DC-SRF Photoinjector

DC-Superconducting Hybrid High Rep-rate Guns at PKU

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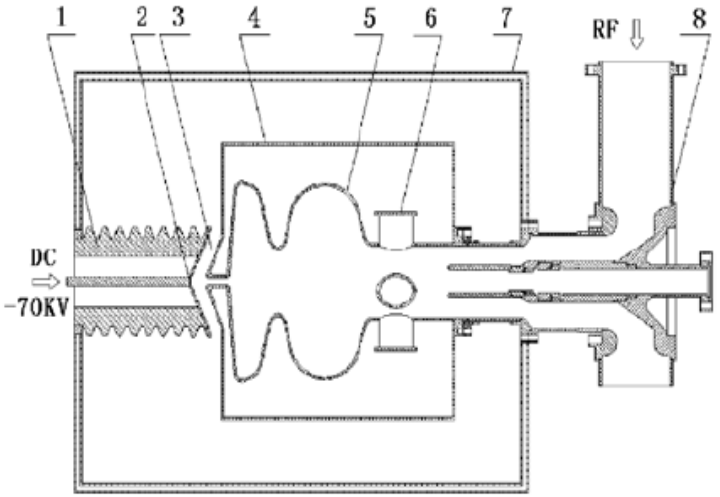
Outline

- DC-Superconducting hybrid high rep-rate guns at PKU
- A brief overview of DC-SRF-I operation
- From DC-SRF-I to DC-SRF-II
- Progress on DC-SRF-II

DC-SRF – the idea

- Combine DC gap and SRF cavity (1.3 GHz)
- Proposed in 2001 as a variant to SRF gun
- **Advantages:**
  - Good compatibility between semiconductor photocathode and SRF cavity (compared to SRF gun);
  - Less stringent requirement on DC voltage (compared to DC gun);
  - Compact structure for high repetition rate, high average current, MeV e-beam generation.



K. Zhao et al., NIMA 475 (2001), 564

Stages of DC-SRF Photoinjector

- Prototype (2003 - 2004)

  Feasibility preliminarily proved @ 4.2 K

- 1st-generation (2007 - 2016)

  Stable operation in 2014, shut down in 2016

  Operation resumed shortly in Sep. 2020

  Delivered to Shanghai in Aug. 2021

- 2nd-generation (2017 -)

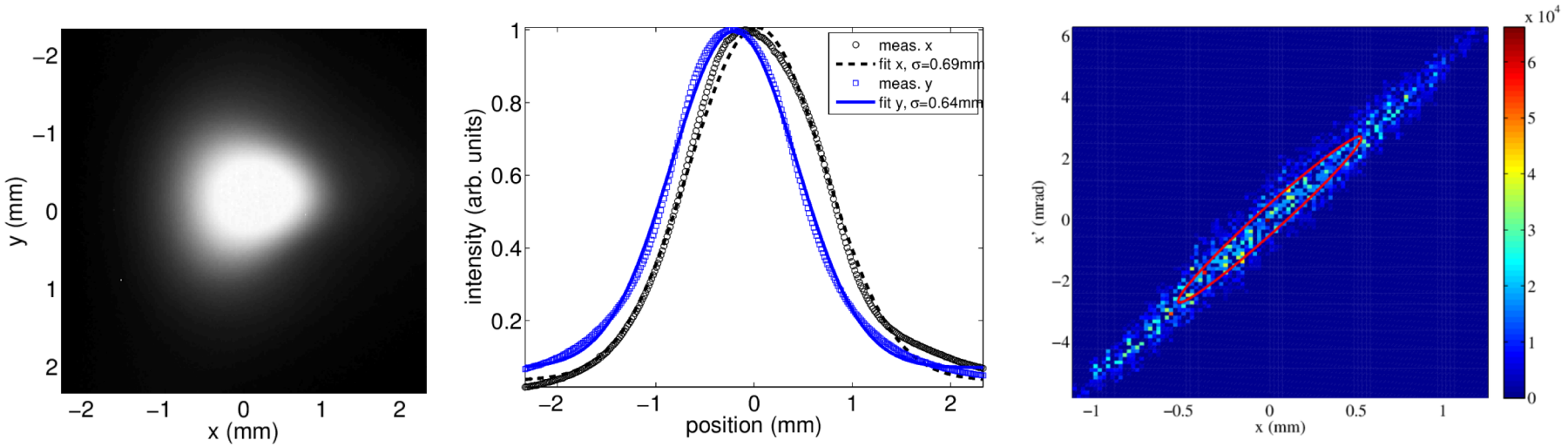
  Assembled in Jan. 2021

  Cooling down on April 20, 2021

  First-stage beam test started on April 29, 2021

A Brief Overview of DC-SRF-I Operation

Stable operation in 2014

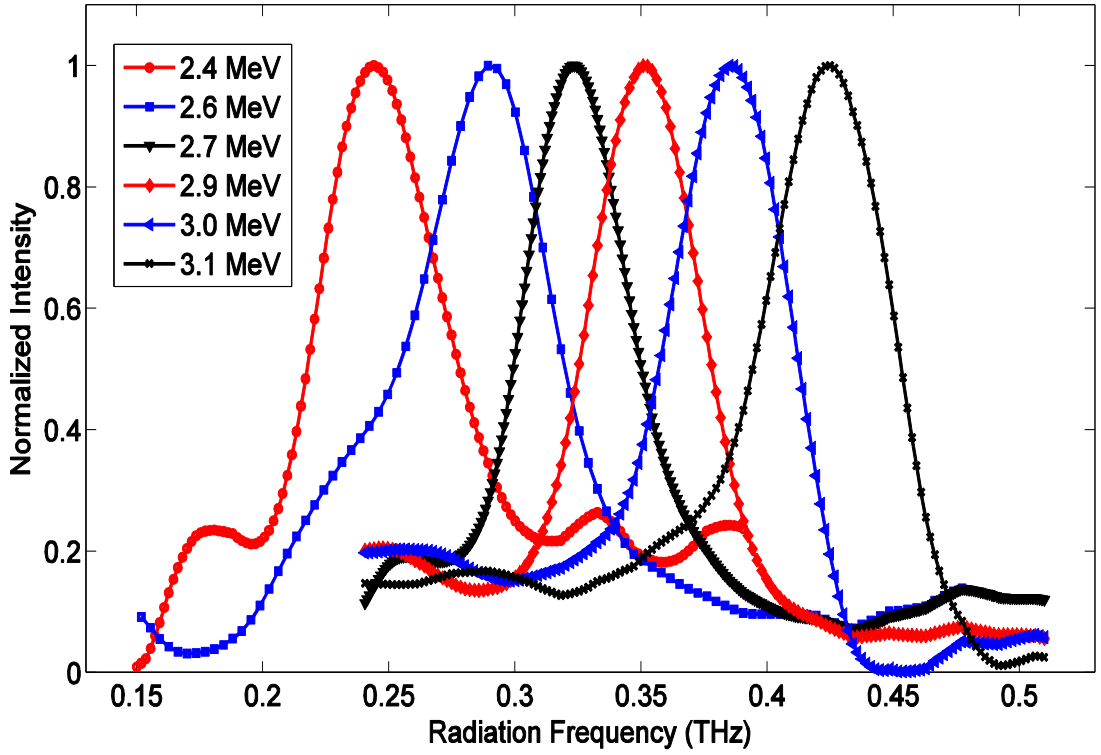


- Beam energy ~3.4 MeV
- Pulsed operation, avg. current ~1 mA in 2 ms macro pulse (1st-gen RF coupler)
- RMS emittance (95%) ~1.5 mm-mrad @25 pC
- Low dark current (< 1 nA)

S. Quan et al., NIMA 798 (2015), 117

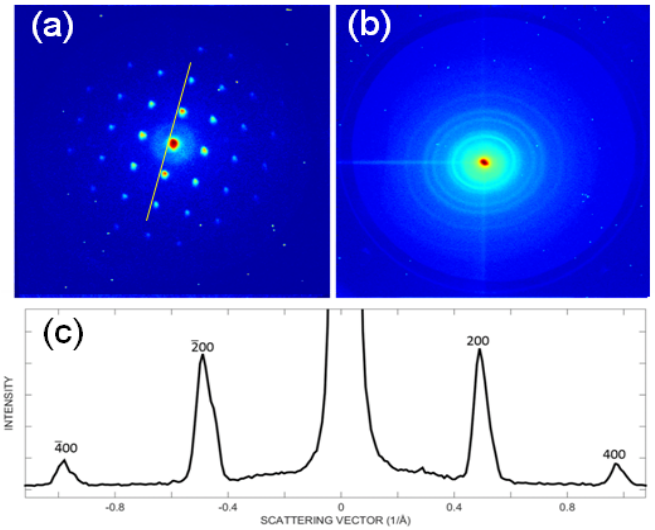
High Rep-Rate THz Generation (2014-2015)

THz superradiant undulator radiation experiments demonstrated stable velocity bunching and flexible e-beam energy tuning.

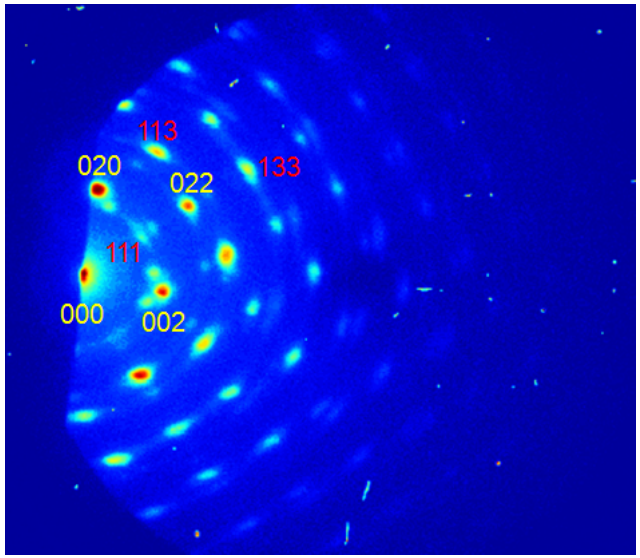


X. Wen et al., NIMA 820 (2016) 75-79

MHz MeV UED (2014-2015)



Measured electron diffraction patterns from a single-crystalline Au foil (a) and a polycrystalline Al foil (b) [repetition rate: 812.5 kHz, integration time: 200 ms, total charge: 33 pC]; (c) Intensity projections along the (200) and (400) spots in (a).



