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U.S. DEPARTMENT OF ENERGY

MSU/FRIB | Accelerator Physics/Engineering Seminars (APES)

Superconducting Radiofrequency Photoinjectors: a quest for high-brightness CW electron beams

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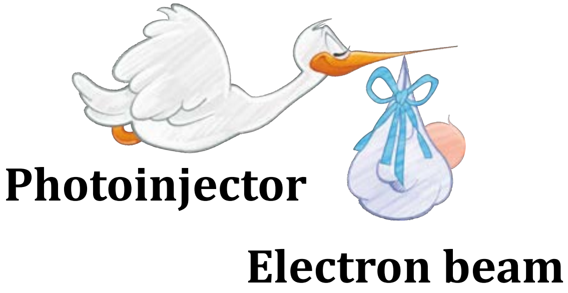
Outline

- Where do electron beams come from and why do we want to build an SRF gun?
- The essential components of an SRF gun and how to make the right choice of the components.
- Overview of the existing SRF guns.
- Case Study: BNL 113 MHz SRF gun.

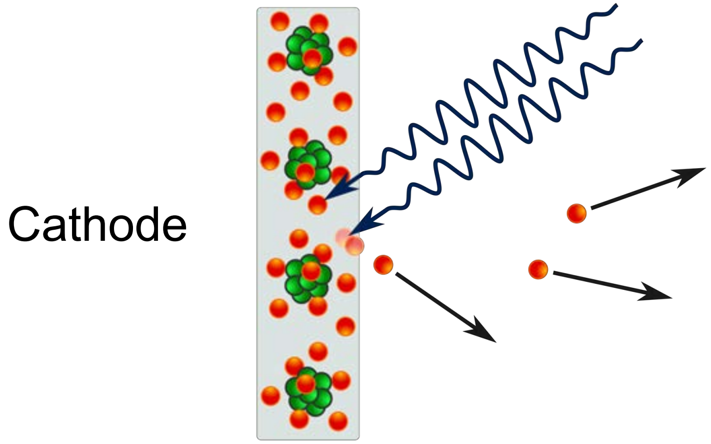
Where do electron beams come from?



The **photoelectric effect** is the emission of *electrons* when electromagnetic radiation, such as *light*, hits a material. Electrons emitted in this manner are called **photoelectrons.**

Quantum efficiency (QE) is a ratio of the number of electrons emitted to the number of incident photons.

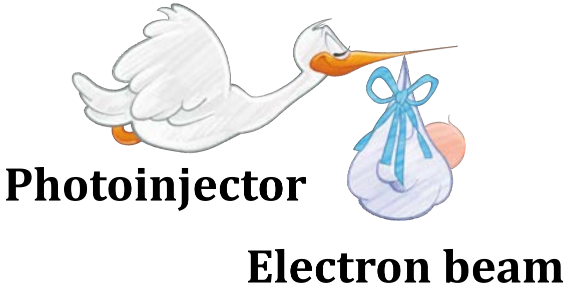
$$QE = \frac{\text{number of emitted electrons}}{\text{number of incident photons}}$$



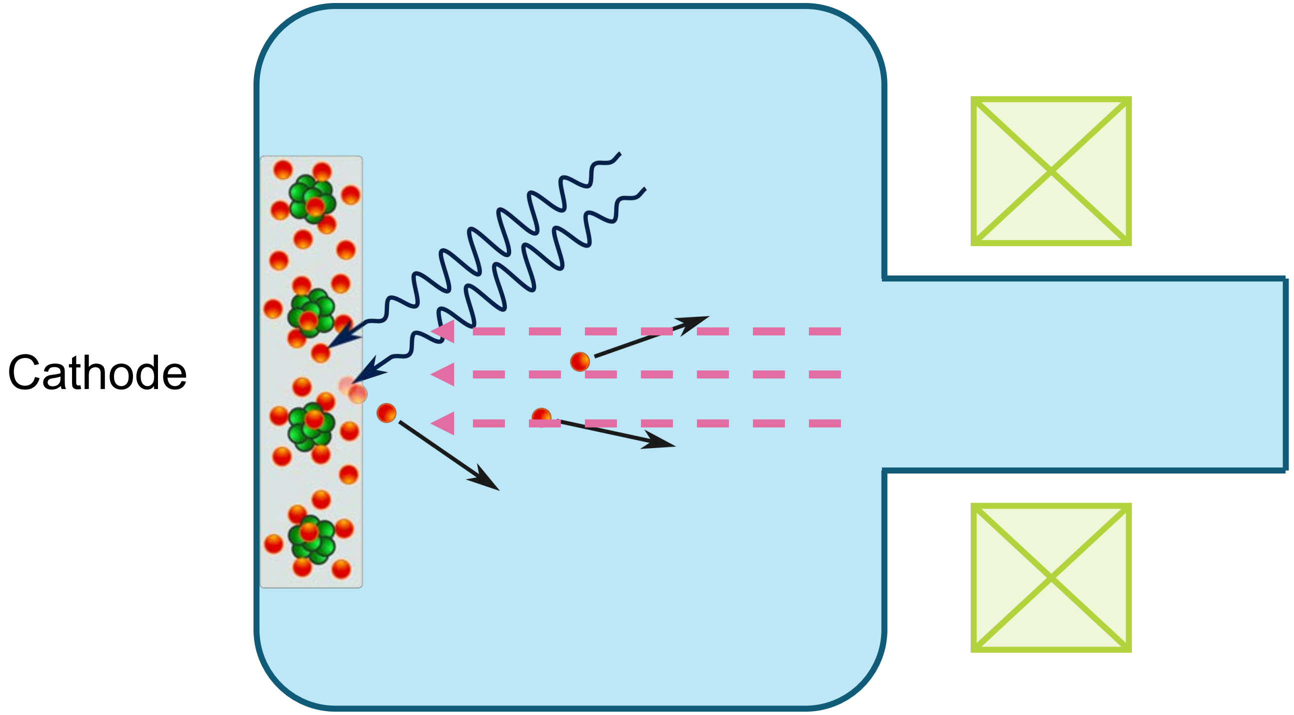
The E_{MTE} is **the mean of the squared momentum in a direction along the photocathode's surface**.

$$E_{\mathrm{MTE}} = \frac{p_\perp^2}{2m_e}$$

Where do electron beams come from?



Photocathode + Laser + Accelerating Cavity = Photoinjector



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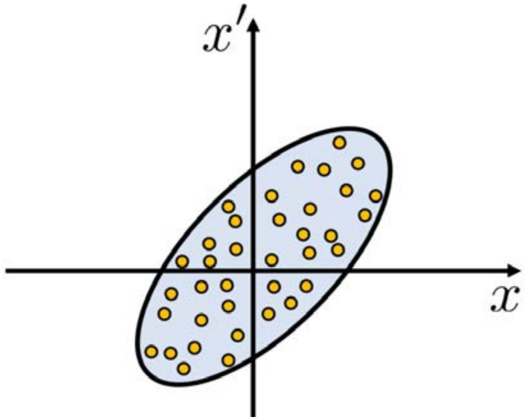
What are our goals in designing an electron gun?

Beam charge:

the value of the **electric field at the surface of the photocathode**, $E_{\rm em}$, defines the **maximum charge density**, σ, of the generated electron bunches.

$$\sigma = \frac{E_{\rm em}}{4\pi}$$

Beam emittance (ε) – measure of the area occupied by a beam in phase space.



$$\varepsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}, \text{ with}$$

$$\langle x^2\rangle = \sigma_x^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)^2,$$

$$\langle x'^2\rangle = \sigma_{x'}^2 = \frac{1}{N}\sum_{i=1}^{N}(x'_i - \langle x'\rangle)^2,$$

$$\langle xx'\rangle = \sigma_{xx'} = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)(x'_i - \langle x'\rangle).$$

Normalized emittance (ε_n): $\varepsilon_n = \varepsilon\gamma\beta$

We want to minimize the emittance of our electron beam!

Example: for the new generation XFELs we want 100 pC, 8 ps bunches with ε_n<0.4 mm-mrad!

What are our goals in designing an electron gun?

Beam emittance:

emittance of the beam extracted from a photoinjector depends on the value of the **electric field at the cathode** at the moment of emission, E_{em} , and **the bunch shape**:

Pancake-shaped beam

$$\varepsilon_n \propto \sqrt{q \frac{E_{MTE}}{E_{\mathrm{em}}}}$$

Cigar-shaped beam

$$\varepsilon_n \propto \frac{\sqrt{E_{MTE}}}{E_{\mathrm{em}}} \left(\frac{q}{\Delta t}\right)^{2/3}$$

ε_n — normalized transverse emittance
q — bunch charge
Δt — bunch length

The goal #1 is to increase the electric field at the cathode surface

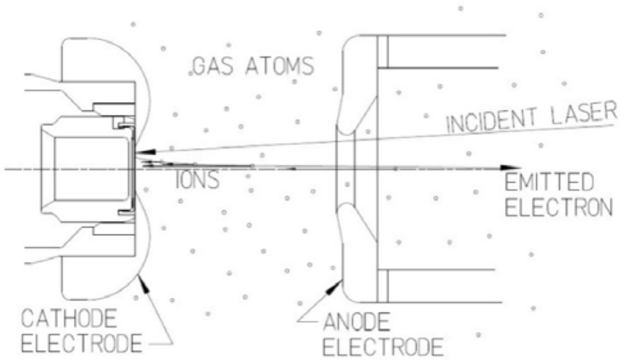
Space charge:

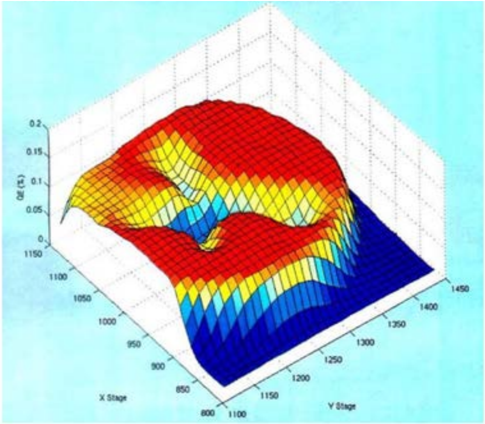
“self-fields” produced by the electron bunch itself and are responsible for emittance degradation.

$$F_{\mathrm{sc}} \propto \gamma^{-3}$$

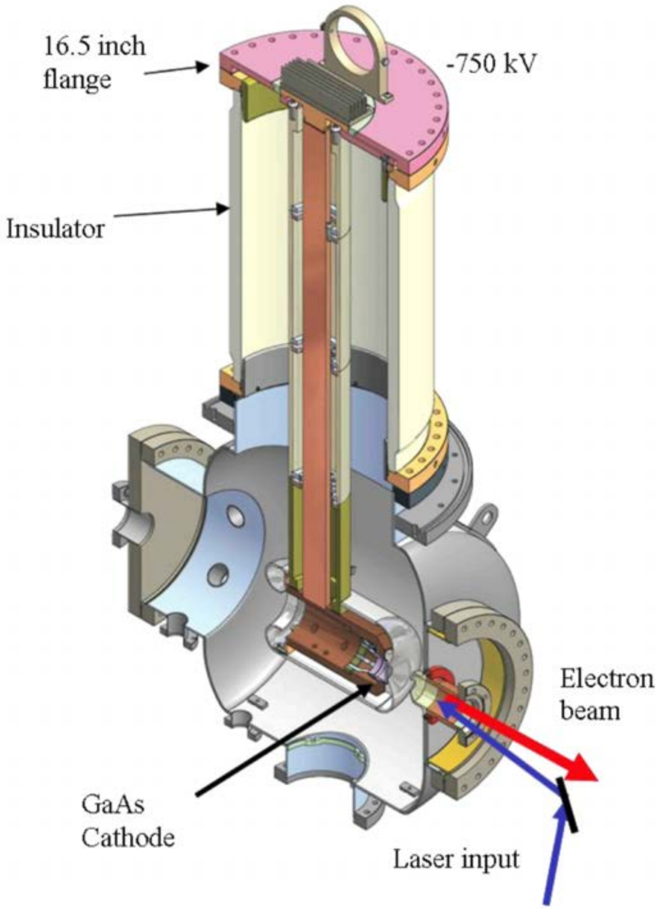
The goal #2 is to accelerate the beam to higher energies fast

Photoinjector: Option # 1 DC gun





Cornell 750 kV DC gun



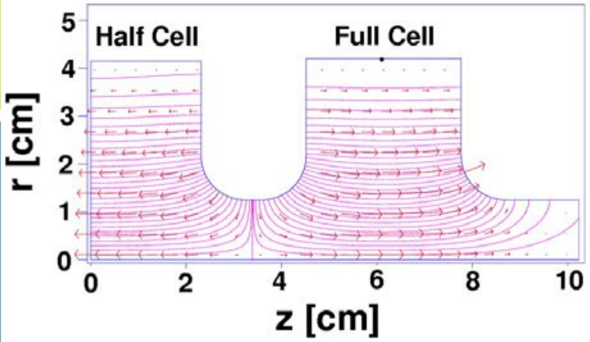
+ Well **established**, can **produce good quality beams.**
- Gun **voltage is limited to about 0.25-0.4 MV**
  - Continuous **dark current**.
  - Electrical **breakdown**.
- Limitations in voltage results in E_{em} **< 10 MV/m**.

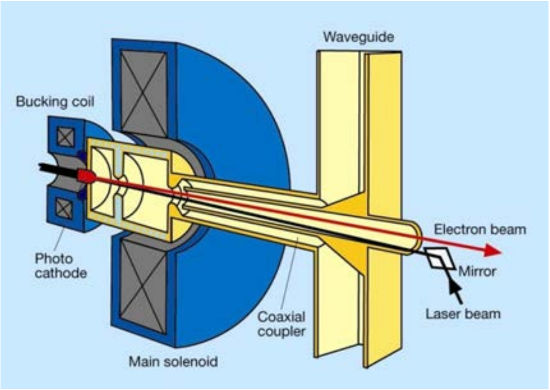
- Another challenge for DC guns is **photocathode bombardment by ions** generated by the electron beam scattering from residual gas: the ions naturally travel back to the cathode in the DC electric field. This problem can be partially mitigated by off-axis generation of the electron beam.

Let's switch to RF guns!

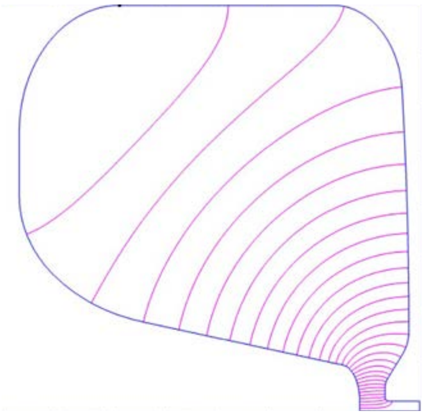
Photoinjector: Option # 2 Normal Conducting (NC) RF gun

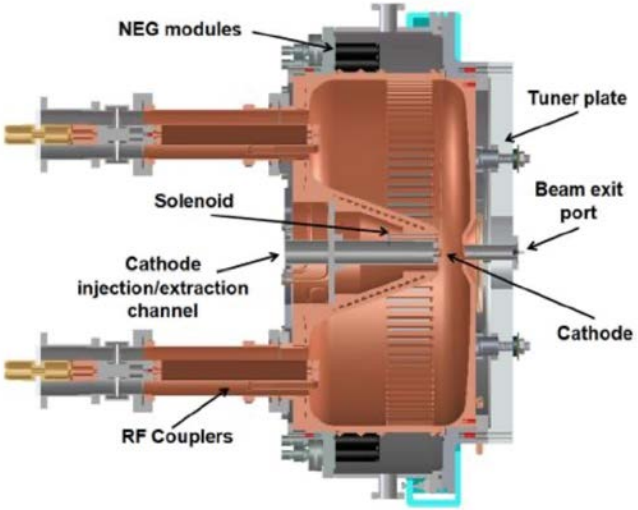
PITZ 1.3 GHz gun





LBNL 186 MHz 750 kV gun





+ NCRF guns produce high quality beams.

- Presently are delivering **accelerating voltage of ~0.75 MV**.
- We have to **compromise**:
  - Relatively **low repetition rate** with **high accelerating gradient**.
  - **High repetition rate** with **low accelerating gradient**.

Let's switch to SRF guns!

