ISTW 2022
The 21st International Spherical Torus Workshop

ENN 新奥

Overview of EXL-50 Research Progress and Future Plan

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For ENN Fusion Research Center

ENN Science and Technology Development Co., Ltd

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Outline

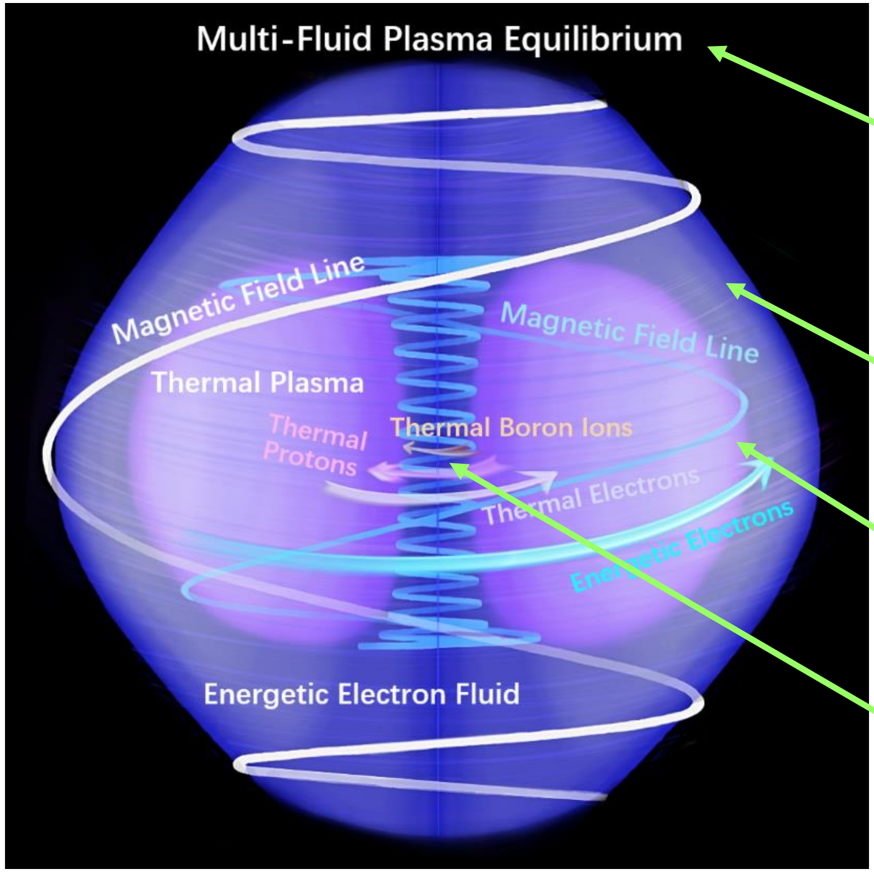
I. Introduction: ENN XuanLong-50 (EXL-50)
- Innovation and Mission
- Device and machine status

II. Research Progress on EXL-50
- Progress of Solenoid-free current drive experiments
- Investigation of plasma current drive mechanisms
- Energetic electrons and Multi-fluid equilibrium model
- High density experiment

III. Summary and Future Plan

ENN's target: p-^{11}B Fusion Reactor based on ST*

p-^{11}B Fusion Plasma Physics Model & Assumptions(Y.K.M.Peng彭元凯)



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 and velocity distribution anisotropy ease Lawson Criterion triple product $Tn\tau$

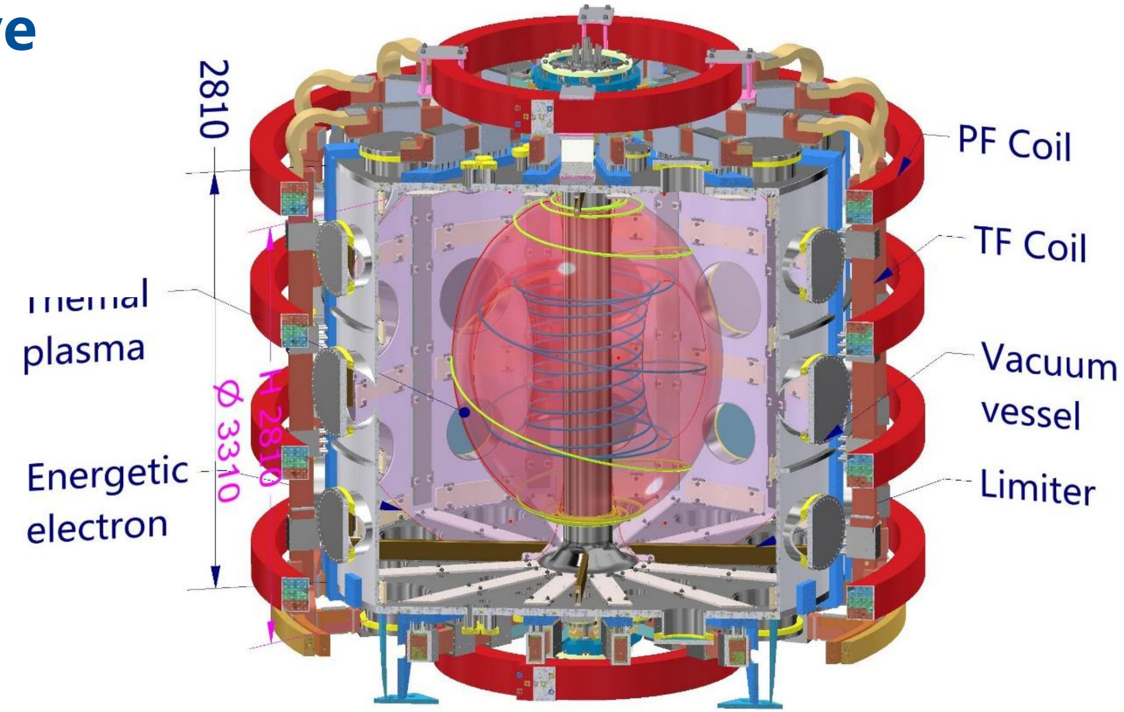
Experiment and Analysis will Update Model and Continue ST Reinvention.

*Huasheng Xie's report in this session

Mission of EXL-50：Experimental Verification of Physics Feasibility

- **Steady-state solenoid-free current drive**
- **Verification of multi-fluid equilibrium**
- **Investigation of energy confinement performance**

Parameters	Values
Plasma current	0.5 MA
Thermal ions major radius R_i	0.58 m
Toroidal magentic field at R_i	0.5T
Energetic electron cloud radius	0.7m
Thermal ions aspect ratio (LCFS)	1.5
Elongation	≈2
Thermal ions temperature	1 keV
Energetic electron temperature	0.23 MeV
Electron density	2 x10^{19}/m^3
Discharge TF flattop duration	5s @ 0.5T 20s @ 0.3 T



Diameter	3.31 m
Height	2.81 m
Volume	24 m^3
Materials	S.S 316L
Weight	23 t
Baking Temperature	200 ℃
Vacuum Level	1×10^{-6} Pa

EXL-50 Device

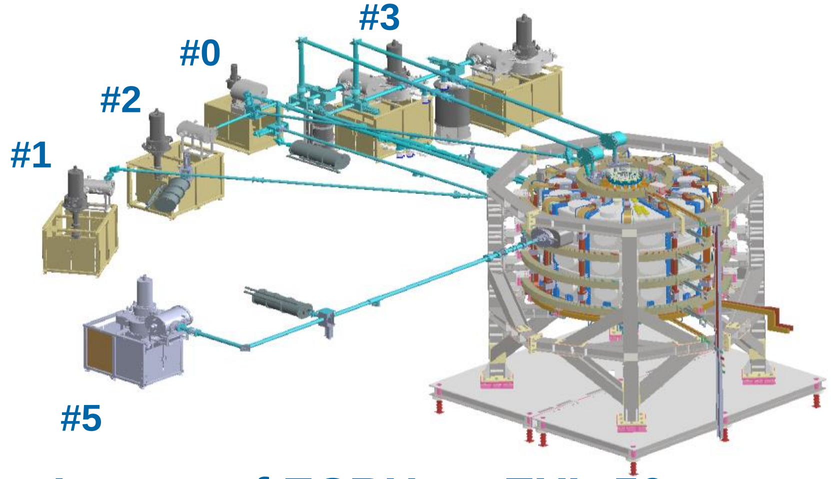
- Design started in Oct.2018
- Completion of machine construction **and first plasma** in Jul. 2019
- A medium-size ST without central solenoid(CS)
- Benefits of CS-free ST
  - Simplification of center stack structure
  - Improvement of operation reliability
  - Enhancement of toroidal magnetic field

$B_T\uparrow \Rightarrow I_p\uparrow,\ n\uparrow,\ T\uparrow,\ \tau_E\uparrow$

$P_{fusion} \propto \langle p\rangle^2 \propto \beta_T^2\, B_T^4$

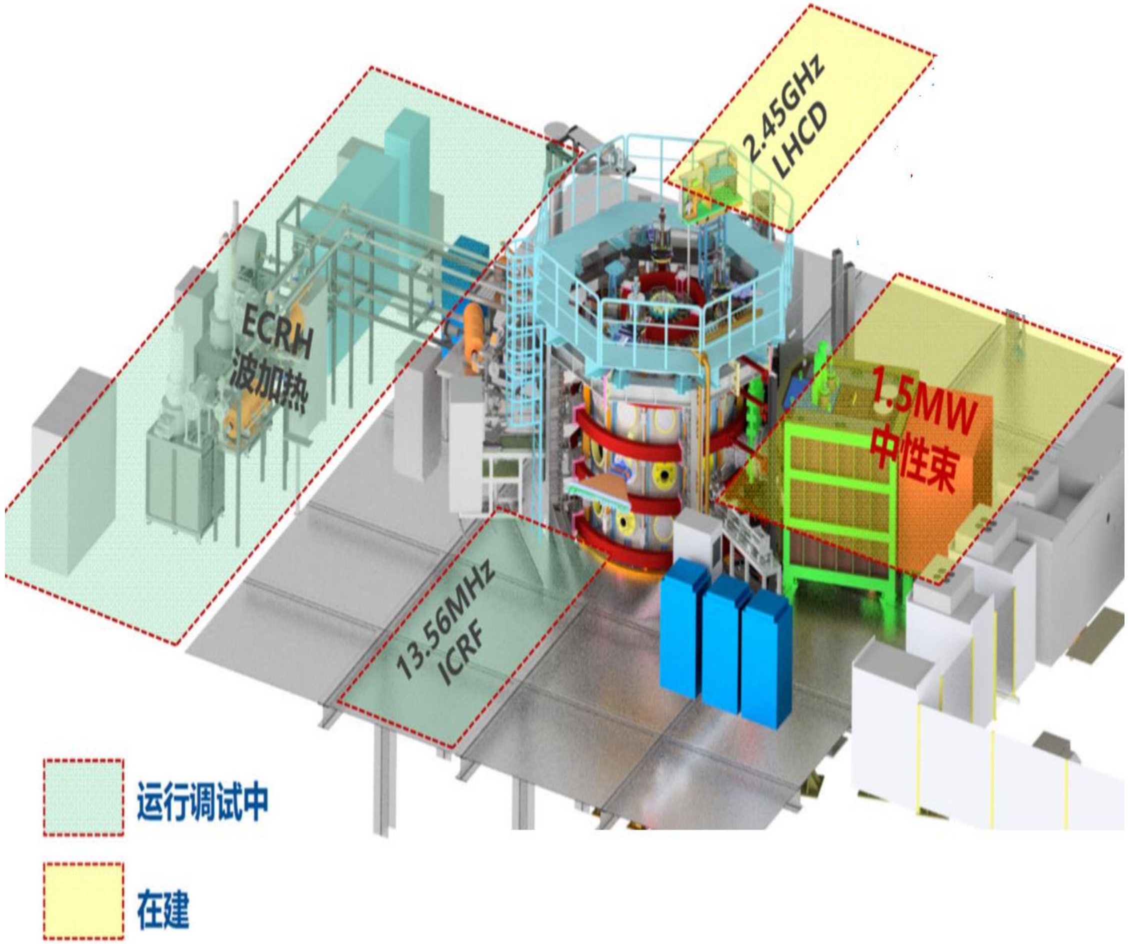
Is steady-state current drive possible for CS-free device?

