High-Gradient, Millimeter Wave Accelerating Structure

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Outline:

1. Problems of normal conducting millimeter wave structures

2. Helical accelerating structure with asynchronous transverse fields

3. Calculation methods: perturbation theory and HFSS simulations

4. Optimization in comparison with classical structures

5. Beam dynamics simulation by CST Microwave Studio

6. First results of low-power tests

7. Conclusion

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High-Gradient Mm-wave Accelerating Structure Based on Helical Waveguides

Recently Tantawi et al. (2014) showed **GV/m** level accelerating gradient in 116 GHz structure fed by short rf pulse produced by FACET's electron bunch. This experiments inspires to invent mm-wave accelerating structures having new properties:

1. Feeding by short, high repetition rate rf pulses (τ**<20 ns**), in order to avoid breakdown and excessive pulse heating according to scaling laws:
$$E_s^p \tau = const, \, p = 5-6. \quad H_s^2 \sqrt{\tau} = const.$$

2. Wide (≥ 1 cm) channel in whole section without junctions for electron beam channeling and efficient pumping.

3. Because loss factor for excitation of wakefields is scaled as $\sim 1/a^2$ (a – structure's aperture), it is expected that beam emittance grows up with wavelength even faster (due to wakefields excited by geometry mistakes), one should preserve bunch emittances.

4. High coupling coefficient of cells to avoid strong sensitivity to spread of geometric parameters.

5. Smooth transverse beam focusing due to the ponderomotive (Miller's) force is also desirable.

Relativistic Cherenkov Electronics in Russia

There are GW level Cherenkov amplifiers with ~1 kHz repetition rate.
RF phase is controllable by low power stable RF source (proven in experiments).
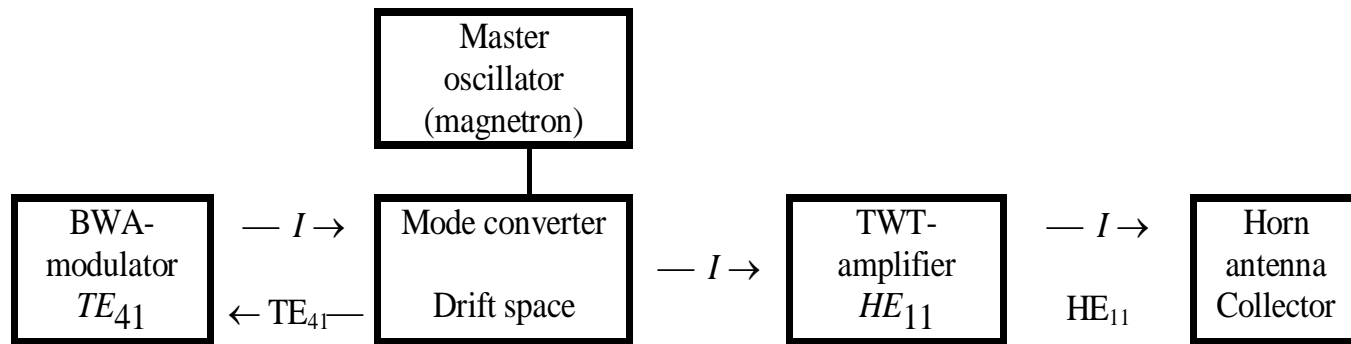
Block diagram of GW level , 20 ns, X-band amplifier

Device	Wavelength cm	Power MW	Efficiency %	Gain dB	Voltage MV	Current kA
BWO+TWT[7]	3.3	1100	20	47	0.8	6
TWT[8]	0.8	100	10	44	0.5	2

Short pulse superradiant BWO: 38 GHz, 1 GW, 3 ns, 100 Hz

# Radiation beam cooling inside linear accelerator

$$P_\gamma[GeV/m] = 3.3 \cdot 10^{-13} \gamma^2 B^2[T]$$ - radiation cooling rate in a periodic DC-magnet field.

Emittance change is described by: $$\log \varepsilon_{out} = \log \varepsilon_{in} - \frac{aB^2Wz}{2},$$ where W – particle energy.
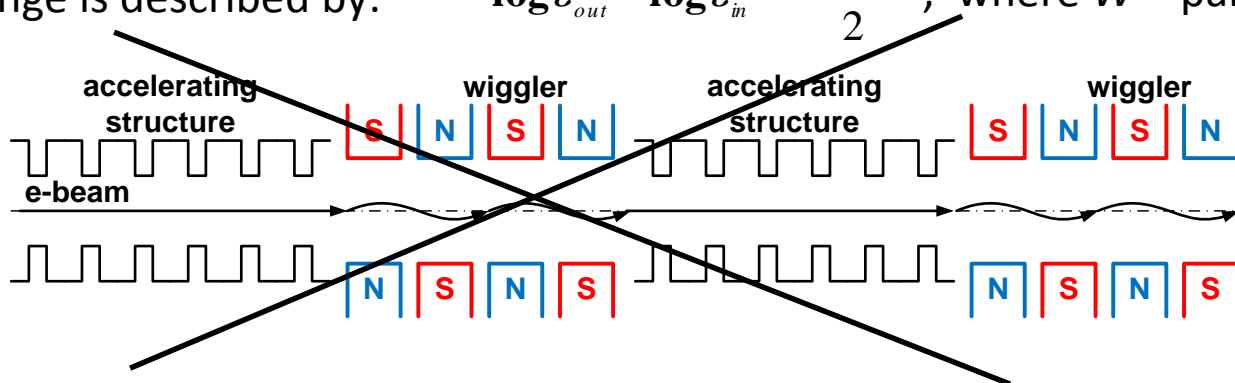
H.H. Braun et al. Potential of Non-standard Emittance Damping Schemes for Linear Colliders, 2004.

The accelerator with alternating accelerating sections and wigglers **reduces average gradient**.
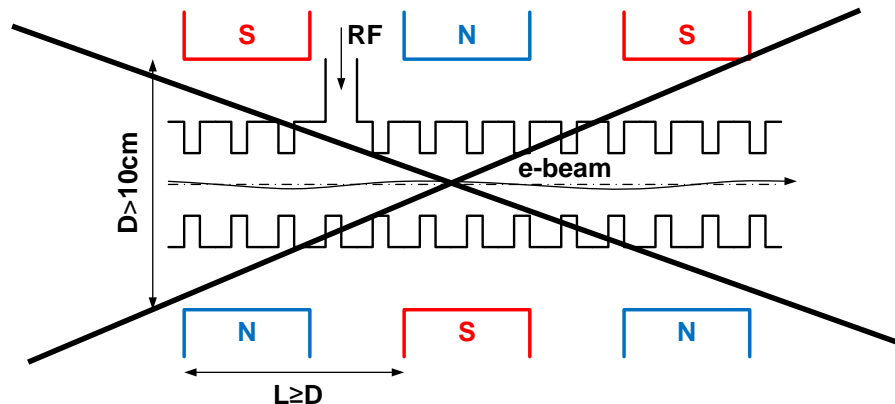
Such accelerating structure is **impractical**, because DC magnet system conflicts with feeding, focusing, and diagnostic systems. Inevitably large period does not allow to preserve small enough emittance, because an achievable emittance is proportional to squared wiggler period L.

Helical Accelerating Structure

Accelerating structure + RF undulator (+ lens)

$$r(z,\varphi) = R + a \cdot \sin(\frac{2\pi \cdot z}{P} + \varphi)$$
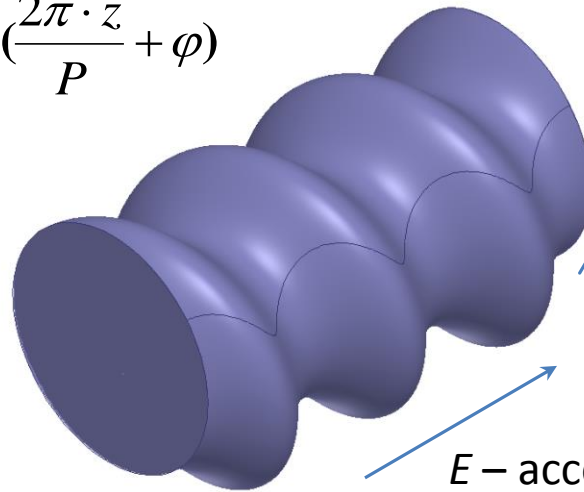
Copper ma...

transverse field components
(far from Cherenkov synchronism)

E – accelerating field (synchronous with particles)

0   10   20 (mm)

Appealing features:

1. Non-synchronous transverse field components might provide: 1) emittance control (beam cooling due to synchrotron radiation of particles); 2) near axis beam focusing

2. A new structure has smooth shape of constant circular cross-section (no expansions or narrowings) and big aperture (no small irises)

