Fast ferroelectric tuner for L-band

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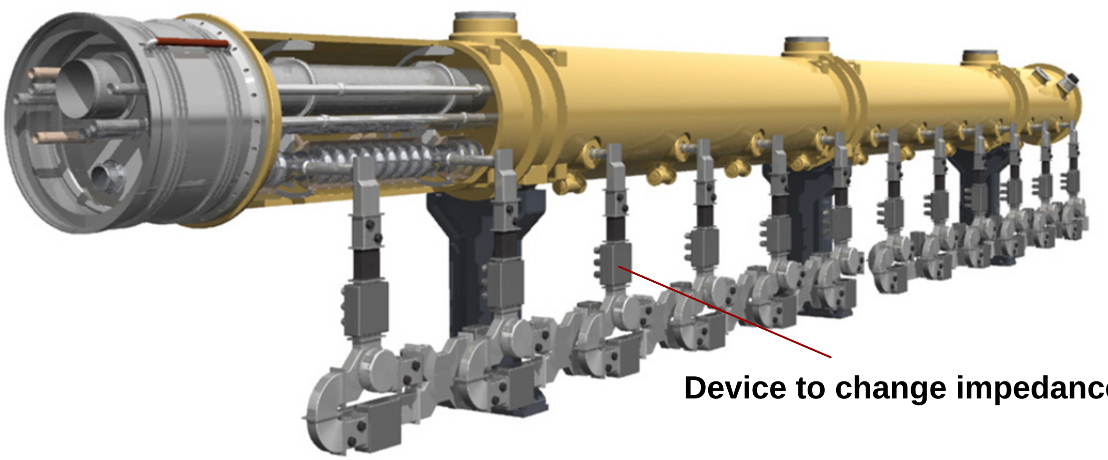
Motivation:

The necessity to have L-band phase shifter for ILC with convenient control is obvious – big number of accelerating structures are fed by one klystron and should be phased independently.

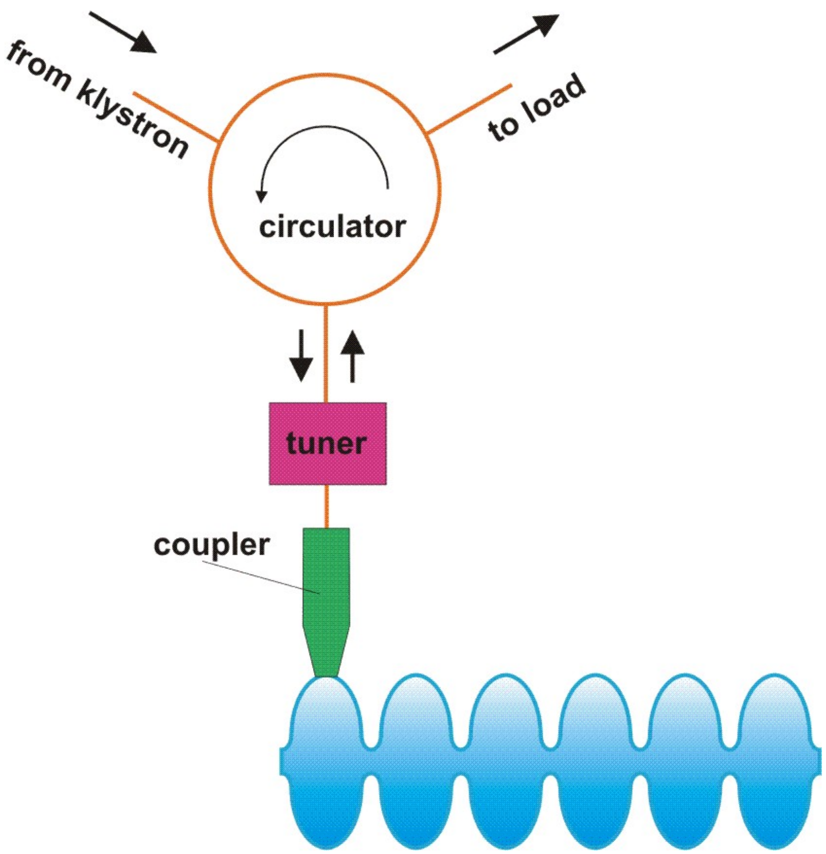
In the same time, we can build device (tuner) on the base of phase shifter, which can change the coupling of acceleration structure. If this tuner is fast enough, it can change coupling during pulse and, as result, decrease the duration of RF pulse and heating of accelerating structure. It will decrease total power consumption of collider noticeably.

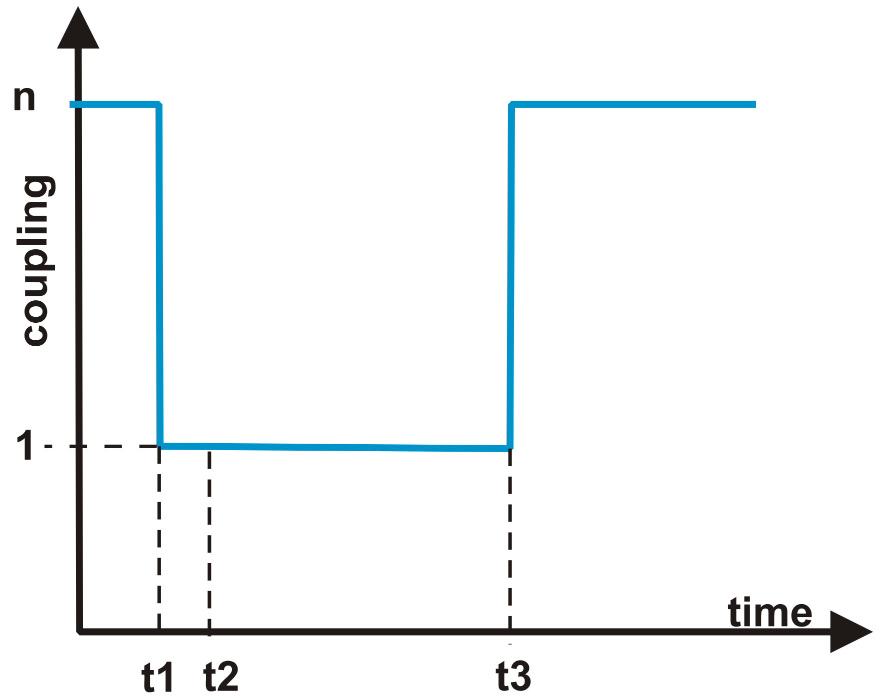
Tuner can serve as protection for structure blocking RF power



Idea of tuner:

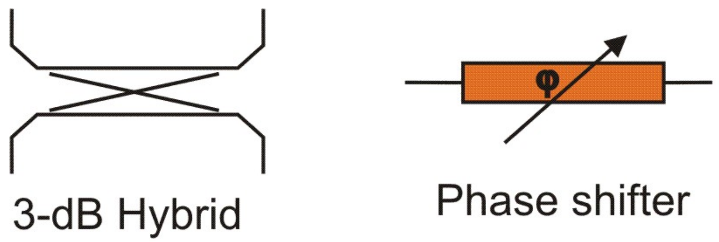
Bigger coupling at the pulse beginning and after the train – to decrease time of RF energy in accelerating structure. It causes less losses in the structure and decrease RF pulse duration. Total linac power decreases.



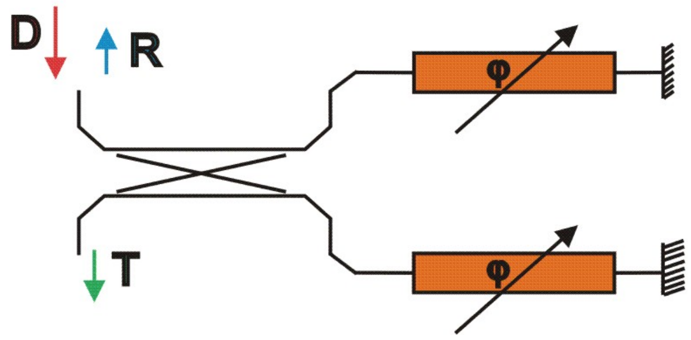


t1 – coupling switch time
t2 – filling time
(t3-t2) – train duration
t3 – RF pulse duration

