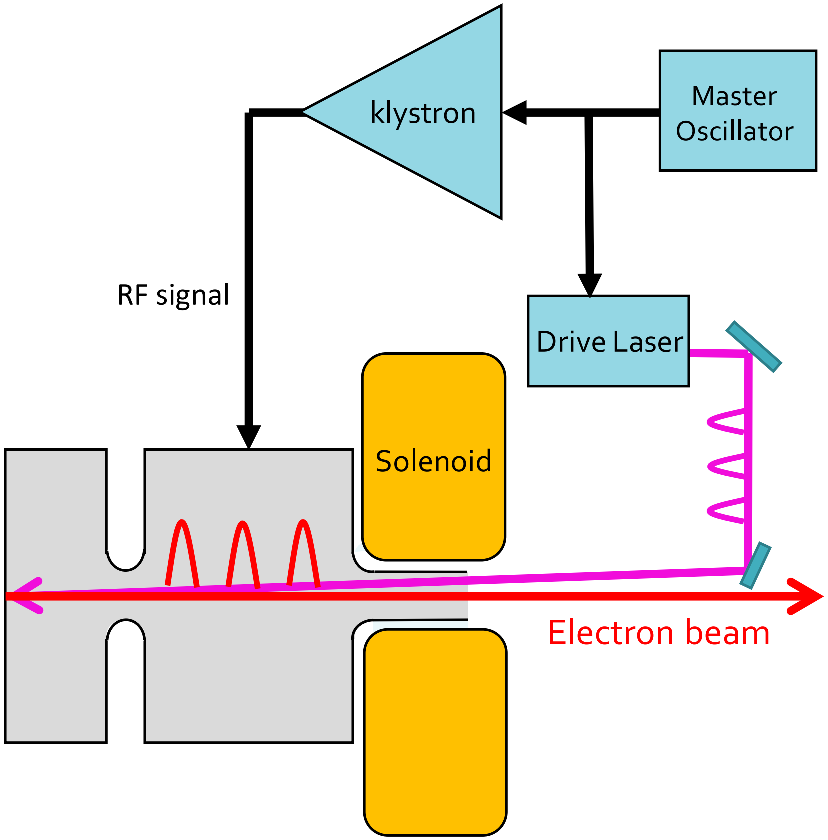
Experience #1:
RF characterization of an Aluminum model of the ELI-NP S-band RF-Gun

RF photocathode electron Gun

- Electrons are generated by photoelectric effect.
- Very short pulse laser strikes a metallic photocathode, which is embedded in an electromagnetic accelerating structure.
- SW structure composed by two RF cavities
- The emitted bunch of electrons is trapped and accelerated by the em field in the device (accelerating em field from the klystron and solenoidal magnetic field from the solenoid)
- Employ fast laser pulses to produce bunch-trains. Picosecond bunches can be formed at the RF repetition rate, easing the following electron-bunching structure system
- The ratio of the number of electrons emitted per incident photon is called Quantum Efficiency (Q_e) which is a function of the photon energy. For metals, the minimum-energy photons are typically in the ultraviolet range (λ(Cu) < 267nm).

