

CURRENT STATUS AND TEST PROGRAMS
FOR THE “STEPPED” STAVE

INFN-Genoa

M.Olcese

Outlines

We are close to complete all preliminary design tasks!

No design change has been or is going to be introduced, as all tests performed on the last prototypes shows:

- a quasi-perfect agreement with the predictions/calculations
- that all the major design goals have been met

4th stepping stave prototypes

- Two new prototypes have been manufactured and extensively tested, each one implementing a different omega lay-up (0-15-0 and 0-90-0)
- new graphite tools have been used
- new omega prepreg material (Fiberite 954-2A resin + Toray M60J carbon fibers) has been introduced
- CIBA Araldite 420 A/B glue has been used to bond the c-c tile on the omega piece
- due to reliability problems with the C-C impregnation tooling:
 - the c-c used for the 0-15-0 omega stave has not been impregnated
 - the c-c used for the 0-90-0 omega stave has a deep impregnation over the 60 % of the stave length and a surface impregnation (not affecting the sealing) over the rest

The current manufacturing process

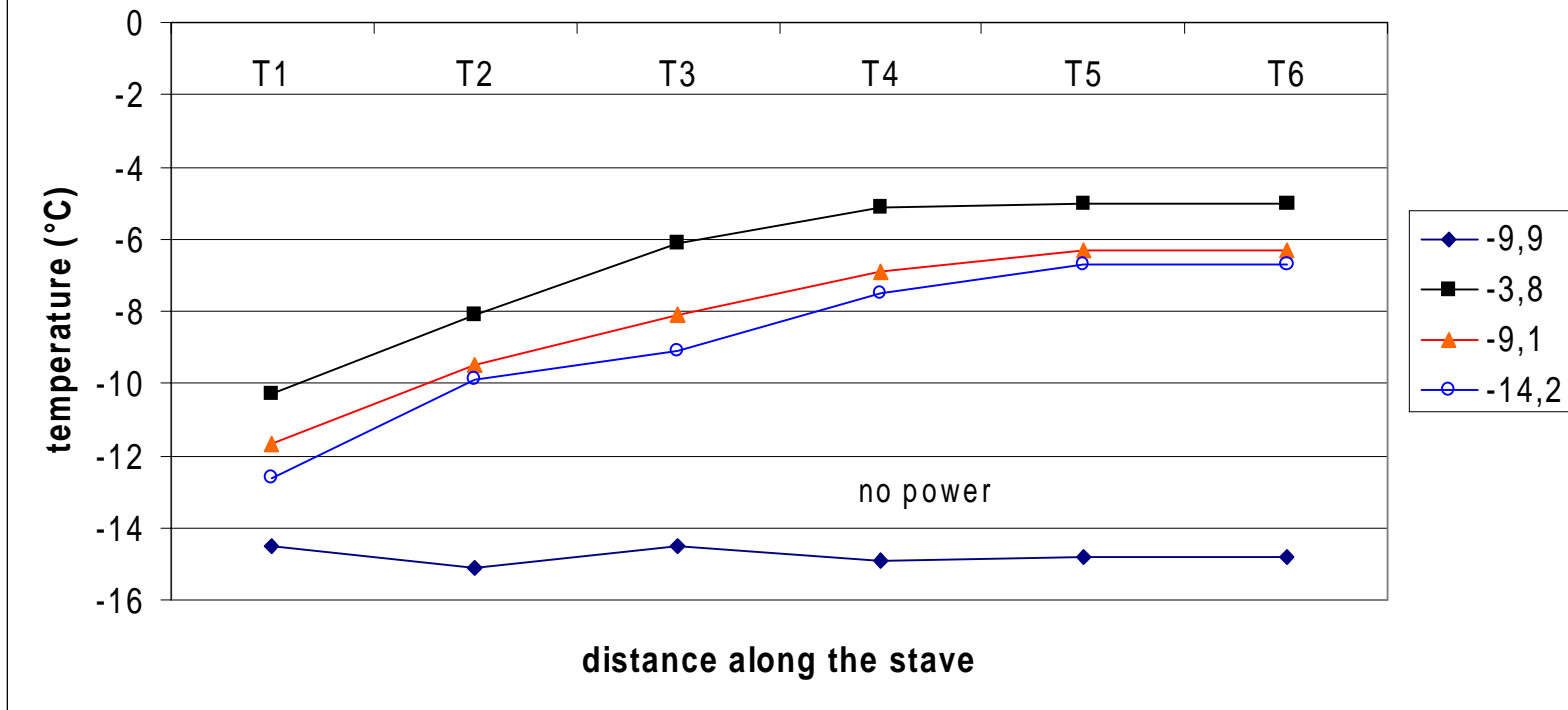
- Omega forming using a graphite mould
- c-c pre-machining to 20x1,2 mm cross section plates (with no step)
- c-c impregnation
- c-c re-machining to the final step sequence and thickness
- gluing of the 4 (now, 2 in the next prototype) c-c piece together
- c-c + omega gluing (curing at room temperature + a post-curing at 60 °C to enhance the glue joint strength)
- stave post milling (side thinning of the upper steps)

Stave thermal performances

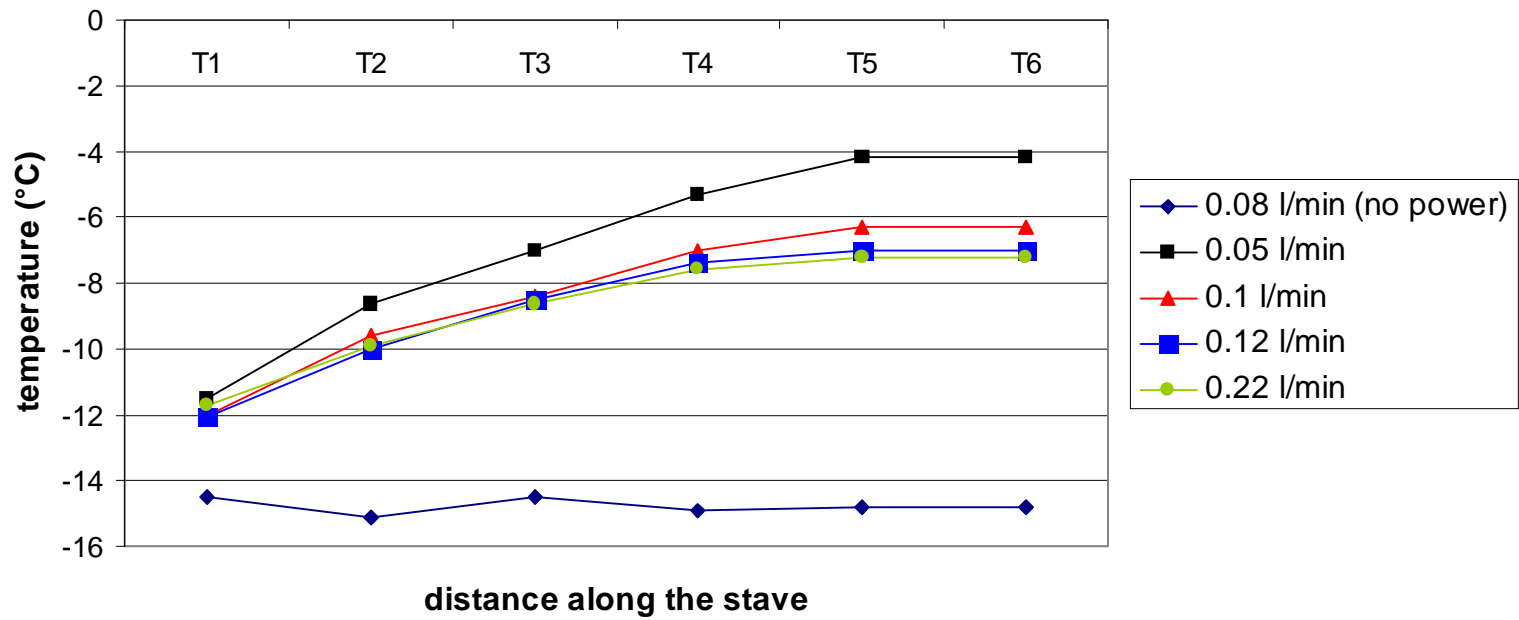
Finally we met the goal!

- The thermal performances are even better than expected
- Tests with binary ice fluid (-16.5 °C inlet temperature, 0.12 l/min flow rate) show that the silicon temperature can be kept below -7 °C all along the stave at full power (80 W)
- tests have been carried out with three different coolant flows (water-ethanol BI mixture, water-methanol BI and single phase mixture,) to fully characterize the stave performances at different operating conditions

