Optimized cavity shape for TESLA

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Main topics

- Limitations of fields in the TESLA cavities today:

  E-limit and H-limit
- The Code and Geometry for calculations
- Results of calculation: Optimization Curve
- Multipacting Calculations and FabricationOne step more: Sliding Phase Structure (SPS)
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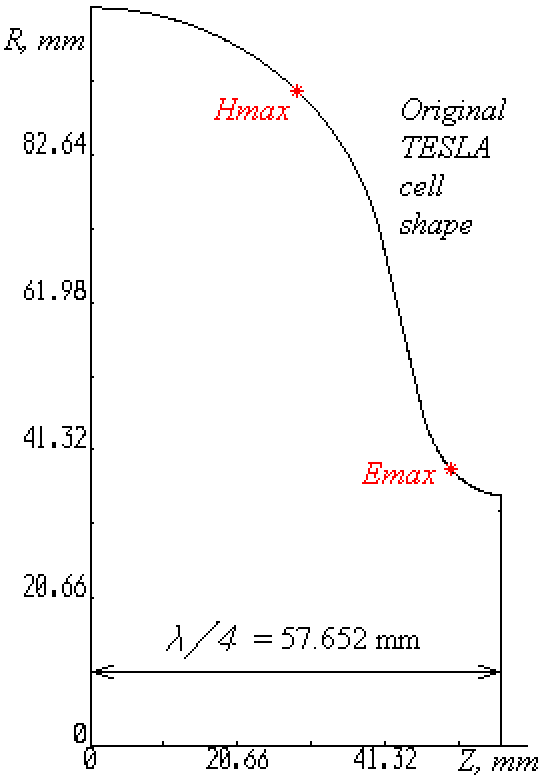
- Summary of results, Conclusions

Limitations of fields in the TESLA cavities today: E-limit and H-limit

- TESLA 9-cell cavities today reach
  Eacc = 35 – 37 MV/m needed for
  the 800 GeV to 1 TeV upgrade.
  The limit is set by quench at high magnetic
  field, or Q-slope at high magnetic field
  (37 MV/m <-> 1554 Oersted)
- Although field emission is present, it doesn't present a brick wall limit.
  Because
  - high pressure Water Rinsing eliminates field emission by eliminating the field emitters (particles)
  - high power available for beam can be used to burn up any residual emitters
- **This means: *Esurface* is not as important as *Hsurface*!**



Equalization of limits

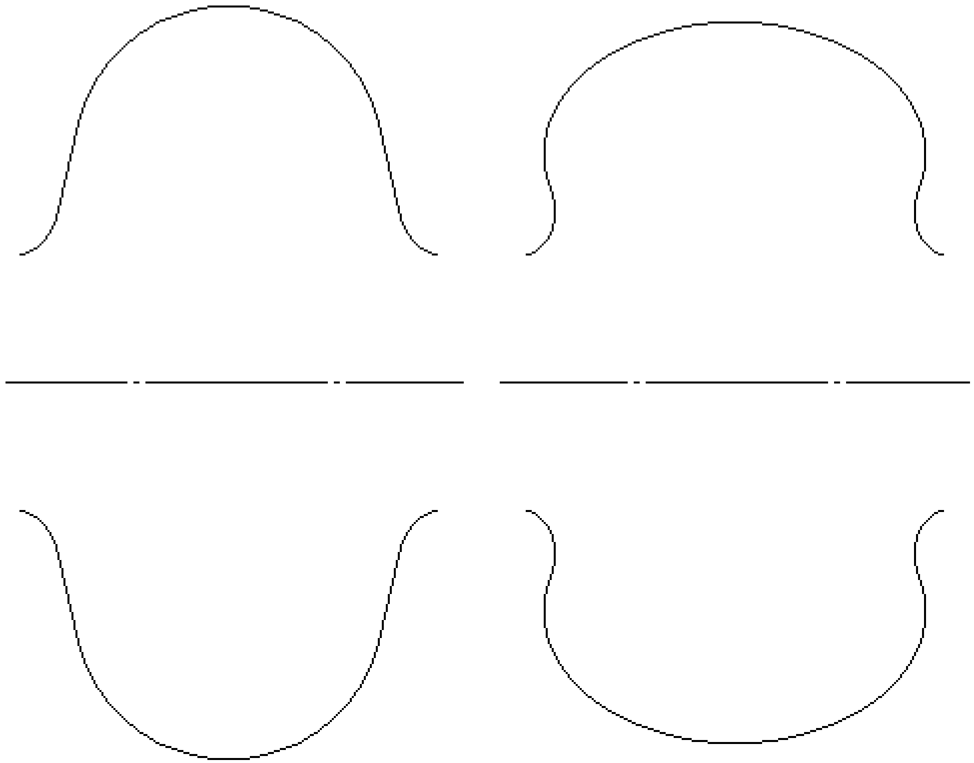
- We look for cavity shapes with lower ***Hsurface/ Eacc*** than the TESLA shape, even if we have to sacrifice ***Esurf.***
- The goal is to lower ***Hsurf*** by at least 10%. (37 MV/m would translate to >**40 MV/m**!)
- This is better than superstructure which increases effective ***Eacc*** by increase the filling factor of cavity/cryostat.

