*Fermi National Accelerator Laboratory*
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# High-power RF sources and components for linear colliders

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# Outline:

❑ **Warm technology**

▪ **History of development of RF sources for LC with examples from work at BINP**

▪ **Windows for high power X-band sources**

▪ **X-band pulse compression systems**

❑ **Cold technology**

▪ **TOSHIBA 10 MW L- band klystron**

▪ **Coupler with capacitive cold window**

▪ **Phase-shifters**

History of linear colliders probably started in 1978 from BINP. See preprint: V.E. Balakin, G.I.Budker, A.N. Skrinsky "Feasibility of creating superhigh energy colliding electron positron beam facility".

At that time a new laboratory was organized at BINP especially to develop technologies necessary for future linear super-collider ( V.E. Balakin – head of laboratory)

Many pioneering results were achieved, including

- accelerating gradient ~ 100 MV/m was experimentally demonstrated
- new type of damping of beam instability was invented (BNS damping)
- flat beams

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- And several new types of type RF sources were experimentally investigated:

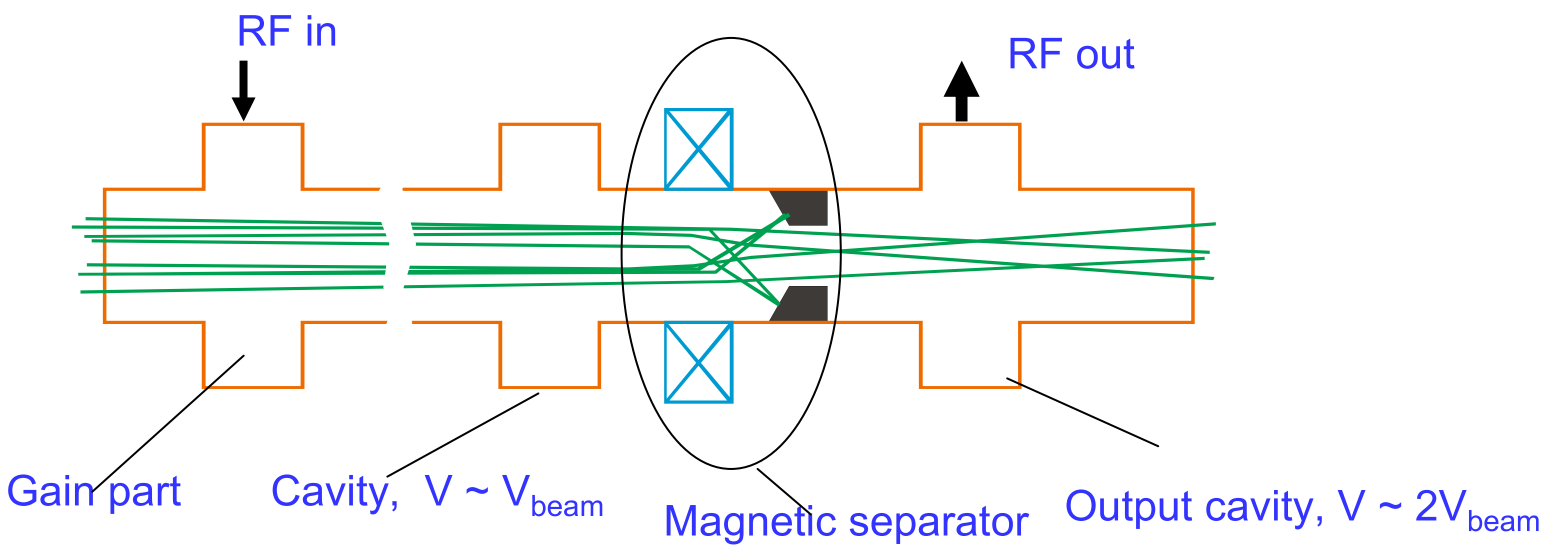
Separatron, multi-cavity gyrocon, "linear gyrokon", PPM klystron.
Klystrons with annular beam with conventional and magnetic bunching were studied theoretically.

It became clear from the beginning that a linear collider would require RF sources with enormous output power, which did not exist and must be created.

## Some exotic devices

First project was S-band normal conducting collider. RF source for this type of collider should emit of 100's of MW of RF power to keep the number of sources within an acceptable limit. But high power means high voltage for the electron beam, maybe relativistic.  But a relativistic beam it is not easy to bunch by changing its velocity -  the device would become very long.  A couple of clever schemes were invented.

**Separatron*** (V.Balakin, N.Solyak, A Mikhalichenko):

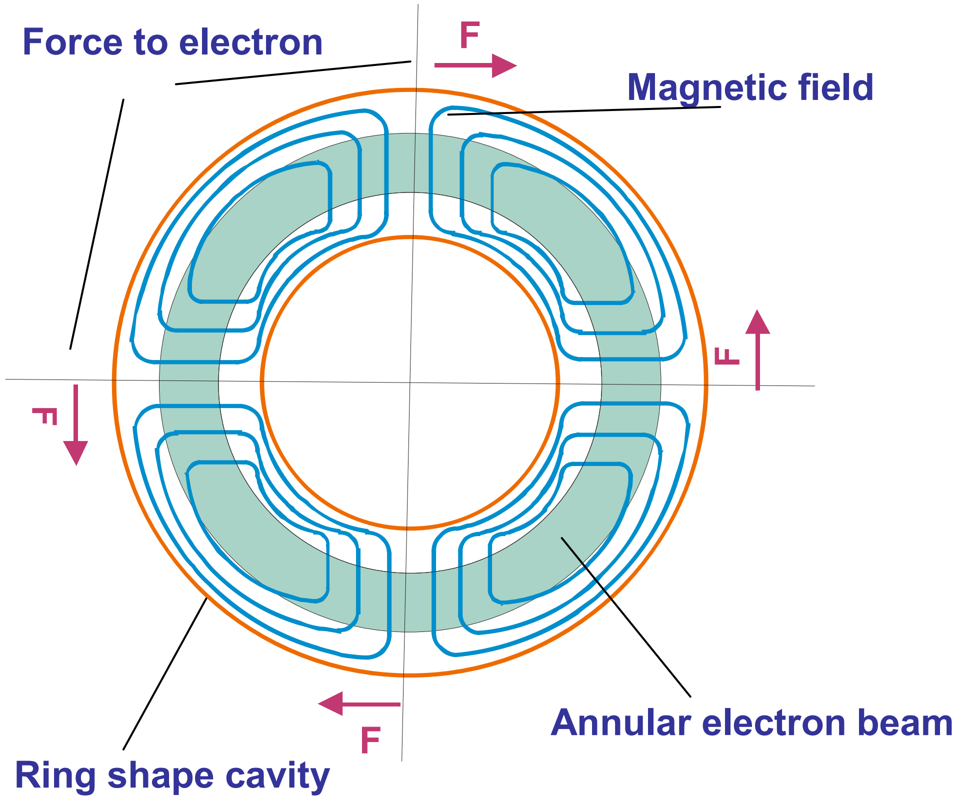


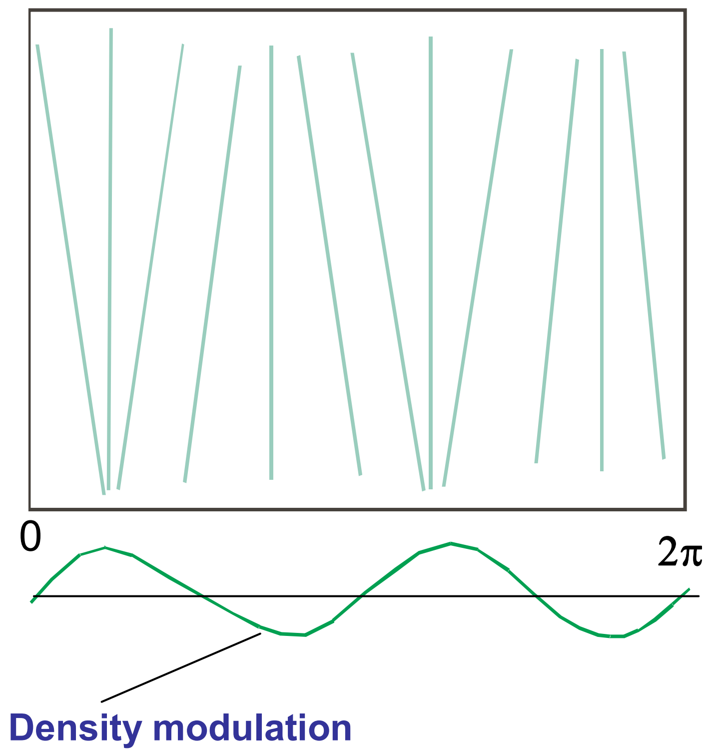

S-band device was built and tested.

Problems: corrosion of separating iris, double voltage of output cavity

* N.A. Solyak, "Studying of Separatron - a new RF power source", Diploma thesis, Novosibirsk 1976

# Klystron with modulation by magnetic field (V.Balakin, N. Solyak)

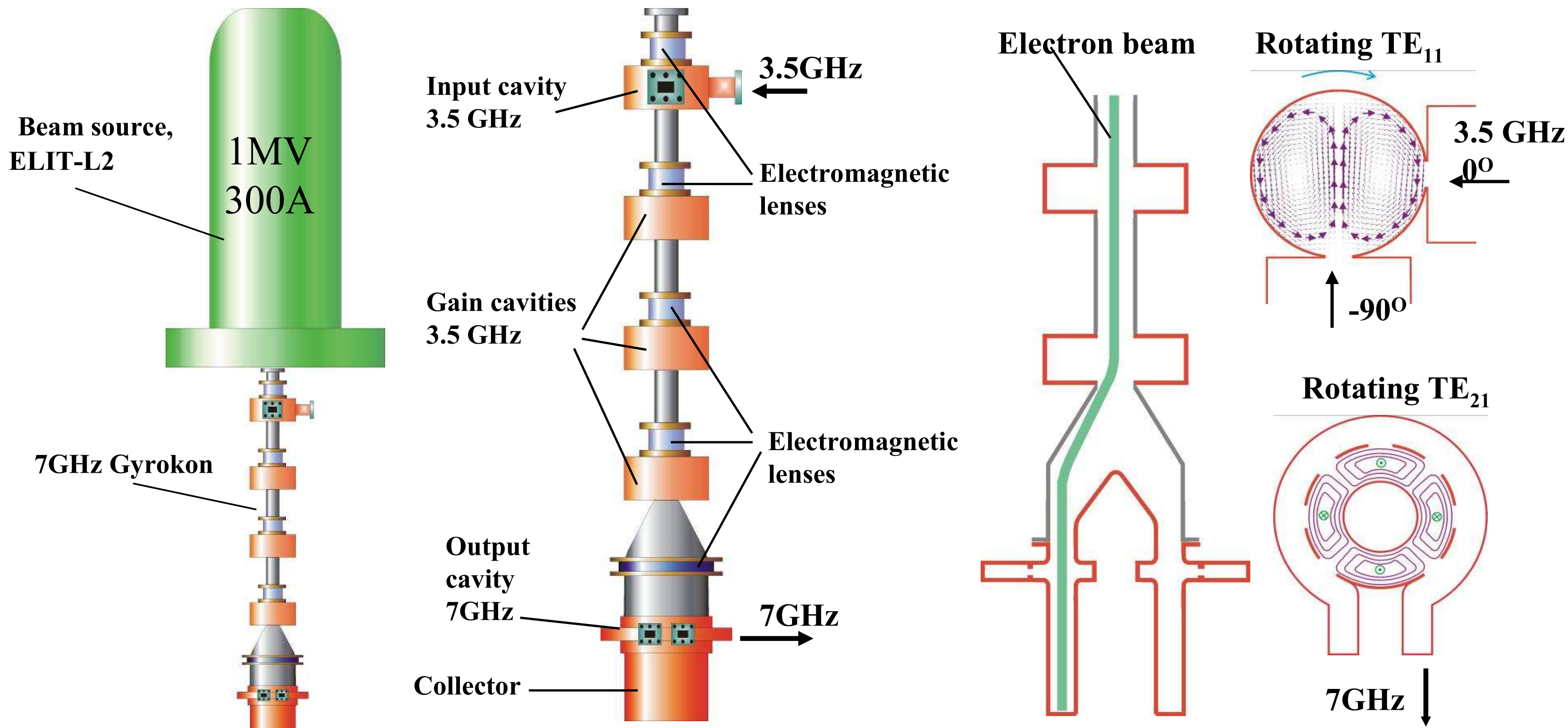



Wave in cavity can be traveling

# Frequency of VLEPP project was changed, 3 GHz -> 7GHz

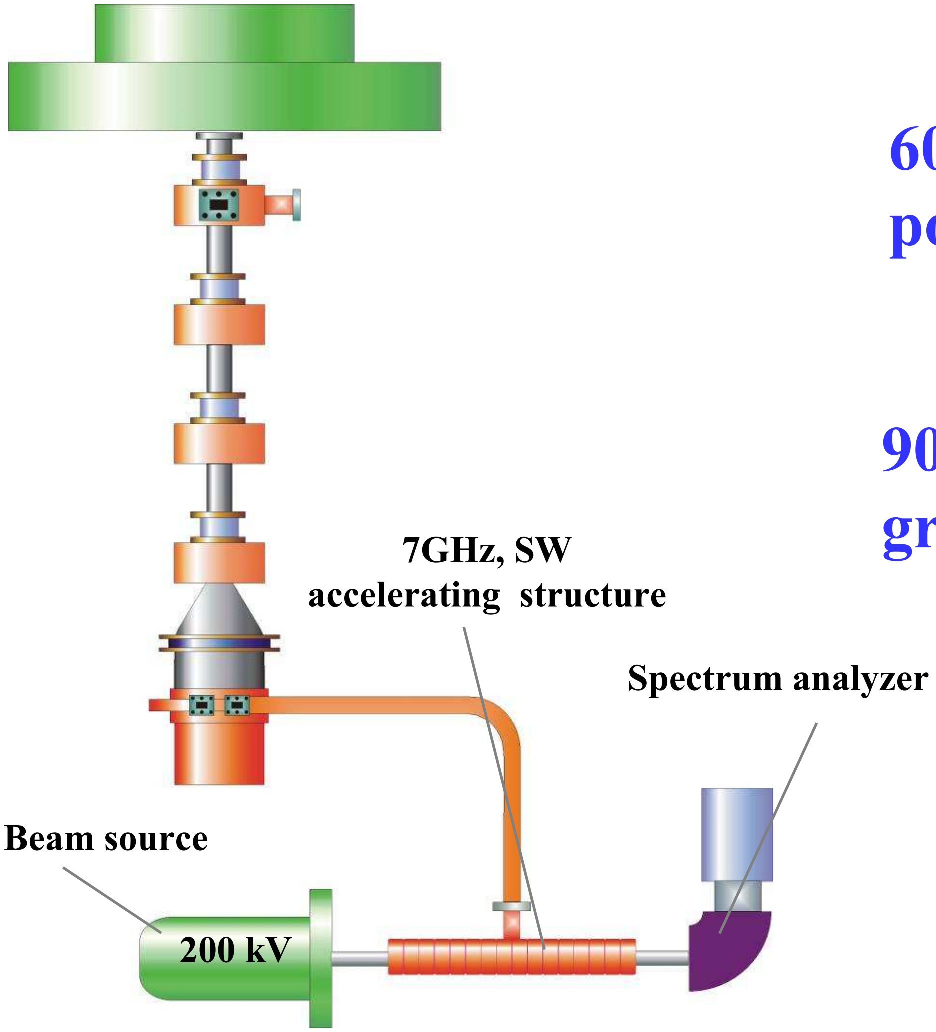
## Candidate for collider RF source became a multi-cavity gyrocon*




Gyrocon worked as frequency multiplier.


*Balakin V.E., Kazakov S.Yu, Solyak N.A, "RF deflection system of Gyrocon", Workshop on Relativistric RF electronics, Gorkii, 1982.
Balakin V.E., Kazakov S.Yu., Solyak N.A.,"Gyrocon", Proc. of the Intern. Workshop on Next-generation Linear Colliders SLAC,1988.

## Gyrocon was used as RF source for high accelerating gradient experiment.




**60 MW, 1μs output power was achieved.**

**90 MV/m accelerating gradient was reached**

But cost optimum of linear collider lies in higher frequency region. VLEPP frequency was doubled, 7GHz ->14GHz. Laboratory started design of a **14 GHz klystron**

VLEPP klystron was design on basis of several very bold ideas:

- DC voltage 1 MV (!)
- Gridded gun with multi-beam big cathode
- Permanent magnetic system
- TW output structure

Great challenge !

Table 1: VLEPP klystron, designed and achieved parameters.

| Parameter | Design | Experiment |
|---|---|---|
| Operating frequency | 14 $GHz$ | 14 $GHz$ |
| Peak output power | 150 $MW$ | 60 $MW$ |
| Beam energy | 1 $MeV$ | 1 $MeV$ |
| Beam current | 300 $A$ | 150 $A$ |
| Grid voltage | 25 $kV$ | 20 $kV$ |
| Pulse duration | 0.5 $\mu sec$ | 0.5 $\mu sec$ |
| Saturation gain | 80 $dB$ | 90 $dB$ |
| Cathode | 37 microcathodes | |
| Emitter type | oxide | |
| Cathode diameter | 120 $mm$ | |
| Type of magnetic system | MPFS | |

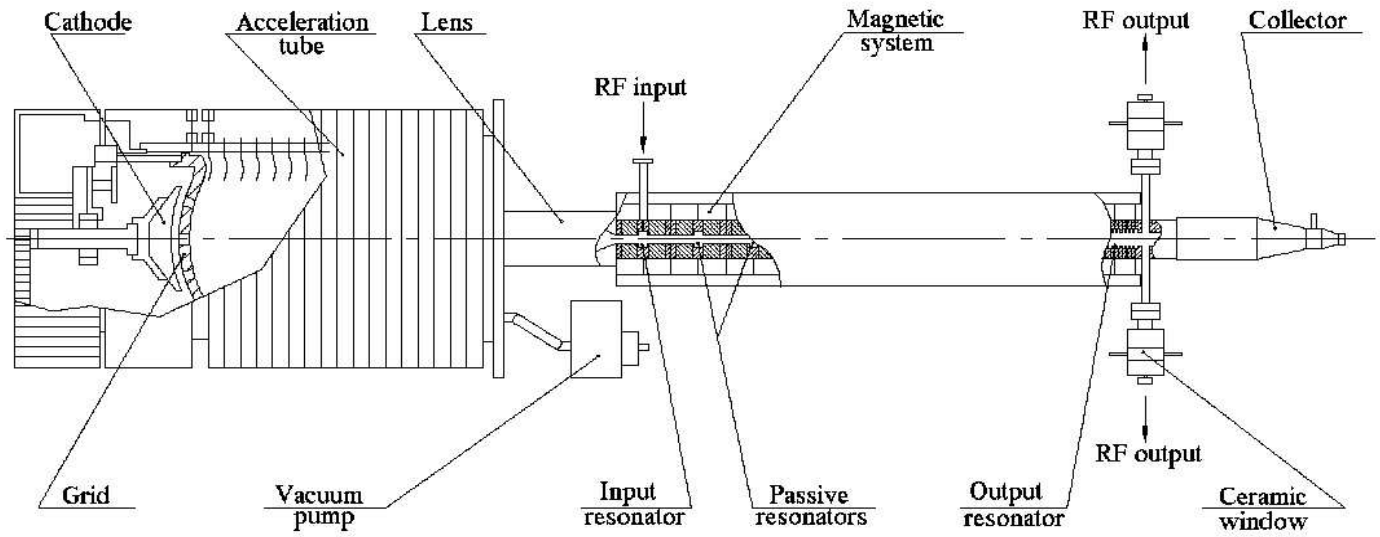
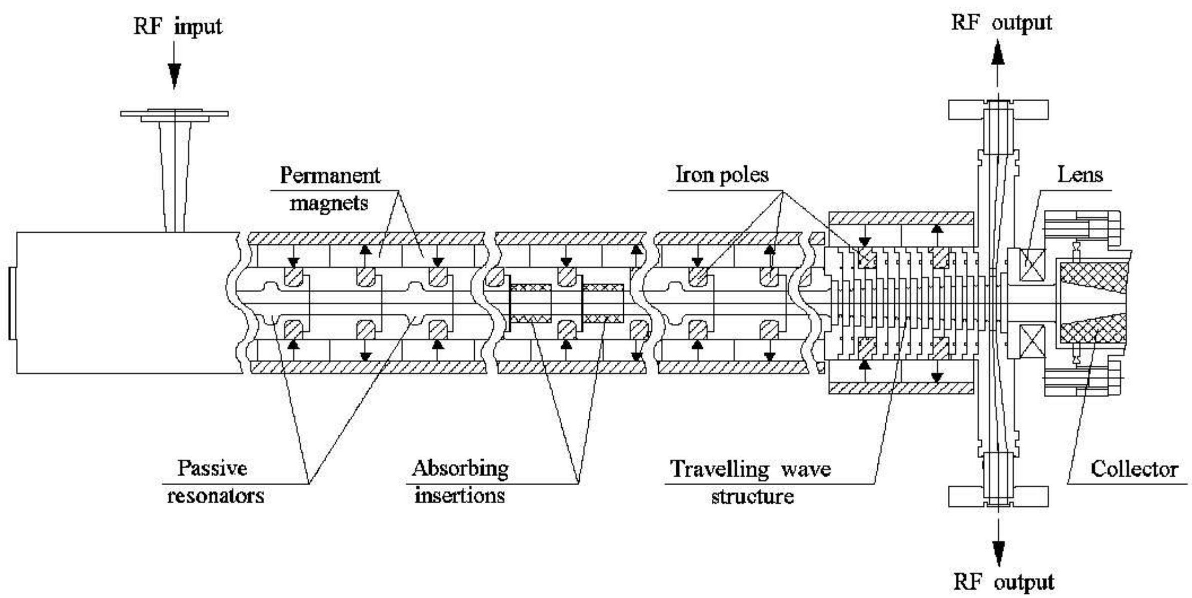
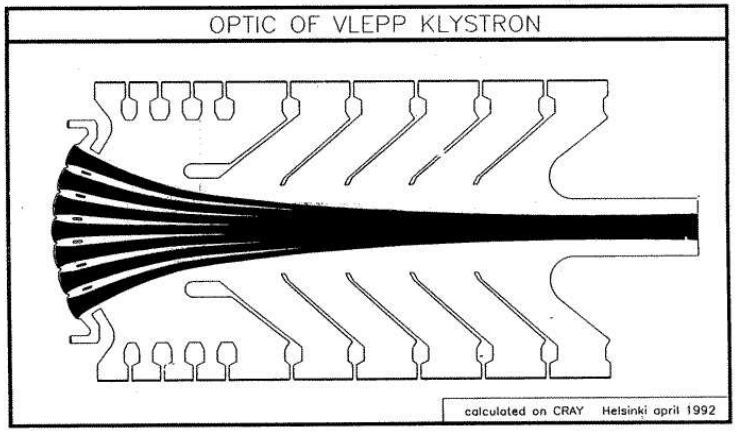



Diagram of VLEPP klystron




Cavities and magnetic systems of klystron




**Cathode of VLEPP klystron**

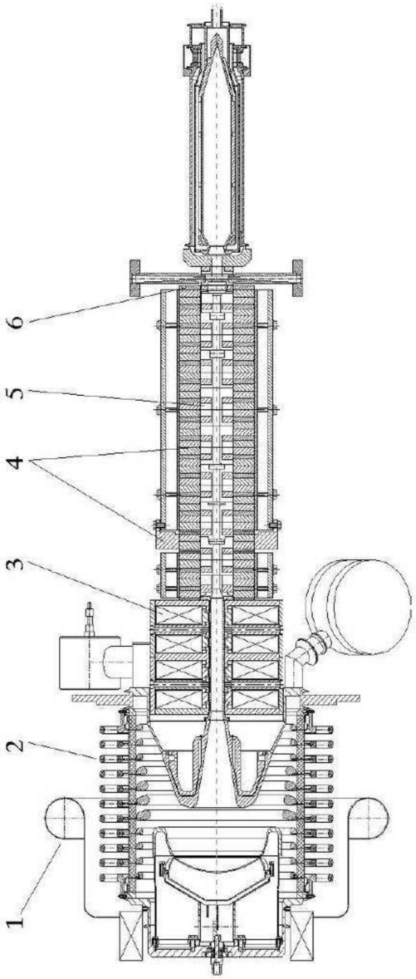
***VLEPP gridded klystron with PPM focusing.***

***Achieved parameters :***

| | | | |
|---|---|---|---|
| Frequency | = *14 GHz* | RF power | = 60 \| 50 *MW* |
| Voltage | = *1000 kV* | Gain | = 75 \| 90 *dB* |
| Current | = 150 *A* | Pulse length | = 0.7 *μs* |

***(Sorry for pictures quality. At that time a digital camera did not exist yet)***

**VLEPP klystron did not achieved design parameters, but it made great impact to modern klystron design. Following VLEPP klystron, SLAC and KEK designed their own 11.4 GHz 75 MW klystrons.**



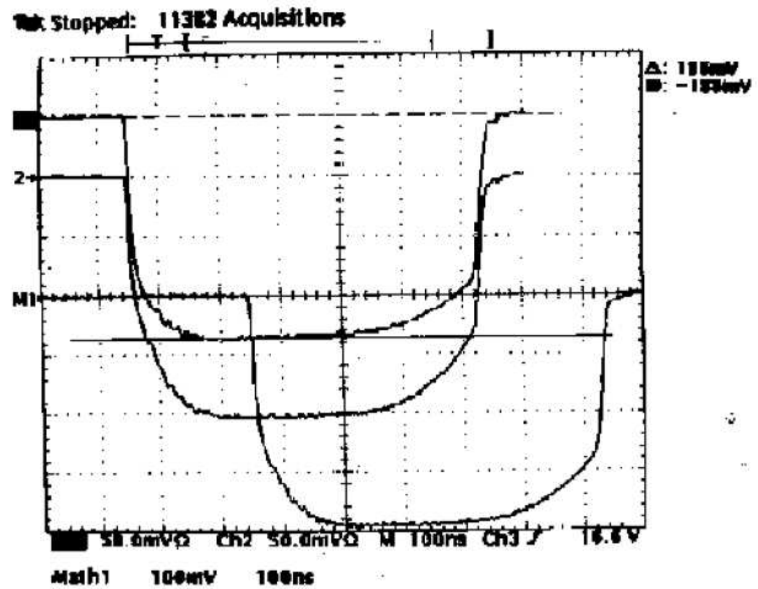




Figure 11: $P_{output} = 50$ MW, $\tau = 600$ ns. 1 -, 2 - signals of RF loads M1 - a total signal.