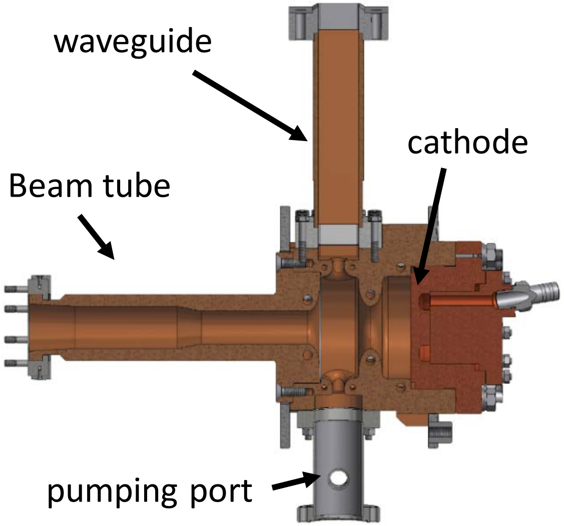


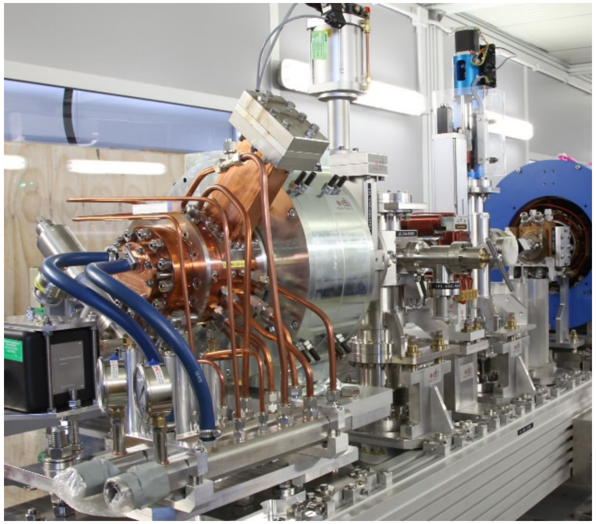
ELI-NP Linac RF electron Gun

1.6 cell photoinjector of the BNL/SLAC/UCLA type with new features:

- elliptical shaped irises with larger aperture
- Symmetric port to compensate the dipole field component
- coupling hole rounded to **reduce** the **pulsed heating**
- **cooled cathode**
- fabrication **without brazing** using the clamping gasket technique

RF frequency	GHz	2.856
Rep. Rate	Hz	100
Working Mode	π mode (SW)	
Max Rf input power	MW	16
RF peak field at the cathode	MV/m	120
Average dissipated power	kW	1.5
Unloaded Q factor	14500	
Coupling coefficent β	3	
Working temperature	°C	33 - 34
Filling time	ns	420
Shunt Impedance	MΩ/m	1.64
Type of cathode	copper	

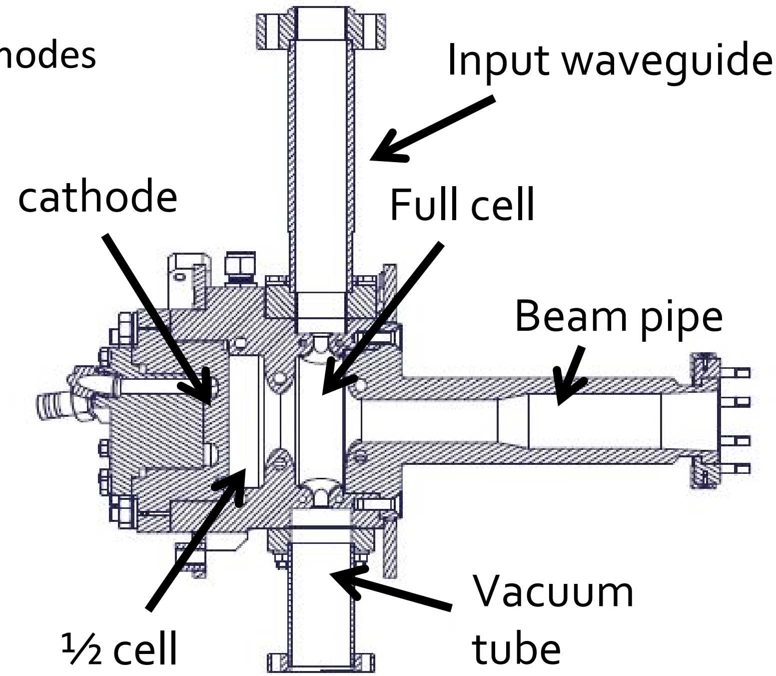


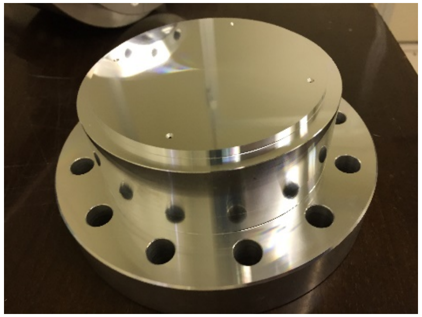


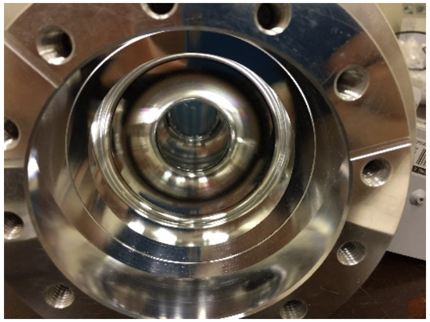
RF electron Gun Alluminum Prototype

Two cavities coupled together -> Two resonant modes
The π mode is used as accelerating mode

Main Parameters	π-mode	0-mode
Mode frequency		
Freq. separation		
Input coupling coeff. (β)		
Q_L		
Q_0		
R/Q factor		-
Filling time		-

