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PETS On-Off demonstration in CTF3

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Introduction

The PETS On-Off mechanism is required for the future linear collider CLIC serving to a basic function permitting switching PETSs on and off individually. This function should notably increase the reliability and rigidity of the CLIC collider by resolving the following critical operation issues leading to a drastic luminosity fall:

1) smooth recovering after a spontaneous vacuum increase in the RF delivery system, which can provoke RF breakdowns;
2) prevention series of RF breakdowns in accelerating structures and PETS, which can significantly change the dynamics of beam passing through it;
3) disabling a two-beam module in case of a hardware failure, this allows postponing the repair.

The CLIC PETS On-Off mechanism has been introduced and developed as a compact external extension to PETS consisting of two high power RF variable reflectors (see section 5.4.2.4.d). Two prototypes of these reflectors have been manufactured in order to demonstrate the validity of the mechanism using the beam based setup TBTS in CTF3.

Experiment setup

In September 2011 the RF recirculation loop used for high power extraction tests in the TBTS in CTF3 was dismounted. And two variable prototype reflectors were installed on its place. The first reflector, so-called phase-reflector, was connected to the first, following the beam direction, PETS RF extractor and the second, so-called split-reflector, was connected to the last extractor through a T-type RF waveguide (fig. 1). The phase-reflector is a one port devise, which delays RF reflection depending on the position of the piston thereby it allows controlling the relative RF phase. And the split-reflector allows adjusting the ratio between the transmitted power to accelerating structures and the power reflected back to the PETS.

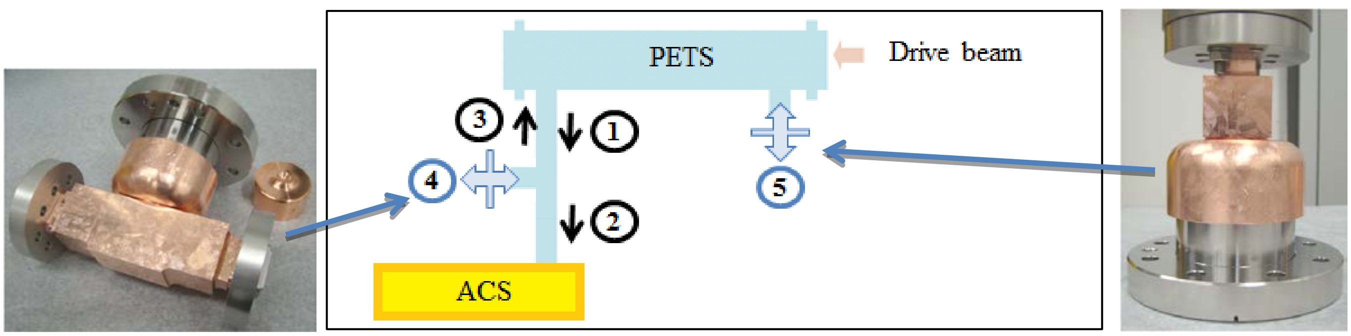

Fig. 1 Layout of PETS On/Off setup in TBTS: 1) the RF power extracted from the PETS; 2) RF power transmitted to the accelerating structure; 3) RF power reflected back into the PETS; 4) movable RF split-reflector; 5) movable RF phase-reflector.

After the installation new components were processed using the RF power extracted from the beam. The power level was controlled by the reflectors in a way to keep the vacuum at a level of 10^{-6} Torr. This strategy gave an excellent result: after 3 days (~200k pulses) the system was conditioned. The comparison of the vacuum level clearly indicates it: after 50 hours of operation – the extracted power is 80 MW, the vacuum level is ~10^{-6} Torr and after 120 hours - the power is 100 MW, the vacuum level is $<2\times10^{-7}$ Torr (Fig. 2). The other way to see the progress is to follow the history of the beam intensity, which system could accept without breaking down: it started from 3 Amps and it reached 16 Amps basically with a longer pulse length of 220 ns. The PETS On-Off setup was tested and validated at different power levels and with different beam combination schemes: ×1 (3 GHz), ×2 (6 GHz), ×3 (9 GHz), ×4 (12 GHz), ×8 (12 GHz). At all conditions the system behaved as it predicted by the model thereby confirming and proving the principle for the CLIC PETS. The summary of results is presented at the end in the Table 1.

