Initial Experimental Results from the DIII-D Negative Triangularity Campaign

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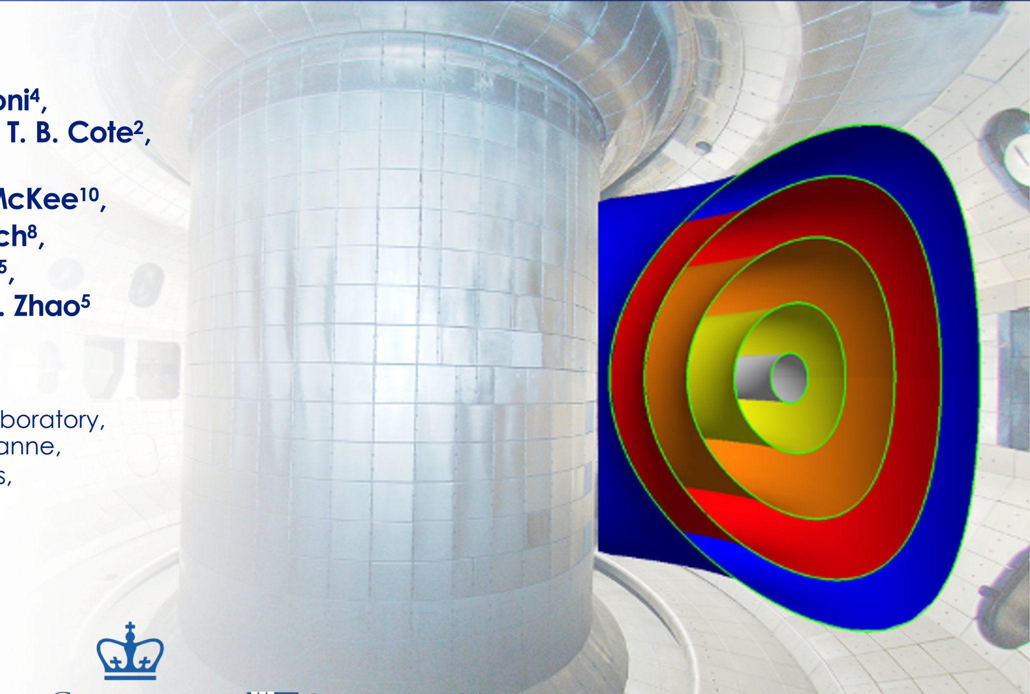

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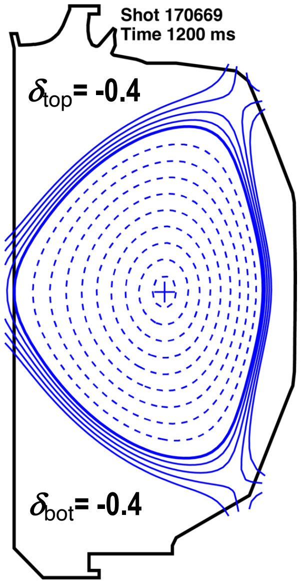
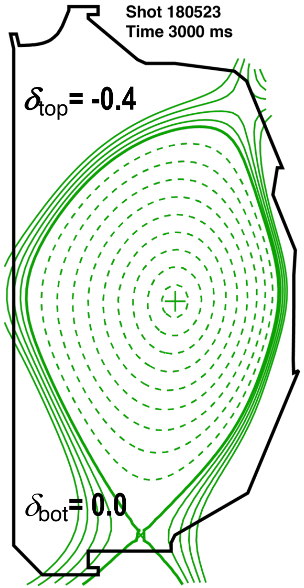
History of Negative Triangularity (NT) plasmas on DIII-D

First made in 2016



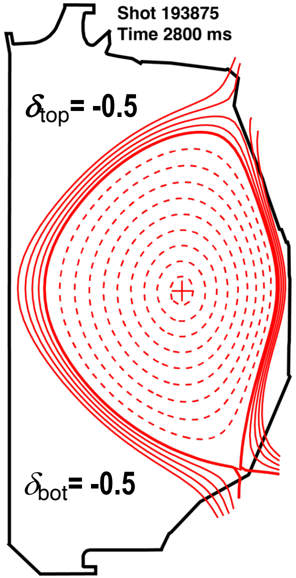
Inner wall limited

2018

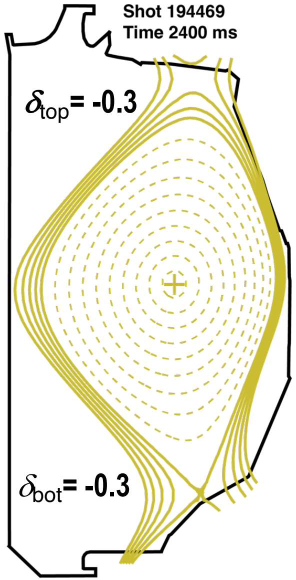


Hybrid

2023 Armor Campaign Shapes



Campaign (baseline)



