Overview on CW RF Gun Developments for Short Wavelength FELs.

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

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Outline

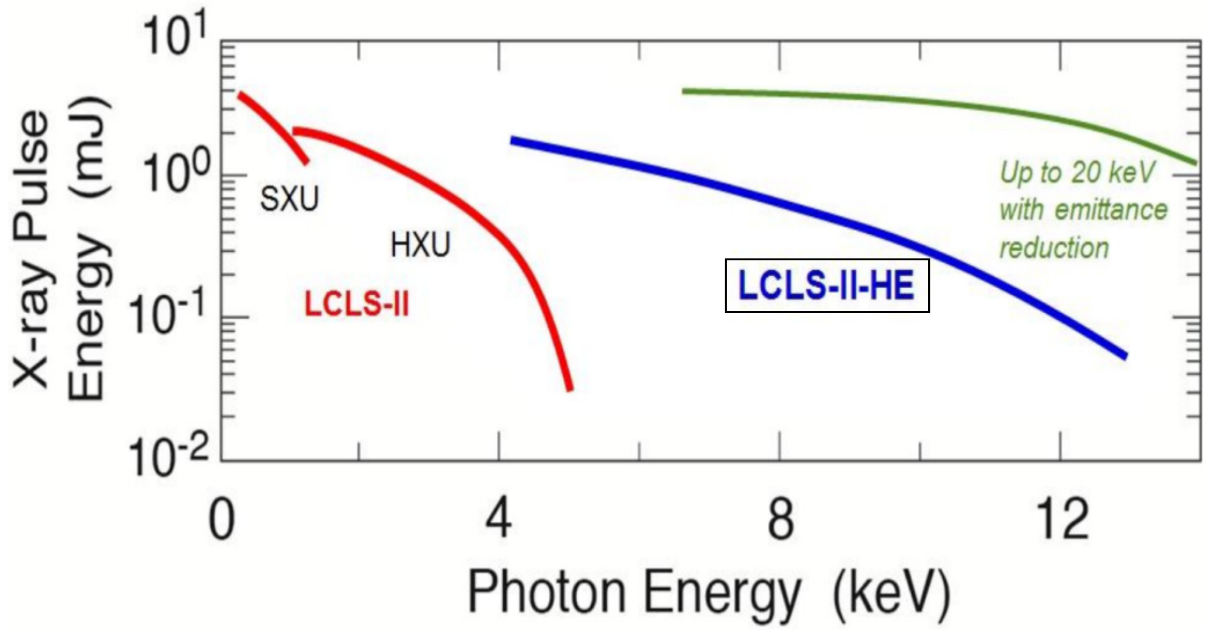
- Introduction
- Review of CW normal conducting guns
- Review of CW superconducting guns
- Conclusions and outlook

Next generation XFELs need brighter electron source

0.1 µm.rad @ 100pC is required

- Next generation XFELs are going towards CW mode
  - More flexible photon pulse time pattern
  - Higher average brightness
- Next generation XFELs need brighter electron source
  - CW linac beam energy is lower than pulsed linac
  - Short wavelength is requested by users

$$\varepsilon_n \propto \gamma_{linac} \frac{\lambda_{Xray}}{4\pi}$$



	LCLS-I CuRF (pulsed)	XFEL SRF (pulsed)	LCLS-II (CW)	LCLS-II-HE (CW)	SHINE (CW)
Electron energy (GeV)	14.3	17.5	4	8	8
Max photon energy (keV)	8	25	5	13-20	25

High brightness injector for XFELs

On ‘pancake’ and ‘cigar’ photoemission

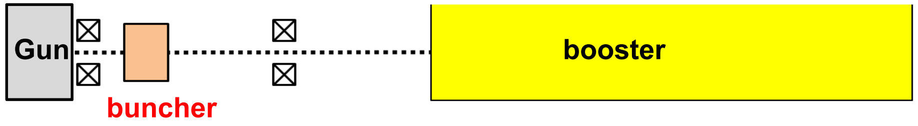
- High gradient gun based injector

- ‘Pancake’ emission brightness

$$\frac{Q}{\epsilon^2} \propto \frac{E_{emission}}{MTE}$$

  - Short laser, high emission current
  - High gradient → high frequency gun
- High gradient pulsed guns (L-band, S-band)
  - $E_{emission}$ 40~60 MV/m, (50~70)% of E_{cath}
- **SC CW gun** has the potential to reach similar field
  - L-band gun (HZDR, HZB, DESY, KEK, PKU)
  - VHF-band **Q**uarter **W**ave **R**esonator (QWR) gun (BNL, SLAC)

- Medium to low gradient gun based injector



- ‘Cigar’ max emission brightness

$$\frac{Q}{\epsilon^2} \propto \frac{E_{emission}^{1.5}}{MTE} \frac{t_{laser}}{\sqrt{R_{laser}}}$$

  - Long laser, low emission current
  - Long laser → low frequency gun
- DC gun based ERL injector
  - E_{cath}<5 MV/m, V_{gun} <500 kV
- VHF-band **NC CW gun** (LBNL)
  - $E_{emission}$ ~20 MV/m, V_{gun} ~750 kV

A brief overview on normal conducting CW gun developments worldwide:

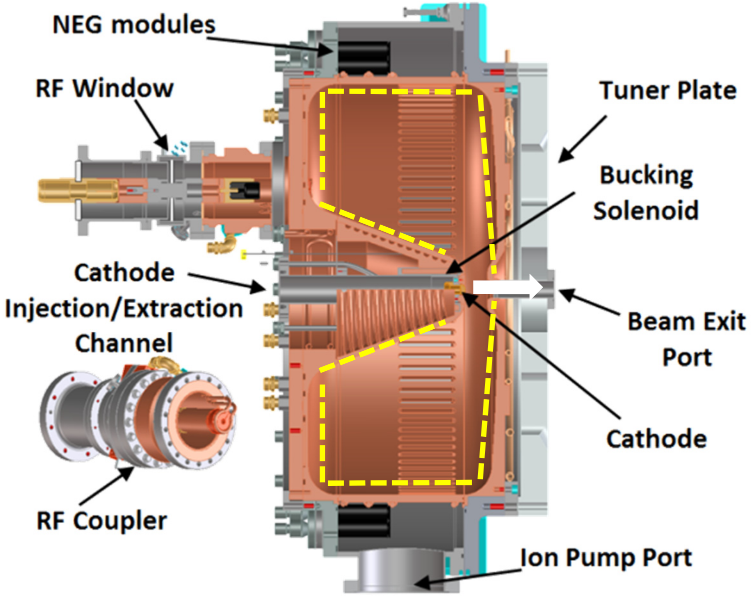
@ LBNL, SLAC, DESY and SHINE

APEX gun @ LBNL

Gun and cathode performance demonstrated in CW mode

Based on mature NC VHF-band RF technology

- Low frequency gun
  - $E_{emission} \approx E_{cath}$
  - Large longitudinal acceptance (~15 ps/deg)
  - Better for heat dissipation & vacuum pumping
- Reentrant cavity → Enhanced E_{cath} and R_{sh}
- 2006~2016, from concept to demonstration

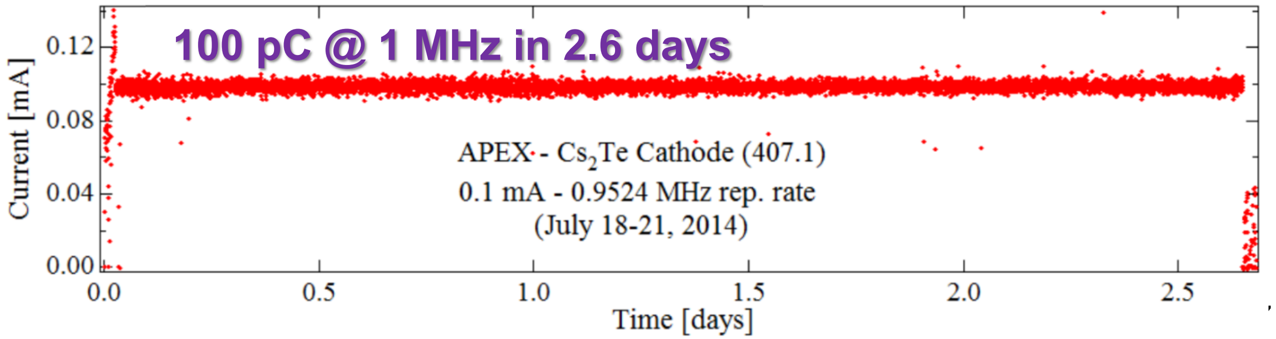


Measured gun parameters

Frequency	185.7 (1300/7)	MHz
Cathode gradient	19.5	MV/m
Gun voltage	750	kV
Average RF power	90	kW
Q0	30900	
Shunt impedance	6.25	Mohm
Peak surface field	24.1	MV/m
Peak wall power density	25	W/cm^2
Diameter/Length	69.4/35.0	cm
Operating pressure	$10^{-10} \sim 10^{-9}$	torr
Dark current	~0.1	nA

Cs_2Te cathode performance @ CW mode

- QE: 16% → 11%, in ~7 days' integrated operation
- Thermal emittance: 0.7-0.8 μm.rad/mm @ 266 nm



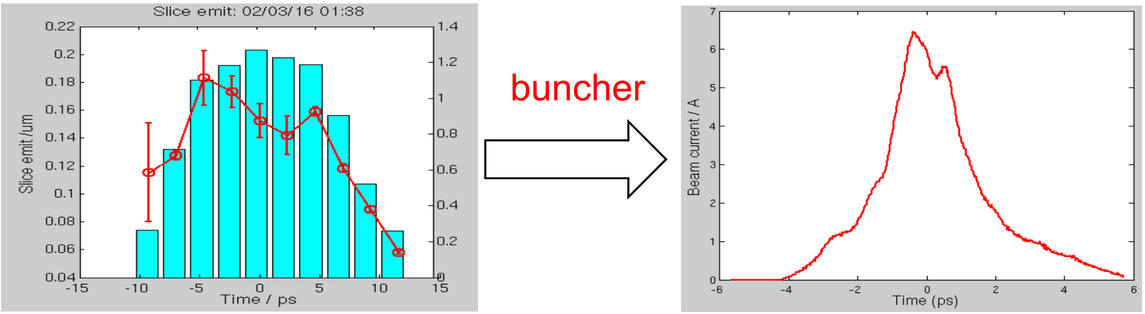
APEX gun @ LBNL

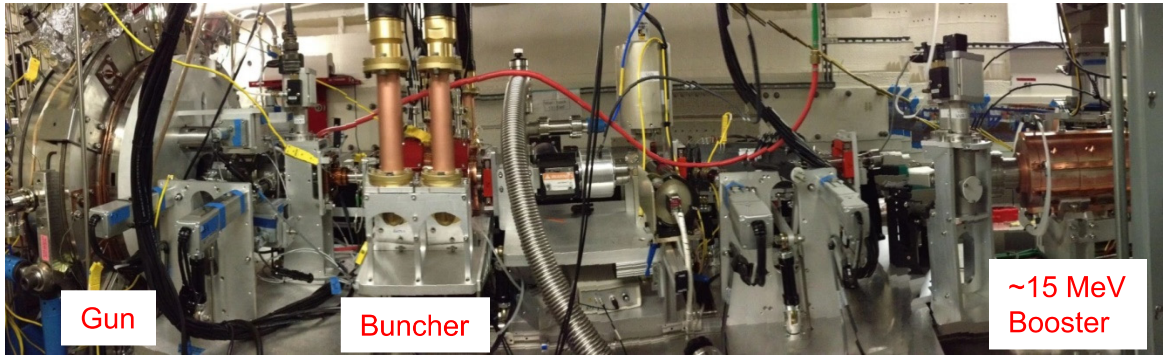
APEX 20 pC beam measurements, LCLS-II injector simulations

