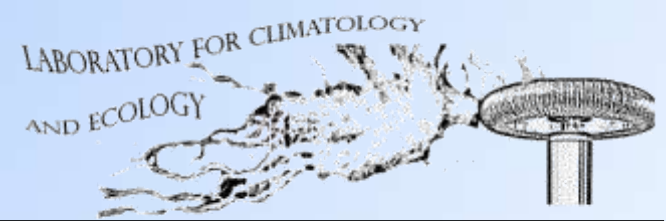




School of Electrical Engineering  
University of Belgrade



# Tesla's magnifying transmitter principles of working

**Dr Jovan Cvetić, full prof.**  
**School of Electrical Engineering**  
**Belgrade, Serbia**  
[cvetic\\_j@etf.rs](mailto:cvetic_j@etf.rs)



# Contents

*The development of the HF, HV generators with oscillatory (LC) circuits:*

I - Tesla transformer (two weakly coupled LC circuits, the energy of a single charge in the primary capacitor transforms in the energy stored in the capacitance of the secondary, used by Tesla before 1891). It generates the damped oscillations. Since the coils are treated as the lumped elements the condition that the length of the wire of the secondary coil = quarter the wave length has a small impact on the magnitude of the induced voltage on the secondary. Using this method the maximum secondary voltage reaches about 10 MV with the frequency smaller than 50 kHz.

II – The transformer with an extra coil (Magnifying transformer, Colorado Springs, 1899/1900). The extra coil is treated as a wave guide. Therefore the condition that the length of the wire of the secondary coil = quarter the wave length (or a little less) is necessary for the correct functioning of the coil. The purpose of using the extra coil is the generation of continuous harmonic oscillations of the great magnitude (theoretically infinite if there are no losses). The energy of many single charges in the primary capacitor are synchronously transferred to the extra coil enlarging the magnitude of the oscillations of the stationary wave in the coil. The maximum voltage is limited only by the breakdown voltage of the insulation on the top of the extra coil and by its dimensions.



## Contens (continued)

III – Tesla magnifying transmitter (Wardenclyffe tower 1901/1917). It is the advanced, more powerful, but essentially the same version of the transformer with the extra coil used in the experiments in Colorado Springs. According to Tesla's patent No. 1,119,732 (applied in 1902, patented in 1914) with some changes in the shape of the dome. The maximum voltage  $< 30\text{MV}$ . Estimated power for the wireless energy transmission is about 10 MW.

IV – Advanced Tesla magnifying transmitter with an independent excitation of the outer LC circuit (described in Tesla's notes during 1900 and 1901). It represents considerably enhanced and improved version of the magnifying transmitter with the extra coil from Colorado Springs. The magnifier represents the generator which excites a separate, independent circuit consisting of the dome (or the cupola having capacitance) and the tower (having inductance). The frequency of the oscillations of this independent circuit can be easily tuned with the oscillations of the standing waves created on the Earth surface. Multiple increase of the voltage of the cupola and the emitting power. Maximum estimated voltage greater than 100 MV. Maximum power estimated for energy transmission is greater than 1GW.



# I -Tesla transformer (1891)

*Tesla's contribution to the development of the generators of alternating current of the high frequency (HF) and the high voltage (HV):*

- Alternators with protruding poles (max 20 kHz, until 1891).
- Oscillatory LC circuits (with the frequency greater than 1MHz) 1891/1892 used in the lectures given in USA (Columbia University), and in Europe (Universities in London and Paris).
- Two weakly coupled resonant LC circuits, the primary circuit with a few turns and the secondary circuit with a great number of turns are named Tesla transformer (TT). TT generates the damped periodic oscillations. This is very simple and very cheap HF and HV source. The shortage of this device is the lack of independent and continuous regulation of the amplitude and the frequency of the current because these parameters are mutually coupled.



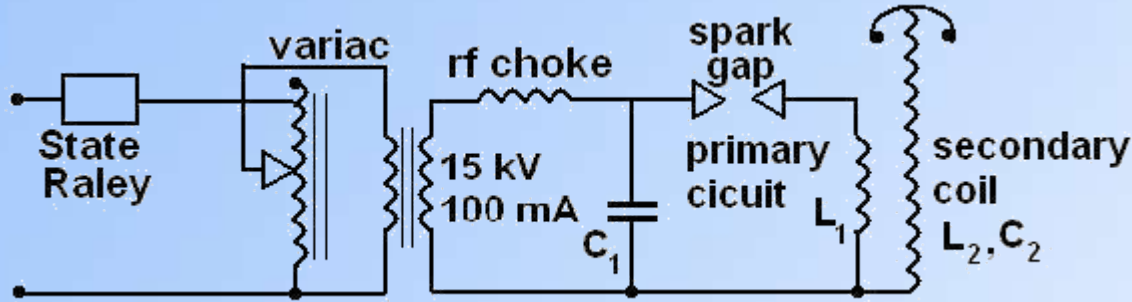
- The first rigorous mathematical analysis of the TT is performed by A. Oberbeck in 1895 and P. Drude in 1904 and 1905. An exact theoretical result (in closed analytical form) is possible only in the case of lossless circuits (without resistance) and without other effects which leads to the different kinds of losses that is for example skin effect, proximity effect in turns etc.

*Oberbeck A., Über den Verlauf der elektrischen Schwingungen bei den Teslaschen Versuchen, Annalen der Physik und Chemie, Band 55, 1895.*

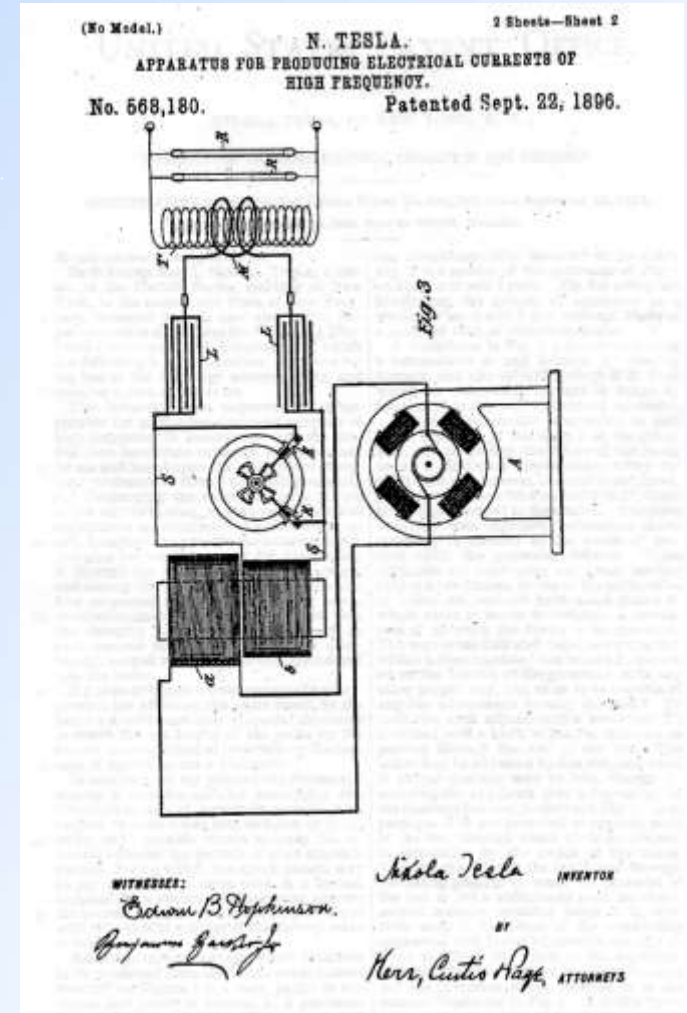
*Drude P., Über induktive Erregung zweier elektrischer Schwingungskreise mit Anwendung auf Perioden- und Dämpfungsmessung, Teslatransformatoren und drahtlose Telegraphie, Annalen der Physik, Band 13, p. 512-561, 1904.*

