Review of CW guns for XFELs

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SLAC NATIONAL ACCELERATOR LABORATORY

Contents

- CW XFEL requirements for the injector
- Highlights of demonstrated CW injector performances
    - DC gun
    - SRF guns
    - Normal conducting RF gun
- Ultra-low emittance preservation issues in the injector and through bunch compressions
- LCLS-II CW injector status

Worldwide CW XFEL projects

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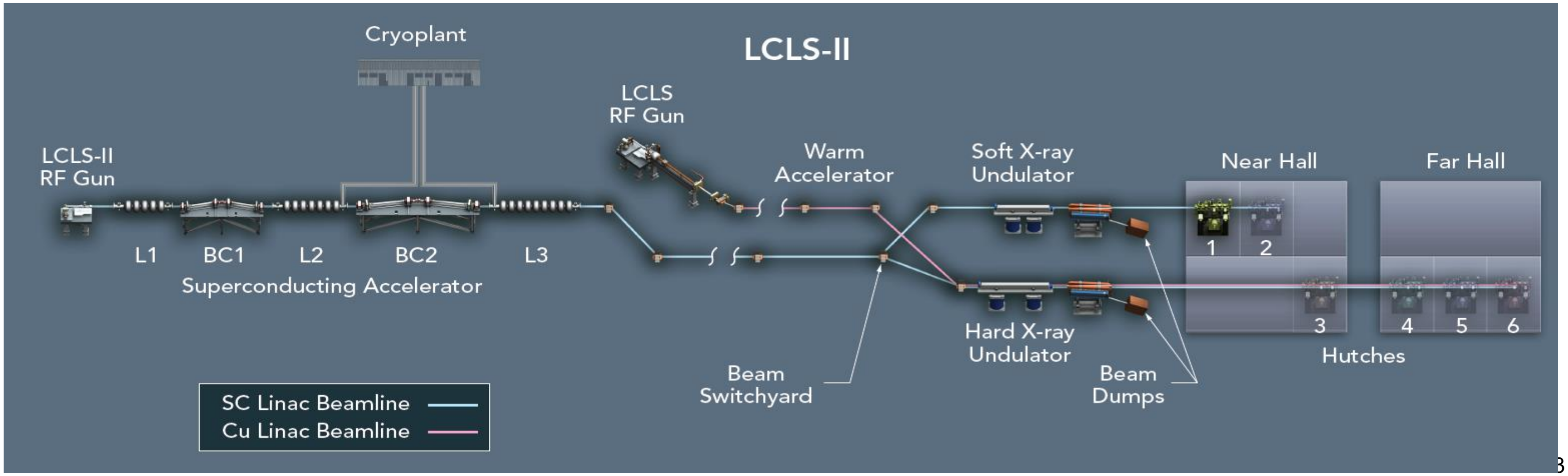
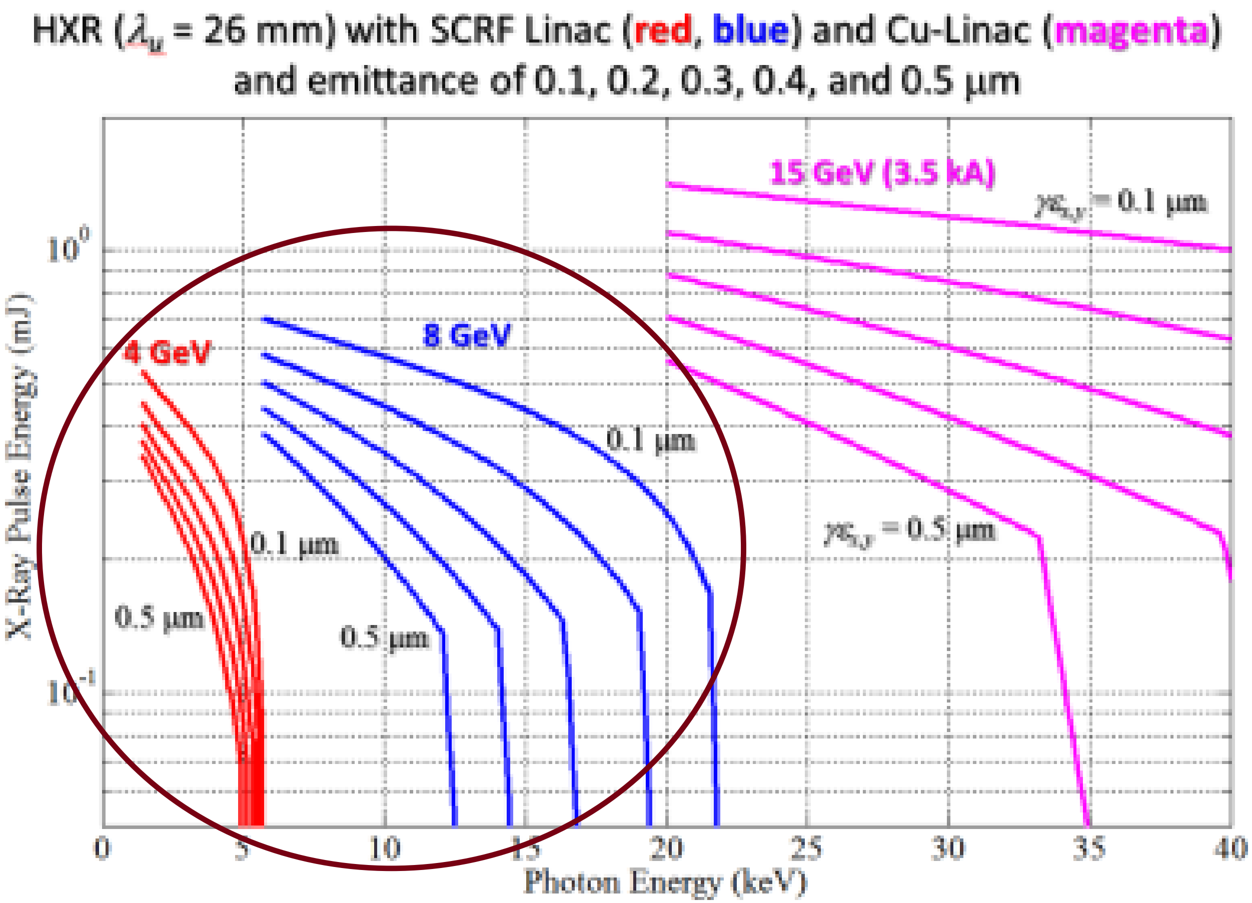
- Worldwide CW XFEL projects:
  - LCLS-II 4-GeV XFEL under construction, and LCLSII-HE 8-GeV XFEL in approval process
  - 8-GeV Shanghai XFEL approved
- Requires high-brightness CW e-beam feeding undulators

	LCLS-II	LCLSII-HE Shanghai XFEL
Charge (pC)	100	100
Emittance (μm)	0.4	0.4
Peak current (A)	1000	1000
Linac energy (GeV)	4	8
Repetition rate (MHz)	1	1
Photon energy (keV)	Up to 5	Up to 12