20 pC measurements with CsK_2Sb cathode at APEX

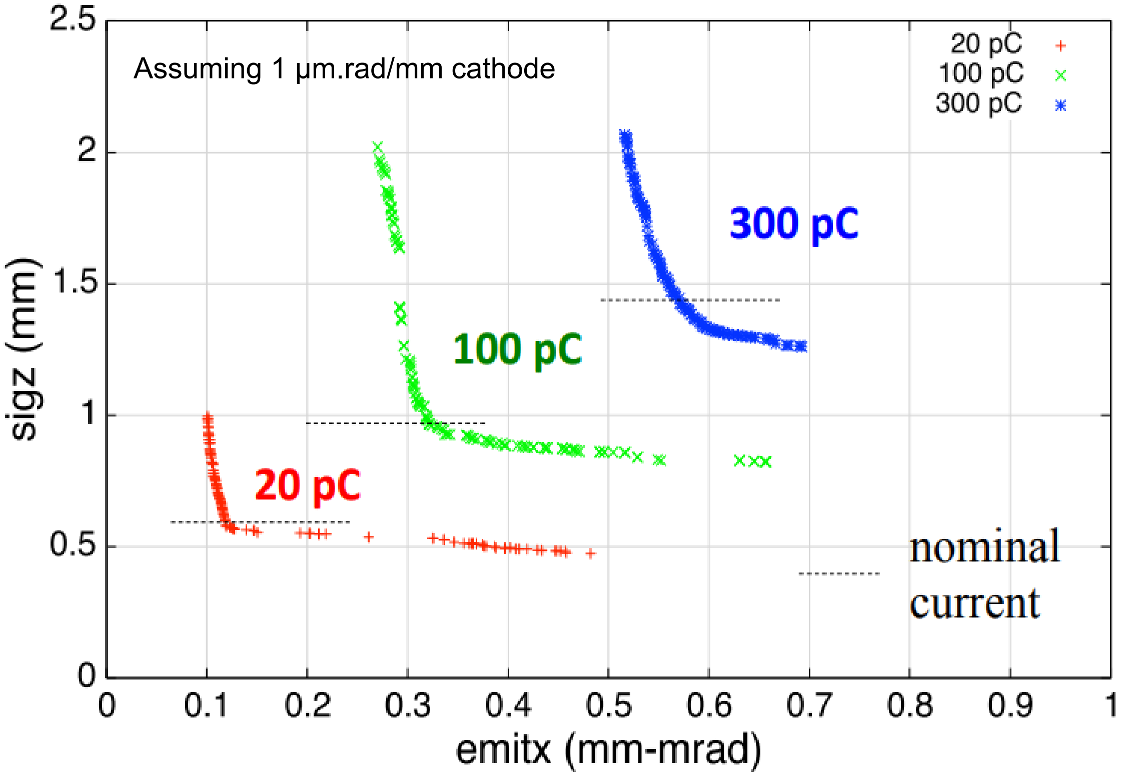
- Thermal emittance measurement: ~0.6 µm.rad/mm @ 257.5 nm.
- Bunch compression: 1.2 A → 6.5 A
- 20 pC beam emittance <0.2 µm @ 6.5 A peak current.

I_{peak}~ 1.2 A $\qquad$ I_{peak}~ 6.5 A





APEX gun simulations for LCLS-II injector



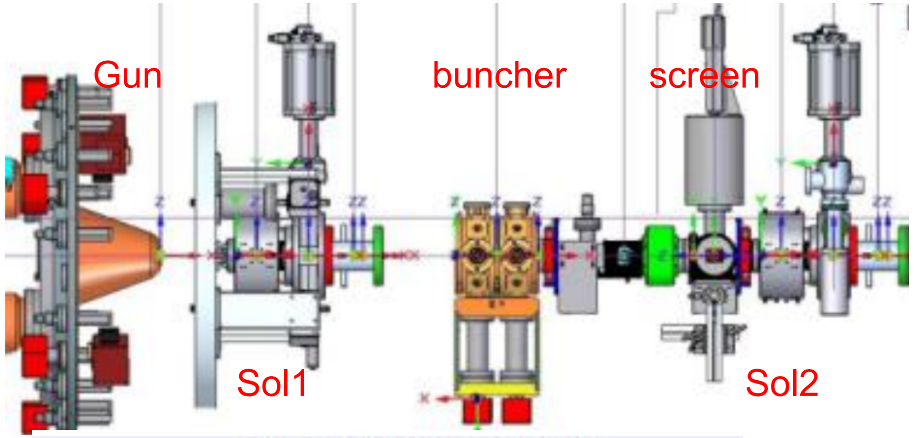
LCLS-II injector baseline requirements are met.

LCLS-II gun @ SLAC

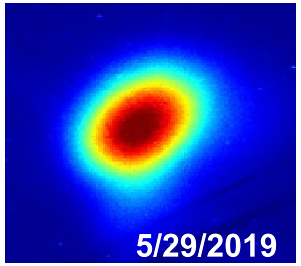
A modified AEPX gun for LCLS-II, under commissioning

LCLS-II low energy beamline commissioning started in summer 2018

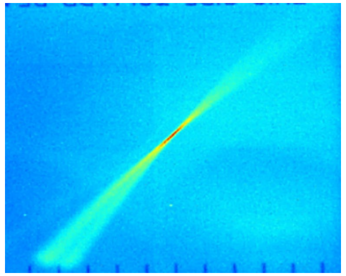
Gun: 87kW CW operation

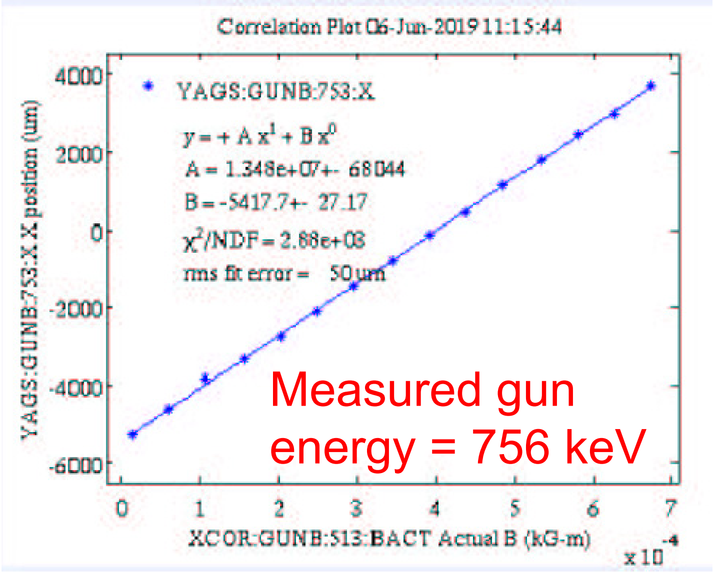


1st photoelectrons



10-20 nA dark current





Next steps:

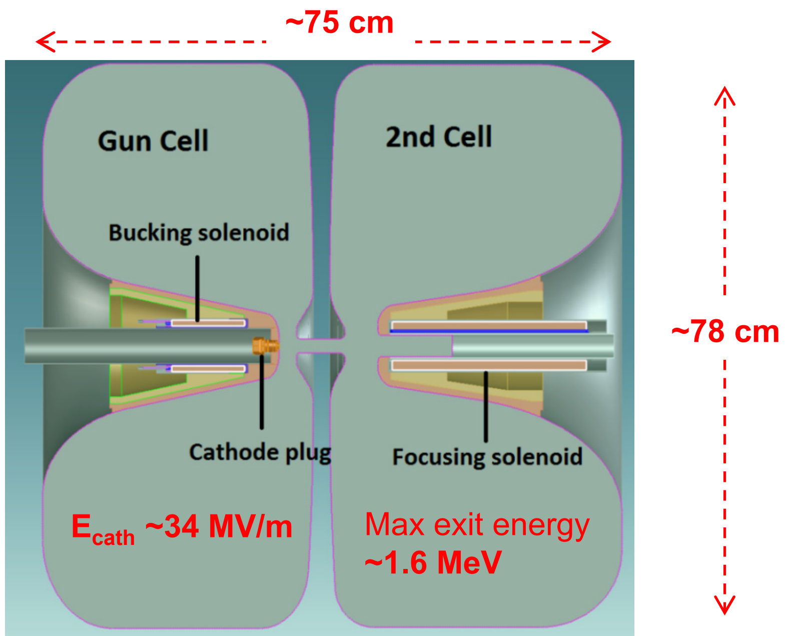
- Replace the dummy cathode with Cs_2Te cathode
- Fully characterize/optimize electron beam
- Gain operating experience with up to 1 MHz beam operation

APEX2 gun @ LBNL

Physics & mechanics design studies, status report

Next generation NC VHF gun

- Aim for electron source brightness improvement (>4 fold) for X-ray FEL and UED/UEM
- Two-cell VHF gun
  - No coupling between two cells
  - Cell 1 for higher cathode gradient
  - Cell 2 for boosting gun energy



APEX2 gun vs APEX gun RF design

	APEX gun	APEX-2 gun Cell 1	APEX-2 gun Cell 2	
Frequency	185.7	162.5	162.5	MHz
Peak acceleration field	19.5	34	25	MV/m
Gun voltage	750	820	820	kV
Average RF power	90	91	85	kW
Shunt impedance	6.3	7.3	7.8	Mohm
Peak surface field	24.1	37	25	MV/m
Peak thermal power density	25	32	30	W/cm^2
Diameter/Length	69.4/35.0	78.6/38.7	78.2/36	cm

