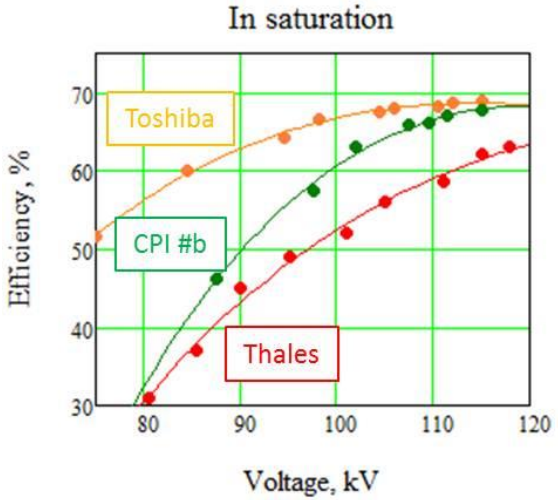
Prospects for high-efficiency klystrons

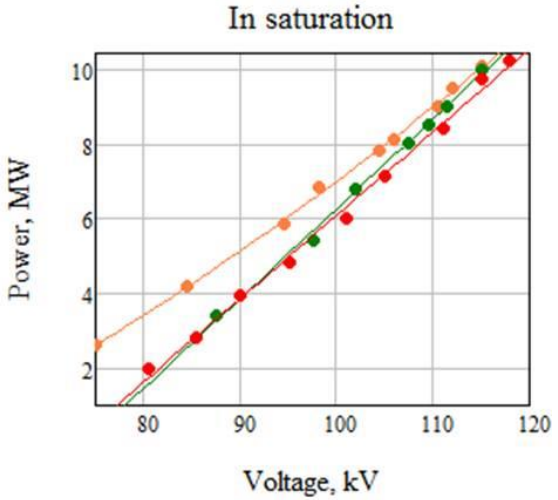
I. Syratchev, CERN

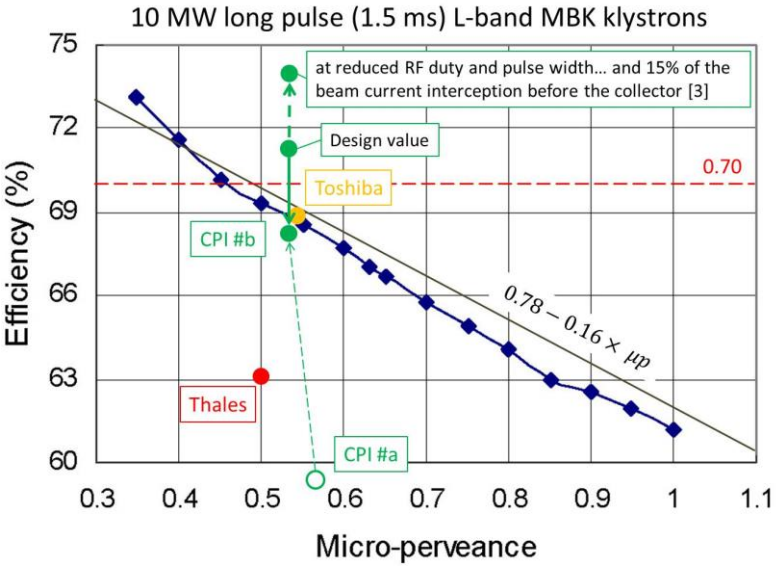
State of art: L-band 10 MW MBK klystrons for ILC.

Thales Toshiba CPI #a CPI #b

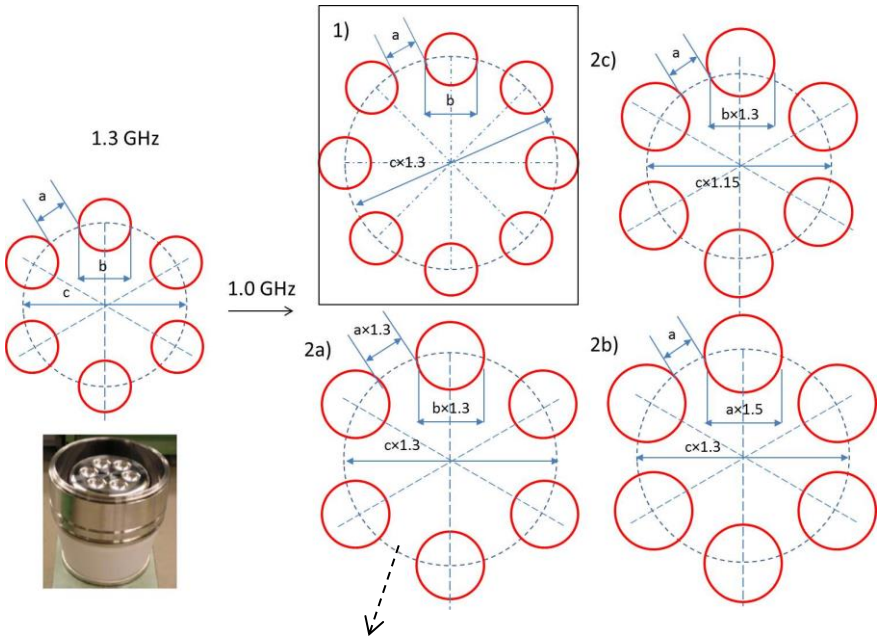
In terms of achieved efficiency at 10 MW peak RF power level, the existing MBK klystrons provides values very close to the 70%, as is specified in CLIC CDR.





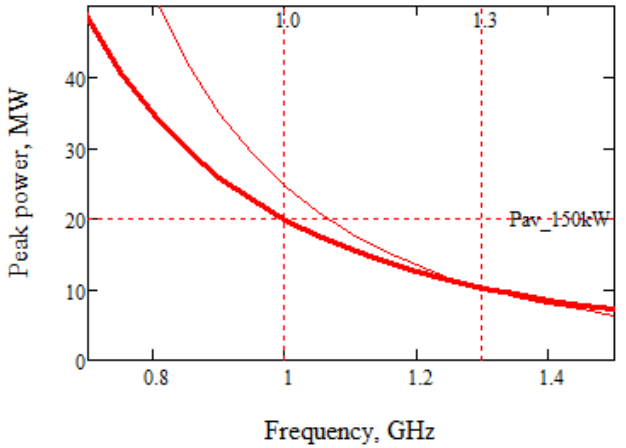


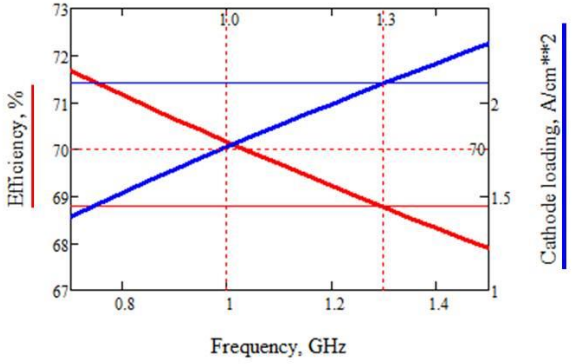
Extending technology: L-band 20 MW MBK klystron for CLIC.

