H&CD in DEMO: some thoughts

M. Q. Tran, with contributions from colleagues from EUROfusion WP HCD, China, India, Japan, Korea
From yesterday

• Quite a lot of discussion on H&CD yesterday:
  ✓ NBI: the system you love to hate
  ✓ How many systems to be implemented? Not all of the existing one, please
  ✓ Consideration on TRL: Physics has a high TRL, technology (including H/CD systems) being lower
  ✓ Example of the discussion of H&CD functions by V. Chan, showing that we have the tools to design H&CD on a DEMO

• We were reminded about considerations given at the previous DEMO Workshop
Some preliminary considerations/plan of the talk

• We should discuss about H&CD based on the present views of DEMO → A review (non exhaustive) of DEMO proposals
• What should we know to design a H&CD system from physics? Going through the making of a DEMO plasma
• What would be important considerations for the design of HCD systems for DEMO?
Use of H&CD during a pulsed plasma (ITER diagram)
A few proposals as illustration

- Not to be considered as an exhaustive list, but to show the variety of parameters
- CFETR
- EU DEMO
- Indian DEM
- Korean DEMO

Variety of approach towards H&CD systems
Engineering design and large scale R&D will start soon
New Larger CFETR Reduces Heating and Current Drive Requirements, and Lower Divertor and Wall Power Loading

<table>
<thead>
<tr>
<th></th>
<th>Previous</th>
<th>New Phase I</th>
<th>New Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0, a$ (m)</td>
<td>5.7, 1.6</td>
<td>6.6, 1.8</td>
<td>6.6, 1.8</td>
</tr>
<tr>
<td>$P_{NBI}, P_{ECH}$ (MW)</td>
<td>68.5, 8.0</td>
<td>35.8, 20.0</td>
<td>33.9, 20.1</td>
</tr>
<tr>
<td>Fusion Gain $Q_{FUS}$</td>
<td>2.0</td>
<td>3.0</td>
<td>14.9</td>
</tr>
<tr>
<td>Fusion Power $P_{fus}$ (MW)</td>
<td>150</td>
<td>169</td>
<td>811</td>
</tr>
<tr>
<td>$B_T$, $I_p$ (MA)</td>
<td>5.0, 10.0</td>
<td>6.0, 7.6</td>
<td>6.0, 10.0</td>
</tr>
<tr>
<td>Bootstrap Fraction $f_{BS}$</td>
<td>43.3%</td>
<td>63.6%</td>
<td>84.4%</td>
</tr>
<tr>
<td>Normalized beta $\beta_N$</td>
<td>1.90</td>
<td>1.89</td>
<td>3.15</td>
</tr>
<tr>
<td>$H_{98Y2}$</td>
<td>1.0</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Neutron Wall Loading $\Gamma_{NW}$ (MW/m²)</td>
<td>0.22</td>
<td>0.19</td>
<td>0.92</td>
</tr>
<tr>
<td>Diverter Loading $P_{DIV}/R_0$ (MW/m)</td>
<td>15.7</td>
<td>10.4</td>
<td>25.8</td>
</tr>
</tbody>
</table>

**Fully non-inductive CFETR scenarios** have been developed with a self-consistent core-pedestal-equilibrium model.

**New larger CFETR** reduces heating and current drive requirements, lower divertor heat flux and neutron wall loading, **higher bootstrap current fraction** and $H_{98Y2}$ at similar $\beta_N$.

**Higher $\beta_N \sim 3.2$ Phase II configuration** requires a close conducting wall for $n = 1, 2$ ideal stability but for Phase I dont need the conducting wall.

by GA-CFETR team
Other important R&D for CFETR

- **Auxiliary Heating & CD:**
  - Off-axis NBI (0.8MeV) + ECRH (top, 190, 230GHz)
  - LHCD (HF, 4.6GHz) + ECRH (top, 230GHz)
- Advanced Superconducting Magnet
  - TF ($\text{Nb}_3\text{Sn}, 7.0\text{ T}$); CS (Bi 2212 CICC)
- Advanced Divertor (X-Divertor, >20MW/m²)
- Blanket (He gas, water cooled)
- T-Plant (99.9% T recovery)
- Materials (First wall, structure)
- RH
R&D for RF Sources