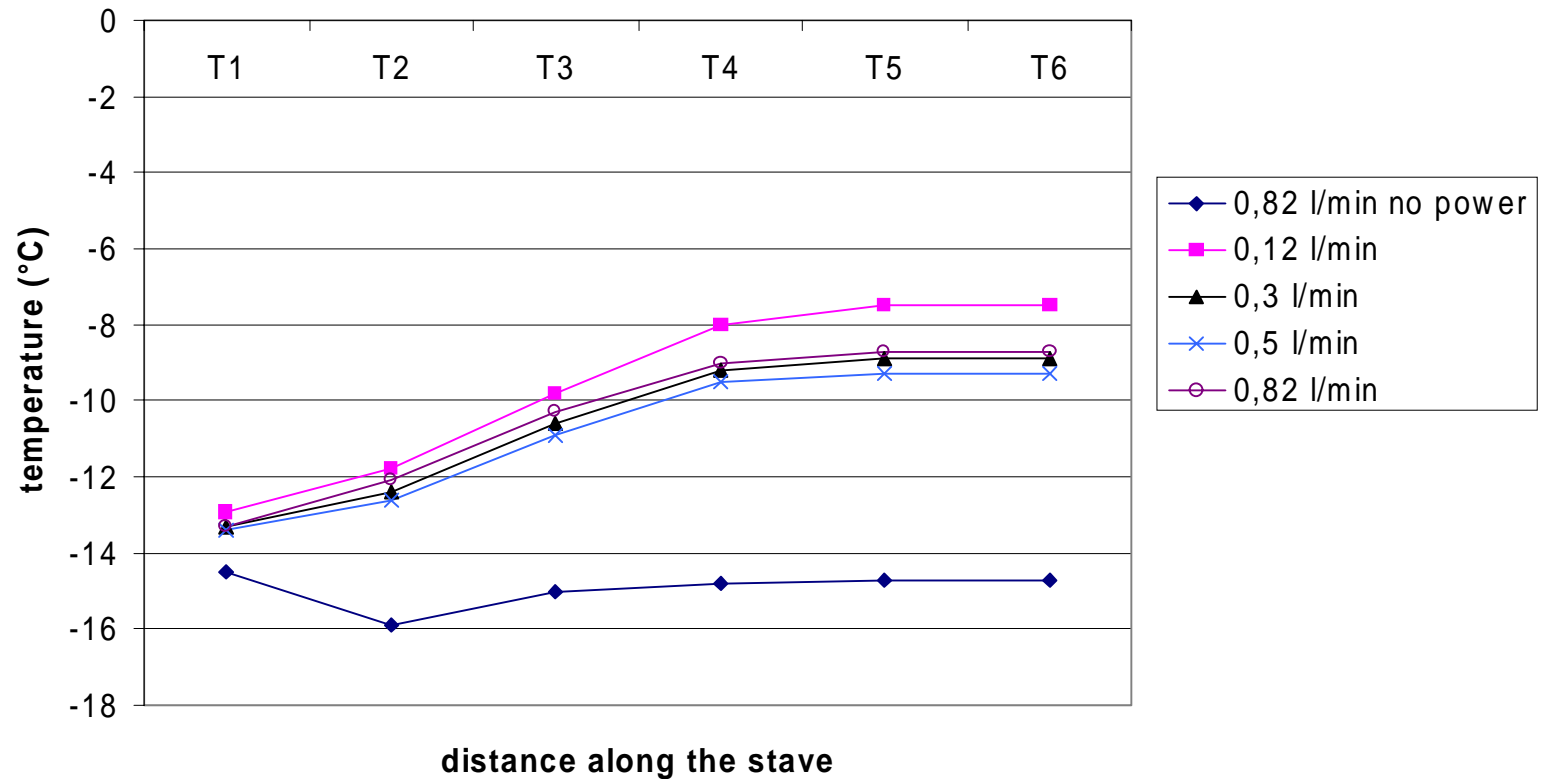
water-ethanol binary ice mixture
Temperature profile as function of box temperature
(fluid inlet temperature -16.5 °C, ice = 5%, flow rate = 0.1 l/min)



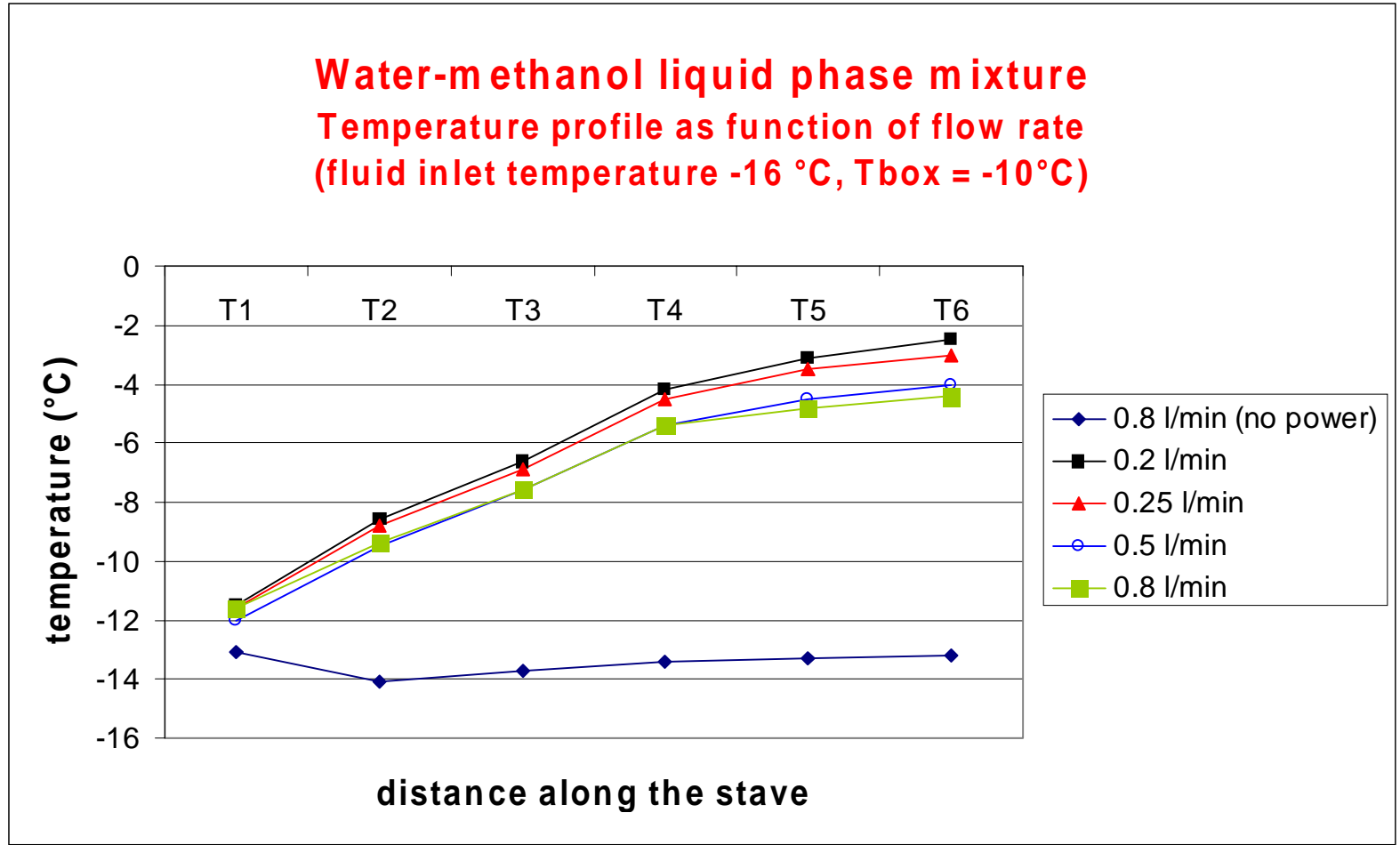
water-ethanol binary ice mixture
Temperature profile as function of flow rate
(fluid inlet temperature -16.5 °C, ice = 5%, T_{box} = -10 °C)



water-methanol binary ice mixture
Temperature profile as function of flow rate
(fluid inlet temperature -17 °C, T_{box} = -10 °C)



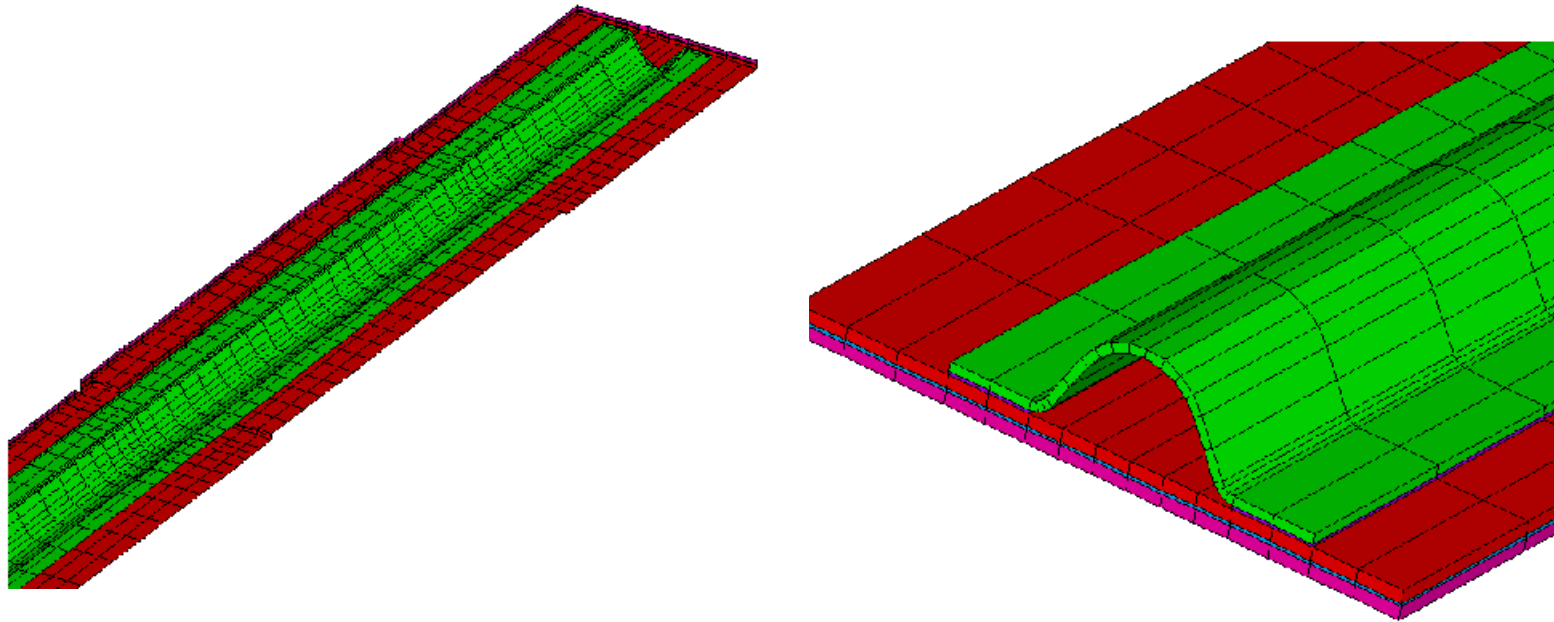
Water-m ethanol liquid phase mixture
Temperature profile as function of flow rate
(fluid inlet temperature -16 °C, T_{box} = -10°C)



Stave geometry and dimensional stability

- A new detailed FEA model (taking into account the effects of the three omega CFR layers with different orientations) has been built to simulate the stave structural performances
- The as built stave geometry has been fully investigated
- the cool-down deflections and loads on supports have been calculated and measured
- the deflections due to weight have been calculated
- the effect of the coolant fluid pressure has been evaluated
- moisture pick up deflections have been estimated

