Operation challengers for CFETR and suggestions

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1. **Usual challengers**
2. **Special challengers for CFETR**
3. **Summary**

1. Usual challengers

Similar to ITER, CFETR will face some usual challengers, as briefly mentioned below

1.1 Disruptions

* The disruption prediction and mitigation should be studied and developed in advance.

* ECRH/ECCD/LHCD for disruption avoidance should be studied and developed in advance.

1.2 ELM mitigation

*** Install RMP coils for ELMs mitigation?**

*** Pellet pace-making?**

*** Studies are required to understand ELMs and their mitigation mechanisms.**

1.3 Compatibility of Core and Radiative Divertor

*** Predicted narrow power deposition on divertor plate between ELMs.**

*** requires plasma detachment from the divertor.**

*** Excessive core impurities due to seeding for radiative divertor.**

Possible measures:

*** Impurities may be limited by high power core electron heating.**

1.4 Other issues

* H-mode power threshold?
* density limit/peaking?
* Vertical instability control
* ...

2. Special challengers for CFETR

2.1 Design requirements and machine parameters

Requirements

Fusion power	50～ 200MW
Based on Standard H-mode	H=1
duty time	0.3 ～ 0.5；
Tritium self-sufficiency for DT fuel cycle	TBR $\geq$ 1.2

Major parameters

B_{to}	5.3 / 4.5	T
I_p	12 / 10/ 07	MA
R_o	5.5	m
a	1.6	m
Elongation K	1.8	
Blanket thickness：	1.0	m

2.2 Estimations based on scaling laws

In order to carry out calculations, the following assumptions are made:

1) Same magnet technology as ITER's.

2) The normalized beta value is assumed to be $\beta_N \leq 2.5$.

3) H-mode factor H_h=1.0 (conventional H-mode).

4) The current drive efficiency is assumed to be

$$\gamma = I_{cd} * R * \langle n_e \rangle / P_{cd} = 0.2 * 10 ** 20 \ \mathrm{A/(m^2 W)}$$

I_{cd} is the driven current,

$\langle n_e \rangle$ the volume averaged electron density,

R the major radius,

P_{cd} the non-inductive current drive power.

5) Hydrogen plasma for energy confinement time and L-H transition power threshold.

6) The electron density is $\langle n_e \rangle = 0.8 n_{GW}$

Under above assumptions, some calculation results are given below.

2.2.1 $B_t = 5.3$ T, $I_p = 12.0$ MA

Major/minor radius	$R/a = 5.5/1.6$ m
Toroidal field	$B_t = 5.3$ T
Plasma current	$I_p = 12.0$ MA
Energy confinement time	$\tau_E = 2.47$ s (for $P_{heating} = 73$MW)
L-H transition power	$P_{L\text{-}H} = 99.5$ MW
Safety factor	$q_{95} = 2.89$
Normalized beta value	$\beta_N = 2.5$
Bootstrap current fraction	$f_{bs} = 0.298$
Total volt-seconds	$\Phi_{tot} = 71$ Wb ($\Phi_{inductive} = 58$ Wb)
Burning time	$T_{burn} = 545.8$ s
Electron density (vol. average)	$\langle n_e \rangle = 1.194$ ($10^{20}/m^3$)
Non-inductive current drive fraction	$f_{cd} = 0.5$
Non-inductive current drive power	$P_{cd} = 197$ MW

comments: $q_{95} = 2.89 < 3$, $P_{cd} = 197$ MW for 545.8 s burning time, with assumed $B_t = 5.3$ T, $I_p = 12.0$ MA, $\beta_N = 2.5$ and $f_{cd} = 0.5$.

2.2.2 B_t = 5.3 T, I_p=10.0 MA

Major/minor radius	R/a = 5.5/1.6 m
toroidal field	B_t = 5.3 T
Plasma current	I_p = 10.0 MA
Energy confinement time	τ_E = 1.94 s (for $P_{heating}$= 73MW)
L-H transition power	$P_{L\text{-}H}$ = 89 MW
Safety factor	q_{95} = 3.47
Normalized beta value	β_N = 2.5
Bootstrap current fraction	f_{bs} = 0.358
total volt-seconds	Φ_{tot} = 71 Wb ($\Phi_{inductive}$ = 48 Wb)
Burning time	T_{burn} =1609 s
Electron density (vol. average)	$\langle n_e \rangle$ = 0.995 ($10^{20}/m^3$)
Non-inductive current drive fraction	f_{cd} = 0.5
Non-inductive current drive power	P_{cd} = 136.8 MW

comments: P_{cd} = 136.8 MW for 1609 s burning time, with assumed B_t = 5.3 T, I_p = 10.0 MA, β_N = 2.5 and f_{cd} = 0.5.