  The gain for superstructure is 6 %.
- Two major ideas:

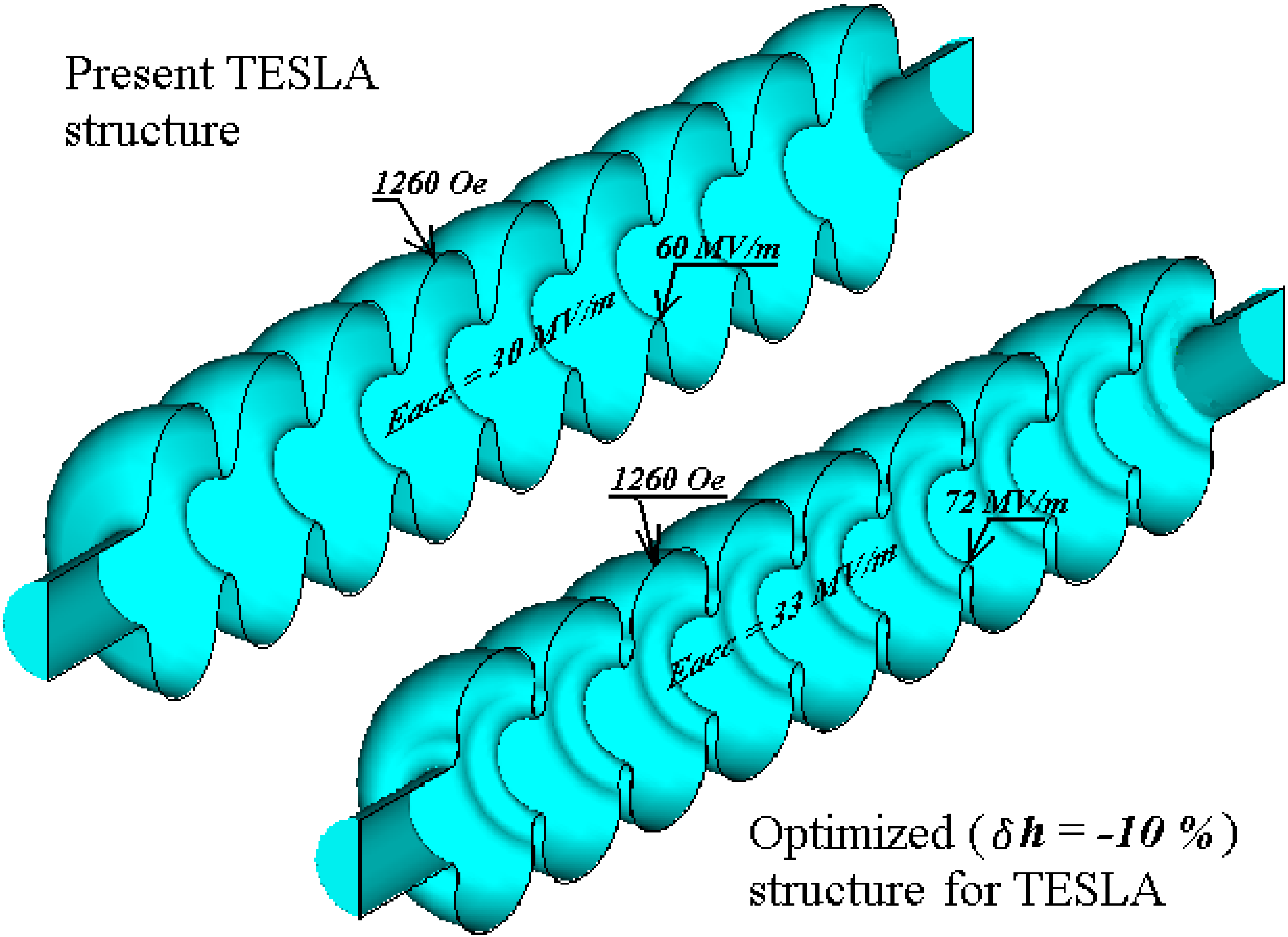
  - re-entrant shape

  - sliding phase
- It may be possible to combine these two ideas and the idea of SuperStructure and get larger gain

Present TESLA shape and shape with a 10% lower magnetic field



In the following we show that the maximal magnetic field can be decreased by 10 % if the maximal electric field is increased by 20 %. The change in the cell shape for this exemplary case is presented in Fig.


Present TESLA
structure
1260 Oe
60 MV/m
Eacc = 30 MV/m
1260 Oe
72 MV/m
Eacc = 33 MV/m
Optimized (δh = -10 %)
structure for TESLA

Some definitions

For comparison of different shapes one can use the ratios of the peak electric and magnetic field strength on the cell surface to the acceleration rate achievable in the given cell:

$$E_{pk}/E_{acc} = E_{pk}/(\Delta W/L) = E_{pk}/(2\Delta W/\lambda), \qquad H_{pk}/E_{acc} = H_{pk}/(2\Delta W/\lambda)$$

Here ΔW is the energy gain (in volts) obtained at the cell length L equal to half wavelength (π-mode).

