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Active pulse compression results

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OUTLINE OF TALK

1. **Introduction**

   In active compressor the microwave energy is accumulated during long time in high-Q cavity and fast extracted due to Q-modulation by active element

2. **Novel resonance switch**

   2.1 An idea of active switching by electron beam

   2.2 Design of the switch and the principal of its operation

   2.3 X-band two-channel compressor with resonance switches

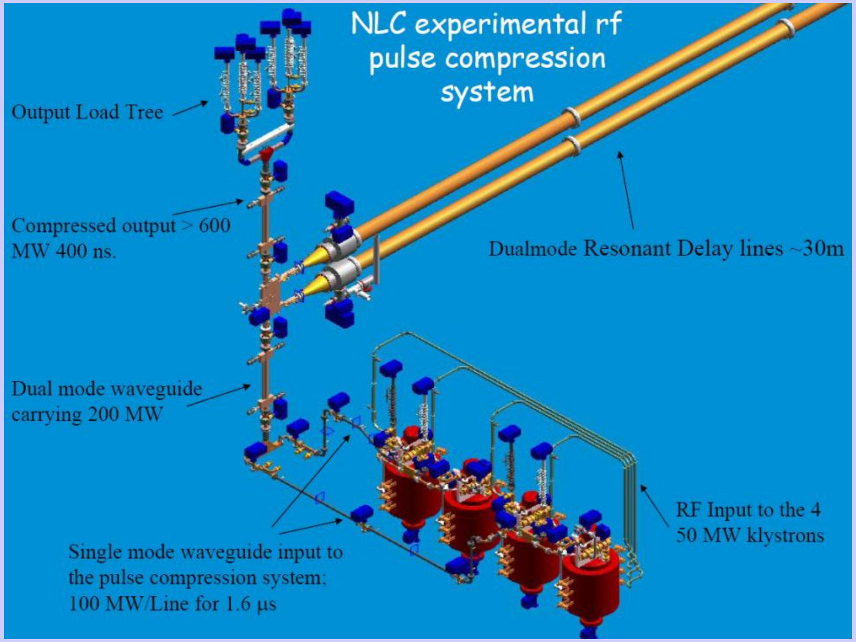
   2.4 Results of high-power tests

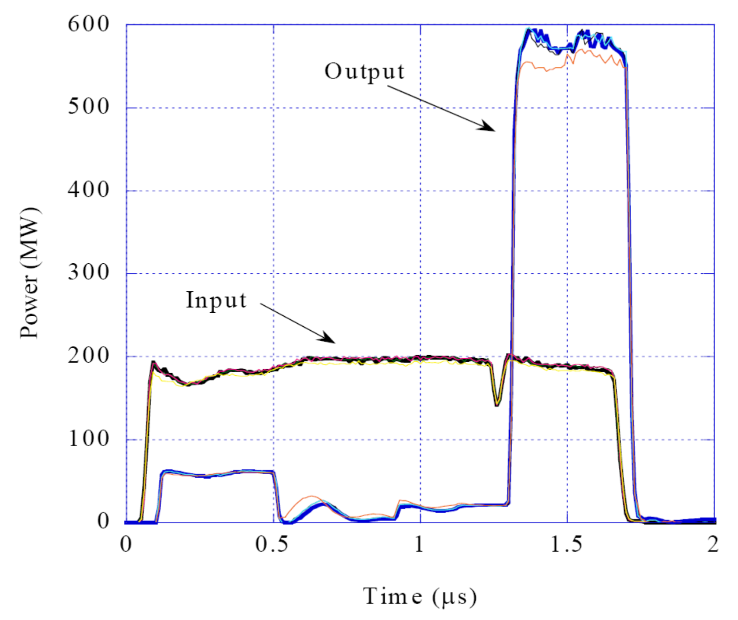
3. **Expected parameters of resonant delay lines with e-beam triggered switches**
4. **Conclusion**

Passive compressors

Time compression of RF pulses is a promising direction for development of a source of high-power nanosecond microwaves. The widely studied compressors are based on storage of microwave energy in high-Q cavity and subsequent quick extraction of the energy to a load. Microwave compressors are divided into passive and active. Passive compressors contain no elements with time-dependent electrodynamics parameters; but do require rapid phase modulation within the incident pulse.

The best up to date result obtained by passive compression (SLED II at SLAC)



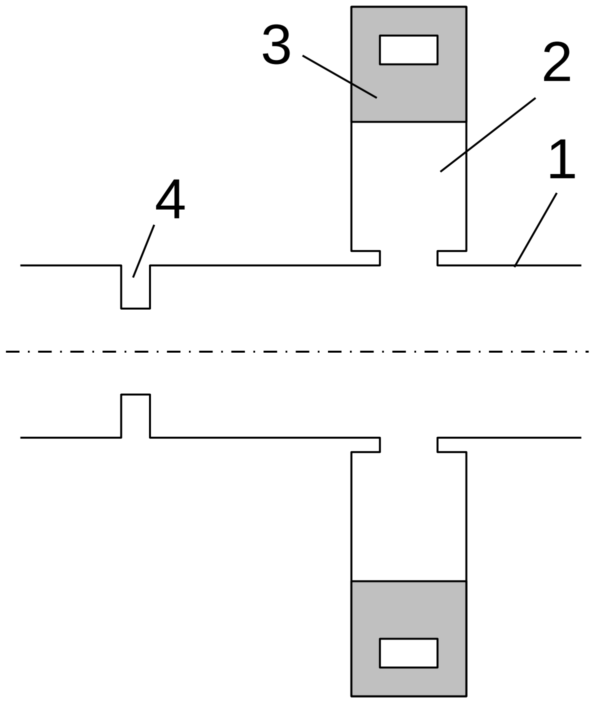


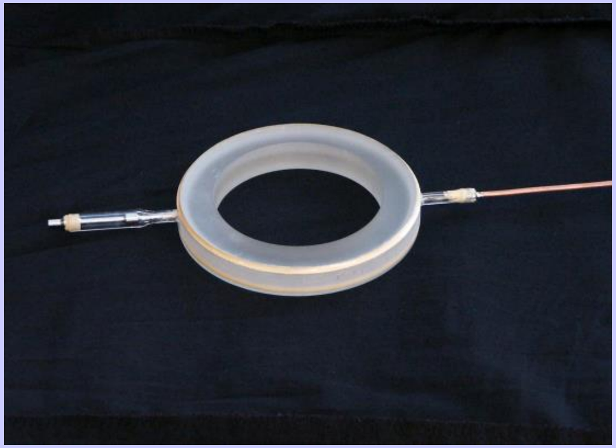
Frequency 11.424 GHz
Pinput = 190 MW (4 klystrons)
Poutput = 580 MW
Power gain ~ 3
Pulse duration 400 ns

S.G. Tantawi, et.al., // Phys. Rev. ST Accel. Beams 8, 042002 (2005)

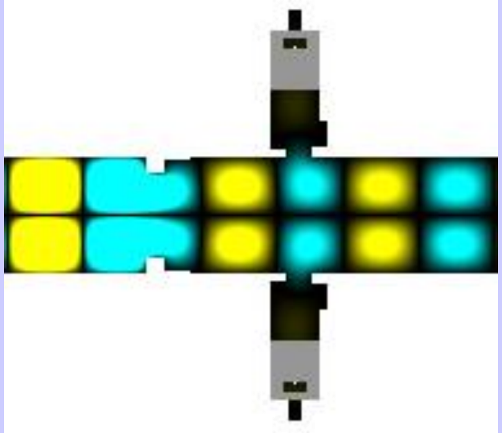
F. Wang, et.al., // Phys. Rev. ST Accel. Beams 14, 010401 (2011)