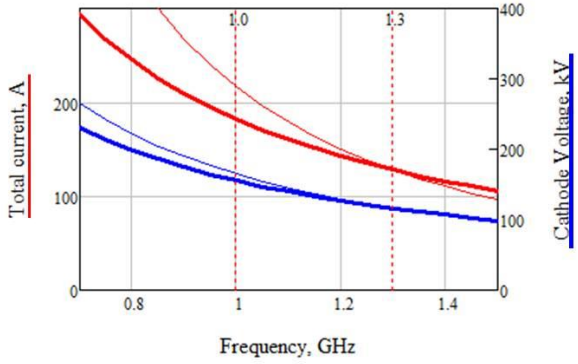


- We made a study which indicates that the scaling of existing tubes down in frequency may end up in rather powerful (>20 MW) and efficient (>70%) MBK.
- *Currently we are in process of purchasing such a tube(s).*

	2a)
Frequency, GHz	1.0
N beams	6
Cathode diam., cm	4.94
Cathode loading A/cm²	1.76
μ–perveance/beam	0.453
Peak power (max), MW	20.3
Cathode Voltage, kV	164.3
Cathode current, A	181.6
Efficiency, %	70.15
Average power, kW	148.5
Tube length, m	2.65

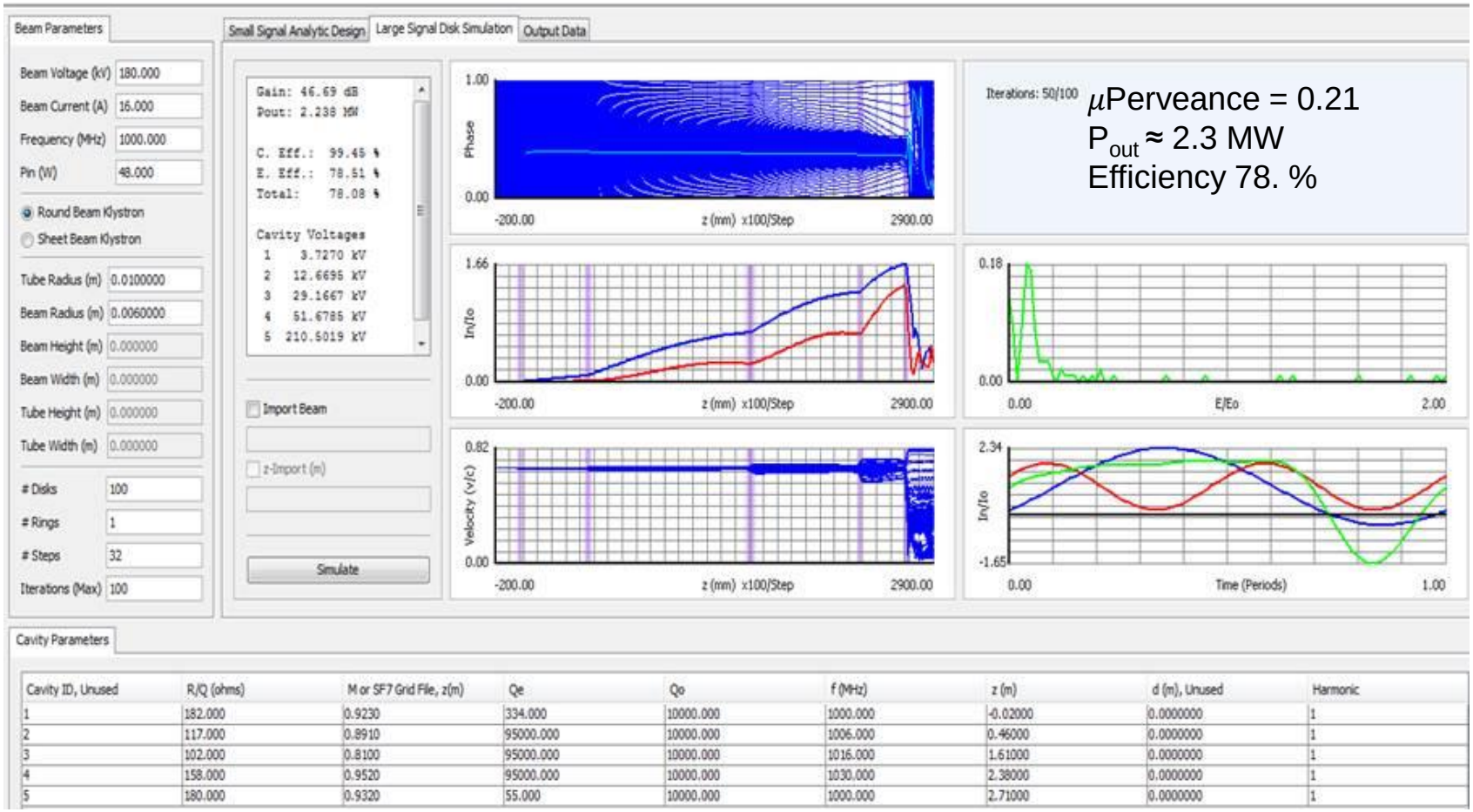






Designing the klystron

AJDISK (1-beam klystron optimised by C. Marrelli)

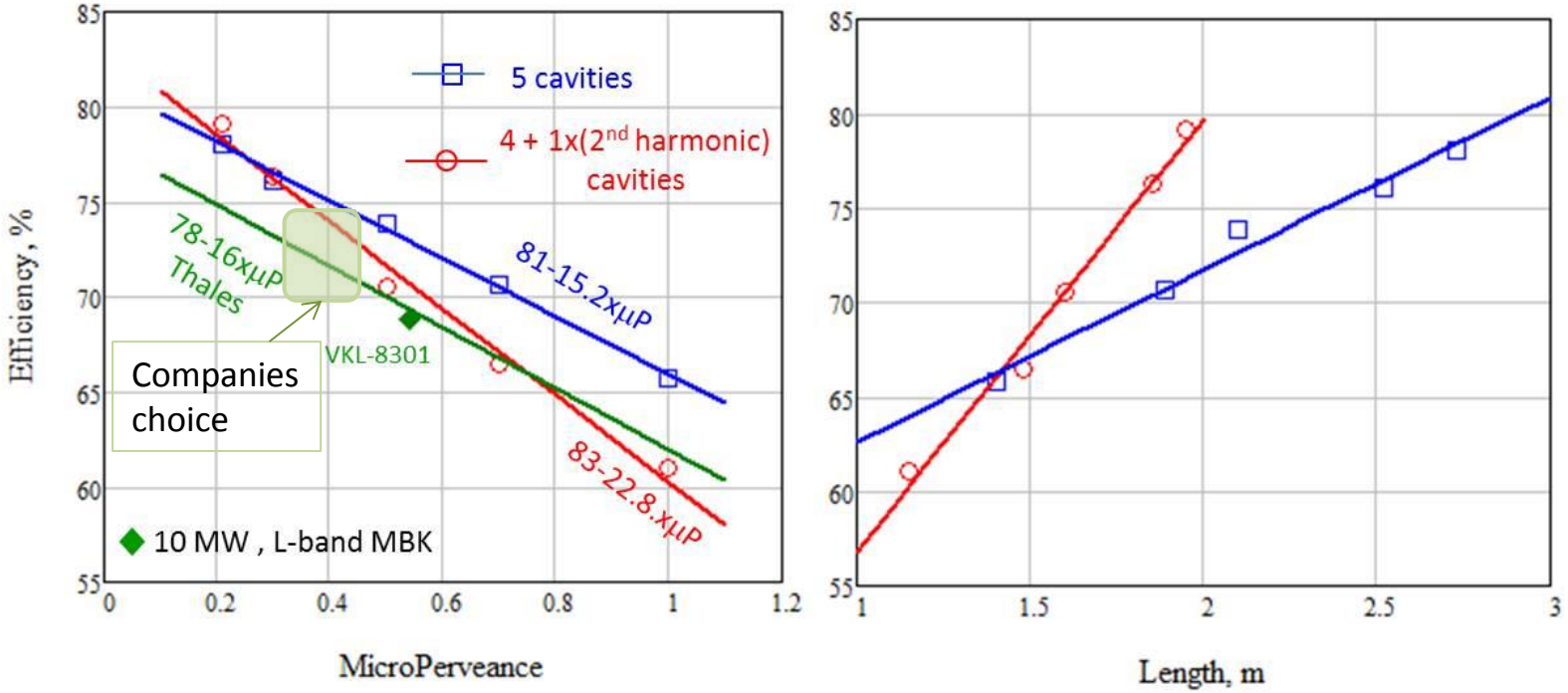


Cavity ID, Unused	R/Q (ohms)	M or SF7 Grid File, z(m)	Qe	Qo	f (MHz)	z (m)	d (m), Unused	Harmonic
1	182.000	0.9230	334.000	10000.000	1000.000	-0.02000	0.0000000	1
2	117.000	0.8910	95000.000	10000.000	1006.000	0.46000	0.0000000	1
3	102.000	0.8100	95000.000	10000.000	1016.000	1.61000	0.0000000	1
4	158.000	0.9520	95000.000	10000.000	1030.000	2.38000	0.0000000	1
5	180.000	0.9320	55.000	10000.000	1000.000	2.71000	0.0000000	1

During optimisation, the tuning of all parameters is done to provide the highest bunched current harmonics at the entrance of the input cavity. The obtained solution is not unique and does not give enough information about the inner structure of the bunch, which also must be optimal in terms change density and electron velocities distributions to get highest efficiency.

