PRINCETON
PLASMA PHYSICS
LABORATORY

Heating and current drive options for a Spherical Tokamak Advanced Reactor

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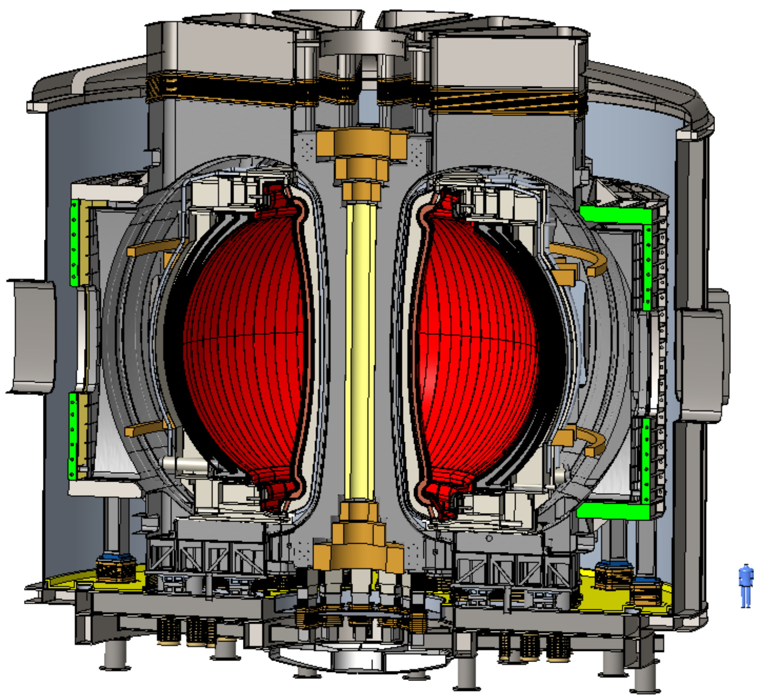
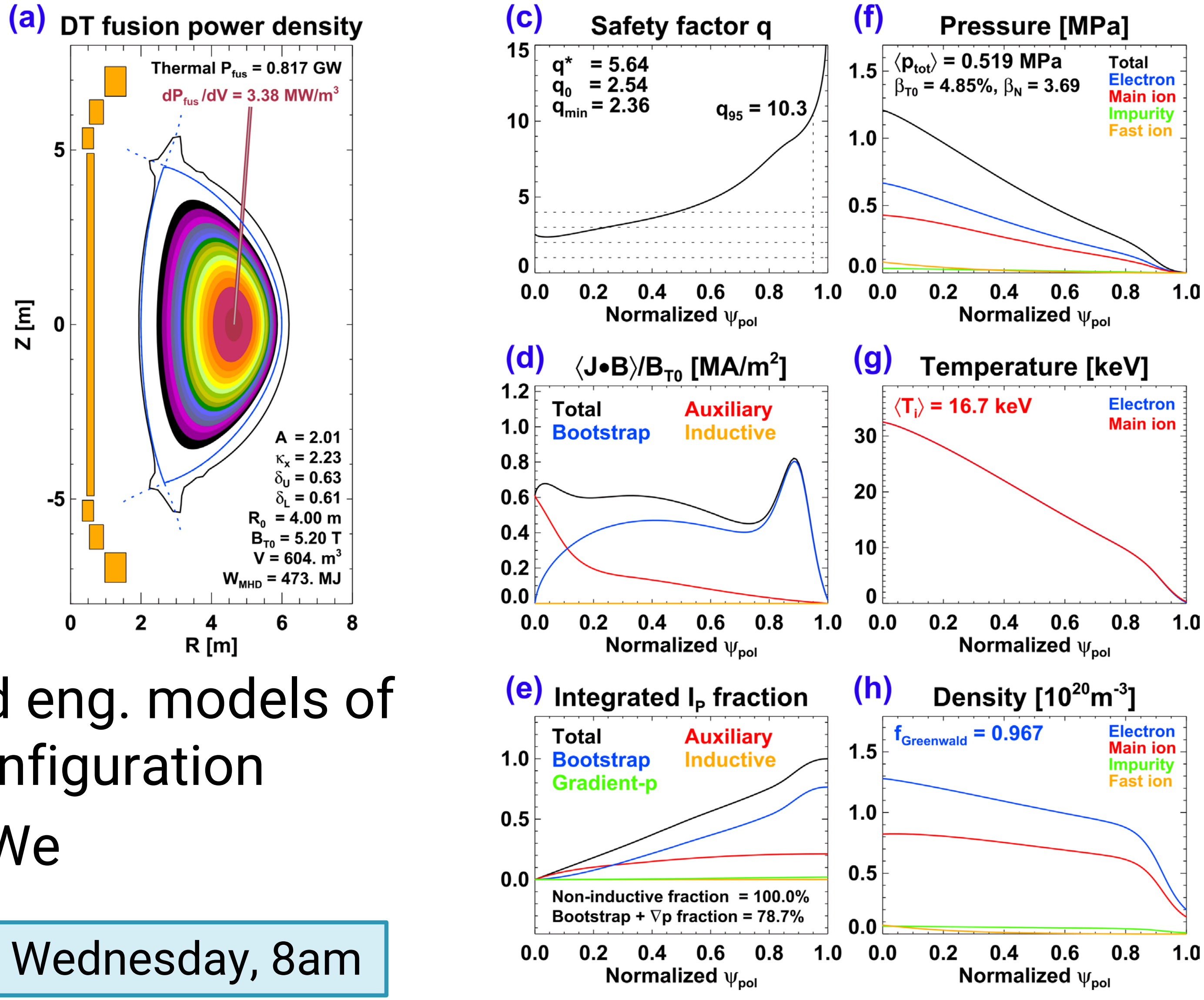
The Spherical Tokamak Advanced Reactor (STAR) design project





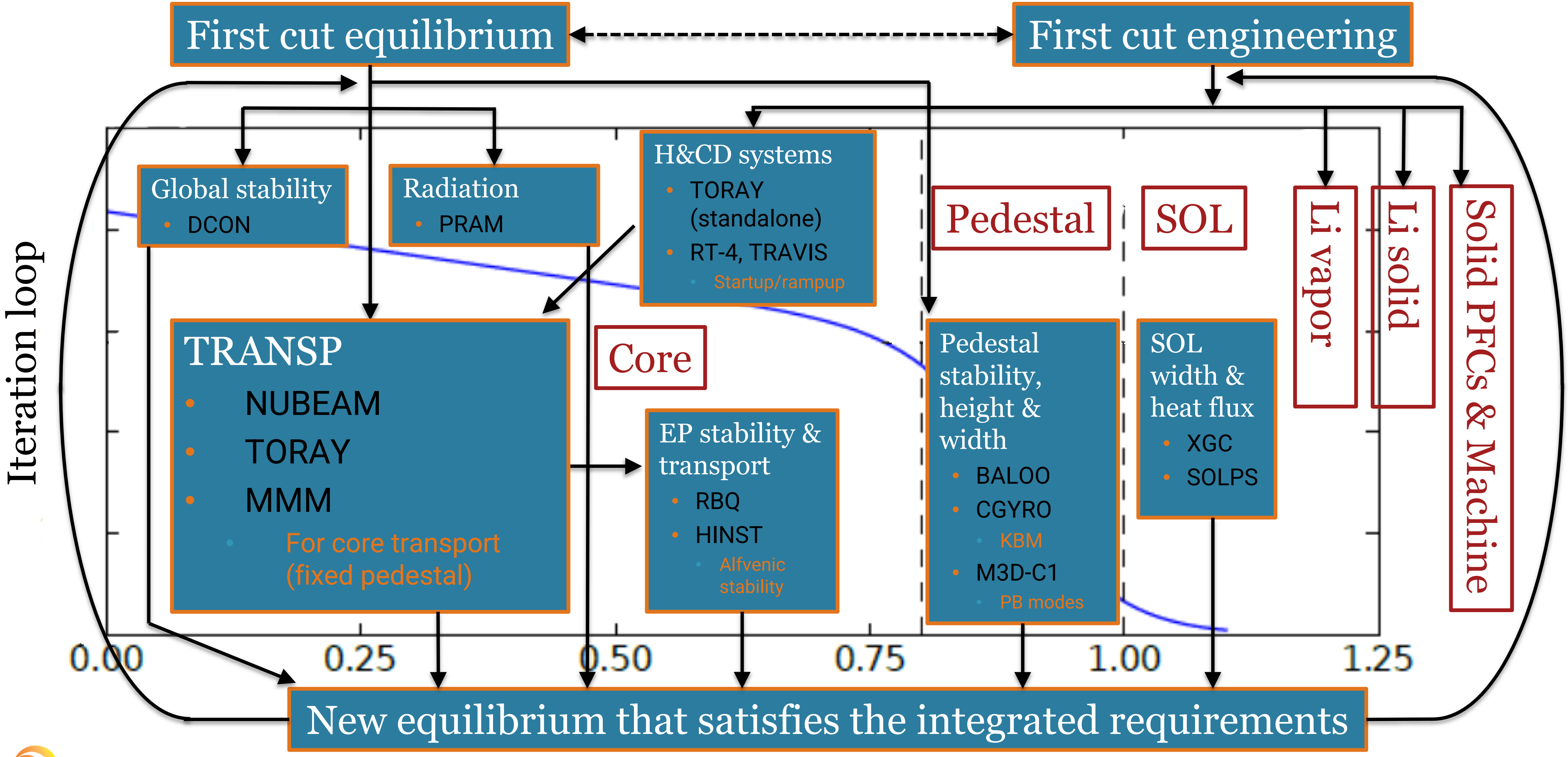
- Developing high fidelity physics and eng. models of R = 4 m, A = 2, B_T = 5.2 T, κ = 2.2 configuration
- P_{fus} = 0.5-1.5 GW, P_{net} = 100-500 MWe

