PRINCETON PLASMA PHYSICS LABORATORY

PLASMA EXHAUST VIA A MAGNETIC DIVERTOR

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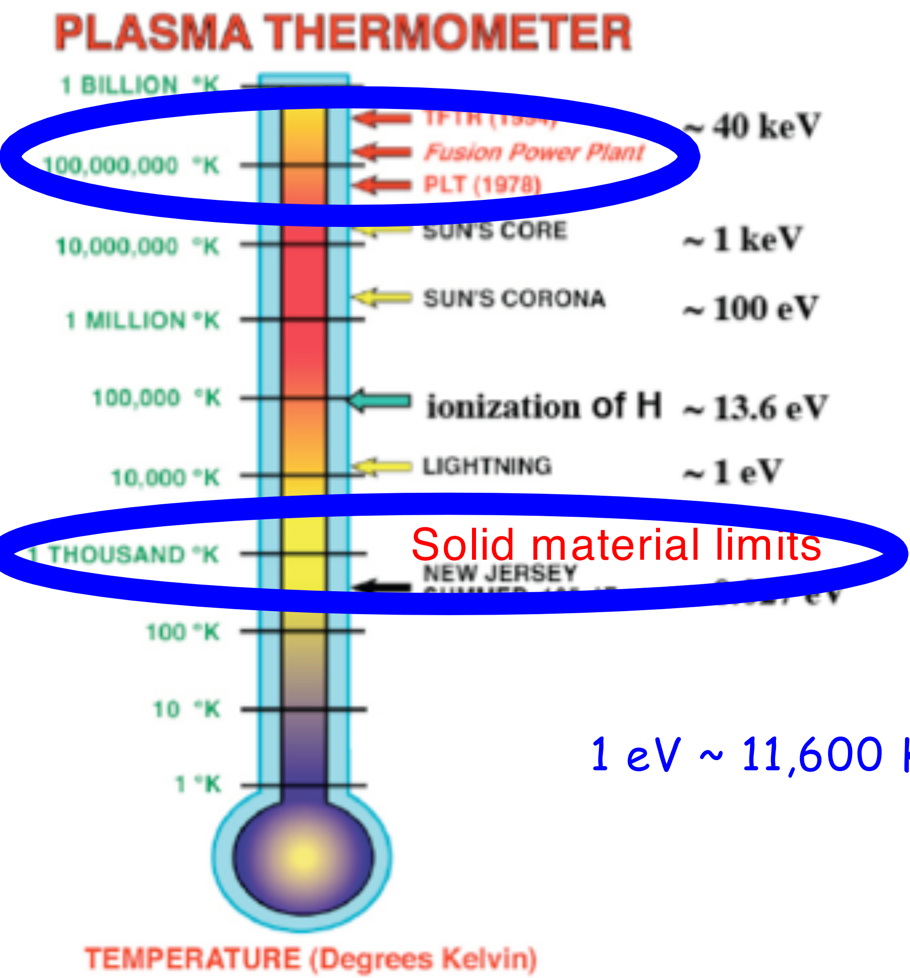
SULI summer lecture
July 11, 2019
Princeton, NJ

Outline

- Introduction to magnetic confinement and tokamaks
- Plasma exhaust via magnetic X-point divertors
  - Particle exhaust
  - Momentum and power exhaust
  - Recently identified challenges to attractive core-edge plasma scenarios with W walls
- Types of transient events, and their impact

Critical challenge for fusion: keeping the core hot and and the plasma facing components 'cold'

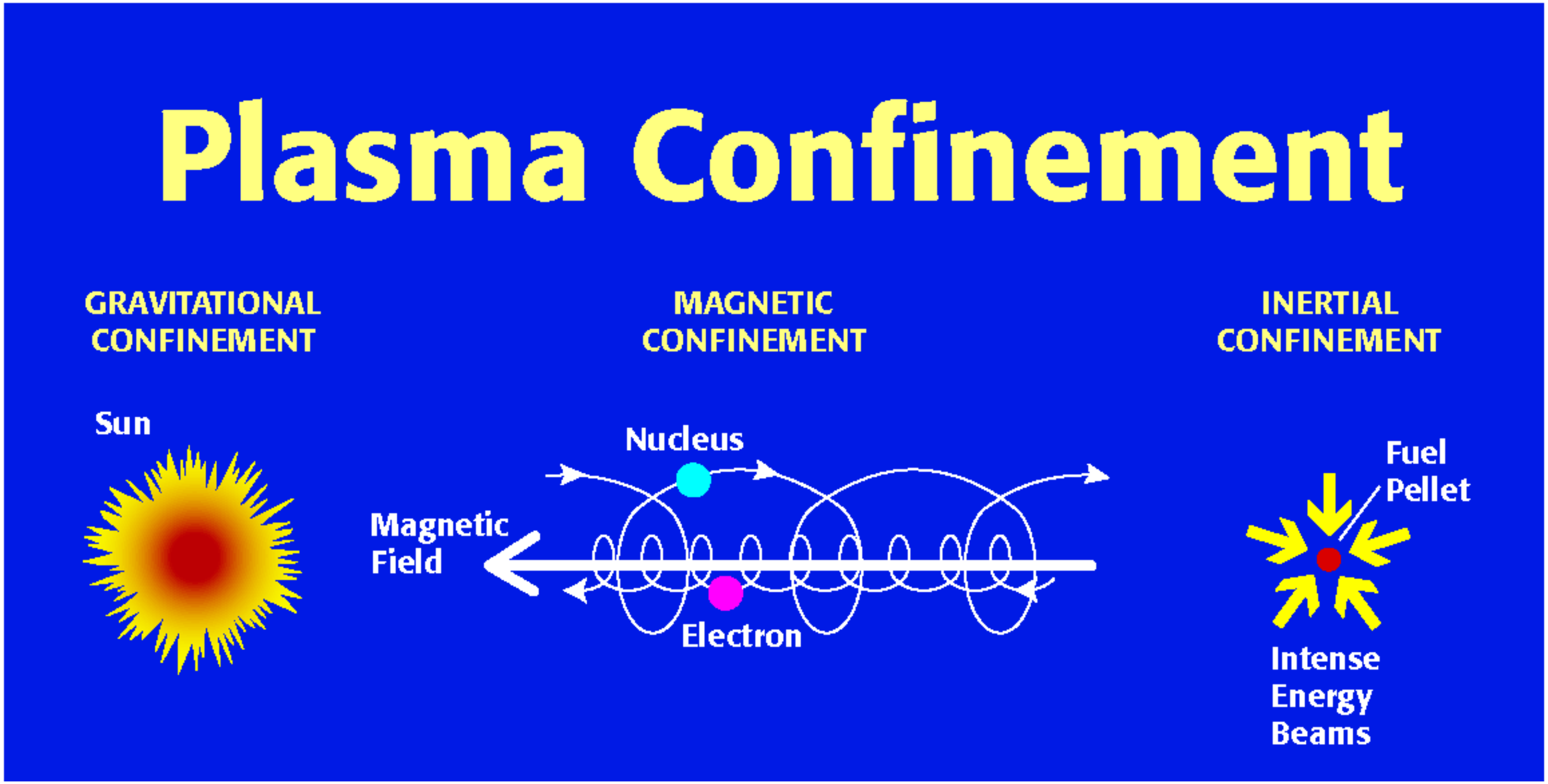


1 eV ~ 11,600 K

<u>Need to exhaust</u>

- Plasma particles
- Plasma momentum
- Plasma energy

Ways of confining plasmas



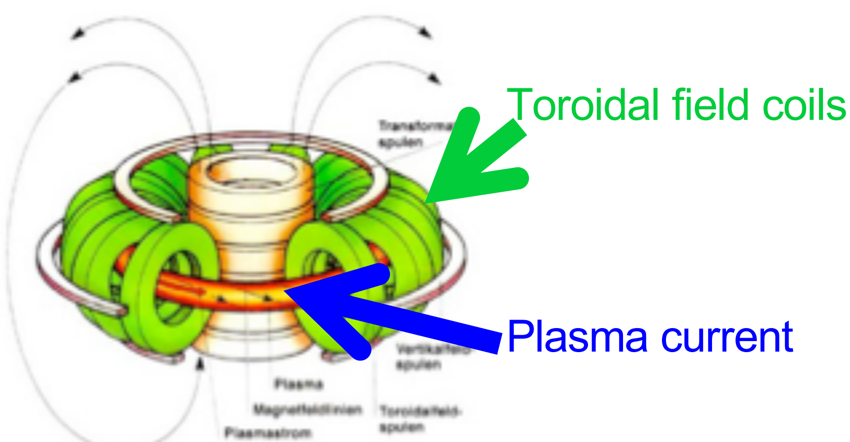
Requires large amounts of mass!

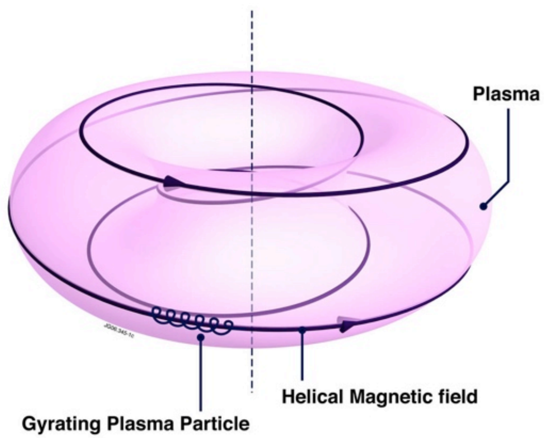
Confines the plasma in the direction across the magnetic field

Energy and defense relevant

Origin of the tokamak

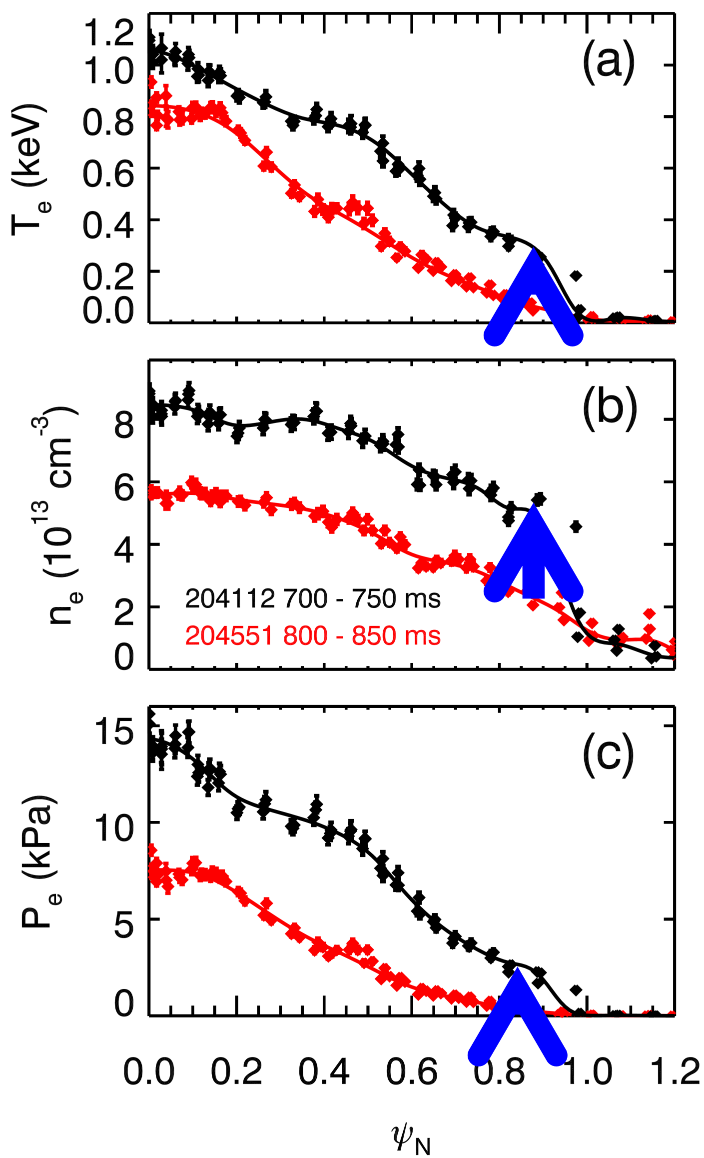
- Original idea was to use a concentrated magnetic field on the end of a linear system, to reflect particles back into main chamber (‘magnetic mirror’)
  - Suffered from ‘end loss cone’
- In the 1960’s, Russian scientists proposed a doughnut-shaped device with ‘axial’ or toroidal magnetic field for stability, and ‘azimuthal’ or poloidal field for confinement, driven by a current in the plasma





  - Particles saw no beginning or end -> high confinement!

'H-mode': a strong gradient of density, temperature & pressure near plasma edge

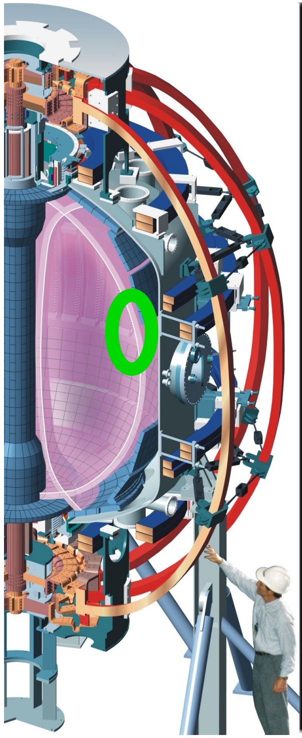


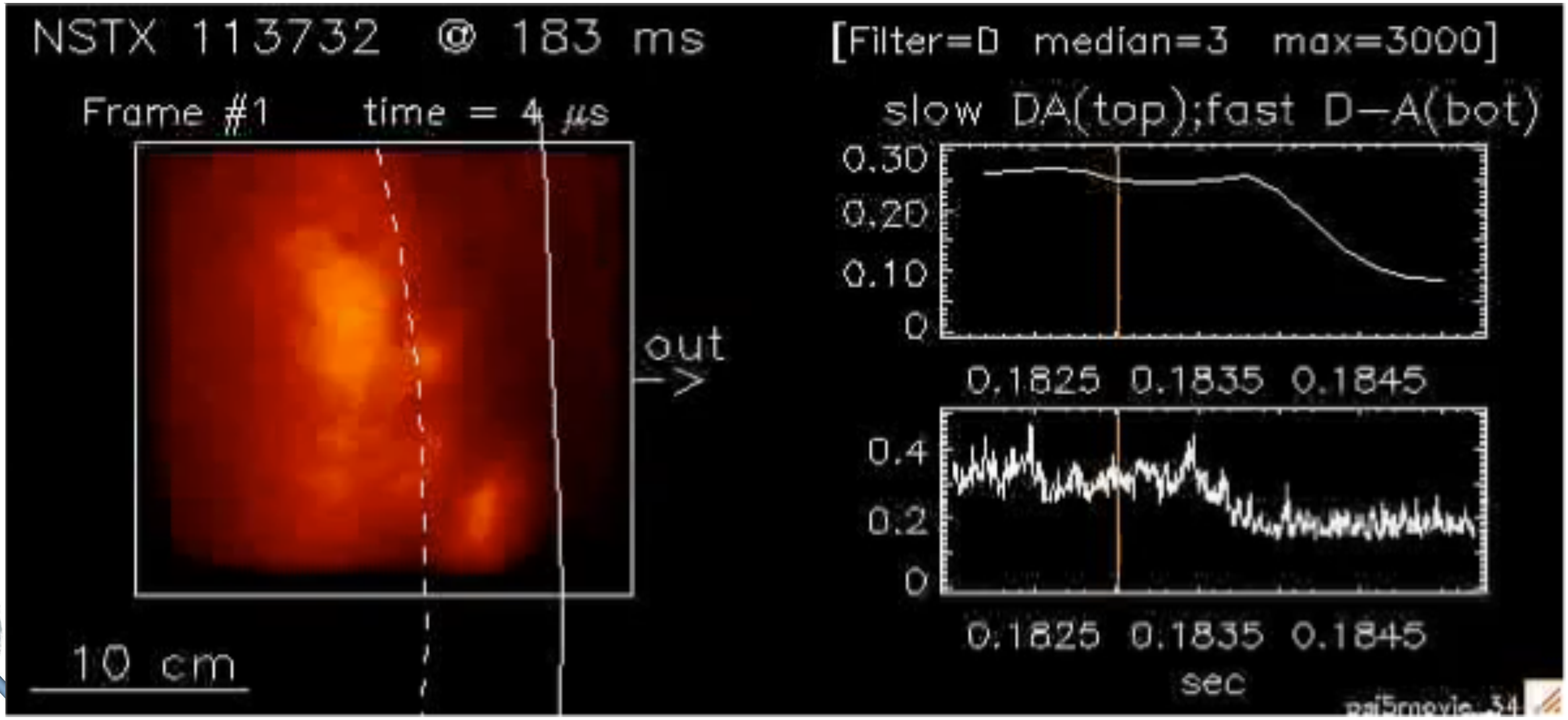
- Sharp increase in edge density, temperature, pressure observed in tokamaks in 1982 – called 'H-mode'
- Core sits on top of a 'pedestal' – more stored energy for same input power –> improved energy confinement

