REALISTIC EVALUATION OF LOCAL FIELD ENHANCEMENT BASED ON PRECISION PROFILOMETRY OF SURFACE DEFECTS

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Abstract

The limitation of accelerating gradient is one of the current major issues in preparation of high-gradient superconducting RF accelerator structures for the International Linear Collider. Although some of accelerator structures happen to reach high gradients, many are still limited to low gradients by field emission and thermal breakdown due to surface imperfections. Magnetic field enhancement at geometrical surface defects can give rise to thermal breakdown through local heating at low gradients. Profilometry-based defect modeling has been developed and applied to a realistic evaluation of local field enhancement effect.

LIMITATION OF ACCELERATING GRADIENT

Owing to development of high purity material production and improvement of surface processing technology, the maximum accelerating gradient achieved in superconducting niobium RF structures has been escalating. KEK has been fabricating, processing and testing 9-cell structures for the International Linear Collider as well as single-cell test cavities. Although some of single-cell cavities and a few of 9-cell structures have occasionally seen accelerating gradients over 50 MV/m and 40 MV/m respectively, many are still limited to lower gradients. Gradient limitations today are mainly attributed to field emission and thermal breakdown due to surface imperfections.

It is known that the fundamental limitation of accelerating gradient is set by quench or breakdown of superconductivity which happens even to a perfect superconducting surface when surface magnetic field exceeds a certain RF critical magnetic field. Thermal breakdown, however, takes place at lower gradients in the presence of surface imperfections including geometrical surface defects.

KEK is making an extensive effort to clarify mechanisms of low gradient limitations and to improve the gradient performance. Effects of geometrical surface defects are also under investigation.

PROFILOMETRY-BASED MODELING OF DEFFECTS

Magnetic field enhancement at small surface defects can give rise to thermal breakdown at low gradients through local heating. However it needs simulating field enhancement effect and thermal behavior to determine if a suspicious defect is really responsible. A simulation with an imaginary simple geometrical model is totally unrealistic since real existing defects have complicated and irregular geometries. A realistic simulation requires a high-fidelity modeling which should be based on microscopic precision profilometry of existing defects.

An event of thermal breakdown is accompanied by a temperature rise on a cavity wall surface, making a hot spot, which is detected and localized by thermometry with a temperature mapping system wrapping the cavities. Surface defects are often found in hot spot areas. Replicas are molded in resin pressed to defected surfaces and laser-scanned for profile measurement [1]. Figure 1 presents an example of height map of a defect replica. Height is actually depth since molding is a reverse transcription.

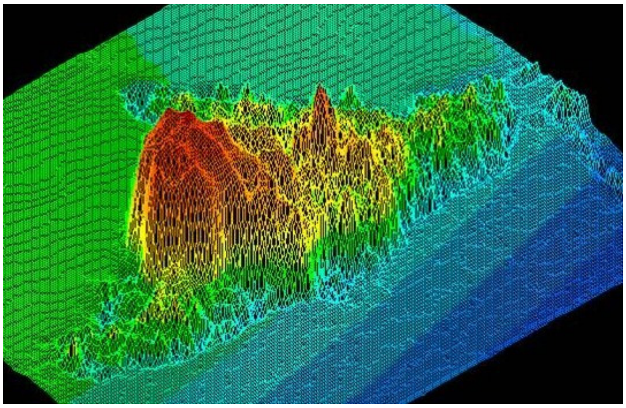

Figure 1: Laser-scanned height map (taken by K. Watanabe). The scan pitch is 0.72825 μm and the height resolution is 0.01 μm. Seen here is a convex replica of a concave surface defect found in a TESLA-type 9-cell structure (MHI-08) which suffered thermal breakdown at 16 MV/m. The size of defect is about 600 μm in length, 300 μm in width and 100 μm in depth. Height (or normal dimension) is emphasized in comparison to horizontal (or tangential) dimensions.

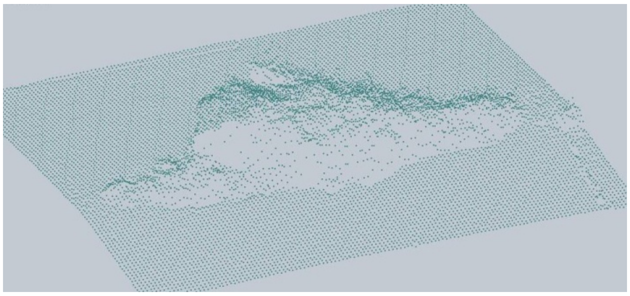

Figure 2: Point cloud representing surfaces of defect.