Heating and current drive system on EXL-50



Layout of ECRH on EXL-50

H&CD system	Parameters
ECRH	1.75MW 0# 1 x 28GHz/50kW/30s 1#-3# 3 x 28GHz/400kW/5s 5# 1 x 50GHz/500kW/1s
ICRF	0.14MW 3-26MHz/100kW 13.56MHz/40kW
LHCD	0.2MW 2.45GHz/200kW
NBI	1.5MW 50keV/1.5MW
Total design power	3.59MW



Sketch of H & CD on EXL-50

Diagnostics on EXL-50

Magnetic measurements:

Rogowski loops, flux loops, magnetic probes,
Mirnov coils, diamagnetic loops

Operational parameters:

Visible/IR camera,
pressure gauges, RGA

Electron density/Te/Ti:

Combined interferometer, TS, Probe, PHA, XCS, Vis spec

Impurities and radiation:

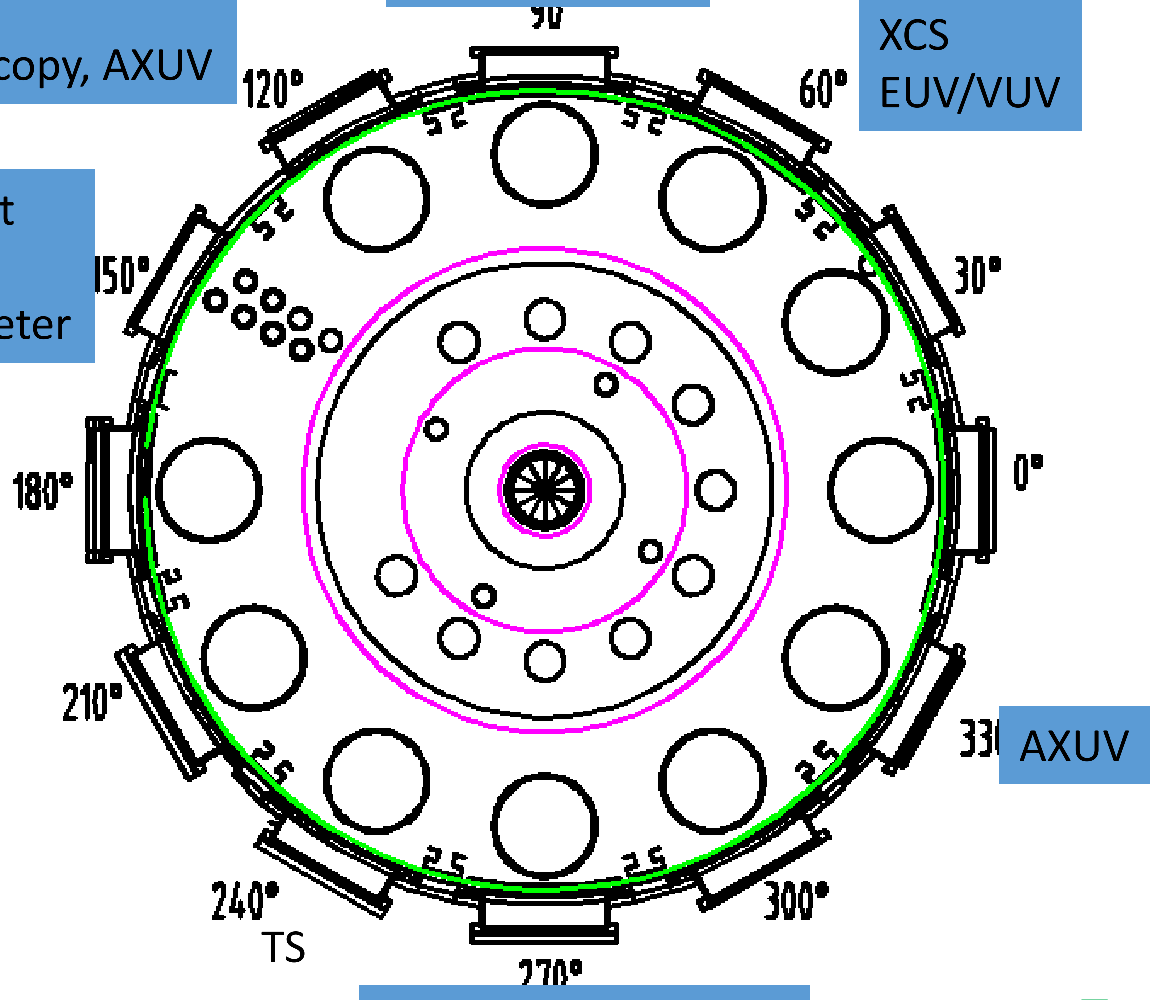
Vis spec, Ha, CIII/OII, AXUV , VUV, EUV, sniffer probe(microwave stray radiation)

Energetic particles:

HXR, ECE

Multi-scale fluctuations:

Probe, ICE



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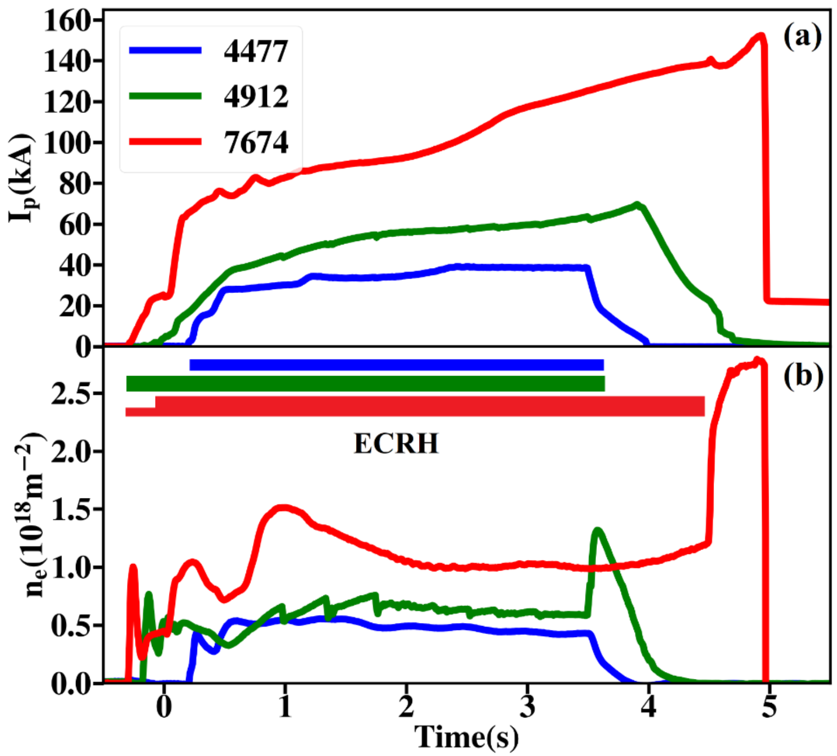
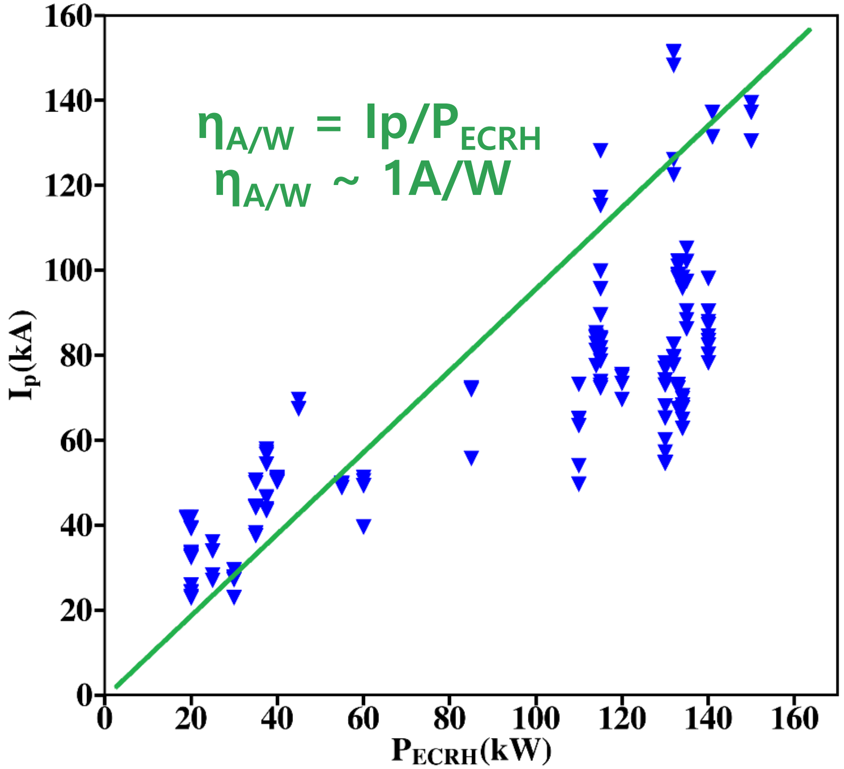
*Solenoid-free current drive via ECRH in EXL-50 spherical torus plasmas, Yuejiang Shi, Bing Liu, Songdong Song, Yunyang Song, Xianming Song, et al., Nucl. Fusion. 086047(2022)

High-efficiency current drive with ECRH on EXL-50

P_{ECRH}	I_P
20kW	40kA
45kW	70kA
115kW	140kA

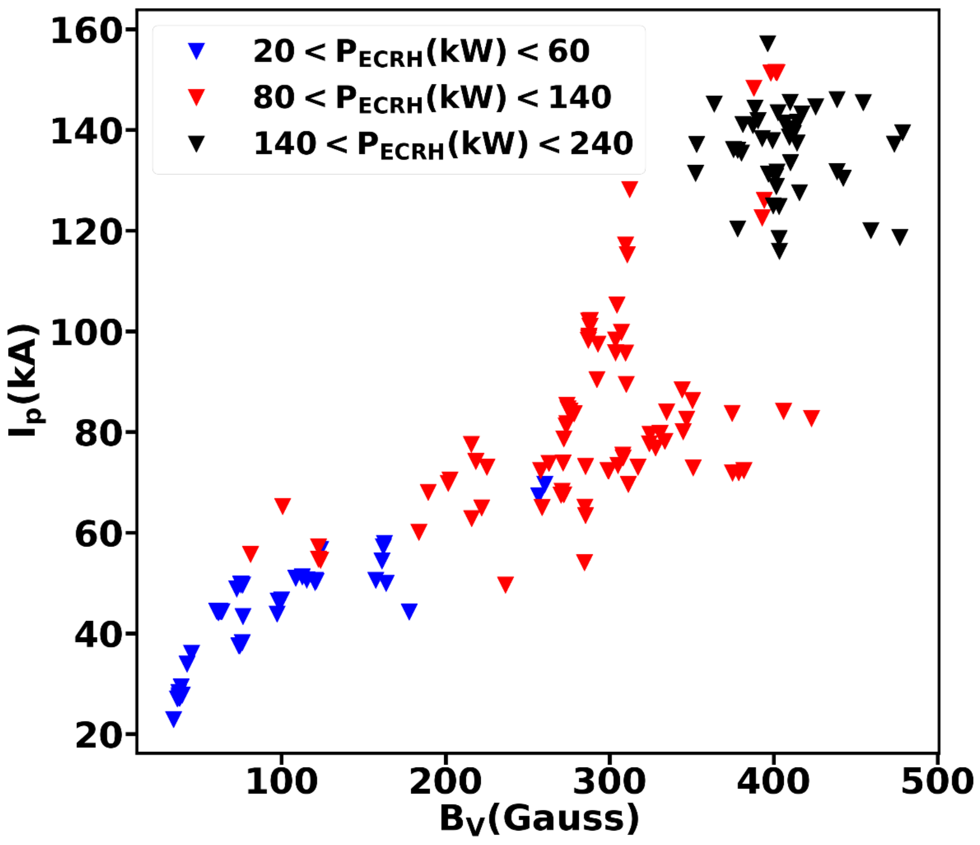


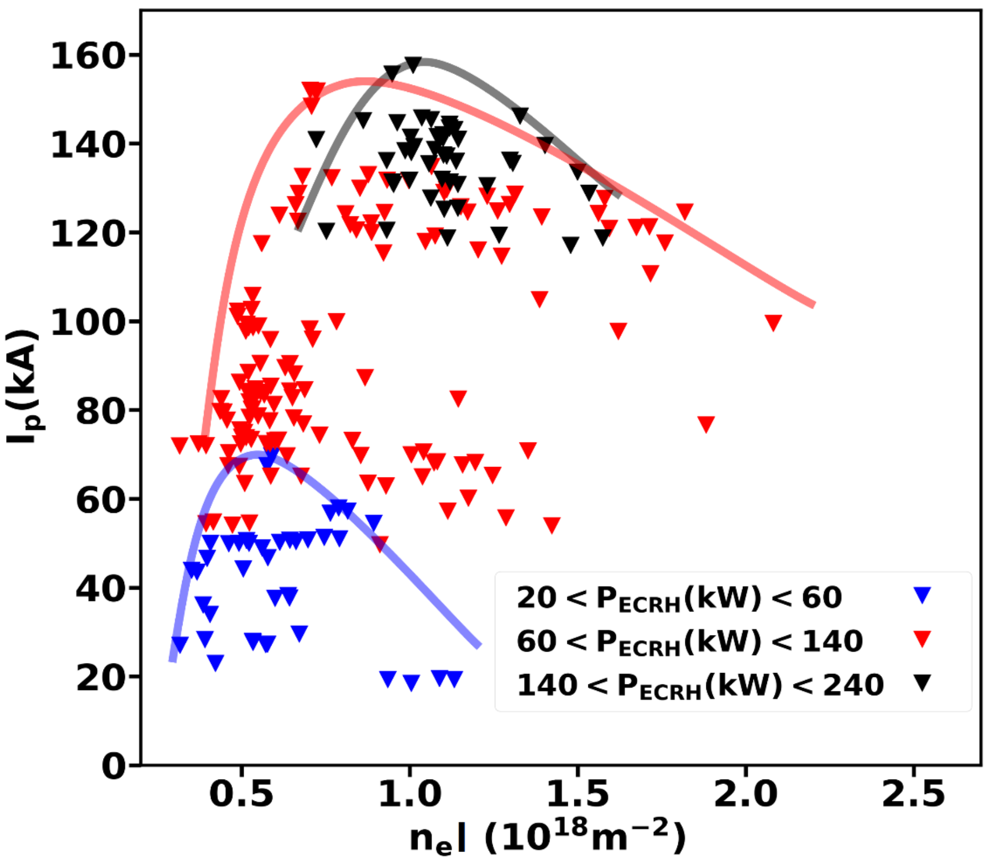
Optimized discharge waveforms for different 28GHz ECRH heating power.



Ip versus P_{ECRH} for 200 successful shots in EXL-50

High-efficiency current drive with ECRH on EXL-50





Plasma current in the flattop phase versus external B_v

- Ip increases with field B_v in the appropriate P_{ECRH} range.
- Bv is not a plasma current driving source, but it affects the maximum plasma current driven by ECRH

Ip/P_{ECRH} v.s. density

- Too low density is not conducive to an increase in plasma current.
- The suitable density for high Ip increases with P_{ECRH}

Which current drive mechanism dominates in EXL-50?