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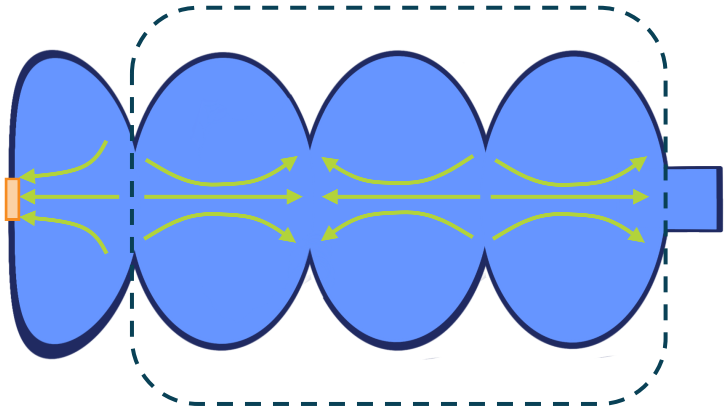
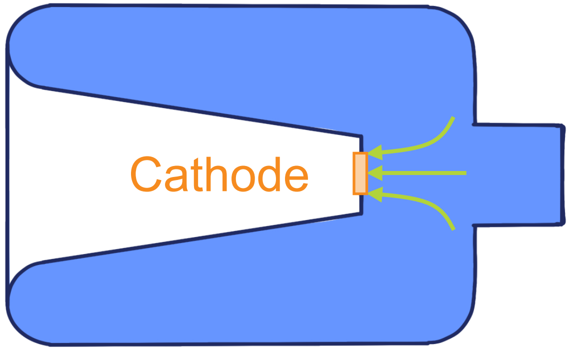
Photoinjector: Option # 3 SRF gun

Elliptical ½+ cells:

Cathode



Quarter Wave Resonator (QWR):

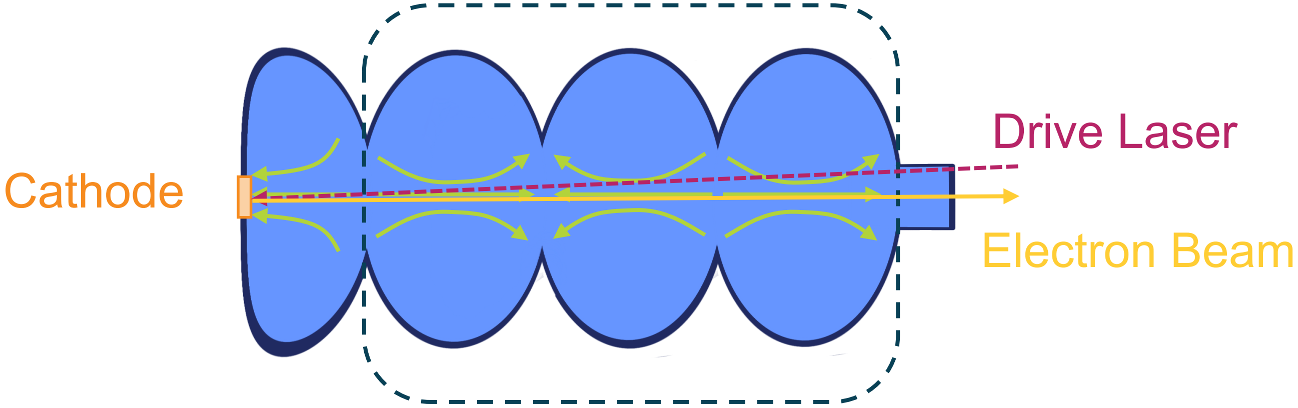


+ **Good vacuum** inside Nb cavity at 2K/4K.
+ **High accelerating gradients**
+ **CW operation**

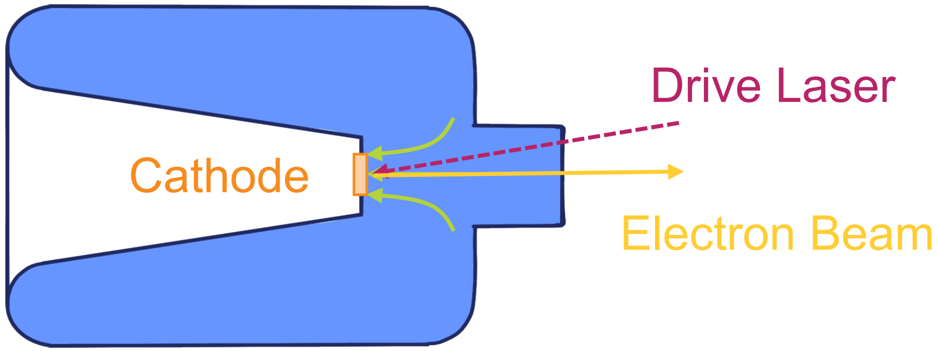
? **Are high-QE photocathodes compatible** with the SRF environment?
? **Can high-QE cathodes survive** in an SRF cavity?
? **Cryopumping**

Photoinjector: Option # 3 SRF gun

Elliptical ½+ cells:



Quarter Wave Resonator (QWR):



Photoinjector: Option # 3 SRF gun

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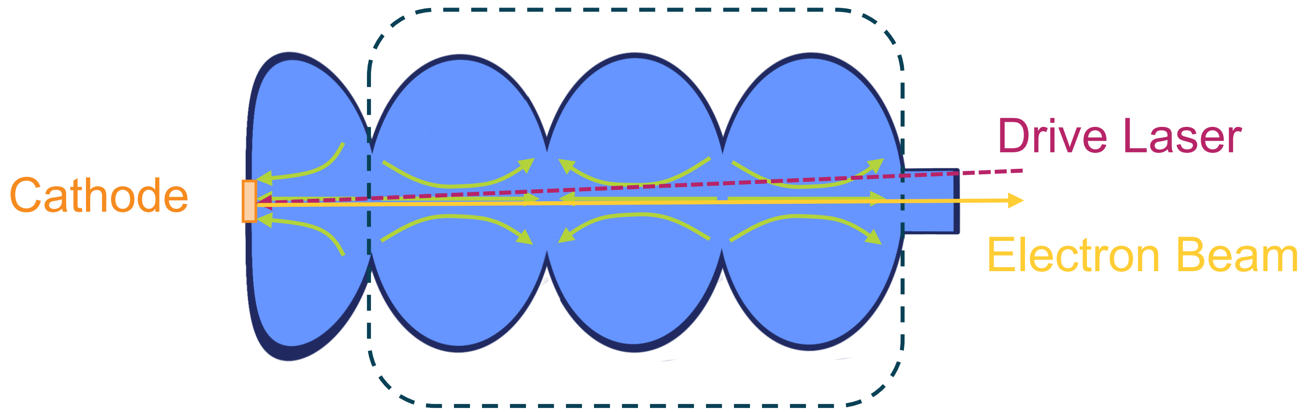

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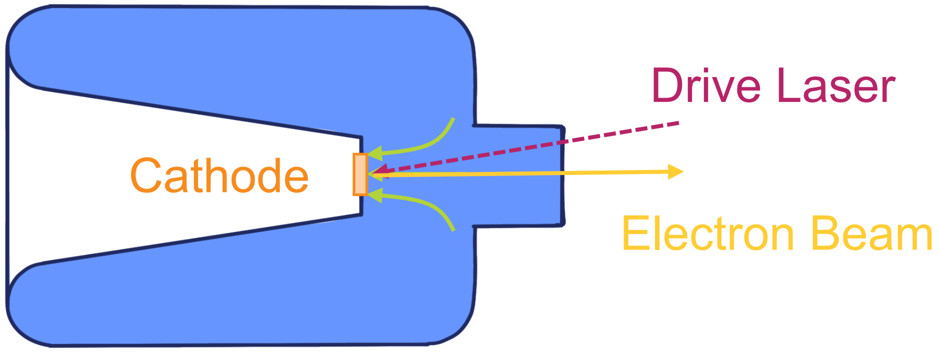
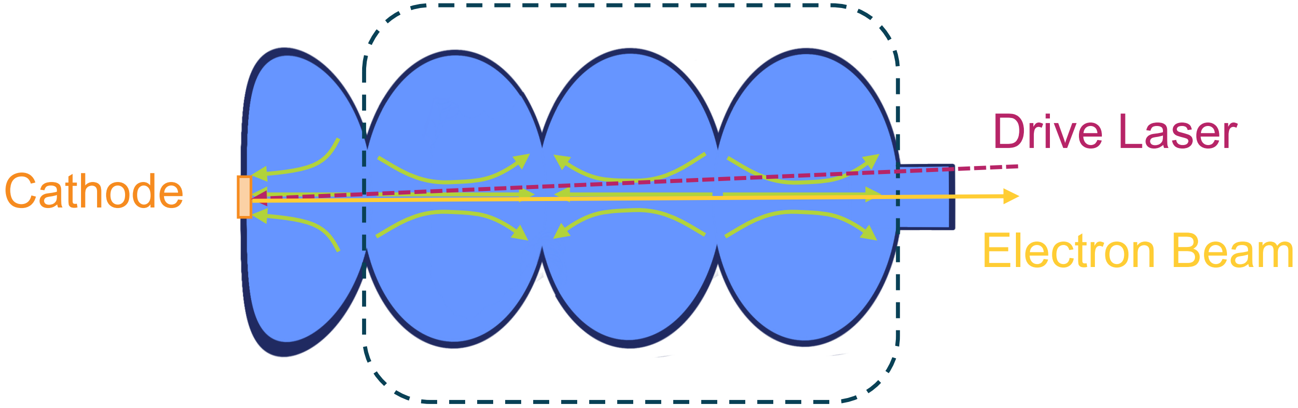


Which one to choose?

- QWRs usually operate at **lower frequencies**:
  - elliptical cavities ~1.3-1.5 GHz.
  - QWR ~100-200 MHz.
- Lower frequency → **reduced RF losses**.
- Lower RF losses → **relaxed cryostat temperatures**:
  - elliptical cavities operate at 2 K.
  - QWRs operate at 4 K.

Photoinjector: Option # 3 SRF gun

Elliptical ½+ cells:



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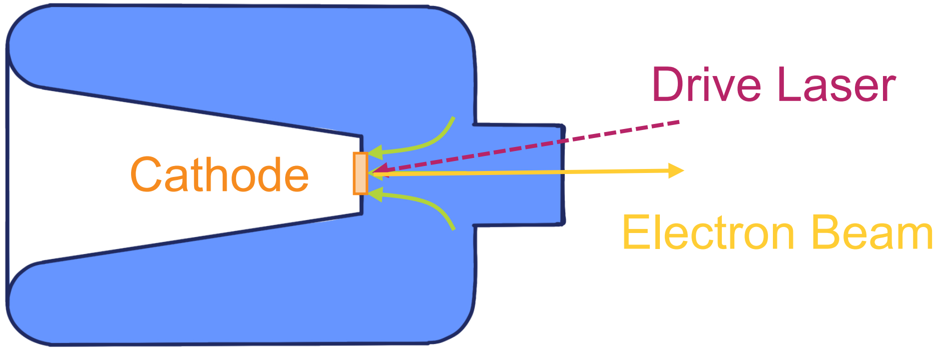
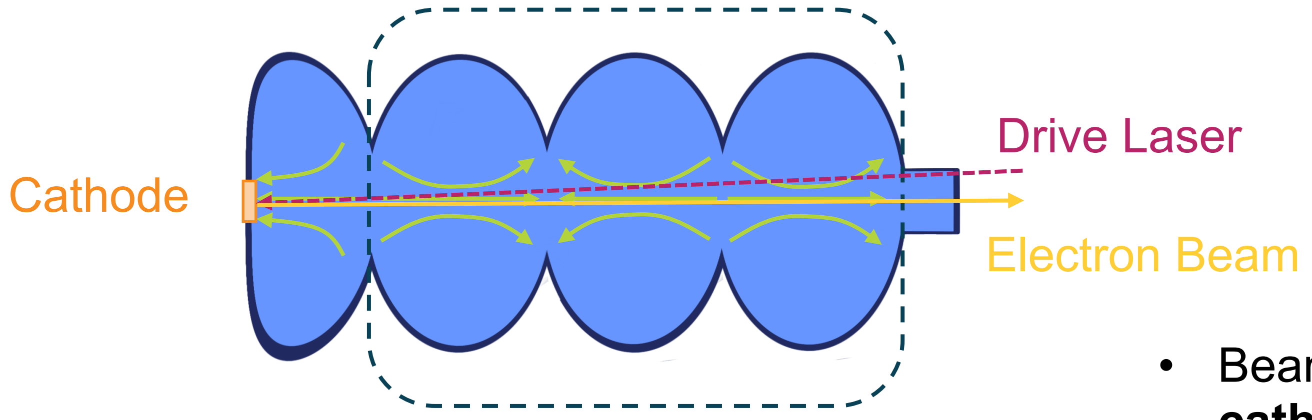


Which one to choose?

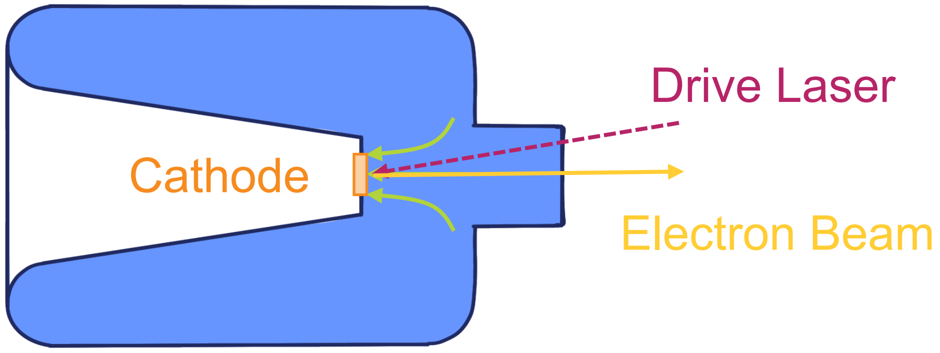
- QWRs have a **shorter accelerating gap compared to the cavity frequency** → higher transit time factor.
- QWR **almost acts as a DC gun** – beneficial for the beam quality.

Photoinjector: Option # 3 SRF gun

Elliptical ½+ cells:



Quarter Wave Resonator (QWR):



Which one to choose?

- Beam parameters depend on the **electric field at the cathode** at the moment of emission:
  - Cigar-shaped beam emittance
  - Pancake-shaped beam emittance
  - Charge density
- Electric field at the cathode at the moment of emission:

$$E_{\mathrm{em}} = E_{\mathrm{max}}\sin(\phi)$$

- Phase of emission, ϕ, is selected to **maximize the beam energy gain**.
- It depends on the geometry of the RF cavity, accelerating gradient E_{acc} and the RF frequency.

Elliptical (HZDR): $\phi = 12.5°,\ E_{\mathrm{em}} = (0.2 - 0.25)E_{\mathrm{max}}$

QWR (BNL): $\phi = 78.5°,\ E_{\mathrm{em}} \sim 0.98 E_{\mathrm{max}}$

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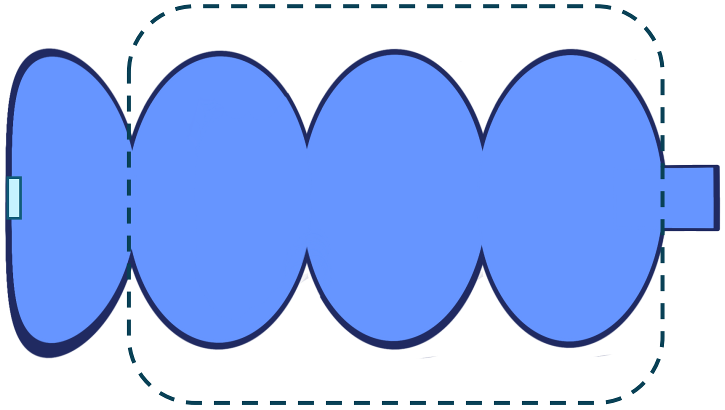
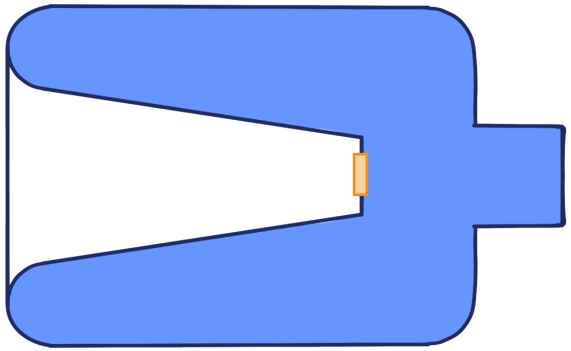
Photocathode options for SRF guns

Cold cathode

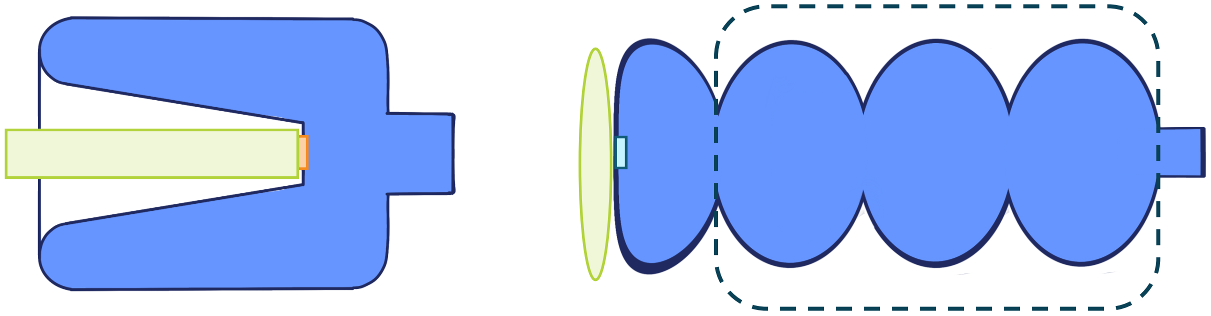


Warm cathode



Which one to choose?

