue	Current Knowledge	Expected from ITER	R&D needs
Can ELMs be predicted – size frequency and/or onset	?	?	?
What are the predictions for ELMs in the design points	?	?	?
Can the ELMs be controlled by discharge control	?	?	?
Will internal coils work to control ELMs	?	?	?
Can options for ELM-free operation be applied in DEMO	?	?	?
Is a double null divertor better	?	?	?
Will DEMO require radiative divertor, core and mantle radiation	?	?	?

Propose to summarize each question specifying 'current knowledge' and 'knowledge expected from ITER'

Issue	Current Knowledge	Expected from ITER	R&D needs
What is of the distribution of the energy dump from ELMs between the first wall and the divertor	?	?	?
What is the toroidal and poloidal distribution	?	?	?
How does energy distribution differ between ELMs and during an ELM	?	?	?
Are MARFEs an issue	?	?	?
How can the energy be extracted from wall, blanket, and divertor	?	?	?
What additional maintenance issues arise as a result of divertor loads	?	?	?
How localized is the erosion on divertor plates	?	?	?

Some Answers: Disruptions

Can the likelihood of disruptions be quantified in a deterministic versus statistical sense

The majority of disruptions in DIII-D are caused by either hardware failures, safety system trips (which aren't really designed to minimize disruptions but to protect hardware), or casual operator 'error' (we don't pay a lot of attention to preventing disruptions since they are generally of little consequence to DIII-D). Some of these are 'statistical' and some are determined by the operating mode chosen, but all could be greatly reduced if that became a priority. Neglecting those 'externally induced' disruptions, roughly 10% of all shots end in 'plasma induced' disruptions.

To my knowledge there hasn't been a study at DIII-D investigating the detailed causes of all plasma induced disruptions, but one at ASDEX concluded that all disruptions there are deterministically caused by exceeding some stability boundary that triggers some type of MHD that ultimately leads to disruption. So in that sense all plasma induced disruptions are deterministic

Some Answers: Disruptions

How much confidence is there that the design point will be disruption free over the length of the pulse or through steady state

– Pretty high. Unpublished data shows that once a DIII-D discharge has survived for a couple seconds after reaching its maximum beta_n it continues with zero disruptability until rampdown. But the kicker is that it has to survive the first couple seconds at high beta_n. I interpret this to mean that once a 'good' trajectory through I_p and beta_n rampup is found, discharges will be disruption free as long as that trajectory is followed. I have no idea how closely it must be followed, though. The mantra today that if steady-state is *really* steady/stationary, with some finite margin against disruption onset (see v, below), then the pulse will be 'disruption-free' unless external conditions intervene. External condition involves hardware reliability, unpredictable events (falling flakes, vacuum window breaks, hardware and/or control system failures) and Murphy's Law. Basis of prediction for the latter is meager.

– ITER may need to dedicate significant experiment time to validating avoidance and/or mitigation efficacy: ie, run a standard shot over and over and do a real world test of the integrated plant and system to see how successful it is.

Some Answers: Disruptions

Are disruptions during startup and rampdown a problem

– Disruptions in rampdown is a subject that has had little attention here at DIII-D, though devices where disruptions are a concern (JET, JT-60U for instance) may have some insight

Some Answers: Disruptions

What level of control over the discharge is required to maintain the requisite level of confidence in disruption avoidance

- The plasma cannot be allowed to touch a wall, and ramping the plasma current DOWN is an invitation to disrupt. But I suspect that unless the discharge is kept very close to a stability limit that minor shape changes will not affect the plasma disruptivity – unless the cause of the shape change induces a sizable change to the plasma current profile. The magnitude of allowable change is a complex question that will depend on how far the baseline plasma state is from any stability boundary that leads to disruption
- A workable discharge scenario needs finite margin to allow for control 'noise', lack of ideal measurement and small real-world variances. How much depends on the robustness of the scenario, the degree of active control needed and a host of real-world considerations. As a trivial example, there has been success in operating within a few % of the ideal MHD beta limit without disruption. But the limit may change if machine/wall conditions are different. Then one has to operate within a few % of that limit

Some Answers: Disruptions

What design and engineering requirements are needed for mitigation of unavoidable disruptions

– The device had better be able to withstand at least a few worst-case disruptions. Bringing the machine up to full parameter operation will require charting a trajectory that leads to disruption free steady state, and this charting will inevitably lead to some disruptions at high beta_n along the way, and of these the mitigation system may fail to act. While chances of the mitigation system failing may be made small, I suspect they cannot be made small enough to bet several billions on

What can be done to mitigate unavoidable disruptions

– Many disruptions can be mitigated if we have time for pre-emptive mitigation. Consequences of many types of hardware failures may be slow enough to take avoidance, soft-landing or mitigation action. In some cases, avoidance actions can be taken; in other cases, pre-emptive and or after-onset mitigation can be effective at reducing some (but not necessarily all) disruption consequences.

