Novel Concepts of a High-Brightness RF Gun

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Outline

1. High cathode fields produced by short high-power RF pulses
2. Low-temperature diamond cathode
3. Pre-acceleration by a single-cycle THz pulse and ultrafast field emission gating
4. Conclusion

Brightness and emittances

$$B = \frac{2I}{\varepsilon_{\perp}^{2}}, \qquad \varepsilon_{\perp}^{2} = \varepsilon_{th}^{2} + \varepsilon_{sc}^{2} + \varepsilon_{RF}^{2}$$

- High emission current and low space charge emittance become possible in case of high RF cathode field*:

$$\varepsilon_{sc} = \frac{I}{\gamma' \cdot I_A \cdot (3\sigma_r / \sigma_z + 5)}, \qquad \gamma' = \frac{eE_{cathode}}{m_e c^2}$$

High fields ≥200 MV/m are obtainable with short pulses only according to scaling laws for breakdown and pulse heating:

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

- Short bunch length σ_z and low temperature semiconductor are also desirable:

$$\varepsilon_{RF} = \gamma' \cdot k_{RF}^2 \cdot \sigma_r^2 \cdot \sigma_z^2$$

-RF induced emittance for a bunch injected in the correct phase

$$\varepsilon_{th} = \frac{R_c}{2}\sqrt{\frac{k_B T_c}{m_e c^2}}$$

-thermal emittance

where R_c is cathode radius, σ_r, σ_z are transverse and longitudinal bunch sizes respectively, T_c – temperature of the cathode.

*J.B. Rosenzweig et. al. “Next Generation High Brightness Electron Beams From Ultra-High Field Cryogenic Radiofrequency Photocathode Sources”, arXiv:1603.01657 (2016).

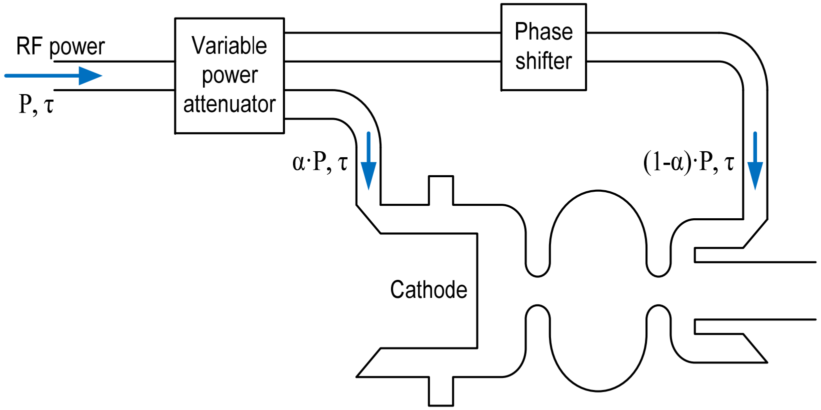
RF system of high cathode field photoinjector

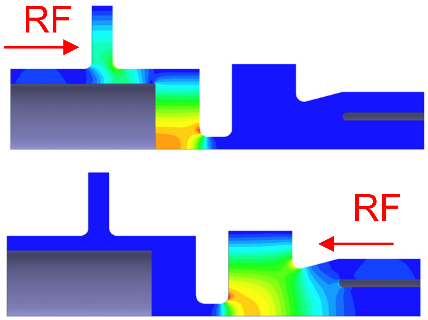
High fields are necessary in the first short cell only.

1) Standing wave structure

$E_{cathode}^{max} \approx 500 MV/m$ in the first cell at 11.7 GHz

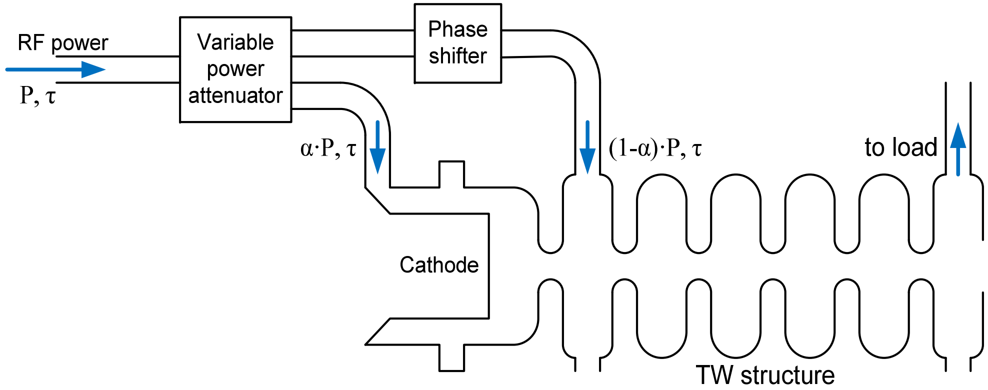
Up to **300 MW**,
10 ns at 11.7 GHz
(experiment in
ANL with the
structure excited
by bunch train)

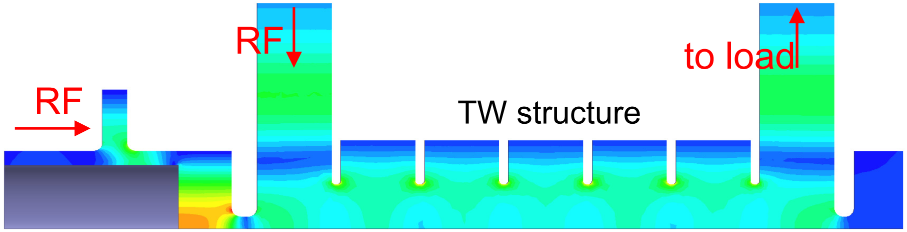




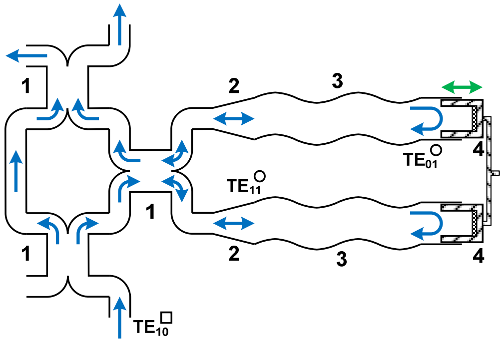
$Q \approx \pi \cdot f \cdot \tau = 370$ at 11.7 GHz for 10 ns

