Technische Universität Berlin

THEORETISCHE ELEKTROTECHNIK

Performance Estimate of a 90GHz Helical Groove-Guide TWT

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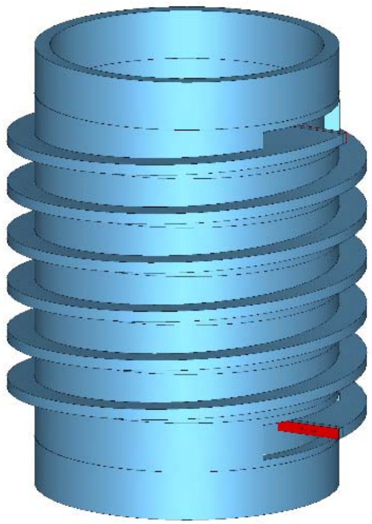
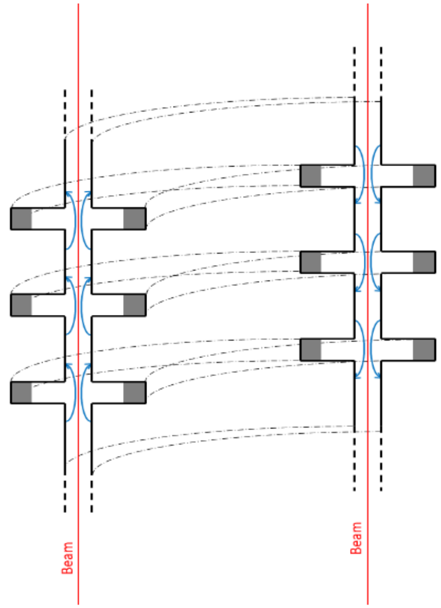
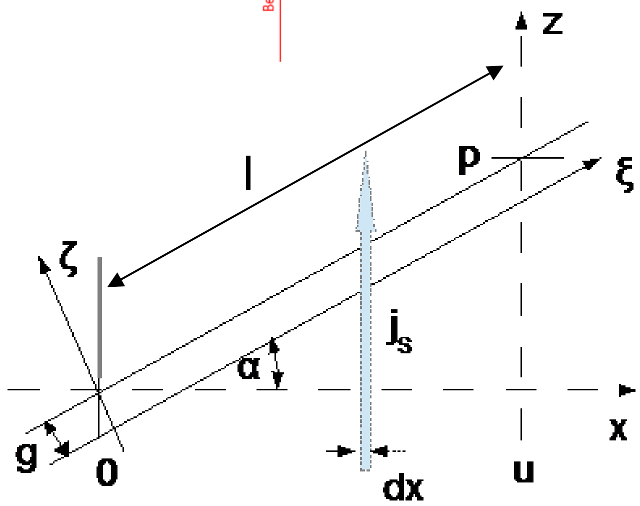




One projected turn with geometrical parameters and current element



l length of one winding
p pitch between windings, p=l sin(α)

A current element $j_S dx$ excites waves traveling in ±ξ-direction with amplitudes A/2. The sum of all contributions yields the field

$$E_\zeta = E_0 \exp(-ik_\xi \xi) + \frac{1}{2}\int_0^{\xi} A(\xi')\exp(-ik_\xi(\xi-\xi'))d\xi' + \frac{1}{2}\int_{\xi}^{Nl} A(\xi')\exp(+ik_\xi(\xi-\xi'))d\xi'$$

where N is the number of windings of length l. Differentiating twice and using z=ξ sinα results in the circuit equation

$$\frac{d^2 E_z}{dz^2} + \left(\frac{k_\xi}{\sin\alpha}\right)^2 E_z = i\left(\frac{k_\xi}{\sin\alpha}\right)^3 K' j_S$$

The equation of motion for the electrons gives the electronic equation

$$\frac{d^2 j_s}{dz^2} + i\,2k_0 \frac{dj_S}{dz} - k_0^2 j_s = i\frac{k_0}{2uR_0} E_z$$

where $R_0=V_0/I_0$, $k_0=\omega/v_0$, $u=2\pi r=\sqrt{(l^2-r^2)}$, v_0 beam velocity, r structure radius.

Small Signal Gain

For a fixed position x the field is represented by space-harmonics corresponding to the periodic arrangement of the waveguide gaps. Synchronism between fields and beam is given when the 0th order space-harmonic and the space-charge wave have the same propagation constant γ.

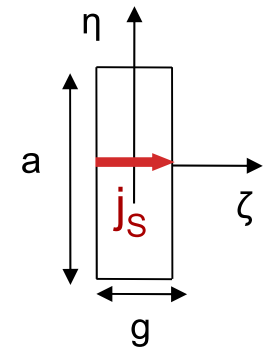
This yields an equation for γ with the three well-known solutions

$$\gamma_1 = i k_0 (1 - C), \qquad \gamma_2 = i k_0 \left(1 + \frac{C}{2}\right) + \frac{\sqrt{3}}{2} k_0 C, \qquad \gamma_3 = i k_0 \left(1 + \frac{C}{2}\right) - \frac{\sqrt{3}}{2} k_0 C, \qquad C^3 = \frac{K'}{4 u R_0}$$

where C is the Pierce gain parameter and K‘ the interaction impedance.

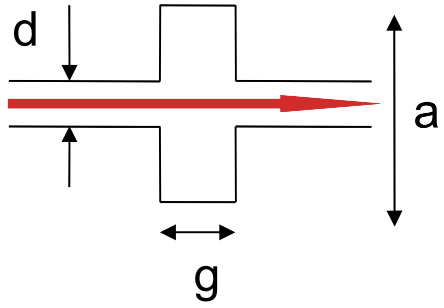
In order to determine K‘ we calculate the increase of the 0th order space-harmonic by means of the Lorentz reciprocity theorem for a closed rectangular waveguide supporting a TE_{10}-mode only

$$dE_{0\xi} = -\frac{\omega \mu g}{k_\xi a p} j_S \, d\xi \, M^2 = \frac{1}{2} A = -\frac{k_\xi^2}{\sin(2\alpha)} K' j_S, \qquad M = \frac{\sin(k_0 g/2)}{k_0 g/2}$$



In an open groove-guide the field is reduced by

$$\frac{1}{\cosh(k_0 d/2)}$$



As an example we take a copper groove-guide with

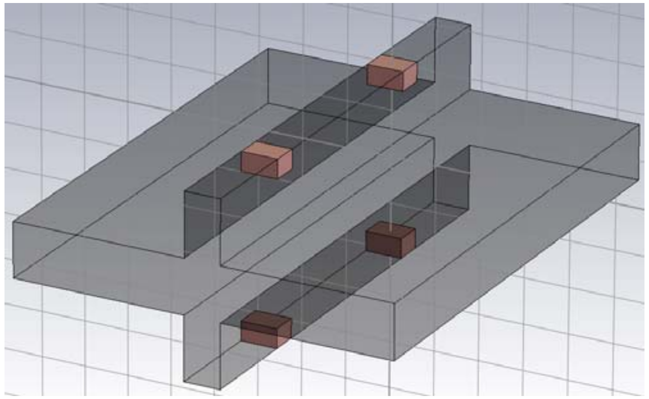
$$a = 1.8mm,\ g = d = 0.4mm,\ l = u/\cos\alpha = 52.7mm,\ \alpha = 3.5°,\ p = 3.21mm$$

