Development of a Systematic, Self-consistent Algorithm for the K-DEMO Steady-state Operation Scenario

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SEOUL NATIONAL UNIVERSITY

OAK RIDGE National Laboratory

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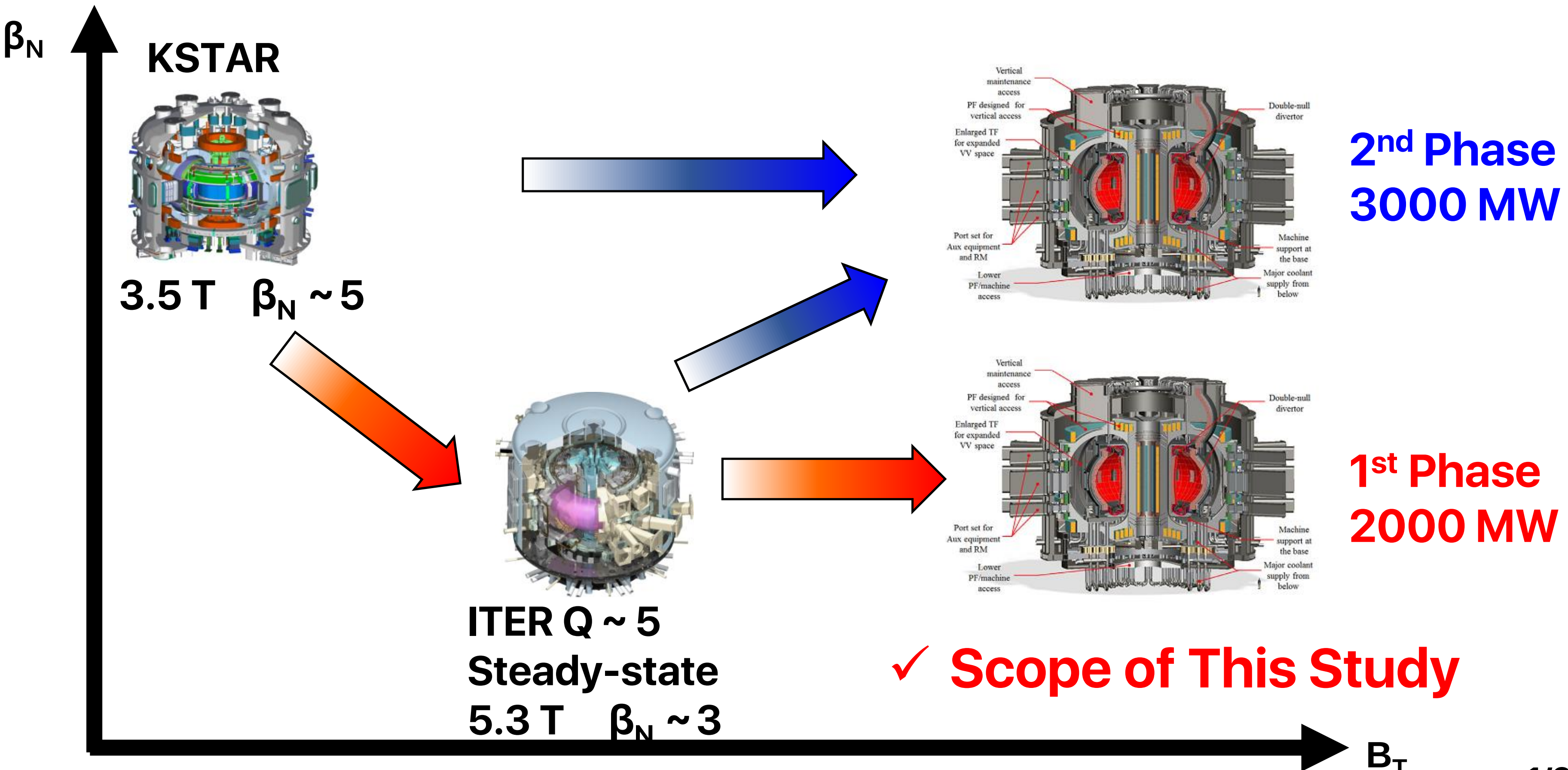
K-DEMO Goal: Demonstrate a Net Electricity Generation

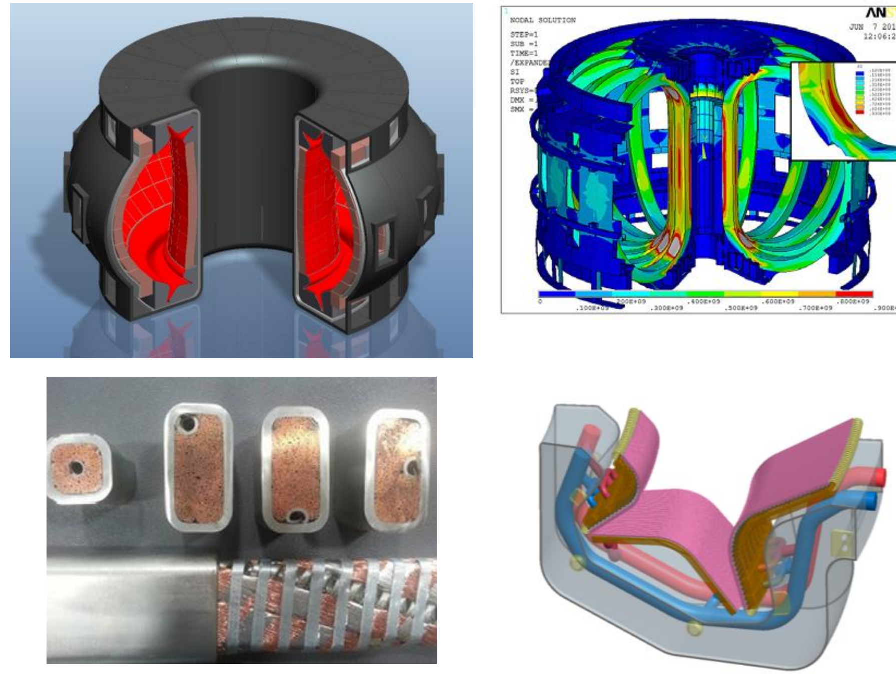
- 1^{st} phase High B_T
- 2^{nd} phase High B_T & β_N

- Pressure Limit $\propto B_T \cdot \beta_N \cdot I_P$
- $f_{BS} \propto B_T \cdot \beta_N / I_P$



K-DEMO Design Parameters

Major Radius (R)	6.8 m
Minor Radius (a)	2.1 m
Toroidal Magnetic Field	7.4 T
Elongation / Triangularity	2.0 / 0.6
β_N	< 4
Fusion Power (P_F)	2000 MW (1st) 3000 MW (2nd)
Fusion Gain	20
Divertor Operation	Double-null



< K-DEMO Magnet & Divertor Analysis [1]>

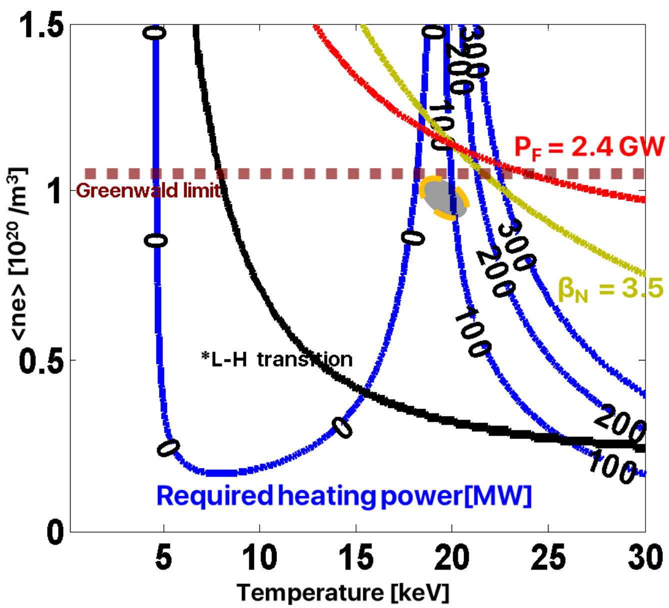
- Size & aspect ratio similar to those of ITER & KSTAR.
- Nb_3Sn configuration/stress analysis/test fabrication.
- Tungsten mono-block type divertor, RAFM cooling tube, high pressure water-cooling.
- Ceramic pebble type breeder blanket, high pressure water cooling.

[1] Kim, K., et al, "Design concept of K-DEMO for near-term implementation", Nucl. Fusion 55 (2015) 053027.

0-D System Analysis to Identify Fusion Performance & Operating Regime

<Operation Regime for K-DEMO[1]>

[1] Kang, J.S., et al, Fusion. Eng. Des. 109-111, Part A (2016) 724.



