Technical Readiness Level For Plasma Control

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Control Of Plasma Shape And Profiles Requires Four Steps: Essentially Measuring A Quantity And Modifying It

- **Identification of the required parameter value and acceptable range:**
  - This is defined by the design process and performance requirements
- **Diagnosis of the current state:**
  - Diagnostic measurement
  - How are the parameters measured ?
- **Actuator to modify the profile:**
  - How are they modified - what is the input controller ?
- **Algorithm to translate required change in profile to actuator signal:**
  - What is the algorithm for translating the required change in parameters to the needed change in controller ?

- **Ultimately the diagnostic and actuator technologies need to survive in a BPX environment**

Technology Readiness Level: Concept Development

TRL		Generic Definition	Issue-Specific Definition
1	Co nc ept	Basic principles observed and formulated.	Development of basic concepts for diagnostics and actuators for controlling plasma shape and profiles.
2	Co nc ept	Technology concepts and/or applications formulated.	+Design of systems and hardware to diagnose profiles and systems to modify profiles in open loop in a moderate β plasma. Development of robust algorithms for translating diagnostic measurements to actuator signals.
3	Co nc ept	Analytical and experimental demonstration of critical function and/or proof of concept.	+Demonstration of techniques for controlled plasma shape and profiles within approximate limits in closed loop in a moderate β laboratory plasma.

\+ This can be performed in either a dedicated laboratory plasma physics experiment or one of the current national facilities

Technology Readiness Level: Proof Of Principle

TRL		Generic Definition	Issue-Specific Definition
4	PoP	Component and/or bench-scale validation in a laboratory environment.	#Demonstration of controlled plasma shape and profiles within approximate limits in closed loop in a current high temperature plasma confinement experiment.
5	PoP	Component and/or breadboard validation in a relevant environment.	#Self-consistent integration of multiple techniques to control each of the required plasma parameters in closed loop in a current high temperature plasma confinement experiment.
6	PoP	System/subsystem model or prototype demonstration in relevant environment.	¶ Scale-up of diagnostic and actuator technologies to realistic fusion conditions. Demonstration that excursions from transient phenomena can be kept to a tolerable level.

This should be performed in one of the current national facilities

¶ This step should be performed in a dedicated planned experiment such as KSTAR

Technology Readiness Level: Proof Of Performance

TRL		Generic Definition	Issue-Specific Definition
7	Pe rfo rm an ce	System prototype demonstration in an operational environment	†Demonstration of the integrated plasma shape and profile control system with control of excursions from transient phenomena in a high performance reactor grade plasma in long pulse, essentially steady state operation.
8	Pe rfo rm an ce	Actual system completed and qualified through test and demonstration	§Demonstration of the integrated plasma shape and profile control system in a steady state burning plasma configuration.
9	Pe rfo rm an ce	Actual system proven through successful mission operations	Demonstration of the integrated plasma shape and profile control system in a steady state burning plasma configuration for lifetime conditions.

† This step can be performed in KSTAR or in ITER running in high power mode.
§ ITER might be able to satisfactorily complete this step but it may require a burning plasma experiment. This may be a dedicated experiment or DEMO.

Plasma Parameters Requiring Diagnostics And Control Can Be Broken Down Into Seven Categories

- **Global parameters:**
  - Fusion power
  - Plasma beta
  - Confinement quality
  - Heat and radiation loads
- **Plasma shape:**
  - Elongation
  - Triangularity
  - Higher order shaping
- **Plasma kinetic profiles:**
  - Pressure
  - Density
  - Temperature
- **Plasma current density profile:**
  - Current density
  - Safety factor
- **Plasma rotation profile**
- **Plasma composition profiles:**
  - D-T ratios
  - Impurities
- **Power handling control**

Control Of Global Parameters: Fusion Power, Beta Confinement, And Power Loads Is Well Understood

- **Required values and range set by fusion power requirements and POPCON calculations**
- **Measurements using:**
  - Equilibrium reconstruction
  - Neutron rates and power flows to material surfaces
- **Parameters modified by:**
  - Fueling, D-T ratios
  - Control of transport barriers
- **Translation algorithm requires:**
  - Time dependent 1 1/2 D transport calculations
- **Overall, control of global parameters is unlikely to be an obstacle:**
  - ⇒ Modest extrapolation scenario: Current TRL = 4
  - ⇒ Advanced concept scenario: Current TRL = 4
  - Very high confidence that the techniques currently available will scale if applied in a BPX

Control Of Plasma Shape Is Also Well Advanced

- **Required values and range set by ARIES-AT design**
- **Measurements using:**
  - External magnetic loop measurements
  - Equilibrium reconstruction
- **Parameters modified by external poloidal field coils**
- **Translation algorithms are well established:**
  - Routinely applied in all major tokamaks
  - Elongations up to 3 to 1 and triangularity ~ 1
- **Overall control of plasma shape rates a moderate TRL:**
  - $\Rightarrow$ Modest extrapolation scenario: Current TRL = 4
  - $\Rightarrow$ Advanced concept scenario: Current TRL = 3
- **High confidence techniques currently available will scale to a BPX:**
  - Divertor requirements may limit the higher triangularities needed for the most advanced scenarios

