EXL Fusion Power Technology R&D – An Introduction

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Fusion Energy: Achievements and Opportunities 2020
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Plasma Fusion Energy — An Ideal Achievable Power

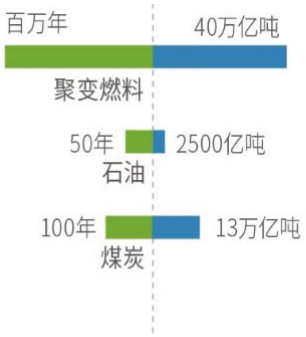
In a plasma with over tens of millions of degrees in temperature, ions of two lighter nuclei can fuse into a heavier nucleus and release energy.

$D+T \Rightarrow He + n + 17.6\ MeV$
$D+D \Rightarrow He + n + 3.3\ MeV$
$p+^{11}B \Rightarrow 3*He + 8.7\ MeV$

Plasma fusion temperature ~ 0.2B °C
~ 1B °C
~ 2B °C

Abundant Fuel

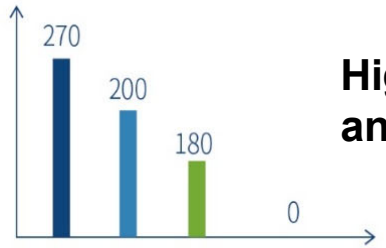
Extract from water or certain rocks



Low Fuel Consumption

City of a million residence

Friendly to Environment



Relative carbon release

Higher Safety and Reliability

Advantages over fission

Magnetic Confinement Fusion Milestones and Plans — Increasing Contributions from Spherical Tokamaks (ST)

1919 Fusion reaction discovered

1934 D-D fusion realized

1952 First H-bomb detonated

1957 In toroidal pinch ZETA ions reached 5 million °C

1968 In tokamak T-3 ions reached 5.8 million °C; fusion power *Q* (D-D) reached one billionth

1980 In large magnetic mirror 2X and Baseball II, ions reached 10 million °C

1991 In JET tokamak, ions reached 200 million °C; *Q* (D-T) reached 0.2

1993 In TFTR, ions reached 500 million °C; *Q* (D-T) 0.28

1997 START observed 40% β_T, showing increased plasma stability in ST

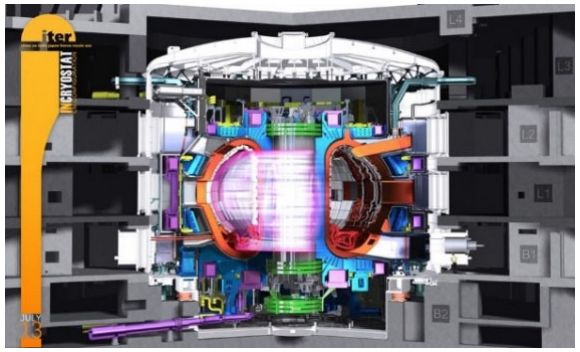
2003 In JET Q reached 0.65 and ions 100 million °C, releasing 16.1 MW D-T power

2006 In JT-60U ions reached 300 million °C; D-T equivalent Q 1.3

2018 In EAST high-confinement plasma sustained for 102 s

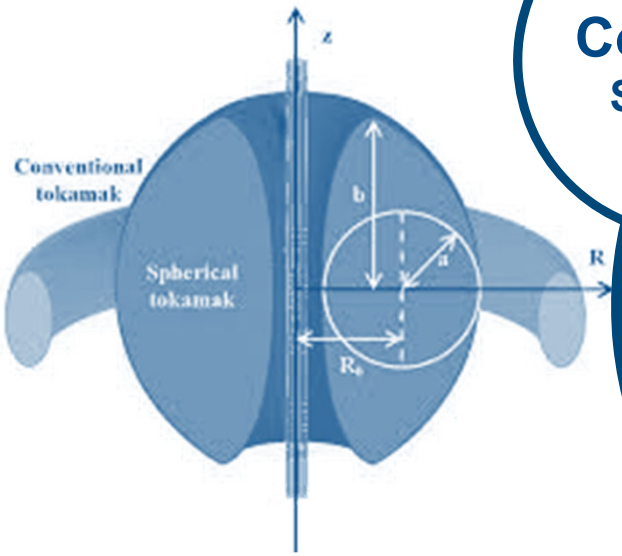
2019 Great Britain invested £220M in "ST for Energy Production" to create an investible concept design

2035+ ITER projects to produce a burning D-T plasma with Q of 10



Tokamak is the mainline configuration of the world's magnetic fusion energy R&D. The ITER Project is its flagship experiment. An estimated cost of construction of $25 billion is being born by the EU (45%), China, India, Japan, Korea, Russia, and US. D-T burning plasma experiment is expected to commence in 2035.

