Charting the Roadmap to Magnetic Fusion Energy

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Outline

- Motivation
- Assumptions
- Demo goals and prerequisites
- Roadmap logic and risk management
- A pilot plant as the pre-Demo step.

Motivation: Why Does MFE Need a Roadmap?

- ITER means that MFE is on an energy path.
- We need to understand the path all the way to commercial MFE.
  - Need a plan that can be explained and justified.
  - Need a framework for ordering priorities, deciding on next steps, and managing risks.

Planning Assumptions

- Fusion is urgent. The schedule matters.
- Target is DT, magnetic fusion, electricity-generating commercial plants.
- A Demo is needed to convincingly demonstrate fusion's readiness for commercial deployment.
  - The step from Demo to a commercial plant, in scale, design, and operation, must be small.
  - Demo must use the same technologies and plasma scenarios as a commercial plant.
  - Demo must demonstrate reliable operation as an integrated fusion system.

F. Najmabadi, *et al.*, STARLITE report, UCSD ENG-005 (1997)

Demo Socio-Economic Goals

From Starlite (1997):

1. Net electric output > 75% of commercial
2. Availability >50%; ≤ 1 unscheduled shutdown per year including disruptions. Full remote maintenance of the power core.
3. Closed tritium fuel cycle.
4. High level of public and worker safety, low environmental impact, compatible with day-to-day public activity.
5. Competitive cost of electricity.

Demo Goals Leave Fusion Developers with Significant Freedom in Choosing the Best Roadmap

- Science and Technology choices, e.g.
  - Magnetic configurations (tokamaks, stellarators)
  - Plasma scenarios (pulsed, steady-state)
  - Heating and current drive (neutral beams, waves)
  - Blankets (liquid, solid)
  - First wall (liquid, solid)
- Risk management choices, e.g.
  - Level of risk tolerance.
  - Risk tradeoffs (technical *vs.* schedule)
  - Risk mitigation (strategies, level of investment)

Development Tasks in S&T Terms

Plasma Configuration
- Burning Plasma
- Steady-state operation
- Divertor performance
- Disruption avoidance
- Stellarator-specific issues

Control Technology
- Diagnostics and control systems
- Heating, current drive and fueling
- Superconducting magnets

In-Vessel Systems & Tritium
- First wall / blanket / vacuum vessel
- Tritium processing and self-sufficiency

Plant Integration
- High Availability and Remote Handling
- Electricity generation
- Power plant licensing

Plasma Goals & Prerequisites

	Demo Goal	Demo Prerequisite (Ideal Case)
Burning Plasma	$Q \approx 30$	Demonstrated control at $Q >> 10$.
Steady-state operation	Continuous operation for 9-12 months	Demonstrated continuous operation for 4-6 months.
Divertor performance	$\langle P/S \rangle \approx 1$ MW/m^2, $T \geq 600$ C, compatible with low impurity, high-performance plasma.	$\langle P/S \rangle \geq 0.5$ MW/m^2, $T \geq 400$ C, compatible with low impurity, high-performance plasma.
Disruption avoidance	< 1 unmitigated disruption per year	Demonstration of < 1 unmitigated disruption in 6 months, demonstrated mitigation schemes (if required).
Stellarator-specific		Same

- Demo prerequisite: reliable plasma operation at high-gain, high heat flux for several months.
- Shortfall = more risk.

Control Technology Goals & Prerequisites

	Demo Goal	Demo Prerequisite (Ideal Case)
Diagnostics and control systems	Effective for all scenarios, reliable, compatible with tritium self-sufficiency	Demonstrated effectiveness, reliability, and TBR > 1 compatibility of an integrated system.
Heating, current drive and fueling	Efficient and effective for all scenarios, reliable, compatible with tritium self-sufficiency.	Demonstrated efficiency, effectiveness, reliability, and TBR > 1 compatibility of an integrated system.
Superconducting magnets	Effective, reliable for life of facility	Demonstrated success of design and operation under Demo-like conditions.

- Demo prerequisite: demonstrated effectiveness, efficiency, compatibility with TBR > 1, and reliability.