- **Cold cathodes** typically have **lower QE**
- Cathodes have limited lifetime – need a replacement during operation:
  - Cold cathodes can be deposited as a layer of Pb on the back wall – “infinite” lifetime
  - Warm cathodes need to be replaced
- **Removable cathodes** introduce a risk for **RF power leaking** out of the cavity along the cathode channel (i.e., the mechanical gap between the cathode and the gun cell body). For this reason, different kinds of **choke filters** are used to keep the rf power inside the cavity.
- Choke filters are complicating the cavity cleaning process.



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Photocathode options for SRF guns

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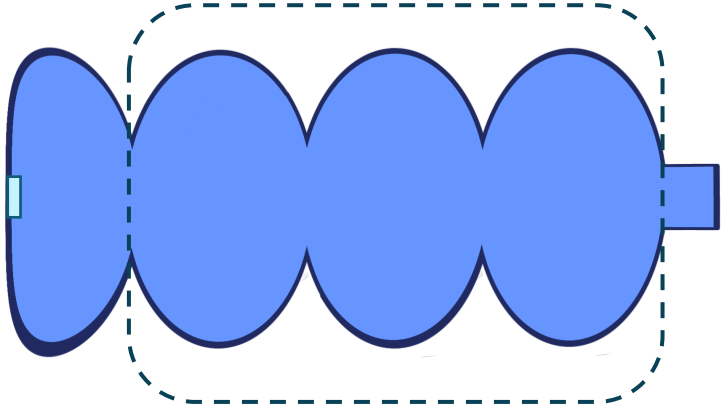
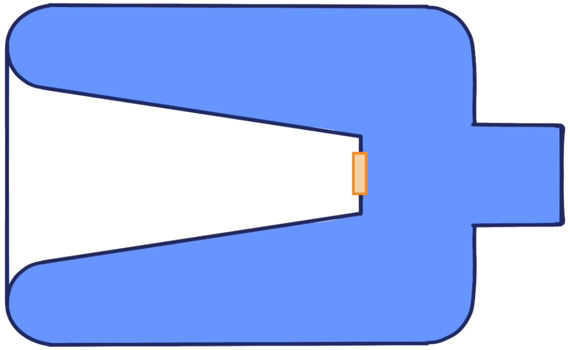


Warm cathode



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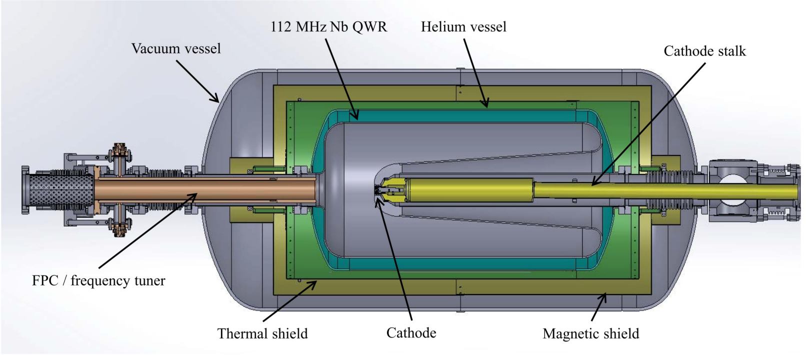

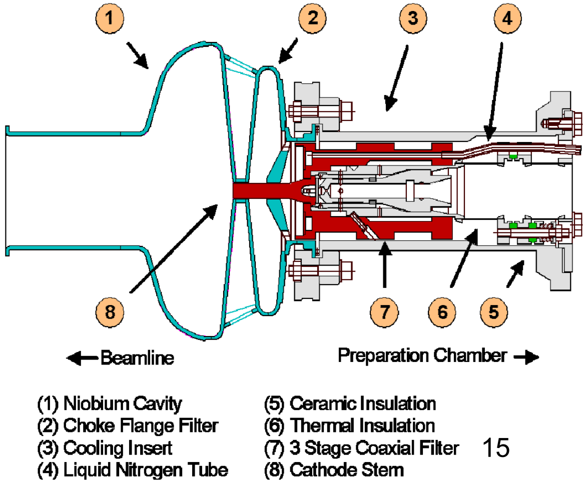

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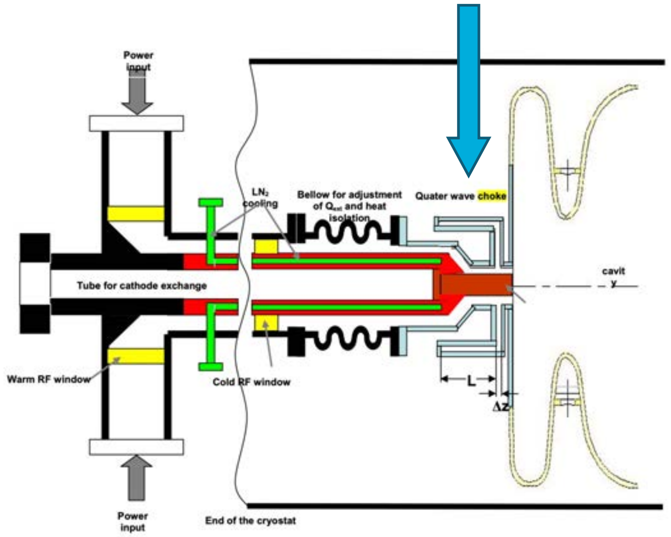
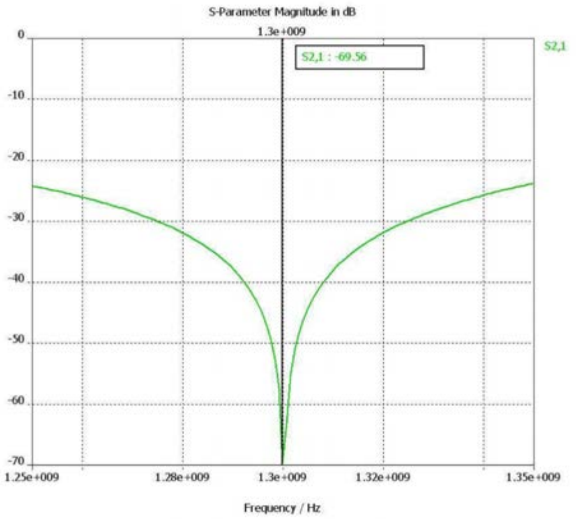
Preventing RF power leak

RF choke filter:

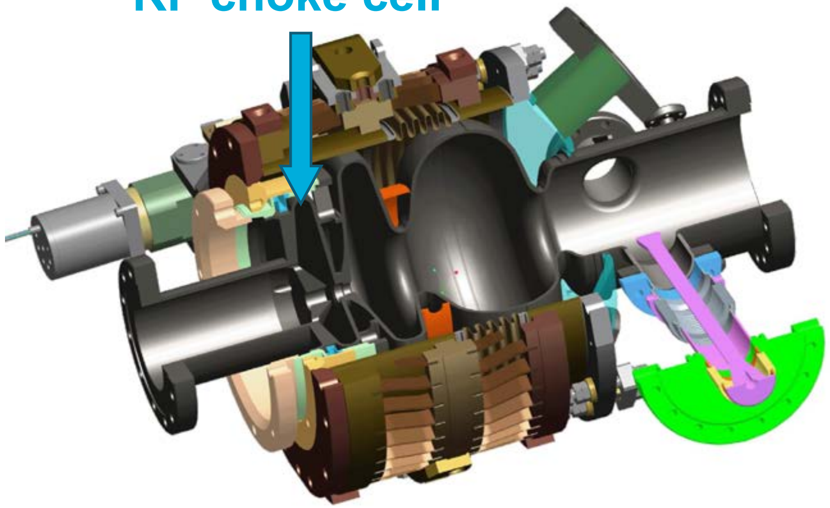
- **Resonant choke filter** is needed to prevent the RF power leak.
- It surrounds the cathode and prevents the RF power from leaking out of the cavity. In this manner it works as a **bandpass filter**.
- Band-stop/band-rejection/notch filter is a filter that **passes most frequencies unaltered but attenuates those in specific range** to very low levels.

RF choke filter





RF choke cell



RF choke cell:

- The operation of the **choke-cell is the same as quarter wave choke filter** with similar S_{21}-parameter distribution.
- Advantages of choke-cell:
  - Better **cleaning** possibilities.
  - **Less** probable and less stable **multipactor** discharge.
  - **Tuning** procedure is simpler and can be realized with well-developed SRF cell tuners.

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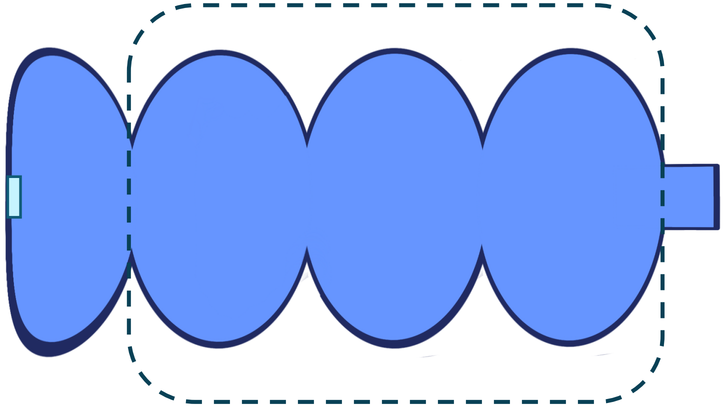
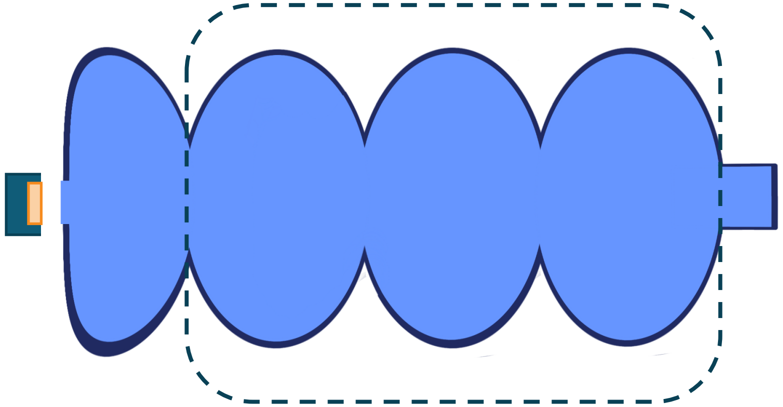
Photocathode options for SRF guns

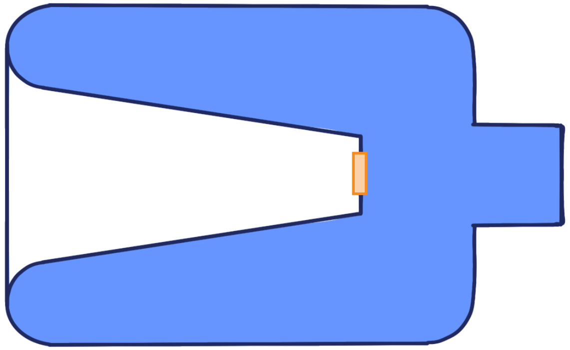
Cold cathode



Warm cathode outside + DC gap

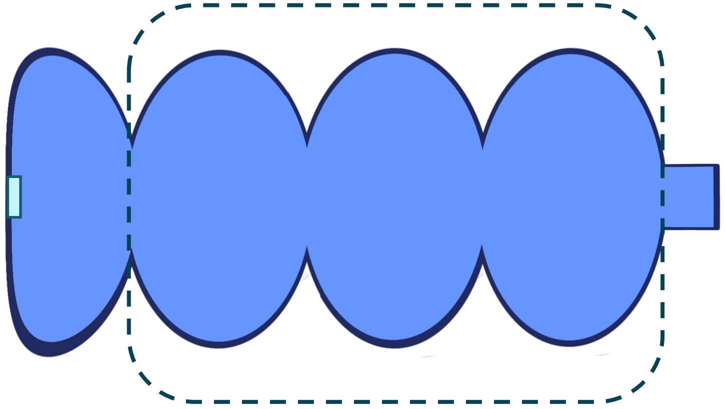


Warm cathode

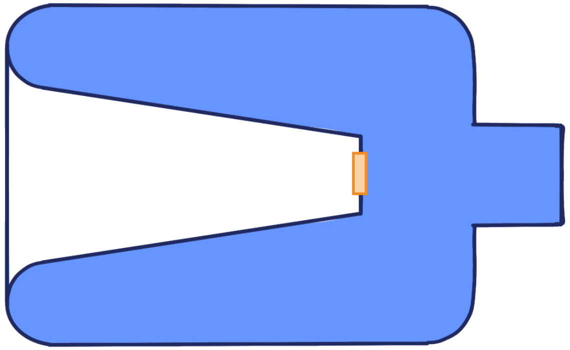


Photocathode options for SRF guns

Cold cathode



Warm cathode



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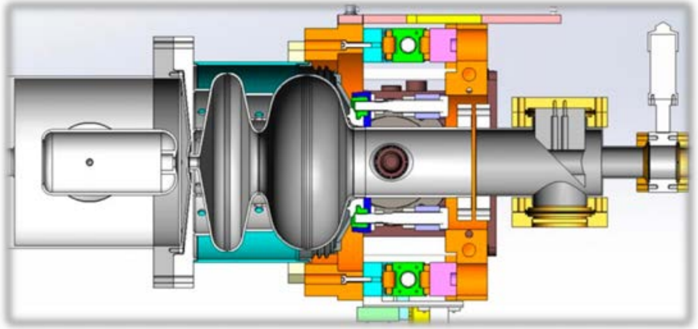


Current status of SRF guns worldwide

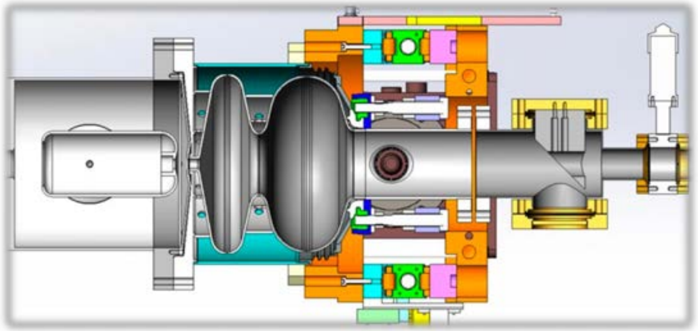
As of now:

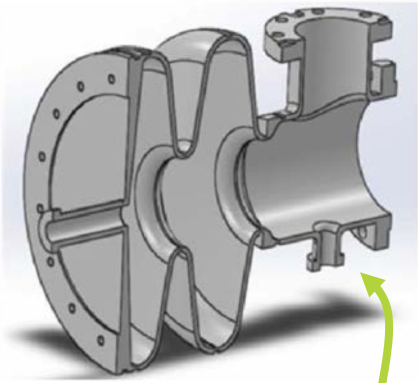
2 SRF guns are in routine operation
4 SRF guns are in R&D stage
1 SRF gun is at the early stage of design

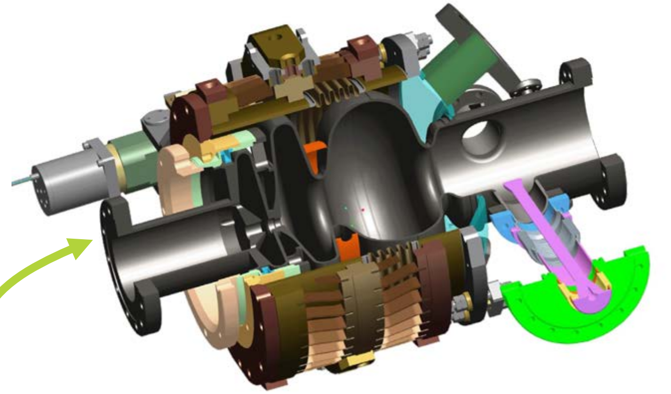
Different approaches are utilized:

DESY: elliptical cavity with SC cathodes
HZDR, **KEK**, **HZB**: elliptical cavities with NC cathodes in choke filter
PKU: elliptical cavity with NC cathodes in DC module
BNL, **SLAC**: QWR with NC cathodes and choke filter

