OUTCOMES OF THE LRFF (LHC RF FINGERS) TASK FORCE IN 2012

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Some people installed this in the LHC and are very happy!

OUTLINE (1/2)

- Introduction
- Why do we need RF fingers and/or ferrite (absorbers)?
- What we planned to do
- What was done
- RF fingers
  - Several designs
  - Possible issues to consider
  - Example of nonconformity in warm modules found with X-rays
  - Guidelines

OUTLINE (2/2)

- Ferrite absorbers
  - Several types, criteria and guidelines
  - Measurements of the EM properties
  - Figure of merit and design guidelines for the ferrite heating
  - Measurements of the vacuum properties
- Pros and cons of RF fingers and ferrite absorbers
- What was wrong with the PIMs in the cold part of LHC?
- Follow-up of VMTSA issues in 2011
- Conclusions and recommendations
- Appendix: List of all the (92) nonconformities

INTRODUCTION (1/3)

- Beam-induced heating has been observed in several LHC components during the 2011 run when the bunch/beam intensity was increased and/or the bunch length reduced
- In particular 8 bellows, out of the 10 double-bellows modules (called VMTSA) present in the machine, were found with the spring, which should keep the RF fingers in good electrical contact with the central insert, broken
- SS spring deformed and brazed to the CuBe RF fingers with RF fingers permanently deformed => Estimated temp. of ~ 800 - 1000 °C

INTRODUCTION (2/3)

- **Proposition made during the LMC meeting # 119 (18/01/2012) to review the design of all the components of the LHC equipped with RF fingers => LRFF (LHC RF Fingers) Task Force before LS1**
- **Web site: http://emetral.web.cern.ch/emetral/LRFF/LRFF.htm**
  - 1st (kick-off) meeting: 20/03/2012
  - 20th (last) meeting: 27/11/2012
- **Members**

- Elias Metral (chairman, BE/ABP).

- Jose Miguel Jimenez (alternate, TE/VSC) => Could be replaced by Sergio Calatroni.

- For TE/VSC (Vacuum, Surfaces and Coatings): Vincent Baglin and Giuseppe Bregliozzi (alternate).

- For EN/STI (Sources, Targets & Interactions): Oliver Aberle and Roberto Losito.

- For TE/ABT (Accelerator Beam Transfer): Wim Weterings (mechanical issues) and Mike Barnes (impedance-related aspects).

- For BE/RF (Radio Frequency): Fritz Caspers, Alexej Grudiev and Oleksiy Kononenko.

- For BE/BI (Beam Instrumentation): Rhodri Jones and Raymond Veness (alternate).

- For BE/ABP (Accelerators and Beam Physics): Benoit Salvant, Hugo Day and Olav Berrig (EM simulations and wire measurements), Ralph Assmann (task leader of the "Intensity limitations in the LHC" task within WP2 of the HL-LHC project) and Stefano Redaelli (LHC Collimation project leader).

- For EN/MME (Mechanical & Materials Engineering): Alessandro Bertarelli and Marco Garlasche.

- For TE/MSC (Magnets, Superconductors and Cryostats): Vittorio Parma.

- Others?

  - Someone from the Design Office (i.e. designer of a particular equipment) might be needed at some point => Alessandro Bertarelli will be the link person.
  - Someone from Cryo could be invited at some point (after the first recommendations of the Task Force).

INTRODUCTION (3/3)

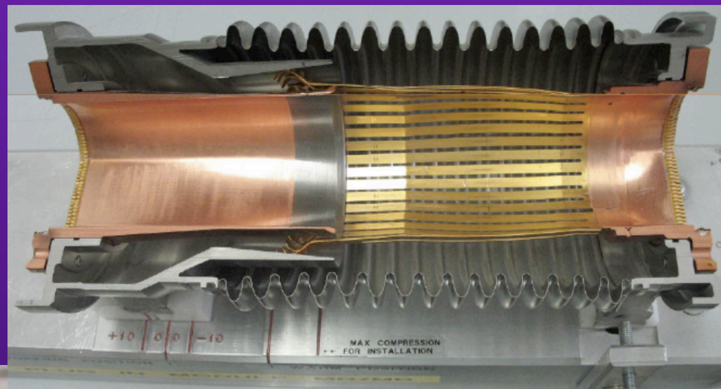
- **Mandate**
  - Review the design of all components of the LHC equipped with RF fingers, evaluate the compatibility with ultimate (and HL-LHC) bunch populations (i.e. up to 2.2E11 p/b for the 25 ns beam and 3.5E11 p/b for the 50 ns beam) and (rms) bunch lengths (i.e. 7.5 cm but also ~ 4 cm which could be an option) regarding impedance and HOM screening and provide a list of maximum bunch currents, acceptable bunch lengths etc.
  - Evaluate all associated mitigation solutions like ferrite absorbers and their collateral effects, in particular the induced heating and resulting outgassing
  - Make proposals of design changes and/or mitigation measures for each configuration depending on its criticality for beam operation
  - Approve functional specifications for all equipments by the end of the year (2012)

WHY DO WE NEED RF FINGERS AND/OR FERRITE? (1/5)

- To avoid having too large impedances (longitudinal or transverse) due to (big) changes of geometry for moving equipments, which can lead to
  - Beam-induced RF heating (if real part of longitudinal impedance)
  - Longitudinal or transverse beam instabilities (if real and/or imaginary parts of longitudinal or transverse impedances)

- Example of RF fingers:

  PIMs = Plug-In Modules



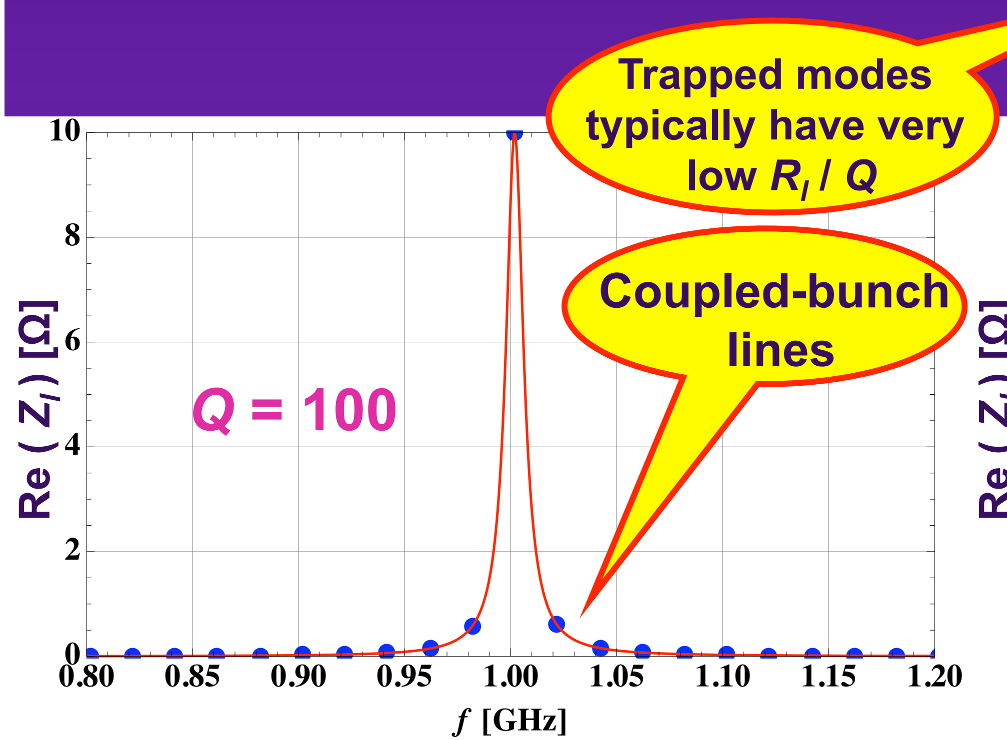
- Example of ferrite tiles:

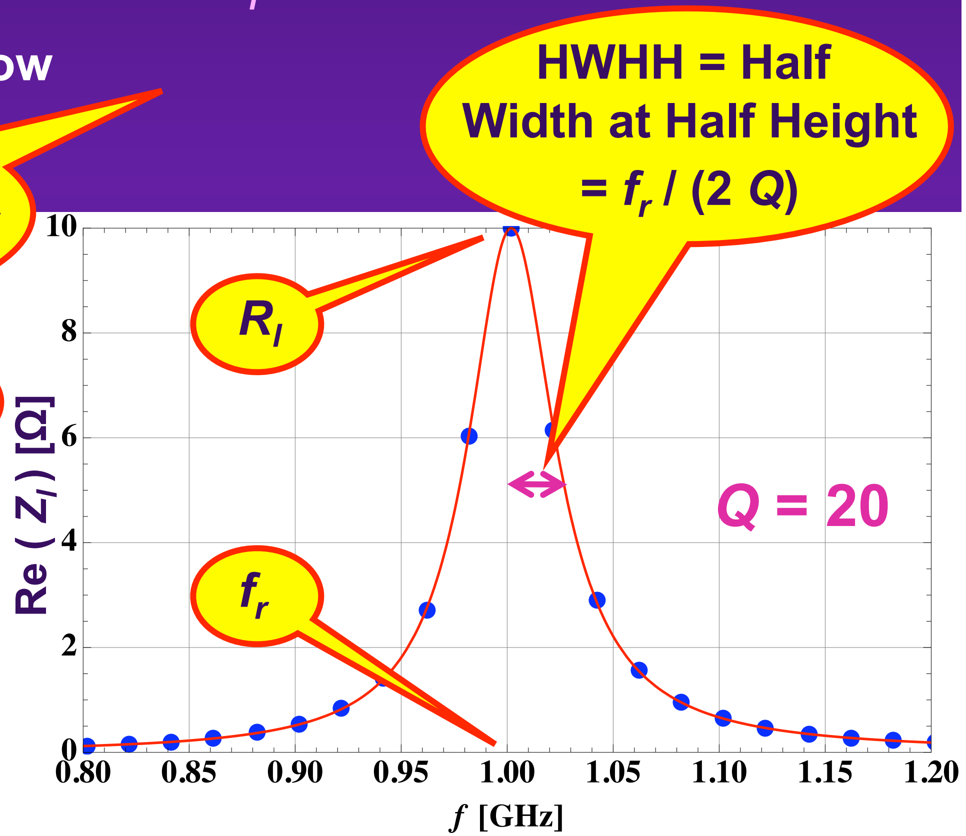
  Installed in the new VMTSA in 2012

Initial dimensions (quickly available!): ~ 12 cm × 3 cm × 1 cm

WHY DO WE NEED RF FINGERS AND/OR FERRITE? (2/5)

- **Example for the RF heating => Consider the case of a narrow resonance (trapped mode due to the geometry) => 3 parameters (obtained from EM simulations):**
  - Resonance frequency => Assumed to be here f_r = 1 GHz
  - Shunt impedance => Assumed to be here R_l = 10 Ω
  - Quality factor Q => Scanned below





WHY DO WE NEED RF FINGERS AND/OR FERRITE? (3/5)

- **Power loss formula for the case of a (sharp) resonance (i.e. with only 1 line)**

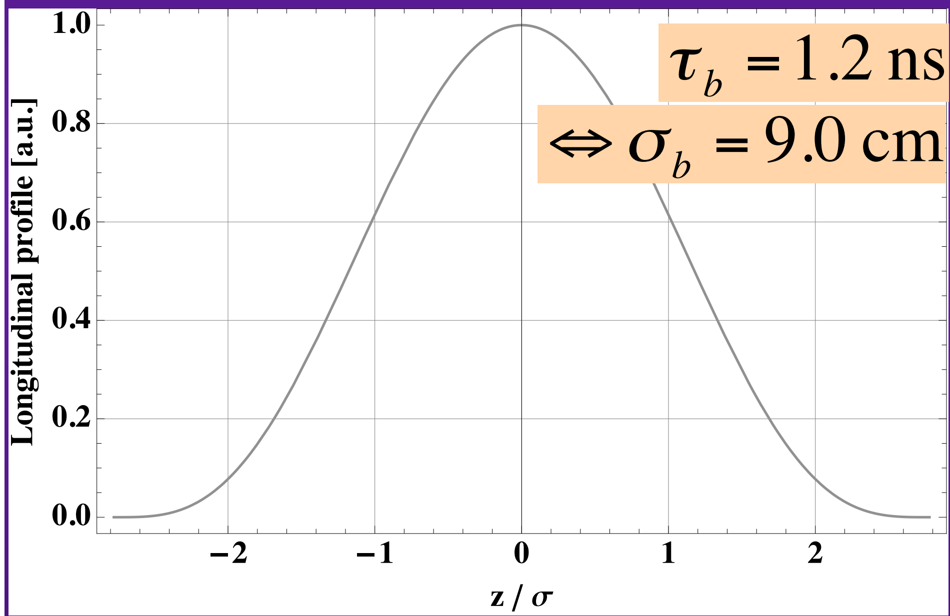
$$P_{loss} = \left(M \, I_b \right)^2 \times 2 \, R_l \times 10^{\frac{P_{dB}\left(f_r \right)}{10}}$$

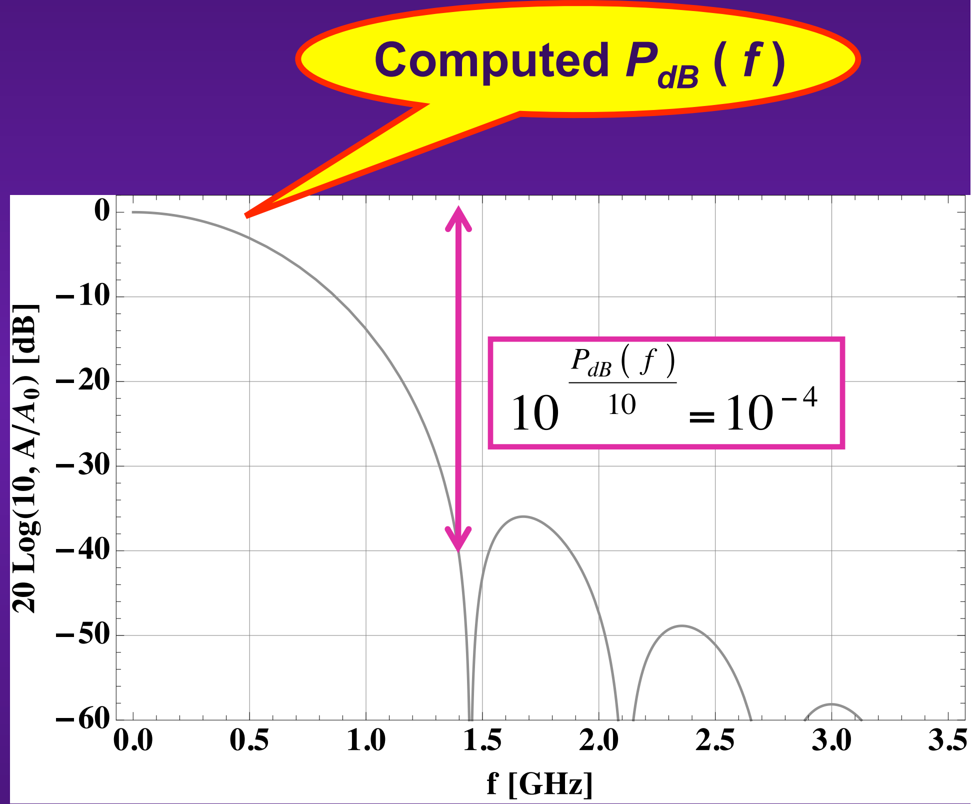
Total beam current:
M **= # bunches**
$I_b = N_b \, e \, f_0$

$P_{dB} (f_r)$ **is the power in dB read from a power spectrum (computed or measured) at the frequency** f_r