In-Vessel Systems & Tritium Goals & Prerequisites

	Demo Goal	Demo Prerequisite (Ideal Case)
First wall / blanket / vacuum vessel	$\langle NWL \rangle \approx 1$ MW/m^2, blanket lifetime neutron fluence 20 MW-yr./m^2, $\langle P/S \rangle \approx 1$ MW/m^2, TBR > 1, vessel lifetime neutron fluence $\geq$ 120 MW-yr./m^2	Demonstrated $\langle NWL \rangle \approx 1$ MW/m^2, blanket lifetime neutron fluence > 3MW-yr./m^2, $\langle P/S \rangle \geq$ 0.5 MW/m^2, TBR > 1, vessel lifetime neutron fluence $\geq$ 20 MW-yr./m^2
Tritium processing and self sufficiency	Tritium self sufficiency, low inventory.	Demonstrated tritium self sufficiency, low inventory.

- Demo prerequisite: demonstrated performance at high NWL and heat flux, credible extrapolation in reliability and lifetimes. Tritium self-sufficiency.

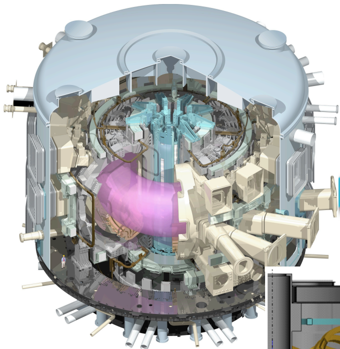
Plant Integration Goals & Prerequisites

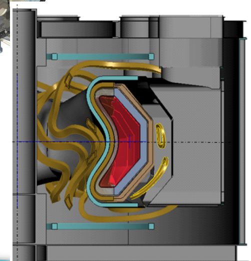
	Demo Goal	Demo Prerequisite (Ideal Case)
High availability and remote handling	Availability > 50%	Demonstrated availability 10-30%
Electricity generation	~750 MWe net electricity	Demonstrated electricity generation
Power plant licensing	Licensable by competent authority for commercial plants.	Demonstrated licensability by appropriate authority, data base for Demo licensing.

- Demo prerequisite:
  - Demonstrated integration of power plant technologies and operating needed to generate net electricity.
  - Credible extrapolation in availability.
  - Public acceptability.