3. A new technology of the mass production seems possible which allows avoiding junctions inside long accelerating section
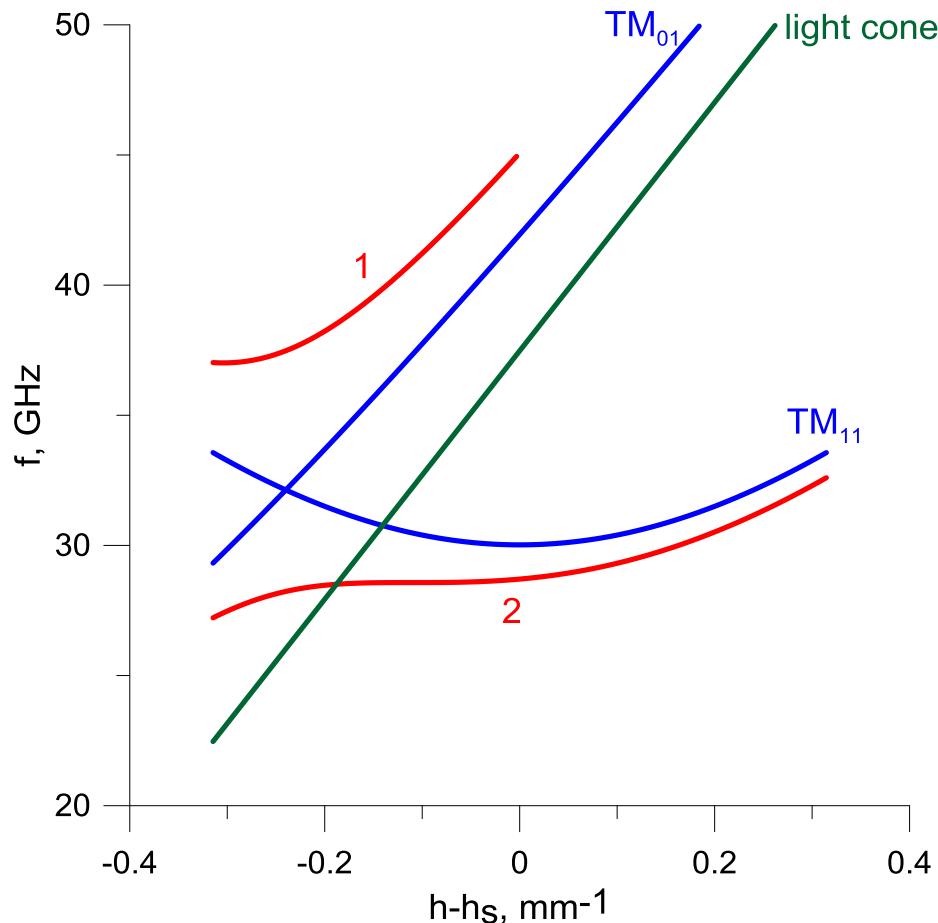
Partial waves: 1) travelling TM_{01} mode + 2) near to cut off rotating TM_{11} mode

TM_{01}: $E_z \neq 0$ at axis, $E_z \sim \mathbf{exp}(jhz - j\omega t)$ $V_{ph} \approx c$
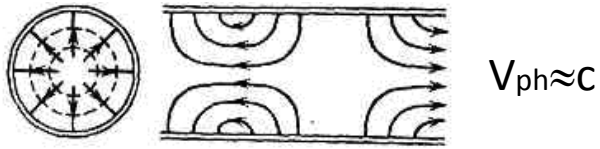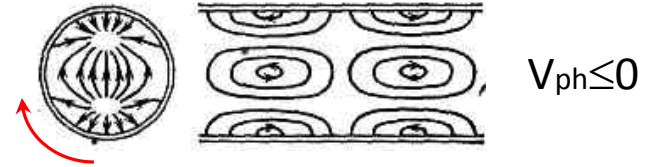
TM_{11}: $E_z = 0$ at axis, $E_\perp$ and $H_\perp \neq 0$ at axis, $V_{ph} \leq 0$

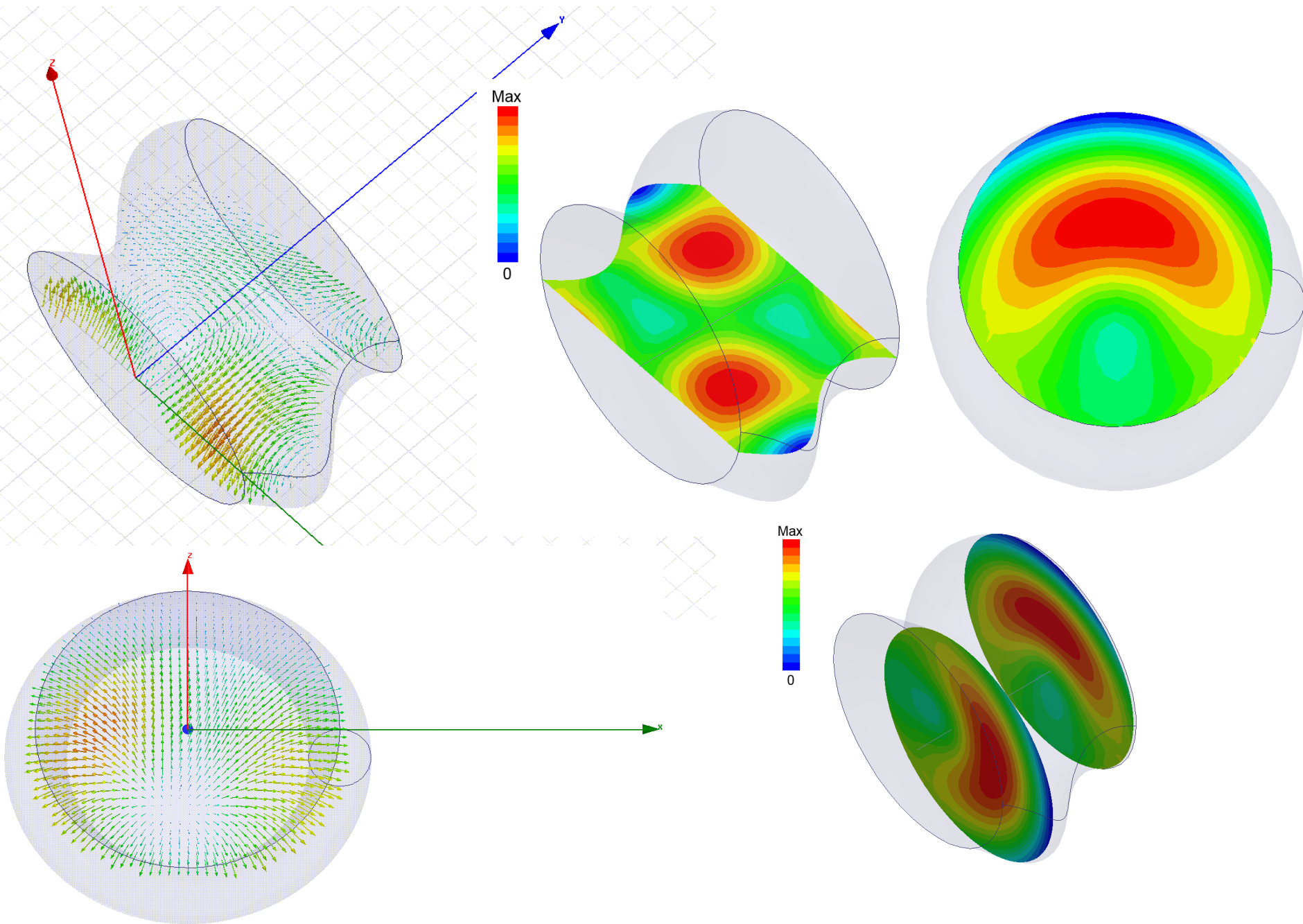$E_\perp, H_\perp \sim \exp(j(h - h_s)z - j\omega t),\ h - h_s \to 0$

Partial waves (blue)

Normal waves (red)

Slow normal wave 2 ($v_{gr} \times v_{ph} > 0$) consists of partial TM01 and TM11 waves.

The wave 2 is the operating wave (might be in synchronism, it has low group velocity).

