Millimeter and Submillimeter Wave Accelerating Structures Fed by High-Power Ultra-Short Pulses

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Outline:

1. ***Short pulse high-gradient acceleration concept:***
    a) ***Breakdown threshold***
    b) ***Efficiency***
    c) ***Life time***
2. ***Experiments with nanosecond X-band components;***
3. ***THz single-cycle structures;***
4. ***Mm- and cm- single-cycle structures:***
    a) GV/m wakefield structures
    b) multi-mode wakefield structures.

Pulse Length Scaling & Challenges

•Feeding by short, high repetition rate pulses, in order to avoid breakdown and excessive pulse heating according to scaling laws:

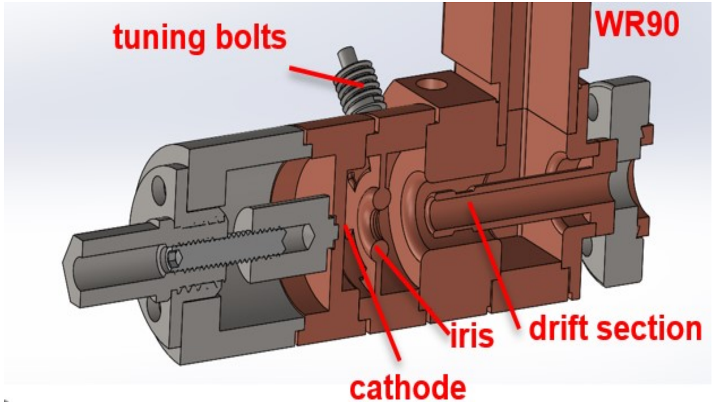
$$E_s^p \tau = const, p = 5-6. \qquad H_s^2 \sqrt{\tau} = const.$$

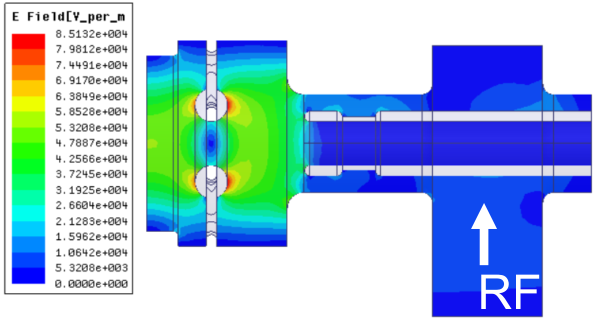
•Accelerating fields more than 100 MV/m have already been obtained at ~100 ns pulses in X-band. Extrapolating scaling law one must conclude that in order to reach **1 GV/m,** as short as ~ **1 ps (1 THz width)** pulses are needed.

Challenges:

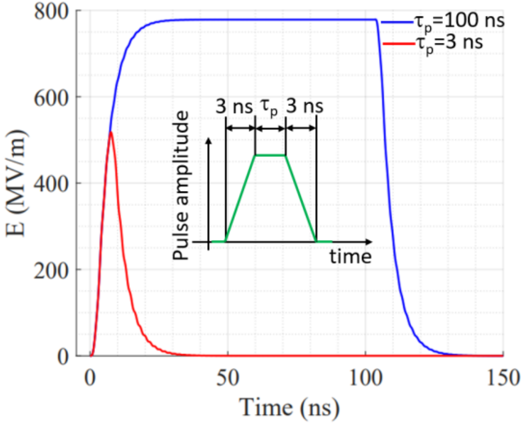
- Broad band systems are necessary;
- High repetition rate;
- High efficiency;
- Structure life time must be large enough.

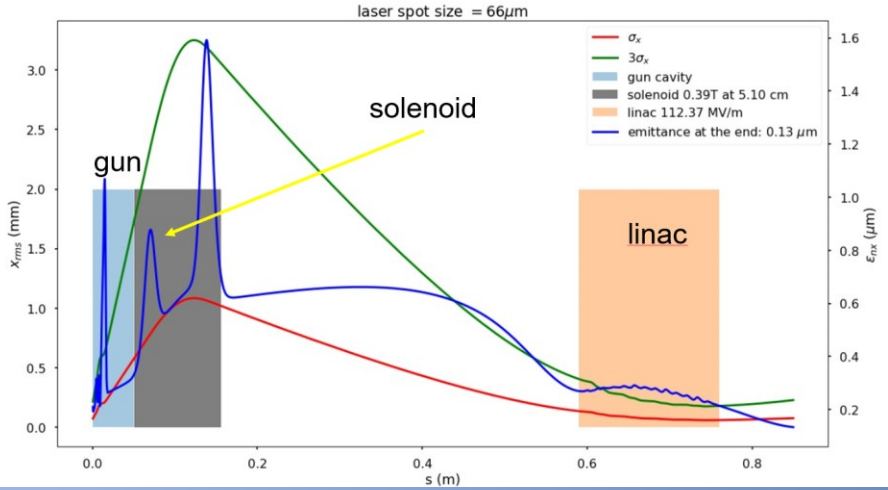
High-Gradient X-Band Gun Fed by 9 ns RF Pulses

