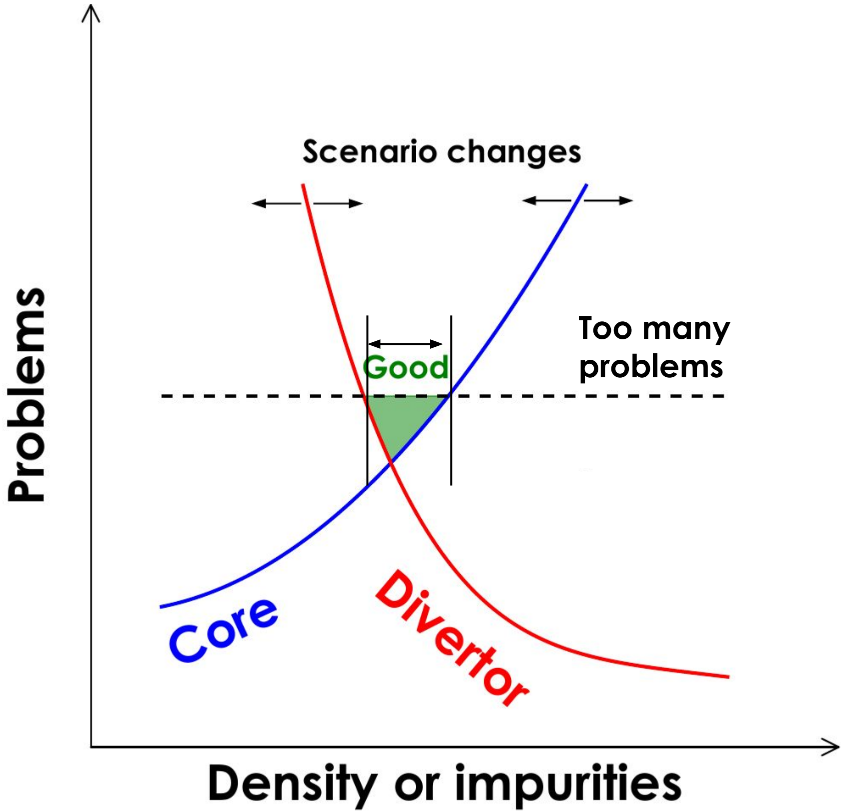
First wall heat load control, ELM and divertor, detachment control

David Eldon
with some figures borrowed from the literature



Presented at the
11th ITER International School
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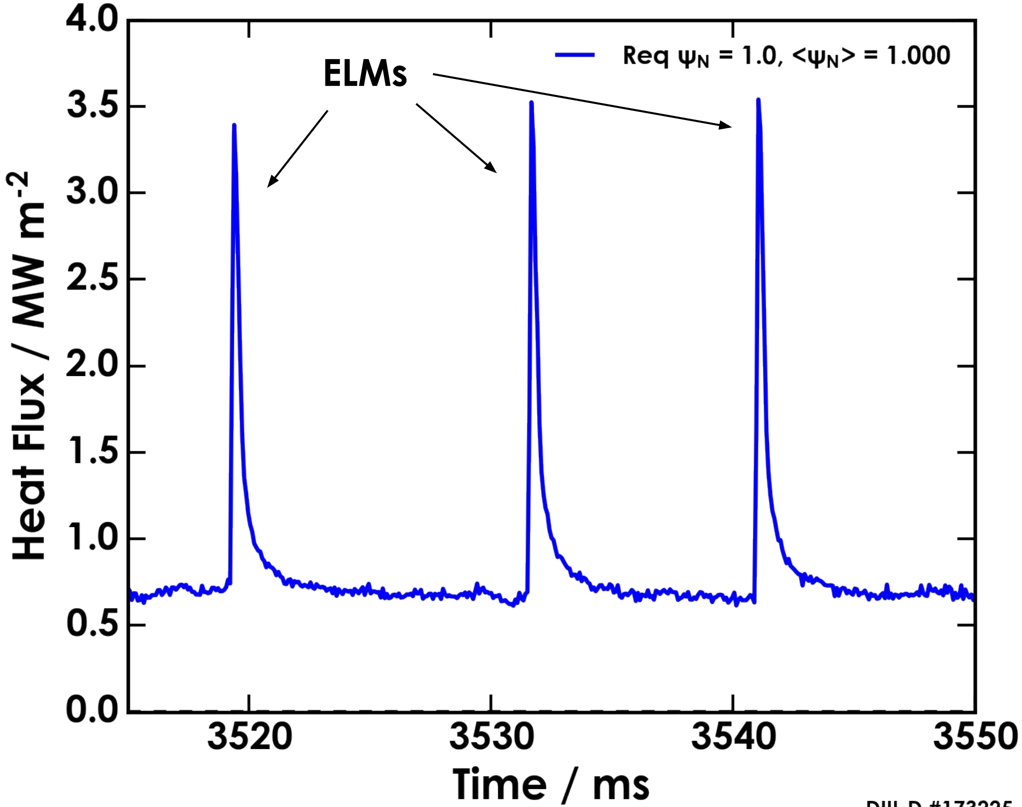
ITER requires dissipation of heat exhaust to avoid exceeding material limit

- **ITER's divertor tolerates steady heat flux ≲15 MW m^{-2}**
- **H-mode requires ≈150 MW across LCFS**
  - ≈½ to outer divertor → 75 MW
- **Footprint area = $2\pi R_{div} \lambda_{int} f_x f_{tw}$ = 0.9 – 2 m^2**
  - R_{div} = 5.6 m
  - $\lambda_{int} \approx \lambda_q + 1.64\, S$ = 3.5 – 8.5 mm
    - Based on λ_q = 1–6 mm, S = 1.5 mm
  - f_x = 9
  - $f_{tw} \approx$ 0.8
- **q_{div} = 70–170 MW m^{-2}**
- **q_{div}/tolerance = 4.7–11 → need *roughly* 79% – 91% dissipation**
- **Literature estimates: 60-80% radiated, 70% radiated**

Divertor heat load tolerance:R. Pitts, et al., Nucl. Mater. Energy 20, 100696 (2019) http://dx.doi.org/10.1016/j.nme.2019.100696
H-mode access: F. Ryter, et al., Nucl. Fusion 36, 1217 (1996) https://doi.org/10.1088/0029-5515/36/9/11
Footprint stuff: J. Horacek, et al., Nucl. Fusion 60, 066016 (2020) https://doi.org/10.1088/1741-4326/ab7e47
Radiation requirements: R. A. Pitts, et al., Phys. Scr. T138, 014001 (2009) http://dx.doi.org/10.1088/0031-8949/2009/T138/014001
A. S. Kukushkin, et al., Nucl. Fusion 49, 075008 (2009) http://dx.doi.org/10.1088/0029-5515/49/7/075008

ELMs transiently increase heat flux & must be addressed

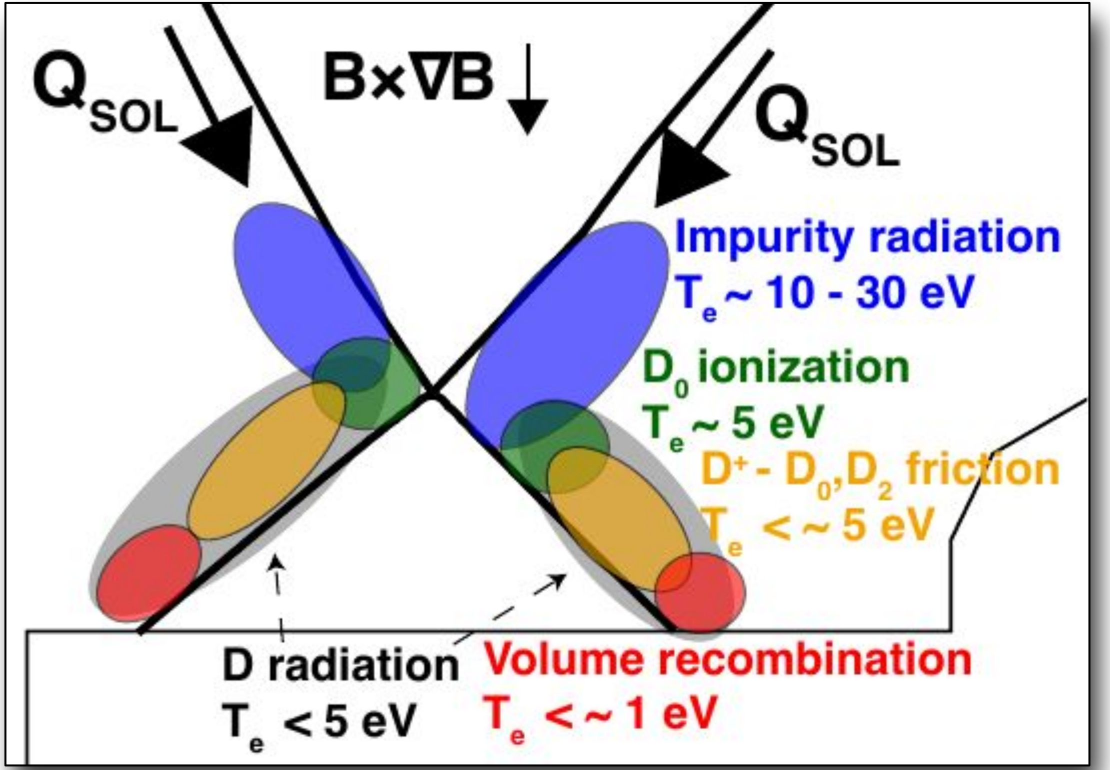
- **Driven by peeling-ballooning instability**
- **Briefly (~1 ms) increase heat load**
- **ELM suppression techniques available, but must work with dissipation method**



DIII-D #173225

ELM physics: P. B. Snyder, et al., Phys. Plasmas 9, 2037 (2002) http://dx.doi.org/10.1063/1.1449463
RMP ELM suppression: T. E. Evans, et al., Nucl. Fusion 45, 595 (2005) http://dx.doi.org/10.1088/0029-5515/45/7/007
Impurity ELM suppression: E. P. Gilson, et al., Nucl. Mater. Energy 28, 101043 (2021) https://doi.org/10.1016/j.nme.2021.101043

Impurities + high density → heat dissipation → divertor cold enough for neutrals → plasma-neutral interaction detaches from target plate



- **Extrinsic low-Z impurity seeding**
- **High density**
- $P_{rad} = n_e n_Z L_Z(T_e)$

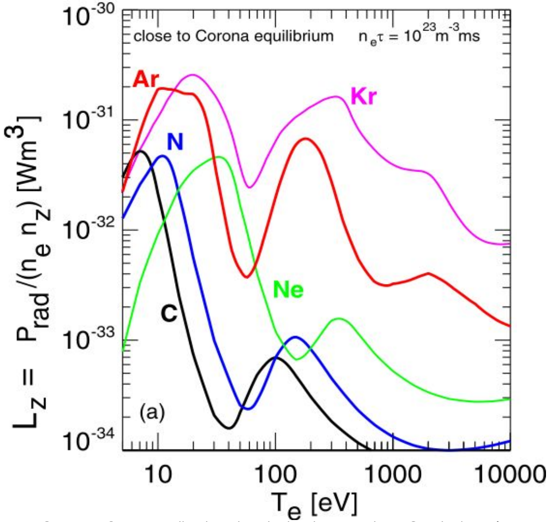


FIGURE FROM A. Kallenbach, et al., Plasma Phys. Control. Fusion 55, 124041 (2013)
http://dx.doi.org/10.1088/0741-3335/55/12/124041

The two-point model can help us understand dissipation terms

- **Two-point model or 2PM relates "upstream" and "target" conditions**
- **Considers plasma connected along a flux tube**
- **Relatively simple**

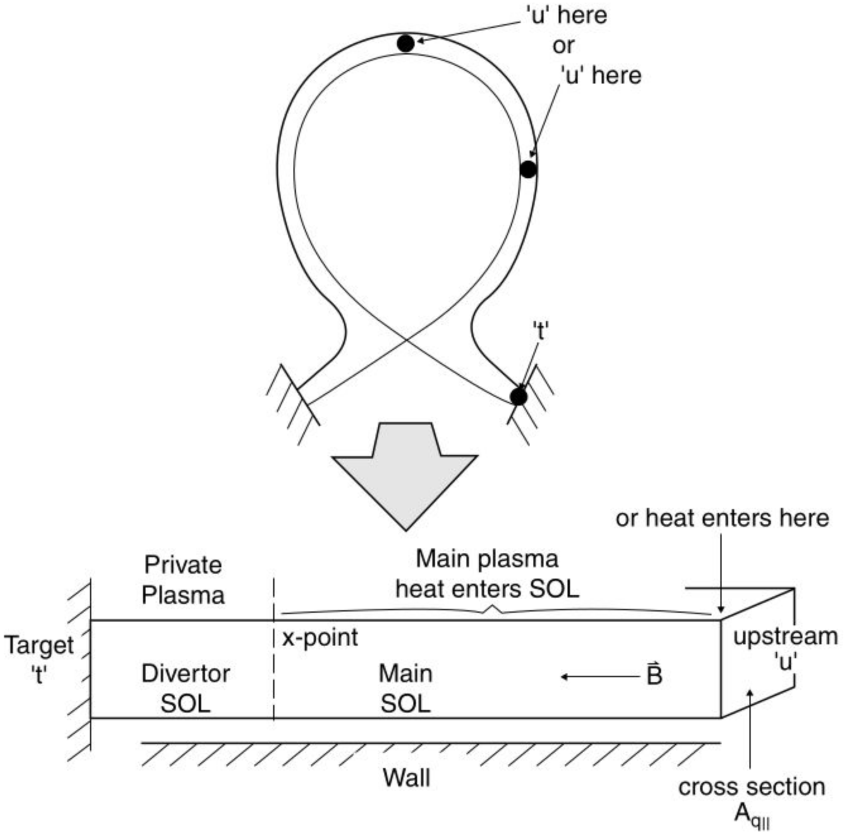


FIGURE: P. Stangeby, "The Plasma Boundary of Magnetic Fusion Devices" p. 222 (2000) ISBN 9780750305594 https://doi.org/10.1201/9780367801489