✓ **0-D power balance**

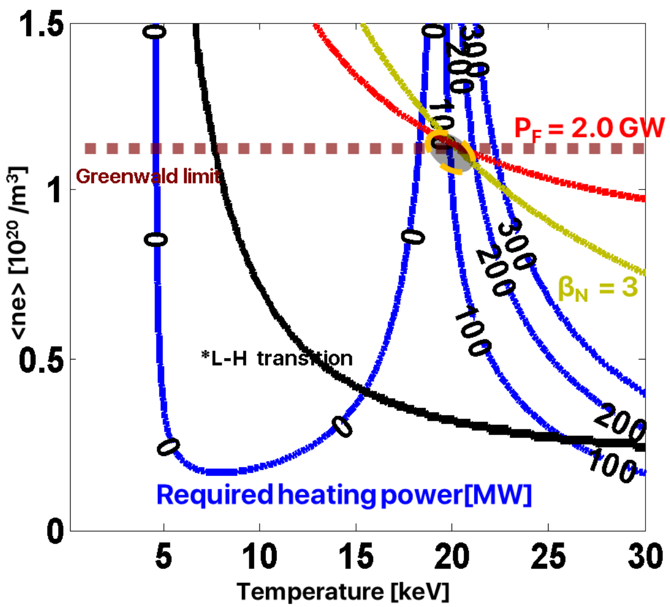
P_F = 2000 MW, Q = 20

n_{eavg} = 0.87x10^{20} m^{-3}, T_e = 20.0 keV

0-D System Analysis to Identify Fusion Performance & Operating Regime

<Operation Regime for K-DEMO[1]>

[1] Kang, J.S., et al, Fusion. Eng. Des. 109-111, Part A (2016) 724.

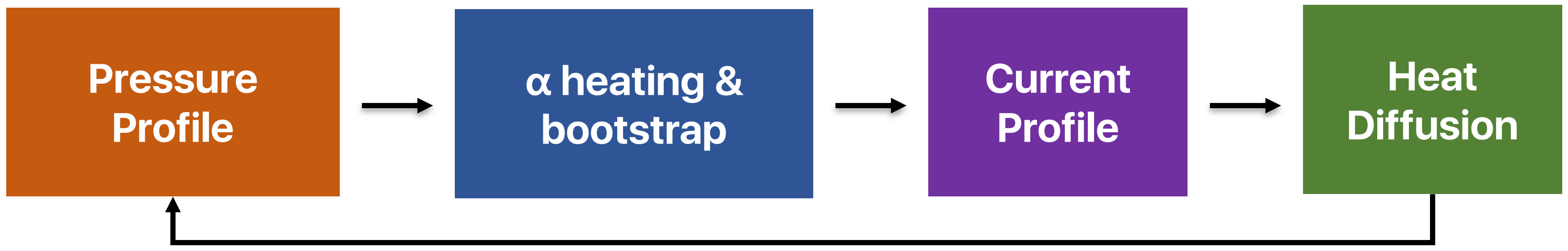


- ✓ **0-D power balance**

P_F = 2000 MW, Q = 19

n_{eavg} = 1.2x10^{20} m^{-3}, T_e = 20.0 keV

- ✓ **Burning plasma profile effect (self H/CD) change optimum operation regime.**

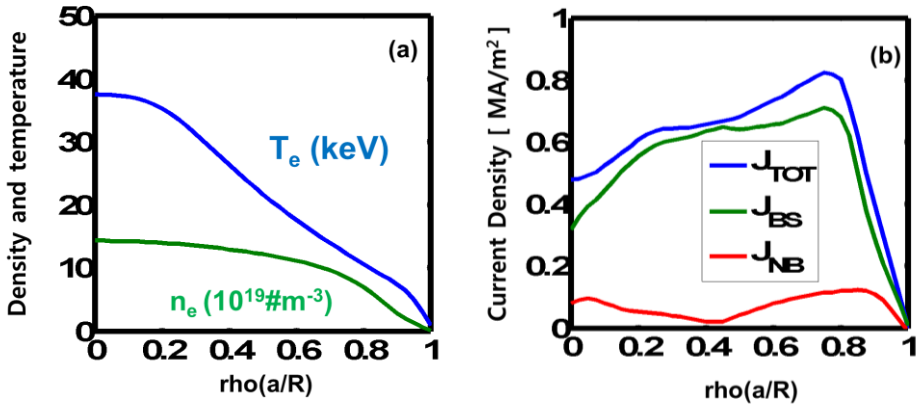


➡ **Need a self-consistent integrated modeling!**

Previous K-DEMO Integrated Modelling

✓ **Target pressure and current profile are achieved intuitively.**

<1-D KDEMO n, T, J profile[1]>



Modelling with prescribed heating schemes

(1) 1 beam 1 MeV 100 MW on-axis
(2) 2 beams, on-axis (1.5 MeV 50 MW) off-axis (0.6 MeV 50 MW)
(3) 2 beams, on-axis (1.3 MeV 40 MW) off axis (0.8 MeV 80 MW)
(4)
(5) ⋮
(6)

Try ⇒ Select the maximum fusion gain one

➡ **Systematic approach is required!**

[1] Kang, J.S., et al, Fusion. Eng. Des. 109-111, Part A (2016) 724.

A Systematic Algorithm for K-DEMO Burning Plasma Design is Developed

- Find p & j profiles and corresponding H&CD specification to maximize Q, systematically and self-consistently.

$$f(p, j) = \max\{Q\}$$

p : pressure profile j : current profile

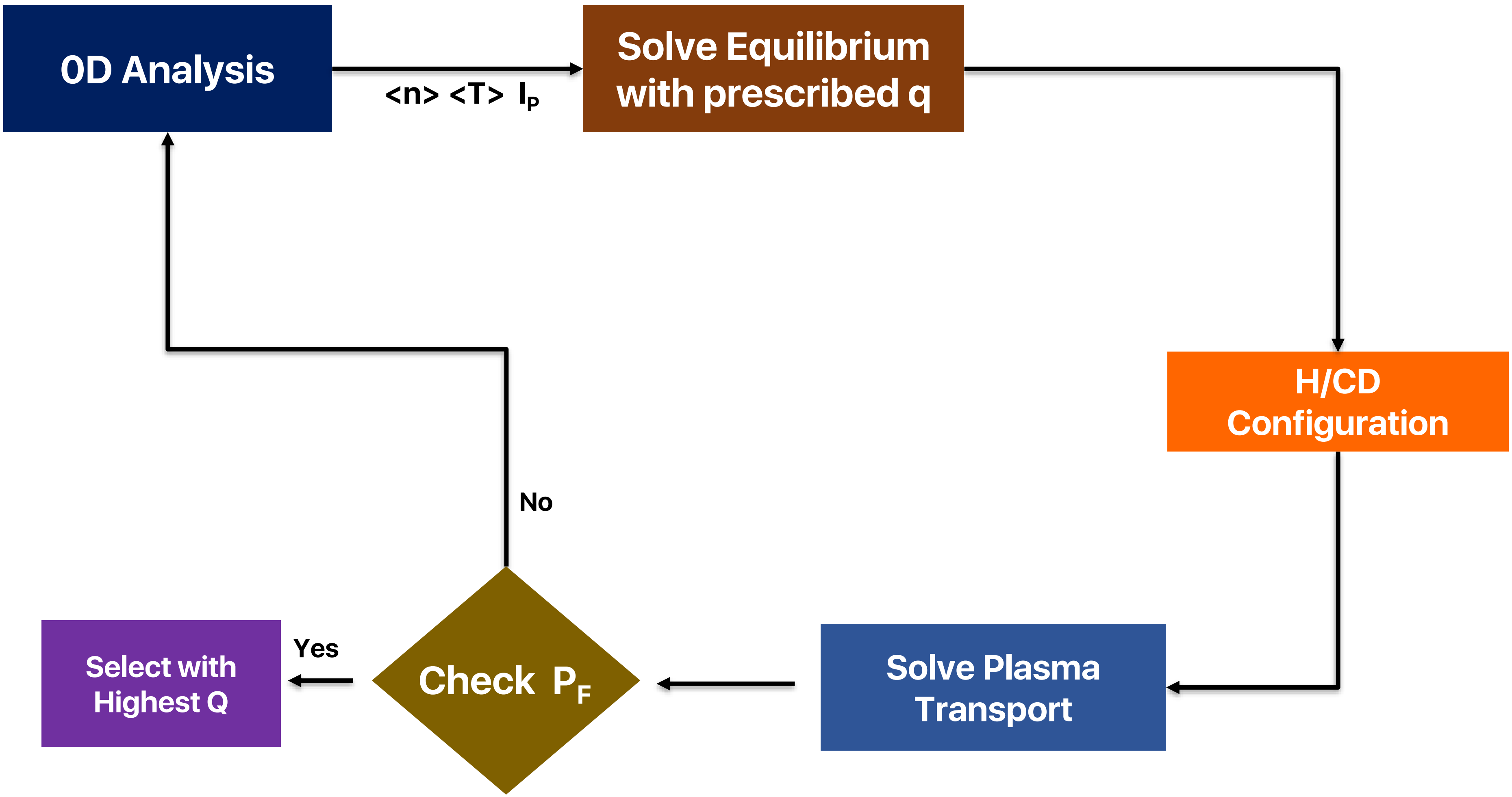
High performance steady state operation needs optimization of P&J profiles.

