EFFICIENCY OF AN ELECTROMAGNETIC PULSE TRANSMISSION IN THE VACUUM CONCENTRATOR OF ANGARA-5-1 INSTALLATION

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SSC RF TRINITI (ANGARA-5-1)

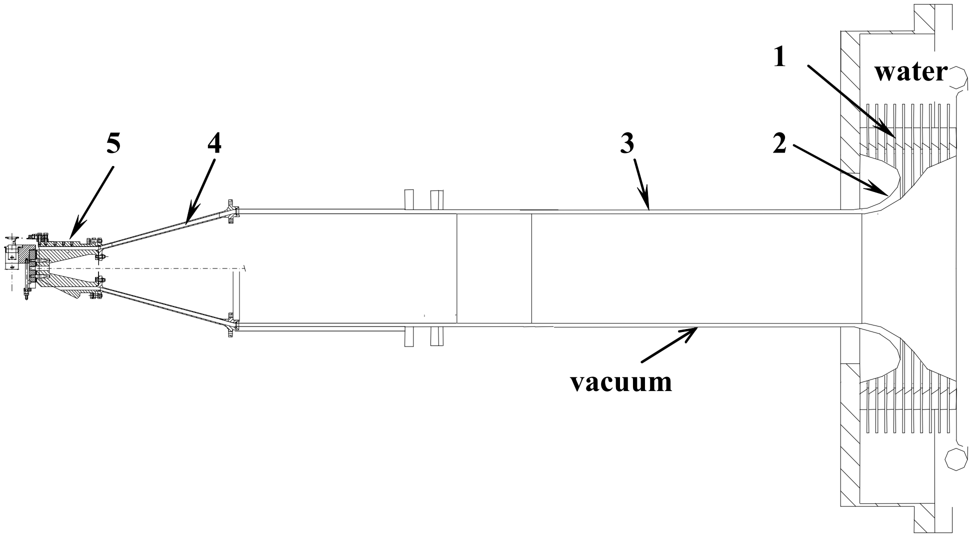
ANGARA-5-1 INSTALLATION

NUMBER OF THE MODULES – 8　　MAX. VOLTAGE NEAR LOAD ≤ 0.8 MV

CURRENT IN THE LINER ≤ 3.5 MA　　CURRENT PULSE FRONT ~ 100 ns

VACUUM CONCENTRATOR OF ANGARA-5-1

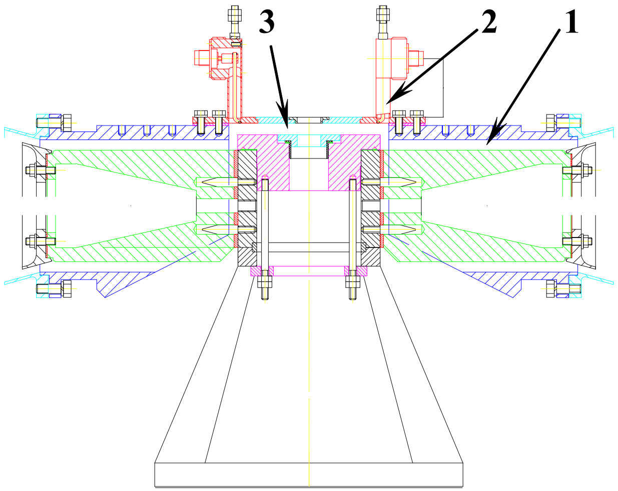
MIVTL of module of the Angara-5-1



1 - the water-vacuum interface insulator

