

Development and testing of in-vessel magnetic sensors for ITER

progress on in-Vessel pick-up coils

presented by G. Chitarin (Univ. of Padova and Consorzio RFX)

acknowledgements to:

S. DalBello, S. Peruzzo, C. Taccon

L. Lotto, L. Ranzato, A. Sottocornola

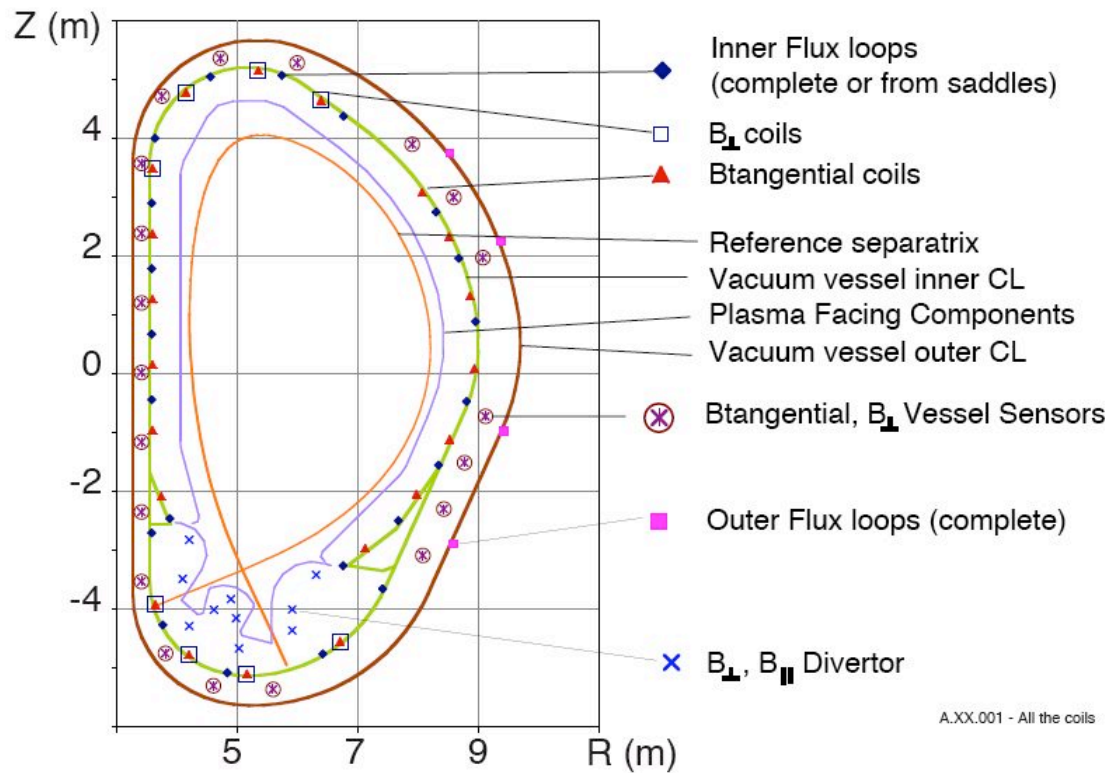
- background on magnetic measurements at RFX
 - design targets for ITER in-Vessel pick-up coils
 - proposed design concept for equilibrium pick-up coils
 - design rationale & weak points
 - prototype construction procedure
 - prototype tests procedure & results
 - present alternatives and conclusions
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- experience with JET-EP Halo sensors

JET-EP (Enhancement Projects):

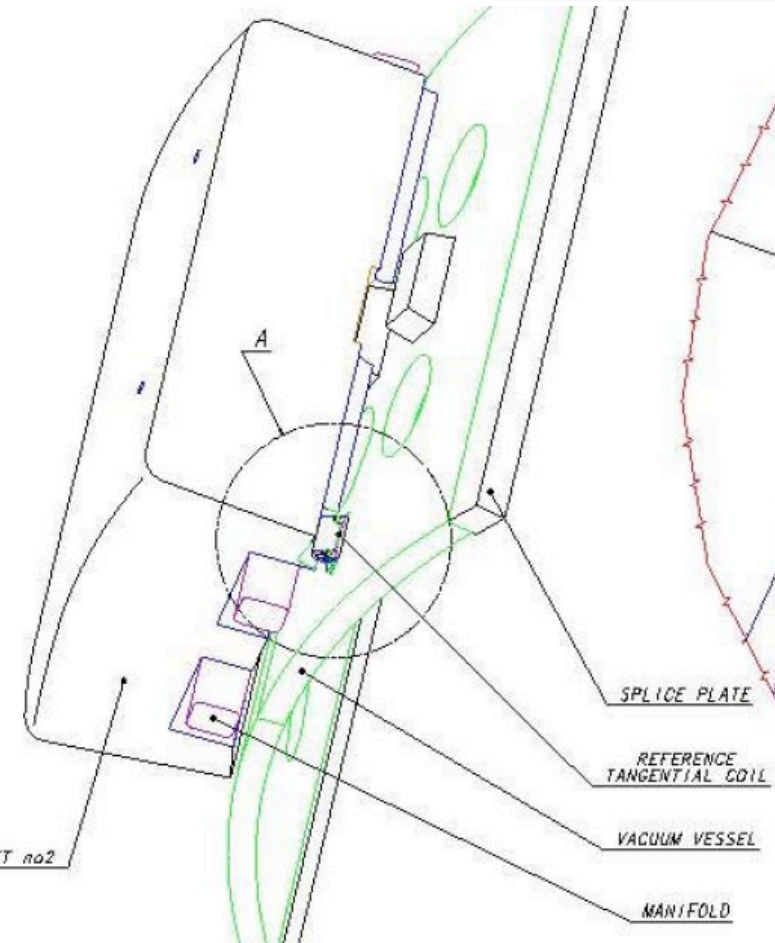
- JET Magnetics Enhancements (2002-2006) :
 - in-Vessel sensors (upper coils and outer poloidal limiter coils)
 - ex-Vessel sensors (pick-up coils, Hall probes, flux sensors)
- JET Halo Current measurement system: (2001-2006)
 - Halo rogowski coils (behind first wall CFC tiles)
 - Halo TF pick-up coils (behind first wall CFC tiles)

ITER :

- Re-evaluation and optimization of the sub-system for measuring Halo currents in ITER (2004)
- Design study of the ITER magnetics diagnostic (2005)
 - Inner-vessel tangential and normal coils
 - External flux loops
 - Halo current sensors
 - Steady-state sensors
- Development and testing of Magnetic Sensors (2006)
 - Inner-vessel tangential and normal coils
 - Blanket and Divertor Halo rogowski sensors



A.XX.001 - All the coils



tangential pick-up coils:
 maximum field
 measurement error target
 frequency bandwidth
 overall sensor dimensions

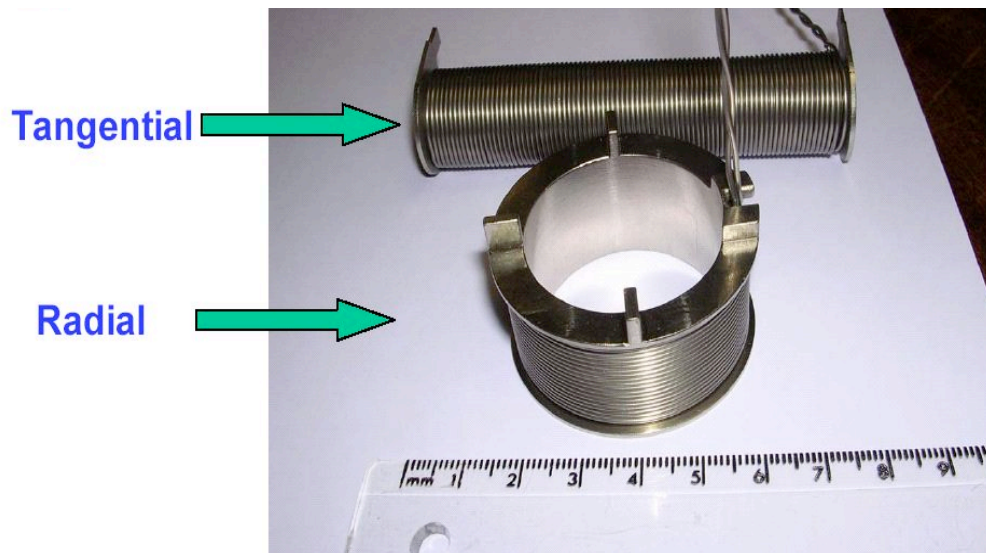
≈ 1 T
 ± 0.7 %
 $10^{-4} - 10^4$ Hz
 90mm x 50mm x 45mm

operating temperature	$\approx 150-200\text{ }^{\circ}\text{C}$
maximum temperature	$600\text{ }^{\circ}\text{C}$
temperature excursions (500 cycles)	$200\text{ }^{\circ}\text{C}$
neutron flux	$< 3 \cdot 10^{18}\text{ n/m}^2\text{ s @blanket gaps}$
max nuclear heating	$\approx 1\text{ W/cm}^3\text{ (in steel)}$
vacuum outgassing rate (one sensor)	$< 10^{-11}\text{ Pa/m}^3\text{s}$
typical electric field in the insulation	$< 250\text{ V/mm}$
rated voltage for insulation to ground	<i>(tbd)</i> 500 V (JET required 1 kV)
tolerable neutron fluence for permanent sensors	<i>(tbd)</i> 10^{24} n/m^2