Dispersion curves: R=6.09 mm, P=8 mm, a=1.25 mm $(h_s = 2\pi / P)$
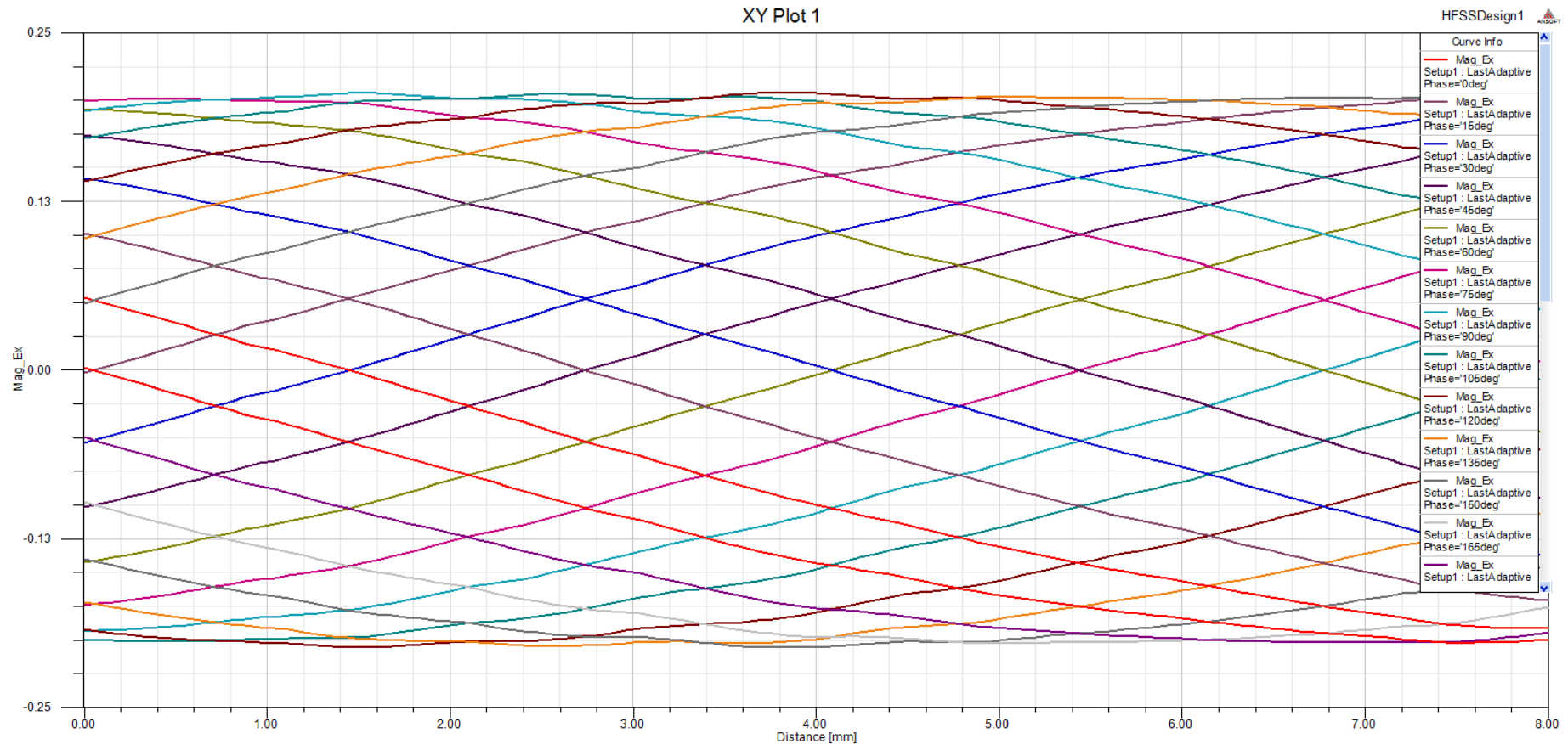
# Electric field in helical accelerating structure. Calculation by HFSS
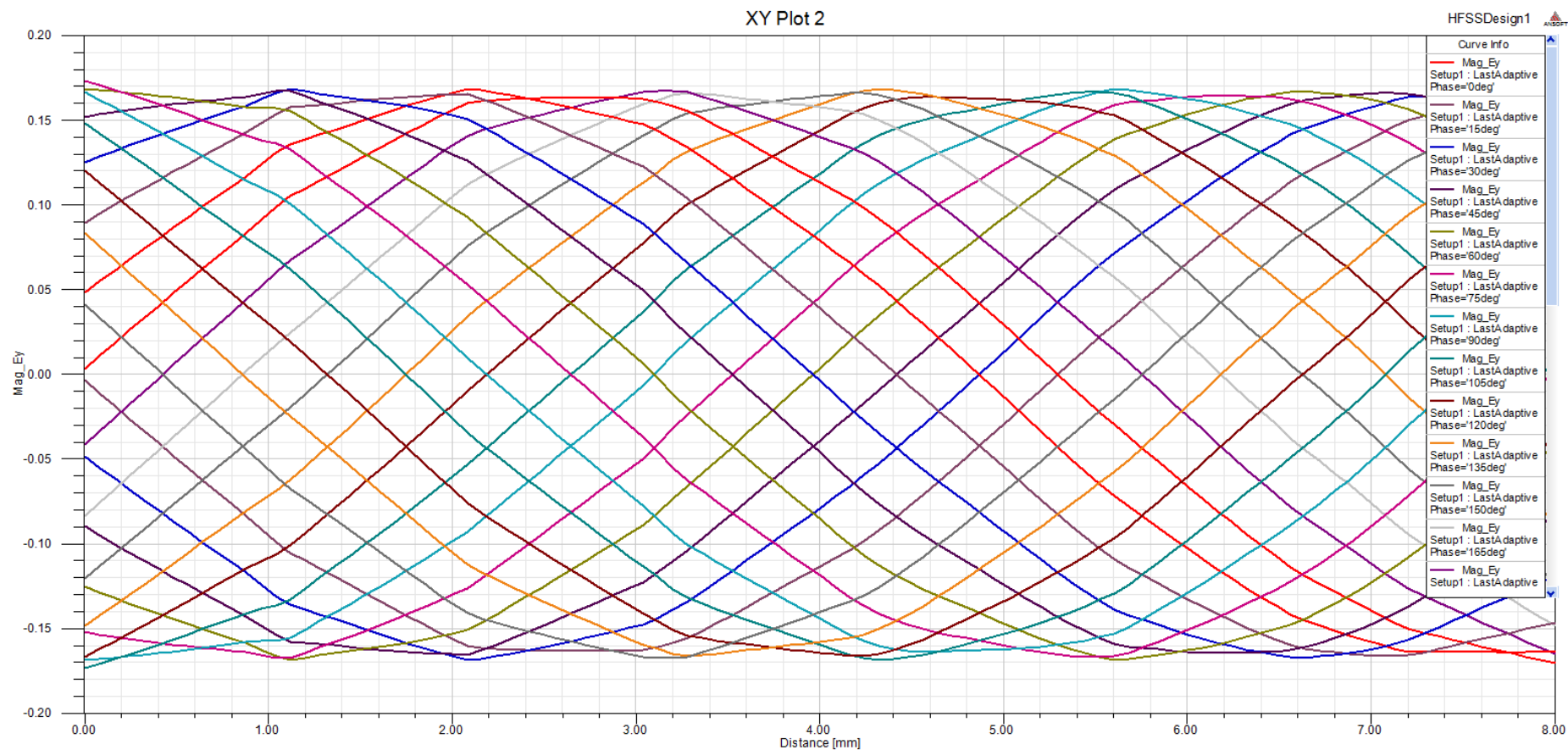
Accelerating field component vs longitudinal coordinate for different phases (with step 5°)

Accelerating component is uniform at beam line.

Transverse electric field components at beam line vs length for different phases

Transverse components are also uniform and have much longer spatial period in comparison with period of the accelerating component.
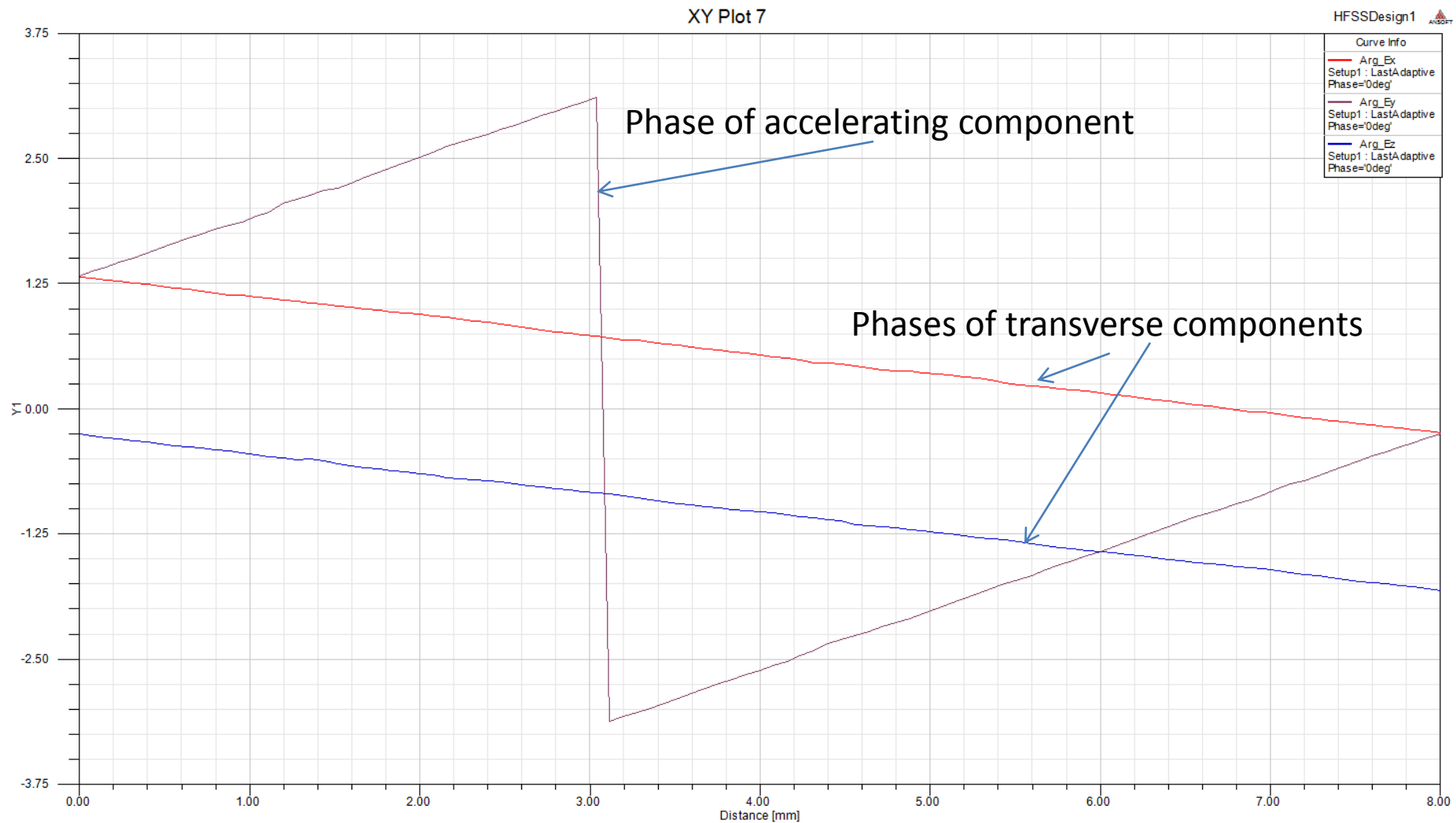
Phases of electric field components at beam line

Accelerating E-field and transverse E-fields have opposite phase velocities!
Phase velocity of the accelerating component actually equals the light velocity.