Charting the Roadmap to Fusion Energy

ITER

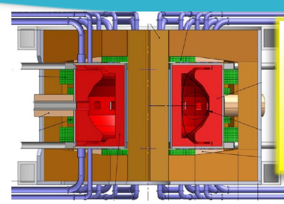




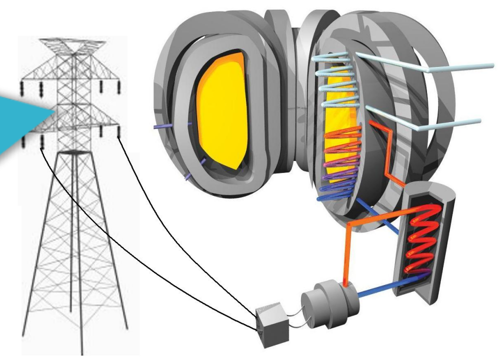
Pilot plant

Demo

Fusion Nuclear Facility



Component test facility (CTF)*



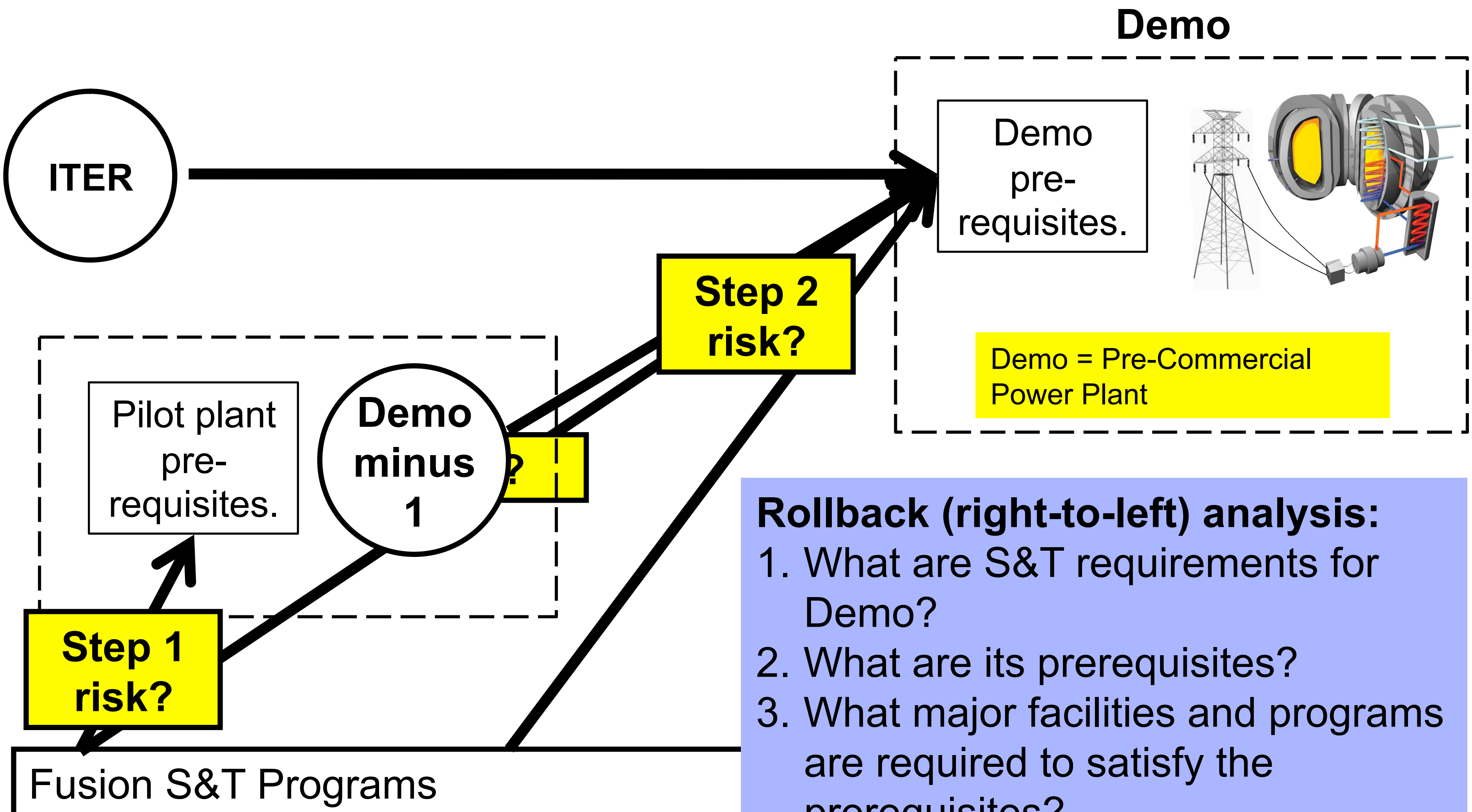
Supporting Physics and Technology

- **High performance, steady state**
- **Materials R&D**
- **Plasma Material Interface**

*a.k.a. Fusion nuclear science facility (FNSF)

Requires a technical evaluation of missions, requirements, and prerequisites for Demo and next-step facilities.

