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

J. Madsen and N. Vianello

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Main focus of topic 21 is shoulder formation

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.

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

Outline

- ✓ Background
- ✓ Plans
- ✓ Discussion

background

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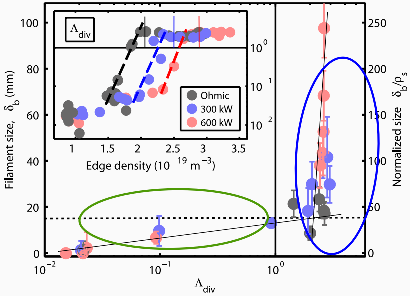
4. Observations exhibit various other dependencies e.g., divertor collisionality, plasma current, seeding. Results from different devices not fully reconciled and the underlying mechanism is not fully understood.
5. Studies of shoulder formation in H-Mode are so far limited

I-mode

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

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

controls shoulder formation



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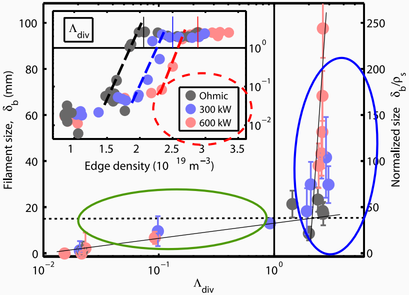

L-Mode studies: AUG/1

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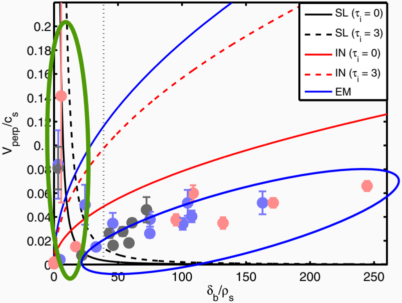

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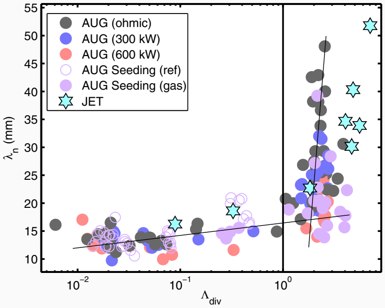
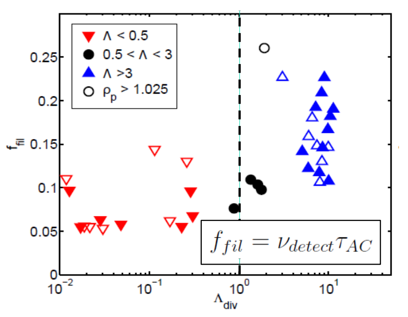
Λ_{div} rules the density profile scale length

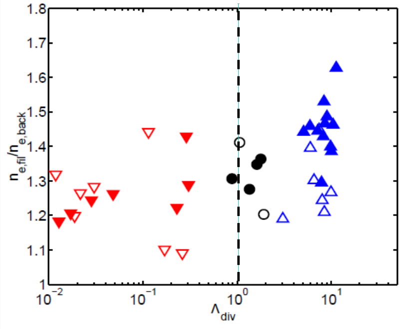


✓ Profile modified by an increase of blob-size and change of packing fraction: $f_{fil} = \nu_{fil}\tau_{AC}$



L-Mode studies: AUG/2

- ✓ Profile modified by an increase of blob-size and change of packing fraction: $f_{fil} = \nu_{fil}\tau_{AC}$ and filament relative density (Carralero 2016 in preparation)



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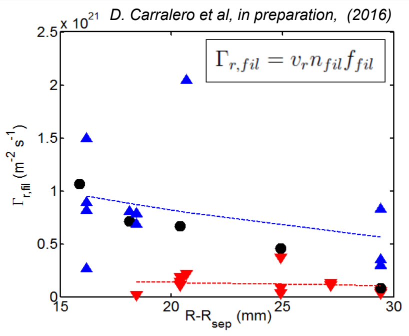

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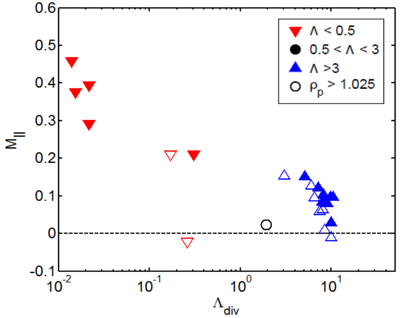
- ✓ Parallel flow is strongly reduced whenever we increase the divertor collisionality



