國家同步輻射研究中心
National Synchrotron Radiation Research Center

Photo-injector Technology

李安平

同步輻射研究中心高亮度注射器小組

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Introduction of Photo-injector

What is low emittance important?

Brightness

$$B = \frac{N_e}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}$$

- The brightness of a charged particle beam, defined as the number of electrons within the 6-D phase space volume, dictates its luminosity.
- The wavelength λ of the free-electron laser (FEL) is governed by the emittance ε_n of the electron beam which sets the lower limit on the wavelength deliverable by an FEL.
- As the wavelength of the FEL gets shorter, the required emittance gets lower and thereby brightness increases.
- In the free electron laser , the beam quality is set ultimately by the injector and electron source.

$$\frac{\varepsilon_n}{\gamma} < \frac{\lambda_{FEL}}{4\pi}$$

Why to use the photo-injector?

- Photo-injector generates low emittance (<1μm) electron beams
- Many free electron laser facility (LCLS, Pohang XFEL, European XFEL, Shanghai SXFEL,…) are based on photo-injectors.
- Photo-injector are also used in other applications such as energy recovery linac (ERL), Compton scattering sources, ultrashort electron bunch diffraction.

Introduction of Photo-injector

Why electron injector is so important ?

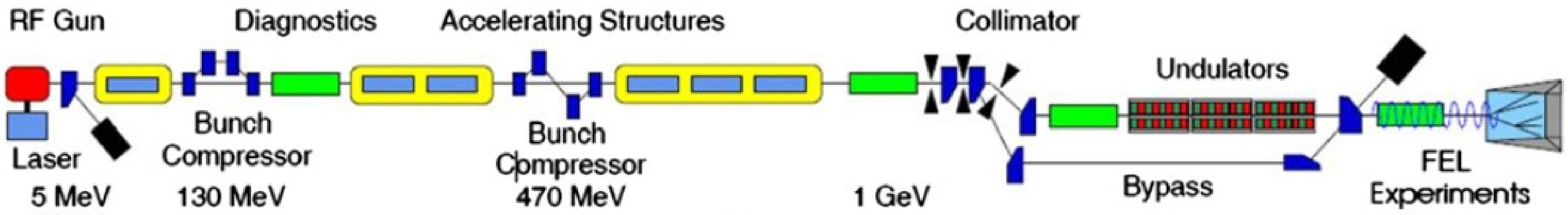
Any linac based short wavelength, high brilliance light source contains the following main components:

- **electron source** →space charge force
- **accelerating sections** → wake field
- **bunch compressor** → coherent synchrotron radiation
- **undulator to produce FEL radiation**
- **beam dump**

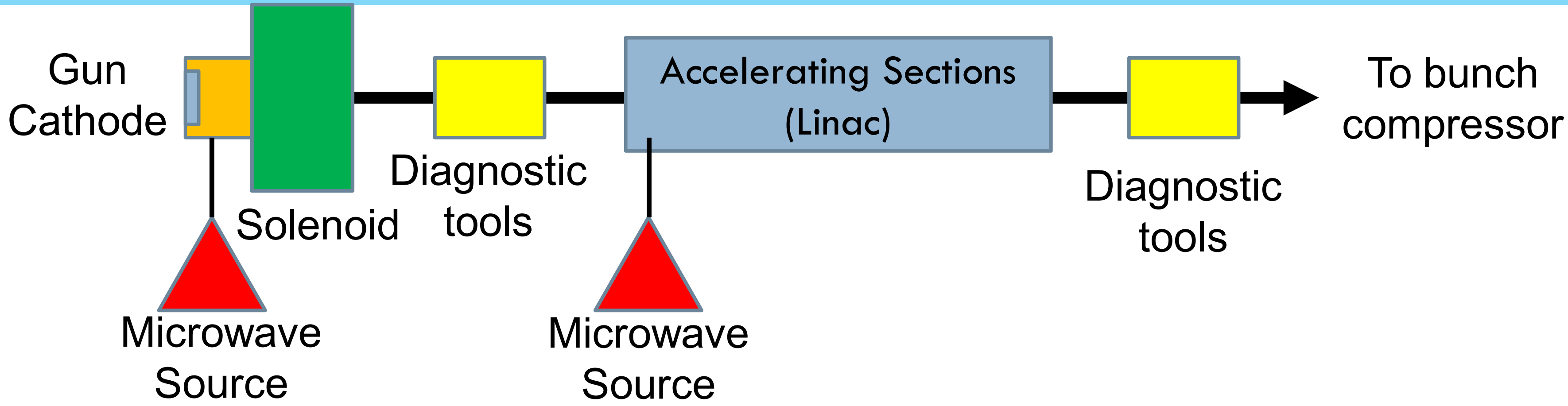
⇨ Increase ε_n !

Beam quality will degrade during accelerating
→ The Injector has to produce lowest possible emittance

Example : Flash, the VUV FEL at DESY



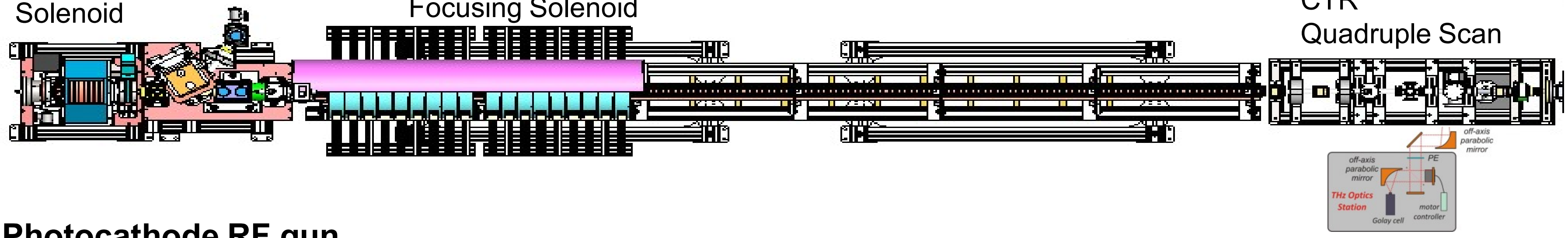
Typical Photo-injector



A photo-injector has the following major components:

- ELECTRON GUN (either DC or RF) : electron bunches are generated from the cathode and accelerated by DC Electric field or RF field from rest.
- SOLENOID : it is used to performs the emittance compensation.
- DRIVE LASER : laser pulses are illuminated on the cathode than electrons are emitted from the photocathode .
- LINEAR ACCELERATOR : it is used to accelerate the electrons exiting the gun to sufficiently high energy.
- HV or RF SOURCE : the power source (such as a klystron) provides EM power for the electron gun and the linac.
- DIAGNOSTIC TOOLS : used to characterizes electron beams such as beam profile monitor, current transformer, deflecting cavity, spectrometer magnet,….

NSRRC Photo-injector



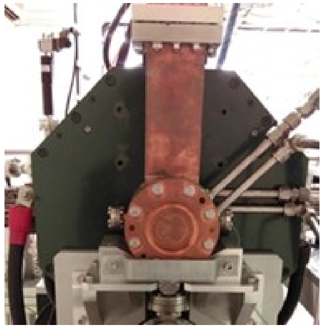
Photocathode RF gun
- S-band 1.6-cell copper cavity
- Cu photocathode (QE:10^{-6}~10^{-5})
- Emittance compensation solenoid

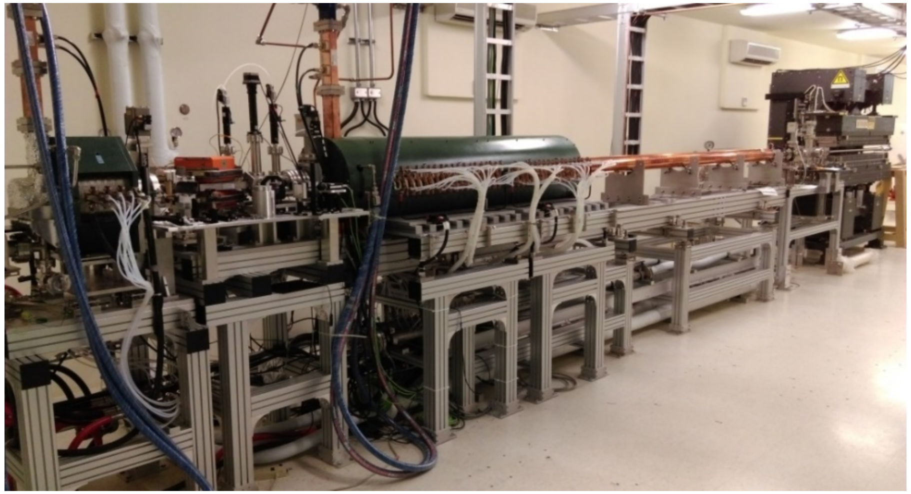
Laser system
- IR(800 nm) & UV (266 nm) sources
- Beam shaping elements

RFSystem
- Thalas 35MW pulsed klystron
- Power devider and Phase shifter

Beam Diagnostic Tools
- ICT, Faraday cup, YAG screen, multislit, spectrometer, quadruple scan, CTR…

Linac
- S-band, 5.2 m, 156-cell copper, constant gradient
- Focusing Solenoid





Electron Gun

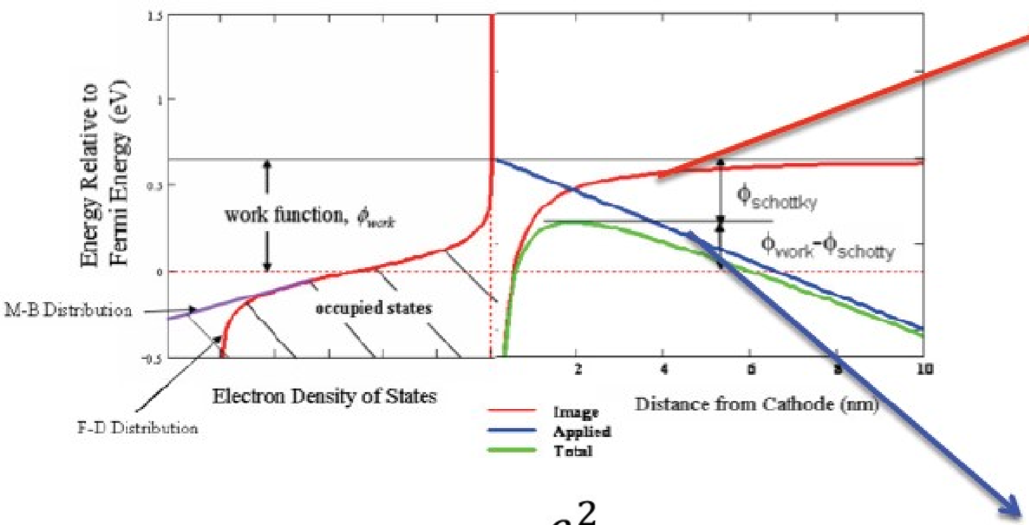
- ***Photocathode***
- ***RF Gun***

Photocathode

- Cathodes are illuminated by laser pulses than emits electrons.
- In the lower charge regime, the ultimate emittance performance of a linac is set by the cathode thermal emittance.
- The ideal cathode should allow for high brightness (have a low thermal/intrinsic normalized emittance, low energy spread, high current density) full control of the bunch distribution, and long lifetimes.

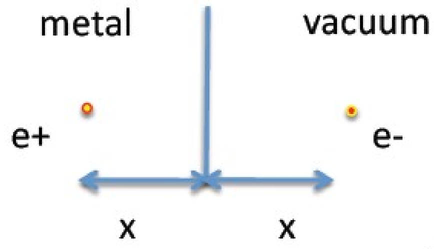
- The Quantum Efficiency QE is defined as the number of photo-emitted electrons per photon impinging on the cathode. $QE = \frac{n_e}{n_p} = \frac{h\nu[eV]}{E_{laser}[J]} q[c]$
- The minimum photon energy or wavelength λ required for generating photoemission from the cathode.
- Maximum charge density that can be extracted from a cathode is important when high charge/bunch are required with relatively small emittance
- Lifetime.
  - Chemical reactivity
  - Robustness to ion/electron back-bombardment.

Effective Potential



$$\Phi_{tot} = \Phi_{work} - \frac{e^2}{16\pi\epsilon_0} - eE_0 x$$

Image charge:



$$F_{+,-} = -\frac{e^2}{4\pi\epsilon_0(2x)^2}$$

$$V_{+,-} = -\frac{e^2}{16\pi\epsilon_0 x}$$

Shottky effect:

$$V_{sh} = -eE_0 x$$

Emission electron needs to overcome the barrier: $E_{el} > \Phi_{tot,max}$

Cathode Emittance

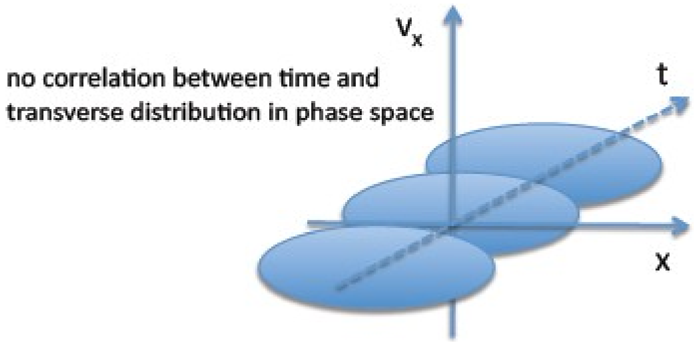
The usual definiton of RMS emittance is:

$$\epsilon_{n,x} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

There is not correlation between angle and position. The initial normalized emittance is calculated as:

$$\epsilon_{n,\perp} = \sigma_\perp \frac{\sqrt{\langle p_\perp^2\rangle}}{mc} = \sigma_\perp \beta_\perp$$

$$\beta_\perp = \sqrt{\langle \beta_\perp^2\rangle} = \frac{\sqrt{\langle p_\perp^2\rangle}}{mc}$$



The transverse momentum is determined by the emission process, and the beam size by the size of the source (laser pulse, emitter,…)

Photoemission

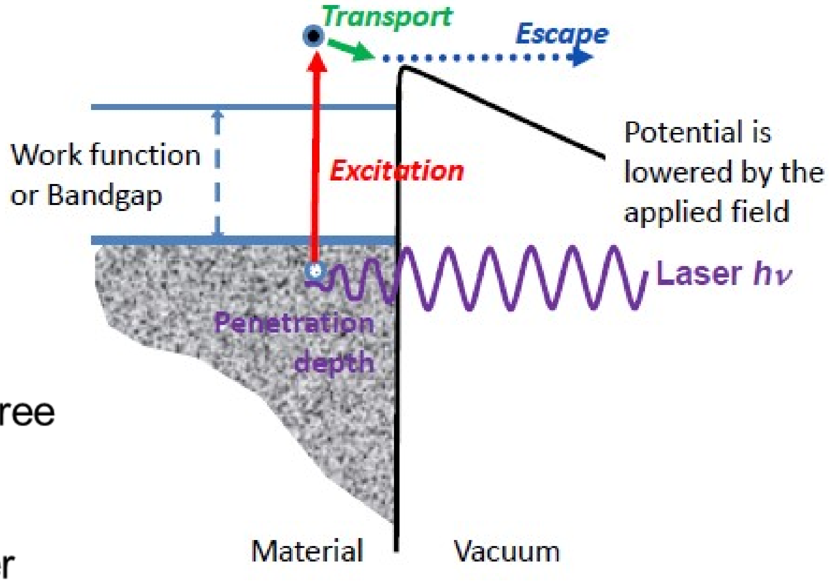
Spicer's three step model:

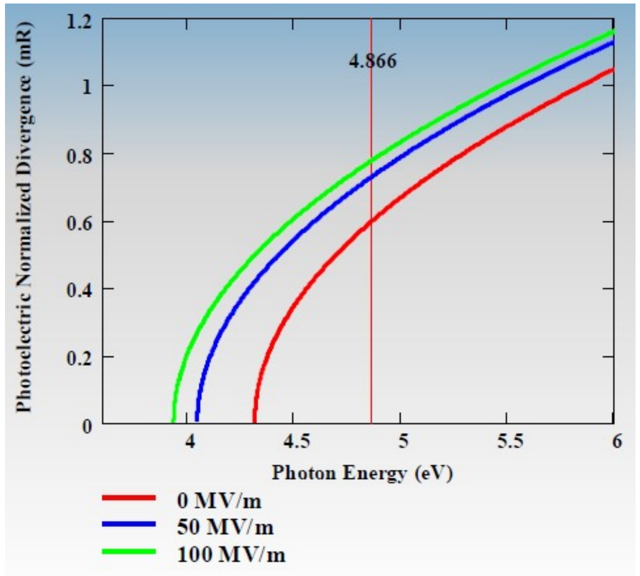
(Bergland & Spicer used it to explain photo-emission)

