



Filamentary transport in high-power H-mode conditions and in no/small-ELM regimes to predict heat and particle loads on PFCs for future devices

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Objectives:

1. Use the new HHF probe on AUG to study filamentary transport under high-power H-mode conditions and under different plasma configurations (SN, DN).
2. Study the role of ELM regimes, neutral compression, and particle density in filamentary transport and related shoulder formation.
3. Identify the contribution of collisionality and seeding on filamentary transport and related shoulder formation.
4. Extend the studies to quiescent H-modes as well as to other small-ELM regimes.
5. Determine the effect of filaments and shoulder formation on target heat loads in different H-mode plasmas.
6. Investigate the effect of plasma shape and configuration on ELM-induced heat loads.

Motivation: Particle and energy transport in the SOL is crucial for the lifetime of plasma facing components in ITER and DEMO

Outline



- ✓ Background
- ✓ Plans (we will not make a detailed list of the proposal, we already tried to combine and summarize them)
- ✓ Discussion

BACKGROUND

Present status





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5. Studies of shoulder formation in H-Mode are so far limited

L-MODE

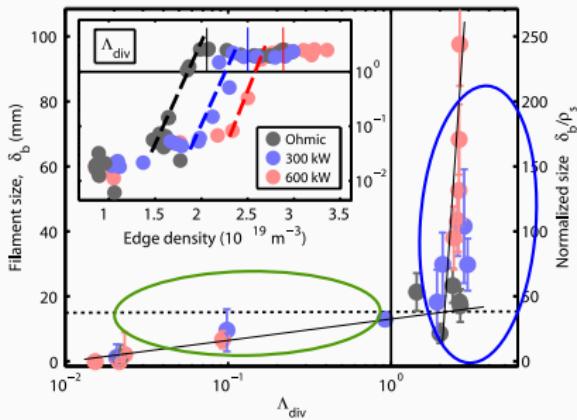
L-Mode studies: AUG/I



- ✓ AUG and JET (Carralero *et al.* 2015) suggest that divertor collisionality

$$\Lambda_{\text{div}} = \frac{L_{\parallel}/c_s}{1/\nu_{ei}} \frac{\Omega_i}{\Omega_e}$$

controls filaments size



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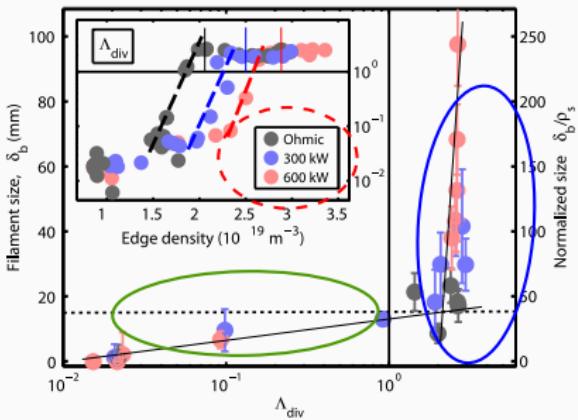


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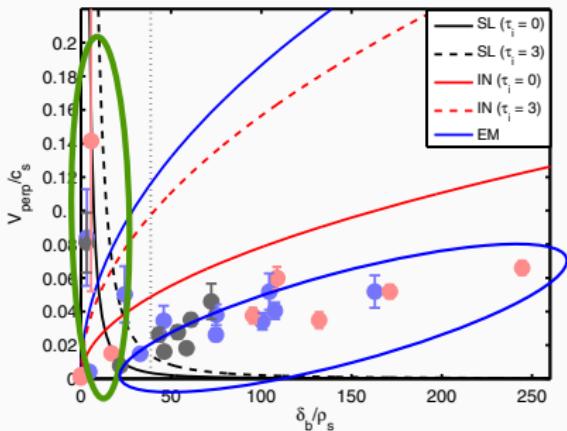


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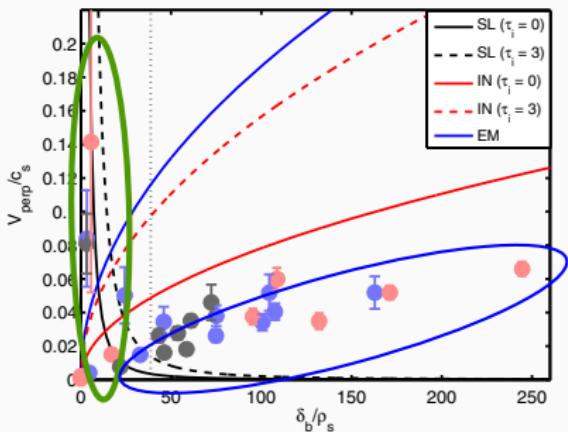


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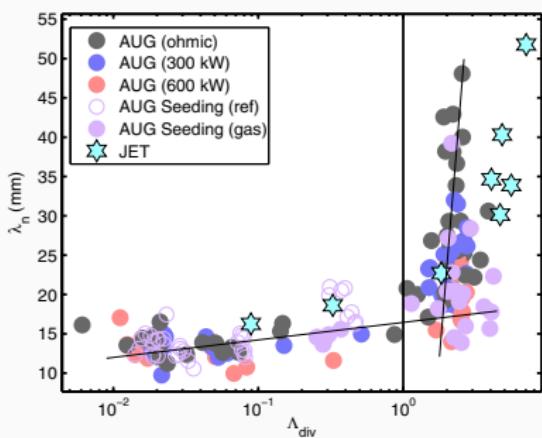


