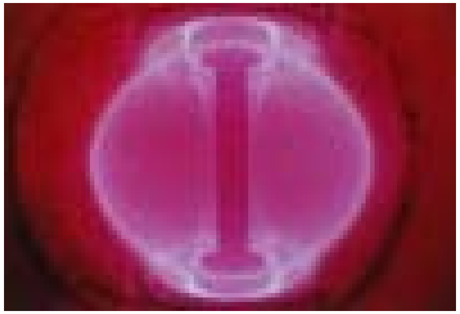
Göran Eriksson, ABB Corporate Research / COMSOL Conference 2009, Milan, Italy

Modeling of Complex Structures in Electromagnetic Technology

Professional background



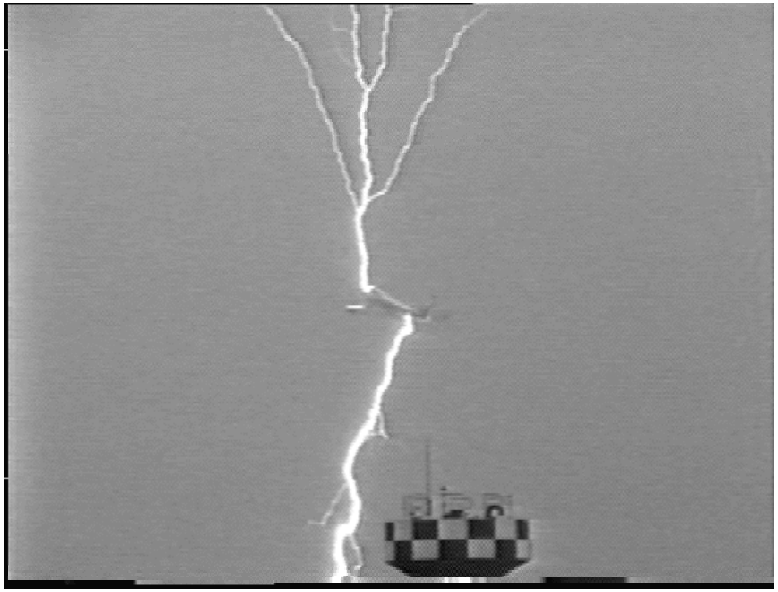
- Academic research in fusion plasma physics (Uppsala University, Sweden). MagnetoHydroDynamic (MHD) modeling.

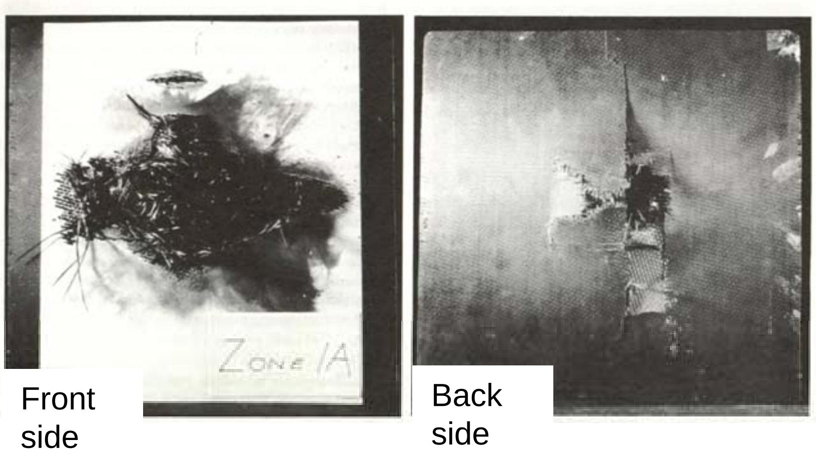
- Electromagnetics specialist at Saab (aircraft and defense) in Linköping, Sweden. ElectroMagnetic Compatibility (EMC), Lightning protection and antennas.

- Since August 2008 with ABB Corporate Research, Västerås, Sweden. Computer simulation of electromagnetic phenomena in high voltage/current products for power transmission systems.

Thermal lightning damage in complex material aircraft structure (1) (With Saab and FMV)

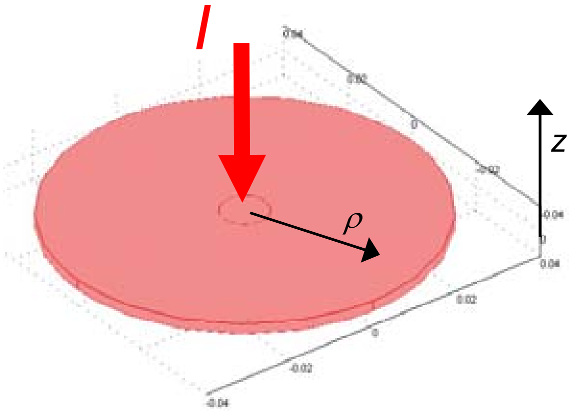
- Modern aircraft are built using composite materials having electric conductivity 1000 times lower than traditional aluminum structures
- Lightning damage due to heating is therefore much more severe
- Extreme edges and corners covered by radar absorbing coatings are particularly vulnerable (this is also where the probability for lightning attachment is the highest).





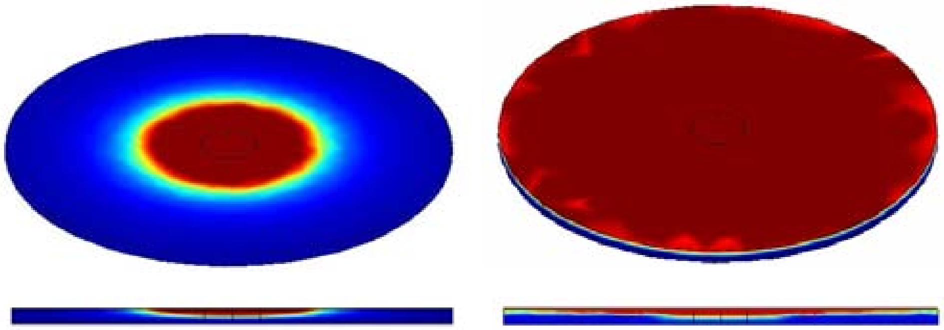
Taken from *Lightning Protection of Aircraft* by Fisher, Perala and Plumer

Thermal lightning damage in complex material aircraft structure (2)