APEX2 gun vs APEX gun beam dynamics

Simulations	APEX gun	APEX-2 gun	
$\varepsilon_{cath}/\sigma_{laser}$	1.0	**0.6**	μm.rad/mm
ε_{xn} (100%)	0.3	**0.08**	μm.rad
ε_{xn} (95%)	0.2	0.07	μm.rad
Peak current	14.5	12.5	A
E_k	97	130	MeV
HOM*	9.6	**3.3**	keV/c

CW VHF gun activities @ DESY & SHINE

Further development of APEX gun, status report

DESY 216.7 MHz VHF gun

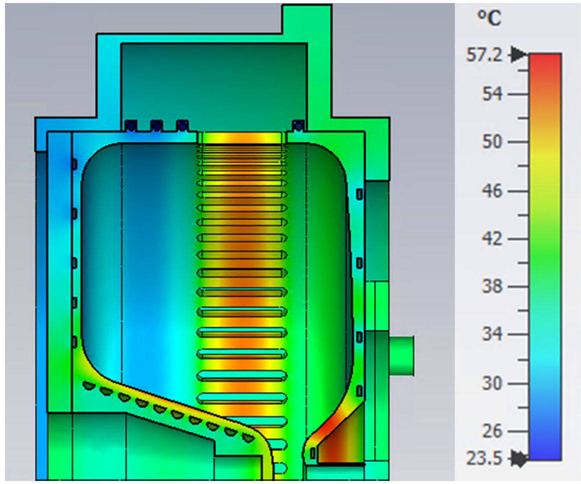
- **Backup option** for European XFEL
- 216.7 MHz, lower breakdown risk
  - $E_{kilp} \propto f^{\frac{1}{2}}$ (2*E_{kilp} ~30.4 MV/m)
- 1-cell VHF gun, E_{cath} ~28 MV/m, V_{gun} ~830 kV
  - 1.0 µm.rad/mm → 0.2 µm.rad
  - 0.5 µm.rad/mm → 0.12 µm.rad

SHINE 162.5 MHz VHF gun

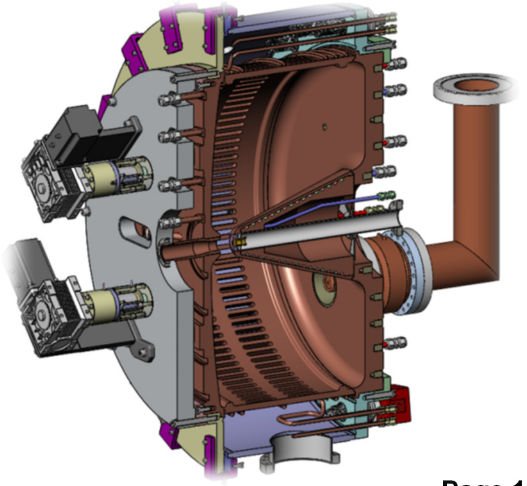
- **Baseline gun technology** for SHINE
- 162.5 MHz, reduce cavity heating, $R_{surf} \propto f^{\frac{1}{2}}$
- 1-cell VHF gun, 70-120 kW
  - 750 kV, 23.5 MV/m @69 kW
  - 1 MV, 31 MV/m @ 119 kW

	DESY	SHINE	Units
Frequency	**216.7**	**162.5**	MHz
Cathode gradient	**28**	**23.5~31**	MV/m
Gun voltage	**830**	**750~1000**	kV
Average RF power	**100**	**69~120**	kW
Shunt impedance	6.9	8.2	Mohm
Peak surface field	30.6	28.4~37.5	MV/m
Peak power density	37	16.9~29.5	W/cm^2
Diameter/Length	68/26.8	80/42	cm

DESY



SHINE



Summary of NC VHF guns

Green parts have been realized with beam in CW mode

RF parameters	APEX	LCLS-II	APEX2	DESY	SHINE	Units
Status	Routine operation	Commissioning	Design	Design	Prototyping	N/A
Frequency	185.7		162.5	216.7	162.5	MHz
Cathode gradient	19.5		34	28	23.5~31	MV/m
Gun voltage	750		1640	830	750~1000	kV
Average RF power	90		176	100	69~120	kW
Shunt impedance	6.3		15.2	6.9	8.2	Mohm
Peak surface field	24.1		37	30.6	28.4~37.5	MV/m
Peak power density	25		32	37	16.9~29.5	W/cm^2
Diameter/Length	69.4/35		78.6/74.7	68/26.8	80/42	cm
Beam parameters	**Partially measured**		**Simulation**			
Bunch charge	20/100/300	20/100/300	100	100	100	pC
Repetition rate	1	1	1	1	1	MHz
Dark current	~0.1	10~20	/	/	/	nA
Projected emittance	~0.2 (20 pC @6 A)	0.2/0.4/0.6 (5-30 A)	0.08 (12 A)	0.2 (11 A)	/	µm.rad
Cathode	Cs_2Te (CsK_2Sb)	Cs_2Te	K_2CsSb	/	/	/
Thermal emittance	~0.75 (~0.6)	/	0.6	1.0	/	µm/mm
Cathode assembly	Loadlock, RF spring					
Lifetime in gun	~2 months (~2 weeks)	/	/	/	/	/

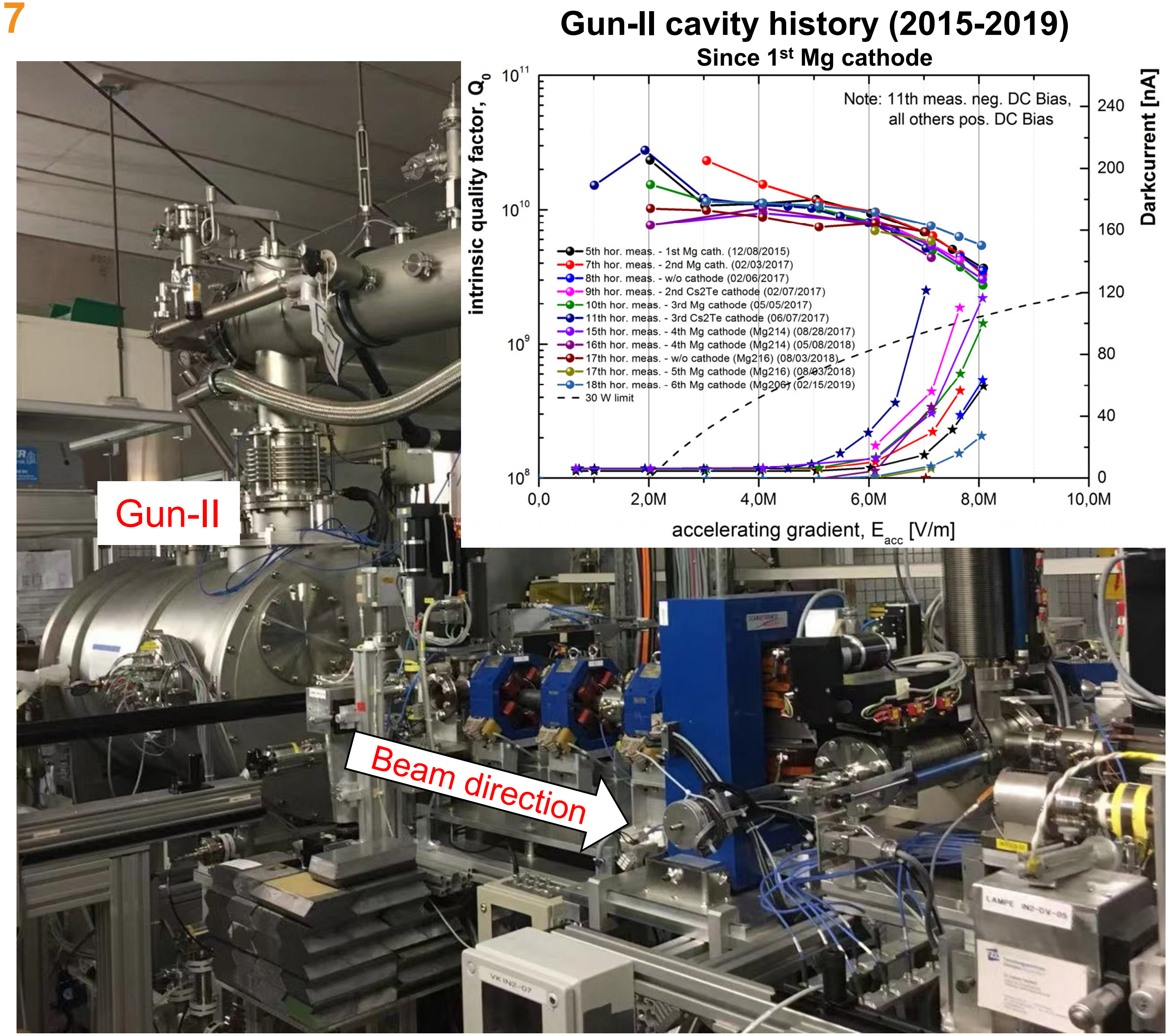
A brief overview on superconducting CW gun developments worldwide:

@ HZDR, HZB, KEK, DESY, PKU, BNL & SLAC

HZDR – SRF gun for ELBE (THz FEL)

~20 years' SRF gun R&D, user operation since 2017

Routine beam parameters	3.5 cell SRF Gun
bunch repetition rate [kHz]	100
bunch charge [pC]	Up to 300
transverse emittance [µm]	2 to 15
beam energy at gun exit [MeV]	3-4
RF parameters	
operation frequency [GHz]	1.3
accelerating gradient [MV/m]	8
electric field at cathode [MV/m]	12
peak on axis field [MV/m]	20
Cathode	
material	Mg (Cs_2Te)
assembly	Load lock, RF choke

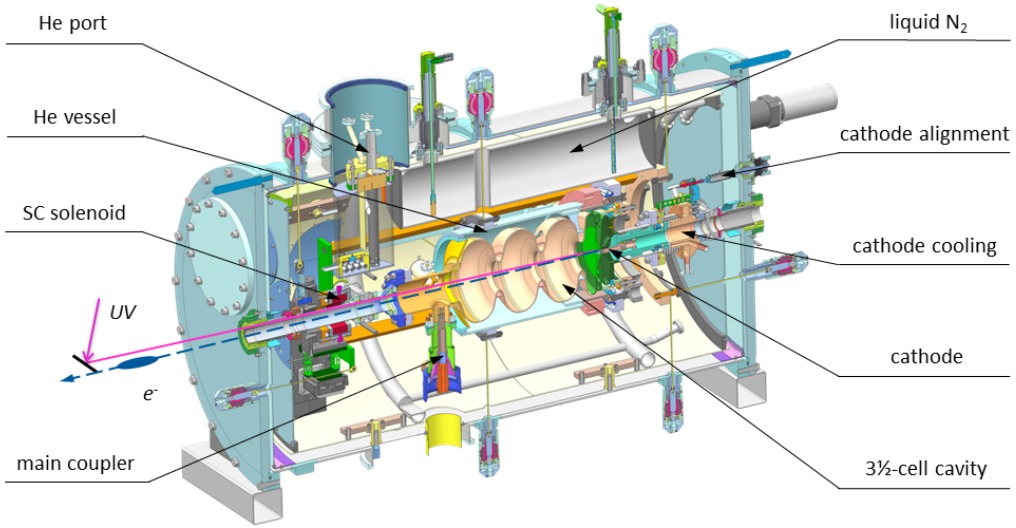


HZDR – SRF gun for ELBE (THz FEL)