- Photon energy absorption by electron
  - Optical depth (~14nm for UV light on copper)
- Electron motion toward the crystal surface
  - Electron-electron (phonon) scattering; mean free path ~5,6nm for 4.5eV exited electrons
- Electron escape to the through the potential barrier
  - maximum angle of emission; p_z
- By the 3-step model:

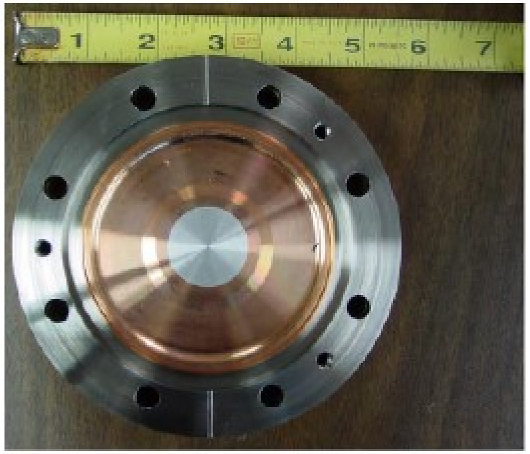
$$\rightarrow QE = A(h\nu - \phi_0 + \alpha\sqrt{E})^2$$

$$\epsilon_n = \sigma_x \sqrt{\frac{h\nu - \phi_{effect}}{3mc^2}}$$



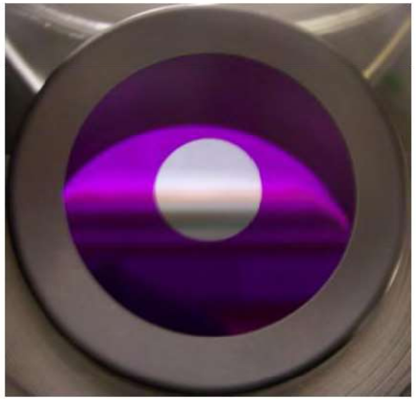


Examples of Cathodes



- **Metal: Cu**
  - <~sub-picosecond pulse capability
  - minimally reactive; requires ~ 10^{-8} Torr pressure
  - low QE ~ 10^{-5}~10^{-4}
  - requires UV light
  - for nC, 120 Hz reptition rate, ~ 2 W of IR required

- **PEA Semiconductor: Cesium Telluride Cs_2Te**
  - <~ps pulse capability
  - relatively robust and un-reactive (operates at ~ 10^{-9} Torr)
  - Successfully use in NC RF and SRF guns
  - high QE > 5%
  - photo-emits in the UV ~250 nm (3rd or 4th harm. conversion from IR)
  - for 1 MHz reprate, 1 nC, ~ 10 W 1060nm required



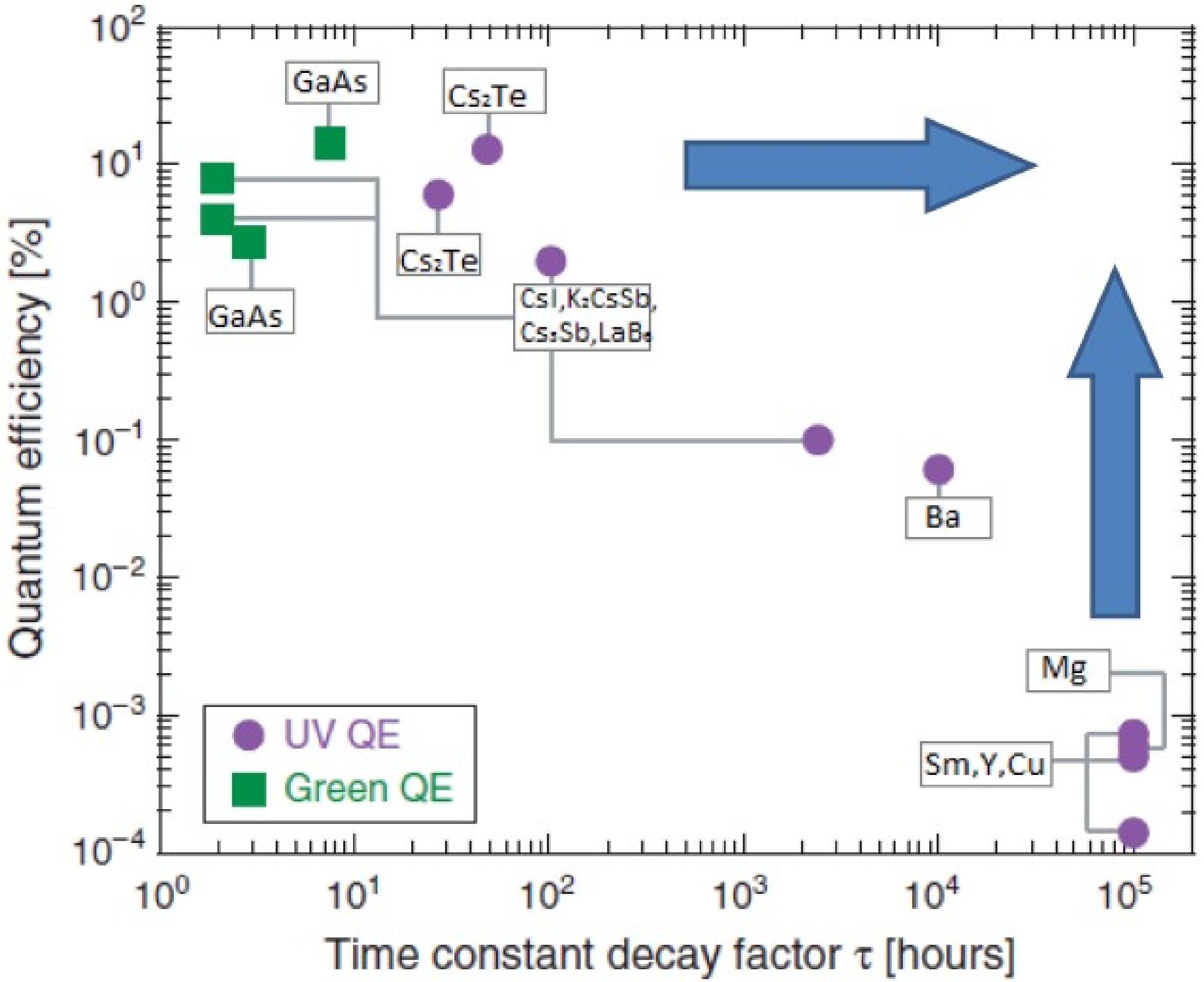
- **NEA Semiconductor: Gallium Arsenide GaAs**
  - tens of ps pulse capability with phonon damping
  - reactive; requires UHV <~ 10^{-10} Torr pressure
  - high QE (typ. 10%)
  - Photo-emits already in the NIR,
  - for nC, 1 MHz, ~50 mW of IR required
  - operated only in DC guns at the moment
  - Allow for polarized electrons

In general :
- Metal cathodes are more robust but show much lower QE.
- Semiconductor cathodes have high QE. but short life time.

Photocathode Life Time vs. QE

Dream cathode ??

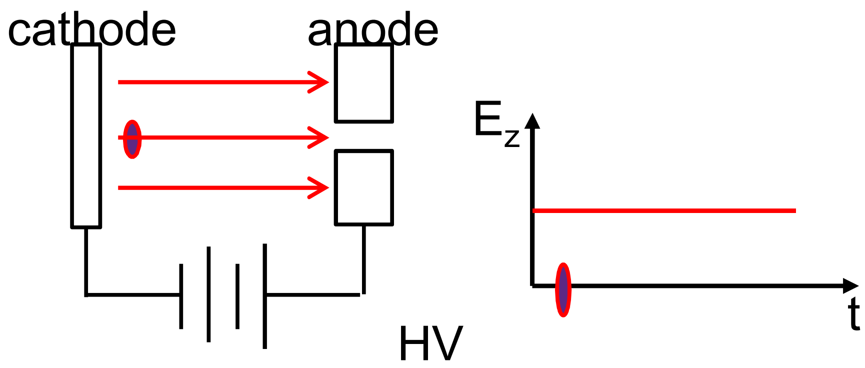
- Low work function
- High current density
- Long lifetime
- Low emittance



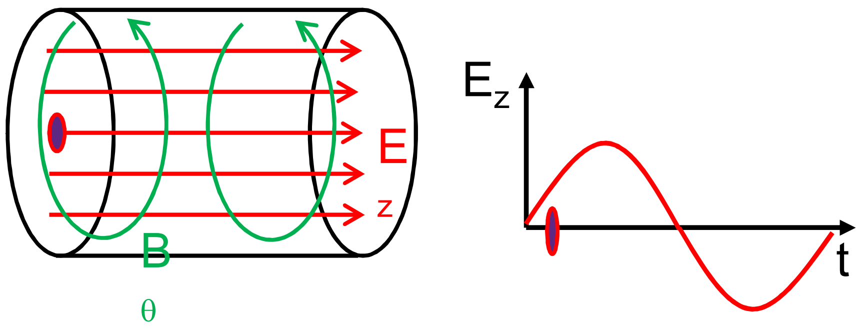
Jensen & Montgomery, J. of Comp. and Theo. Nanosci. **6**, 1754-1769 (2009).

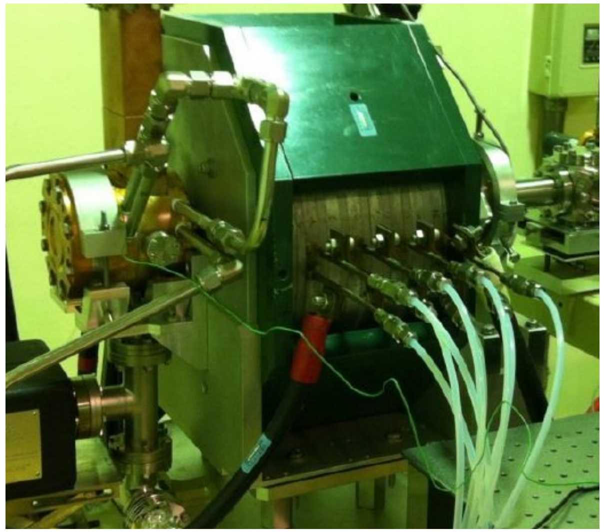
DC and RF Acceleration

DC acceleration



RF acceleration





TM modes in a Pillbox Cavity

$$E_z = E_0 J_m(k_{mn}r)\cos(m\theta)\cos(k_l z)e^{j\omega t}$$

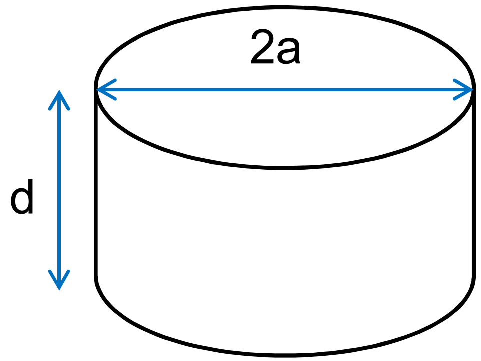
$$E_r = -\frac{jk_l}{k_{mn}} E_0 J_m'(k_{mn}r)\cos(m\theta)\sin(k_l z)e^{j\omega t}$$

$$E_\theta = -\frac{k_l m}{k_{mn}^2 r} E_0 J_m(k_{mn}r)\sin(m\theta)\sin(k_l z)\, e^{j\omega t}$$

$$B_r = \frac{\omega m}{k_{mn}^2 c r} E_0 J_m(k_{mn}r)\sin(m\theta)\cos(k_l z)\, e^{j\omega t}$$

$$B_\theta = \frac{j\omega}{k_{mn} c} E_0 J_m'(k_{mn}r)\cos(m\theta)\cos(k_l z)\, e^{j\omega t}$$

$$B_z = 0$$

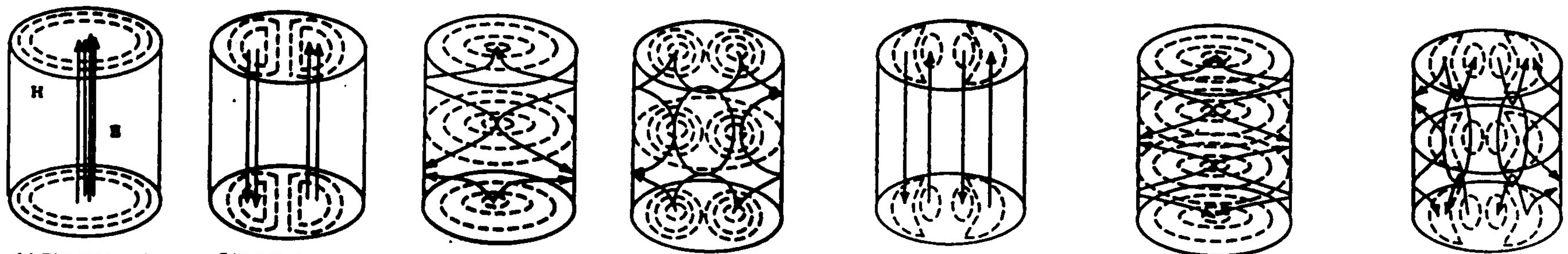


Where $k_l = l\pi/d$, $l = 0,1,2,\ldots$

$k_{mn} = x_{mn}/a$

The n[th] zero of $J_{mn}(x)$

Resonant frequency : $f_{mnl} = \frac{c}{2\pi}\sqrt{\left(\frac{l\pi}{d}\right)^2 + \left(\frac{x_{mn}}{a}\right)^2}$



(a) TM 010 mode (b) TM110 mode (c) TM012 mode (d) TM112 mode (e) TM120 mode (f) TM013 mode (g) TM122 mode

Cavity Mode for Particles Acceleration

The lowest-frequency TM mode is TM010 with cell length = $\lambda/2$.

$$E_z = E_0 J_0(k_{01} r) e^{j\omega t}$$

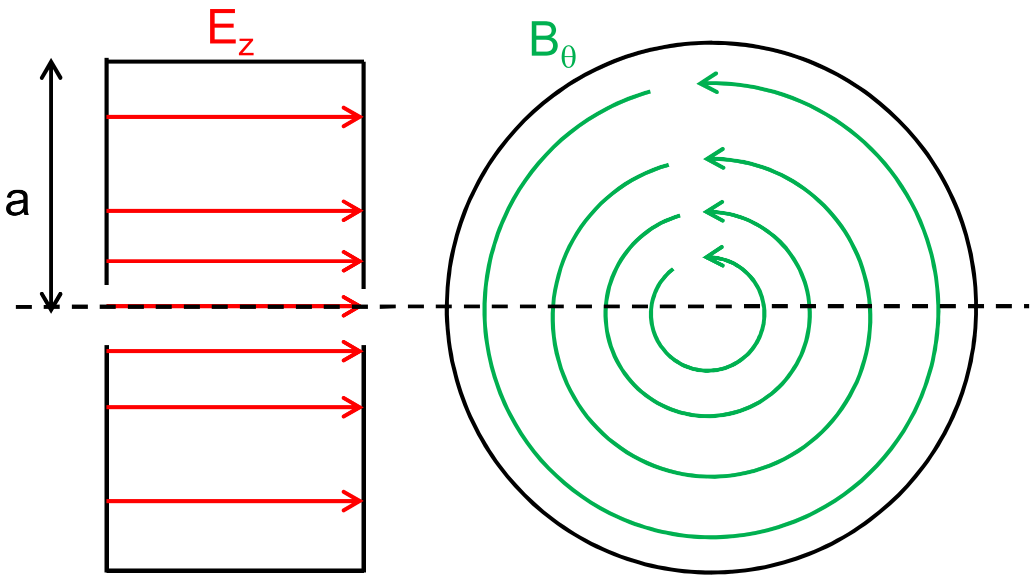
$$E_r = 0$$

$$E_\theta = 0$$

$$B_\theta = \frac{j\omega}{k_{01} c} E_0 J_0{}'(k_{01} r) e^{j\omega t}$$

$$B_r = 0$$

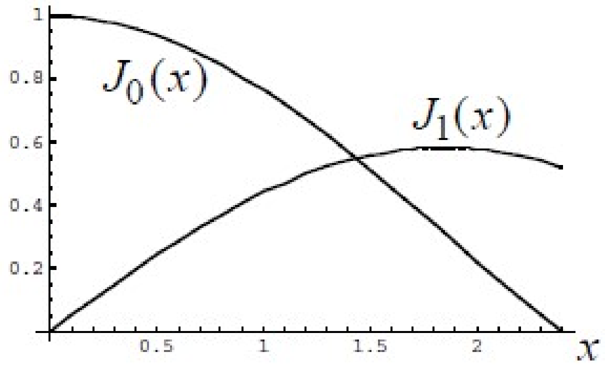
$$B_z = 0$$



TM010 resonance frequency :

$$f_{01} = \frac{2.405}{2\pi}\frac{c}{a}$$

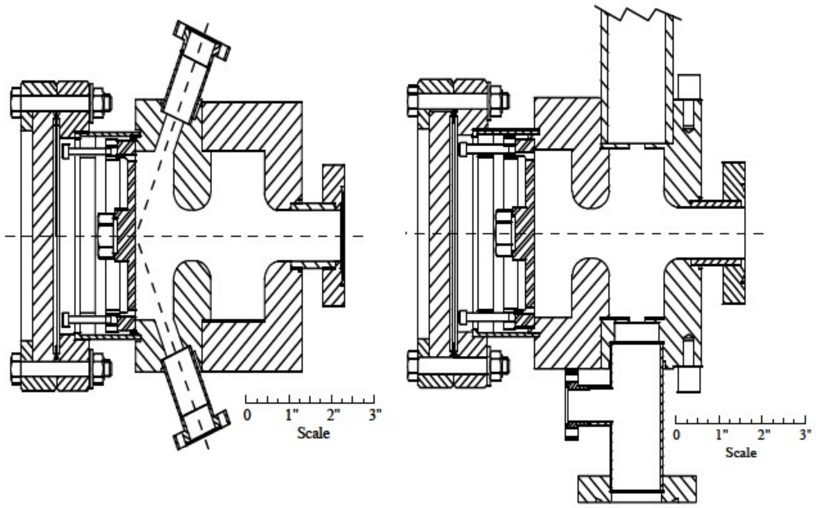
Example : *a = 3.825 cm*, $f_{01} = 3\ GHz$