Plasma switch for active SLED II pulse compressor



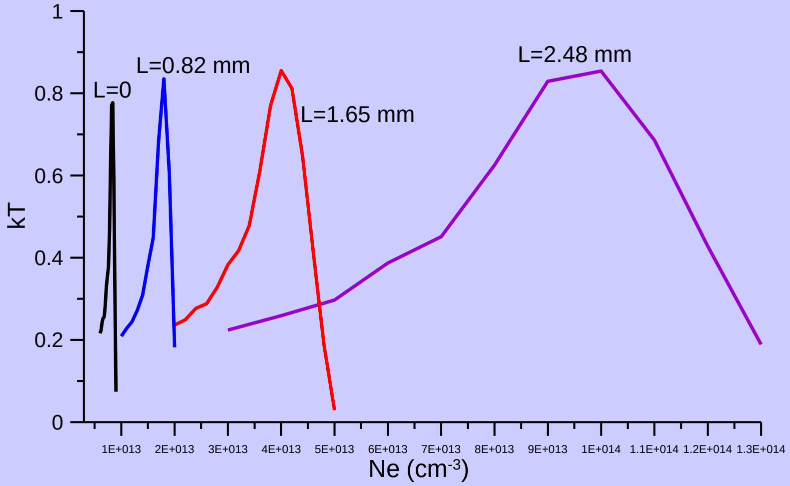


Design of gas-discharge tube



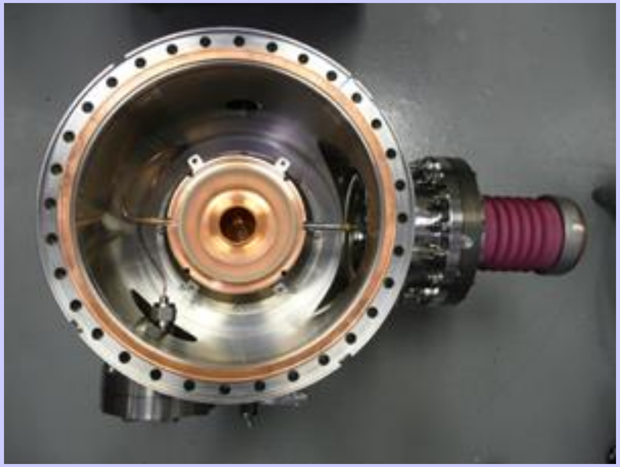
energy storage

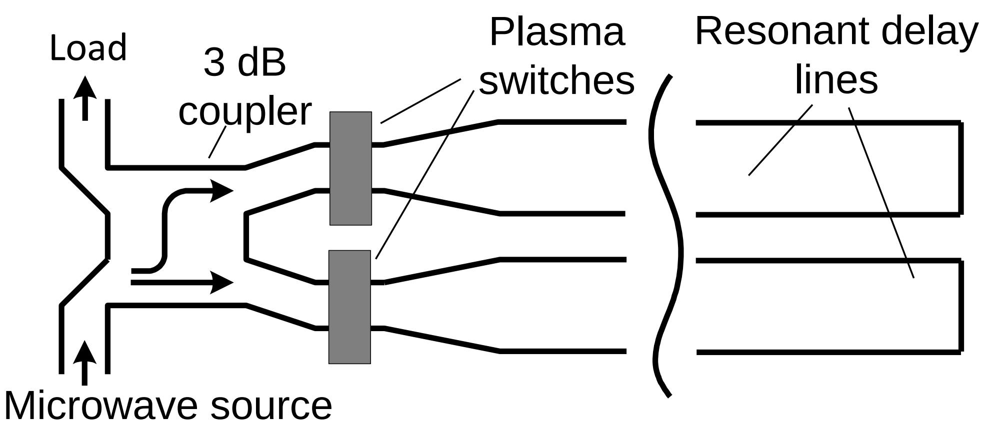
1 – waveguide 38 mm in diameter, 2 - stepped widening, 3 – ring-shaped quartz discharge tube, 4 – diaphragm.

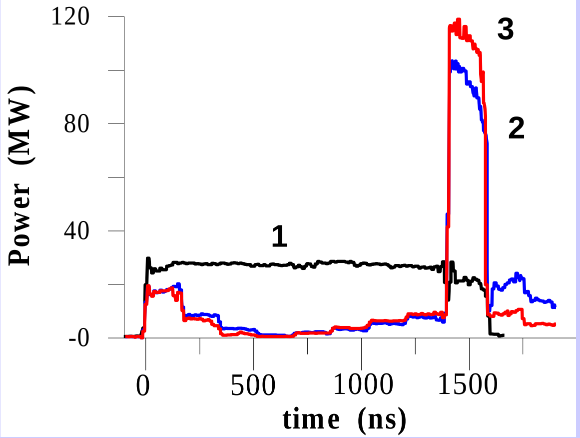


Instantaneous electric field distribution in the plasma switch and dependence of the transition coefficient on electron density at different position of adjusting short.

General view of an active SLED-II compressor with plasma switch







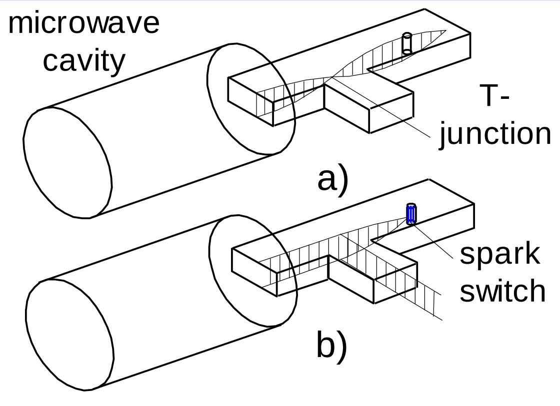
Frequency 11.424 GHz Pinput = 25.2 MW Poutput = 112 MW Power gain ~ 4.3 Pulse duration 173 ns

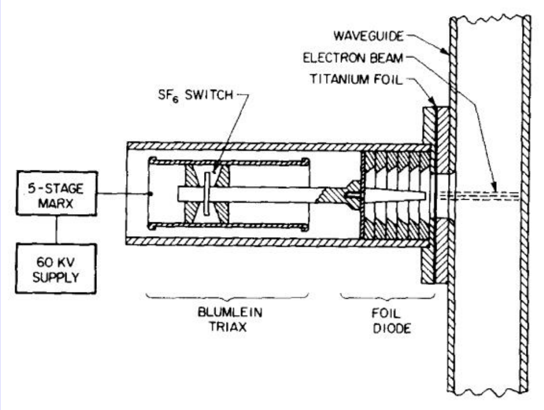
A.L. Vikharev, O.A. Ivanov, A.M. Gorbachev, M.A. Lobaev, V.A. Isaev, S.G. Tantawi, J.R. Lewandowski, J.L. Hirshfield // Phys. Rev. ST Accel. Beams 14, 121302 (2011)

Active compressors

Active compression is based on the storage of energy in a high-Q cavity, followed by a rapid increase of the coupling between the cavity and the load (Q-switching) using the active element, e.g. a fast switch.

The widely used switch based on T-junction of standard single mode waveguide with a gas discharge gap in one elbows





Parameters of electron beam

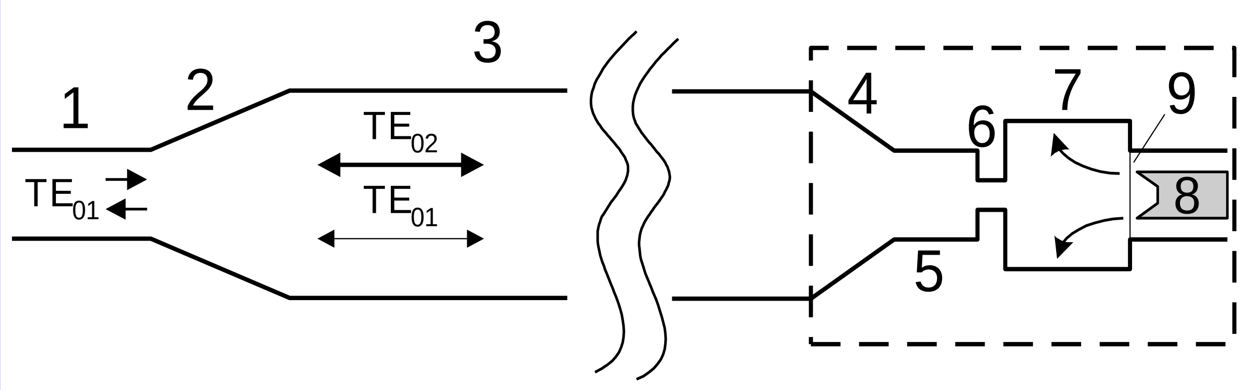
Voltage $U = 300$ kV

Beam current $I = 8$ kA

Pulse duration $\tau = 5$ ns

D.L. Birx, D.J. Scalapino, // J. Appl. Phys., 51(7), (1980)

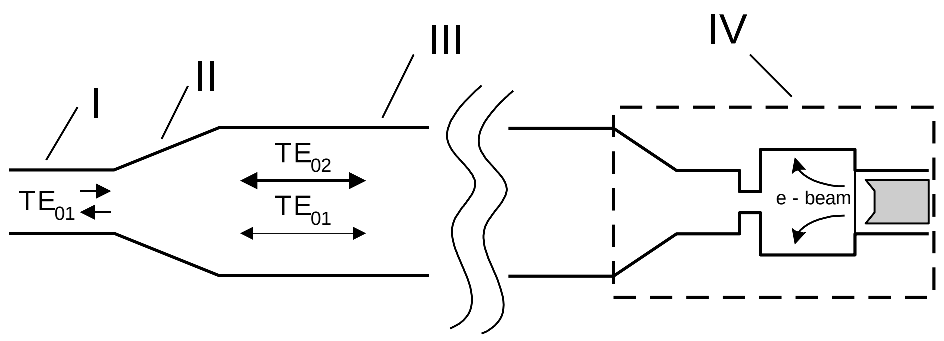
Resonance switch employing electron beam triggering



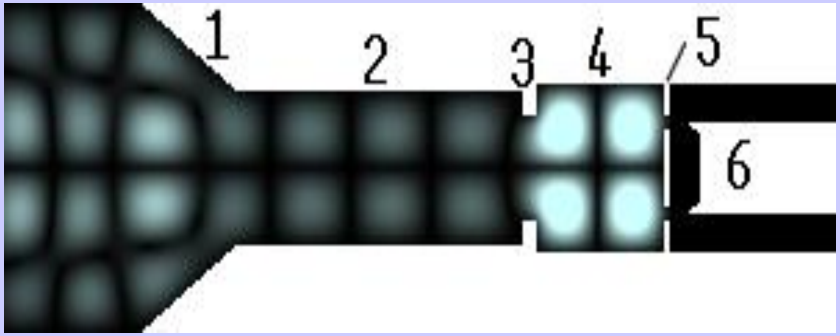
1- input TE01 mode waveguide; 2- input taper; 3- cylindrical waveguide cavity; 4- conical taper; 5- waveguide section; 6- diaphragm; 7- TE012-mode switch cavity; 8- cathode; 9- anode plate.

