High Brightness CW Electron Beams From Superconducting RF Photoinjector

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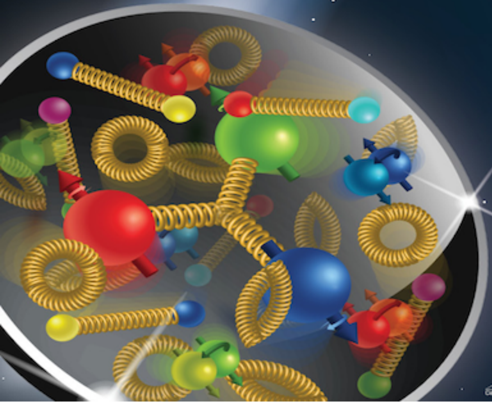

Electron Ion Collider – eRHIC

CASE Center for Accelerator Science and Education
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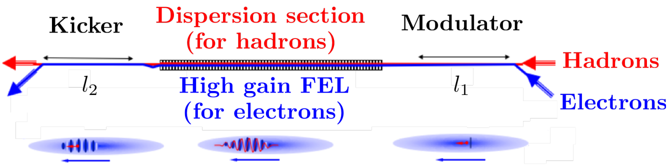
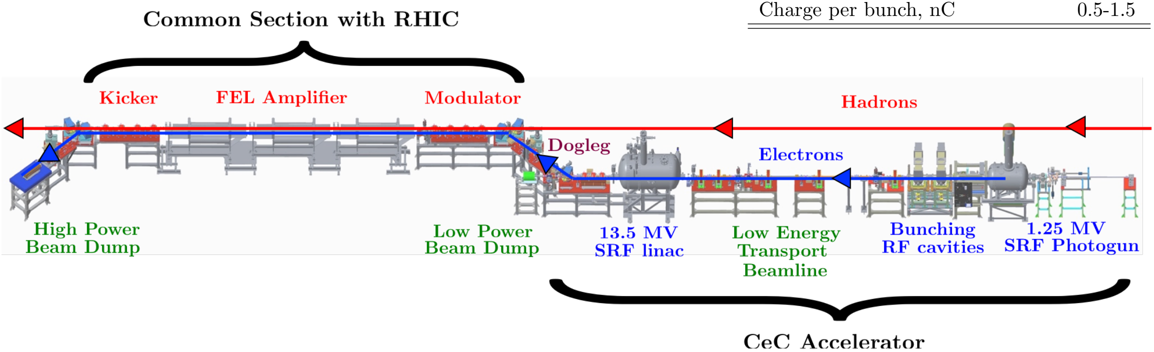
Contents

1. Coheren electron Cooling Proof of Principle Experiment
2. Brief overview of existing SRF photoinjectors
3. 113 MHz SRF photoinjector: design, challenges and performance
4. Conclusions and future plans

Coherent electron Cooling: Proof of Principle Experiment



Required e-beam parameters	
Relativistic factor γ	28.5
RMS energy spread	$3 \cdot 10^{-4}$
Normalized emittance, mm-mrad	<8
Peak current, A	50-100
Relative energy spread,%	0.1
Charge per bunch, nC	0.5-1.5



For updates check out: TUPLM07, TUPLH24.

SRF photoinjectors—challenging, but rewarding creations

Pros:

- Good vacuum inside Nb cavity at 2K/4K
- Relatively high accelerating gradients
- CW operation

Cons/Questions:

- Are high-QE cathodes compatible with SRF?
- Can high-QE cathodes survive in an SRF cavity?
- How to keep cathodes at room temperature without causing multipacting (MP)?
- How to get to operational voltage without causing MP and killing cathode?
- Dark current?
- Cryopumping?

It is expensive and challenging—hence, there are very few operational SRF guns!