Scaling of the klystron parameters

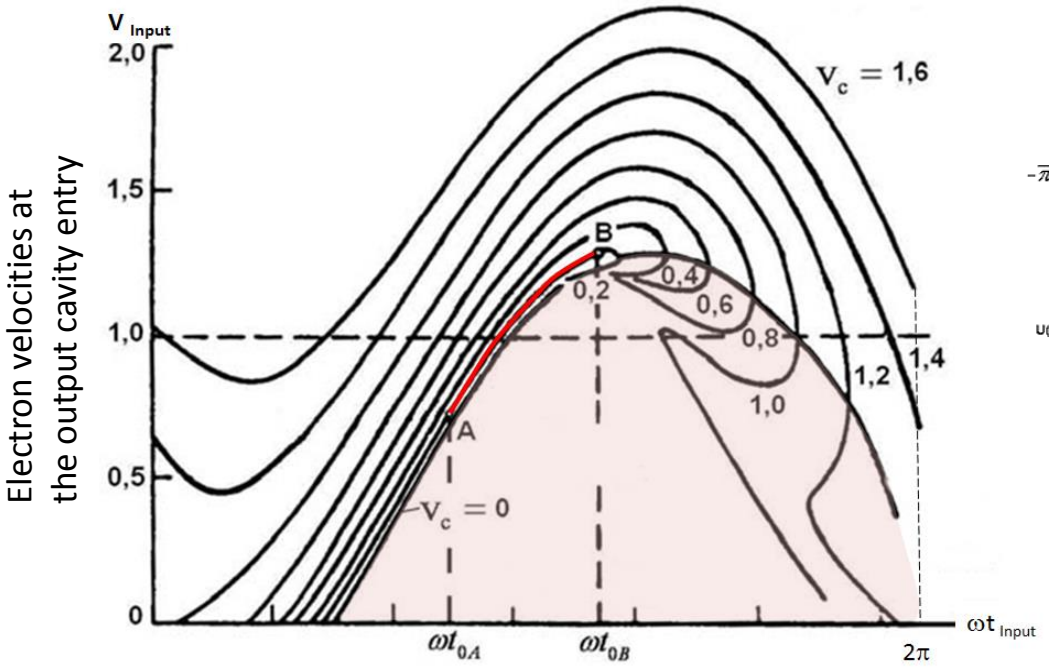
Dedicated campaign to make parametric study of the high efficiency klystrons was conducted by Chiara Marrelli (Manchester/CERN) using 1D klystron computer code AJDISK:

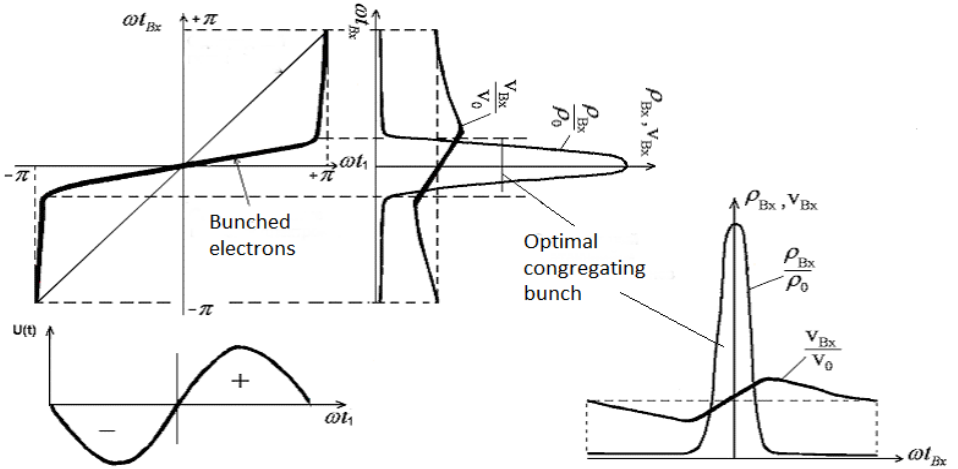


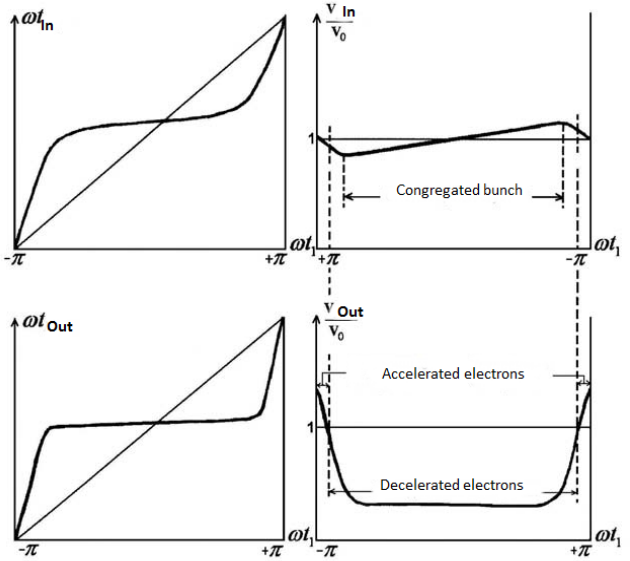
Perveance $K = I/V^{3/2}$ indicates how much beam current comes out of the cathode when the voltage V is applied between the cathode and the anode.

Perveance can be considered as well as a measure of space charge forces. Lower perveance beam with weaker space-charge forces enables stronger bunching and thus consequently higher efficiency.

Congregated bunch







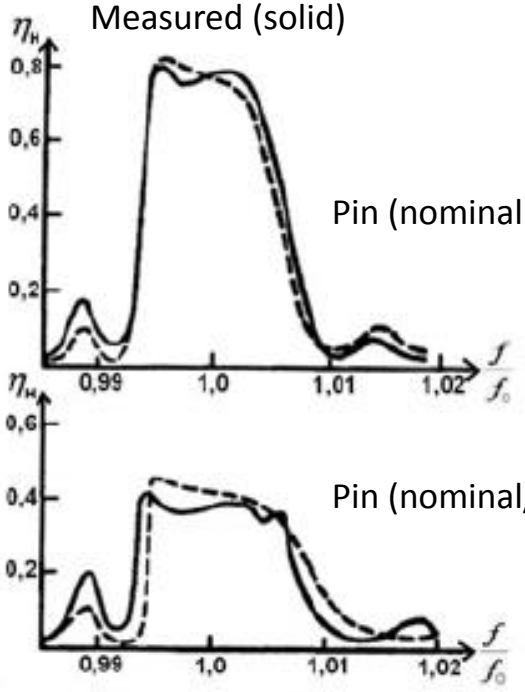
For the optimal bunch, the input velocity distribution along the RF phase must be “congregating” – when each consequent electron entering the cavity has higher velocity than preceding one.

If then, at the cavity exit all the electrons have equal velocities – the ultimately high efficiency can be obtained.

For the given beam power and output cavity impedance this solution is unique.

The first (and only?) ~80% efficient 7-beam MBK built in 1974-6 by S. Lebedinskiy, USSR.

