Impedance of Clearing Electrodes

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- Desirable features for clearing electrodes
- Electrostatic simulations
- Metallic and “invisible” clearing electrodes
- Longitudinal and transverse impedance calculations
- Clearing efficiency

Motivation

- In several simulations and experiments is has been shown that localized clearing electrodes can effectively suppress electron multipacting close to the electrode
- Distributed clearing electrodes could be used to fight the electron cloud effect over longer regions of an accelerator => we discuss this option

Desirable features

Clearing electrodes should fulfil as many as possible of the following points:

- Good mechanical stability
- Good vacuum properties
- Limited aperture reduction
- Low longitudinal and transverse impedance
- In case a significant heat load is expected: good thermal contact between the electrode and some heat sink, e.g. the beam pipe
- Low secondary emission yield (SEY)
- Electrodes should stand baking in case this is needed
- They should stand a DC voltage of the order of 1 kV
- Radiation hardness

The properties of enamel

Enamel as an insulating dielectric deposited in the beam pipe offers

- Good mechanical stability, strength and adhesion
- Good thermal contact to the beam pipe
- It can stand a few kV
- It can stand baking at 300 degrees or more

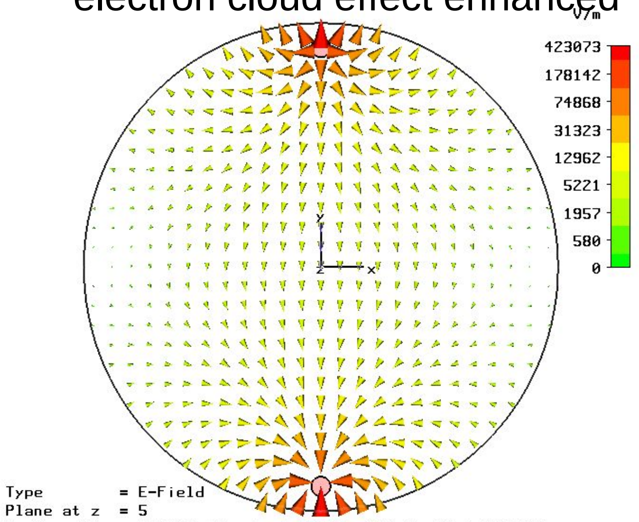
- For these reasons it could be an interesting candidate for the insulator of clearing electrodes
- With appropriate electrode geometries it should be possible to minimize the aperture reduction by the electrode
- Impedance issues are discussed later in this talk

- Vacuum properties, SEY and radiation hardness have yet to be analysed in more detail

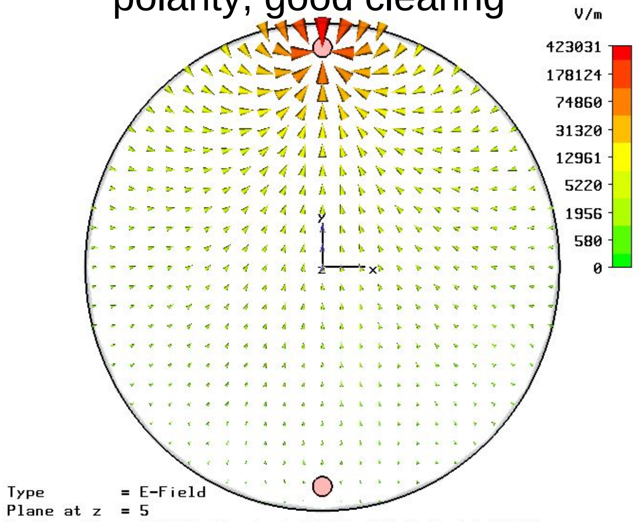
How many electrodes?

- Simulation results for the electron cloud clearing efficiency with two wire electrodes in KEKB show an interesting effect [1]
  - With one electrode at +1 kV and the second at -1 kV multipacting is enhanced, probably due to high energy gain close to positive electrode
  - For only one electrode with negative polarity good electron clearing is found
  - With both electrodes at negative polarity the clearing effect is slightly enhanced
- A similar effect was found by Wang et al. [2]
- If these results can be applied to other machines, one single cleaning electrode should be enough => good for impedance, aperture, manufacturing,…

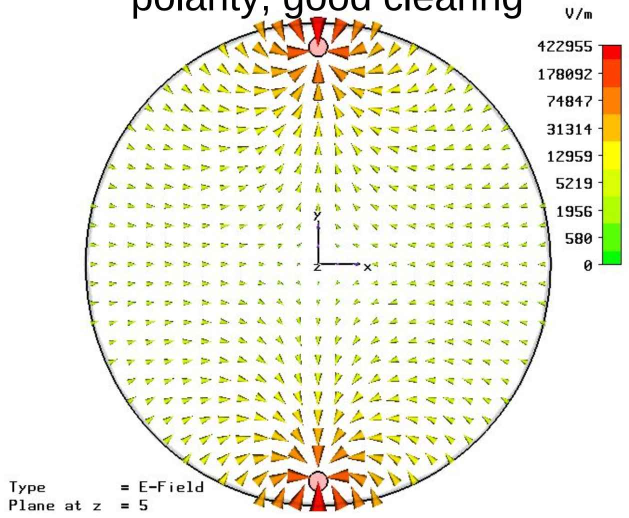
Electrodes at opposite polarity, electron cloud effect enhanced



One electrode at negative polarity, good clearing



Both electrodes at negative polarity, good clearing



[1] F. Zimmermann, Beam Sizes in Collision and Electron-Cloud Suppression by Clearing Electrodes for KEKB, CERN-SL-Note-2001-022
[2] L. F. Wang et al., Mechanism of electron cloud clearing in the accumulator ring of the Spallation Neutron Source, PRST 7, 034401, 2004

