U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Probing the electron density and temperature on fast time scales

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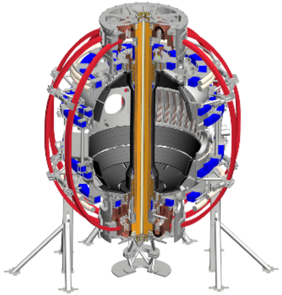
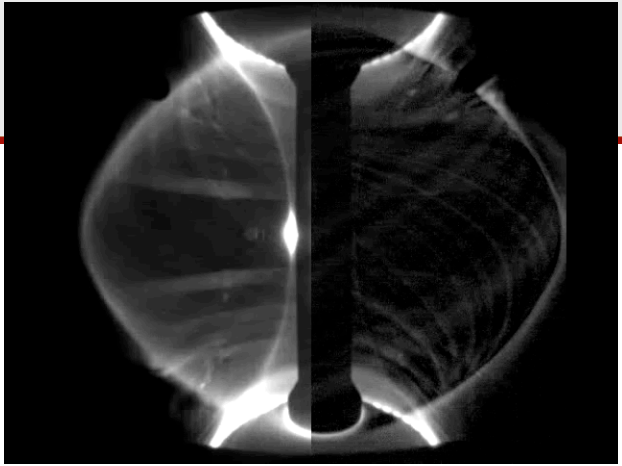
Princeton Plasma Physics Laboratory

~~NUF~~-SULI seminar - ~~2016~~
2017

PPPL



Transient phenomena such as edge localized modes are predicted to cause deleterious effects to the walls of ITER



MAST tokamaks

Solar flare

- Wide angle image of Dα emission showing edge localized mode (ELM) eruption on MAST.
- While progress on ELMs research has been made, there remains open questions
  - Dynamics of the edge until ELMs
  - Physics of the ELM onset?
- Pave the way for edge plasma control

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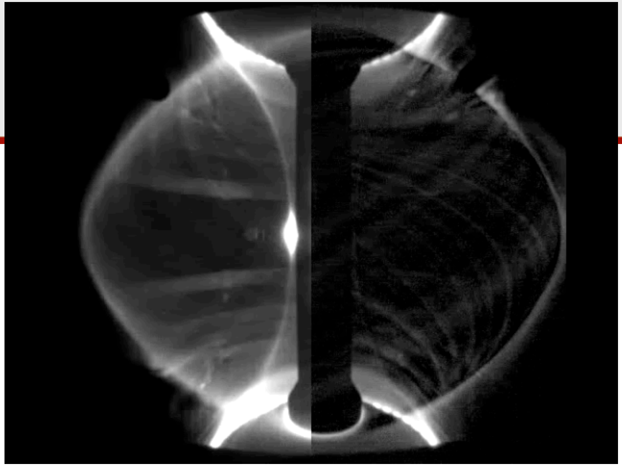

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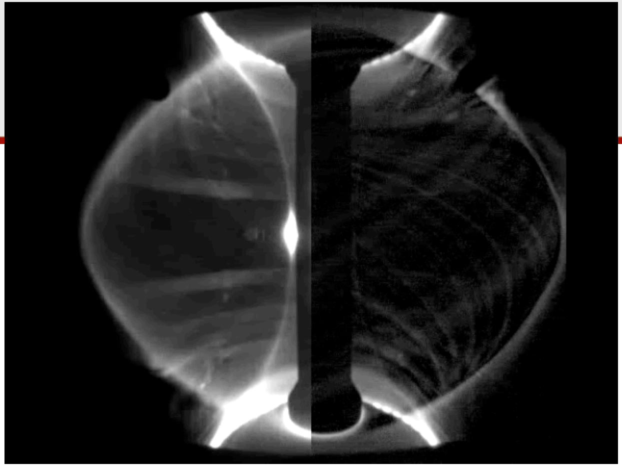

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What is Our Current Understanding of the Pedestal Evolution Between ELMs?

- **EPED1 is a pedestal model with predicts pedestal pressure height and width**
  - based on two key limiting instabilities
    - non-local peeling–ballooning (P–B)mode ➙ trigger for edge-localized mode (ELM)
    - nearly local kinetic ballooning modes (KBMs) ➙ regulate transport between ELMs

Connor, PoP (1998); Wilson, PoP (2002); Snyder, PoP (2001); Snyder, NF (2011)

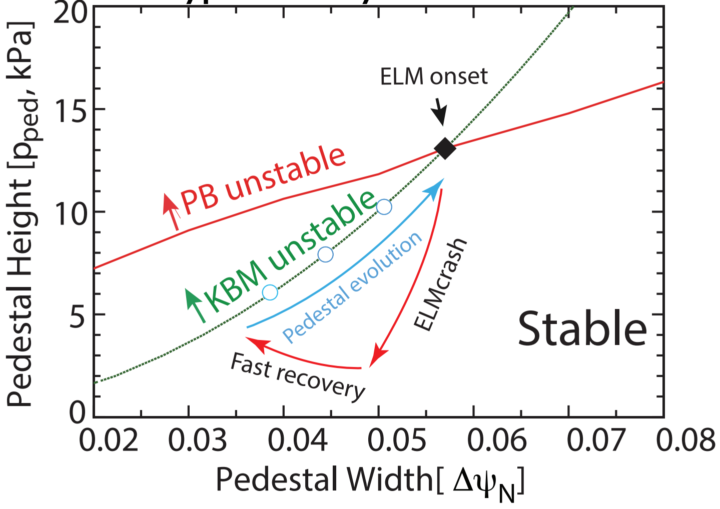
- **Broadband density fluctuations were observed during ELM recovery**

Yan, PoP (2011)

- **JRT results showed that the pedestal evolves on the KBM stability line at low current**

Groebner, Nucl Fusion 2013

Type I ELM cycle cartoon



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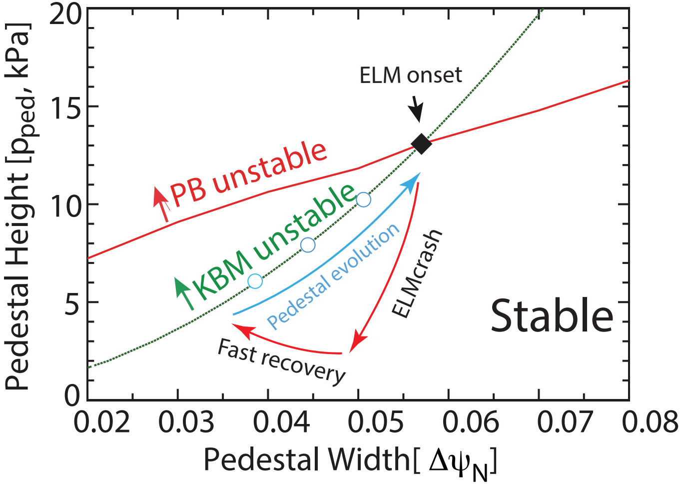
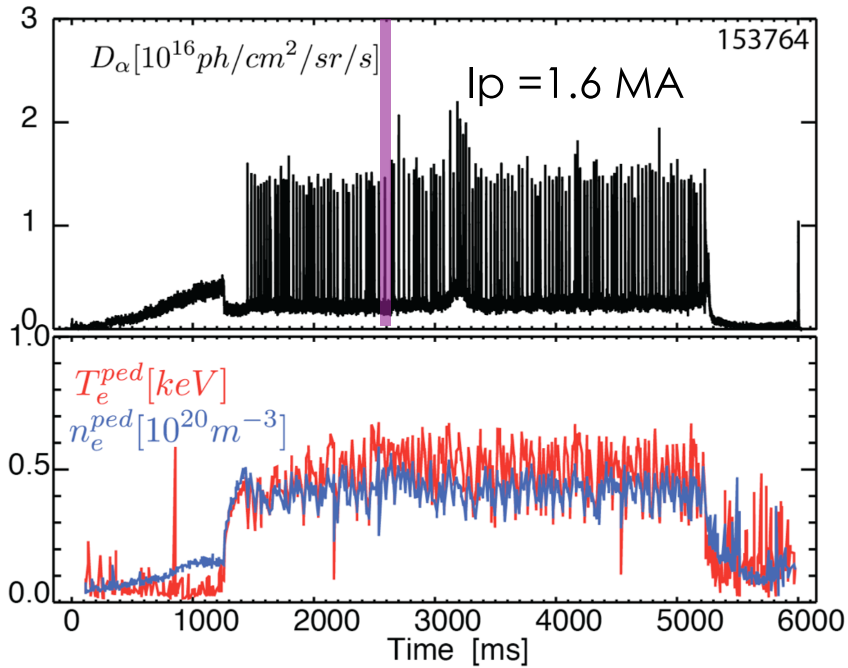
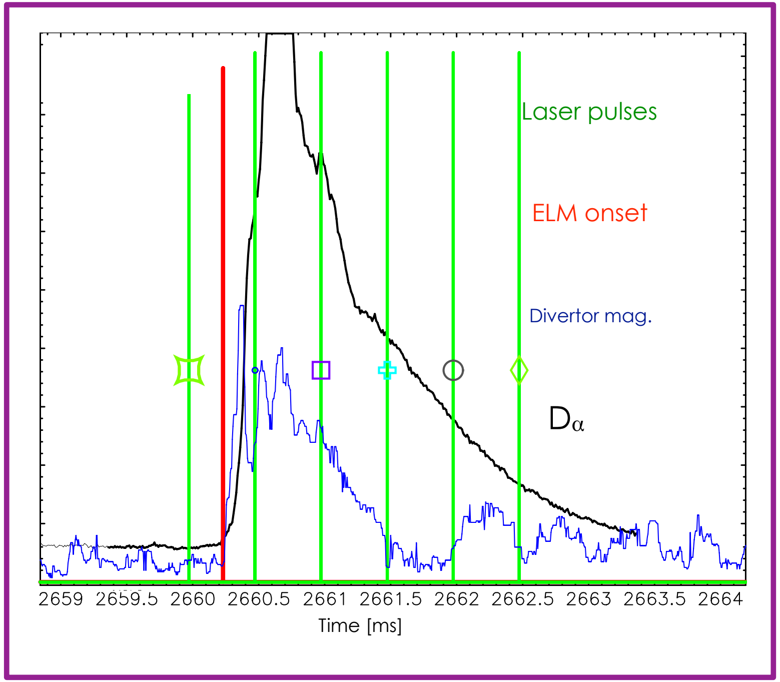