The two-point model can help us understand dissipation terms

$$T_t = \frac{q_{\|}^2}{n_{sep}^2}\left(\frac{2\kappa_e}{7q_{\|}L_{\|}}\right)^{4/7}\frac{2m_i}{\gamma^2 e^2}\frac{(1-f_{pow})^2}{(1-f_{mom})^2(1-f_{conv})^{4/7}}$$

$$\Gamma_t = \frac{n_{sep}^2}{q_{\|}}\left(\frac{7q_{\|}L_{\|}}{2\kappa_e}\right)^{4/7}\frac{\gamma e^2}{2m_i}\frac{(1-f_{mom})^2(1-f_{conv})^{4/7}}{(1-f_{pow})}$$

Attached values

Dissipation terms

Power loss

Pressure / momentum loss

Parallel convection

$$q_{\|,t} = \gamma\Gamma_t T_{e,t} = q_{\|}(1-f_{pow})$$

$$q_{\perp,t} = \sin\alpha\,(\gamma T_{e,t} + E_i)\Gamma_t$$

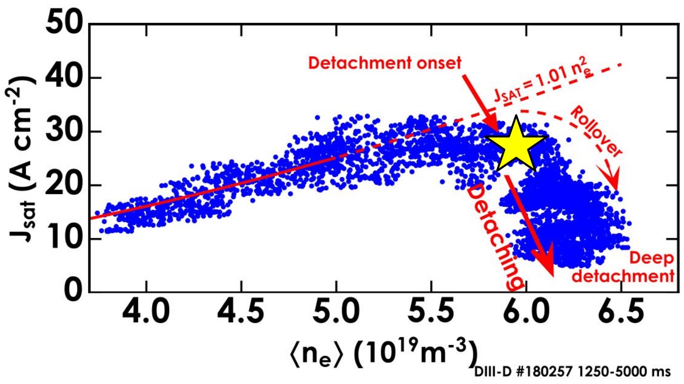
$$q_{\perp,t} = \sin\boldsymbol{\alpha}\,(q_{//}(1 - f_{pow}) + E_i\boldsymbol{\Gamma}_t)$$

Detachment review: A. W. Leonard, Plasma Phys. Control. Fusion 60, 044001 (2018) https://doi.org/10.1088/1361-6587/aaa7a9

Key definitions

J_{sat} = ion saturation current density = $e Z_i \Gamma_t$

- Measured by Langmuir probes



Rollover: J_{sat} first increases with increasing density, then "rolls over" & decreases with increasing density

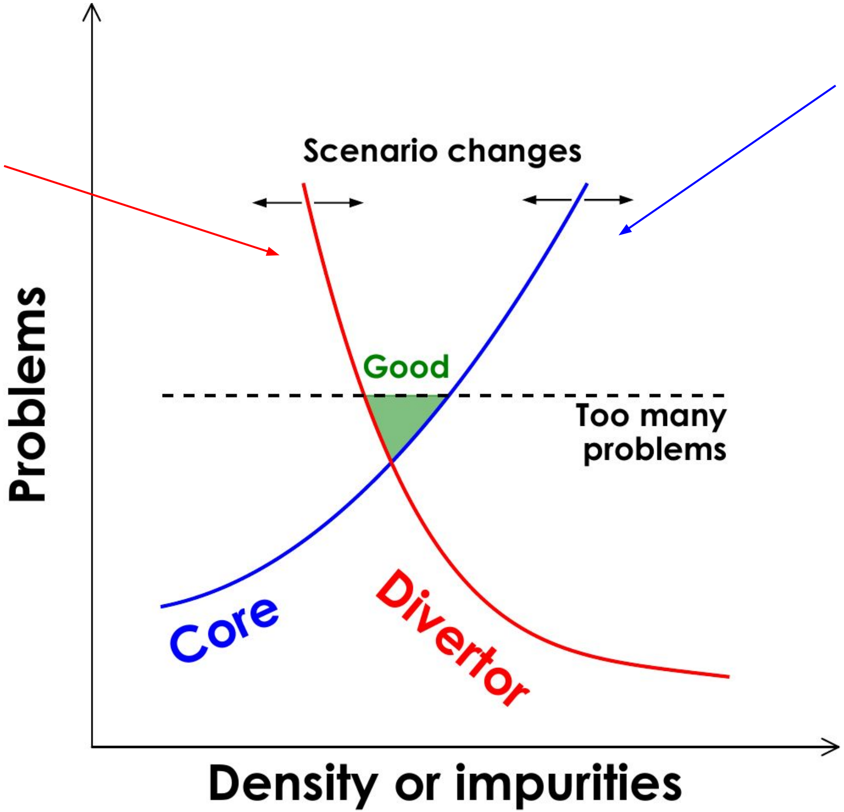
$$\text{Degree Of Detachment} = \text{DOD} \equiv \frac{\text{Expected } J_{sat} \text{ for attached plasma}}{\text{Measured } J_{sat}} = \frac{1}{\text{Attachment fraction}}$$

- Easy, readily available diagnostics: average density + Langmuir probes
- Quantifies divertor dissipation processes

DOD: A. Loarte, et al., Nucl. Fusion 38, 331 (1998) https://doi.org/10.1088/0029-5515/38/3/303

Impurity seeding can harm core plasma → controller must manage flow rate

- Melting
- Sputtering



- Disruption risk
- H-L transition
- Tearing modes
- Reduced confinement quality
- Fuel dilution

Example of reduced performance in detachment

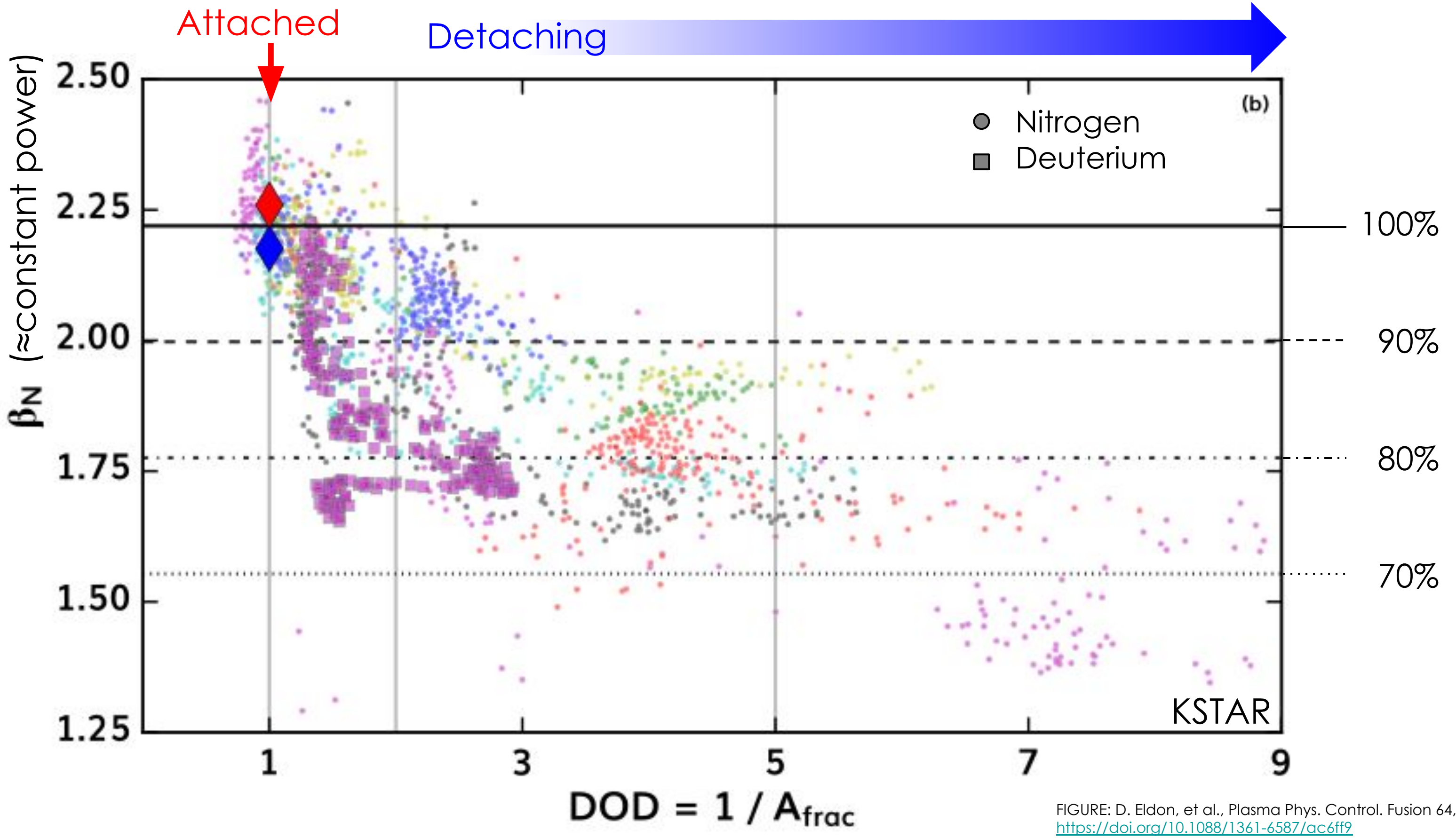


FIGURE: D. Eldon, et al., Plasma Phys. Control. Fusion 64, 075002 (2022)
https://doi.org/10.1088/1361-6587/ac6ff9

Confinement quality vs DoD relationship can be changed

- **Scenario development allows one to change these curves**
  - (H98 is not the only parameter)
- **We'll talk about developing controllers for moving along these curves**

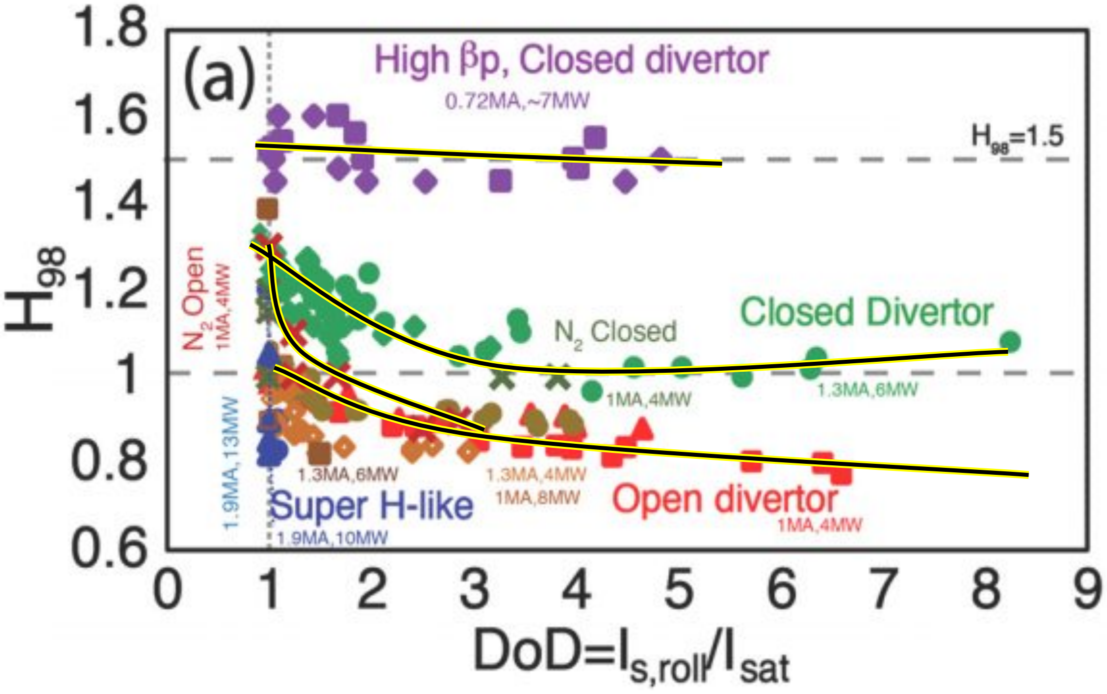


FIGURE: H.Q. Wang, et al., Phys. Plasmas 28, 052507 (2021) https://doi.org/10.1063/5.0048428

Many single-input, single-output controllers have been tested

1. Obtain a control variable in real-time by processing sensor signals
2. Use a control policy to transform measurement and target into command
3. Command sent to actuator
4. The plasma responds

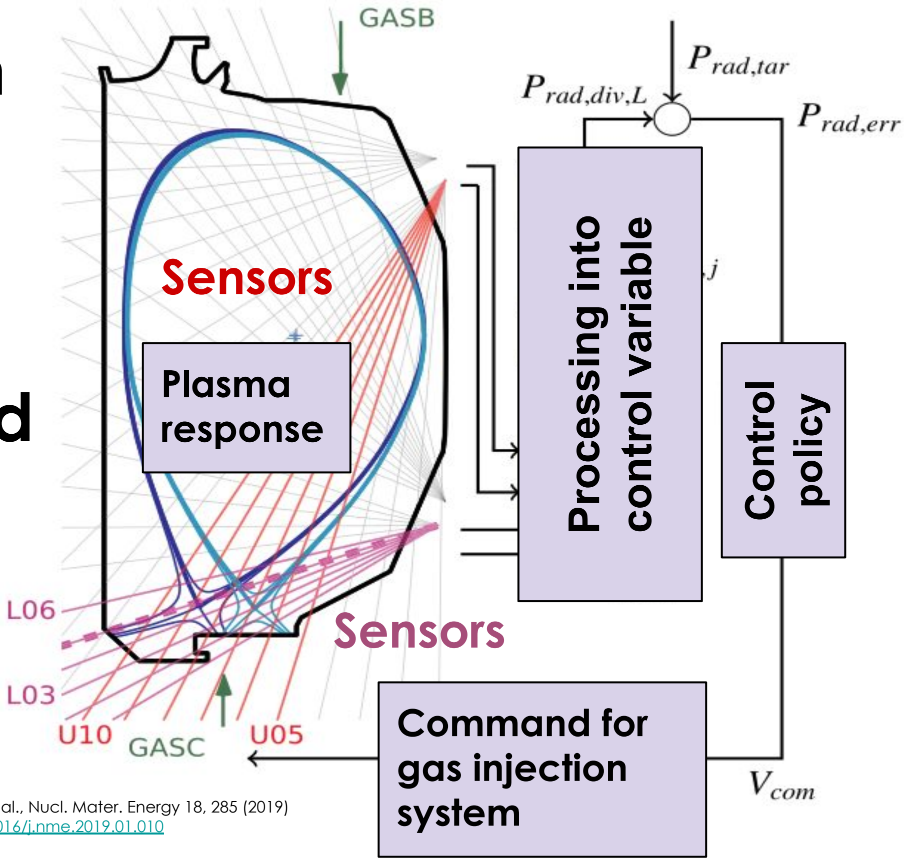
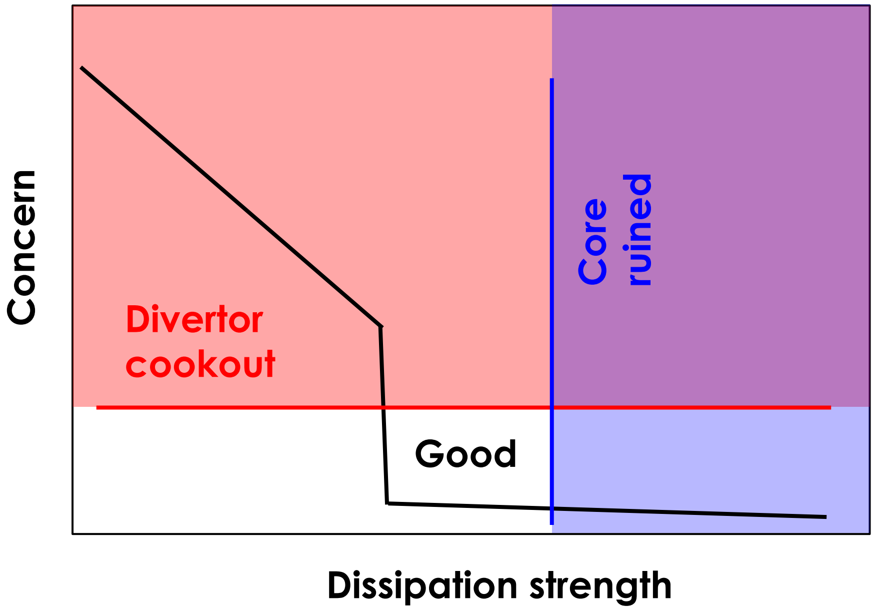