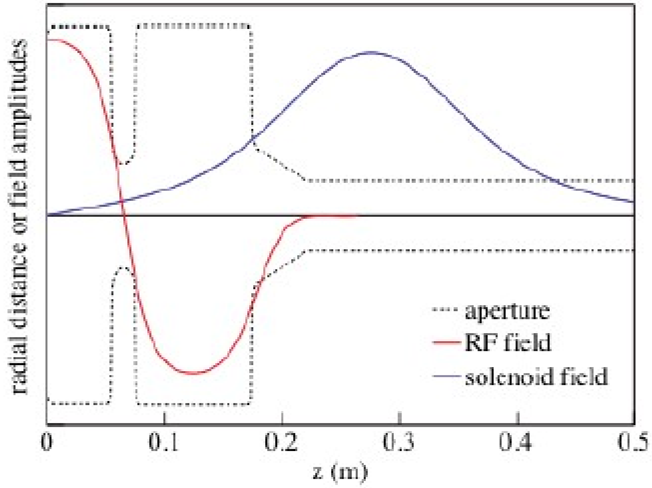


Photocathode RF Gun

- RF guns are used to produce high peak current electron beams
- Usually operate at low repetition and GHz frequencies range (typically 3GHz).
- The cavity structure is usually n+1/2cell(n=1,3…)
- Standing wave structure, TM mode to accelerate the beam (need of Ez)
- The cathode is placed in the half cell (max field)
- The most unique property of the radio frequency gun lies in its capability to bring the photoelectrons, emitted almost on rest at the photocathode surface, up to a relativistic speed ***in a time shorter than the RF period.***

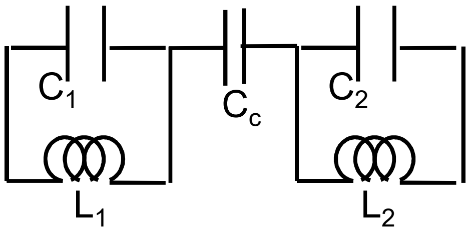
The BNL/SLAC/UCLA photocathode RF Gun





Modes of 2-Cell Cavities

Circuit model of Two-cell cavities



Solve the equation :

$$\frac{d^2 I_1}{dt^2} + \omega_0^2 (1-\kappa_c) I_1 = -\kappa_c \omega_0^2 I_2$$

$$\frac{d^2 I_2}{dt^2} + \omega_0^2 (1-\kappa_c) I_2 = -\kappa_c \omega_0^2 I_1$$

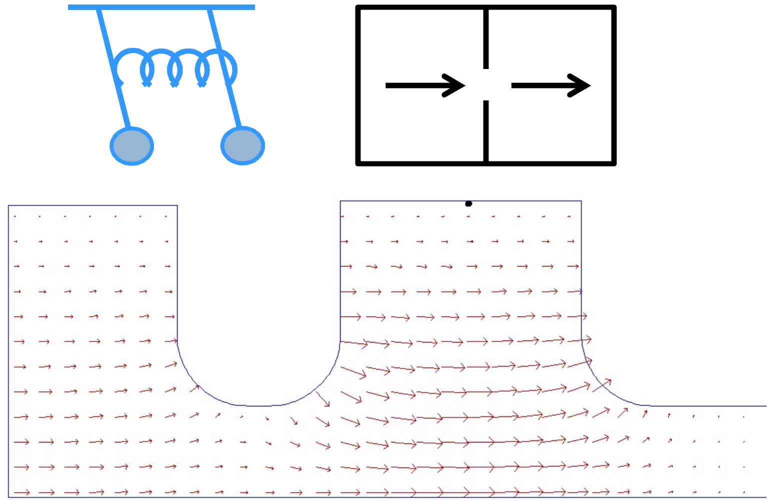
$$\omega_0^2 = \frac{1}{LC}$$

Two eigenvalues

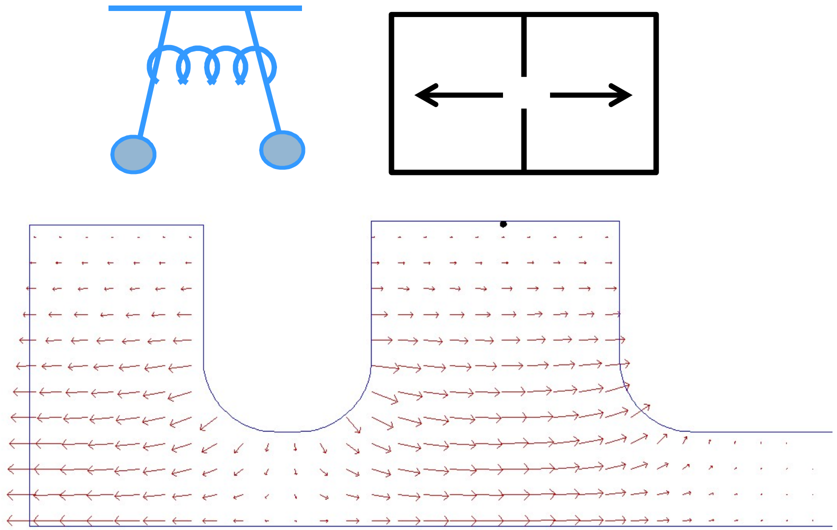
0-mode $\quad \omega = \omega_0$

π-mode $\quad \omega = \omega_0 (\sqrt{1+2\kappa_c})$

0-mode



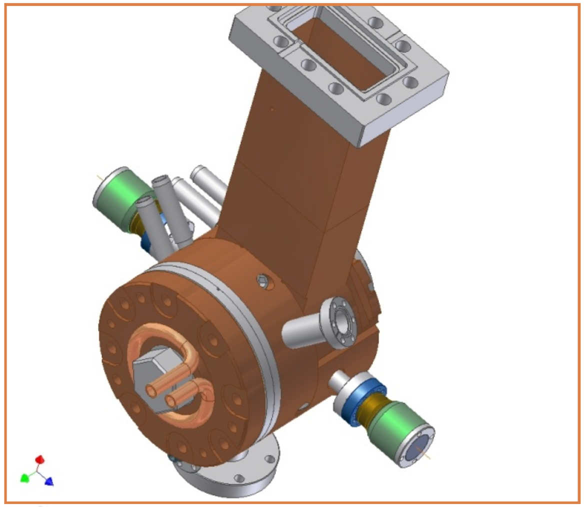
π-mode

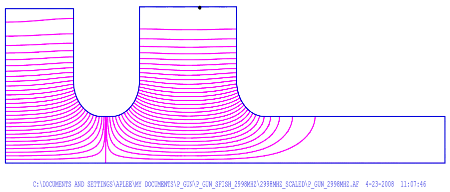


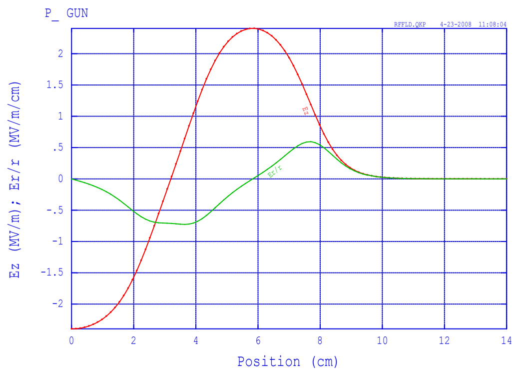
Design RF Gun & Simulation

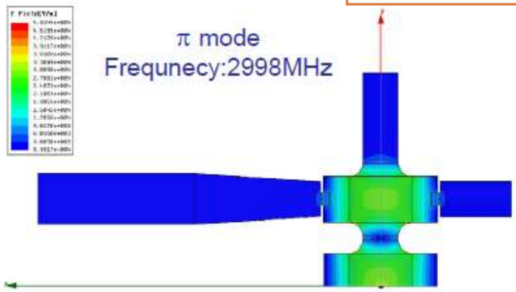
Gun design parameter

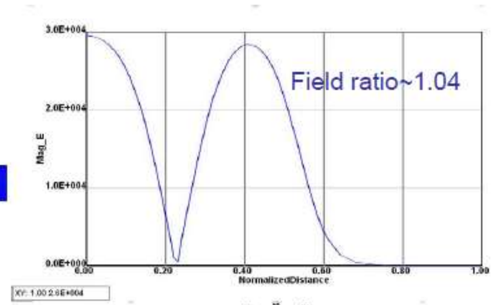
Gun type	*BNL/SLAC/UCLA*
RF frequency	2998 MHz
Beam energy	6 MeV
Bunch length	10 psec flattop
Bunch rep. rate	10 Hz
Cathode material	Cu