- **Can we characterize the edge instability during the early recovery of the pedestal?**
- **Does edge instability limit pedestal evolution?**

The Burst Thomson Scattering (TS) Provides the Means to Probe the Inter-ELM Dynamic of the Pedestal





- **Normal B_T =1.9 T with q_{95} = 3 in Type I ELMy H-mode**
- **The laser was fired in burst mode to increase the temporal resolution**

Simultaneously resolve the local electron density & temperature to probe various transient phenomena in plasmas

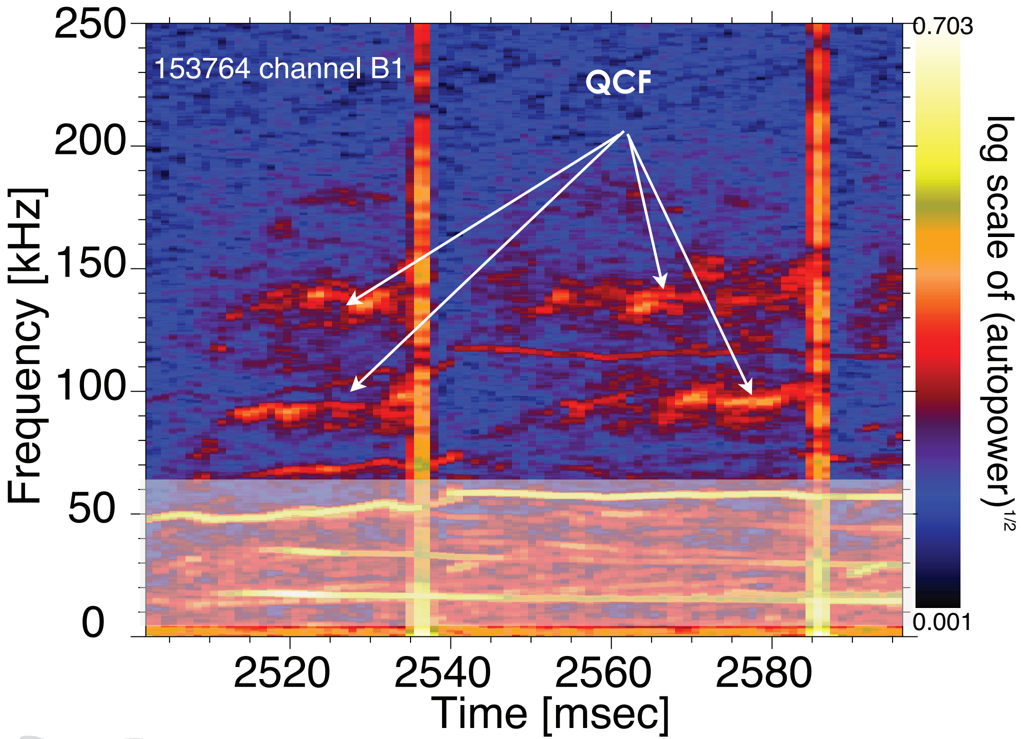
- Langmuir probes allow routine measurements of electron density & temperature in low temperature plasmas.
  - These probes can be perturbative to the local plasma but provide good temporal resolution.

- High temperature plasma are routinely probed using laser scattering (e.g. Thomson scattering) for non-perturbative local measurements.
  - This approach lacks good temporal resolution.

ECE and reflectometry provide density and temperature but ECE is not available in ST

DIII-D: Inter-ELM Magnetic Fluctuations Also Exhibit QCFs Preceding the Onset of ELMs

Magnetic fluctuations spectrogram

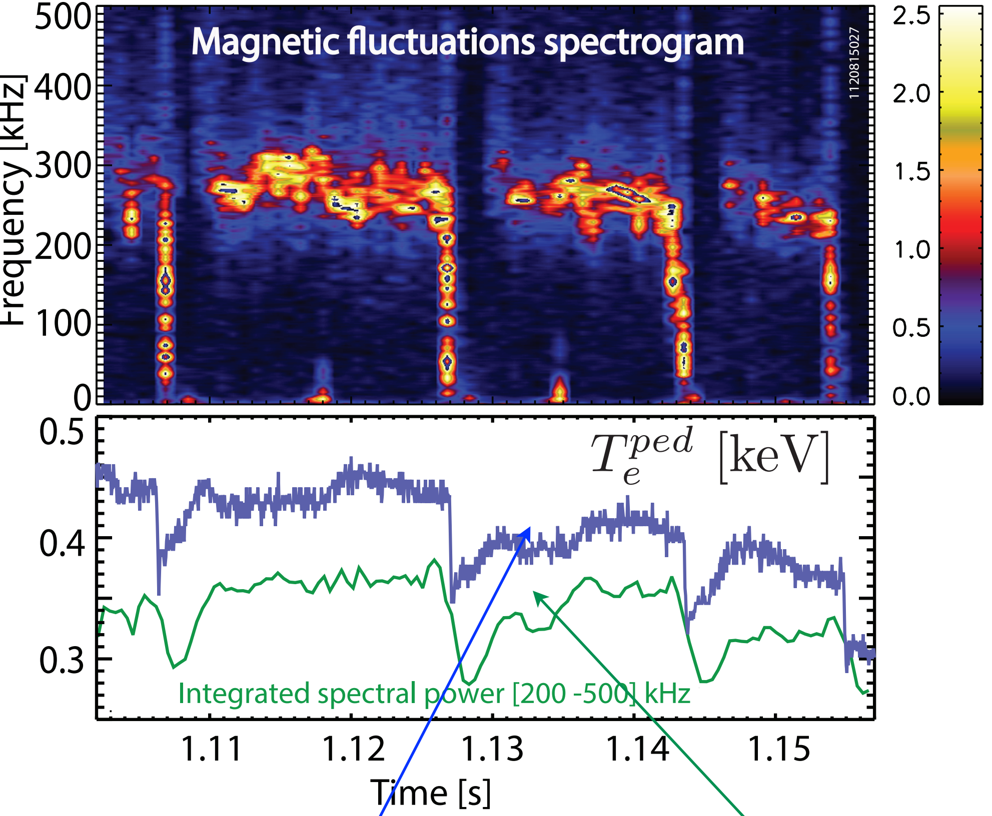


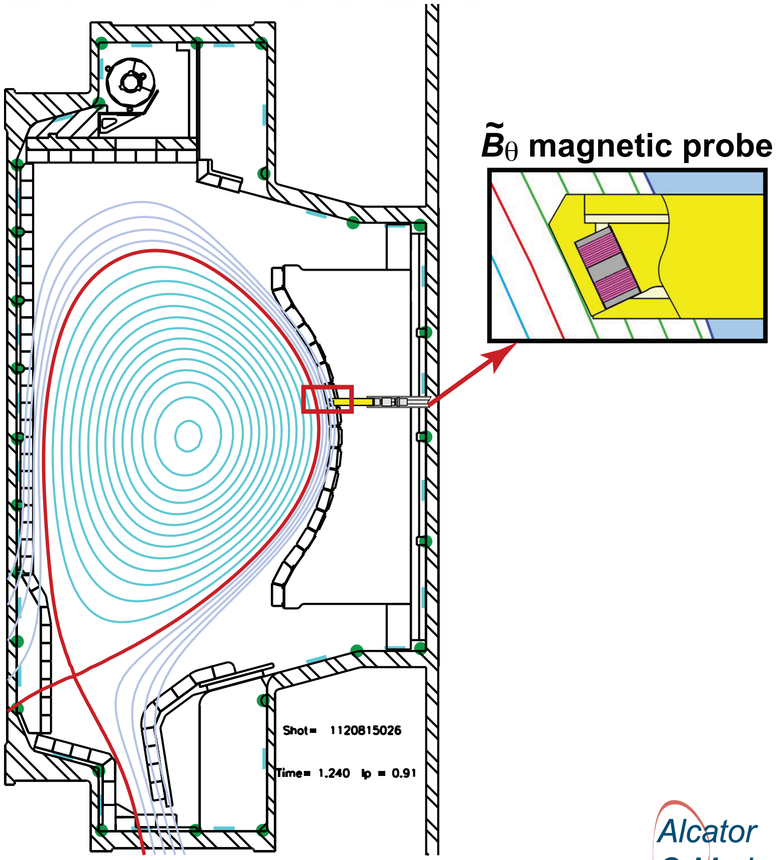
- **Outboard mid plane magnetic probe shows drop in fluctuations after an ELM**
- **Followed by a quiet period during which the density gradient recovers quickly**
- **Subsequently an onset and evolution of quasi-coherent fluctuations**
  - similar to the washboard modes on JET

Perez, PPCF 2004

DIII-D NATIONAL FUSION FACILITY

Pedestal Top Temperature (from ECE) Evolution is Correlated With Magnetic Fluctuation Amplitudes on C-Mod



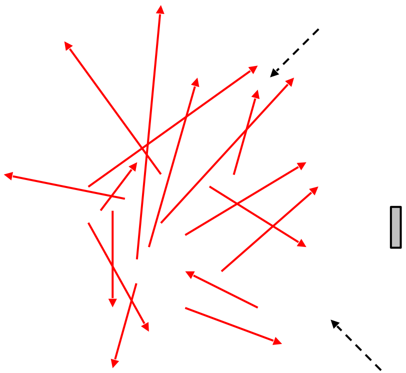


- **Pedestal temperature and QCF track each other**

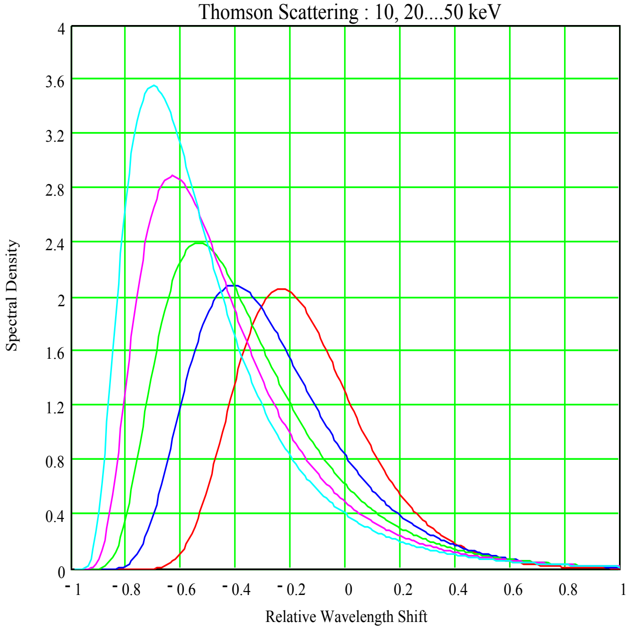
Alcator C-Mod

Thomson scattering: what's it all about?