NSTX-U data,

Courtesy of D. Battaglia

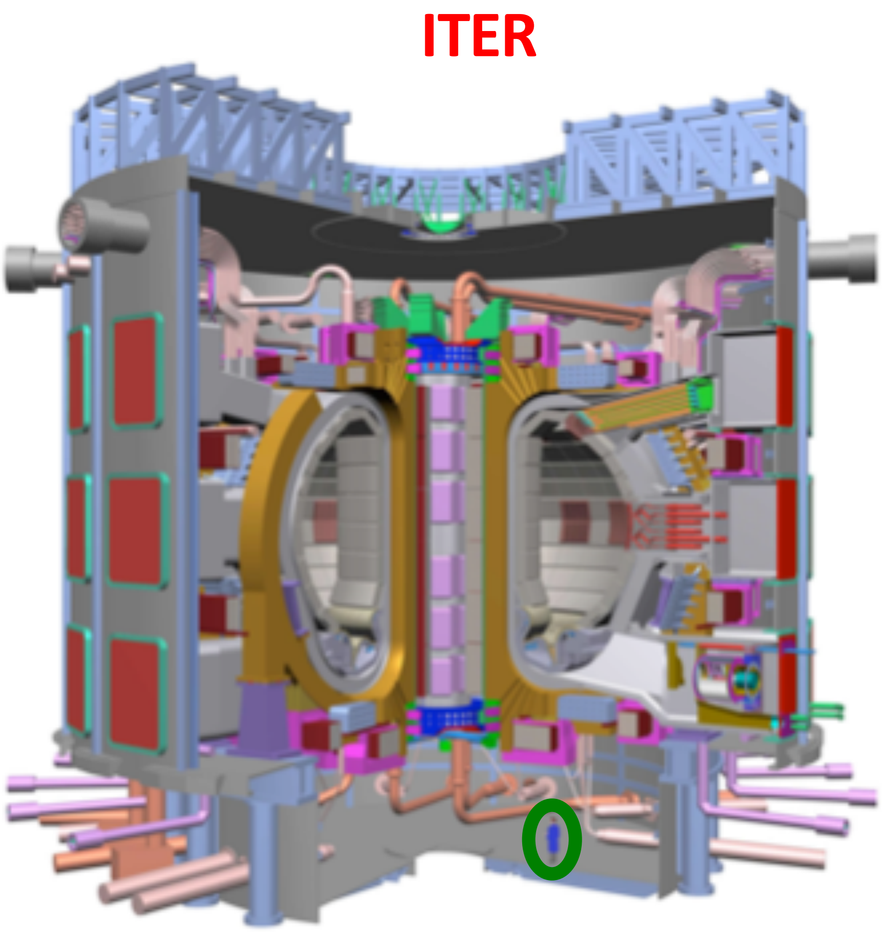
'H-mode': a strong reduction in edge plasma turbulence





NSTX data, Courtesy of S. Zweben

The international fusion community has agreed to build a large tokamak toward energy production

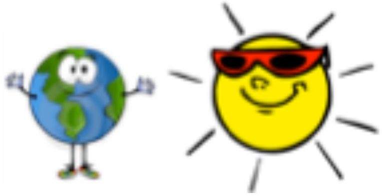


- Seven international partners
  - EU
  - Japan
  - US
  - Russia
  - China
  - Korea
  - India
- Being built in France
  - First plasma ~ Dec. 2025

- P_{fusion} = 500 MW for 1000 sec discharges
- P_{fusion} = 250 MW in steady state

Plasma-material interactions: how do you keep the hot part hot and the cold part cold?

- Answer: mass difference!
  - In ITER, there is less than ½ gram of deuterium and tritium in the core
  - The total mass of ITER is nearly 50 million pounds; a fraction of this is in the plasma facing components, which will absorb the heat
  - The internal components of ITER will be actively cooled to keep temperature below melt limits
    - **The key is to maximize heat dispersal area**
- The present technological heat flux removal limit for solids is about 10 MW/m^2
  - A rocket nozzle has average heat flux of 1 MW/m^2!
  - The sun's radiant heat flux on earth ~ 1400 W/m^2



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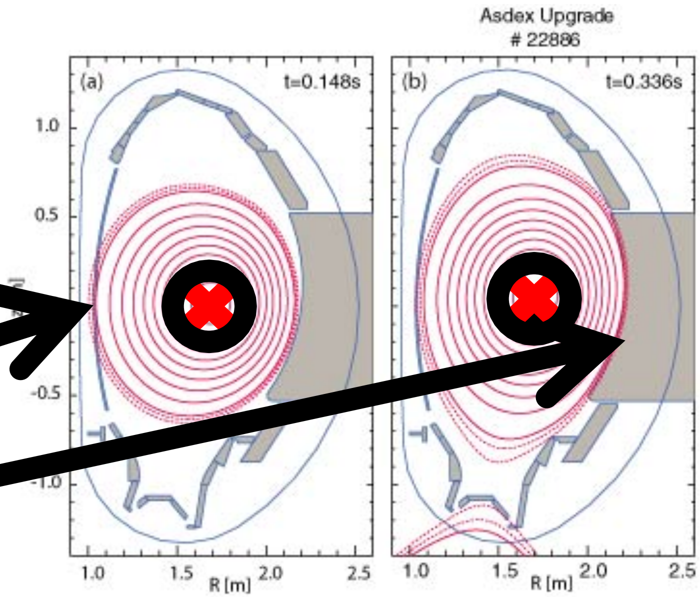
- **Plasma exhaust via magnetic X-point divertors**
  - **Particle exhaust**
  - **Momentum and power exhaust**
  - Recently identified challenges to attractive core-edge plasma scenarios with W walls

- Types of transient events, and their impact

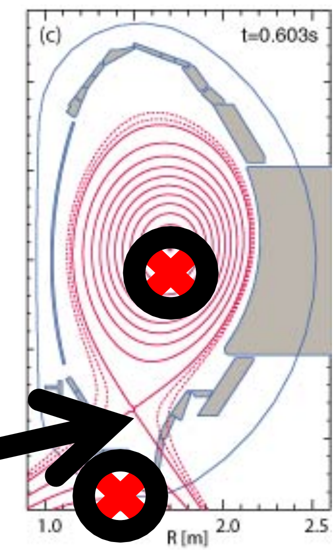
R. Maingi, *'Plasma Exhaust',* chapter in *Magnetic Fusion Energy: from Experiments to Power Plants,* G.H. Neilson, editor, Woodhead Publishing, Elsevier Press, *(2016) 31-59.*

Limiters and divertors used to exhaust plasma

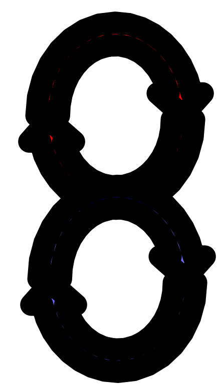
- A **limiter** is a surface in contact with the plasma
  - Can be inserted (sacrificial) or part of surrounding wall structure
  - Examples of inner wall and outer wall limiters shown at right



- If external current is run in the same direction as plasma current *outside* of the confined plasma, then one component of the field can be canceled, creating an **X-point divertor**

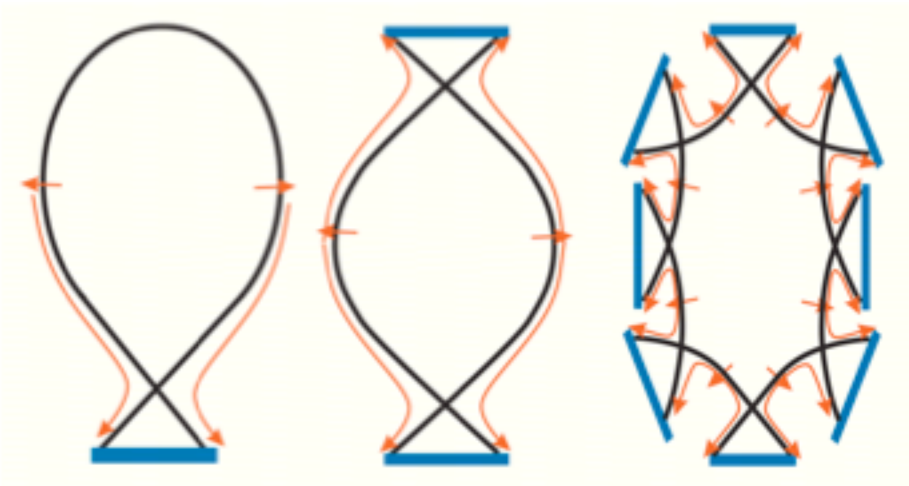


$B_\theta = I/(2\pi a)$

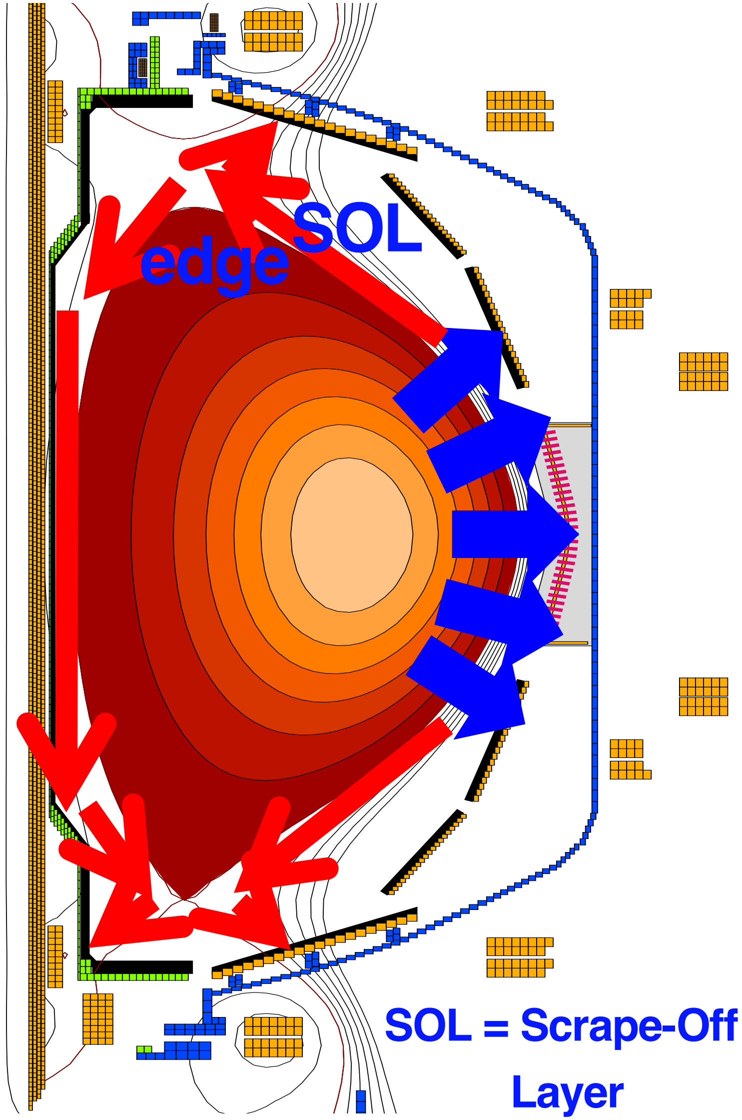


Divertors used to exhaust plasma and reduce PMI at wall

- In a **divertor**, edge plasma flows across closed magnetic flux surfaces into the scrape-off layer
- Plasma flows along open magnetic field lines in the SOL to the divertor target
  - Can have one or more X-points, e.g. 1, 2, or even 8!

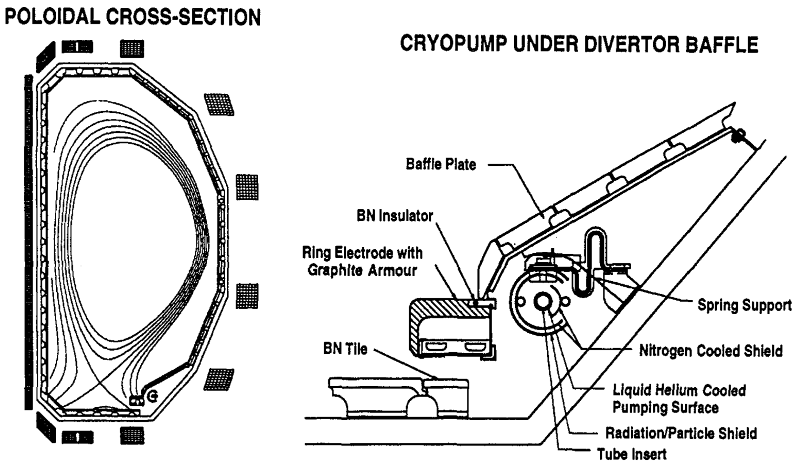


Y. Feng et. al., Nucl. Fusion **46** (2006) 807

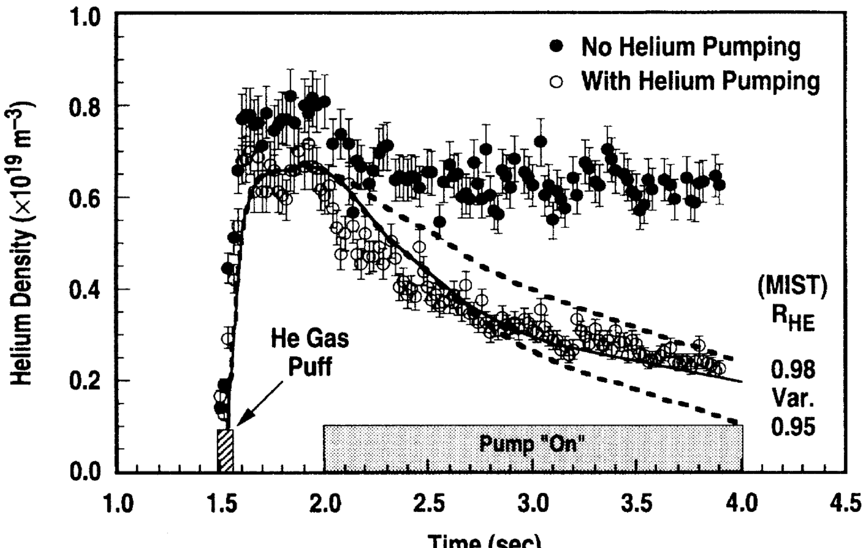


Divertors, cryopumps, and structures to restrict neutral flow (baffles) can provide particle control