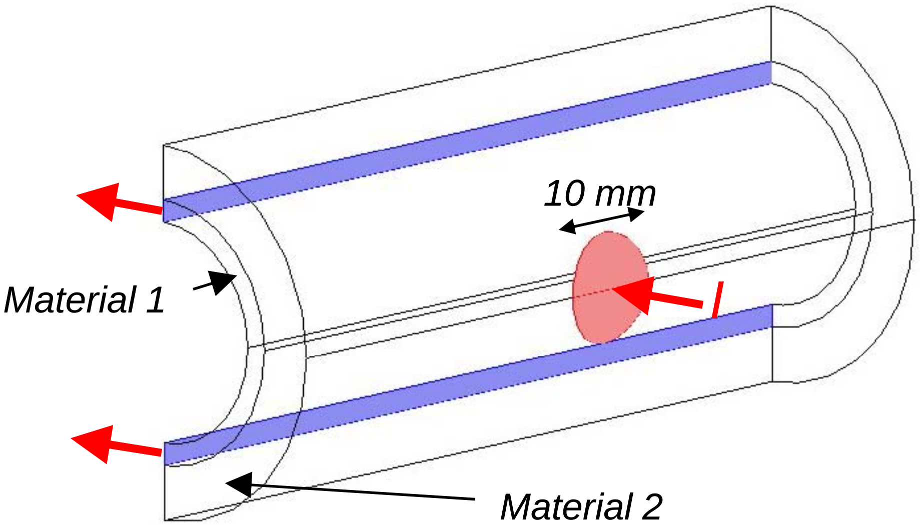
- Validation against experiments made by British Aerospace
- Composite material strongly anisotropic
- 3D COMSOL simulation with radiation heating from the plasma column included gives perfect match to measured damage on test panel

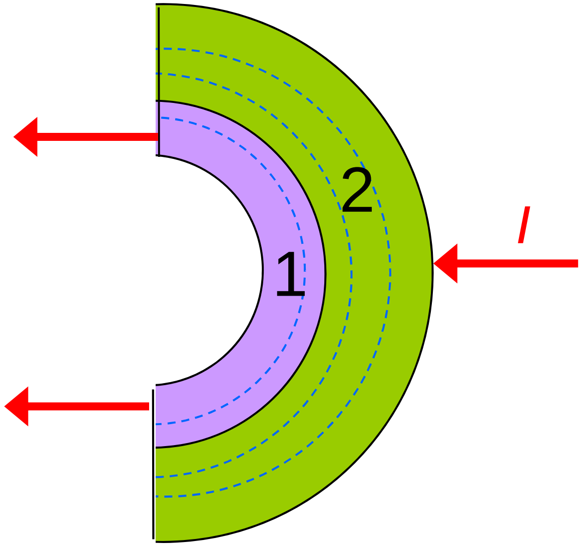
	Damage radius (mm)	Damage depth (mm)
Experiment (BAe)	45 ± 15	0,5 - 0,7
3D COMSOL MP simulation. No radiation heating	13	0,7
3D COMSOL MP simulation. With radiation heating	40 - 50	0.7



Final temperature distribution without (left) and with (right) radiation heating included

Thermal lightning damage in complex material aircraft structure (3)



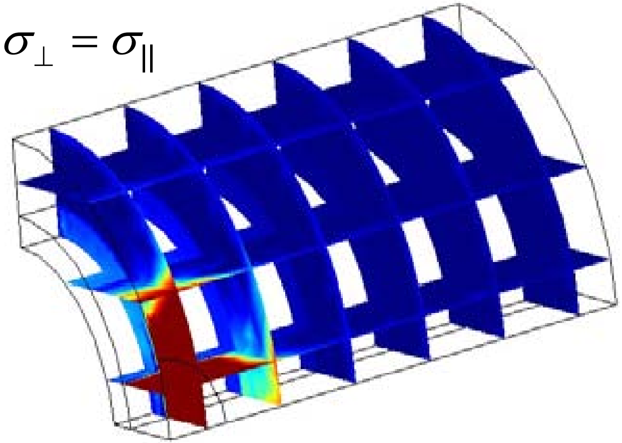


- 3D model of a wing leading edge made up of two different radar-absorbing materials having strongly anisotropic electric and heat conductivities

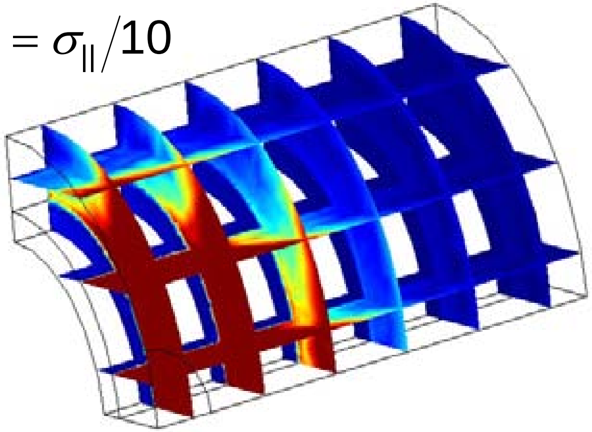
$$\vec{\sigma} = \begin{pmatrix} \left(\dfrac{\sigma_\perp x^2 + \sigma_{||} y^2}{x^2 + y^2}\right) & (\sigma_\perp - \sigma_{||})\dfrac{xy}{x^2 + y^2} & 0 \\ (\sigma_\perp - \sigma_{||})\dfrac{xy}{x^2 + y^2} & \left(\dfrac{\sigma_\perp y^2 + \sigma_{||} x^2}{x^2 + y^2}\right) & 0 \\ 0 & 0 & \sigma_{||} \end{pmatrix}$$

Thermal lightning damage in complex material aircraft structure (4)

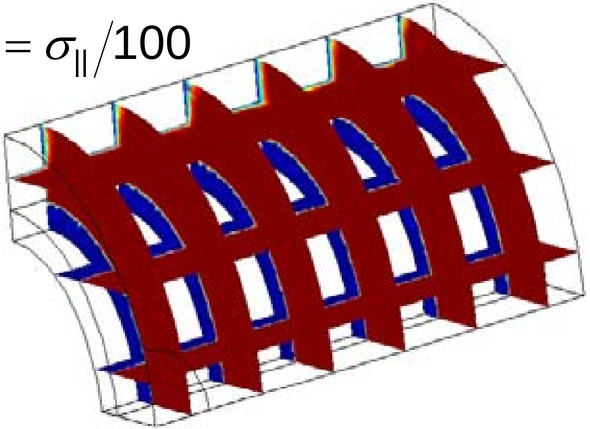
- Temperature rise due to an injected lightning current pulse
- Material 1 and 2 different with $\sigma^{(1)}_{\perp,\|} = 100 \cdot \sigma^{(2)}_{\perp,\|}$
- Dark red colour denotes regions where the resin has vaporized, i.e. where the temperature has reached T_{max} = 300 °C