ENN Fusion R&D Mission — Compact Clean Commercial Power

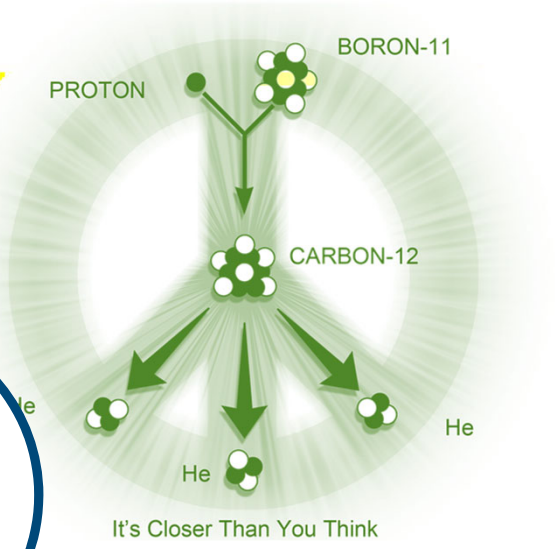


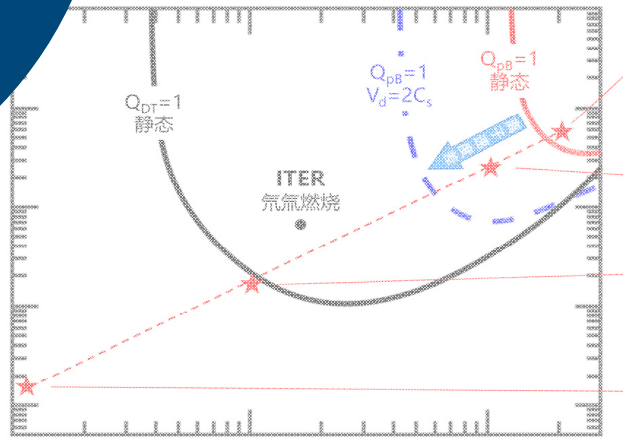
Compact
Simplify

Protect Environ't
Aneutronic
Tritium-free

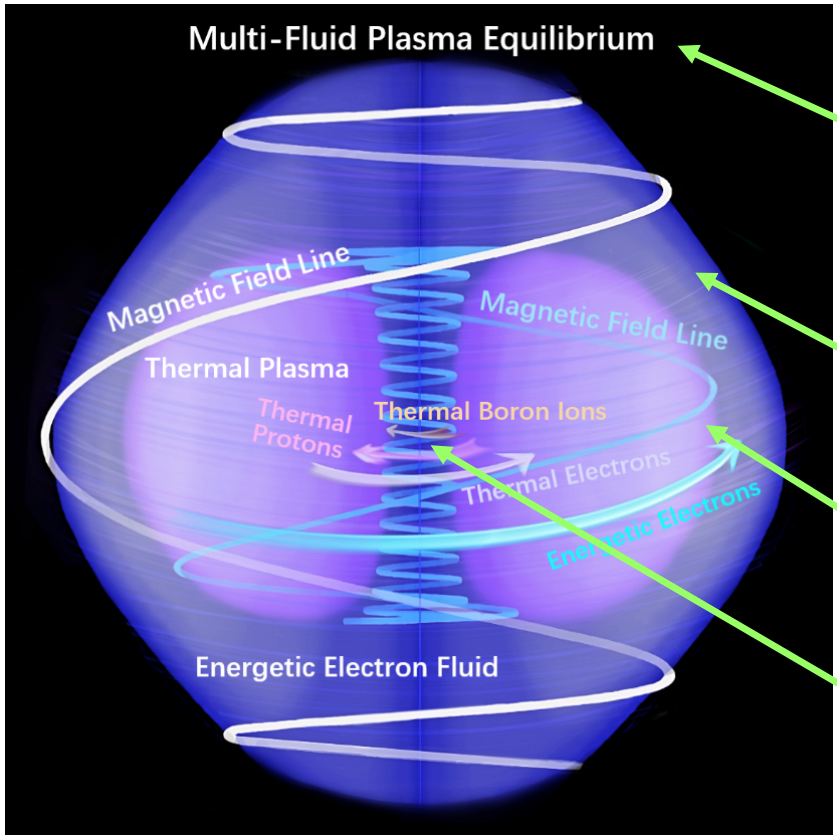
Fusion ENN

Low Unit Cost
Mass Produced
~6c/kW-hr
(2020 RMB)





EXL p-^{11}B Fusion Plasma Physics Theoretical Model & R&D Goals



Distinguishing features & R&D goals:

- **Multi-fluid spinning plasma equilibrium (axisymmetric distributed macroscopic force-balance)**
- **Orbit-confined energetic electrons raise current-drive efficiency**
- **LCFS protected from edge recycling, improving plasma confinement**
- **Ion velocity differential eases Lawson Criterion triple product Tnτ**

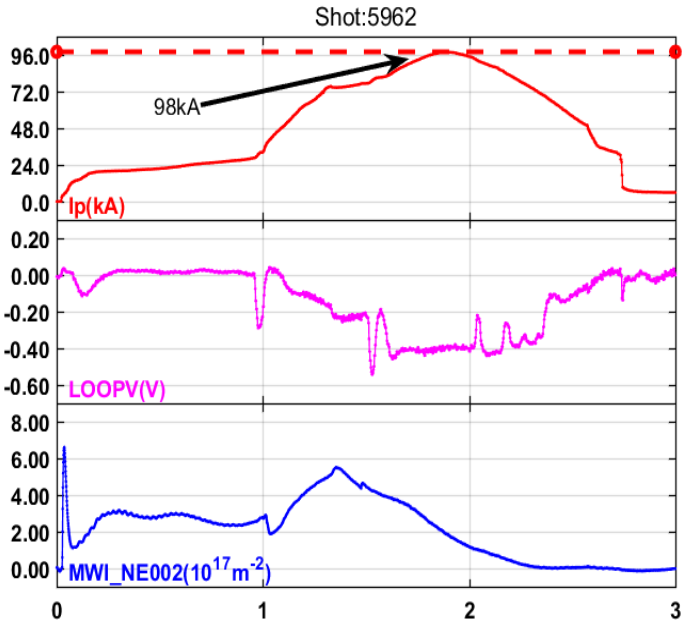
Experiment and Analysis will Update Model and Continue ST Reinvention.