**PPM klystron designed and built by BINP for KEK**

SLAC 75 MW PPM klystron


TOSHIBA / KEK 75 MW PPM klystrons

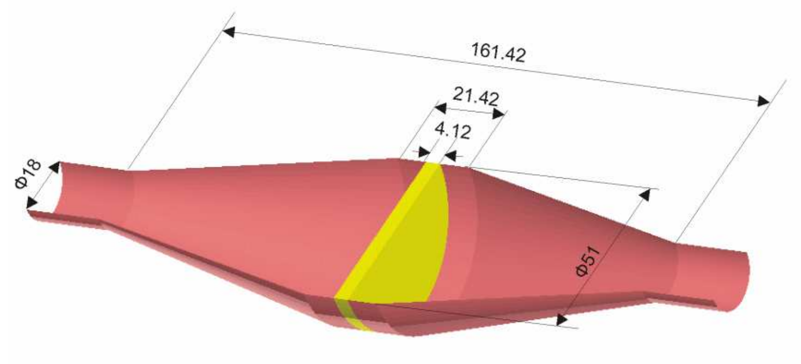
**Critical elements of X-band power klystrons are the windows.
The window power density was more then one order higher then in prior S-power klystrons. Old type "Pill-box" windows did not work.
New ideas and approaches were needed.**

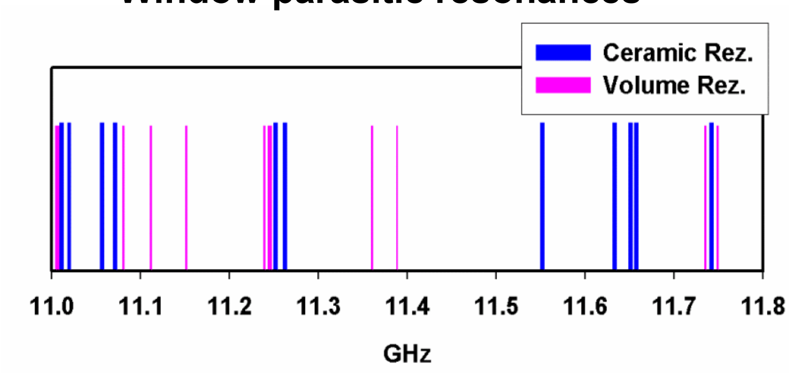
**Examples of attempts to make powerful
X-band window in different laboratories:**

| X-band window | Ceramic sizes | Limiting power |
|---|---|---|
| λ/2, KEK | 22.86 x 10.16 mm | 11 MW / 70 ns |
| Pill-box, KEK | ∅ 28.2 mm | 30 MW / 200 ns |
| Pill-box, SLAC | ∅ 27 mm | 80 MW / |
| Long pill-box, KEK | ∅ 28.2 mm | 48 MW / 80 ns |
| Taper type, KEK | ∅ 51 mm | 84 MW / 700 |
| Taper type, BINP | ∅ 66 mm | 50 MW / 800 |
| Taper typer, SLAC | ∅ 47 mm | 20 MW / |

**Windows are needed which can reliably operate with power ~ 40 MW/1.6 us.
If we take into account possible full reflection from a load, it means window should sustain 160 MW/1.6 us working into a matched load.**

# Example of BINP/KEK type tapered λ/2 window for 11.4 GHz*



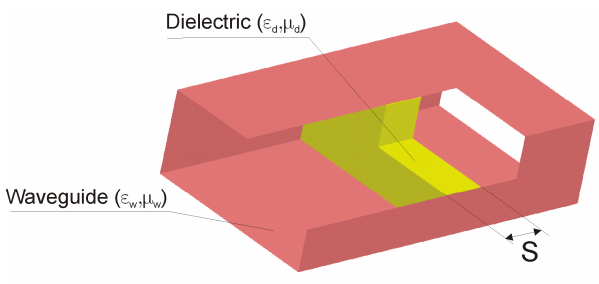

Window was broken at 84 MW / 0.7us

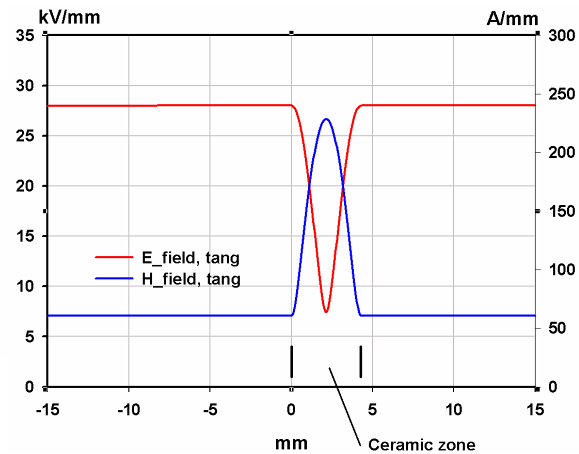
**The problem – it is difficult to increase ceramic size further because of high density of ghost modes in ceramic and trapped mode in volume. Not easy to match and field at the ceramic for a non-ideal TE11 mode.**

***Y.Otake, S.Tokumoto, S.Y.Kazakov, J.Odagiri, H.Mizuno, "High-Power Tests of X-Band RF Windows at KEK., KEK Preprint 96-84, July 1996.**

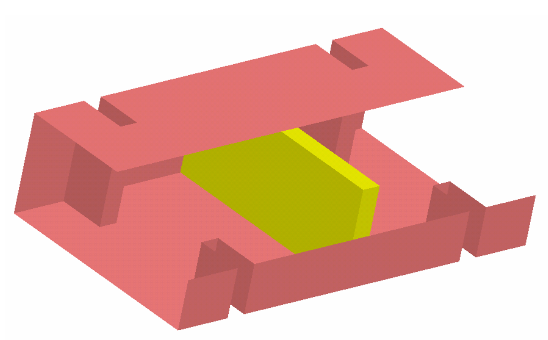
# The big step was made when the TW window was invented

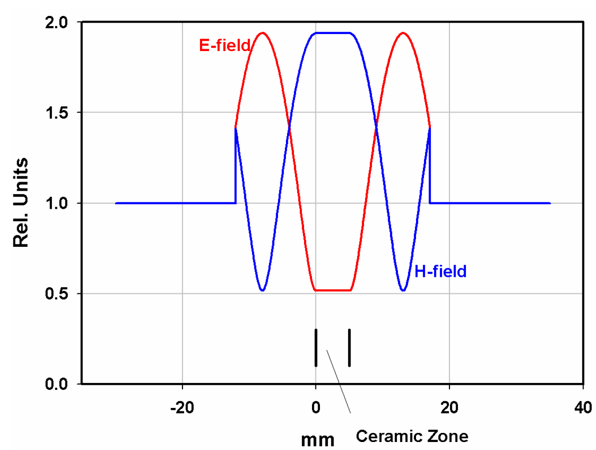
## λ/2 window



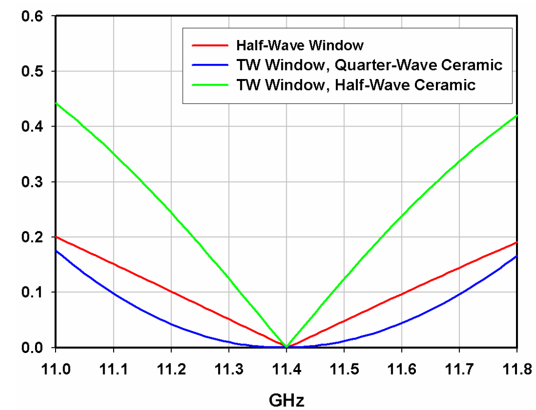




## TW window



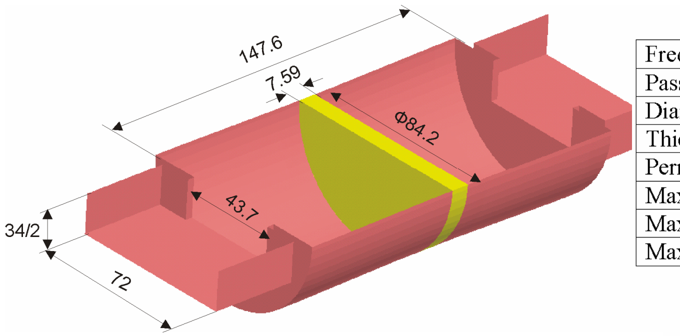



## TW window has wider passband

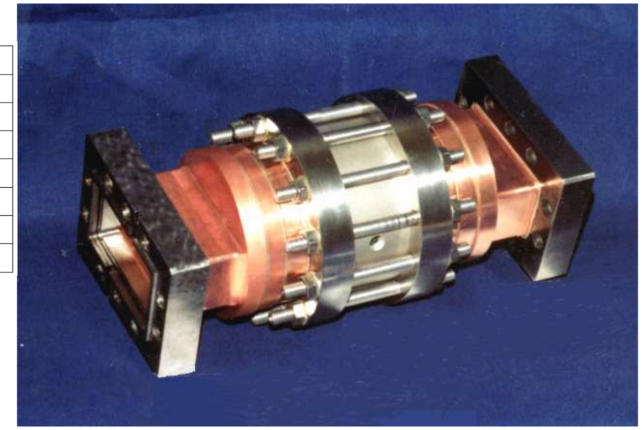


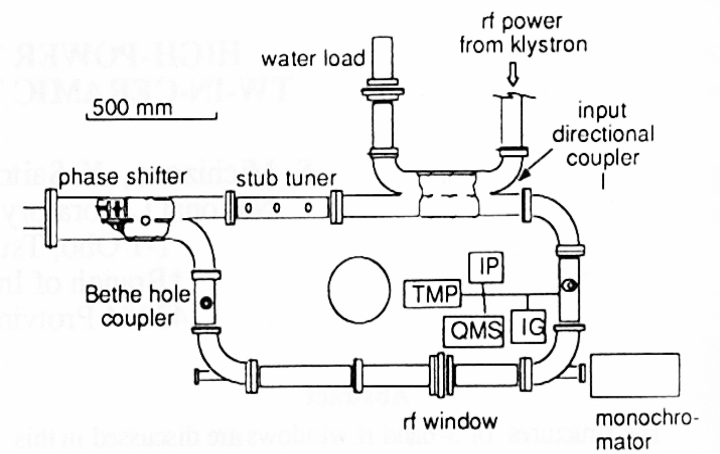

TW window can transmit $\sqrt{\varepsilon}$ times more power. For $Al_2O_3$ it is about 3 times.

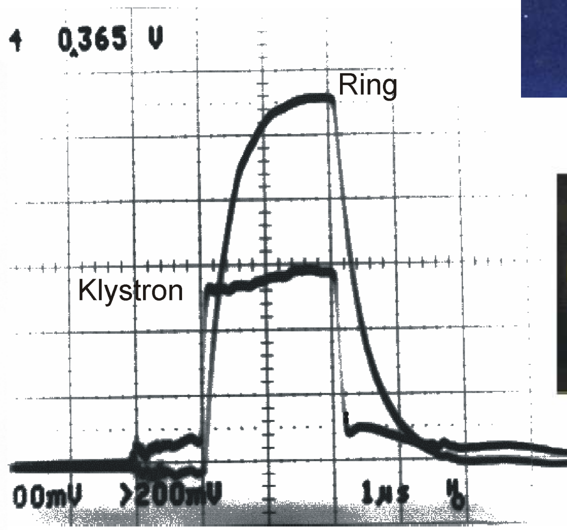
# Idea was checked in S-band window*

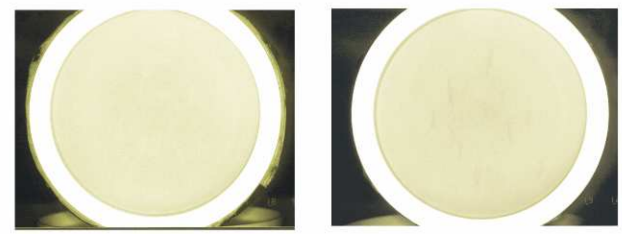



| | |
|---|---|
| Frequency | 2856 MHz |
| Passband (SWR < 1.2) | 100 MHz |
| Diameter of ceramic | 84.2 mm |
| Thickness of ceramic | 7.59 mm |
| Permittivity of ceramic | 9.8 |
| Max. E-tang. on the cer. surface | 3.1 kV/mm (100 MW) |
| Max. E-norm. on the cer. surface | 0.0 kV/mm (100 MW) |
| Max. E on the metal | 18 kV/mm (100 MW) |





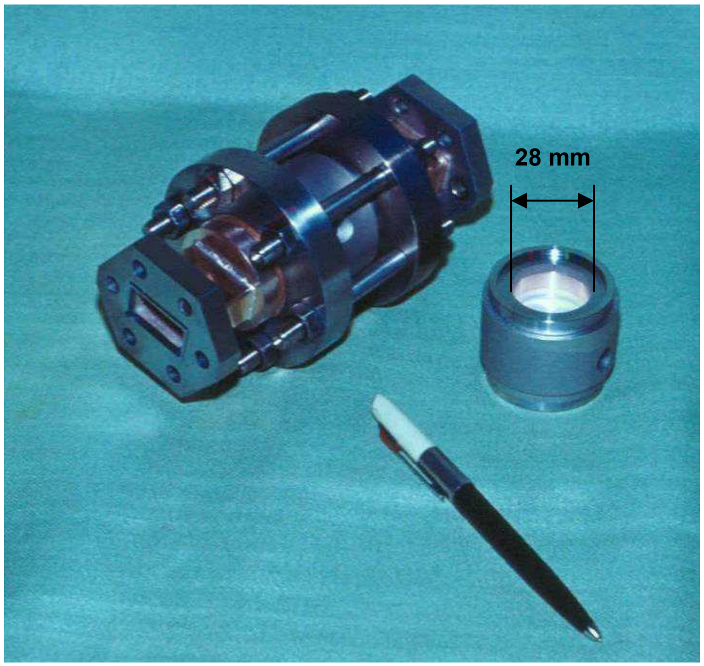



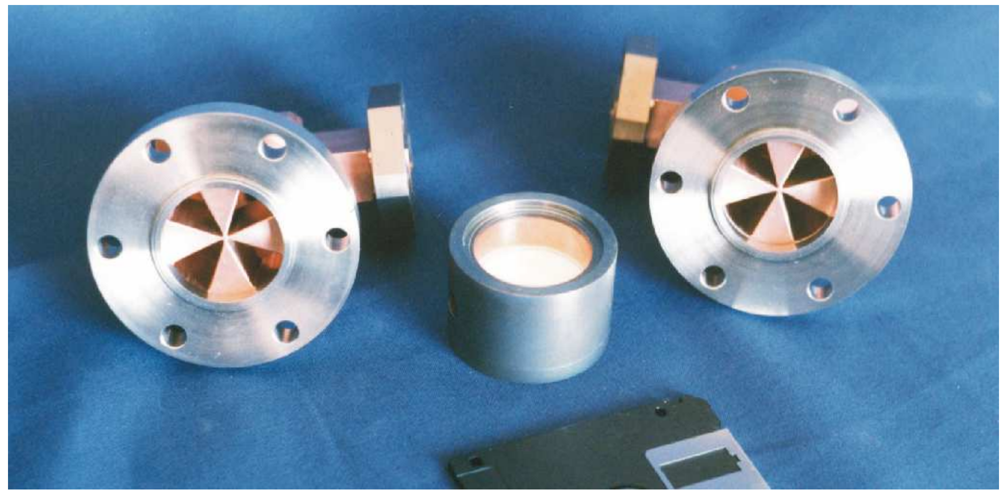
Upstream Downstream

**Window was successfully tested up to 470 MW / 2 us / 50pps (1 kJ in the pulse). Power was limited by resonant ring, not window. Window was not broken. We do not know the power limit for this window.**

*S.Michizono, Y.Saito, H.Mizuno, S.Yu.Kazakov,"High Power Test of Pill-Box and TW-in Ceramic Type S-Band Windows", Proceedings of the 17th International Linac Conference (LINAC94), Tsukuba, Japan, August 21-26, 1994

# Examples of X-band TW windows



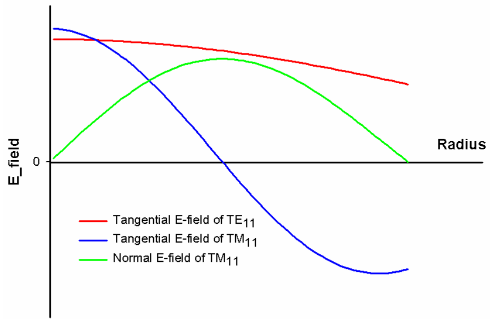



**TW TE01 window with mode converters, not tested**

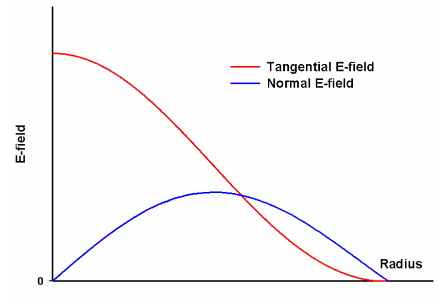
**TW TE11 window. It was tested up to 80 MW / 0.2 us/ 25 pps and 40 MW / 0.7 us / 25pps. Power was limited by breakdown in metal part. Ceramic survived.**

# New, more interesting idea was generated – Mixed-mode TW window.

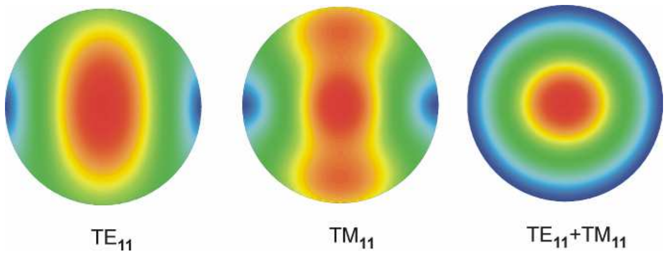
The weakest part of window is the place of brazing metal with ceramic.
The idea was to use mode mixture to decrease field at the brazing place.



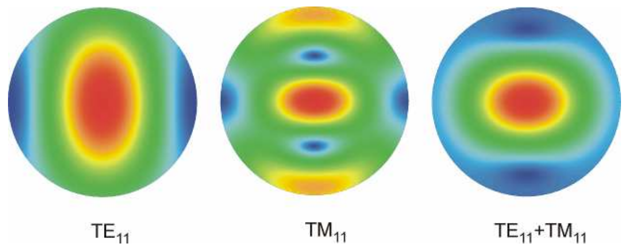

**Electric fields of $TE_{11}$ and $TM_{11}$ modes in the circular waveguide**




**Electric fields of summation of $TE_{11}$ and $TM_{11}$ modes in the circular waveguide**



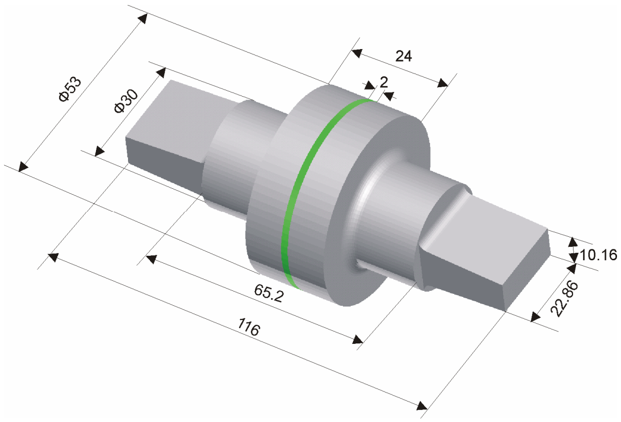

**Electric fields of $TE_{11}$ and $TM_{11}$ modes and their summation in circular waveguide**




**Magnetic fields of $TE_{11}$ and $TM_{11}$ modes and their summation in the circular waveguide**

***S.Kazakov , "A New Traveling-Wave Mixed- Mode RF Window with a Low Electric Field in …", KEK Preprint, Tsukuba, Japan, August 1998**

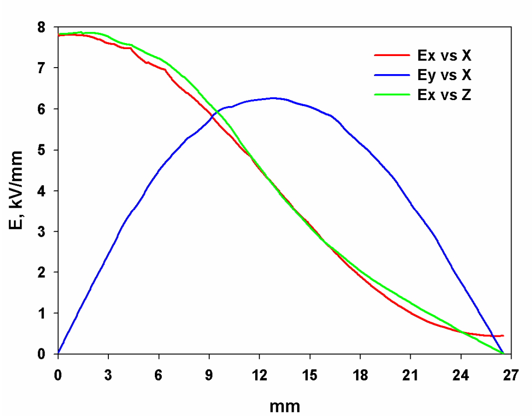
## It is not a trick to mix a couple of modes, but we have to provide TW condition for both modes. To our big surprise it turned out , that the geometry of window  is very simple!

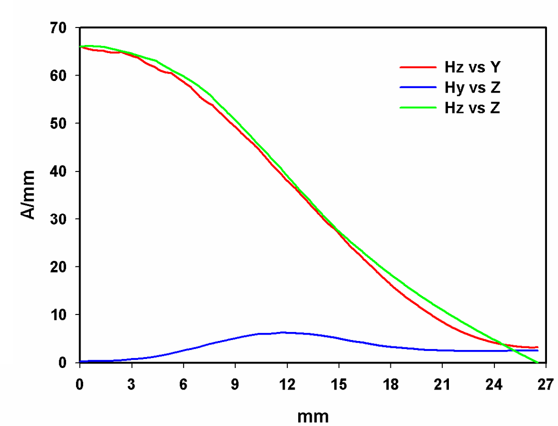


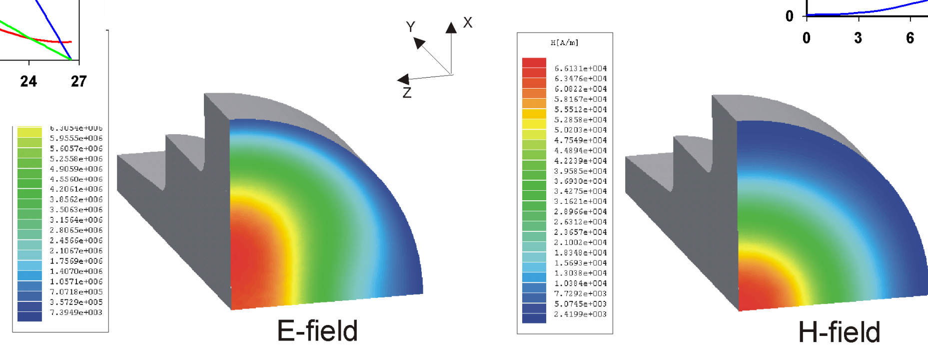

**Geometry of X-band travelling wave mixed-mode window**

**Parameters of X-band TW mixed-mode window**

| | |
|---|---|
| Operating frequency | 11424MHz |
| Ceramic diameter | 53 mm |
| Ceramic thickness | 2 mm |
| Ceramic permittivty | 9.8 |
| Passband (SWR < -1.2) | 440 MHz |
| Max. E-field on the ceramic  (100 MW) | 7.8 kV/mm |
| Max. E-field on the periphery (100 MW) | 0.44 kV/mm |
| Max. E-field on the metal       (100 MW) | 52 kV/mm |



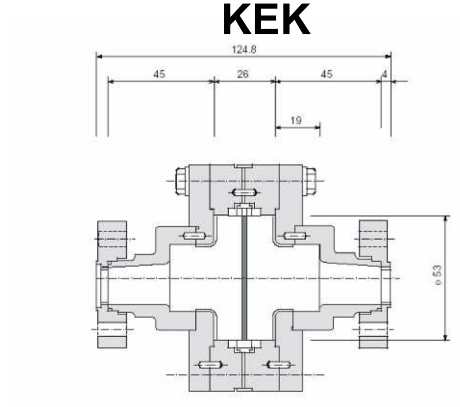



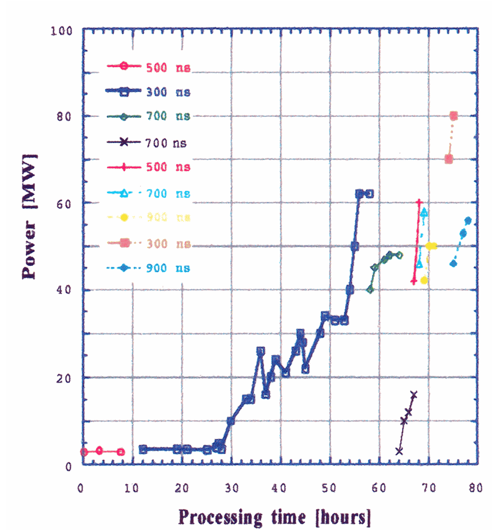



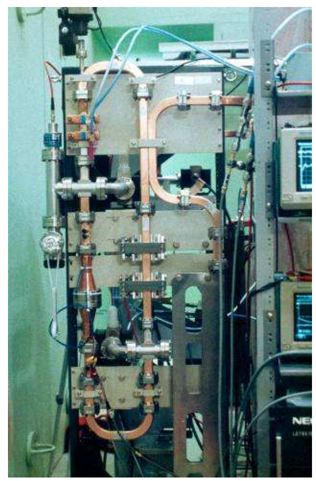

**Electric and magnetic fields distributions on the ceramic of X-band TW mixed-mode window at power of 100 MW**

# TW Mixed-Mode window was tested in KEK and SLAC*

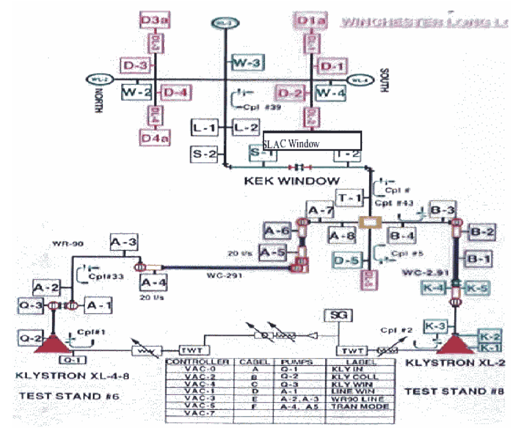
## KEK

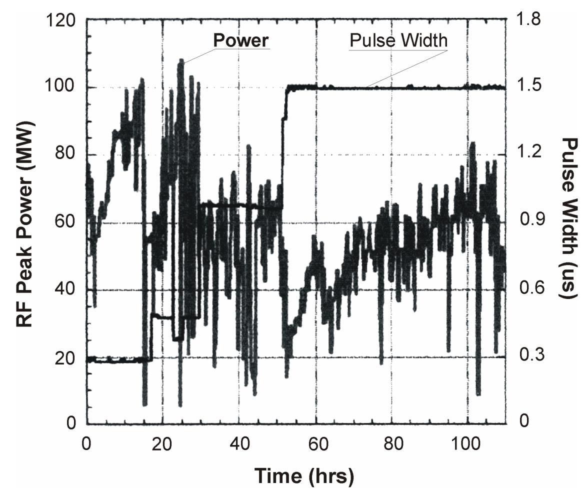


## SLAC

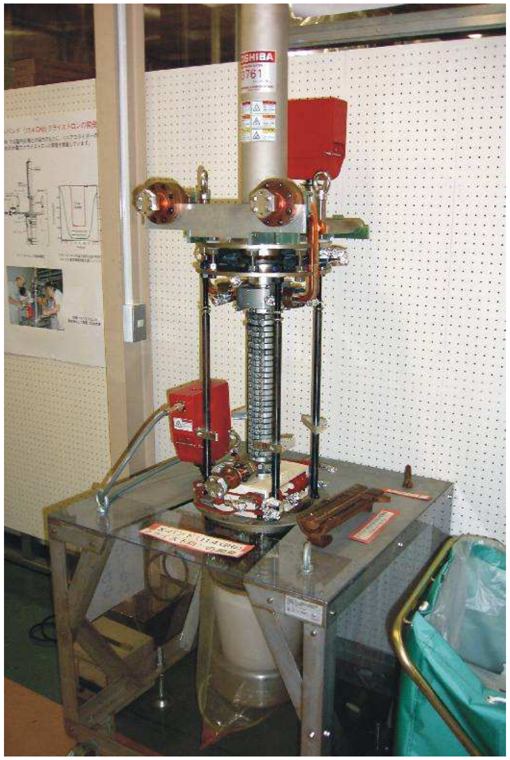
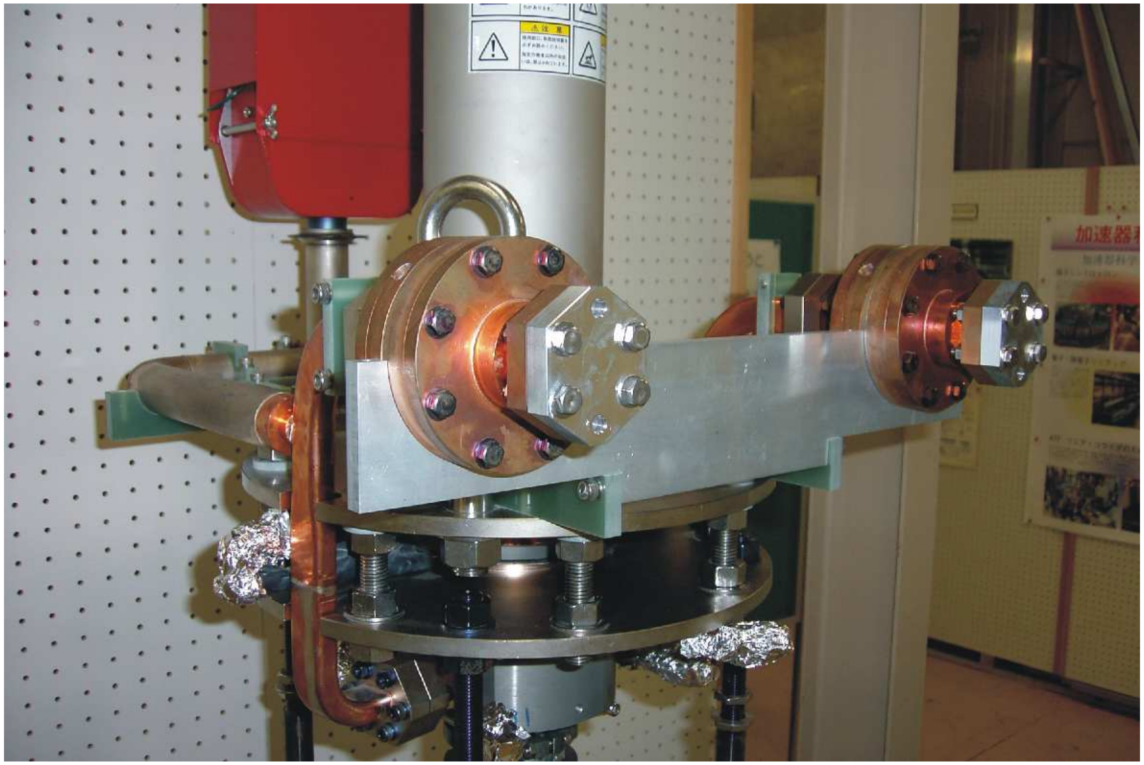



