Современные фотоинжекторные комплексы: состояние и перспективы

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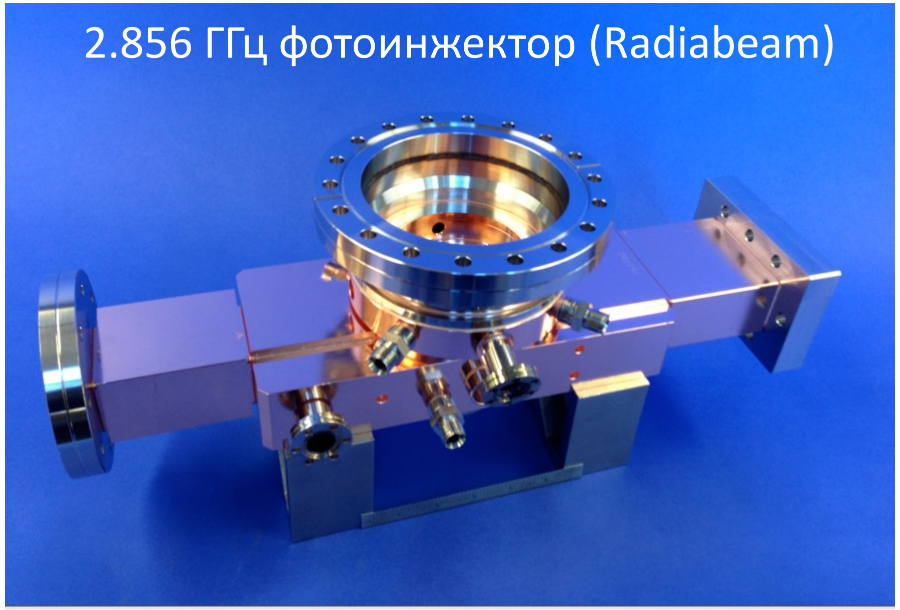


Яркость электронного пучка и светимость коллайдера

1. Free Electron Lasers

$$B = \frac{I}{8\pi^2 \varepsilon_{n,x} \varepsilon_{n,y}}$$

I – ток пучка,

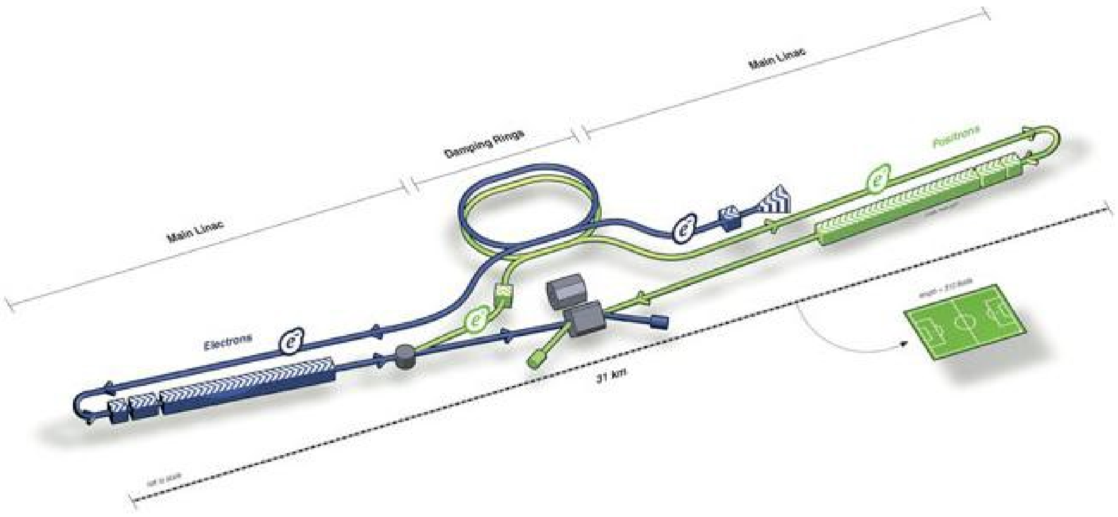
$\varepsilon_{n,x}$, $\varepsilon_{n,y}$ – поперечные эмиттансы

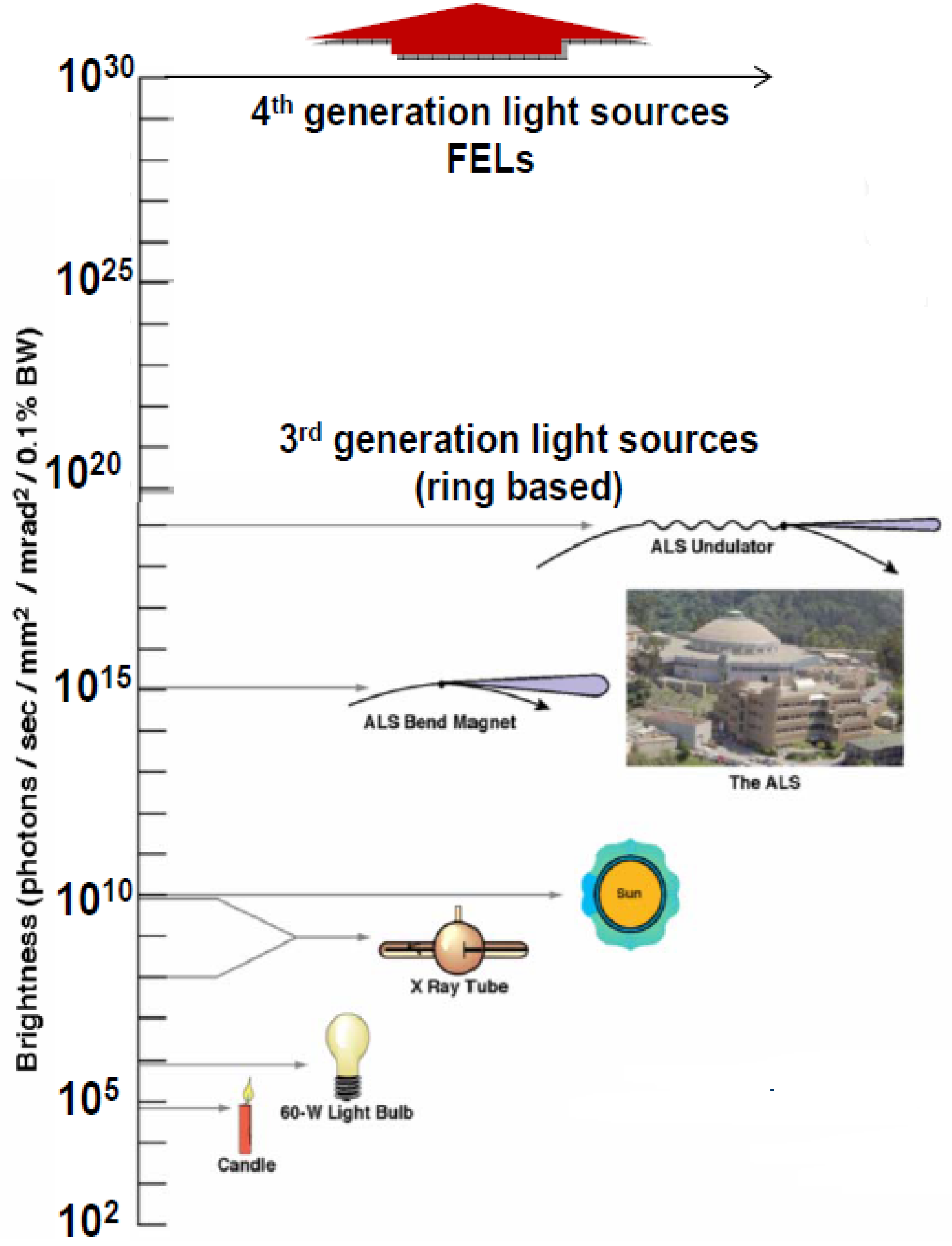
2. Colliders and high-energy accelerators

$$L = \frac{N_1 N_2}{4\pi \sigma_x \sigma_y} f_{rep}$$

N_1, N_2 – число частиц в сгустках,

σ_x, σ_y – поперечные размеры сгустков.





Поперечный эмиттанс пучка

Эмиттанс является сечением шестимерного фазового пространства плоскостью (x, p_x) или (y, p_y).

$$x' = \frac{p_x}{p_z}$$

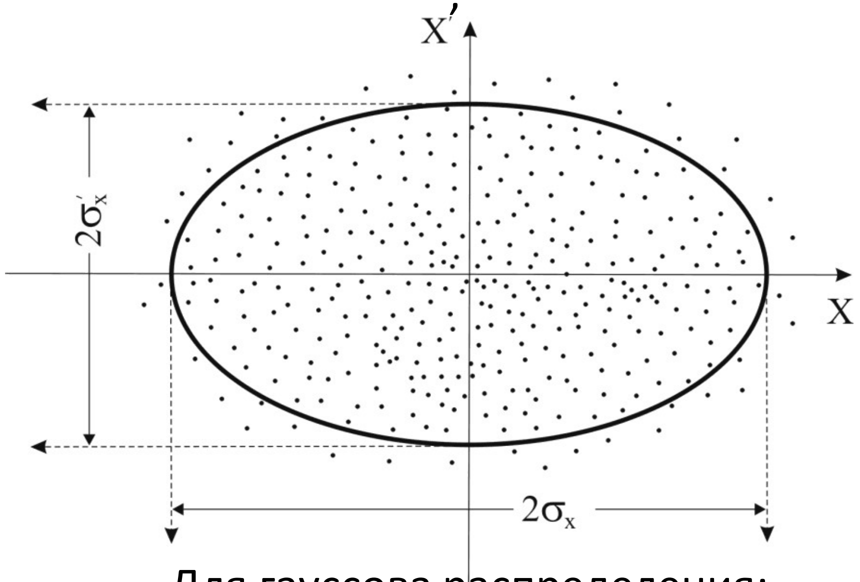
Поперечный эмиттанс характеризует распределение частиц пучка по поперечным координатам и импульсам.
Принято вводить два поперечных эмиттанса:

$$\varepsilon_x = \delta x \cdot \delta x'$$

$$\varepsilon_y = \delta y \cdot \delta y'$$

$$\varepsilon_x = \pi \cdot \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \qquad (\langle x \rangle = 0, \langle x' \rangle = 0)$$

Поперечный эмиттанс измеряют в мм×мрад (или π × мм×мрад).



Для гауссова распределения:

$$\varepsilon_x \approx \pi \cdot \sigma_x \sigma'_x$$

По мере ускорения продольный импульс частиц растет, $p_z = m_0 v\gamma = m_0 c\beta\gamma$
а поперечный эмиттанс, следовательно, уменьшается.
Поэтому вводят понятие нормализованного поперечного эмиттанса, не зависящего от энергии пучка:

$$\varepsilon_{N,x} = \beta\gamma\varepsilon_x$$

$$\varepsilon_{N,y} = \beta\gamma\varepsilon_y$$

3. Ultrafast Electron Microscopy

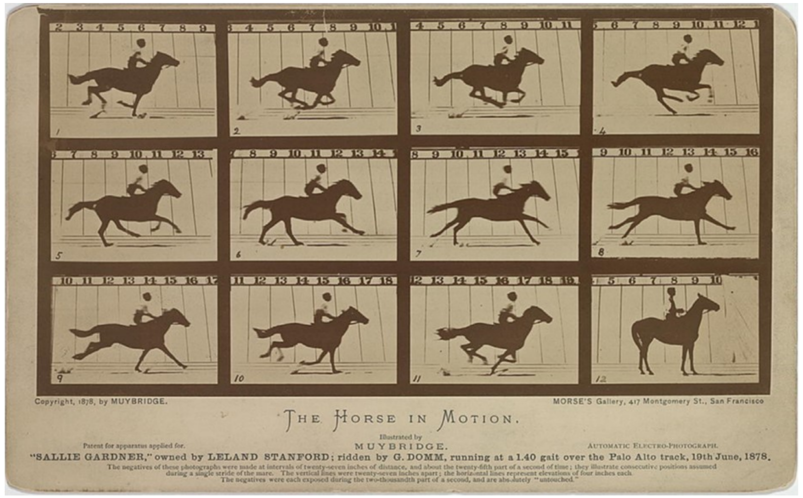
The UEM's application is for investigating ultrafast (sub-picosecond) structural and chemical dynamics in materials at the nanoscale using electrons, an exciting area of emerging science.

It includes:

•a tunable femtosecond laser with a high repetition rate

•multiple routes to produce a pulsed MeV-level electron beam

•a synchronous laser-pumped, pulsed transmission electron microscope that is outfitted with high-sensitivity cameras and electron energy filtering.



One of the first "movies" in history.

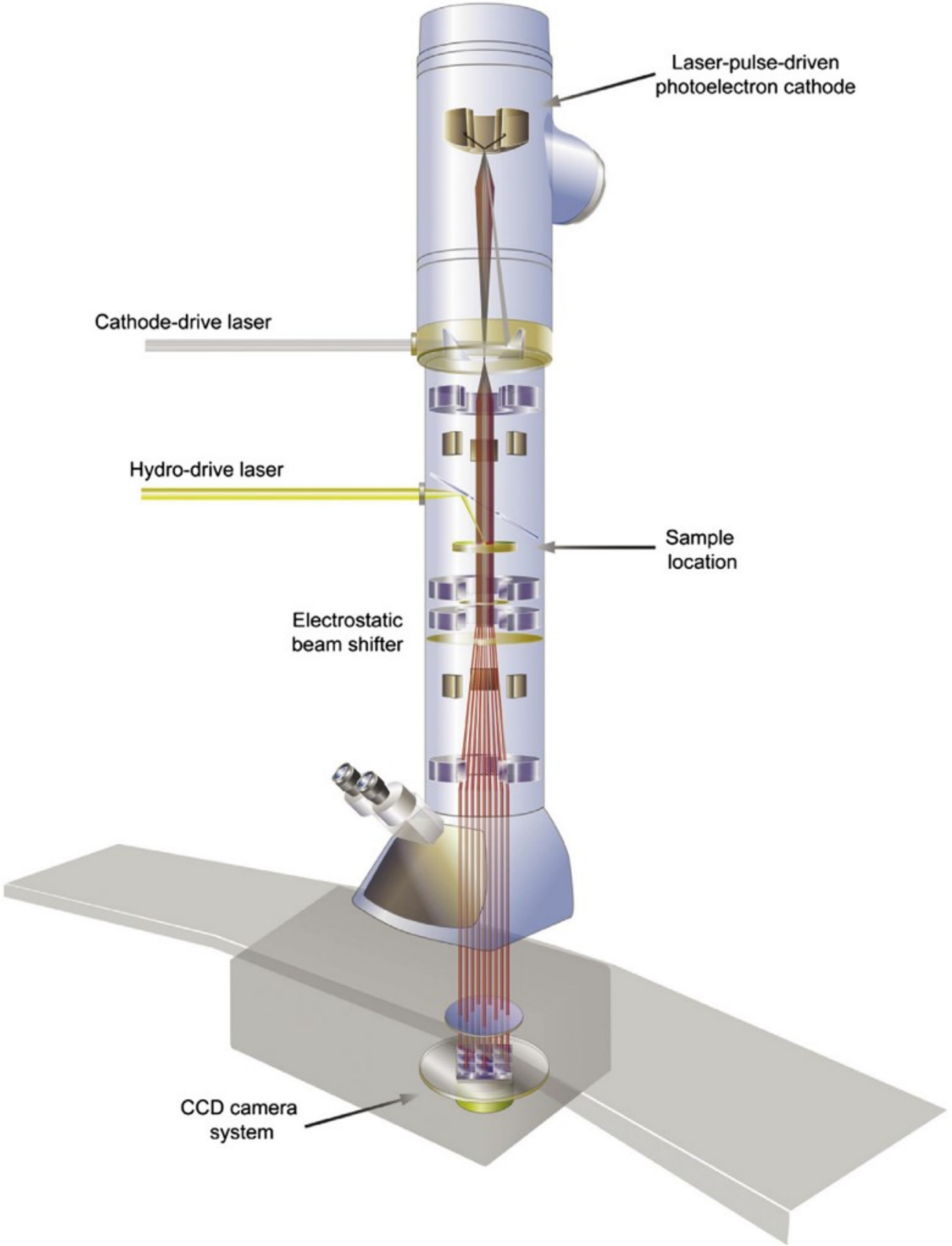
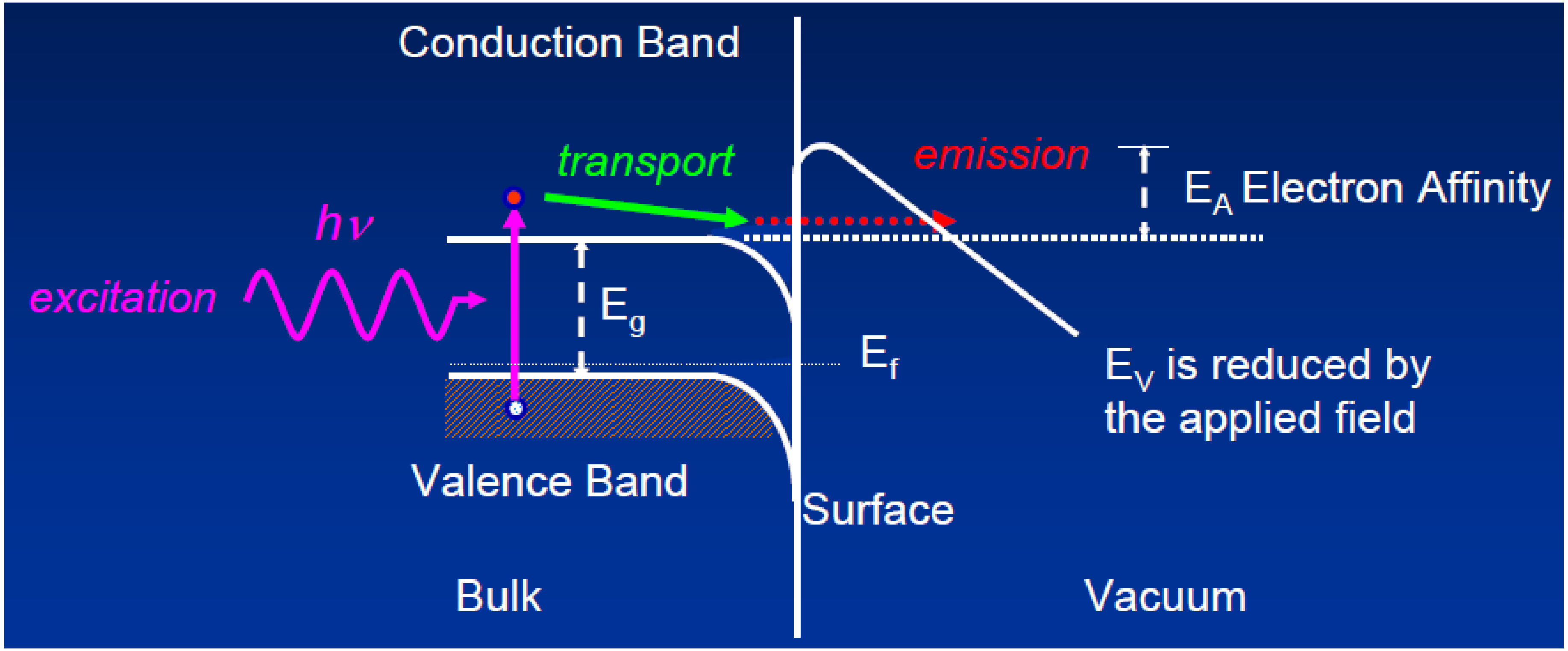


Photo-emission in a Semiconductor Photocathode

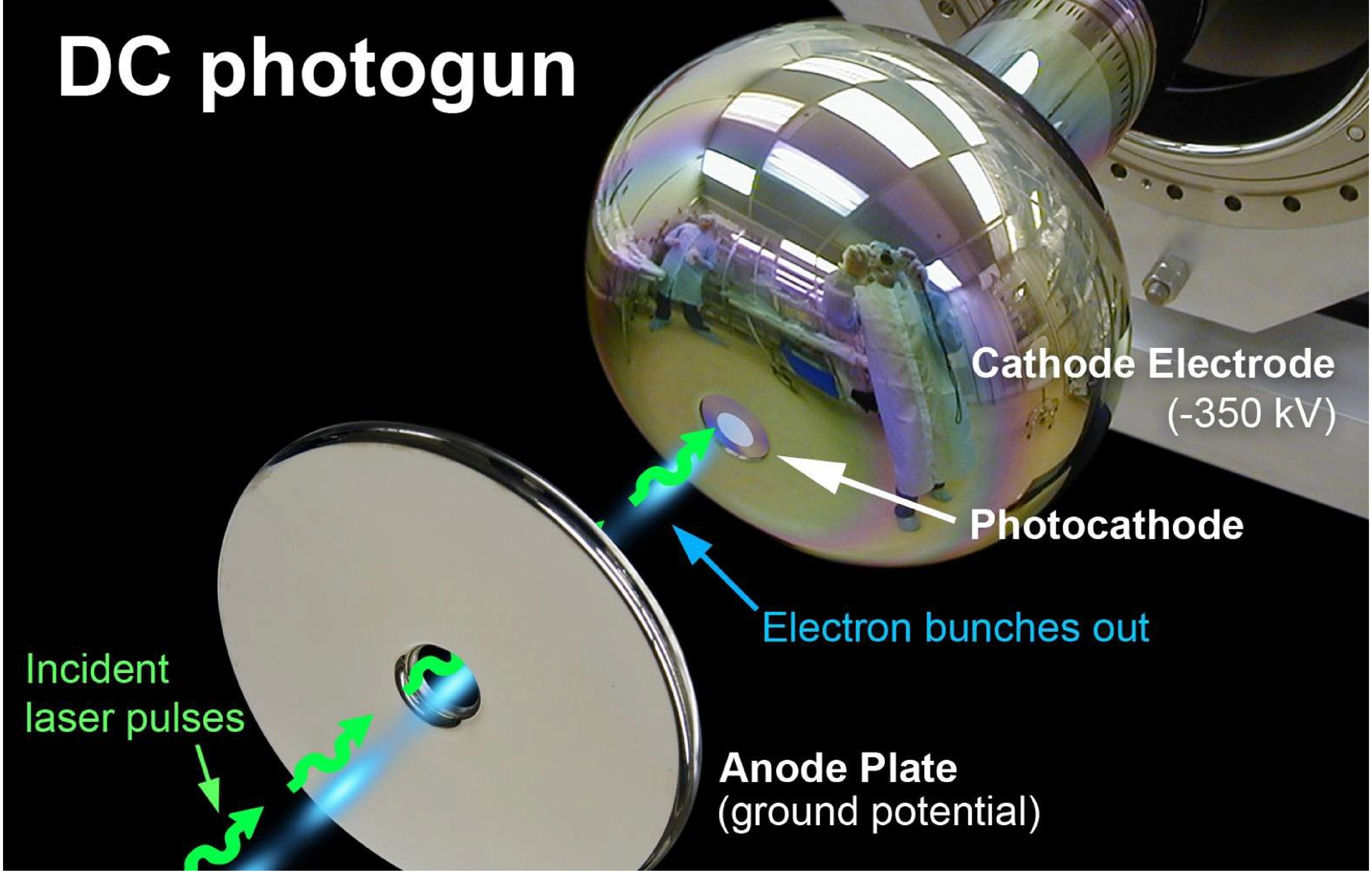


•Electrons are excited by the laser from the valence band to the conduction band.