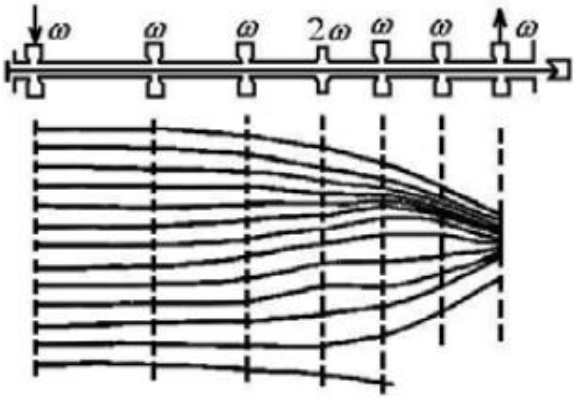
Simulations (dash)
Measured (solid)

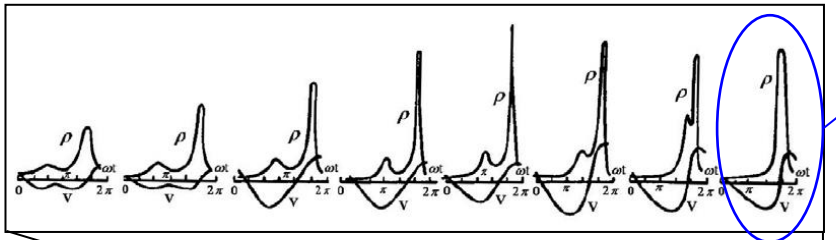


Pin (nominal)

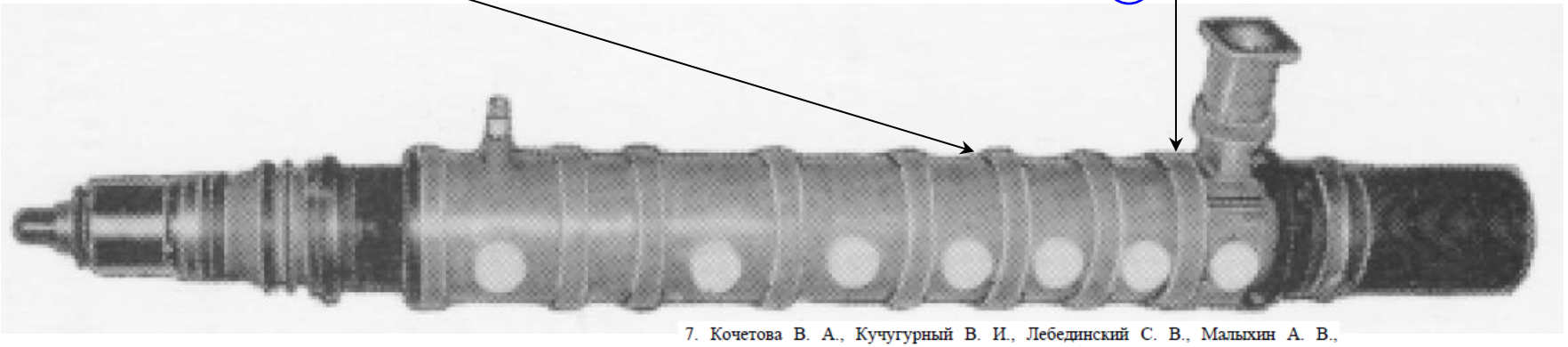
Pin (nominal/2)

Frequency: 0.71 GHz
N beams: 7
I total: 2.5 A
V beam: 14 kV
P out: 27.5 kW
Efficiency: 78.6%



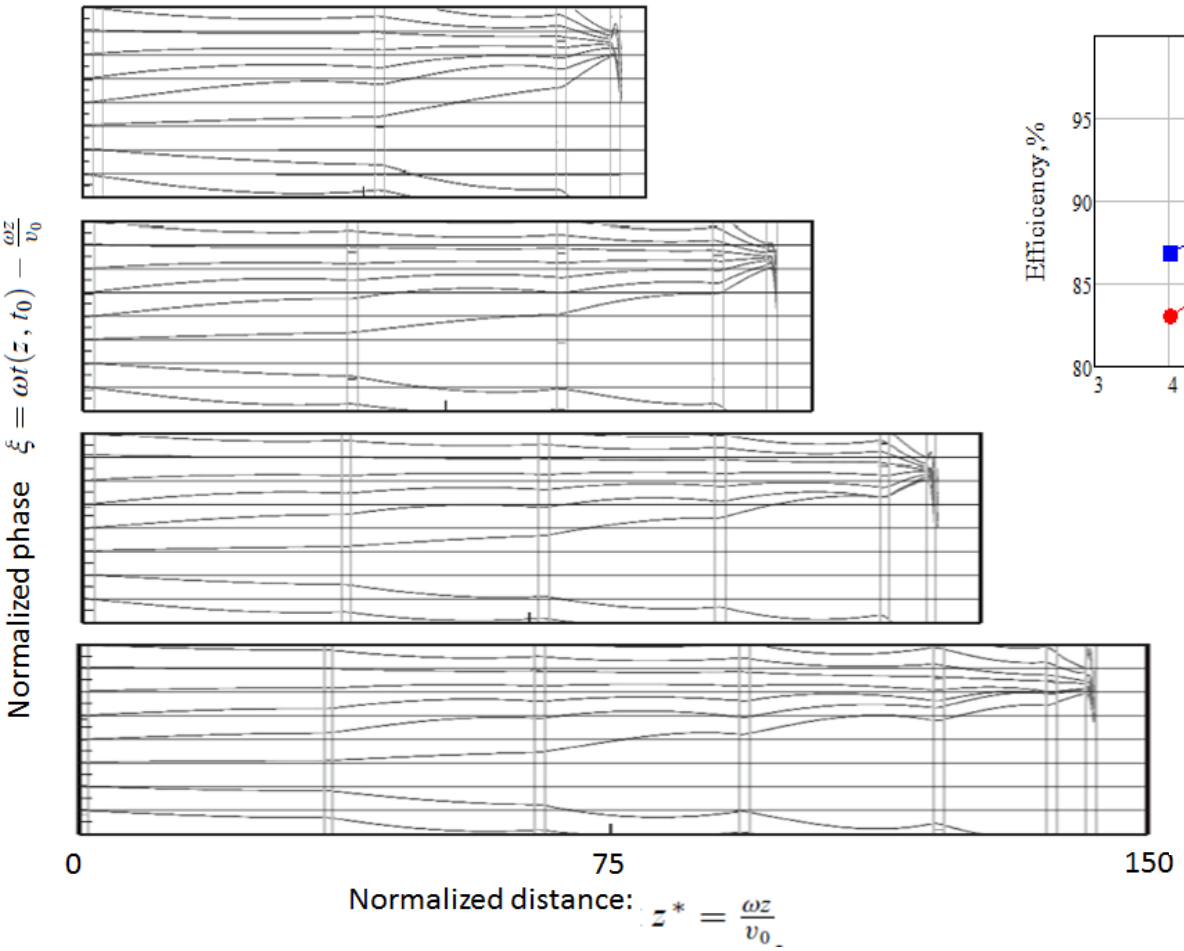


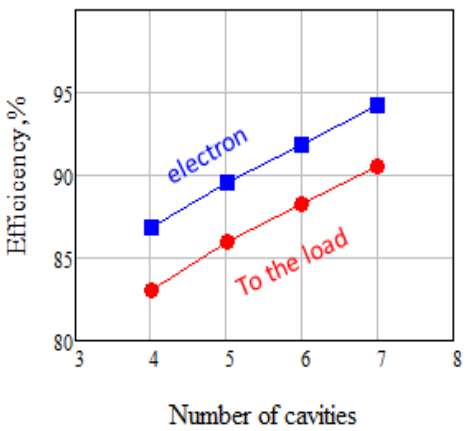
Congregated bunch

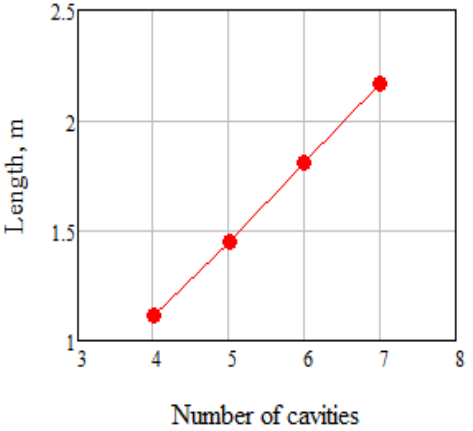


7. Кочетова В. А., Кучугурный В. И., Лебединский С. В., Малыхин А. В., Петров Д. М. Радиотехника и электроника – Москва: 1981, том.26, № 1, с.132-145).

90% efficient klystron.