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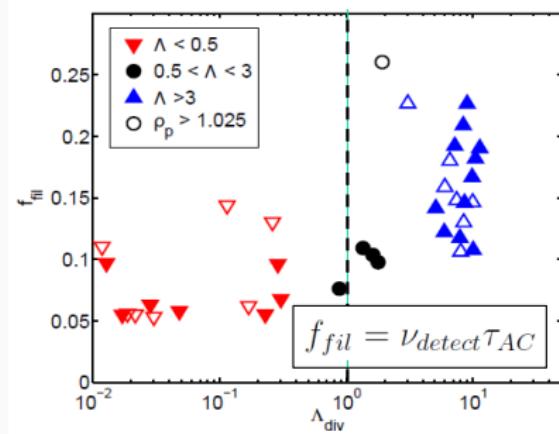
- ✓ Tested by changing n_e and T_e through fueling/seeding/heating
- ✓ This determines a change of the velocity-size scaling from sheath-limited to inertial regime. Λ_{div} rules the density profile scale length
- ✓ This finally determines the shoulder formation



L-Mode studies: AUG/2



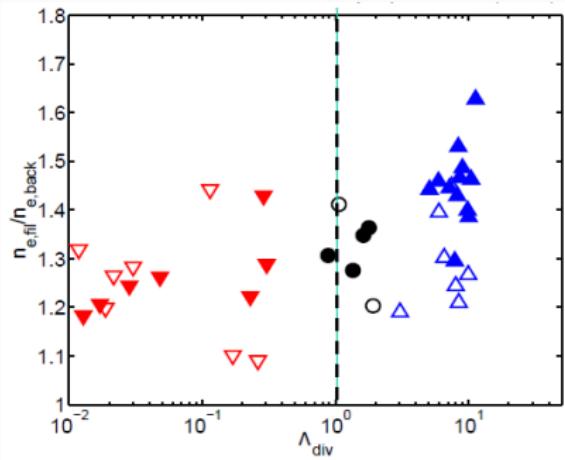
- ✓ Profile modified by an increase of blob-size and change of packing fraction: $f_{fil} = \nu_{fil} \tau_{AC}$



L-Mode studies: AUG/2



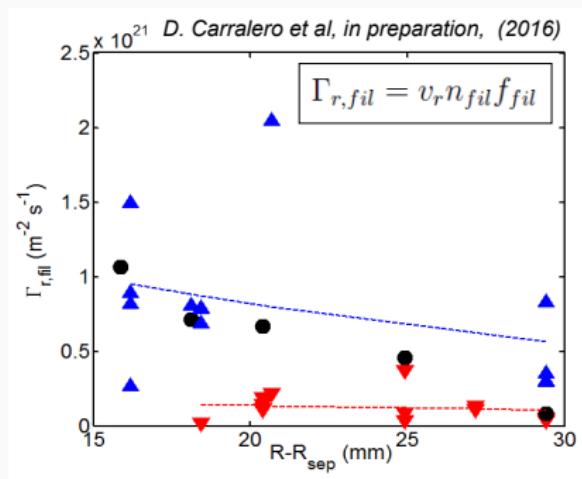
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L-Mode studies: AUG/2



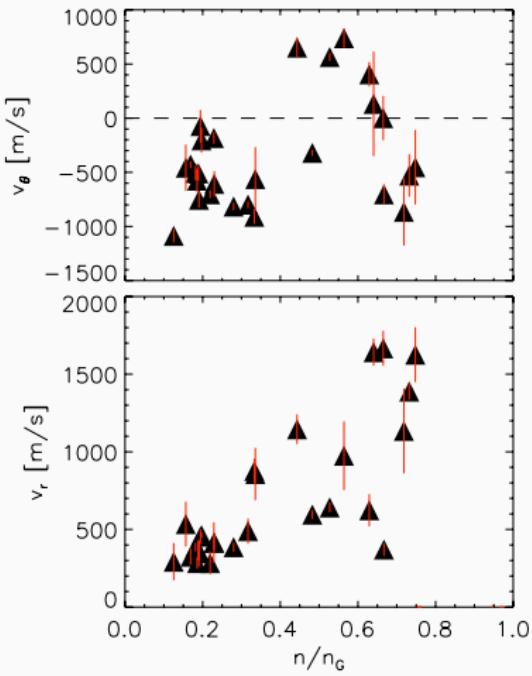
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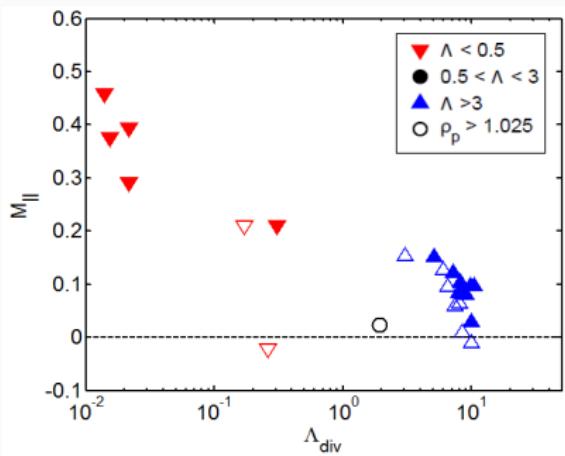
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- ✓ Beware the change of frequency may be due to a modification of fluctuation velocity which is known to vary with densities ad normalized greenwald fraction (Agostini et al. 2011)