Results of HFSS optimization
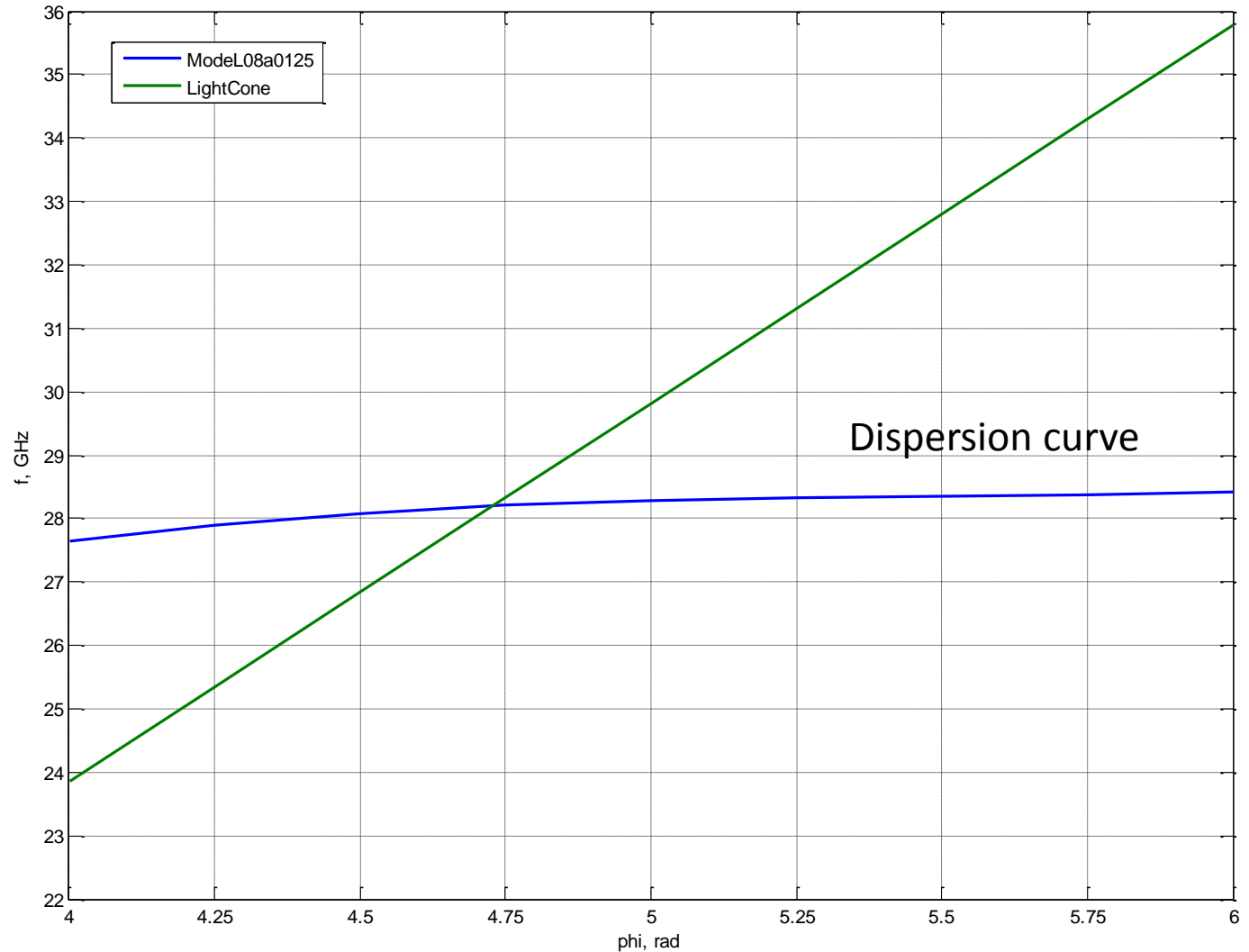
R=6.09 mm

a=1.25 mm

P=8 mm

hP=4.727

f=28.2 GHz
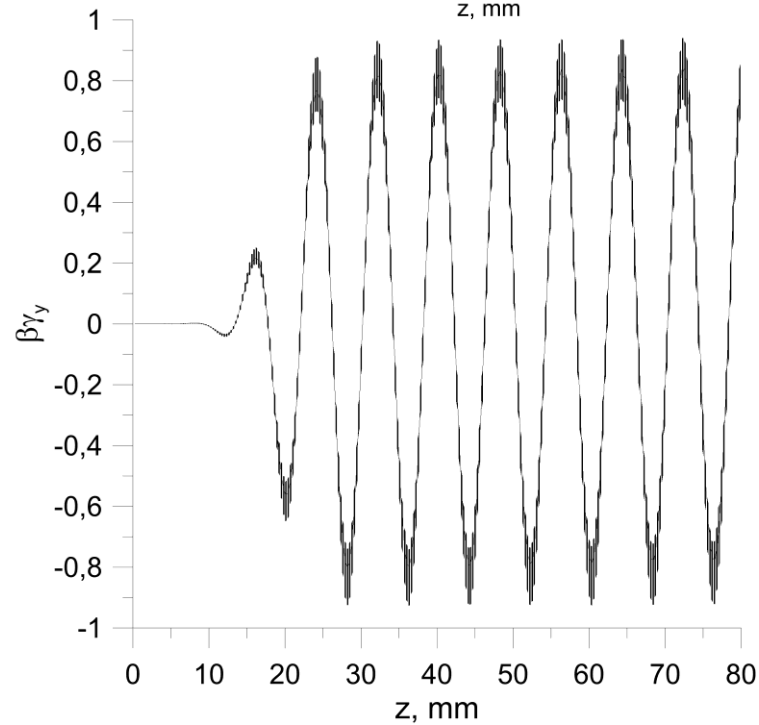
Q=10800

E_{acc}/E_{surf}=0.307

R_{sh}/L=18.9 MOhm/m
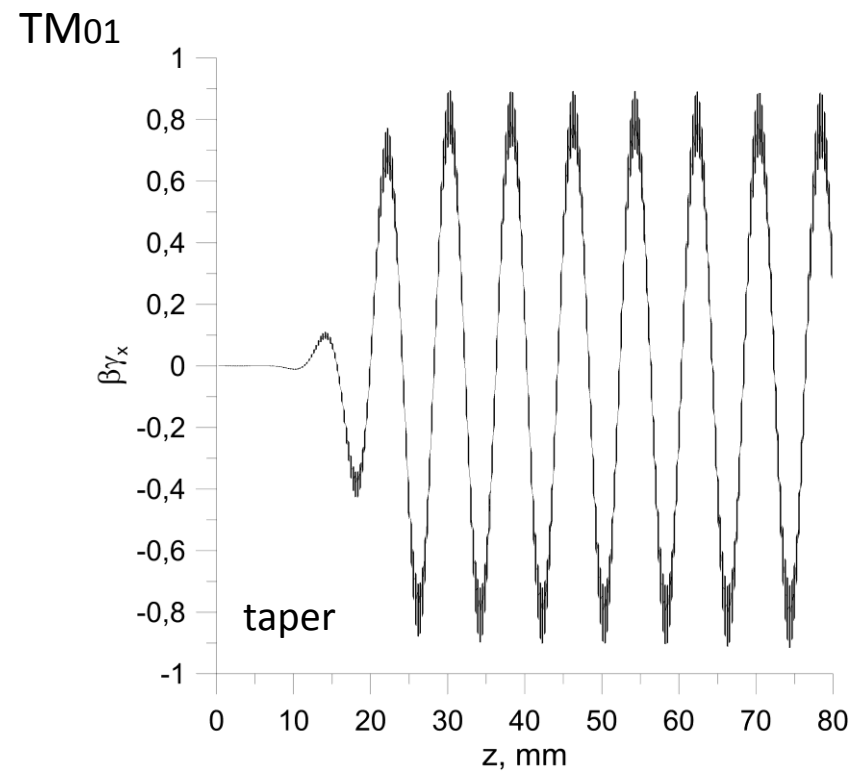

Dispersion curve

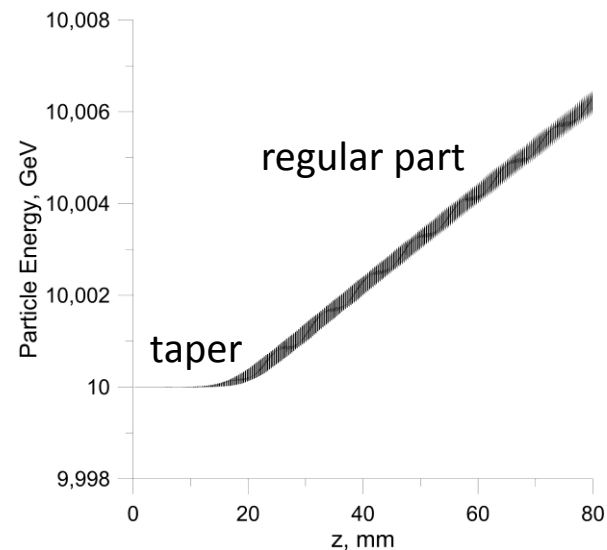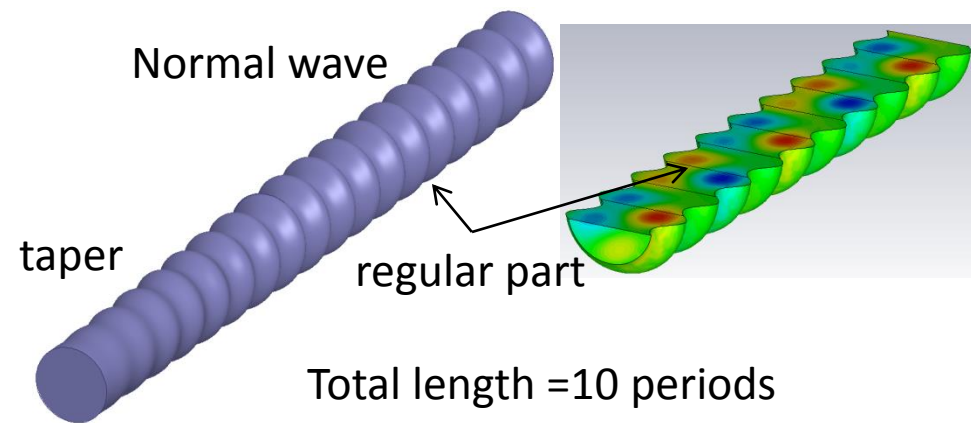Example:

f= 30 GHz structure, $G=E_{acc}$=100 MV/m, then B=0.75 T,

Beam energy W=25 GeV (γ=49000),

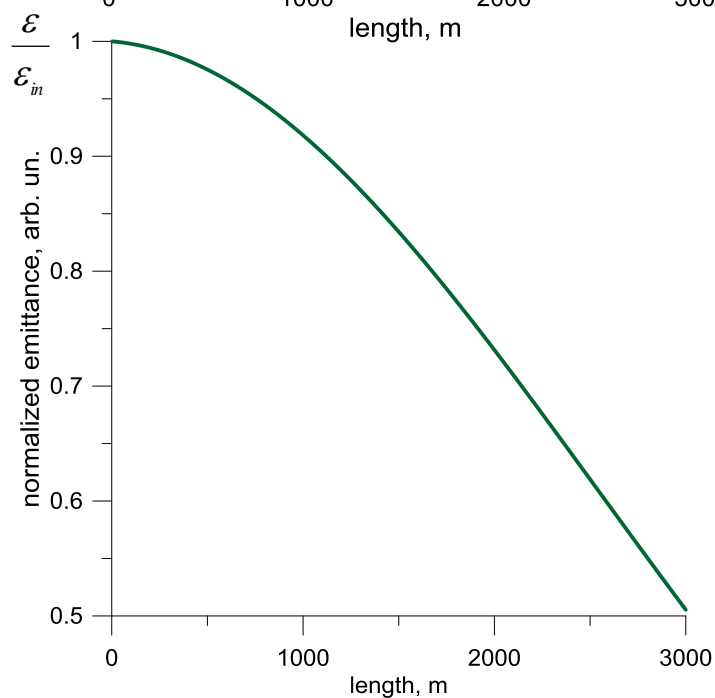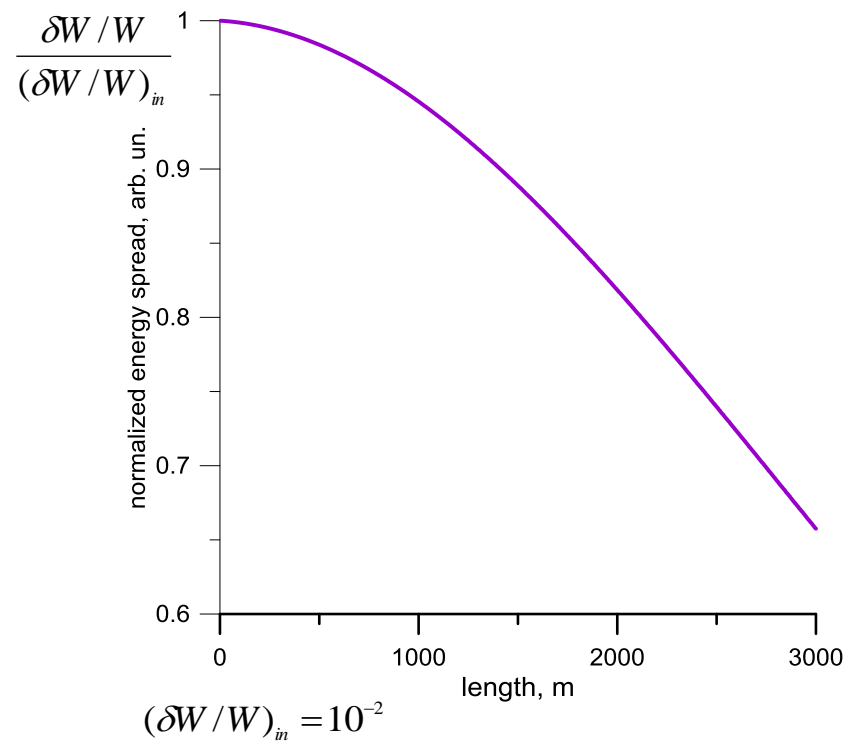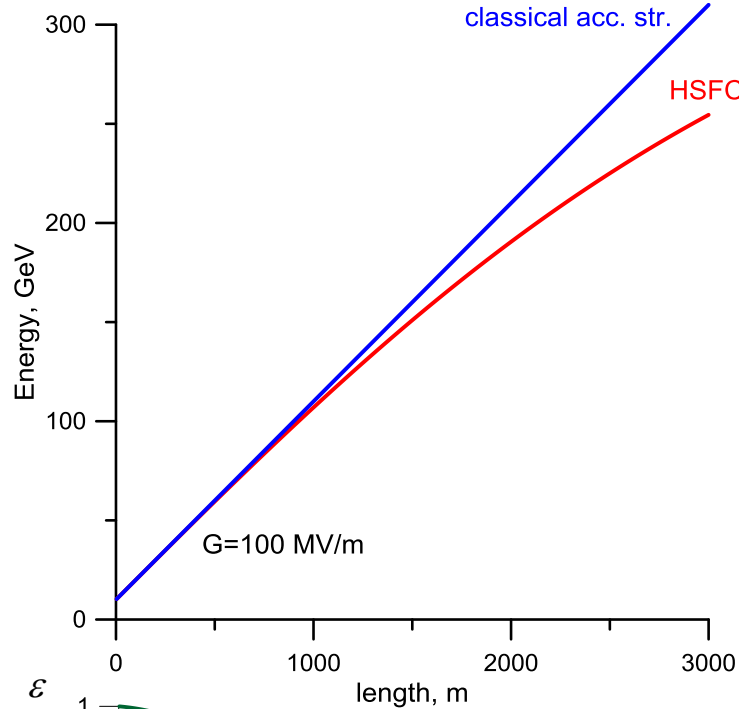then necessary decay distance $\approx$ 2800 m.

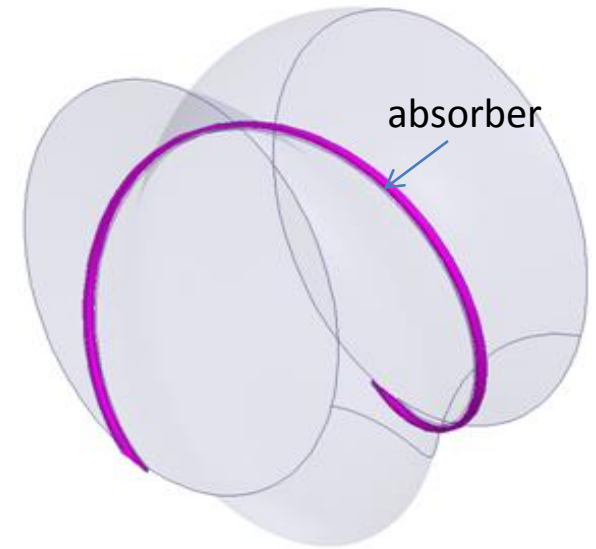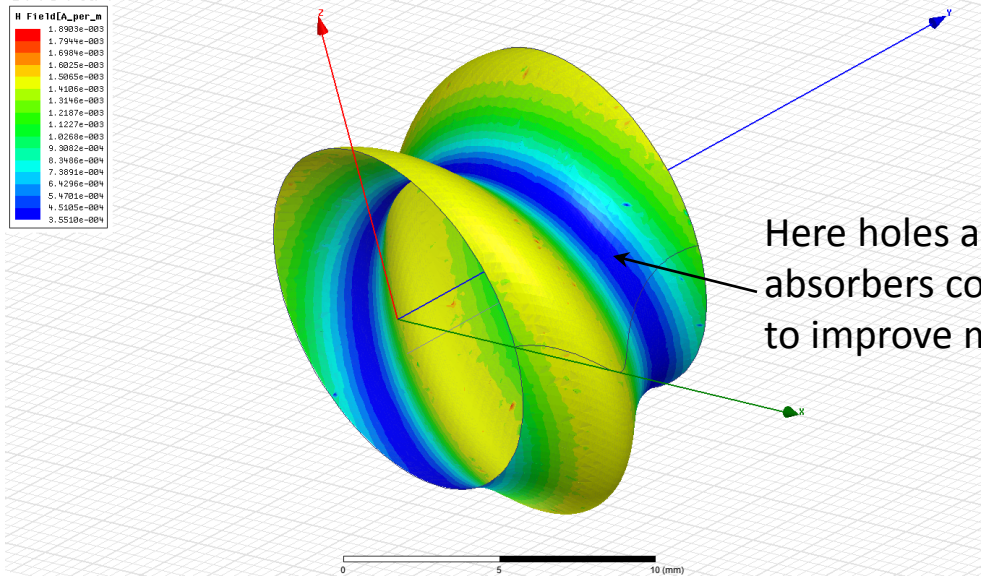# Simulation of particle motion in 100 MV/m accelerating structure by CST Microwave Studio

Normal wave

taper

regular part

Total length =10 periods

TM01

Transverse particle momentums

Parameters of cooling in 100 MV/m structure

classical acc. str.

HSFC

G=100 MV/m

Energy, GeV

length, m

$$\frac{\delta W / W}{(\delta W / W)_{in}}$$

normalized energy spread, arb. un.

length, m

$$(\delta W / W)_{in} = 10^{-2}$$

$$\frac{\varepsilon}{\varepsilon_{in}}$$

normalized emittance, arb. un.

length, m

$$\varepsilon_{in} = 1.4 mrad \times mm$$

Mode selection properties

Here holes and/or absorbers could be inserted to improve mode selection

Surface magnetic field

absorber
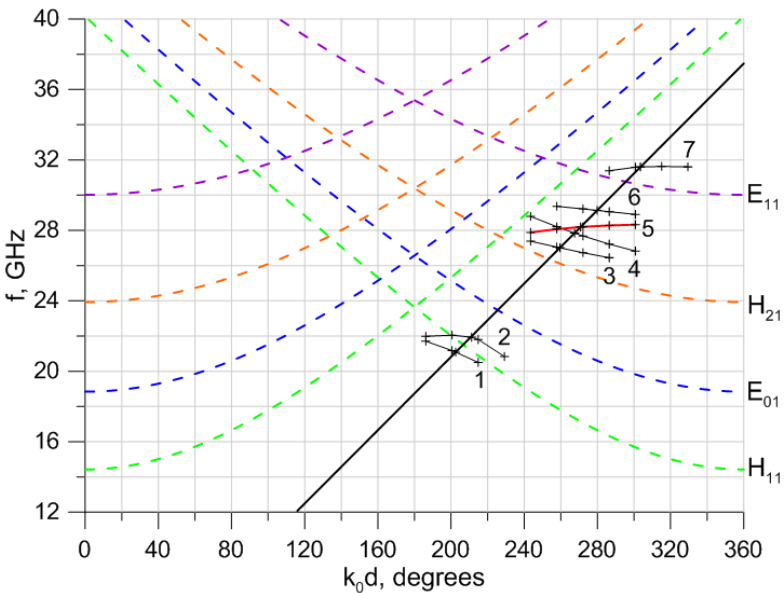
Mode	Rotation	Phase, rad	No absorber		Absorber	
			Frequency, GHz	Q-factor	Frequency, GHz	Q-factor
H_{11}	ccw	3.5346	21.0869	9255	21.0862	2607
H_{11}	cw	3.687	21.9336	8832	21.9368	3464
H_{21}	ccw	4.53	27.0125	7141	26.9984	1650
H_{21}	cw	4.67	27.8435	7869	27.8277	2623
E_{11}	ccw	4.727	28.193	10824	28.193	8168
E_{11}	cw	4.885	29.1356	9940	29.1345	6391
H_{01}	-	5.2975	31.6039	14856	31.5939	3004