FEA model



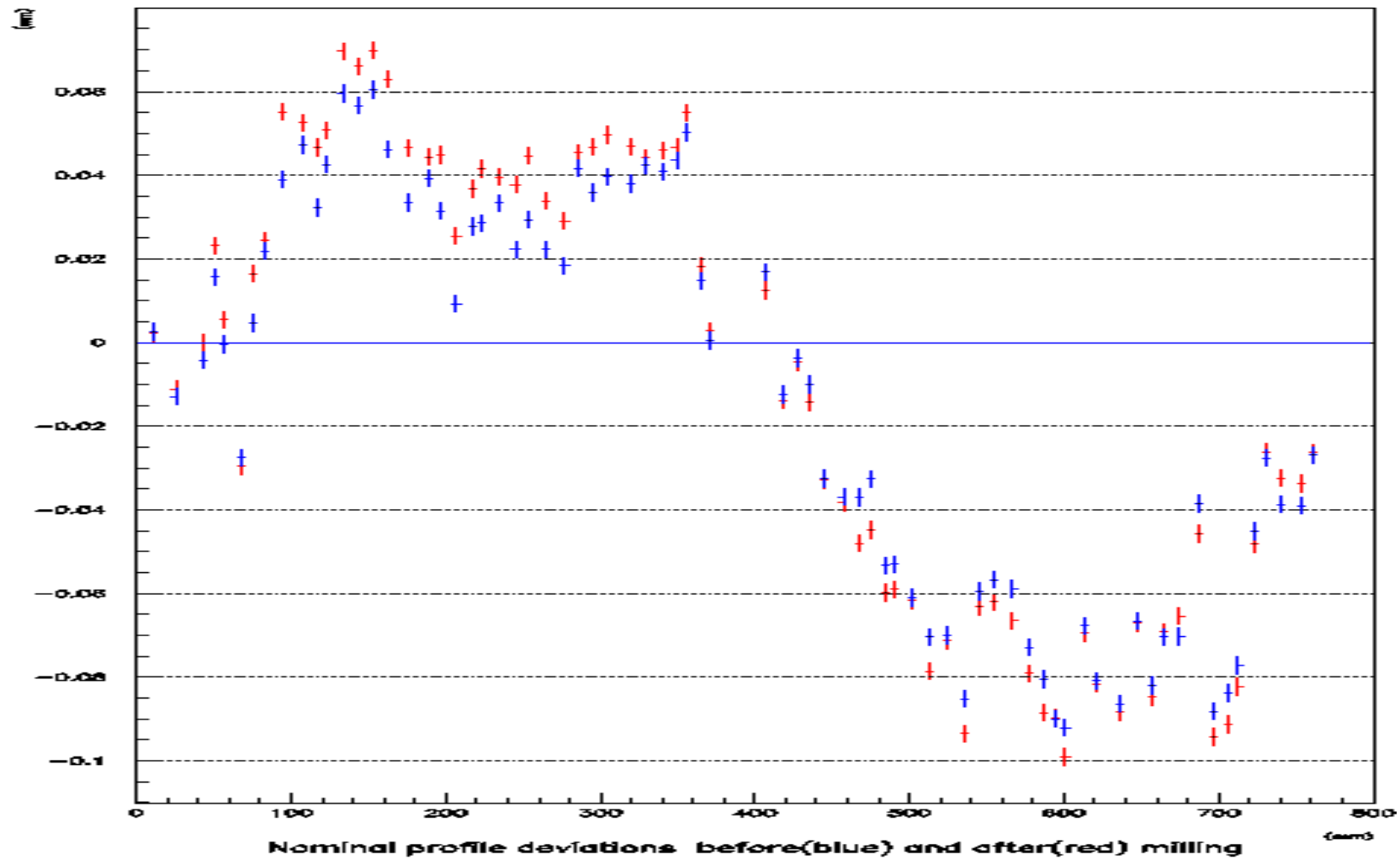
AS BUILT GEOMETRY (room temperature)

	natural		aligned on three supports		
	bowing (mm)	twisting (Δy (mm))	max r displacement (μm)	avg. step side tilting (Δy (μm))	step avg. flatness (μm)
0-15-0 omega	2	2	-		
0-90-0 omega	4	0	-		
0-15-0 stave	0	0,5	60 (1)	< 30	30
0-90-0 stave	0,5	0	150 (2)	< 30	30

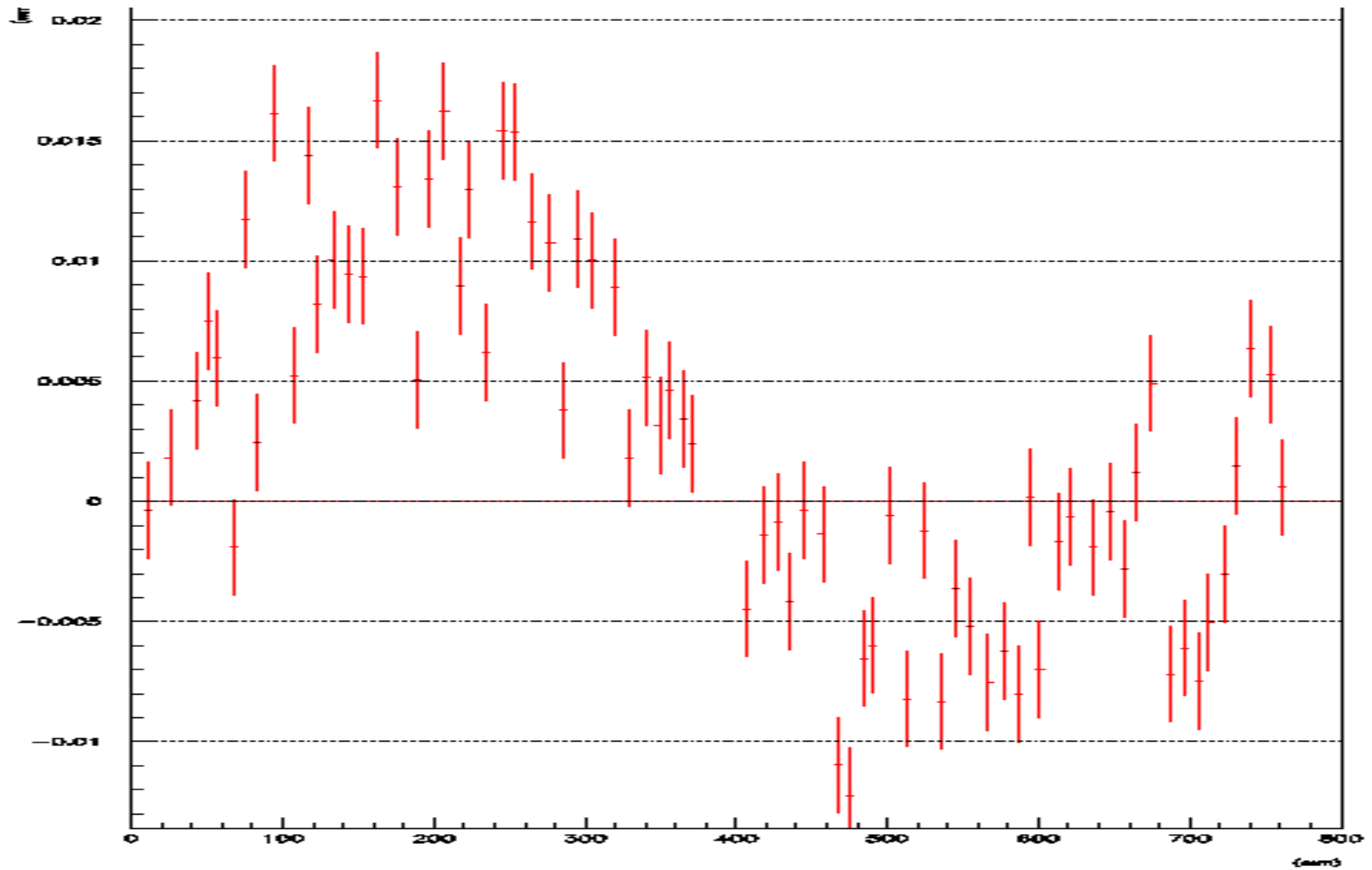
(1) mainly due to the non-symmetric (with reference to the stave mid support) layout of the 4 C-C plates glued together: this problem will be almost entirely eliminated with the next prototypes

(2) same as (1) plus a non complete accommodation of the initial omega bowing

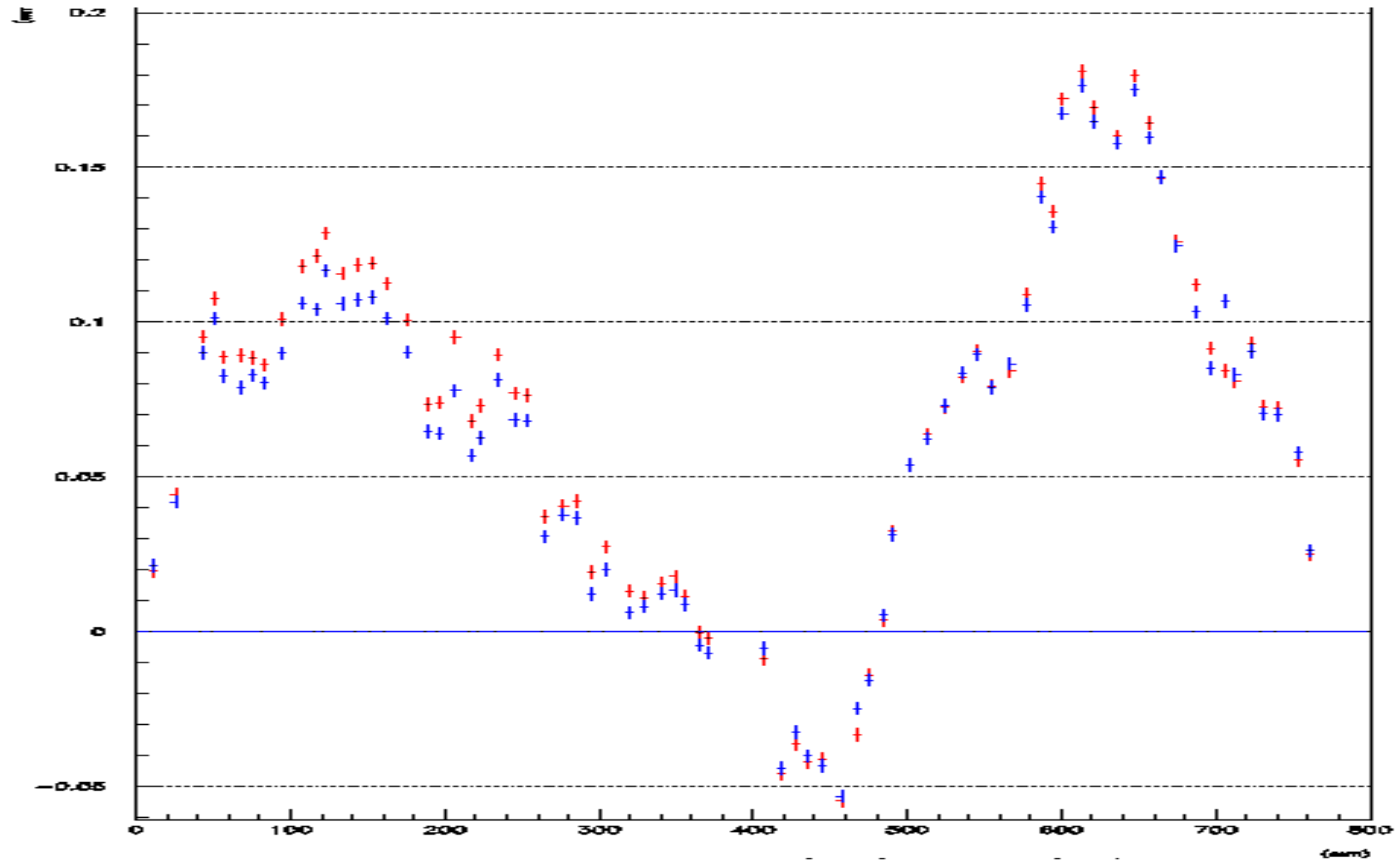
0-15-0 stave: room temperature profile measurements



