The Progress of X-Band "Open" Cavity RF Pulse Compression Systems

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Abstract

The recent results of the low RF power tests of the single cavity 11.124 GHz and 14 GHz "Open" cavity RF pulse compression systems are presented. Some new methods for the RF pulse shape correction of the mentioned above systems are described.

1 INTRODUCTION

Future linear collider is supposed to operate at high acceleration gradient about 100 MeV per meter, this requires very high peak RF power about 150-200 MW at frequencies greater than 10 GHz and pulse duration about 100 ns. Now it seems that the most suitable candidate to be applied as a pulsed high power RF generator for powering of the normal-conducting e^+e^- collider is klystron. Most of klystron projects that are under R&D now have close general parameters, some of them are summarized in Table 1. [1].

Table 1. *X-band high-power klystron projects.*

Klystron	Wave-length cm	Power out MW	Pulse-lengt μs	Voltage KV
SLAC XC	2.63	100	1	550
KEK	2.63	120	1	550
VLEPP	2.14	150	0.7	1000

Present day experience shows that some fundamental limitations on acheivement of higher RF power level in this device in nearest future are exist. RF pulse compression is one of the methods to increase by several times peak power that klystron deliver. Pulse compression principle of operation is based on storing the RF energy from klystron during the most pulse duration and then reemmiting of the energy during rather shorter period in aliance with klystron into accelerating section. Typical efficiency of such a process is about 60-70%, while power gain 4-6. There are some reasons, why RF pulse compression devices are quite usefull to be applied in RF power supply of the future linear collider. Being passive devices they have no such problems as have devices based on beam-RF interaction, the total number of klystrons that are required for whole the collider operation can be reduced at least by factor of two or more, estimations for the VLEPP project gives 2.4 in particular. This fact is very important as there is general agreement now that RF system will be the most expensive component of the future linear collider.

There are some advanced scheme realizations of RF pulse compression system that are under RF high power exploitation and tests or are close to this. The SLAC Energy Doubler (SLED) [2] historicaly was the first, it was succesfully applied in SLC operation. SLED contain pair of cylindrical cavities for the RF energy storing, that cause output pulse shape in the form of a decaying exponential which may limits the applicability of this scheme especialy for the multibunch collider. In SLED II [3] cavities are replaced by long resonant delay lines, hence the pulse top is rather flat, now SLED II is planed to be used in NLC test facility operation at SLAC. Another scheme - Binary Pulse Compression (BPC) [4] where delay lines are also applied, is currently acting as driver for testing experimental accelerator sections and RF elements at high RF power level at SLAC.

For the VLEPP project in Russia it was designed another scheme of RF pulse compression system - VLEPP Power Multiplier (VPM), as an attempt to create rather compact, simple and effective device. Preserving the same principle of operation as SLED and SLED II, VPM differs in its energy storage element design and RF operation regime, also some methods how to organize pulse flat top were proposed, that will be described in this paper.

2 "OPEN" CAVITY SHORT THEORY

Direct application of SLED scheme in X-band and higher frequency ranges finds some troubles. If one try to obtain high Q-factor (more than 100 000) in normal conducting cooper cylindrical cavity, operating on H_{01N} mode at frequencies higher than 10 GHz, to provide sufficient efficiency of whole the system, it will be necessary to use H_{01N} mode with large number of longitudal field variations N (more than 10 - 15 at least). This means that cavity modes frequency spectrum will be rather dense, consequently some danger of coupling of neighbours parasitic modes with operating one through coupling slot exists. This can effect on pulse shape and pulse RF phase structure distortion. To obtain sufficient quality factor, preserving reasonably rare modes frequency spectrum in VPM storage cavity, it was proposed to use so called "Barrel Open Cavity" (BOC) [5,6].

Cavity shape of the BOC (Fig.1) is choosen by such a way, that only oscillations with large number of azimuthal variations can be excited (so called "whispering galery" modes), while the other modes that have weak azimuthal dependence can not be formed . Being repeatedly reflected from the cavity walls, electromagnetic field of the mode with large azimuthal index, is concentrated in a relatively small value close to the cavity surface, and is protected from radiation in outer space with so called "caustic" surfaces.