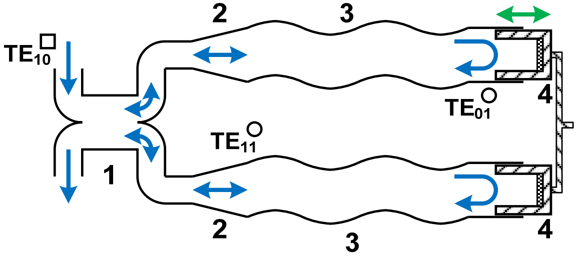
2) Travelling wave structure





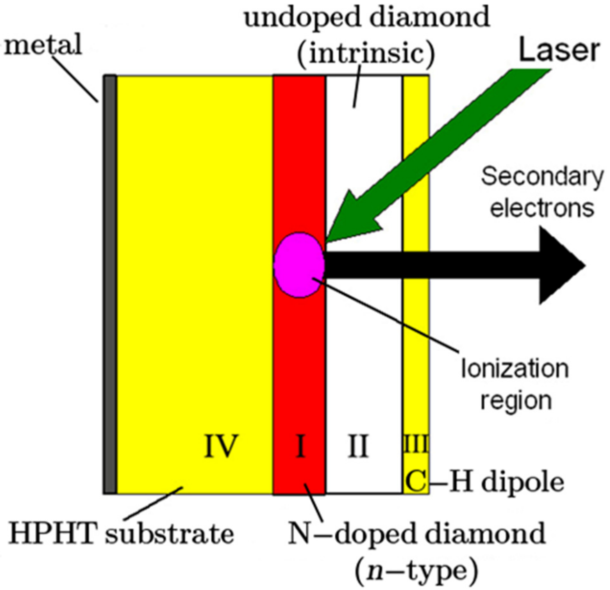
Power attenuator and phase shifter:

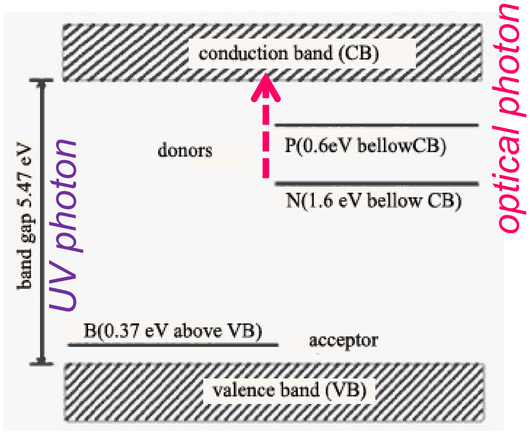




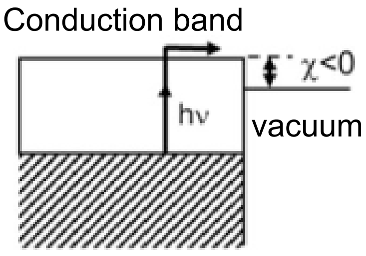
High-brightness RF gun based on cold diamond photocathode with NEA

1. True negative electron affinity is obtainable at H-terminated surface.
2. Doped diamond cathode can be driven by optical laser.
3. Diamond does not require high vacuum.
4. Multi-layered CVD mono-crystal diamond is available.

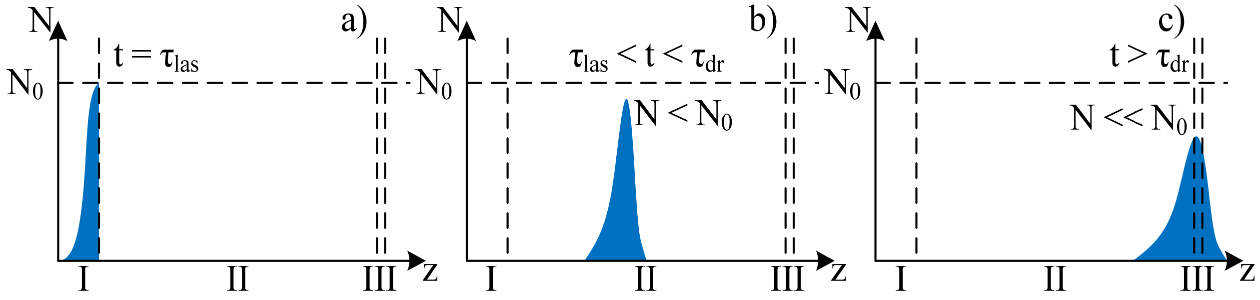




Energy diagram and doping impurity levels in the band gap of diamond



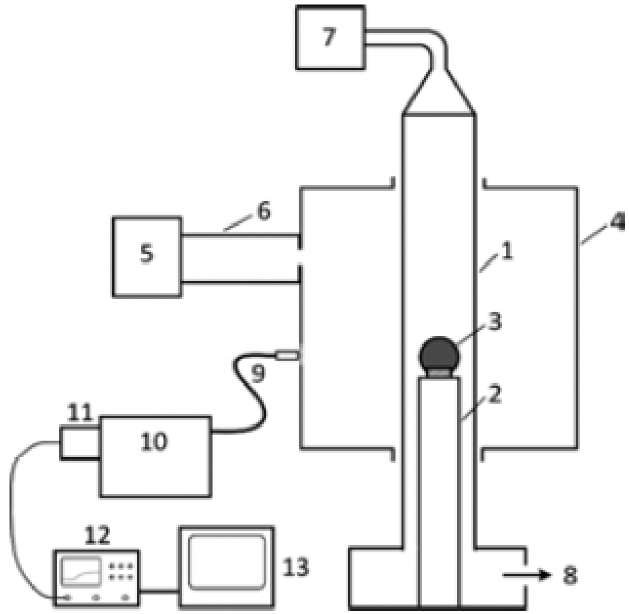
True NEA



Layer I is a heavily *n*-doped diamond (source of free carriers).

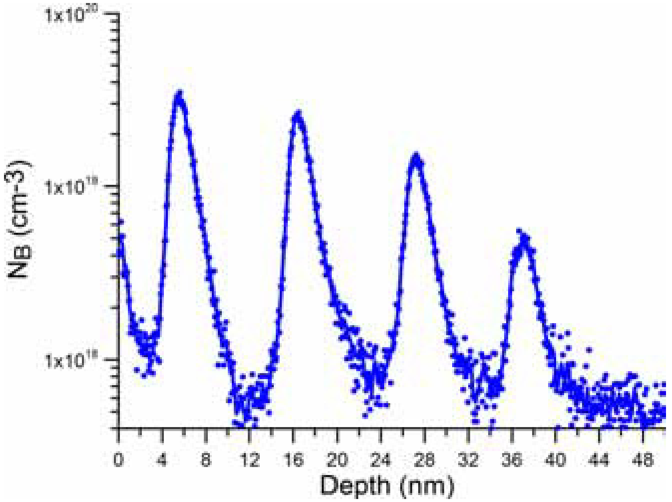
Layer II is nearly impurity-free intrinsic diamond (thermalizing layer).

Layer III is the H-terminated surface possessing the NEA property (emission layer). This layer should be Boron doped, in order to remove trapped electrons between pulses.

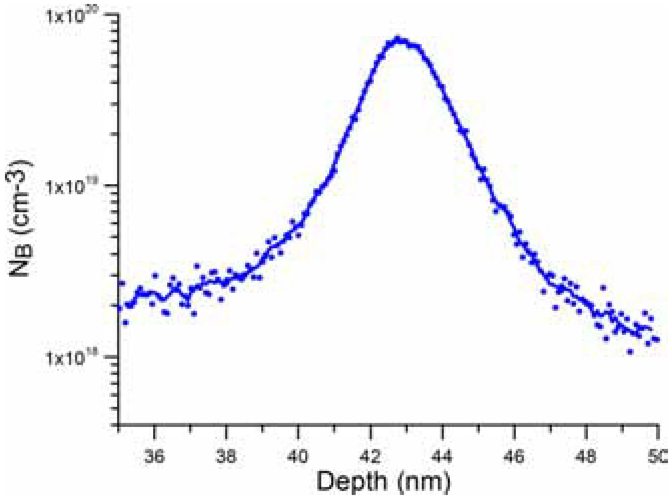


2.45 GHz MPACVD reactor for diamond delta-doping*:

1 - quartz tube, 2 - substrate holder, 3 - plasma, 4 - cavity, 5 - 2.45 GHz magnetron, 6 - rectangular waveguide, 7 - gas feeding system, 8 - gas pumping system, 9 - optical fiber, 10 - SOLAR TII monochromator, 11 - PMT, 12 - oscilloscope, 13 - PC.