Flat electrodes versus wires (1)

- Let's consider two electrode geometries among the many options: Flat electrodes and wires
- When wires are moved close to the beam pipe wall, the electrical field in the center E_c and the potential U_c decrease fast
- For a comparable spacing from the wall flat electrodes provide a higher clearing field in the center

Beam pipe radius 50 mm

Top electrode at -1 kV

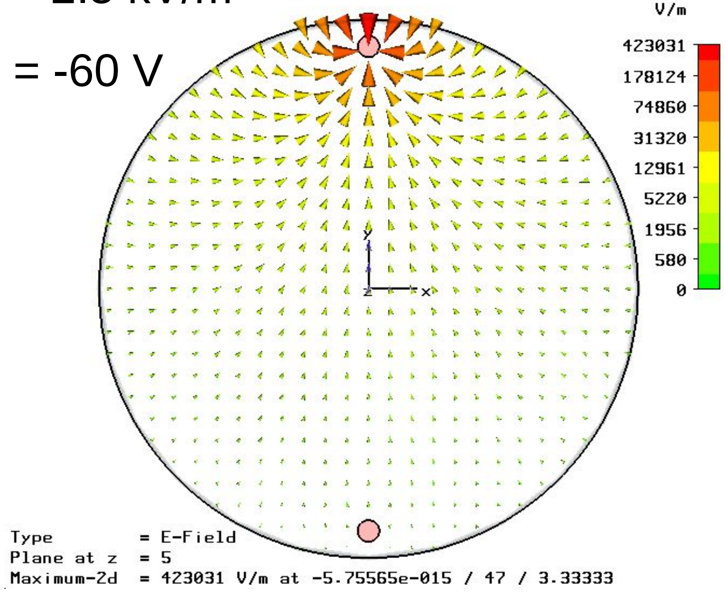
Electric field plotted [log. scale]

Left: 2 mm radius electrode 5 mm from the wall

Right: 20 mm wide and 1 mm thick electrode 1 mm from the wall

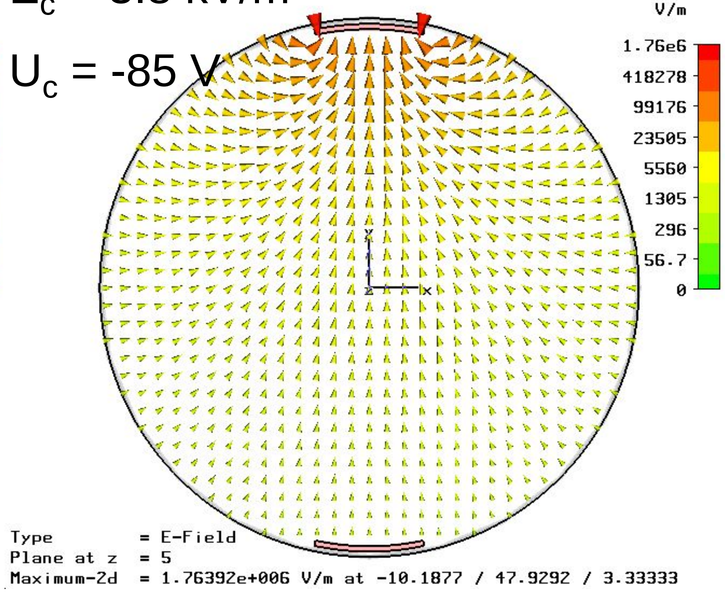
E_c = 2.5 kV/m

U_c = -60 V



E_c = 3.8 kV/m

U_c = -85 V



Flat electrodes versus wires (2)

- When the spacing between a flat electrode and the wall is reduced, E_c and U_c decrease rather slowly
- A dielectric between the electrode and the wall gives limited reduction in E_c and U_c.
- Flat electrodes retain a substantial field strength in the center even when moved close to the wall => aperture reduction can be minimized

Beam pipe radius 50 mm

Top electrode at -1 kV

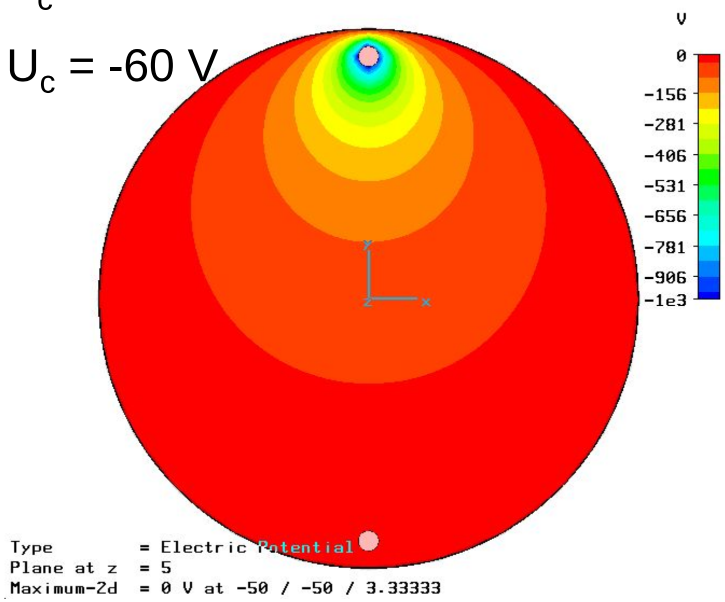
Potential plotted [lin. scale]

