Fusion Nuclear Science - Pathway Assessment

C. Kessel, PPPL

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Basic Flow of FNS-Pathways Assessment

1. Determination of DEMO/power plant parameters and requirements, over an appropriate range to represent "conservative" to "aggressive". Roll these back to where we are.

2. Systems level analysis of possible "missions" in the pathway to DEMO/power plant.

3. Identification of critical R&D needs, with initial assessment of how to address the needs (but more detailed assessment to follow this exercise).

1. Identify DEMO/power plant parameters and requirements, over an appropriate range to encompass "conservative" to "aggressive" visions

- For example, ARIES-I ($\beta_N < 3$) to ARIES-RS/AT ($\beta_N < 5.5$) for the tokamak

- This will include plasma physics and engineering/technology

- This will necessarily include parameters that are representing a number of additional hidden parameters, for example, FW lifetime > 3-5 years, which is driven by reasonable replacement times, represents nuclear damage limits, plasma interaction limits, and must provide the proper mechanical and thermal behavior over this life.

- Critically examine assumptions used in power plant visions, are these feasible projections with R&D.

- Tentative identification of missions in the FNS pathway, determined by evolution of critical parameters on the path toward DEMO (for example neutron damage, plasma duration, duty cycle/availability, etc.)

A short listing of power plant parameters derived for the ReNeW effort on high performance steady state plasmas

These used ARIES-1 to ARIES-AT as a range of target parameters

$\beta_N^{no\ wall} < \beta_N < \beta_N^{with\ wall}$	normalized plasma pressure
$\beta_N^{ped} \approx 0.5\text{-}1.0$	normalized plasma pressure near the plasma edge
$3 < q_{95} < 5$	degree of magnetic field twist near the plasma edge
$I_{non\text{-}inductvie}/I_{plasma} = 1$	fraction of plasma current not provided by a external solenoid
$0.65 < (I_{bootstrap}/I_{plasma}) < 0.90$	fraction of plasma self-generated current
$n/n_{Gr} \approx 1$	ratio of plasma particle density relative to an empirical limit
$P_{alpha}/P_{input} \approx 4\text{-}9$	ratio of plasma self-generated power to externally injected power
$P_{rad,core}/(P_{alpha}+P_{input}) \approx 0.35\text{-}0.5$	ratio of power radiated from the plasma core relative to the total power heating the plasma
$Z_{eff} < 2.5$	weighted sum of ion charge in the plasma
$\tau_{pulse} >> \tau_J$ and τ_{PFC}	plasma operation time compared to the current profile redistribution and plasma facing component equilibration times
$3 < \tau_p^* / \tau_E < 10$	ratio of the global particle confinement time inside the vacuum chamber to the plasma energy confinement time
$q_{peak,div} \leq 10\ MW/m^2$	peak heat flux on the divertor material surface from particles and radiation
$q_{peak,\ FW} < 0.5\text{-}1.0\ MW/m^2$	peak heat flux on the first wall material surface from particles and radiation
$P_{rad,div}/(P_{alpha}+P_{input}) > 0.45$	ratio of power radiated in the divertor region relative to the total plasma heating power
$\tau_{FW,lifetime} > 3$ years	lifetime of first wall material before replacement
$\tau_{div,lifetime} > 3$ years	lifetime of divertor material before replacement
$T_{FW} > 500\text{-}1000^oC$	operating temperature of first wall material surfaces
Supporting elements	
Efficient fueling and pumping, with particle control of the DT fuel, He ash, and impurities.	
Efficient coupling of heating and current drive power into the plasma.	
Consistent pedestal density and temperature to provide high core performance with fueling and divertor compatibility.	
Multi-level feedback control on parameters ranging from plasma shape to current profile to MHD modes.	
Plasma sustainment over many current diffusion and PFC times (considered the longest time constants for the core plasma and PFC material evolution) without disruptions and with acceptable transients.	
Controlling the tritium inventory in plasma facing materials, production of debris (dust), and material lifetimes for the required time scales.	