*Drude P., Rationelle Konstruktion von Teslatransformatoren, Annalen der Physik, Band 321, p.116-133, 1905.*





*Principal schema of Tesla transformer*



*One of Tesla's patents of HF oscillator dated from 1896.*



# Tesla transformer – general features

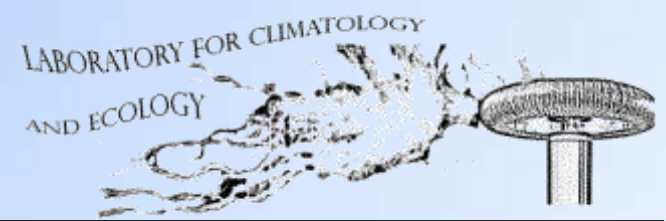


- The resonant transformer with two weakly coupled LC circuits with air core, with the primary with a few turns, the secondary is one-layer coil with many turns.
- HV (up to 10 MV), HF (up to 1 MHz), higher the voltage smaller the frequency and vice versa.
- Coupling coefficient of coils should be 0.1-0.3.
- The primary is usually in the form of Archimedes spiral (for a better insulation vis-a-vis secondary). Densely coiled secondary, capacitance ratio pr./sec.= 1000 (this determines the voltage on the secondary).
- Efficiency during energy transfer from primary to secondary is usually 50 to 80%.

*TT manufactured at ETF in Belgrad in 2006. Maximum output voltage 0.7 MV, resonant frequency 105 kHz, power 2.5 kVA*



School of Electrical Engineering  
University of Belgrade

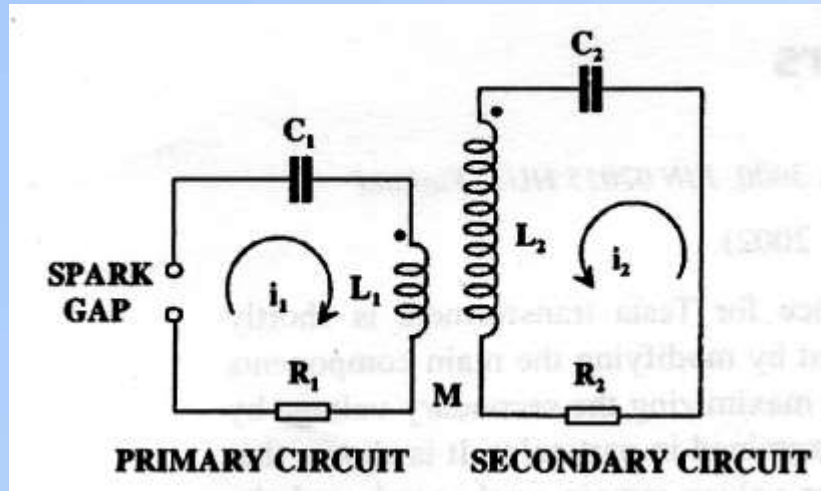


*The TT manufactured at ETF in Belgrad for the opening ceremony of 25th Summer Universiade 2009. Output voltage 1.5 MV, frekvencija 52 kHz, power 10 kVA. Produced discharges up to 3m.*





# Theoretical considerations



$$w_1 = \omega_2 \left[ \frac{1 + T - \sqrt{(1 - T)^2 + 4k^2T}}{2(1 - k^2)} \right]^{1/2}$$

$$w_2 = \omega_2 \left[ \frac{1 + T + \sqrt{(1 - T)^2 + 4k^2T}}{2(1 - k^2)} \right]^{1/2}$$

$$T = \frac{\omega_1^2}{\omega_2^2} \quad k = \frac{M}{\sqrt{L_1 L_2}} \quad \omega_i = \frac{1}{\sqrt{L_i C_i}}, i = 1, 2$$

- The output secondary voltage of TT

$$v_2(t) = \frac{2kV_1 \sqrt{L_1/L_2}}{[(1 - T)^2 + 4k^2T]^{1/2}} \cdot \sin \left[ \frac{w_1 + w_2}{2} t \right] \cdot \sin \left[ \frac{w_2 - w_1}{2} t \right]$$

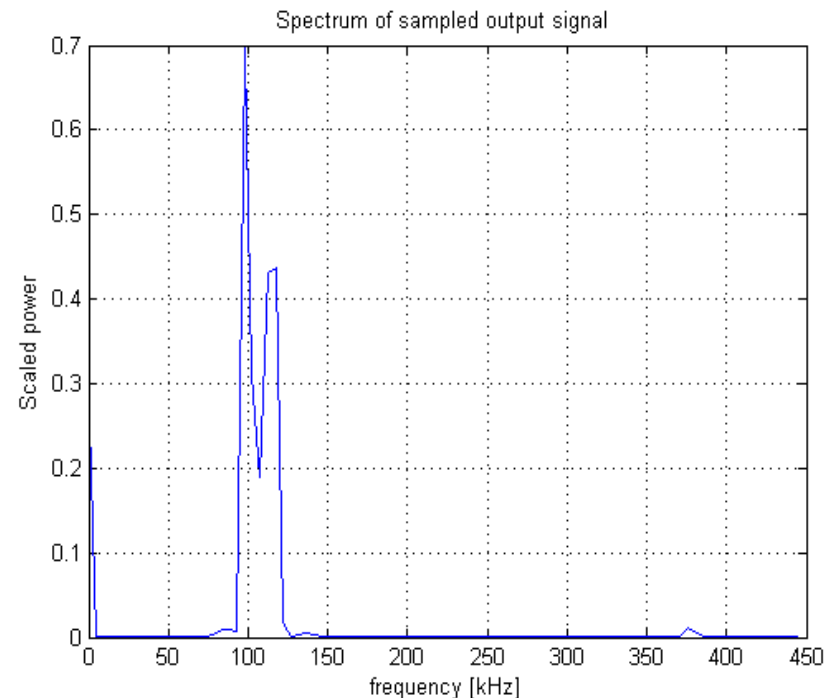
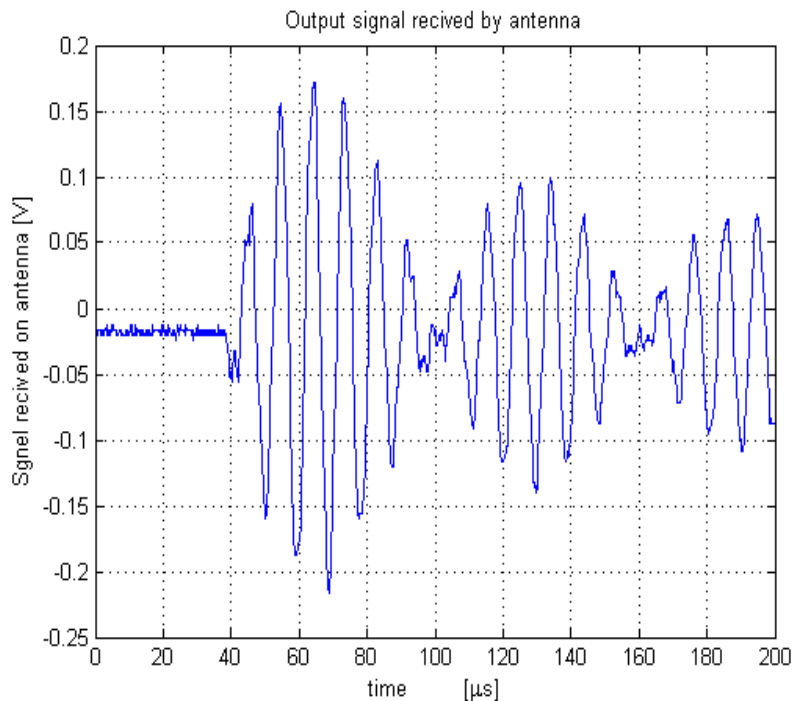
- Both coils are modeled as lumped elements.
- Wave characteristics of the secondary coil could be neglected.
- Exact theoretical analysis is possible neglecting coil resistivities that is  $R_1=R_2=0$ .