2.2.3 $B_t = 4.5$ T, $I_p = 10.0$ MA

Major/minor radius	$R/a = 5.5/1.6$ m
toroidal field	$B_t = 4.5$ T
Plasma current	$I_p = 10$ MA
Energy confinement time	$\tau_E = 1.89$ s ($P_{heating} = 73$MW)
L-H transition power	$P_{L\text{-}H} = 78$ MW
Safety factor	$q_{95} = 2.946$
Normalized beta value	$\beta_N = 2.5$
Bootstrap current fraction	$f_{bs} = 0.30$
total volt-seconds	$\Phi_{tot} = 71$ Wb ($\Phi_{inductive} = 48$ Wb)
Burning time	$T_{burn} = 1165$ s
Electron density (vol. average)	$\langle n_e \rangle = 0.995$ ($10^{20}/m^3$)
Non-inductive current drive fraction	$f_{cd} = 0.5$
Non-inductive current drive power	$P_{cd} = 136.8$ MW

comments: $P_{cd} = 136.8$ MW for 1165 s burning time, with assumed $B_t = 4.5$T, $I_p = 10$MA, $\beta_N = 2.5$ and $f_{cd} = 0.5$.

2.2.4 B_t =4.5 T, I_p = 10.0 MA

Major/minor radius	$R/a = 5.5/1.6$ m
toroidal field	$B_t = 4.5$ T
Plasma current	$I_p = 10$ MA
Energy confinement time	$\tau_E = 1.89$ s ($P_{heating} = 73$MW)
L-H transition power	$P_{L\text{-}H} = 78$ MW
Safety factor	$q_{95} = 2.946$
Normalized beta value	$\beta_N = 2.5$
Bootstrap current fraction	$f_{bs} = 0.30$
total volt-seconds	$\Phi_{tot} = 71$ Wb ($\Phi_{inductive} = 48$ Wb)
Burning time	T_{burn} = infinity
Electron density (vol. average)	$\langle n_e \rangle = 0.995$ ($10^{20}/m^3$)
Non-inductive current drive fraction	$f_{cd} = 0.7$
Non-inductive current drive power	$P_{cd} = 191$ MW

comments: $P_{cd} = 191$ MW for steady operation, with assumed $B_t = 4.5$T, I_p =10MA, $\beta_N = 2.5$, and $f_{cd} = 0.7$.

2.2.5 B_t = 4.5 T, I_p = 7.0 MA

Major/minor radius	R/a = 5.5/1.6 m
toroidal field	$B_t = 4.5$ T
Plasma current	$I_p = 7.0$ MA
Energy confinement time	$\tau_E = 1.17$s ($P_{heating} = 73$MW)
L-H transition power	$P_{L\text{-}H} = 63$ MW
Safety factor	$q_{95} = 4.2$
Normalized beta value	$\beta_N = 2.5$
Bootstrap current fraction	$f_{bs} = 0.43$
total volt-seconds	$\Phi_{tot} = 71$Wb ($\Phi_{inductive} = 34$ Wb)
Burning time	T_{burn} = infinity
Electron density (vol. average)	$< n_e > = 0.696$ ($10^{20}/m^3$)
Non-inductive current drive fraction	$f_{cd} = 0.57$
Non-inductive current drive power	$P_{cd} = 76$ MW

comments: $P_{cd} = 76$ MW for steady operation, with assumed $B_t = 4.5$T, I_p =7.0 MA, $\beta_N = 2.5$ and $f_{cd} = 0.57$.

2.2.6 $B_t = 4.0$ T, $I_p = 7.0$ MA

Major/minor radius	$R/a = 5.5/1.6$ m	
toroidal field	$B_t = 4.0$ T	
Plasma current	$I_p = 7.0$ MA	
Energy confinement time	$\tau_E = 1.15$ s	($P_{heating} = 73$MW)
L-H transition power	$P_{L\text{-}H} = 57$ MW	
Safety factor	$q_{95} = 3.74$	
Normalized beta value	$\beta_N = 2.5$	
Bootstrap current fraction	$f_{bs} = 0.386$	
total volt-seconds	$\Phi_{tot} = 71$ Wb	($\Phi_{inductive} = 34$ Wb)
Burning time	T_{burn} = infinity	
Electron density (vol. average)	$\langle n_e \rangle = 0.696$	($10^{20}/m^3$)
Non-inductive current drive fraction	$f_{cd} = 0.62$	
Non-inductive current drive power	$P_{cd} = 83$ MW	

comments: $P_{cd} = 83$ MW for steady operation, with assumed $B_t = 4.0$T, $I_p = 7.0$ MA, $\beta_N = 2.5$ and $f_{cd} = 0.62$.