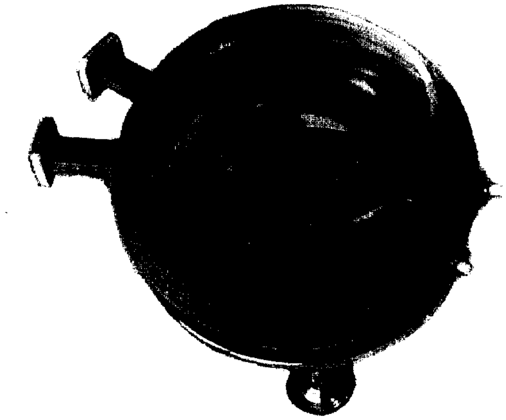

Figure 1. *View of Barrel Shape Open Cavity.*

Without considiration of the diffraction losses, modes frequencies of the BOC satisfy next correlation [7]:

$$ka = \nu_{mn} + \frac{(q - \frac{1}{2})\alpha}{sin\theta} \quad (1)$$

where k - wavenumber in a free space, a - cavity radius at the median plane $z = 0$, m - azimuthal, q - longitudinal indexes of the mode, ν_{mn} – n-th positive root of Bessel function order of m for E_{mnq} modes and its derivative for H_{mnq} modes. Angle α defines as:

$$sin\alpha = \sqrt{\frac{a}{r_0}} sin\theta \quad (2)$$

where θ - wavebeam sliding angle at the cavity median plane $z = 0$:

$$cos\theta = \frac{m}{\nu_{mn}} \quad (3)$$

where r_0 cavity curvature radius at plane $\phi = const$.
Field structure of E_{mnq} and H_{mnq} modes at the median plane of the BOC is similar with the field structure of the same named oscillations of the cylindrical cavity. Inner caustic surface radius a_m for both types of cavities defines as:

$$a_m = acos\theta \quad (4)$$

In contradistinction to the open cylindrical cavities, where modes can exist only due to reflection from the cavity edges, in the BOC, one can obtain outer caustic surfaces formation, which provides protection of modes with large azimuthal index from radiation into outer space. This formation is possible when curvature radius r_0 is smaller then cavity radius a. The position of outer caustics at the cavity wall is: $z = \pm z_{q-1}$, where

$$z_{q-1} = \tau_{q-1}\sqrt{\frac{asin\theta}{kcos\alpha}} \quad (5)$$

and

$$\tau_{q-1} = 2\sqrt{q - \frac{1}{2}} \quad (6)$$

Quality factor of the BOC can be expected the same as of cylindrical one, determined only with ohmic losses and can be approximatly defined as:

$$Q_E = \frac{a}{\sigma} \quad (7)$$

for E_{mnq} modes, and

$$Q_H = \frac{2(a - a_m)}{\sigma} \quad (8)$$

for H_{mnq} modes,
where a – cavity radius, a_m – inner caustic radius and σ – penetration depth of the cavity media. It is easy to see, that for cooper cavity of normal conductivity for E_{mnq} modes, if ratio $2a/\lambda$ is more than 5, then quality factor will be greater than 100 000. Detailed investigation of the BOC showed that at a fixed cavity geometry, those modes that have radial – n and longitudinal – q indexes greater than 1, have heights of the outer caustics than higher, than greater their indexes value. This means that this modes have large radiation losses in comparison with modes that have n and q equal to 1, thus cavity spectrum practically becomes more rare, even if to take into account all the modes with sufficiently large azimuthal index.

For the experimental investigations of the BOC properties three types of cavities were manufactoried. First one for studies of the main characteristics – Q-factor, frequency spectrum, radiation etc., the other two as a prototypes of the cavities to be applied in 11.4 GHz and 14.0 GHz RF pulse compression systems. Special technology was developed to provide highest quality of the cavity surface and maximall identicity of the cavity shape to theoretical one. During tests, radial and azimuthal field distributions were inspected for modes identification. Accuracy of Q_0 measurement was less than 5%. Tests results are presented in Table 2.

Table 2. *Three types of barrel open cavity*

Mode	Diameter cm	Freq. GHz	$Q_0/10^5$ measured	$Q_0/10^5$ calc.
$TM_{51,1,1}$	40	14	3.1	3.3
$TM_{31,1,1}$	26	14	2.0	2.1
$TM_{25,1,1}$	26	11.4	1.9	1.9

The next picture represents experimental results of 14 GHz BOC frequency spectrum measurements. There one can see that spectrum of the BOC shortened with conducting plates is rather dense in comparison with open one. The same amplitudes of operating resonance for the both cases, inderectly confirm that this mode does not radiates.

Common view of VPM (JLC) presented at Fig. 4, and the same in vacuume chamber at Fig. 5. The next picture shows the results of low RF power level testing of the VPM (JLC), they showed good agreement with computer simulation of the system.