Left: 2 mm radius electrode 5 mm from the wall

Right: 20 mm wide and 1 mm thick electrode 1 mm from the wall

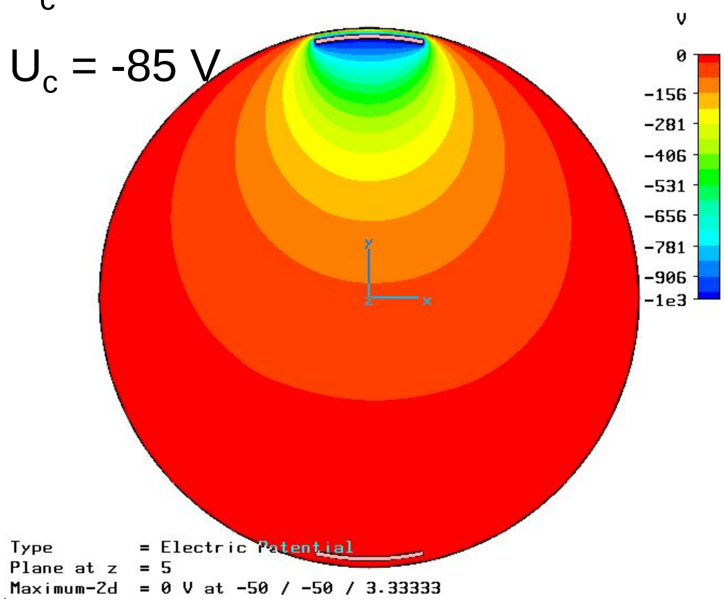
E_c = 2.5 kV/m

U_c = -60 V



E_c = 3.8 kV/m

U_c = -85 V

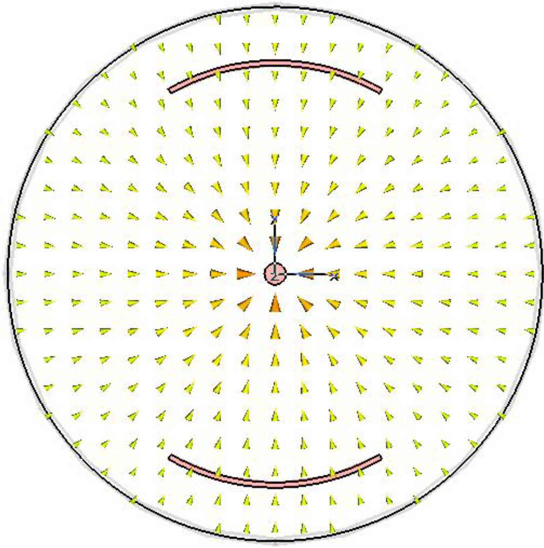


Metallic versus high resistivity electrodes

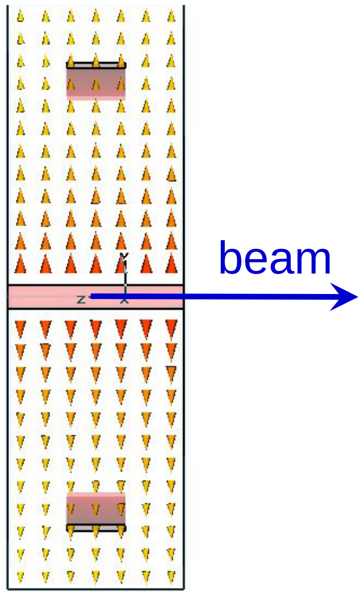
- In dependence of the conducting material we can have
  - Metallic clearing electrodes: A good conductor supported by some dielectric material
  - A highly resistive layer: If the layer’s surface resistance is much higher than the free space impedance such an electrode is “invisible” to the electromagnetic wave in the sense that it does not act like a metallic electrode. The electrode rather behaves like a dielectric. In analytic calculations and simulations this electrode was approximated as a dielectric strip.

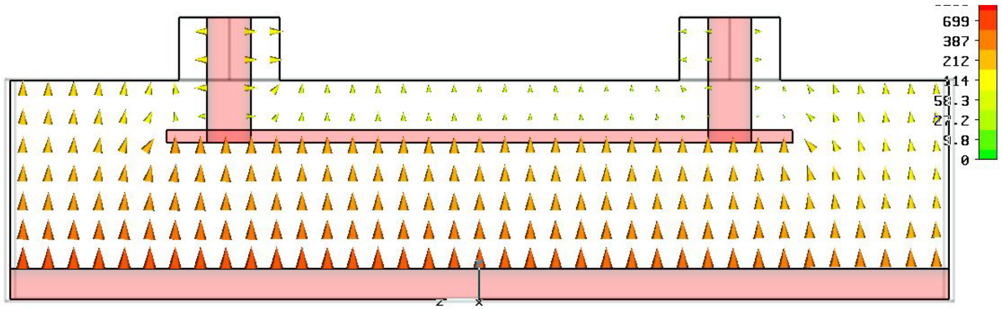
Metallic electrode (1)