L-Mode studies: AUG/2



- ✓ Profile modified by an increase of blob-size and change of **packing fraction**: $f_{\text{fil}} = \nu_{\text{fil}} \tau_{AC}$ and **filament relative density** (Carralero 2016 in preparation)
- ✓ As a consequence the contribution of filaments to radial transport increases
- ✓ Parallel flow is strongly reduced whenever we increase the divertor collisionality



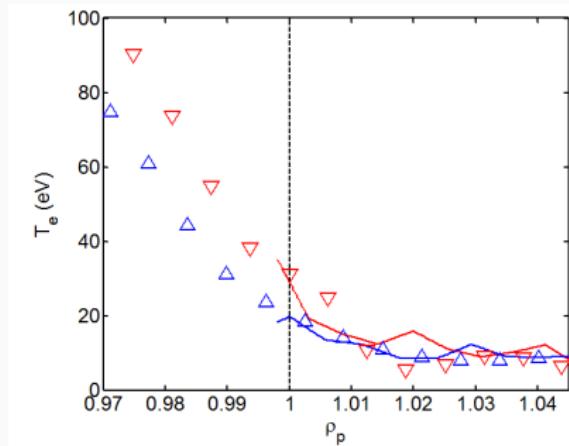


- ✓ Electron and ions behave differently

L-Mode studies:AUG/3



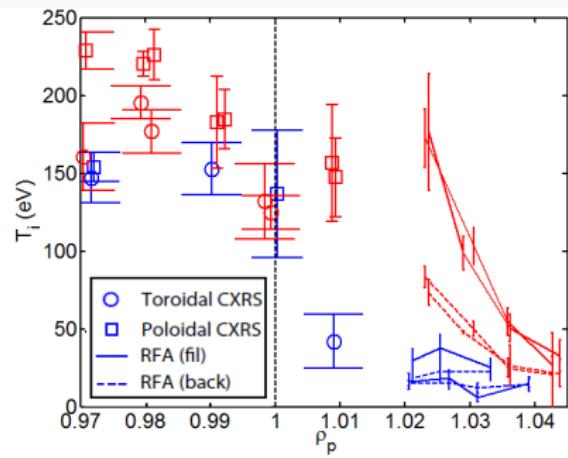
- ✓ Electron and ions behave differently
- ✓ $T_{e,fil} \sim 1.2T_{e,bk}$ roughly constant across the SOL and slightly affected by the increase of divertor collisionality



L-Mode studies:AUG/3

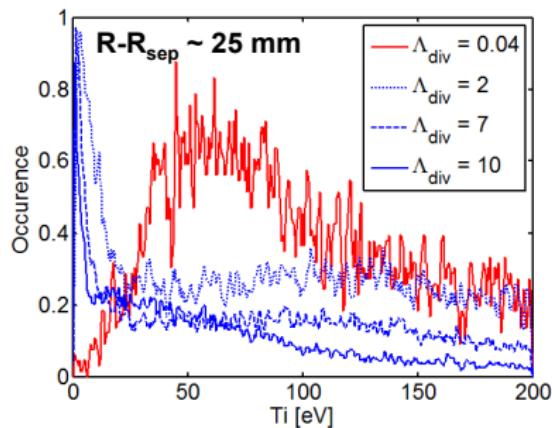


- ✓ Electron and ions behave differently
- ✓ Ions are strongly affected: for $\Lambda_{div} < l$
 $T_{i,fil} > T_{i,bk}$ and $\lambda_{T_i} \sim 30$ mm.
 $\Lambda_{div} > l$ $T_{i,fil} \sim T_{i,bk} \sim 25$ eV and
 $\lambda_{T_i} \sim 8$ mm





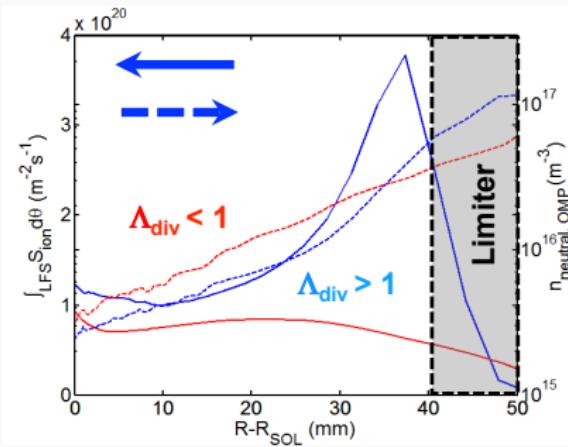
- ✓ Electron and ions behave differently
- ✓ Ion energy spectrum from $\mathbf{E} \times \mathbf{B}$ analyzer shrinks towards lower energy for $\Lambda_{\text{div}} > 1$