2, 3, 4, and 5 - the first, second, third, fourth and fifth sections of MIVTL

The MIVTL convolution and load unit



1 - an intermediate MIVTL of the module

2 - a current probe at a radius of 55 mm from the load axis

3 - a disc section of MIVTL of the load unit

MOTIVATION

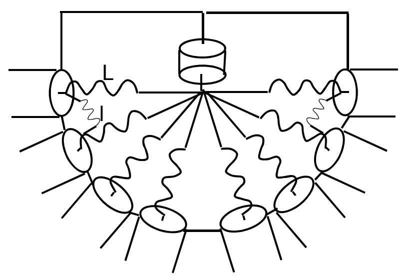
- CURRENT LEAKAGE TAKE PLACE IN A FRONT OF PULSE

$$I = 8.5(\gamma^2 - 1)^{1/2} / \ln(R/r) \quad \text{, кА}$$

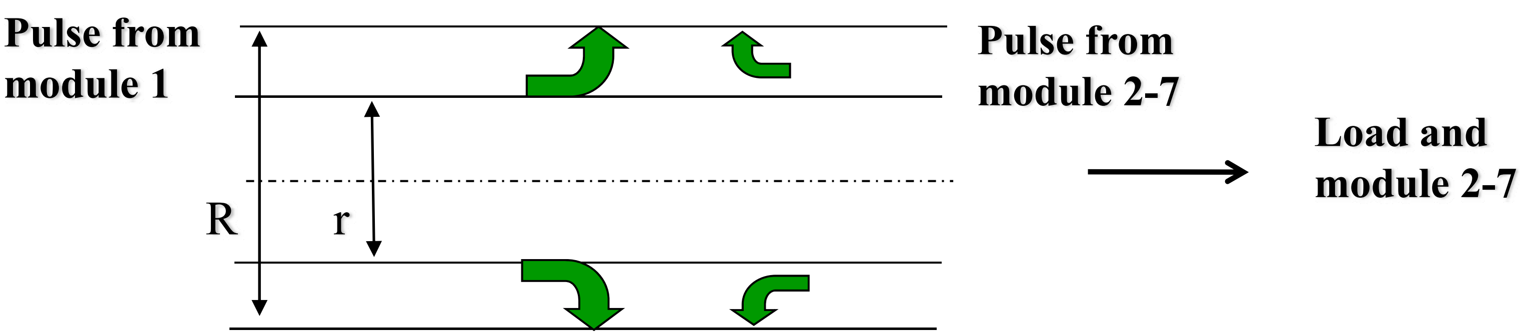
$$\gamma = 1 + U(МэВ)/0.51$$

- CURRENT LEAKAGE TAKE PLACE AT A ZONE WITH ZERO OF MAGNETIC FIELD