Simulation of Conditions for the Maximal Efficiency of Decimeter-Wave Klystrons

A. Yu. Baikov[a, b]*, **, O. A. Grushina[a], and M. N. Strikhanov[a]

[a] National Research Nuclear University (MEPhI), Kashirskoe sh. 31, Moscow, 115409 Russia
[b] Moscow University of Finance and Law, Bol'shaya Cheremushkinskaya ul. 17-A, Moscow, 117447 Russia
e-mail: obkv@mail.ru
*e-mail: baikov@mfua.ru
** e-mail: a_yu_baikov@mail.ru

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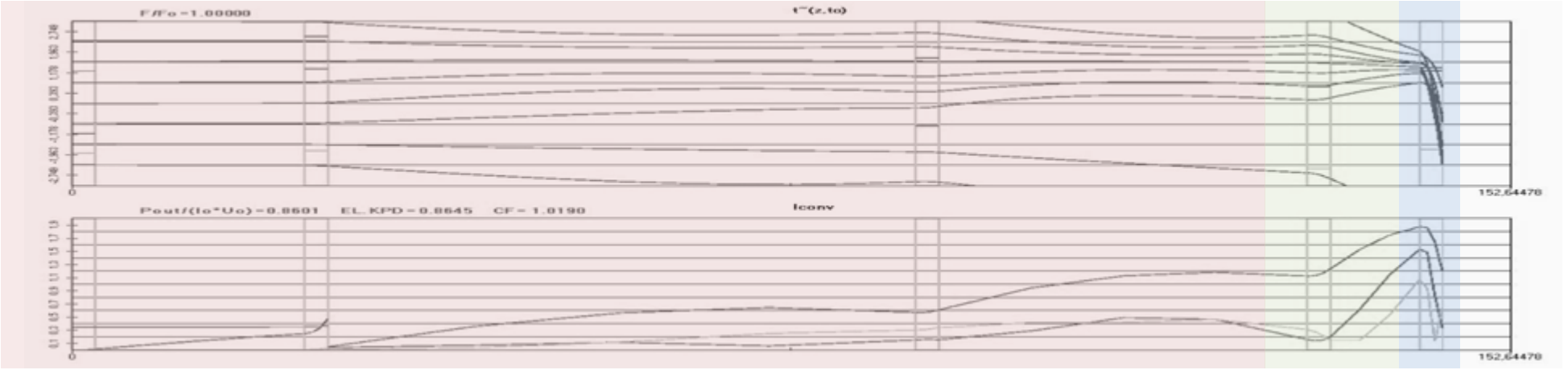
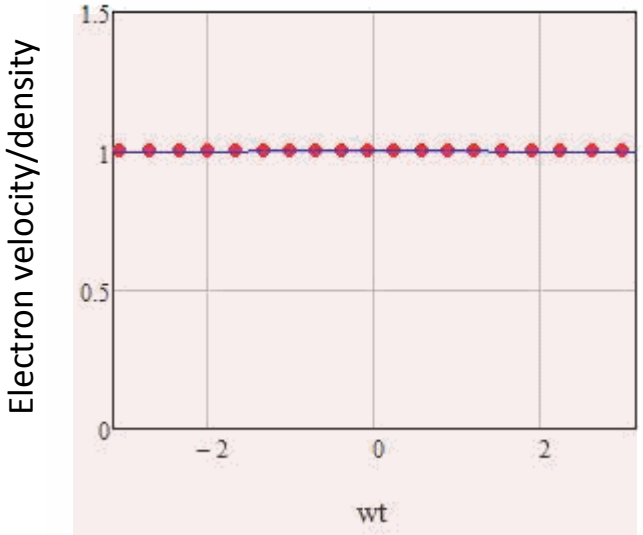
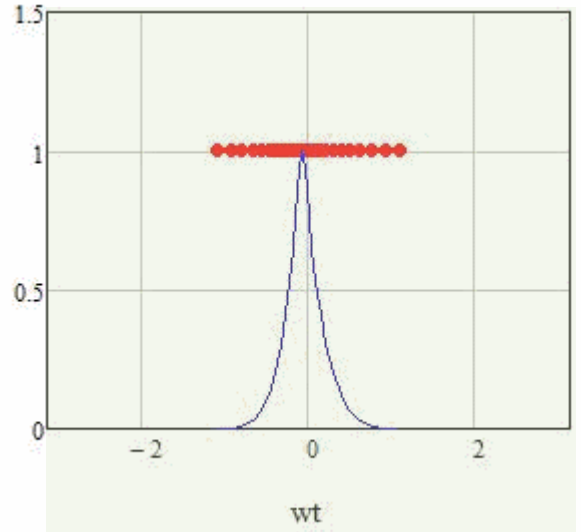
To achieve very high efficiency, peripheral electrons should receive much stronger relative phase shift than the core electrons and this could happens only, if the core of the bunch experiences oscillations due to the space charge forces, whilst the peripherals approach the bunch centre monotonously.

Personal recollection of the process in the high efficiency klystron (for illustration only)

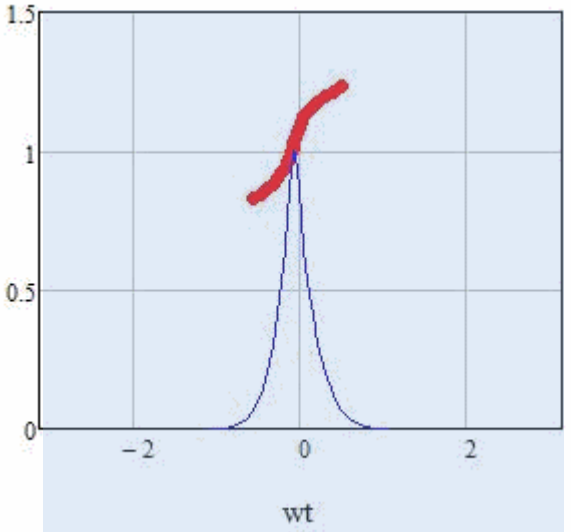




The 'ideal' bunching (the core oscillations are switched off to simplify illustration).



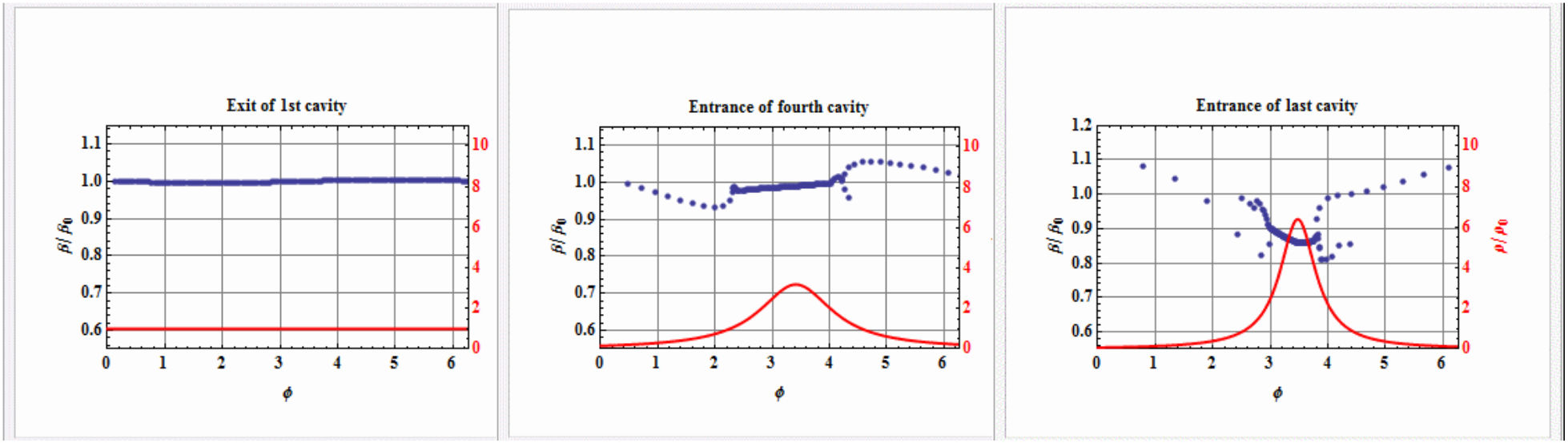
Final compression and bunch rotation prepare 'perfect' congregating bunch.