Pfirsch-Schluter current $I_{PS} = 2 < P > S/R\, B_v$

PS maybe important in breakdown and initial start-up phase
I_{PS} **is less than 1kA for the plasmas with closed flux field (CFS) equilibria in EXL-50**

Bootstrap current $f_{PS} \sim \nabla P$

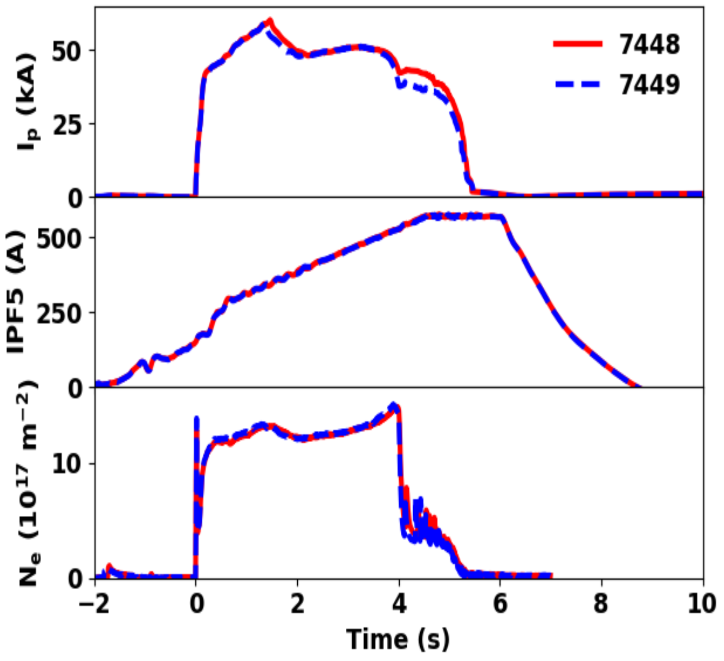
f_{PS} **is several percents for EXL − 50′S plasmas**

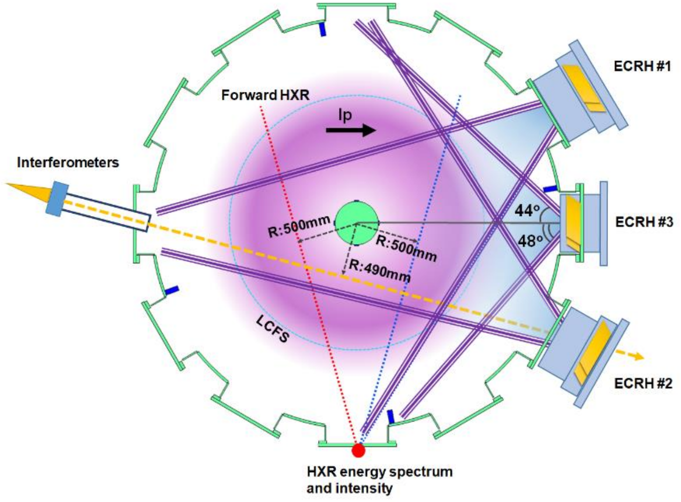
Traditional ECCD (Fisch-Boozer or Ohkawa) ?

to be estimated for the thermal plasma

Conclusion of the following result?

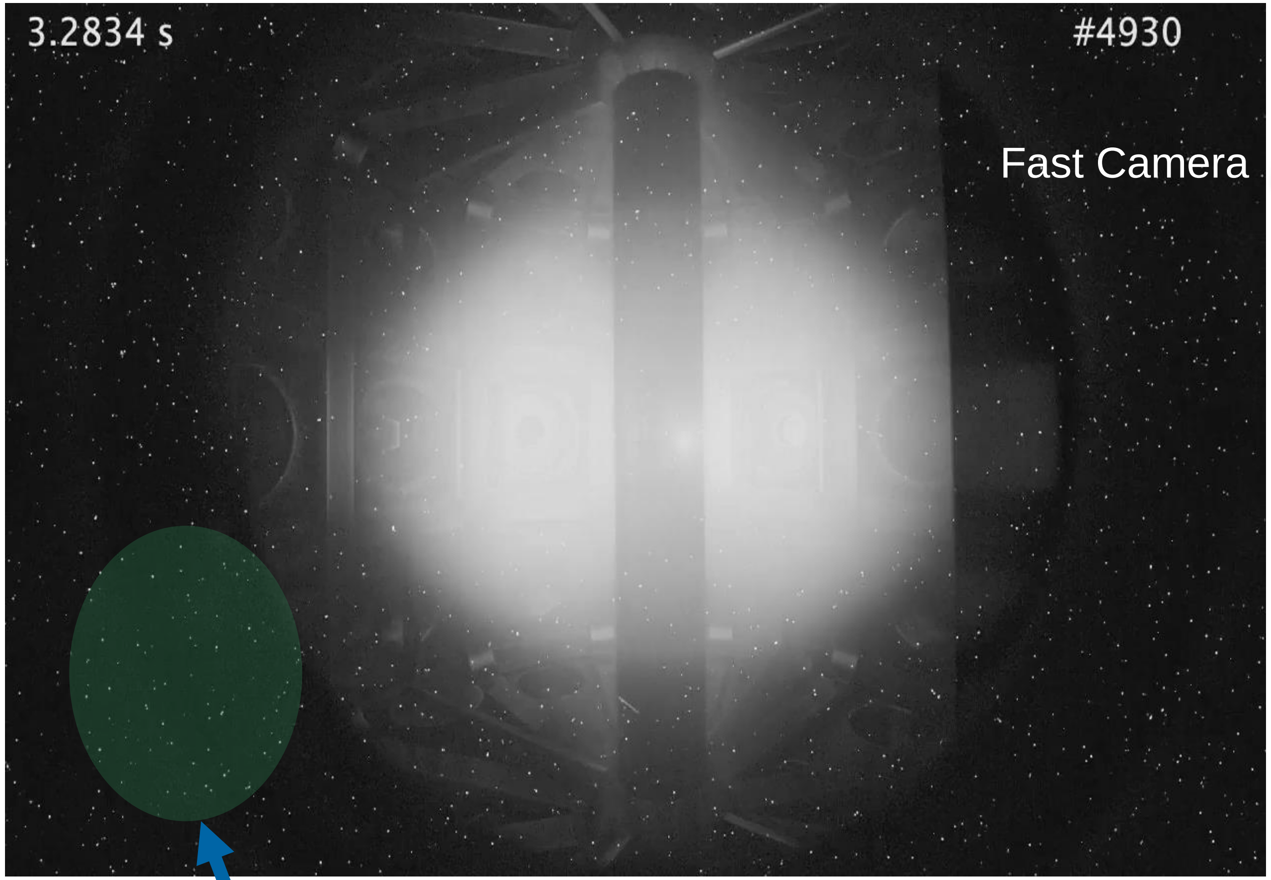
Two identical shots with same density, ECRH power and PF current. The toroidal angle for the ECRH antenna is setting as -16^0 for counter-current drive in shot 7448, and 17^0 for co-current drive in shot 7449.



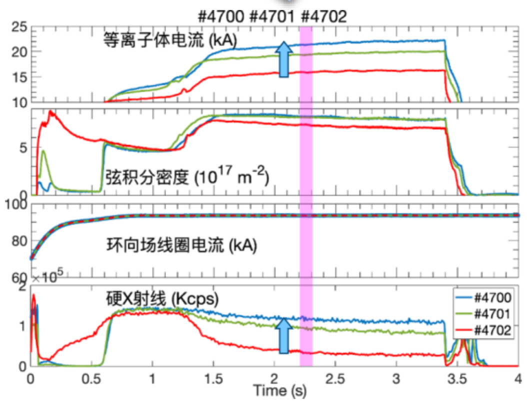


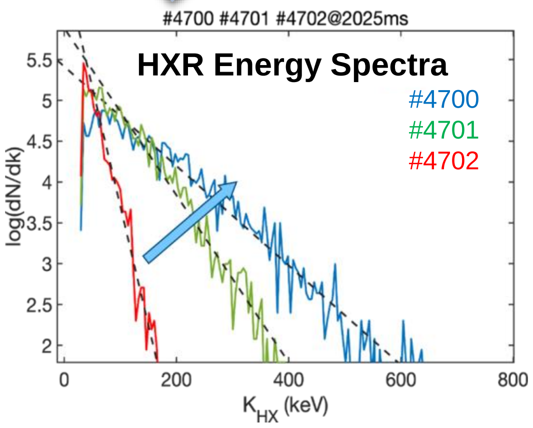
Traditional ECCD also can be neglected in current EXL-50's plasma

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



Copious Confined Energetic Electrons



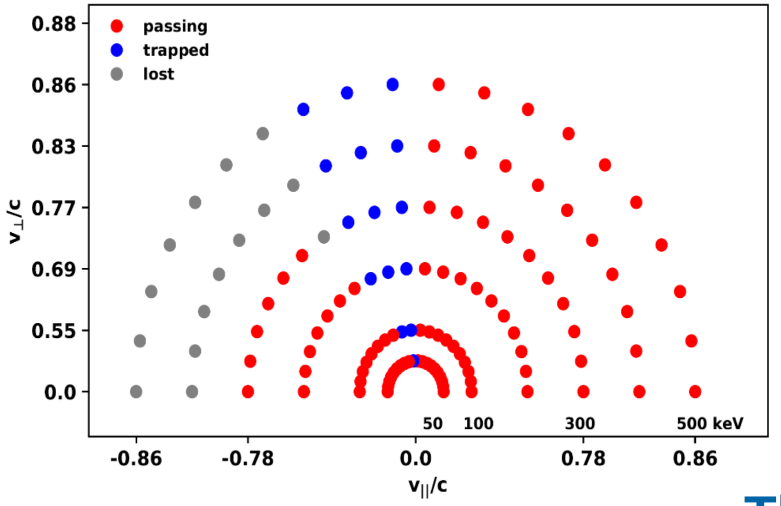


Random white spots indicate X-ray bombardment

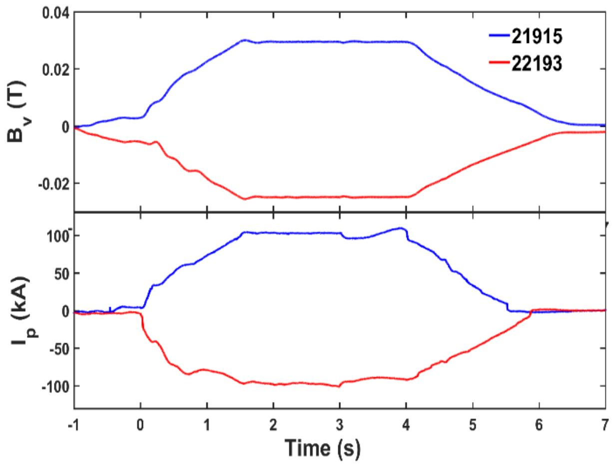
Plasma current, energetic electrons (Bremsstrahlung HXR intensity) and energy content (HXR energy spectrum) are observed to increase conjointly

Additional likely explanation for high current driven efficiency

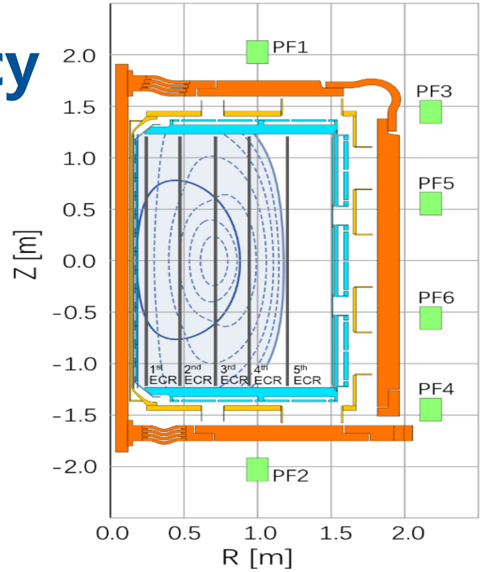
- ➢ Asymmetric velocity distribution of energetic electrons based on orbit confinement*
- ➢ Multi-harmonic resonance
- ➢ Multiple reflections and Multi-pass absorptions



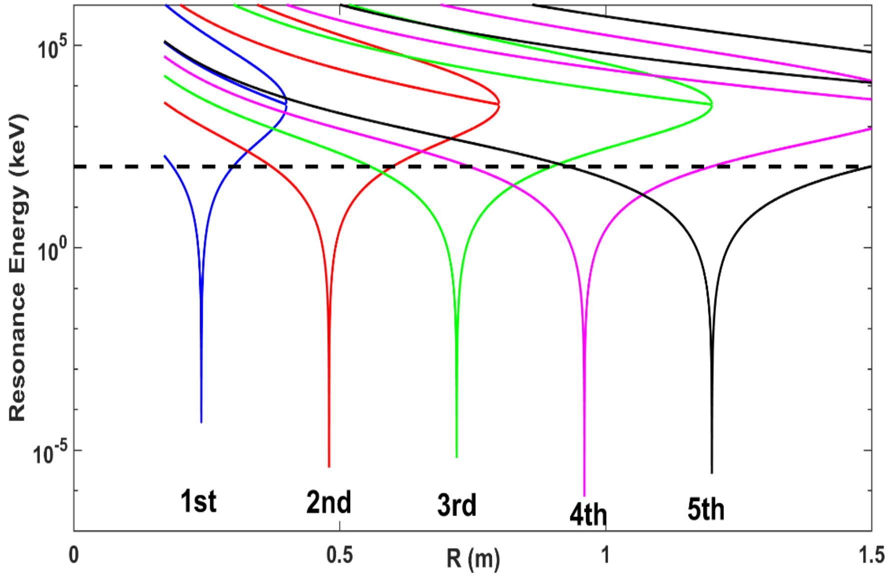
Velocity distribution of energetic electrons



The direction of I_p depends on the direction of B_V which determines the asymmetric of $v_{//}$.



