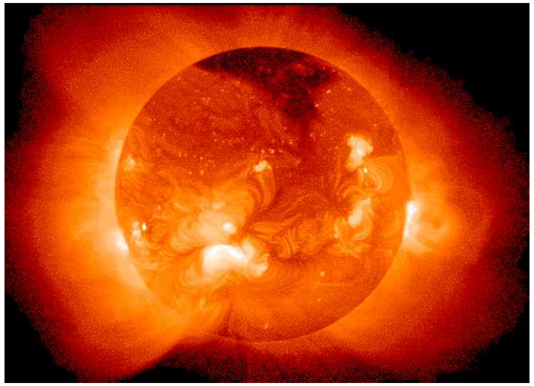
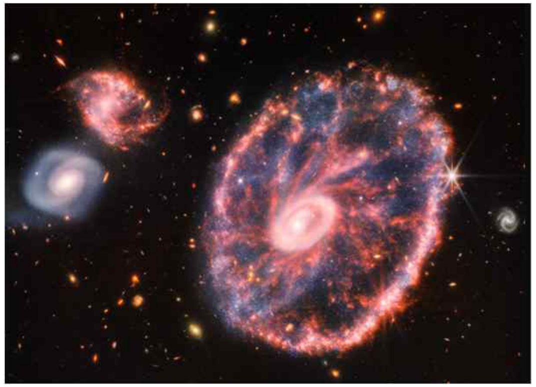
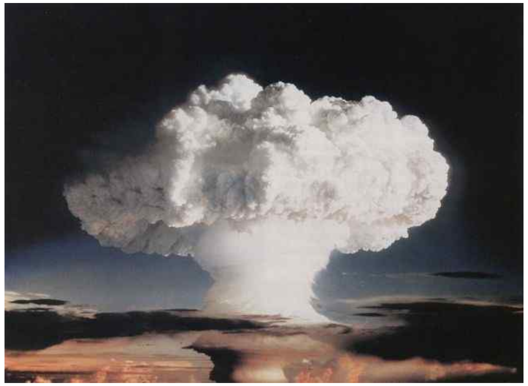
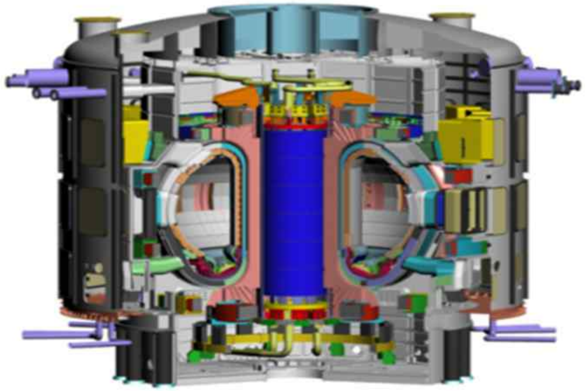
History, Science and Perspective of the Magnetic Fusion



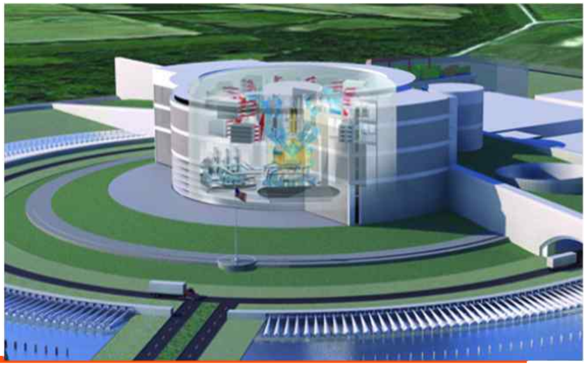






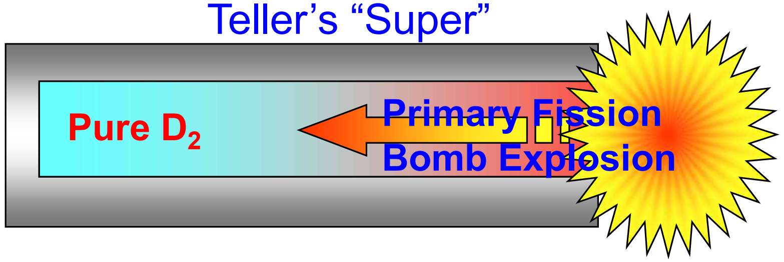
Hyeon K. Park
Ulsan National Institute of Science and Technology

Colloquium at LLNL
on
February 15, 2024



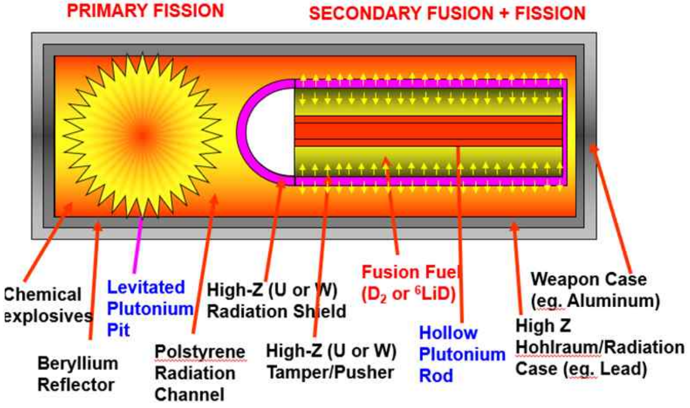
Fusion (D^+ + Li_6} Experiment (1950s) followed by "Oppenheimer"

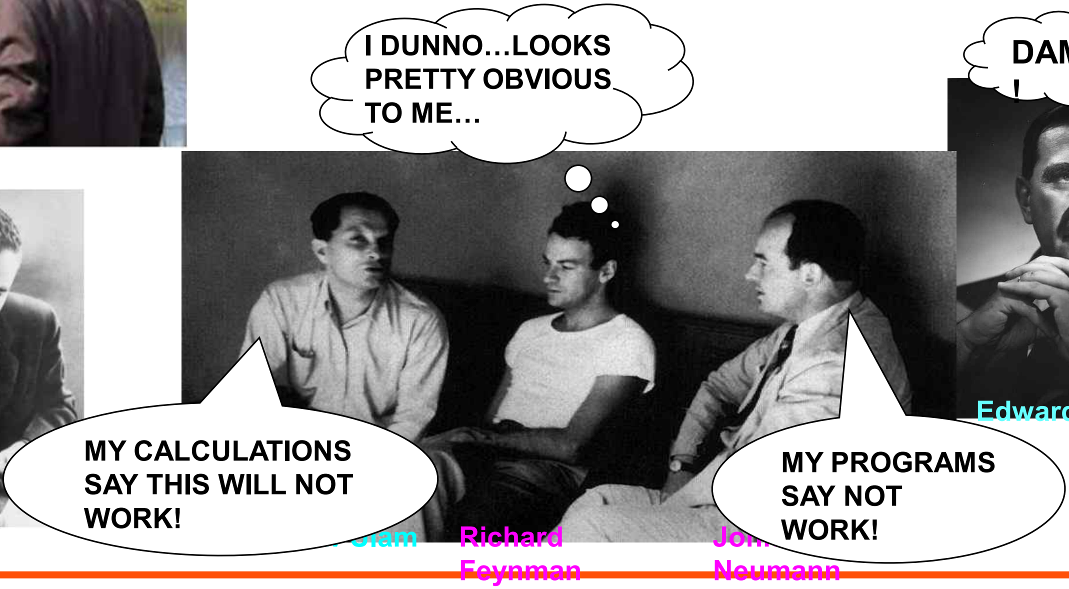
Teller's "Super"

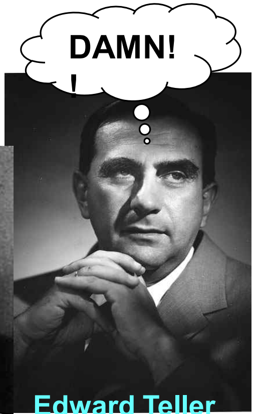


Fusion Ignition (heated by the intense radiation from the primary fission explosion)

Teller & Ulam design







"Bravo" 1954, Bikini Atoll,
LiD Fuel (Est 5 Mt Actually 15 Mt!!)

Current success of Ignition experiments at LLNL will accelerate Teller's dream (Machine gun laser fusion)

Historical Progress

History and progress of toroidal fusion devices

Evolution of operation modes and confinement scaling

Progress toward ignition and ITER

The Beginning of the Fusion Concept

1928: *Concept of fusion reaction – energy radiated by stars [R. Atkinson & F. Houtermans, Physik, **54** (1929)]*

- J. Jeans was skeptical; A. Eddington retorted: " I suggest they find a hotter place"

1932: *Fusion reactions discovered in laboratory by M. Oliphant*

- Lord Rutherford felt possibility of fusion power using beam-solid target approach "moonshine"

1935: *Basic understanding of fusion reactions - tunneling through Coulomb barrier – G. Gamow et al.*

- Fusion requires high temperatures (~10keV for DT)

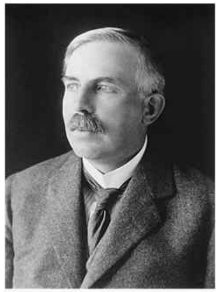
1939: *Fusion power cycle for the stars: H. Bethe*

- Nobel prize 1967 "for his theory of nuclear reactions, especially his discoveries concerning the energy production in stars"