Menard, Monday 1pm

Gupta + Khodak, Wednesday, 8am

[J. Menard et al., IAEA FEC (2023) P/8 2215]

The design process for STAR involves integrating all parts of the plasma and machine requirements



First cut equilibrium

First cut engineering

Iteration loop

Global stability
- DCON

Radiation
- PRAM

H&CD systems
- TORAY (standalone)
- RT-4, TRAVIS
  - Startup/rampup

Pedestal

SOL

Li vapor

Li solid

Solid PFCs & Machine

TRANSP
- NUBEAM
- TORAY
- MMM
  - For core transport (fixed pedestal)

Core

EP stability & transport
- RBQ
- HINST
  - Alfvenic stability

Pedestal stability, height & width
- BALOO
- CGYRO
  - KBM
- M3D-C1
  - PB modes

SOL width & heat flux
- XGC
- SOLPS

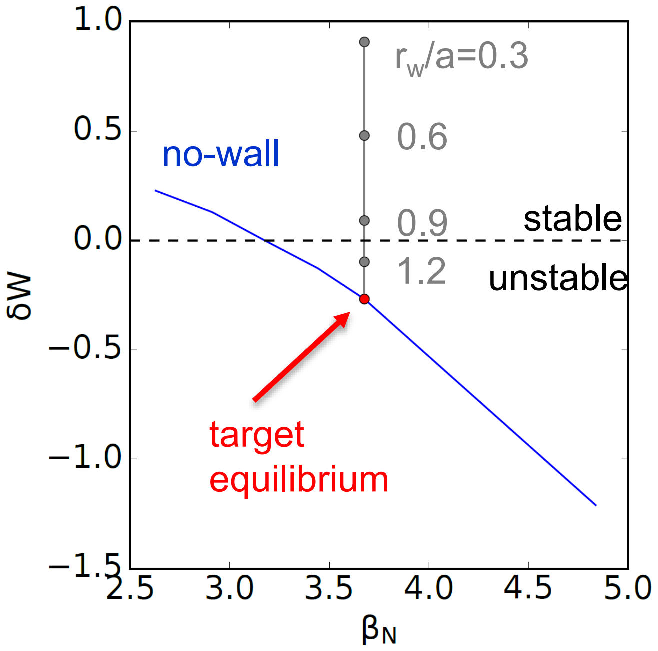
New equilibrium that satisfies the integrated requirements

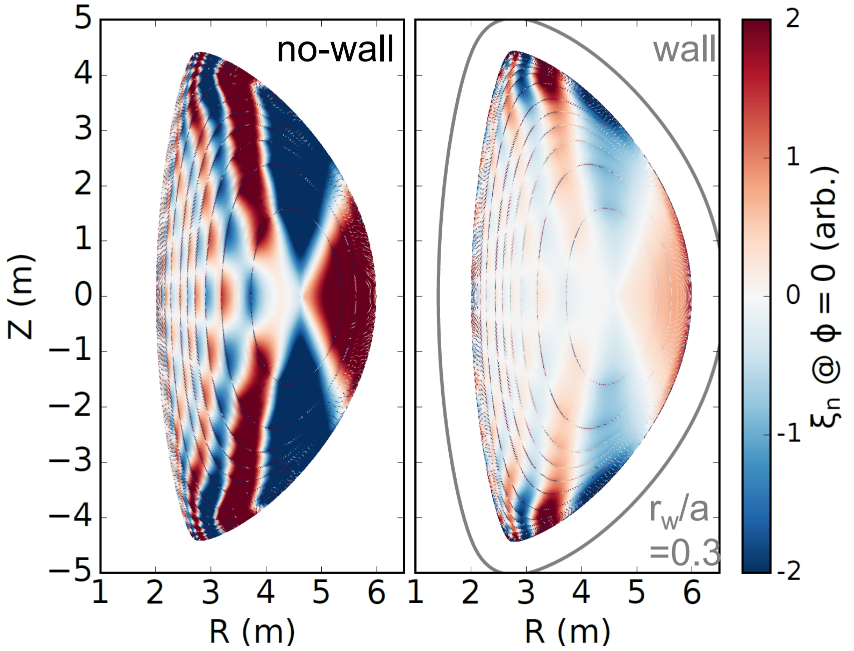
Outline

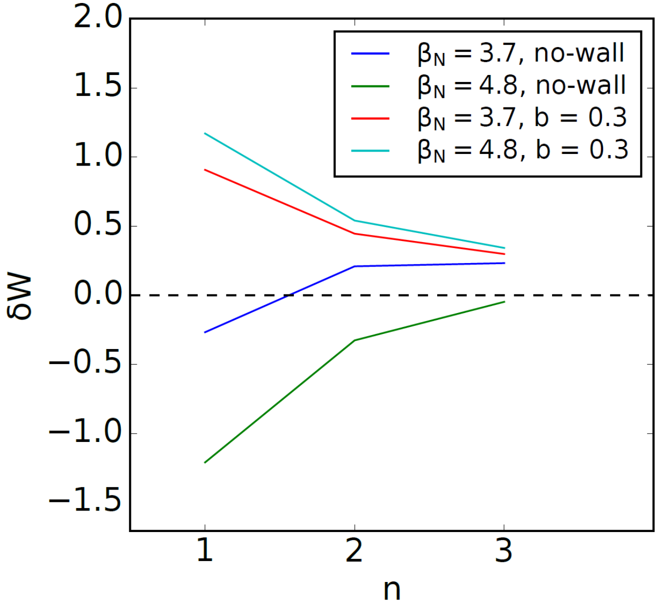
- Is the designed STAR plasma stable?
- Will ECCD/ECH be able to start-up and ramp-up the current and temperature of the STAR plasma?
- Will ECCD or NBI be able to drive the necessary auxiliary current for non-inductive steady state operation?
- Will ECH or NBI be able to sustain the plasma temperature in steady state, vs. thermal transport?
- What rotation, and radiation might be expected?

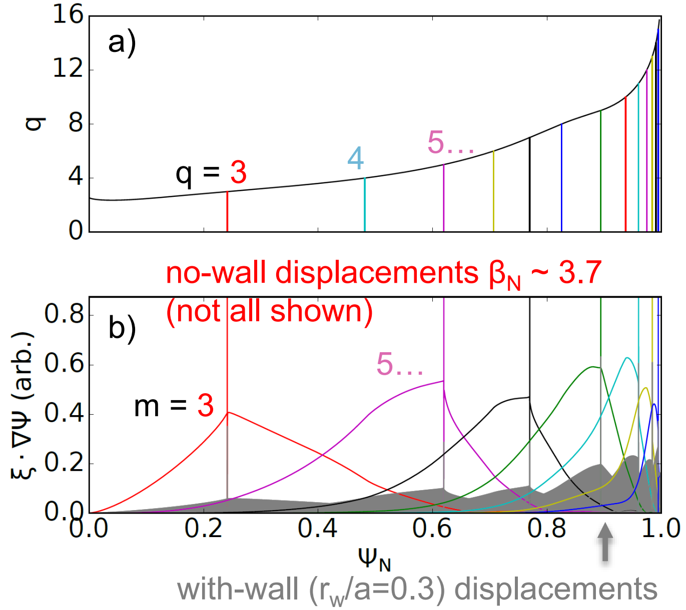
STAR aims to operate just above the global ideal MHD n = 1 limit

- The target equilibrium of β_N~3.68 is <u>unstable</u> to ideal MHD
  - no-wall limit at β_N~3.2
- Including a conformal wall stabilizes the global ideal MHD instability (converts to a resistive wall mode)
  - RWM kinetic stability or active control TBD
  - STEP is planning $\beta_N > 5$