Electron diffraction pattern from a single-crystalline Au foil (repetition rate: 27 MHz, integration time: 30 ms, total charge ~ 1 nC)

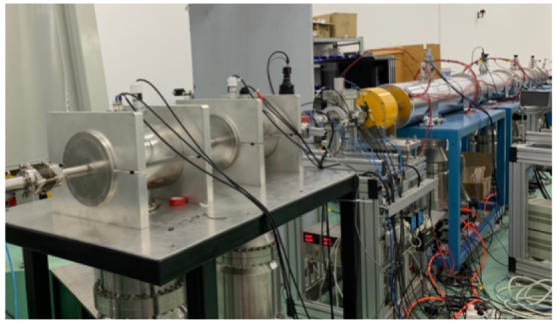
L. Feng et al., APL 107, 224101 (2015)

Joint Operation with SRF Linac (2015)

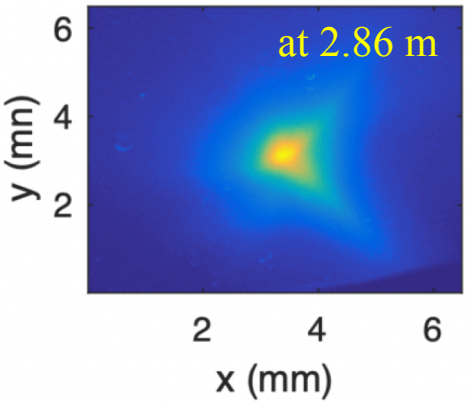
- Deliver beam to a 2×9-cell SRF linac for further acceleration in 2015
- Cavity degradation has not been observed after long-term operation

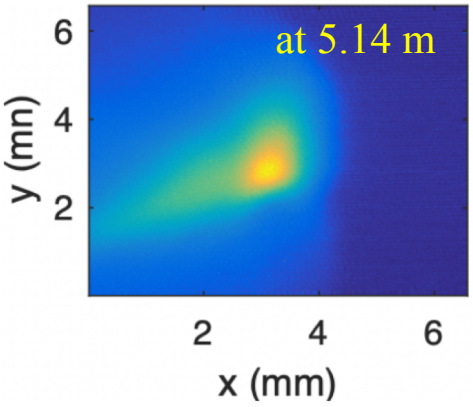
Milestone for PKU SRF: Capability for high-quality SRF cavity fabrication, small-scale SRF accelerator R&D and operation … (good foundation for 2nd-generation DC-SRF photoinjector)

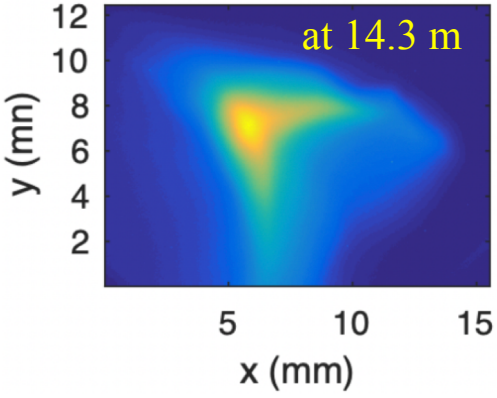
Operation Resuming Test in 2020



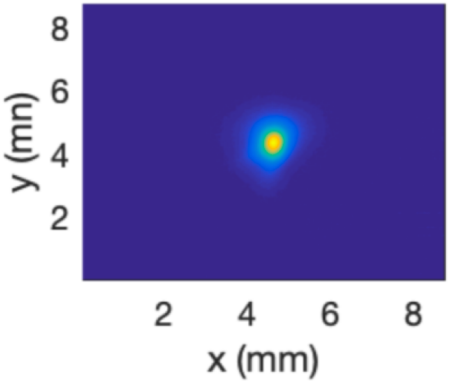
Beam line: DC-SRF + 2 solenoids

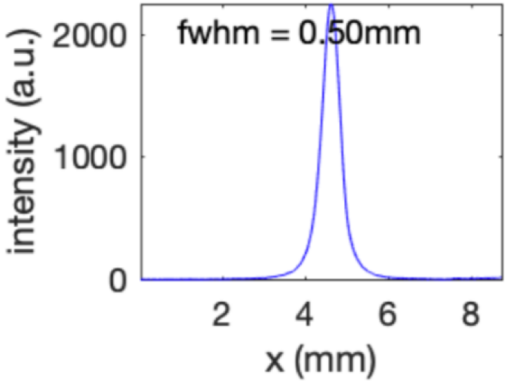


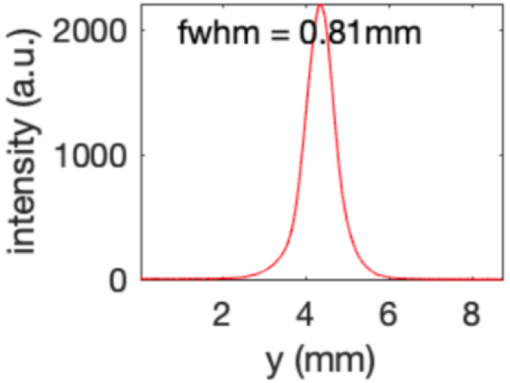




Beam profiles



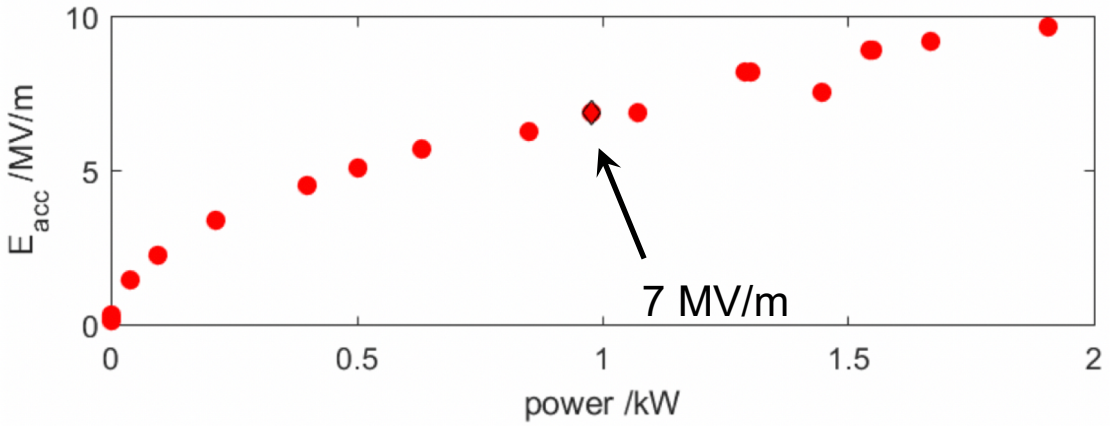




Quadrupole correction test

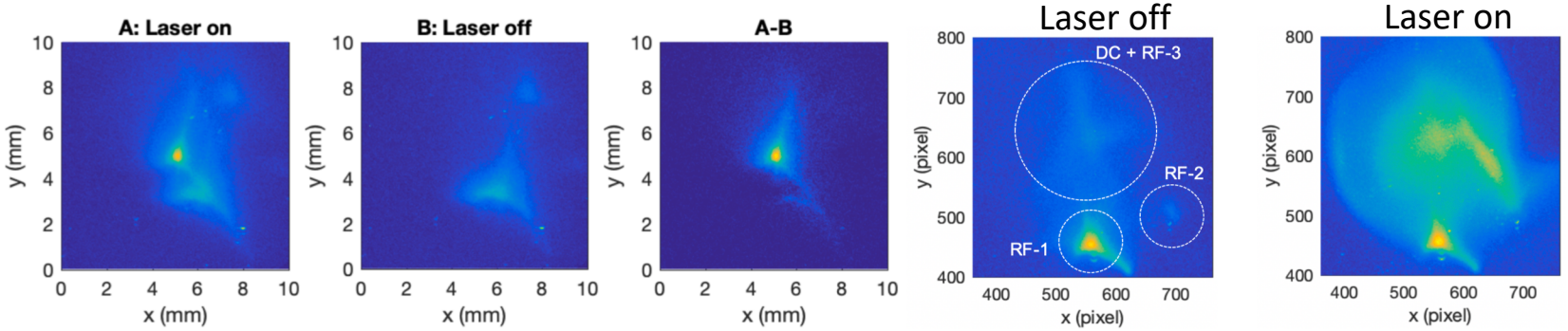
Operation Resuming Test in 2020

- Strong field emission in the SRF cavity when $E_{acc} > 5$ MV/m (cavity contaminated; exposed to air for several times after 2016)



For beam test:
Macro pulse duration: 1-10 ms
Repetition rate: 10 Hz
$E_{acc} = 7$ MV/m (1 kW)

- Dark current



RF-1+RF-2: 1.2 nA;
DC+RF-3: 0.53 nA (0.4 nA when DC off)
Dark current from DC: 0.13 nA
Dark current from RF: 1.6 nA

DC-SRF-I Operation Parameters

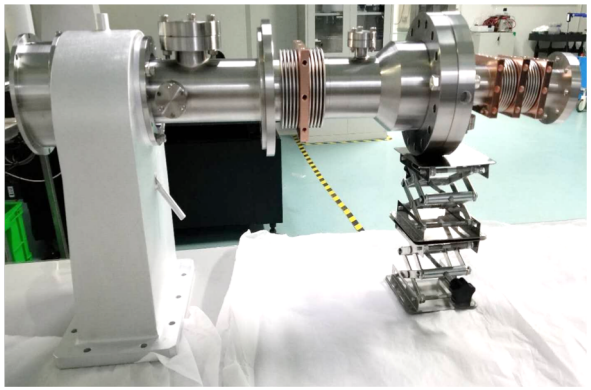
Parameters	2020	2014-2016
DC voltage	**50 kV**	**45 kV**
SRF cavity frequency	1.3 GHz	
SRF cavity gradient	**7 MV/m**	**9 MV/m**
Driven laser longitudinal profile	Gaussian (nearly)	
Driven laser transverse profile	Gaussian (nearly)	
Driven laser pulse width (RMS)	**1.5 ps**	**5-6 ps**
Driven laser radius (RMS)	1 mm	
DC dark current	**0.13 nA**	**< 1 nA (total)**
RF dark current	**1.6 nA**	
Electron energy	2.7 MeV	3.4 MeV
Bunch charge	**40-80 pC**	**10-40 pC**
Bunch repetition rate	**1 MHz, 10 MHz**	**0.8125 - 81.25 MHz**
Macro pulse length	1 - 10 ms	1 - 7 ms
Macro pulse repetition rate	5 - 10 Hz	
Average current in macro pulse	0.8 mA (max.)	0.5 - 1 mA