**Window was successfully tested up to 100 MW /0.5 us and 85 MW /1.5 us. Window was not broken.**

*S.Yamaguchi, S.Matsumoto, S.Tokumoto, H.Mizuno, Y.H.Chin, S.Kazakov, "High-Power Test Results of Kazakov RF Window", LC99, Frascati, Italy, October, 1999

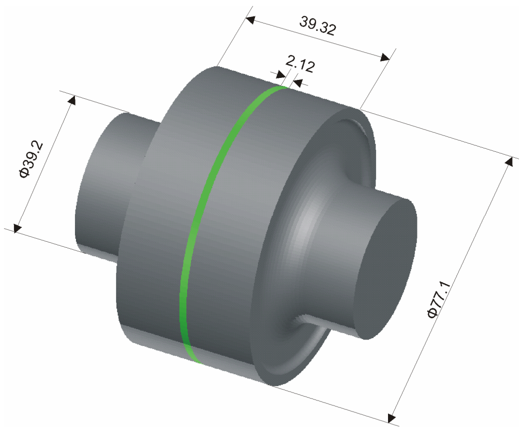
*S.Tokumoto, Y.H.Chin, H.Mizuno, K.Ohya, S.Yamaguchi, S.Kazakov, R.Loewen, R.Fowkes, A.Menegat, A.Vlieks, "High Power Tasting Results of the X-Band Mixed-mode RF Windows for Linear Colliders", LINAC 2000, Monterey, CA, USA, August, 21-25, 2000.

**X-band TW mixed-mode window in the 75MW E3761 Toshiba klystron**

# And more powerful window!*

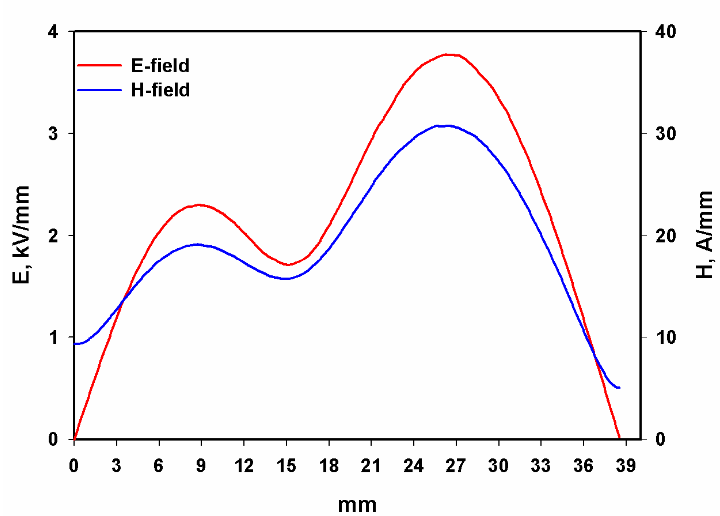
## $TE_{01}$-$TE_{02}$ TW window

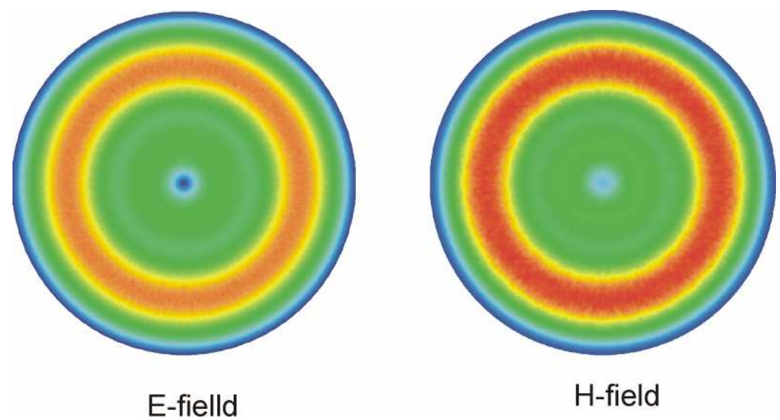



### Parameters of $TE_{01}$-$TE_{02}$ TW window

| | |
|---|---|
| Operating frequency | 11424 MHz |
| Passband (SWR < 1.2) | 600 MHz |
| Ceramic diameter | 77.1 mm |
| Ceramic thickness | 2.12 mm |
| Ceramic permittivity | 9.8 |
| Max. E-field on the ceramic (100 MW) | 3.77 kV/mm |
| Max. E-field on the periphery | 0 |
| Max. E-field on the metal | 0 |

**Expected power limit 450 MW ! (8 kV/mm)**

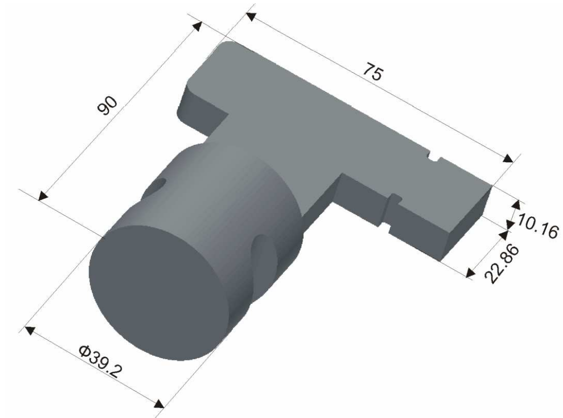



Electric and magnetic fields on the ceramic surface of X-band $TE_{01}$-$TE_{02}$ TW window at power of 100 MW

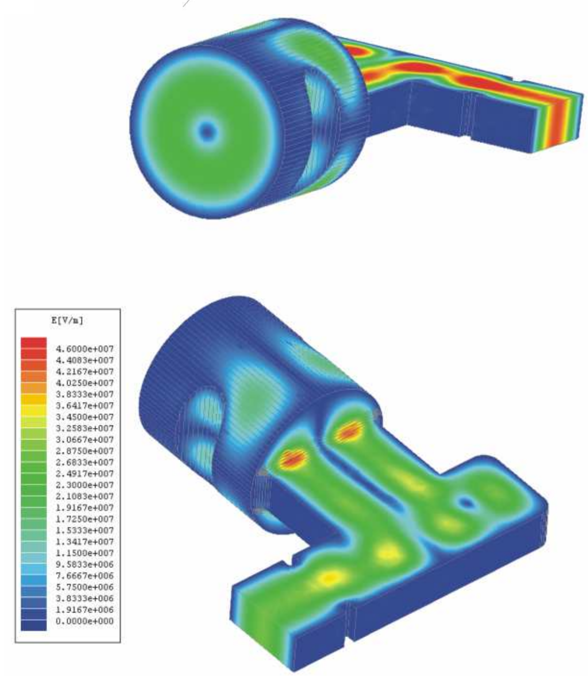
*S.Kazakov, "New Compact TE10 – TE01 Mode Converter and TE01-TE02 Window", ISG-8, SLAC, June 2002.

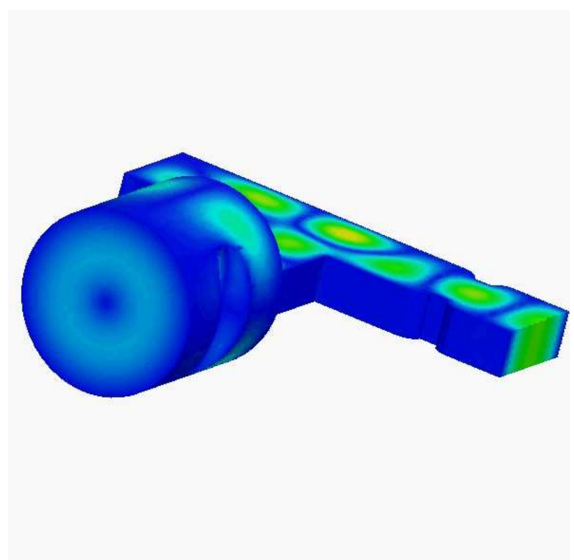
## But we need TE10-TE01 mode convertor for this window.
## The mode converter with wonderful simple geometry was design.



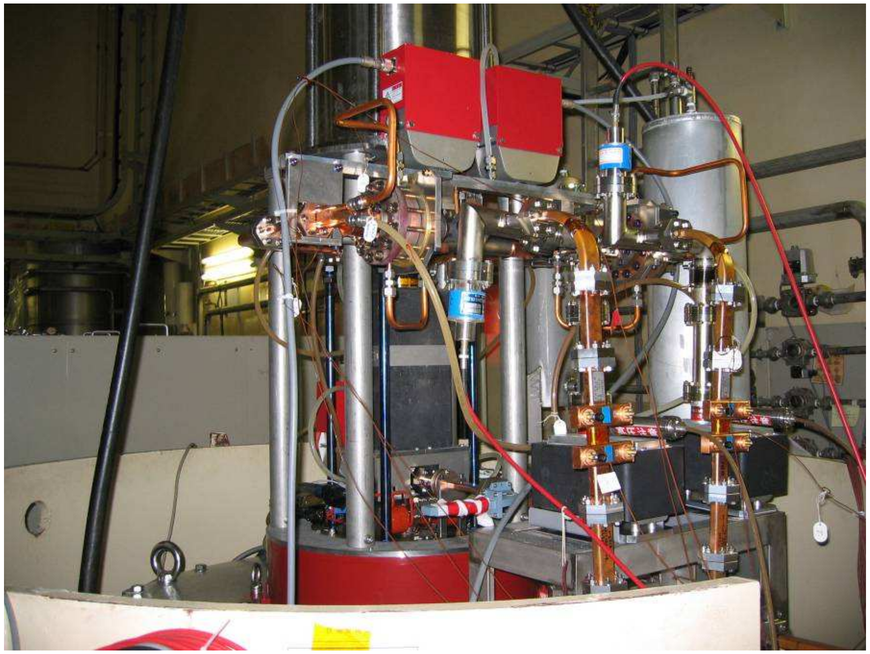

**Parameters of $TE_{10}$-$TE_{01}$ mode converter**

| | |
|---|---|
| Operating frequency | 11424 MHz |
| Modes to convert | $TE_{10} \leftarrow\rightarrow TE_{01}$ |
| Efficiency of conversion | 99.99% |
| Passband (Eff. > 99%) | 240 MHz |
| Max. E-field on the surface (at 100 MW) | 46 kV/mm |

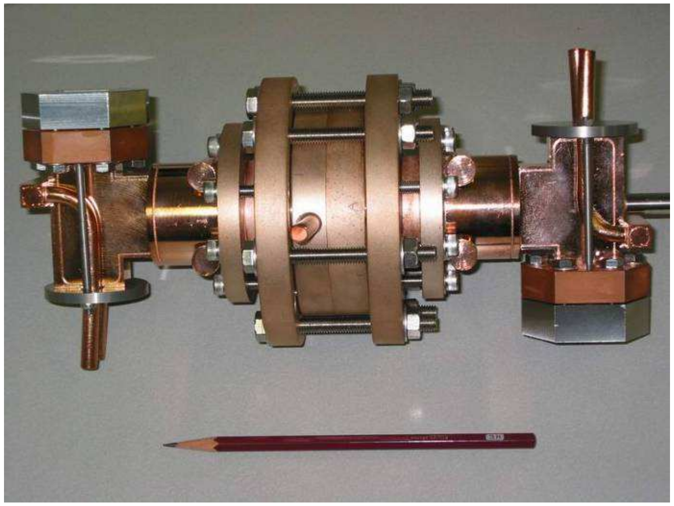




Window without converters



Toshiba/KEK X-band klystron with new windows



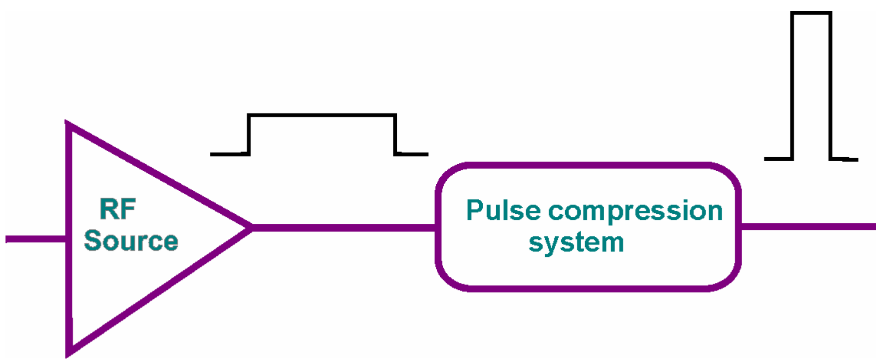
Assembled window with converters.

**Behavior of new window is much “quieter” then behavior of previous type.**

# Pulse compression.

Experience says that it is easer (cheaper) to create RF sources with lower power and longer pulse then higher power and short pulse.

We can reduce cost by using the lower power / longer pulse RF sources together with less expensive pulse compression systems

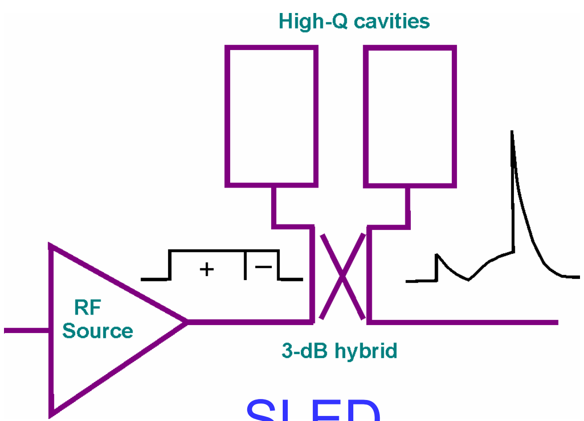


Pulse compression systems can by divided into “active” and “passive” systems

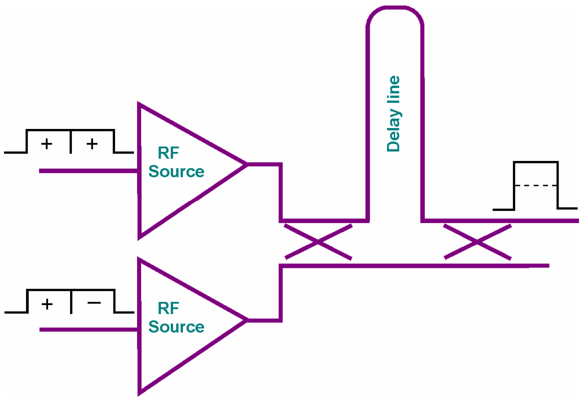
Active systems use “active” elements, which change their RF properties under external control.
Several laboratories work on active systems:
SLAC (silicon, ferromagnetic), Nizhniy Novgorod (plasma tubes, silicon), Omega-P/Yale (ferroelectrics).

But powerful enough active pulse compression system still does not exist.

Elements of passive systems do not change RF properties. Systems utilize only phase manipulation of RF sources. Passive systems can be divided roughly into SLED type and delay line type.



SLED



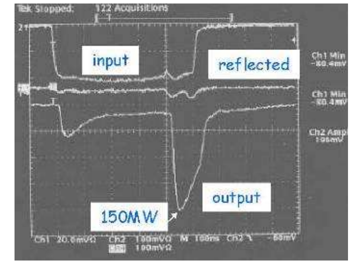
BPC (Delay line type)

**SLED Type:**

**Classic SLED (Z.D. Farkas,P.B. Wilson)**

**VPM (VLEPP Power Multiplier), based on open cavity (V.E. Balakin, I.V. Syratchev)**

**Advantage: compactness.**
**Disadvantages: efficiency < 80%, 'funny' output shape**




**14GHz VPM and pulses during test**

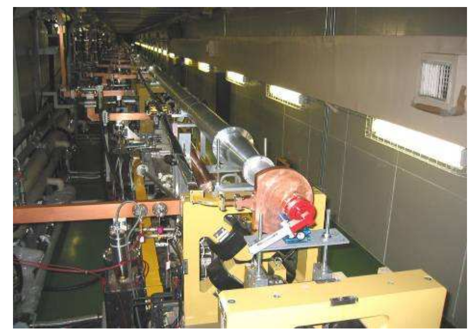
---

**Delay line type**

**Binary Pulse Compression System (BPC) (Z.D.Farkas)**

**Delay Line Distribution System (DLDS) (H.Mizuno)**

**Advantages: high efficiency, flat pulse shape.**
**Disadvantages: big sizes**



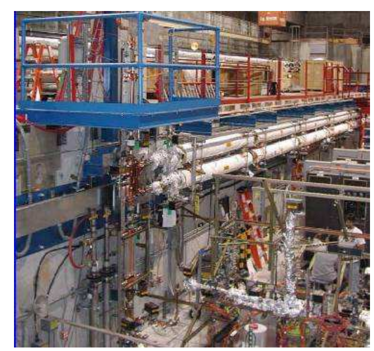
**Cold model of DLDS in KEK tunnel**

---

**"Hybrid" Type (SLED + Delay line)**

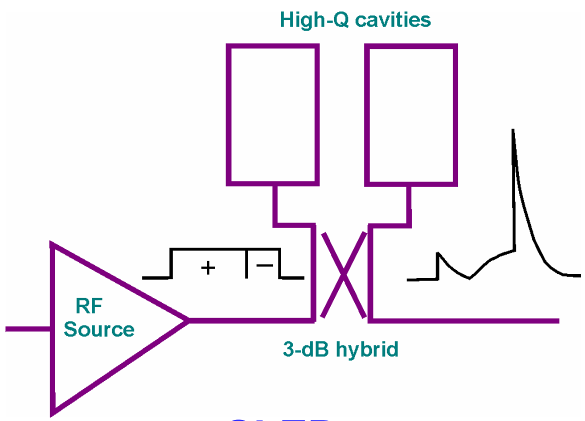
**SLED-II (P.B. Wilson, Z.D. Farkas, R.D. Ruth)**

**Advantages: flat pulse shape, smaller size then BPC and DLDS**
**Disadvantages: not 100% efficiency, still big sizes**

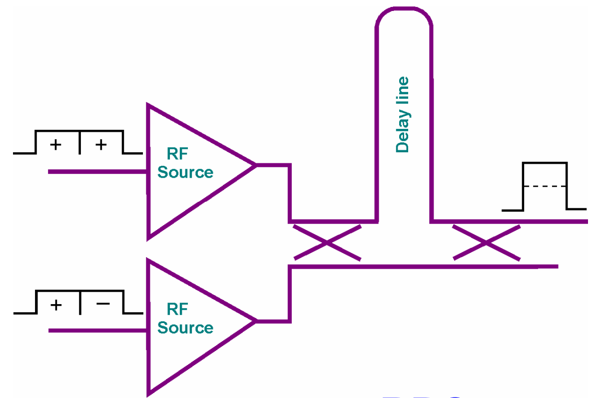


**SLED-II pipes in SLAC**

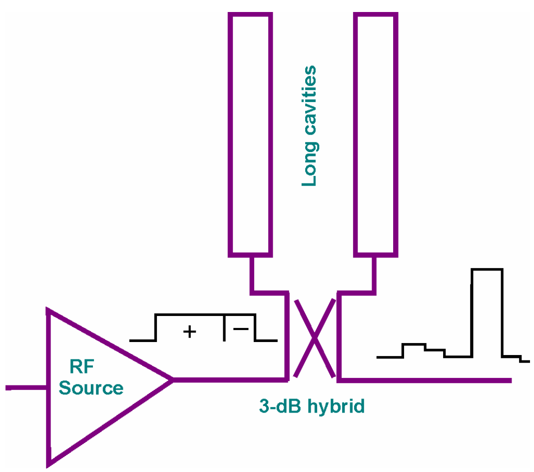
# Principle of operation



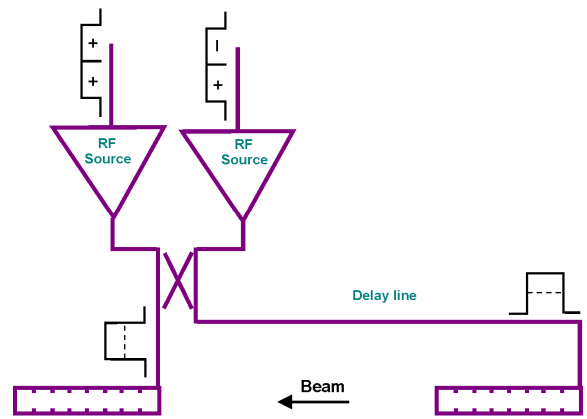

**SLED**




**BPC**



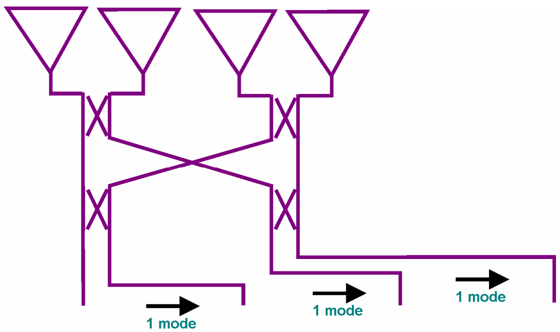

**SLED-II**



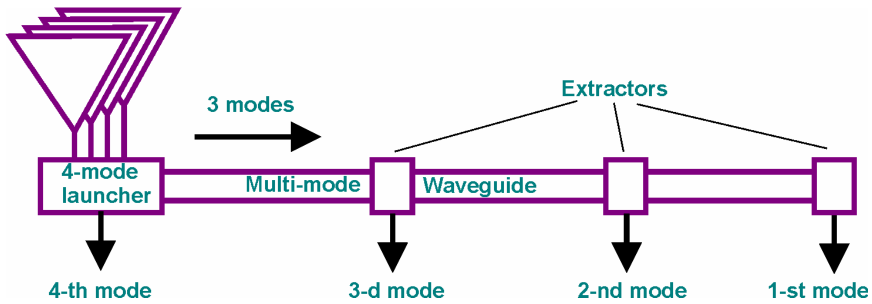

**DLDS**

We were excited when H. Mizuno invented DLDS –flat top pulse, 100% efficiency and length of pipe was twice smaller than for BPC.

DLDS can have several output ports and can be multimode:



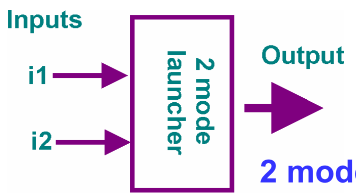

Single mode, 4 port DLDS




4 mode, 4 port DLDS

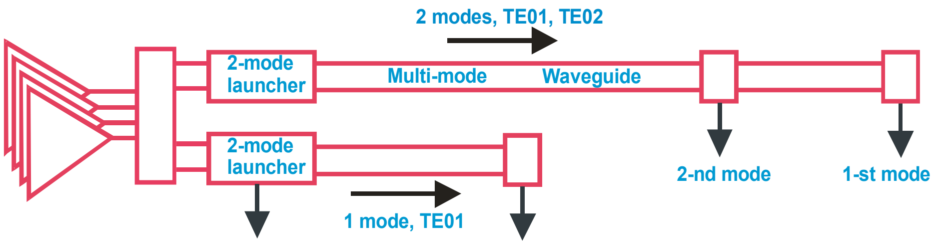
DLDS was chosen as Pulse Compression System for JLC and NLC.
SLAC choose 4 mode 4 port DLDS.
KEK was more cautious and choose 2 mode 4 port scheme.