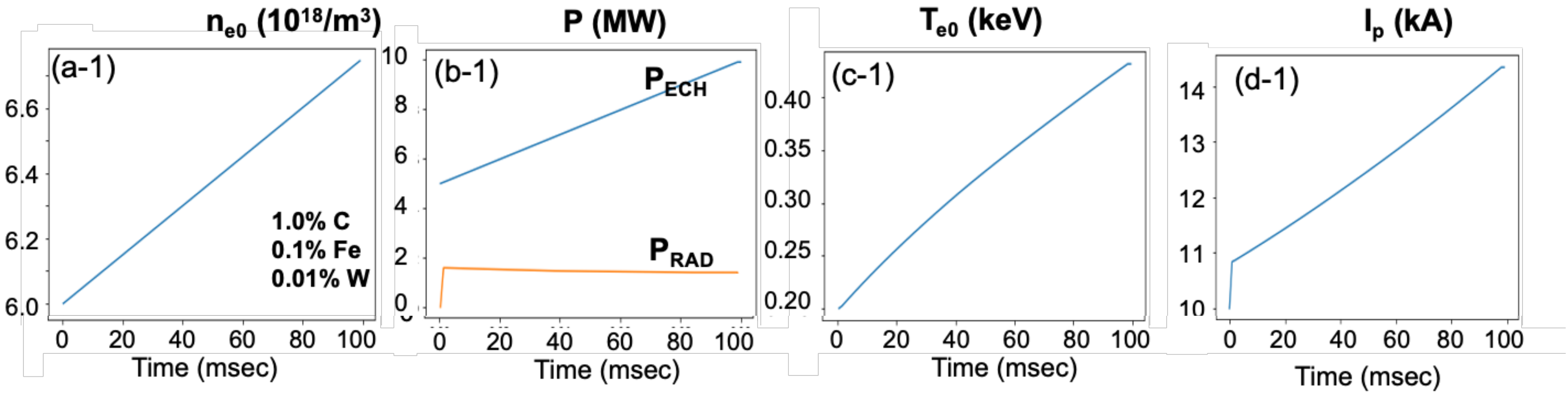


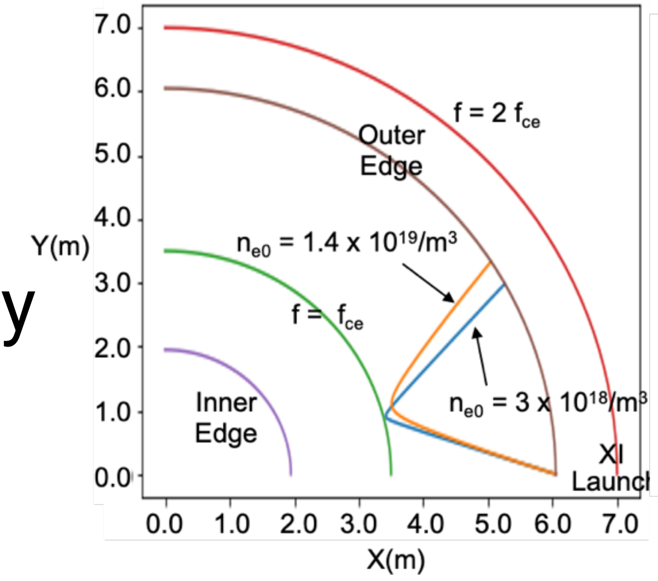
Outline

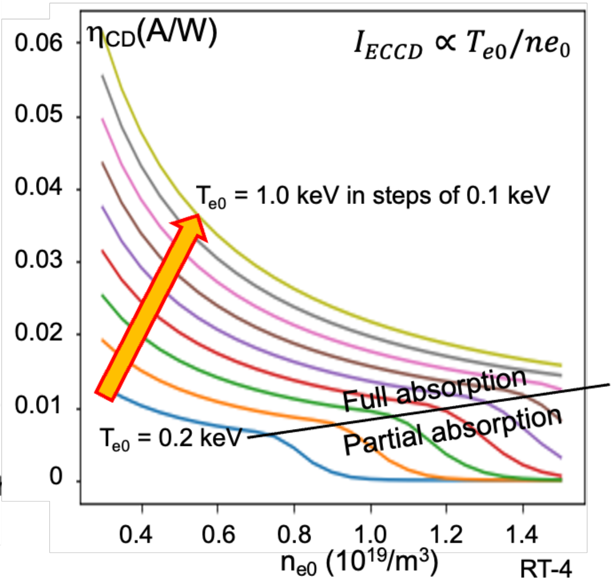
- Is the designed STAR plasma stable?
  - Maybe? (Hopefully!)
- Will ECCD/ECH be able to start-up and ramp-up the current and temperature of the STAR plasma?
- Will ECCD or NBI be able to drive the necessary auxiliary current for non-inductive steady state operation?
- Will ECH or NBI be able to sustain the plasma temperature in steady state, vs. thermal transport?
- What rotation, and radiation might be expected?

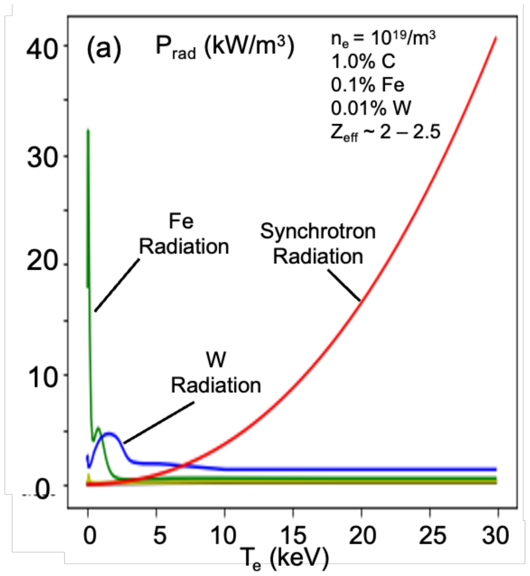
Time dependent modeling shows that start-up, burn-through, possible

- Starting up: raise n, T, current
- At low density, X-I EC absorption possible, even at low T_e
  - At low density, rays approach closer to cyclotron resonance
- Minimizing high Z impurities necessary to keep $P_{rad} < P_{ECCD}$
  - Synchrotron dominates at high T_e







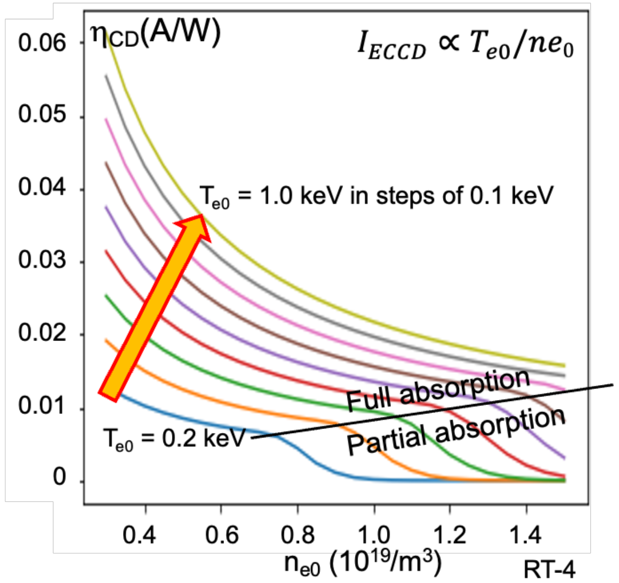


[M. Ono et al., Nucl. Fusion 64 086021 (2024)]

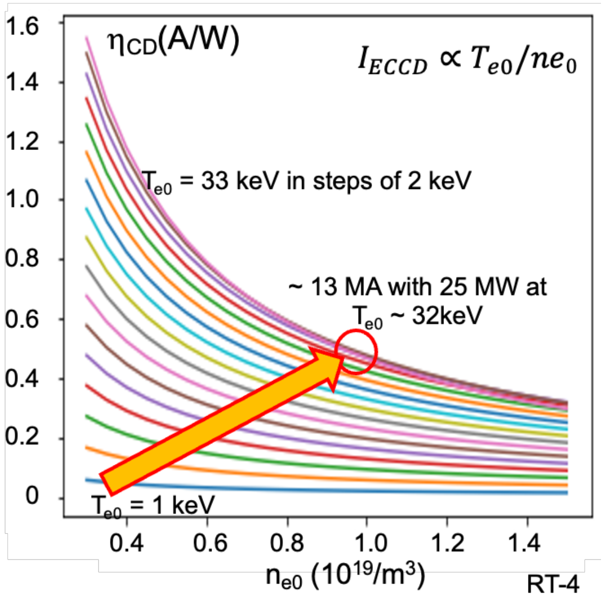
After start-up, the time dependent model determines a full ramp-up

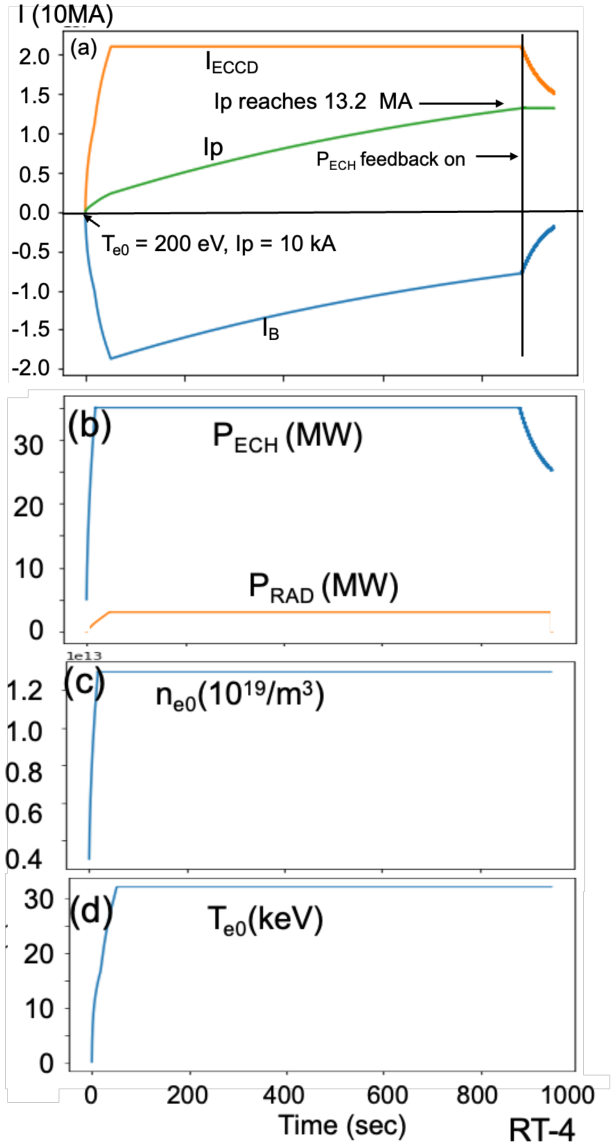
- Start-up to 1 keV at low n_e, ramp-up to 25 keV
- Ramp-up of density and plasma shape is prescribed in the model
  - Everything else calculated consistently for the evolving plasma: T_e, I_{ECCD}, I_p, P_{ECH}, and P_{rad}
- Plasma current ramp-up takes much longer (~1000 s) because of decaying back EMF (I_B)

Start-up



Ramp-up





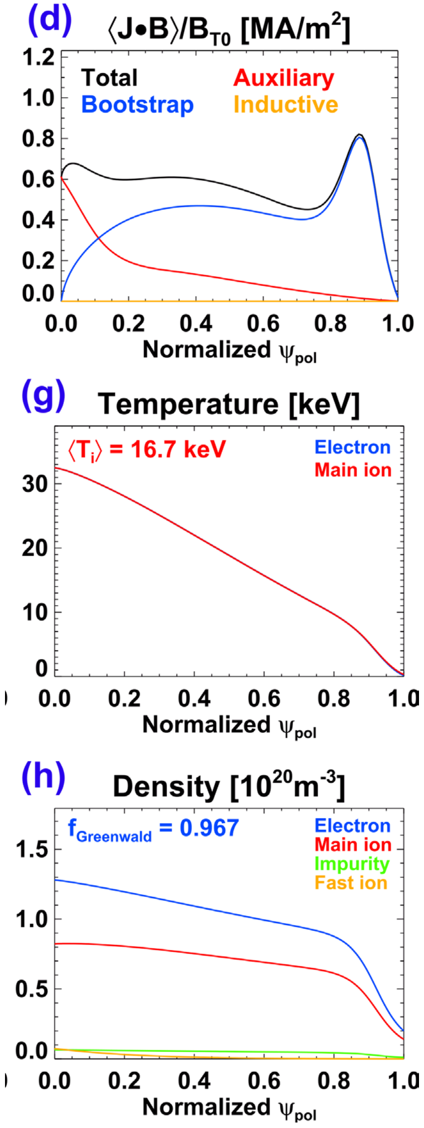
[M. Ono et al., Nucl. Fusion 64 086021 (2024)]