L-Mode studies:AUG/3



- ✓ Electron and ions behave differently
- ✓ Ion energy spectrum from $\mathbf{E} \times \mathbf{B}$ analyzer shrinks towards lower energy for $\Lambda_{\text{div}} > 1$
- ✓ EMC3-Eirene simulation suggests that such a reduction can't be accounted for thermalization process. An ionization front builds in front of the limiter shadow





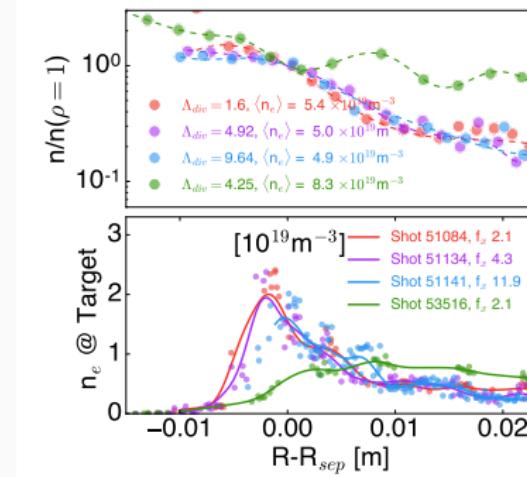
- ✓ Flexibility has allowed to test Λ_{div} dependence on L_{\parallel} by varying flux expansion f_x :

$$f_x = \frac{(B_p/B_t)_{MP}}{(B_p/B_t)_{SP}}$$

in ohmic density ramps (Vianello *et al.* 2016)

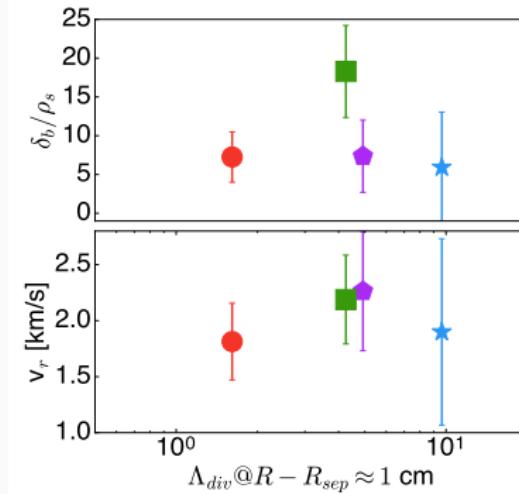


- ✓ Slight variation of density profiles at the target but due to direct dependence on L_{\parallel} large increase of Λ_{div} . Upstream profiles only varies whenever we reach a certain amount of $\langle n_e \rangle$



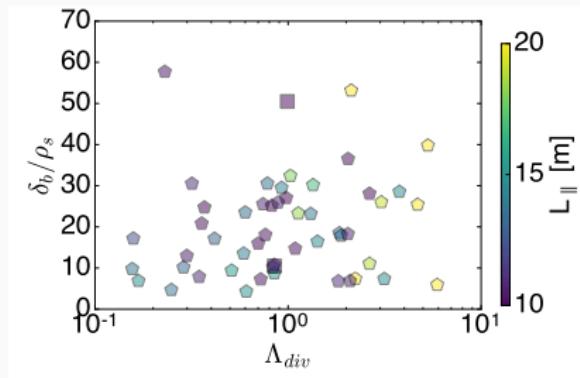


- ✓ Weak dependence of blob-size from Λ_{div} ,



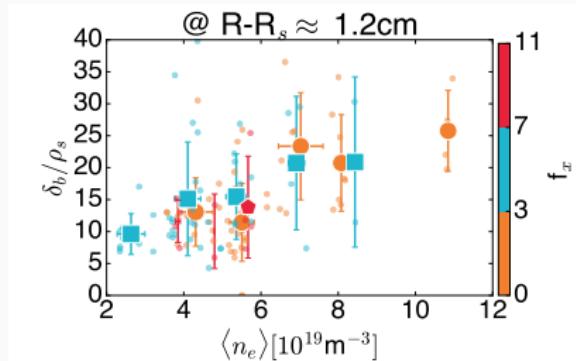


- ✓ Weak dependence of blob-size from Λ_{div} , also on a statistical basis.



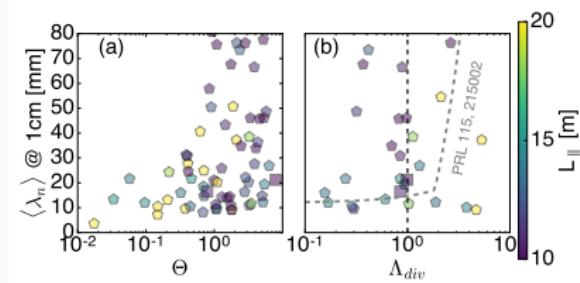


- ✓ Weak dependence of blob-size from Λ_{div} , also on a statistical basis. Strong dependence on average density, independent of L_{\parallel}