L-Mode studies:AUG/3

✓ Electron and ions behave differently

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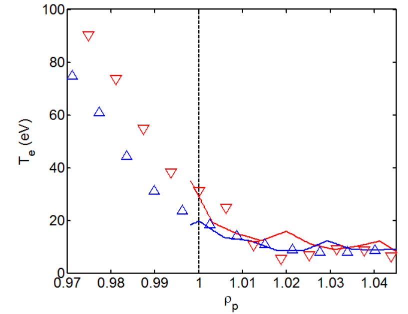
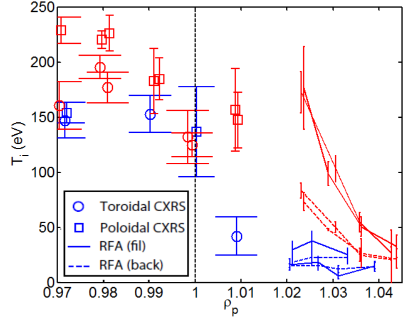
- ✓ $T_{e,fil} \sim 1.2 T_{e,bk}$ roughly constant accross the SOL and slightly affected by the increase of divertor collisionality



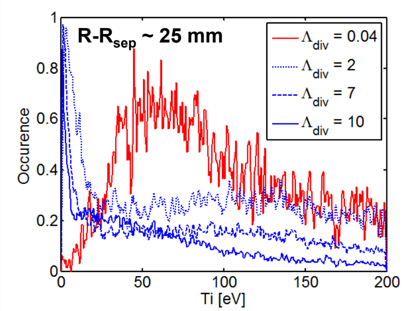
L-Mode studies:AUG/3

- ✓ Electron and ions behave differently
- ✓ Ions are strongly affected: for $\Lambda_{div} < 1$ $T_{i,fil} > T_{i,bk}$ and $\lambda_{T_i} \sim 30$ mm. $\Lambda_{div} > 1$ $T_{i,fil} \sim T_{i,bk} \sim 25$ eV and $\lambda_{T_i} \sim 8$ mm



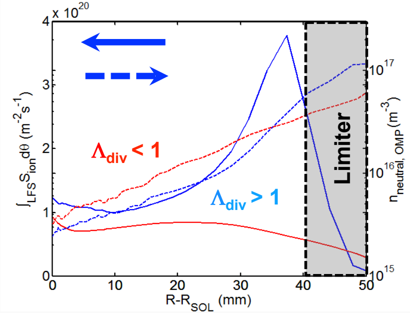
L-Mode studies:AUG/3

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



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 $\Lambda_{div} > 1$
- ✓ 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



L-Mode: TCV

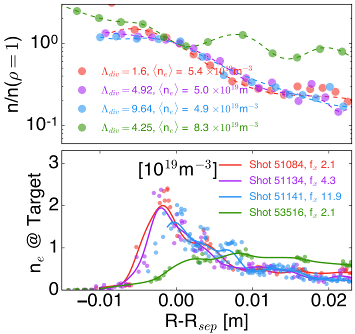
✓ Flexibility has allowed to test Λ_{div} dependence on $L_{||}$ by varying flux expansion f_x:

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

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

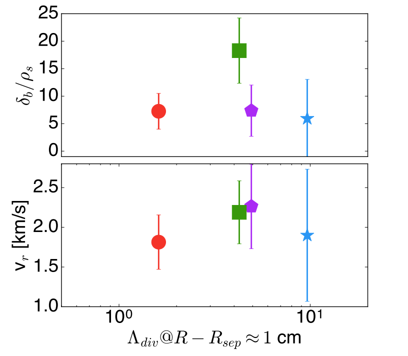
L-Mode: TCV

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



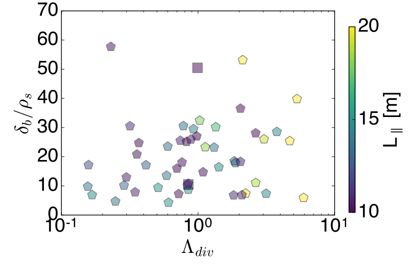
L-Mode: TCV

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



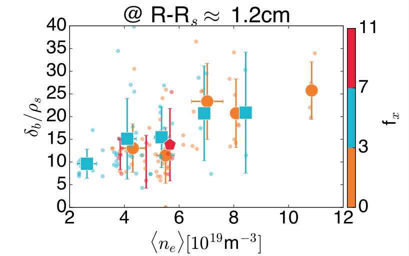
L-Mode: TCV

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



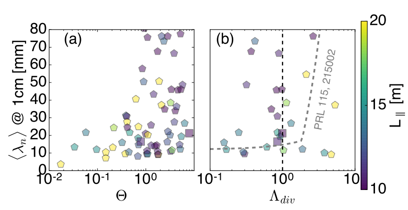
L-Mode: TCV

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



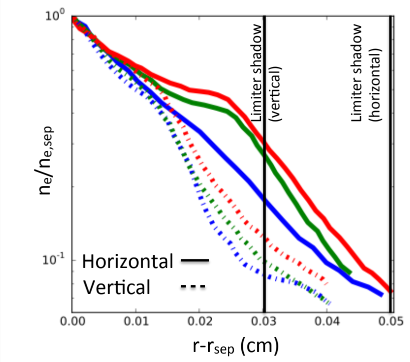
L-Mode: TCV

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



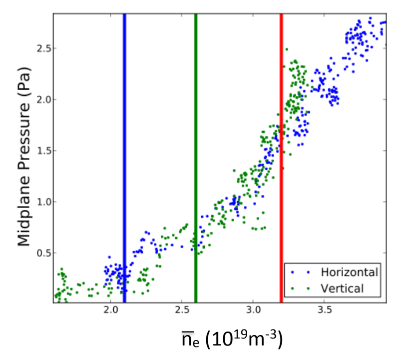
L-Mode: JET

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



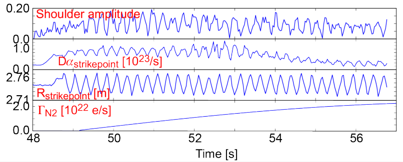
L-Mode: JET

✓ 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



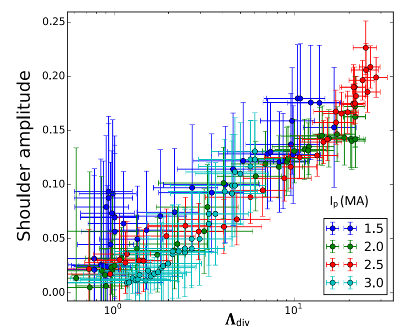
L-Mode: JET

- ✓ 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



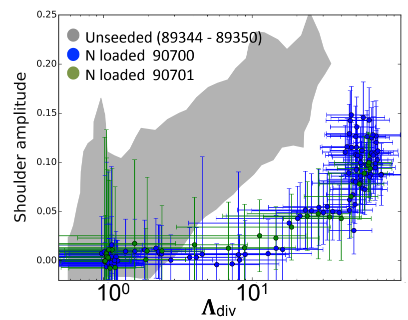
L-Mode: JET

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



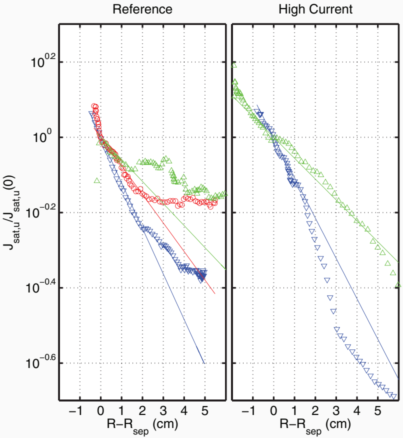
L-Mode: JET

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



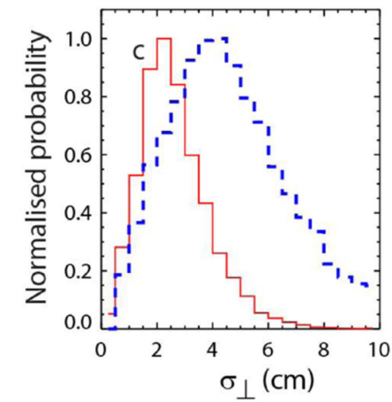
L-Mode: MAST

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



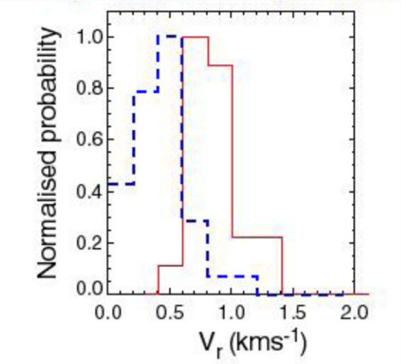
L-Mode: MAST

✓ Filaments binormal dimension increases with current (Kirk *et al.* 2016) or equivalently decreases with $L_{||}$