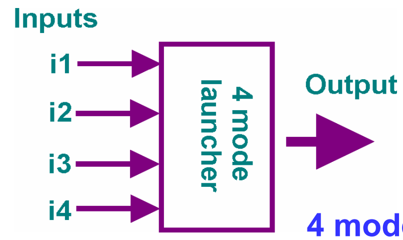
# Key element of multimode DLDS is mode launcher




2 mode in
1 waveguide

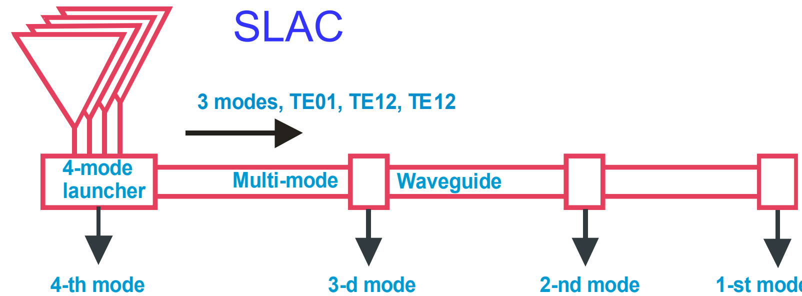
KEK



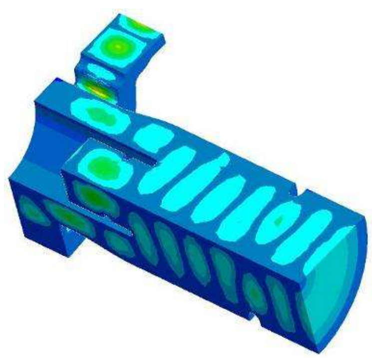




4 mode in
1 waveguide

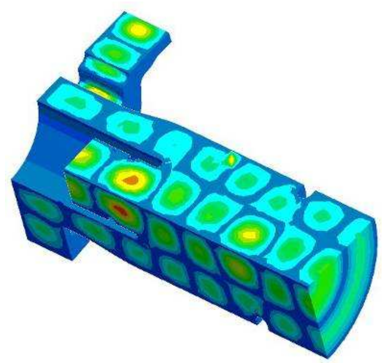
SLAC



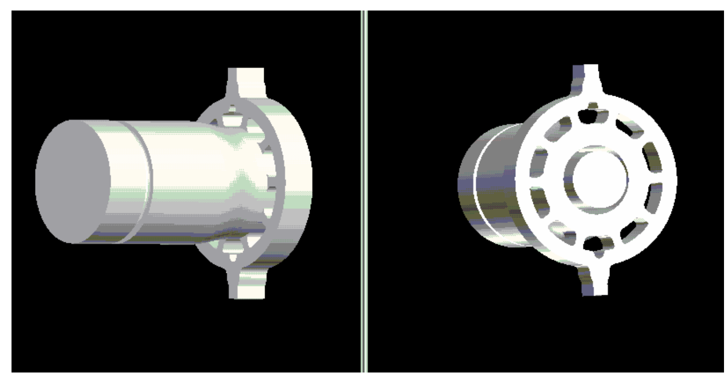

## $TE_{01}$-$TE_{02}$ launcher-extractor*



Launching $TE_{01}$



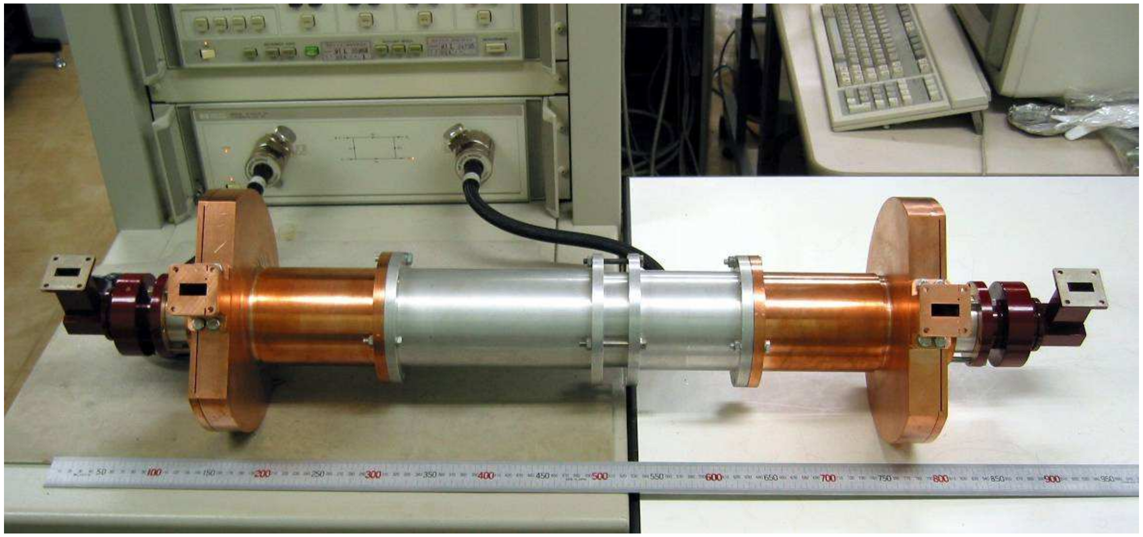
Launching $TE_{02}$



*S.Kazakov, “TE01-TE02 DLDS Elements”, RF Rulse Compression Distribution Workshop, SLAC, Octouber 2001

# $TE_{01}$-$TE_{02}$ launcher-extractor

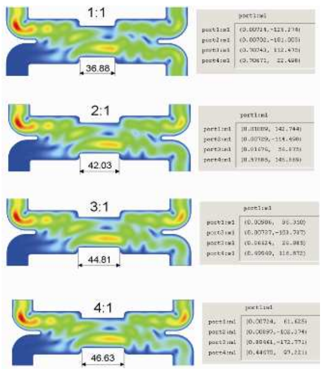
Part before brazing



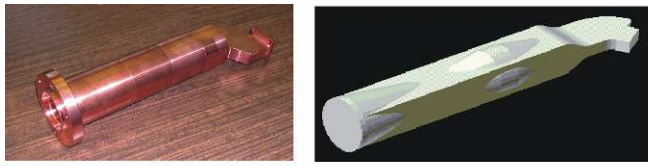
Under test

Assembled with tapers

# Menagerie of elements designed for Pulse Compression



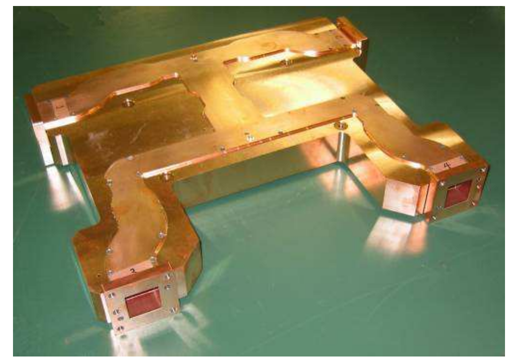

**Power divider for any ratio**



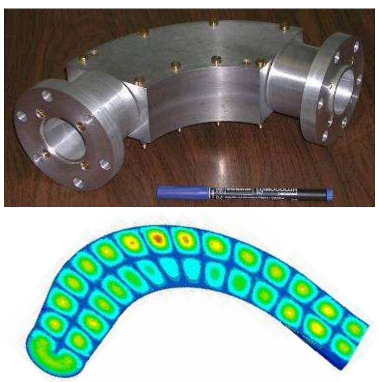
$TE_{10}$-$TE_{01}$ Converter-Launcher

**TE11-TE12 mode converter**

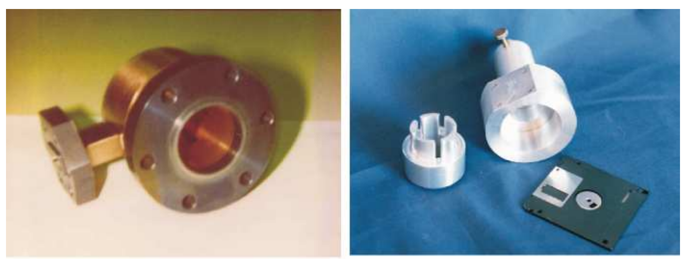
**TE01 power splitter**



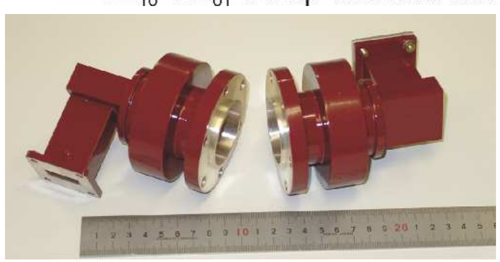
**Oversized SLED-II head**



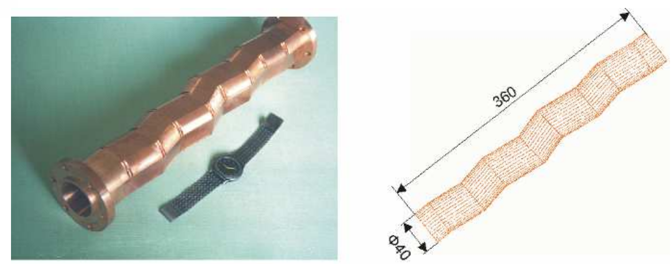
**TE01 bend**



$TE_{10}$-$TE_{01}$ Wrap-around Mode Converter

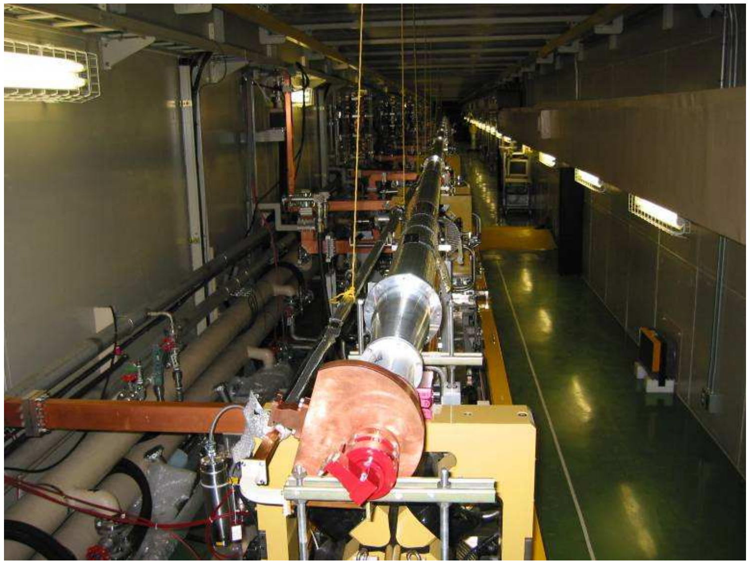


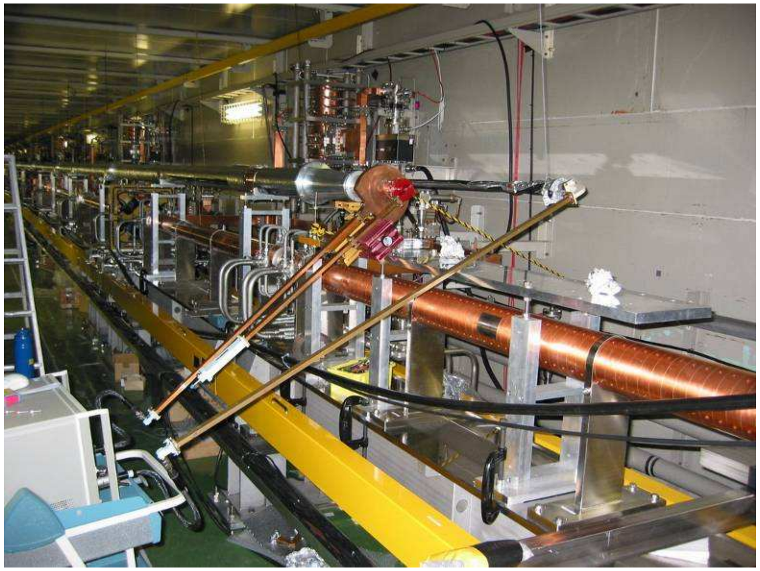
$TE_{10}$-$TE_{01}$ Choke Mode Converter




$TE_{11}$ -$TE_{01}$ Zigzag Mode Converter

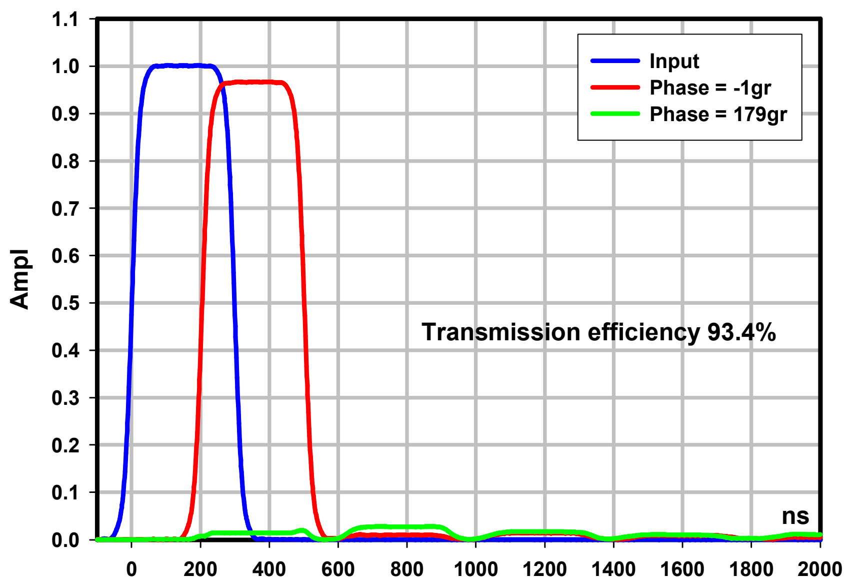
## Cold measurements of one 55-m arm of TE01-TE02 DLDS was carried out.



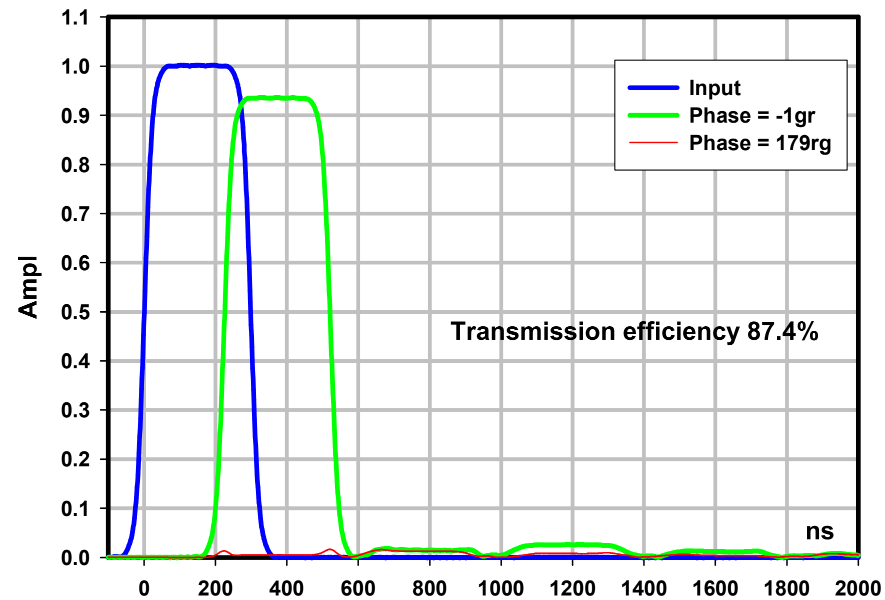


# Results of cold measurements of 55 m $TE_{01}$-$TE_{02}$ DLDS arm.

Extaction through D2_port_1 (TE01)




Extraction through D2_port_2 (TE02)

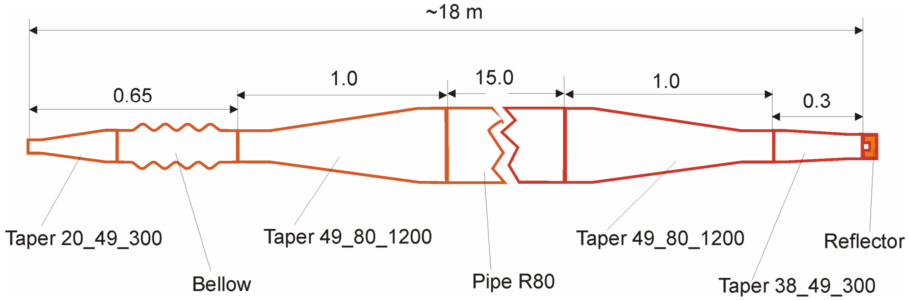


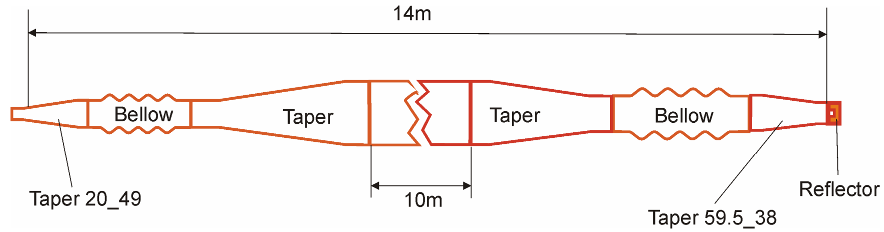

**Conclusion:**

The results of cold measurements are in good agreement with theoretical estimation.
Based on the results we can expect efficiency about **90%** for TE01 part ( 0.922 * Eff. Another 50m part) and **88%** for TE02 part. Average efficiency about **89%.**

**Elements of TE01-TE02 DLDS were successfully designed and tested.**

# Some interesting ideas now to make delay shorter for SLED – II*




**The efficiency (without loss in 3dB hybrid etc.) ~ 82%. Power gain ~ 3.26.**

---

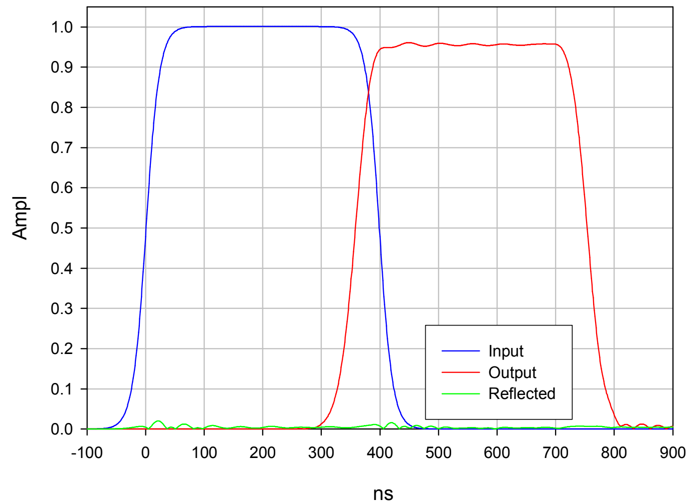
**It was surprising, but for simple cylindrical overmoded cavity there is combination of sizes when pulse is transmitted without distortion but with a big delay. Delay time is close to L*N_mode/C. Input mode is $TE_{01}$, N_modes - $TE_{0n}$ modes**

***S.Kazakov, "Multi-mode delay lines", ISG-XI, KEK, December 2003**

**Transmission through 32 cell**

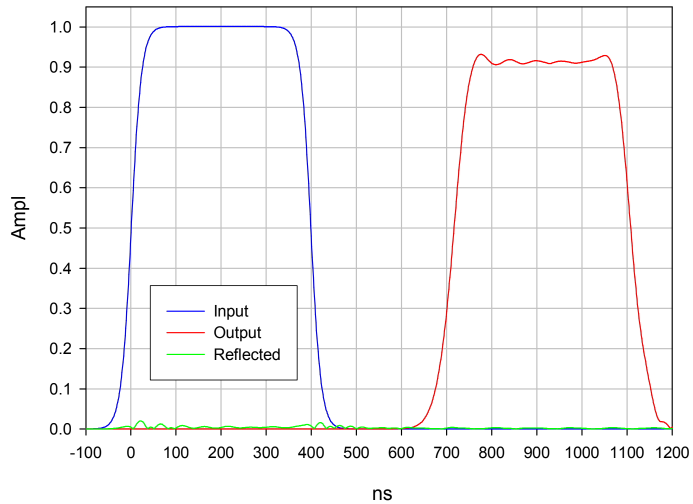
**Eff = 0.9118, Loss = 0.02477%/ns**

**Del = 21.33ns/m, Shape = 1.23e-2**

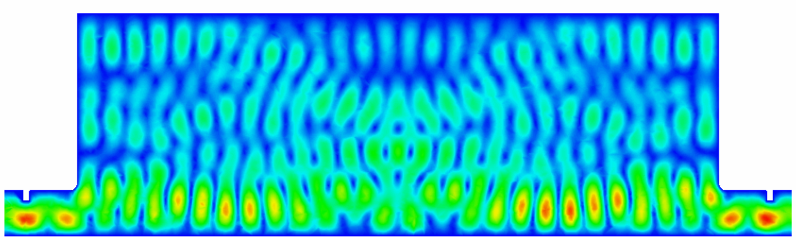



**Transmission through 64 cell**

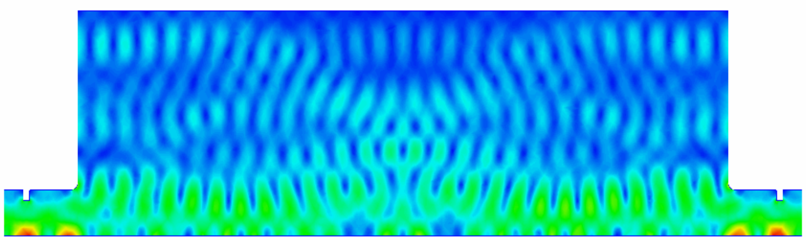
**Eff = 0.8311, Shape = 3.20e-2**




# Field patterns in the cell

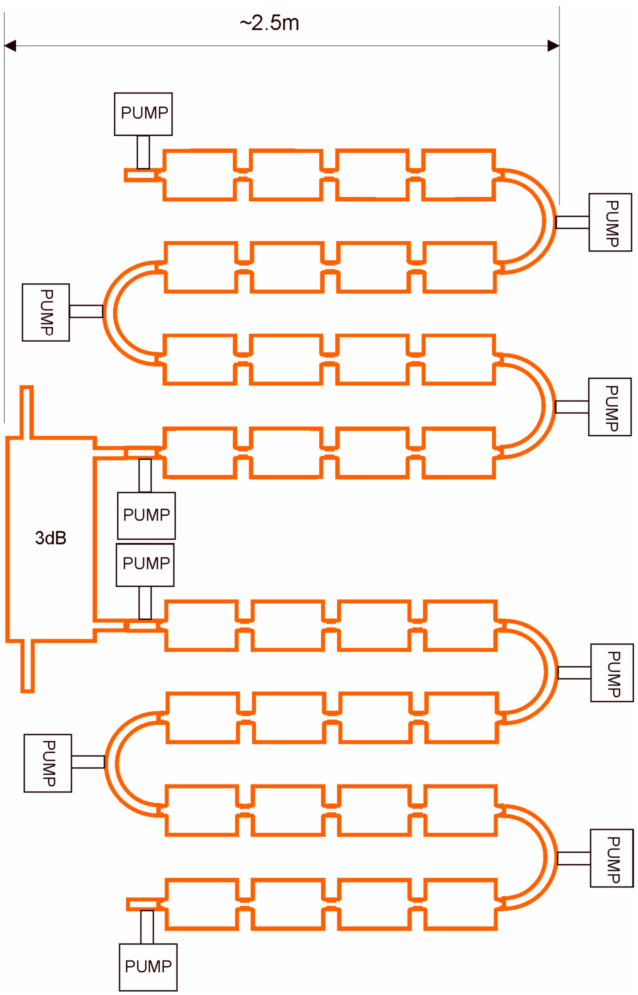


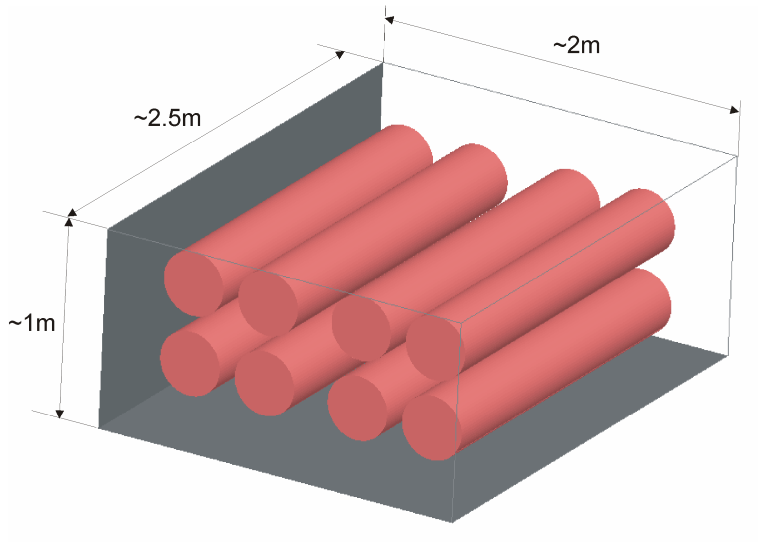
Electric field

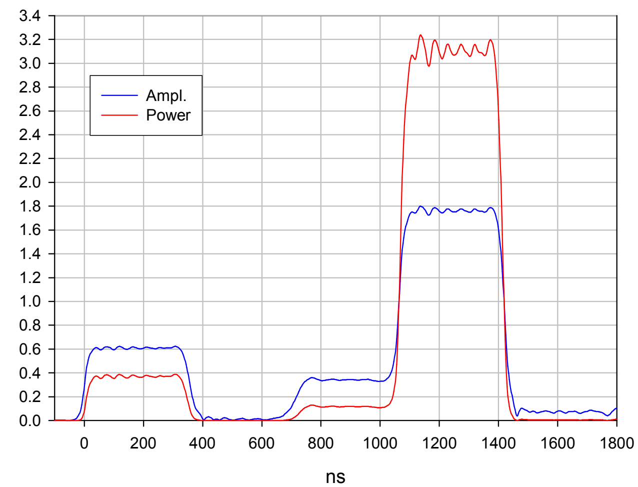


Magnetic field

# SLED-II can be packed into a box 1m x 2m x 2.5m:




**Result of simulation of SLED-II based on 16-cell delay lines.**

**Power gain ~ 3.1, Power variation ~ 7%,**

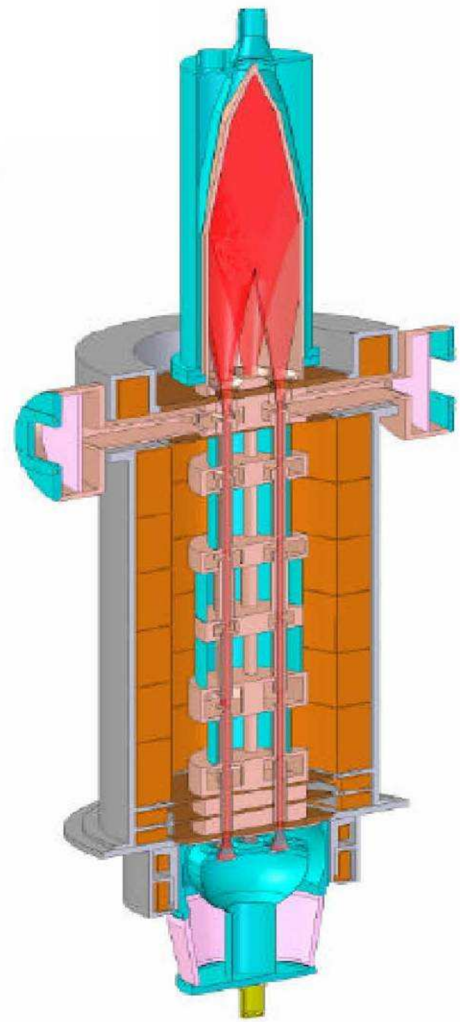

*Then climate changed suddenly*...

