Multipacting Simulations for the CeC PoP Superconducting Photo-electron Gun

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Overview

Photoinjectors Overview

There are 3 types of photoinjectors:

- DC gun:
  - + easily provide continious wave (CW) electron beams;
  - – low electric field strength at the cathode surface;
  - – short accelerating gap;
- Normal Conducting RF (NCRF) gun:
  - + produce high quality beams;
  - – high dissipated RF power;
- Superconducting RF (SRF) gun:
  - + dissipated power is reduced by several orders of magnitude;
  - – but...

Advantages and Challenges of SRF Guns

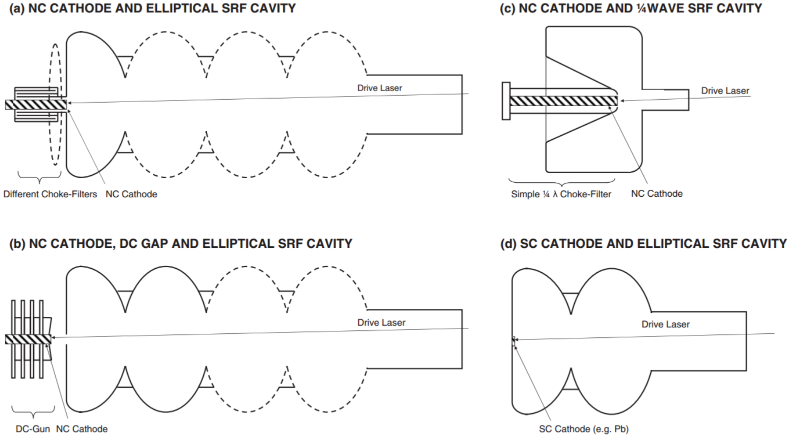
Advanatges:

- Operation in CW mode
- Low RF power losses
- Higher rate of acceleration

Disadvanatges:

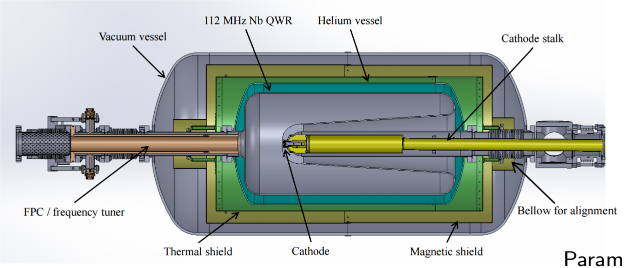
- Cryogenic plant is required with its power consumption;
- Cathode must be inserted into the SRF cavity → degradation of the cavity performance;
- Removable cathodes are needed → power is leaking out of the cavity along the cathode channel;
- Emittance compensation by solenoid magnets placed around the cavity is impossible → breakdown;
- Multipacting.

Types of SRF guns



A. Arnold and J. Teichert *Overview on superconducting photoinjectors*.

112 MHz SRF gun at BNL



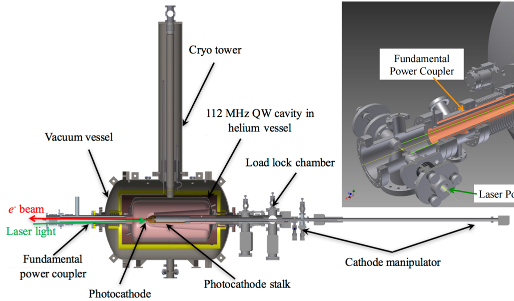
Parameters of the SRF Gun

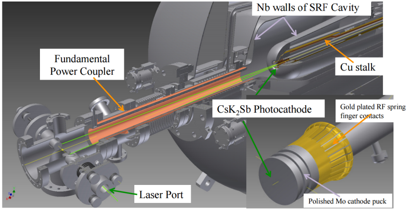
Frequency	112 MHz
Geometry factor	38.2 Ohm
R/Q	126 Ohm
Quality factor w/o cathode	$3.5 \cdot 10^9$
Operating temperature	4.5 K
Accelerating voltage	1.5 to 2.0 MV

T. Xin et. al. *Design of a High-bunch-charge 112-MHz Superconducting RF Photoemission Electron Source.*

112 MHz SRF Gun: FPC and the cathode

- Fundamental RF power coupling and fine frequency tuning is accomplished via a coaxial beam pipe at the beam exit port;
- With the travel of ± 2 cm, the tuning range will be ~ 4 kHz;

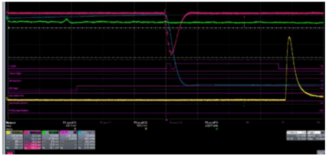




S. Belomestnykh et.al., Commissioning of the 112 MHz SRF Gun

- A small cathode puck is inserted inside the stalk and can be replaced when necessary with a new one.