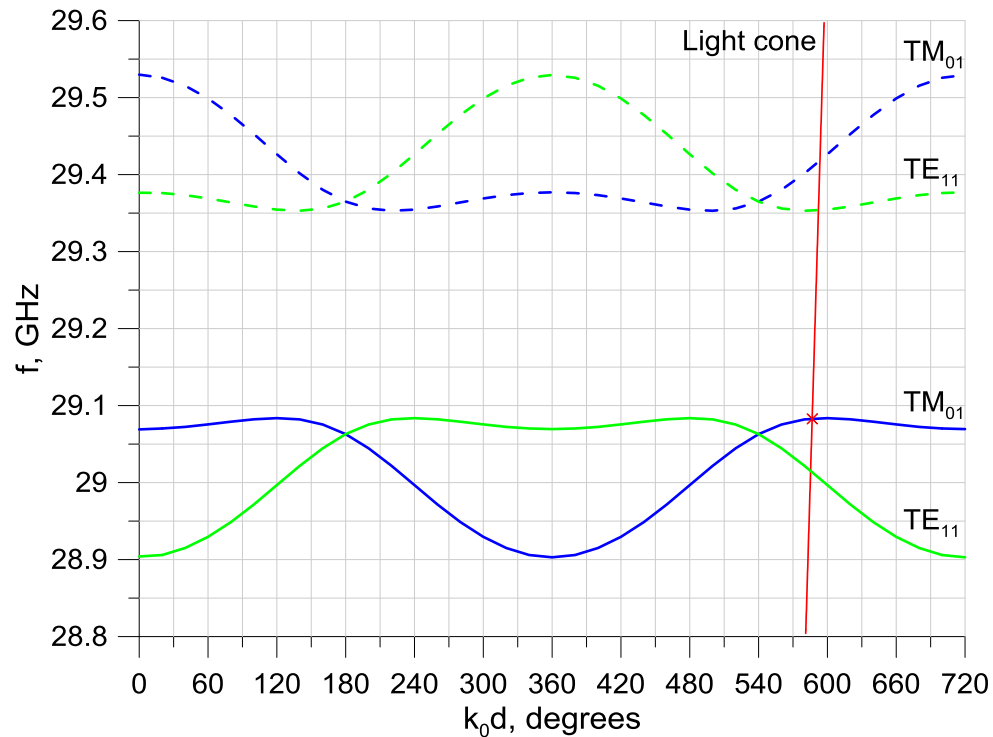# High shunt impedance in bi-periodic accelerating structure

The first period is shaped by irises which are shifted transversally with twice bigger period.
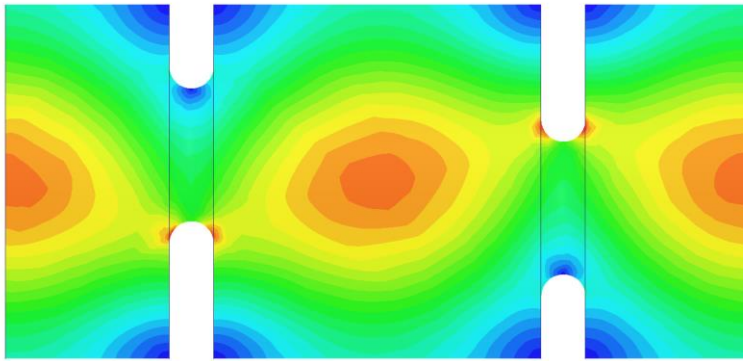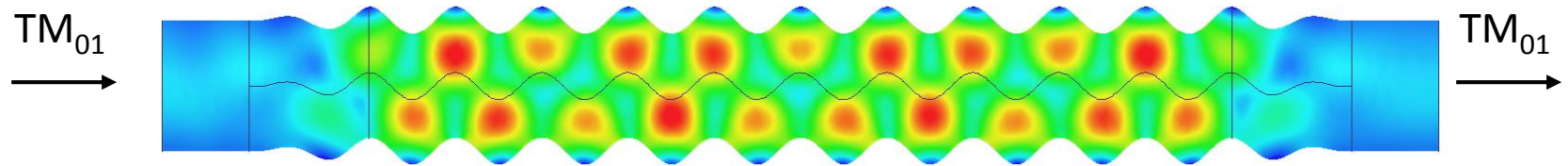

Average E-field
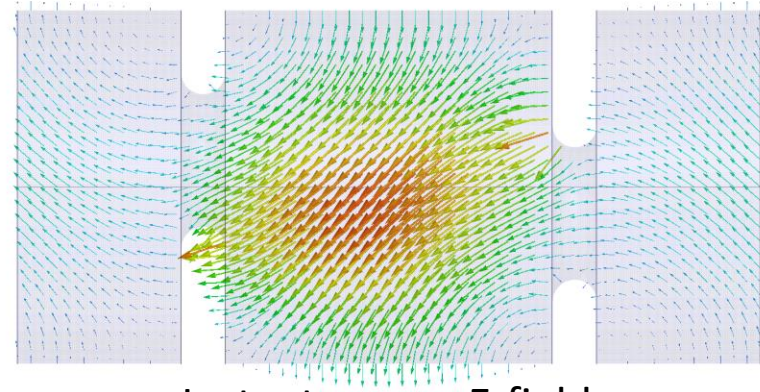
Instantaneous E-field

At 30 GHz shunt impedance exceeds 90 MOhm/m.

But some advantages of the primary idea are lost in this design.

Couplers for Helical Accelerating Structure

1) Reflections of the left and right ends compensate each other. In this case the length of the whole structure is fixed.

TM_{01} TM_{01}

2) Each end is matched by its own Chebyshev's matcher (short section of the smaller corrugation rotated by proper angle relative to main corrugation). In this case the length of the structure can be arbitrary.