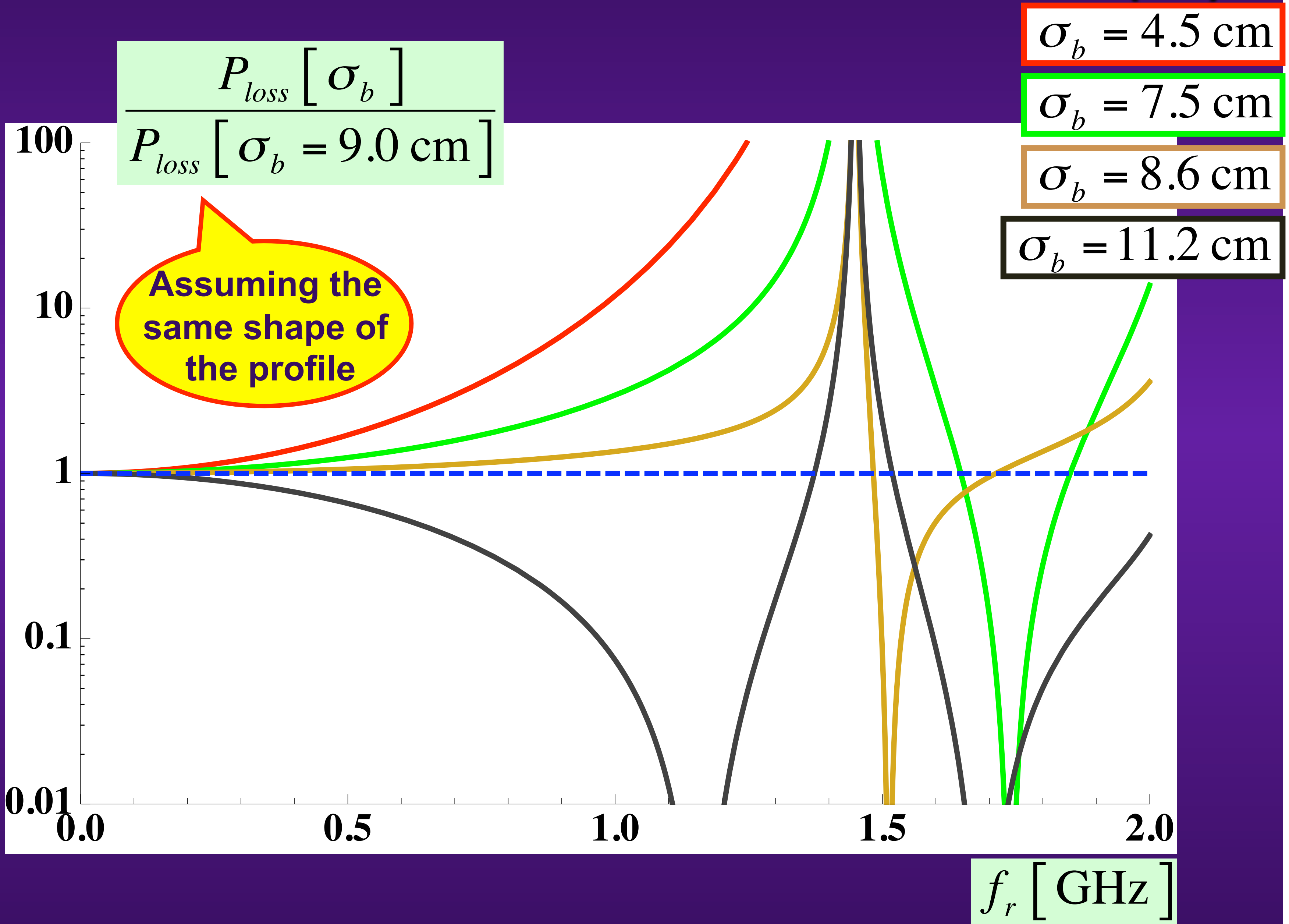
WHY DO WE NEED RF FINGERS AND/OR FERRITE? (4/5)

- Consider the following (analytical) distribution





WHY DO WE NEED RF FINGERS AND/OR FERRITE? (5/5)



WHAT WE PLANNED TO DO

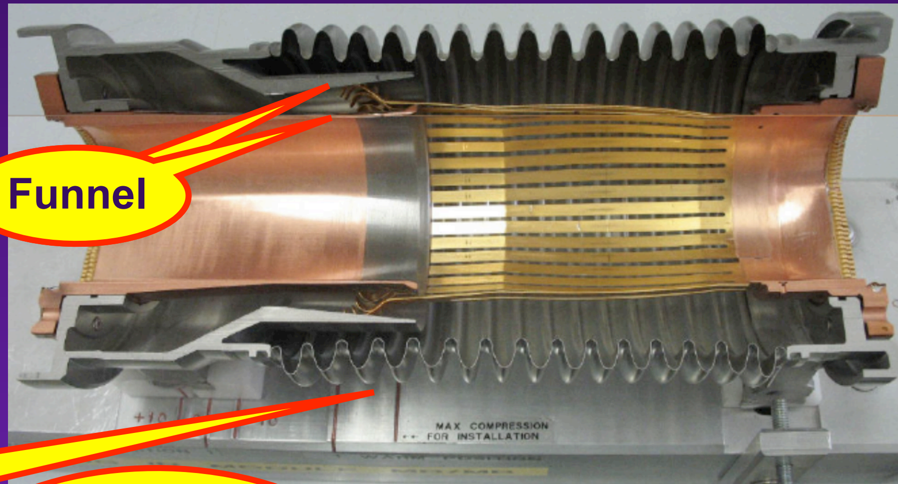
- Exhaustive review of all the equipments with RF fingers
- Ranking by criticality and action plan
- First recommendations of the Task Force
- New design and/or mitigation measures
- List of endorsed actions presented by the Task Force => To be presented at the LMC

WHAT WAS DONE

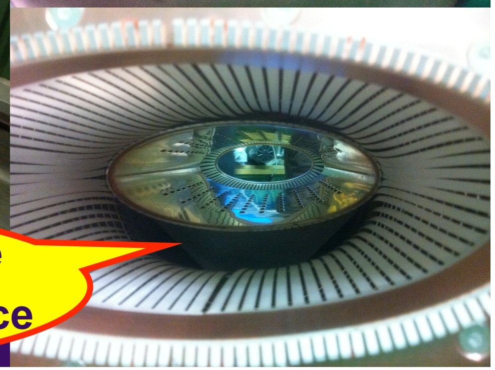
- 1) Follow-up of the VMTSA: EM and heat transfer simulations
- 2) Review of past work and issue with the PIMs (what was wrong with the Plug-In Modules in the cold part of the LHC?)
- 3) Review of past development work on RF contacts
- 4) Review of equipments from TE/VSC, BE/BI, TE/ABT, collimators from EN/STI-MME (and past impedance studies with RF fingers), wake field suppressor in the LHCb VELO
- 5) New design for RF fingers proposed by TE/VSC and impedance studies
- 6) Review of nonconformities in warm modules following the X-ray campaign => Typical defects and complete list of all of them
- 7) Review of recent contacts' issues in the SPS (after 35 years without any problem) => In power transmission lines (not machine)
- 8) Guidelines for the use of ferrite: EM and heat transfer simulations

SEVERAL DESIGNS FOR RF FINGERS (1/4)

- **1) Funnel for the PIMs**
  - For case of longitudinal movement (only)
  - Good for contact / gap
  - Possible issue with buckling and aperture restriction

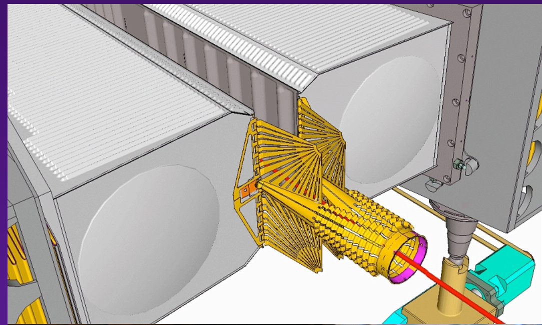


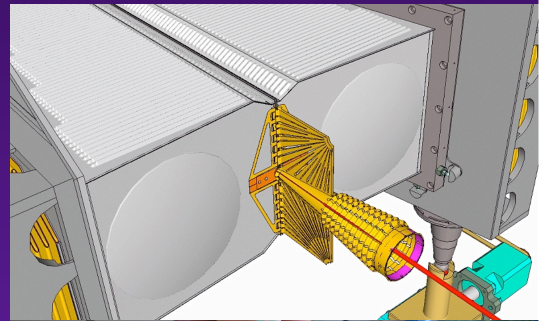
- **2) Spring for the VMTSA**
  - For case of transversal movement
  - Possible issue with contact / gap (due to elliptical shape) => RF heating
  - Possible issue with aperture restriction

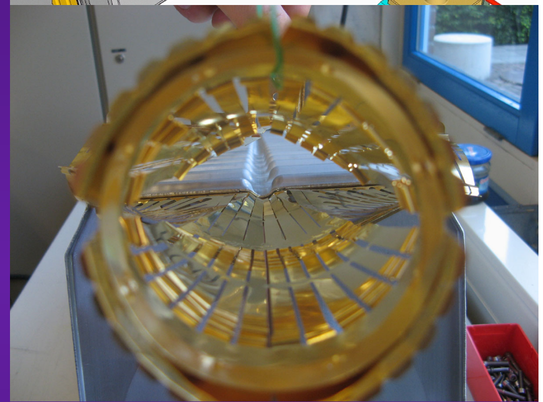


SEVERAL DESIGNS FOR RF FINGERS (2/4)

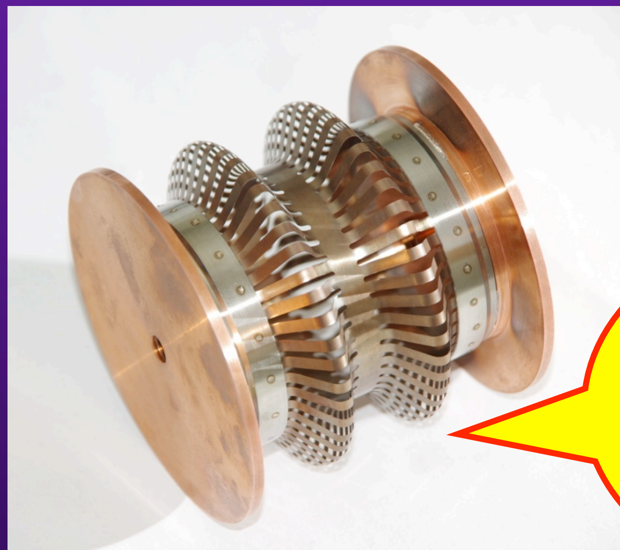
- **3) Fixed extremities for the LHCb VELO (VErtex LOcator)**
  - Seems to work very well!
  - Well-studied VELO design in terms of impedance effects paid off => No issue observed
  - Future upgrade: Reduction of the inner radius of the foil (from 5.5 to 3 − 4 mm)







- **4) New RF design from TE/VSC**
  - 1st prototype based on 2 convolutions manufactured this year. Tests ongoing
  - Issue: Imaginary part of the longitudinal impedance (if many)



Device EM longer than mechanically due to induced current having to follow the convolutions

SEVERAL DESIGNS FOR RF FINGERS (3/4)

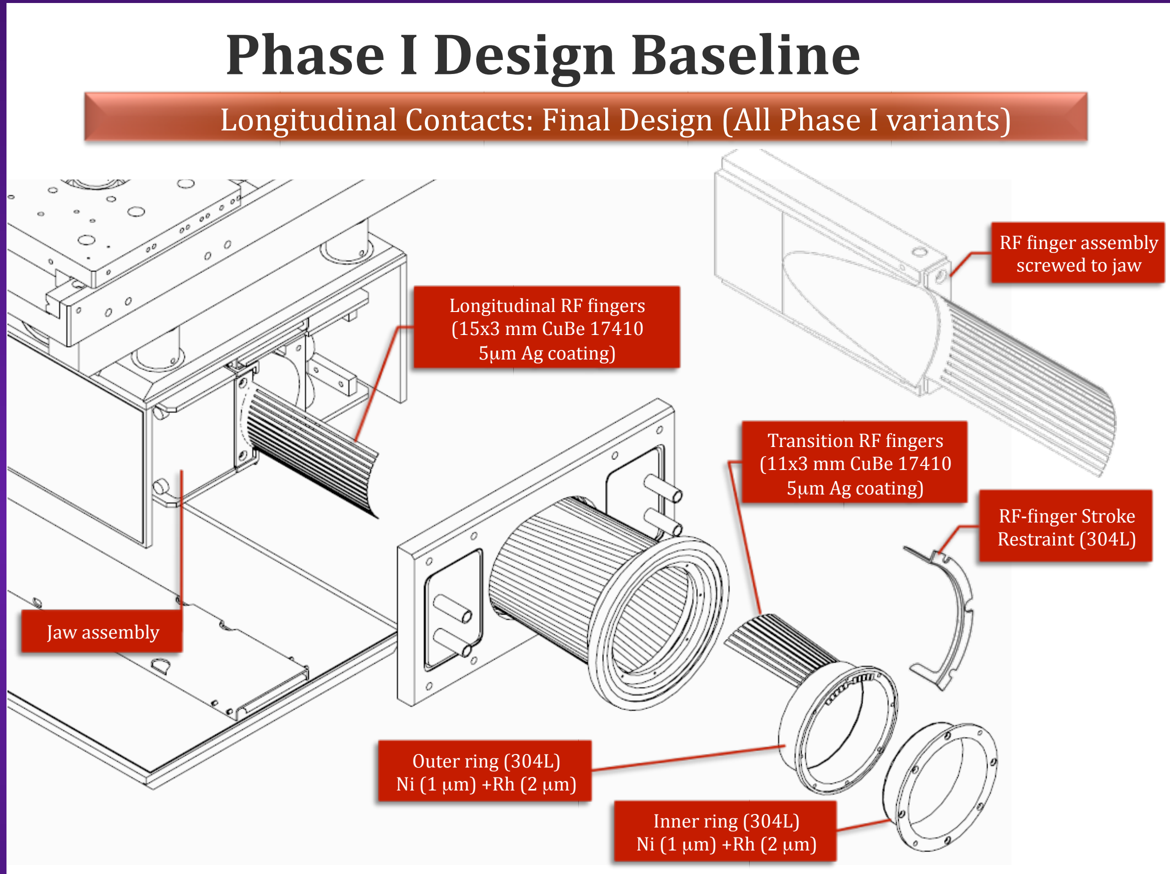
- The longitudinal impedance depends on how much the RF fingers are stretched
- The impedance is close to zero in either completely compressed state or completely stretched state
- The maximum normalized longitudinal impedance is

$$\mathrm{Im}\,[Z_l \,/\, n] \approx 1.5\ 10^{-4}\ \Omega$$

- Should not be used for all the PIMS for instance as the total LHC budget is ~ 0.1 Ω (i.e. only 667 times more) and there are ~ 1700 PIMs / ring

SEVERAL DESIGNS FOR RF FINGERS (4/4)

- **5) Longitudinal sliding contacts for collimators**
  - Initial proposal for 1st (SPS) prototype (2003)
  - Uncoated CuBe fingers sliding on C/C
  - Electrical contact resistance ~ 30 mΩ (specification: 1 mΩ) => Redesign necessary



POSSIBLE ISSUES TO CONSIDER WITH RF FINGERS (1/2)

- **RF fingers for PIMs**
  - Low contact resistance < 0.1 mΩ (i.e. 3 mΩ / RF finger as there are 30 RF fingers in //)
  - No cold welding
  - Low friction
  - Good formability properties
- **RF fingers for collimators**
  - Same as above with contact resistance < 1 mΩ
  - Resistance to bake out: 250°C / 1000 h
  - Resistance to heating => Good thermal conductivity
  - Wear after many cycles "open-close of the jaws" (1500 cycles ~ 4 years)
- **Good electric contacts requires**
  - Low surface roughness
  - Soft metals (at least one)
  - No oxide layer at the surface

POSSIBLE ISSUES TO CONSIDER WITH RF FINGERS (2/2)

- Resistive-Wall impedance for LHC collimators

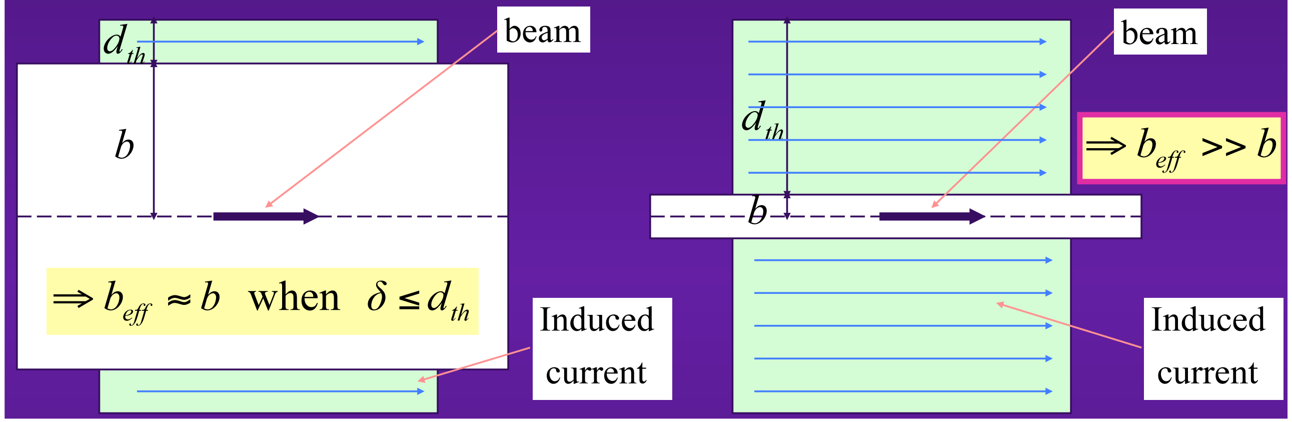
New findings have been made over the last few years for the impedance at low frequency => Bad conductor is better! But high frequency also important…

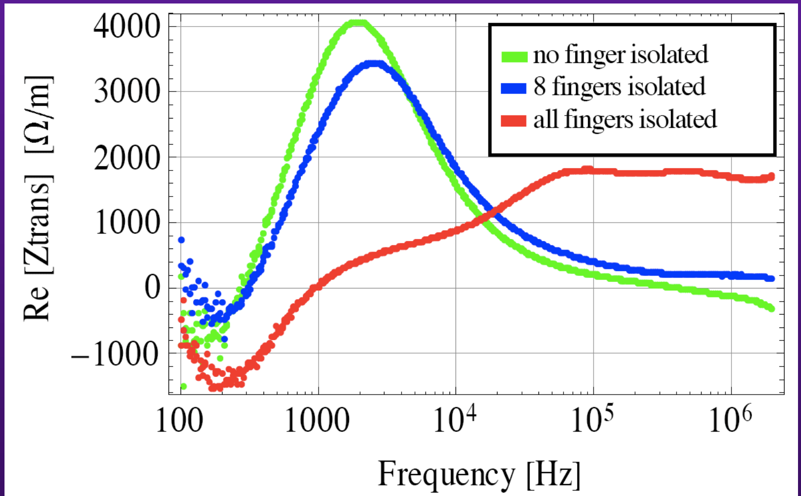
- Contact resistance for the PIMs

$\Rightarrow$ A new physical regime was revealed by the LHC collimators: the resistive impedance is ~ 2 orders of magnitude lower at ~ 8 kHz!