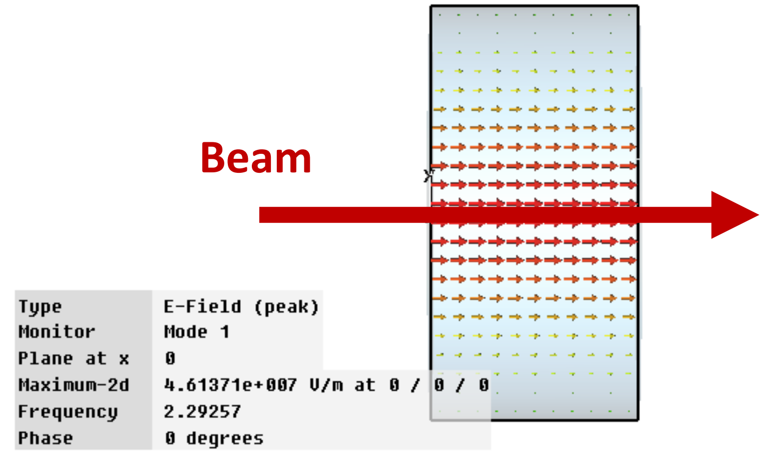


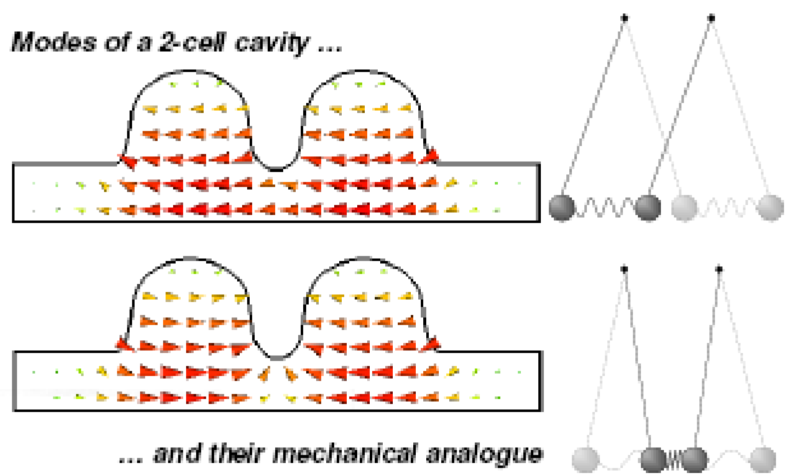




Cavity and multi-cell cavity

- Almost every RF cavity operates using the TM_{010} accelerating mode.
- This mode has a longitudinal electric field in the centre of the cavity which is suitable for particle acceleration.
- In general to have a more efficient acceleration more cavities are coupled together.
- The N-cells structure obtained behaves like a system composed by N oscillators coupled together.





Slater theorem

For a cavity on resonance, the electric and magnetic stored energies are equal. If a small perturbation is made on the cavity wall, this will generally produce an imbalance of the electric and magnetic energies, and the resonant frequency will shift to restore the balance. The Slater perturbation theorem describes the shift of the resonant frequency, when a small volume ΔV is removed from the cavity of volume V. The general result is