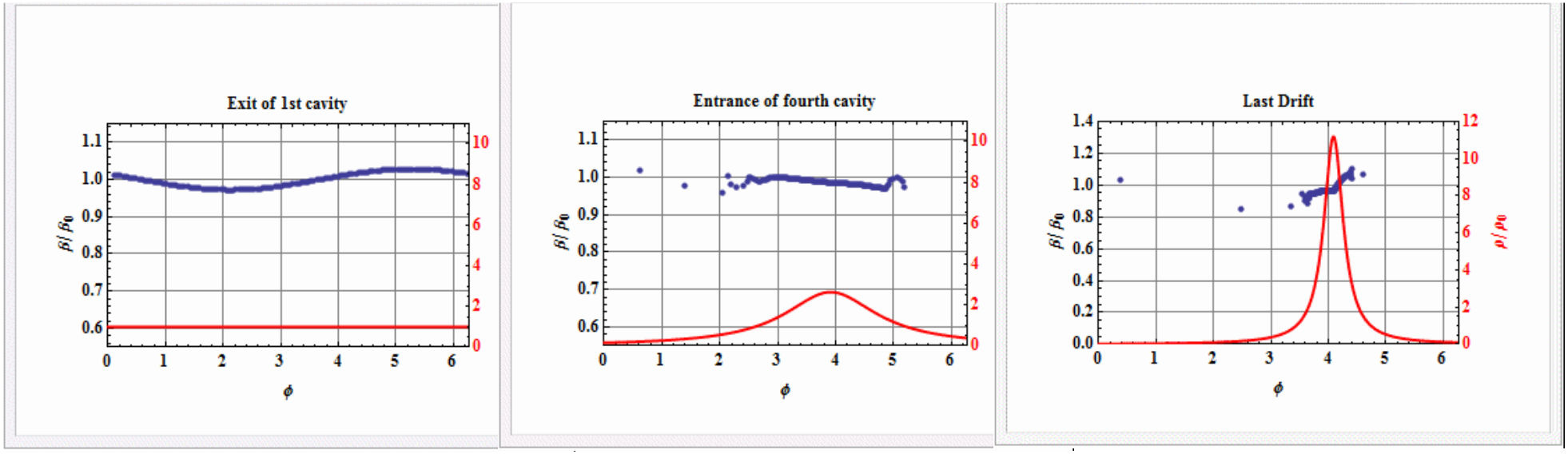
After deceleration all the electrons have identical velocities.

Mission accomplished

20 MW, 8 beams 5 cavities MBK originally simulated by Chiara Marrelli

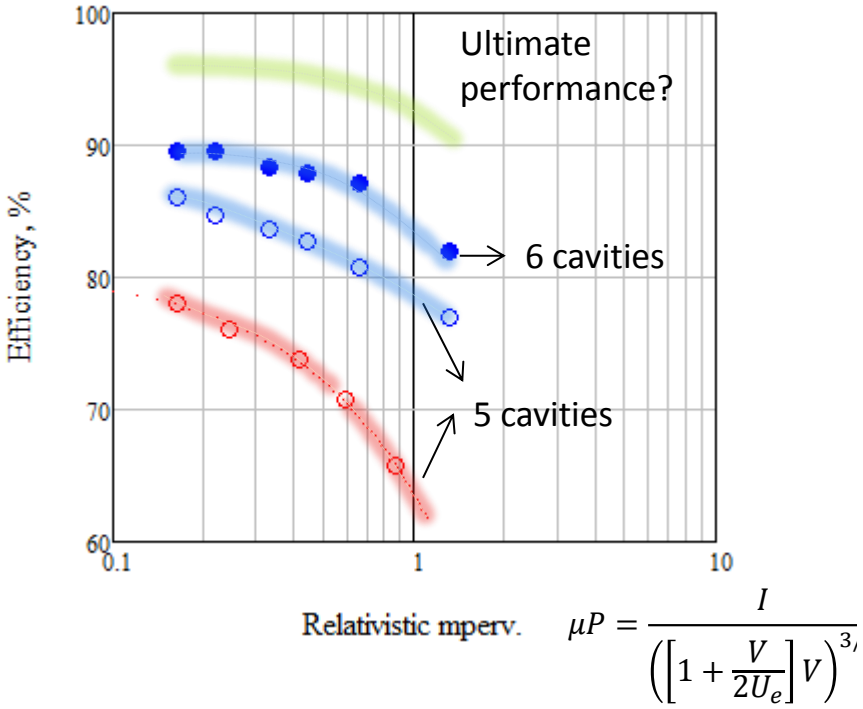


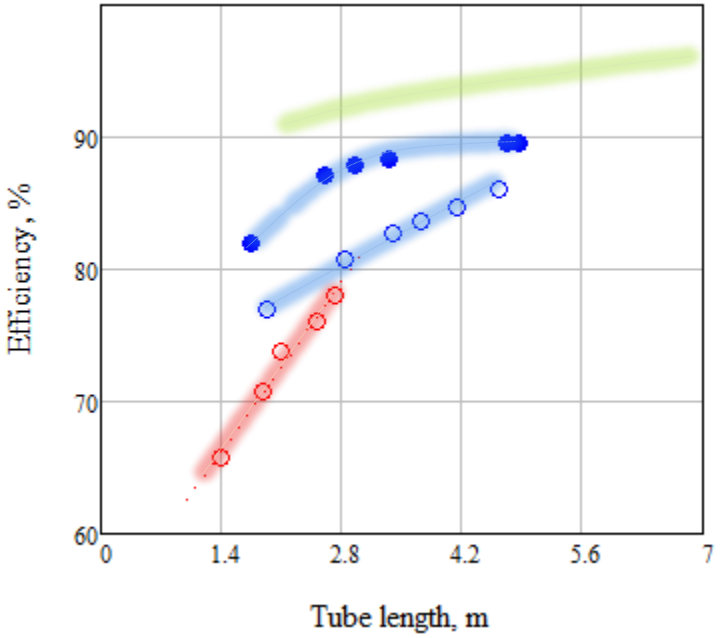
20 MW, 8 beams 5 cavities MBK with 'core oscillations' simulated by Andrey Baikov



The klystron performance curves

Red colour: 20 MW, 8 beams MBK originally simulated by Chiara Marrelli. The perveance was changed by changing both the current and voltage (fixed number of beams).
Blue colour: 20 MW, 180 kV MBK simulated by Andrey Baikov ('global' optimum with core oscillations). The perveance was change by changing the number of beams (fixed voltage).

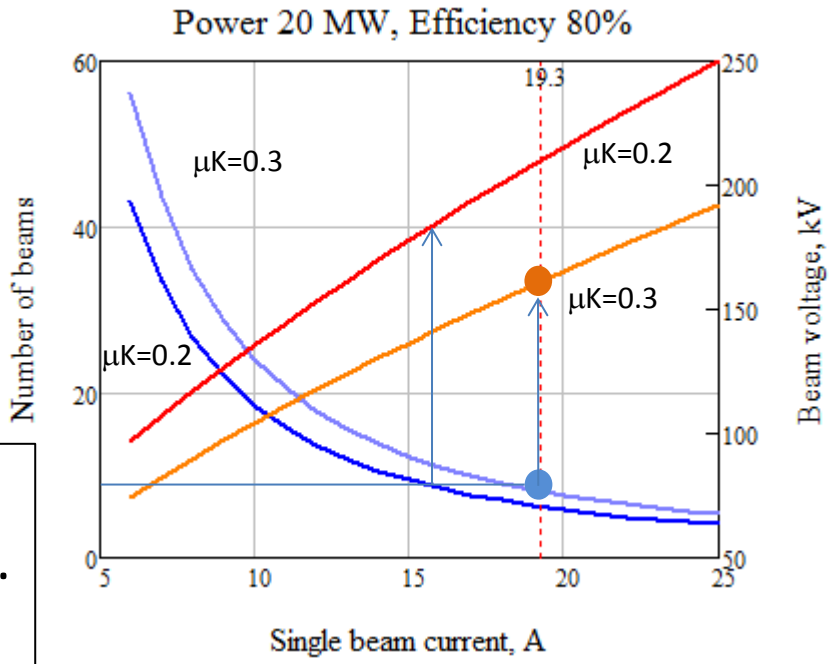




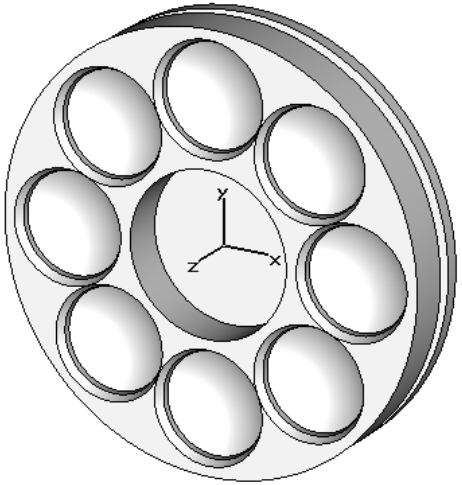
When going towards bigger number of the cavities (from 5 to 6 on our case), the klystron efficiency shows some saturation features. Technically, it allows to choose reasonably high perveance as an operating point without considerable reduction in efficiency. However the 1D code simulations results for the tubes with high perveance are less confident (overestimated).