Usual regime : $d_{th}, \delta < b$

New regime : $d_{th} >> b$, $\delta \le d_{th}$

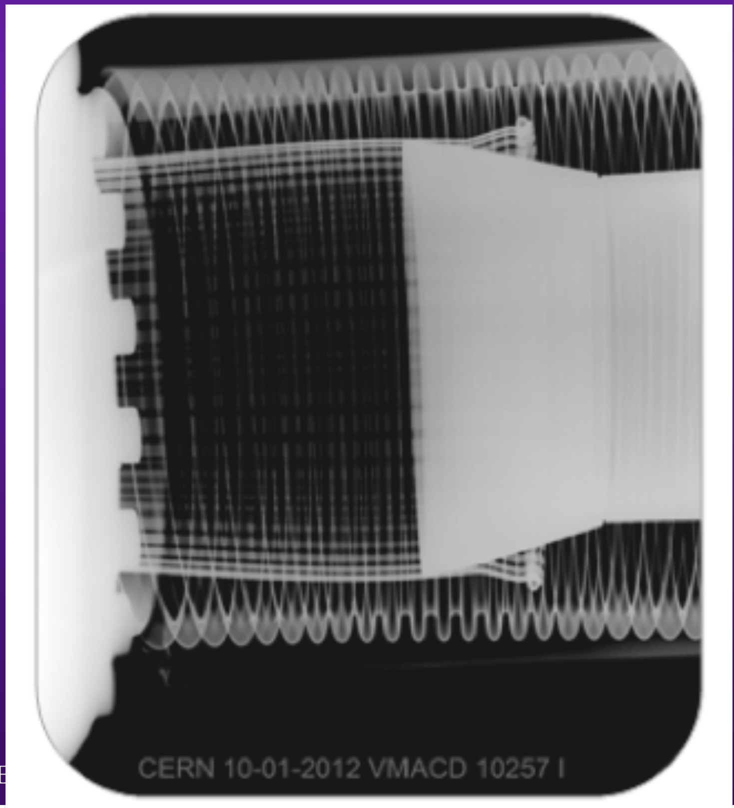




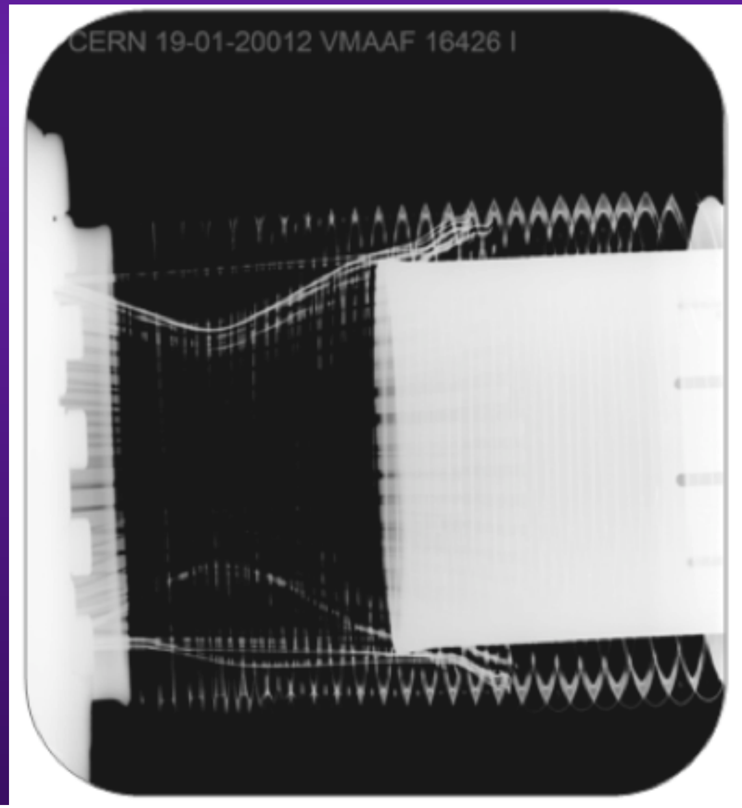
EXAMPLE OF NONCONFORMITY IN WARM MODULES FOUND WITH X-RAYS

- **1800 X-rays taken**
- **92 NC (~ 5 %)**
- **58 vacuum sector concerned out of 190 at room temperature (88 sectors at cryogenic temperature)**

CONFORMITY



NONCONFORMITY



GUIDELINES FOR (SLIDING) RF FINGERS (1/4)

- Material to be used for the RF fingers => CuBe (grade very important in case of bake-out => C17410): good conductor, good adhesion of coatings, weldability by e- beam, good formability properties, low magnetic permeability (low content of Ni, but contains Co – small enough amount for RP, but more than Be…), higher elasticity than Cu alone, etc.
- CuBe is a good conductor but still too high surface impedance => Coating needed to increase surface conductivity + reduce contact resistance + avoid cold welding
- No cold welding => 2 solutions
  - Put a diffusion barrier between the 2 metals (oxide layer) => Bad for the electrical contact
  - Choose metals with lowest solubility => Solution adopted and the best materials' pair is Au-Rh (best enemies => Almost no solubility). Ag-Rh is quite similar

GUIDELINES FOR (SLIDING) RF FINGERS (2/4)

- **Contact resistance measurements**
  - With a plating of the CuBe RF finger in Au and a plating of the base material (Cu) in Rh, the resistance was measured to be ~ 3 mΩ for 1 RF finger (i.e. ~ 0.1 mΩ for 1 PIM) => It was measured to be ~ 35 mΩ for the baseline Ag / SS contacts (i.e. ~ 1.2 mΩ for 1 PIM)
  - The use of Ag instead of Au led to ~ 2 mΩ but Au was chosen for the PIMs for the cold welding reason
  - Contact surface on the insert => Electro-polished before putting the Rh coating
- **Bake-out for the collimators (250°C)**
  - Au cannot be used because of the bake-out at 250°C (due to the diffusion of the Cu into Au and then the Au layer disappears). The same problem happens with Ag but at a higher temperature => Au was replaced by Ag for the collimators

GUIDELINES FOR (SLIDING) RF FINGERS (3/4)

- **Bake-out for the MKI injection kickers (~ 350°C)**
  - **SS (instead on CuBe, but still Au plated) is used for the MKI RF fingers because of the bake-out at ~ 350°C, which would lead with CuBe to a very small residual elasticity of ~ 20% only (see next slide)**
- **Finally, any gap should be avoided as it can be fatal (depends on real geometry) => Try and design a robust mechanical design to keep all the RF fingers in contact**

GUIDELINES FOR (SLIDING) RF FINGERS (4/4)

Stress relaxation resistance for high conductivity alloy (at 75% stress)

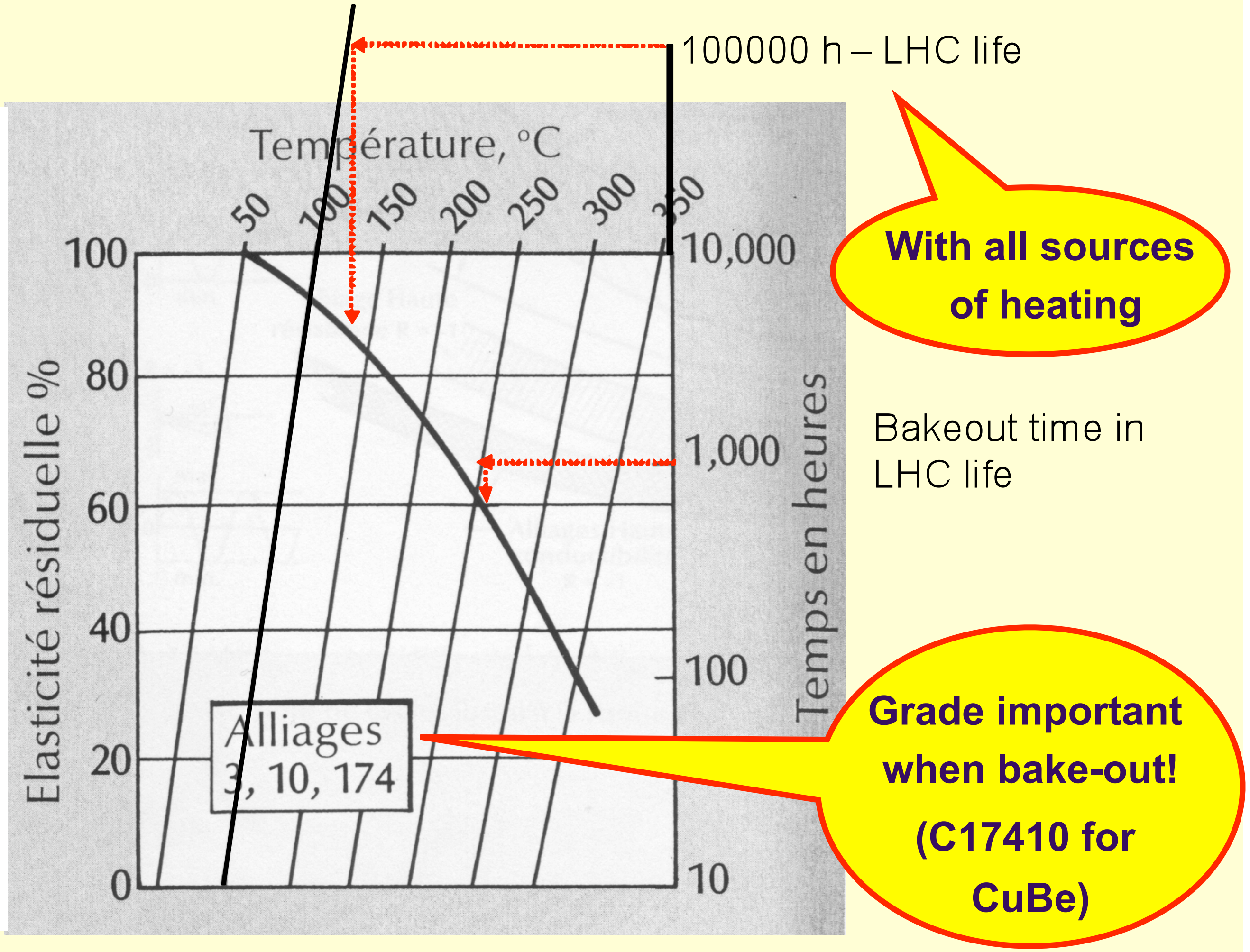
- **How to read it?**

1) Choose Temp line
=> Ex: 250°C (bake-out)

2) Then choose # hours of bake-out => Ex: 1000 h

3) Go vertically from this point to the curve

=> Gives the residual elasticity in %: 60% here (goal is to keep it as high as possible)



FERRITE: SEVERAL TYPES, CRITERIA & GUIDELINES (1/4)

- **Location of the ferrite (assuming known EM properties)**
  - EM simulations and put the ferrite at (close to) the maximum of the magnetic field of the mode to be damped (at the metallic wall)
  - Should not be seen directly by the beam (if possible)…
- **Penetration depth**

$$\delta(f) = \frac{c}{2\pi f} \times \frac{1}{\mathrm{Re}\left[\sqrt{1-\varepsilon_{rc}(f)\,\mu_{rc}(f)}\right]}$$

with f frequency c speed of light

$$\varepsilon_{rc}(f) = \varepsilon' - j\,\varepsilon'' = \varepsilon'\left(1 - j\tan\delta_{\varepsilon}\right)$$ relative complex permittivity

$$\mu_{rc}(f) = \mu' - j\,\mu'' = \mu'\left(1 - j\tan\delta_{\mu}\right)$$ relative complex permeability

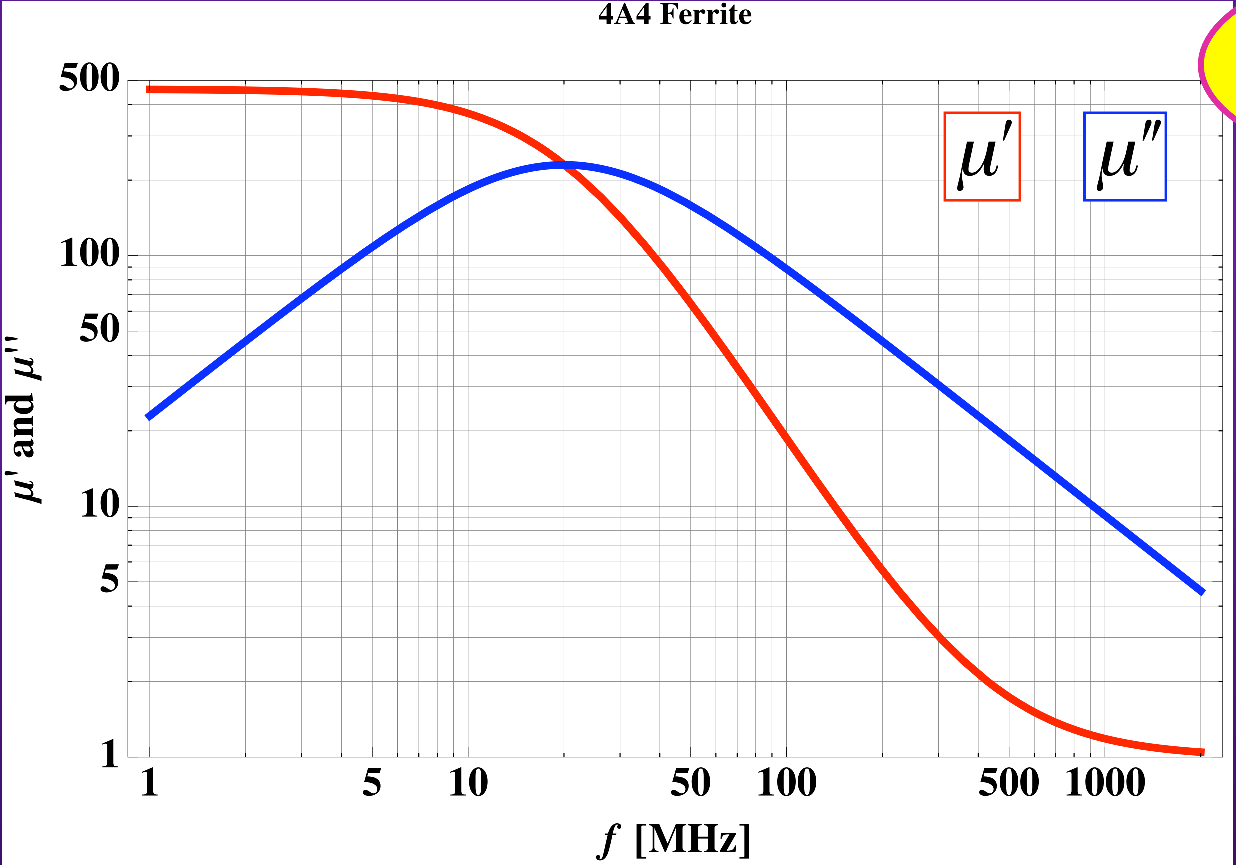
FERRITE: SEVERAL TYPES, CRITERIA & GUIDELINES (2/4)

