NSTX-U

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Fusion Energy Sciences

Core mode identification effort

Lucas Morton

Rob La Haye, Jon Menard, Luis Delgado-Aparicio, Kevin Tritz, Ron Bell

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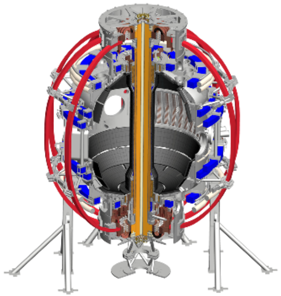
ORAU

GENERAL ATOMICS



Mode identification is prerequisite for stability analysis

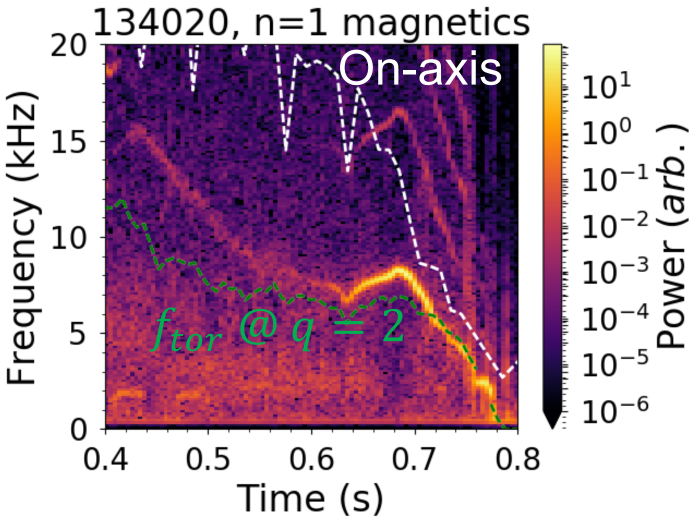
- Goal: study tearing stability
  - Classical / linear
  - Neoclassical / nonlinear
- Method: fit modified Rutherford equation to $w(t)$
  - Assumptions: single-mode, pure tearing parity
  - $w \propto \sqrt{\tilde{B}_{n=1}}$, calibrate width from profile diagnostic flat-spots
- Potential issues:
  - Possibility for multiple coupled modes
  - Need to know mode structure is tearing-parity

Mode identification is not trivial on NSTX

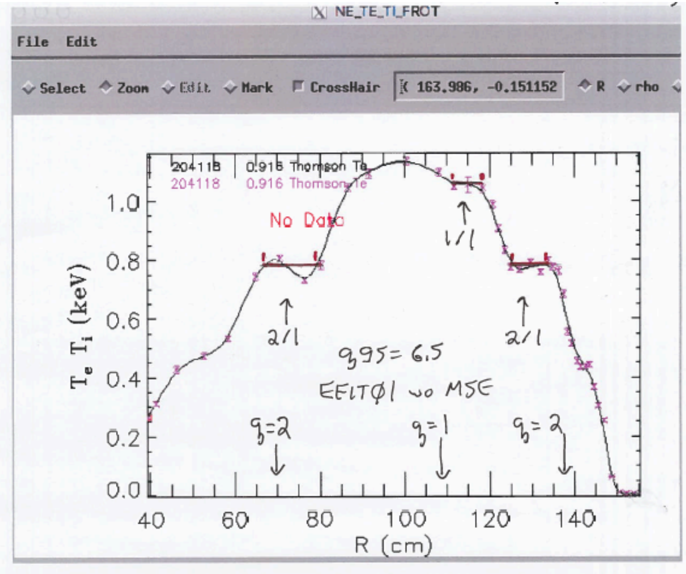
- Existing 3D magnetics not sufficient
  - E. Fredrickson, priv. comm.
- No ECE
- TS T_e has low sampling rate ~ 60 Hz
- CHERS T_i phase-averaged ~ 100 Hz
- Neither TS, CHERS can tell $m = 0$ from $m = 2$
  - *Can* distinguish even/odd m
- Island width measurements limited by radial resolution

Best efforts so far: combine everything

- Poloidal mode number:
  - $q(R) + \omega(R) + f_{n=1}$



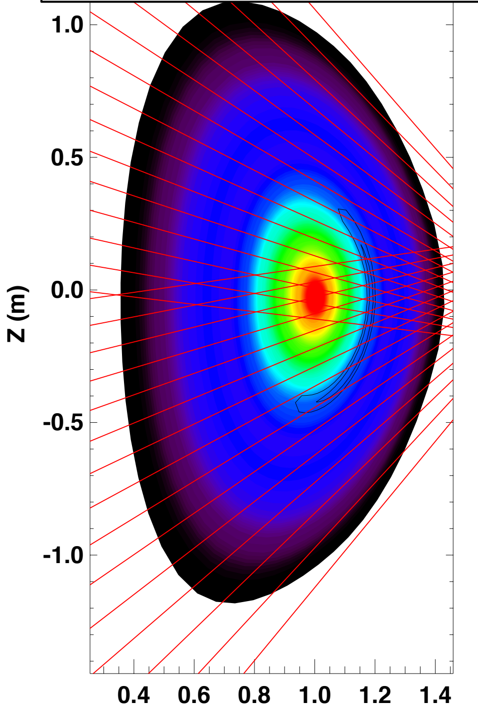
- Island width:
  - T_i, T_e flat-spots (+ magnetic mode phase…)



USXR could offer improvements

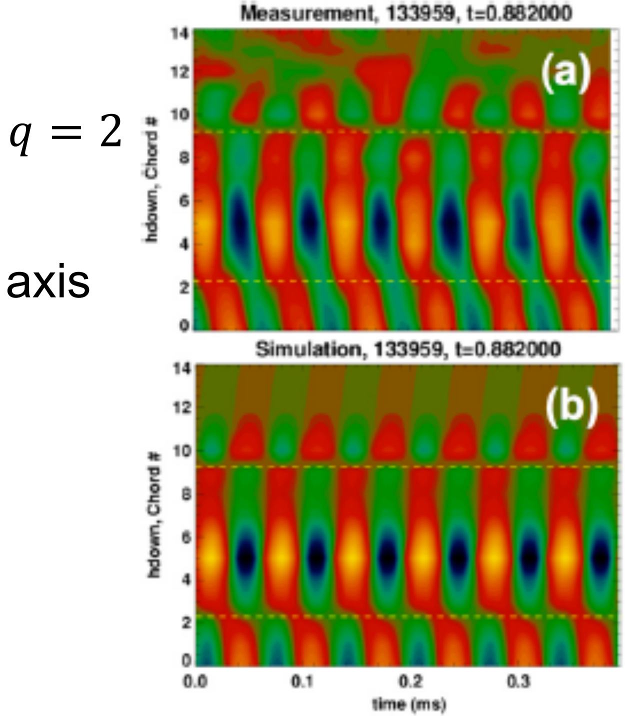
- High time resolution
  - *Can* distinguish $m = 0$ from (rotating) $m = 2$
  - Can provide mode phase @ TS times
- Moderate spatial resolution
  - Line-integrated
  - Mainly odd/even
- Requires more effort to interpret
  - Inversion / geometric effects
  - Emissivity physics?
- Questions:
  - Can we recover perturbation strength accurately?
  - Can we distinguish coupled/pure, kink/tearing?