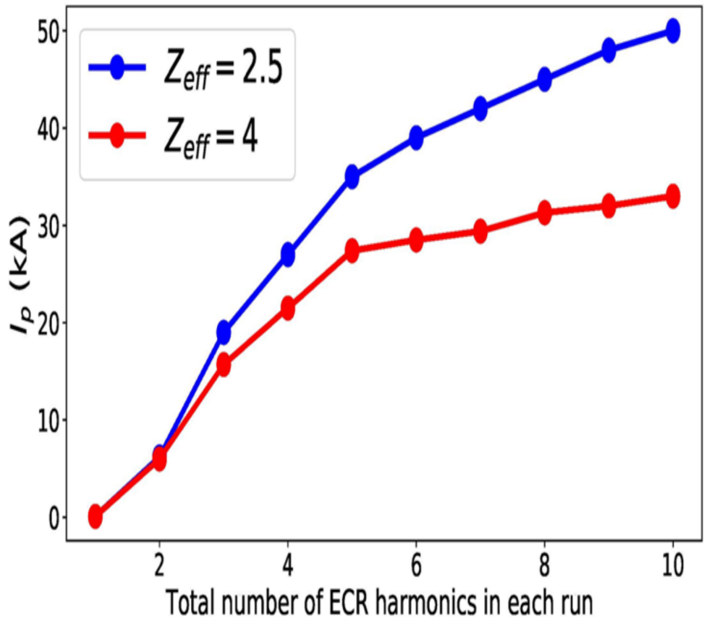
- ➢ Up to five harmonic resonance layers exist in the vessel



- ➢ Overlapping ECRH area for energies above 100keV

*1.Experimental study of non-inductive current start-up using electron cyclotron wave on EXL-50 spherical torus, M.Y.Wang, D.Guo, Y.J.Shi, et al,PPCF(2022)075006 *2.Particle orbit description of cyclotron-driven current-carrying energetic electrons in the EXL-50 spherical torus, T Maekawa, YKM Peng, W Liu, submitted to Nucl. Fusion

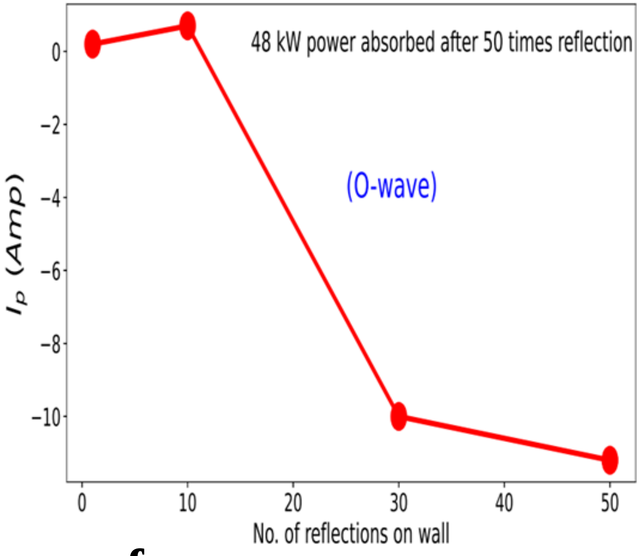
➢ Multi-harmonic resonance*
➢ Multiple reflections （OX mode conversion） and Multi-pass absorption*



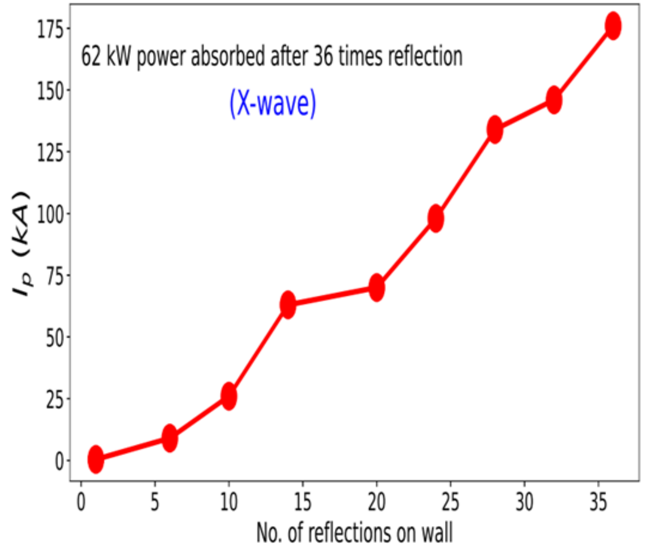
Simulation of 120kW Single-pass X-mode EC wave for EXL-50's plasmas

- ➢ **Ip increases with harmonic numbers**
- ➢ **Driven current (20-35kA) up 5^{th} harmonic with single-pass is much lower than experimental results (140kA)**

- ➢ **Current drive efficiency of O-mode ECW is very low**



(a)



(b)

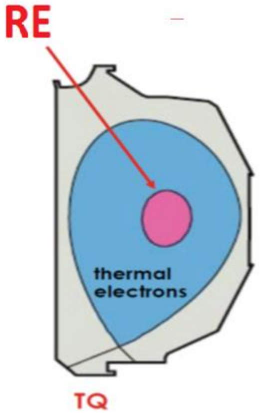
- ➢ **Multi-harmonic ECW current drive through multi-pass absorptions**

*Investigation of the effectiveness of non-inductive `multi-harmonic' electron cyclotron current drive through modeling multi-pass absorptions in EXL-50--D. Banerjee, et al., https://arxiv.org/abs/2109.04161

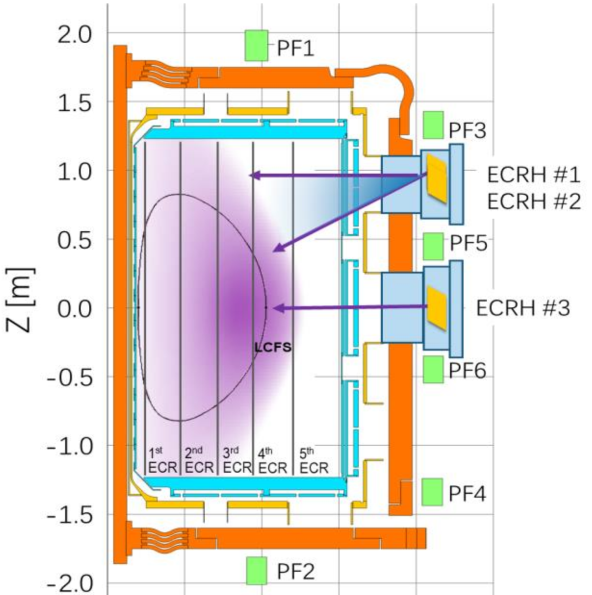
What is the difference between EXL-50's energetic electron and tokamak's runaway electron?

What is the role of induction drive current in EXL-50's discharge?

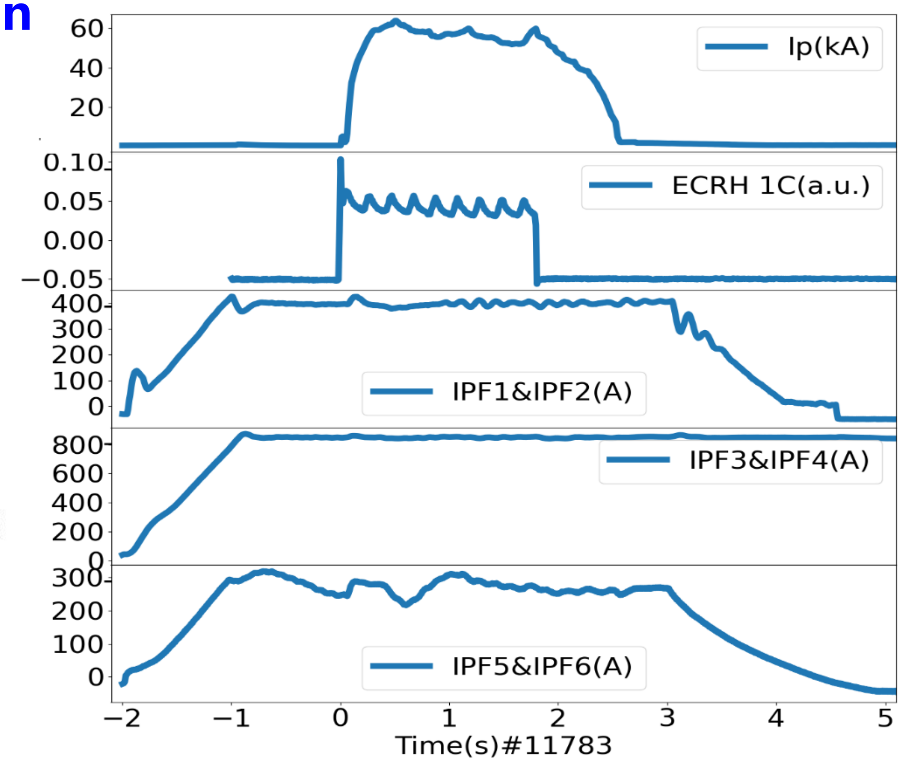
	Runaway electron	Energetic electron
Driven source	toroidal electron field	ECRH
Velocity distribution	$P_{//} >> P_{\perp}$	$P_{//} \sim P_{\perp}$
Spatial pattern	inside core	Wide distribution



Real image of RE beam in EAST (Y.J.Shi, RSI2010)



Themal plasma inside LCFS
Energeric electrons exist inside and outside LCSF



Although there is no CS coils on EXL-50, changes in PF coil current can induce toroidal electric field.

However, discharges with constant PF currents indicate that inductive plasma current can be neglected in EXL-50.

Four-fluid equilibrium model with relativistic energetic electrons based on a relativistic dynamic magneto-fluid model*

- **Multi-fluid equilibrium model with relativistic effect**

$\nabla \cdot (\gamma n \boldsymbol{u}) = 0$

$m\gamma u \boldsymbol{\nabla}(\gamma u g_{ep}) + \boldsymbol{\nabla} T + T\boldsymbol{\nabla} \ln n + q\gamma \boldsymbol{\nabla} V_E = q\gamma \boldsymbol{u} \times \boldsymbol{\Omega}$, where $\boldsymbol{\Omega} \equiv q^{-1}\boldsymbol{\nabla} \times \boldsymbol{P} = \boldsymbol{B} + \boldsymbol{\nabla} \times (q^{-1} m\gamma g_{ep} \boldsymbol{u})$

$\nabla \times \boldsymbol{B} = \mu_0 \sum_\alpha \boldsymbol{j}_\alpha$ where $\boldsymbol{j}_\alpha = q_\alpha \gamma_\alpha n_\alpha \boldsymbol{u}_\alpha$

$\nabla \cdot \boldsymbol{B} = 0$

$\sum_\alpha q_\alpha \gamma_\alpha n_\alpha = 0$ (the charge neutrality condition)

$g_{ep} \equiv \frac{\epsilon + p}{mnc^2} = \frac{K_3(1/T^*)}{K_2(1/T^*)}$ with $T^* \equiv T/mc^2$ and $K_n(z) = \frac{\sqrt{\pi}\left(\frac{z}{2}\right)^n}{\Gamma(n+\frac{1}{2})} \int_1^\infty dt e^{-zt}(t^2 - 1)^{n-\frac{1}{2}}$

γ represents relativistic effect due to macroscopic motion in the laboratory frame;

g_{ep} represents relativistic effect due to random motion of particles contained in a fluid element concerned.

For non-relativistic fluid component, i.e., thermal plasmas, γ=1 and g_{ep}=1.

- **Four-fluid equilibrium model will be used for analyzing p-B plasmas including ion velocity differentials, and for EXL-75 design.**

Four-fluid = Thermal protons + Thermal borons + Thermal Electrons + Relativistic Energetic Electrons

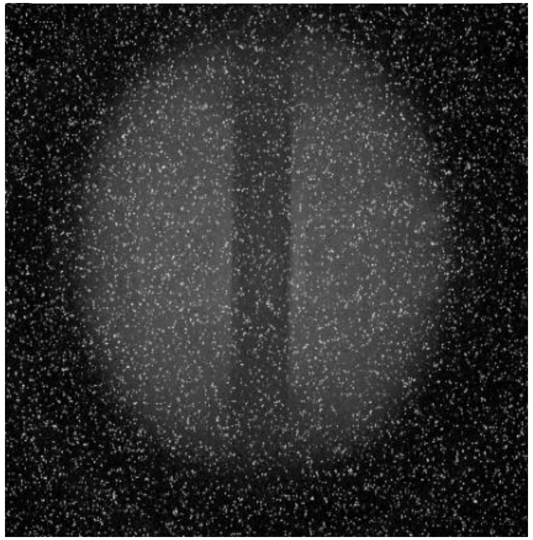
* Four-Fluid Axisymmetric Plasma Equilibrium Model Including Relativistic Electrons and Computational Method and Results--A Ishida, YKM Peng, W Liu; Physics of Plasmas, 28(2021)032503

Three-fluid equilibrium theory and computation compare well with experimental data

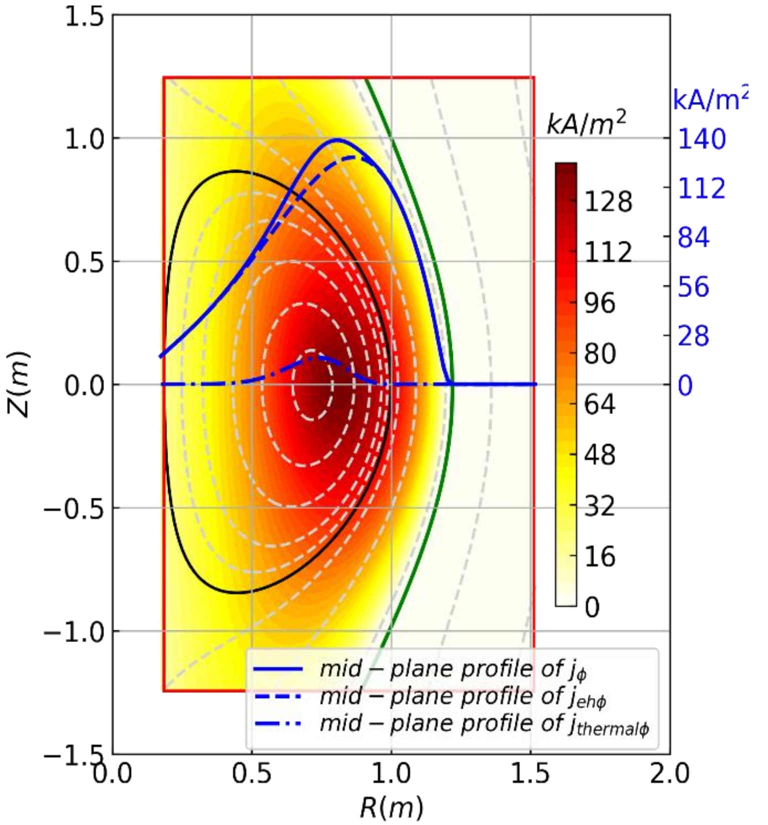
A 3-fluid equilibrium near-reproduction of an EXL-50 Plasma #9551@2.45s