# Output voltage of TT (time and frequency domain)

The results of the measurements of the secondary voltage of TT in time and frequency domain.

$$\omega_1 = \omega_2 \left[ \frac{1 + T - \sqrt{(1 - T)^2 + 4k^2T}}{2(1 - k^2)} \right]^{1/2} = 100.5\text{kHz}$$
$$\omega_2 = \omega_2 \left[ \frac{1 + T + \sqrt{(1 - T)^2 + 4k^2T}}{2(1 - k^2)} \right]^{1/2} = 116.9\text{kHz}$$





## II - Tesla magnifying transmitter Colorado Springs (1899/1900)

- Based on earlier findings Tesla intended to make the transmitter of great power with continuous oscillations for the transmission of messages, sound and pictures over the entire Earth surface.
- He intended to investigate the way of wave propagation over the Earth surface as well as in the atmosphere.
- During the experiments in Colorado Springs he has accidentally discovered (thanking to one big and lasting storm with a lot of lightning discharges) the existence of standing electromagnetic waves on the ground surface which gave him an idea of the energy transmission without wires.
- He modified his originally defined experiments and the apparatus generating standing waves successfully by using his magnifying transmitter.
- He studied in details the different conditions influencing the formation of the standing waves. He concluded that the frequency of the transmitter should not be greater than 20 kHz for small wave attenuation.



## II - Tesla magnifying transmitter Colorado Springs 1899/1900 (continued)

- The current magnitude at the antenna top was about 1 kA (maximum current magnitude in antennas around 1916 was 200 do 250 A).
- The maximum voltage on the antenna top was 3.5-4 MV (average voltages in antennas around 1916 were up to 30 kV).
- Capacitance of the antenna was 550 do 660 pF, average energy of the impulse in the extra coil was around 5 kJ.
- He spent his funds of about \$70,000 (today about \$2,100,000).
- He has chosen the region of Colorado Springs because three phase system with 60 Hz, 550V was already installed in surrounding towns.
- The maximum length of the discharges on the antenna top (the sphere with 0.75m in diameter) were about 30m. This length could be achieved only by use of standing waves.
- The height of the cylindrical steel antenna rod (with average diameter of about 25cm) was 51m.





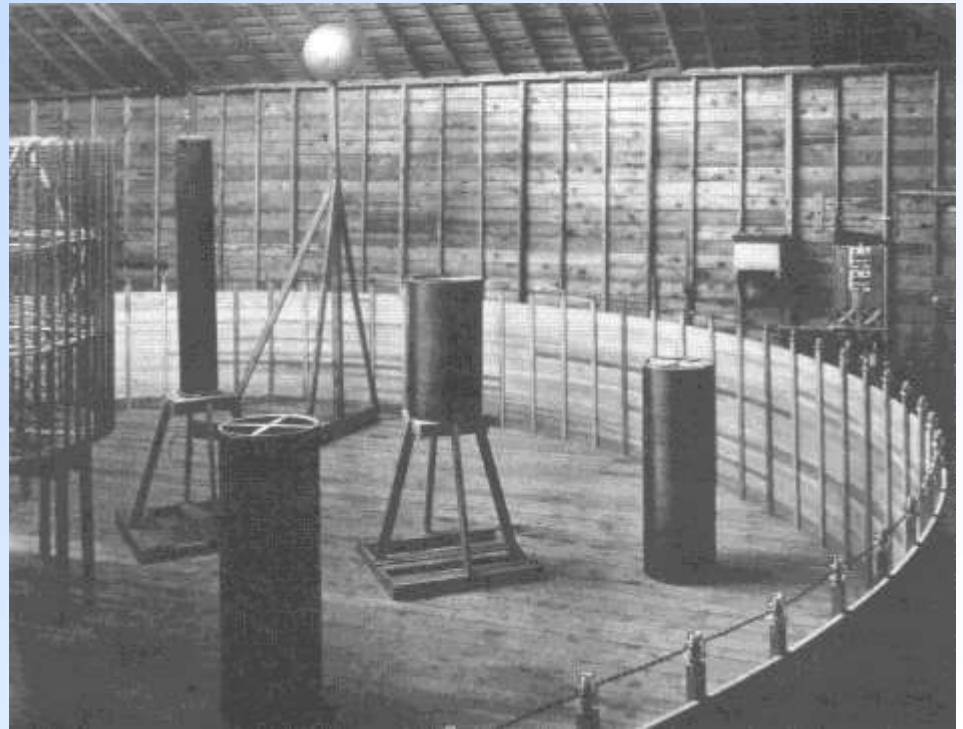
## II - Tesla magnifying transmitter Colorado Springs 1899/1900 (continued)

- On 14<sup>th</sup> December 1899, after a few months of research and testing of different combinations and schemas for the wireless transmission of signals Tesla eventually assembled the final circuit configuration with the following parameters:
  - Power supply unit was the Westinghouse transformer with the great leakage inductance ( $U_s=100\%$ ), oil insulated. Transformer input voltage 200/220V, 60 Hz. Output voltage up to 60 kV. Continuous power about 50 kVA.
  - The coil diameter of “ideal transformer” was about 15m. The primary coil consisted of 2 turns (bundle of 37 wires No.9 AWG, each with the cross-sectional area of  $2.9 \text{ mm}^2$ , with the rubber insulation and twisted) which could be connected either in series or parallel, the secondary coil consists of up to 48 turns, (bundle of wires No.10 AWG,  $2.6 \text{ mm}^2$  each) the number of the fires in the bundle depended on the number of the secondary turns so that the primary and the secondary have the same mass of copper.



## II - Tesla magnifying transmitter Colorado Springs 1899/1900 (continued)

- This condition is now known as the impedance matching of two circuits for maximum power transfer.
- The great extra coil in the center of the experimental station. The diameter and the height of the extra coil were about 2.5m, with 100 turns, wire No.6 AWG  $13.3\text{mm}^2$  for continuous current of 75A (670A ten seconds), total wire length 790m, resonant wave length 3.16 km (for the length of the wire equals the quarter of the wave length).