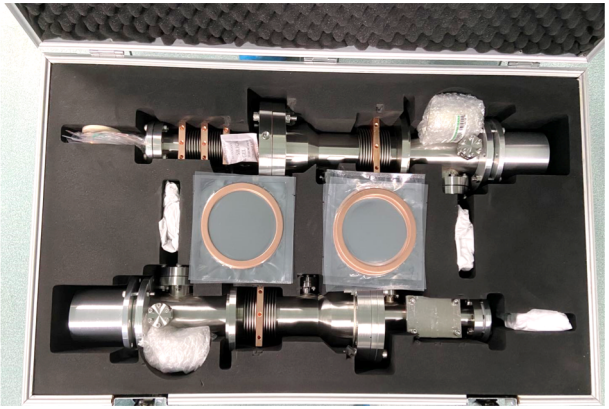
DC-SRF-I for Shanghai Test Line

Delivered to Shanghai in August, 2021

RF coupler to be replaced with the upgraded version

Cavity: high pressure rinsing to be performed in Shanghai

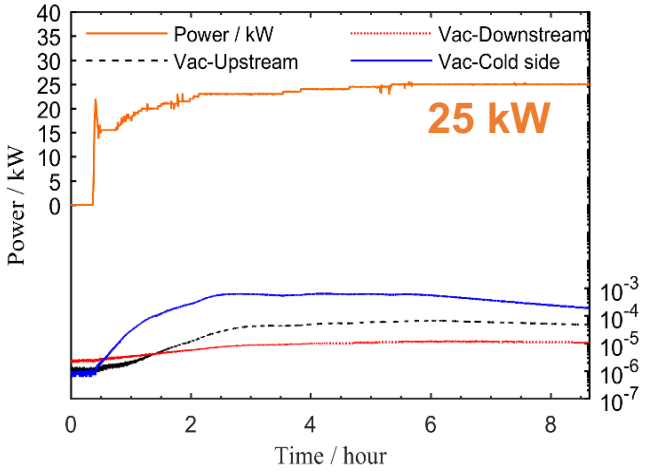


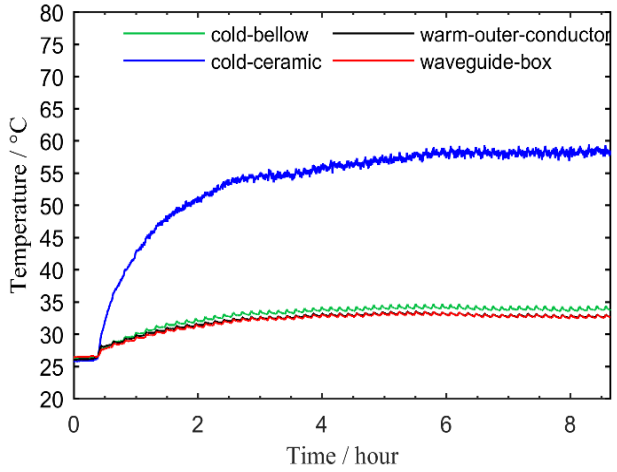


DC-SRF-I for Shanghai Test Line

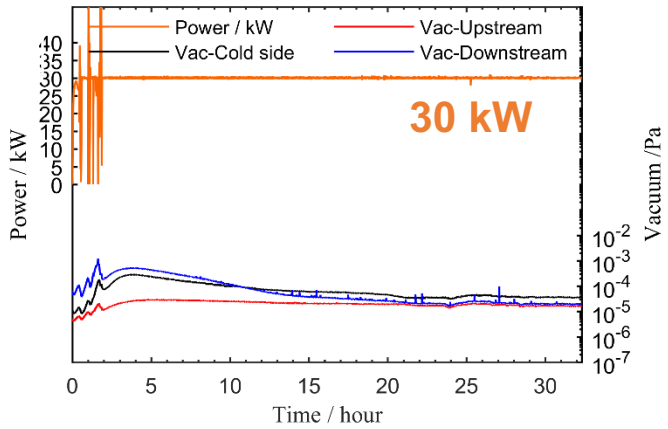
RF coupler test results (CW)

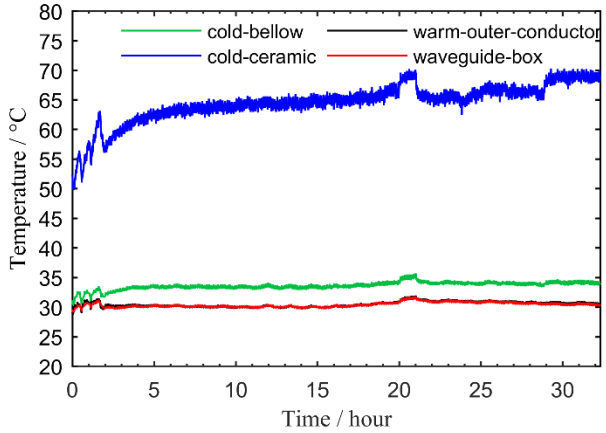
w/o DC bias





DC bias (3 kV)





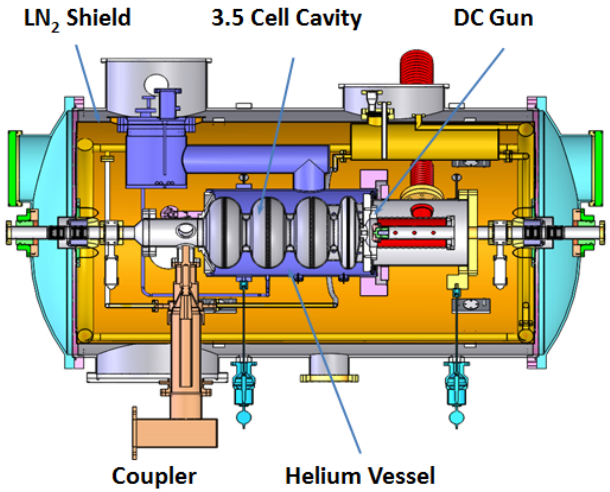
From DC-SRF-I to DC-SRF-II

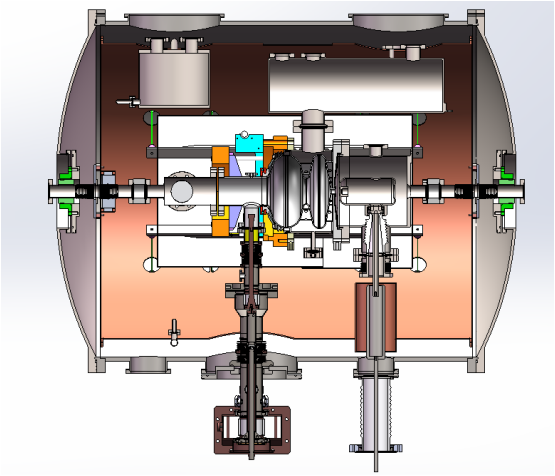
Motivation

(1) R&D of high-performance superconducting photoinjector for CW XFEL, as part of a national project in cooperation with SINAP (Jul. 2016- Jun. 2021, funded by National Key Research and Development Program of China Grant No. 2016YFA0401904)

(2) R&D of high average current (1-10 mA) electron source

From DC-SRF-I to DC-SRF-II



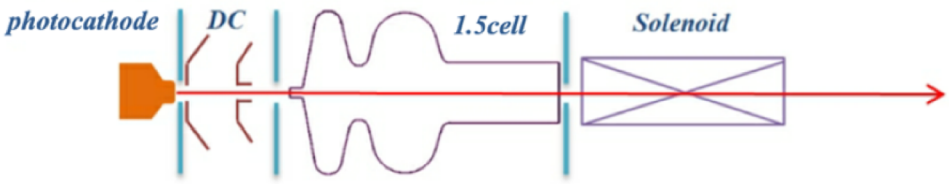


	DC-SRF-I (operation)	DC-SRF-II (design)
DC voltage	45-50 kV	100 kV (DC structure redesigned)
SRF cavity	3.5-cell, 7-9 MV/m	1.5-cell, 14 MV/m
Cathode	Cs_2Te	K_2CsSb
Drive laser	266 nm; w/o shaping, ~5 ps	532 nm; transversely truncated Gaussian (1σ); longitudinally uniform, ~20 ps

✓RF coupler upgraded

Lower emittance + CW operation

An optimized case with modest parameters



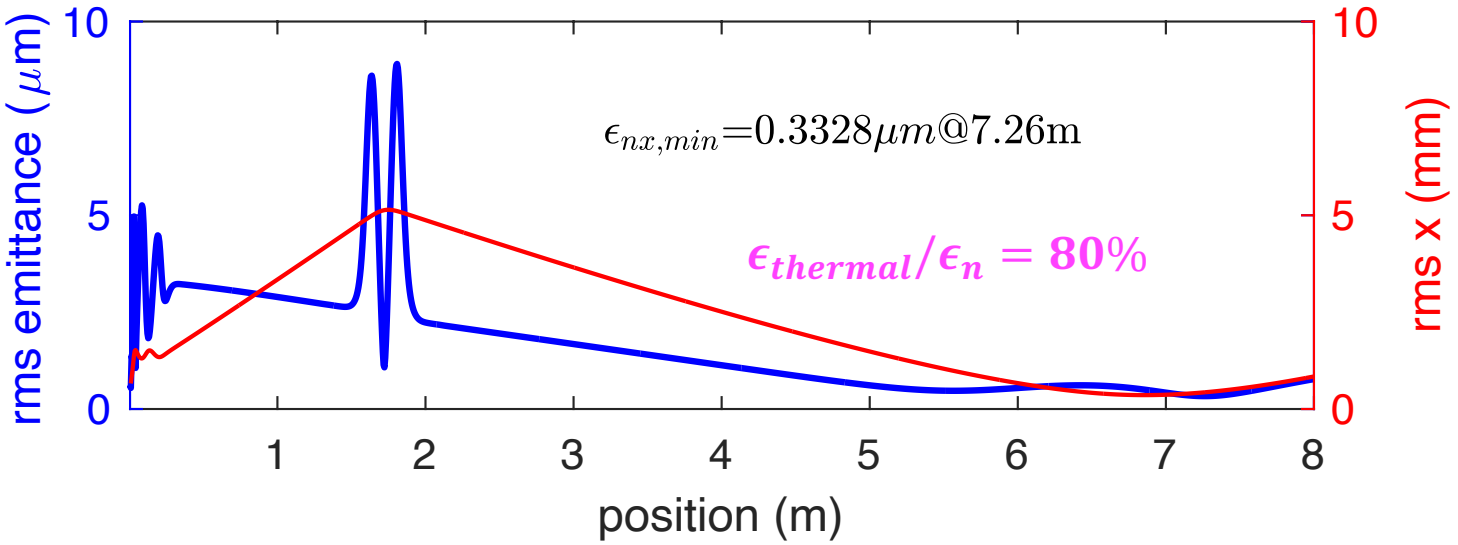
DC-SRF (1.5-cell) + Solenoid + Drift
@100 pC bunch charge