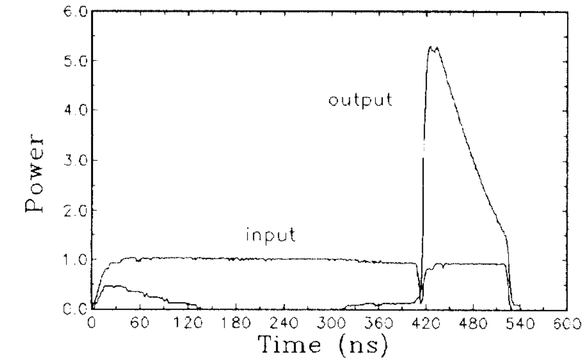

Figure 5. *VPM (JLC) output pulse from low RF power testing.*

Present design of the VPM does not require any mechanical fine tuning system. Water cooling sytem with high level of temperature stabilization is used there for the fine frequency adjusting. Frequency sensetivity of VPM to the temperature is measured about 3 MHz per 10 degree temperature and the operating temperature of device is planning to be about 30°C.

The first high RF power tests of the VPM are planned to be done in KEK (Japan) in middle 1994 with one of the klystrons from XB72 series that is under installation in KEK now.

4 RF PULSE SHAPE FORMATION IN PULSE COMPRESSION

In some modern projects of the future liner collider - NLC (USA), JLC (Japan) is supposed to use multibunch regime of operation. This defines new requirements on RF pulse compresion system characteristics, as an original single cavity devices like SLED and VPM now can not be applied due to the shape of their output pulse which is exponentially decaing. SLED II which uses delay lines as a storage elements provides required flat top and stable RF phase of the output pulse, but desire to have rather compact and simple device forces to find some other solution of the problem. Some methods of RF pulse shaping in pulse compression are examined below. Scheme realizations of this methods can be separated into two branches - passive, which uses upgrade of RF energy storage elements, and active one, with complex modulation of the RF input pulse.

4.1 Passive methods

Coupled multicavity system [9-11]. In this method is used a chain of coupled cavities as an analogue of delay line. With optimal choice of coupling between cavities and their own frequencies one can form a line with paramerets that can provide quite flat top of the output pulse. Application of the BOC, operting in TW regime also simplifies the system. The next pictures shows two-cavity VPM output pulse from low RF power testing. General parameters of this device are very close to the single cavity VPM [10].

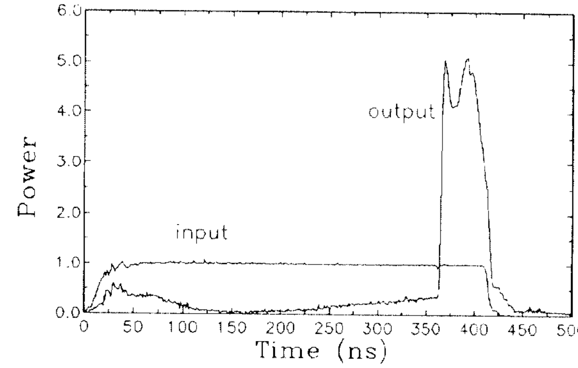

Figure 6. *Output pulse of two-cavity VPM.*

TW cavities coupled through the waveguide [12]. This method allows to obtain a flat pulse with stable phase after conventional SLED-type pulse compression system by adding several TW cavities with relatively low Q-factor and small size. The main idea of the method is to use separated cavity for each mode which participates in quazy-line spectrum forming, instead of usage modes spectrum of the chain of coupled cavities as in a previous method. This method has some advantages, because each cavity can be tuned and loaded individually. Stable output RF phase of such a system makes it possible to realize its kascading, like SLED II.

4.2 Active methods

Amplitude modulation [13] of the RF input pulse can be done in such a way that pulse waveform will compensate an exponential decaying of SLED-type pulse compression system output pulse. This method requires high RF power generator with special waveform of the output pulse, but efficiency of such device will be much lower than in conventional klystron with rectangular pulse, that seriously limits applicability of the method in power supply of the future linear collider.