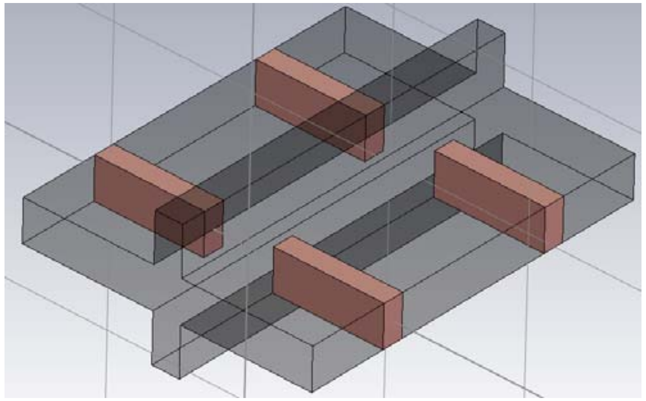
and beam parameters V_0=15kV, I_0=1A. Then the electronic gain per winding is

G=1.40dB

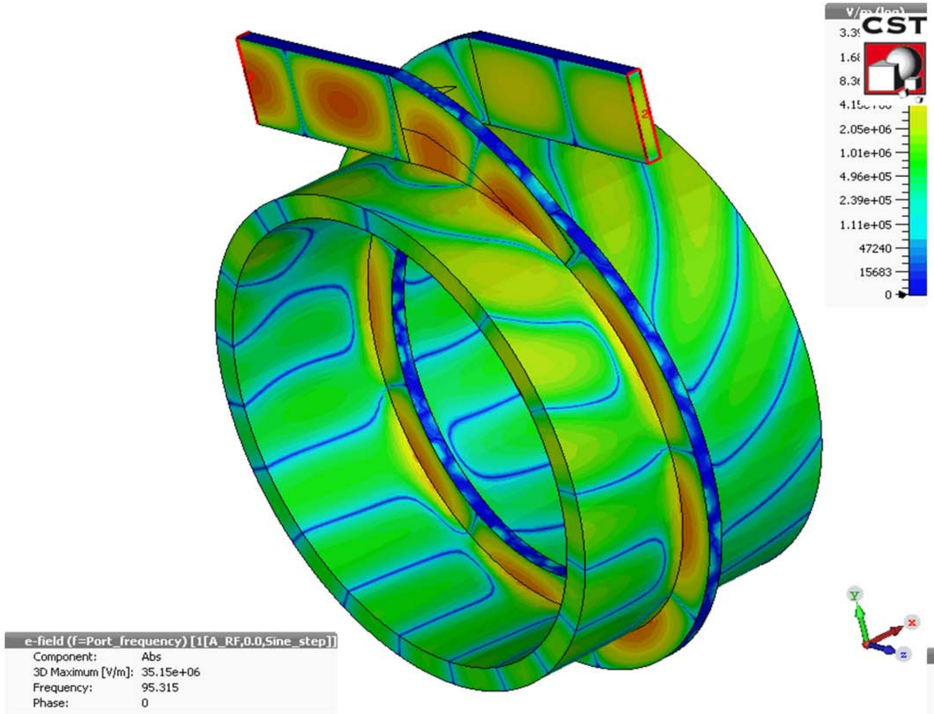
and the total gain G=0.60dB, if the losses in the guide are taken into account.

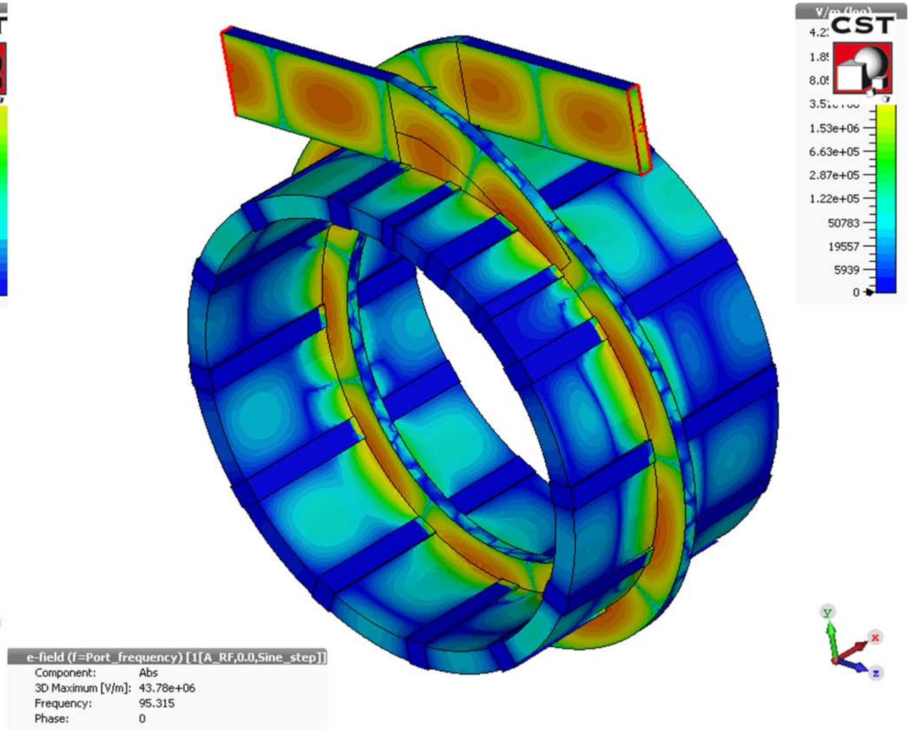
Slight improvement of the dispersion diagram by transforming groove-guide into a pass-band structure through periodic loading.





Fins suppress at the same time beam-pipe modes.



