IMPROVEMENT IN 3D COMPUTATION OF RF-LOSSES IN RESONANT CAVITIES

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Abstract

In 1997, a cold model of a so-called optimized proton accelerating structure was measured. It turned out that predictions of RF losses in the region of coupling holes had been dramatically under-estimated by the simulation codes. Since that time, a study made on the IPHI RFQ [1] pumping slots showed that the problem occurred when a surface current line runs along a sharp reentrant corner. This suggested a new way to compute losses and lead to an improvement in the MAFIA post-processor. We tested this new tool on the Trispal cavity geometry: the computed Q-drop caused by coupling slots is now very close to experimental values.

1 INTRODUCTION

Power losses in RF structures is a critical issue in high power accelerators for two reasons. Firstly, global losses govern both the installation cost (number of RF high-power amplifiers and associated systems) and the operating cost (electricity consumption). Secondly, local power losses in RF structures can have catastrophic consequences if the metal reaches its melting temperature. So, there is a challenge for accurate predictions of RF power losses.

The most common analysis of wall losses in resonant cavities starts with the assumption of perfectly electric conducting (PEC) walls, which together with lossfree material fillings (e.g. vacuum as assumed in the following equations) leads to real-valued eigenvalue problems: $curl\ curl\ E = (\omega/c)^2 E$. In a second step, the losses in the walls due to a finite conductivity are taken into account. As the current density in the wall vanishes rapidly in normal direction, we consider only the surface current j_s, i.e. the current density integrated along normal direction. From Ampere's law we get: $j_s=H$, in which the limit magnetic field H at the PEC surface is tangent to it ($H_\perp=0$). So, the power loss density generated by this surface current is $p=½\cdot R_s\cdot H^2$, in which $R_s=(\mu_0\omega\rho/2)^{1/2}$ is the surface resistance, ρ being the resistivity.

The present paper shows that high losses occur when a surface current line runs along a reentrant corner. What would be then the loss distribution in the vicinity of the corner? Assimilating the quasi-magnetostatic potential to the holomorph function $f(z)=K\cdot z^n$, one can prove (thanks to Eric Bertin) that the general solution of the magnetic field in the immediate vicinity of a sharp π/n angle is such as: $|H|=K\cdot r^{n-1}$. There is a singularity at $r=0$: on such a corner, current density (and also local loss) is infinite! With n=2/3 (270° inner angle), current density varies like $r^{-1/3}$ in the vicinity, and power density like $r^{-2/3}$: both of them has finite integral values, i.e. total current and loss are both finite.

2 TWO METHODS FOR LOSSES

Field and loss calculations can also be performed based on a numerical field solution, as provided by the program package MAFIA, which is based on the Finite Integration Technique [2]. The field solutions are related to a pair of staggered grids (e.g. Cartesian coordinate grids), and as a consequence, the components of the magnetic field strength are only available at distinct geometrical locations, namely the edges of the dual grid (fig.1). Thus, for computing the power loss density, some extrapolation has to be applied. The two extrapolation methods presented in this paper yield identical results for losses in infinitely extended walls, but considerably differ in the case of a reentrant corner.

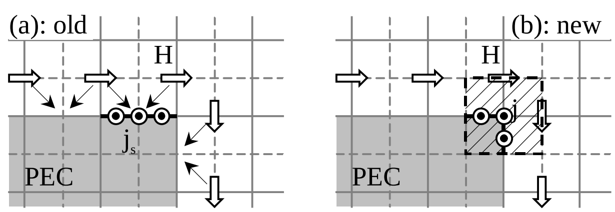

Figure 1. Two different methods for loss computation. (a): From H in neighboring cells. (b): from local H-curl.

In the 'old' method, the power loss is calculated by a facet-based algorithm. For each facet of the primary grid (solid line), which is identified as an interface between a normal and a PEC material, the neighboring magnetic field components, which is known on dual-grid (dashed lines) segments, are interpolated to be used in the loss-formula (fig.1a). In the 'new' method, the surface current related to a dual-grid cell at the interface is calculated from a discrete curl of the H-components. This current is then distributed among the corresponding parts of the interface, which may consist of parts from more than one primary facet (fig.1b). By this procedure, the total surface current remains consistent to the magnetic field solution of the FIT approach.

A fine study of equations shows that in the case of a 270° inner angle with a current line running along the edge (as on fig.1), the new method differs from the old one only for the current line on the corner itself, where a folding factor 4 appears in the loss formula. What method should be preferred ? Considering integrated current or density, the contribution of the corner cell tends to zero as the grid step size tends to zero. So, the two methods converge to the right values. But, as seen in next sections, the convergence speed is not equivalent.

