

A Retrofittable Electron Cloud Suppression Insert for the SPS

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Motivation

- ◆ In several simulations and experiments it 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
- ◆ For the SPS a retrofittable solution that can be implemented without opening the magnets would be highly desirable

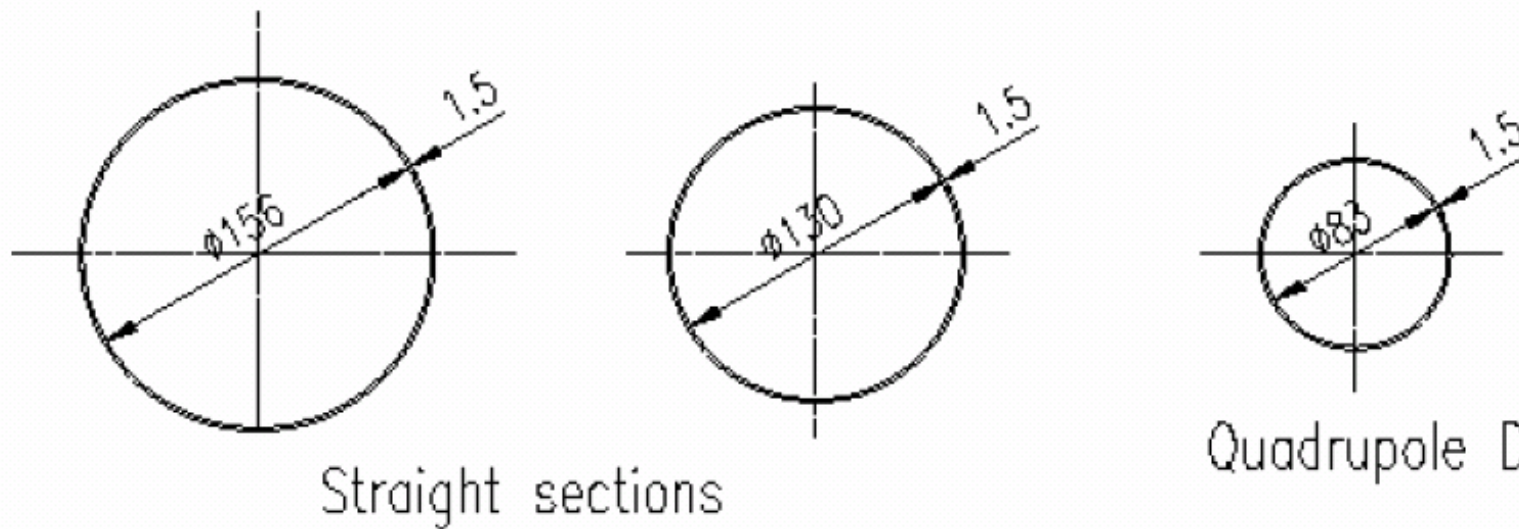
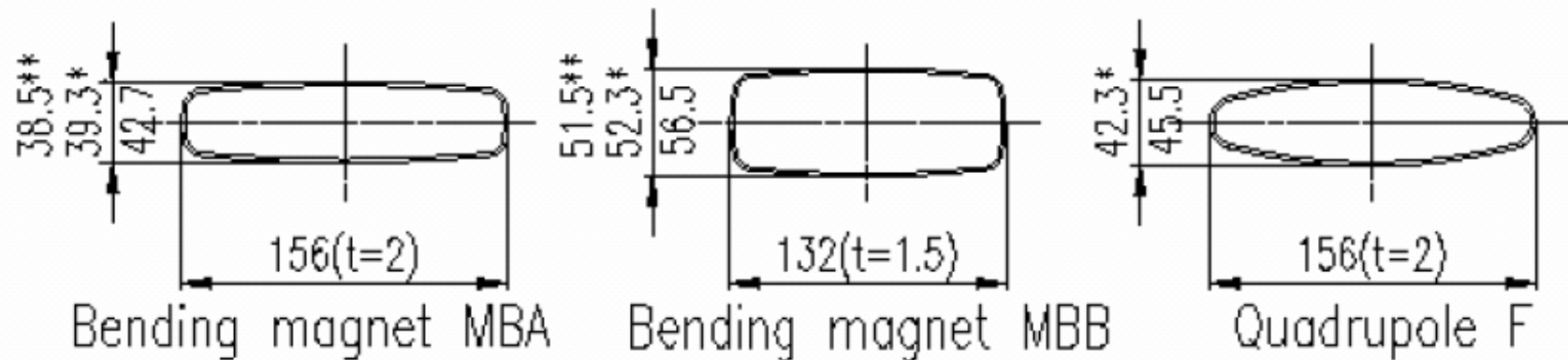
Desirable features for clearing electrodes