Robert Atkinson

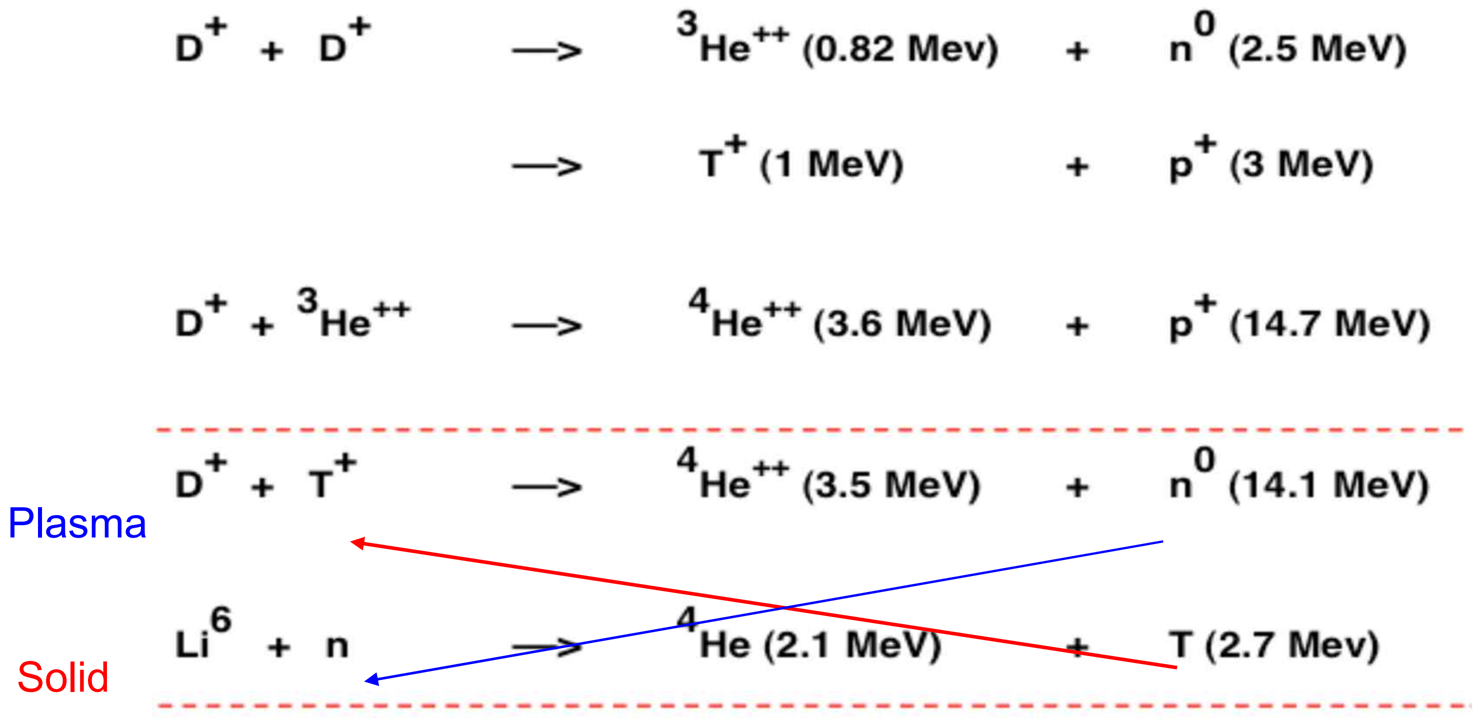

Fritz Houtermans


Oliphant in 1939


Rutherford c. 1920s


Gamow, George | Departme...
physics.columbian.gwu.edu

Fusion Reactions of Interest for Terrestrial Fusion Power



$D^+ + D^+ \longrightarrow {}^3He^{++}$ (0.82 Mev) $+\ n^0$ (2.5 MeV)

$\longrightarrow T^+$ (1 MeV) $+\ p^+$ (3 MeV)

$D^+ + {}^3He^{++} \longrightarrow {}^4He^{++}$ (3.6 MeV) $+\ p^+$ (14.7 MeV)

$D^+ + T^+ \longrightarrow {}^4He^{++}$ (3.5 MeV) $+\ n^0$ (14.1 MeV)

Plasma

$Li^6 + n \longrightarrow {}^4He$ (2.1 MeV) $+\ T$ (2.7 Mev)

Solid

Fuel Cycle $D^+ + Li^6 \longrightarrow 2\ {}^4He + 22.4$ MeV

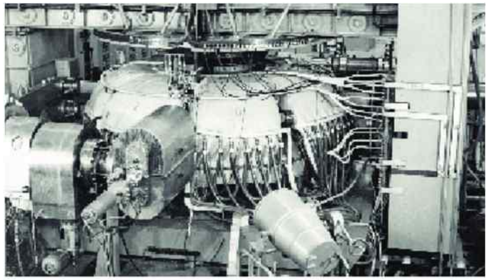
- DT burn is easiest at Ti~10keV and advanced reaction needs even higher Ti

Large Tokamak era and Superconducting Tokamaks

1958: *Concept of Tokamak [Igor Tamm and Andrei Sakharov]; T3 (~1keV of Te by UK team)*

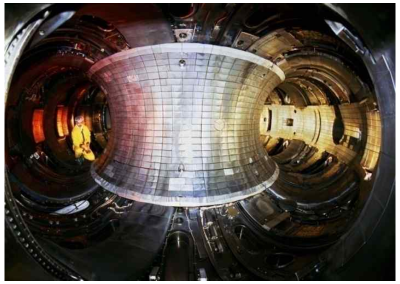
1960: *US, JAPAN, EU initiated many interesting programs and IAEA led the worldwide fusion research*

1980: *Three large tokamak era: Cu coils (pulse length is limited by the cooling system < ~ 20sec.)*

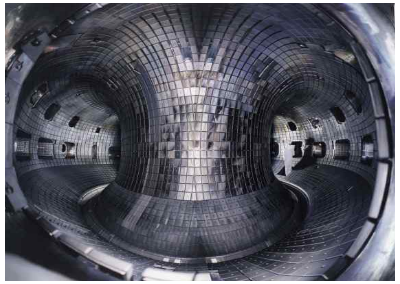


The T-3A tokamak at the Kurc n around 1967; reproduced wit
ermission from the NRC 'Kurc

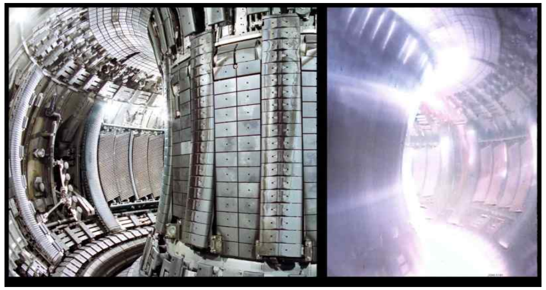
T3 tokamak



TFTR (US)

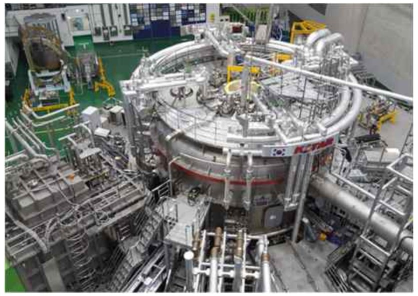


JT60-U (Japan)

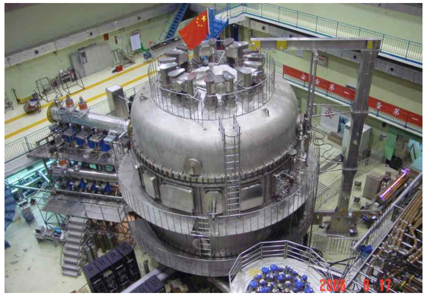


JET: (EU)

2000s: *Steady state capable devices are critical for physics and engineering basis*



KSTAR, Korea



EAST, China

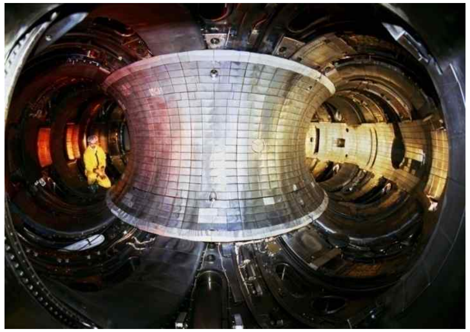
LHD, Japan

Wendelstein 7-X, Germany

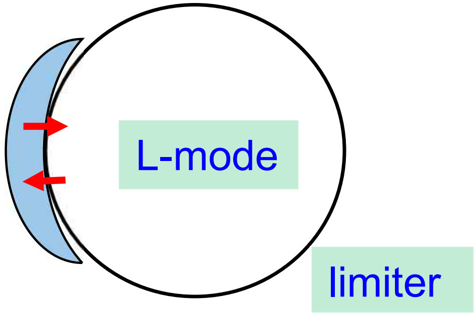
JT-60SA, Japan.

Evolution of Toroidal Plasma Operation Mode

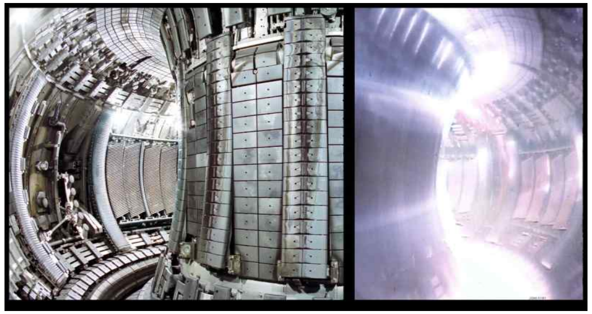
- ❑ *Circular plasma with limiter*
  - ❑ *Confinement time is low - L-mode*



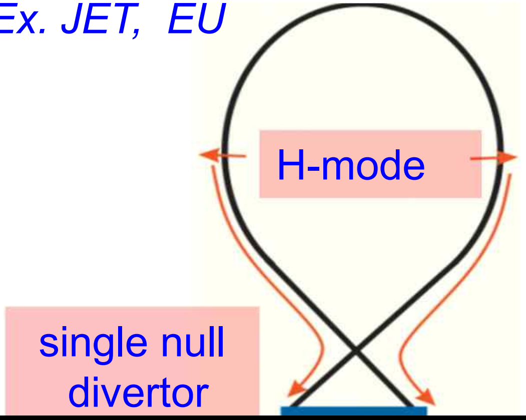
Ex. TFTR, USA



- ❑ *Shaped plasma with divertor*
  - ❑ *Confinement time is high – H-mode*

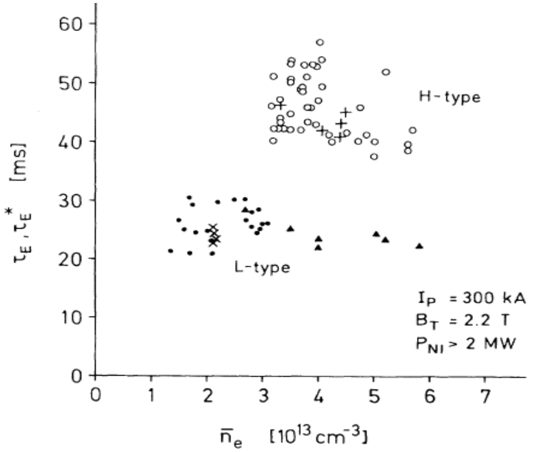


Ex. JET, EU



- ❑ *ASDEX, Germany: first divertor plasma*
  - ❑ *H-mode was discovered and physics of H-mode has been pursued for 4 decades*
  - ❑ *Turbulence suppression physics became social program*