## Climate changed suddenly, but not too suddenly. Some time before, the design of L-band Multi-Beam Klystron (MBK) was started to have some MW for cold time.

**Design team:**
**Y.H. Chin (guidance)**
**A.Larionov (gun, optic)**
**V.Teryaev (RFstructure)**
**S.Kazakov (3D output cavity)**
**TOSHIBA (mechanical design, thermal analysis, manufacturing)**

### Design parameters

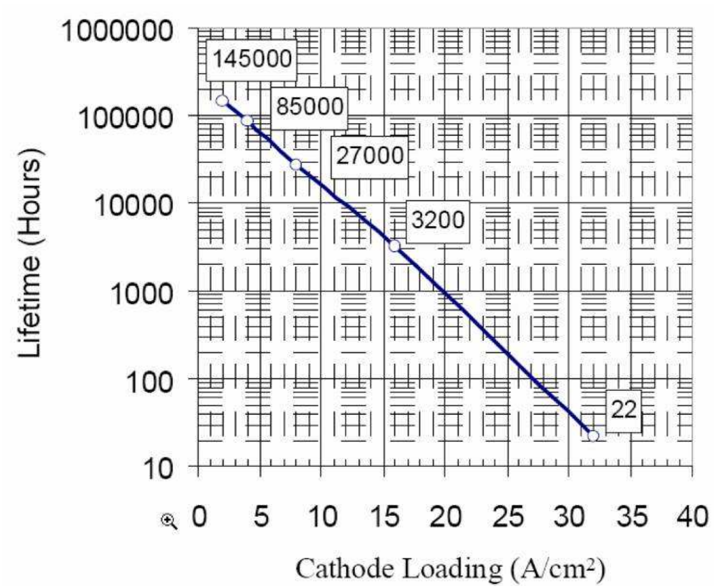
| | | |
|---|---|---|
| Frequency | 1300 | MHz |
| Output Power | 10 | MW |
| Average Output Power | 150 | kW |
| Beam Voltage | 115 | kV |
| Beam Current | 132 | A |
| Efficiency | >65 | % |
| RF Pulse Width | 1.5 | ms |
| Repetition Rate | 10 | pps |
| Saturation Gain | 47 | dB |
| Number of Beams | 6 | |
| Cathode Loading | <2.1 | A/cm$^2$ |
| Structure | 6 | cavities |
| RF Window | Pill Box WR-650 | |
| Tube Length | 2270 | mm |
| Solenoid Power | <4 | kW |



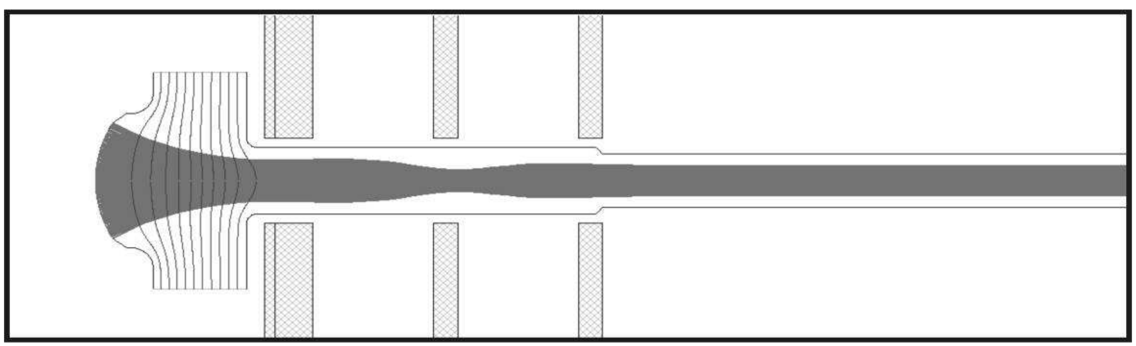
THE TOSHIBA E3736 MULTI BEAM KLYSTRON
S. Miyake, A. Yano (Toshiba Electron Tubes & Devises Co., Ltd. , Japan)
S. Kazakov, A. Larionov, V. Teryaev (BINP, Russia)
Y. H. Chin (KEK, Japan)

## To increase the lifetime of cathodes, the cathode current density was reduced < 2.1 A/cm

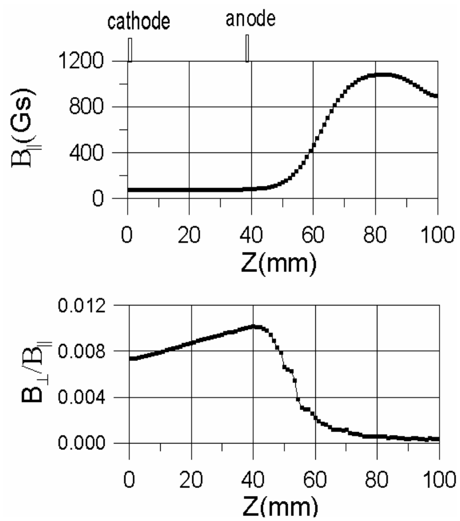
M-type dispenser cathode (CPI data)



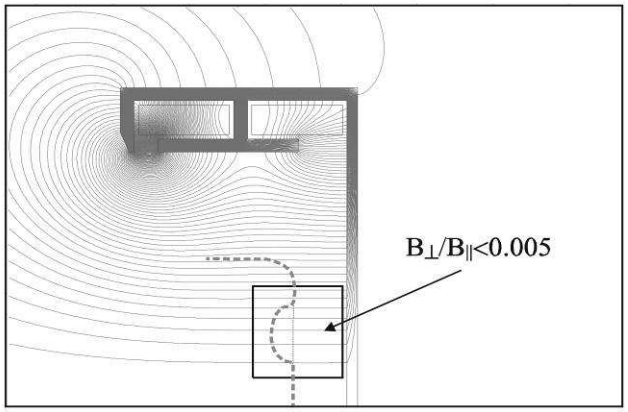

Cathode of TOSHIBA E3736 MBK



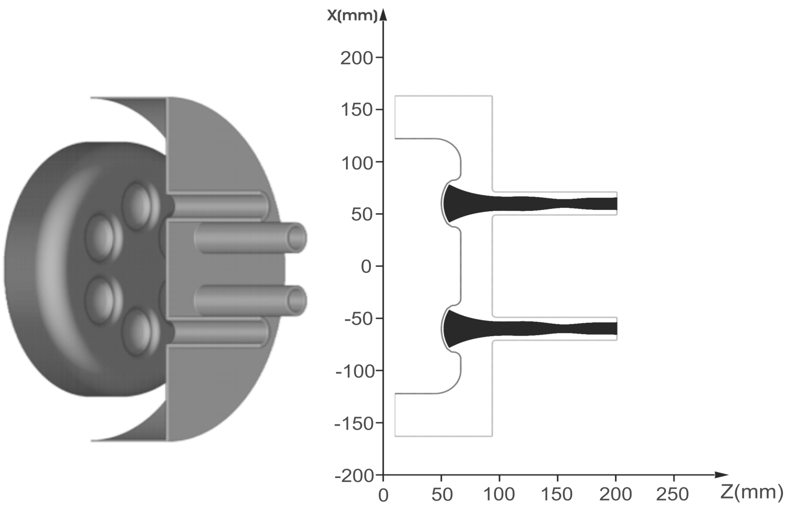
The main challenge was to form magnetic field with high local "axial" symmetry at the aria of beamlets, by making beamlets 2D.



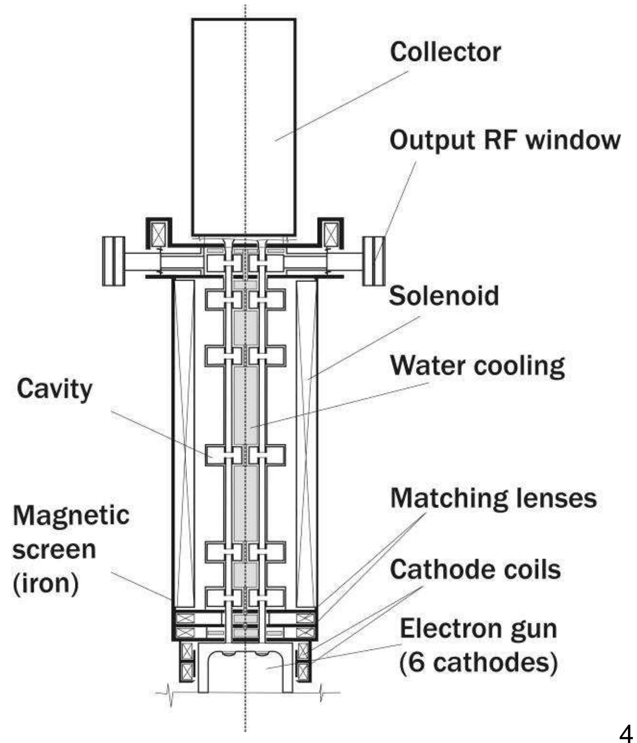

Magnetic field distribution along axis of the individual beamlet.



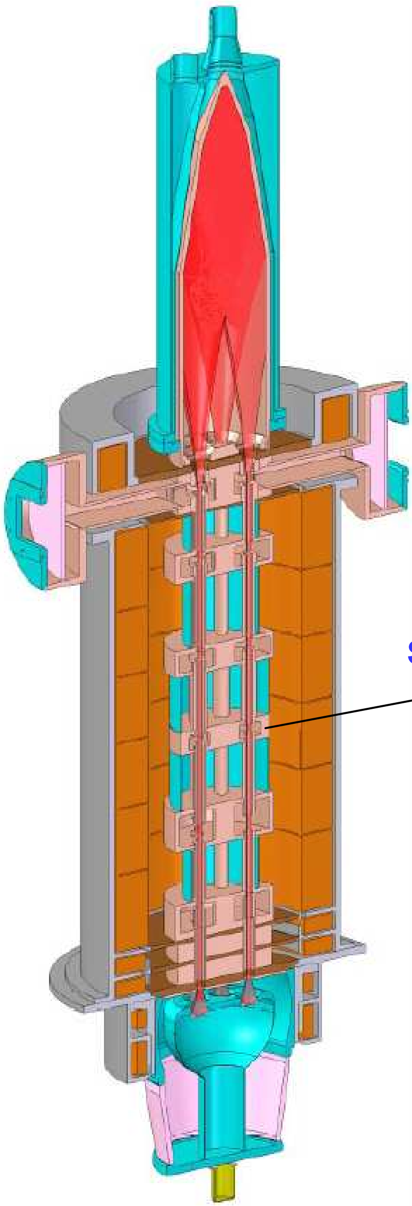

2D analog of magnetic system for the magnetic field forming at the gun (A.Larionov)



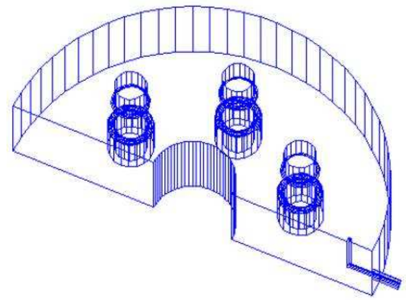

Example of gun modeling by GUN3D code. (A.Larionov)



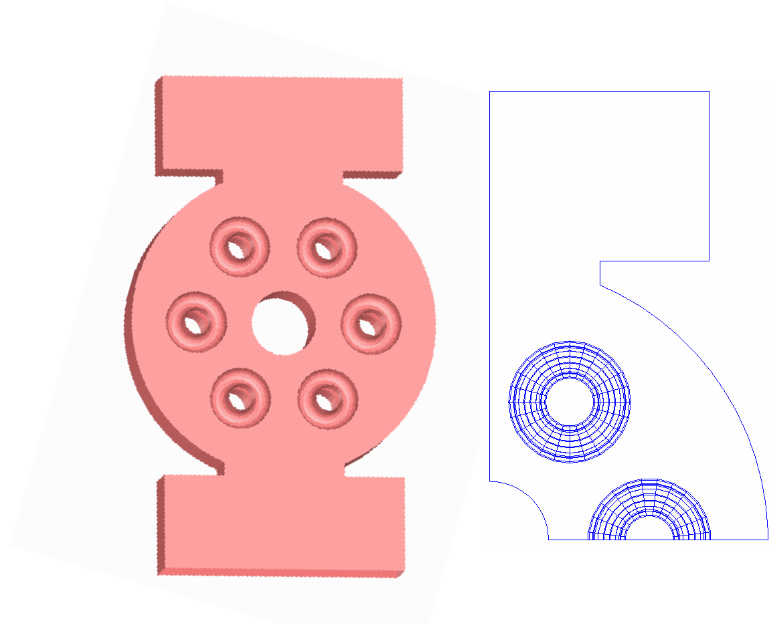
# Cavity system of MBK



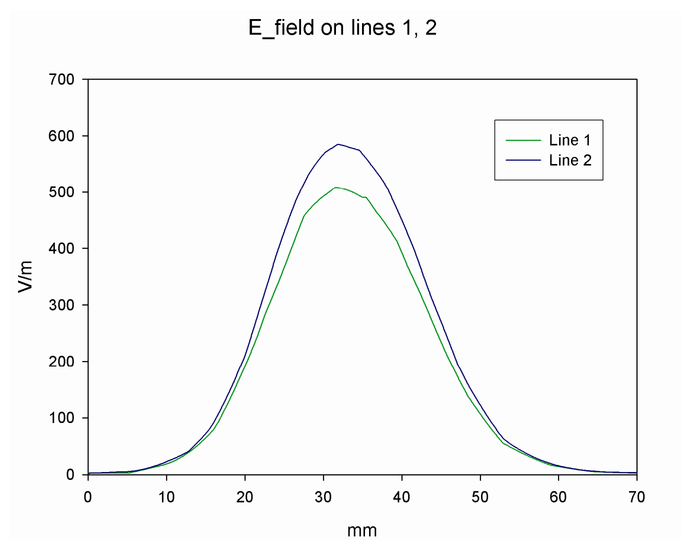

Second harmonic cavity made klystron noticeably shorter



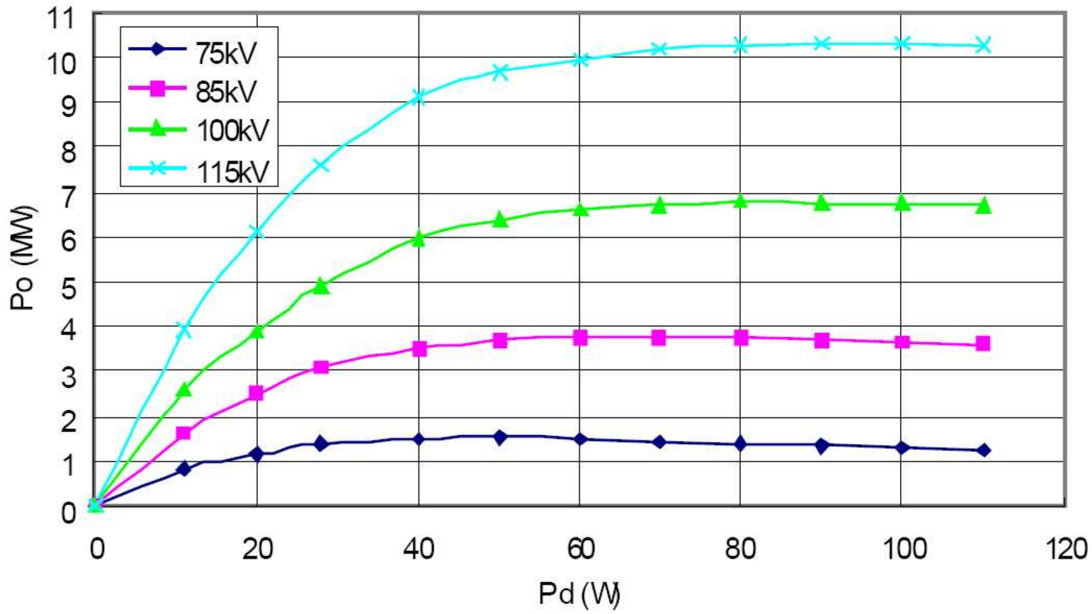
**Input cavity (half)**



**Output cavity**



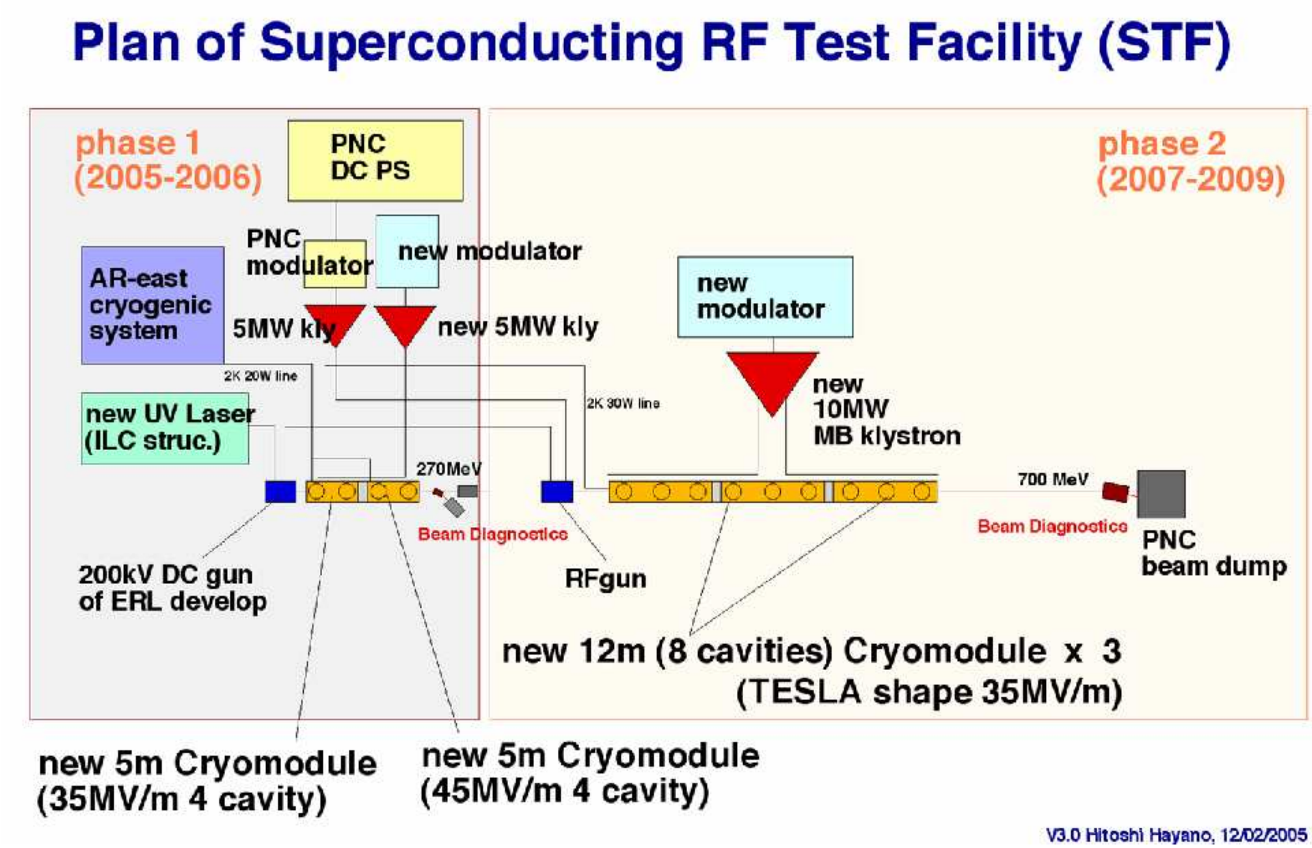

**Electric field profile at the axis of different beamlets**



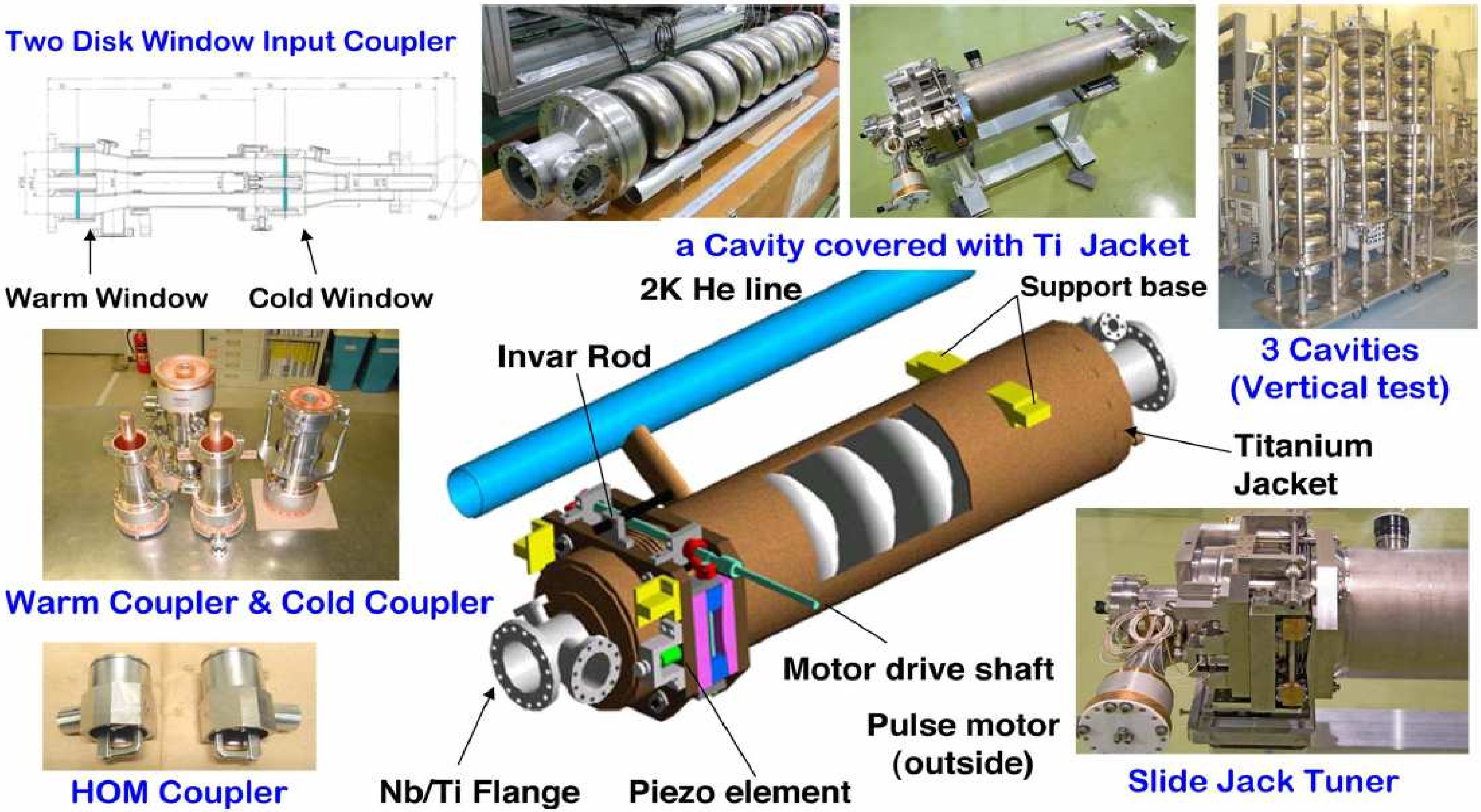

Measured performance

- Voltage: 115kV
- Current: 135A
- Output Power: 10.4MW
- Efficiency: 67%
- Pulse duration: 1.5ms
- Rep. Rate: 10Hz

# STF in KEK

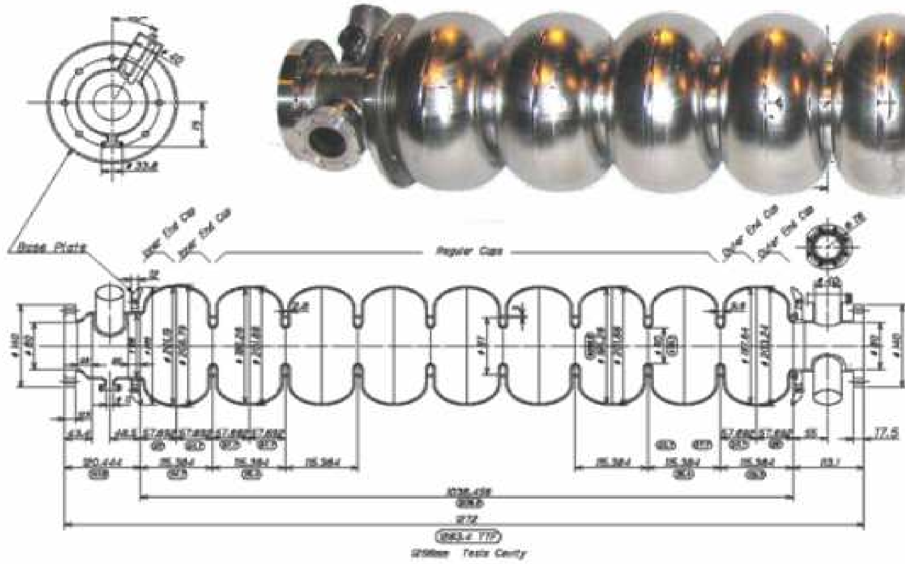

Plan of Superconducting RF Test Facility (STF)
phase 1
(2005-2006)
PNC
DC PS
phase 2
(2007-2009)
PNC
modulator
new modulator
AR-east
cryogenic
system
5MW kly
new 5MW kly
new
modulator
2K 20W line
2K 30W line
new
10MW
MB klystron
new UV Laser
(ILC struc.)
270MeV
700 MeV
Beam Diagnostics
Beam Diagnostics
PNC
beam dump
200kV DC gun
of ERL develop
RFgun
new 12m (8 cavities) Cryomodule x 3
(TESLA shape 35MV/m)
new 5m Cryomodule
(35MV/m 4 cavity)
new 5m Cryomodule
(45MV/m 4 cavity)
V3.0 Hitoshi Hayano, 12/02/2005