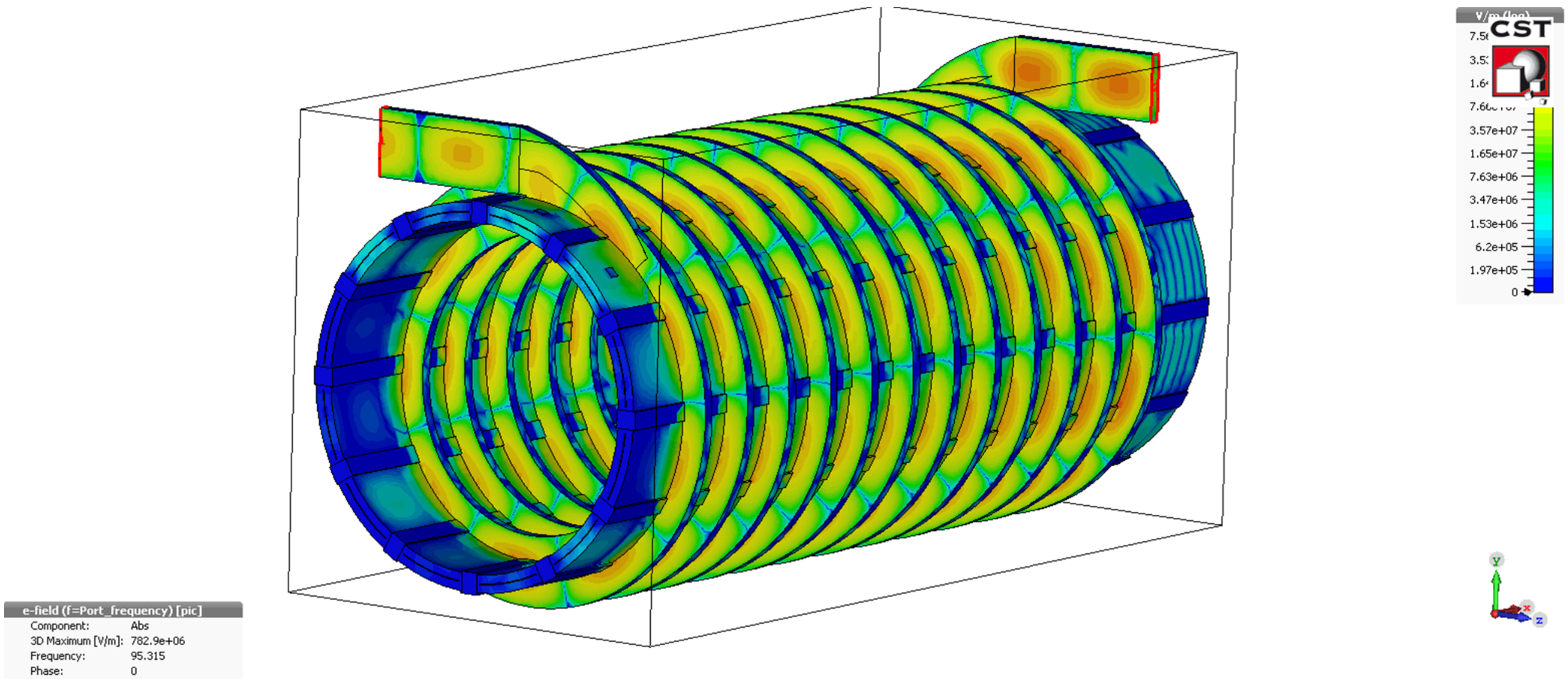


Unbalanced coupler excites beam-pipe fields.

Longitudinal fins suppress partially beam-pipe fields and improve coupler symmetry.

RF-structure with 12 windings, 6 wavelengths per winding, radius 5 mm, beam channel modes nearly suppressed by axial fins.

RF-couplers not balanced, not matched nor optimized.



For synchronism, the longitudinal velocities of wave and beam have to be equal

$$v_{ph}\sin(\alpha)=v_0 \qquad \rightarrow \qquad \sin(\alpha)=\frac{v_0}{v_{ph}}=\frac{p}{l}$$

p pitch, l length of one winding, v_0 beam velocity.

Then the phase difference between wave and beam vanishes

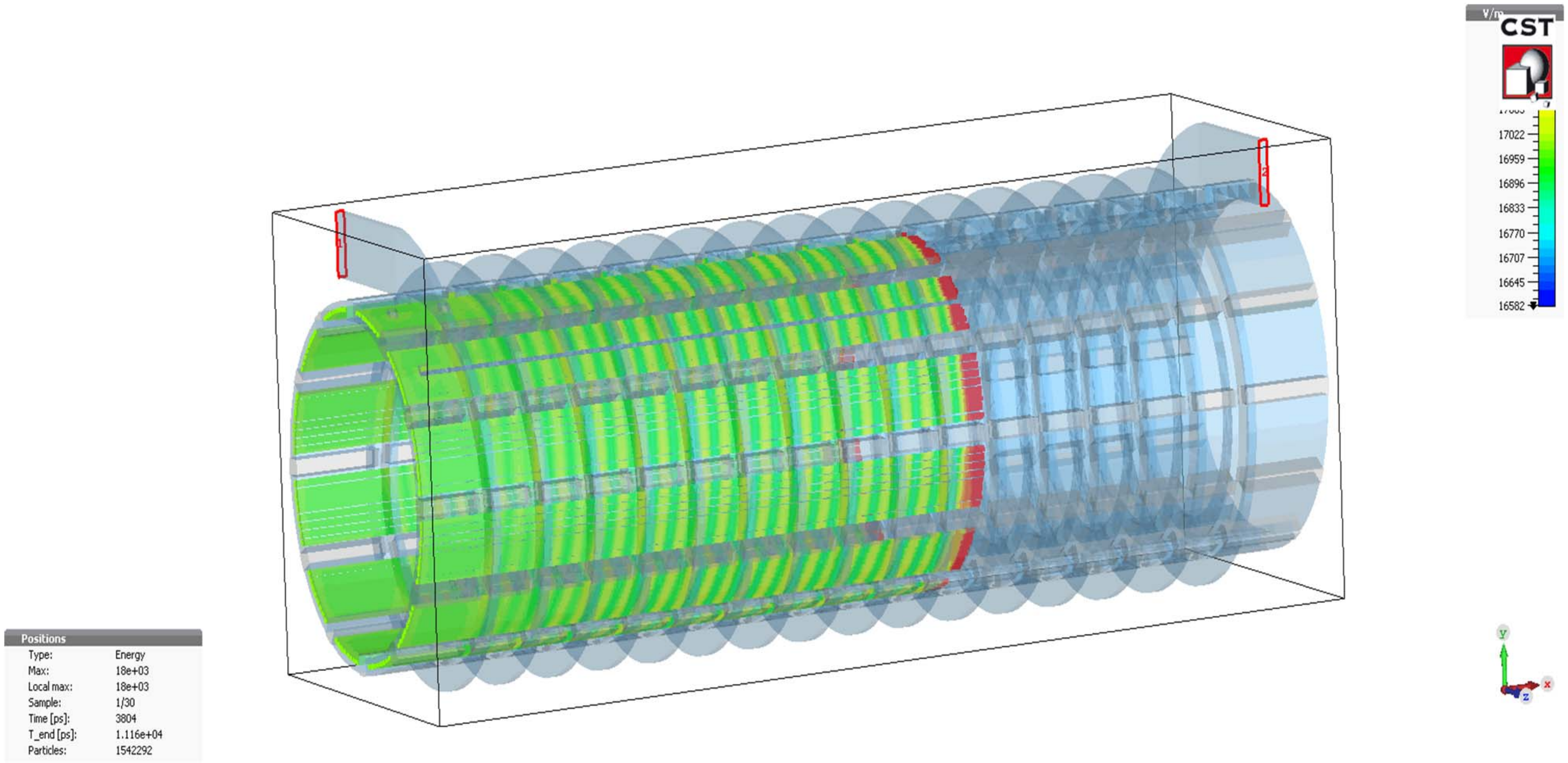
$$\Delta\varphi=k_{wg}l-k_0 p=\frac{l}{d}[\varphi-2\pi\frac{f}{v_0}d\sin(\alpha)]=\frac{l}{d}[\varphi-2\pi f\frac{d}{v_{ph}}]=0$$

$$\text{where} \quad k_{wg}d=\varphi=2\pi\frac{f}{v_{ph}}d, \quad \text{d period length}$$