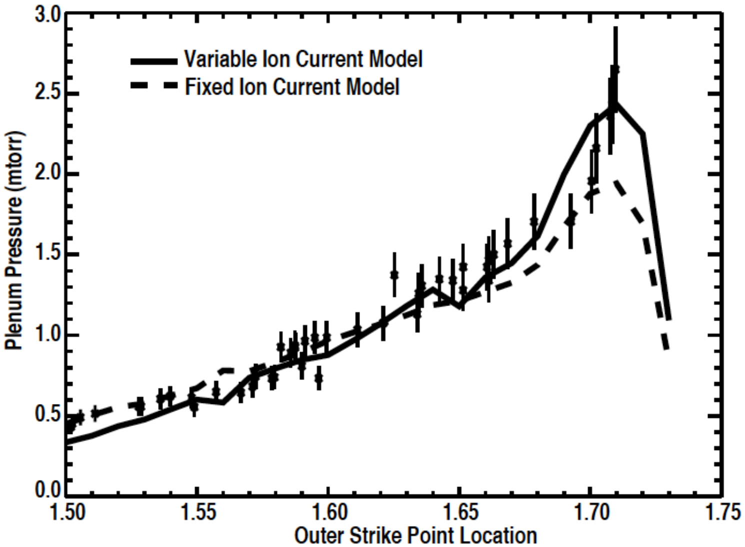
- Both D/T (fuel) and He (ash) need to be exhausted
- In-vessel cryopumps control deuterium and He inventory
  - Divertor particle flux can be captured and exhausted
  - ITER designed with cryos



M.A. Mahdavi et. al., J. Nucl. Mater. **220-222** (1995) 13



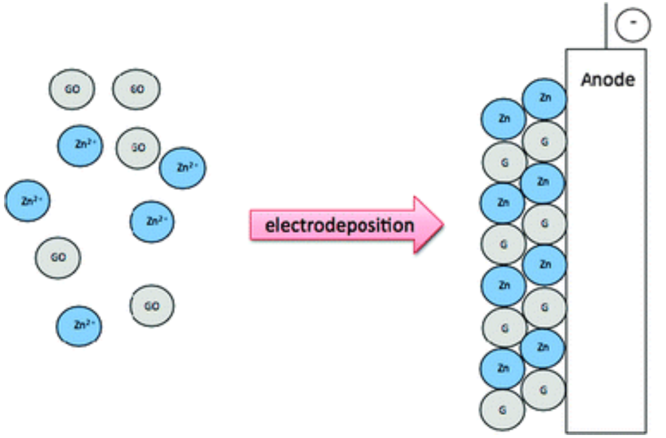
M. Wade et. al., PRL **74** (1995) 2702



R. Maingi et. al., Nucl. Fusion. **39** (1999) 1187

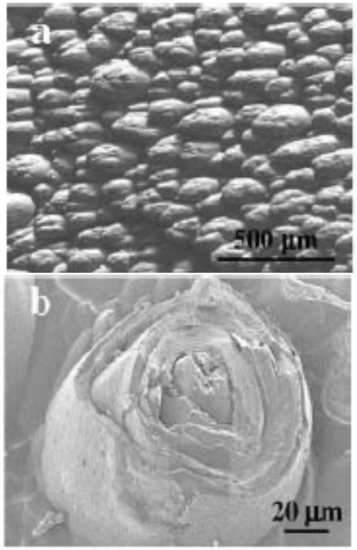
Tritium retention is a central element of particle exhaust, and strongly affected by choice of PFC materials

- Graphite was PFC of choice in 90's, but it captures hyrogenic species via unsaturable co-deposition
  - e.g. Graphene & Zn shown on right



- C advantages
  - Good power handling, good thermal shock and thermal fatigue resistance (low crack propagation)
  - Doesn't melt (but sublimes), low radiated power
  - Good joining technology, low-Z
- C disadvantages
  - Chemical erosion and co-deposition; dust generation
  - May require conditioning
  - Physical and mechanical properties degrade w/low neutron fluence

Co-deposits in Tore Supra



G. Federici et. al., Nucl. Fusion **41** (2001) 1967

Roubin et al., J. Nucl. Mater. **390-391** (2009) 49

W chosen for divertor & Be for wall of ITER

- W advantages
  - Low physical sputtering yield; high threshold
  - No chemical sputtering with hydrogen
  - Low in-vessel tritium retention at T < 500 ^{o}C
  - Reparable by plasma spray; good joining technology

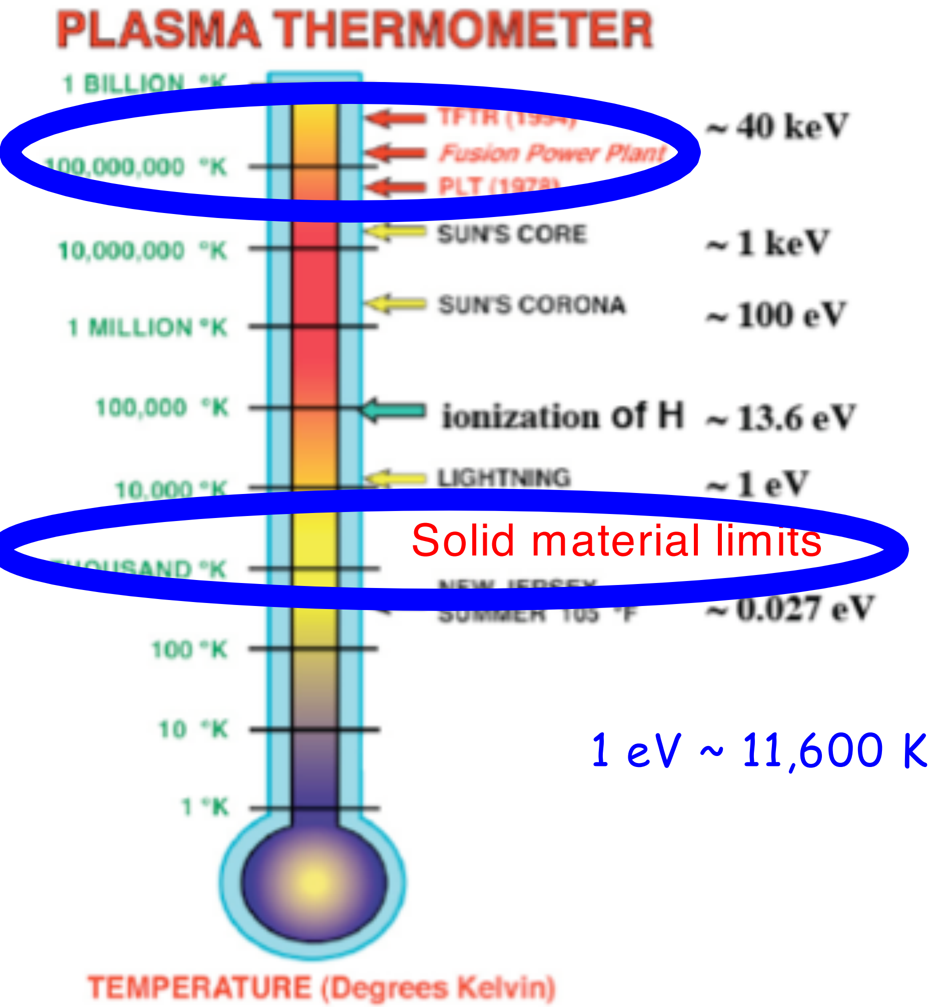
- W disadvantages
  - Low allowable core concentration
  - Melts under large transient loads
  - High ductile-brittle transition temperature
  - Recrystallizes (embrittles) at temperatures >1500 K
  - High activation
  - Blisters and generates ‘fuzz’ under He bombardment
  - Confinement reduced in tokamaks as compared with carbon PFCs

G. Federici, et. al., Nucl. Fusion **41** (2001) 1967

Components in present and past fusion devices

Device	Lim/Div	PFC mat'l	Device	Lim/Div	PFC mat'l
JET (2012+)	Divertor	W div. & Be wall	JET	Divertor	Carbon
ASDEX-U	Divertor	W divertor & wall	ASDEX-U	Divertor	Carbon
C-Mod	Divertor	Mo divertor & wall	DIII-D	Divertor	Carbon
NSTX	Divertor	C Wall/Li coating	NSTX-U plan	Divertor	High-Z + Liq. Li
RFX	Limiter	Liq. Li - Mo mesh	LTX	Limiter	Liq. Li on SS
JT-60U	Divertor	Carbon	TFTR	Limiter	Carbon
Tore Supra	Limiter	Carbon	West	Divertor	W wall
EAST	Divertor	W upper, Mo wall, C lower	KSTAR	Divertor	Carbon
MAST-U	Divertor	Carbon	COMPASS	Divertor	Carbon

Critical challenge: keeping the core hot and and the plasma facing components 'cold' via magnetic divertors



Need to exhaust

- Plasma particles
  - Recapture tritium

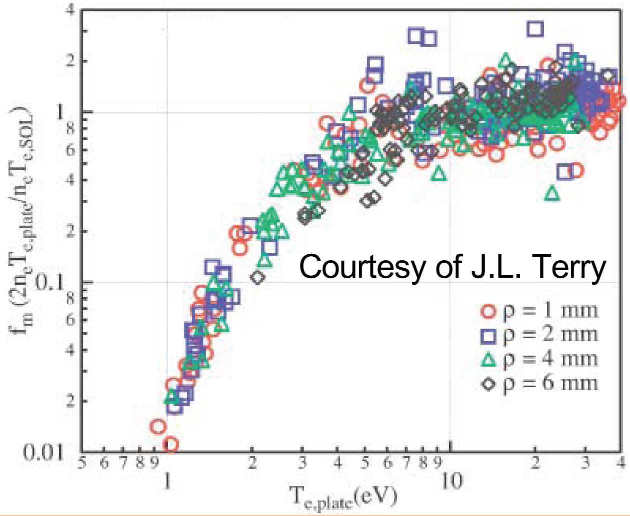
B.L. LaBombard et. al., Phys. Plasmas **2** (1995) 2242

- **Plasma momentum**
  - Plasma is spinning in the core, either spontaneously or from momentum injection
  - Sheath accelerates ions at PFCs

- **Plasma energy**
  - Plasma heated by fusion, simulated with neutral beams & RF heating

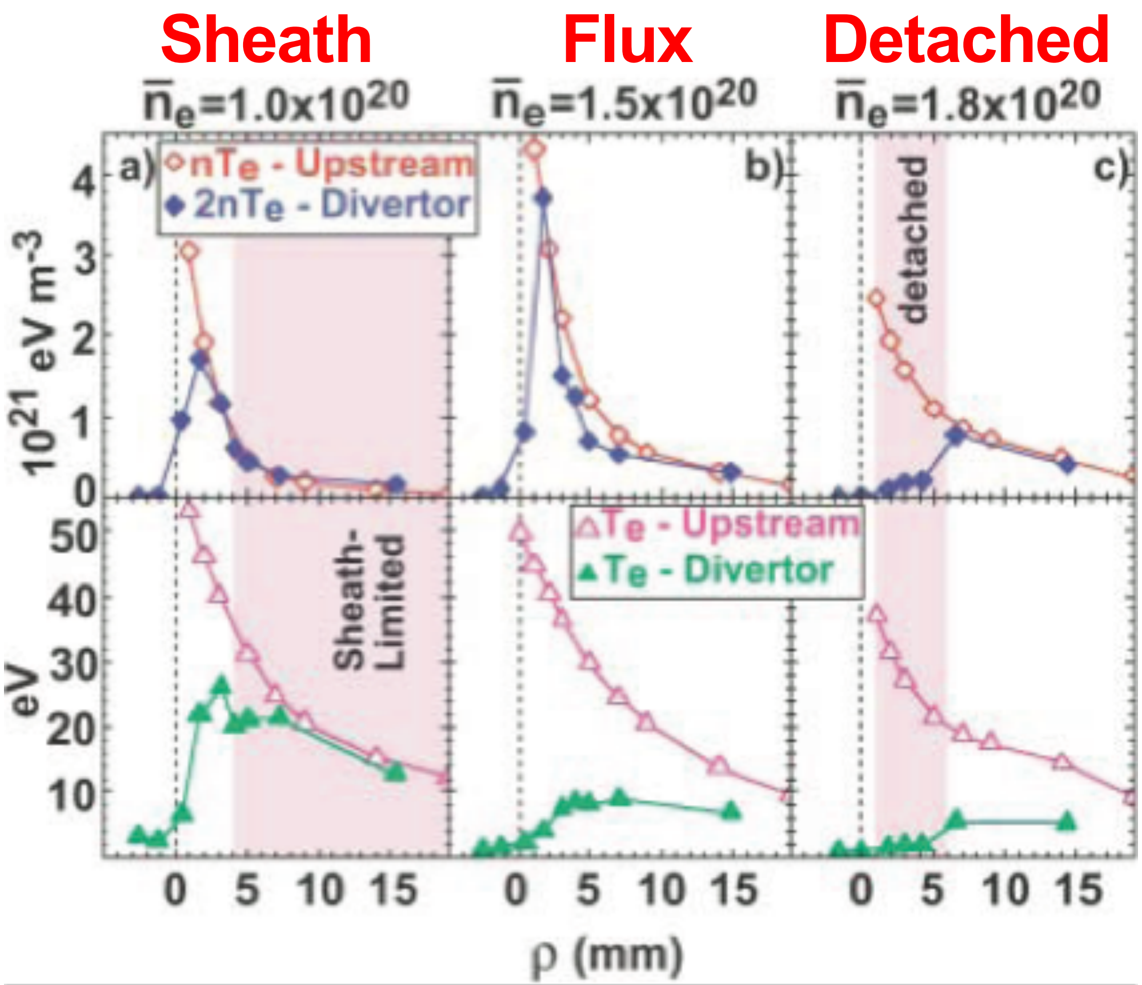
Plasma momentum exhaust

- Plasma spins in the core spontaneously, which is good for stability and confinement
  - Problem if rotation goes to zero (locked mode) – confinement loss
- Sheath forms at PFC for equal ion and elec. flux
  - Pre-sheath accelerates ions to sonic speed
    - ➢ Bohm criterion: local Mach number $\upsilon/c_s = 1$
  - Sheath accelerates ions through a ~ 3kTe potential drop
  - This plasma momentum is naturally exhausted at PFCs
- Charge exchange between plasma ions and neutrals (recycling, beam input) reduces plasma momentum
  - Becomes important for T_e < 10 eV
  - Manifests as a reduction in plasma pressure at low T_e



Power flow in the scrape-off layer to the divertor depends on density and collisionality

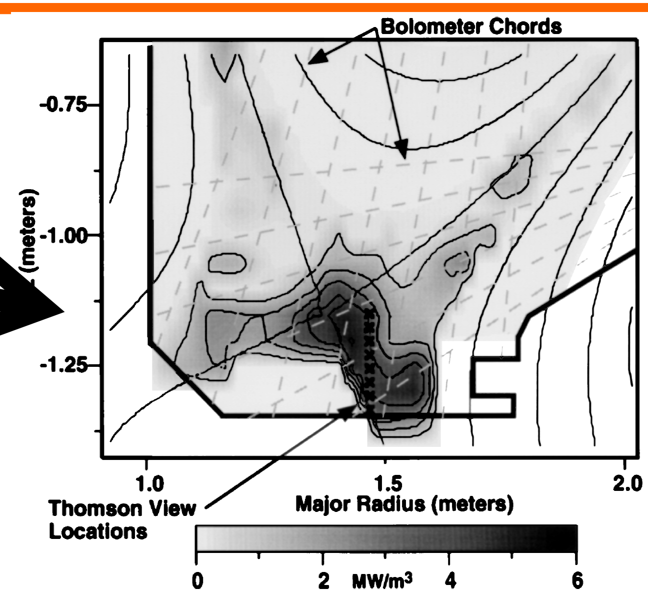
- **S**heath-limited: the midplane and divertor T_e are about equal
  - Pressure is same at midplane and divertor
- **F**lux-limited: the divertor T_e is below midplane
  - Pressure is same at midplane and divertor
- **D**etached: the divertor T_e is ~ 1-2 eV
  - Pressure in divertor well below midplane
  - Recombination observed