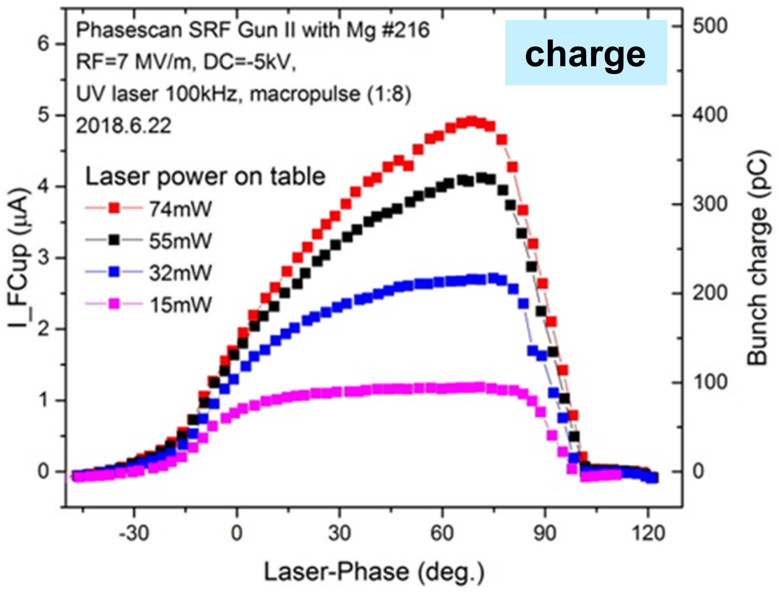
present R&D status

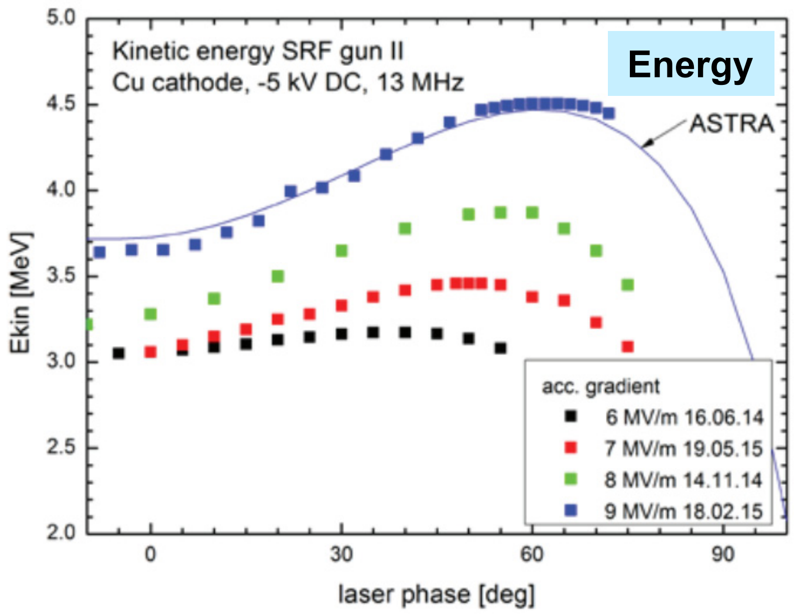
Further developments presently concentrate on:

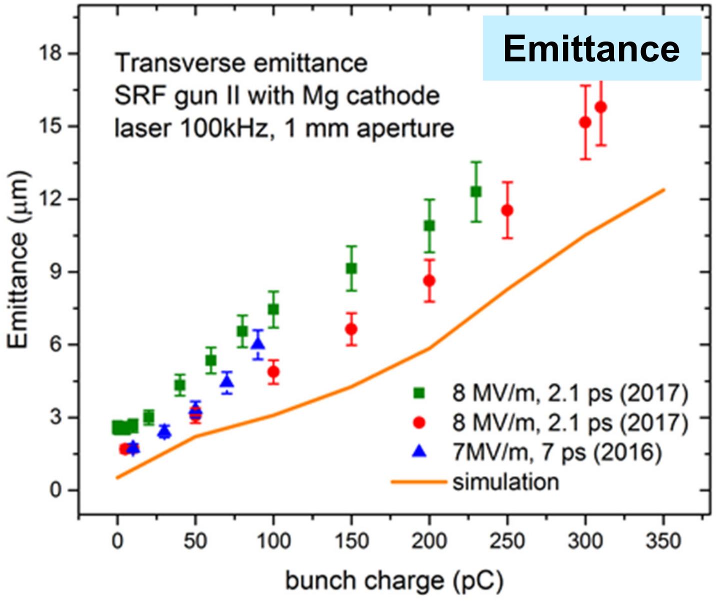
- Improve cathode cooling
- Re-establish Cs_2Te for high bunch charge operation
- Study other cathode materials for SRF gun
- Establish a dedicated gun-lab



Achieved beam properties







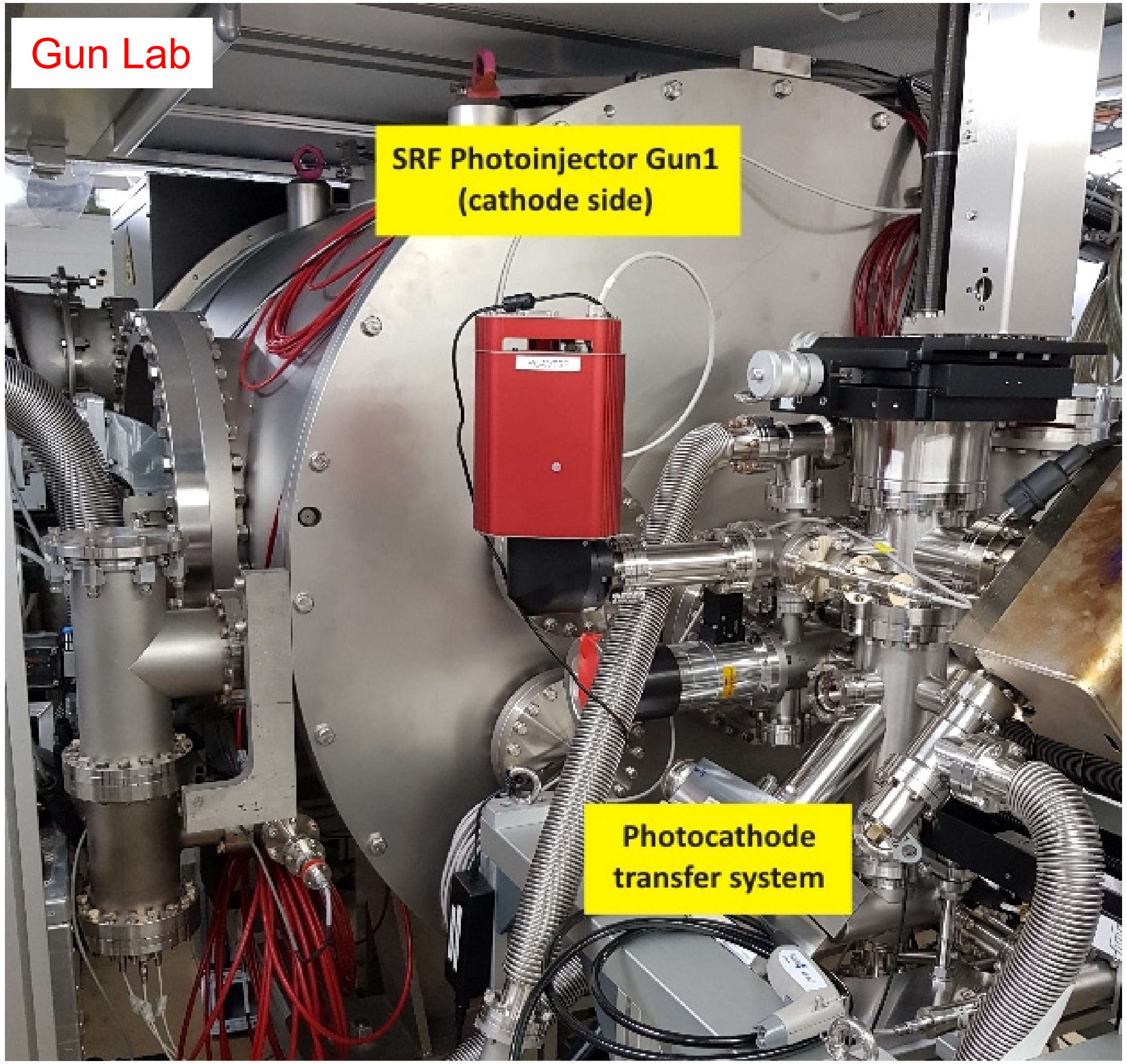
HZB – SRF gun for bERLinPro

~10 years' SRF gun R&D

design beam parameters	1.4 cell SRF Gun
bunch repetition rate [GHz]	1.3
bunch charge [pC]	77
transverse emittance [µm]	< 0.5
beam energy at gun exit [MeV]	2

RF parameters	
operation frequency [GHz]	1.3
accelerating gradient [MV/m]	21
electric field at cathode [MV/m]	26
Peak on axis field [MV/m]	30