$\sigma_\perp = \sigma_\|$

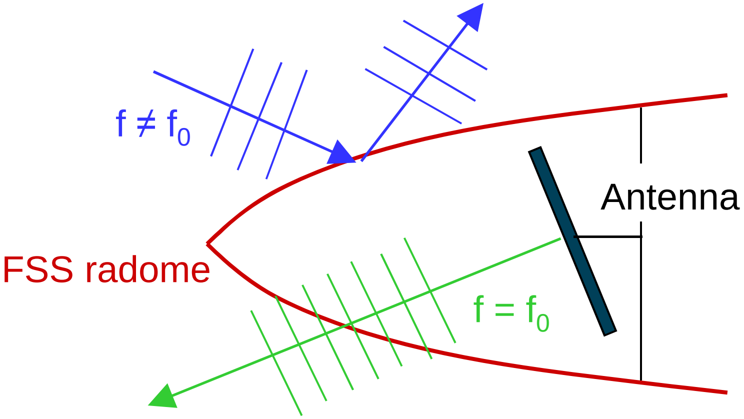


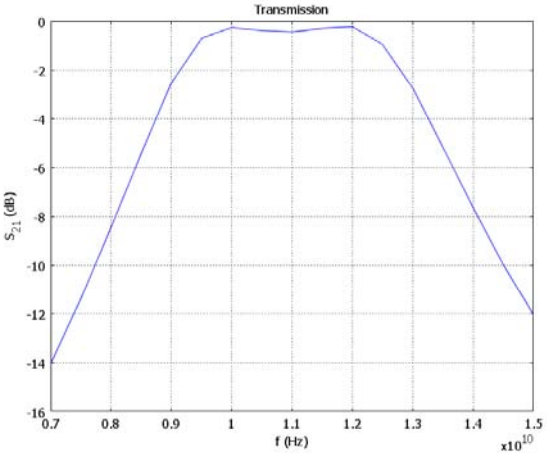
$\sigma_\perp = \sigma_\| / 10$



$\sigma_\perp = \sigma_\| / 100$

Developing robust Frequency Selective Surface radome structures (1) (With Saab, ACAB and FMV)



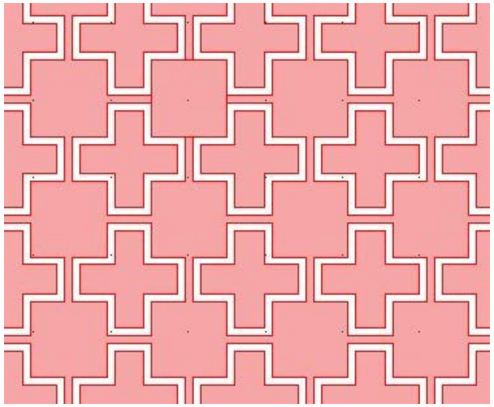


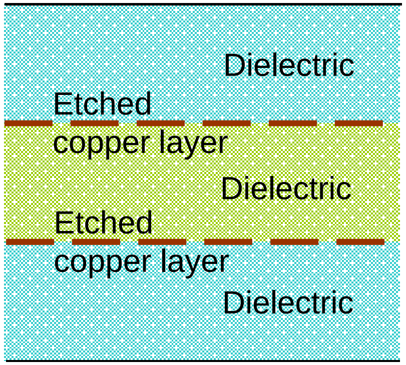
Transmission passband around $f = f_0$ = 11 GHz

- A Frequency Selective Surface (FSS) radome is transparent to your own radar beam at the frequency $f = f_0$
- At other frequencies it acts as a solid metallic surface in order to reduce the radar cross section for enemy radars

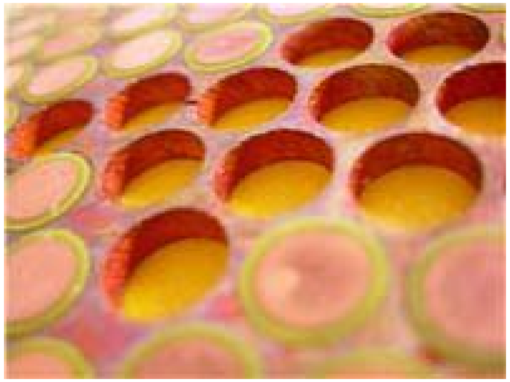
Developing robust Frequency Selective Surface radome structures (2)

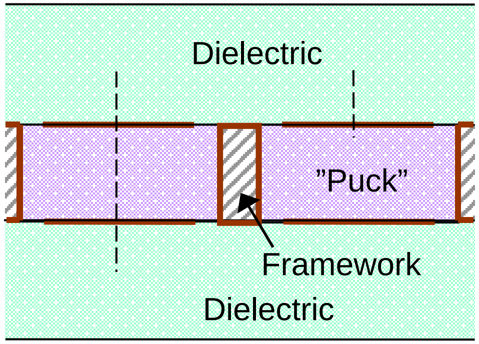
- Two types of FSS structures:





- Two thin copper layers with etched periodic patterns

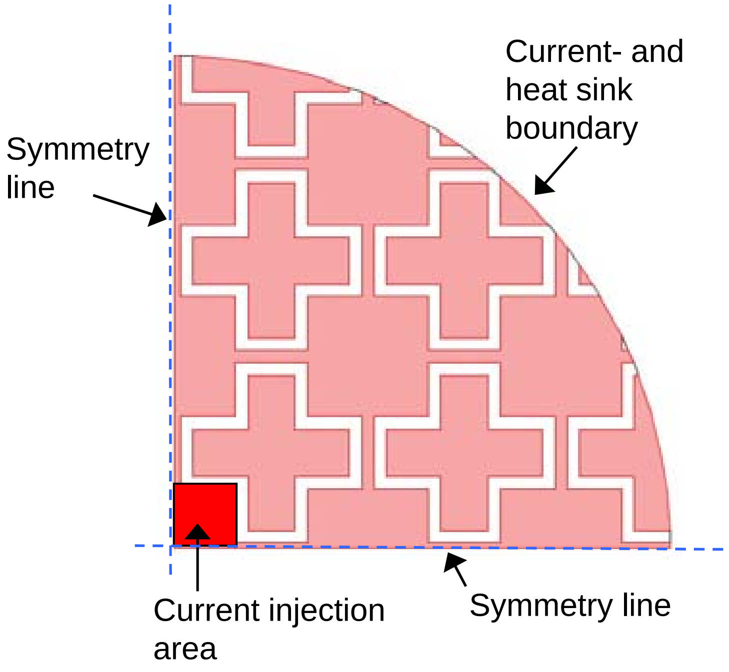


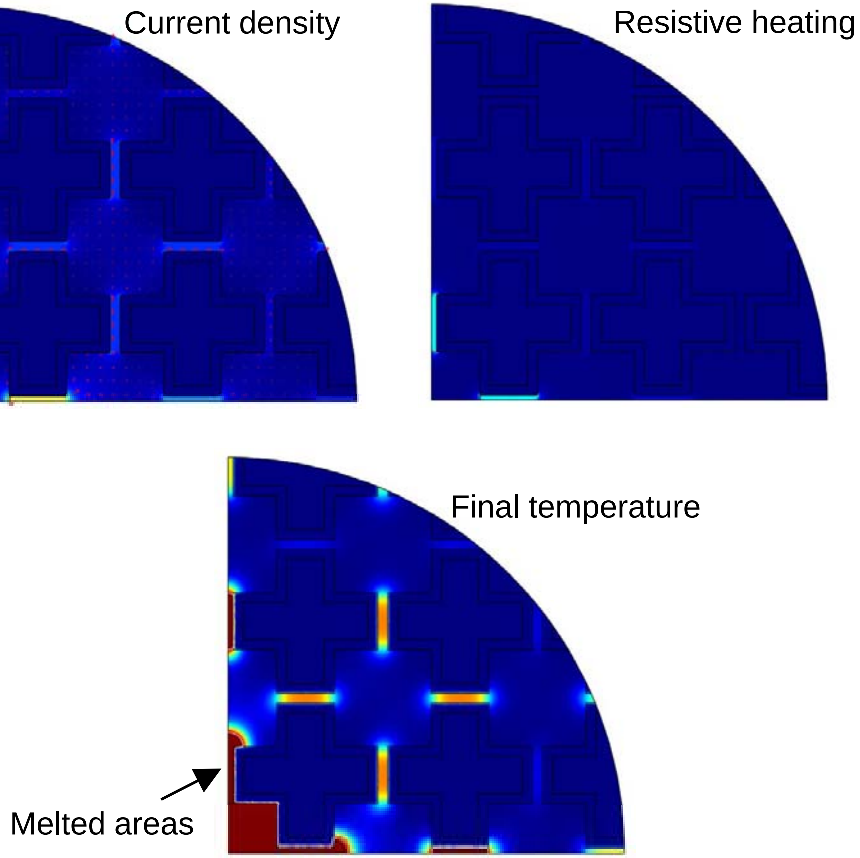


- Artificial Puck Plate (APP) 3D structures with puck-shaped resonators

Developing robust Frequency Selective Surface radome structures (3)

- Lightning damage is a concern. COMSOL is used to simulate the heating due to an injected lightning current pulse.

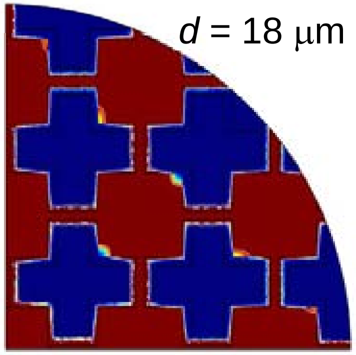




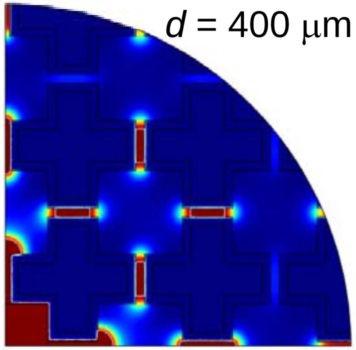
Developing robust Frequency Selective Surface radome structures (4)

- Final temperature distributions after a 200 kA current pulse, calculated for different copper layer thickness *d*

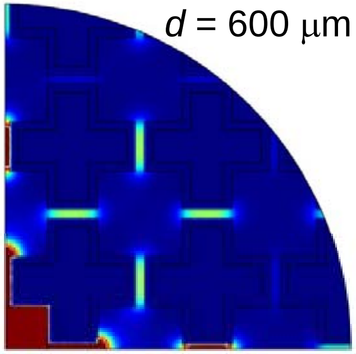
Two-layer



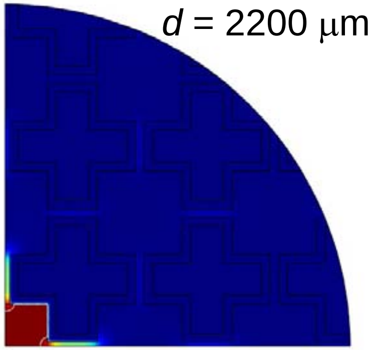
d = 18 µm



d = 400 µm

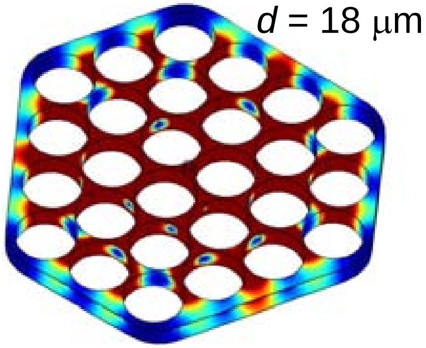


d = 600 µm

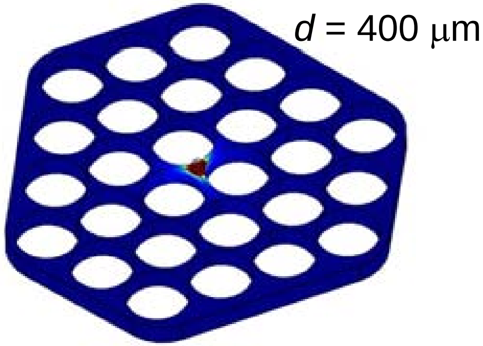


d = 2200 µm

APP



d = 18 µm

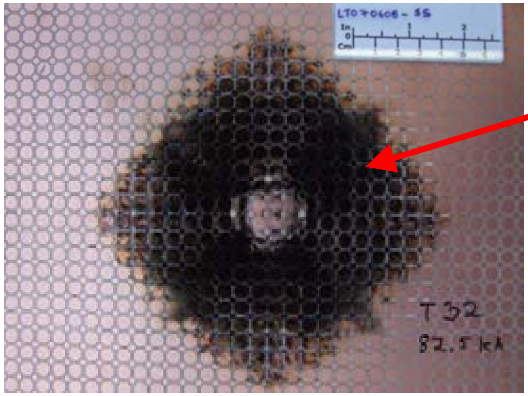


d = 400 µm

- Conclusion: Extensive damage that may break up the radome and jeopardize flight safety is less likely in an APP FSS structure