Electrons: velocity distribution: hence, TEMPERATURE



?

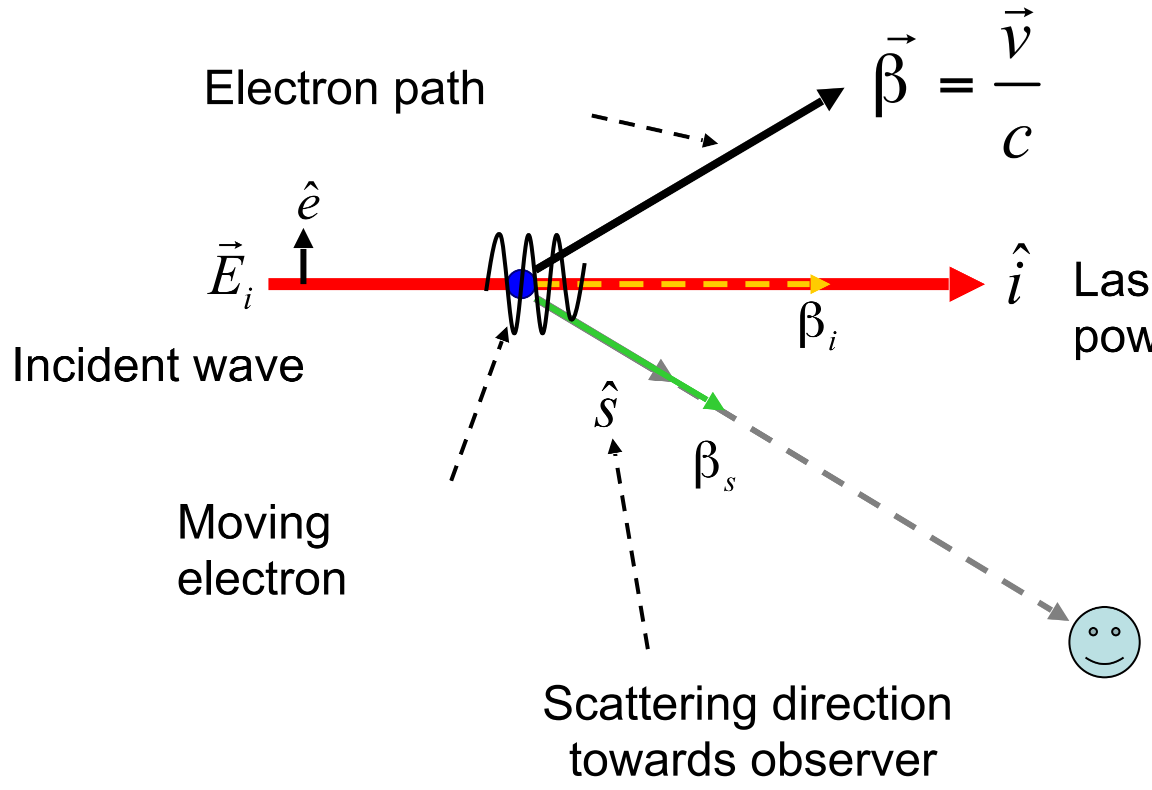


Plasma

Scattering volume

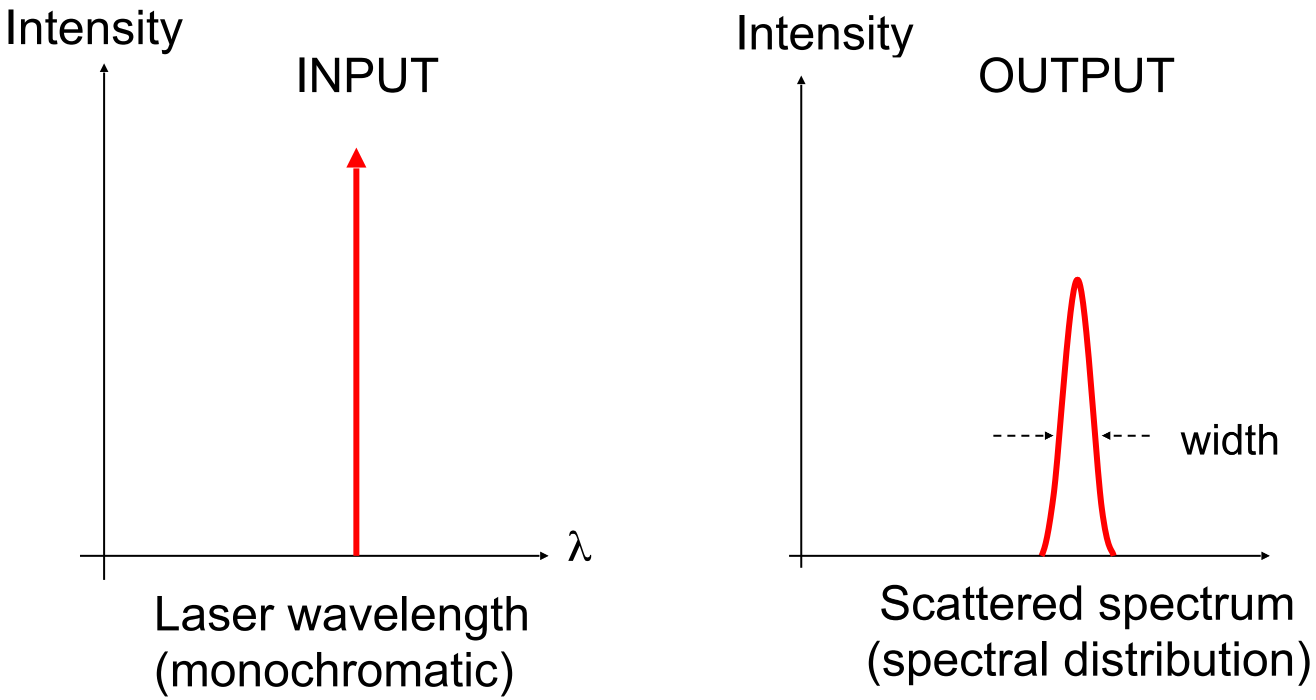
Scattered spectrum (hence; temperature of the plasma is known)

Another view: Vector form



Observer sees a frequency shift in the laser frequency due to the radiation scattered of the moving electron

Thomson Scattering



Width of the scattered spectrum is related to the plasma temperature

and the integrated intensity is proportional to the electron density

Thomson scattering is central to many analyses in fusion devices

- Thomson scattering is a robust and accurate diagnostic for local density & temperature measurements.
- *Limitations:*
  - Temporal resolution has been limited to tens of Hz @ Joule level energies.
  - Increase of this repetition rate is usually achieved by interleaving multiple lasers.
    - Difficult to scale in order to achieve kHz rep rate.
- In low and high temperature plasmas, **transient** physics require kHz rep rate lasers.

Outline

- Two approaches to achieve fast temporal resolution @ Joule level energies.
  - Thin disk

    Immune to thermal lensing and capable of 1 kHz - ongoing work
  - Flashlamp (this talk)

    Limited to fast burst but capable to achieve tens of kHz.

- Characterization of the pulse burst laser system.

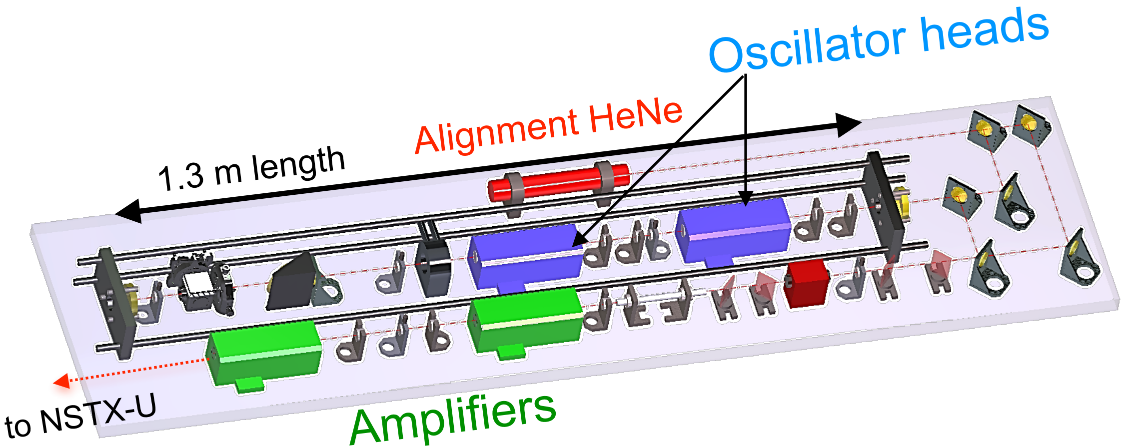
- Benefits of synergy between TS and modern x-ray-based impurity measurements.

Fast Thomson scattering measurements can be achieved using a pulse burst laser system (PBLS)

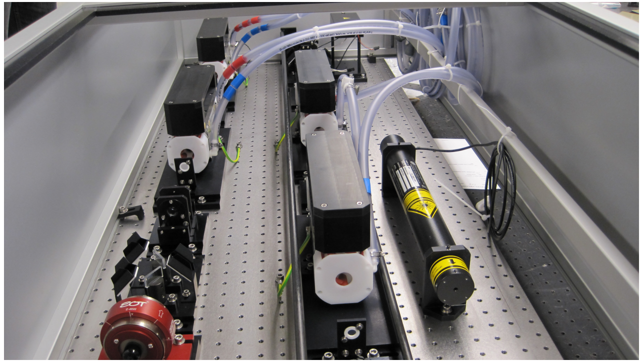
- PBLS has been pioneered at Madison Symmetric Torus (MST).