EXL-50 Proof-of-Principle Experiment

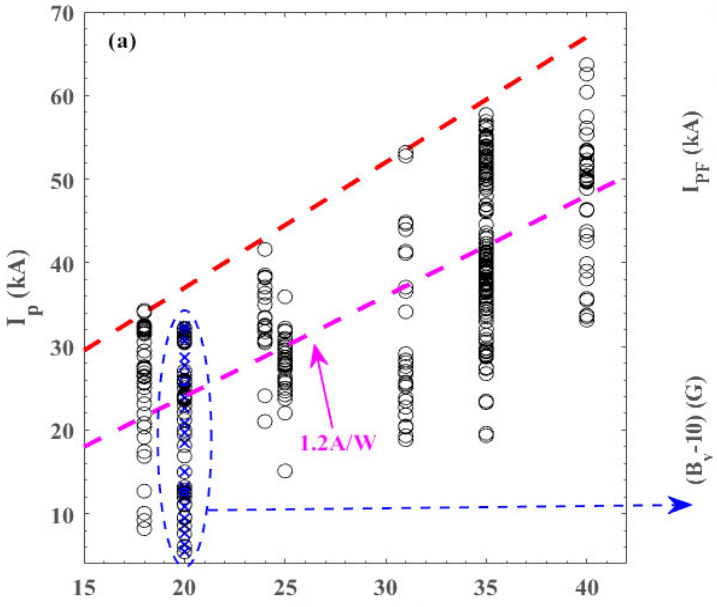
Parameter	Goal
Plasma Current I_p	500 kA
Toroidal Field B_T	0.46 T
Major Radius R	0.58 m
Minor Radius a	0.41 m
Elongation k	1.8-2.2
Triangularity δ	0.1-0.4
Pulse Length t_d	5 s

Observed High Amp/(ECRH Source Watt) at Low Power & Density

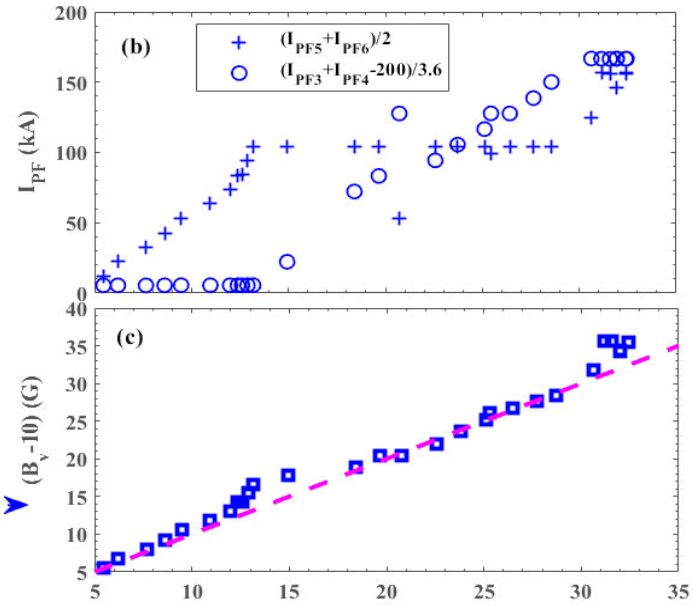
- ✓ Drove up to 98kA in absence of solenoid, against induced $-E\phi$
- ✓ Averaged to 1.2A/W, based on < 200 discharges
- ✓ $I_p \propto B_V$ holding B_T constant, consistent with force balance



Plasma Discharge Time (s)