Plasma parameters #9551@2.45s	EXL-50 Data	Calculated equilibrium
Flattop Ip (kA)	141.04	142 .51 (error=1.0%)
Line density (m^{-2})	1.04E+18	1.06E+18 (error=2.1%)
Energetic electron temperature (keV)	~200 (HXR, R~0.27m)	208 (peak=237)
Thermal electron temperature (eV)	**~60-100 (TS, R~ 0.7m)**	**81 (peak=84)**
Thermal ion temperature (eV)	**~20-30 (HeII ion)**	**25**
Rlcfs (m)	~1.013 (OFIT)	1.0 (error= -1.3%)
Major radius(m)	~0.60 (OFIT)	0.593
Minor radius(m)	~0.41 (OFIT)	0.407
Aspect ratio of lcfs	~1.46	1.46
Energetic electron edge location (m)	/	1.218
Energetic electron peak density(m^{-3})	/	3.15E+16 (成分=2.6%)
βt of thermal plasma	**/**	1. 4%
Total βt	/	1.1%
Total βp	/	1.576
Total energy (kJ)	**/**	**4.4**

camera figure

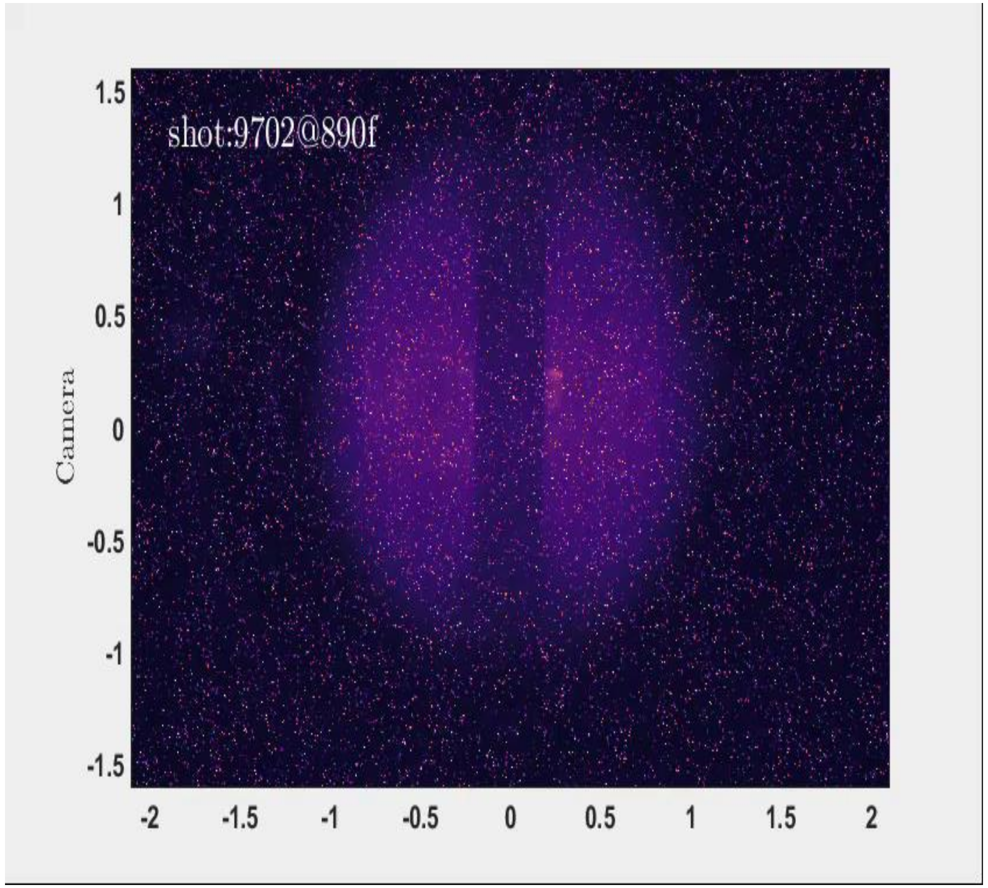


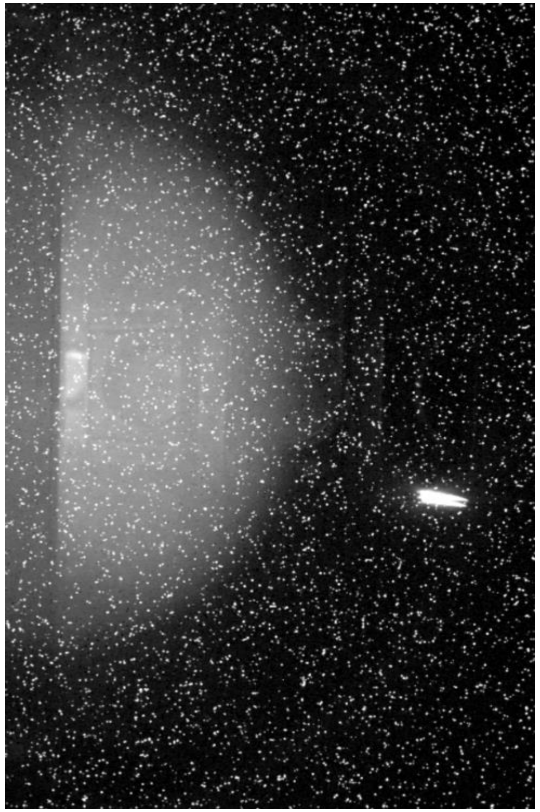
Contours of flux and current density

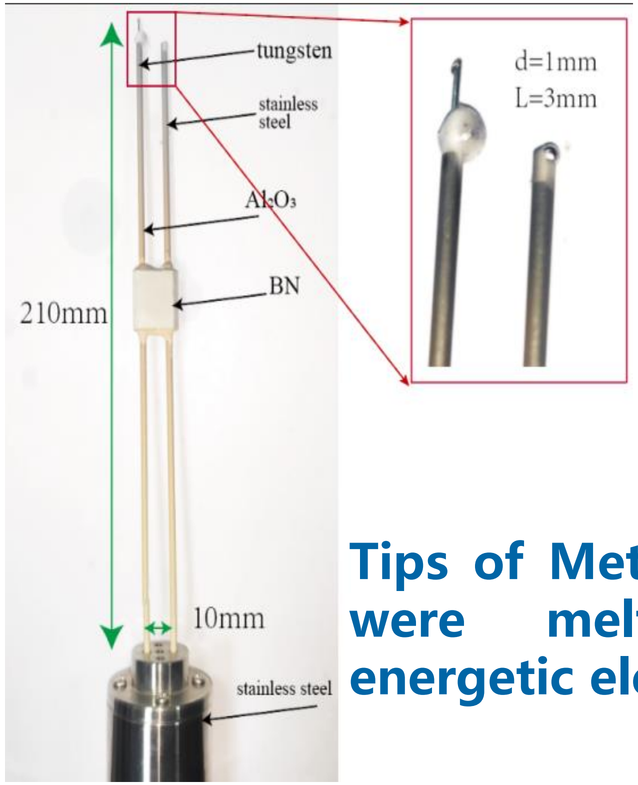


- **Three-fluid equilibrium is shown to exist in EXL-50 by computing equilibrium that nearly reproduces available measurements**
- **Energetic electrons can exist also in open-field-line region, carry most toroidal current, and form LCFS**

Investigation of energetic electrons outside LCFS* → Verification of multi-fluid equilibrium model







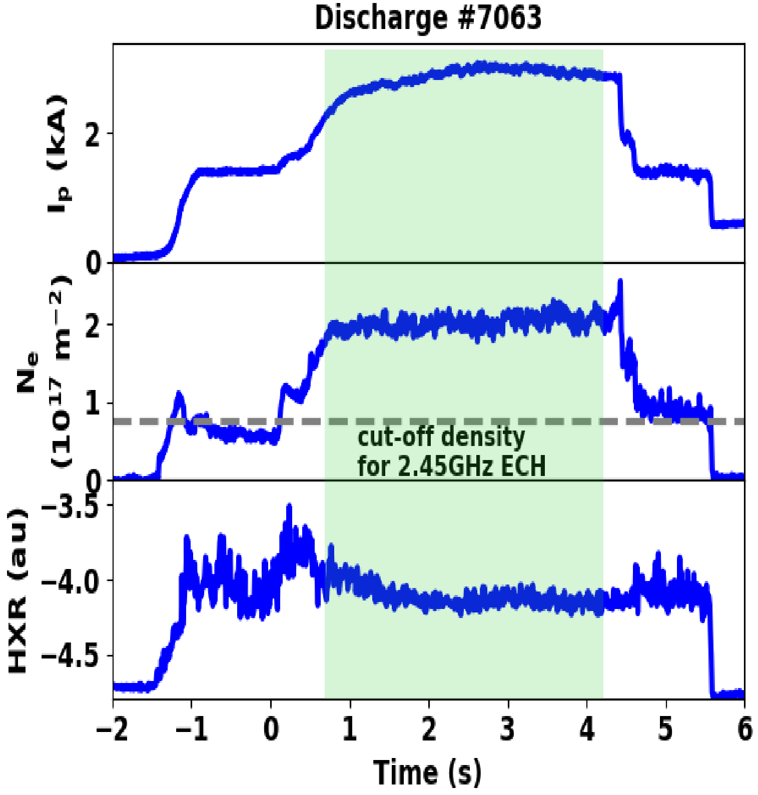
Tips of Metal probe were melted by energetic electrons.

Metal probe far from LCFS are lighting by energetic electrons

* Experimental study of the characteristics of energetic electrons outside LCFS in EXL-50 spherical torus -- D.Guo, Y.J.Shi, W.J.Liu, T.T.Sun, B.Liu et al.; Plasma Phys. Control. Fusion 64(2022)055009

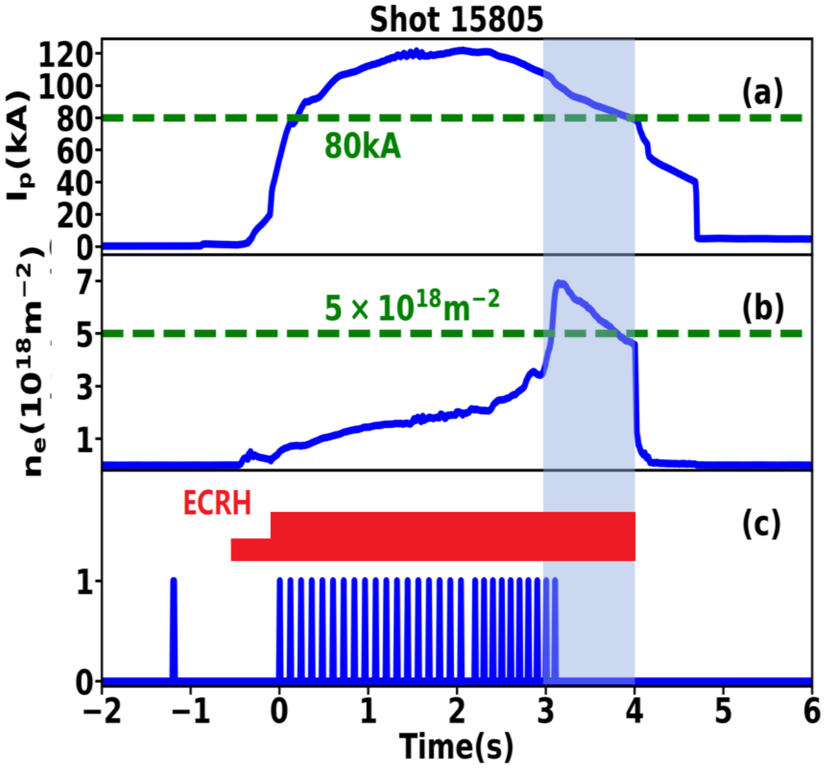
High density current drive experiment on EXL-50

High-density discharges with 2.45 GHz ECRH at low B_t.

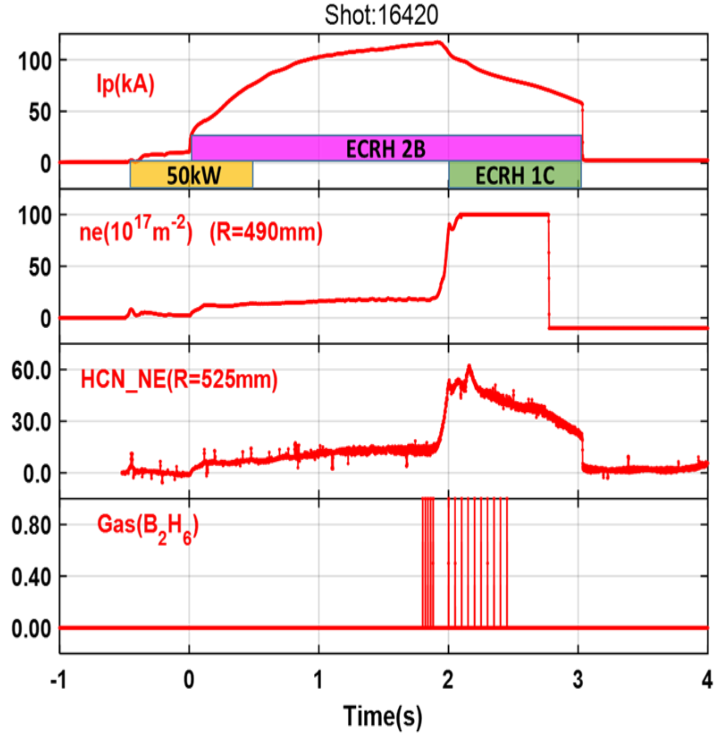


P_{ECRH} is 20 kW. The density is about three times as the ordinary mode (O-mode) cut-off density