*The interior appearance of the Colorado Springs laboratory during the experiments*



## II - Tesla magnifying transmitter Colorado Springs 1899/1900 (continued)

- The resonant frequency of the extra coil should be 95 kHz. Tesla measured the resonant frequency of that coil to be 86.8 kHz (wavelength 3.46 km) calculating the coil inductance of 18 mH. It is obvious that the length of the wire of the coil is smaller than the quarter of the wave length for about 10%.
- The capacitors in the primary coil of the transmitter are made as a series or parallel connection of the elementary capacitor units. To make the capacitor unit the glass bottles with a green and a dark glass are used filled with the rock salt solution. Due to the parallel connection the capacitors units are submersed into common metallic box. Each unit had the capacitance of 1.06nF (Tesla's measurements performed on 11<sup>th</sup> august 1899) or for the larger bottles 3nF, for the maximum voltage of about 22.5 kV.
- The maximum height of the antenna was 51m with the ball on the top which diameter was 0.75m.
- Tesla designed and made a lot of different kind of mercury switches and rotary spark gaps, maximum number of breaks up to 60 kHz.



## II - Tesla magnifying transmitter Colorado Springs 1899/1900, experiments

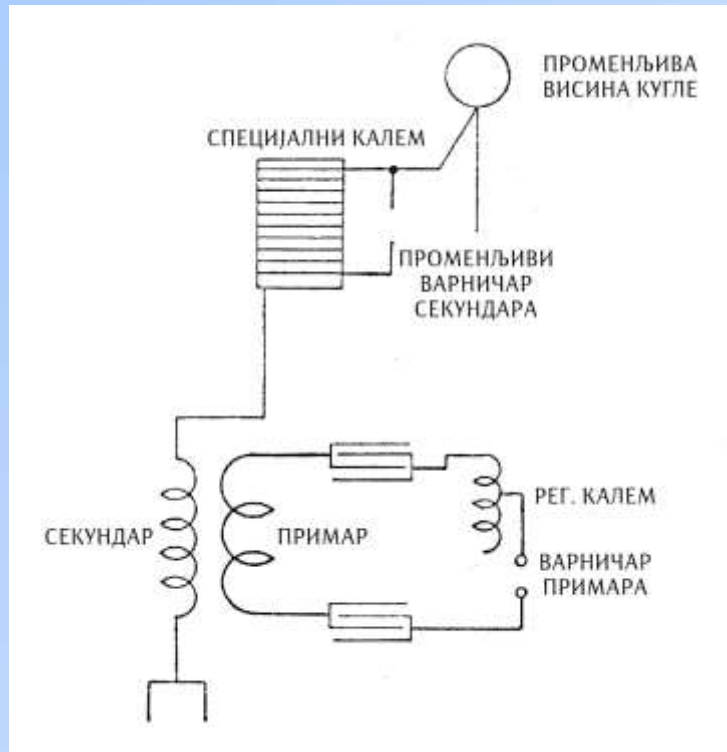


*The external appearance of Tesla's laboratory in Colorado Springs in 1899. The dimensions of wooden building were approximately 18m x 21m*





## II - Tesla magnifying transmitter Colorado Springs 1899/1900, basic schema



*One of the electric configurations examined during the experiments in Colorado Springs, on 5<sup>th</sup> October 1899.*

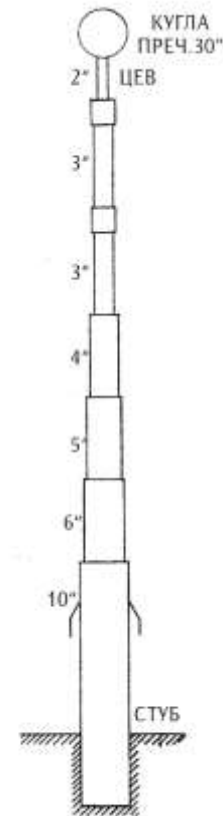
- The primary and the secondary of the great transformer are strongly coupled (ideal transformer). The transmission ratio is greater than 1:10.
- The power source of the extra coil is in the coil base.
- Additional inductance (the coil with a variable inductance) is in the primary circuit providing the oscillations.
- The oscillations of the extra coil are correlated with the oscillations of the primary circuit.
- The extra coil oscillates freely, with a weakly damped oscillations.
- The breaking of the current in the primary is synchronized with the oscillations of the extra coil.
- The local pipes for water supply are used for the grounding.



## II - Tesla magnifying transmitter Colorado Springs 1899/1900, antenna

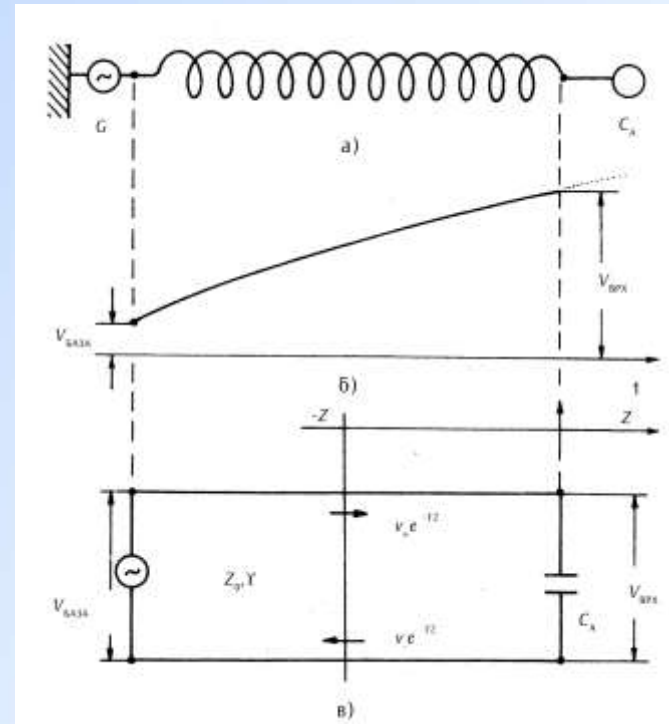
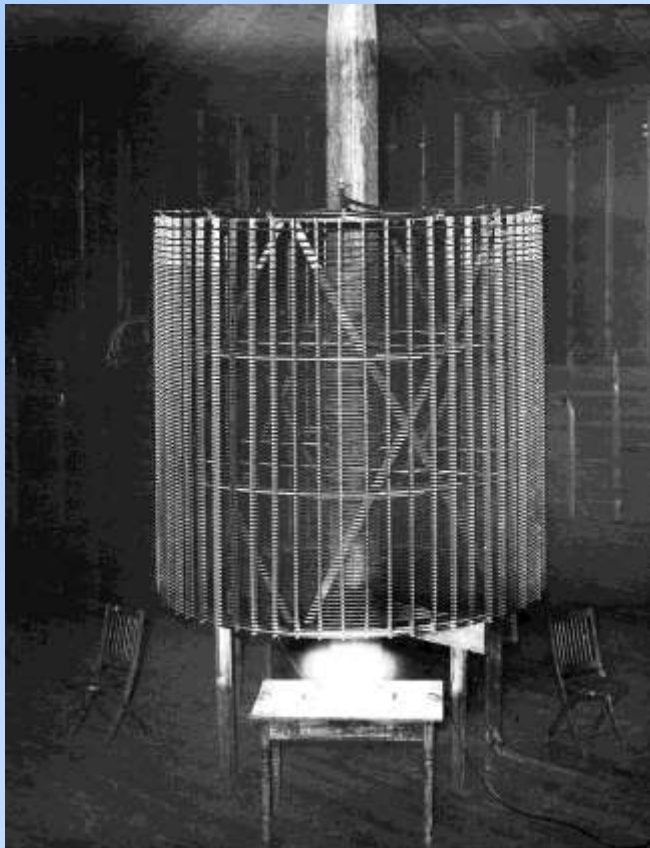
- The maximum height of the antenna was 51m with brass ball on the top, ball diameter was about 0.75m. The antenna consists of 6 steel pipes which could be inserted one into the other changing the antenna height that is its capacitance.
- The antenna holder is 6m height wooden (fir) timber with quadratic cross section (30x30cm). The antenna is electrically very short, its length is only 1% of the wave length. Therefore it does not radiate space electromagnetic waves.