USXR viewing geometry



Previous work shows evidence of mixed modes

- Phase flip @ $q = 2$ → $m = 2$
- Odd parity @ core → odd m
- Maybe $m = 3$ also?
  - $\tilde{B}_{n=1}$ may not be pure $m = 2$!



S. P. Gerhardt *et al*, *Nucl. Fusion* **51,** 033004 (2011)

Outline

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- SXRFIT model
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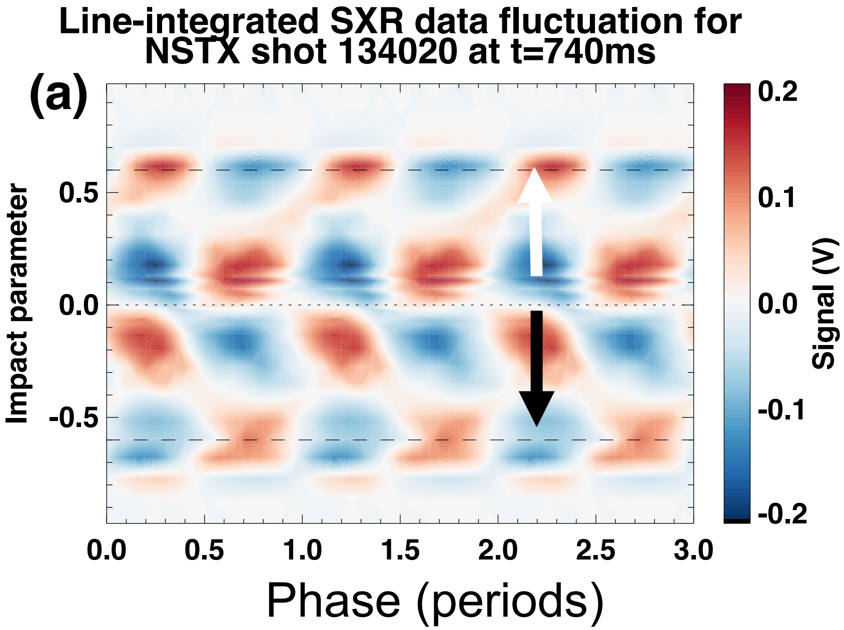
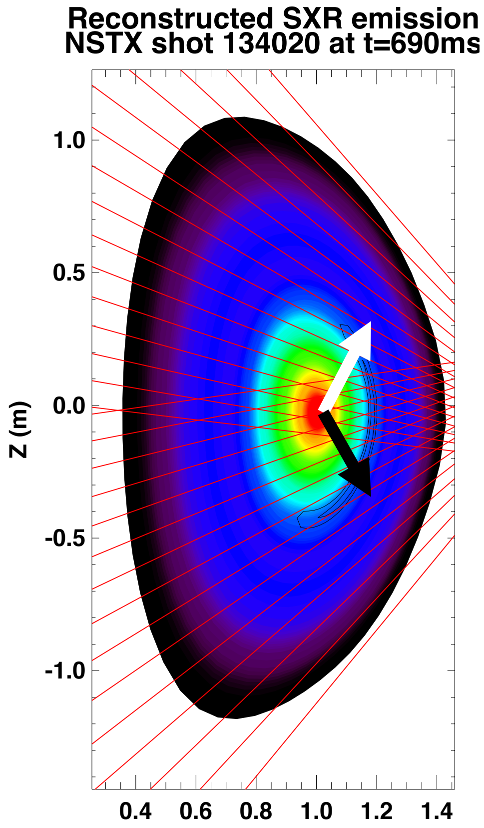
Both USXR arrays combined using impact parameter

- More intuitive/informative view
- Chords from two arrays interleaved





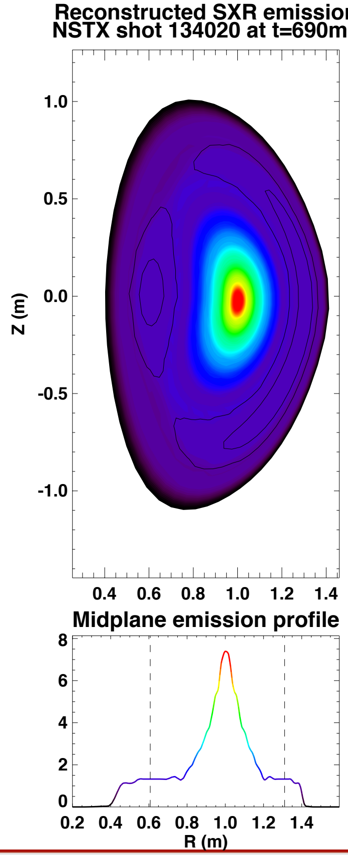
SXRFIT* model developed by Menard

*J. Menard *et al*, *Nucl. Fusion* **45,** 539 (2005)

- Need assumptions to make inversion unique
  - 3D ← 2D ill-posed problem
  - Use physics knowledge to reduce solution space
  - Maintain linearity of problem → fast to solve
- Assume ψ single-helicity (2D): $\psi(\rho, \theta, \phi) = \psi(\rho, m\theta - n\phi)$
  - Ensure existence of flux surfaces
- Assume emissivity is a (1D) flux surface function $\epsilon(\psi)$
  - Treat island interior as special case
  - Minimizes number of free parameters

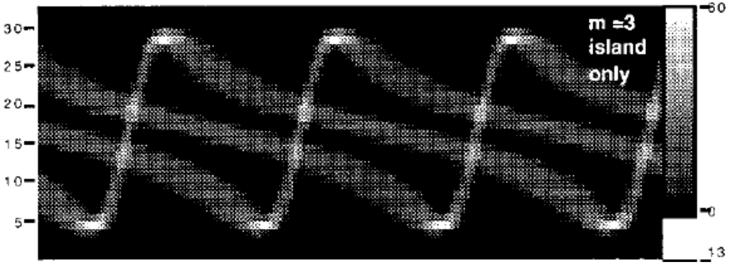
SXRFIT reconstructs 1D $\epsilon(\psi)$ profile

- $\epsilon(\psi) \approx \sum_i c_i b_i(\psi)$ basis function model
- Find sensitivity matrix S by integrating contribution of each basis to each chord
  - As function of phase
- Model for observation: $S \cdot \boldsymbol{c} = \boldsymbol{m}$
- Invert model to find best-fit coefficients $\boldsymbol{c}$
  - No emissivity physics
  - Axisymmetric emissivity is strong constraint
  - Fluctuation follows from this (self-consistently!)