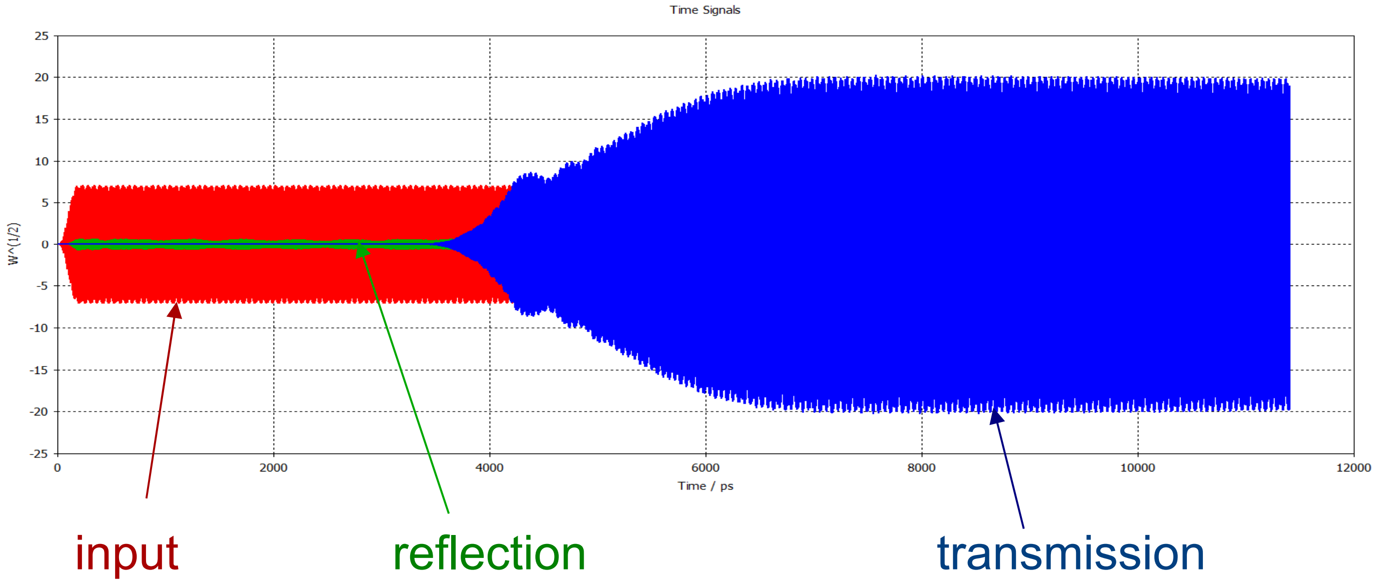
and the derivative of Δφ w.r.t. f vanishes if $v_g = v_{ph}$

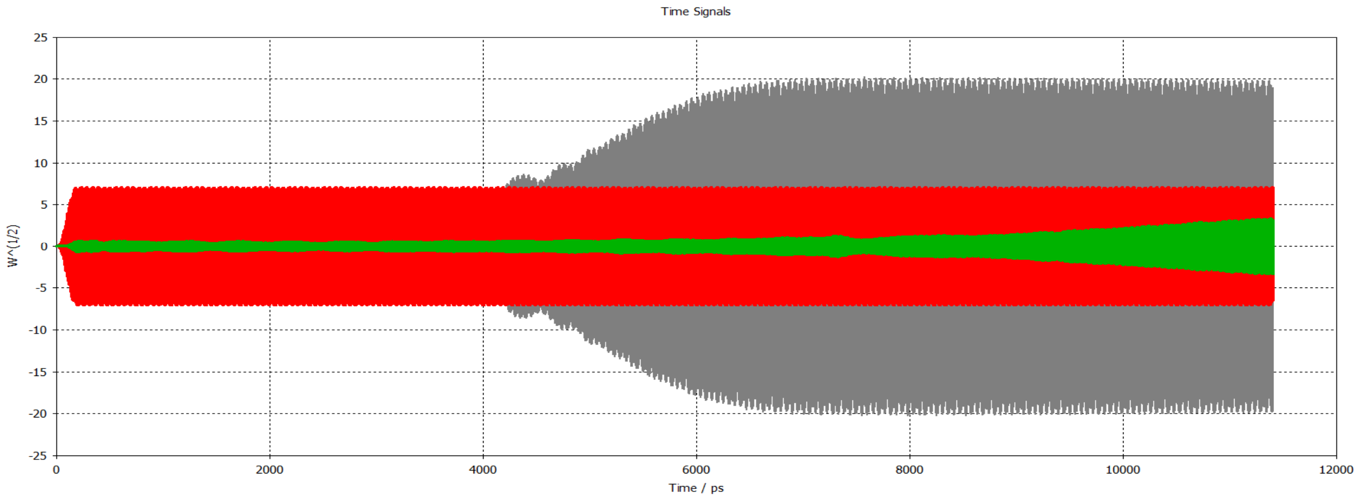
$$\frac{\partial\Delta\varphi}{\partial f}=\frac{l}{d}[\frac{\partial\varphi}{\partial f}-2\pi d\frac{\sin(\alpha)}{v_0}]=\frac{l}{d}[\frac{2\pi d}{v_g}-\frac{2\pi d}{v_{ph}}]=0$$

PIC results with 12 beamlets between axial fins in an RF-structure with 16 windings. Without any optimization a clear bunching is visible.