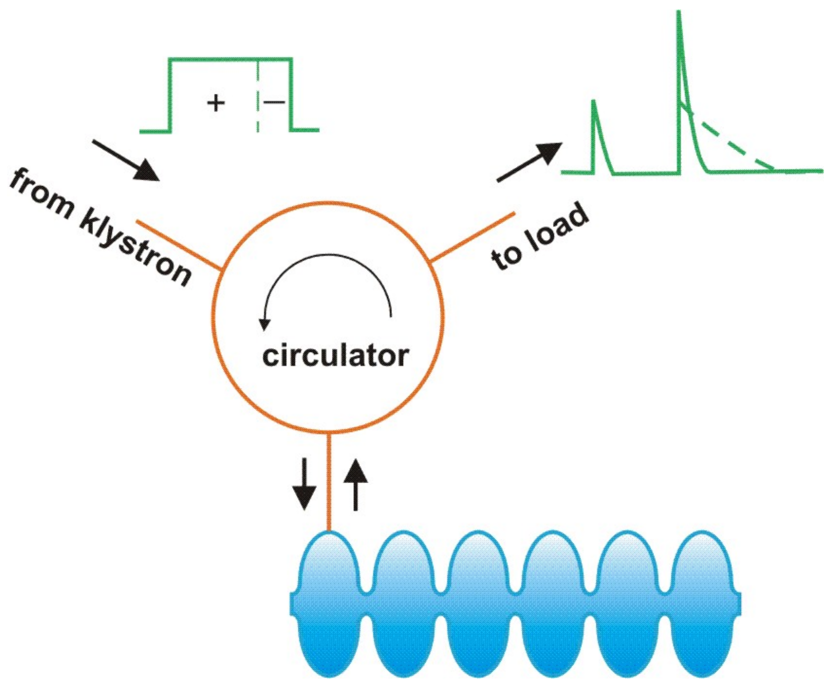
Combination of couple phase shifter and hybrid



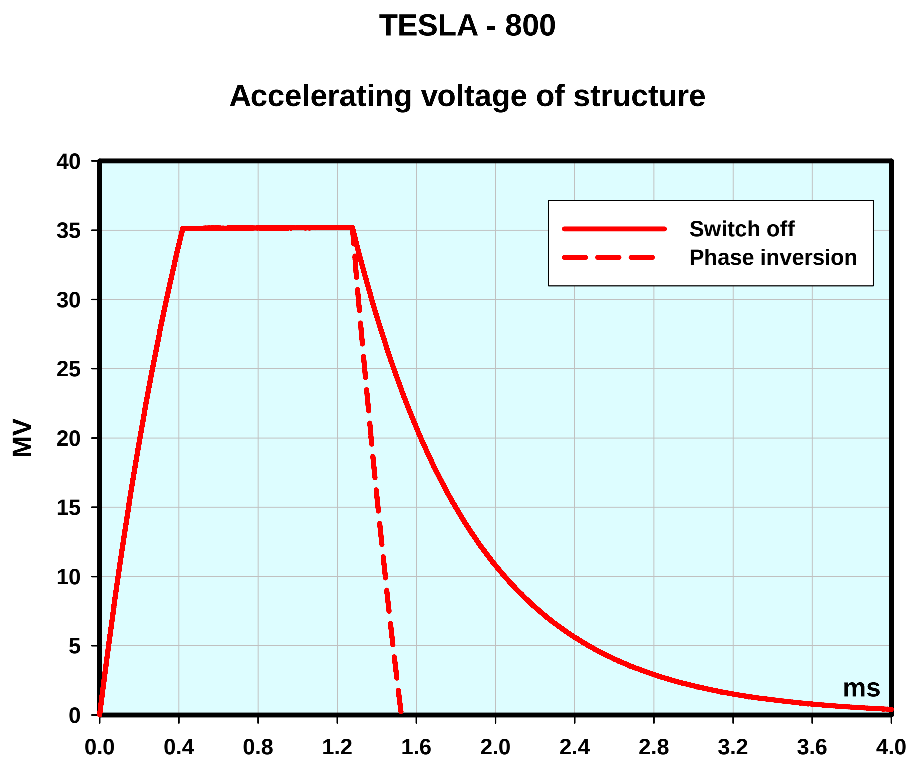
Combination gives us a 'tuner' - device, which can provide any impedance in the line

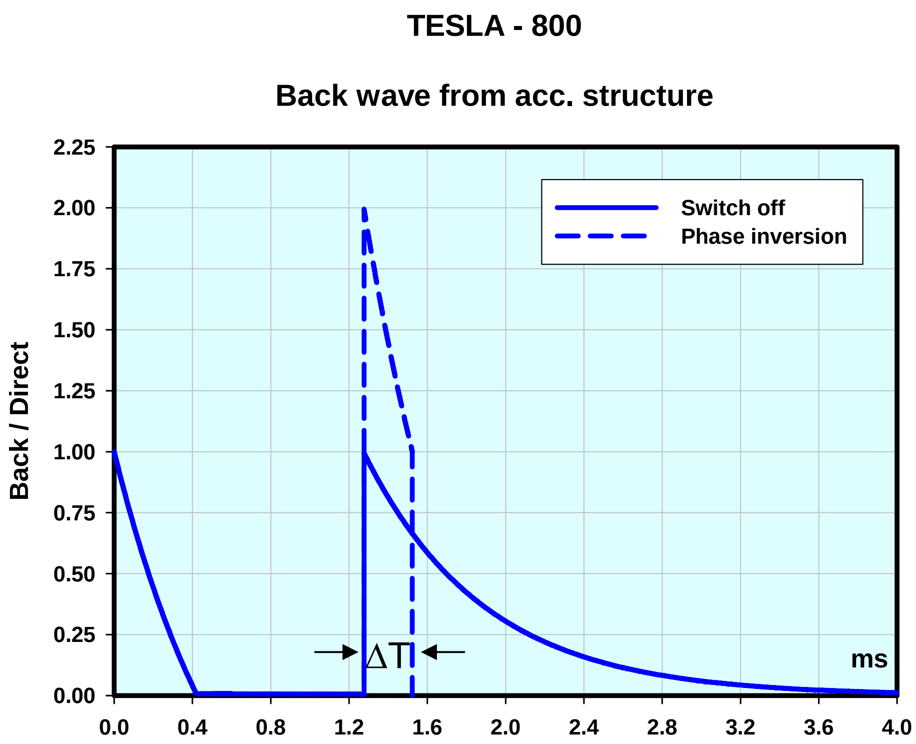


A simple idea to flip phase after bunch train for quick energy radiation from accelerating structure does not work (S.Tantawi, first LC Workshop).
It decreases loses in accelerating structure and power of cryogenic facilities.
But it needs more longer RF pulse. Total linac power increases.



