LTCC and thick-film ceramic magnetic sensors for tokamak nuclear fusion

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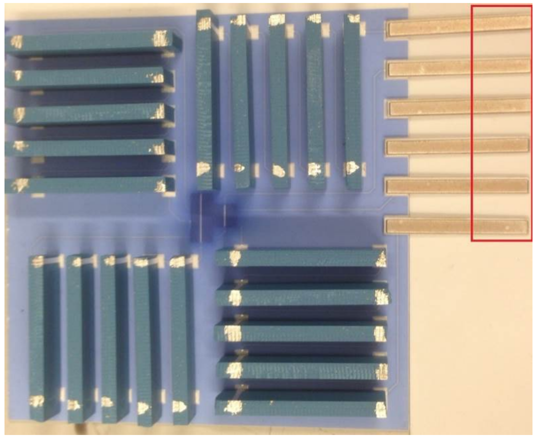
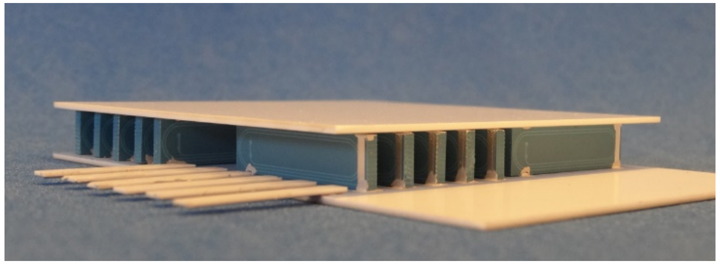
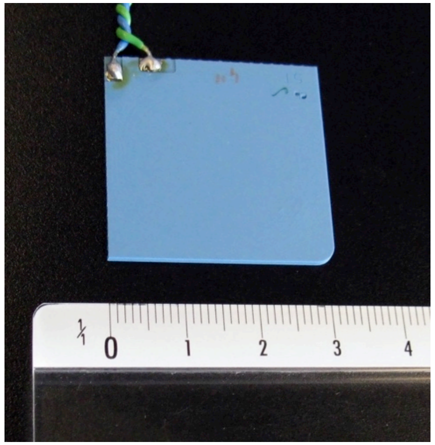
1) EPFL–LPM / *Laboratoire de production microtechnique*
2) EPFL – SPC / Swiss Plasma Center







Outline

1. Introduction
2. Coil-type magnetic sensors
3. LTCC 1D sensor
4. LTCC 3D sensor
5. Connection issues
6. Conclusion & outlook

Outline

1. **Introduction**

- **Tokamak nuclear fusion**
- **LTCC & thick-film technology**

2. Coil-type magnetic sensors
3. LTCC 1D sensor
4. LTCC + thick-film 3D sensor
5. Interconnection and packaging
6. Conclusion & outlook

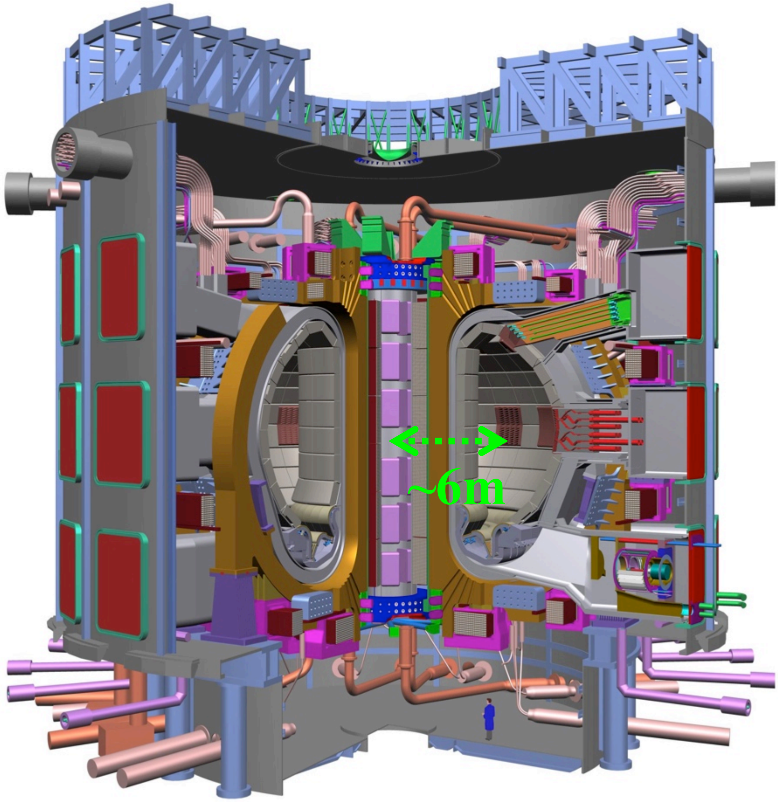
ITER – Int'l thermonuclear exp. reactor

Goal: demonstrate feasibility of fusion energy for peaceful purposes

- Tokamak machine
- *Q* ≥ 10 *more energy from fusion than required for plasma heating*
- Burning plasma physics
- Power: $P_{\text{fusion}} \geq 500$ MW

Plasma Volume: 840 m^3
Nominal Plasma Current: 15 MA
Typical Temperature: 20 keV
Typical Density: 10^{20} m^{-3}
Pulse Length >1’000 s

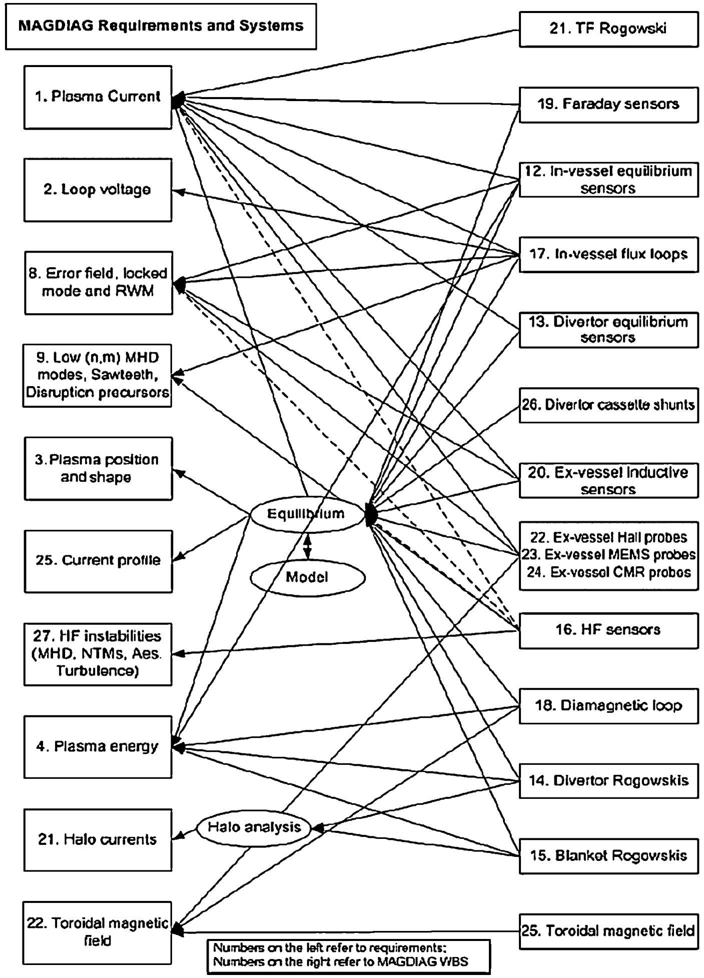
$R \sim 6.2$ m; $B_T \sim 5.3$ T;
$I_p \sim 15$ MA



Magnetic diagnostics

> 1'000 sensors envisioned for ITER!

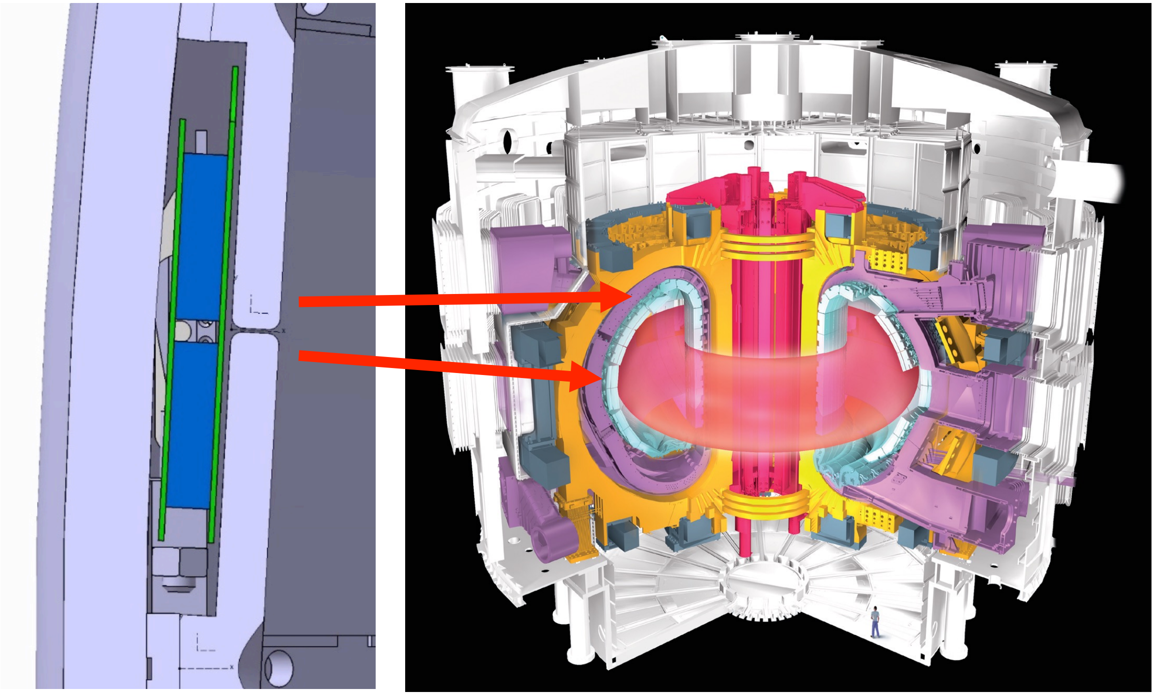
- Redundancy -> reliability
- Different technologies
  - Many sensor types
  - In-vessel & ex-vessel
  - Different environments
    - More or less harsh (*T, ΔT*)
  - High neutron flux
- Magnetic coils:
  - LF, equilibrium, < ~ 1 kHz
  - HF, MHD instabilities, < ~ 300 kHz



Testa-D Chavan-R Guterl-J Lister-JB et al., IEEE Transactions on Plasma Science 38 (3), 284-294, 2010.

Magnetic sensors in walls

- Magnetic sensors behind the protection tiles
- Measure magnetic field disruptions (both LF and HF)
- Different sensors for LF & HF domains

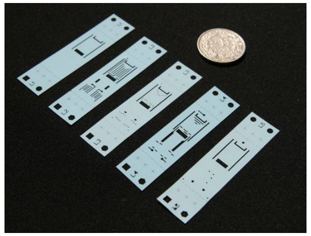


Cross-section of the external walls

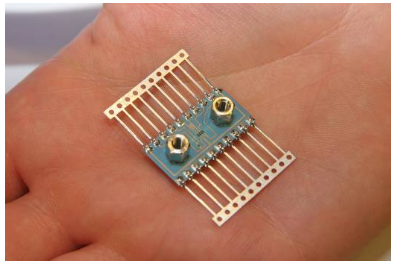
Tokamak

Thick-film technology & LTCC

- Thick-film / LTCC circuit : series of layers
- Each layer comes as a paste:
  - Functional material (as powder)
  - Organic vehicle: binder + solvent
  - Conductors, resistors, dielectrics, catalyst
  - Screen-printing with a mask



	Thick-film	**LTCC**
Substrate	Alumina	LTCC tape
Multilayer dielectric	Extra printed ink	LTCC tape
Firing	Sequential	Together (co-firing)

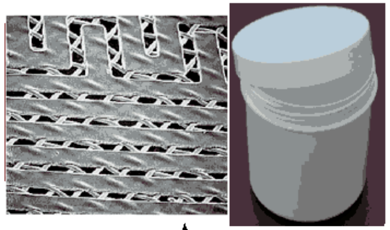


Thick-film - process flow

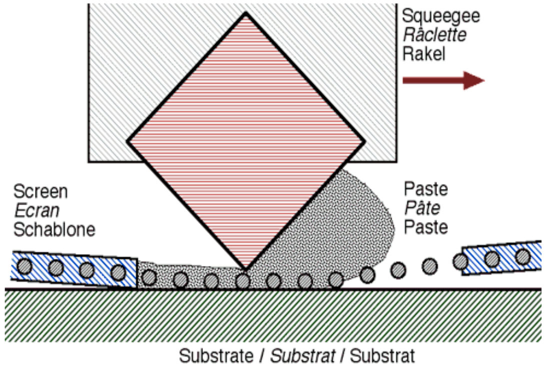
Sequential firing

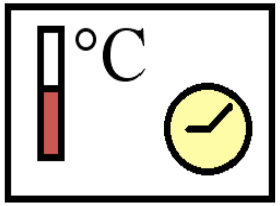
Substrate
Substrat

1 **Screen & paste**
Ecran & pâte
Maske & Paste



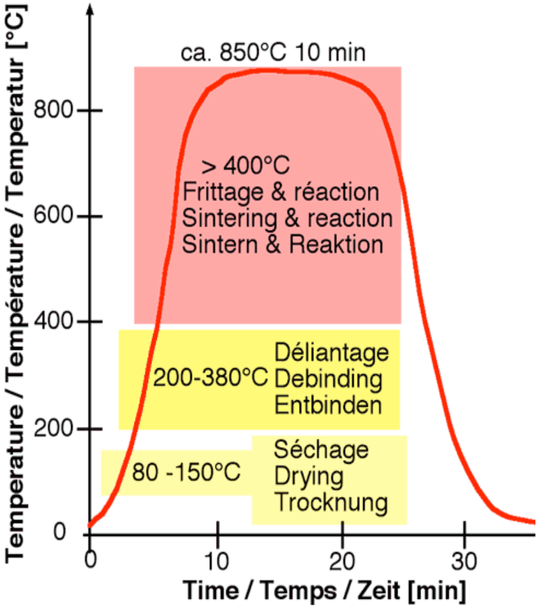
2 **Screen printing**
Sérigraphie
Siebdruck