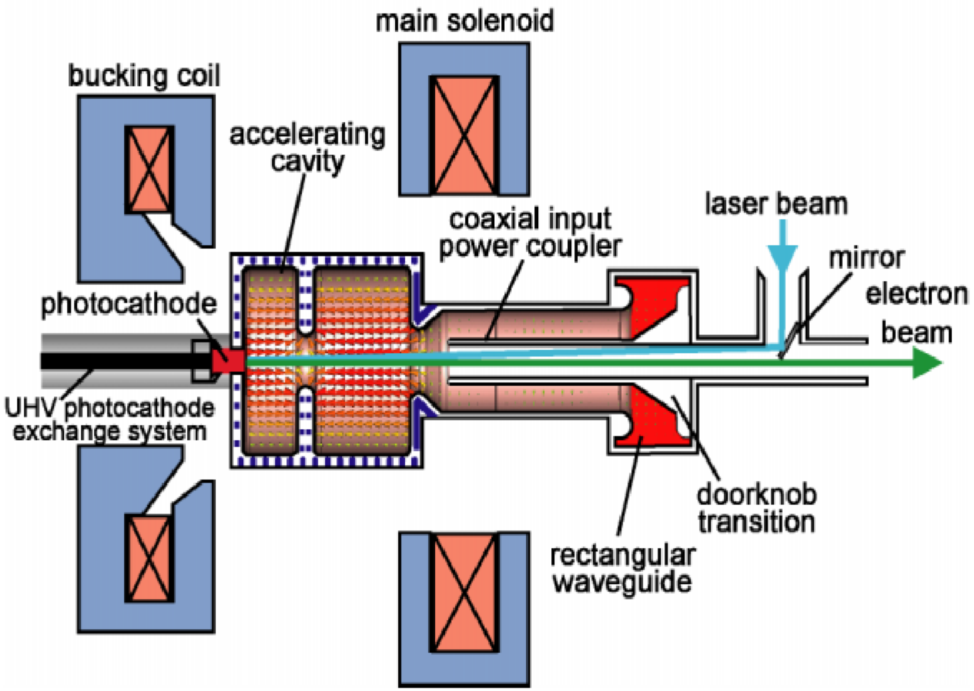
• Photoemission occurs as a tunneling process through the potential barrier at the solid-vacuum interface.

•The barrier height is determined by the electron affinity and the barrier width is determined by the applied electric field.

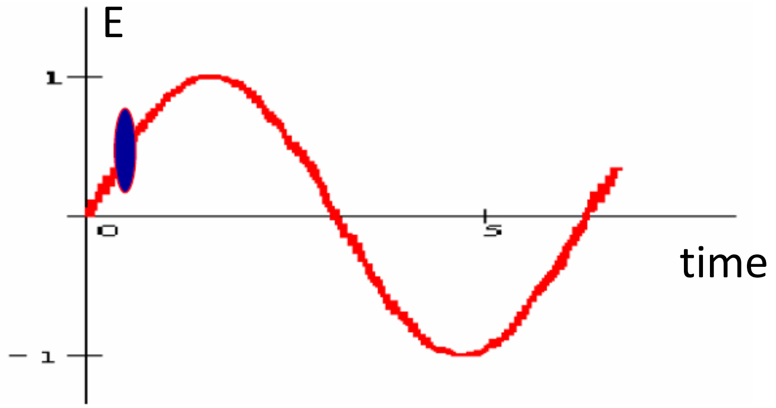
DC photogun


Cathode Electrode
(-350 kV)
Photocathode
Electron bunches out
Incident
laser pulses
Anode Plate
(ground potential)

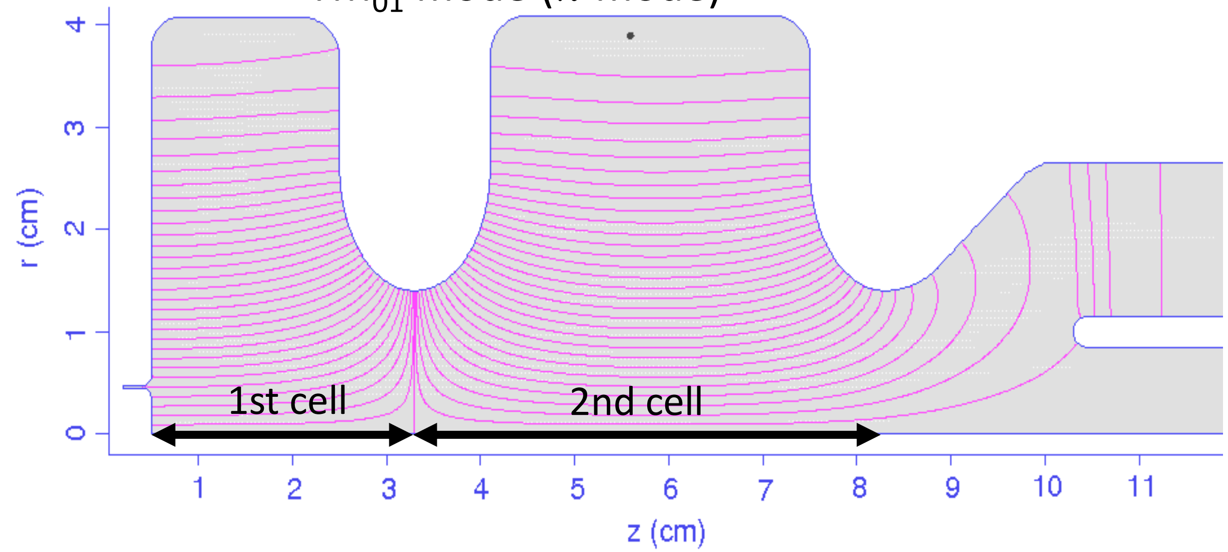
RF Photoinjectors (classical design)



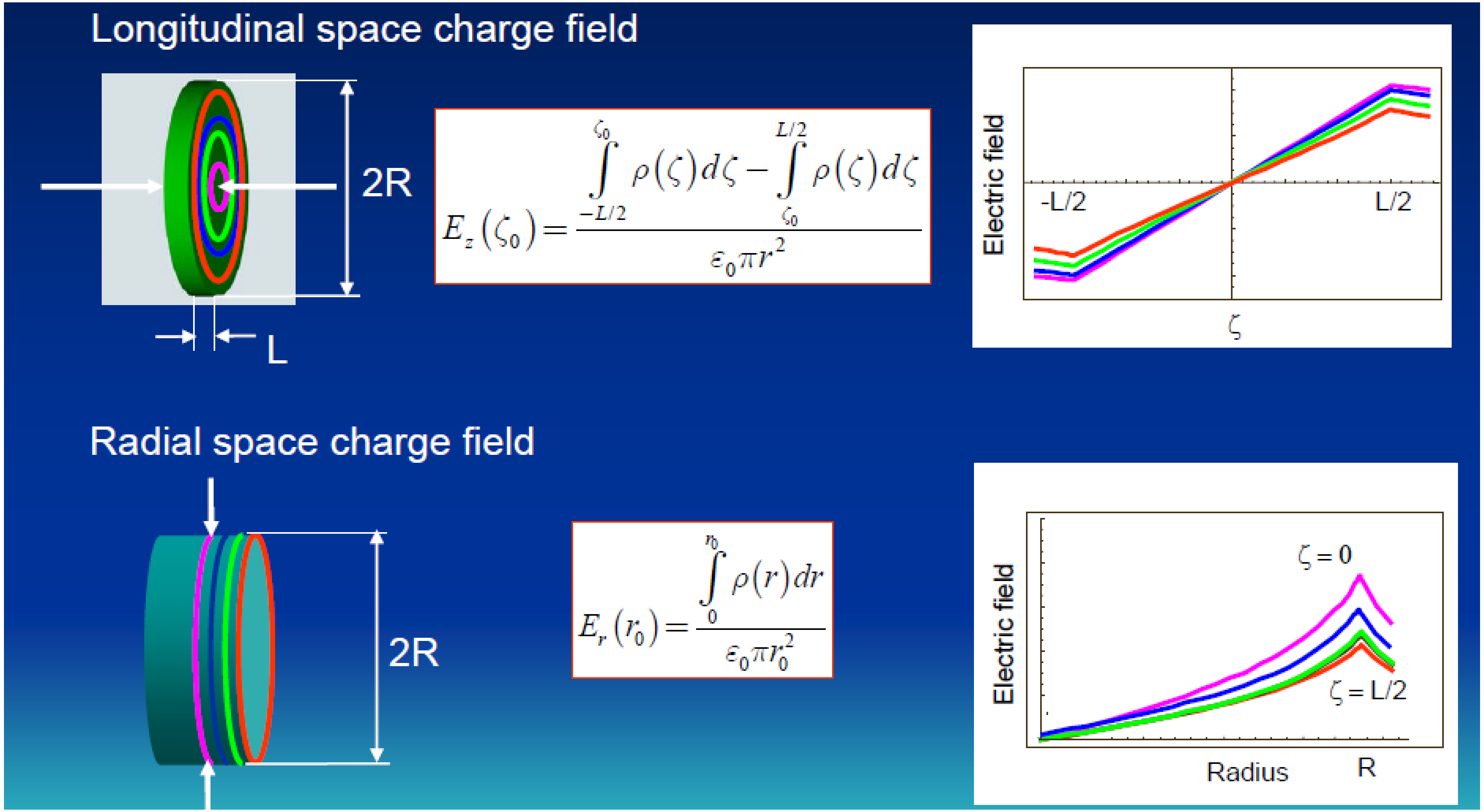
FLASH L-band gun
Coaxial coupler
Main solenoid around the gun



TM$_{01}$ mode (π-mode)



Great Challenge: Space Charge Effects



Envelope Equation in Drift Space

Envelope equation for electron beams in a drift (no acceleration or focusing)

Peak current

Thermal emittance

$$\boxed{\sigma'' - \frac{I}{\beta^3\gamma^3 I_0 \sigma} - \frac{\varepsilon_T^2}{\beta^2\gamma^2\sigma^3} = 0}$$

$$\varepsilon_T = \sigma_0\sqrt{\frac{kT}{mc^2}}$$

$$\sigma'' = \frac{d^2\sigma}{dz^2}$$

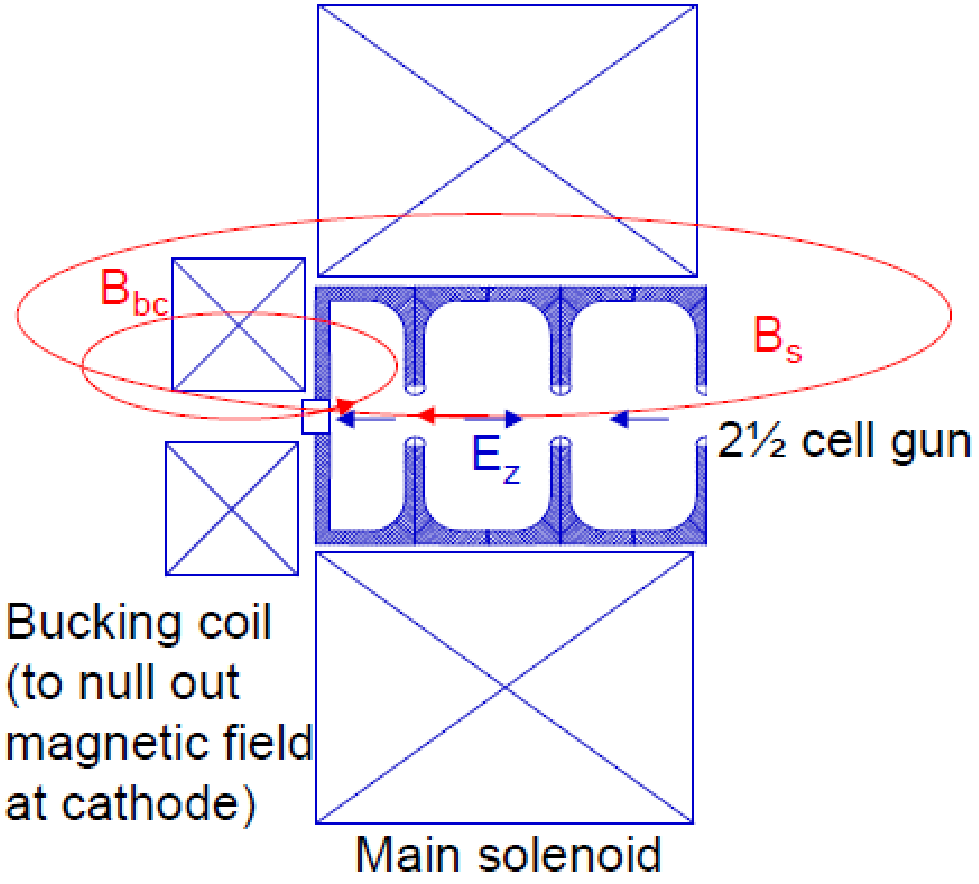
$$\beta = \frac{\upsilon}{c}$$

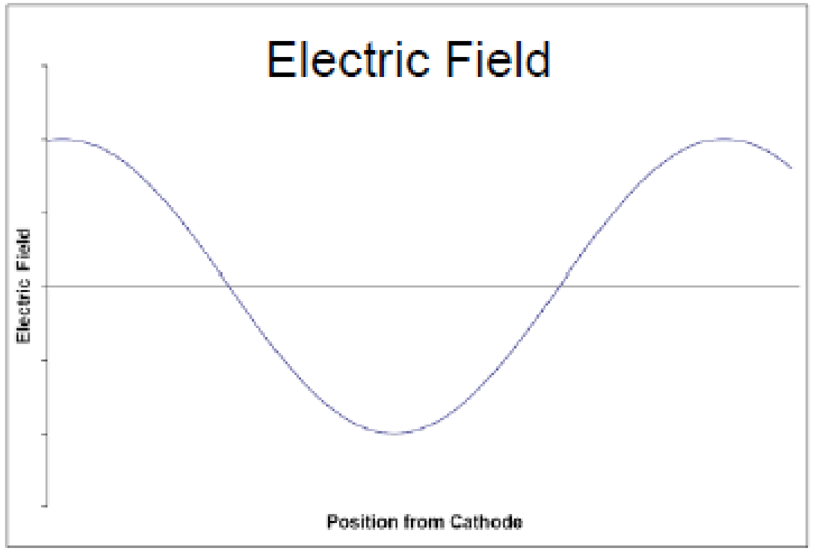
rms radius

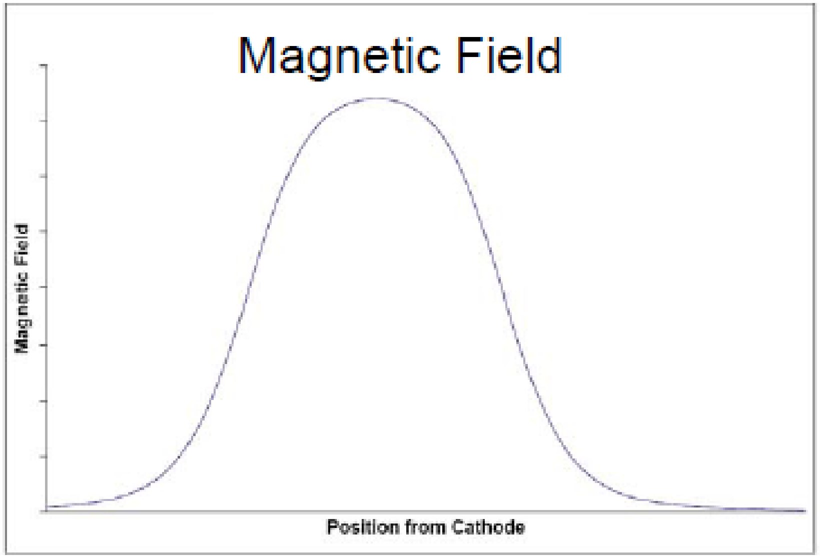
Alfven current (17 kA)

The beam envelope equation describes the forces acting on the beam envelope radius. The signs of both terms on the left hand side (other than the second derivative term) are negative, indicating the beam sees defocusing forces. The second term is the space-charge induced expansion. The third term is the thermal emittance expansion. Note the use of β because the low-energy beams are not quite relativistic in the drift.