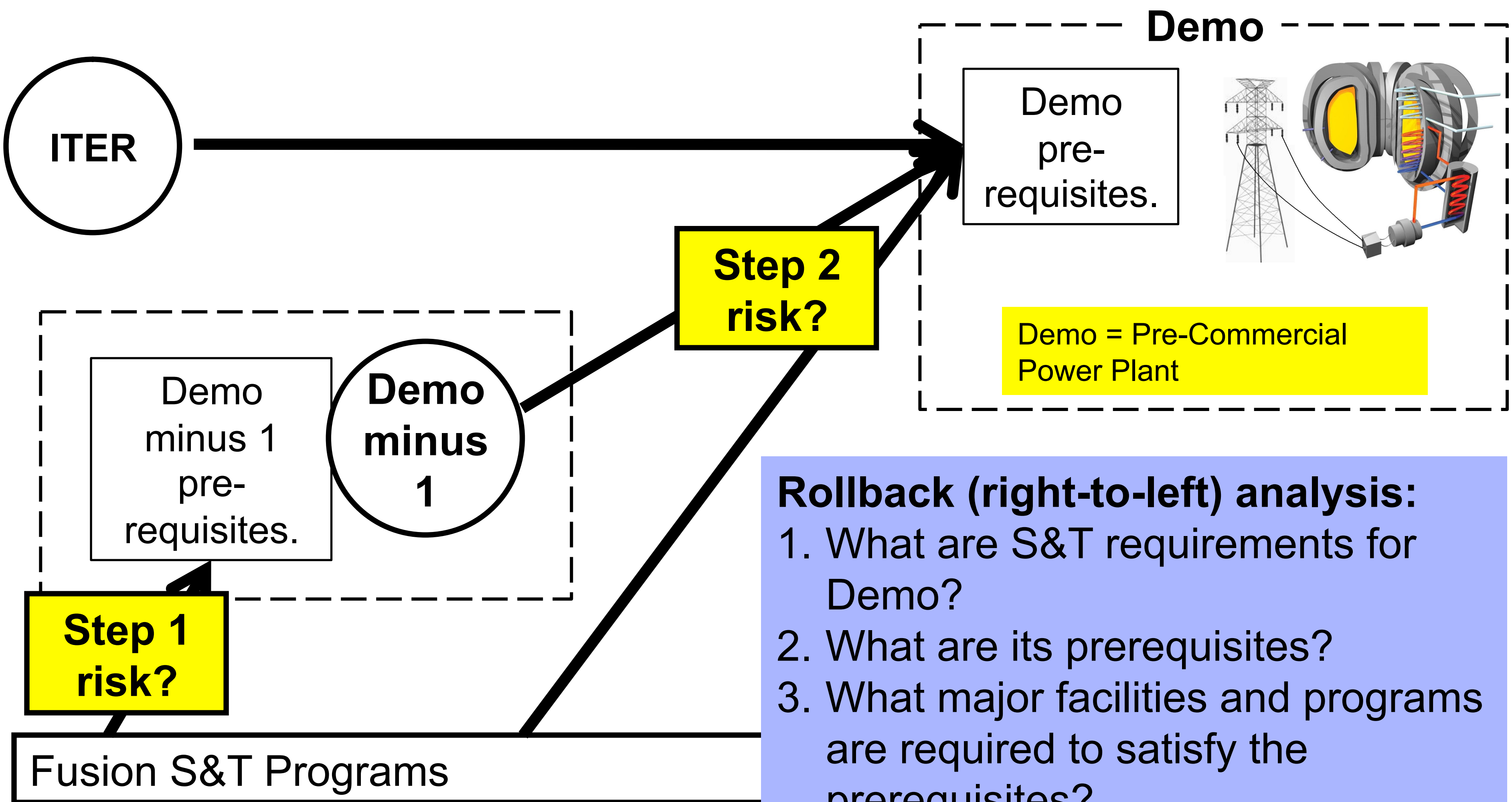
Roadback Logic and Risk Management



Rollback (right-to-left) analysis:

1. What are S&T requirements for Demo?
2. What are its prerequisites?
3. What major facilities and programs are required to satisfy the prerequisites?
4. What are the risk tradeoffs?

Roadback Logic and Risk Management



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Roadmap Building Blocks Come in Two Types

Major Integration Facilities

- Nuclear (e.g., ITER, Demo, Demo minus 1)
- Time consuming
- Best for integrated testing and demonstration.

S&T Research and Development Programs

- Develop physics scenarios and technology elements individually or in subsets.
- Less integrated, more modular, more flexible.
- Range of sizes from small to > $1B.
- Best for developing and down-selecting options for integration facilities.

12 S&T Research and Development Programs

Plasma Configuration

- Steady-state burning plasma physics.
- Heat and particle exhaust solutions.
- Disruption avoidance and mitigation solutions
- Plasma configuration optimization.
- Predictive simulation

Control Technology

- Diagnostics compatible with Demo
- Efficient heating, current drive, and fueling solutions.
- Superconducting magnets.