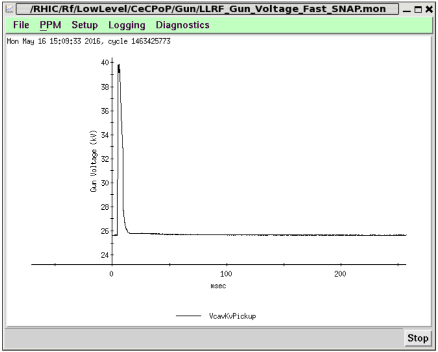
Gun performance issues during Run'16



I. Pinayev et.al.,Commissioning of the CeC PoP

- When turning on the RF power strong multipacting was observed, which substantially reduced quantum efficiency of the cathode.
- Main multipacting levels are:
  - 2.3 kV;
  - 19 kV;
  - 27.5-28 kV;
  - 40 kV

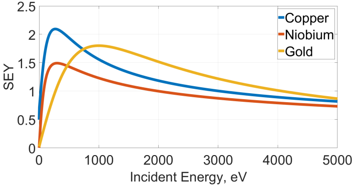
- 3.7 nC beam charge was observed during the commissioning;
- achieved cavity voltage was 1.2 MV;
- duration of the laser pulse was 1 ns.

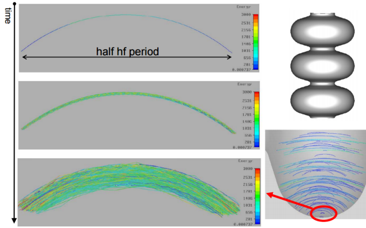


What is multipacting?

Multipactor discharge (multipacting) is a resonant process in which an electron avalanche builds up within a small region of the cavity surface and is determined by the following factors:

- electric field levels;
- geometry of the cavity;
- material properties — Secondary Emission Yield (SEY).

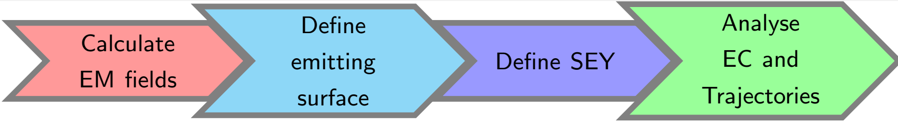


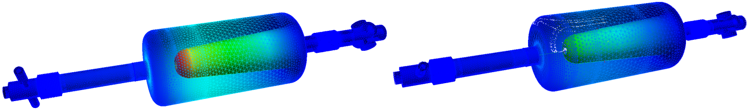


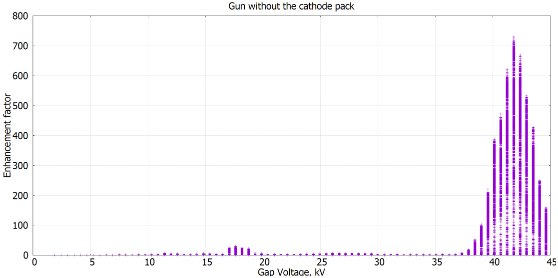
CST PS Manual

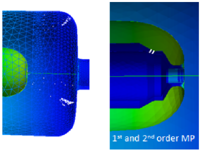
An electron avalanche absorbs large amounts of RF power and deposits it as a heat.

How to perform a MP simulation:









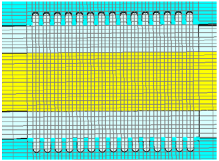
CST: slow simulation with a poor mesh

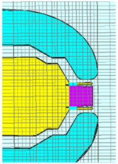
Advantages:

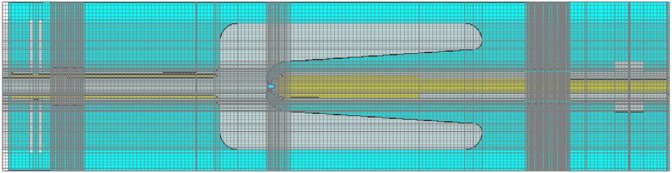
- Allows to set all material properties;
- Allows to do simulations with external magnetic field.

Disadvantages:

- Its possible to use only Hexahedral mesh;
- Simulations take a long time (days) with 2 license spots being available.

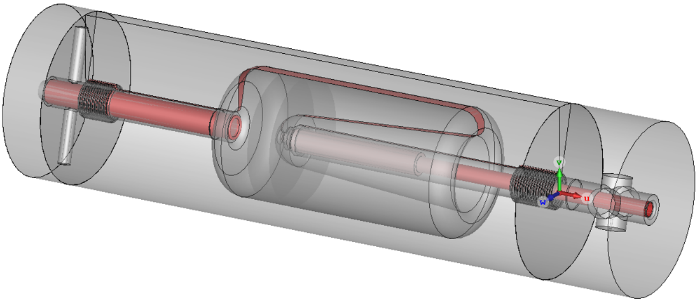






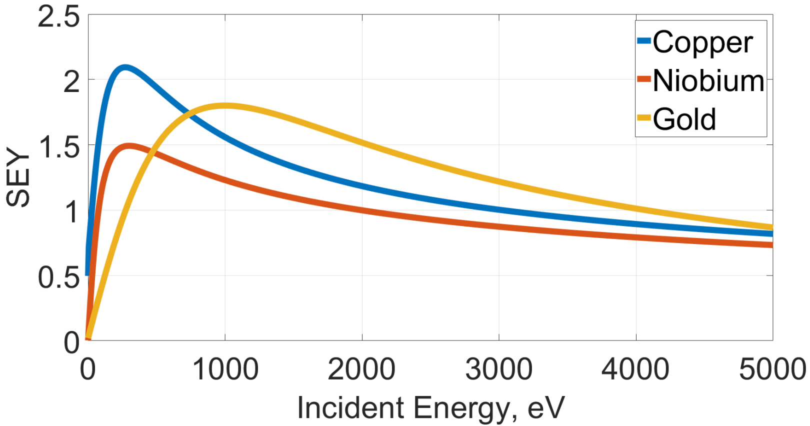
CST: General Settings

Source of the primary particles:



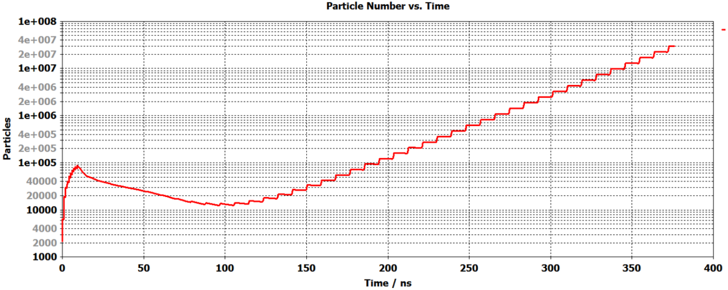
- SEY for all materials is taken from the CST material library except for CsK_2Sb SEY $= 100$;
- Primary particles emit during first 10 RF cycles;
- Simulations were performed for at least 40 RF cycles.

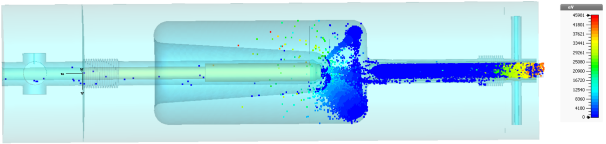
CST: SEY


Copper
Niobium
Gold
SEY
Incident Energy, eV
0
0.5
1
1.5
2
2.5
0
1000
2000
3000
4000
5000

CST: 40 kV level is found!

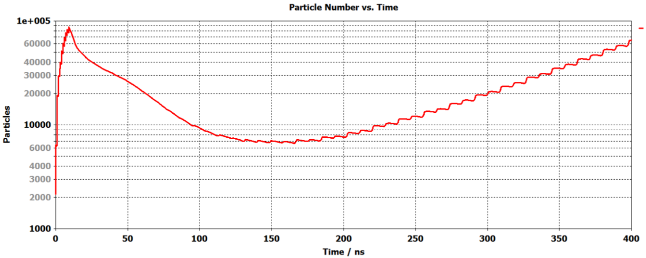
Known MP level at 40 kV:

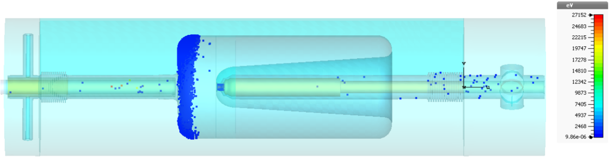




CST: 28 kV level is found!

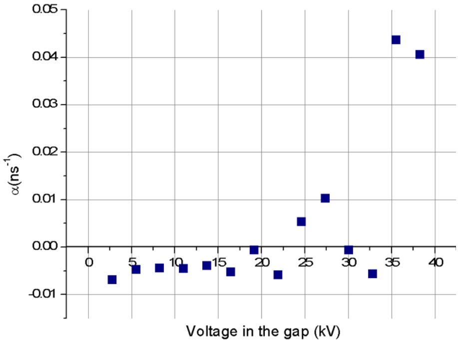
Known MP level at 28 kV:

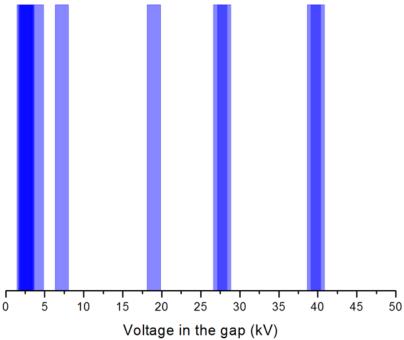




CST vs. Conditioning: didn't find all the levels

If we describe the exponential multipacting growth as $N = N_0 e^{\alpha t}$:





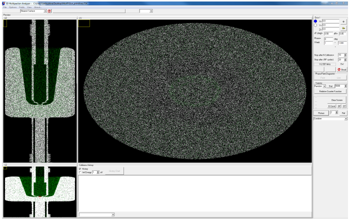
MultP-M: software from NRNU MEPhI

Advantages:

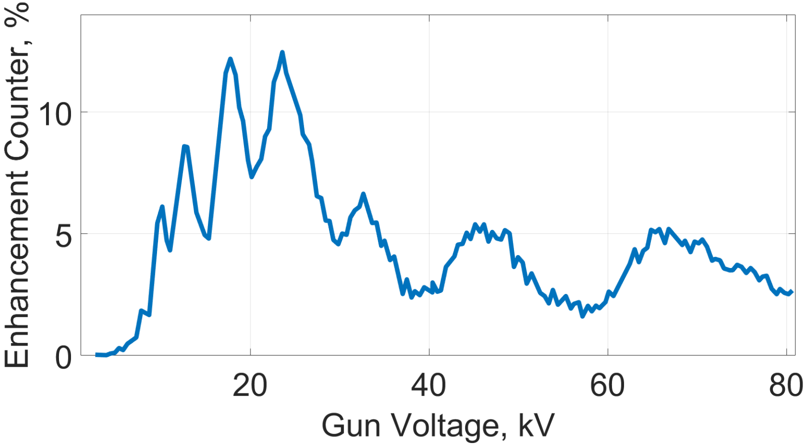
- Allows to calculate Enhancement Counter and study single trajectories;
- It's possible to do simulations with external magnetic field.