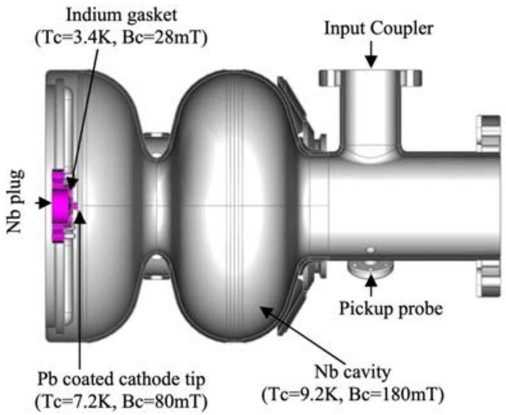
Current status of SRF guns worldwide

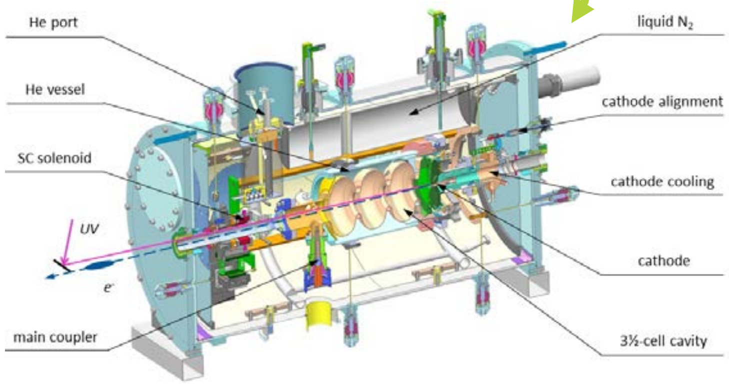


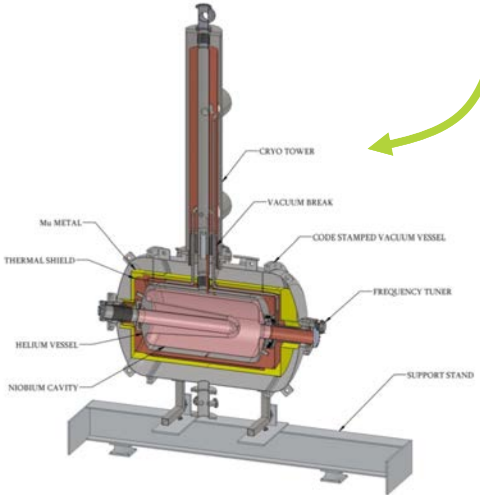


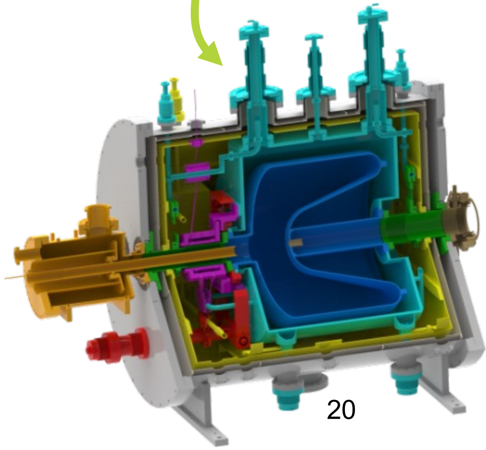


	DESY	PKU	HZDR	KEK	HZB	BNL	SLAC
Cavity Type	1.6-cell elliptical	1.5-cell elliptical	3.5-cell elliptical	1.5-cell elliptical	1.4-cell elliptical	QWR	QWR
RF frequency [MHz]	1300	1300	1300	1300	1300	113	186
Operation temperature [K]	2	2	2	2	2	4	4
Field at cathode [MV/m]	40	6	14	23	24-27	15	30
Cathode	Pb	CsK_2Sb	Mg, Cs_2Te	CsK_2Sb	Cu or CsK_2Sb	CsK_2Sb	CsK_2Sb (?)
Laser wavelength [nm]	UV	519	262	532	521-523	532	532
Bunch charge [pC]	20-250	100	0-250	80	77	100-20000	100
Status	R&D	R&D	User Operation	R&D	R&D	Operation	In plan



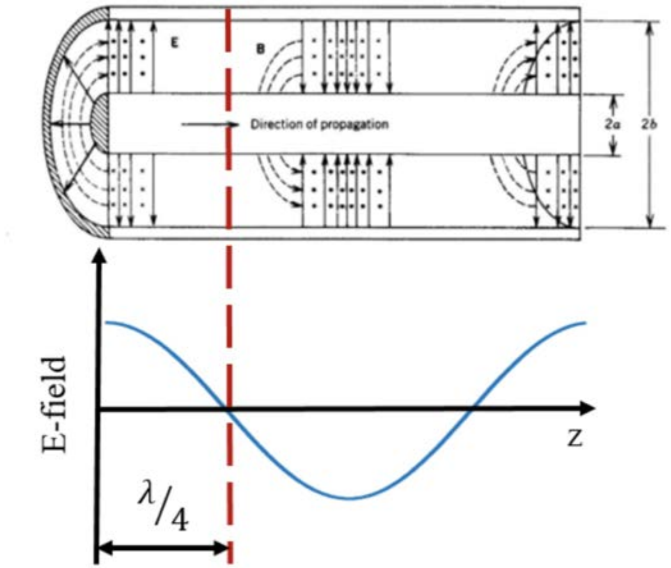






BNL 113 MHz SRF gun

BNL 113 MHz gun anatomy



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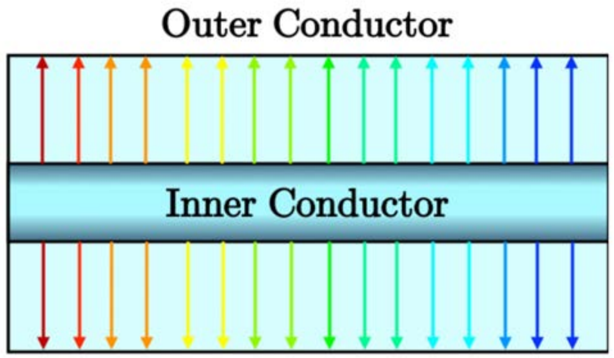

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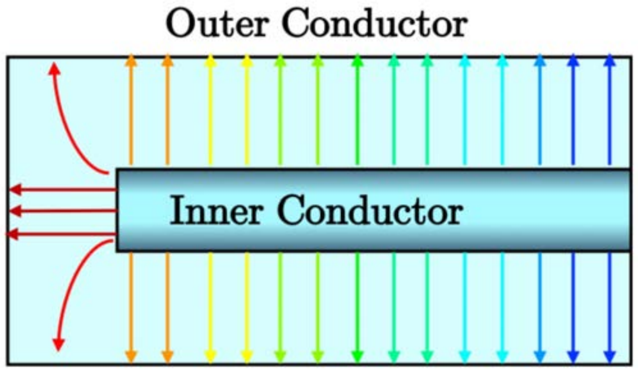

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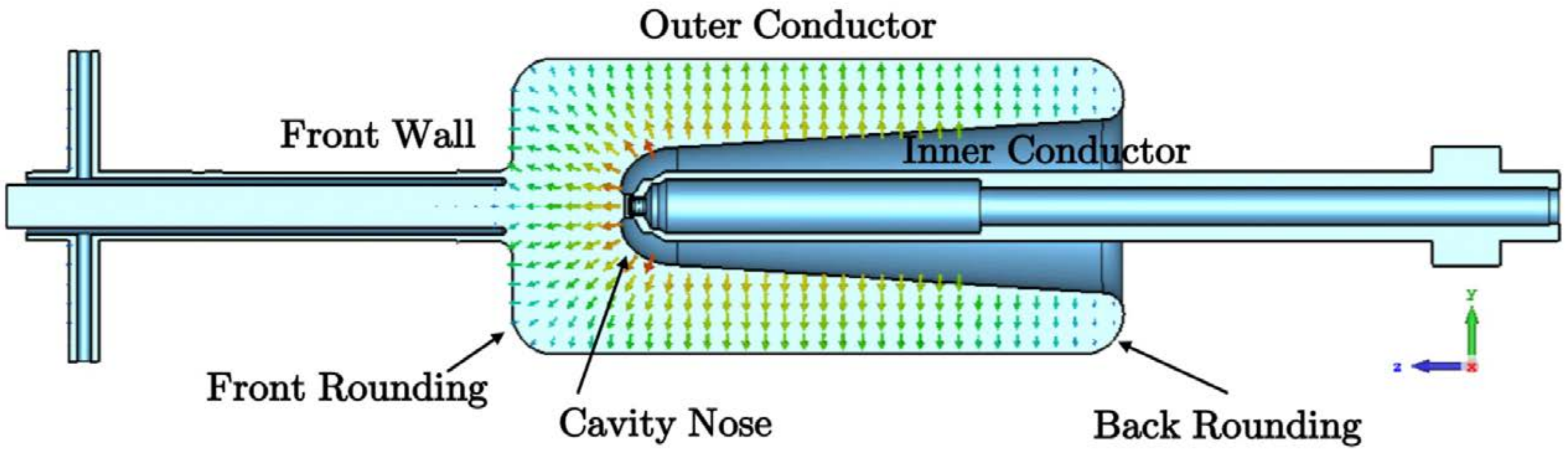

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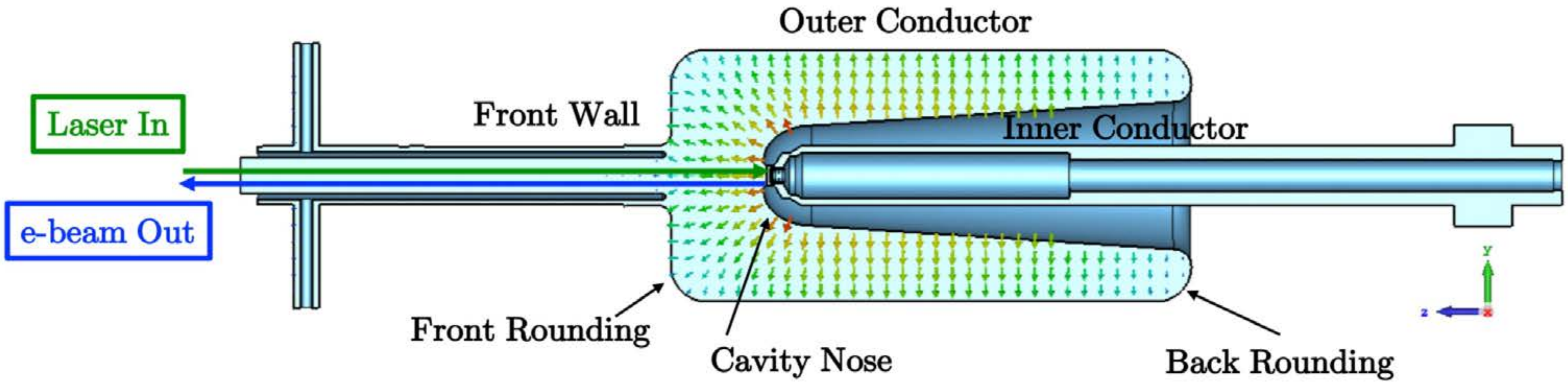
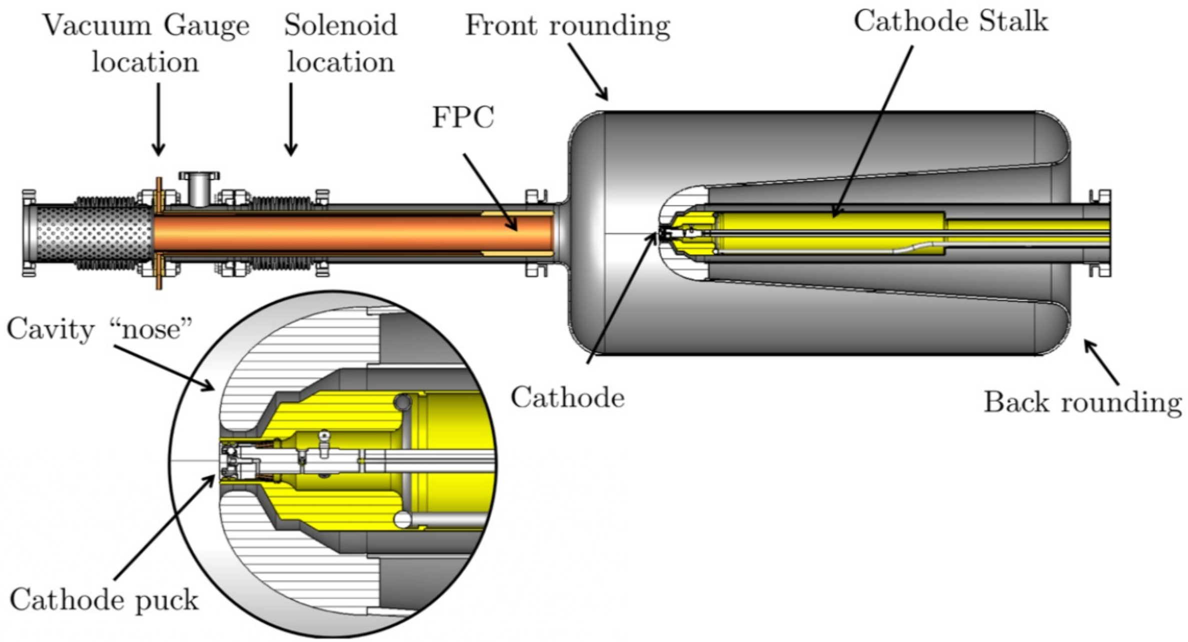
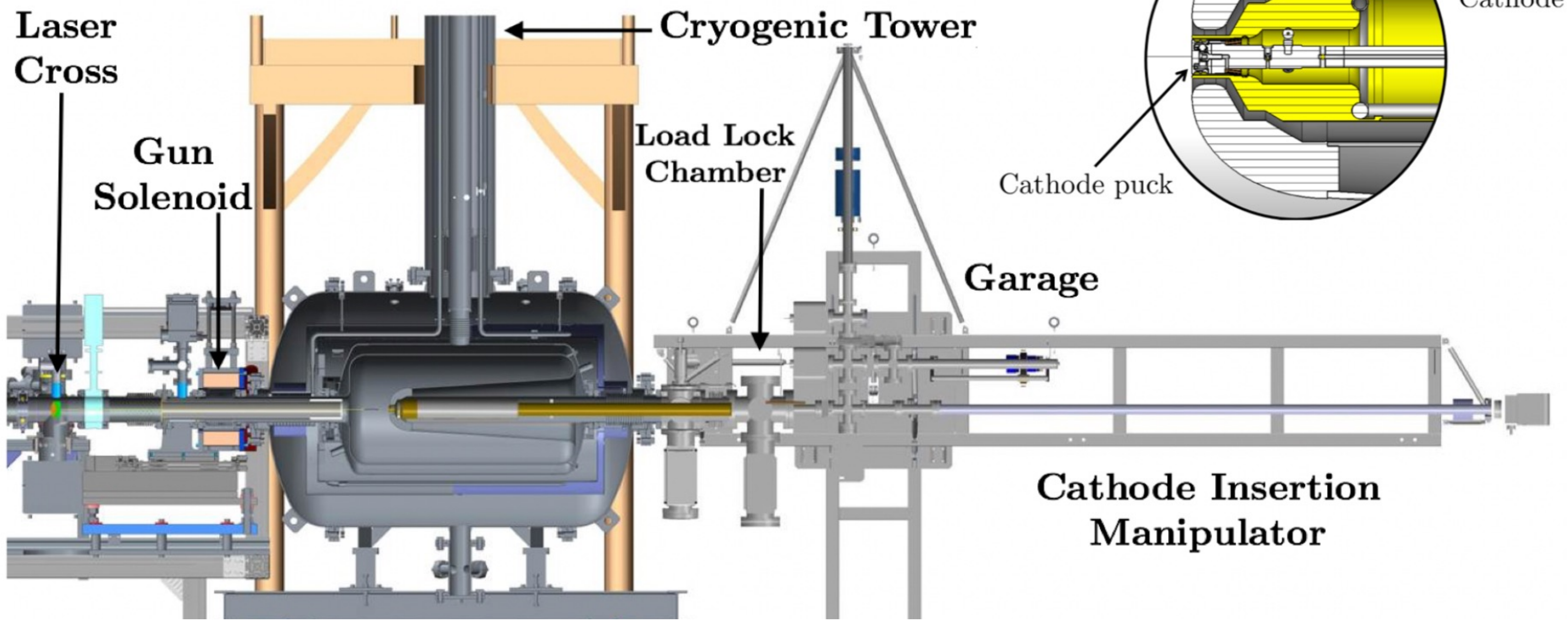