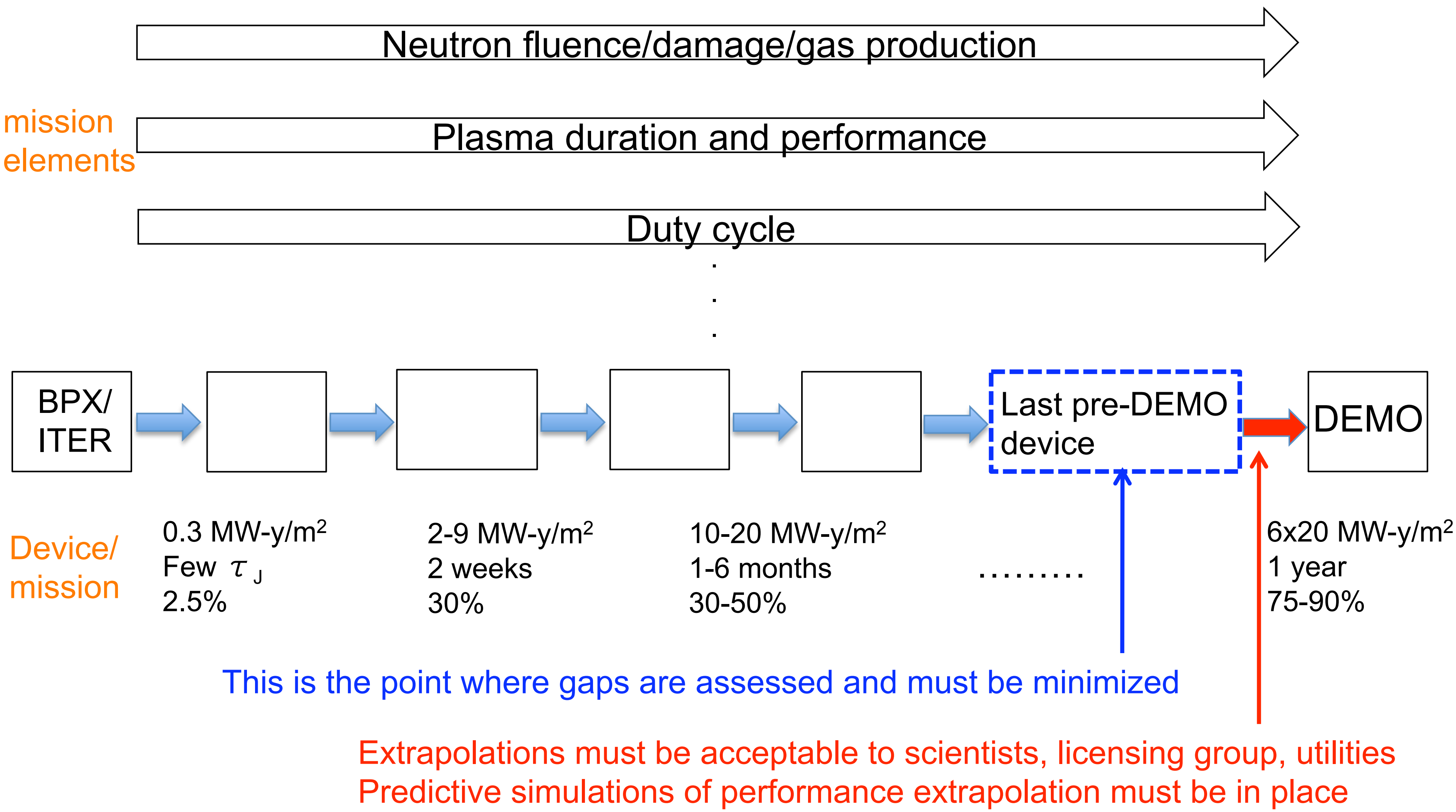
2. Systems level analysis of “missions” along the FNS path to a DEMO/power plant

- Operating space approach to systems analysis is used, which scans a number of parameters and provides a number of viable operating points, allowing one to examine sensitivities. Smallest or cheapest or conservative or aggressive or other features can be isolated.

- Approach has a physics component and an engineering component (and also a costing if necessary) component. The viable physics points can represent conservative to aggressive plasmas. The engineering component will reflect aggressive and conservative assumptions, engineering limits, and the device mission through constraints and other criteria.