Transverse requirement for injector

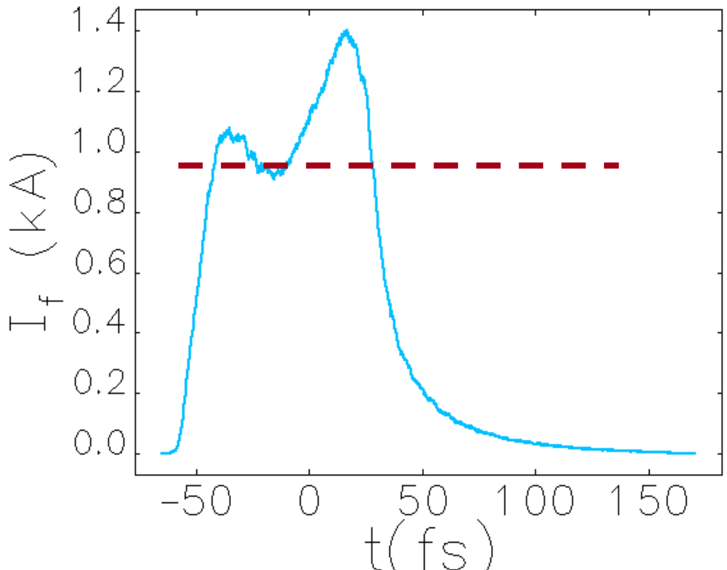


Paul Emma, DOE BES workshop, 2016

Longitudinal requirement for injector

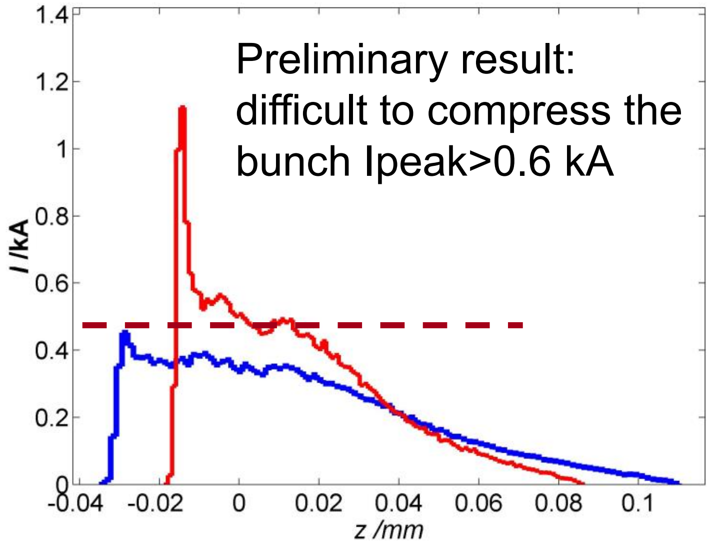
- High peak current at the injector (>10A for 100 pC) thereby requiring less bunch compression through linac
- Small nonlinear (>2nd order) δ_E for high efficiency of bunch compressions .

through LCLS-II 4-GeV linac



Starting w/ 100MeV injector beam based on 750 keV APEX gun (13 keV of δ_E)

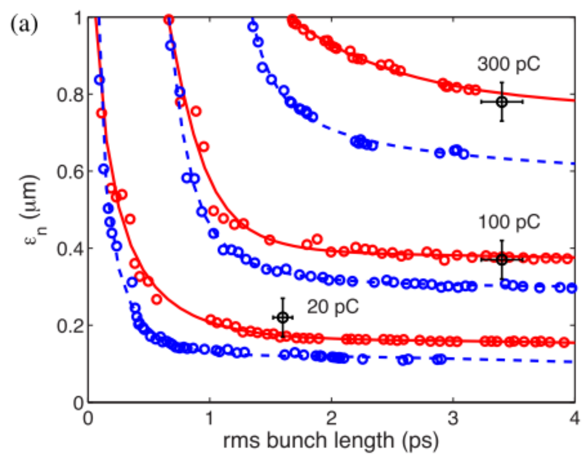
through LCLS-II 4-GeV linac

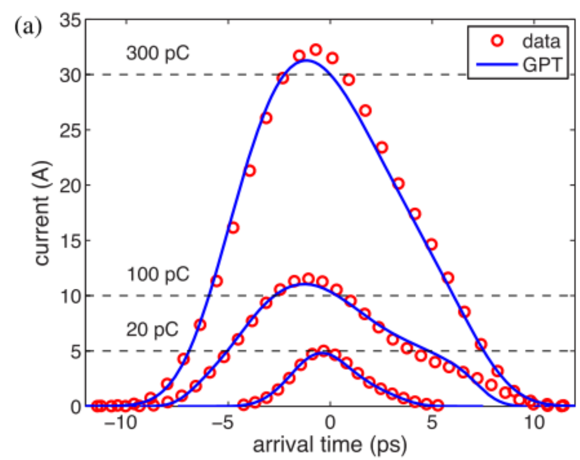


Starting w/ 100MeV injector beam based on 400 keV Cornell DC gun (35 keV of δ_E)

Cornell 400-kV DC-gun injector performance

- Routinely demonstrated reliable 400 kV gun operation, and excellent vacuum and compatible with green light Alkali cathodes of 5-10% QE.
- Routinely demonstrated 0.4 μm of ε and 12 A peak current (100 pC).



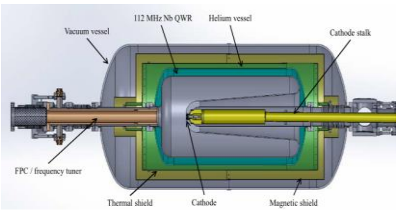


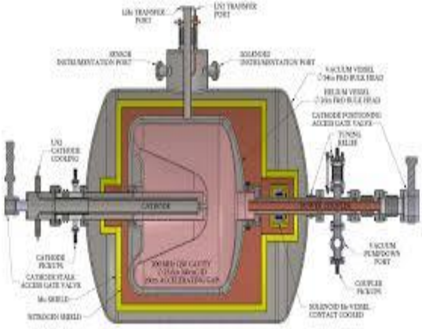
Bartnik, et al., PRAB 18, 083401, 2015

- Challenges:
  - The preliminary simulations show δ_E (>2nd order) is large making bunch compressions difficulty
  - Technology limits DC-gun to ~400 keV kinetic energy and gradient on the cathode <10MV/m, preventing further enhancing beam brightness.

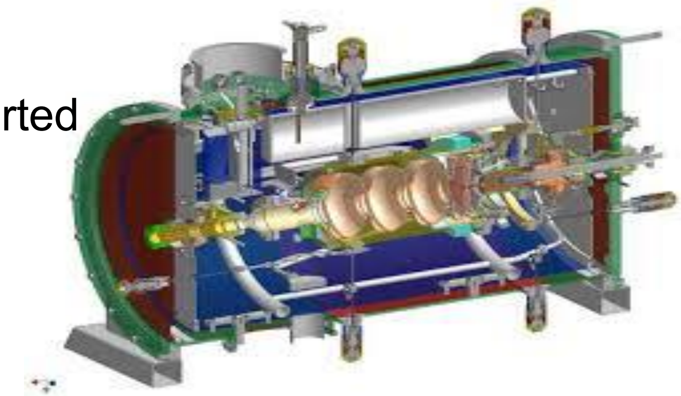
SRF guns

- Advantages:
  - Potential higher gradient >40 MV/m
  - Potential a few MeV energy gain
  - Demonstrated excellent vacuum

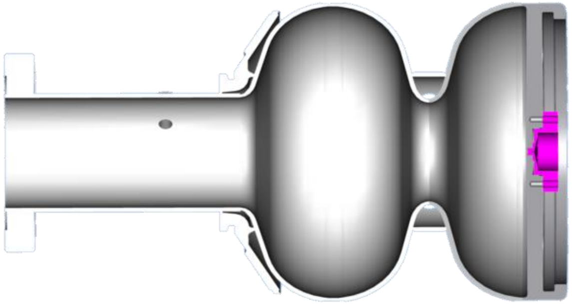




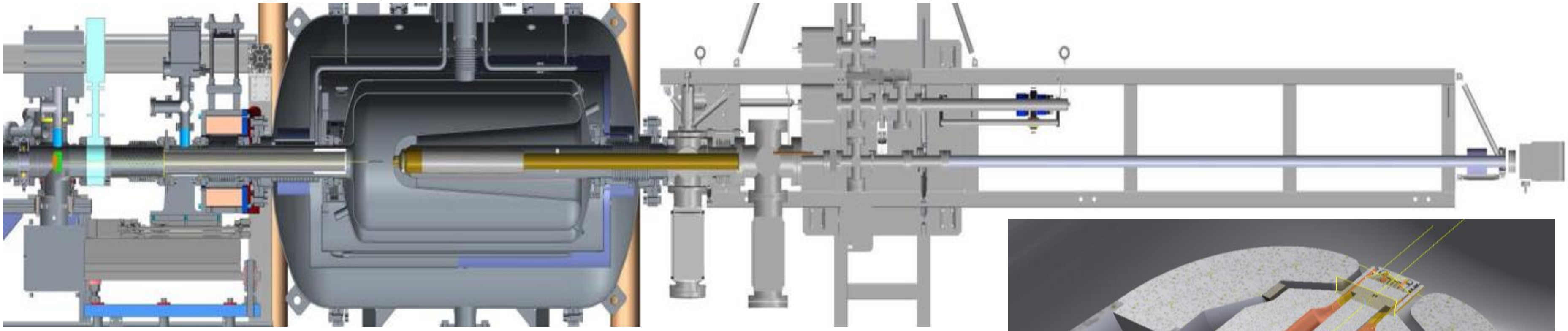
- Challenges:
  - Difficult integration of high QE semiconductor cathodes into the SRF gun and cathode change
  - Difficult to reach >20MV/m CW with cathode inserted due to particulate generation during cathode insertions/extractions and multipacting
  - Difficult to arrange solenoid close to the gun, compromising emittance compensation