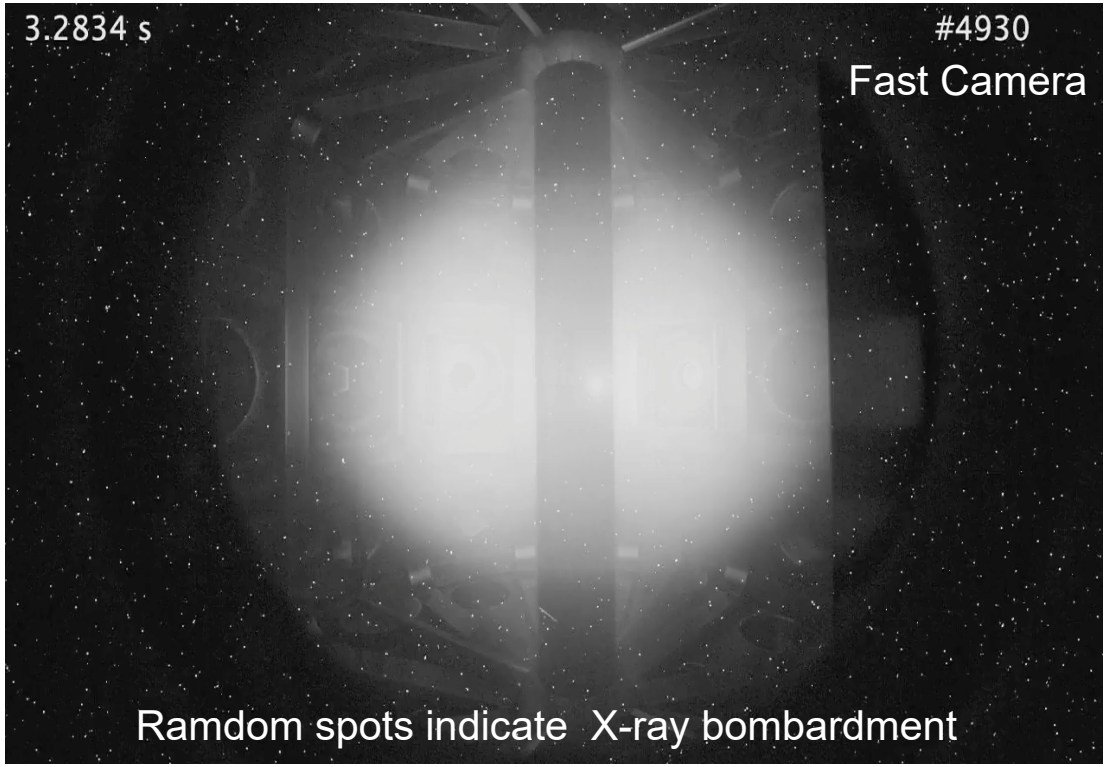


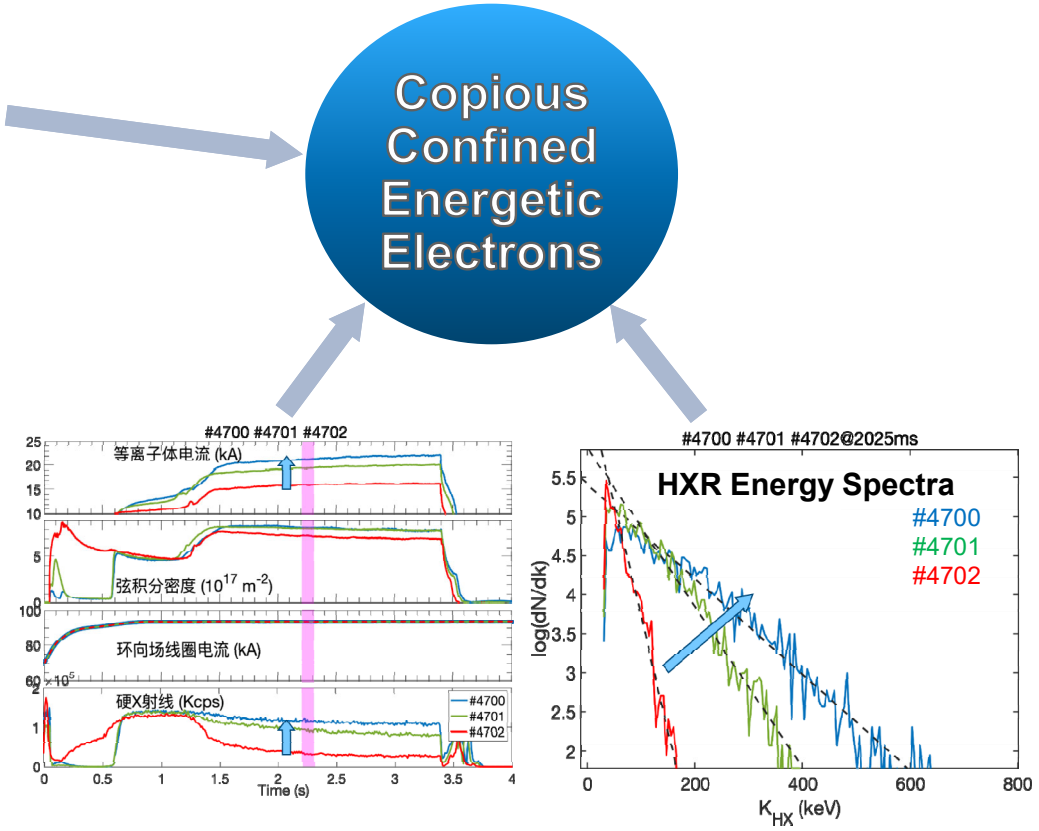
Gyrotron Electron Beam Power (kW)



Plasma Current (kA)