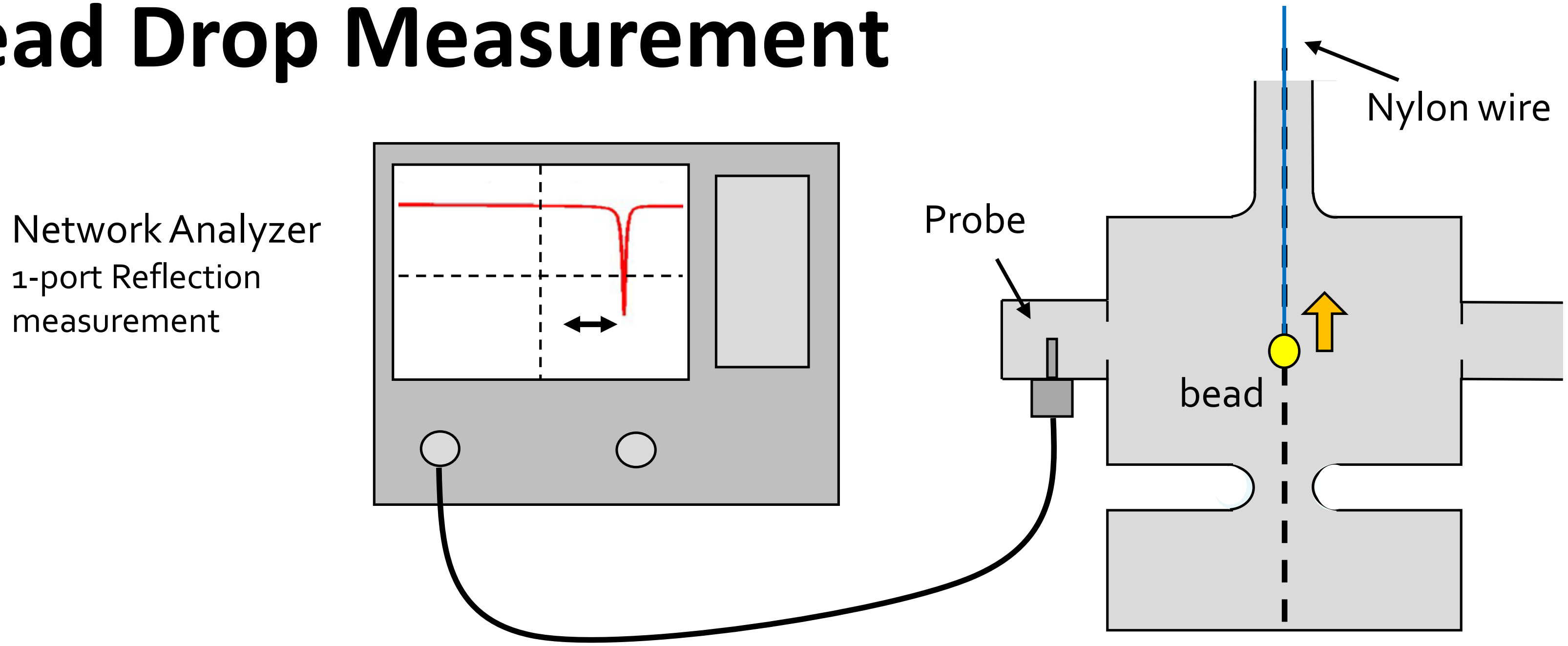
$$\frac{\omega_{pert}-\omega_0}{\omega_0}=\frac{\int_{\Delta V}\left(\mu H^2-\varepsilon E^2\right)d\tau}{\int_{V}\left(\mu H^2+\varepsilon E^2\right)d\tau}=\frac{\Delta U_H-\Delta U_E}{U}$$

Where U is the total stored energy.

This theorem can be used also to measure the field profiles in the cavity by inserting a perturbing object and measuring the frequency shifts while moving it along selected paths. The theorem mathematical expression is different in this case and form factors need to be introduced because field lines are strongly deformed in this case, while they are almost unperturbed when the boundary is slightly deformed.

$$\frac{\omega_{pert}-\omega_0}{\omega_0}=\frac{1}{4U}\int_{\Delta V}\left(k_{B_\parallel}\mu B_\parallel^2+k_{B_\perp}\mu B_\perp^2-k_{E_\parallel}\varepsilon E_\parallel^2-k_{E_\perp}\varepsilon E_\perp^2\right)d\tau$$

Bead Drop Measurement



If the perturbing object (bead) is a perfectly conducting sphere the values of the form factors are:

$$k_{E_{\parallel}} = k_{E_{\perp}} = 3\,; \qquad k_{B_{\parallel}} = k_{B_{\perp}} = \frac{3}{2}$$

If a sphere of radius a is moved along the beam axis of a cavity the E field profile and the R/Q of a resonant accelerating mode can be estimated according to:

$$E^2 \approx \left|\frac{(\omega_{pert} - \omega_0)}{\omega_0}\right| \frac{U}{\varepsilon\pi a^3} \qquad \frac{R}{Q} = \frac{1}{2\pi\omega_0\varepsilon a^3}\left|\int_L \sqrt{\left|\frac{(\omega_{pert} - \omega_0)}{\omega_0}\right|}\, sign(z) e^{j\omega_0 z/c} dz\right|^2$$

Sign of the E-field profile

Summary:

1. RF Gun characterization in reflection with Network Analizer

    - Localize the two resonating modes (no calibration needed) measuring the S11 in reflection (NA settings: f_{start}=2.8GHz f_{stop}=2.86GHz)
    - Estimate the frequency separation between the two modes.
    - Measure the resonant frequency and the $S11|_{fres}$ (calibration needed) and compute the coupling factor β for the two modes (NA settings: $f_{center}=f_{res}$ span=4MHz) (NOTE: the π-mode is overcoupled β>1, the 0-mode is undercoupled β<1)