Cathode	
material	CsK_2Sb
assembly	Load lock, RF choke

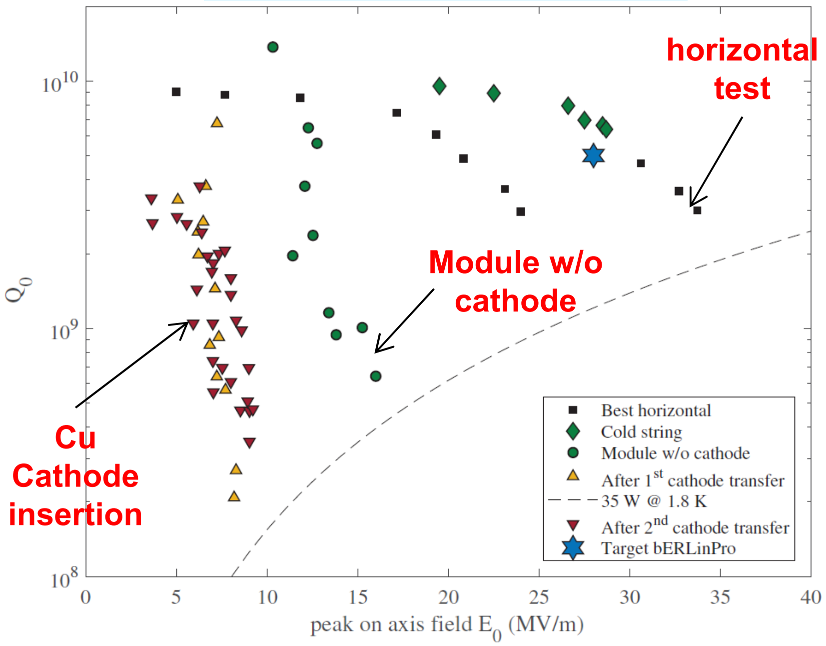


		purpose	cells	cathode
done	Cav. 0.1	learn operating SRF guns	1.6	Pb coated area on Niobium backplane
2 MeV done	Cav. 0.2	gain of further experience, improvements: cathode on removable Nb plug	1.6	exchangeable plug, Pb coated
In progress	Cav. 1.1	optimized for high peak brightness operation, insertion of a normal conducting high QE cathode	1.4	variable, CsK_2Sb

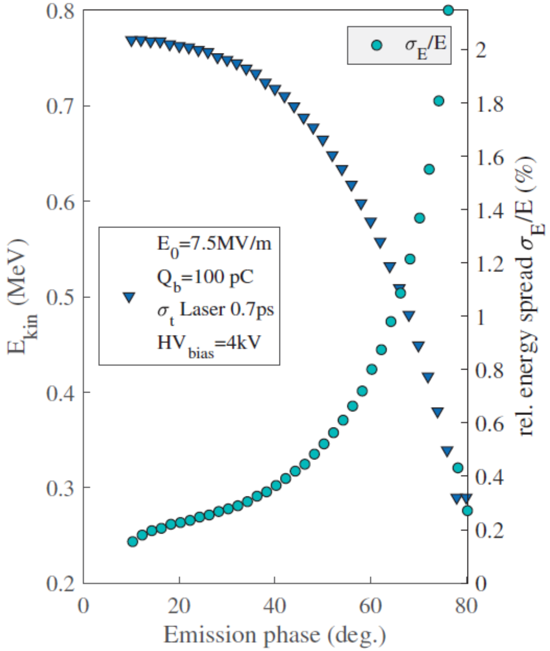
HZB – SRF gun for bERLinPro

present R&D status

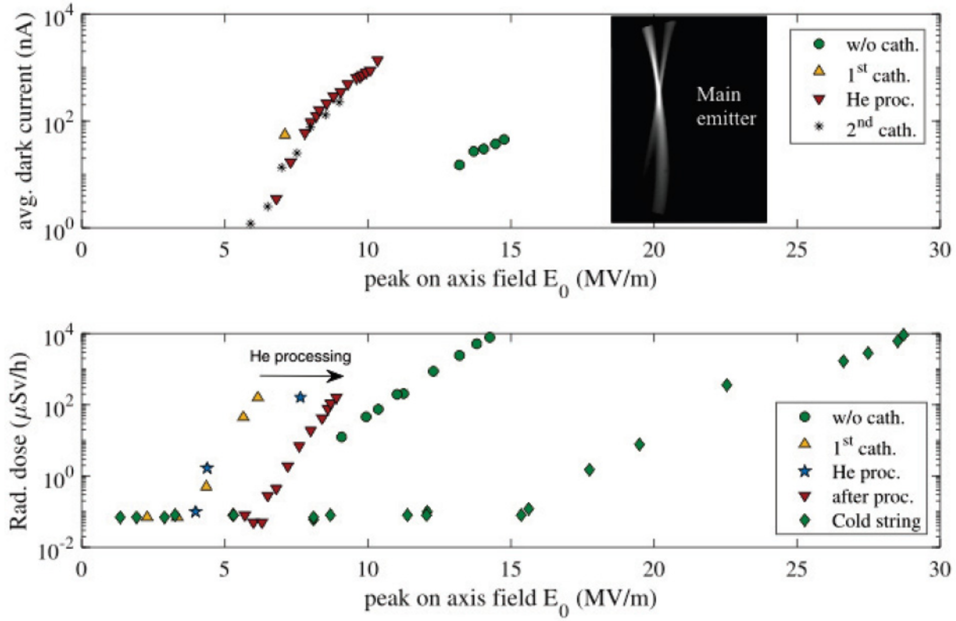
Gun 1.1 cavity history



100 fC beam energy



Dark current & radiation does



The current emphasis of the R&D work lies on the cathode and the cathode exchange system:

- Improve cathode/cavity interface to get a green CsK_2Sb cathode into the gun

- Next step - moving into the bERLinPro accelerator hall

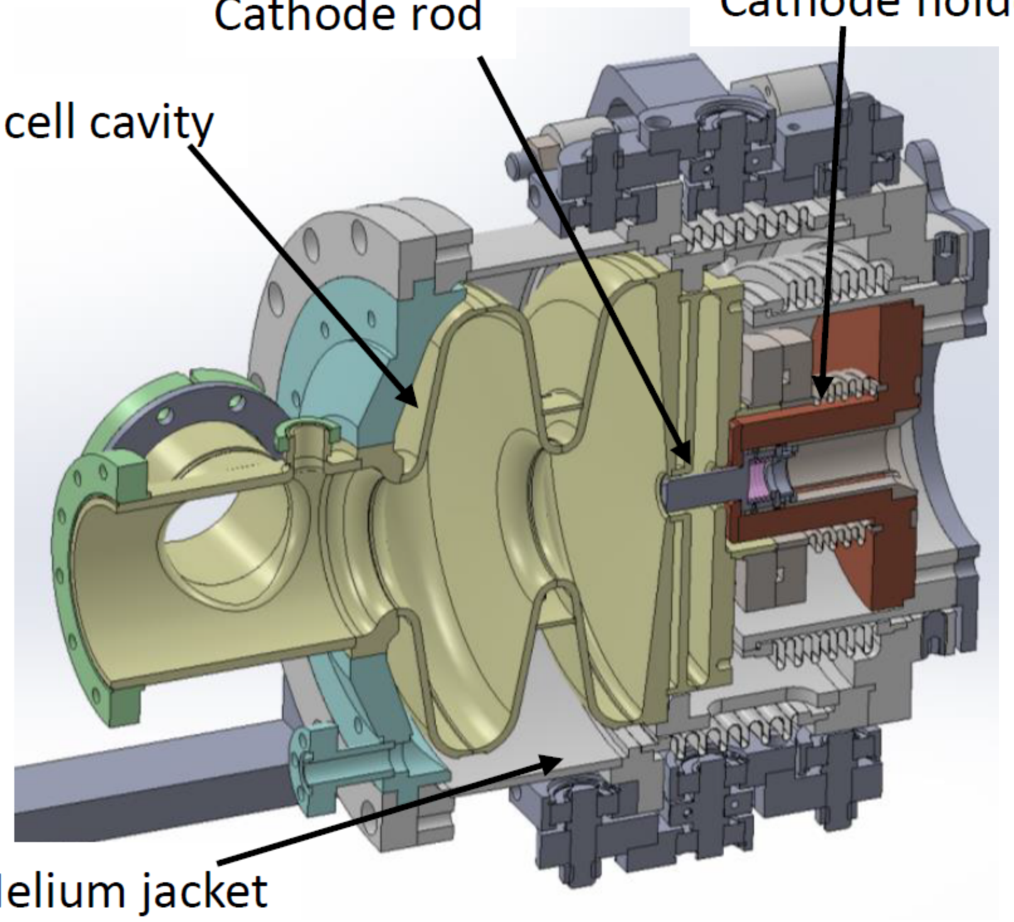
KEK – SRF gun for KEK-ERL

Since 2013

design beam parameters	1.5 cell SRF Gun
bunch repetition rate [GHz]	1.3
bunch charge [pC]	80
transverse emittance [µm]	0.6
beam energy at gun exit [MeV]	2

RF parameters	
operation frequency	1.3 GHz
accelerating gradient [MV/m]	16
electric field at cathode [MV/m]	23
Peak on axis field [MV/m]	31.5

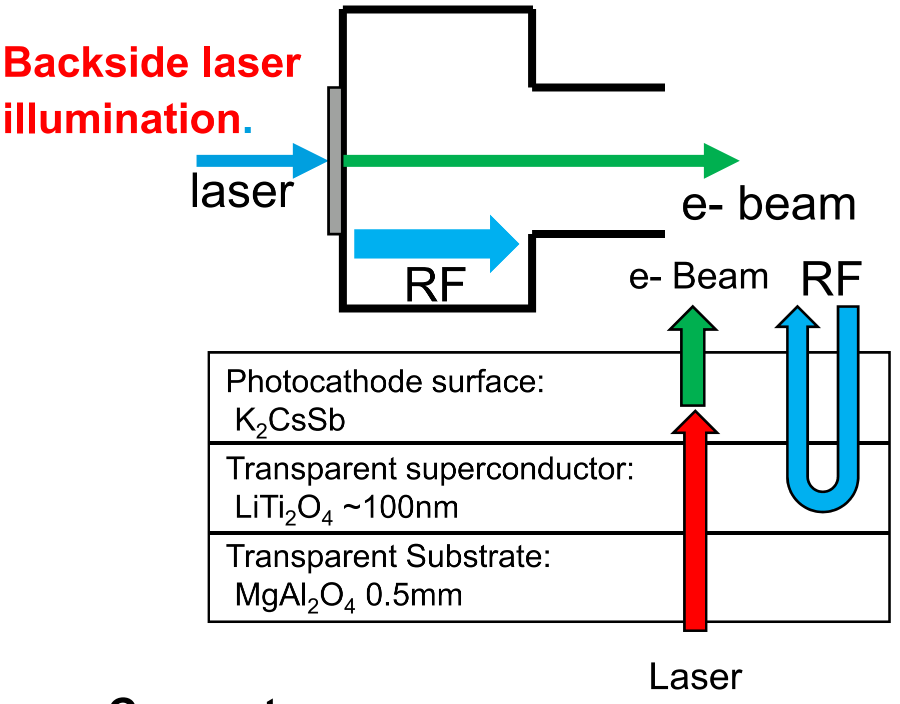
Cathode - excited from the backside!	
material	CsK_2Sb
assembly	Load lock, RF choke



