Chinese Fusion Energy Strategy

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Outline

- Introduction
- Progresses and activities of CFETR
- Future Plan
- Summary
Top Priorities of CN-MCF

- Make ITER successful
- Promoting Domestic MCF
- Build CFETR when it is ready
CN MCF Roadmap

Phase I: Q=10, 400 s, 500 MW, Hybrid burning plasma

Phase II: DEMO validation, Q>10, CW, 1 GW, >50 dpa

I: Q=1-5, steady state, TBR>1, >200MW, <10 dpa

II: DEMO validation, Q>10, CW, 1 GW, >50 dpa

EAST: Advance PFC, steady-state advanced operation

HL-2M: Advanced divertor, high power H&CD, diagnostics

J-TEXT: Disruption mitigation, basic plasma

2015 2020 2025 2030 2035 2040 2045 2050 2055 2060
Tokamak Experiments

Outcome:
500 SCI papers
5 PRL
50 NF
40 Invite talks
200 PhD
300 Master

EAST
30MW H&CD
80 Diagnostics
W-divertor
10MW/m2
Long pulse
AD SSO

HL-2A 15MW, 50 diagnostics
HL-2M 25MW, 60 diagnostics
J-TEXT, 20 diagnostics
CFETR mission

1. \( P = 200-1500 \text{MW} \)
2. \( Q = 1-10 \), SSO, hours
3. \( Q = 20-30 \) hours-SSO
4. High energetic \( \alpha \) heating

5. Hybrid (OH+BS+CD)
6. SSO (Ext H&CD + Higher \( f_b \))
7. PSI on the first wall

9. T-breeding by blanket
10. T-plant: extract & reprocessing
11. Materials&components
12. Reliable and quick RH
13. Licensing&safety

Obtained Burning Plasma for fusion power

Steady-state operation for fusion energy

Breeding Tritium for T self-sustained
Strategy of CFETR-centralized team
The key points changed:

- **Larger size:**
  \[ R = 7-7.5\text{m}(5.7), \]
  \[ a = 2-2.5\text{m}(1.6) \]

- **Higher \( B_t \):** 5.0-7.0 T (5)

- **Advanced CS magnet:** \( \geq 480 \text{ VS} \)

- **Lower Ip:** 6-12MA

- **16 TF coils** for easy RH, H&CD

- **More reliable Plasma targets**

- **Higher confidence for STE goals**
New version of design (7m, 6.5-7T)

<table>
<thead>
<tr>
<th>CFETR pulse mode</th>
<th>Case A.1 Hybrid</th>
<th>Case B.1 L-mode</th>
<th>Case A.2 Hybrid</th>
<th>Case B.2 L-mode</th>
<th>Case A.3 Hybrid</th>
<th>Case B.3 L-mode</th>
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<td>417</td>
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<td>Ptransport across separatrix</td>
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<td>0.62</td>
<td>0.87</td>
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<td>0.84</td>
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</table>
## New version of design (7m, 6.5-7T)

### H/He
- 1-2 years

### DD
- 1-2 years

### DT < 100MW
- 1 year

### DT
- 200MW, 5 years

### SSO, T fuel cycle
- SSO, TBR > 1, 3 years

### DEMO validation
- DT 1GW, 5 years

### Advance Scenario
- > 1.5GW, Q ~ 30
- 2-3 years

### Total
- 15-20 years

<table>
<thead>
<tr>
<th>CFETR</th>
<th>Case A.1 200MSS</th>
<th>Case A.2 500MSS</th>
<th>Case A.3 1GWSS</th>
<th>Case A.4 1.5GWSS</th>
<th>Case A.5 1GW OH</th>
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<td>Stored Energy</td>
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<td>6.15</td>
<td>7.20</td>
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</table>
CFETR Physics design (SSO)

- 0D system code + 1.5D integrated modeling (OMFIT, EFIT, ONETWO, GATO, TGYRO/TGLF, NEO, ELITE)

- Off-aix NBI + ECCD, EC+LHCD are major H&CD tools together with bootstrap current for SSO

- Using 800 kV NBI (1.1MA/10MW) +190GHz ECCD for early phase operation.
16 TF Coil design (High Performance Nb$_3$Sn)

Parameters for TF magnet

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Coil 1</th>
<th>Coil 2</th>
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</thead>
<tbody>
<tr>
<td>strand</td>
<td>high $J_c$ (2700A/mm$^2$) Nb$_3$Sn</td>
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<tr>
<td>No. of SC strand</td>
<td>1350</td>
<td>270</td>
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<tr>
<td>Turns</td>
<td>66</td>
<td>154</td>
</tr>
<tr>
<td>Operating current for $B_t$=7.0T</td>
<td>58kA</td>
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<tr>
<td>$B_{\text{max}}$ in coil</td>
<td>15.5T</td>
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<tr>
<td>Max Force</td>
<td>760MPa</td>
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CS Model Coil – Nb3Sn (baseline)