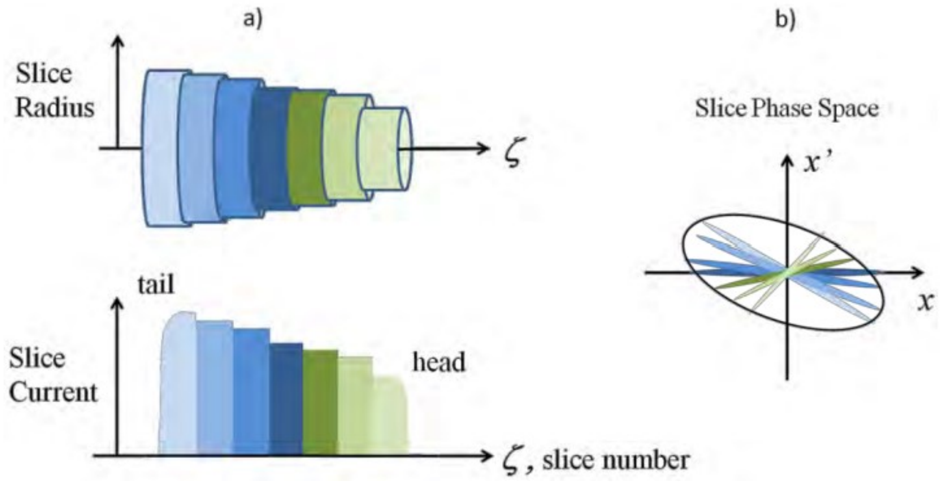
RF Electric and DC Magnetic Fields



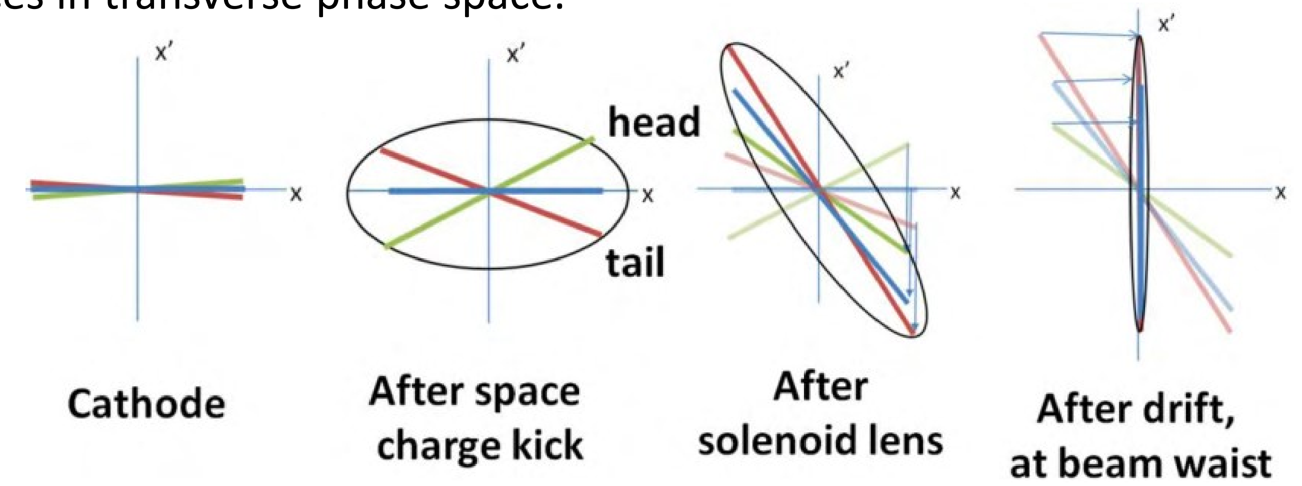




Emittance Compensation, Carlsten et al.



a) The bunch is modeled by dividing it into thin sections or slices along the bunch ζ-axis. Each slice is δζ long. b) The areas and orientations of the slices in transverse phase space.



Transverse phase space dynamics during emittance compensation. The transverse phase space is shown for different slices along the bunch. The bunch head slice is shown as a green line, the tail slice is red and the center slice is blue. An ellipse has been drawn around the three slices to indicate the projected phase space of the three slices.

Beam Envelope Equation

Electron beam envelope equation in an RF injector

$$\boxed{\sigma'' + \sigma'\left(\frac{\gamma'}{\beta\gamma}\right) + k_B^2\sigma - \frac{I}{\beta^3\gamma^3 I_0 \sigma} - \frac{e}{\beta\gamma mc^2}\left(E_r - v_z B_\theta\right) - \frac{\varepsilon_T^2}{\beta^2\gamma^2\sigma^3} = 0}$$

Thermal emittance

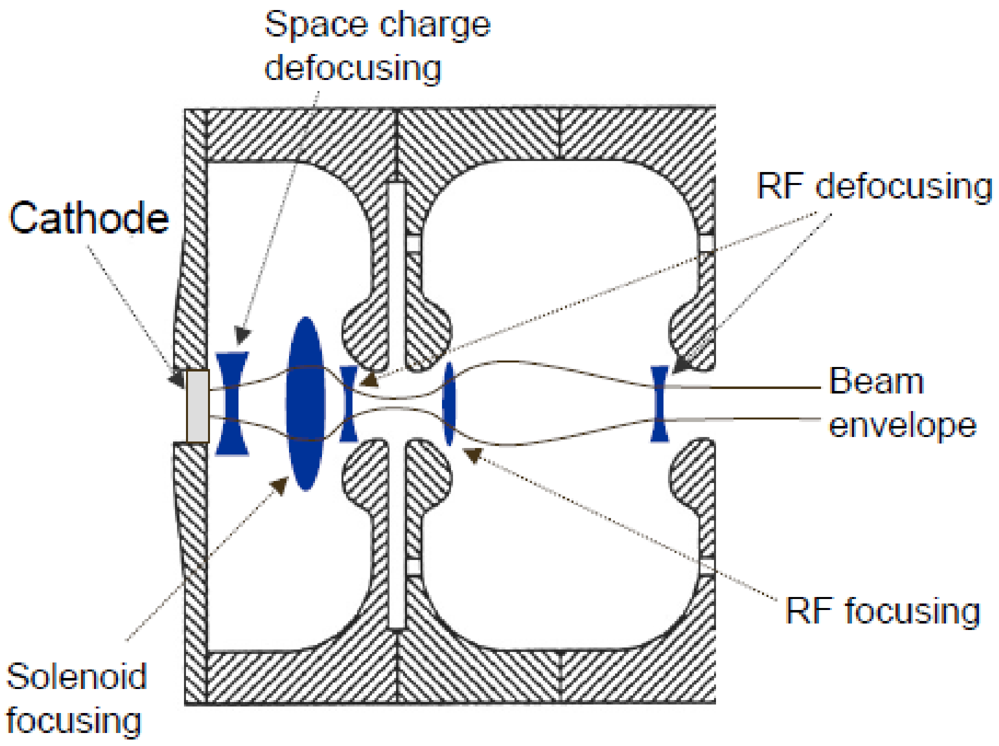
RF focusing due to azimuthal magnetic field

Solenoidal focusing

RF focusing & defocusing due to radial electric field

Acceleration damping

Space charge expansion



Space-charge induced emittance

$$\boxed{\varepsilon_{n,sc} = \frac{I}{\gamma' I_A \left(\frac{3\sigma_r}{\sigma_z} + 5 \right)}}$$

RF induced emittance

$$\boxed{\varepsilon_{n,RF} = \gamma' k_{RF}^2 \sigma_r^2 \sigma_z^2}$$

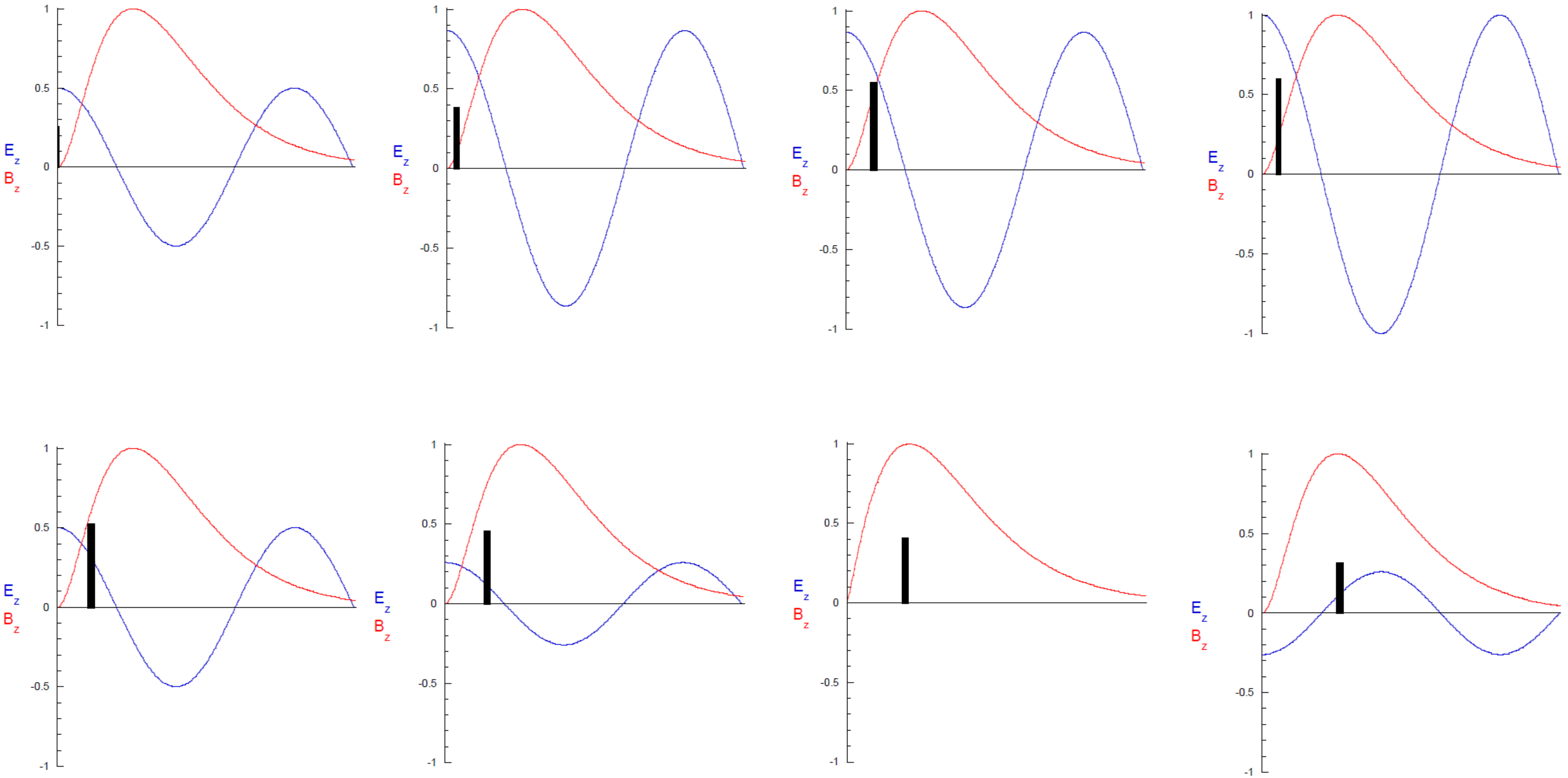
Thermal emittance

$$\boxed{\varepsilon_{n,thermal} = \sigma_r \sqrt{\frac{kT}{mc^2}}}$$

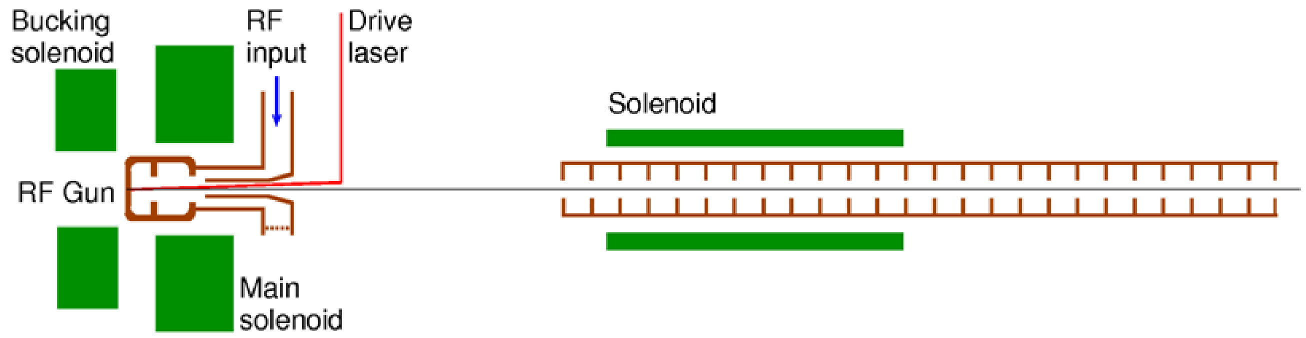
$$\boxed{\varepsilon = \sqrt{\varepsilon_{n,sc}^2 + \varepsilon_{n,RF}^2 + \varepsilon_{n,thermal}^2}}$$

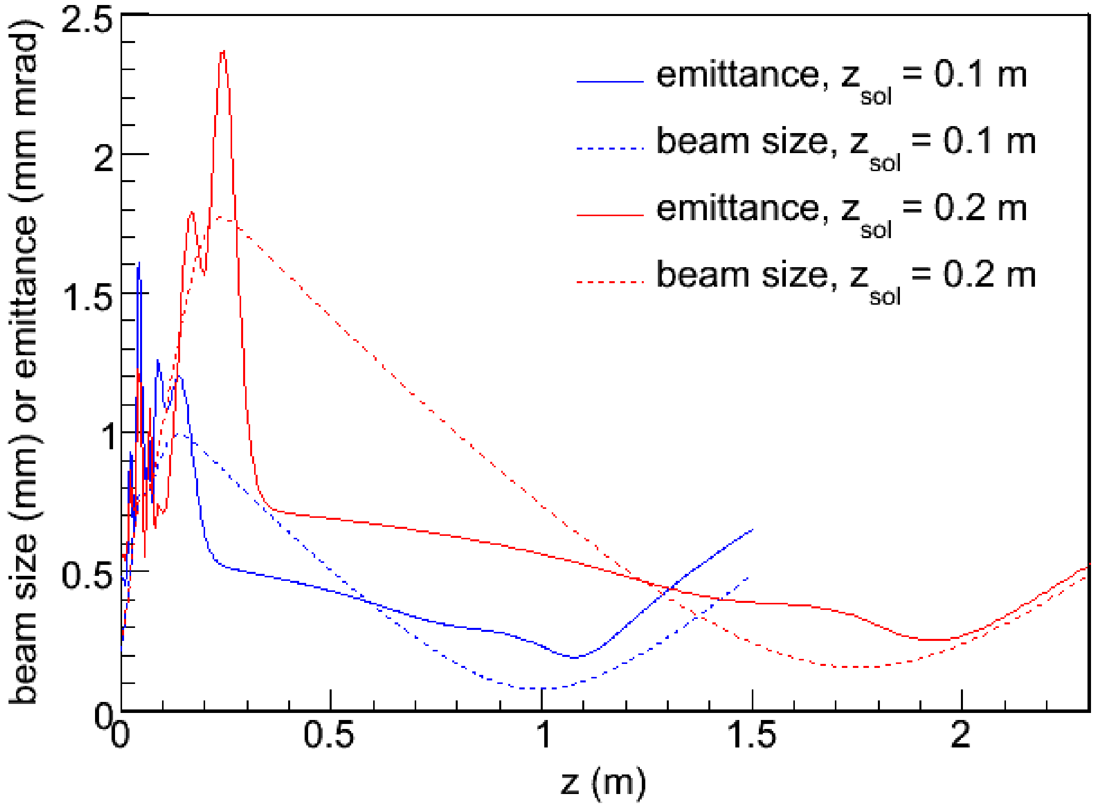
- Space charge is reduced by using large radius, high gradient, and long electron bunch.
- RF effects are reduced with small radius, solenoid focusing, short electron bunch, and low frequency.
- Thermal emittance is reduced with small radius, cold semiconductor cathodes

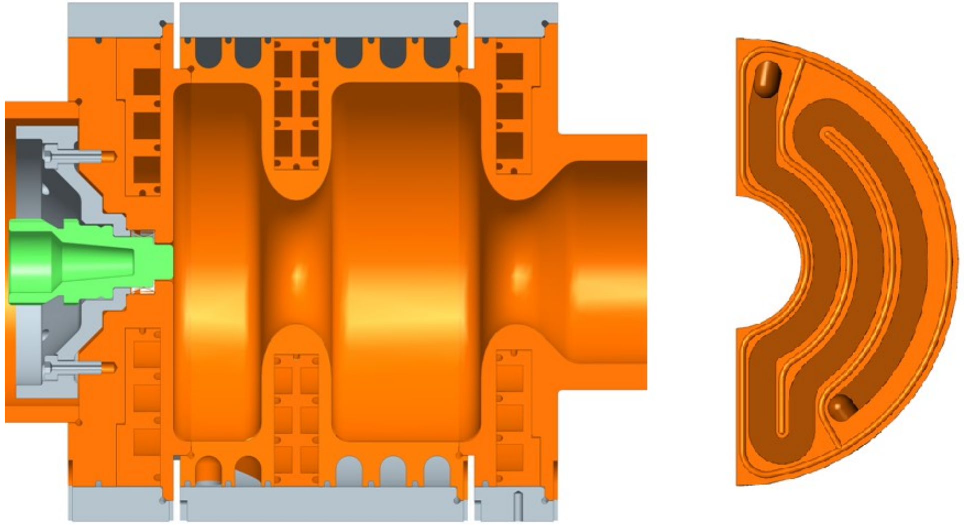
Transverse and Longitudinal Beam Dynamics

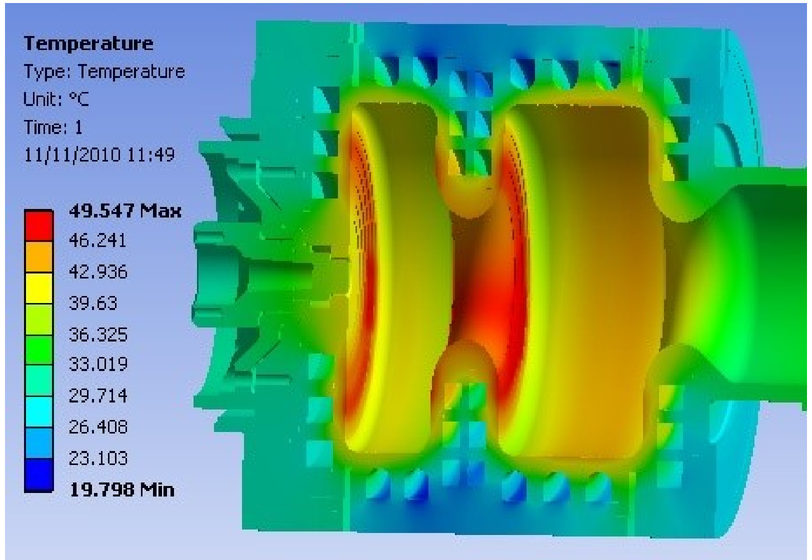


Gun + linac:


Bucking solenoid
RF input
Drive laser
Solenoid
RF Gun
Main solenoid


emittance, z_{sol} = 0.1 m
beam size, z_{sol} = 0.1 m
emittance, z_{sol} = 0.2 m
beam size, z_{sol} = 0.2 m
beam size (mm) or emittance (mm mrad)
z (m)
0
0.5
1
1.5
2
2.5




Temperature
Type: Temperature
Unit: °C
Time: 1
11/11/2010 11:49
49.547 Max
46.241
42.936
39.63
36.325
33.019
29.714
26.408
23.103
19.798 Min

Short-Pulse RF gun Concept

E-injector (300 - 400 MV/m @ 10 ns)

$\varepsilon \downarrow$

$E_a \uparrow$

$+$

$\tau \downarrow$ —

For a fixed breakdown rate

$$E_a \cdot \tau^{1/6} = const$$

CLIC / SLAC studies

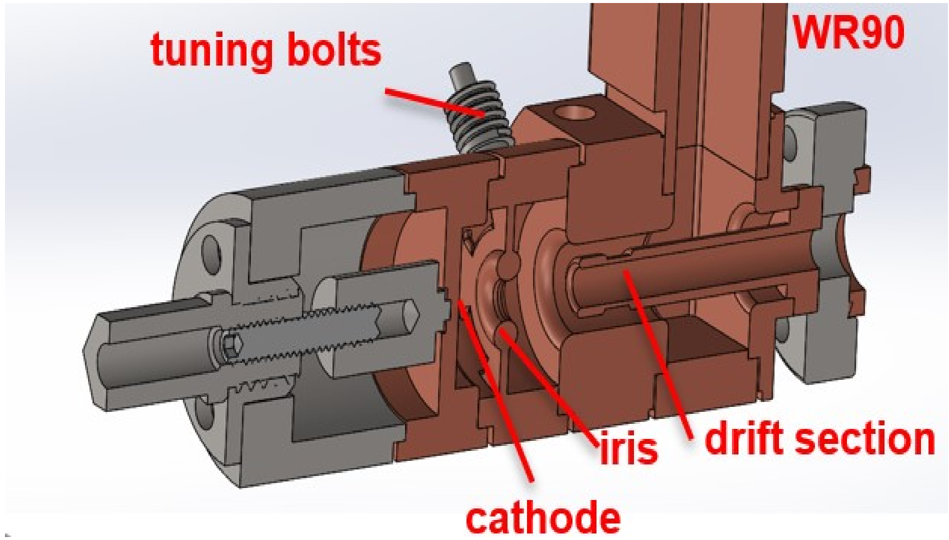
RF design is a subject of SBIR project

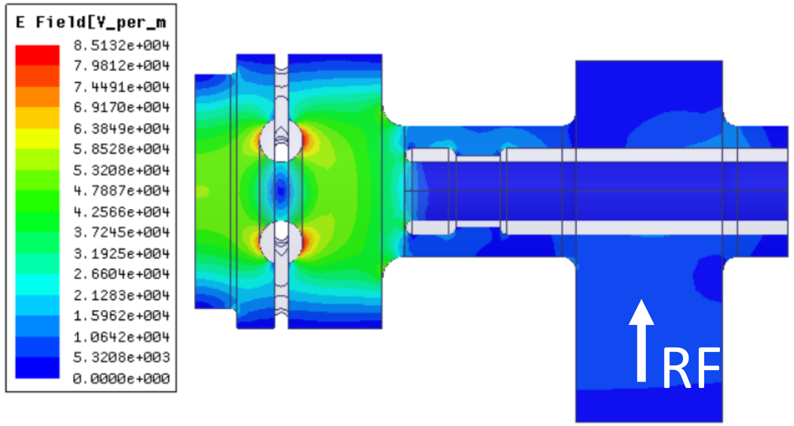
To obtain high brightness beams it was proposed to raise the accelerating voltage in the gun mitigating repealing Coulomb forces. An ultra-high gradient is achieved utilizing a short-pulse technology. We have designed a room temperature X-band 1,5 cell gun that is able to inject 4 MeV, 100 pC bunches with as low as 0.15 mcm normalized transverse emittance. The gun is operated with as high gradients as 400 MV/m and fed by 200 MW, 10 ns RF pulses generated with Argonne Wakefield Accelerator (AWA) power extractor.