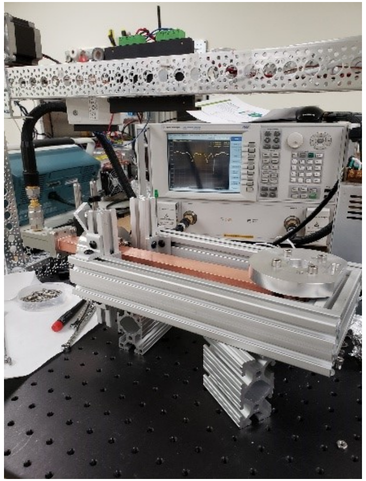


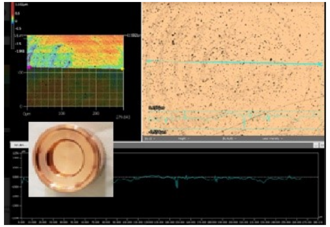


11.7 GHz field structure

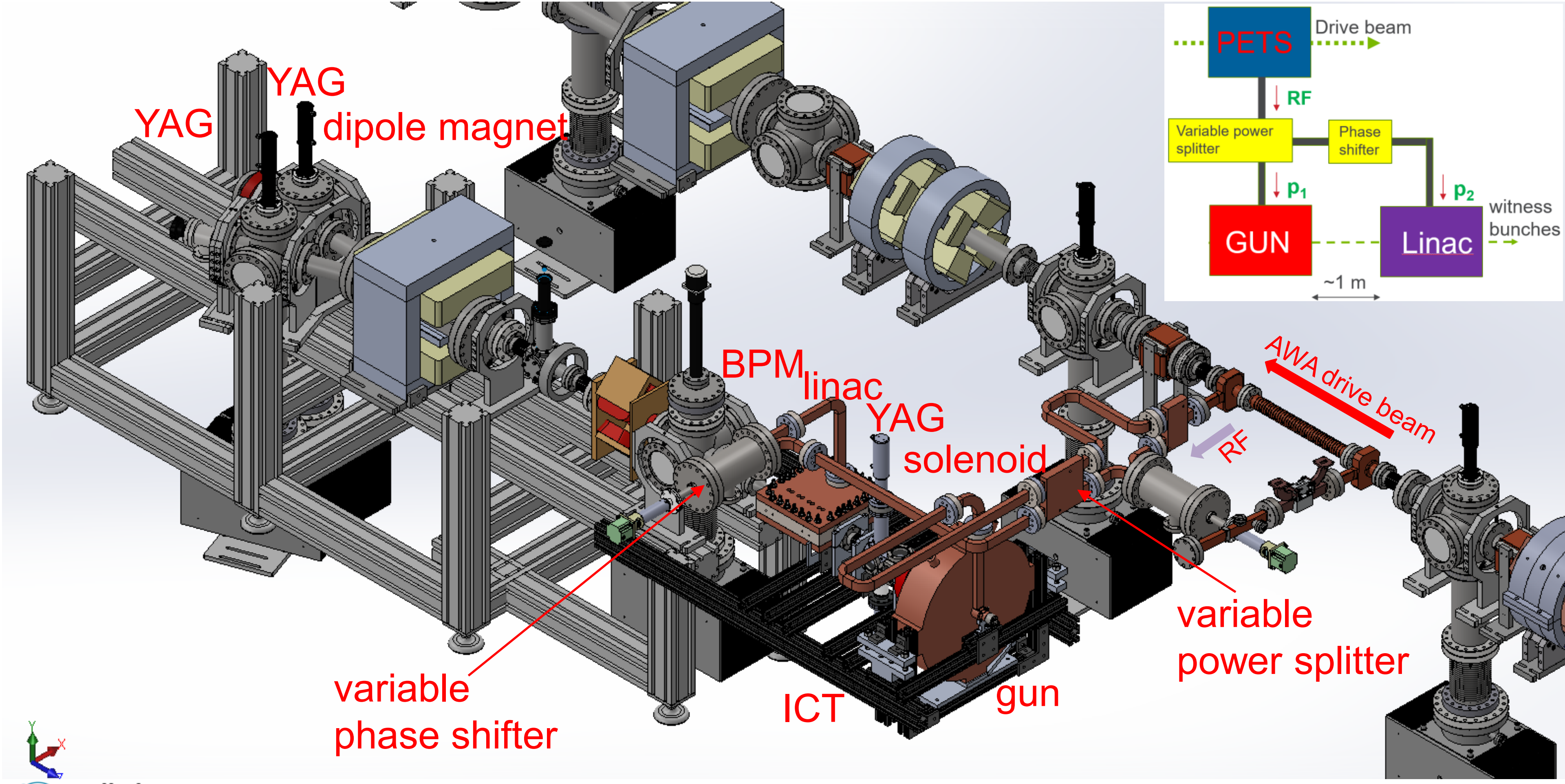






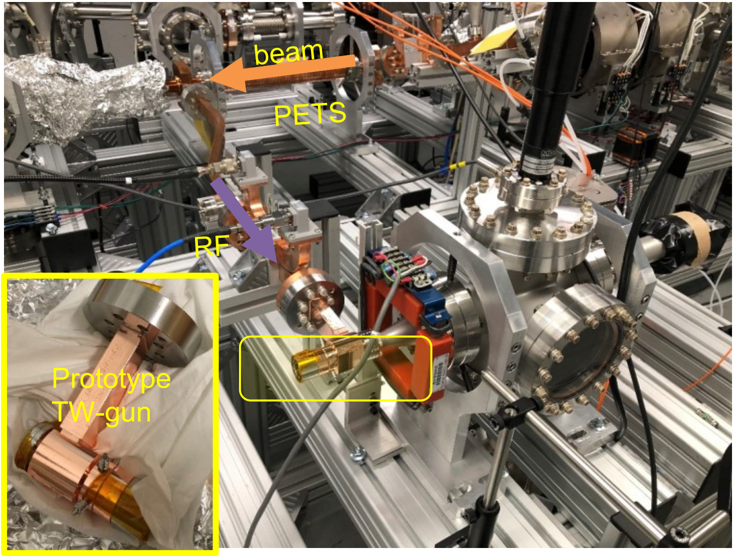


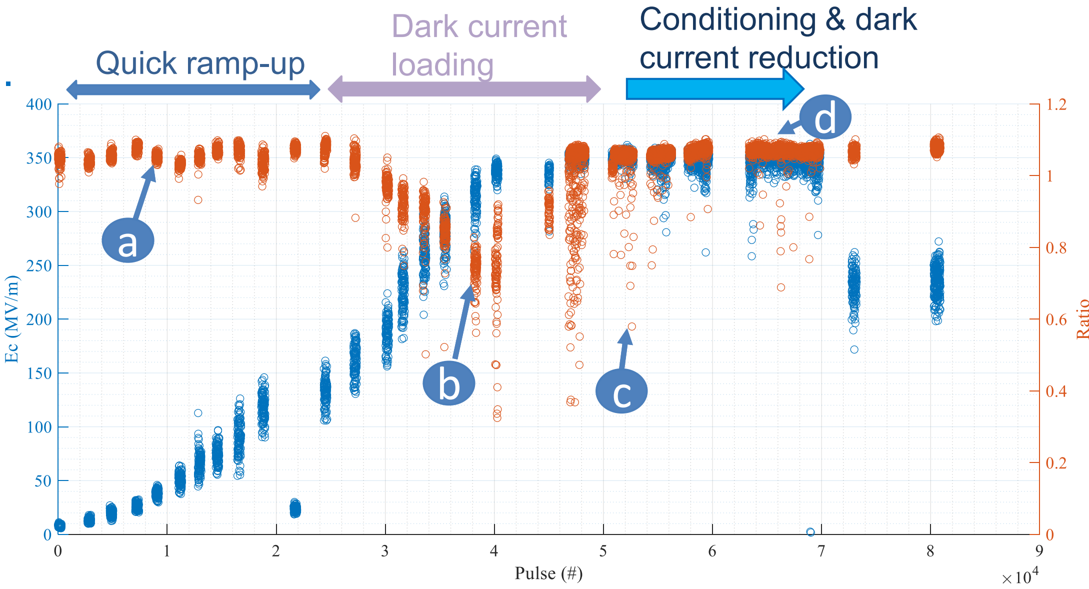
Gun's Beamline Design (experiment #3)

