Strategic Approach 1 (SA-1): Use present physics and technology basis for DEMO.

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1. Brief description of the strategic approach - primarily intended to orient the reader to the strategic approach, not a detailed roadmap or strategy

The “SA-1” roadmap is based on the main current approach to fusion energy, progressing from the present machines to a DEMO-like reactor (envisioned not as a specific device, but as the first, practical, reliable and integrated demonstration of fusion energy production). Given that the tokamak concept is the most promising and advanced concept in the current state of affairs, this development path assumes the tokamak configuration throughout, and evaluates the key progress required in several topical areas to achieve fusion energy demonstration (from the core and edge plasma, to its interface with the PMI and H&CD systems and power handling, to the materials for walls, blankets, vessel, magnetic confinement and tritium cycle).

Since numerous uncertainties exist for the handling of the “interface” sections, such as various options for a divertor solution, breeding blankets and PMI concepts that all have low Technology Readiness Levels (TRLs) and directly impact the viability of a DEMO, we identified three scenarios (paths) within this approach that involve successively increasing level of risk and decreasing number of intermediate steps (i.e. machines). A summary of these options is given in figure 1. Scenarios “A”, “B”, and “AB” address current knowledge gaps in different ways, and provide different levels of TRLs and R&D information for various elements necessary to achieve DEMO’s goals.

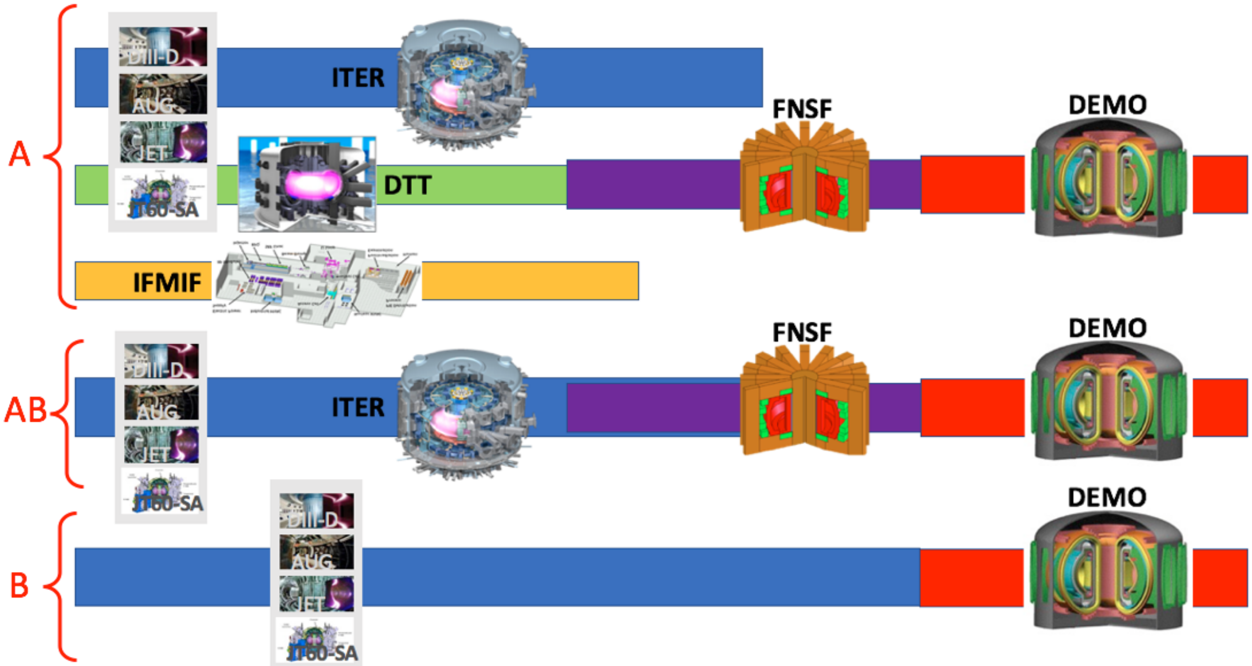

Figure 1: Summary of the three main paths assessed in the SA-1 working group.