Phase/frequency modulation [14] also uses complex modulation of the input RF pulse. Serious advantage of the method is that modulation is applied to the input pulse of klystron at low RF power level by mean of special waveform RF phase modulator placed between drive generator and klystron. Generaly modulation consists of two stages - fast RF phase switching by $\pi/2$ to initiate pulse formation and continious RF phase changing under special law to provide the most flat top of the output pulse (Fig. 7a,b). Theoretical evidence of the method requires much place, so here we will only demonstrate the results of computer simulations. Actually method have some disadvantages:

1. Phase/frequency modulation is enable to provide full compensation of SLED-type compression system energy exponetial decaing, that effects in decreasing of total efficiency of the device by 4-5%. Nevertheless efficiensy is

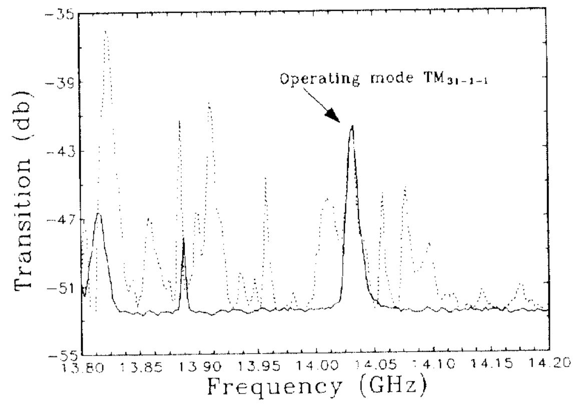

Figure 2. *Measured spectra of the BOC: 1 – fully open cavity, 2 – cavity shortened with conducting plates.*

3 SINGLE CAVITY VLEPP RF POWER MULTIPLIER

The principle of operation of RF pulse compression is discussed in details, then here we will concentrate on the features that are intrinsic in VPM.

One of the problems to be solved with any open cavity operation is nonresonant radiation from coupling slot, because the specific feature of the open cavities is that only part of RF feeding energy is used for oscillation exitation and the other one radiates through cavity edges in outer space, forming nonresonant background. The field structure of "whispering galery" modes in the BOC helps to overcome this problem. Large number of azimuthal variations of this modes, makes it possible to use traweling wave regime of operation. That can be realized with feeding of the cavity through large number of coupling slots in the common wall of the cavity and feeding waveguide, which laying around the perimeter of the cavity. Proper choice of the waveguide width provides the same phase velocities in the cavity and waveguide, that organizes best coupling and matching of the cavity and guide.

The other effect of such an exitment can be explained in terms of antennas technique. It is known that long sloted wavegude can provides very narrow beam which radiation angle depends on correlation between slots displacement and operating wavelength. If at fixed frequency, wave phase velocities in the guide and outer media are the same and distance between slots is equal to $\lambda_g/4$, then radiation will be parallel to the guide axis. Adapting this fact to the BOC feeding, one can expect a considerable reduction of the nonresonant background, as feeding wave becomes squeezed to the cavity surface. Experemental estimations of radiation background were done from comparison of calculated and measured values of inserted waveguide losses, at frequencies close to the operating resonance. The difference was less than 0.05 *db*, this means that the part of RF energy that was radiated in outer space was less than 1%.

Traveling wave regime of operation of the VPM has another advatages in comparison with SLED and SLED II, as there is no needs to use doubling of the storage cavities or delay lines and 3-*db* couplers for the system matching. Measured value of SWR at the operating frequency was in range 1.1-1.2 for different samples of the device. Also large number of coupling slots solves the problem of single slot electrical strength at high RF power level operation.

Two types of the VPM to be applied in RF power supplies of VLEPP (Russia) and JLC (Japan) accelerator test fascilities were designed and manufactoried [8]. Their parameters obtained at low RF power level tests are presented in Table 3.

Table 3. *Parameters of two types VPM.*

	VPM (VLEPP)	VPM (JLC)
Frequency (GHz)	14.000	11.424
Q loaded $/10^4$	1.1	0.9
Input pulse duration (nsec)	500(700)	500
Compression	5(7)	5
SWR	< 1.15	< 1.13
Inserted losses (db)	< 0.2	< 0.22
Compression efficiency %	74(68)	72
Total effic. %	70(64)	68
Power gain	3.7(4.0)	3.6