Anticipated Gun Parameters

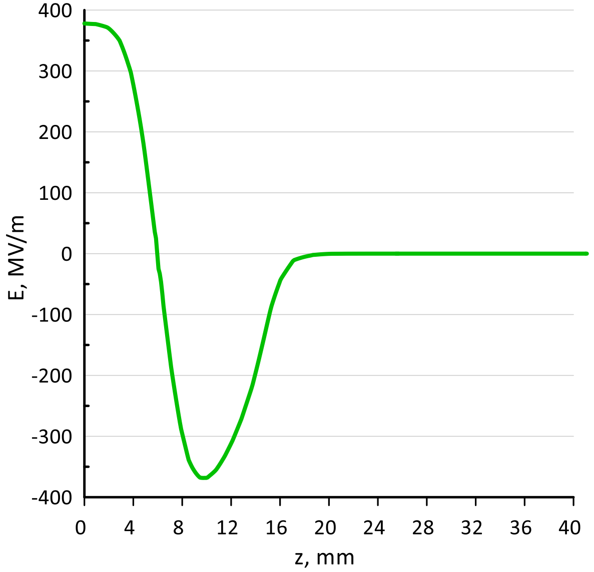
Parameter	Value
Frequency	11.7 GHz
Mode quality factor	180
Mode separation	250 MHz
RF pulse length	9 ns (3 ns flat top)
RF peak power	up to 300 MW
Maximum field at cathode	350 MV/m
Energy of electrons	4 MeV
Bunch charge	100 pC
RMS bunch radius at cathode and at exit	0.07mm, 0.13 mm
RMS bunch length	4 ps
Normalized emittance	0.15 mm×mrad (with linac)
$\Delta E/E$	2.5×10^{-3}

RF Gun Design

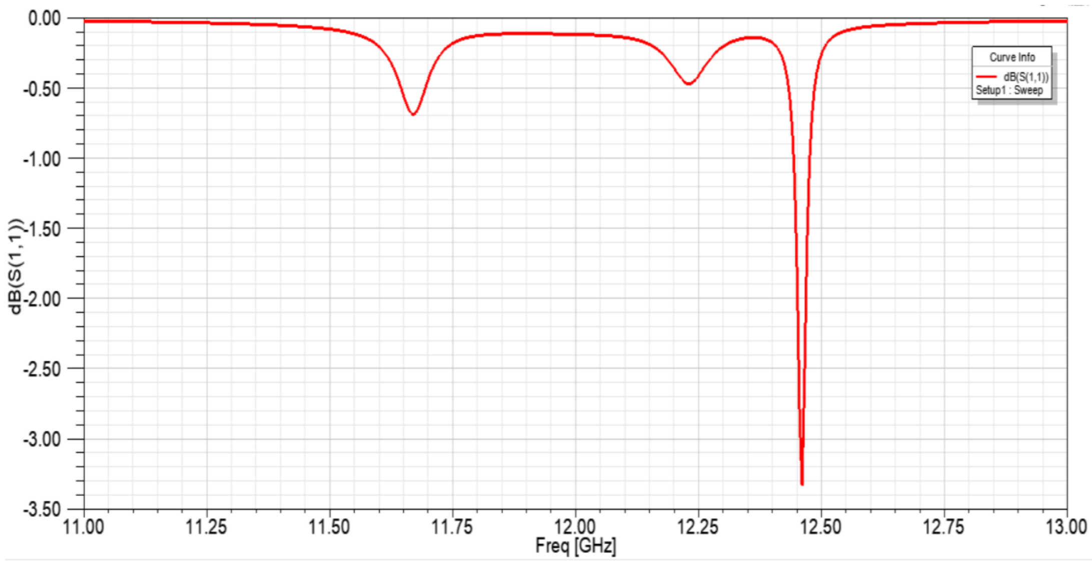




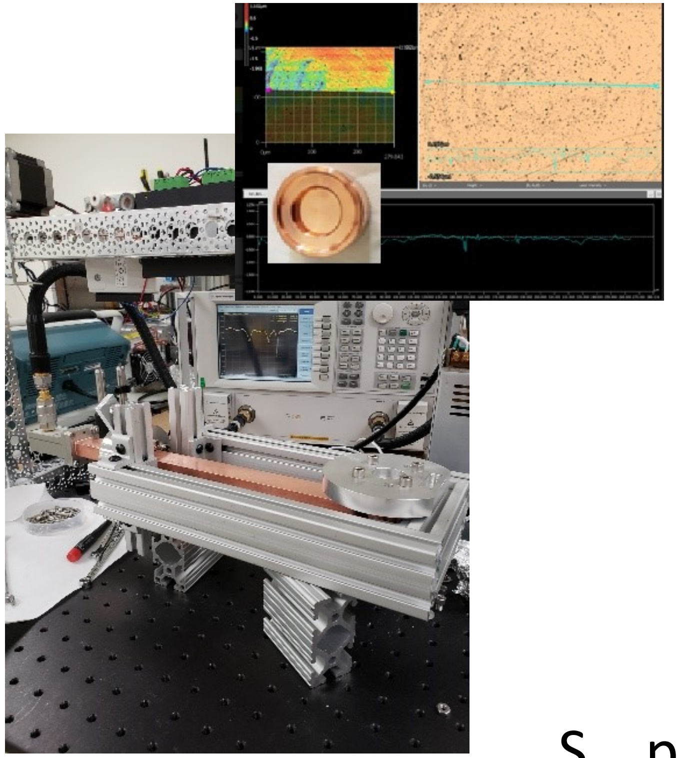
11.7 GHz field structure

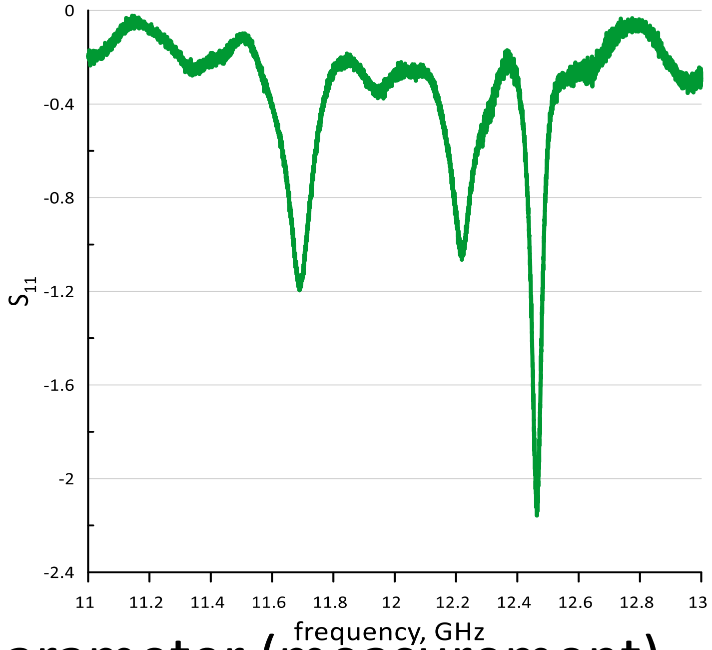


11.7 GHz field structure at axis for 100 MW of incident power



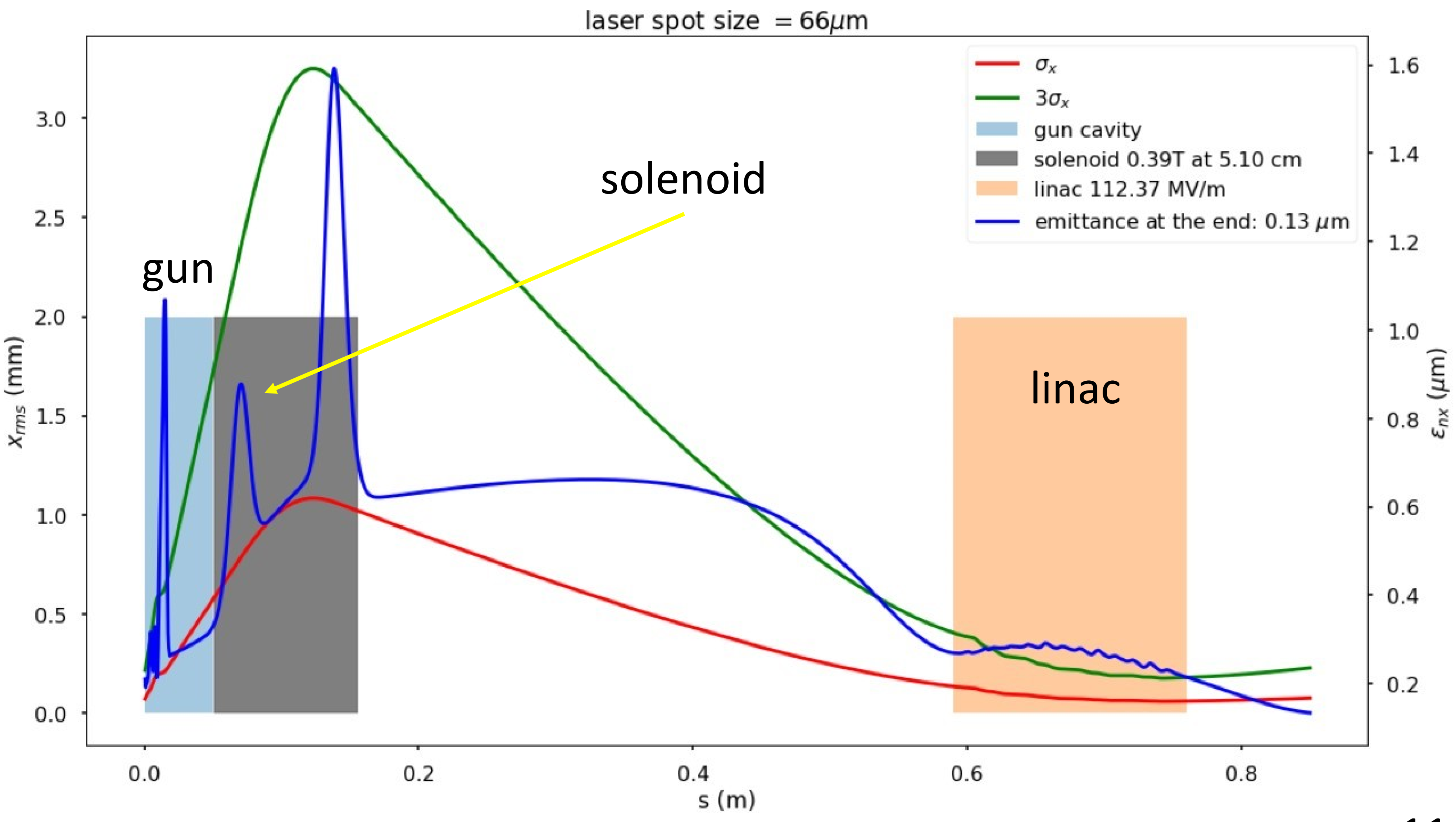
S_{11} parameter (simulation)

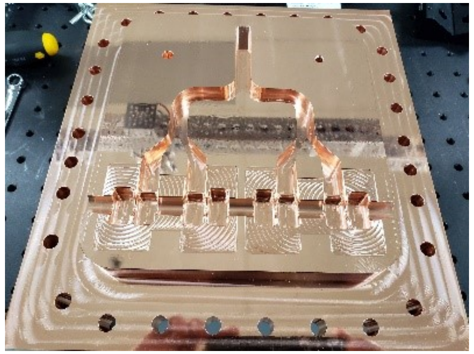




S_{11} parameter (measurement)

Emittance Simulations

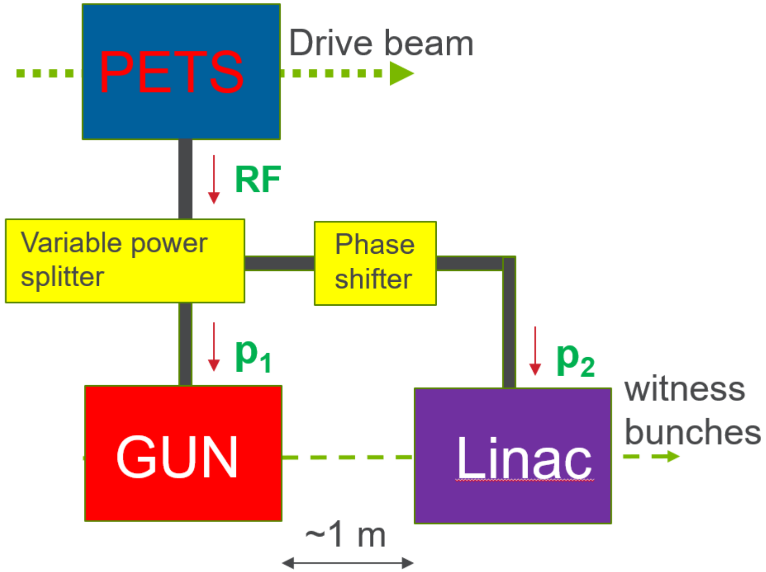


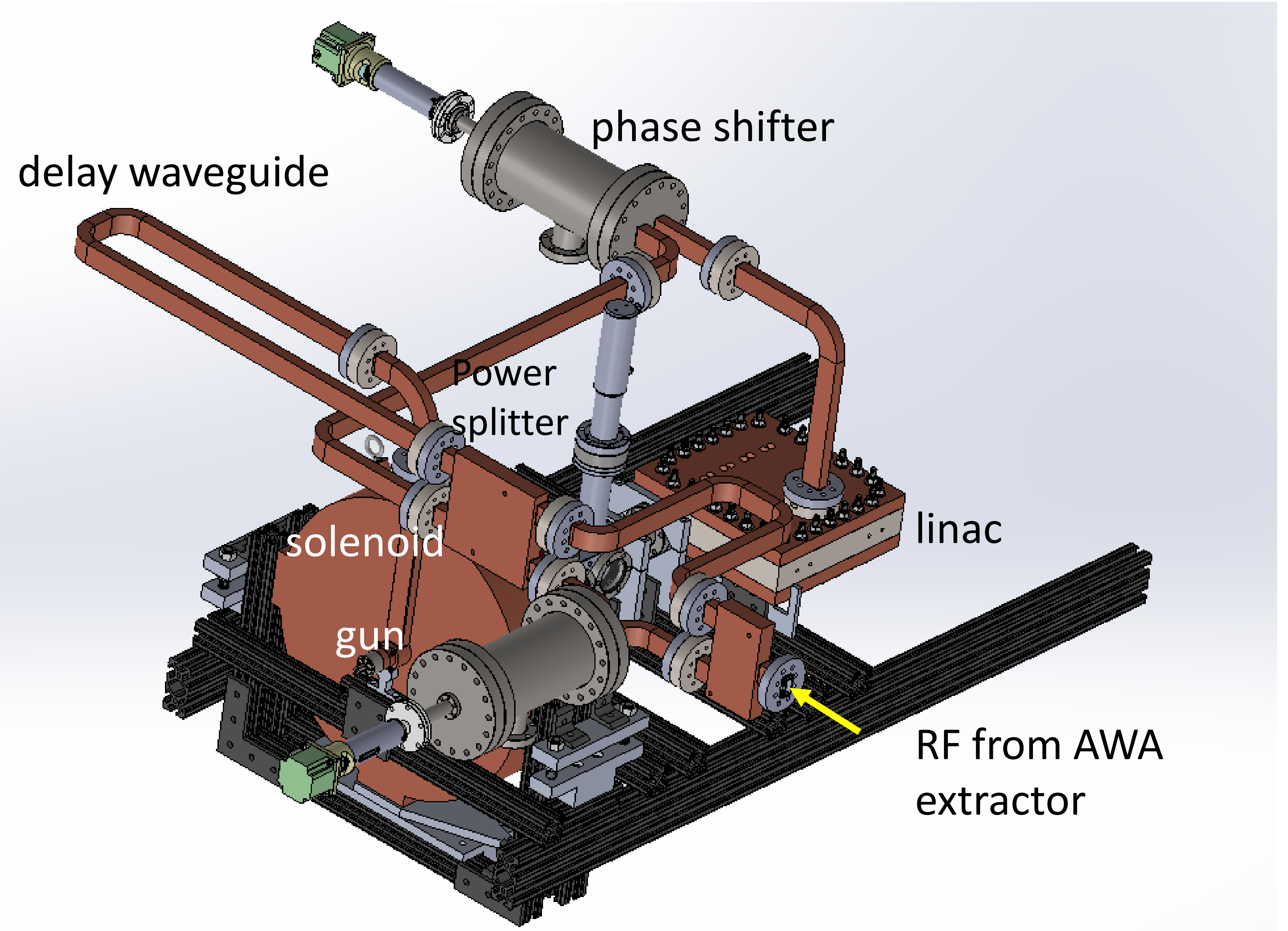


Linac tested at AWA at 180 MW.