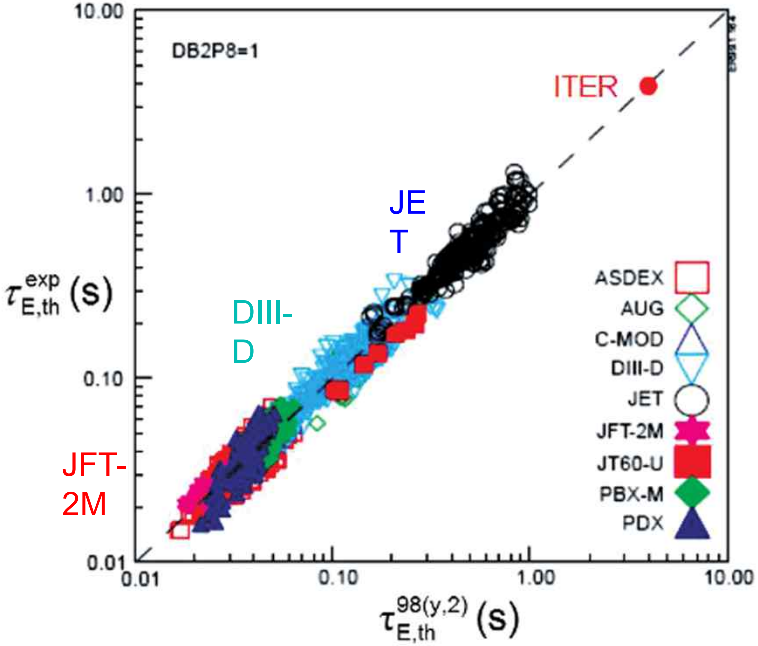
(F. Wagner, PRL, 1982)

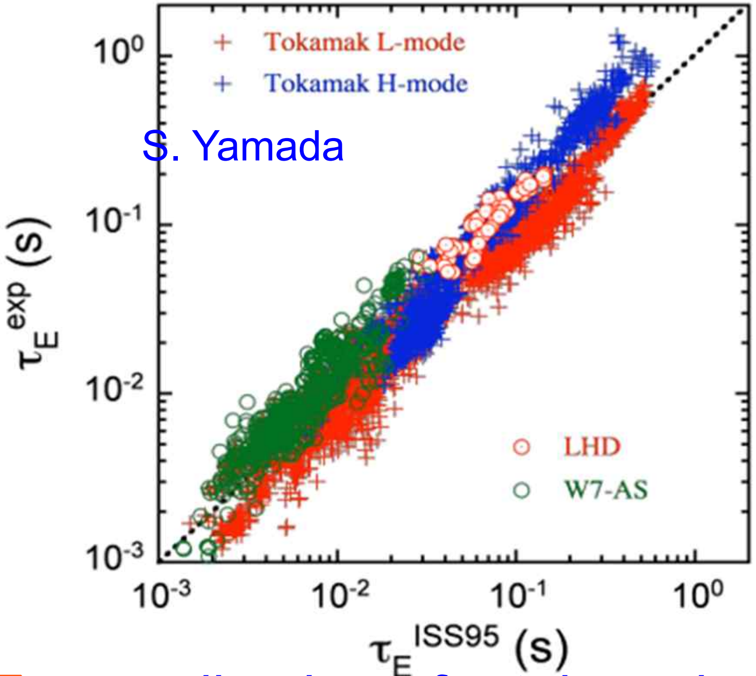


Discovery of "H-mode" was a hope for magnetic fusion in a relatively smaller device

Basis of the Magnetic Fusion Device is Scaling laws

Lawson's criterion - $n_e \tau_E > 1\text{x}10^{20} s/m^3$ at T_i~10keV





$$\tau_E = \frac{n(T_e + T_i)}{P_H}$$

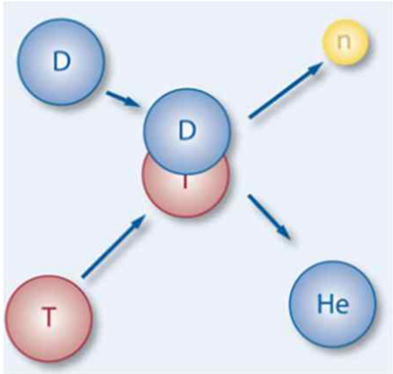
P_H: no distinction of heating sources

- *Clear size dependence (R and a)*
- *ITER size can achieve τ_E~5 sec*
- *τ_E scaling laws for tokamaks and stellarators are quite similar and ITER size stellarator can have τ_E~5 sec*

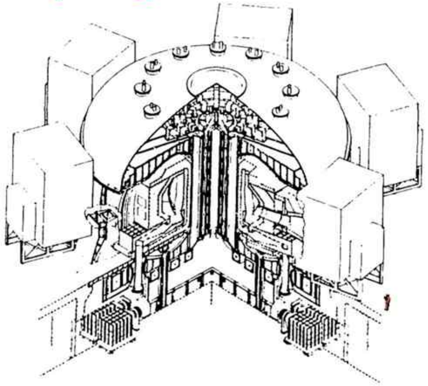
Scaling data for tokamak plasmas are dominated by ion heating system

International Fusion Program (ITER)

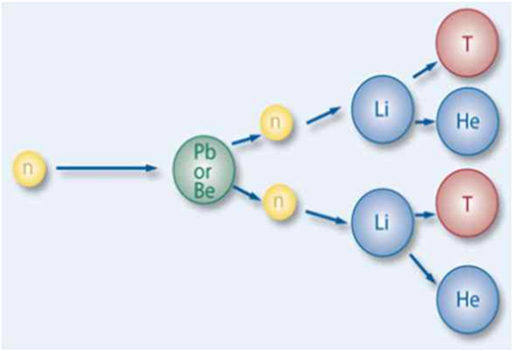
- *INTOR project (1978)*
  - *Objective and design were very much like the current ITER*
  - *3 years effort by international steering committee*
  - *Transformed into ITER program in 1987*



α-heating

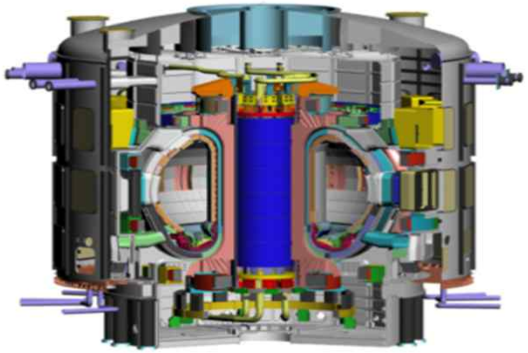


Rendering of INTOR



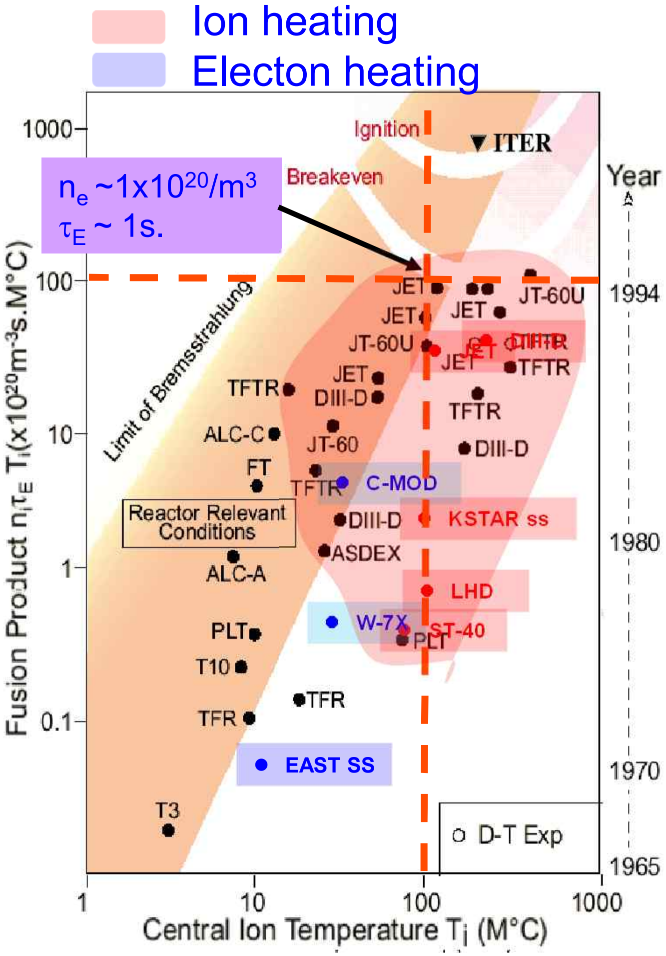
Tritium breeding

- *ITER Project*
  - *The first ITER proposal was based on L-mode (~1GW)*
  - *Current ITER is based on H-mode (~500MW) – reduced size*
- *ITER design and performance are based on scaling laws and performance projection from tokamak data including DT experiments*



Rendering of ITER

Performance data for the last half century



$$n\tau_E T_i = n\frac{n(T_e+T_i)}{P_H}T_i \cong \frac{n^2T_i^2}{P_H} = \frac{W_i^2}{P_H} \propto \frac{S_n}{P_H} = Q$$

