NSTX-U

MAST-U

NSTX/NSTX-U Theory, Modeling and Analysis Results
&
Overview of New MAST Physics in Anticipation of First Results from MAST Upgrade

IAEA FEC, Oct. 23, 2018

J.E. Menard for S.M. Kaye (PPPL), J. Harrison (CCFE) and the NSTX-U and MAST-U Teams

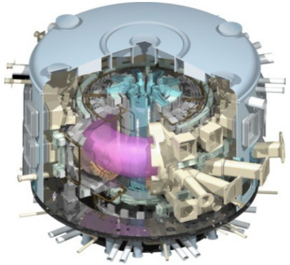
PPPL PRINCETON PLASMA PHYSICS LABORATORY

CCFE CULHAM CENTRE FOR FUSION ENERGY

PRINCETON UNIVERSITY

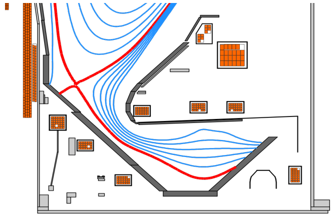
Missions of NSTX(-U) and MAST(-U)

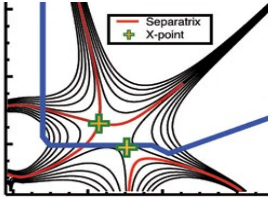
- Exploit unique Spherical Tokamak (ST) parameter regimes to advance predictive capability - for ITER and beyond
- Develop solutions for plasma-material interface (PMI)
- Explore ST physics towards reactor relevant regimes (e.g., Fusion Nuclear Science Facility and Pilot Plant)



ITER

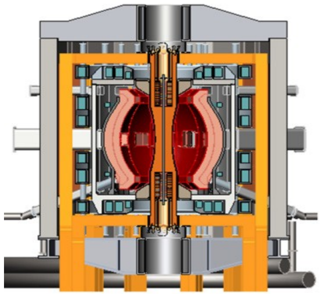
Super-X

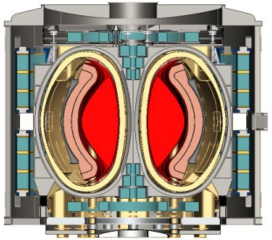




Snowflake/X

ST-FNSF / Pilot-Plant





NSTX(-U) and MAST address urgent issues for fusion science, ITER and next-step devices

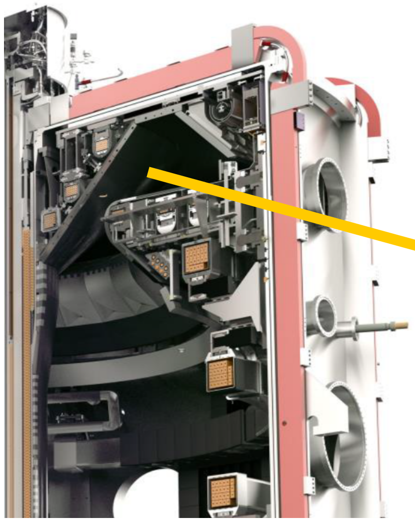
- Spherical Tokamaks (STs) can investigate turbulence over an extended range in β (tens %)
  - Electrostatic and electromagnetic effects
- STs Energetic Particle (EP) physics spans phase space expected in Burning Plasmas
  - $v_{fast}/v_{Alfvén}$ vs β_{fast}/β_{tot}
  - Develop predictive and control methods
- Reduced aspect ratio expands range of field line connection length to study and mitigate divertor heat flux

MAST-U will emphasize boundary physics

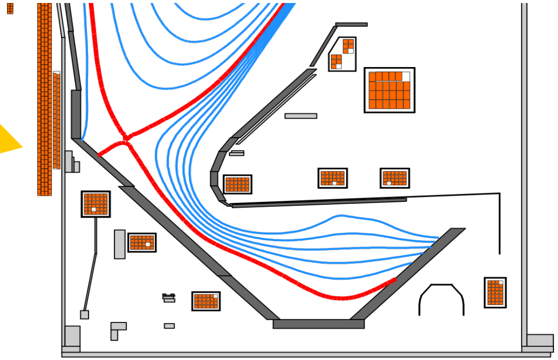
Maximum Parameters

		MAST	MAST-U
I_p	≤	1.3	2 MA
RB_T	≤	0.44	0.64 m-T
P_{NBI}	≤	3.5	10 MW
τ_{pulse}	≤	0.7	5 s

On and off-midplane NBI



Super-X divertor configuration

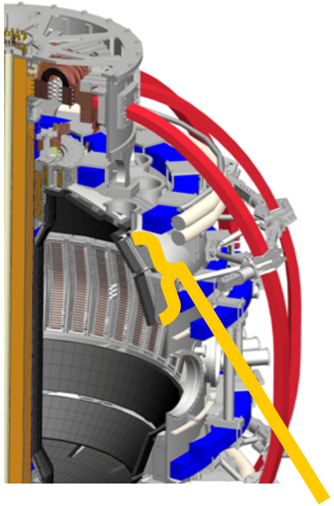


- Flexible divertor with Super-X capability for exhaust research
- Off-midplane 3D magnetic coils for edge instability control

NSTX-U will emphasize core physics

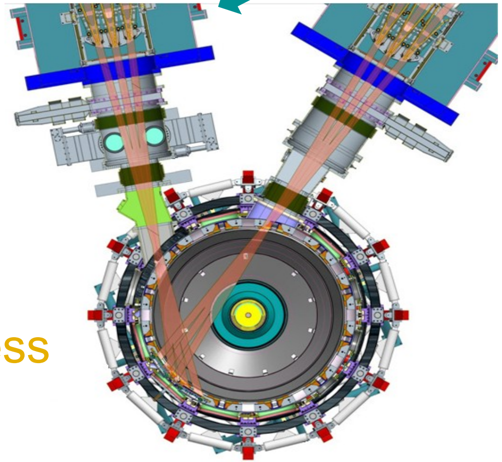
Maximum Parameters

		NSTX	NSTX-U
I_p	≤	1.4	2 MA
RB_T	≤	0.47	0.94 m-T
P_{NBI}	≤	6	15 MW
P_{RF}	≤	6	6 MW
τ_{pulse}	≤	1	5 s



Conducting plates can suppress global kink instabilities

New tangential NBI for j(r) control



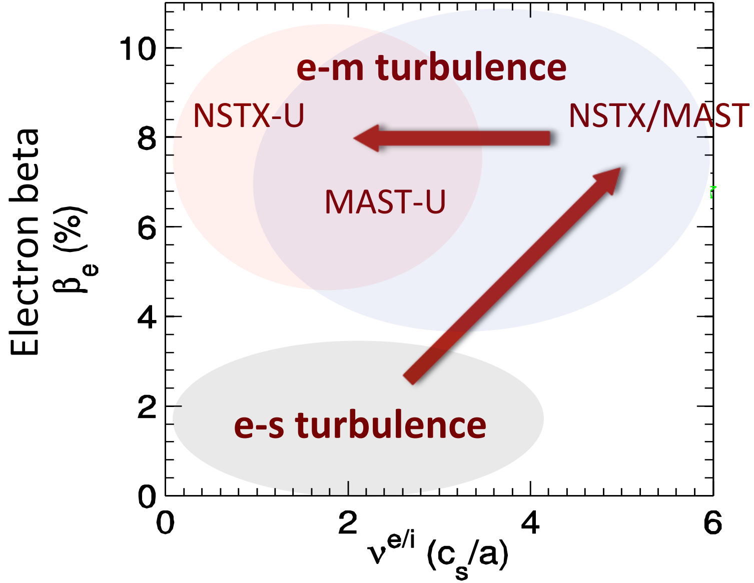
- High B_T (1 T at R_0) ➔ projected largest range in β and (lower) ν_* in an ST
- Greater stability ($\beta_n/l_i \leq 14$) + flexible NBI ➔ high non-inductive current

This talk will cover recent complementary results from NSTX(-U) and MAST

- Core transport and stability physics
- Energetic particle physics/mode stability
- Boundary and divertor physics
- Future plans