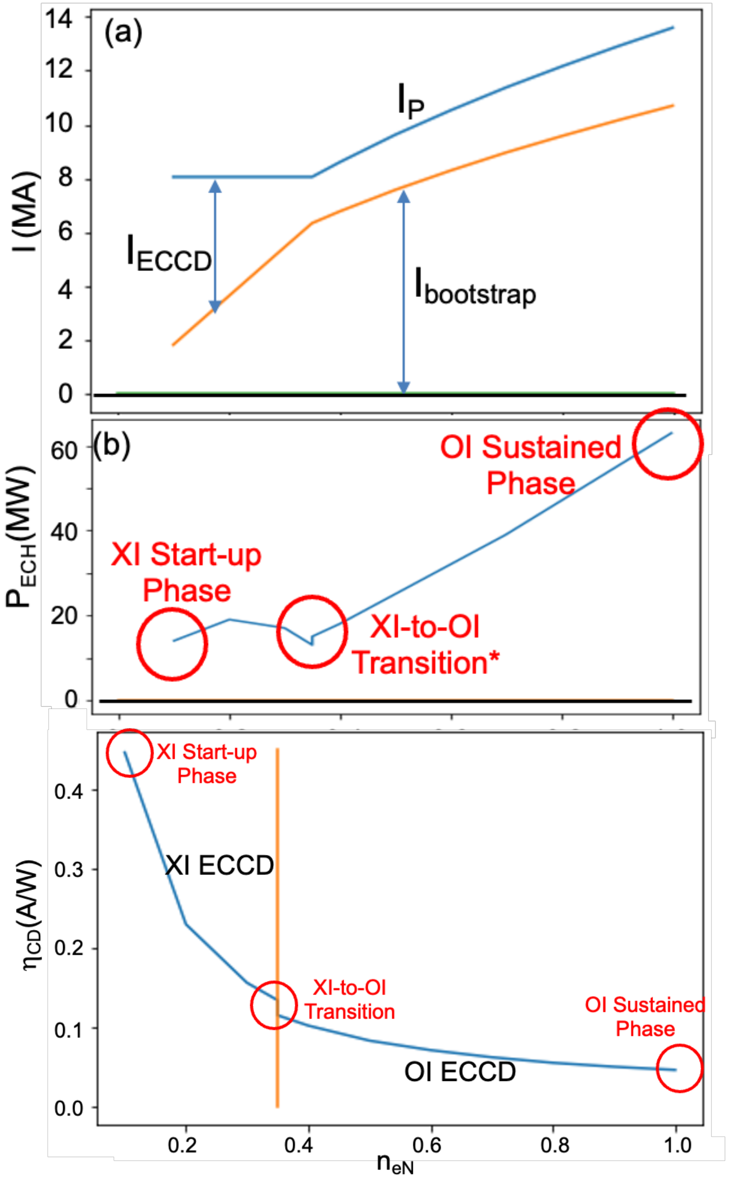
Outline

- Is the designed STAR plasma stable?
- Will ECCD/ECH be able to start-up and ramp-up the current and temperature of the STAR plasma?
  - Yes (if radiation is under control)
- Will ECCD or NBI be able to drive the necessary auxiliary current for non-inductive steady state operation?
- Will ECH or NBI be able to sustain the plasma temperature in steady state, vs. thermal transport?
- What rotation, and radiation might be expected?

At the transition to the sustained phase, the needs for CD change

- An auxiliary current profile was *assumed* to create the target equilibrium with high density and temperature
- When density is increased to full level, envisioned to switch from X-I to O-I with a polarizer
  - (Also now switching to TORAY/TRANSP calculations)
- Or, switch to neutral beams

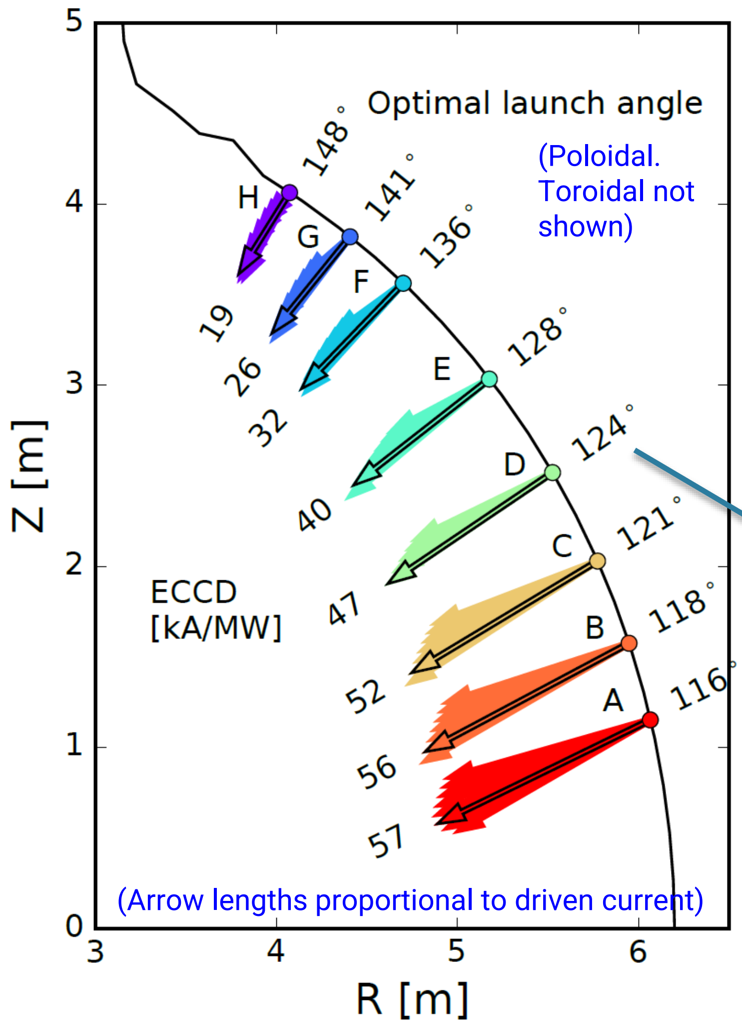


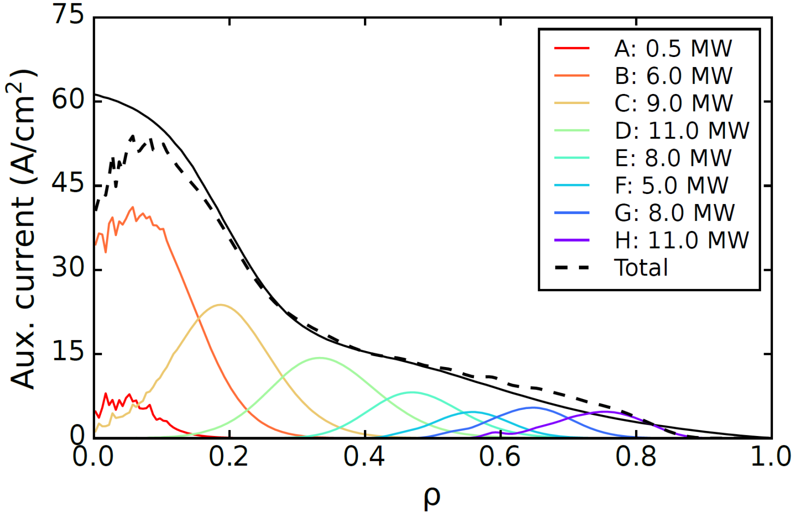


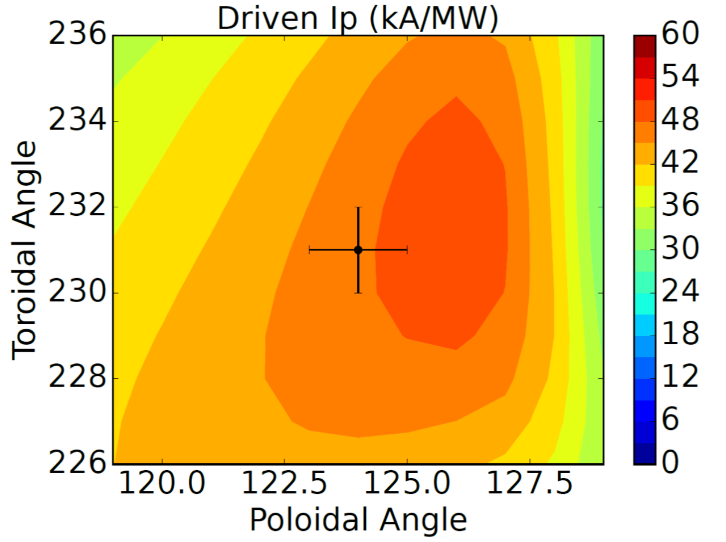
[M. Ono et al., Nucl. Fusion 64 086021 (2024)]

Systematic assessment of ECCD from varying launch locations shows that the necessary current profile can be achieved

- TORAY scans of toroidal and poloidal launch angles finds optimal CD at six different launch locations
  - All 170 GHz, fundamental O-mode
- A combination of launchers gives good CD efficiency spread over the desired radial extent