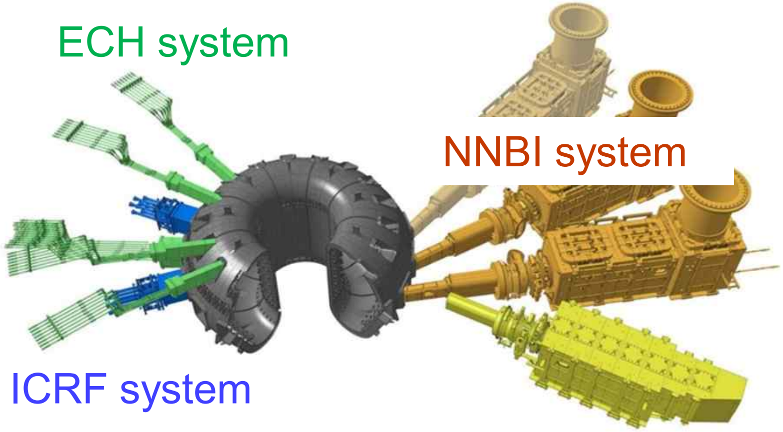
for discharges with $T_i >> T_e$

- *Heating system is critical (discharges with ion heating system dominates high Q discharges)*
- *$n_e\tau_E T_i$ ~ 1x10^{23}m^{-3}sM^{0}C (ignition condition) is the target of the ITER?*
  - *τ_E~5 seconds is from scaling law ($\tau_E(0)>>5$)*
  - *n_e > 1x10^{20}m^{-3} is feasible with higher B_T and I_P*
- *T_i >>10keV is necessary for ignition in ITER*
  - *"Super H-mode" type with "electron heating" is the only choice*
- *What is "Super-H mode"?*
- *What is the choice of heating system for ITER?*

History repeats and high performance data (Ti>10keV) are dominated by ion heating

Heating Systems in Magnetic Confinement Device

- ☐ Ion heating system: direct ion heating
  - ➢ PNBI: Positive Neutral Beam Injection [PNBI]- beam energy up to - 120 keV
    - ✓ Effective and widely used technology
    - ✓ Application to large device/high density has limit
- ☐ Electron heating system: indirect ion heating
  - ➢ NNBI: Negative Neutral Beam Injection [NNBI]- beam energy above - 250 keV
    - ✓ Effective current drive
    - ✓ Technically challenging and expensive
  - ➢ ECH/LH/ICRF: Narrow resonance layer
    - ✓ ECH: application to high field/high density device is technically challenging and expensive
    - ✓ ICRF/LH needs many antennas for high power application: coupling uncertainty makes deposition power uncertain



Latest news: ~60MW ECH for heating

Rendering of ITER heating systems

ICRF and LH systems on Tore-Supra, CEA

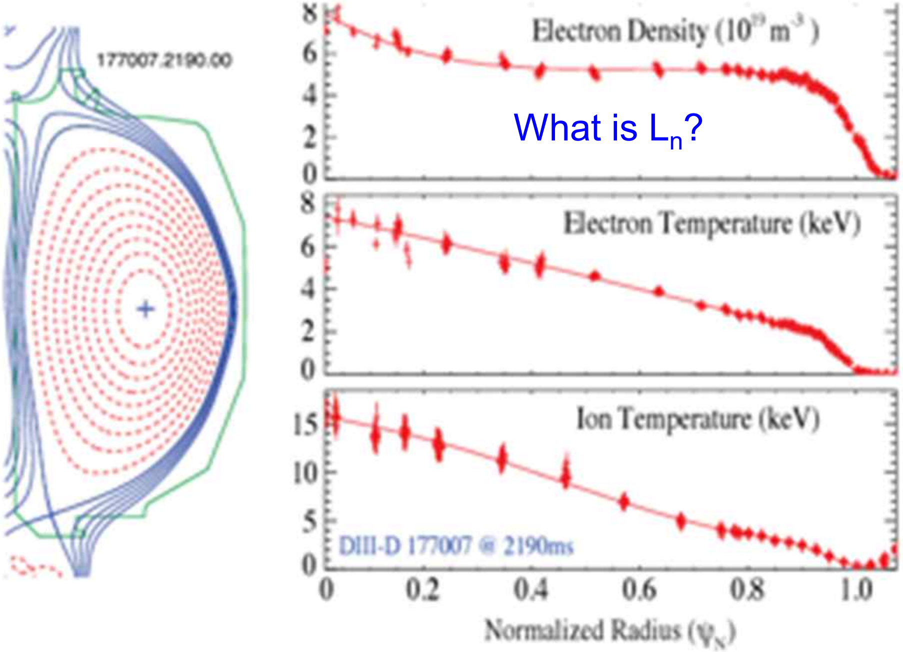
Ion heating sysem has advantage over the electron heating system

Evolution of Improved Confinement regimes

- *L-mode edge → L-mode, Supershot, RS, ERS, High-β_P, Hot ion mode, etc.*
- *H-mode edge → H-mode, VH-mode → Super H-mode, I-mode and Hot ion mode*
- *Basis of these modes of operation? ITG marginality η_I (=L_n/L_{Ti})?*

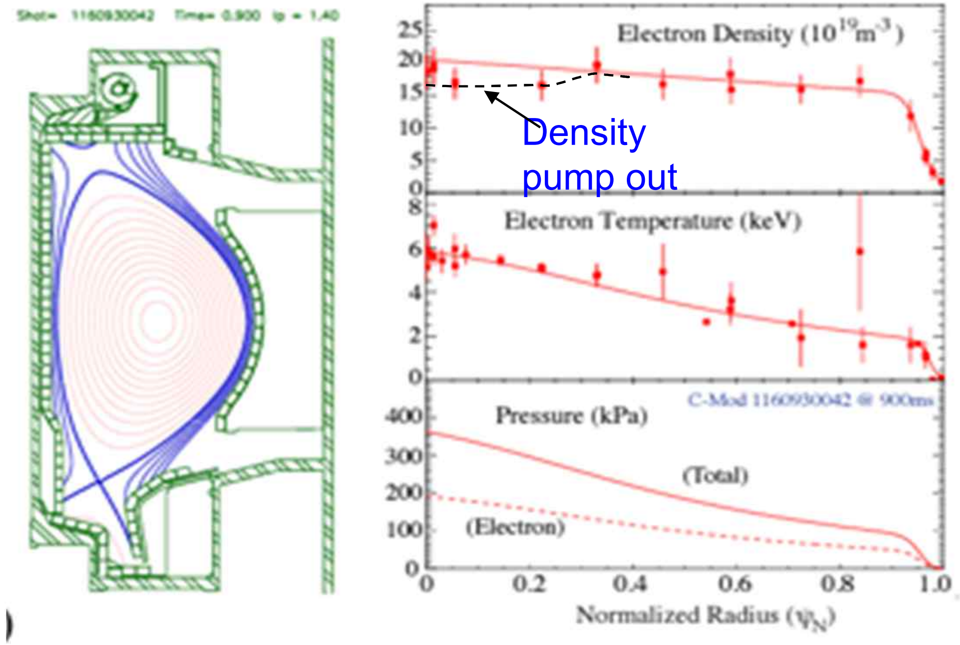
Examples of the best performance so far (“super H-mode”)

DIII-D: (T_i/T_e>1) Ion Heating (PNBI) & T_e clamping



What is L_n?

(C-MOD:T_e/T_i>1) Electron Heating (ICRF) & T_i clamping



Density pump out

Confinement Physics

Magnetic configuration and intrinsic transport

Heating systems for toroidal plasmas

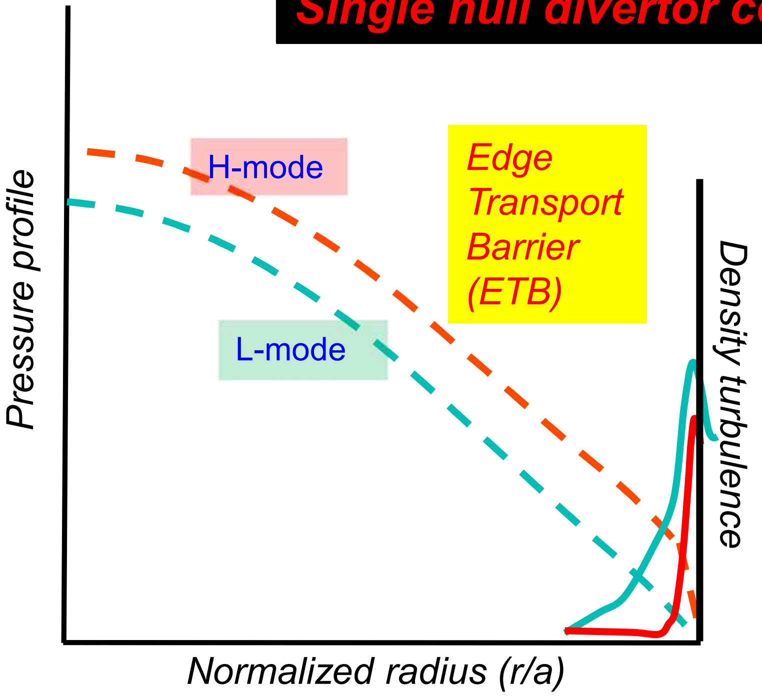
Turbulence suppression is the answer?