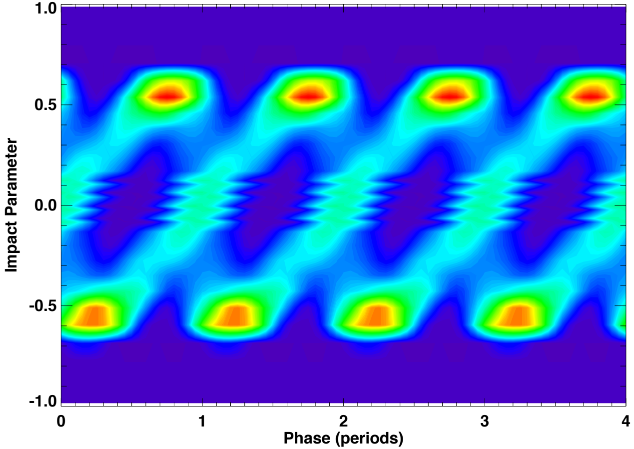
Mode helicities clear in impact/phase space

- Emission from *within* island separatrix

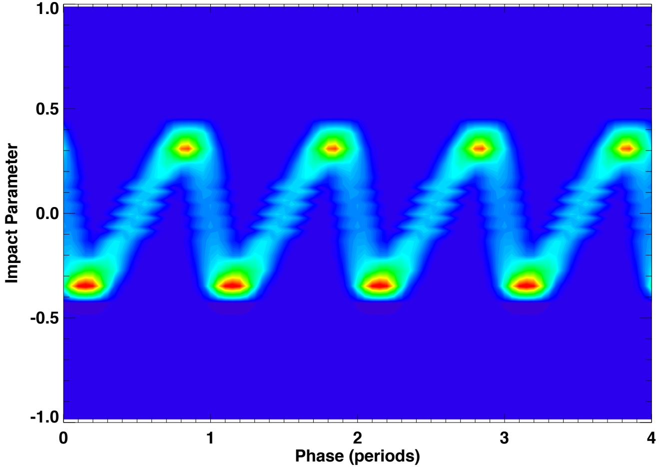


Stutman *et al*,
RSI **70**, 572 (1999)

$m = 2$



$m = 1$

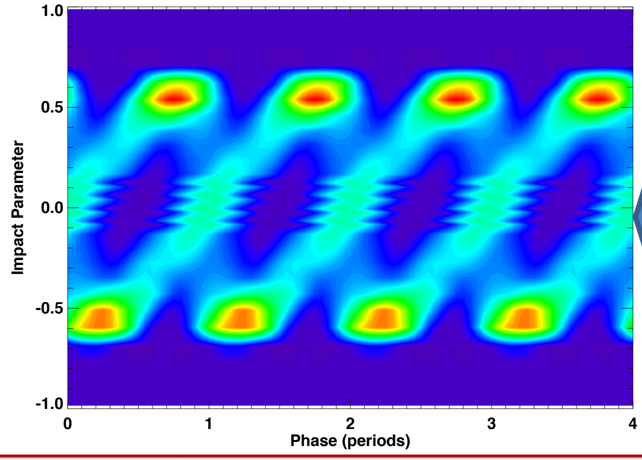


Mode helicities clear in impact/phase space

- Emission from *within* island separatrix
- Toroidicity effects noticeable

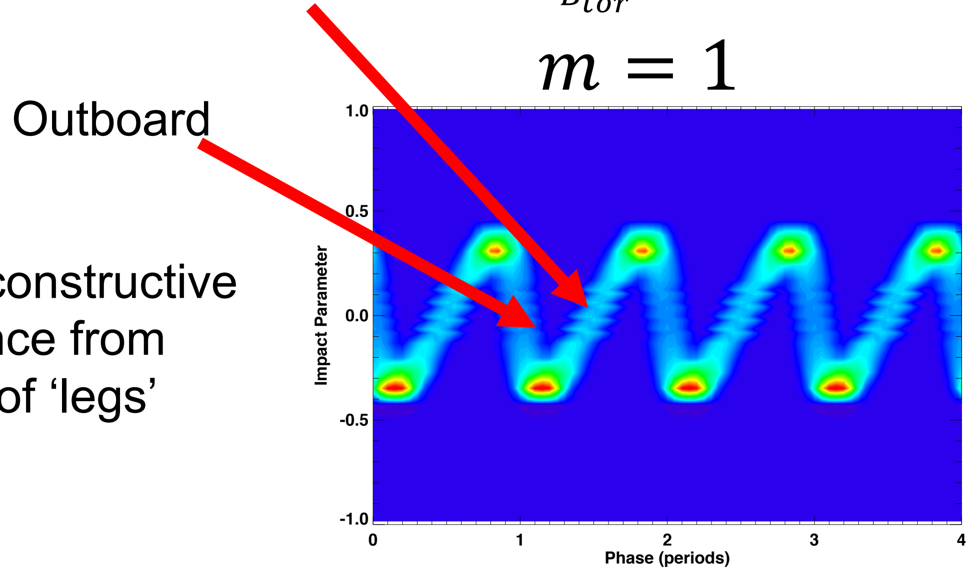
Inboard (shallower slope ← smaller $\frac{B_{pol}}{B_{tor}}$ ← larger B_{tor})

$m = 2$



On-axis constructive interference from crossing of 'legs'