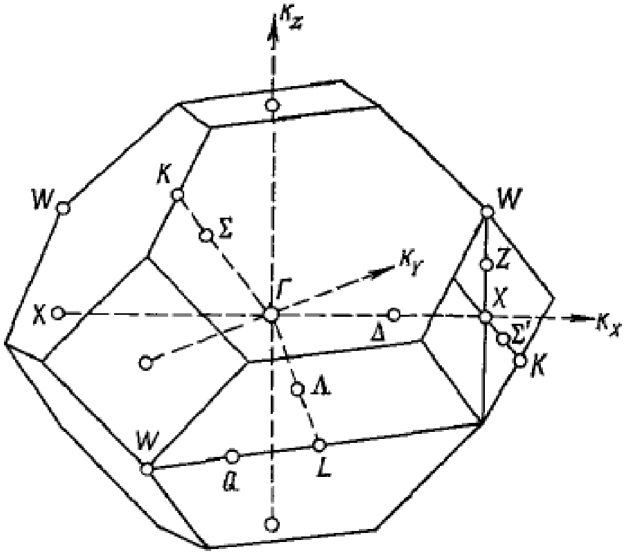
SIMS characterization of four boron delta-doped layers. Total thickness of CVD diamond is about 50 nm, the measurement started on the growth surface (depth = 0).

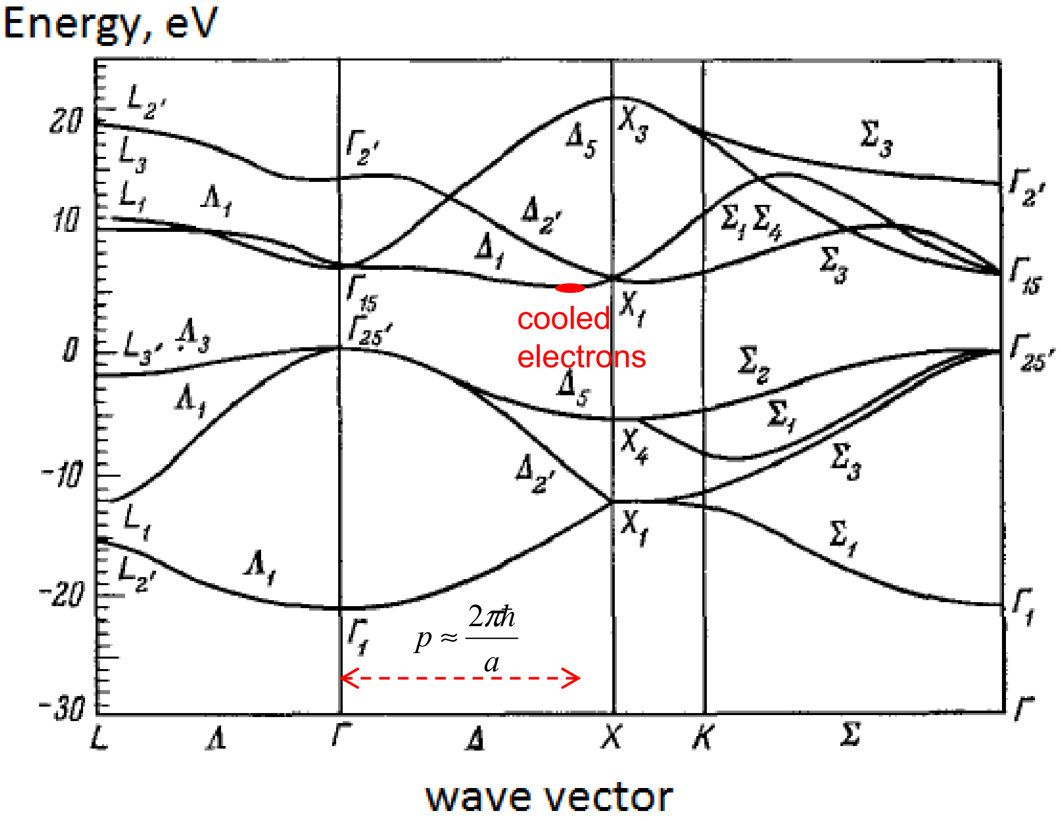


SIMS characterization of nanometric boron delta-doped layer. FWHM of the boron peak concentration is about 2 nm; the SIMS analysis starts from growth surface (depth = 0).

**A.L. Vikharev et al.* “Nanometric diamond delta doping with boron”, Physica status solidi (RRL) - Rapid Research Letters 10, 324 (2016).

Band structure of diamond





cooled electrons

$p \approx \dfrac{2\pi\hbar}{a}$

Diamond has indirect band structure. Nevertheless, the cooled electrons in conducting band, being near minimum in the energy-momentum diagram (ε-p), move with close to zero velocity $v=d\varepsilon/dp$ [1].

So such electrons at a low temperature T can be emitted from diamond having small NEA surface in a free space with near to zero velocity ($v=(2kT/m)^{1/2}$) independently on particular orientation of a crystal with respect to emitting surface.

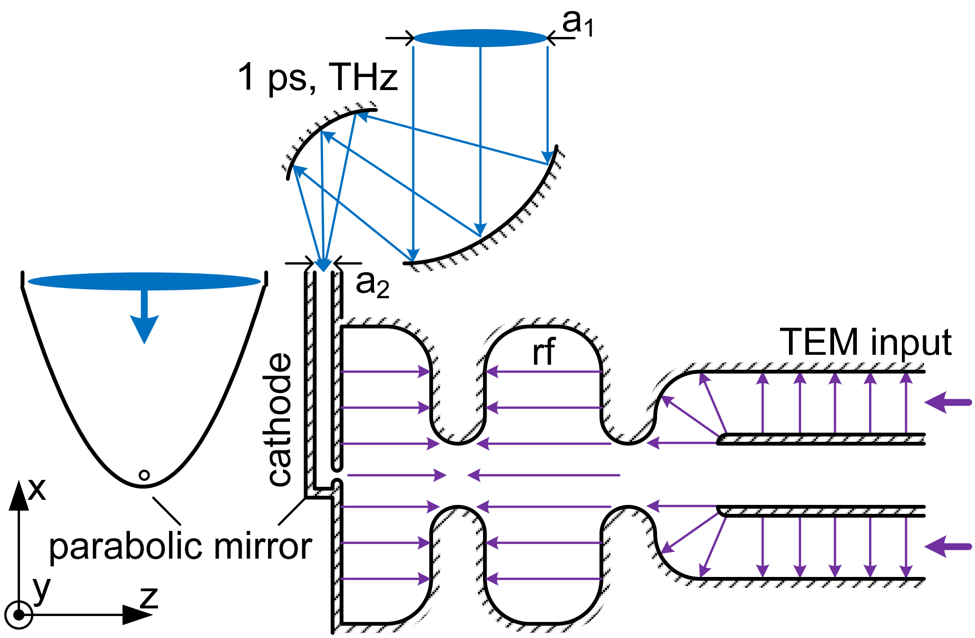
[1] L.D. Landau, L.M. Lifshitz. “Course of Theoretical Physics”, Vol. 9, Statistical Physics, part 2, 55, Pergamon Press, 1981, p.227.