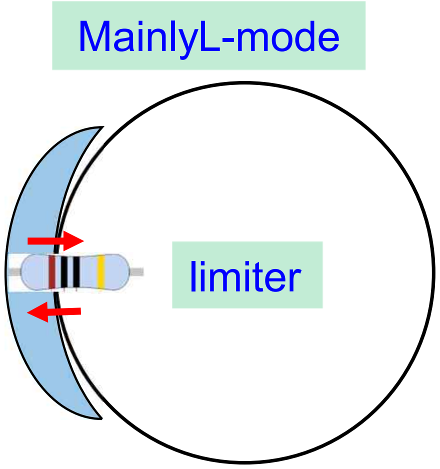
Source of edge pedestal pressure and turbulence (Origin of H-mode and and L-mode)

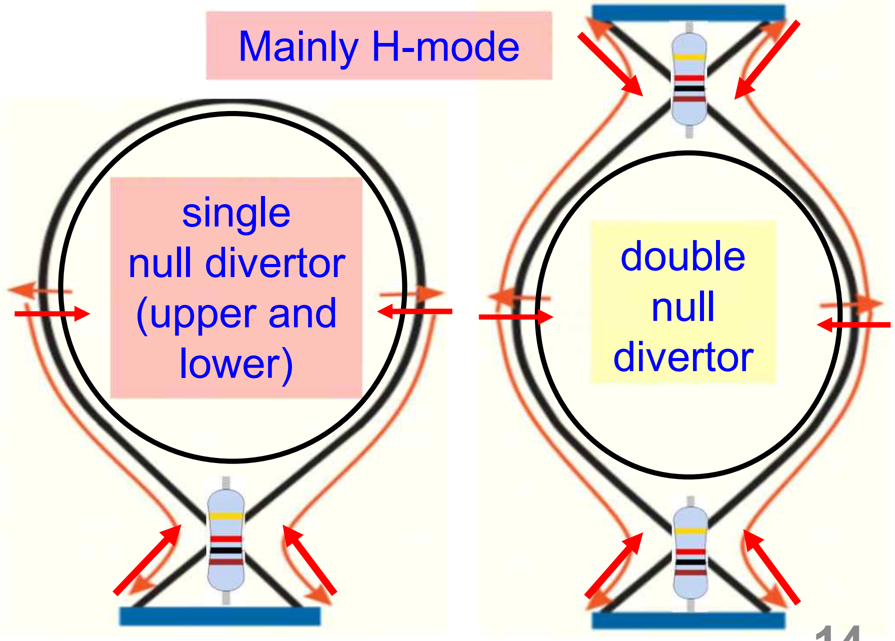
Plasma Pressure Profiles and Magnetic Configurations

- Plasmas/limiter (mainly L-mode): Easy flow of plasma (low impedance) in & out of the LCFS
- Plasmas/divertor (mainly H-mode): Difficult flow of plasma (high impedance) in & out of the LCFS
  - Multiple X-point system is similar to the limiter case ($1/R = 1/R_1+1/R_2+1/R_3+\ldots.$)
  - Transport of the core plasmas in two magnetic configurations should be the similar

Single null divertor configuration is the best choice for confinement

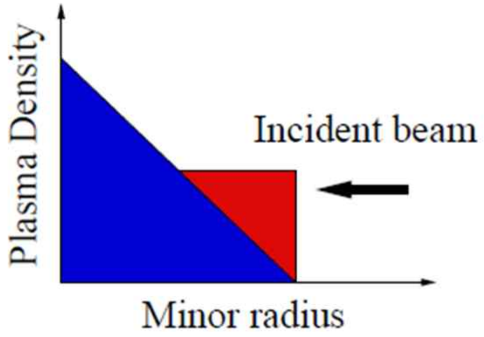




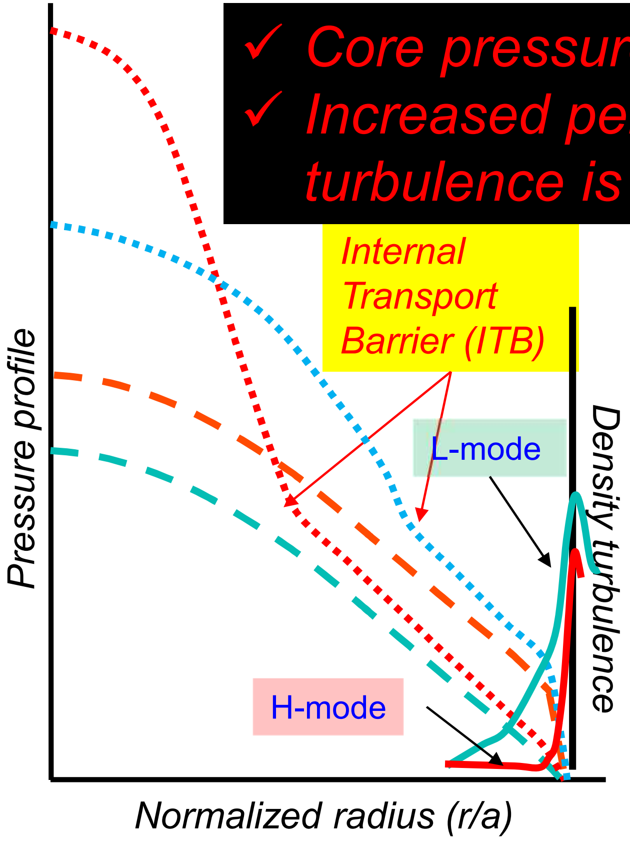


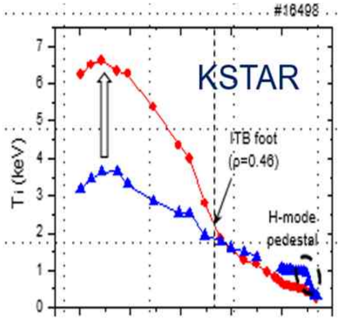
Pressure Profiles of Improved Confinement with ITBs

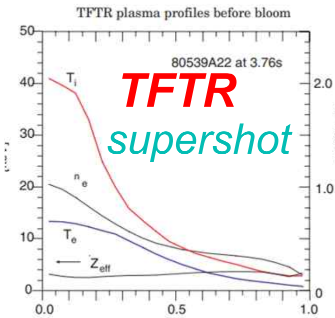
- ❑ *Improved core region has lowest turbulence level (suppress further??)*
- ❑ *ITB ($T_i/T_e>1$) is primarily driven by foot-prints of beam fueling (TFTR, JT-60U, JET, DIII-D, KSTAR, etc. have similar NBI geometry) (H. Park)*

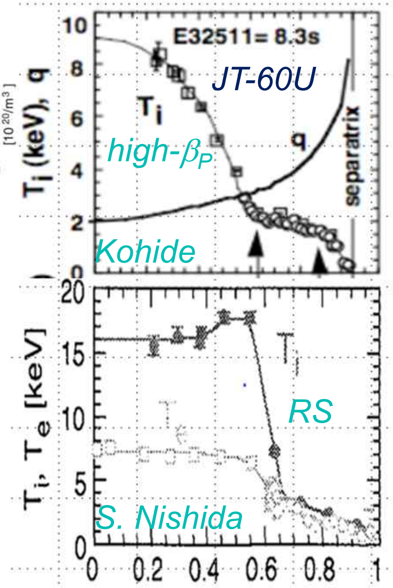


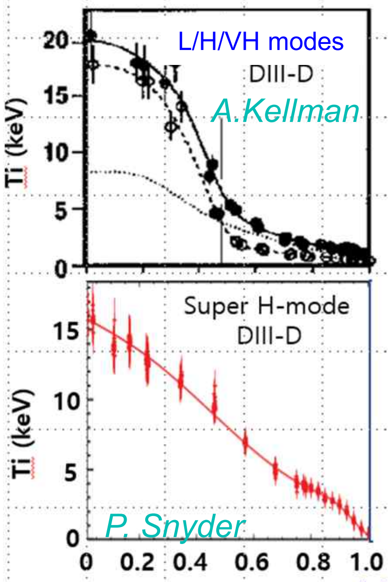
- ✓ *Core pressure increase is primarily from core heating*
- ✓ *Increased performance is mainly where the turbulence is lowest (core region)*







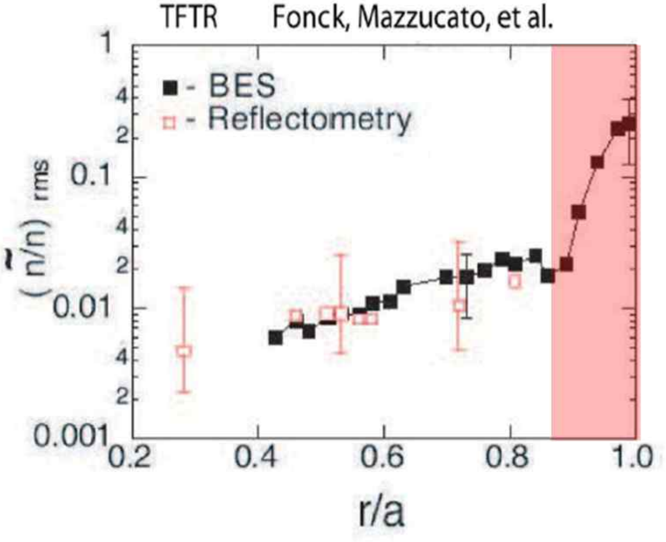




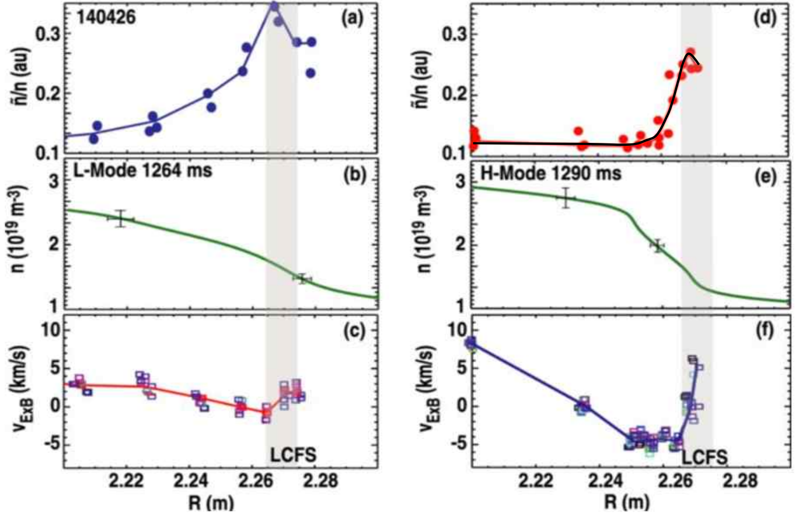
Add off-axis heating to the on-axis heating

Edge Turbulence Profiles in L & H Modes

Limiter plasma. (TFTR)