*The construction of the steel monopole antenna in the experiments in Colorado Springs, the lower part of the pillar (antenna holder) is fir timber.*





# II - Tesla magnifying transmitter Colorado Springs 1899/1900, extra coil



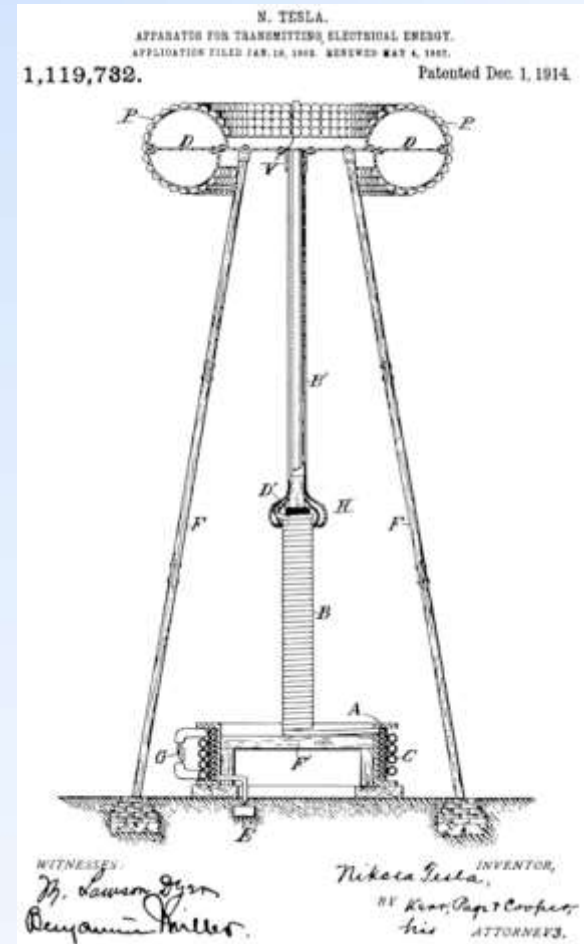
*The extra coil represents a waveguide which is closed with the capacitance at the upper end, the power source (G) is in the coil base.*



## II - Tesla magnifying transmitter Colorado Springs 1899/1900, extra coil

- The extra coil has the maximum inductance and minimum self-capacitance, when its height and the diameter are approximately equal. According to Tesla it is the best configuration. However, in the patent application he draws a “slim” extra coil!
- The turns near the coil top are a little spaced (visible in the previous slide) since Tesla determined in situ the optimal wire length of the coil (not to rewind the entire coil with a different spacing) for the maximum voltage on the coil top. Physically, the space enlarging between the upper turns means the increase of the phase velocity of the electromagnetic wave at the coil top. It leads to the “shortening” of the wire length of the coil for optimal performance.

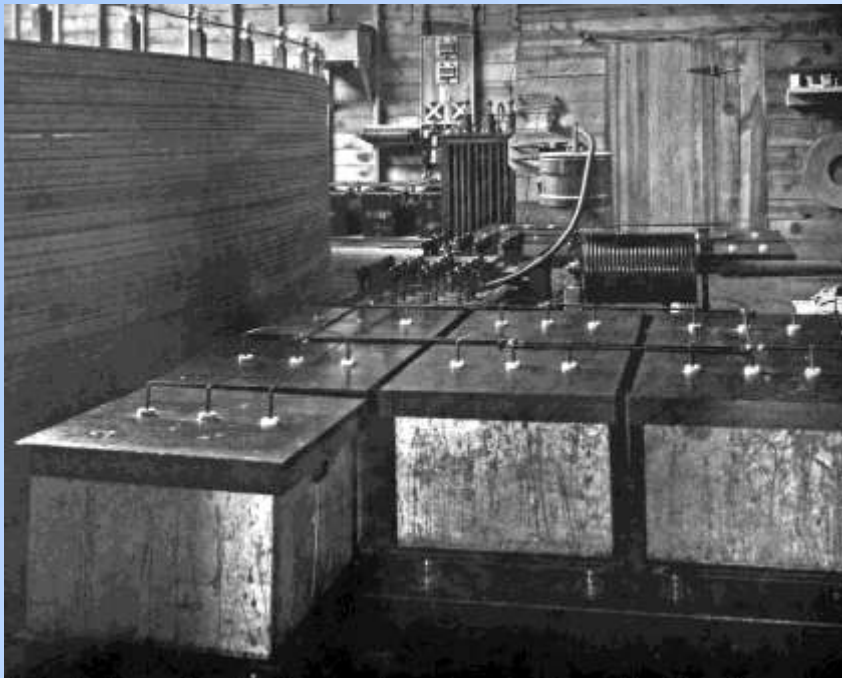
*Tesla's patent No. 1,119,732 "Apparatus for Transmitting electrical energy" filled in 1902, patented in 1914.*