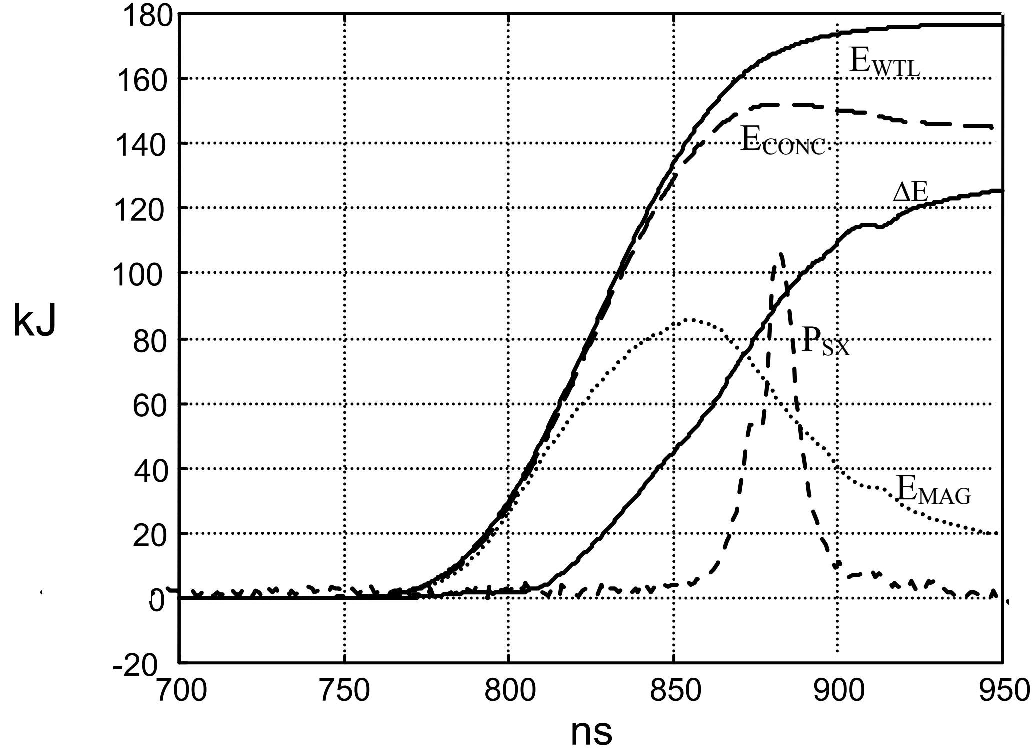
Scheme of modules VTL connection



- CURRENT LEAKAGE TAKE PLACE FOR A LARGE MODULE JITTER

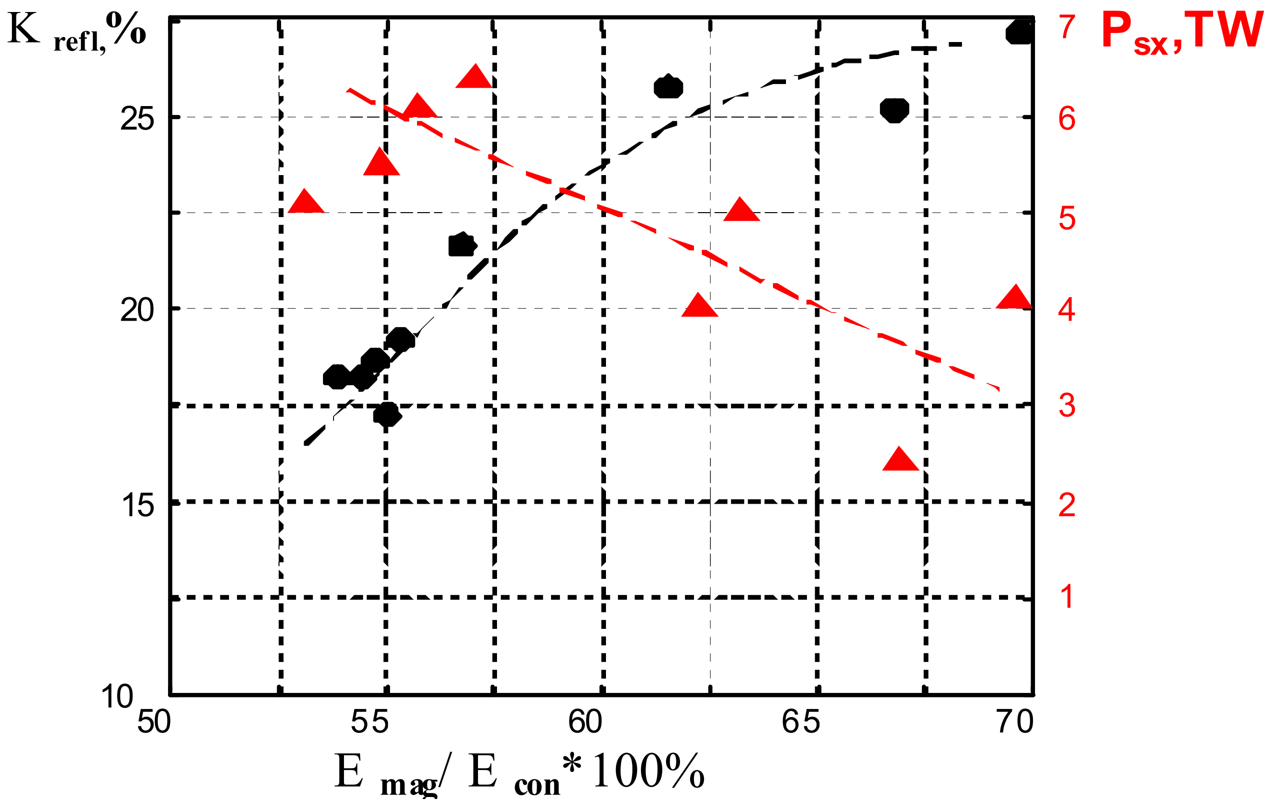


ENERGY TRANSFER EFFICIENCY FROM THE GENERATOR TO THE LOAD



Time profiles of the energy delivered in water line (E_{WTL}), the energy delivered in vacuum concentrator (E_{CONC}), the magnetic energy of the concentrator MIVTL (E_{MAG}), difference of E_{CONC} and E_{MAG} (ΔE) and a pulse of soft X-ray power (P_{SX}, A.U.) for shot #4645.