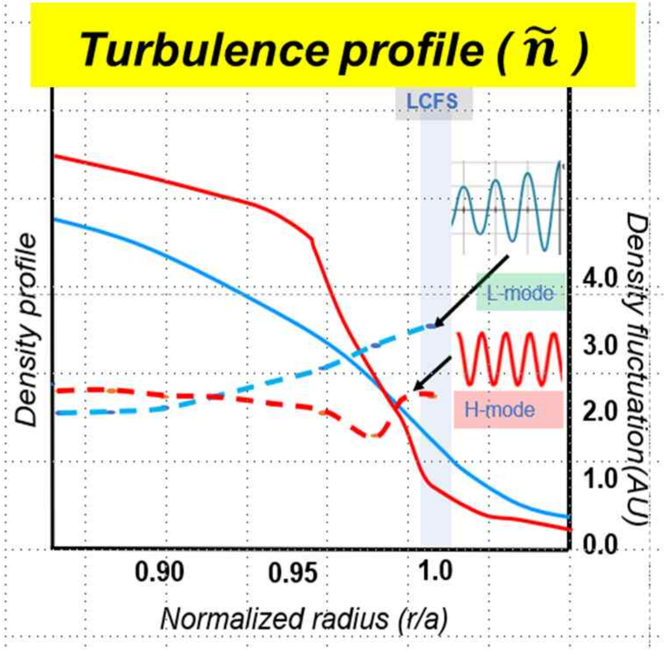


Divertor plasma. Tynan (DIII-D)



L-mode

H-mode



- ➢ *Limiter: direct contact with the limiter plate*
  - ➢ *helicity provides a highway for instant turbulence spread (parallel/poloidal/radial)*
- ➢ *Divertor: indirect contact with the divertor plate through X-point (H/L-mode)*
  - ➢ *Turbulence suppression by E_rxB is convincing in relative turbulence plot ($\tilde{n}/n$)*

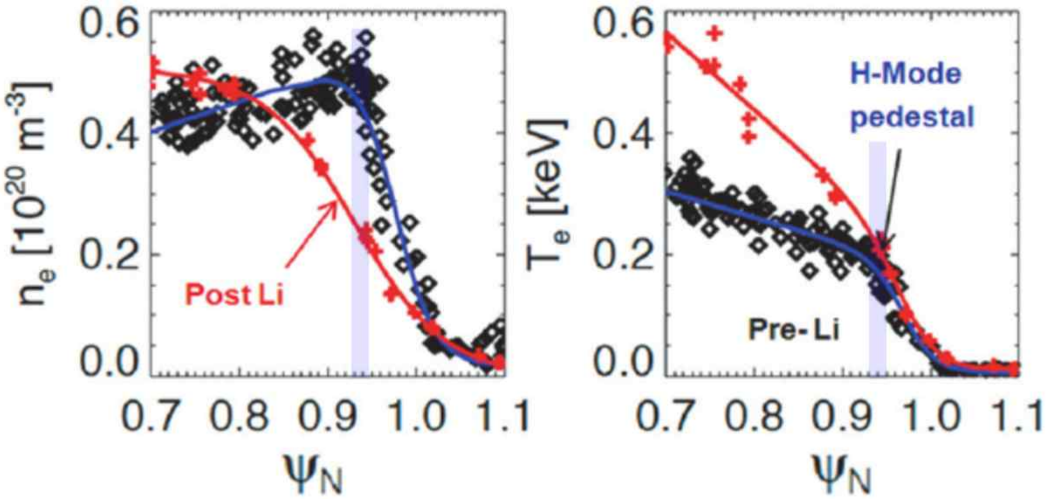
✓ *Core plasma has lowest turbulence level. Lowering further?*

✓ *Turbulence may have nothing to do with the edge pedestal pressure*

Source of Pedestal Density Build-up (ETB) in H-mode

- *First wall and surface of Limiter and Divertor plate conditioning: To reduce recycling gas and impurities low Z materials (Li, Be, B < C) have been used*
- *High Z material causes impurity accumulation (Ex. W accumulation in plasmas with W limiter/divertor in PLT, JET and many other ITER relevant devices)*

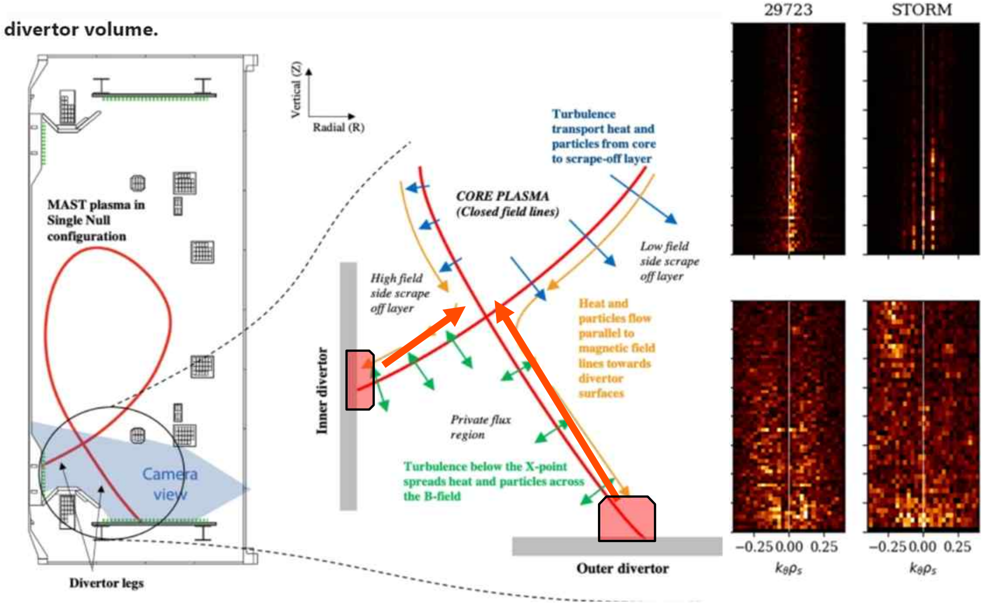
- *Particles from outside (divertor): Pedestal density in H-mode is largely from influx plasmas from divertor plate through X-point*
  - *Divertor plate conditioning with Li (Ex: NSTX "rabbit ear",*
  - *Pedestal height can be controlled by Li coating: G. Taylor, NSTX*



✓ *Massive density build up from influx plasma originated from divertor*
✓ *Plasmas from divertor may not be quiescent one (highly turbulent plasmas)*

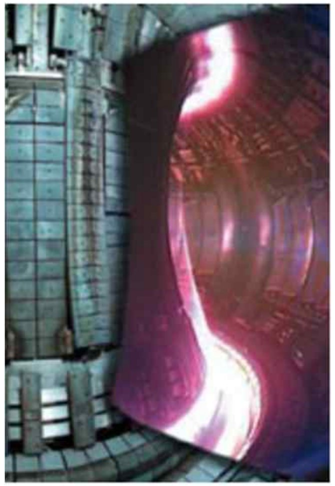
Limiter/Divertor as Source of Particles and Turbulences

Low field side leg has more turbulence

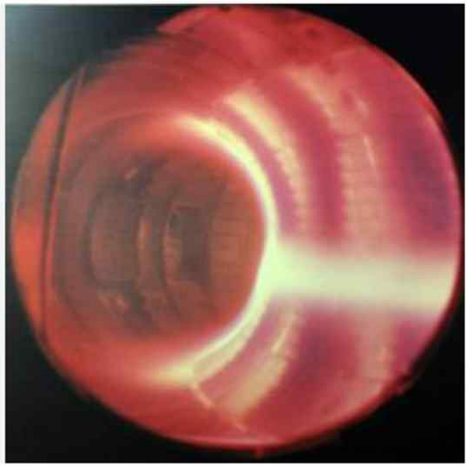


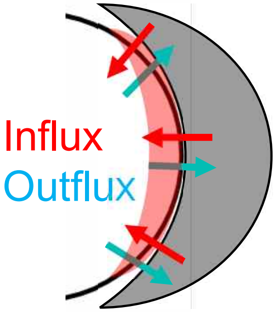
N. Walkden (MAST), 2022

JET divertor plasma



TFTR limiter plasma





- *Glows at the divertor and limiter plates represent ionization of plate material and recycling gas due to outflux plasma*
- *Influx plasmas with high turbulence level are originated from divertor and limiter plates*

✓ *Strong visible lights from divertor/limiter surfaces represents "strong ionization"*

✓ *Influx plasmas following the field lines is NOT quiescent*

Stability Physics

Stability control system is too complicated

New insights of MHD physics by visualization (Examples)

Internal Kink Instability (m/n=1/1),

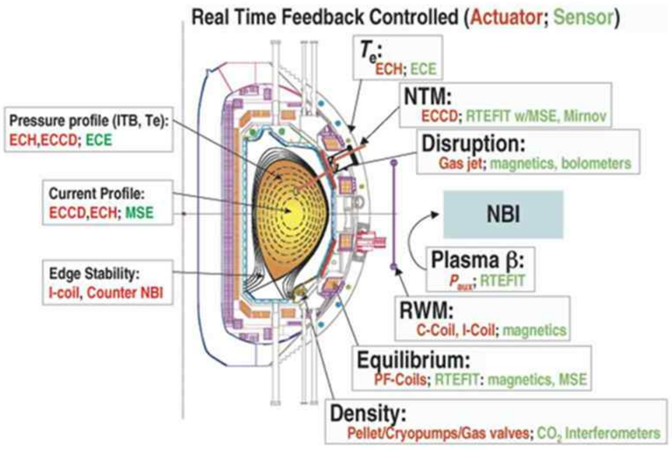
Neo-classical Tearing Mode (m/n=2/1)

Edge Localized Modes (high n/m)

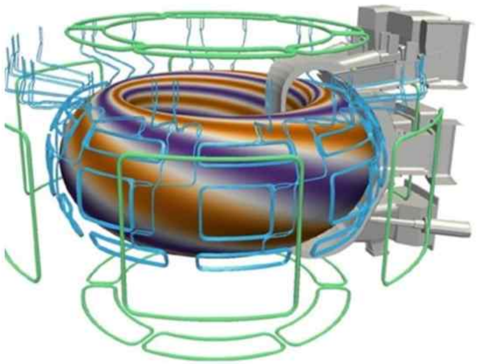
Control is difficult ? Avoid it !!