- Case of the 4A4 ferrite

$$\mu_{rc}\left(f\right) \approx 1 + \frac{460}{1 + j\,\dfrac{f}{2 \times 10^{7}}}$$

$$\varepsilon_{rc}\left(f\right) \approx \varepsilon'$$

The ε'' is usually small and can be neglected

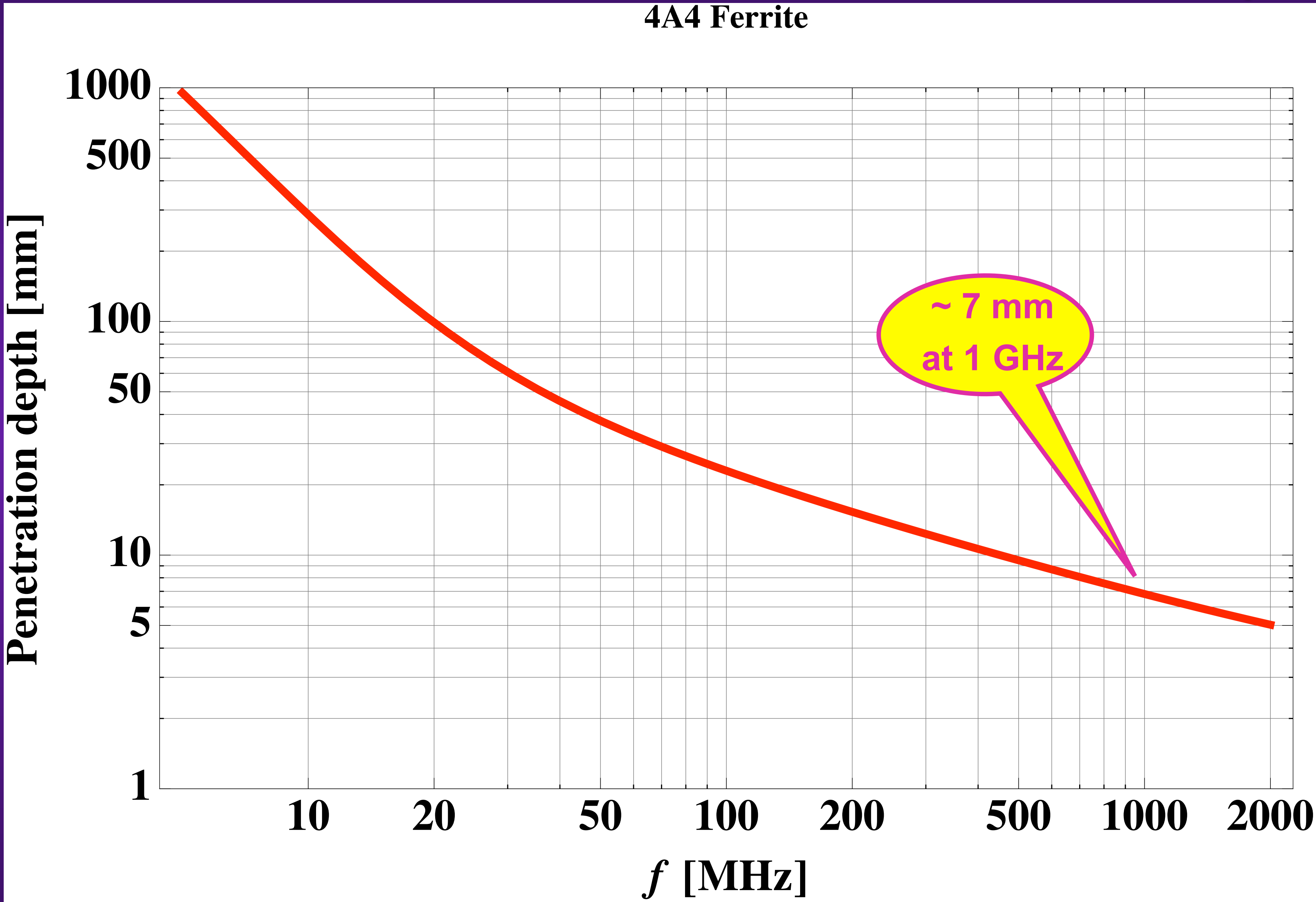


$$\varepsilon' \approx 12$$

$$\sigma \approx 10^{-6}\ S/\mathrm{m}$$

ε_0 vacuum permittivity

FERRITE: SEVERAL TYPES, CRITERIA & GUIDELINES (3/4)



FERRITE: SEVERAL TYPES, CRITERIA & GUIDELINES (4/4)

- To damp a mode at a frequency *f*, a ferrite's thickness equal to the penetration depth at frequency *f* is an upper limit => It is enough to have less, say (as a 1st guideline, but it should be confirmed by simulation for the particular case under study):

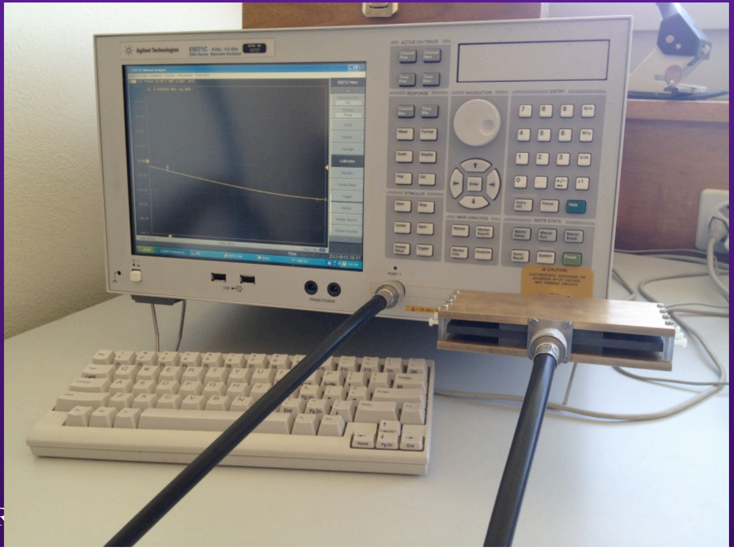
  Ferrite thickness ≈ penetration depth / 2

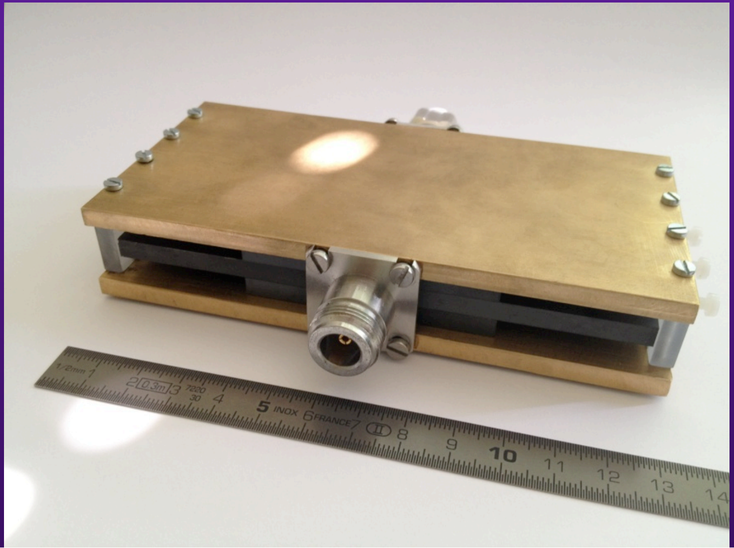
- Example with the previous (fitted) 4A4 ferrite: if one wants to damp a mode at 1 GHz, a thickness of ~ 3-4 mm is OK

- Remarks:
  - Depending on the frequency, one has to optimize the ferrite to be used
  - A lower limit for the ferrite's thickness is given by mechanical considerations => Should be > few mm for ferrite's tiles. For plasma sprayed ferrite (under study to improve heat conduction, see later), the thickness is dictated by the technology (maximum of few hundreds μm)

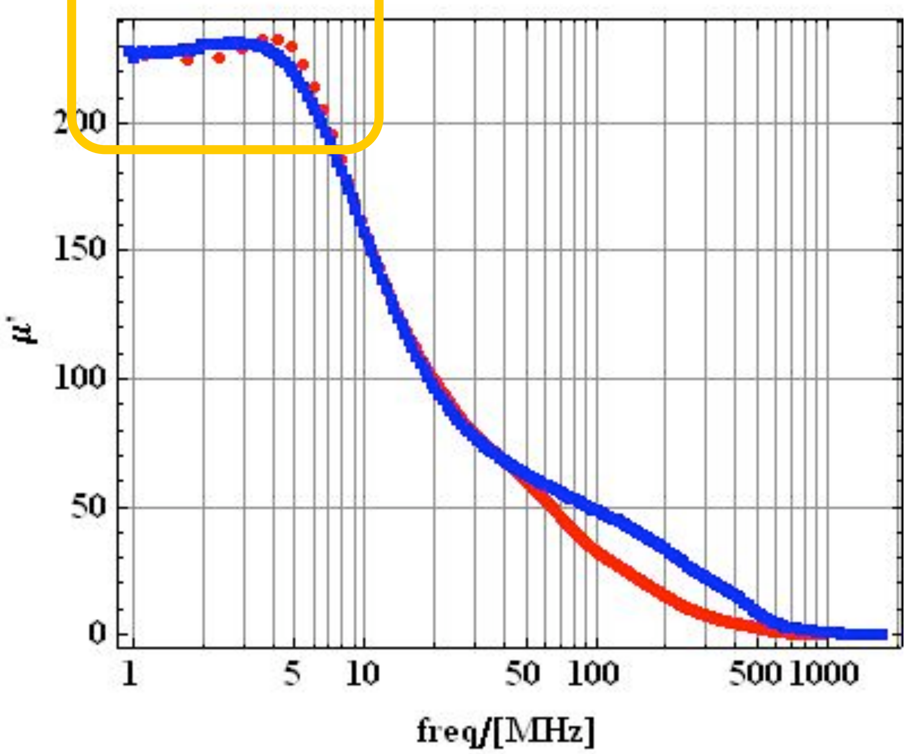
MEASUREMENTS OF THE FERRITE EM PROPERTIES (1/2)

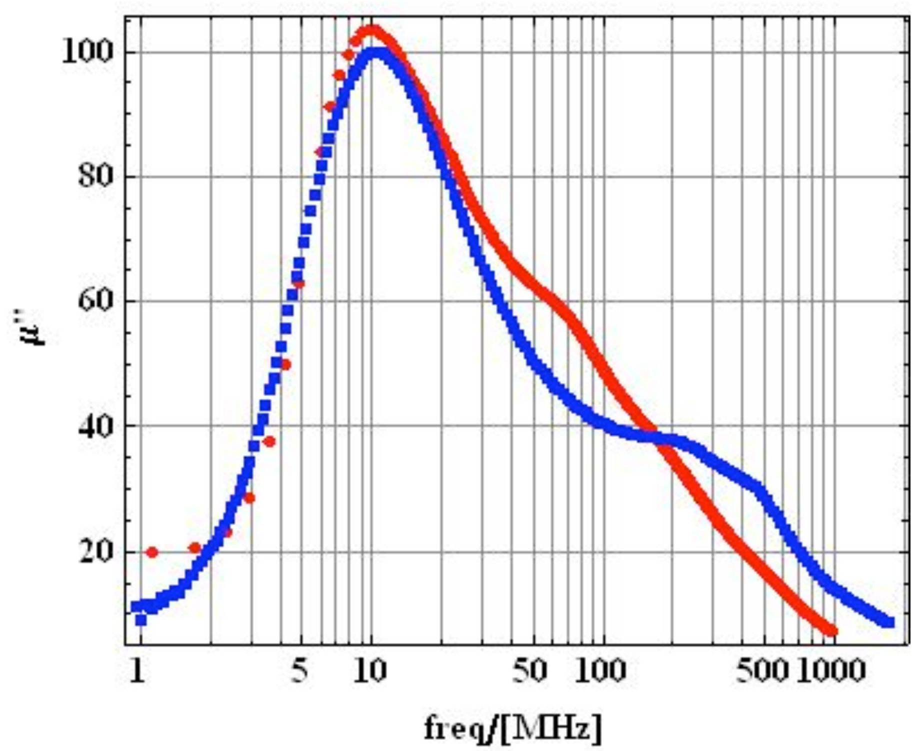
- **Nominated "ferrite responsible persons" at CERN: Fritz Caspers and Christine Vollinger**
- **EM measurements of the TT2-111R ferrite**
  - **This ferrite is readily available in tiles of 6 cm x 6 cm and 5 mm thickness**
  - **Material samples are "wrapped" around an inner conductor**
  - **This allows a non-destructive (transmission & reflection) meas.**
  - **Without any machining of the ferrite => It is much simpler to machine metal than ceramics with adequate accuracy**





MEASUREMENTS OF THE FERRITE EM PROPERTIES (2/2)





Red = Measurement in SH-sample holder

Blue= Measurement provided by TT

FIG. OF MERIT & GUIDELINES FOR FERRITE HEATING (1/6)

- **Goal: Determine figures of merit for the maximum RF induced power on ferrite before T_{Curie} is reached**
- **Several assumptions**

  1) Steady-state regime and uniform ferrite temperature distribution (regardless of actual RF power deposition)

  2) Ferrite tile is of arbitrary cross section

  3) Ferrite radiates from all sides with equal emissivity (0.8)

  4) Completely surrounding heat sink & no intermediate components between ferrite & sink (ferrite view factor equal to 1)

  5) 2D simplification of ferrite tile => Infinitely long geometry (no end effects)

  6) Heat sink with uniform emissivity and temperature

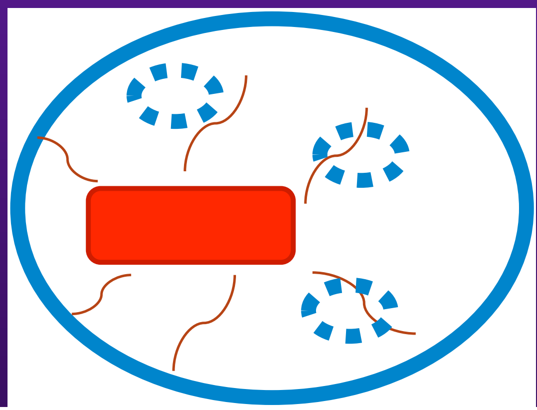
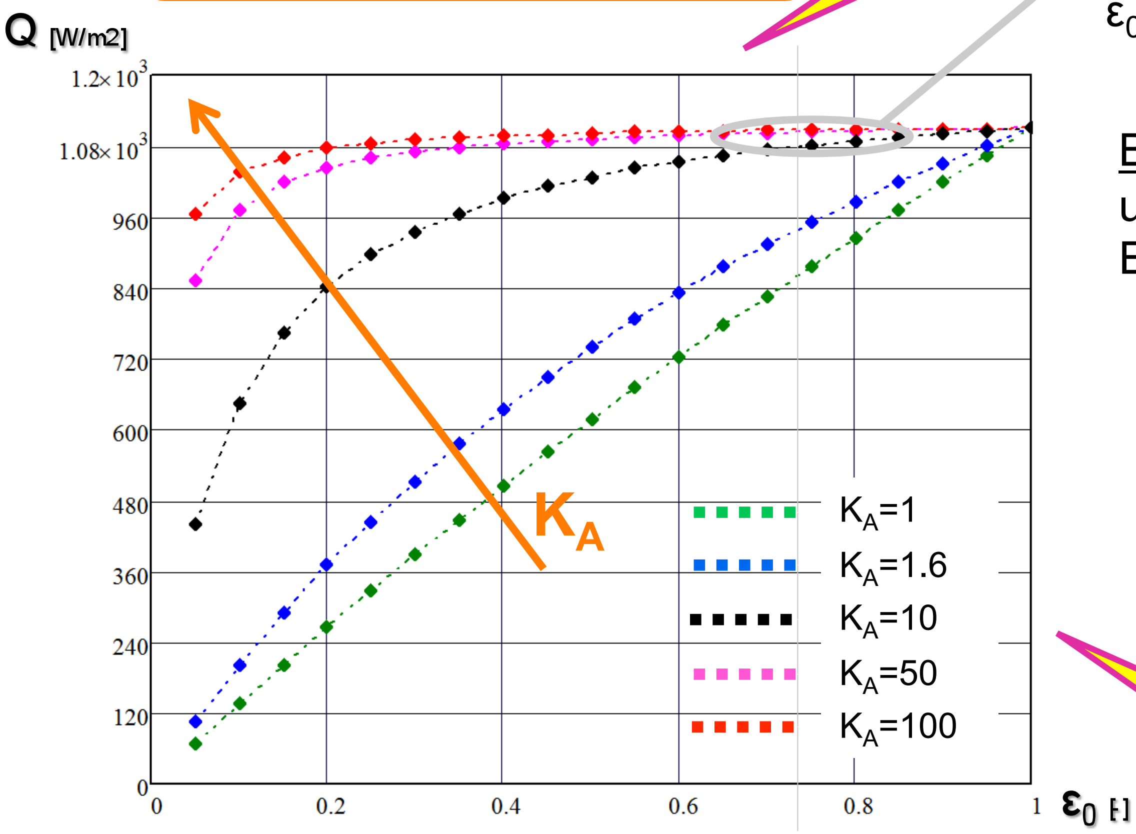