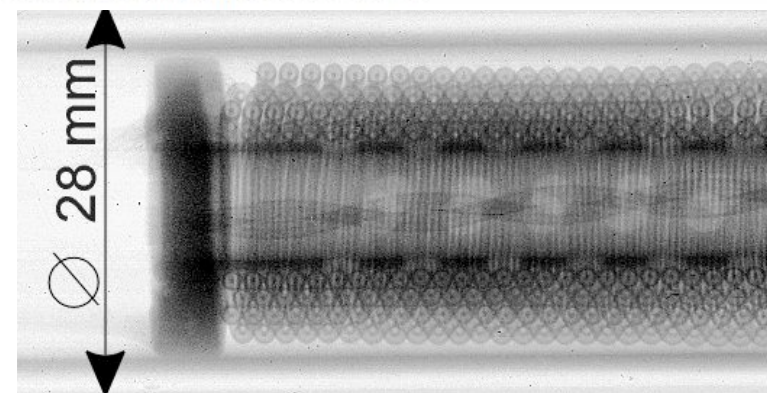
magnetic equivalent area	0.3 m^2
typical voltage output	300 mV
peak output voltage @ 100T/s	30 V
max flux	0.3 Vs
allowable flux error	2 mVs
allowable voltage offset for 3600s operation	$< 1\text{ }\mu\text{V}$
typical RIEMF/TIEMF temperature coeff. *	$\approx 0.5\text{ }\mu\text{V/K}$
allowable ΔT within the coil due to nuclear heating	$< 10\text{ }^{\circ}\text{C}$

•RIEMF = radiation induced electromotive force; TIEMF = thermally induced electromotive force
 (see papers by G. Vayakis, T. Sugie, R. Vila, E.R. Hodgson, R. Van Nieuwenhove and L. Vermeeren in references)

JET in-vessel pick-up coils



Insulant:	High Purity Magnesium Oxide 99.4 % min
Sheath material	INCONEL 600
Conductor material	Chromel P
Sheath outer diameter	1.0 mm
Sheath thickness	0.18 mm
Conductor diameter	0.22 mm
Insulant thickness	0.21 mm
Dimensional tolerances:	max ± 10 %
Piece length:	min 30 m
Max operating temperature	1100 °C



Original design concept of ITER magnetics (DDD 5.5) based on Mineral Insulated Cables (MIC), similar to those successfully used for JET in-vessel magnetics [<http://users.jet.efda.org/pages/mags/index.html>].

However:

- MIC can have large RIEMF/TIEMF coefficient
- nuclear heating and difficult thermal contact between MIC imply large temperature gradient in the MIC winding pack larger.
- improved thermal anchor and copper felt around the winding pack are not sufficient to reduce ΔT below 100 °C

- ➔ integration drift due to RIEMF/TIEMF voltage exceeds acceptable measurement error
- ➔ improved design with low thermal gradient required for ITER in-Vessel pick-up coils

	Mineral insulated conductors (MIC)	Flexible ceramic-coated conductors with "potted" fluid ceramic filling	Bare conductors with solid spacers and fluid ceramic filling
Mechanical strength of the insulation	very good	Poor, but not relevant after ceramic filling	good
Electrical insulation level	good	Fair, can be tested before winding	good
Thermal conductivity of the winding pack	poor even with copper felt	fair	fair
RIEMF/TIEMF properties	poor	expected to be fair, but still to be tested	good
Filling factor of the winding pack (active conductor area / total area)	bad	good	very bad
Degassing properties	good	expected to be fair, but still to be tested	expected to be fair, but still to be tested
comments	simple construction	fairly simple. delicate ceramic-coated conductor requires transition to other conductor to be inside coil case	solid spacers are mechanically complex and space-consuming pieces. cast or machined ceramic can be used, but insulation thickness cannot be smaller than 1 mm around each conductor

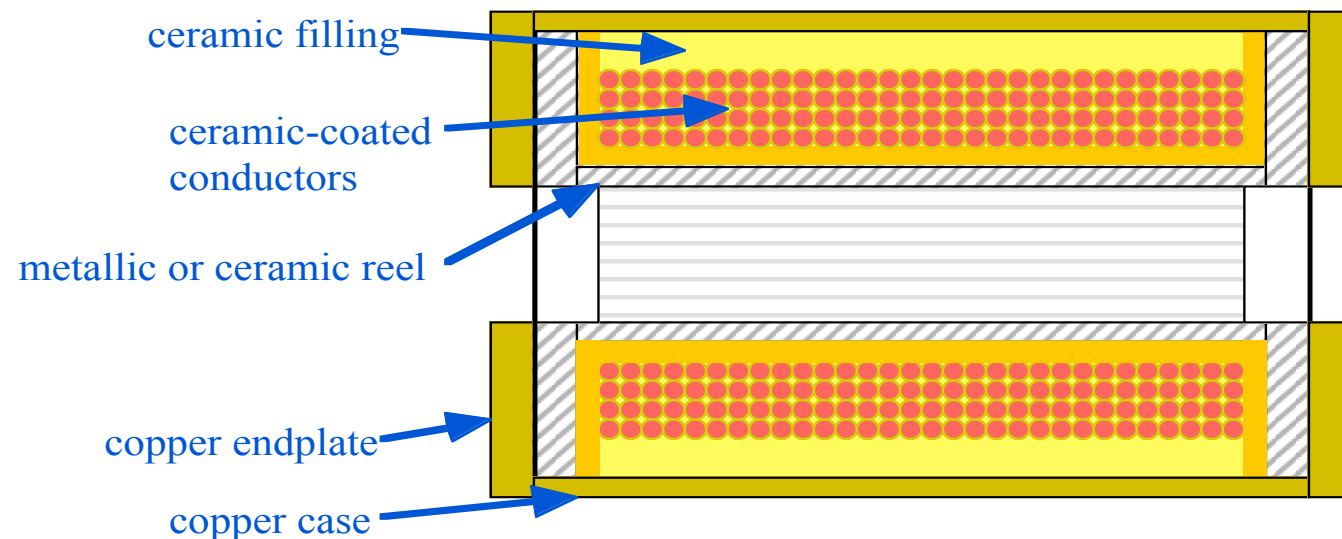


worth being tested first

Rationale:

reduce RITES/TIEMF voltage, which is directly related to the thermal gradient in the coil, caused by nuclear heating

- avoid vacuum spaces between conductors
- select materials for high thermal conductivity and low TIEMF cables
- reduce paths to thermal sink (ITER vacuum vessel)
- reduce coil and reel mass (in order to reduce the nuclear power generated)



Implementation concepts:

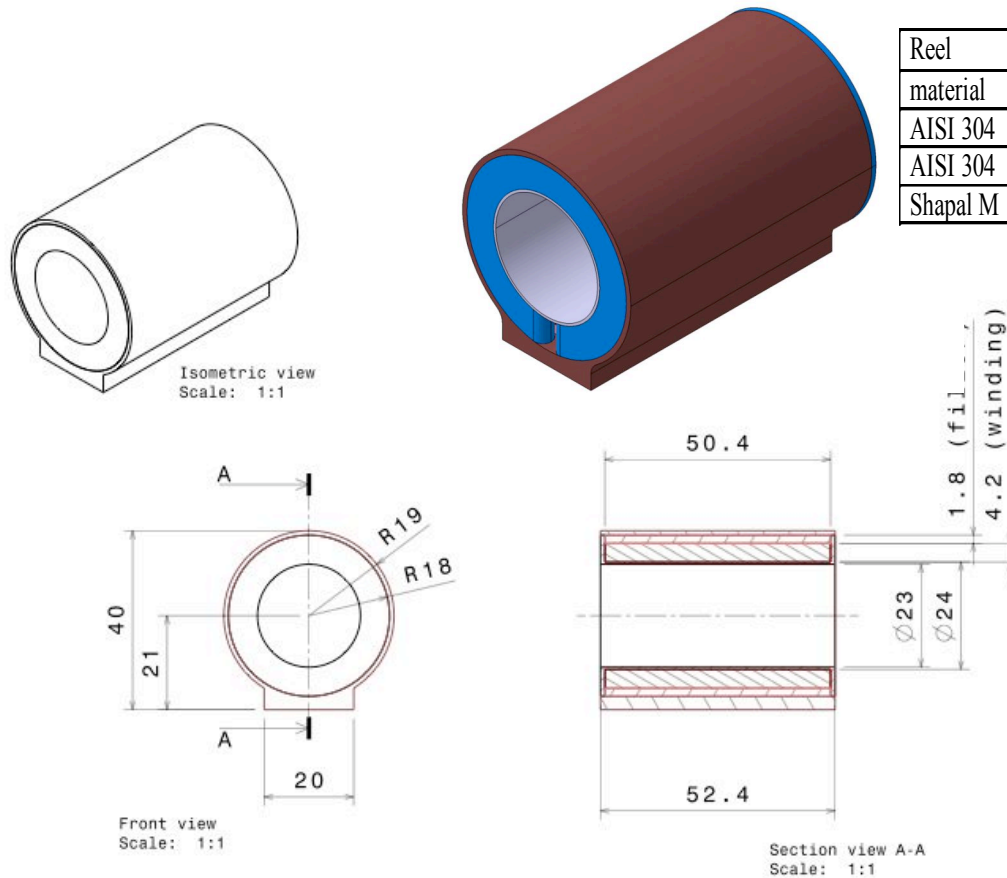
- **Fluid ceramic filling** ("potting") for improved thermal conductivity between turns and to the external case
- **Flexible ceramic-coated conductors** (thin inter-turn insulation)
- thin stainless-steel or machinable ceramic reel
- copper external Case and Endplate providing good thermal anchor to the vessel
- ground insulation only if necessary (plasma sprayed or fibreglass tape)

Expected advantages:

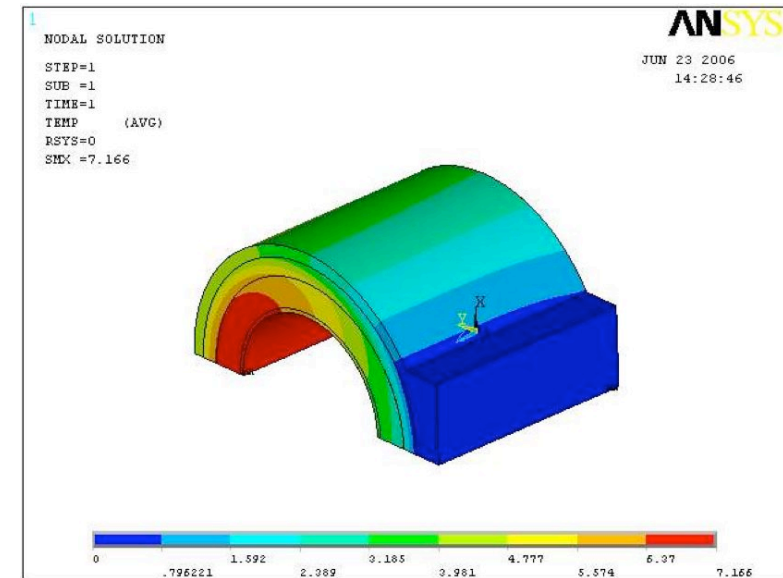
- better thermal conductivity of the winding pack (conductor volume/total volume ratio ~10 times larger)
- larger conductor cross-section, lower coil resistance and larger signal with the same sensor volume
- expected lower RIEMF/TIEMF in comparison with MIC conductors (to be confirmed)
- porous ceramic insulation constitutes a good surface for the adhesion of the fluid ceramic
- Insulation withstand voltage and reliability expected to improve with potting