Some Answers: Disruptions

How do we translate the physics limits into design guidelines:

- Key disruption guidelines have been established for ITER and are published in the ITER Physics Basis
- Extrapolation to DEMO is probably reasonably straightforward

What design and engineering requirements are needed for mitigation of unavoidable disruptions

- Concepts that can respond to and at least partially mitigate ‘unavoided’ (not pre-emptive mitigated) are lacking or likely infeasible (brick injection to stop a RE beam). This is a big R&D item for DEMO and likely for ITER too.
- After-onset mitigation is more problematical and will not necessarily be 100% effective
- Knowledge today is inadequate to predict what the mix of outcomes and resulting ‘impact’ on device function and reliability will be for ITER, much less DEMO. ITER experience will be a critical ‘benchmark’ for DEMO, but it is likely that major extrapolation will remain.

Some Answers: Power Handling

Can ELMs be predicted

- An identified R&D need is a scaling law for these. This is highly complex, depending on a large array of plasma edge and core parameters.
- A database of $\delta W/W_{ped}$ does exist and may provide some information.
- Some information may be obtainable simply from L-H transition scaling
- Scaling of flux expansion is needed as well
- Kotschenreuther 2006 APS has some scaling proposals

What are the total steady state power levels

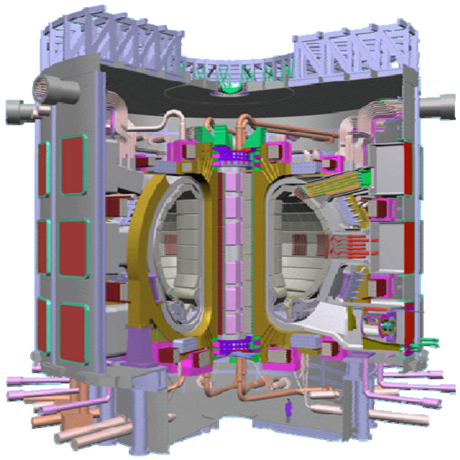
- The general view seems to be that even ITER is unlikely to tolerate any level of transient activity so even small ELMs may not be acceptable. Even the steady state (between ELM) power fluxes are marginal. Power fluxes in DEMO are expected to be at least as large – both steady state and ELM power flows. Given this, can DEMO anticipate something different.

Edge Localized Mode and pedestal control using resonant magnetic perturbations

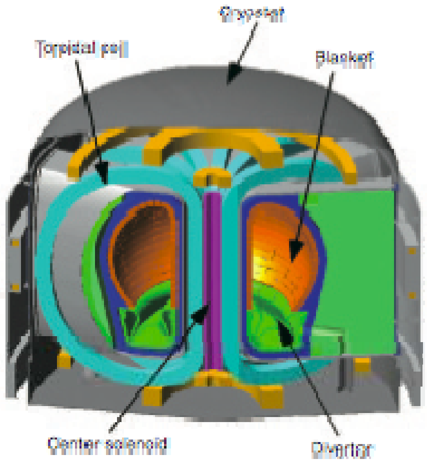
T. E. Evans

- Transient heat flux excursions are a critical ITER issue:
  - Transient energy impulses to material surface must be < 45-60 $MJm^{-2}s^{-1/2}$ (ideal ablation limit)
    - Implies transients (ELMs ~0.5 ms) < 6-8 MJ (assuming in-out and axisymmetric target distribution)
    - Scaling from present tokamaks→~12-20 MJ
- In DEMO transients heat flux excursions are expected to be at least 5X large than in ITER
- A reliable ELM control system is essential for DEMO
- Resonant Magnet Perturbations (RMPs):
  - Produce complete ELM elimination
    - at reactor relevant collisionalities
    - with robust edge transport barriers and
    - somewhat improved T_e^{ped}
  - Appear to be scalable to reactor plasmas
  - Provide pedestal and steady-state heat flux control that may lead to improved H-mode performance

ITER 2007-**2016→2037**



DEMO 2024-**2036→**



RMP ELM control in DEMO requires developing scalable physics models and optimized coil designs

- Current RMP experiments are providing valuable basic physics data:
  - Current physics understanding $\rightarrow$ large pedestal resonances with minimal core resonances and non-resonant components
    - Currently restricted to suboptimal coils (using field-error correction and RWM control coils)
- ITER attempting to shoehorn RMP ELM control coils into its design but facing:
  - Rigid constraints on coil design parameters
    - Suboptimal design, reduced spectral flexibility
    - No provisions for mid-course coil optimization
- The program is facing a significant gap in the development of RMP ELM control for DEMO that will not be filled by ITER
- This gap could be filled with a dedicated new device or a significant upgrade (~100M$) of an existing device
  - Optimized RMP coil design tightly integrated into device design
    - Options for mid-course coil and divertor changes based on developing physics understanding ($\rightarrow$ strongly integrated theory, modeling and experiments)
  - New physics understanding $\rightarrow$ potential for improved DEMO performance