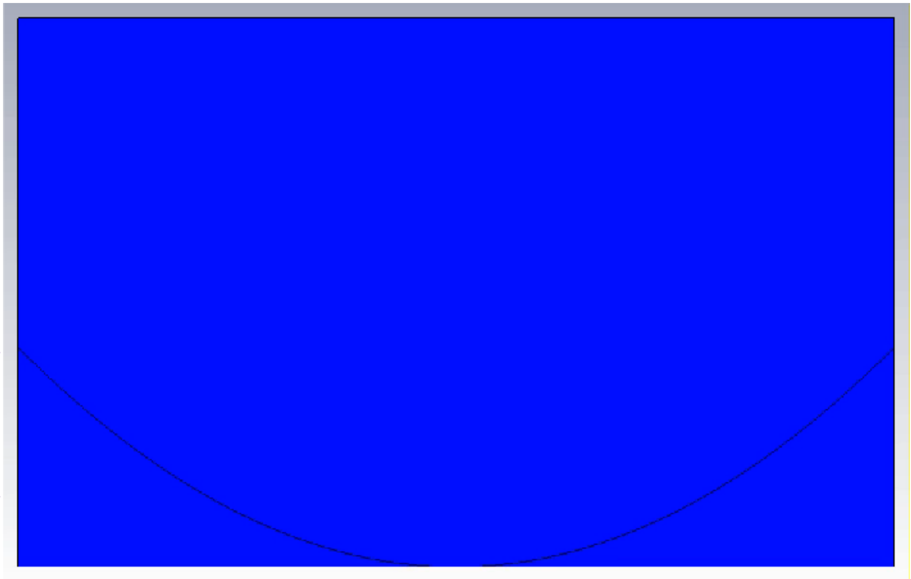
Diamond photocathode performance, and anticipated parameters of the 11.7 GHz gun based on this photocathode:

Laser pulse duration (ps)	0.1	0.3	0.5
Cathode radius (mm)	3	3	3
Wavelength (nm)	250-532	250-532	250-532
QE	10^{-3}-10^{-2}	10^{-3}-10^{-2}	10^{-3}-10^{-2}
Bunch charge (pC)	100	100	100
Maximum electric field on cathode (MV/m)	500	500	500
Parameter $\alpha = \frac{e \cdot E_{RF} \cdot \lambda_{RF}}{4\pi \cdot m_e \cdot c^2}$	1.99	1.99	1.99
Launch phase (deg.)	75	75	75
ε_{th} at 80 K (mm×mrad)	0.17	0.17	0.17
ε_{sc} (mm×mrad)	0.2	0.2	0.2
ε_{RF} (mm×mrad)	1.4×10^{-2}	0.13	0.35
Brightness (A/m^2×rad^2)	2.9×10^{16}	7.8×10^{15}	2.1×10^{15}

RF gun with fast preliminary acceleration by short high-power THz pulses

- High-power, single cycle THz pulses (*E* up to 10 GV/m) can be produced by means of a rectification of laser pulses in nonlinear media.
- These pulses are able to inject high charge (up to 1 nC) and to accelerate electrons at high gradient.



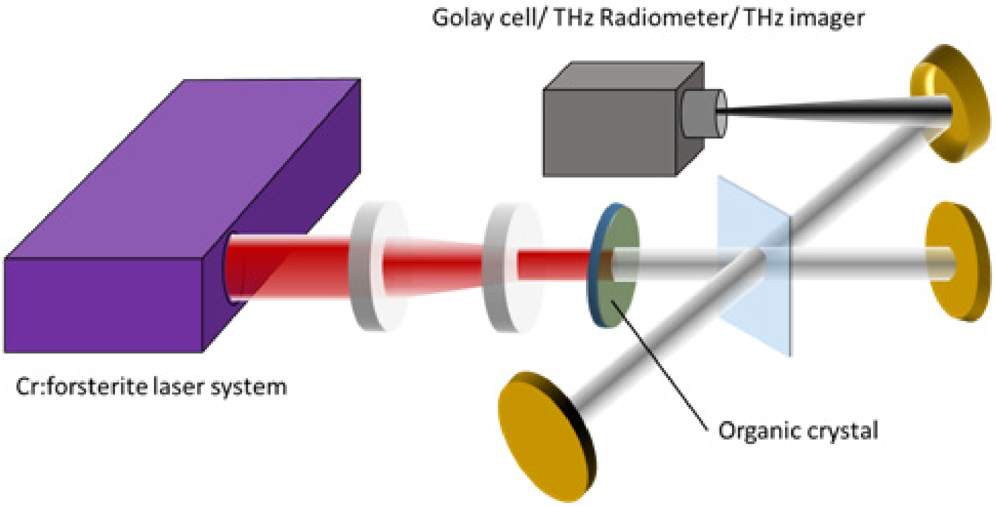


Scheme of conventional RF gun supplemented by THz accelerating section

Focusing of 1ps THz pulse by parabolic mirror

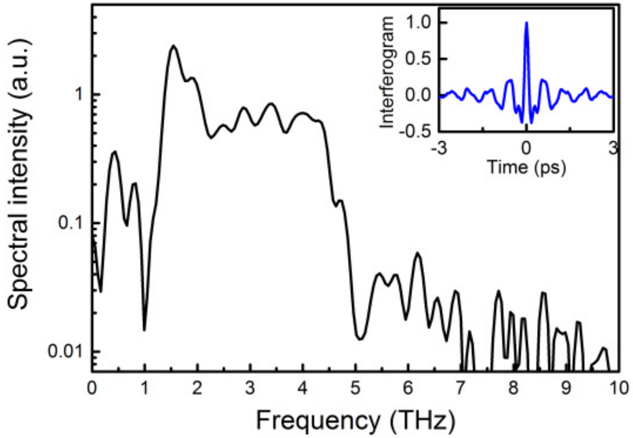
Generation of mJ Single Pulses with Electric Field Exceeding 80 MV/cm*

*C. Vicario, A.V. Ovchinnikov, S.I. Ashitkov, M.B. Agranat, V.E. Fortov, and C. P. Hauri. Optics Letters, Vol. 39, Iss. 23, 2014.