Expected disadvantages:

- conductor insulation layer is very thin (< 0.1 mm) and potentially delicate
- insulation rated voltage is < 600 V at best (lower than usually required for insulation in JET) supplementary ground insulation is necessary if this level is considered not large enough
- conductor insulation is porous and can absorb moisture from the air or dirt during handling, bakeout in vacuum necessary
- transition to other kind of conductor inside the pick-up coil copper Case is necessary



Reel		Case		EndPlate		ΔT
material	thickness	material	thickness	material	thickness	
AISI 304	1 mm	AISI 304	1 mm	Copper	2 mm	22 °C
AISI 304	0.5 mm	Copper	1 mm	Copper	2 mm	7.1 °C
Shapal M	5 mm	Copper	1 mm	Copper	2 mm	5.1 °C



Vayakis coil
drawn by S.Peruzzo
date:8/6/2006

- ➔ ΔT can be reduced below 10 °C, i.e. below the expected background thermal gradient values
- ➔ thermal conduction coefficients of ceramic filling contact with conductors and case still to be verified by experimental tests
- ➔ further thermal optimization useless if presently assumed conduction coefficients are confirmed

Two types of cables have been proposed for the prototype tests (**manufacturer's specifications**):

Flexible ceramic-coated wires	Wire #1	Wire #2
Supplier	California Fine Wire	Ceramawire
Wire name and conductor composition	ALCAL type E stainless steel (AISI 304) (copper also available)	Kulgrid HT nickel-clad copper core: Cu (99,2%) cladding: Ni (99%)
bare conductor diameter	0.5 mm	0.5 mm
Insulation name and chemical composition (%weight)	Alcal type E: Al ₂ O ₃ (?) SiO ₂ (?) + volatile binder (?) (composition is proprietary)	Kulgrid : Pb Oxide (30-50%) Ti Oxide (15-25%) Si O ₂ (15-25%) Mg O ₂ (8-15%) B, Ni, Co, Al Oxides (<5%) (exact composition is proprietary)
Insulation thickness	0.1 mm	< 0.05 mm
Insulation Voltage rating	600 V	200 V
Continuous operation temperature	700 °C	550 °C
comments	needs curing at 700 C mechanically delicate insulation, particularly after curing	low rated voltage, but mechanically robust insulation



Both are worth being tested

A large number of fluid ceramic compounds is available on the market based on previous experience with JET magnetics, two types of fluid ceramic have been proposed for the ITER prototype tests:

Fluid ceramic	Fluid Ceramic #1	Fluid Ceramic #2
Supplier	Aremco	Aremco
type and composition	Ceramabond 503 (adhesive)	Ceramacast 575N (potting/casting material)
Volume resistivity	10 ⁷ Ohm m at RT 10 ³ Ohm m at 550 °C	10 ⁷ Ohm m
Major constituent	Al ₂ O ₃	Al ₂ O ₃
Dielectric strength at RT	10 kV/mm=250 V/mil	6 kV/mm=150 V/mil
temperature limit	1650 °C	1650 °C
Thermal expansion coeff	7.2 10 ⁻⁶ /K	7.5 10 ⁻⁶ /K



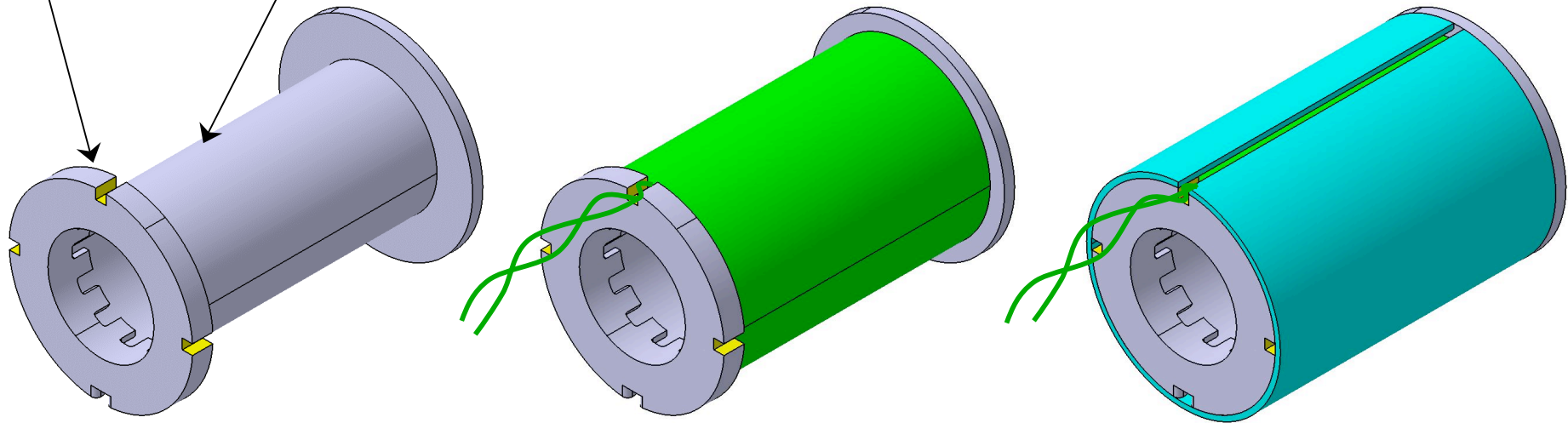
a protective & insulating ceramic paint (CorrPaint from Aremco) has also been tested, but abandoned because of large grain size

1. Viscosity of the fluid ceramic and complete filling of the winding pack during potting process
2. Adhesion of solidified ceramic to ceramic conductors, stainless steel and copper
3. Formation of cracks and cavities in ceramics during solidification (affecting equivalent thermal conductivity of winding pack)
4. Effect of potting fluid on conductor coating (affecting/increasing withstand voltage of insulation)
5. Different thermal expansion of solidified ceramics, copper and stainless steel, behavior under thermal cycling
6. Degassing rate of potted winding pack
7. RIEMF/TIEMF properties of ceramic-coated conductors
8. chemical compatibility of ceramic coating with ITER in-vessel environment, behavior of ceramic insulation material under neutron radiation,

- ➔ **Prototype construction and test necessary**
- ➔ **Tests on prototypes are in progress at Consorzio RFX for issues 1-6 in the frame of EFDA task.**

Plate with openings for ceramic filling

AISI304 wire cloth cover



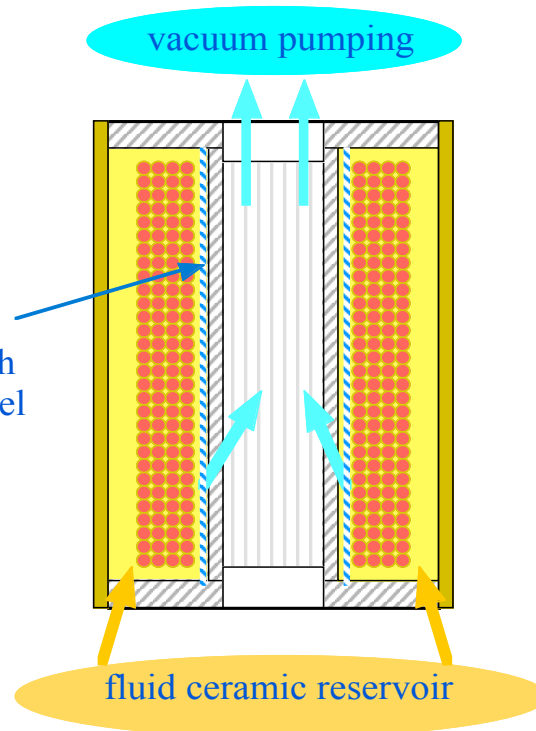
Coil reel

Coil winding

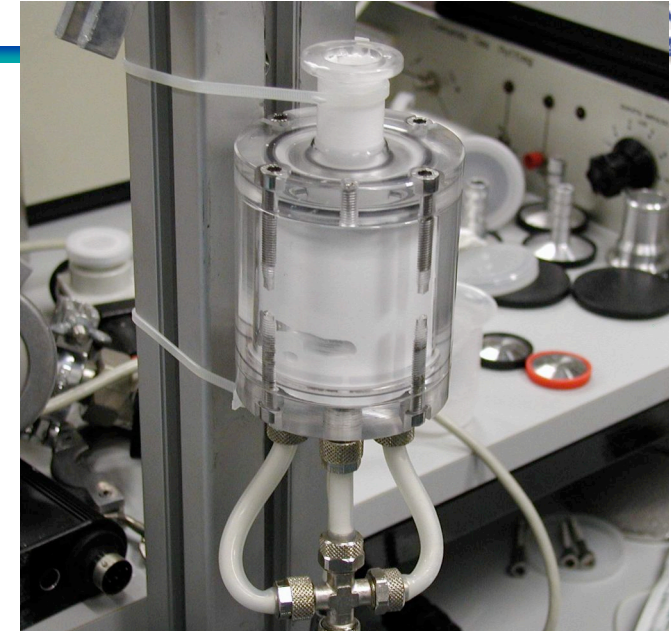
Coil case with slot to limit eddy currents (not used for first prototypes)



slitted reel covered with stainless steel wire cloth



Impregnation test rig



- slitted reel covered with stainless steel wire cloth (permeable to air but not to fluid ceramic), stainless steel might be substituted with insulating fibreglass fabric
- coil assembly "vacuum impregnated" with radial fluid ceramic flow
- fluid ceramic cured at 370 °C