Disadvantages:

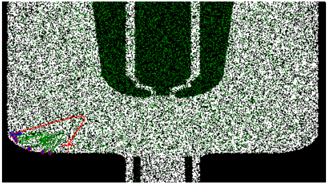
- Relatively slow (few hours);
- Allows to use only 1 SEY for the whole geometry.



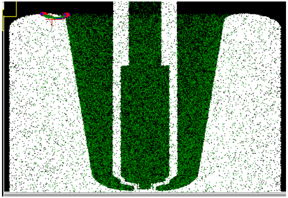
MultP-M: Enhacement Counter



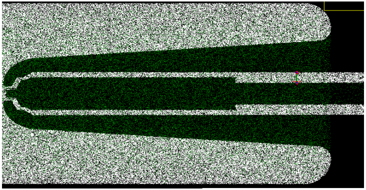
MultP-M: stable trajectories



32-90 kV $2^{nd}\&1^{st}$



160-710 kV



412-1034 kV, 1034-1200 kV, 1^{st}

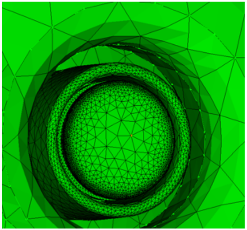
ACE3P: the best approach so far

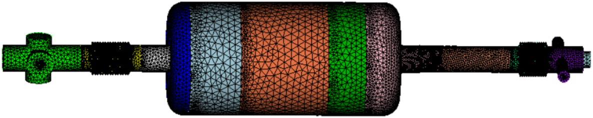
Advantages:

- Using parallel computing at NERSC;
- Allows to do simulations with external magnetic field;
- Performs Enhamcement Counter calculations along with the single trajectory tracking.

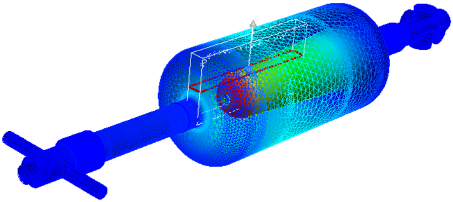
Disadvantages:

- Its possible to set only 2 different SEY curves;
- Not very user-friendly.

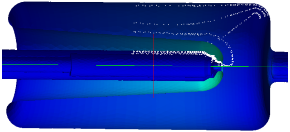




Track3P: General Settings



Source of the primary electrons.

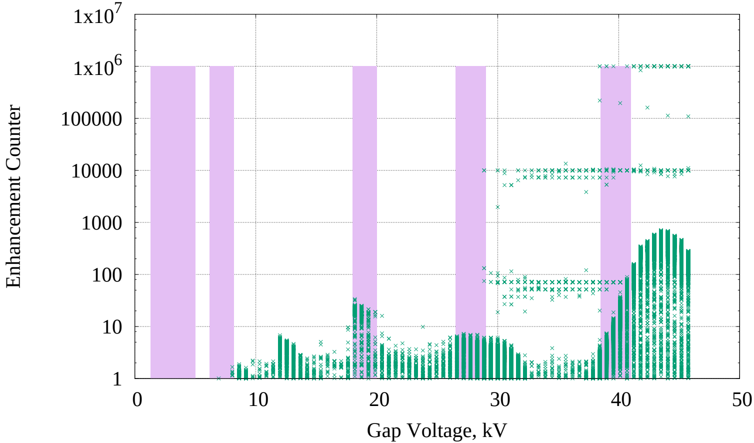


Close-up of the primary electrons source.

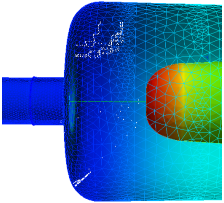
Material settings:

- Cathode - SEY = 100 for all energies;
- Everything else - copper.