In-Vessel Systems and Tritium

- First wall and blanket systems, including materials.
- Tritium processing

Plant Integration

- Integrated designs compatible with net electricity generation, high availability, safety, and licensing.
- Remote handling systems.

Do we have all these bases covered?

A Pilot Plant as “Demo minus 1”

Mission

- Test internal components and tritium breeding in a steady-state fusion environment (“CTF” mission)
- Prototyping a maintainable design and maintenance scheme for a power plant, and
- Generate net electricity.

Motivation

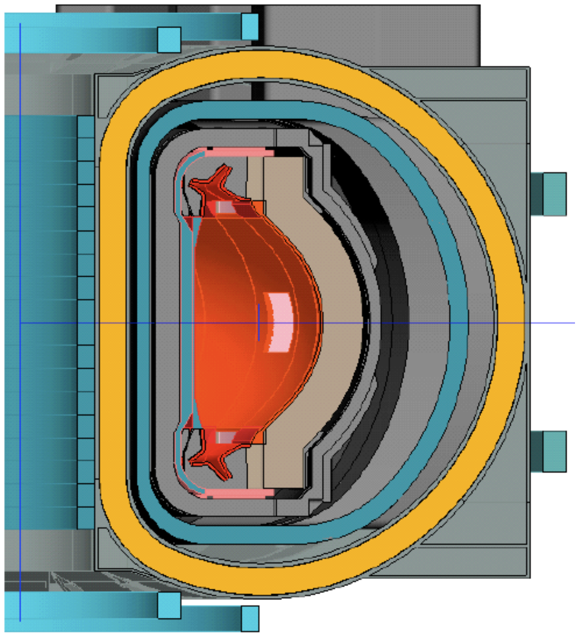
- Try to minimize the gap to Demo after Demo minus 1.
- A pilot plant would:
  - Integrate science and technology of a fusion power plant.
  - Demonstrate overall system efficiency
  - Convincingly demonstrate fusion’s potential.
- Option must be understood when next-step decisions are taken.

Pilot Plant is Within a Factor ~2 of Demo in Key Metrics

	ITER	Pilot Plant	Demo
Plasma duration (s)	500-3000	10^6-10^7	$3\text{x}10^7$
Engineering gain		1 - 3	4-6
Tritium sustainability (TBR)	none	1.0+	1.1
Avg. neutron wall load ⟨NWL⟩ (MW/m^2)	0.5	1-2	3-4
NWL at the test modules (MW/m^2)	0.7	1.5-3	4.5-6
Life of plant in years	20	20-30	30-40
Life of plant fluence (MW-y/m^2)	0.3	6-20	120-160
Life of blanket fluence (MW-y/m^2)		≥ 3	6 - 20
Blanket lifetime damage (dpa)		≥ 30	60 - 200
Total availability	2.5-5%	10-30%	50-85%
Plasma fusion gain, Q	5-10	5-7 (AT) 17-42 (CS)	~30
Fusion Power (MW)	500	300-600	2,500

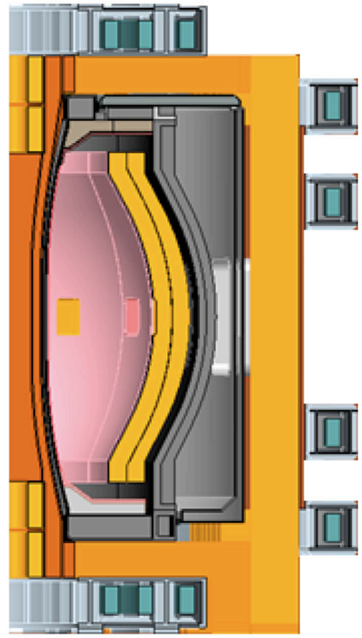
- Largest remaining gap is fusion gain Q (factor ~6), unless Pilot Plant is a stellarator.