Divertor optimized

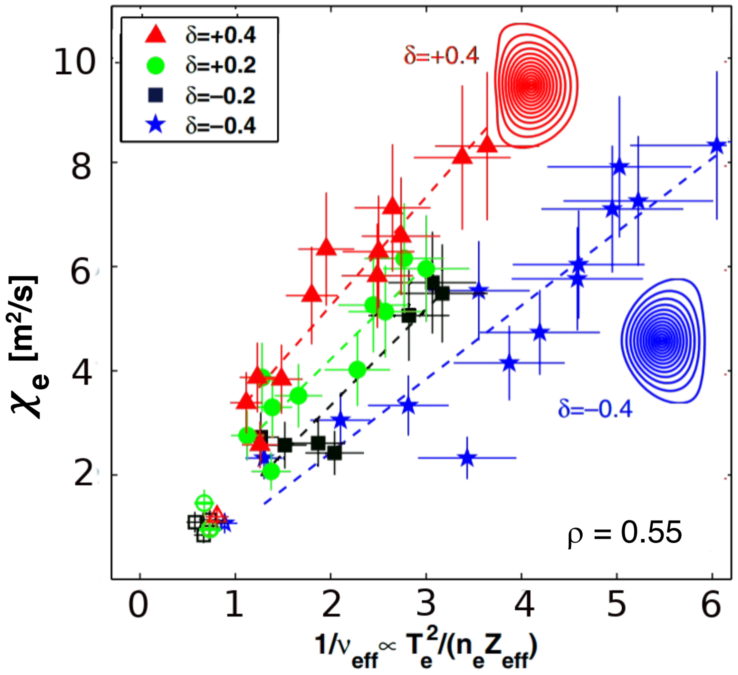
Shape development & control were the greatest technical issues

Earliest NT experiments inspired by results from TCV

- NT first explored in '70/'80s experimentally and theoretically
  - *mostly abandoned after predicted to **not have access to second stability***

- NT potential first **demonstrated on TCV with observation of 2x improvement in confinement**

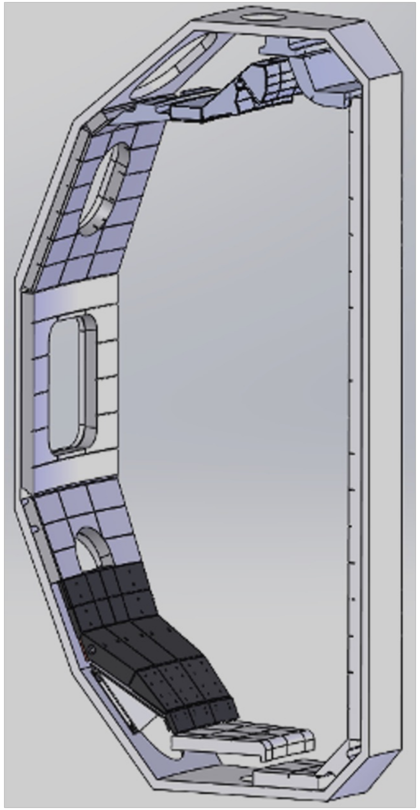
TCV: Impact of Negative Triangularity on Transport

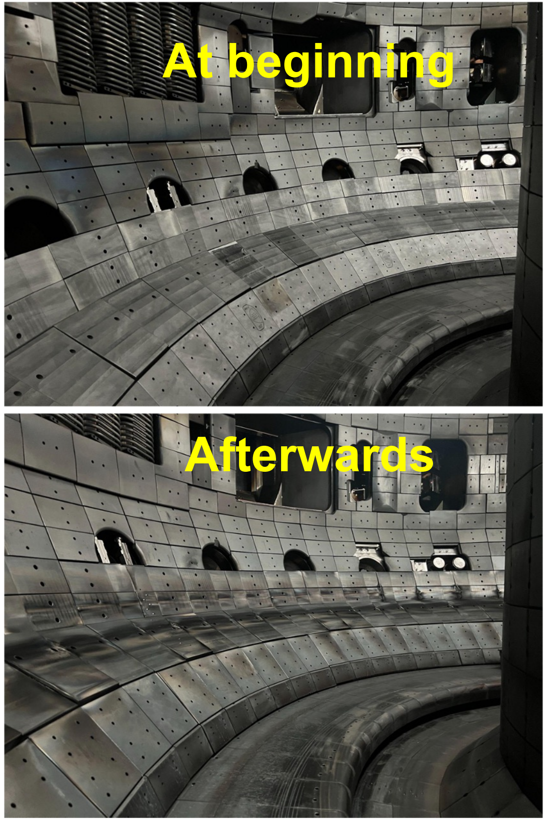


[Camenen, et al. NF 2007]

2023: Ran dedicated NT "Armor Campaign" to answer key questions

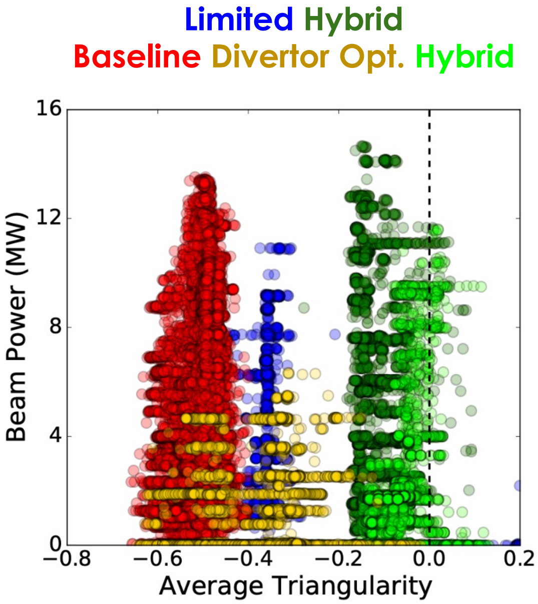
- **Goal: determine if the fusion community should continue exploring NT scenarios**
  - 13 experiments focused plasma confinement, stability, L-H transition, advanced scenarios, and core-edge integration
  - One full month of dedicated NT operation