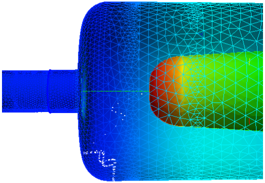
Puck 0 Recess Vs. Commissioning Data



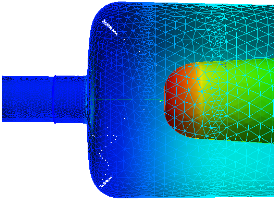
Peak at 11 kV and 18 kV



11 kV, 5^{th} order

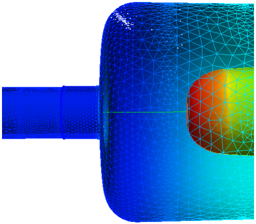


18 kV, 2^{nd} order, impact energy 350 eV

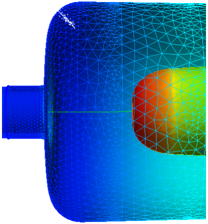


18 kV, 2^{nd} order

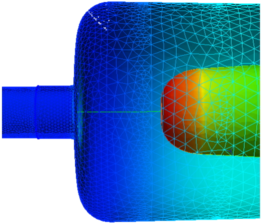
27-37 kV



27 kV, 2^{nd} order, impact energy 220 eV

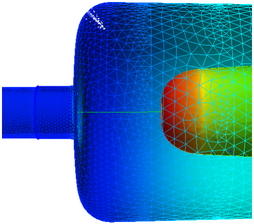


27 kV, 2^{nd} order, impact energy 215 eV

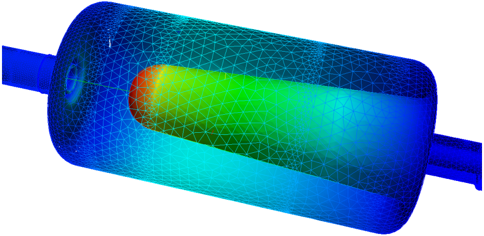


36 kV, 1^{st} order, impact energy 200-300 eV

40-45 kV

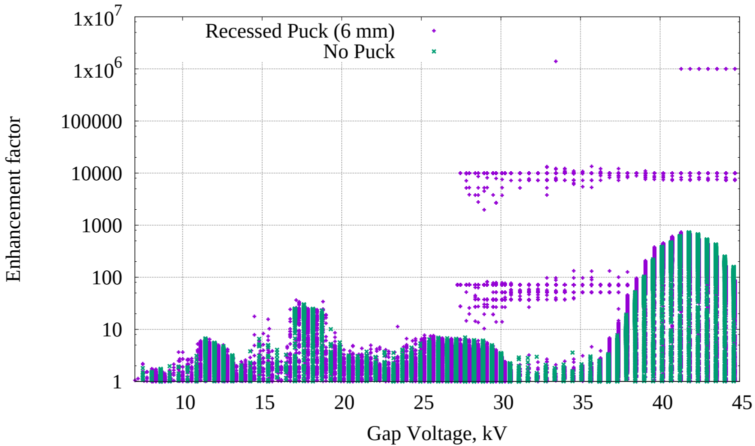


45 kV, 1^{st} order, impact energy 1.43 keV

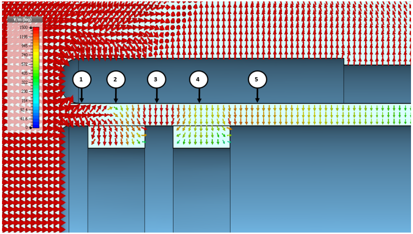


45 kV location of the MP trajectories

No Puck Vs. With Puck (6 mm)



MP in the stalk-to-cathode gap



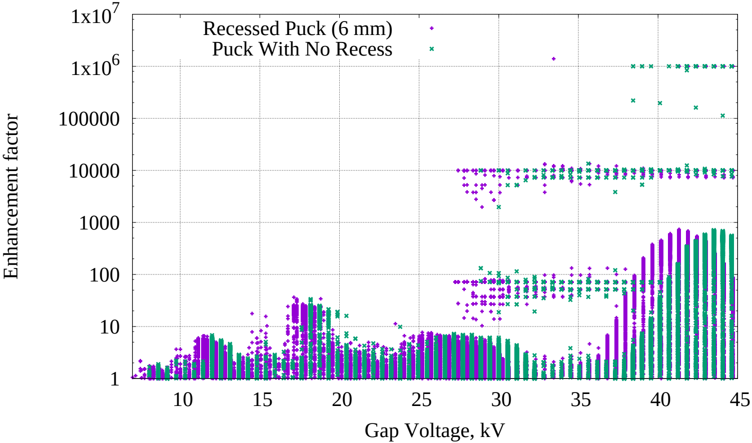
$$V_{min} = \frac{m\omega^2 x^2}{e} \frac{1}{\sqrt{4 + (2n+1)^2\pi^2}}$$

where x - distance between the two surfaces, ω - resonant frequency, m, e - mass and charge of an electron.

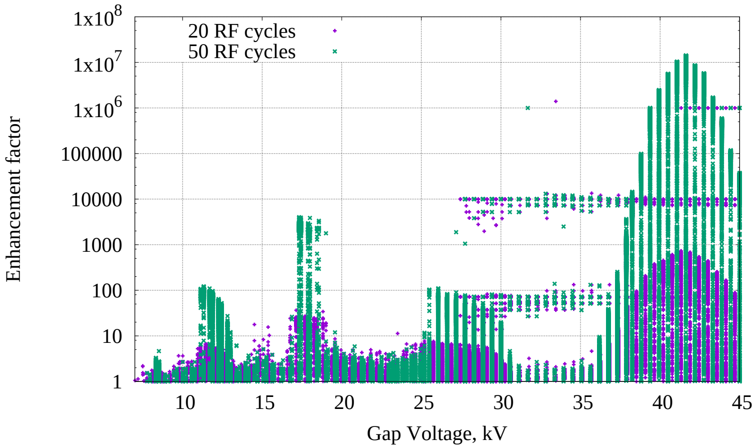
$$V_{max} = \frac{m\omega^2 x^2}{2e}$$

Gap #	$V_{min}(n=2)$, kV	$V_{min}(n=1)$, kV	V_{max}, kV
1	-	-	-
2	159	414	771
3	65	167	312
4	473	1224	2280
5	158	408	760