Resonance switch employing electron beam triggering

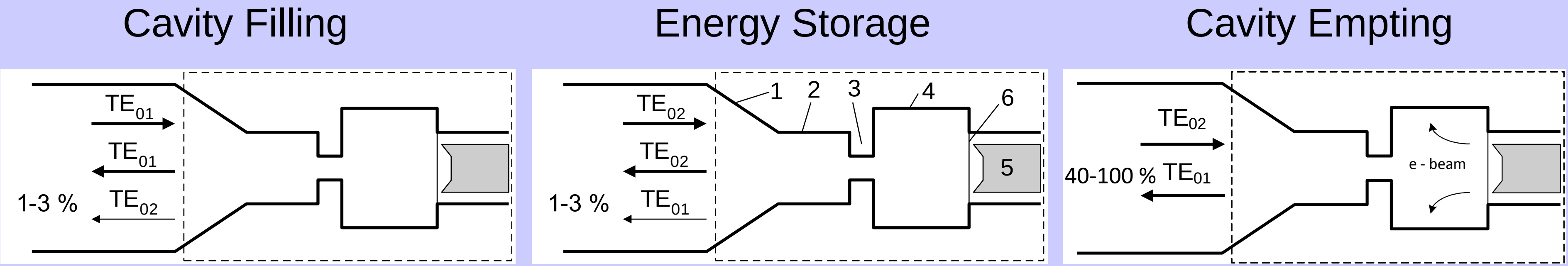
The operating principle of the switch is based on a sharp increase in the $TE_{02} \leftrightarrow TE_{01}$ coupling coefficient, when an electron beam is injected into the switch resonator.



Schematic diagram of a pulse compressor with the switch employing an electron beam, illustrating switch operation in the energy storage regime I – input TE_{01} mode waveguide, II input horn, III–cylindrical waveguide cavity, IV – electron beam switch



Instantaneous distribution of the amplitude of the electric field in the switch in regime of energy storage : 1 –taper, 2 - cylindrical waveguide, 3 – diaphragm, 4 – switch resonator, 5 – anode with slit, 6 – cathode.


Cavity Filling

Energy Storage

Cavity Empting

1 – taper, 2 – circular waveguide, 3 – iris, 4 – switch cavity, 5 – cathode, 6 – anode (special diaphragm)

O.A. Ivanov, V.A. Isaev, M.A. Lobaev, A.L. Vikharev, J.L. Hirshfield // Phys. Rev. ST Accel. Beams 14, 061301 (2011)

Principle of operation of e-beam switch

The reflection coefficient at frequency ω from a cavity tuned to ω_0 is

$$R = 1 - \frac{2\beta}{(1+\beta)\left(1 + 2 \cdot i \cdot Q_L \frac{\omega - \omega_0}{\omega_0}\right)}$$

where $\beta = Q_0/Q_e$, Q_0 is the intrinsic Q-factor of the cavity, Q_e is the coupling Q-factor, and $Q_L = Q_0 Q_e/(Q_0 + Q_e)$ is the loaded Q-factor.

For $\beta >> 1$, and $\omega = \omega_0$, $R = -1$.

For $\beta >> 1$, and $| \omega - \omega_0 | >> \omega_0 / 2Q_L$, $R = 1$.

Therefore , if an over coupled cavity is rapidly driven out of resonance, the phase of the reflected wave will change by π while $|R|$ remains ≈ 1.

This can change the $TE_{02} \leftrightarrow TE_{01}$ coupling coefficient from ~3% to ~100%.

The transition time is $\tau_\pi \sim Q_L/\omega_0$ For $Q_L \sim 200$ and $f_0 = 11.4$ GHz, $\tau_\pi \approx 5.5$ ns

Principle of operation of e-beam switch

$$R = 1 - \frac{2\beta}{(1+\beta)\left(1 + 2iQ_L\frac{\omega-\omega_0}{\omega}\right)}$$

$$Q_0 >> Q_e$$

$$Q_L(\omega-\omega_0)/\omega_0 >> 1$$

$$\Delta\varphi \approx \pi$$

R is reflection coefficient from the resonator

Q_0 is inherent Q-factor,

Q_e is the coupling Q-factor,

Q_L is the loaded Q-factor

ω_0 is the resonance frequency of the resonator

ω is the frequency of the incident wave.

$$Q_L = Q_0 Q_e / Q_0 + Q_e$$

$$\beta = Q_0 / Q_e$$

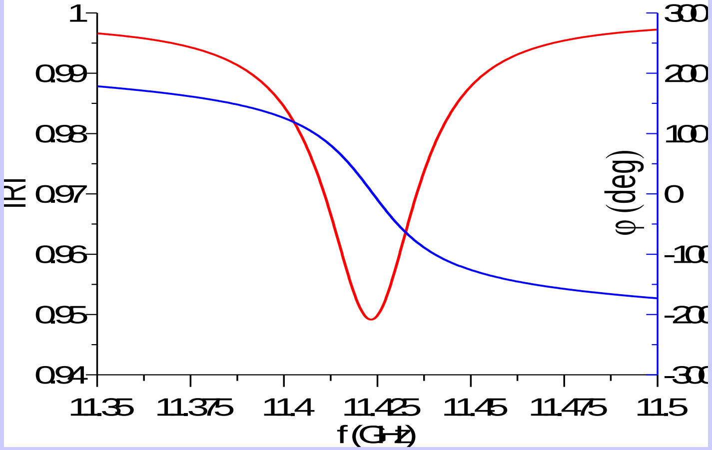
$$\tau_r = Q_0/\omega_0$$

$$Q_L = 380$$

$$\beta = 75$$

$$\tau_r = 5\,ns$$

Dependence of the phase and reflection coefficient on the frequency of the incident EM wave



Parameters of an electron beam required to change the phase of the electromagnetic wave reflected from a switch resonator

$$\frac{\Delta f}{f_0} = \frac{1}{2N_c}\,\frac{\int_{V_{pl}} N_e E_q^2\,dV}{\int_{V_r} E_q^2\,dV}$$

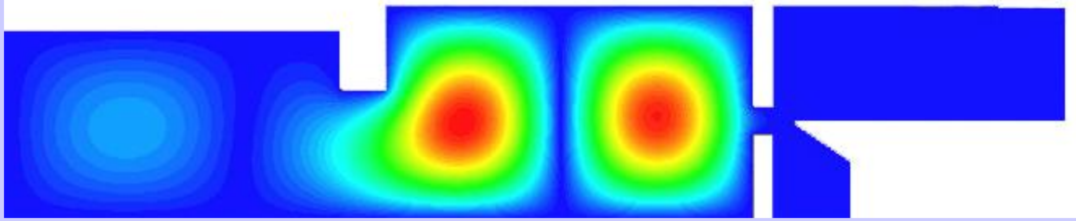
The total number of electrons, NΣ required to drive the resonator off resonance when the beam is injected can be evaluated from perturbation theory.

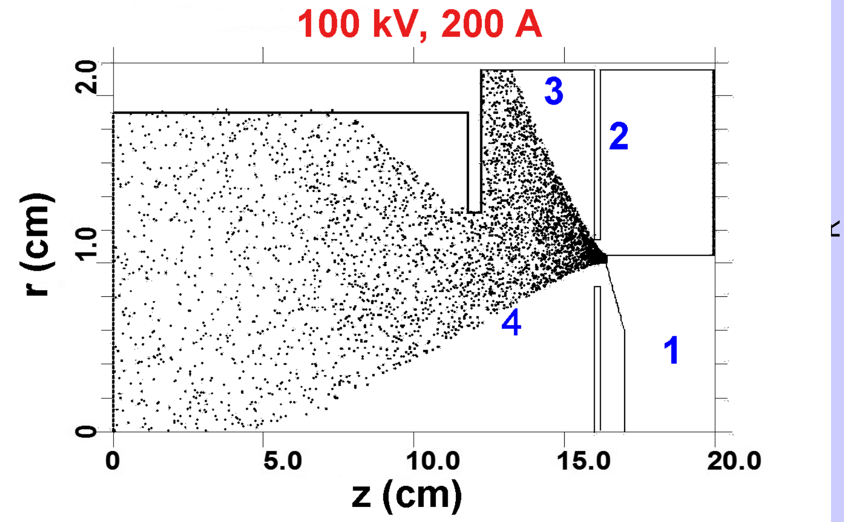
$$I = eN_c V_e / L = eN_\Sigma V_e /$$

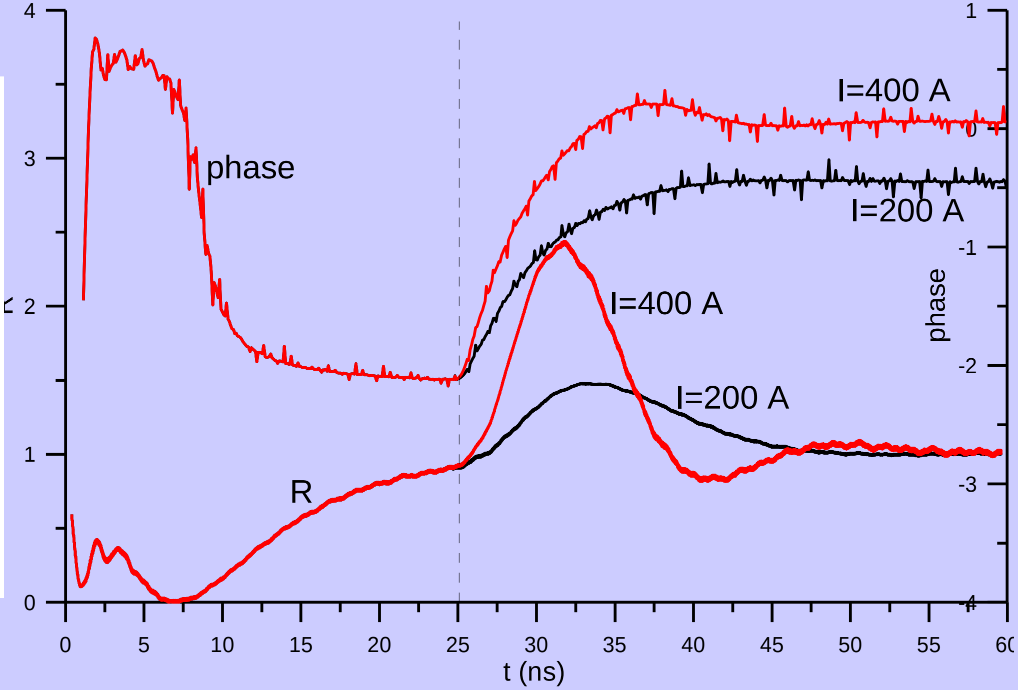
$$V_e = 5.9\cdot 10^7\sqrt{U}$$

The calculation showed that the beam current must be no lower than 200 A for $N_\Sigma \geq 10^{11}$ at *U* ~ 100 kV and *L* ~ 1 cm