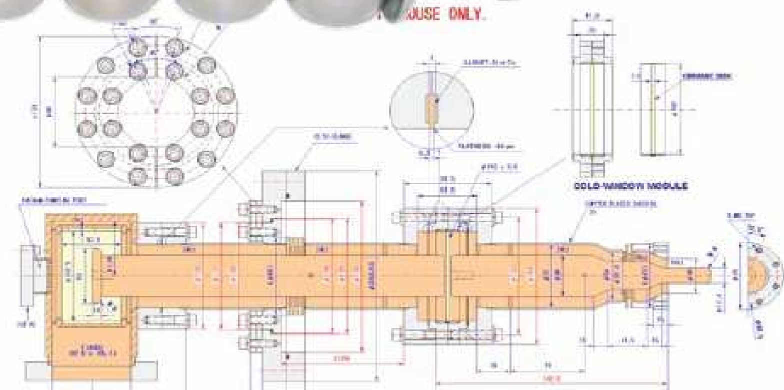
# TESLA style Baseline Cavity Package



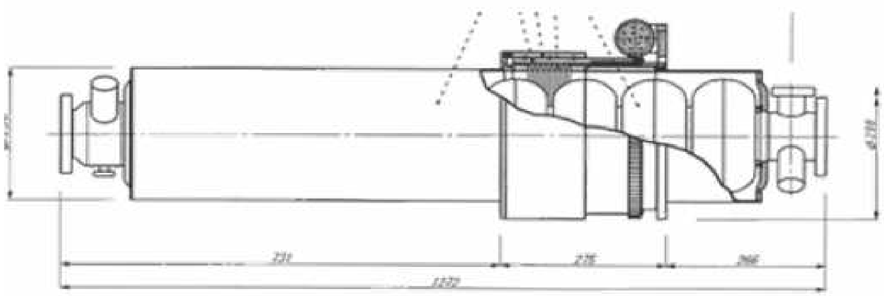

**Total 4 9-cell cavity were fabricated.**

# LL ICHIRO cavity package for High Gradient





Input Coupler using capacitive coupling



**Coaxial ball screw tuner**

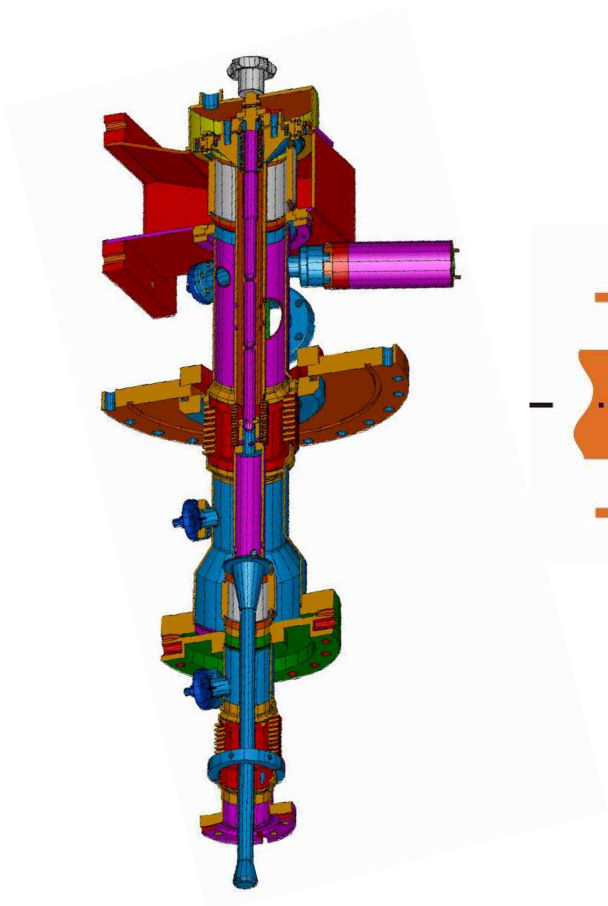
Dia:276mm

Lead: 40mm

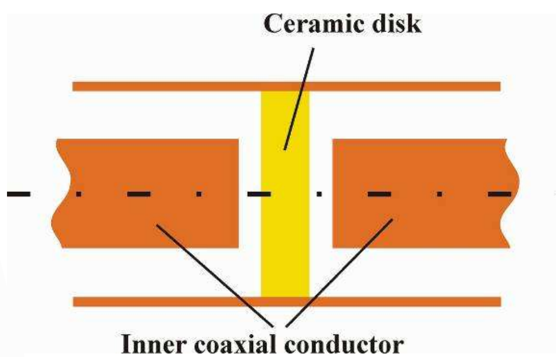
Ratio: 21:1

Tuner test stand

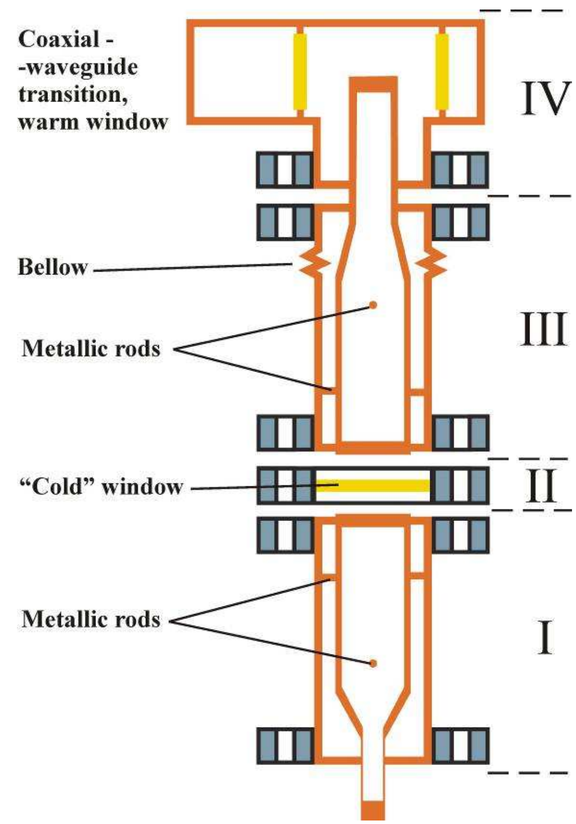
The present TTF-III coupler is quite complicated end expensive. We decided to try to design and build a cheaper coupler. As cold window we chose a simple disk window. In this case connection between cold and warm part become simple and coupler can be divided into several modules.



TTF-III Coupler



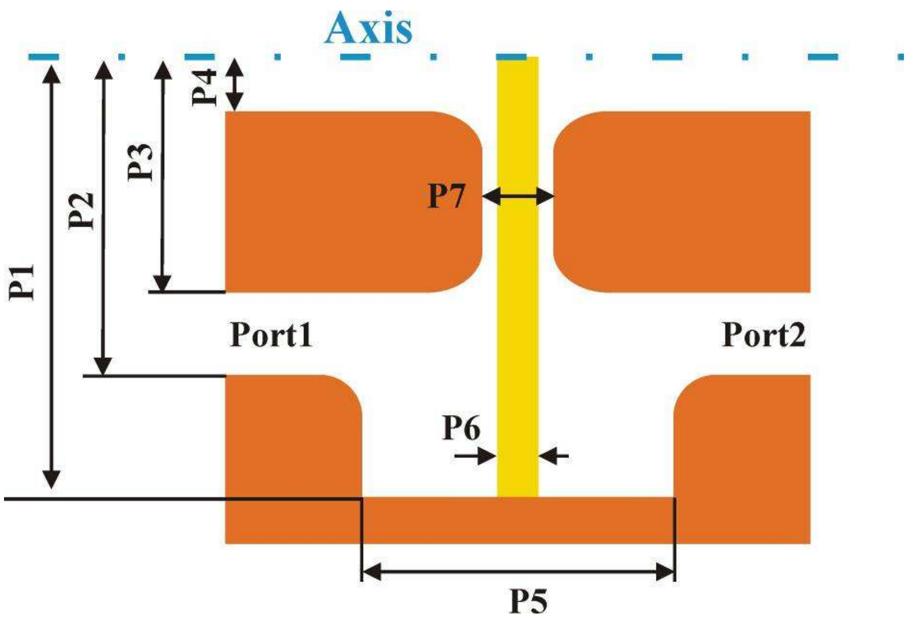

Idea of cold window with capacitive coupling

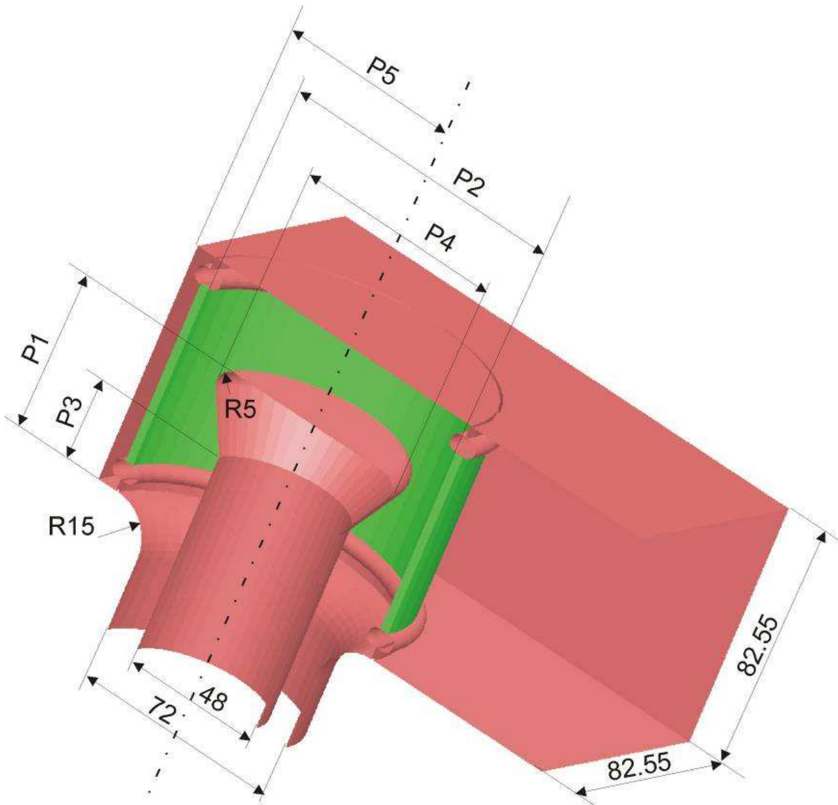



Possible module structure of new coupler

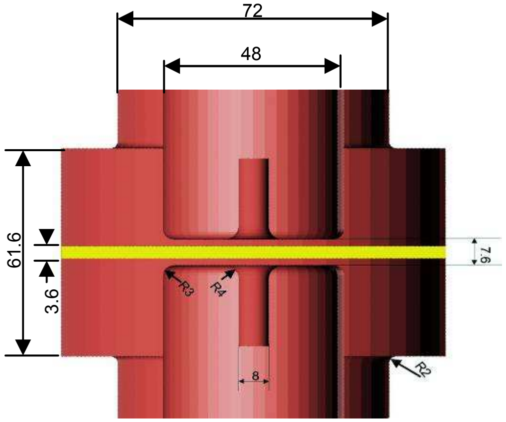
S. Kazakov, H. Matsumoto, "Input coupler with capacitive window", KEK,Japan, March, 2005

Cold and warm window were optimized in automatic regime to minimize electric field at the ceramic and in air and to maximize passband. Many thousands of version were analyzed.

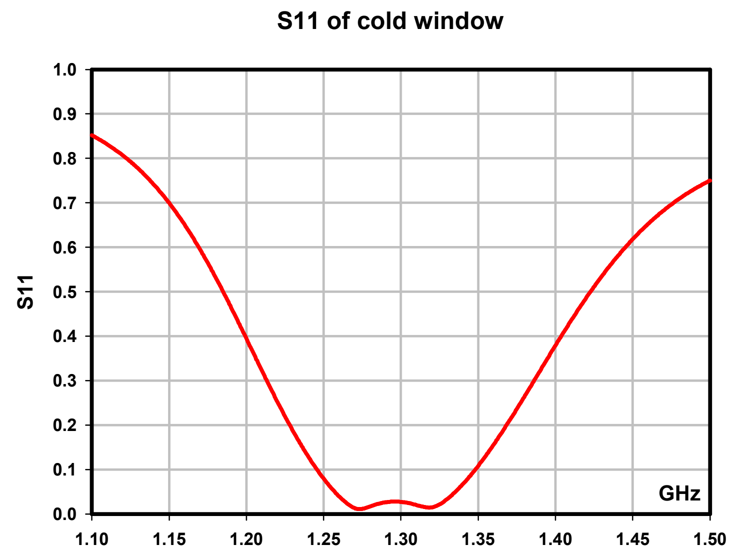



Geometries of cold and warm windows and parameters of optimization ($P_1$-$P_N$)

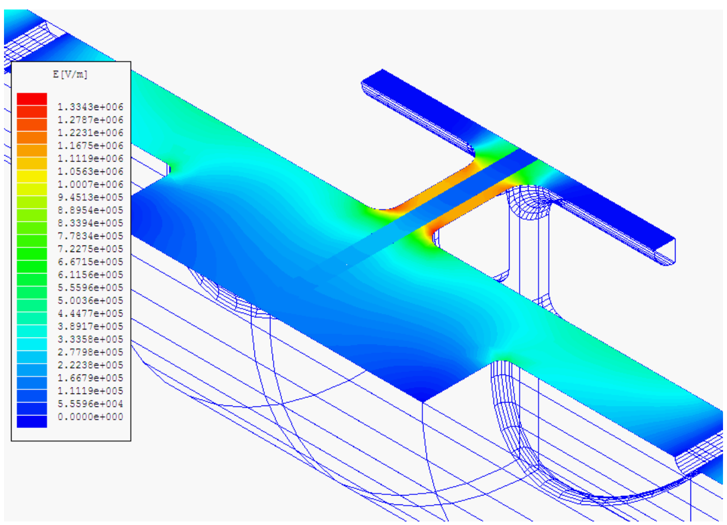


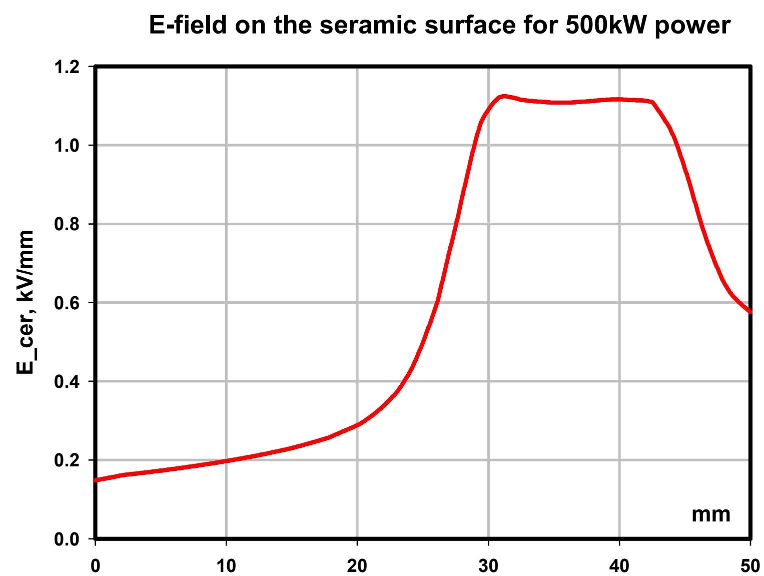

# Cold window



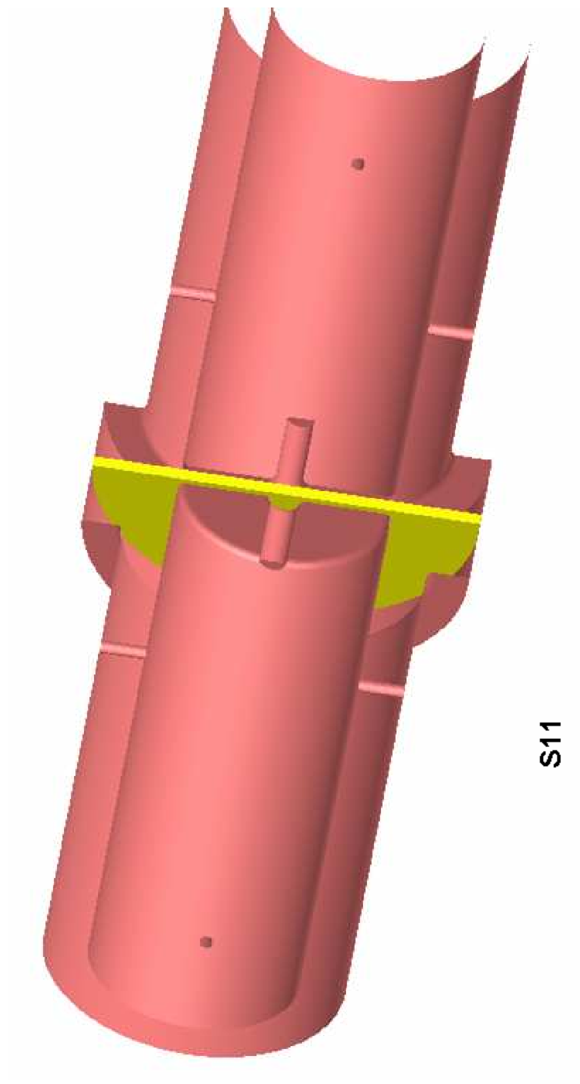

**Parameters of cold window:**

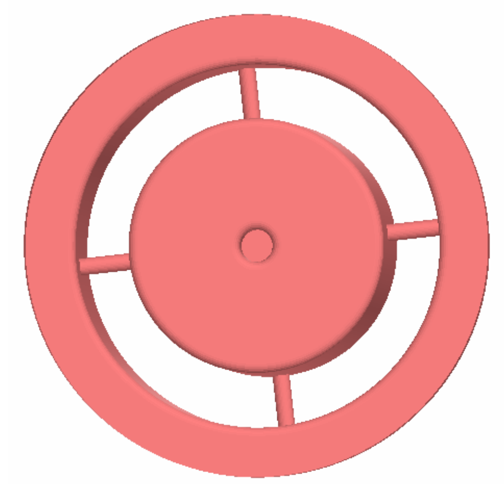
| | |
|---|---|
| Ceramic diameter | 102mm |
| Ceramic thickness | 3.6mm |
| Outer coaxial conductor | Φ72mm |
| Inner coaxial conductor | Φ48mm |
| Passband | 100MHz |
| Max. E-field on ceramic (500kW) | 1.15 kV/mm |



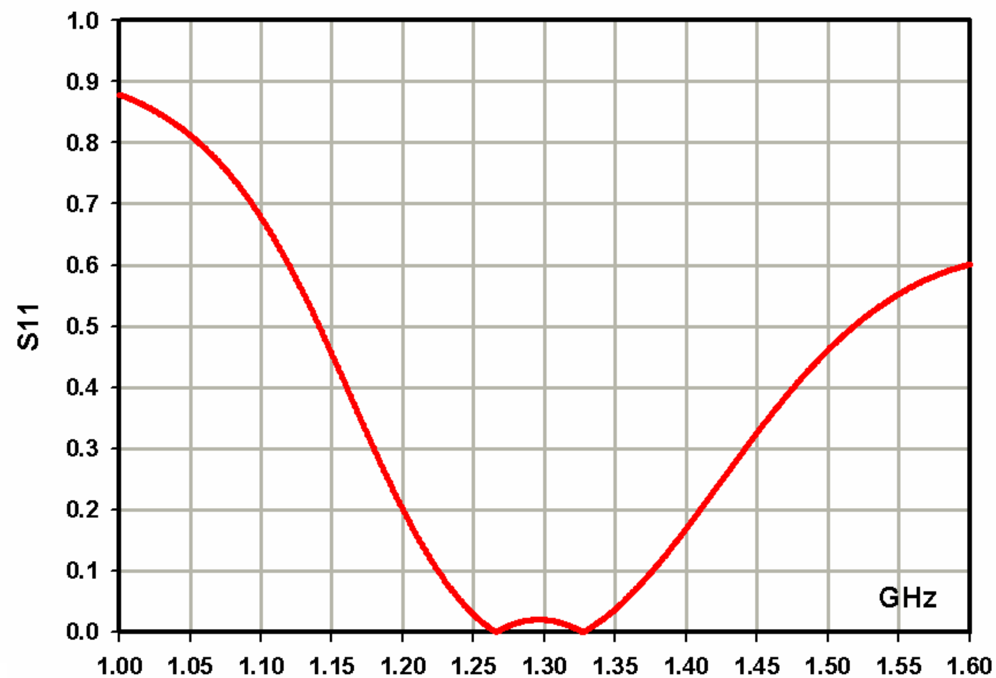


# Supports of inner conductors

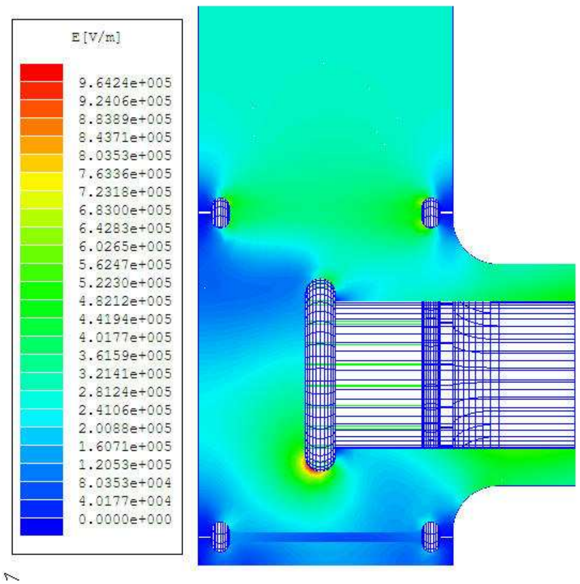




Window r3_5912_4423_1161
supports 180gr,
configuration W, -27mm, S, 12mm, S

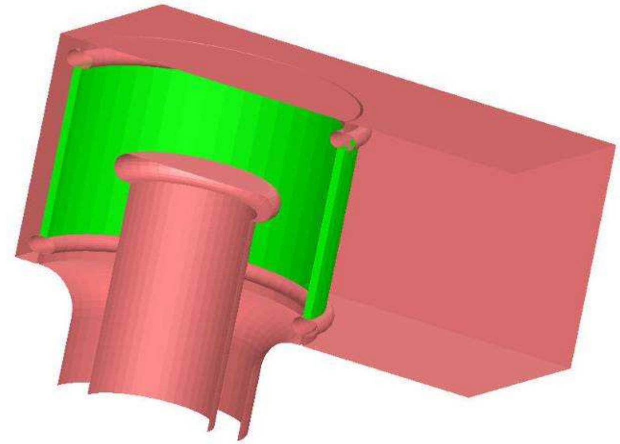


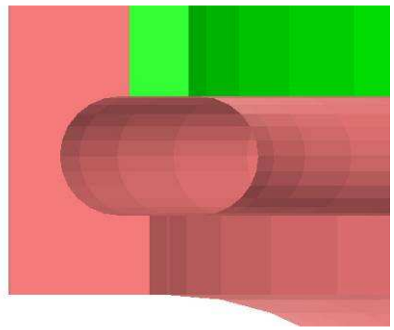
# Warm window



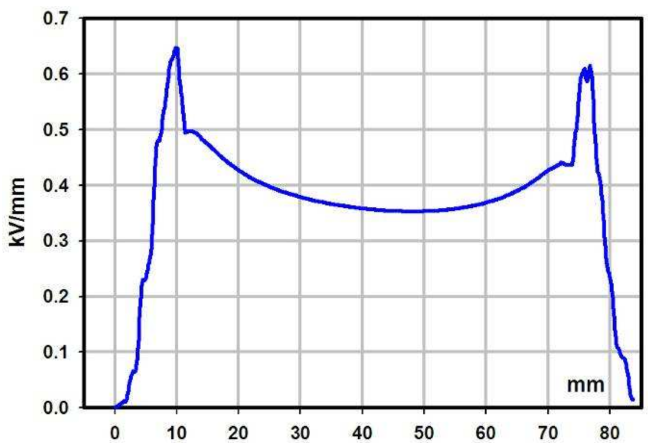

Electric field, 500 kW

P1 = 48
P2 =102.5
P3 = 38
P4 =63
P5 = 61.94
R = 3





Geometry of ceramic-metal joint

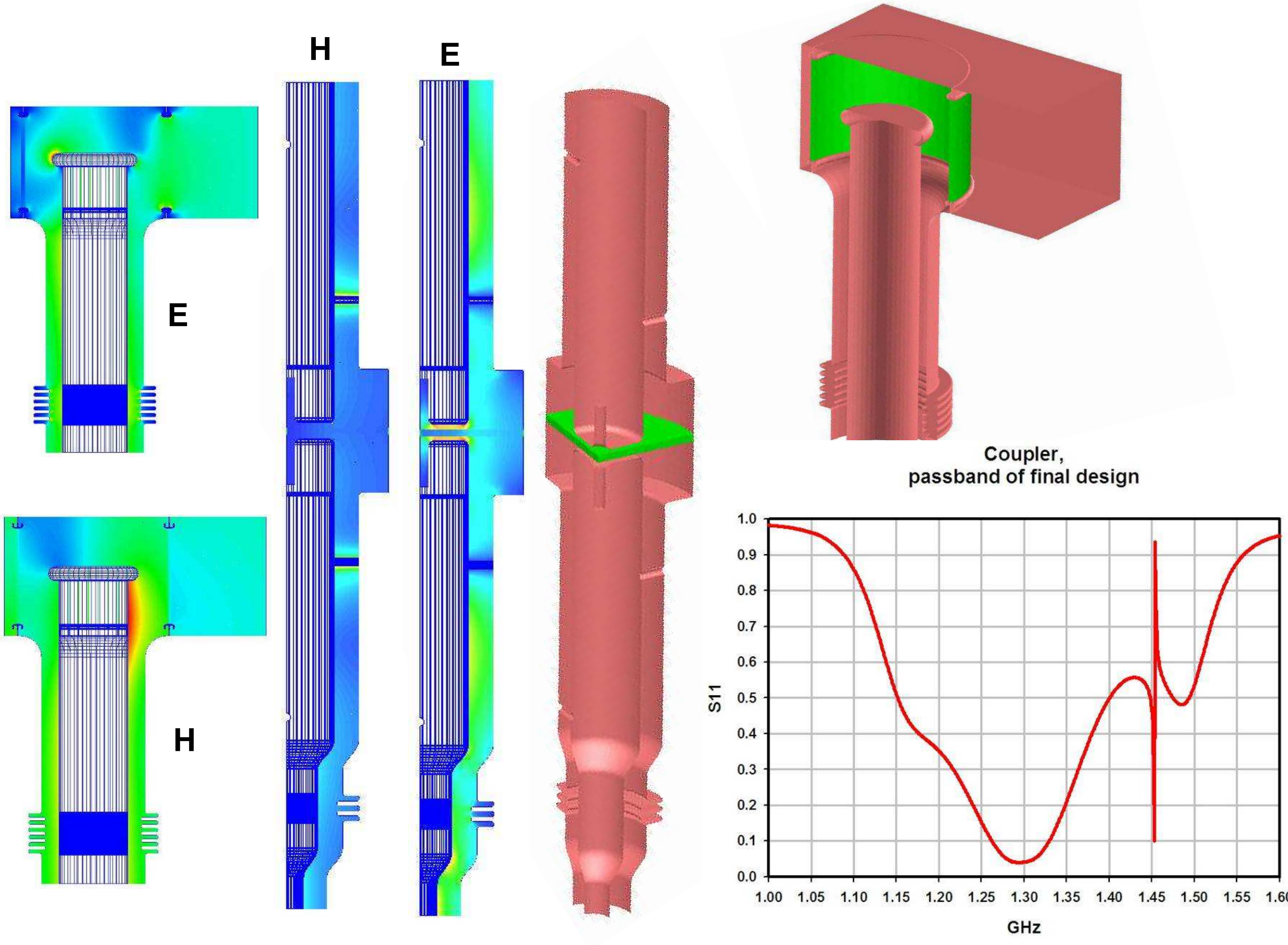



Electric field in air


**Parameters of warm window (500kW):**

| | |
|---|---|
| Passband | 109 MHz |
| Max. E-field in air | ~ 0.65 kV/mm |
| Max. E-field on the ceram. | ~ 0.5kV/mm |

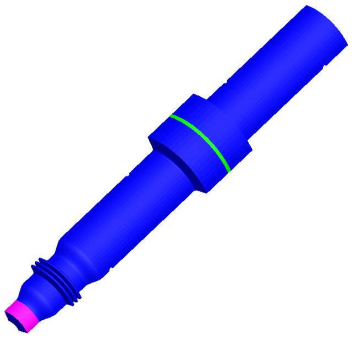
# Full geometry, example of simulation and passband of coupler.