ANALYSIS OF ENERGY TRANSFER EFFICIENCY FROM THE GENERATOR TO THE LOAD



● - the part of energy reflected from concentrator in dependence on a ratio of the energy of the magnetic field in concentrator and energy delivered in concentrator

▲ - the power of X-ray pulse in dependence on a ratio of the energy of the magnetic field in concentrator and energy delivered in concentrator

CALCULATION MODEL

$$L\frac{\partial I}{\partial t}+\frac{\partial V}{\partial x}=0,\quad C\frac{\partial V}{\partial t}+\frac{\partial I}{\partial x}=-j_e,\quad 0<x<l_{VTL}$$

- The system of 1-D equations for an electromagnetic wave with electron leakage in MIVTL

Where: t[ns] is the time, x[cm] – coordinate, l_{VTL} – length of the VTL; I[MA] – current in VTL; V[MB] – voltage of the VTL; J_e [MA/cm] – a current density of electron leakage.

$$I|_{x=l_{VTL}}=I_L,\quad \begin{cases} V|_{x=l_{VTL}}\le V_D, & I_L=0\,, \\ V|_{x=l_{VTL}}>V_D, & \frac{d}{dt}\left(L_C+2H\ln(1/r)\right) I_L = V|_{x=l_{VTL}} \end{cases}$$

- The boundary condition at the VTL output

Where: I_L [MA] – current, L_c - inductance of the load unit to a single radius of the load, H – the load height, r – the load radius.

$$\frac{dr}{dt}=u,\quad \frac{du}{dt}=-\frac{0.01 I_L^{\,2}}{m_L\, r}$$

- The 0-D approximation of the load motion

Where: m_L [μg/cm] - the load mass per unit length, r [cm] - radius, u [cm/ns] – velocity.

$$j_e(V,I)=j_{CL}(V)\,F_e(Y),\qquad F_e(Y)=\begin{cases}\sqrt{1-Y^2}, & Y<1\\ 0, & Y\ge 1\end{cases}$$

$$Y=I/I_m(V)$$

- The electron leakage density is limited by the space charge and the shielding effect of the magnetic field

Where: $j_{CL}(V)$ is the current density limited by the space charge; I_m is the minimum current of magnetic self-insulation within the Brillouin model.

$$K(t,[E],p)=\begin{cases}0, & E_{max}\le E_{*1}\\ \left|\sin\left(\frac{\pi}{2}\frac{E_{max}-E_{*1}}{E_{*2}-E_{*1}}\right)\right|^p, & E_{*1}<E_{max}<E_{*2},\\ 1, & E_{*2}\le E_{max}\end{cases}$$