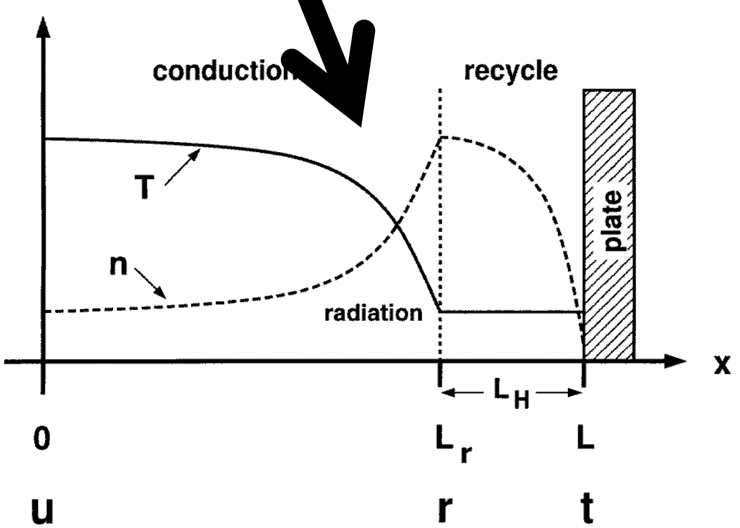
B.L. LaBombard et. al., Phys. Plasmas **2** (1995) 2242

Divertor radiation and detachment used to reduce plasma heat flux onto PFCs

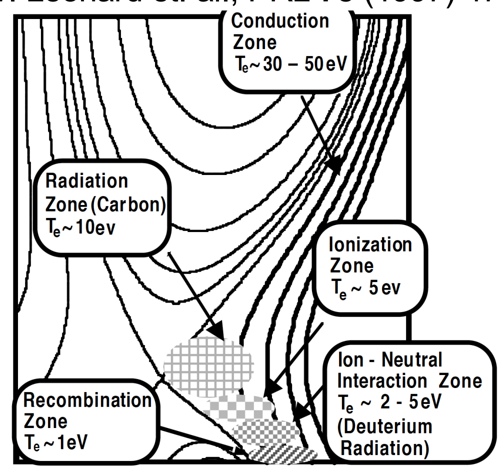
- At high density, divertor radiation occurs somewhere between the X-point divertor and PFC
  - Low-Z impurity radiation zone: 1-10 eV
  - Deuterium ionization front: 5 eV
  - Recombination zone: 1-2 eV
- Can be represented in 1-D



A.W. Leonard et. al., PRL **78** (1997) 4769



C.S. Pitcher et. al., Plasma Phys. Contr. Fusion **39** (1997) 779



M.E. Fenstermacher et. al., Plasma Phys. Contr. Fusion **41** (1999) A345

Difficulties for W PFCs to achieve attractive, self-consistent core-edge scenarios have been identified

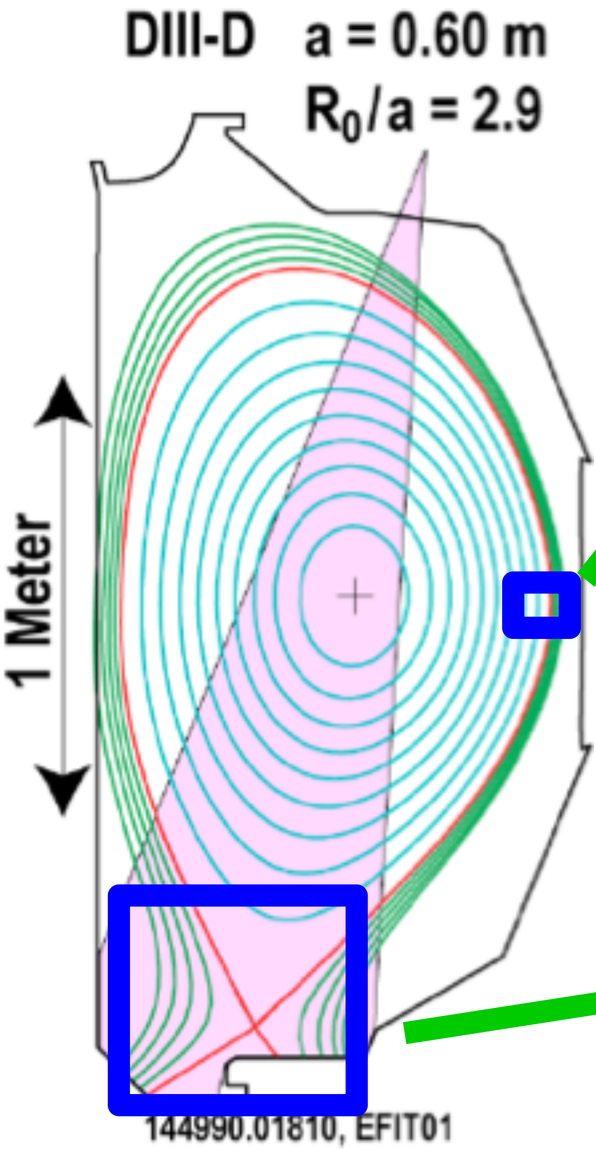
Outline

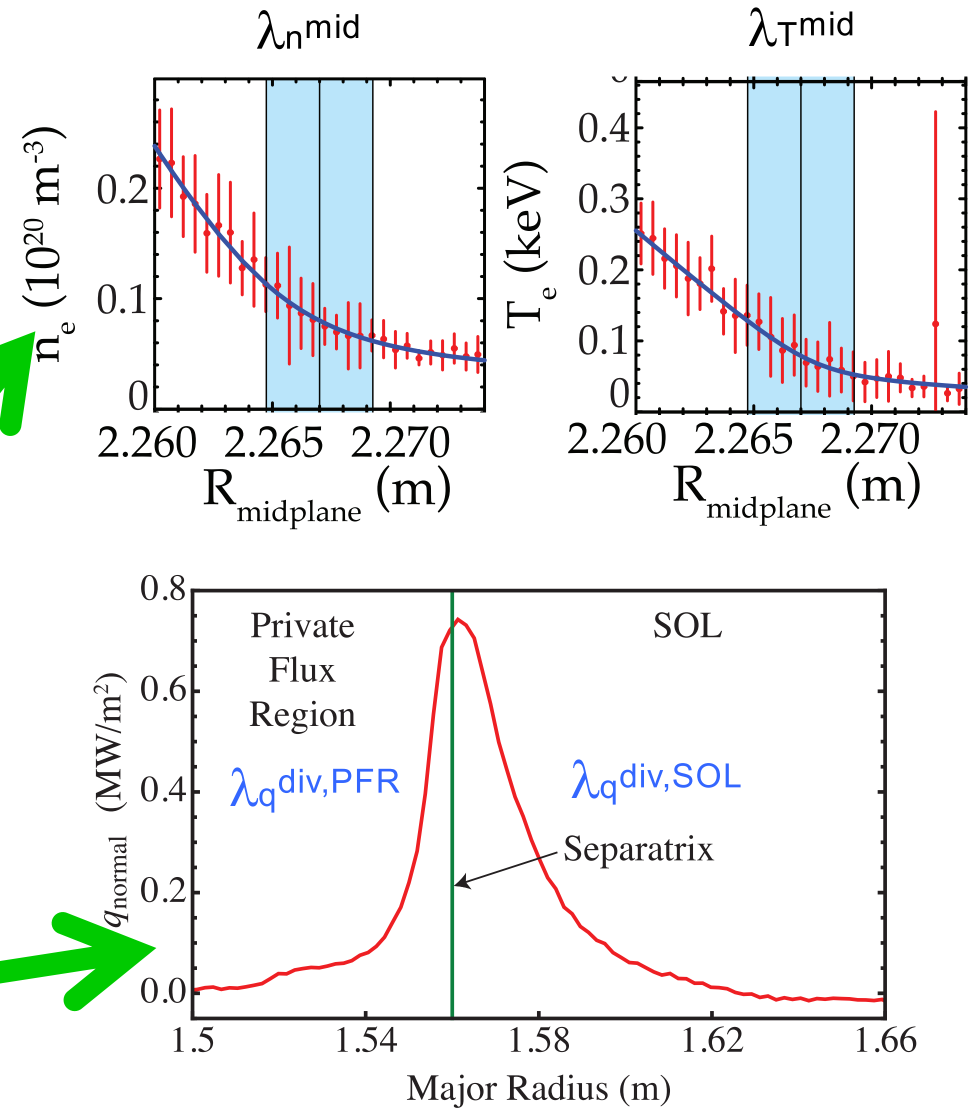
- Plasma exhaust via magnetic X-point divertors
  - Particle exhaust
  - Momentum and power exhaust
  - **Recently identified challenges to attractive core-edge plasma scenarios with W walls**

- Power exhaust challenge harder than thought
  - Heat flux footprint decreases with I_p; no increase with R
    - Both steady and transient loads can exceed solid PFC limits

- Confinement difficult with bare high-Z PFCs
  - Good confinement is challenging with high-Z walls in e.g. JET

Heat flux profile measured in divertor with infrared thermography & compared to midplane n_e and T_e profiles

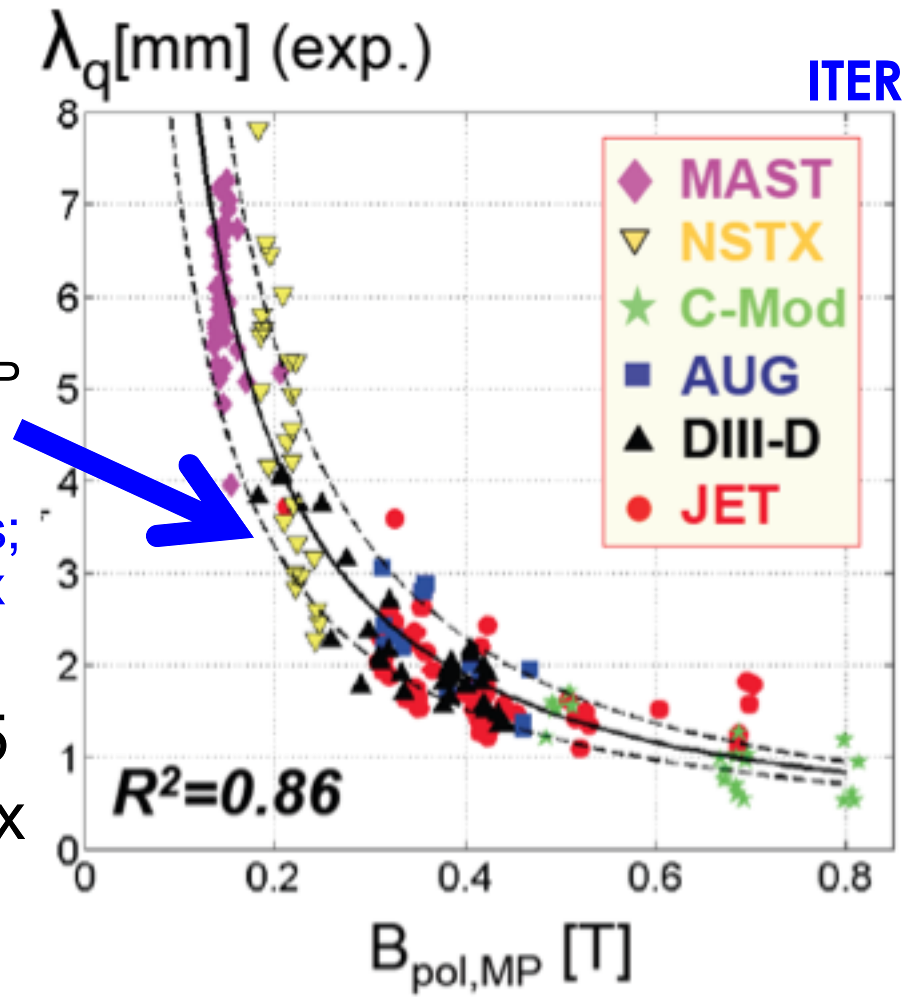




M.A. Makowski et. al., Phys. Plasmas **19** (2012) 056122

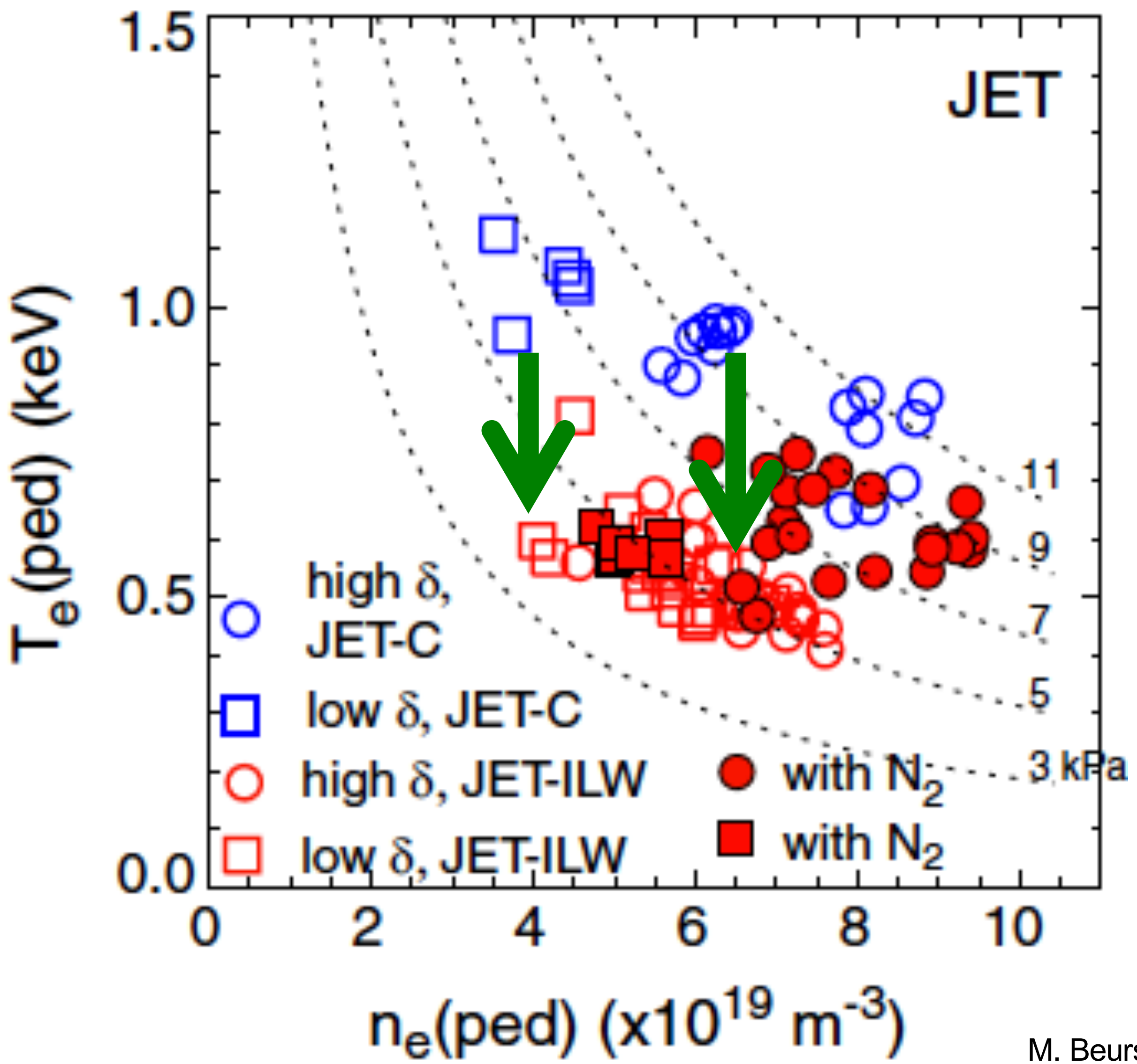
Steady heat flux flows in the SOL in a very narrow channel