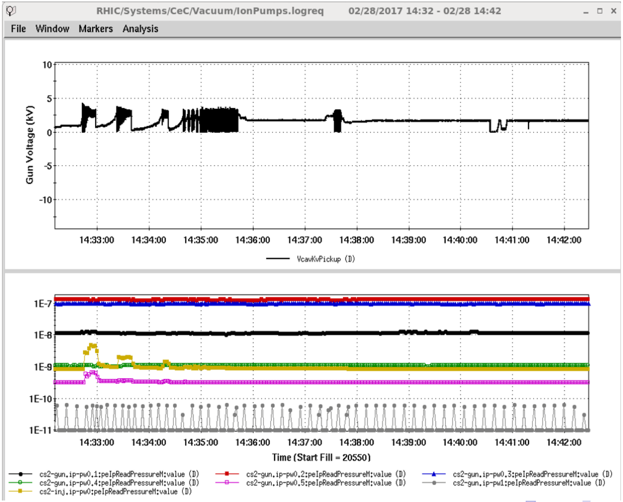
Puck 0 Recess Vs. Recessed Puck (6 mm)



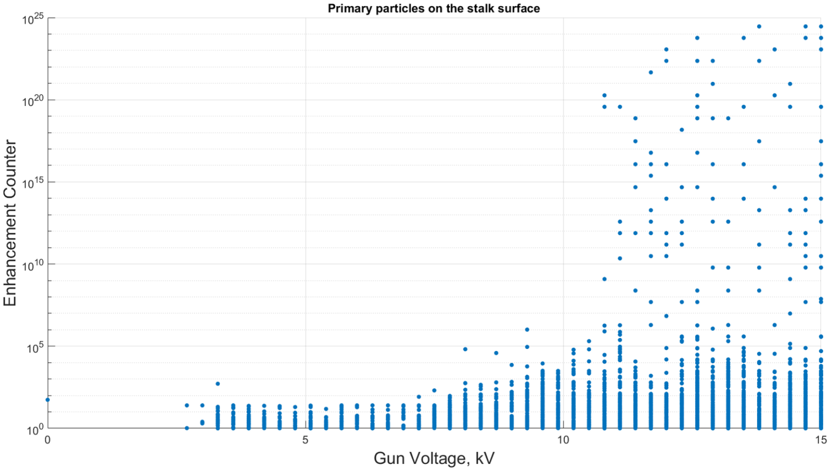
Recessed Puck after 20 and 50 RF cycles



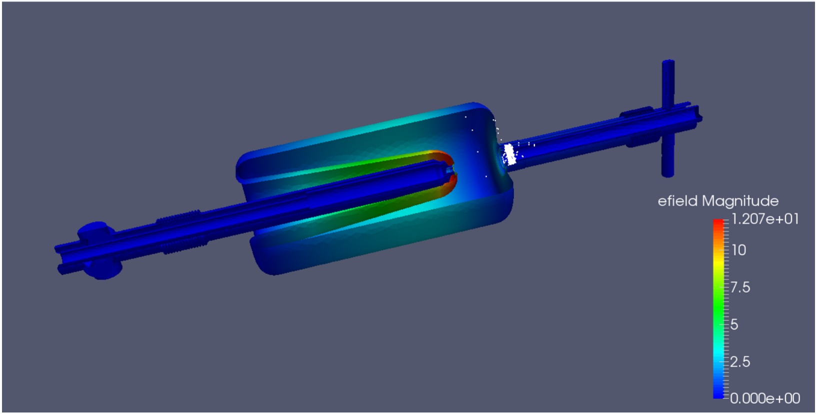
Pressure rise in the stalk at low voltage



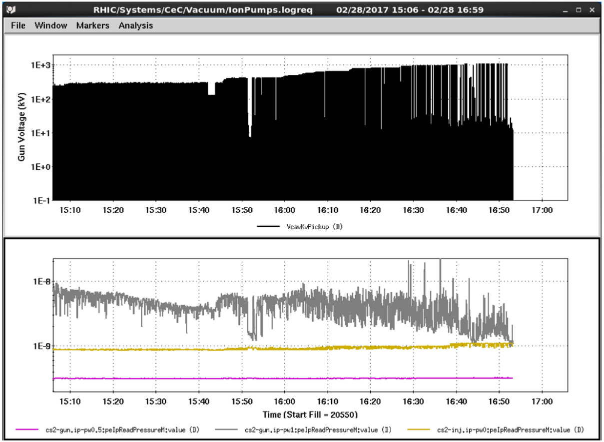
MP in the stalk is found!