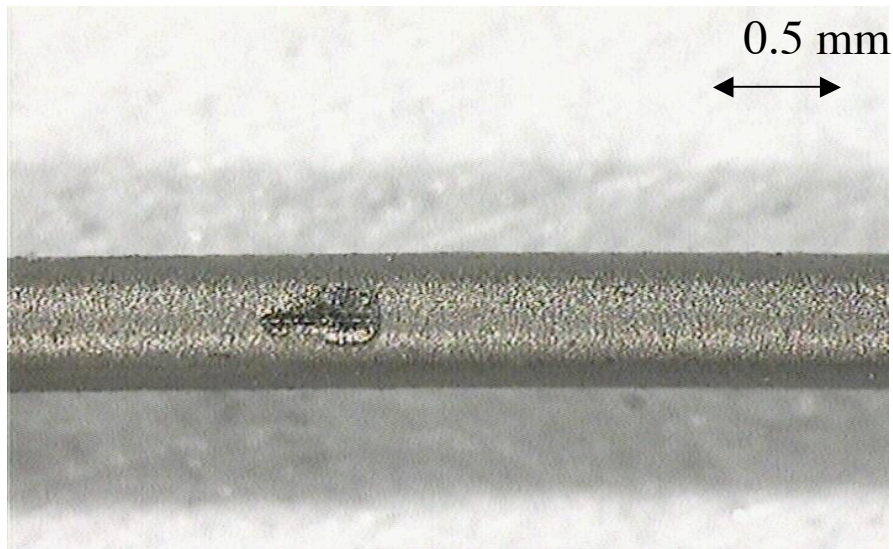
On the basis of the expected critical issues, a test plan has been defined on samples of ceramic-coated conductors and on a number of prototype coils.

1. Insulation resistance test of conductor samples (after vacuum bakeout) up to breakdown voltage level.
2. Insulation resistance test of potted prototype coils up to rated voltage level.
3. Thermal test with measurement of thermal conductance of winding pack
4. Insulation resistance test of potted prototype coils up to breakdown voltage level (before or after thermal cycles)
5. micrographic analysis of coil section for the evaluation of bubbles and cracks (before or after thermal cycles)
6. residual gas analysis during out-gassing
7. X-ray tomography (if necessary)
8. measurement of magnetic effective area and sensitivity to transverse fields

total number of prototype coils ≈ 20 , depending on results, first prototypes without copper case.



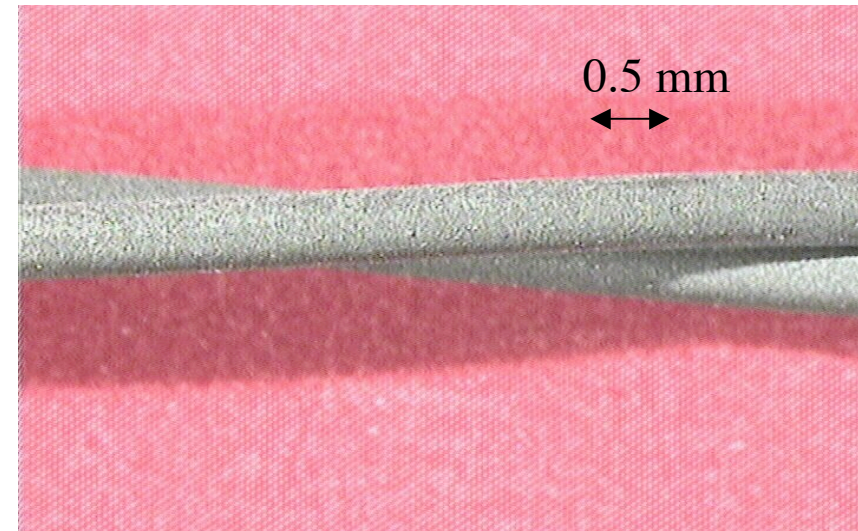
1. perform test cycle on initial series of prototypes
2. evaluate first test results
3. define transition and connections to MIC or Sulzer cables
4. update design and drawings on the basis of the first experimental results
5. prepare technical specifications for construction of new prototypes
6. proceed with second test cycle
7. evaluate second test cycle results
8. assess performances of optimal design



Wire #1

- After curing for 45 min at 700°C, the insulation is transformed into a thin layer with the consistence of ash
- insulation resistance value is 600 MOhm at 100V.
- Insulation breakdown occurred at a voltage value of ~ 250 V, well below the rated voltage of 600 V.

Damage of the insulation was found in several points of the wire just after delivery. Electrical tests were carried out on specimens of wire apparently undamaged.

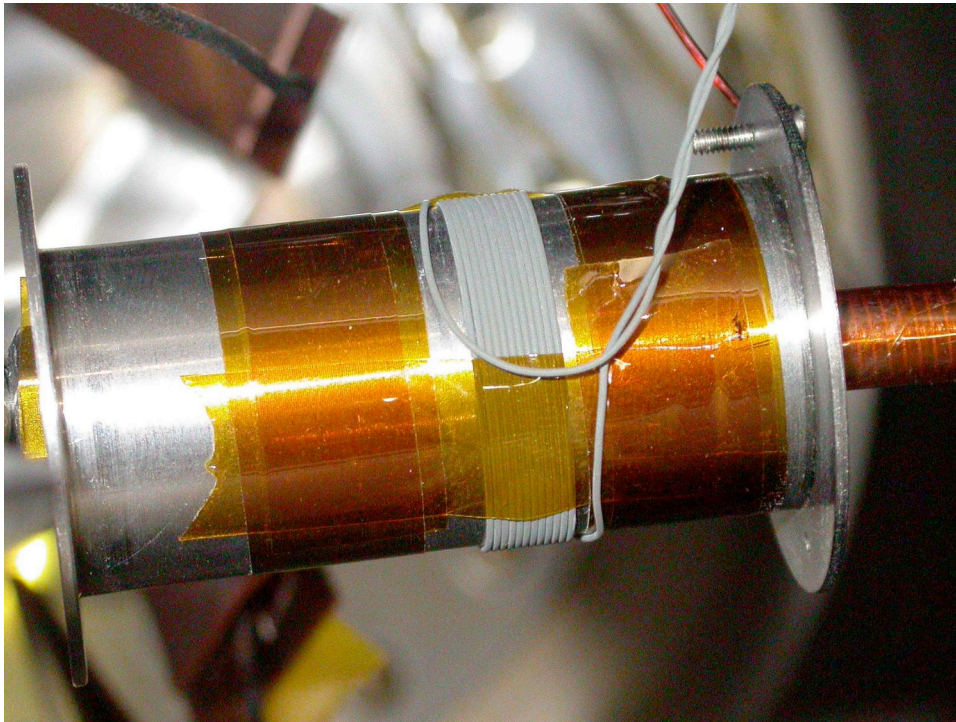


Wire #2

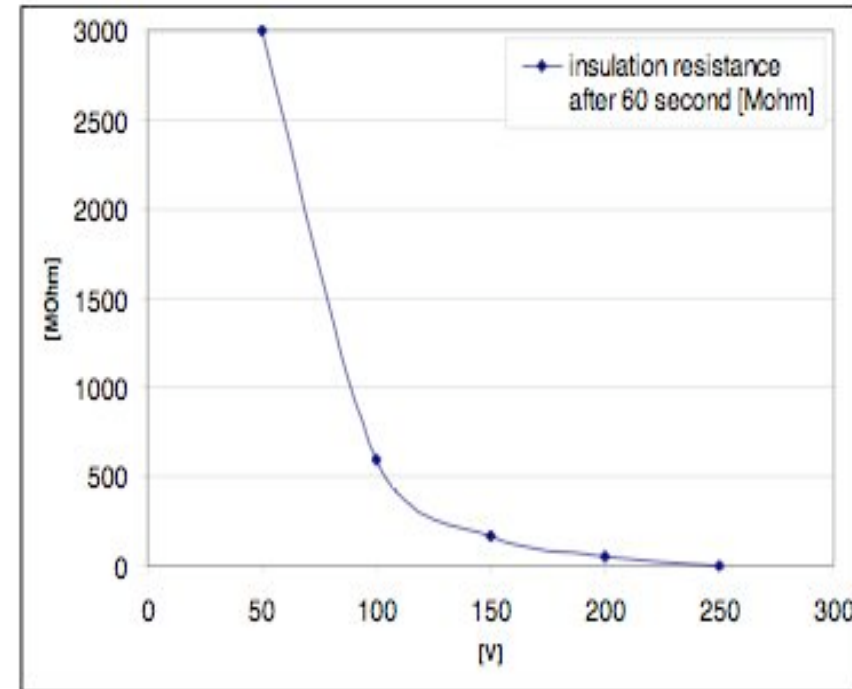
- insulation resistance to ground quickly diminishes during the application of voltage and its value is low ($\approx 1\text{M}\Omega$) even at few tens of Volt.
- Insulation breakdown occurred at a voltage level <50 V, well below the rated voltage of 200 V

•effect of humidity adsorption from the air seems to be little related to the problem, tests repeated after longer vacuum bakeout at 140 °C gave marginal improvement

**Manufacturers have been have been questioned, but have given little help so far.
Manufacturer's specifications not confirmed by tests.**