For the TESLA accelerating cavity these values are [2]:

$$E_{pk}/E_{acc} = 2.0, \quad H_{pk}/E_{acc} = 42\ \mathrm{Oe}/(\mathrm{MV/m})$$

We will compare values of calculated fields with these values and introduce for this purpose the normalized peak electric and magnetic fields:

$e = E_{pk}/(2E_{acc})$, $h = H_{pk}/(42E_{acc})$. So, for the regular TESLA cells [2] $e = 1$, $h = 1$.

[2] TESLA Test Facility Linac –Design Report. Editor D.A.Edwards. DESY Print, March 1995, TESLA 95-01.

The code …

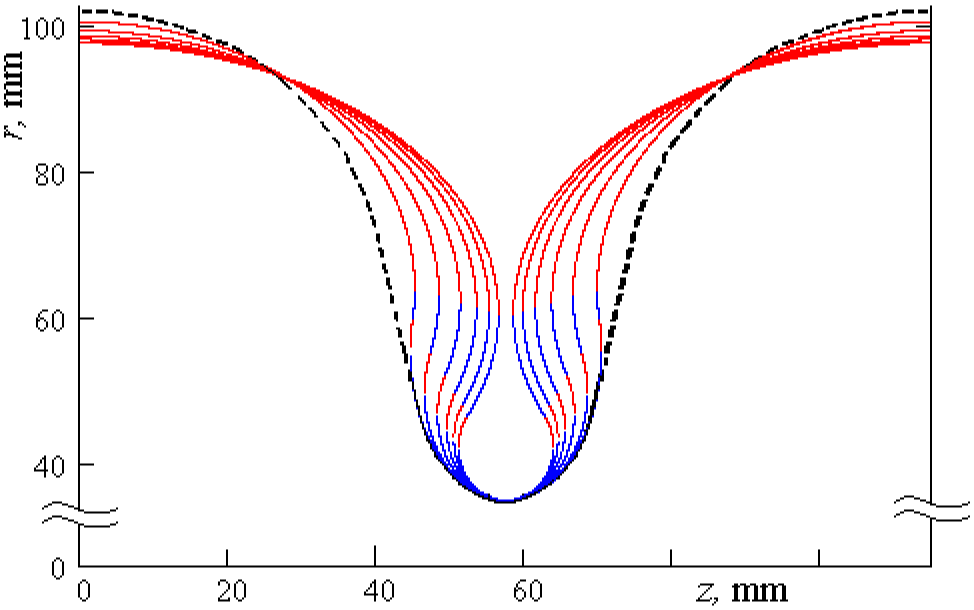
- We used for optimization the SLANS code [3]. With SLANS we can expect accuracy better than 0.1 % for field ratios [4].

[3] D.G. Myakishev, V.P. Yakovlev. The new possibilities of SuperLANS code for evaluation of axisymmetric cavities. 1995 PAC and Int. Conf. on High-Energy Accel. May 1-5, 1995. Texas. Pp. 2348-2350.

[4] S. Belomestnykh. Spherical cavity: *Analytical formulas*. *Comparison of computer codes*. Cornell University LNS report SRF 941208-13. 1994.

…and geometry for calculations

- The profile line of the original TESLA cell is constructed as two arcs: elliptic and circular, and a segment of a conjugated straight line between them (the dashed line in Fig). It is felt that more intricate line could give better values of *e* and *h*.



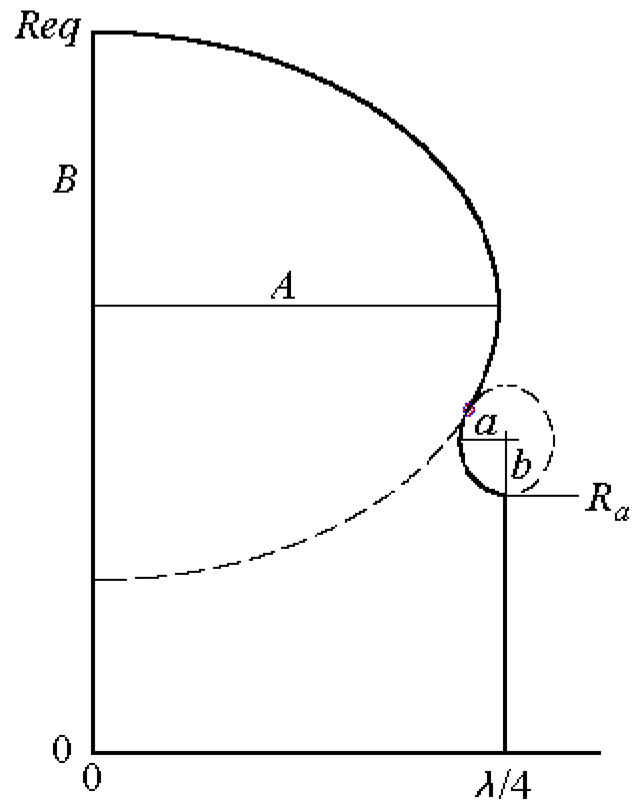
Two conjugated ellipses: one for *E*, another for *H*

Reducing the peak *electric* field by shaping the iris edge in an ellipse has already been explored a long time ago [7]. Let us now apply an ellipse to the inductive part of the cell to address the possibility of reducing the *magnetic* field.