Laser pulse length @ 20 ps, transverse size @ 2 mm (full width)

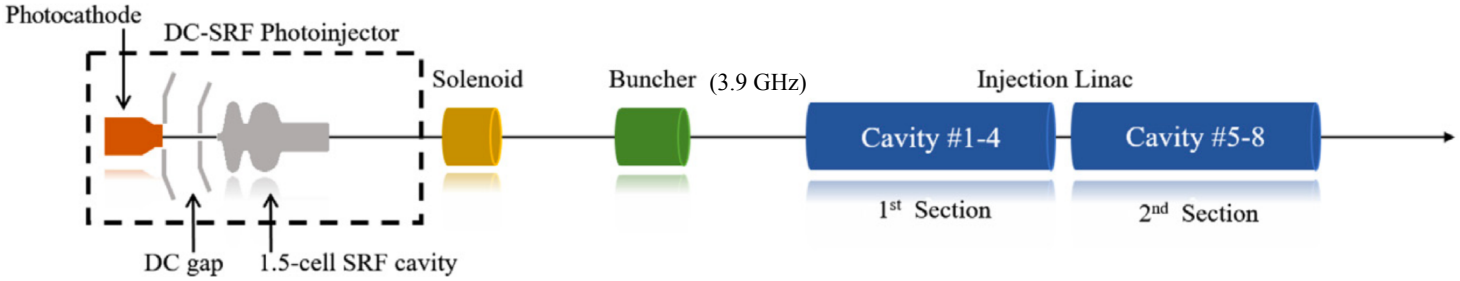
DC voltage @ 100 kV, SRF cavity gradient ~ 14 MV/m

Solenoid B-field @ 500 Gs

ASTRA simulation results



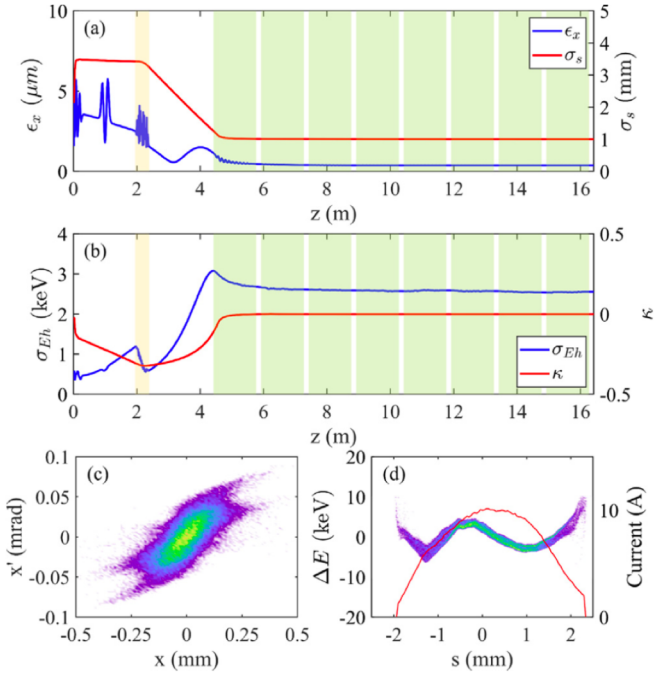
A Possible Layout of CW XFEL Injection Line



- Normalized RMS emittance ~ 0.37 μm
- High-order RMS energy spread ~ 2.75 keV (Bunch charge @ 100 pC)
- RMS bunch length ~ 1.0 mm
- Current skewness ~ 0

Main parameters of the XFEL injection line with a harmonic (3.9 GHz) bunching cavity.

Parameter	Value	Unit
DC-SRF-II		
RF cavity phase	−6.08	degree
RF cavity amplitude	26.11	MV/m
Solenoid		
Central position	1.0	m
Strength	0.0628	T
Bunching cavity		
Entrance position	1.95	m
Amplitude	3.4315	MV/m
Phase	−162.27	degree
Injection linac		
Entrance cavity position	4.42	m
1st–4th cavity amplitude	22.09	MV/m
1st–4th cavity phase	−3.15	degree
5th–8th cavity amplitude	25.46	MV/m
5th–8th cavity phase	−6.05	degree



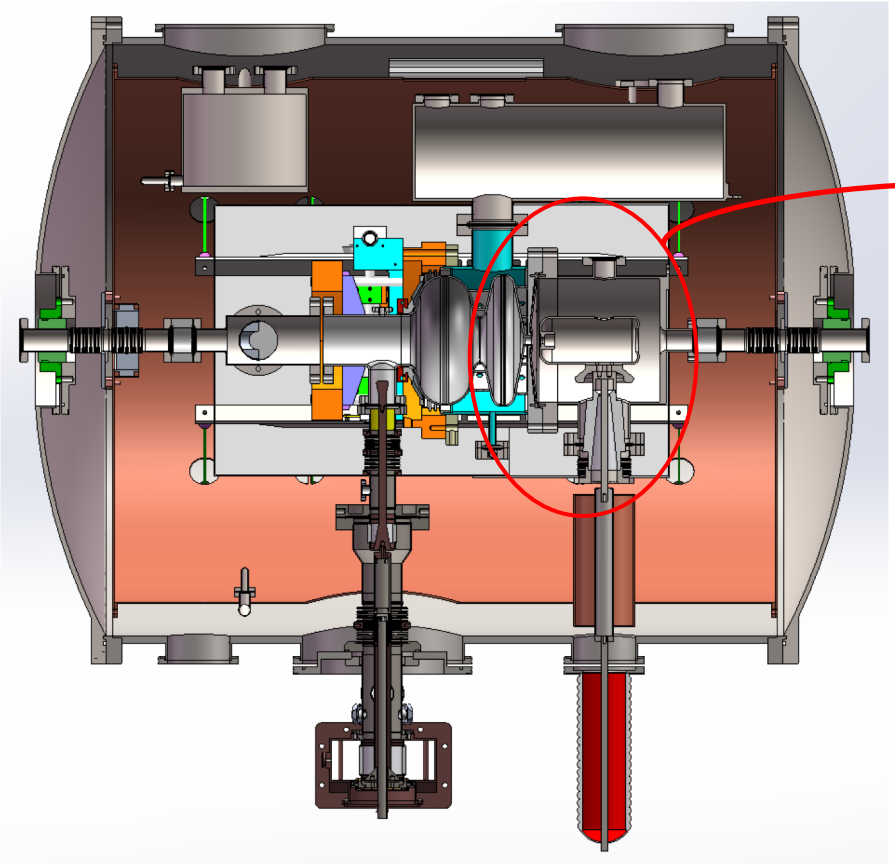
S. Zhao et al., NIMA 1018 (2021), 165796