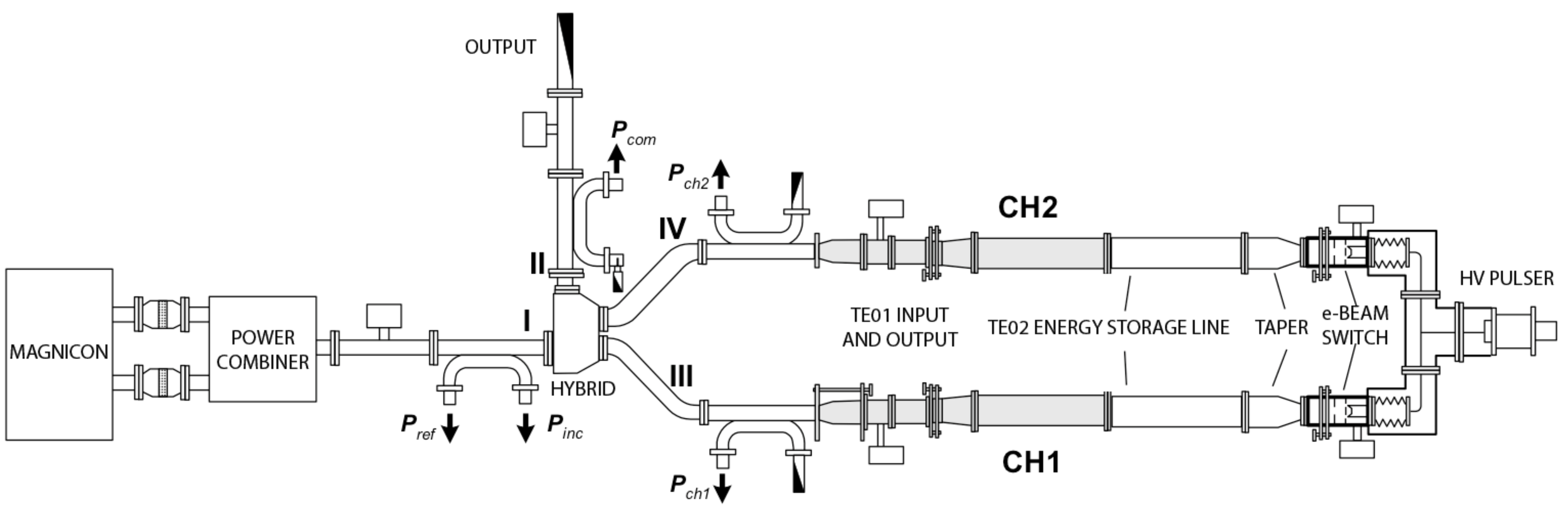
Dependence of the switch reflection amplitude and phase on the beam current





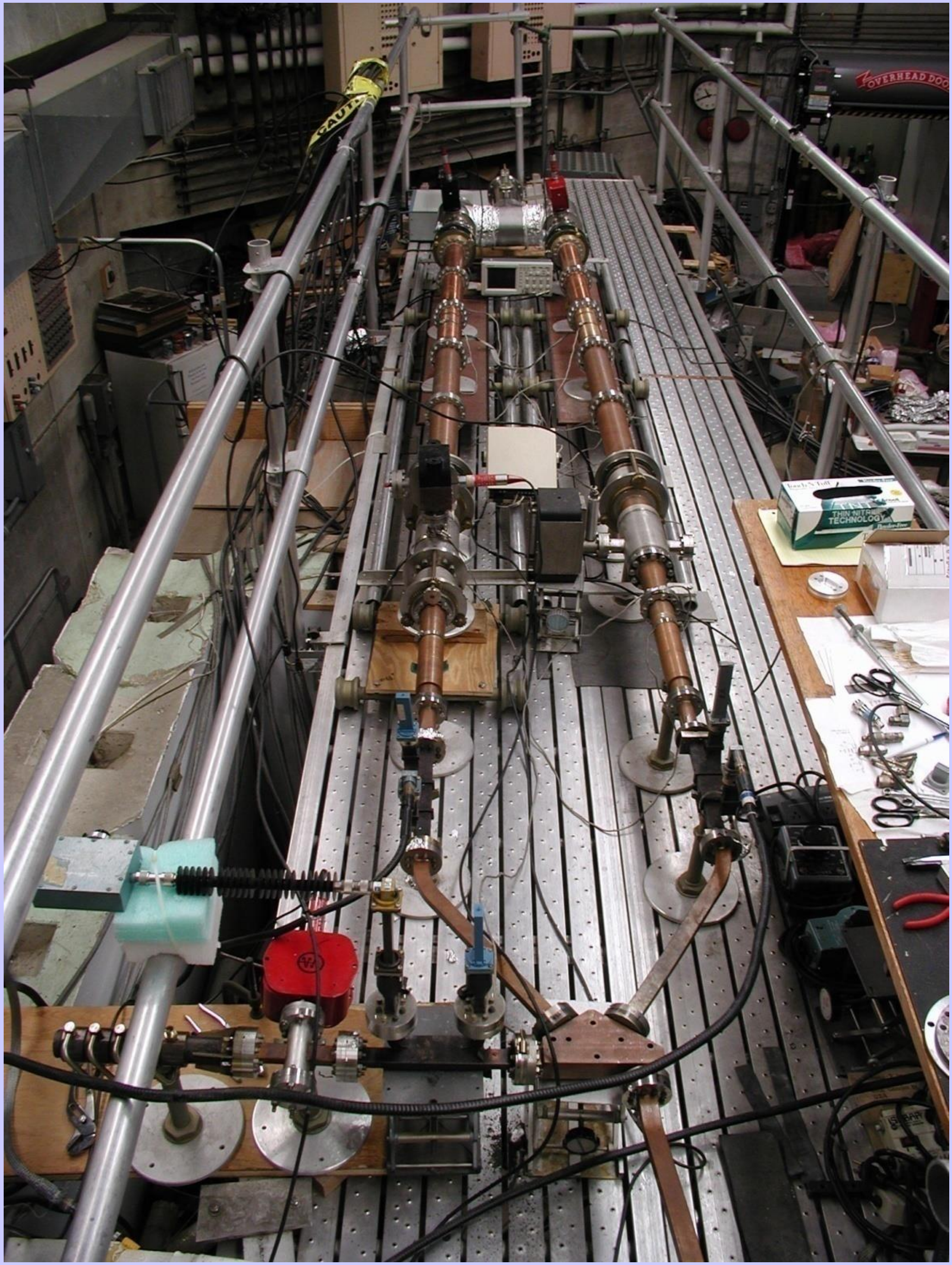


X-band two-channel compressor with resonance switches



Magnicon parameters:
Input power 7-9 MW
Pulse duration 1.2 µs
Frequency 11.424 GHz