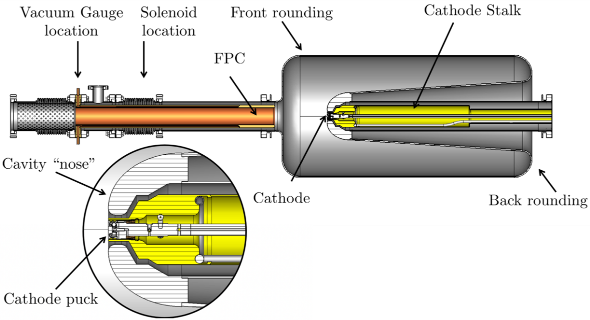
Overview of existing SRF photoinjectors

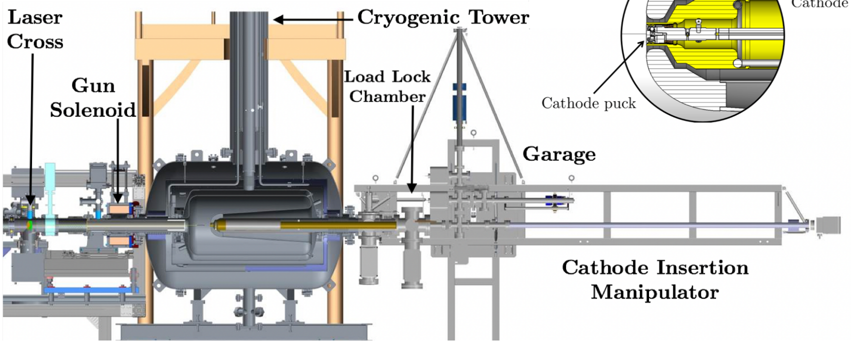
Parameter	CeC PoP	FZD[1]	HZB[2]	NPS[3]	UW[4]
Cavity type	QWR*	Elliptical	Elliptical	QWR	QWR
Number of cells	1	3.5	1.4	1	1
RF frequency, MHz	113	1300	1300	500	200
LiHe Temperature, K	4	2	2	4	4
Beam energy, MeV	1.25-1.5	3.3	1.8	0.47	1.1
Charge per bunch, nC	10.7	0.3	0.006	0.078	0.1
Beam current, μA	150	18	0.005	<0.0001	<0.1
Dark current, nA	<1	120	-	<20,000	<0.001
E_{cath}, MV/m	10-20	5	7	6.5	12
Photocathode	CsK_2Sb	Cs_2Te	Pb	Ni	Cu

*QWR—Quarter Wave Resonator

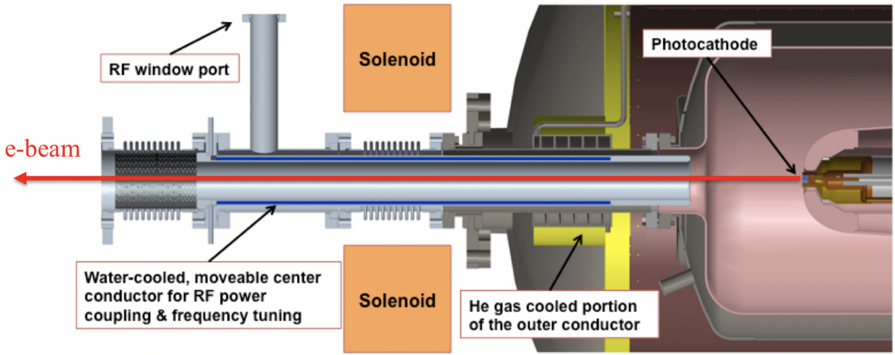
113 MHz SRF gun with warm CsK_2Sb photocathode

- 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





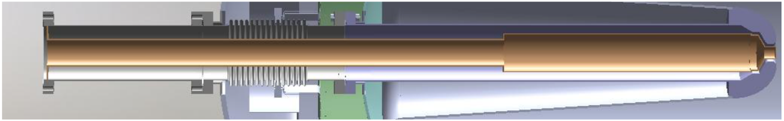
Fundamental Power Coupler (FPC)/ Frequency Tuner