This talk will cover recent complementary results from NSTX(-U) and MAST

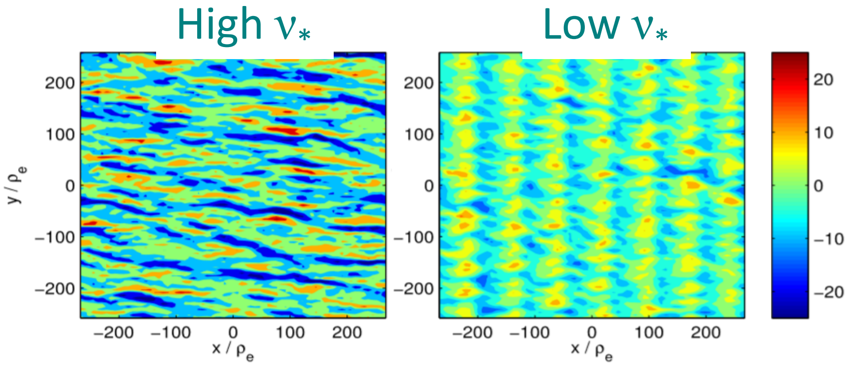
- **Core transport and stability physics**
  - ST confinement trends differ from those at higher aspect ratio
    - NSTX/MAST: $\tau_E \sim I_p^{0.5} B_T^{1} \sim \nu_*^{-0.8}$
      (ITER-Basis: $\tau_E \sim I_p^{1} B_T^{0} \sim \nu_*^{0}$)
  - Stability control methods necessary for high-β operation



Normalized collisionality (~n/T²)

Core: Measurements and theory help in understanding the turbulence that underlies confinement trends in STs

- ITG turbulence often suppressed by flow shear
  - **MAST** BES measurements of ITG ñ show flow shear breaks symmetry of turbulence in space (tilt) and amplitude (skewed PDF)
- Collisionality dependence controlled by electron transport due to
  - electrostatic dissipative TEM/electromagnetic microtearing modes on **NSTX**
  - electrostatic ETG on **MAST**



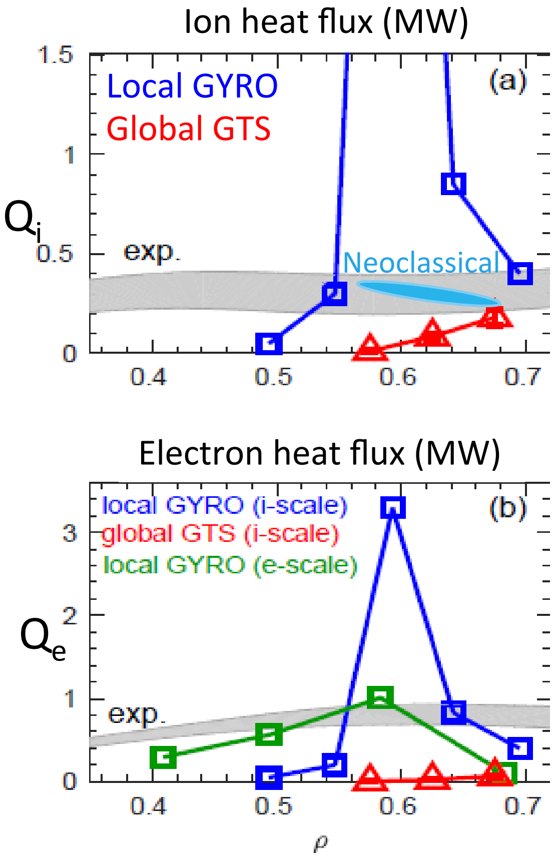
MAST

- ETG sims initially produce streamer-like structures before forming 'vortex streets'
  - Collisionality dependence due to damping of zonal flows

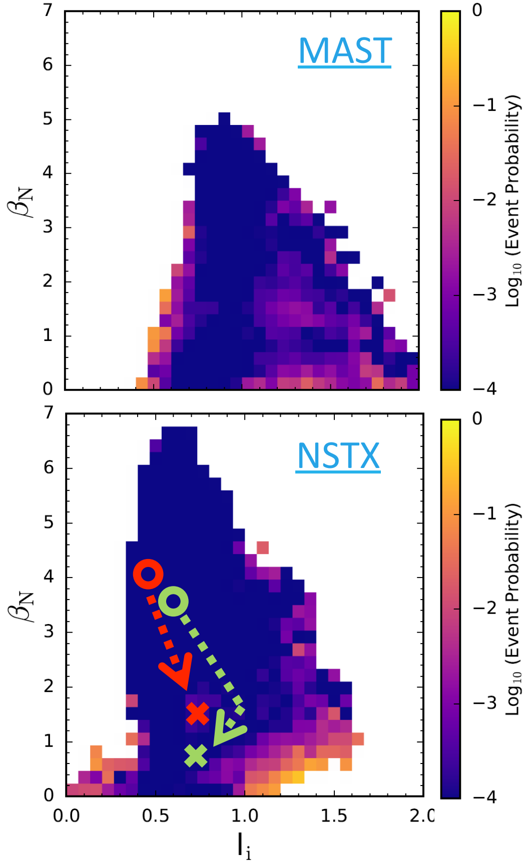
[G. Colyer et al., PPCF **59** 055002 (2017)]
[M. F. J. Fox et al., PPCF **59** 034002 (2017)]
[F. van Wyk et al., PPCF **59** 114003 (2017)]

Core: Multi-scale and non-local effects potentially important for understanding underlying turbulence

- Ion-scale (ITG/TEM) non-linear simulations (GTS) for **NSTX** L-mode illustrate importance of global effects
  - Transport from global (GTS) lower than from *local* (GYRO) simulations → *profile shearing effects at large ρ_* important*
    - $1/\rho_*$ ~ 75 (NSTX), 200 (DIII-D), 350 (JET)
- Electron-scale (ETG) non-linear simulations predict significant Q_e; close to expt'l
  - Similarity in $Q_{e,\ high\text{-}k}$ and $Q_{i,\ low\text{-}k}$ indicates cross-scale coupling may be important



Core: Disruption Event Characterization and Forecasting (DECAF) code used to provide a cross-machine comparison of disruptivity

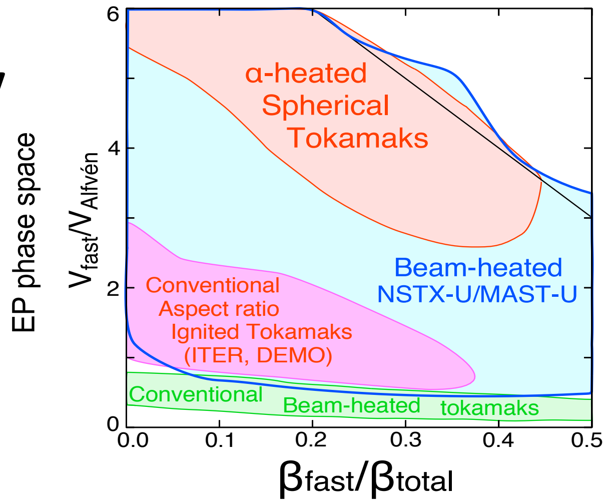


- DECAF analysis of disruption event
  - Shots analyzed at 10 ms intervals during Ip flat-top
  - MAST: 8,902 plasmas analyzed; NSTX: 10,432 plasmas
- Supports published result that disruptivity doesn't increase with β_N
- Disruptivity plots provide important information, but can be misleading when used incorrectly
  - Plasma conditions can change significantly between first problem detected and when disruption happens
  - **Circles** mark the key region to study with DECAF: where events that lead to disruptions **(X's)** start

[Sabbagh et al., EX/P6-26 (DECAF)]

This talk will cover recent complementary results from NSTX(-U) and MAST

- **Energetic particle physics/mode stability**
  - Energetic particle-driven instabilities may reflect those in ITER, next-step devices
  - Will show examples of fast ion distribution effects by sawteeth, high-frequency AE to develop understanding, predictive capabilities, and control methods
  - Instabilities in both frequency ranges may be important for ITER



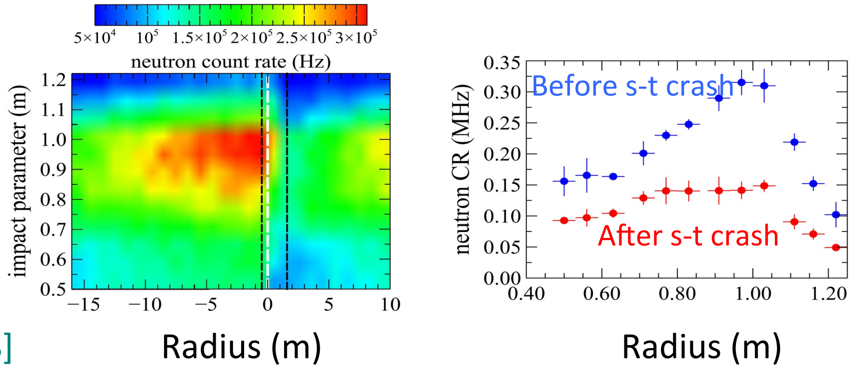
~ (EP-instability drive)/(EP-instability damping)