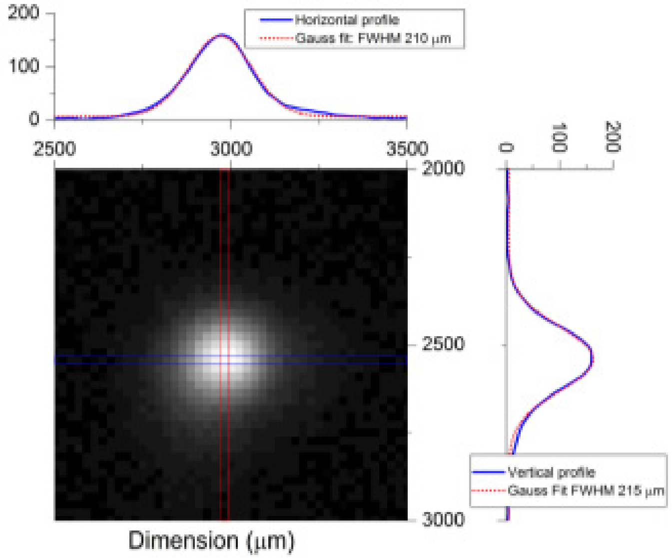
The single-cycle, phase-stable THz pulse parameters:

- 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

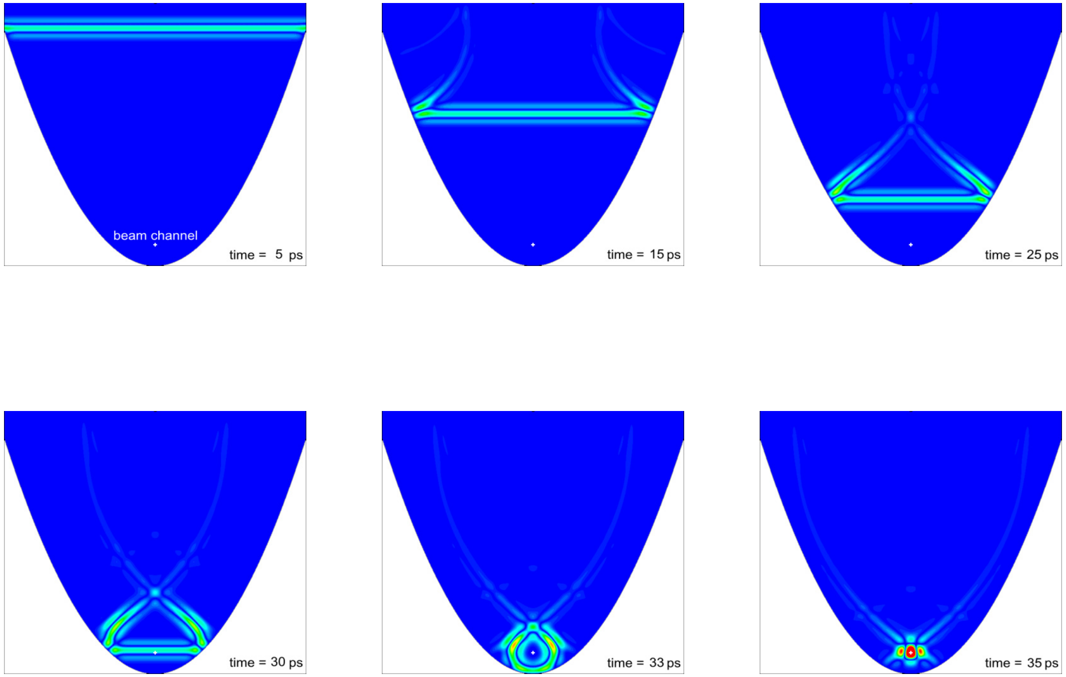


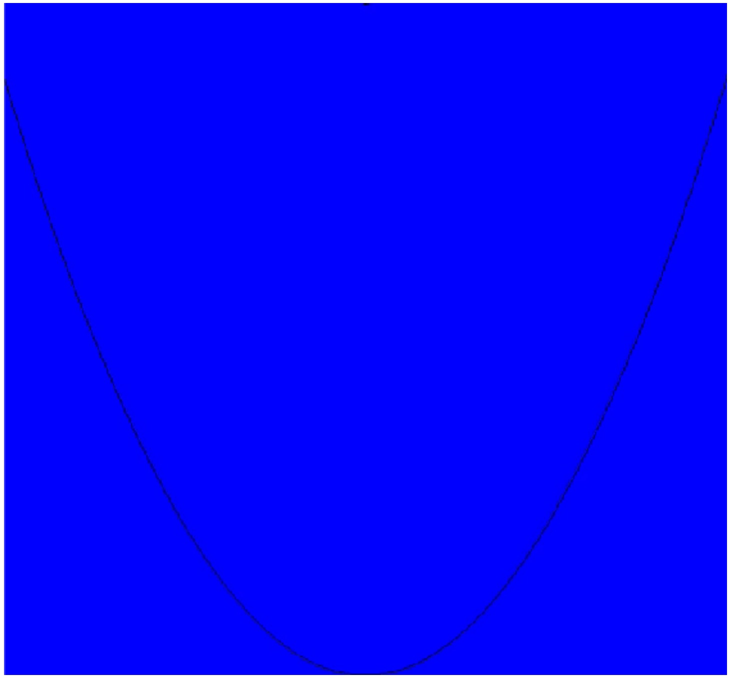
Emitted THz spectrum retrieved by the interferometric autocorrelation (blue curve in the inset) using a THz Michelson interferometer.

THz beam profile for DSTMS



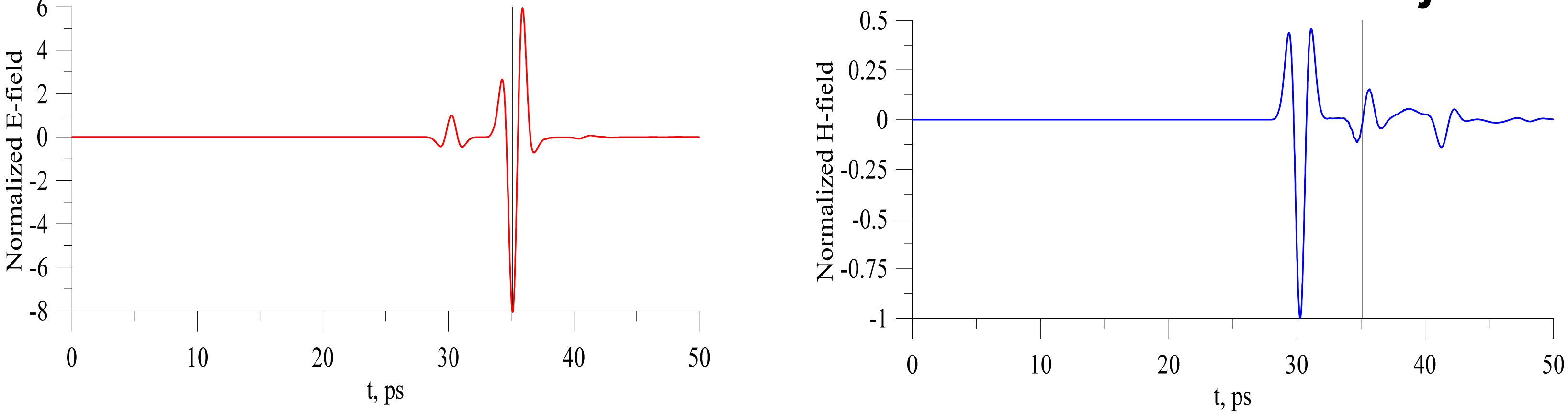
High-field THz have been produced by optical rectification in a large-size organic crystal by a powerful pump lasing. The phase-locked single-cycle pulses carry peak fields of more than **80 MV/cm** at diffraction limited spot size. The scheme has **3%** conversion efficiency.