- Scenario "A" assumes US participation in ITER in parallel with work on present facilities (such as DIII-D, AUG, JET, JT60-SA, EAST, ...), as well as two facilities to test options for high performance divertors and the nuclear materials irradiation issues. We will refer to the latter as "a DTT" and "an IFMIF" in the following. This is followed by a fusion science & technology integration facility which brings together a high performance plasma core and the interface solutions addressed in DTT and IFMIF in order to validate proposed approaches for heat exhaust and tritium breeding and extraction (referred to as "an FNSF" type machine). The DTT and IFMIF steps are envisioned to be carried out in parallel to the ITER research plan, with the possibility of being an international endeavor; collectively these 3 next-step facilities are intended to achieve TRL>5 in their respective constituent elements. This path is the lowest risk case and involves construction of the largest number of facilities. Given that many of these can be designed and built in parallel to the exploitation of the present devices and ITER, and would ensure that the next steps, as well as (most importantly) DEMO, will be built with a single design set based on the knowledge acquired in the previous, smaller, machines. This will decrease the time and cost of the DEMO stage, which wouldn't require testing of different divertors, PMI and H&CD solutions.
- Scenario "B" addresses the possibility that the US withdraws its participation in ITER, and a direct path to DEMO is pursued. In this case we envision that the present US and international machines (with limited H&CD and diagnostic upgrades) will provide the last available information on the plasma core and possibly some limited small scale material testing and divertor simulations (dependent on the existence of relevant upgrades), to directly

design a full scale steady-state reactor, integrating the present level of knowledge on the "interface" systems. This path entails the highest risk, by leaving most of the unknowns to the final product stage. This may be more likely to lead to the failure of the development path, or to excessive construction costs to accommodate numerous design uncertainties, and/or construction of extra facilities or changes to the only existing facility, to correct for significant unknowns in the present knowledge base. This path would also likely lead to extreme delays, as well as significant increases in cost, because of the high probability of having to duplicate the "DEMO" stage *in toto*, due to likely failures and high level of unknowns in the design elements, which are only considered and discovered in this last step. Therefore, the cost and development duration for this scenario would be the smallest, only in the case that every assumption and design choice proves correct at the present level of knowledge, for a final product >30 years in the future.

- Scenario "AB" is an intermediate path where the US participates in ITER, the present machines are used (potentially with some upgrades) to inform plasma operations and a partial study of divertor and PMI solutions, while an FNSF-like facility is built (during ITER operations), to address the integration of a steady-state plasma core with a few divertor test solutions under high fluence conditions and at least a partial tritium breeding and extraction cycle. This path entails a medium risk for retiring all the knowledge gaps, leaving most of the testing of blankets and PMI issues to DEMO itself, but it still benefits from a meaningful intermediate step understanding the needs for materials and the tritium cycle in a relevant fusion environment.

A high-level gap and metrics analysis involving 13 technical performance topics was performed on each of the three paths, with the output comparing the score on the following key elements of the knowledge base and technology necessary to meet DEMO's goals:

1. Core and edge plasma → demonstrate steady-state operation, high gain, integrated with divertor heat and particle exhaust:
   - P_{fusion}, P_{alpha}>50%
   - Gain: Q_{plasma} >20, Q_{engr}>4
   - Steady-state or long duration
   - Divertor solution at high gain in nuclear environment
   - Control and mitigate burning plasmas near operational limits (βN <= βwith-wall)
   - Predict and optimize plasma and reactor design (theory/computation)
2. Plasma interface
   - Test and demonstrate divertor and first wall materials for large heat, particle and neutron loads
   - Demonstrate diagnostic solutions in nuclear environment
   - Knowledge and demonstration of H&CD systems in nuclear environment
   - ECF, ICF, NBI sources
   - EC, IC coupling in high heat, high flux plasma
3. Materials for structures, blankets, tritium, magnetic confinement
   - high performance reduced activation structural components with >10-15 MW-yr/m^2 lifetime neutron wall loading capability