Energetic Particles: Sawteeth on MAST and NSTX-U have a significant effect on the fast particle population

- **MAST** neutron camera measurements show drop in neutron rate (fast ion distribution) across profile
  - Modeling indicates that sawteeth have **comparable** effect on both trapped and passing particles

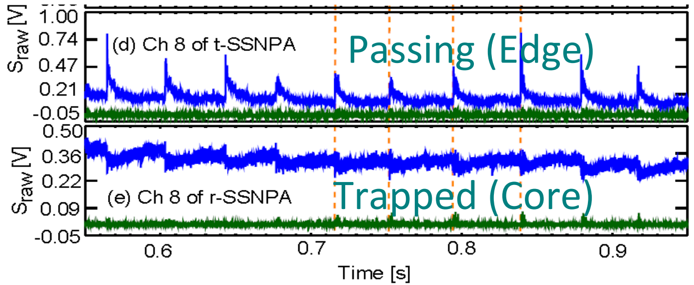
[M Cecconello et al., PPCF **60** 055008 2018]

MAST – Neutron Camera



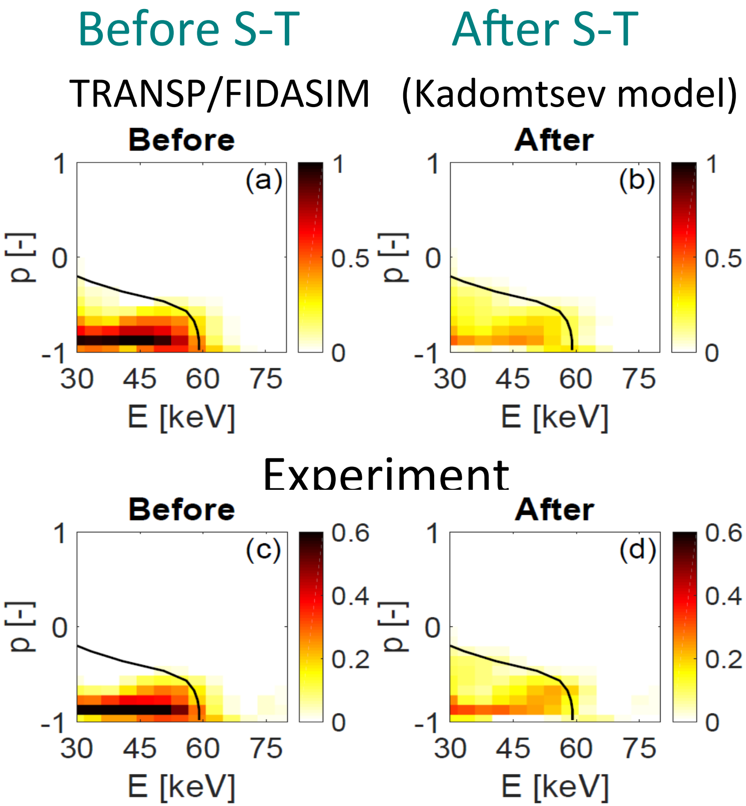
- FIDA & solid-state NPA measurements on **NSTX-U** indicate that passing particles strongly expelled from core by sawteeth
[Liu, Nuc. Fusion (2018)]
  - Little effect on trapped particles

NSTX-U ssNPA



Energetic Particles: Different sawtooth models on **MAST** and **NSTX-U** show agreement with experiment

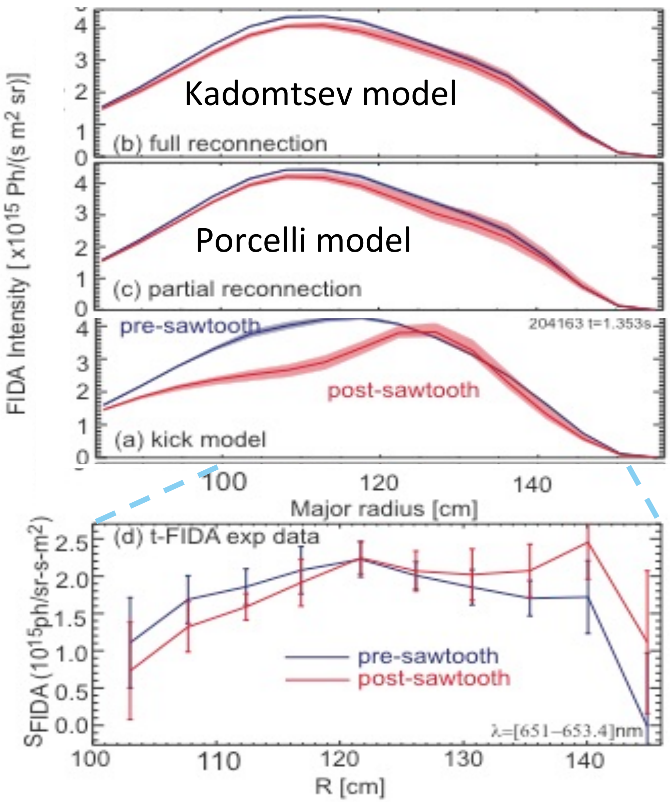
- Full reconnection model (Kadomtsev) consistent with measurements in **MAST**
  - Inversion of real and synthetic FIDA data show expulsion of trapped and passing particles from core
- Simple sawtooth models cannot reproduce spatial redistribution of fast particles in **NSTX-U** [Kim, EX/P6-33]
  - "Kick" model [Podesta, PPCF (2014)], based on orbit-following calculations of fast ions, lead to better agreement



[B. Madsen et al., RSI **89** 10D125 (2018)]

Energetic Particles: Different sawtooth models on **MAST** and **NSTX-U** show agreement with experiment

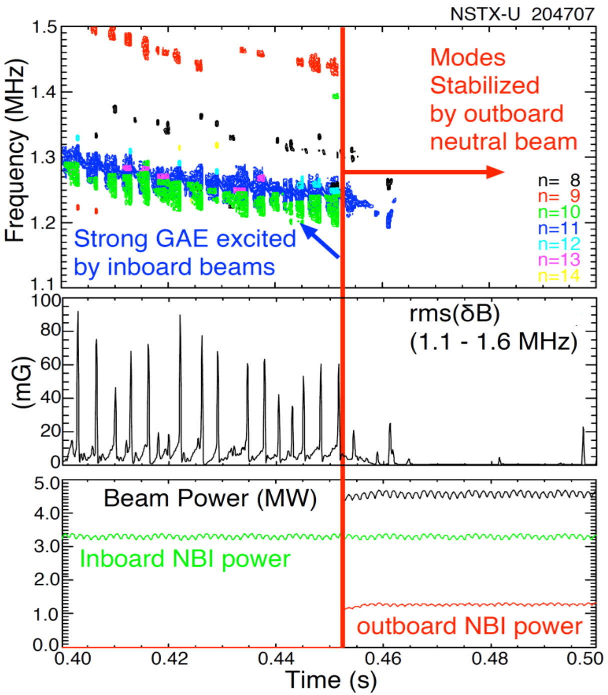
- Full reconnection model (Kadomtsev) consistent with measurements in **MAST**
  - Inversion of real and synthetic FIDA data show expulsion of trapped and passing particles from core
- Simple sawtooth models cannot reproduce spatial redistribution of fast particles in **NSTX-U** [Kim, EX/P6-33]
  - "Kick" model [Podesta, PPCF (2014)], based on orbit-following calculations of fast ions, lead to better agreement



Are differences due to differences in injection energy, phase space distribution of EP?