Complex Control Systems for Steady State Operation

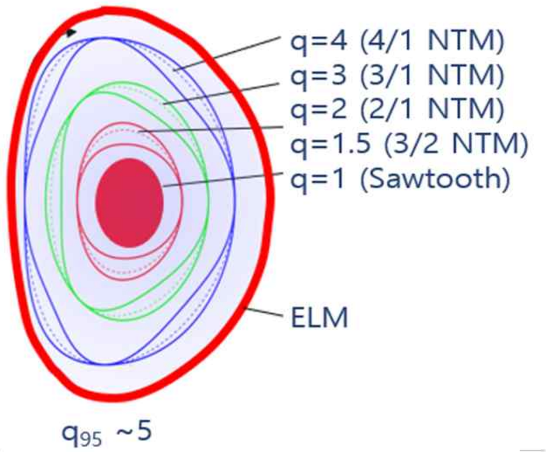
- *Control of transport physics and MHD instabilities (actuators)*
    - *ECH, LHCD, Helicon, etc. - Current/pressure profile*
    - *ECH and External MP - Sawtooth, NTMs at each rational surfaces, RWM, ELM-crash, disruptions, etc.*
- *Improved understanding of MHD physics with 2-D ECEi system*
    - *Sawtooth (m/n=1/1 mode) at the q=1*
    - *NTM (m/n=2/1 mode) at the q=2*
    - *ELM (high m/n) at the edge pedestal*
- *Develop a mode of operation with minimum MHD instabilities*
    - *Suppress NTM and ELM instabilities*



. Real-time FB controlled parameters with actuators and sensors in DIII-D.

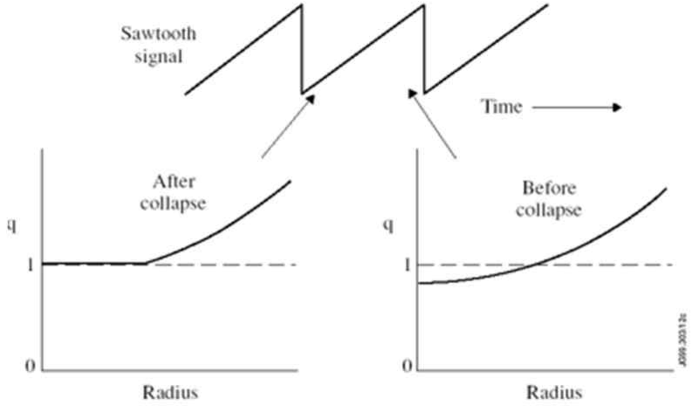


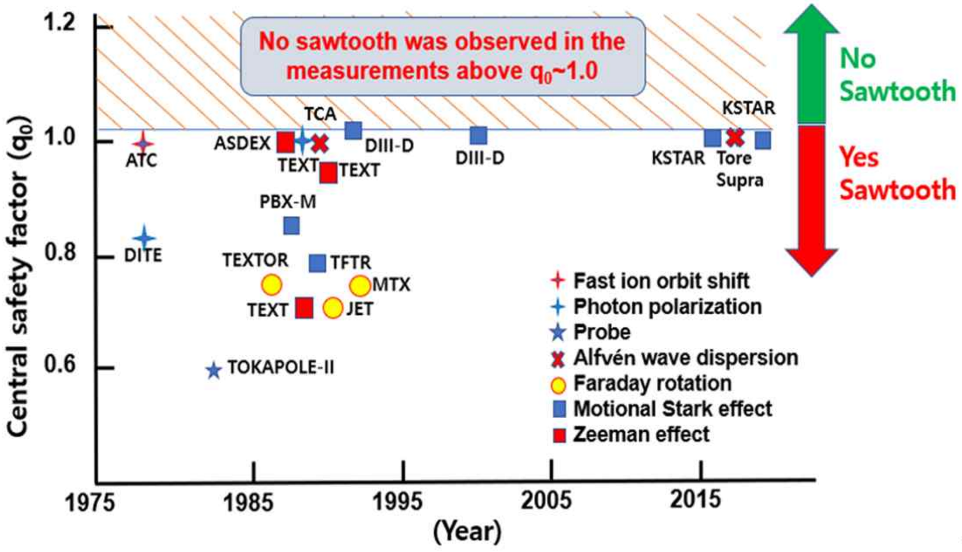
ELM-crash control coils for ITER (late T. Evans)

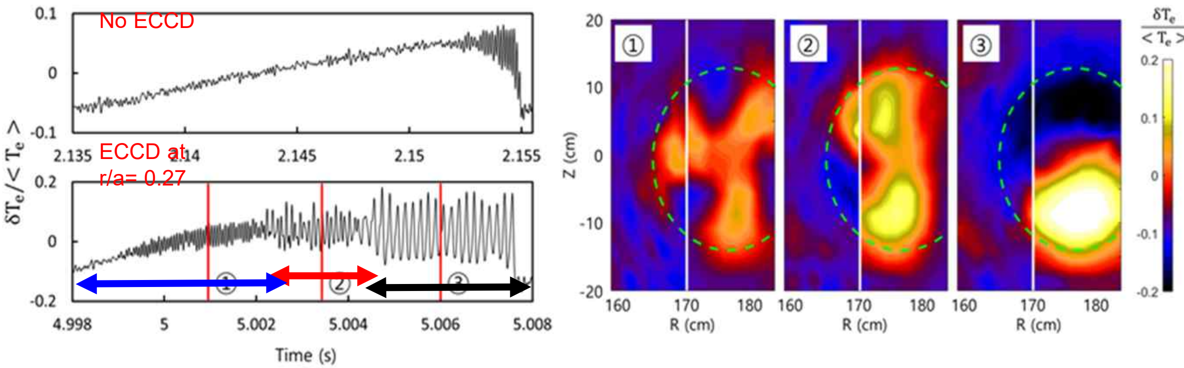


Sawtooth Instability by 2-D images (H. Park)

- ❑ *Kruskal-shafranov limit for internal kink instability (m/n=1/1 mode) is valid for Sawtooth case*
  - ❑ *Excess plasma current responsible for sawtooth is fully discharged (99%)*





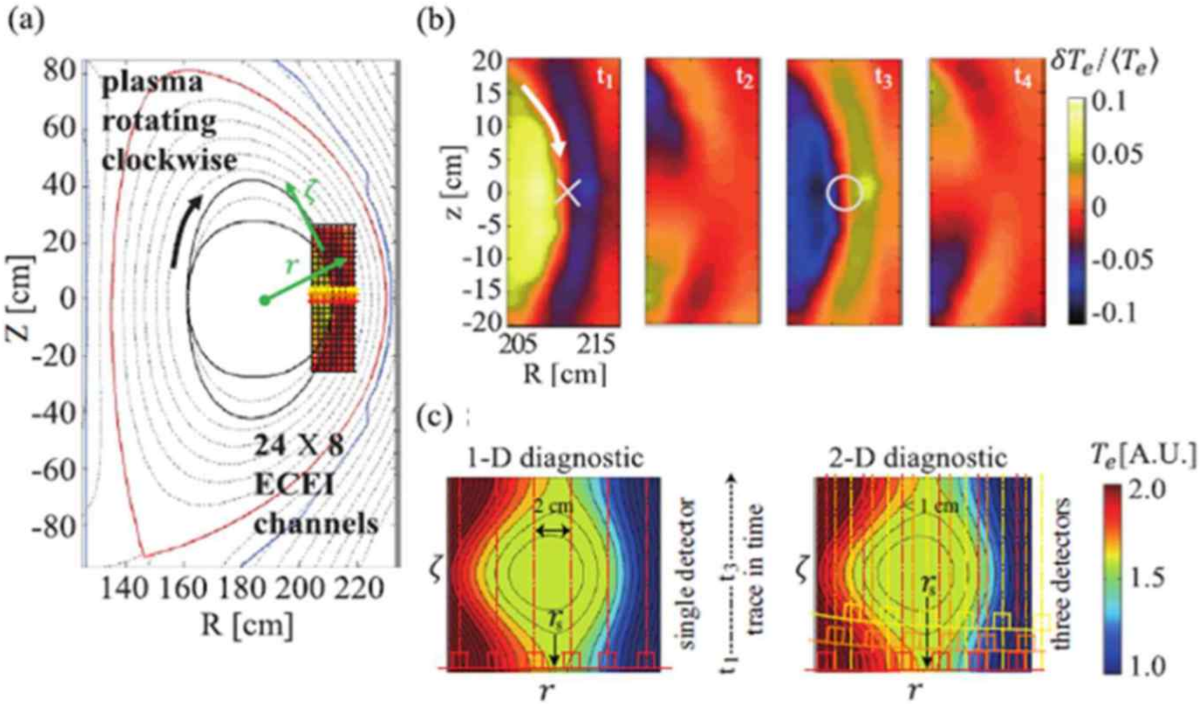


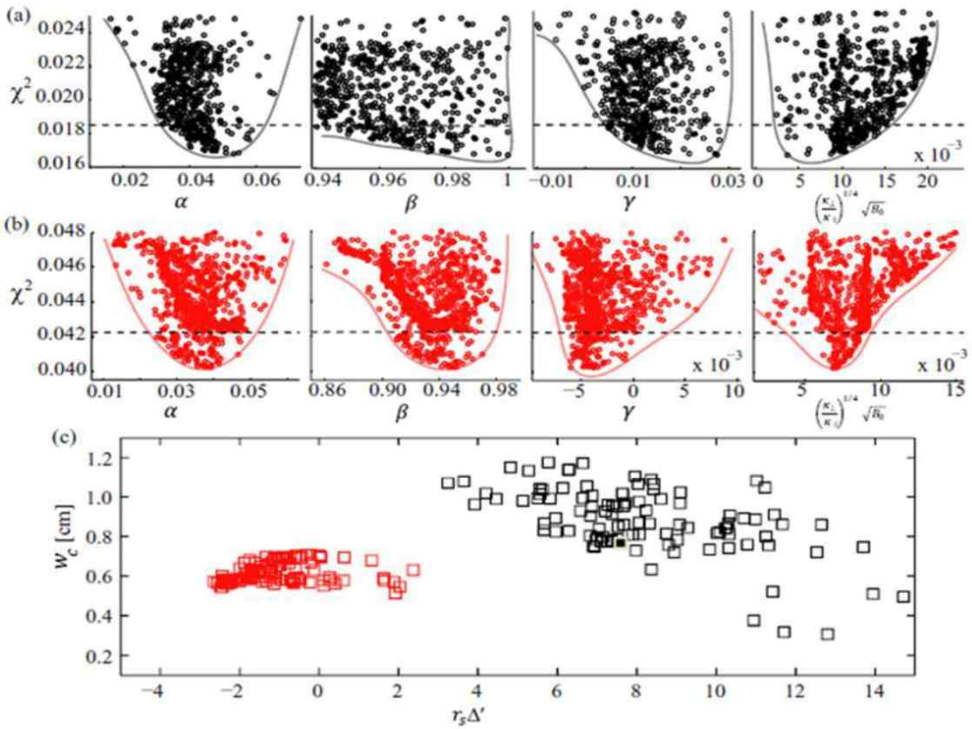
- ➢ *Direct measurements of q_0 for ~50 years*
- ➢ *Validation of q_0>1.0 after the crash by excitation of higher order modes (2/2, 3/3, etc.) after the crash*