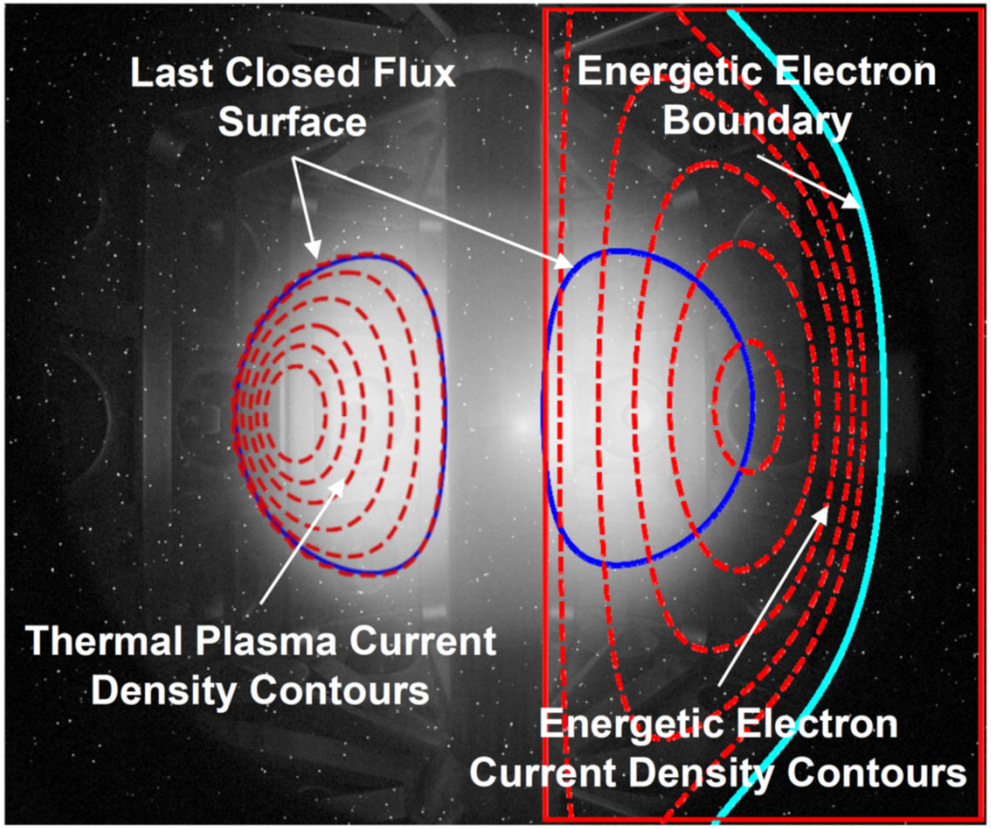
Observed Copious Confined Energetic Electrons, Carrying Large Fraction of Toroidal Current (2020.4)





Plasma current, energetic electrons (Bremsstrahlung HXR intensity) and energy content (HXR energy spectrum) are observed to increase conjointly

Multi-Fluid Equilibrium Theory vs. Experiment — Large Toroidal Current Can Exist in Wide, Open Field-Line Region



A 3-fluid equilibrium near-reproduction of an EXL-50 Plasma #4851@3s

3-Fluid Equilibrium Theory & Model Application

Measurements vs. **Computation**

Thermal Ions + **Thermal Electrons** + **Energetic Electrons**

- **Three-fluid equilibrium is shown to exist in EXL-50 by computing equilibrium that nearly reproduces available measurements**
- **Energetic electrons are observed to exist also in open-field-line region, carry most toroidal current, and form a Last Closed Flux Surface (LCFS)**

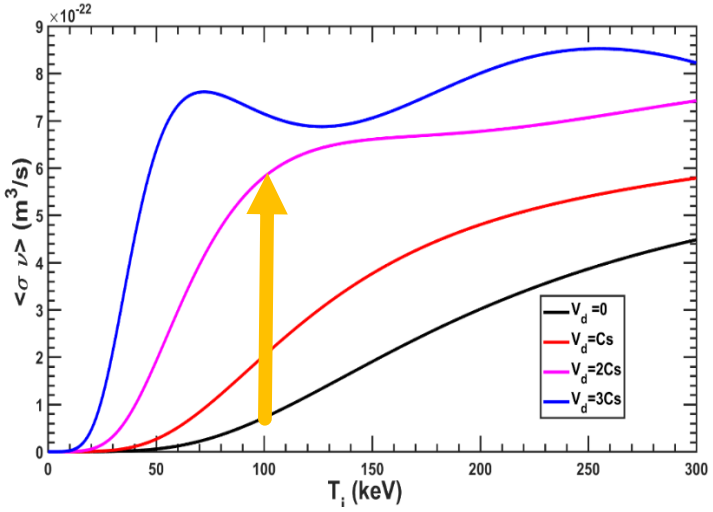
Three-Fluid Axisymmetric Equilibrium Model and Application to Spherical Torus Plasmas Sustained by RF Electron Heating, https://doi.org/10.1585/pfr.10.1403084.

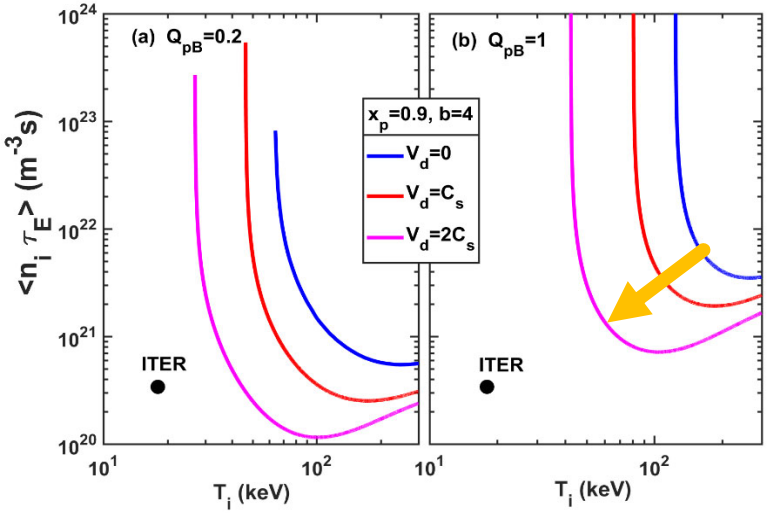
Introduced Theory That a Velocity Differential V_d Between Proton and Boron Ions Can Reduce the Lawson Criterion for Fusion Burn