$m = 1$

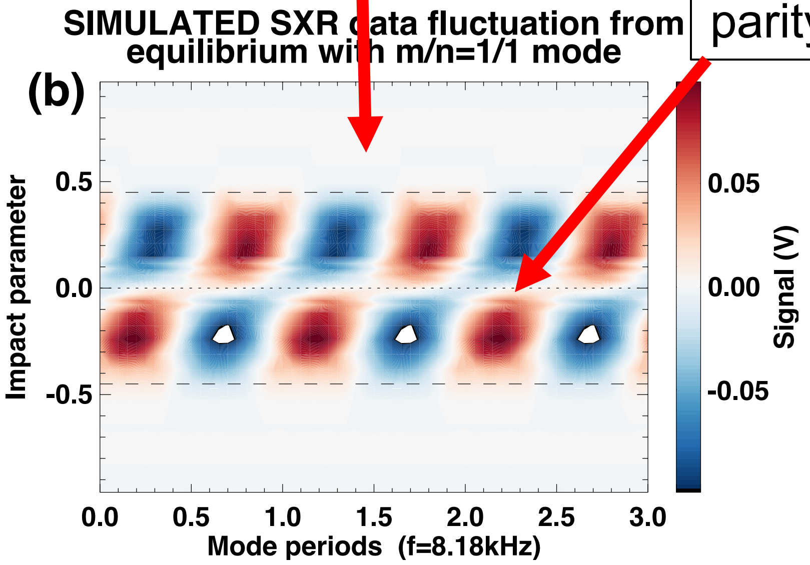


Fluctuations from full model are distinctive

$m = 1$ kink

Nothing outside rational surface

Odd core parity

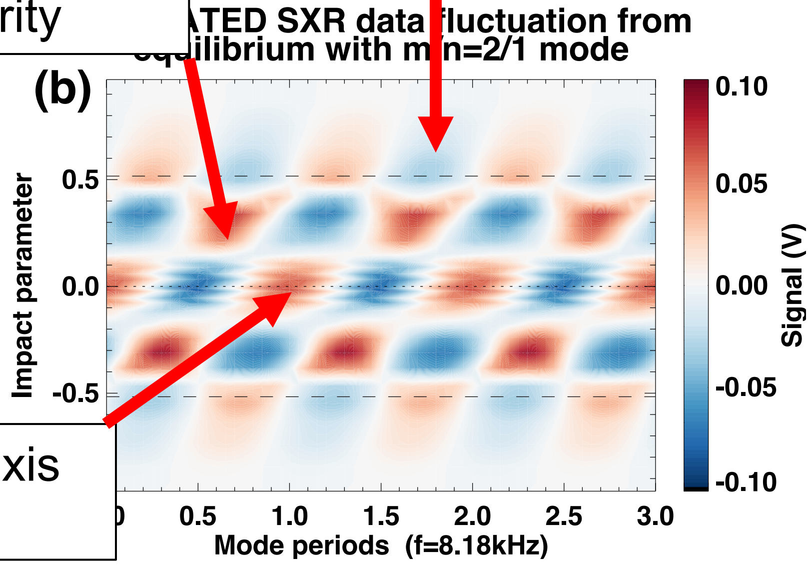


$m = 2$ tearing

Even core parity

Phase flip outside rational surface

On-axis node



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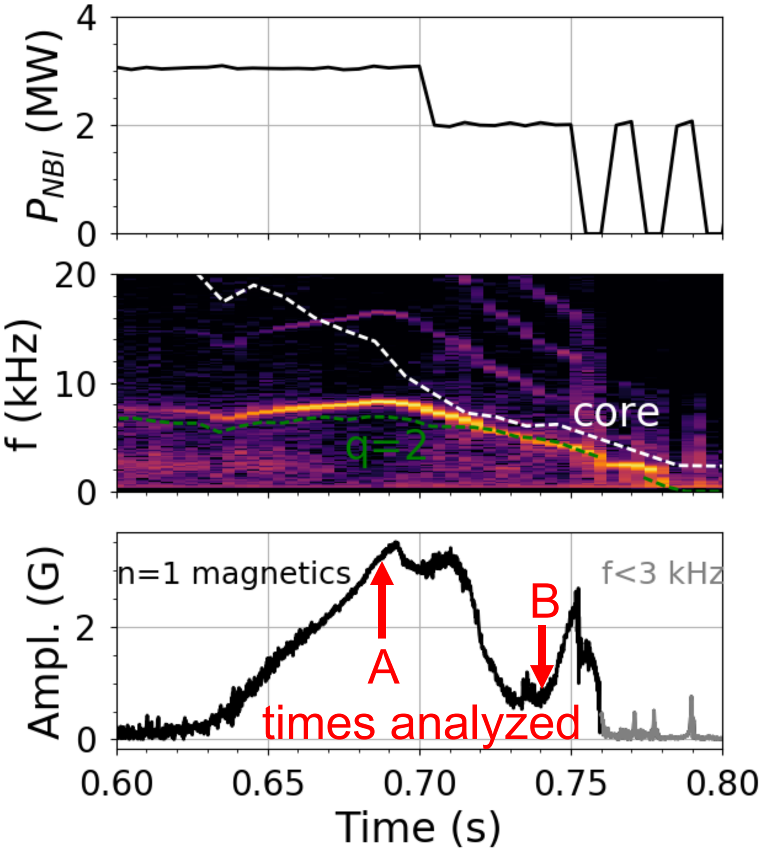
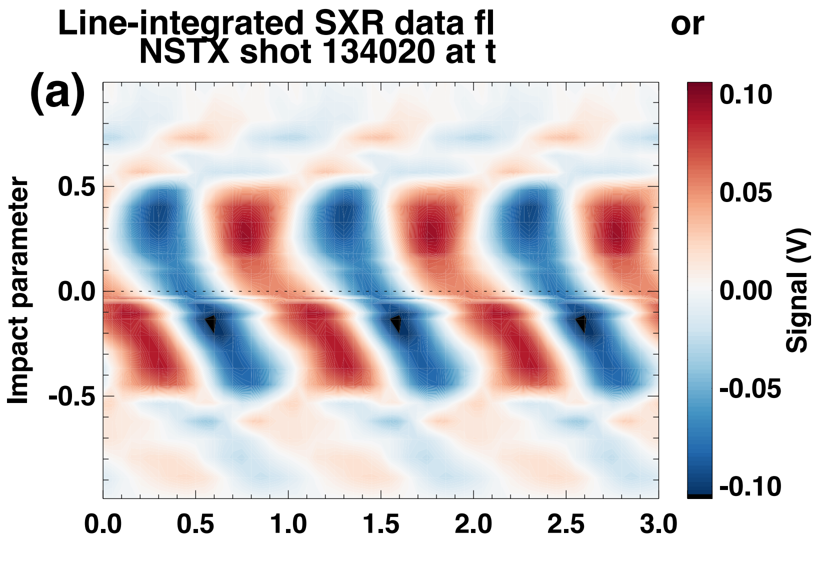
Shot 134020: test case