High-density discharges with 28 GHz ECRH

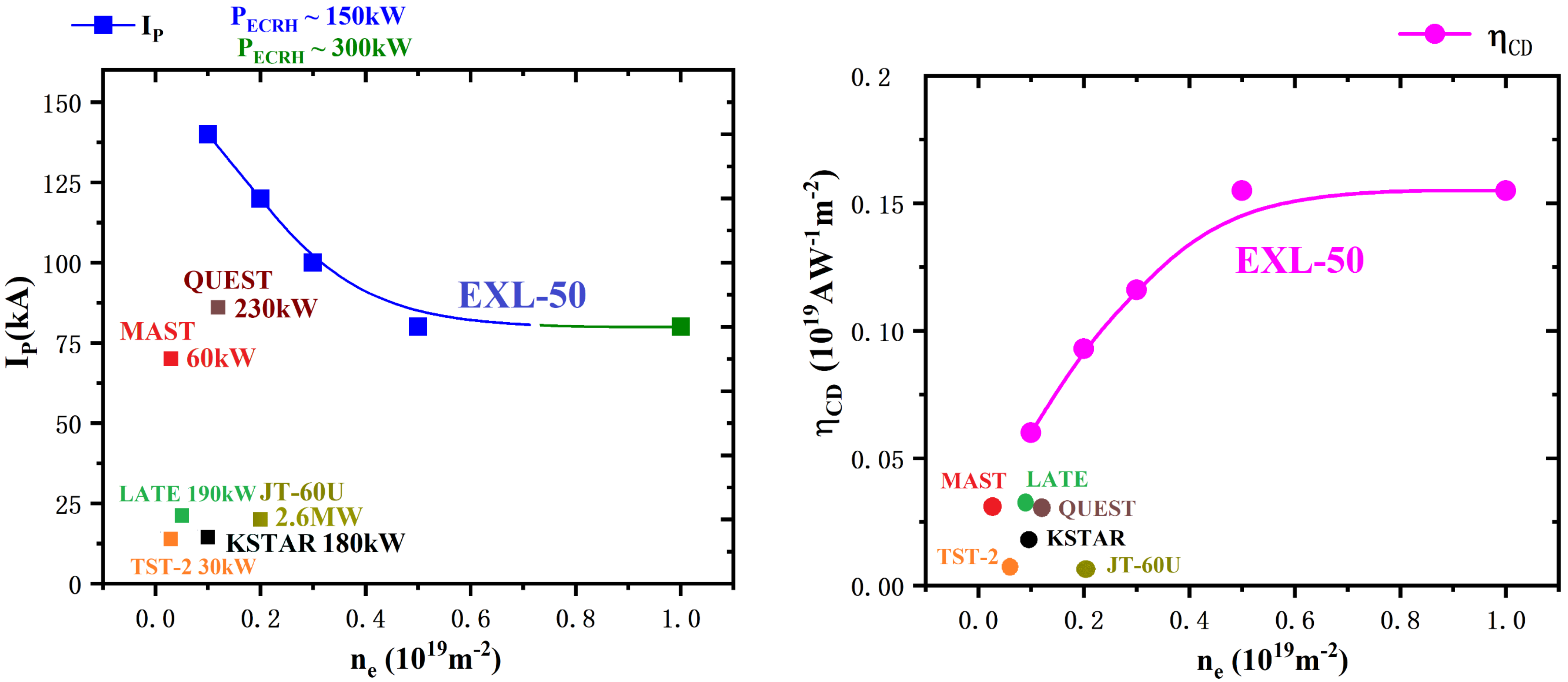


The plasma current reaches Ip > 80 kA for high density (>5 × 10^{18} m^{-2}) discharge with 150 kW ECRH.



High density ($1{\times}10^{19}$m^{-2}) discharge with 300kW ECRH

Survey of CS-free current drive with RF (ECRH or LHCD)



- ➢ **Both the plasma current and current drive efficiency have reached new records in the CS-free RF experiments on EXL-50.**

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Summary of EXL-50 progress

- Demonstration of high efficiency steady-state CS-free current drive with ECRH

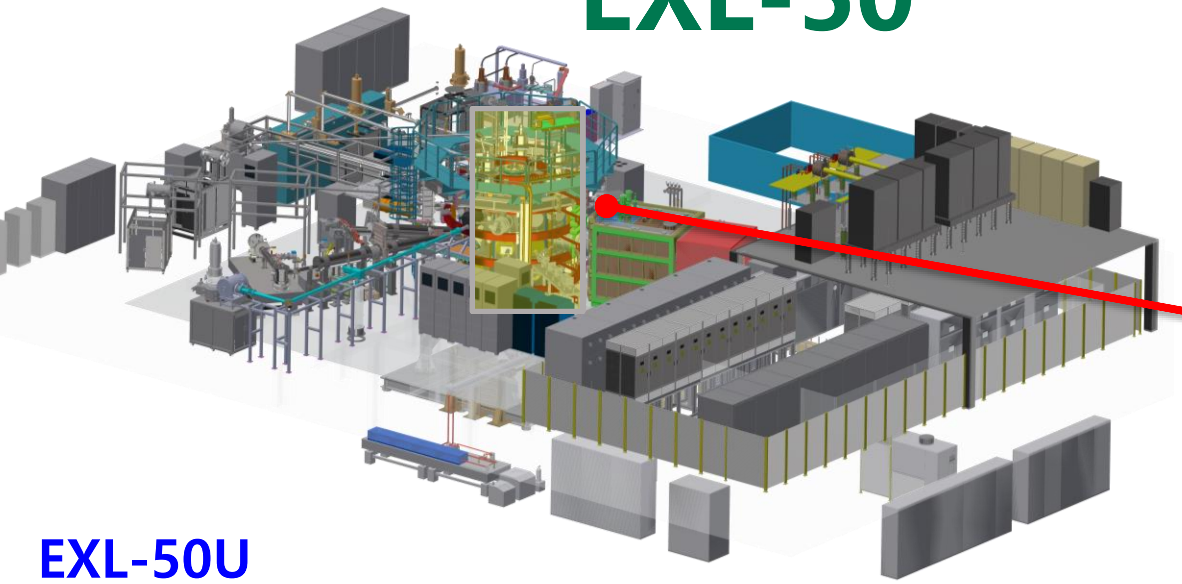
  $\eta_{A/W} \sim 1A/W \qquad \eta_{CD} \sim 0.15\times10^{19}\ AW^{-1}\,m^{-2}$

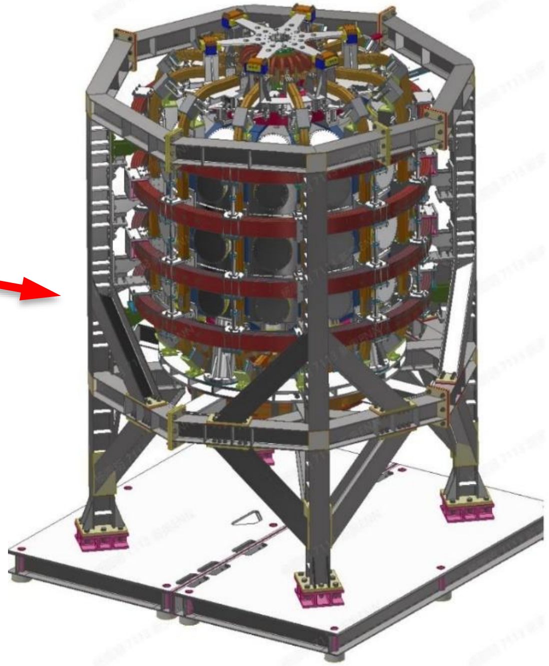
- Experimental verification of multi-fluid equilibrium model
- Achievement of high density ($0.5\sim1\times 10^{19}\ m^{-2}$) current drive with ECRH alone

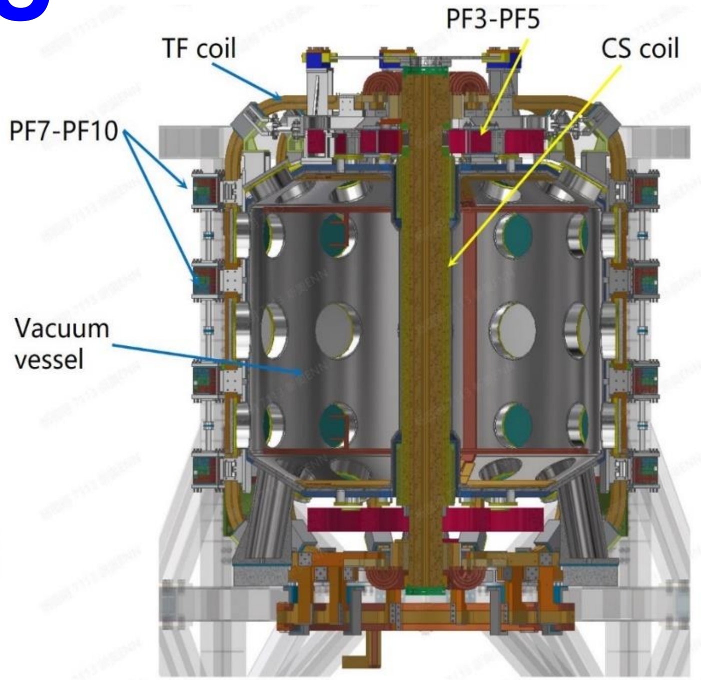
Experiment goal in 2023

- Higher density current drive via 50GHz +28GHz ECRH
- High ion temperature plasma via NBI
- Confirmation of energy confinement time

EXL-50 → 2024 Upgrade → EXL-50U







Cross sectional view of the EXL-50U

EXL-50U

- New vacuum vessel and TF&PF magnetic coils
- $B_t \rightarrow 1.2$ T at R=0.6m
- Flexible plasma shaping and current control

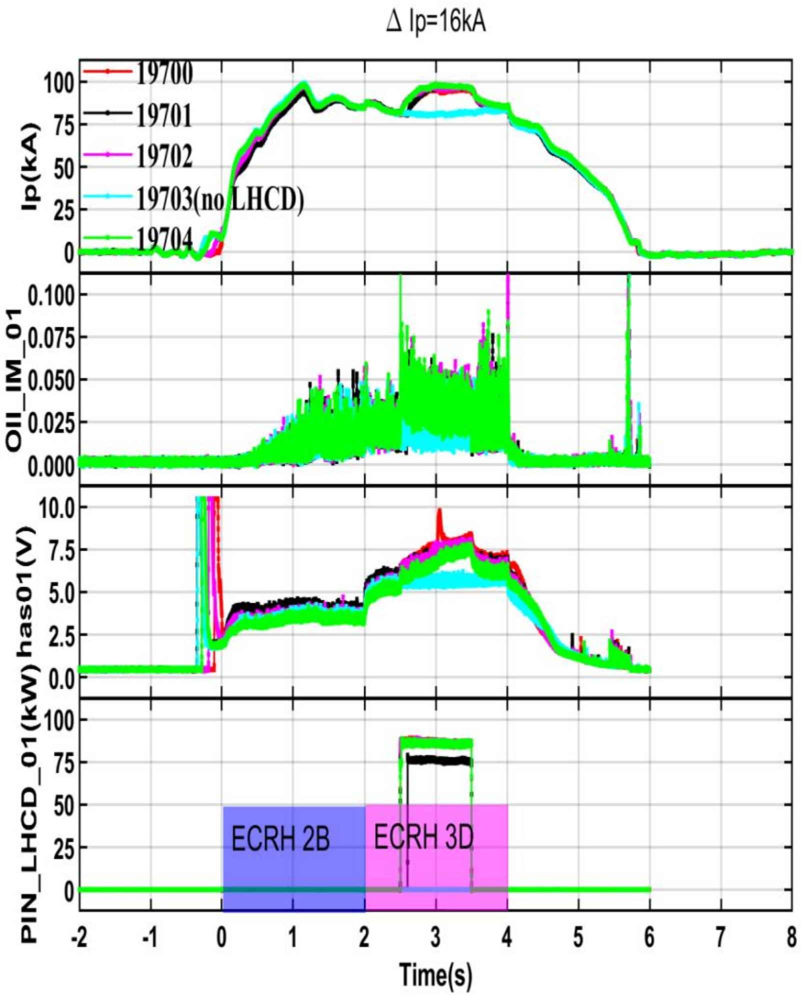
Main physics issues of EXL-50U

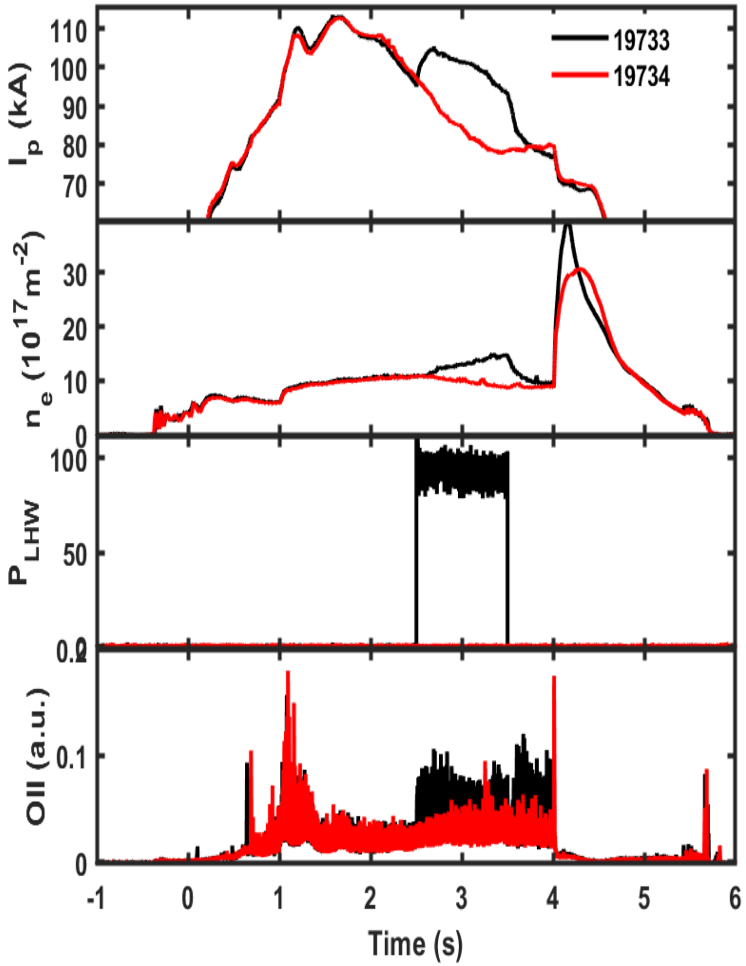
- Hot ion mode for ST ($T_i/T_e > 1.5$, T_i = 3~5keV)
- ST Energy confinement scaling for wide range scan of aspect ratio (1.4~1.8) and B_t (0.5~1.2T)
- Other issues (MA non-inductive current drive ,....)

ENN Vision **To become a respectable, innovative and intelligent enterprise by creating a modern energy system and improving the quality of people's life.**

Welcome to ENN for R&D of p-B^{11} ST fusion research!