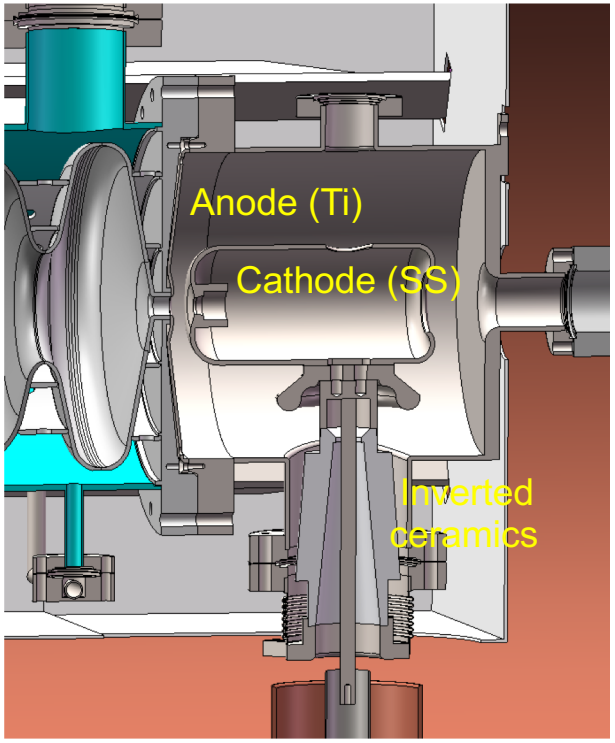
DC-SRF-II

Important changes

DC structure SRF Cavity RF coupler

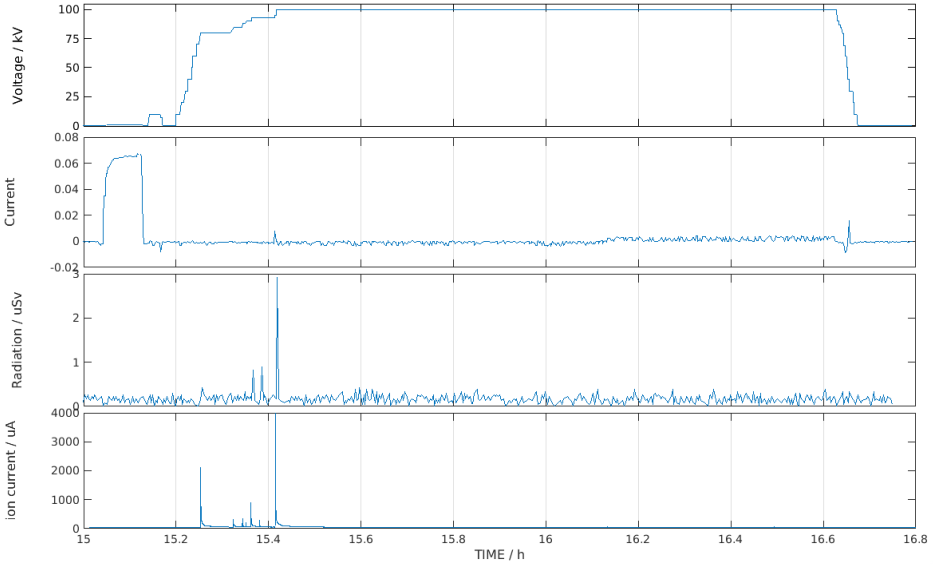
Cathode Drive laser

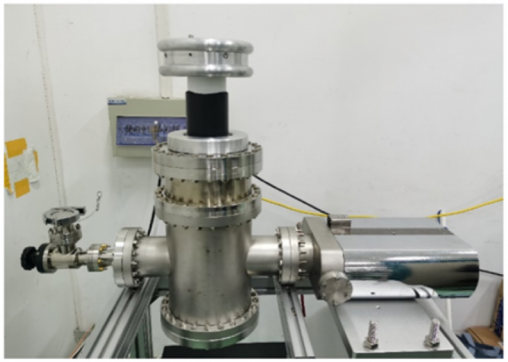




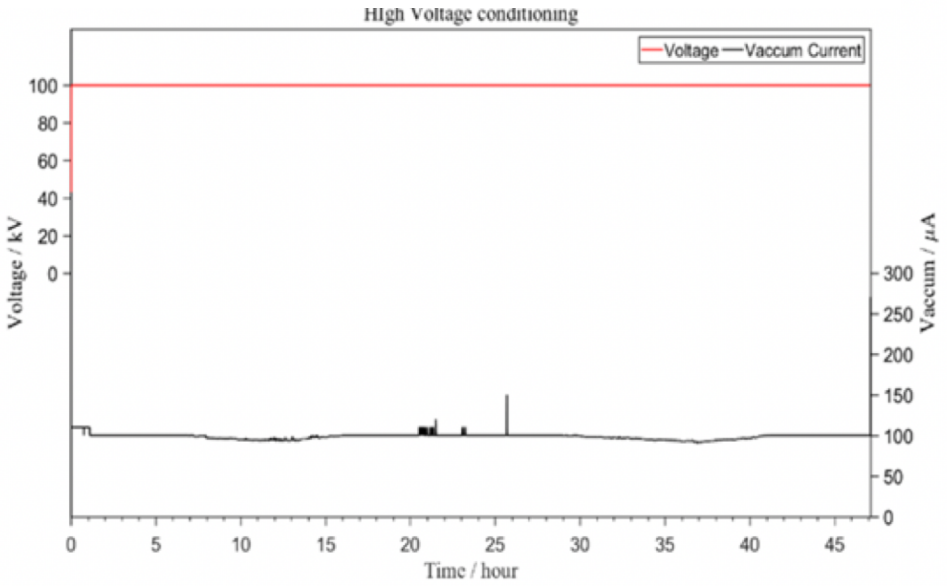
DC Electrodes and Ceramics

Electrodes tested @ 100 kV



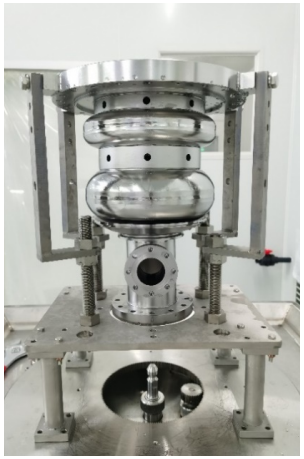


Ceramics tested @ 100 kV



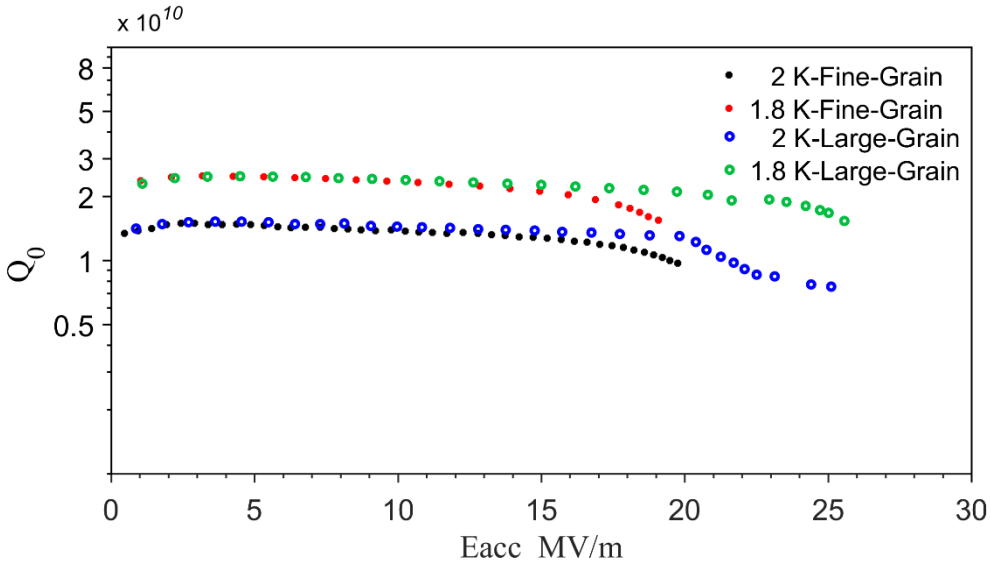
SRF Cavity

- One large-grain cavity and one fine-grain cavity fabricated
- Vertical test results
  - ✓ Both cavities achieved the gradient higher than 15 MV/m;
  - ✓ Large-grain cavity has a maximum gradient 25 MV/m and an unloaded quality factor 1.1E10 @ 20 MV/m.



Large-grain
(used)

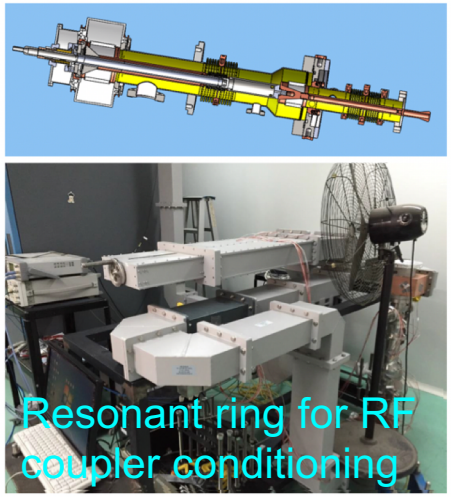
Fine-grain

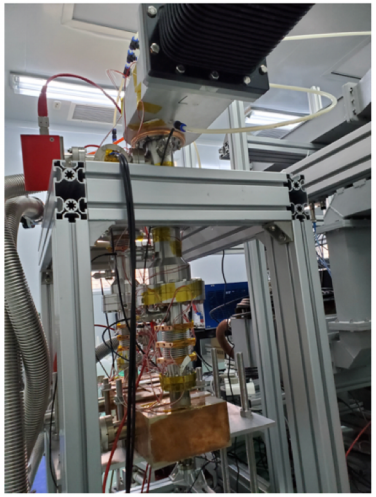


RF Coupler

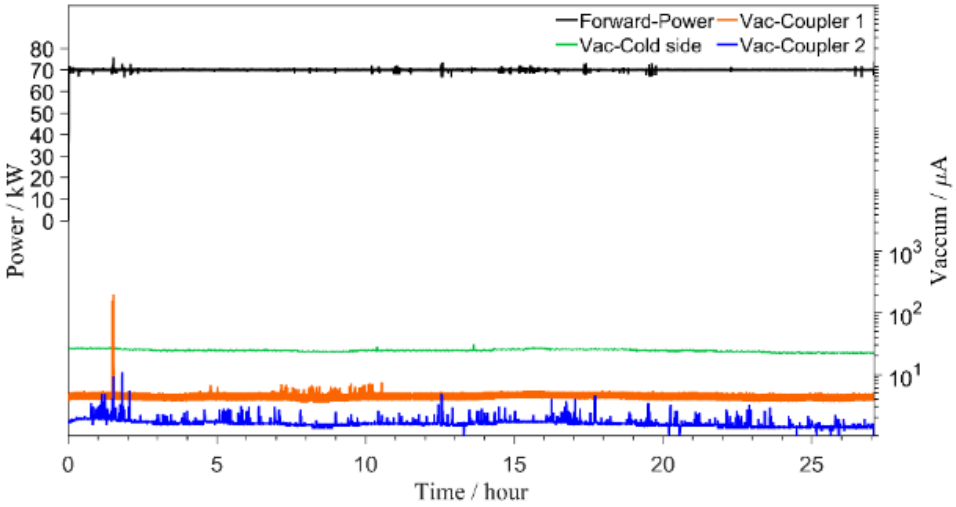
Room temperature RF test

- ✓ pulse mode, 10% duty factor: 70 kW forward power (> 24 h)
- ✓ CW mode: 20 kW forward power (> 30 h, no significant vacuum fluctuation)

