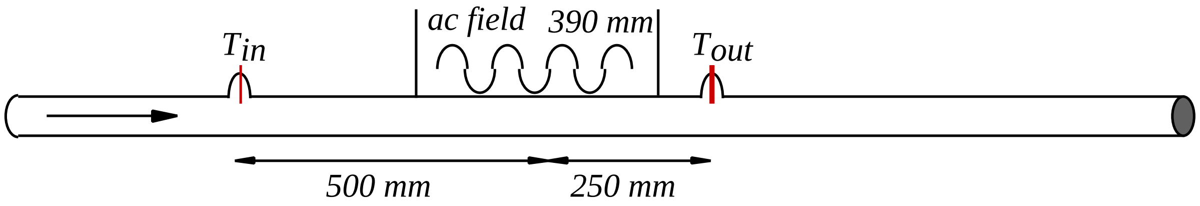
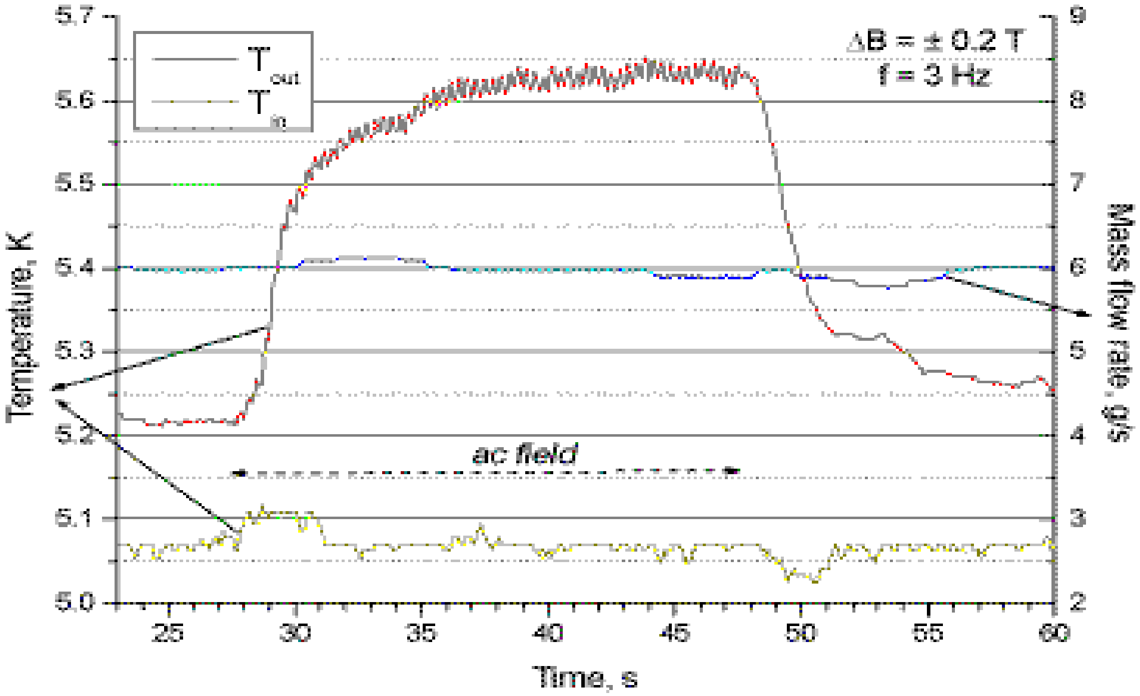
Learning about hydraulic and stability through an ac loss test

- To measure ac loss on CICC at 0 current by gas flow calorimetry, an ac field is applied to a 390 mm long section of CICC at constant inlet temperature, pressure and mass flow rate
- The ac field is applied as long as a steady state temperature is observed downstream
- A temperature increase ΔT is observed downstream of the ac field
- The power loss is $P = \dot{m}\Delta H \approx \dot{m}\,\overline{C}_p\,\Delta T$

NbTi, SnAg coated, lossy conductor, 336 wires, no hole, no wrap





- AC loss Power ≈ 10 W
- Power density ≈ 0.2 W/cm³
- Steady state within < 10 s
- He speed variation < 2 %
- Effective heat removal
- Stable operation