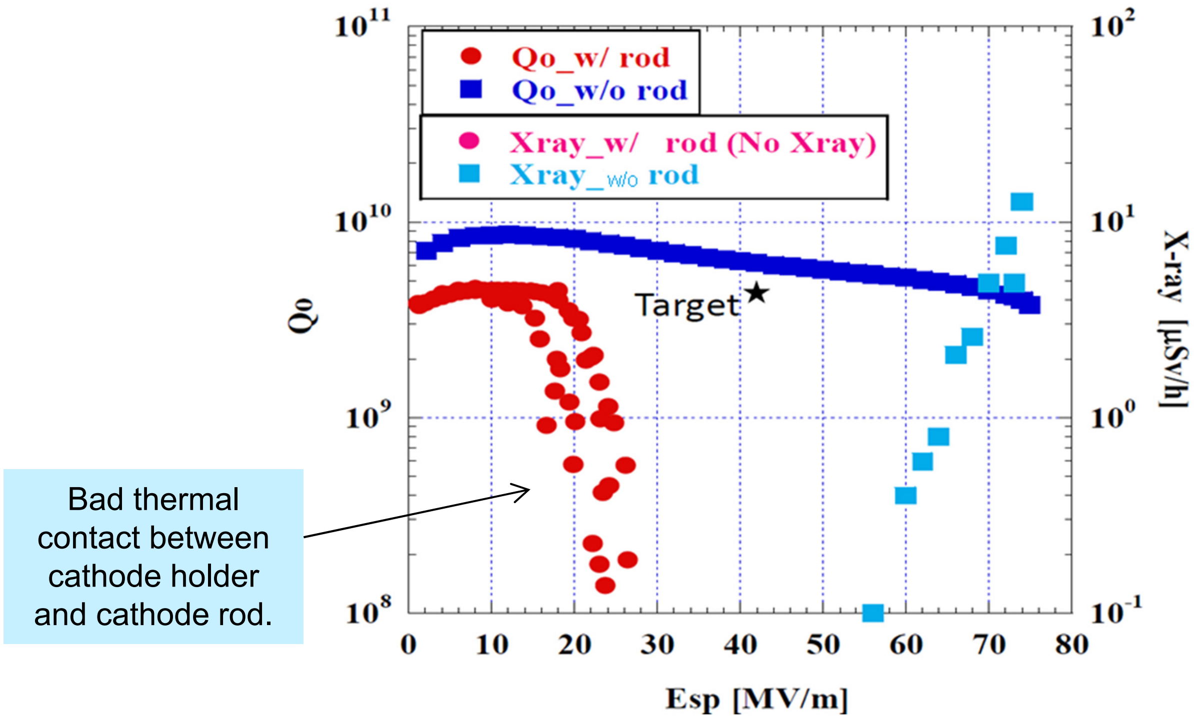
	Purpose
Gun #1	Vertical test, understand cavity treatment
Gun #2	Beam test

KEK – SRF gun for KEK-ERL

present R&D status and activities



Both Gun1 and 2 vertical test reached ~57 MV/m peak on axis gradient w/o cathode rod.



Concept:

- simple laser transport and spot control
- cathode needs being at 2 K due to 13 K transit temperature of transparent SC

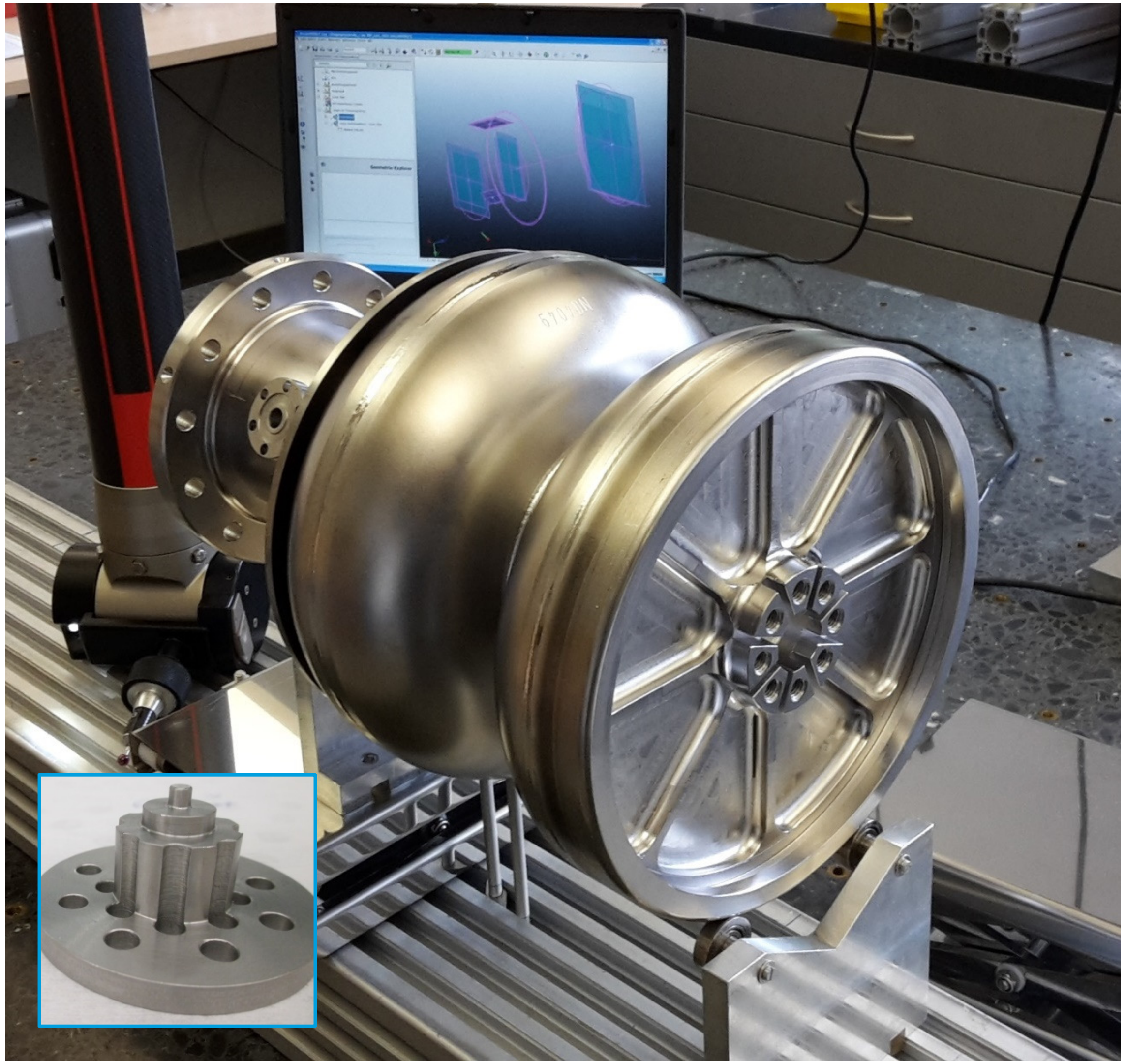
Further developments and R&D plans:

- Cathode rod cooling test.
- Particle free cathode rod transportation.
- Horizontal test, small current beam test

DESY – All SC gun for European XFEL CW operation mode

design parameters and setup

design beam parameters	1.5 cell SRF Gun
bunch repetition rate [kHz]	1000 -100
bunch charge [pC]	20 to 250
transverse emittance [µm]	0.4 to 0.8
beam energy at gun exit [MeV]	> 3
RF parameters	
operation frequency [GHz]	1.3
accelerating gradient [MV/m]	21
electric field at cathode [MV/m]	40
Peak on axis field [MV/m]	42
Cathode	
material	Pb
assembly	screwed to back-wall



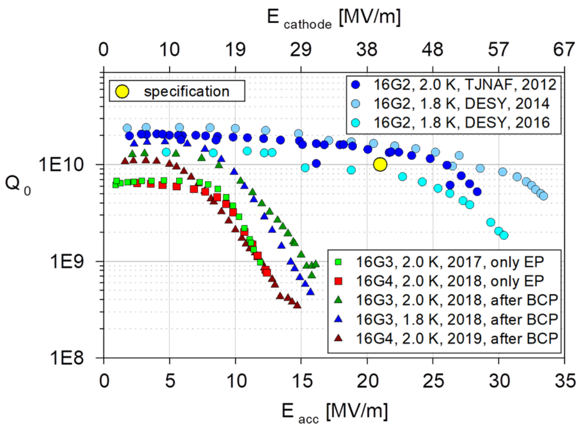
DESY - All SC Gun for European XFEL CW operation mode

present R&D status and activities

Present main R&D topics:

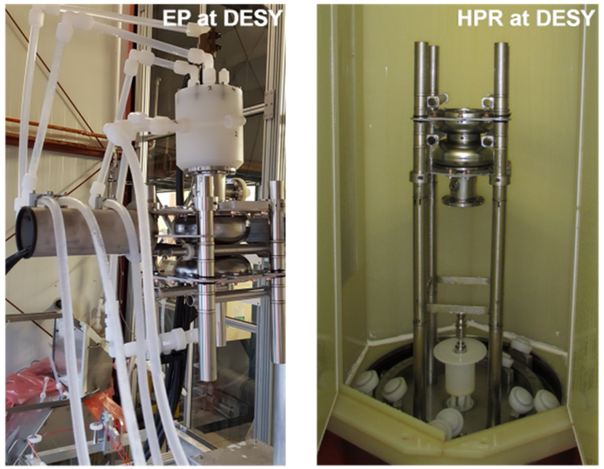
- mechanical back-wall stability
- mechanical fabrication
- surface treatment by
  - BCP (buffered chemical polishing)
  - EP (electro polishing)
  - HPR (high pressure rinsing with ultra pure water)
- surface examination and inspection
- vertical tests examining e.g.
  - cavity performance
  - thermal properties
- material examination (Nb is ok)
- studies for next generation cavity
  - cathode position
  - power coupler position, HOM filters needed?
  - pick up antenna for better RF control