Burning plasma algorithm must integrate various physics/engineering.

Optimization Algorithm Consider Constraints

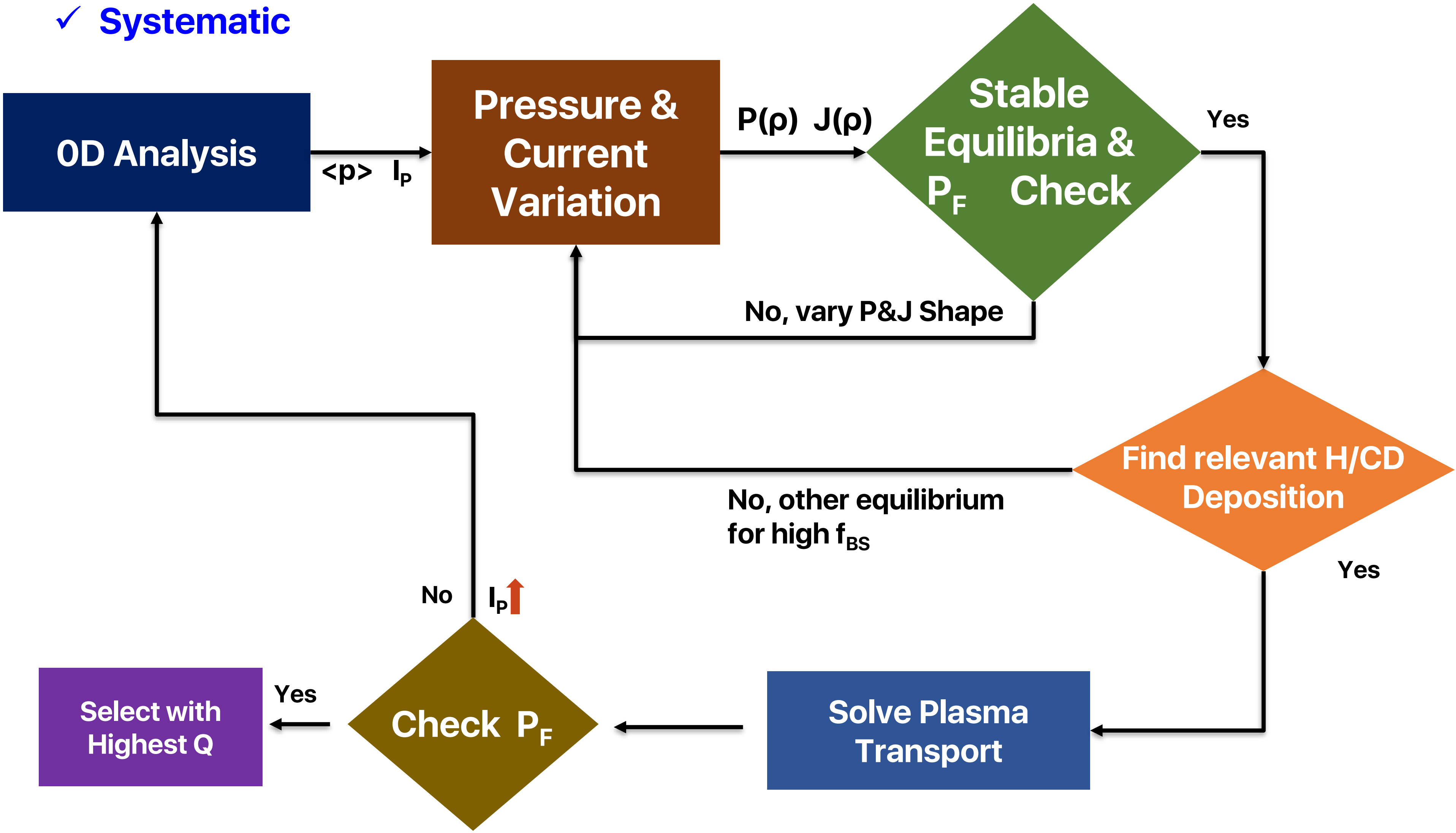
Confinement	MHD stability	H/CD

Previous Flowchart of K-DEMO Target P&J

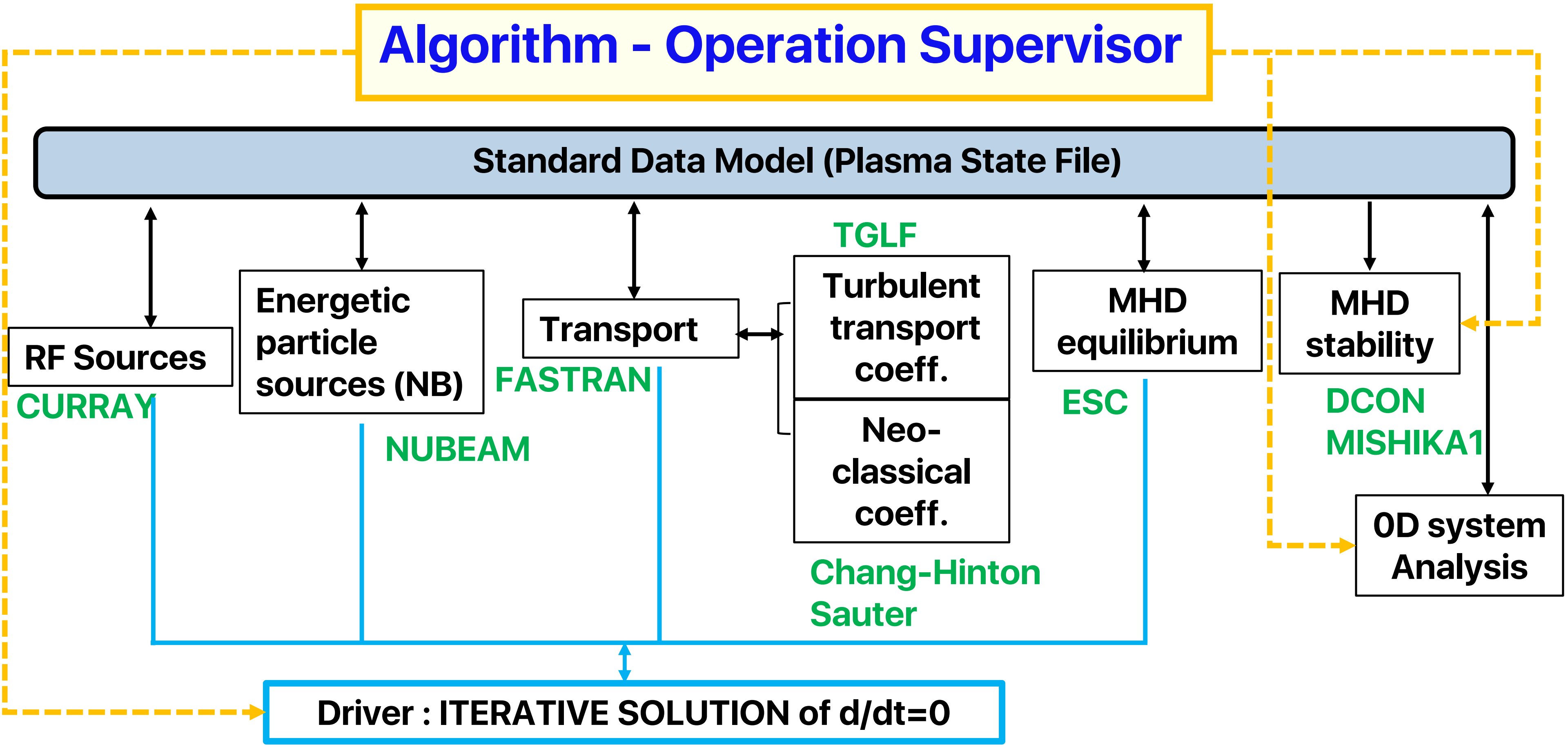


K-DEMO Burning Plasma Target Scenario Algorithm Flowchart

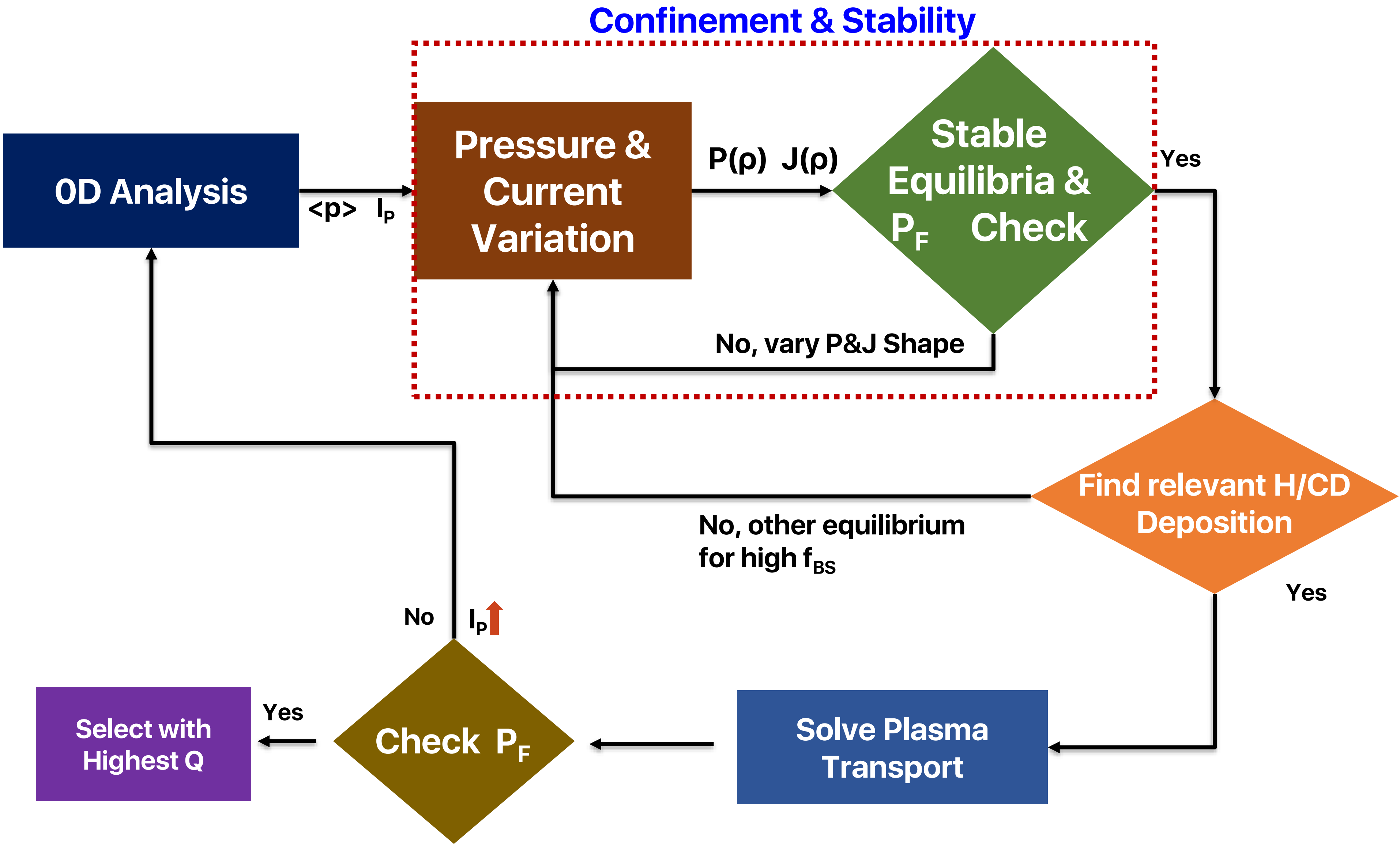
- ✓ **Confinement, Stability, and H/CD are simultaneously satisfied.**
- ✓ **Systematic**



FASTRAN/IPS is Adopted for Numerical Apparatus to Implement Algorithm