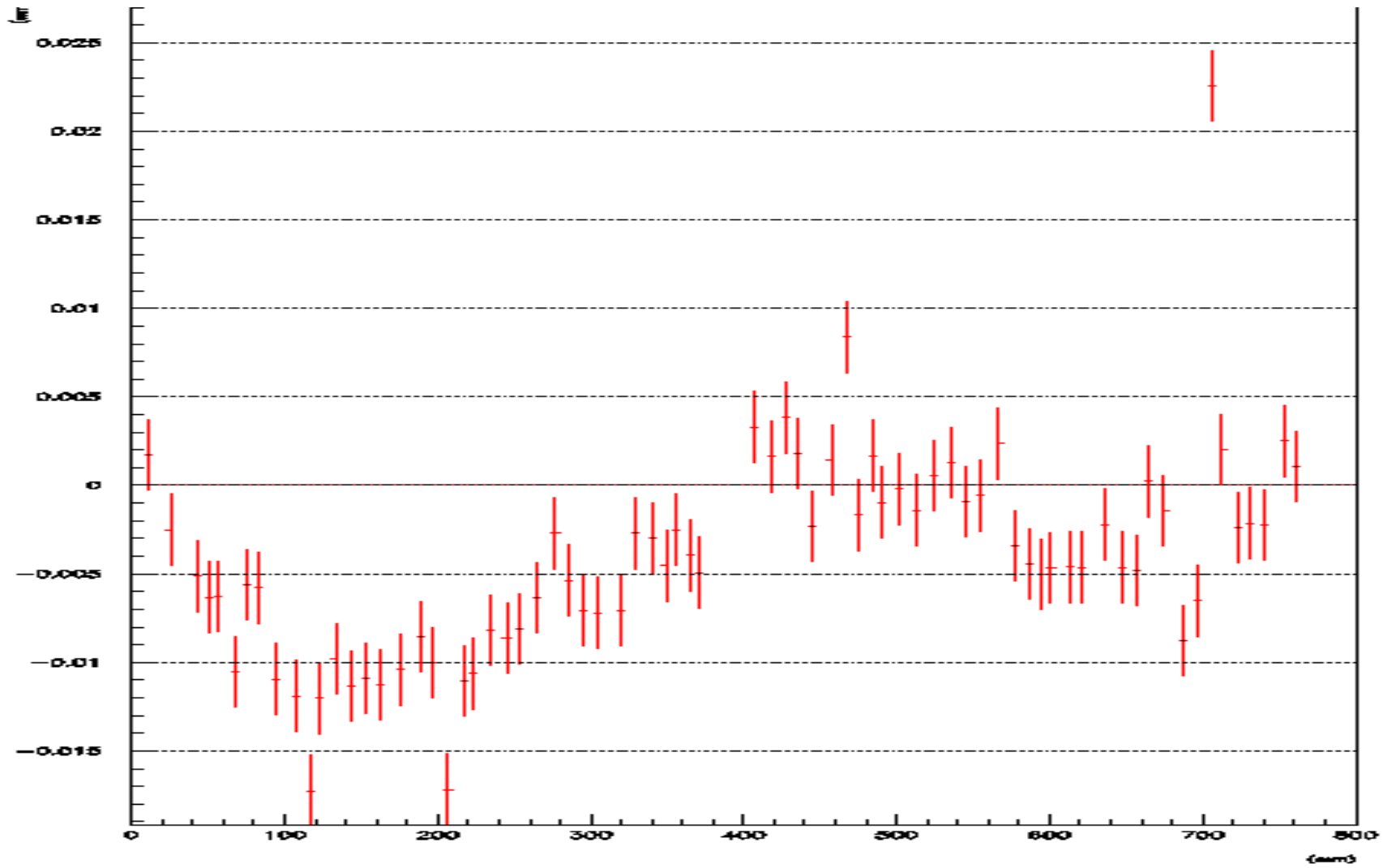
0-15-0 stave: room temperature milling distortions



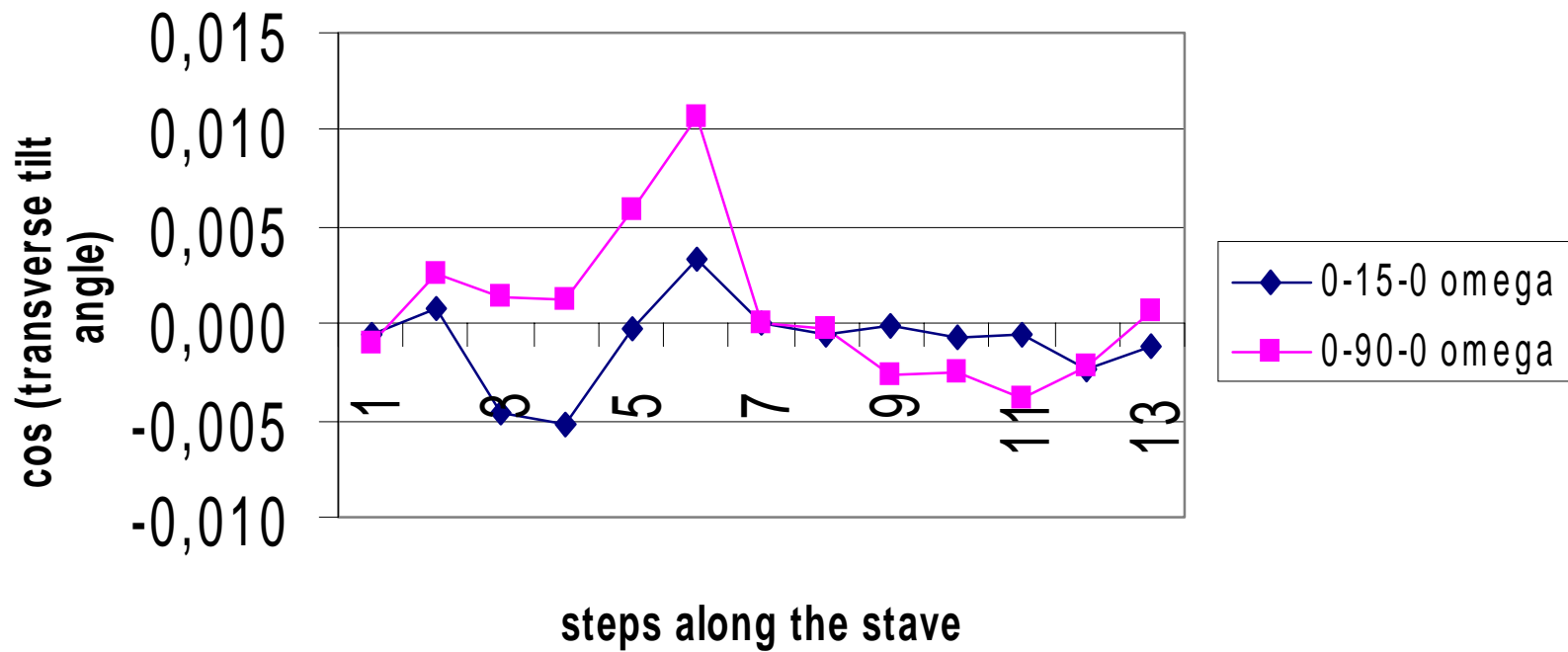
0-90-0 stave: room temperature profile measurements