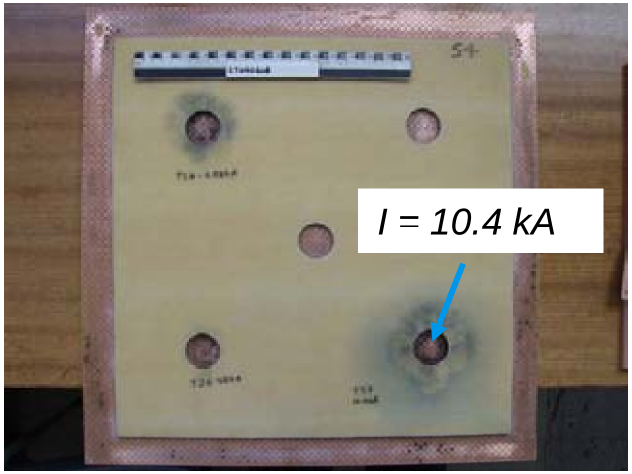
Developing robust Frequency Selective Surface radome structures (5)

- Testing was carried out at Culham Lightning Lab, UK



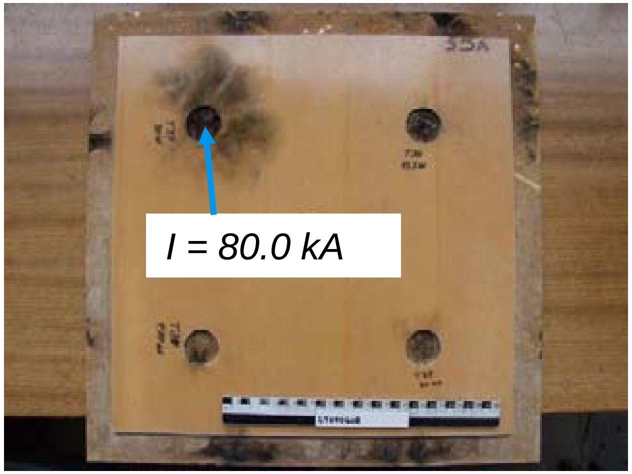
One-layer structure

- Size and shape of damaged area agree well with simulations
- The APP structure is confirmed to be more robust than the two-layer structure and the ratio is well predicted by the theory



I = 10.4 kA

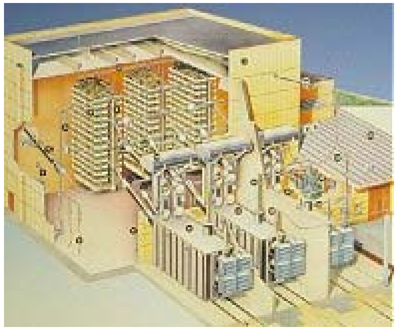
Two-layer structure

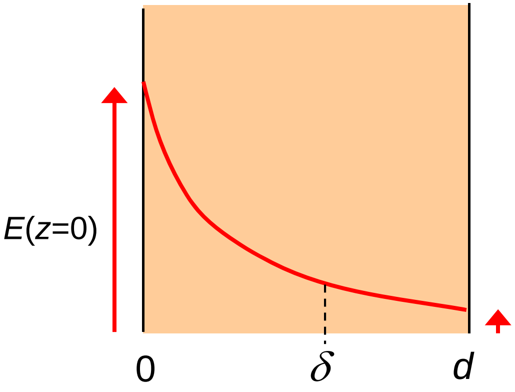


I = 80.0 kA

APP structure

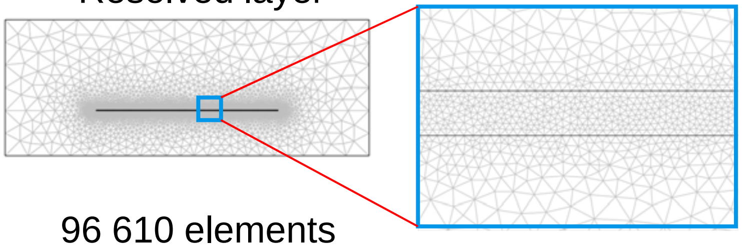
Effective modeling of thin conductive layers and walls (1)





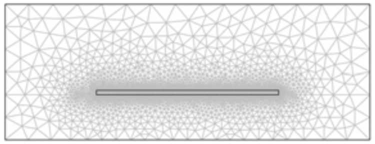
- This problem is relevant for many applications, ranging from thin foils for shielding high frequency fields to metal walls enclosing power transmission installations
- Simulating conducting layers or walls is challenging when the thickness *d* is comparable to the skin depth $\delta = \sqrt{1/\pi\mu\sigma f}$.
- When $d \ll \delta$ the "Transition Boundary Condition (BC)" model can be used and when $d \gg \delta$ one can use the "Surface Impedance BC" model
- Traditionally, if $d \sim \delta$ one has to resolve the layer interior which requires much memory, although a kind of scaling technique makes some improvement

Resolved layer



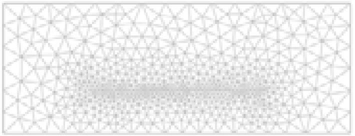
96 610 elements

Resolved scaled layer



10 249 elements, $\alpha = 10$

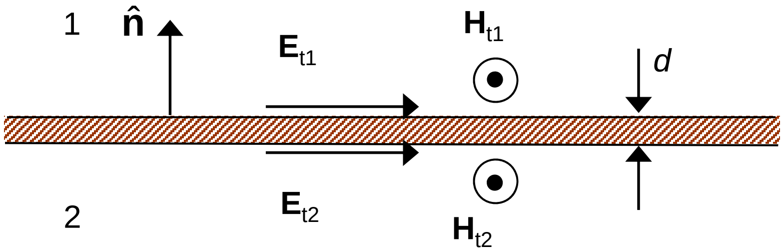
BC layer model



1228 elements

Effective modeling of thin conductive layers and walls (2)

- A BC layer description, valid for all d/δ, was given by Horton et al. 1971



$$\hat{\mathbf{n}}\times\mathbf{H}_{t1}=(Z_S\mathbf{E}_{t1}-Z_T\mathbf{E}_{t2})\big/(Z_S^2-Z_T^2)$$