FIGURE: D. Eldon, et al., Nucl. Mater. Energy 18, 285 (2019)
https://doi.org/10.1016/j.nme.2019.01.010

Choosing control variables and actuators

- **The control variable has to change when the actuator is used**
- **The actuators are methods of putting different elements into the plasma**
  - Gas puff (fuel or impurity)
  - Pellet launcher
  - Powder dropper
- **Types of control variables:**
  - Direct protection: heat flux (melting) or T_e (sputtering)
  - Control dissipation process: radiated power, T_e
  - Control the detachment state: A_{frac}, radiator position
  - All: more impurities/density → less divertor head load
- **Pick one that can be measured reliably and has a manageable response to available actuators**

Pick a manageable response: depending on plasma scenario, surface measurements might not provide early warning



Actuator responses are not the same across devices

- **Different T_e ranges**
- **Different SOL opacity and compression into divertor**
- **Common thinking: neon in ITER will behave the way nitrogen behaves in DIII-D**
  - (except for sticking to walls, which nitrogen does)

Considerations for controlling heat flux to the divertor

- **Directly address hardware limits**
- **Measure with infrared thermography, surface thermocouple, LPs, or calculate with model**

Cameras for IR thermography may have difficulty seeing key surfaces in closed divertor

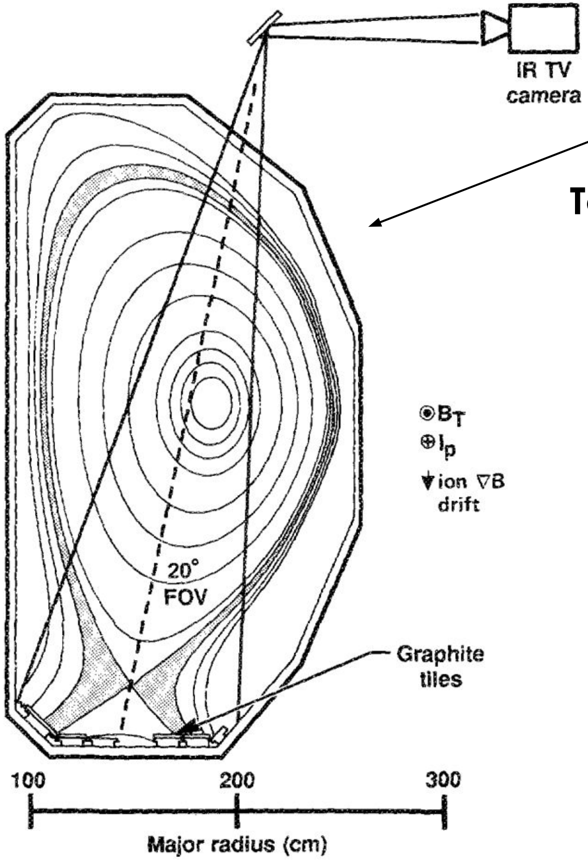


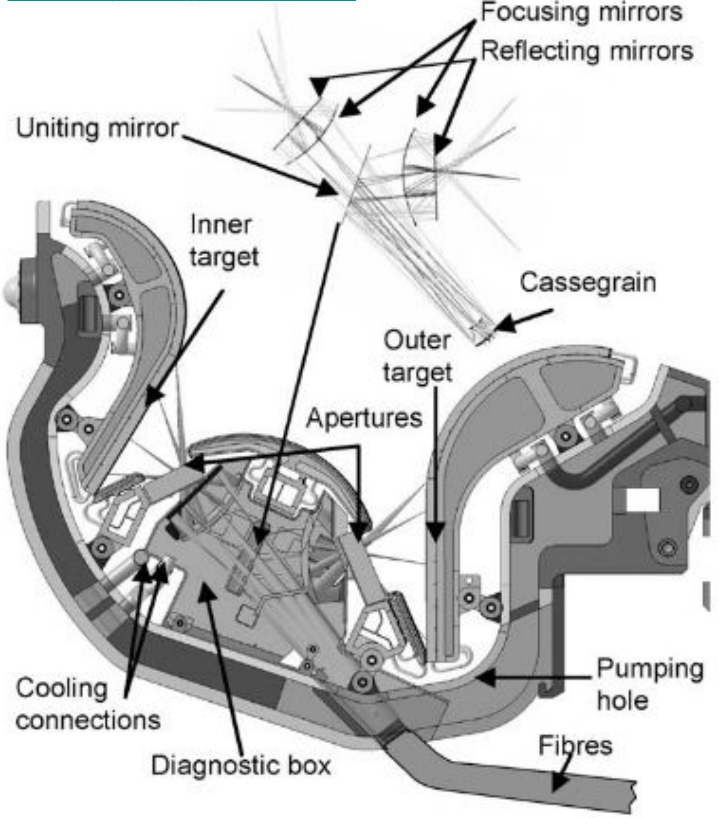
Figure: D. N. Hill, et al., Rev. Sci. Instrum. 59, 1878 (1988) http://dx.doi.org/10.1063/1.1140040

- Open divertor: easy to see

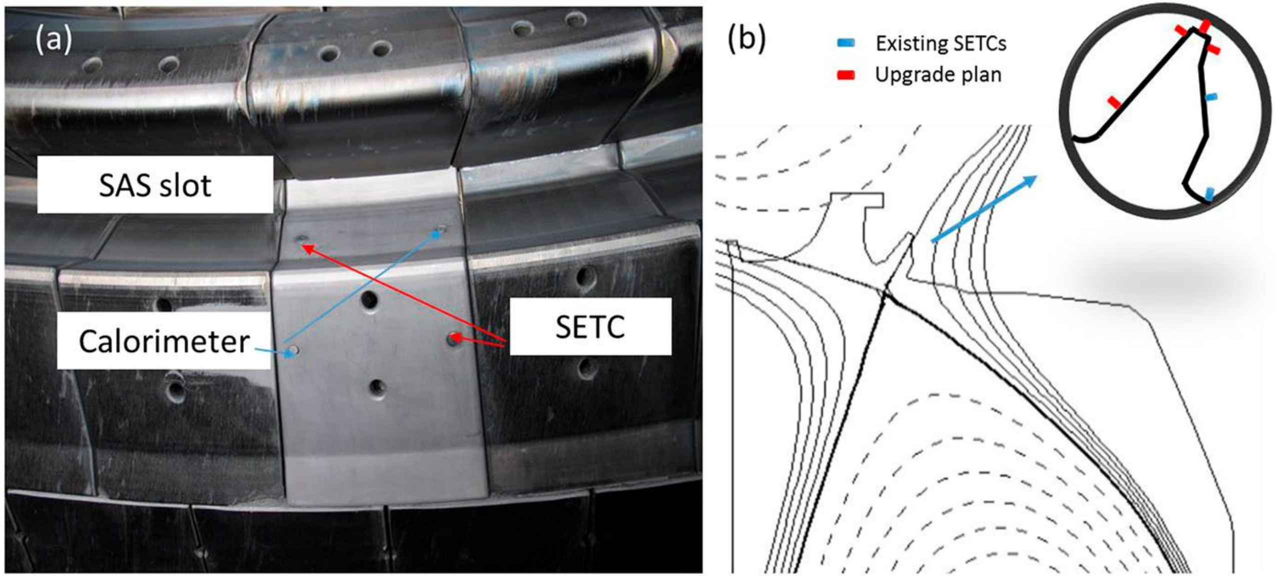
To see closed divertor:

- Optics embedded in divertor cassette (which gets replaced periodically in DEMO plans): too hard to maintain?
- Mirrors close to the action: alignment issues during thermal cycles? Coatings?
- Fibers close to neutron source: darkening?

Figure: R. Reichle, et al., J. Nucl. Mater. 390, 1081 (2009) https://doi.org/10.1016/j.jnucmat.2009.01.293



Surface Eroding ThermoCouples measure heat flux and could tolerate ITER-relevant heat flux



- **Expected to withstand 10–20 MW m^{-2}**
- **Relevant to first wall & divertor**
- **Can be mounted in hard to image places**
- **Might lose control sensitivity in detachment**

Figure: J. Ren, et al., Review of Scientific Instruments 89, 10J122 (2018); https://doi.org/10.1063/1.5038677
SETC heat tolerance: M. D. Palma, and M. Spolaore, IEEE sensors journal 21, 17898 (2021); https://doi.org/10.1109/JSEN.2021.3085478

Models for *attached* heat flux exist, but accurately modeling dissipation terms in detachment is challenging

- **Accurate real-time model for first wall peak heat flux in attached plasma**
- **First wall (of main chamber) or divertor heat flux**

$$q_{\parallel 0,\mathrm{main}} = \frac{B_{\phi,\mathrm{OMP}} P_{\mathrm{SOL}}}{4\pi R_{\mathrm{OMP}}(\lambda_{q,\mathrm{main}} + R_q \lambda_{q,\mathrm{near}}) B_{\theta,\mathrm{OMP}}},$$

$$R_q \equiv \frac{q_{\parallel 0,\mathrm{near}}}{q_{\parallel 0,\mathrm{main}}}$$

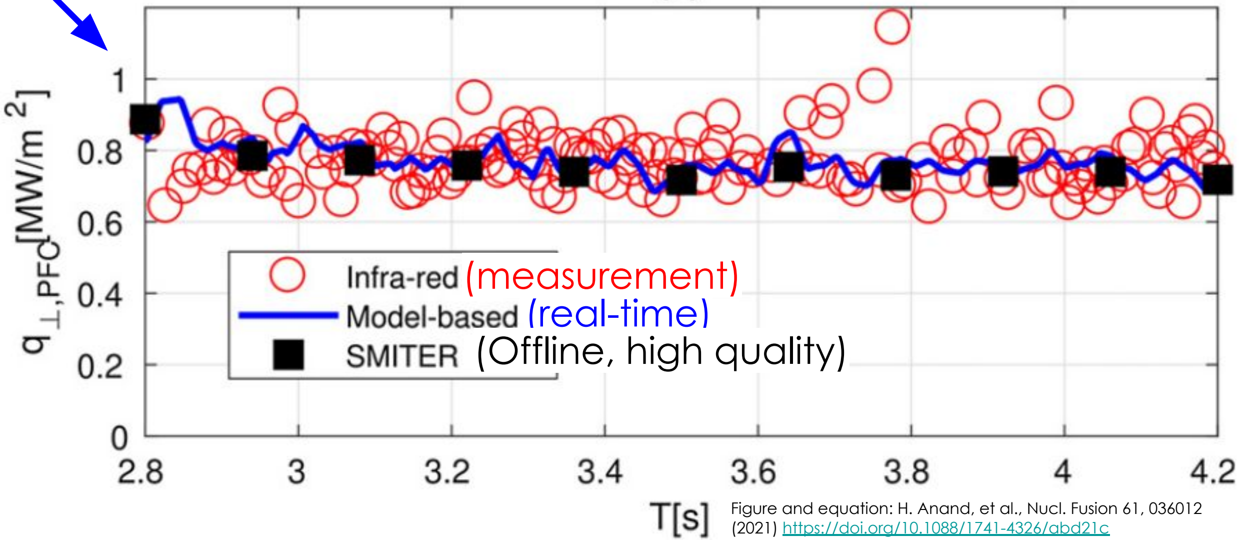


Figure and equation: H. Anand, et al., Nucl. Fusion 61, 036012 (2021) https://doi.org/10.1088/1741-4326/abd21c

Controlling T_e addresses ≲8 eV sputtering limit & can leverage sensitivity of dissipation processes to T_e

- **Divertor T_e from Thomson scattering, LPs (esp. 3-tip LPs)**
- **EAST 3LP test had trouble reaching <5 eV targets**