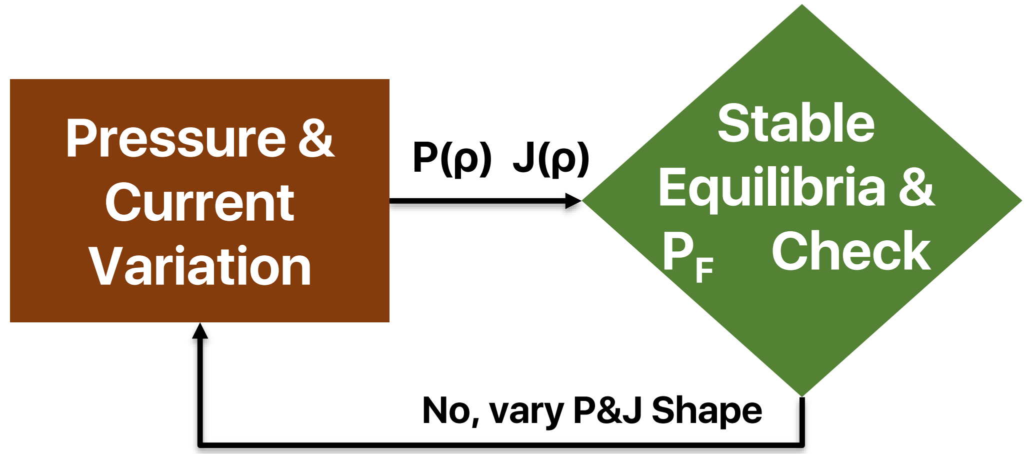


Loop 1: Find Stable Equilibrium Satisfying P_F

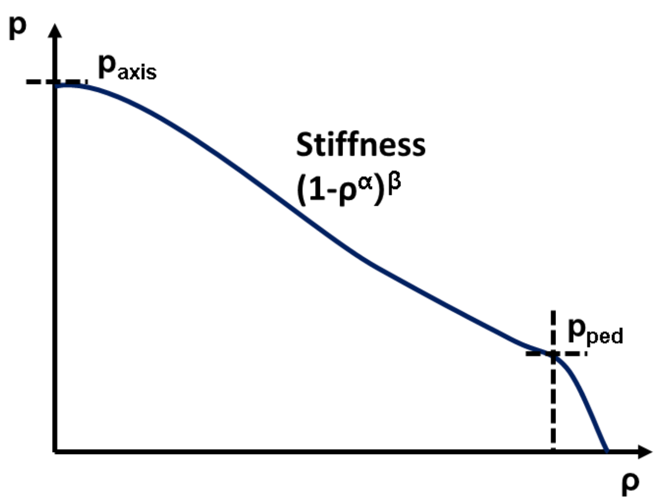


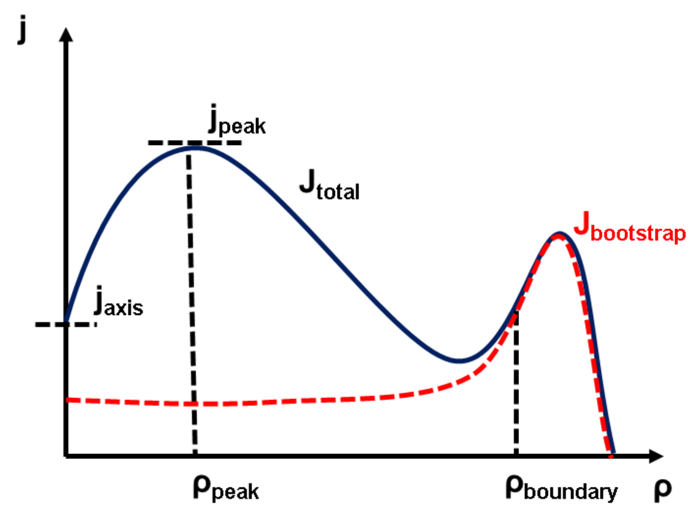
Loop 1: Find Stable Equilibrium Satisfying P_F

Target P&J
Profiles are Explored.



Control Knobs – p_{axis}, α, β, p_{ped}, j_{axis}, j_{peak}, ρ_{peak}, $\rho_{boundary}$

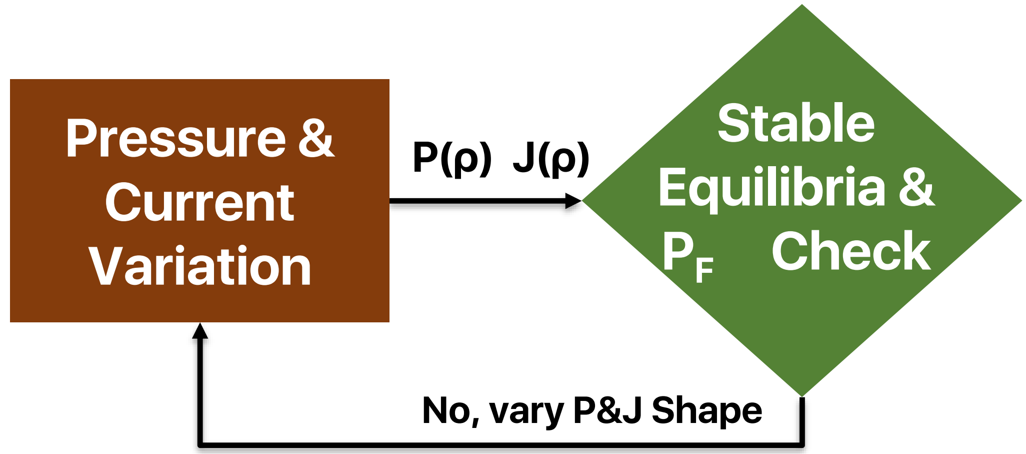




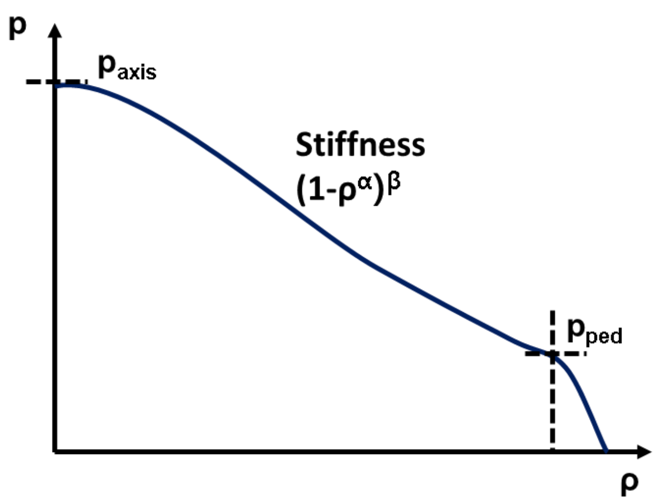
Δped = 0.1 benchmark from ITER.