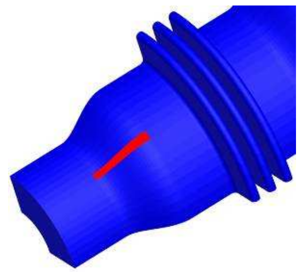


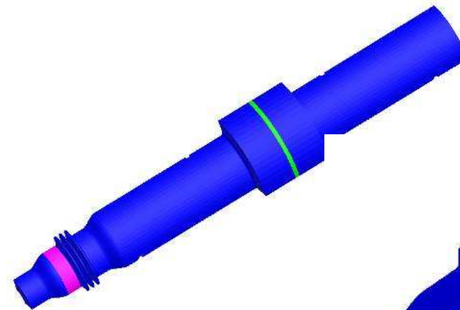
# Design parameters of coupler

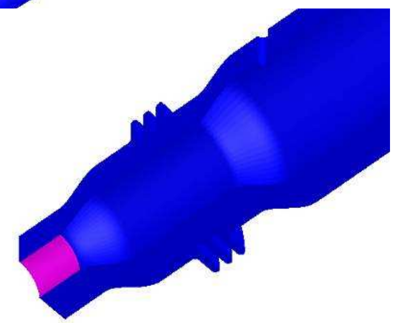
| | |
|---|---|
| Frequency | 1.3 GHz |
| Input | Waveguide, WR650 |
| Output | Coaxial, D40mm x 17.4mm |
| Passband | 70 MHz (SWR < 1.2) |
| Max.E-field, cold window | 11.5 kV/cm (500kW) |
| Max.E-field, warm window | 5 kV/cm (500kW) |
| Max.E-field, air | 7 kV/cm (500kW) |

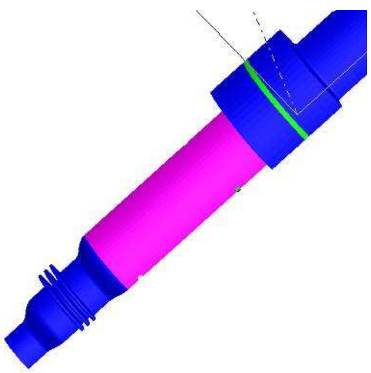
# Example of analyses of dynamic loss

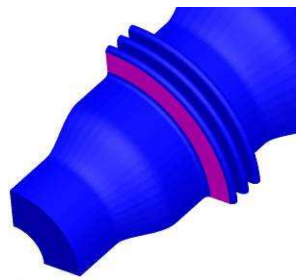


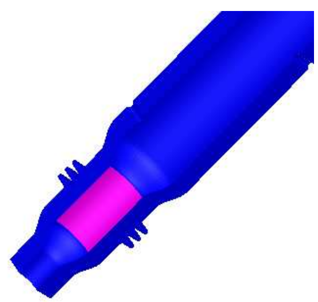


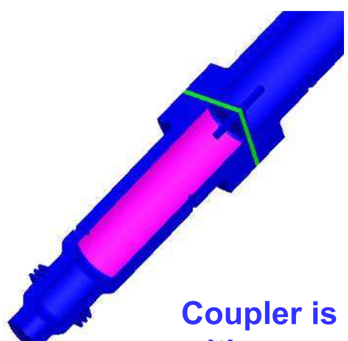


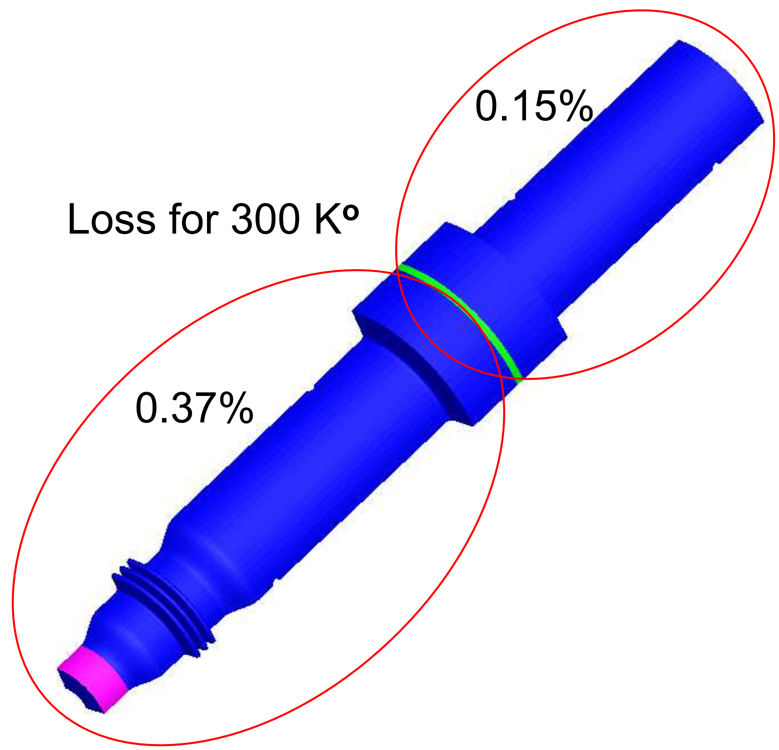






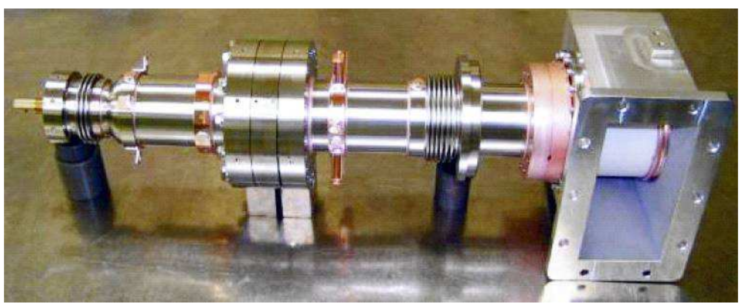


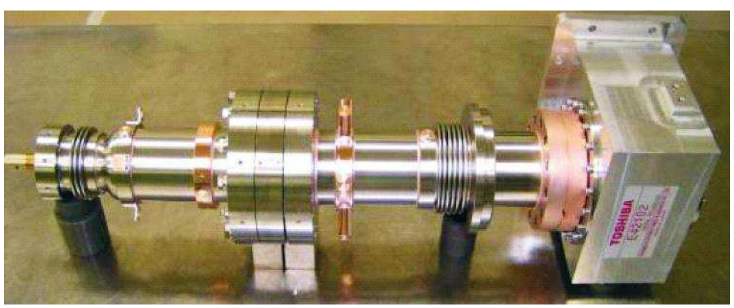





Coupler is made mostly from stainless steel coated with copper. Loss strongly depends on RRR of coating. As we found lately the current technology provides rather poor RRR =3

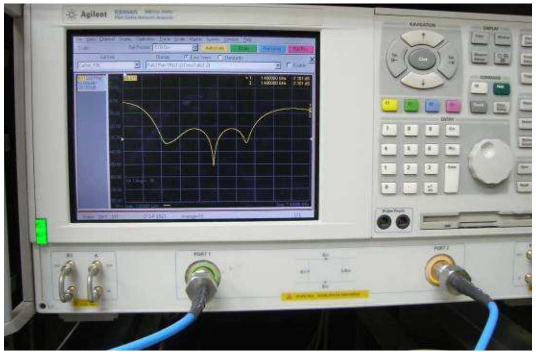
# TOSHIBA made four couplers

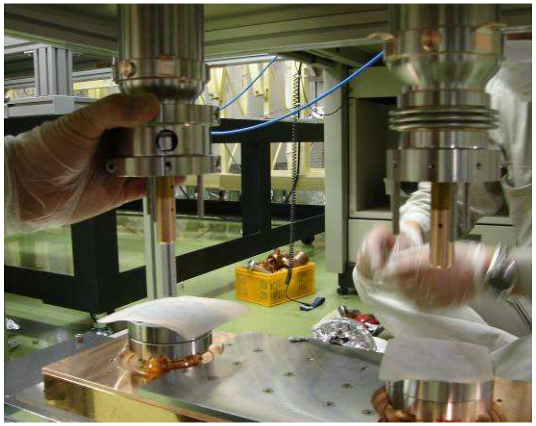


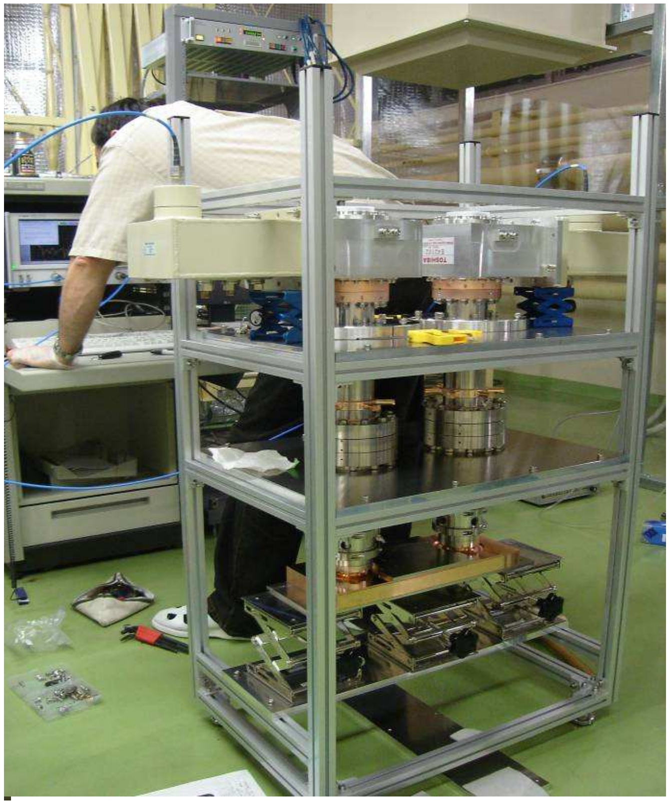


## Cold measurement.

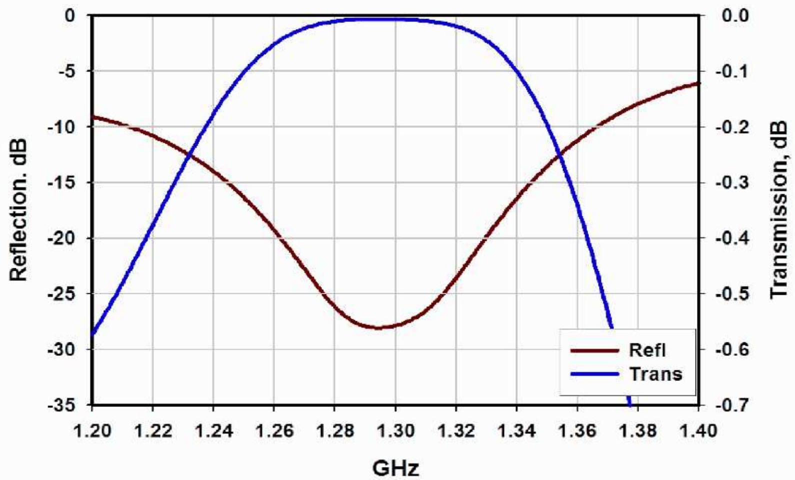
TOSHIBA did mechanical job perfectly! These rather complicated devices was built without any single preliminary RF cold measurements. But we got good SWR instantly just after assembling! It was a big relief.



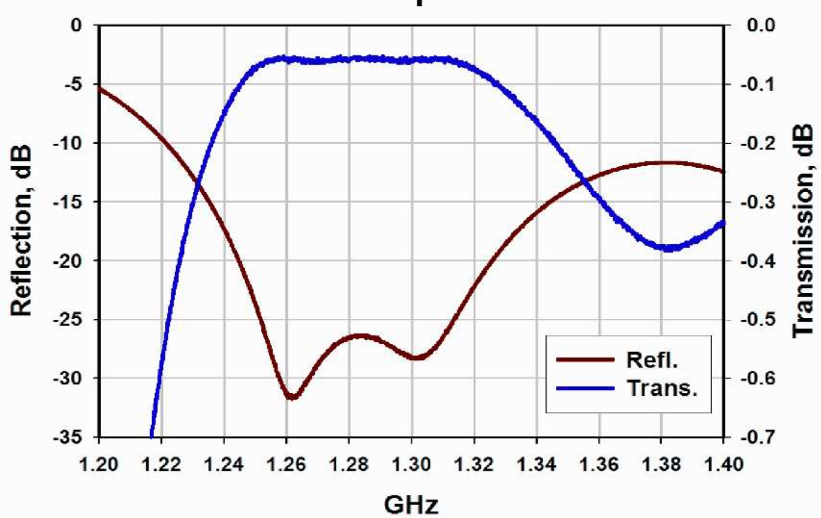





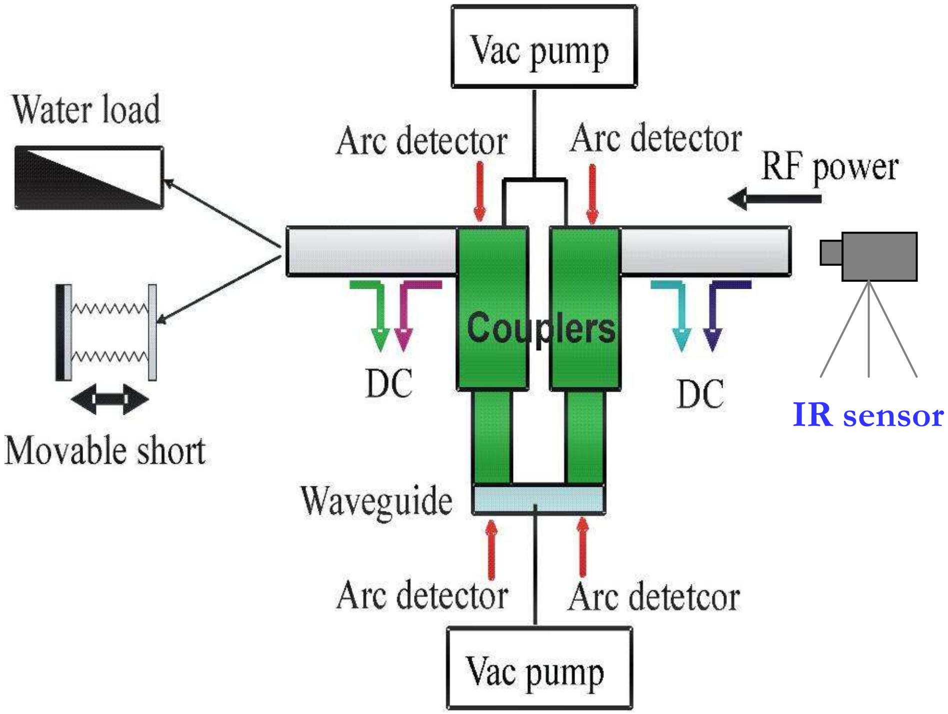
## Calculated passband of single coupler



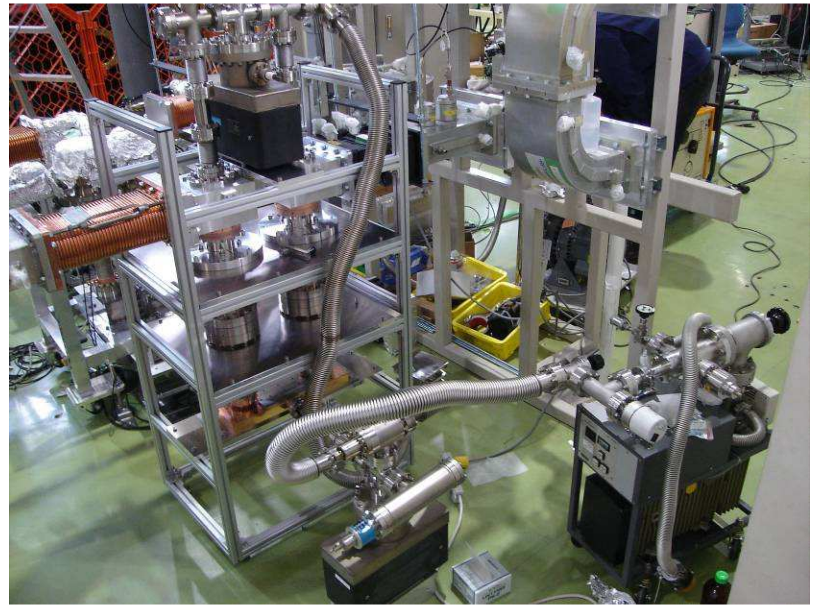

## Measured passband




# High power test stand

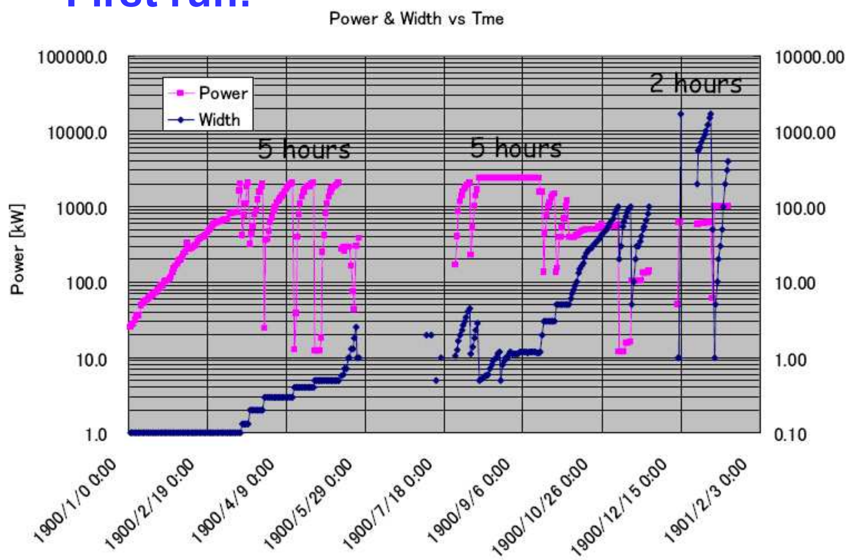



# High power test

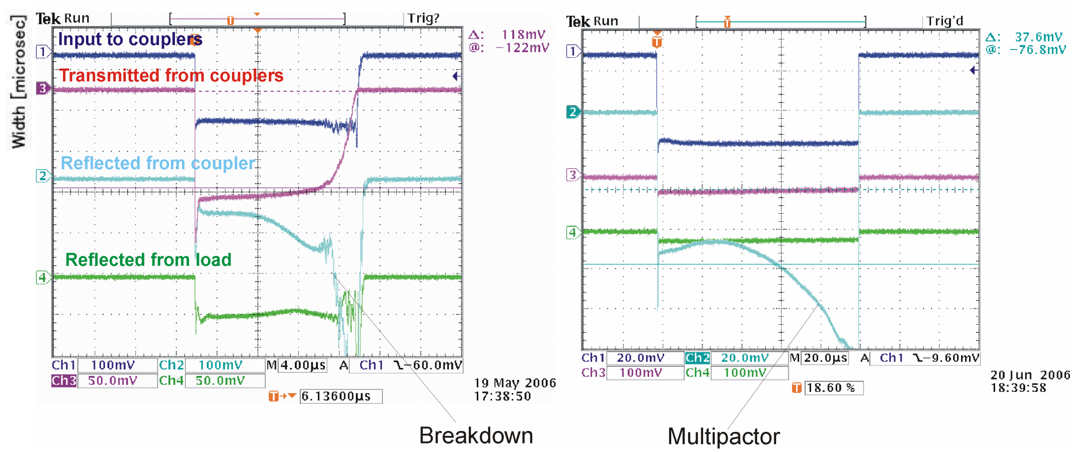


# Two run were performed.

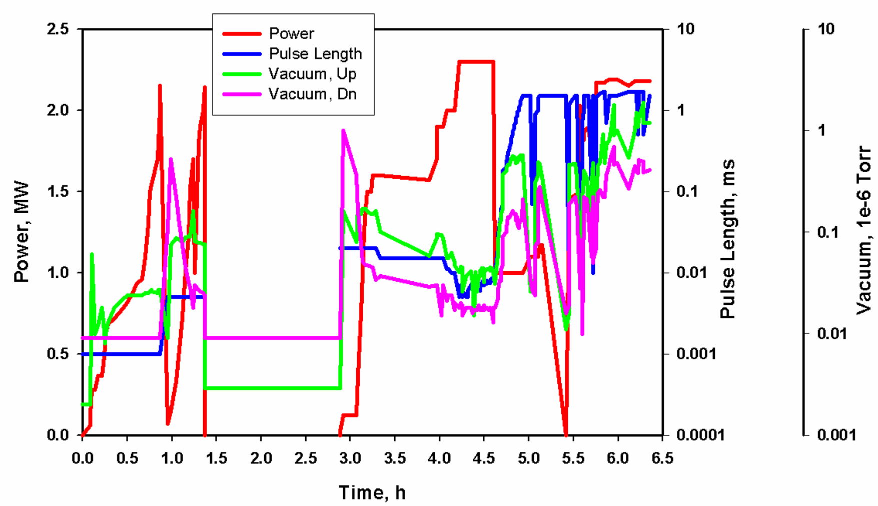
## First run:




## Typical pulse shapes at beginning of conditioning



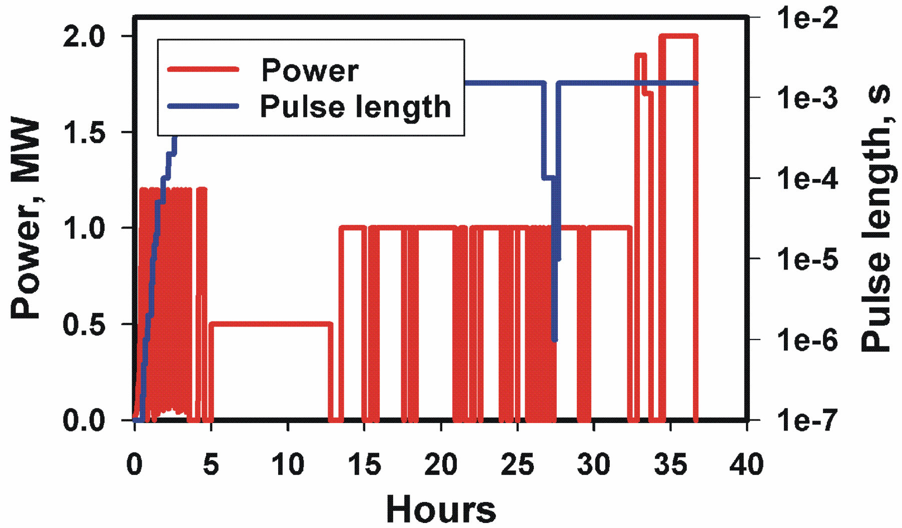

## First run, last day:

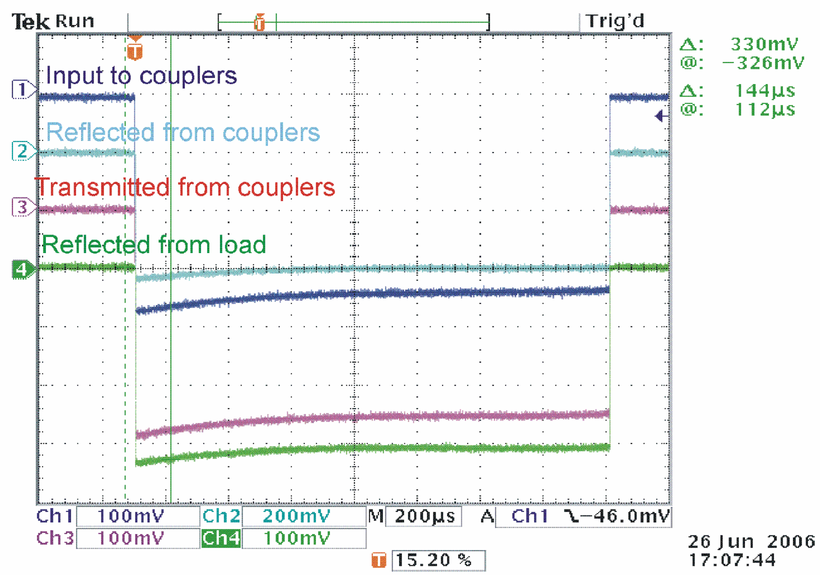



**Power was raised up to 2.3MW x 1.7ms x 5pps (~20kW av.) At this level warm window was destroyed by thermal stress.**

Second run.
Warm window was replaced and couplers were baked.