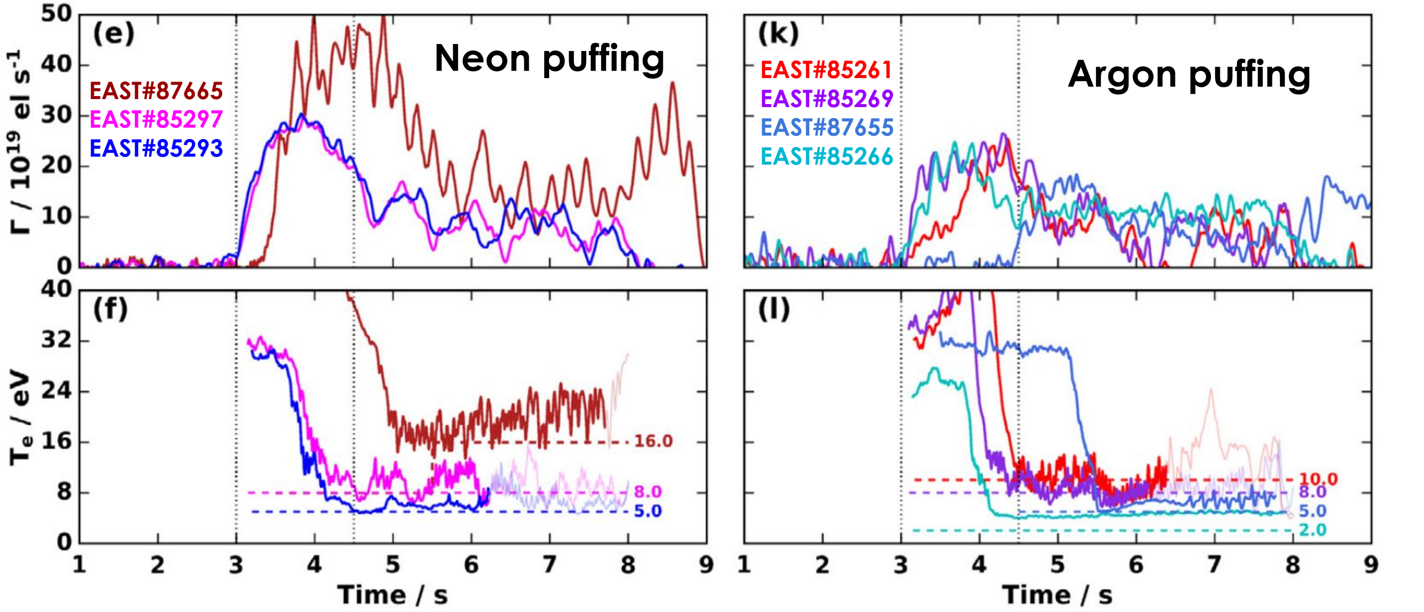


Figure: D. Eldon, et al., Nucl. Mater. Energy 27, 100963 (2021) https://doi.org/10.1016/j.nme.2021.100963

Once detached, T_e (from LPs) is relatively insensitive to increasing DOD: not easy to control

- Gain used to access detach with T_e will be too small to control deepening detach
- Real variation in T_e becomes harder to distinguish from noise
- Meanwhile, J_{sat}/J_{roll} works smoothly

Figure: D. Eldon, et al., Nucl. Mater. Energy 27, 100963 (2021)
https://doi.org/10.1016/j.nme.2021.100963

The "T_e cliff" is the ultimate expression of the dramatic change in sensitivity of T_e to gas puff

- **Sometimes happens with B×∇B drift into divertor**
- **A sudden jump between ~1 eV and ~10 eV** (endpoints vary) **resulting from small changes in controllable parameters (gas flow, density, ...)**

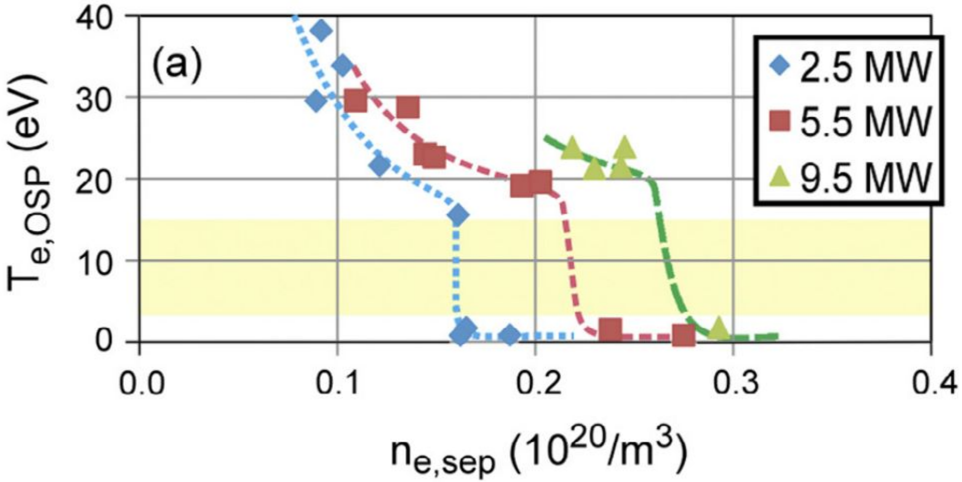


Figure: A. G. McLean, et al., J. Nucl. Mater. 463, 533 (2015) http://dx.doi.org/10.1016/j.jnucmat.2015.01.066

P_{rad} is closely linked to f_{pow} dissipation term and measured by ubiquitous bolometers

$$q_{\perp,t} = \sin\alpha\,(q_{//}(1 - f_{pow}) + E_i\Gamma_t)$$

$$P_{rad} = n_e n_Z L_Z(T_e)$$

- **Relatively simple relationship with actuator**
- **Most widely implemented dissipation control system**
  - AUG
  - Alcator C-Mod
  - DIII-D
  - EAST
  - JET
  - JT-60U

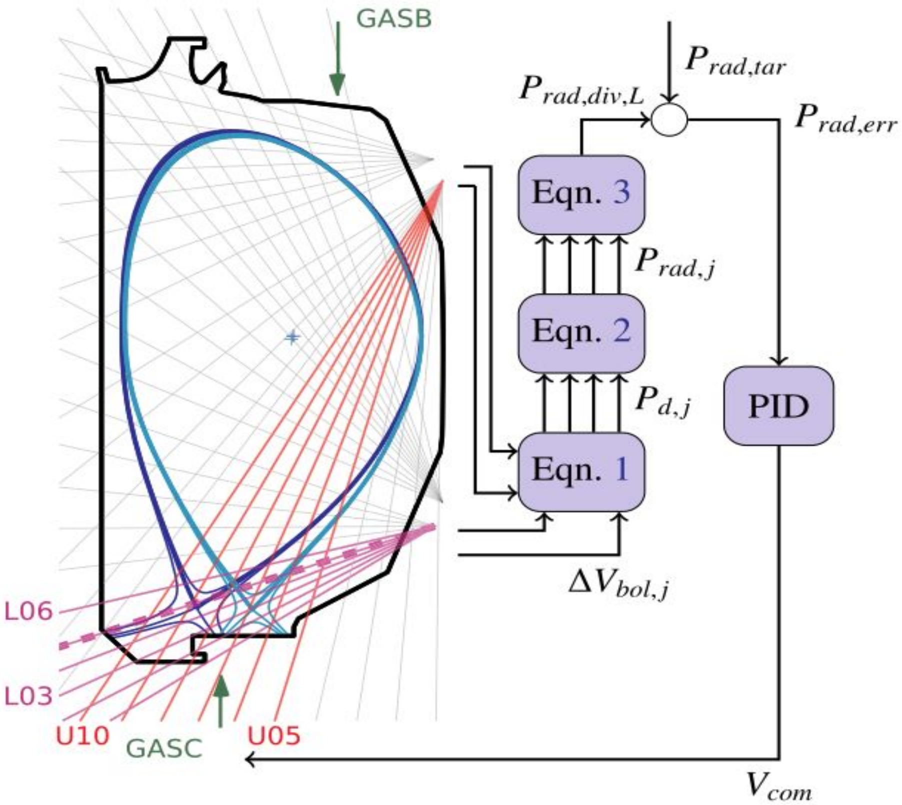
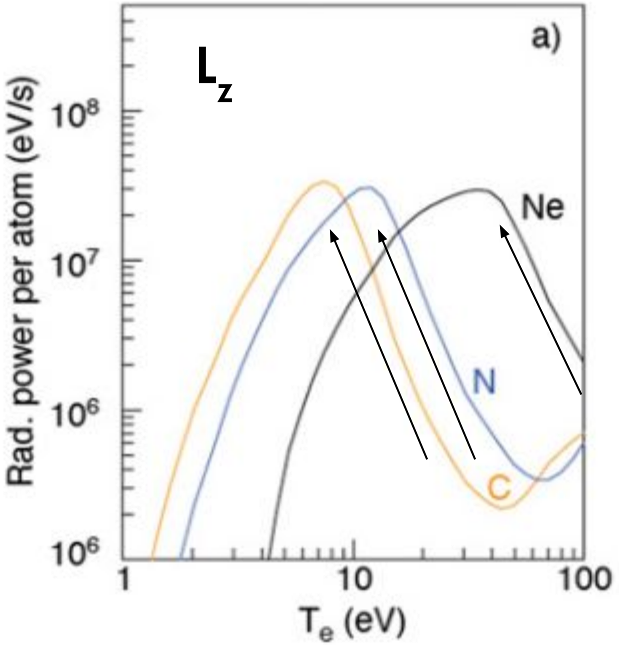


FIGURE: D. Eldon, et al., Nucl. Mater. Energy 18, 285 (2019)
https://doi.org/10.1016/j.nme.2019.01.010

Watch out for radiation condensation

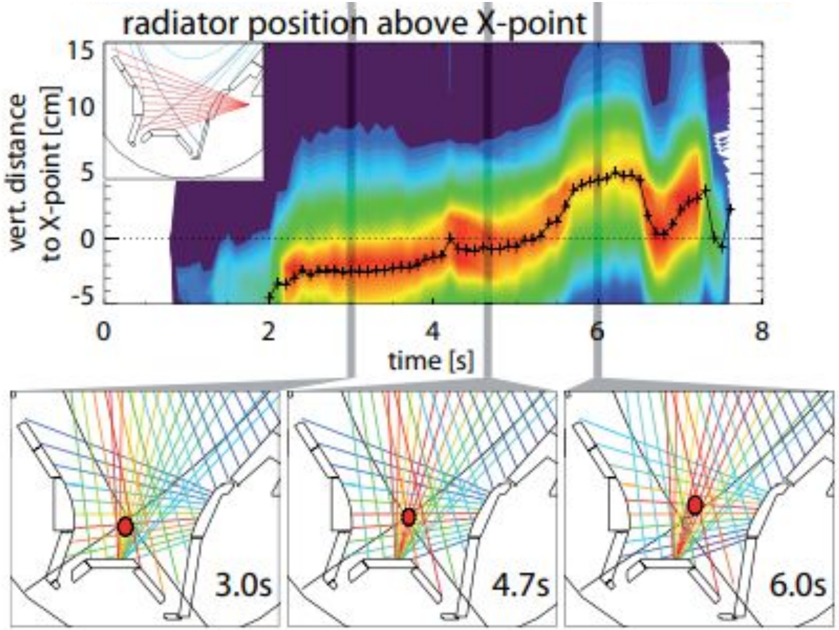


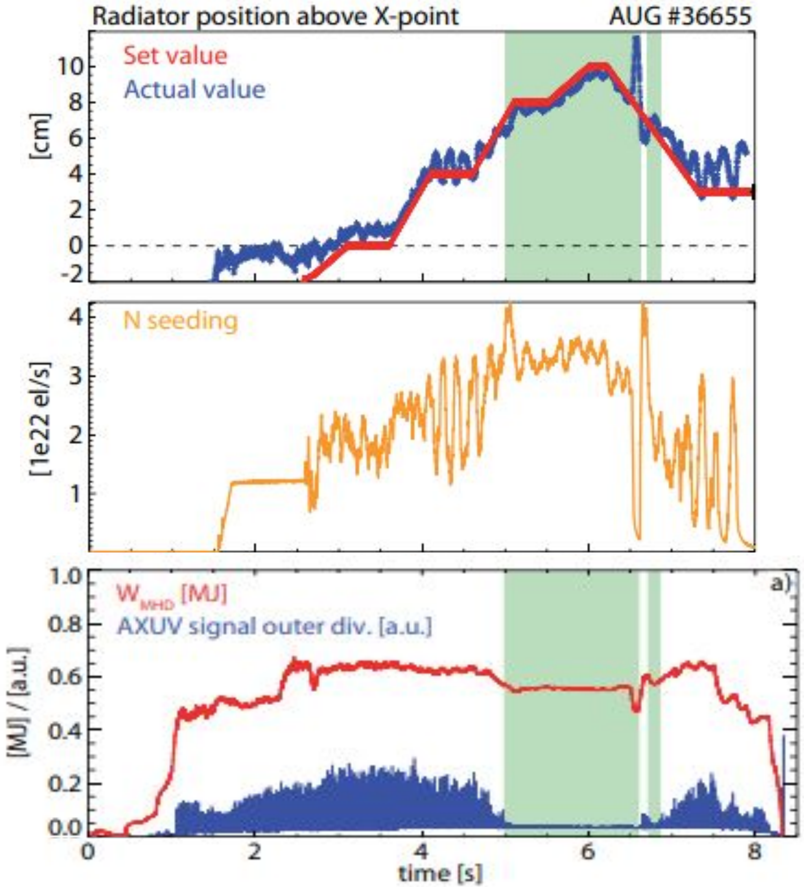
L. Casali, et al., Nucl. Fusion 62, 026021 (2022)
https://doi.org/10.1088/1741-4326/ac3e84

- $P_{rad} = n_e \, n_Z \, L_z(T_e)$
- P_{rad} tends to reduce T_e
- if $d(L_z)/d(T_e) < 0$, reducing T_e increases P_{rad}
- **Rad. condensation does not automatically ruin everything always: large volume of plasma with range of T_e**

The position of a radiation source near the X-point can be controlled

- **Non-ELMing regime accessed when radiator 5-7 cm above X-point**





Figures: M. Bernert, et al., Nucl. Fusion 61, 024001 (2021) https://doi.org/10.1088/1741-4326/abc936

A_{frac} control access a good metric for detachment level

- **A_{frac} instead of DOD to avoid noisy denominator**
- **KSTAR A_{frac} control builds on lessons learned from the JET A_{frac} control design**
  - Normalize by modelled attached I_{sat} instead of rollover I_{sat}

Typical scaling used in DOD

Adaptation for parameter changes, especially power

$$I_{sat,attached} = C' \langle n_e \rangle^2 q_{\|,a}^{-\frac{3}{7}}$$

Includes fudge factor as well as real constants

$$A_{frac} = \frac{I_{sat,measured}}{C' \langle n_e \rangle^2 q_{\|,a}^{-\frac{3}{7}}}$$