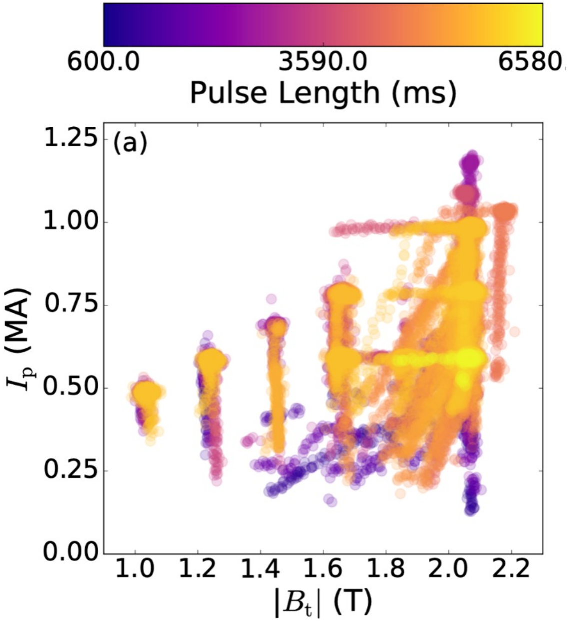




NT Campaign experiments covered wide operational space

- Full DIII-D NT dataset now includes ~890 discharges
  - 6-fold increase due to this campaign





Plasma parameters:

I_p = 0.5 – 1.2 MA

B_T = 1.0 – 2.2 T

q_{95} = 2.4 – 7.0

P_{aux} = 0 – 15 MW

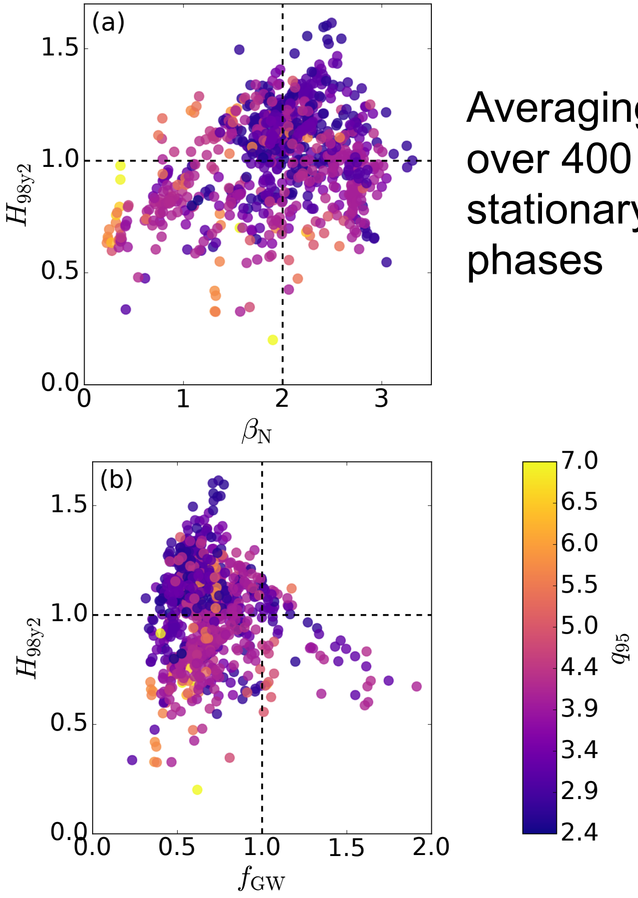
T_{inj} = -4 – 10 Nm

n_e = 2 – 14 x10^{19} m^{-3}

τ_{pulse} ~ 4 – 6.5 s

Initial experimental observations from campaign promising for an FPP

- **Reliable vertically stable plasmas constructed that lasted the entire discharge length**
- **High performance achieved in an ELM-free regime with H_{98}>1 and β_N>2.5**
- **Operation at q_{95}<3**
- **Greenwald fraction f_{GW}~ 2 demonstrated**
- **Dissipative edge solution obtained with divertor detachment**

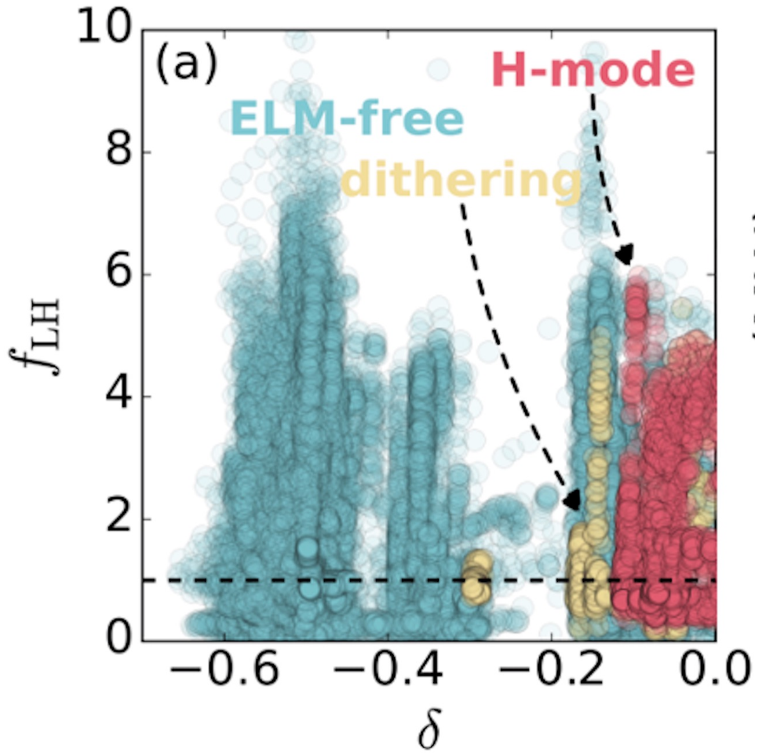


Averaging over 400 ms stationary phases

DIII-D NATIONAL FUSION FACILITY

NT plasmas are completely ELM-free as long as $\delta < \delta_{crit}$

- **Figure shows 20ms timeslices from 890 DIII-D discharges**
  - every DIII-D shot with δ < 0
- **ELMs and H-mode only achieved at δ > -0.18**
  - LCO-like activity at δ > -0.3
- **At strong NT, H-mode access NOT dependent on:**
  - density
  - injected power
  - torque