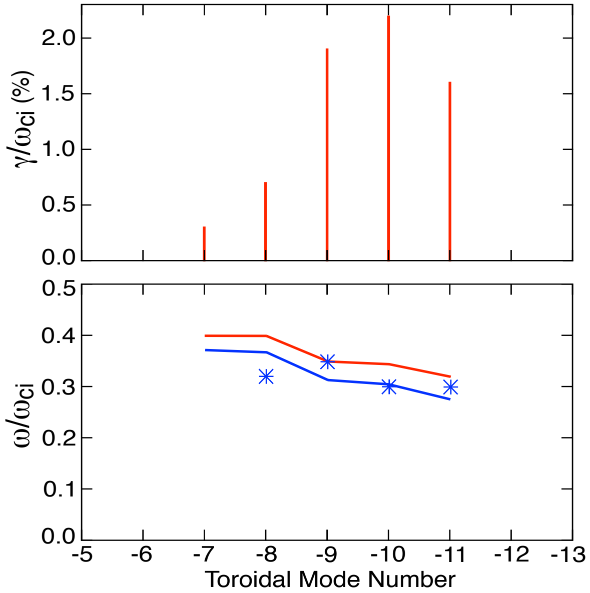
Energetic Particles: Progress in developing tool for phase-space engineering of EP-driven instabilities in **NSTX-U**

- High frequency global Alfvén Eigenmodes (GAEs) suppressed by off-axis beam injection
  [Fredrickson PRL (2017), Nuc. Fus. (2018)]
- Non-linear HYM simulations show unstable counter-rotating GAEs
  - Maximum growth rates for toroidal mode numbers -7 to -11
  - Predicted frequencies match measurements
  - Peak saturation amplitudes δB/B ~ 5e-3
  - Effect on electron transport under investigation



Energetic Particles: Progress in developing tool for phase-space engineering of EP-driven instabilities in **NSTX-U**

- High frequency global Alfvén Eigenmodes (GAEs) suppressed by off-axis beam injection [Fredrickson PRL (2017), Nuc. Fus. (2018)]
- Non-linear HYM simulations show unstable counter-rotating GAEs
  - Maximum growth rates for toroidal mode numbers -7 to -11
  - Predicted frequencies match measurements
  - Peak saturation amplitudes $\delta B/B$ ~ 5e-3
  - Effect on electron transport under investigation



- EP phase space engineering will be explored in **MAST-U** using on/off-midplane NB and off-midplane RMP coils

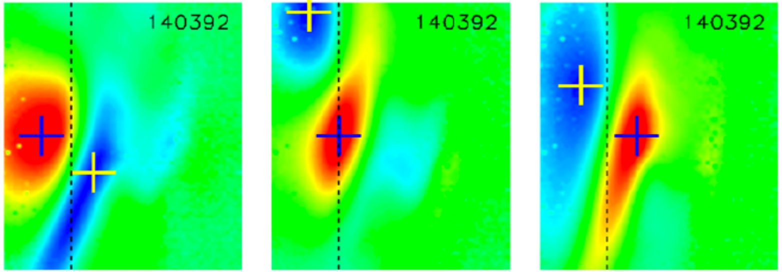
This talk will cover recent complementary results from NSTX(-U) and MAST

- **Boundary and divertor physics**
  - Turbulence studies at midplane and in divertor SOL for aid in understanding processes controlling heat flux amplitude and profile

Boundary: Gas puff imaging & theory being used to study edge turbulence near the midplane in **NSTX**

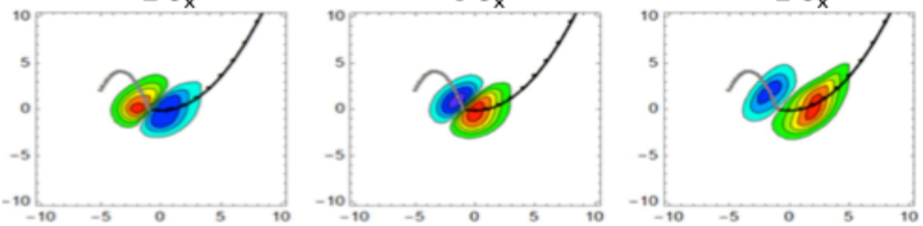
- GPI measurements of edge turbulence show dipole-like 2-D spatial correlations with large negative regions (blue)

origin inside separatrix *origin near separatrix* *origin outside separatrix*



- Semi-analytic model assuming blob-hole pairs shows similar 2D correlation patterns, dipole flip across separatrix
  [Myra, PPCF (2018)]

radially out →



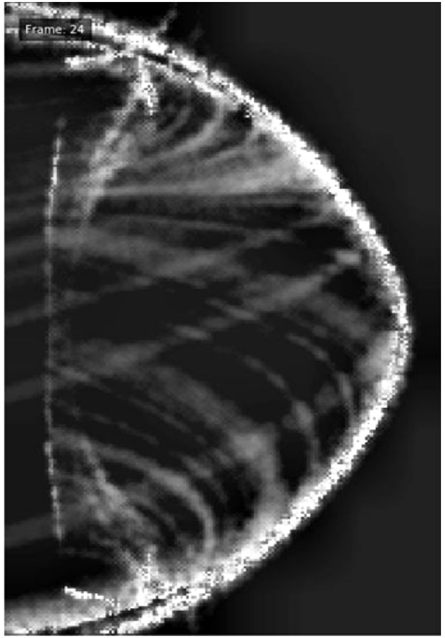
- Edge turbulence is being better understood through a combination of semi-analytic models and numerical simulation (e.g. XGC1)

Divertor: Fast camera imaging of the divertor provides new insights into SOL turbulence

- Non-linear 3D drift-fluid simulations (STORM/BOUT++) of SOL turbulence performed in realistic **MAST** geometry [Militello TH/7-1]
  - Reproduces filaments seen in fast camera videos of main chamber and divertor
    - SOL D_α profiles well described by superposition of independently moving filaments
  - Quiescent region in SOL near X-point has been identified [Walkden et al., Nuc. Fus. **57** 126028 (2017)]
  - Synthetic diagnostics developed to enable direct comparison with experiments

Background subtracted fast camera data

BOUT++ simulation

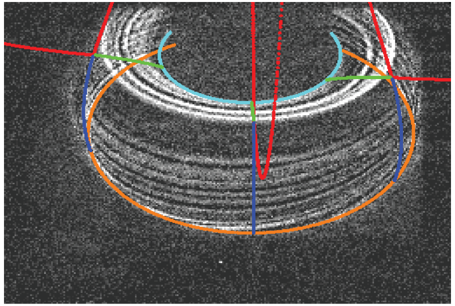


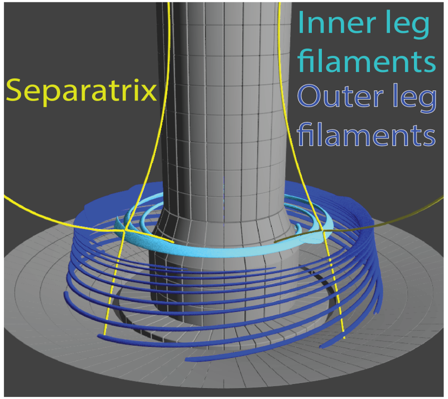
Divertor: Fast camera imaging of the divertor provides new insights into SOL turbulence

- Divertor leg fluctuations observed by fast imaging in **NSTX-U**
  - Intermittent; localized to bad curvature side
- Evidence for X-point disconnection
  - Inner and outer filament legs not correlated
  - Divertor filaments/midplane blobs not correlated
- Simulations with ArbiTER code find unstable resistive ballooning modes

[Baver, CCP (2016)]

Images in CIII emission





Rendering

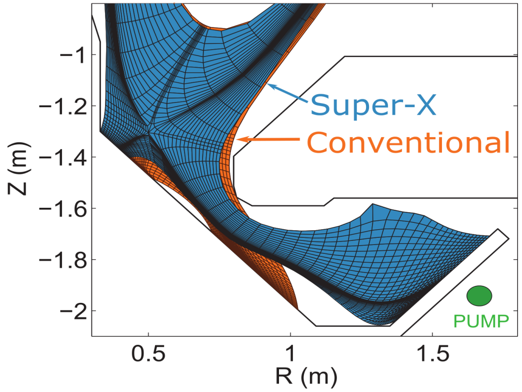
[Scotti, Nuc. Fusion (2018)]

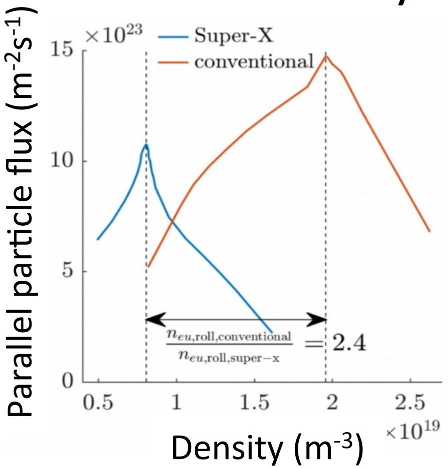
This talk will cover recent complementary results from NSTX(-U) and MAST

- **Future plans**

Expected benefits of Super-X divertor will be tested during first experimental campaign of **MAST-U**

- Super-X expected to improve exhaust mitigation and control of detachment front position
- Detachment in Super-X expected at lower density than in conventional