D J Den Hartog, J R Ambuel, M T Borchardt, J A Reusch, P E Robl, and Y M Yang
Journal of Physics: Conference Series 227 (2010) 012023

- On NSTX-U, we plan to **A** extend the pulse duration and, **B** add a baseline mode to increase the regular (60 Hz) TS temporal resolution.
  - PBLS will enhance the existing TS system



Picture of the laser head



Pulse burst laser - Design parameters

- Pulse energy ⇛ 1.5 J per pulse.
  - Pulse width ⇛ 10 ns (FWHM).
  - Beam diameter ⇛ 10 mm @ 0.5 mrad.
- Three modes of operation.
  - Base mode @ 30 Hz to be compatible with the current NSTX-U rep rate.
  - Slow burst mode: 1 kHz rep rate for 50 ms.
  - Fast burst mode: 10 kHz rep rate for 5 ms.

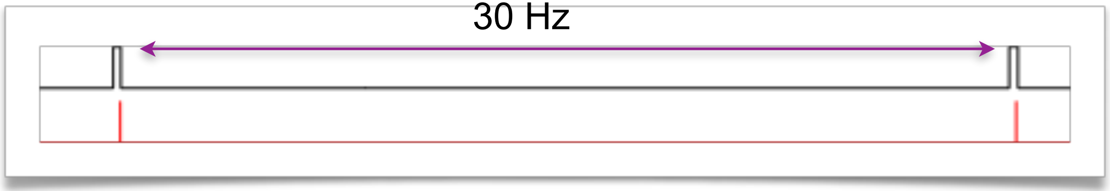
  } **Limited by thermal lensing**
- Take advantage of Nd:YAG larger rod diameter (9 & 12 mm) for thermal inertia.

Three of modes of operation have been implemented

Baseline

Flashlamp

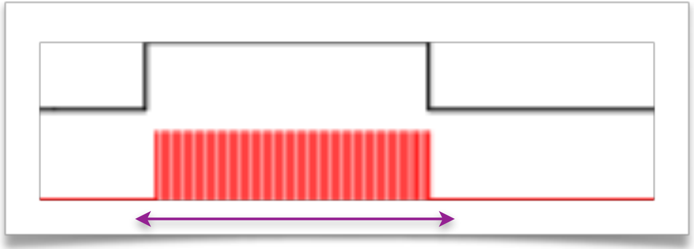
Q-switch



1 kHz for 50 ms

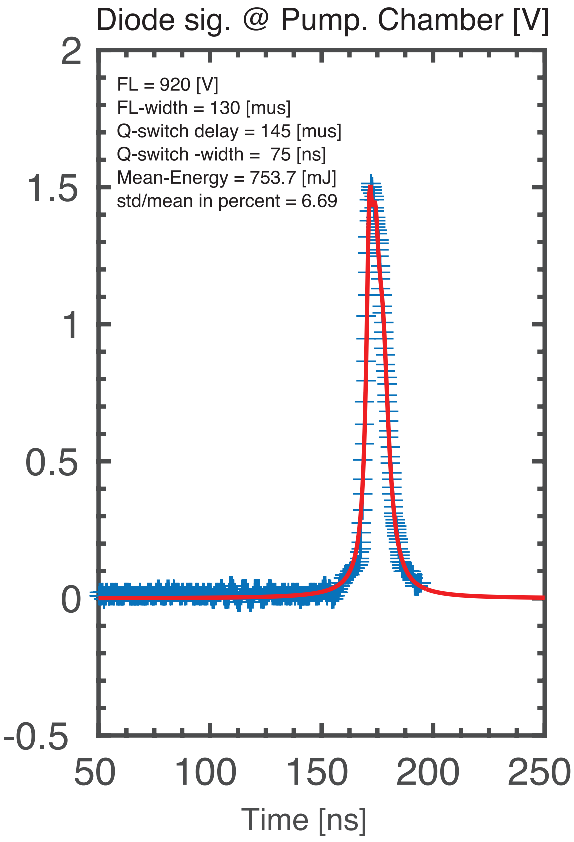
Slow burst

Fast burst



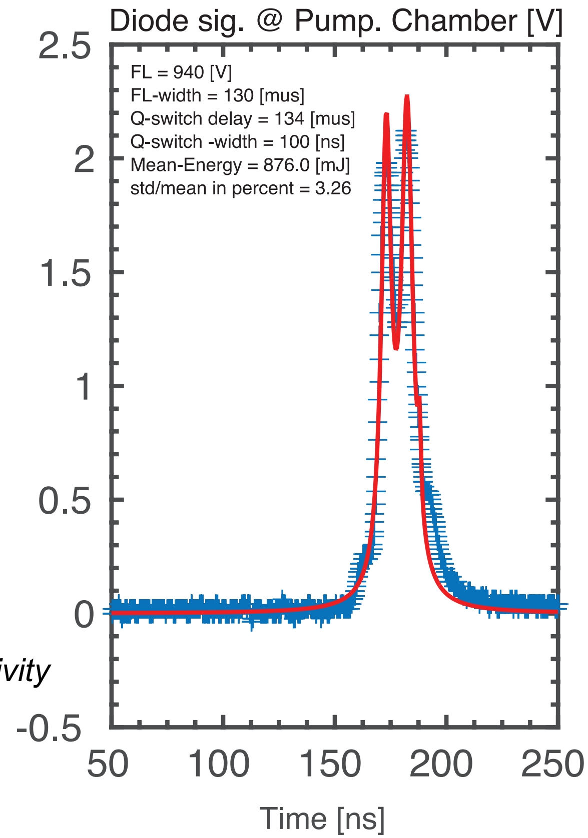
10 kHz for 5 ms

Two types of pulse shape have been observed at the exit of the oscillator

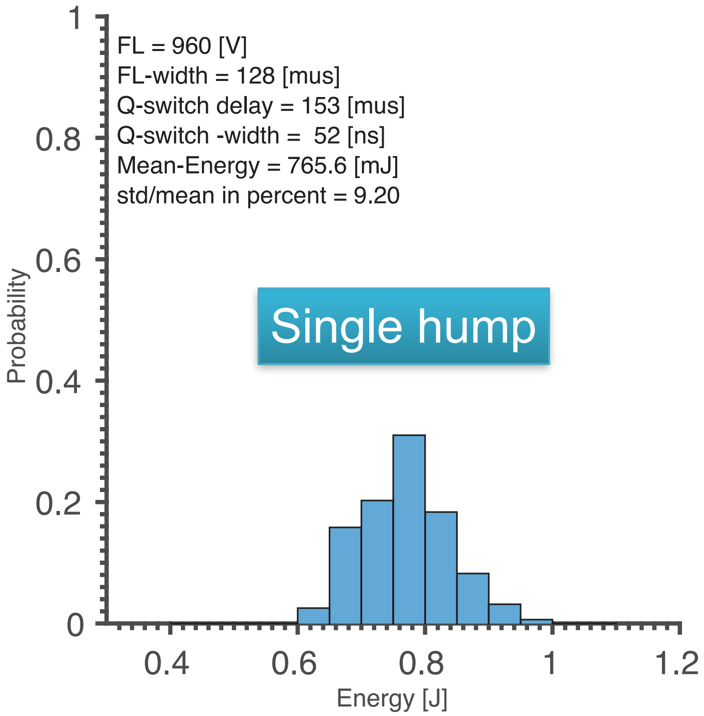


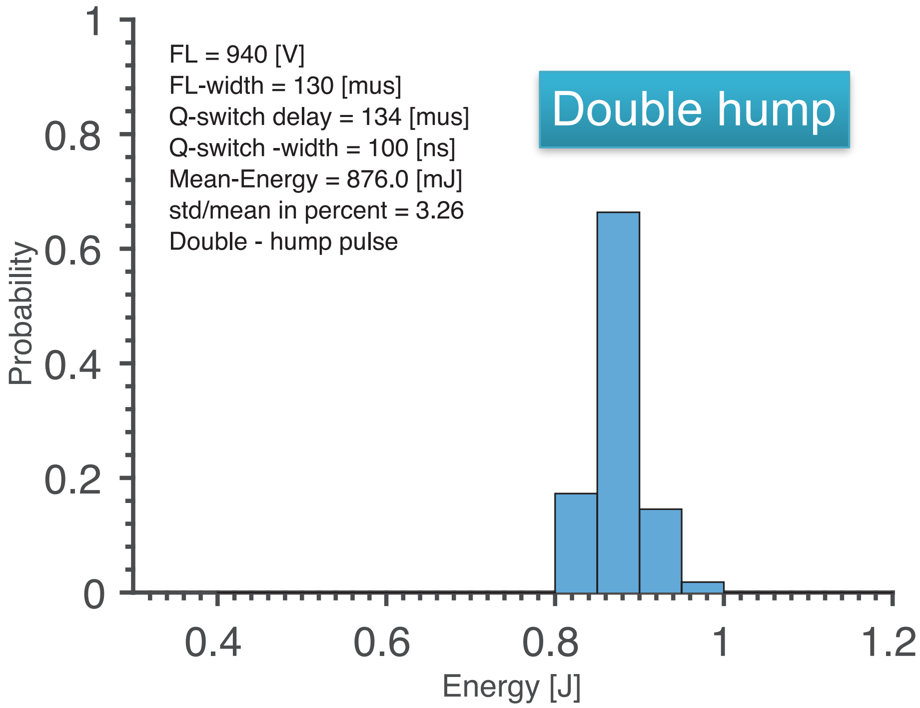
- Single and double hump pulses.
- Minimal impact of the NSTX-U TS analysis.