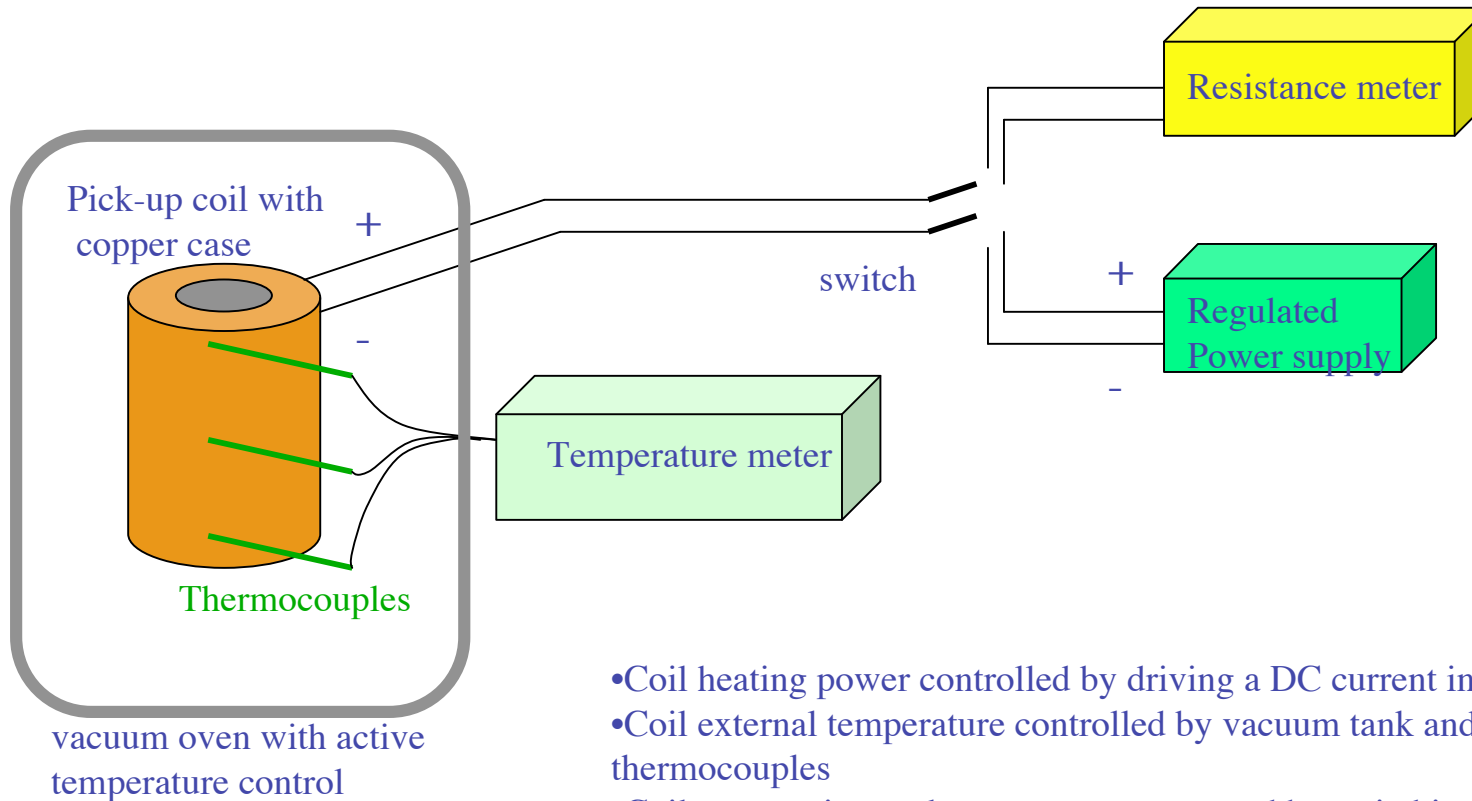


Ceramawire conductor insulation after vacuum bakeout



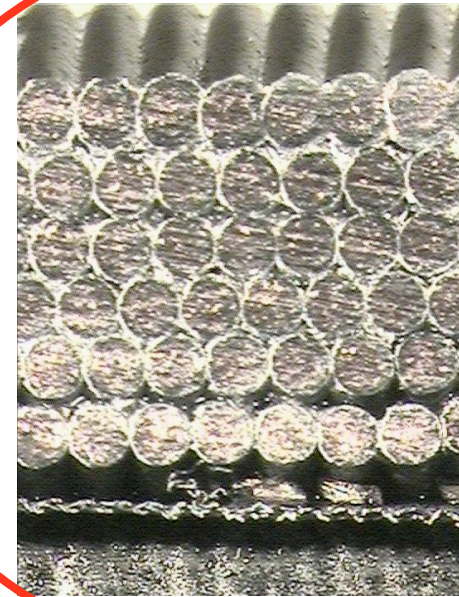
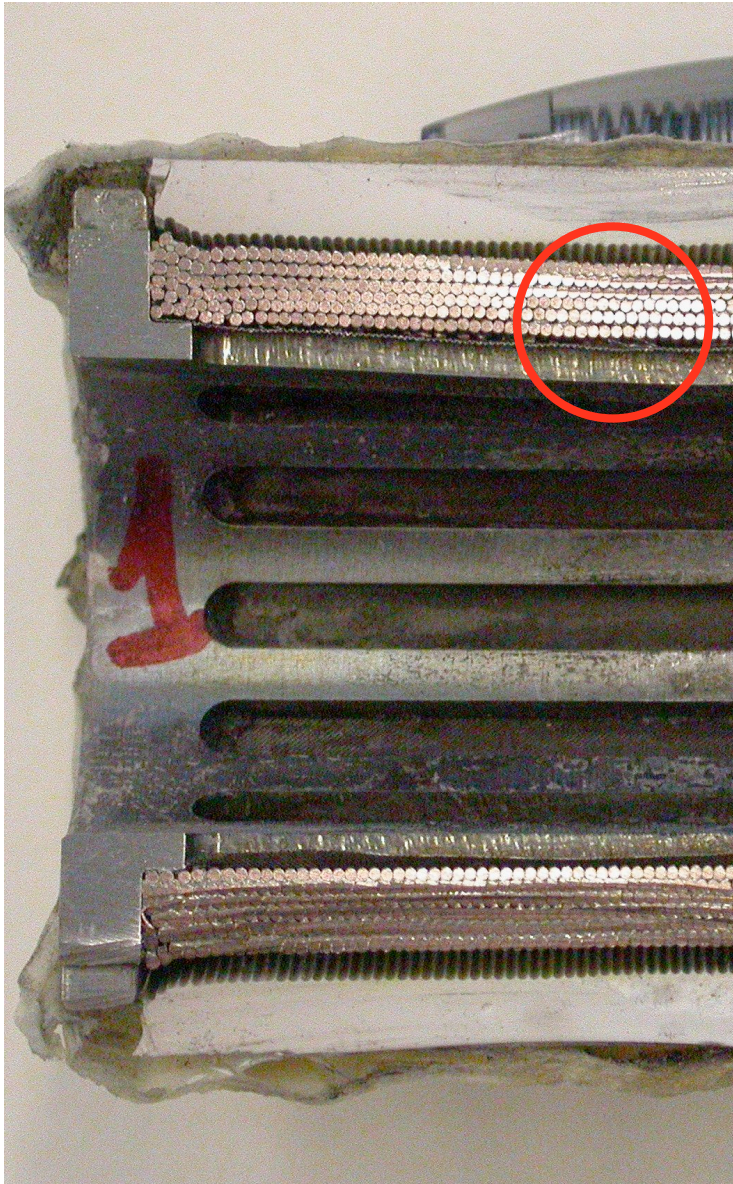
Calfinewire Conductor insulation resistance after vacuum bakeout at 140 °C

The results of the insulation tests on potted prototype coils were not better than those of the conductor samples, in all cases the coil insulation brakes down below 50 V.



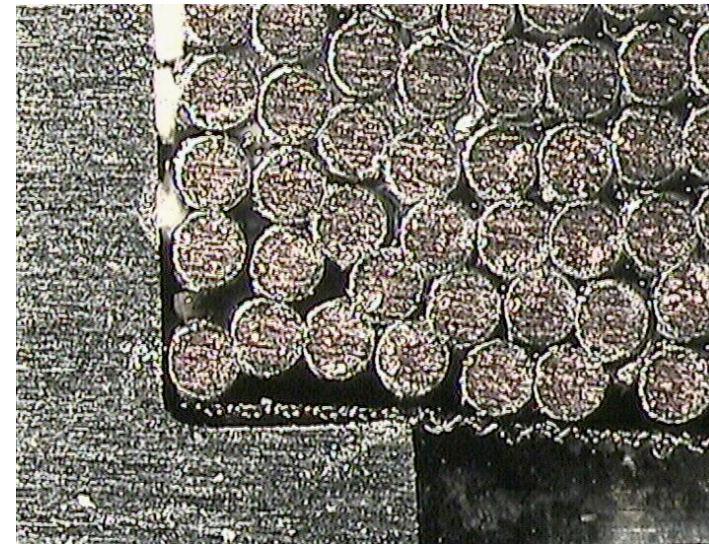
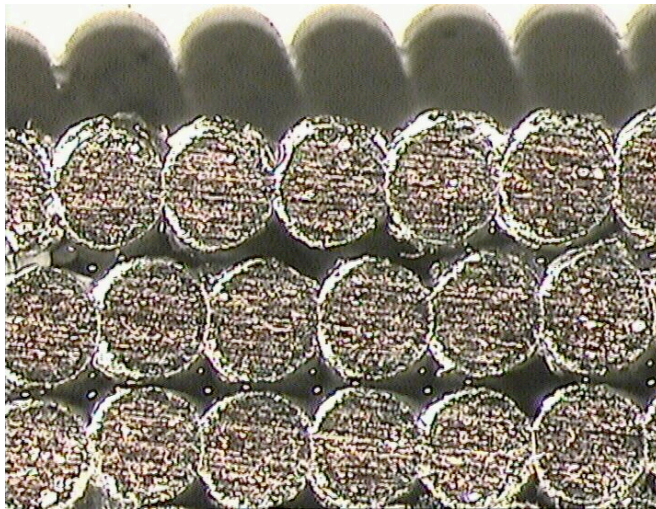
- Coil heating power controlled by driving a DC current in coil conductor
- Coil external temperature controlled by vacuum tank and measured with thermocouples
- Coil average internal temperature measured by switching off briefly the power supply and recording the resistance variation with respect to a calibration value obtained at zero power and uniform oven temperature.