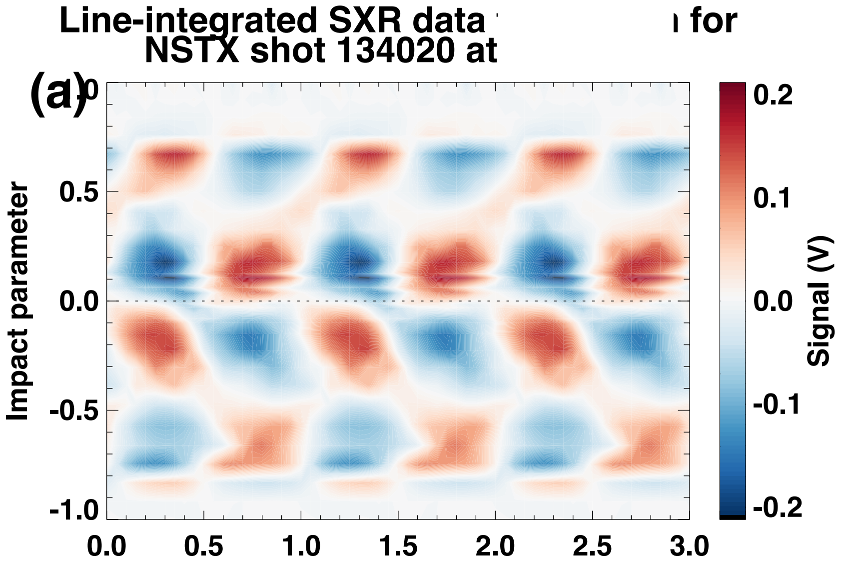
- High-β H-mode
- $n = 1$ onsets, saturates
  - Mode rotates near $q = 2$ freq.
- NBI step-down
  - Core, $q = 2$ rotation converged
- Mode decays, but stops
- Mode rebounds
  - Different poloidal/radial structure?



Pop quiz: guess the mode



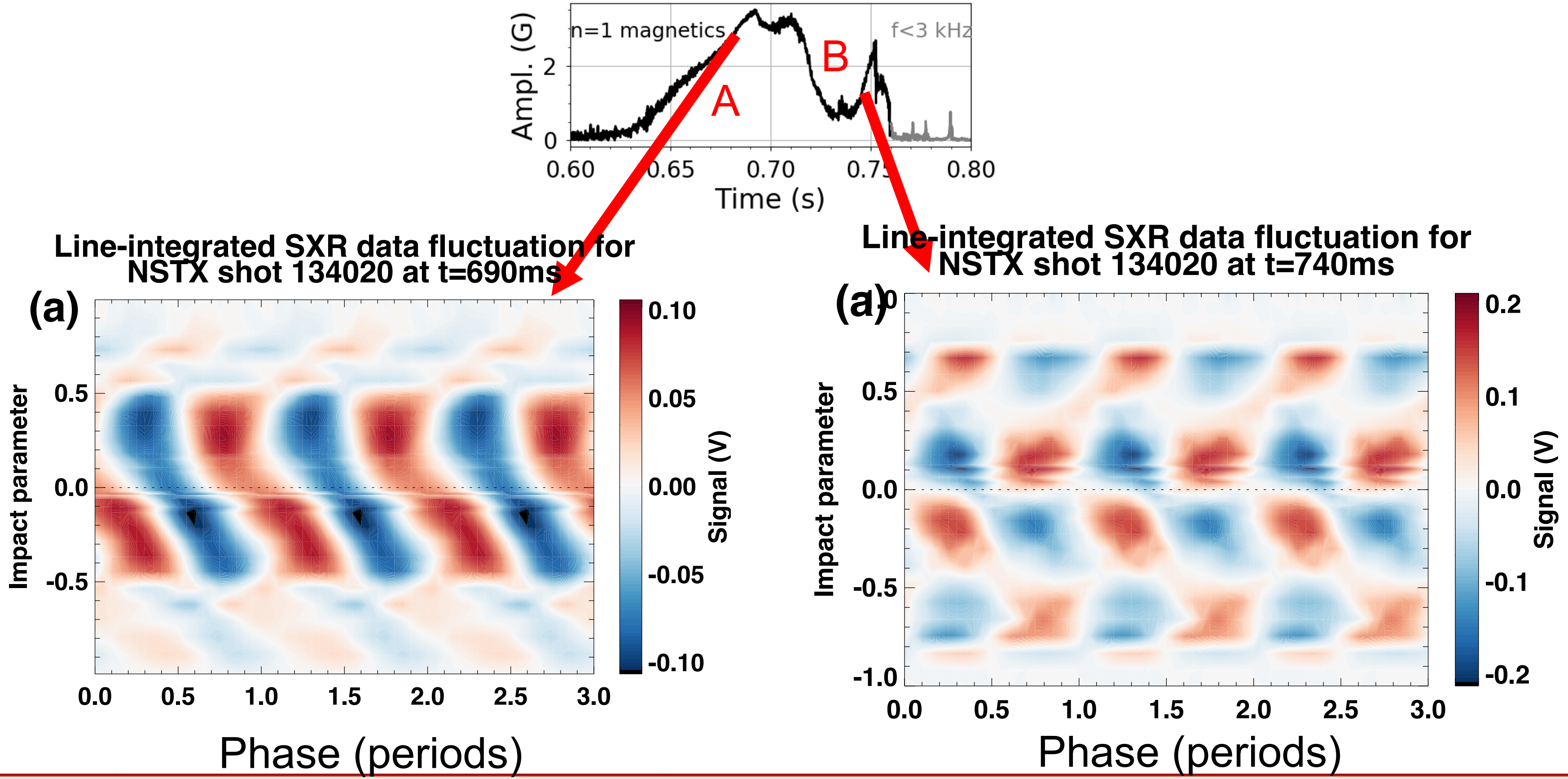
Phase (periods)



Phase (periods)

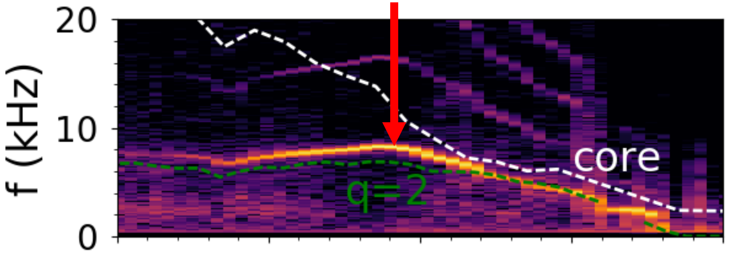
Ready?