### Coil Parameters

<table>
<thead>
<tr>
<th>Design Parameters of CFETR CS Model Coil</th>
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<tbody>
<tr>
<td>Max. field</td>
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<tr>
<td>Max. field rate</td>
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<tr>
<td>Inner radius</td>
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<tr>
<td>Coil structure</td>
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<tr>
<td>Inner: Nb3Sn coil</td>
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<tr>
<td>Conductor type</td>
</tr>
</tbody>
</table>

Start experiments @ 2017.12 in new ASIPP site (Huainan)
Bi2212 - High temperature Superconducting Central solenoid

Max. 240 V/s
Max. 20 T

Conservative: enhanced Nb₃Sn: 360VS 4-6h
Ideal: 2212 CICC, 2x480VS, ~8h (for Ip=13MA)

Batch production for 200-m long Φ1.0mm wires
4.2K, 14T: \(J_{\text{ce}} > 750\text{A/mm}^2\), \(\text{ITER} \sim 320\text{A/mm}^2\)
4.2K, 20T: \(J_{\text{ce}} > 660\text{A/mm}^2\), \(\text{ITER} \sim 200\text{A/mm}^2\)

high pressure sintering process is on the way, \(J_{\text{c}}-B\) property may be increased for 3 times.

Bi2212-High temperature Superconducting Central solenoid
CS coils include eight Bi2212 coils. Each coil consists of 14 double pancake
Water cooled ceramic breeder blanket design

Material section
- Mixed breeder of Li$_2$TiO$_3$ and Be$_{12}$Ti
- A bit of Be to improve neutrons multiplying.
- RAFM steel as structural material.
- Tungsten as armor material of the FW

Main features
- Coolant: 15.5MPa, 285 °C inlet/325 °C outlet
- The cooling plates and the breeder zone parallel to the FW
- The compact coolant enlarges the breeder zone.
- Purge gas is directed in the toroidal direction to reduce its pressure drop.

For Phase-I
- 4 (Rad.)×4 (Tor.) mixed breeder zones and 2 (Rad.)×4 (Tor.) thin Be layers
- TBR: 1.21

For Phase-II
- 8 (Rad.)×4 (Tor.) mixed breeder zones and 2 (Rad.)×4 (Tor.) thin Be layers
- TBR: 1.1

Shielding capability for TFC

<table>
<thead>
<tr>
<th>Item</th>
<th>Limits</th>
<th>Value</th>
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<tbody>
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<td>Fast neutron (&gt;0.1MeV) fluence in TFC conductor (n/cm$^2$)</td>
<td>$1 \times 10^{19}$</td>
<td>$3.67 \times 10^{16}$</td>
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<td>Fast neutron (&gt;0.1MeV) fluence in TFC insulator (n/cm$^2$)</td>
<td>$5 \times 10^{17}$</td>
<td>$1.10 \times 10^{17}$</td>
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<td>Nuclear heating rate in TFC case (W/cm$^3$)</td>
<td>$2 \times 10^{-3}$</td>
<td>$2.19 \times 10^{-5}$</td>
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<tr>
<td>Nuclear heating rate in TFC conductor (W/cm$^3$)</td>
<td>$1 \times 10^{-3}$</td>
<td>$1.88 \times 10^{-5}$</td>
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**Helium cooled ceramic breeder blanket design**

### Material section
- \( \text{Li}_4\text{SiO}_4 \) as tritium breeder
- Be as neutron multiplier.
- RAFM steel as structural material.
- Tungsten as armor material of the FW

### Main features
- Modularized breeding unit
- Multi-layer back plates manifold

### Coolant
- 8 MPa, 300 °C inlet/500 °C outlet

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**For Phase-I**
- 5 (Tor.) \( \times \) 2 (Pol.) breeding unit, each has one U-shape breeder unit.

**TBR:** 1.213

**Typical module structure**

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**For Phase-II**
- 6 (Tor.) \( \times \) 5 (Pol.) breeding unit, each has two U-shape breeder unit.