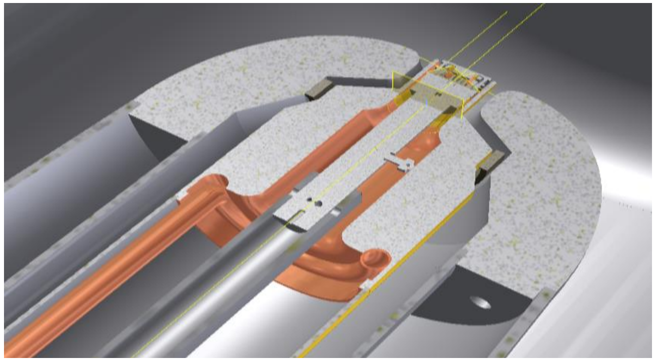
- Two typical types of SRF guns:
  - Quarter wave (113 MHz BNL and 200 MHz Wisconsin/SLAC)
  - 1.3 GHz SRF guns (HZDR, DESY/HZB).



BNL quarter wave SRF gun (113 MHz)



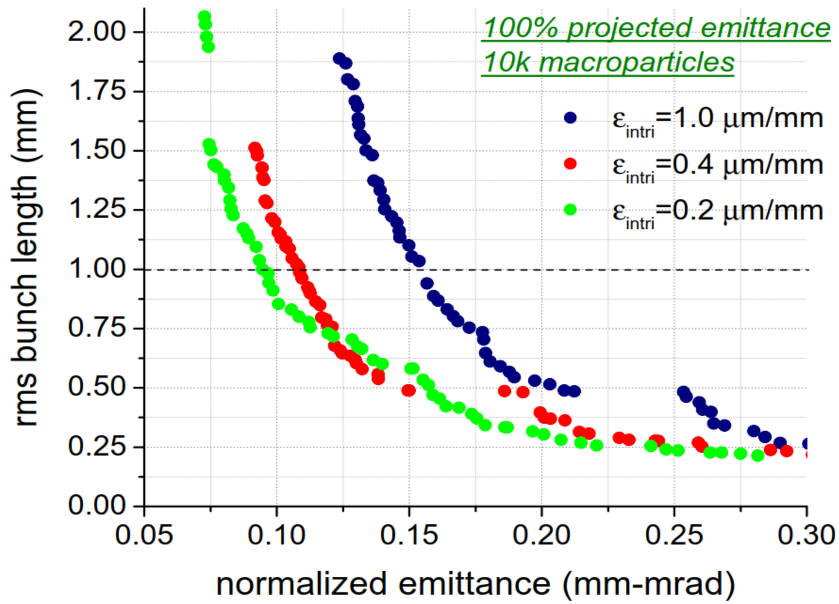
- Demonstrated >10 MV/m gradient (CW) with cathode and 1-1.5 MeV energy gain
- Demonstrated sub-μm emittance for <0.5 nC but with 500 ps bunch (buncher off) (<<1A current)
- Demonstrated 5% QE with CsK_2Sb cathode at room temperature, compatible to the SRF cavity although the process is still complicated
- Demonstrated excellent vacuum resulting in long cathode lifetime

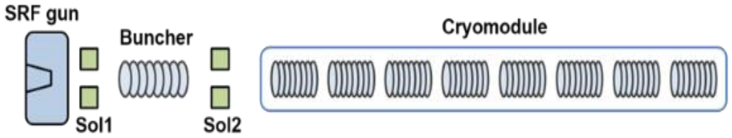


Photocathode end assembly

Courtesy Igor Pinayev

Wisconsin quarter wave SRF gun (200 MHz)





- Demonstrated 20 MV/m CW with cathode (45 MV/m design)
- Operated at 12 MV/m and 1.1 MeV energy gain; estimated ε of 1.5μm for 100 pC
- Solenoid in cryostat, preventing it close to the gun to avoid the quench, compromising emittance compensation
- Cu cathode, multipacting
- Continue to be tested at SLAC; simulation shows emittance could be reduced by a factor of 2 with 40 MV/m gradient in comparison to LCLS-II gun

1.3 GHz 3.5-cell SRF gun (HZDR)

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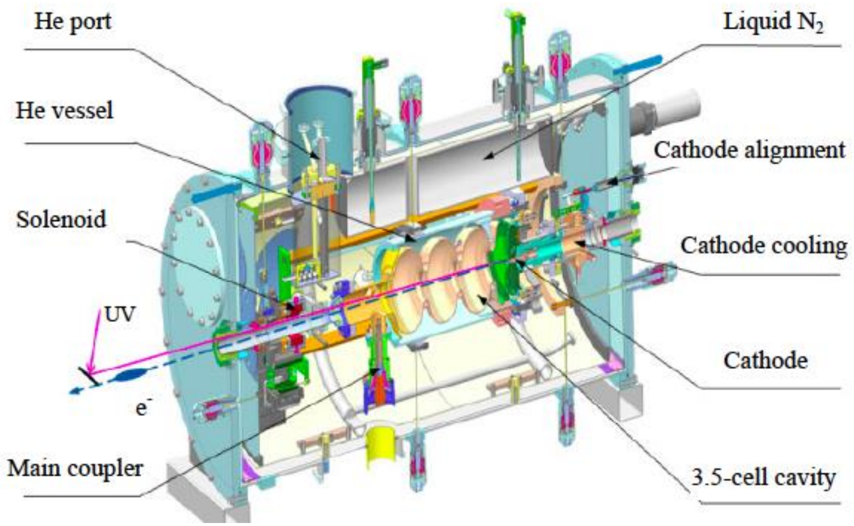
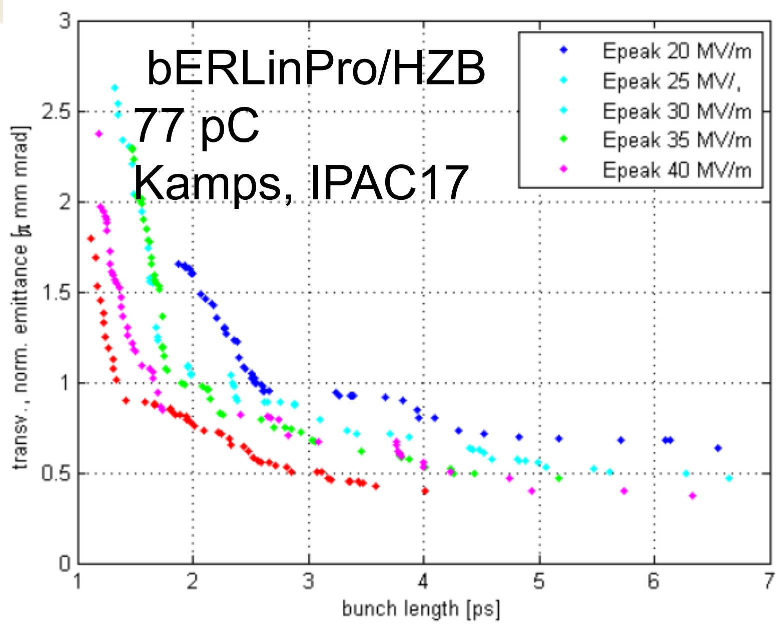
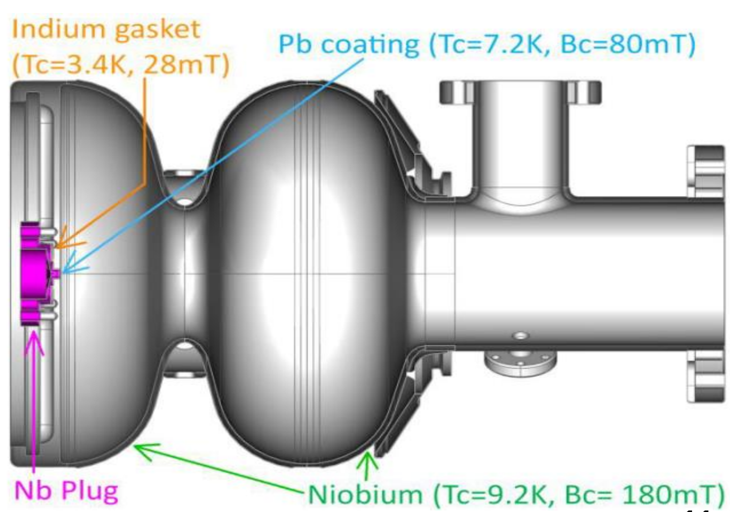
- Demonstrated 3.5-4 MeV energy gain for 3.5 cell rf gun (9.5 MeV design energy)
- Demonstrated 12-15 MV/m of gradient on the cathode
- Cold solenoid: the emittance compensation may be not in optimum due to the solenoid location – design emittance is 1μm for 77 pC
- Extra choke filter cell prevents the RF field leakage into the cathode support system.
- Cs_2Te contamination of the cavity; QE for metal cathodes ~0.1% with laser cleaning
- Emittance is a few μm for 200 pC (design 1μm for 77 pC)
- Under beam tests