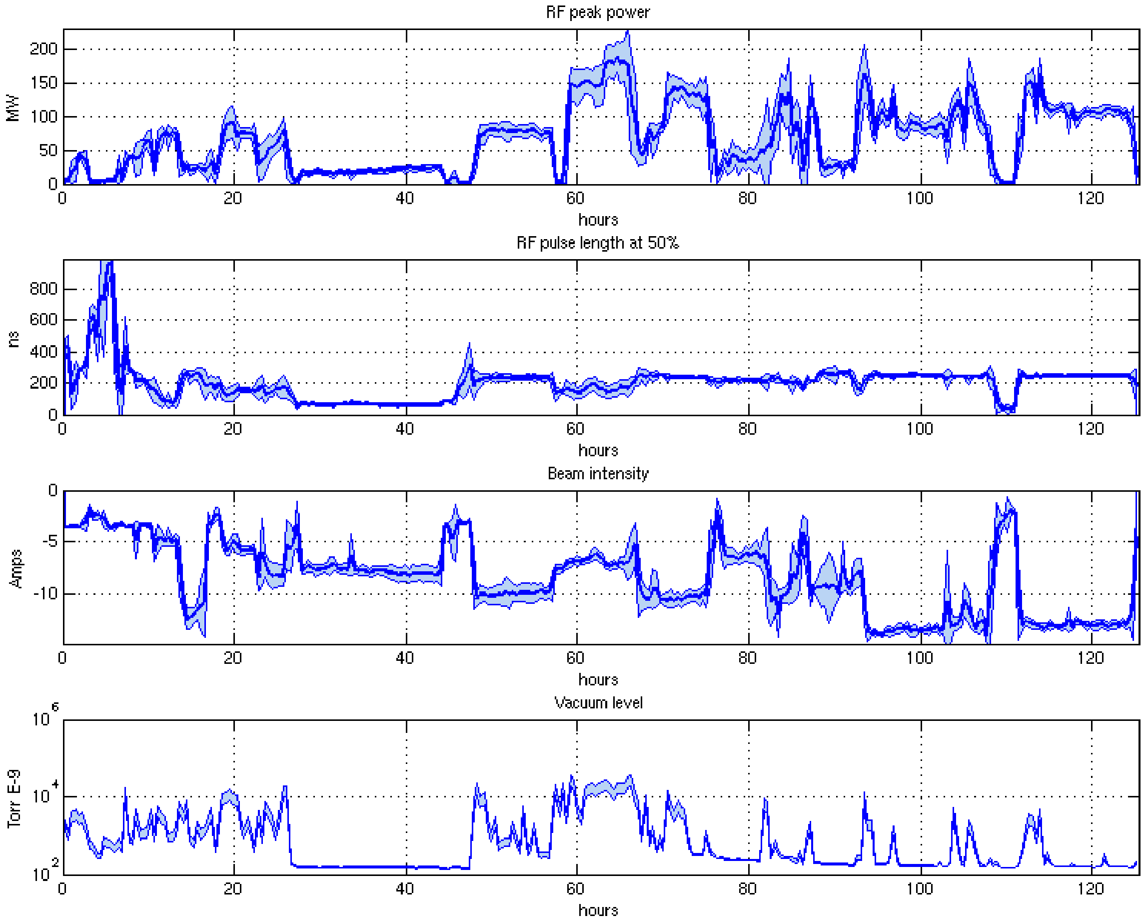

Fig. 2 PETS On-Off processing history.

Principle of operation

The PETS, reflectors and all intermediate RF components are designed and fabricated as almost linear for such wide bandwidth range that a dispersionless approximation model is sufficient for the comparison of the expected RF behavior in the system and measured signals during the tests. Assuming an ideal beam with equally spaced identical bunches the RF power extracted from the PETS, RF power reflected back into the PETS and RF power transmitted to the accelerating structure can be expressed as following:

where is the beam current averaged over the PETS fill time 4 ns, is the single bunch form factor, , and are PETS parameters listed in the Table 1. and parameters are defined by the position of the split-reflector , and is defined by the position of the phase-reflector as following:

where is a constant.
When the PETS is on (,), all RF power goes to the accelerating structure:

When the PETS is off (,), RF is reflected back to the PETS by the split-reflector, then it is reflected from the phase-reflector to the PETS and then it is extracted from the PETS with a phase advance after a turnaround time :

The demonstration of the smooth transaction from the mode on to off has been performed by moving only the slit-reflector and fixing the phase-reflector at (Fig. 3).

