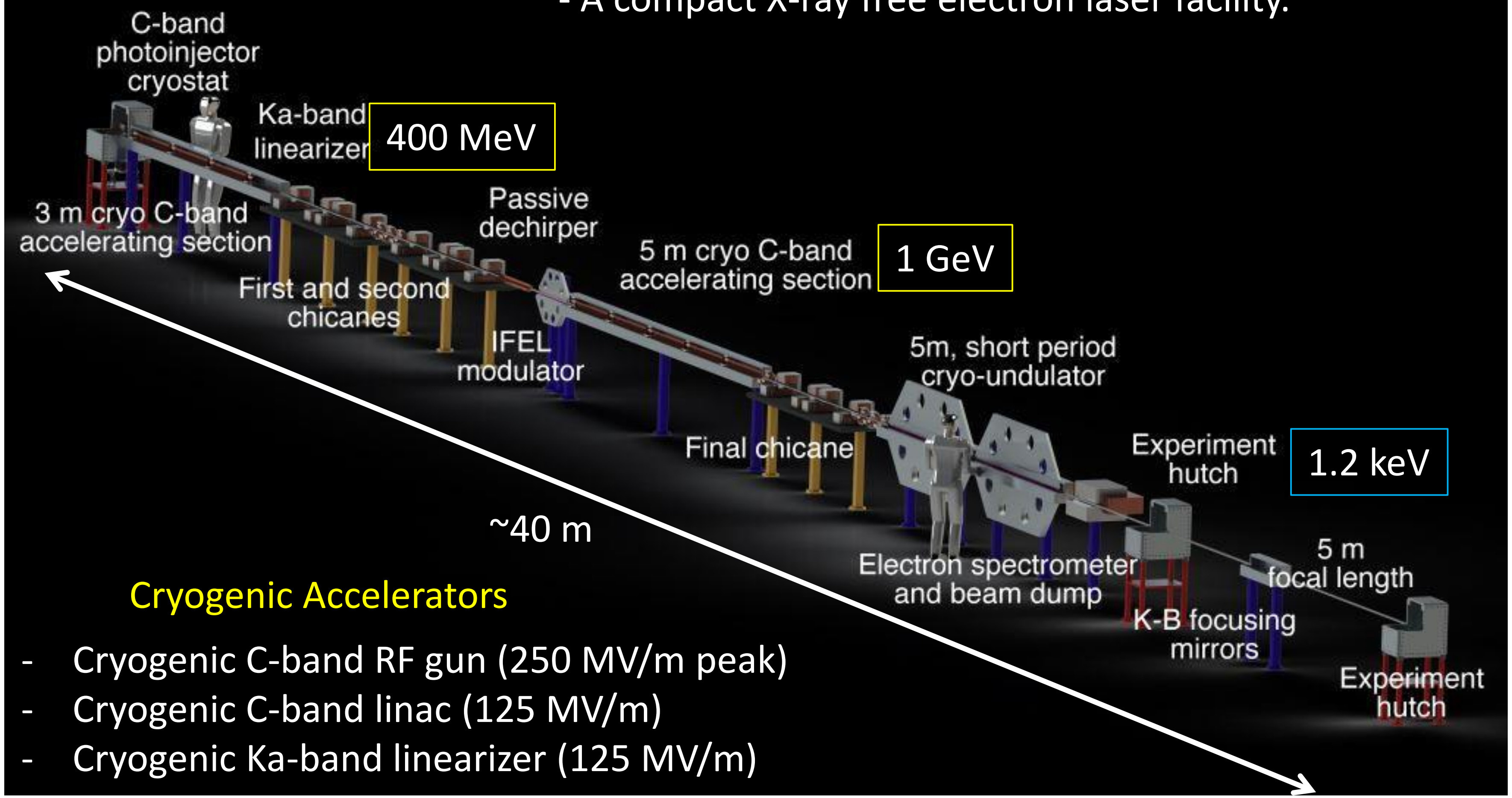
C-band High Gradient Cryogenic Photoinjector Research at UCLA

Apr. 19-21, 2021
International Workshop on Breakdown Science and High Gradient Technology (HG2021)

Atsushi Fukasawa
University of California Los Angeles, United States

Concept of UC-XFEL

- A compact X-ray free electron laser facility.



Cryogenic Accelerators

- Cryogenic C-band RF gun (250 MV/m peak)
- Cryogenic C-band linac (125 MV/m)
- Cryogenic Ka-band linearizer (125 MV/m)

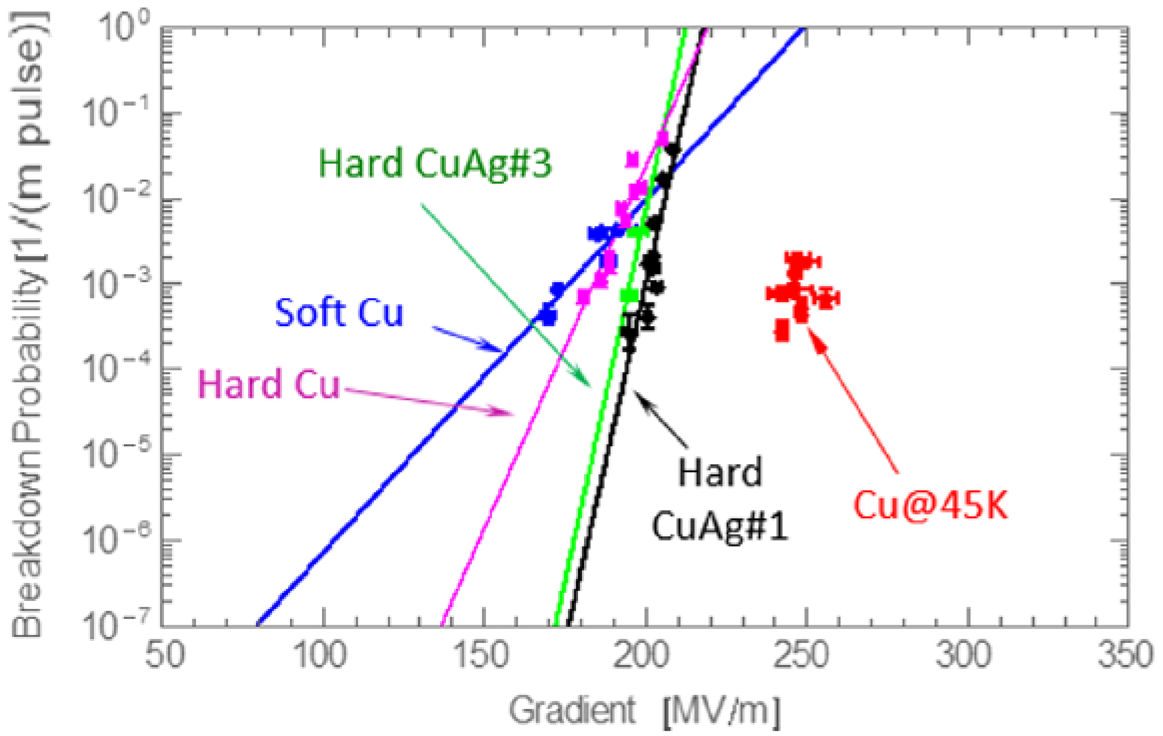
Parameters	Values
Energy	1.0 GeV
Norm. Emittance	80, 60 nm
Charge Micro-bunch (Total)	14 pC (100 pC)
Peak Current	4 kA
Undulator Period	6.5 mm
Undulator K	0.6
Undulator L	4 m
Photon Energy	1.2 keV
Rad. Peak Power	25 GW

J. B. Rosenzweig et al., New J. Phys. 22 (2020) 093067

Collaborators of UC-XFEL

- UCLA: J B Rosenzweig, N Majernik, R R Robles, G Andonian, O Camacho, A Fukasawa, A Kogar, G Lawler, Jianwei Miao, P Musumeci, B Naranjo, Y Sakai, R Candler, B Pound,
- SLAC: C Pellegrini, C Emma, A Halavanau, J Hastings, Z Li, M Nasr, S Tantawi
- LANL: P. Anisimov, B Carlsten, F Krawczyk, E Simakov,
- INFN: L Faillace, M Ferrario, B Spataro
- Arizona State Univ: S Karkare,
- Cornell Univ: J Maxson
- UC Merced: Y Ma,
- UC Berkeley: J Wurtele,
- Radiabeam Technology: A Murokh,
- ANL: A Zholents,
- Univ of Rome 'Tor Vergata': A Cianchi,
- LBNL: D Cocco
- Pulser Physics: S B van der Geer