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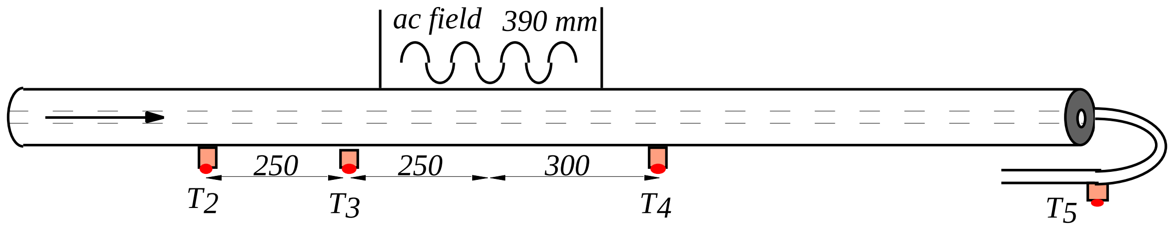
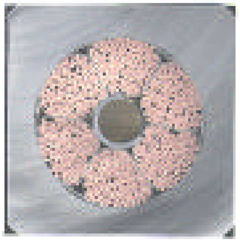
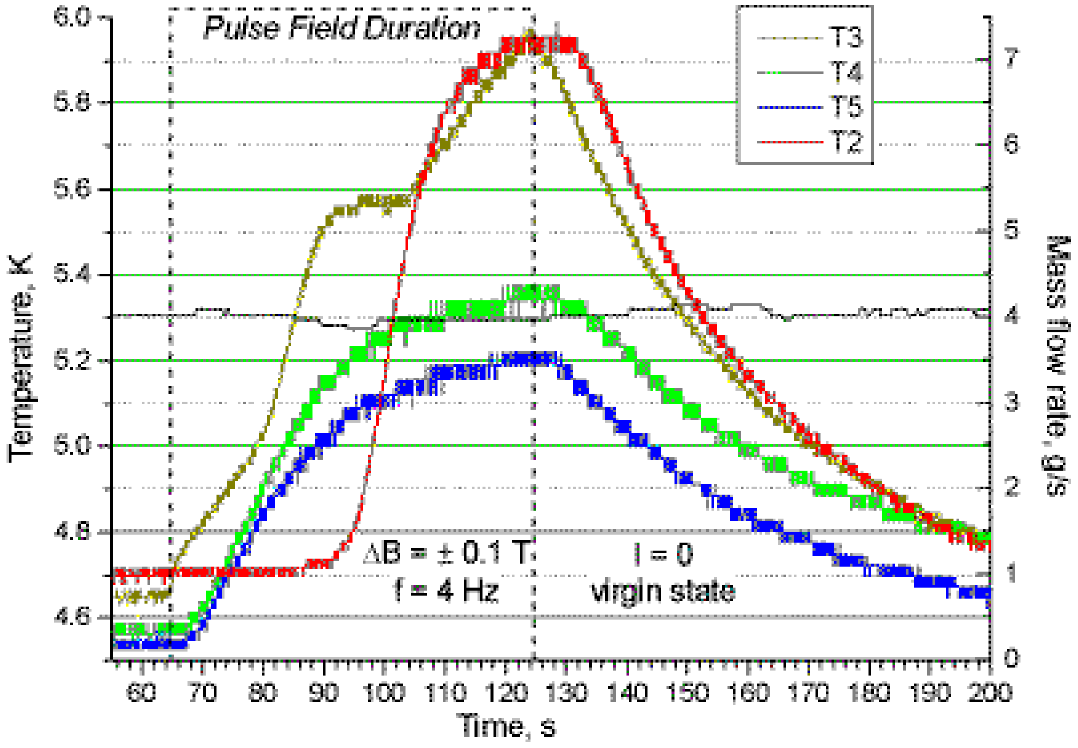
Full size NbTi, no coating, lossy conductor, with hole and wrap







- *Power ac loss ≈ 10 W*
- *Power density ≈ 0.04 W/cm³*
- *Steady state after ≈ 60 s*
- *Overall dm/dt almost constant*
- *Sensor T3 increases very rapidly in two steps*
- *After 25 s, sensor T2, upstream of ac field, starts to increase, i.e. the He stagnates in the bundle and a hot bubble expands*
- *Heat removal non effective*
- *Small power densities cause stagnation and thermal runaway*