Raw data of height map needs pre-processing to reduce noise and data size, and it also needs converting into a

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point cloud such as shown in Figure 2 in advance of processing for modeling.

The generated point cloud is imported into a CAD modeler to make curves and to form a mesh. Figure 3 shows an example of mesh composed of polygons.

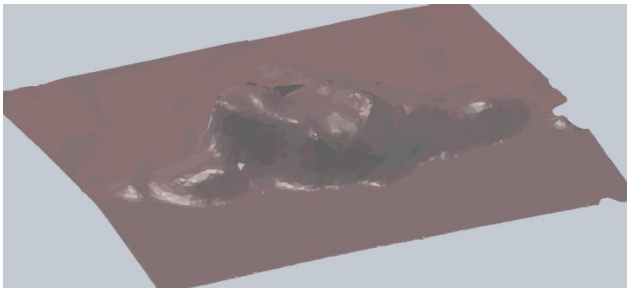

Figure 3: Mesh made up of polygons covering the point cloud.

Surfaces are fit to the mesh and then extruded to form a solid. A solid model of defect is finally implanted in a cavity model, reproducing a geometry of a defected cavity as shown in Figure 4.

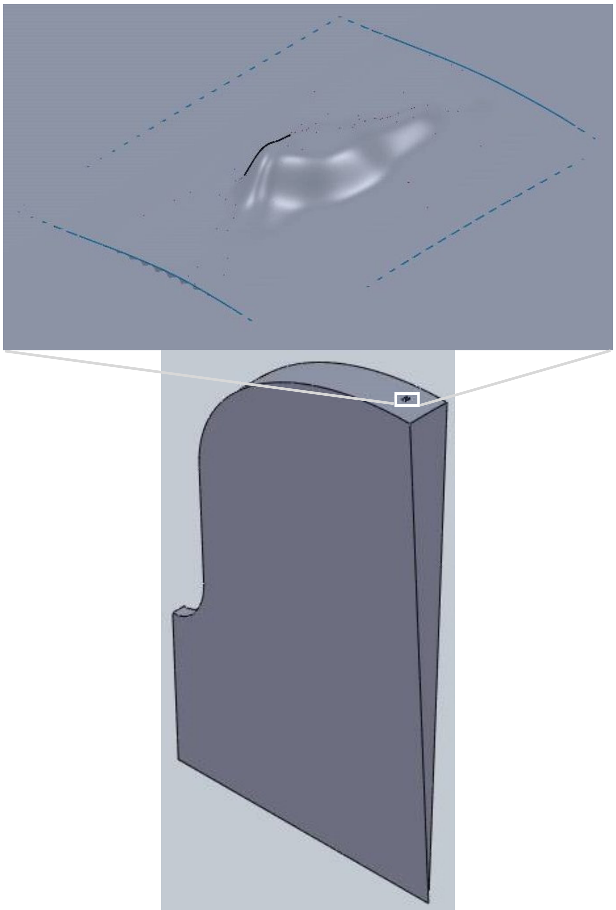

Figure 4: Solid model of defect (magnified view above) implanted in a surface layer of a sector of the cavity model.

The cavity model seen here has only a sector geometry, which is, however, sufficient for computation of field analysis since introduced field asymmetry and distortion are localized only in the vicinity of a defect. The validity of sector geometry has been examined in a preparatory study [2].

HIGH-RESOLUTION FIELD ANALYSIS

The model of a cavity with a surface defect is meshed so finely that the element model can keep a high fidelity to the real geometry and can give a sufficient resolution to field analysis particularly at and around the defect. The example shown in Figure 5 has a maximum element size of the order of 100 μm in the cavity interior volume, of the order of 10 μm on the cavity surface and of the order of 1 μm at the defect. The total number of elements amounts to about 1.4 million.