Reduction of Break Down Rate by Cooling the Cavity

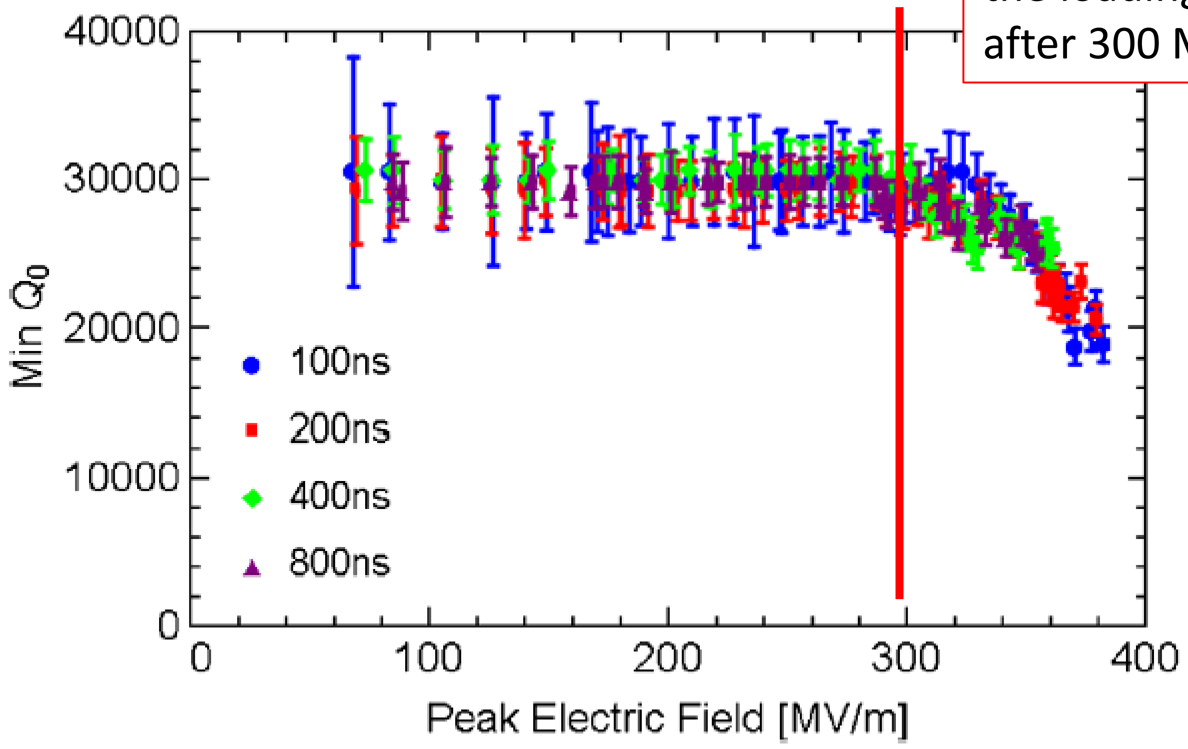


Operation at the cryogenic temperature is the game changer for the high gradient accelerator.

A. Cahill et al., PRAB 21 102002 (2018)

Dark Current Loading

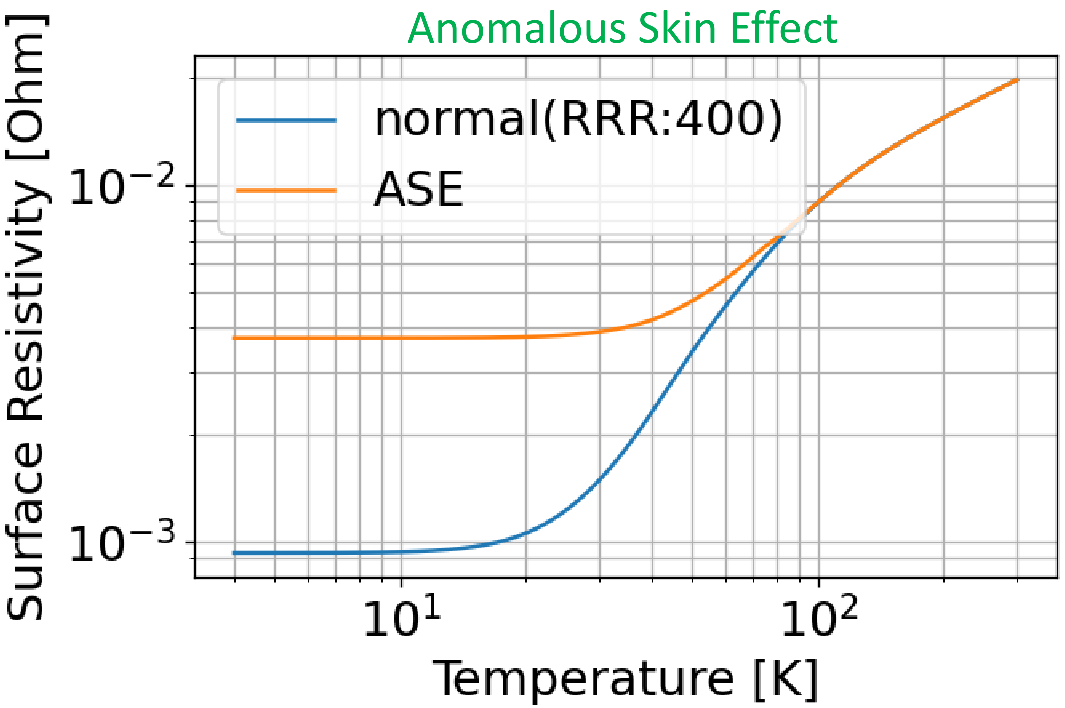
Degradation of cavity Q due to the loading of the dark current after 300 MV/m.

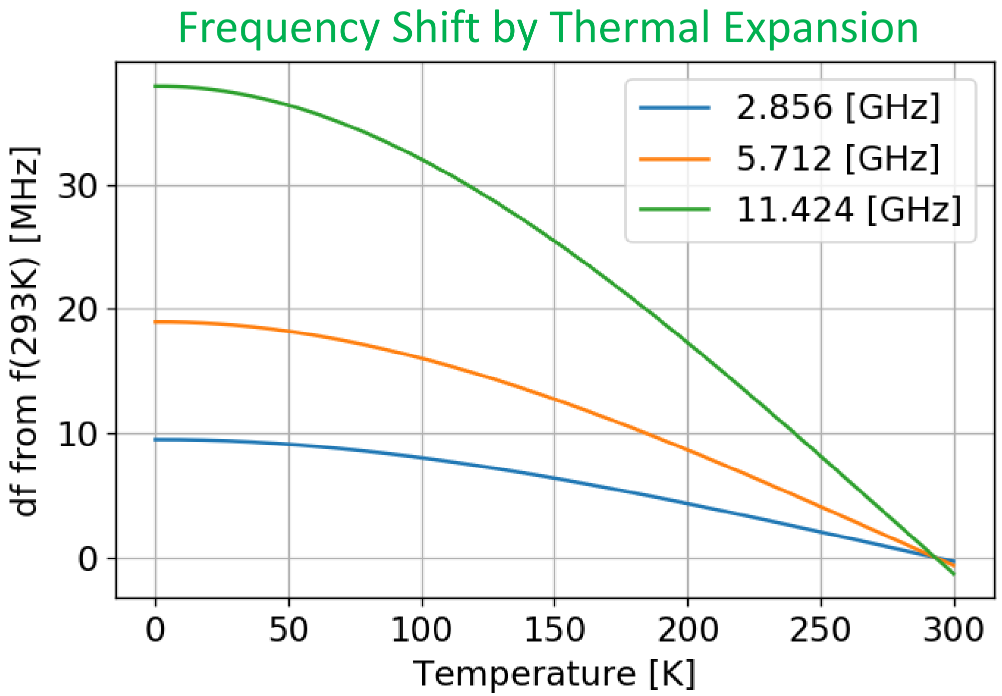


We set 300 MV/m on the cavity wall as the design limit.

A. Cahill et al., PRAB 21 061301 (2018)

Basic Copper Properties at Cryogenic Temperature.





- RF skin depth < electron mean free path at the low temperature.
- The surface resistivity can be reduced by cooling down but not as much as the DC bulk predicts.
- The final temperature tuning range is narrower than one at the room temperature.

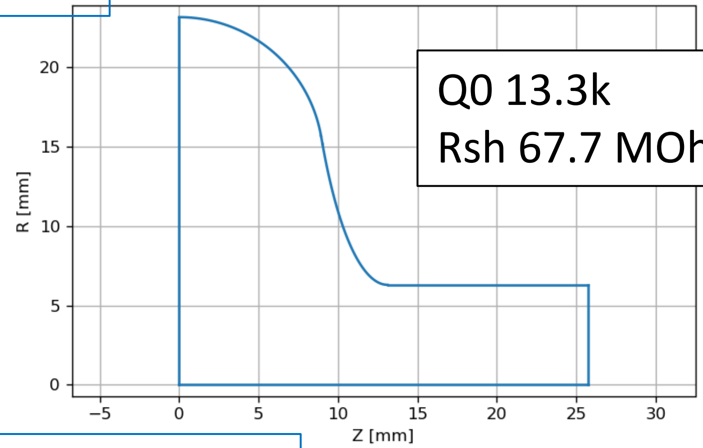
(MHz)

	S-band (2856)	C-band (5712)	X-band (11424)
293 => 77 K	8.58	17.17	34.34
293 => 40 K (77 => 40 K)	9.23 (0.65)	18.46 (1.29)	36.93 (2.59)