- Knowledge and demonstration of superconducting magnets, working in high mechanical and EM stress and nuclear environment
- Test and demonstrate the full tritium breeding cycle for TBR>1 (T_2 production in blanket with no permeation to other locations; high-efficiency continuous tritium extraction)

Given the different level of TRLs and knowledge base for each element, the different paths A, B, and AB result in a significantly different readiness and gap closing capability (from which the different level of risk, and potential length of the path, arises). As a brief summary (table 1), analysis of path A indicated 13 feasibility-resolved, 3 partial-information, and no "insufficient information" topical areas; path AB had 9 feasibility-resolved and 4 partial-information; and path B had 2 feasibility-resolved, 3 partial-information and 8 insufficient-information topical areas (in some cases, more than one major device contributed to improved TRL for the 13 evaluated performance topics). The full results are available in the appendix.

Table 1: Summary of TRLs and plans for risk retirement and knowledge resolution for 13 topical areas identified as basis for proceeding to DEMO for the three different paths explored in this section.

PATH	Feasibility resolved	Partial information	Insufficient information
A	10	3	0
AB	9	4	0
B	2	3	8

2. Benefits: What are the potential advantages of this strategic approach? E.g., relative readiness to proceed, maturity of physics basis, U.S. leadership, resilience to political changes, improved product/attractiveness, risk mitigation, anticipated cost

The different paths assessed in this strategic approach have different benefits. More generally, the approach to take the present, most advanced and highest performing concept (i.e. the tokamak, in its current machines and ITER incarnation) has the obvious advantage of being based on the most robust knowledge base, the best demonstrated performance and scaling capability, and the largest scientific workforce being versed in its study and operation. The present tokamaks and ITER have the highest readiness to proceed based on real experimental results. This allows to close almost all the gaps necessary to produce and sustain a steady-state, Q=5-10 core plasma, with magnet technology that already exists and a partial test of blanket integration and heat+particle exhaust at high gain – in the first step of paths A, AB, and B alike. The sections on detailed divertor solutions, PMI and tritium fuel cycle are an unknown for every path (including the other SA's). The risk level and its mitigation is also well covered by the three alternatives, which allows for varying cost and political attitudes towards new facilities and international cooperation. The US leadership would appear prominent in the area or steady-state, high performance core plasmas, advanced diagnostics and, if a DTT and/or IFMIF set of facilities are envisioned, also in the realm of materials testing and tritium handling (depending in part on the location of such facilities).

3. Strategic Elements: What are the most impactful/important strategic elements from the Madison and Austin workshops (and other sources as necessary) enabling the strategic approach? In addition, what strategic elements require early attention to implement the overall strategic approach in a timely manner?

The main elements envisioned in this approach are: (1) the present machines, both in the US and abroad, crucial to provide scaling of the core and divertor performance to ITER and beyond; (2) ITER itself (i.e. the US full participation with access to the direct operation of the machine and its results), (3) a combination, or merging, of a Divertor Test Tokamak facility and an IFMIF-like facility (these can be designed, built and operated in parallel to ITER and the present faclities, and with the possibility of being international partnerships), and finally (4) an FNSF-like reactor, that couples a high performance, high fluence core to a series of divertors and blanket modules, with all the related technology for diagnostics, heat and tritium extraction, and particle control and exhaust. All these elements were largely covered in both the Austin and Madison meetings, at various stages of development. The uniqueness of this strategic approach is that it can be conceived for various levels of acceptable risks, with all elements still based on the highest knowledge base and best performing concepts to date – thus eliminating the additional risk of unknowns in the plasma capability of producing fusion power and the necessary neutron load and duration that would come from using a less capable burning plasma configuration. More research is needed on H&CD solutions for high fluence neutron environments, high heat and particle exhaust and long pulse operation to enable a high gain DEMO step. Advances in theory and modelling of core and edge plasmas are a central part of this path to enable meaningful scaling of present plasma performance, including alpha heating, MHD stability and ELM suppression, to the realm of a self-sustaining core, with little external control, limited diagnostics and large size. The latter topics were also part of the outcome of the Austin and Madison meetings, featured prominently in the need for integration of theory and computation, and possibly exascale computing.