Storage cavity L = 2 m long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OVERHEAD DOO
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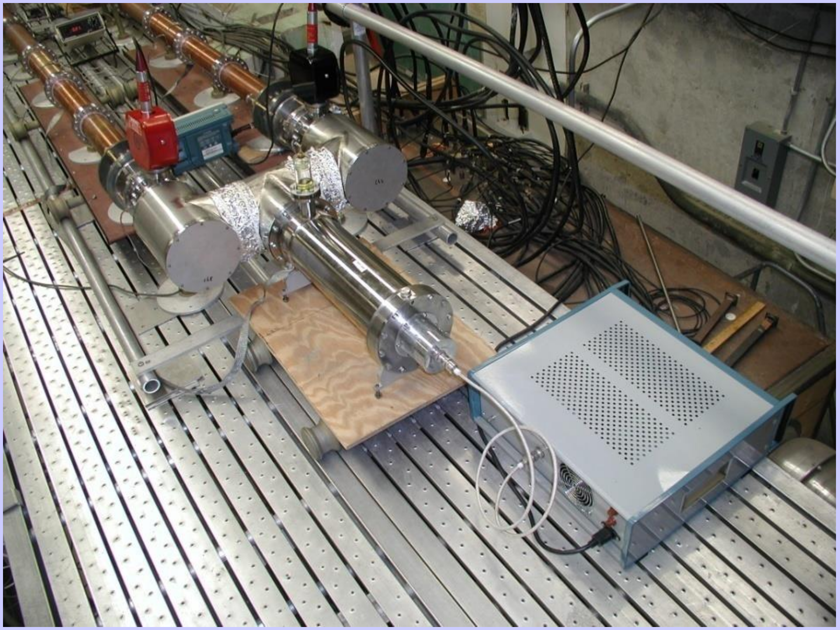
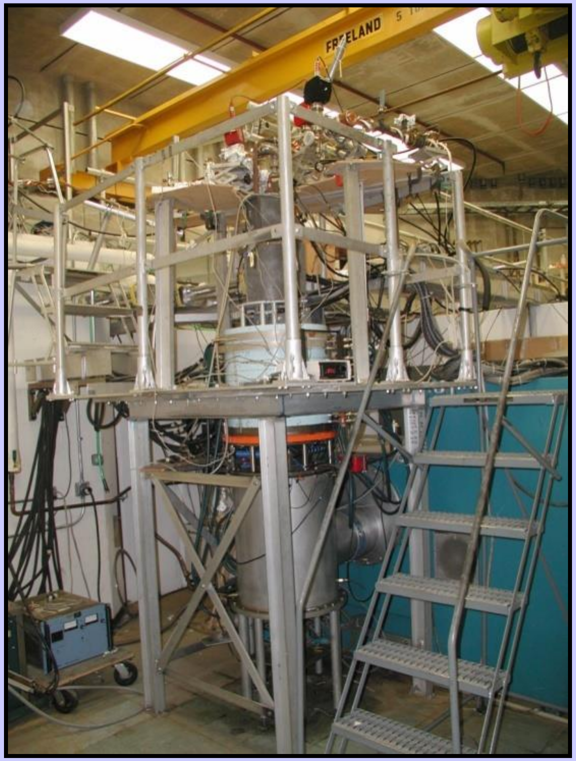
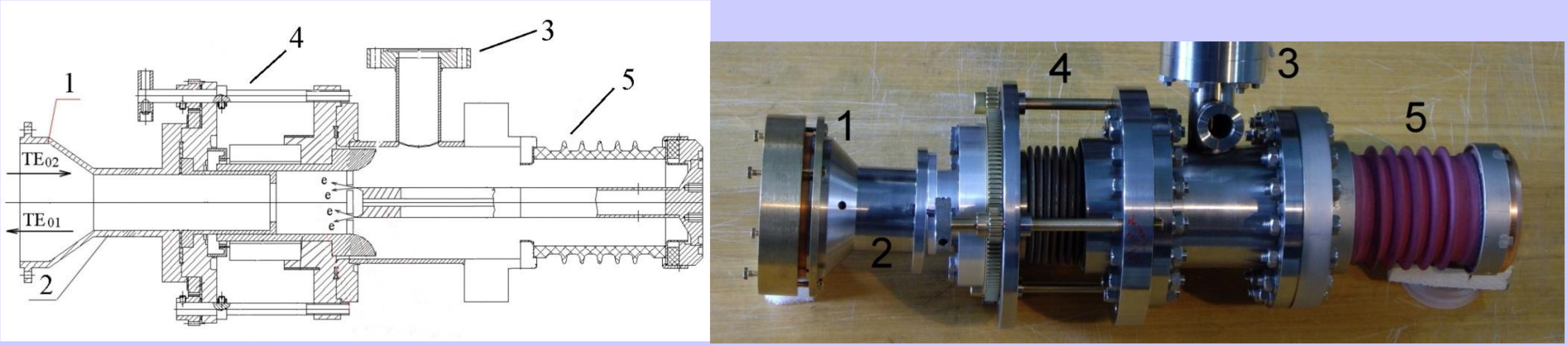



FREELAND

Scheme and general view of the switch



1 – taper, *2* - cylindrical waveguide, 3 - pumping port, 4 - external tuning mechanism, 5 - insulator

The electron beam was produced by a cylindrical cathode with sharp edges

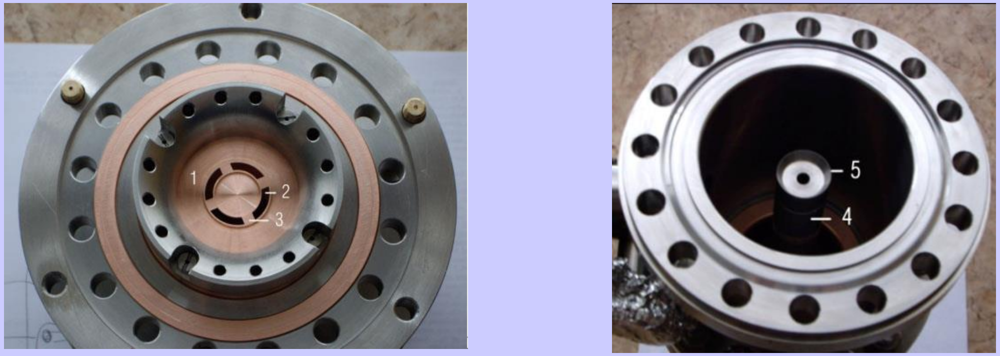
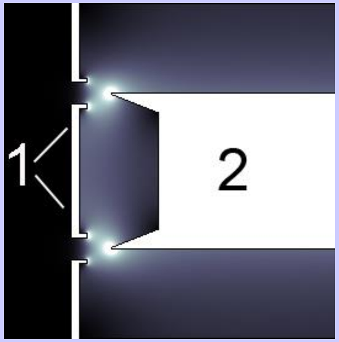


Photo of the anode and cathode parts of the switch: 1 – anode disk, 2 – slit, 3 – leg, 4 – cathode holder, 5 – cathode edge.