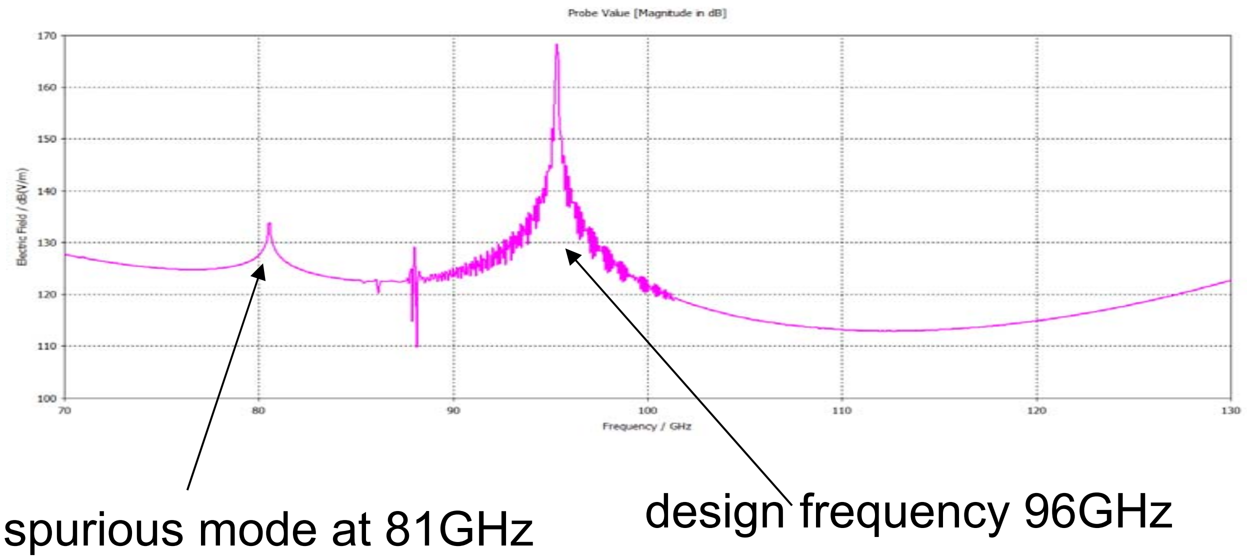


No optimization and unmatched couplers. Gain 9.0dB.