Assuming that the US will have access to ITER in its present schedule (which is the first element requiring timely attention), the most crucial elements that require early implementation are a divertor solution and progress on closing the tritium fuel cycle. These steps are fundamental and unavoidable for any strategy that leads to fusion energy production, and they are, at the same time, currently underemphasized in the US fusion research portfolio. Work on these elements should be reinvigorated to proceed largely in parallel to ITER, with the possibility of machine significant advances for reduced cost, in present machines with relevant upgrades; under the envisioned scenarios A or AB, a DTT or FNSF machine would also provide a meaningful test bed for advanced plasmas and core reactor studies.

4. Impact of ITER: What would the impact of access to ITER (or lack thereof) have on the strategic approach?

As noted earlier, access to ITER is a fundamental part of this plan. The basis of an advanced core plasma physics knowledge and experience is the starting point for any fusion reactor based on the tokamak concept, and ITER is the machine furthest along in its construction, as well as most complete design to date. Both plans A and AB rely on the US having access to direct operation of ITER and its results, while plan B has been envisioned to describe the large gap in knowledge and scalability if the landscape ends up missing the ITER step.

If the US loses access to ITER as a full partner, another source of information and experience with burning plasmas, steady-state conditions, nuclear-ready diagnostics and divertor testing at high gain will be necessary. Since there are no machines being constructed at the moment that cover the breadth of operational parameters and integrated technology as ITER, and the design and construction of a nuclear facility of that scale (or smaller) takes a significant amount of time, it is likely that turning to another burning plasma facility, necessary to cover the gap between the present machines and DEMO, would significantly delay progress in the fusion program. One solution could be to meet the goals of ITER (or similar) on the plasma core+edge side, and couple that to a tritium breeding and nuclear material testing facility of the FSNF type, before moving to DEMO. That would put significant risk on the viability of the plasma core for the necessary PMI and tritium cycle testing, but it may be an acceptable risk for a step that does not require high gain or high reliability. All the risk of producing a high gain, high reliability, high fusion power plasma, integrated with a heat and particle exhaust would then be delayed to testing in DEMO itself.

5. International Context: In what areas would this strategic approach and the associated strategic elements support, complement, and potentially leapfrog activities in the broader international fusion energy R&D portfolio?

ITER is the first element that will define the internationality of the SA-1 approach. The US would have a great opportunity to lead the international community in a fundamental – and understudied – topic, if they took over the research on divertor solutions and the tritium breeding and extraction cycle. These aspects being necessary for any fusion concept, and essential for fusion energy in general, building a DTT or an IFMIF facility would be relatively low cost, with high reward. This can be done in parallel with ITER and the present machines, providing crucial knowledge to close the gaps on PMI/divertors/tritium breeding and extraction. The DTT could be an international facility, possibly led by the US, to reduce the US portion of the facility cost, or could potentially be realised more cost-effectively with significant upgrades to one or more existing facilities. On the other hand, an IFMIF type facility, with a smaller scale, absence of fusion core plasma and likely lower cost of construction and operation, could potentially be handled directly by the US.

6. Decision Points: What are the most important logical linkages (prerequisites, decision points) between strategic elements constituting the strategic approach? What are the key decision points within the strategic approach? i.e. when in the timeline is critical

information needed for decisions on follow-on activities.

