NIMROD SPI Simulations of DIII-D Dual Injector Experiments

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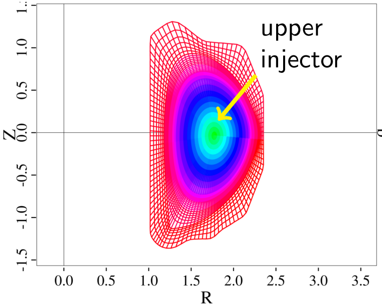
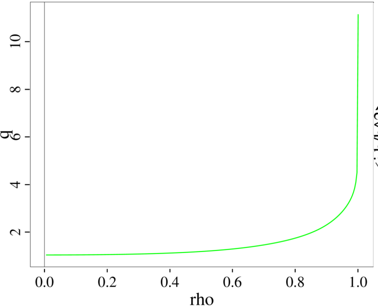
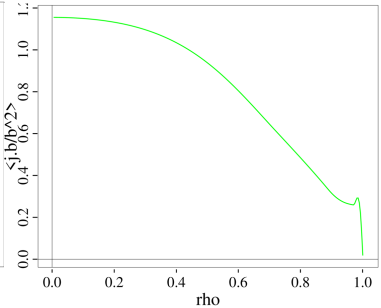
DIII-D 160606@02990ms[1], TE=0.7MJ, 1.28MA, q_{min}=1.05, q_0=1.11



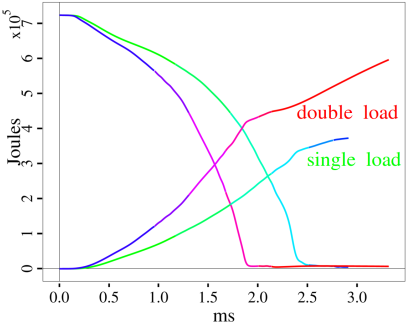




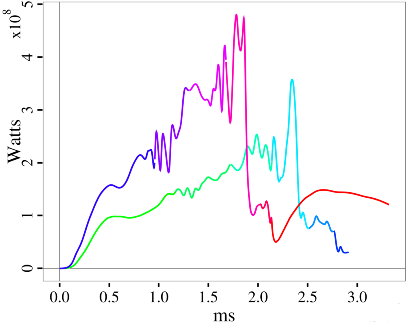
- 96x112 poly_degree=3 n=[0,21], Spitzer resistivity
- density diffusion: 3m^2/s, viscosity: 250.0m^2/s, $\chi_\perp$=0.2m^2/s, $\chi_\parallel$=1.0×10^9m^2/s
- single injector : 200 pure neon fragment, r_p=2.0mm, v=120m/s $\frac{\Delta v}{v}$=0.5, $\Delta\theta_{hw} = 20^\circ$
- nominal experimental inventory $\simeq 20\times$larger $\rightarrow$ reduced inventory for higher assimilation
- deposition: r_d=3.0cm, $d\phi = 0.3 \times 2\pi$
- dual injector separated by 120°, identical fragment parameters

[1]D. Shiraki, PoP 23, 062516 (2016)

Single Injector Double Load Improves Quench Efficiency



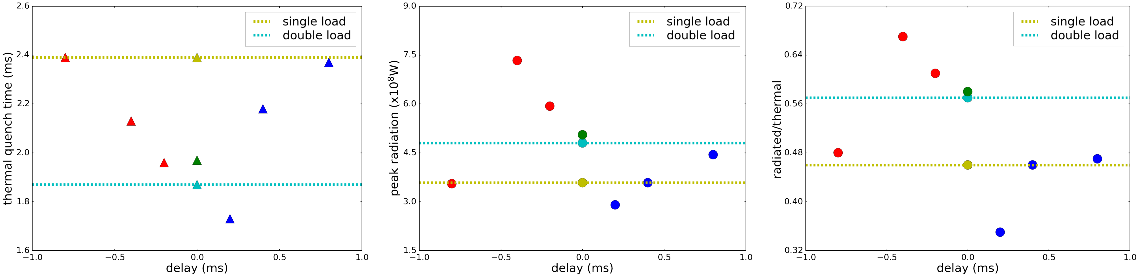
Thermal and Radiated Energy



Radiated Power

- double load = $2\times$single load : 400 r_p=2.0mm pure neon fragments
  - faster thermal quench : 2.39ms $\rightarrow$ 1.87ms
  - higher radiation fraction : 46% $\rightarrow$ 57%
  - higher peak radiation : 3.6×10^8W $\rightarrow$ 4.8×10^8W