Typical $I_{sat,attached}$ scaling: A. Loarte, et al, Nucl. Fusion 38, 331 (1998) https://doi.org/10.1088/0029-5515/38/3/303
First implementation of Afrac control: C. Guillemaut, et al, PPCF 59, 045001 (2017) https://doi.org/10.1088/1361-6587/aa5951
Control using this Afrac definition: D. Eldon, et al., Plasma Phys. Control. Fusion 64, 075002 (2022) https://doi.org/10.1088/1361-6587/ac6ff9

A_{frac} control access a good metric for detachment level

- **Effective control**
- **A particular A_{frac} value doesn't guarantee that divertor won't melt**
- **ITER Langmuir probe survivability uncertain**

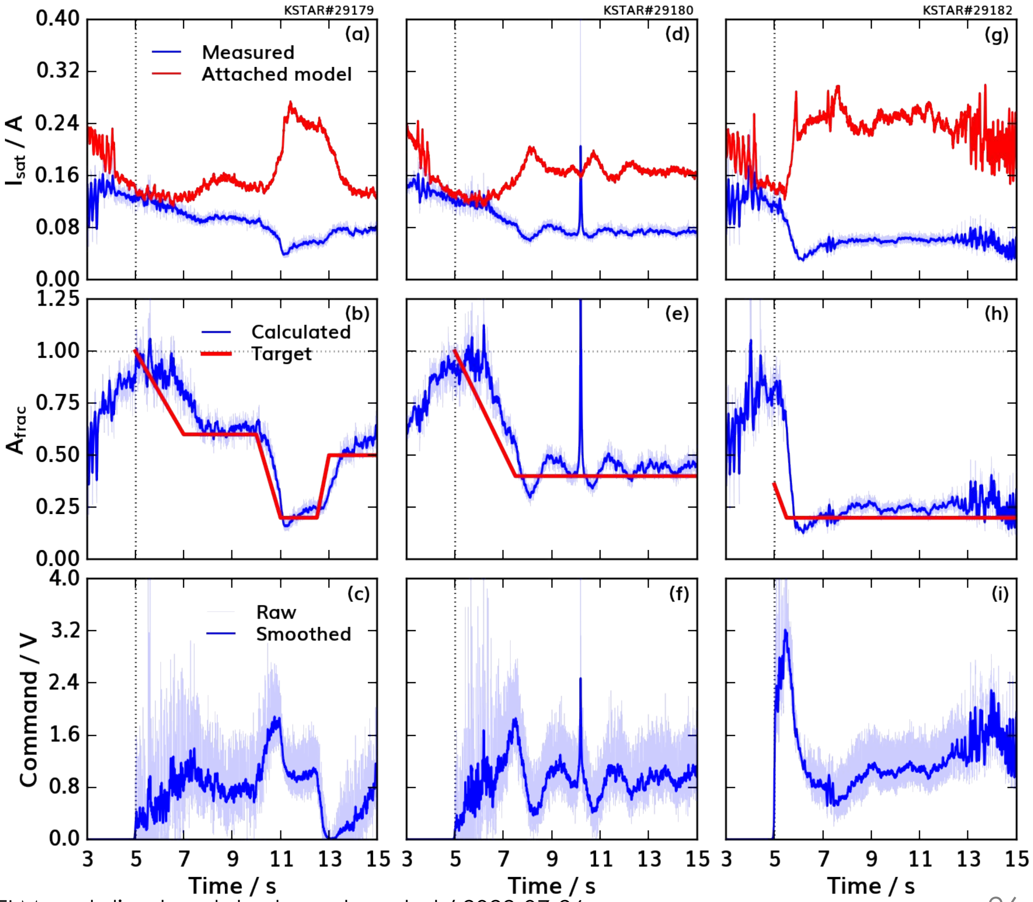


Figure: D. Eldon, et al., Plasma Phys. Control. Fusion 64, 075002 (2022) https://doi.org/10.1088/1361-6587/ac6ff9

The device and core scenario impose some constraints on divertor/SOL dissipation control

- H-mode access requirements define minimum P_{SOL}
- Pedestal requirements may constrain upstream density
- Device geometry & coils define flux expansion, divertor leg angle, and closure
- $B \times \nabla B$ drift probably into divertor for H-mode access
- Excess P_{rad} will destroy the pedestal / radiative collapse / disruption. What is excess? Depends on how core plasma responds.
- Minimum core fuel purity for fusion power
- Must be compatible with ELM removal

Avoid minimum P_{SOL} for H-mode access by ditching H-mode

- **Negative triangularity can reach high power and performance in L-mode**
- **No H-mode → no P_{SOL} requirement**
- **Strike pt @ large R**
- **Also no pedestal & no ELMs**

Standard positive triangularity (accesses H-mode)
Negative triangularity (supports high performance L-mode)

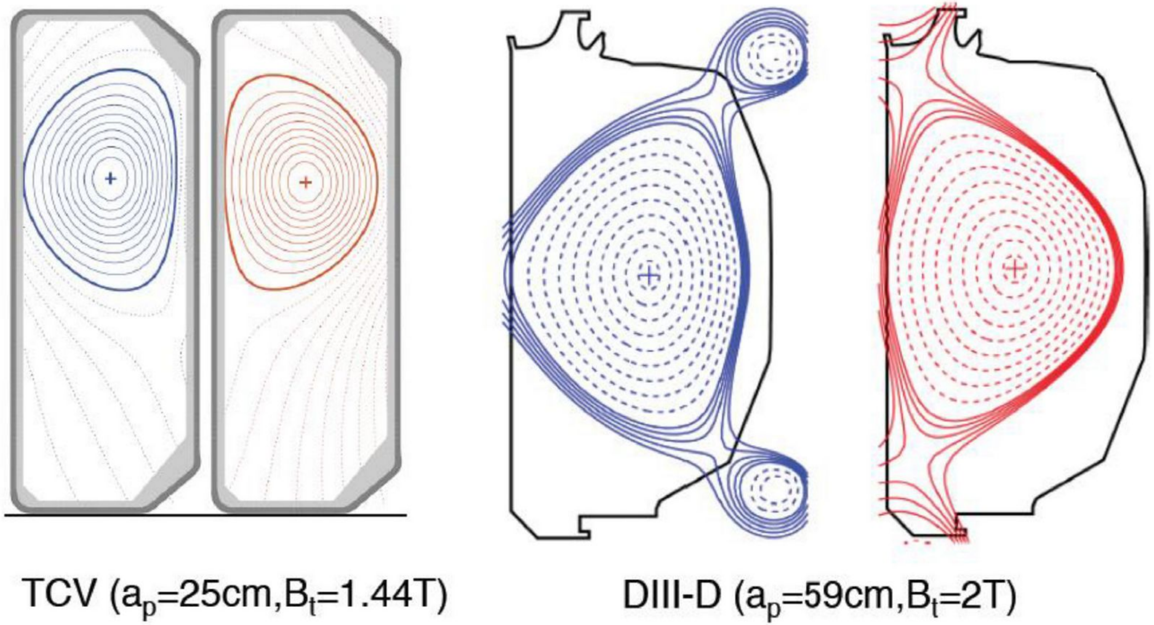


Figure and background: M. Kikuchi, et al., Nucl. Fusion 59, 056017 (2019) https://doi.org/10.1088/1741-4326/ab076d

Avoid sensitive pedestal requirements by supplementing with internal transport barrier (ITB)

- **Internal Transport Barrier (ITB) leads to steep gradient in core**
- **Impurity seeding → reduced pedestal height → reduced confinement in most scenarios**
- **In high β_p: reduced pedestal → increased ITB**
- **Confinement stays high**

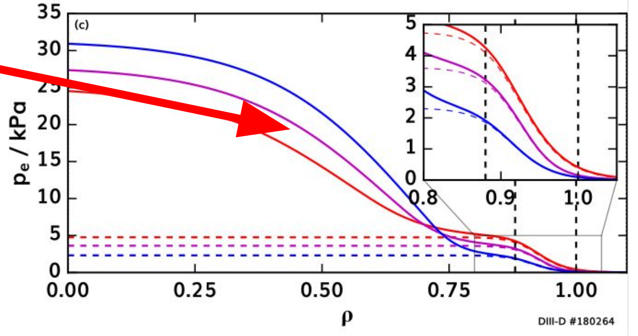


Figure: D. Eldon, et al., Nucl. Mater. Energy 27, 100963 (2021) https://doi.org/10.1016/j.nme.2021.100963

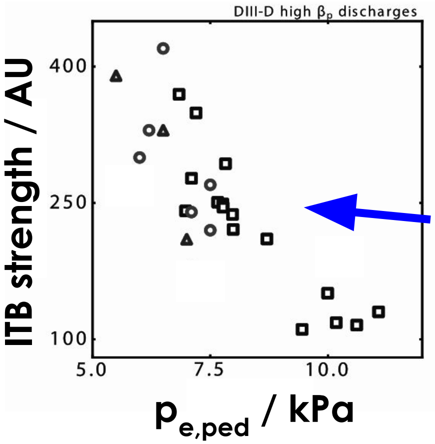


Figure: L. Wang, et al., Nature Comm. 12, 1365 (2021) https://doi.org/10.1038/s41467-021-21645-y

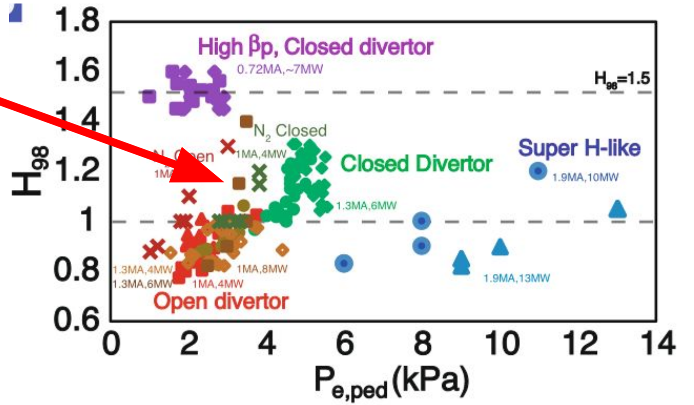


FIGURE: H.Q. Wang, et al., Phys. Plasmas 28, 052507 (2021) https://doi.org/10.1063/5.0048428

Exotic divertor configurations can make detachment easier

- **MAST-U takes this furthest with super-X chamber**
  - TCV also tries exciting things
- **Super-X box:**
  - High flux expansion
  - Long leg
  - Strike pt @ large R
  - Tight closure

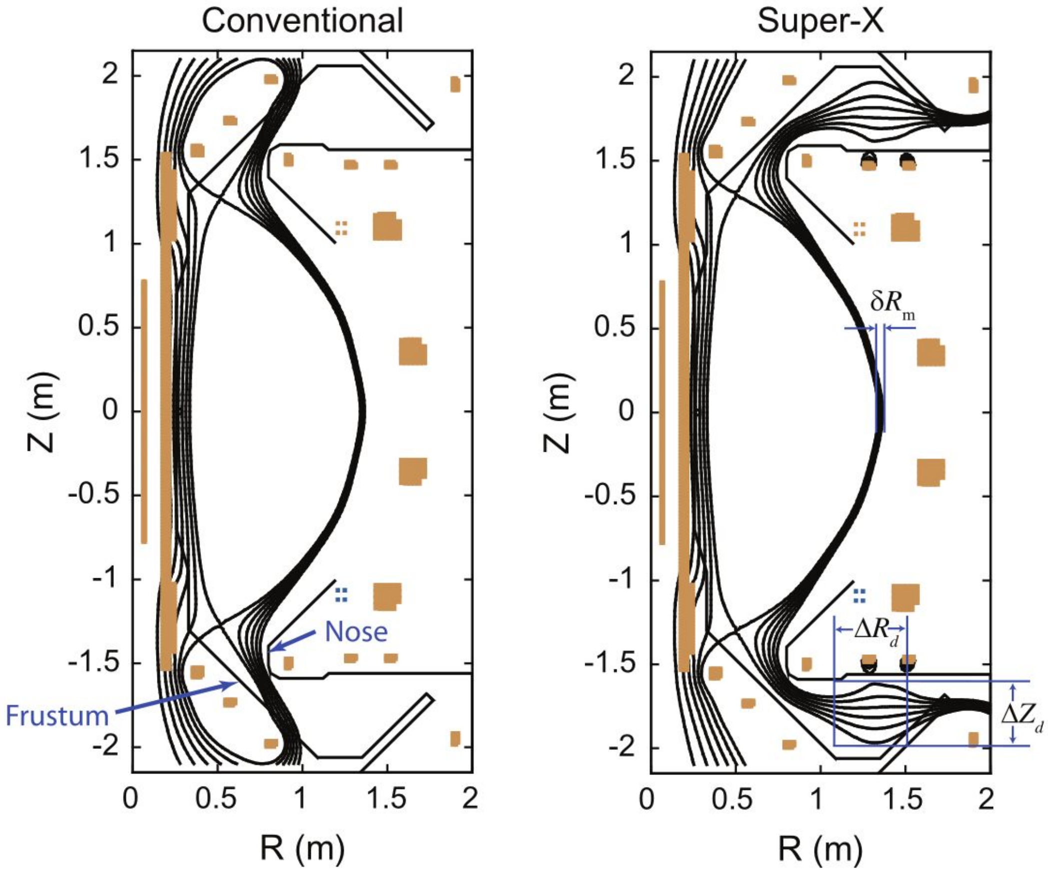
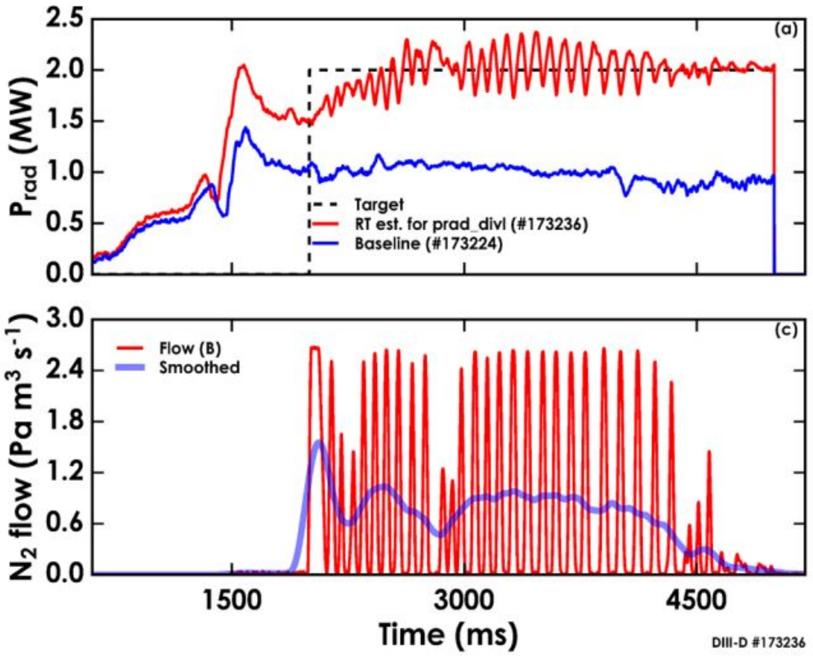