Field distributions at the parabolic mirror while focusing the short THz pulse, for six sequential instants in time.

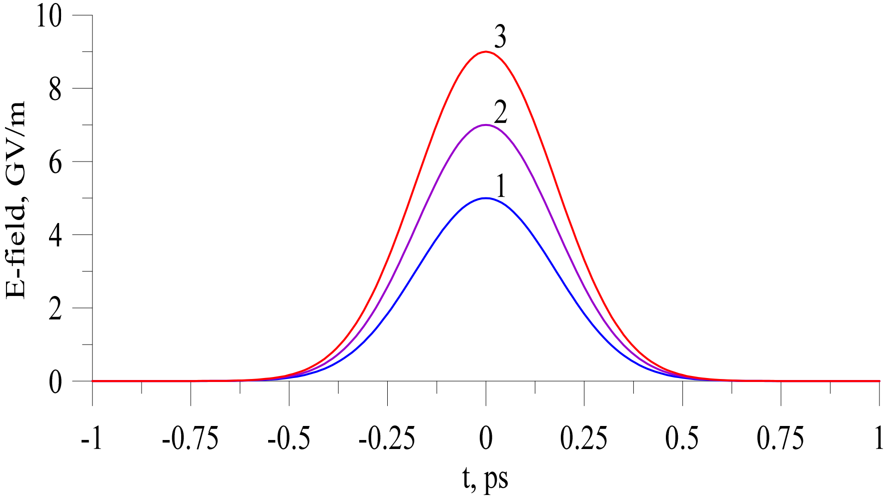
Deflecting magnetic field is zero at injection time!

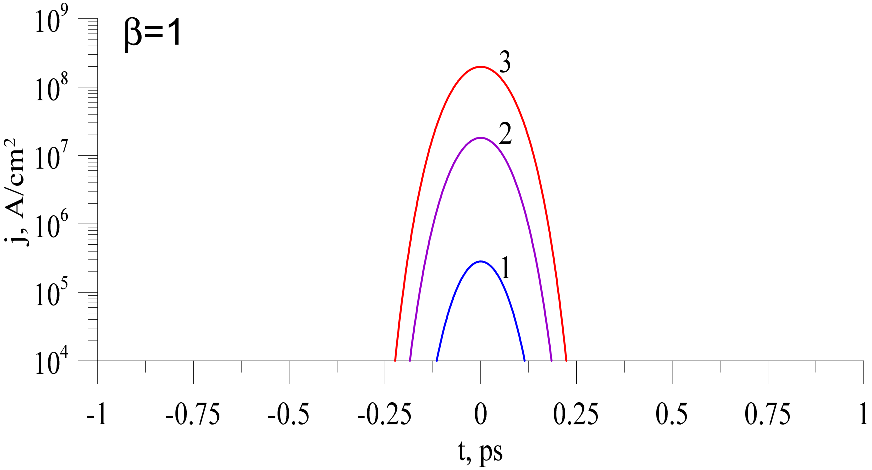


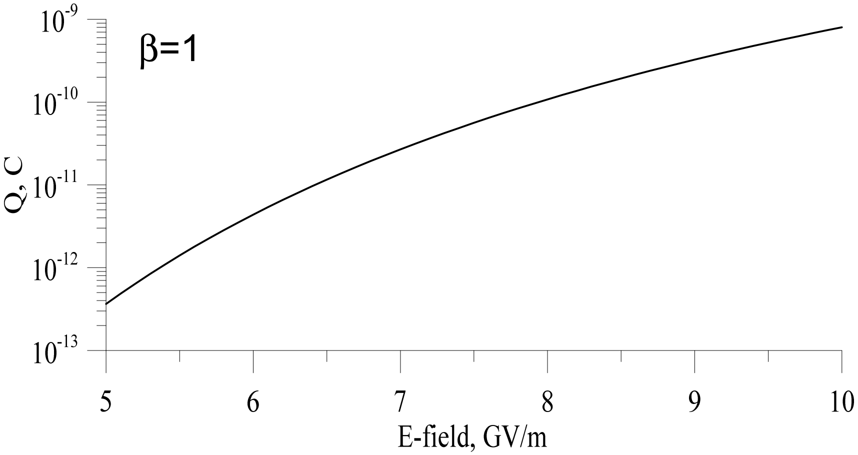
Electric (a) and magnetic (b) field components at the focus of the parabolic mirror.

Fawler-Nordheim current:

$$J_{FN} = \frac{1.54\cdot 10^{-6}}{\phi} F^{2} \exp\left(\frac{-6.83\cdot 10^{7}\phi^{3/2} f(3.79\cdot 10^{-4}\sqrt{F}/\phi)}{F}\right)$$



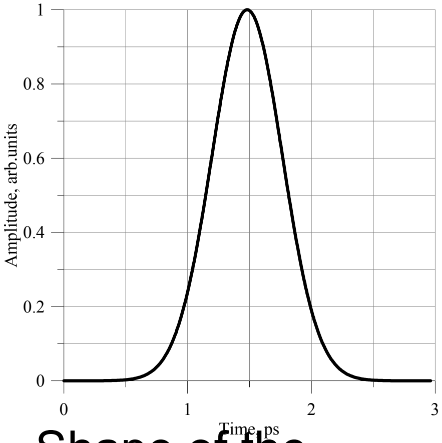




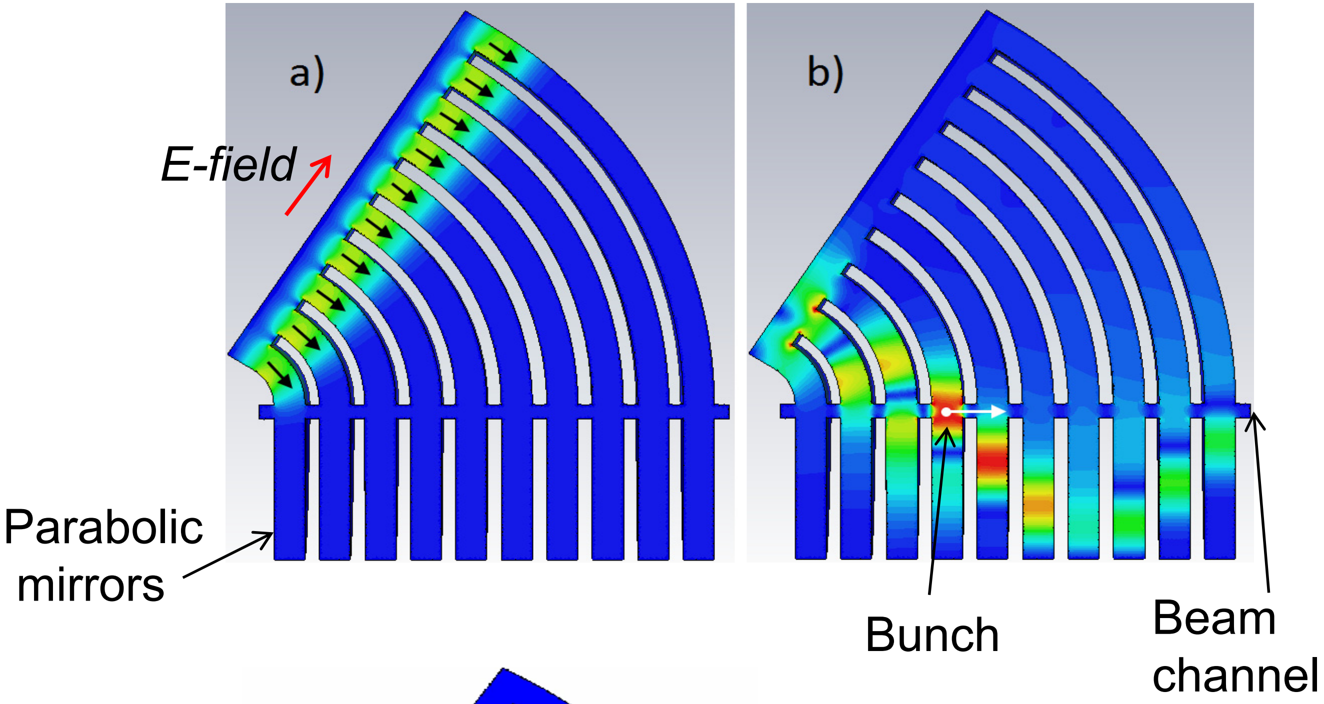
Anticipated parameters of the targeted THz-gated injector