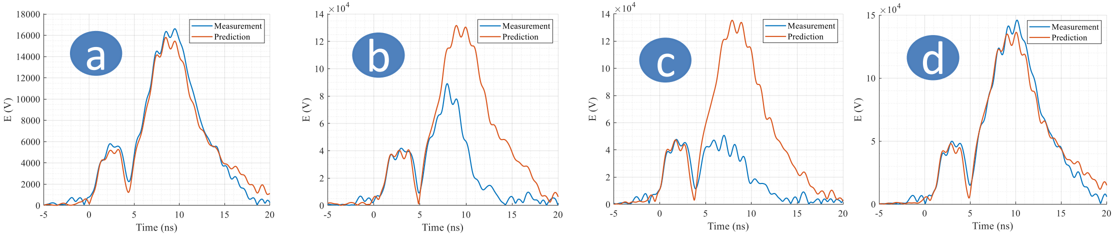


BREAKDOWN TEST OF A GUN AT AWA

- ➢ Achieved 400 MV/m on cathode (600 MV/m at the first iris).
- ➢ It only took 70k pulses for a full condition.
- ➢ No measurable dark current,
- ➢ BDR~10^{-6} , 100 pC, 3 MeV.

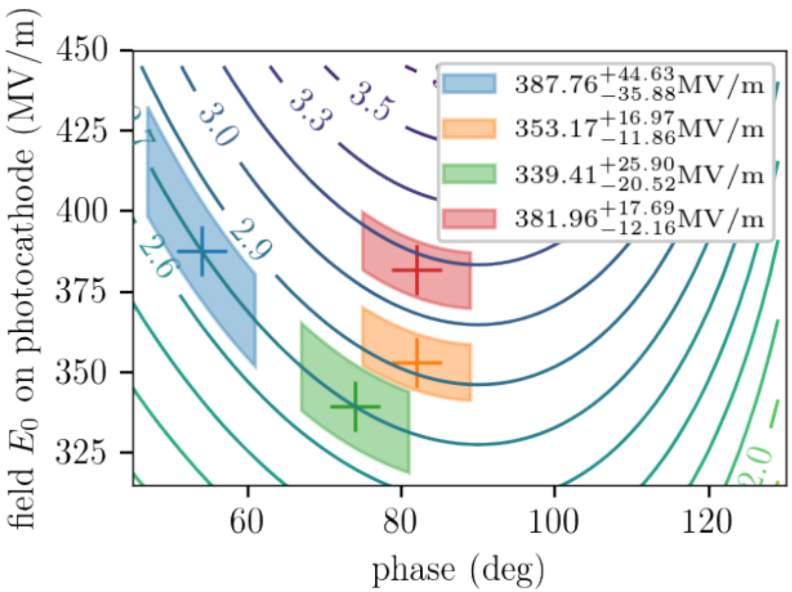




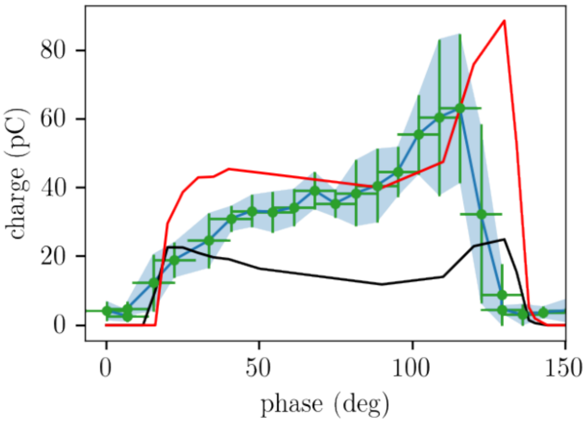


Reflection signal from bi-directional coupler

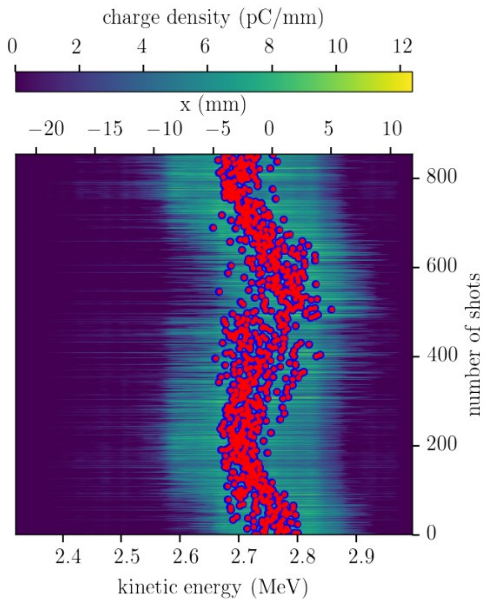
FIRST OPERATION OF A GUN AT AWA



Simulated kinetic-energy isoclines as function of RF gun operating conditions $K(E_0, \varphi)$ and retrieved operating points for four sets of measurement (cross symbols).



Photoemitted bunch charge as a function of laser phase (filled green circles with shaded area indicated the uncertainty) compared with numerical simulations with (red solid line) and without (black dash line) including the Schottky effect.



Continuous shots.