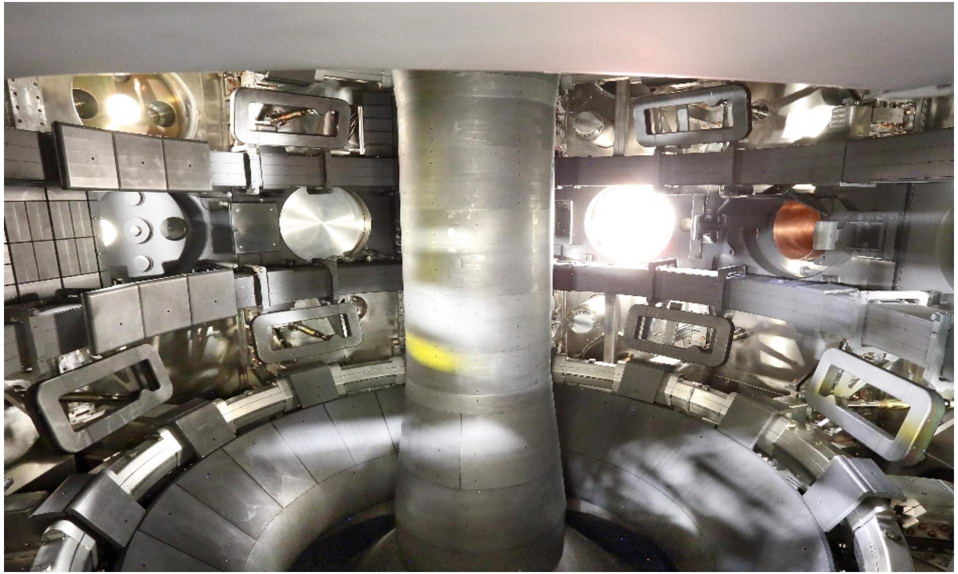


[D. Moulton et al., Proc 44th EPS Conf. 2017]
[B. Lipschultz, et al., NF **56** 056007 2016]

- Parallel heat flux gradients along Super-X leg should improve detachment control
  - Scales with $B_{x\text{-}pt}/B_{target}$; can be higher is STs (~3) than at conventional aspect ratio (~1-2)

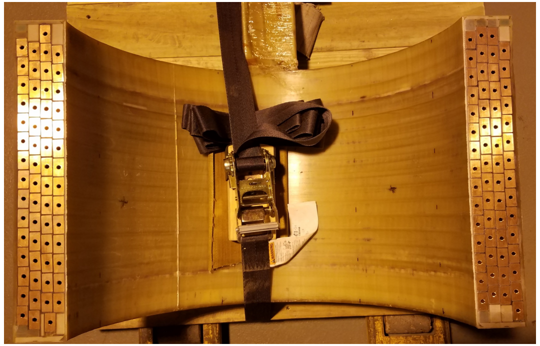
MAST-U preparing for operation

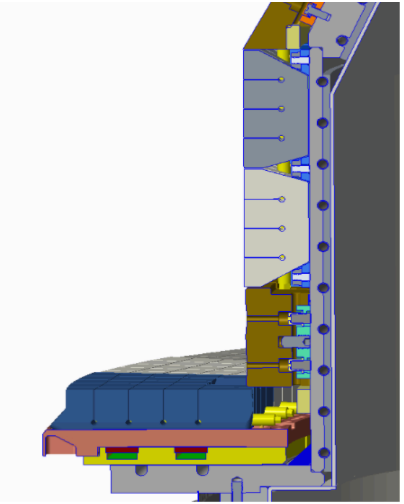
- MAST-U presently baking out; modifying TF linkages
- Expected physics operation Autumn 2019
- Detailed characterization of intrinsic error field carried out to optimize correction and broaden operating space
- New diagnostics
  - **Divertor**: 850 Langmuir probes, divertor TS, IR & visible cameras, bolometers
  - **Energetic particles**: ssNPA, FILD



NSTX-U Recovery underway

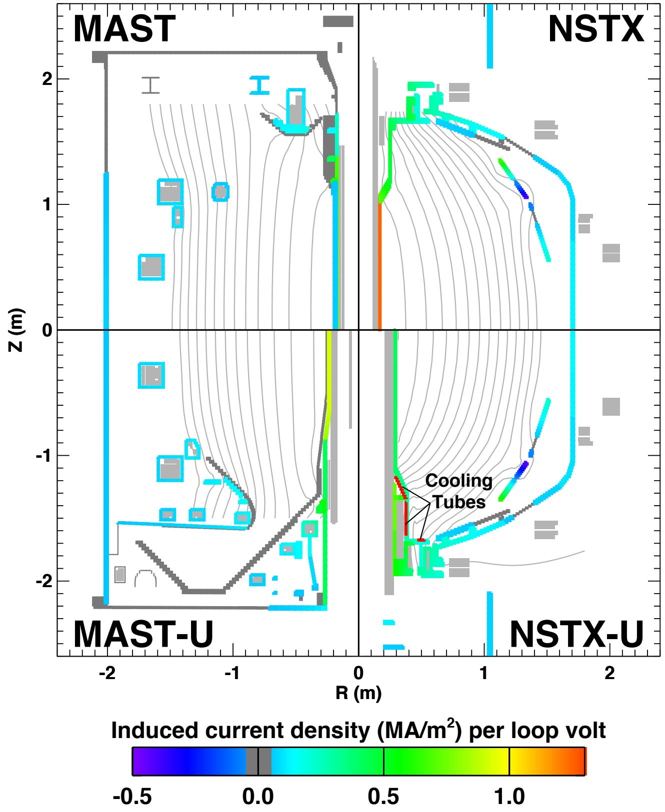
- NSTX-U operated for 10 weeks in 2016, achieving good H-mode performance, surpassing magnetic field and pulse duration of NSTX
- Run ended prematurely due to divertor PF fault
- Full repair will consist of installing improved PF coils, graphite PFCs to handle heat fluxes of high-power, long-pulse scenarios, minimized error fields to increase reliability [Gerhardt, FIP/P3-63]
- Projected to commence operations in early 2021
  - Study transport and stability physics at high-β/low ν_* ($B\tau \sim \nu_*^{-0.8}$)
  - Demonstrate full non-inductive operation (j(r) control with NBI)





Close collaboration between NSTX-U and MAST-U on developing startup scenarios

- Vacuum field calculations support magnetic calibrations and inductive startup scenario development
- Procedure for producing MAST-U first plasma being developed using the PPPL-LRDFIT code
  - Results from NSTX(-U) provide basis for first-plasma scenarios on MAST-U
  - Extended on-site (CCFE) visits facilitate collaboration



Summary: NSTX(-U) and MAST address urgent issues for fusion science, ITER and next-step devices

- Core transport & turbulence studied over an extended range of β and ν_*
  - Electrostatic and electromagnetic effects drive strong favorable ν_* scaling
  - Multi-scale effects (low- & high-k) must be considered
- Energetic particle effects and instabilities studied in portions of parameter space expected for α-burning plasmas
  - Low and high frequency modes can have profound effect on EP distribution
  - Predictive models and phase-space engineering techniques being developed
- Boundary and divertor studies address processes controlling heat flux width
  - Filamentary structures/turbulence
  - Heat flux mitigation through innovative divertor designs
- When operation commences, NSTX-U and MAST-U will be the most capable devices in the world-wide ST program