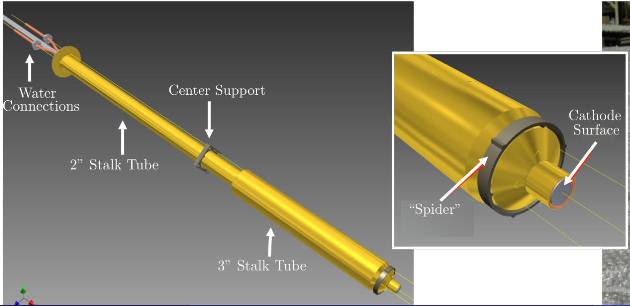


- Fundamental RF power coupling and fine frequency tuning is accomplished via a coaxial beam pipe and the beam exit port.
- With the travel of ± 2 cm, the tuning range is $\sim$6 kHz. Rough tuning is accomplished manually via mechanical linkages outside the cryomodule.
- The center conductor and RF windows 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.

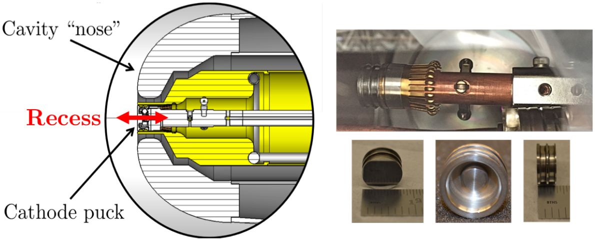
Cathode Stalk Design

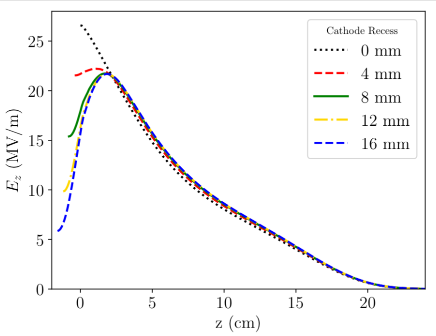
- The cathode stalk is a hollow center conductor of the coaxial line formed by the stalk and the cavity.
- The stalk is shorted at one end and is approximately half wavelength long.
- A quarter-wave step from the short creates an impedance transformer → reduces RF losses in the stalk from ∼65 W to ∼25 W.
- The gold plating reduces radiation heat load from the stalk.