0-90-0 stave: room temperature milling distortions



stave transverse tilting after milling at room temperature



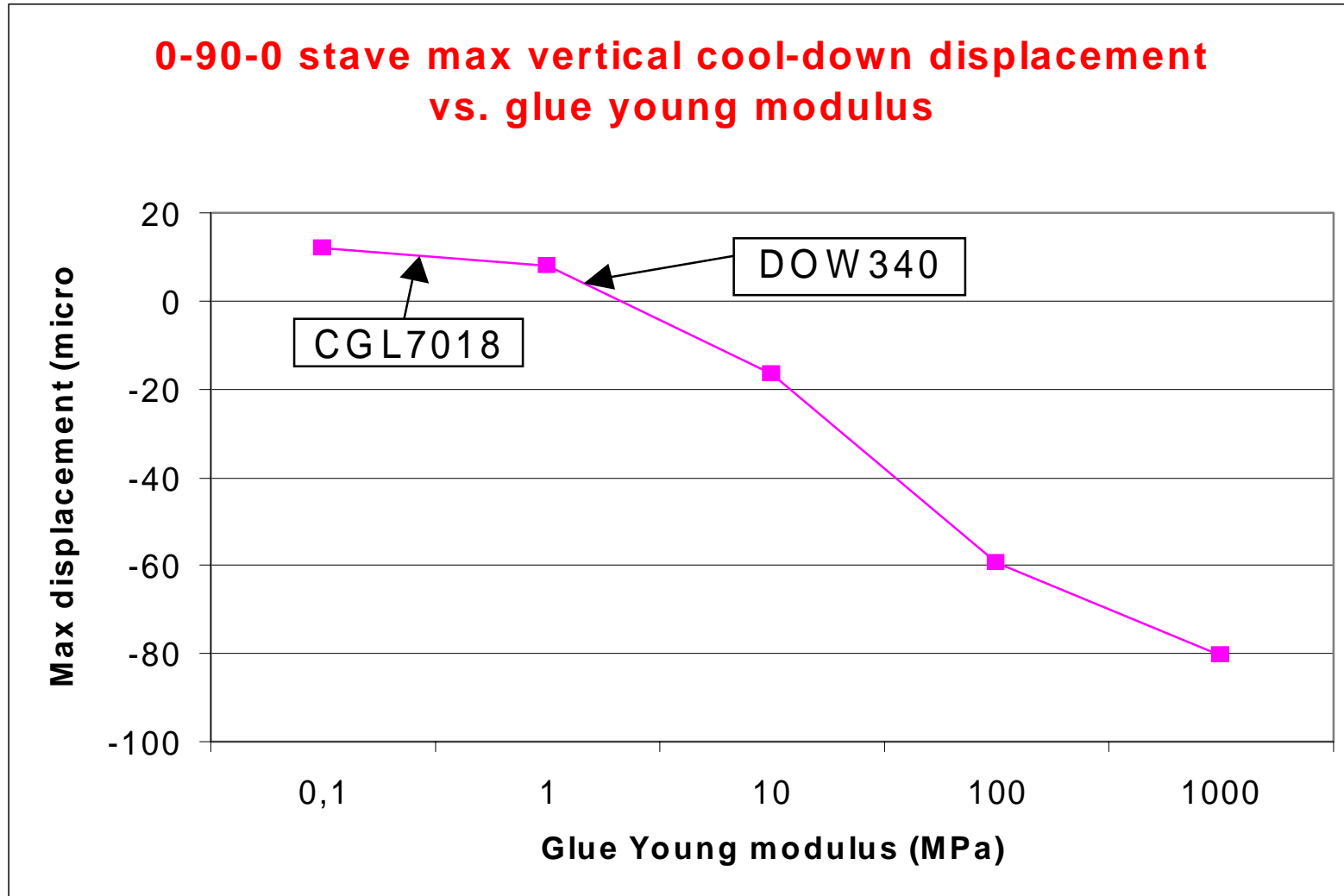
CTE estimation

- Since the CTE mismatches between the omega piece and the c-c tile are the responsible for the cool-down distortions, it's crucial to use the right numbers
- an independent test on the two omega lay-ups has been performed to determine the omega CTE:
 - $CTE_{0-90-0} = -0.73 \text{ ppm}^\circ\text{C}^{-1}$
 - $CTE_{0-15-0} = -1.41 \text{ ppm}^\circ\text{C}^{-1}$
- the two omega CTE's have then been used to calculate the M60J carbon fibers CTE ($-1.47 \text{ ppm}^\circ\text{C}^{-1}$) with an higher accuracy than the supplier value
- deflection tests on the two staves with different omega lay-ups (showing deflections in opposite directions) with the support of FEA calculations, let us to evaluate a more accurate value of the c-c CTE ($-1.08 \text{ ppm}^\circ\text{C}^{-1}$) (the approximated value ($-1 \text{ ppm}^\circ\text{C}^{-1}$) given by BF-Goodrich leads to unacceptable errors ($\sim 30\%$ on the stave deflection))
- finally the CTE for the impregnated c-c has been evaluated ($-0.97 \text{ ppm}^\circ\text{C}^{-1}$)
- the good agreement between tests and calculations confirm the validity of the approach

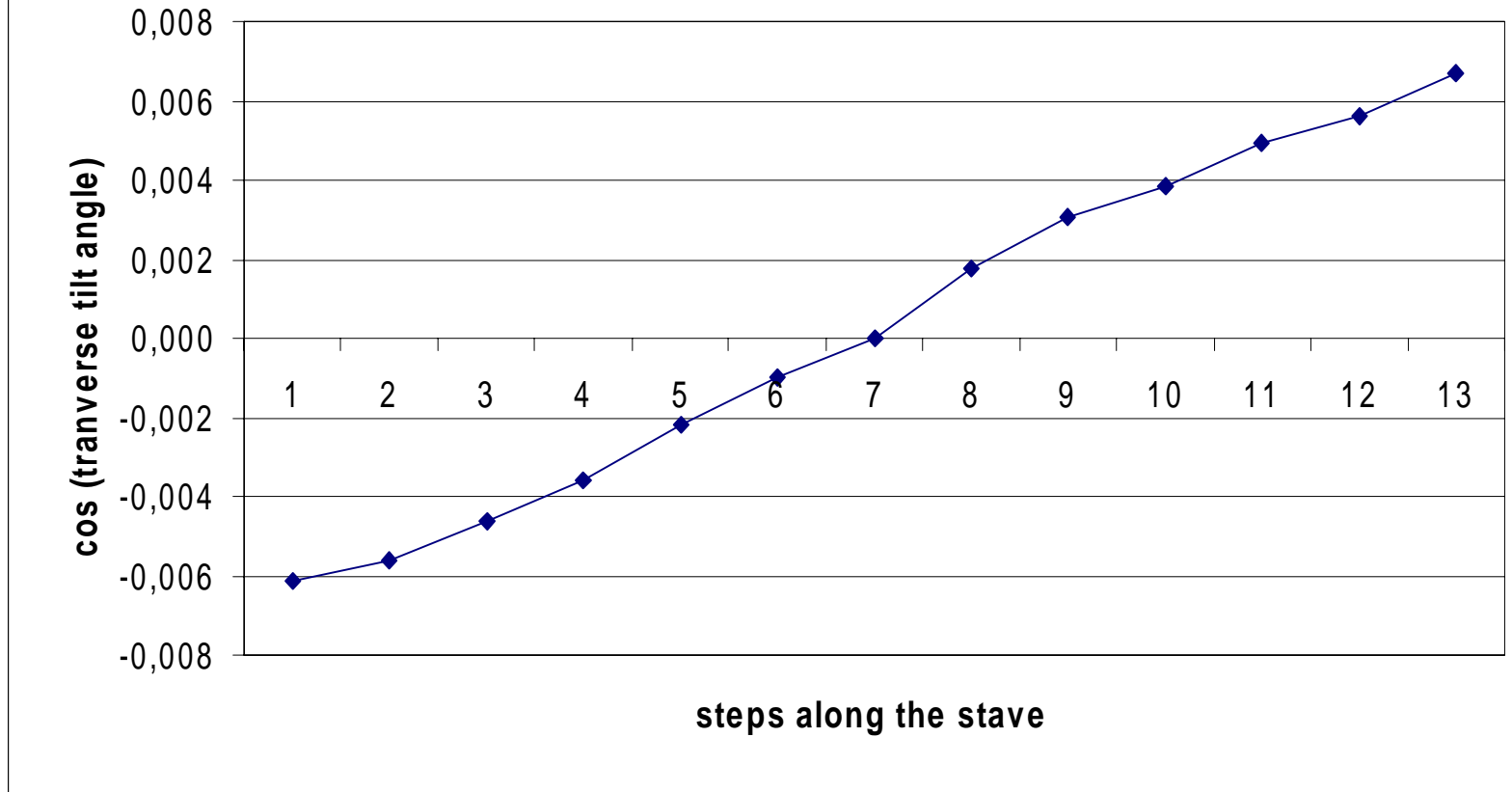
Stave dimensional stability

- The two staves with different omega lay-ups show max vertical displacements, due to **cool-down**, of the same order, but smaller for the 0-90-0 stave (**max 12 μm**)
- Beside a longitudinal bowing, the cool-down induces, as expected, an additional twisting effect (only on the 0-15-0 stave) due to the non-balanced lay-up with a non-planar configuration; even if it is a small effect it causes a **moment** acting on the two ends supports (**13 Nmm**) **not negligible**, since it is an undesirable extra load on the global support structure
- a first evaluation of the effect of the moisture absorption (with reference to water) by the stave resins leads to the conclusion that only a **10% variation** of the stave deflection due to cool-down should be expected
- max deflection due to **weight** (75 g) is about **40 microns**
- the **out-of-plane** of each stave step induced by the weight and cool-down is **lower than 1 μm**

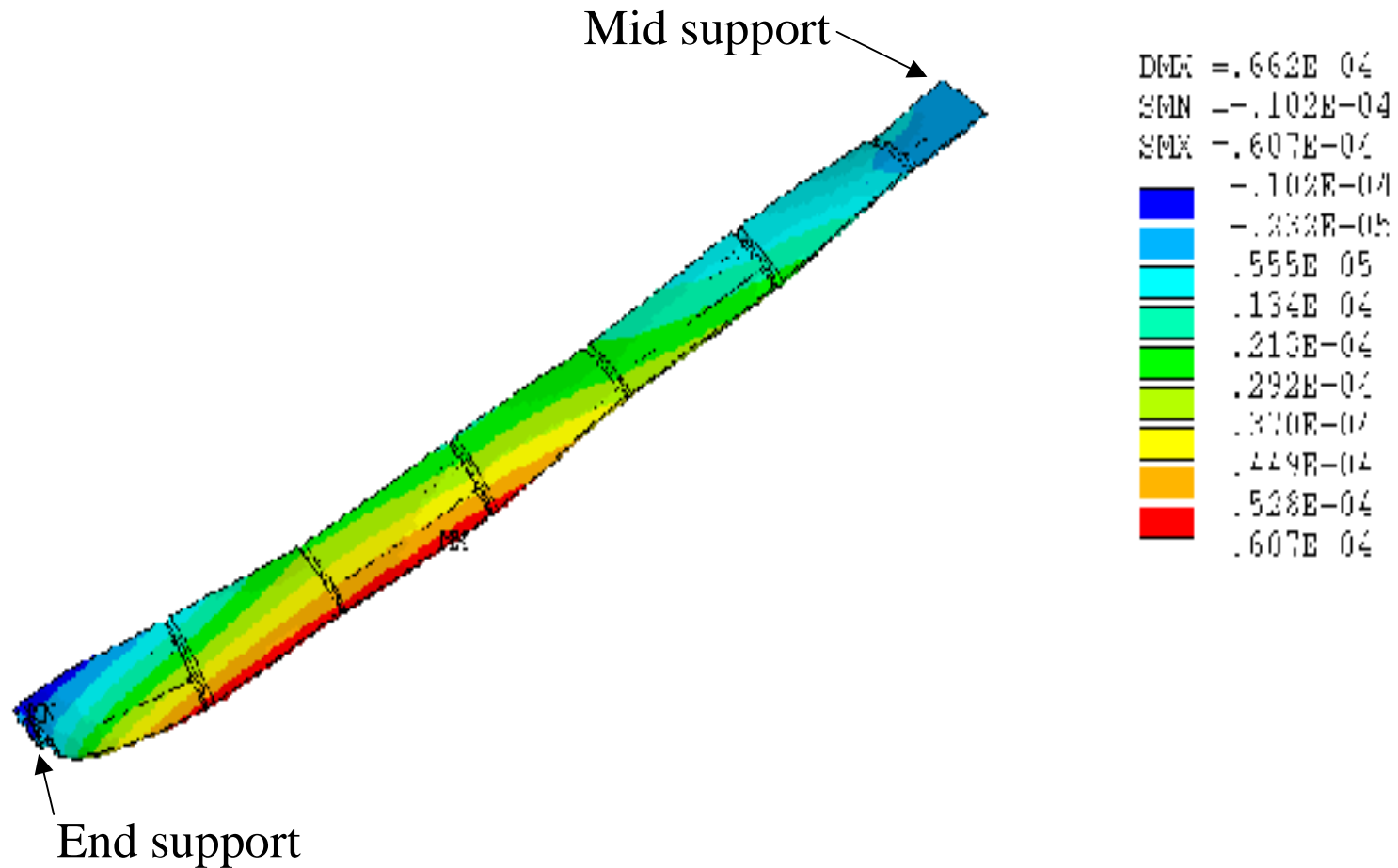
0-90-0 stave max vertical cool-down displacement vs. glue young modulus