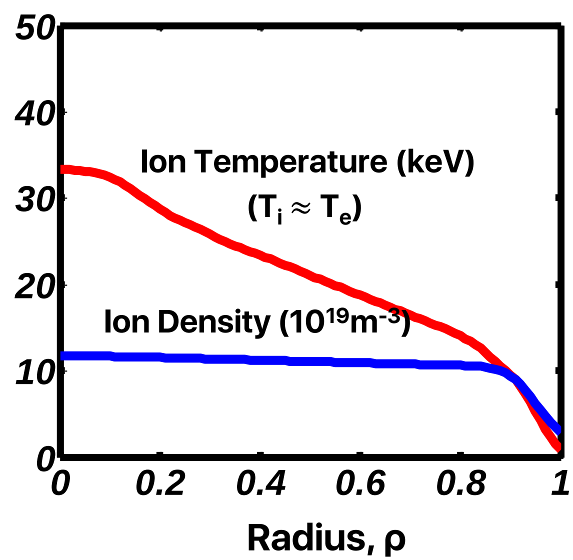
Loop 1: Find Stable Equilibrium Satisfying P_F

Target P&J Profiles are Explored.



✓ **P_F Evaluation with T_i / n_i**



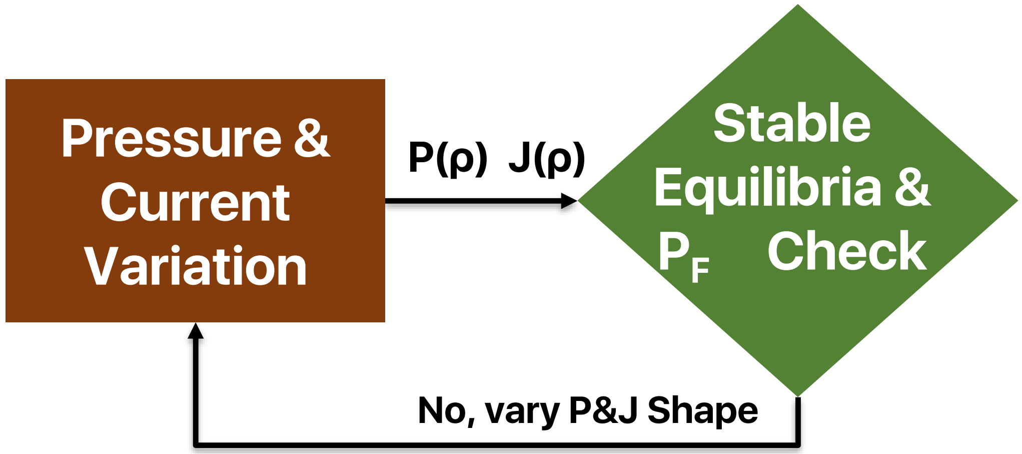


Z_{eff} Z_{imp} f_{imp} from ITER

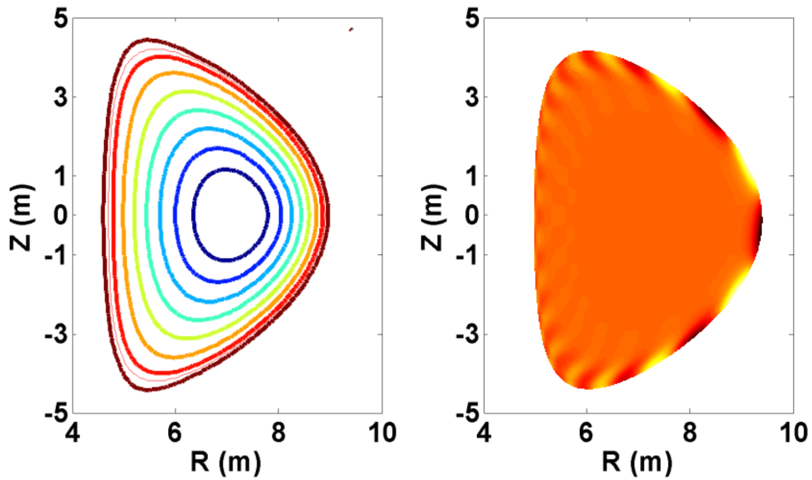
Prescribed n_e ($f_{GW} = 1$)
$n_{axis}/n_{ped} = 0.8$
$n_{ped}/n_{sep} = 0.3$

Loop 1: Find Stable Equilibrium Satisfying P_F

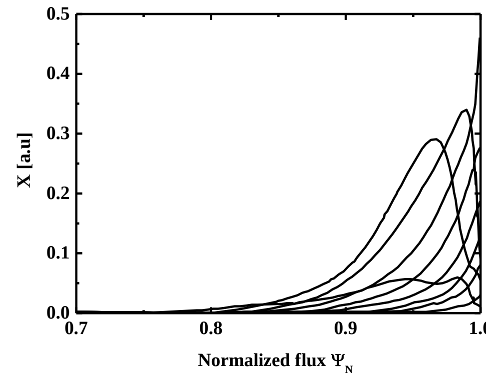
Target P&J Profiles are Explored.



✓ **Linear Ideal MHD Evaluation with DCON[1] & MISHIKA1[2]**

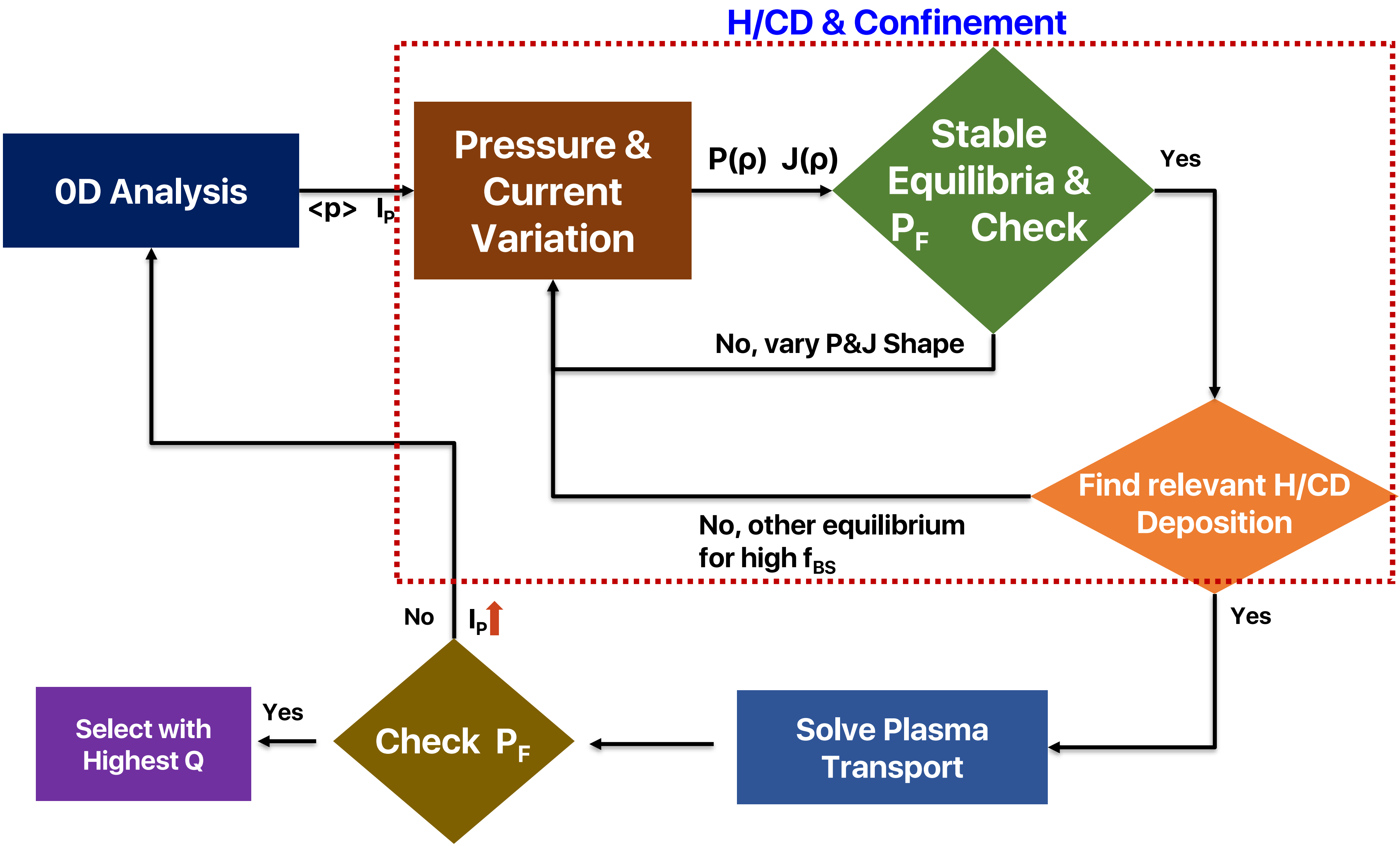


- T_{ped} < ideal MHD P-B mode [3] limit.
- n = 3 mode structure.