LHW:
EAST: 2.45GHz, 200kW, CW
   4.6 GHz, 0.3MW,CW
CFETR: 4.6 GHz, 0.3-0.5MW,CW
   7.5GHz, 0.5MW, CW

EC:
EAST: 140GHz, 1MW, CW
   170GHz, 1MW, CW
CFETR: 170GHz, 1MW, CW
   230GHz, 1MW, CW

Gyrotron: Start commissioning @ 2016.12

5x8 hours testing for Klystrons
EU DEMO (1)

- **Approach:** until 2020, DEMO studies in the frame of EUROfusion are in the pre-conceptual phase. This means that various set of parameters (“Baselines”) could be proposed, and eventually down-scoped.
- **Next period (2021-2027) Conceptual design phase**
- **Two versions of DEMO is under consideration:**
  1. A pulsed DEMO (DEMO1) of 2 hours plasma duration
  2. A steady state plasma DEMO (DEMO2)

Work from the design point of view is focused on the EU DEMO 1 2015 (pulsed plasma), but modelling is also pursued for DEMO2
## EU DEMO: Parameters

<table>
<thead>
<tr>
<th></th>
<th>DEMO 1</th>
<th>DEMO 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius</td>
<td>9.1 m</td>
<td>7.5 m</td>
</tr>
<tr>
<td>Aspect ratio AR</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Toroidal magnetic field (B_T)</td>
<td>5.7 T</td>
<td>5.6 T</td>
</tr>
<tr>
<td>Number of toroidal field (TF)coils</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Central electron density</td>
<td>(1.01 \times 10^{20} \text{ m}^{-3})</td>
<td>(1.22 \times 10^{20} \text{ m}^{-3})</td>
</tr>
<tr>
<td>Central electron temperature</td>
<td>27.4 keV</td>
<td>34.6 keV</td>
</tr>
<tr>
<td>(I_P / I_{BS} / I_{CD})</td>
<td>19.6 MA / 6.9 MA / 1.9 MA</td>
<td>21.6 MA / 13.2 MA / 8.4 MA</td>
</tr>
<tr>
<td>External power during flat top (P_{FT})</td>
<td>50 MW</td>
<td>133 MW</td>
</tr>
<tr>
<td>L-H threshold power (ITPA scaling)</td>
<td>133 MW</td>
<td>128 MW</td>
</tr>
<tr>
<td>Fusion power</td>
<td>2037 MW(_{th})</td>
<td>3255 MW(_{th})</td>
</tr>
<tr>
<td>Net electricity</td>
<td>500 MW(_{e})</td>
<td>953 MW(_{e})</td>
</tr>
<tr>
<td>Assumed total recirculating power corresponding to (P_{FT} / \text{Wall plug efficiency})</td>
<td>125 MW(_{e}) / 45%</td>
<td>266 MW(_{e}) / 50%</td>
</tr>
</tbody>
</table>

R. Wenninger et al. Nucl. Fusion, 57 (2017) , 016011
View of the EU Demo 1-2015

NB beam tangential radius options under study:
34° - 8.14m (see Fig. 1)
30° - 7.09m (not shown)

Central Solenoid
Cryostat
Equatorial Port
Vacuum Vessel
Lower Port

8139.89mm

NB Injector
Toroidal field coils
Poloidal field coils
Breeding Blanket
Divertor
EU DEMO Heating and Current Drive strategy

• Since DEMO1 is still in a pre-conceptual, no selection of the heating mix(es) is performed
• Three heating systems are under study: EC, IC and NBI. The assumed power per system is 50 MW, albeit the total installed power is not fixed yet
• Physics studies are only performed to assist the design and integration of the heating and current drive systems, based on existing codes
• Selection of the heating mix(es) to be performed by the 2024 based on a global analysis of each system
– Production of more than 1 GW of net electricity
– with 30 % availability
– Less aggressive (any improvement will be a boost)
– Try to improve the availability
– Performance of reactor and its optimization