- $V_d = 2C_s$ would reduce the triple product for p-^{11}B burn to ~7x10^{22} m^{-3} s keV*

$$\langle \sigma v \rangle = \frac{1}{V_d}\left(\frac{\beta}{\pi}\right)^{1/2} \int_0^{\infty} \sigma(v) v^2 \{\exp(-\beta(v-V_d)^2 - e\exp(-\beta(v+V_d)^2)\} dv \qquad v = |v_p - v_B|, \ \beta = \frac{M_{pB}}{2T}$$

- Raise p-^{11}B fusion plasma reaction rate to ~7x10^{-22} m^3/s (T_i>100keV)





*Toroidal plasma conditions where the p-^{11}B fusion Lawson criterion could be eased, DOI: 10.21203/rs.3.rs-93644/v1.

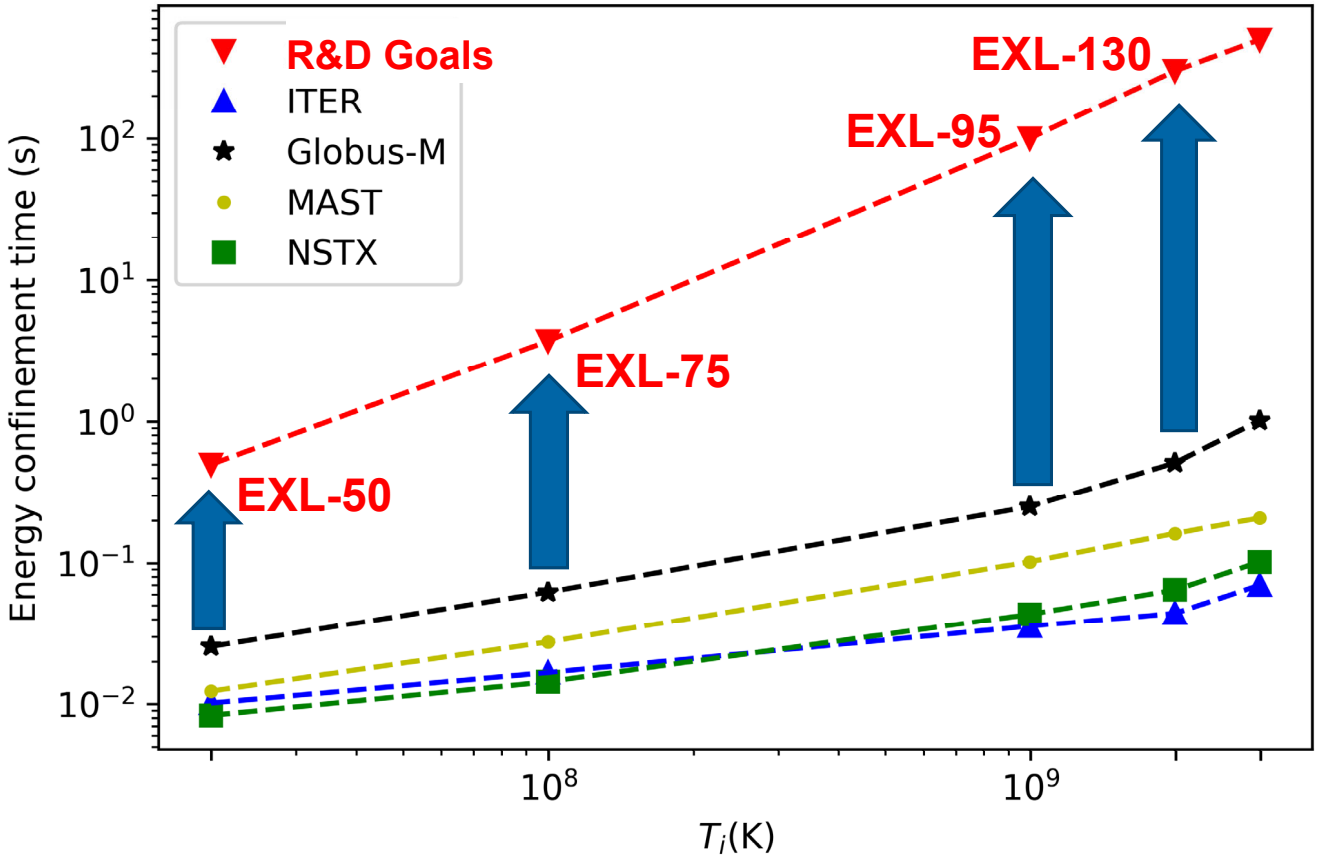
*Four-Fluid Axisymmetric Plasma Equilibrium Model Including Relativistic Electrons and Computational Method and Results, http://arxiv.org/abs/2010.08116.