A Nanosecond Accelerating Structure with Individually Fed Cells

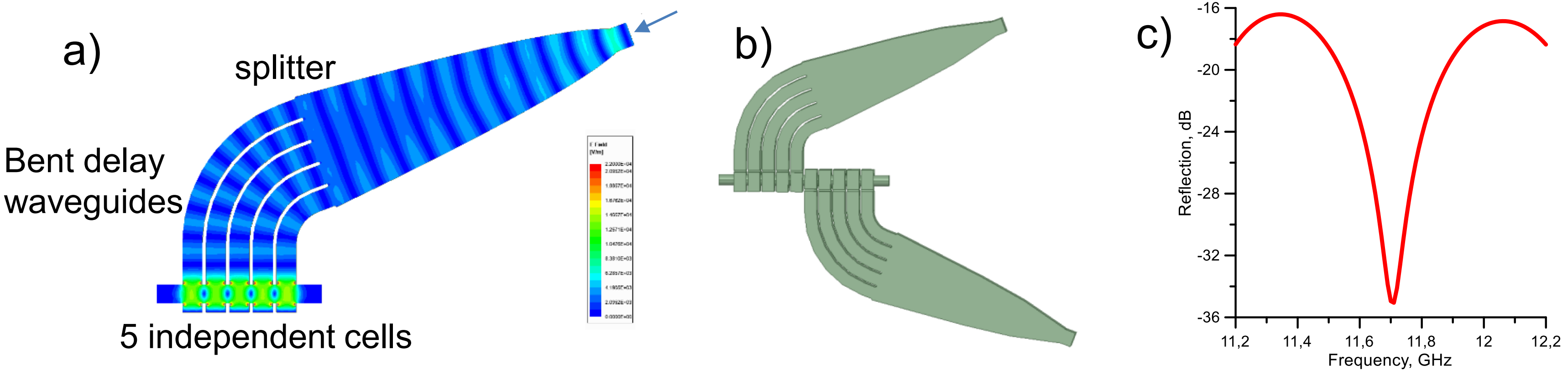
The TM_{010} accelerating cells are powered individually!

This principle allows:

- to mitigate the influence of RF breakdown if appears in one cell;
- to increase the shunt impedance due to the smaller than usual beam channel;
- to reduce sensitivity to the tolerances on the size of the cells.

Power	150 MW
RF pulse length	10 ns
Q-factor	350
Accelerator type	π-mode
Bending angle	69.2°
Beam channel	∅10 mm
Shunt impedance	44 MΩ/m
Surface E_{max}	750 MV/m
Surface B_{max}	0.8 MA/m

Parameters of the 11.7 GHz, 300 MV/m, 5-cell structure (*T*=300 K).



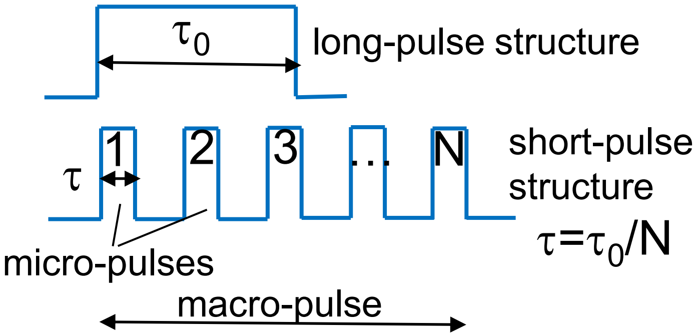
5-cell side coupled accelerating structure: E-field structure of the operating mode at 11.7 GHz (a), several structures assembly (b), S_{11} for the feeding antenna (c).

Estimations for Structure Life Time

Because the luminosity is required to be high, the repetition rate for a short-pulse structure must be increased by factor of pulse length reduction. It could be as high as sub-MHz level.

$BDR = E^{30}\tau_0^5$ for a long-pulse structure.

$BDR_N = NE^{30}\tau^5 = E^{30}\tau^4\tau_0$ for N short pulses, i.e. $E \sim \frac{1}{\tau^{2/15}}$.



Let us take BDR_N=BDR and assume that in case of breakdown event full RF power stored in a cell can be deposited in material erosion:

$$\varepsilon_0 \int_V E^2 dV = q_e \rho V_p.$$

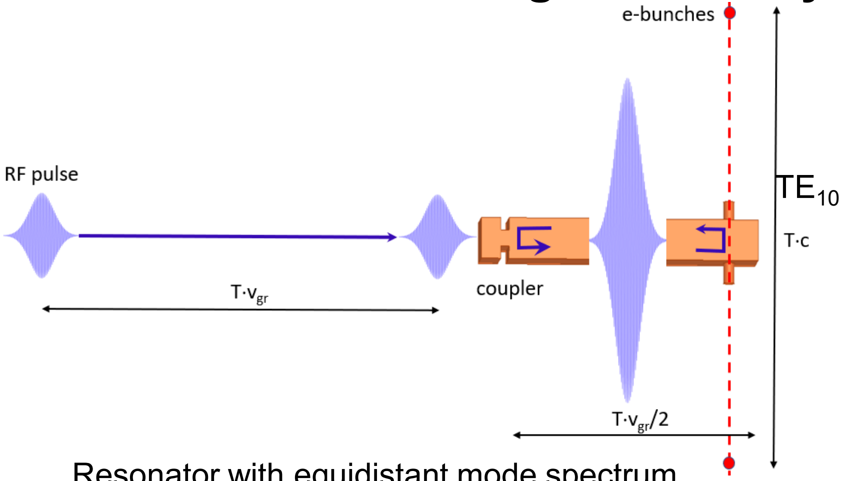
To "kill" the structure completely one need evaporating as much material as:

$$\frac{V_p^{total}}{V} = \frac{1}{Q} = \frac{1}{\pi f \tau}.$$

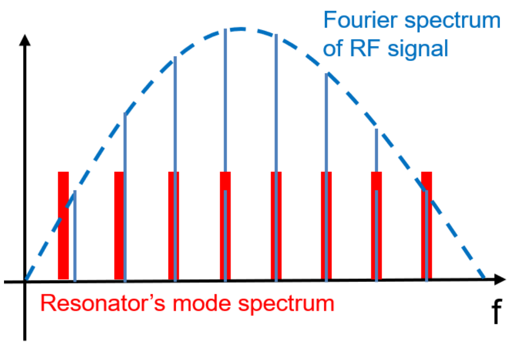
Eventually, the full number of macro- pulses to destroy the structure:

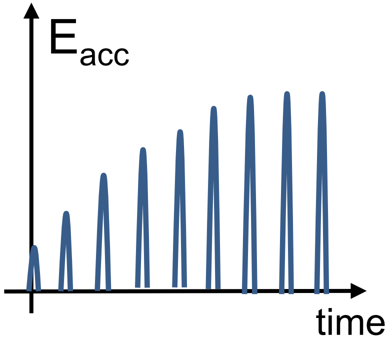
$$N_{LT} \approx \frac{1}{\pi f \tau}\frac{V}{V_p}\frac{1}{BDR_N} \sim \frac{1}{\tau^{11/15}}.$$

High-Efficiency Short Pulse Acceleration

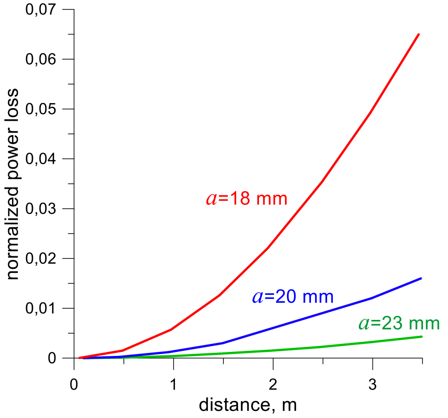


Resonator with equidistant mode spectrum.