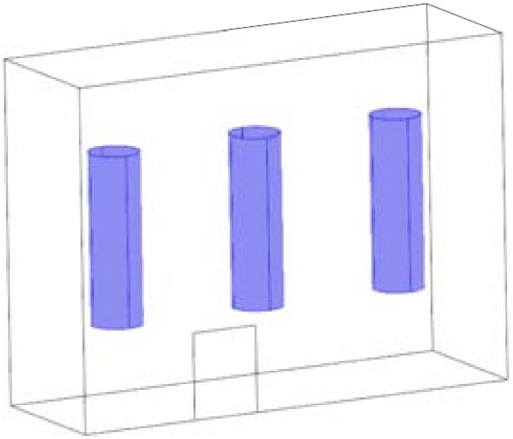
$$-\hat{\mathbf{n}}\times\mathbf{H}_{t2}=(Z_S\mathbf{E}_{t2}-Z_T\mathbf{E}_{t1})\big/(Z_S^2-Z_T^2)$$

$$Z_S=-\frac{j\omega\mu}{k}\frac{1}{\tan(kd)}\qquad Z_T=-\frac{j\omega\mu}{k}\frac{1}{\sin(kd)}\qquad k=\omega\sqrt{(\varepsilon+(\sigma/j\omega))\mu}\approx\sqrt{-j\sigma\mu\omega}$$

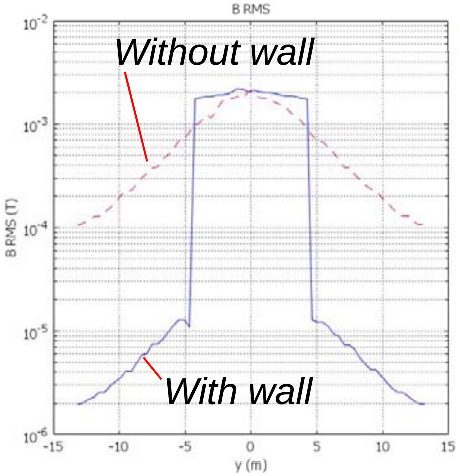
- This can easily be implemented in COMSOL (Eriksson G., Proc. 2007 IEEE Symp. Electromagnetic Compatibility, Honolulu, 2007)
- Since d, μ, and σ appear as parameters the parametric solver can be used to scan over wide ranges of these quantities

Example of thin wall modeling; Low frequency leakage and heating of a reactor hall enclosure

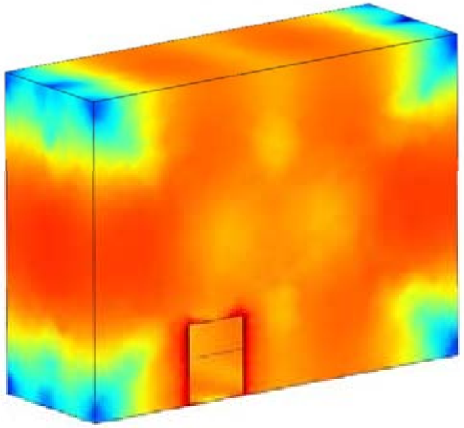
- A 22 m tall building contains three phase reactor coils carrying large currents causing induced wall currents to heat up the metal wall



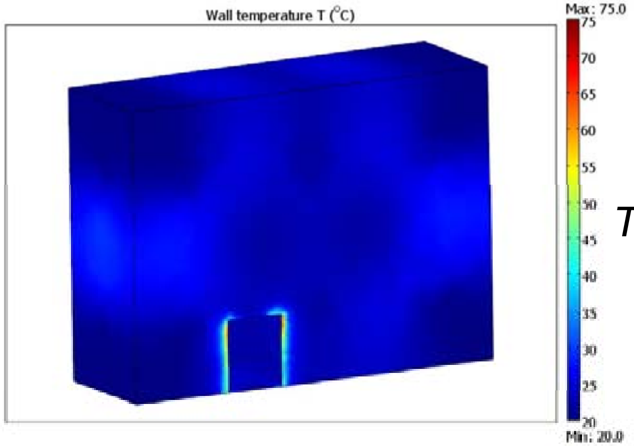
Geometry model



Magnetic field profile



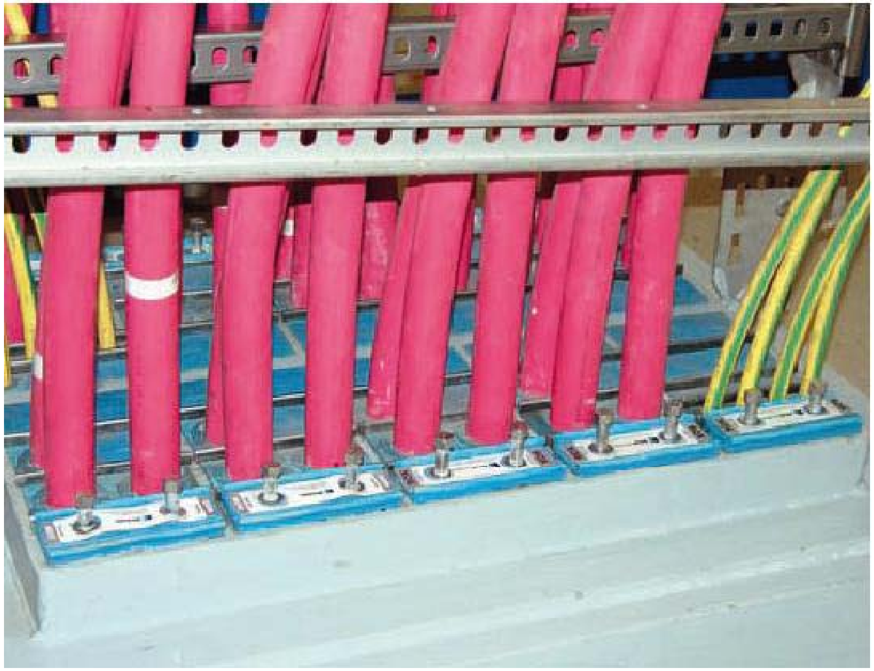
Resistive heating



Temperature

Example of thin wall modeling; Wall sealings for high current cables (1)