1.3 GHz 1.5-cell SRF gun (HZB/DESY)

- HZB: 1.4-cell SRF gun with cold solenoid and warm cathode
  - Cathodes: Pb first, CsK_2Sb then
  - Complication of the solenoid
  - Simulated >1μm emittance for 77 pC and 1mm bunch length
  - Under beam tests
- DESY: 1.5 cell SRF gun with a superconducting cathode simplifies the design but cathode is not exchangeable:
  - Need two guns for swapping; certainly not good for operations – particularly for short QE lifetime in CW operation
  - Pb coating with laser cleaning could increase QE to 0.02%, but insufficient for 100-300 pC 1-MHz operation for 1% laser efficiency

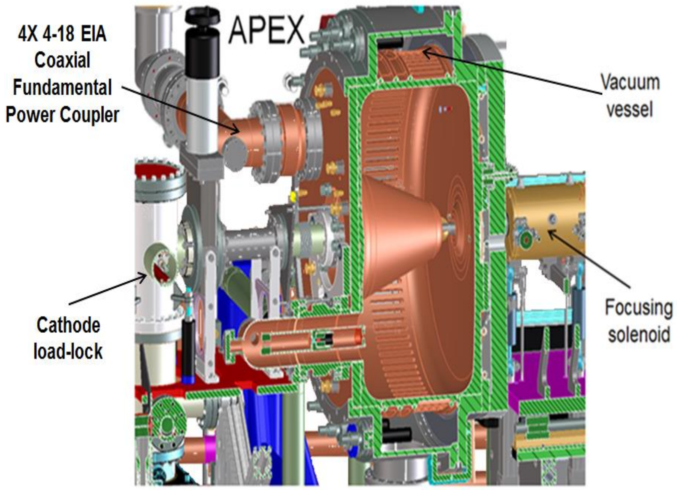




Courtesy Sekutowicz

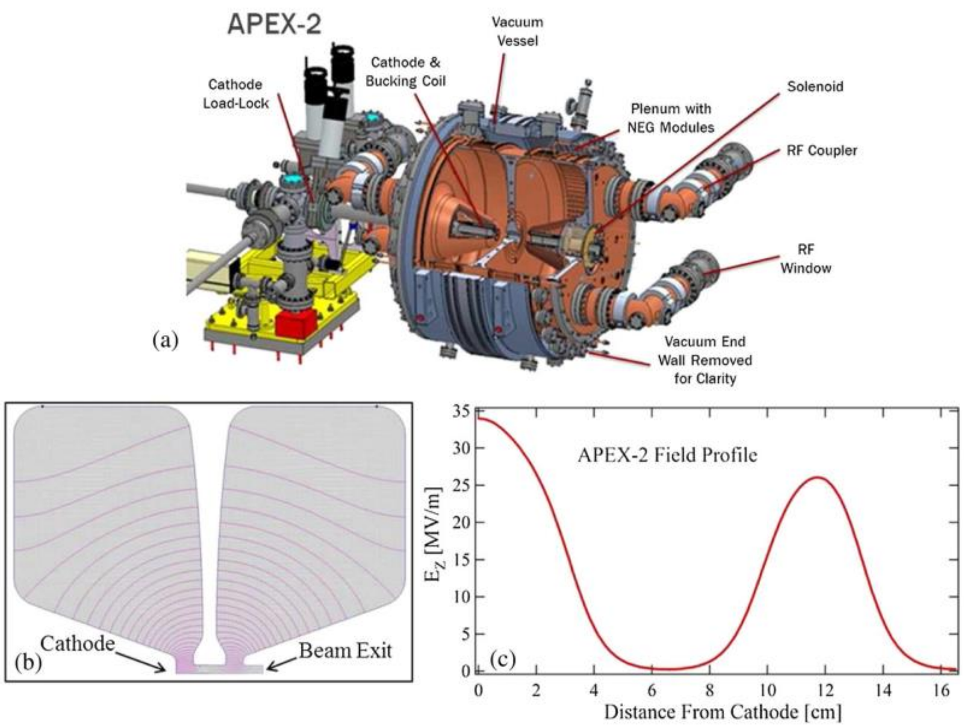
LBNL 186-MHz NC RF gun performance (APEX gun)

- Routinely operated 20MV/m on cathode and 750 keV energy gain
- Routinely demonstrated 5-10% of QE with Cs_2Te cathodes and QE lifetime 2-3 weeks for CW operation
- Routinely demonstrated 20 pC performance for LCLS-II requirements: 0.2 μm emittance and 5-7 A of peak current through bunch compression
- Demonstrated 100 pC emittance ~1 μm with very preliminary beam tuning due to the limited resources:
  - Simulations show strong space charge effect is still included in the APEX measurement at ~15 MeV beam energy
  - We believe LCLS-II specifications 0.4 μm/12 A (100 pC) can be achieved after optimizing varieties of injector parameters which had not been performed at APEX