Relevant IAEA contributions follow

NSTX(-U)/MAST(-U) related IAEA presentations

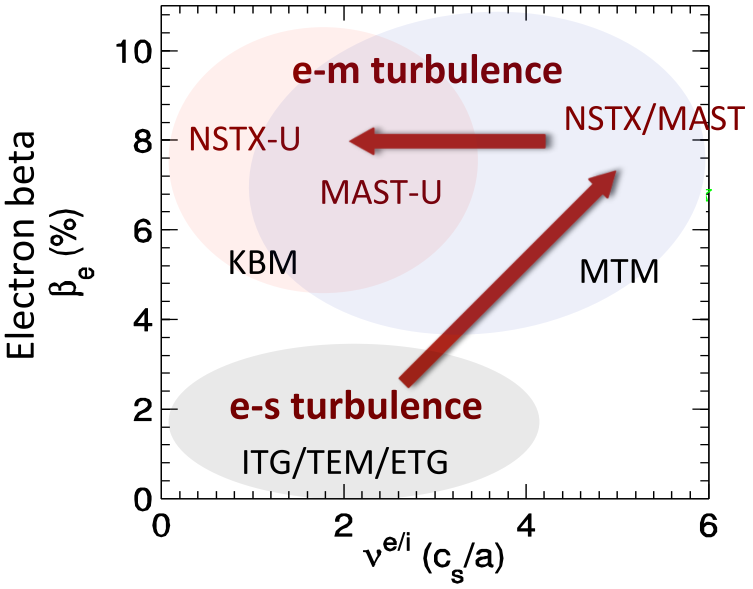
1. J. Menard: Fusion energy development utilizing the Spherical Tokamak OV/P-6 (Mon AM)
2. R. Lunsford: Electromagnetic particle injector FIP/P1-51 (Tues AM)
3. M. Podesta: Reduced EP transport models EX/1-2
4. E. Belova: Numerical simulations of GAE suppression TH/P2-16 (Tues PM)
5. S. Pamela: ELM and ELM-control simulations OV/4-4
6. S. Gerhardt: NSTX-U Recovery physics and engineering FIP/P3-63 (Wed AM)
7. V. Menon: Performance of large and small R/a fusion tokamaks FIP/P3-60
8. N. Bertelli: Impact of H^+ on HHFW in NSTX-U TH/P4-13 (Wed PM)
9. G.Z. Hao: Centrifugal force driven low-f modes in STs TH/P5-13 (Thurs AM)
10. T. Rafiq: Effects of microtearing modes on Te evolution in NSTX TH/P5-10
11. S. Sabbagh: Disruption characterization and forecasting EX/P6-26 (Thurs PM)
12. N. Ferraro: EF impact on mode locking and divertor heat flux in NSTX-U EX/P6-40
13. E. Fredrickson/M. Podesta: GAE stability dependences on fast ion distribution EX/P6-32
14. D. Kim: Fast ion redistribution by sawteeth on NSTX-U EX/P6-33
15. L. D-Aparacio: Rotation-induced electrostatic potentials and density asymmetries in NSTX EX/P6-33
16. R. Goldston: Development of Li vapor box divertor for controlled plasma detachment FIP/3-6
17. T. Brown: A toroidal confinement facility to study liquid lithium divertor (Fri AM)
18. A. Hakim: Continuum g-k simulations of NSTX SOL turbulence with sheath-limited geometries TH/P7-33
19. I. Krebs: Nonlinear 3D simulations of VDEs in tokamaks TH/P8-10 (Fri PM)
20. F. Militello: Predicting Scrape-Off Layer profiles and filamentary transport for reactor relevant devices TH/7-1

Backup

NSTX(-U) and MAST research address urgent issues for fusion science, ITER and next-step devices

MOVE TO BACKUP?

- STs can investigate turbulence over an extended range in β (tens %)
  - Electrostatic and electromagnetic effects at large ρ_*
- STs EP physics spans phase space expected in Burning Plasmas
  - Develop predictive and control methods
- Reduced connection length and surface area can lead to increased q_{target} in conventional divertors in STs
  - Developing strategies to mitigate heat fluxes in STs critical

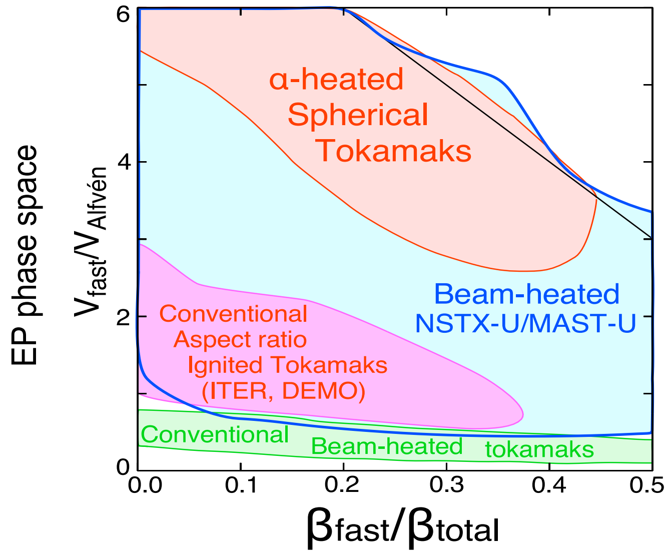


Normalized collisionality (~n/T²)

NSTX(-U) and MAST research address urgent issues for fusion science, ITER and next-step devices

MOVE TO BACKUP?

- STs can investigate turbulence over an extended range in β (tens %)
  - Electrostatic and electromagnetic effects at large ρ_*
- STs EP physics spans phase space expected in Burning Plasmas
  - Develop predictive and control methods
- Reduced connection length and surface area can lead to increased q_{target} in conventional divertors in STs
  - Developing strategies to mitigate heat fluxes in STs critical



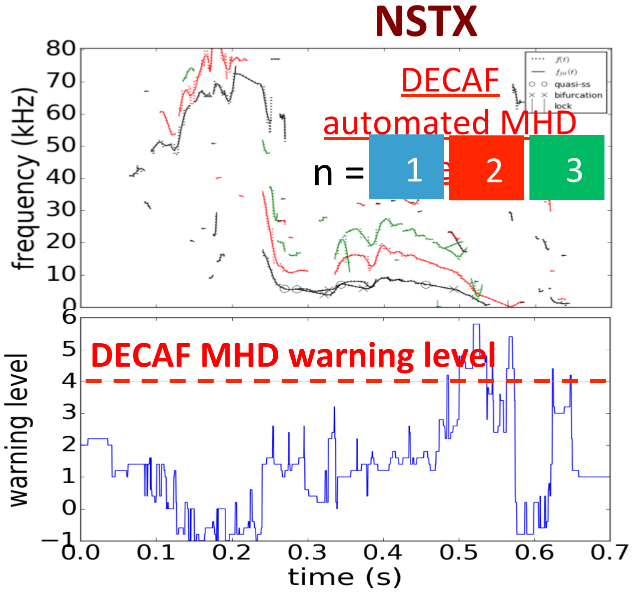
~ (EP-instability drive)/(EP-instability damping)

Core: Disruption Event Characterization and Forecasting (DECAF) algorithm being developed for stable operation

- DECAF utilizes physics-based models as much as possible to identify event chain leading to disruptions in a time-evolving fashion [Sabbagh et al., EX/P6-26]
  - Couple to real-time control system for stable operation, disruption mitigation

DECAF event chain

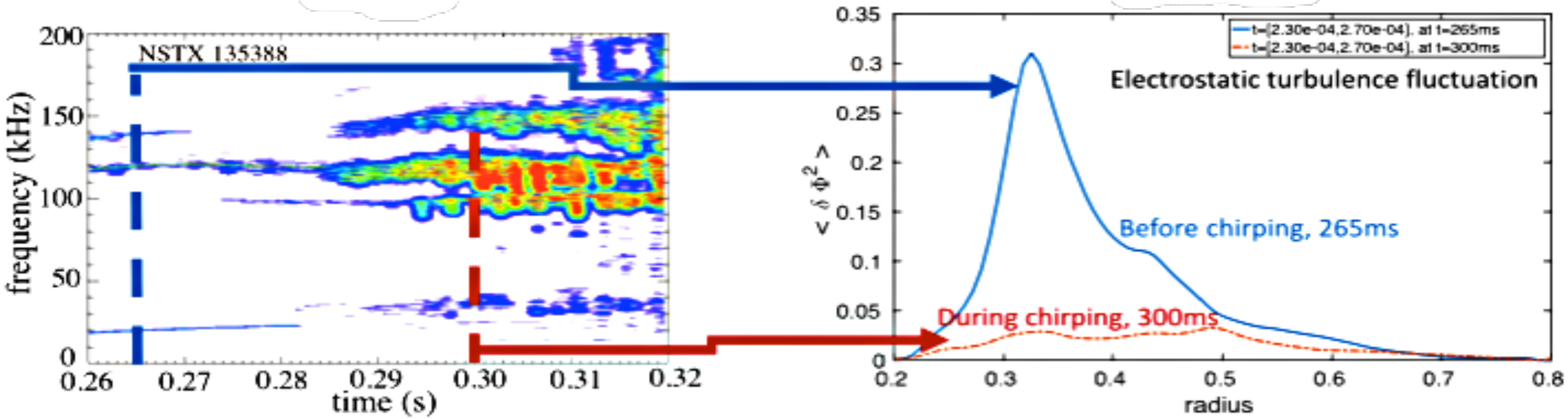
n=1 appears	n=1 locks	p(r) peaks	large dI_p/dt	hits wall	disruption	VDE
MHD-n1	LTM-n1	PRP	IPR	WPC	DIS	VDE
(0.490s)	(+.045s)	(+.068s)	(+.073s)	(+.073s)	(+.077s)	(+.080s)