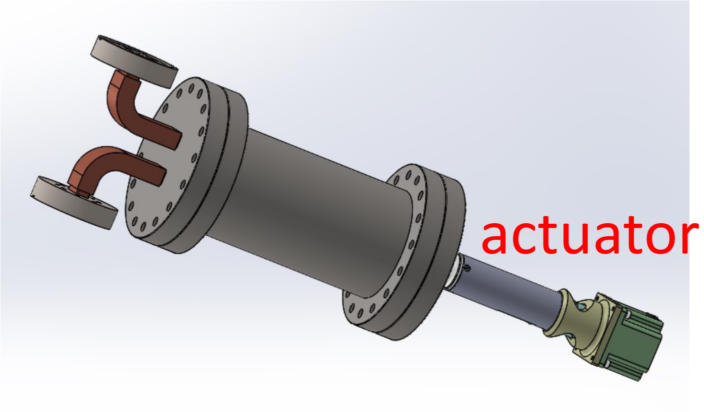
11.7 GHz 1,5 cell Gun

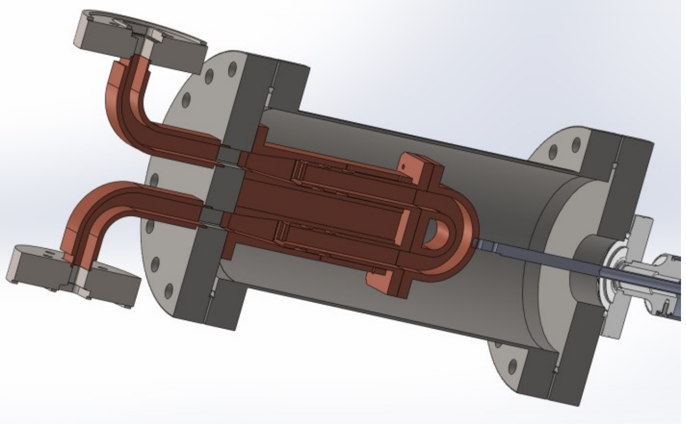
Experiment #3: RF Feeding of Gun and Linac from the Same Power Source