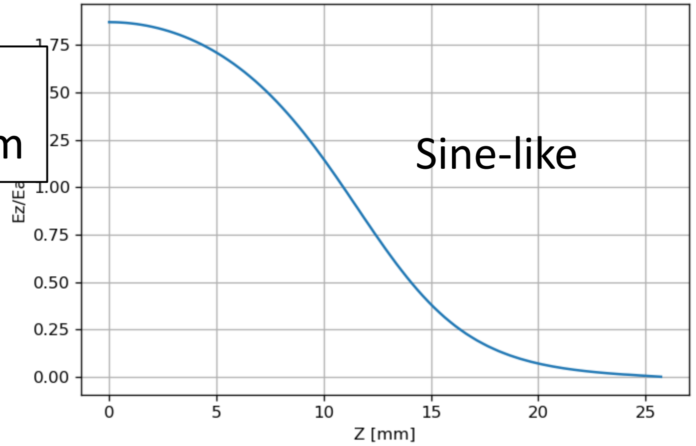
Tesla vs SLAC reentrant shape

Shape | Ez on Axis | E and H on wall

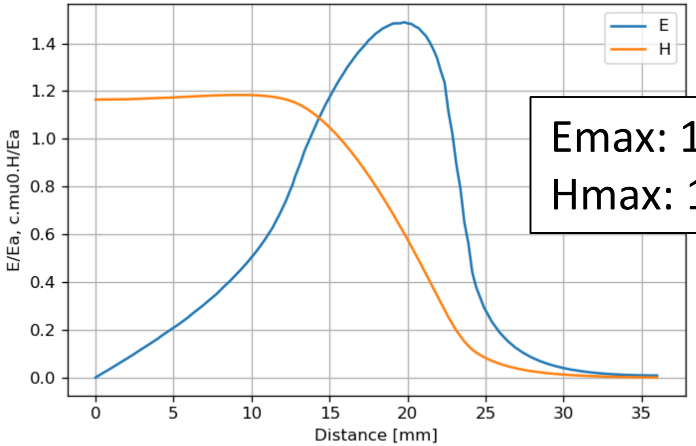
Tesla



Q0 13.3k
Rsh 67.7 MOhm

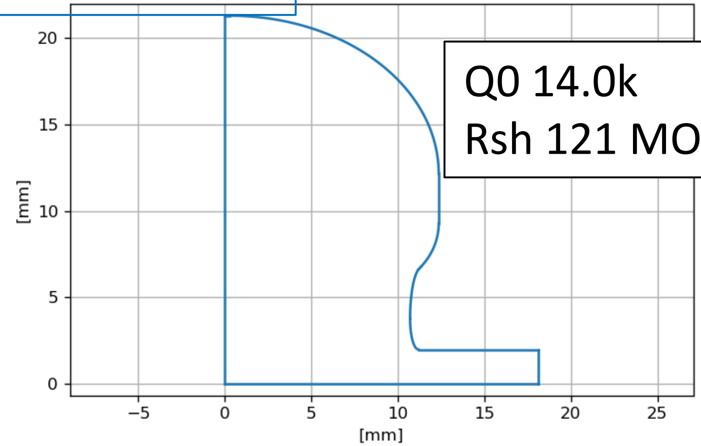


Sine-like

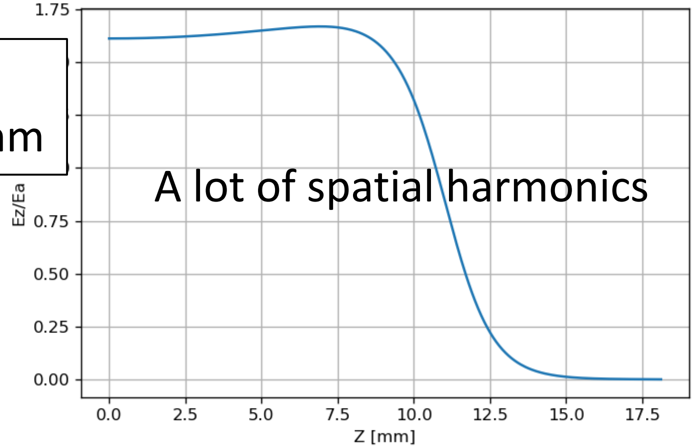


Emax: 1.49
Hmax: 1.19

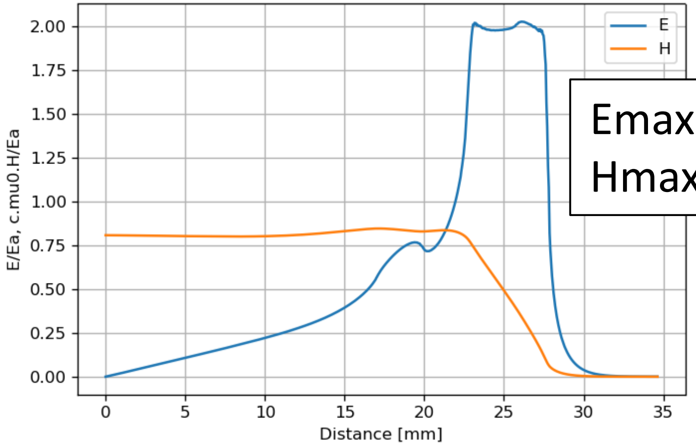
SLAC reentrant



Q0 14.0k
Rsh 121 MOhm



A lot of spatial harmonics



Emax: 2.03
Hmax: 0.85

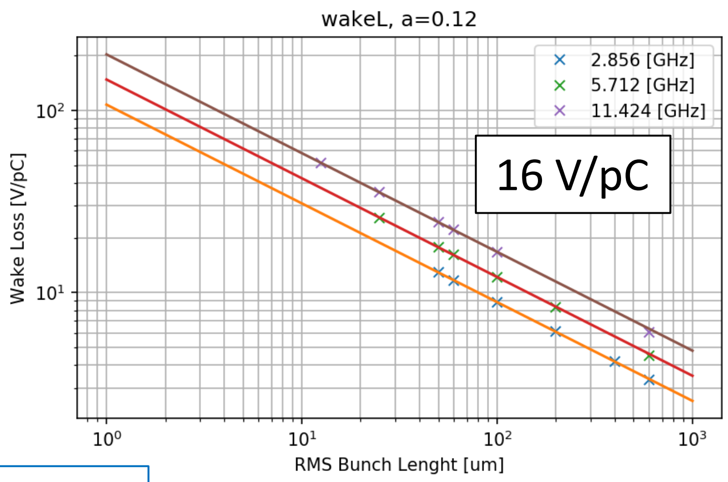
- SLAC-reentrant type has a big advantage in the Shunt impedance.
- When Emax is problem and Hmax is not important, Tesla shape will be a great option.

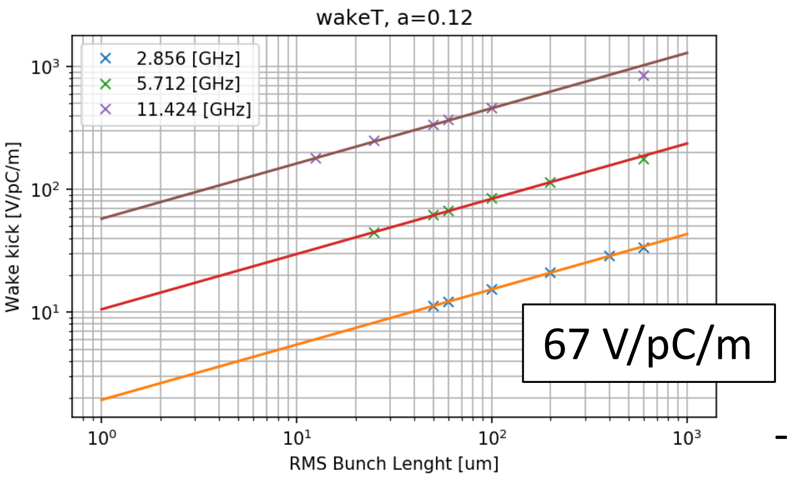
Short Range Wakefields (ECHO 2D)