2. RF Gun characterization in transmission with Network Analizer

    - Measure the S21 of the device and using the «Bandwidth» function (Marker Search -> Bandwidth) measure the Loaded Quality Factor Q_L
    - Calculate the Unloaded Quality Factor Q_0

3. Longitudinal electric field profile measurement with "bead-drop" technique (mode π):

    - Ticks drawn on the nylon wire are equally spaced every 5 mm
    - Fill a spreadsheet with: bead position (z [m]) and measured f_{res}
    - Calculate and plot (f-fres)/fres vs z;

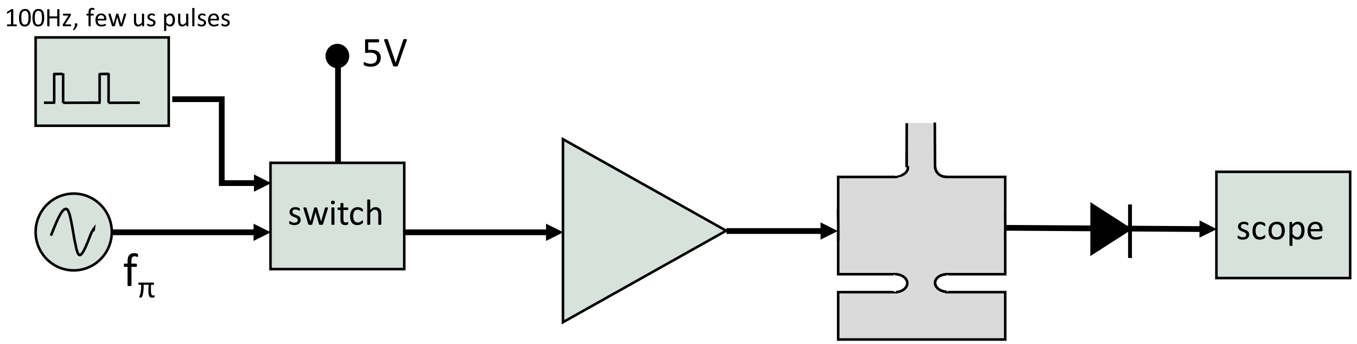
4. Accelerating voltage and R/Q calculation:

- ❑ From the spreadsheet, calculate R/Q (Note: The spherical bead radius is a=0.0018m, ε=8.85418781762E-12, c=299792458)

5. Filling time measurement (time domain with realistic RF pulse)

- ❑ The filling time, is the time for the energy stored in the cavity with loaded Q = Q_L to build to 1/e of its saturation point

- ❑ Connect the RF signal generator through a switch and an amplifier to the Gun and read the output probe through the oscilloscope



- ❑ Measure the filling time τ of the gun. Compare it with the one evaluated from Q_L.

6. Longitudinal electric field profile measurement with "bead-drop" technique (mode 0)

- ❑ Repeat the procedure of point 3 for the 0 mode

Useful Formulae and definitions

Accelerating voltage on axis

$$V = \left| \int_L \hat{E}_z(z) e^{j\omega_0 z/c} dz \right|$$

Loaded Q factor

$$Q_L = \omega_0 \frac{U}{P_{diss}} \rightarrow Q_L = \frac{\Delta\omega_0|_{3\ dB}}{\omega_0}$$

Cavity filling time

$$\tau = \frac{2Q_L}{\omega_0}$$

External Q factor

$$Q_{ext} = \omega_0 \frac{U}{P_{out}}$$

Unloaded Q

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \rightarrow Q_0 = (1+\beta) Q_L$$

Coupling coefficient β

$$\beta = \frac{Q_0}{Q_{ext}} = \frac{P_{out}}{P_{diss}} \cong \begin{cases} \dfrac{1+\rho}{1-\rho} & if\ overcoupled \\ \dfrac{1-\rho}{1+\rho} & if\ undercoupled \end{cases}$$

R/Q and Accelerating field from the perturbation measurement

$$E^2 \approx \left| \frac{(\omega_{pert} - \omega_0)}{\omega_0} \right| \frac{U}{\varepsilon \pi a^3}$$

$$\frac{R}{Q} = \frac{1}{2\pi\omega_0 \varepsilon a^3} \left| \int_L \sqrt{\left| \frac{(\omega_{pert} - \omega_0)}{\omega_0} \right|} sign(z) e^{j\omega_0 z/c} dz \right|^2$$