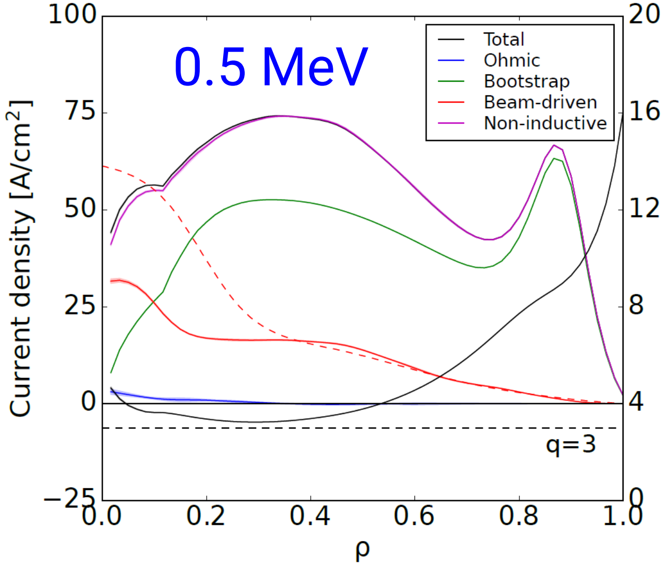


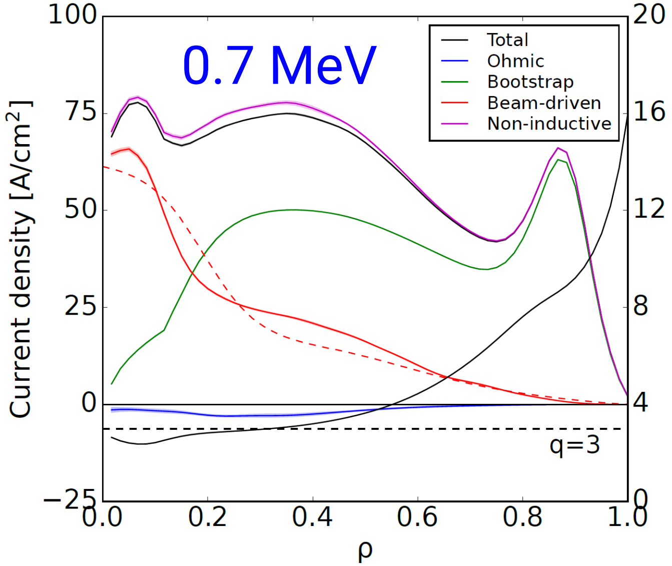


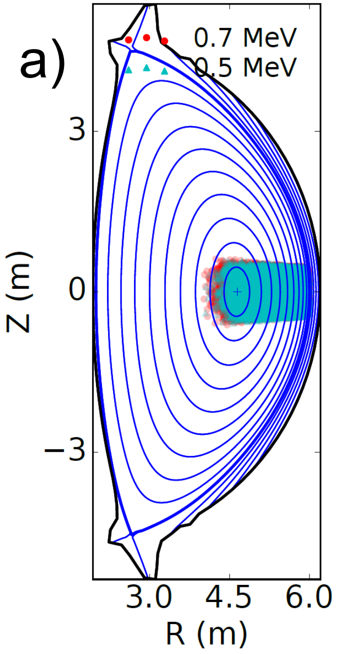
[M. Ono et al., Nucl. Fusion 64 086021 (2024)]

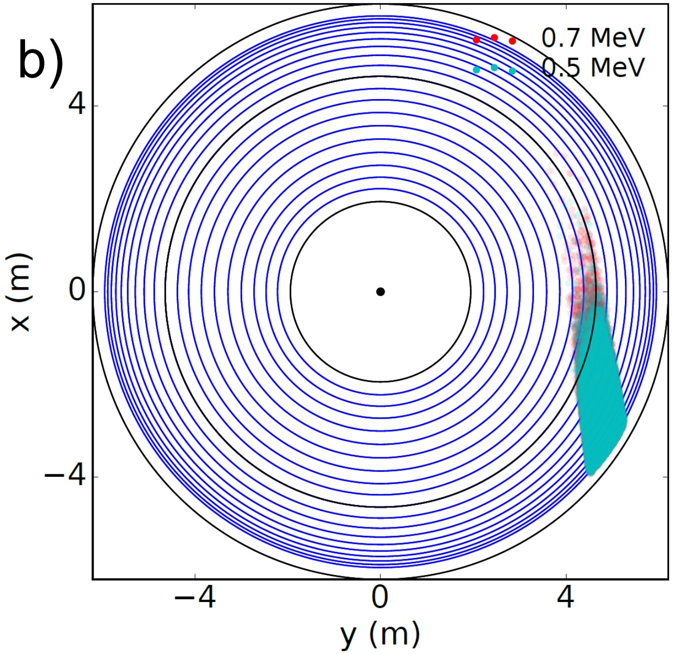
NBI is also able to drive the necessary current, once beam energy is optimized

- With higher enough beam energy, NBI can drive on-axis current
  - 0.5 MeV led to current shortfall, reversed q shear
  - This has stability implications, and core heating, rotation…
- NBI is a “blunter” instrument
  - Matches CD generally, but not perfectly









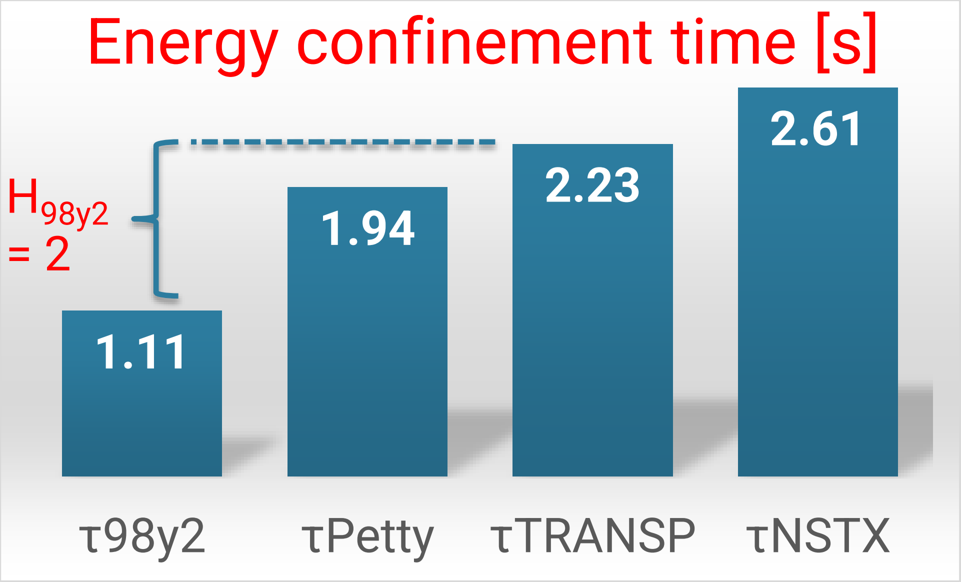
Mention CIGALE beam?

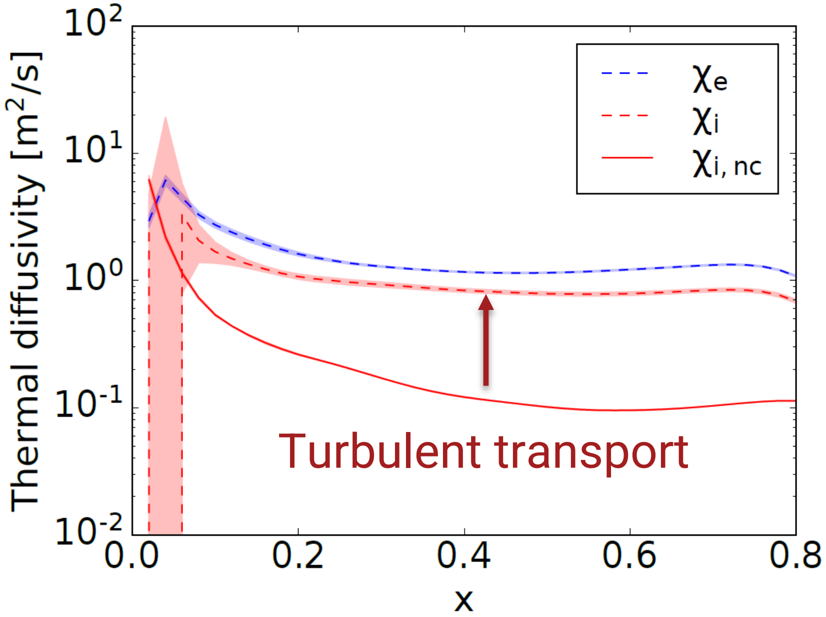
Mention beam vs.ec pros and cons?

Outline

- Is the designed STAR plasma stable?
- Will ECCD/ECH be able to start-up and ramp-up the current and temperature of the STAR plasma?
- Will ECCD or NBI be able to drive the necessary auxiliary current for non-inductive steady state operation?
  - Yes!
- Will ECH or NBI be able to sustain the plasma temperature in steady state, vs. thermal transport?
- What rotation, and radiation might be expected?