$$E_{max}(t)=\max_{t'\le t} E(t',x)$$

- Coefficient K is emission ability of the cathode

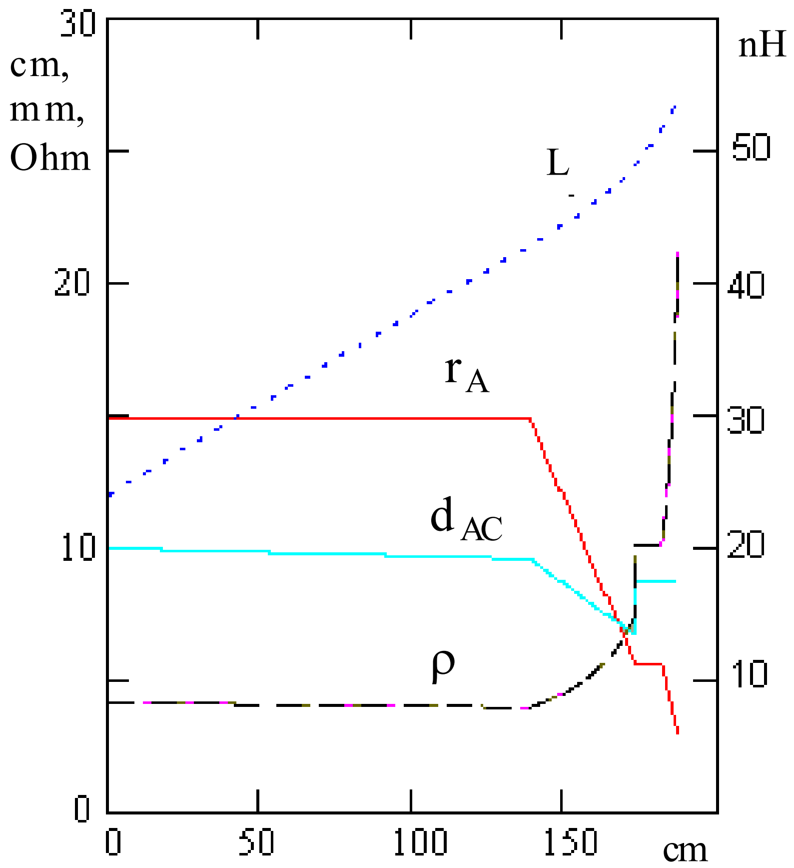
Coefficient K is introduced to the density of electron leakage. It depends on its surface state and the strength of the electric field. Where: E_{*1}, E_{*2} are the intervals within which the emission ability (the value K) grows from 0 to 1.

$$\frac{d}{dt}\sum_n L_{mn} I_n = V_m\quad ,\ m,\ n=1,2\ldots 8$$

- A symmetrical matrix of inductance L_{mn} for the load unit

The voltage at the output of each module is calculated as $V_m=2A_m-\rho I_m$ where A_m, ρ and I_m are the amplitude of the incoming wave of voltage, wave resistance and current, respectively, all of them at the VTL output.