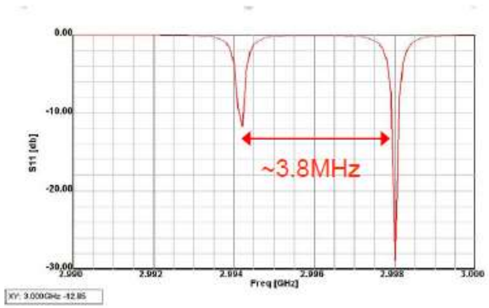


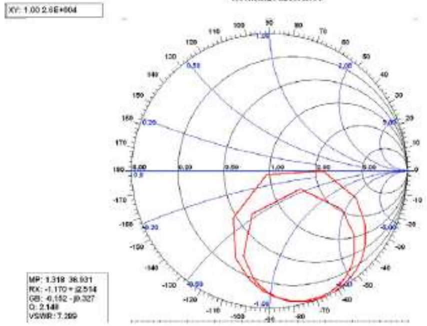




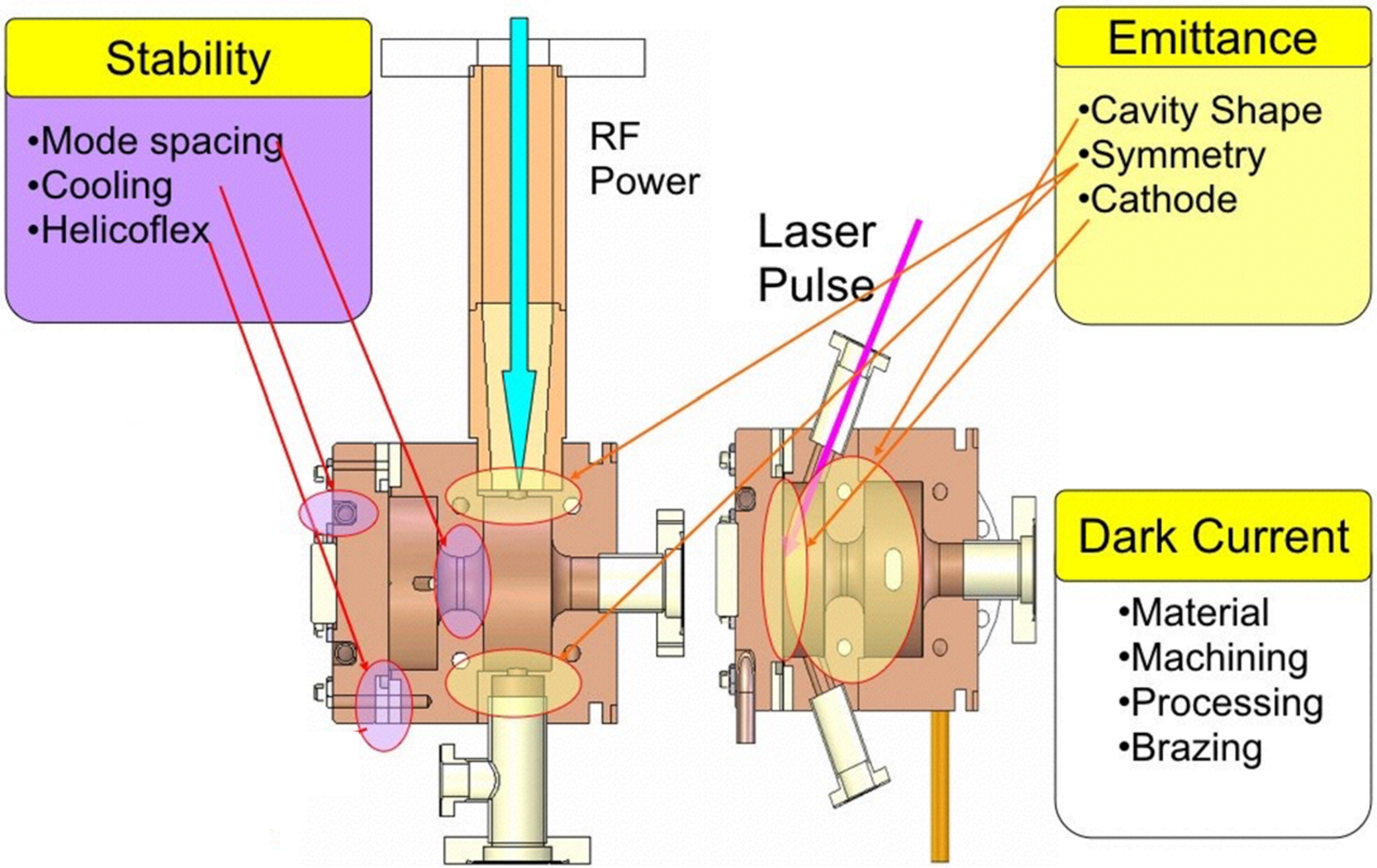




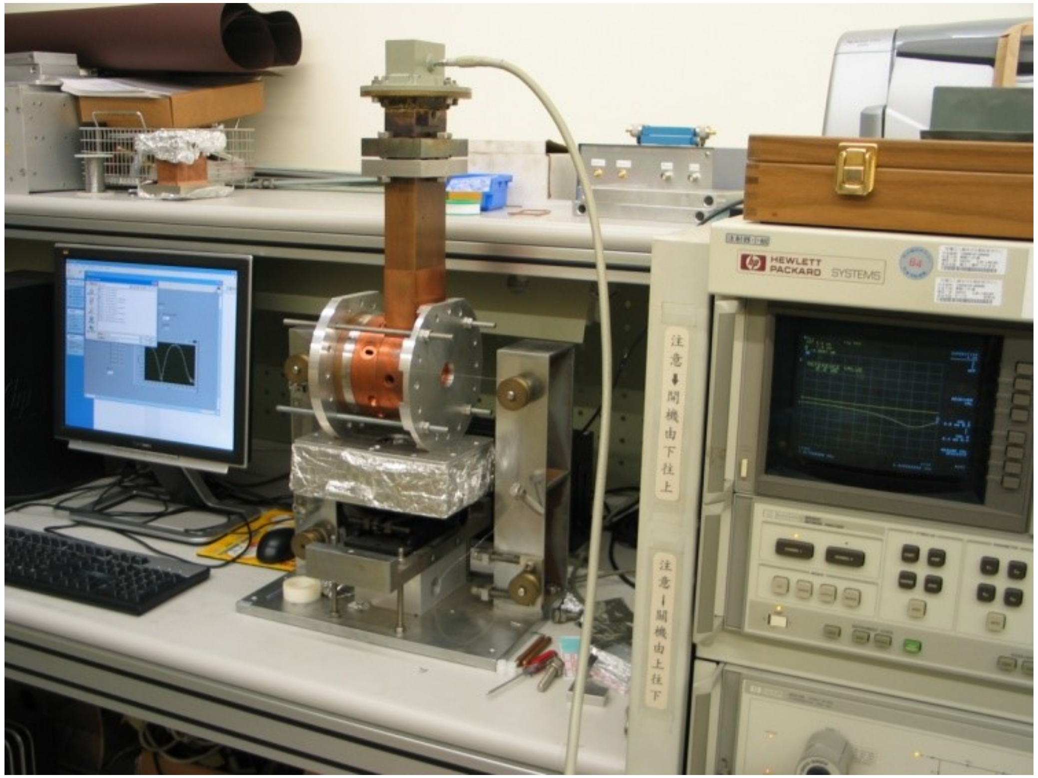


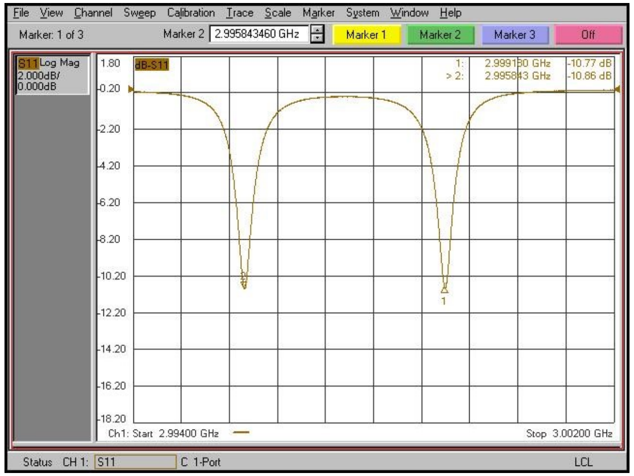


Real Cavity Design



Gun Cold Test





- Cavity frequency tuning and mode identification
- Measure microwave properties, Q_0, β and S_{11}
- Mapping of longitudinal field along beam axis

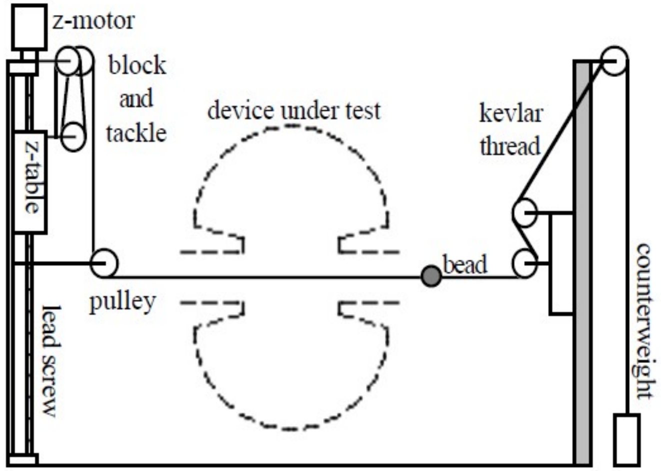
Field Mapping

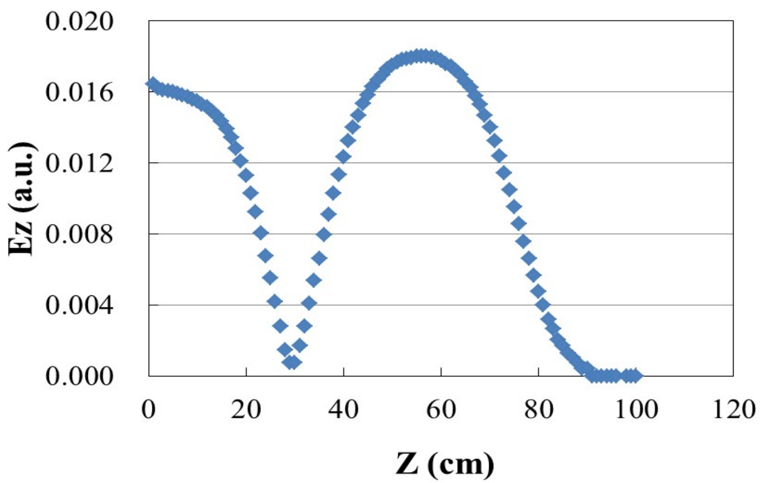
- Use so-called "bead-pull" technique via Slater's theorem
- Metallic of dielectric bead (on optical fiber)
- Metallic bead on-axis gives negative frequency shift (electric field energy displaced, No magnetic effects on-axis for accelerating mode)
- Slater's Theorem:

$$\frac{\Delta\omega}{\omega} = -\frac{\pi a^3}{U}\left(\varepsilon_0 \frac{\varepsilon_r - 1}{\varepsilon_r + 2} E_0^2 + \mu_0 \frac{\mu_r - 1}{\mu_r + 2} H_0^2\right)$$

For dielectric bead $\frac{\Delta\omega}{\omega} = -\frac{\pi a^3}{U}\left(\varepsilon_0 \frac{\varepsilon_r - 1}{\varepsilon_r + 2} E_0^2\right)$

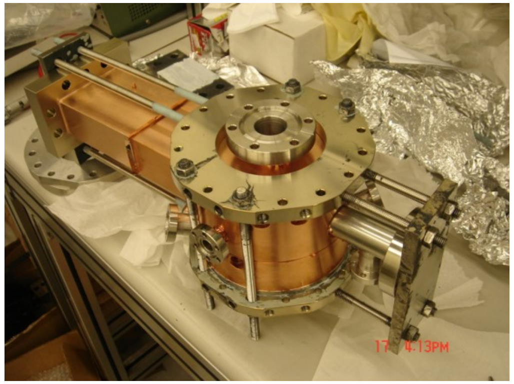
For metal bead $\frac{\Delta\omega}{\omega} = -\frac{\pi a^3}{U}\left(\varepsilon_0 E_0^2 - \frac{\mu_0}{2} H_0^2\right)$



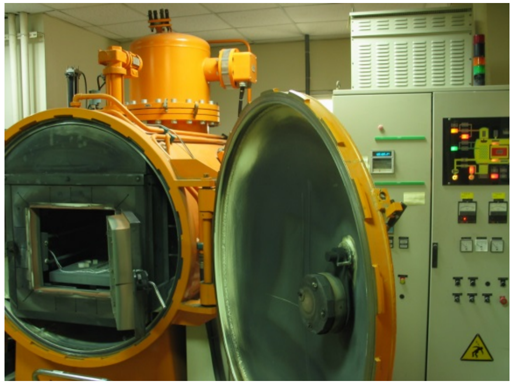


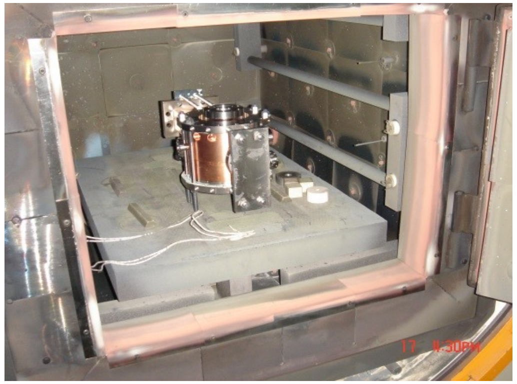
Gun Fabrication and Brazing

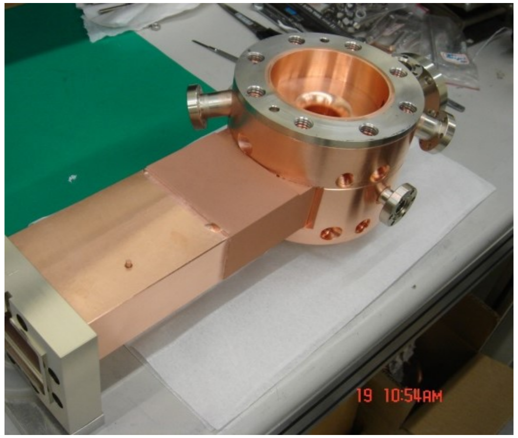
Fabrication



Vacuum Brazing

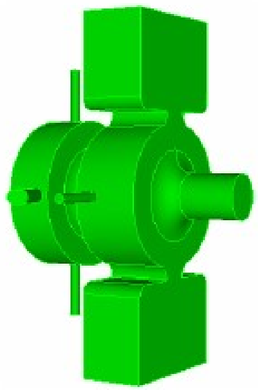


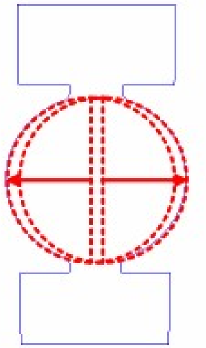


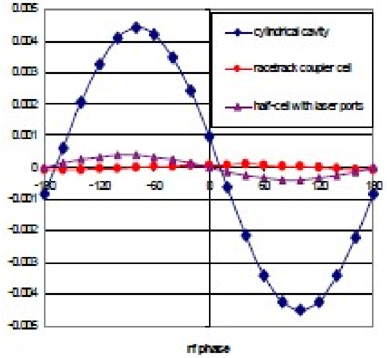


LCLS S-BAND NC RF Gun

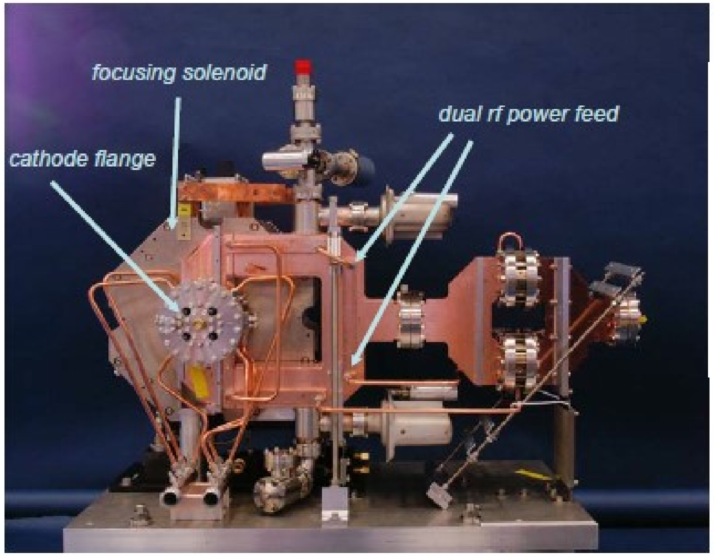
The LCLS S-Band Gun

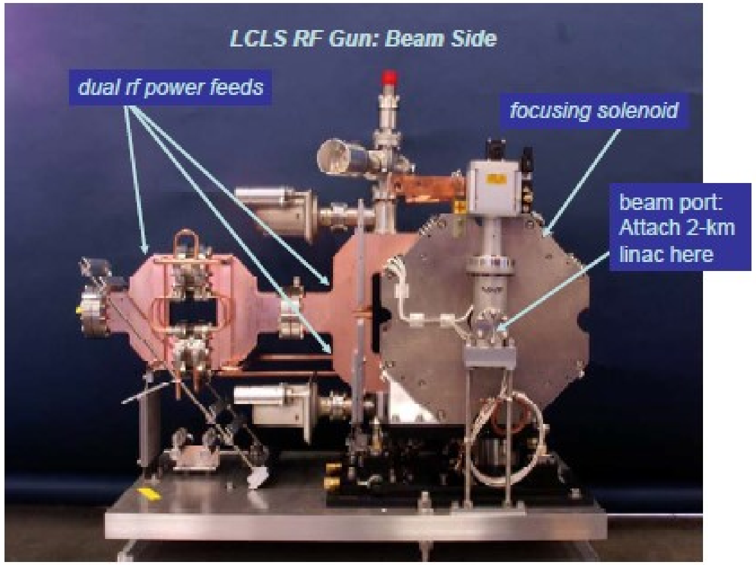






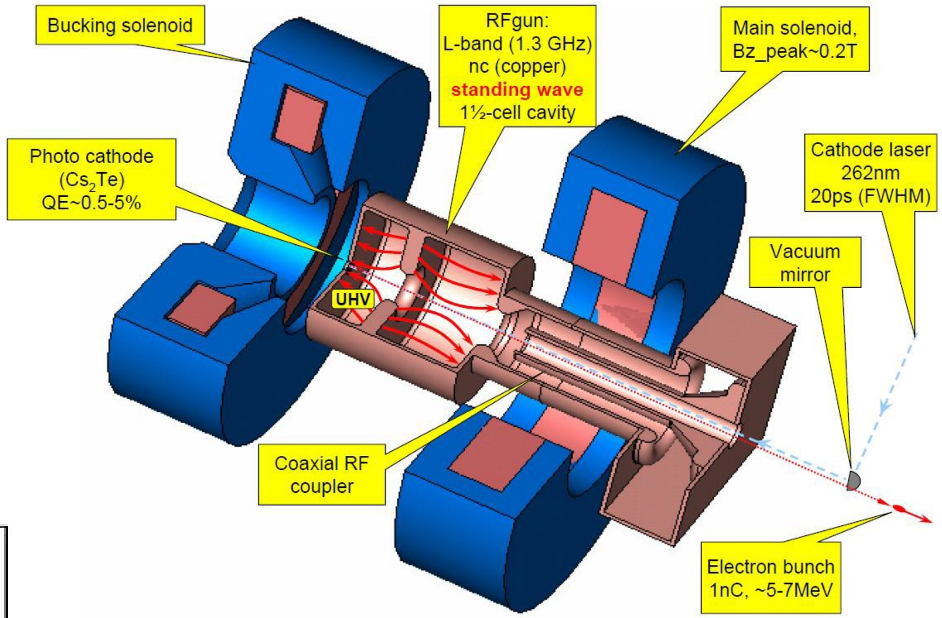
Frequency = 2,856 MHz
Gradient = 120 MV/m
Exit energy = 6 MeV
Copper photocathode
Bunch repetition rate = 120 Hz
Norm. rms emittance = 0.4 mm at 250 pC
= 0.14 mm at 20 pC

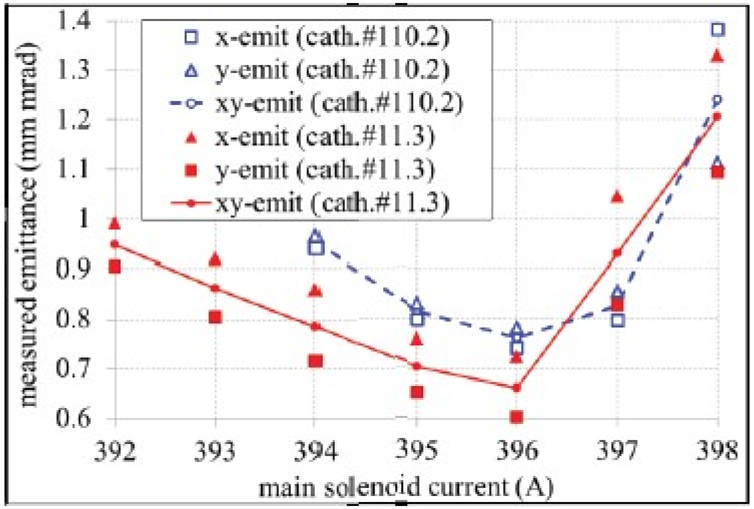




PITZ NC RF Gun

PITZ L-band Gun
Frequency = 1,300 MHz
Gradient = up to 60 MV/m
Exit energy = 6.5 MeV
Cs2Te photocathode
800 bunches per macropulse
Normalized rms emittance
1 nC   0.70 mm
0.1 nC 0.21 mm