Ideal floating electrode



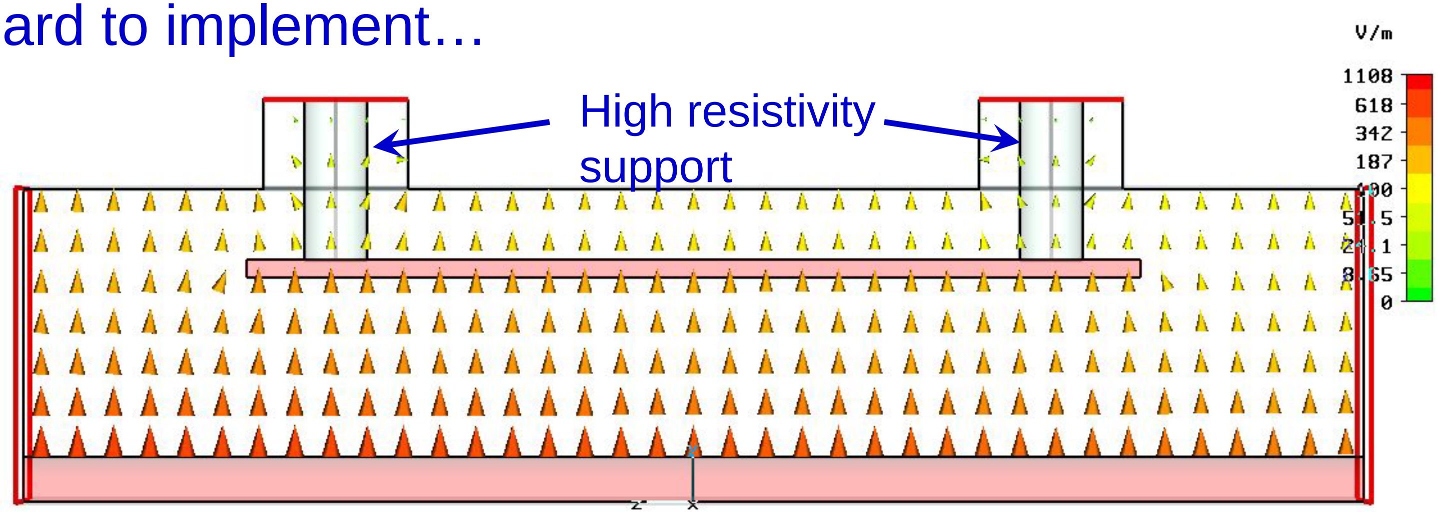
- An infinitely thin perfectly conducting electrode ideally has no longitudinal impedance, since it is normal to the unperturbed electric field and thus does not change the field pattern (electric field of wire simulation plotted on the right)
- However, once dielectric supports are inserted, the waves propagating inside the structure and between the electrode and the walls are out of phase => they don't recombine perfectly after the end of the electrode => impedance
- If a metallic connection to the outside of the beam pipe is made, we have a strip line pick-up. It may have a substantial impedance and heat dissipation… In order to prevent resonances on the electrode the feedthroughs should be situated at its ends and matched





Metallic electrode (2)

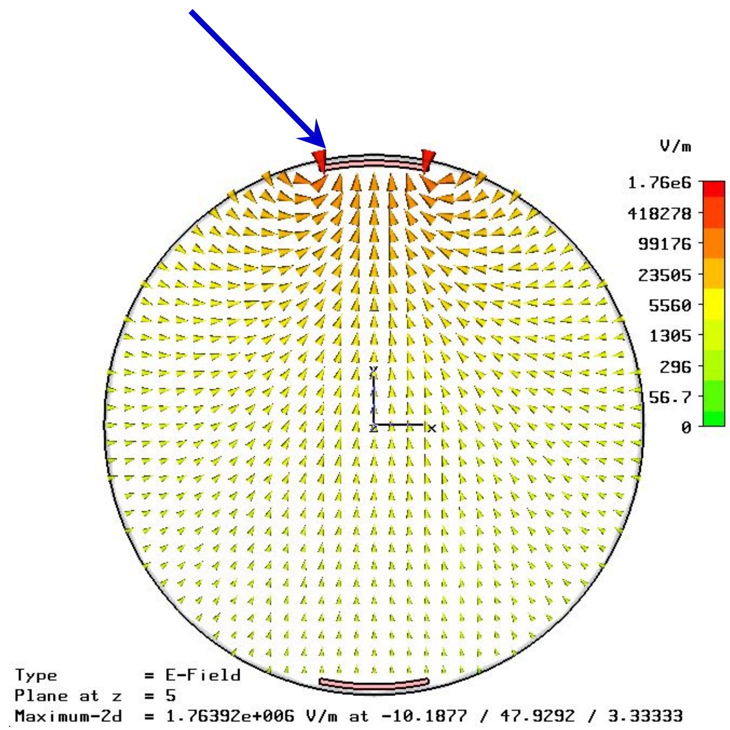
- The use of a high-resistivity connection for the clearing voltage could be possible. At high frequencies such an electrode would approximately have an open circuit on either side
- The impedance would come from any dielectric put underneath the electrode; resonances are possible!
- For impedance issues the amount of dielectric should be minimized. This conflicts with mechanical requirements and good heat transfer to the beam pipe.
- Even if the impedance is acceptable, such a structure might be hard to implement…



High resistivity electrode

- The idea consists of building a thin electrode structure directly attached to the beam screen. Let's assume a 50 mm radius pipe.
- As the insulating dielectric a thin enamel layer can be used, e.g. a single 25 mm wide strip with 0.5 mm thickness
- On top of that a highly resistive 20 mm wide strip is deposited
- At one end of the strip a feedthrough is installed to bias the resistive strip to say -1 kV to ground (beam pipe)
- Each section of the electrode could have to length of up to a few meters and be installed in straight sections as well as in magnets
- Such a structure has a several advantages:
  - Good mechanical stability
  - Small aperture reduction
  - Good thermal contact to the beam pipe
  - The SEY of the electrode should probably not have such a large impact, since it repels electrons