2.2.7 B_t = 3.5 T, I_p = 7.0 MA

Major/minor radius	$R/a = 5.5/1.6$ m
toroidal field	$B_t = 3.5$ T
Plasma current	$Ip = 7.0$ MA
Energy confinement time	$\tau_E = 1.1$s (${P_{heating}} = 73$MW)
L-H transition power	$P_{L\text{-}H} = 52$ MW
Safety factor	$q_{95} = 3.27$
Normalized beta value	$\beta_N = 2.5$
Bootstrap current fraction	$f_{bs} = 0.34$
total volt-seconds	$\Phi_{tot} = 71$Wb ($\Phi_{inductive} = 34$ Wb)
Burning time	T_{burn} = infinity
Electron density (vol. average)	$< n_e > = 0.696$ ($10^{20}/m^3$)
Non-inductive current drive fraction	$f_{cd} = 0.67$
Non-inductive current drive power	$P_{cd} = 90$ MW

comments: $P_{cd} = 90$ MW for steady operation, with assumed $B_t = 3.5$T, $I_p = 7.0$ MA, $\beta_N = 2.5$ and $f_{cd} = 0.67$.

2.3 Special challengers for CFETR

2.3.1 Steady state operation

- **Steady state operation is favorable for fusion power plants.**
- **However, 191 MW power is required for non-inductive current I_p=10MA (see 2.2.4).**
- **Assuming the "wall-plug" efficiency to be 0.33, the required input power for the current drive system will be 573MW.**

  Note: "wall-plug" efficiency is the ratio between the output and input power for the non-inductive current drive system.
- **The technology and reliability of the non-inductive current drive system should be significantly improved.**

- **Some issues such as the coupling and current drive efficiency in high density operation and possibly with some amount of impurities have to be further studied.**
- **Heating/Current drive system selection?**
- **Calculations and experiments are still required.**

2.3.2 Divertor heat load

- **With 100-200MW power input for current drive, the power load on the divertor plate will be significantly increased**
- **Steady operation further increases the technical requirements.**

2.3.3 Tritium self-sufficiency for the DT fuel cycle

- * The potential of achieving tritium self-sufficiency depends on many system physics and technology parameters.
- * Compared with DEMO with >1GW fusion power, 100MW fusion power for CFETR are much lower, and the required TBR could be much higher.

* Calculations are required to show the consistency：

To identify physics and technology options and parameters that have large effects on attaining a realistic “window” (ranges of plasma and technology parameters) for tritium self-sufficiency.

2.4 Suggestions

2.4.1 Long pulse rather than steady operation?

(single operation time > 2 hours)

- If long pulse operation, one has to increase the central solenoid size for larger volt-seconds.
- This choice is simple but increase the machine construction cost.
- However, there are advantages:
  - Lower operation cost.
  - Lower divertor heat load.
  - Higher operation reliability.

2.4.2 Steady operation only for Ip=7MW or lower rather than 10MA.

- For Ip=7MA, 76-90 MW non-inductive current drive power is still required for steady state operation (see 2.2.5 - 2.2.7).

2.4.3 Explore the hybrid (improved H-mode) or advanced mode.

- * Increase the bootstrap current fraction for reducing the required current drive power.
- * but this choice contradicts design principle: based on standard H-mode.
- * Studies on the Hybrid (improved H-mode) are still going on. Further studies are still required.
- * Maybe we should not exclude the hybrid (improved H-mode) or advanced mode.
- * High power current drive increases the possibility to obtain and sustain the Hybrid (improved H-mode) or advanced mode.

3. Summary

1. **Will the design be based on long pulse or steady operation?**
2. **Calculations are required for optimizing machine parameters.**
3. **Shall we have more than one option in this phase and make a choice later?**
4. **Special attention is required on the “parameter window” for tritium self-sufficiency.**

Thank you for your attention