FIG. OF MERIT & GUIDELINES FOR FERRITE HEATING (2/6)

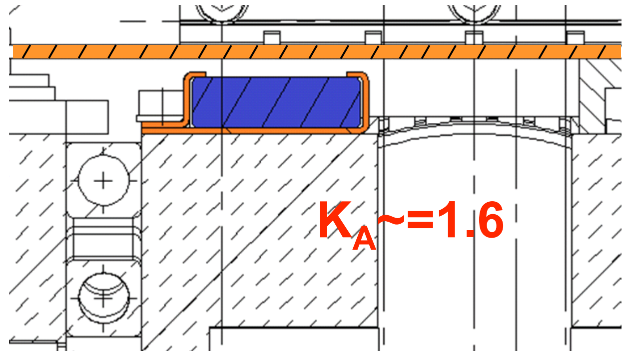
CASE:
$\varepsilon_{FERRITE} = 0.8$
$T_{CURIE} = 150°C$
$T_0 = 22°C$ (i.e. cooled heat sink)

Radiated heat / ferrite surface unit



If K_A is high → no need for very high ε_0

<u>But</u> ferrite needs to be held, i.e. K_A is usually near to one.
E.g. TCTP collimator:



K_A = Surface of the sink / surface of the ferrite

FIG. OF MERIT & GUIDELINES FOR FERRITE HEATING (3/6)

CASE:

$\varepsilon_{FERRITE}$ =0.8

T_{CURIE} = 150°C

T_0=22°C (i.e. cooled heat sink)

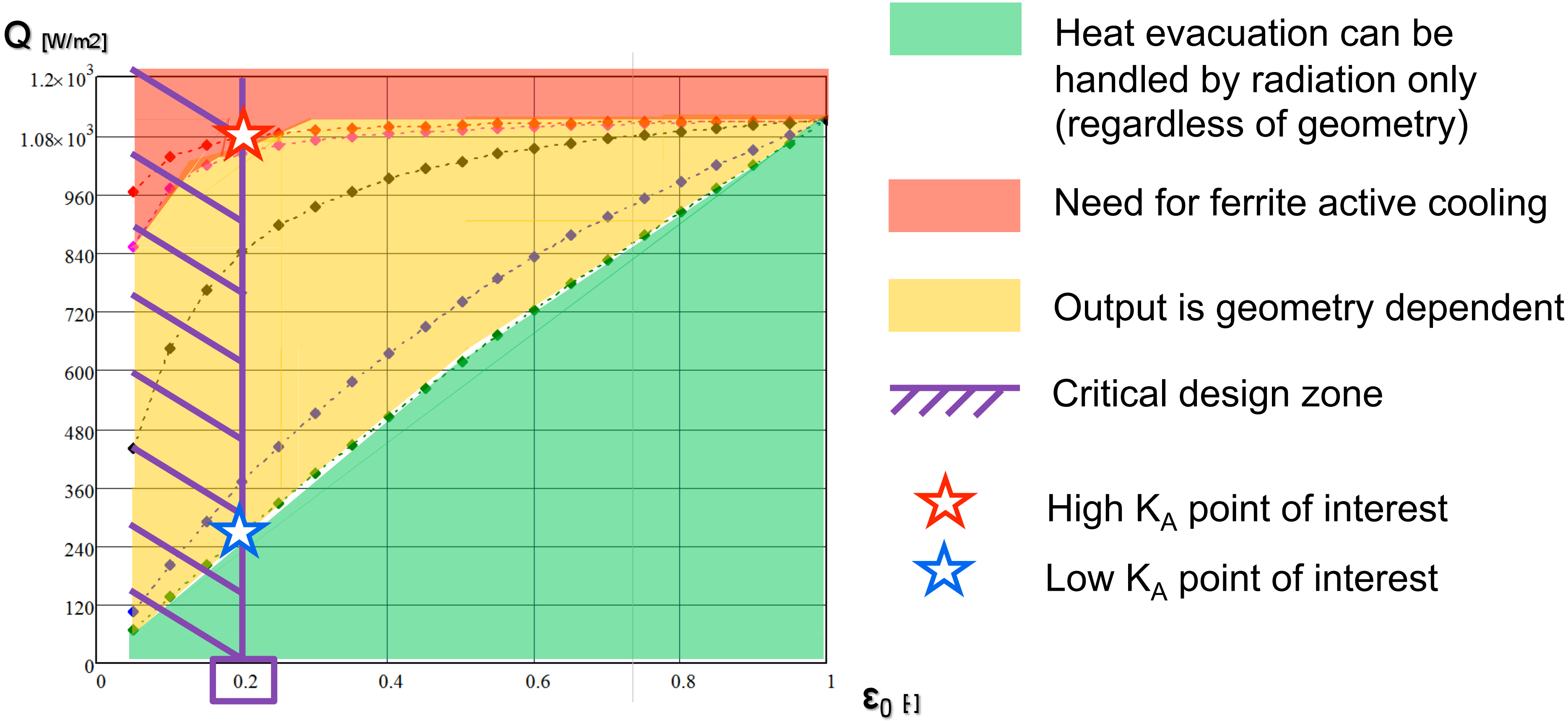


FIG. OF MERIT & GUIDELINES FOR FERRITE HEATING (4/6)

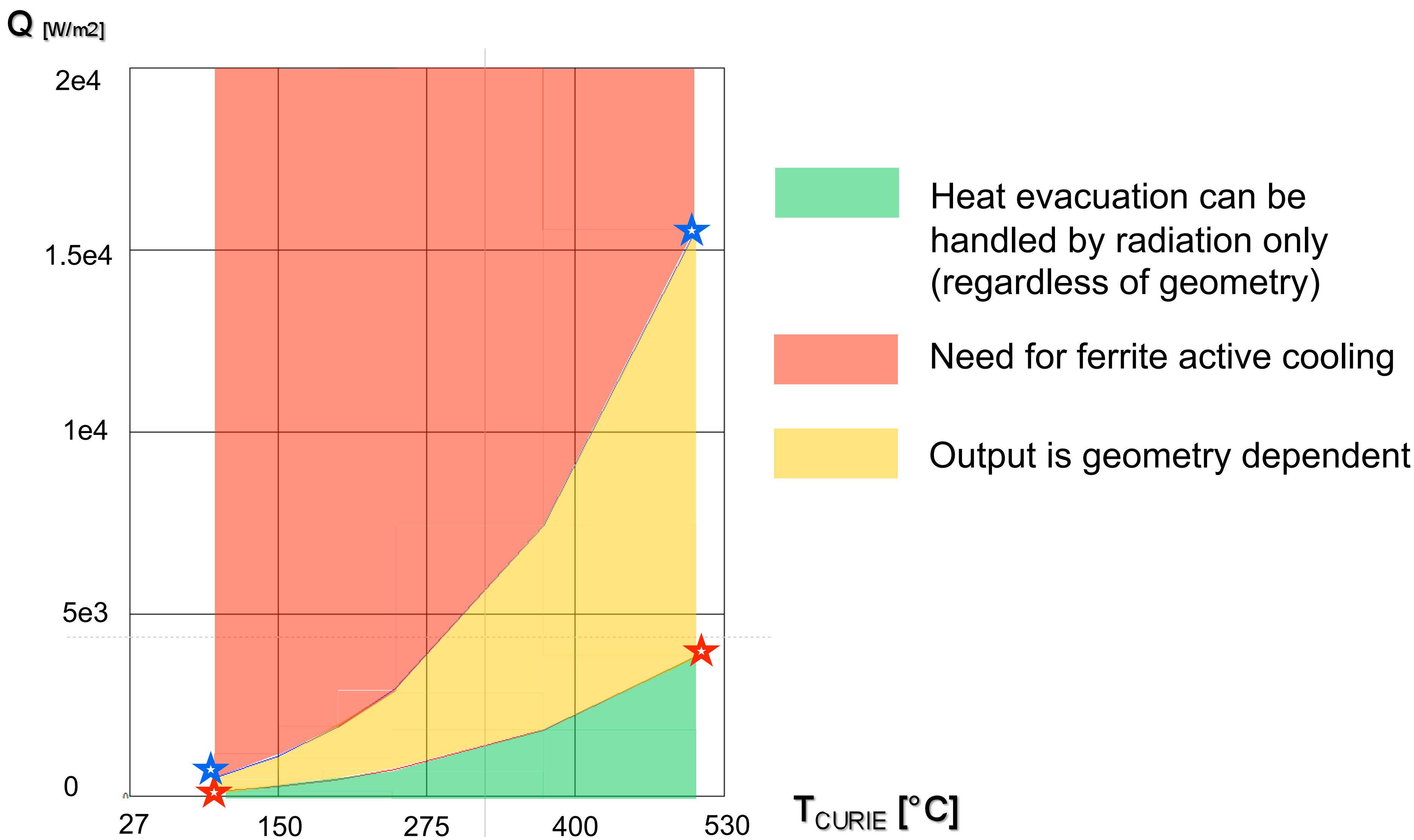


FIG. OF MERIT & GUIDELINES FOR FERRITE HEATING (5/6)

- **How can we cool the ferrite if it becomes too hot?**
  - Try and improve the conduction from ferrite as most of the time only radiation is used (given the general brittleness of the ferrite we cannot apply big contact force/pressure)
  - Plasma spray (for better conduction) => Collaboration with Aachen university (FritzC)

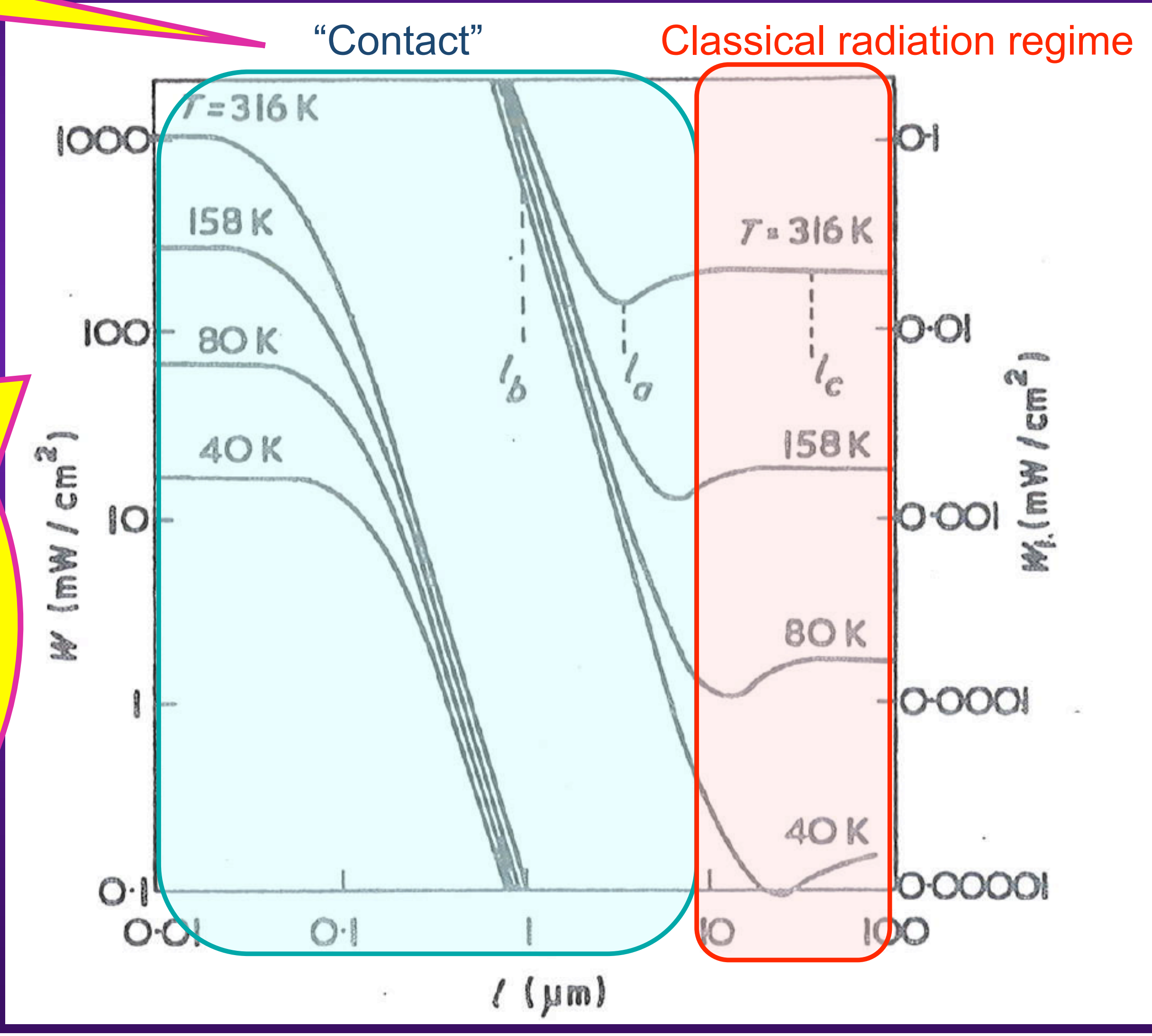
- **Ferrite proposed for TCTP collimators**
  - TT2-111R (Trans-Tech) due to high Curie Temperature of ~ 375˚C
  - Best solution for the support material? Several cases studied: pure copper OFE, SS, copper OFE with CrO coating. The latter is the best choice from the thermal point of view, temperature on ferrite decreased by 25-30% with respect to SS (this reduction could be ~ 40% when the upper screen is also coated with CrO). But, is the chrome coating on copper a potential UFO generator (as black chrome presents a dusty surface, i.e. risk of particles detachment)?