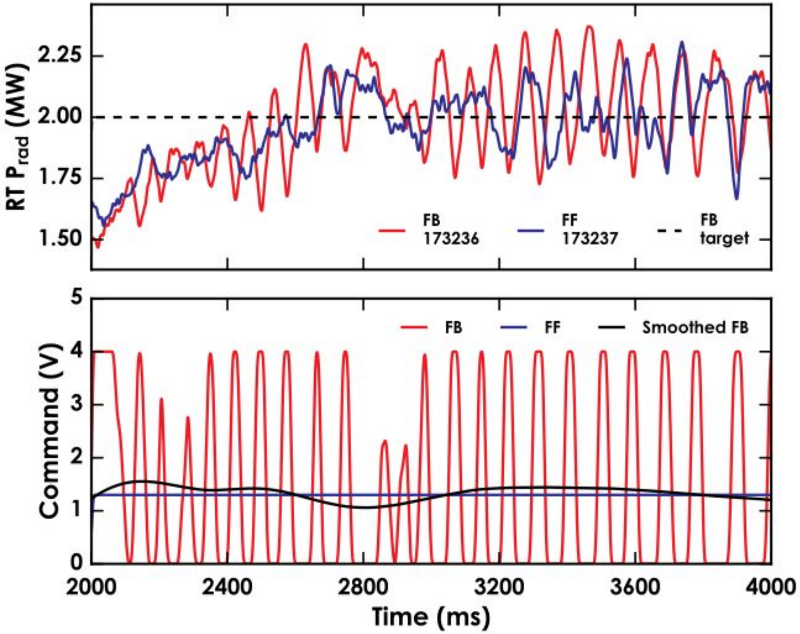
Figure: G. Fishpool, et al., J. Nucl. Mater. 438, S356 (2013) http://dx.doi.org/10.1016/j.jnucmat.2013.01.067

Periodic pedestal collapses can happen at high radiated power fraction, with or w/o feedback control

Looks like bad control causes oscillation



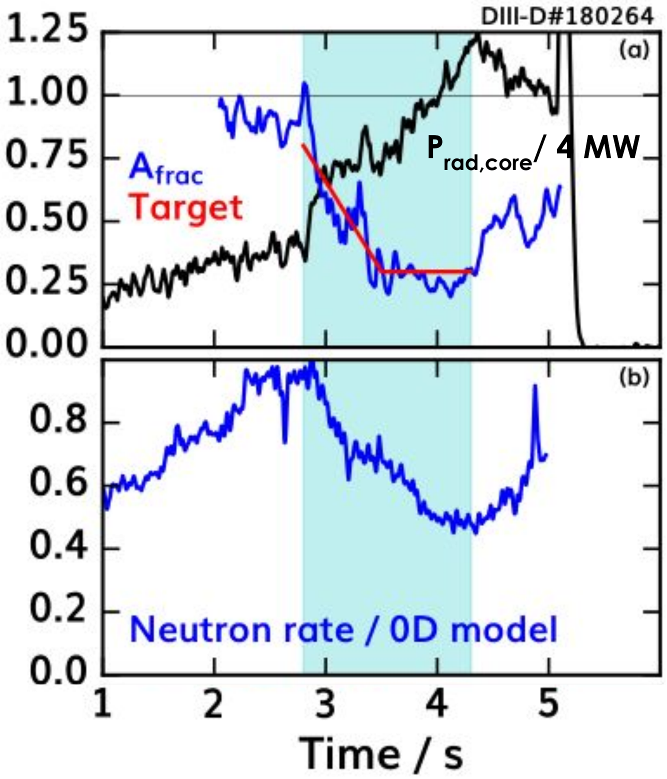
Average the feedback command and apply as constant feedforward command: still oscillates → this scenario just does this @ ≈80% frad



Figures: D. Eldon, et al., Nucl. Mater. Energy 18, 285 (2019) https://doi.org/10.1016/j.nme.2019.01.010

Nitrogen / neon plasmas don't fuse so well: must maintain adequate fuel purity

- **A_{frac} control (J_{sat}/J_{roll} definition) worked well**
- **Neutron rate dropped substantially during seeding**
  - Normalize measurement by 0D model for neutron rate to isolate dilution
- **Core P_{rad} was not stationary: A_{frac}—neon loop is not good**
  - A_{frac}—nitrogen is fine



Detachment control must be compatible with ELM removal

ELM removal/suppression/avoidance options:

- **Resonant Magnetic Perturbations (RMPs)**
- **QH mode**
- **Impurity-driven ELM suppression**
- **L-mode (such as negative triangularity)**

RMPs prevent pedestal from growing to P-B unstable level, but have collisionality / density limitations

Special coils apply a toroidally-varying magnetic field perturbation

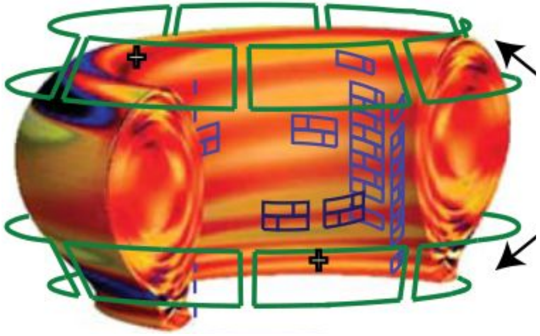


Figure: J. D. King, et al., Phys. Plasmas 22, 112502 (2015)
http://dx.doi.org/10.1063/1.4935486

This blocks inward growth of the pedestal, preventing it from reaching P-B instability

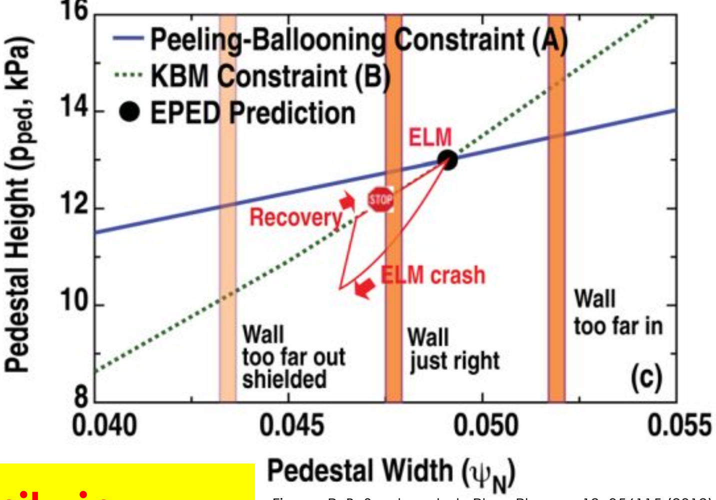


Figure: P. B. Snyder, et al., Phys. Plasmas 19, 056115 (2012)
http://dx.doi.org/10.1063/1.3699623

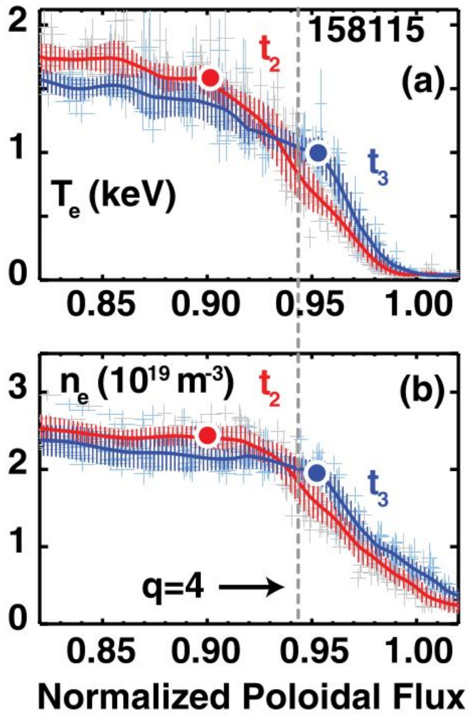
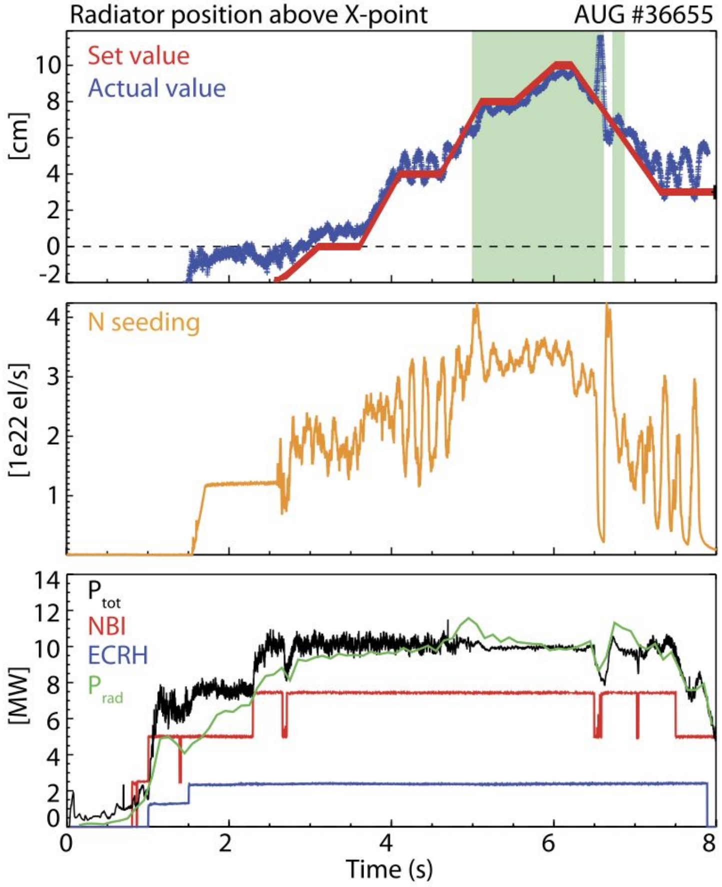
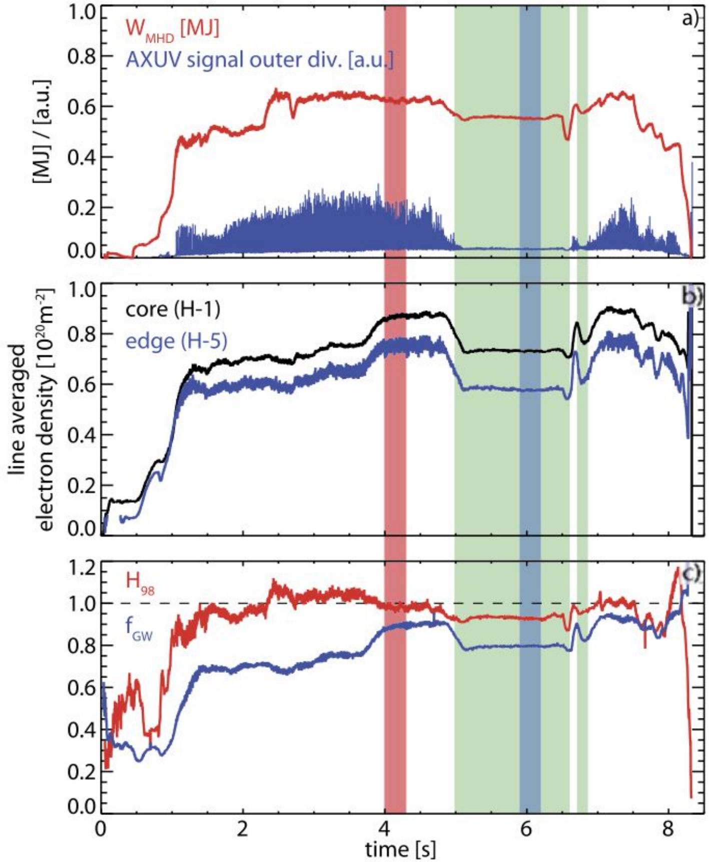


Figure: R. Nazikian, et al., Phys. Rev. Lett. 114, 105002 (2015)
http://dx.doi.org/10.1103/PhysRevLett.114.105002

- **RMPs don't work at high density in present devices: probably collisionality limit that won't apply to ITER**
- **But can't study RMP + detachment yet**

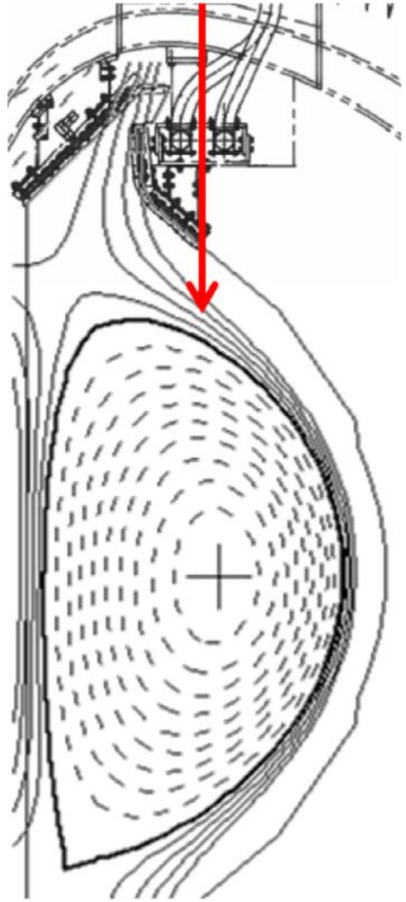
ELM suppression has been achieved with impurity seeding: AUG gas puff