[Nelson, *ArXiV 2023*]

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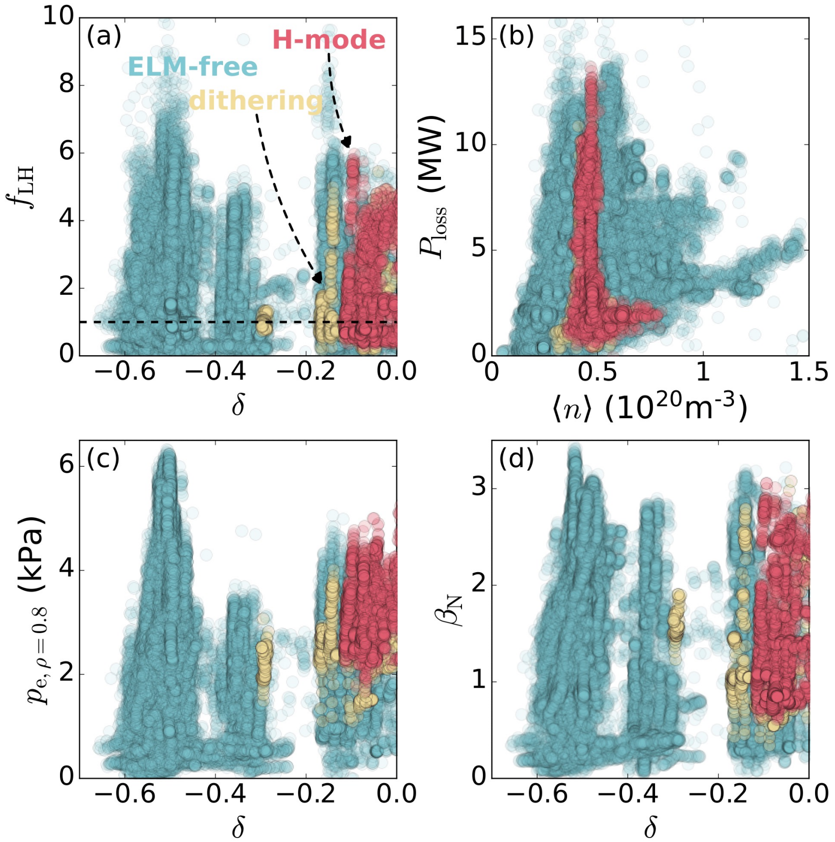
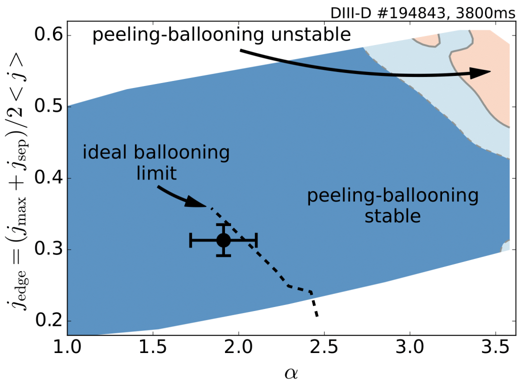
[Nelson, *ArXiV 2023*]

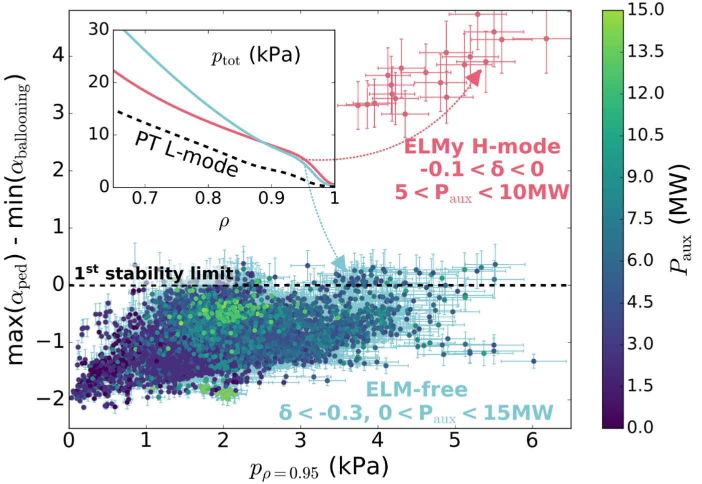


NT ELM suppression consistent with ideal ballooning limit

- **$\delta < \delta_{crit}$: access to the 2nd stability region closes**
  - H-mode typically accessed in "2nd stability region" [Nelson, *et. al.*, NF 2022 also Saarelma, PPCF2021]
  - Ideal ballooning (infinite-n) boundary clamps pedestal height below ELM limit

- **ELM suppression on DIII-D consistent with infinite-n ballooning mode**
  - NT geometry closes access to 2nd stability, so pedestal gradients limited by the 1st stability boundary
  - **Robust ELM suppression at $\delta < \delta_{crit}$**
  - Only part of the story – still variation in the pedestal height

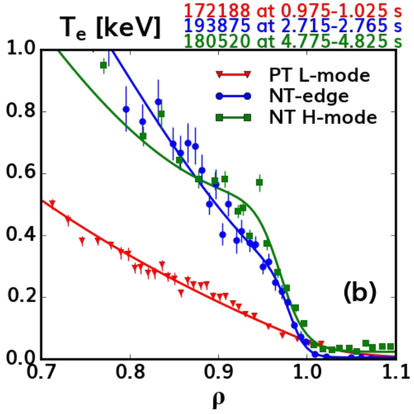




(Courtesy of Oak Nelson)