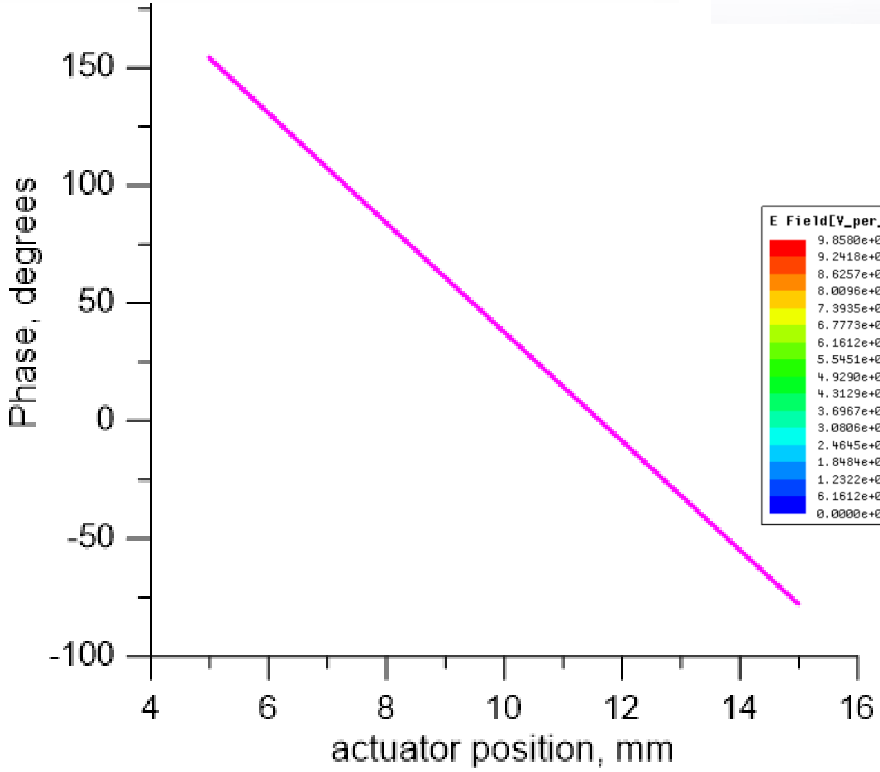


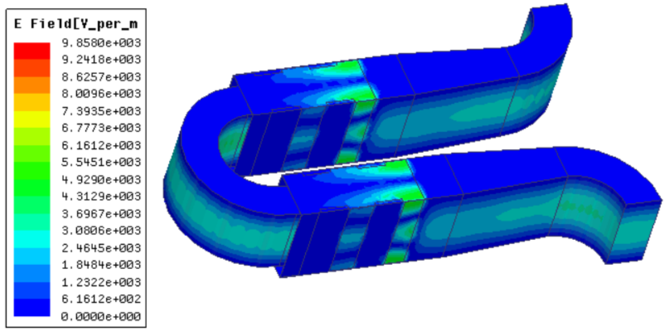


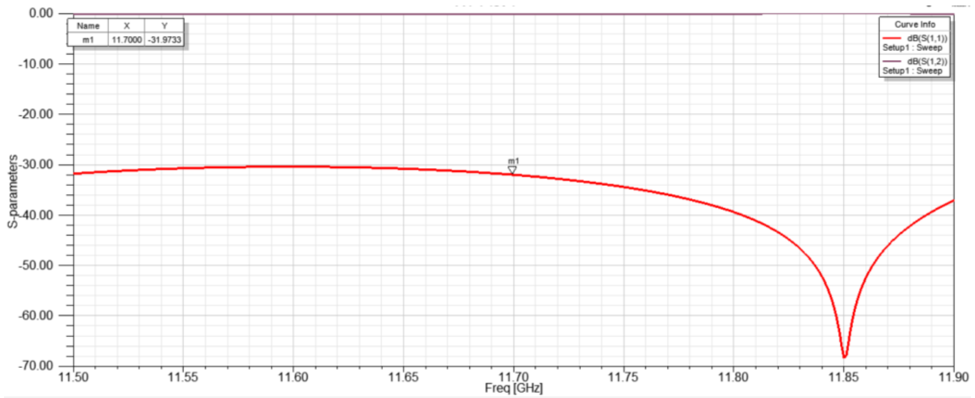
RF Phase Shifter

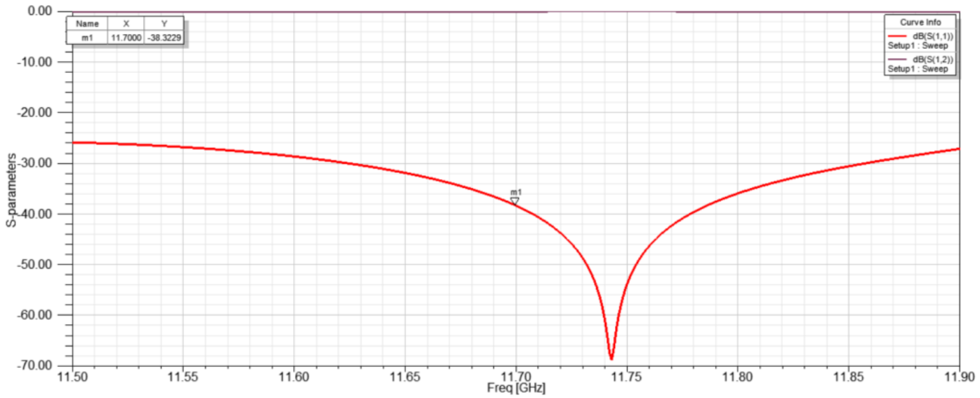


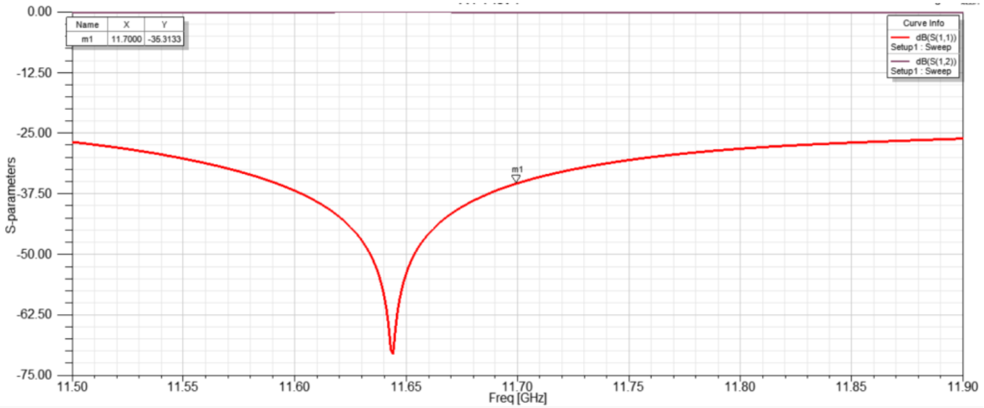




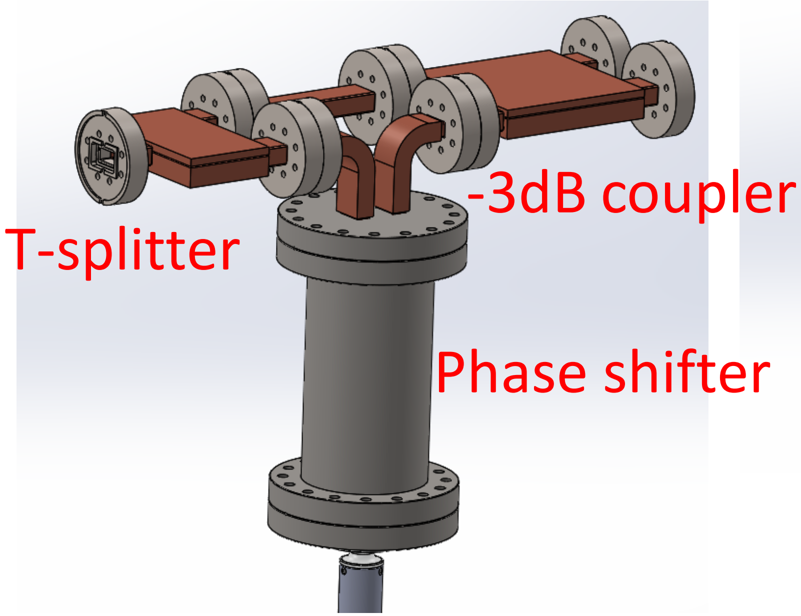


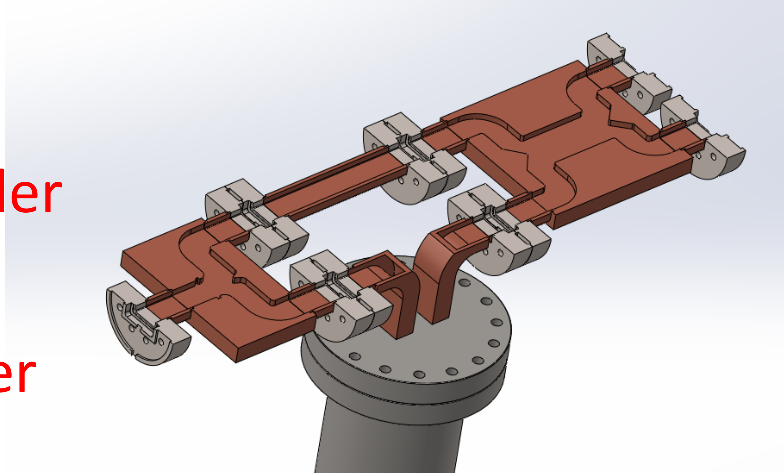


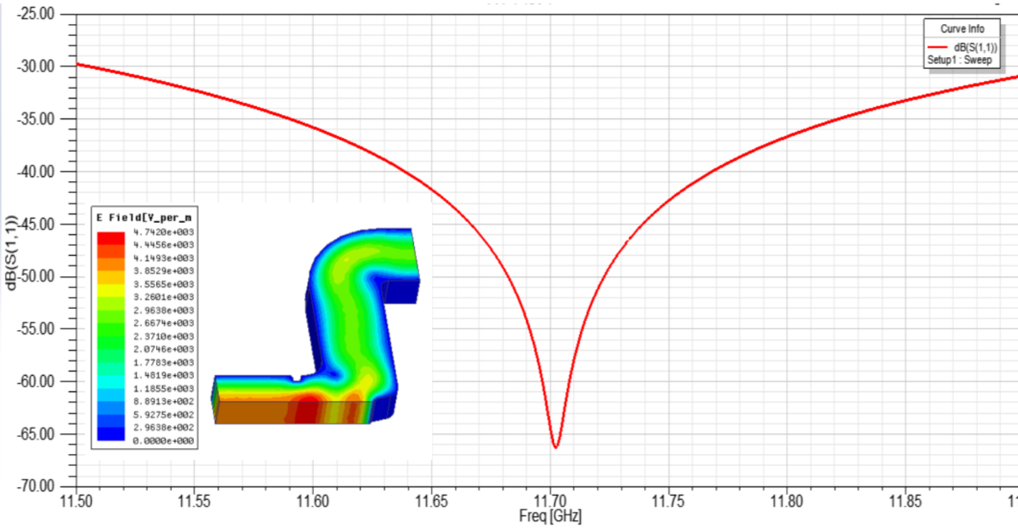


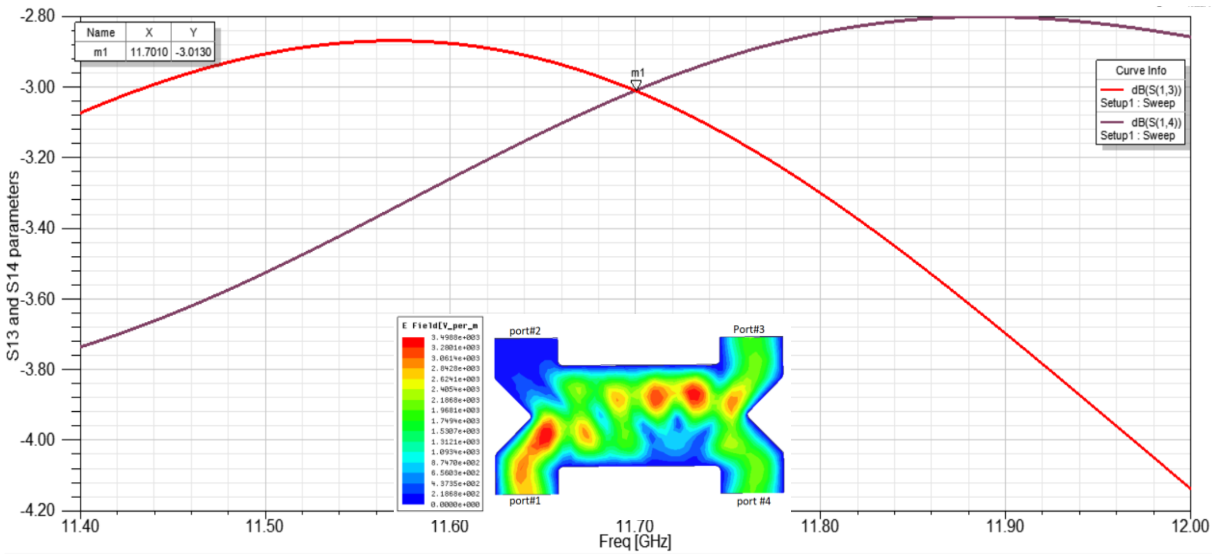


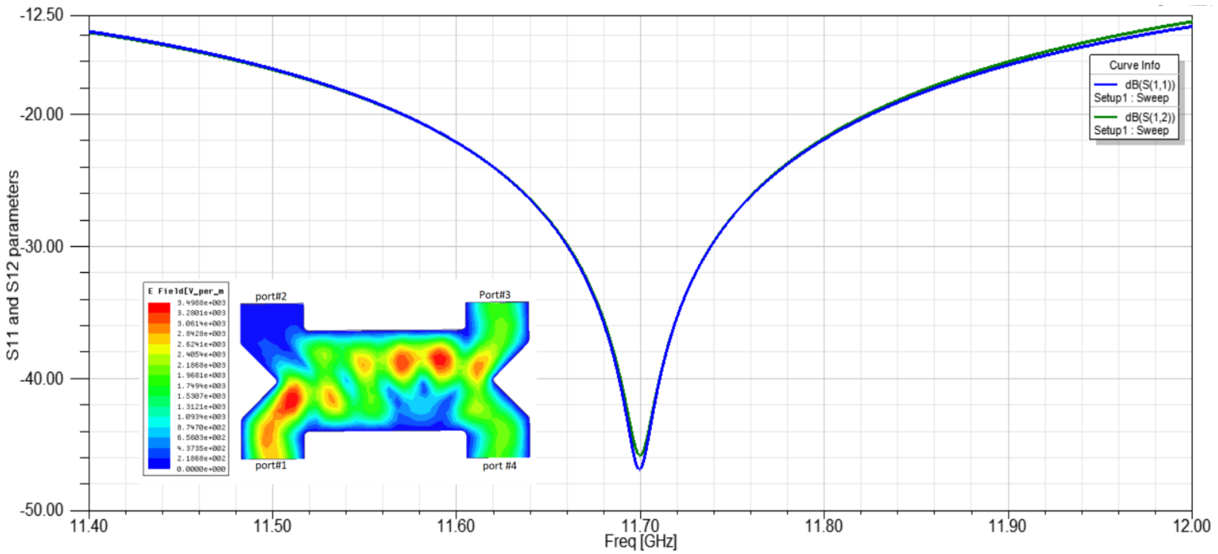
RF Power Splitter



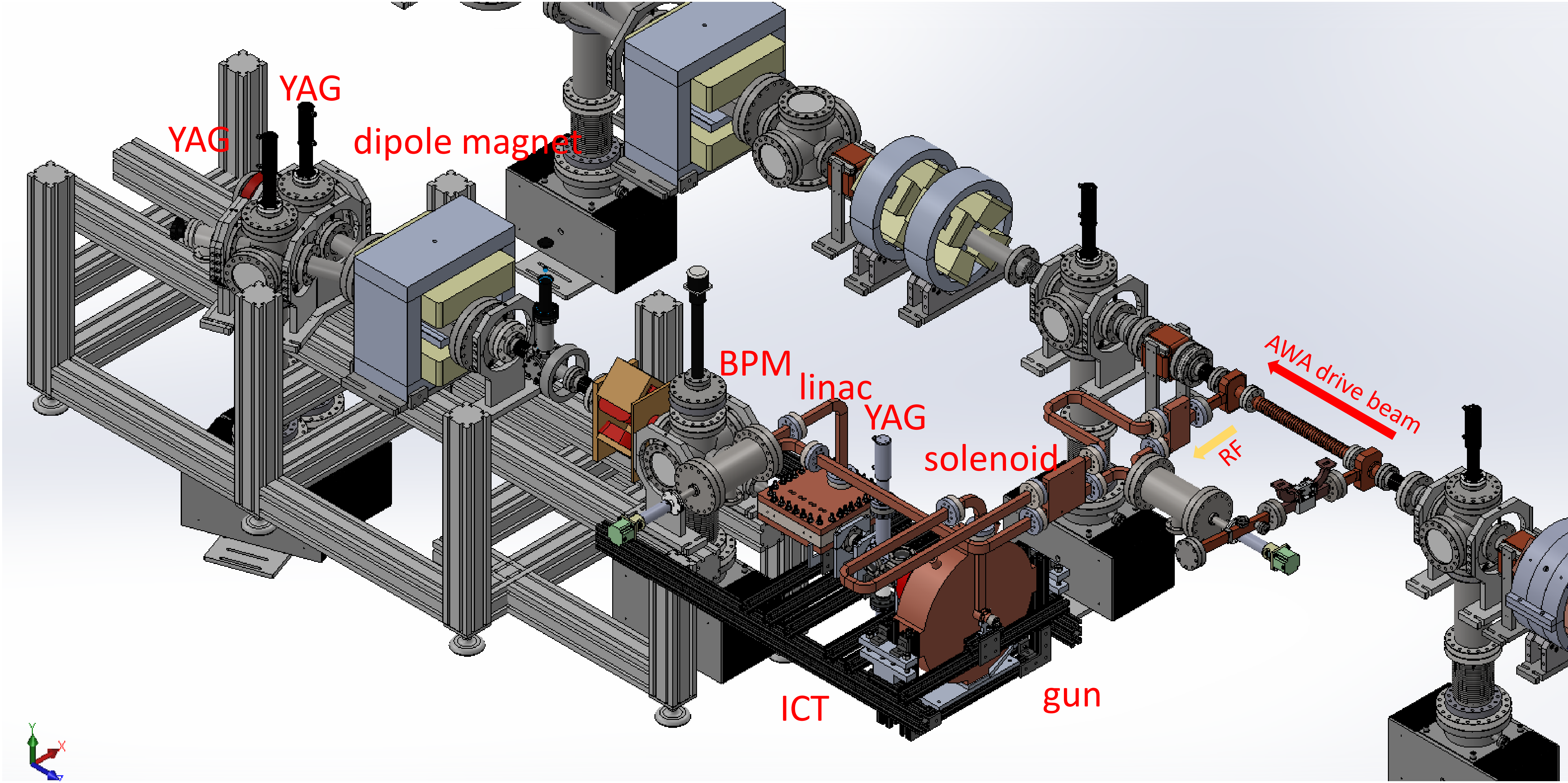






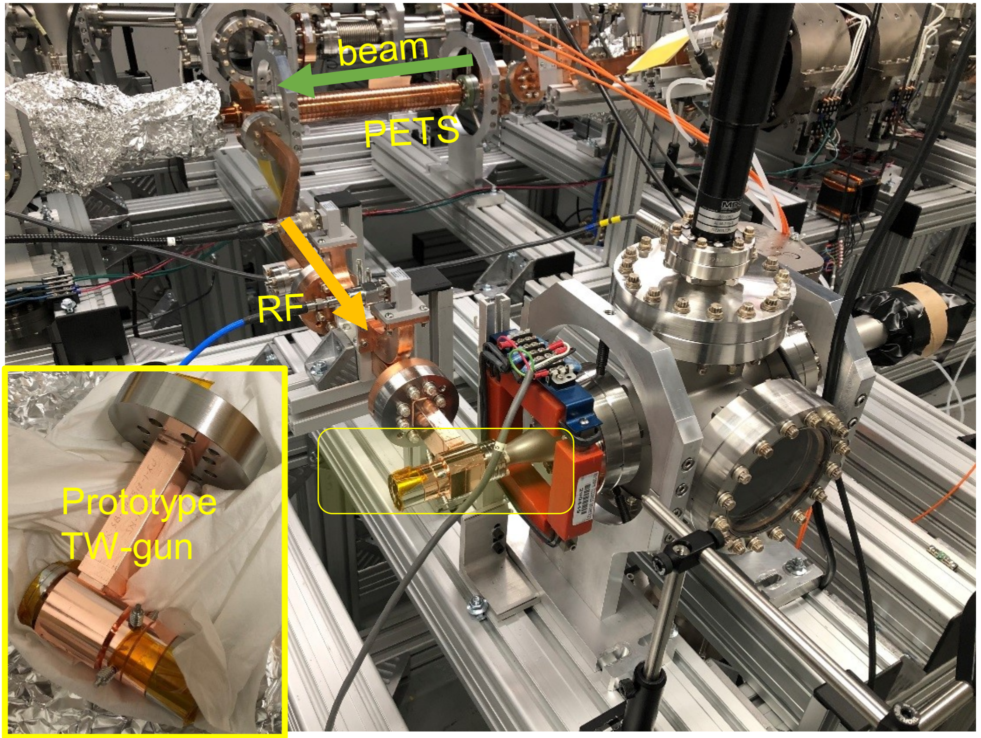


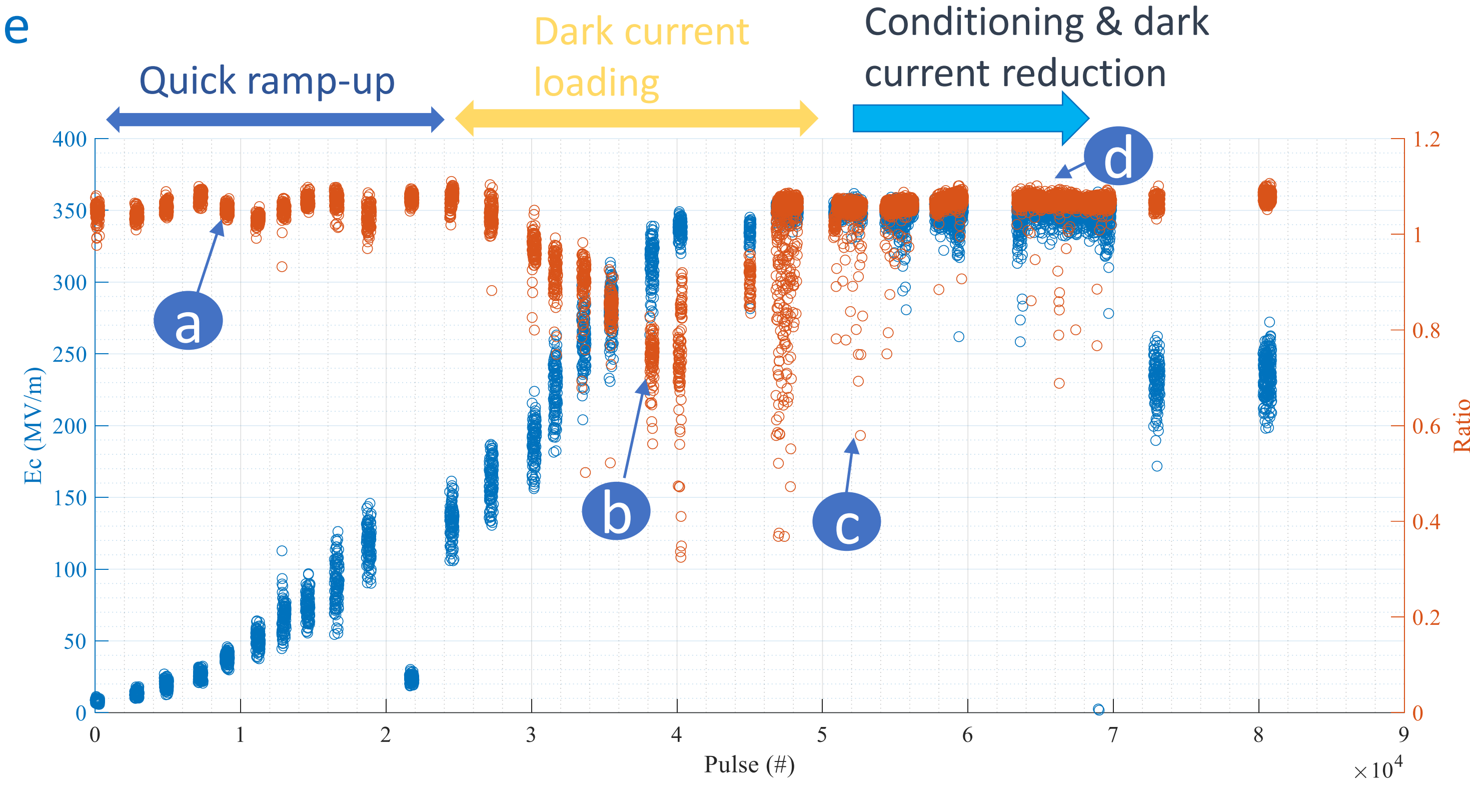
Beamline Design (experiment #3)

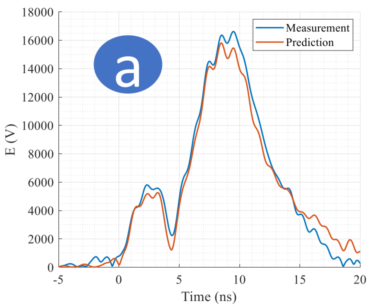


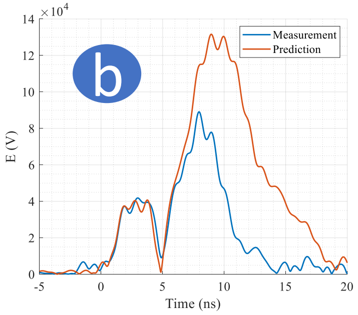
BREAKDOWN TEST OF A PROTYPE GUN AT AWA (2020)

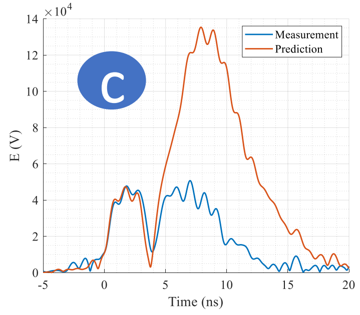
- Achieved 350MV/m on cathode
- Observed strong dark current loading regime but quickly conditioned away
- It only took 70k pulses for a full condition
- Back to 200MV/m to 250MV/m region, no breakdown, no measurable dark current.

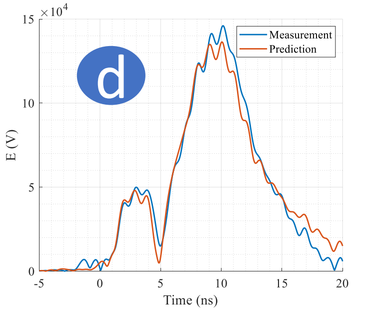












Reflection signal from bi-directional coupler

“Холодный” фотоинжектор

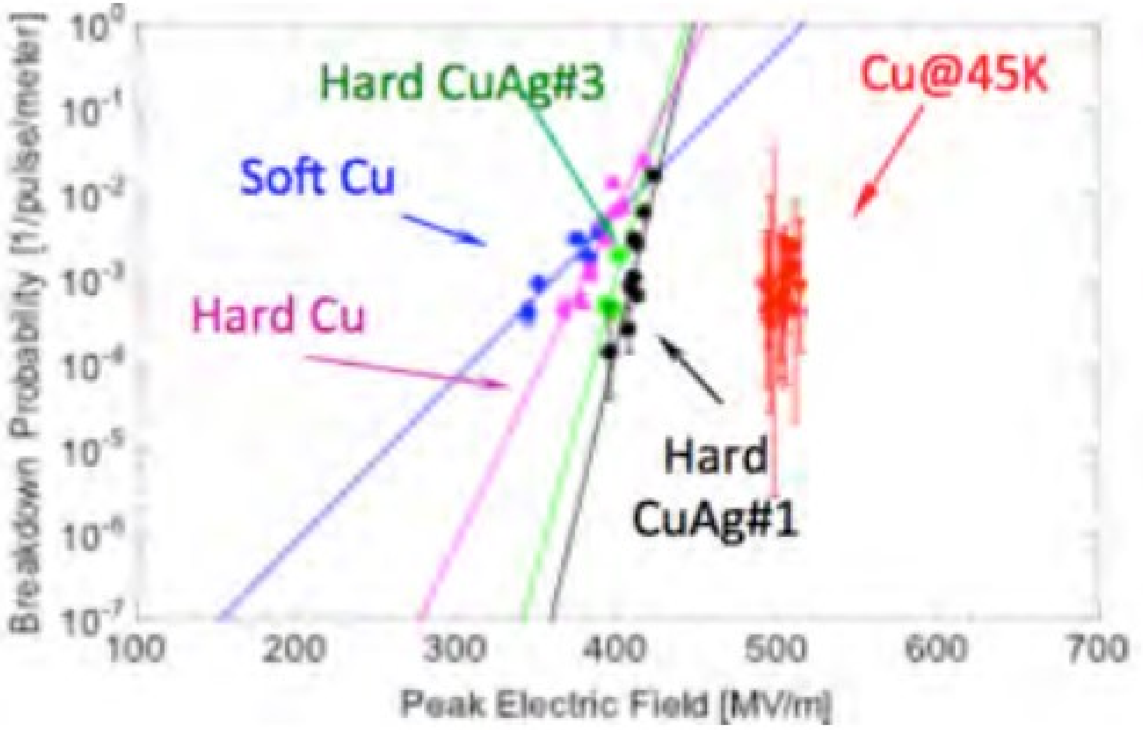
Next Generation High Brightness Electron Beams From Ultra-High Field Cryogenic Radiofrequency Photocathode Sources

J.B. Rosenzweig[1], A. Cahill[1], V. Dolgashev[2], C. Emma[1], A. Fukusawa[1], R. Li[2], C. Limborg[2], J. Maxson[1], P. Musumeci[1], A. Nause[1], R. Pakter[1], R. Pompili[3], R. Roussel[1], B. Spataro[3], and S. Tantawi[2]

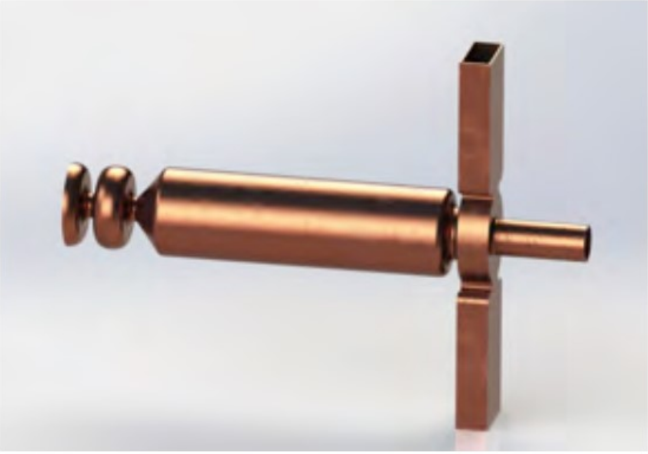
[1]*Department of Physics and Astronomy, University of California, Los Angeles*

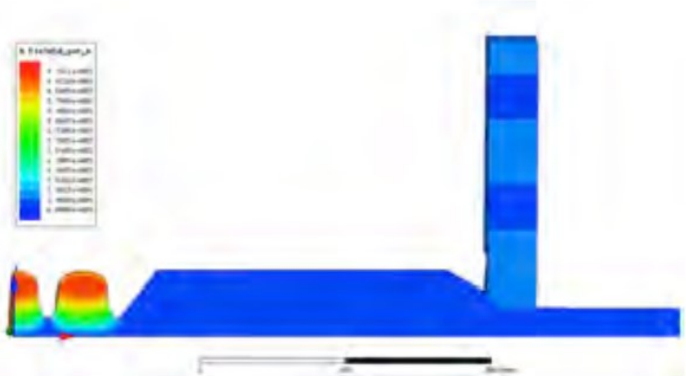
[2]*SLAC National Accelerator Laboratory, Stanford University*

[3]*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Frascati, Italy*

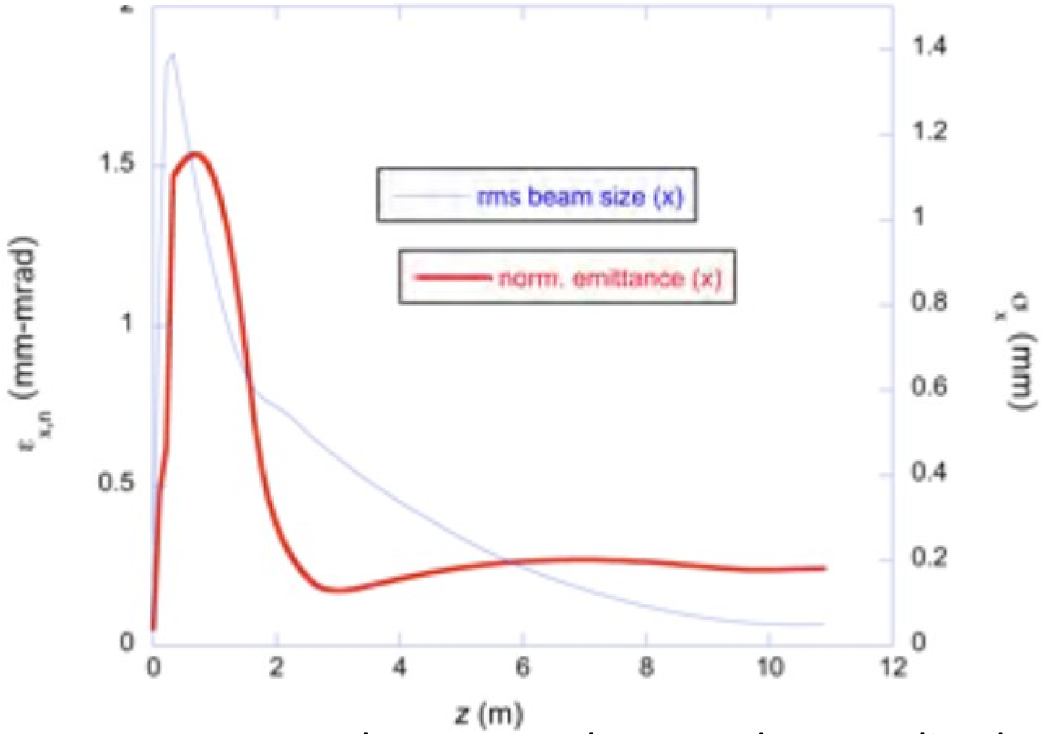


Breakdown probability as a function of peak electric field in single cell X-band accelerating structure tests. The introduction of a harder alloy improves the breakdown as predicted; the effect of operation at 45 deg K is more dramatic, permitting surface electric fields of 500 MV/m

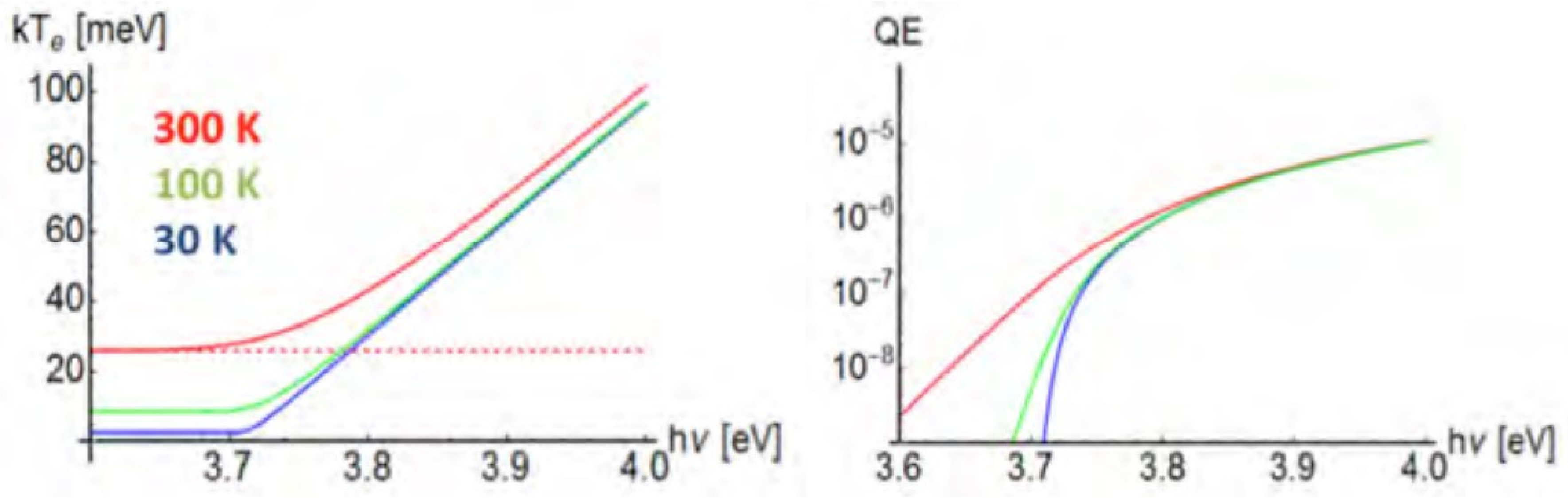




Laser pulse length	35 fs FWHM,
Laser spot size (cut transverse Gaussian)	Hard edge at 262 μm, 1.6σ, (120 μm rms)
RF gun format	1.45 cell π-mode standing wave
Peak cathode electric field	250 MV/m
Launch phase	82 degrees
Focusing solenoid (SPARC-type) field	5.4 kG
Post-acceleration linac average field	20 MV/m



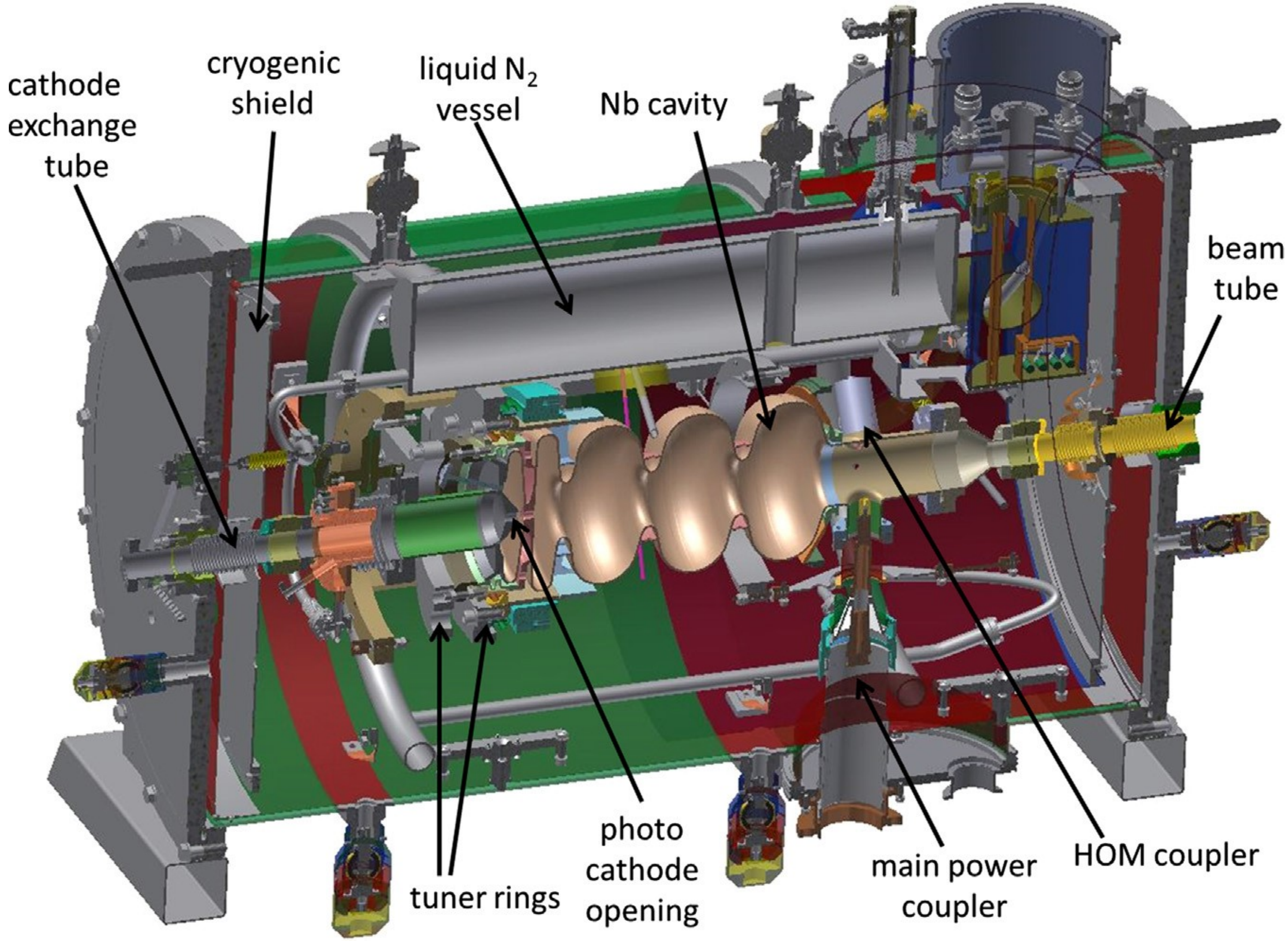
Transverse rms beam envelope and normalized emittance evolution in 125 pC blowout regime case.