FIG. OF MERIT & GUIDELINES FOR FERRITE HEATING (6/6)

Near-field effects

Infra-red tunneling region

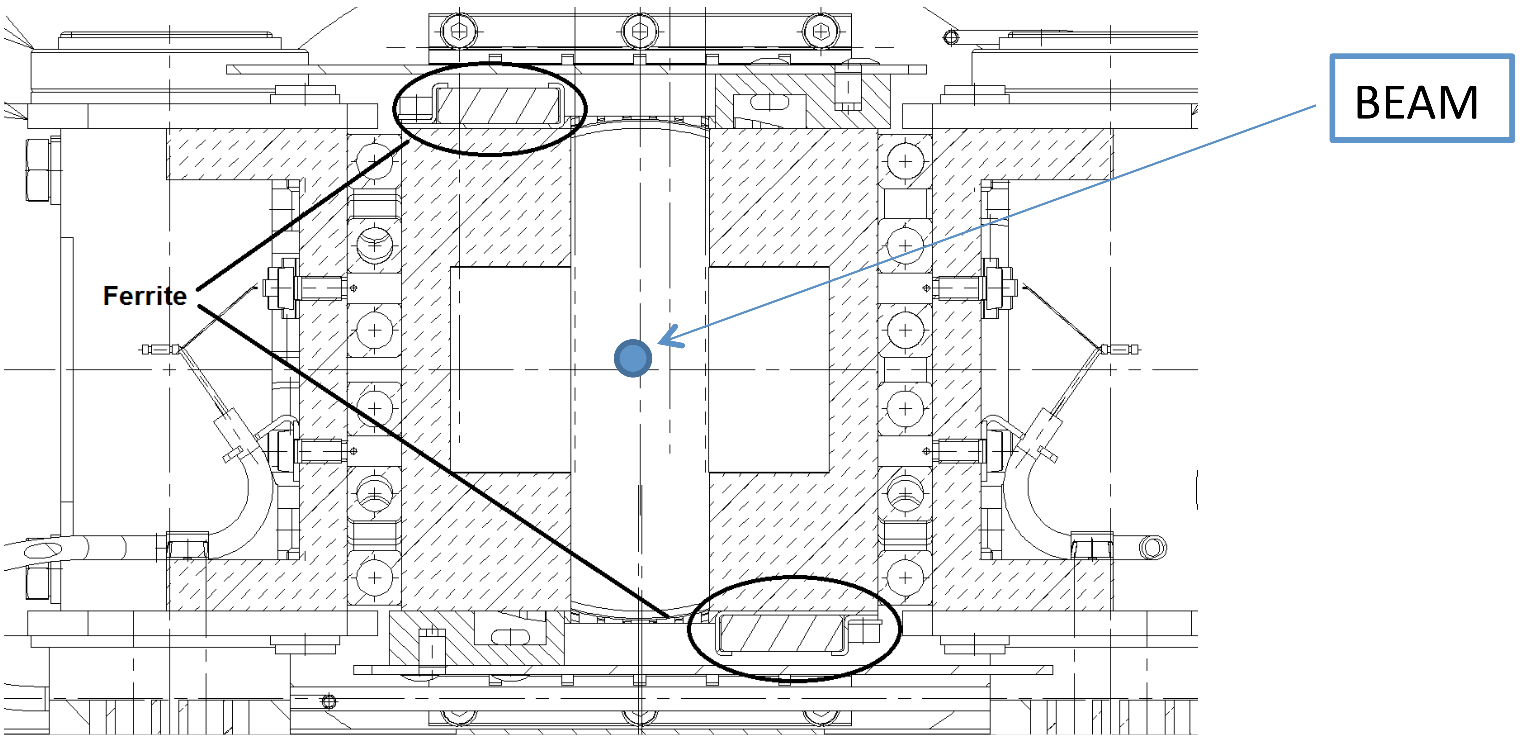
Total radiative transfer between 2 // surfaces spaced by *l* => Smooth transition between radiation and contact regimes. Applying a mechanical pressure, the gap is reduced



MEAS. OF THE FERRITE VACUUM PROPERTIES (1/4)

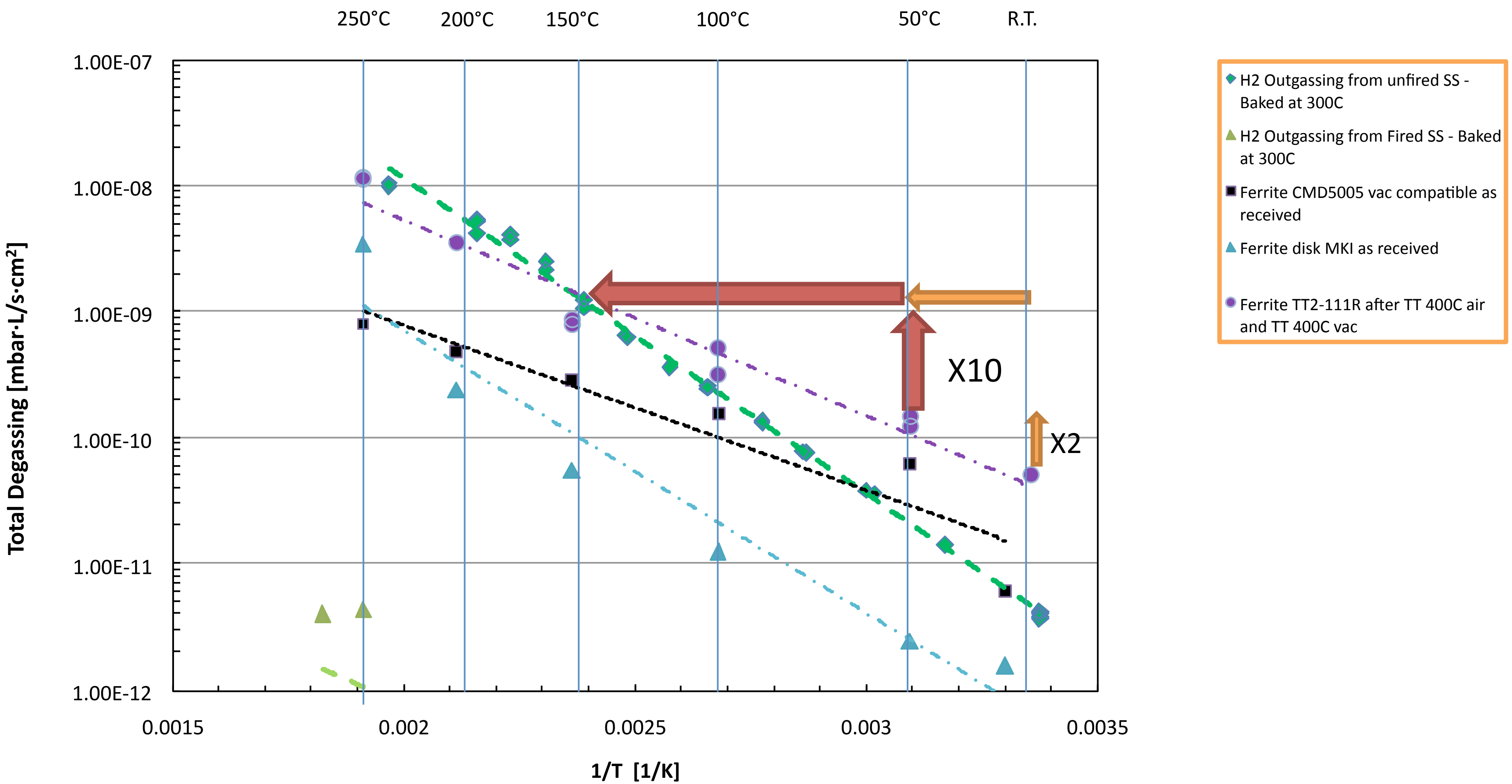
- **The ferrite has to be compatible with UHV => Vacuum approval**
- **Ex. of vacuum (outgassing) measurements of the TT2-111R ferrite**

Cross cut of a TCTP collimator:



Total surface of ferrite per collimator = 1600 cm^2

MEAS. OF THE FERRITE VACUUM PROPERTIES (2/4)



➔Factor 10 gain in outgassing rate for 100°C temperature increase

MEAS. OF THE FERRITE VACUUM PROPERTIES (3/4)

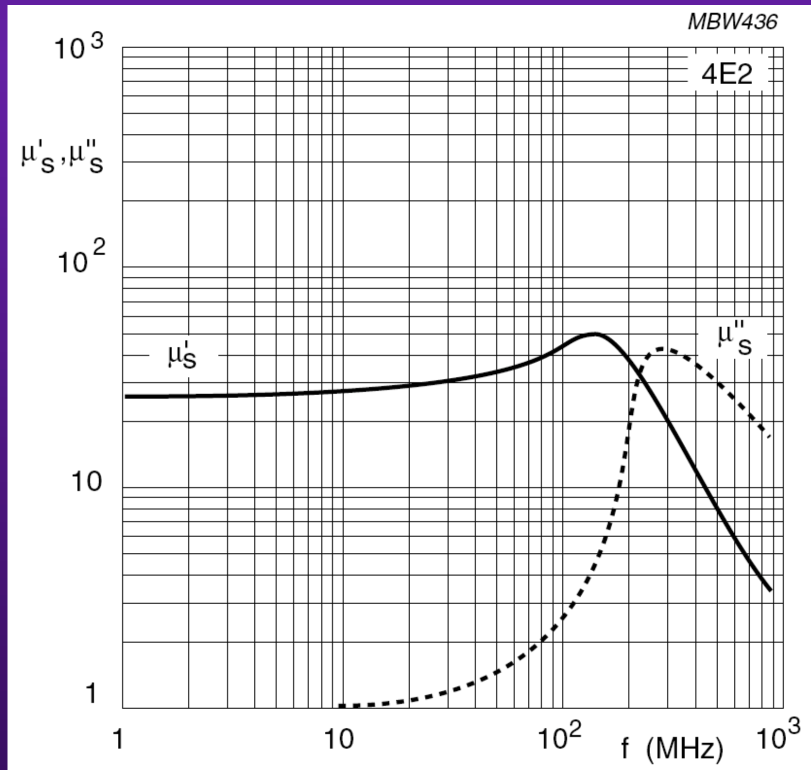
- Scaling this to 1 TCTP collimator, the outgassed flow is close to the LHC vacuum specification limit of 10^{-7} mbar l / s
- RGA (Residual Gas Analyzer) analysis shows no contamination
- The present solution does not present any safety margin in order to remain within the LHC vacuum specification should the ferrite temperature increase

  => VSC proposal: Vacuum test of ferrite with increased thermal treatment temperature (results should not be available before next year)

Very serious finding! Would have thought to be fine due to past experience

MEAS. OF THE FERRITE VACUUM PROPERTIES (4/4)

- **TT2-111R ferrite interesting due to its high Curie temperature (~ 375°C) but the vacuum outgassing studies still need to be finalized**
- **Another ferrite with a high Curie temperature (> 400°C) was recently found (4E2 from Ferroxcube) => Some samples are being ordered to perform some EM and outgassing measurements**



PROS & CONS OF RF FINGERS AND FERRITE (1/2)

RF FINGERS

- Avoid the changes of geometry and therefore the creation of (big) impedances
- Optimization of the material of the RF fingers and the insert (contact resistance, cold welding, etc.)
- Should not restrict the machine aperture (should not fall inside, buckling, etc.)
- Should not go far away from the insert and create gaps (funneling, spring, fixed at both ends, etc.)

=> Biggest worry: assembly and mounting issues

FERRITE

- Here, there are already big impedances created and one wants to damp them
- Ferrite should not be seen directly from the beam (if possible)
- Position of the ferrite depends on the maximum of the magnetic field for the mode one wants to damp => Detailed EM simulations needed
- Ferrite's thickness depends on the penetration depth at the frequency of the mode one wants to damp
- The ferrite will absorb the remaining (normally much smaller) power => Will heat. How to cool it?

PROS & CONS OF RF FINGERS AND FERRITE (2/2)

- Due to some past issues with RF fingers (believed not to be related to impedances) the idea emerged to avoid RF fingers when possible and replace them by ferrite tiles (but there are not doing the same thing!) => For collimators only (transverse RF contacts)
  - Phase II collimators RF design was based on this idea
    - Potential issue with dust creation due to the movement
    - Potential issue with ferrite heating etc. => Studied in detail
    - Potential issue with chrome coating on copper (to reduce the ferrite's temperature) => Potential UFO generator (as black chrome presents a dusty surface)
    - Potential issue with vacuum => Ongoing studies

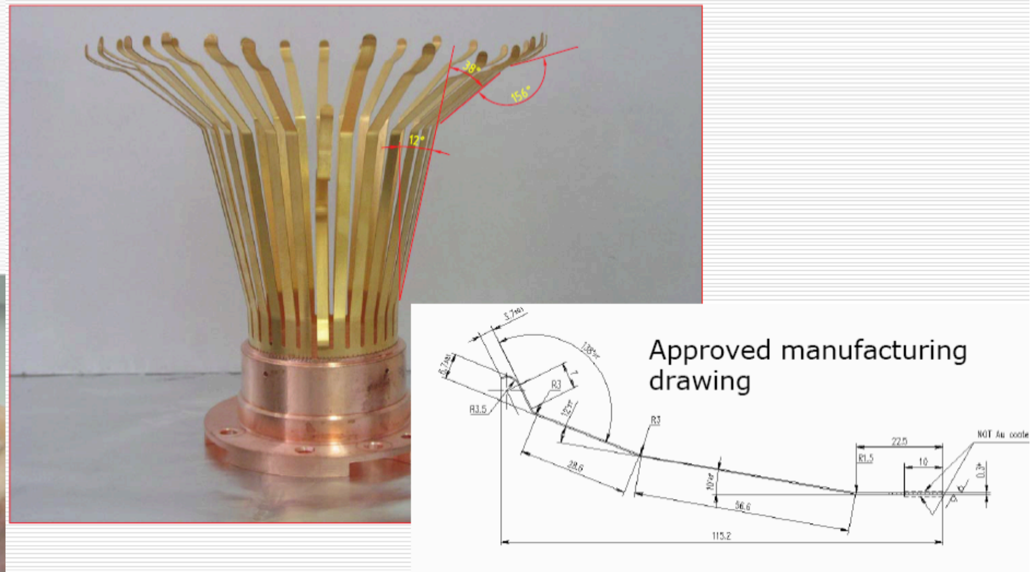
- Why not using ferrite for the PIMs?
  - Ferrite would not work due to the vicinity of magnets
  - The resonance cavity is so high that we don't need to care

WHAT WAS WRONG WITH THE PIMs IN THE COLD PART OF LHC (1/4)

- **August 2007 => After warm-up of sector 7-8, a buckled PIM was discovered in interconnect QQBI.26.R7 with the radar (microwave beam pipe reflectometer)**
- **Was rapidly discovered to be due to a nonconformity during the manufacturing: bending angles out of tolerance. The angle should have been 12 deg (see also next slide)**

QQBI.26R7 line V2

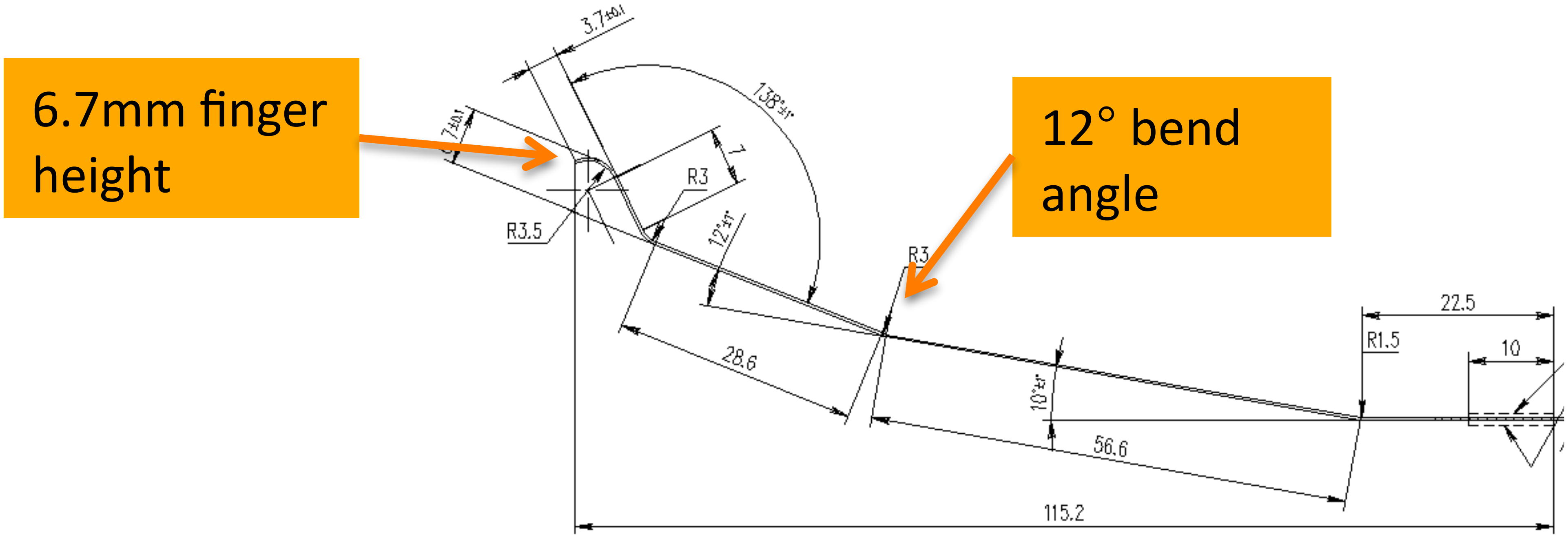
QQBI.26R7 V1 bending angles out of tolerance



WHAT WAS WRONG WITH THE PIMs IN THE COLD PART OF LHC (2/4)