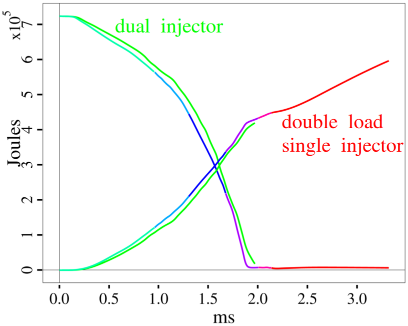
DIII-D Dual Injector Scan Shows Surprising Asymmetry!



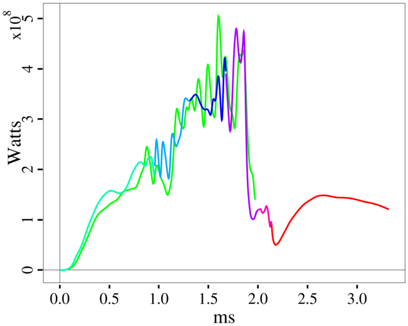
thermal quench time   radiated power   radiated/thermal energy

- thermal quench time symmetric about dt=0.0ms - "V" structure to results
  - bounded by single and double load single injectors
- radiated power and radiation fraction → linear between dt=[-0.4,+0.4]ms
  - exceed double load single injectors
- simultaneous dt=0.0ms similar to single injector double load
- *dt=+0.2ms numeric termination*

Single Injector Double Load and Dual Injector(dt=0) Surprisingly Similar



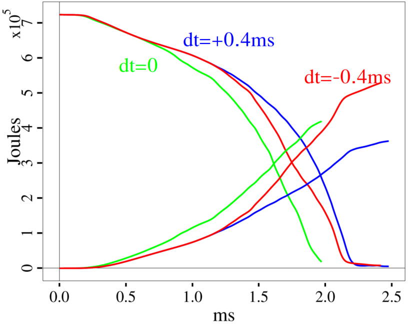
Thermal and Radiated Energy



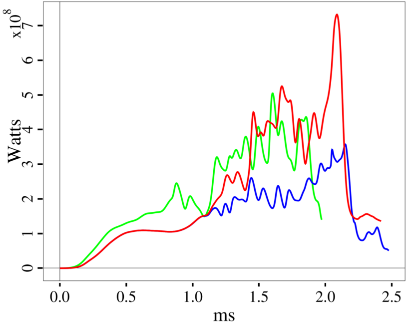
Total Radiated Power

- simultaneous dual injector thermal energy and radiation look similar to double load
- can be inferred that toroidal radiation peaking is reduced
- *comparison of current spike behavior might be interesting but academic*

