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

Thomas Maeder¹, Caroline Jacq¹, Duccio Testa², Matthieu Toussaint², Yannick Fournier¹, Martin Stöck¹², Gaël Farine¹, Adrien Corne¹², Xinyue Jiang¹, Lucas Güniat¹², Benoît Ellenrieder¹², Philipp Windischhofer¹², Christian Schlatter², and Peter Ryser¹

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
- \( Q \geq 10 \text{ more energy from fusion than required for plasma heating} \)
- Burning plasma physics
- Power: \( P_{\text{fusion}} \geq 500 \text{ MW} \)

\( R \sim 6.2 \text{ m}; \ B_T \sim 5.3 \text{ T}; \ I_p \sim 15 \text{ MA} \)

Plasma Volume: 840 m\(^3\)
Nominal Plasma Current: 15 MA
Typical Temperature: 20 keV
Typical Density: \( 10^{20} \text{ m}^{-3} \)
Pulse Length >1’000 s
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 ($T, \Delta T$)
    - High neutron flux
- Magnetic coils:
  - LF, equilibrium, $< \sim 1$ kHz
  - HF, MHD instabilities, $< \sim 300$ kHz

Magnetic sensors in walls

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

1. Introduction – magnetic sensing for tokamaks

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

<table>
<thead>
<tr>
<th></th>
<th>Thick-film</th>
<th>LTCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Alumina</td>
<td>LTCC tape</td>
</tr>
<tr>
<td>Multilayer dielectric</td>
<td>Extra printed ink</td>
<td>LTCC tape</td>
</tr>
<tr>
<td>Firing</td>
<td>Sequential</td>
<td>Together (co-firing)</td>
</tr>
</tbody>
</table>
Thick-film - process flow

1. Introduction - Thick-film processing

Sequential firing

1. Screen & paste
   - Ecran & pâte
   - Maske & Paste

2. Screen printing
   - Sérigraphie
   - Siebdruck

3. Drying
   - Séchage
   - Trocknen

4. Firing
   - Cuisson
   - Einbrand

Substrate
- Substrat

Circuit
- Schaltung

Temperature / Temperature / Temperatur [°C]

Time / Temps / Zeit [min]

- ca. 850°C 10 min
- > 400°C Frittage & réaction
- Sintering & reaction
- Sintern & Reaktion

- 200-380°C Déliantage
- Debinding
- Entbinden

- 80-150°C Séchage
- Drying
- Trocknung

ca. 150°C 15 min
Co-firing

1. Introduction – LTCC processing
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


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

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

- **ITER reference design**
  - 80×40×40 mm$^3$ – bulky!
  - $NA_{\text{eff}} \sim 670$ cm$^2$ - OK
  - Slotted stainless-steel body
  - Ceramic guides
  - Two layers of W wire
  - Wire exposed
  - W stiff, brittle -> difficult

- **Need compact, monolithic solution**

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, …)

- Presumably more robust
- Low profile – mounting in wall, behind protection tiles
Magnetic coils for tokamaks

Signal (ideal):
\[ U_{AC} = i \cdot \omega \cdot B_{AC} \cdot N A_{\text{eff}} \]

- \( U_{AC} \): signal voltage
- \( \omega \): angular frequency
- \( B_{AC} \): magnetic field
- \( N A_{\text{eff}} \): effective integral coil area

- Signal \( U \)?
- Capacitance \( C \)?
- Inductance \( L \)?
- Resonance:

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

Multiple turns parallel and perpendicular to the magnetic field

2. Coil-type magnetic sensors for tokamaks
Magnetic coils for tokamaks

Long cables due to high-energy neutron flux!

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

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

Coaxial cable

$\sim 10$ pF/m, $\sim 0.3$ $\mu$H/m

$C_{\text{cable}} \sim 500$ pF, $L_{\text{cable}} \sim 15$ $\mu$H

$L \sim 50$ m

Electronics

Sensor @wall

Tokamak

2. Coil-type magnetic sensors for tokamaks
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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) mm³
- 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

1st generation 1D sensor & coil design

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

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1D LTCC HF magnetic sensor results

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

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

**Measurement vs modelling**

**3. 1D LTCC HF magnetic sensor**
Some design rules:

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

3. 1D LTCC HF magnetic sensor results

Results $MM = 5, 10, 20$

Model $MM = 1...20$
1D LTCC HF magnetic sensor results

Some design rules:

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

- **Interlayer:**
  - Staggered winding not needed (small effect, only on $C_{\text{self}}$)
  - Increase spacing to especially decrease $L_{\text{self}}$
  - 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!