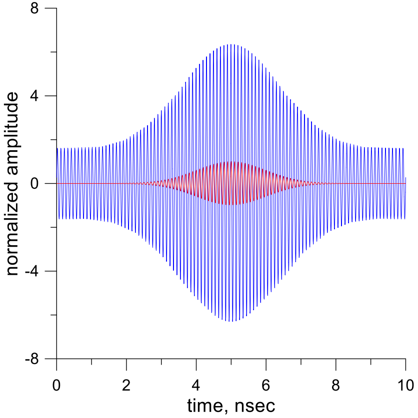




Field in resonator.



Losses of RF pulse per round trip.

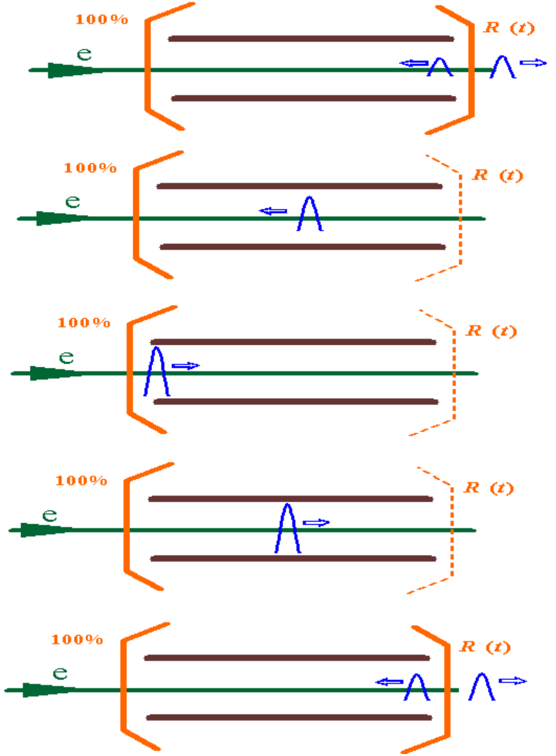


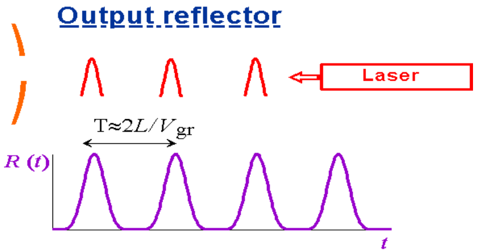
Steady state traveling RF pulse (blue) and the feeding RF pulse (red).

Frequency	10 GHz	10 GHz
Waveguide type	WR90	WR90
RF pulse duration	1 ns	0.5 ns
RF pulse period	10 ns	5 ns
Peak RF power	170 MW	140 MW
Power gain	47	55
Bunch charge	1 nC	3.5 nC
Efficiency	0.7%	6%

500 MV/m accelerating structure

High-Power Short-Pulse RF Sources

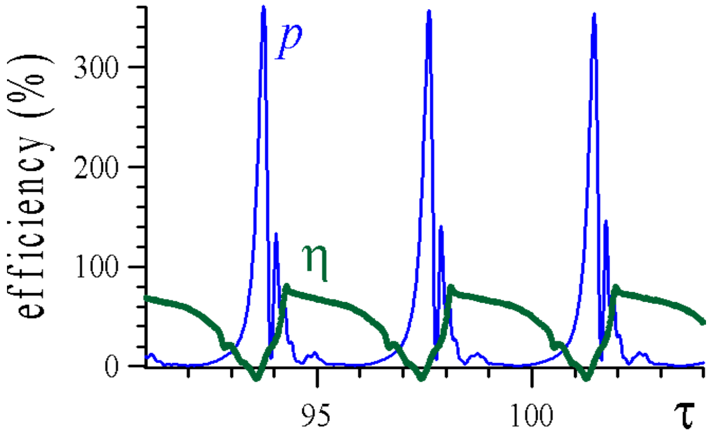




BWO with Q-switching:

- Stationary pulse-periodic generation of short rf pulses.
- RF pulses are phase locked by Q-modulation shape.

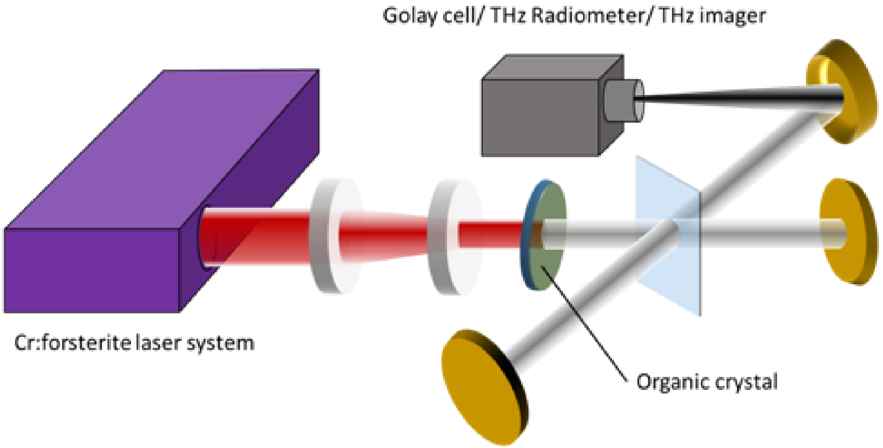
U =400 kV L= 10 λ

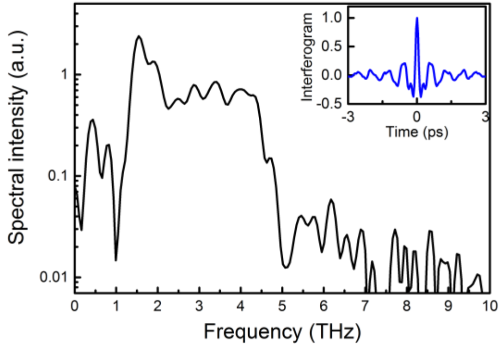


Q-switched BWO :
Efficiency = 60-70%
peak rf power = 350 %

1. G. G. Denisov, S. V. Kuzikov, A. V. Savilov. Q-switching in the electron backward-wave oscillator, *Physics of plasmas* 18, 103102 (2011).
2. S.V. Kuzikov, A.V. Savilov, Parametric Phase Locking in an Electron RF Oscillator, *Phys. Rev. Lett.* 110, 174801 (2013).