**TBR:** 1.15

**Typical module structure**

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**Stress analysis**

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**Modularized breeding unit**

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**Temp. distribution**

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New Divertor validation

Physics: field expansion + radiation; Reduce the heat detail simulations (5y) + experimental validation (5-8y)

Engineering: design & manufacture of key components

W mono-block: >20MW/m²
W-Cu mono-block: >20MW/m² (5-10y)

Inner+external coils optimization is underway up 15MA (12MA)

H₉₈>1.1, nₑ/nₑ_W₉₈=1.1-1.3, Vₚ=0, 1/15 heat load
R&D for Divertor Target

Monoblock W/Cu
5000 cycles at 10MW/m²
300 cycles at 20MW/m².

Efforts for 30MW/m²

3D printing full W block: Tw=1700C

Flat tile W/Cu
5000 cycles at 10MW/m²
1000 cycles at 20MW/m²

Flat tile W/ODS-Cu
Tw = 1650C
Tcu = 520C
Tritium cycling systems (T-plant)

- 3 main loops for tritium recovery:
  - Inner cycling:
    - Tritium recovery, isotopic separation from plasma exhaust gases and re-fueling to torus.
  - Outer cycling:
    - Tritium extraction and measurement from in the full breeding blanket.
  - Tritium confinement and effluent detritiation.
- Main parameters for tritium process flow (4500s of time span for cycling):
  - Inner cycling: \(~357\text{g T/shot}, 2\text{m}^3 (\text{D}_2, \text{T}_2)/\text{h}\) for TEP and SDS, \(>4\text{m}^3/\text{h}\) for ISS.
  - Outer cycling: tritium extraction every two weeks to get more than 200g of pure tritium from the breeders.
  - Tritium confinement: 3g/a of enviromental tritium release at current stage, to be minimized as 0.6 g/a for the future.
- Key technologies development for each sub-system are in progress.

![Simple block diagram of CFETR tritium plant](image)
In-Pile Tritium Release and Extraction Test

Maximum load 500 g
Tritium production 1 Ci/day
Online refueling, irradiation
Irradiation temperature 300-750 °C
Neutron flux ~$5 \times 10^{13}$ n cm$^{-2}$s$^{-1}$

Maximum load 400 g
Tritium production 1 Ci/day
Online thermal conductivity test
Irradiation temperature 400～850 °C
Neutron flux ~$5 \times 10^{13}$ n cm$^{-2}$s$^{-1}$

China Mianyang Research Reactor

China Advanced Research Reactor
R&D on VV 1/8 mock-up

NG-TIG system

Test bench for installation, replacement of VV components by RH

Overview of CFETR VV Design

Welding samples

Laser Tracker Measurement on VV Sector

R&D of Narrow Gap TIG Welding on VV

Assembly of VV Poloidal Sectors
RH—Starts from design
## Roadmap of materials

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<th>2020</th>
<th>2030s</th>
<th>2040</th>
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<td><strong>FW: W, W alloy</strong></td>
<td>3-5dpa</td>
<td>10dpa, CFETR</td>
<td>20dpa, CFETR</td>
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<td><strong>Advanced W</strong></td>
<td>1E25-1E28 PSI</td>
<td>CFETR</td>
<td>CFETR</td>
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<td><strong>Divertor</strong></td>
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<td><strong>ODS-Cu, Cu alloy</strong></td>
<td>10dpa</td>
<td>50dpa, CFETR</td>
<td>100dpa, CFETR</td>
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<td>fix, CFETR</td>
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<td>500C, 1000</td>
<td>500C, 1E4, CFETR</td>
<td>500C, 1E5, CFETR</td>
</tr>
</tbody>
</table>
Materials Research Activities

(Simulation, manufacture, validation)

- **Low Activation Martesitic steel**
  - Nominal compositions: 9Cr1.5W0.2V0.15Ta0.45Mn0.1C
  - 5 ton smelting with good control of main compositions

- **Irradiation properties and TBM Fabrication**
  - High-dose neutron irradiation experiments
    - (Spallation source ~20dpa)
    - (High Fluence Engineering Test Reactor ~2dpa)
  - Fabrication of test blanket module (TBM)
    - (1/3 scale P91 TBM, 1/3 scale CLAM first wall)

- **Plasma-facing materials: W**

  **W material study scope:** W alloy; W coating; W/Cu component

  - **Conventional Powder Metallurgy Samples:** High Purity W, W-TiC
    - High heat-flux test facility
  - **SPS Samples:** Pure W, W-TiC, W-La2O3
  - **Deposition rate:** 0.2-1mm/h
  - **(Chemical vapor deposition) CVD-W**
    - W/Cu
    - W/OFHC-Cu
    - W/FGM-W/Cu
    - W/RAFM Steel
    - W/graphite