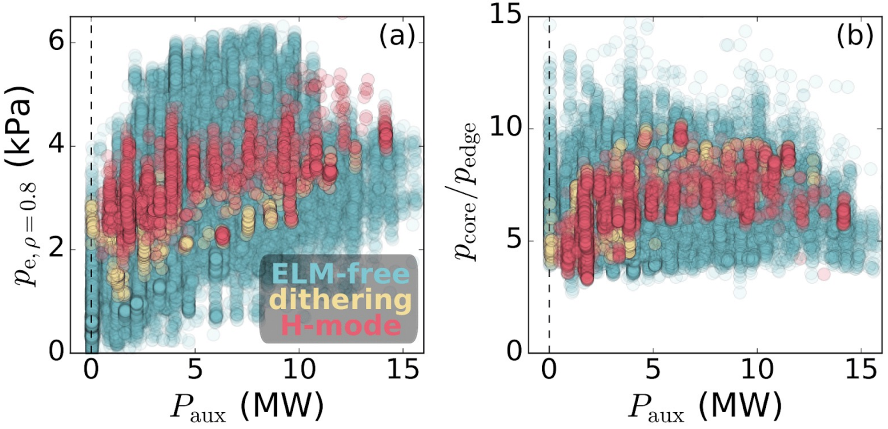
T_e pedestals in the "NT Edge" are higher than typical L-mode

- **Temperature pedestals observed in both inner-wall limited and diverted NT**
  - n_e profiles remain L-mode-like
  - Similar to I-mode
  - Higher T_e pedestal contributes to 20-30% increase in stored energy



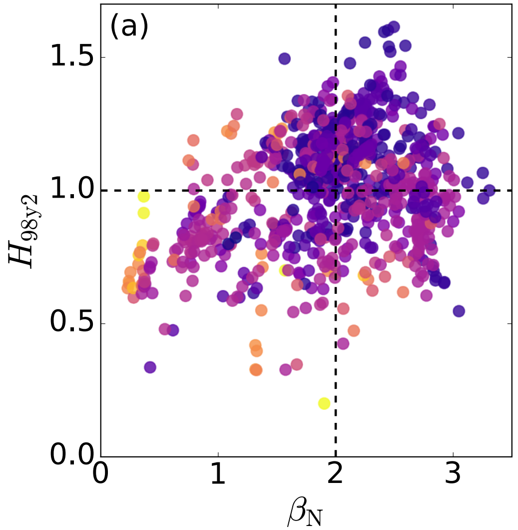
(Courtesy of K. Thome)

- **Transport in NT edge is NOT stiff**
  - Allows for high pressures in NT as far out as ψ_N ~ 0.8
  - ELM-free NT plasmas can achieve higher pressures than weak NT H-modes

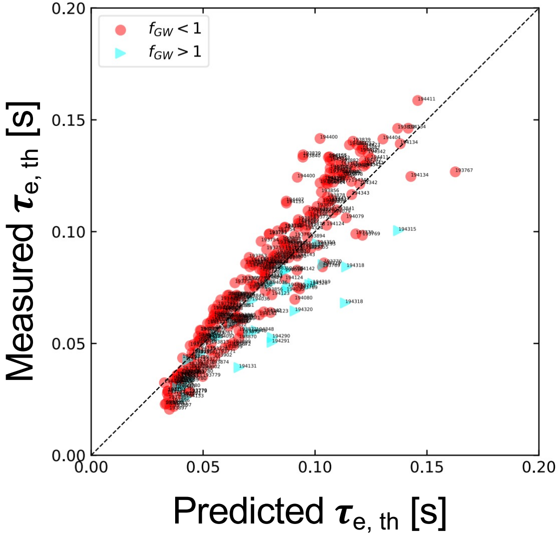


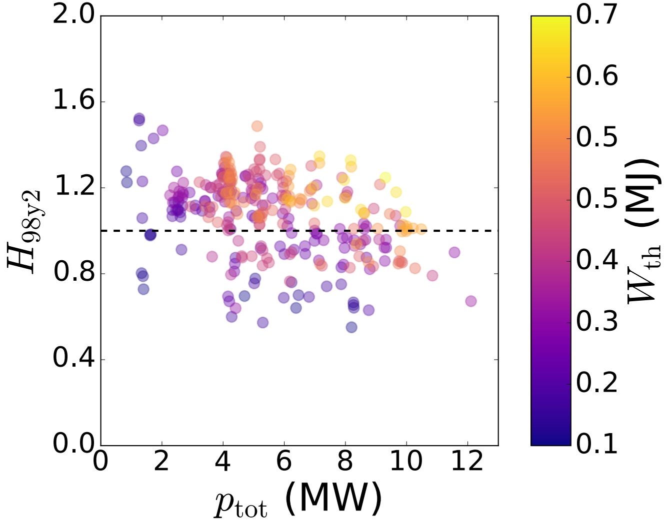
Energy confinement consistent with IPB98y,2 scaling

- **Power degradation at least as strong as IP98y,2 scaling**
  - Currently assessing collinearities between parameters and uncertainties



H-mode scaling law (IPB98y,2)[1]