Laser head can in principle produce a stable single-hump pulse by optimizing the oscillator output coupler reflectivity (subject of future upgrade)

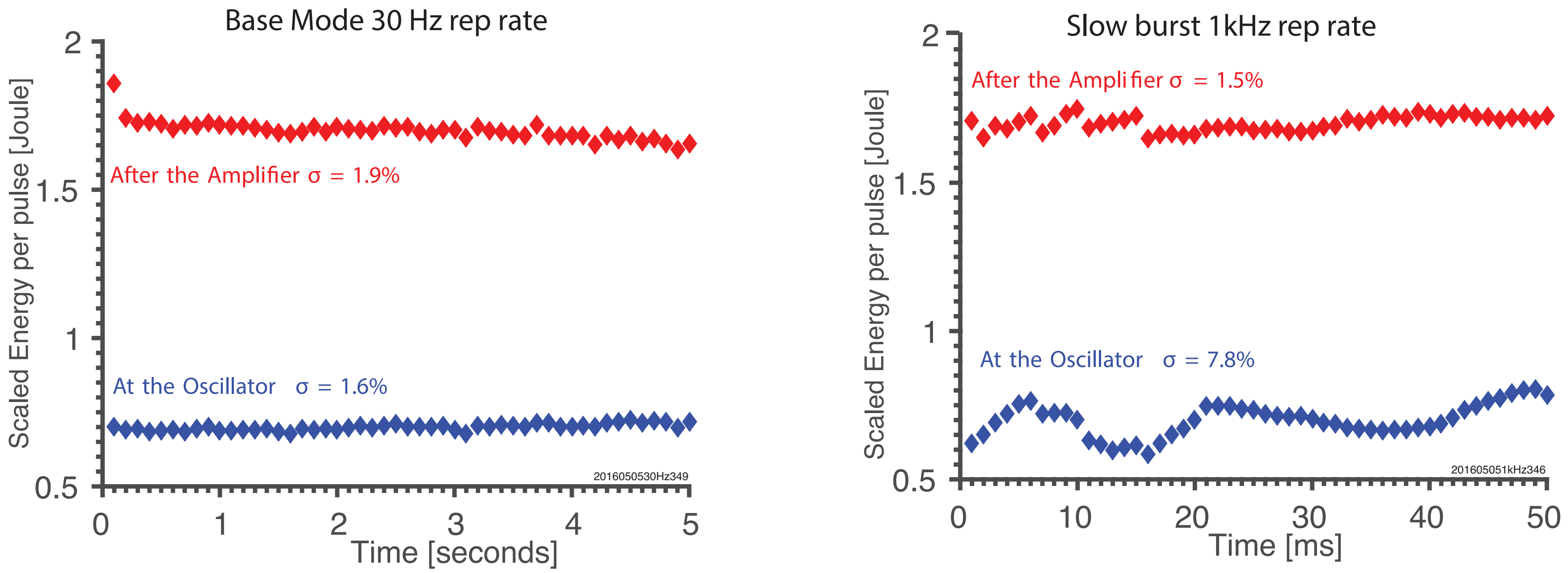


Double hump pulse exhibits a better pulse-to-pulse energy reproducibility

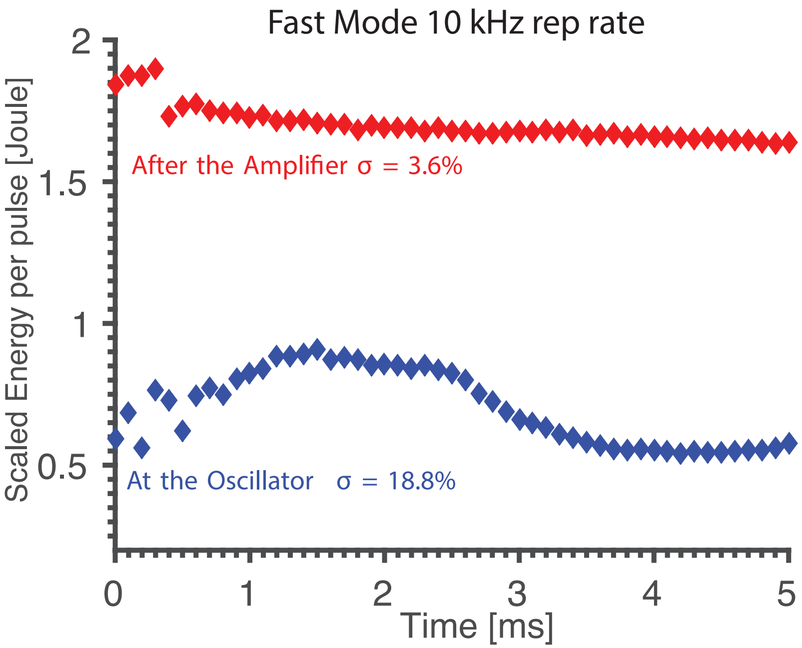


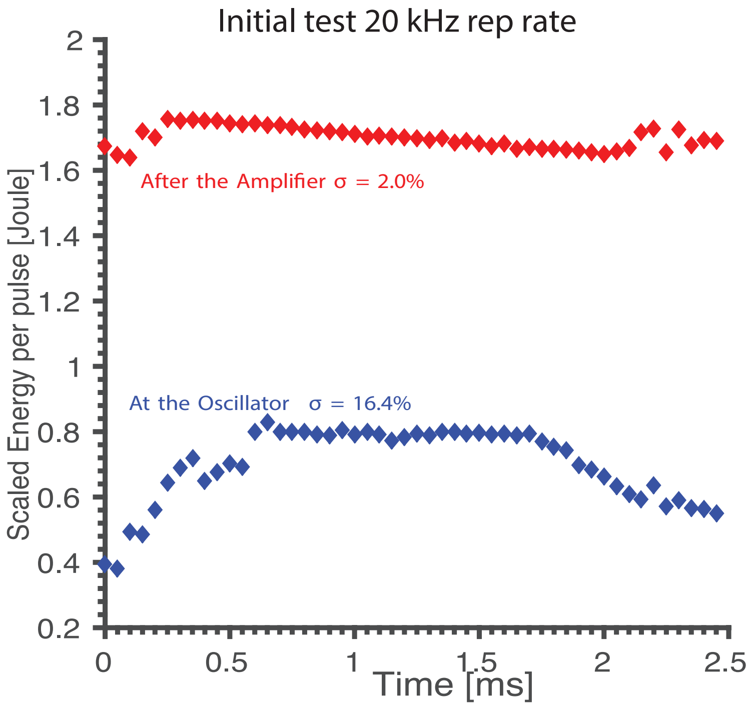


Energy levels needed for the base and slow burst modes were achieved

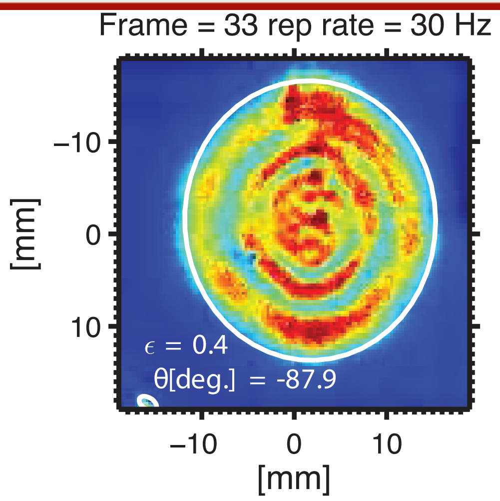


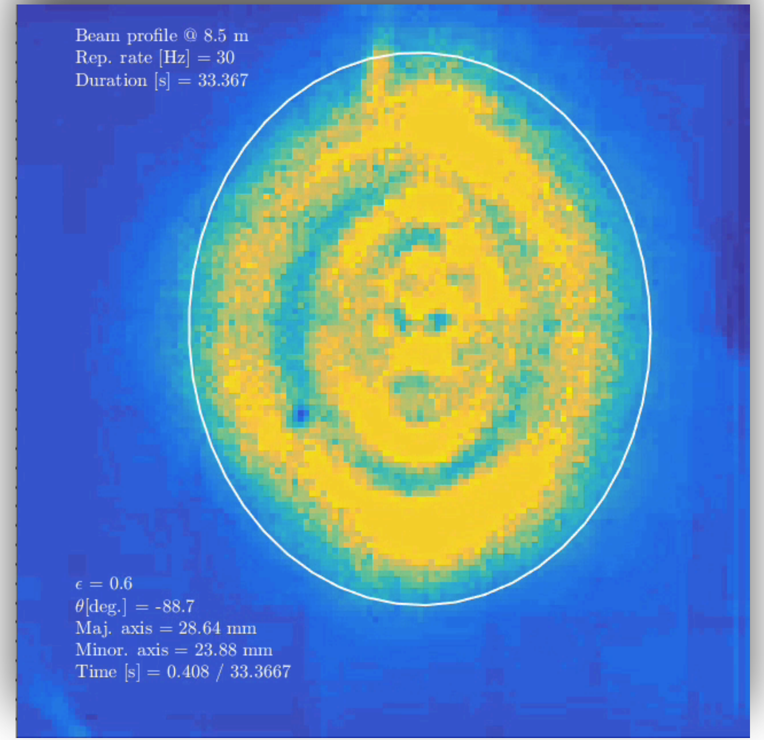
Similar reproducibility are obtained for two fast bursts scenarios: 10 kHz & 20 kHz





Base mode exhibits good beam profile and far field stability *(Imaging a reticle at 8.5 m)*





Key beam profile parameters using fast framing camera

Major & minor axis
Tilt of major axis
Pointing stability

Thanks to F. Scotti , R. Perkins, M. Jaworski, for the initial assistance in operating the camera.