3 Candidate Pilot Plant Configurations



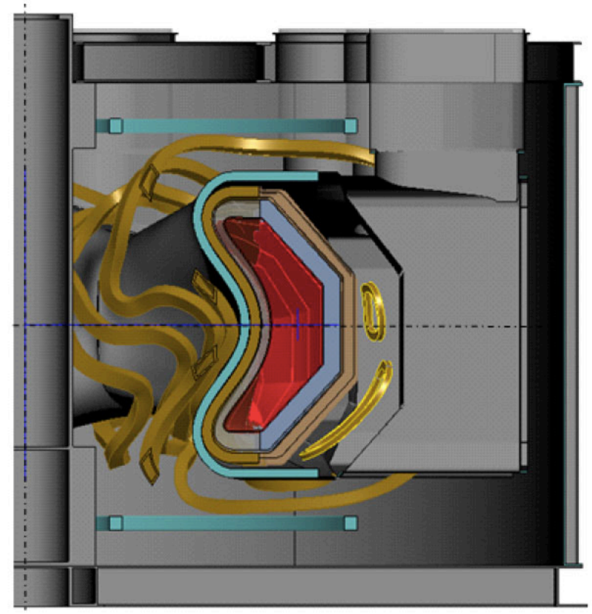
Advanced Tokamak (AT)

Most mature physics & technology



Spherical Tokamak (ST)

Potential for high wall and divertor loading, attractive maintenance scenario.



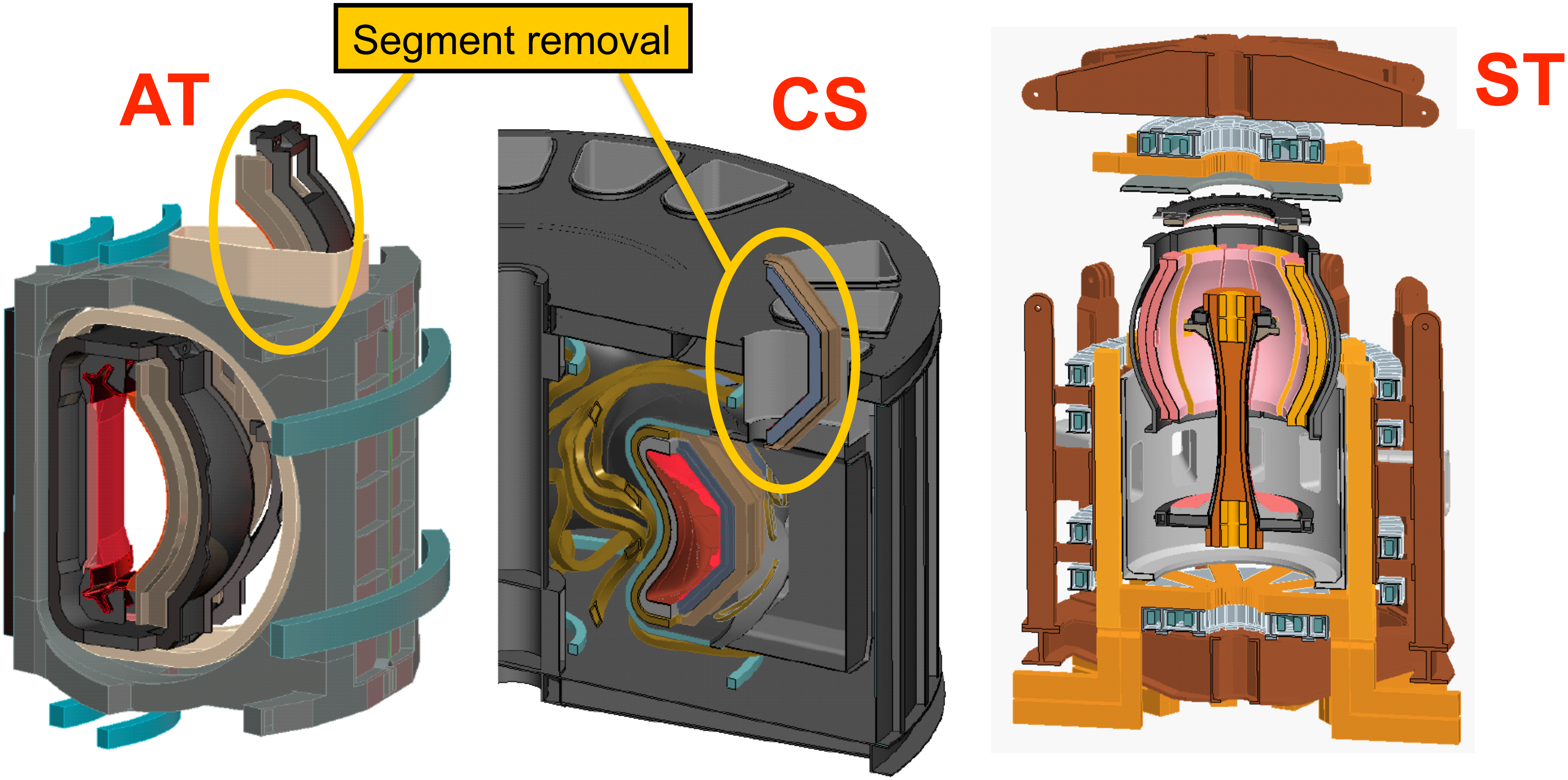
Compact Stellarator (CS)