L-Mode: MAST

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

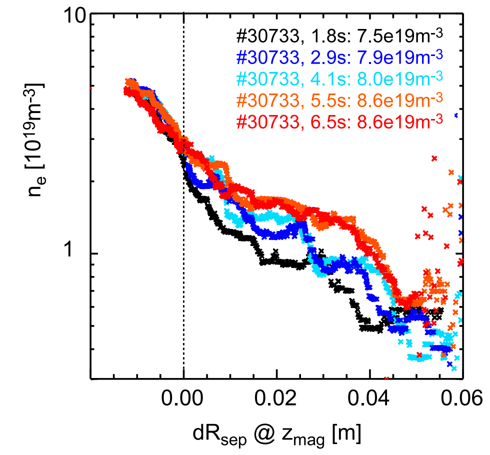


h-mode

AUG: H-Mode

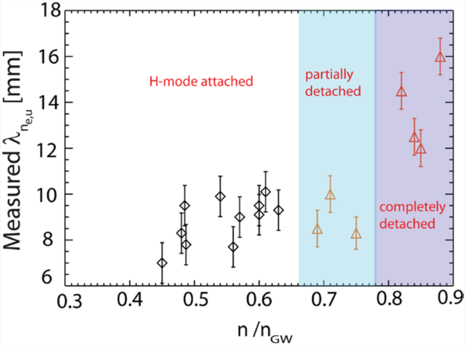
- ✓ SOL profiles in H-Mode so far investigated on AUG

  (Müller *et al.* 2015; Sun *et al.* 2015)



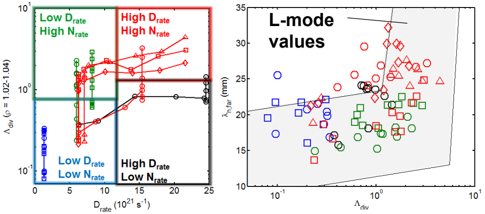
AUG: H-Mode

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



AUG: H-Mode

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



D. Carralero et al, PSI, (2016)

open issues

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5. Do we observe same behavior in L and H-Mode? So far no as shown in H-Mode AUG. We need higher detachment condition and we need enough fueling
6. Is the density shoulder accompanied with an ion temperature shoulder?

topic 21 experiments

$n_{\text{proposed shots}} \gg n_{\text{allocated shots}}$

- ✓ 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 !!!!!!!1SHOULD WE ADD PRELIMINARY DATES FOR THE EXPERIMENTS??
- ✓ However, total number of proposed shots: **449**
- ✓ Several of the proposed experiments can be combined. <u>But we must prioritize</u>
- ✓ Reaching all goals is not possible with the current number of allocated shots.

Focal points

- ✓ MST1 uniquely facilitates cross comparison between machines
- ✓ Several of the proposed experiments overlap
- ✓ 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.

L-mode experiments

✓ The role of neutrals in the shoulder formation is not understood (proponents: Carralero, Militello, Vianello, Walkden)

1. We envisage to measure neutral gas profiles at the outboard midplane using fast cameras and reciprocating Langmuir probes
2. Reciprocating probes and fast cameras available on all machines

✓ Disentangle the roles of I_p, q_{95}, and $L_{||}$. (proponents: Carralero, Militello, Vianello, Tsui, Walkden)

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. 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? NBI, pellet fueling?
- ✓ H-mode density limit(**Bernert:2015ppcf**) must be dealt with

Optimizing cross machine comparison

✓ Machines are fundamentally differently designed

✓ Strive for similar configurations of the machines:

1. Single-Null
2. $\boldsymbol{B} \times \nabla B$ 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

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

1. Reciprocating probe at OM measuring:
   - ✓ I_{sat} on minimum three pins poloidally and radially separated (filamens speed and size).
   - ✓ Electron temperature
   - ✓ If possible $M_{||}$
2. Camera viewing OM for measuring neutrals
3. Divertor measurements of n and T_e (probes). Collisionallity
4. Density profile measurements (Li-Bes, Reflectometry, Edge Thomson scattering)

Proposed shot plan - AUG

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, Militello, Vianello

✓ 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
3. Strike-point sweep if feasible?
4. In all shots, particle acceleration in ELMs will be studied using microwaves, soft X-rays, and FILD (proposal by McClements)
5. Reflectometry measurements of density profiles and fluctuations at multiple poloidal

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 $\boldsymbol{B} \times \nabla B$
4. Move plasma vertically. Disentangle q_{95} and $L_{||}$

✓ 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.

Preliminary shot plan - MAST-U

- ✓ L-mode (6 shots)
  1. New machine. No reference shot yet
  2. Same I_p and q_{95} scans as on AUG. Availability of multi pin probe?
  3. Try varying fueling location
  4. RFEA measurements during shoulder formation
- ✓ 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 machines
- ✓ Same I_p and q_{95} scans as on AUG

There are urgent experiment which cannot be addressed

- ✓ Detailed ion temp measurements
- ✓ Topology investigations
- ✓ Strikepoint sweeping and cryo pump
- ✓ Parameters scans in H-mode
- ✓ X-point probes

Future and Miscellaneous

- ✓ Possibility to piggybag on Quescient/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
- ✓ Filament database

Discussion agenda

1. Priorities. Do we agree?
2. Common measurement techniques. E.g. I_{sat} instead if ϕ_f for filament velocities?
3. Publications