Balance between heating and transport is being examined by TRANSP



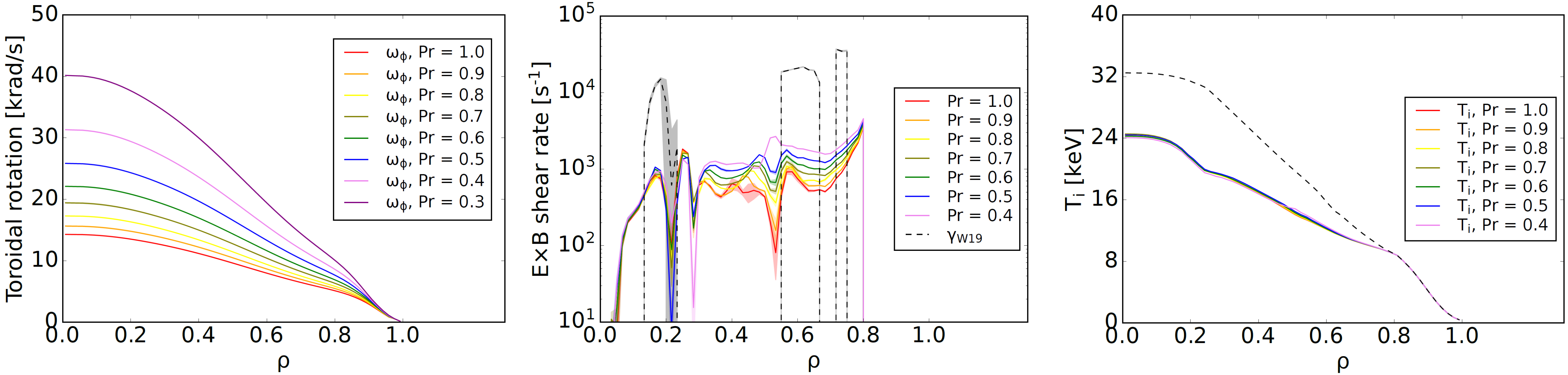


Implied TRANSP diffusivities for given heating and temperature profiles

- The energy confinement time calculated by TRANSP is twice the ITER scaling, but in between Petty and NSTX scalings, as projected for *A* = 2
  - With 50 MW ECH injected power plus ~150 MW of alpha heating
- Implied diffusivities from interpretive TRANSP for the given temperature profile shows significant turbulent transport
  - For NSTX, ions are typically close to neoclassical

[J. Menard et al., Phil. Trans. A 377, 20170440 (2018)]

The Multi-Mode Model currently predicts that turbulent transport of energy is too high to sustain the STAR temperature profile



- Toroidal rotation profiles estimated for STAR using a simple momentum balance in TRANSP (not fully consistent calculation yet)
  - These provide ExB shearing rates which are too low to influence turbulence
- At present, it appears that MMM predicts turbulent thermal transport will lead to a lower temperature profile than desired

When NSTX-U returns to operations it will provide much-needed data in this gap

Outline

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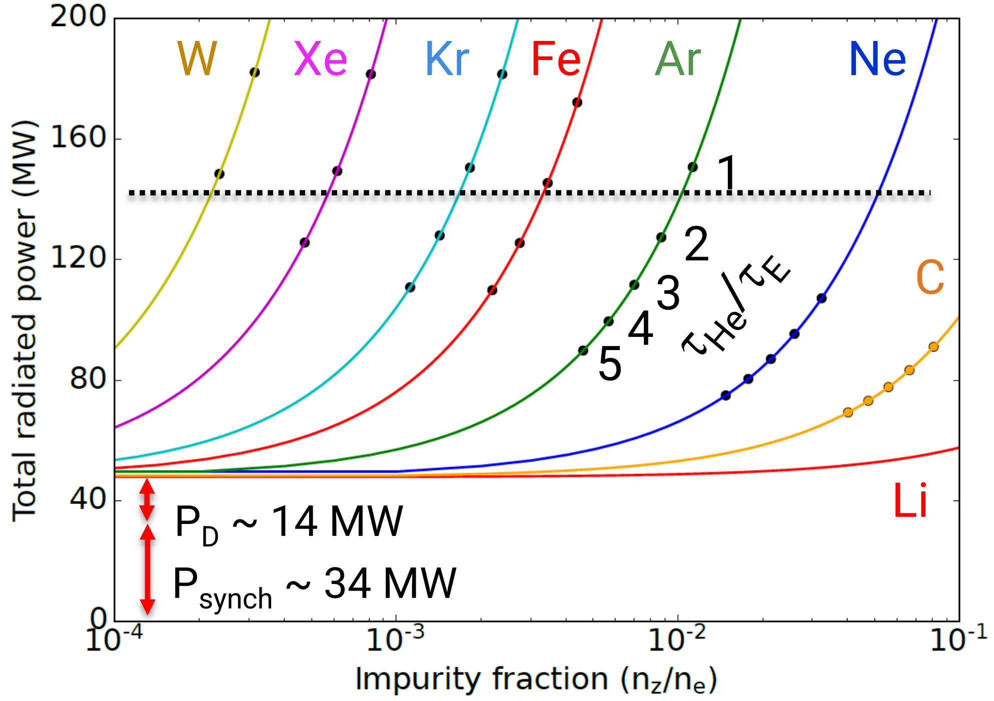
- Will ECCD/ECH be able to start-up and ramp-up the current and temperature of the STAR plasma?
- Will ECCD or NBI be able to drive the necessary auxiliary current for non-inductive steady state operation?
- Will ECH or NBI be able to sustain the plasma temperature in steady state, vs. thermal transport?
  - Not looking good at the moment, but much work to be done
- What rotation, and radiation might be expected?

Radiated power may be desired (noble gases) or undesired (metals), and may not be symmetric due to rotation

- STEP plans to radiate about 2/3 P_{heat} with Xenon
  - For STAR, that would require ~0.05% Xe, but this might not be possible, based on depletion, alpha build-up…

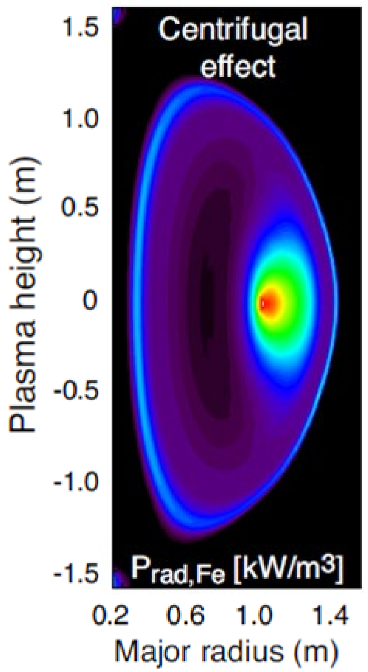


P_D ~ 14 MW

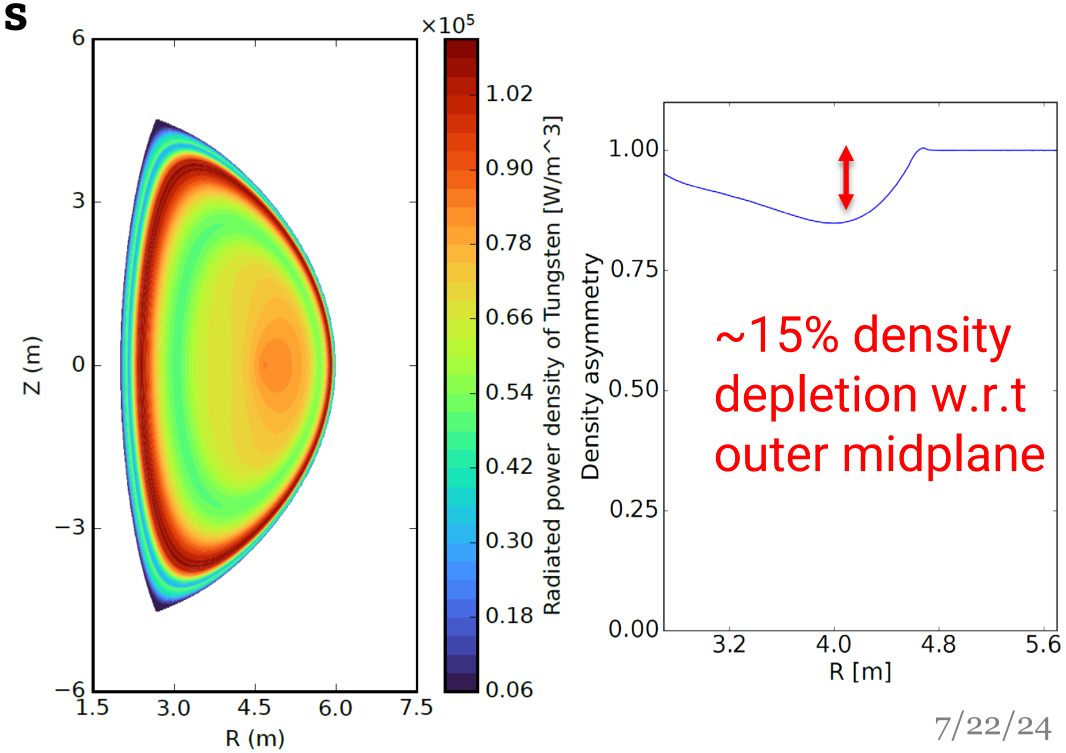
P_{synch} ~ 34 MW

- Heavy metals in NSTX can be very asymmetric due to centrifugal force
  - Due to lower rotation, however, W in STAR predicted to be only a few % asymmetric