Dual Injector: dt=-0.4ms and dt=+0.4ms - Clear Asymmetry



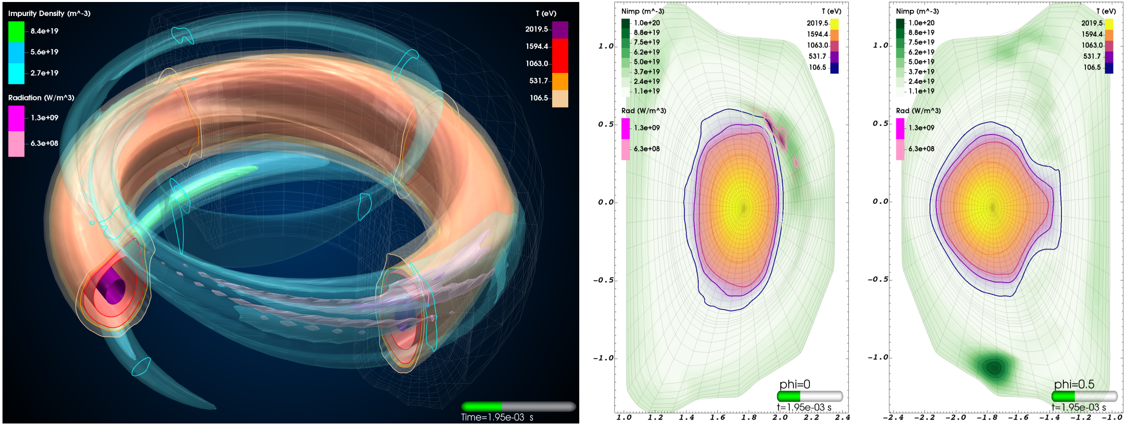
Thermal and Radiated Energy



Total Radiated Power

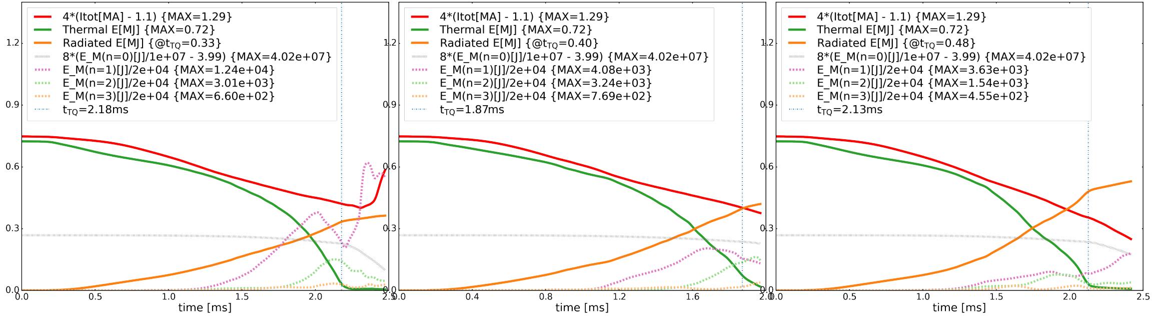
- dt=+0.4ms and dt=-0.4ms identical until t≃1.1ms
- @t≃1.1ms dt=-0.4ms plasma intercepts second fragment plume
  - radiation fraction increases from 46% to 58% to 67%
  - radiation peak increases from 3.6×10^8W to 5.1×10^8W to 7.3×10^8W
  - thermal quench time about the same 2.18ms and 2.13ms, a little later than 1.97ms

Magnetic Helicity Cause of Asymmetry



- single injector visualization shows helical distortion of quenching plasma
- ablated impurities flow along field lines with some radial drift
- cross sections at injector plane and $+180^\circ$ show motion/distortion of flux surfaces
- plasma motion/distortion may intercept or avoid lagging fragments

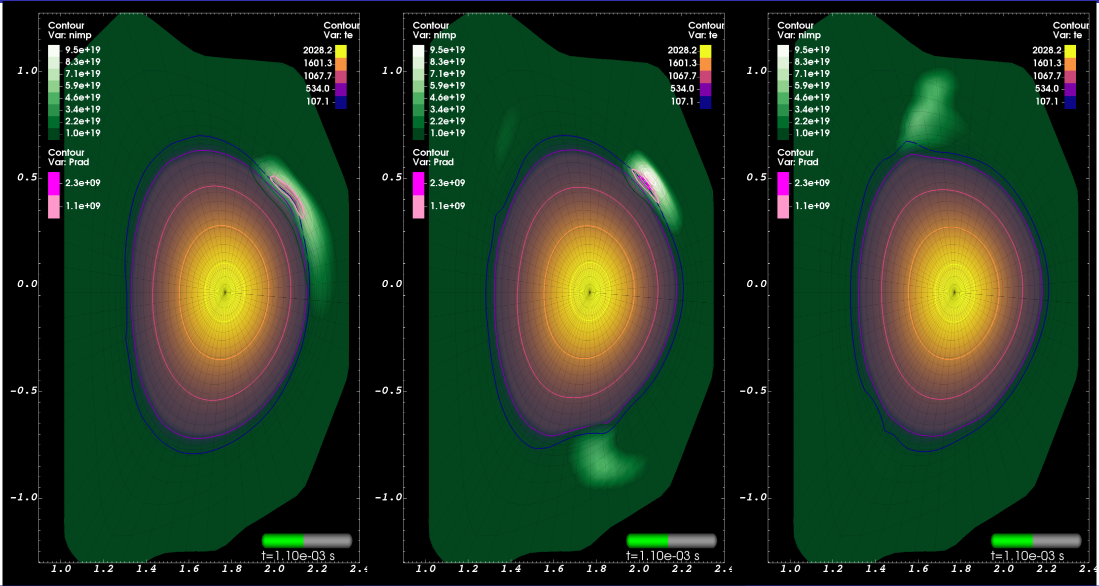
Improved Thermal Quench Correlates with Reduction in MHD