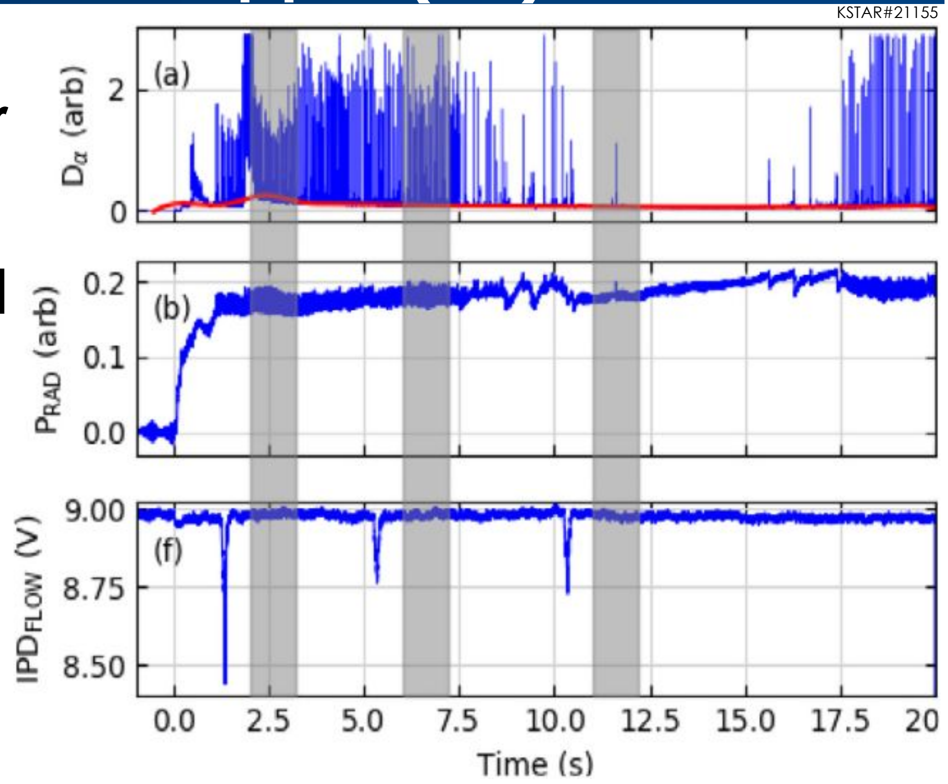


Figures: M. Bernert, et al., Nucl. Fusion 61, 024001 (2021) https://doi.org/10.1088/1741-4326/abc936

ELM suppression has been achieved with impurity seeding: KSTAR impurity powder dropper (BN)



- **Boron is good for wall conditions**
- **Can be dropped as powder**
- **Also removes ELMs**



Figures: E. P. Gilson, et al., Nucl. Mater. Energy 28, 101043 (2021) https://doi.org/10.1016/j.nme.2021.101043

Many control policies are possible

- Can be simple and rely on empirical system identification
- Can leverage complicated models
- Let’s cover two examples

Proportional-Integral-Derivative (PID) control is simple & can be applied to a black box after limited system identification

- **Command is proportional to control error + integral to correct for persistent error + derivative to be proactive**

$$u = G_p \left(E + \frac{1}{T_i} \int dtE + T_d \frac{d}{dt} E \right), \qquad E = T - y$$

u: command

settings

E: control error

y: measured control variable

T: target value for control variable

- **Good for simple, low-noise systems**
- **Doesn't even require electronics (can be implemented with hydraulics or pneumatics – 100 years old)**
- **Doesn't require a high fidelity model of the system**
- **Tuned for a potentially narrow range around a single operating point**
- **Could be used to trim the output of a more sophisticated controller**

There exist heuristics for translating system dynamics into PID gains

1. Apply actuator and observe response
2. Fit with First Order Plus Dead Time (FOPDT) model
3. Plug the FOPDT coefficients into a formula to get gains
4. Run the system with the gains
5. Make minor adjustments as needed

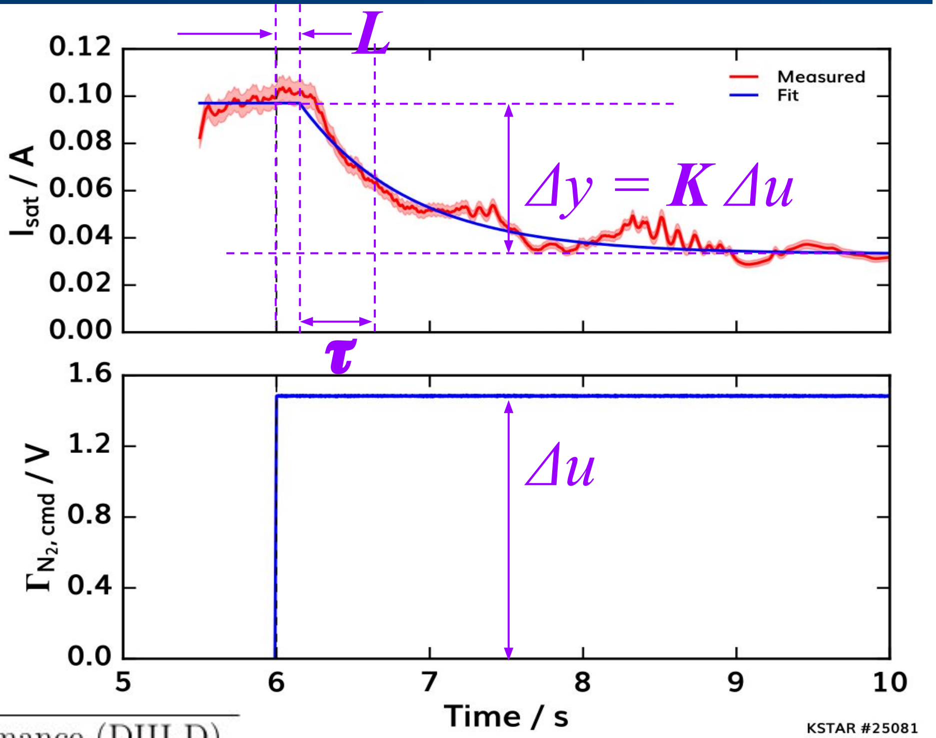
There exist heuristics for translating system dynamics into PID gains

FOPDT fit gives

- K = system gain
- τ = timescale
- L = dead time or lag

$$\Delta y(t) = K\left(1 - e^{-(t-L)/\tau}\right)\Delta u; \qquad t > L$$
$$= 0; \qquad t \leqslant L$$

$$G_p = C_p \frac{1}{K}\frac{\tau}{L}$$
$$T_i = C_i L$$
$$T_d = C_d L$$



Rule	C_p	C_i	C_d	Useful for / tested in	Performance (DIII-D)
Classic Z-N	1.20	2.00	0.50	Low noise systems	Bad
Modified Z-N	0.60	2.00	1.33	≈ general	Marginal–okay
A_{frac} control	0.25	2.67	0.35	High β_p, N_2	Good–excellent

Figure + use case with new constants: D. Eldon, et al., Plasma Phys. Control. Fusion 64, 075002 (2022) https://doi.org/10.1088/1361-6587/ac6ff9

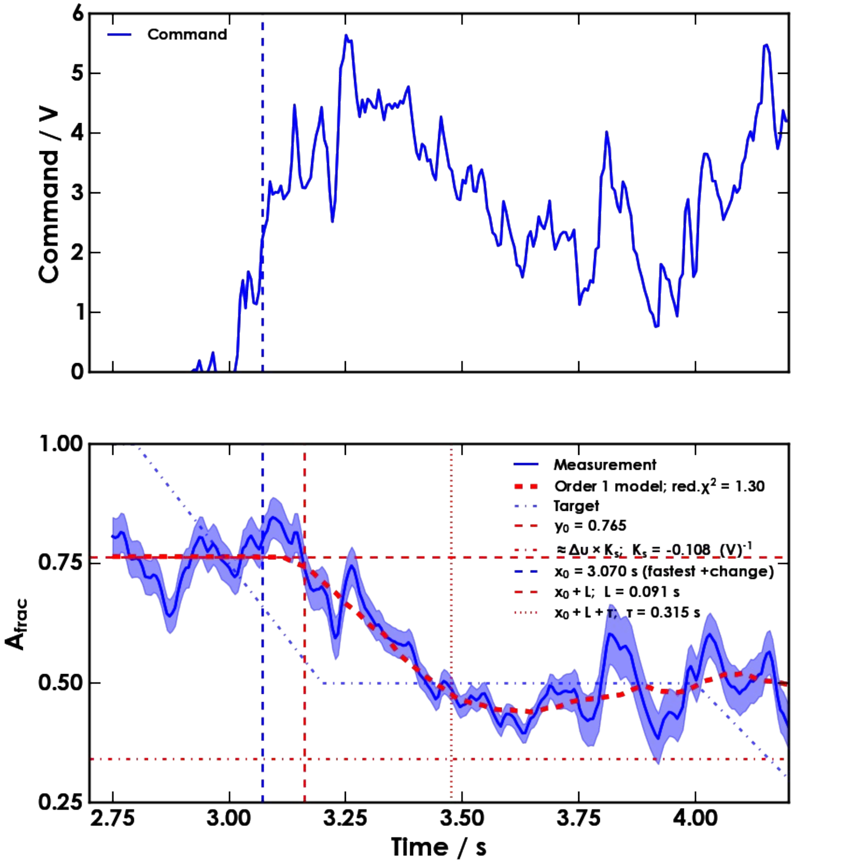
FOPDT for tuning in tokamaks: E. Kolemen, et al., Nucl. Fusion 50, 105010 (2010) http://dx.doi.org/10.1088/0029-5515/50/10/105010

Old tuning rule: J. G. Ziegler and N. B. Nichols, Transitions of the ASME, 64, 759 (1942) https://doi.org/10.1115/1.2899060 http://davidr.no/iiav3017/papers/Ziegler_Nichols_%201942.pdf

FOPDT fitting does not require a simple step

$$\tau \frac{dy(t)}{dt} = K_s \left[u(t-L) - u(t_0)\right] - \left[y(t) - y(t_0)\right]$$

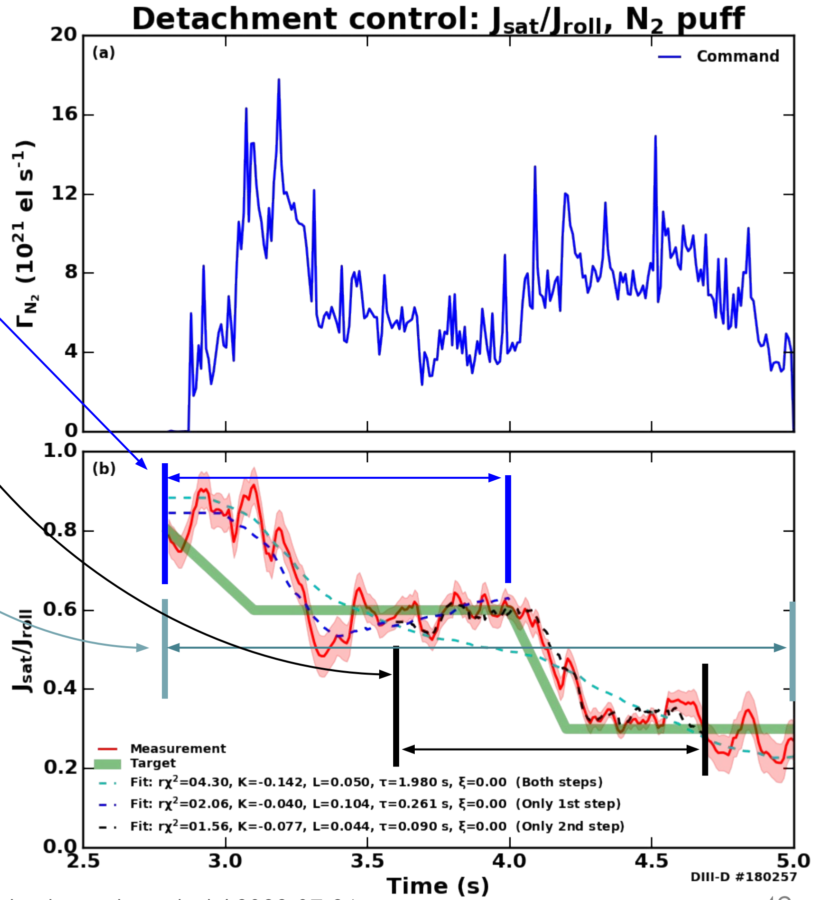
- **Can predict response to arbitrary commands**



DIII-D #180256

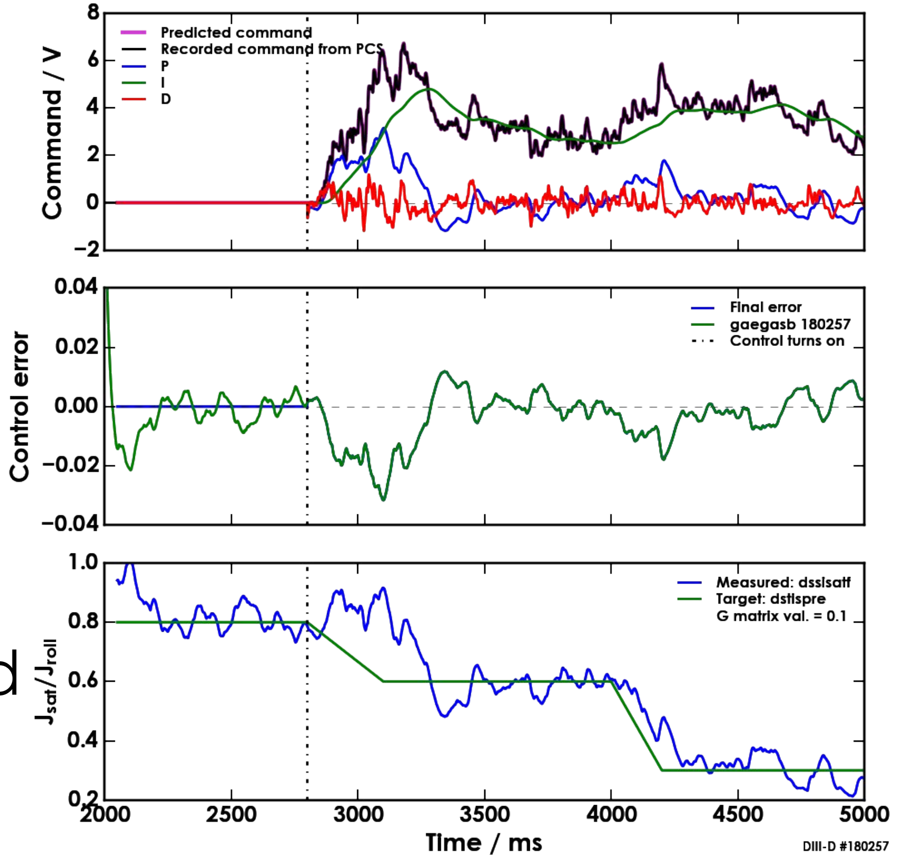
Warning: this is an attempt to fit a complicated, nonlinear system with a first order model

- **Example: different fit coefficients for two steps; no consistent fit to both steps**
- **K = -0.040, -0.077**
- **L = 104, 44 ms**
- **τ = 261, 90 ms**



Open loop PID simulations can spot some blunders and help guide changes

- **Open loop sim: control error won't change**
- **Shows P, I, D breakdown**
  - Are those spikes coming from the D term?
  - Is the I term driving the oscillation?
  - Is the D term's phase lead cancelled by lowpass filter phase lag?