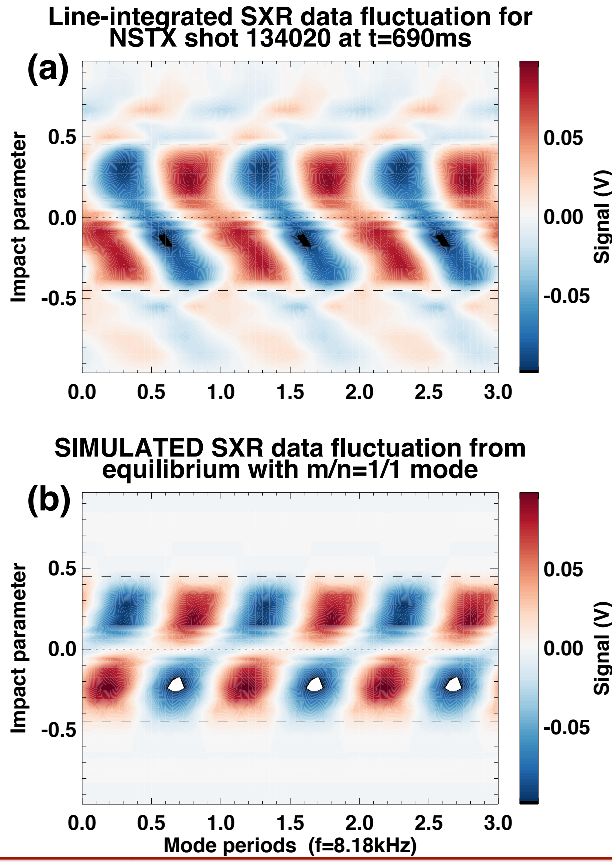
Shot 134020: revealed



$t = 690\text{ ms}$: predominantly $m = 1$ kink?

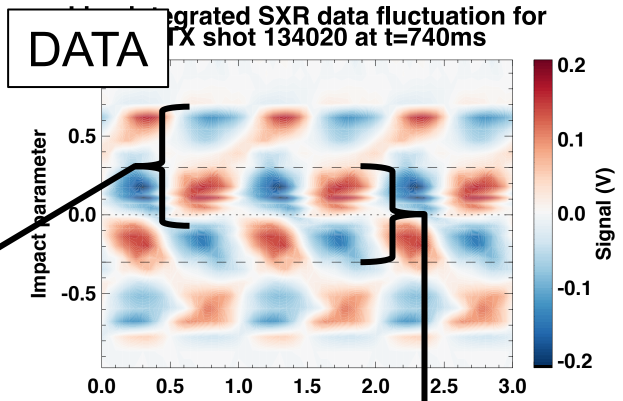
- Everything *except* USXR indicates $m = 2$ tearing mode at this time
- Possible weak $m = 2$ tearing part
  - But coupled to strong $m = 1$ core kink?
- USXR structure rotating at $f_{q=2}$
  - Doesn't jive with strong coupling to core

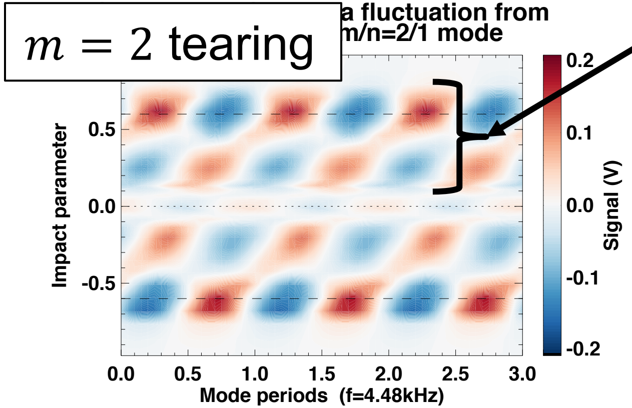


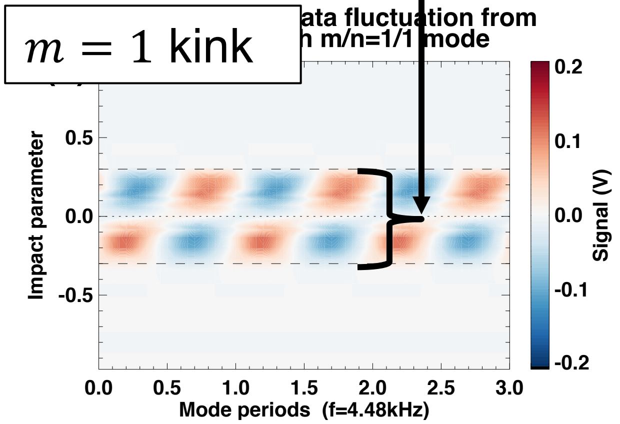


$t = 740$ ms: coupled 2/1+1/1?

- Core consistent with $m = 1$
- Outer region more like $m = 2$ tearing
- Mode coupling permitted by rotation flattening?
  - Unlike $t = 690$ ms







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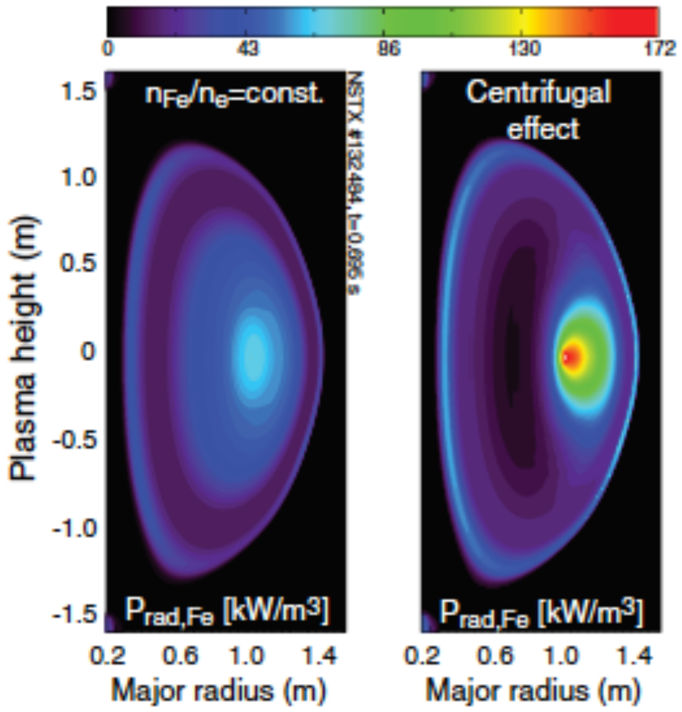
Centrifugal impurity asymmetry may be significant

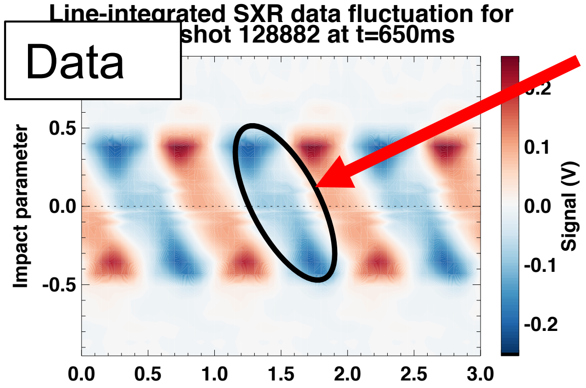
- Centrifugal force slings 'heavy' species outboard
  - Wesson, *Nuc. Fus.* **37**, 577 (1997):
  - $n_j(R) = n_{j,0} \exp\left(\frac{{}^{1}/{}_{2} m_j \omega^2 (R^2 - R_0^2) - e Z_j \phi(R)}{T_j}\right)$
- Can be large in NSTX
  - Large impurity Mach number