TM_{01} TM_{01}

Chebyshev's matcher   Chebyshev's matcher
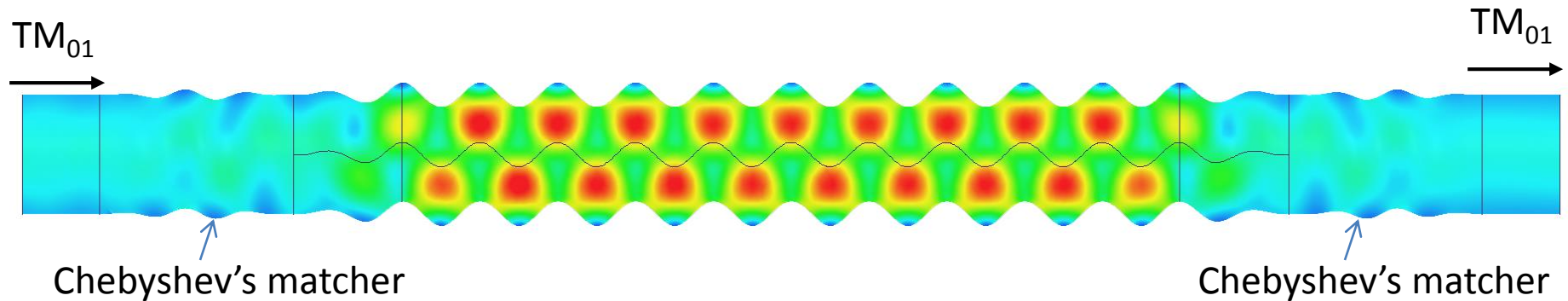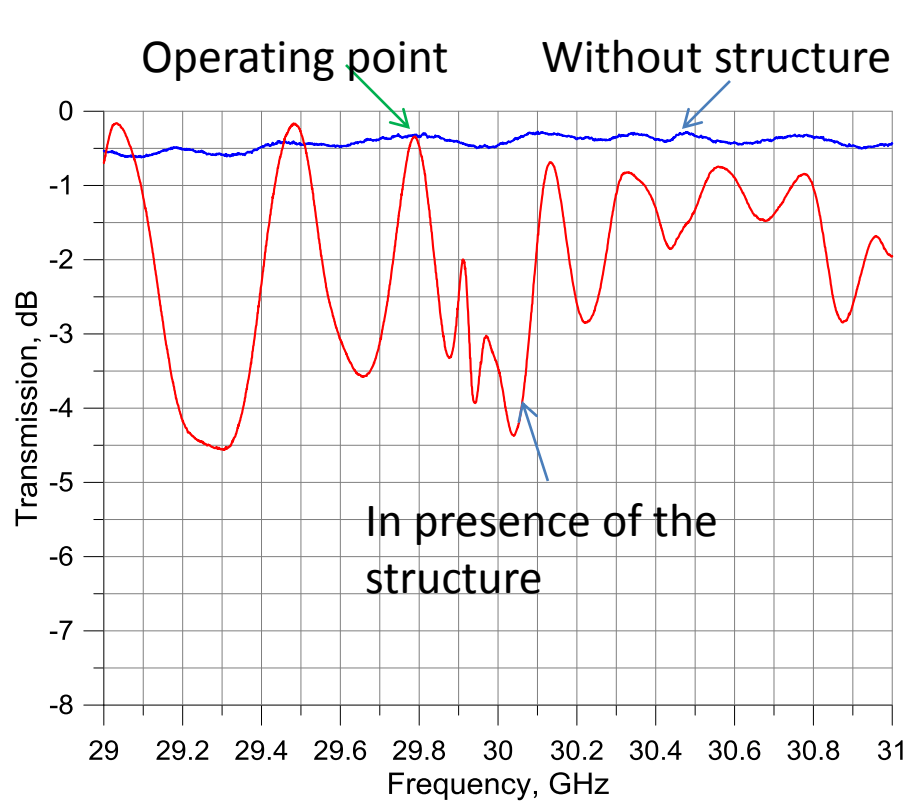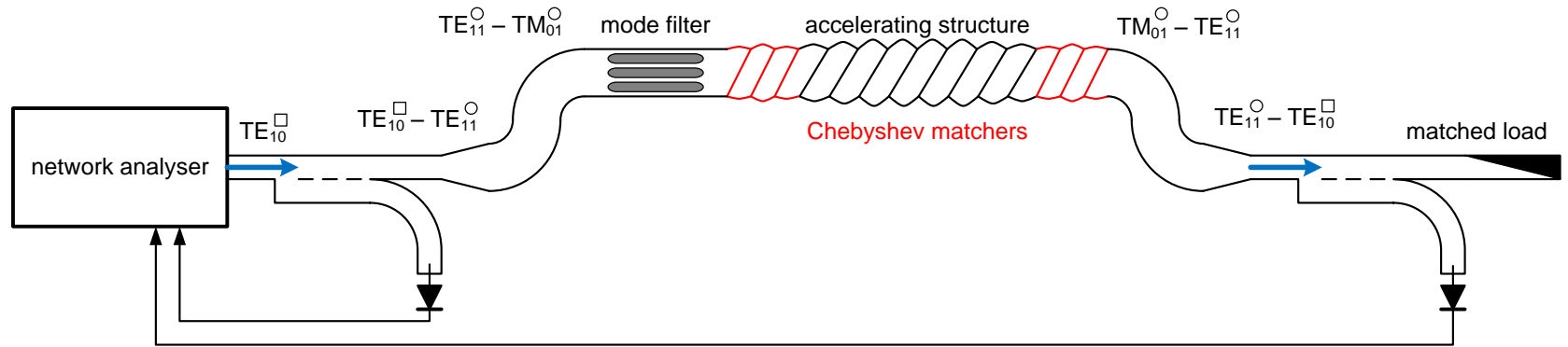
First low-power tests
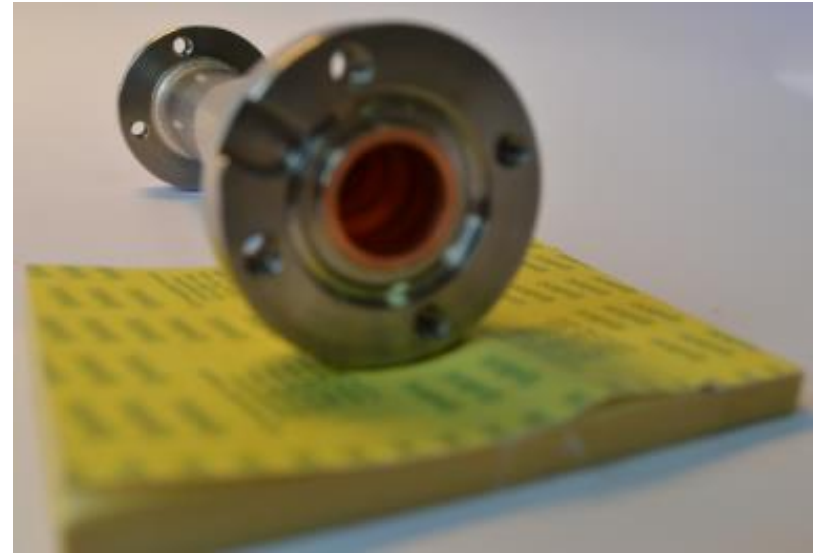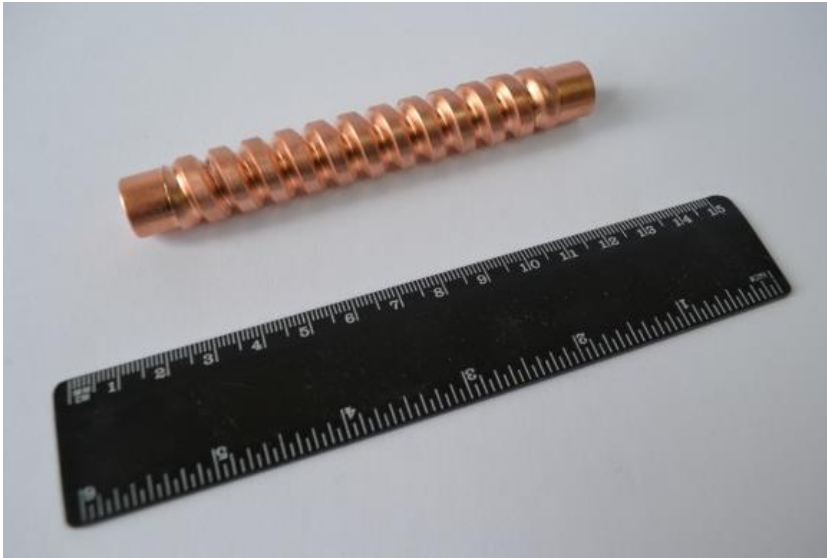
Photographs of the copper prototype and the equipped structure

Experimental setup

Measurements of efficiency using transmission scheme

$TE_{11}^{\bigcirc} - TM_{01}^{\bigcirc}$ mode filter   accelerating structure $TM_{01}^{\bigcirc} - TE_{11}^{\bigcirc}$

$TE_{10}^{\square}$ $TE_{10}^{\square} - TE_{11}^{\bigcirc}$ Chebyshev matchers $TE_{11}^{\bigcirc} - TE_{10}^{\square}$ matched load