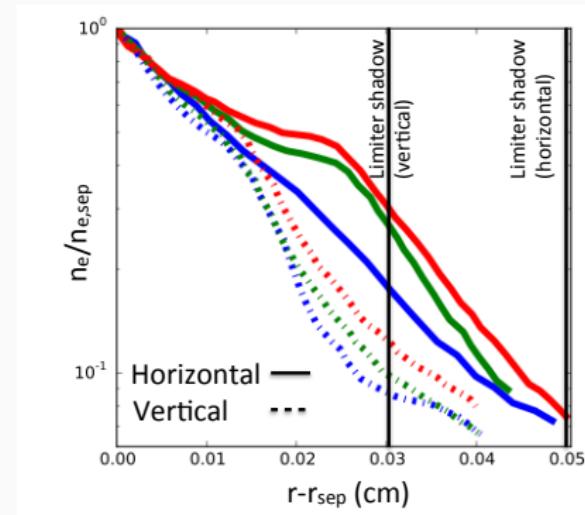


- ✓ λ_n depends clearly on blob-size whereas the dependence on divertor condition is less obvious. Λ_{div} necessary but not sufficient



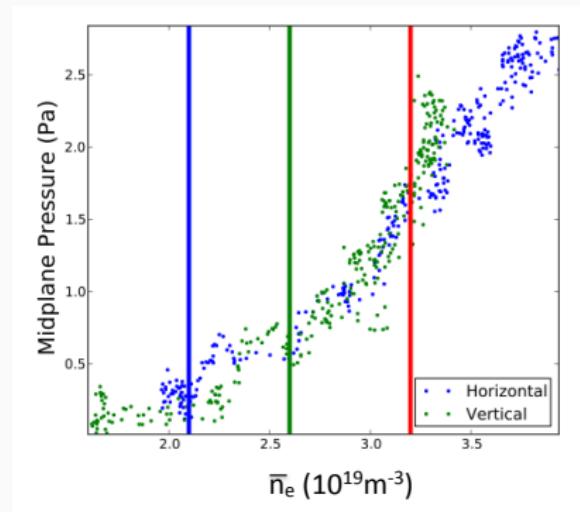


- ✓ The shoulder formation strongly depends on divertor geometry, disappear with vertical target and strike point closest to cryogenics pumps (Wynn et al. 2016)



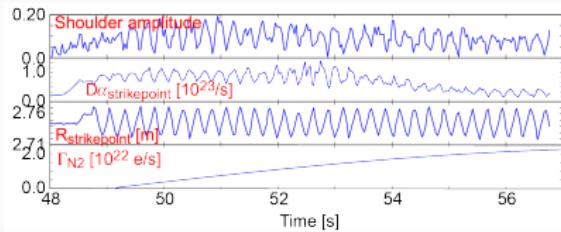


- ✓ The midplane pressure from baratrons is equivalent between the different divertor. This would indicate that SOL neutral density at the outboard midplane does not play any role



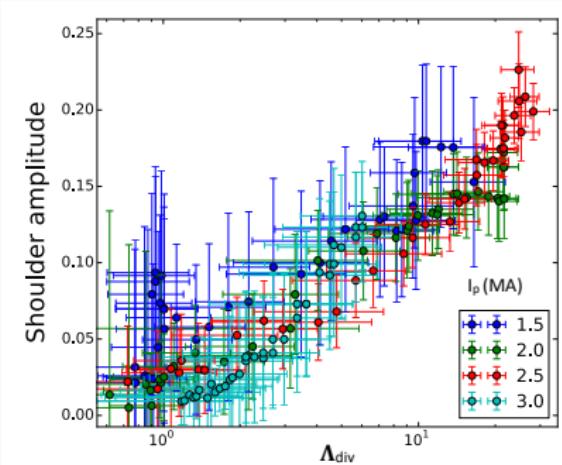


- ✓ In the horizontal target configuration the results indicate that the shoulder forms right at the transition from sheath-limited to high-recycling where also Λ_{div} strongly increase



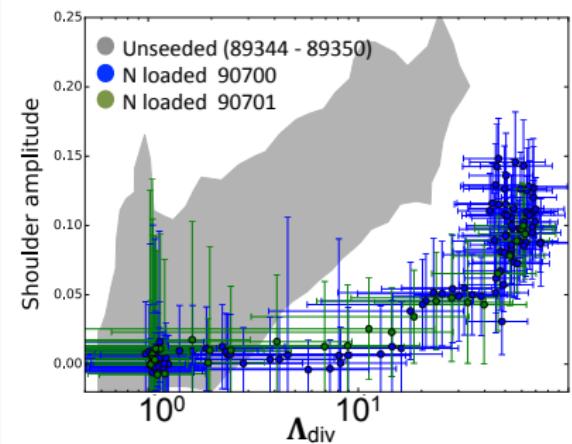


- ✓ Shoulder amplitude correlates with strike points position. Shoulder, ionization and $\Gamma_{ion,plate}$ larger when R_{strike} smaller away from the pump



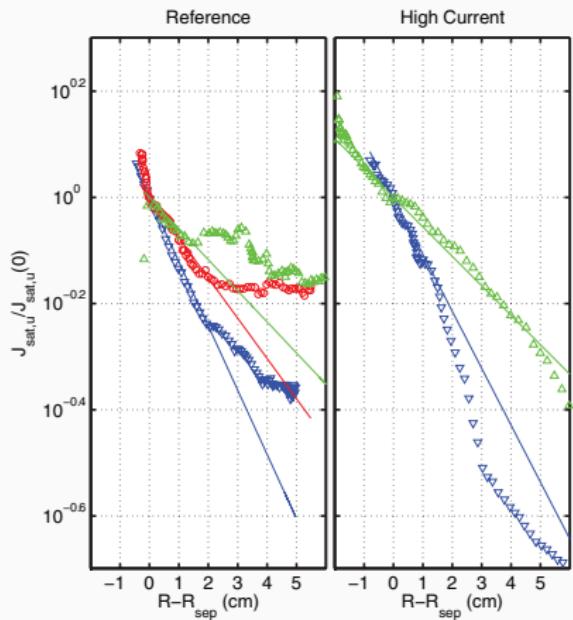


- ✓ In seeded discharges the transition observed at very high level of $\Lambda_{div} >> 1$