## History of processing and pulse shape after conditioning:



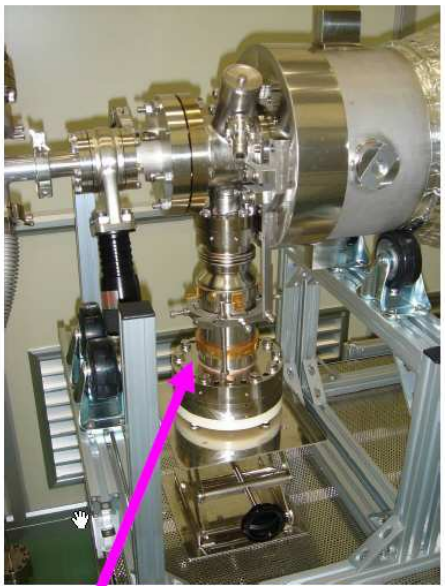




## Summary of long run of coupler:

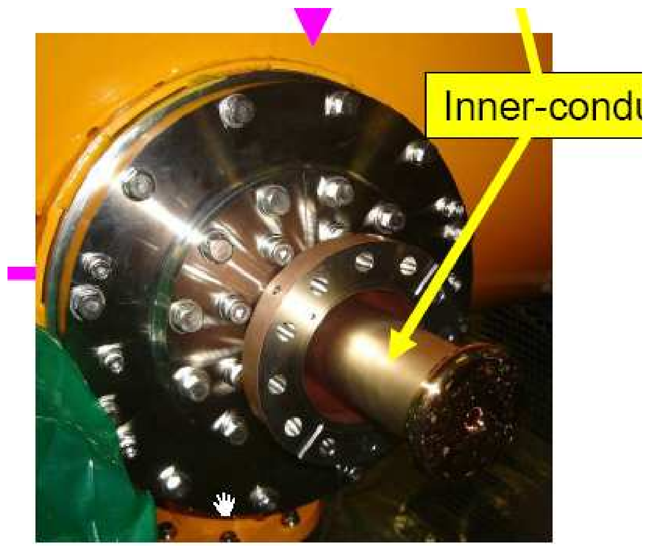
| | |
|---|---|
| 500 kW x 1.5ms x 5Hz | ~8 h |
| 1 MW x 1.5 ms x 5Hz | ~18 h |
| 2 MW x 1.5 ms x 3Hz | ~3.5 h |

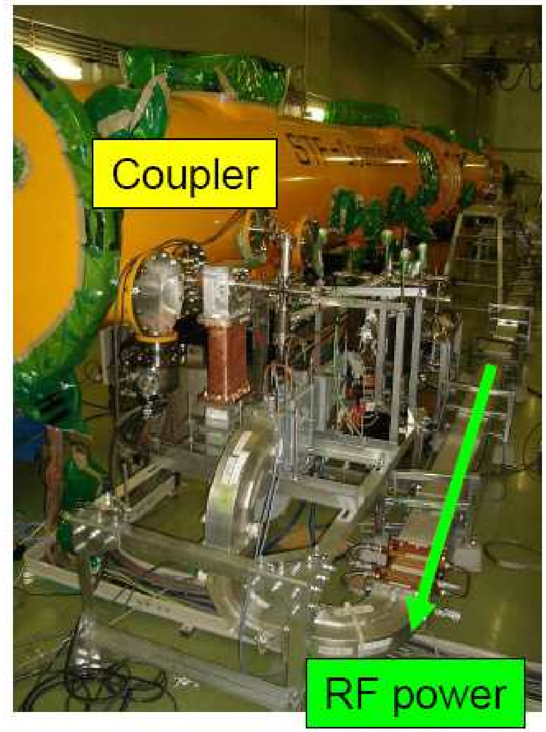
High power test demonstrated that couplers can successfully operate with pulse 1MW x 1.5 x 5pps and 2MW x 1.5ms x 3pps for matched load and pulse 500kW x 1.5ms x 5pps for short.
Effect of multipactor is weak. Upper limit of multipactor is about 200 kW.

**Recently coupler was installed in cryomodule and processed.**

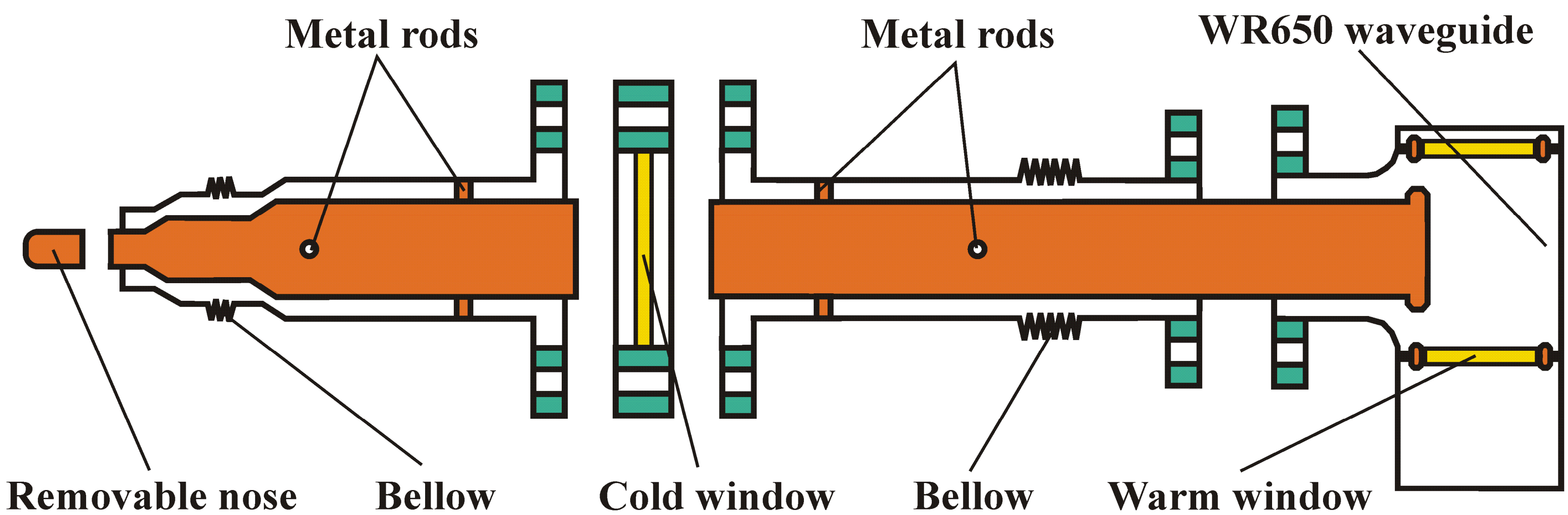


Assembly of Cold side of CC coupler



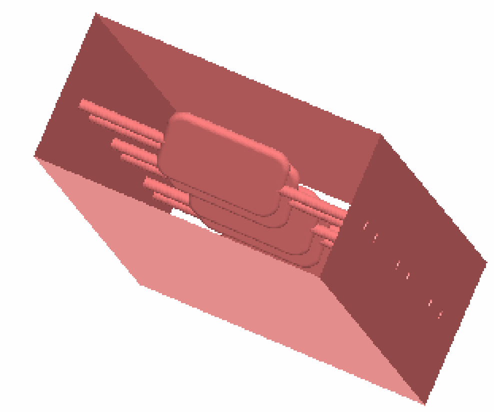

**Processing of assembled CC coupler was done at room temperature.**
**RF power = 250 kW**
**Pulse width = 1.5 ms**
**Repetition rate = 5Hz**
**was achieved within the processing time of 31 hours**

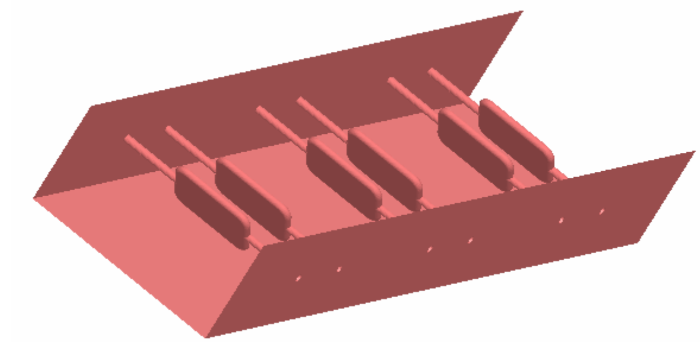



**Coupler can be modified to have changeable coupling.**
**Two bellows allow to move middle part of coupler with antenna.**

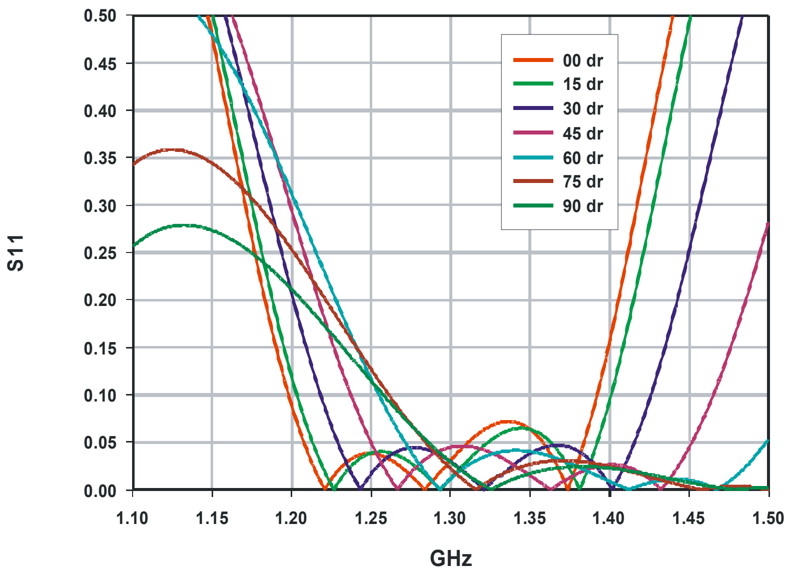
# Other designs for L-band

## Mechanically controlled phase shifter

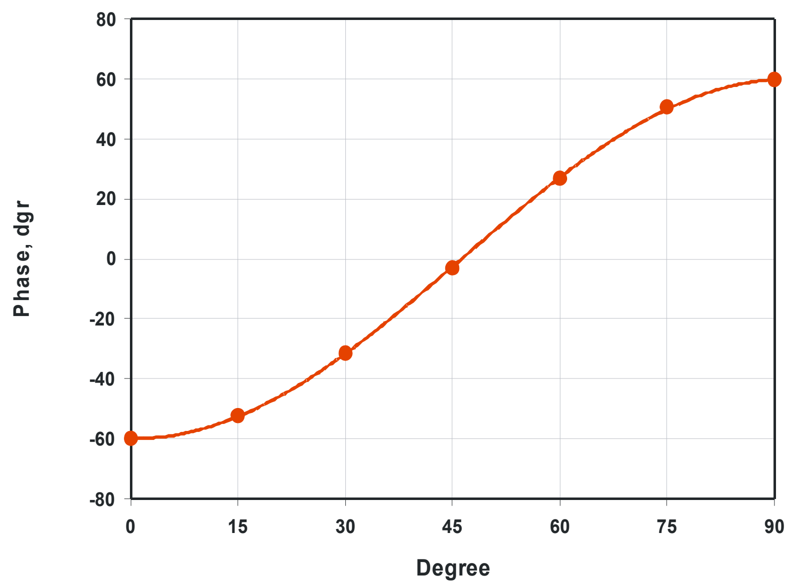




Passband
8mm-44mm



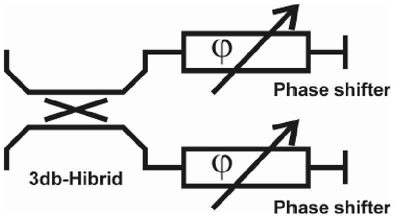

Phase vs plate angle,
plate 8mm-44mm

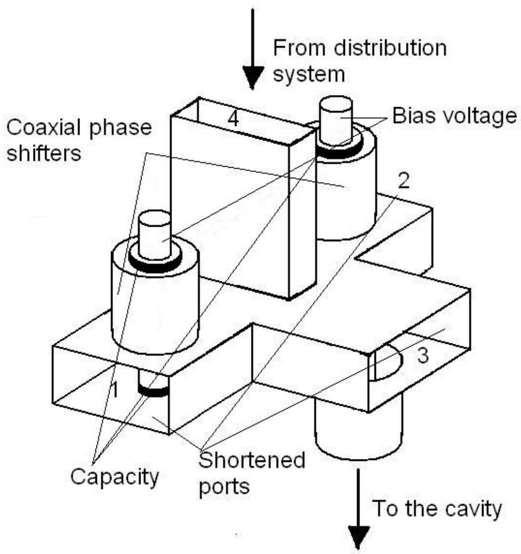


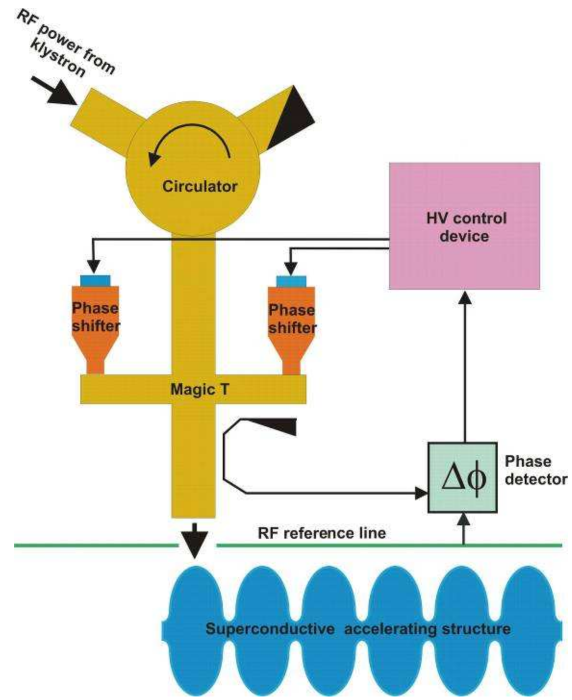

**Phase shifter was built and work as predicted. Expected power limit in air is 2 MW**

# Ferroelectric phase shifter (tuner)*

Interesting project is under developing in the Omega-P/Yale Beam Lab. We trying to build ultra-fast (~1us) electrically controlled phase shifter/tuner using ferroelectric ceramic. It can be used for fast control of coupling of accelerating structures ( phase and/or amplitude). It can be used as fast external tuner to control resonance frequency of cavity as well.

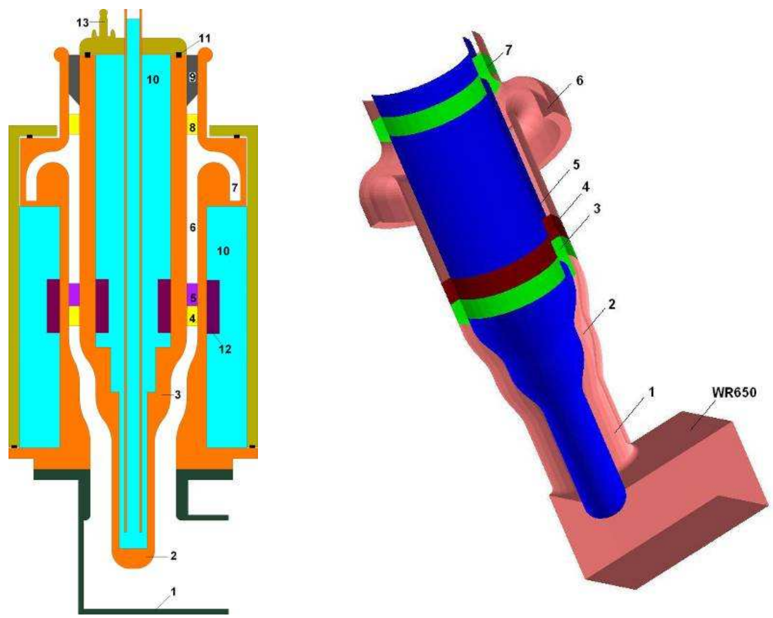


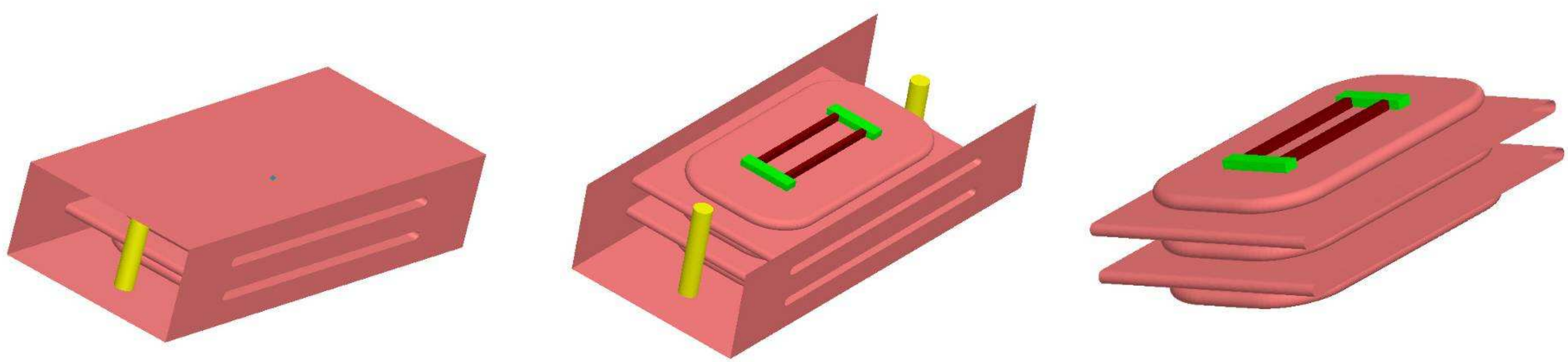

*S.Yu. Kazakov, V.P. Yakovlev, J.L. Hirshfield, "Fast Ferroelectric Tuner for L-band", 27th WG5-Asia Meeting, KEK, Japan, November 2005.

*Work supported by US DoE, OHEP.*

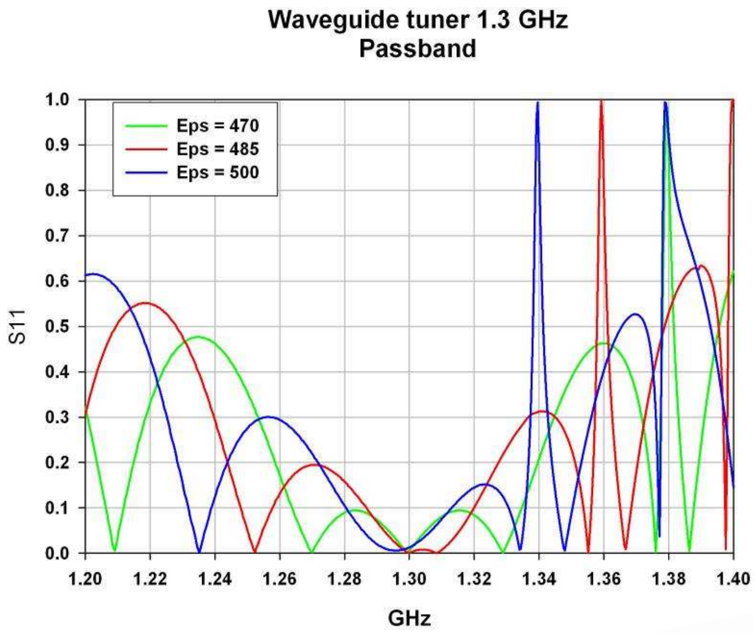



**Coaxial design of phase shifter (shorted)**

| | |
|---|---|
| dielectric constant, $\varepsilon$ | ~500 |
| tunability, $\partial\varepsilon/\partial E_{bias}$ ($E_{bias}$ is the bias field) | > 2/(kV/cm) |
| response time | < 10 ns |
| loss tangent at 1.3 GHz, tg$\delta$ (preliminary measurements) | ~$10^{-3}$ |
| Breakdown limit | 200 kV/cm |
| thermal conductivity, $K$ | 7.02 W/m-ºK |
| specific heat, $C$ | 0.605 kJ/kg-ºK |
| density, $\rho$ | 4.86 g/cm$^3$ |
| coefficient of thermal expansion | $10.1\times10^{-6}$ /ºK |
| temperature tolerance, $\partial\varepsilon/\partial T$ | 3 /ºK |



**Waveguide design of phase shifter**

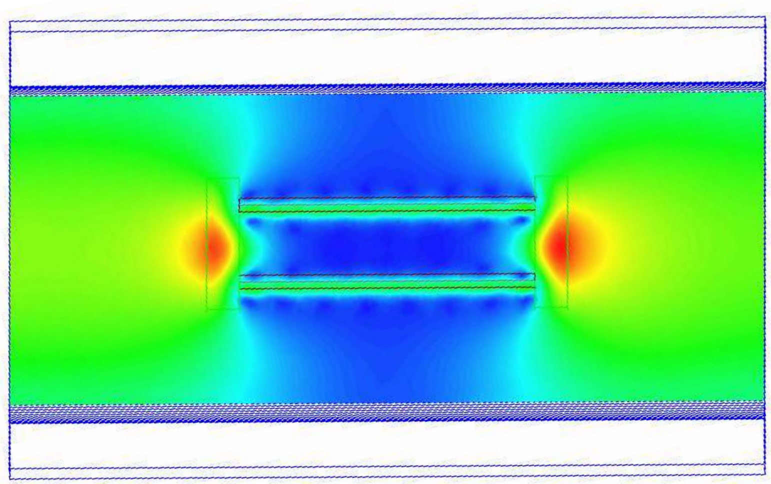


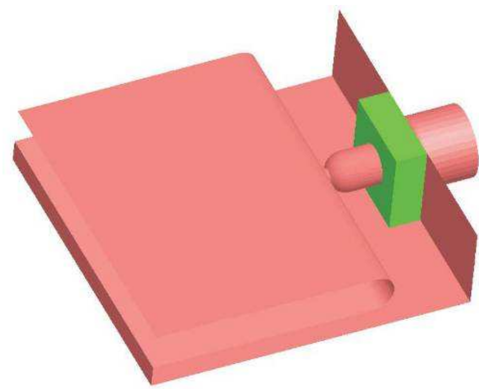

**Parameters of waveguide phase shifter**
**( 500 kW x 1.3ms x 5pps – ILC parameters)**

| | |
|---|---|
| **Max. E-field in ferroelectric** | **3.0 kV/cm** |
| **Avrg. E-field in ferroelectric** | **2.0 kV/cm** |
| **Max. E-field in ceramic** | **5.9 kV/cm** |
| **Max. E-field in air** | **6.1 kV/cm** |
| **One way phase shift** | **~ 115 deg (15 kV/cm bias)** |

| | |
|---|---|
| **One way loss** | **6.0 %** |
| **Ferroelectric pulse heating** | **0.2 K (d_eps = 0.6)** |
| **Ferroelectric average heating** | **0.9 K (d_eps = 2.7)** |

**(Loss and heating were calculating for 5e-4 ferroelectric loss tangent and for 1e-4 other ceramics loss tangent**



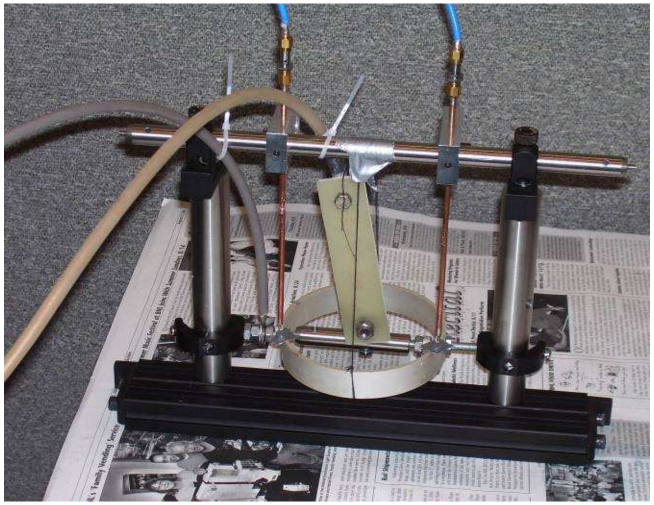


HV input

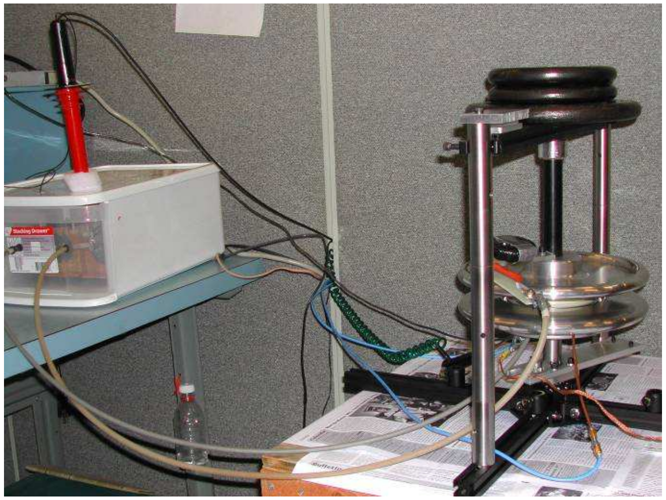
The procedure of the phase shifter tuning is developed in order to prevent EM field spread (and thus, the field enhancement) in different ferroelectric slabs.

# Measurements of properties of ferroelectric ceramic

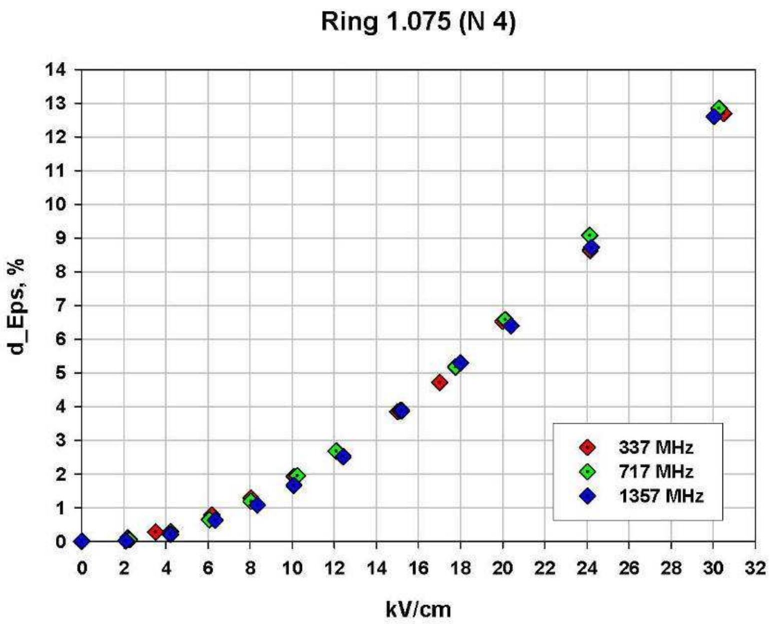
Ferroelectric ring



Tools for tunability measurements in the oil.



Two-disk resonator



**Thank you for your attention!**