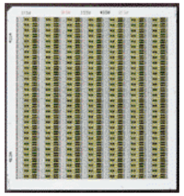


ca.
150°C
15 min

3 **Drying**
Séchage
Trocknen



4 **Firing**
Cuisson
Einbrand

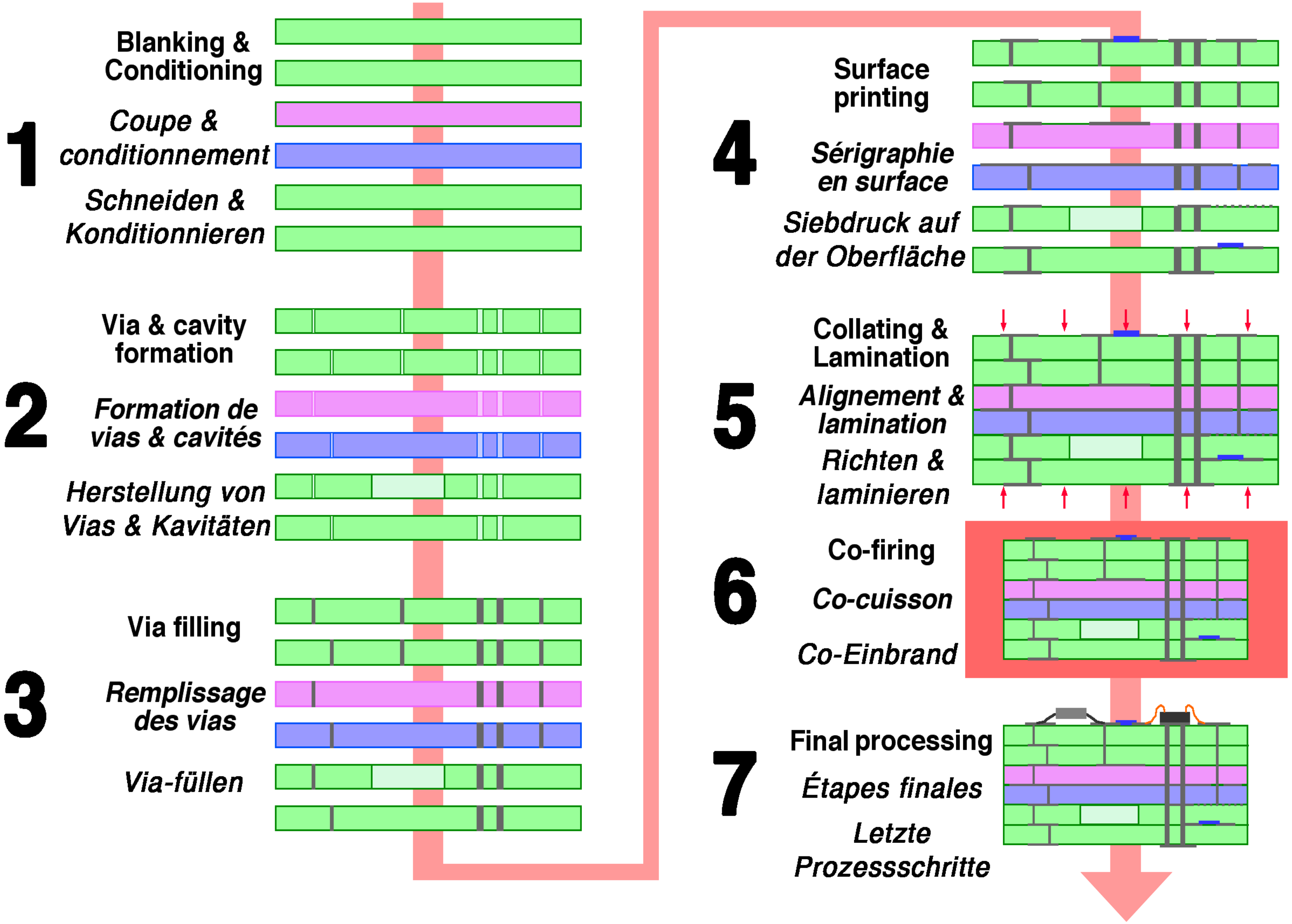


Circuit
Schaltung

LTCC - process flow

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Co-firing



1

Blanking & Conditioning

Coupe & conditionnement

Schneiden & Konditionieren

2

Via & cavity formation

Formation de vias & cavités

Herstellung von Vias & Kavitäten

3

Via filling

Remplissage des vias

Via-füllen

4

Surface printing

Sérigraphie en surface

Siebdruck auf der Oberfläche

5

Collating & Lamination

Alignement & lamination

Richten & laminieren

6

Co-firing

Co-cuisson

Co-Einbrand

7

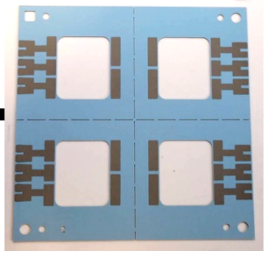
Final processing

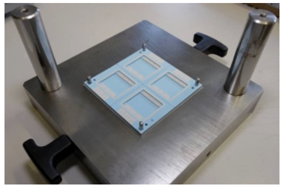
Étapes finales

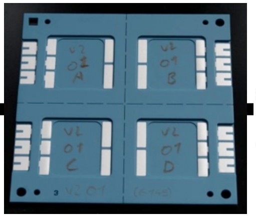
Letzte Prozessschritte

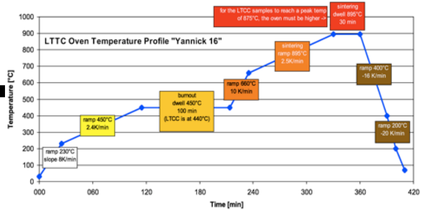
LTCC - principle

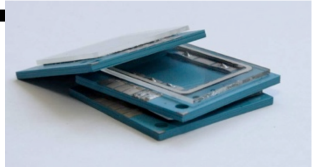
1. Raw sheets easily cut
   (laser, punch tool)
2. Formation of vias & cavities
3. Vias filled for interlayer contacts
4. Layers individually printed
   (multilayer circuits)
5. Stacking & lamination of layers to
   get a 3D structure
6. Firing
   -> sintering, monolithic circuit
7. Individualisation and post-firing
   (assembly by soldering)









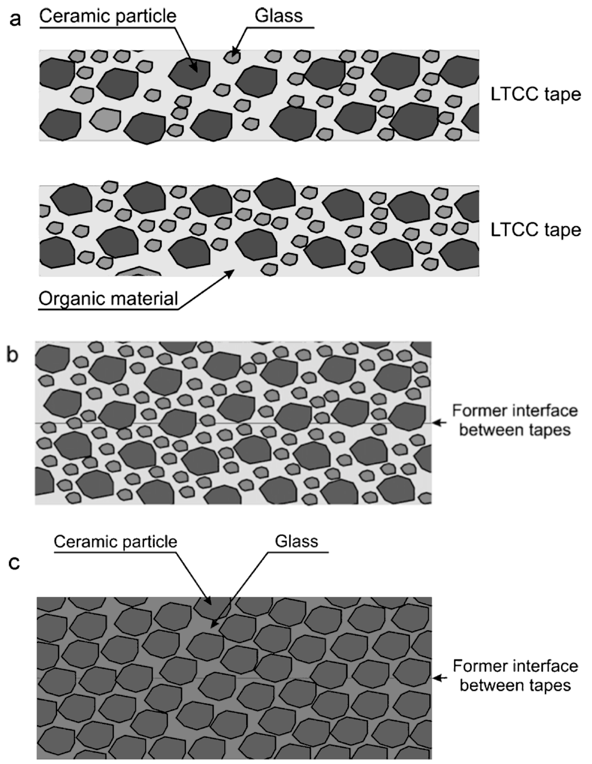


LTCC – the material

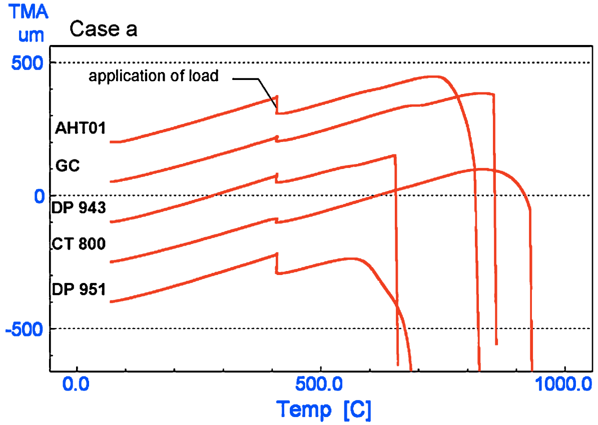
a. **Tapes**
   - Organic binder matrix
   - Glass + ceramic powder

b. **Lamination**
   - Joining through organic binder

c. **Firing**
   - Debinding – ***critical step!***
   - Viscous sintering with glass
   - Crystallisation by **glass-ceramic** reaction



Jurków-D Golonka-L, "Low-pressure, thermo-compressive lamination", J. Eur. Ceram. Soc. 32 (10), 2431–2441, 2012.



Bienert-C Roosen-A, Journal of the European Ceramic Society 30 (2), 369-374, 2010.

All compositions OK @500°C //
DuPont / DP951

Outline

1. Introduction
2. **Coil-type magnetic sensors**
3. LTCC 1D sensor
4. LTCC + thick-film 3D sensor
5. Interconnection and packaging
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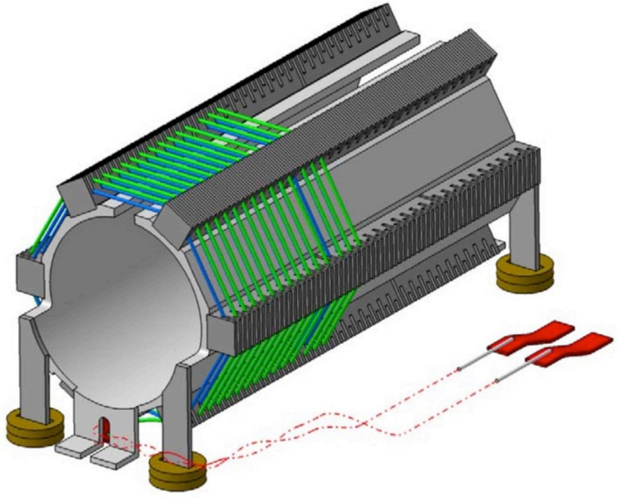
- **Classical Mirnov coils**
- **Monolithic ceramic coils**
- **Materials & design issues**

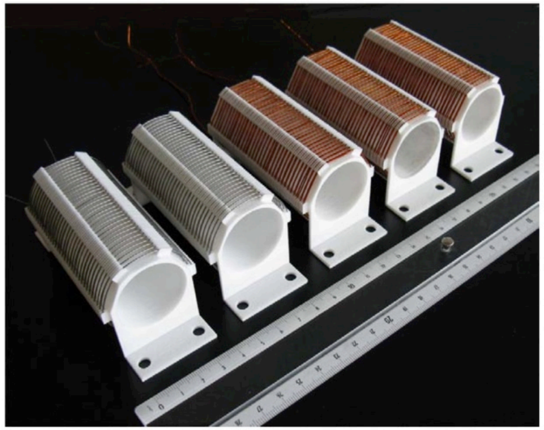
Mirnov-type coils

- ITER reference design
  - 80×40×40 mm³ – bulky!
  - NA_{eff} ~670 cm² - OK
  - Slotted stainless-steel body
  - Ceramic guides
  - Two layers of W wire
  - Wire exposed
  - W stiff, brittle -> difficult
- ***Need compact, monolithic solution***

Toussaint-M Testa-D Baluc-N Chavan-R Fournier-Y Lister-JB Maeder-T Marmillod-P Sanchez-F Stöck-M, Fusion Engineering and Design 86 (6-8), 1248-1251, 2011.