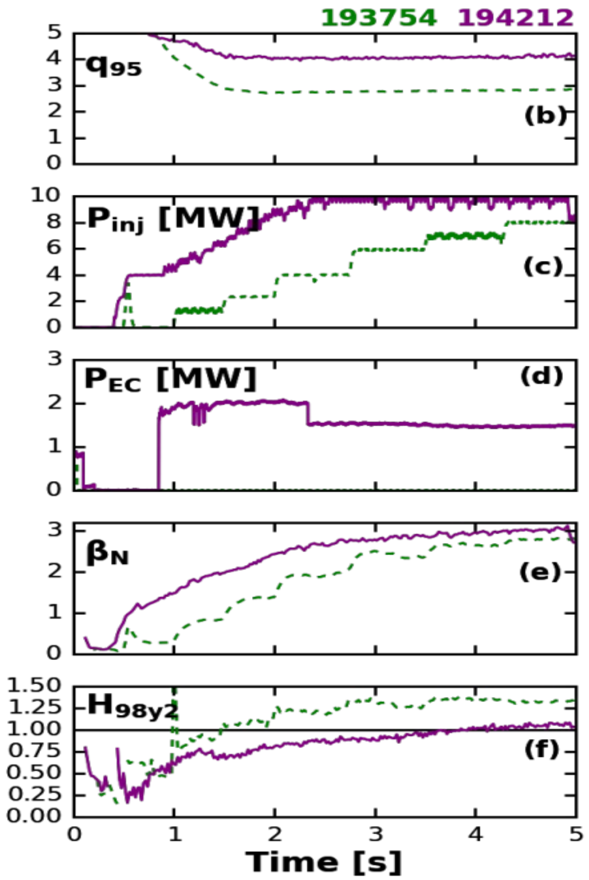




(Courtesy of P. Lunia)

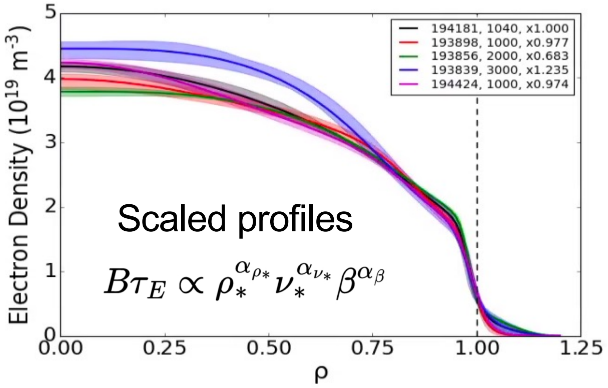
Robust ELM suppression allows for advanced core scenarios

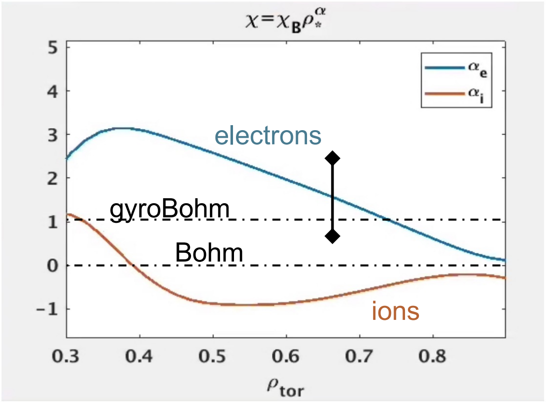
- **ELM suppression is robust to changes in core**
  - Allows for tailoring of NT scenario!
  - Synergy between core and edge solutions
- **Inductive high-gain discharge** at lower q_{95}=2.7 and **advanced "steady-state like"** at q_{95}=4 **both achieved**
  - Ohmic, neutral beams, electron cyclotron and mixed heating used
  - Both achieved high performance H_{98}~1 and β_N>2.5 with q_{min} ~1 in q_{95}=2.7 and q_{min} > 1 in q_{95}=4 discharges
  - More energetic particle transport at high q_{95}



Ongoing: ρ* and ν* dependence on energy confinement time

- **To study confinement scaling**, dimensionless parameters **collisionality (ν*) varied by x3** and **relative gyroradius (ρ*) by x1.4**
  - Low magnetic field discharges prone to density peaking and instabilities
  - Density profiles difficult to match
  - ν* similar to positive triangularity H-mode
- Initial indications: **ions are Bohm-like and electrons are gyroBohm-like** leading to mixed transport
  - *Similar to seen w/ L-mode plasmas on DIII-D*
- Needs to be validated with data from other machines



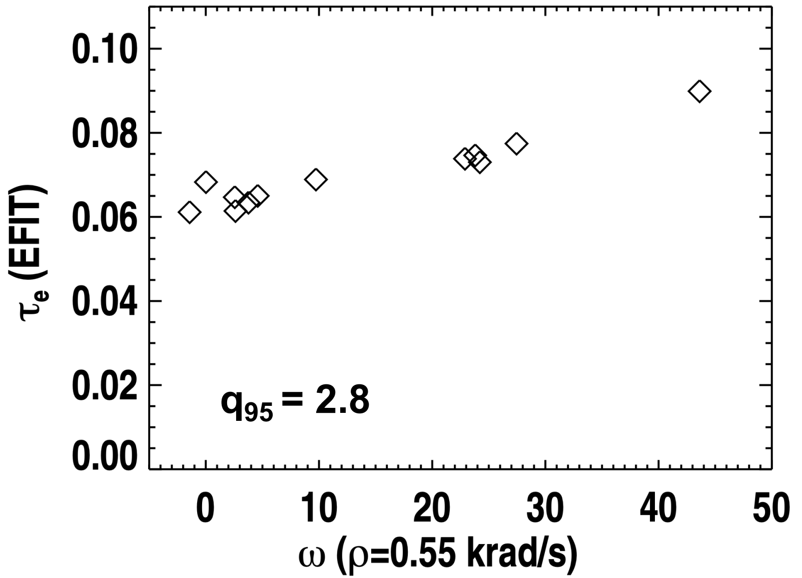


(Courtesy of A. Marinoni and C. Chrystal)

Energy confinement decreases as rotational shear decreases

- **When torque changed from strongly co-current to nearly balanced**
  - At q_{95}=2.8, τ_e reduced by 35%
  - At q_{95}=4, τ_e reduced by 25%
- **At low rotation, MHD not a problem and generally absent**
  - (unlike typ. high performance PT plasmas)
- **Similar response to positive triangularity H-modes**