- Heat flux profile width λ_q measured in divertor
  - λ_q projected to outer midplane with flux expansion
- International effort found that λ_q varies inversely with $B_{pol,MP}$
  - No increase with R, P_{SOL}
  - Low gas puff attached plasmas; some broadening and heat flux dissipation with detachment
- Projected width in ITER ~ 1/5 previous value; peak heat flux 5x higher unless mitigated
- *Much more challenging for reactors, due to higher P_{fusion}*



T. Eich et. al., Nucl. Fusion **53** (2013) 093031

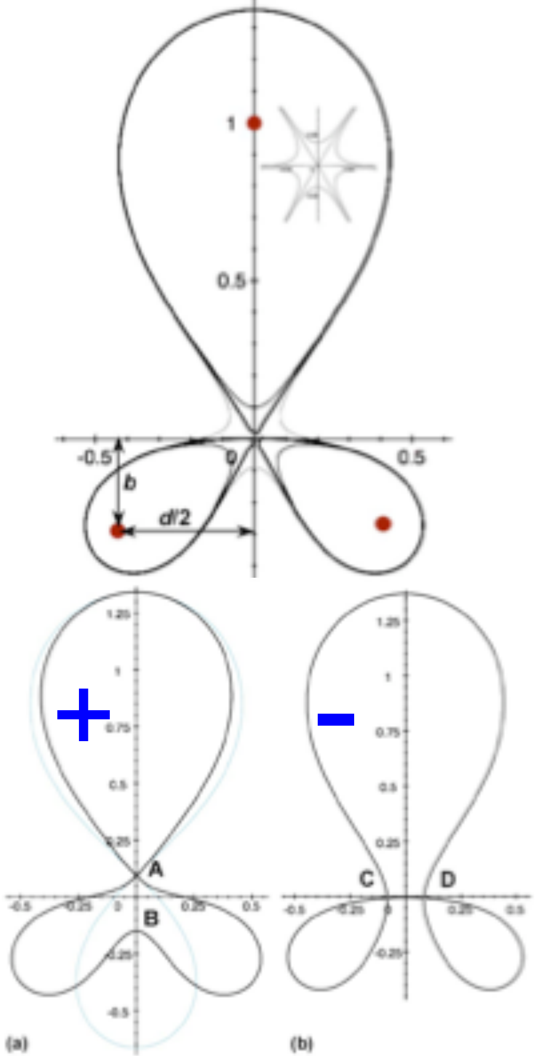
Edge and core plasma temperature and confinement was reduced in JET scenarios with installation of ITER-like wall



M. Beurskens et al., PPCF **55** (2013) 124013

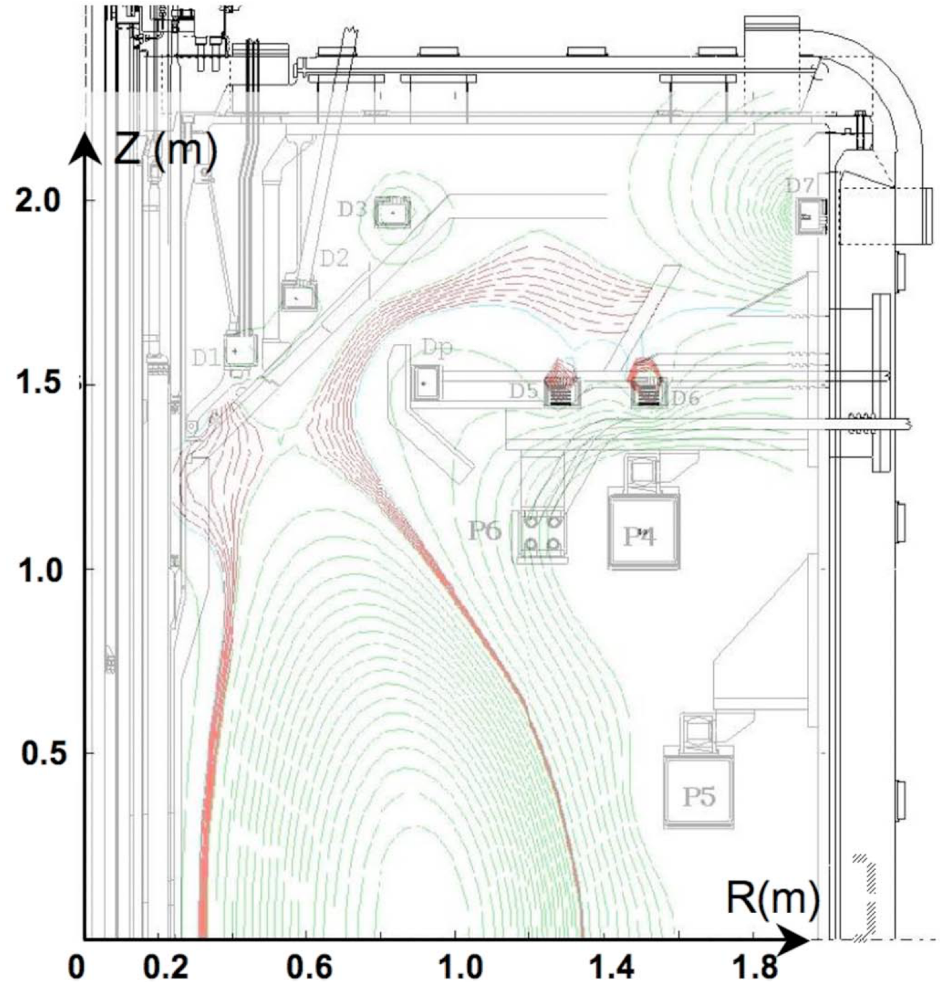
Several divertor innovations may increase the heat dispersal area for future (and present!) devices

Snowflake divertors



D. Ryutov et. al., Phys. Plasmas **14** (2007) 064502

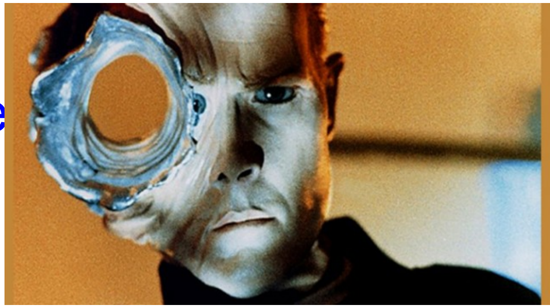
Super-X divertor in MAST-Upgrade



P. Valanju et. al., Nucl. Fusion **16** (2009) 056110

Liquid metal PFCs are an option to solid PFCs, but have substantial R&D needs to assess viability

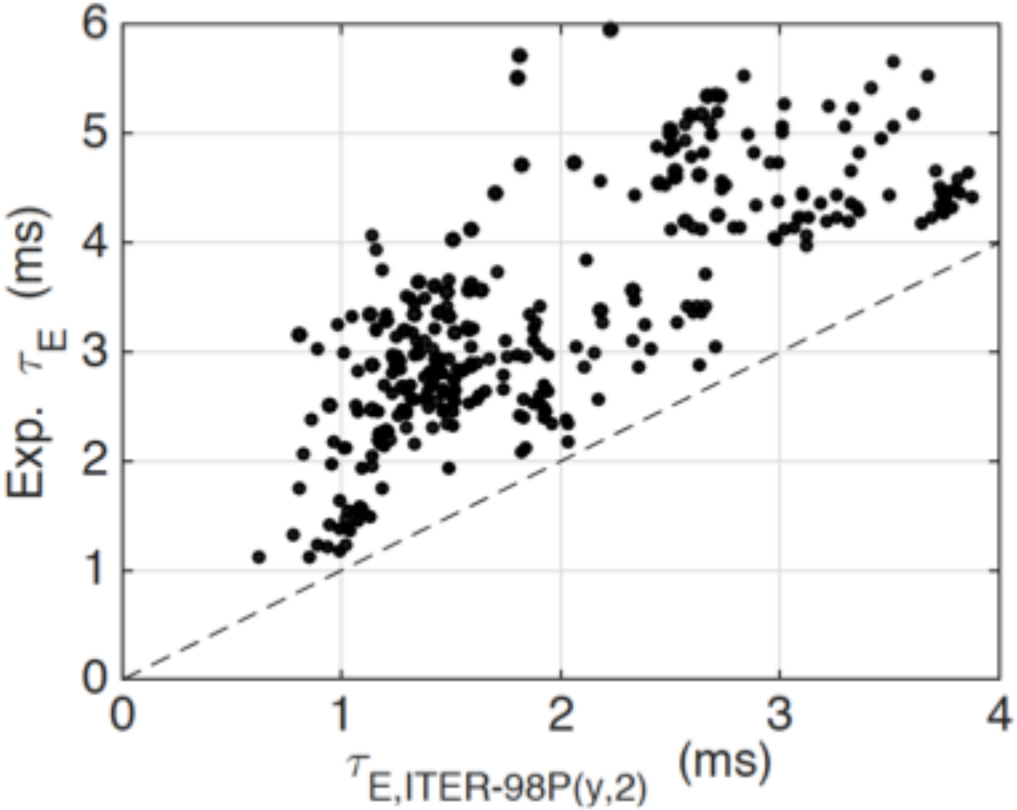
- Advantages
  - Erosion tolerable from PFC view: self-healing surface
  - No dust; main chamber material and tritium transported to divertor could be removed via flow outside of tokamak
  - Liquid metal is neutron tolerant; protects substrate from PMI
  - Liquid (and solid) lithium offer access to low recycling, high confinement regimes under proper conditions
  - Very high steady, and transient heat exhaust, in principle (50 MW/m^2 from electron beam exhausted; also 60 MJ/m^2 in 1 μsec)
- Disadvantages and R&D needs
  - Liquid metal surfaces and flows need to be stable
  - Liquid metal chemistry needs to be controlled
  - Temperature windows need optimization



* *Most of experience in fusion is with Li, but Sn and eutectics (e.g. Sn-Li) offer some promise in terms of broader temperature windows*

Lithium (solid and liquid) PFCs can enhance confinement

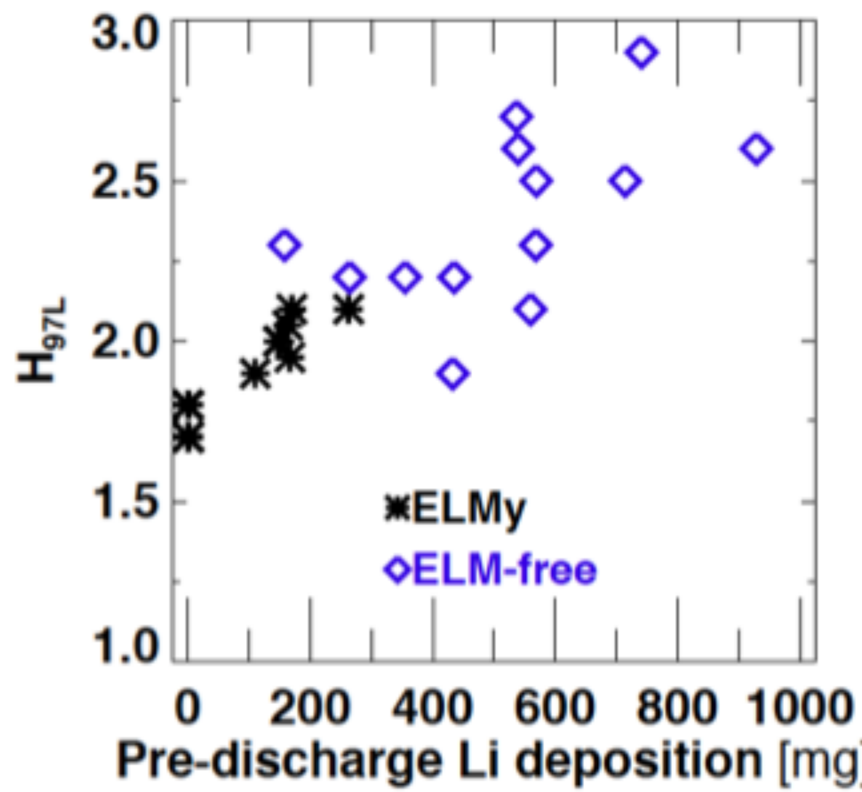
LTX



- 2-4x improvement over ITER98P(y,2) (H-mode scaling)

J.C. Schmitt et al, Phys. Plasmas **22** (2015) 056112

NSTX



- H98y2 increased from 0.8 -> 1.4 (H-mode scaling)

D.P. Boyle et al., J. Nucl. Mater. **438** (2013) S979

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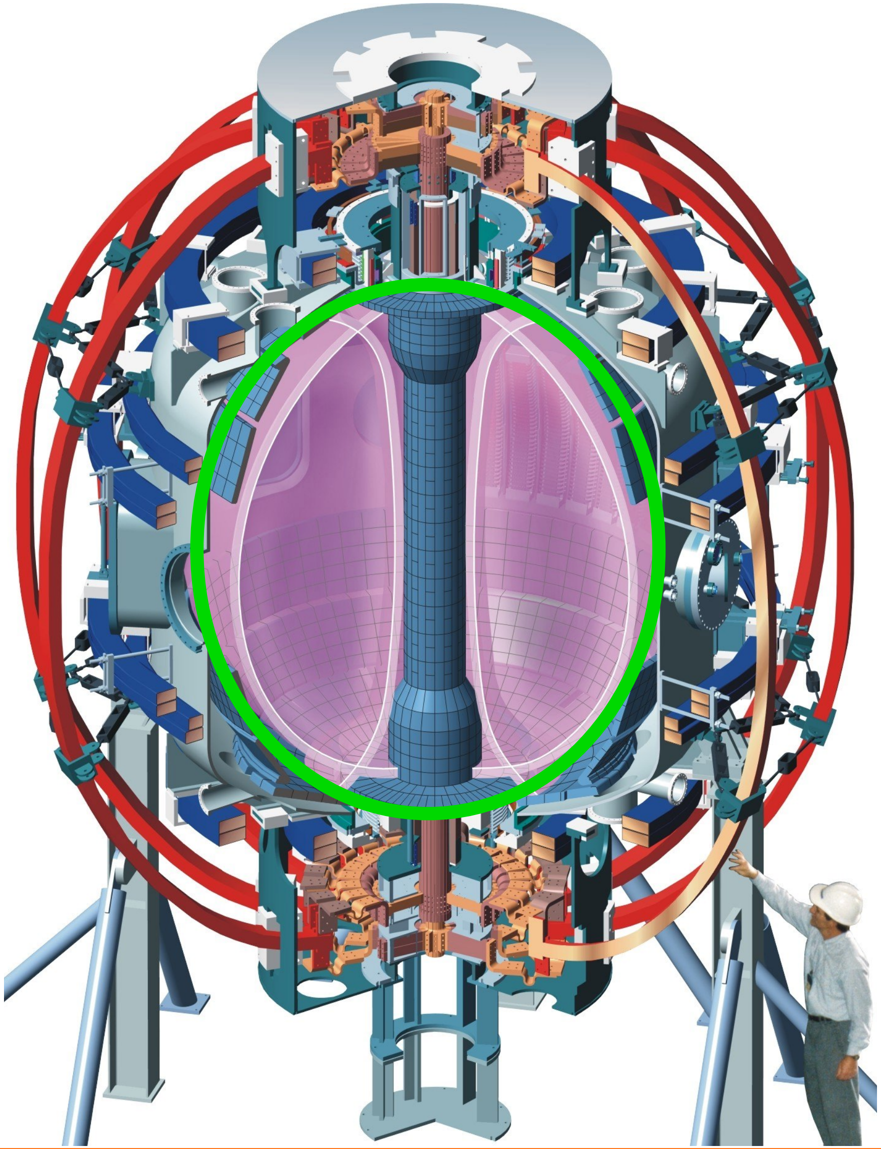
What if the heat flux from the plasma is time-varying?