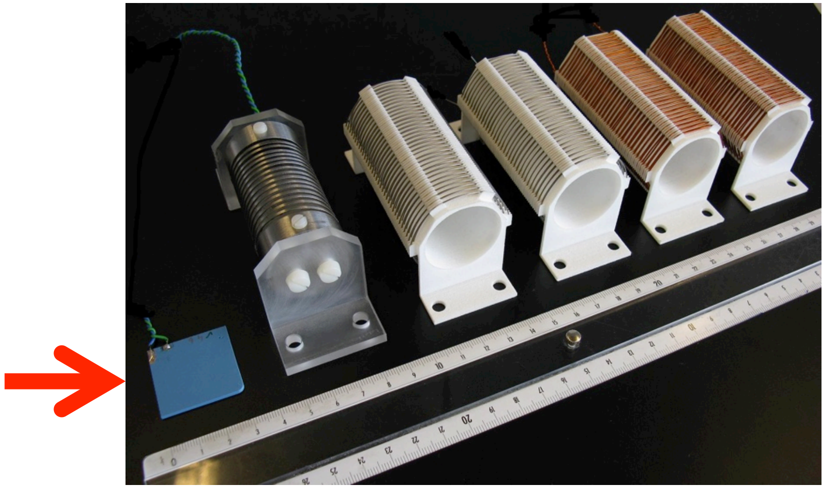
ITER reference design: 80×40×40 mm³



Alternative designs (W or Cu wire)

LTCC magnetic sensors for tokamaks

- Much smaller sensor than traditional Mirnov coils
  - Volume ~1:20!
- Similar effective area & properties
- Intimate contact between winding and ceramic support
- Winding shielded from external environment (plasmas, …)



LTCC 1D sensor (left) vs traditional Mirnov coils (right)

- **Presumably more robust**
- **Low profile – mounting in wall, behind protection tiles**

Magnetic coils for tokamaks

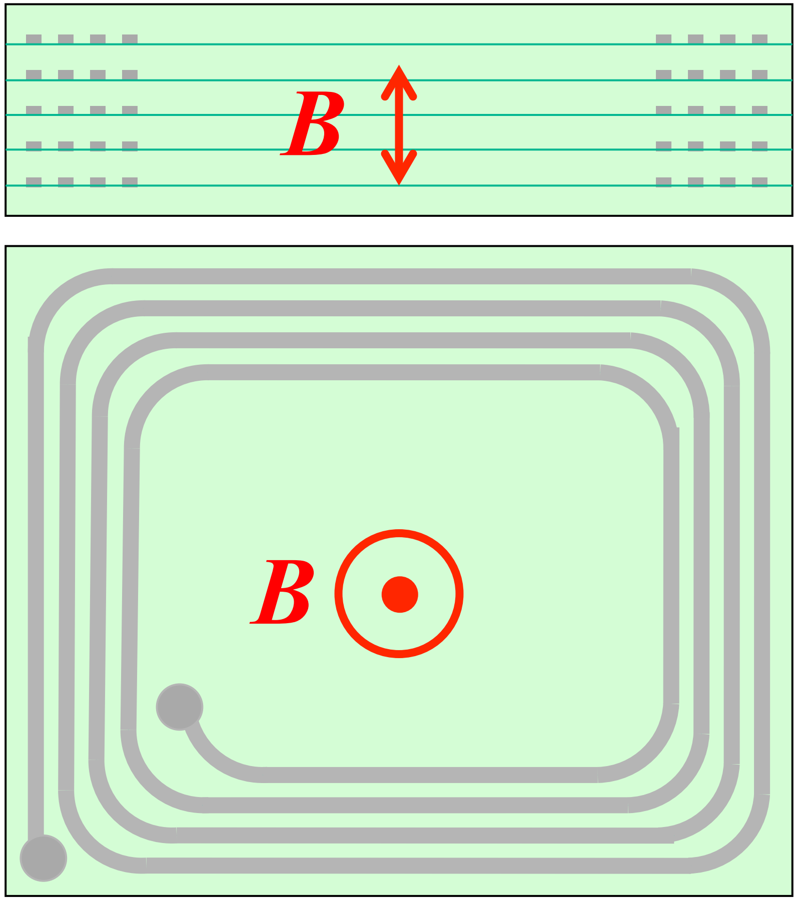
Signal (ideal):

$$U_{\mathrm{AC}} = i \cdot \omega \cdot B_{\mathrm{AC}} \cdot NA_{\mathrm{eff}}$$

- U_{AC} : signal voltage
- ω : angular frequency
- B_{AC} : magnetic field
- NA_{eff} : effective integral coil area

- Signal U ?
- Capacitance C ?
- Inductance L ?
- **Resonance:**

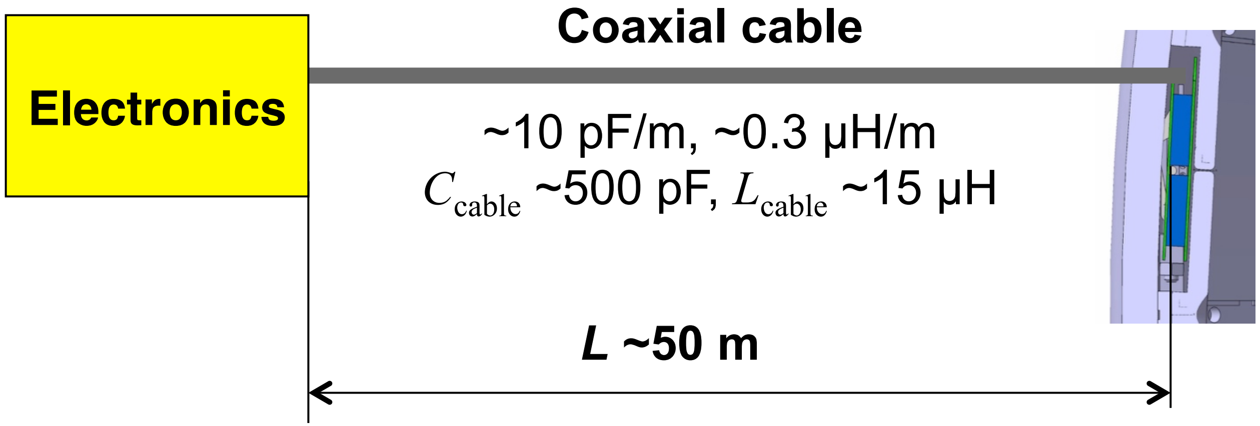
$$2\pi \cdot f_{\mathrm{res}} = \omega_{\mathrm{res}} = (L \cdot C)^{-0.5}$$



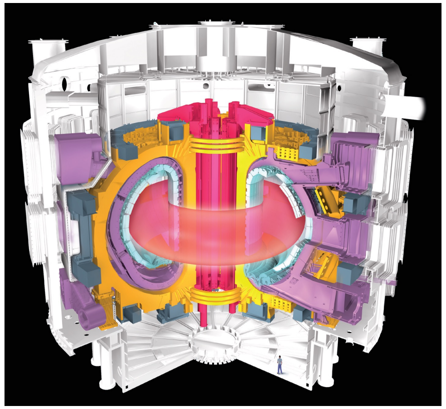
Multiple turns parallel and perpendicular to the magnetic field

Magnetic coils for tokamaks

Long cables due to high-energy neutron flux!



Sensor @wall



Tokamak

- Capacitance C : C_{cable} dominant
- Inductance L : L_{self} dominant – **minimise!**
- **Resonance:**

$$2\pi \cdot f_{\text{res}} = \omega_{\text{res}} = (L \cdot C)^{-0.5}$$

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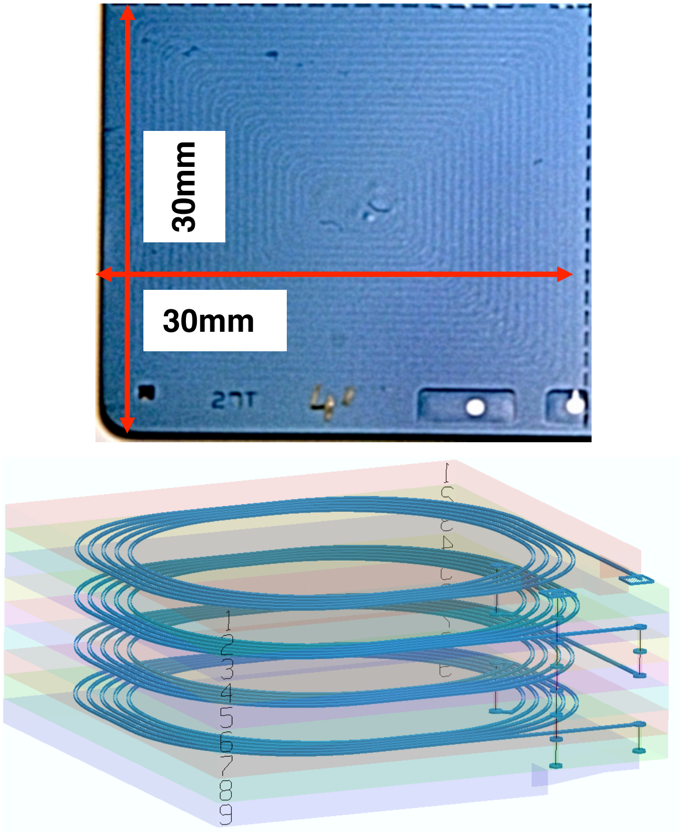
- **Design & variants**
- **Results**
- **Conclusion - design rules**

1D LTCC HF magnetic sensor design

- Size: 30 x 30 x (0.7…2.4) mm^3
- Body material: LTCC glass-ceramic
  - DuPont / DP 951
- Wire material: silver / Ag
- Stack of layers electrically connected by via holes filled with metallic ink
- Metallic ink printed on each active layer



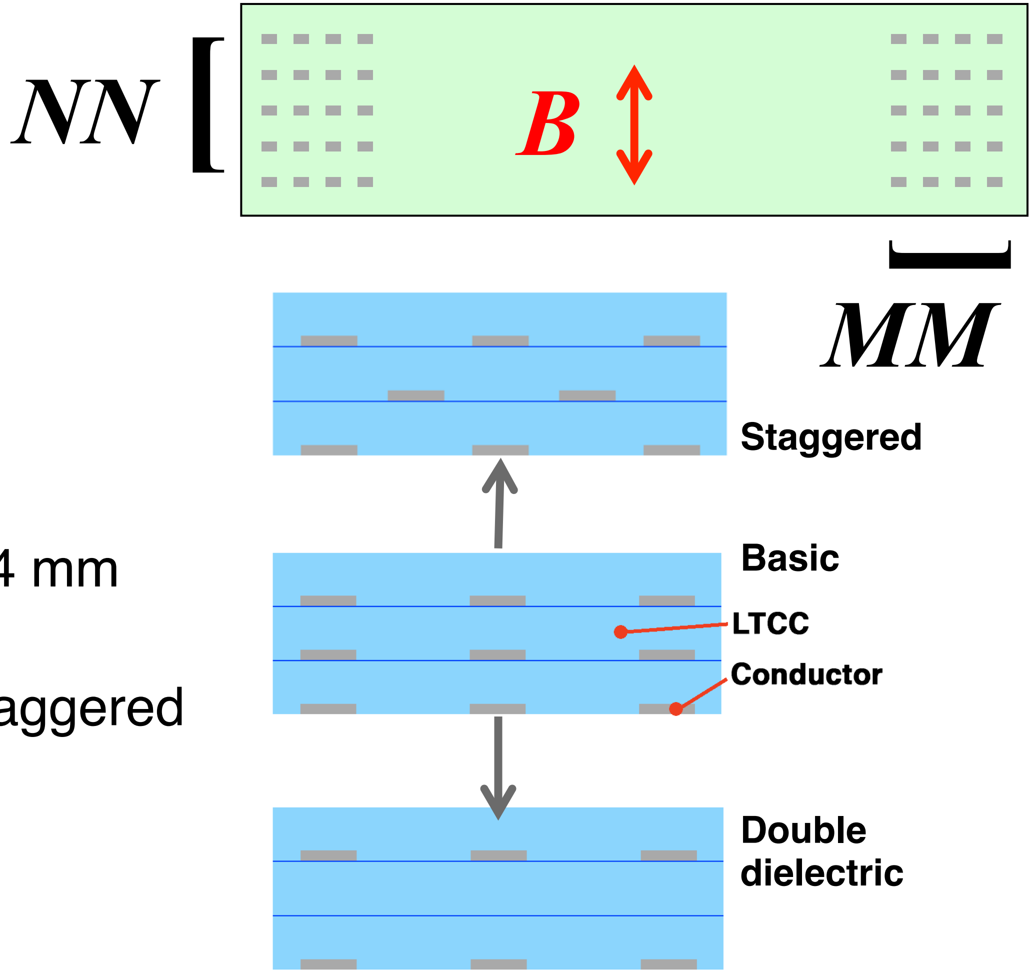
1^{st} generation 1D sensor & coil design

Testa-D Fournier-Y Maeder-T Toussaint-M Chavan-R Guterl-J Lister-JB Moret-JM Schaller-B Tonetti-G, Fusion Science and Technology 59 (2), 376-396, 2011, http://infoscience.epfl.ch/record/164698

1D LTCC HF magnetic sensor variants

Parameters

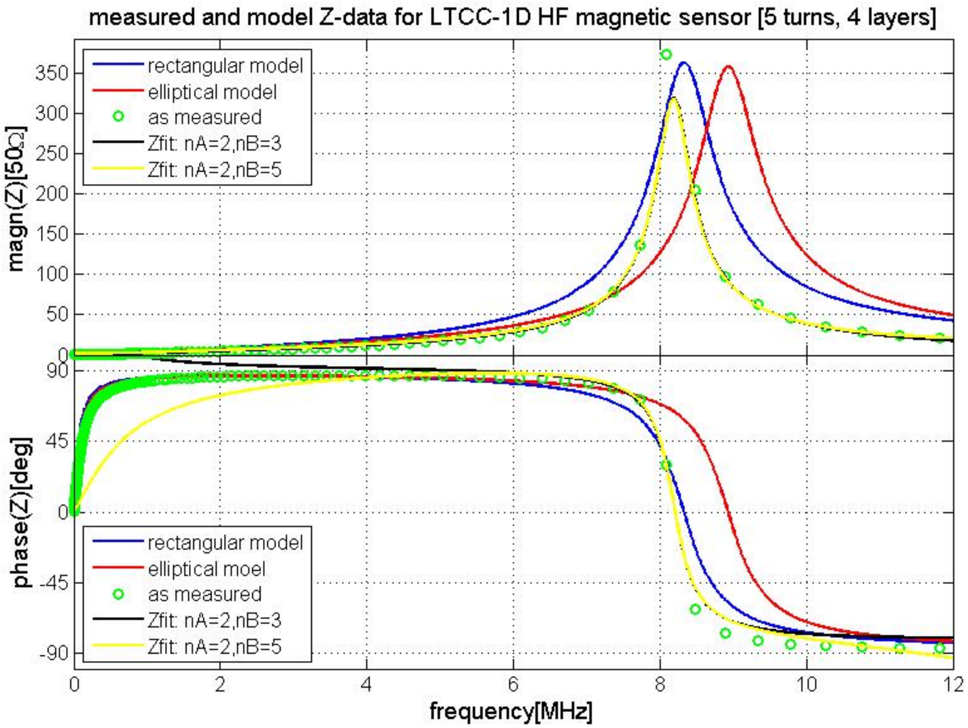
- Number of turns/layer:
  - MM = 5, 10 and 20
- Number of layers:
  - NN = 2, 4, 6, 8 and 10
- Interlayer
  - Thickness: 0.22 mm or 0.44 mm (1 or 2 LTCC tapes)
  - Arrangement: straight or staggered



Testa-D Fournier-Y Maeder-T Toussaint-M Chavan-R Guterl-J Lister-JB Moret-JM Schaller-B Tonetti-G, Fusion Science and Technology 59 (2), 376-396, 2011, http://infoscience.epfl.ch/record/164698