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

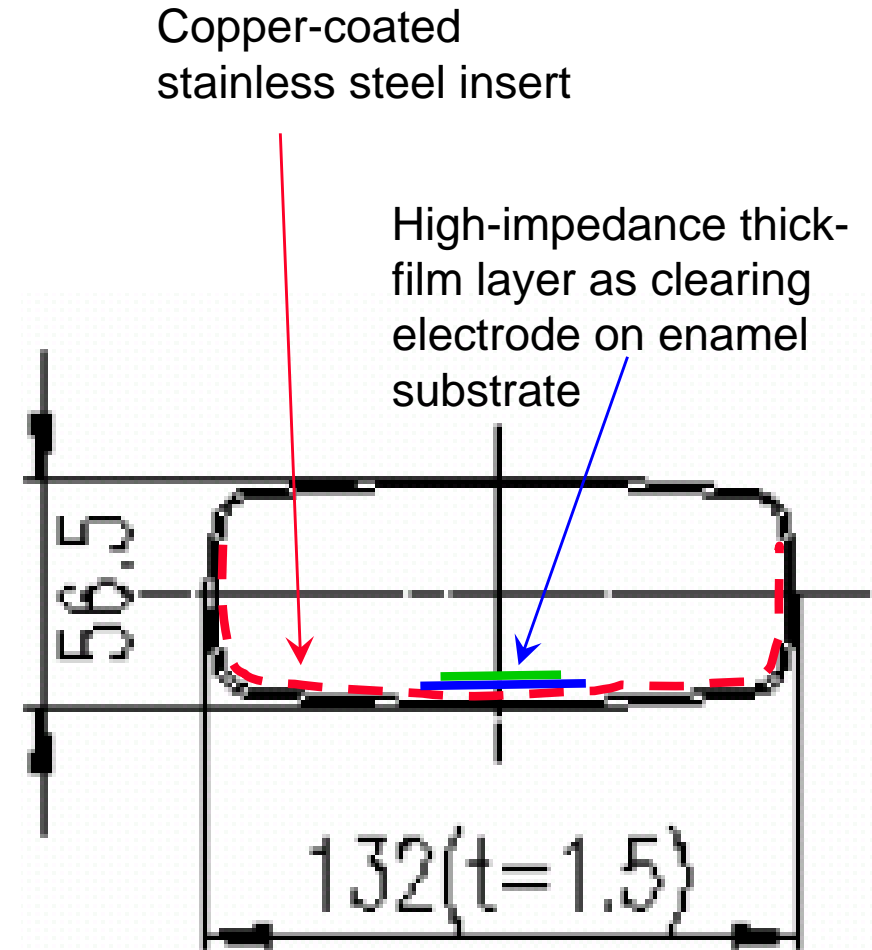
SPS Main Vacuum Chambers

Source: LHC design report, Vol. 3



Proposed potential solution (1)

- ◆ We propose a U-shaped insert that can be slid into the magnet
- ◆ Material: thin stainless steel sheet of about 0.1 to 0.3 mm thickness
- ◆ Can be copper-coated on the side facing the beam for impedance and contact issues
- ◆ It should be perforated with small longitudinal slots for vacuum reasons, like the pumping slots in the LHC liner
- ◆ In the center of the insert an about 20 mm wide and ~0.1 mm thick is deposited enamel strip or another suitable material as isolator
- ◆ On top of the dielectric a ~15 μm highly resistive thick film layer acts as “invisible” clearing electrode



Proposed potential solution (2)

- ◆ Well-defined RF end contacts can be implemented e.g. by small longitudinal cuts of ~10 to 20 mm length having a few mm spacing. They are pre-bent and act as contact fingers.
- ◆ The aperture reduction would be less than
 - about 0.5 mm in the center
 - a few mm on the sides, where it is less critical

Impedance issues

- ◆ The impedance was scaled from the results given in [1], see Appendix.
- ◆ The resistive coating is much thinner than the skin depth in the frequency range of interest (<10 GHz) \Rightarrow it acts as a dielectric \Rightarrow only the imaginary part of the impedance is affected
- ◆ Longitudinal as well as the transverse impedance are flat in frequency
- ◆ Estimation for a single electrode with a realistic enamel thickness of 0.1 mm, a width of 20 mm, $\epsilon = 5$, installed all around the SPS, ~ 40 mm vertical aperture:
 - Longitudinal impedance: $\text{Im}(Z/n) \approx 0.3 \Omega$ (entire machine today: $Z/n \approx 10 \Omega$)
 - Transverse impedance: $\text{Im}(Z_{\text{TR},y}) \approx 4 \text{ M}\Omega/\text{m}$ (entire machine today: $Z_{\text{TR}} \approx 20 \text{ M}\Omega/\text{m}$)

[1] T. Kroyer, F. Caspers, Impedance of Clearing Electrodes, ECL2 Workshop, CERN, Geneva, 2007

Additional options

- ◆ The inserts may be equipped with longitudinal grooves with a depth and spacing of fractions of 1 mm. Such grooves do not need have depths of several mm. They should also work if the aspect ratio (depth over width) is large enough (to be checked!). Since the grooves can be made on a flat metal sheet and not inside a pipe, the technological issues should be much more relaxed. This would be similar to the saw-tooth pattern in the LHC liner
- ◆ A low SEY coating can also be applied on the inner side of the insert, e.g. TiN.

Conclusion

- ◆ A concept for a retrofittable solution to reduce the electron cloud impact in the SPS has been proposed
- ◆ This concept involves one or more of the following options:
 - Highly resistively coated clearing electrodes on a dielectric. Feedthrough for an external polarization are required for this option
 - Grooves machined into the insert
 - A low SEY coating applied onto the insert
- ◆ Simulations have shown that for the PS a sufficient clearing field can be applied with such electrodes (to be checked for the SPS)
- ◆ Electrodes do have a non-negligible impedance, but the impact of the additional impedance could be acceptable for the present SPS
- ◆ Vacuum properties, RF contacts and aperture limitation issues look not too bad but have to be checked in detail
- ◆ If this suggestion is to be considered for further evaluation, a dedicated test set-up appears mandatory like for any other proposal