Longitudinal Wakes

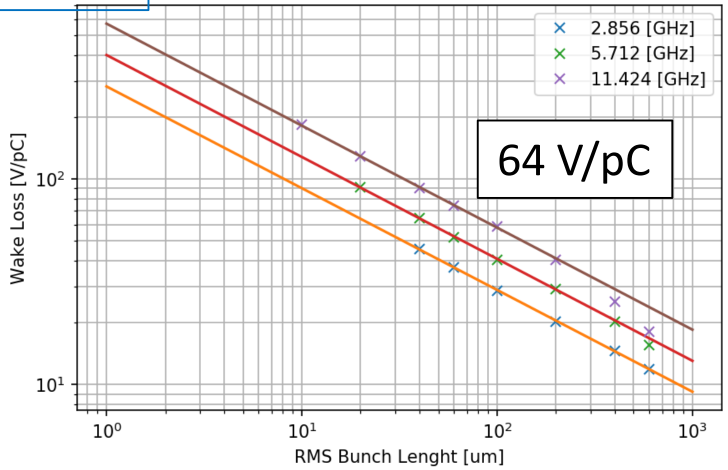
Dipole Wakes

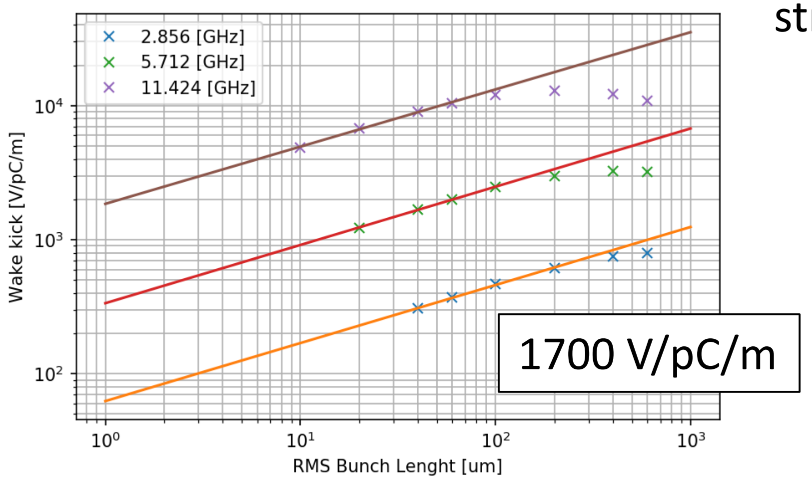
Tesla





SLAC reentrant

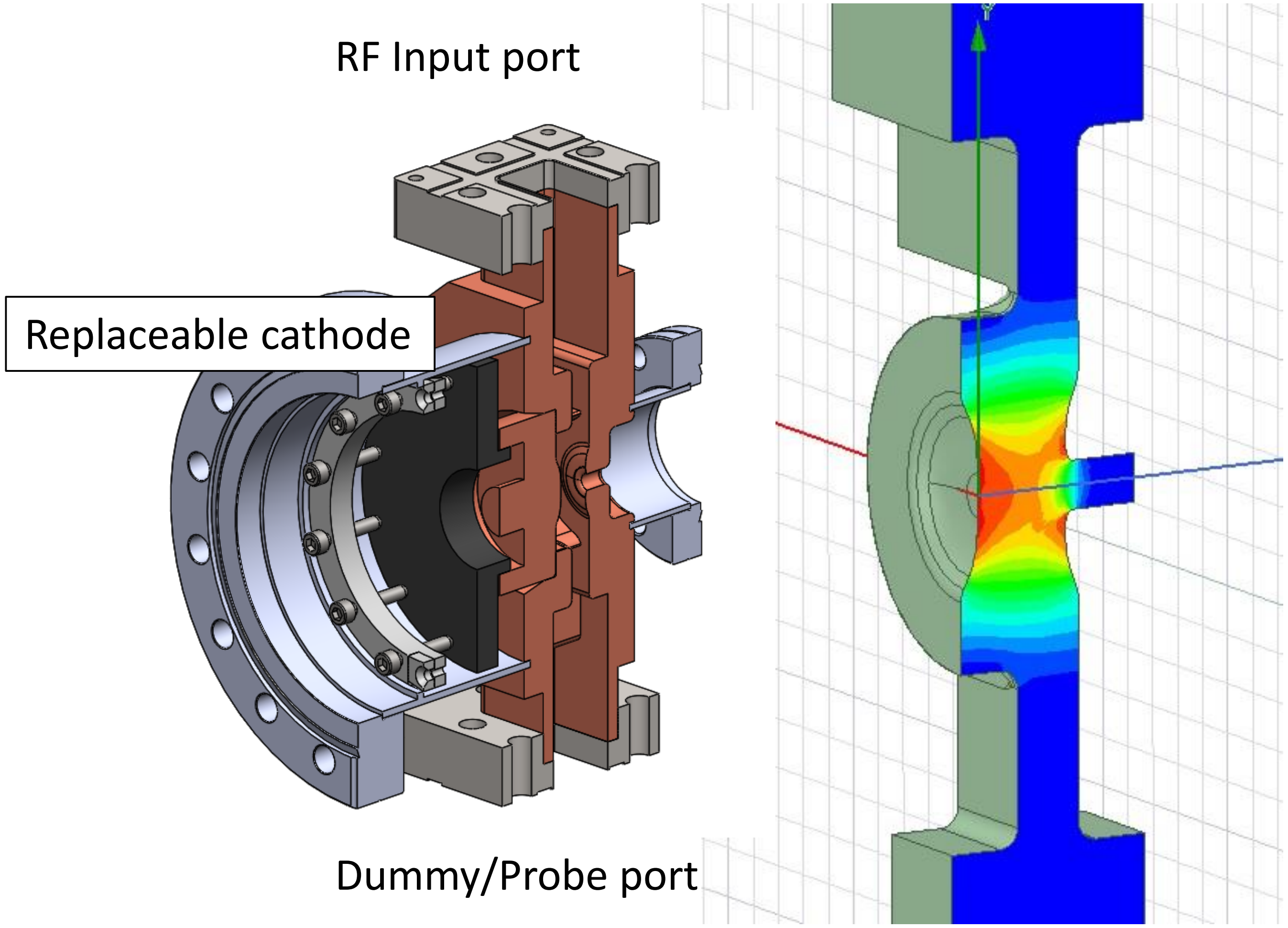




- Due to the tiny aperture, SLAC reentrant shape generates very strong wakefields.

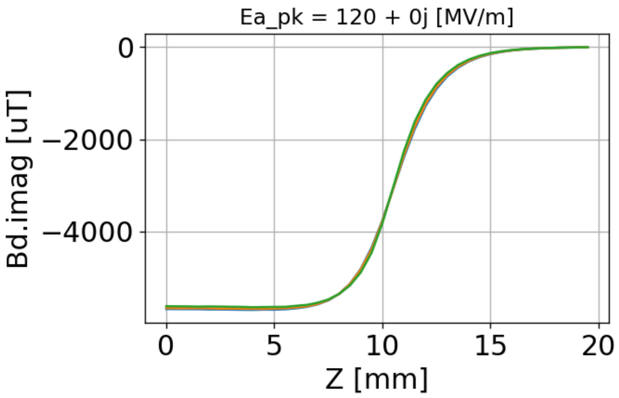
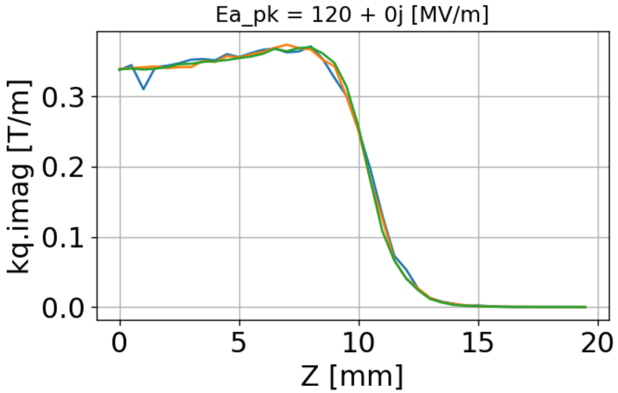
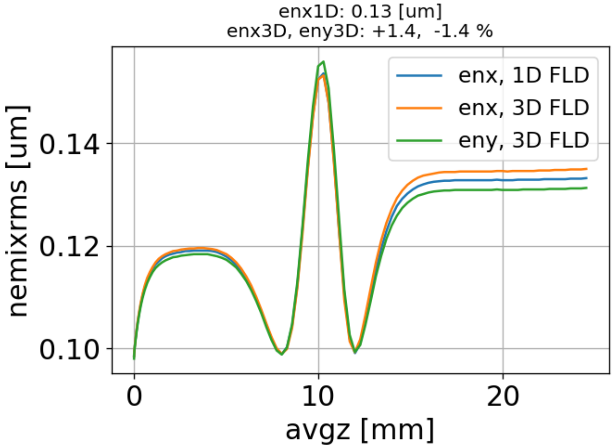
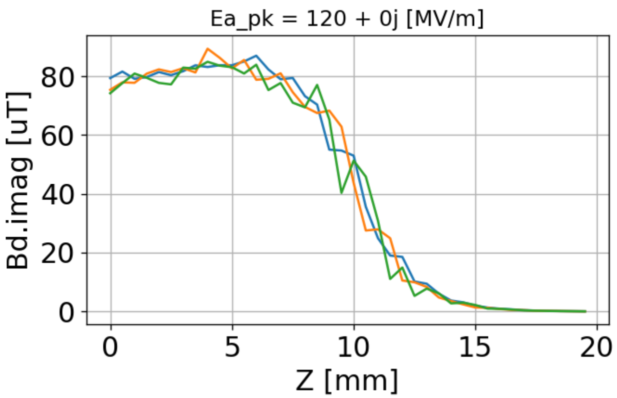
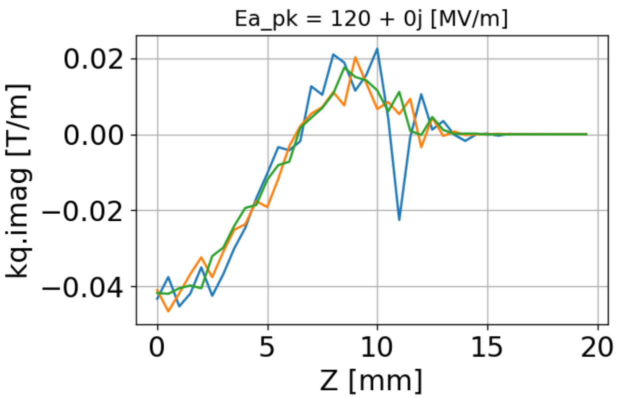
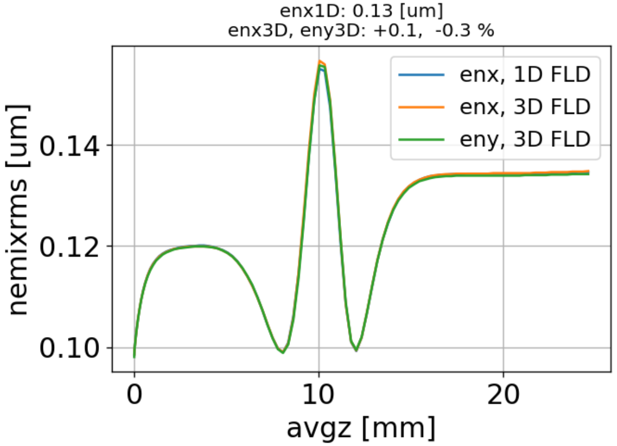
Boxed values are for the bunches with 60 um rms length at C-band cavity.