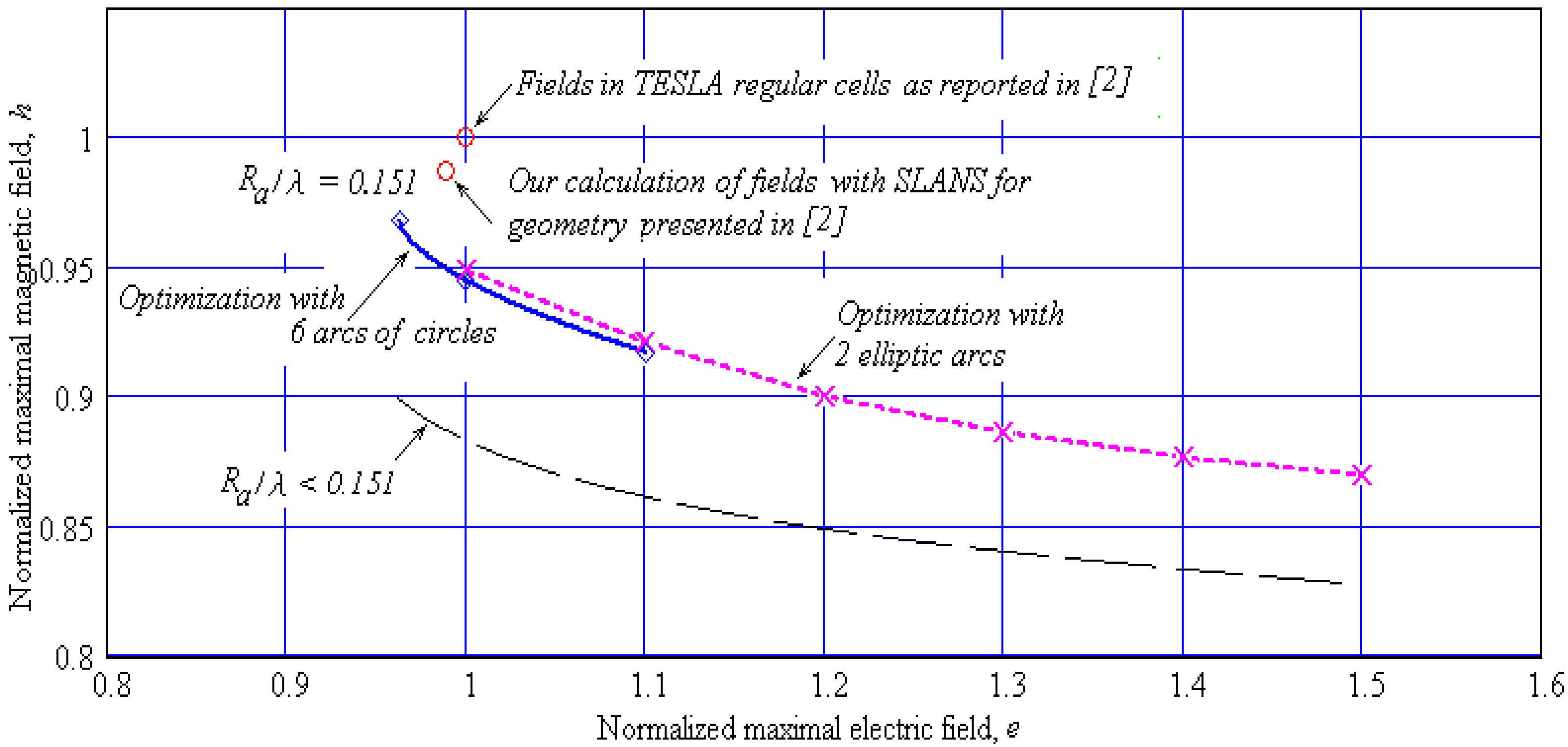
[7] M.M. Karliner, O.A. Nezhevenko, B.M. Fomel, V.P. Yakovlev. *On the problem of comparison of accelerating structures operated by stored energy*. Preprint of INP 86-146, Novosibirsk, 1986.

More about ellipses

- After initial optimization the straight line conjugated to both ellipses vanished (maybe not for all further cases!) and we ended up with the shape of the regular cell consisting of two conjugated elliptic arcs. Now we have **only 3 independent variables** to search for the optimum:
  - 2 half-axes of one ellipse (*A, B*) and
  - one half-axis (*a*) of another ellipse
- because the conditions for the frequency, and the length of the cell define other dimensions:
  - another half-axis (*b*) and
  - the radius of the cell equator *Req*.
- The aperture was taken as in the TESLA cell, *Ra* = 35 mm. This keeps the wakefields nearly the same.