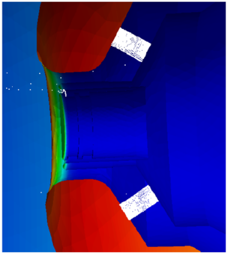


MP trajectories migrated to FPC



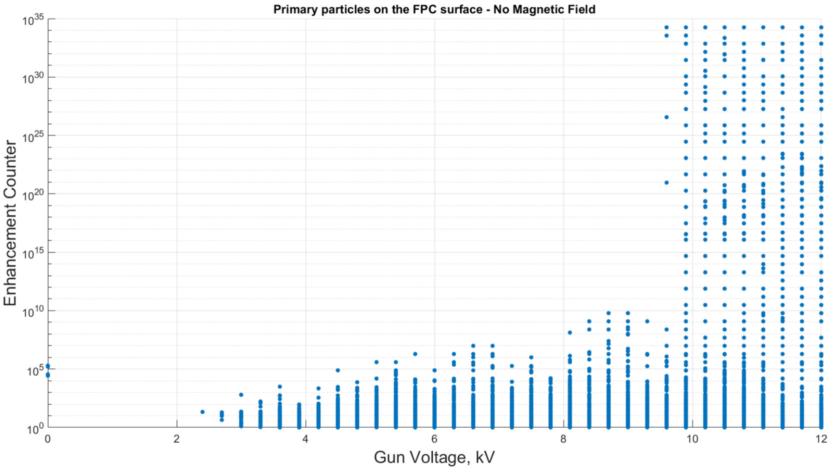
MP at high voltages in the stalk



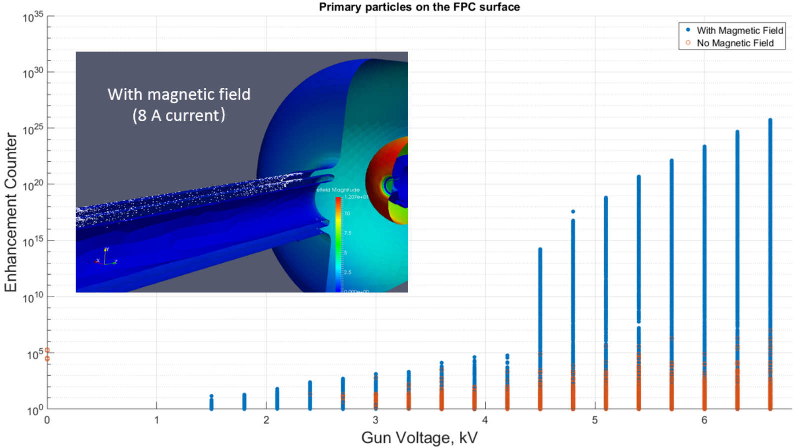


Stable trajectories at 850 kV

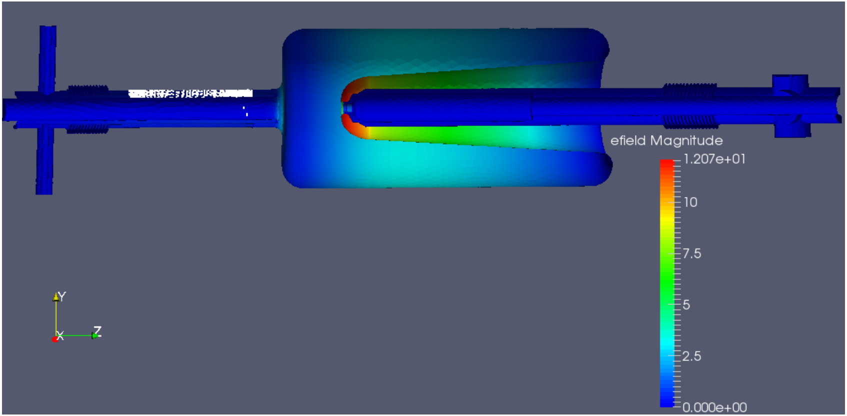
MP in FPC - no magnetic field



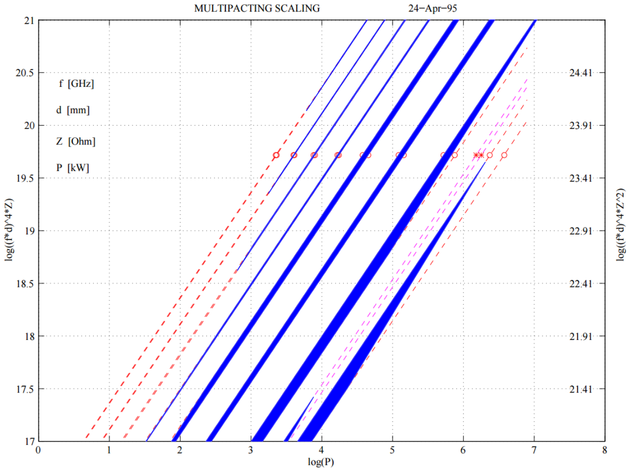
MP in FPC: with and without magnetic field



Stable trajectories in FPC



Analytical Approach



Multipacting bands in coaxial lines. Analysis of multipacting in coaxial lines, E. Somersalo

Comparison: not a good agreement

Cavity region	MP levels (kV) and order			
	Omega3P	CST	MultP	Estimations
Top rounding	11-13, 5^{th} 17-18, 2^{nd} 27-37, $2^{nd}\&1^{st}$ 40-45, 1^{st}	24-30, 34-44	32-90 $2^{nd}\&1^{st}$	-
Bottom rounding	-	-	$160 - 710$	-
Stalk	-	-	412-1034, 1034-1200, 1^{st}	327 - gap
FPC	1.5 - ?	-	Nothing	8.6-22
FPC+Solenoid	3 - ?	-	-	-

Conclusion

- Multipacting is an important phenomena which can be a serious issue for the performance of SRF cavities;
- All the methods of MP simulation found that the 112 MHz SRF gun undergoes multipacting at levels of voltage around 30-45 kV with stable trajectories located in the top rounding of the cavity;
- FPC undergoes multipacting at low levels of the gun voltage, and the stable trajectories in this area and stalk area must be studied in more details.

Thank you for your attention!

References

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- T.P. Wangler, *RF Linear Accelerators*, 2008.