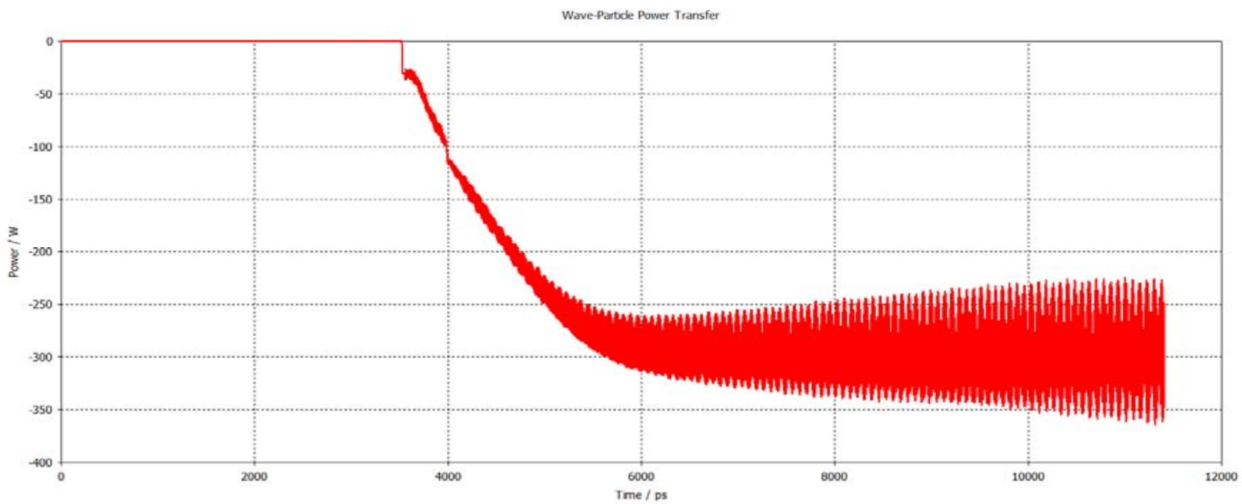




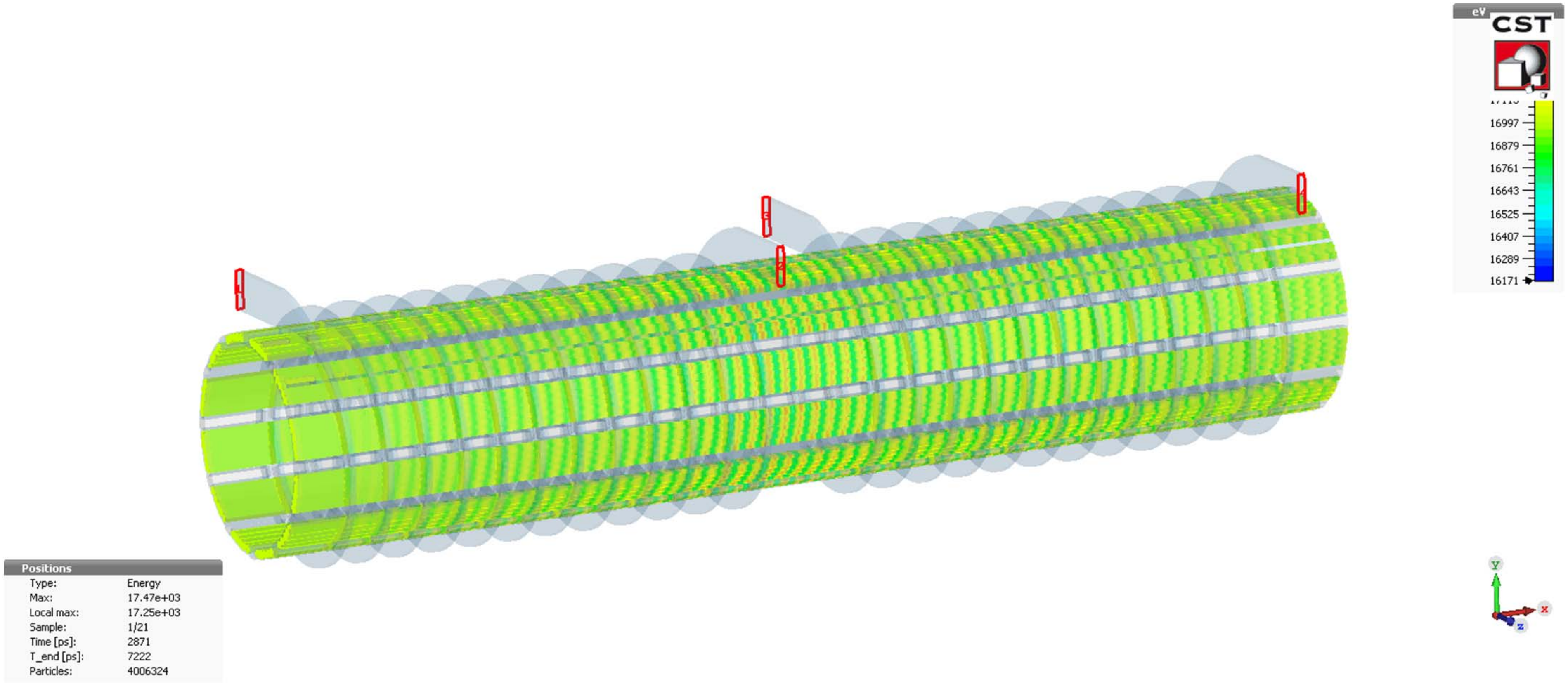
Fourier transform of output signal



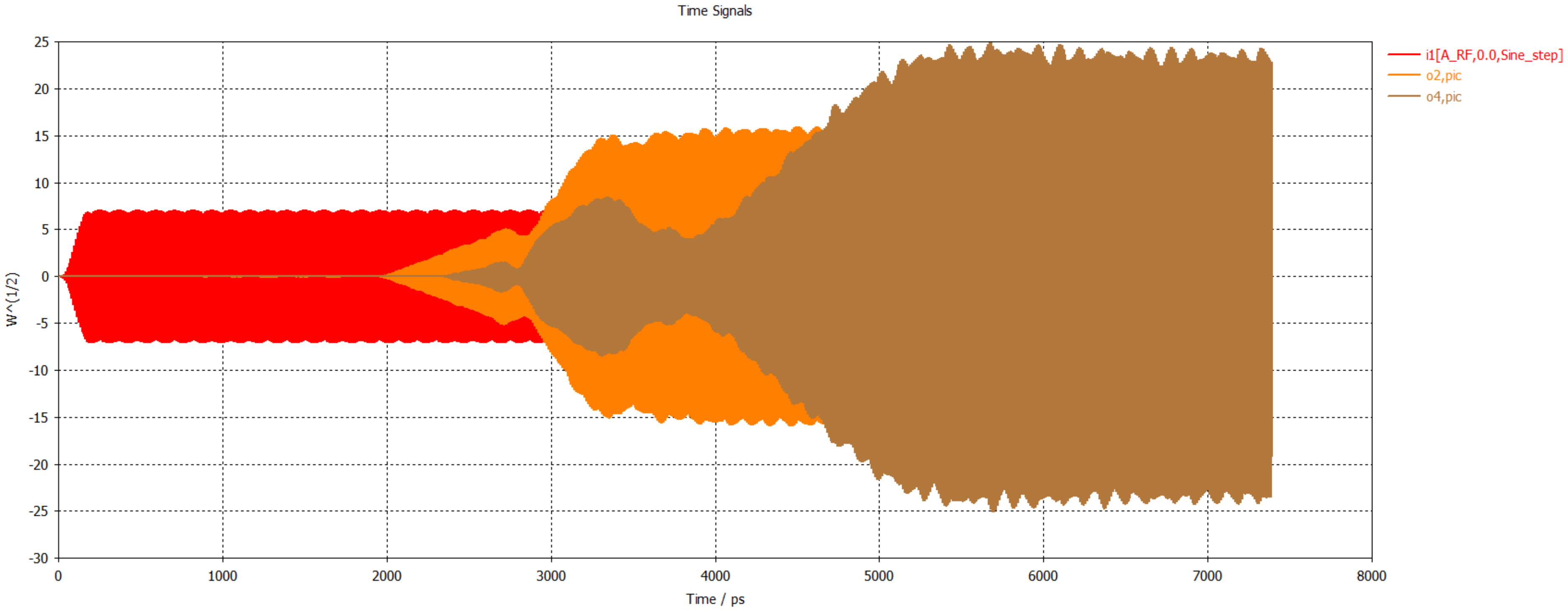
Wave-particle power transfer



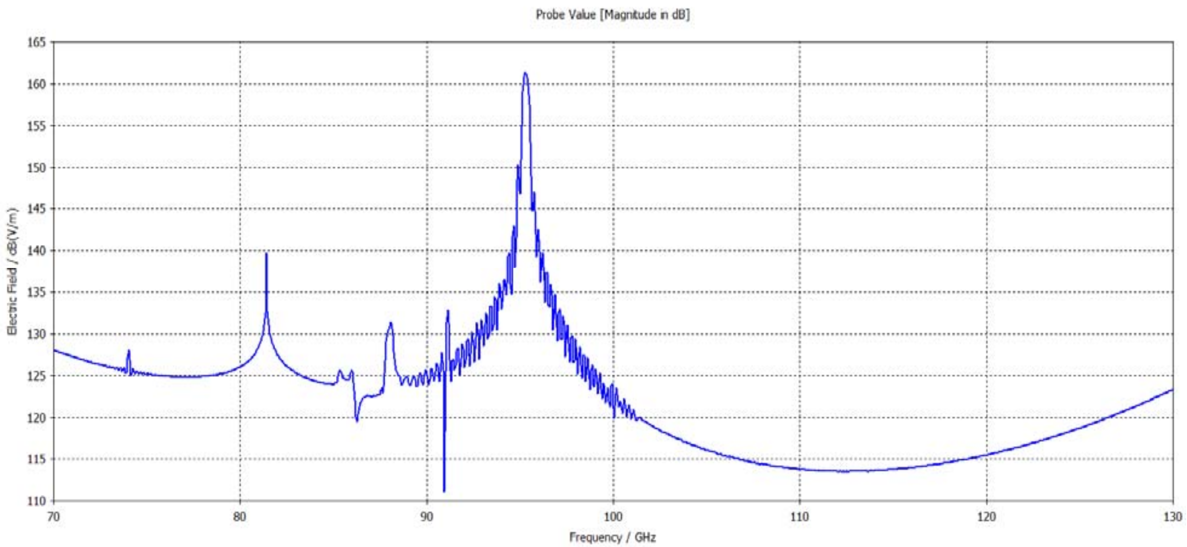
Amplifier


eV
CST
16997
16879
16761
16643
16525
16407
16289
16171
Positions
Type: Energy
Max: 17.47e+03
Local max: 17.25e+03
Sample: 1/21
Time [ps]: 2871
T_end [ps]: 7222
Particles: 4006324
Y
X
Z