Estimation for TESLA - 800



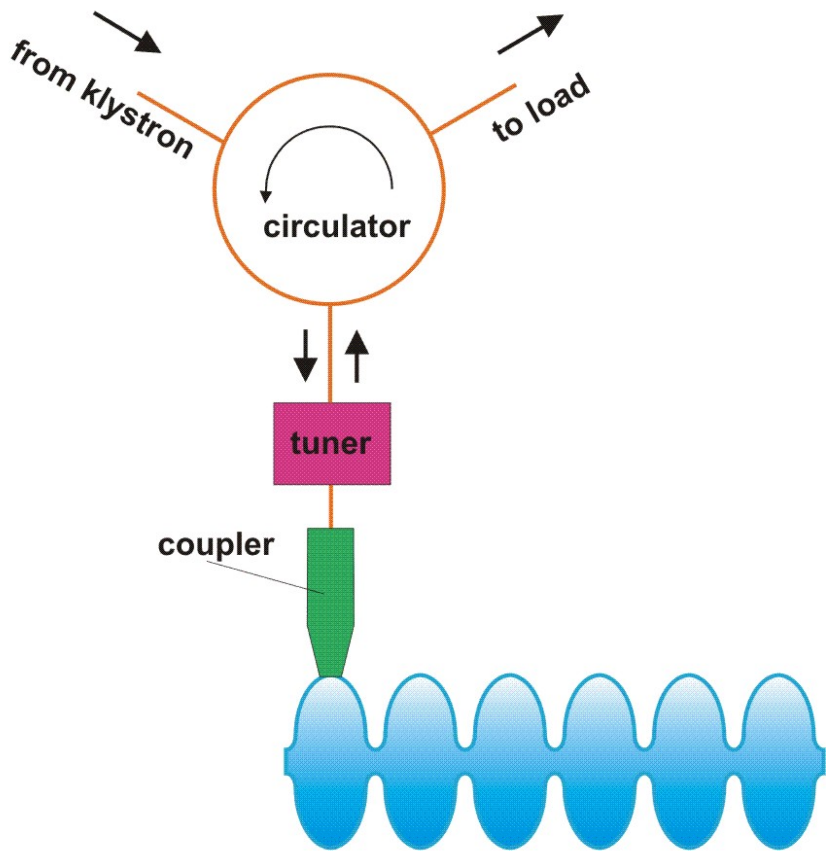


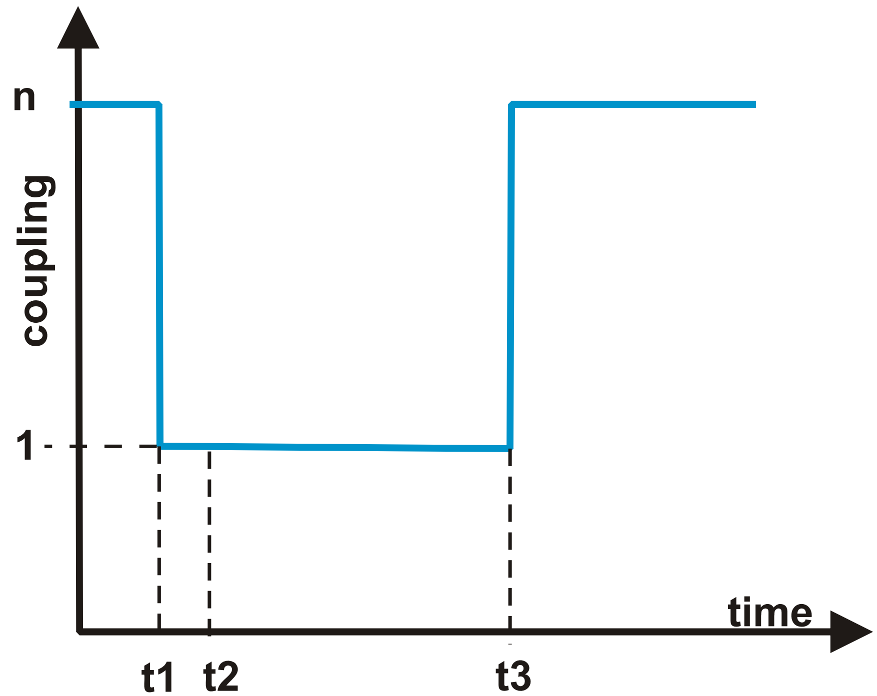
Results:

Cryogenic plant	- 4.6 MW
RF plant	+ 21 MW
Total	+ 17 MW

Phase flipping does not save total power

Tuner case





t1 – coupling switch time
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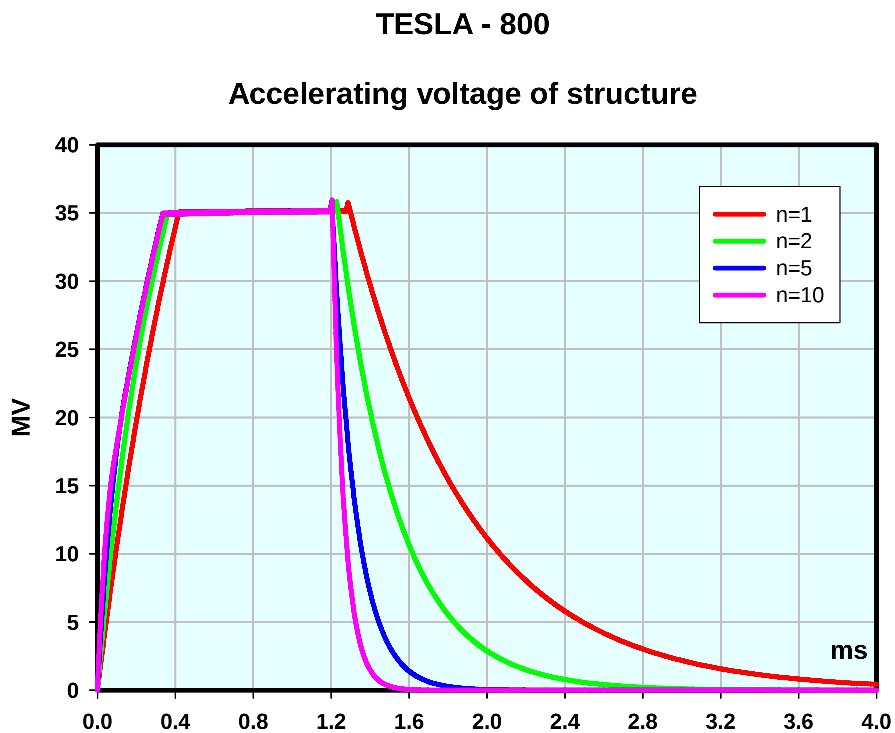
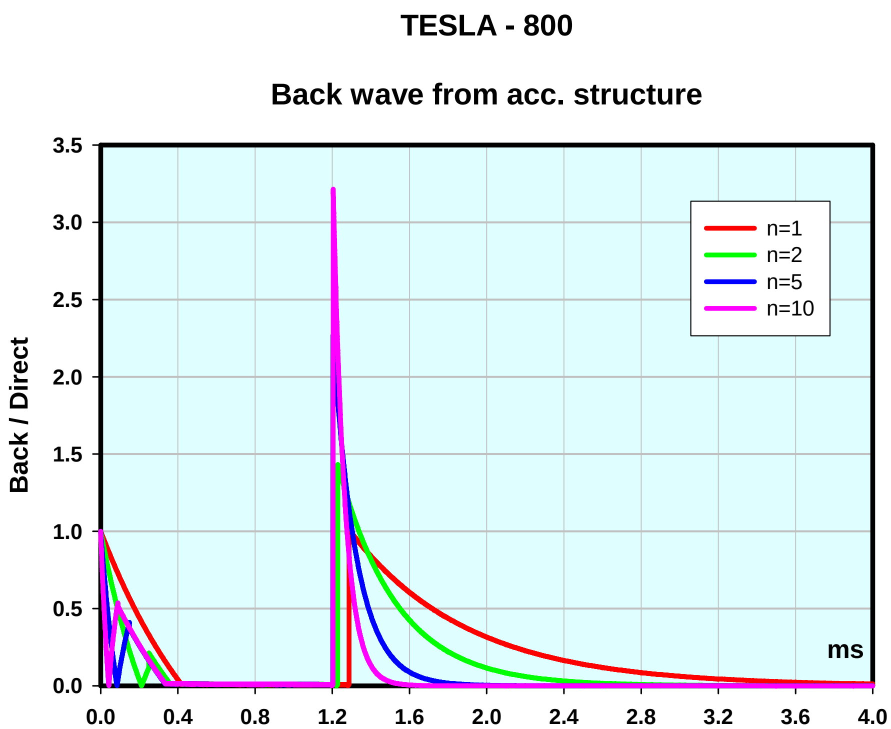
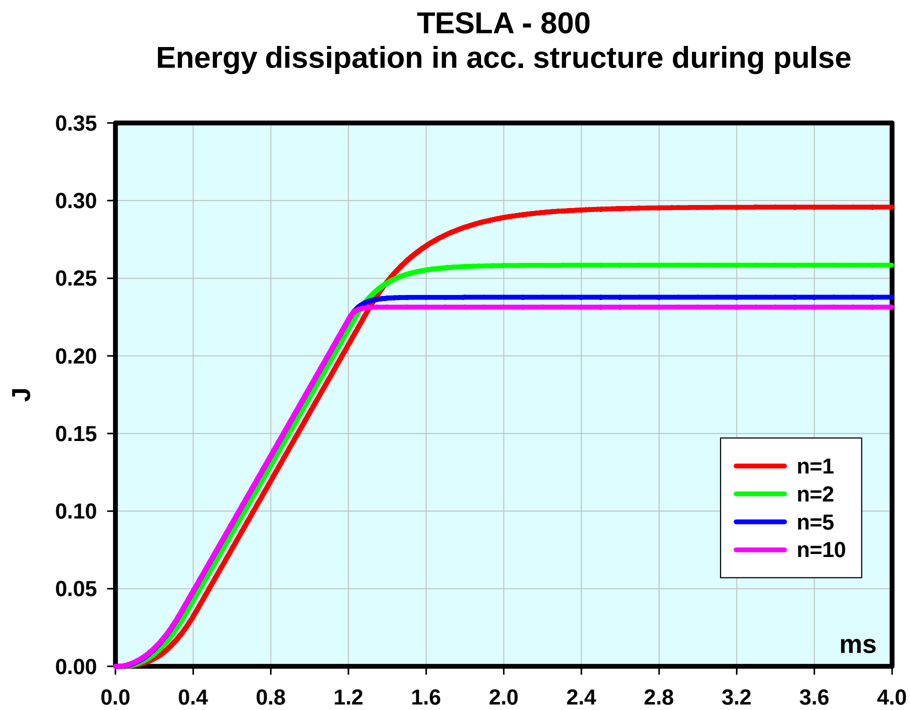
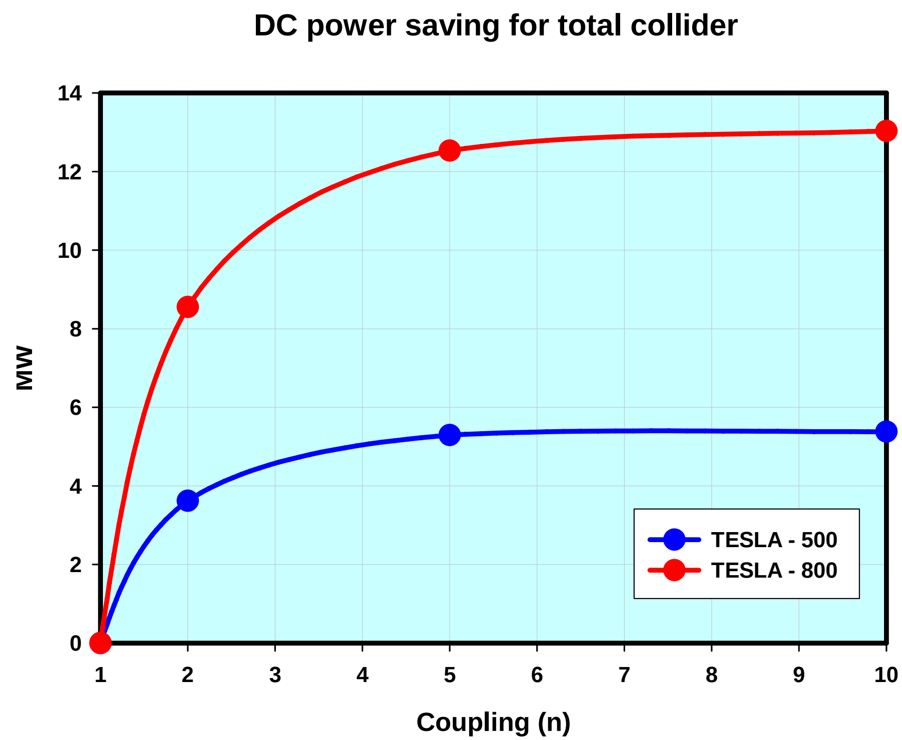
(t3-t2) – train duration
t3 – RF pulse duration