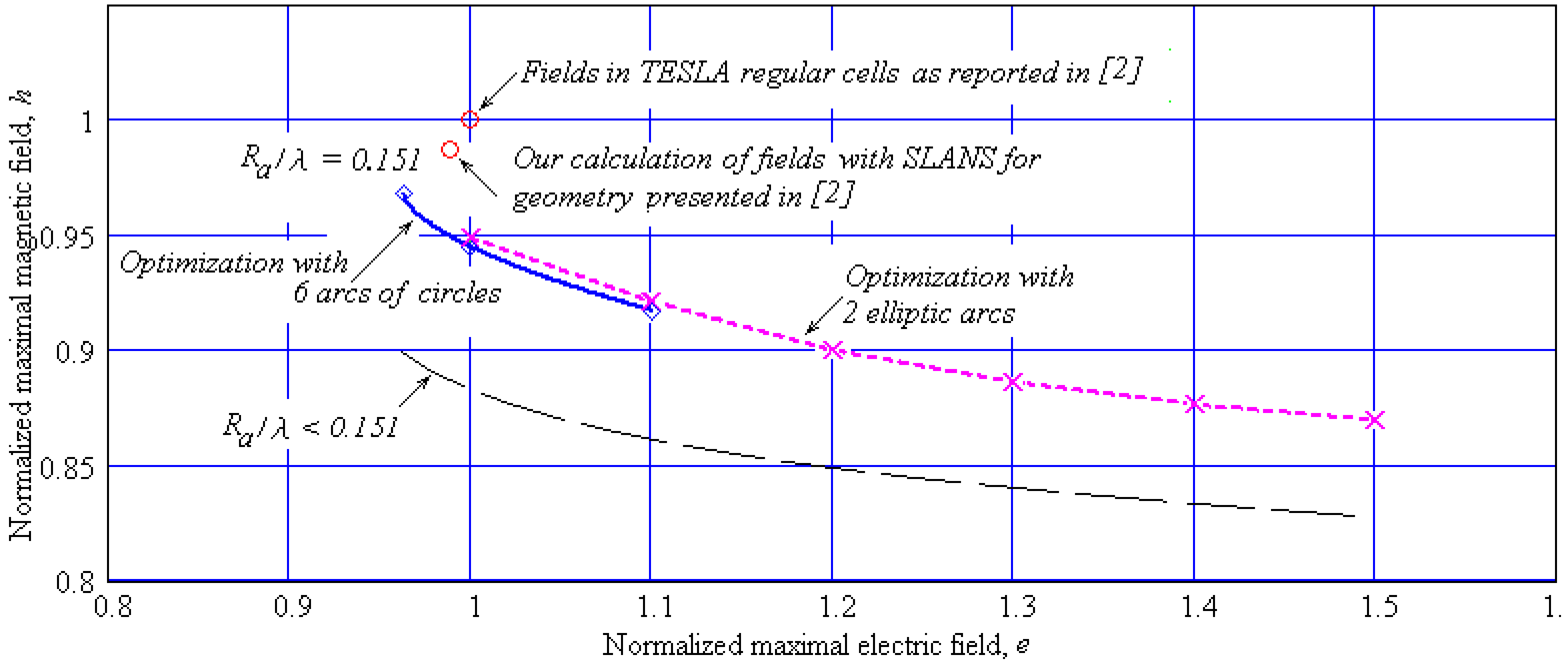


Optimization curve for TESLA inner cell geometry



The process of optimization consists in searching a cell shape with a minimal value of the peak normalized surface field in a cell. The optimized parameters are ***Epk/Eacc*** and ***Hpk/Eacc*** (or *e* and *h*). If we want to avoid high ***E*** field then go Left. If we want to avoid high ***H,*** go Right.

Optimization curve for TESLA inner cell geometry (2)



The results obtained by optimization can be used at any operation frequency because the values of ***e*** and ***h*** depend on the shape only, not on the dimensions of the resonant cavity. On the other hand, the value of the critical field ***H*** depends on the frequency and the choice of the working point on the curve can be different for different frequencies.