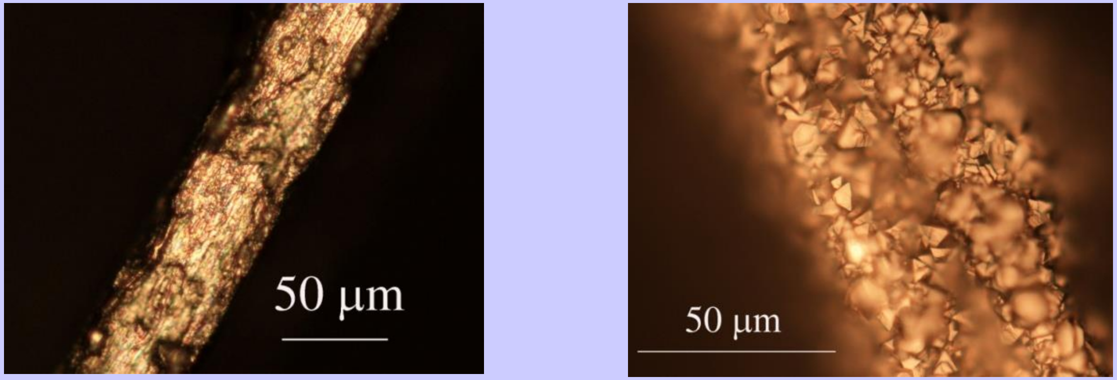


The distribution of the module of static electric field in the switch

Explosive-emission cathode

2 cm

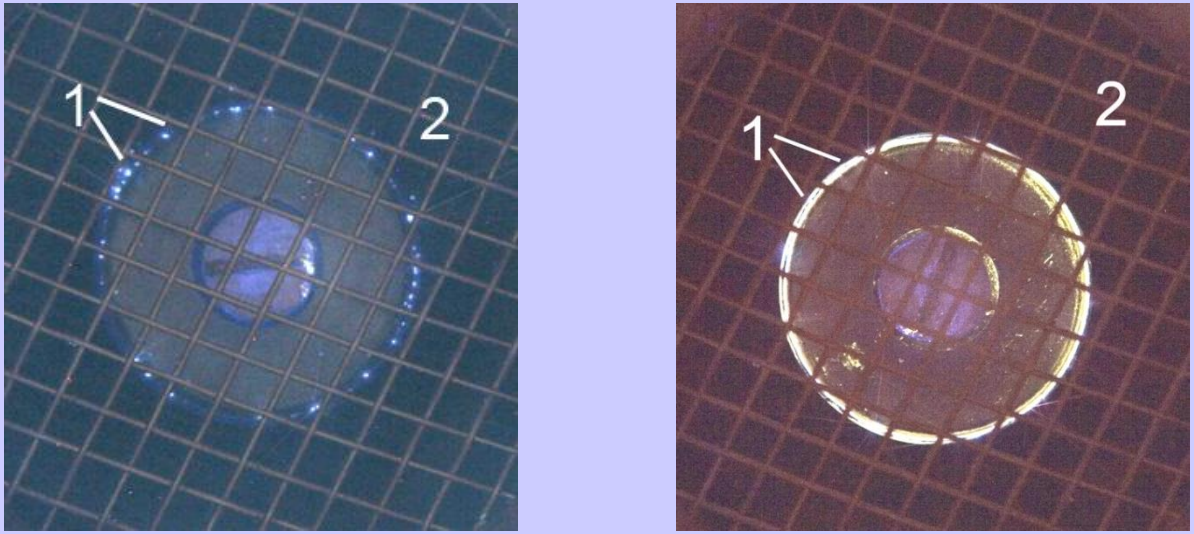
Edge of blade molybdenum cathode



Before

After diamond film deposition

Cathode Emission Test

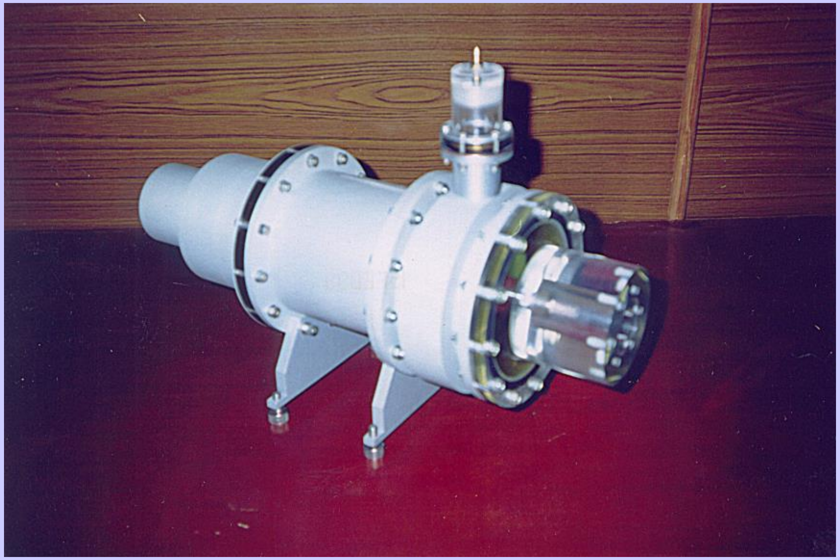


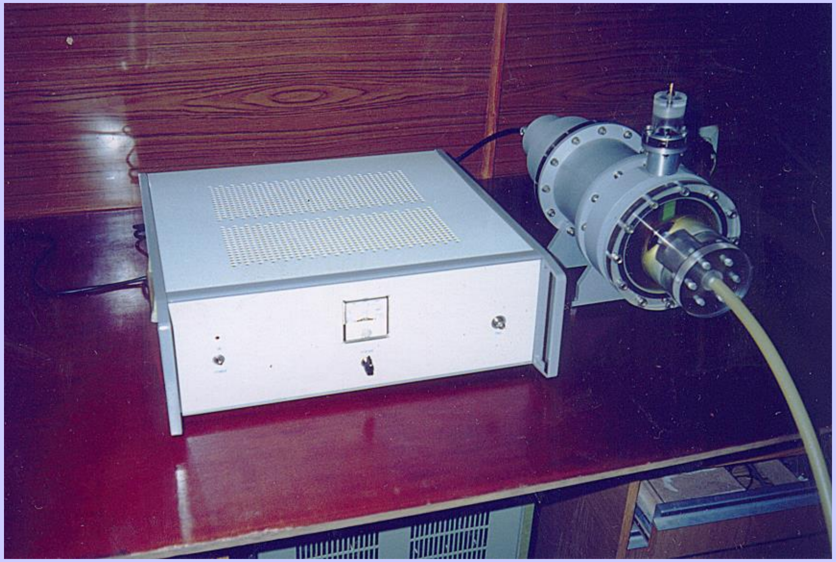
Uncoated Mo cathode

Cathode with diamond film

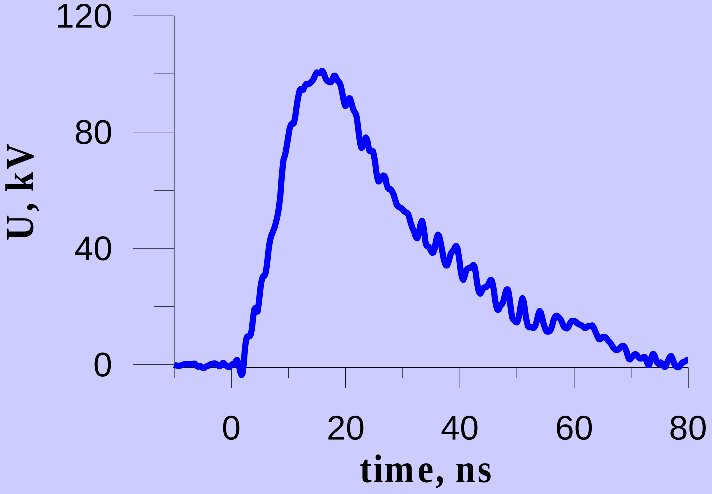
1- blade edges of the cathode 2 – anode grid

High-voltage pulse generator





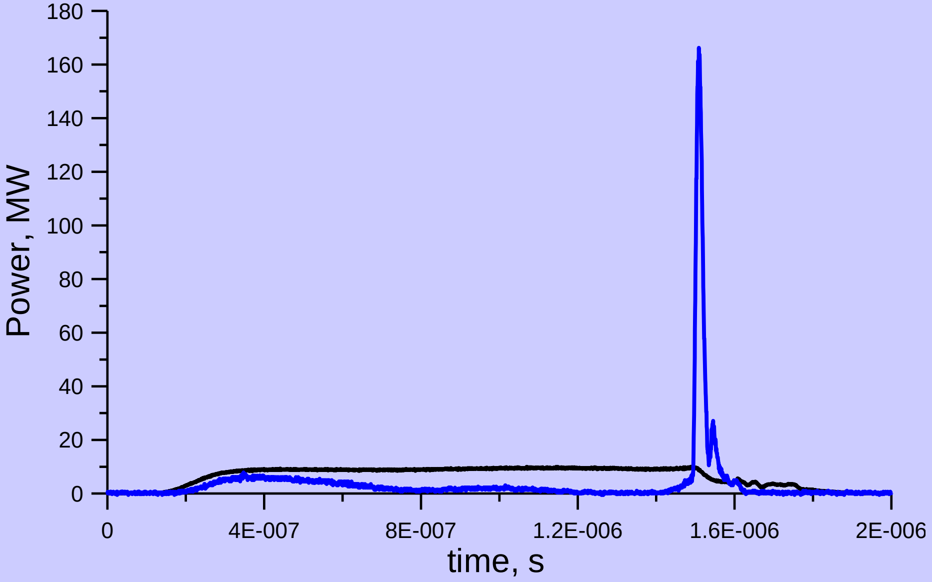
U = 100 kV
I = 500 A
T = 80-100 ns
F = 10 Hz

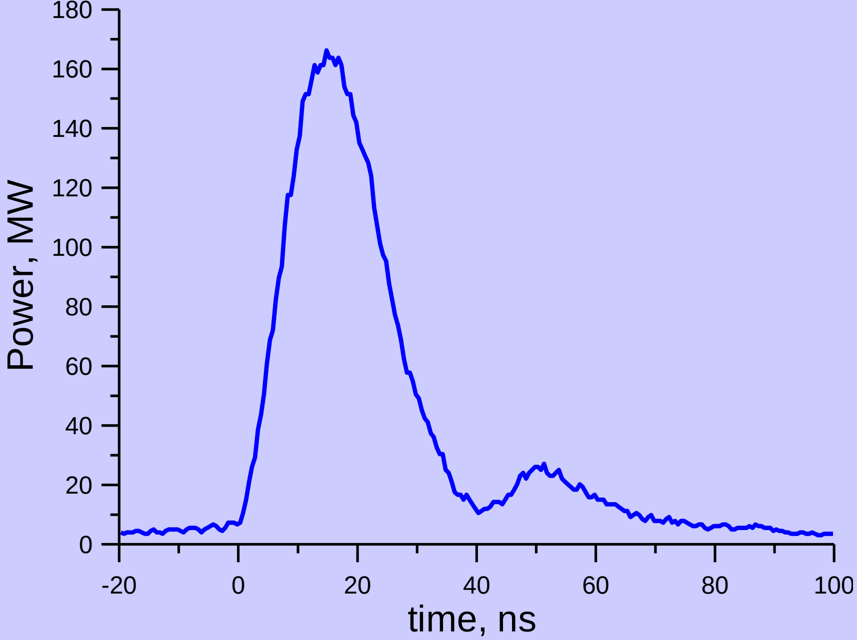


Trace of high voltage pulse

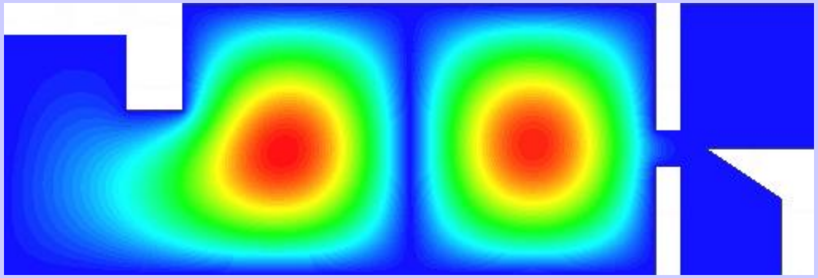
Results of high-power tests (2012)