- **The specified electrical contact DC resistance of 0.1 mΩ could not be reached (due to large surface roughness from Rhodium layer)**
- **To compensate it was decided to increase the contact force**

  => The bending angle was modified, which led to buckling issues



WHAT WAS WRONG WITH THE PIMs IN THE COLD PART OF LHC (3/4)

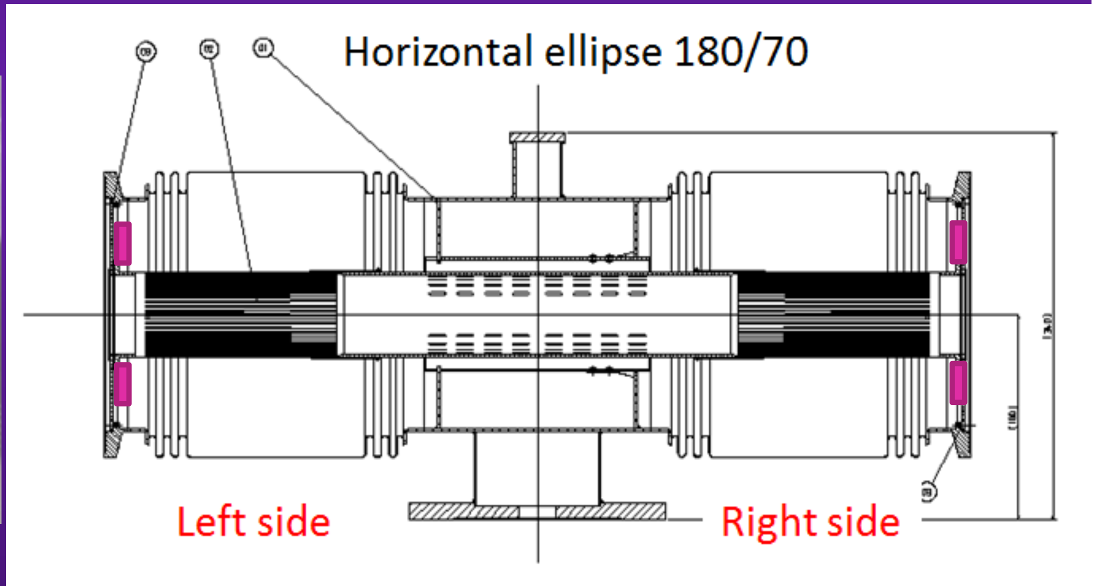
- **Corrective actions taken**
  - A tooling was designed to restore the correct geometry of the fingers => Back to conforming PIM (both angle and finger height at the tip)
  - SSS moved by 2 mm to reduce the span of the QQBI => The stroke is smaller (we have gain 2 mm in the stroke)
- **Summary**
  - The PIM pb was the too high (out of tolerance) electrical DC contact resistance which led to a mechanical pb (to reach the required contact resistance)
  - It has been fully understood
  - Nonconforming PIMs can be repaired
  - Strategy for replacement has been defined and is applied

WHAT WAS WRONG WITH THE PIMs IN THE COLD PART OF LHC (4/4)

- We still have this "Epee de Damocles" each time we will do a warm up we can have buckling
  - Warm-up to room temperature (or even > ~ 150 K) can damage the PIMs => At each Technical Stop the warm-up is done below ~ 150 K to avoid buckling
- Means of detection of damaged PIMS:
  - RF transmitter (the "ball"), pushed by a draft (2 m/s through the sector)
  - The radar (microwave beam pipe reflectometer)

FOLLOW-UP OF VMTSA ISSUES IN 2011 (1/5)

- **Reminder: 10 modules (each of 2 bellows) in total in 2011. 8 bellows were found with defects. 2 modules removed for 2012**
- **Remark 1: No issues have been observed in 2012 (with shorter RF fingers + bent to reduce possible gap + ferrite tiles at both extremities => Final situation close to pictures below)!**



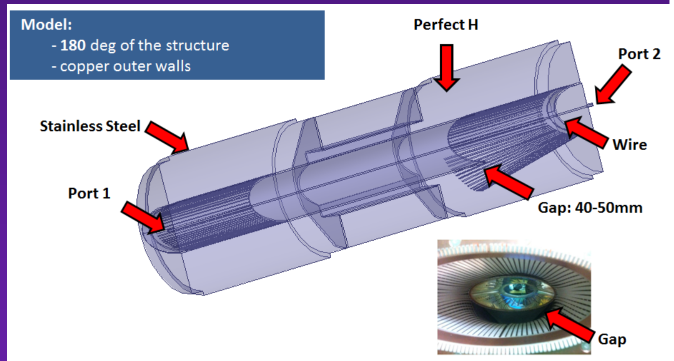
- **Remark 2: After LS1 there will be no VMTSA anymore as the 2-in-1 collimator will be removed (VMTSA used only for 2-beam coll.)**

FOLLOW-UP OF VMTSA ISSUES IN 2011 (2/5)

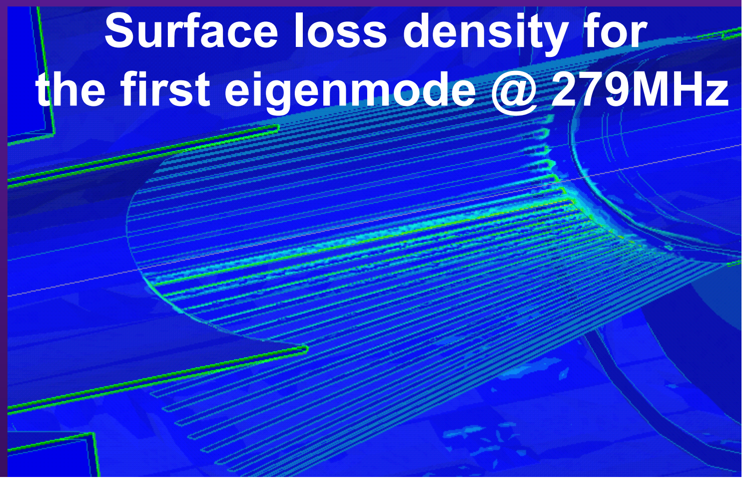
- **Current interpretation of what happened to the VMTSA in 2011**
  - There must have been a heat source in the spring (as it melted whereas it has a higher melting point than the RF fingers)
  - We lost for any reason one or few contacts from RF fingers
  - The induced current which did not go to the 1st (main) contact (due to a gap) went to the 2nd contact (done by the spring) and the spring acted as a fuse
  - Due to the very small cross section of the spring and the too high current density it melted, broke and then released the bottom RF fingers due to gravity
  - A test revealed that ~ 1 W in the spring was sufficient
  - What has been simulated is the validation of what happened after (i.e. with a gap)

FOLLOW-UP OF VMTSA ISSUES IN 2011 (3/5)

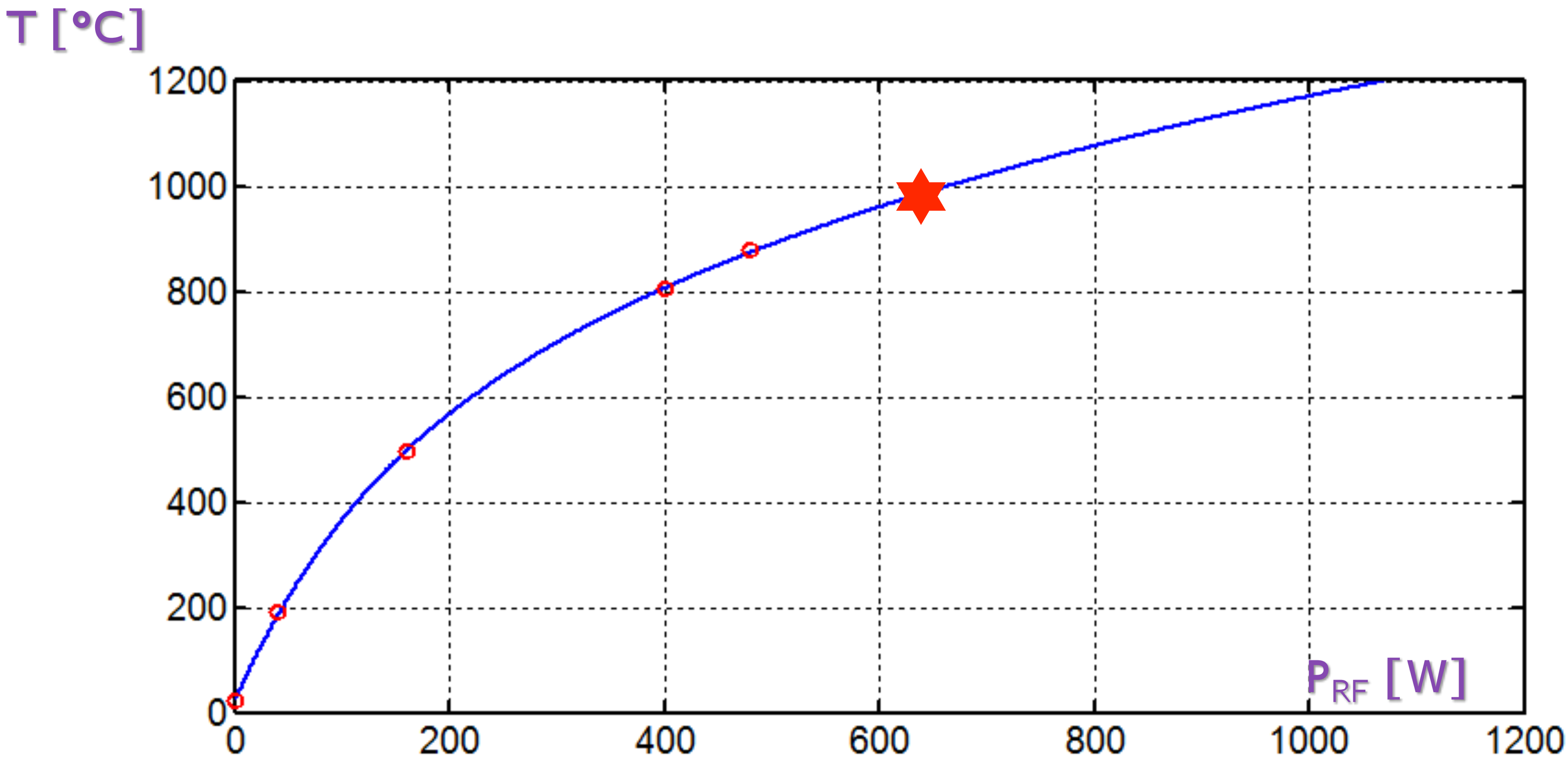
- EM simulations revealed that even a small gap between the RF fingers and the central insert could be fatal for the VMTSA operation => One should avoid "any" gap



- Simulated power deposited for the 2011 case
  - ~ 650 W for a gap of 40 mm
  - ~ 460 W for a gap of 50 mm
- Thermal evolution has been studied to try and answer to 2 questions: Is RF power deposition compatible with expected failure temperatures? Limit for power value?
- Reminder on melting temperatures
  - For 316L spring: ~ 1350°C
  - For CuBe RF fingers: 865°C / 1025°C (C17200 and C17410 respectively)



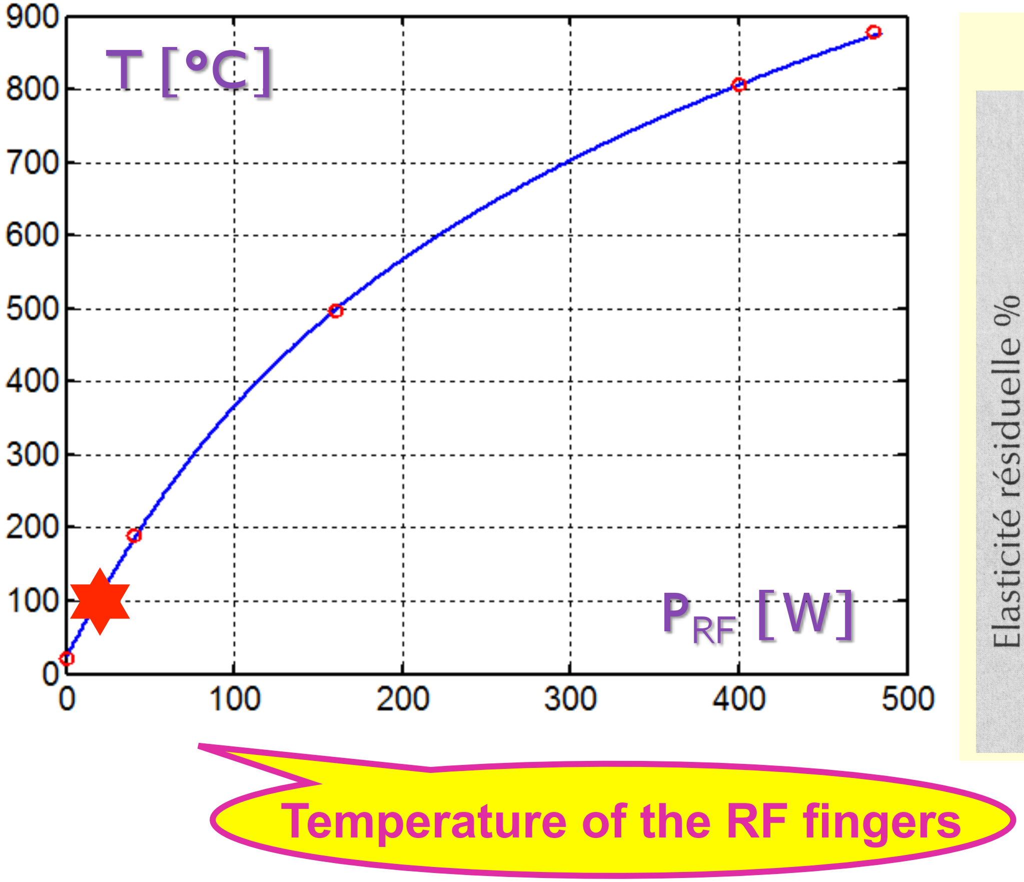
FOLLOW-UP OF VMTSA ISSUES IN 2011 (4/5)



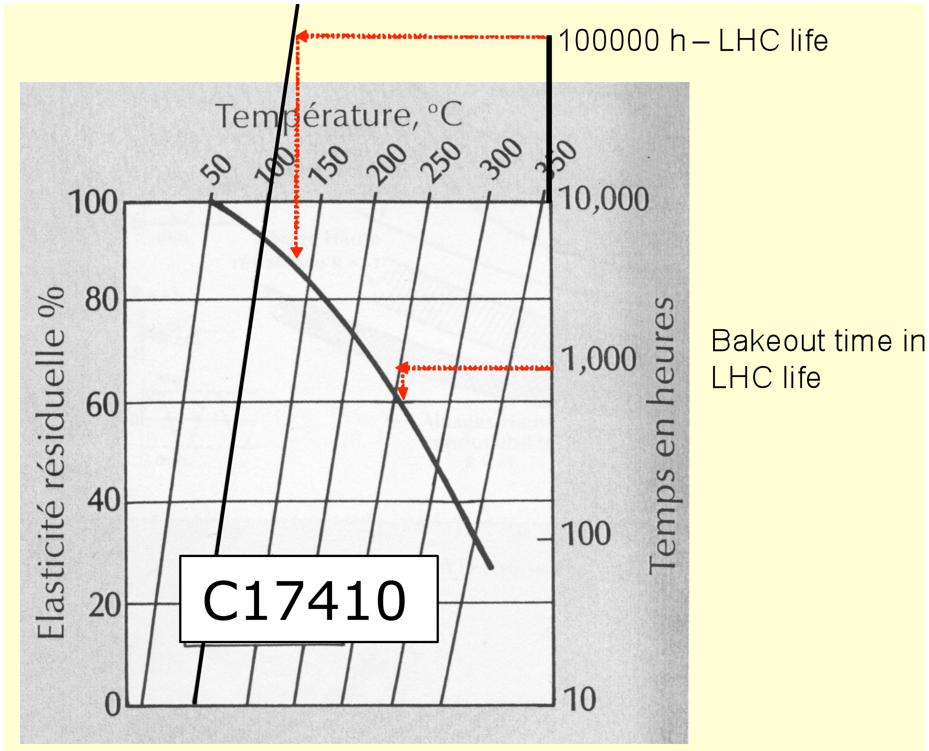
Temperatures expected for 650W (40mm gap)? ***990°C***

Power expected for 1000°C? ***670W***

FOLLOW-UP OF VMTSA ISSUES IN 2011 (5/5)



Stress relaxation resistance (75% stress)



What could be a reasonable Power limit due to fingers failure?