➔ Measurement of heat conductance of winding pack not possible on prototypes, due to conductor insulation failure



Section of the coil showing that:

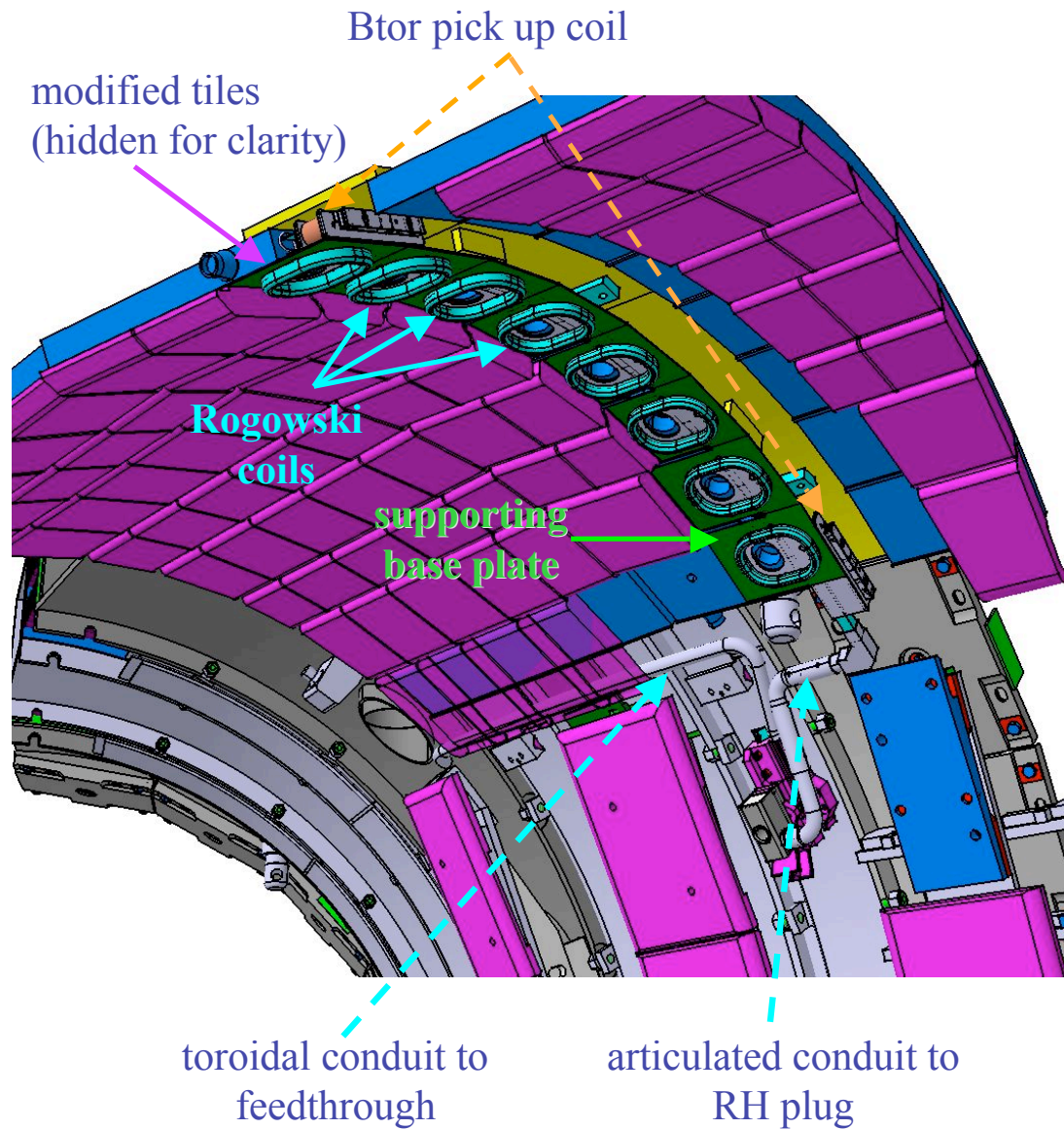
- the winding pack is filled with fluid ceramic
- only in a few areas the space between conductors is not filled with ceramic
- during the cutting process a large deformation of the reel has occurred, which caused the detachment of the winding pack from the outer ceramic layer and from the inner stainless steel fabric layer



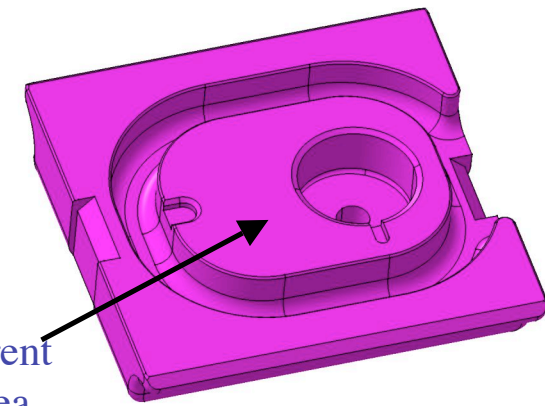
- the adhesion of cured ceramic is poor when the ceramic layer is thin, the ceramic tends to be pulverized under stress.
- the "impregnation" technique shall be improved to ensure that all volume is properly filled
- the sectioning technique should be improved, precision cutting machine purchased for repetitive tests, x-ray tomography might be used

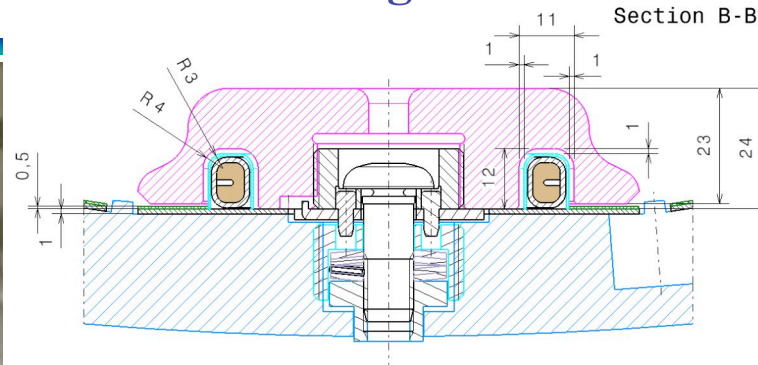
- ➔ Ceramic-coated flexible conductors are still an option, but the reliability of their electrical insulation is critical
- ➔ Continue with present design concept, with suitable ground insulation layer
- ➔ Alternatives presently under consideration:
 1. **flexible conductors with braided fibreglass insulation** "P.O.Zh. conductor", produced by a Russian manufacturer. Very promising, does not require major modification of the present design.
 2. **stack of ceramic plates with printed metallic deposit**. The technology for the metallic deposit of printed circuits on ceramic substrate is available for microwave and some automotive applications. Good electrical and thermal properties are expected, RIEMF/TIEMF properties of metallic deposit and of the brazing/welding between adjacent layers should be verified. The design of the pick-up coils shall be completely changed. (see also Takahashi [4])
 3. **bare conductors with solid insulating spacers** (fluid-ceramic potted or not).
 4. **flexible ceramic-coated wires with plasma-sprayed ceramic between each layer** of conductors. Even if the turn-to-turn insulation is poor, the plasma-sprayed ceramic should ensure good insulation to ground and between layers. Requires collaboration with a plasma-spray industry.

- [1] G. Vayakis, T. Sugie, et al. “**Radiation-induced thermoelectric sensitivity (RITES) in ITER prototype magnetic sensors**” Review of Scientific Instruments Volume 75, Number 10 October 2004
- [2] R. Vila, E.R. Hodgson: “**RIEMF in MgO and Al₂O₃ insulated MI cable ITER magnetic diagnostic coils**” , Journal of Nuclear Materials 329–333 (2004)
- [3] R. Van Nieuwenhove and L. Vermeeren, “**Experimental study of radiation induced electromotive force effects on mineral insulated cables**”, Review of Scientific Instruments Volume 74, No 11 November 2003
- [4] H. Takahashi, S. Sakakibara, Y. Kubota, H. Yanada " **Magnetic probe construction using thick-film technology** " Rev. Sci. Instrum vol 2, n 8 2001
- [5] Design study of the ITER magnetics diagnostic TW4-TPDS-DIASUP, EFDA 04-1210 contract, D6.2 Final Report (Association Euratom-ENEA, Consorzio RFX, Padova, Italy) Jun 2006.
- [6] Thermo-mechanical tests for ITER in-vessel tangential pick-up coil prototypes (RFX internal report IP-NT-159) 6/11/2006
- [7] Procedure of electrical tests on ceramic coated conductors and on prototype in-vessel coils for ITER (RFX internal report SM-NT-278) 7/11/2006
- [8] Results of electrical tests on ceramic coated wires (Calfinewire) (RFX internal report SM-NT-279) 07/12/2006
- [9] Results of electrical tests on ceramic coated wires (Ceramawire) (RFX internal report SM-NT-280) 25/1/2007