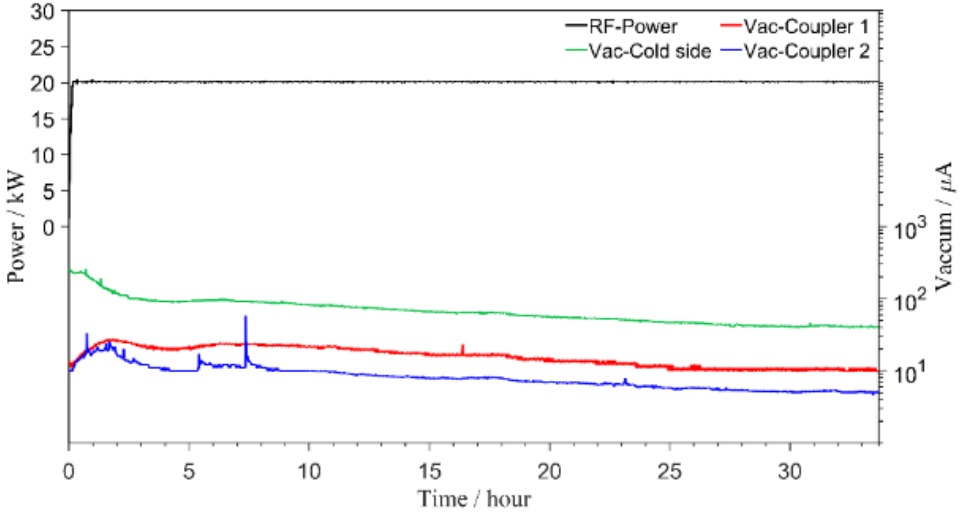




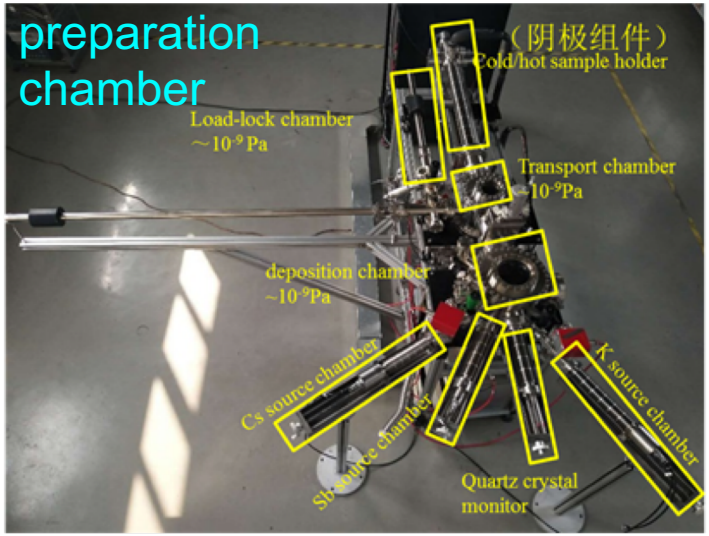
Pulse mode

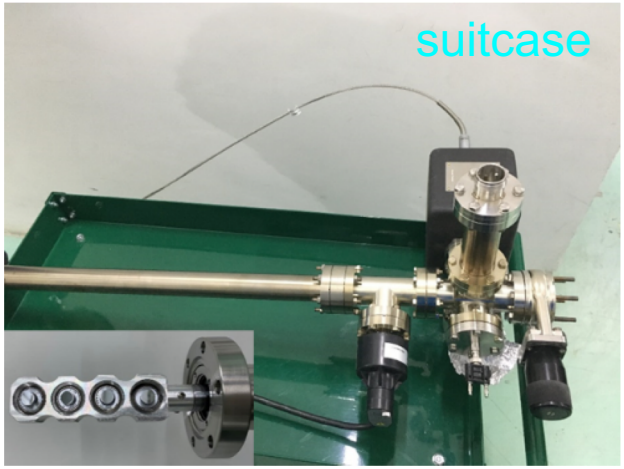


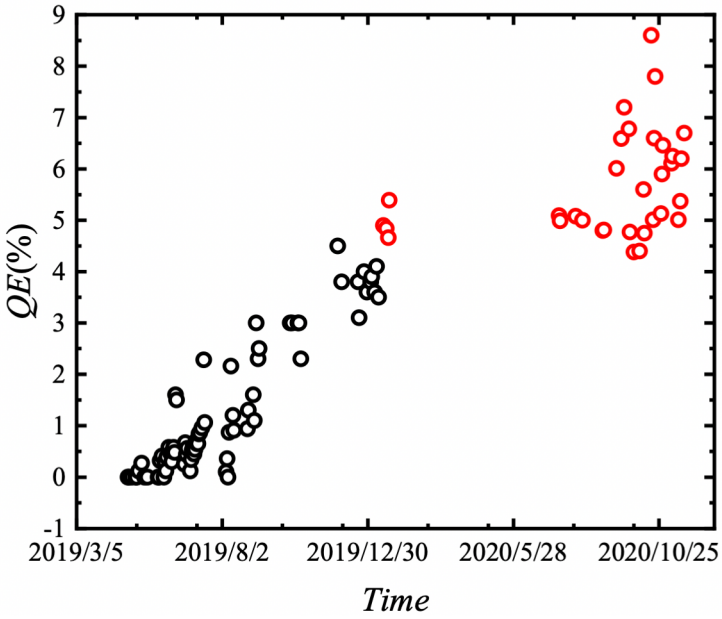
CW mode

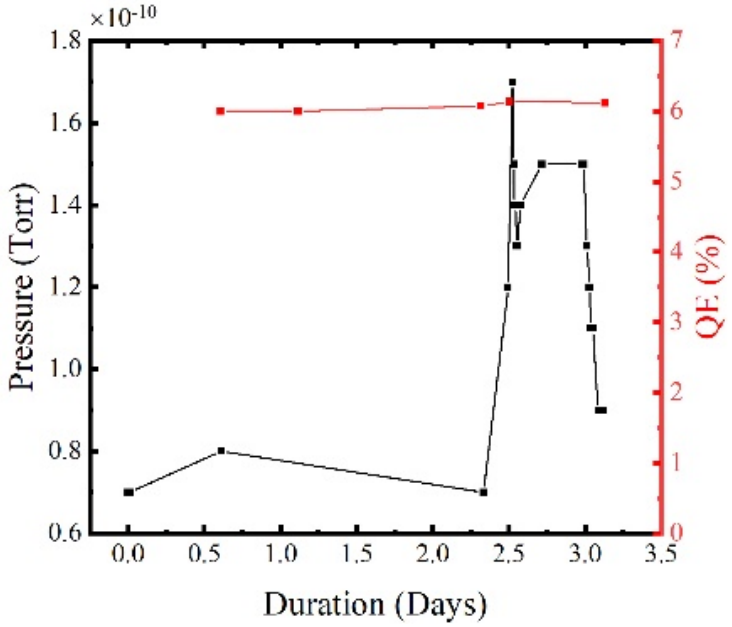


Cathode (Bi-alkali)





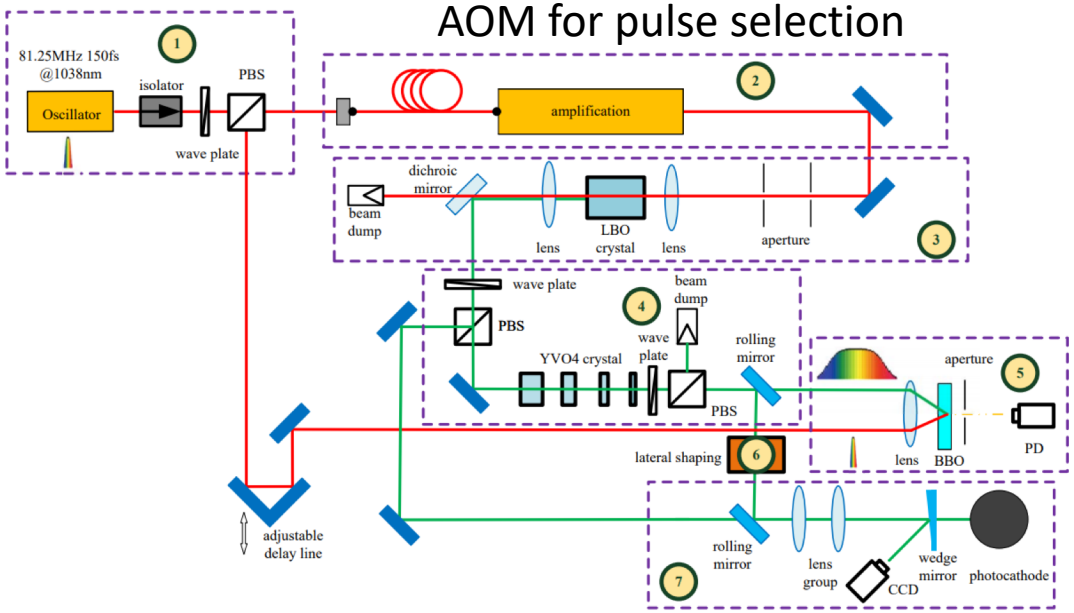


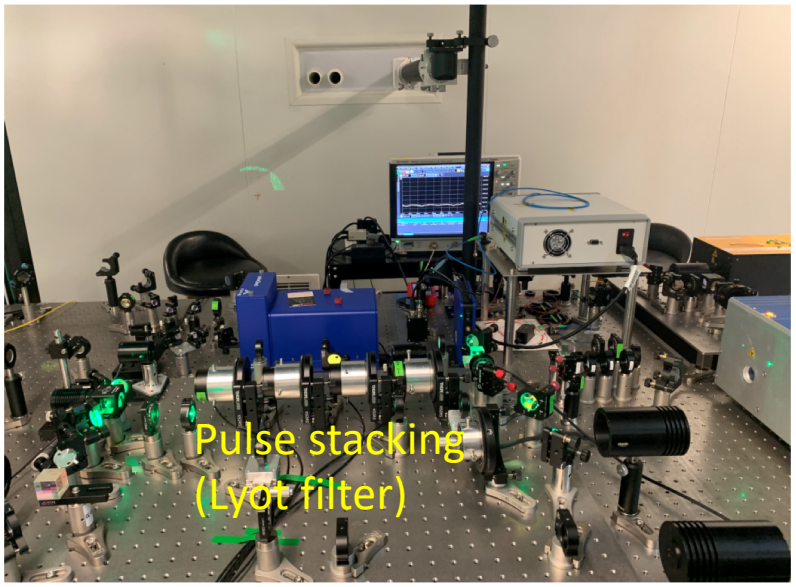


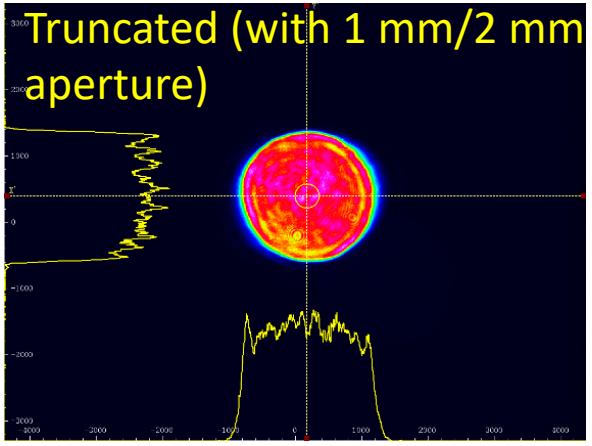
Cathode Drive Laser

Fiber oscillator

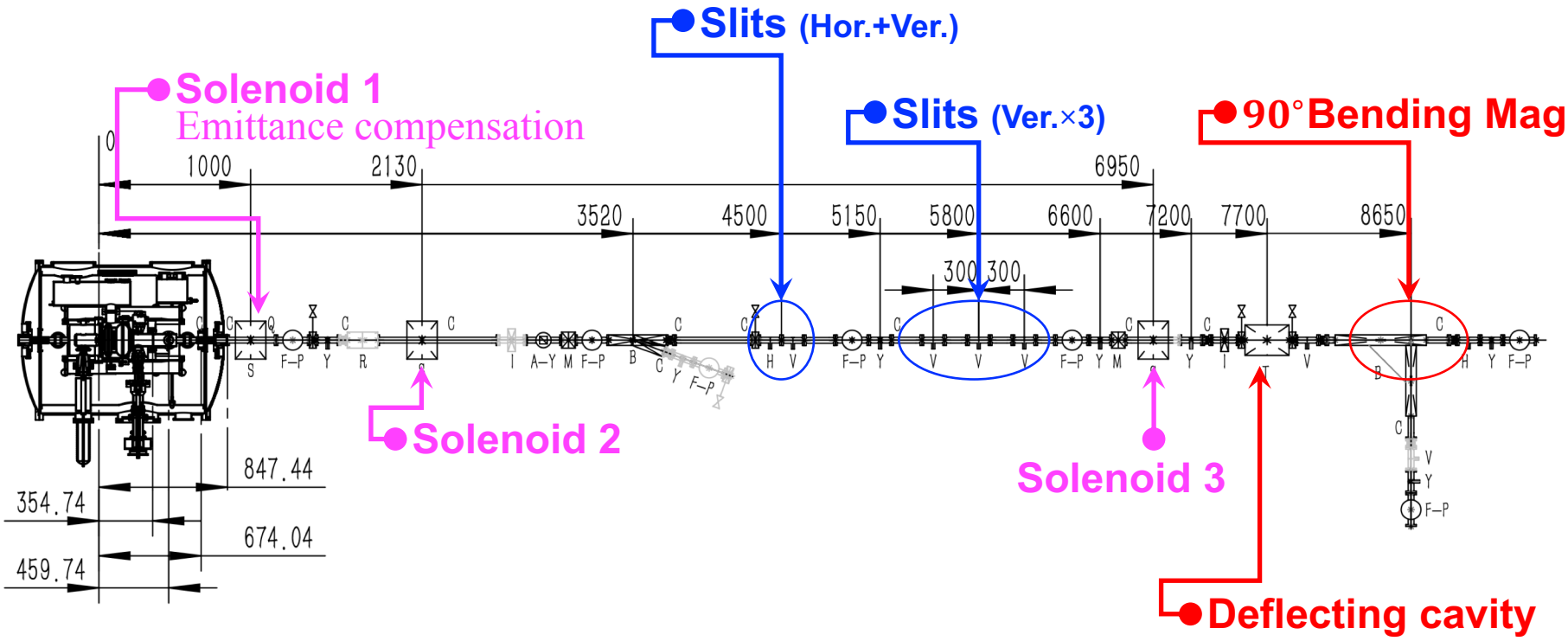
fiber amplifier (1 MHz)
AOM for pulse selection