Appendix

Impedance of Clearing Electrodes

Tom Kroyer, Fritz Caspers, CERN-AB-RF
ECL2, March 2, 2007

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

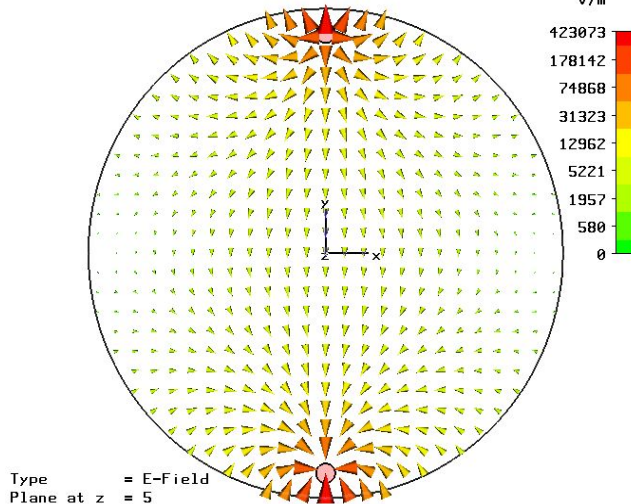
- ◆ For these reasons it could be an interesting candidate for the insulator of clearing electrodes
- ◆ With appropriate electrode geometries it should be possible to minimize the aperture reduction by the electrode
- ◆ Impedance issues are discussed later in this talk

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

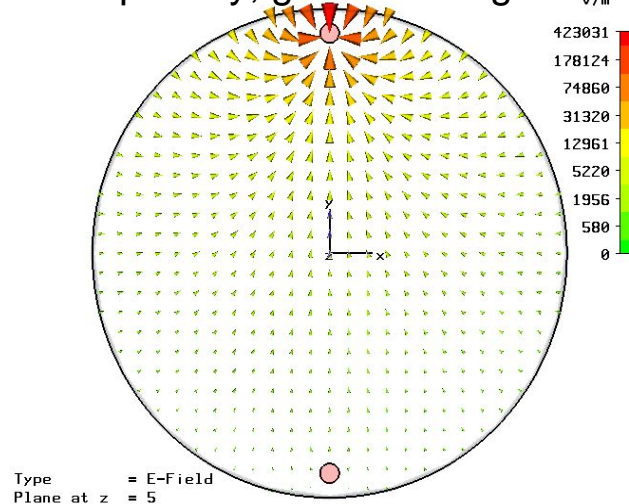
How many electrodes?

- ◆ 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,...

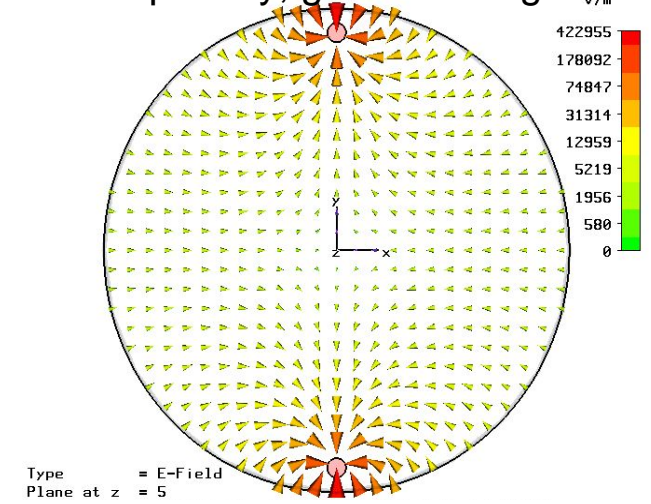
Electrodes at opposite polarity, electron cloud effect enhanced



One electrode at negative polarity, good clearing



Both electrodes at negative polarity, good clearing



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

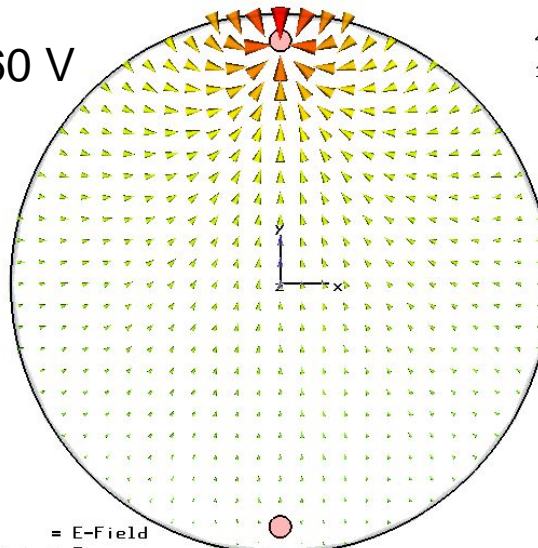
Electric field plotted [log. scale]

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

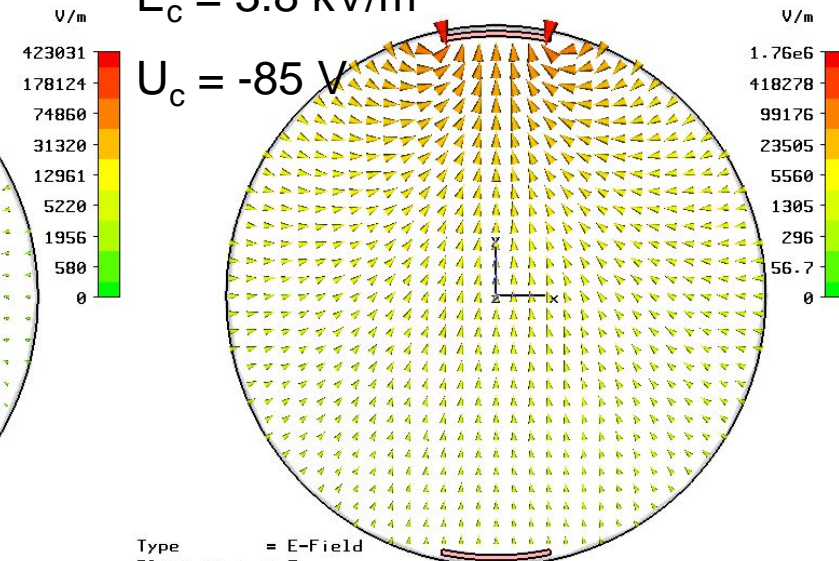
$U_c = -60$ V



Type = E-Field
Plane at z = 5
Maximum-2d = 423031 V/m at -5.75565e-015 / 47 / 3.33333