Initial LHCD experimental results on EXL-50





100kW LHCD can drive 20kA current in ECRH plasmas

基于玄龙高密度电流驱动实验的推测驱动效率与ECRH频率和磁场的关系

玄龙 2.45GHz 0.1T $\eta_{CD} \sim 0.011\times10^{19}\, MA\, MW\, m^{-2}$

玄龙 28GHz 0.5T $\eta_{CD} \sim 0.13\times10^{19}\, MA\, MW\, m^{-2}$

假定η_{CD}与频率或磁场强相关： $\eta_{CD} \propto f_{ECRH}^{\alpha}$ or $\eta_{CD} \propto B_T^{\beta}$

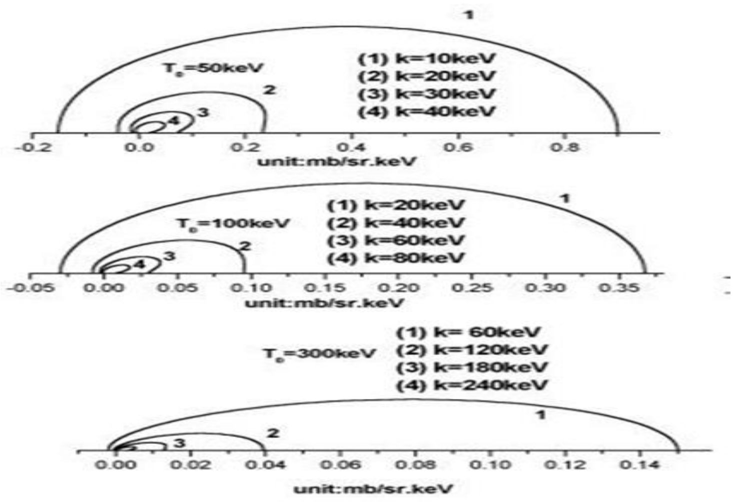
基于玄龙数据： $\alpha = 1,\quad \beta = 1.5$

外推170GHz ECRH和3.5T的ST：η_{CD} ： $0.79\ or\ 2.4\ \times10^{19}\, MA\, MW\, m^{-2}$

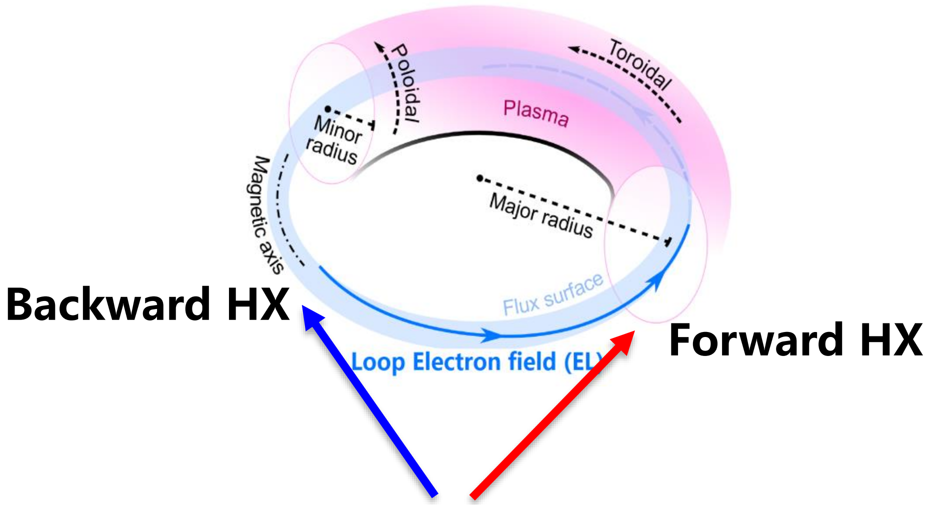
R=1m的3.5T反应堆级别的ST：4-10MW 的170GHz的ECRH可以启动5MA电流（密度$2\times10^{19}m^{-3}$）

➢ **动量分布**

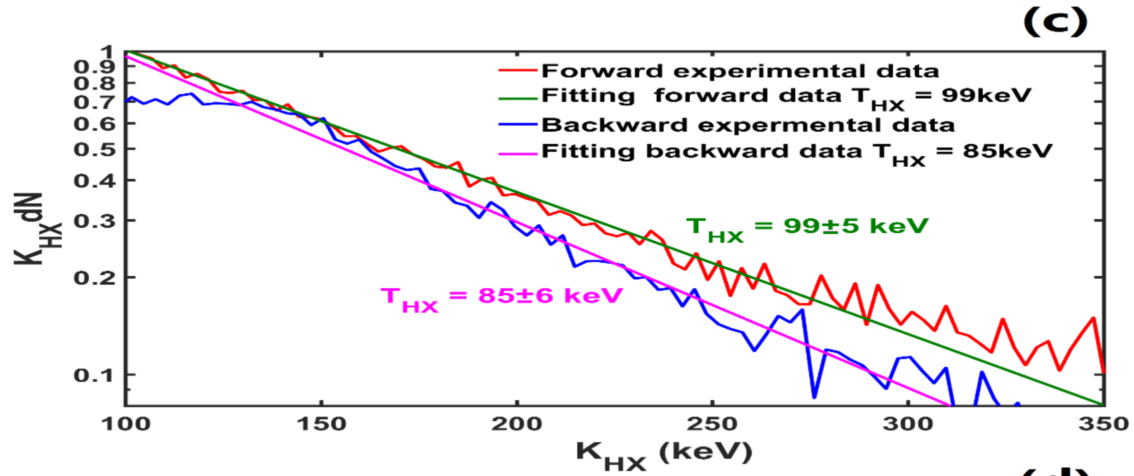
	逃逸电子	超热电子
	$P_{//} >> P_{\perp}$	$P_{//} \sim P_{\perp}$

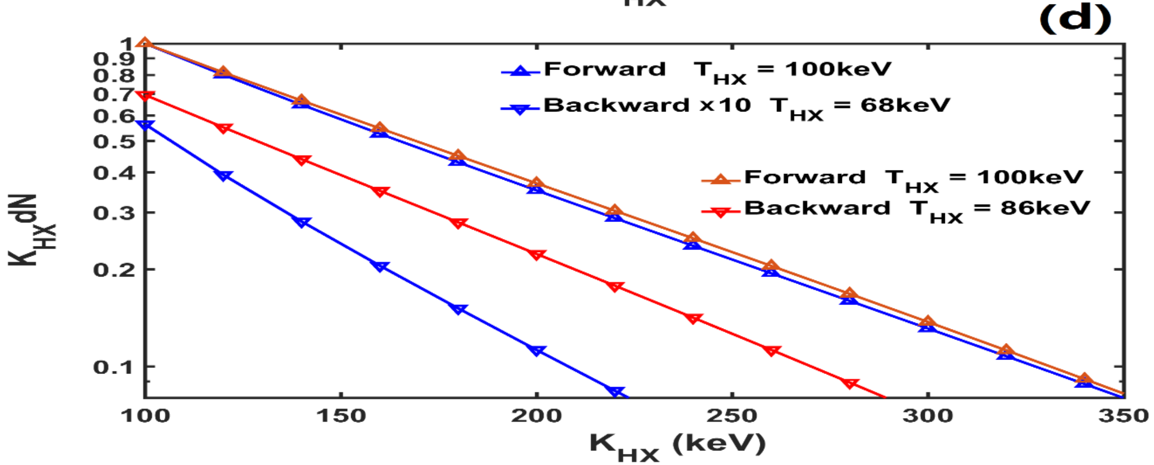


电子-离子韧致辐射产生X射线截面分布



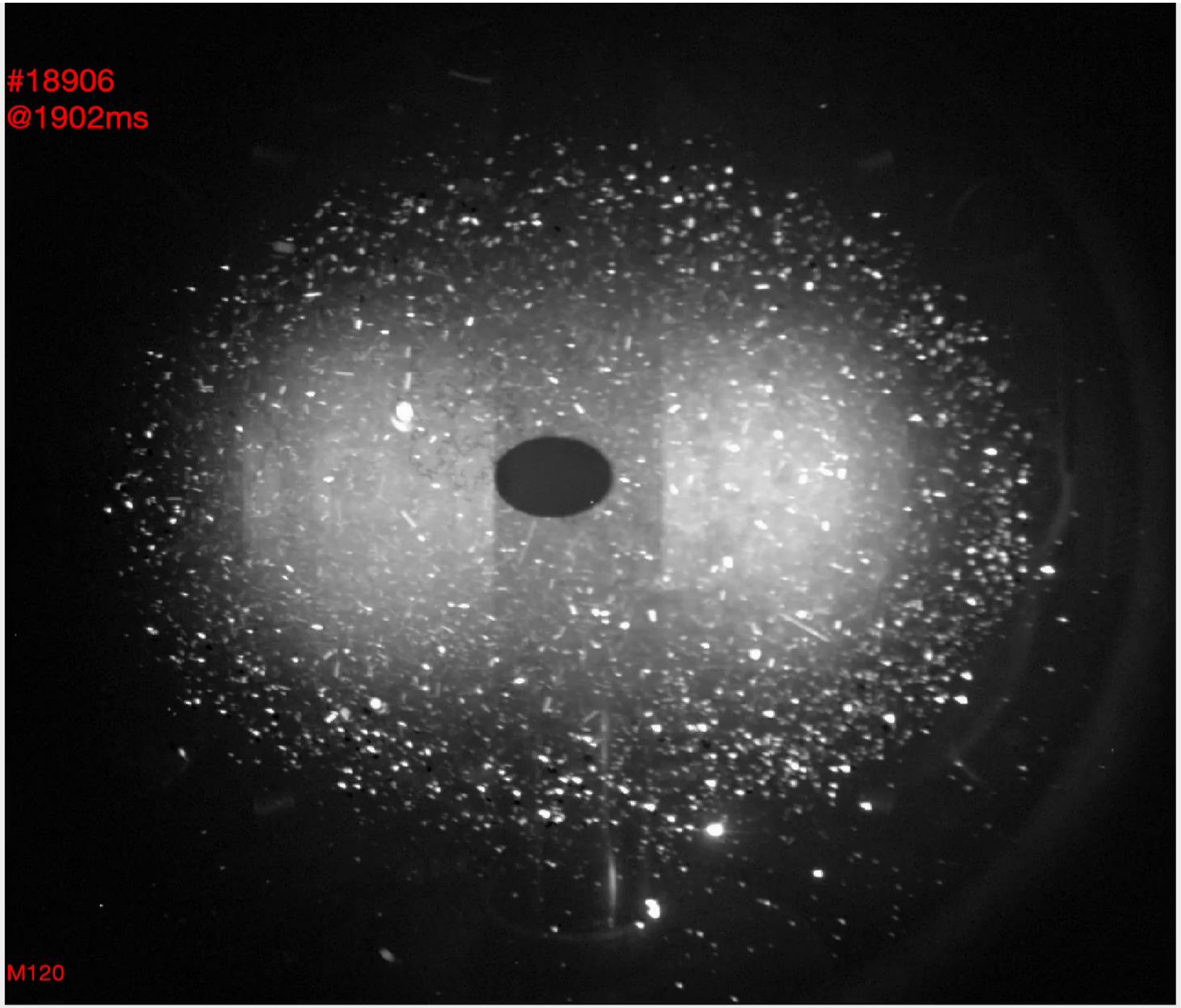
玄龙超热电子动量分布推算



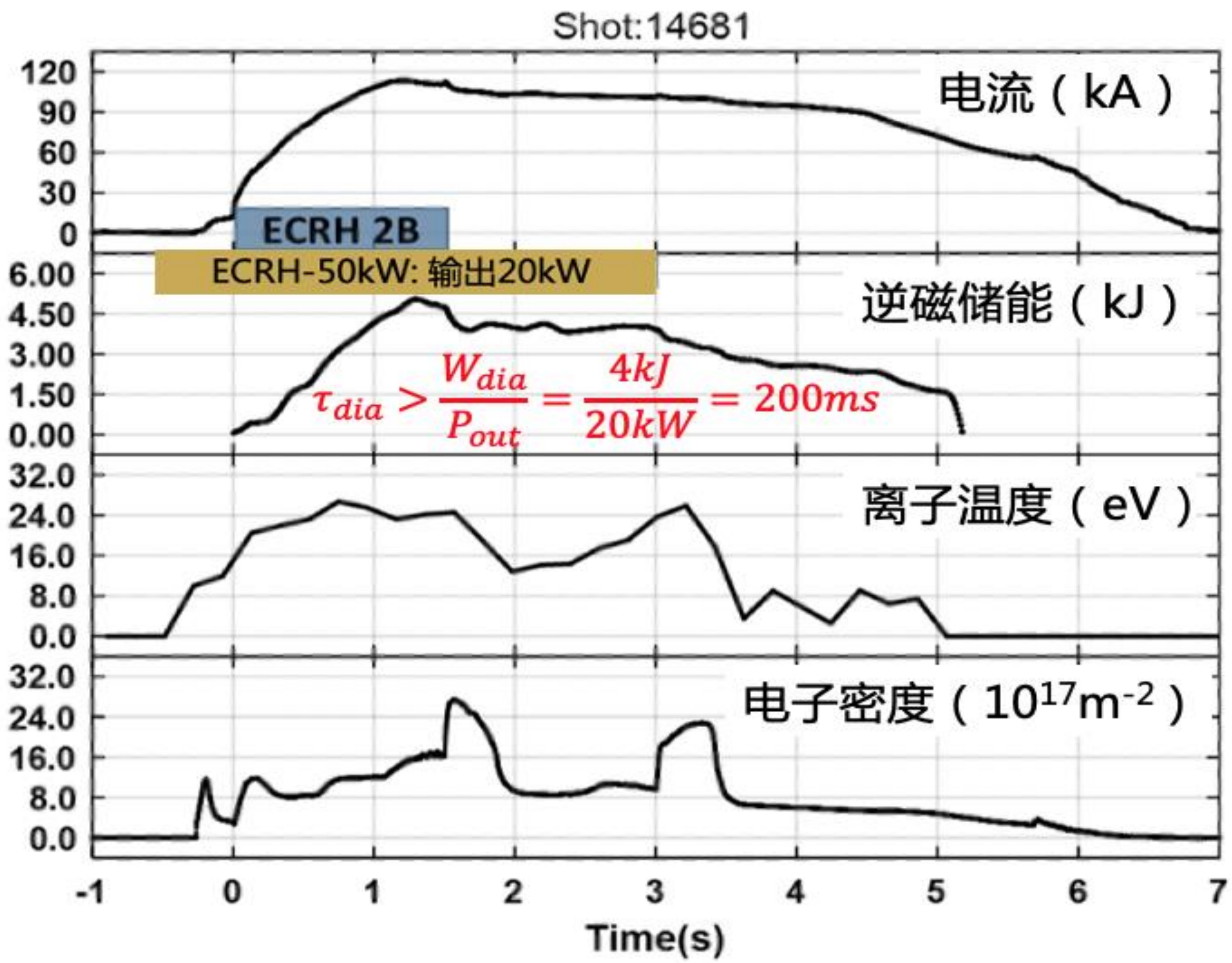


(c) HX实验数据（红色：前向能谱，蓝色反向：能谱）
(d) 三温度模型HX射线模拟数据.
蓝色: $T_{//F}=10T_{\perp}=10T_{//B}$. 对应逃逸电子分布
红色：$T_{//F}=T_{\perp}$, $T_{//B}=0.75T_{//F}$. 对应ECRH产生的高能电子分布.