CALCULATION MODEL

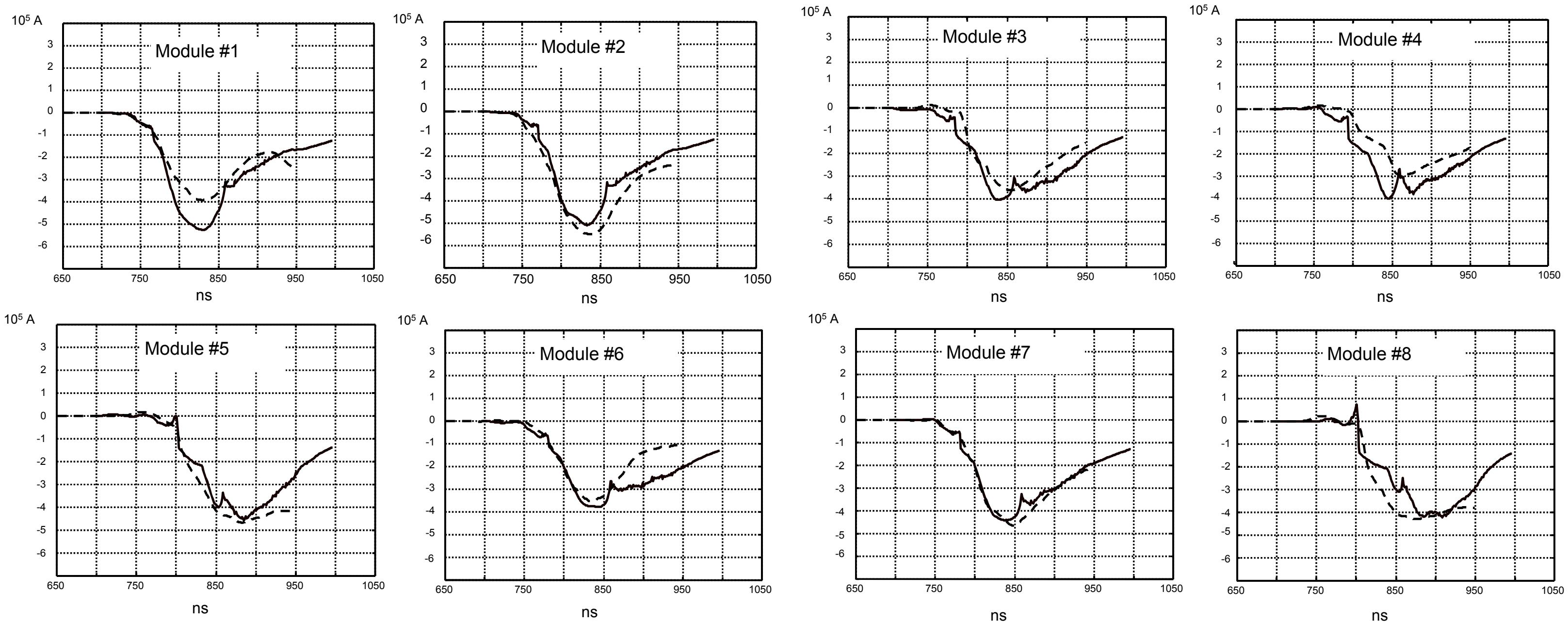


The design and electrical parameters of a module of the installation.

Where: r_A is the anode radius of VTL; d_{AC} - anode-cathode gap of VTL; ρ - wave resistance of VTL; and L – inductance of VTL.

COMPARISON RESULT OF CALCULATION AND EXPERIMENT DATA

The time jitter of the start of modules was ≤15 ns.

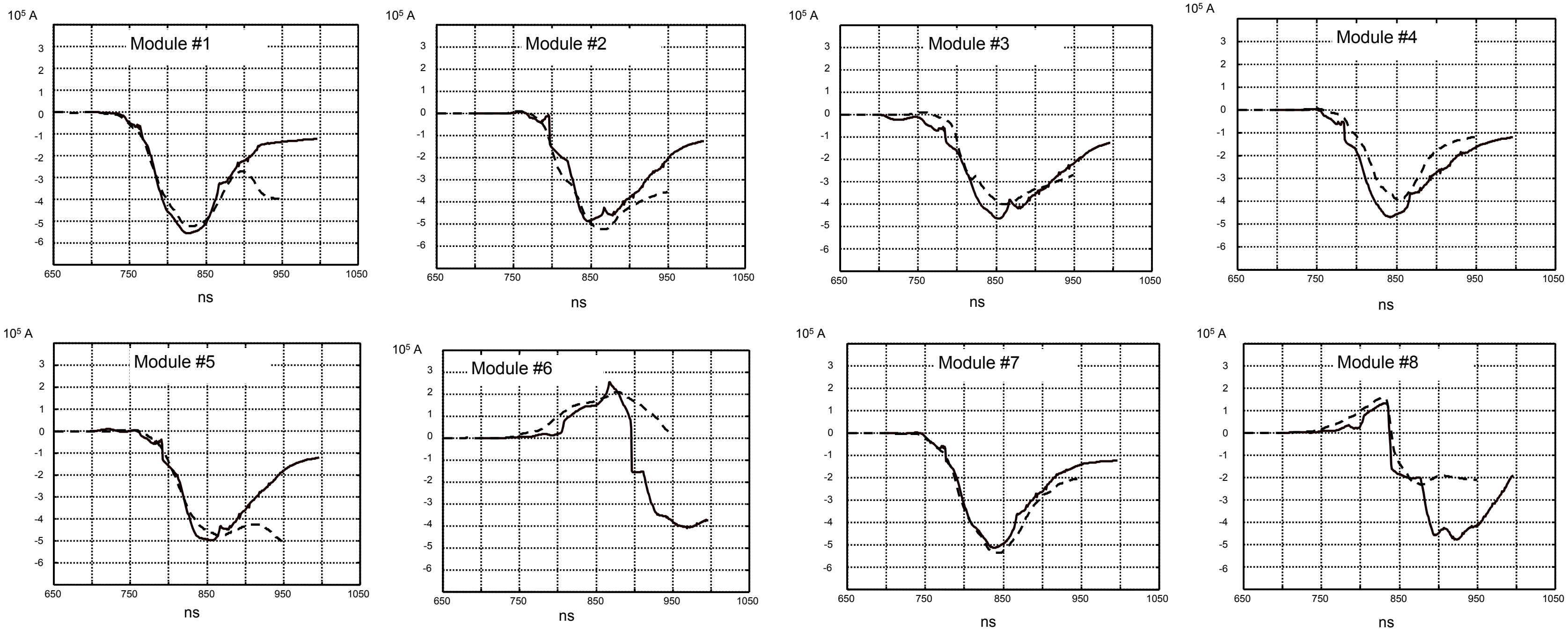


Calculated (solid line) and experimental (dotted line) current pulses at the input of the third section of VTL for each of eight modules.