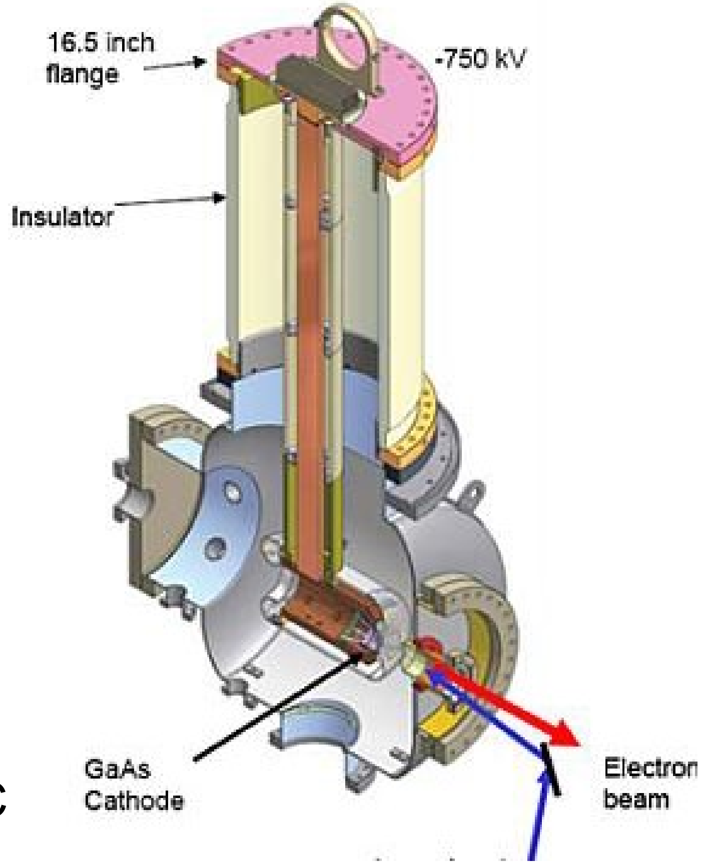


Parameters	FLASH	European XFEL
max. RF repetition rate	10 Hz	10 Hz
max. train length	800 µs	600 µs
bunch spacing	1 µs	0.2 – 1 µs

Corrnell DC Gun

DC guns use a large ceramic insulator to stand off the high voltage between a cathode and an anode, creating accelerating gradients of a few hundred V/m. Present operation limited to ~ 350kV to limit field emission and minimize probability of field punctuation of the ceramic

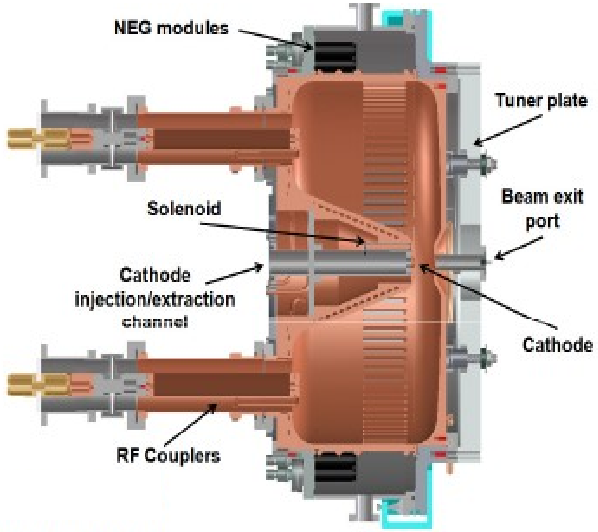
Cornell DC gun
Gradient = 5 – 10 MV/m
Gun exit energy = 0.35 MeV
GaAs and K2CsSb photocathodes
Bunch repetition rate = 1300 MHz
Norm. rms emittance = 0.5/0.3 mm at 80 pC
Average current = 65 mA (at 50 pC)

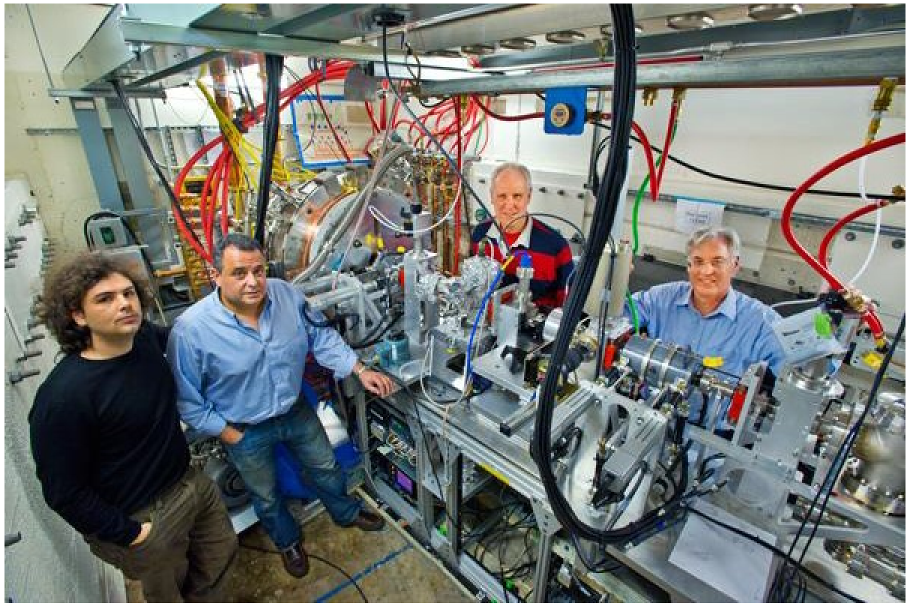


LBNL CW NC VHF RF Gun

LBNL VHF Gun

- LBNL proposed a NCRF gun design in 2009.
- At the VHF frequency, the cavity structure is large enough to withstand the heat load at a level that conventional cooling techniques can be used to run in CW mode
- The long wavelength allows for large apertures and thus for high vacuum conductivity





Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	$< 10^{-11}$ Torr

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Accelerating Structures
and
Microwave System

Dispersion Curve for TM_{01} Mode in a Cylindrical Waveguide

TM01 mode in a cylindrical waveguide :

$$E_z = E_0 J_0(k_{01} r)\cos(kz - \omega t)$$

$$E_r = kE_0 J_1(k_{01} r) sin(kz - \omega t)$$

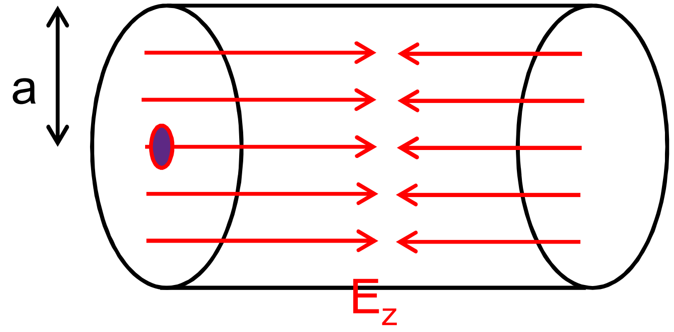
$$B_\theta = \frac{\omega}{k_{01} c} E_0 J_1(k_{01} r)\sin(kz - \omega t)$$

$$k = \frac{\omega_c}{c} = \frac{2.405}{a} \qquad k = \frac{\sqrt{\omega^2 - \omega_c^2}}{c}$$

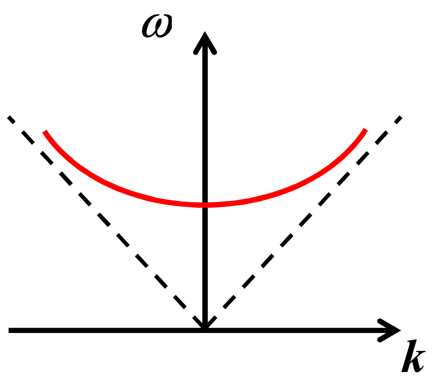
The phase velocity is $v_p = \frac{\omega}{k} = \frac{c}{\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}} > c$

The group velocity is $v_g = \frac{d\omega}{dk} = c\sqrt{1 - \left(\frac{\omega_c}{\omega}\right)^2} < c$

Cylindrical waveguide



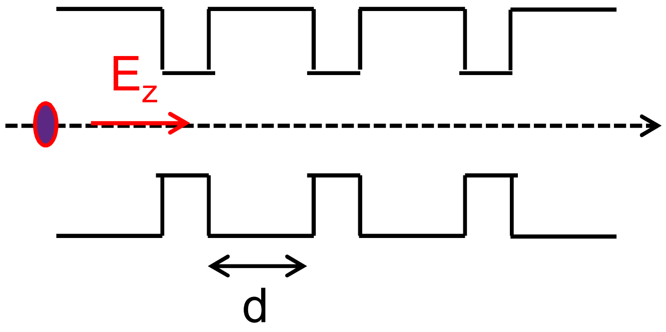
Dispersion diagram

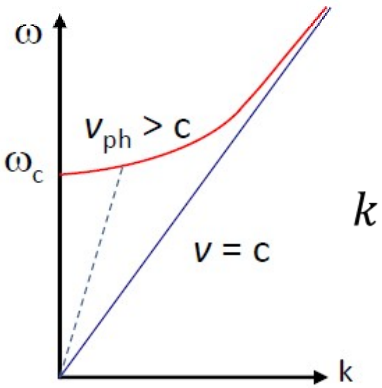


In order to be able to accelerate charged particles over any reasonable distance, the wave and the particle must have the same velocity. The waveguide is "loaded" with periodic structures to make this happen.

Periodic Structure

- Periodic structures can be used to obtain $v_p \approx c$.
- Periodic accelerating structures can be described as a periodic array of coupled resonant cavities. The iris-loaded structure may be viewed as an array of pillbox cavities that are coupled through the irises.
- Periodically loaded cavity in which can slow the wave.

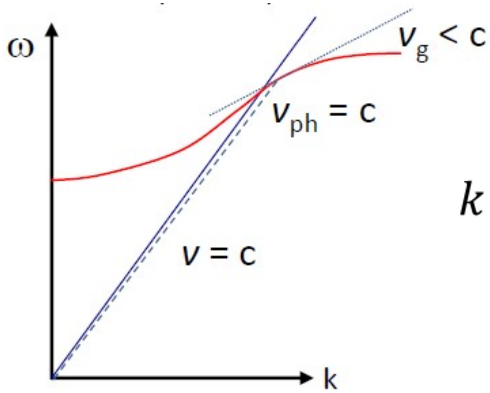




$$k = \frac{\sqrt{\omega^2 - \omega_c^2}}{c}$$

The phase velocity of a waveguide

$$v_p = \frac{c}{\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}} > c$$

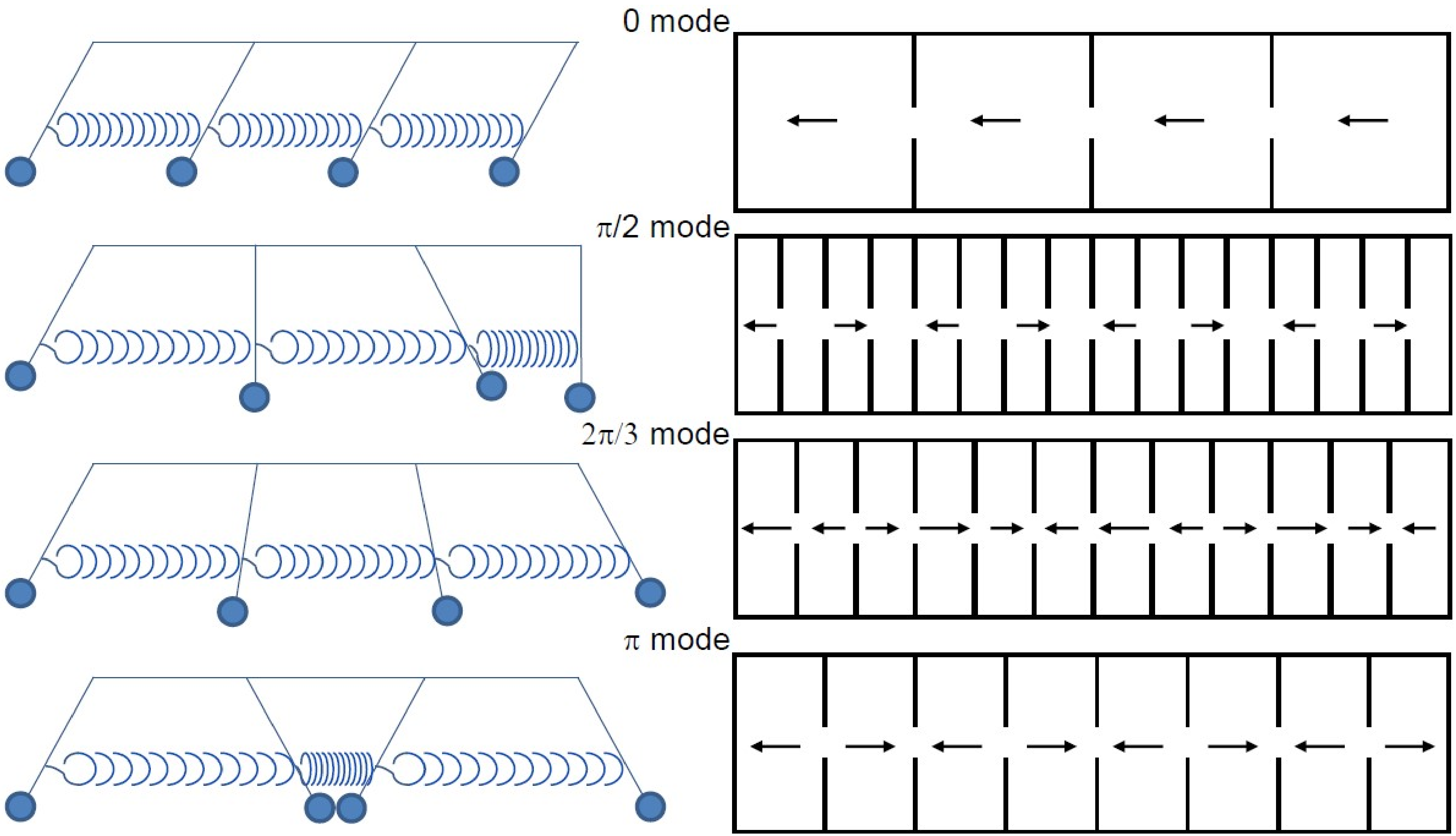


$$k = \frac{\omega_0}{c} + \frac{2\pi n}{d}$$

The phase velocity of a loading structure

$$v_p = \frac{\omega}{\frac{\omega_0}{c} + n\left(\frac{2\pi}{d}\right)}$$

Modes of a Periodic Structure

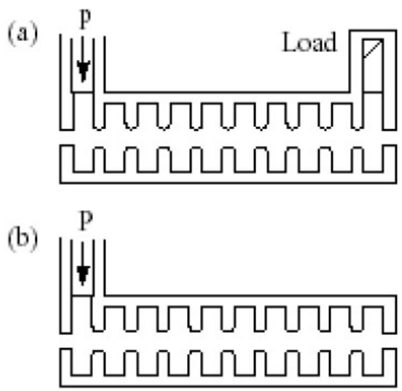


Mode is defined as the "phase shift" or "phase advance" per structure period:

Phase shift / cavity = 2π/(cavity number per wavelength)

Structures of Linac

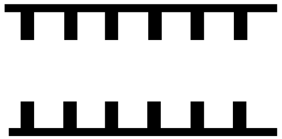
Structure Types



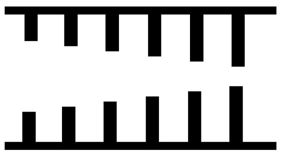
(a) Traveling Wave (TW) Structure

(b) Standing Wave (SW) Structure

- In a traveling wave (TW) structure, the accelerating wave is co-propagating with the particles.
- To keep particles and accelerating wave front synchronous all along the structure, we must have $v_p \approx \beta c$. This is ensured by the irises that "slow down" v_p.
- In a standing wave (SW) structure, Ez is resonating with multiple reflections back and forth.



constant impedance TW



constant gradient TW

- Constant impedance TW structures: electric field decreases exponentially with length. The disc irises have constant radius.
- Constant gradient TW structures : the electric field is constant along the structure. The iris have decreasing radius.