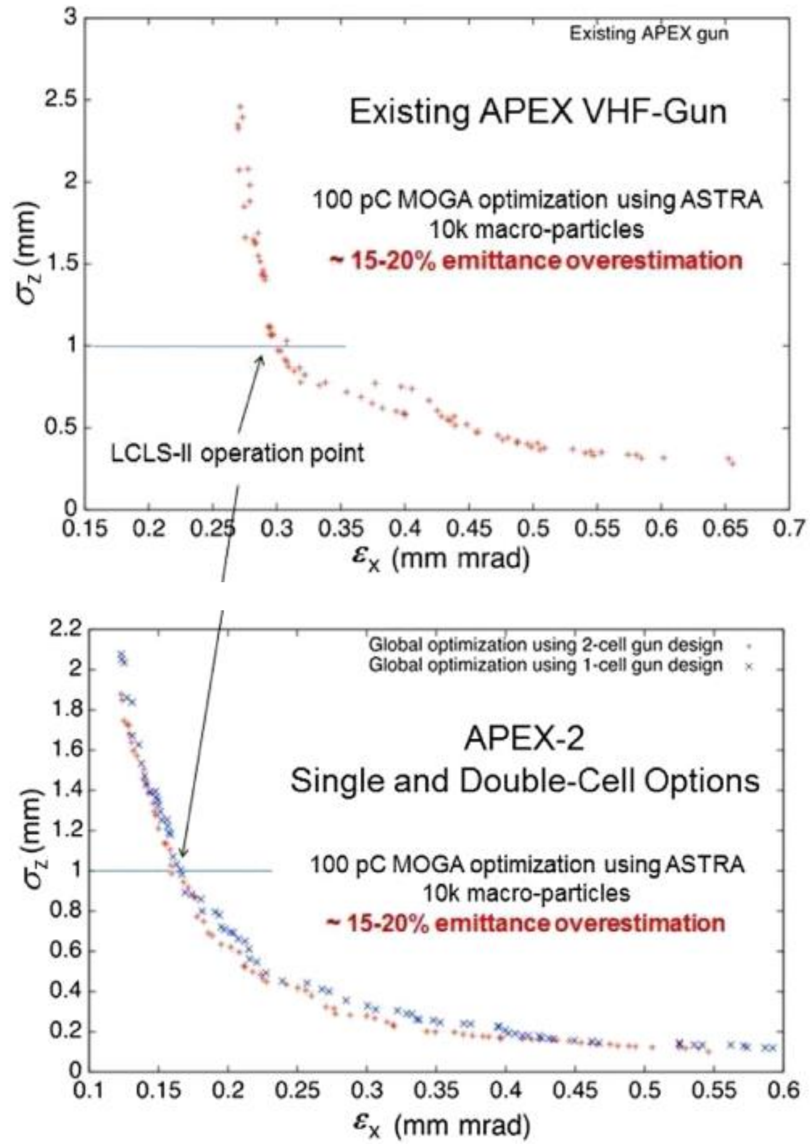


APEX-2 gun – LBNL team working on the design

- 1-cell gun option: 35 MV/m, 2 MeV
- 2-cell gun: adding another cell based on current APEX gun (1.5 MeV)
- ε is 0.15μm (100%, 100pC), improved by a factor of 2



Sannibale, PRAB 20, 113402 (2017)



Demonstrated CW injector performances

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	DC gun	BNL SRF gun	APEX gun*
Gradient on cathode (CW)	<10 MV/m	~10 MV/m	20 MV/m
Kinetic E	0.4 MeV	~1 MeV	0.75 MeV
Solenoid for emittance compensation	Optimum	Compromising	Optimum
Cathode	Alkali family Easily Compatible to gun	Alkali family Compatible to the gun but complicated	Cs_2Te Easily compatible to the gun
E-beam performance	- ε~0.4 μm & I=12 A (100 pC) - larger nonlinear δE is of concern	- ε~0.3-0.7 μm & I<<1 A (150-500pC)	- ε~0.2μm & I>5 A (20 pC) - ε~1 μm (not optimized) and I~10 A (100pC)

* LCLS-II CW injector adopts APEX gun technology

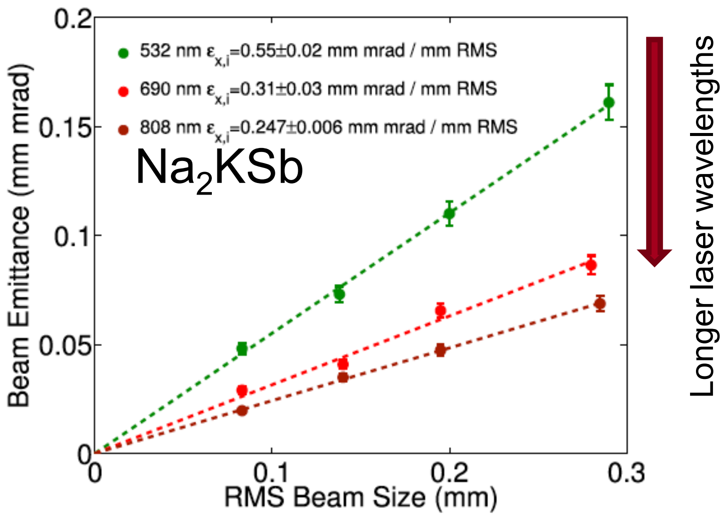
Many components impacting emittance

- Gun is only one of important components impacting emittance
- Many other ‘simple’ components having significant impact to the emittance:
  - Cathode: low thermal emittance without compromising QE
  - Beamline optics: optimizing solenoid/buncher location, solenoid field shape, and correcting harmonic fields
  - Laser profiles

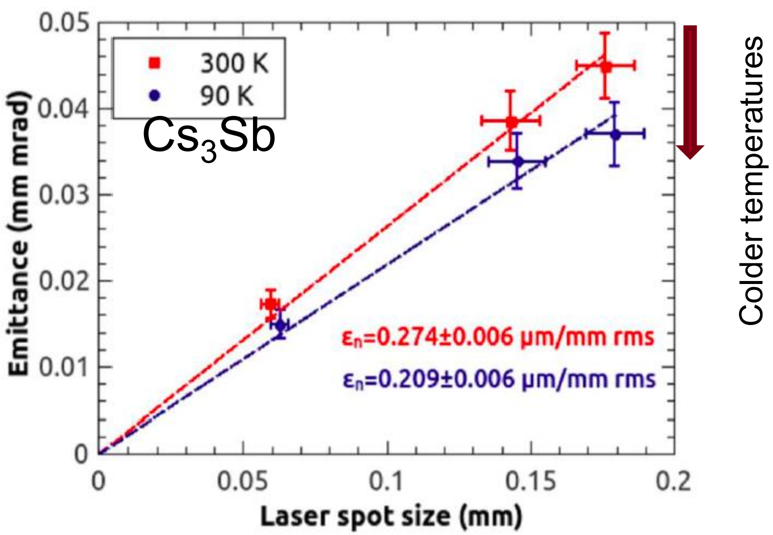
These impacts to the emittance cannot be lightly weighted for <0.4 μm emittance

Alkali-type photocathodes

- Operate alkali-type photocathodes at:
  - Excitation wavelength near the bandgap, and
  - Cryogenic temperatures
- This cathode family can provide up to a 2X reduction in thermal emittance compared to LCLS-II Cs_2Te cathodes
  - But significantly sacrifice QE



Cultrera et al, APL 108, 134105 (2016)



Cultrera et al, PRAB 18, 113401 (2015)

Optics corrections for harmonic fields

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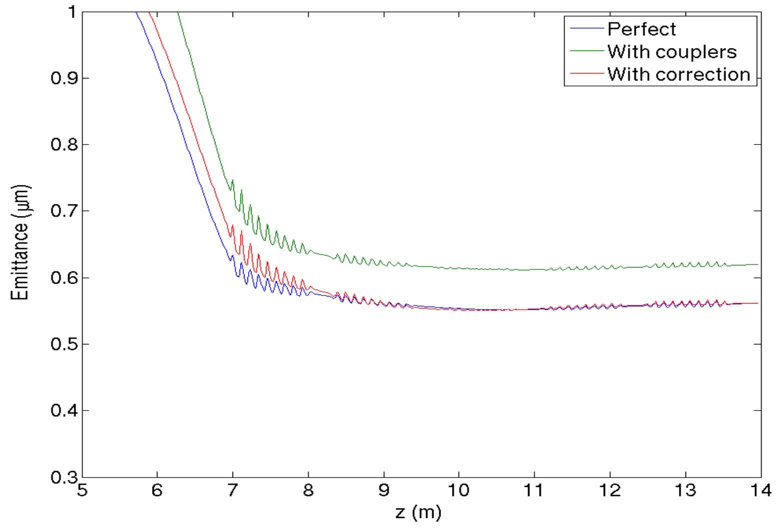
- Correction of quadrupole in RF couplers with a skew quad:

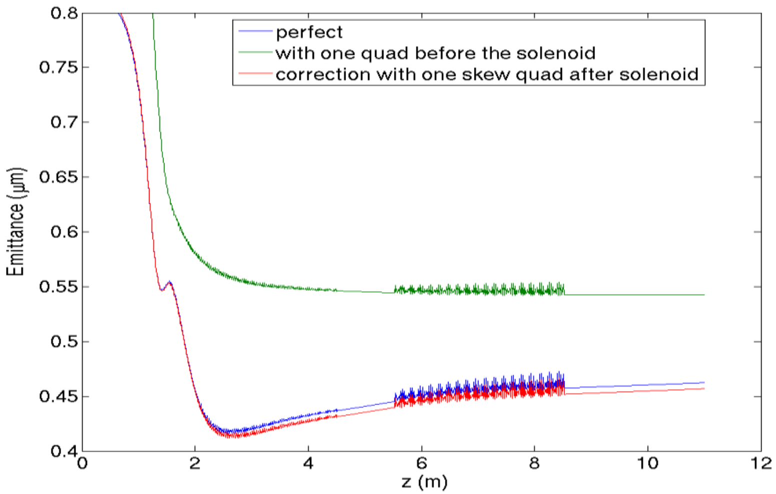
$$\begin{pmatrix} x' \\ y' \end{pmatrix}_{total} = \begin{pmatrix} x' \\ y' \end{pmatrix}_{coupler} + \begin{pmatrix} x' \\ y' \end{pmatrix}_{quad}$$

$$= \begin{pmatrix} \left\{ \tilde{v}_{xx} - \frac{\cos 2\alpha_{cor}}{f_{cor}} \right\} x + \left\{ \tilde{v}_{xy} - \frac{\sin 2\alpha_{cor}}{f_{cor}} \right\} y \\ \left\{ \tilde{v}_{xy} - \frac{\sin 2\alpha_{cor}}{f_{cor}} \right\} x - \left\{ \tilde{v}_{xx} - \frac{\cos 2\alpha_{cor}}{f_{cor}} \right\} y \end{pmatrix}$$



- Correction of quadrupole in a solenoid with a skew quad:

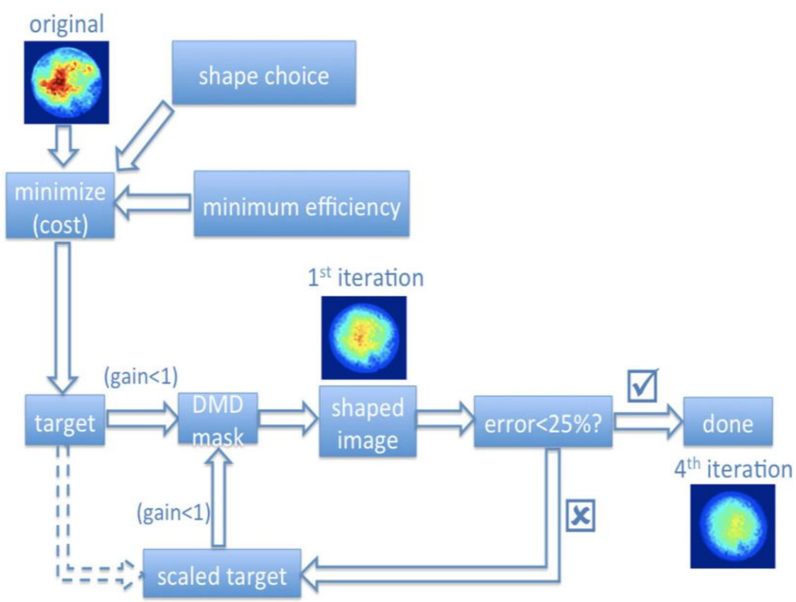
$$\epsilon_{n,qsq} = \beta\gamma \left| \frac{\sigma_{x,sol}\sigma_{y,sol}}{f_1} \sin 2(KL + \alpha_1) + \frac{\sigma_{x,cor}\sigma_{y,cor}}{f_{cor}} \sin 2\alpha_{cor} \right|$$

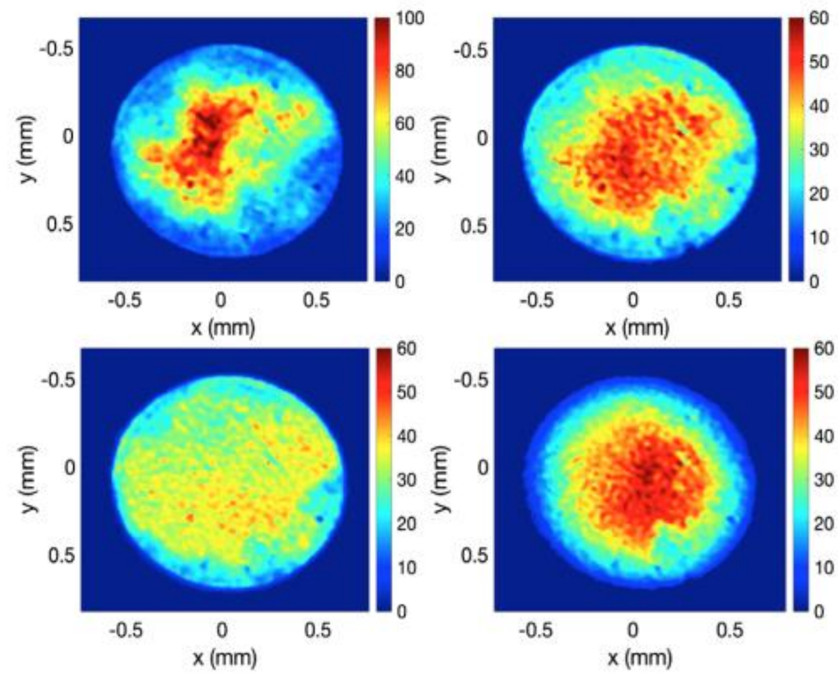


Dowell, Zhou, and Schmerge, PRAB 21. 010101 (2018)

Ultra-low emittance preservation – drive laser

- Drive laser is the major impact for LCLS injector emittance preservation according to 10-year LCLS operations.
- Can we get static laser profile on the cathode?
  - Adaptive drive-laser shaping for LCLS was tested but optics damage arises.

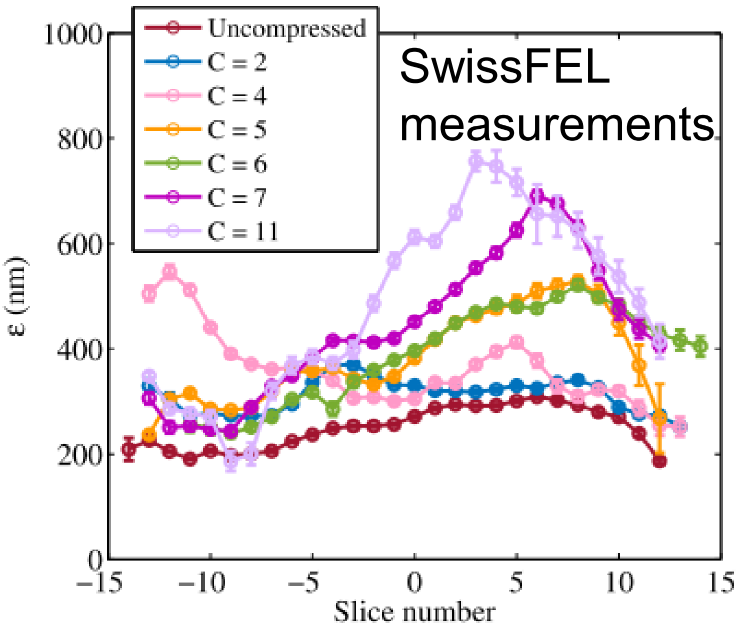




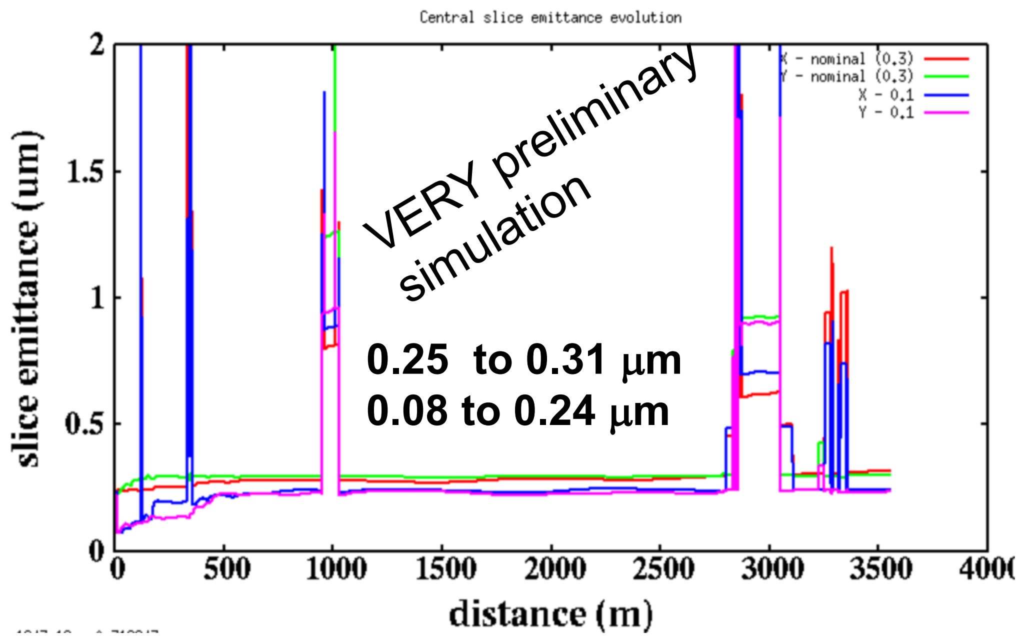
S. Li, PRAB 20, 080704 (2017)