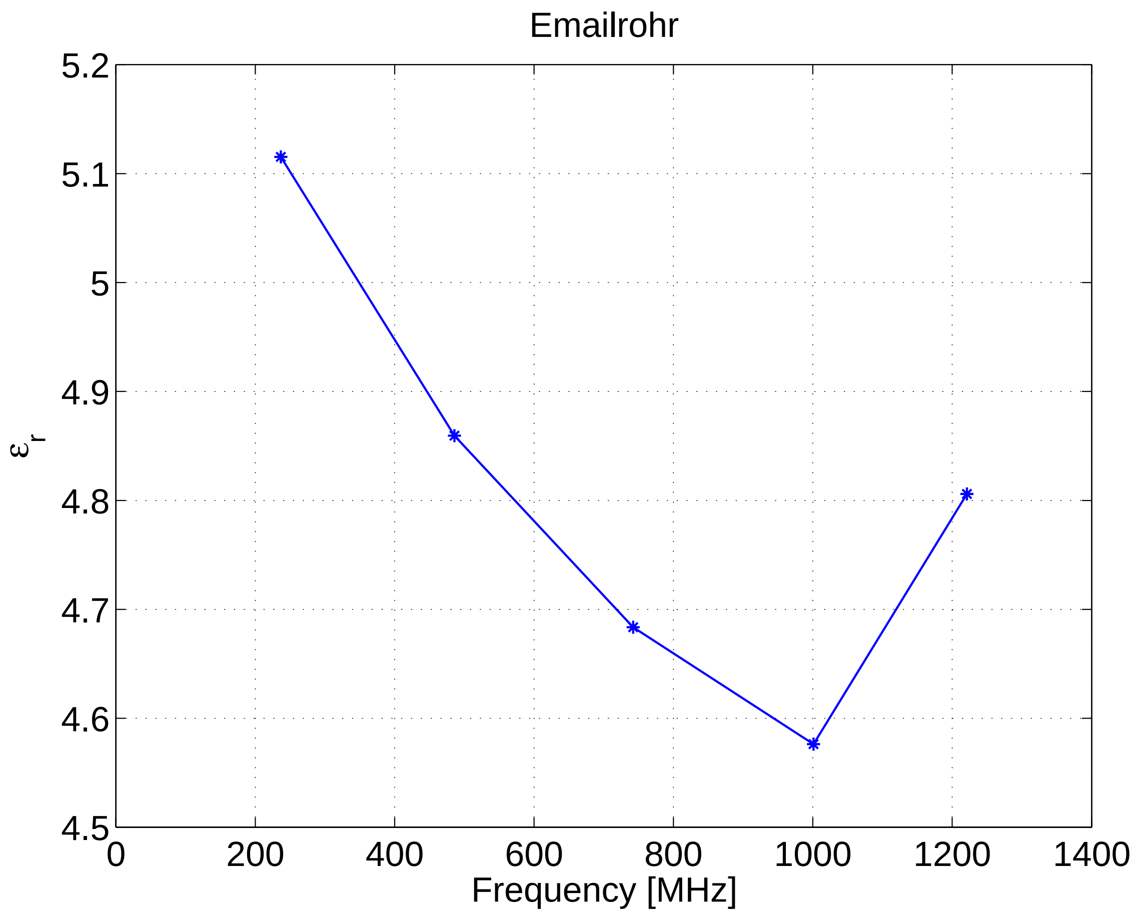
An insulating enamel layer on the beam pipe, on which a resistive layer is deposited that acts as an "invisible" electrode



Enamel permittivity

- For a sample of insulating enamel the permittivity ε in the 100 MHz to 1 GHz range was determined using a stripline resonator technique
- $\varepsilon_r \approx 5$
- The dielectric loss factor could not be reliably measured this way, since the losses were dominated by resistive losses in the added metal strip

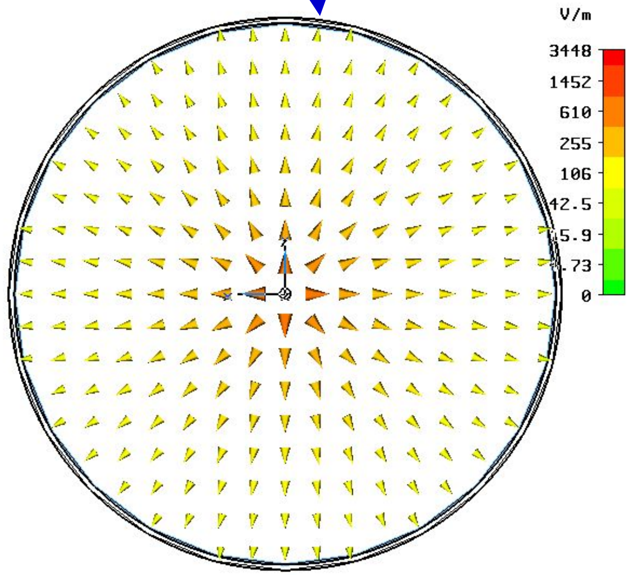
Measured relative permittivity



High resistivity electrodes – Z/n (1)

- The insulating and the highly resistive dielectric strips are approximated by a dielectric with permittivity ε
- The longitudinal impedance was estimated analytically for a structure with rotational symmetry
- It was assumed that in analogy to a TEM line the dielectric acts mainly by introducing a phase shift => imaginary part of longitudinal impedance Im(Z/n)
- This corresponds to the change in group velocity on a TEM line
- For thin dielectric layers
  - Im(Z/n) is proportional to the dielectric cross-section
  - Im(Z/n) increases with ε
- A quick scaling yields the simulated Daphne clearing electrode impedance [1] to within a factor 2