Energy Gain in RF Structures

$$V_{acc}(z) = q\sqrt{2r_L P_0} L \frac{1-e^{-\tau_0}}{\tau_0} \cos\varphi_s$$

Constant impedance TW

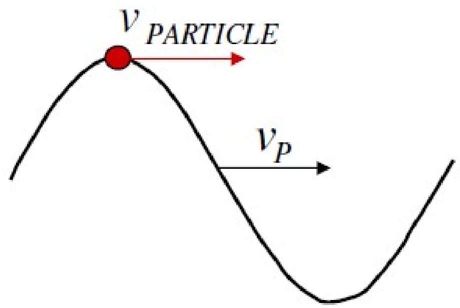
$$V_{acc}(z) = q\sqrt{r_L P_0 L (1-e^{-2\tau_0})}\, cos\varphi_s$$

Constant impedance TW

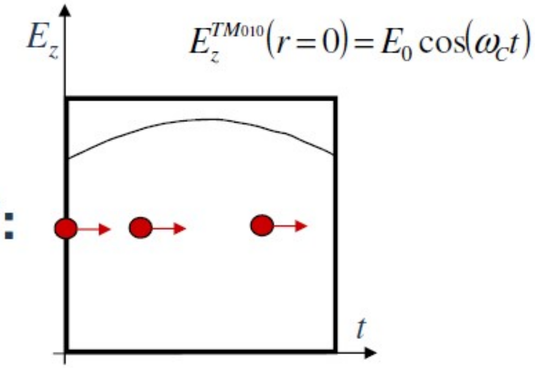
$$V_{acc}(z) = q\sqrt{r_s P_0 L}\, \frac{sin\left(\frac{\omega\lambda_{RF}}{4v_{particle}}\right)}{\left(\frac{\omega\lambda_{RF}}{4v_{particle}}\right)}$$

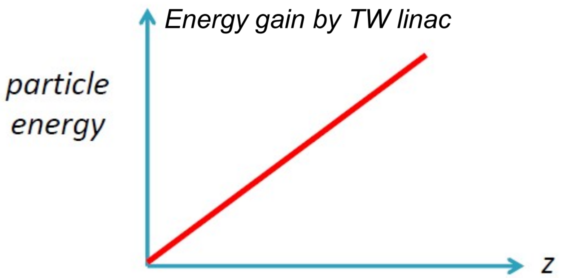
Standing Wave

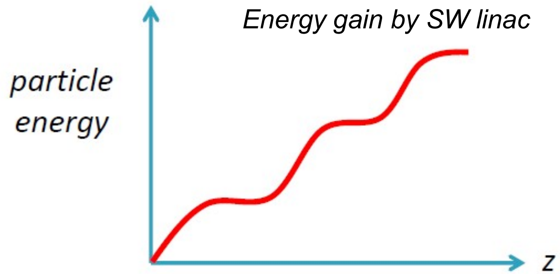
TW:



SW:







Normal Conducting RF Linac

- NCRF linac technology choices
  - Traveling-wave linac
  - Constant-impedance
  - Constant-gradient
  - Standing-wave linac
  - Electrically coupled
  - Magnetically coupled
  - Frequency

- Typical operating conditions
  - Room-temperature copper
  - Pulsed, low repetition rate
  - High gradients at high frequency
  - Requiring high RF power (RF compression)

	S-Band	C-Band	X-Band
	SLAC	XFEL/Spring-8	NLC Test
Klystron	• SLAC 5045 • 65 MW, 3.5 μs, 120 Hz	• Toshiba E3746 • 50 MW, 2.5 μs, 60 Hz	• SLAC XL4 and XL5 • 50 MW, 1.5 μs, 60 Hz
Linac	• CG TW • 20 MV/m, 900 ns	• CG Choke mode • 35 MV/m, 300 ns	• 80 MV/m, 400 ns • 90MV/m, 1.2 μs single cell tests

The 5.2 m constant gradient traveling wave linac structure

Superconducting RF Linac

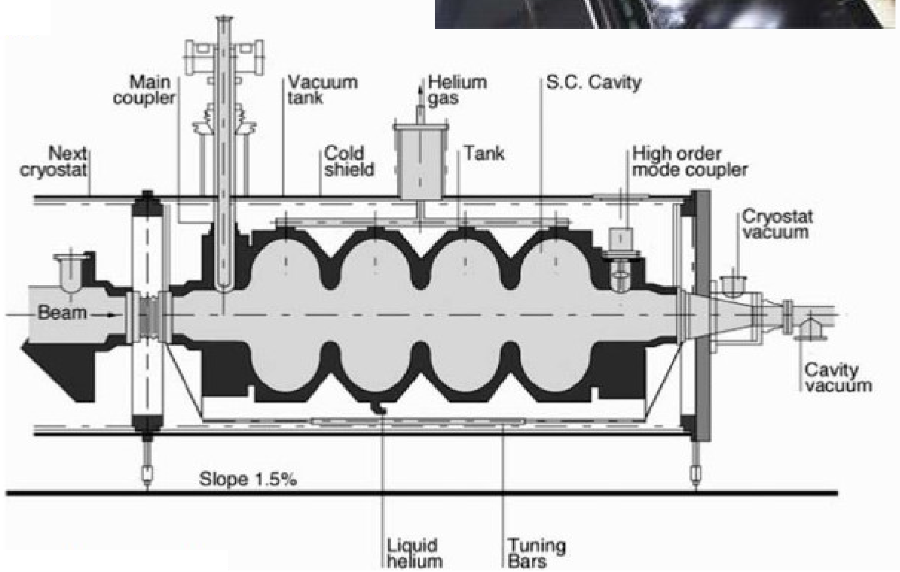
SCRF linac technologies

•The most common material for SCRF cavities is Nb, a type-II superconductor. Nb becomes superconducting at temperature below 9.2K (Tc).

- π mode standing-wave structures
- High average power operation
- Energy recovery is possible
- Liquid He cryogenic system required
- 500, 1300 and 1500 MHz multi-cell structures have been developed (structures at high frequencies are rare)

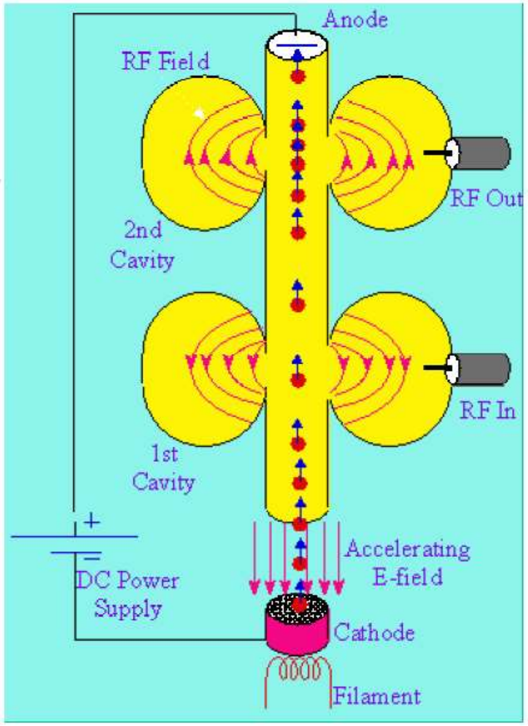
Typical operating conditions

- Liquid-helium cooled niobium
- High repetition rate or CW
- Medium-gradient
- Gradient is limited to lowest performing cells



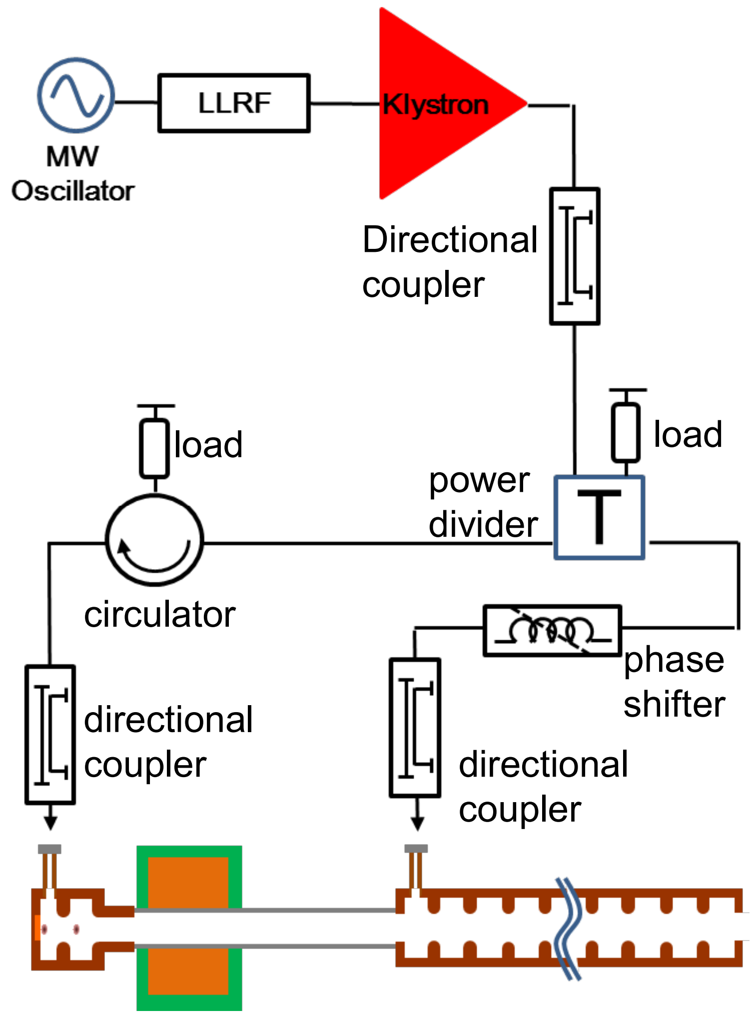
Klystron

- The filament boils electrons off the cathode
- The velocity (or energy) of the electrons is modulated by the input RF in the first cavity
- The electrons drift to the cathode
- Because of the velocity modulation, some electrons are slowed down, some are speed up.
- If the output cavity is placed at the right place, the electrons will bunch up at the output cavity which will create a high intensity RF field in the output cavity
- Klystrons need a minimum of two cavities but can have more for larger gain.



the Thales TH2100A
3 GHz, 35 MW
pulsed klystron

High Power Microwave Systems



- Driver amplifier to power klystron
- Klystron is used to generate high peak power
- Need to transport power to the accelerating structure
- Waveguide is used (under vacuum) to propagate and guide electromagnetic fields
- Windows (dielectric material, low loss ceramic) are used to isolate sections of the waveguide
- Termination loads (water loads) are used to provide proper rf match and to absorb wasted power
- Power splitter is used to divide power in different branches of the waveguide run
- Phase shifter is used to adjust the RF phase

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Beam Diagnostics

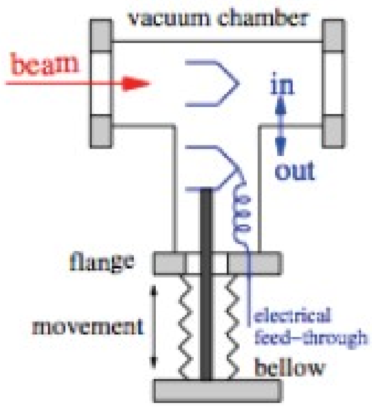
Beam Diagnostics

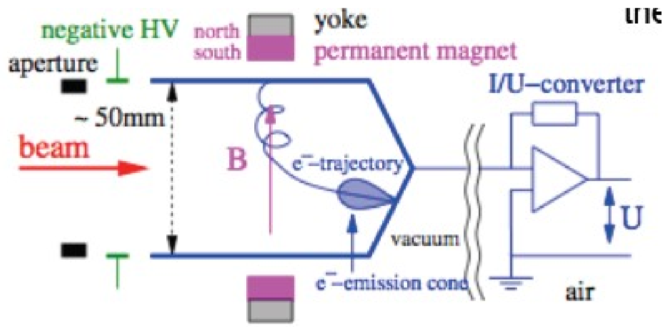
- **Cathode characterization and diagnostic:**
  - QE
    - beam charge measurement
    - Need to measure laser pulse energy
  - Phase Scan
    - Beam charge as function of injection phase in the gun
- **Beam measurements:**
  - Energy and energy spread
    - Dipole
    - Focusing system
    - Imaging system
  - Transverse emittance in space charge regime
    - Slit system
    - Imaging system
  - Transverse emittance in emittance regime
    - Focusing system
    - Imaging system
  - Bunch length measurement
    - Mechanism to induce transverse to longitudinal correlations
    - Imaging system

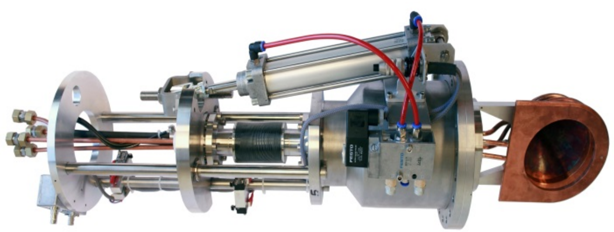
Charge Measurement

Intercepting diagnostic: ***the Faraday cup***

- The FC is a beam stopper that can be inserted when needed in the beamline.
- An isolated metal cup stops the beam. The electron current is *directly* read by a readout electronics connected to the cup.
- Secondary electron production can add systematic errors to the measurements. When electrons hit the cup surface low energy SE can be created. If they exit from the cup they lower the readout (less charge in the cup) .
- To avoid this:
- longer FC
- HV (~100V) at the exit pushing back the SE.
- Solenoid field to create spirals and have the SE hit the wall



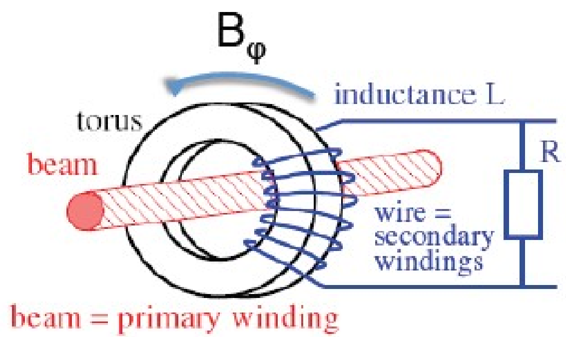




Charge Measurement

Non-Intercepting diagnostic: the ***beam current monitor***

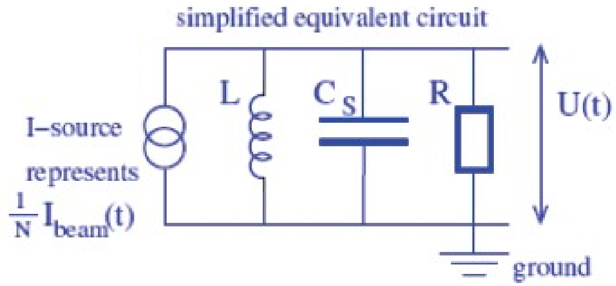
• Beam used as primary winding of a transformer:



$$B_\varphi = \frac{\mu_0 I_b}{2\pi r}$$ Biot Savart

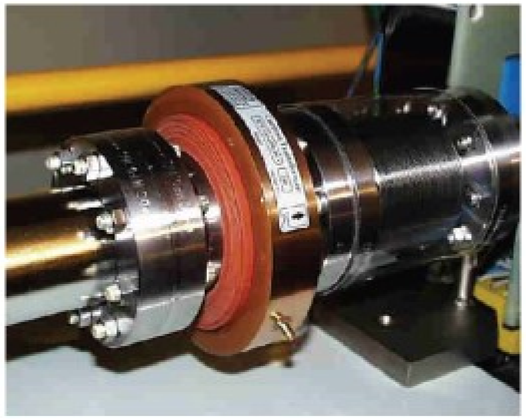
$$I_s = \frac{N_1}{N_2} I_1 = I_b / N_s$$ → low N_s high sensitivity

$$L_s = \frac{\mu_0 \mu_r}{2\pi} ln(\frac{r_{out}}{r_{in}}) \Delta z N^2$$ → low N_s low inductance