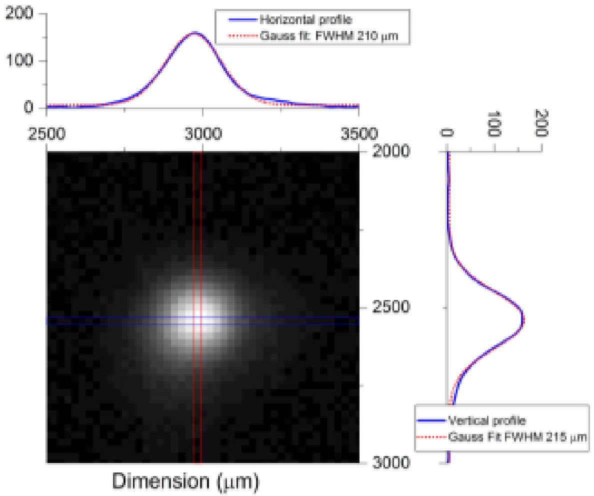
Generation of mJ Single THz Pulses with Electric Field Exceeding 80 MV/cm*





Emitted Terahertz spectrum

THz beam profile for DSTMS

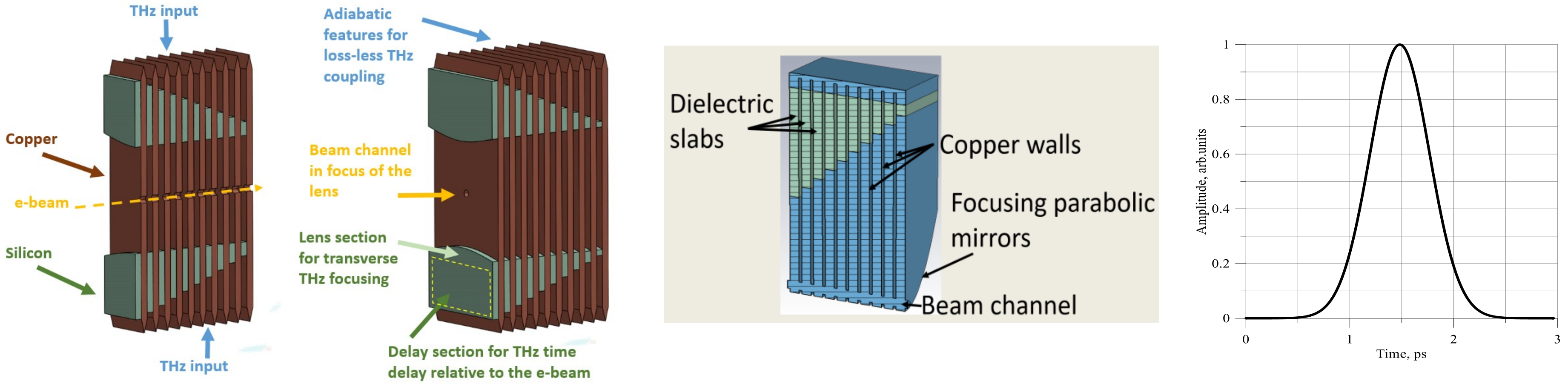


*C. Vicario et al. Optics Letters, Vol. 39, Iss. 23, 2014.

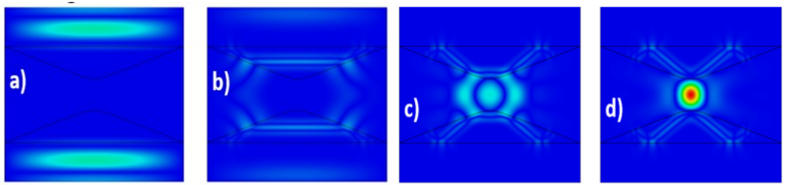
The single-cycle, phase-stable THz pulse parameters:

- THz pulse energy up to 1 mJ
- Conversion efficiency > 3%
- THz field strength 80 MV/cm
- Frequency range 0.1 – 5 THz
- Power up to 10 GW

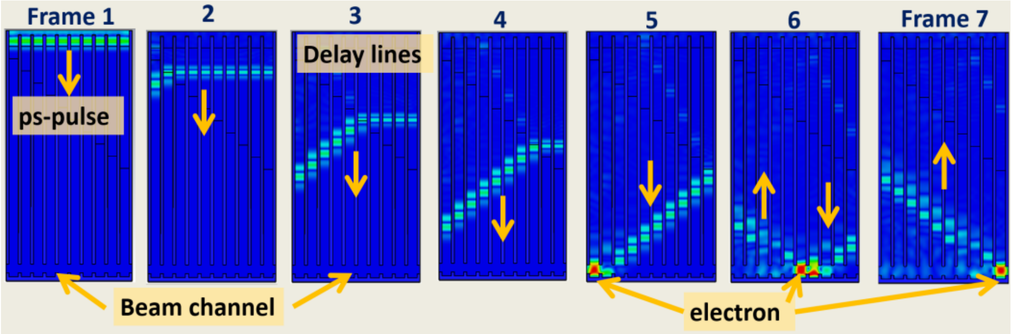
Multi-Cell Accelerating Structures Driven by a Focused THz Pulses



Sketch of broad band THz structures.