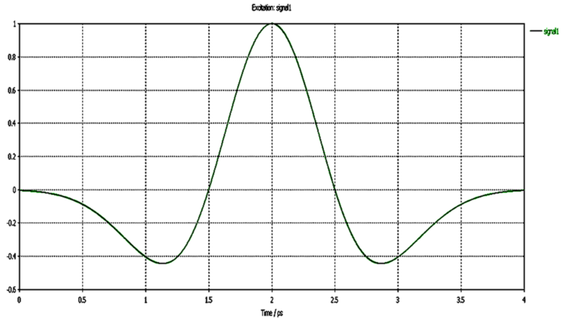
Maximum electric field on cathode (GV/m)	8
Effective bunch length (ps)	0.13
Effective cathode radius (mm)	8×10^{-3}
Bunch charge (pC)	25
ε_{th} (mm×mrad)	9×10^{-4}
ε_{sc} (mm×mrad)	0.13
ε_{RF}, (mm×mrad)	7×10^{-3}
Brightness (A/m²×rad²)	2.2×10^{16}

Several THz high-gradient accelerating gaps are able to enhance energy of bunches considerably.

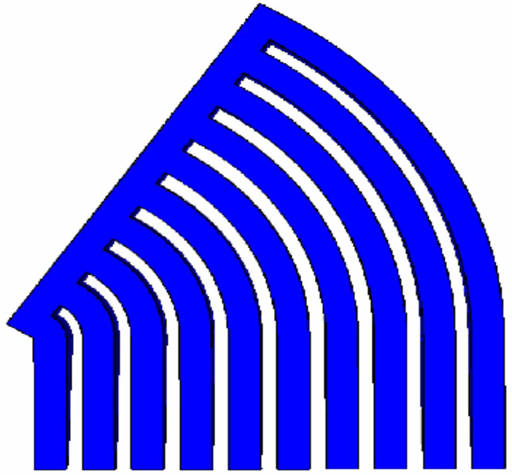


Shape of the incident THz pulse



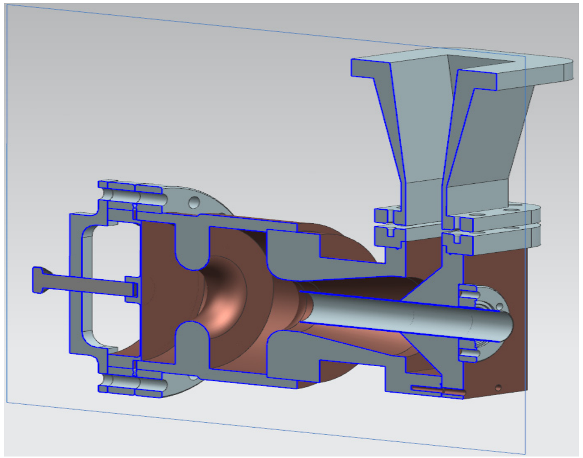


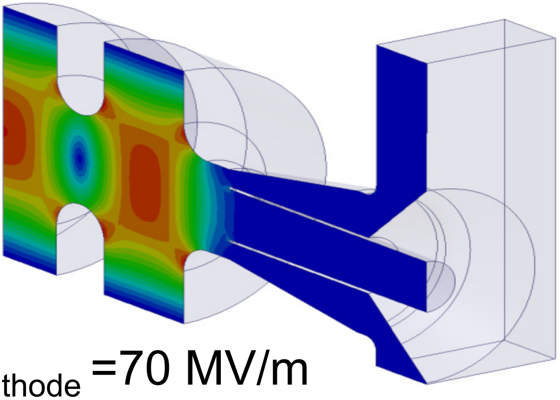
Shape of the incident THz pulse



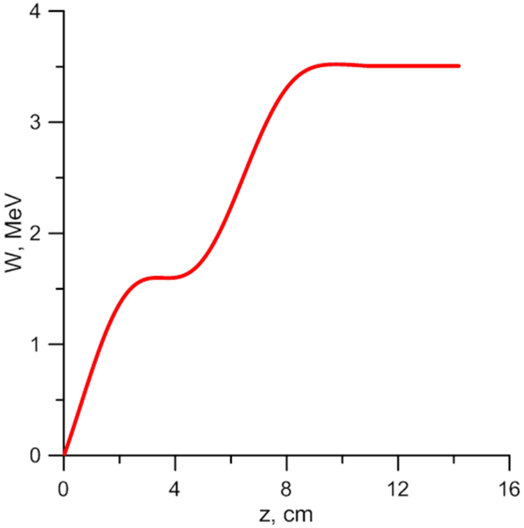
Period – 150 μm, gap between cells - 50 μm, beam channel size – 50 μm, aperture of parabolic mirror – 2 mm, focus – 0.5 mm, field in focal point – 1 GV/m, bunch length – 6 ps, gained energy – 0.4 MeV (gradient is about 300 MV/m)

A 2.45 GHz Photoinjector gun at IAP RAS





$E_{cathode}$ =70 MV/m



Conventional 1,5 cell design:

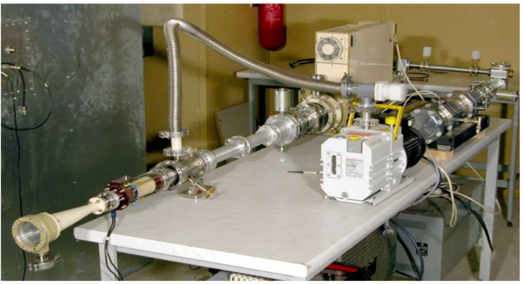
Parameters	Value
Frequency	2.45 GHz
Cavity length	11.74 cm
Laser pulse duration	10 ps
Magnetic field	1.07 T
Bunch charge	100 pC
Laser spot radius	1 mm
Cathode field	70 MV/m
Injection phase	-40°
Average energy	3.5 MeV
Transverse emittance	1,4 mm×mrad
Energy spread	0.2%