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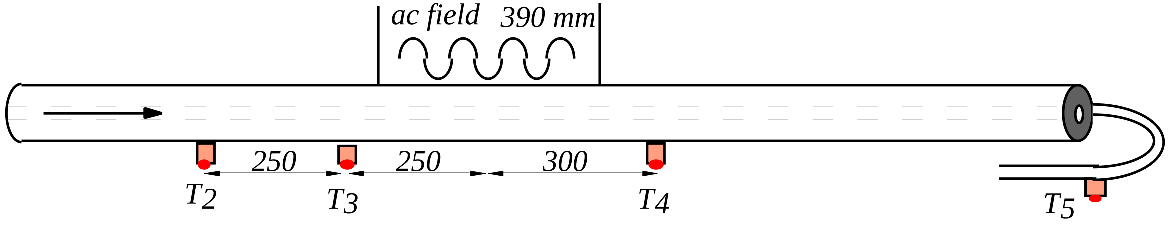
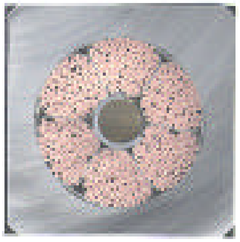
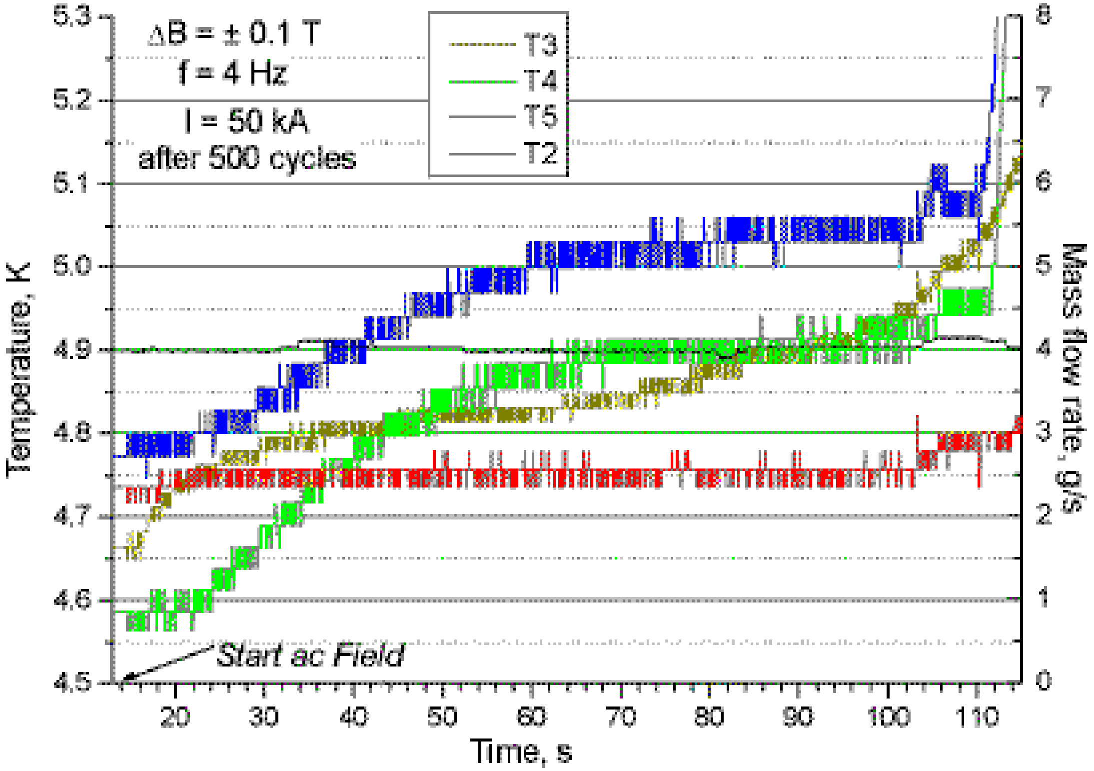
The same, after 500 cycles, with 50 kA transport current







- *ac loss down to < 4 W, similar to joint power*
- *Overall temp. increase 0.25 K*
- T_{cs} - T_{op} ≈ 1.2 K
- *Sensor T2 stays low, i.e. limited expansion of stagnant He, but T3 runaway*
- *Very small power densities cause thermal runaway and quench, disregarding the ΔT*

Warning !!!

A pressure release channel in the CICC dramatically limits the local power removal capability in the strand bundle

Power densities as small as 15 mW/cm^3 over a length of 390 mm are sufficient in the ITER conductor to choke the flow in the bundle and initiate a thermal runaway.

The subcable wraps worsen the situation further, hampering the radial mass exchange and causing expansion of the stagnant zone well beyond the power generation zone

Due to the poor radial heat conduction in CICC, high thermal gradients build up before achieving a steady state equilibrium between power generated in the bundle and removed in the central channel

Within few seconds, the current sharing temperature is exceeded and a runaway starts for local input power one order of magnitude smaller compared to CICC without central channel

The threshold to unstable transition (I_c to I_q) is also heavily affected by the central channel, as the lower speed in the bundle depresses h. For NbTi, the transition drops from ≈600 A/mm^2 (no hole conductor) to less than 200 A/mm^2 (hole + wraps).

Feed back

- *Remove the subcable wraps from the CICC (this is anyway the conclusion from ac loss and transient stability)*
- *Whenever compatible with safety and He residence time, avoid the central channel*
- *If the central channel cannot be removed, reduce it to the smallest possible size*
- *Avoid a reduction of the void fraction in the bundle, as this worsen the dc stability*
- *Improve the tolerance to transverse load by cable texture with high transverse modulus and high void fraction*

For example…

Go for two-in-hand winding in both PF and TF coils, to reduce the hydraulic length

Fill the “central hole” with a highly compacted Cu cable (1 + 6 + 12) made of 2 mm thick, Ni coated wires

In the PF conductor, put braids of NbTi strands, Ni coated, around the central Cu cable (no segregated Cu in the braids), no wraps, target void fraction 40%

In the TF conductor, put braids of Cr coated Nb_3Sn strands around the central Cu cable, Cu:non-Cu = 1, no segregated Cu in the braids, no wraps, target void fraction 40 %. Place the remainder of Cu as an outer layer of Cu wires, Ni coated