Knowledge of burning plasmas, high gain operation integrated with a divertor and nuclear-ready diagnostics are the crucial knowledge base to reduce the gap between present machines and a DEMO-like plasma core. In plans A and AB, this is mostly covered by knowledge acquired in present devices (if possible with upgrades) and ITER, as well as, at some level, by a low gain, but high fluence plasma in an FNSF facility. On the other hand, the decision and design of a DTT and an IFMIF do not rely on ITER or burning plasma results, and can be started and carried on in parallel, to shorten the timeline for the choice of plan A, with continuation of the work in present facilities. In this scheme, some of the burning plasma result from current machines and ITER, along with the outcome of the DTT and IFMIF experiments, will help identify the best options for a high performance and long duration plasma, with a heat and particle extraction solution, that would be the basis and complement for the neutronics and tritium research in FNSF. However, if the decision is made to skip the DTT and IFMIF, plan AB calls for a direct test of divertors and blankets with a high fluence plasma core in an FNSF-like machine, with a somewhat lager scope. This path can also be viable, having ITER as a basis for the burning plasma core (with small or no extrapolation to FNSF on this aspect), some information on divertor and PMI solutions and modelling based on present machines results, and taking more risk with extrapolating present technology for divertors and tritium blankets directly to FNSF.

7. Timing: What are the short term, medium term and long term objectives?

The long-term objective is obviously a DEMO-like device, whose goals are to demonstrate tritium self-sufficiency, net electricity production, high availability, and nuclear safety. This would be the last device build with a partnership between government funds and private investments (if any), and is the marker for the US having the capability to produce practical fusion energy in the international market.

The short-term objective of SA-1 is the demonstration of a burning plasma capable of sustaining high gain and net fusion power (in the MW range), without deleterious events damaging the machine or its main systems, and with H&CD and diagnostics systems compatible with a high heat, nuclear environment. This is covered by ITER, along with the results of the experiments of the present machines, which help inform and scale the main physics issues on which ITER is built (fast-ion confinement, H&CD coupling and efficiency, divertor power and particle exhaust, etc). Therefore we consider a crucial short term goal to upgrade and fully exploit existing machines that are relevant to burning plasmas, high temperature nuclear diagnostics, divertor and PMI testing. This is likely the most cost-effective and quickest way to ensure that we make rapid progress on the "plasma" and "interface" paths, informing and speeding the development time to transition to the integration of a high yield core with a workable divertor and blanket solution. A short term goal is also the design and construction of a DTT and/or IFMIF facility in the US, as a single or multiple country endeavour, which can proceed in parallel to ITER and the present machines. This would have relatively limited scope and cost, and would significantly reduce the gap in knowledge base and technology readiness in the PMI and materials areas. Enhanced base program R&D on tritium science issues would still be needed in parallel to DTT and/or IFMIF type facilities, since tritium issues would not be their major focus. This would inform the decision on a divertor solution and ideas for closing the tritium breeding cycle that needs to be integrated to a high performance, long duration plasma core in an FNSF machine – or in DEMO directly if the latter is excluded from the plan.

The main intermediate step between the present machines (or ITER) and DEMO, in this approach, would be a larger scope FNSF facility, if the DTT+IFMIF steps are skipped or carried out as an international collaboration without a US-based device. An FNSF-like facility would help reduce the extrapolation in the plasma core and edge physics knowledge and control from ITER to the higher gain, higher availability and limiter controllability DEMO. As noted in the previous section, this intermediate step is necessary to retire part of the risks on divertor solutions, PMI knowledge gaps and tritium blanket operation that are only partially addressed in ITER, thereby greatly reducing the significant extrapolation and likelihood of failure from ITER to a DEMO environment.

8. Appendix. Gap and knowledge analysis

GAP and metrics analysis: PATH A (low risk) – 1/3 (plasma)

ITER → IFMIF+FNSF+DTT (some in parallel) → DEMO

GAPS	Predict performance + Optimize design	Demonstrate steady-state integrated advanced burning plasma (Q_{plasma}>5)	Diagnostics in nuclear environment	Control and mitigate BP near operational limits
Elements addressing the gaps	Theory and empirical scalings. Present tokamaks actually tests these	With DD, present tokamaks like JET, DIII-D, JT60-SA have reached DT-like Q=0.3-0.6	ITER will test and demonstrate part of this	DIII-D, JET, JT60-SA can do passively stable steady-state β_N<=3.5; DIII-D+JT60-SA off-axis CD upgrades is predicted to reach β_{lim}>=5, enough for ITER
	ITER will be crucial test bed for confinement, stability predictions	ITER will demonstrate Q=10 pulsed (400 s), Q=5 steady-state (high gain) (then DEMO Q>=20)		ITER will test operation at β_N=3-5