Delgado-Aparicio *et al*, *RSI* **85,** 11D859 (2014)

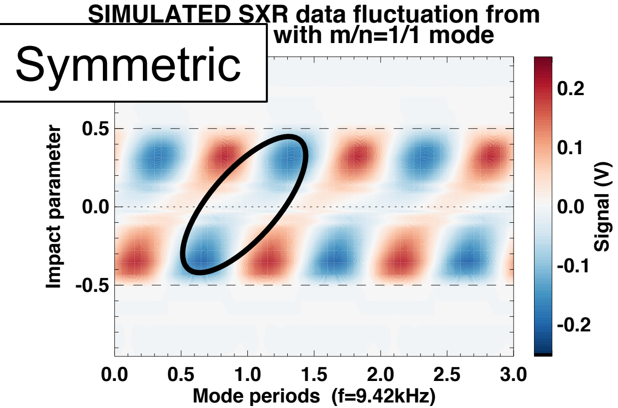


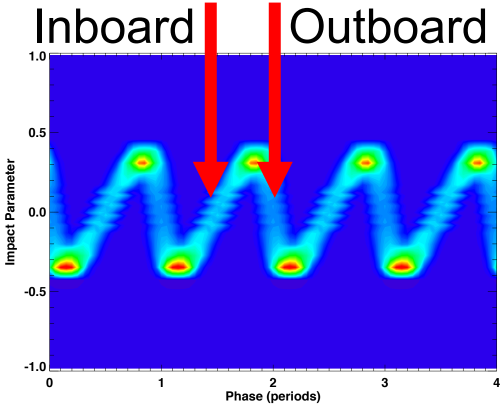
Centrifugal asymmetry solves slope discrepancy

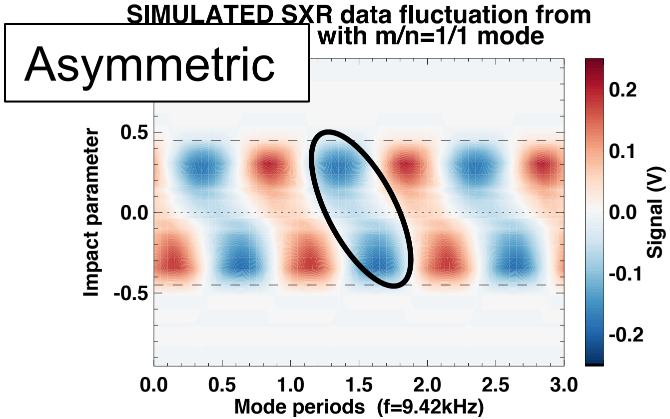
- Ad-hoc R^4 asymmetry
- Modeled mode:
  - $m/n = 1/1$
  - $\rho_s = 0.45 - 0.5$



Outboard 'leg' stronger in data







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Conclusions

- Centrifugal asymmetry fixes core slope discrepancy
  - Emphasizes outboard ‘leg’ of mode
- Coupled 2/1 + 1/1 mode indicated in some cases
  - Unsurprising given prior work by Menard, Gerhardt
- Surprising discrepancy in mode structure in other cases
  - Profile diagnostics + EFIT → $m = 2$ tearing
  - USXR signature → $m = 1$???

More work is needed

- Need to go beyond helical-symmetry approximation
  - Multiple poloidal mode numbers
    - Validity of modified Rutherford equation uncertain here
  - Centrifugal impurity effect
- Ideas for the future
  - Integrate more diagnostics to SXRFIT
    - TS T_e (mostly accomplished)
    - CHERS T_i profiles
  - Incorporate emissivity physics (including asymmetry)
    - Let impurity profiles be free parameters
  - Ghost surface method for multi-mode 'flux surfaces'

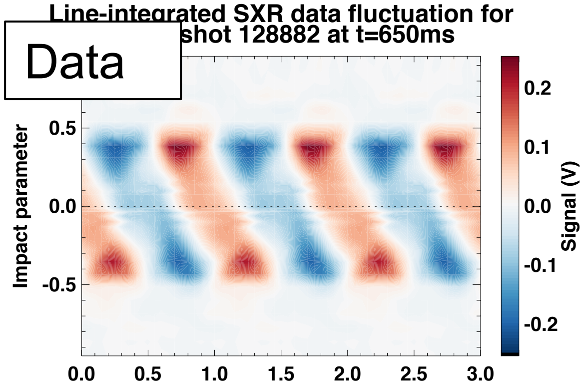
Back-up slides

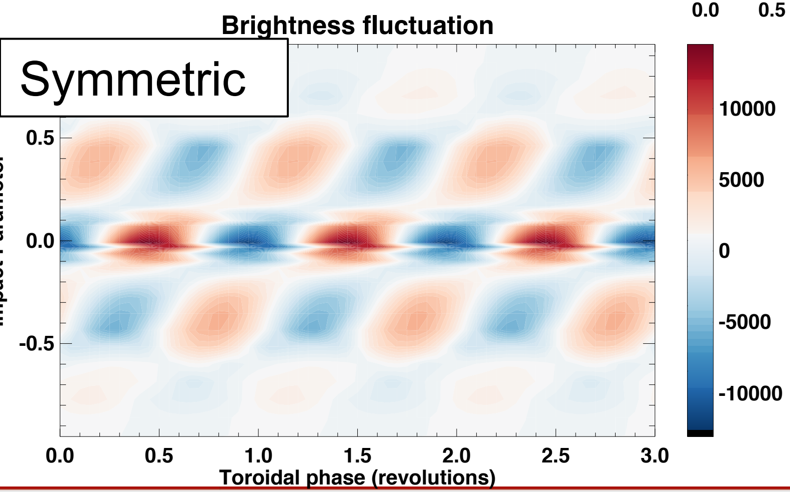
Recent improvements to SXRFIT

- *Non-negative* least squares solver
  - Previously discarding negative values returned
- Profile smoothness constraint
  - Hi-res basis functions w/o pathology
- Option to weight mean, fluctuations independently
- Option to use M3D-C1 perturbed flux
- Ad-hoc model for centrifugal impurity asymmetry
  - Full model in the works

Full centrifugal model applied to $m = 2$

- Using centrifugal physics
- Ad-hoc fluctuation model
  - $\delta\epsilon \propto \epsilon_0 \cdot \delta\psi/\psi_0$





