Design of 6MW Peak Power S - band Klystron with operating voltage below 60 kV

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Technical specification

Klystron shall include and be compliant with the parameters and conditions shown in Table 1 here under.

Parameters	Specifications	Units
RF Frequency	2.99855	GHz
Peak RF power	>6	MW
RF gain	>45	dB
Efficiency	>60	%
RF pulse length	>7.5	µs
Pulse repetition rate	300	Hz
Klystron voltage	<60	kV

Table 1: Characteristics of klystron and modulator performance

Other parameters, such as duty cycle, cathode current, heater voltage, heater current and water-cooling parameters should be provided by contractor.

Basic design - commercially available klystron for accelerators KIU-147A

General parameters	Available
Working frequency, GHz	2.856
Output pulse power, MW	6
Output mean power, kW	25
Cathode voltage, kV	52
Efficiency, %	45
Gain, dB	50
Mass with focusing system, kg	90
Used in	accelerators

Technical parameters of klystron KIU-147A are close to required characteristics, with one significant difference – lower efficiency, 45% instead of 60%.

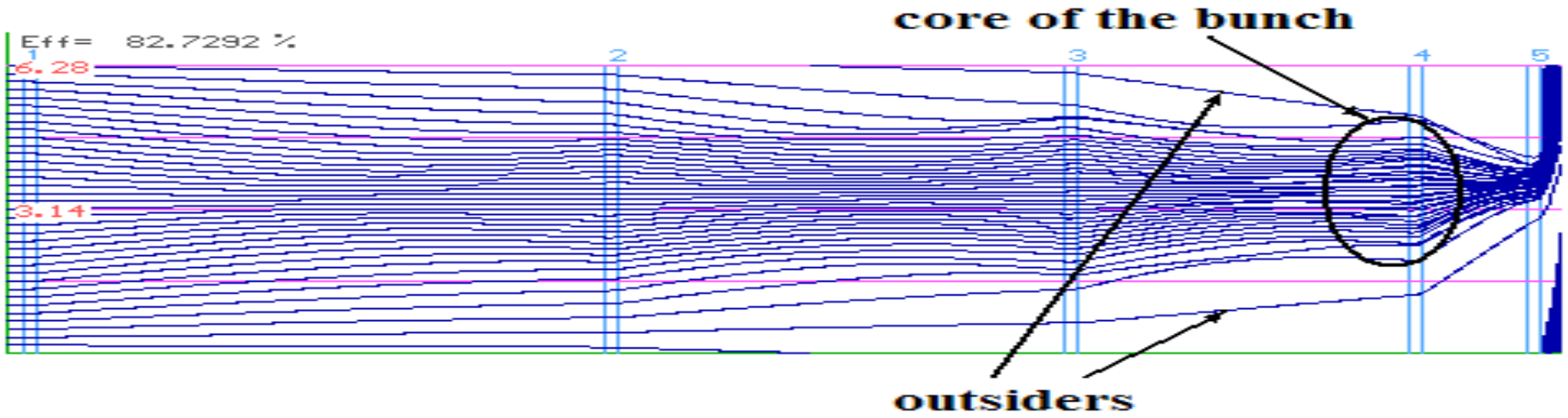
1. **Low cathode voltage** (2-3 times lower as compared with single beam analogues)
2. Compact **low weight PPMFS**, which is integral part of the device.
3. Klystrons are capable to operate in any spatial position and can operate in the moving state.
4. Use of the MBK permits to decrease accelerators dimension, weight and cost and make it possible to build mobile installations.

Basic units for present design

Some units such as **cathode unit** with 40 separate cathodes and high voltage insulator, **periodic permanent focusing system**, **collector** with cooling system, **input and output windows with wave guides** will not change and don't consider in the present design except of their characteristics.

Methods to get high efficiency

1. Space Charge De-bunching method by A.Baykov, D.Petrov



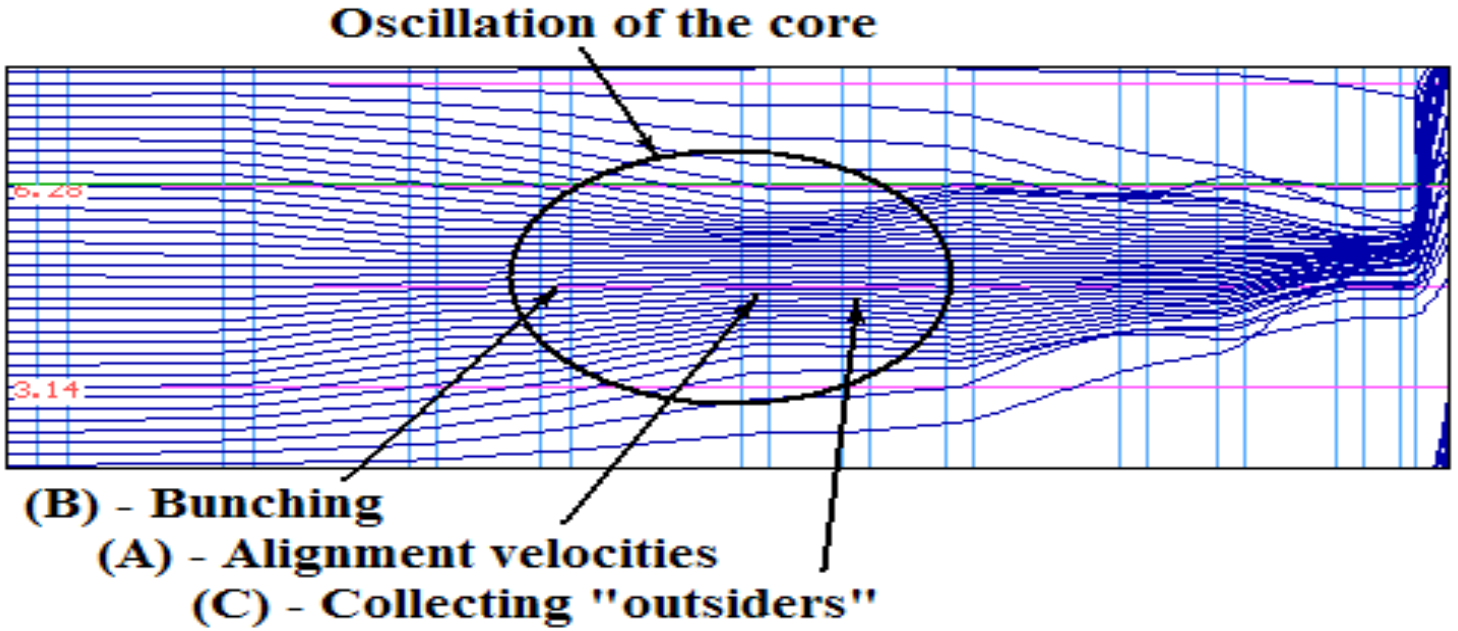
Bunching should have **non-monotonic wavelike character**: the central particles of bunch (core of the bunch) periodically approach to the center of the bunch, and move apart again, while the peripheral ones (outsiders) monotonically go to the center of the bunch.

The process is possible, if the **de-bunching forces** exist. These are the **space charge forces** in the method.

Efficiency rises together with the number of core oscillations and reaches **88-90% for 4-5 oscillations.**

Methods to get high efficiency

2. BAC method by I. Guzilov



Electrons of the core in the BAC method **also make oscillatory movements** to get high efficiency. To accelerate the process of oscillations of the core **de-bunching cavity** (A – for Alignment velocity spread of electrons) **add**. Resonant frequency of this cavity A is lower than the working frequency.

Using of BAC method **allows to reduce the length** of the interaction space twice in comparison with Space Charge De-bunching method, **while maintaining high efficiency**.

Programs for calculations of circuit

1. **Klypwin by A. Baykov**

   Simplified model of bunching that is based on the **"frozen beam" approximation**. This model was compared with the quasilinear model used earlier and it was noted that the obtained results are correct.

2. **KLYS 4.5 by A. Malykhin et al**

   The code is based on **one-dimensional disc model of the electron beam**. Disc (particle) field is being obtained as result of numerical solution of two-dimensional Poisson equation (Hockney-method). E-field distribution in the gap is the result of numerical solution of two-dimensional Laplace equation with real geometry of cavities.

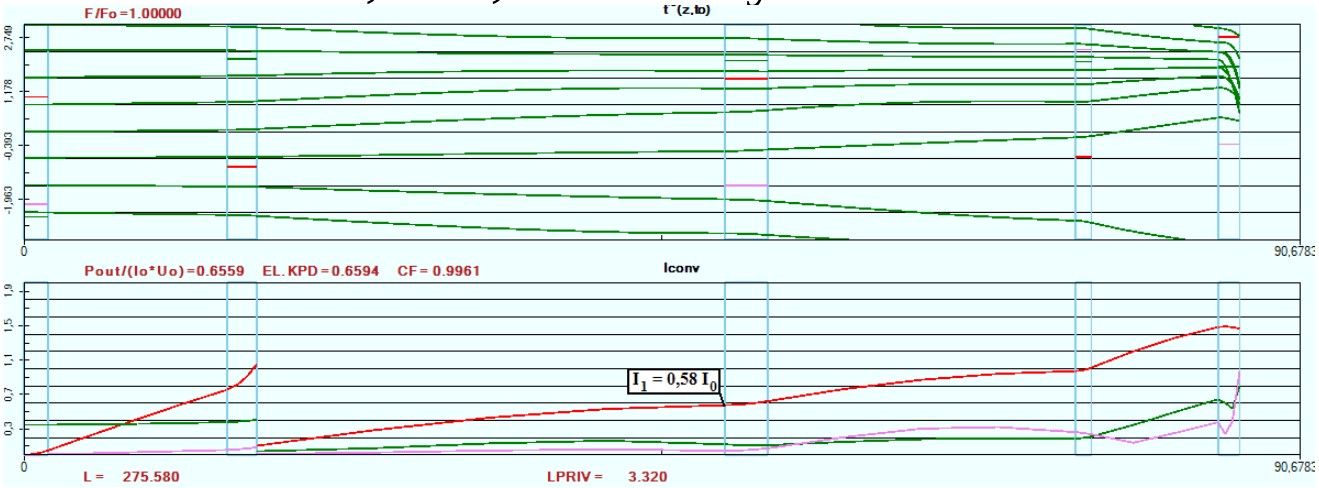
3. **Dev 5.1 by A. Konnov**

   Electric field pattern along gap is calculated in electrostatic approximation in r, z coordinates. Laplace equation is written in finite-difference form using five-point symmetrical stencil and is solved by successive over-relaxation method.