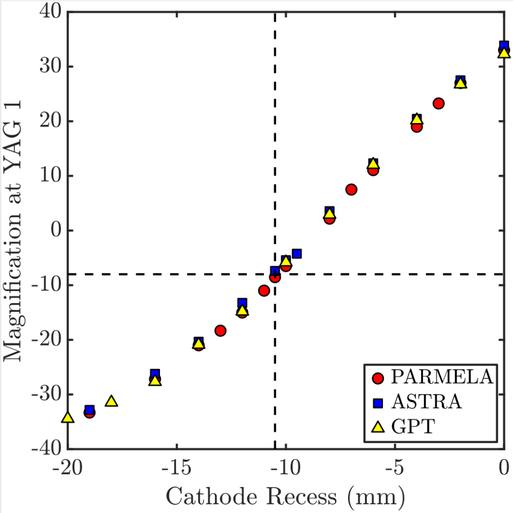




Controlling cathode recess → initial focusing of the beam

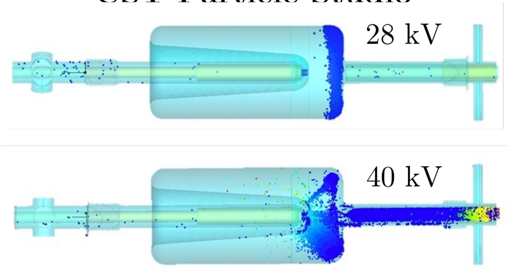


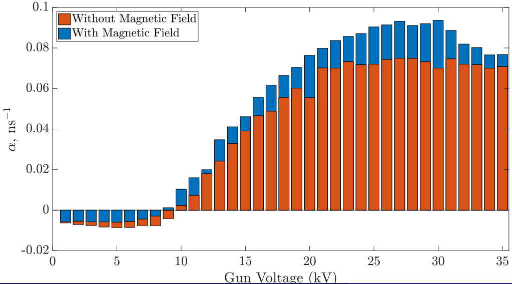




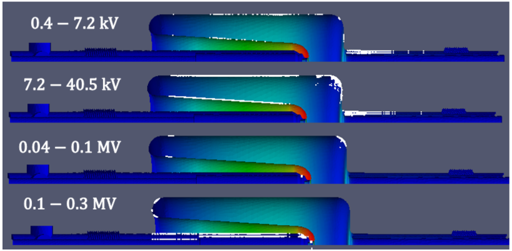
Multipacting: good agreement between the predictions and experiment

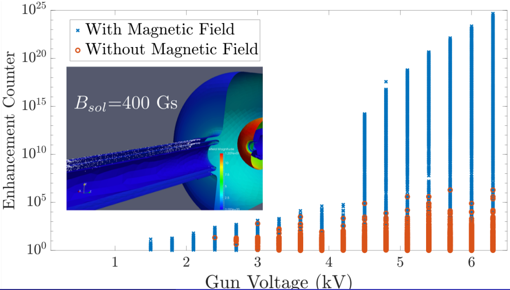
CST Particle Studio



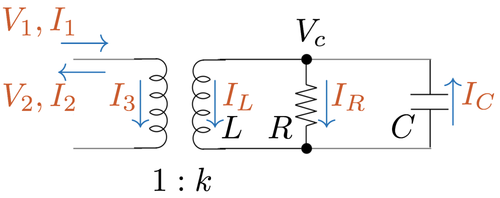


ACE3P (Track3P)

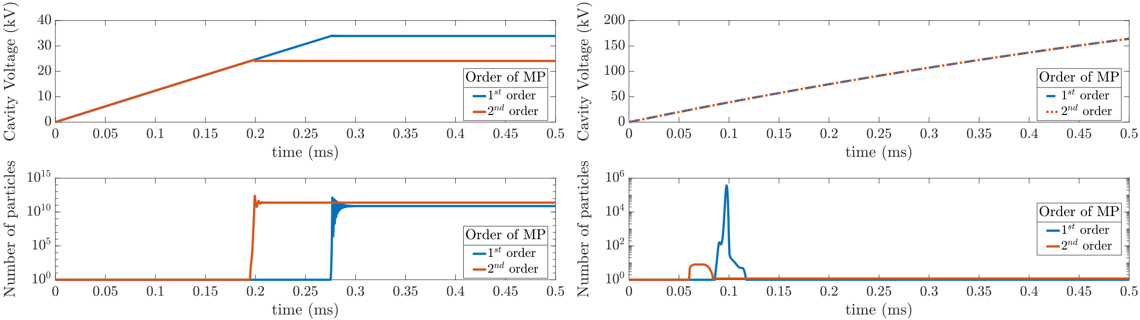




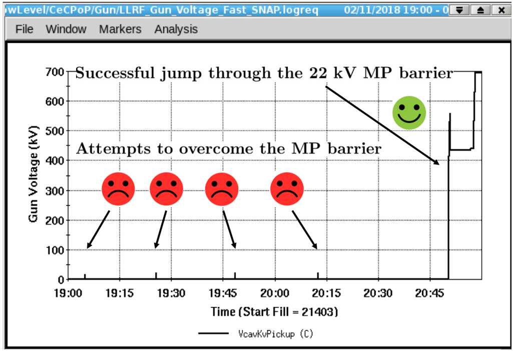
Multipacting Well Studied and Understood