3 PUMPING SLOT SIMULATION

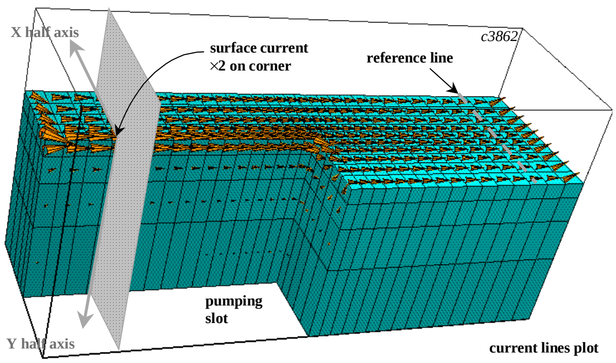

Figure 2: Surface currents deviated by a pumping slot.

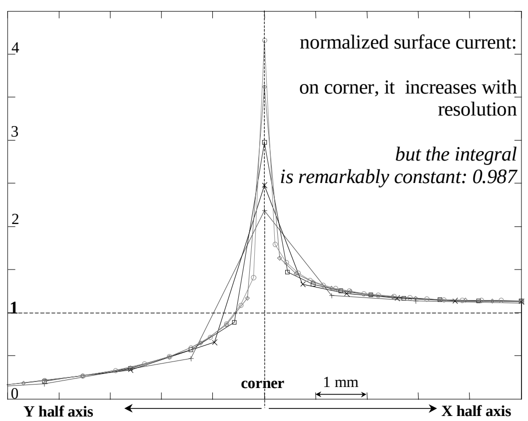

Figure 3. Surface currents for varied resolutions.

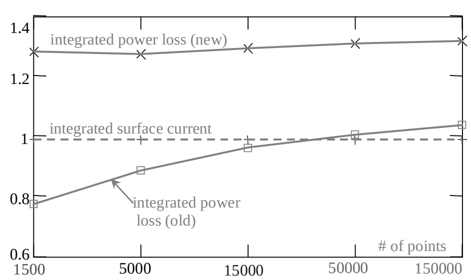

Figure 4. Integrated current and losses vs. resolution.

The progress in RF losses computing mentioned in this paper was initiated by a the study of the pumping holes for the IPHI RFQ [1]. A simplified 350-MHz cavity with an approximately uniform magnetic field on the bottom wall was simulated. Then, a rectangular hole was made in the wall in order to represent a pumping slot (fig.2). The slot length is perpendicular to the magnetic field. The slot width (5 mm) is much shorter than the wavelength: the magnetic field does not penetrate deeply inside the slot. As the slot deviates surface current lines, a higher current density is expected in the vicinity of the corner.

Five different step sizes were used near the corner: 1.4 mm to 0.21 (0.85 on fig.2). Right on the corner, computed surface current on primary-grid nodes depends on the grid step size Δx (fig.3). This is due to the singularity of the magnetic field at that spot. Actually, it varies, as expected, like $\Delta x^{-1/3}$. Normalized to the total current far from the slot (reference line on fig.2), the integrated current, is 0.987 at any resolution: the wall current is almost conserved, except 1.3 % which turns into electric field line in the slot (displacement current).

With power losses computed with the 'old' method, convergence is rather slow. The integrated normalized loss (square of normalized surface current) is even less than unity for low resolution, meaning that the slot would have globally reduced the total power! With 'new' losses, the integrated value (about 1.3) is almost step-size independent. This more credible conclusion means that the slot increases the dissipated power (in its area) by 30 %, just because of current-line concentration.

4 PILL BOX SIMULATION

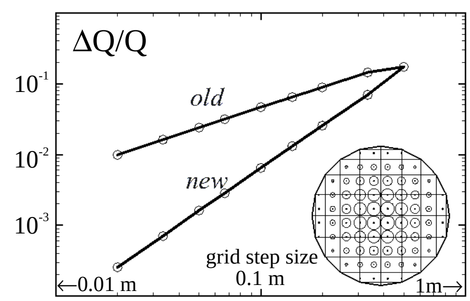

Fig 5. Q-calculation in a pillbox cavity.

The loss-computation method has also some influence on simple cavities without reentrant angles. We simulated a 1m-radius 1m-long cylindrical copper cavity (conductivity= *58 MS/m*). With this geometry, the difference between the two methods results from angles (slightly below 180°) between adjacent boundary elements. So, this test shows that the new method is also a valid improvement in the case of such quasi-flat inner angles, though it was originally developed for 270° angles. Nevertheless, one has to keep in mind that a good absolute Q value is obtained in this simple case, just because all the boundary grid steps fit on the ideal surface, which is not the case in general 3D MAFIA simulations (see next section).

Fig.5 shows the relative deviation of the simulated Q to the analytical value (81044.97) for different grid step sizes. Both method exhibit a smooth convergence to the analytical value. The new one (with consistent surface currents), however, yields not only smaller relative errors, but also a higher order of convergence.