闭合磁面外存在高能电子



ECRH稳定阶段整体能量约束时间估算（优化运行）

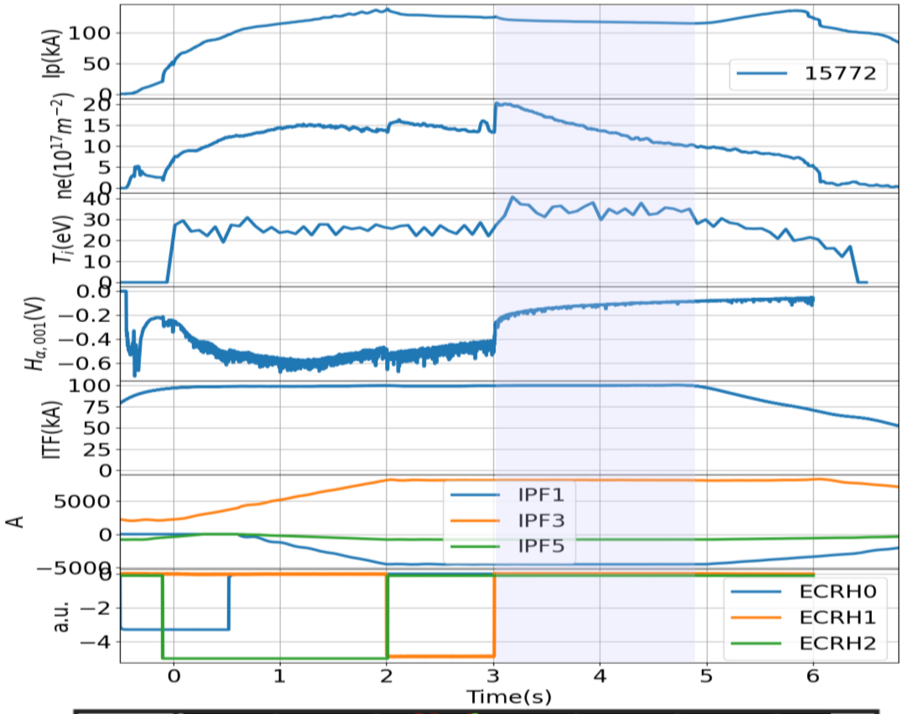


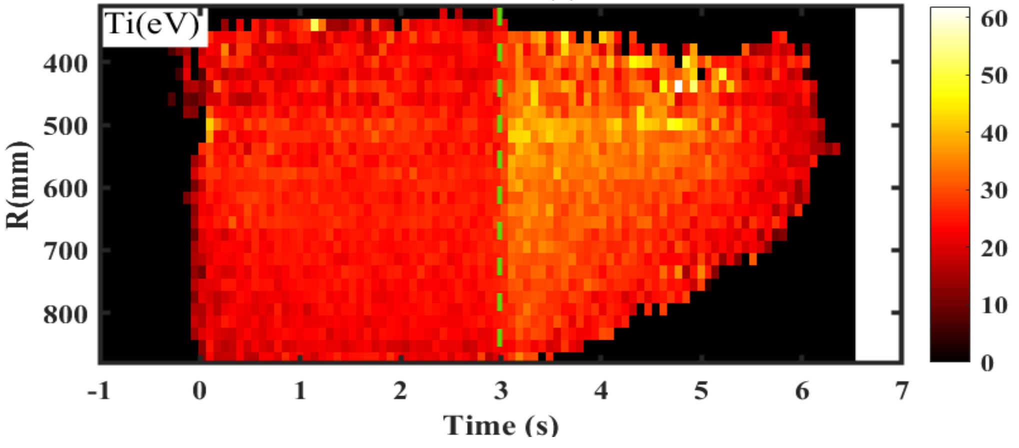
- 基于逆磁测量的整体能量（包含高能电子和主等离子体）约束时间（τ_{total}）分析：
  - ECRH关断：$\tau_{total} > 300ms$
  - ECRH加热：$\tau_{total} = 200-300ms$

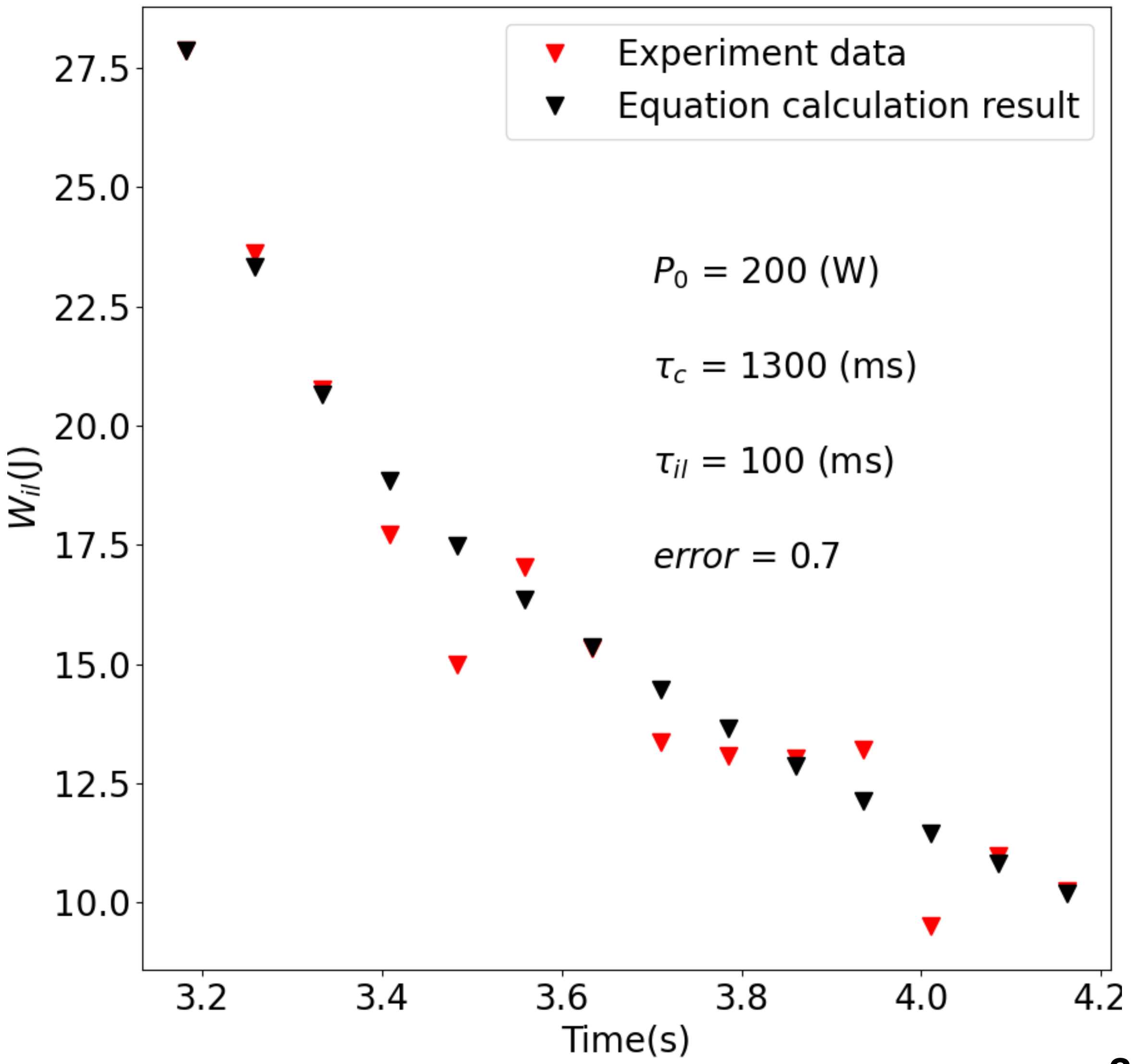
挑战：

- 整体储能中，高能电子贡献占主导，主等离子体贡献较小，估算主等离子体能量约束时间存在较大不确定性
- 需要主等离子体加热，提高主等离子体储能贡献

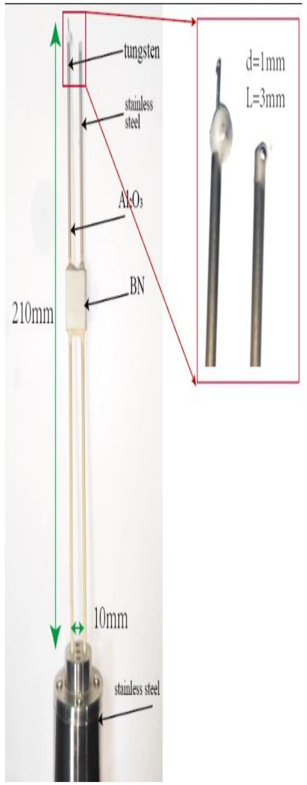
热离子能量约束时间初步估算-15772

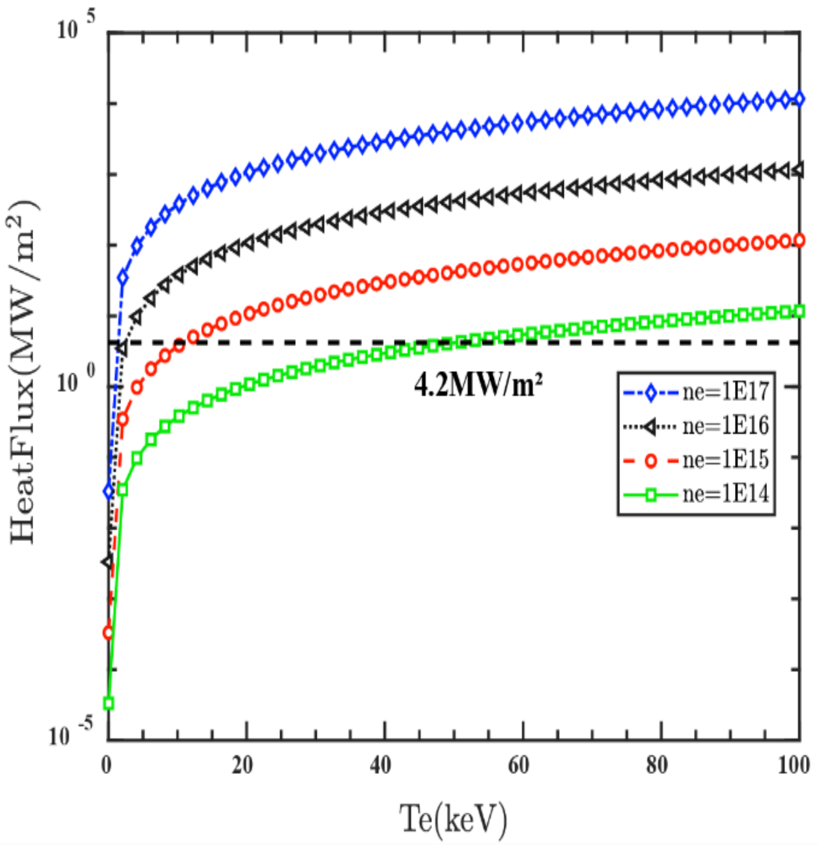


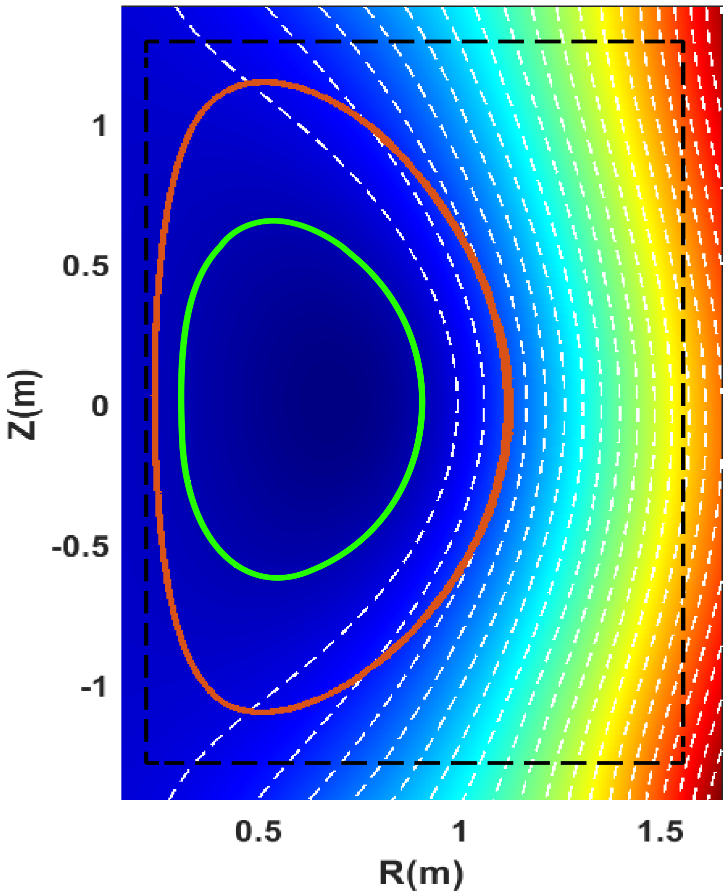




玄龙-50外层超热电子估算







- 工程模拟了可以造成钨融化的边界边界热流阈值 ~4.2MW
- 用边界热流计算公式给出了等离子体的热通量，进而在假设超热电子密度的条件下可以给出探针扫描区域的超热电子平均能量范围。