<table>
<thead>
<tr>
<th>Plasma parameters</th>
<th>Indian DEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_0</td>
<td>7.7</td>
</tr>
<tr>
<td>a</td>
<td>2.6</td>
</tr>
<tr>
<td>A</td>
<td>2.96</td>
</tr>
<tr>
<td>B_{t} (T)</td>
<td>6.0</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>17.8</td>
</tr>
<tr>
<td>f_{bs} (%)</td>
<td>50</td>
</tr>
<tr>
<td>P_{loss} (MW)</td>
<td>720</td>
</tr>
<tr>
<td>P_{fusion} (MW)</td>
<td>3300</td>
</tr>
<tr>
<td>P_{aux} (MW)</td>
<td>110</td>
</tr>
<tr>
<td>Q</td>
<td>30</td>
</tr>
<tr>
<td>n/n_{GW}</td>
<td>0.93</td>
</tr>
<tr>
<td>&lt;T&gt; keV</td>
<td>21.5</td>
</tr>
<tr>
<td>\beta_N</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Choices for Indian DEMO

- TF with Nb$_3$Sn
- Plasma facing components with W and W-alloys
- Blanket concept: LLCB with Pb-Li and LiTi$_2$O$_3$
- Structural: IN-RAFMS
- VV: SS316LN
- Shielding: borated steel
- Allowable dpa on structural material < 50 (?)
- Double null or Single null
- Thermal efficiency with 30 %

Design will have many variants with mid-term, long-term projections. Few choices on dream materials or concepts have to be made and pursued
Heating and CD requirement from Indian DEMO

- Total auxiliary power needed is about 110 MW
  - NBI is about 80 MW
  - ICRH is about 40 MW
  - LHCD and ECRH will be 20 MW each

- NBI
  - RF generator for ion source
  - 1 MV with power supplies
  - Required ion source technologies

- RF
  - 170 GHz ECRH source
  - 5 GHz LHCD source
  - Development of other RF components like PAM, transmission lines, etc.
Japan DEMO studies


• More recently revision of the parameters has been conducted (See for example Y. Sakamoto et al. IAEA FEC 2014 Paper FIP/3-4Rb) + Poster yesterday
# Parameters

<table>
<thead>
<tr>
<th></th>
<th>Pulse 2 hours</th>
<th>Steady state</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Major radius</strong></td>
<td>8.5 m</td>
<td>8.5</td>
</tr>
<tr>
<td><strong>Aspect ratio AR</strong></td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>(I_p/% I_{BS}/ % I_{CD})</strong></td>
<td>12.3 MA / 46%/ 32%</td>
<td>12.3 MA / 61% / 39%</td>
</tr>
<tr>
<td><strong>B_T</strong></td>
<td>5.94</td>
<td>5.94</td>
</tr>
<tr>
<td><strong>P_{add}</strong></td>
<td>83.5MW</td>
<td>83.7MW</td>
</tr>
<tr>
<td><strong>(P_{fusion} / P_{elec net})</strong></td>
<td>1085</td>
<td>1462</td>
</tr>
<tr>
<td><strong>(T_e , \text{keV} / n_e(10^{20} \text{ m}^{-3}))</strong></td>
<td>12.9 / 6.5</td>
<td>16 / 6.6</td>
</tr>
</tbody>
</table>
Possible Heating and Current Drive systems

• 2 heating systems:
  1. EC at 170-220GHz
  2. Negative ion beam source (1-2 MeV)
K-DEMO Parameters

Main Parameters
- \( R = 6.8 \) m
- \( a = 2.1 \) m
- \( B\)-center = 7.0~7.4 T
- \( B\)-peak = 16 T
- \( \kappa_x = 2.0 \)
- \( \delta_x = 0.625 \)
- Plasma Current > 12 MA
- \( T_e > 20 \) keV
- \( f_{bs} \sim 0.7 \)

Other Feature
- Double Null Configuration
- Vertical Maintenance
- Total H&CD Power = 80~120 MW
- \( P\)-fusion = 2200~3000 MW\(_{th}\)
- Net electricity > 400 MWe at Stage II
- Number of Coils : 16 TF, 8 CS, 12 PF
Mission & Strategy

**Mission:** To demonstrate the sustainable generation of electricity from fusion power

**Strategy:**
- **Natural Path:** KSTAR → ITER → DEMO (tokamak)
- To mitigate risks in the course of DEMO development → Two-Phased Operation strategy
- **The operation Stage I** → not considered as a final DEMO
  - At least one port will be designated for the CTF including blanket test facility.
  - To demonstrate the net electricity generation \( Q_{\text{eng}} > 1 \) and the self-sufficient Tritium cycle \( \text{TBR} > 1.05 \).
- **The operation Stage II**
  - Major upgrade of In-Vessel-Components
  - To demonstrate the net electricity generation > 400 MWe.
  - To demonstrate the competitiveness in COE.