NSTX Iron case:
132484 @ 0.695 s



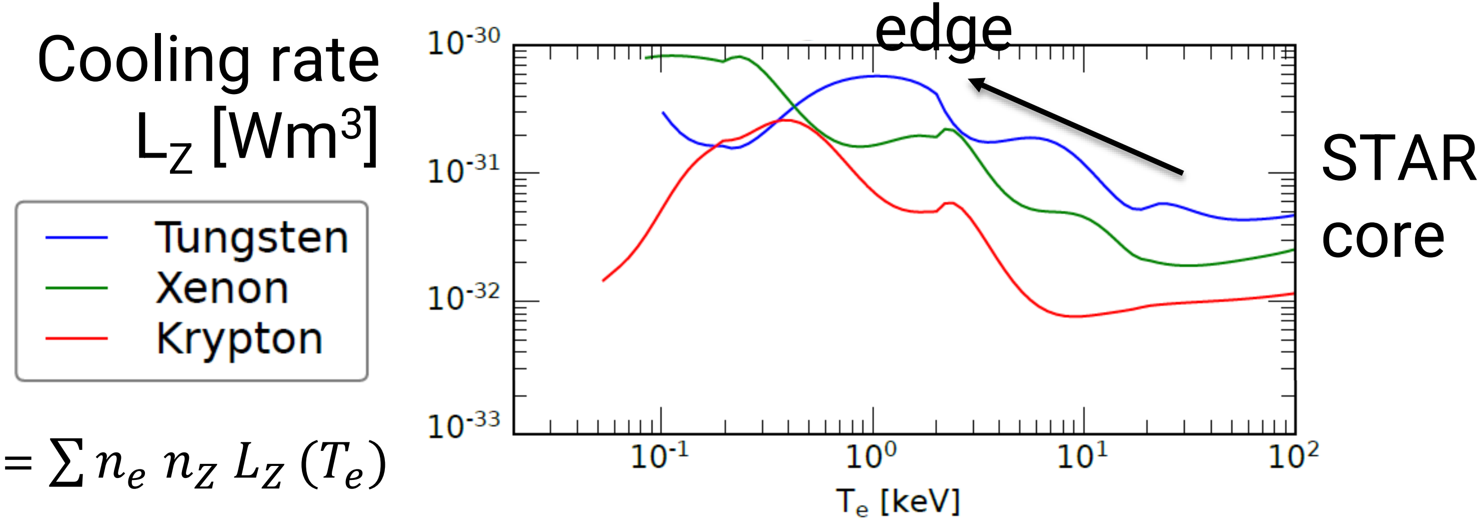
STAR Tungsten case



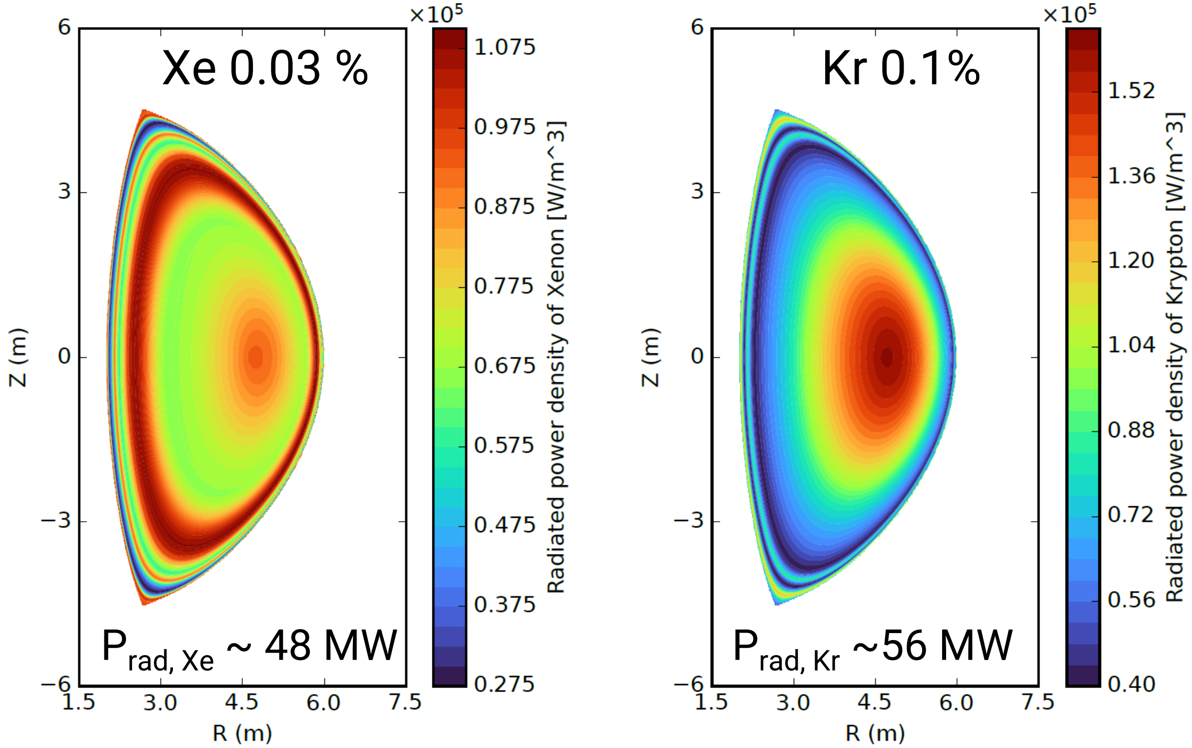
~15% density depletion w.r.t outer midplane

Some impurities radiate more at temperatures lower than STAR's core, leading to off-axis radiation

- STAR central temperature of 32 keV is past the peak of several cooling rates
  - If this effect can overcome the ~n_e^2 factor, radiation peaks near the edge, not core
- The implications of this are not yet self-consistently worked out
  - Could possibly be a good thing (keep core temperature high)



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



Conclusions

- The STAR project is investigating a spherical tokamak advanced reactor
- ECCD/ECH should be able to start-up and ramp-up the current and temperature of the STAR plasma
- ECCD or NBI should be able to drive the necessary auxiliary current for non-inductive steady state operation
- It remains to be seen whether ECH or NBI will be able to sustain the plasma temperature in steady state, vs. thermal transport
  - Investigation with predictive TRANSP continues
- The rotation level of STAR is not yet well known and this can affect the predicted transport, but shouldn't lead to radiation asymmetries
- Purposeful power radiation from noble gasses requires careful study to determine dilution and off-axis effects

Backup

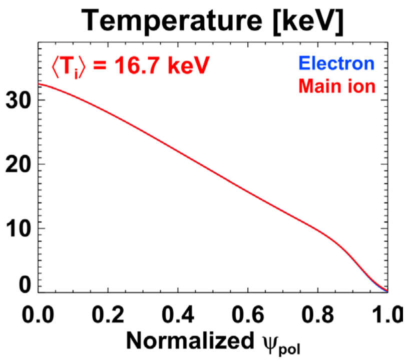
Dimensionless efficiencies

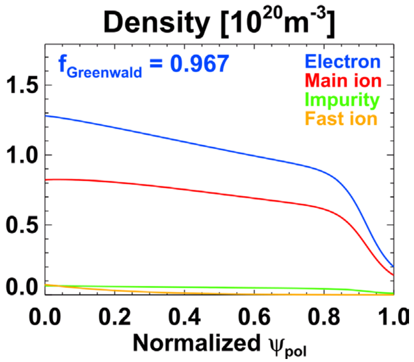
$$\eta_{CD} = I_{ec}[\mathrm{kA}]/P_{in}[\mathrm{MW}]$$

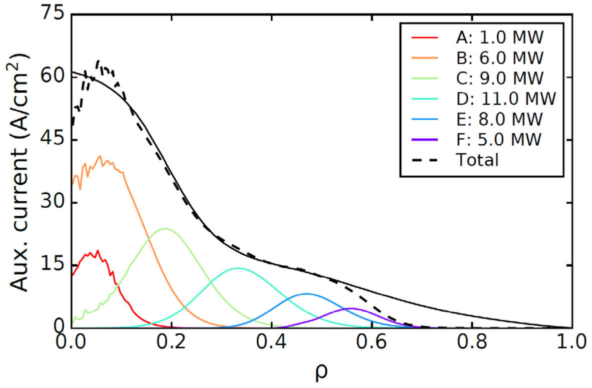
$$\gamma_{CD} = 10^{-3} n_e[10^{20}\mathrm{m}^{-3}] R_0[\mathrm{m}] \eta_{CD}$$

$$\zeta_{CD} = 32.7 \gamma_{CD}/T_e[\mathrm{keV}]$$

4 m

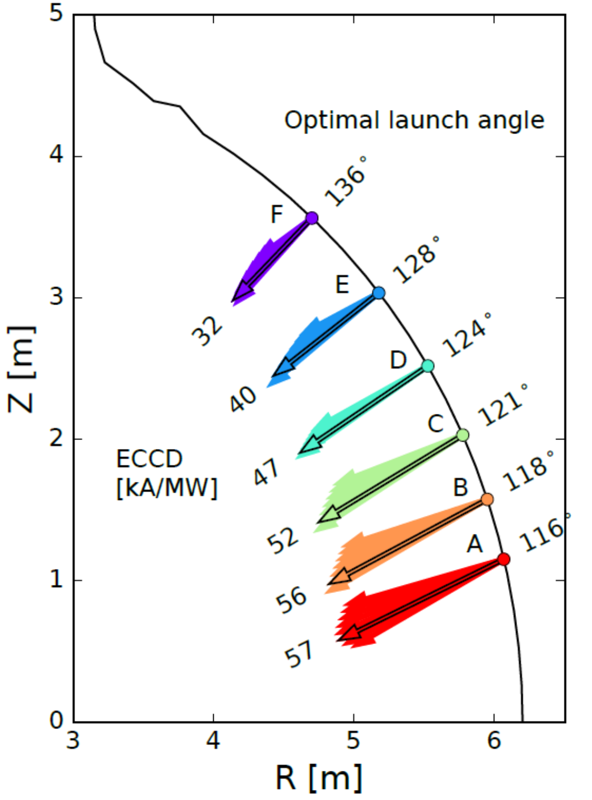






TORAY

Position	ρ_{max}	n_e (ρ_{max}) [10^{20} m^{-3}]	T_e (ρ_{max}) [keV]	η_{CD} [kA/MW]	γ_{CD}	ζ_{CD}
A	0.06	1.28	32.44	57	0.29	0.29
B	0.09	1.28	32.32	56	0.29	0.29
C	0.19	1.25	31.21	52	0.26	0.27
D	0.34	1.18	27.29	47	0.22	0.27
E	0.48	1.09	21.88	40	0.17	0.26
F	0.56	1.04	18.44	32	0.13	0.24