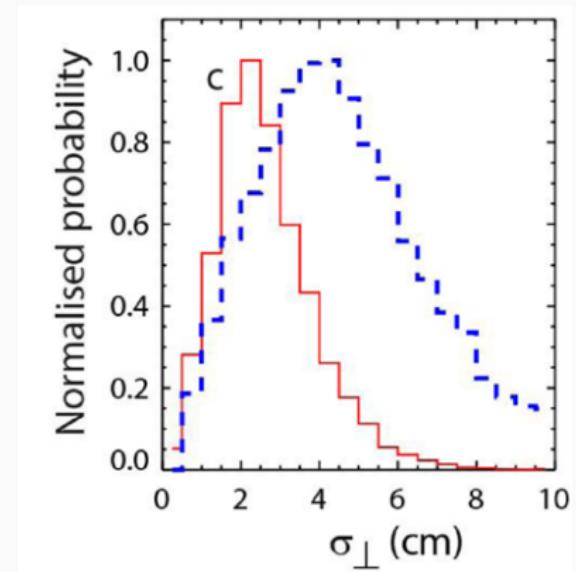


- ✓ Strong dependence on I_p (Militello et al. 2016). Increasing I_p at constant toroidal field shoulder disappears. Consistent with observation in other devices



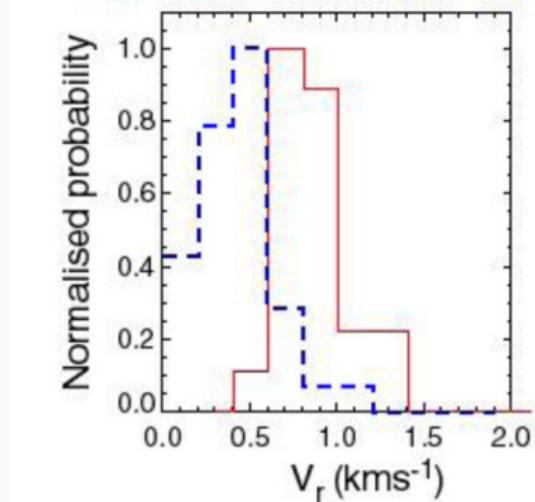


- ✓ Filaments binormal dimension increases with current (Kirk et al. 2016) or equivalently decreases with L_{\parallel}





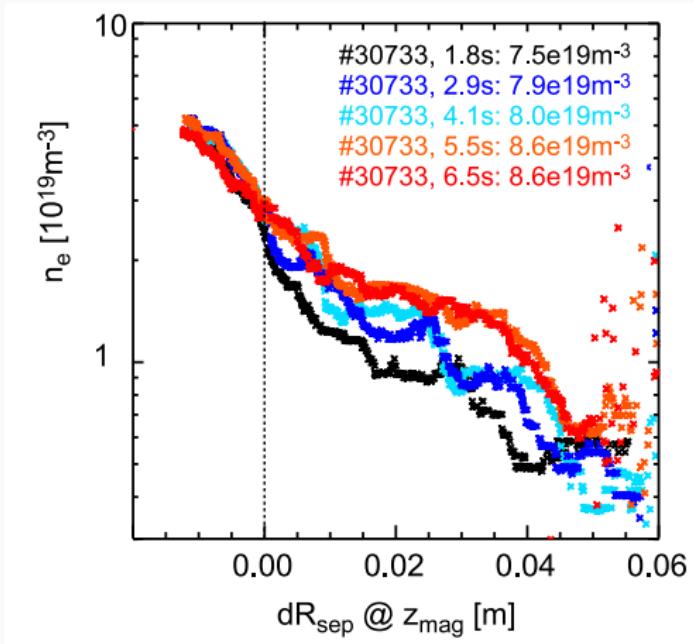
- ✓ Filament radial velocity decreases with current as well as the radial dimension
(Kirk et al. 2016)



H-MODE

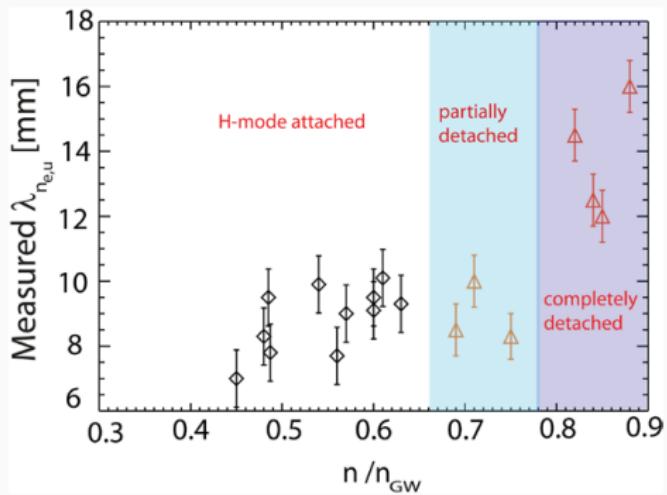


- ✓ SOL profiles in H-Mode so far investigated on AUG
(Carralero et al. 2016; Müller et al. 2015; Sun et al. 2015)