$E_c = 3.8$ kV/m

$U_c = -85$ V



Type = E-Field
Plane at z = 5
Maximum-2d = 1.76392e+006 V/m at -10.1877 / 47.9292 / 3.33333

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

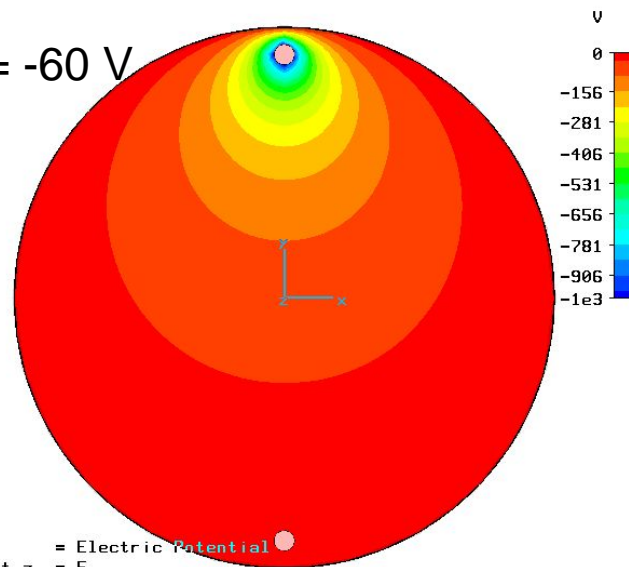
Potential plotted [lin. scale]

Left: 2 mm radius electrode
5 mm from the wall

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

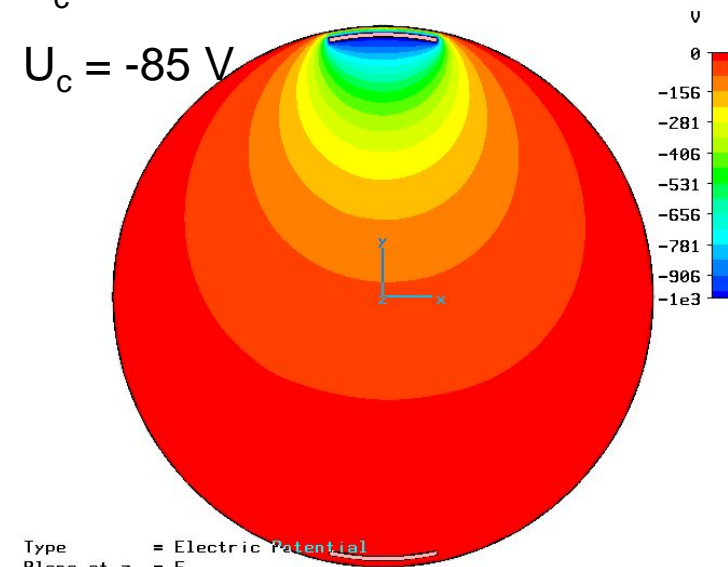
$E_c = 2.5$ kV/m

$U_c = -60$ V



$E_c = 3.8$ kV/m

$U_c = -85$ V



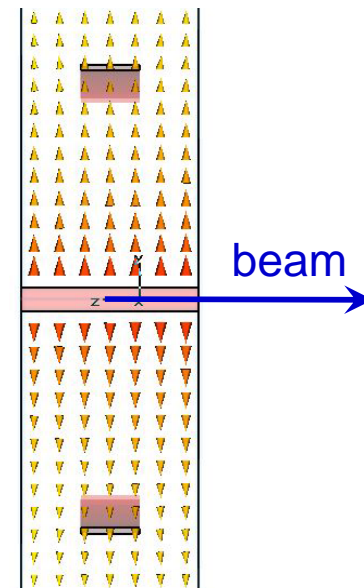
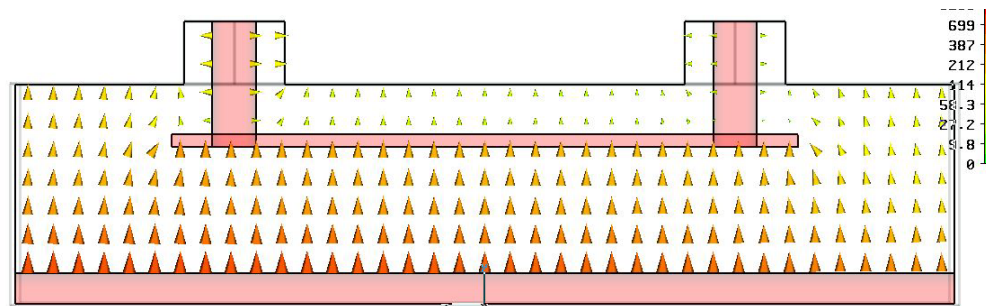
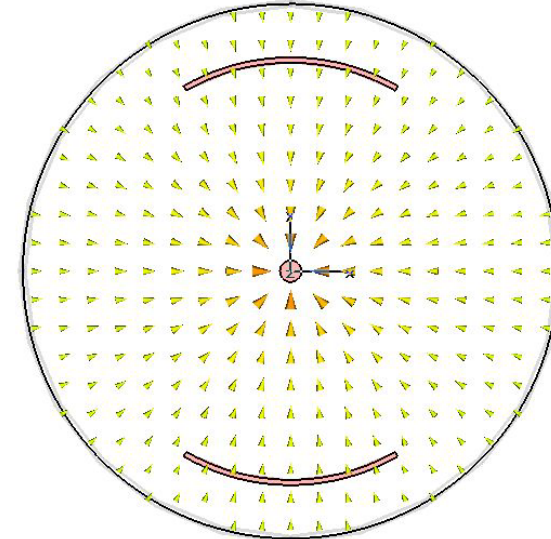
Metallic versus high resistivity electrodes