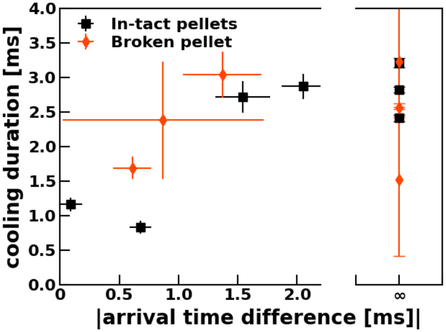
dt=+0.4ms | dt=0 | dt=-0.4ms

- plasma current, thermal energy, radiated energy, and magnetic energy for n=[0,1,2,3]
- increase in radiated energy correlates with decrease in magnetic mode energy of n=[1,2,3]
  - reduced mode activity reduces stochasticity
  - “optimal” interaction with dt=-0.4ms second plume
- not correlated with total ablation : dt=+0.4ms 18%, dt=0.ms 26%, dt=-0.4ms 21%

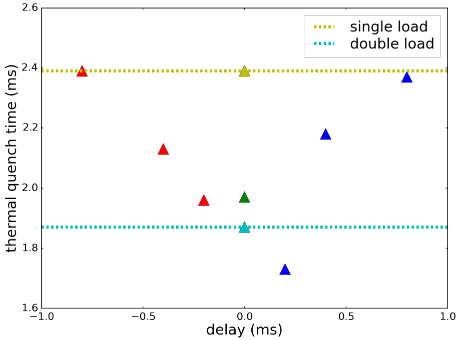
Dual Injector delay dt=0 and dt=-0.4ms cross section and 3D animation



Comparison of Thermal Quench Time Shows expected "V" Structure



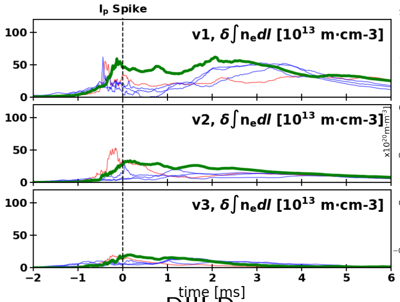
DIII-D



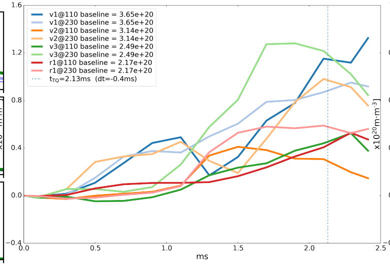
NIMROD

- similar "V" structure for thermal quench time vs injector delay
  - experiment is a deeper "V" but more variability in fragment parameters
- narrow window for acceptable delay between injectors

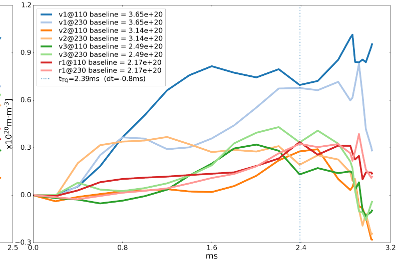
Line Integrated Density



DIII-D



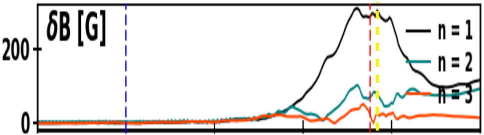
dt=-0.4ms



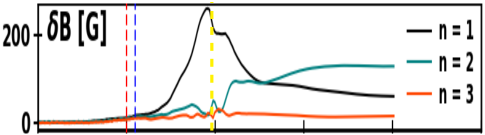
dt=-0.8ms

- $\sim \times$2-3 larger in DIII-D experiment
  - tracking down discrepancy
- relative location of diagnostic matters
  - impurities are localized
- experimental signal persists beyond quench?