1 mm dielectric layer inside a radius 50 mm pipe

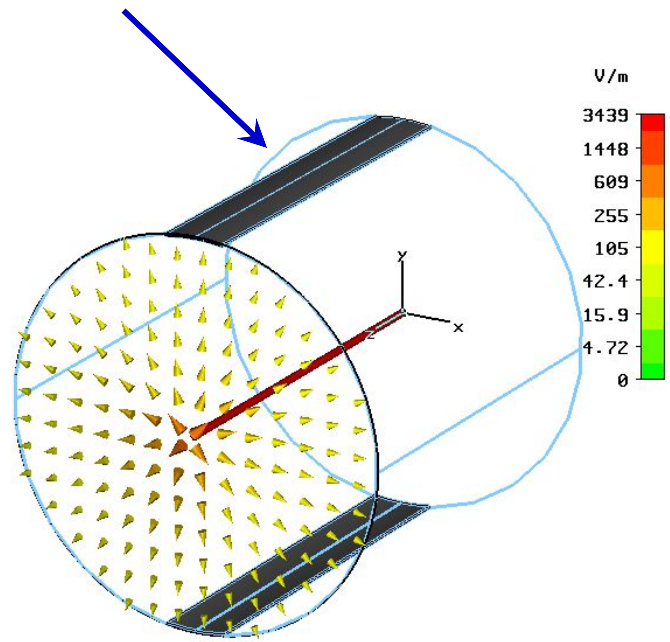


[1] B. Spataro, M. Zobov, Wake Fields and Coupling Impedance of the Daphne Electron Ring, Daphne Technical Note G-64, 2005

High resistivity electrodes – Z/n (2)

- The analytical results were checked with numerical simulations under CST Microwave Studio and HFSS.
- A very good agreement was found for thick layers (within 10 % for a 10 mm thick layers in 100 mm diameter pipe), for thinner layers the maximum discrepancies are somewhat higher (within 50 % for a 1 mm thick layer)
- In addition, in simulations it was verified that Im(Z/n) is about proportional to the dielectric volume also when the dielectric does not cover the full azimuth
- Im(Z/n) is flat up to very high frequencies
- Estimations for two 0.5 mm thick electrodes with $\varepsilon = 5$ in a round pipe around the entire machine
  - PS (pipe radius 50 mm, 25 mm dielectric width): Im(Z/n)= 0.7 Ω (entire machine today: Z/n≈20 Ω)
  - SPS (pipe radius 25 mm, 20 mm dielectric width): Im(Z/n)= 2.8 Ω (entire machine today: Z/n≈10 Ω)

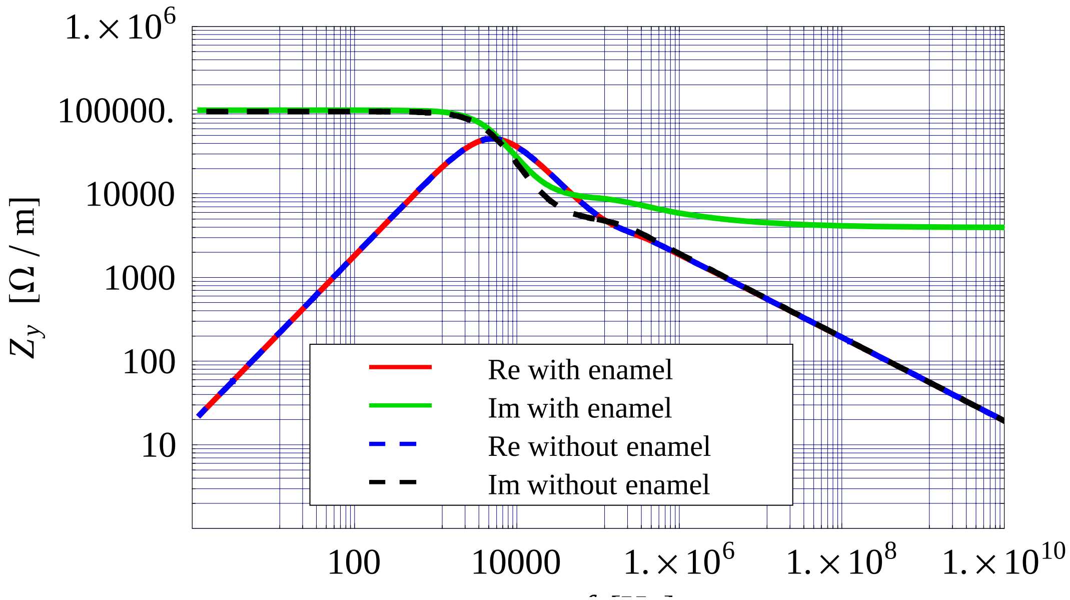
Two 0.5 mm thick dielectric strips inside a radius 50 mm pipe



High resistivity electrodes – Z_{TR} (1)

- First approach: Calculate the transverse impedance Z_{TR} analytically using the Burov-Lebedev formula for structures with rotational symmetry
- At low frequencies no difference from resistive wall
- At high frequencies no change in Re(Z_{TR}) but a constant Im(Z_{TR})

1) For the SPS (1 m long stainless steel pipe with a radius of 25 mm)