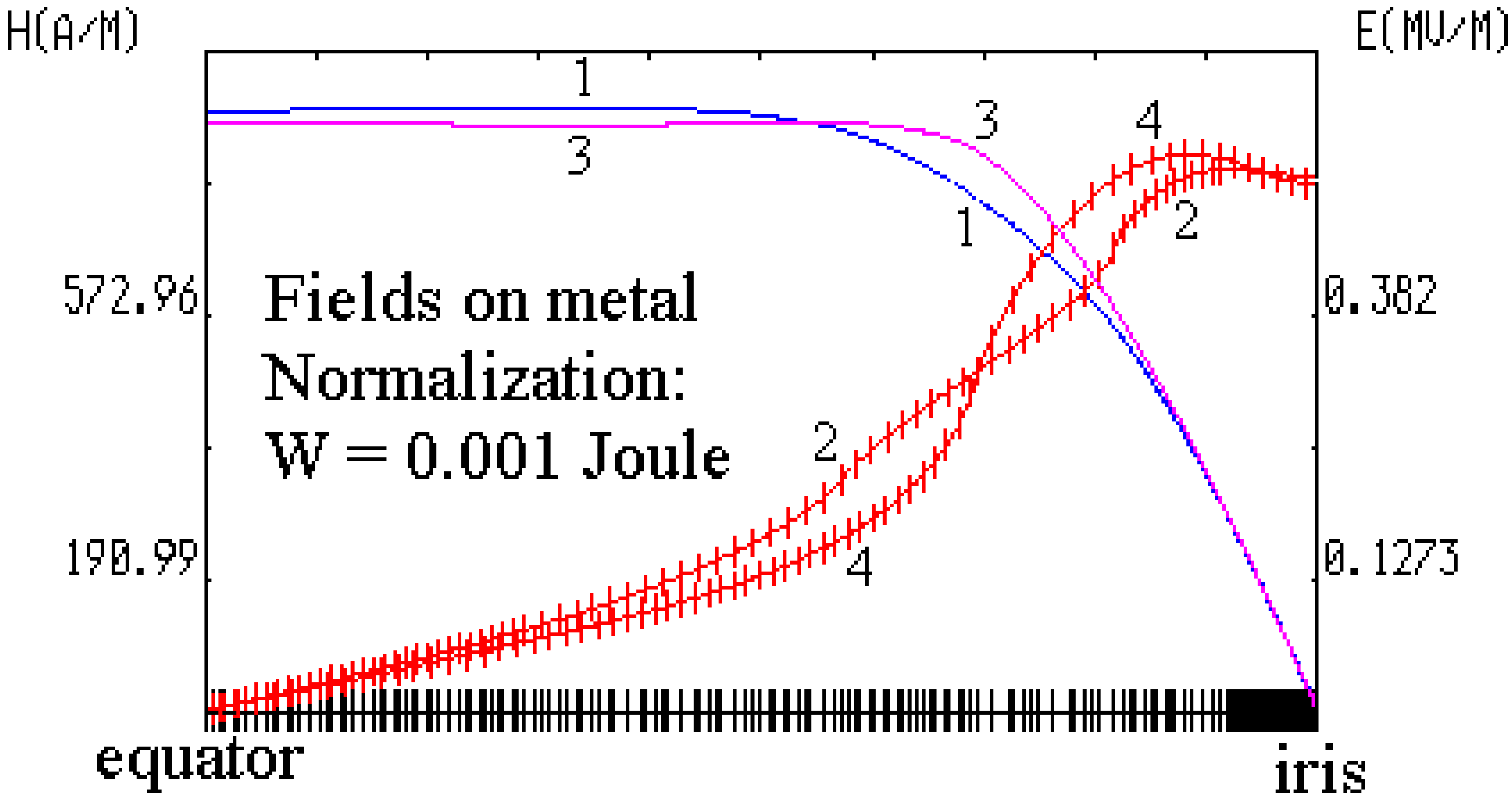
For different ratios of the aperture to the wavelength, ***Ra/λ***, the optimization curves will be different: the larger values of ***h*** for a given ***e*** on these curves will correspond to larger values

of ***Ra/λ*** . It would be useful to have a map for different values of this ratio.

δe (%)	δh (%)	*k* (%)	*d* (mm)
0	-5.07	1.90	24.80
+10	-7.92	2.10	18.30
+20	-10.00	2.38	12.52
+30	-11.36	2.64	8.14
+40	-12.30	2.88	4.74
+50	-12.99	3.06	2.18