Half Cell Gun Project



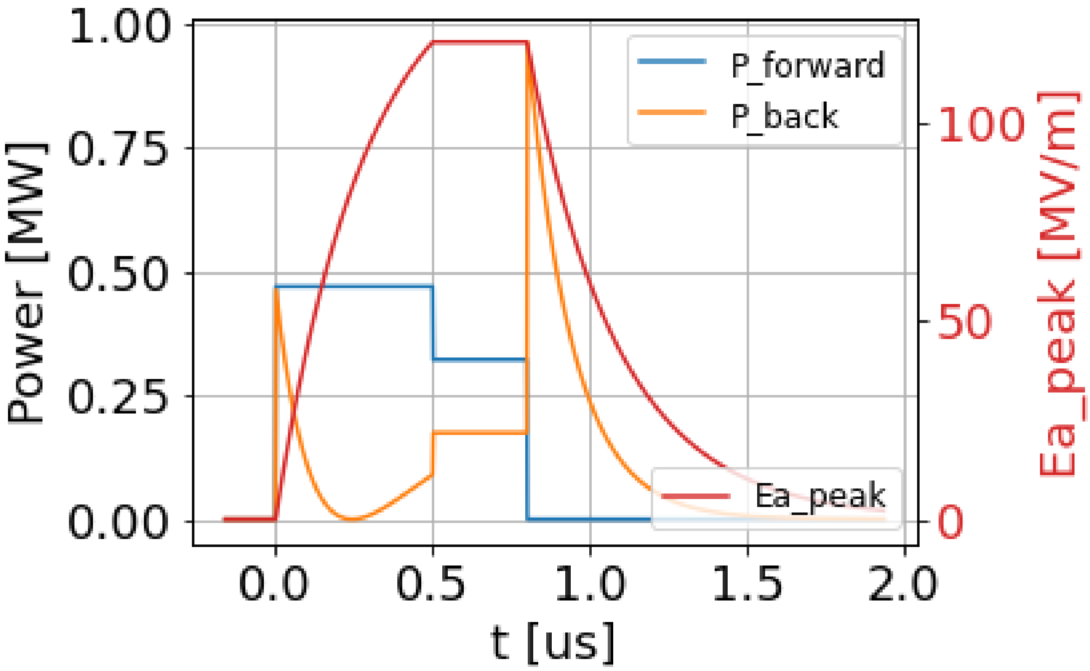
- Study on Cathode Physics under the high RF field at cryogenic temperature.
  - Thermal emittance and QE measurement with a tunable drive laser.
  - Temporal response of photoemission.
  - Various cathode material including semi-conductors.
- Load lock system.
- (Evaporation chamber)

Dipole and Quadrupole Suppression

	Dipole	Quadrupole	Beam emittance
Not Optimized			
Racetrack + dummy port			

- With racetrack shape and a dummy port, the dipole and quadrupole components are well suppressed.
- Instead of a dummy port, adding offset works well too. But we wanted a dummy port to probe the cavity field.

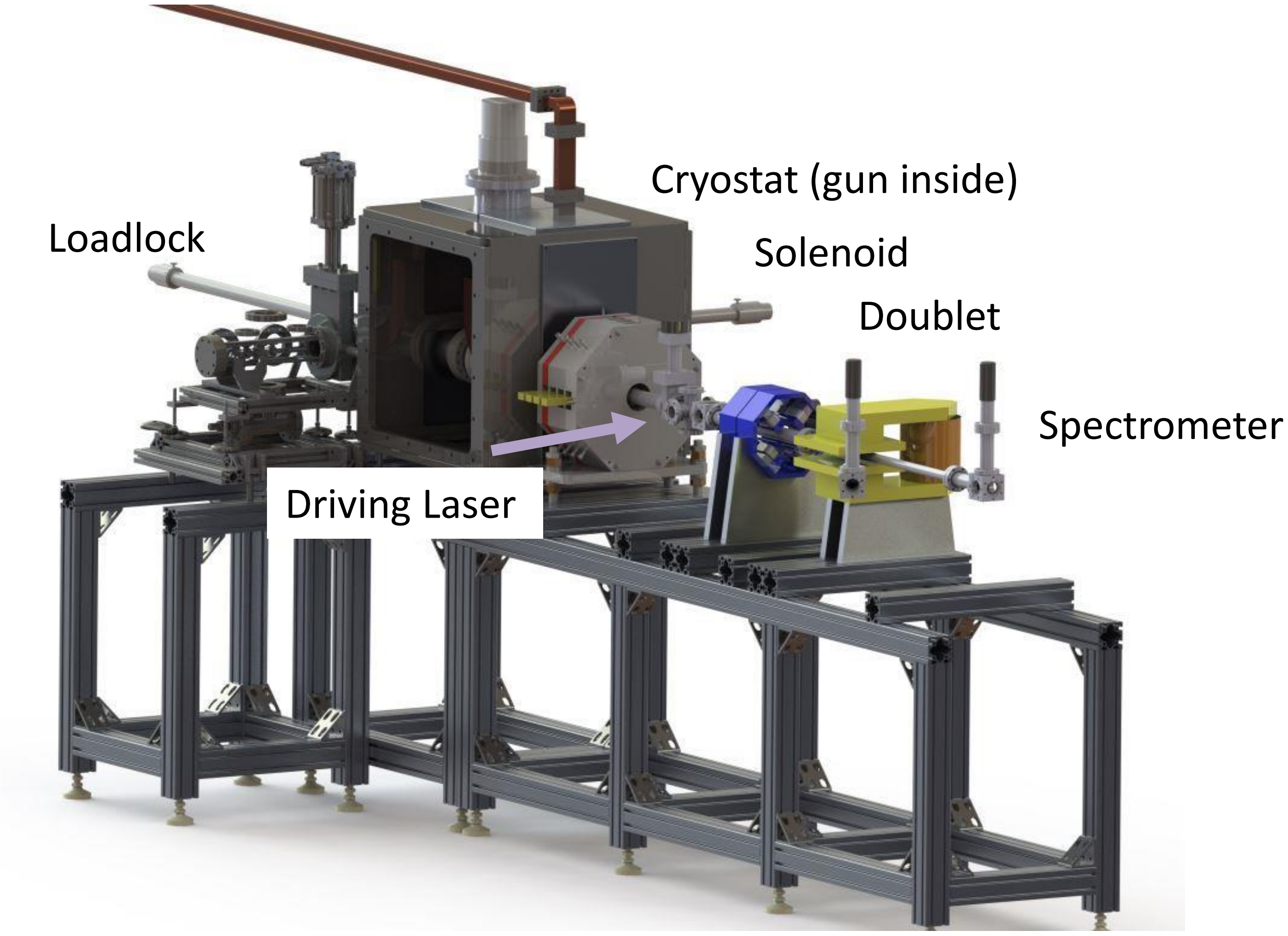
RF Power Requirement

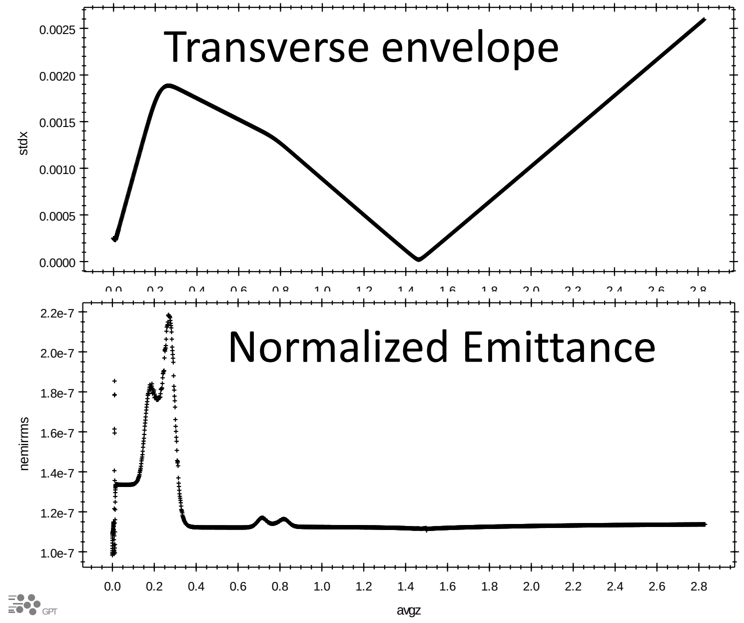


	Case 1	Case 2	Case 3
Temperature	40 K	77 K	100 K
Frequency	5713.3 MHz	5712.0 MHz	5710.8 MHz
Q0	38,000	23,000	18,000
Coupling beta	6.6	4.0	3.1
Filling Time	280 ns	260 ns	250 ns
Input Power (500 + 300 ns)	0.48 + 0.32 MW	0.52 + 0.38 MW	0.56 + 0.42 MW
Power dissipation	0.10 J/pulse	0.17 J/pulse	0.22 J/pulse

- We would like to operate over some range of temperature.