Courtesy: Elias Metral

2 mm thick stainless steel pipe, 25 mm radius, 1 m length

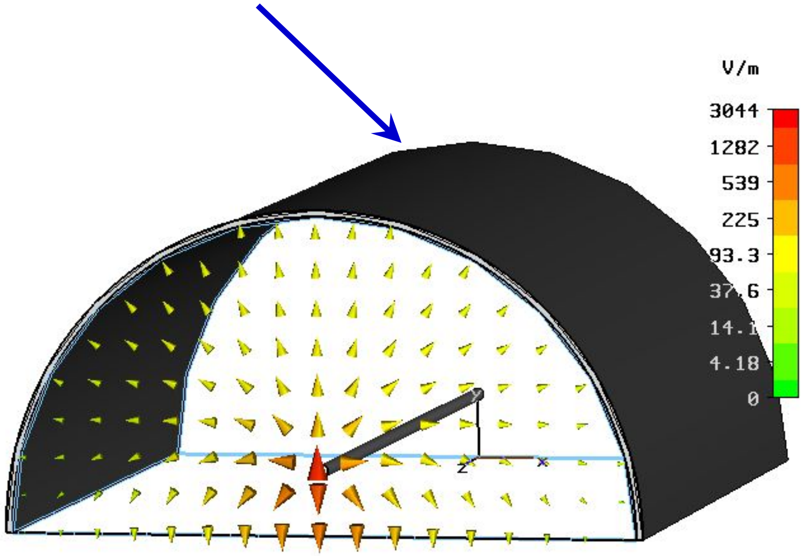
0.5 mm thick ε = 5 enamel layer all around, dielectric losses neglected

High resistivity electrodes – Z_{TR} (2)

- Z_{TR} was simulated with CST Microwave Studio
- Check with analytical calculated: for a 1 mm thick dielectric covering the full azimuth the agreement is within 10 %
- For thin layers Z_{TR} is proportional to the dielectric thickness

- Reducing the dielectric coating to strips on the top and bottom of the beam pipe reduces a lot $Z_{TR,x}$.
- $Z_{TR,y}$ only goes down by about a factor 2 for two electrodes covering $\pi/10$ (36 degrees) compared to a fully coated pipe

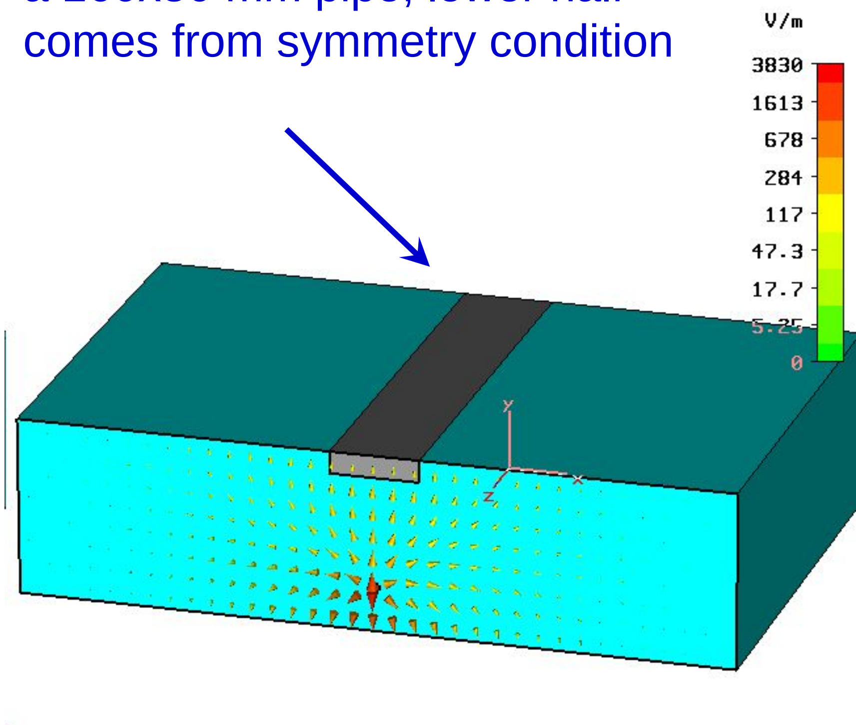
1 mm thick dielectric layer inside a radius 50 mm pipe



High resistivity electrodes – Z_{TR} (3)

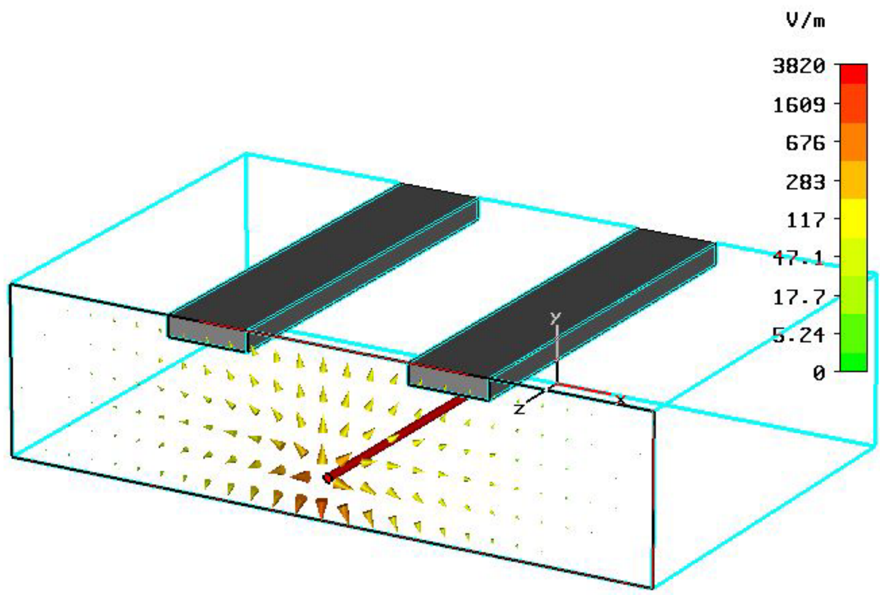
- In the following rectangular geometries were used, dimensions (like M. Furman's build up simulations):
  - PS: 80x40 mm half axes
  - SPSx: 60x20 mm half axes, same circumference as current SPS assumed
- The electrodes were made as thin as possible while checking convergence
- Preliminary results scaled to two 0.5 mm thick centered electrodes with $\varepsilon = 5$ along the entire machine
  - PS (electrode width 20 mm): $\mathrm{Im}(Z_{TR,y}) = 0.25\ \mathrm{M\Omega/m}$ (entire machine today: $Z_{TR} \approx 5\ \mathrm{M\Omega/m}$)
  - SPSx (electrode width 15 mm): $\mathrm{Im}(Z_{TR,y}) = 20\ \mathrm{M\Omega/m}$ (entire machine today: $Z_{TR} \approx 20\ \mathrm{M\Omega/m}$)
- The huge difference between PS and SPSx comes from the smaller SPSx vacuum pipe and the larger ring