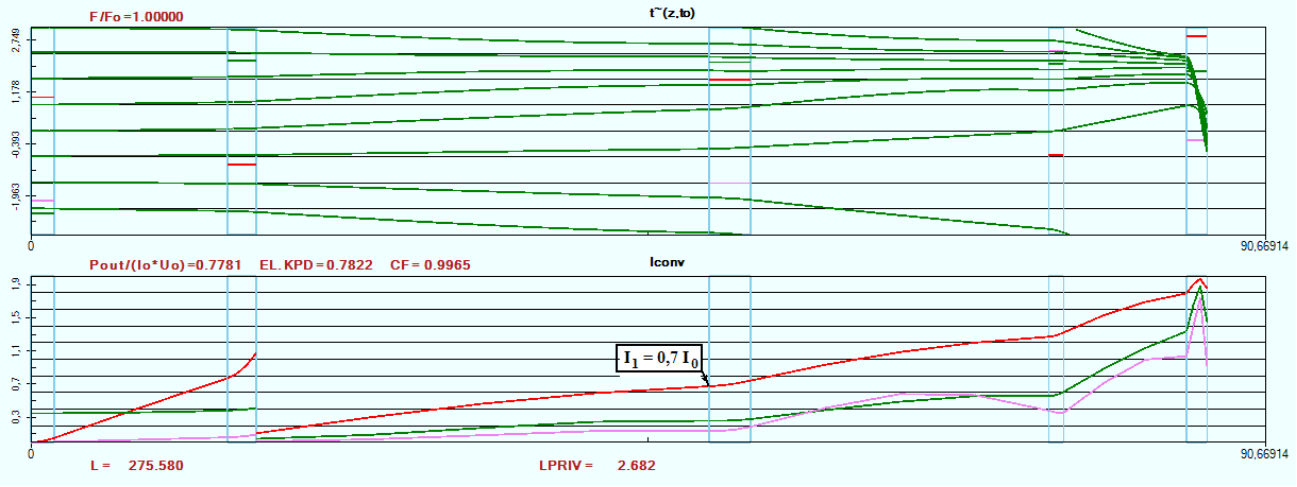
Example: bunching with different beam radius