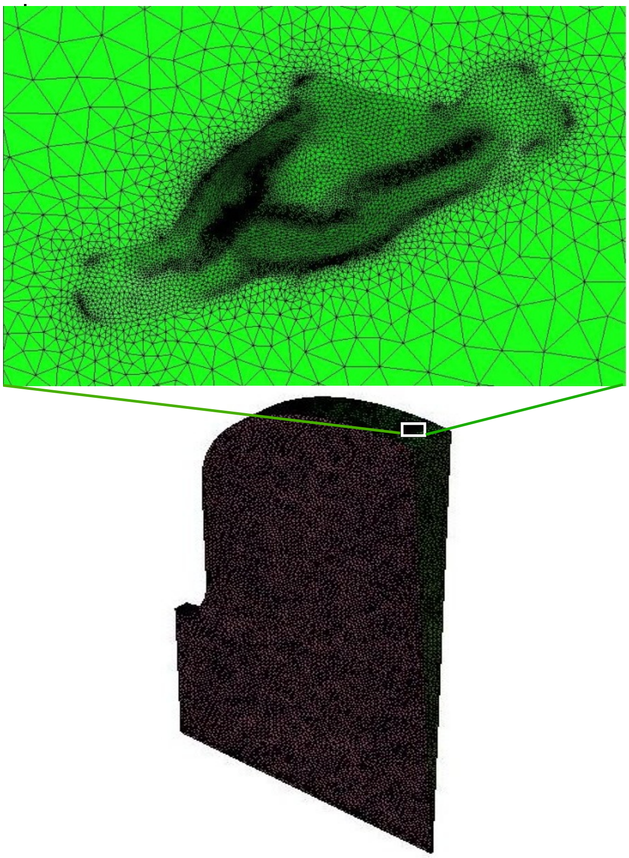

Figure 5: Element model with a high-density mesh. Higher density is applied locally to the defect region (magnified view above) in order to precisely compute fields there in detail. The size of defect is about 600 μm in length, 300 μm in width and 100 μm in depth.

Computed surface magnetic field is plotted on a contour map in Figure 6. An edge of the defect gives the maximum surface magnetic field with an enhancement factor of 1.5.

A TESLA-type 9-cell structure is supposed to have a field ratio Hsp/Eacc of 42.6 Oe/(MV/m) [3], where Hsp is the peak surface magnetic field and Eacc is the accelerating gradient. Assuming a critical RF magnetic

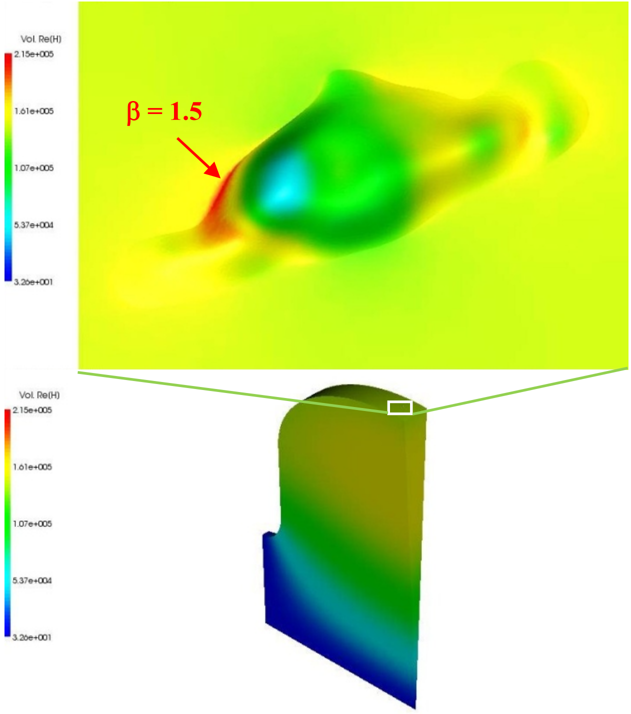

Figure 6: Magnetic field contour. The maximum surface magnetic field appears at an edge of the defect (magnified view above) as a result of field enhancement effect, where the enhancement factor β is 1.5.

field of 1900 Oe which is derived from a ratio Hsp/Eacc of 35.5 Oe/(MV/m) and a gradient of 53.5 MV/m attained in single-cell cavities of KEK high-gradient model (so-called Ichiro) [3], the accelerating gradient should be limited below 29.7 MV/m (= 1900 Oe / 42.6 Oe/(MV/m) / 1.5). In addition the limit can be further lowered to 16 MV/m by local heating and thermal or thermo-magnetic instability.

REMARKS

Profilometry-based modeling of surface defects has been developed and applied to local surface field analysis. It virtually reproduces complicated geometries of actually observed surface defects and provides realistic models for precision computation of local fields in detail. High-resolution field analysis with this high-fidelity defect geometry gives a reliable value of local field enhancement factor.

Coupled multi-physics analysis covering thermal processes is now ongoing for further quantitative understanding and interpretation of the experimentally observed gradient limitation due to thermal breakdown by geometrical surface defects.

REFERENCES

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