Vertical Test Results

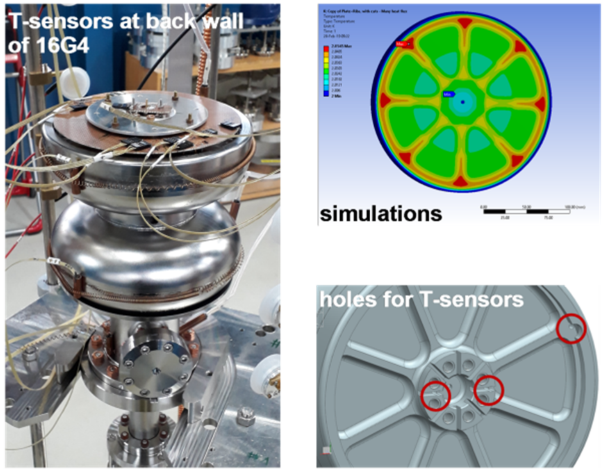


Four Generations 1.6 Cell Cavities

Surface Treatment by EP & HPR



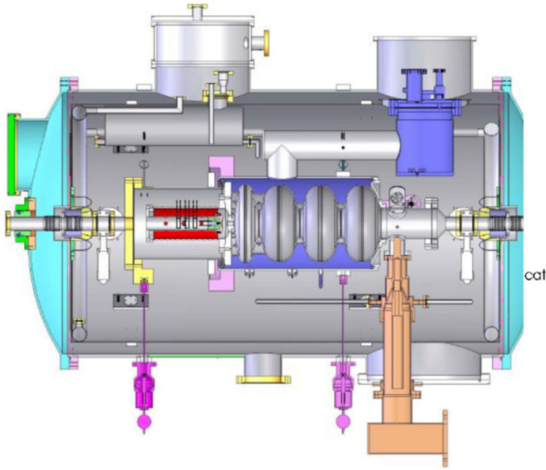
Thermal Properties of 16G3/4

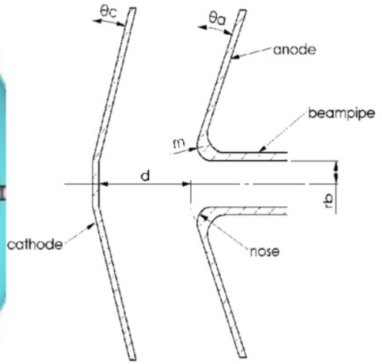


PKU – DC-SRF gun

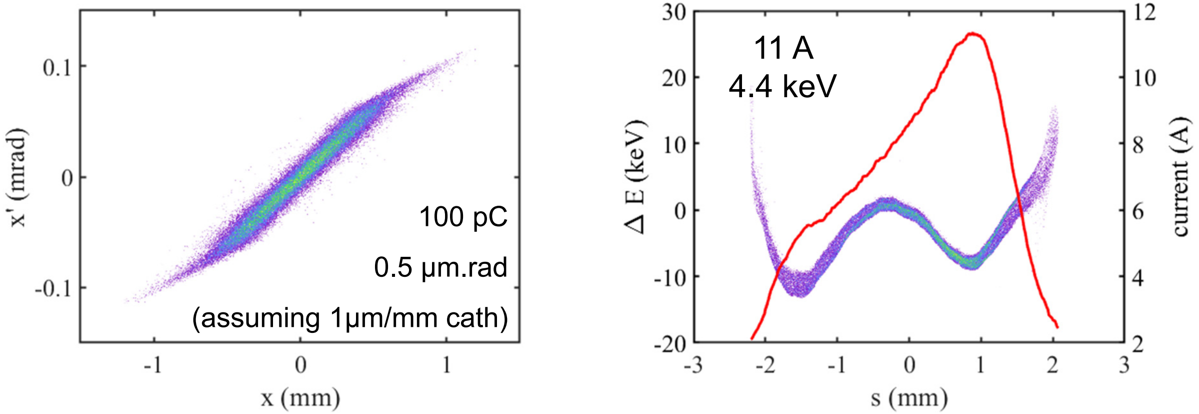
~20 years' SRF gun R&D, routine operation since 2014

beam parameters	DC-SRF Gun	
	3.5 cell	1.5 cell
bunch repetition rate [MHz]	27	1
bunch charge [pC]	20 - 50	100
transverse emittance [µm]	1.5	<0.5
beam energy at gun exit [MeV]	3.4	2.8
RF parameters		
operation frequency [GHz]	1.3	
accelerating gradient [MV/m]	12	14
electric field at cathode [MV/m]	2.56	6
Peak on axis field [MV/m]	22	26.6
Cathode		
material	Cs_2Te (K_2CsSb)	
assembly	Loadlock, screw in	





Simulation results for CW FEL injector (1.5 cell gun with buncher)



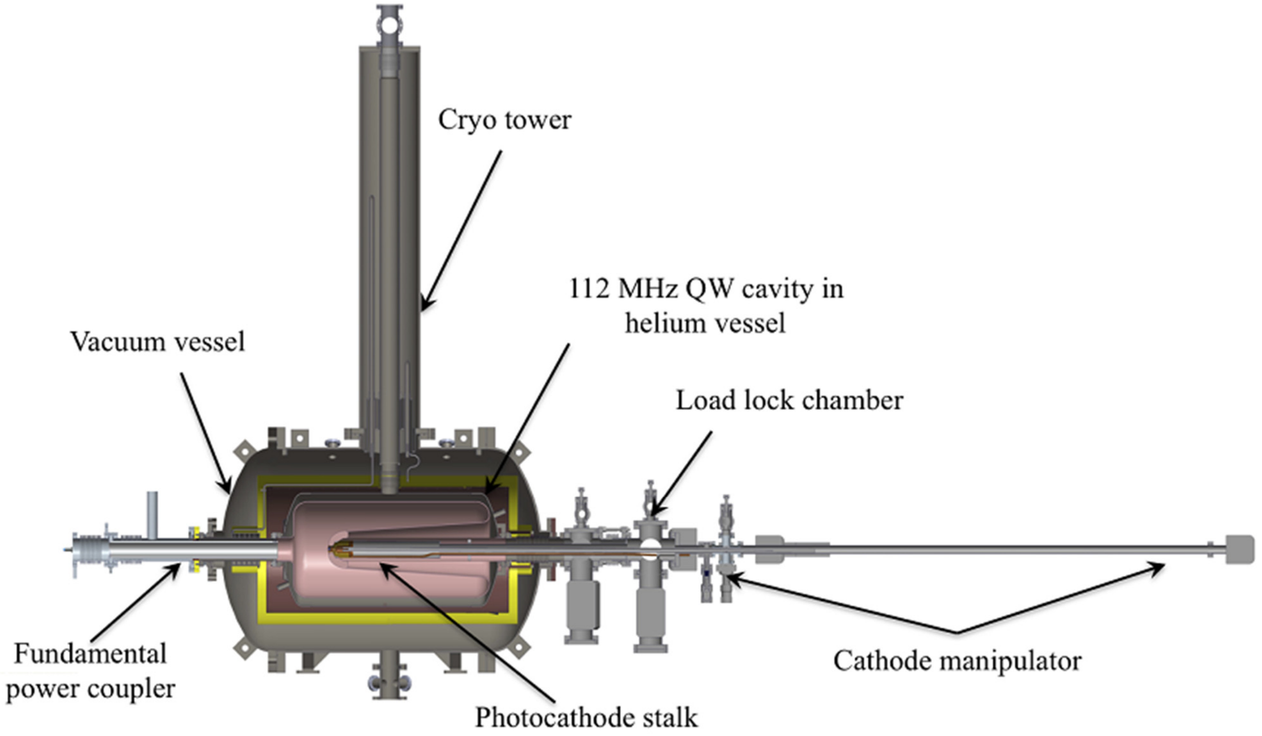
Further gun developments and R&D plans:

- 1.5 cell DC-SRF gun construction & emittance reduction
  - DC voltage 50 kV → 100 kV
  - Cathode Cs2Te → K2CsSb
  - Laser shaping
  - Beamline optimization

BNL – SRF gun for cooling hadrons

Routine operation since 2016

beam parameters	QWR SRF Gun
bunch repetition rate [kHz]	78
bunch charge [nC]	up to 10.7
transverse emittance [μm]	5
beam energy at gun exit [MeV]	1.25 to 1.5
RF parameters	
operation frequency [MHz]	113
accelerating gradient [MV/m]	8
electric field at cathode [MV/m]	10 to 20
Peak on axis field [MV/m]	20
Cathode	
material	CsK_2Sb
assembly	Loadlock + RF choke



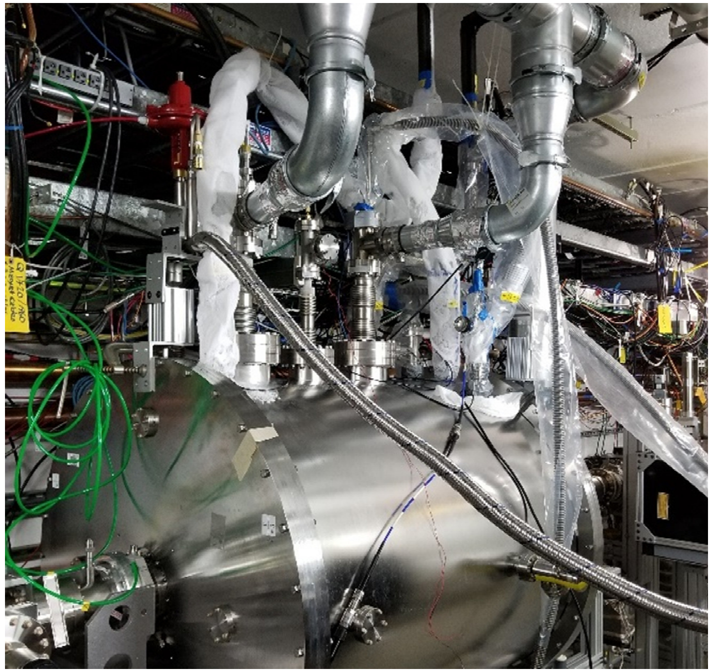
Achievements

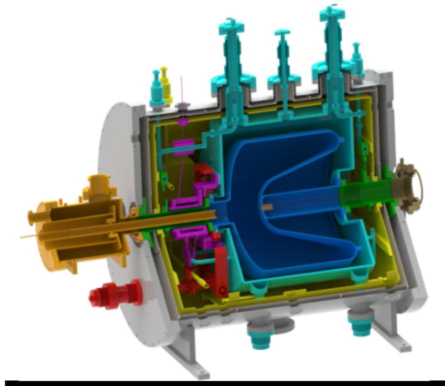
- A turn-on procedure is developed to jump multipacting barriers (0~1 hour).
- Routine beam time up to ~100 days per year.
- 1-2 months lifetime of high QE for CsK_2Sb cathode.
- 0.32 μm emittance measured for 0.5 nC beam (~500 ps long)
- 0.15 μm emittance measured for 0.3 nC beam (~250 ps long)

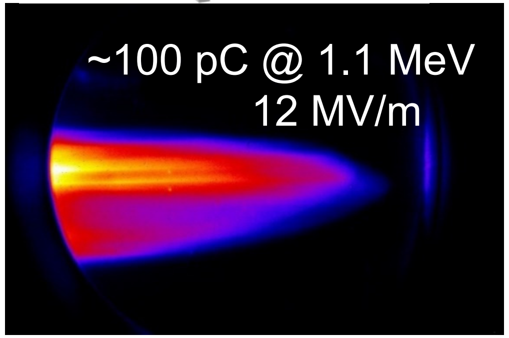
Wisconsin/SLAC/ANL - SRF gun for LCLS-II HE & UED/UEM

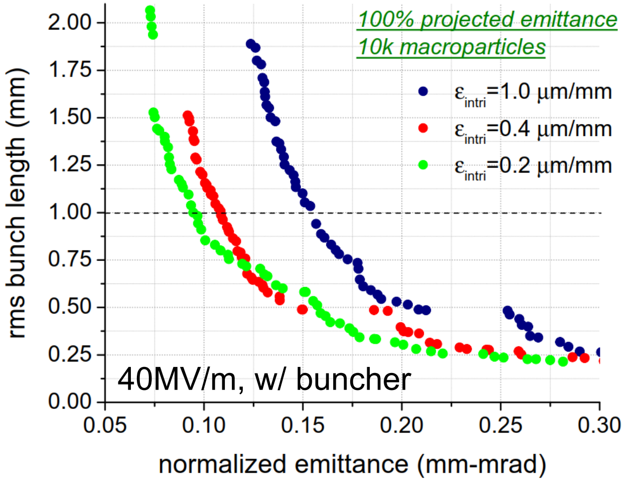
Wisconsin gun → SLAC → ANL

design beam parameters	QWR SRF gun
bunch repetition rate [MHz]	1
bunch charge [pC]	100
transverse emittance [µm]	1
beam energy at gun exit [MeV]	4
RF parameters	
operation frequency [MHz]	200
accelerating gradient [MV/m]	/
electric field at cathode [MV/m]	45
Peak on axis field [MV/m]	45
Cathode	
material	Cu
assembly	RF choke









Next steps:

- transfer from SLAC to ANL for further tests due to availability of cryogenic plant at ANL.