- ◆ 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)

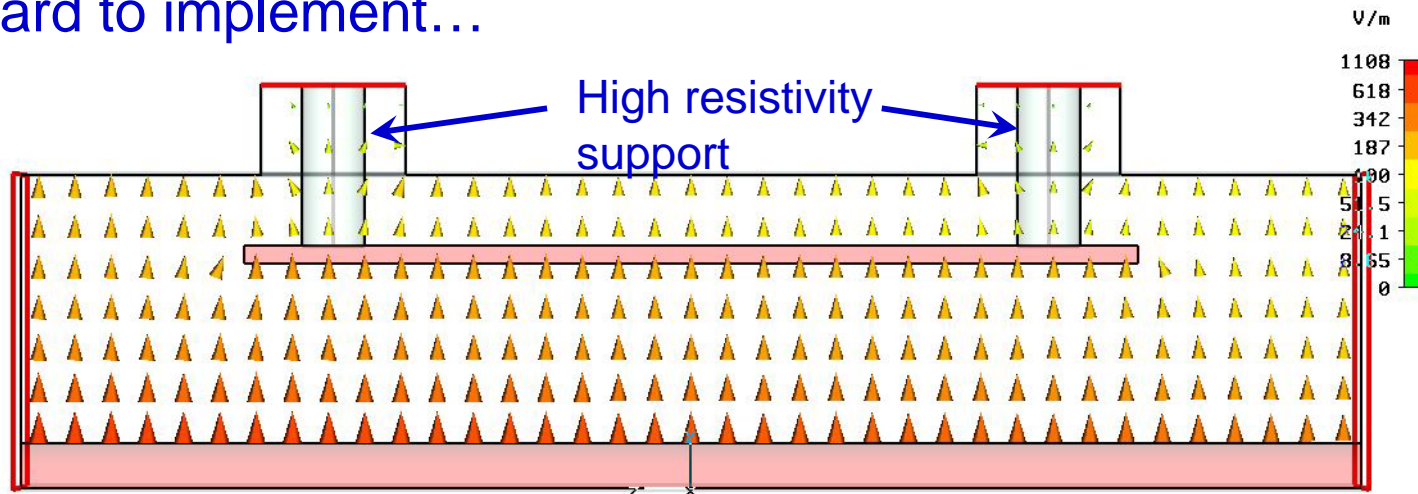
- ◆ An infinitely thin perfectly conducting electrode ideally has no longitudinal impedance, since it is normal to the unperturbed electric field and thus does not change the field pattern (electric field of wire simulation plotted on the right)
- ◆ However, once dielectric supports are inserted, the 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

Ideal floating electrode



Metallic electrode (2)

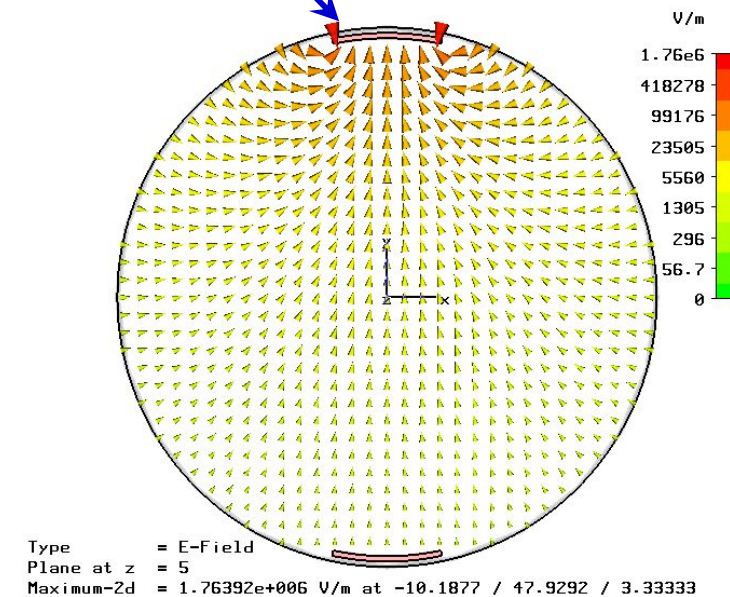
- ◆ The use of a high-resistivity connection for the clearing voltage could be possible. At high frequencies such an electrode would approximately have an open circuit on either side
- ◆ The impedance would come from any dielectric put underneath the electrode; resonances are possible!
- ◆ For impedance 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