Photoemission temperature and quantum efficiency QE as a function of photon energy, for atomically clean Cu using an applied field of 250 MV/m. The scale of the quantum efficiency curve is such that at zero field, 270 nm photons produce a quantum efficiency of, near what was attained in [61] . The energy at 300 K is shown by the dotted red line.

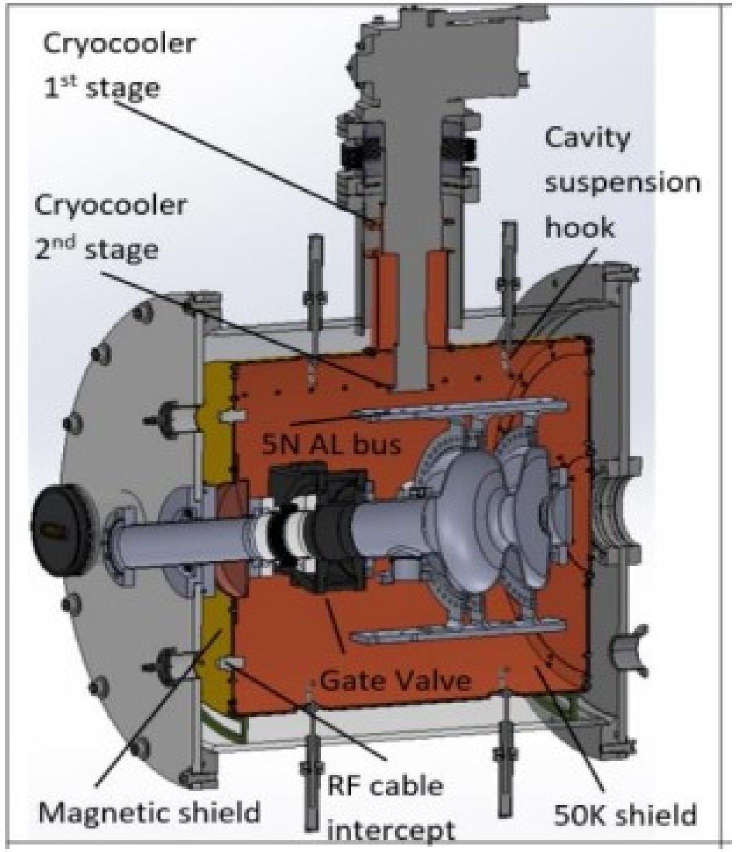
Сверхпроводящие СВЧ фотоинжекторы

Основное преимущество – возможен CW режим с высокой частотой следования сгустков.
Основная трудность – невозможна фокусировка статическим магнитным полем внутри ускоряющего резонатора.

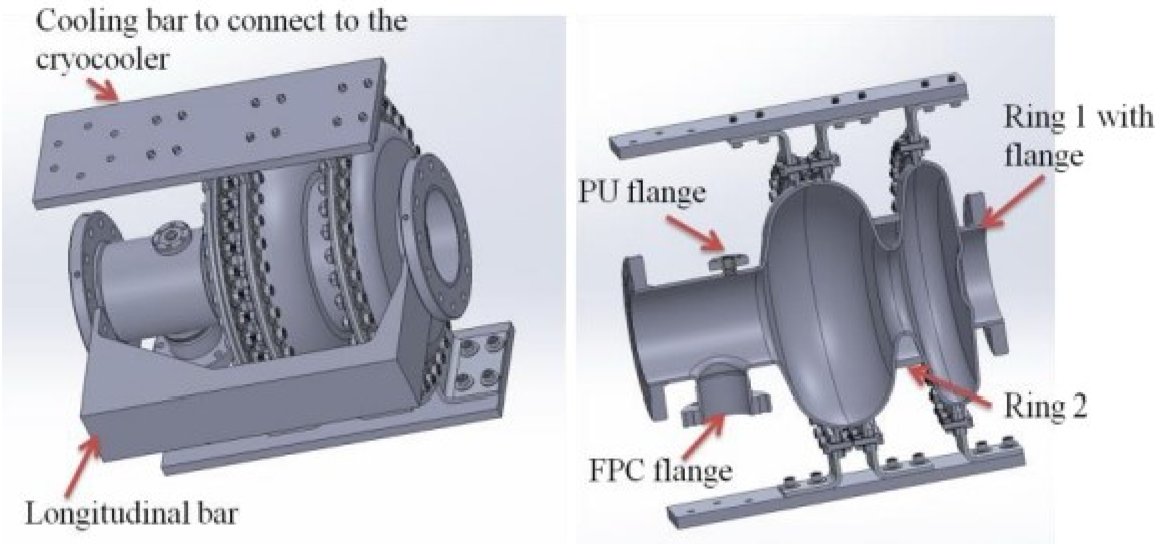


Example: The HZB BERLinPro injector is envisioned as operating with a 1.6-cell SCRF gun. The injector for BERLinPro must deliver 100 mA average current, with 1 μm emittance and 77 pC bunch charge. To support high average beam currents, the BERLinPro injector's baseline cathode is Cs_2KSb on a normal conducting insert. RF power is provided via a coaxial coupler into the beam pipe. The design frequency of the BERLinPro injector is 1.3 GHz for compatibility with the remainder of the linac. Its nominal beam energy is 1.5 MeV; the beam will be followed by a booster linac to raise the beam energy to 5-10 MeV

AN SRF PHOTOCATHODE GUN FOR MEV ULTRAFAST ELECTRON MICROSCOPY

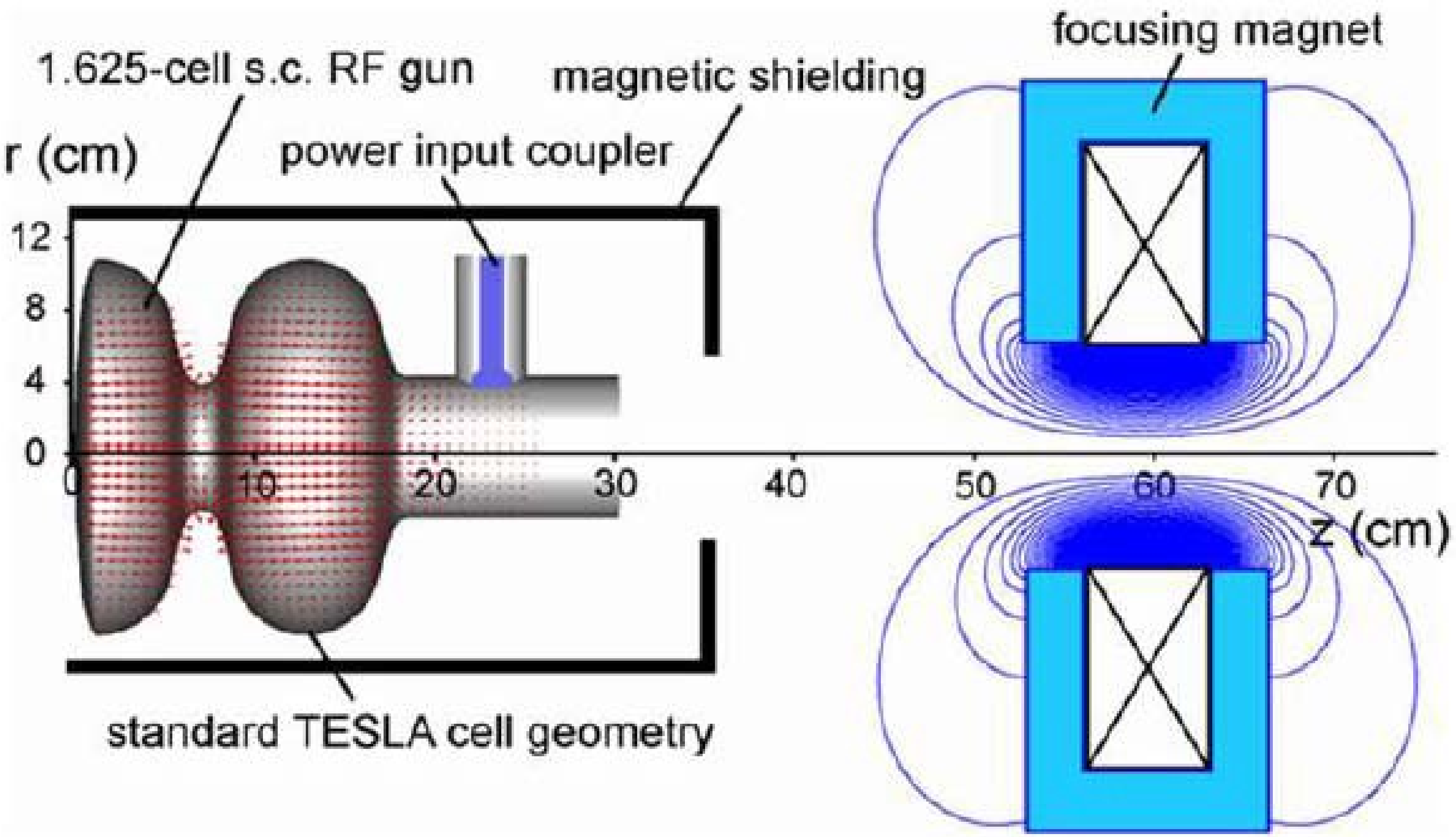


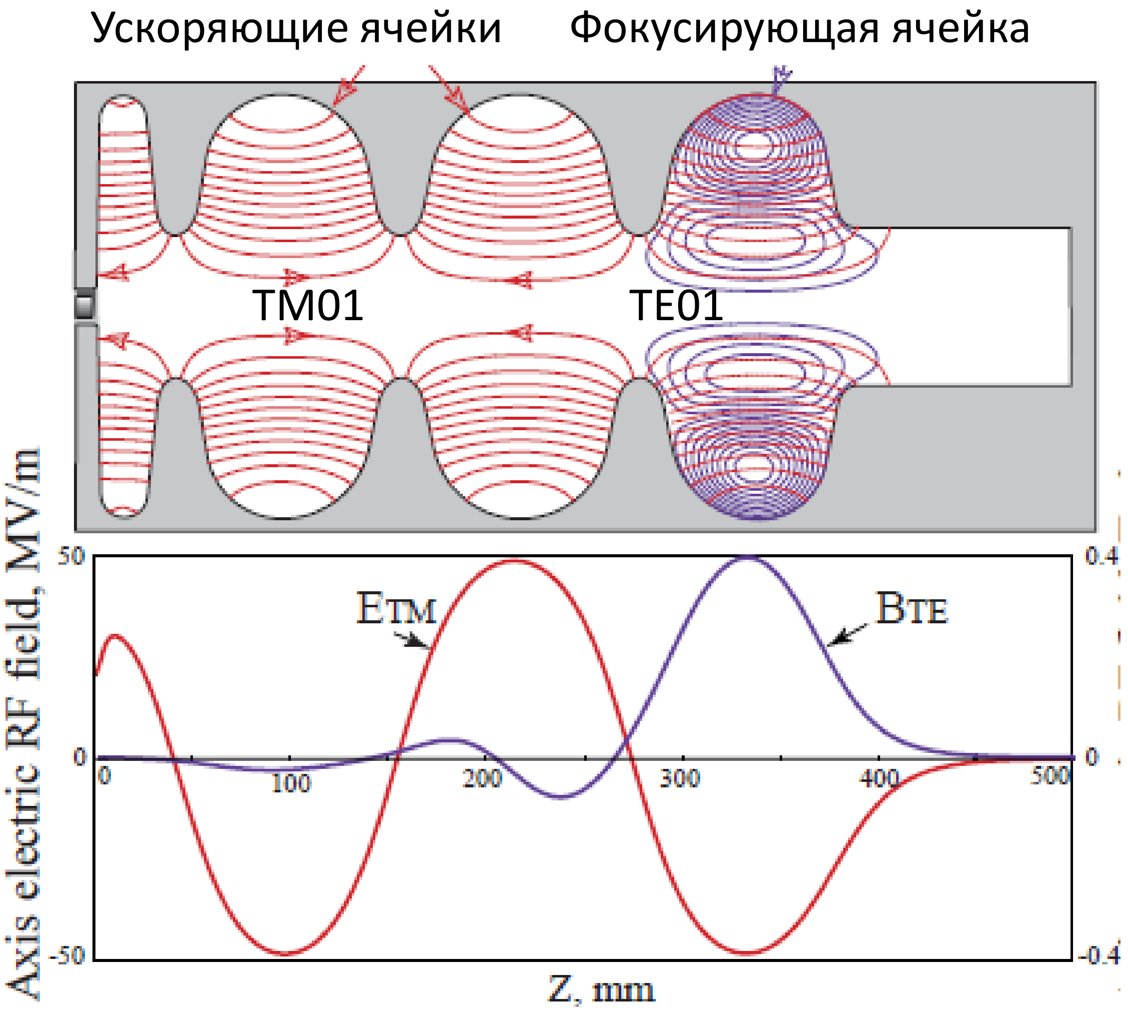
Euclid LLC
Fermilab



Parameter	*Value*	
Application	*UED*	*UEM*
Beam energy	*1.655 MeV*	*1.655 MeV*
Charge	*5 fC*	*0.5 pC*
Laser pulse length, FWHM	*15 fs*	*70 fs*
Laser spot size	*36 μm*	*180 μm*
Beam bunch length, rms	*167 fs*	*741 fs*
Beam emittance	*6.6 nm*	*39 nm*
Energy spread (relative)	1.3×10^{-5}	6.4×10^{-5}

Emittance Compensation with an External Solenoid





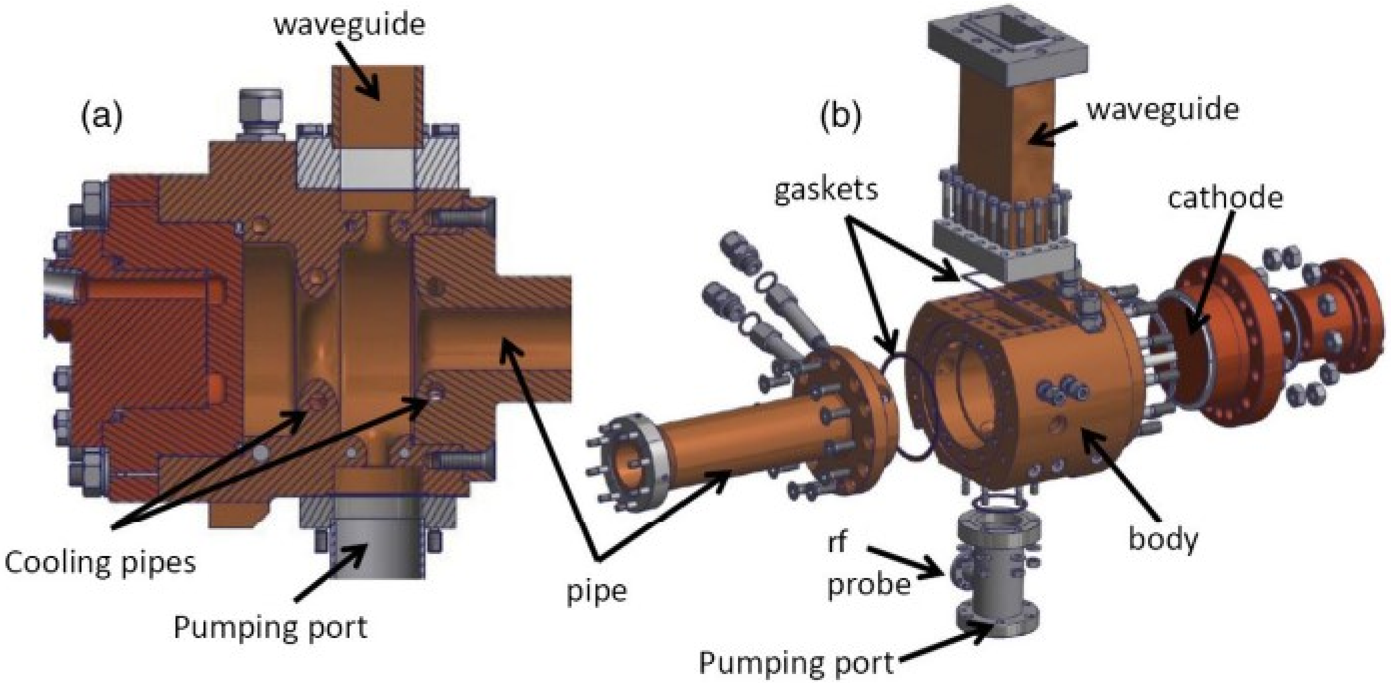
Ускоряющие ячейки
Фокусирующая ячейка
TM01
TE01
ETM
BTE
Axis electric RF field, MV/m
Z, mm
50
0
-50
0.4
0
-0.4
0
100
200
300
400
500

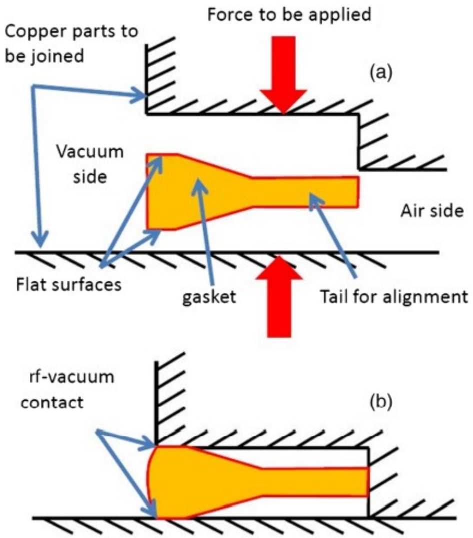
Summary of Results

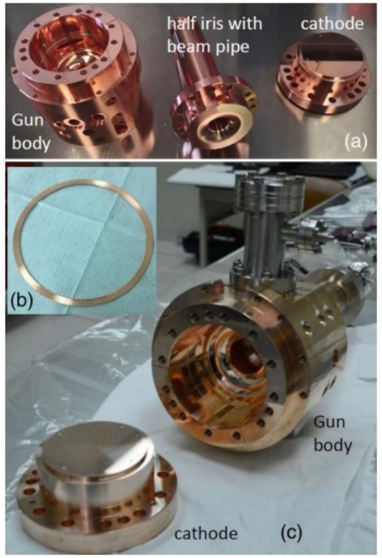
	DC gun	NCRF gun	SRF gun
Gradient, MV/m	6	100-250	10-20
Energy, keV	350	~5000	~2000
Bunch charge, pC	100	10-1000	0.001-10
Average current, mA	10	0.001-30	>100
Transverse emittance, mm×mrad	10	0.1-1	0.001-1
Energy spread, %	<0.1	0.1-1	~0.1
Bunch length, ps	50	0.5-50	~10
Cathode type	GaAs	Cu, Cs_2Te, K_2CsSb	Cu, Cs_2Te
Photon energy, eV	~2	2-4	4
Photon wavelength, nm	500	266-500	266
Lifetime	days	hours-months	months