• *CTF: Component Test Facility, COE: Cost of Electricity*
Key Idea of K-DEMO Design

■ Current Drive and Magnetic Field
  • Considering the size, a **steady state Tokamak** is selected as a K-DEMO.
  • Because of high neutron irradiation on ion sources, NBI is not practical for the main off-axis current drive of K-DEMO. → However, NBI could be used in Stage I.
  • Because of high density of K-DEMO plasma, high frequency ECCD systems (> 240 GHz) are required in order to minimize the deflection of wave.
  • In order to match with the high frequency ECCD, a high toroidal magnetic field Tokamak is required and the magnetic field at plasma center requires > 6.5 T.
  • Also, \( I_{p,\text{limit}} \propto B \), \( n_{e,\text{limit}} \propto B \), and Power \( \propto R^3B^4 \) \[\text{[Reactor Cost} \propto R^3B^2\]\]

■ Choice of Coolant and Blanket System
  • **Pressurized water** (superheated water) is considered as a main coolant of K-DEMO considering BOP(Balance of Plant).
  • Supercritical CO\(_2\) is also considered as a future coolant.
  • Helium is also a candidate as a coolant of K-DEMO, but there are concerns about its low heat capacity, a required high pumping power and BOP.
  • Both of **ceramic and liquid metal blanket system** is considered at this stage. But even in the liquid blanket system, the liquid metal will not be used as a main coolant and a water cooling system will be installed inside the liquid metal blanket.
Study on Operation Scenario and H&CD Analyses

- Time-dependent current and heating power (TSC/TRANSP) – with assumed constant $\eta_{CD}$

![Graph showing powers over time with total input $P_{total} \approx 120$ MW]

![Graph showing parallel current density vs. $\rho (r/a)$]

![Graph showing Ip vs. time with total input at different locations]

![Graph showing power density vs. $\rho (r/a)$]
Study on Operation Scenario and H&CD Analyses

- Scanning on Heating parameters to find optimum conditions with the dedicated H&CD codes
  - LHCD (5 GHz, LSC)
  - NBCD (~1 MeV, NUBEAM)
  - ECCD (225~300 GHz, Horizontal-/Elevated-launch, GENRAY)
  - FWCD (< 100 MHz, TORIC)

- Helicon wave – study on-going
Are there gaps?

- The physics basis of heating and current drive, necessary to design heating systems to be implemented on DEMO, exists (See for example F. Wagner et al. Plasma Phys. Control. Fusion 52, (2010) 124044)
- Many DEMO concepts have selected/proposed their main heating
- Physics modelling codes are routinely used to design and perform the integration of antenna
- In this sense, I believe that the Community have the necessary tools to proceed forward to an integrated design
Are there gaps? ....But

- The scenarios modelling is of importance. System code is used to predict the power required for a given desired fusion power (Cf. Vincent’s talk yesterday)

- Another example: EU DEMO1

  Power $P_{FT}$ during burn phase $50 \text{ MW}$ to get $2 \text{ Gw}_{\text{fusion}}$ from system code

  ✓ Example of requirement during $I_p$ ramp-up (and H mode access) and ramp down

  ✓ IC novel concept

  ✓ Control of event during burn
Power during ramp up and H mode access

- Simulations performed by P. Vincenzi et al. (SOFT 2016, submitted to Fus. Eng. Design) using METIS code. $I_p$ ramp rate is about 100 kA/s. A total of about 150 MW of installed power is recommended to have robust H mode transition

From P. Vincenzi et al. SOFT 2016
A technical remark on the installed power in summary

• The ITPA L-H threshold scaling has a wide range for 95% confidence level. It is important to be able to reduce this range so that the installed power can be reduced.