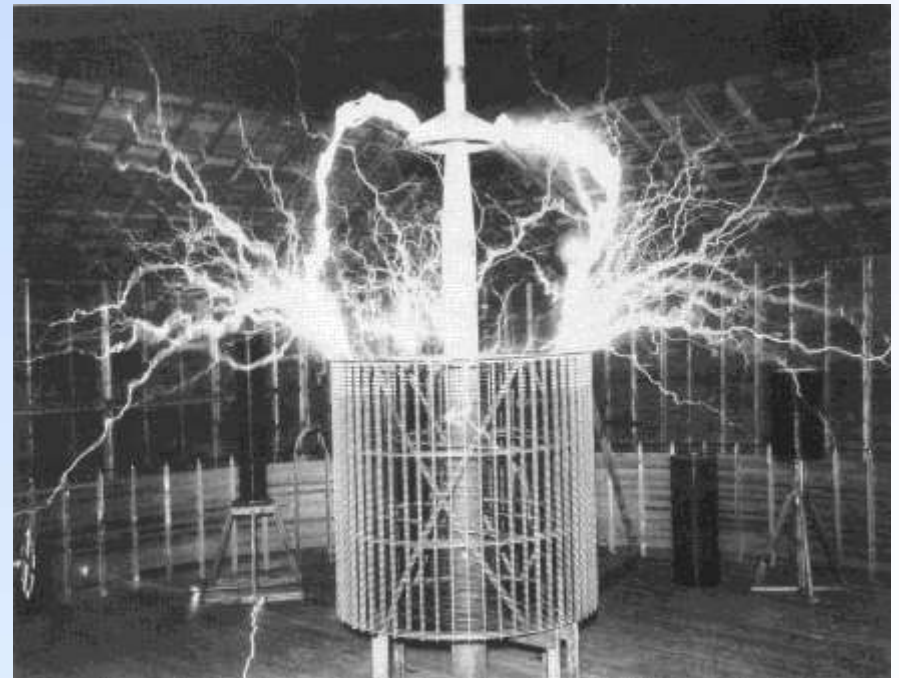




## II - Tesla magnifying transmitter Colorado Springs 1899/1900, experiments



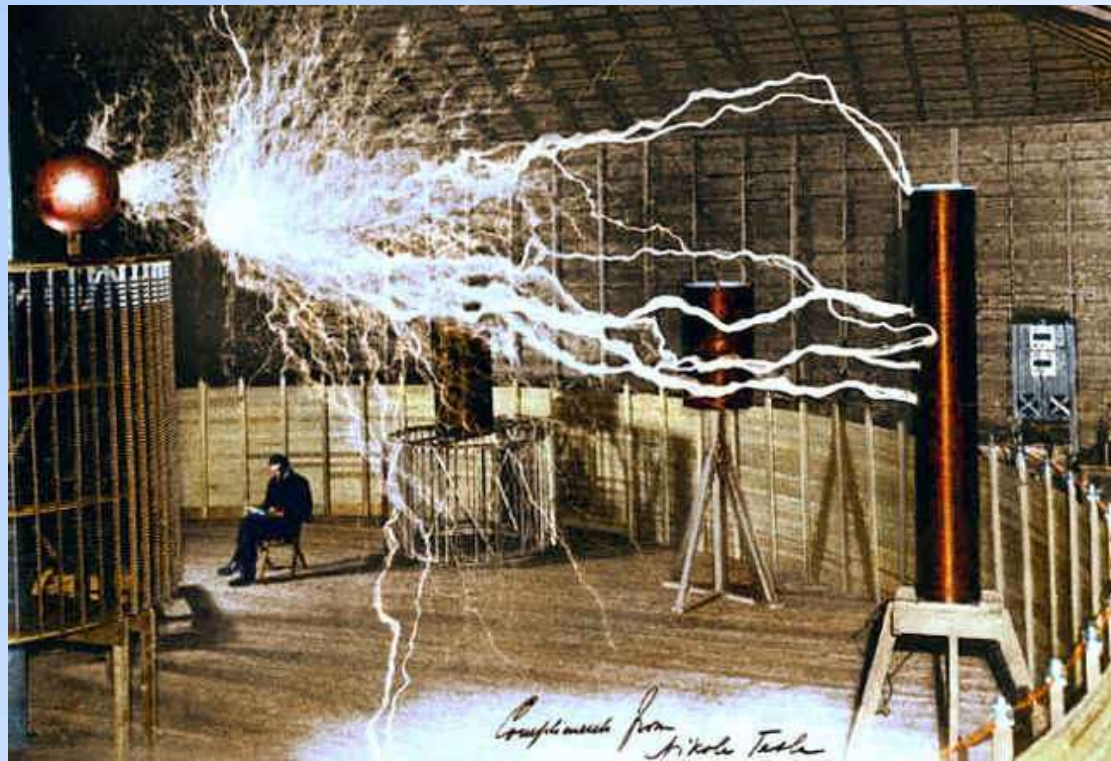
*The battery of capacitors and the variable inductance for the primary circuit of the Colorado Springs transmitter.*



*The discharges on the top of the extra coil during the experiments in Colorado Springs.*



## II - Tesla magnifying transmitter Colorado Springs 1899/1900, experiments



*The electric discharges of about 7m length from the extra coil in the center of the laboratory in Colorado Springs (double exposition)*



## III – Tesla magnifying transmitter Wardenclyffe tower (continued)

- According to Tesla's testimony on court 1916 he spent in total about \$500,000 (today about \$15,000,000).
- The tower height was 57m, the wooden lattice structure with replaceable elements and the steel connecting plates (project designed by Mr. Stanford White).
- The distance from tower to the laboratory was approximately equal with the tower height. During the testimony on the court in 1916 Tesla revealed that it was calculated that distance was the minimal distance which could not cause the discharge between the cupola and the chimney of the laboratory.



*Wardenclyffe tower (Long Island) in 1902  
with finished platform of the cupola*





## III – Tesla magnifying transmitter Wardenclyffe tower (continued)

- On the tower top it was planned to set up a spherical metallic dome (cupola) covered by the copper sheath. The dome diameter was 20.7m, with the total copper mass of 55 tons. The inside construction of the dome is made of steel ribs.
- 30 Half spherical shells on the dome surface was provided aiming to increase its own capacitance. Tesla calculated the total dome capacitance to be about 1 nF.
- He stated that the capacitance of the dome against the ground should be much smaller compared to its self-capacitance in aim the transmitter “pumps the unbound” charges as efficiently as possible through the ground.



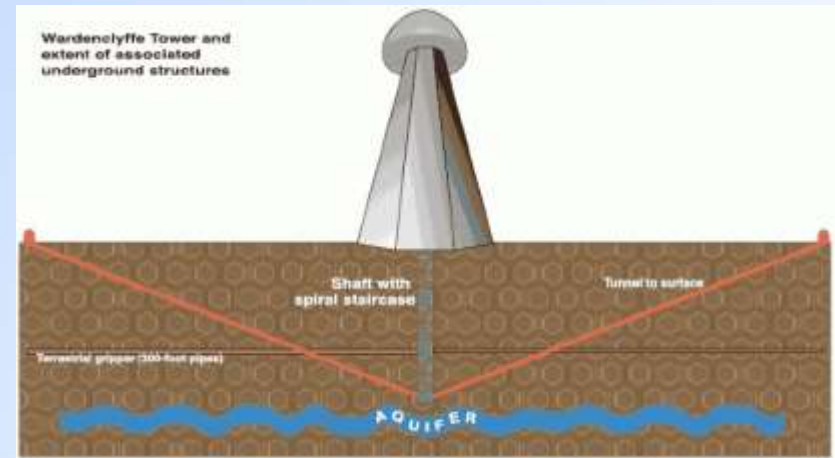
*Wardenclyffe tower (Long island) in 1903  
with the steel ribs without the copper sheath*





## III – Tesla magnifying transmitter Wardenclyffe tower (continued)

- During the construction of the Wardenclyffe facility, Tesla devoted more time to underground than to overhead works on the tower.
- More than a half of funds (of total \$150,000, invested by Mr J.P.Morgan) is spent on the manufacturing of the vertical well (tunnel of 4m in diameter, 30m depth with spiral stairs) and the digging of the grounding (vertically buried additional 100m in depth).
- The aquifer layer is found at 30m depth below the surface. He decided to dig additional 4 tunnel from that layer leaning to the surface.
- The purpose of these 4 tunnels is most likely the evacuation of the generated steam from the grounding electrode. For example, if the grounding resistance equals 1 ohm when the current magnitude is 1 kA, the thermic dissipation is 1 MW! And it's mostly on the contact surface of the grounding electrode and the ground.