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*

- **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 $N A_{\text{eff}}$ easy

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

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4. 3D thick-film + LTCC magnetic sensor
3D ceramic magnetic sensor – Z coil

Single coil on back of base

- \( N_{\text{eff}} = 178 \text{ cm}^2 \)
- \( R_{\text{self}} = 17 \Omega \)
- \( L_{\text{self}} = 7.4 \mu\text{H} \)
- \( f_{\text{res}} > 12 \text{ MHz} \)
  - Still good with cables due to low \( L_{\text{self}} \)
  - With \( C_{\text{cable}} = 500 \text{ pF} \), ~2.6 MHz

- Favourable, high \( N_{\text{eff}} \) with low \( R_{\text{self}} \) & \( L_{\text{self}} \)


4. 3D thick-film + LTCC magnetic sensor
### 3D sensor – XY coil – LTCC optimisation

<table>
<thead>
<tr>
<th>Type</th>
<th>( MM )</th>
<th>( NN )</th>
<th>( N_{\text{eff}} ) [cm(^2)]</th>
<th>( R_{\text{self}} ) [( \Omega )]</th>
<th>( L_{\text{self}} ) [( \mu \text{H} )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old</td>
<td>4.5*</td>
<td>13</td>
<td>77</td>
<td>28</td>
<td>60</td>
</tr>
<tr>
<td>New</td>
<td>2.5*</td>
<td>9</td>
<td>38</td>
<td>9</td>
<td>12</td>
</tr>
</tbody>
</table>

- Turns = \( MM \times NN + 0.5 \) (in base) = 59 / 23
- Sensor V2

#### Ratios
- \( N_{\text{eff}} \): \( \sim 2:1 \)
- \( R_{\text{self}} \): \( \sim 3:1 \)
- \( L_{\text{self}} \): \( \sim 5:1 \)

#### Numbering up simpler elements to minimise \( L_{\text{self}} \) & \( R_{\text{self}} \)

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### 3D sensor – XY coil – overall

<table>
<thead>
<tr>
<th>(New LTCC coils)</th>
<th>$N_A^{\text{eff}}$ [cm$^2$]</th>
<th>$R_{\text{self}}$ [Ω]</th>
<th>$L_{\text{self}}$ [µH]</th>
<th>$f_{\text{res}}$ [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor X</td>
<td>298</td>
<td>127</td>
<td>158</td>
<td>~5.5</td>
</tr>
<tr>
<td>10 x single</td>
<td>376</td>
<td>90</td>
<td>123</td>
<td>&gt;12</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>−78</td>
<td>37</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>$\Delta_{\text{rel}}$</td>
<td>−21%</td>
<td>+41%</td>
<td>+28%</td>
<td></td>
</tr>
</tbody>
</table>

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

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

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4. 3D thick-film + LTCC magnetic sensor
3D sensor – XY coil separation

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
  - $\Delta L/L \sim +28\% \rightarrow \Delta f/f$ should be $-(\Delta L/L)^{0.5} \sim -13\%$

Corne-A, "Capteur de champ magnétique 3D pour fusion nucléaire", Projet de semestre, Section de microtechnique, LPM, EPFL, Lausanne (CH), 2014.
LTCC-3D sensor-V1: electrical data

- Design OK: $L_{SELF,TOT} \propto N_{TURNS} \times L_{TURN} + L_{MUT}$ instead of $\propto (N_{TURNS})^2 \times L_{TURN}$

- However significant improvements are needed:
  - $\delta B_{POL}$ (x-axis), $\delta B_{TOR}$ (y-axis): clearly different electrical characteristics (should be exactly the same) and very large parasitic coupling ($NA_{PAR}/NA_{EFF} > 10\%$)
  - Parasitic effective area $\delta B_{RAD}$ (z-axis) also too large, $\sim 10\%$ (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

measured impedance for final as-built 11x LTCC-3D magnetic sensors

- X-axis: MeanValue/20
- Y-axis: MeanValue/20
- Z-axis: MeanValue

frequency [kHz]

abs(\frac{Z_{MEAS}}{50}) [\Omega]
3D sensor – conclusions

Working 3D sensor developed

- Innovative modular concept for XY
  - Simple LTCC edge-mounted solenoids
  - Good yield, separation -> low $L_{\text{self}}$

- Sufficient $N A_{\text{eff}}$
  - X/Y/Z : ~300/260/180 cm$^2$

- High resonance frequencies
  - XY : ~5.5 MHz ; Z : > 12 MHz
  - With $C_{\text{cable}} = 500$ pF: XY/Z ~0.6/2.6 MHz

- Mounted in EPFL-SPC TCV
  - Tokamak à Configuration Variable
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Mounting LTCC sensors onto base

Preparation

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

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

Cabling – brazing cable to alumina

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

CTE ~ 17 ppm/K
Cable braze dense Ag
CTE ~ 7 ppm/K alumina

Cracking

Cabling – porous metallisation

- 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

Cabling – porous metallisation

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

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)

Cabling – other solutions

Results:

1. **Short beams: OK**
   - ~20 vs 45 mm free length

2. **Porous dielectric:**
   - failure – broken dielectric

3. **Silver wire: OK, best**
   - Mechanical decoupling
   - Also: screw / crimp attach
   - Bonding with Ag/glass to substrate

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

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

6. **Brazing to Ag wire – crimping also possible**

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5. **Interconnection and packaging**

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Eurosensors 2016 Budapest – Ceramic magnetic sensors
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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

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
Thank you for your kind attention

Questions?
Further reading / references

Packaging & interconnection


1D LTCC sensors


- G.Chitarin et al., Technology developments for ITER in-Vessel equilibrium magnetic sensors, Fus. Eng. Des. 84 (2009), 593

3D LTCC sensors

Further reading / references

3D HTCC sensors:

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

Mirnov-type HF magnetic sensors for ITER:
- D. Testa et al., Prototyping conventional wound high frequency magnetic sensors for ITER, Fus. Sci. Tech. 61 (2012), 19