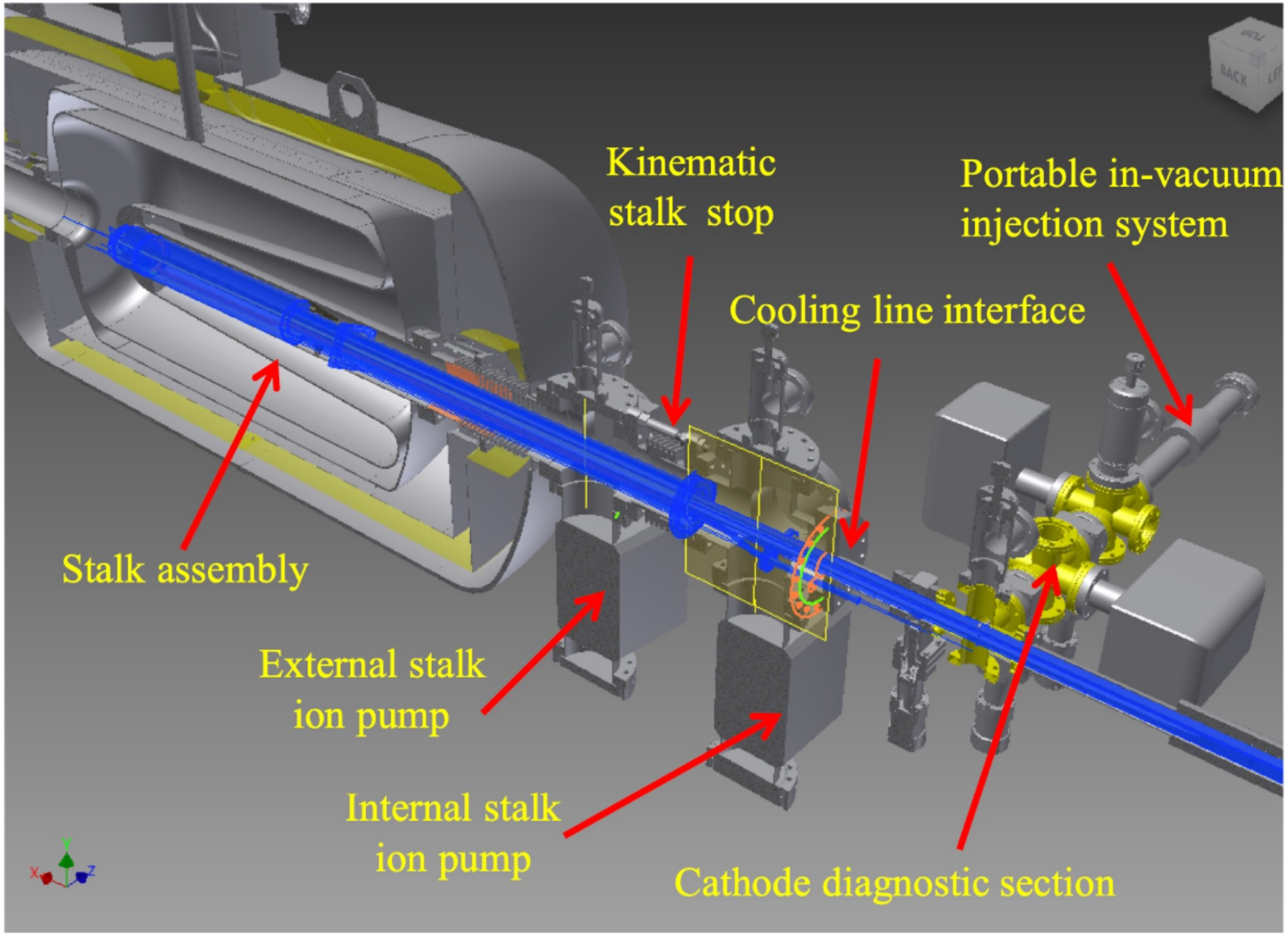
113 MHz SRF gun with warm CsK_2Sb photocathode

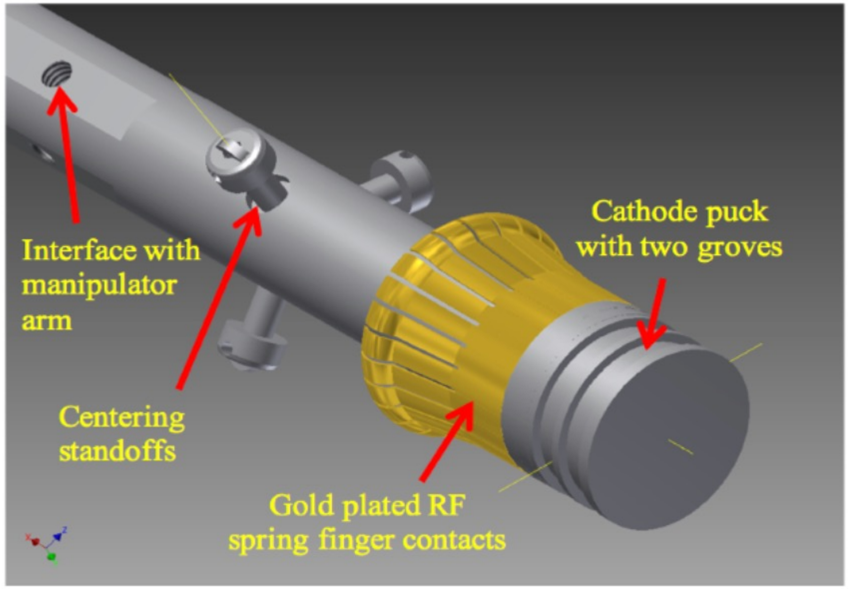
- Operating temperature: 4 K
- Room temperature CsK_2Sb photocathode
- Photocathode QE lifetime: 1-2 months
- CW operating voltage: 1.25 MV
- 4 kW CW solid state power amplifier

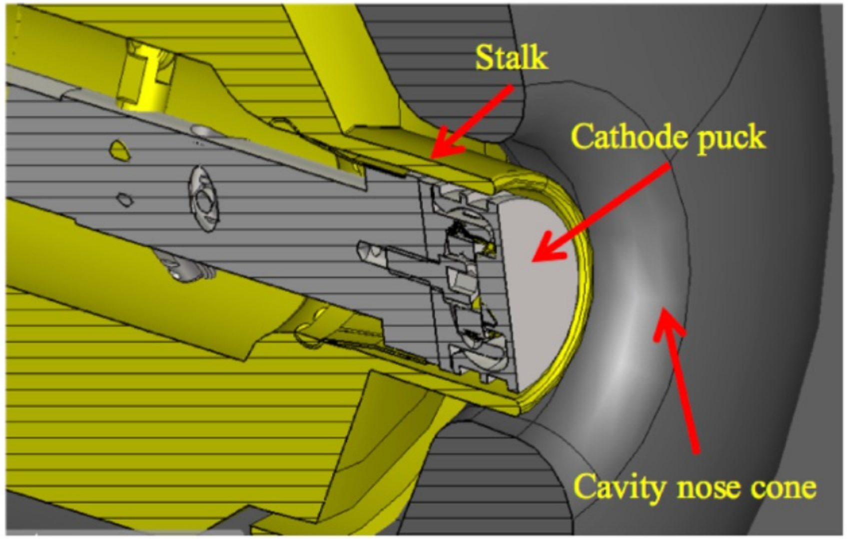




Cathode insertion system







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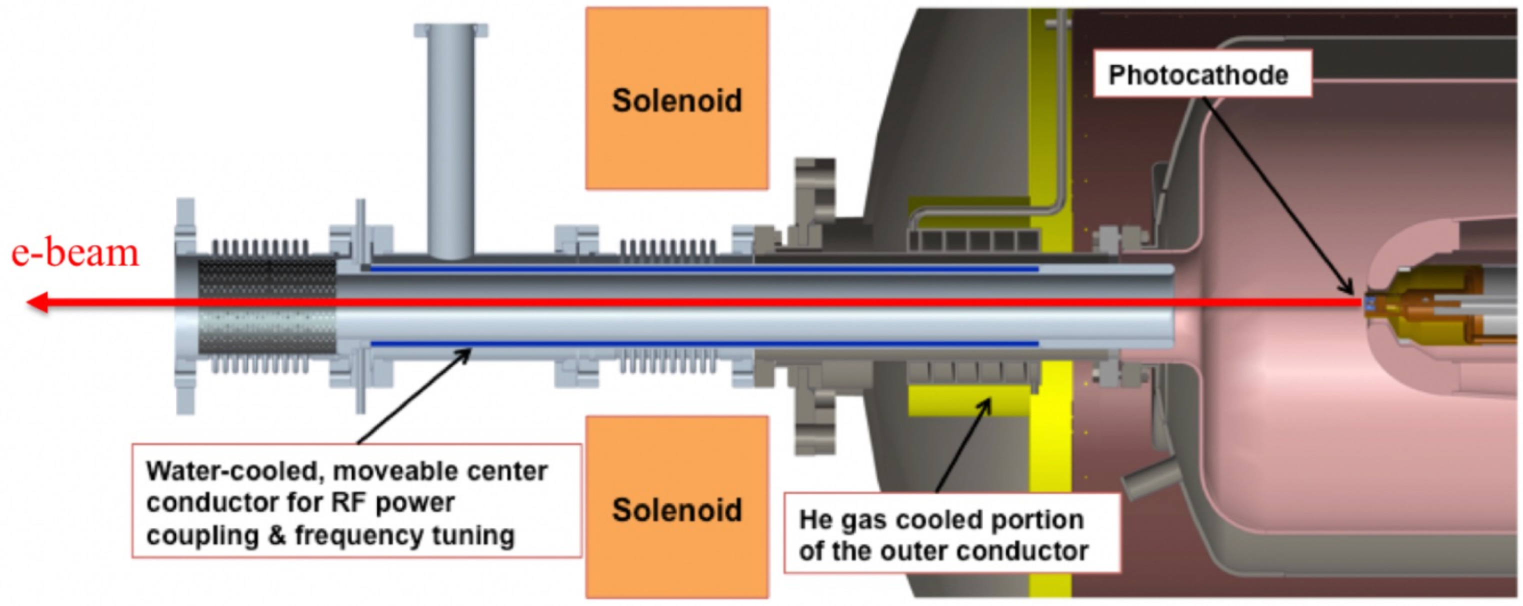
Fundamental Power Coupler (FPC)/ Frequency Tuner



- Fundamental RF power coupling and fine frequency tuning is accomplished via a coaxial beam pipe and the beam exit port.
- With the travel of $\pm$2 cm, the tuning range is ~6 kHz.
- The center conductor and RF windows are water-cooled. The outer conductor copper coated bellows are air-cooled.
- The center conductor is gold-plated to reduce heat radiated into the SRF cavity.

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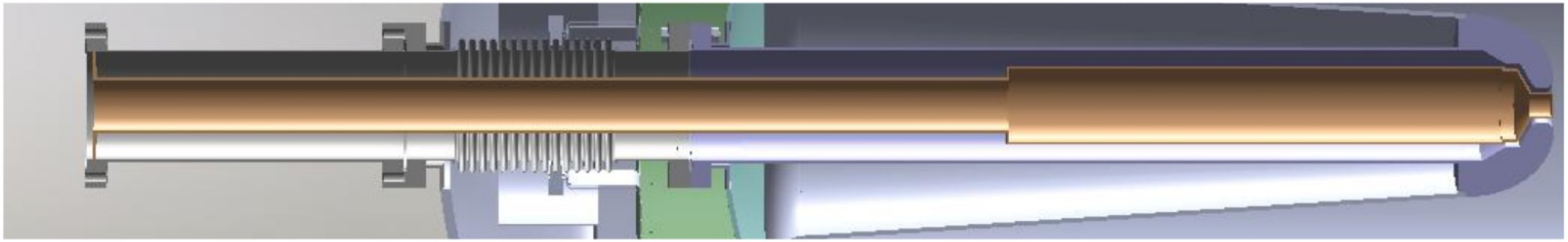
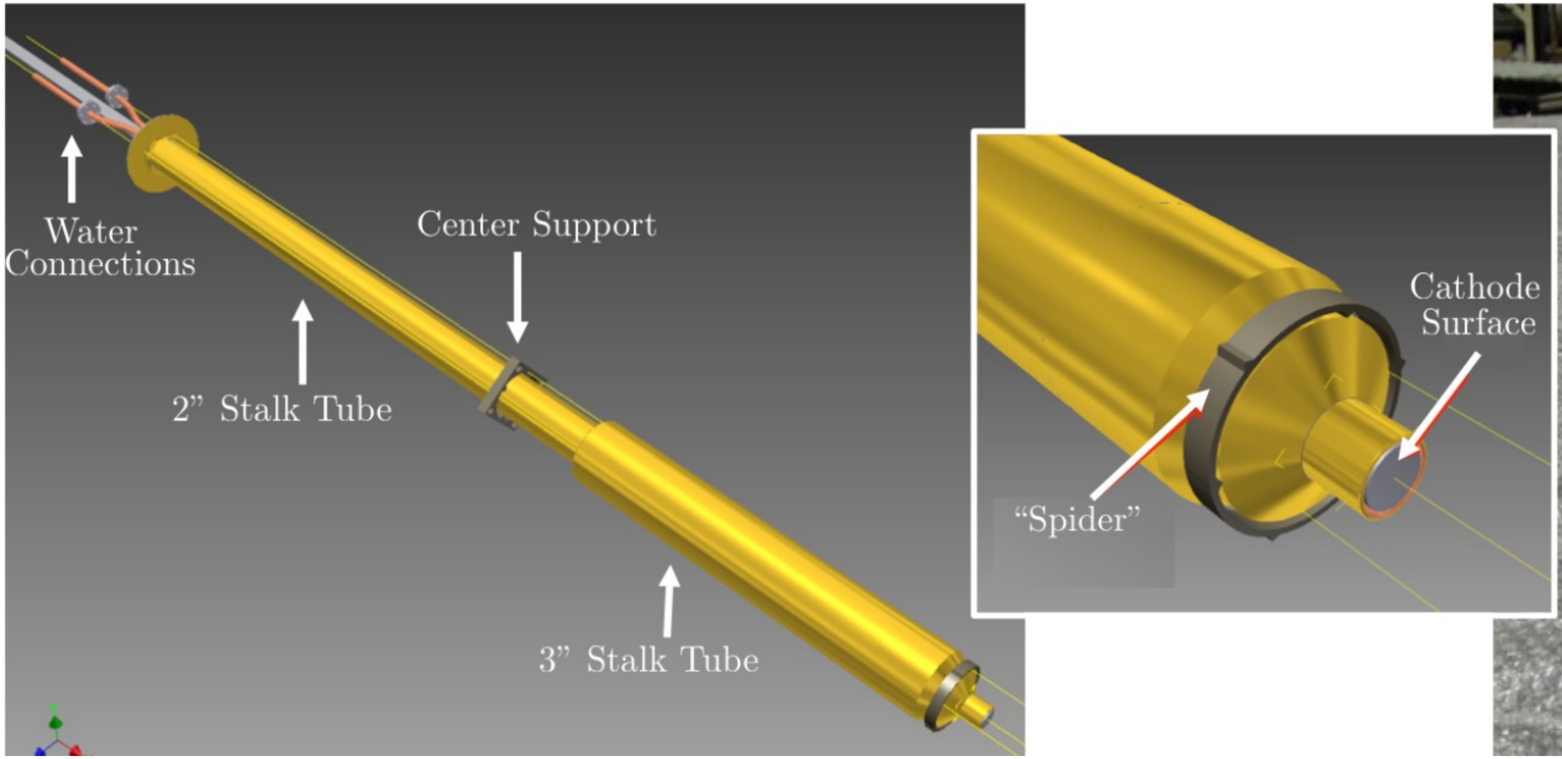
Cathode Stalk Design

- The stalk is shorted at one end and is approximately half wavelength long.
- A step from the short creates an impedance transformer → reduces RF losses in the stalk from ~65 W to ~25 W.
- The gold plating reduces radiation heat load from the stalk.