No current drive, no disruptions

J. Menard, *et* al., at IAEA FES-2010, Daejeon, S. Korea; submitted to *Nuclear Fusion*.

Availability is a Key Driver in Pilot Plant Configuration Development

Exploring power plant prototypical maintenance approaches.



T. Brown, *et* al., "An Overview of Pilot Plant Designs…," this conference.

Pilot Plant Parametric Trends

- All are ~2/3 the size of corresponding ARIES power plant designs.
- ST has highest fusion power and NWL.
- CS has highest Q_{ENG}.

$$Q_{DT} = P_{fus}/P_{aux}$$

$$Q_{ENG} = \frac{\text{Electricity produced}}{\text{Electricity consumed}}$$

	AT		ST		CS	
η_{th}	0.30	0.45	0.30	0.45	0.30	0.45
$A = R_0 / a$	4	4	1.7	1.7	4.5	4.5
R_0 [m]	4	4	2.2	2.2	4.75	4.75
P_{fus} [MW]	553	408	990	630	529	313
P_{aux} [MW]	79	100	50	60	12	18
$\langle W_n \rangle$ [MW/m^2]	1.8	1.3	2.9	1.9	2	1.2
Peak W_n [MW/m^2]	2.6	1.9	4.5	3.0	4.0	2.4
Q_{DT}	7.0	4.1	19	10.5	42	17
Q_{eng}	1	1	1	1	2.7	2.7

Stellarator Pilot Plant as Demo minus 1

Risks reduced by following a stellarator path

- Steady state control
- Disruptions
- Plasma-wall interactions (high density operation)
- Current drive

Risks accepted (but can be managed / mitigated)

- Performance uncertainty due to less mature physics basis.
  - *Mitigation: LHD, W7-X.*
- Engineering- compatible with high availability?
  - *Mitigation: design optimization, targeting engineering metrics.*
- Large size
  - *Mitigation: quasi-symmetry.*

Assessment of Pilot Plant *vs.* Demo Prerequisites

Plasma Configuration

- Large gap in Q unless stellarator path is chosen.
- Otherwise, could fully satisfy.

Control Technology

- Could satisfy up to pilot plant performance and conditions.

In-Vessel Systems and Tritium

- Could satisfy up to pilot plant performance and conditions.