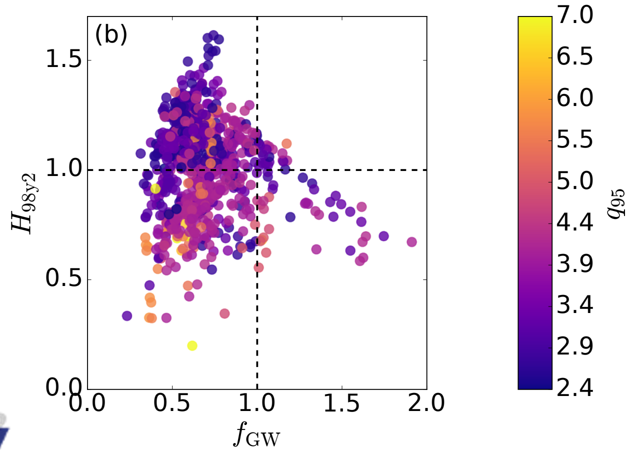
Consistent with GK simulation predictions [Marinoni, AAPPS 2021]



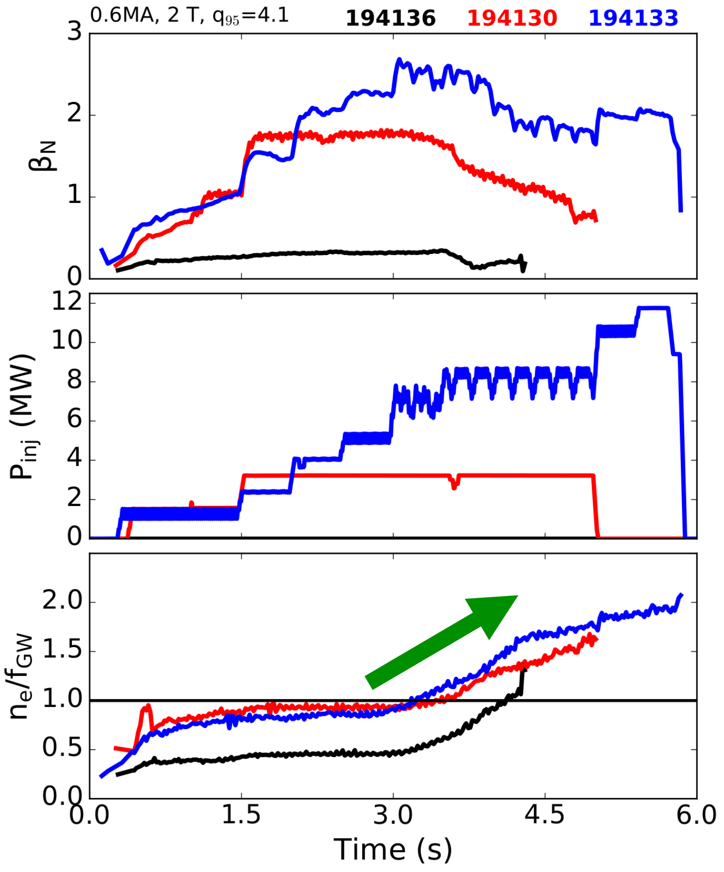
(Courtesy of C. Chrystal)

High Greenwald fractions accessible in NT with high power input

- In ohmic NT plasmas, density is limited by Greenwald fraction
- **As neutral beam applied power increased, achieved density is increase up to f_{GW} ~ 2**
- Degradation of confinement at high f_{GW} coincides with loss of pedestal



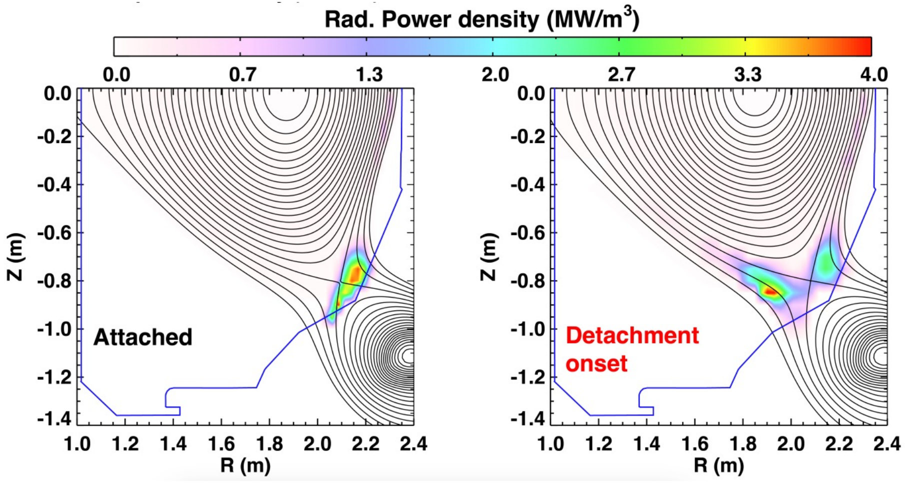
(Courtesy of R. Hong and O. Sauter)