COMPARISON RESULT OF CALCULATION AND EXPERIMENT DATA

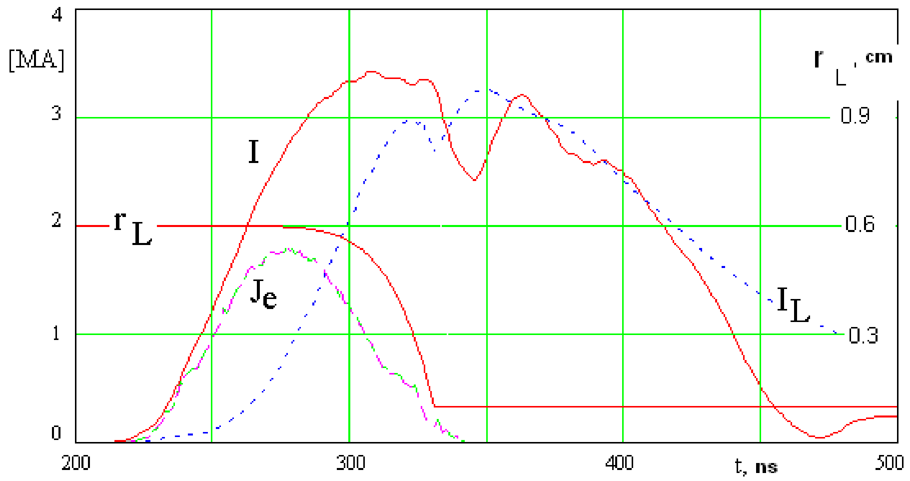
The effect of non-synchronous start of modules

The start of current for modules #6 and #8 was retarded on 40 and 60 nanoseconds relatively other modules.

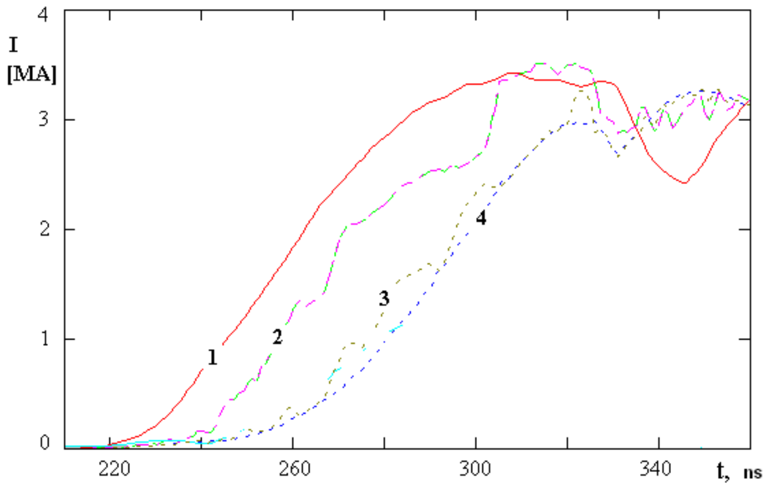


Calculated (solid line) and experimental (dotted line) current pulses at the input of the third section of VTL for each of eight modules.

RESULT OF CALCULATION



Calculated temporal profiles of current: at the input to the vacuum line (**I**); through the load (I_L); of electron leakage ($\mathbf{J_e}$) and time dependence of the load radius (r_L) for shot #4513



Calculated profiles of current pulses.