- The heat flux from the plasma is indeed variable in time, with a 'DC' component and periodic eruptions
  – The biggest problems are 'disruptions', when the plasma current and energy quenches in ~ milliseconds; ITER *must* either avoid disruptions or mitigate their effects!
  – More periodic events include edge localized modes (ELMs), which can eject 10% of the plasma energy in ~ 0.5 msec
  – Turbulence (thermodynamic) and other instabilities can regularly release up a few tenths of plasma energy rapidly

- Substantial research goes into understanding and controlling transient events in fusion devices

NSTX was a fusion research facility at PPPL, presently undergoing a major upgrade



NSTX-U Facility Parameters

Major Radius 0.90 m

Minor Radius ≤ 0.55 m

Plasma Current ≤ 2.0 MA

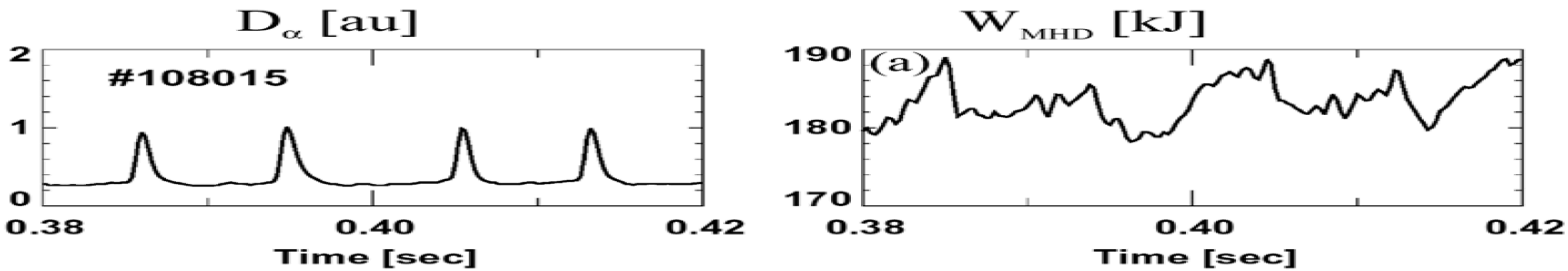
Toroidal Field ≤ 1.0 T

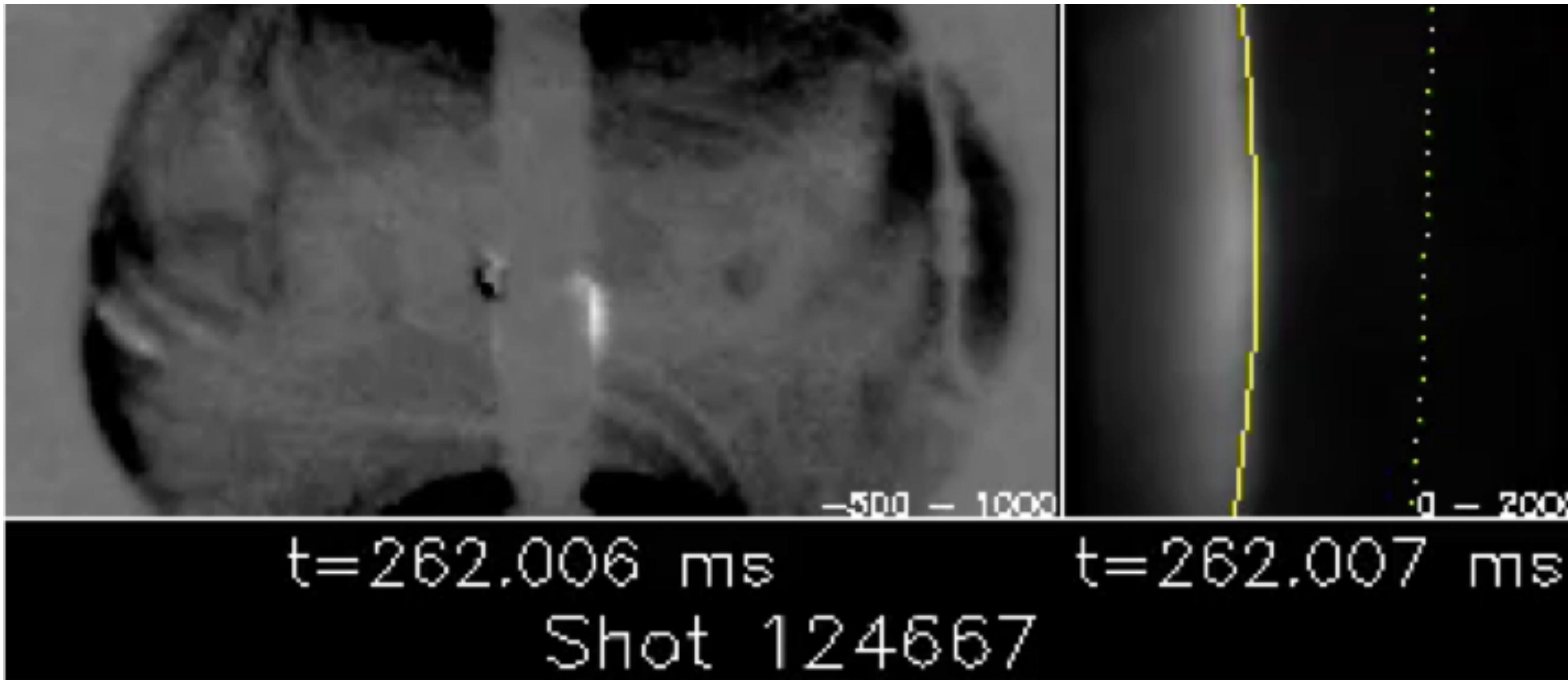
Neutral Beam Power ≤ 12 MW

RF Heating ≤ 6 MW

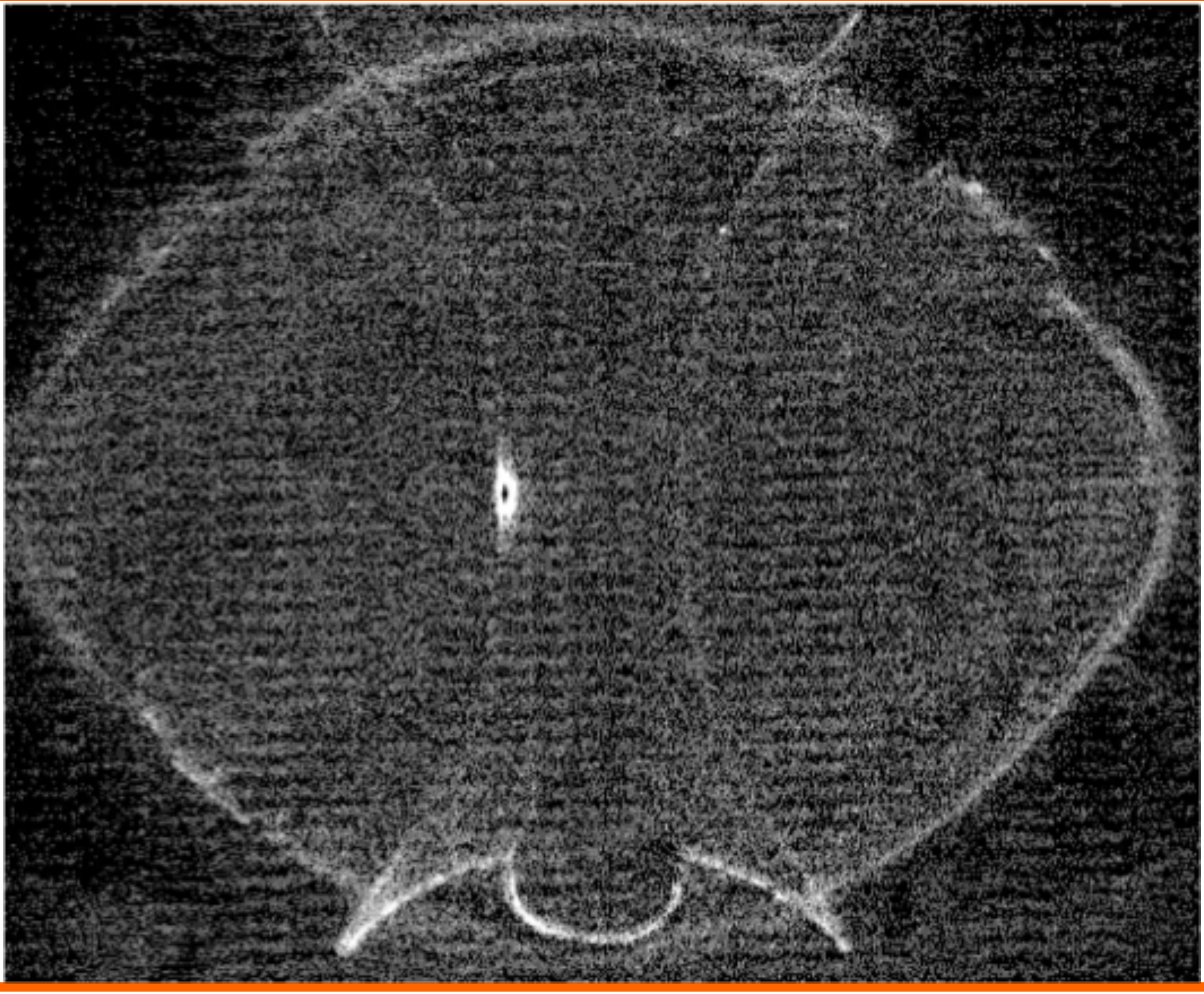
Pulse Length ≤ 10 sec

ELMs are periodic eruptions in ‘H-mode’ plasmas (NSTX)





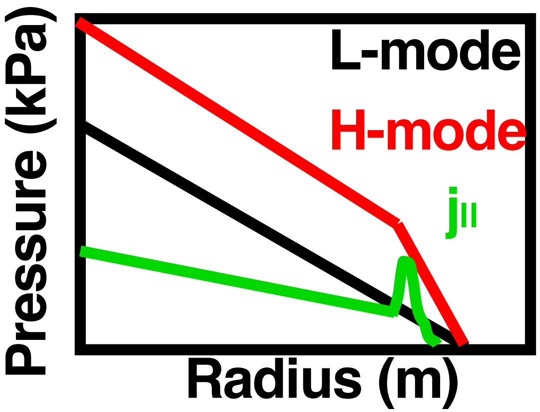
ELMs are periodic eruptions in 'H-mode' plasmas (MAST)

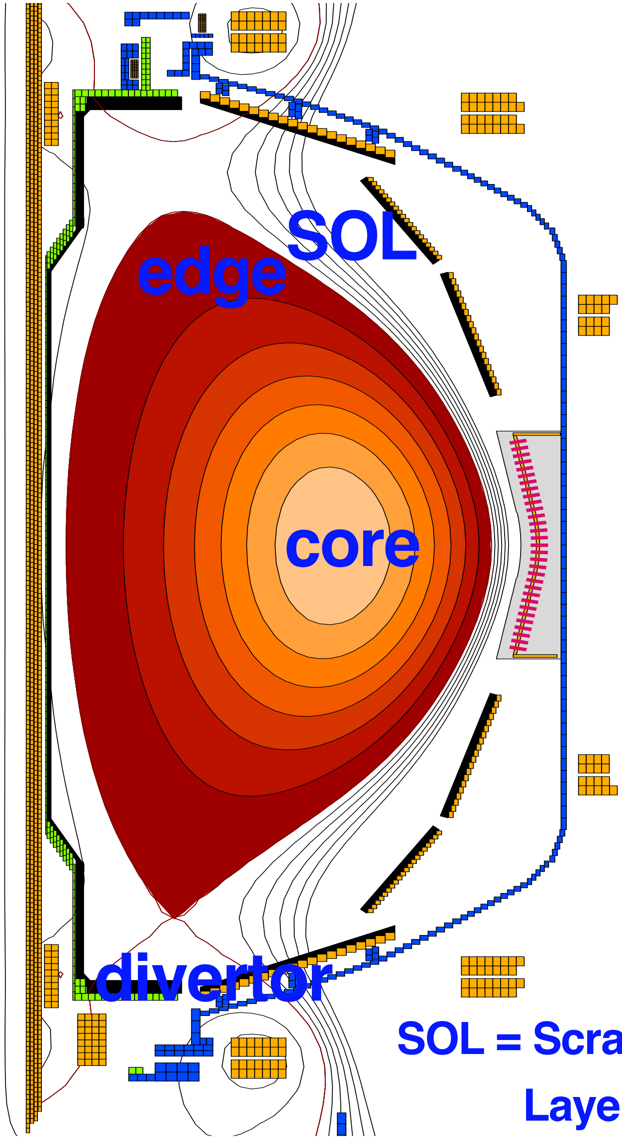


Solar flares are also periodic eruptions

What Are Edge Localized Modes (ELMs)? Most likely violations of ideal or resistive MHD stability limits

- Plasmas undergo a transition from low (L-mode) to high (H-mode) when enough heating power is added
- The edge plasma pressure develops a stair-step or “pedestal” in H-mode

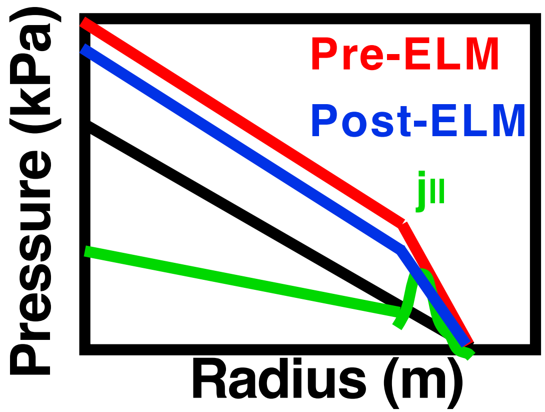




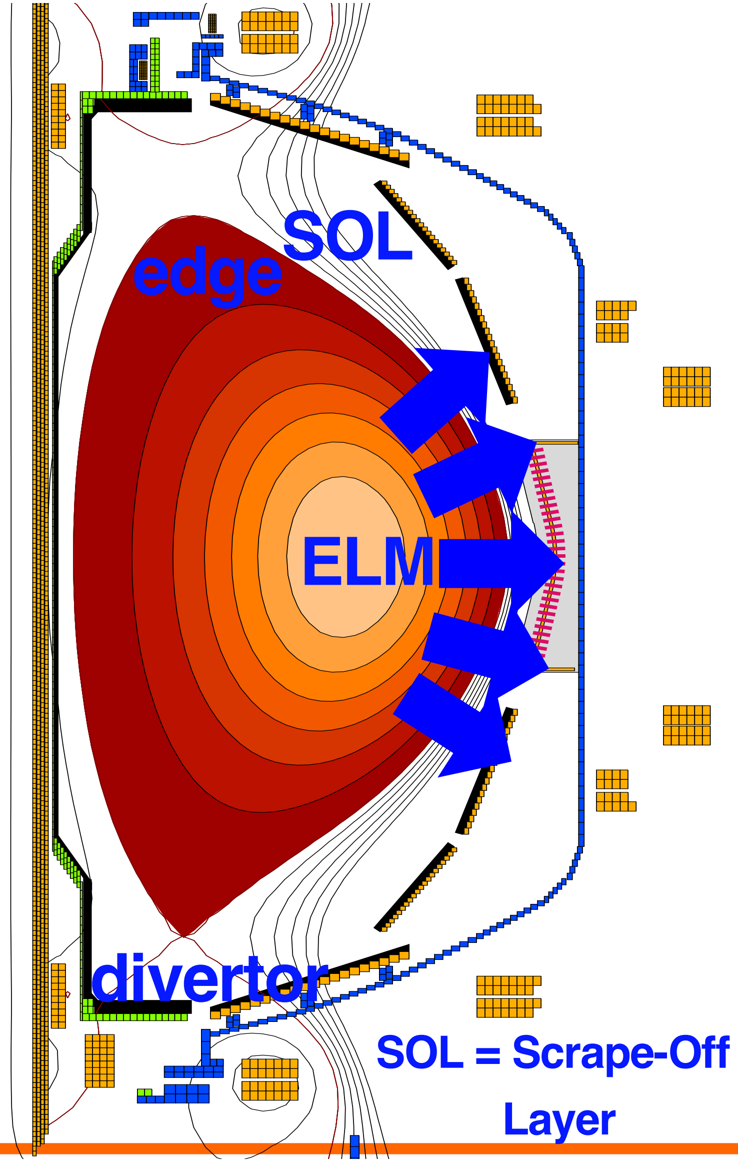
SOL = Scrape-Off Layer

ELMs expel plasma from the low field side, which is prone to ballooning-type pressure driven modes

- Plasmas undergo a transition from low (L-mode) to high (H-mode) when enough heating power is added
- The edge plasma pressure develops a stair-step or “pedestal” in H-mode



- The steep edge pressure gradient and/or edge current can destabilize Edge Localized Modes (ELMs), where a portion of the pedestal pressure and energy is periodically expelled



What Are Edge Localized Modes (ELMs)?