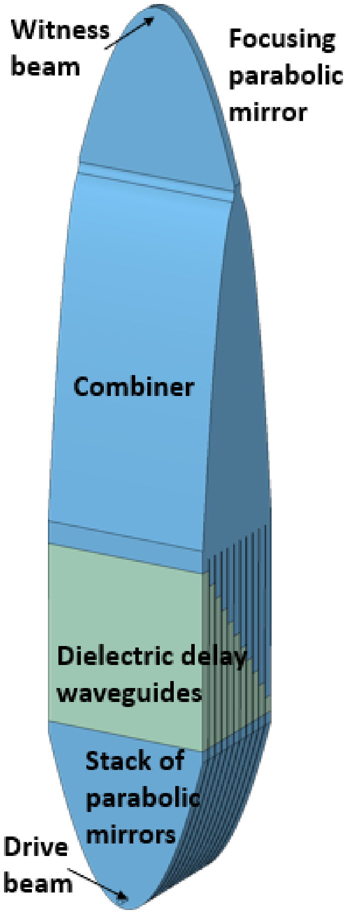


E-field distributions at the lens while focusing the short THz pulse, for the time correspondent to THz pulse arrives to lens (a), for time when focusing begins (b), for time when focusing is close to maximum (c), and in maximum of focusing (d).

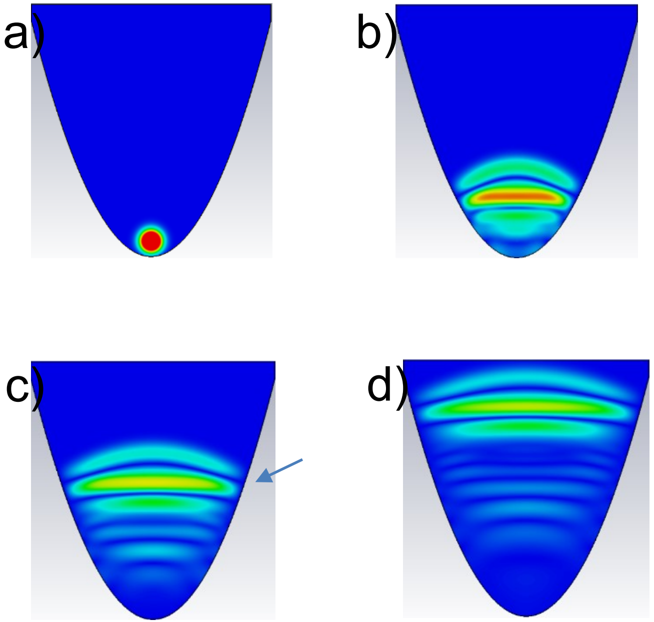


Timing of THz pulses in the structure.

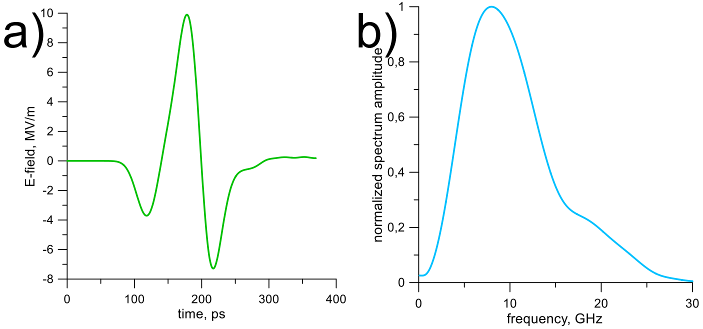
A Wakefield Single-Cycle Accelerating Structure



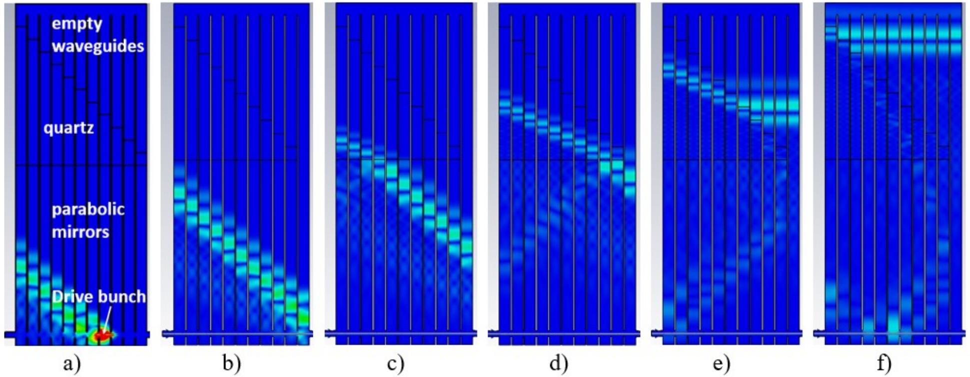
Single-cycle acceleration cell.



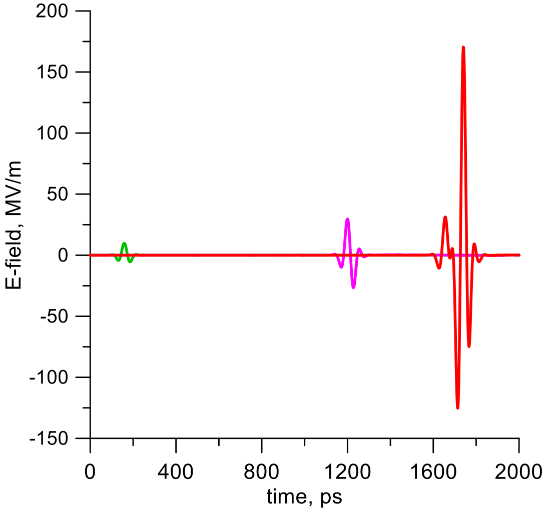
Excitation of a single-cycle wake in a gap with a parabolic shape. Time flows evenly as a-b-c-d.



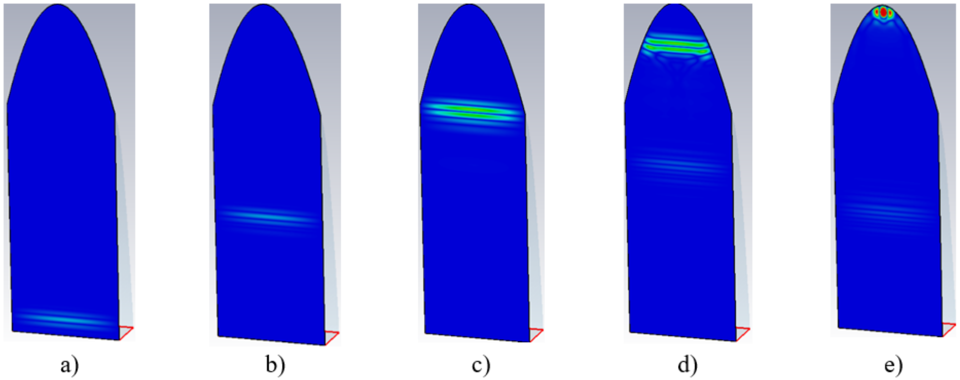
Shape of the single-cycle wake (a) and spectrum of this wake (b) at the output of the parabolic mirror with a length of 9.6 mm and an aperture of 150 mm generated by a 50-nC, 5-mm-long (Gaussian) single bunch.