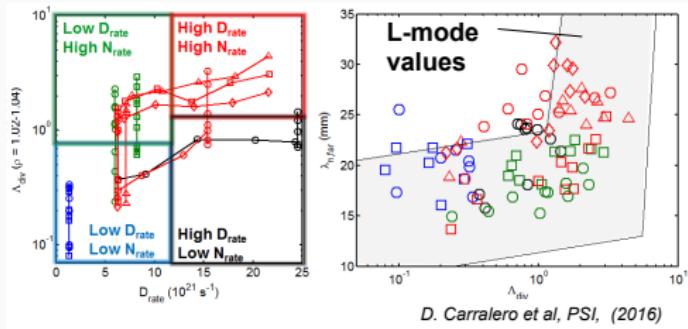


- ✓ Differently from L-Mode, complete detachment suggested to be mandatory for increasing of λ_n (Sun et al. 2015)





- ✓ In weak H-Mode (Carralero et al. 2016) shoulder depends on a combination of Λ_{div} and fueling rate. Complete detachment seems instead not necessary although very weak shoulder



OPEN ISSUES

Open and unresolved issues



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Open and unresolved issues



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2. If neutrals play a role is it at the divertor and/or at the midplane? Contradictory results if one include experiments with midplane puffing, JET and EIRENE simulations

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6. Is the density shoulder accompanied with an ion temperature shoulder?

TOPIC 21 EXPERIMENTS



- ✓ 15 were proposals submitted to Topic 21
- ✓ Proposals include experiments on all three machines
- ✓ There are overlaps between several of the proposals
- ✓ Preliminary shot allocation. AUG: 14. MAST: 13. TCV: 23
- ✓ However, total number of proposed shots: **449**
- ✓ Several of the proposed experiments can be combined. But we must prioritize
- ✓ Reaching all goals is not possible with the current number of allocated shots.



- ✓ MSTI uniquely facilitates cross comparison between machines
- ✓ Several of the proposed experiments overlap and will be combined
- ✓ A cross machine experiment has the makings of settling open issues
- ✓ Therefore, we will allocate shots for cross-machine comparison
- ✓but also to other proposed experiments
- ✓ Cross machine L-mode experiments:
 1. Investigate the role of neutrals
 2. I_p and q_{95} scans
- ✓ Cross machine H-mode experiments.



- ✓ The role of neutrals in the shoulder formation is not understood (proponents:
Carralero (# 7), Militello (# 1, 2), Vianello (# 13), Walkden (# 9))
 1. We envisage to measure neutral gas profiles at the outboard midplane using fast cameras with D_α filter, density and temperature SOL profiles and appropriate code (e.g. KNID as in (Lipschultz et al. 2016, 2005))
 2. Reciprocating probes and profiles available on all machines
 3. Investigate role of fueling location (MAST)
- ✓ Disentangle the roles of I_p , q_{95} , and $L_{||}$. (proponents: Carralero , Militello, Vianello, Tsui, WalkdenCarralero (# 7), Militello (# 1, 2), Vianello (# 13), Walkden (# 9), Tsui (# 15))
 1. Carry out parameter scans on all machines
 2. Strive after similar machine configurations

H-mode experiments



- ✓ ITER and DEMO will operate in H-mode
- ✓ We must know what parameters control shoulder formation
- ✓ Shoulder formation parameter regime is unclear on all machines
- ✓ Main priorities:
 1. Investigate if clear shoulder formation exists and what plasma parameters required?
 2. Investigate the SOL (filamentary) transport properties. Whenever main diagnostic is reciprocating probes → limits heating power
 3. Experiments must gradually increase power and density.
- ✓ Fueling in H-mode is problematic due to transport barrier. Is there a way to overcome it? NBI, pellet fueling?
- ✓ H-mode density limit (*Bernert et al. 2015*) must be dealt with



- ✓ Machines are fundamentally differently designed
- ✓ Strive for similar configurations of the machines:
 1. Single-Null
 2. $\mathbf{B} \times \nabla B$ towards active divertor
 3. Strike-point and cryo pump location (AUG and MAST-U)
 4. Heating
 5. Fueling location
 6. Seeding (species, location, rate)

Required diagnostics and competences



In order to compare experiments the following diagnostics must be available:

I. Filaments analysis in the Outboard midplane:

- ✓ Through Reciprocating probe then I_{sat} on minimum three pins poloidally and radially separated (filaments speed and size).
- ✓ Electron temperature (fast T_e measurements can be achieved with BPP in MAST-U (N. Walkden #11))
- ✓ If possible $M_{||}$

2. Camera viewing OM for measuring neutrals

3. Divertor measurements of n and T_e (probes) plus spectroscopy and bolometry
4. Density profile measurements (Li-Bes, Reflectometry (# 6 Acquiam, # 8 Vicente), Edge Thomson scattering)
5. Sami and Field for fast particles acceleration (piggy back on developed scenario # 4 McClements)