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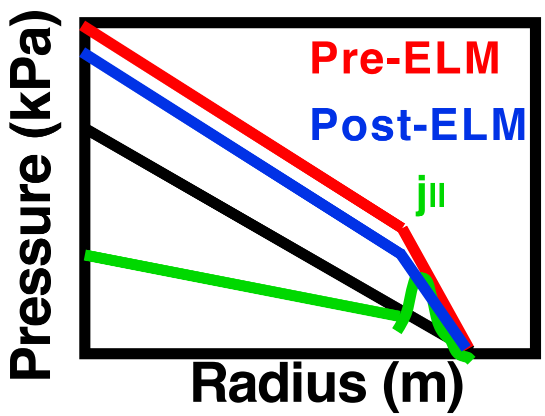

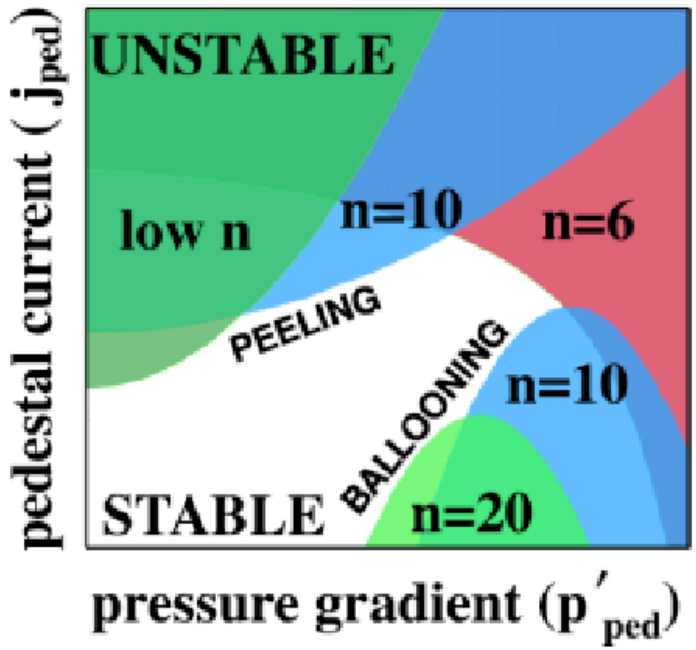

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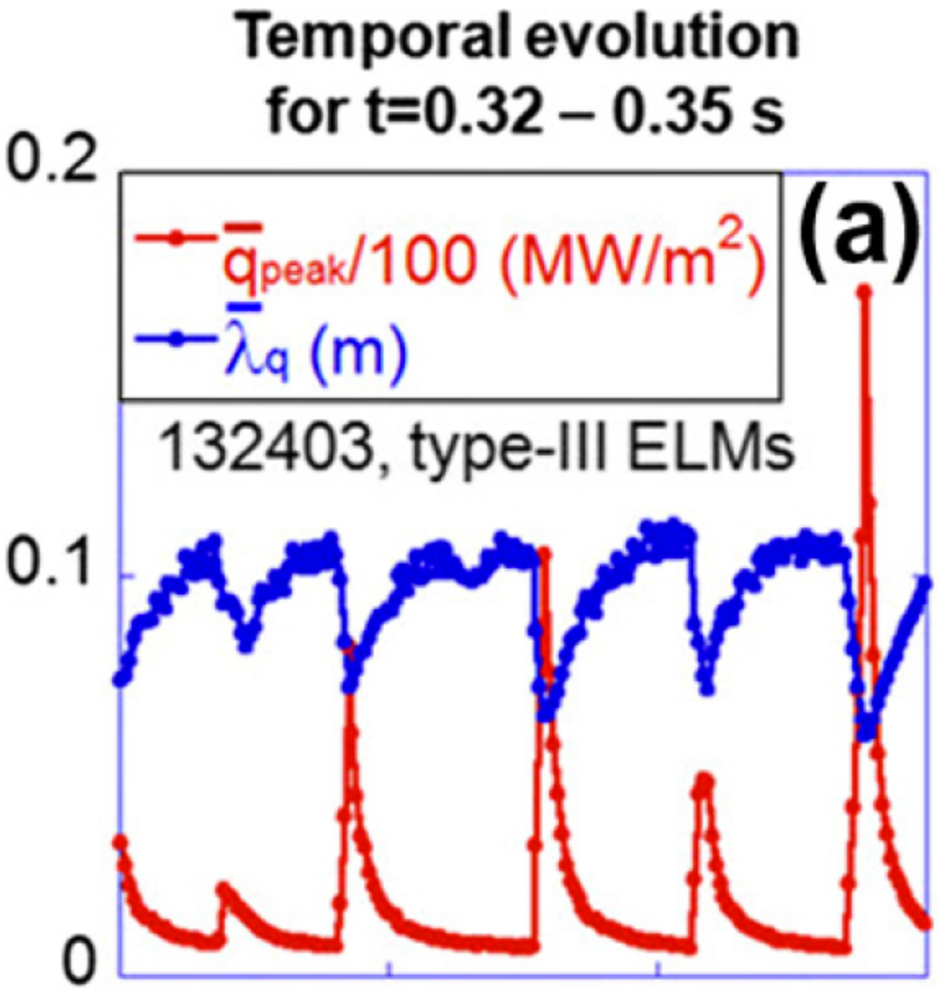
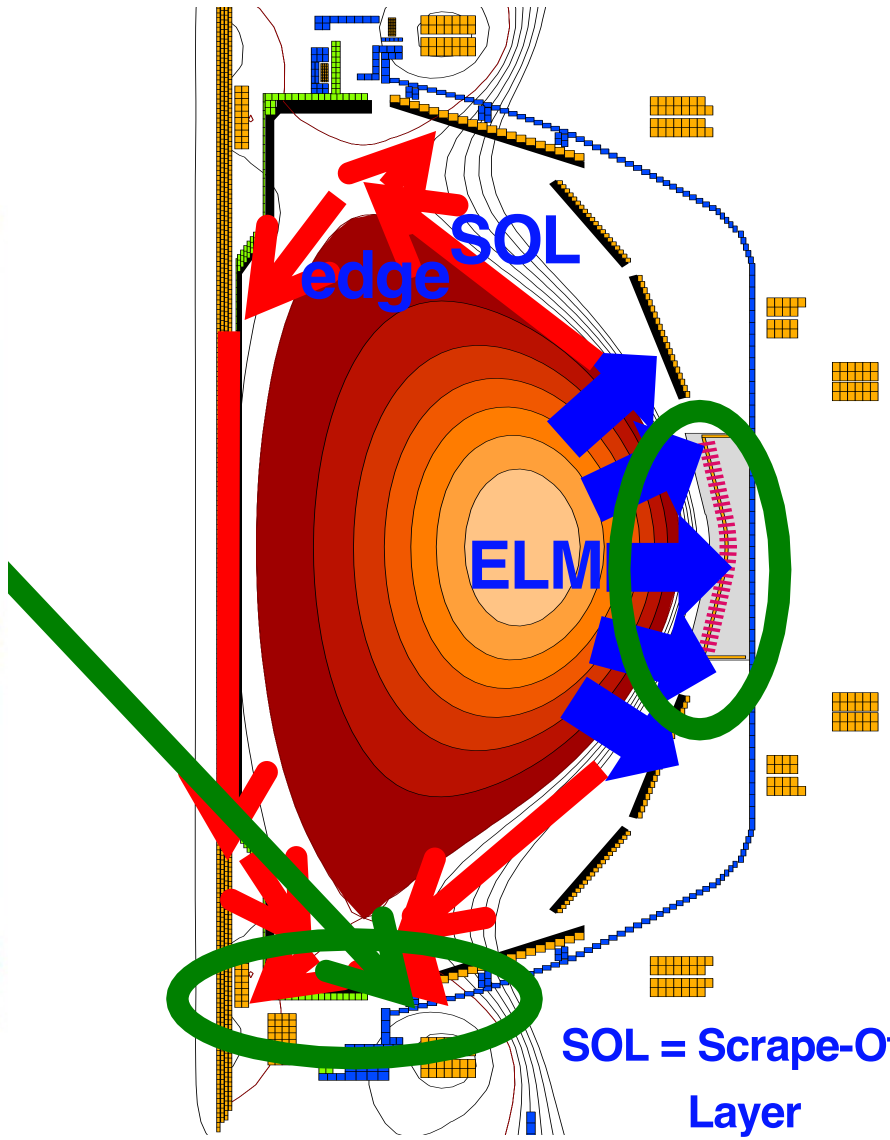
Plasma fluxes from ELMs on outer wall and divertor are 10 times higher than steady inter-ELM fluxes

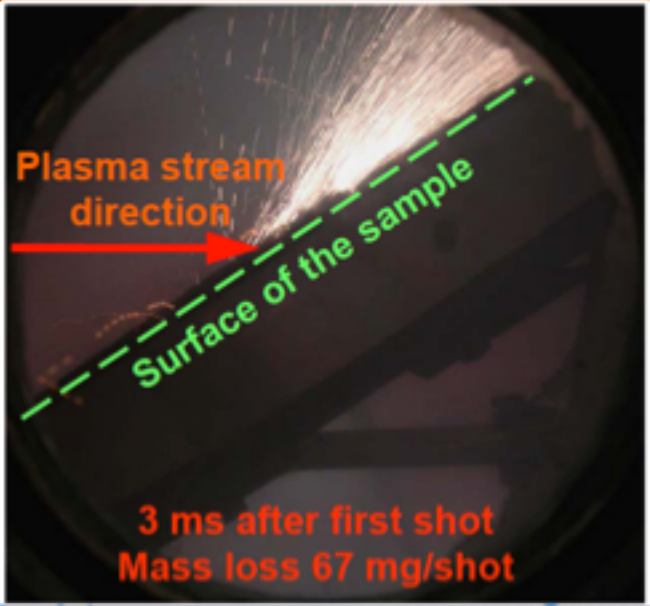


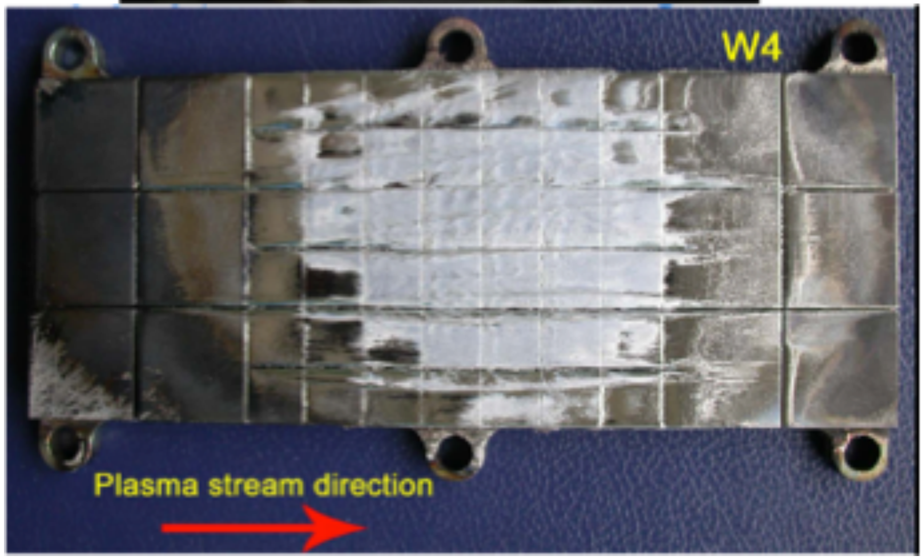
J.W. Ahn et. al., J. Nucl. Mater. **438** (2013) S317



SOL = Scrape-Off Layer

ELM simulators used to assess ELM heating limits in ITER





- Russian ELM simulator, showing damage to Tungsten surface with ITER ELM-like plasma bombardment of Tungsten

- After 100 simulated 1.6 MJ ELMs, substantial tungsten melting that covers gaps between tiles

Zhitlukhin et. al. J. Nucl. Mater. **363** (2007) 301

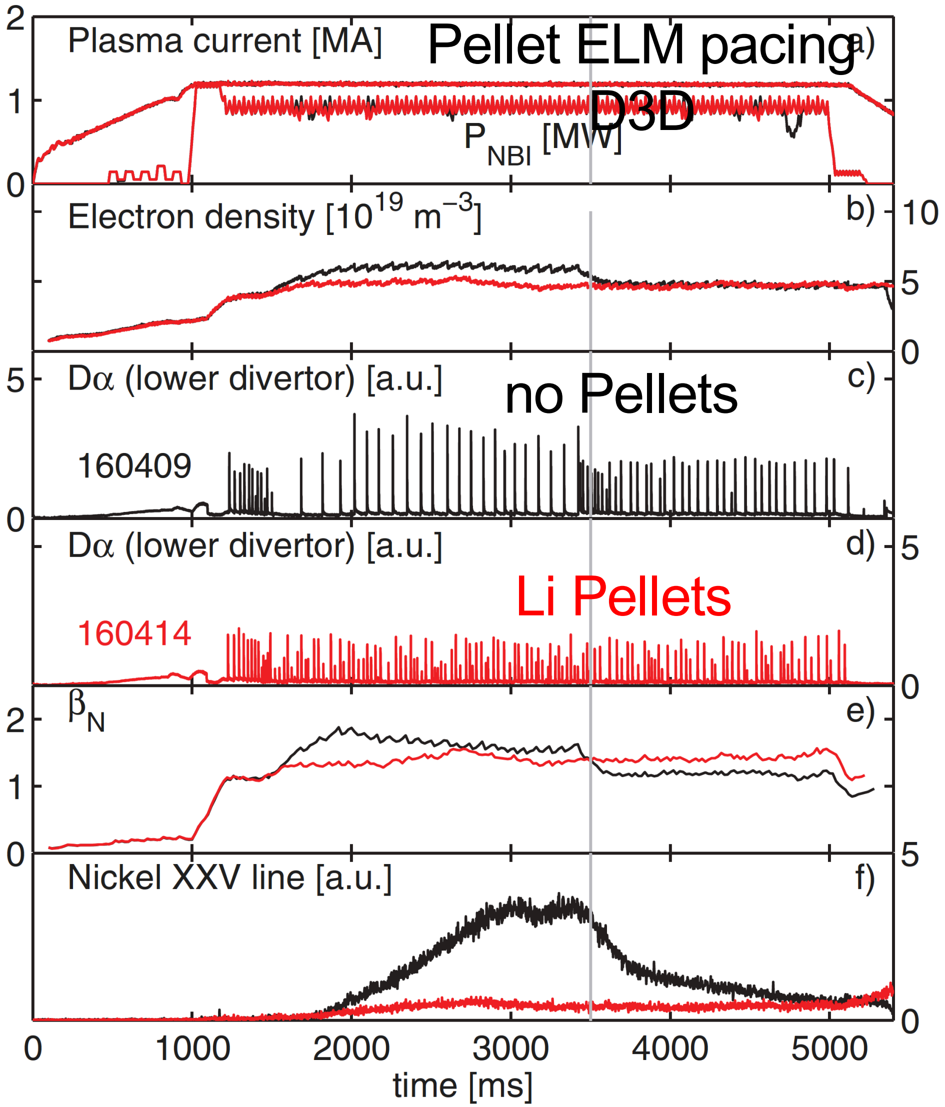
ELMs can be avoided or mitigated in several ways