• In the present scenarios, the supplementary installed power (= Total installed power – \( P_{FT} \)) is used only in short phases or only during the event during the burn phases. This has important impact on the balance of plant.

• Of importance is to narrow the uncertainties in the L-H threshold

• The price tag: a (too) large installed power, which impacts the requirements on the Balance of Plant and which is needed during 200 s!
High ramp down rate (100 kA/s: High loss to be compensated by external power)

From. P. Vincenzi et al., SOFT 2016
IC antenna (1)

- “In port antenna”

JET antenna
IC antenna (2)

- Distributed antenna (EUROfusion WP HCD; IPP; ERM)

Low power $\rightarrow$ Reliable
Very selective in $k_{\parallel}$ $\rightarrow$ good for coupling
Toroidally symmetric $\rightarrow$ avoids impurity production

Development: Coupling of the RF
Optimization of the integration in the Breeding Blanket
Power for control during the burn phase

- In the example of the EU DEMO1, the power during the flat-top (or burn) phase is set at 50 MW yielding a total fusion power of the $2 \, \text{GW}_{\text{fusion}}$
- But the installed power should be sufficient to control event during this phase, taking into account the full plasma scenario.
- Studies are on going
- But again the results will affect the total installed power with strong requirements on availability and reliability and on the Balance of Plant
On the transition to a power plant

- In some operational phase, DEMO will connected to the grid, rendering the availability and reliability of utmost importance.
- Database on the availability and reliability of heating systems is scarce, if not existent.
- Operation of H&CD system in present experiments (including ITER) may not be representative of how DEMO will operate its H&CD system
- Can we establish a methodology for a credible RAMI, under these circumstances?
Future Challenges

Outstanding Technical Issues with Gaps beyond ITER (IAEA FEC 2016 Summary talk)

**Remote Maintenance**
- RH schemes affects plant design and layout
- Significant differences with ITER approach
- Should start from very beginning of DEMO design
- Large size Hot Cell required
- Service Joining Technology R&D is urgently needed.

**Safety**
- Demonstrate that these characteristics lead to excellent safety and environmental performance
- Radioactive inventory
- Waste management

For requirement of licensing, safety considerations must be central to design activities from the beginning

**Structural and HHF Materials**
- Progressive blanket operation strategy (1\textsuperscript{st} blanket 20 dpa; 2\textsuperscript{nd} blanket 50 dpa)
- Embrittlement of RAFM steels and Cu-alloys at low temp. and loss of strength at ~ high temp.
- Need of structural design criteria and design codes
- Selection by Neutron Source (fission, fusion)
- Strong coupling between simulation and

**RAMI**
- Most novel part of DEMO
- Very low for existing facility and too far towards DEMO
- Need code and standard
- ITER will play a key role
- DEMO design activities from the beginning
On the transition to a power plant (2)

- Wall plug efficiency will become an important factor due to the requirement of net electricity production
- As discussed yesterday, may be the next point to study is the inclusion of Technical Uncertainties in System code
- Emphasis should be given on enhancing the H&CD wall plug efficiency (but with the overarching requirement on Reliability and Availability)
On the transition to a power plant (3)

• A design of H&CD systems for DEMO must be performed as part of an integrated design

• A DEMO is a complex machine with many constraints (Remote maintenance, Safety, Tritium Breeding Ratio, Impact on the design of the Breeding Blanket, Dose to workers and to public, Impact on balance of plant, Material compatibility…), while may be the final parameters are not fixed (Example of EU DEMO).

• → Learning by doing but with a “Project” Oriented Vision

• A caveat: DEMO parameters should have a certain stability to allow meaningful work to be performed
Conclusion (1)

- Scenarios modelling, using the existing codes, are most important for the definition of H&CD systems.
- A few points like the L-H transition power, the power to control events during the burn, must be clarified since they have impact on the installed power.
- Design of H&CD systems must be performed in the frame of the integrated design of DEMO.
- The specialised talks will give information on many of the points I raised.
Conclusion (2)

- We should try to reduce H&CD systems on DEMO
- Moving to DEMO needs a shift in mind set:

“Do not ask how you will fix a faulty system, but ask what DEMO can do without it” (to paraphrase President Kennedy)