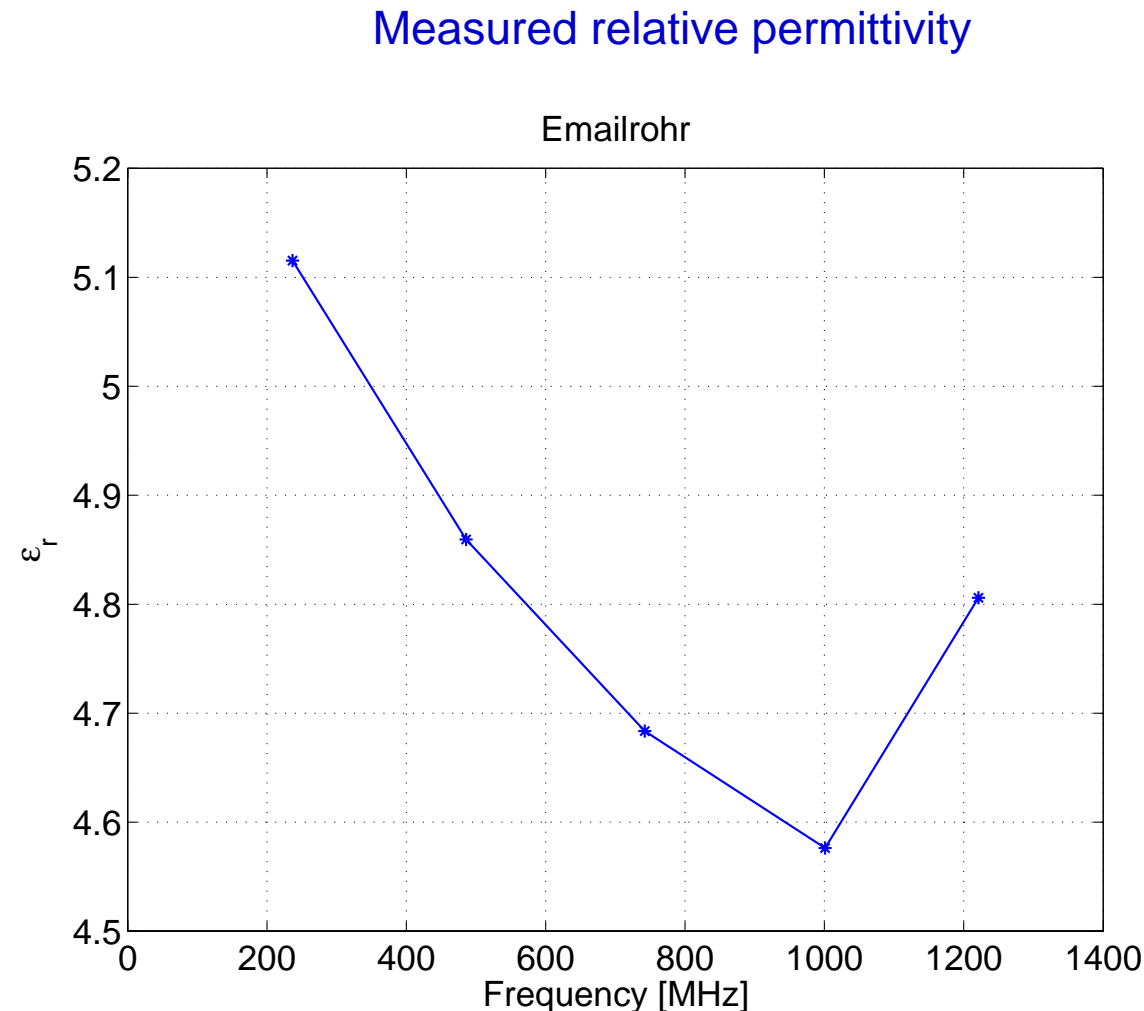
- ◆ The idea consists of building a thin electrode structure directly attached to the beam screen. Let's assume a 50 mm radius pipe.
- ◆ As the insulating dielectric a thin enamel layer can be used, e.g. a single 25 mm wide strip with 0.5 mm thickness
- ◆ On top of that a highly resistive 20 mm wide 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

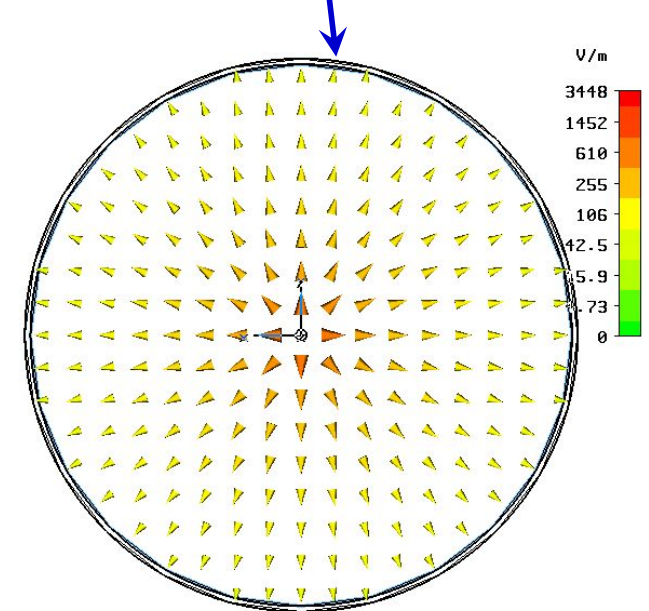
- ◆ For a sample of insulating enamel the permittivity ε in the 100 MHz to 1 GHz range was determined using a stripline resonator technique
- ◆ $\varepsilon_r \approx 5$
- ◆ The dielectric loss factor could not be reliably measured this way, since the losses were dominated by resistive losses in the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



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 \Rightarrow imaginary part of longitudinal impedance $\text{Im}(Z/n)$
- ◆ This corresponds to the change in group velocity on a TEM line
- ◆ For thin dielectric layers
 - $\text{Im}(Z/n)$ is proportional to the dielectric cross-section
 - $\text{Im}(Z/n)$ 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