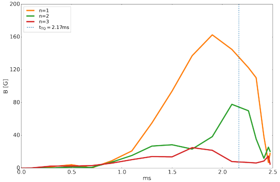
Midplane Magnetic Probes - Fair Agreement Through Thermal Quench



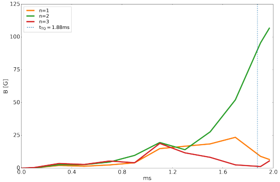
184414 (single)



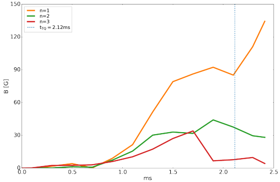
184421 (dual)



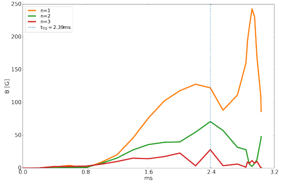
dt=+0.4ms



dt=0

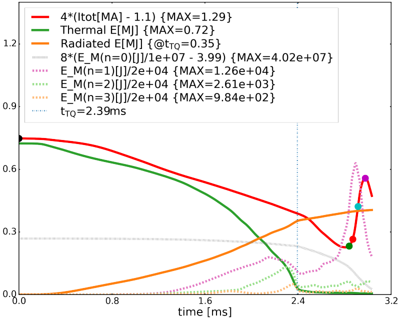


dt=-0.4ms

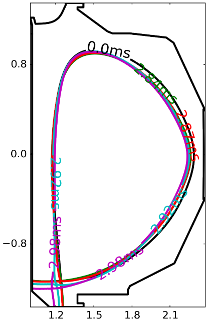


dt=-0.8ms

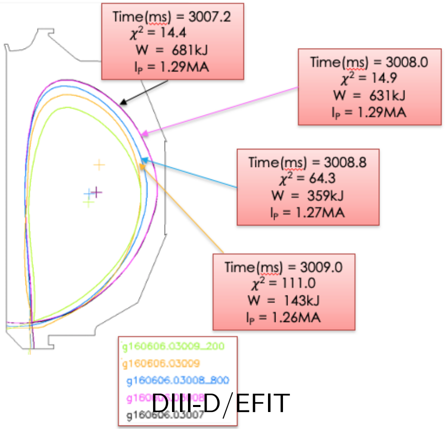
- many similar features between experiment and synthetic midplane probe n=[1,2,3]
- experiment is $\sim 2\times$larger
- n=1 current spike is not as prominent in experiment



dt=-0.8ms



NIMROD



DIII-D/EFIT

- NIMROD n=0 last closed flux surface compared to DIII-D/EFIT
- shrinkage in experiment during thermal quench not observed in simulations
- NIMROD x-point deflects during current spike[2]

[2] V. A. Izzo, PoP 28, 082502 (2021)

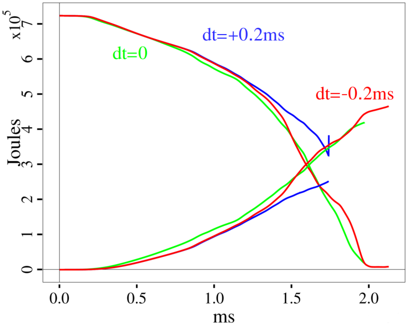
Summary and Conclusions

- surprising asymmetry observed in quench scan of delay in dual injector SPI simulations
  - best thermal quench is NOT simultaneous injectors
- helical motion/distortion of plasma may intercept or avoid second fragment plume
- "optimal" interaction of plasma and fragments at dt=-0.4ms reduces mode activity
  - reduced mode activity reduces stochasticity
  - improves thermal quench efficiency → more radiated loss
  - not due to more ablation
- comparison to experiment shows
  - similar "V" structure in thermal quench time vs delay
  - similar mode activity
  - comparable densities
- understanding MHD important to optimizing SPI DMS
- absent flux shrinkage may indicate missing physics
- working on T-dep thermal conduction simulations
- ITER simulations in progress