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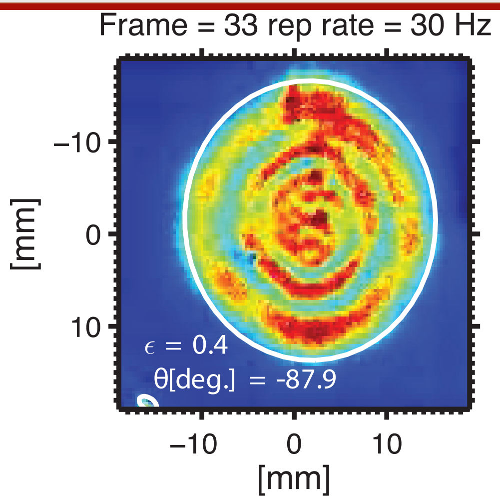

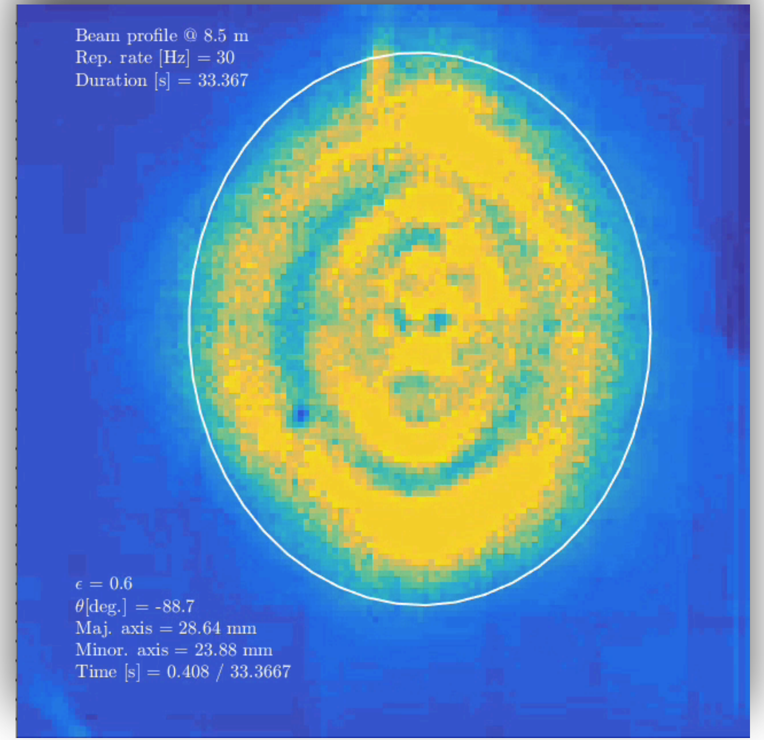

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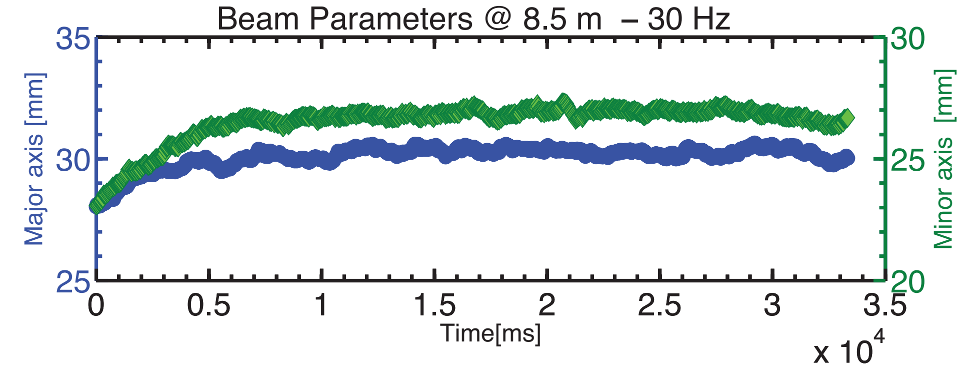
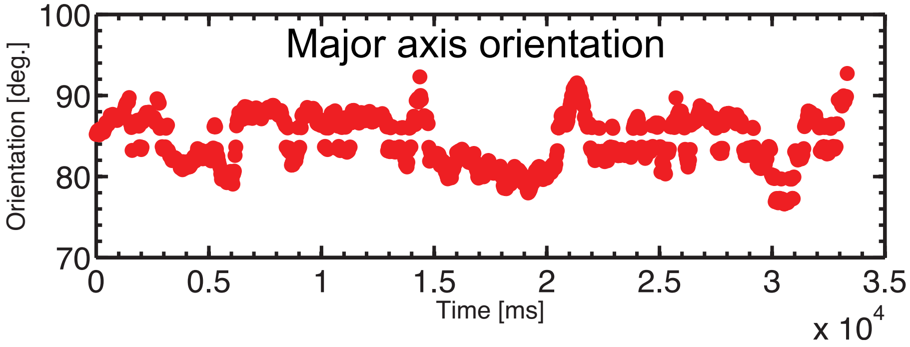
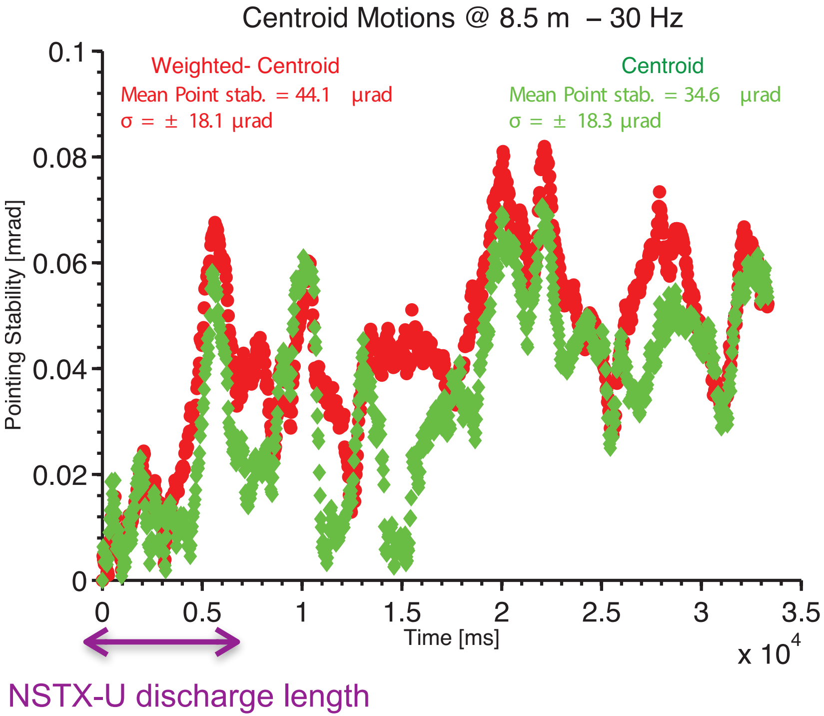
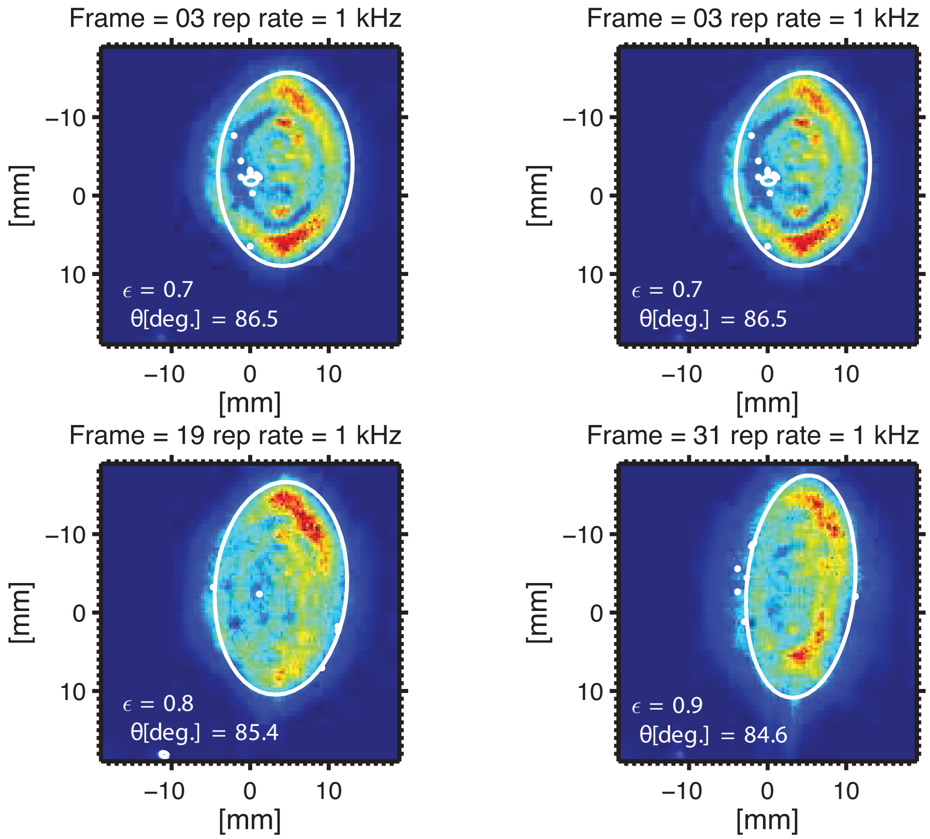
Beam parameters in far field field for base mode are similar to commercially available laser properties