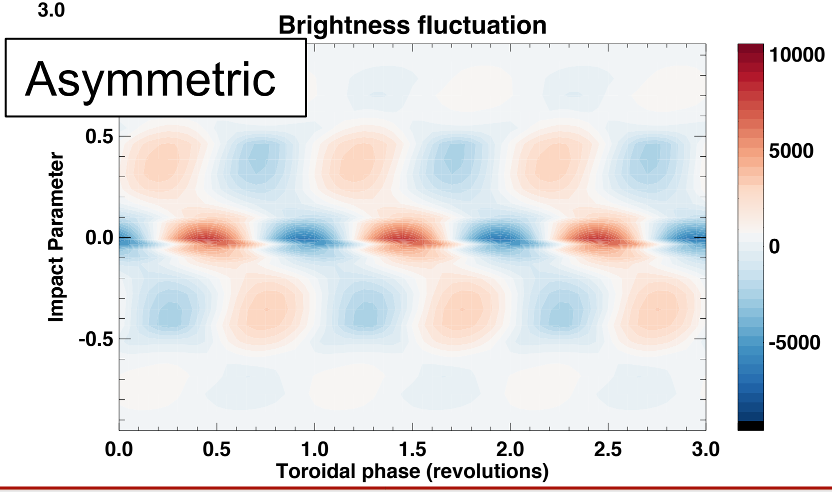
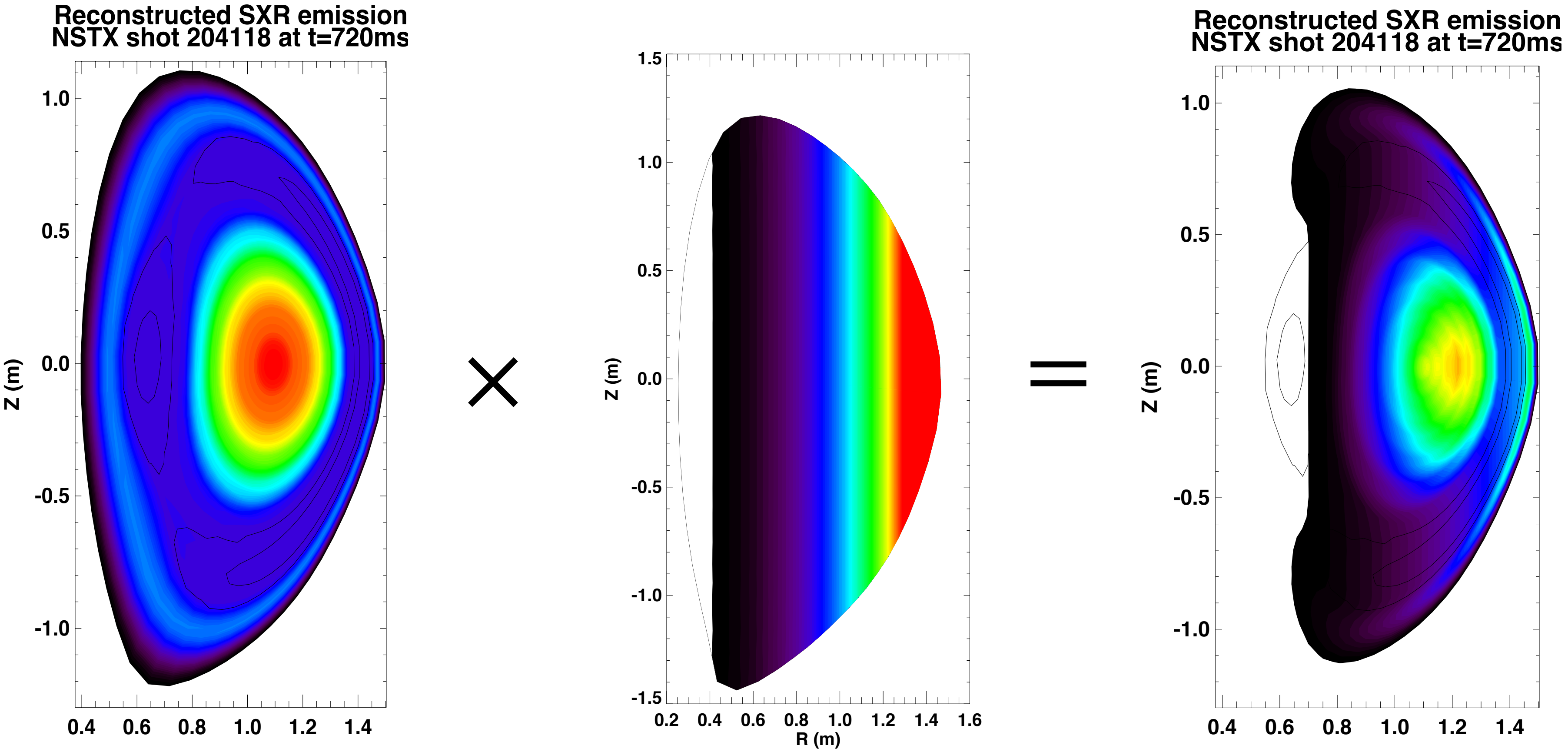
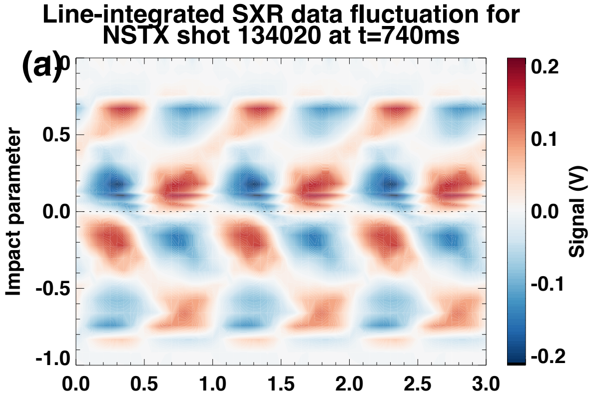


Illustration of R^4 asymmetry

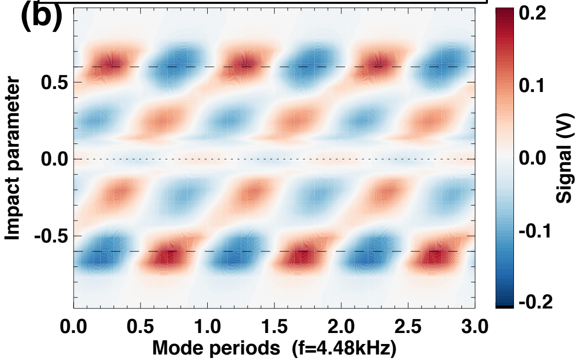


$m = 1$ tearing mode at $q = 2$?

- Shot 134020, $t = 740$ ms



$m = 2$ tearing



$m = 1$ tearing + asym.