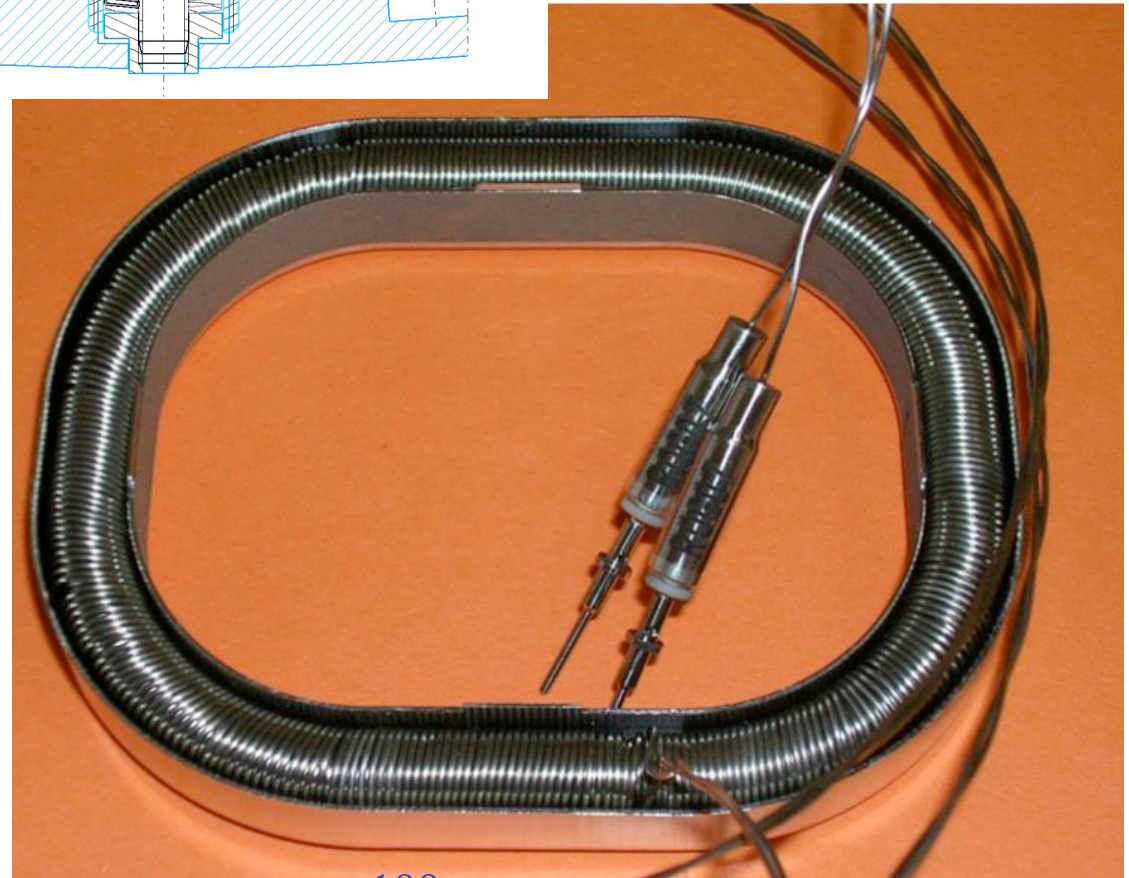


- ↪ Up to 8 rogowski coils
- ↪ 8 modified CFC tiles (modified to house the rogowski coils)
- ↪ Up to 2 toroidal field pick up coils
- ↪ 1 base plate (supporting both the sensors and a conduit along the poloidal direction)
- ↪ 1 articulated conduit to Remote Handling plug & socket
- ↪ 1 toroidal conduit (22.5° long) from RH socket to the feedthrough



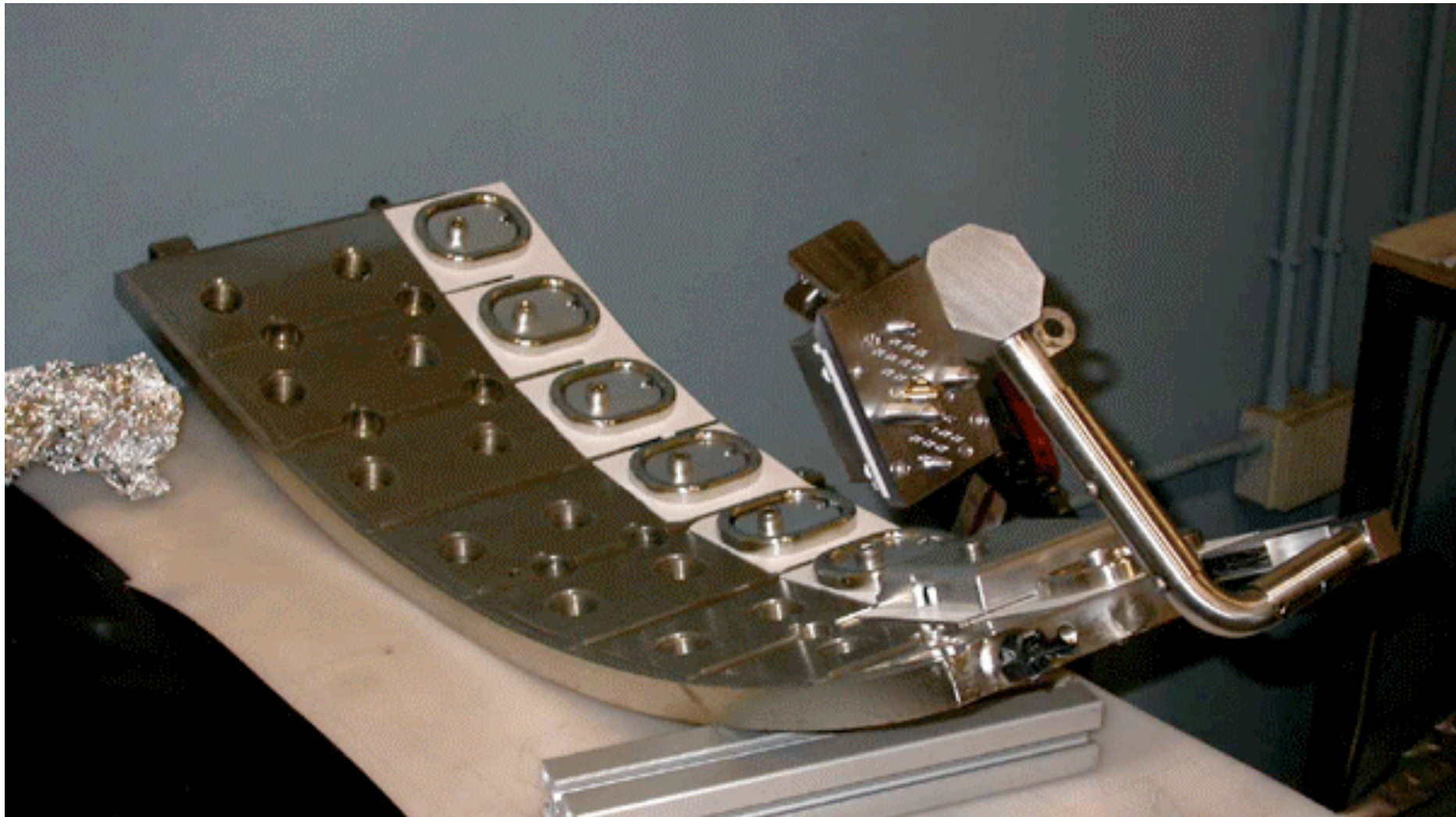


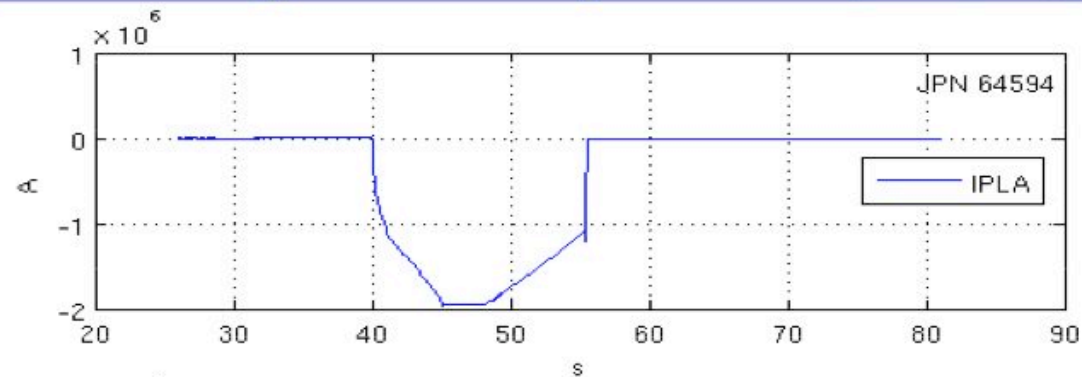
Rogowski equivalent area $\approx 0.03 \text{ m}^2$
Rogowski constant $\approx 10^{-7} \text{ H}$