Test Beam Line

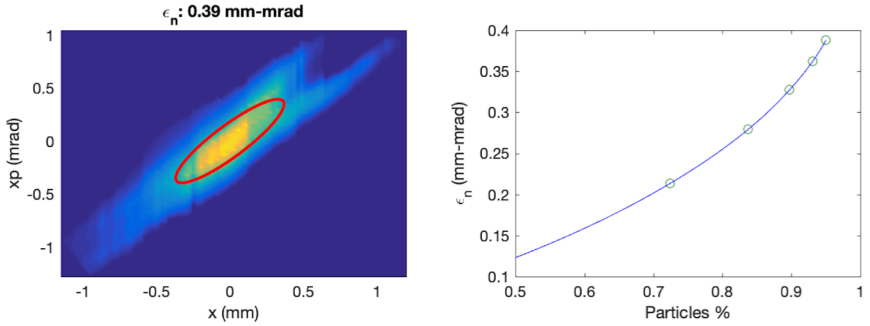


DC-SRF-II

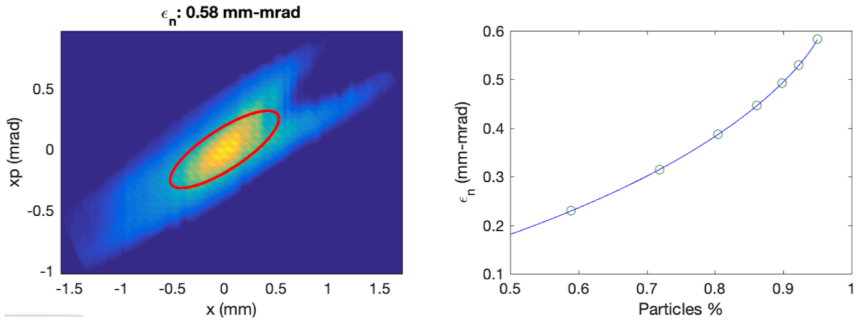
- ✓ Emittance measurement: scanning single slit + YAG
- ✓ Beam current measurement: Faraday cup
- ✓ Beam energy measurement: 90°Bending Magnet

DC voltage 45 kV, SRF cavity gradient 9 MV/m

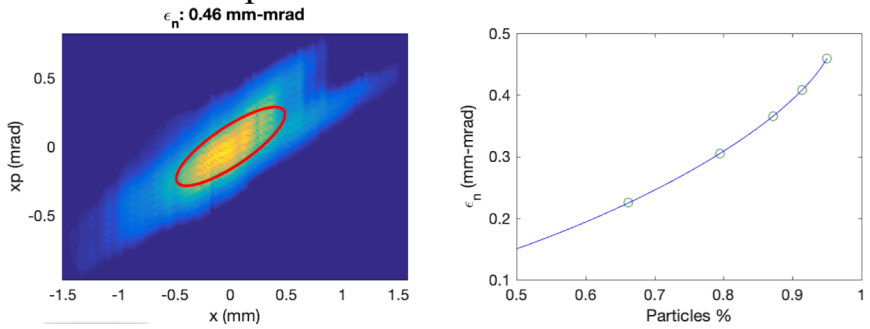
Emittance Measurements



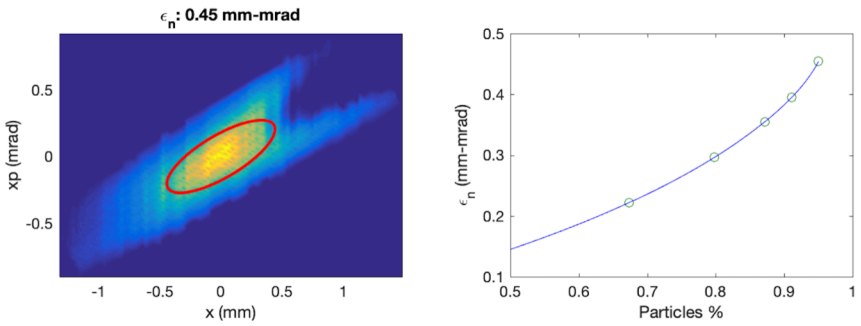
RF phase 36°， S1 current 2.40 A



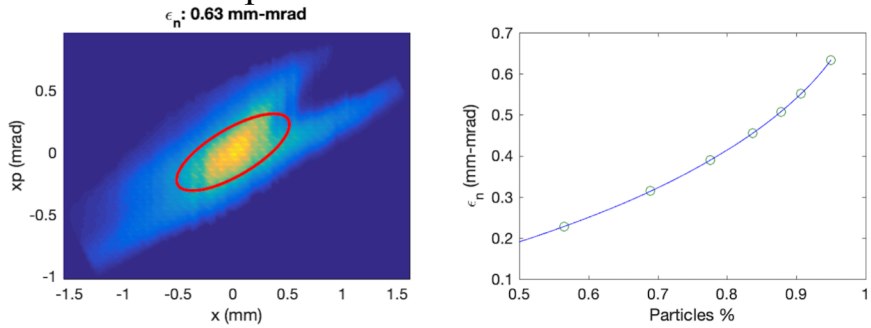
RF phase 31°， S1 current 2.40 A



RF phase 36°， S1 current 2.45 A



RF phase 26°， S1 current 2.40 A

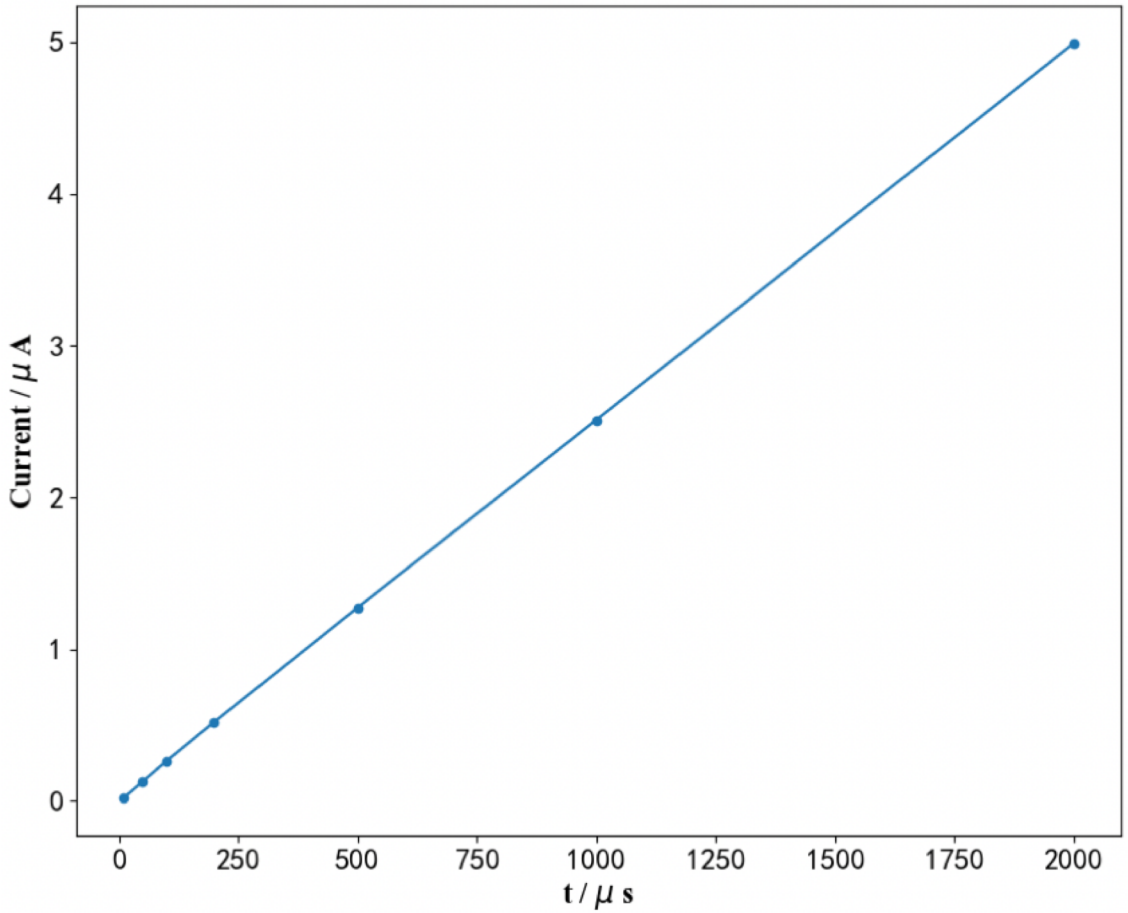


RF phase 36°， S1 current 2.35 A

Normalized rms emittance, 95% particles:
0.4~0.6 mm-mrad @ 22 pC

Bunch Charge Test

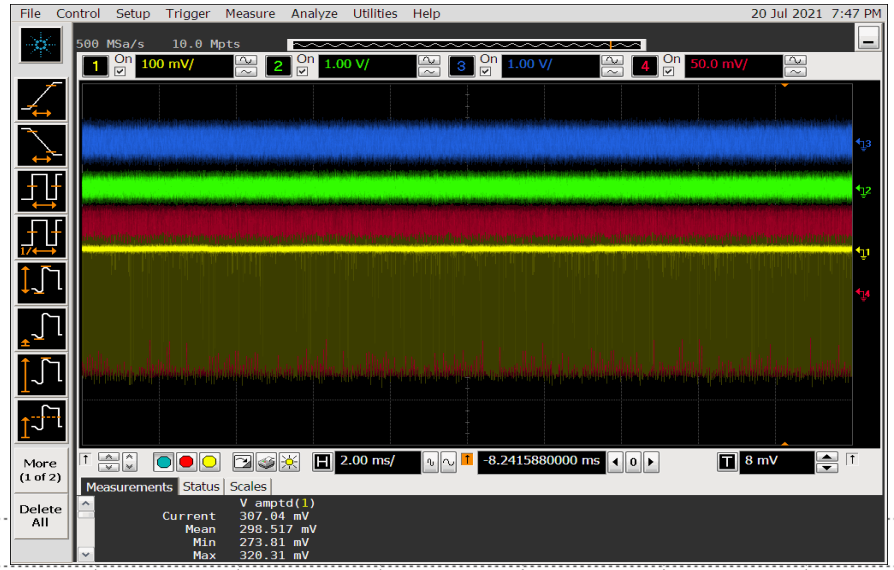
Average beam current vs macro pulse duration