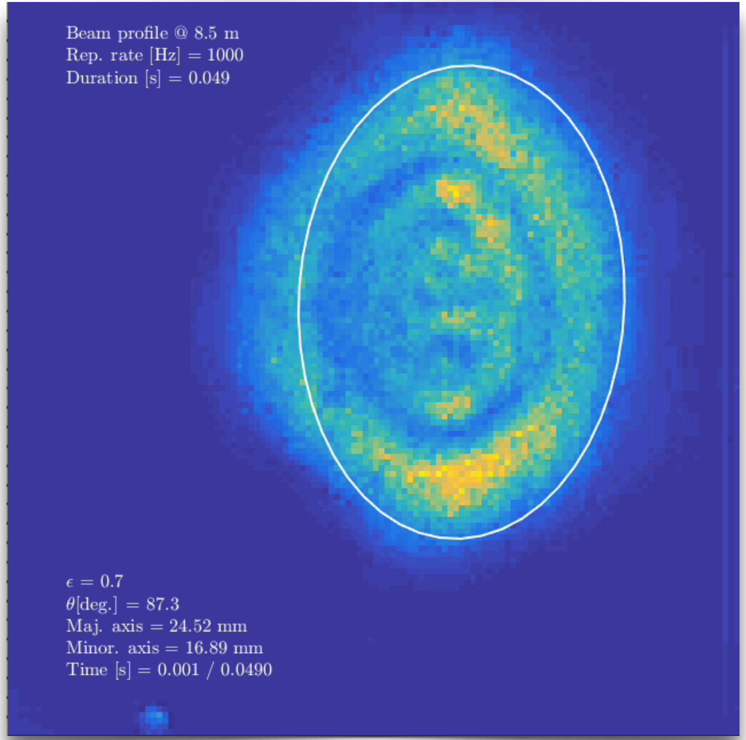






Slow burst mode exhibits an elongated beam profile in the far field





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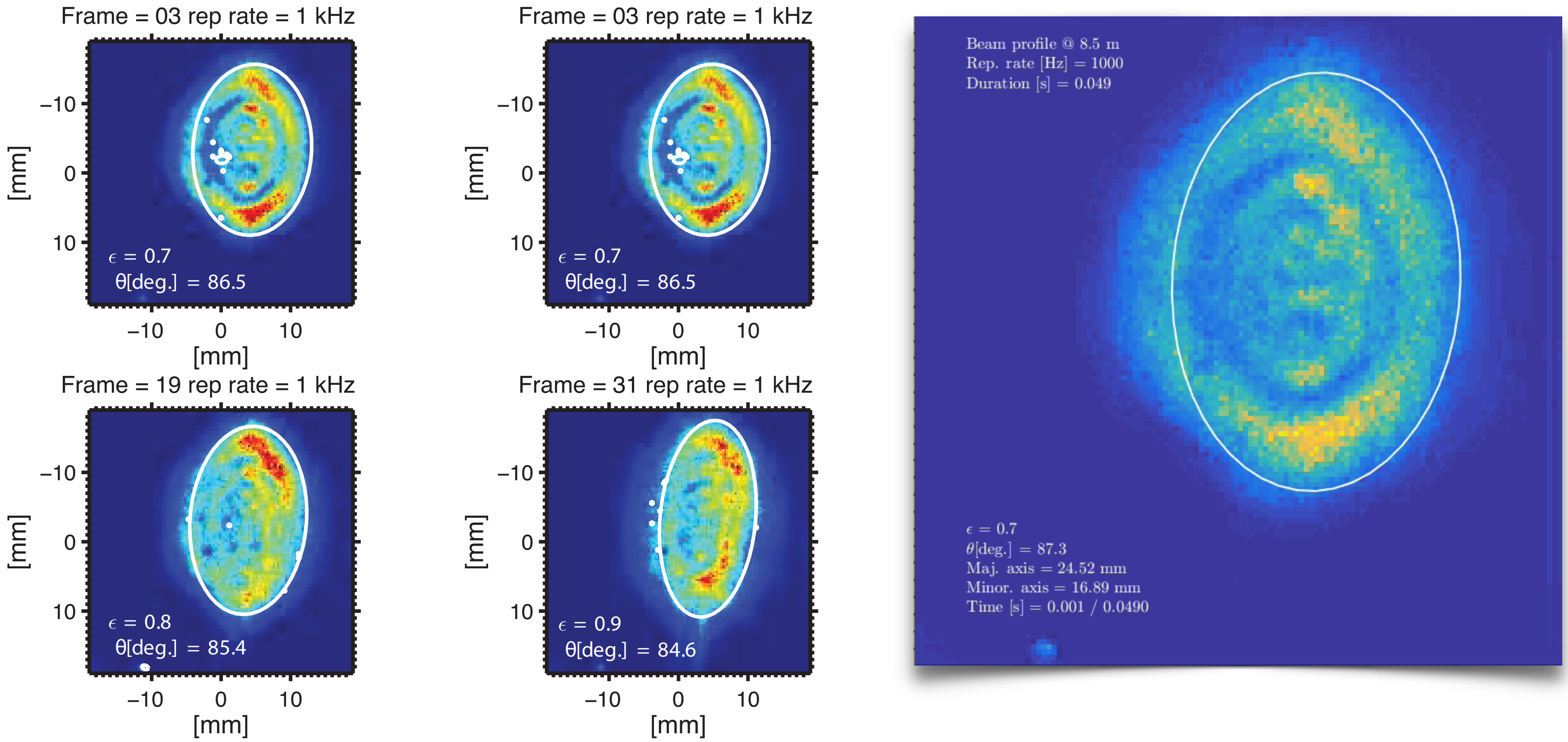
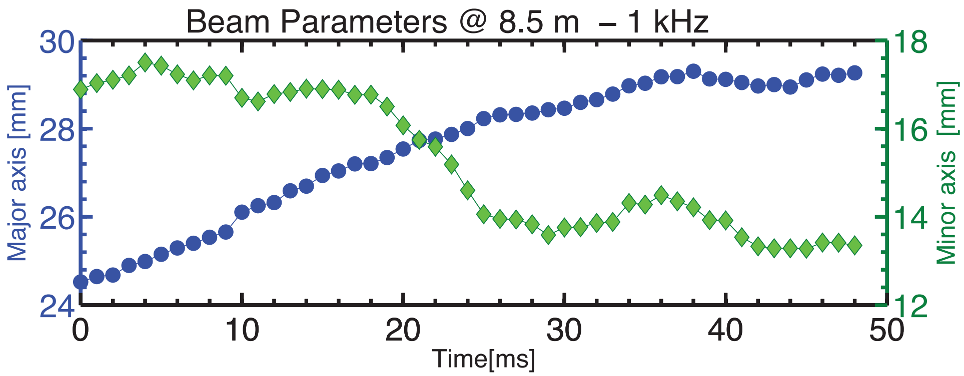
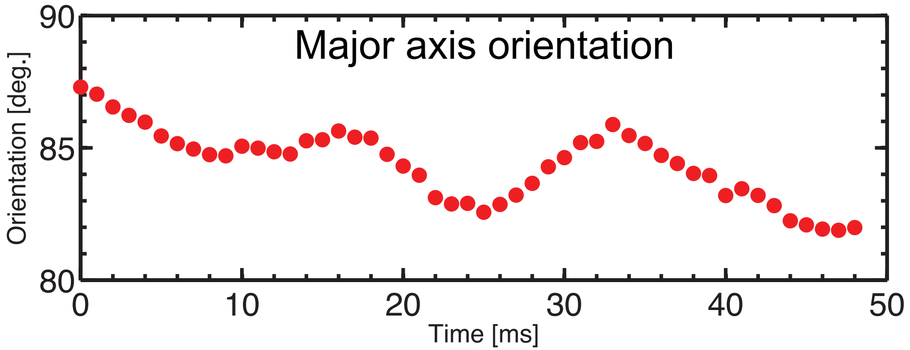
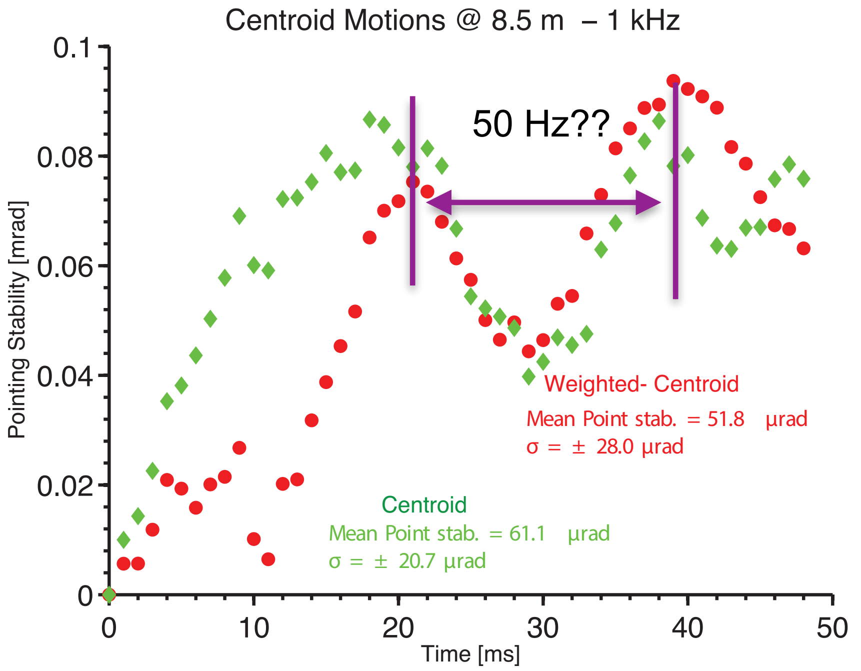


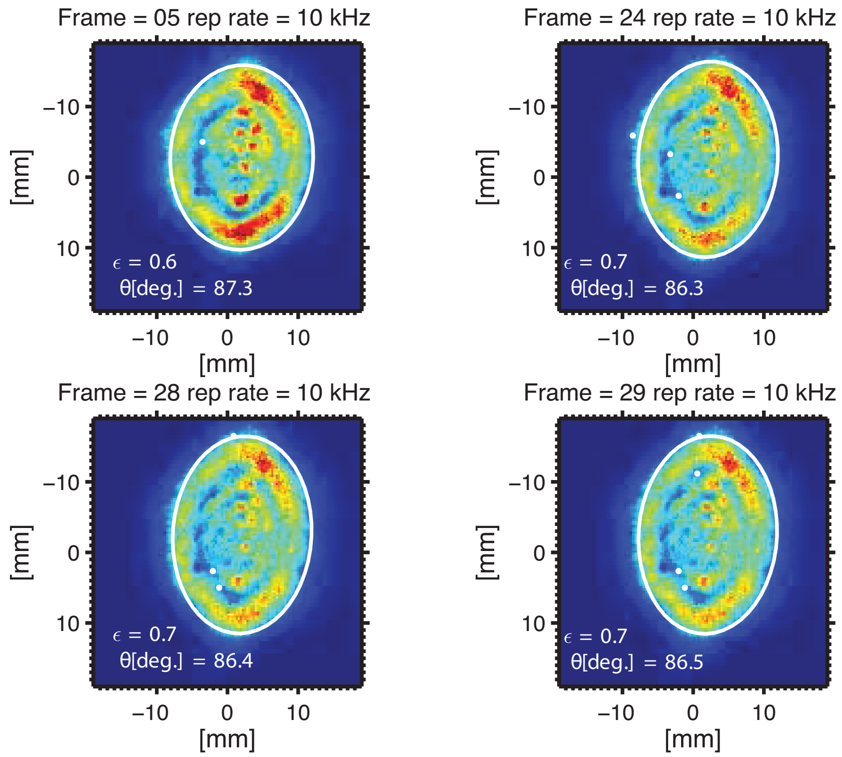
Beam parameters in far field field for the slow burst exhibits some slight focussing