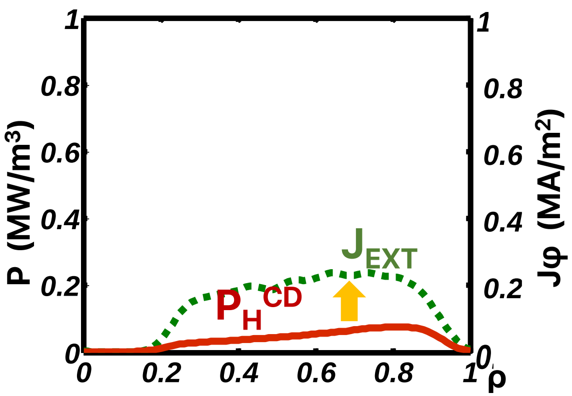
[1] Glasser, A. H., et al., Bulletin of the American Physical Society Vol. 42, p. 1848 (1997).
[2] Mikhailovskii, A. B., et al., Plasma physics reports, 23(10), p. 844 (1997).
[3] Snyder, P. B., et al., Physics of Plasmas 9 (2002) 2037.

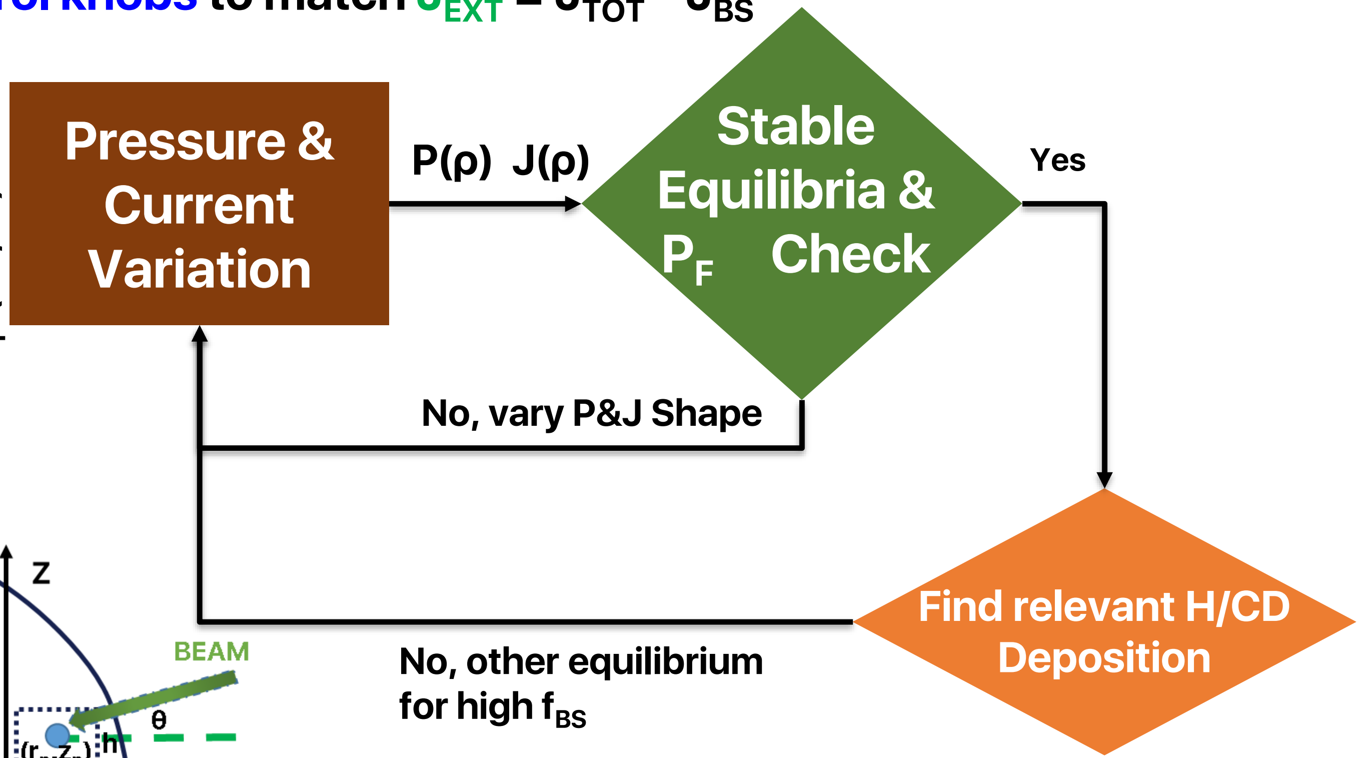
Loop 2: Determine External H/CD Configuration

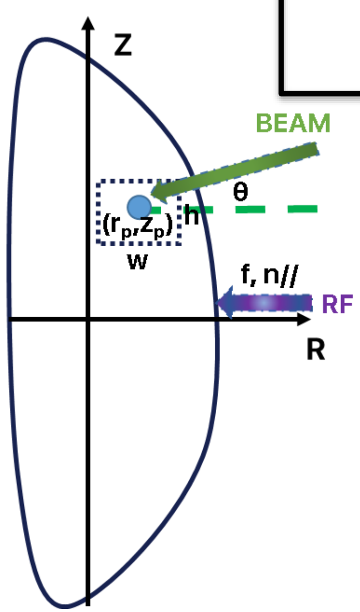


Loop 2: Determine External H/CD Configuration

1. Scanning H/CD control knobs to match $J_{EXT} = J_{TOT} - J_{BS}$







Control Knobs

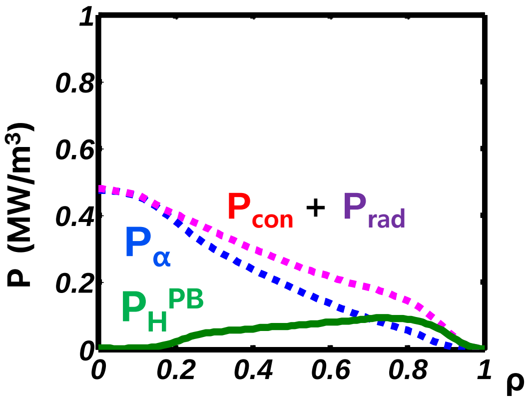
E_{Beam}, P_{NB}, Port location

RF frequency, wave number

NB&FW choice

with ITER technology.