Calculation of Chiara Marrelli klystron by Klypwin

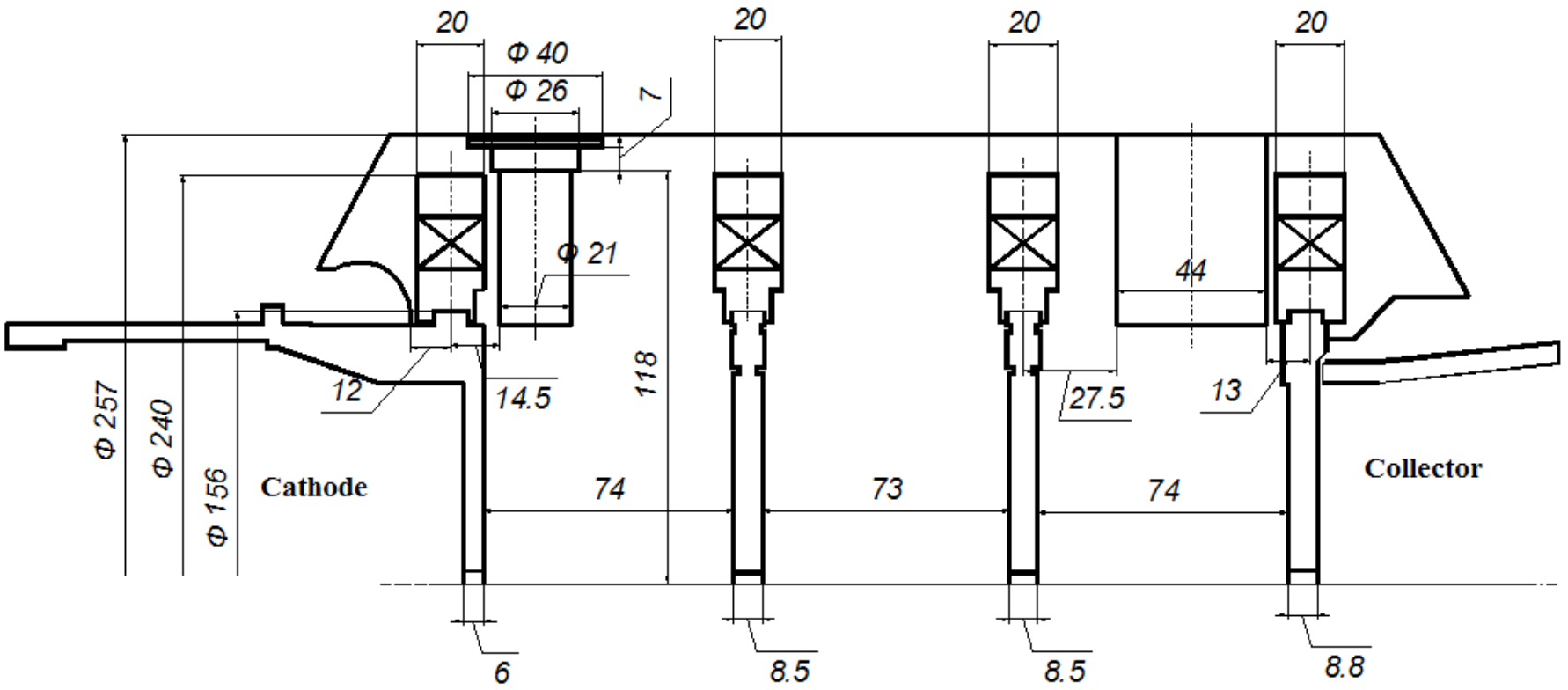
Rb=0,4 Rt; efficiency 66%



Rb=0,6 Rt; efficiency 78%

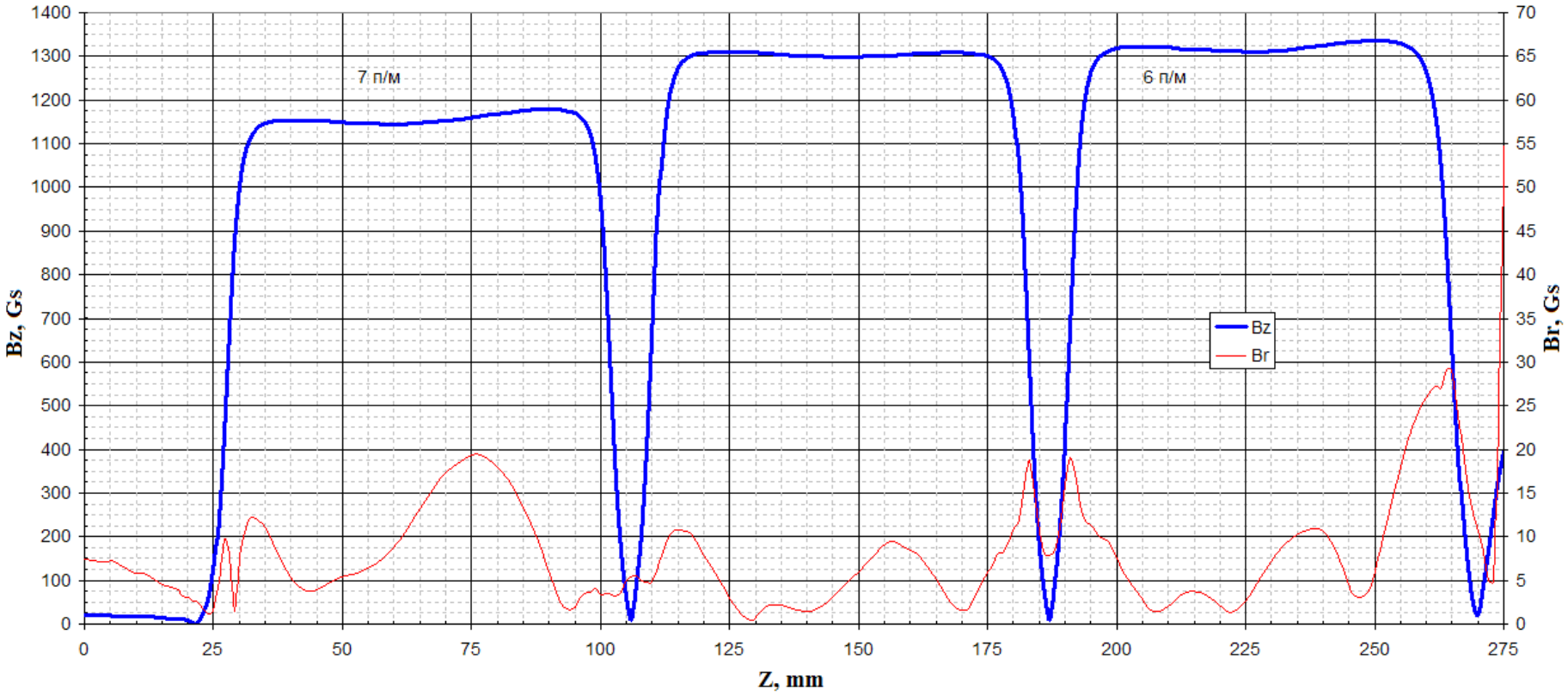


Electron optics – magnetic system



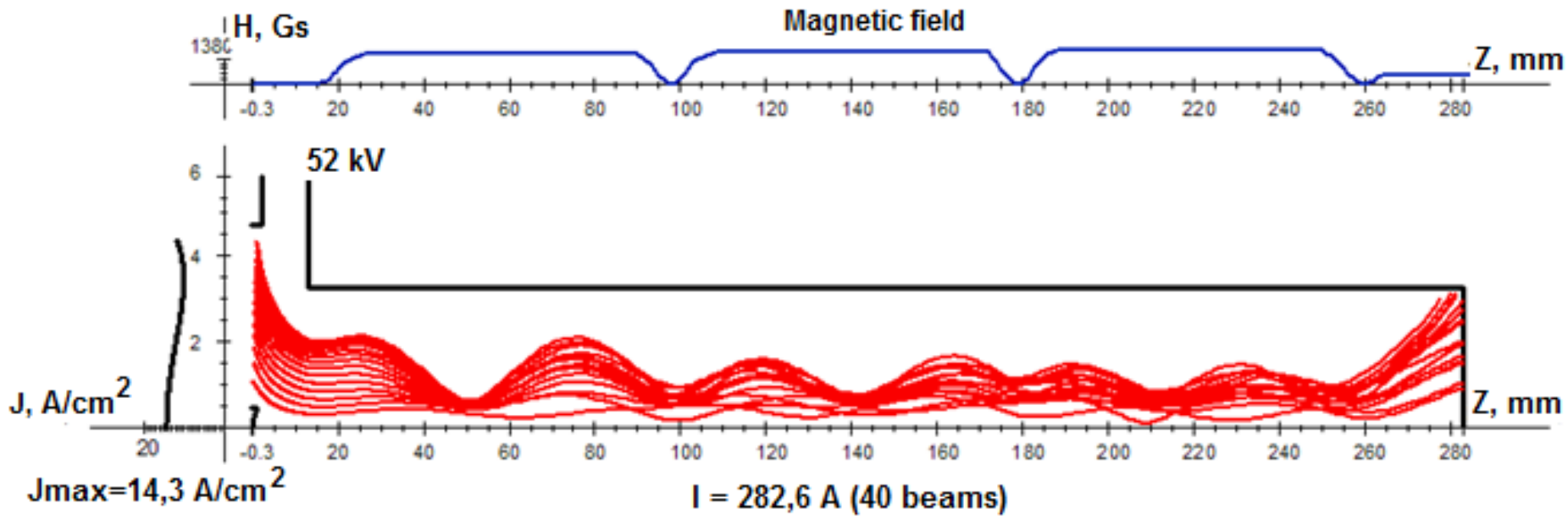
Magnetic system includes 4 poles with radially magnetized magnets and 2 magnetic screens – cathode and collector that is needed for decreasing of magnetic field in appropriate region

Magnetic field



There are 3 regions of magnetic field with 1150, 1300 and 1320 Gs in average. **The increasing of magnetic field is necessary to partly compensate the effect of rising "average bunch" radius** in the cavities closed to output.

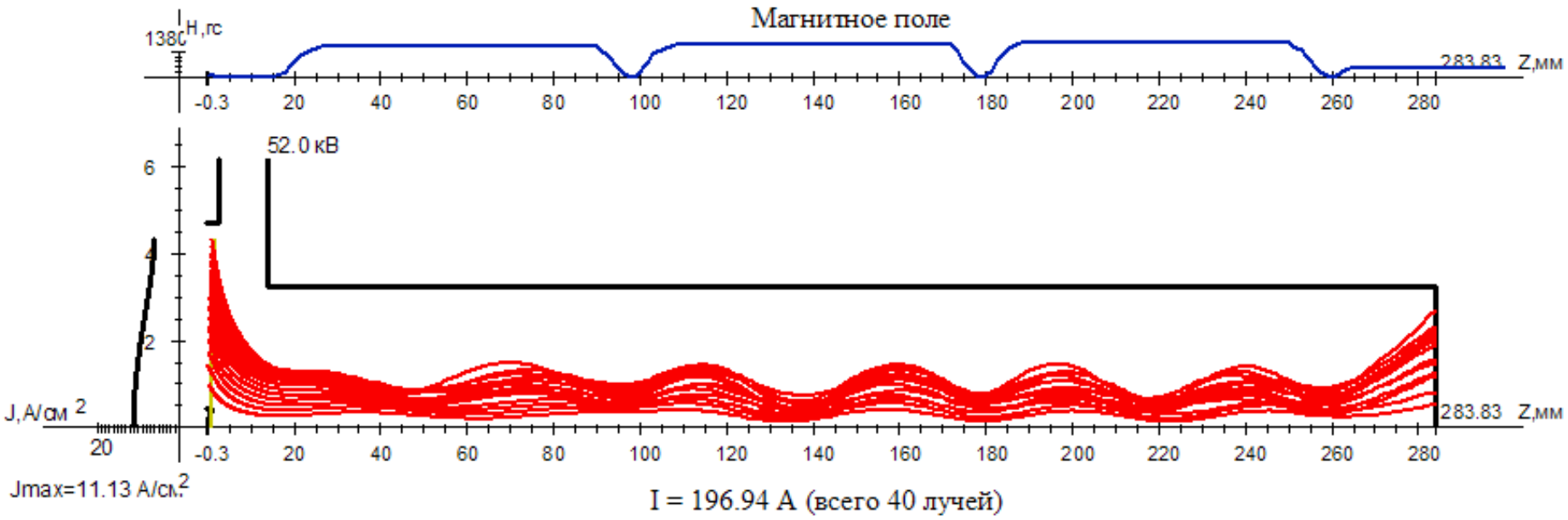
Electron optics of KIU-147A



The total current of 40 beams is 280 A.

The "average beam" radius is $R_{b.av}$= 1,23 mm for Hbr=1180 Gs, 280/40 = 7 A, so the oscillations of beam radius with rather high amplitude occur around this average radius. Minimal beam radius is 0,55 mm, maximum – 1,95 mm.

Electron optics of klystron under development



On the base of KIU-147A optics trajectories for supply were optimized. The results of optimization are presented on the picture. **The aim of optimization was to reduce the maximum radius of the beam, in order to prevent the current loss on the walls of the channels in the presence of the effect of the dynamic expansion of the bunch**. The "average beam" radius $R_{b.av}$= 1,03 mm for Hbr=1180 Gs, I = 195/40 = 4,9 A

Optimization of the circuit

The objective function in optimization was **the maximum of efficiency** in a frequency band. The optimization was done in Klypwin code by A. Baykov for 2 methods of bunching:

1. Space Charge De-bunching method by A.Baykov, D.Petrov
2. BAC method

In second case the length of circuit 200 mm was fixed.

The beam radius for both methods was the same Rb=0,5 Rt

The values of all independent parameters:

the lengths of drift tubes,

detunings (relative deviations of the cavity's eigenfrequencies),

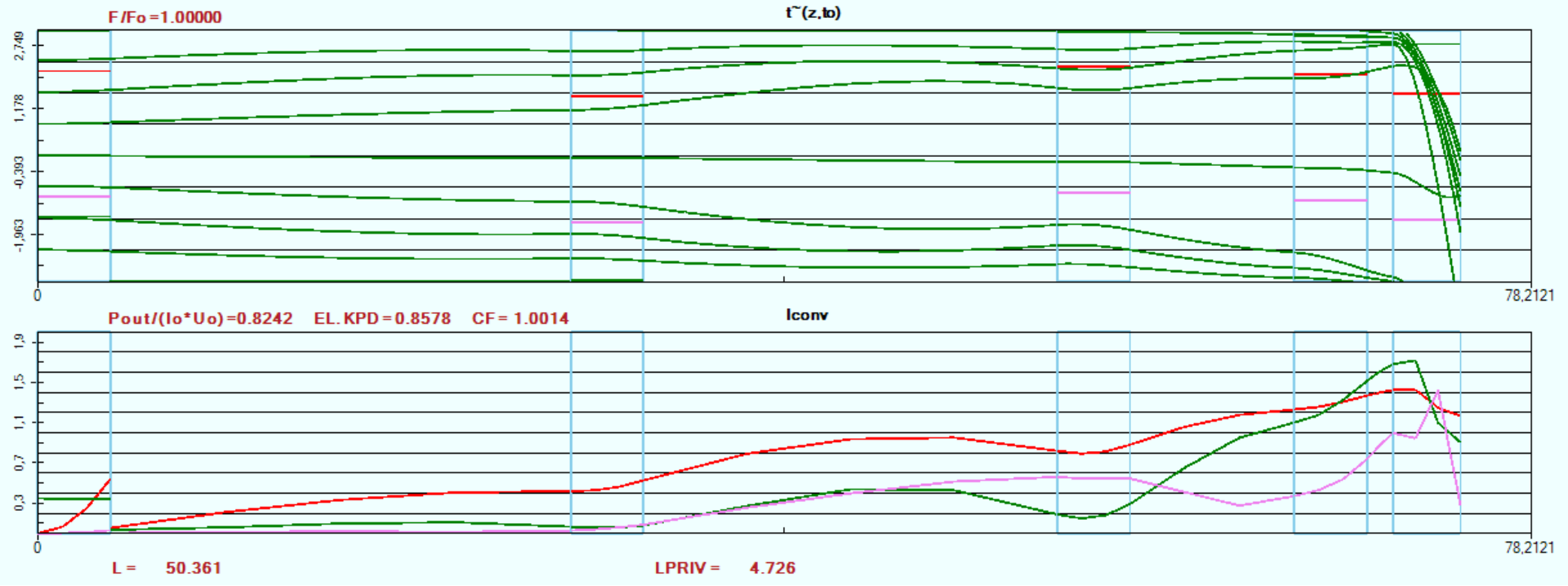
and loaded Q factors of the input and output cavities

have been changed in the optimization process.