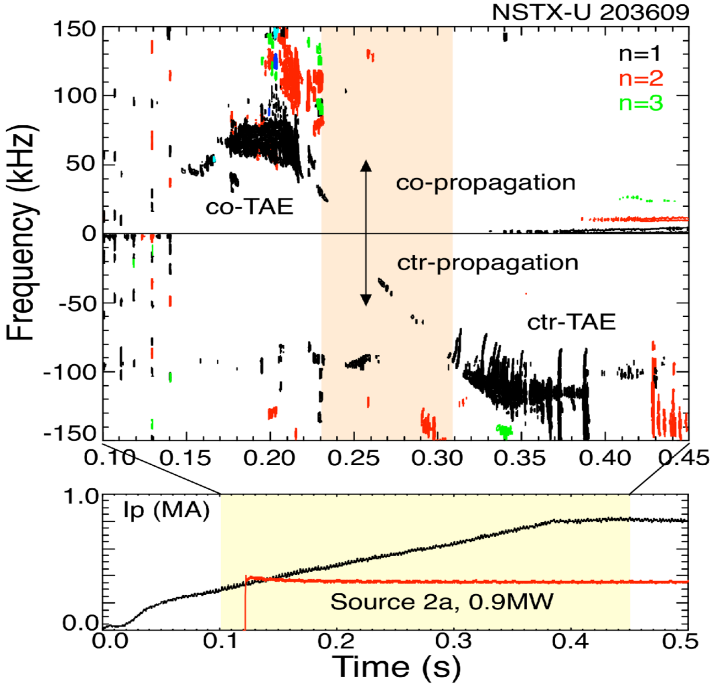
- Multi-institutional effort [**NSTX, MAST**, KSTAR, DIII-D, TCV (so far)]

Energetic Particles: Microturbulence is a mediator of EP instabilities on **NSTX-U**

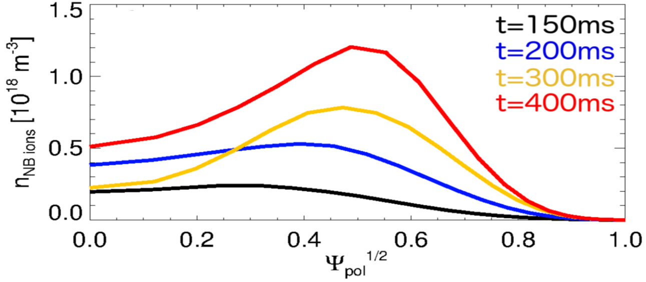
- High β_{fast}, $v_{fast}/v_{Alfvén}>1$ provide significant drive for enhanced wave-particle and nonlinear mode-mode interactions (chirping, avalanches)
  - Seen predominantly at lower than at higher aspect ratio
- Microturbulence can increase scattering of resonant fast ions to reduce chirping and avalanching [Duarte Nuc. Fusion (2018)]
  - Global GTS non-linear simulations support theoretical prediction



Counter-TAEs can be destabilized by off-axis co-NB injection from 2nd NB line

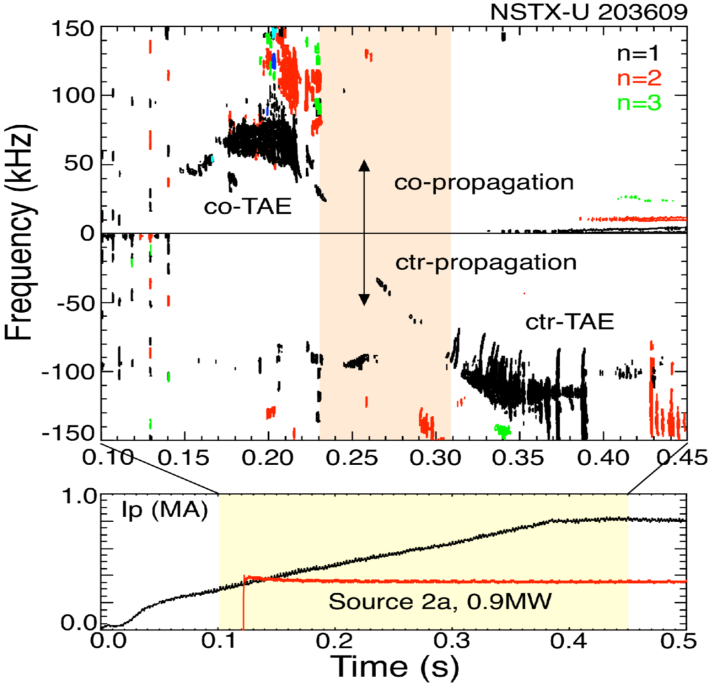


- Single NB source from 2nd NBI
- Low power, P_{NB}~1MW

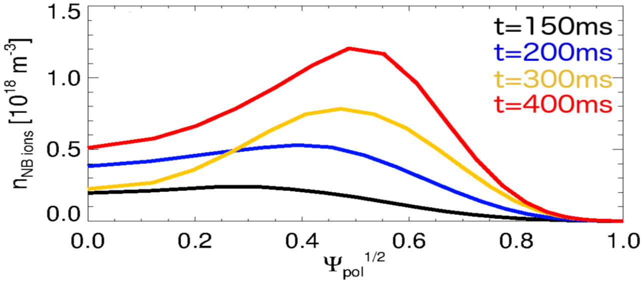


- Off-axis NBI results in broad/hollow NB ion density profile
- A transition is observed from co-TAEs only to cntr-TAEs

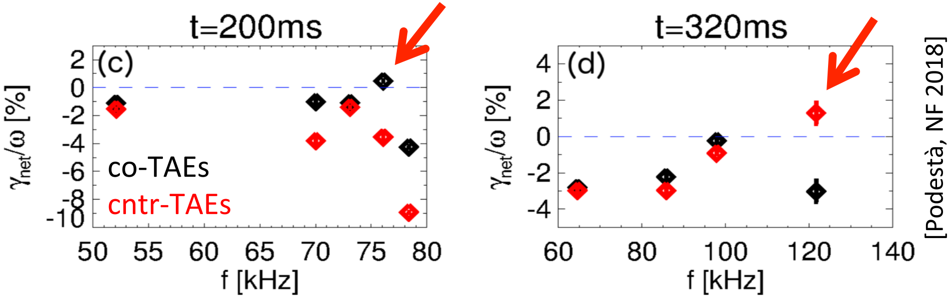
Details of fast ion distribution explain destabilization of *counter*-TAEs by co-NBI



- Single NB source from 2nd NBI
- Low power, P_{NB}~1MW

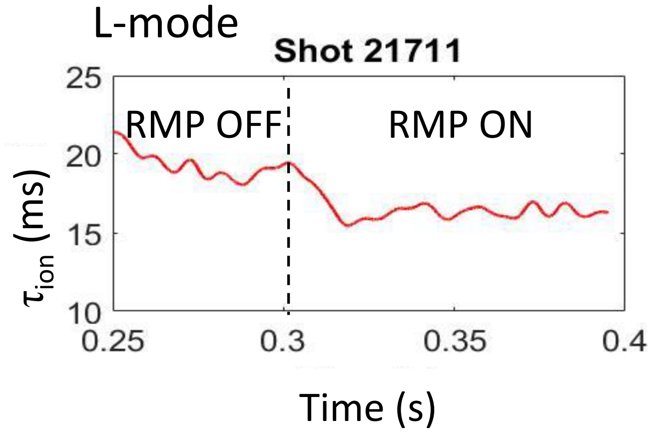


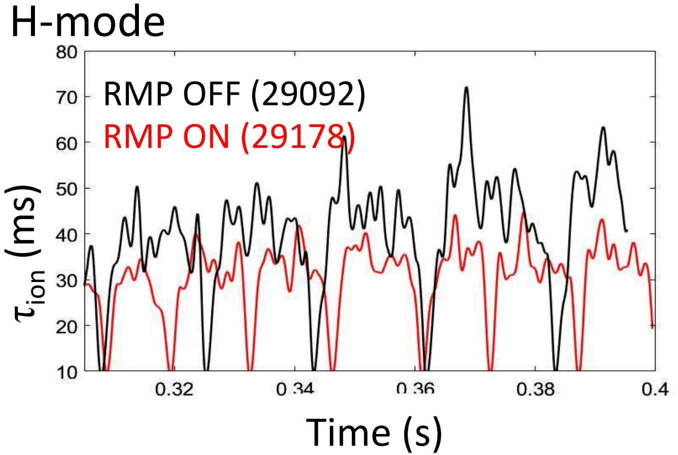
- Stability analysis with TRANSP + kick model recovers observations
- Drive results from competition between gradients in energy and canonical momentum



Boundary: Particle confinement control and turbulence being studied in MAST

- Application of Resonant Magnetic Perturbations (RMPs) reduces particle confinement
  - τ_{ion} reduced by ~20% in L-mode (with n=3 RMP) and 30% in H-mode (with n=4 RMP)