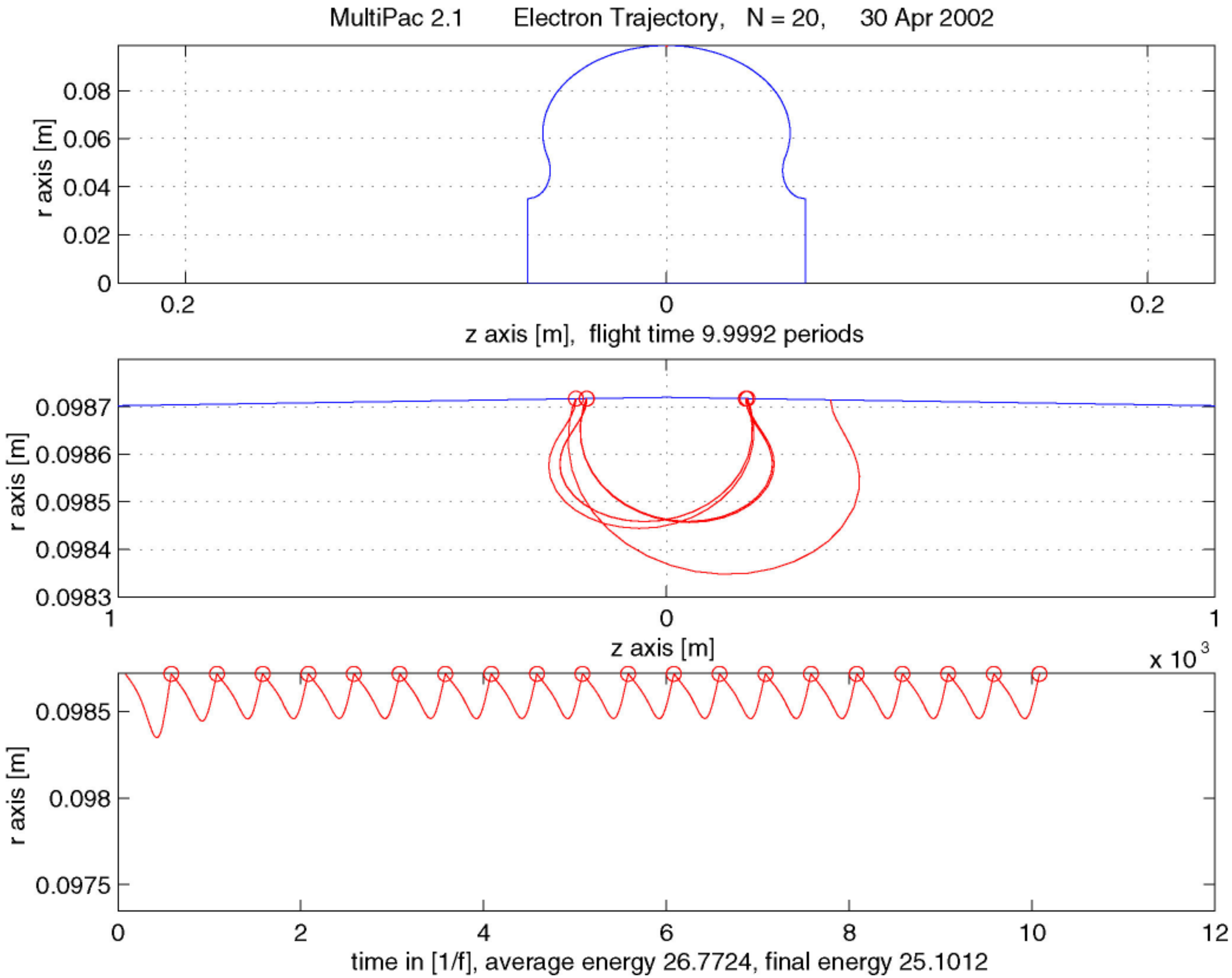
Table 1. δe, δh – change of normalized electric and magnetic fields by optimization with two elliptic arcs, ***k*** – coupling coefficient, ***d*** – minimal distance between the walls of cells.

Fields on the surface of the TESLA cell



The abscissa begins at the cell equator and ends at the iris center. 1, 2 – magnetic and electric fields of the original cell; 3, 4 - magnetic and electric fields of the optimized cell with $e = 1$.

Multipacting Calculations



Fabrication

1300 MHz reentrant cavity cups.

The reentrant shape is a challenge for fabrication. However, two cups were successfully formed by deep drawing 3 mm thick RRR300 sheet Nb, annealed (1200 C, 4 hr , ->RRR500), and welded to beam tubes. We plan to electropolish them before the final equatorial weld.

Some other technological details will be given in the next report (Rongli Geng).

Sliding Phase Structure

TESLA is a π–mode structure. Its cell length is $L0 = \lambda/2$.

Each cell accelerates the bunch.

<u>If we make the cell length *L > L0*</u>, then the phase of the bunch will change in each cell. If the structure is long, we will have a small acceleration in sum.

But TESLA has 9 cells only.

<u>If we make the cell length *L > L0*</u>, then we can increase the value of accelerating voltage *Uacc* of this cell. We can decrease the ratio *Hpk/Eacc* keeping the same *Epk/Eacc* or sacrifice *Epk/Eacc* and even more decrease *Hpk/Eacc*.

If the central cell of a structure has energy gain equal to Uacc,0 then the neighbor cells have (because the phase *slides* from cell to cell)

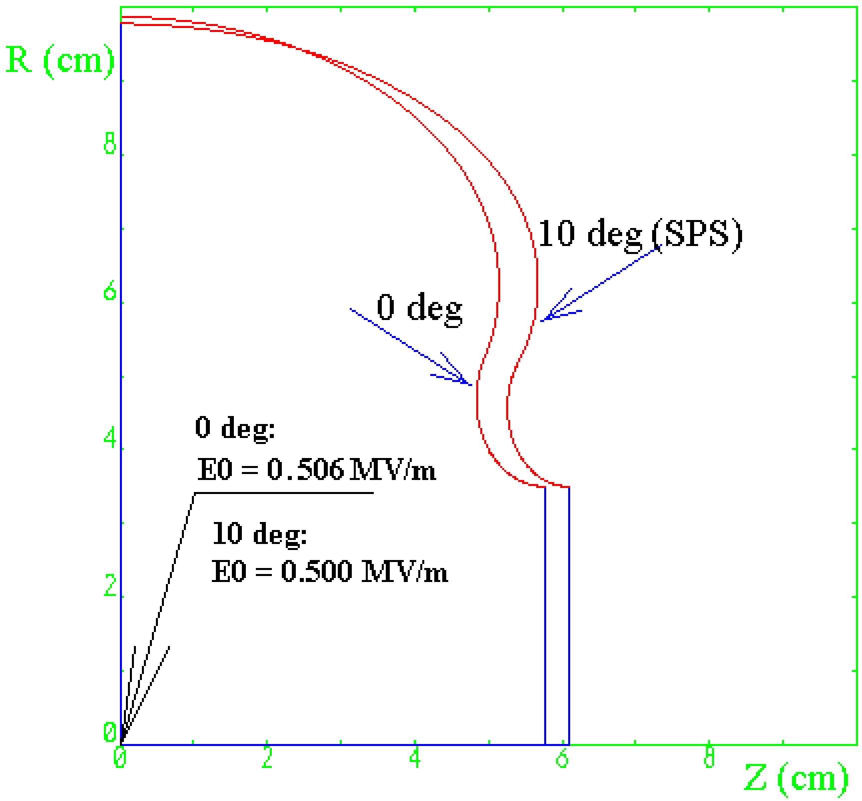
Uacc, +/-n = Uacc,0 *cos (n*ψ), where ψ is defined from