Design of Half Cell Gun Beamline

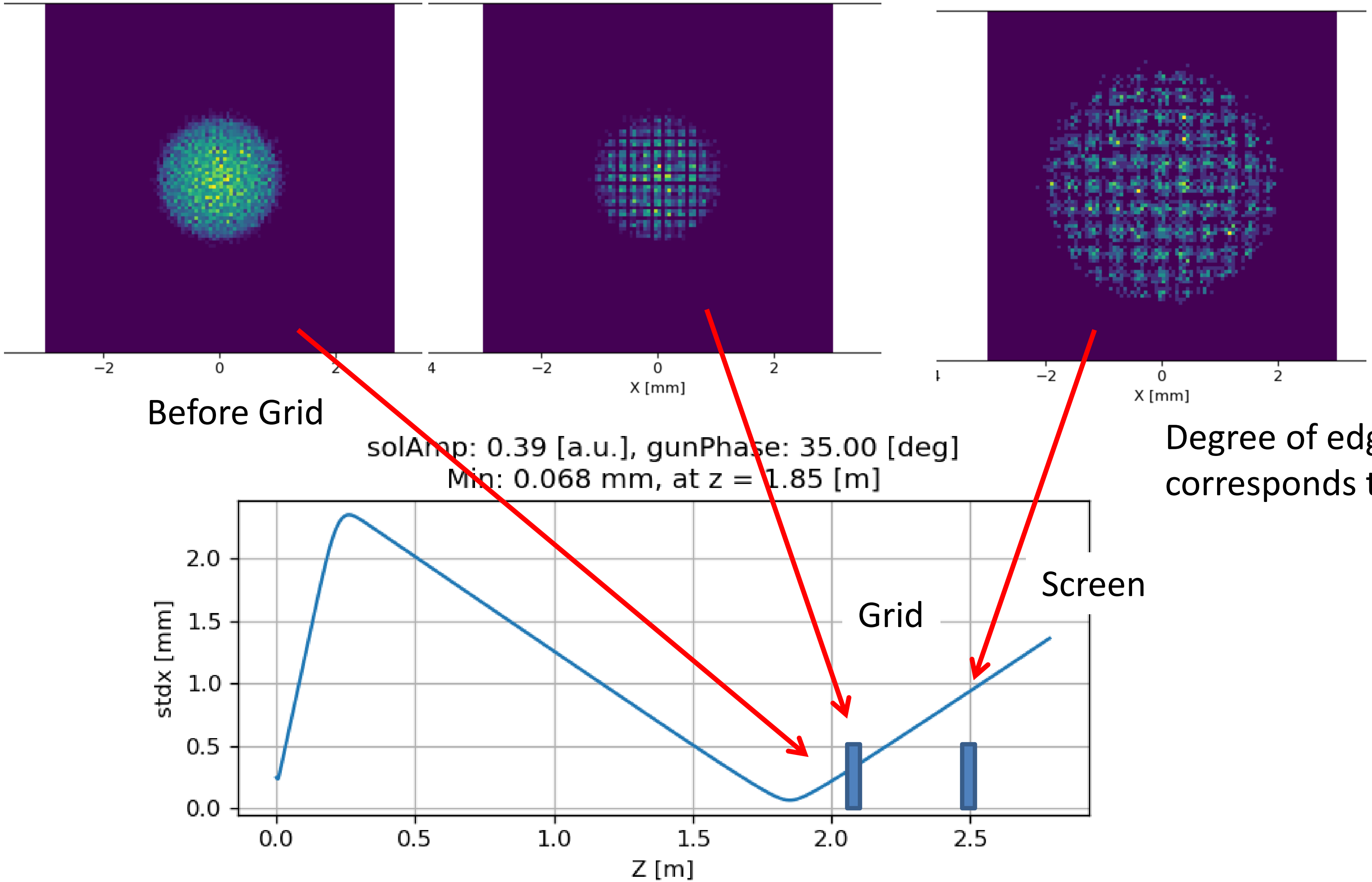




	Typical Values
Epeak on Cathode	120 MV/m
Beam Kinetic E	1 MeV
Charge	100 fC
Emittance Norm	0.1 um

- For the emittance measurement, TEM grid method will be used (not included in the figure).

TEM Grid Method

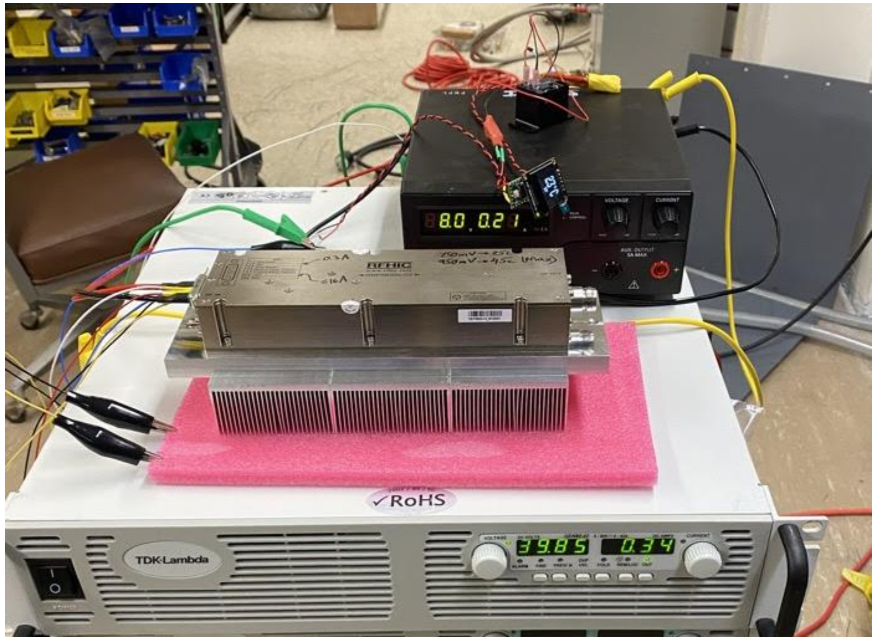


Degree of edge blur corresponds to the emittance.

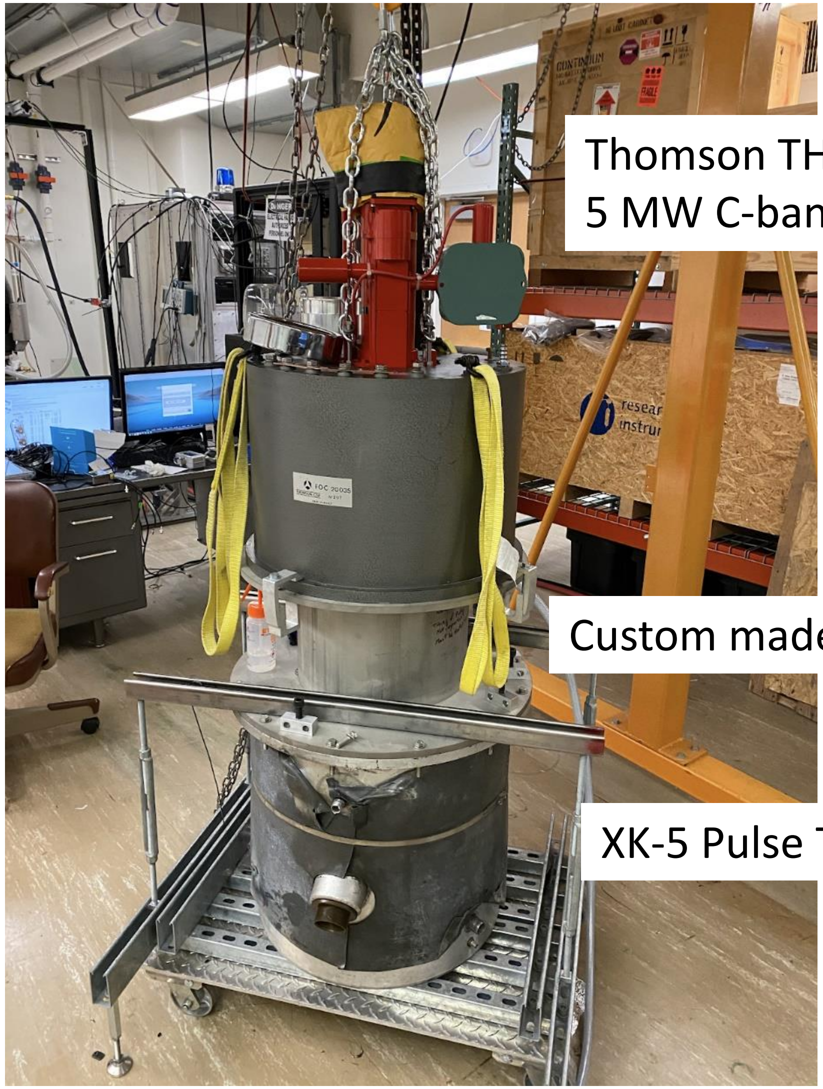
TEM grid method is good for the beam with low charge and low emittance.