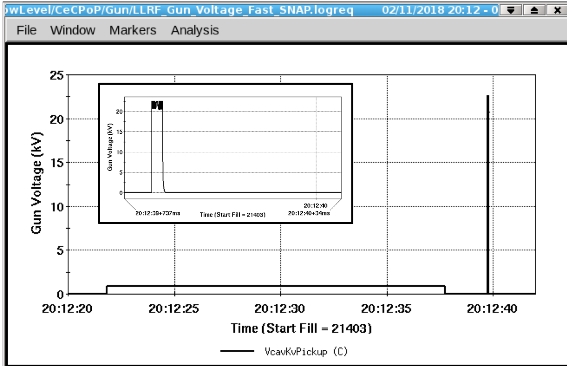
$$\begin{cases} \dfrac{d|V_c|}{dt} = \dfrac{1}{2\tau}\left(|V_0| - |V_c|\right) - f_0 \delta V_{mp} \dfrac{eN_e(t)}{2Q_0|V_c|}\omega_0 R_{sh} \\ \dfrac{dN_e}{dt} = \alpha(|V_c|)N_e \end{cases}$$



Example of Cavity Turn On Attempt with Strong MP

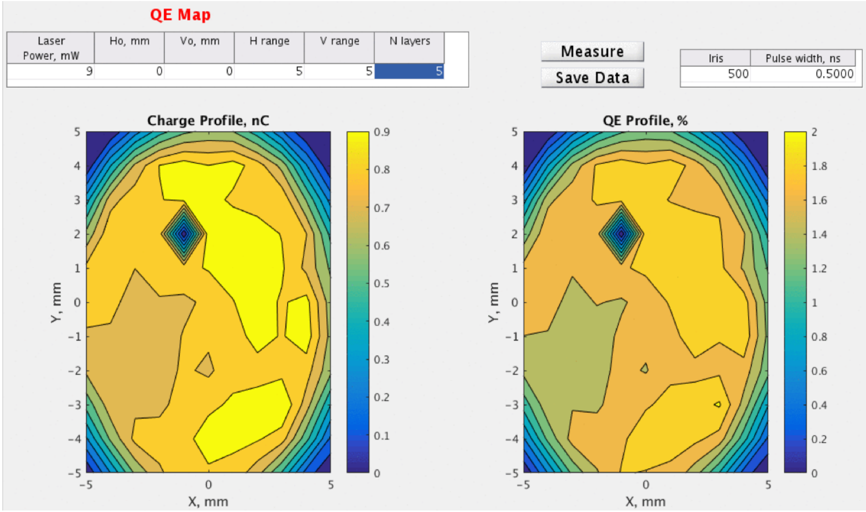


- Four repeated attempts to turn on result in getting stuck at 22 kV MP barrier.
- Attempts last only 20 ms, controlled by LLRF MP trap code.
- Prevents significant energy deposition ⇒ vacuum activity which would kill cathode QE.

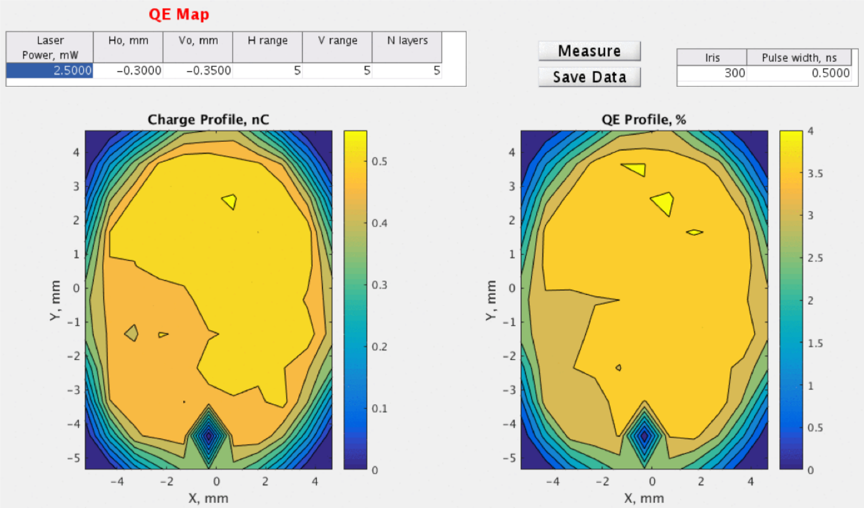


- Lengthen period between attempts from ∼ 20 min to ∼ 40 min ⇒ 5^{th} attempt = successful turn on.
- Cathode QE not impacted by turn on attempts as MP related vacuum activity is kept minimal.