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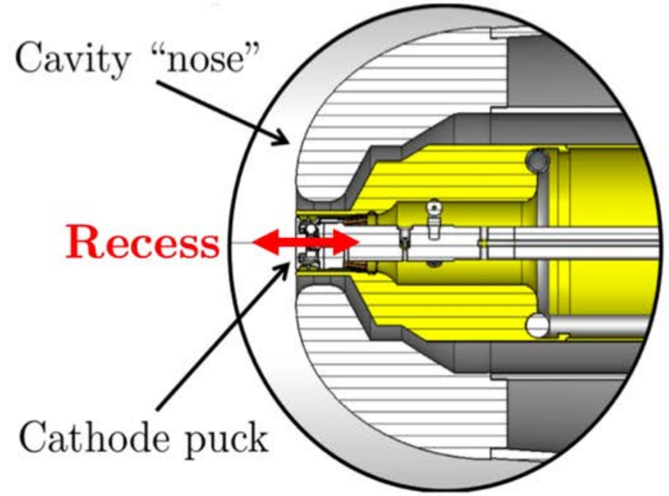
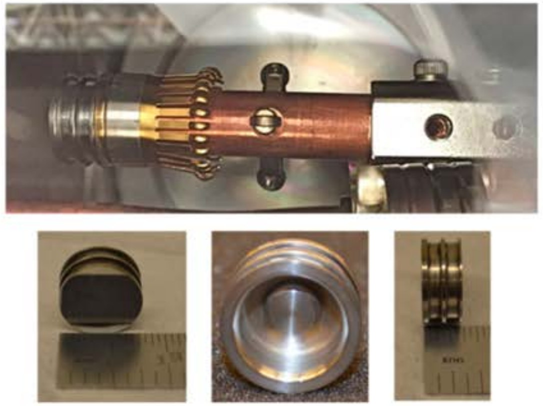
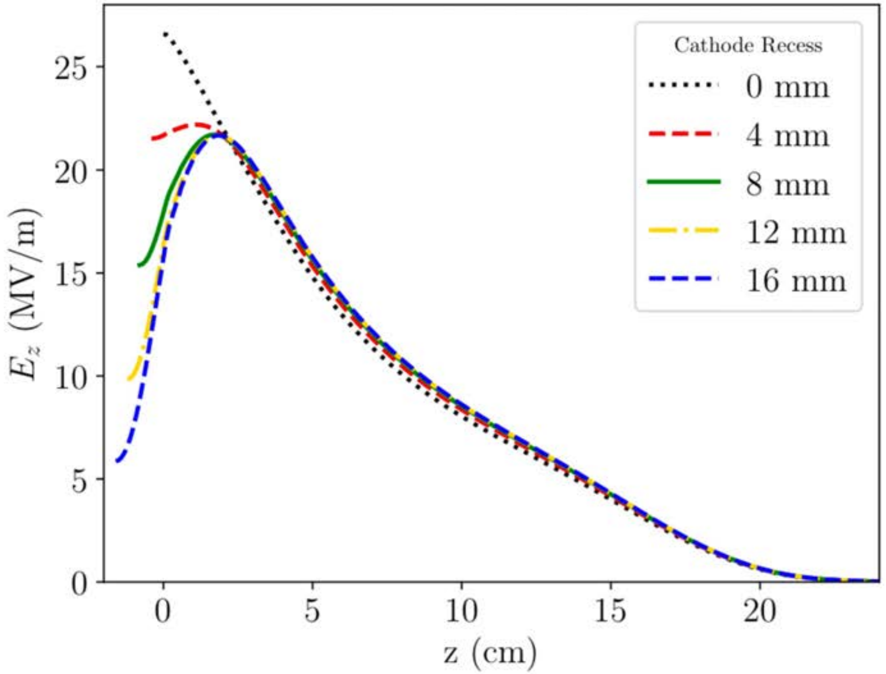
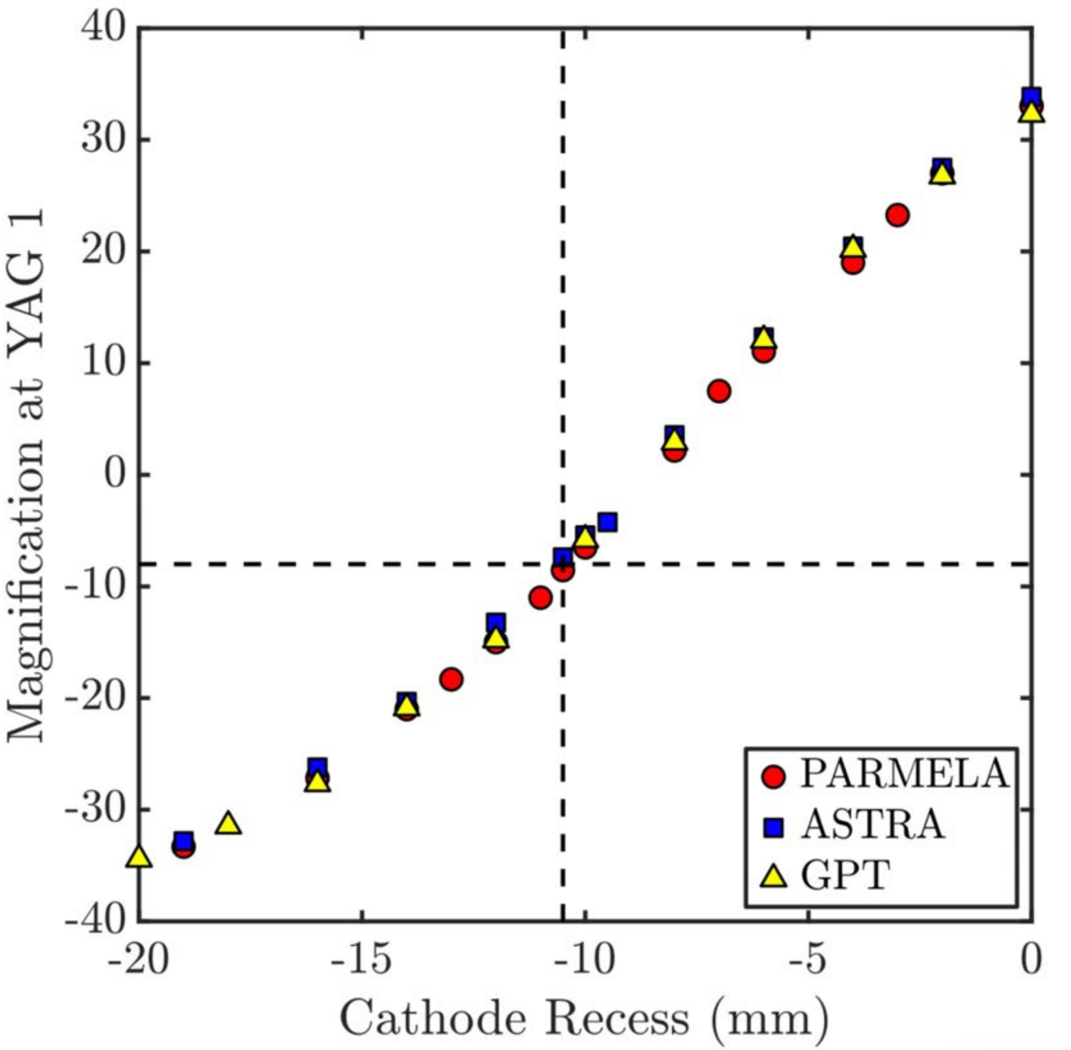
Controlling cathode recess ⟶ initial focusing of the beam









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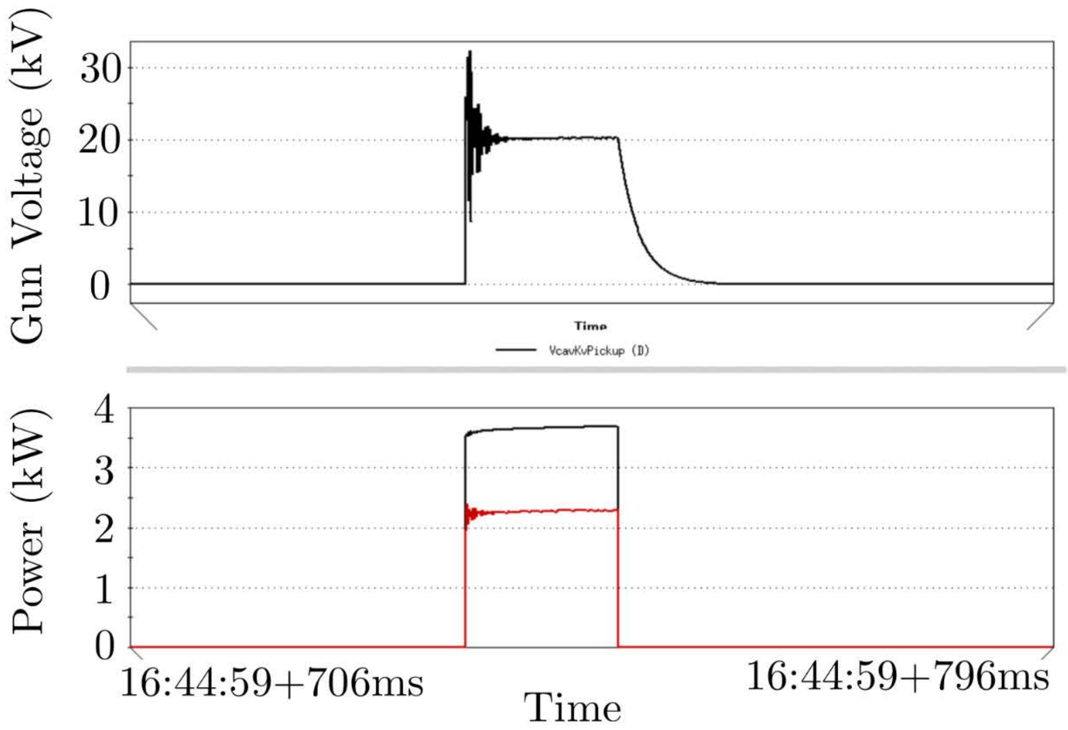
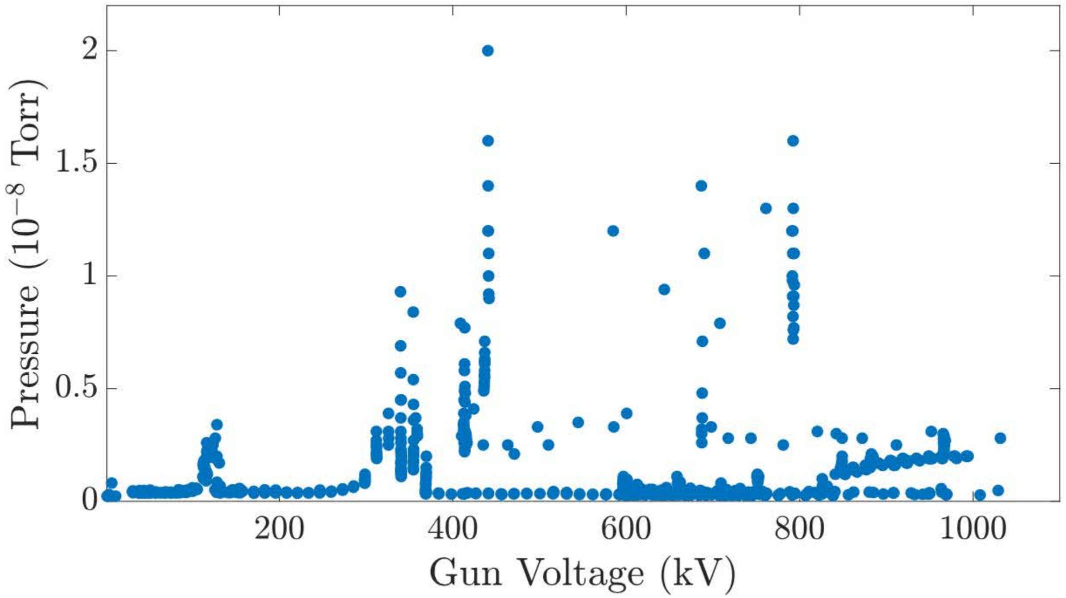
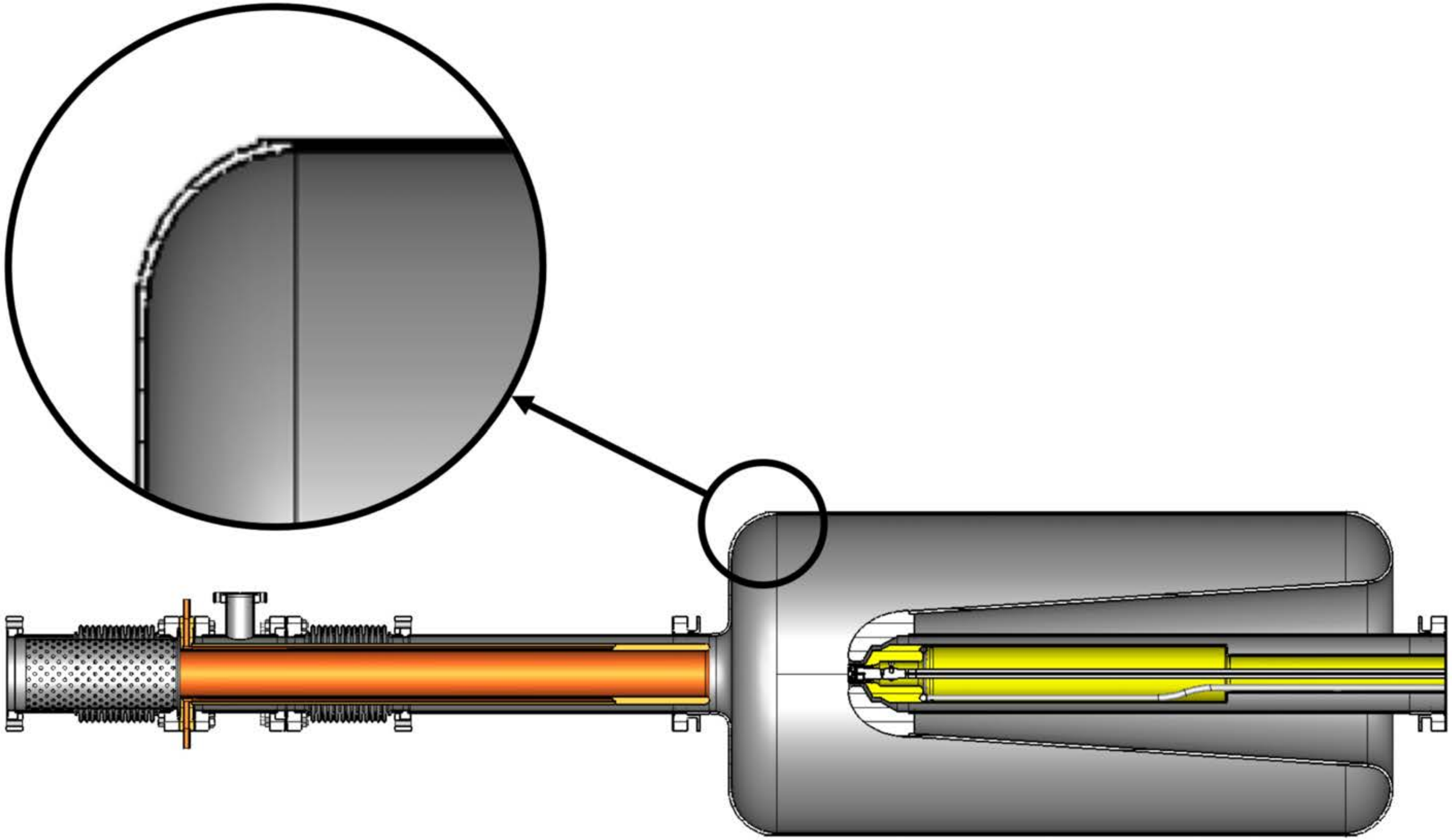
Issues with multipacting during the first years of operation!