Approximated PS geometry: Two 5 mm thick dielectric strips inside a 160x80 mm pipe, lower half comes from symmetry condition



High resistivity electrodes – Z_{TR} (4)

- It appears that $Z_{TR,y}$ can be reduced significantly by moving the electrode off-center, even if two electrodes are needed
- $Z_{TR,x}$ rises significantly in this case
- The clearing voltage would have to be increased accordingly



Clearing efficiency

- The electron cloud build-up in the PS was simulated with ECLOUD for different clearing electrode geometries
- For a magnetic field of 10 G substantial multipacting in predicted (blue trace)
- A single very wide electrode (46 mm width) is very efficient in suppressing the ecloud (green trace)
- A single 20 mm wide enamel electrode in the center of the beam pipe at -1 kV works, too (yellow trace)
- For a single 20 mm wide electrode 30 mm offset from the beam pipe center -1 kV does not suffice (light blue trace)

Courtesy: Frank Zimmermann

Parameters:

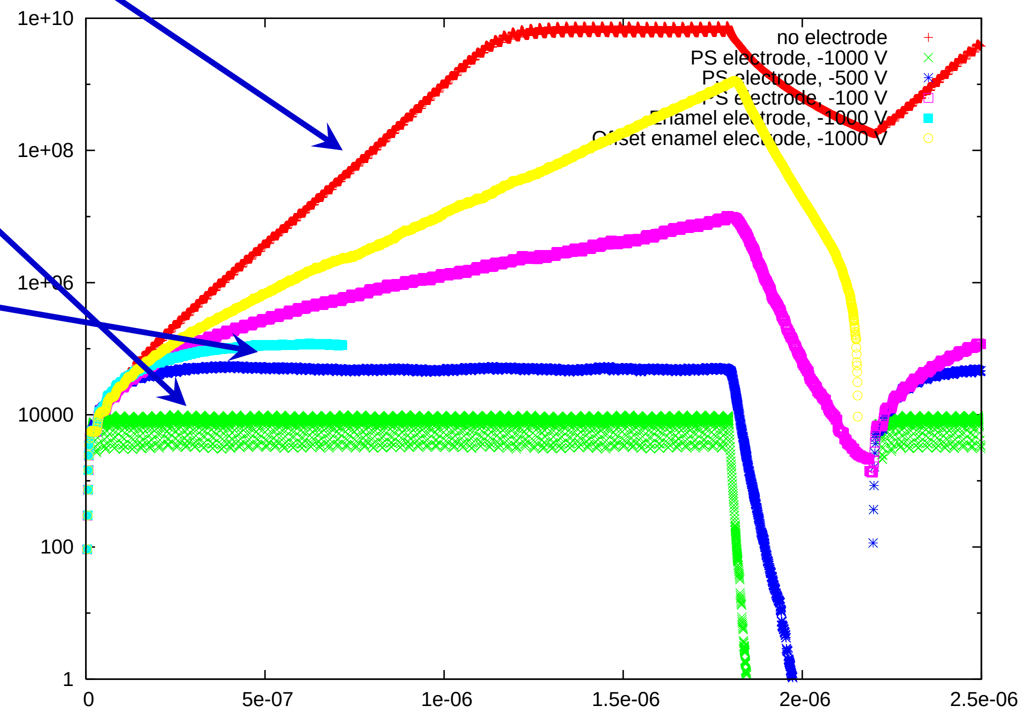
10 ntorr pressure, delta_max=1.5

epsilon_max=239.5 eV

73mm x 35 mm half aperture

sigmax=1.58 mm, sigmay=0.42 mm, sigmaz=75 cm

10 Gauss dipole field



Conclusion

- The potential of enamel as a material for electron cloud clearing electrodes was discussed
- A high resistivity coating on an insolating enamel strip looks like an interesting candidate for distributed clearing electrodes
- A sufficient clearing field can be applied with such electrodes, and a clear clearing effect is predicted by simulations for PS

- However, such structures do have a non-negligible impedance, but it should be possible to limit it by minimizing the enamel thickness
- Vacuum properties, SEY and radiation hardness of enamel should be researched in more detail

Acknowledgements

- We would like to thank Joerg Wendel, Peter Hellmold and Franz-Josef Behler from the German enamel industry for the fruitful exchange of ideas
- Thanks a lot to Elias Metral for help with the transverse impedance simulations and Frank Zimmermann for running the electron cloud build-up simulation
- Thanks to Warner Bruns and Elena Benedetto for inspiring discussion and to Elena Chapochnikova and Trevor Linnecar for support