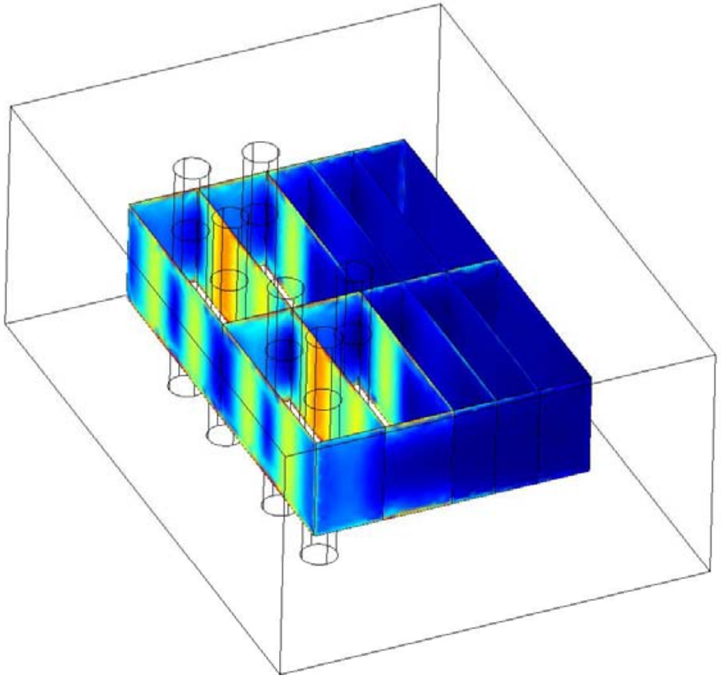
- The Roxtec company (www.roxtec.com) manufactures sealings for cable transitions through walls
- Simulations can be used to compute the heating of the bushing frame due to eddy currents induced by high cable currents



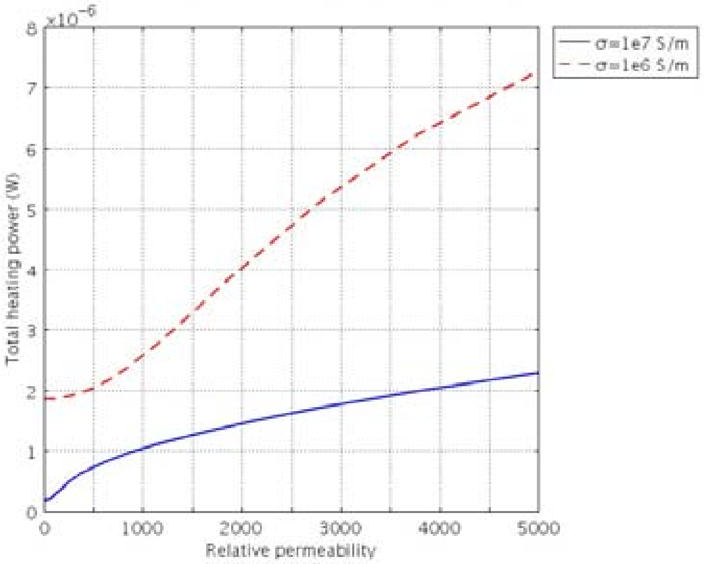
Installations of Roxtec sealings

Example of thin wall modeling; Wall sealings for high current cables (2)

- The general BC layer description can be used to model the heating of the sealing frame
- Fast parametric scans can easily be performed



Distribution of resistive heating power

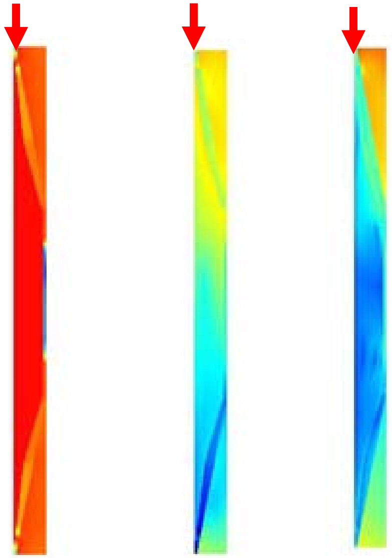


Integrated heating power as function of permeability, for two values of the conductivity

Simulating high voltage bushings

- A high voltage bushing contains a large number of concentric aluminum foil layers which are reducing the electric field stress between the cable and the grounded wall
- Simulations where all foils are included can be used to study the impact of incoming transients on the bushing, in particular the resulting E-field distribution

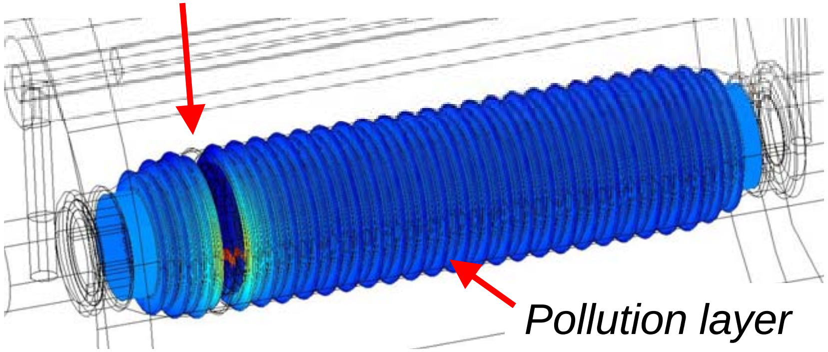
800 kV transformer



f = 50 Hz *f* = 10 MHz *f* = 100 MHz

Simulating flashover mechanisms on insulator surfaces

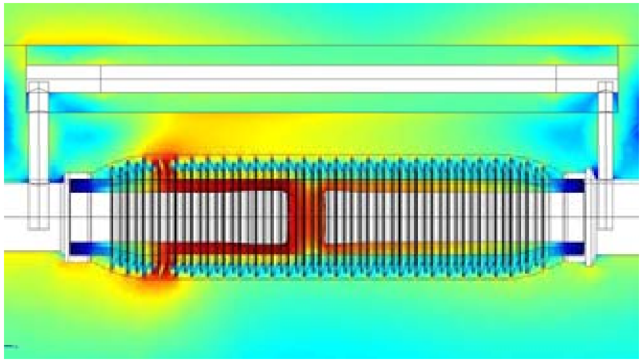
- So-called dry-band arcing can cause flashover on insulator surfaces covered by a slightly conducting wet pollution layer
- A 3D model of a high voltage breaker surrounded by a porcelain insulator was developed



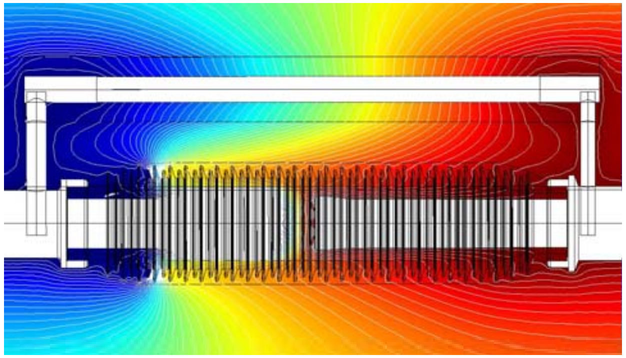
Dry non-conducting gap with a narrow conducting bridge