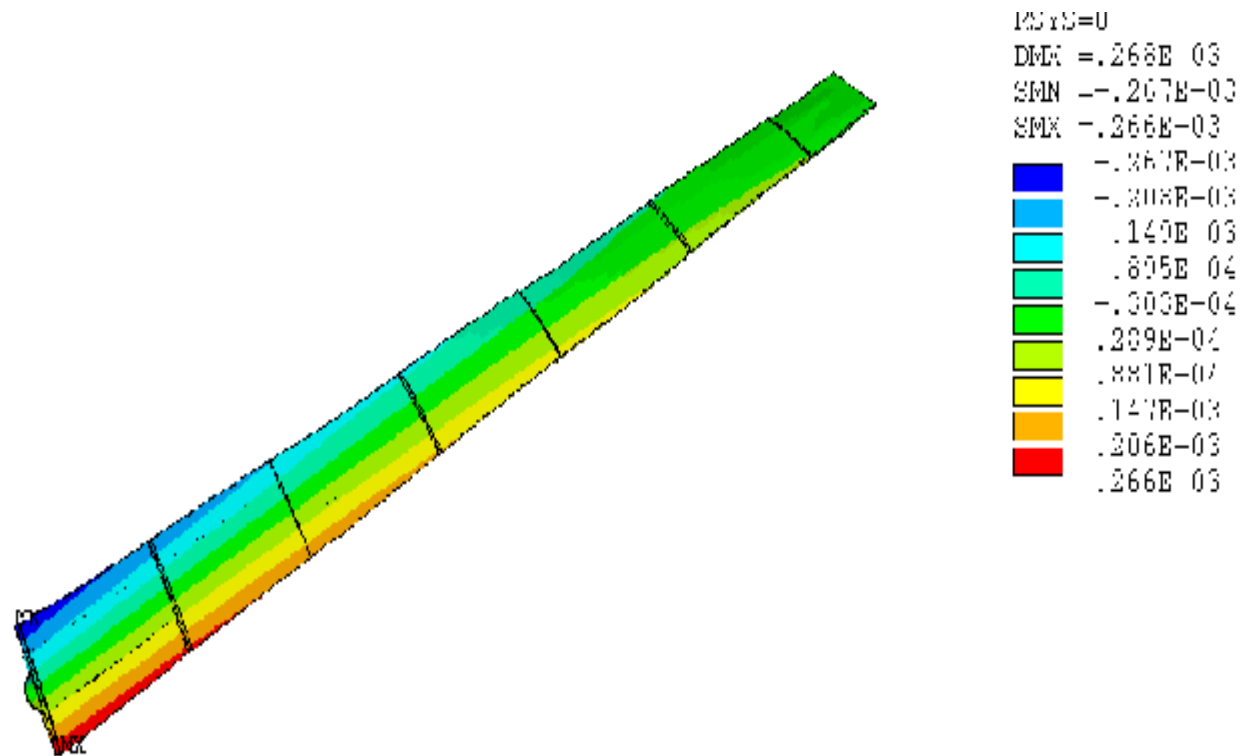
0-15-0 stave measured transverse tilting due to cool down



0-15-0 stave cool-down twisting: locked ends



0-15-0 stave cool-down twisting: free ends



Prototypes n°4: measurements vs. calculations

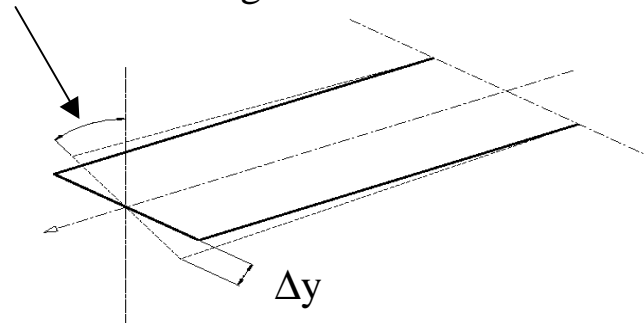
OMEGA TYPE	C-C IMPREGNATED	MODULES ON glued with CGL7018	COOL-DOWN DEFLECTIONS (μm)		COOL-DOWN TWISTING (Δy (μm))	
			calculated	measured	calculated	measured
0-15-0	no	no	-20	~ - 20	266 (1) 20 (2)	~60 (3)
0-15-0	no	yes			220 (1)	
0-90-0	no	no	20	~20	0	0
0-90-0	yes	no	13	15	0	
0-90-0	yes	yes	12		0	

(1) stave free to rotate around z at the two ends

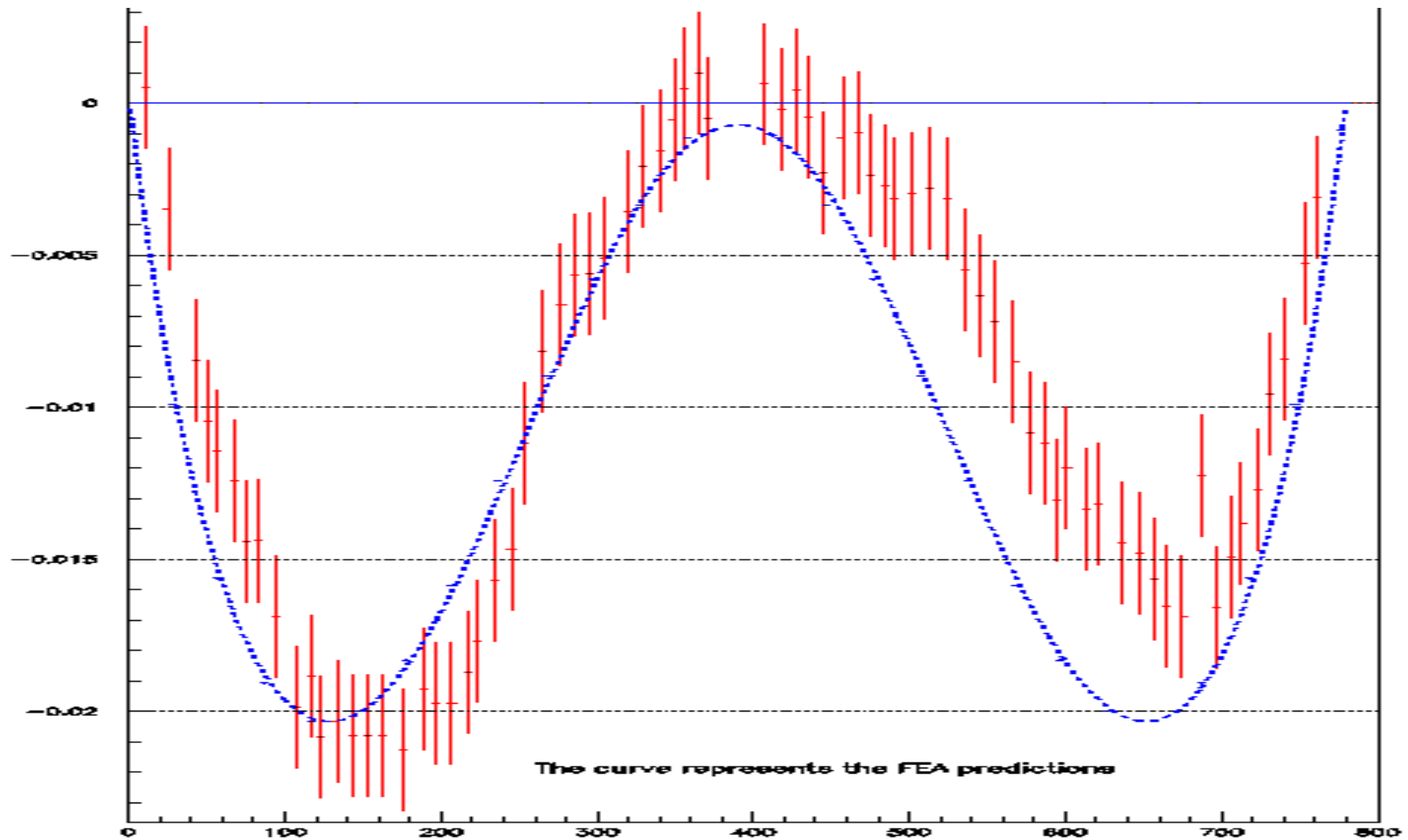
(2) rotation around z locked at the two ends: max tilting occurs at $z=300$ mm from the centerline, torque to prevent rotation at each end = 13 Nmm

(3) rotation only partially constrained at the two ends (spring constraint)