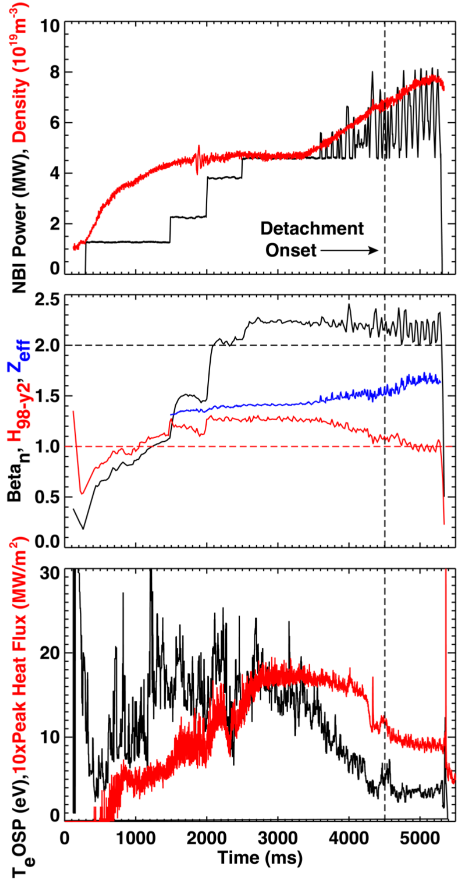


Dissipative divertor demonstrated with gas puffing at high density

- On TCV, detachment only achieved with impurities
- **In DIII-D campaign, high density allowed for detachment without impurities**
- Higher normalized densities were needed than PT, consistent with the short parallel connection length

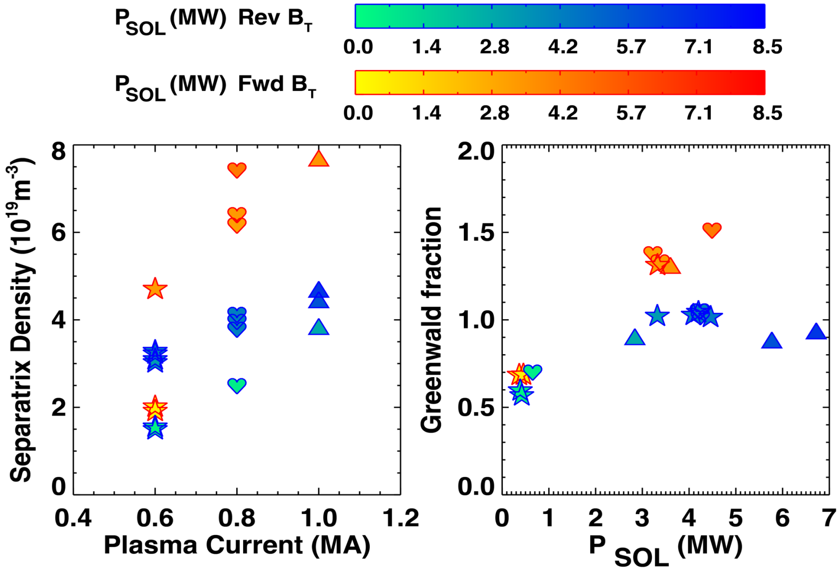
(Courtesy of F. Scotti and M. Zhao)





Higher density ($f_{GW} > 1$) needed to detach with favorable Grad_B

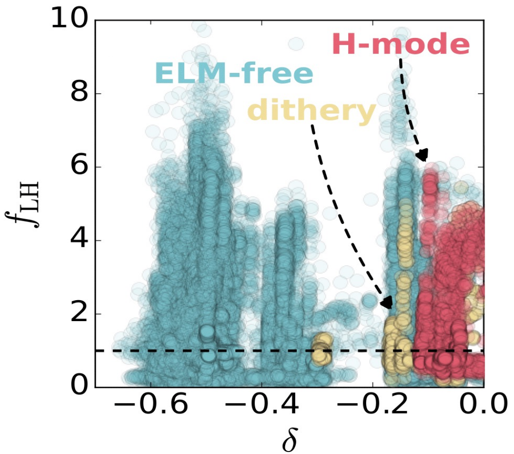
- **Higher separatrix densities needed for detachment in FwdBT (favorable ion gradB drift direction)**
  - Reproduced in UEDGE modeling
  - Similar to PT (though more severe since B_T at x-point is ~30% lower in NT plasmas)
- **Higher $n_{e,sep}$ required to detach with increasing I_p**
  - Consistent with shorter $L_{//}$ and observed narrowing of λ_q.
- **No "detachment cliff" observed** [A. E. Jaervinen, PRL 2019]
  - Smooth transition instead

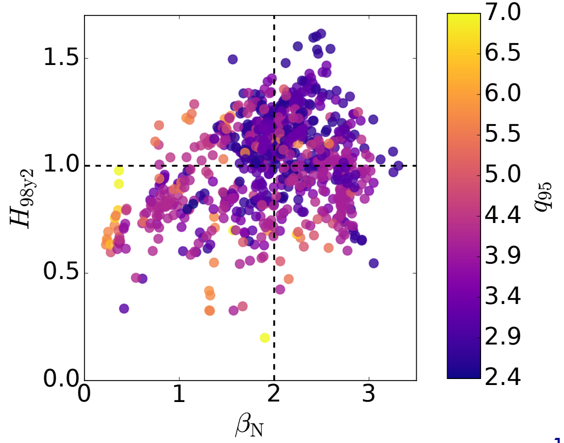


(Courtesy of F. Scotti and M. Zhao)

Summary: DIII-D NT Initial Results are Promising for a Reactor

- NT plasmas exhibit good confinement **H_{98}>1 in a robust ELM-free regime**
  - has benefits for not triggering MHD as well
- **Non-seeded detachment achieved** with similar dependencies as positive triangularity
- Greenwald fraction **f_{GW}~2 achieved**
- **Vertical stability controllable** in baseline shape
- **Low impurity retention** observed
- Questions about scalings to reactors remain
- Need a proper divertor to better study core-edge integration





Future Work Planned for DIII-D

- **Increase plasma volume and improve shape control**
  - Potentially requires new hardware
  - "Best triangularity" not yet known
  - Explore maximum elongation
- **Add baffled divertor with a longer connection length**
  - Needed to answer key core-edge integration problems
  - Can be done by removing some diagnostics
- **More RF power and dedicated runtime**
  - Facilitate energy confinement studies with strongly RF-heated plasmas
  - Push β_N at high q_{min} for steady-state plasma exploration