100°C→ $\boldsymbol{P_{RF}=18W}$

CONCLUSIONS AND RECOMMENDATIONS (1/4)

- A lot of experience has been accumulated at CERN over the past decades for the use of RF fingers and/or ferrite absorbers
- This experience needs to be (and will be) summarized in a forthcoming internal report
  - Guidelines for the use of RF fingers
  - Guidelines for the use of ferrite absorbers
- Several designs of RF fingers are used in the LHC depending on the requirements
  - Some have been studied in great detail => Takes time but it paid off! Should really be done at the design stage: material, mechanics, beam-induced power, heat transfer etc.
  - Some less (due to time constraint, missing manpower etc.) but it can lead to big damages or intensity / bunch lengths limitations
  - New design from TE/VSC under checks => Should be carefully evaluated
  - Ferrite can be used in some cases as a back-up for RF fingers but it

CONCLUSIONS AND RECOMMENDATIONS (2/4)

cannot be put like that => Requires detailed EM simulations (knowing the ferrite EM properties) to determine the frequency of the trapped mode(s), the location of maximum of magnetic field (where ideally the relevant ferrite should be put, ideally not seen by the beam) etc.

- Ex: It was found by detailed EM simulations that the ferrite installed during a crash program ~ 1 year ago in the new VMTSA should not be effective as wrongly positioned…

- The VMTSA issues observed in 2011 have been reproduced by simulations and traced back to be due to a gap between some RF fingers and the central insert
  - Any gap is fatal for this equipment!
  - The spring acted as a fuse => Robust mechanical design needed
  - No issue at all this year => Our modifications during last year Xmas break's crash program were sufficient to assure a good contact
- Full list of the 92 nonconformities revealed in warm modules after X-rays campaign => Should be repaired during LS1

CONCLUSIONS AND RECOMMENDATIONS (3/4)

- For the cases studied, we didn't see any problem with impedance for conforming RF fingers => No (big) pb expected for HL-LHC bunch populations (i.e. up to 2.2E11 p/b for the 25 ns beam and 3.5E11 p/b for the 50 ns beam)

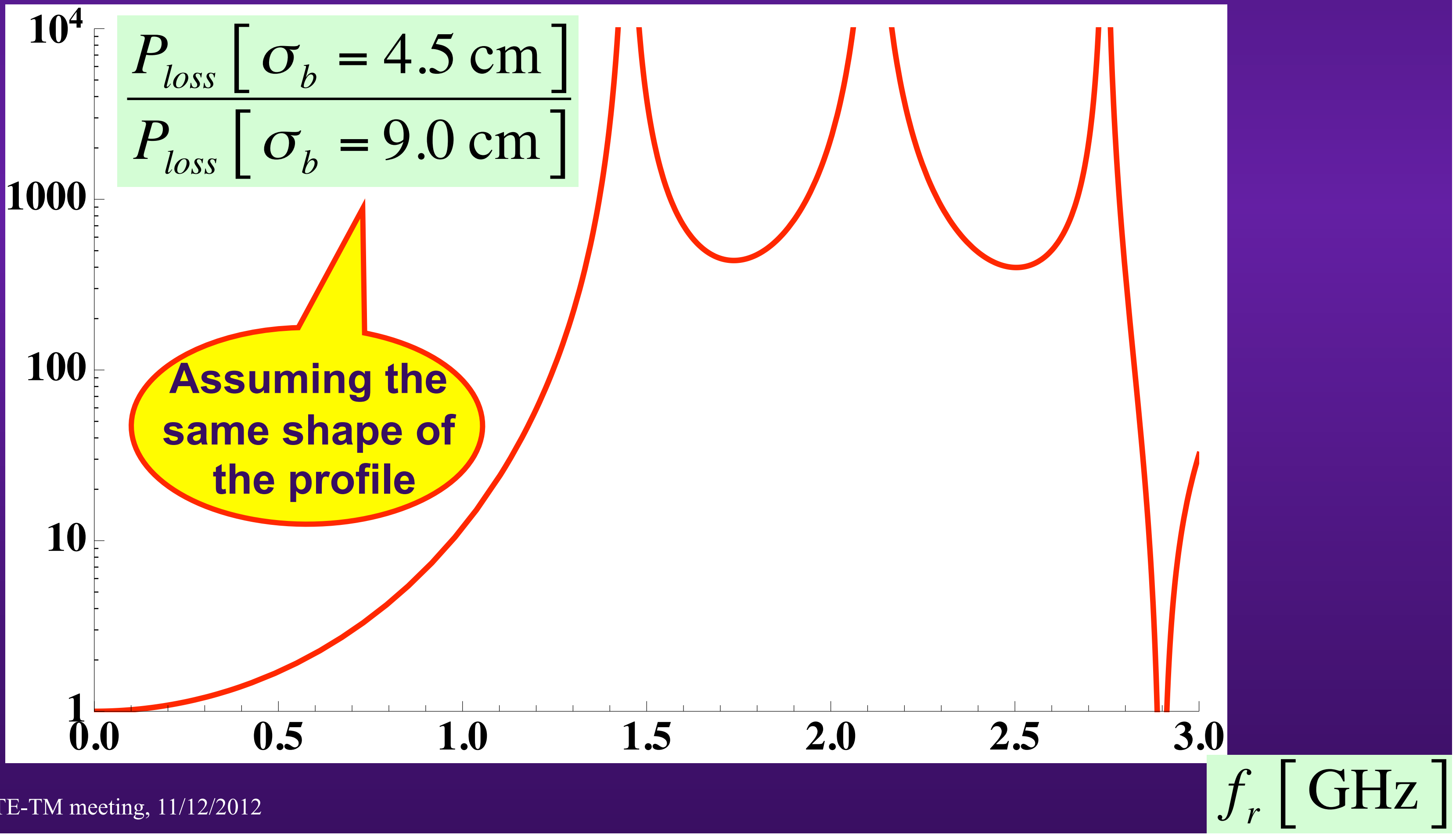
  => Top priority for the future: Robust mechanical design to keep the contacts of all the RF fingers (e.g. with funnel as for the PIMs) + Very careful installation

- The beam-induced RF power loss of a trapped mode scales with the square of the total beam intensity
  - Already done in the machine (1380 50 ns bunches, 1.6E11 p/b): 0.4 A
  - Nominal case (2808 25 ns bunches, 1.15E11 p/b): 0.58 A => Factor 2.1
  - HL-LHC case 1 (2808 25 ns bunches, 2.2E11 p/b): 1.11 A => Factor 7.7
  - HL-LHC case 2 (1404 50 ns bunches, 3.5E11 p/b): 0.89 A => Factor 4.9

Assuming the same bunch length

CONCLUSIONS AND RECOMMENDATIONS (4/4)

- **BUT the big problem is the possible very short bunch of ~ 4 cm**
  - 2012 run made with ~ 10 cm rms bunch length
  - Nominal (rms) bunch length = 7.5 cm (for both LHC and HL-LHC) and ~ 4 cm was also considered for HL-LHC => Needs many careful checks!!



APPENDIX: LIST OF ALL NONCONFORMITIES (1/3)

Satus 3-9-2012

#	LSS	VACSEC	Name	DCUM	nature	niveau de non conformite
1	LSS1	A4L1.C	VMBGG	26525.3832	Ressort hors logement	2
2	LSS1	A4L1.C	VMBGA	26544.2832	Ressort hors logement	2
3	LSS1	A4L1.C	VMBGG	26563.1832	distance recouvrement nulle	2
4	LSS1	A4L1.C	VMCKB	26573.8872	absence de contact, demontage pour echange ressort	2
5	LSS1	A4L1.C	VMCKB	26578.1272	absence de contact, demontage pour echange ressort	2
6	LSS1	A4L1.C	VMCKG	26582.3932	absence de contact, demontage pour echange ressort	2
7	LSS1	A4L1.C	VMCKB	26586.6592	absence de contact, demontage pour echange ressort	2
8	LSS1	A4L1.C	VMCKG	26590.9252	absence de contact, demontage pour echange ressort	2
9	LSS1	B1L1.X	VMAAA	26600.7112	distance recouvrement nulle	2
10	LSS1	A4R1.C	VMCKG	76.016	distance recouvrement nulle	2
11	LSS1	A4R1.C	VMBGA	101.6	Ressort hors logement, doigts deformes et bloques	2
12	LSS1	A4R1.C	VMBGG	133.1	Doigts Rf a l'interieur insert, ressort autour doigts mais hors logement	2
13	LSS1	A4R1.C	VMEGB	139.4	absence d'insert RF	1
14	LSS1	A4R1.C	VMZAW	144.72	absence totale de contact, demontage pour echange ressort	1
15	LSS1	A7R1.R	VMAAE	245.866	Quelques doigts hors ressort	2
16	LSS2	A6L2.B	VAMSF	3139.5124	ressort hors logement	2
17	LSS2	C1L2.X	VMAAA	3263.0624	distance recouvrement nulle	2
18	LSS2	B1R2.X	VMAAA	3401.4584	distance recouvrement nulle	2
19	LSS3	A7L3.R	VMAAE	6425.1158	Ressort hors logement	2
20	LSS3	A4L3.R	VMGLA	6642.3808	distance recouvrement nulle	2
21	LSS3	IP3.R	VMGLA	6686.8608	Ressort hors logement, doigt au milieu (!?)	1
22	LSS4	A7L4.R	VMAAB	9743.6662	Ressort hors logement	2
23	LSS4	A7L4.R	VMAAE	9780.1662	Ressort hors logement	2
24	LSS4	E5L4.R	VMAAA	9881.6222	distance recouvrement nulle	2
25	LSS4	B5L4.B	VMADE	9963.7292	insert Rf inverses	3
26	LSS4	B5L4.B	VMADF	9973.1992	insert Rf inverses	3
27	LSS4	B5L4.R	VMADE	9973.1992	insert Rf inverses	3
28	LSS4	B5R4.R	VMADF	10020.6632	insert Rf inverses	3
29	LSS4	B5R4.R	VMADE	10030.1332	insert Rf inverses	3
30	LSS4	B5R4.B	VMADE	10020.6632	insert Rf inverses	3

APPENDIX: LIST OF ALL NONCONFORMITIES (2/3)

31	LSS4	D5R4.B	VMAAB	10056.0122	distance recouvrement nulle	2
32	LSS4	D5R4.B	VMBGA	10063.3122	ressort hors logement, leger flambage interne des doigts	1
33	LSS4	D5R4.R	VMAAF	10063.1472	ressort hors logement	2
34	LSS4	E5R4.B	VMAAE	10084.9402	ressort hors logement, leger flambage interne des doigts	1
35	LSS4	E5R4.R	VMAAF	10084.9402	ressort de traction hors logement, doigts deformes	2
36	LSS4	E5R4.R	VMANC	10114.1402	doigts RF formant cavite vers l'exterieur	1
37	LSS4	A7R4.B	VMAAB	10176.6962	Ressort hors logement,deformation, distance nulle	2
38	LSS5	A6L5.R	VM_XRPT1	13109.58	pas d'insert RF a l'interieur (pot romain)	3
39	LSS5	A6L5.R	VM_XRPT2	13115.58	pas d'insert RF a l'interieur (pot romain)	3
40	LSS5	A5L5.B	VMANC	13137.7346	inser Rf inverses	3
41	LSS5	A5L5.B	VMAAF	13148.3286	ressort hors logement, qq doigts deformes et coinces dans soufflet	2
42	LSS5	A5L5.B	VMACB	13154.3186	ressort hors logement	2
43	LSS5	B4L5.R	VM_XRPT1	13179.1	pas d'insert RF a l'interieur (pot romain)	3
44	LSS5	B4L5.R	VM_XRPT2	13180.33	pas d'insert RF a l'interieur (pot romain)	3
45	LSS5	A4L5.C	VMBGG	13208.5416	distance recouvrement nulle	2
46	LSS5	A4L5.C	VMBGG	13221.1416	distance recouvrement nulle	2
47	LSS5	A1L5.X	VBX	1330811.16	absence de ressort, distance recouvrement nulle	2
48	LSS5	A4R5.C	VMBGA	13431.0416	absence ressort, qq doigts Rf coinces dans ondulations	2
49	LSS5	A4R5.C	VMBGA	13443.6416	absence ressort, qq doigts Rf coinces dans ondulations	2
50	LSS5	A4R5.C	VMEGB	13468.8416	vide !	1
51	LSS5	B4R5.B	VM_XRPT1	13478.52	pas d'insert RF a l'interieur (pot romain)	3
52	LSS5	B4R5.B	VM_XRPT2	13479	pas d'insert RF a l'interieur (pot romain)	3
53	LSS5	A5R5.B	VMAAF	13510.2546	distance recouvrement nulle	2
54	LSS5	A5R5.B	VMACC	13521.4656	ressort hors logement, leger flambage interne des doigts	1
55	LSS5	A6R5.B	VM_XRPT1	13544.21	pas d'insert RF a l'interieur (pot romain)	3
56	LSS5	A6R5.B	VM_XRPT2	13549.28	pas d'insert RF a l'interieur (pot romain)	3
57	LSS6	C5L6.R	VMAAB	16442.47	flambage externe	2
58	LSS6	C5L6.R	VMAAF	16426.357	reduction ouverture	1
59	LSS6	C5L6.R	VMAND	16449.77	1 doigt Rf hors logement	3
60	LSS6	A5L6.B	VMADE	16485.494	insert Rf inverses	3

APPENDIX: LIST OF ALL NONCONFORMITIES (3/3)

61	LSS6	A4L6.B	VMZAN	16538.022	doigts bloques, leger flambage interne des doigts	1
62	LSS6	A4L6.R	VMTAB	16516.662	flambage externe des doigts	1
63	LSS6	A4L6.R	VMZAM	16542.266	distance recouvrement nulle	2
64	LSS6	A4L6.R	VMZAD	16558.383	distance recouvrement nulle	2
65	LSS6	IP6.R	VMAAF	16617.527	correction alignement	3
66	LSS6	IP6.R	VMSDU	16624.827	vide !	1
67	LSS6	IP6.R	VMSDO	16698.477	vide !	1
68	LSS6	IP6.R	VMZAK	16707.212	Ressort hors logement,deformation extremite doigt	2
69	LSS6	IP6.B	VMSDO	16624.827	vide !	1
70	LSS6	IP6.B	VMSDR	16664.107	absence de contact	1
71	LSS6	IP6.B	VMSDU	16698.477	vide !	1
72	LSS6	IP6.B	VMAAB	16708.247	Ressort hors logement,deformation extremite doigt	2
73	LSS6	A4R6.B	VMZAD	16764.871	correction alignement	3
74	LSS6	A4R6.B	VMTAB	16813.792	doigts coinces entrainant un flambage externe	1
75	LSS6	A4R6.R	VMZAN	16776.314	ressort hors logement	2
76	LSS6	A4R6.R	VMAAB	16804.472	ressort hors logement	2
77	LSS6	A5R6.B	VMAND	16837.82	extremite doigts Rf deforme	3
78	LSS6	A5R6.B	VMANC	16866.17	ressort hors logement	2
79	LSS6	C5R6.B	VMAAF	16884.847	plusieurs doigts non tenu par ressort, leger flambage interne	2
80	LSS6	E5R6.R	VMACD	16927.887	ressort hors logement	2
81	LSS7	IP7.R	VMTQB	19997.9624	flambage plusieurs doigts	1
82	LSS7	IP7.R	VMAND	20035.2624	Insert inverses sur VAGLC	3
83	LSS7	A5R7.B	VMTQB	20089.1584	ressort hors logement	2
84	LSS7	B5R7.B	VMGLA	20115.0334	absence de ressort - recouvrement nul	2
85	LSS7	A7R7.B	VMACC	20251.9914	ressort hors logement - doigts Rf dans ondulations soufflet	1
86	LSS7	A7R7.R	VMACD	20251.9914	ressort hors logement - doigts Rf dans ondulations soufflet - absence contact	1
87	LSS8	A6L8.B	VMACC	23137.5178	distance recouvrement nulle	2
88	LSS8	B1L8.X	VMAAA	23246.0048	distance recouvrement nulle	2
89	LSS8	B1R8.X	VMAAA	23384.4008	distance recouvrement nulle	2
90	LSS8	A6R8.B	VMANC	23494.8128	absence totale de contact, flambage externe	1
91	LSS8	A6R8.R	VMSIN	23507.8508	ressort hors logement	2
92	LSS8	A6R8.R	VMACC	23552.0568	ressort hors logement, doigts deformes	2