- Identifying a range of possible “facilities” for a given “mission”, impact of broader or narrower “mission” on device definition, plasma performance assumptions required and their sensitivities, sensitivity to engineering/ technology assumptions, motivations for R&D, etc.

Step by step view of devices or phases of FNSF (this is for illustration purposes)



What does a given device or phase infer?

Is this a device or a phase of a facility?

What is the timeframe for R&D to support these elements? Pre-requisite R&D vs in operation R&D

Break-in
FDF-like

Break-in nuclear phase, $\langle N_w \rangle$ ~1-3 MW/m^2
Plasma duration 10 min – 2 weeks
Duty cycle 1-5%, 0.06 $MW\text{-}yr/m^2$
to
Duty cycle 30%, 8.9 $MW\text{-}yr/m^2$

Tritium breeding (breeder choices, tritium removal, TBR, n-multiplier,…)

Plasmas that are 100% non-inductive (no disruptions, weak nominal transients, f_{BS} vs f_{CD}, conservative parameters required for mission …)

Plasma materials interaction issues (dust production, material surface degradation and transport, …)

Qualified structural materials and coolant/breeder compatibility (ferritic steel up to 20 dpa?, He coolant, stationary breeder, …)

Maintenance/replacement strategies (“as simple as possible”, construct device remotely, …)

More on Systems Analysis

Systems analysis flow

physics → engineering → build out/cost

physics	engineering	build out/cost
Plasmas that satisfy power and particle balance	Inboard radial build and engineering limits	Top and outboard build, and costing
Scan several plasma parameters to generate large database of physics operating points	Screen physics operating points thru physics filters, engineering feasibility, and engineering filters	Surviving feasible operating points are built out and costed, graphical display of parameters (COE)

More on Systems Analysis, cont'd

Physics calculation, produces large database of solutions directly read by engineering module

- Power balance
- Particle balance
- Peripheral physics (bootstrap current, current diffusion time, etc.)
- Scan several variables (R, A, Bt, q_{95}, β_N, T profile, n profile, n/n_{Gr}, Q, κ, δ, η_{CD}, τ_p^*/τ_E, impurities)

Engineering calculation, filters solutions

- Plasma and radiated powers
- Peak heat flux on divertors
- Power balance (thermal, electric, thermal conversion)
- Inboard radial build
  - FW, blanket, shield
  - TF coil
  - Bucking cylinder
  - PF coil

Outboard/divertor build and costing

More on Systems Analysis, cont'd

Input
A = 4.0
δ= 0.6
κ= 2.0
α_n = 0.47
α_T = 0.96
τ_p^*/τ_E = 10
η_{CD} = 0.3

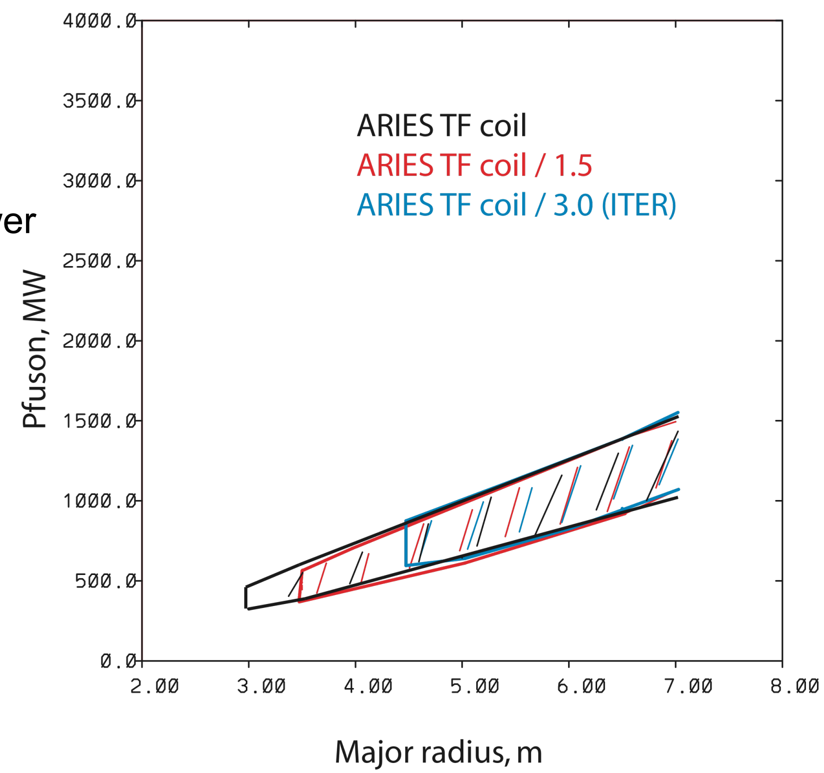
Scanned
Bt = 5-9 T
β_N = 0.03-0.06
q_{95} = 3.2-4.6
n/n_{Gr} = 0.5-1.0
Q = 10-30
R = 2.5-7.0 m
f_{Ar} = 0.1-0.3%