*The tunnels under the tower were probably used for the evacuation of the steam and pressure that would be created in the grounding due to the strong currents*



## III – Tesla magnifying transmitter Wardenclyffe tower (continued)

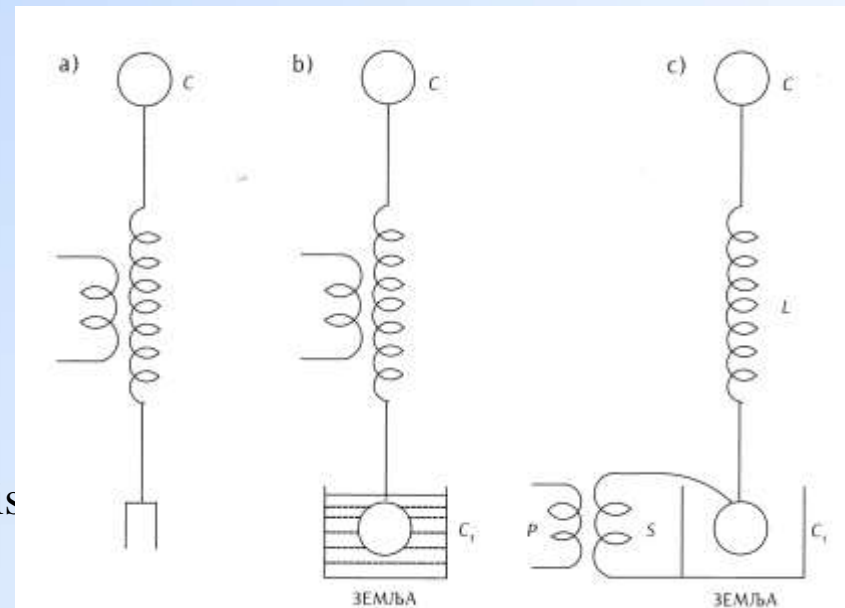


*The interior appearance of the building-laboratory in Wardenclyffe in 1903.  
Left: the room for the experiments. Right: the workshop with the lathes and tools*



## III – Tesla magnifying transmitter Wardenclyffe tower (continued)

- Tesla occasionally performed some measurements and tunings at Wardenclyffe facility from 1904 until 1907.
- He calculated the excitation of the dome as quasi quarter-wave monopole or quasi half-wave dipole antenna (quasi antenna - since it was not used as a classical antenna transmitter which radiates).
- Predicted version of Wardenclyffe tower is essentially the same as the transmitter in Colorado Springs according to patent No. 1,119,732., excitation a) in the right figure.
- He rented the Westinghouse generators of 300 kVA.



*Tesla considered different kind of the excitation for the transmitter at Wardenclyffe facility*

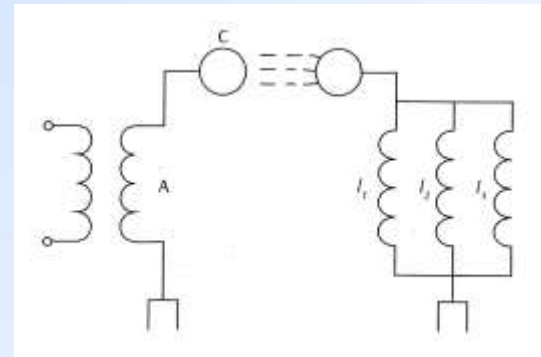
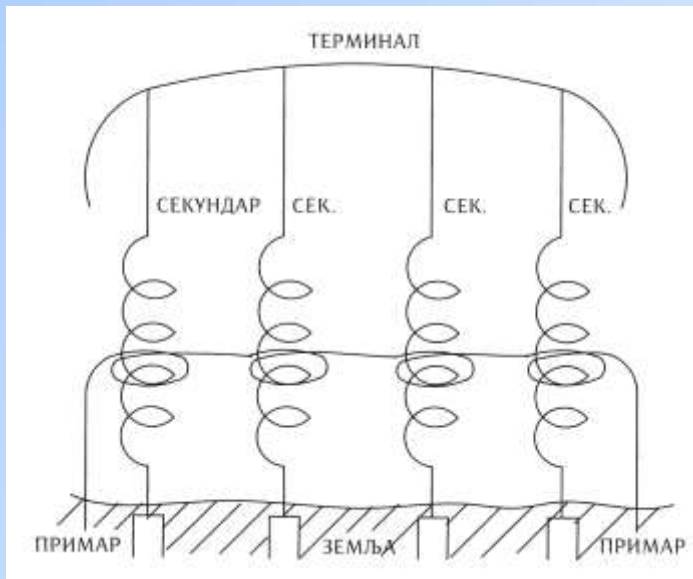
- a) Quasi quarter-wave monopole antenna*
- b) Quasi half-wave dipole asymmetrical antenna with capacitive ground coupling*
- c) Combined antenna excitation*





## III – Tesla magnifying transmitter Wardenclyffe tower (continued)

- During 1900/1901 he performed a few important experiments in his laboratory in New York, the measurements and the calculations for the future transmitter in Wardenclyffe facility and he tested different kind of sensitive receivers.
- Tesla predicted the protected multi-channel signal transmission using four-coil secondary circuit in the transmitter (that is in the extra coil) and three-coil primary circuit in the receiver.



*The receiver with three primary coils in parallel for the realization of the protected multi-channel signal transmission*

*Complex excitation of the transmitter in Wardenclyffe facility for the realization of the protected multi-channel signal transmission*





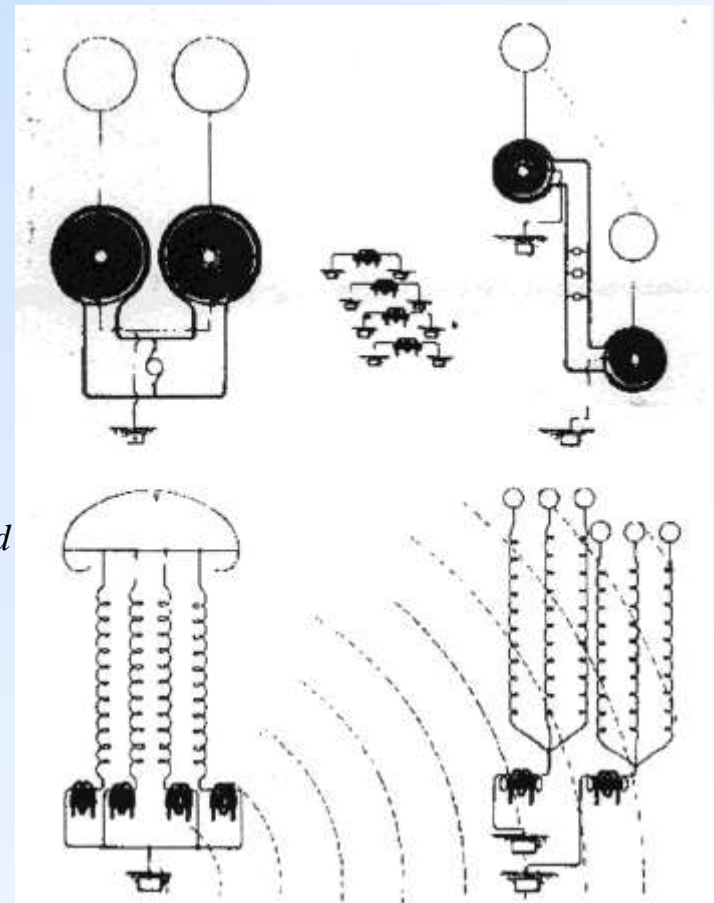
## III – Tesla magnifying transmitter Wardenclyffe tower (continued)

- In the un-submitted patent application (most likely due to unfinished transmitter in Wardenclyffe, see figure on the right) he suggested two possible ways of signal transfer:
- Standard way, already proven way through the “Hertzian” waves which travel above ground.
- By use of a new way of wave transmission using “the waves through Earth”.