Quantitative estimations:



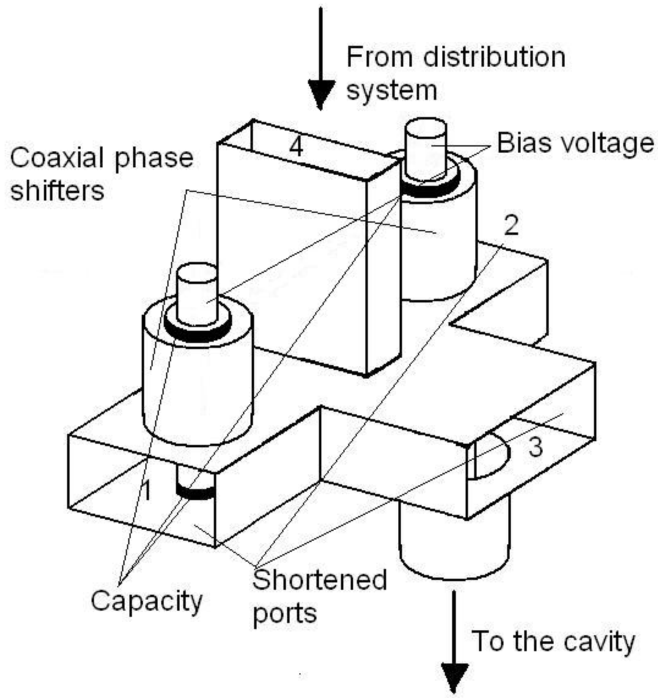






Coupling	t1, ms	t2, ms	t3. ms	$t3_1$-$t3_n$ ms	Saving, cryo. MW	Saving, RF MW	Total MW
1	---	0.420	1.288	0	0	0	0
2	0.25	0.361	1.229	0.059	3.39	5.16	8.55
5	0.150	0.336	1.204	0.084	5.18	7.35	12.53
10	0.09	0.3375	1.206	0.0825	5.80	7.23	13.03

Possible solution for tuner:



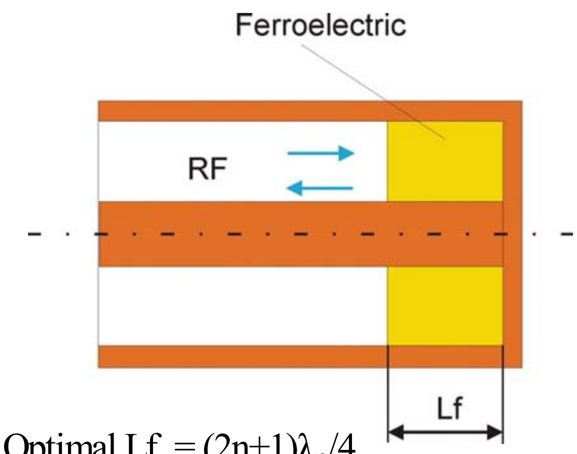
Advantage of phase-shifter with full reflection:
no need to worry abut good SWR;
easy to apply bias voltage

Possible active material can be ferroelectric ceramic.

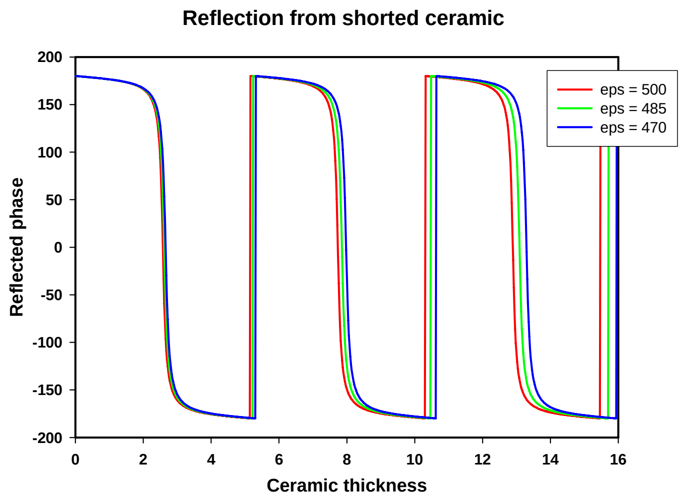
Euclid Concepts LLC recently developed and tested a modified bulk ferroelectric based on a composition of barium strontium titanate (BaxSr1-xTiO3, or BST) ceramics, magnesium compounds, and rare-earth metal oxides that has a relative permittivity ε = 500, and 20% change in permittivity for a bias electric field of 50 kV/cm. The loss tangent already achieved for large bulk samples is about 4×10^{-3} at 11 GHz ,which corresponds to about $4\text{-}5\times10^{-4}$ at 1.3 GHz

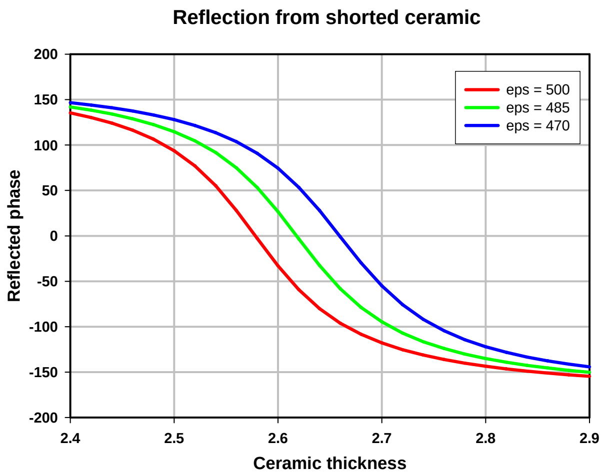
If it is supposed that device is air-filled, the bias electric field 0-15 kV/cm will provide 500-470 permittivity deviation. We should find geometry of phase shifter, which gives 0^{O} – 180^{O} (360^{O})

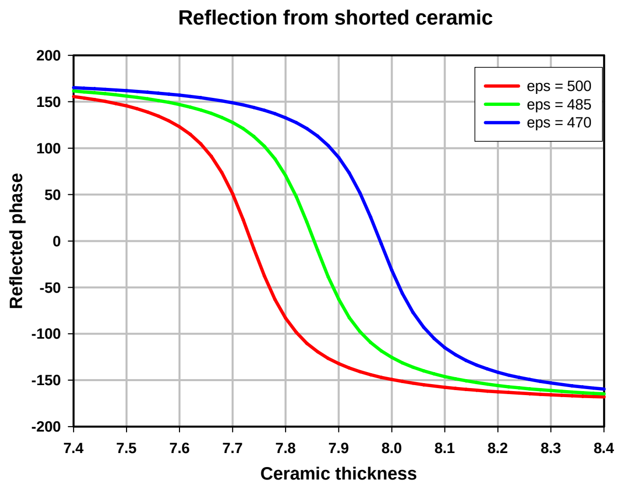
Simplest solution:

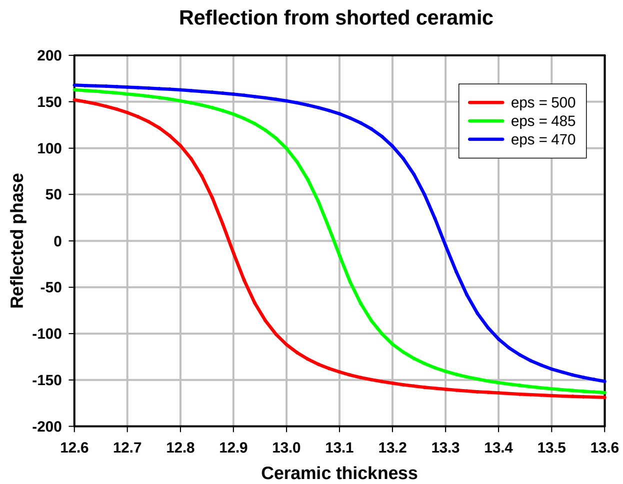


Optimal Lf $= (2n+1)\lambda_f/4$



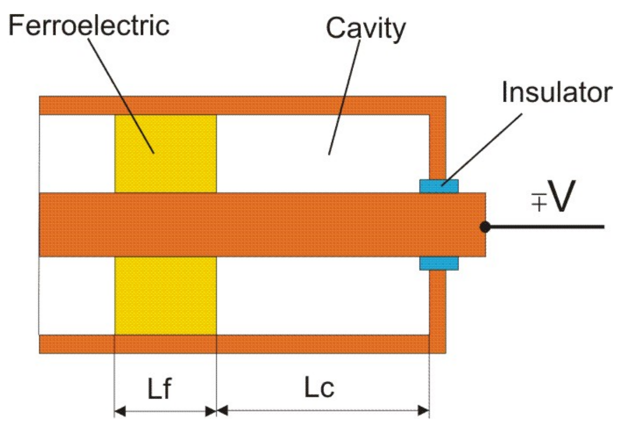




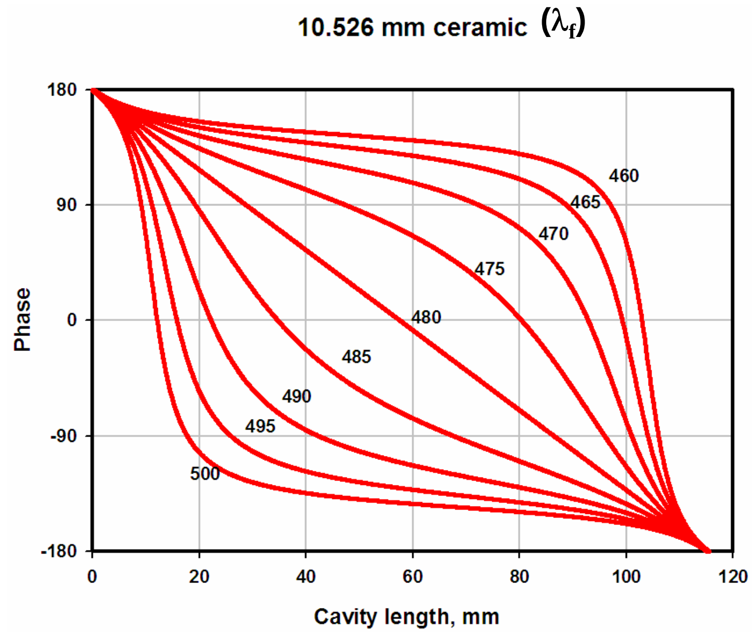


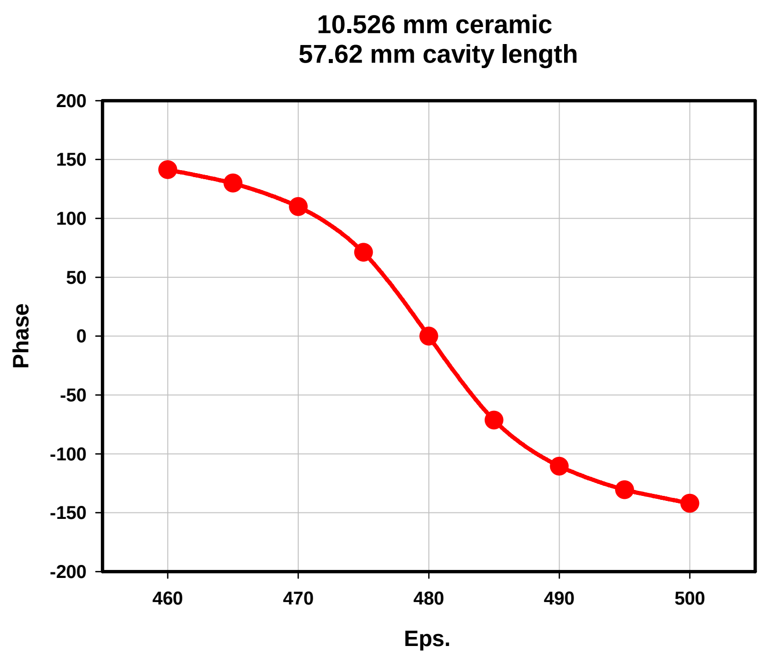
How to apply bias voltage?

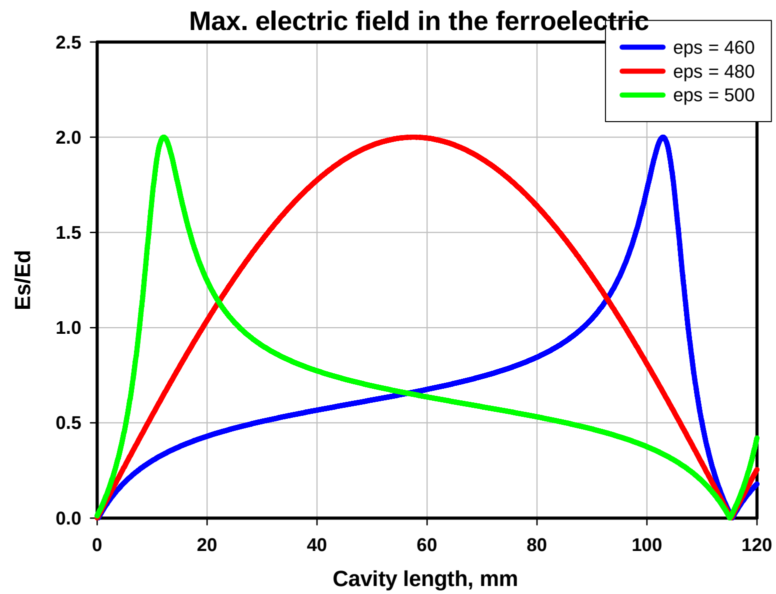
Or:



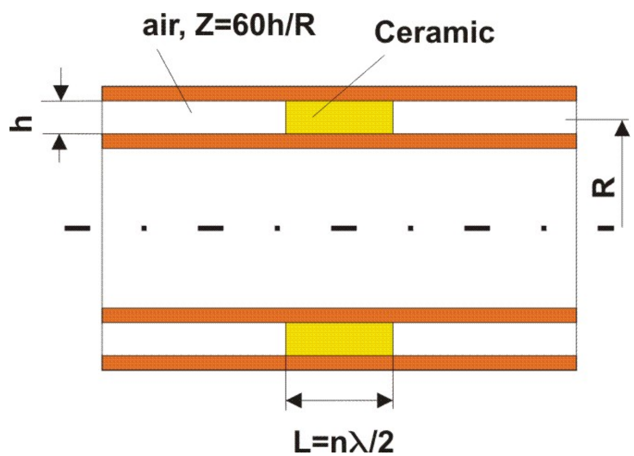
Simulations show that optimal Lf = nλ_f







Problems are average and pulse temperature rises of ceramic.
Temperature sensitivity of considered ferroelectric is $d\varepsilon / dT = 3/K$
For phase shifter with deviation $\Delta\varepsilon = 30$ (470 – 500),
1K corresponds 10~20 degree of phase



$$\Delta T_{av} = \frac{\pi\varepsilon\delta t_p n_p Z P}{2k\lambda Z_0}$$ average heating

$$\Delta T_{pls} = \frac{4\pi\varepsilon\delta t_p Z P}{\rho\lambda h^2 Z_0 C_c}$$ pulse heating