C-band RF sources

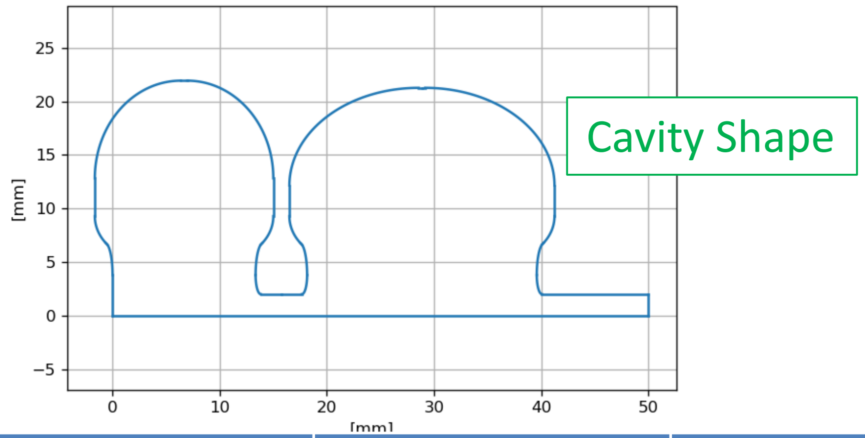
RFHIC RNP58200-C2
200W C-band GaN Power Amplifier



- The 200 W amplifier worked successfully.
- We have confirmed 0.5 MW output from the klystron.
- There is a problem in the heater circuit.
- There is still a room of increasing the cathode emission.
- We will not try to push the output more than 1 MW, where we can operate the half cell gun.

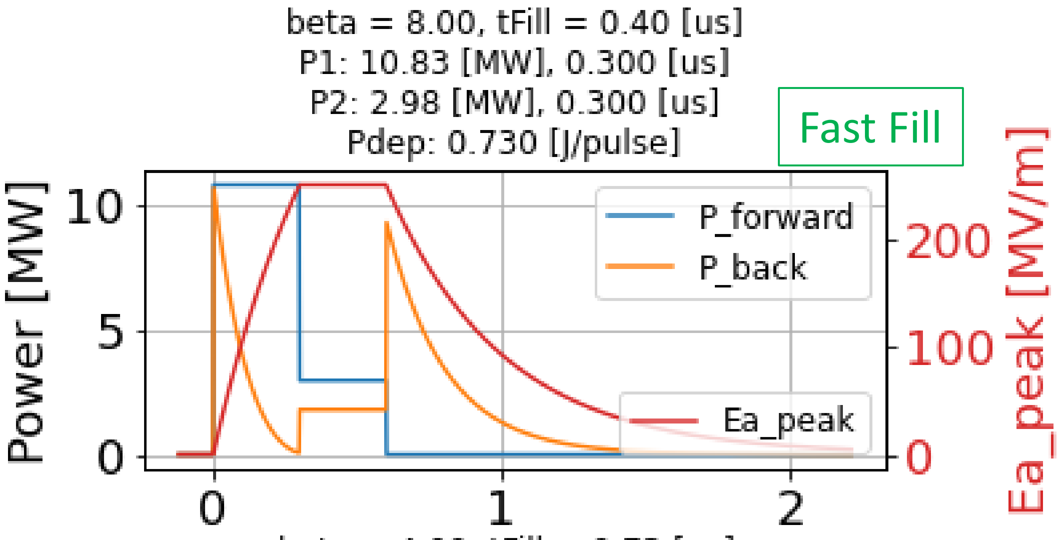


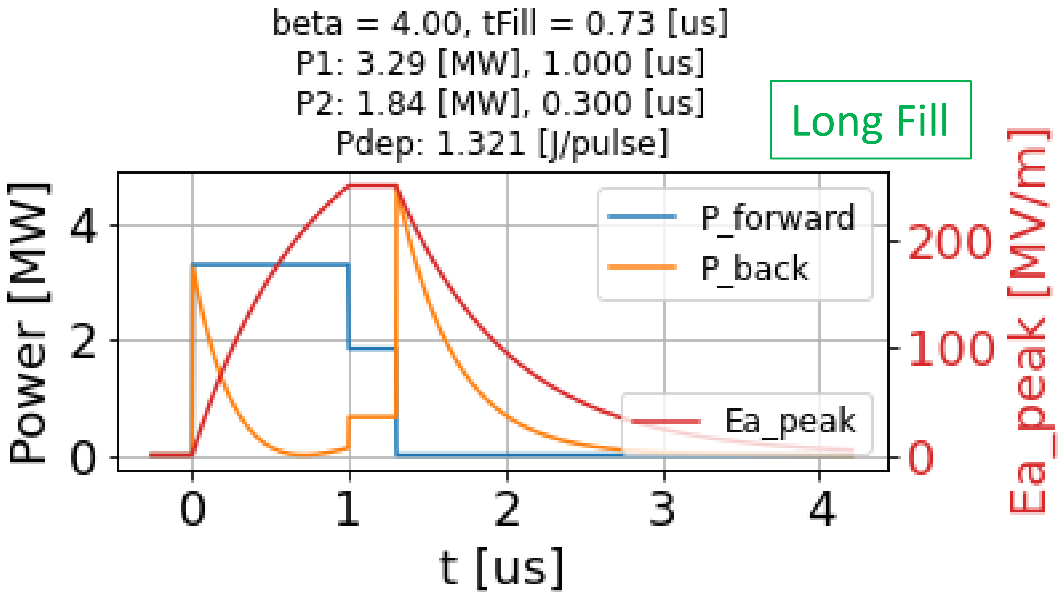
Properties and Power Requirement for 1.6 cell gun



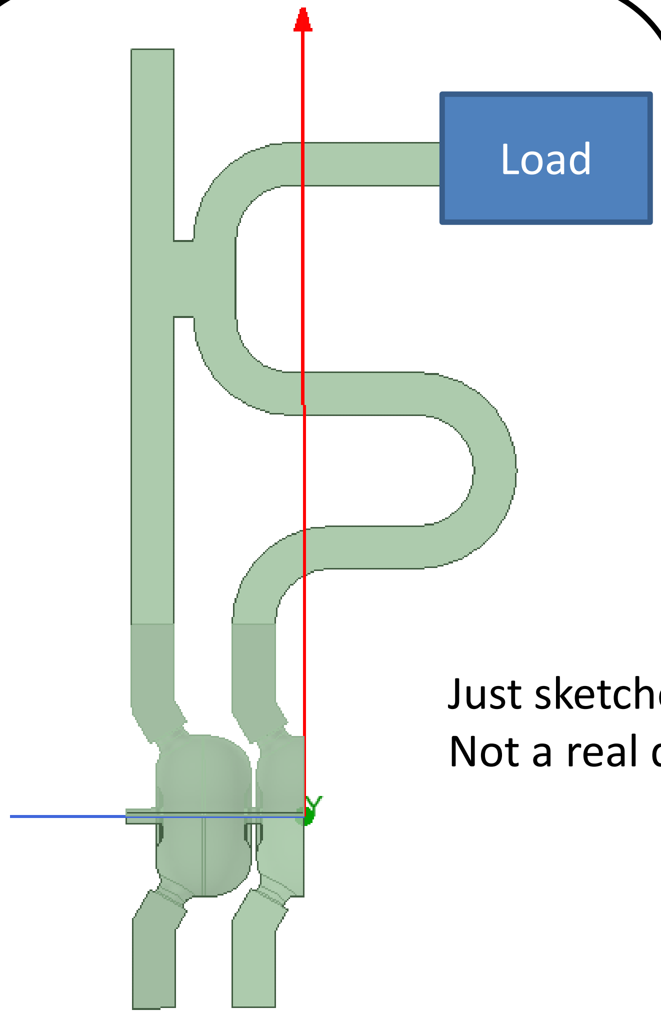
	HC	FC
Q0 (293 K)	12 k	14 k
Q0 (40 K)	56 k	65 k
Beta = 8.0 300 + 300 ns	4.8 +1.6 MW 0.39 J	10.7 + 3.0 MW 0.72 J
Beta = 6.0 600 + 300 ns	2.4 + 1.3 MW 0.51 J	5.1 + 2.4 MW 0.98 J
Beta = 4.0 1000 + 300 ns	1.6 + 1.0 MW 0.69 J	3.3 + 1.8 MW 1.3 J

- The required power is significantly reduced with longer pulse.
- The longer pulse dissipates more power.
- The longer pulse will result in higher break down probability.