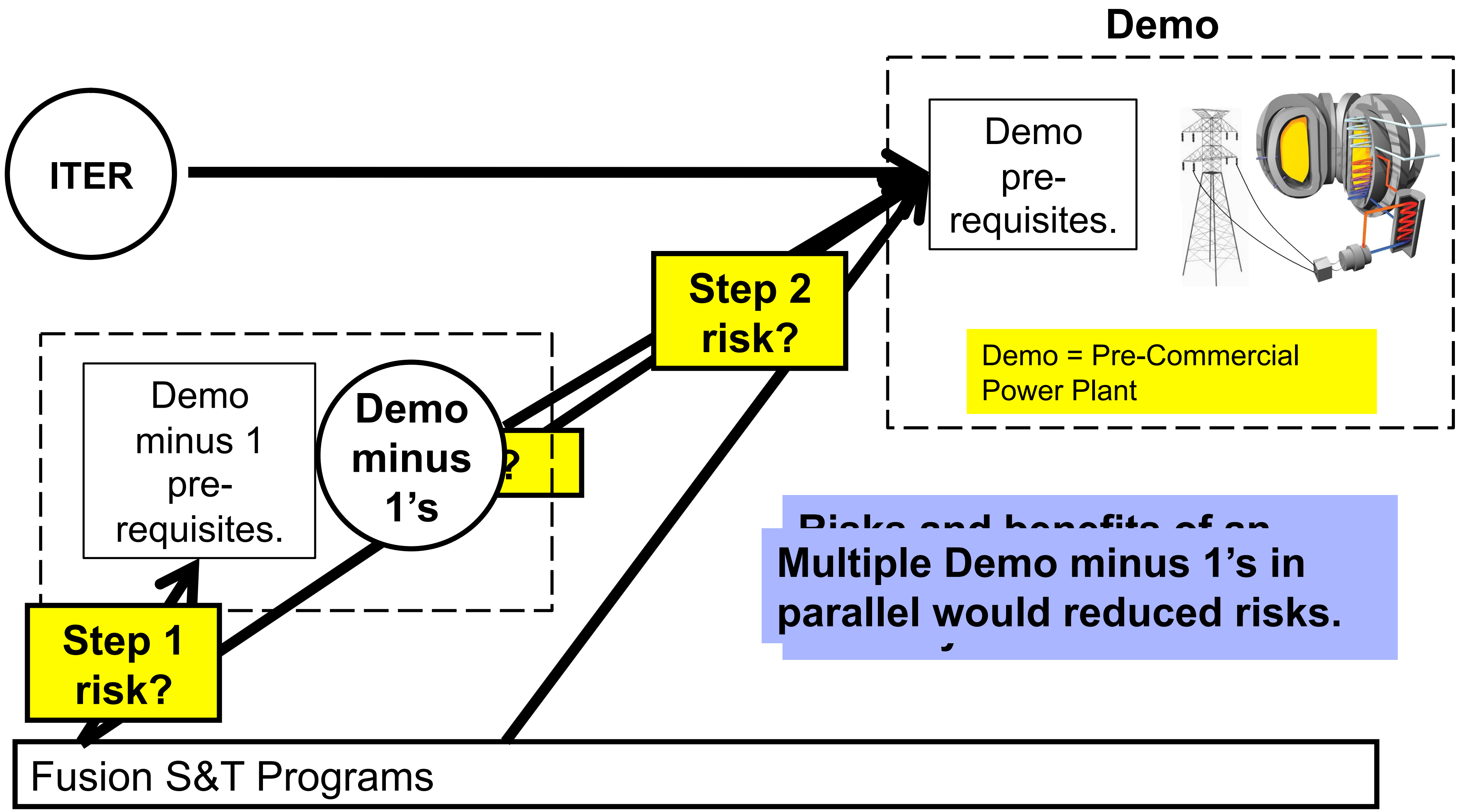
Plant Integration

- Could fully satisfy, including *net* electricity demonstration.

Caveats

- Assumes all necessary S&T Research and Development programs succeed.
- Readiness to move directly to a pilot plant needs to be analyzed. What are the prerequisites, and what is needed to satisfy them?

Other Roadmap Strategies



International Workshop

MFE Roadmapping in the ITER Era

Princeton, New Jersey, USA

7-10 September, 2011

Conclusions

- MFE is on an energy path. We need a roadmap now.
- Enough is known about required power plant characteristics to establish a target end product (Demo), and do roll-back planning.
- Risk management must play a central role in planning and decision-making.
- Demo science and technology must be developed in supporting R&D programs, tested in integration facilities.
- A pilot plant comes close to completing Demo prerequsites, but readiness to build a pilot plant needs to be checked.