“Новые” идеи

- Brazeless technology

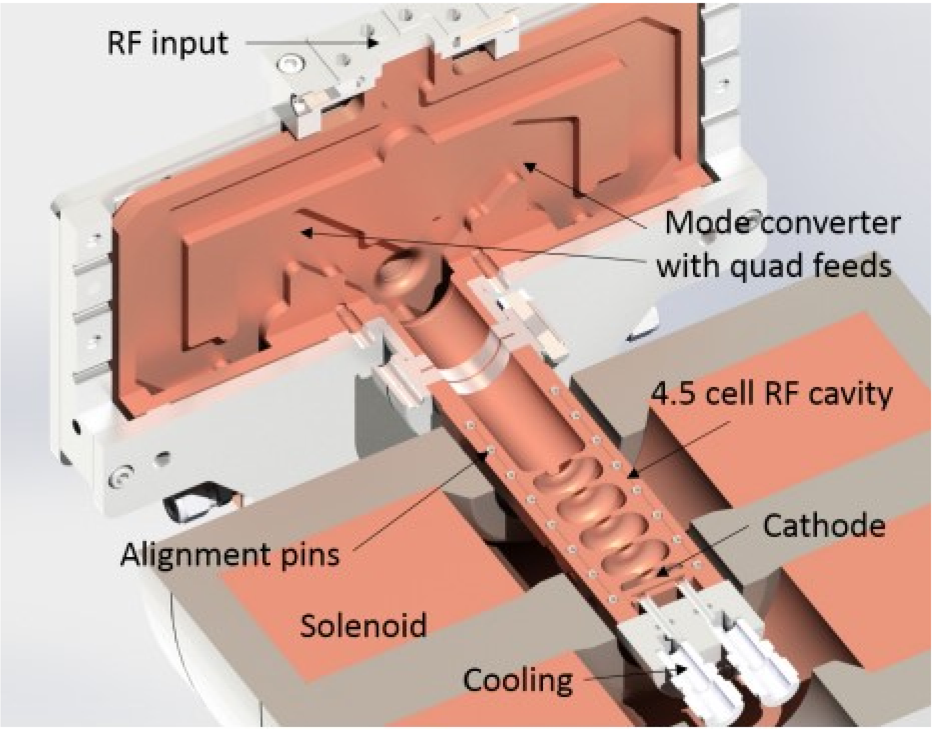




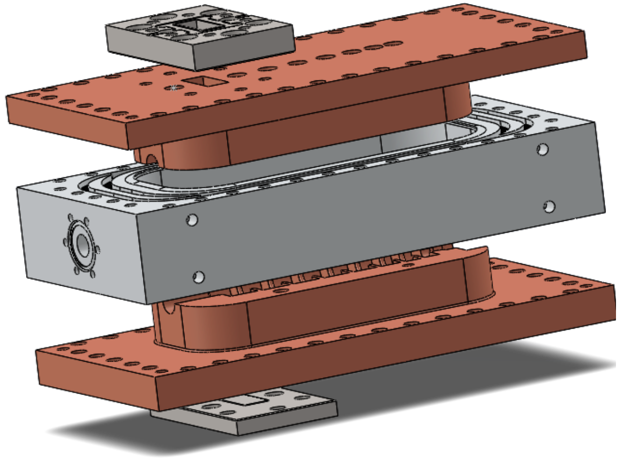


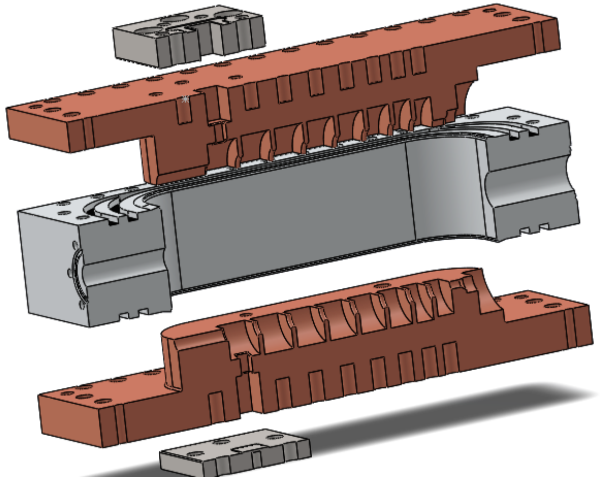
David Alesini et al. Design, realization, and high power test of high gradient, high repetition rate brazing-free S-band photogun (2018).

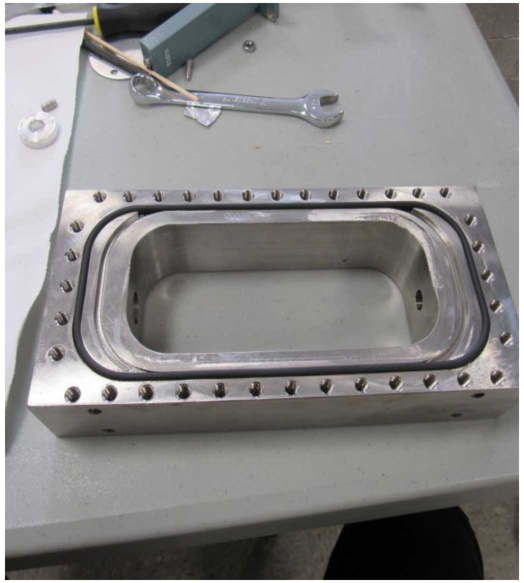
Split-Block Brazeless Design

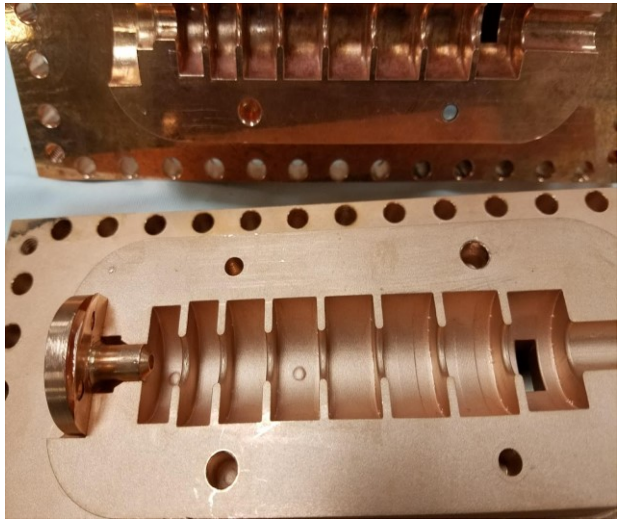


W.S. Graves et al. DESIGN OF AN X-BAND PHOTOINJECTOR OPERATING AT 1 kHz, 2017.





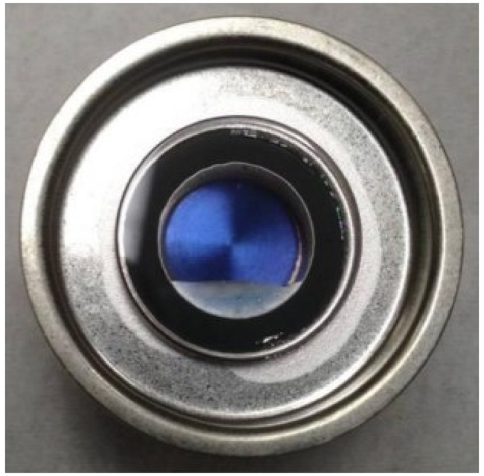
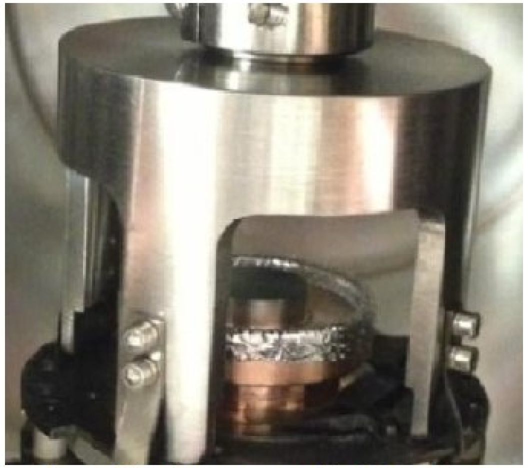




S. V. Kuzikov et al., Compact 1 MeV Electron Accelerator, NAPAC2019 Conference, Lansing, MI, 1–6 September, 2019.

RF Sputtering Coating of Electron Transparent Materials for Photocathode Encapsulation

Encapsulation through a thin layer of coating has great potential to significantly increase the cathode robustness in medium vacuum or even poor vacuum, thus enabling the possibility to conveniently transport the photocathodes to other sites and prolong the cathode lifetime in order to be used in continuous wave (CW), normal-conducting RF guns.

Capsule-sealed Photonis photocathode with the cap on (left) and removed (right) [Smedley]

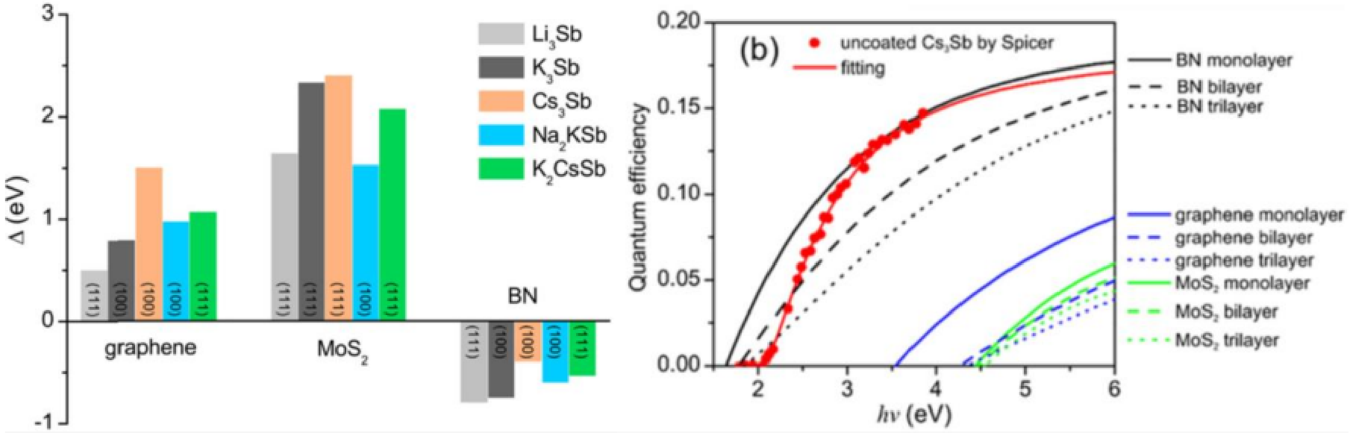


Figure 6. Change of work function for different monolayers coated on semiconducting photocathodes (left) and QE with and without coating layers (right). Figure by G. Wang et. al.

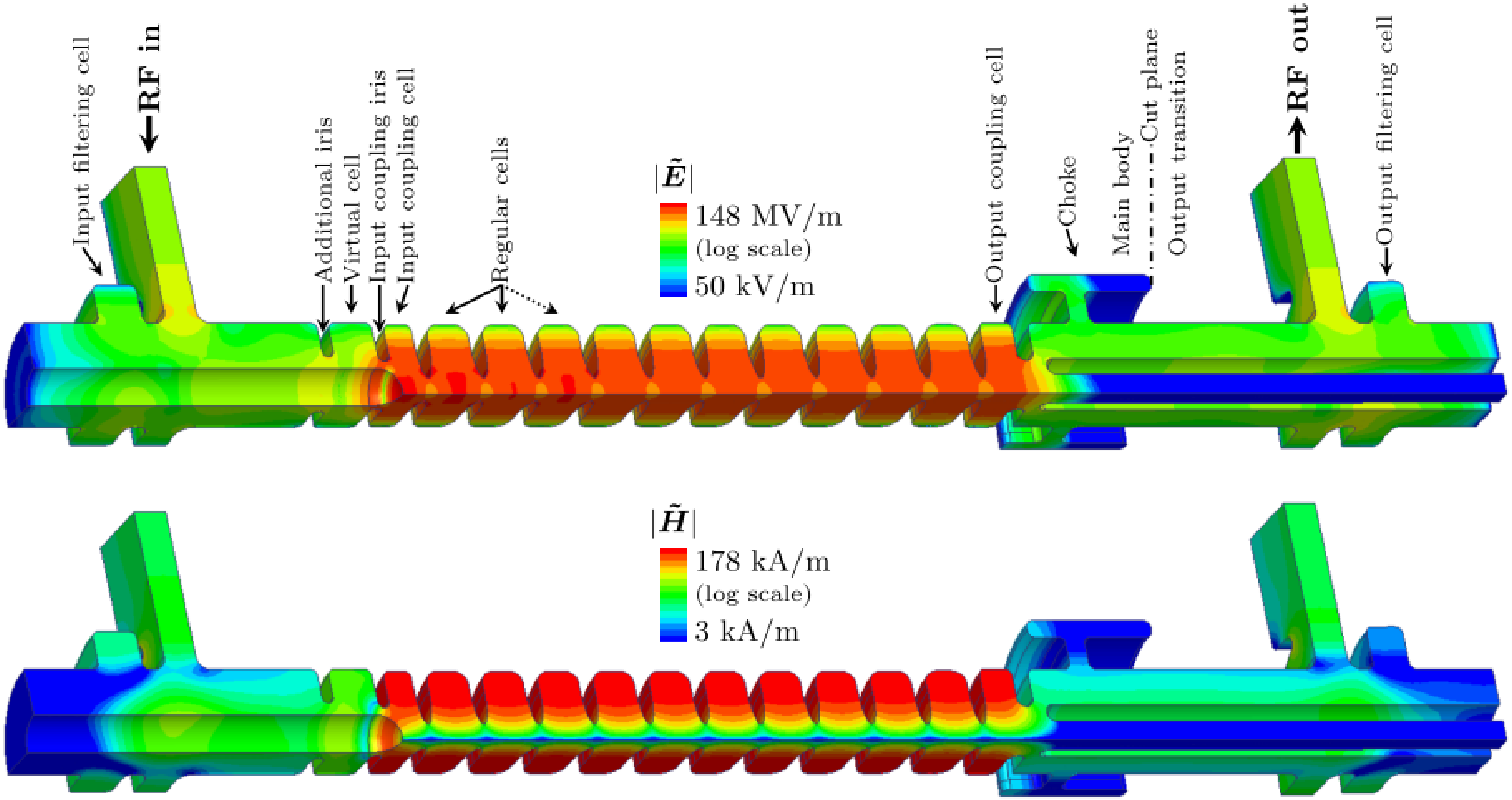
rf traveling-wave electron gun for photoinjectors

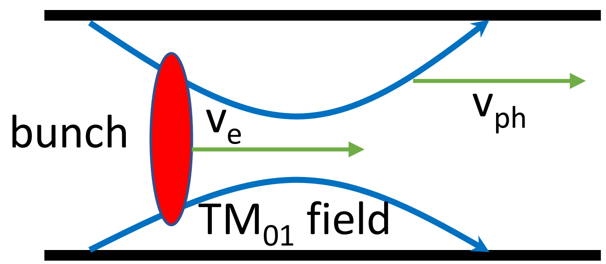
Mattia Schaer,* Alessandro Citterio, Paolo Craievich, Sven Reiche,
Lukas Stingelin, and Riccardo Zennaro

Paul Scherrer Institut, CH5232 Villigen PSI, Switzerland

(Received 21 December 2015; published 12 July 2016)

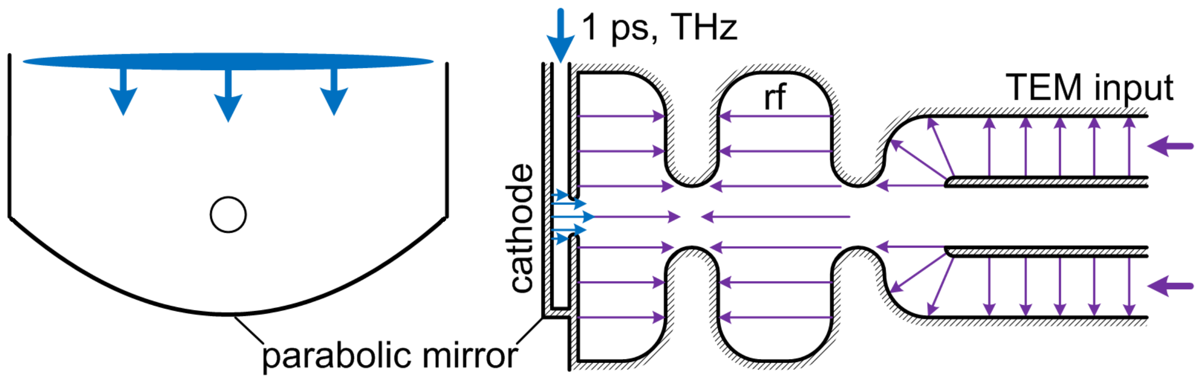
Travelling wave design for RF gun allows E-field focusing in order to avoid heavy and expensive solenoid.



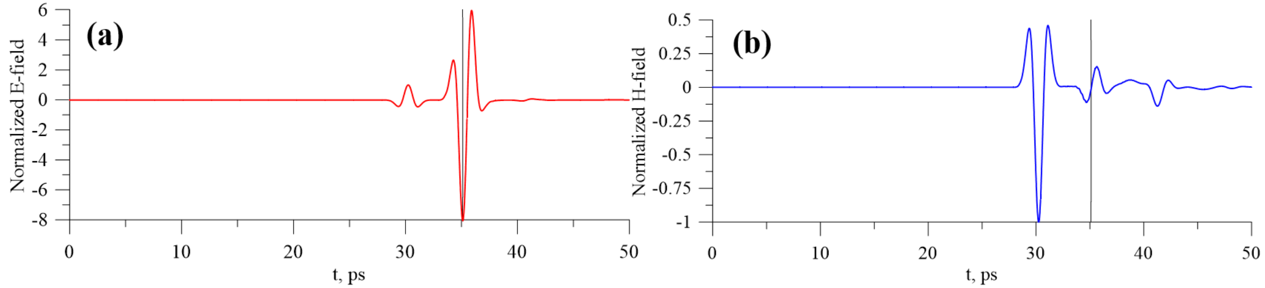


High Brightness Beam Generation by Ultrafast Field Emission Gating

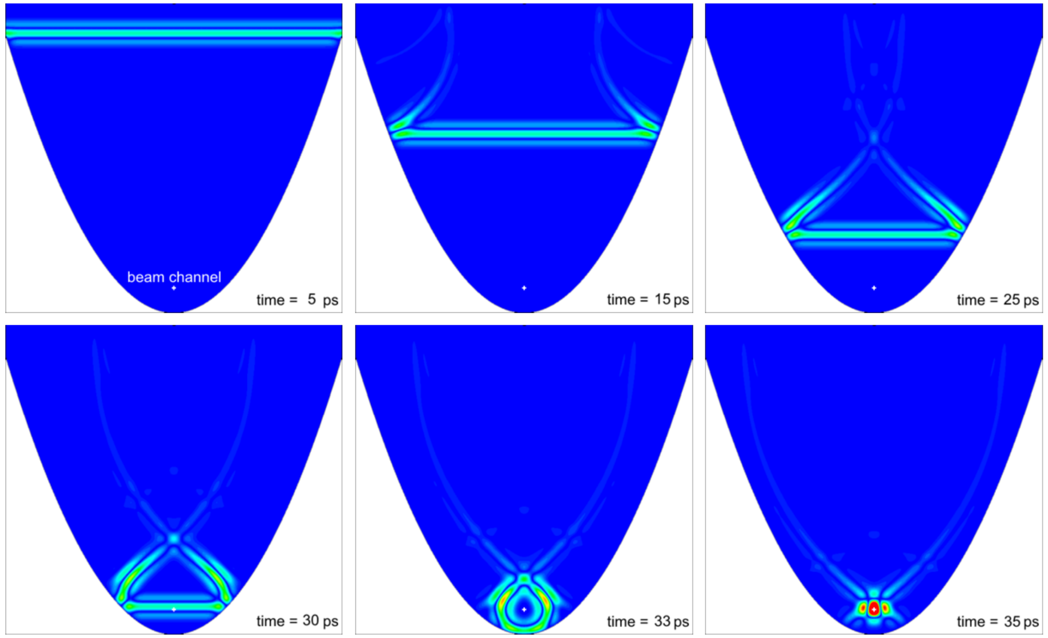
Euclid LLC proposed to build a high brightness gun based on a gated picosecond flat field-emission cathode. Laser-based single-cycle THz pulse production by optical rectification and semiconductor switching yields high intensity, ~ 1 ps long THz pulses. The 1 GV/m field strength of the THz pulse, combined with the RF gun accelerating field of ~100 MV/m, results in the emission of a short current pulse from the cathode. Compared to a standard photocathode, the beam brightness is increased due to the high additional accelerating field provided by the THz pulse. This allows considering the possibility of creating electron bunches with a brightness of 10^{16} A/m^2×rad^2 with bunch charges at the 100 pC level.



RF gun wherein electron emission is controlled by a picosecond THz pulse irradiating a metallic cathode



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



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

Thank you!