➢*q(0) is above 1.0 (~1.04) after the crash and Kadomtsev model for Sawtooth is valid*

2/1 Tearing Mode (TM/NTM) by 2-D images

M. Choi et al



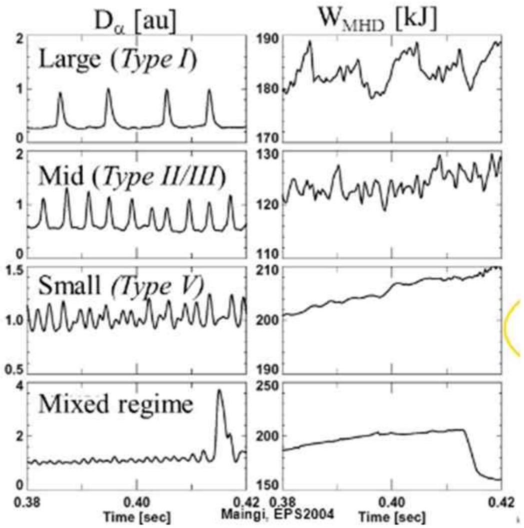


- Solution of the Modified Rutherford Equation for stability and island growth
  - 2-D data/2-D model has tighter solution compared to the 1-D data/1-D model
  - Solutions are exclusive each other and need better transport model

➢ Two solutions (1-D and 2-D) for island size and stability parameter are not consistent

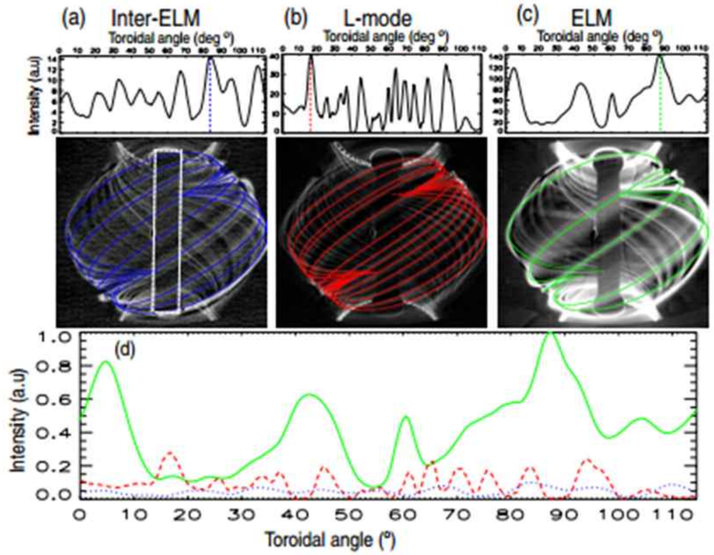
Evolution of Edge Localized Mode (ELM) Study

(NSTX)



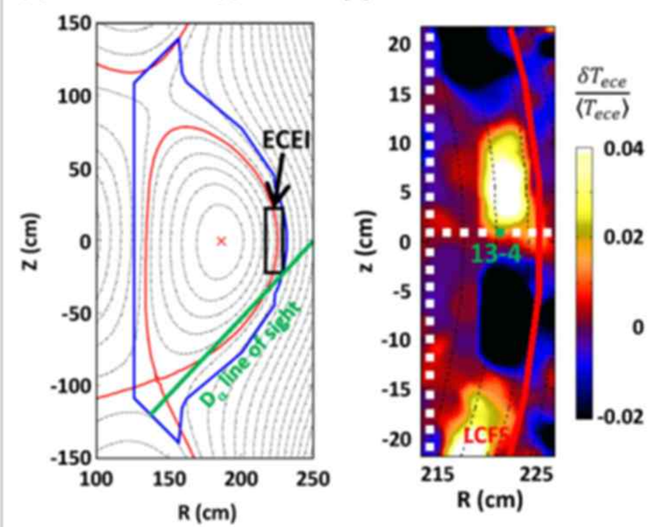
Divertor Hα emission; R. Maingi

(MAST)



Fast camera images of the ELMs, N. Ayed

(KSTAR)



2-D ECE image of the ELM; M. Kim

- *Backward approach to understand the ELM-crash for last ~30 years*
  - *Divertor Hα → Fast camera images at the separatrix (L-mode, inter- ELM-crash, ELM-crash) → ECEi images of the ELMs at the pedestal region)*

- *Remedy (RMP) is too complicated and only find a narrow windows of operation*
  - *Eliminate ELM-crash by avoiding high edge pedestal (H-mode)*

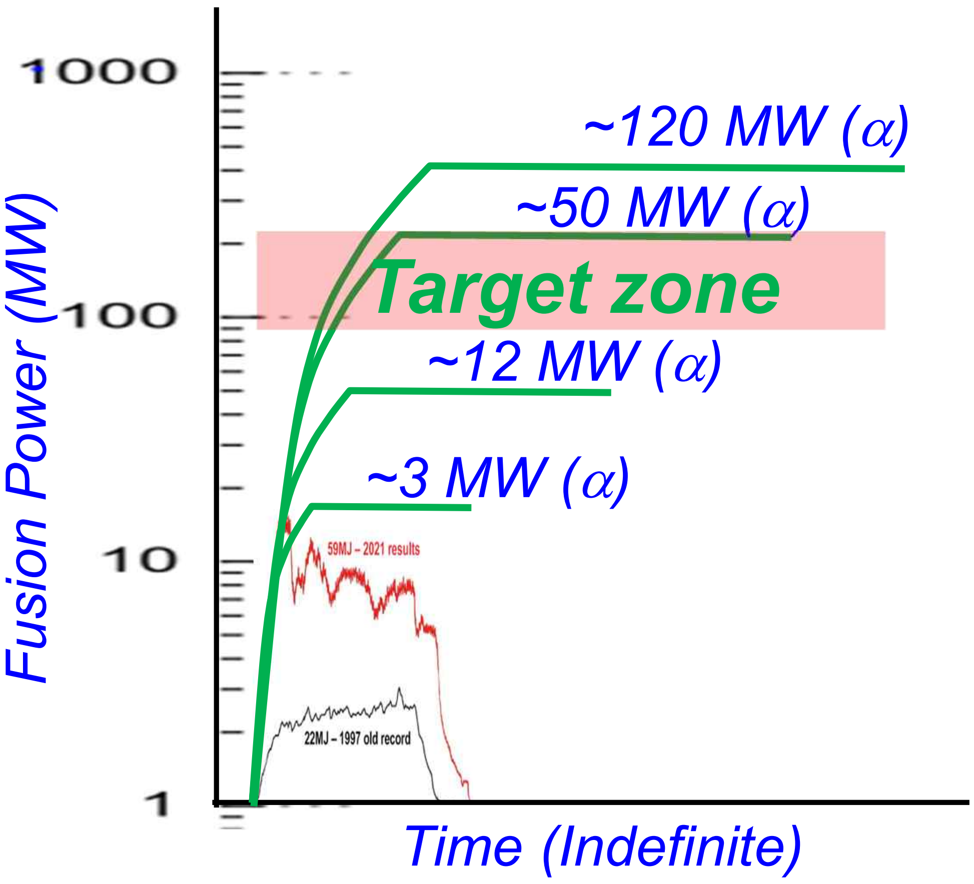
Perspective of Ignition Device

Primary Goal of Ignition Device

How compact the ignition device can be?

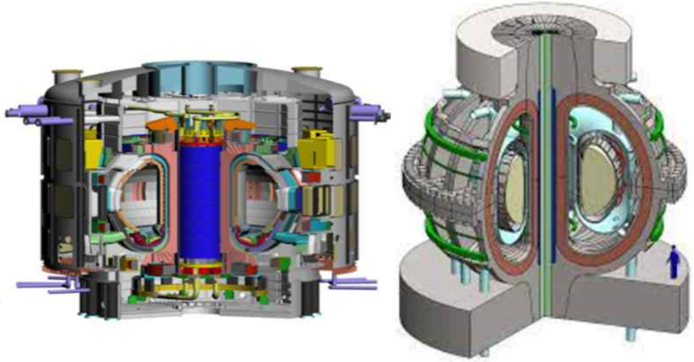
Sustained Ignition in Toroidal Devices?

- *Test of electron heating at high density is "MUST" for ignition*
  - *Direct electron heating to ignition is challenging*
    - *NNBI: technically difficult and insufficient fueling*
    - *ICRF: ~50 MW power system needs many antennas*
    - *ECH: ~ 60 gyrotrons and technically challenging at high B_T and high density*
  - *α-particles are effective electron heating source without antennas at high density*
    - *α-heating profile is identical to the 14 MeV neutron profile (central heating)*
- *Adequate α-power level is critical for the size of compact ignition device*



Compact Ignition Device?

- ITER (V_p~800m^3) and ARC (V_p~200m^3) may not have sufficient α-particle to sustain Ti >> 10keV
  - Physics: Insufficient data for electron heating system and Ti clamping
  - Engineering: ITER & ARC – Electron heating only and ARC may not have easy control (CD/MHD control at high field)



Rendering of ITER and ARC

- DIII-D (V_p~20m^3), KSTAR (V_p~23m^3) feasibility?
  - "super H-mode" (optimum core heating) is close to the limit
  - $n_e \tau_E T_i$ needs factor ~20 or more for ignition

Genie in the bottle

- ~200MW fusion power (~50MW α-power) is the goal
  - V_p~200m^3 (ARC) with moderate Bt and Ip for higher n_e, τ_E and β–limit: τ_E is better than H-mode scaling (i.e., "super H-mode" type)
  - PNBI of ~40MW with optimized geometric factors (κ, δ , etc.)

?

Thank You

Comprehensive approach will accelerate realization of the fusion energy in both ICF and MCF