Pollution layer

Surface current distribution on the polluted insulator surface



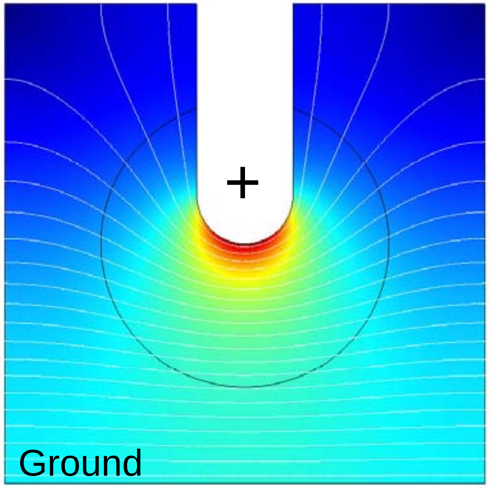
Electric field strength



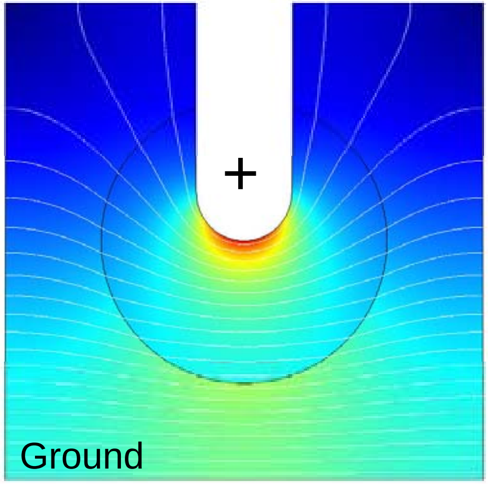
Equipotential curves

Application of nonlinear field grading materials to reduce field stress in high voltage products

- At high voltage, electric breakdown (flashover) may occur at sharp conductor edges where the electric field becomes strong
- By applying materials having a nonlinear field-dependent conductivity, $\sigma = \sigma_0 \cdot [1+(E/E_b)^{\alpha}]$, the field stress can be significantly reduced
- COMSOL is used to model the different characteristics of these materials at DC, AC, and transient conditions

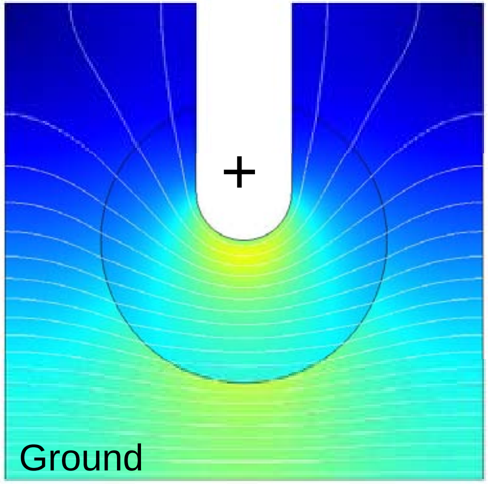


No Field Grading Material



Linear Field Grading Material

$\sigma = \sigma_0$



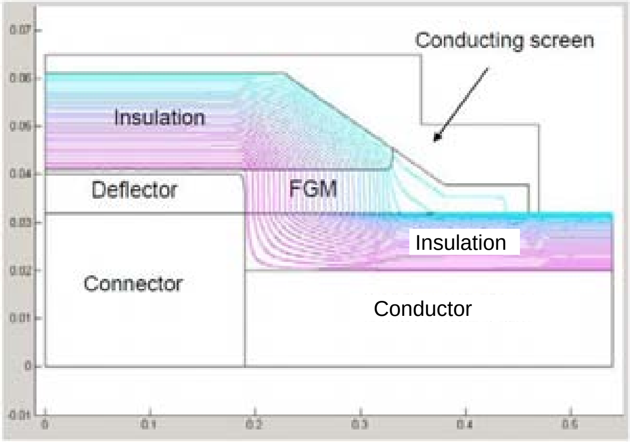
Nonlinear Field Grading Material

$\sigma = \sigma_0 \cdot [1+(E/E_b)^{\alpha}]$

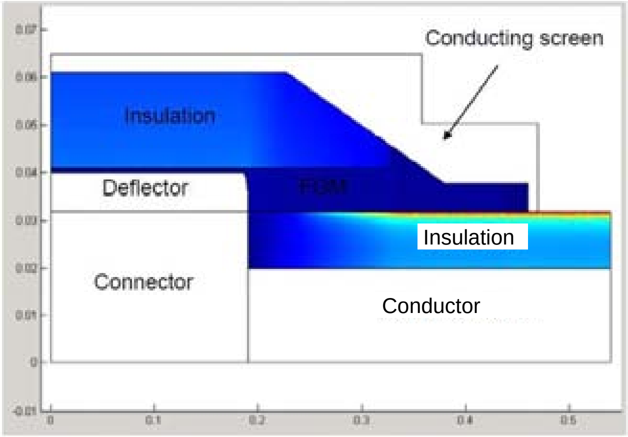
FGM in high voltage cable joints (1)

- Cable joints need to be carefully designed in order to avoid flashover between the high voltage inner conductor and the grounded cable screen

Cable joint

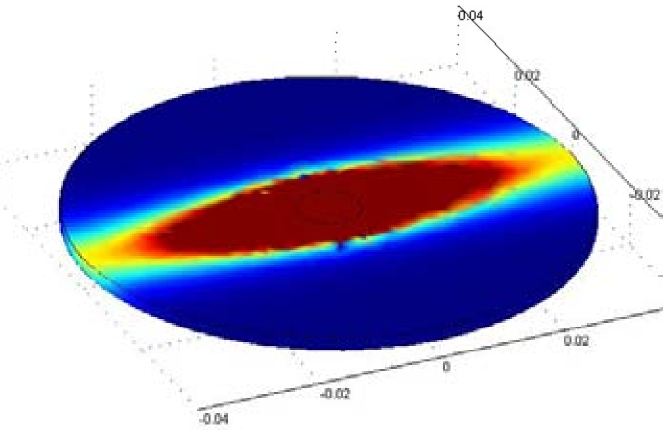


Equipotential curves



Electric field strength

Conclusions



- In electromagnetic technology applications the finite element method is very well suited for a wide range of problem types
- For many cases, in particular when inhomogeneous materials having complex properties are involved as well as when multiphysics couplings are essential, it is the only option available
- The somewhat unfavourable performance scaling with problem size is becoming increasingly compensated by more powerful computers and more efficient solver routines
- A technique to self-consistently include wires and slots, thinner than the element size, would be highly appreciated

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