  **Materials Research Activities**
  - (Simulation, manufacture, validation)
  - **HIP(0.8x1.8m)**
  - **400kW EM facility**
  - **15kW laser welding (0.05mm)**
**Material testing neutron sources**

<table>
<thead>
<tr>
<th>The Materials Irradiation Facility in China (CMIF)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target</strong></td>
</tr>
<tr>
<td></td>
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<td></td>
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<tr>
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<tr>
<td><strong>Beam</strong></td>
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<tr>
<td><strong>Cost</strong></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>energy (MeV)</th>
<th>20</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux (D+Be) Y (n·cm⁻²·mA⁻¹·s⁻¹)</td>
<td>3.6*10¹³ *5 mA</td>
<td>2*10¹⁴ *10 mA</td>
</tr>
<tr>
<td>Flux (D+Be) Y (n·cm⁻²·mA⁻¹·s⁻¹)</td>
<td>9.81*10¹⁴ *20mA</td>
<td>2*10¹⁵ *30 mA</td>
</tr>
</tbody>
</table>

**BISOL Project**

- Hefei DT 14MeV: 1-5X10¹² **now**
- CMIF 6-20MeV: 2X10¹⁴-2X10¹⁵ **2020**
- BISOL 5-20MeV: 1-2X10¹⁵ **2025**
Experiments validation (EAST + DIII-D)

Bottom Divertor: CFETR-like, 20MW/m², AD configuration

4MW CW 170GHz EC, new ICRF, HFLHCD(7.5GHz)

1. Q=1,100MW, L-mode, hybrid or Steady state
2. Q=3, 200MW, H (betaN =1.9, H=1.2, fbs50%), hybrid or SSO
3. Q=10,500MW, H (betaN =3, H=1.2, fbs60%), hybrid or SSO
4. Q=20, 1500MW, H (betaN =3, H=1.5, fbs80%), hybrid or SSO
CFETR Detail Engineering design starts (30M$)

1. Physics design (14 tasks)
2. Nuclear design (16 tasks)
3. Tokamak detail engineering design (64 tasks)
4. Aux. Detail functional design (18 tasks)
5. Database IDM (6 tasks)

Fully Open to international cooperators

T-Plant + Plasma exhaust + breeding Blanket
**CFETR 5 years Plan--Large scale R&D**

**Blanket:**

small size mockup (14MeV),

thermal hydraulic Testing Full size, water & He gas configurations

**Magnets:**

full size CICC Nb$_3$Sn (TF), Nb$_3$Al (PF), Bi 2212 Conductor (CS)

CS mockup coil, 1/6 Nb$_3$Sn, 1:1 prototype Nb$_3$Sn TF, small 2212 CS

**Gyrotron:**

10s 1MW, 140GHz, 170GHz,

design 230GHz
NNBI: -200keV, 3600s,

ECRH: full size 4MW,

ICRF: 2MW, full size

LHCD: 4.6GHz, 2MW, High field PAM

RH: Vertical + MPD

Assembling testing facility: installation and RH

Larger SC testing facility (CICC conductor, CS, prototype TF)

Experimental verification(8): EAST

SS L mode, SS H-mode, Hybrid long pulse... with diagnosis, control, divertor, up to 1000s 10keV
Education—Training next generation tenants

10 scientists + 10 engineers/year, 0.5M$/person 4 years

• Encourage to join EAST, HL-2A experiments

• Encourage to join Th&Simulation

• Encourage to join CFETR

• Basic plasma science

• Fusion engineering and technology

More than 30 top universities
Education—Training next generation tenants

- 清华SUNIST
- 等离子体所HPPX
- 哈工大FLARE
- 大学Helimak
- 等离子体所HT-7
- 中国科大KTX
- 中国科大LMP
- 工物院氚渗透装置
- 北航STEP
- 浙大直线等离子体装置
- 兰州化物所LEPS
- 中国科大KMAX
International cooperation

- More than 30 years cooperation with USA
  7 US-CN workshop, T&sim., Exp., Engineering, CFETR
- 20 years cooperation with EU
  Joint workshop, exp., Engineering, joint lab.
- 20 years cooperation with Japan
  CUP(10+5 years), A3, CN-JP-KO DAs, >1000 papers
- 10 years cooperation with KO
  A3, CN-KO DAs, , CN-JP-KO Das
- Good cooperation with RF, IN
Summary

- CN-MCF development has made significant progresses during the past decade.
- EAST will play a key role for advanced steady-state operation during next decade.
- CN makes our best efforts for ITER success.
- CFTER engineering design starts and large scale R&D will start before the end of this years.
- It is hoped that the proposal for CFETR construction can be approved by government within next 5 years.
Thanks!