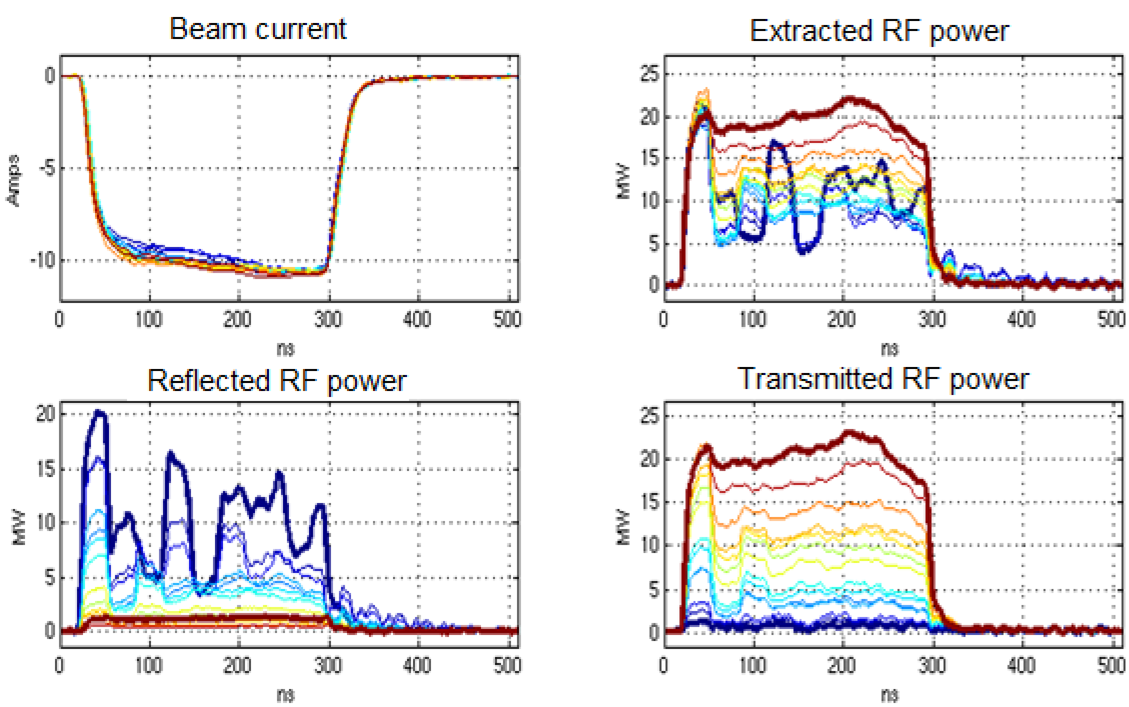

Fig. 3 TBTS PETS On-Off demonstration: bold red lines – PETS is On; bold blues lines – PETS is Off; slim lines – intermediate positions between On and Off of the slit-reflector.

PETS On-Off power properties

The power reduction can be estimated in case of the steady state ( ) as:

Experiments have performed with relatively short pulses, even than the power reduction was measured below 50%. The peak power seen by PETS is the same in the both modes appearing at the begging of pulse for a short period of time.

Assuming a rectangular beam current of a pulse length ( ) the integrated power reduction can be estimated as following:

where and is an integer — . The estimation agrees with the measured value $\boxed{58\%}$.

Measurements also showed that the reflectors do not introduce any additional losses during the normal RF power production mode:

Resonance mode

The PETS On-Off in TBTS can be used not only to attenuate the power production, but also to amplify it by adjusting the reflectors. The PETS has a resonance mode, in which it produces the maximum power under the following conditions:

, .

And the maximum power produced from a homogenous beam pulse ( ) is:

Fixing the split-reflector at the off-position and adjusting the phase-reflector allowed measuring the insulation coefficient of the accelerating structure (Fig. 4):

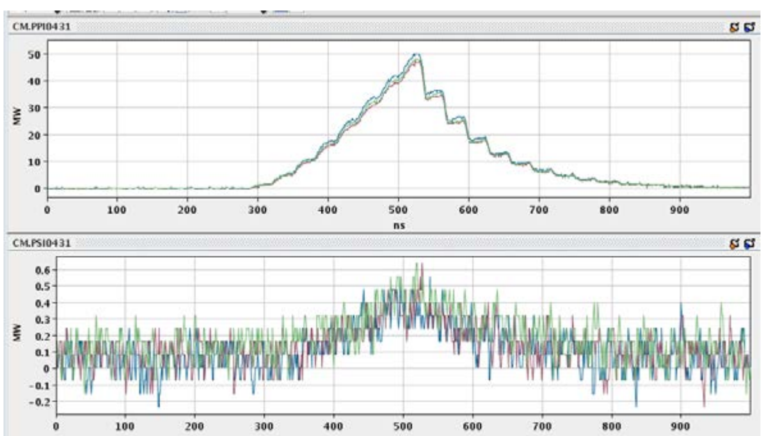

Fig. 4 Measurement of the insulation coefficient. The slit-reflector is set at the off-position. PETS extracted peak (top plot) power is 50 MW, the transmitted power (bottom plot) is 0.5 MW. The insulation is -20 dB.