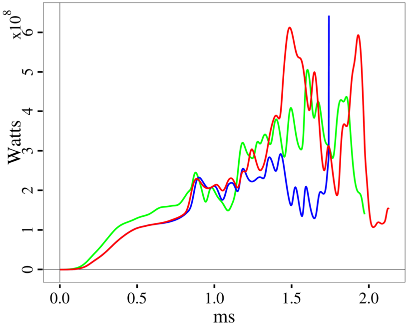
DIII-D Dual Injector - Summary of Injector Delays

	thermal quench time τ_{TQ}(ms)	peak radiation $\times 10^8$(W)	radiated/thermal energy
single load	2.39	3.58	0.46
double load	1.87	4.80	0.57
dt=+0.8ms	2.37	4.44	0.47
dt=+0.4ms	2.18	3.58	0.46
dt=+0.2ms	1.73	2.90	0.35
dt= 0.0ms	1.97	5.05	0.58
dt=-0.2ms	1.96	5.93	0.61
dt=-0.4ms	2.13	7.33	0.67
dt=-0.8ms	2.39	3.55	0.48

Dual Injector: dt=±0.2ms - Incomplete Comparison



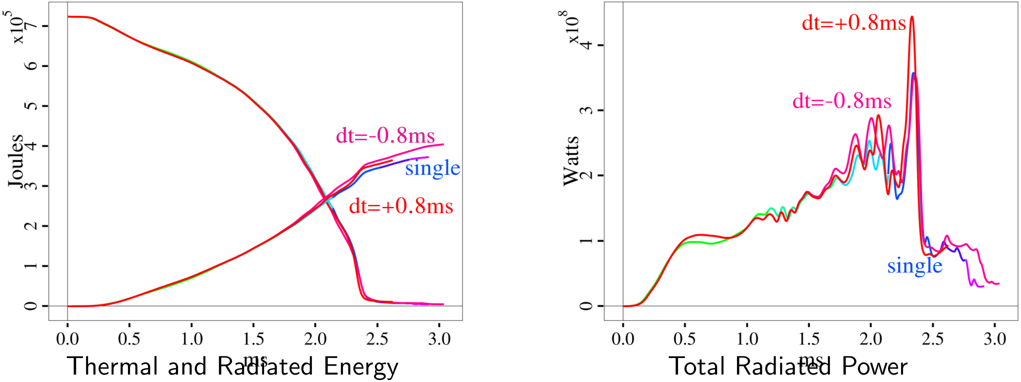
Thermal and Radiated Energy



Total Radiated Power

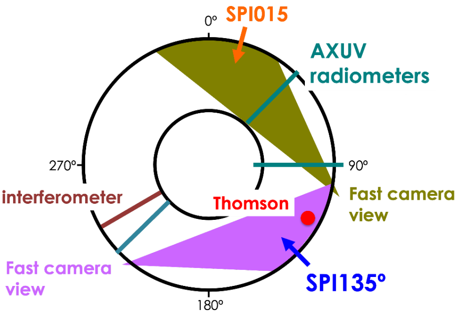
- radiation shows early difference between dt=0.0ms and [dt=-0.2ms,dt=+0.2ms]
  - dt=+0.2ms and dt=-0.2ms begin similarly
- difference in dt=+0.2ms and dt=-0.2ms begins at t$\simeq$ 1.2ms
- dt=+0.2ms early numeric termination - incomplete comparison

Dual Injector: dt=±0.8ms Reverts to Single Injector Single Load

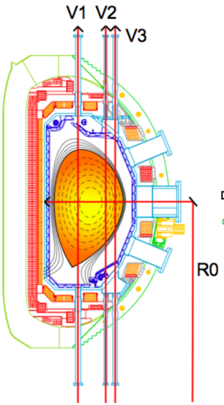


- dt±0.8ms show similar behavior to single injector
- delay too large for second plume to make much impact
  - some late interaction observed, e.g. larger peak for dt=+0.8ms