Maximum number of these parameters was 20 for 9-cavity klystron.

Unfortunately, it is impossible to take into account the effect of the expansion of the bunch - the radius of the beam is fixed in Klypwin code, so optimization results were verified and refined in other programs – Klys4.5 and Dev5.1

Result of optimization for Space Charge De-bunching method by A.Baykov



Number of cavities is 5.

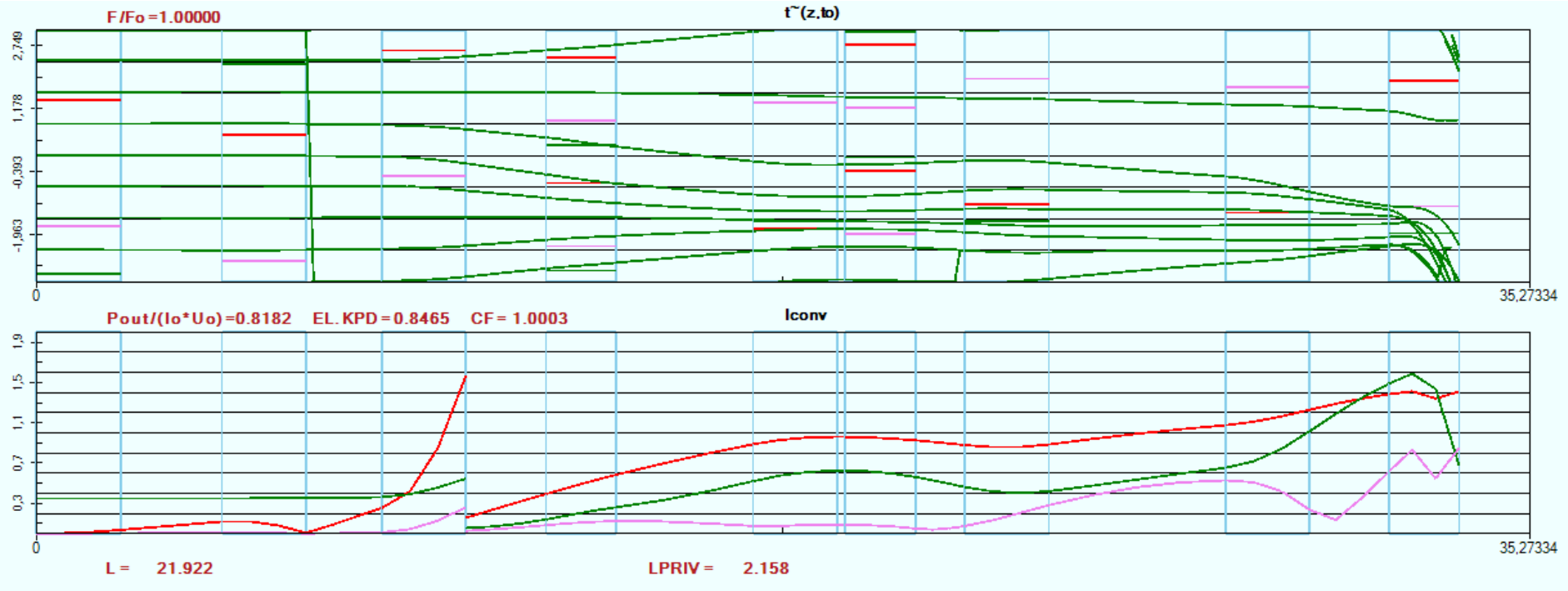
Optimization was carried out **without restrictions on the total length** of the klystron.

The value of total length is **503 mm**.

The efficiency is **82,4%**

Rb=0,5 Rt

Result of optimization for BAC method (Rb=0,5 Rt)



Number of cavities is 9.

Optimization was carried out with **restriction on the total length of the klystron – 220 mm**.

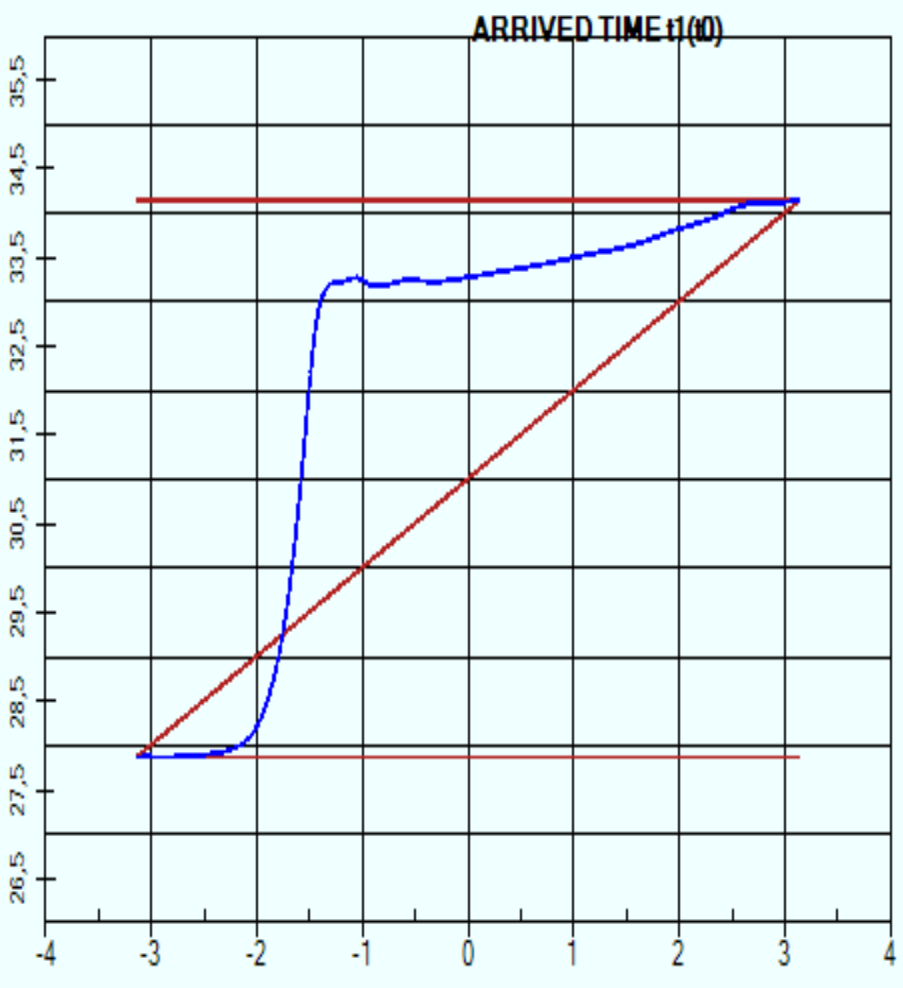
The value of total length is **219 mm**.

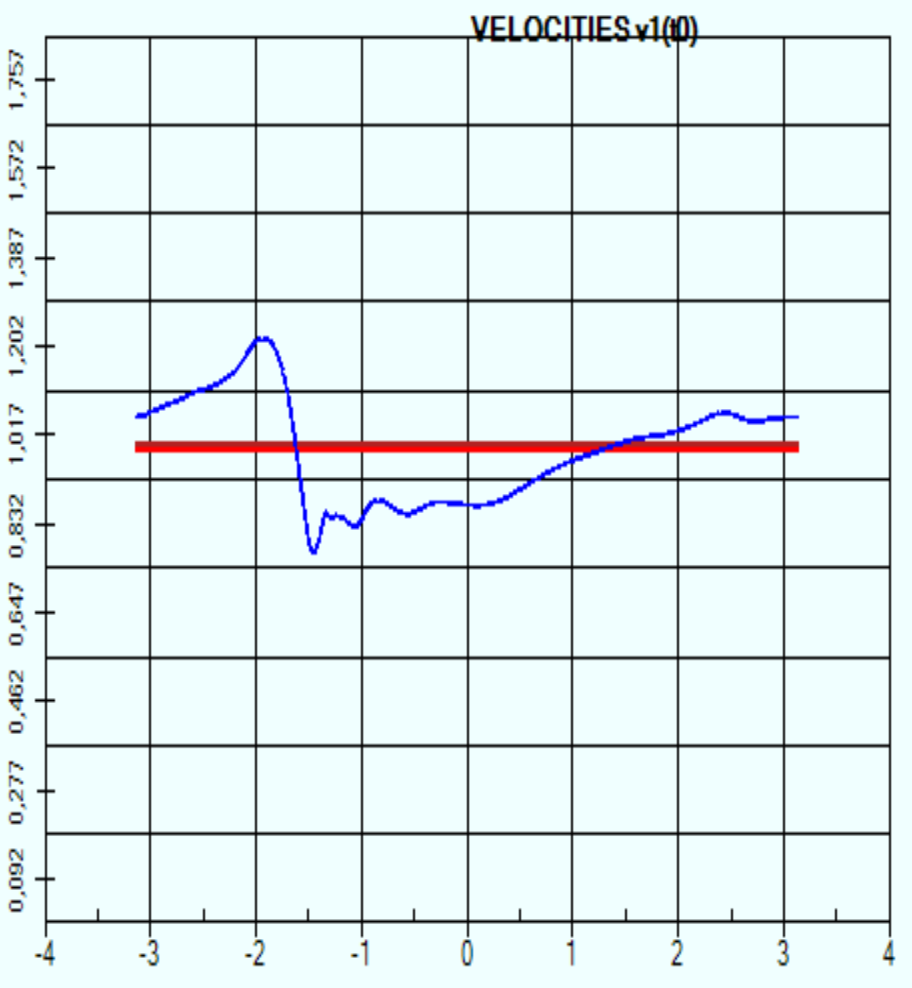
The efficiency is **81,8%**

Rb=0,5 Rt

Total length is 44% of the length at the SCD method for the same efficiency!!!