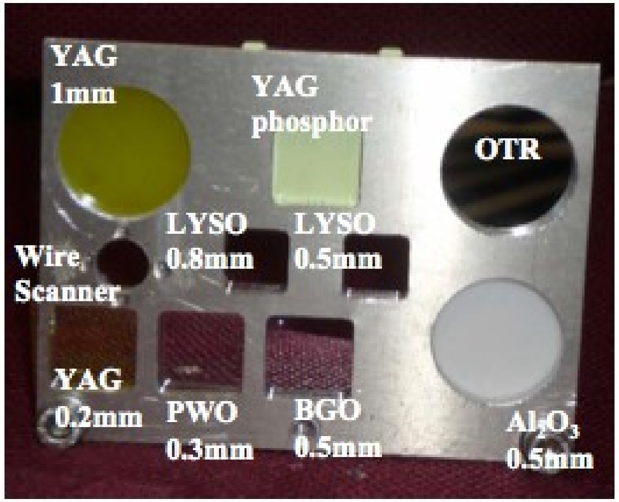
$$Z \to jwL_s, \quad low\ f$$ → need high L_s to measure long bunches
This is in contrast with the sensitivity

$$Z \to 1/jwC_s, \quad high\ f$$ → need low C_s to measure short bunches



Profile Measurement

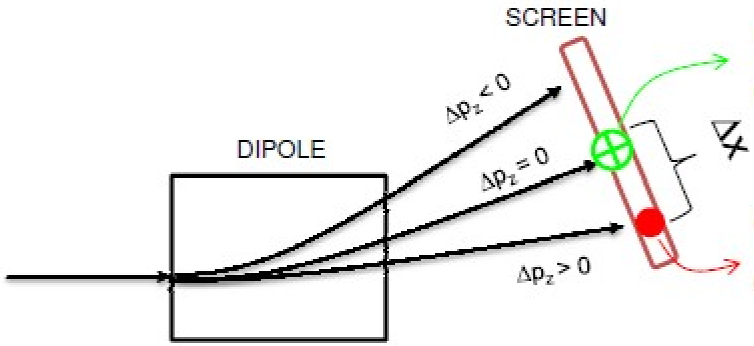
- Destructive Measurement
- Measure current density as function of transverse coordinates
- Must verify screen and detector not saturated
- Common Screen Materials
  - Phosphor
  - YAG
  - OTR
  - Wire scaner



Screen	Resolution	Dynamic Range	Time Response
Phosphor	≈ 50 μm	small	ms
YAG	≈ 20 μm	medium	< ms
OTR	≈ 10 μm	large	fs
Wire	≈ 10 μm	large	ns

Energy Measurement

Mean energy (Spectrometer)



"on-energy" particle centers the screen: $\langle p_z \rangle \left[\frac{GeV}{c}\right] = 0.3 \cdot B_{y,0}[T] \cdot R[m]$

"off-energy" particle follows a different (dispersive) path: $p_z = \langle p_z \rangle \left(1 + \frac{\Delta x}{\eta_x} \right)$

- **How to proceed:**

1. geometry of the ref. trajectory (q, R) is fixed by the mechanical assembly,
2. B_y is chosen to center the beam onto the detector (screen or BPM),
3. calculate $\langle p_z \rangle$.

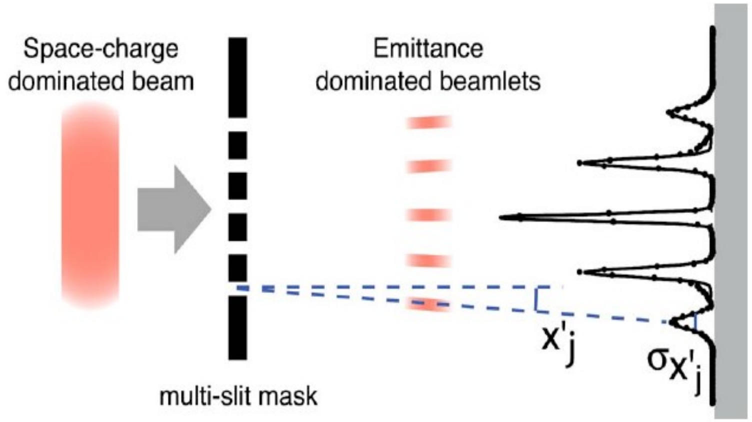
- **Measurement errors:**

• trajectory distortion before / after the dipole magnet,
• dipole field calibration errors (vs. the supplying current),
• misalignment of the dipole / detector.

Typical error is of the order of 1 MeV at energies higher than tens of MeV.

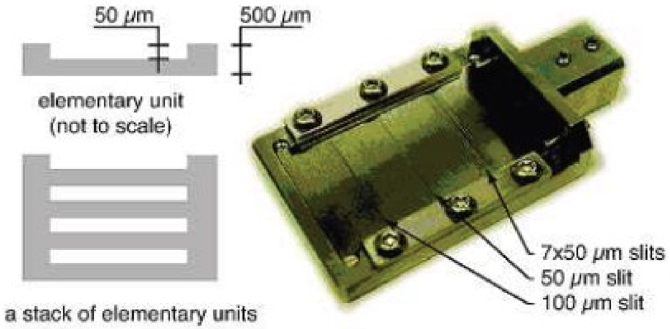
Multi-slit or Pepper Pot

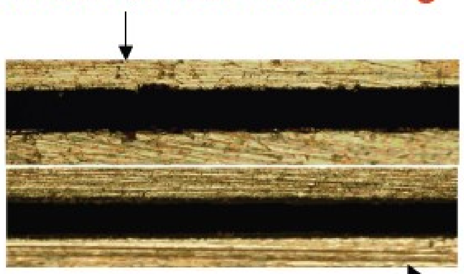
- To measure emittance requires emittance dominated beam
- Space charge dominated beam must be converted to emittance dominated
- N measurements made simultaneously
- Measure angle and spread downstream of slit on a screen as a function of slit position

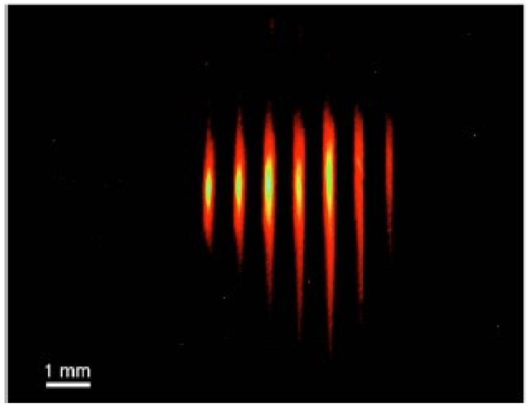


$$\epsilon_x{}^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2$$

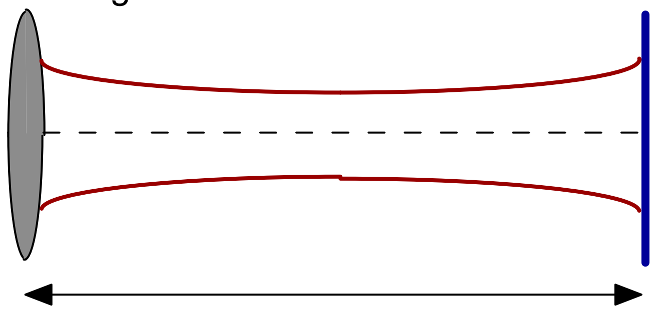
$$\approx \frac{1}{N^2}\left\{\left[\sum_{j=1}^{p} n_j\left(x_{sj}-\bar{x}\right)^2\right]\left[\sum_{j=1}^{p}\left[n_j\sigma_{x_j'}{}^2 + n_j\left(\overline{x_j'}-\bar{x}\right)^2\right]\right] - \left[\sum_{j=1}^{p} n_j x_{sj}\overline{x_j'} - N\bar{x}\overline{x'}\right]^2\right\}$$







Quadrupole Scan



- Neglecting space charge we can write an equation for σ^2 based on the Twiss parameters of the beam.

$$\sigma_2^2 = \varepsilon\left(\beta_1 - 2\alpha_1 L + L^2\gamma_1\right) - \frac{\varepsilon}{f}\left(2L\beta_1 - 2L^2\alpha_1\right) + \frac{\varepsilon}{f^2}\left(L^2\beta_1\right)$$

- The procedure then, is to measure σ^2 (the mean square beam size) versus the focal length of the lens and fit the resulting curve to calculate the emittance.

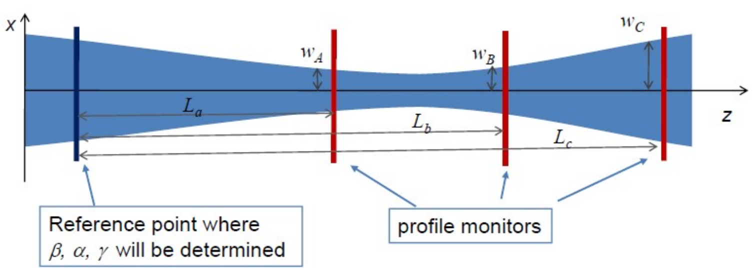
Measure projected emittance only

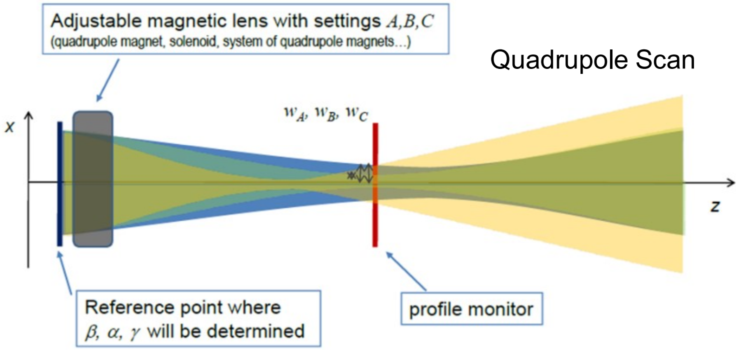
Emittance Measurement

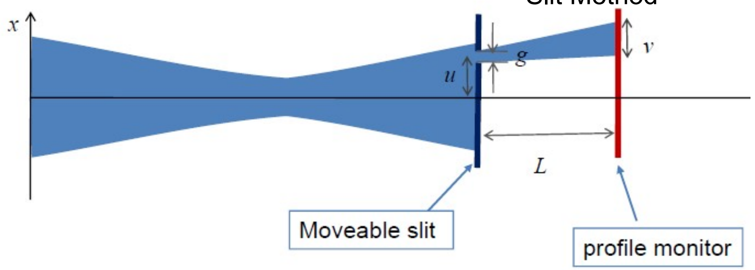
- Quadruple scan for high energy beam when linear beam optics is valid, i.e. when space charge forces are small and energy spread is not too large

- Slit method for low energy beam when space charge forces are small, and beam can be stopped by the slit mask

	High Energy	High Space Charge Force	Large Energy Spread
3 Screen	+	-	+
Quadruple Scan	+	-	-
Slit	-	+	+







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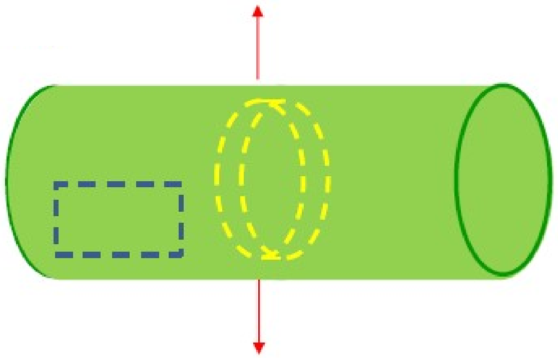
Space Charge Emittance Compensation

Transverse Space Charge

Consider a cylindrical electron bunch with current *I, uniform charge and current density r and J:*

$$\rho = \frac{I}{\pi a^2 \upsilon_z} \qquad J = \frac{Ir}{\pi a^2}$$



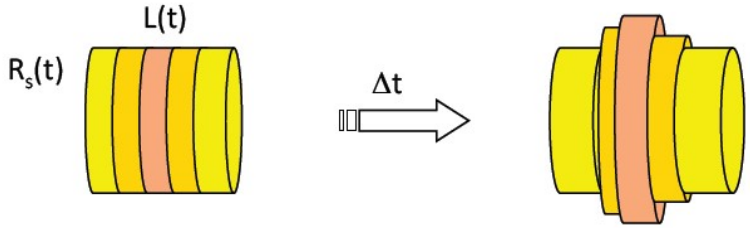
Transverse space charge fields for *r < a:*

$$E_r = \frac{1}{2\varepsilon_0}\rho r \qquad B_\theta = \frac{\mu_0}{2} J r = \frac{\upsilon_z}{c^2} E_r$$

Lorentz force

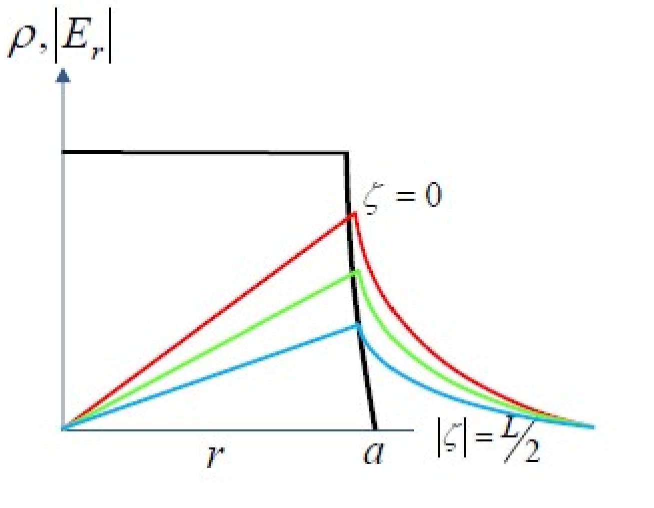
$$F_r = -e\left[E_r - \upsilon_z B_\theta\right] = -eE_r\left(1-\beta^2\right)$$

$$F_r = -\frac{eE_r}{\gamma^2}$$

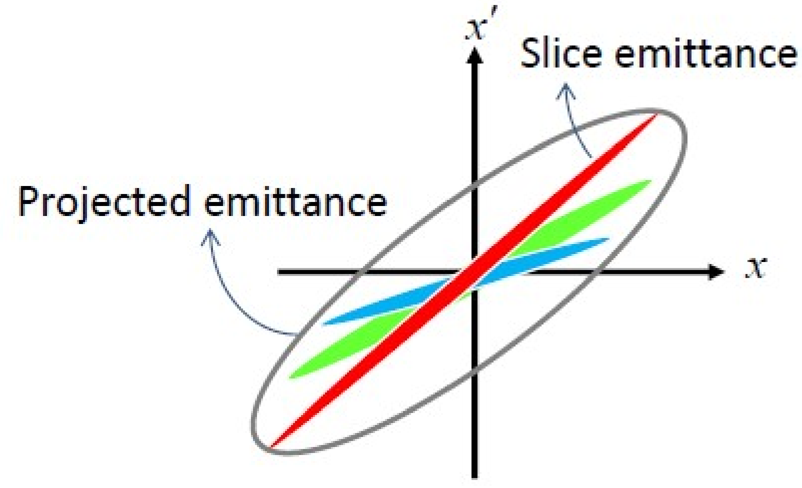


Transverse SC force scales with $1/\gamma^2$

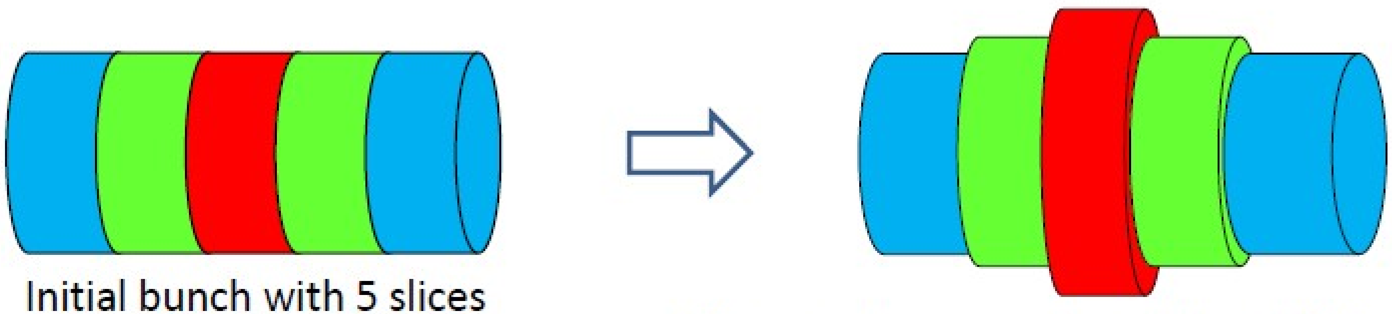
Space Charge Emittance



Transverse force is highest at $\zeta = 0$



Trace-space plots



Initial bunch with 5 slices

Different slices expand radially at different rates

Solenoid Induced Emittance Oscillation

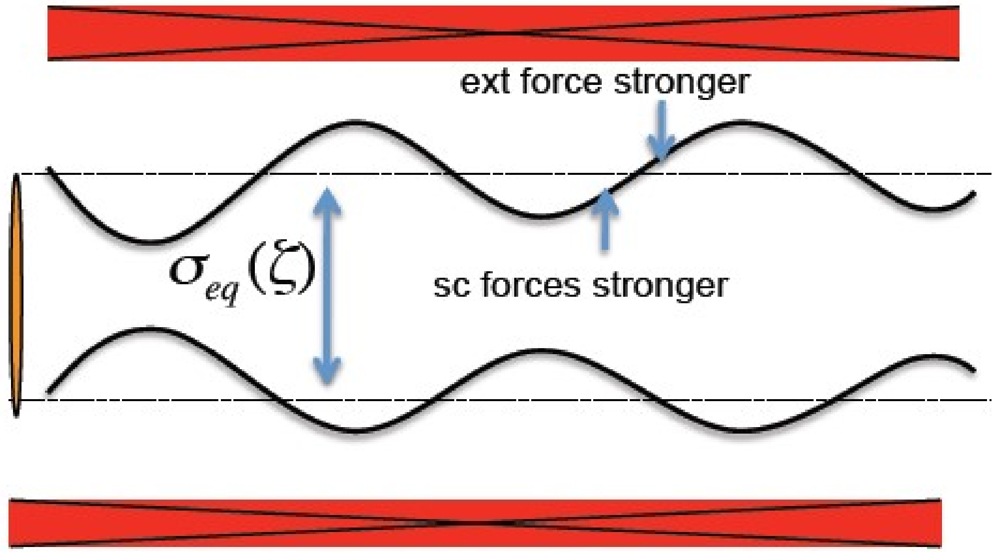
Consider now the *envelope equation in a long solenoidal focusing channel*. The beam is strongly space charge dominated and the emittance term can be neglected:

$$\sigma_r'' + K_r \sigma_r - \frac{K(\zeta)}{\sigma_r} = 0$$

The equilibrium solution:

$$\sigma_r'' + \sigma_r (K_r - \frac{K(\zeta)}{\sigma_r^2}) = 0$$

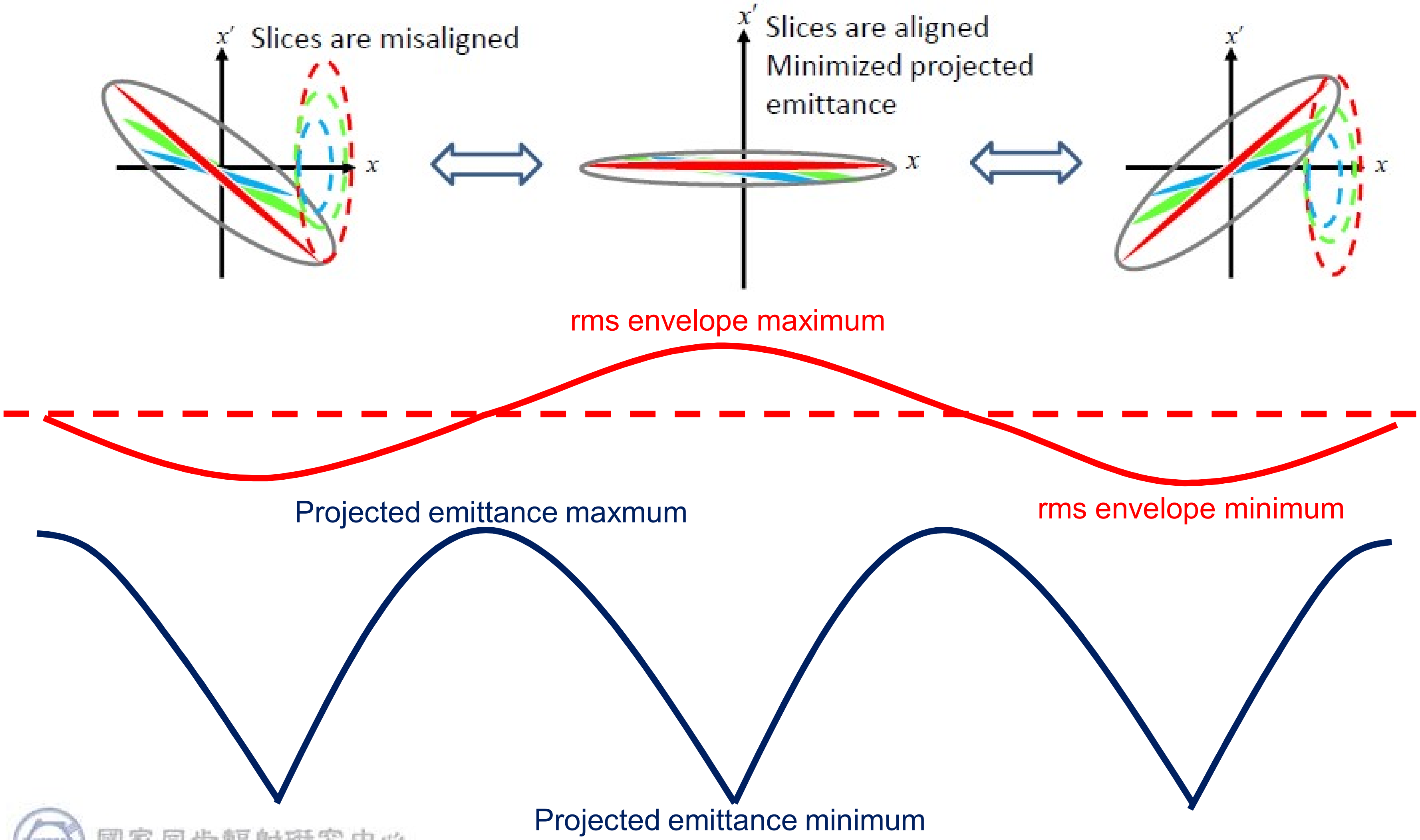
$$\longrightarrow \quad \sigma_{eq}(\zeta) = \sqrt{\frac{K(\zeta)}{K_r}}$$



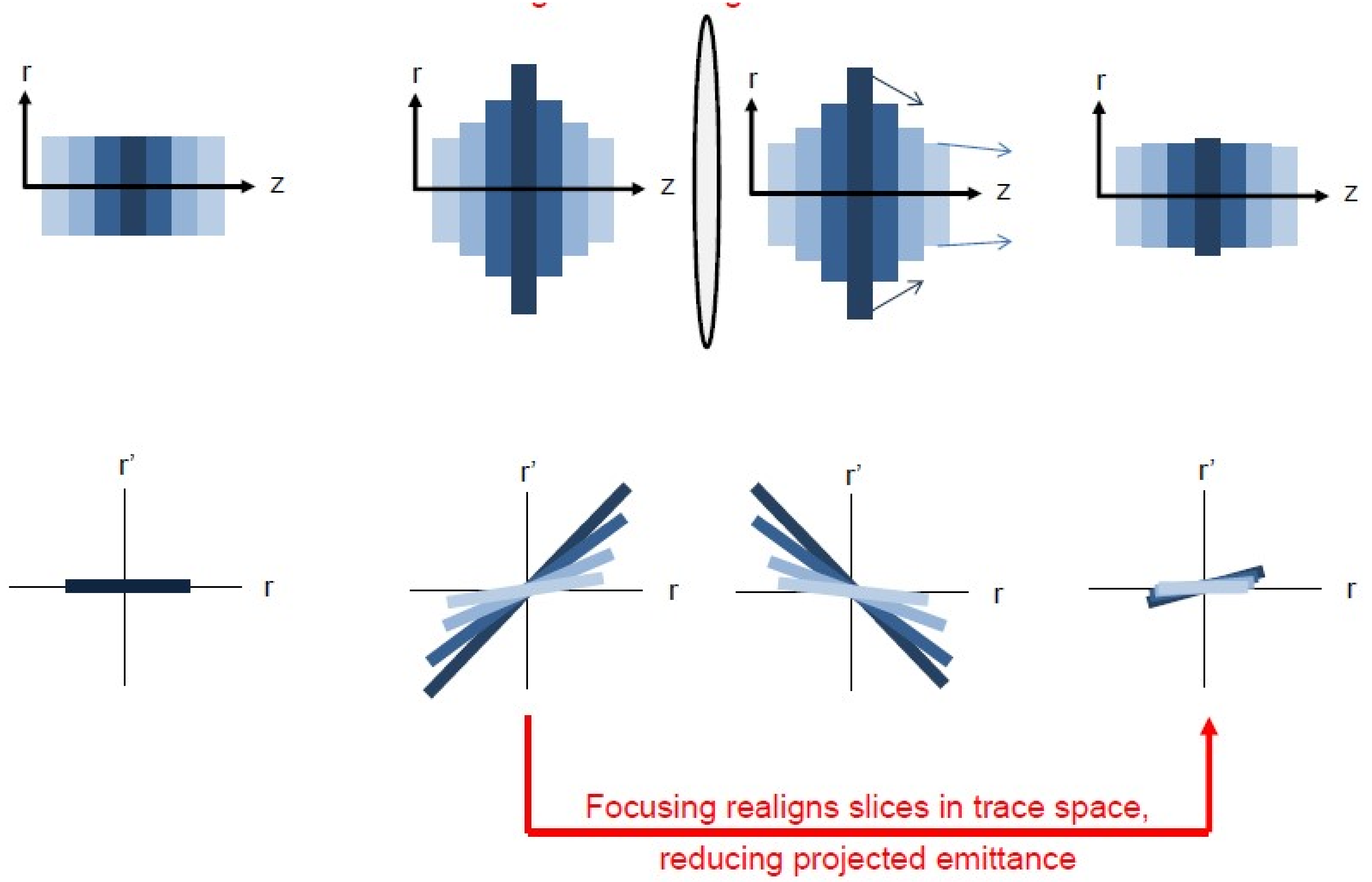
Solenoid wave number:

$$K_r = \frac{qB}{2mc\beta\gamma}$$

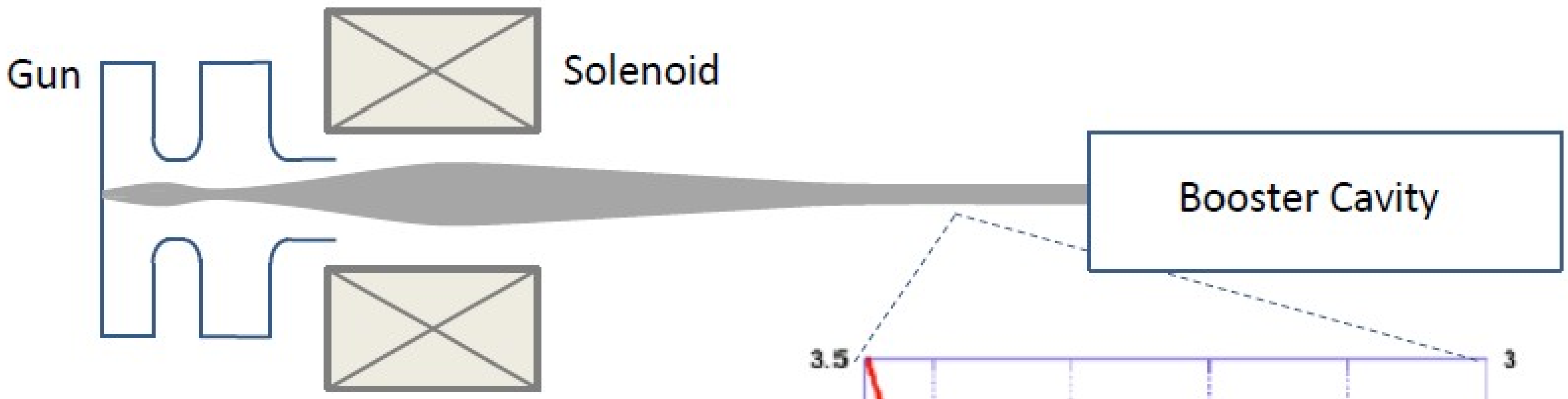
Envelope and Emittance Oscillation



Emittance Compensation



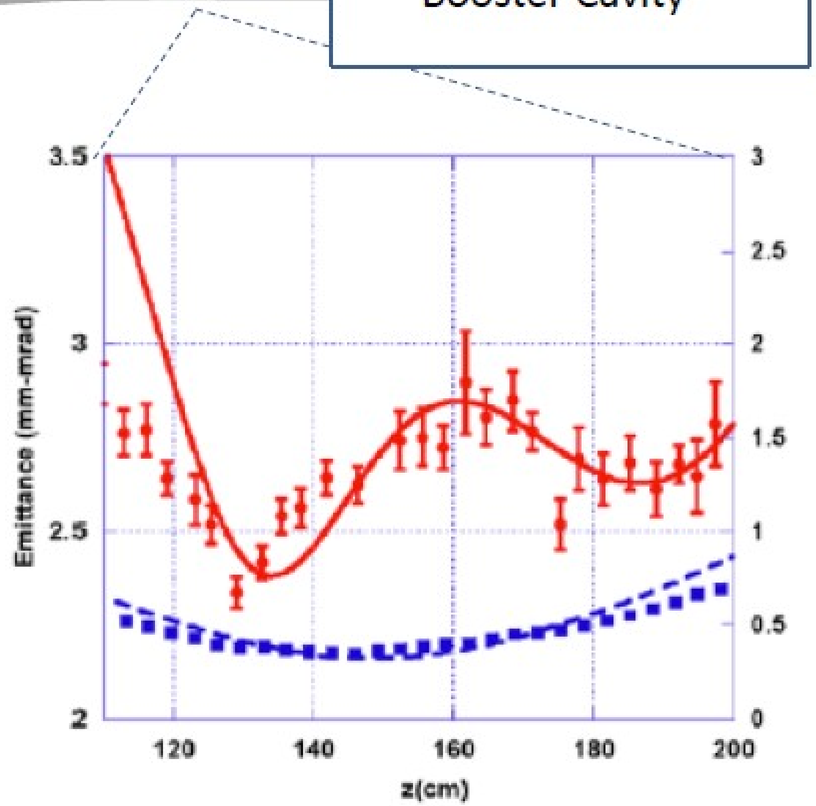
Emittance Double Minima



Emittance oscillations produce two emittance minima after the solenoid.

This behavior has been seen in many particle-tracking simulations and experimentally observed at the SPARC photoinjector in Italy.

Ferrario et al., PRL 99, 234801 (2007)



Matching to Linac

- How can be keep the low emittance obtained, preventing the oscillations to start again with a consequent emittance growth? Can we freeze the oscillations exactly in the point we want?

  The answer is: ***by acceleration.***

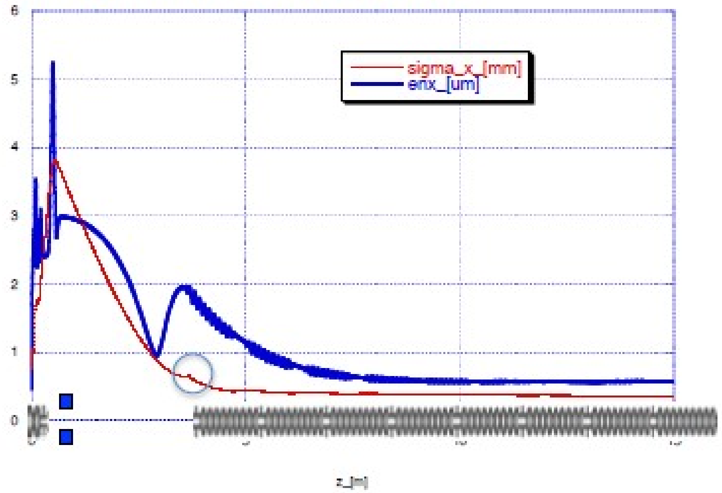
- Is there an optimum injection condition?

  Yes, it is called the ***invariant envelope.***

The invariant envelope matching condition into the Linac:

$$\sigma_{in} = \frac{2}{\gamma'}\sqrt{\frac{I_p}{2I_0\gamma}} \qquad \sigma'_{in} = -\frac{\gamma'}{2\gamma}\sigma_{in}$$

The beam is naturally matched in a waist!



$$\sigma' = 0; \qquad \gamma' = \frac{2}{\sigma}\sqrt{\frac{\hat{I}}{2I_0\gamma}}$$

$$\gamma' = \frac{eE_0}{mc^2}$$

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National Synchrotron Radiation Research Center

Thanks for your attention!

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