Ultra-low emittance preservation – bunch compression

- Can 0.1-0.2 μm emittance from the injector be preserved through X100 bunch compressions?
- Demonstrating ultra-low emittance (e.g., <0.2 μm for 100 pC) in the injector cannot be isolated.



Bettoni, PRAB 19, 034402 (2016)



Courtesy of T. Raubenheimer

LCLS-II CW injector

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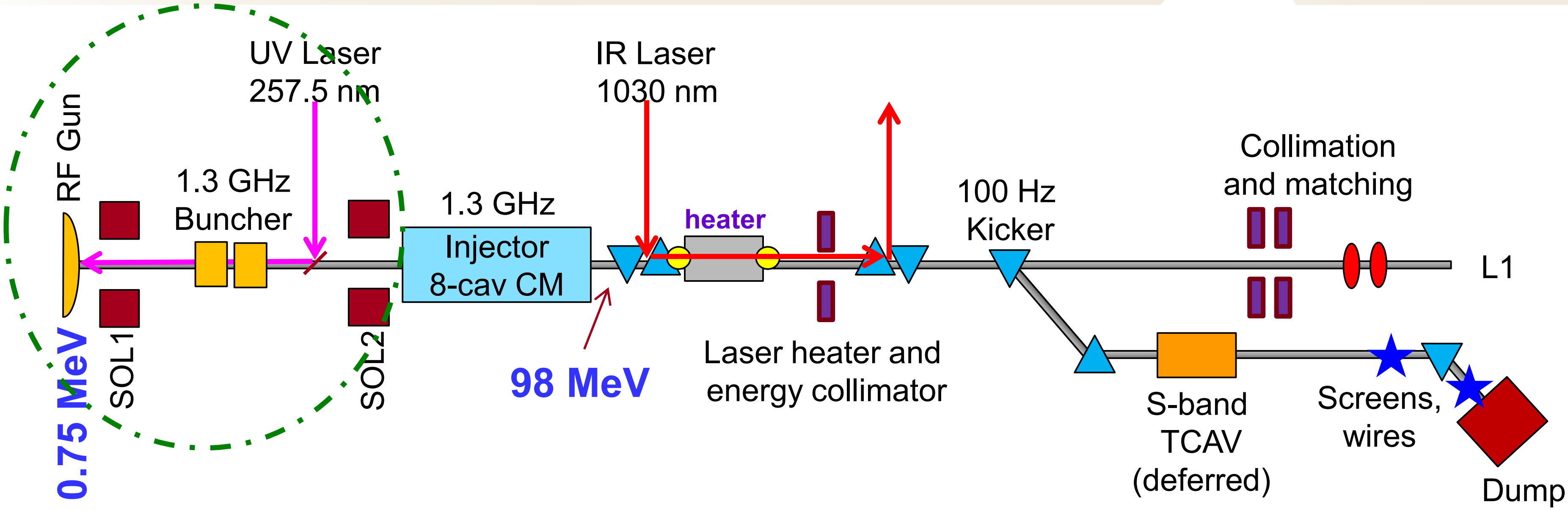
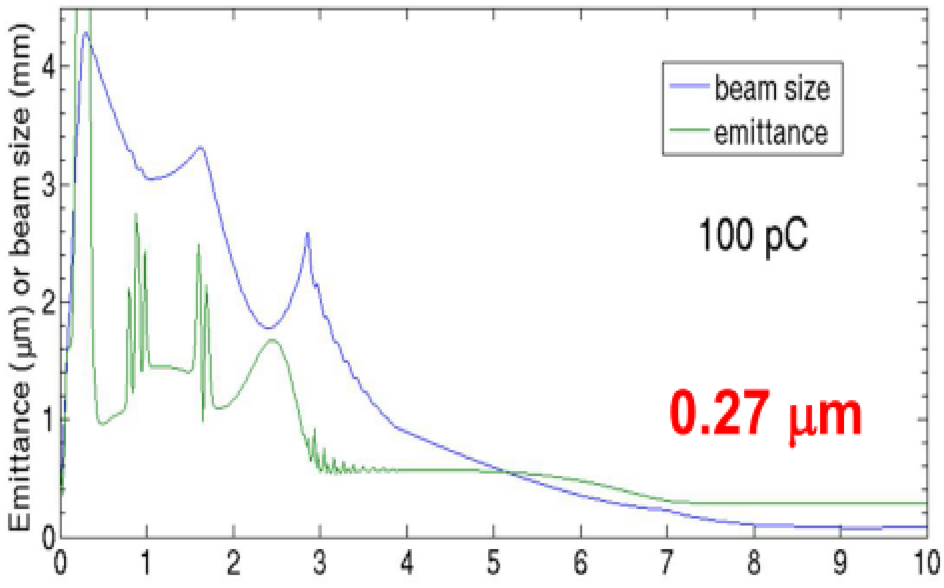


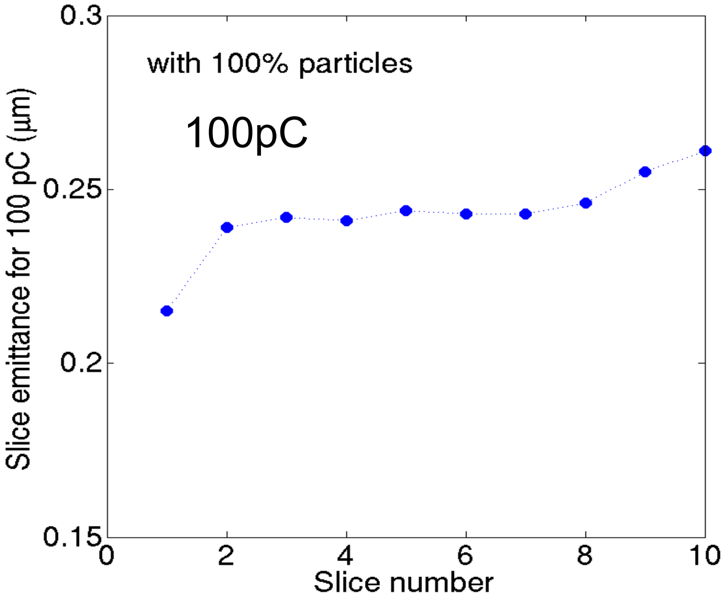
- 186 MHz NC APEX gun technology is chosen
- Gun + 1.3 GHz buncher + 1.3 GHz CM: 100 MeV
- Cs_2Te cathode: 5-10% QE, QE lifetime 2-3 weeks for CW operation
- 50 W IR laser conversion to UV
- 1MeV injector commissioning starts late April 2018
- 100MeV injector commissioning starts early 2020

RF gun gradient	20 MV/m
RF gun energy	750 keV
Injector energy	>95 MeV
Repetition rate	1 MHz
Emittance (100 pC)	0.4 µm
Peak current	>10 A