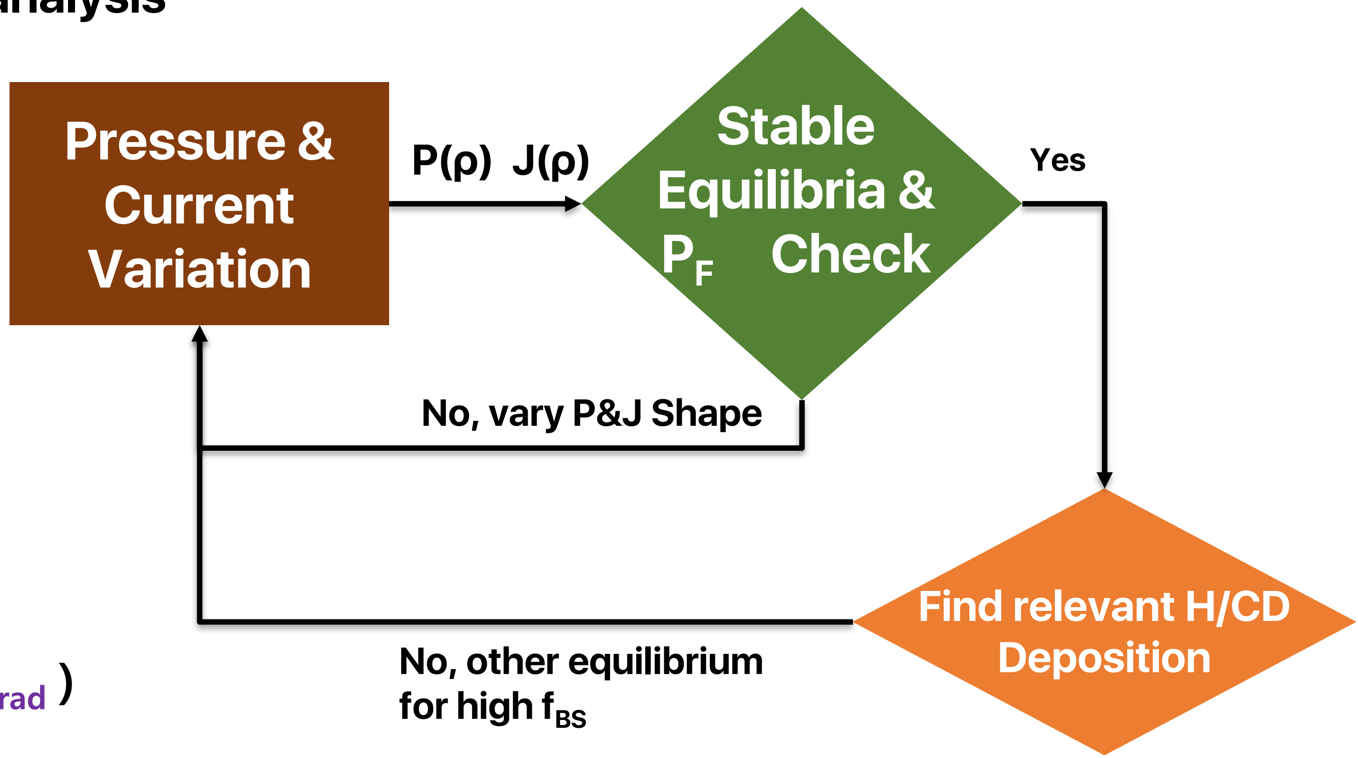
2. 1-D power balance analysis



Calculate P_H^{PB} to match 1-D power balance.

$$P_H^{PB} = P_\alpha - (P_{con} + P_{rad})$$

P_{CON} from diffusion model & n,T profile
P_α P_{RAD} from n, T profile(Loop 1 Result)



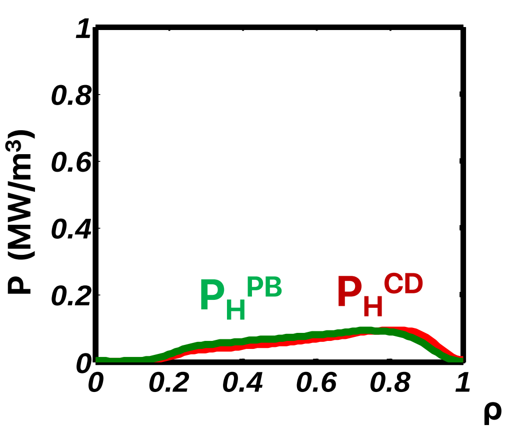
Loop 2: Determine External H/CD Configuration

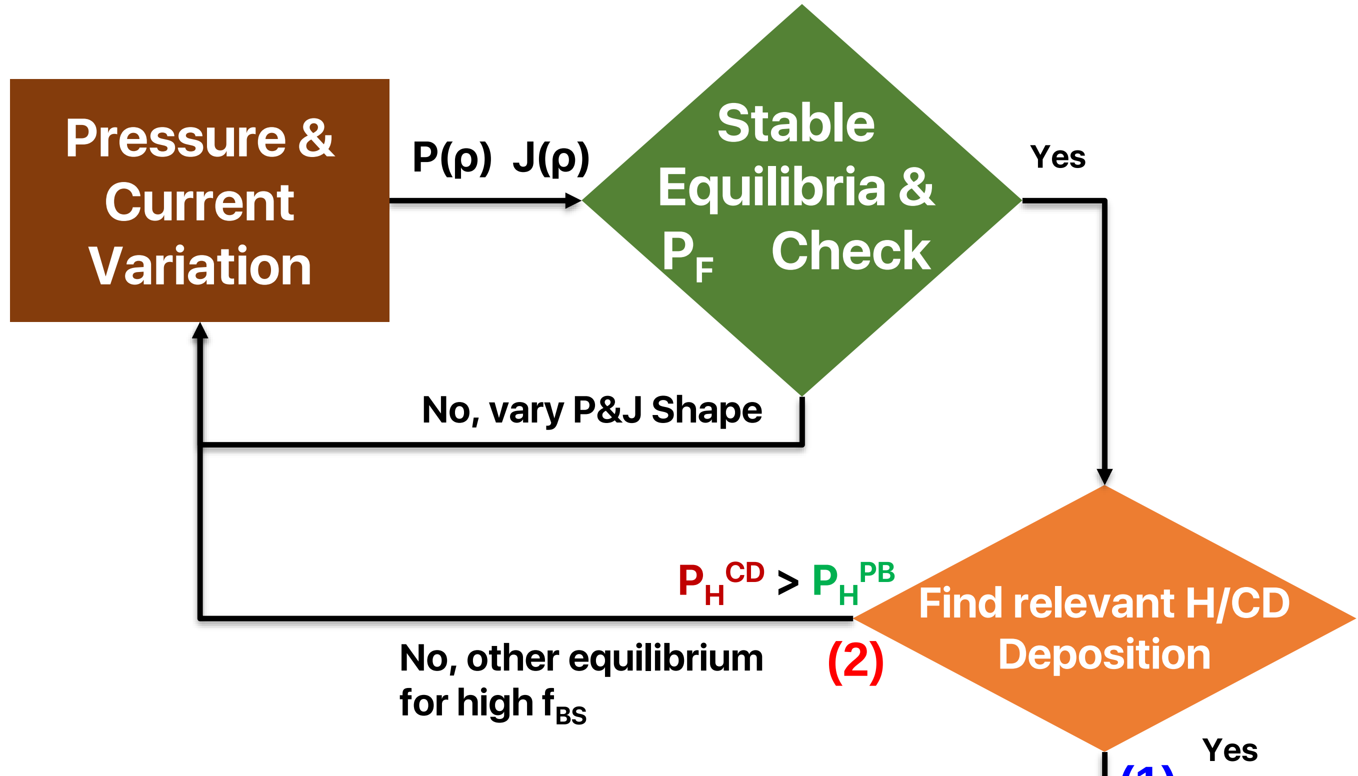
3. Compare P_H^{CD} & P_H^{PB}

(1) $P_H^{CD} \sim P_H^{PB}$

(2) $P_H^{CD} > P_H^{PB}$

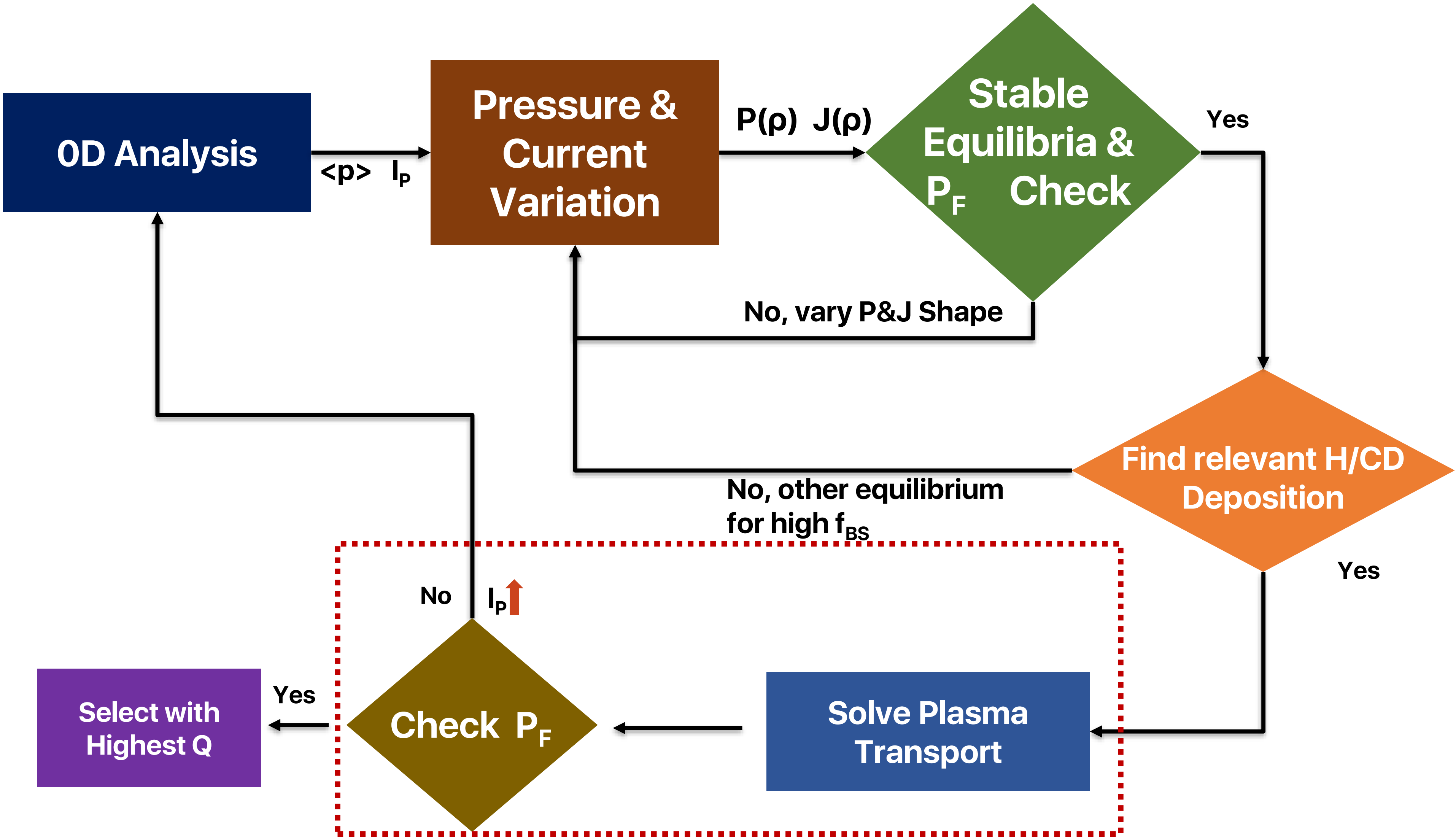
(3) $P_H^{CD} < P_H^{EXT}$(Discard)