1D LTCC HF magnetic sensor results

- **Self-resonance frequency**
  - $f_{\mathrm{res,self}}$ from 1.1 to >15 MHz
- **Resistance:**
  - R_{self} = 7…100 Ω
  - Model easy, only requires total wire length
- **Inductance**
  - L_{self} = 5…595 µH
  - Very sensitive to design, accurate model needed
- **Capacitance**
  - C_{self} : 22…58 pF
  - Much smaller than that due to signal cables ~10 pF/m -> 500 pF
  - Accurate model not needed



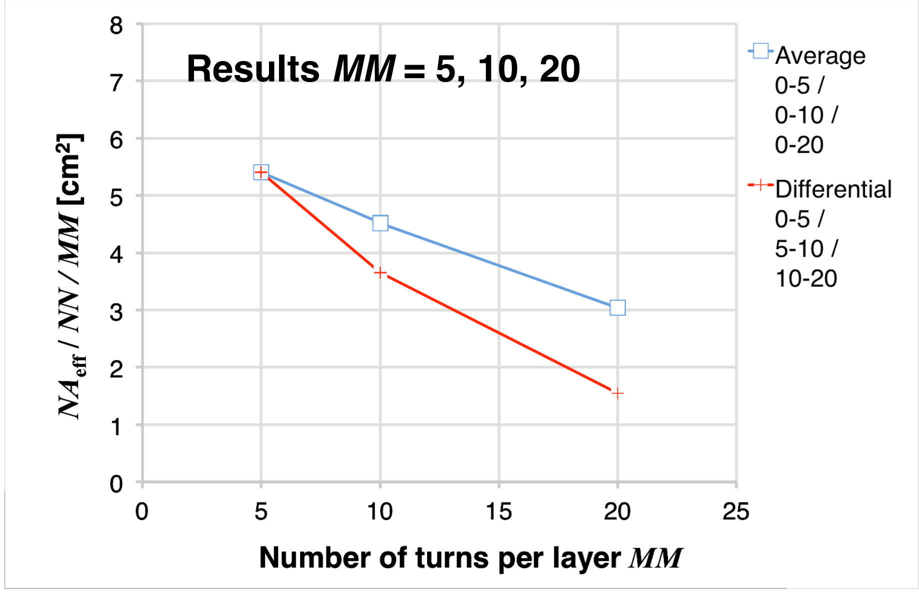
Measurement vs modelling

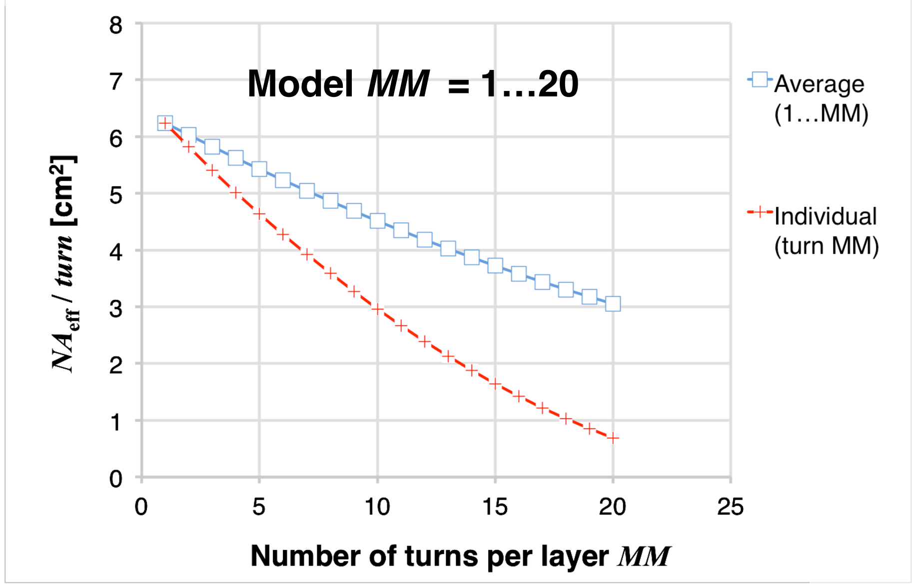
- Good agreement between circuit models & measurements
- **Meeting ITER requirements possible in principle**

1D LTCC HF magnetic sensor results

Some design rules:

- **Turns per layer MM : compromise**
  - Small contribution of inner turns to NA_{eff}
  - Increase of L_{self}
  - Surface / resistance ~ perimeter
  - **But: low-cost, reliable** (no additional layers)

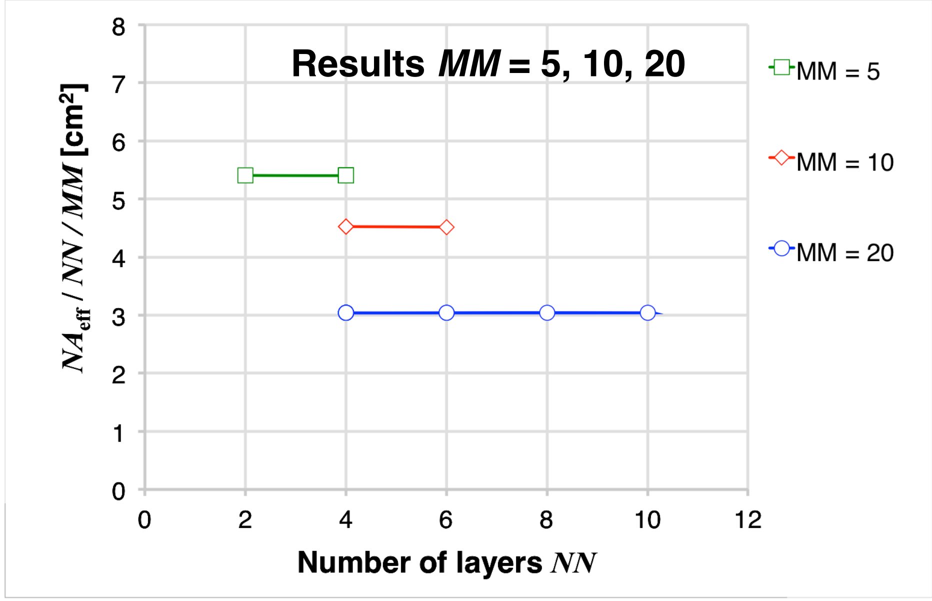




1D LTCC HF magnetic sensor results

Some design rules:

- **Layers NN : increase**
  - Linear contribution to NA_{eff}
  - But: strong increase of L_{self}
    - ~NN^2 for 0 diel. thickness, in practice smaller
  - More layers required (complexity, yield, cost)



- **Interlayer:**
  - Staggered winding not needed (small effect, only on C_{self})
  - **Increase spacing to especially decrease L_{self}**
  - More vias, more cost
  - *Other alternatives for 3D*

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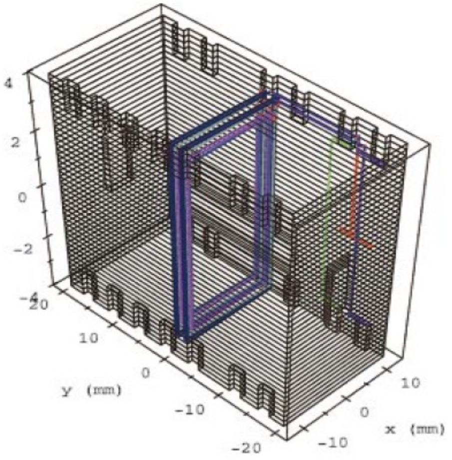
- **Introduction – previous work**
- **New concept & design**
- **Conclusion - design rules**

3D ceramic magnetic sensor

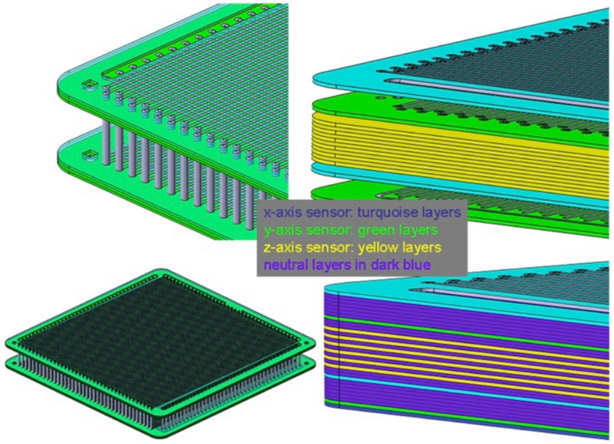
- **Sensing in X, Y, Z**
  - Practical, compact sensor
  - Crosstalk, fabrication ???

- **Previous work**
  - First 3D attempts at PPPL using HTCC technology in 1999
  - Idea abandoned due to high cost, poor yield (1'000s of vias)
  - Also: difficult to design, high coupling, …

- **New ideas needed!**



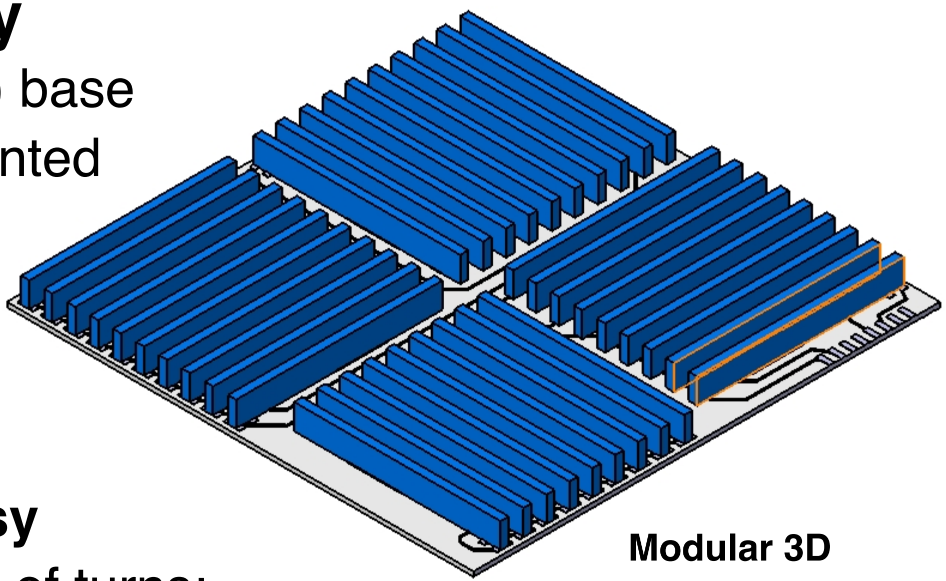
Takahashi-H Sakakibara-S Kubota-Y Yamada-H, Review of Scientific Instruments 72, 2001, 3249-3259



Our first 3D sensor concept

3D ceramic magnetic sensor concept

- **Mixed, modular technology**
  - Z: classical thick-film (alumina) base
  - XY: LTCC modules, edge-mounted
  - Relatively low-profile
  - *Separation between XY coils*



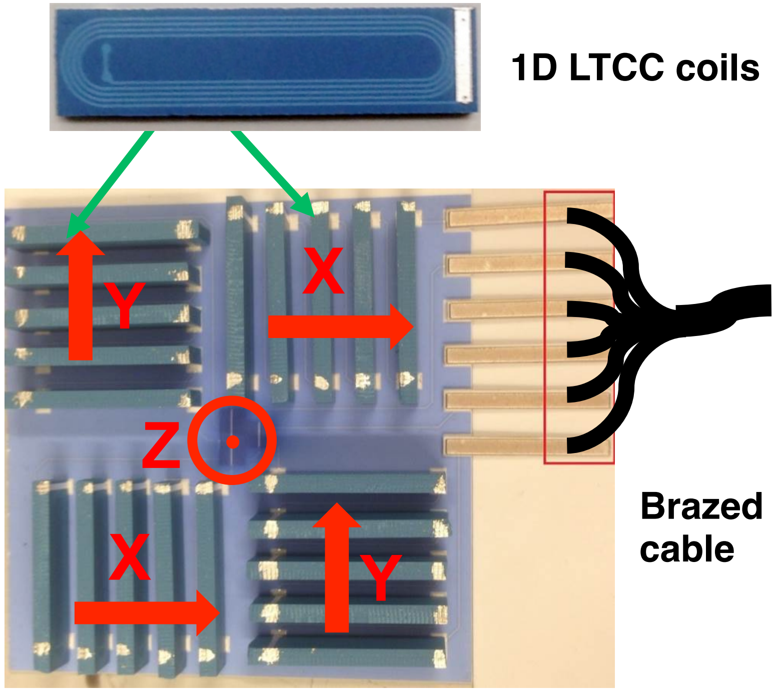
Modular 3D sensor concept

- **Production**
  - Base with ~square Z coil – **easy**
  - LTCC "sticks" with low number of turns:
    - Production easy, winding in LTCC plane
    - Simple, low via count – **good yield**
    - Can be pre-tested before mounting – **good overall yield** as well
  - **Issue: assembly**

3D ceramic magnetic sensor design

- **Design – Z**
  - Large area in base, high NA_{eff} easy
- **Design – XY**
  - Small area – low height
  - **Small 1D LTCC X & Y modules**
  - Multiply to achieve higher NA_{eff}
  - Fully coupled $L_{\mathrm{self}} \sim N^2$
  - Fully separate: $L_{\mathrm{self}} \sim N$
  - Compromise: 10 in series with low N, mounting at some distance to minimise inductive coupling

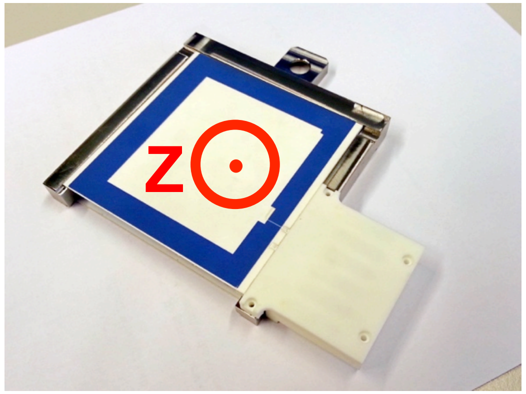
Testa-D Corne-A Farine-G Jacq-C Maeder-T Toussaint-M, "3D, LTCC-type, high-frequency magnetic sensors for the TCV Tokamak", Fusion Engineering and Design 96-97, 989-992, 2015, http://infoscience.epfl.ch/record/206105