Definition of multipacting



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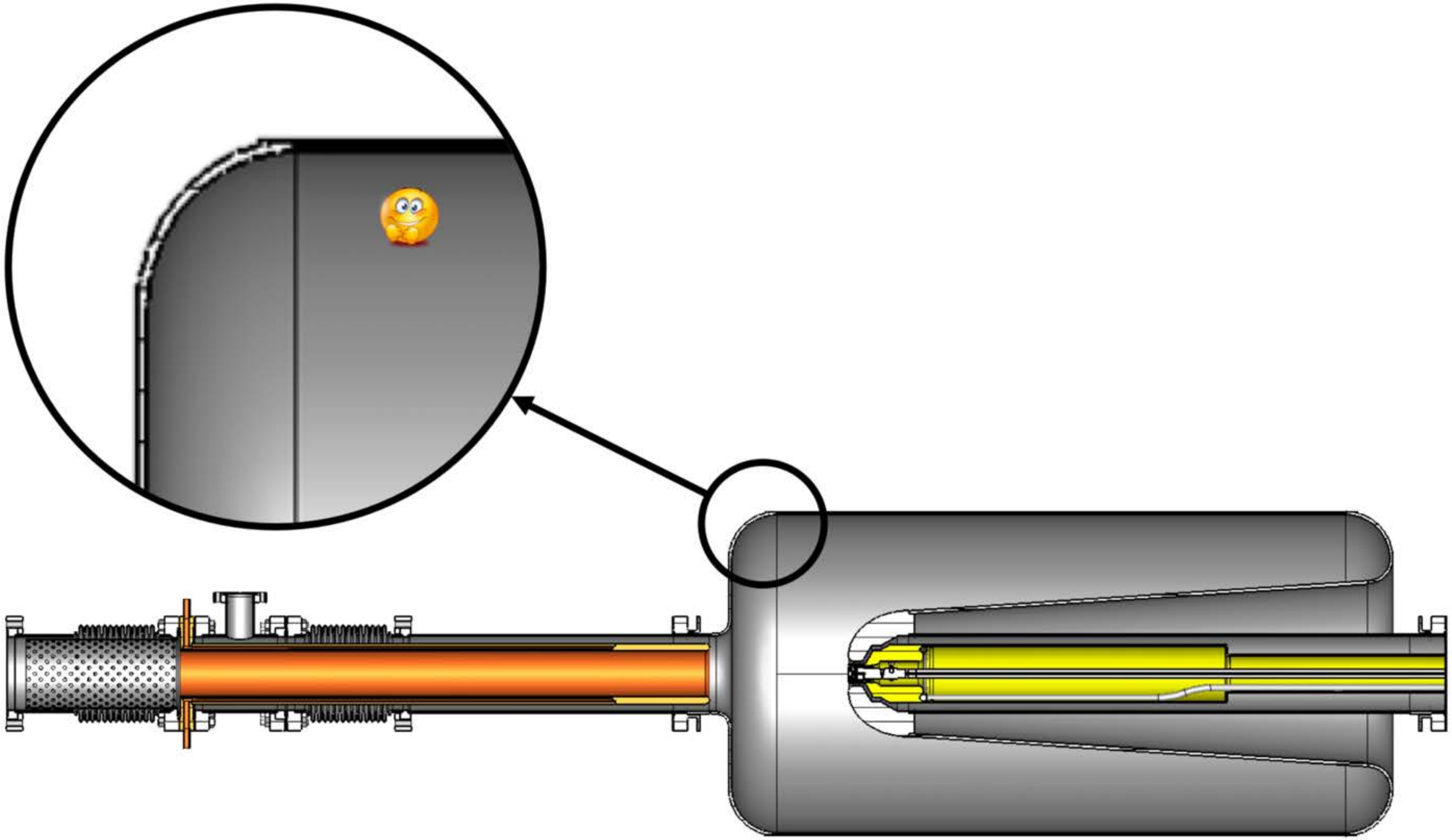
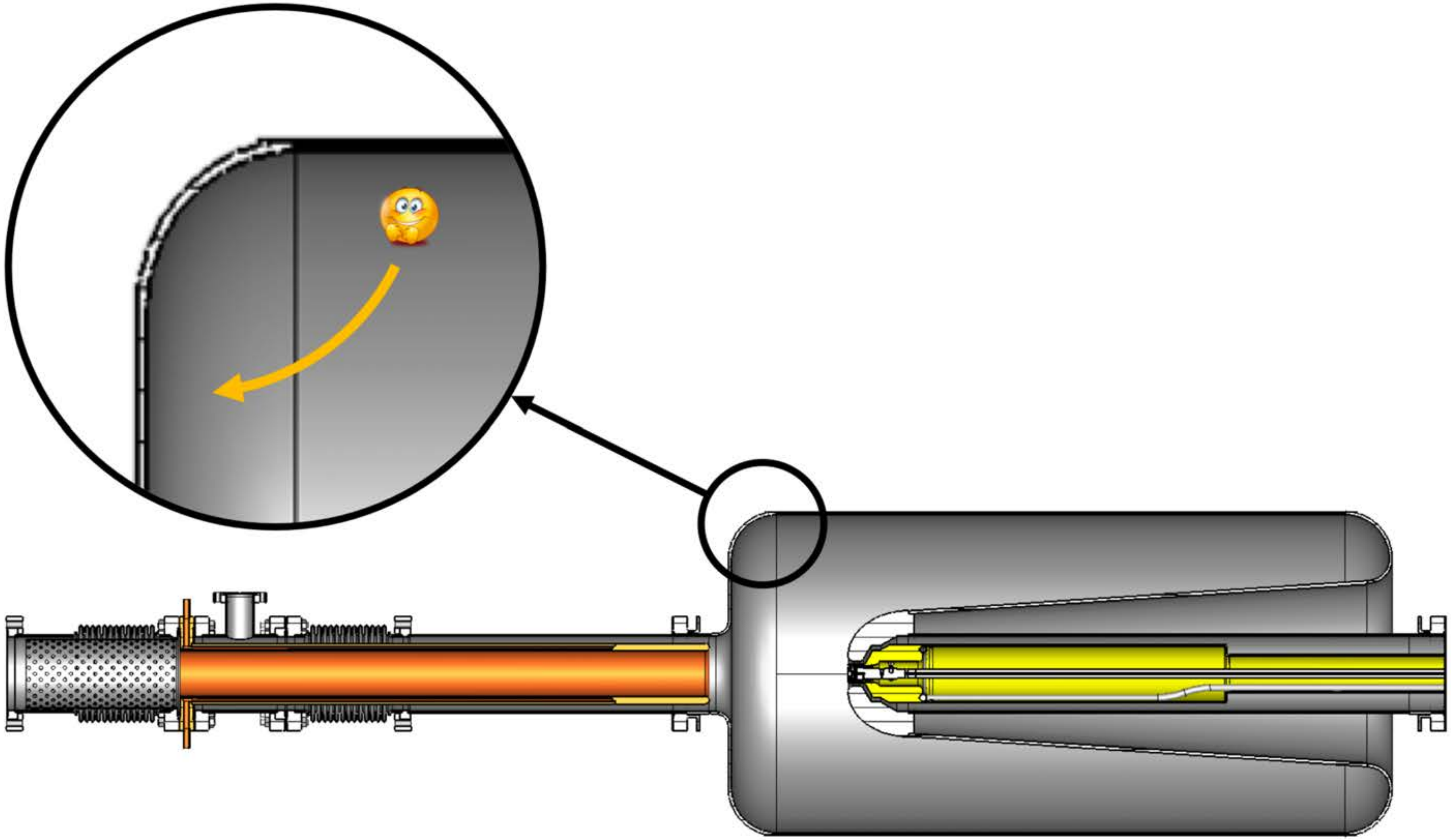
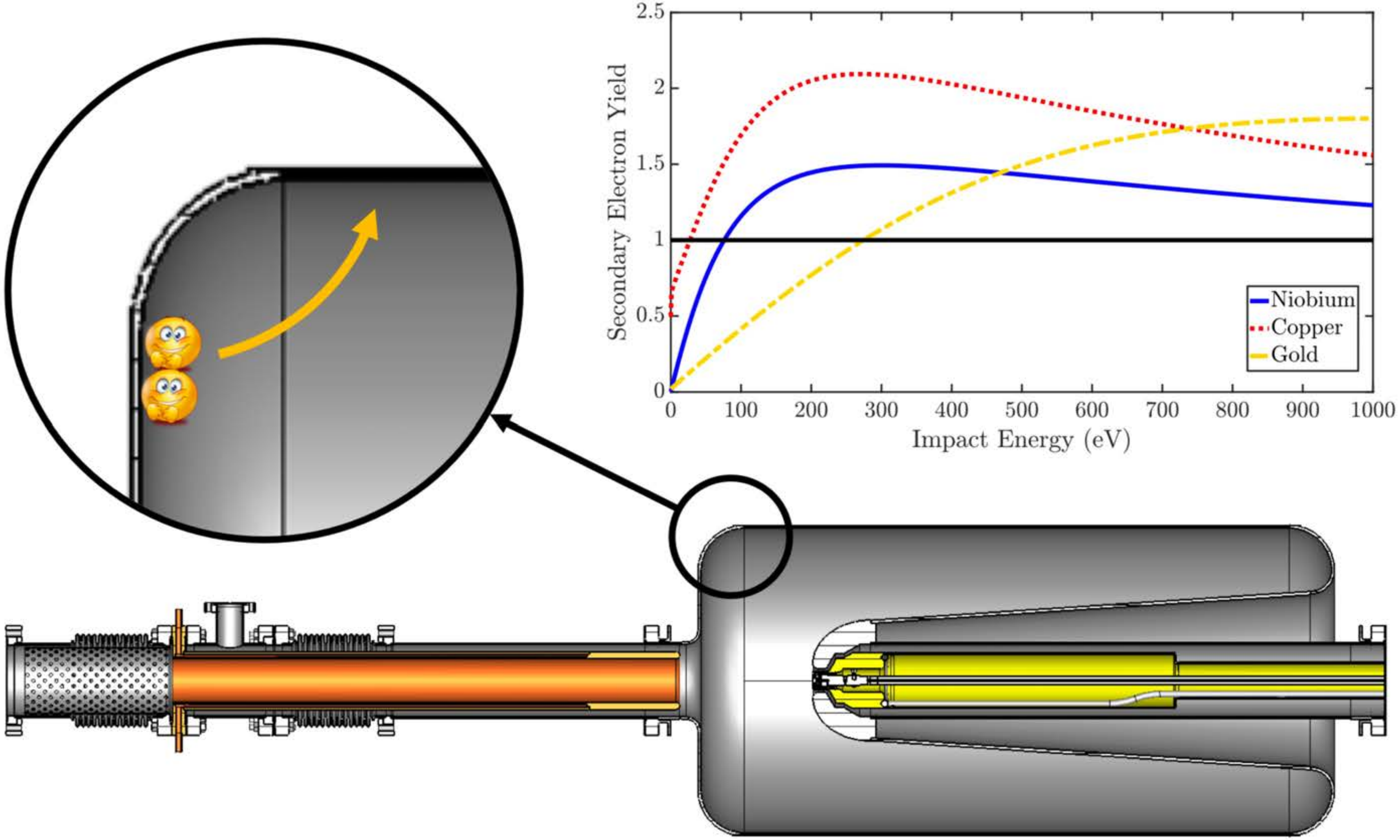
Definition of multipacting



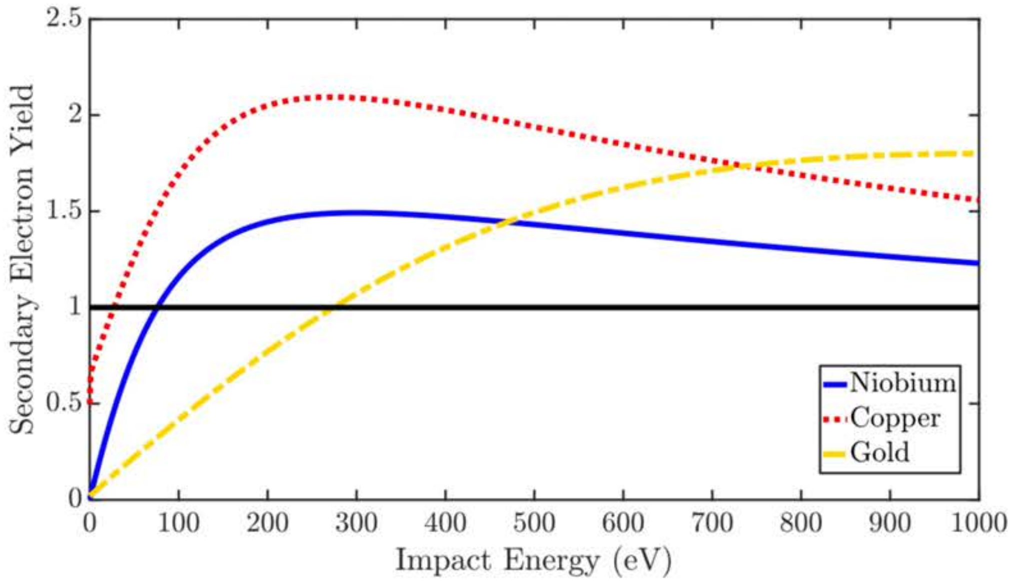
Definition of multipacting

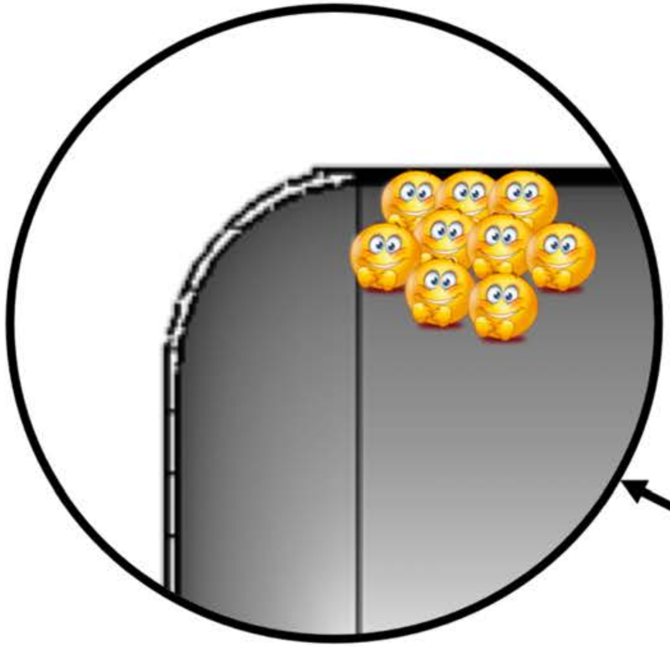


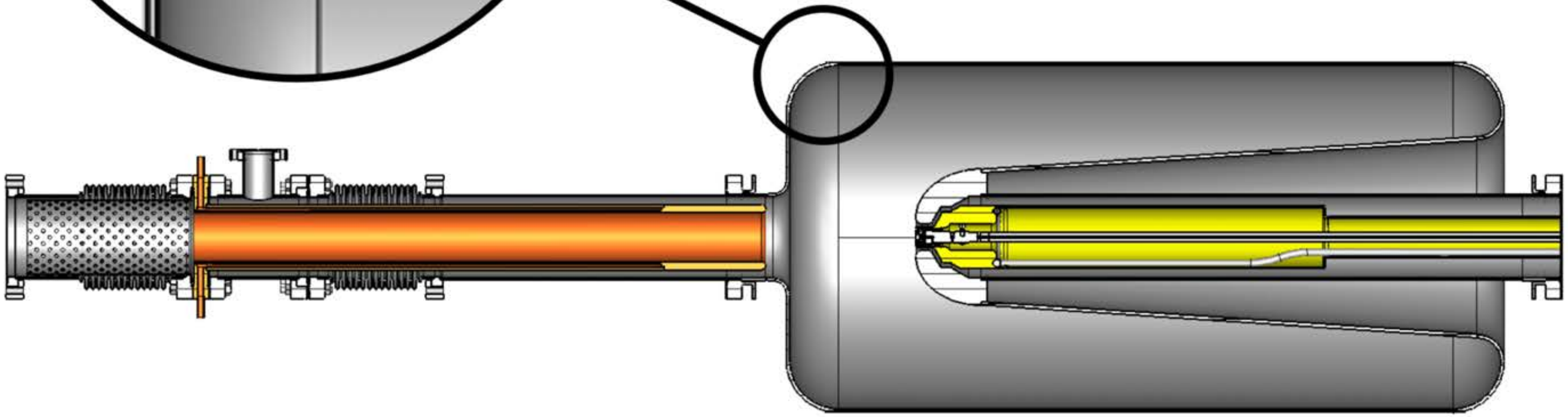
Definition of multipacting



Definition of multipacting

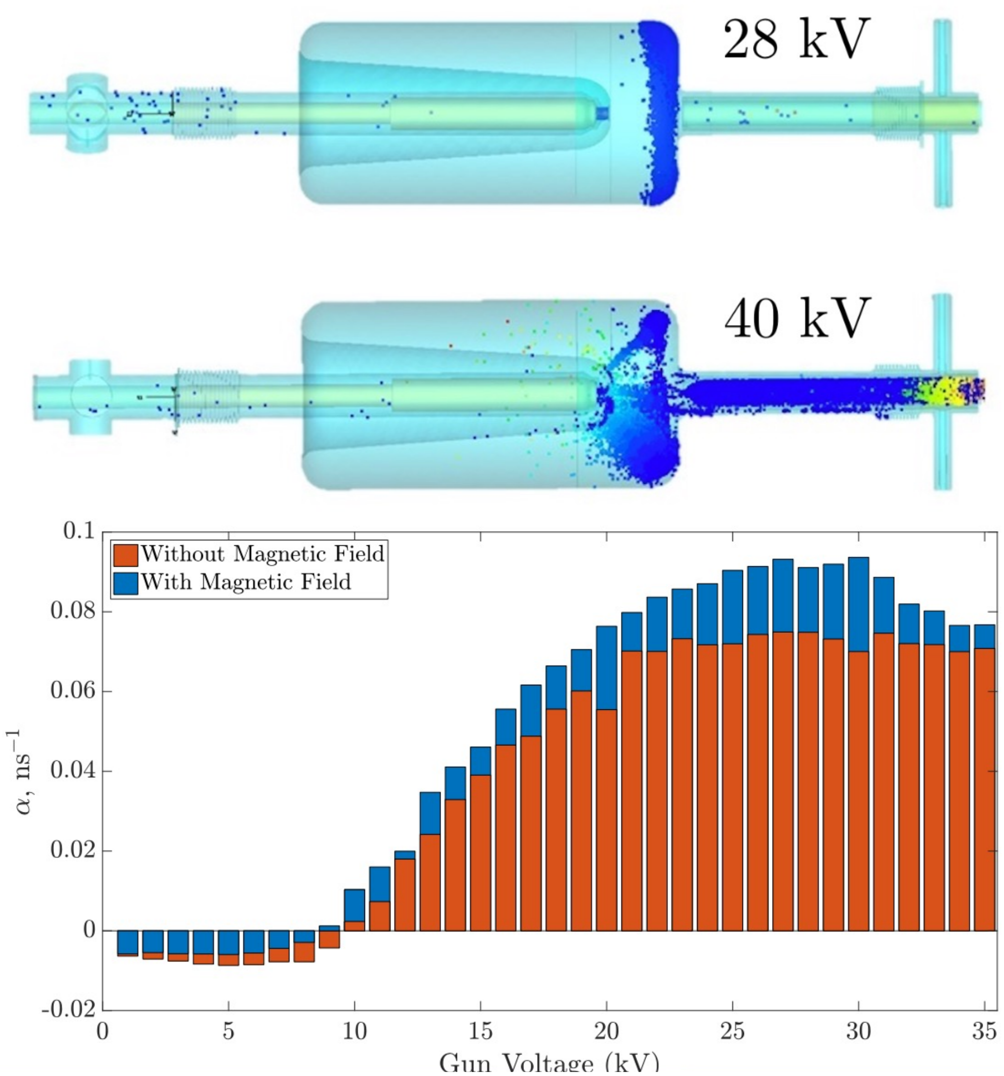




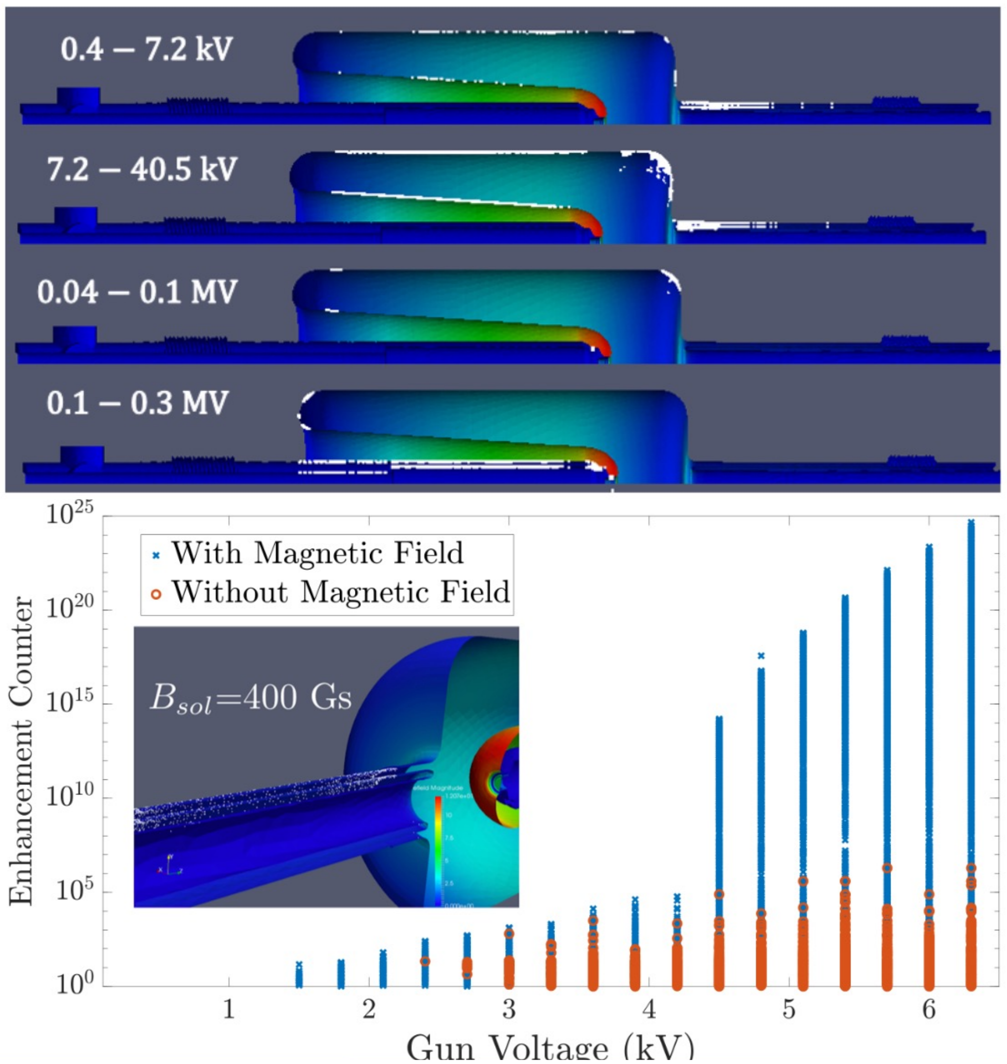


Multipacting Simulations

CST Particle Studio



ACE3P (Track3P)