GAP and metrics analysis: PATH A (low risk) – 2/3 (interface/matls)

ITER → IFMIF+FNSF+DTT (some in parallel) → DEMO

GAPS	Knowledge of RF launchers, wave coupling and NBI	Knowledge and demonstration of superconducting magnets	Tritium cycle	Divertor+wall materials
Element addressing the gap	ITER tests EC and IC in nuclear environment. Need more development for negative ion beams	Gap closed - using present technology	ITER: demonstrates partial blanket integration in EM and nuclear environment	ITER: partially tests heat+particle exhaust at high gain
			IFMIF: plasma-less neutron source, test small material samples for heat+neutrons	DTT-type: low gain, high heat+fluence plasma, tests divertor solutions at scale
			FNSF: low gain plasma with high fluence, tests materials and tritium breeding at scale	
			In parallel: small non-plasma studies, then prototypes, for tritium extraction	

Plasma metrics: present devices to PATH A (low risk) – 3/3

ITER → IFMIF+FNSF+DTT (some in parallel) → DEMO

Plasma core+edge metrics	P_{fusion}	Q_{plasma}	$n x \tau$ (1e20 m-3s); Ti(0) (keV)	MHD & kinetic limits	Avoid damage from disruptions, ELMs, runaways
How are our relevant elements doing?	Present=0	Present DD=0; present DD--> DT=0.3-0.6	Present long duration (>2 τ_R) pulsed = 1.5e20 at 2 keV	Present tearing limits β_N=4	Present tokamak: minimal disruption risk for reactor relevant q_{95}=5
	ITER=500 MW	ITER pulsed (inductive) Q=10; ITER steady-state Q=5	Present long duration (>2 τ_R) steady-state = 0.5e20 at 6.4 keV	DIII-D and JT60-SA OA-heating upgrades predicted at β_N=5	Present tokamaks and upgrades testing and demonstrating ELM suppression
	DEMO=200-500 MW	DEMO Q=20-30 (probably steady-state)	Present short duration (1 τ_E) pulsed = 0.2 at 6-11 keV	ITER β_N=5, need β_{lim}~5.5?	ITER is tasked to test predictions, ONFR systems and RMP ELM suppression
			ITER: 2-3 at 11-12 keV for Q>1; ITER: 3.4 at T=18 keV		

GAP and metrics analysis: PATH AB (intermediate risk) – 1/2

ITER → FNSF+ → DEMO

GAPS	Predict performance + Optimize design	Demonstrate steady-state integrated advanced burning plasma (Q_{plasma}>5)	Diagnostics in nuclear environment	Control and mitigate BP near operational limits
Elements addressing the gaps	Theory and empirical scalings. Present tokamaks actually tests these	With DD, present tokamaks like JET, DIII-D, JT60-SA have reached DT-like Q=0.3-0.6	ITER will test and demonstrate part of this	DIII-D, JET, JT60-SA can do passively stable steady-state β_N<=3.5; DIII-D+JT60-SA off-axis CD upgrades is predicted to reach β_{lim}>=5, enough for ITER
	ITER will be crucial test bed for confinement, stability predictions	ITER will demonstrate Q=10 pulsed (400 s), Q=5 steady-state (high gain) (then DEMO Q>=20)		ITER will test operation at β_N=3-5

GAP and metrics analysis: PATH AB (intermediate risk) – 2/2

ITER → FNSF+ → DEMO

GAPS	Knowledge of RF launchers, wave coupling and NBI	Knowledge and demonstration of superconducting magnets	Tritium cycle	Divertor+wall materials
Element addressing the gap	ITER tests EC and IC in nuclear environment. Need more development for negative ion beams	Gap closed - using present technology	ITER: demonstrates partial blanket integration in EM and nuclear environment	ITER: partially tests heat+particle exhaust at high gain
			FNSF+: low gain plasma with high fluence, tests materials and tritium breeding at scale	FNSF+: low gain, high heat+fluence plasma, tests divertor solutions at scale
			In parallel: small non-plasma studies, then prototypes, for tritium extraction	