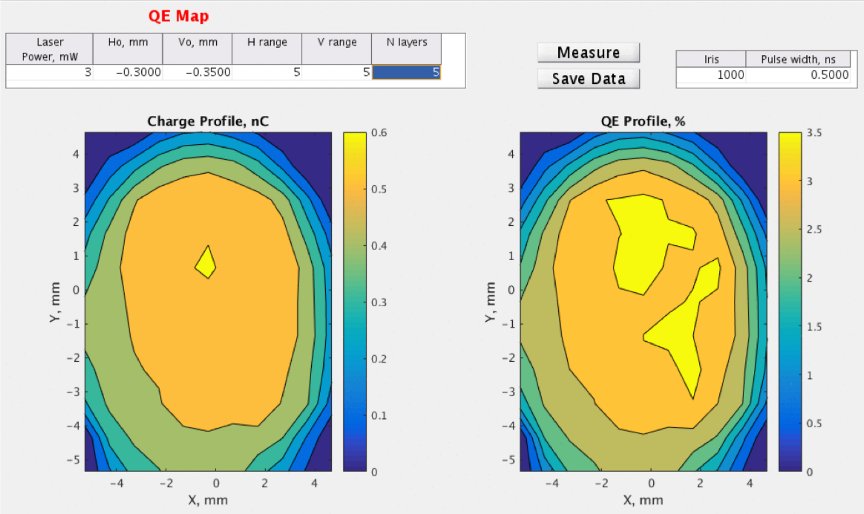
Initial QE map: June 7, 2018



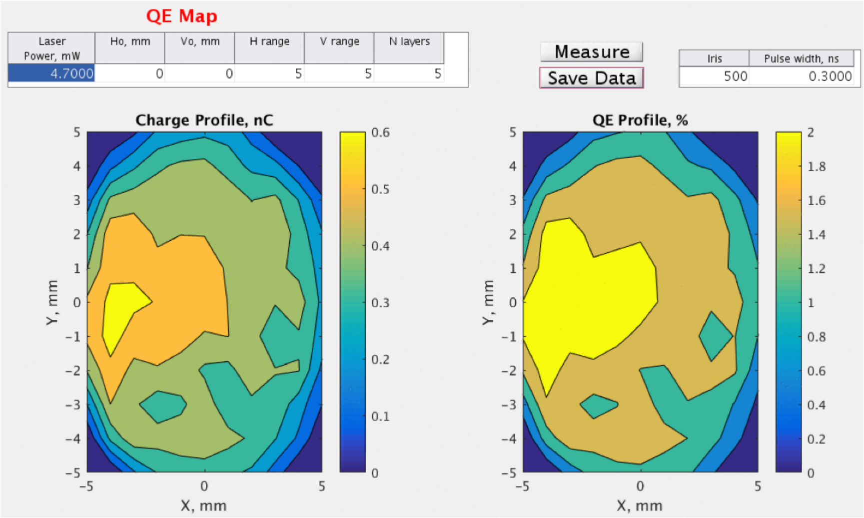
QE map: June 9, 2018



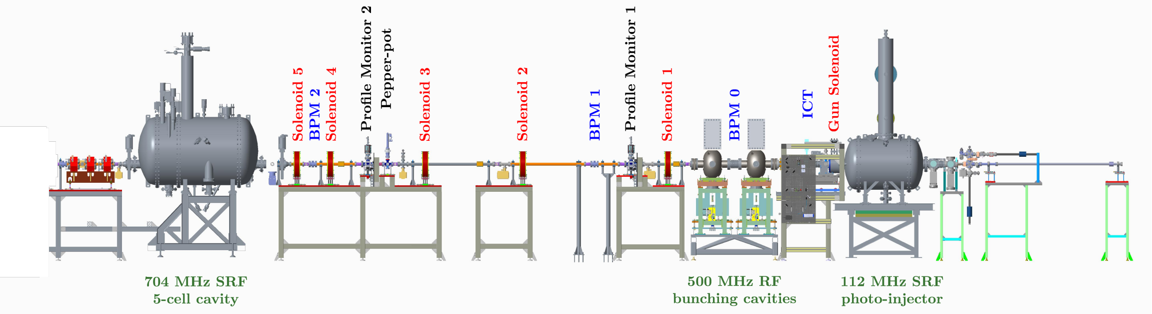
QE map: June 11, 2018



QE map after 1 month of operation



Unexpected and Exciting Results: Very Low Transverse Emittance

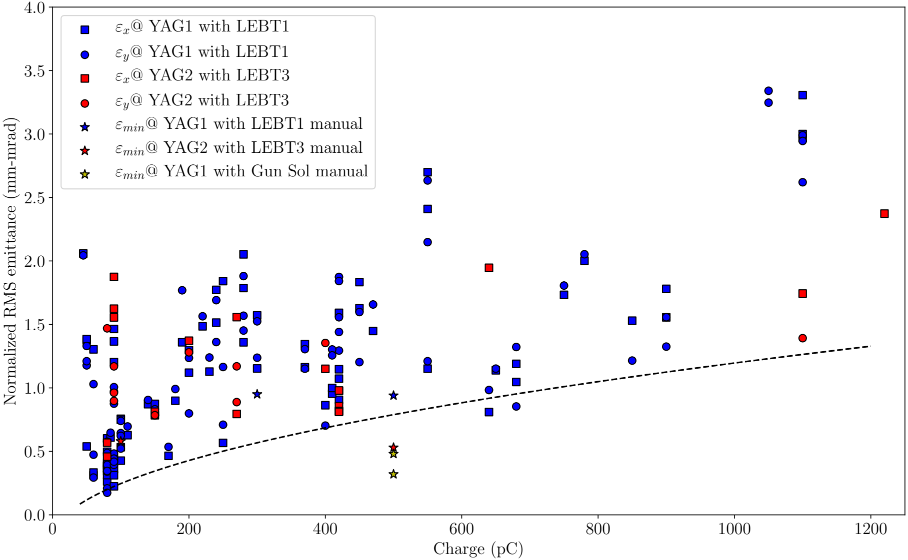


Normalized emittance for a 100 pC, 400 ps e-beam	
Projected emittance, mm-mrad	0.30
Slice emittance, mm-mrad	0.15

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!

Emittance Measurements for a variety of settings during 2017-2018



Conclusions

- We have demonstrated the record parameters for the SRF CW gun:
  - Normalized emittance as low as 0.35 mm-mrad for a 600 pC bunch was measured.
  - Relative energy spread 3×10^{-4} was demonstrated.
- Photocathode at room temperature has high QE
- Low frequency of the gun allows to generate electron beams close to conditions in a DC gun, and fully utilize available field gradient
- Good vacuum inside the SRF gun provides for a long lifetime of the cathode
- Quality of the beam is surprisingly good and we plan to improve our diagnostics to measure ultimate performance of our SRF gun with CsK_2Sb, Na_2KSb and CsTe coated GaAS photocathodes
- We are submitting proposals to demonstrate 100 mA CW current from our SRF gun

Thank you for your attention

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- **LLRF group:** G. Narayan, F. Severino, T. Hayes, K. Smith
- J. Tuozzolo[1], J.C. Brutus[1], S. Belomestnykh[3], C. Boulware[2], C. Folz[1], T. Grimm[2], P. Inacker[1], D. Kayran[1], G. Mahler[1], M. Mapes[1], T. Miller[1], T. Rao[1], J. Skaritka[1], Y. Than[1], E. Wang[1], B. Xiao[1], T. Xin[1], A. Zaltsman[1].

[1] Brookhaven National Laboratory, Upton, NY, USA

[2] Niowave Inc., Lansing, MI, USA

[3] Fermilab, Batavia IL, USA

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