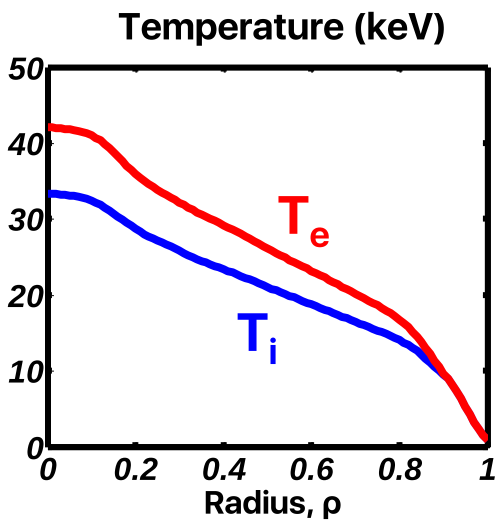
✓ Consider required H/CD alignment together.

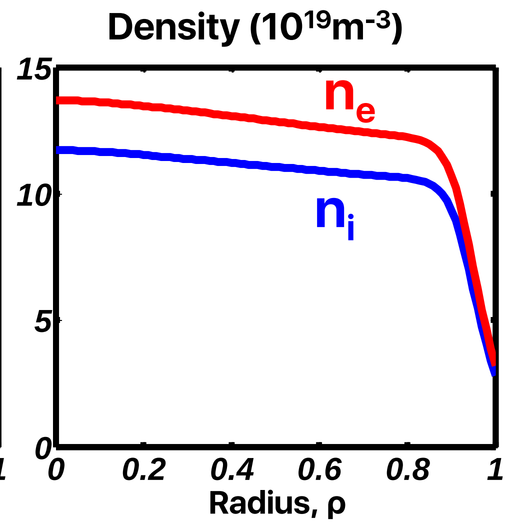
Loop 3: Check Self-consistency between Plasma Profiles and H/CD Configuration by Integrated Modelling

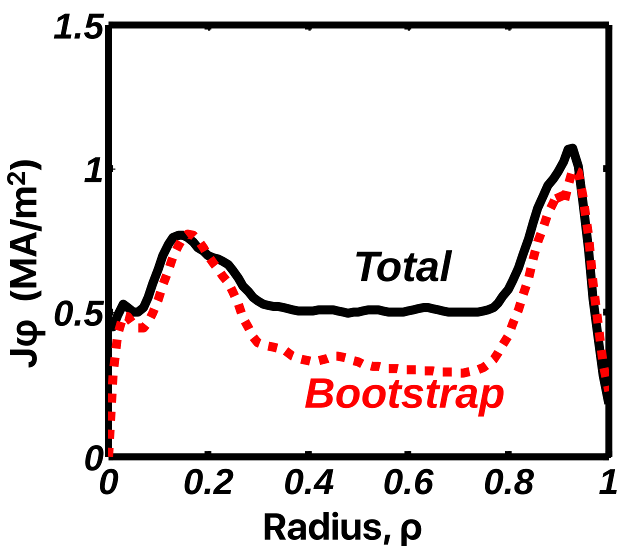


An Optimum Target P&J is Attained through Algorithm with Integrated Transport Modeling

A fully non-inductive target plasma is finally achieved.

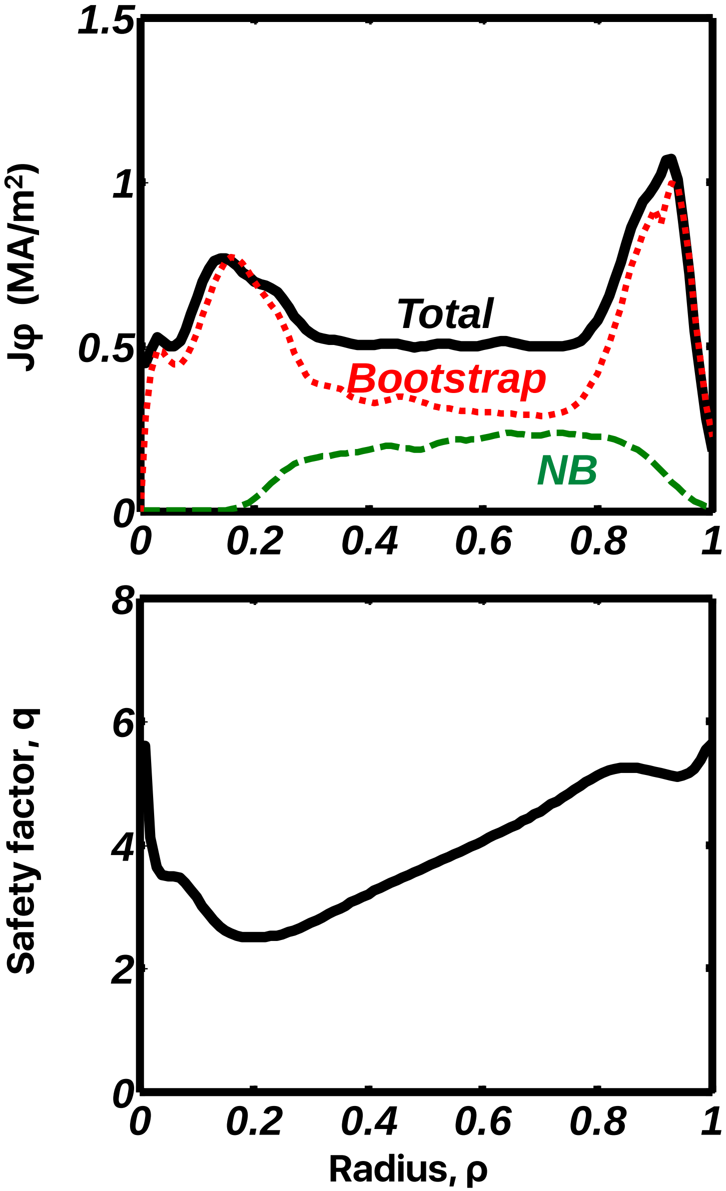






	Result	0 D
P_F (MW)	2080	2000
Q (Fusion Gain)	18.8	20
P_{NB} (MW)	110	100
I_P (MA)	15.5	12
f_{BS}	77 %	75 %
β_N	2.8	3.10
H_{98y2}	1.2	1.3
T_{ped} n_{ped}	8.3 keV $9.9 \cdot 10^{19}$ m^{-3}	

Discussion of Derived H/CD Specification



- **Off-axis NB provide broad J Profile**
  - improved confinement.
- **Single 110MW 500keV NB injection**
  - Alignment with less-bootstrap region.
  - Even half of ITER NBI beam energy.
- **q_{min} > 2 is set to avoid tearing modes.**

Conclusion & Future Work

- **A systematic scenario optimization algorithm maximizing the fusion gain is newly established by integrating equilibrium, confinement, stability, and current drive requirement, self-consistently.**

- **Target pressure & current profile for K-DEMO is derived with designed algorithm.**

  ✓ fusion power of 2080 MW, fusion gain Q of 18.8 and normalized beta β_N of 2.81.

- **Particle Transport/plasma rotation/more detailed stability are planned.**
  ✓ Particle transport and plasma rotation are also key control knobs for stable fusion power production and they will be updated to the systematic algorithm in the near future.
  ✓ Pedestal structure and plasma shaping optimization are expected to address more efficient/accurate target scenario.

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