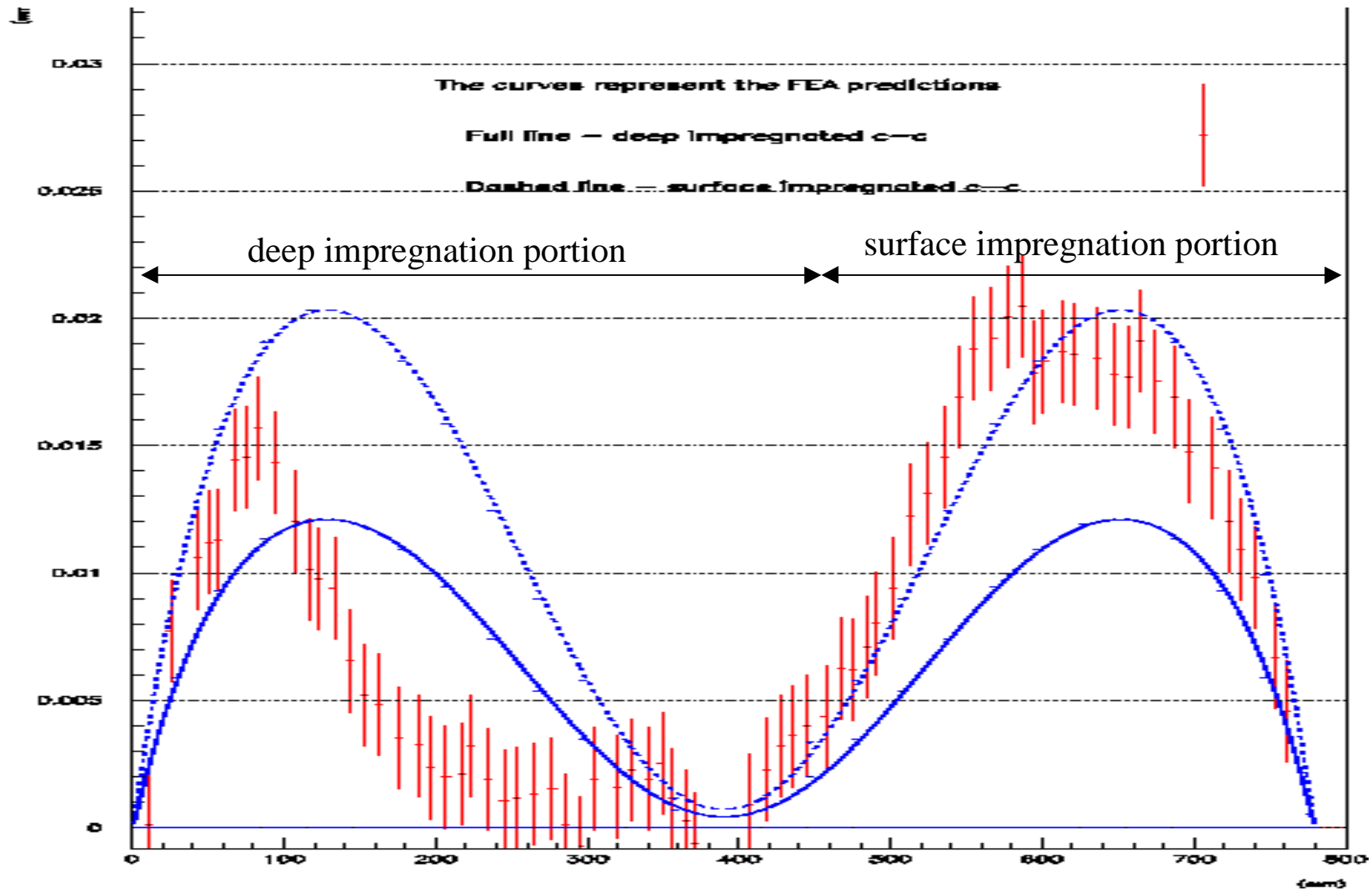
α =transverse tilt angle



0-15-0 stave cool down deflections



0-90-0 stave cool down deflections



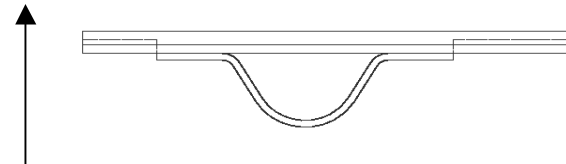
0-90-0 omega stave FEA analysis

Combine cool-down and weight deflections and actions on supports

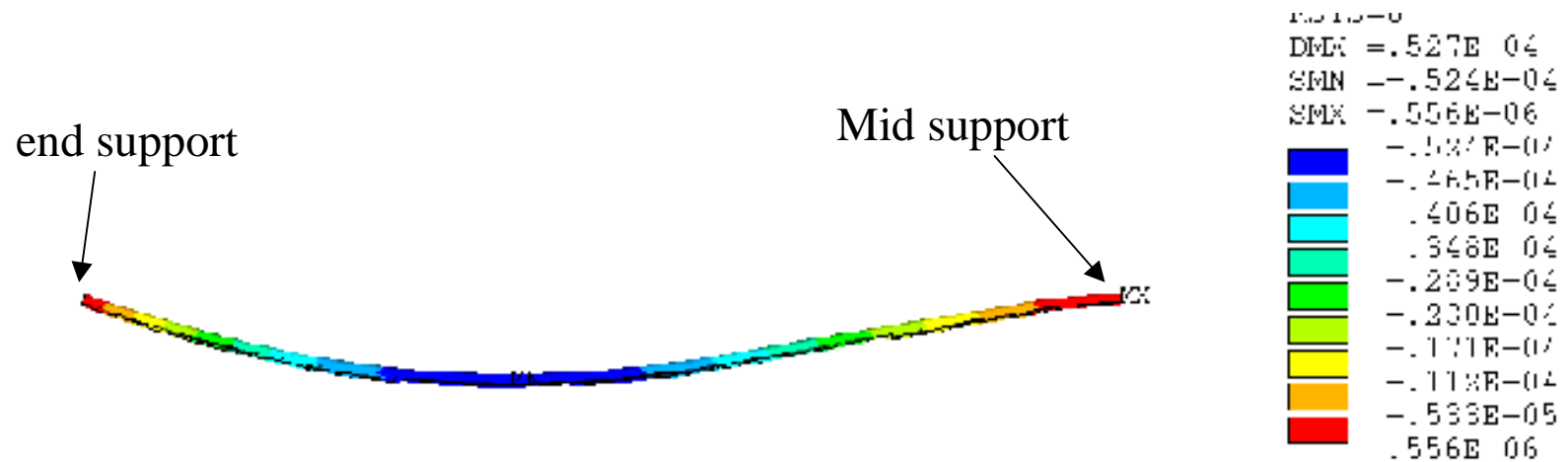
CASE	MAX DISPLACEMENT (μm)	FORCES ON SUPPORTS	
		Rend (g)	Rmid (g)
cool-down only	12	-2,3	4.6 (1)
weight only (stave + silicon = 42 g)	23	7,5	28
weight only (design = 75 g)	42	14	47
cool-down + weight (75g) best case (stave lower position)	-33	-16,3	-42,4
cool-down + weight (75g) worst case (stave upper position)	52	11,7	51,6

(1) measured = 5 g

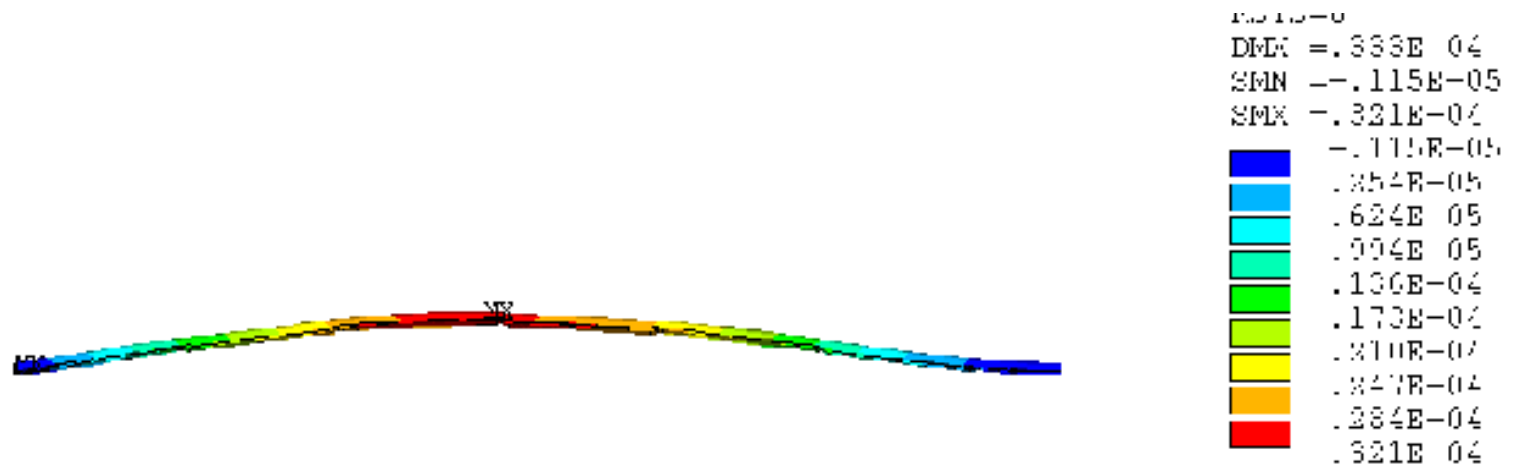
Displacements and forces
positive direction