There are other PID tuning methods

- Purely manual: okay if system runs continuously + low penalty for failure
- Different heuristic formulae to use with step response or FOPDT fit
- Loop shaping

But no matter how it's tuned, PID's only look-ahead capability is the derivative term and it will get in trouble making large changes in nonlinear systems

Despite limitations, PID is still useful

- **Avoid large changes in nonlinear systems → works great**
- **Proof of concept of combinations of sensors and actuators — if PID can do it, MPC should do it even better**
  - Some reasons for PID to fail would ruin other control policies, too (low sensitivity, S/N, etc.)
- **Some failure modes can reveal new control physics challenges**

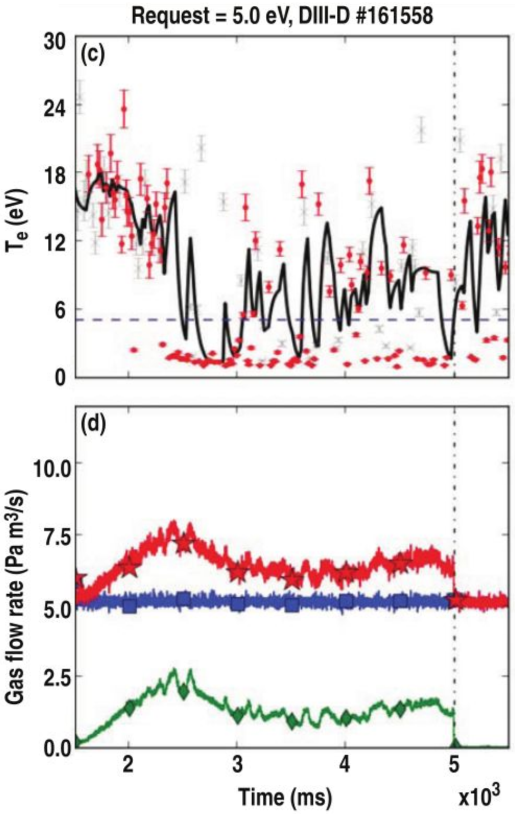
When to use/avoid PID

If given the scenario, the actuator(s), and the sensor(s) and tasked with finding best possible controller, consider alternatives

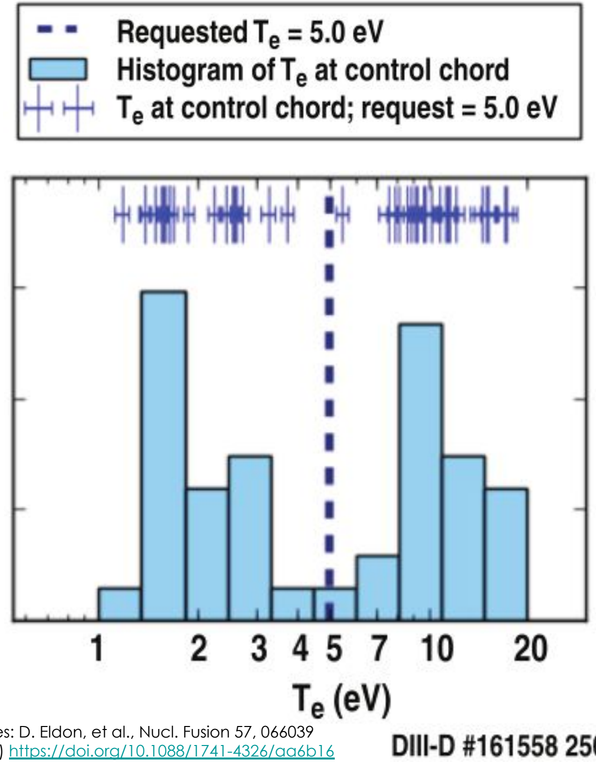
If exploring how scenarios, sensors, and actuators interact with each other in order to advise which ones should be used later in a point design, suboptimal control policy is probably okay

Failed PID control helped explore the "T_e cliff"

Bad control



T_e samples have bimodal distribution: won't settle at 5 eV



Figures: D. Eldon, et al., Nucl. Fusion 57, 066039 (2017) https://doi.org/10.1088/1741-4326/aa6b16

Because a drift system drains the outer divertor at low density but turns off at high density

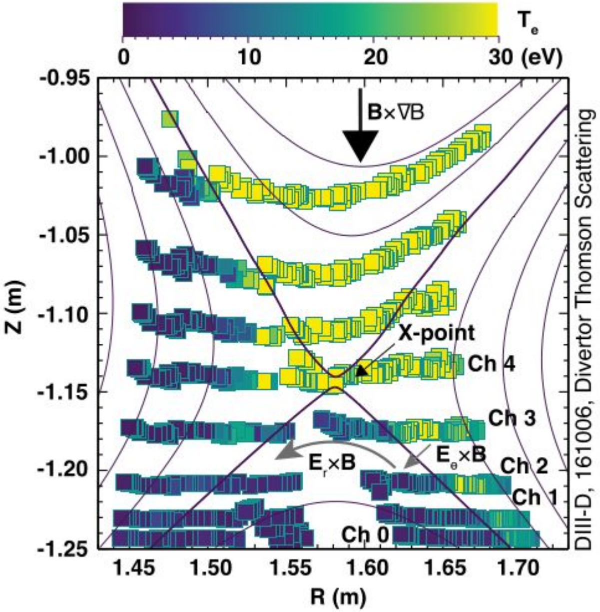
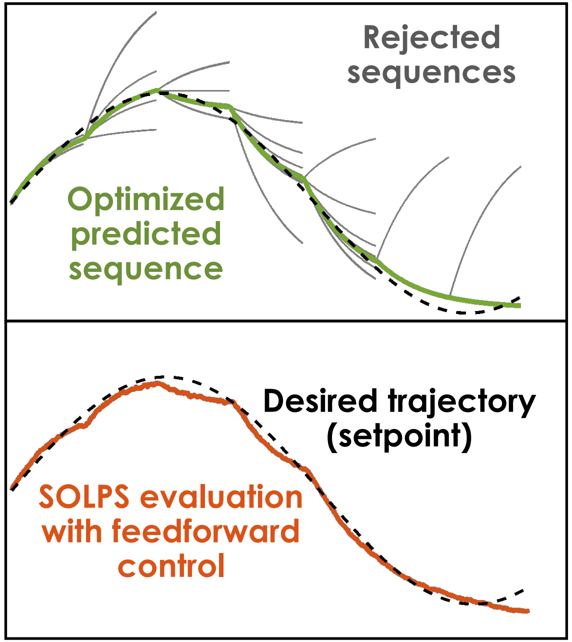


Figure: A. E. Jarvinen et al., Phys. Rev. Lett. 121, 075001 (2018) https://doi.org/10.1103/PhysRevLett.121.075001

Model Predictive Control (MPC) handles complicated systems, but requires a model

- Use model to predict responses to a set of command sequences
- Pick the command sequence that gives best predicted response
- Model should be fast and accurate



J. Lore

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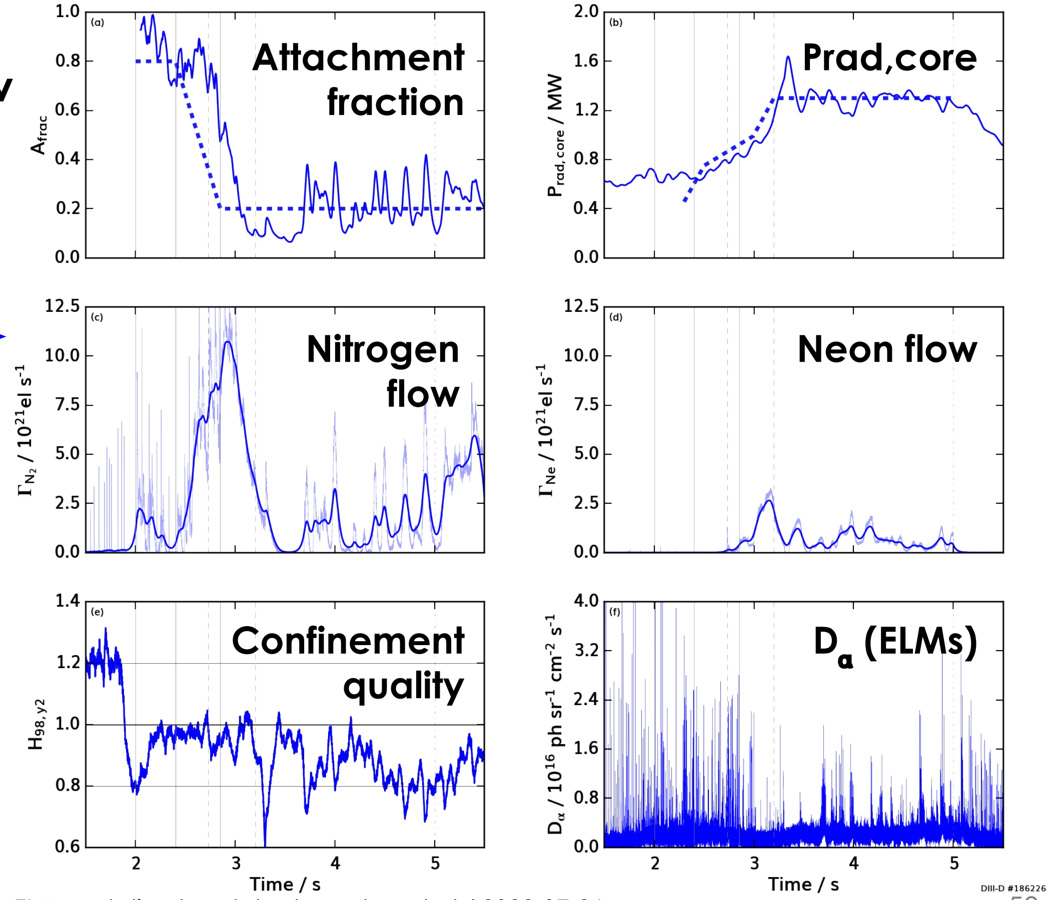
Path forward for a model suitable for real-time MPC

1. **Demonstrate a model with accurate steady state and dynamic predictions**
   a. e.g. SOLPS-ITER seems pretty accurate in steady state
   b. SOLPS-ITER has problems with accurate dynamic responses that are driven by attempts to speed execution
2. **Reduce the model so it can execute in real-time but still provide essential outputs**
   a. Fit a database of code results with a neural net or other functions that can be evaluated quickly

Multiple impurity species and sensors may be used

- Ar—$P_{rad,core}$ + N_2—$P_{rad,div}$ on AUG
- N_2—J_{sat}/J_{roll} + Ne—$P_{rad,core}$ on DIII-D
- Dual single-in, single-out loops with 0 cross terms instead of true multi-in, multi-out



A. Kallenbach, et al., Nucl. Fusion 52, 122003 (2012) http://dx.doi.org/10.1088/0029-5515/52/12/122003

Summary of actuator / sensor pairing demonstrations

	gas puff	SMBI	pellets	powder dropper
DTS Te	DIII-D			
3LP Te	EAST	EAST		
LP + BPP heat flux	COMPASS			
LP Afrac	JET, EAST, DIII-D, KSTAR	EAST		
Foil bolometer, VUV, or XUV Prad	AUG, DIII-D, CMOD, JT-60U, JET	EAST		
Shunt R Pdiv	AUG			
STC Pdiv	CMOD			
X-point radiator Z	AUG			
MANTIS detachment front position	TCV			

Thank you

Abstract

Control systems are implemented to mitigate intense heat flux expected in future fusion devices. Without intervention, heat and particle fluxes reaching divertor target plates tend to concentrate in narrow (~cm in R) regions and thus the peak heat load will likely be well above the material's tolerable limit. Adding extrinsic impurities to the plasma promotes line radiation and other dissipation processes that spread the plasma's heat exhaust across a greater wall area. With strong enough dissipation, the zone of primary interaction between the plasma and neutrals from the surface can detach from the divertor target plate, shielding the plate from most of the direct heat load from the plasma. In wall-limited plasmas, impurity line radiation is useful for spreading heat loads across wider areas. While this is an excellent way to protect the wall and divertor from melting or sputtering, the extrinsic impurities are also a potent means of reducing core plasma confinement quality, diluting fusion fuel, or even prompting a disruption. It is the job of the control system to moderate the flow of impurity gas to achieve divertor/wall protection without harmful excess. It is not guaranteed that every plasma scenario is compatible with both detachment and good core performance at the same time. The detachment control system and core scenario must also be compatible with an Edge Localized Mode (ELM) removal solution, since the intermittent heat flux from an ELM in a reactor would potentially exceed the material's tolerable limit. Further complicating the problem, ability to diagnose and affect plasma conditions in future devices will be limited as many popular diagnostics are unlikely to be feasible in a fusion power reactor, and key actuators will be subject to constraints as well, such as delays due to longer gas lines.

Control system design includes control policy/algorithm design, selection (in flexible devices like DIII-D) or at least awareness (in single-point designs) of the base scenario or operating point, selection of sensors and formulation of control parameters, and selection of actuators, in this case by choosing which gas species to inject into the plasma. Each of these facets will be reviewed, followed by a look at challenges and potential solutions for future devices compared to the current state of the art.