*Schematic view of the signal transmission from Tesla’s un-submitted patent application.*

*Above drawings: two coupled circuits sending complex signal by use of “Hertzian” waves travelling above Earth surface.*

*Below drawings: The multi-channel transmitter (Wardenclyffe) and the receiver for the selective reception of the “waves through Earth”.*





## III – Tesla magnifying transmitter Wardenclyffe tower (continued)

- The magnifying transmitter in Wardenclyffe has the “secret ” function that is the wireless energy transmission.
- Tesla predicted to form the standing wave over the earth surface due to the interference of the emitted wave from point T and its reflection from the antipodal point R.
- Aiming to compress the energy in the concentric circles over Earth surface for wireless energy transmission Tesla has predicted the emission of at least two slightly different frequencies resulting in the formation of the wave group.
- The standing wave of the group is defined with the spatially variable amplitude (known as amplitude-modulated wave group) as depicted in one of the Tesla’s drawings (right).

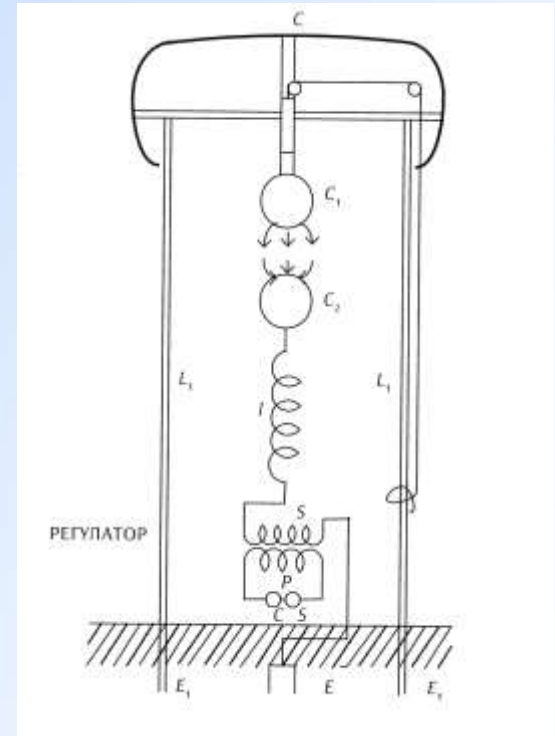


*One of Tesla’s drawing from the notes on 2<sup>nd</sup> June 1901 connected with the formation of the standing waves for wireless energy transmission. The points of maximum energy are represented with the longest lines.*



## IV–Advanced Tesla magnifying transmitter

- Tesla mentioned on 29<sup>th</sup> May 1901 on the first time a new advanced version of the transmitter in Wardenclyffe.
- He analyzed the particular inductances and the capacitance in the drawing, but he did not describe the principle of its working.
- However, in some articles published later he claimed that he devised some improvements enabling the generation of the voltages over 100 MV with the emitting power of over 10 GW.
- In this drawing (right) the extra coil from Colorado Springs serves as the generator for a new circuit (transmitter) consisting of the dome (cupola with the capacitance  $C$ ) and the the body of the tower with the inductance  $L_1$ !
- The advantage of this configuration is obvious: the oscillation of the feeding generator ( $E$ - $L$ - $C_2$ ) is independent of the oscillations in the outer circuit ( $C$ - $L_1$ - $E_1$ )!

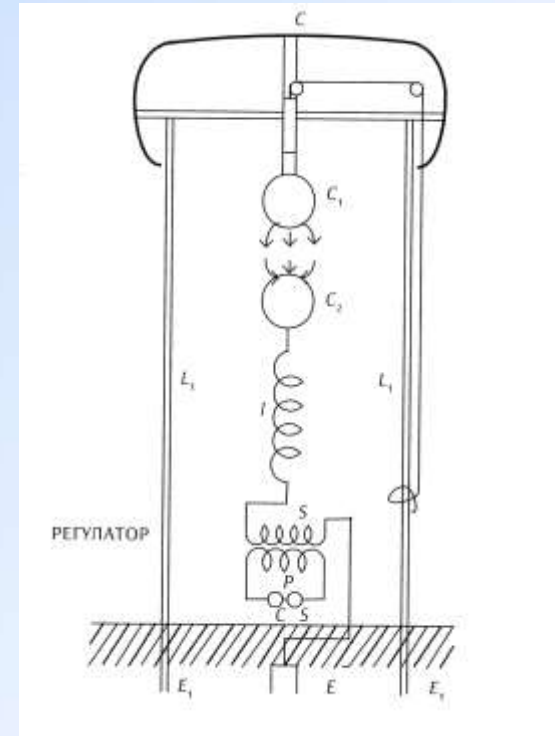


*Tesla's drawing from the notes on 29<sup>th</sup> May 1901 connected with a new version of the Wardenclyffe tower. He added the great spark gap  $C_1$ - $C_2$  and the rope for the distance adjustment.*



## IV–Advanced Tesla magnifying transmitter

- With this configuration the generation of the standing wave is easy!
- The voltages generated on the dome are up to 2 times greater than the voltages on the top of the transmitter patented as No. 1,119,732.
- All this is accomplished only by use of the spark gap C1-C2.
- The body of the tower (its envelope) should be used as a part of the outer circuit (since it has the inductance  $L_1$  meaning that it is conductive) which oscillates with the resonant frequency. It is not clear whether this drawing represents Wardencllyffe tower (which has no conductive parts) with the additional metallic envelope or it is the sketch of the new tower.
- The working principles of the new transmitter (the way of the voltage generation and the synchronization with the inner extra coil) remains unknown.

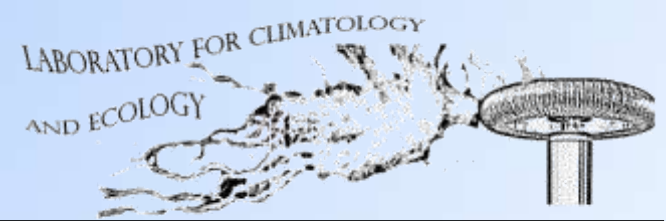


*Tesla's drawing from the notes on 29<sup>th</sup> May 1901 connected with a new version of the Wardencllyffe tower. He added the great spark gap C1-C2 and the rope for the distance adjustment.*





School of Electrical Engineering  
University of Belgrade



**Thank you for your attention !**