L = L0*(ψ+ π)/ π.

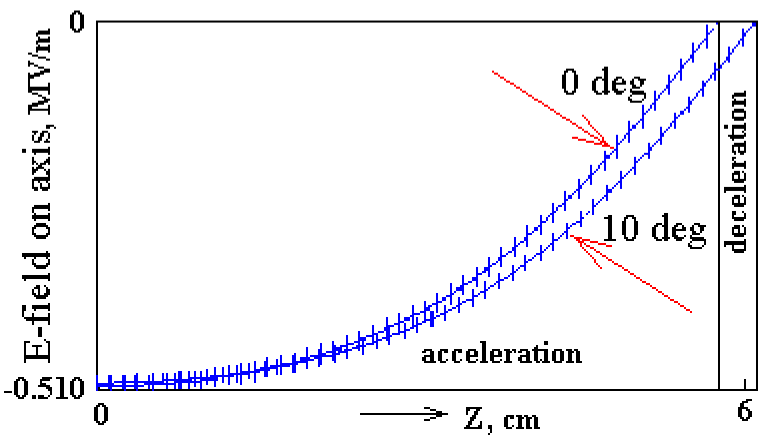
cos ψ ~ 1 – ψ^2/2, but improvement of *Epk/Eacc* or *Hpk/Eacc* can be of the first order of ψ!

This is the idea of a Sliding Phase Structure.

Why ΔW grows with ψ? (ΔW = e * Uacc)



Ψ = 0 deg. δe = + 20 %, δh = -10 %
Epk = 0.653 MV/m
Hpk = 819 A/m
ΔW = 0.0314 MeV



Ψ = 10 deg. δe = + 20 %, δh' = -15.07 %
Epk = 0.667 MV/m
Hpk = 789 A/m
ΔW = 0.0320 MeV

3 remarks

- Normalization for SPS is done with respect to $\lambda/2$, not to the cell length: ***Epk/Eacc = Epk/(2ΔW/λ),*** ***Hpk/Eacc = Hpk/(2ΔW/λ)***. For SPS, we try to increase the value of acceleration <u>per cell</u>.
- The mode of oscillation is kept equal to π. The length of the cell for SPS is longer than $\lambda/2$.
- The end cells are considered (both for optimization only and for optimization with a SPS) having the same parameters that the inner ones. Their optimization should be done separately.

Optimized shape w/o (ψ = 0) and with a sliding phase

	$\Psi = 0$	Ψ= 5 deg		Ψ = 10 deg	
δe, %	δh, %	$\delta h'$, %	δh, %	$\delta h'$, %	δh, %
0	-5.07	-8.81	-8.59		
+10	-7.92	-11.17	-10.89		
+20	-10.00	-12.81	-12.49	-15.07	-13.58

$\delta h' \sim \delta h(0) + k1*\psi$, $M \sim 1-k2*\psi^2$ -> So, exists ψ_{opt} that gives max $|\delta h| = |\delta h' * M|$:

ψ_{opt} -> max $|M* \delta h'|$, $\psi_{opt} \sim 12.8$ deg, $|\delta h_{max}| = 13.8$ %.

This means that the end cells have the sliding phase

$n * \psi_{opt} \sim 51.2$ deg (n = 4 for N = 9)

They work to their half capacity only … and should be removed.

Now $\psi_{opt} \sim 18$ deg, $|\delta h_{max}| = 15.4$ %.

Will we remove the next 2 end cells?

Conclusions

- The hard limit for the increase is the surface magnetic field. One can, for example, sacrifice 20 % of electric field to gain 10 % in magnetic field and so increase the Acc. Rate by 10 %.
- Calculations show that the new shape is free of multipacting.
- The change of the shape leads to some technological complications. First results of fabrication are optimistic.
- Using of the SPS gives next increase of the acceleration per cell.
- Optimized shape + SPS + SuperStructure can increase the Acc. Rate by

$$10\ \% + 5\ \% + 6\ \% > 20\ \%.$$

Remark

10 % of the Accelerator cost is about 100 M$…