1D LTCC coils

Brazed cable

3D magnetic sensor (V2) elements on base

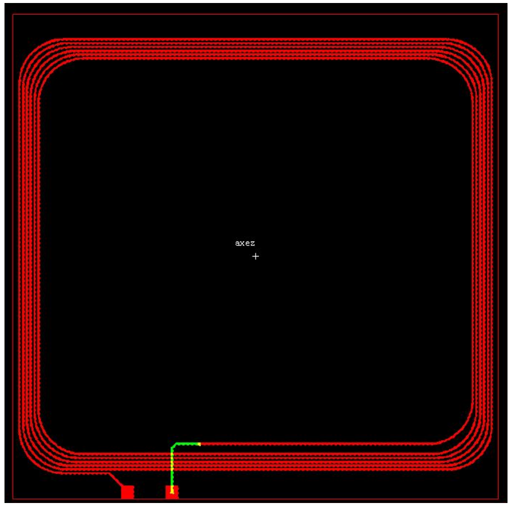


Sensor V2 - bottom of base with Z coil

3D ceramic magnetic sensor – Z coil

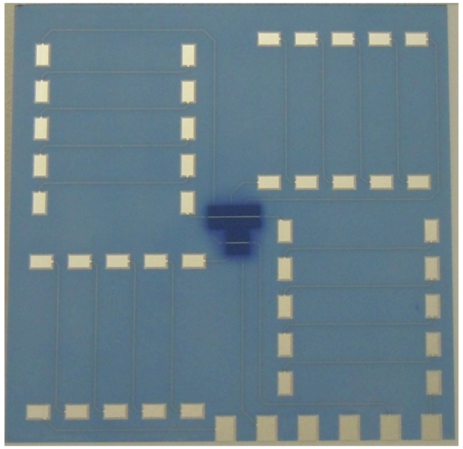
Single coil on back of base

- NA_{eff} = 178 cm^2
- R_{self} = 17 Ω
- L_{self} = 7.4 μH
- f_{res} > 12 MHz
  - Still good with cables due to low L_{self}
  - With C_{cable} = 500 pF, ~2.6 MHz



V2 -bottom of base with Z coil

- *Favourable, high* NA_{eff} *with low* R_{self} *&* L_{self}



V2 - top of base for mounting XY coils (& last half-turn)

Testa-D Corne-A Farine-G Jacq-C Maeder-T Toussaint-M, "3D, LTCC-type, high-frequency magnetic sensors for the TCV Tokamak", Fusion Engineering and Design 96-97, 989-992, 2015, http://infoscience.epfl.ch/record/206105

3D sensor – XY coil – LTCC optimisation

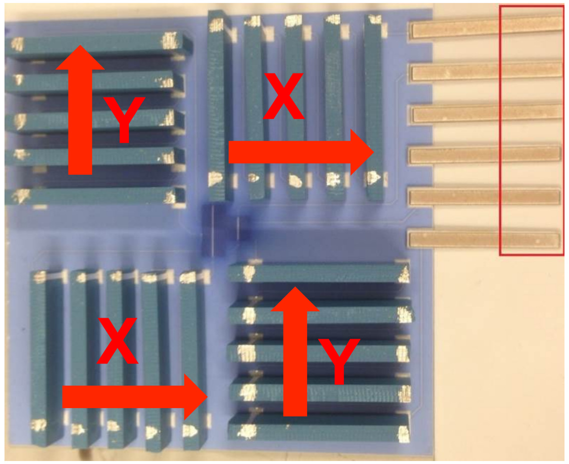
Type	MM	NN	NA_{eff} [cm^2]	R_{self} [Ω]	L_{self} [μH]
Old	4.5*	13	77	28	60
New	2.5*	9	38	9	12

- Turns = $MM \times NN$ + 0.5 (in base) = 59 / 23
- Sensor V2
- **Ratios**
  - NA_{eff} : ~2:1
  - R_{self} : ~3:1
  - L_{self} : ~5:1
- **Numbering up simpler elements to minimise L_{self} & R_{self}**

Testa-D Corne-A Farine-G Jacq-C Maeder-T Toussaint-M, "3D, LTCC-type, high-frequency magnetic sensors for the TCV Tokamak", Fusion Engineering and Design 96-97, 989-992, 2015, http://infoscience.epfl.ch/record/206105

3D sensor – XY coil – overall

(New LTCC coils)	NA_{eff} [cm^2]	R_{self} [Ω]	L_{self} [μH]	f_{res} [MHz]
Sensor X	298	127	158	~5.5
10 x single	376	90	123	>12
Δ	–78	37	35	
Δ_{rel}	–21%	+41%	+28%	

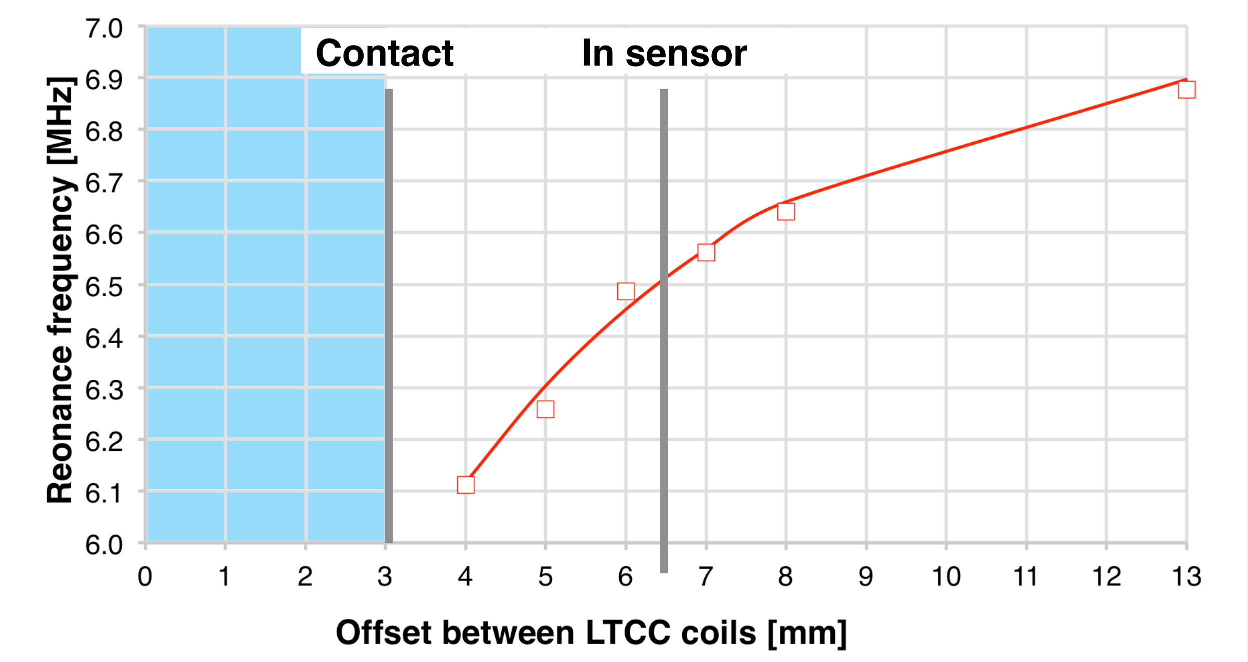


10 x

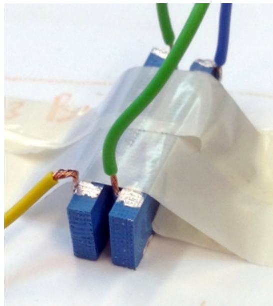
Whole X sensor vs 10x LTCC module (additivity) ?

- NA_{eff} : mounting differences (angles & distance to base)
- R_{self} : extra wiring in base for routing
- L_{self} : mutual coupling between adjacent LTCC modules
- f_{res} : wiring capacitances
  - Not so relevant, as $C_{\text{self}} \ll C_{\text{cable}}$: For 500 pF, 0.57 vs 0.64 MHz

3D sensor – XY coil separation



Corne-A, "Capteur de champ magnétique 3D pour fusion nucléaire", Projet de semestre, Section de microtechnique, LPM, EPFL, Lausanne (CH), 2014.

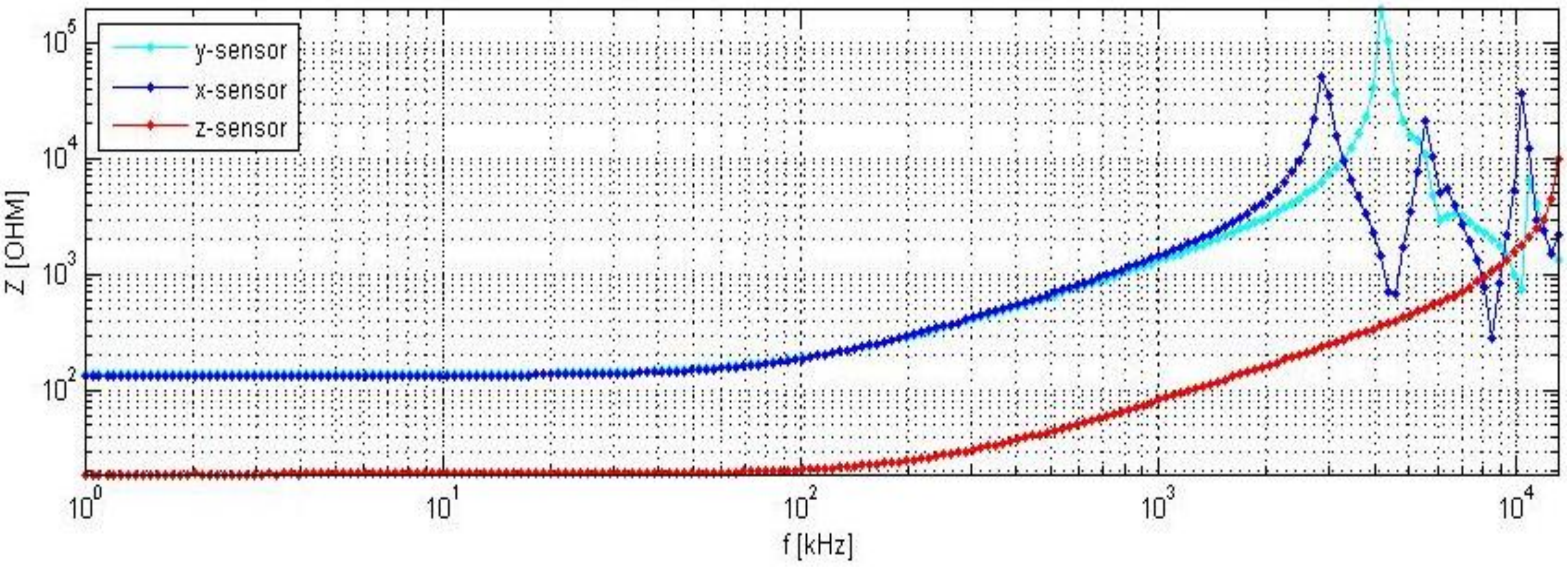


Interaction between two adjacent coils (old type)

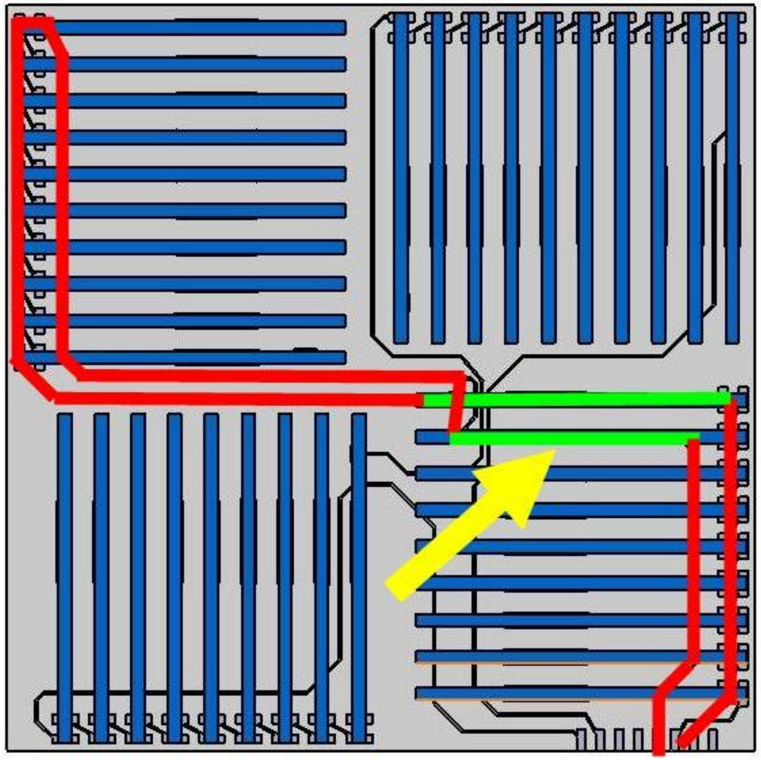
- Narrow coil (max. ~6 mm) – fast decrease with distance
  - Also valid for new coils – same width
- Rough agreement with sensor results
  - $\Delta L/L$ ~ +28% -> $\Delta f/f$ should be $-(\Delta L/L)^{0.5}$ ~ –13%