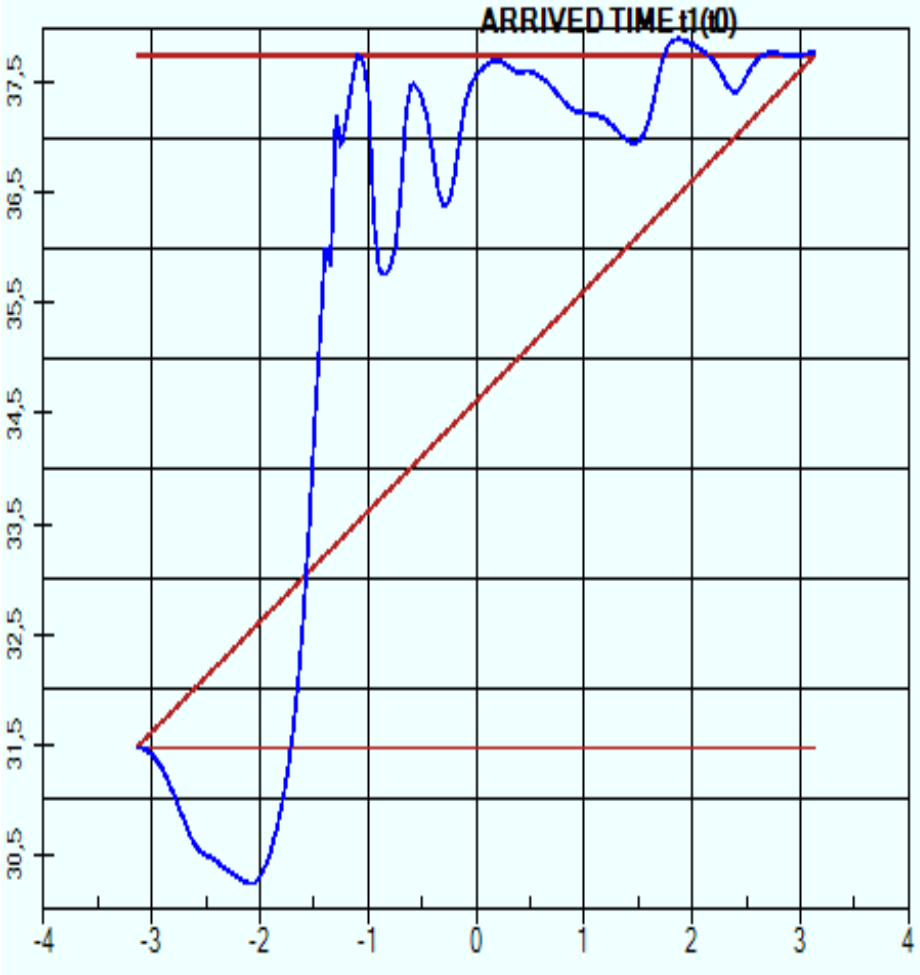
Some parameters after optimization

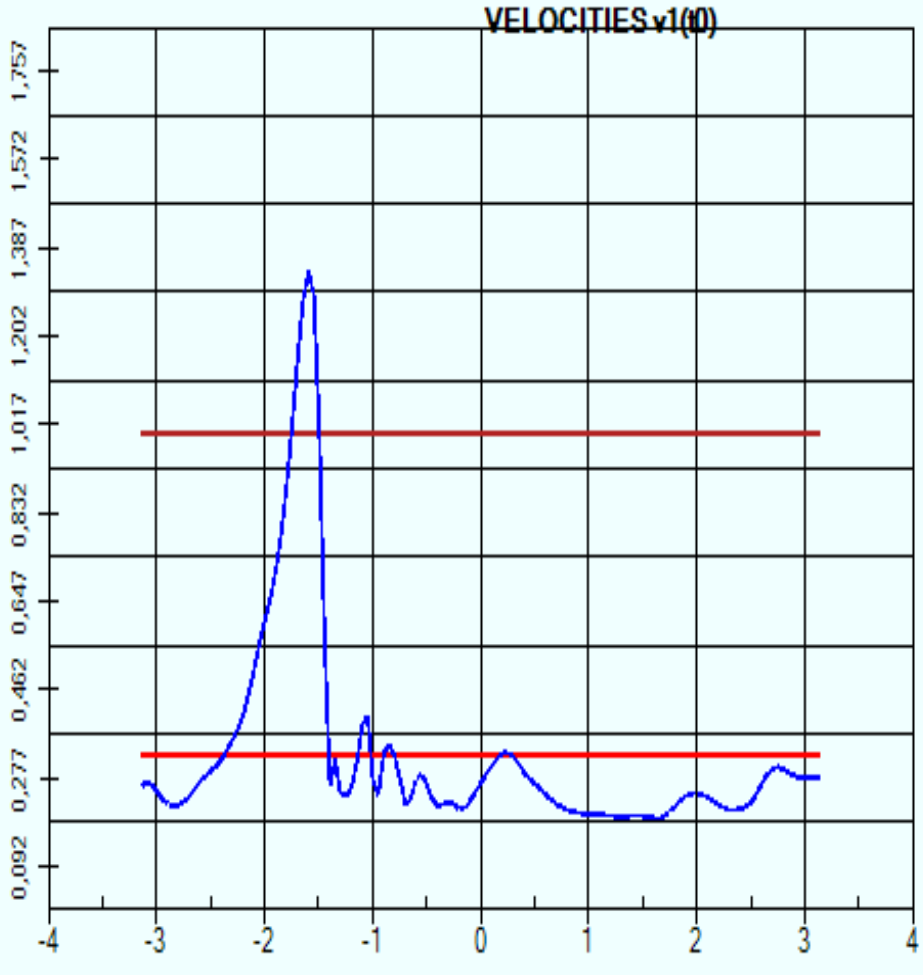




Arrived time and electron velocities before output cavity

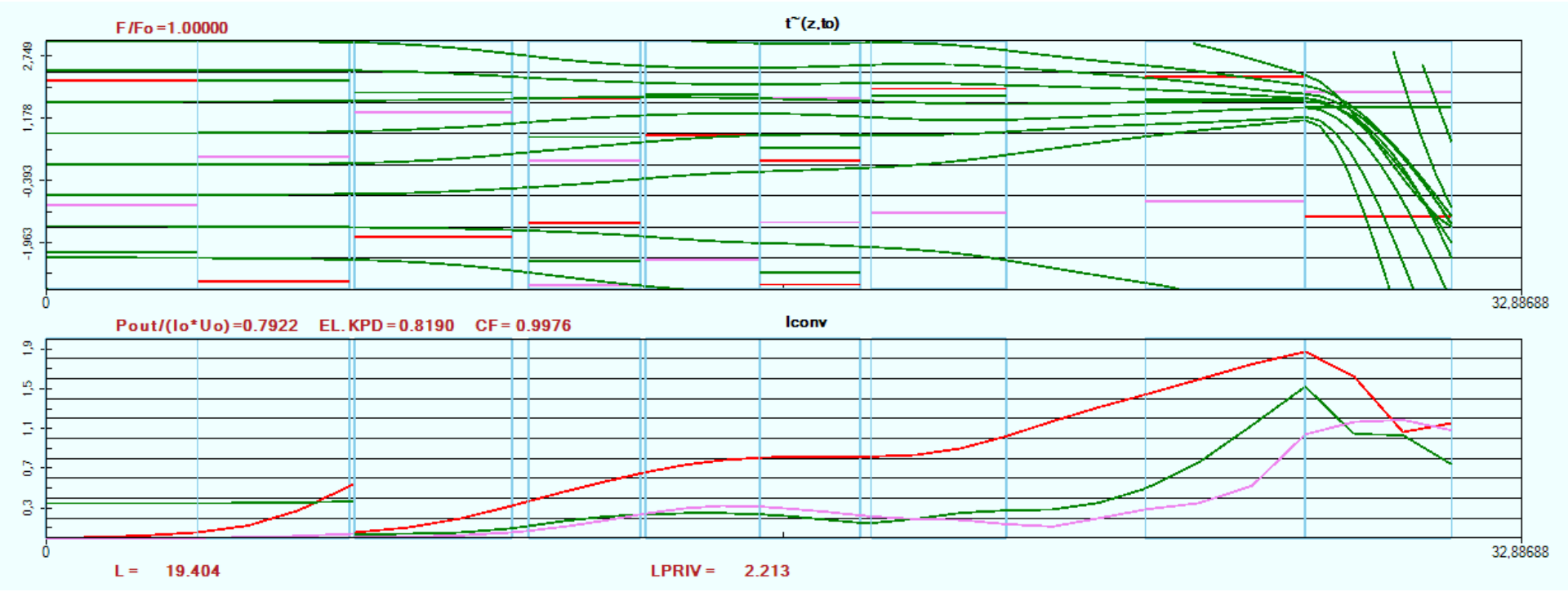
Some parameters after optimization





Arrived time and electron velocities after output cavity

Result of optimization for BAC method for small beam radius (Rb=0,37 Rt)



Number of cavities is 9.