$P_{inc} = 9.2\ \text{MW}$; $P_{com} = 165\ \text{MW}$; $G = 17.9$





TE_{012}

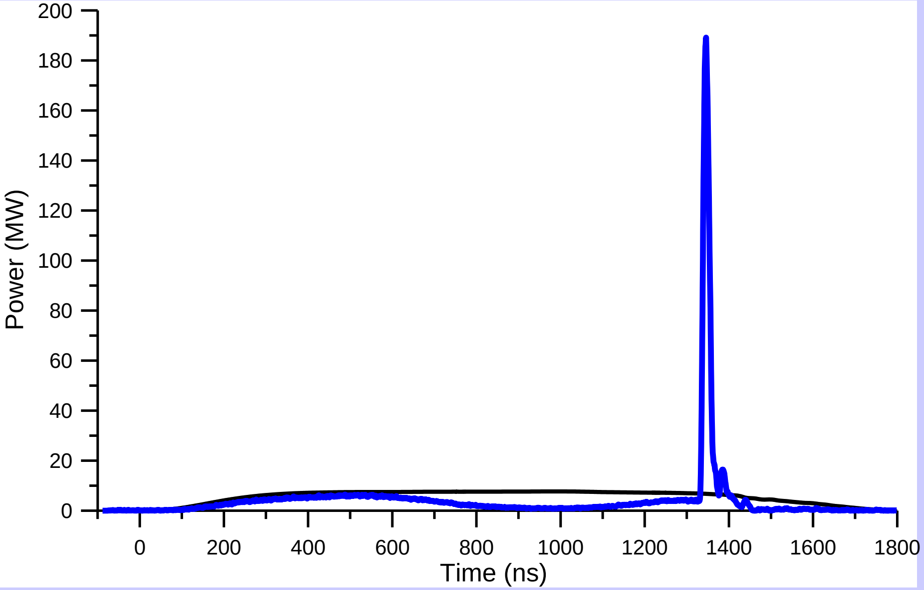


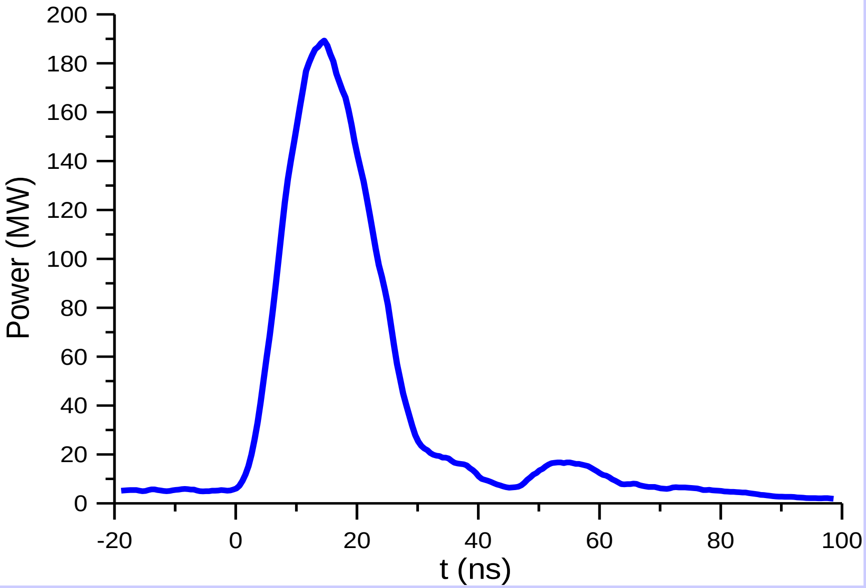
(Q_{switch}~400)

O.A. Ivanov, M.A. Lobaev, A.L. Vikharev, A.M. Gorbachev, V.A. Isaev, J.L. Hirshfield, S.H. Gold, A.K. Kinkead // Phys. Rev. Lett., 110, 115002 (2013)

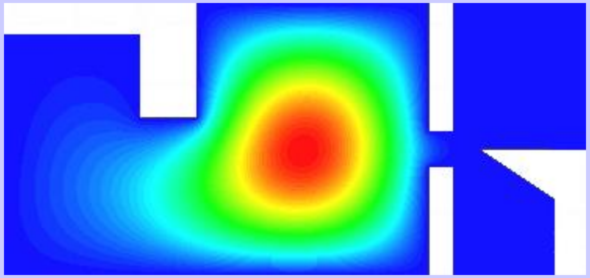
Results of high-power tests (2013)

P_{inc} = 7.4 MW; P_{com} = 190 MW; G = 25.7



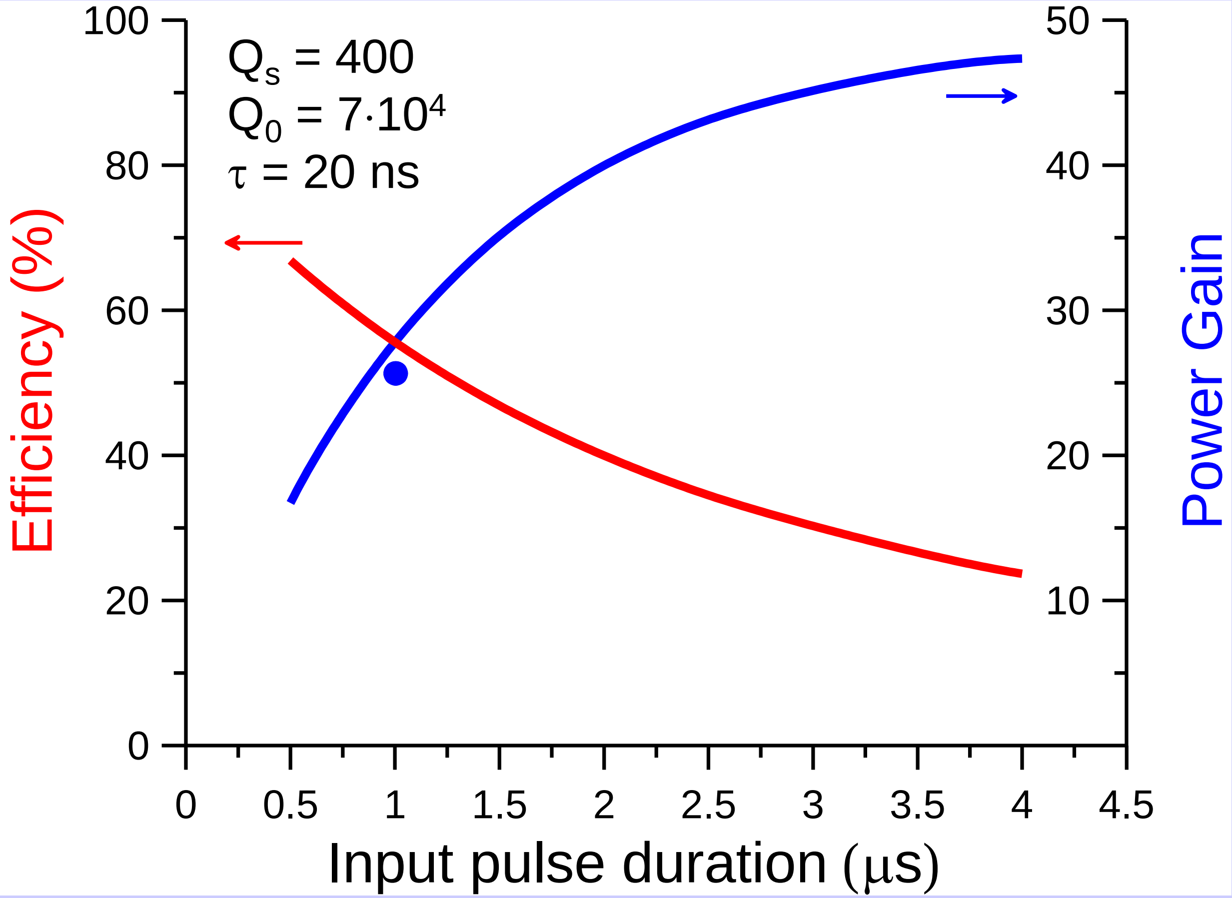


TE_{011}



(Q_{switch}~400)

Expected parameters of X-band microwave pulse compressor with 2 m storage cavity



Pinc = 6 MW T = 4 mcs
Pcom = 284 MW t = 20 ns G = 47.3 h = 23.7 %

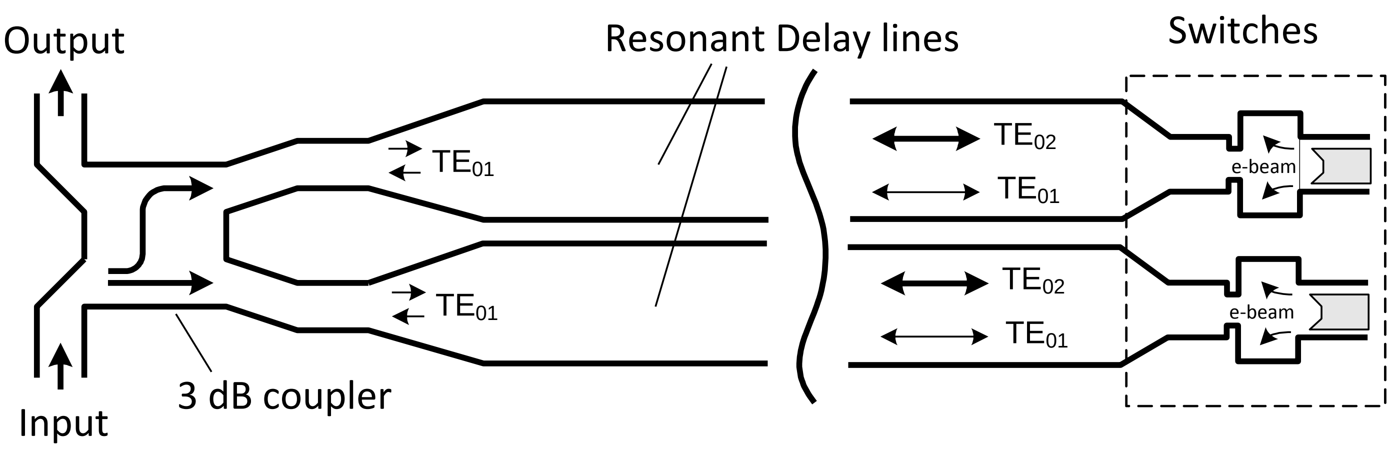
The drawbacks of existing compression systems:

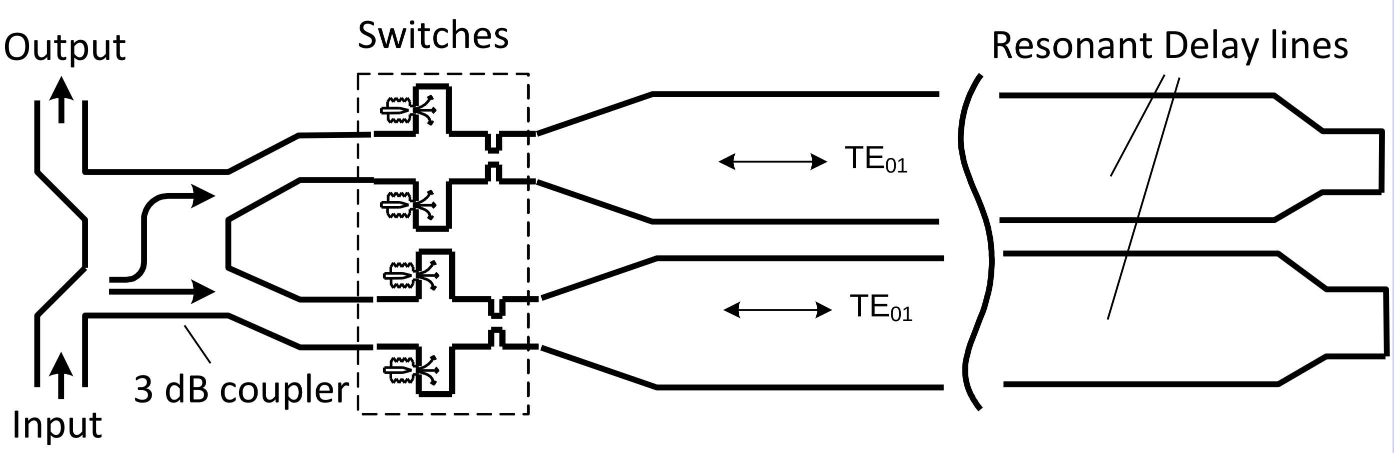
- Among the drawbacks of passive systems, one can mention a relatively low power gain and necessity of fast phase modulation within the incident pulse.
- High RF electric fields on the surface of an active element located within the switch (gas discharge tubes or semiconductors) can cause un-triggered switching due to multipactor or gas breakdown.
- High requirements for the value of electron density or beam current and dielectric permittivity (i.e. RF conductivity) of semiconductors.

- **Better performance can be expected with resonance switch based on the mode conversion and employing electron beam triggering:**

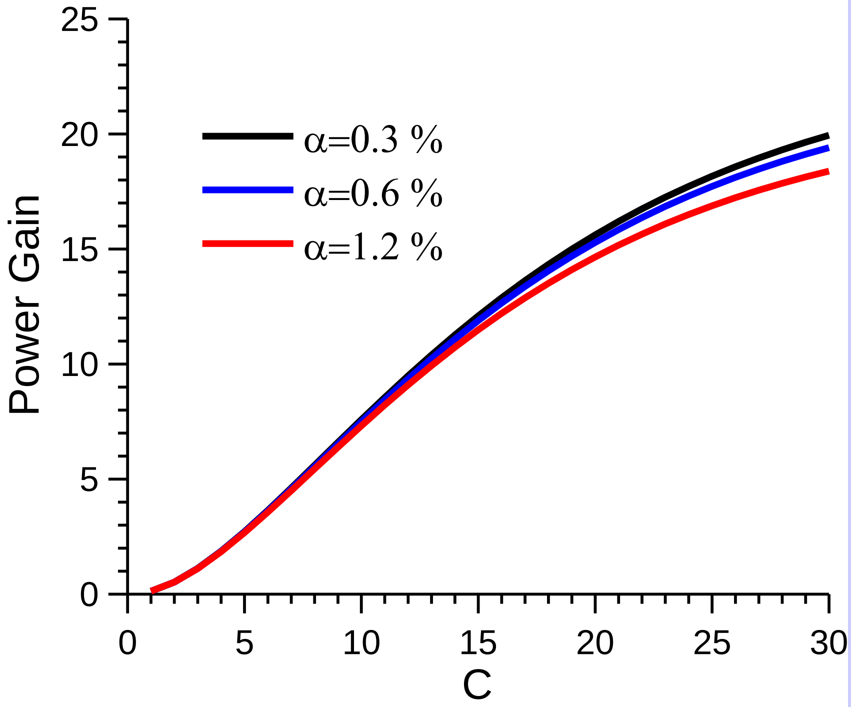
- The switch possessing resonant properties has a significant electrical robust on the stage of energy accumulation in the compressor.
- The use of a switch possessing resonant properties significantly decreases the level of requirements to the current and homogeneity of electron beam.
- The use of resonance switch allows one to place the active element (electron beam) outside of the switch, and hence to increase the magnitude of switched power.

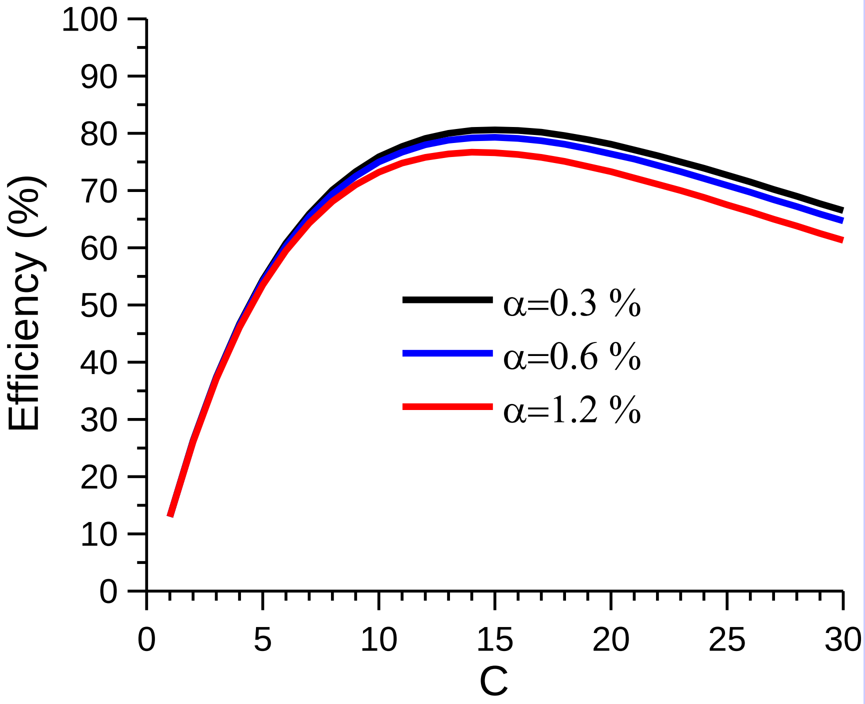
Application of the switches employing e-beam triggering with resonant delay lines





Expected parameters of resonant delay lines with e-beam triggered switches

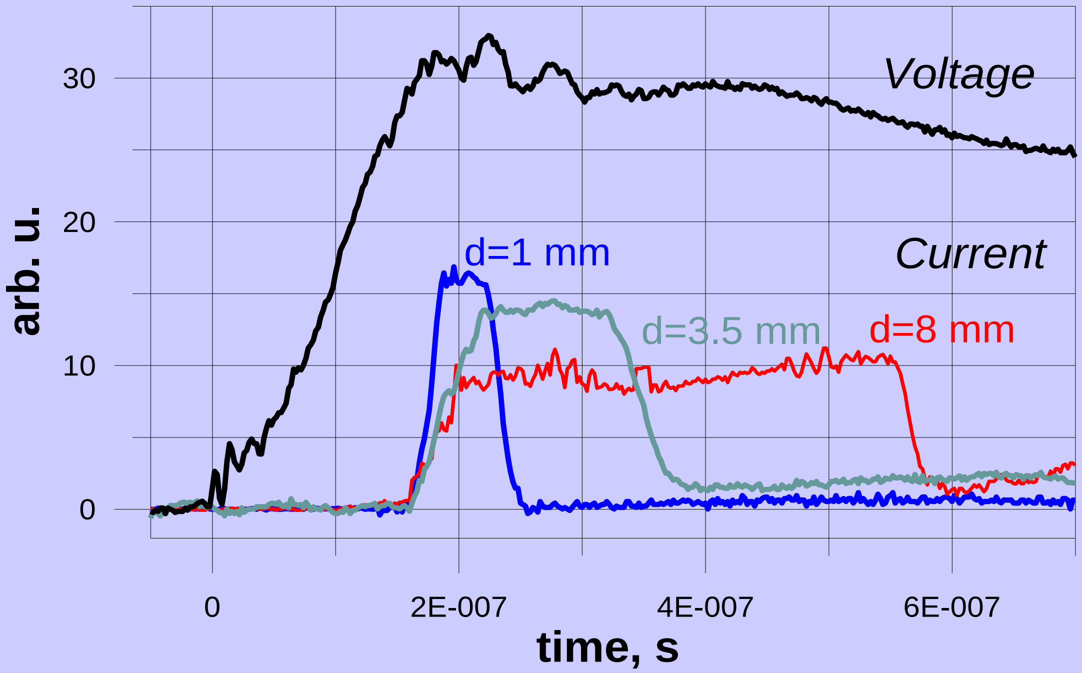




Input pulse (mcs)	1.6	2.6	4
Output pulse (ns)	173	173	250
Compression ratio	9	15	16
Power gain	7	11	12
Input power (MW)	50	50	6
Output power (MW)	350	550	72
Efficiency (%)	77	72	72

At the compression ratio C from 16 to 32 for "active" regime alone the output parameters will be close to "active/passive" regime.

Emission current created by long high–voltage pulses at different distances between cathode and slit anode



High voltage generator: 100 kV, 400 A, 250 ns, 100 Hz

Conclusion

A two-channel dual-mode pulse compressor with e-beam switching was tested at high power level and frequency of 11.424 GHz

The compressed pulse obtained for the incident power 7.4 MW had the power of 190 MW, duration of 20 ns, and the power gain of 25.7

An improved molybdenum blade cathode with thin diamond coating has demonstrated good reproducible emission uniformity with 100 kV, 100 ns HV pulse

Resonance switches employing e-beam triggering can operate with resonant delay lines and the following parameters could be achieved using one generator:

- Compressed pulses with power up to 500 MW
- Duration of output pulses 200-250 ns
- Power gain in the range of 10-12
- Efficiency 70-75%
- High stability and long lifetime of compressor operation

Thank you for your attention