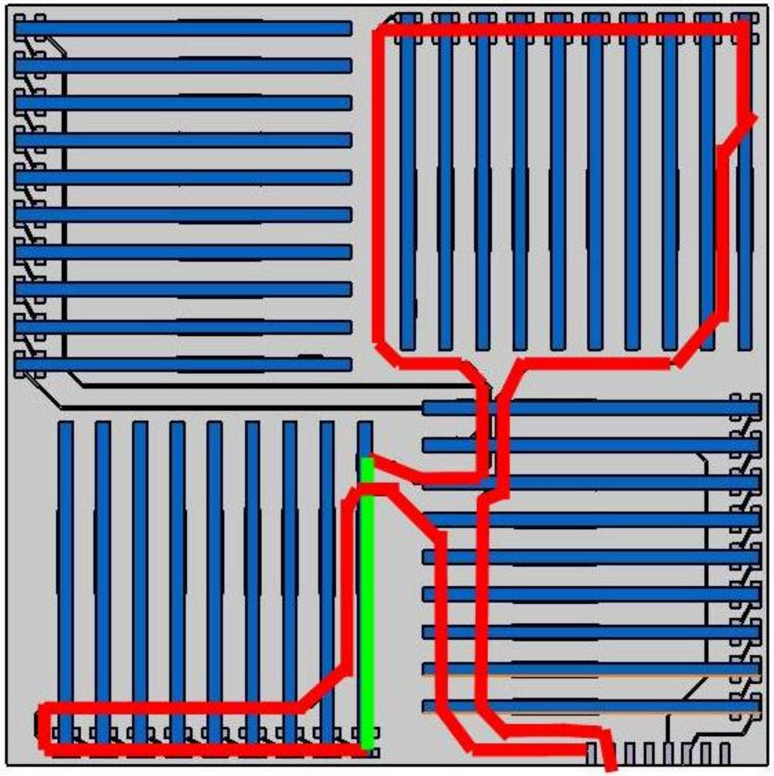
LTCC-3D sensor-V1: electrical data

- Design OK: $L_{SELF,TOT} \propto N_{TURNS} * L_{TURN} + L_{MUT}$ instead of $\propto (N_{TURNS})^2 * L_{TURN}$
- However significant improvements are needed:
  - δB_{POL} (x-axis), δB_{TOR} (y-axis): clearly different electrical characteristics (should be exactly the same) and very large parasitic coupling (NA_{PAR}/NA_{EFF}>10%)
  - Parasitic effective area δB_{RAD} (z-axis) also too large, ~10% (should be <2%)



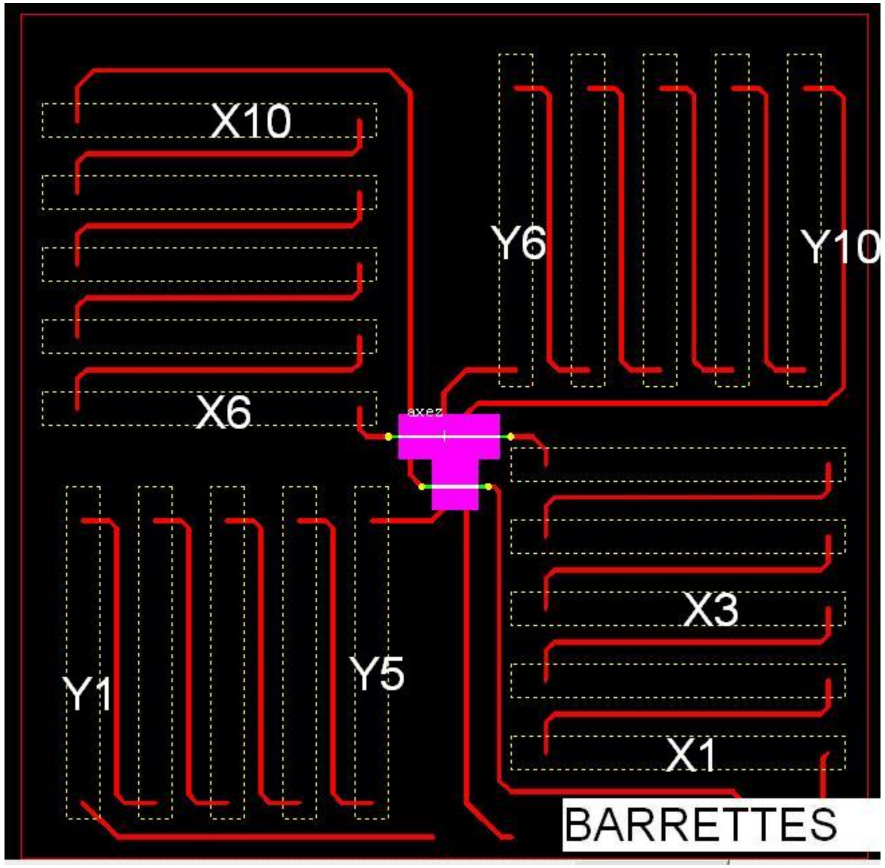
3D sensor V1 – on-board wiring

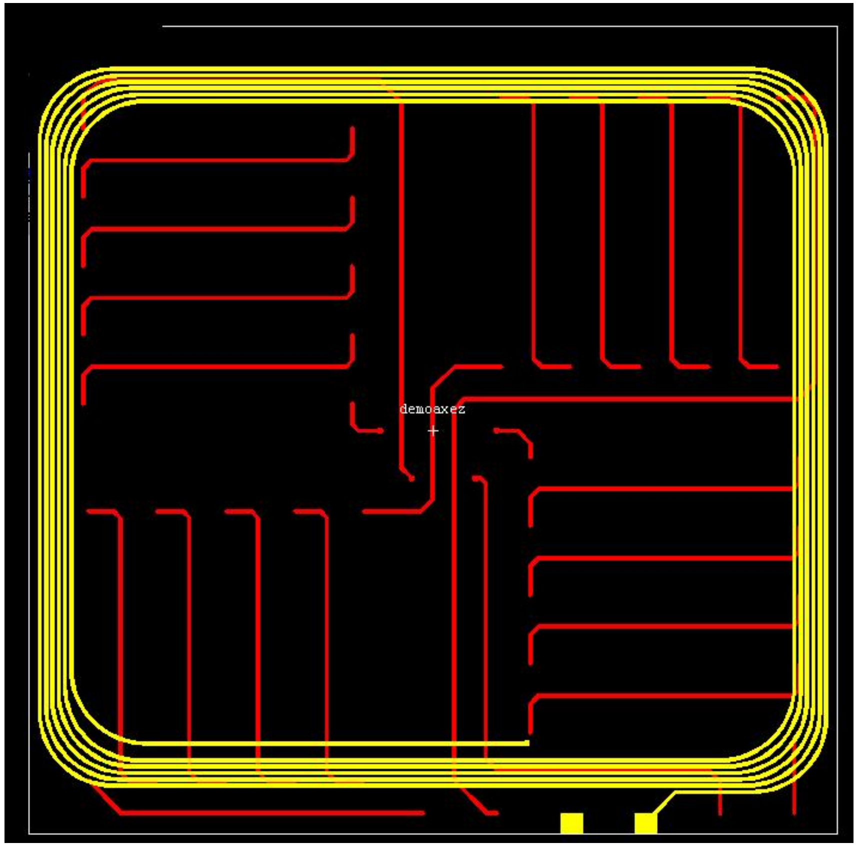




- On-board wiring: large parasitic loops and mutual inductances between all three measurement axes
- Improvement needed: optimise to avoid / reduce loops

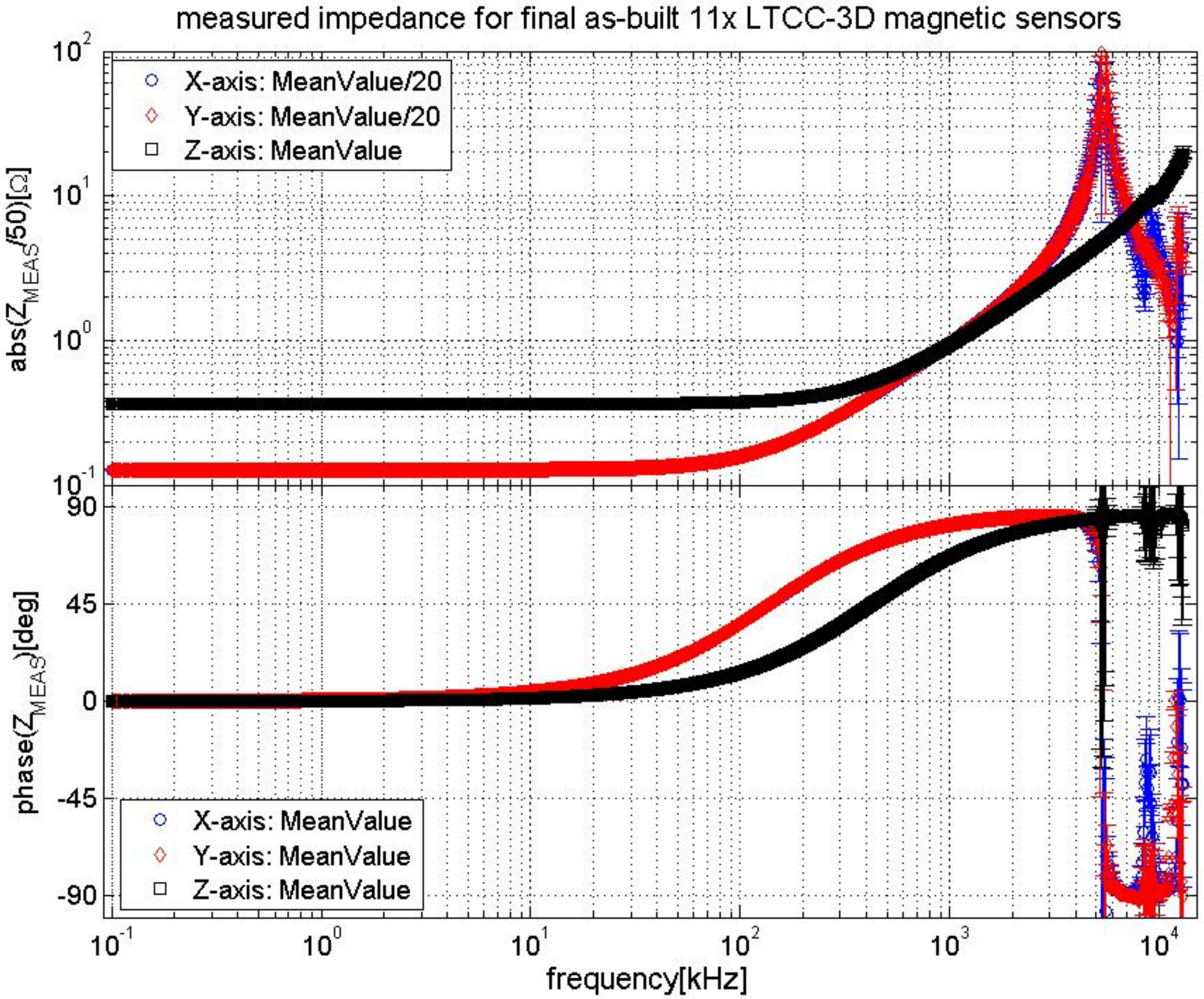
Sensor V2 – optimised on-board wiring





- Optimized design of on-board wiring up to output connection pads
- Reduced parasitic loops and mutual coupling

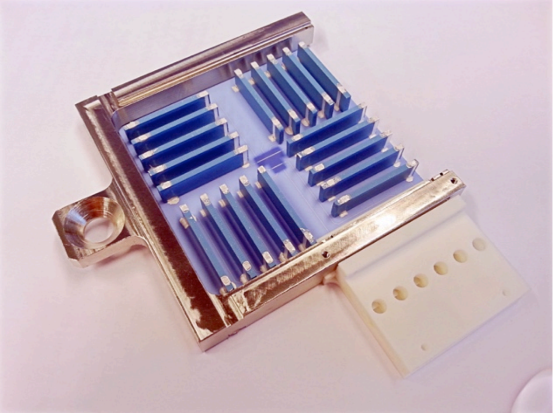
LTCC 3D sensors: impedance data

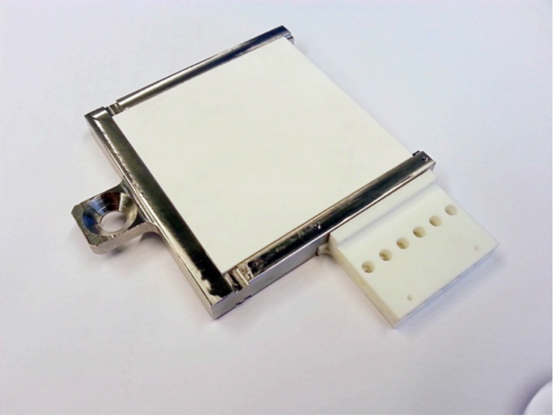


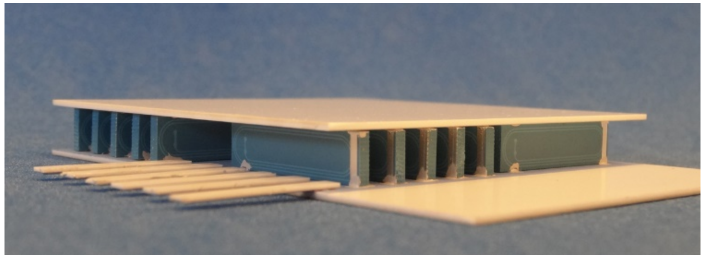
3D sensor – conclusions

Working 3D sensor developed

- Innovative modular concept for XY
    - Simple LTCC edge-mounted solenoids
    - Good yield, separation -> low L_{self}
- Sufficient NA_{eff}
    - X/Y/Z : ~300/260/180 cm^2
- High resonance frequencies
    - XY : ~5.5 MHz ; Z : > 12 MHz
    - With C_{cable} = 500 pF: XY/Z ~0.6/2.6 MHz
- Mounted in EPFL-SPC TCV
    - *Tokamak à Configuration Variable*







Outline (3)

1. Introduction

2. Coil-type magnetic sensors

3. LTCC 1D sensor

4. LTCC + thick-film 3D sensor

5. **Interconnection and packaging**

6. Conclusion & outlook

Mounting LTCC sensors onto base

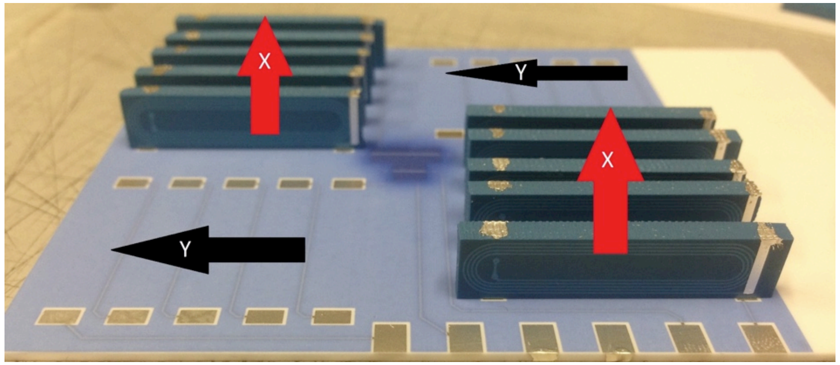
Preparation

- Metallisation of LTCC modules on edges (post-firing Ag conductor)

Corne-A, "Capteur de champ magnétique 3D pour fusion nucléaire", Projet de semestre, Section de microtechnique, LPM, EPFL, Lausanne (CH), 2014.