ε - ceramic permittivity
δ - ceramic loss tangent
Z - coxial line impedance
t_p - pulse duration
n_p - repetition rate
P - power
k - ceramic thermal conductivity
λ_0 - wave-length
ρ - ceramic specific weight
C_c - ceramic thermal capacity
$Z_0 = 377$ Ohm

Examples of heating:

$$\Delta T_{av}(K) = 0.6Z(Ohm) = 36\frac{h}{R}$$

$$\Delta T_{pls}(K) = 0.73Z(Ohm)/h^2(mm) = \frac{44}{Rh}$$

$$Z = 50\ \text{Ohm} \rightarrow \Delta T_{av} = 30^o\ !\quad \text{No way}$$

Parameters:

$\varepsilon = 500$

$\delta = 4*10^{-4}$

$t_p = 1.3*10^{-3}$ s

$n_p = 5$

$P = 2.5*10^5$ W

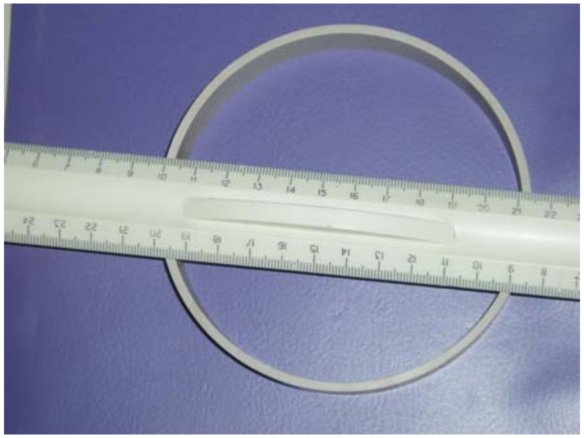
$k = 10\ W/K \cdot m$

$\lambda_0 = 0.23$ m

$\rho = 4869$ kg/m^3

$C_c = 605$ J/kg$\cdot K)$

Thin ring



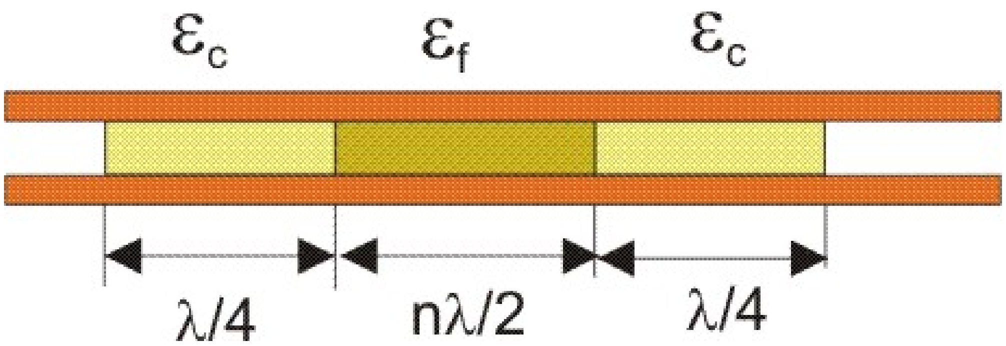
Ferroelectric ring, D=106mm, dR=2.8mm, L=22mm

$\Delta T_{av} = 2^o$

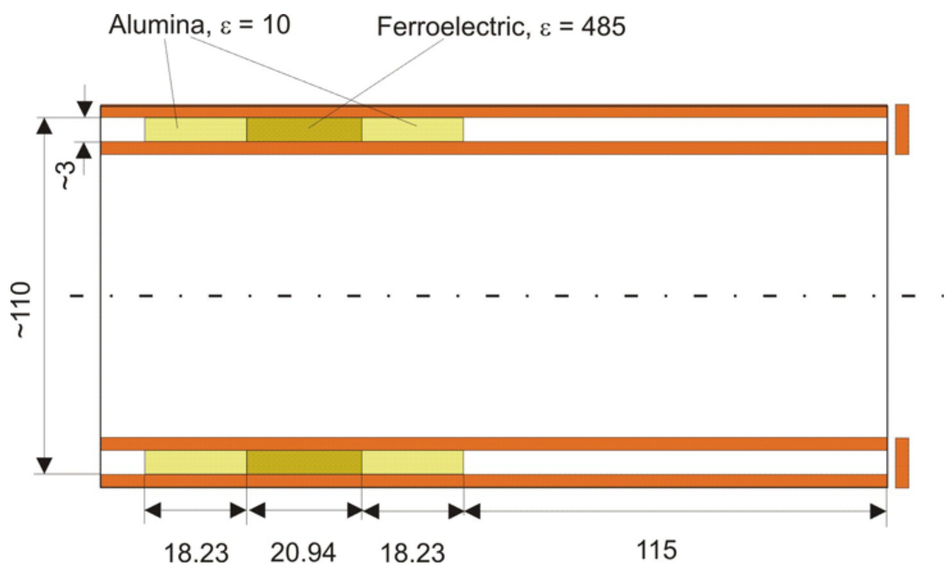
$\Delta T_{pls} = 0.3^o$

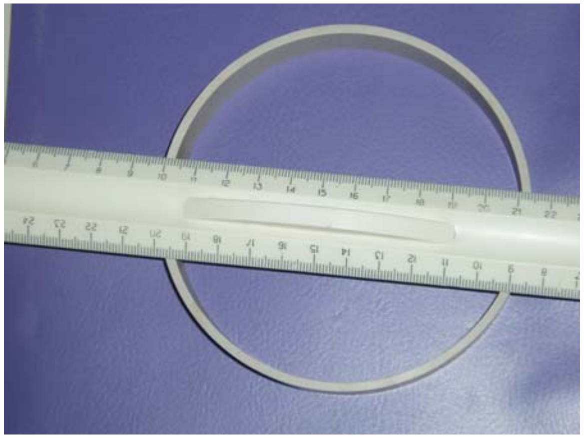
Still too much. We need to decrease the electric field in the ceramic

We found the way to reduce electric field in the ceramic without increasing field in the air part. Using the alumina with eps. = 10 decreases electric field in ferroelectric from 2 to 0.65