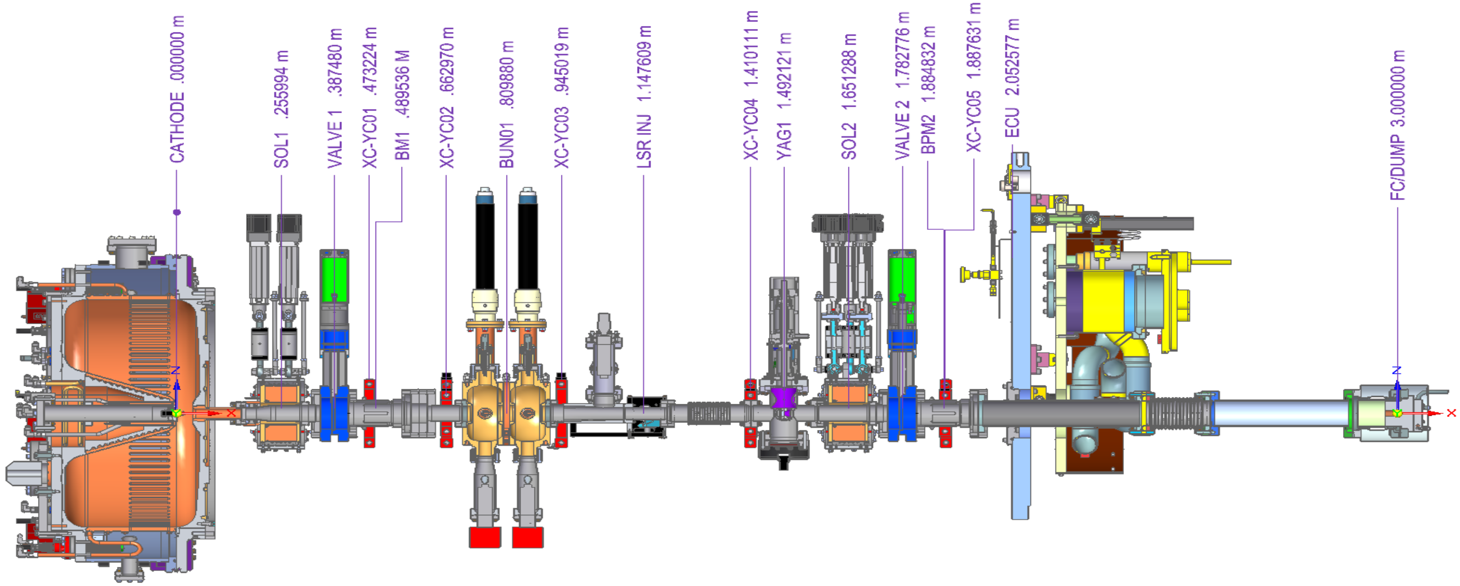
Simulated LCLS-II injector emittance

- 0.27 μm of emittance for nominal 100 pC and corresponding slice emittance is close to thermal emittance:
  - Optimized buncher and solenoid locations
  - Applied conservative thermal emittance (1μm/mm)
  - Applied practical laser profiles





1MeV injector commissioning



- Components installation finished end March 2018
- Commissioning for 1MeV source starts late April 2018 for 1+ yrs:
  - Operate CW gun & buncher
  - Characterize dark current and beam loss
  - Characterize gun energy, and calibrate phase/amplitude for gun/buncher
  - Characterize QE, QE lifetime, and thermal emittance
  - Perform BBA for cathode, buncher and two solenoids
  - Reliability studies and failure modes

1 MeV LCLS-II injector source installed in the tunnel

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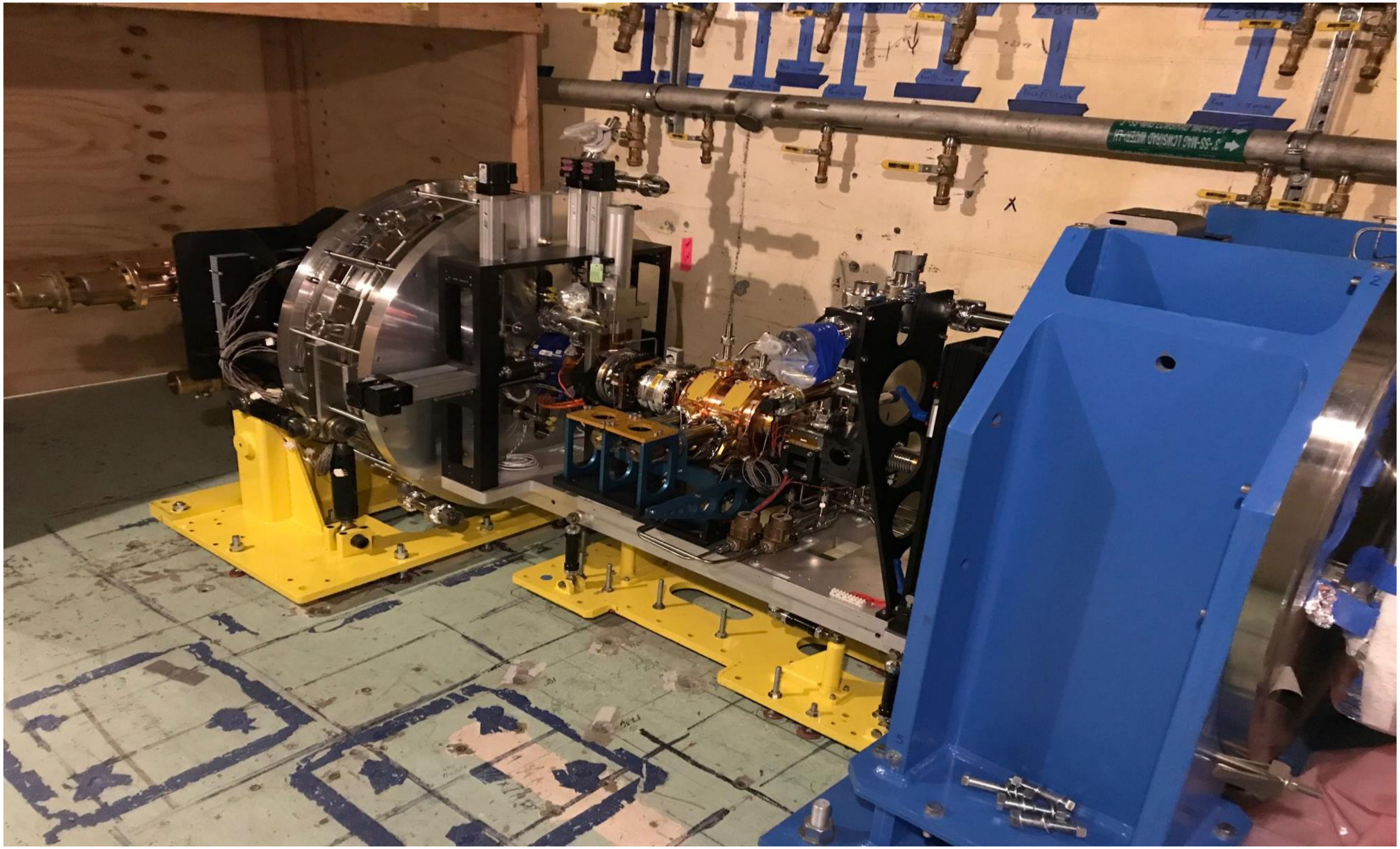

Summary

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- Different gun technology comparison:
  - DC gun demonstrated emittance & peak current but may have larger nonlinear δE making bunch compression difficulty
  - SRF gun potential is attractive but needs to address a few outstanding technical challenges
  - NC gun technology demonstrated at LBNL is mature
- What we should keep in mind for injector R&D:
  - Many other 'simple' components impacting emittance cannot be lightly weighted for such <0.4μm ultra-low emittance
  - Gun and injector development cannot not be isolated – addressing ultra-low emittance preservation issues
- 186MHz NC gun has been adopted for LCLS-II injector:
  - Commissioning 1MeV injector starts late April 2018 for 1+ yrs.
  - Commissioning 100MeV injector starts early 2020.

Acknowledgement

Thanks Dave Dowell, Fernando Sannibale, and John Schmerge for the helpful inputs, and Igor Pinayev for providing BNL SRF gun materials, and many other LCLS colleagues for the inputs.