Assumptions
FW radiation peaking = 1.5
Divertor radiation fraction = 0.75
$q_{FW,\ peak}$ < 1 MW/m^2
($q_{FW,peak}$ > 0.75 W/m^2 reject heat)
$q_{div,peak}$ < 12 MW/m^2
($q_{div,peak}$ > 8.0 W/m^2 reject heat)
λ_{power} from Fundamenski
Neutron energy mult = 1.1
Thermal conv efficiency = 0.3
Wall plug H/CD efficiency = 0.4
Pumping = 3% of thermal power
Subsystems = 4 % of themal power
CS flux to rampup Ip only
Δ_{SOL} = 7 cm
$\Delta_{FW,blnkt,shld}$ = 1.0 m
Bt_{max}, Bp_{max} = 14 T
SC coils

Filtered
0.8 < Q_{eng} < 1.2

Output
Regions of parameter space with viable solutions

An example from the Pilot Plant study



3. Collection of critical R&D needs, with initial assessment of how to address the needs (but more detailed assessment to follow this exercise)

- Identify rollback parameters that point to required R&D
- Identify sensitivities from systems analysis that justify R&D
- Identify potential facilities to address R&D (test stands, fission reactors, a fusion device, etc.)
- Initial estimate of time required to reach needed information from R&D
- Can we see an international opportunity to access this R&D
- Are there existing programs in the US, outside of FES, that we could leverage off of or collaborate with to access the R&D
- Is there a sequence of risk and R&D “completeness” trade-offs?

R&D in support of devices or phases (need several VGs for this)

- Nuclear effects on materials (how long does this actually take?)
  - IFMIF is most perfect “imperfect” neutron source, but….
  - Other facilities that “simulate” damage
  - Other facilities that accelerate damage
  - Qualifying ferritic steels versus material/alloy development
  - Material fabrication influence on nuclear performance (W)

- Breeding blanket (virtually all missions short of the BPX & high Q require breeding)
  - Breeders
  - Tritium behavior in Li compound, within confining structures, …
  - Liquid metals and interface/compatibility
  - Overall design of blankets for nuclear, mechanical, thermal and breeding functions

- Advancing low temperature SC (Nb_3Sn) beyond ITER magnet to reduce size and raise j/B operating space

R&D in support of devices or phases (need several VGs for this)

- Plasma duration
  - Stationary plasma configurations
  - Disruption free operation
  - 100% non-inductive current operation
  - Minimization of nominal transients (like ELMs)
  - Plasma duty cycle, long pulses and short down time between pulses
- Plasma material interface
  - Heat transport
  - Particle transport
  - Material evolution
  - Test stands, present tokamaks, and longer pulse tokamaks
- Reliability, availability, maintenance
  - Remote handling
  - Simplicity to enable rapid replacement
  - Combining long life breeding blanket and test module functions

Deliverables (digging deeper to identify quantitative parameter targets, missions that meet these targets, and R&D to support the missions)

Quantitative characterization of DEMO/power plant requirements to the extent possible (including qualitative where necessary).

Identification of “missions” along the FNS pathway to DEMO.

Operating space systems level analysis of possible devices/facilities to address “missions”, with identified sensitivities to assumptions and constraints.

A list of R&D needs to support the “missions”, within their timeframes, and the path to DEMO/power plants overall.