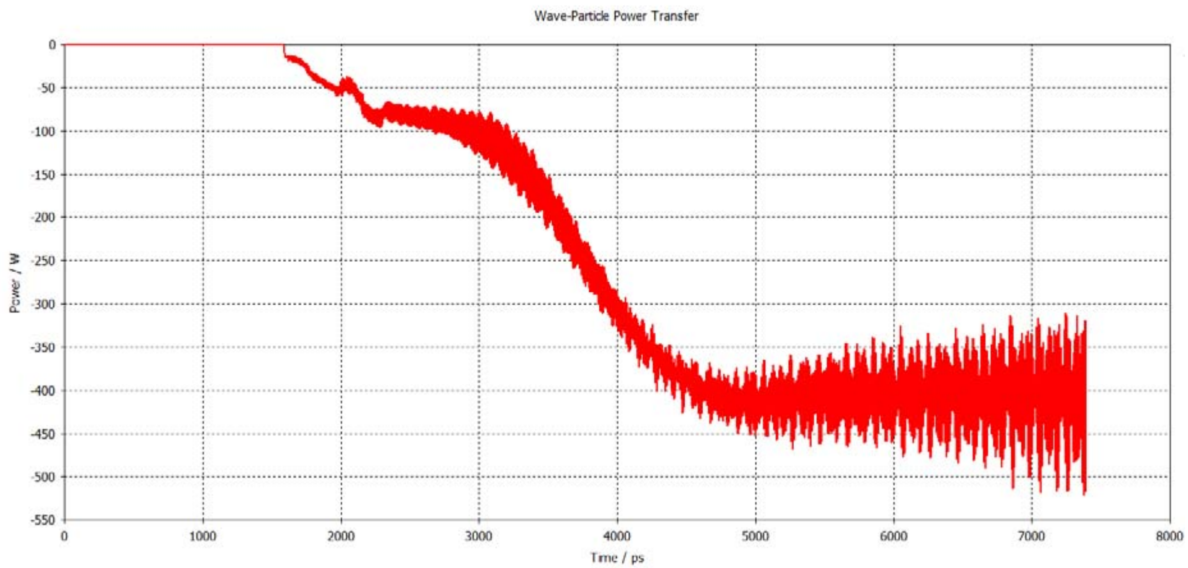
Input, transmission after first and second section and reflected signal.
No optimization and unmatched couplers. Gain 11.dB. Small bandwidth.



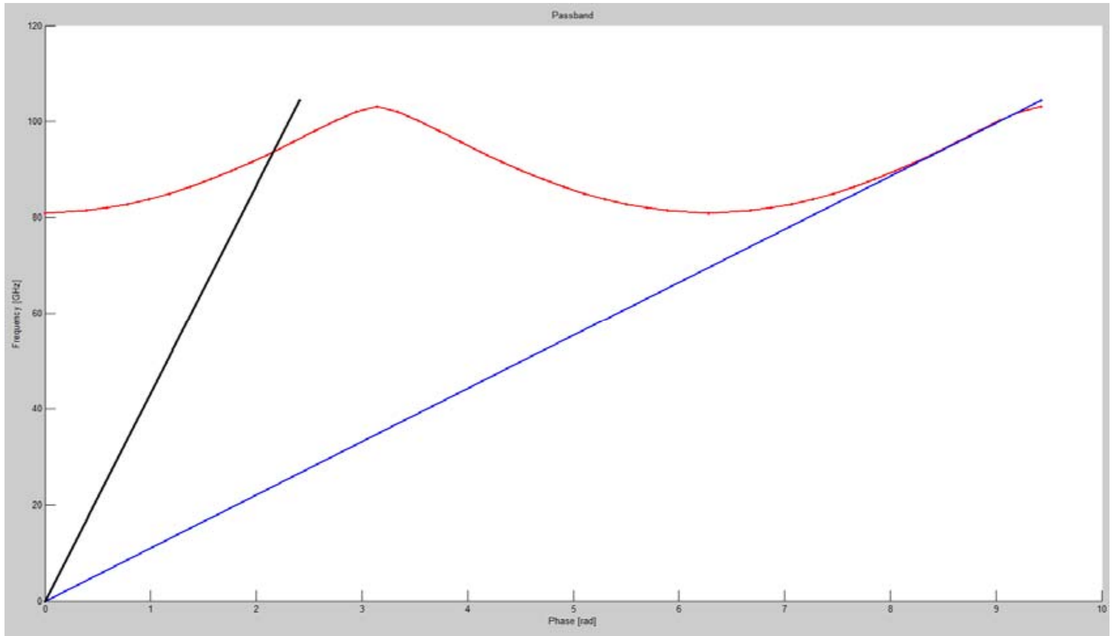
Spectrum of output signal



Wave-particle power transfer

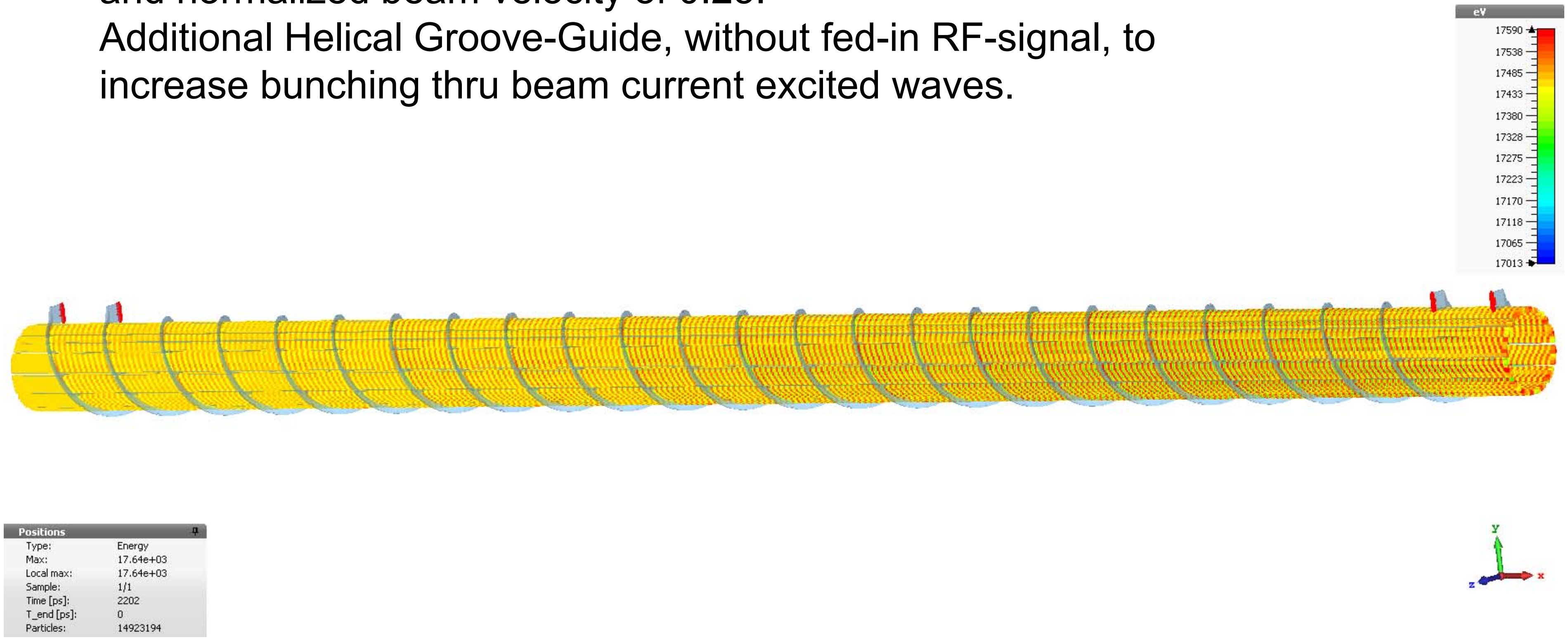


Match with 0-order space-harmonic requires steep dispersion diagram. Only possible if groove-guide is very deep, operational frequency far above cut-off and higher order modes propagate in guide.