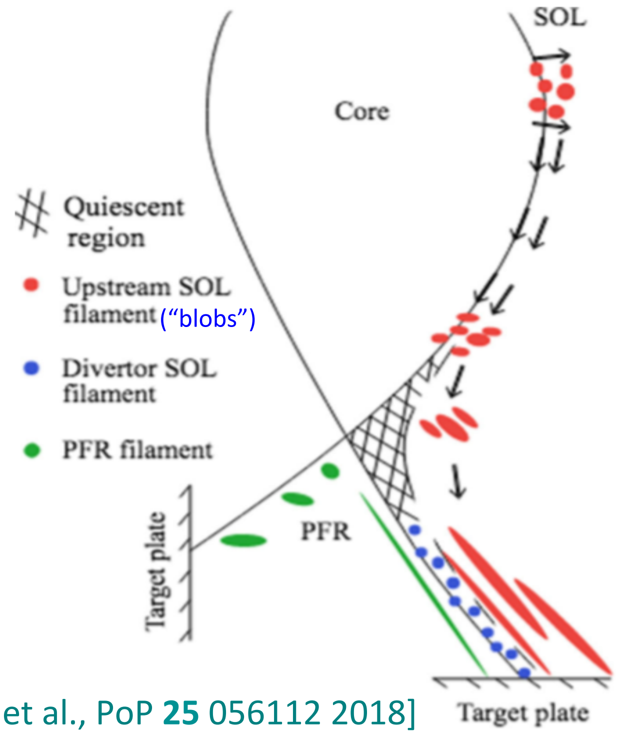




- First estimates of radial wave number of Geodesic Acoustic Mode in an ST in an ohmic L-Mode in good agreement with global 2-fluid simulations [Hnat, PPCF (2018)]
  - Oscillation localized to boundary that can influence L-H transition dynamics
  - 10 kHz, $k_r\rho_p$ ~ -0.15, v_r ~ 1 km/s, located 2 cm inside the separatrix

Divertor Physics: SOL turbulence can contribute of cross-field transport: being studied in both MAST and NSTX-U

- **MAST** SOL density profiles are well described by the superposition of independently moving filaments
  - Quiescent region in the SOL near X-point
- Divertor leg fluctuations observed by fast imaging in **NSTX-U**
  - Intermittent; localized to bad curvature side
  - Connected to divertor target plate
- Evidence for X-point disconnection
  - Inner and outer filament legs not correlated
  - Divertor filaments/midplane blobs not correlated

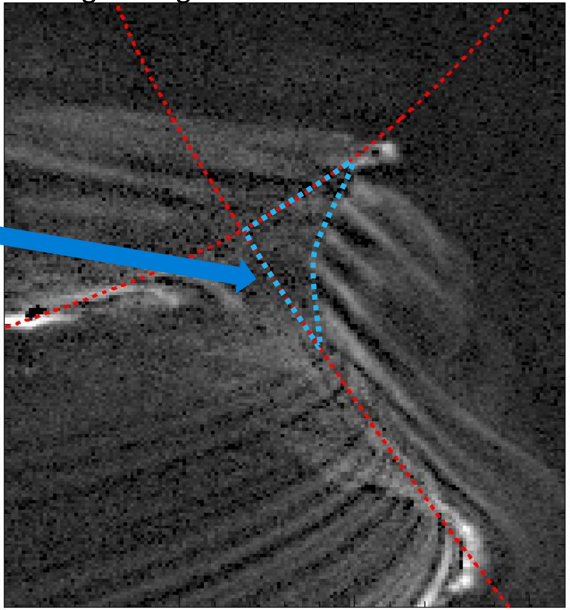


[F. Militello et al., PoP **25** 056112 2018]
[N. Walkden et al., NF **57** 126028 2017]

Divertor Physics: Fast camera imaging of the divertor provides new insights into SOL turbulence

- SOL turbulence being studied in both MAST and NSTX
  - **MAST** SOL density profiles are well described by the superposition of independently moving filaments
- Quiescent region in the SOL near the X-point has been identified
- Divertor leg fluctuations observed by fast imaging in **NSTX-U**
  - Intermittent; localized to bad curvature side
- Evidence for X-point disconnection
  - Inner and outer filament legs not correlated
  - Divertor filaments/midplane blobs not correlated

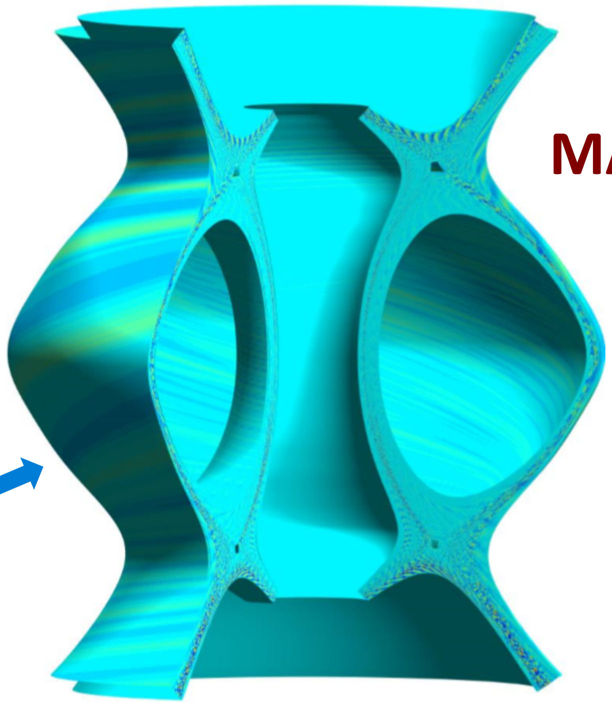
Moving average subtracted unfiltered frame



[F. Militello et al., PoP **25** 056112 2018]
[N. Walkden et al., NF **57** 126028 2017]

Divertor: Linear and non-linear simulations of SOL turbulence being performed in NSTX-U and MAST

- Linear simulations with ArbiTER code for **NSTX-U** find unstable resistive ballooning modes [Baver, CCP (2016)]
  - Higher mode numbers on outer than on inner legs
- Non-linear 3D drift-fluid simulations (STORM/BOUT++) of SOL turbulence performed in realistic **MAST** geometry
  - Reproduces filamentary structures seen in fast camera videos in main chamber and divertor

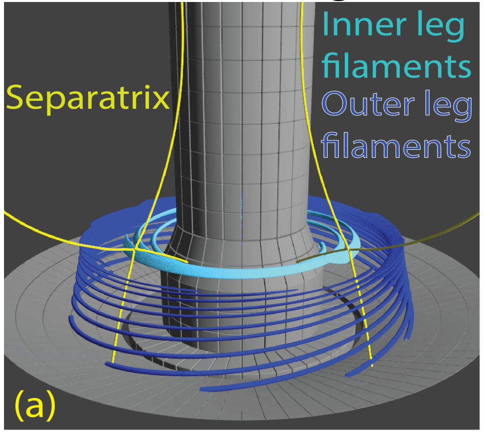


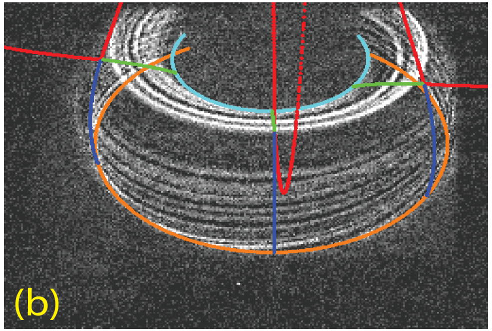
MAST

Divertor Physics: Intermittent field-aligned filaments localized to bad curvature side of divertor legs in **NSTX-U**

- Divertor leg fluctuations observed by fast imaging [Scotti, Nuc. Fusion (2018)]
  - 10-30 kHz, $k_{pol}\rho_i$~0.01-0.1, v_{pol}~1-2 km/s
- Connected to divertor target plate
- Evidence for X-point disconnection
  - Inner and outer filament legs not correlated
  - Divertor filaments/midplane blobs not correlated
- Simulations with ArbiTER code find unstable resistive ballooning modes [Baver, CCP (2016)]
  - Higher mode numbers on outer than on inner legs

Rendering





Images in CIII emission

Edge: **NSTX** is exploring L-H transition physics

Turbulence fluctuation energies

Thermal free energy

Non-zonal ExB energy

$$\frac{n_{e0}T_{e0}}{2}\left(\frac{\tilde{n}_e}{n_{e0}}\right)^2 + \frac{n_0 m_i \langle \tilde{v}_\theta^2 \rangle}{2}$$

P>0 →

← P<0

Zonal ExB energy

$$\frac{n_o m_i \langle \bar{v}_\theta \rangle^2}{2}$$

- Production term, P, related to Reynold’s stress
- Find P<0 just prior to L-H in NSTX
  - Energy transfer from ZF to turbulence
- Inconsistent with Predator-Prey model
  [Diallo, Nuc. Fusion (2017)]