Plasma metrics: PATH AB (intermediate risk) – 2/2

ITER → FNSF+ → DEMO

Plasma core+edge metrics	P_{fusion}	Q_{plasma}	$nx\tau$ (1e20 m-3s); Ti(0) (keV)	MHD & kinetic limits	Avoid damage from disruptions, ELMs, runaways
How are our relevant elements doing?	Present=0	Present DD=0; present DD--> DT=0.3-0.6	Present long duration (>2 τ_R) pulsed = 1.5e20 at 2 keV	Present tearing limits β_N=4	Present tokamak: minimal disruption risk for reactor relevant q_{95}=5
	ITER=500 MW	ITER pulsed (inductive) Q=10; ITER steady-state Q=5	Present long duration (>2 τ_R) steady-state = 0.5e20 at 6.4 keV	DIII-D and JT60-SA OA-heating upgrades predicted at β_N=5	Present tokamaks and upgrades testing and demonstrating ELM suppression
	DEMO=200-500 MW	DEMO Q=20-30 (probably steady-state)	Present short duration (1 τ_E) pulsed = 0.2 at 6-11 keV	ITER β_N=5, need β_{lim}~5.5?	ITER is tasked to test predictions, ONFR systems and RMP ELM suppression
			ITER: 2-3 at 11-12 keV for Q>1; ITER: 3.4 at T=18 keV		

GAP and metrics analysis: PATH B (high risk) – 1/3

No ITER , no Q=5 device → DEMO

GAPS	Predict performance + Optimize design	Demonstrate steady-state integrated advanced burning plasma (Q_{plasma}>5)	Diagnostics in nuclear environment	Control and mitigate BP near operational limits
Elements addressing the gaps	Theory and empirical scalings. Present tokamaks actually tests	With DD, present tokamaks like JET, DIII-D, JT60-SA have reached DT-like Q=0.3-0.6	No testing in present devices	DIII-D, JET, JT60-SA can do passively stable steady-state β_N<=3.5; DIII-D+JT60-SA off-axis CD upgrades is predicted to reach β_{lim}>=5, enough for ITER
	No model validation?	No demonstration of Q=5 or Q=10, take all the risk in Q=30 DEMO	No demonstration, take all the risk in DEMO	May be low risk for DEMO

GAP and metrics analysis: PATH B (high risk) – 2/3

No ITER , no Q=5 device→ DEMO

GAPS	Knowledge of RF launchers, wave coupling and NBI	Knowledge and demonstration of superconducting magnets	Tritium cycle	Divertor+wall materials
Element addressing the gap	No testing of RF coupling or RF and beam sources – all risk to DEMO	Feasible - using present technology	No meaningful solution - uncertain design for DEMO	No meaningful solution - uncertain design for DEMO

Plasma metrics: present devices to PATH B (high risk) – 3/3

No ITER , no Q=5 device → DEMO

Plasma core+edge metrics	P_{fusion}	Q_{plasma}	$n x \tau$ (1e20 m-3s); Ti(0) (keV)	MHD & kinetic limits	Avoid damage from disruptions, ELMs, runaways
How are our relevant elements doing?	Present=0	Present DD=0; present DD--> DT=0.3-0.6	Present long duration (>2 τ_R) pulsed = 1.5e20 at 2 keV	Present tearing limits β_N=4	Present tokamak: minimal disruption risk for reactor relevant q_{95}=5
	Big jump to DEMO=2-500 MW	Factor x50 to DEMO Q=30	Present long duration (>2 τ_R) steady-state = 0.5e20 at 6.4 keV	DIII-D and JT60-SA OA-heating upgrades predicted at β_N=5	Present tokamaks and upgrades testing and demonstrating ELM suppression
			Present short duration (1 τ_E) pulsed = 0.2 at 6-11 keV		
			Factor x2-6 to 3 at 18 keV	May be acceptable	May be acceptable