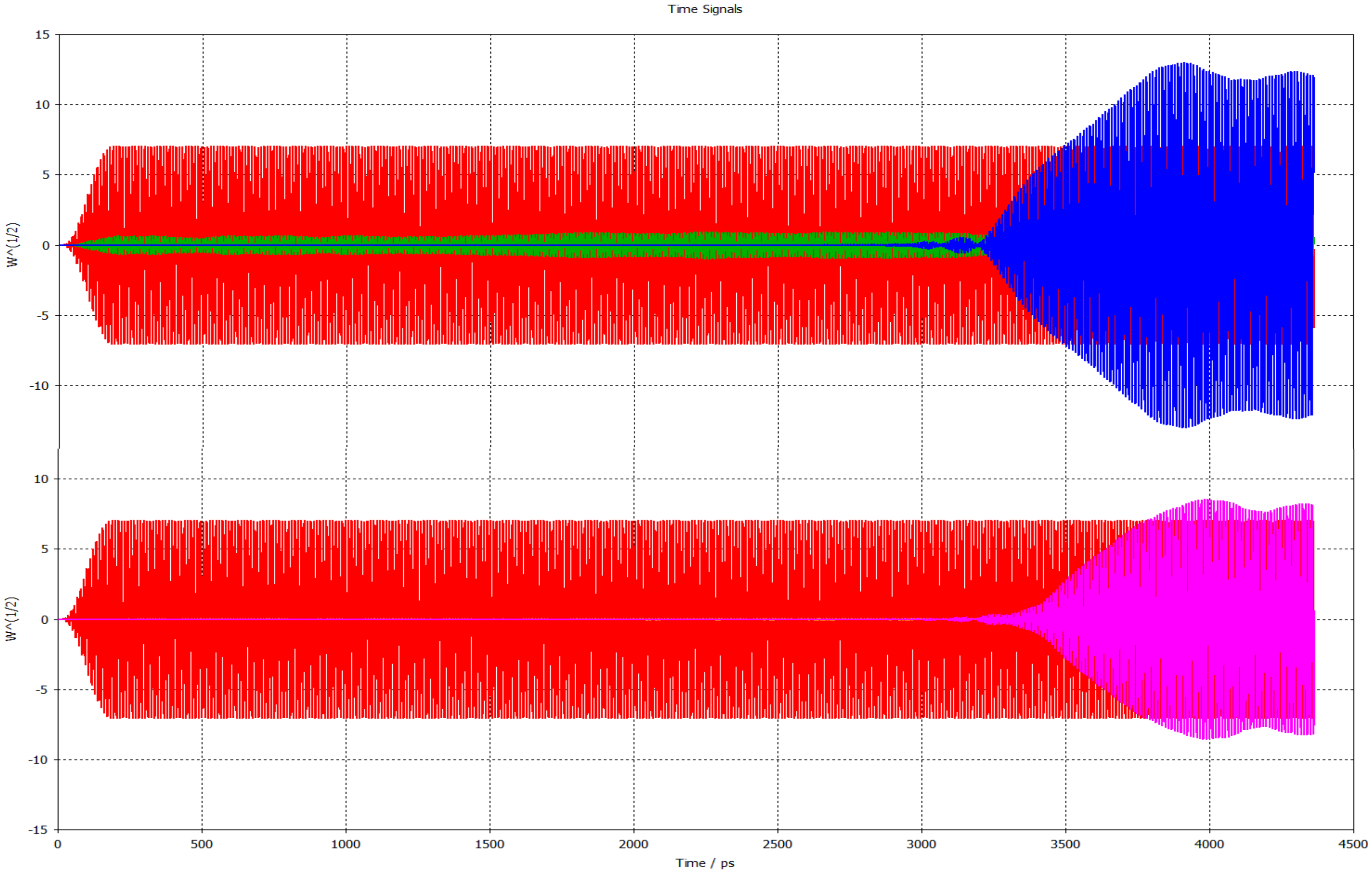


Good and broad-band match with 1st-order space-harmonic is possible. But has very low gain and low phase velocity. As consequence pitch angle is large and structure long.

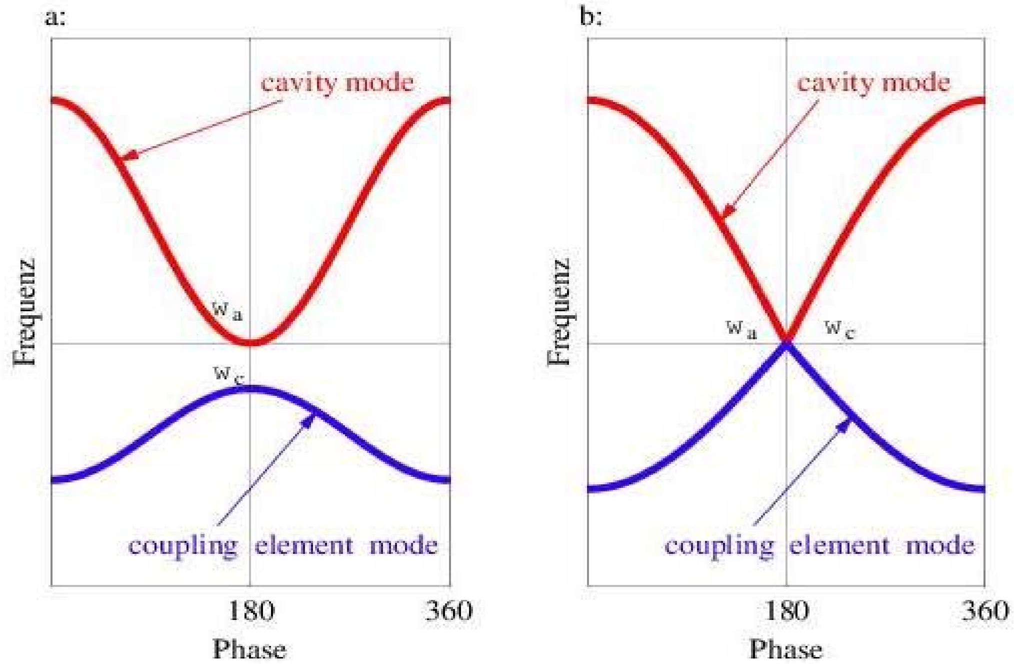
PIC result with 12 windings, pitch angle of 29.33°, pitch of 17.2mm and normalized beam velocity of 0.25.
Additional Helical Groove-Guide, without fed-in RF-signal, to increase bunching thru beam current excited waves.



Input-, out-put and reflected signal.



Transformation of periodic groove-guide into a double-periodic guide with the basic interacting cells and coupling cells.



Tuning coupling cells such that confluence happens. As a result, the dispersion diagram becomes steep at a phase advance of 180° and broad-band. Phase velocity is 2.5 times larger than for the match at 1st-space-harmonic.