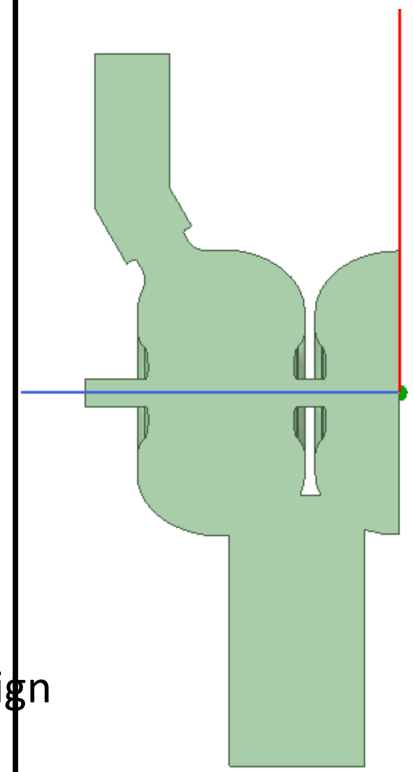


Coupling Configuration



Power Splitter

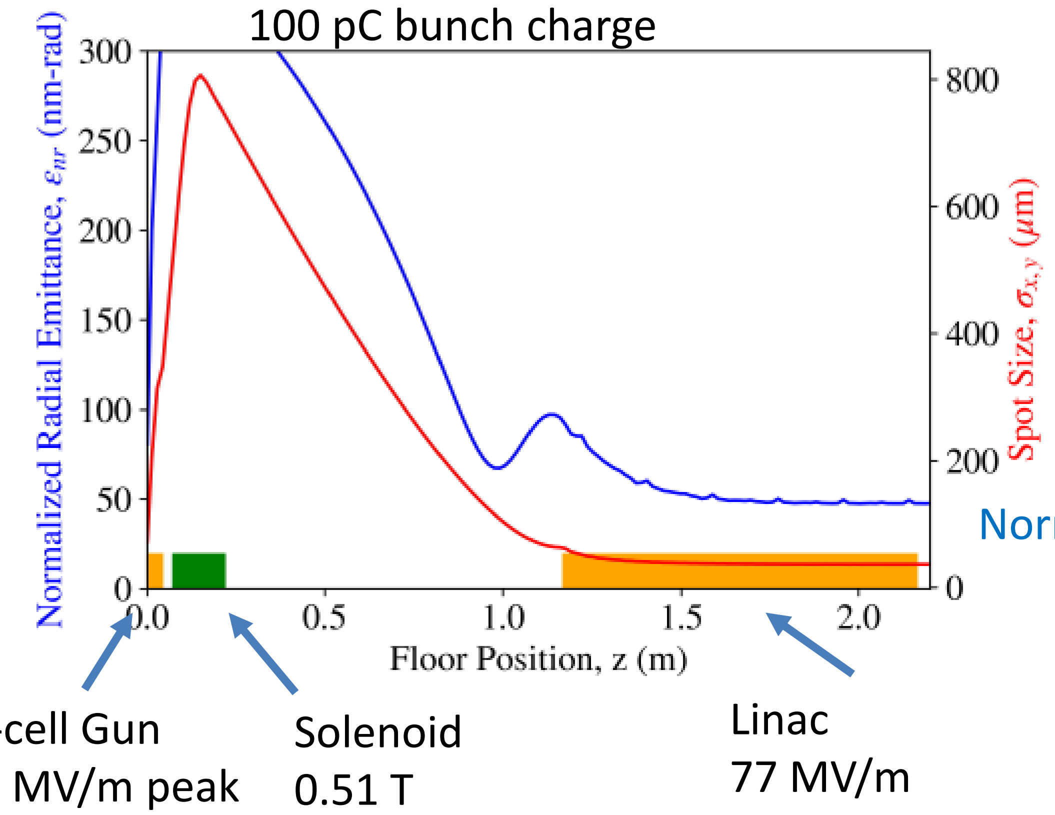
Just sketches
Not a real design

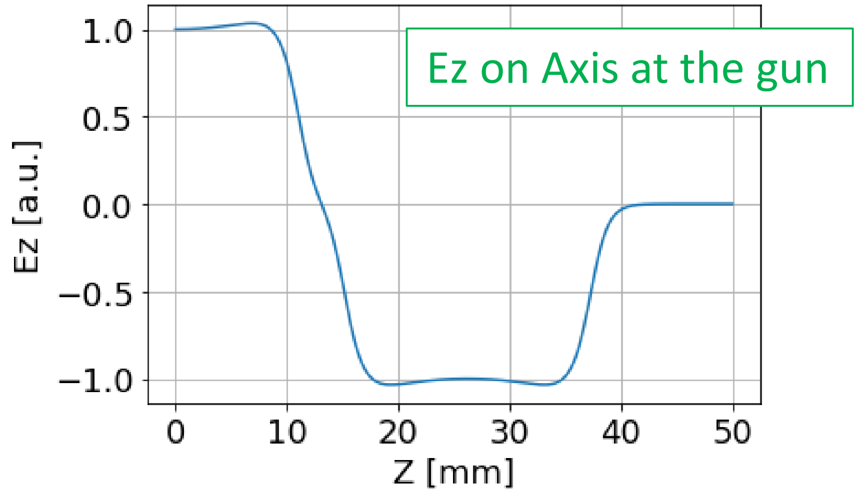


Pi/2

- In case of Power splitter, it might be difficult to use double step input, because of the difference in Q0, coupling beta, and filling time between half cell and full cell.
- Pi/2 mode case need to take care of the magnetic field at the coupling slot.

Emittance Compensation.





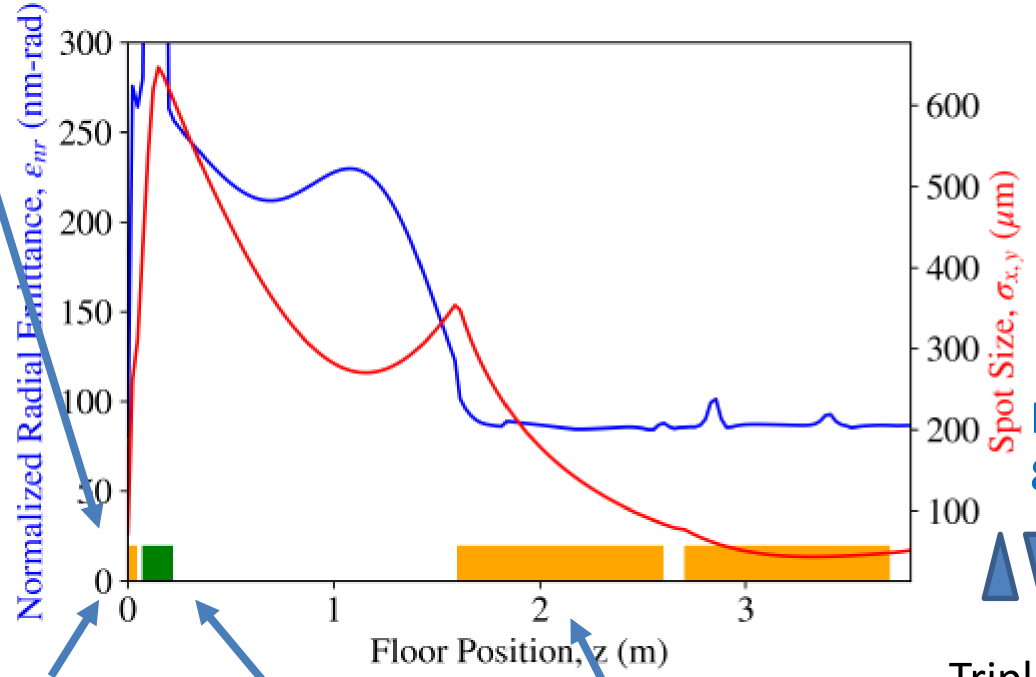
Normalized rms emittance: 45 nm

- Unlike the normal gun, this gun has the field with a lot of spatial harmonics.
- The emittance compensation still works well.
- We assumed that MTE was 140 meV. This could be achieved by the cryogenic cold cathode and using 262-nm driving laser.

R Robles et al, submitted to PRAB, https://arxiv.org/abs/2103.08789

Flat Beam Generation

Backing Solenoid
0.58 T at cathode.



1.6-cell Gun
240 MV/m peak

Solenoid
0.48 T

Linac1
52 MV/m

- The round-flat transformation with the magnetized beam is good for applications such as ILC, slab DWA, DLA.
- Applying 0.6 T at cathode in the cryostat is challenging.
- The emittance compensation scheme worked successfully.
- The beam should be accelerated enough to suppress the space charge effect at the transformation.
- The split ratio, 425, was demonstrated.

Normalized rms emittance:
85 nm => 4 nm and 1.7 um

Triple skew quads
As a round-flat transformer.

R Robles et al, submitted to PRAB, https://arxiv.org/abs/2103.08789

UCLA

Summary

- UCLA is proposing a compact X-ray free electron laser facility.
- We compared a SLAC reentrant cavity with a Tesla type cavity. The former had a big advantage in the shunt impedance and peak magnetic field on surface, but it lost in peak electric field on surface and wakefield.

- We showed the half cell gun design with compensation of dipole and quadrupole components.
- The half cell gun can be operational with 0.6 MW 500 ns filling pulse.
- Preliminary design of the beamline for the half cell gun was introduced.
- We demonstrated 0.5 MW RF output from our 5 MW klystron, while we had a problem in the cathode heater circuit.

- The length of filling RF pulse affects the power requirements a lot for the 1.6-cell gun operation.
- Two configurations of feeding waveguide were considered.
- The emittance compensation scheme was demonstrated successfully in the GPT simulation. It predicted the normalized emittance 45 nm.
- The round-flat transformation with magnetized beam worked well in the simulation. It gave split emittance, 4nm and 1.7 um.