5 EXPERIMENTAL BENCHMARK

Fig. 6. Trispal cavity cold model. The central piece (with holes) can be removed for 1-cell measurements.

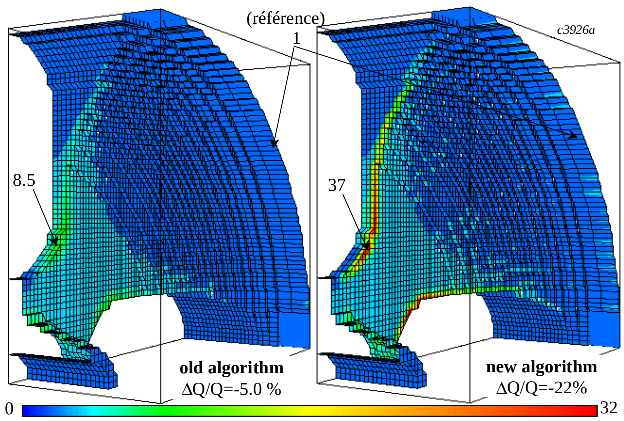

Fig. 7. Losses in the Trispal cavity (π-mode).

Table 1. Q-drop for the Trispal cavity cold model

MAFIA	old	new	measur.
single-cell Q	12236	11032	12880
ΔQ/Q (π-mode)	-5.0 %	-22.3 %	-22.5 %
ΔQ/Q (0-mode)	+11.5 %	-0.2 %	+0.9 %

Finally, the new MAFIA algorithm for loss computation was tested on the Trispal cavity cold model (fig.6) for which accurate experimental data are available [3,4]. It is a 2-cell cavity in which cells are coupled through 4 "petal" holes. It can be mounted in a single-cell configuration to measure the coupling hole influence on Q and frequency. Even if the absolute Q is degraded by the electrical contact in the seal and the surface quality, the ΔQ/Q (defined vs. a single-cell, for a cavity with coupling holes on both side of the cell) is significant.

The new method emphasizes losses on the coupling hole corner (fig. 7): maximum local loss is much higher than with the old method. This maximum computed value is uneasy to interpret, because it depends on resolution. But in the real world, the maximal loss value depends on the corner radius. So, we interpret the computed loss on corner as the actual value in real cavity with an effective corner radius in the range of the grid-step size.

As seen in table 1, Q-drop caused by coupling holes is correctly predicted by the new method for both 0 an π modes. This success shows that the new method gives much more reliable predictions for local losses.

On the other hand, the absolute 1-cell Q is lower than measured, though it should be a little higher (about +5%, according to Superfish) because of surface imperfections and contact quality. Unfortunately, the new algorithm re-enforces the underestimation of absolute Q's, probably because the rectangular grid imposed by MAFIA generates a rough surface with many fake corners.

6 CONCLUSIONS

With the new MAFIA post processor method for loss computations, power loss predictions are much more accurate in critical regions such as re-entrant corners. Indeed, relative Q-drops caused by slots have been computed with accuracy.

On the other hand, global Q values may still not be accurately predicted in complicated geometry because of the rough surface generated by the MAFIA rectangular mesh. This inconvenient should vanish in the future "CST Microwave Studio" software, which is using a new partially filled cell algorithm (PBA) solving the staircase approximation problem [5].

Re-entrant corners cause a dramatic increase of power loss density (when current lines are parallel to the edge). The real peak loss density on corner depends on corner radius (like $r^{-2/3}$). Its value can be somewhat estimated by applying a correction factor from the MAFIA computed value: $(\Delta x/r)^{2/3}$, in which Δx is the local grid step size. If the old algorithm is used, the correction factor has to be further quadrupled. This correction is only valid for peak loss density, and has not to be used for global losses.

Thermal analyses of the IPHI RFQ using these newly computed losses as inputs are currently underway. Our main concerns are pumping grids, vane end undercuts and RF power input ports [6].

REFERENCES

[1] R.Ferdinand et. al., "Status report on the IPHI RFQ", this conference (linac2000, Monterey).
[2] T. Weiland: "On the Numerical Solution of Maxwell's Equations and Applications in Accelerator Physics", Particle Accelerators 15, 1984, pp. 245-291.
[3] P. Balleyguier, "Coupling slots without shunt impedance drop", Linac'96, Geneva, p. 414.
[4] P. Balleyguier, "Coupling Slots Measurements Against Simulation For Trispal Accelerating Cavities", Linac'98, Chicago, p.130.
[5] "MAFIA" and "CST Microwave Studio": available from CST GmbH, Germany (www.cst.de).
[6] P. Balleyguier, "3D Design of the IPHI RFQ cavity", this conference (linac2000, Monterey).