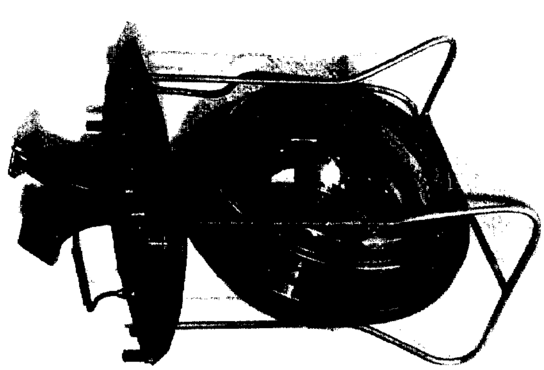

Figure 3. *Common view of the VPM (JLC).*

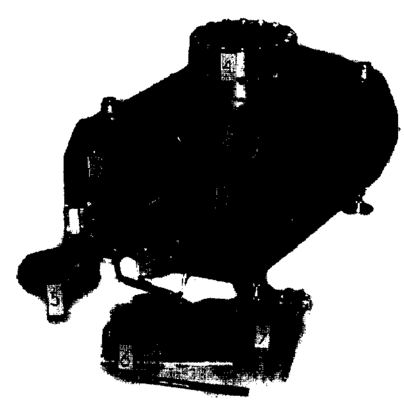

Figure 4. *VPM (JLC) in vacuum chamber: 1 – feeding guide, 2 – Control antenna, 3 – water cooling flange.*

still higher than 65% for the present design single cavity VPM.

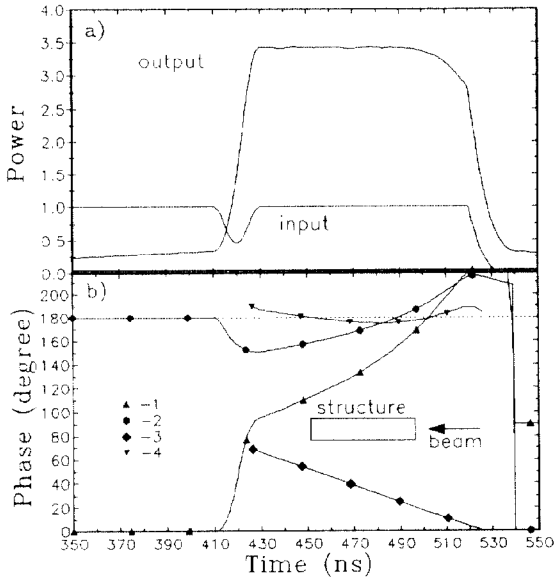

Figure 7. *Output pulse of SLED-type pulse compressor: 1-input RF phase, 2-output RF phase, 3-RF phase along detuned sructure, 4-resulting RF phase along structure.*

2. RF Phase of the output pulse is not stable, it has a character close to linear growthing. As a solution of the problem one can use frequency detuning of the accelerating structure from drive operating frequency in a such way, that difference between bunch and wave phase velocities in sructure will be equal to:

$$\frac{v_{fw}}{c} = 1 + \frac{\Delta\varphi\lambda}{2\pi L} \qquad (9)$$

where $\Delta\varphi$ - amplitude of RF phase deviation of the output pulse, λ - wavelength and L - sructure length. In this case one can obtain RF phase distortion along the stucture (see Fig. 7b curve 3) which can compensate RF phase evolution of the output pulse. Resulting RF phase distribution along the structure see Fig. 7b curve 4. In practice structure detuning can be realized with slight changing of its operating temperature. For example VLEPP structure [5] has temperature sensetivity about 0.8% v_{fw}/c per 10°C, thus required temperature detuning for the case presented at Fig. 7 ($\Delta\varphi = 70^{\circ}$) will be about 5°C. Generaly we have to look at accelerating gradient $E_a(t) \sim \sqrt{P_{RF}}Cos(\varphi)$ For multibunch regime $E_e(t)$ must be constant during all the duration of drive RF pulse. In this terms requrement on exact linearity of drive RF phase and voltage is not general , as one can imagine a lot of different phase - voltage relations which satisfy previewed condition. This point significantly simplifies practical realization of the method.

CONCLUSION: Summurizing presented data, one can see that obtaining parameters close to SLED II, VPM in aliance with system of active RF phase correction of the pulse shape is quite compact and effective RF pulse compressor for X-banb (or higher frequensy bands) and output RF pulse durations more than 100 ns. In mass production the manufactoring expensies of the VPM can be expected several times lower then SLED II cost.

Table 4. *SLED II and VPM components table.*

Components	SLED II	VPM
1. Storage elements	Delay lines (2x11 m)	Open cavity (0.2 m)
2. Aditional RF accesories	-3-db coupler -Mode convertor -90° H-bend	no
3. Controls and adjustments	-Precised movers -Termostab. sys.	-Temp. fine fr. tuning system
4. Low RF pow. controls	-Fast 180 degree RF phase switch	-Special RF ph. modulator

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