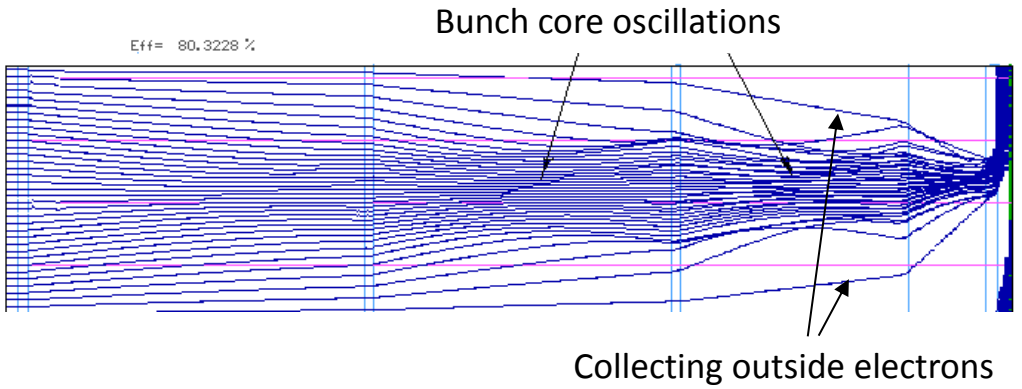
Recipe#1 for 20 MW. 80% efficient L-band MBK for CLIC

1. Stay at a low micro-perveance.
2. Choose as many beams as you comfortable with:
   - Reduces the operating voltage (tube length)
   - Reduces the beam compression (beam dynamics)
   - Reduces current/beam, weaker magnetic focusing
3. Use all the tricks explained previously



Example of the CLIC MBK designed using ‘conventional’ MBK gun technology (8 beams). Simulated by I. Guzilov





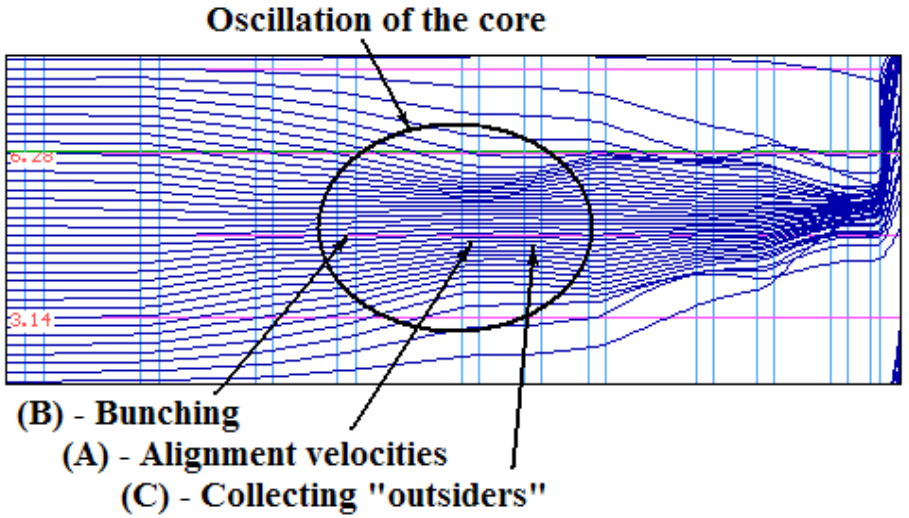
Tube length 3.0 m; 162kV; 80.3%

BAC method. I. Guzilov

In order to intensify the process of the core oscillations, one can use the external forces delivered by additional specially tuned idle cavities– this is the base of BAC method

Each oscillation in BAC method is prepared in 3 stages:

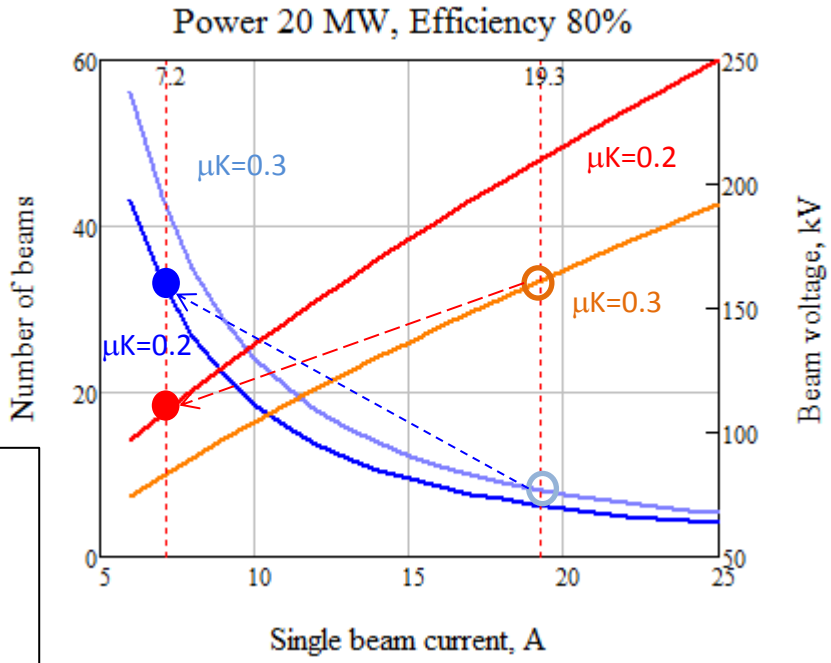
- first cavity gap – traditional bunching;
- second cavity gap - alignment velocity spread of electrons;
- third cavity gap – collecting the peripherals.



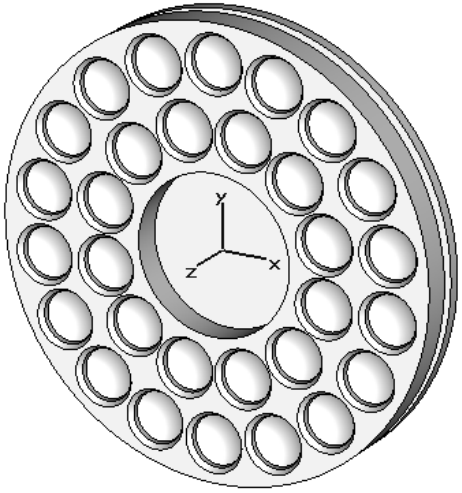
This method of spatial enhancing of the core oscillations frequency allows reducing at least by factor of 2 the length of the interaction space for high efficiency klystrons.

Recipe#2 for 20 MW. 80% efficient L-band MBK for CLIC

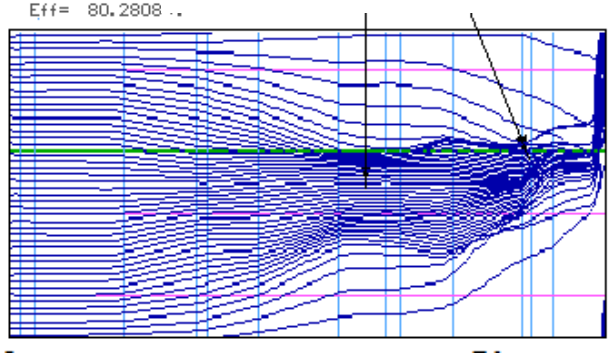
1. Stay at a low micro-perveance.
2. Choose as many beams as you comfortable with:
   - Reduces the operating voltage (tube length)
   - Reduces the beam compression (beam dynamics)
   - Reduces current/beam, weaker magnetic focusing
3. Use all the tricks explained previously
4. Employ BAC method to reduce the tube length.