Stave combined cool-down+weight deflections: worst case



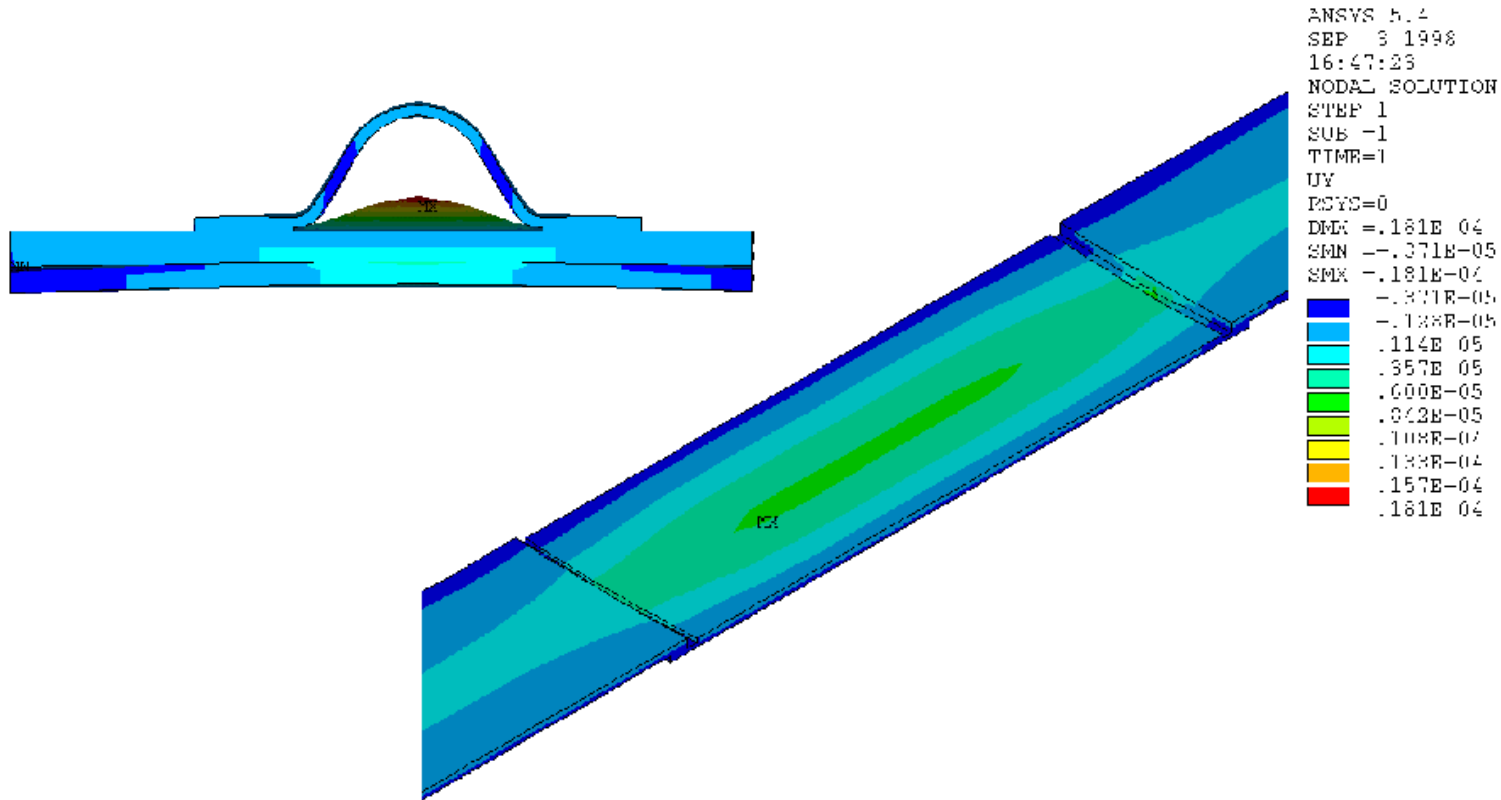
Stave combined cool-down+weight deflections: best case



Effect of the coolant pressure

- The coolant pressure is an internal action: it does not cause any longitudinal bowing of the stave nor forces on supports, but only cross section distortions and since it increases the module out-of-plane
- the calculated max out-of-plane of the module for -1 bar relative fluid pressure is:
 - upper steps: 2 μm
 - lower steps: 12 μm

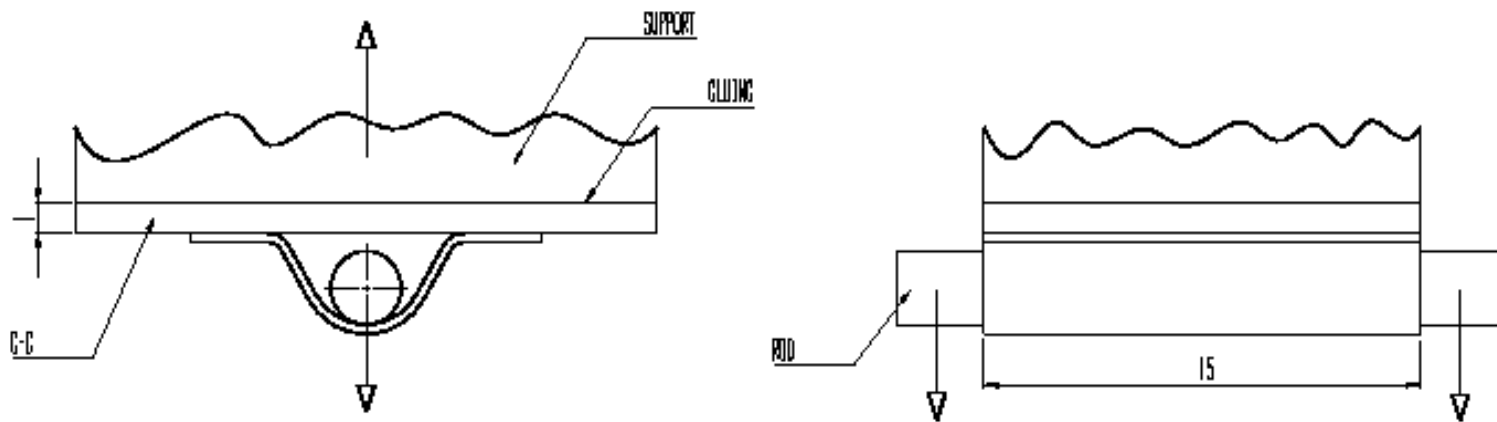
Stave deflections due to internal pressure (-1 barr)



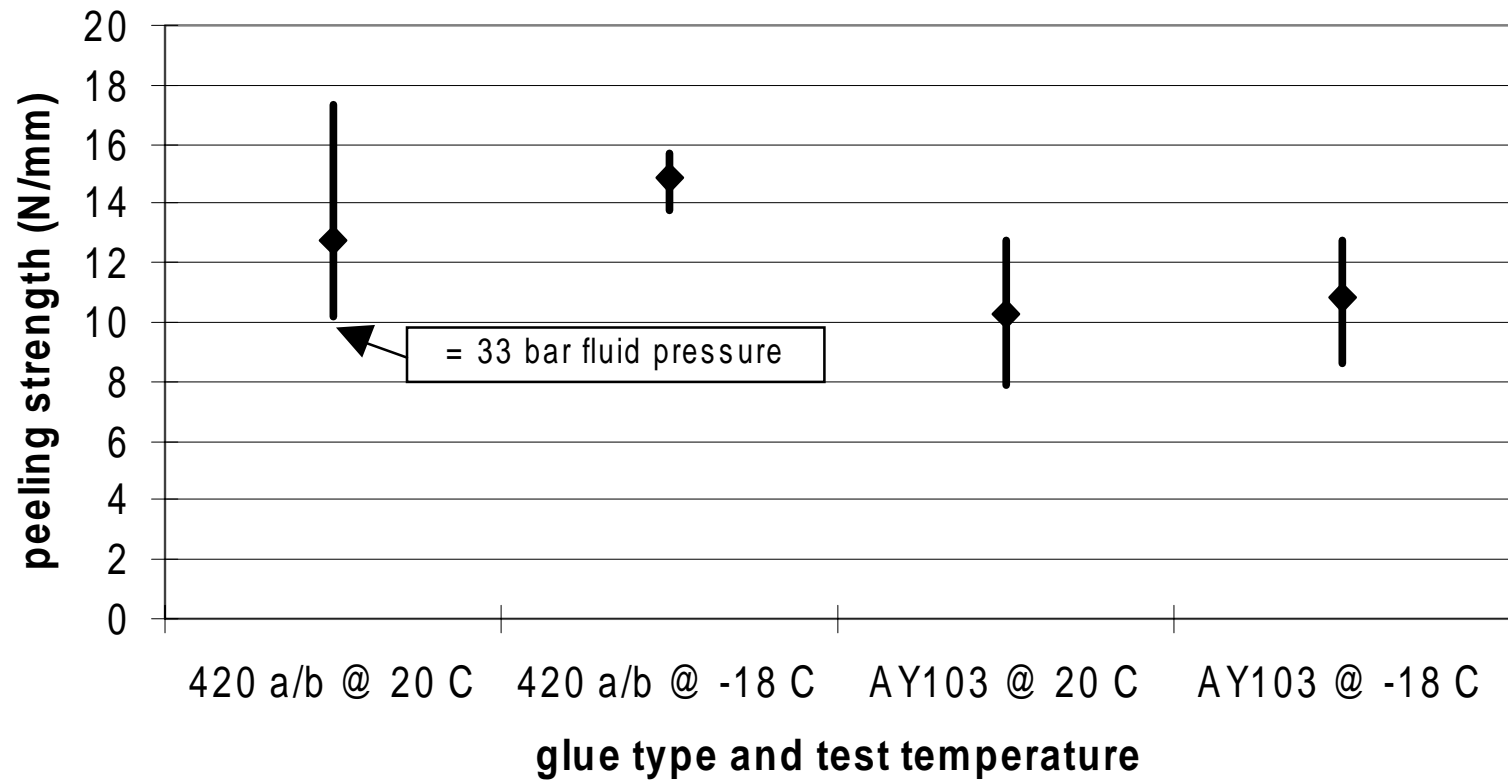
Stave structural integrity

- Peeling tests have been started to check the glue joint strength as function of: temperature, radiation dose, coolant action
- samples (15 mm long) have been prepared using the two different glue candidates (AY103 and 420 A/B)
- first tests results on samples as built indicate that:
 - 420 A/B glue has, as expected, an higher peeling strength than AY103: the minimum peeling stress found corresponds to an inside pressure of 33 bars!
 - the peeling strength is independent from temperature (in the range +20 °C / -18 °C)
- other sets of samples have been irradiated and will be tested by the mid of October
- other sets of samples have been immersed in C6F14 since last July and will be tested by the end of October (to see the effects of the first three months of coolant action)

Peeling tool



Peeling tests on 15 mm stave samples as built



Sealing tests

- Sealing tests performed on a small c-c impregnated piece at LBL show that even after irradiation 33 MRads (6.1×10^{13} 55 MeV protons/cm²) the sample is still leak-tight
- further tests will start on stave samples as soon as a new prototype will be built (we have to accurately investigate the sealing against the fluid action and the radiation dose)

Mechanical actions

The hard job has been completed: only refinements have to be introduced:

- improve the manufacturing process:
 - new molding tool to reduce the natural bowing of the omega piece
 - 2 c-c plates glued, instead of 4, to further reduce the distortion of the stave due to the 3 glue joints
- improve the c-c impregnation process reliability: new impregnation chamber and system closer to the mass production one

Summary and conclusions

- 0-90-0 stave seems to be the best candidate as barrel local support
- all major design issues have been successfully addressed: thermal and structural performances have been deeply investigated and are in agreement with the specifications
- some minor manufacturing refinements are still to be introduced
- few questions are still open, but only long term tests will give an exhaustive answer