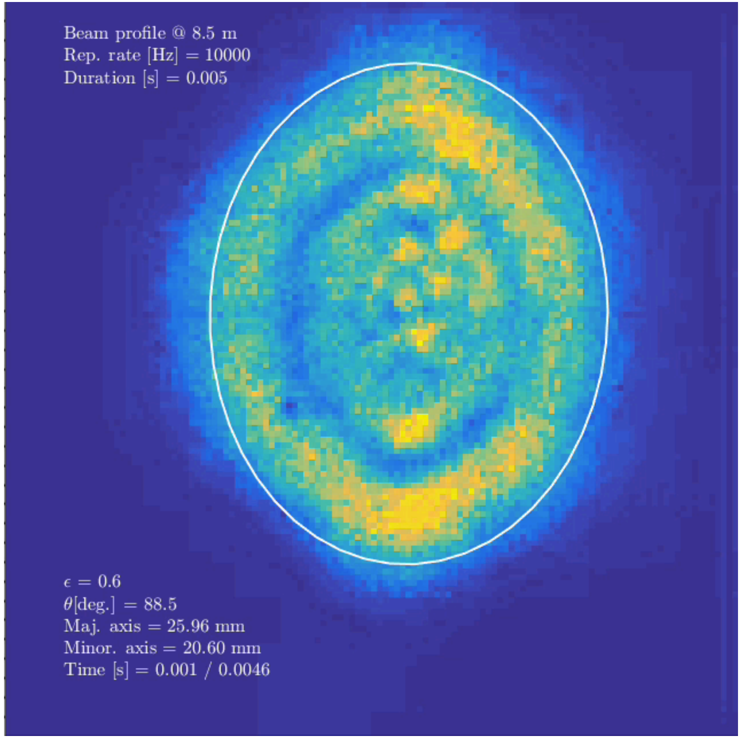






Fast burst mode was successfully achieved with good far-field beam properties





Fast burst was successfully extended to 20 kHz & 27 kHz

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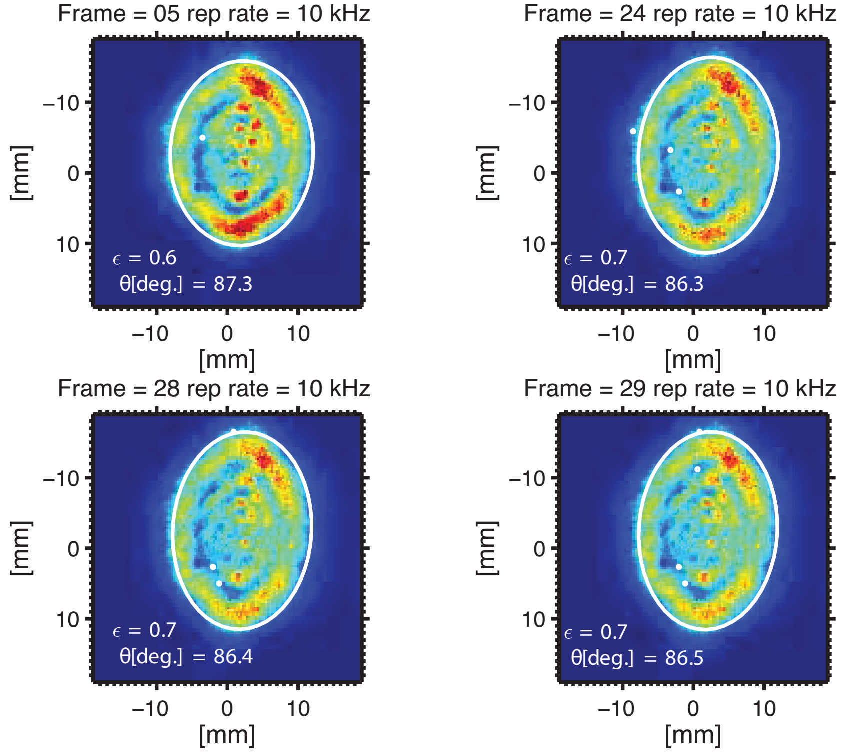

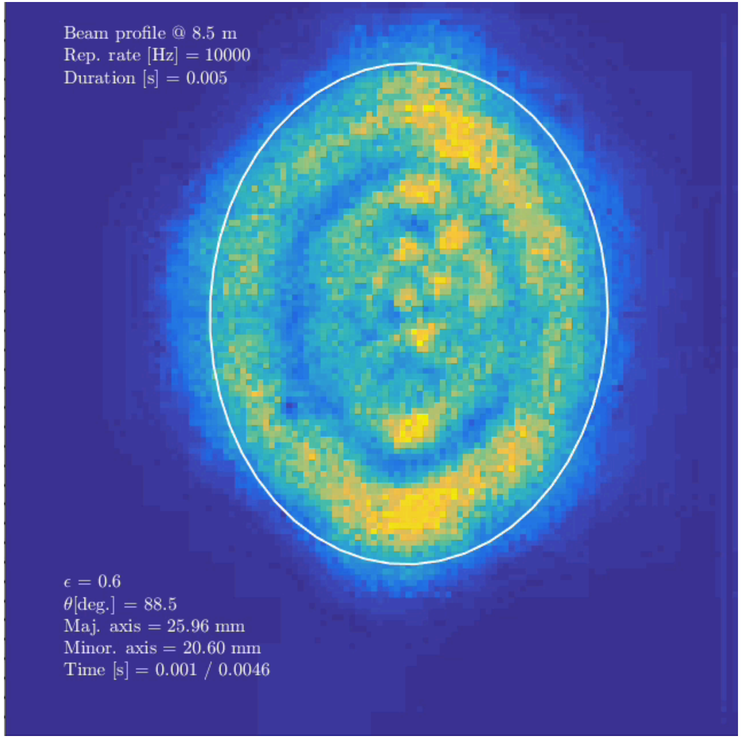

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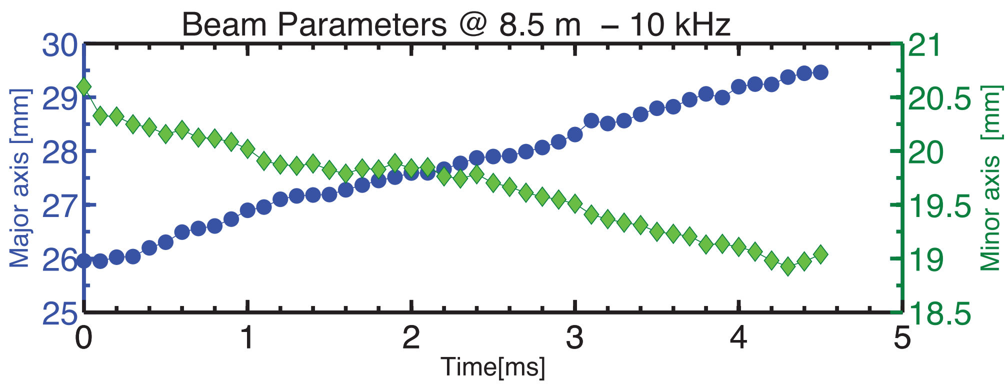
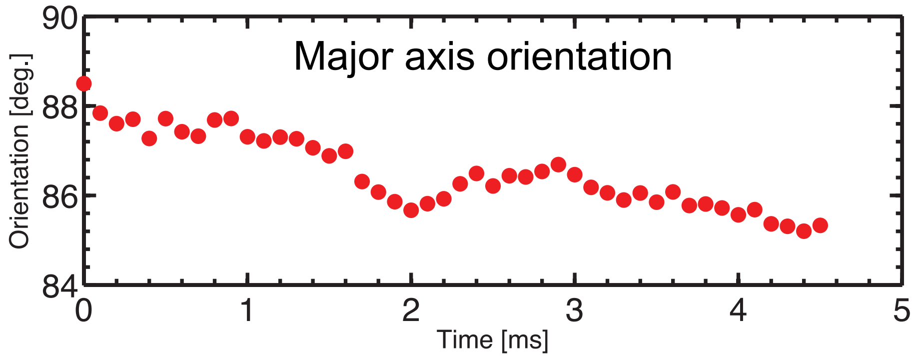
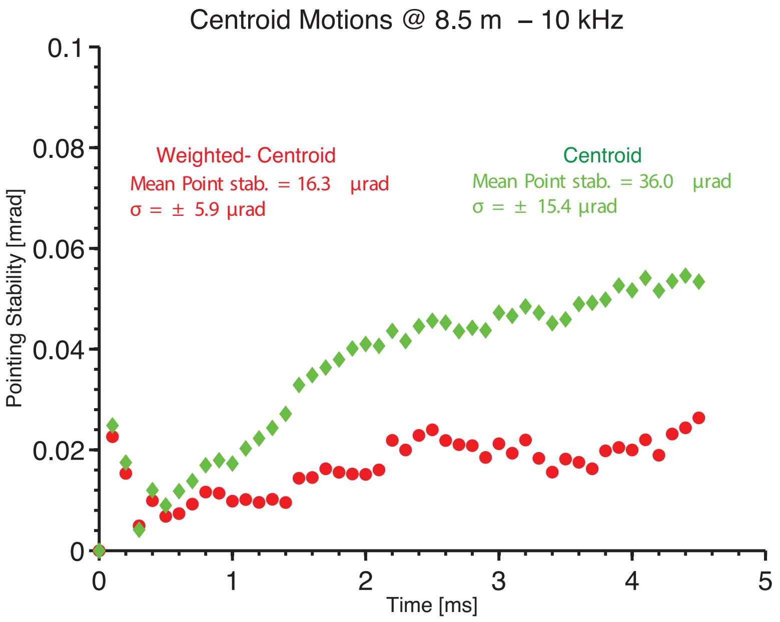
Summary of beam parameters in far field field for fast burst







Fast burst laser system will enable study of a wide range of transient physics

- Good progress in the R&D of the fast laser system for NSTX-U.
  - Good pulse-to-pulse variability at 1.5J/pulse & good beam characteristics in the far field.
  - Capable of operating at up to 27 kHz in burst mode - Ready for next NSTX-U campaign!
- This laser system will offer new **time** resolved measurements capabilities:
  - Fast transients in fusion devices
    - ELM onset physics (≲ 1ms).
    - MHD, *e.g.*, kink and tearing modes (~ sub ms).
    - Disruption physics (~ sub ms).
    - L-H, L-I-H, transitions (≲ 1 ms)
    - Probe the electron distribution induced by RF.
    - Fast ion physics, *e.g.*, density and temperature displacements induced by TAE modes in ST.
    - Edge turbulence (few kHz).
  - Can be extended to low temperature plasma to resolve
    - Spokes in Hall thrusters.
    - Magnetic reconnection experiments.