EXL p-^{11}B Fusion R&D Goals on Plasma Energy Confinement Are Orders-of-Magnitude Above Known Scaling Law Estimates

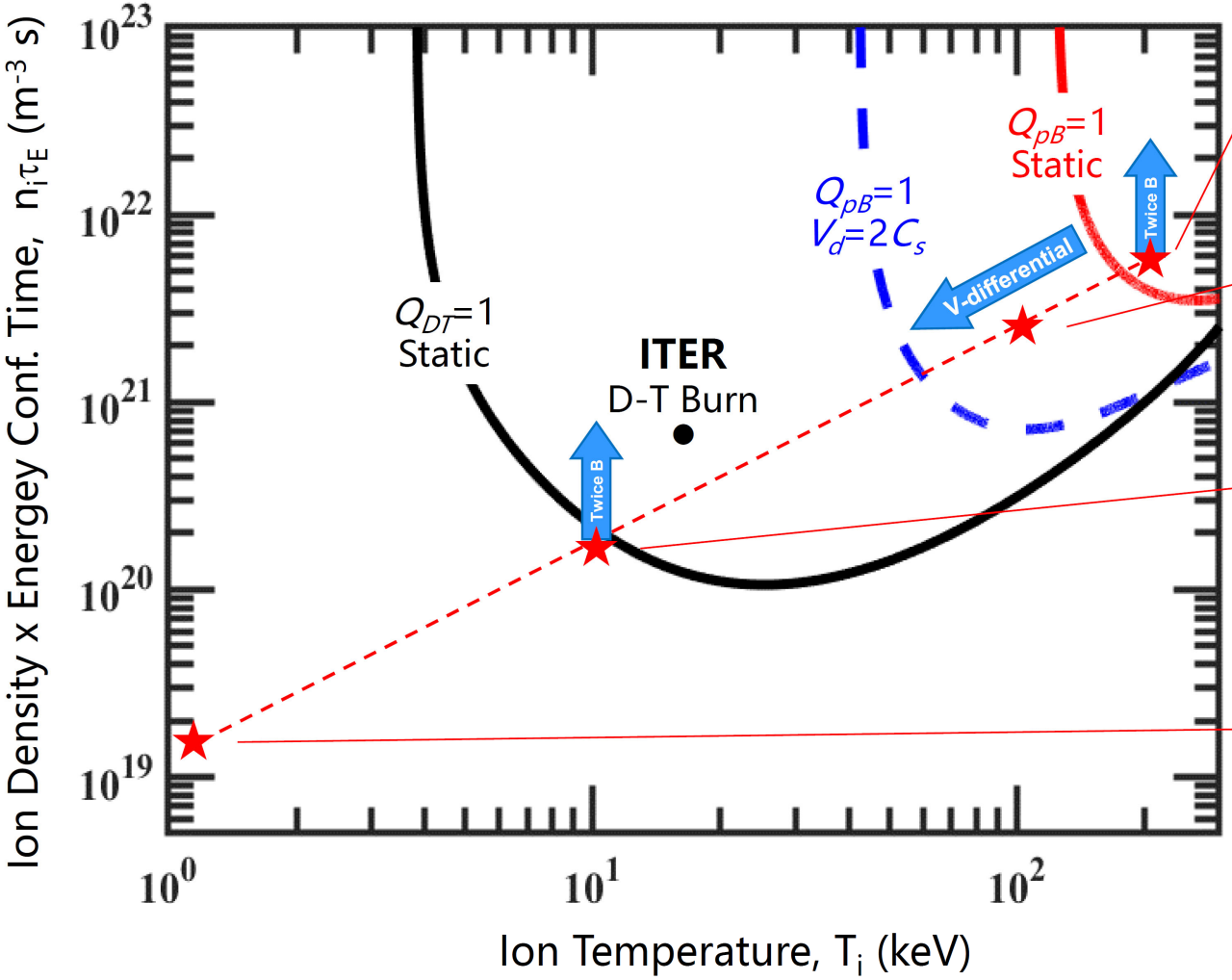
Scale-Up Design Parameters

EXL	50	75	95	130
I_p	0.5	1.6	3.2	7.5
B_T	0.48	0.86	1.33	2.0
P_L	2	12	25	150
n_e	4	3	2	2
M	1.2	1.2	1.5	2
R	0.6	0.72	0.93	1.29
ε	1.5	1.5	1.5	1.5
κ	1.8	1.8	1.8	1.8

Confinement Time Challenges



EXL p-^{11}B Fusion Triple-Product R&D Goals — Challenge of an Aneutronic Fusion, and Potential Leverages in V_d and HTSC



EXL-130
p-^{11}B Burn Exp.
(aneutronic, tritium-free)

EXL-95
p-^{11}B Ignition Exp., HTSC
(⇒D-D, D-^{3}He burn condition)

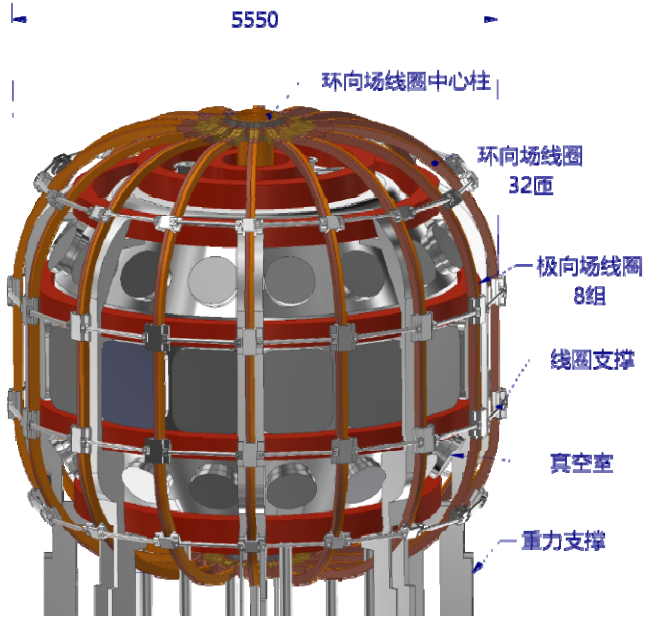
EXL-75
Fusion-Temperature Plasma Exp.
Ion Velocity Differential Research
(⇒D-T ignition-burn condition)