1,5 cell + THz injector design:

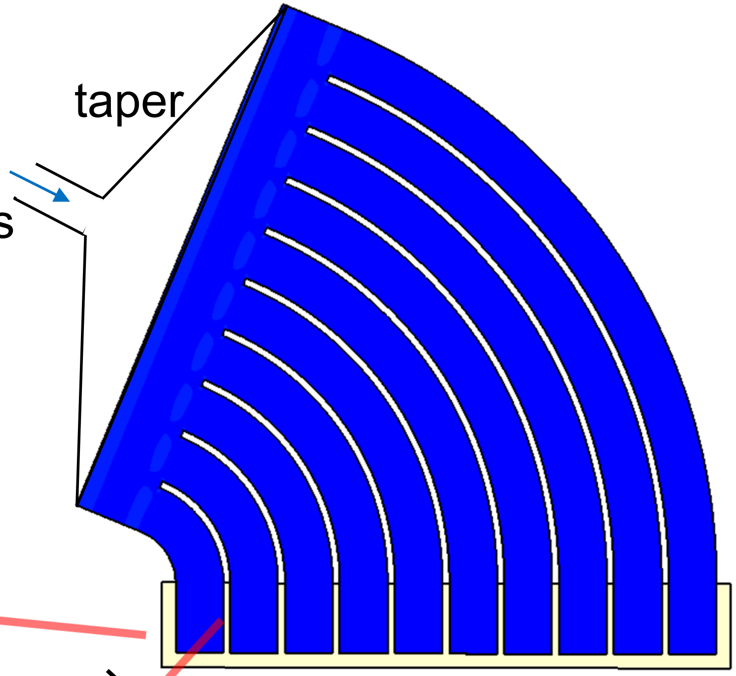
Parameters	Value
Frequency	2.45 GHz
Cavity length	11.74 cm
Bunch duration	0.09 ps
Magnetic field	1.34 T
Bunch charge	>25 pC
Beam radius at cathode	0.1 mm
Cathode THz field	5 GV/m
Injection phase	-27°
Average energy	4 MeV
Transverse emittance	0.9 mm×mrad
Energy spread	1 %

The use of THz injector helps to increase brightness by factor more than 50!

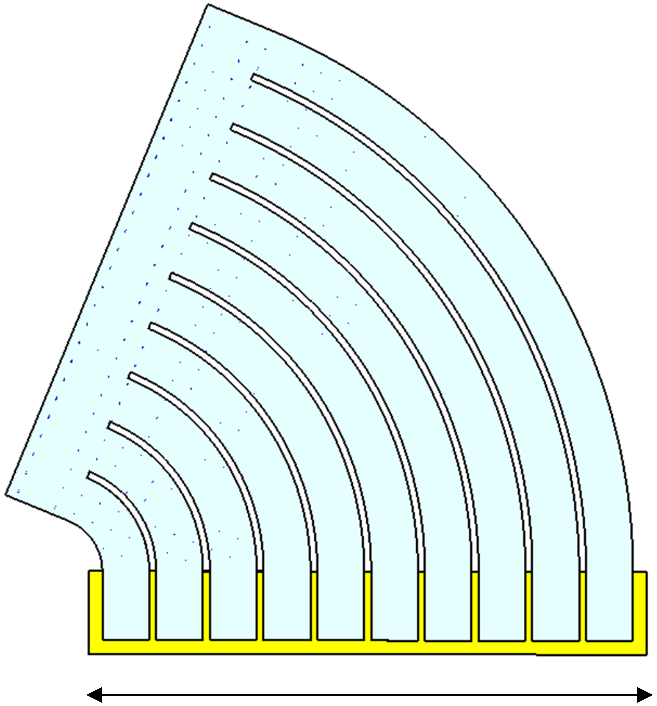
Planned 38 GHz experiment



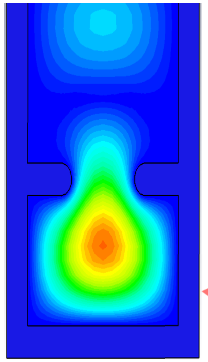
38 GHz, 1-2 GW, 300 ps



Set of resonators

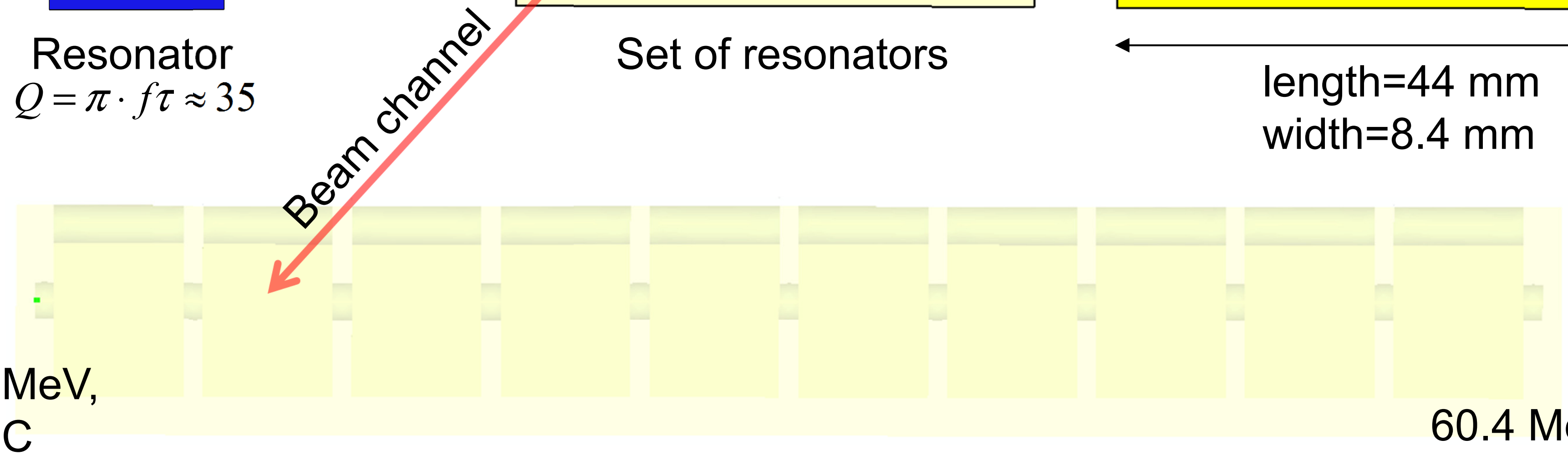


length=44 mm
width=8.4 mm



Resonator

$Q = \pi \cdot f\tau \approx 35$



50 MeV,
1 pC

60.4 MeV

Simulation of acceleration for long bunch (gradient is about 230 MV/m)

Conclusion

Three concepts were proposed:

1) to apply short-pulse, high-power RF sources maintaining high cathode fields;

2) to apply cold diamond photocathode producing low-emittance bunches;

3) to use ultrafast terahertz gating providing preliminary acceleration of bunches.

These concepts are able to provide ~10^{16} A/$m^2 \times rad^2$ beam brightness.