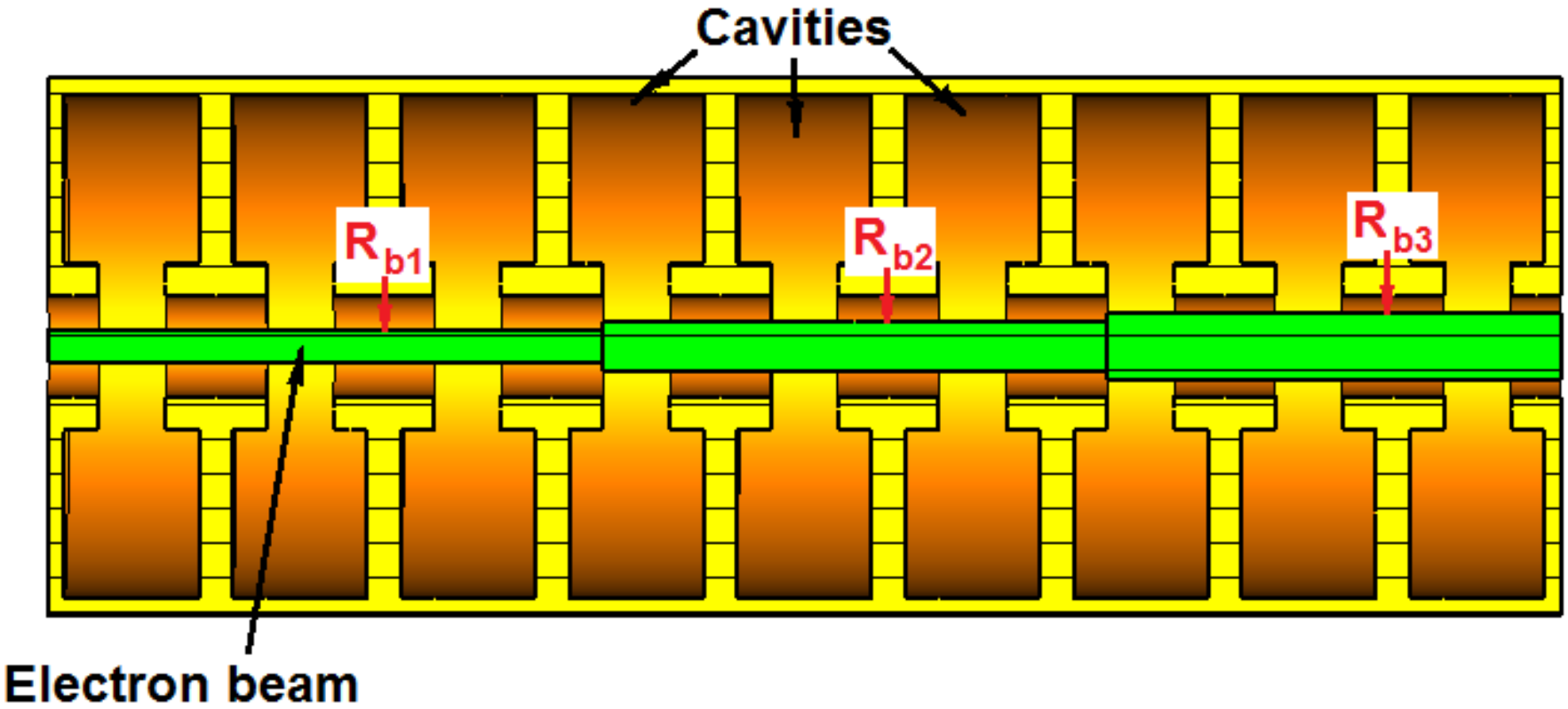
The total length of the klystron body – **194 mm**.

The efficiency is **79,2%**

Total length is 38% of the length at the SCD method.

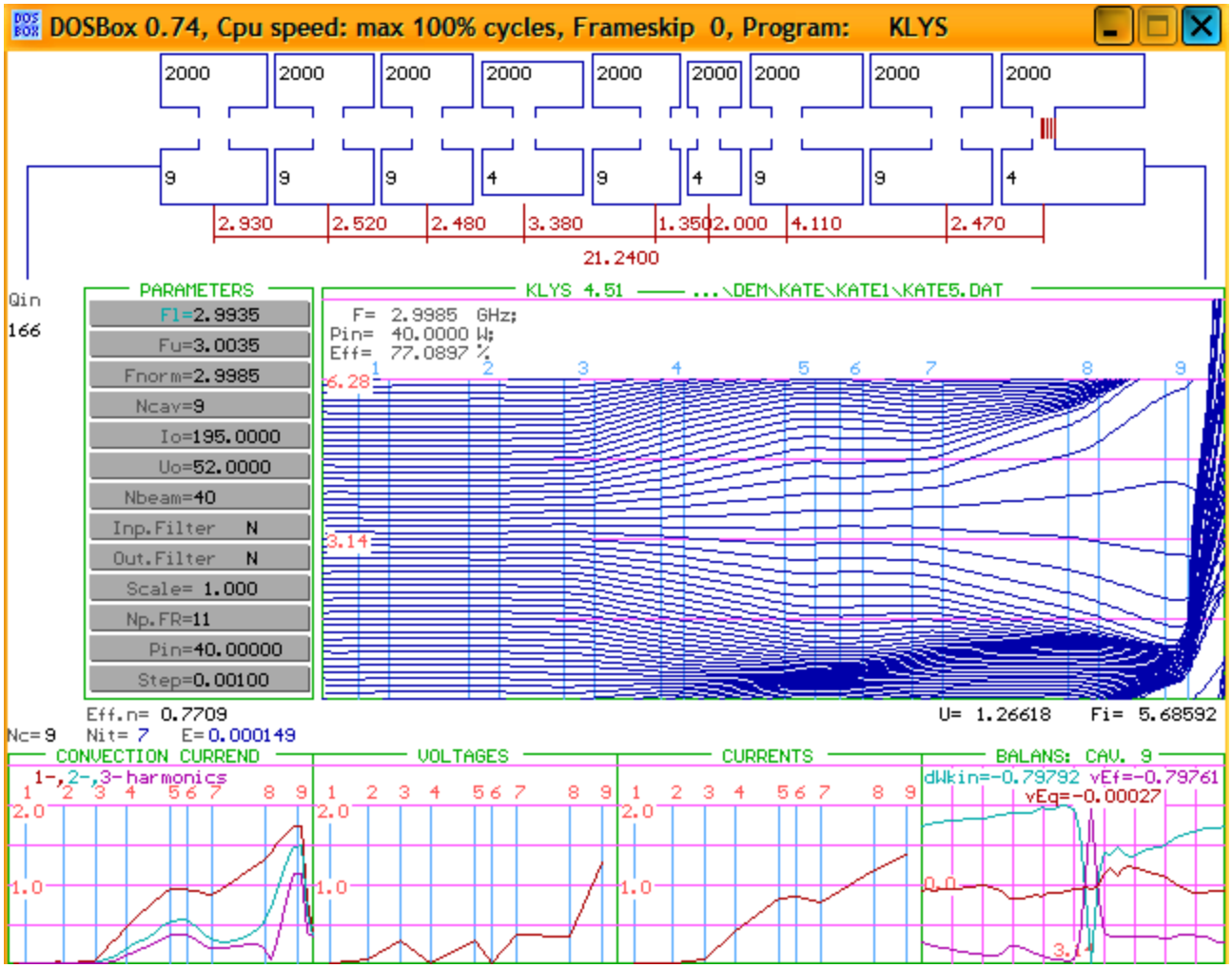
Refining optimization results by Klys4.5 with expansion of the bunch along the interaction space

Model of expansion



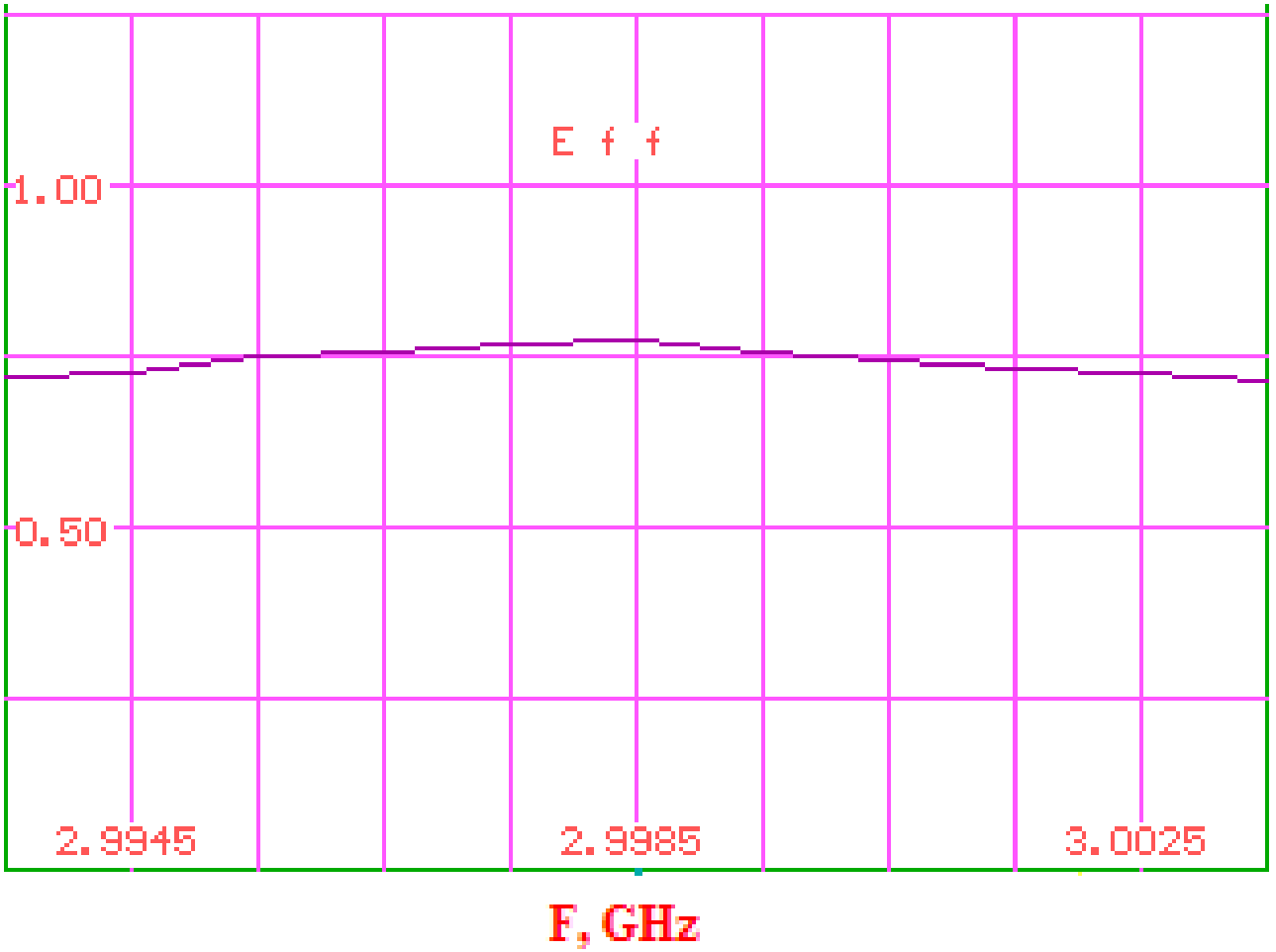
$$R_{b1} = 0{,}4*R_t\,,\ R_{b2} = 0{,}5*R_t,\ R_{b3} = 0{,}6*R_t$$