The beam conditions do not allow extracting RF power over the CLIC level of 134 MW in the direct power production mode. Nevertheless the PETS On-Off mechanism was operated in the resonance mode with a peak power over 150 MW (Fig. 2). Tests performed under conditions of high surface electric fields showed the same system behavior as the model predicts.

PETS break down rate

The PETS On-Off also reduces the break down rate of the PETS itself by switching it off. The scaling break down low BDR~E^{30}Ä^{5} (see sec. 2.8) allows to estimate the order of magnitude of such reduction in the following expression:

where is an analytical expression. In spite that the parameters of the function are different for the TBTS case and CLIC case the estimated BDR reduction is almost the same in both cases (Fig. 5).

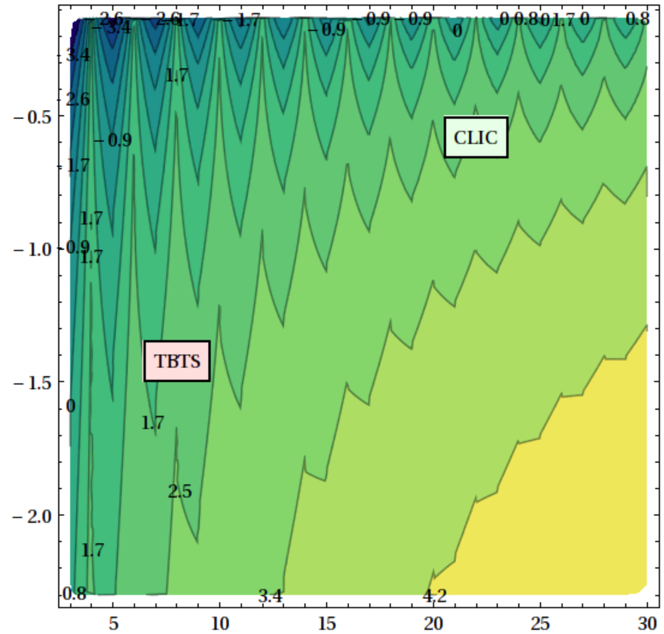

Fig. 5 Estimated PETS BDR reduction ( ) by On-Off mechanism at different system parameters: vertical plan is the round trip ohm losses in dB, horizontal plan is the number of round trips during one beam pulse .

Conclusions

A prototype of the CLIC PETS On-Off mechanism has been developed, manufactured and extensively tested with the beam in TBTS in CTF3. The main principle of switching off the PETS power production has been demonstrated at different beam and RF conditions up to 16 Amps and 200 MW. The model describing RF dynamics agreed with the measurements all along the experiment. In the normal mode operation the introduced RF reflectors do not change the RF behavior and they do not introduce measurable Ohmic losses. When the PETS is switched off, the accelerating structure sees less than 1% of the extracted power, which basically make a break down emergence improbable. And the probability of a break down in the PETS is reduced by a factor 10^2-10^3 due to significant power attenuation in the PETS. The PETS On-Off mechanism in TBTS has very similar relevant parameters to the CLIC mechanism (Table 1). All this above validates and it demonstrates the PETS On-Off principle as a solution to the CLIC issues mentioned in the introduction.

Table. 1 List of the main parameters.

Parameter	Symbols	Unit	TBTS expected	TBTS measured	CLIC
PETS					
R/Q		Ohm/m	2222		2290
Group velocity	V_g/c	%	45.9		45.3
Quality-factor					7200
Active length, m		m	1.0		0.213
Waveguide			WR90		
Length		m	~2.2		~1
Ohmic losses		dB/m	0.098		~0.098
Drive beam					
RF pulse length, ns		ns	270	>250	241
Current		Amps	up to 19	16	101
Extracted RF power		MW	>160	>150	133.7
PETS ON/OFF					
Transmission	—	dB	~0	~0	~0
Isolation	—	dB	<-20	-20	<-20
Peak power	—	%	~100	~100	~100
Power attenuation	—	%	28	<50	26
Integrated power attenuation	—	%	48	58	45
Estimated BDR attenuation (BDR~E^{30}Ä^{5})	—	Log_{10}	-2.3	-2.8	-2.7