1 – at the VTL input

2 – at the input of the conical part

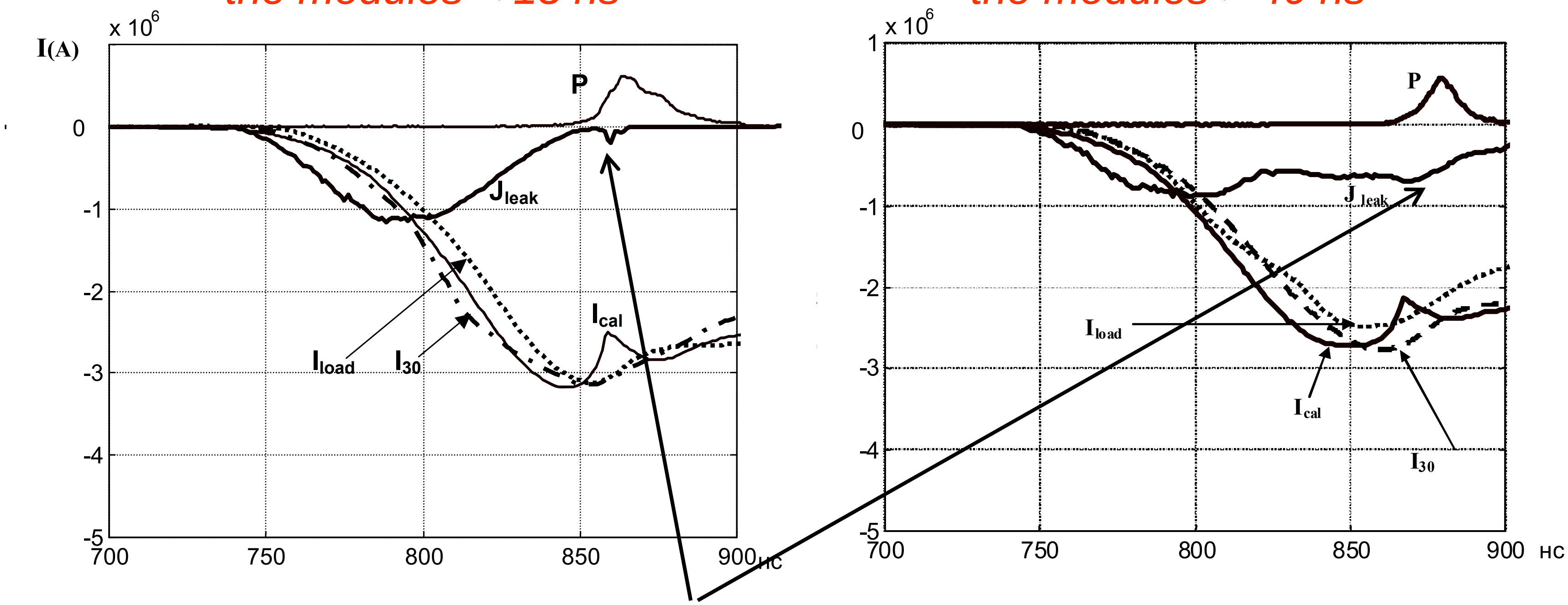
3 – at the output of the conical part

4 - on the load

COMPARISON RESULT OF CALCULATION AND EXPERIMENT DATA

The jitter of start moments of the modules < 15 ns

The jitter of start moments of the modules > 40 ns



The leakage current is there in the moment of compression.

Experimental profiles: the total module current at the conical part of VTL (I_{30}), the total current through the load taken at the radius 55 mm from the load axis (I_{load}), the X-ray pulse power (P) and the total leakage current (J_{leak}) .

Calculated profiles: the total current through the load (I_{cal})

CONCLUSION

- The developed program for the calculation of the vacuum lines with magnetic self-insulation has shown a satisfactory agreement of the theory and experiment.
- The system of telegraph equations with the electron losses including the cathode emission ability and matrix inductance of the load unit proved to be an effective and accurate instrument for the calculation of the «Angara-5-1» concentrator with dynamic load.
- The conducted investigations of energy transfer efficiency from the generator of «Angara-5-1» to the load have shown:

- depending on the load parameters over 74% of the generator energy is transferred to the vacuum concentrator of which 32-52% is stored as the magnetic field energy at the moment of the soft X-ray;

-the concentrator energy stored in the magnetic field decreases also if the reflection coefficient from the concentrator is diminished;

- the loss of current in the load due to electron leakages is less than 10-15 % if the time delay of start of current in one or two modules did not exceed 40-60 ns relatively other modules.