Refining optimization results by Klys4.5 with expansion of the bunch along the interaction space

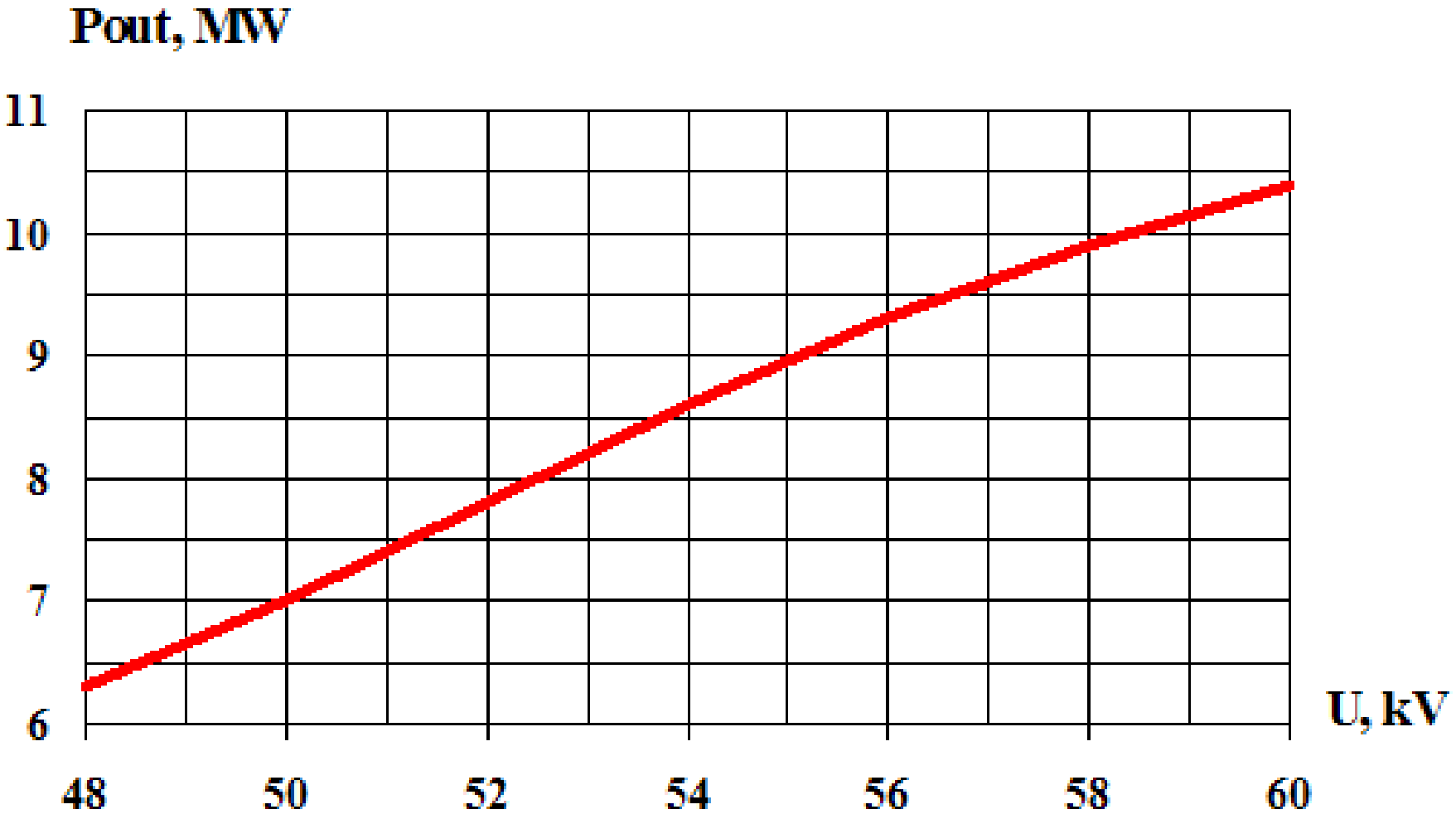


The calculated efficiency is **77.1%**

Efficiency vs frequency

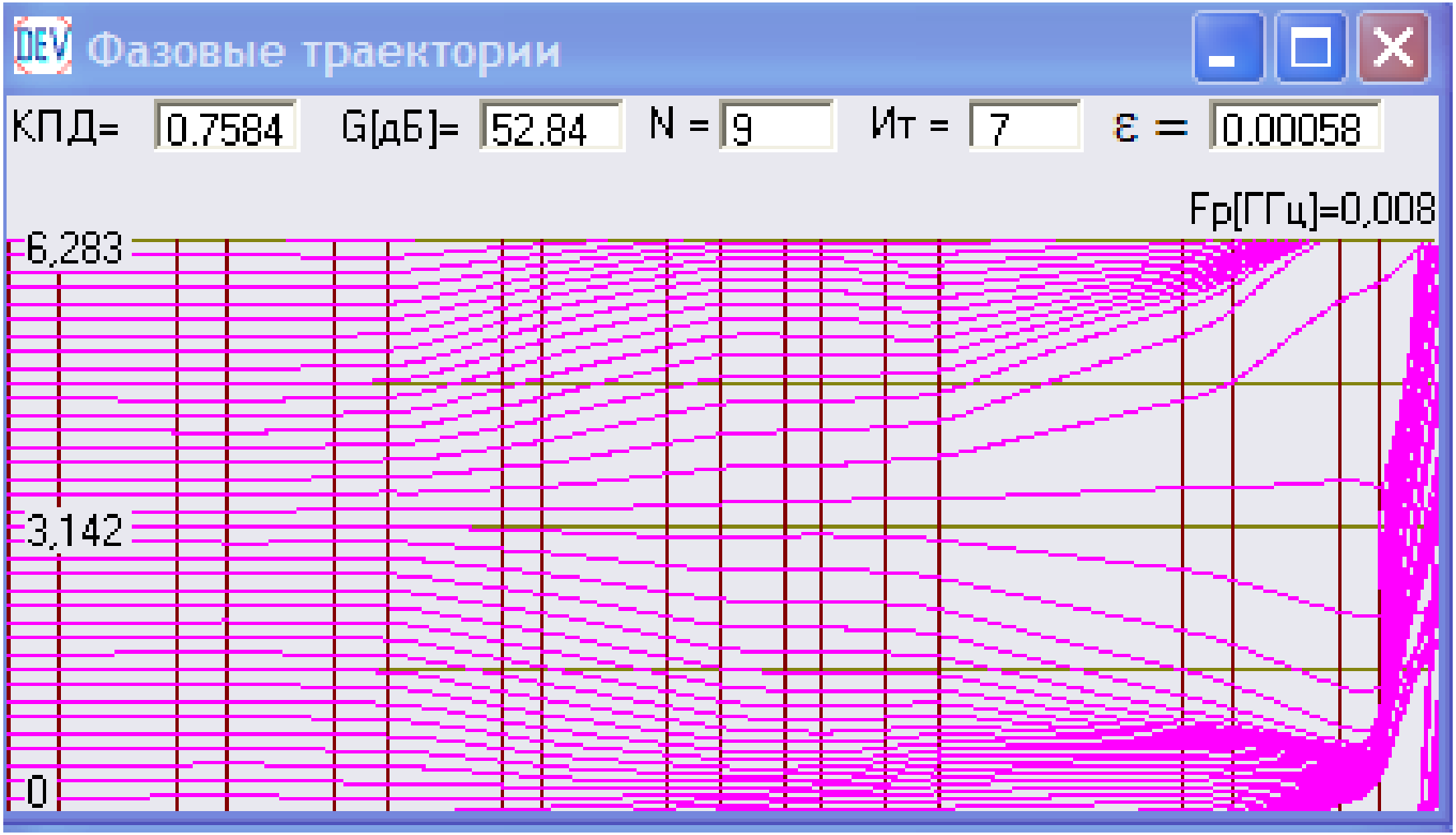


Output power vs voltage



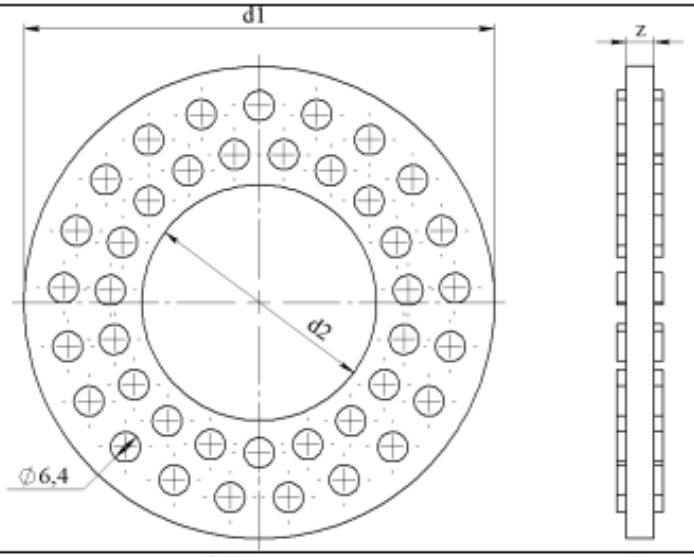
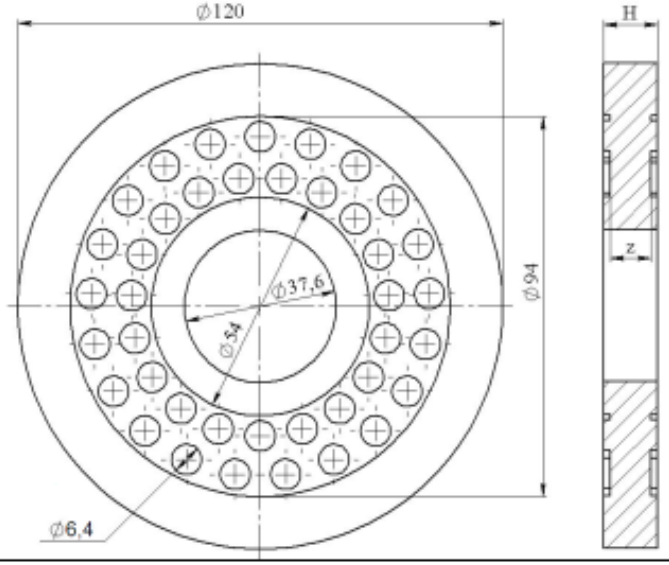
The calculation does not take into account the possible loss of current with increasing voltage

Refining optimization results by Dev5.1 (with constant Rb=0,37 Rt

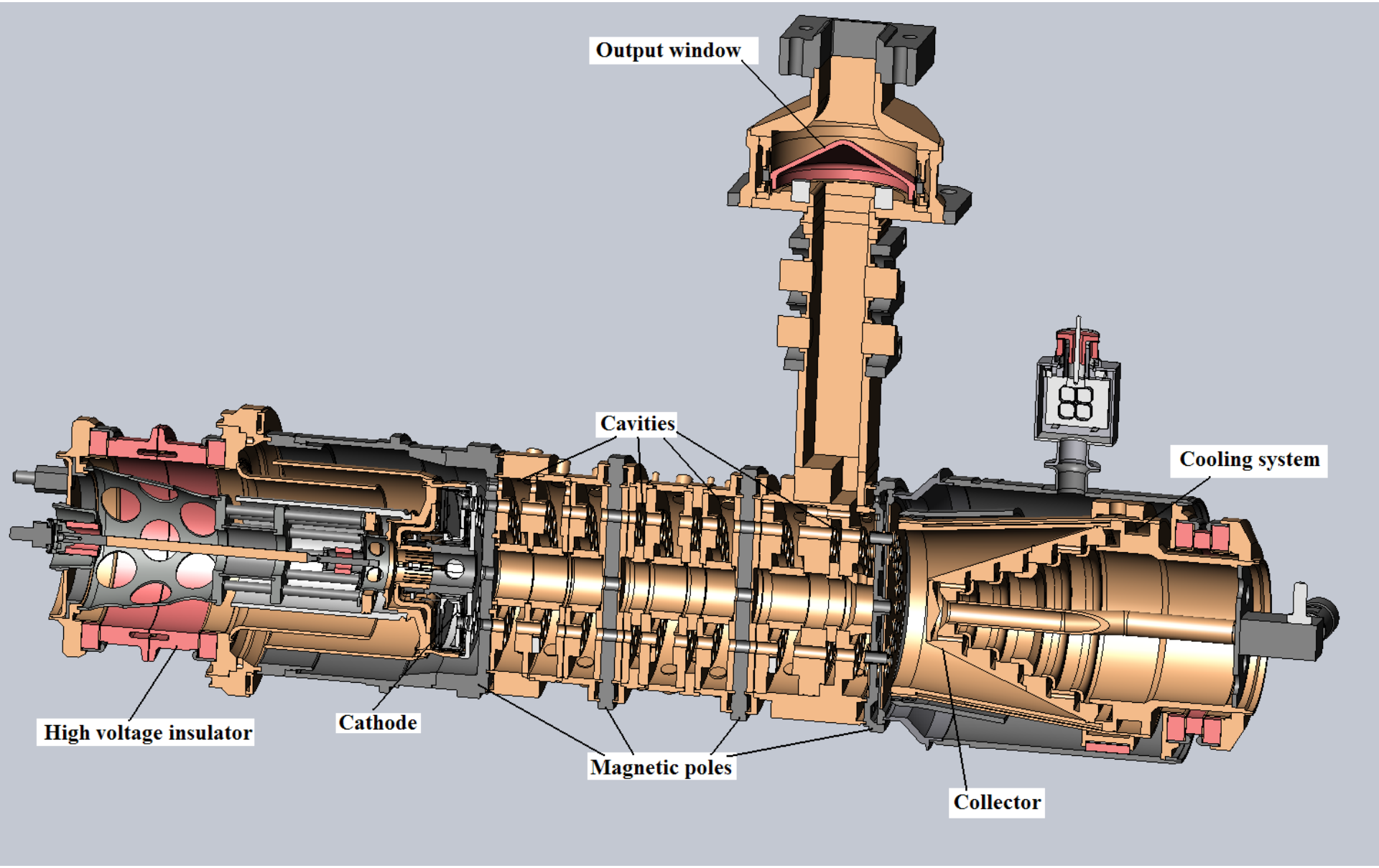


The calculated efficiency is **75,8 %**

Examples of cavities (first and second harmonics)

№ резонатора	тип	f	z	h	d1	d2	ro1	ro2