Low impedance geometry with matching ceramics





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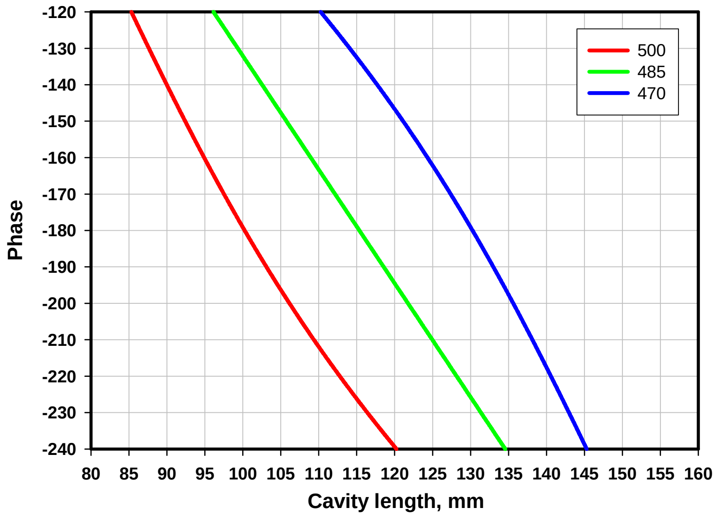
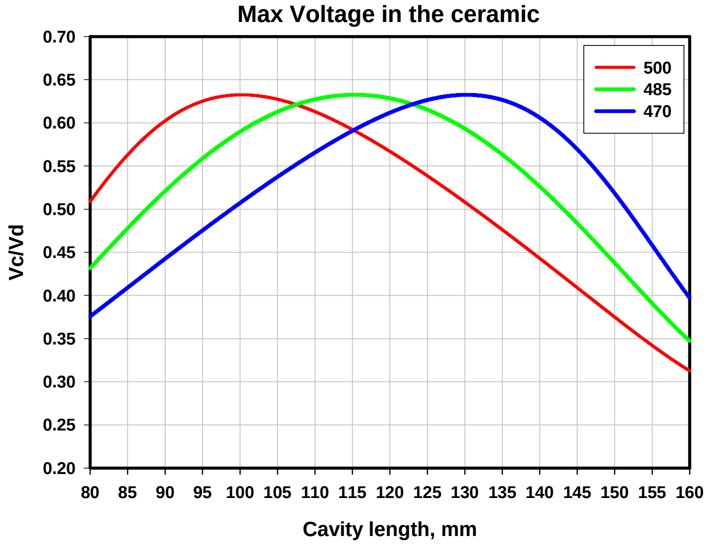
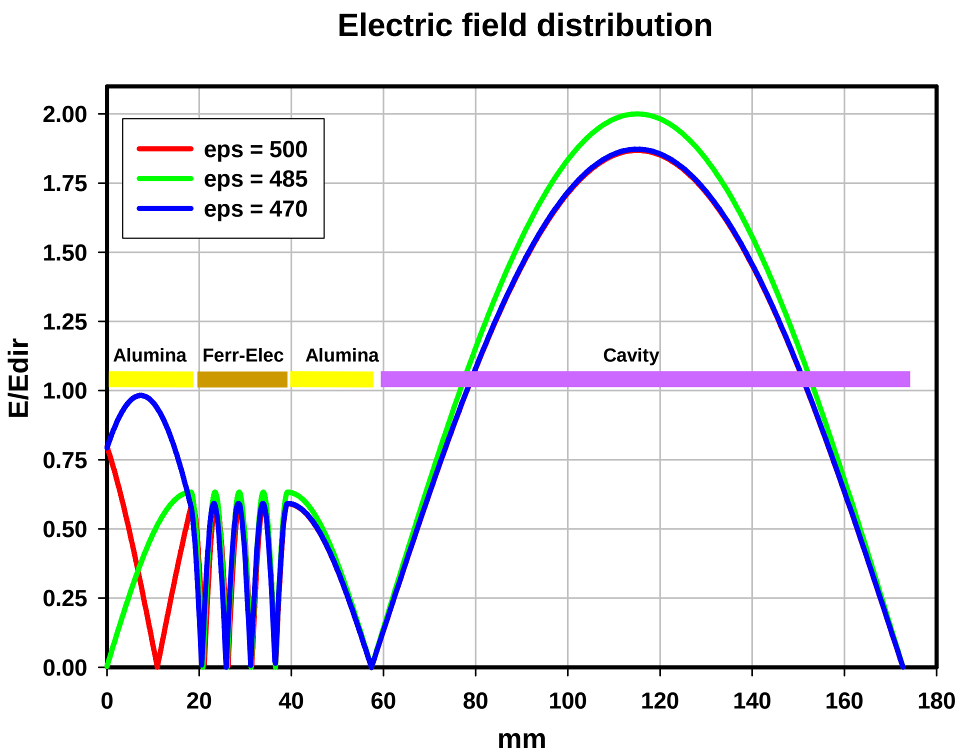
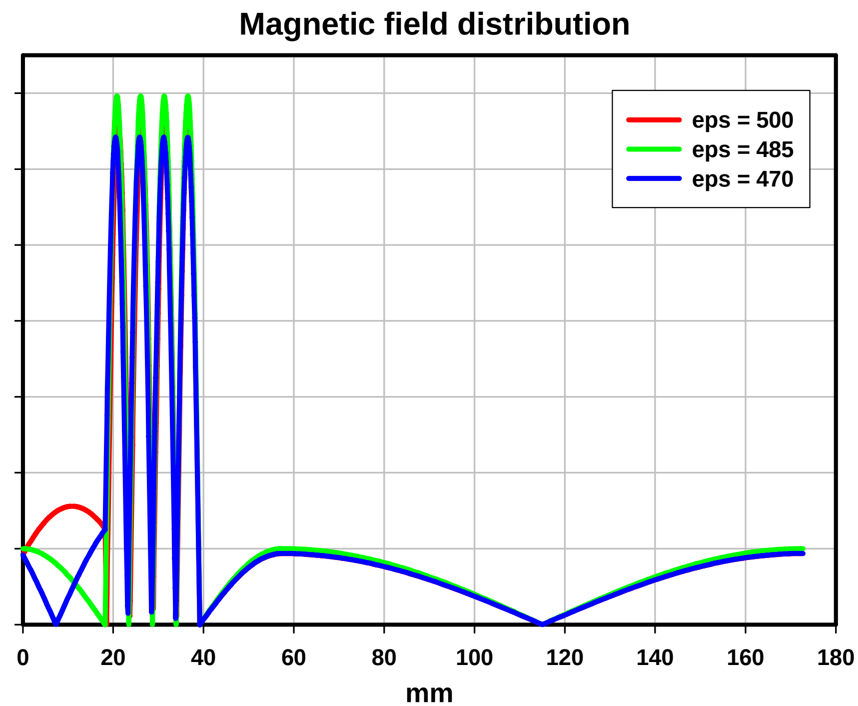




Fields distribution along phase shifter



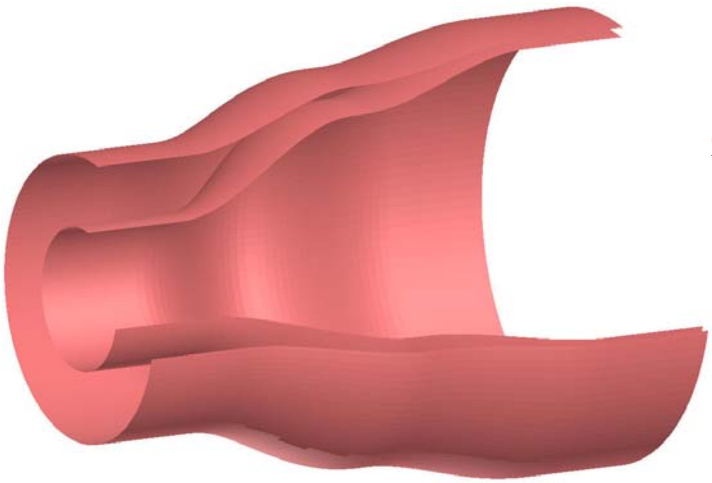


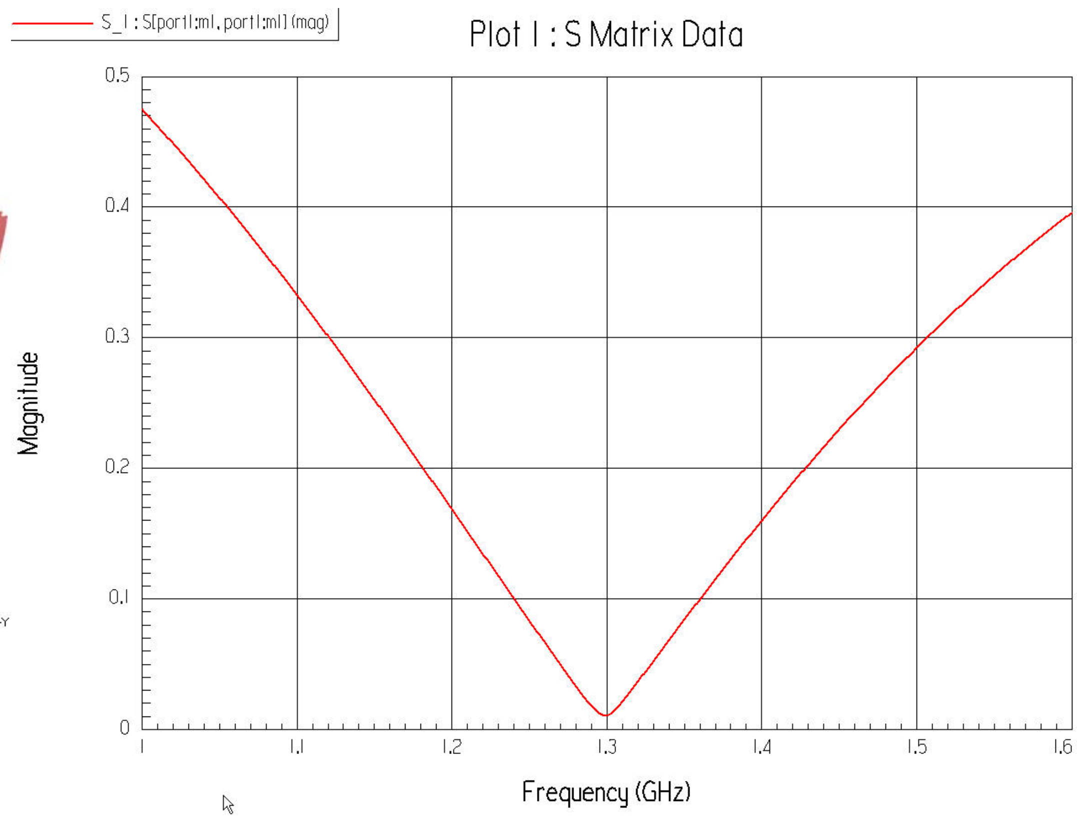
Absolute values for 500kW / two phase shifter :