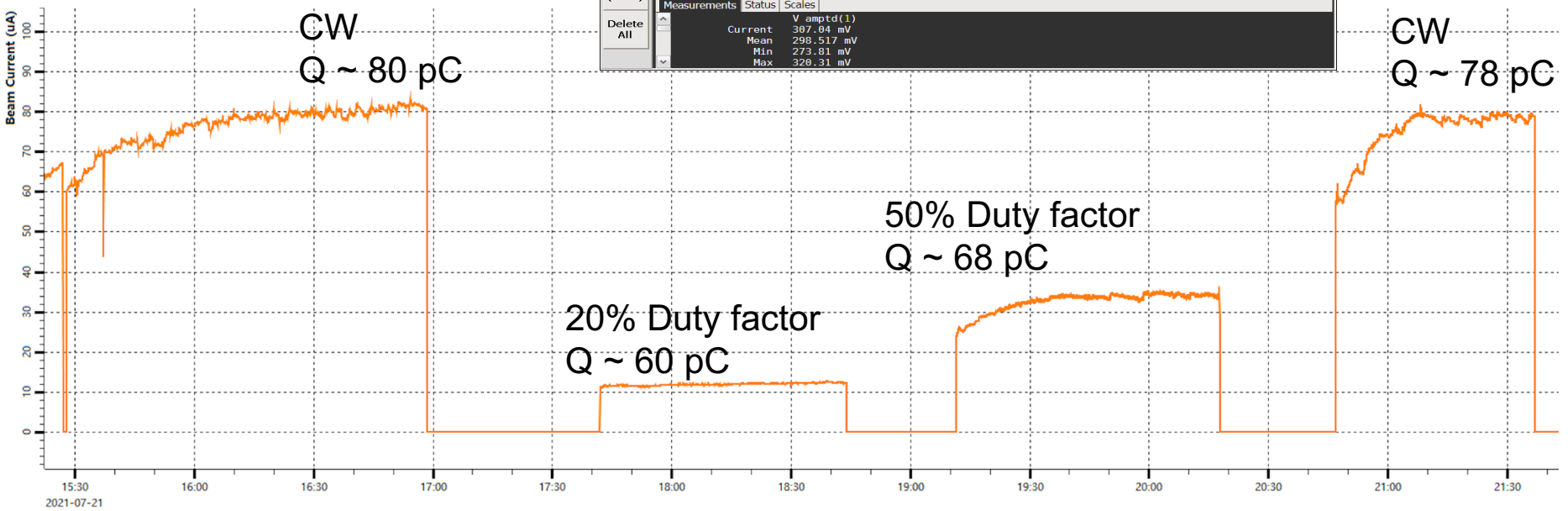


Bunch charge
250 pC

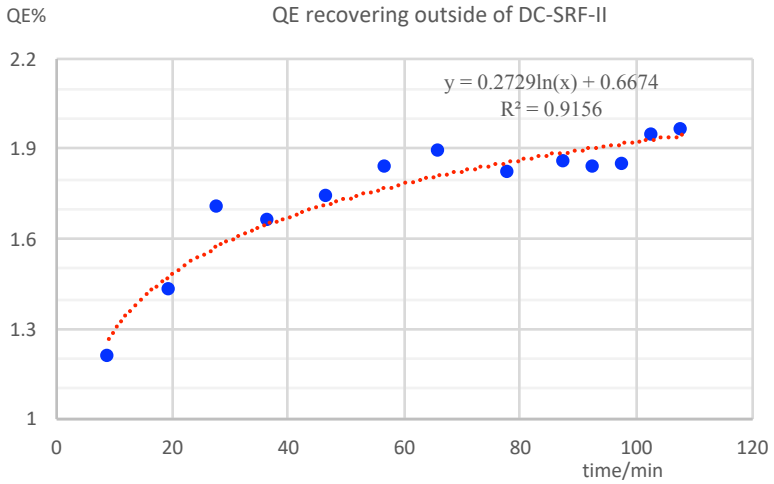
Macro pulse repetition rate 10 Hz
w/o laser shaping

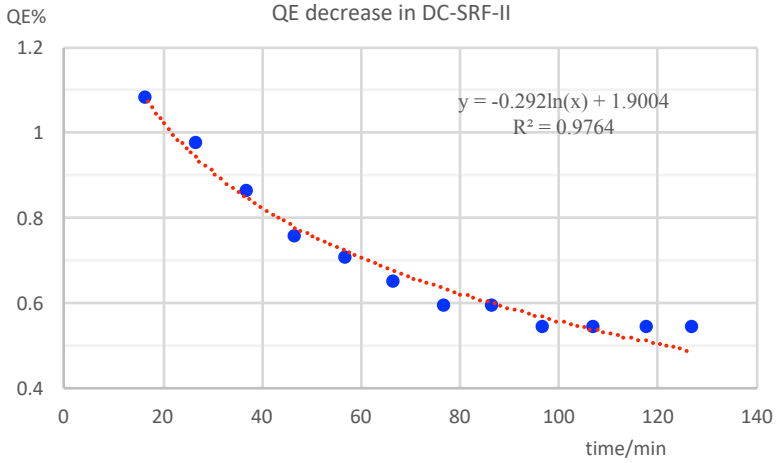
CW Operation Test



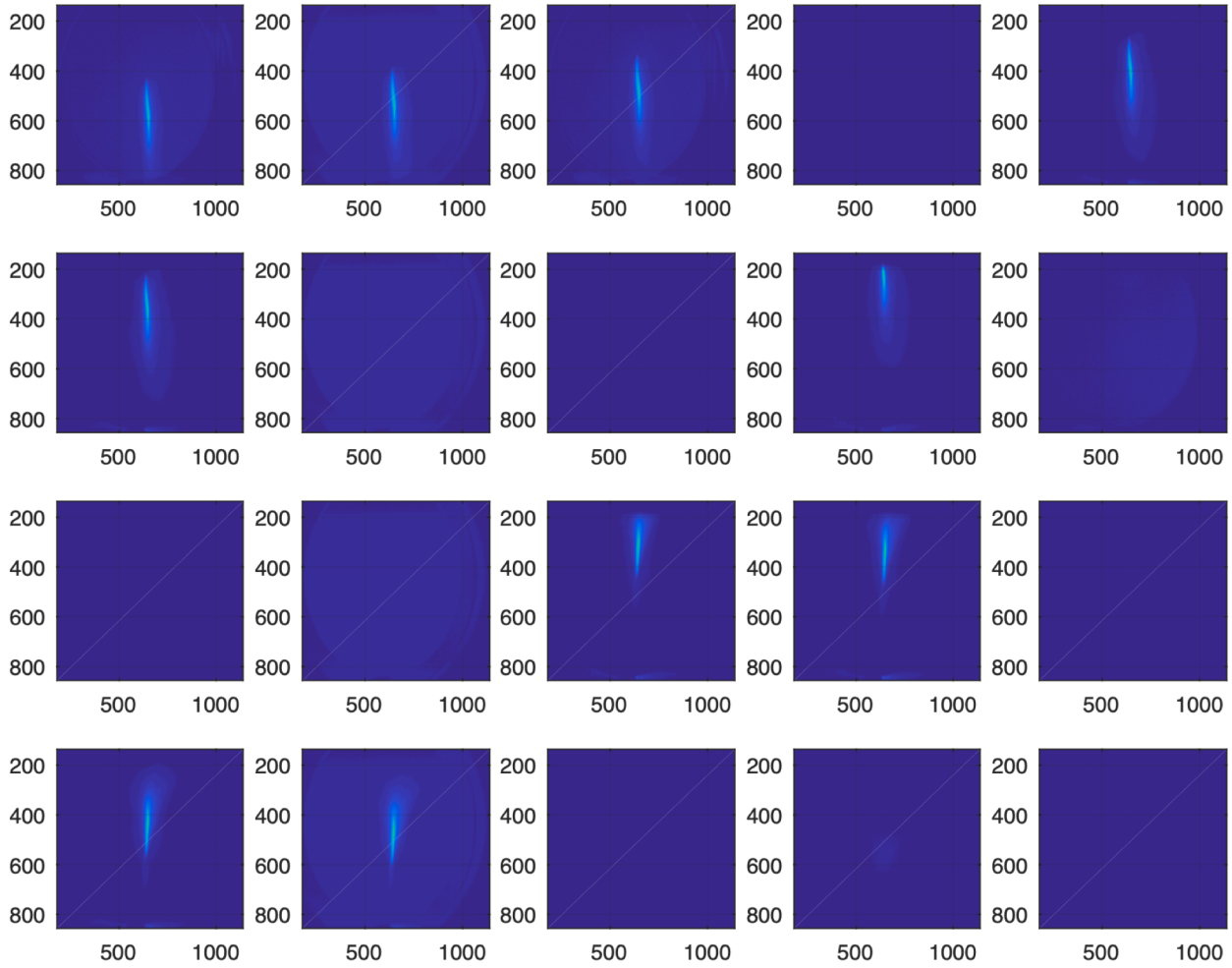


Cathode QE variation





Deflecting Cavity Tests



Electron beam: 100μs, 10 Hz (pulse mode)

2856 MHz NC deflecting cavity used (synchronization problem, to be fixed)

Summary

- DC-SRF-II photoinjector has been tested
  - CW operation of the DC-SRF photoinjector for the first time
  - Sub-micron emittance achieved with DC-SRF photoinjector
- Second stage tests coming around December 2021
  - Hardware problems being fixed
  - DC voltage ~100 kV
  - SRF cavity Gradient > 10 MV/m
  - Bunch charge ~100 pC

Thank You!