4		5.92541	6	-	100.65	50.27	8.36363	8.28613
5		2.83446	8	15	-	-	18.438	18.4617

Appearance of klystron



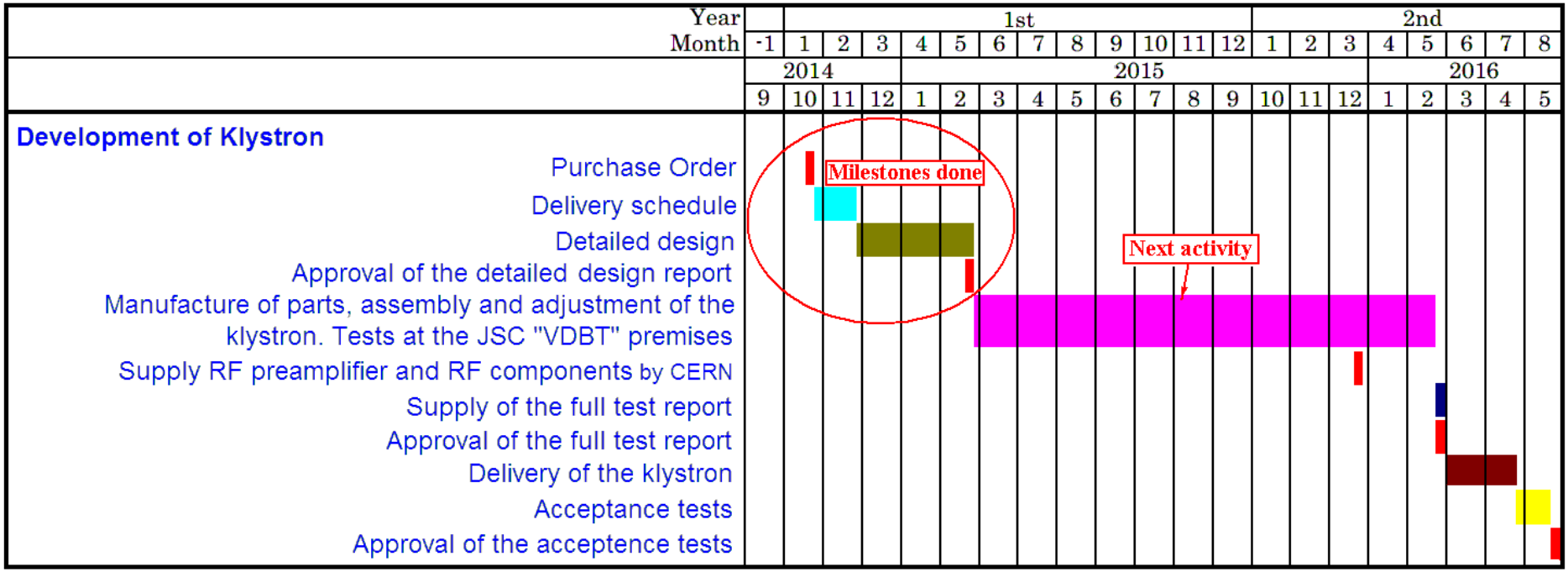
Conclusion

1. Design of klystron of a 6MW Peak Power S - band Klystron with operating voltage 52 kV was presented
2. Efficiency of the klystron calculated by three different codes is no less than **76%.**
3. The total length of the interaction space is **220 mm** (4,5 Le).
4. Usage of BAC method leads to **2,5 times decrease** of body length.

Conclusion

Milestones, 3 GHz Klystron Development

JSC "Vacuum device's basic technologies"
Research dept.
21-Nov.-2014



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I. Syratchev,

M. Yushkin

Thank you for attention!