Proposed shot plan - AUG I



Allocated shots \sim 14 + contingency

- ✓ L-Mode (6 shots)
 - 1. Reference shot # 30276
 - 2. Perform I_p scan (three values) with fixed B_T
 - 3. Perform I_p scan fixing q_{95} (B_T)
 - 4. $B_T = 2.0$ required by proposal 6 (Aguiam). Should be possible for some shots?
 - 5. should we add OM puff to validate neutral measurements?
 - 6. Possibility of strike-point sweeping during shot
 - 7. RFEA measurements in internal program.
 - 8. These shots combines experiments proposed by: Carralero (# 7), Militello (#1), Vianello (#13)
- ✓ H-mode (9 shots)
 - 1. Reference shot # 33059 (AUG15-2.2-3). Aim is to achieve conditions in # 31607 (Sun 6 MW) through careful power and density ramp monitoring new HHF probe
 - 2. With clear shoulder formation repeat with midplane probe at varying radial positions

Proposed shot plan - AUG II



3. Strike-point sweep if feasible?
4. In all shots, particle acceleration in ELMs will be studied using microwaves, soft X-rays, and FILD
5. Reflectometry measurements of density profiles and fluctuations at multiple poloidal locations (Aguiam and Vicente)
6. These shots combine experiments proposed by: Aguiam (#6), Carralero (#7), McClements (#4), Militello (# 1, 2), Vianello (#13), Vicente (#8)

Proposed shot plan - TCV



- ✓ L-mode (11 shots)
 1. Reference shot # 53514
 2. Same I_p and q_{95} scans as on AUG
 3. Two shots with reversed $\mathbf{B} \times \nabla B$
 4. Move plasma vertically. Disentangle q_{95} and L_{\parallel}
 5. These shots combines proposal: Vianello (#13), Tsui (#15), Militello (#1, 2)
- ✓ H-mode (12 shots)
 1. Reference shot # 53352
 2. Since H-mode shoulder is new territory on TCV first shots will be scenario development
 3. As on AUG. Incremental increases of power and density. Close monitoring the midplane probe.
 4. These shots combines proposal: Vianello (#13), Tsui (#15), Militello (#1, 2)



- ✓ L-mode (6 shots)
 1. New machine. No reference shot yet
 2. Same I_p and q_{95} scan to allow cross-machine comparison. Availability of multi pin probe?
 3. Try varying fueling location
 4. RFEA measurements during shoulder formation
 5. These shots combines proposal: Militello (#1, 2, 3), Walkden (#11), Vianello (#13)
- ✓ H-mode (7 shots)
 1. These experiments require the existence of H-mode reference shot. Perhaps not available in 2017
 2. Similar scenario development as on other emachines
 3. These shots combines proposal: Militello (#1, 2, 3), Vianello (#13)
- ✓ Probe head must be changed to allow investigation of both fast T_e (BPP), and T_i (RFEA) but this require careful schedule of machine time



- ✓ COMPASS is not an MSTI device, therefore no operational cost will be provided by MSTI
- ✓ However GA agree that MSTI can provide part of the ppy for running experiments in line with MSTI topics
- ✓ Proposal # 14 is focused filaments dynamics and shoulder formation both in L and H-Mode
- ✓ Experimental plan can be therefore agreed in order to perform similar experiments (e.g. I_p and q_{95} scan in L-Mode) ensuring proper comparison between devices
- ✓ COMPASS suppose 3ppy for running and evaluation of experiment pertaining Topic-21, among Czech and other european laboratories.



- ✓ Detailed ion temp measurements. Must eventually be completed in internal programs. Are you willing to share the information among Topic 21 even though done internally?
- ✓ Topology investigations? For example the comparison USN/LSN/DN is not possible. Upper divertor information is actually less detailed. Better to use reverse B_t or ion $\mathbf{B} \times \nabla \mathbf{B}$ pointing away from X-Point which is known to have influences in detachment as well (McLean et al. 2016)
- ✓ Strikepoint sweeping and cryo pump
- ✓ Parameters scans in H-mode
- ✓ X-point probes



1. Mean field modelling available for AUG (EMC3-EIRENCE) and MAST-U (SOLPS). So far we lack investigation for these scenario targeting TCV.
Manpower needed from edge and SOL modelling
2. Turbulence code: we should need self-consistent interaction with neutrals.
Possible tools **BOUT ++**, **HESEL**, **GBS**. Some of them can be run by people who will, very likely, apply for this topic, some other not



- ✓ Possibility to piggybag on Quiescent/small ELM H-mode shots (Topic 5,6, 18)
- ✓ Shortly after this meeting we will organize a follow-up meeting to reconcile ideas from this discussion (date not fixed yet)
- ✓ All information will be gathered on the wiki
- ✓ Other channels for discussion/sharing. Slack (mst1-topic21.slack.com), Github for code sharing
- ✓ We aim to arrive to a proper shared database of filaments between the machines, where properties will be obtained using agreed approaches so that a cross-machine comparison paper could at the end be finalized at a certain point

Discussion agenda



1. Priorities. These are our personal ideas. Do we agree?
2. Common measurement techniques. Filament properties, Λ_{div} estimate and location, Neutrals, ...