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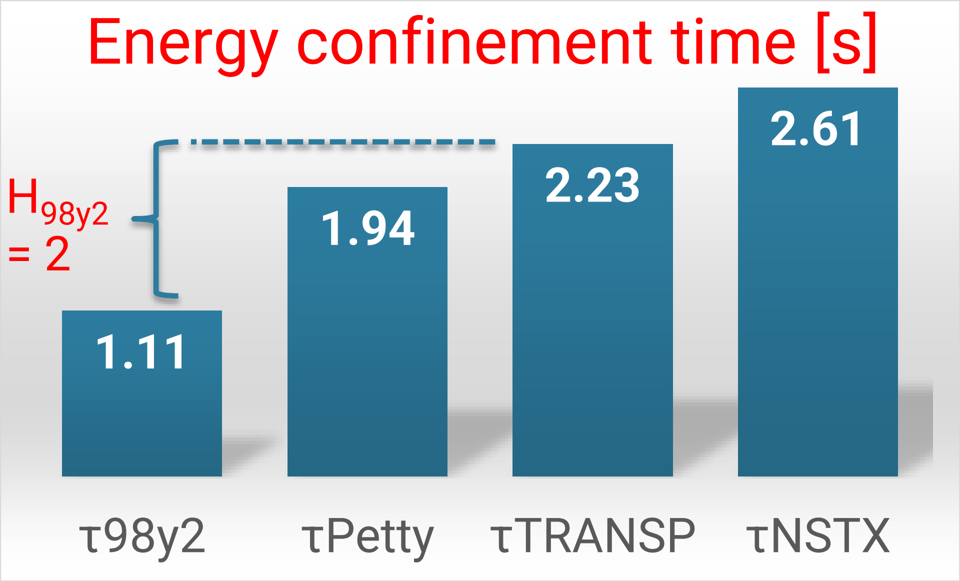
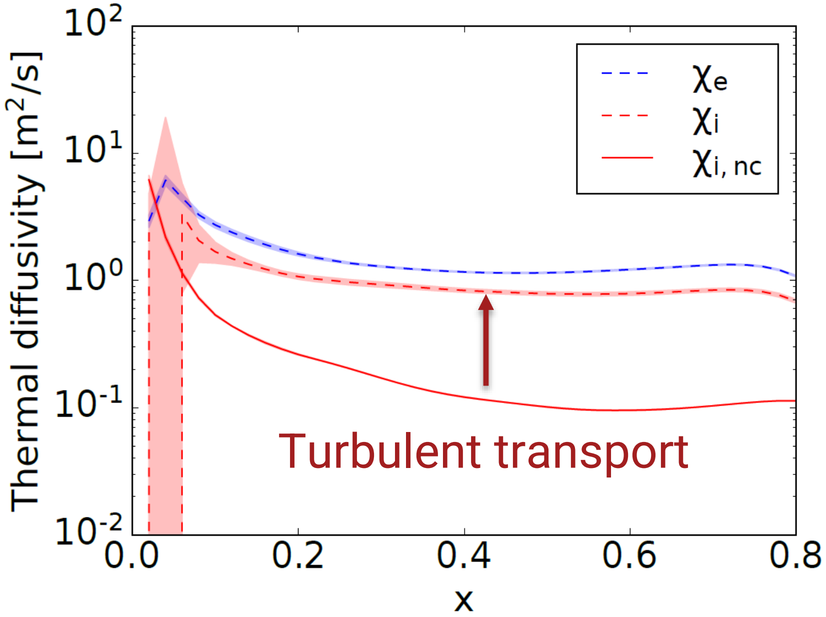




Implied TRANSP diffusivities for given heating and temperature profiles

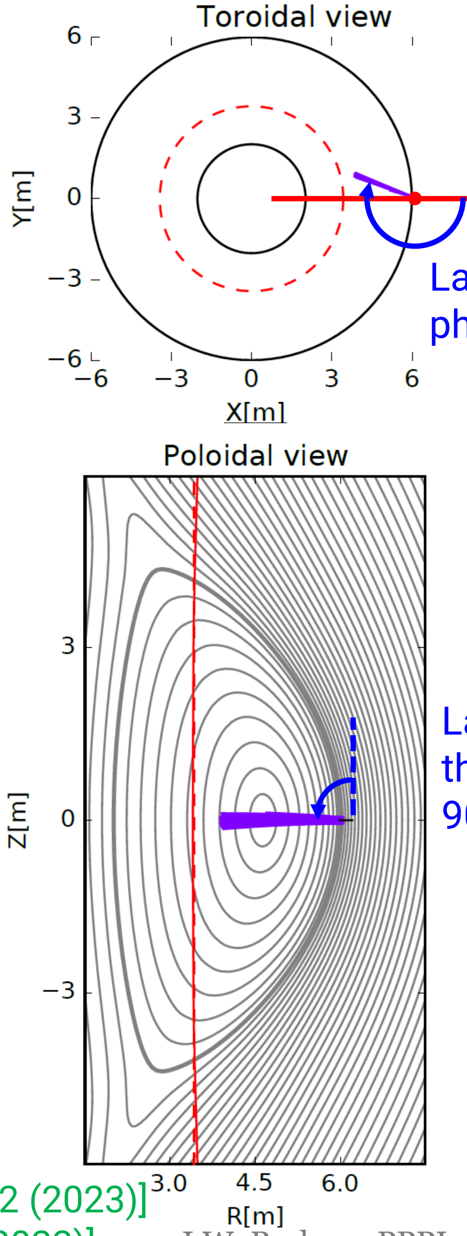
$$\tau_{\text{E-98y2}}[s] = 0.0562 \times I_P[MA]^{0.93} B_T[T]^{0.15} P[MW]^{-0.69} \bar{n}_e[10^{19}\ \text{m}^{-3}]^{0.41} M^{0.19} R[m]^{1.97} \epsilon^{0.58} \kappa^{0.78}$$

$$\tau_{E-Petty08}[s] = 0.052 \times I_P[MA]^{0.75} B_T[T]^{0.30} P[MW]^{-0.47} \bar{n}_e[10^{19}\ \text{m}^{-3}]^{0.32} M^{0.0} R[m]^{2.09} \epsilon^{0.84} \kappa^{0.88}$$

$$\tau_{\text{E-NSTX}}[s] = 0.095 I_P[MA]^{0.57} B_T[T]^{1.08} P[MW]^{-0.73} \bar{n}_e[10^{19}\ \text{m}^{-3}]^{0.44} M^{0.19} R[m]^{1.97} \epsilon^{0.58} \kappa^{0.78}$$

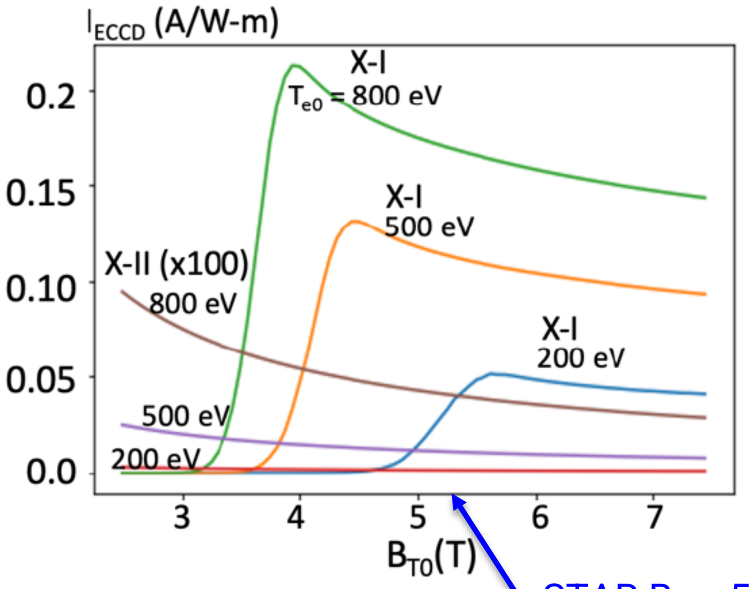
Efficient electron cyclotron current drive is possible with X-I at high B_T

- Non-inductive start-up/ramp-up is important for low-A STs
- At B_T = 5.2 T, 170 GHz, low T_e, X-I efficiency >> X-II
    - X-I ray always stays on the low-field-side of the cyclotron resonance, the Doppler interaction tends to occur for electrons moving in one direction



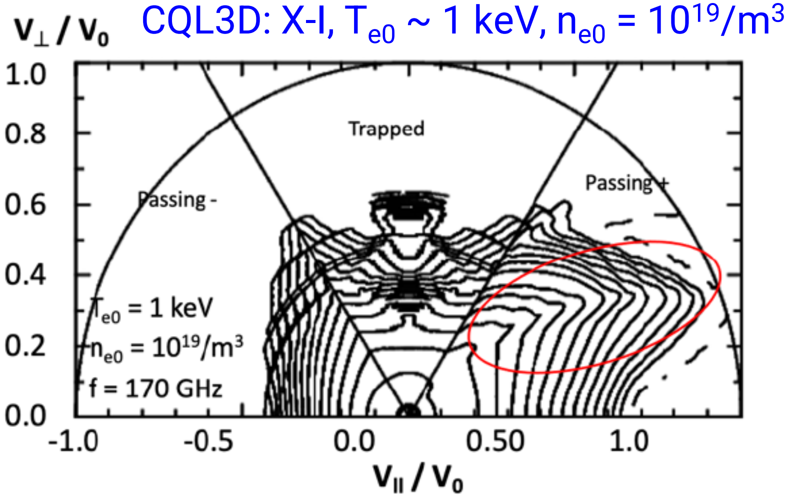
Launch phi = 200°

Launch theta = 90°



STAR B_T = 5.2 T

CQL3D: X-I, T_{e0} ~ 1 keV, n_{e0} = $10^{19}/m^3$



[M. Ono et al., IAEA FEC (2023) P/1 2238]
[M. Ono et al., AIP Conf. Proc. 2984, 110002 (2023)]
[M. Ono et al., Phys. Rev. E 106, L023201 (2022)]