Control Of Pressure, Density, And Temperature Profiles Is A Key Feature Of All Advanced Scenarios

- **Required profiles and ranges set by ARIES-AT design:**
  - $T_i \sim T_e$ and n_e from fusion cross section requirements
  - Range from sensitivity calculations
- **Profile measurements using Thomson scattering and Charge Exchange Recombination (CER) diagnostics**
- **Profiles modified by:**
  - Pellet injection, gas puffing, and Neutral Beam input
  - RF wave heating
  - Divertor pumping
- **Translation of desired profiles to fueling input requires:**
  - Deposition calculations for pellets, RF, beams, and gas
  - Alpha particle slowing down and heating calculations
  - Equilibrium reconstruction
- **Control of kinetic profiles is still an active area of current research:**

  $\Rightarrow$ Modest extrapolation scenario: Current TRL = 4

  $\Rightarrow$ Advanced concept scenario: Current TRL = 3

Current Profile Control Techniques Are Less Developed But Present Experiments Are Moving To Closed Loop

- **Required current profile and allowable range set by ARIES-AT design and sensitivity calculations**
- **Profile measurements using Motional Stark Effect (MSE):**
  - Requires at least a diagnostic Neutral Beam
  - Equilibrium reconstruction from magnetic field pitch angle
- **Current profile modified by noninductive current drive:**
  - ECCD, Lower Hybrid, and ICRF
- **Translation of desired current profile to input current drive requires:**
  - Ray tracing and current drive deposition calculations
- **Current research is actively focused on current profile control:**
  - $\Rightarrow$ Modest extrapolation scenario: Current TRL = 4
  - $\Rightarrow$ Advanced concept scenario: Current TRL = 3
- **MSE diagnostic scales to higher fields but current drive techniques have scaling issues:**
  - Density limitations
  - Efficiency scales with T but required driven current also increases

Plasma Rotation Profile Control Is A Key Issue For Advanced But Not For Modest Extrapolation Scenarios

- **Required rotation values and profile set by resistive wall mode (RWM) stability and possibly confinement requirements:**
  - Minimum generally needs to be satisfied only
  - Low momentum input ⇒ a reactor is unlikely to rotate too fast
- **Rotation profile measurements using:**
  - CER for impurity rotation
  - Main ion rotation is not well diagnosed
- **Rotation profile modified by:**
  - Momentum input from Neutral Beams
  - Possibly external rotating nonaxisymmetric fields
- **Translation of desired rotation to beam input requires:**
  - Beam deposition, angular momentum transport, particle loss, and magnetic drag calculations
- **Rotation profile can be diagnosed but few methods to modify it exist:**
  - ⇒ Modest extrapolation scenario (limited need): Current TRL = 4
  - ⇒ Advanced concept scenario: Current TRL < 2

D-T Ratio Is Relatively Easily Controlled By Fuelling

- **Required values set by fusion yield calculations:**
  - Allowable range needs to be adjustable during operation
- **D-T mix diagnostics:**
  - Global measurements from neutron rates and fusion power
  - No known method for obtaining D-T ratio profile measurements
- **Global mix and profile modified by:**
  - Tritium neutral beam input
  - Pellet fuelling
  - Control of isotopic differential transport rates
- **Translation of desired D-T ratios to fueling input requires:**
  - Deposition calculations for beams
  - Alpha particle slowing down and heating calculations
- **Neutron rates and fusion power easily diagnosed:**
  - Empirically determine needed adjustments in D-T fuelling
  - ⇒ Modest extrapolation scenario: Current TRL = 4
  - ⇒ Advanced concept scenario: Current TRL = 4
  - High confidence current techniques will scale in a BPX

Impurity And Alpha Ash Not Easily Controlled: Requires Control Over Relative Particle And Heat Transport Rates

- **Required values and allowable range set by fusion yield**
- **Impurity profile measurements using CER**
- **Impurity profile modified by:**
  - Altering balance between particle and energy confinement
  - MHD fluctuations from Sawteeth and ELMs
- **Translation of desired ash and impurity concentration to MHD fluctuation size and frequencies requires:**
  - Impurity transport calculations
  - ELM and sawtooth frequency and size control
- **Some techniques exist for selectively transporting impurities but are not yet reactor relevant:**
  - Temperature and density transport barriers
  - Some ELM-free regimes hold some promise

$\Rightarrow$ Modest extrapolation scenario: Current TRL = 3

$\Rightarrow$ Advanced concept scenario: Current TRL = 2

Key Issues For Advanced Scenario Are Scale Up Of Rotation Control And Impurity Control Technologies

Issue	Modest Extrapolation Scenario TRL	Advanced Extrapolation Scenario TRL	Scale up Confidence Level
Global parameters	4	4	Very High
Plasma Shape	4	3	High
Kinetic Profiles	4	3	Moderate
Current Profile	4	3	Moderate
Plasma Rotation	4	2	Low
D-T Ratio	4	4	High
Impurities	3	2	Low-moderate