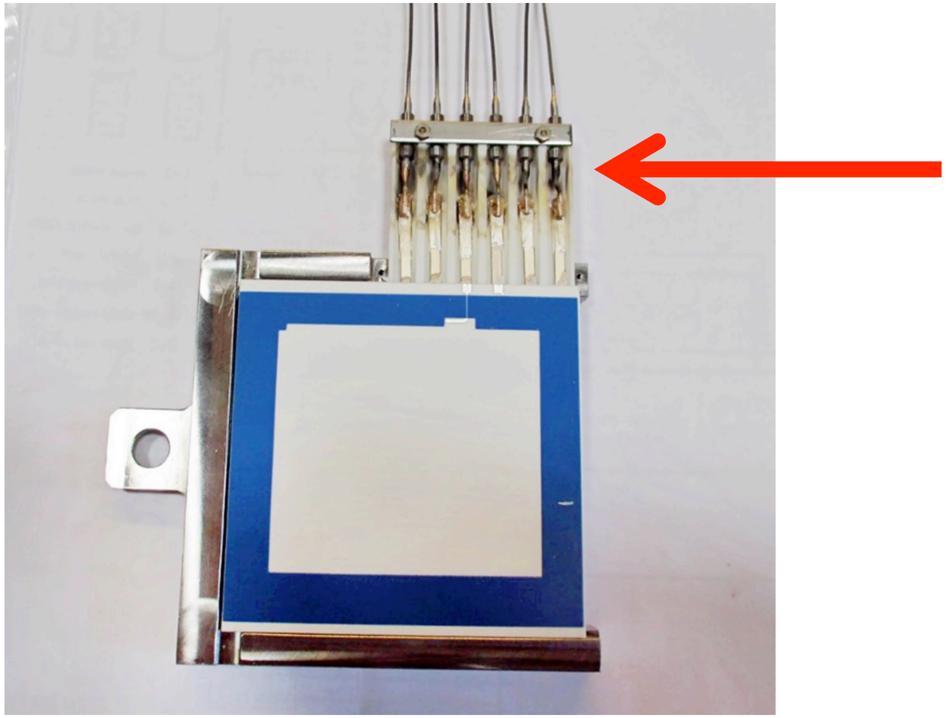
High-temperature connection to base

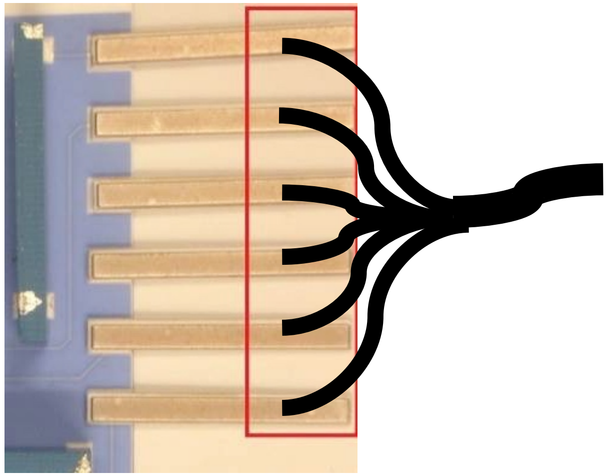
- Fritted Ag conductor + additional low-melting glass to improve bonding
- Also for lid
- Possible alternatives
  - Ag pressure sintering
  - Brazing (risk of Ag leaching)
  - Special soldering (e.g. TLP)



Cabling

- Cables brazed to Ag metallisation
- Cannot braze directly to base
  - Temperature gradients – cracking
  - Metallised alumina beams – mitigation of thermal gradients



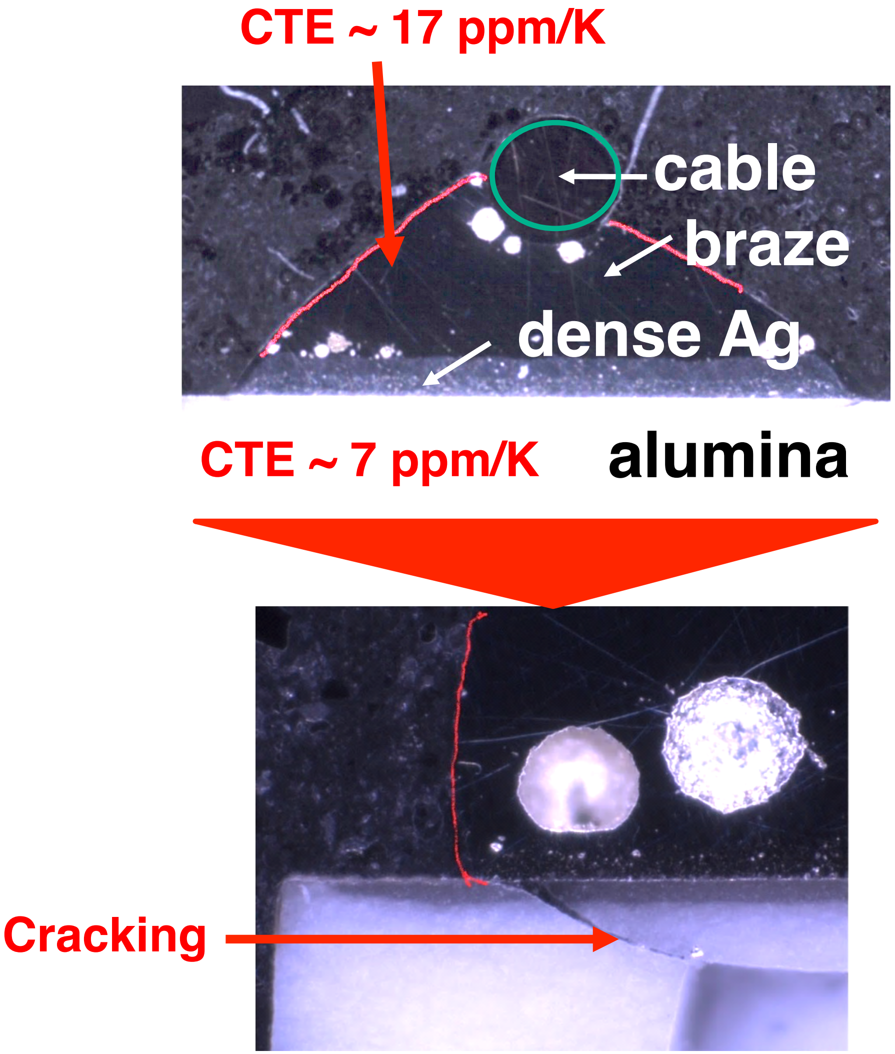


Jacq-C Maeder-T Güniat-L Corne-A Testa-D Ryser-P, Proceedings, IMAPS/ACerS 11th International CICMT Conference, Dresden (DE), 234-238, 2015.

Cabling – brazing cable to alumina

- Issue: **cracking** of alumina due to **local thermal expansion mismatch**
- Dense Ag metallisation too stiff to absorb differential strain

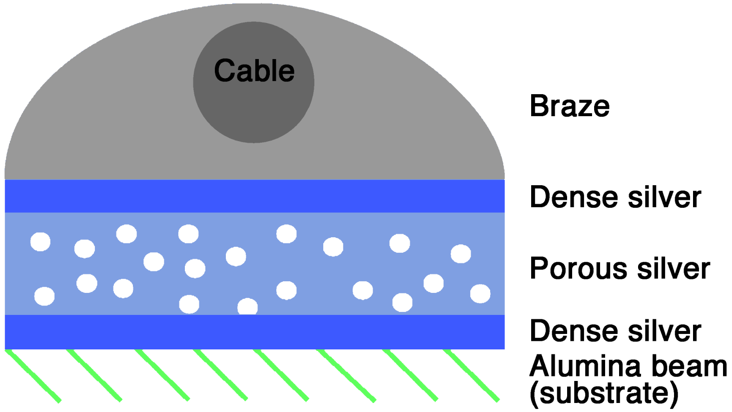
Jacq-C Maeder-T Güniat-L Corne-A Testa-D Ryser-P, Proceedings, IMAPS/ACerS 11th International CICMT Conference, Dresden (DE), 234-238, 2015.



Cabling – porous metallisation

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

- Dense Ag metallisation too stiff to absorb differential strain
- **Use porous interlayer**
  - Sandwich of dense/porous/dense silver
  - Formulation of 7 inks
  - “Rich” binder to allow successive printing of porous layers
  - Parameters: porogen size, volume percent, porous layer thickness
  - Porogen = graphite powder

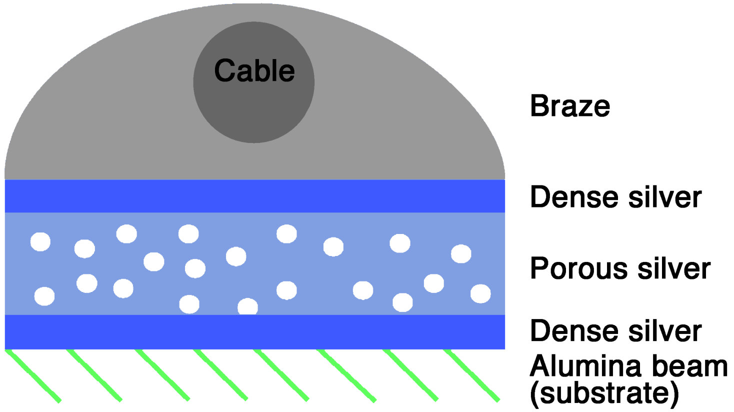


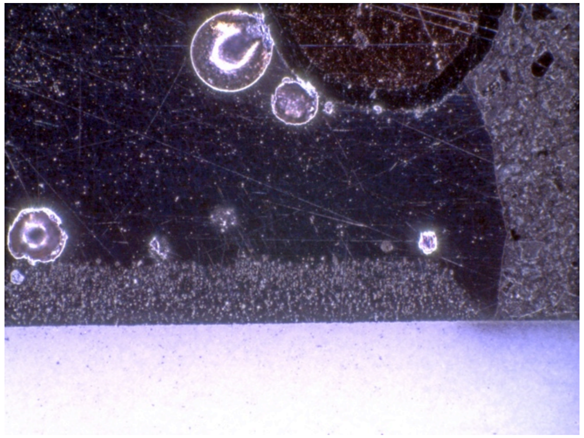
Denomination	Graphite	Particle size (μm)	Volume percent (%)
KS4_50	KS4	< 4	50
KS5-44_10	KS5-44	5-44	10
KS5-44_25	KS5-44	5-44	25
KS5-44_50	KS5-44	5-44	50
KS5-44_75	KS5-44	5-44	75
KS44_50	KS44	< 44	50
KS75_50	KS75	< 75	50

Jacq-C Maeder-T Güniat-L Corne-A Testa-D Ryser-P, Proceedings, IMAPS/ACerS 11th International CICMT Conference, Dresden (DE), 234-238, 2015.

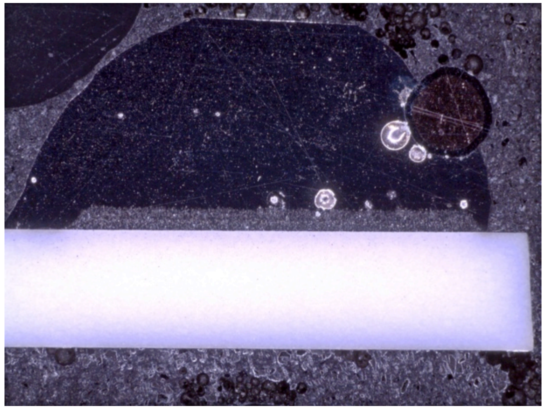
Cabling – porous metallisation

- Cables brazed to porous metallisation
- **No more cracking for porosity ~50%**

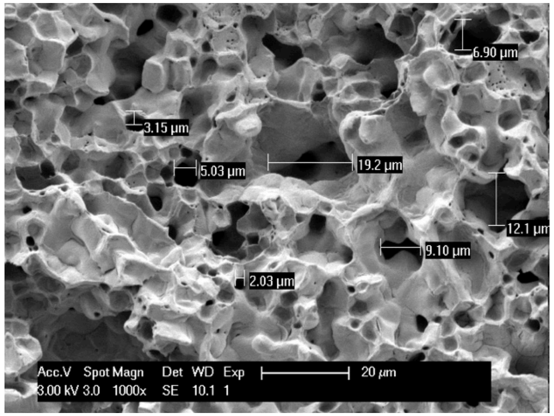




Cross section (zoom)