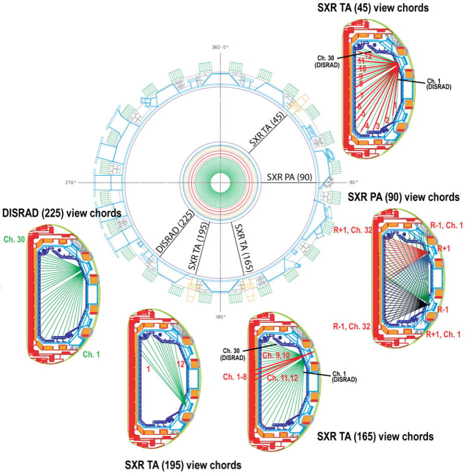
Diagnostic Layout



injectors and diagnostics

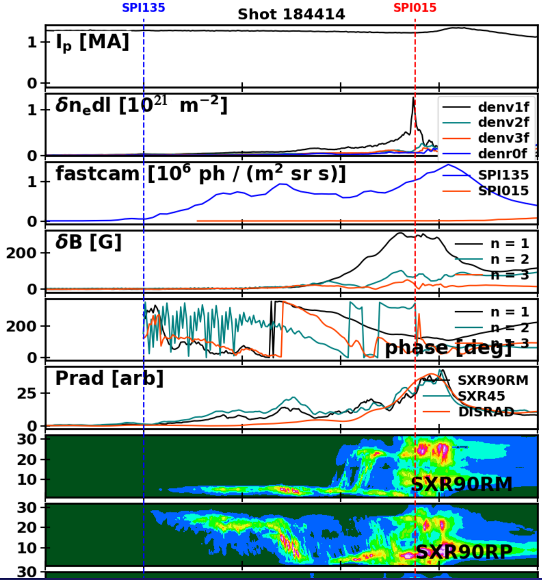


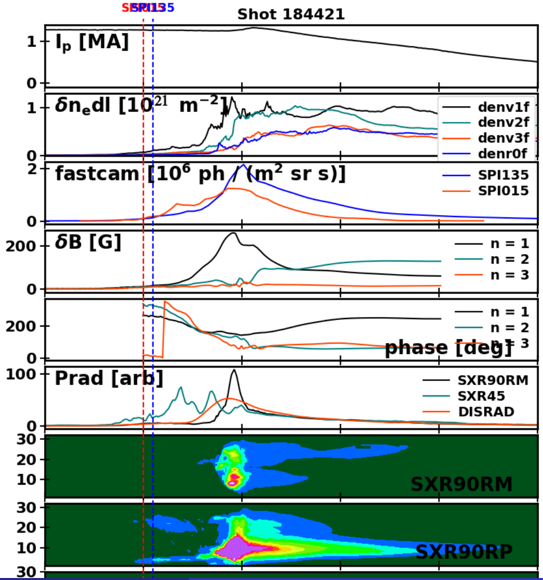
multichannel C02 interferometer



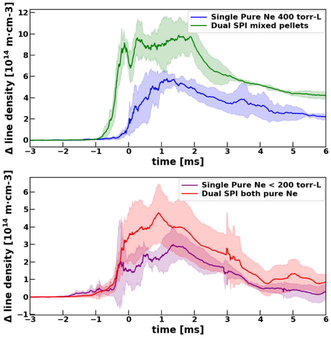
soft x-ray arrays

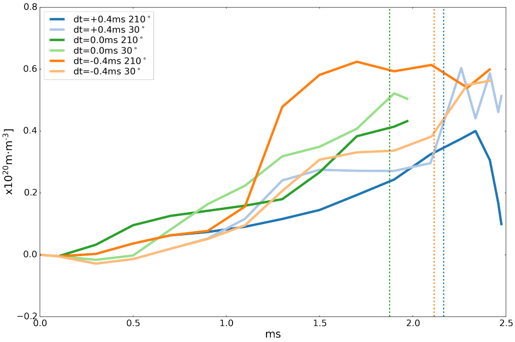
Comparison to Experiment: 184414 (single) and 184421 (dual)





Line Integrated Density - Missing Density? (baseline$\simeq 2\times10^{20}$m·m^3)





- DIII-D more than 10×larger than NIMROD
- implies DIII-D plasma density increasing by several factors (×2-5)!!
  - continues to increase after thermal quench
  - *additional source in DIII-D* - carbon from the inner wall?
    - impact on thermal and current quench?