$\sim 100 \text{ mm}$



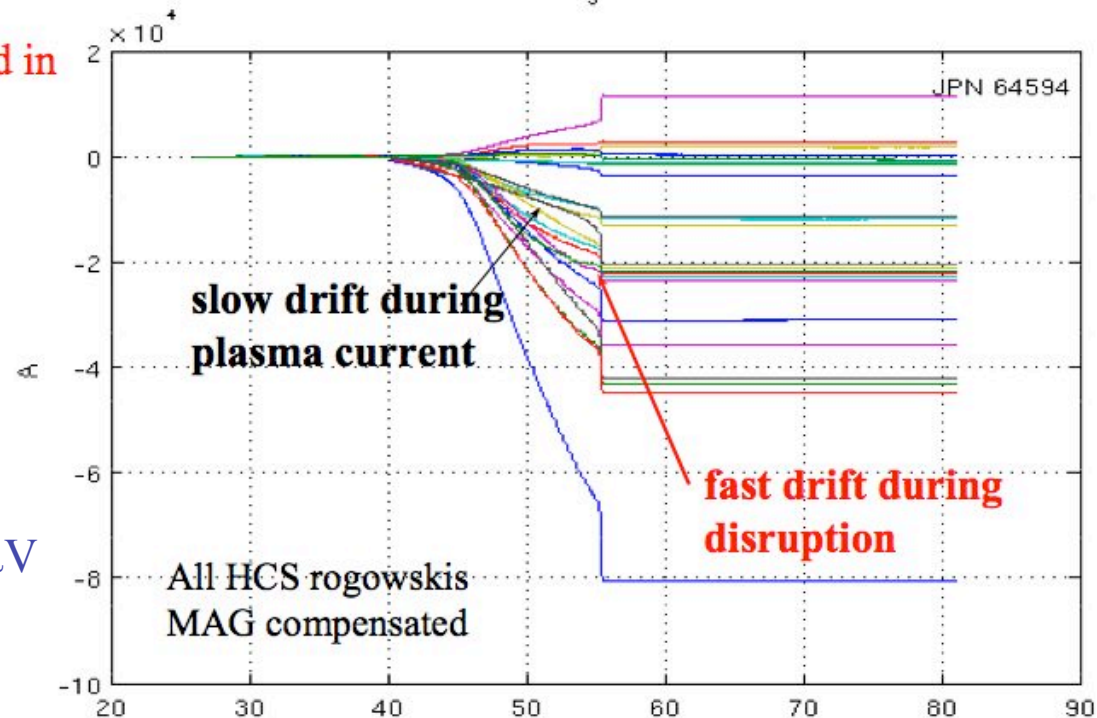


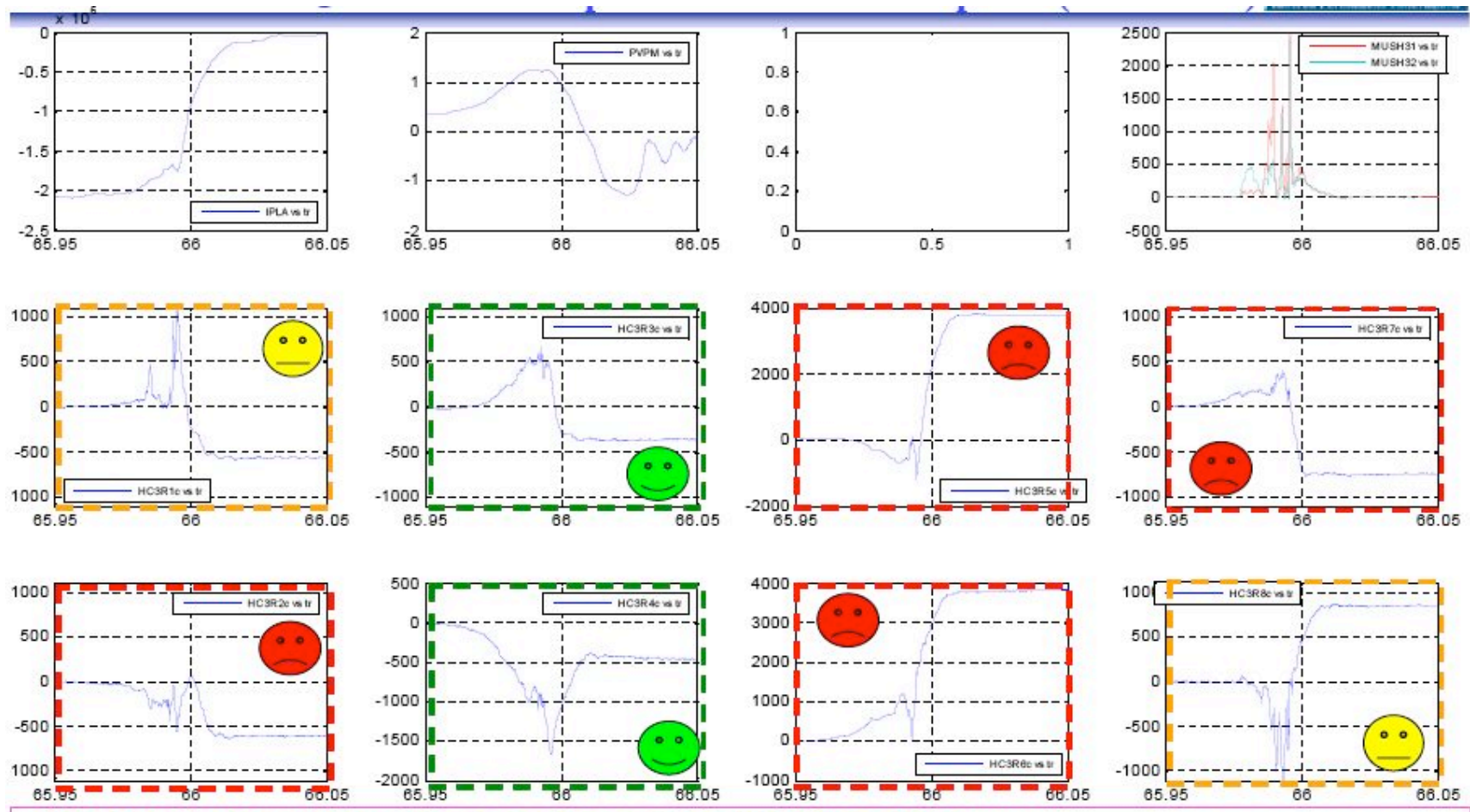


Plasma pulses:

- ✗ Drift during plasma duration and in particular during disruptions
- ✗ amplitude ~1-100 kA
 - ✗ same (higher) order of magnitude of expected halo signals

typical drift ≈ 1 kA/s
typical offset voltage ≈ 100 μ V



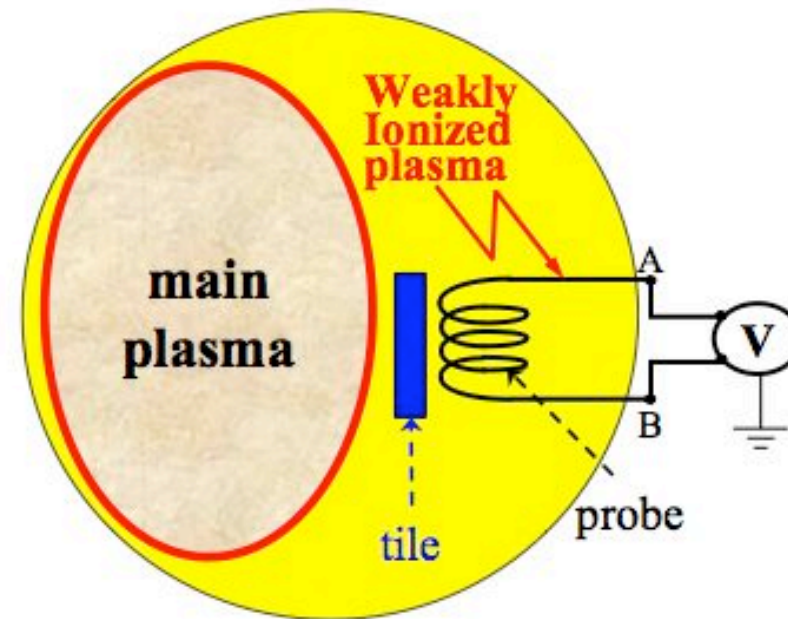


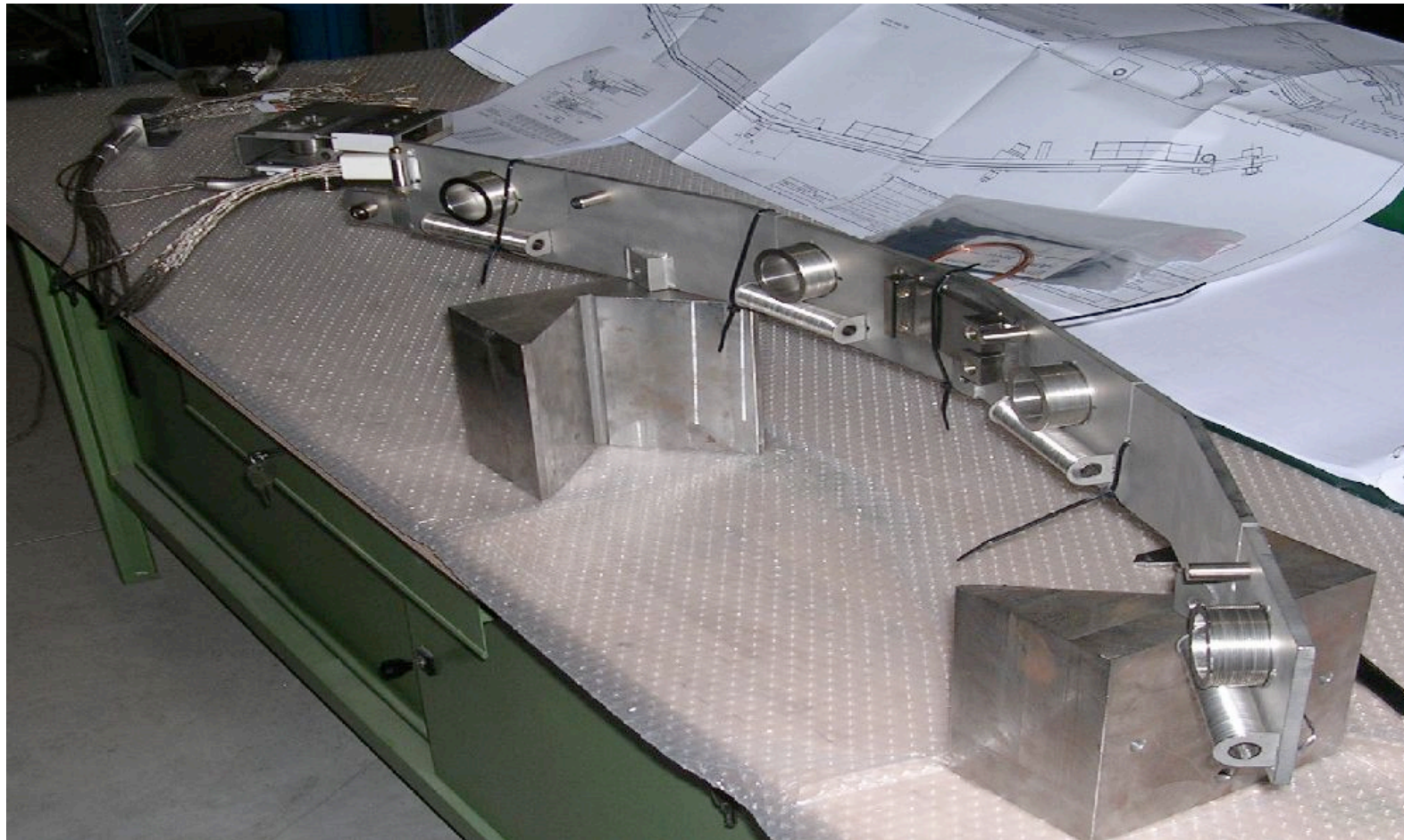
P.Sonato, EP-DIA-HCS-R-063 DVCM Meeting, 13/02/2007 Slide 26

- Many hypotheses have been considered and verified
- Several software and hardware tests carried out in the period March-June 2006, which ended up with the modification of the acquisition system in June 2006

(<http://users.jet.efda.org/pages/codas/ep/kc1h/Commissioning.html>, CODAS Commissioning diary)

- At the end only one hypothesis remained reasonable and interpreted as:
 - **Injection current** due to a small fraction of *Ionized gas* intercepted by the **braided cable and feedthrough** and closed through the conditioning circuit





Thank you for your attention