Cross section w/o cracks



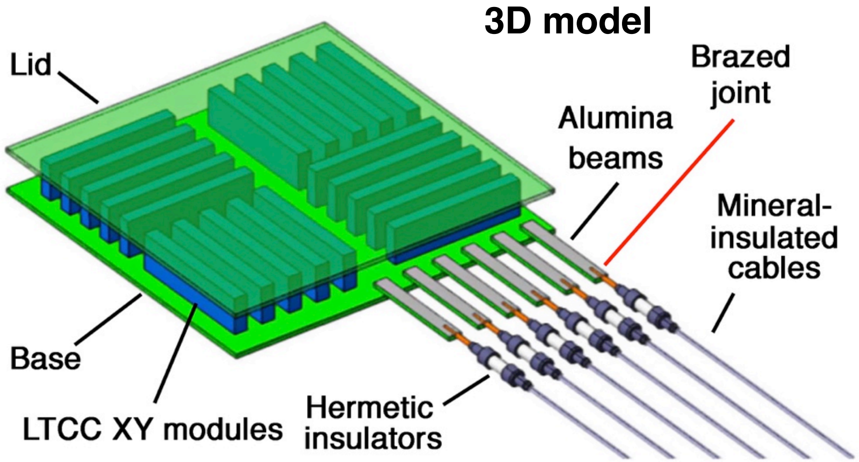
Porous metallisation (SEM)

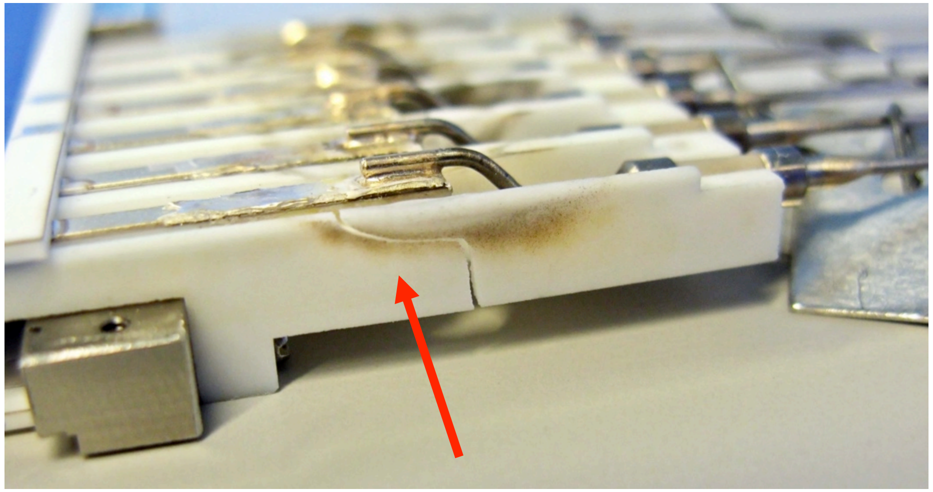
Jacq-C Maeder-T Güniat-L Corne-A Testa-D Ryser-P, Proceedings, IMAPS/ACerS 11th International CICMT Conference, Dresden (DE), 234-238, 2015.

Cabling – other solutions

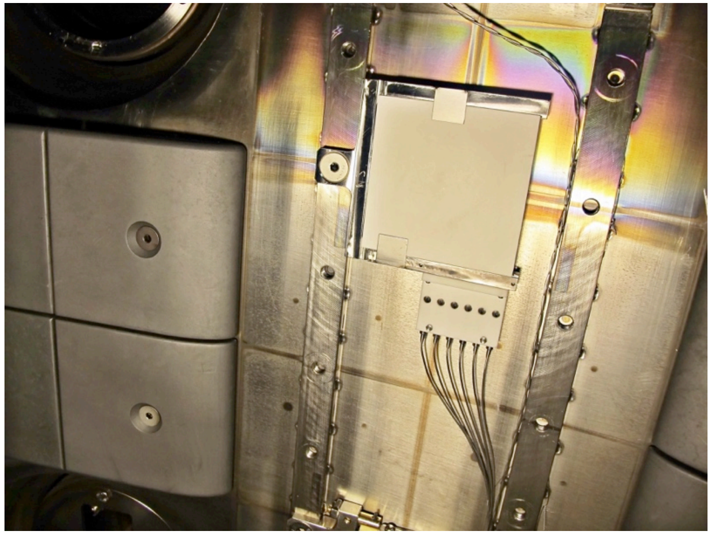
First solution cumbersome:

- Long, fragile alumina beams
- Additional space needed
- Issues with brazing operation
- Workshop cabling, must install whole assembly into tokamak





Cracking of auxiliary ceramic part due to thermal stresses during brazing



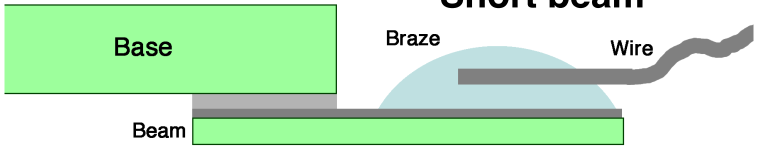
Sensor mounted in TCV tokamak

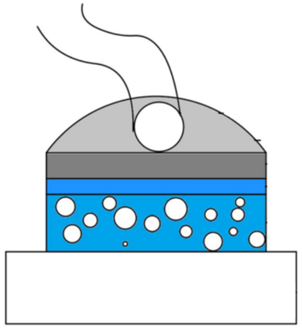
Cabling – other solutions

Three alternatives investigated:

1. Simply shortening the alumina beams
2. Brazing wires directly on base, with porous dielectric thermal insulator
3. Replacing the alumina beams by silver wire (attachment with paste to base)

Short beam





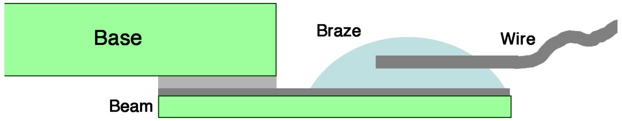
Porous dielectric

Ag wire

Jacq-C Maeder-T Toussaint-M Ellenrieder-BR Windischhofer-P Jiang-X Testa-D Ryser-P, Proceedings, 12th IMAPS/ACerS international Conference on Ceramic Interconnect and Ceramic Microsystems Technologies (CICMT), Denver (USA), 58-63, 2016.

Cabling – other solutions

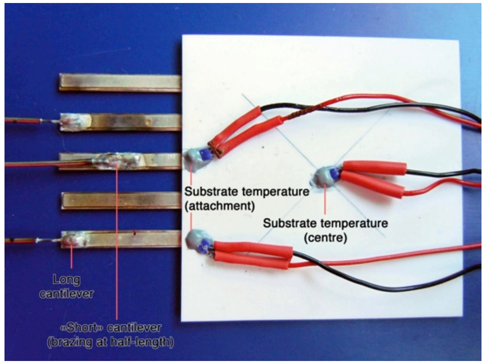
Results:



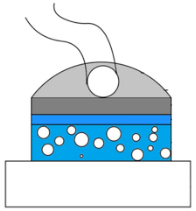
1. Short beams: OK

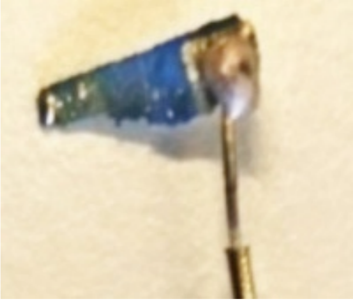
- ~20 vs 45 mm free length

Brazing to long & "short" beams (at half-length)



2. Porous dielectric: failure – broken dielectric



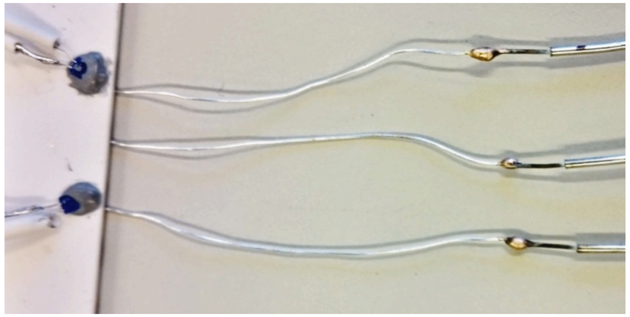


Brazing to porous dielectric – failure of dielectric due to very high thermal gradient

3. Silver wire: OK, best

- Mechanical decoupling
- Also: screw / crimp attach
- Bonding with Ag/glass to substrate

Brazing to Ag wire – crimping also possible



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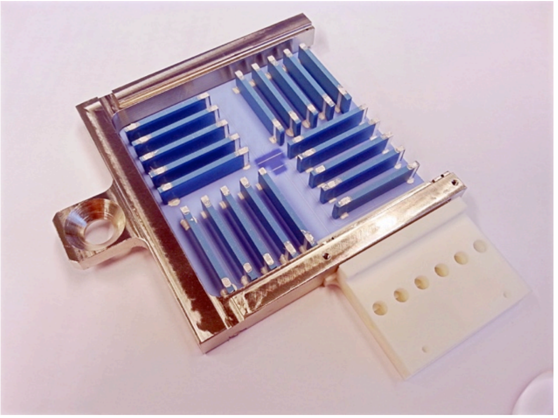
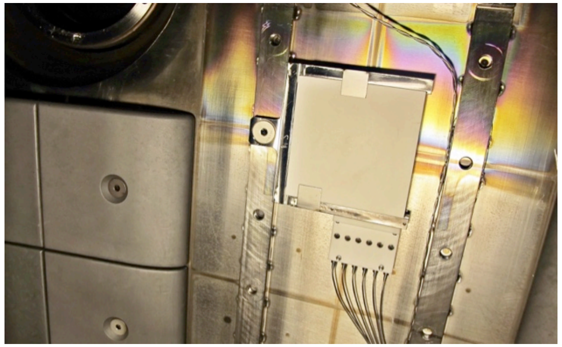
Conclusions

- Ceramic 1D & 3D magnetic sensors designed and produced successfully using LTCC and thick-film technology
- Small size, low profile for mounting behind tokamak wall
- Design rules for coils derived from results
- **3D sensors installed in TCV tokamak**





Outlook

Better packaging technology

- Ag pressure sintering for mounting parts
- Resistance welding / pressure sintering for cables

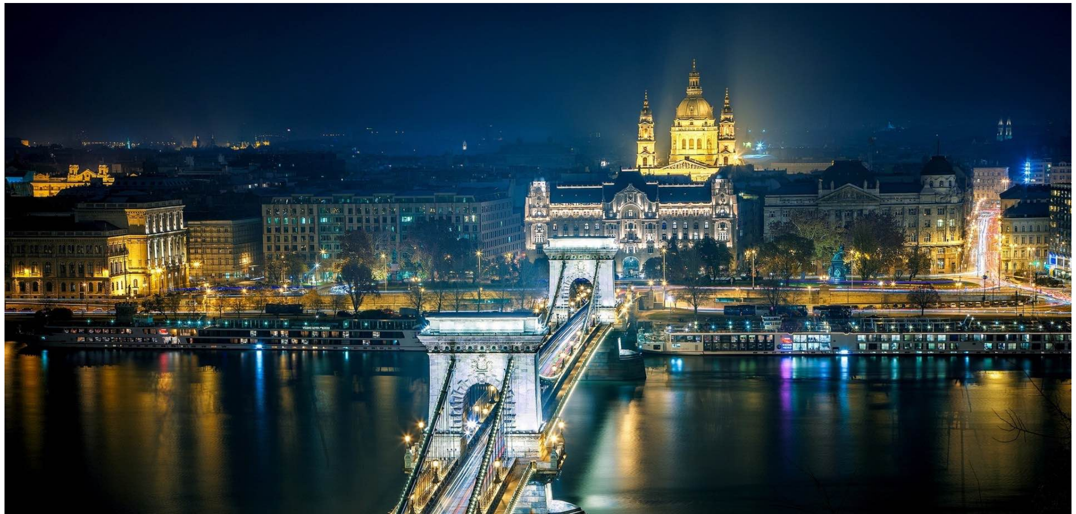
Brazing to Ag wire – crimping also possible

Field-installable electrical connection

- Sensor handled in tokamak without bulky cabling
- HT / HV connectors
- Crimp / screw contact to e.g wire segments attached to base

Merci

Thank you for your kind attention



Questions ?

Further reading / references

Packaging & interconnection

- Jacq-C et al., "Solutions for thermally mismatched brazing operations for ceramic tokamak magnetic sensor", Proceedings, 12th IMAPS/ACerS international Conference on Ceramic Interconnect and Ceramic Microsystems Technologies (CICMT), Denver (USA), 58-63, 2016.
- Jacq-C et al., "Porous thick-film silver metallisation for thermally mismatched brazing operations in tokamak magnetic sensor", Proceedings, IMAPS/ACerS 11th International CICMT Conference, Dresden (DE), 234-238, 2015.

1D LTCC sensors

- D.Testa et al., Prototyping a high frequency inductive magnetic sensor using the non-conventional, low temperature co-fired ceramics technology for use in ITER, Fus. Sci. Tech. 59 (2011), 376
- G.Chitarin et al., Technology developments for ITER in-Vessel equilibrium magnetic sensors, Fus. Eng. Des. 84 (2009), 593

3D LTCC sensors

- D.Testa et al., 3D, LTCC-type, High-Frequency Magnetic Sensors for the TCV Tokamak, Fus. Eng. Des. 96-97 (2015) 989

Further reading / references

3D HTCC sensors:

- H. Takahashi et al., Magnetic probe construction using thick-film technology, Rev. Sci. Instrum. 72 (2001), 3249

ITER magnetic diagnostic system:

- J.Lister et al., The magnetic diagnostics Set for ITER, Fus. Eng. Des. 84 (2009), 295
- D.Testa et al., The magnetic diagnostic set for ITER, IEEE Transactions on Plasma Science 38 (2010), 284
- D.Testa et al., Functional performance analysis and optimization for the high-frequency magnetic diagnostic system in ITER, Fus. Sci. Tech. 57 (2010), 208; and Fus. Sci. Tech. 57 (2010), 238
- D.Testa et al., Assessment of the ITER High-Frequency Magnetic Diagnostic Set, Fus. Eng. Des. 86 (2011), 1149

Mirnov-type HF magnetic sensors for ITER:

- M.Toussaint et al., Design of the ITER high-frequency magnetic diagnostic coils, Fus. Eng. Des. 86 (2011), 1248
- D.Testa et al., Prototyping conventional wound high frequency magnetic sensors for ITER, Fus. Sci. Tech. 61 (2012), 19