- ELMs are caused by having too much pressure and/or current near the plasma boundary

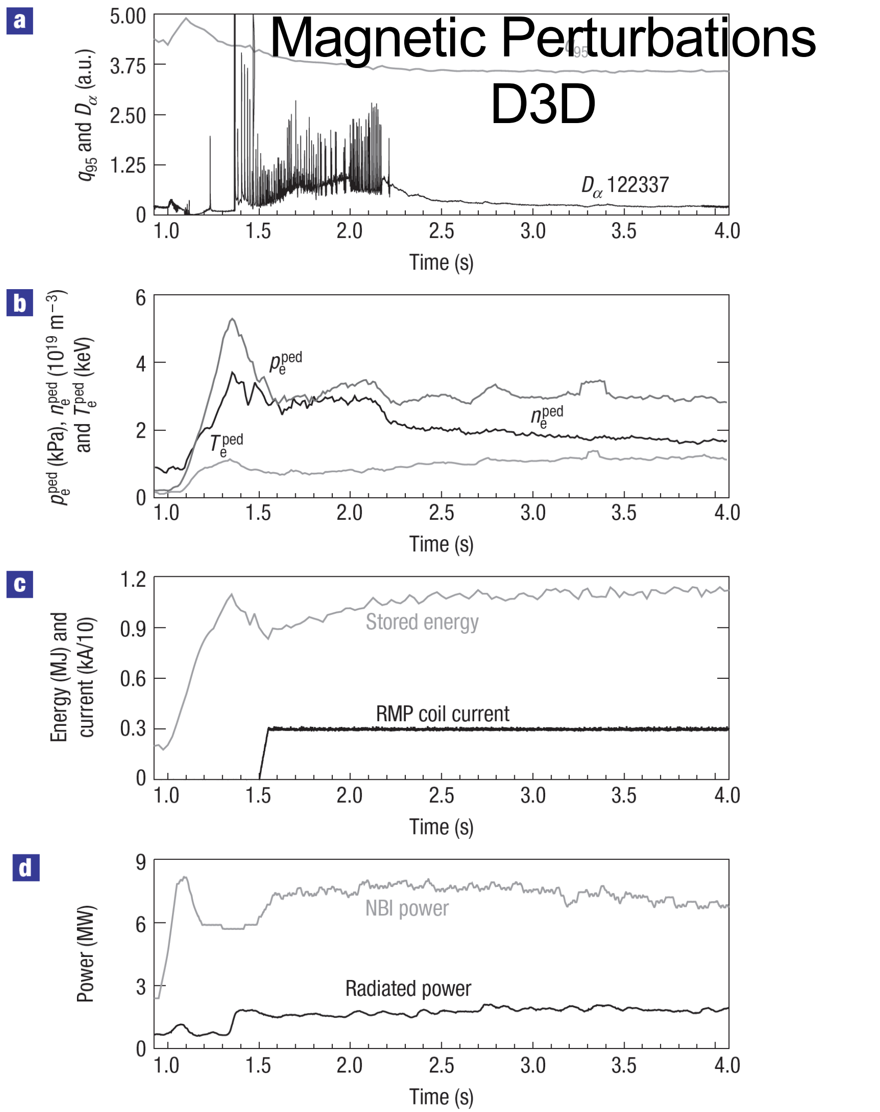
Solutions: Review: R. Maingi, Nucl. Fusion **54** (2014) 114016

- Trigger rapid, tiny ELMs with pellets
- Apply additional 3-D fields to eliminate ELMs
  - Tiny leak in magnetic bottle - pressure relief
- Operate with some other instability that relieves the plasma pressure continuously – 'quiescent' modes
- Operate far away from large, naturally occurring ELM conditions, or in tiny ELM conditions
- Widen the ELM-stable operating window
  - One way to do this is to change the plasma characteristics responsible for ELMs -> lithium or boron powder injection

ELMs eliminated with either 3-D magnetic perturbations, or naturally via access to a Quiescent H-mode



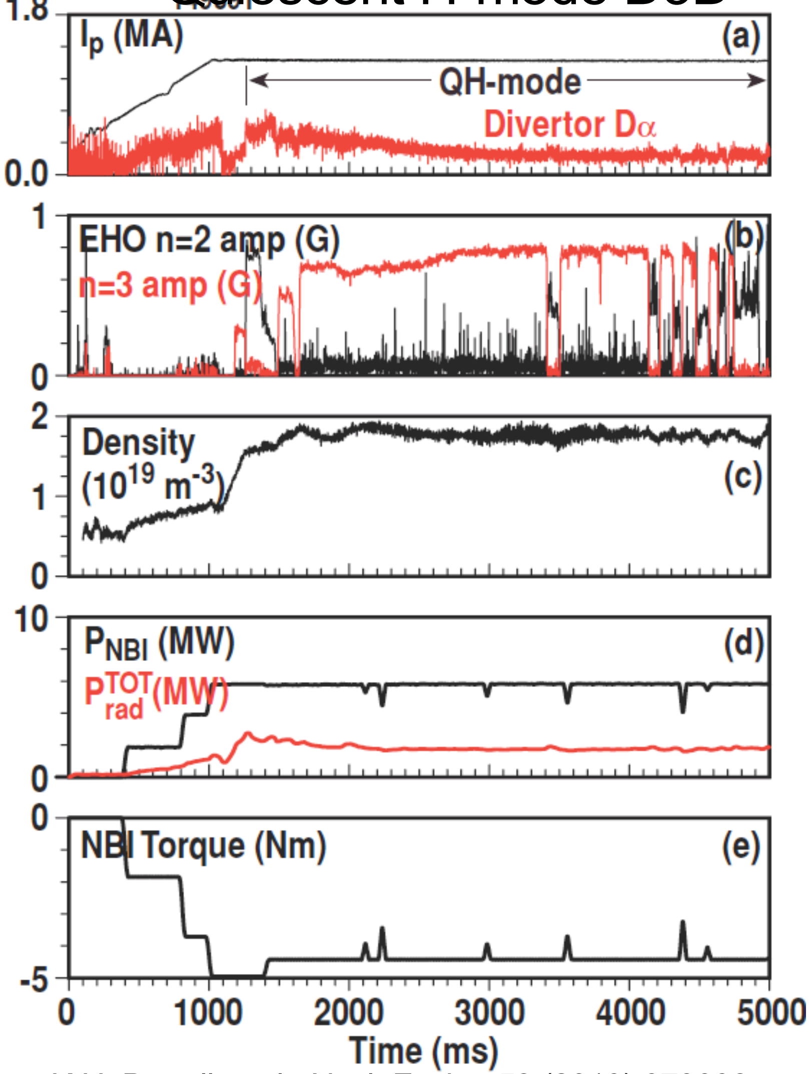
A. Bortolon et al., Nucl. Fusion **56** (2016) 056008



T.E. Evans et al., Nature Phys. **2** (2006) 419

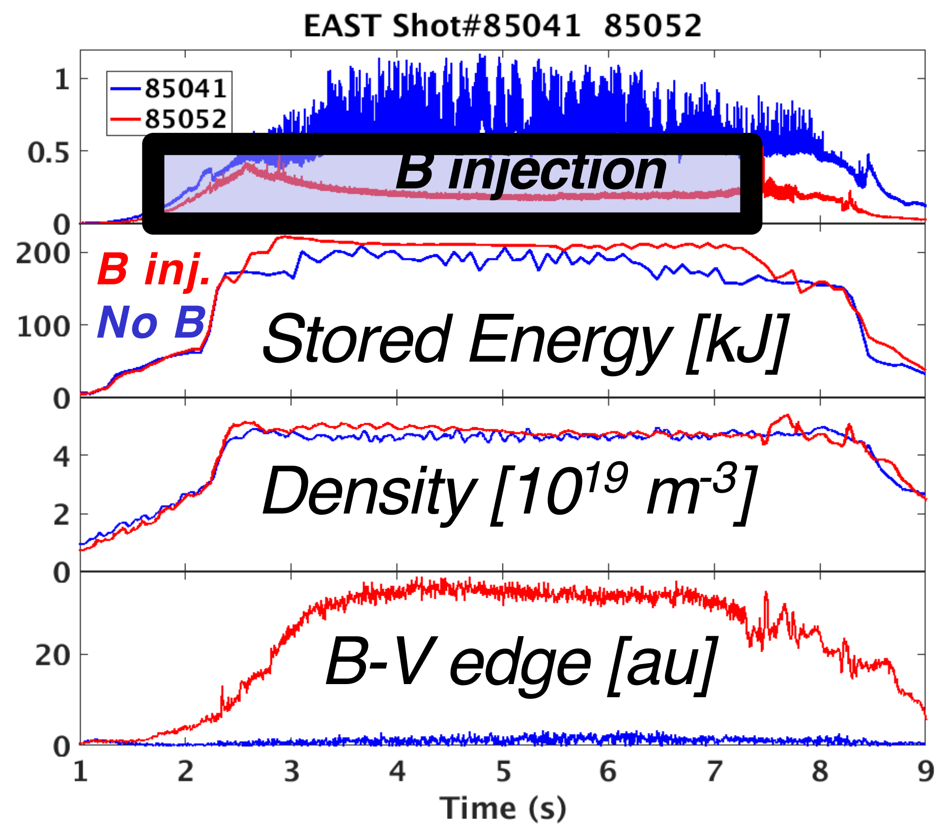
ELMs eliminated naturally via access to a Quiescent H-mode or via boron powder injection triggering quiescence

Quiescent H-mode D3D



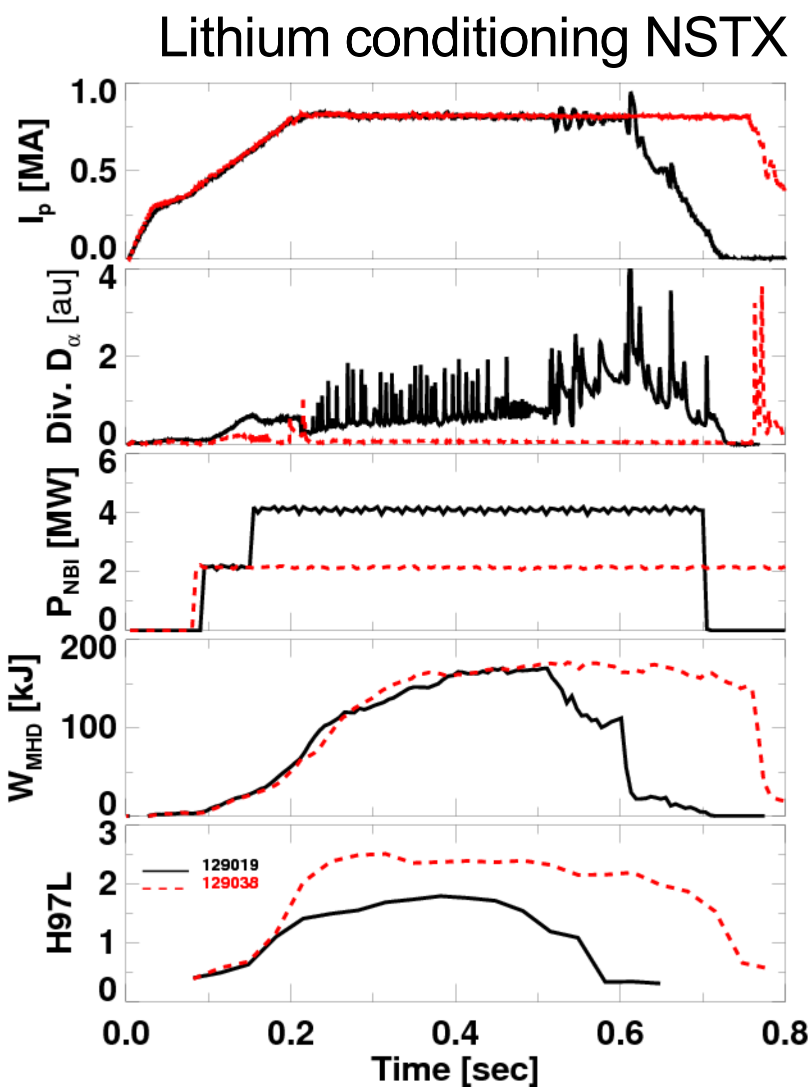
K.H. Burrell et al., Nucl. Fusion **53** (2013) 073038

B powder injection EAST (May 2019)

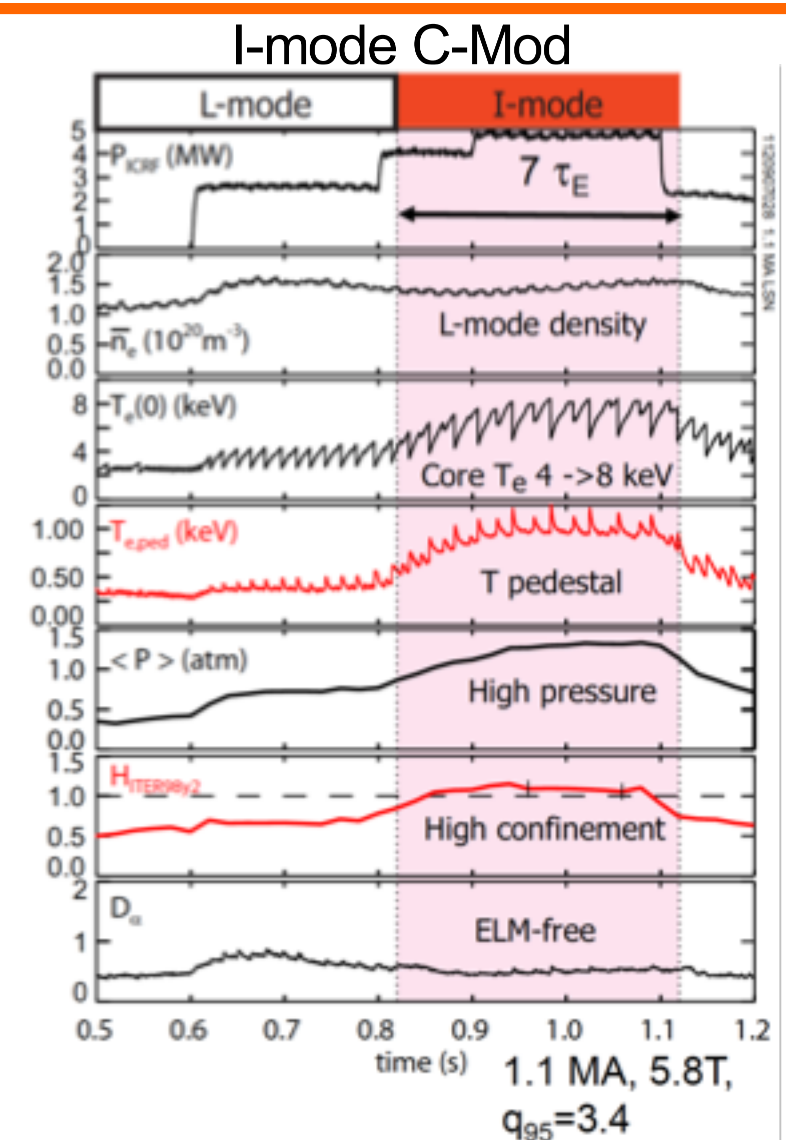


Z. Sun et al., PRL and A. Diallo et al., NF, both in preparation

ELMs eliminated by lithium wall conditioning or by operating far from instability boundaries



R. Maingi et al., PRL **103** (2009) 075001



A.E. Hubbard et al., IAEA 2012 paper

Control of plasma exhaust is an exciting fusion research area with engaging science and technology

- Vibrant topic with substantial domestic and international effort

- Engineering the plasma-material interface is critical to the success of fusion

✓ Expertise needed in all areas beyond physics and NE: materials science, chemistry, large scale computing…

✓ **Early career researchers can make meaningful contributions**

THANK YOU FOR YOUR ATTENDANCE