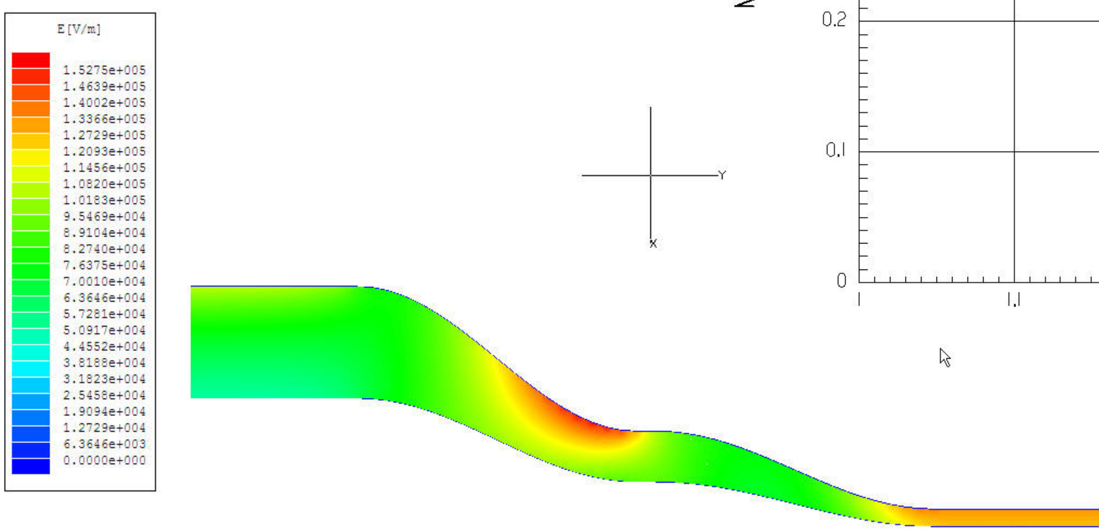
Impedance of air coaxial,	3 Ohm
Voltage of direct wave,	1.224 kV
E -field of direct wave,	4.1 kV/cm
Max. RF electric field in air,	8.2 kV/cm
Max. RF electric field in ferroelectric,	2.6 kV/cm
Average heating,	0.3^{O} C (3gr of phase)
Pulse heating,	0.1^{O} C (1gr of phase)
Capacitance,	13 nF
Switching currant (switch. time 1e-5s)	6 A
Switching pulse power	13 kW
Average switching power	12 W

Phase shift ~ 20^{o}/kV (or 40^{o}/kV for double long ferroelectric)

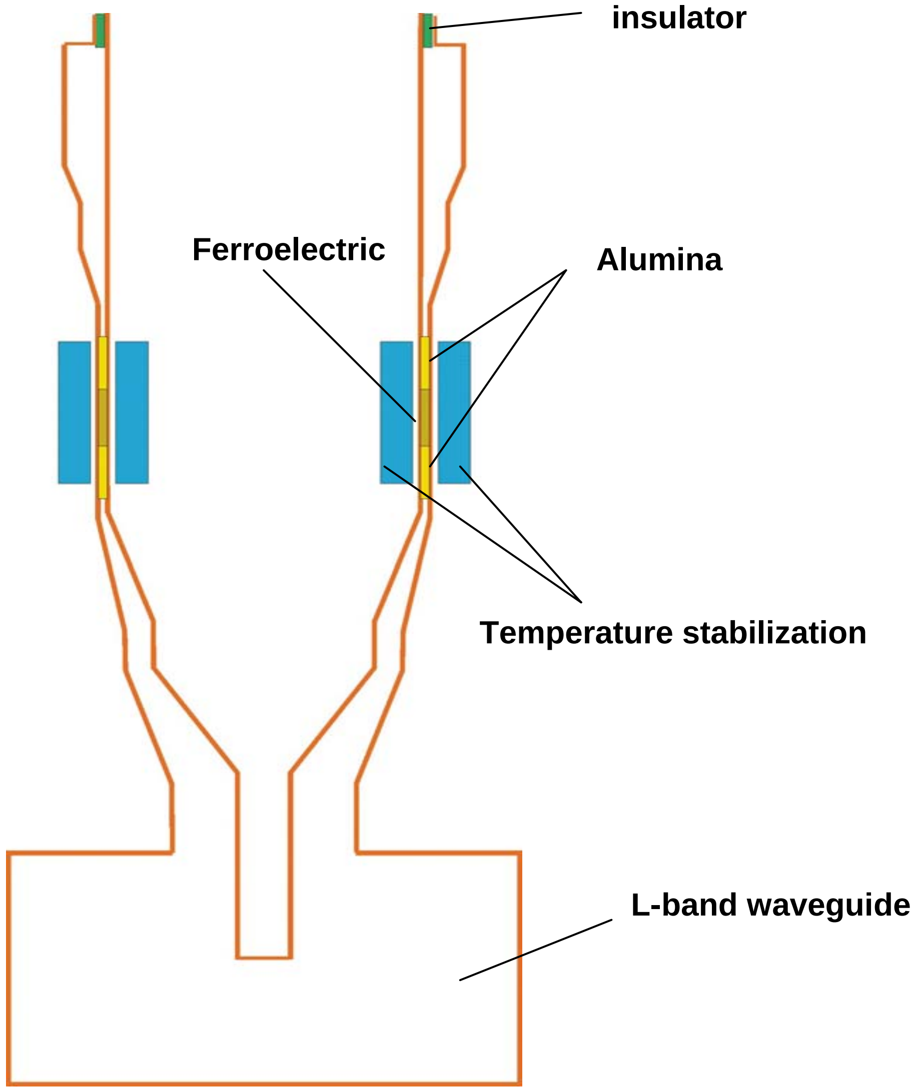
Example of 50-3 Ohm transformer



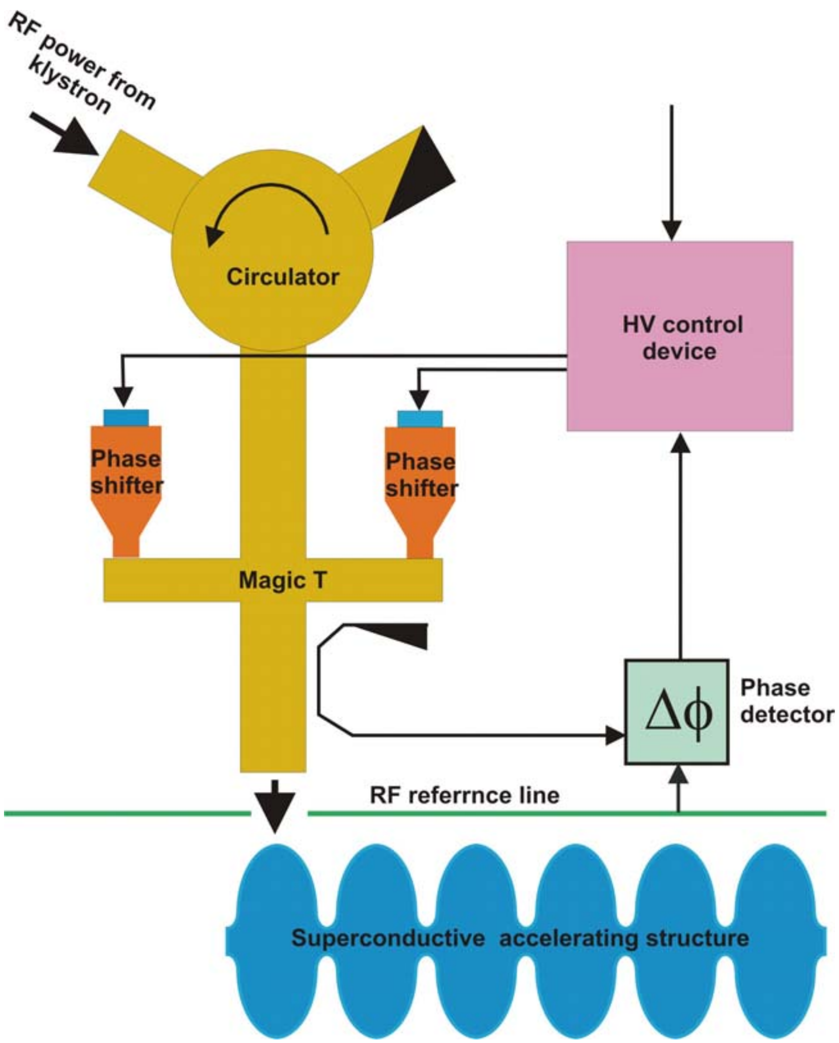




Rough sketch of tuner:



Possible connection of tuner and feedback loop



Conclusion:

The present-day materials allow to make fast phase shifter and tuner, which meet ILC parameters. We are going to try to make them.