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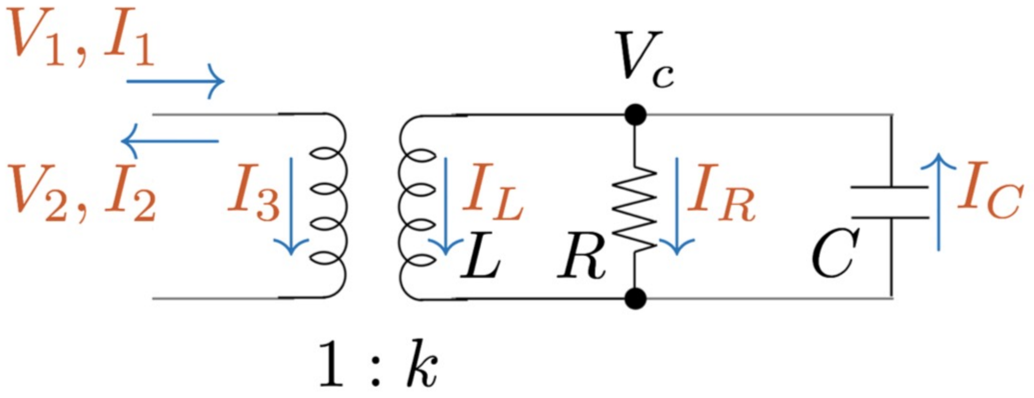
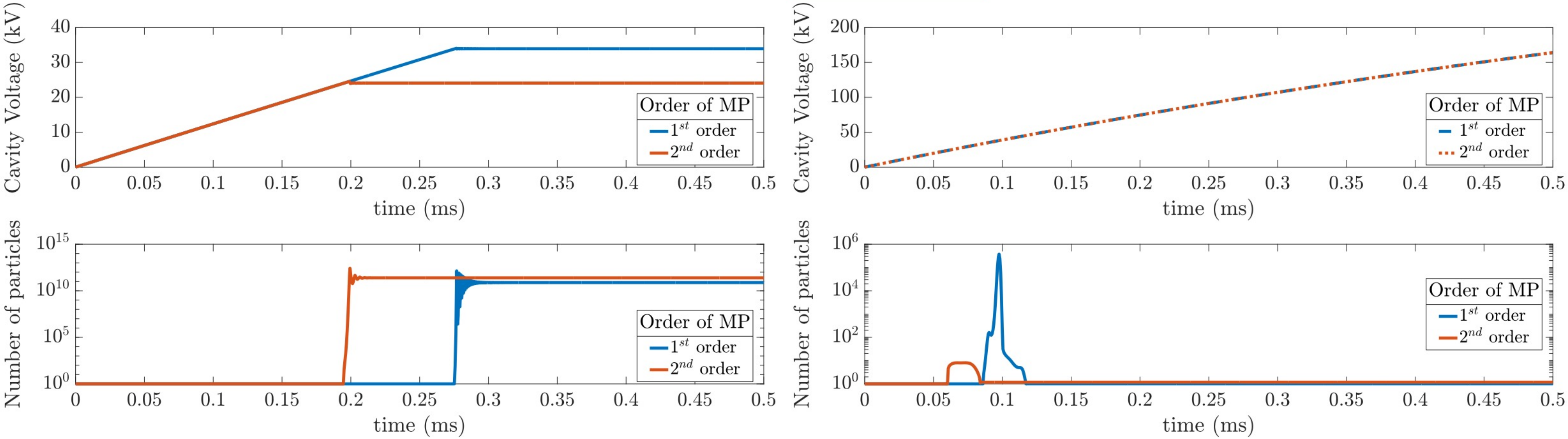
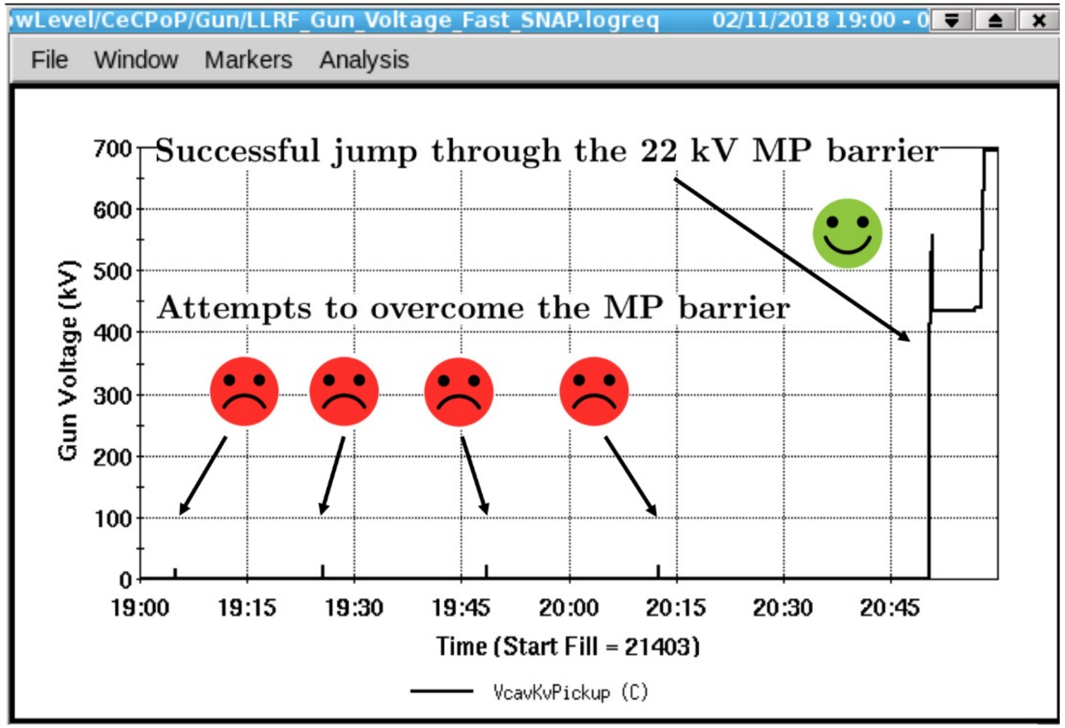
Overcoming multipacting: equivalent cavity model



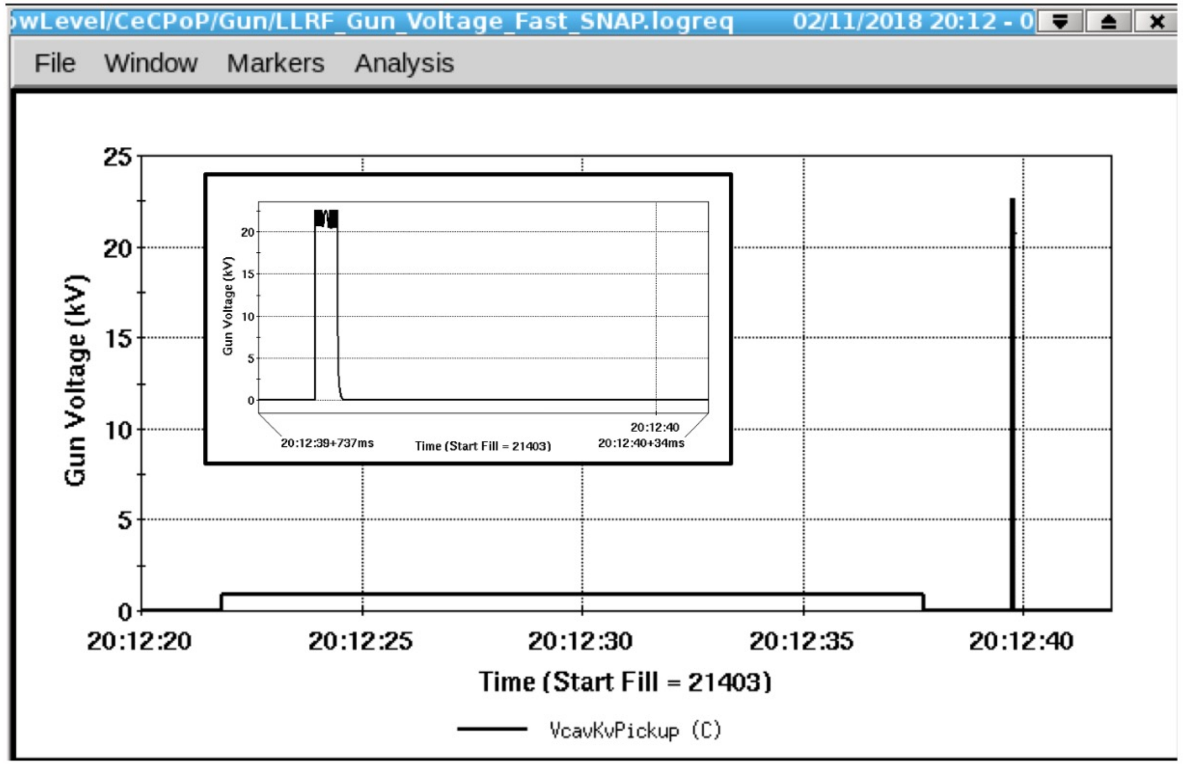
$$\begin{cases} \dfrac{d|V_c|}{dt} = \dfrac{1}{2\tau}\left(|V_0| - |V_c|\right) - f_0 \delta V_{mp} \dfrac{eN_e(t)}{2Q_0|V_c|} \omega_0 R_{sh} \\ \dfrac{dN_e}{dt} = \alpha(|V_c|) N_e \end{cases}$$



Example of Cavity Turn On Attempt with Strong MP



- Four repeated attempts to turn on result in getting stuck at 22 kV MP barrier.
- Attempts last only 20 ms, controlled by LLRF MP trap code.
- Prevents significant energy deposition ⇒ vacuum activity which would kill cathode QE.



- Lengthen period between attempts from ~ 20 min to ~ 40 min ⇒ 5^{th} attempt = successful turn on.
- Cathode QE not impacted by turn on attempts as MP related vacuum activity is kept minimal.

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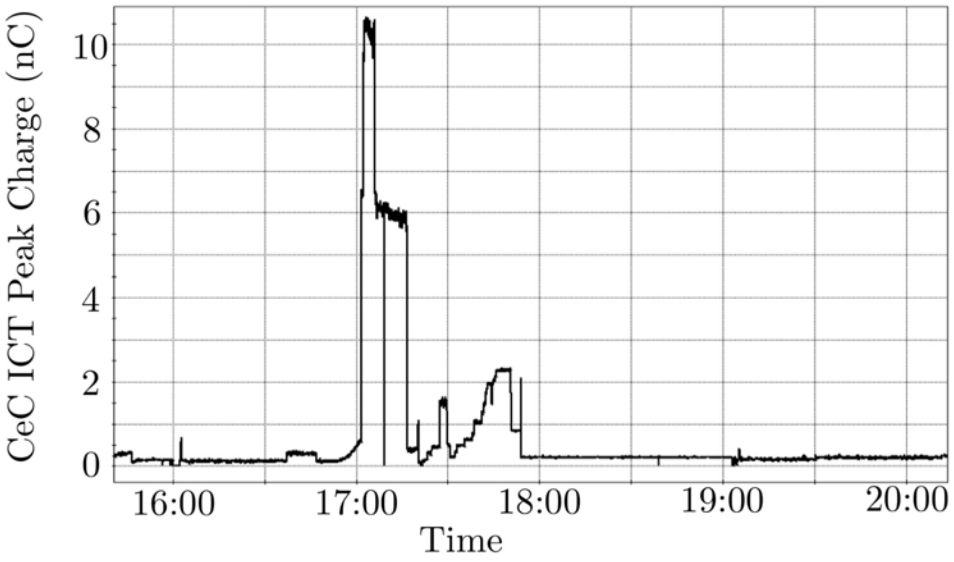
Performance Summary

Good emittance, long cathode lifetime, high bunch charge!

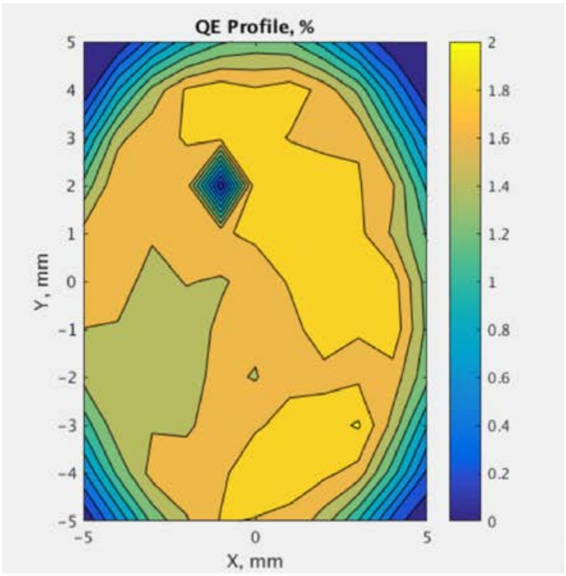
Normalized emittance for a 100 pC, 400 ps e-beam	
Projected emittance, mm-mrad	0.30
Slice emittance, mm-mrad	0.15

Normalized emittance for a 600 pC, 400 ps e-beam	
Projected emittance, mm-mrad	0.57
Slice emittance, mm-mrad	0.35

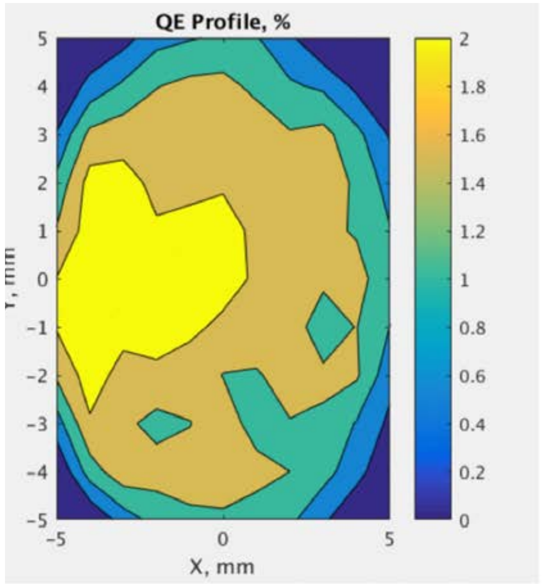
Transverse emittance from our SRF gun satisfies the requirements for a CW X-Ray FEL (0.4 mm-mrad for 100 pC bunches)!



QE map after 1 month of operation



Before



After

What did we learn?

- RF guns have demonstrated reliable performance in routine operation.
- Current designs have the potential to reach the high brightness requirement of modern XFELs and high average current for ERL.
- There are still unanswered questions to be investigated:
  - Proper cathode solution is a key for the successful gun operation
  - Improved cavity gradient is pursued
  - High-QE long lifetime cathodes are a must
  - Effort on lowering the beam emittance: retracted cathode, higher field at the cathode

Thank you for listening!