Summary of SC CW guns

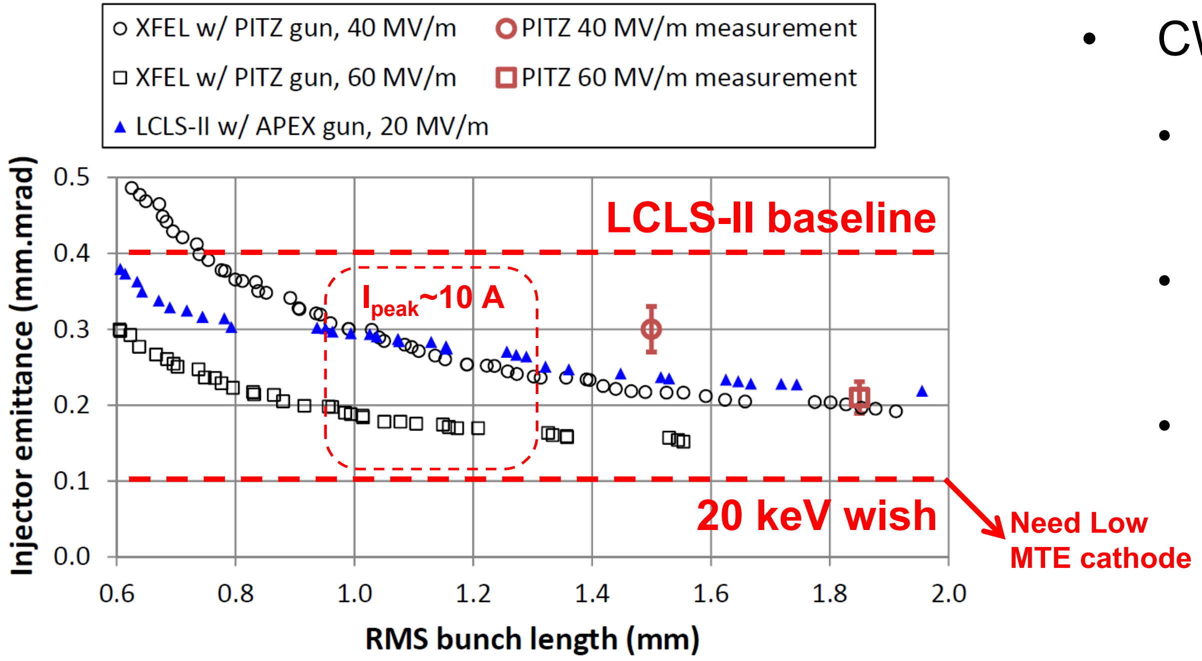
Green parts have been realized with beam in CW mode

RF parameters	BNL	SLAC	HZDR	HZB	KEK	DESY	PKU		Units
Status	Routine operation	R&D	Routine operation	R&D	R&D	R&D	Routine operation		N/A
Frequency	113	200	1300	1300	1300	1300	1300		MHz
Temperature	4	4	2	2	2	2	2		K
Cavity type	QWR	QWR	TESLA (3.5)	TESLA (1.4)	TESLA (1.5)	TESLA (1.5)	3.5	1.5	Cell
Gun energy	1.25	1.1	3-4	0.77	2	>3	3-4	2.8	MeV
Cathode E field	10-20	12	12	7.5	23	40	2.6	6	MV/m
Peak on axis E field	20	12	20.5	7.5	31.5	40	22	26.6	MV/m
Gradient limitation	Field emission	/	Field emission	Field emission	/	/	DC		N/A
Beam parameters									
Bunch charge	up to 10700	100	~200	77	80	100	20-50	100	pC
Repetition rate	0.078	0.001	0.1	1300	1300	0.1	27	1	MHz
Dark current	~1	/	30	100	/	/	~1	/	nA
Projected emittance	0.15 @0.1 nC I_{peak} <1 A	1.5 (I_{peak} ? A)	2-15 (I_{peak} ? A)	<0.5 (I_{peak} ? A)	0.6 (I_{peak} 8 A)	/	1.5 (5-8 A)	0.5-0.3 (~10 A)	µm
Cathode	CsK_2Sb	Cu	Mg (Cs_2Te)	Cu (CsK_2Sb)	CsK_2Sb	Pb	Cs_2Te (CsK_2Sb)		N/A
Cathode assembly	Loadlock RF choke	RF choke	Loadlock RF choke	Loadlock RF choke	Loadlock RF choke	Screw in	Loadlock Screw in		N/A
Lifetime in gun	1 – 2	/	~12	/	/	/	1 - 2		Month

CW gun vs L-band pulsed gun performance

Where are we now?

- CW NC VHF gun vs L-band NC gun
  - E_{axis}^{peak}: 20 MV/m vs ~60 MV/m
  - $E_{emission}$: 20 MV/m vs ~40 MV/m
  - Gun energy: 0.75 MeV vs ~6 MeV
  - Injector **100 pC** emittance: LCLS-II vs Eu-XFEL
    - Simulations uses **1 μm/mm cathode**

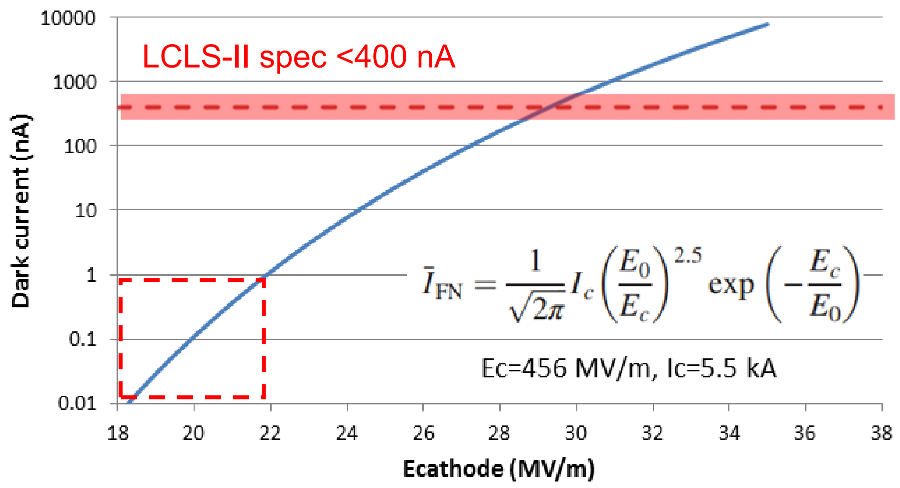


- L-band SC gun vs L-band NC gun
  - E_{axis}^{peak} w/ beam: ~20 MV/m vs ~60 MV/m
  - E_{axis}^{peak} in vertical test: ~67 MV/m vs ~60 MV/m
- VHF-band SC gun vs L-band NC gun
  - E_{axis}^{peak} w/ beam: 10 - 20 MV/m vs 60 MV/m
- CW injector simulation for 0.1 μm @100 pC, 10 A
  - APEX-2 100 pC simulations (injector w/ buncher)
    - 34 MV/m, 0.6 μm/mm cathode
  - SLAC QWR gun 100 pC simulations (injector w/ buncher)
    - 40 MV/m, 0.2-0.4 μm/mm cathode
  - DESY SC gun simulations: ongoing

Future CW RF gun R&D challenges

For even higher gradient

- NC VHF guns (>30 MV/m)
  - Where is the gradient limitation?
    - How far is breakdown
      - $2*E_{kilp}$ @217 MHz ~30.4 MV/m
      - $2*E_{kilp}$ @162.5 MHz ~27.2 MV/m
    - Dark current vs E
      - APEX gun dark current extrapolation
      - 0.1 nA @ 19.5 MV/m → 400 nA @ 29 MV/m



- SC guns (40-60 MV/m)
  - Compatibility between SC cavity and cathode?
    - Cavity cleaning & particle free assembly
    - Particle free cathode exchange
    - Cathode plug over heating
    - Multipacting
  - Dark current vs E
    - HZDR gun dark current extrapolation for Mg cathode
    - ~30 nA @ 20.5 MV/m → ~1 µA @ 41 MV/m

- Common to both guns
  - Compatibility to low thermal emittance cathode is crucial
  - Solenoid position & aberration
  - Laser shaping
  - …

Summary

- **A joint effort is pushing the frontier of high brightness CW RF gun**
  - CW ERL community: HZB/KEK
  - CW FEL community: BNL/DESY/HZDR/SLAC/PKU/SHINE
- **Normal conducting CW gun meets the baseline requirements of hard X-ray FEL**
  - LBNL demonstrated gun/cathode performance, and 20 pC beam brightness
  - High bunch charge brightness is still to be demonstrated by LCLS-II team
  - Next NC CW gun is under study at LBNL/SHINE/DESY towards ~30 MV/m
- **Superconducting gun has the potential to reach similar gradient as pulsed guns**
  - Current gun performance (E_{peak} 10-20 MV/m) with beam is not ready for hard X-ray FEL
  - R&D is ongoing, ~60 MV/m has been measured in vertical tests in two labs, which is yet to be demonstrated in horizontal tests with cathode and beam
  - Many labs (~7) are working together to push the SC gun technology to the next level

Thank you for your attention