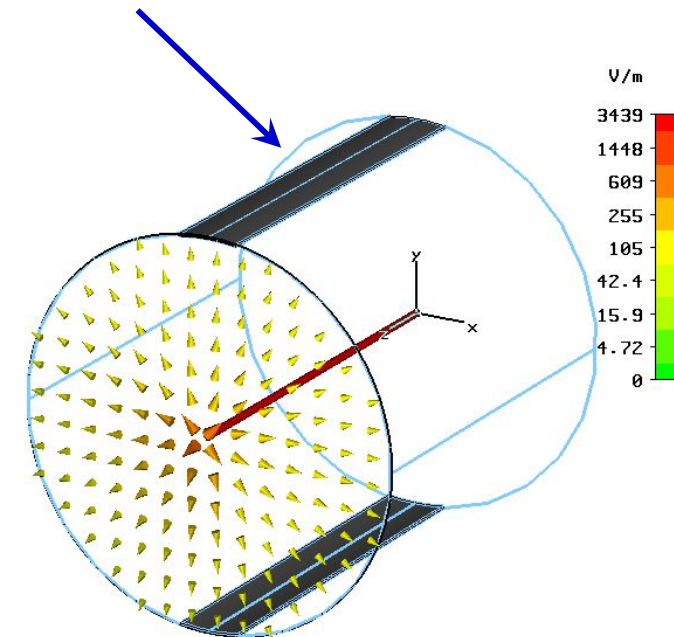


[1] B. Spataro, M. Zobov, Wake Fields and Coupling Impedance of the Daphne Electron Ring, Daphne Technical Note G-64, 2005

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 $\text{Im}(Z/n)$ is about proportional to the dielectric volume also when the dielectric does not cover the full azimuth
- ◆ $\text{Im}(Z/n)$ is flat up to very high frequencies
- ◆ Estimations for two 0.5 mm thick electrodes with $\epsilon = 5$ in a round pipe around the entire machine
 - PS (pipe radius 50 mm, 25 mm dielectric width): $\text{Im}(Z/n) = 0.7 \Omega$ (entire machine today: $Z/n \approx 20 \Omega$)
 - SPS (pipe radius 25 mm, 20 mm dielectric width): $\text{Im}(Z/n) = 2.8 \Omega$ (entire machine today: $Z/n \approx 10 \Omega$)

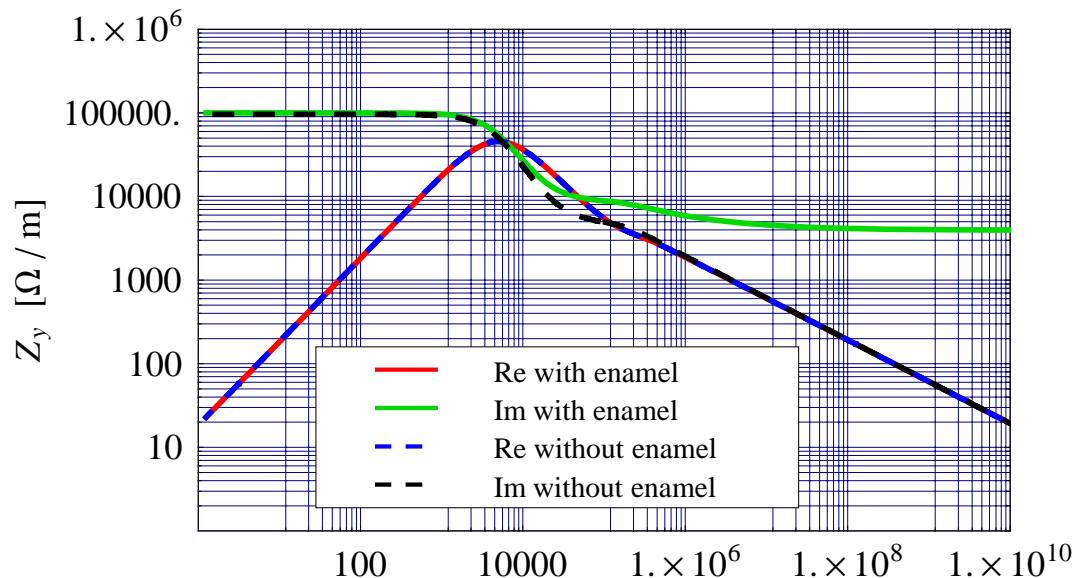
Two 0.5 mm thick dielectric strips inside a radius 50 mm pipe



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 $\text{Re}(Z_{TR})$ but a constant $\text{Im}(Z_{TR})$

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



Courtesy: Elias Metral

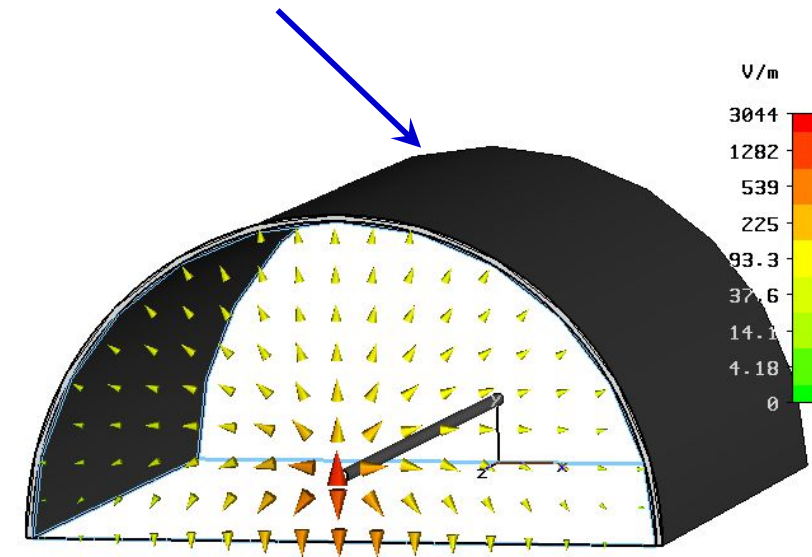
2 mm thick stainless steel pipe,
25 mm radius, 1 m length