Back-up slides

SRF gun requirements:

- **Low Emittance**: high acceleration rate, RF focusing near the cathode, first solenoid as close to the cavity as possible, precise synchronization of a laser with RF;
- **High bunch charge at high repetition rate**: develop high QE photocathode with long life time, high average power, high repetition rate lasers;
- **Stable gun operation**: handling of high average RF power, managing parasitic kicks from input power couplers, effective damping of higher-order modes.

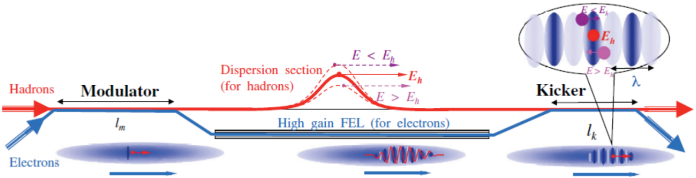
Coherent electron Cooling

Cooling:

reduces beam phase space volume, emittance and momentum spread in order to improve beam quality.

How does it work:

- In the modulator, each hadron induces density modulations in electron beam;
- Density modulation is amplified in the high-gain FEL;
- In the kicker, hadrons interact with the self-induced electric field of the electron beam and receive energy kicks toward their central energy;
- The process reduces the hadrons energy spread, i.e. cools the hadron beam.



Requirements for the CeC

Goal:

demonstration of longitudinal (energy spread) cooling of a single bunch of 40 GeV/u Au ions in RHIC

In order for the CeC to work, it is requered for the electron and hadron beams to have the same velocity:

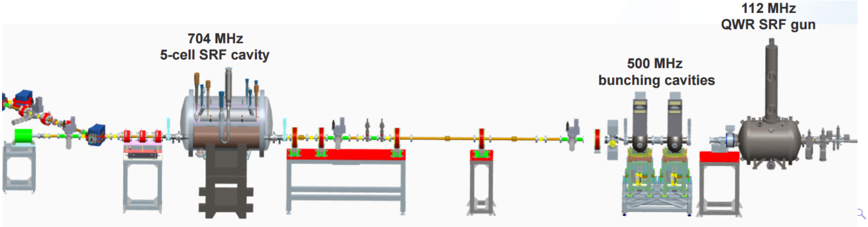
$$\gamma_e = \gamma_h = \frac{1}{\sqrt{1-(v/c)^2}}$$

$$E_e = \gamma_h \cdot m_e c^2 \approx 22 \text{ MeV}$$

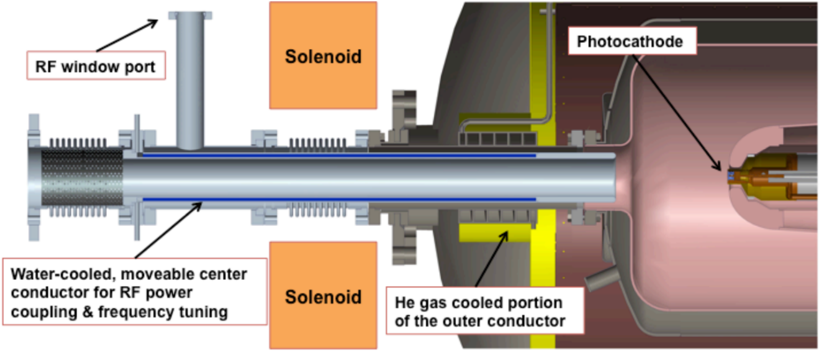
SRF system layout

From right to left:

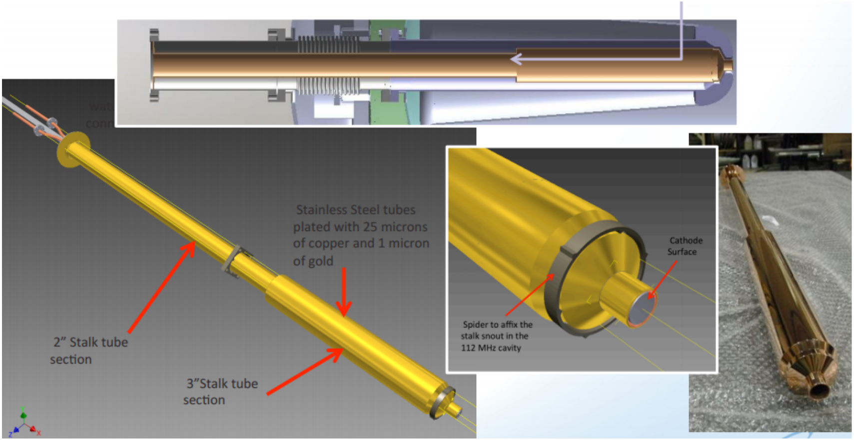
- The SRF gun operating at 112 MHz will generate 2 MeV high-charge (several nC), low repetition rate (78 kHz) electron beam;
- Two single cell normal conducting bunching cavities operating at 500 MHz frequency will provide required energy chirp in the beam creating velocity difference along the bunch;
- The 704 MHz 5-cell SRF cavity (BNL3) is used to achieve desired energy of 22 MeV.



FPC


RF window port
Solenoid
Photocathode
Water-cooled, moveable center conductor for RF power coupling & frequency tuning
Solenoid
He gas cooled portion of the outer conductor

Stalk


Stainless Steel tubes plated with 25 microns of copper and 1 micron of gold
2" Stalk tube section
3"Stalk tube section
Cathode Surface
Spider to affix the stalk snout in the 112 MHz cavity