EXL-50
Proof of Principle Exp.
(⇒NSTX, MAST plasma condition)

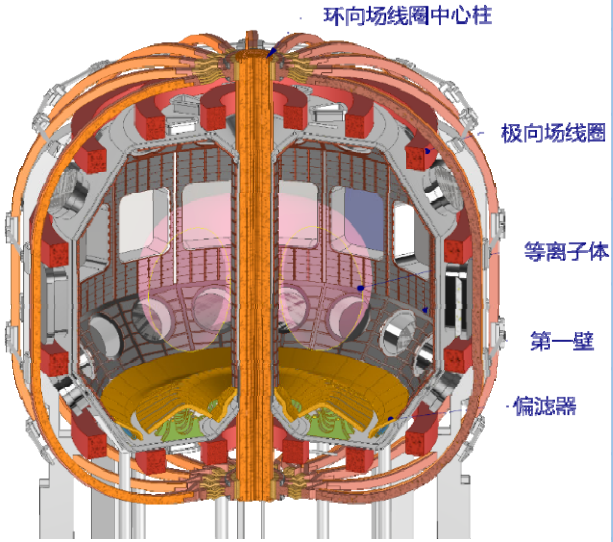
Low-Field (B_t=1T) EXL-75 Concept, ECRH Resonance near 2T

Technical goal:

- A next step in raising plasma parameters, Ip up to 1.6MA;
- p-B plasma confinement, H&CD efficiencies, V_d at 10-keV;
- Comparative tests of limiter and divertor effectiveness.



Vacuum Vessel & Coils



Internal Arrangement, Divertor Option

EXL-75 Parameters

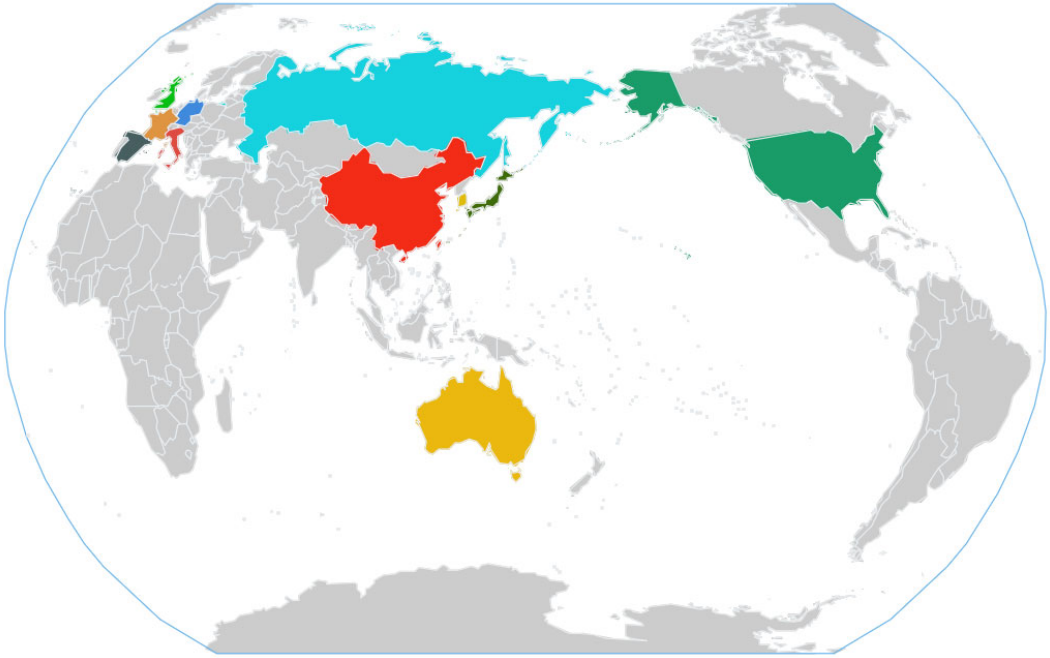
Plasma Current, I_p, MA	1.6
Plasma R, m	0.76
Energetic Electron R_e, m	1.05
Elongation, k	≈1.8
Aspect Ratio, A	1.5-1.6
Toroidal Field at R, B_t, T	1.0
ECRH Power, P_{ECRH}, MW	5
LHCD Power, P_{LHCD}, MW	2
ICRH Power, P_{ICRH}, MW	5
NBI Power, P_{NBI}, MW	10
Discharge Time, t_d, s	5

ENN Fusion Technology R&D Center (2020)

Size	Academic Training		Characteristics
Almost 100 in number	Hebei Key Laboratory of Compact Fusion	Ph.D. degrees 40%	Average Age: 37 With Passion, Courage

Cooperation, Contribution, Moving Fusion Energy R&D Forward

- Promote an efficient and agile p-B fusion R&D effort，be a member of fusion community
- Learning by doing, drawing from expertise in fusion, high-energy particles, laser, materials
- Engage experts from schools, laboratories, industries, power companies, private enterprises



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“Develop Fusion Energy, Benefit Mankind for Generations!”

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