0.5 mm thick $\epsilon = 5$ 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

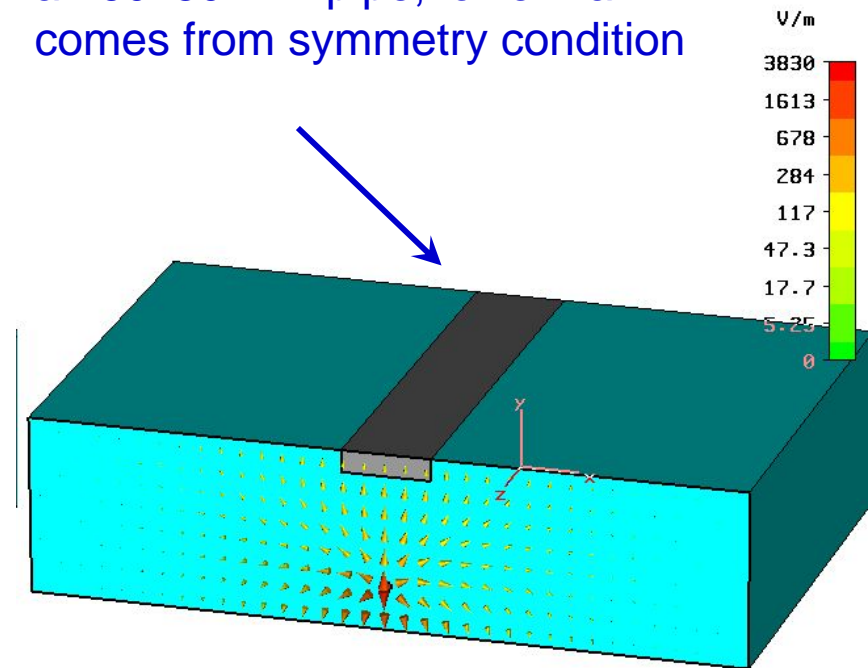
1 mm thick dielectric layer inside a radius 50 mm pipe



High resistivity electrodes – Z_{TR} (3)

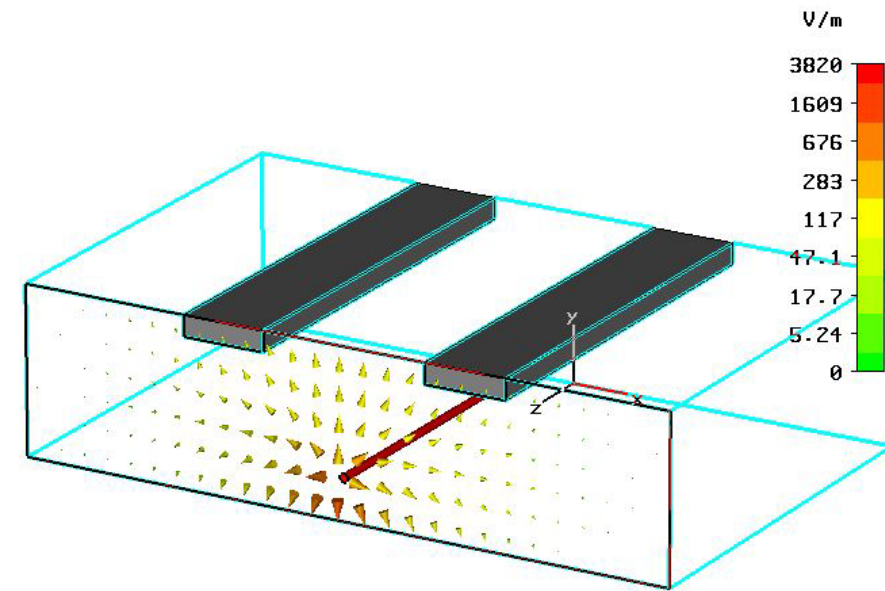
- ◆ In the following rectangular geometries were used, dimensions (like M. Furman's build up simulations):
 - PS: 80x40 mm half axes
 - SPSx: 60x20 mm half axes, same circumference as current SPS assumed
- ◆ The electrodes were made as thin as possible while checking convergence
- ◆ Preliminary results scaled to two 0.5 mm thick centered electrodes with $\epsilon = 5$ along the entire machine
 - PS (electrode width 20 mm): $\text{Im}(Z_{TR,y}) = 0.25 \text{ M}\Omega/\text{m}$ (entire machine today: $Z_{TR} \approx 5 \text{ M}\Omega/\text{m}$)
 - SPSx (electrode width 15 mm): $\text{Im}(Z_{TR,y}) = 20 \text{ M}\Omega/\text{m}$ (entire machine today: $Z_{TR} \approx 20 \text{ M}\Omega/\text{m}$)
- ◆ 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 EPCLOUD for different clearing electrode geometries
- ◆ For a magnetic field of 10 G substantial multipacting in predicted (red 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 (light blue trace)
- ◆ For a single 20 mm wide electrode 30 mm offset from the beam pipe center -1 kV does not suffice (yellow trace)

Courtesy: Frank Zimmermann

Parameters:

10 ntorr pressure, $\Delta_{\max}=1.5$

$\epsilon_{\max}=239.5$ eV

73mm x 35 mm half aperture

$\sigma_{\max}=1.58$ mm, $\sigma_{\text{y}}=0.42$ mm, $\sigma_{\text{z}}=75$ cm

10 Gauss dipole field