network analyser

Operating point   Without structure

Operating band   Without structure

In presence of the structure

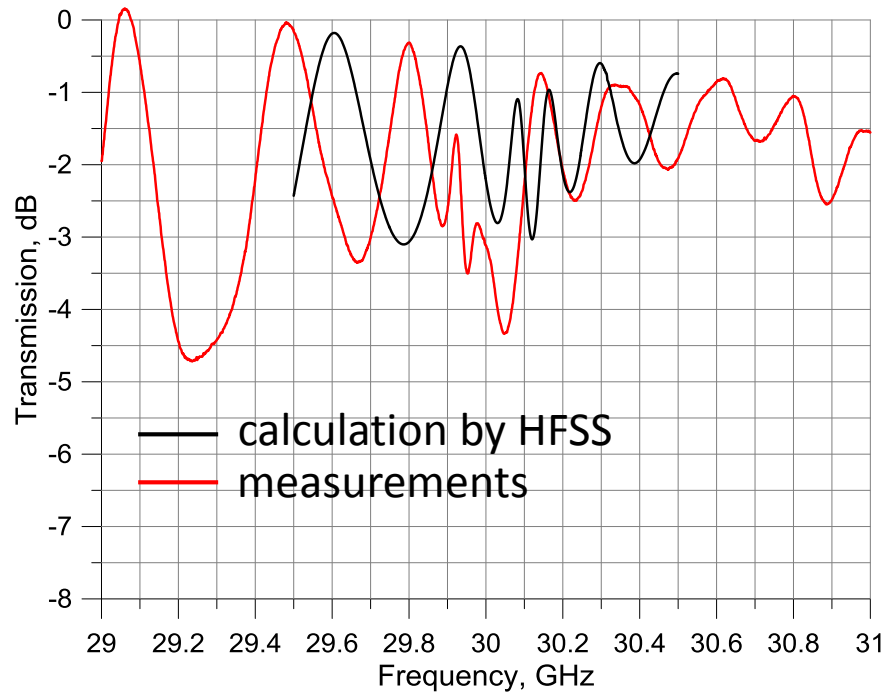In presence of the structure

Transmission, dB

Frequency, GHz

Transmitted power through the structure *without* Chebyshev's matchers
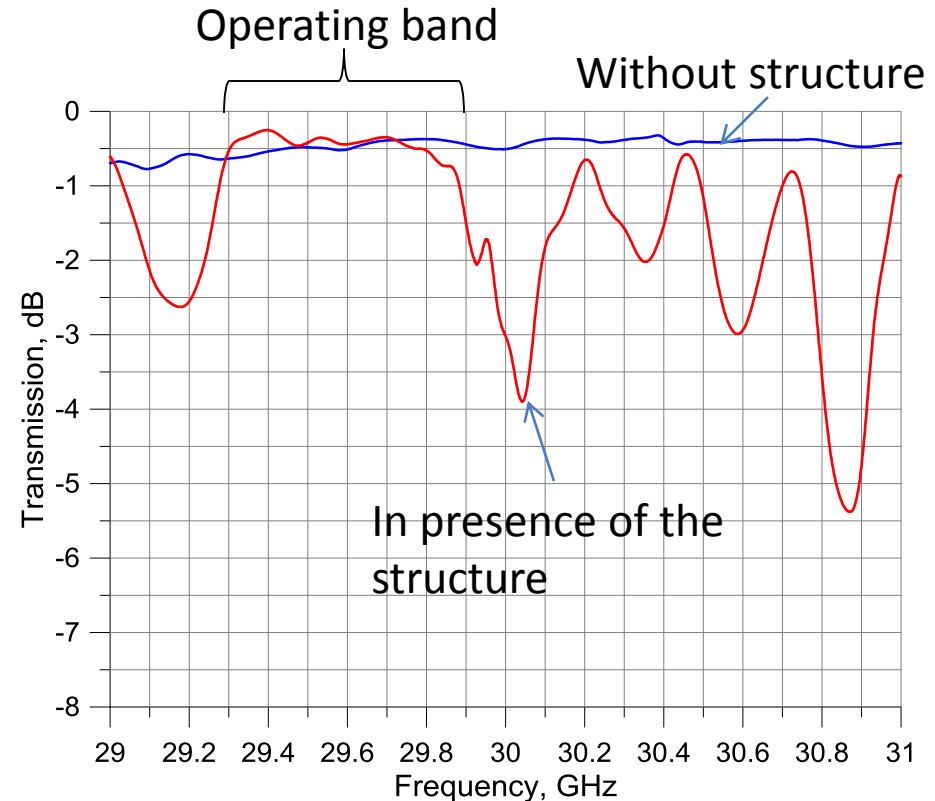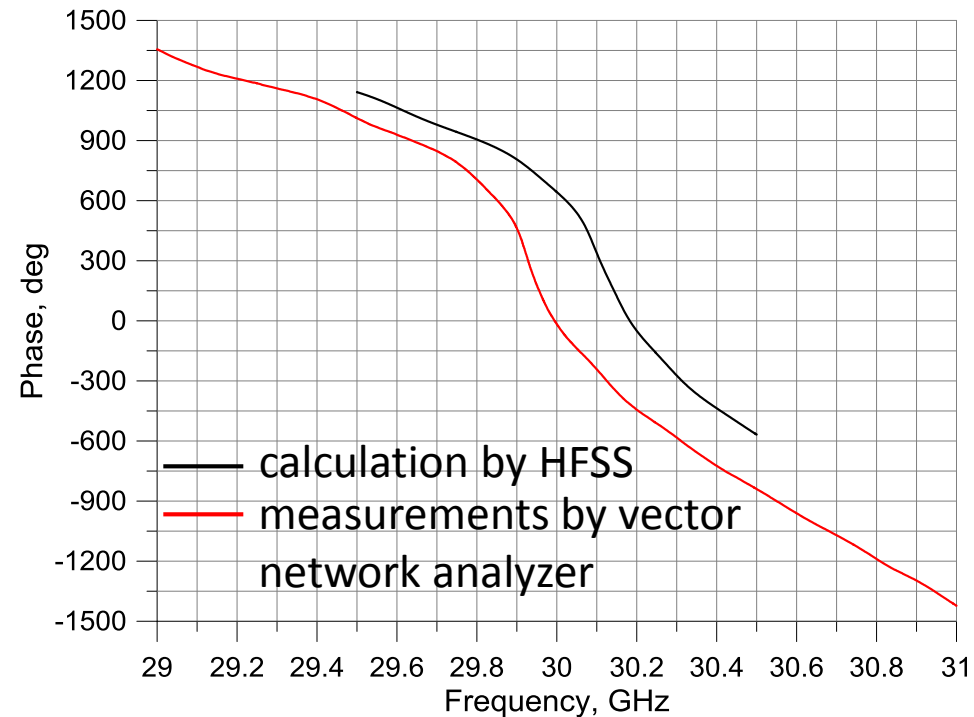
Transmitted power through the structure *with* Chebyshev's matchers

Measurements of frequency shift and dispersion of the structure
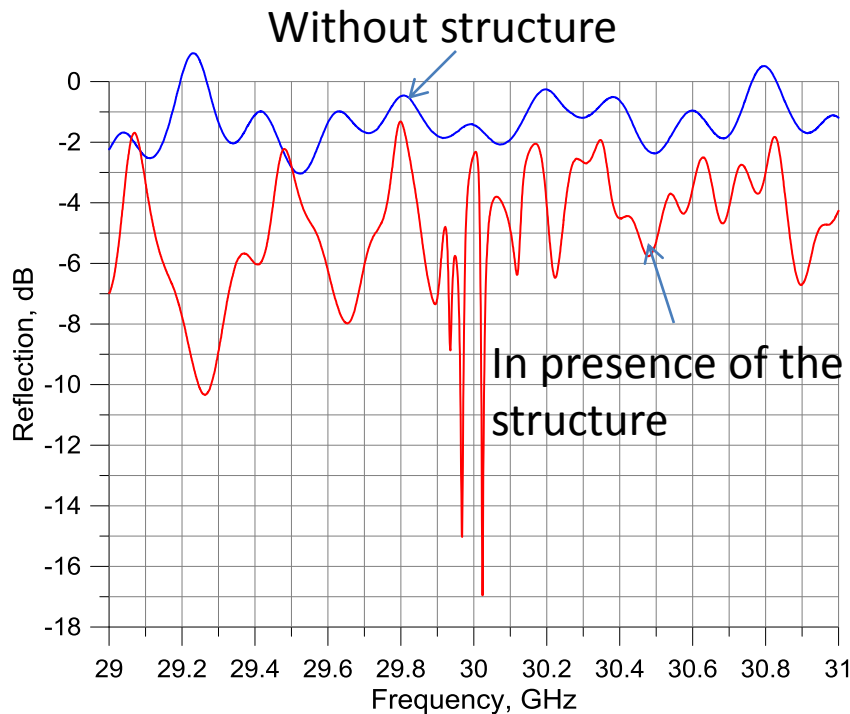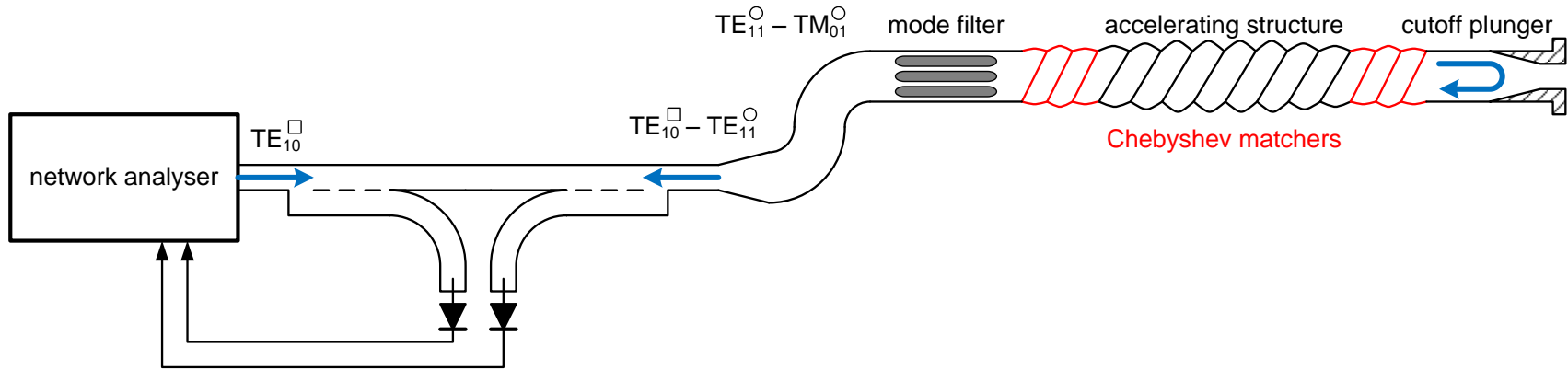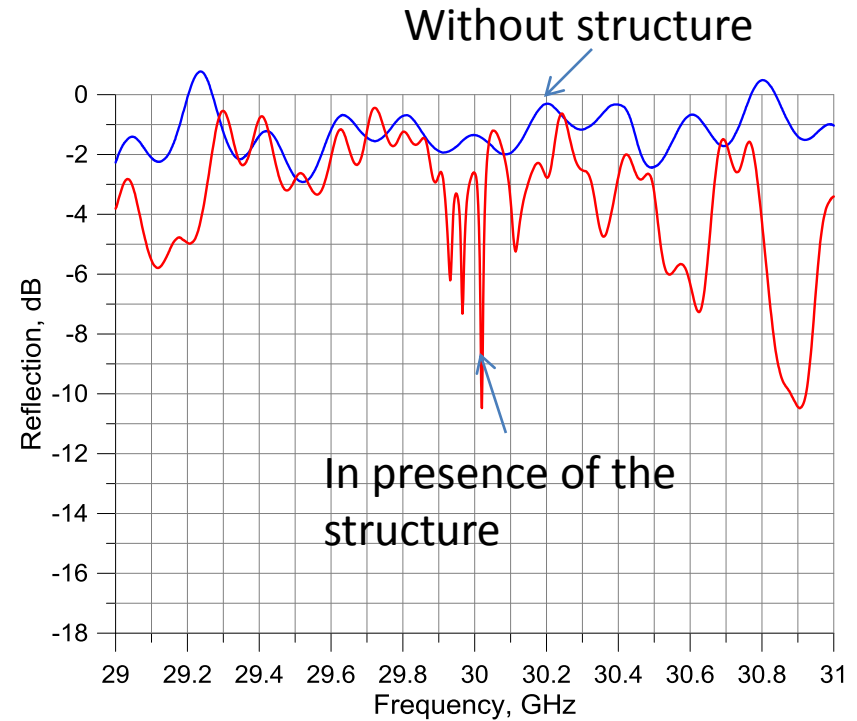

Transmitted power for the structure without matchers

Dispersion of the helical structure without Chebyshev's matchers

We have observed 150 MHz shift between calculation and measurements.
The reason is technological mistake for the average radius of the helical waveguide.

Measurements of efficiency using reflection scheme

$TE_{11}^{O} - TM_{01}^{O}$ mode filter   accelerating structure   cutoff plunger

$TE_{10}^{\Box}$

$TE_{10}^{\Box} - TE_{11}^{O}$

network analyser

Chebyshev matchers

Without structure

In presence of the structure

Reflected power through the structure *without* Chebyshev's matchers

Without structure

In presence of the structure

Reflected power through the structure *with* Chebyshev's matchers

Conclusion

1. $TM_{01} - TM_{11}$ helical accelerating structure has several appealing properties. In particular, non-synchronous electric and magnetic field components are used, in order to preserve low beam emittance and small energy spread. The structure allows high accelerating gradient due to nanosecond filling time.

2. Shunt impedance is slightly less than in a conventional accelerating structure.

3. In order to increase shunt impedance, one might use the design based on irises with periodic off-axis shift.

4. The carried out first low-power tests show promising results.

5. High-power experiment with the use of multi-megawatt 30 GHz FEM to feed the structure is coming.