Example of the CLIC MBK designed using advanced MBK gun technology (30 beams). Simulated by I. Guzilov



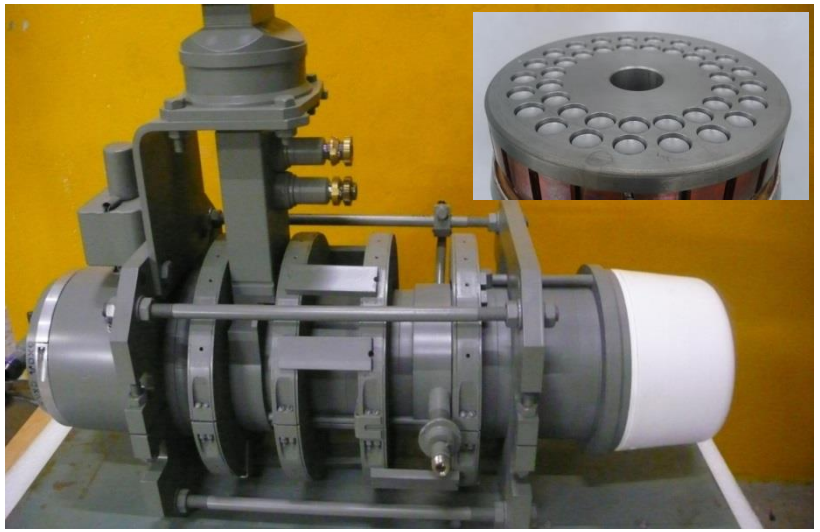
Bunch core oscillations



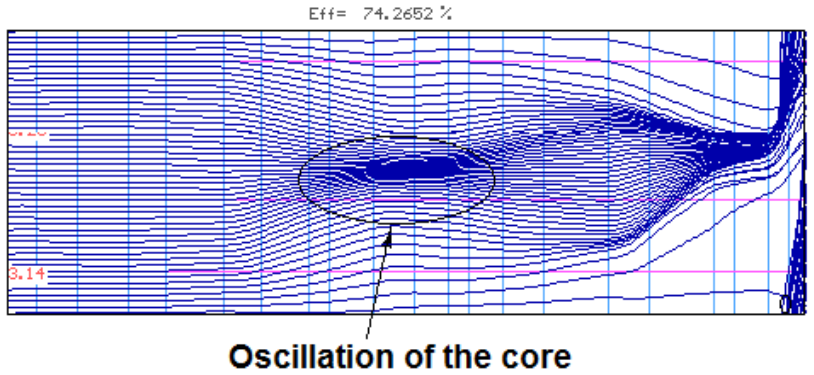
Tube length reduced to 1.2 m (2.5 times); 116 kV; 80.3%

Technology demonstrator tube.
To be built in 1 year (Low risk approach)

KIU-147. 40 beams, S-band, 6 MW, 52 kV, 50% with PPM reversed focusing

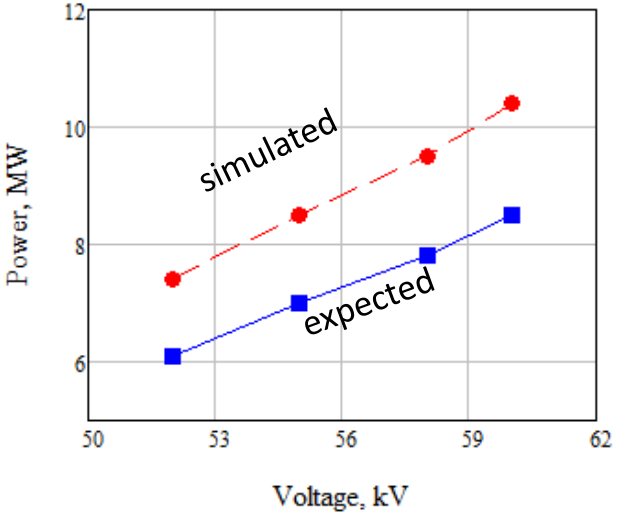


1. Keep the gun, focusing system and collector
2. Replace the klystron body (the same length). Expected efficiency 74.2% :

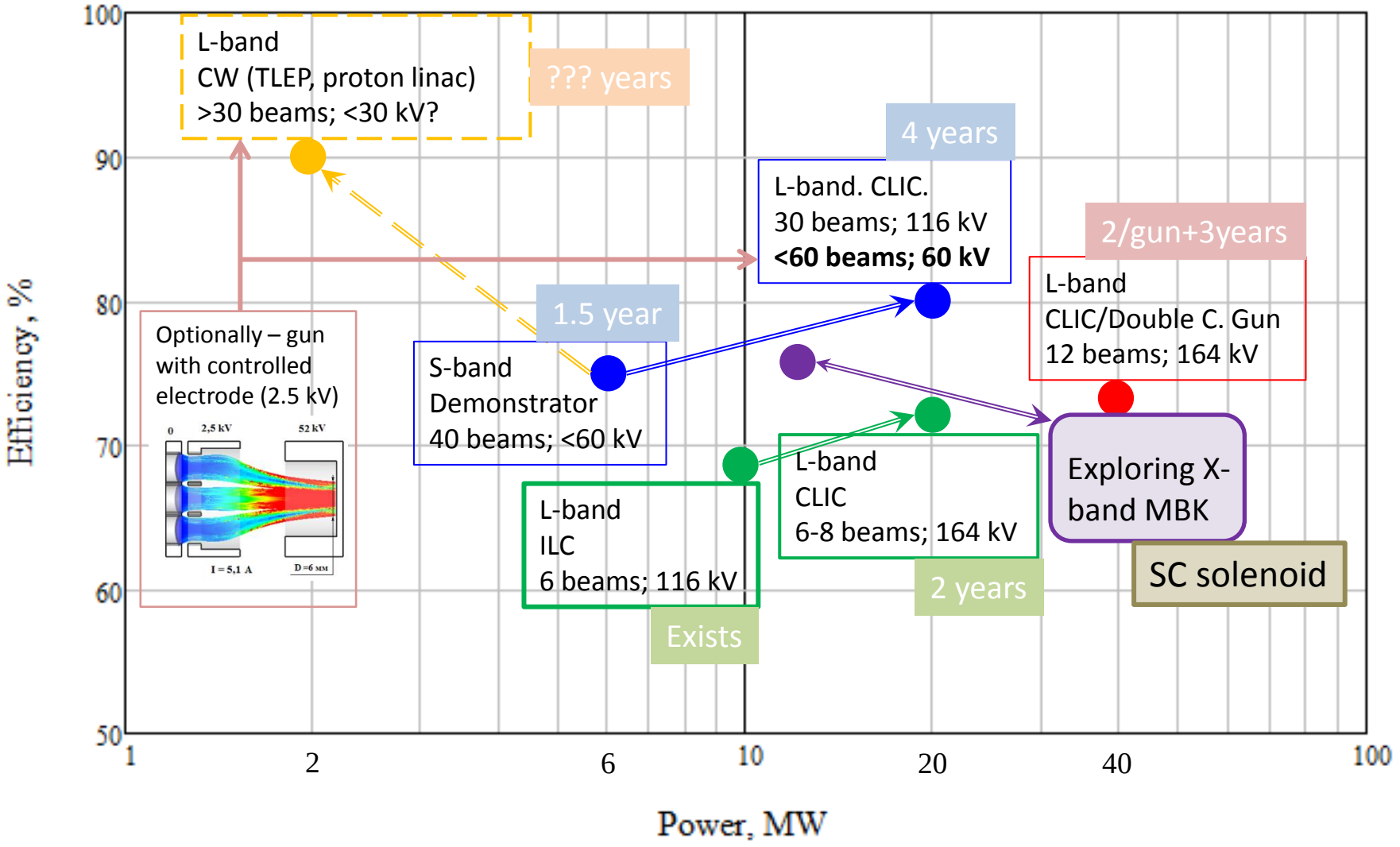


The PPM reversed focusing drawback:
At each reverse of magnetic field there are ~5-7% of beam losses. With two periods, the expected efficiency will be dropped down to ~60 % . At a positive side – klystron will be very light , only 90 kg (0.8 m long).

Considering that 60 kV is safe limit for operation at air (discharge along the gun insulator), klystron will be able to deliver up to 8 MW peak RF power. With 40 kW average power, it will be able to operate at 1 kHz and 5 microsecond long pulses.



Strategy for high-efficiency high RF power klystron development



Special thanks to:

Igor Guzilov
Andrey Baikov
Chiara Marrelli