Field excitation by a single bunch in parabolic mirrors, and evolution of this field in the delay line waveguides. The bunch travels from left to right.



Field shapes for the pulse entering the pulse combiner (green curve), for the pulse at the entrance of the focusing parabola (pink curve), and at the focus of the final parabolic mirror for 50 nC.



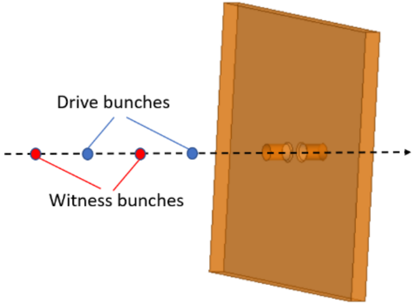
Summation of pulses in the combiner and focusing of the resulted single-cycle pulse by the parabolic mirror. Time flows evenly from left to right.

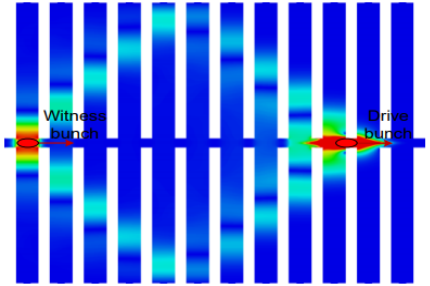
Parameters			
Bunch charge, nC	50	150	250
Number of bunches	5	2	1
Number of cells	11	20	11
Accelerating field, MV/m	170	470	570

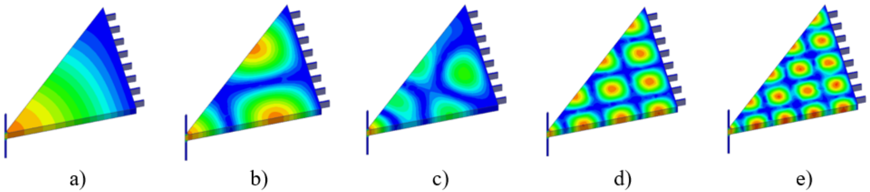
Parameters of the accelerating structures.

A Multi-Mode Wakefield Accelerating Structure

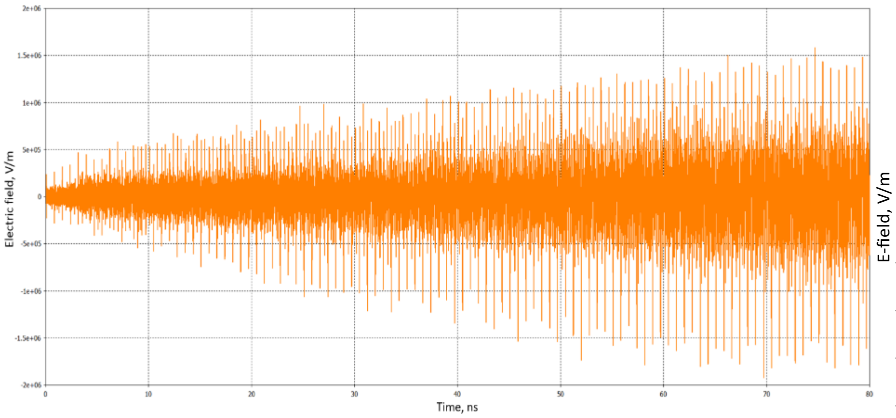
S.V. Kuzikov et al, *Phys. Rev. Lett.* 104, 214801 (2010). S.V. Kuzikov et al. *Phys. Rev. Lett. ST Accel. Beams*, Vol. 13, No.7, 071303 (2010).



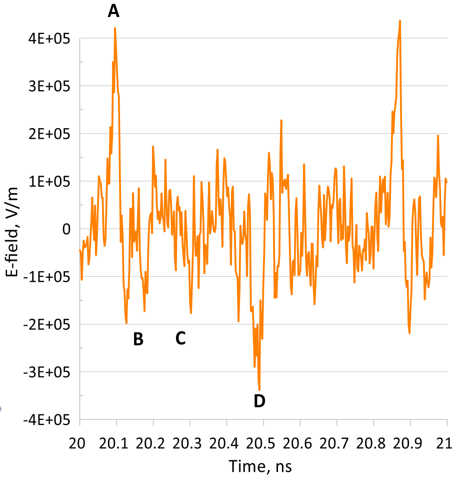




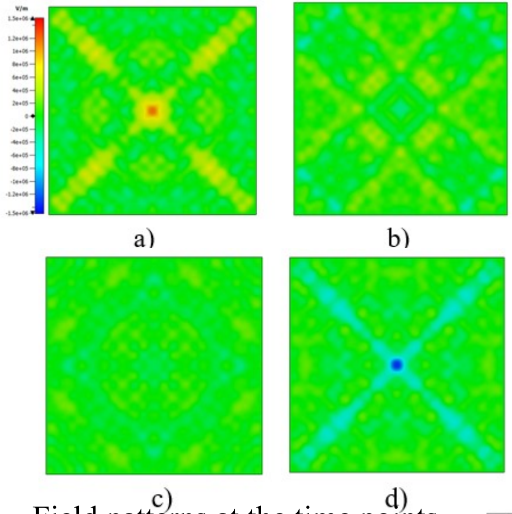
E-field mode structures in a slice of the square resonator: a – $TM_{1,1,0}$, b – $TM_{3,3,0}$, c - $TM_{5,5,0}$, d- $TM_{7,7,0}$, e – $TM_{9,9,0}$.



E-field in the middle of the resonator with mode spectrum correction excited by 100 bunches.



Enlarged portion of the previous figure.



Field patterns at the time points shown in Fig. 5: a – point A, b – point B, c – point C, d – point D.

Conclusion

1. Single-cycle structures show prospects to achieve ~GV/m gradients. Its can have high efficiencies that are comparable with efficiencies of classical structures.
2. Breakdown threshold (theoretical and experimental) study for single cycle RF pulses is needed. The temperature dependence is extremely interesting.
3. High repetition rate, short pulse RF sources are necessary. So far experiments with wakefield class single-cycle structures are available.