Simulation optimization of DC-SRF photoinjector for low-emittance electron beam generation

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Outline

- R&D of DC-SRF photoinjector
- Simulation for low-emittance electron beam generation
- Summary

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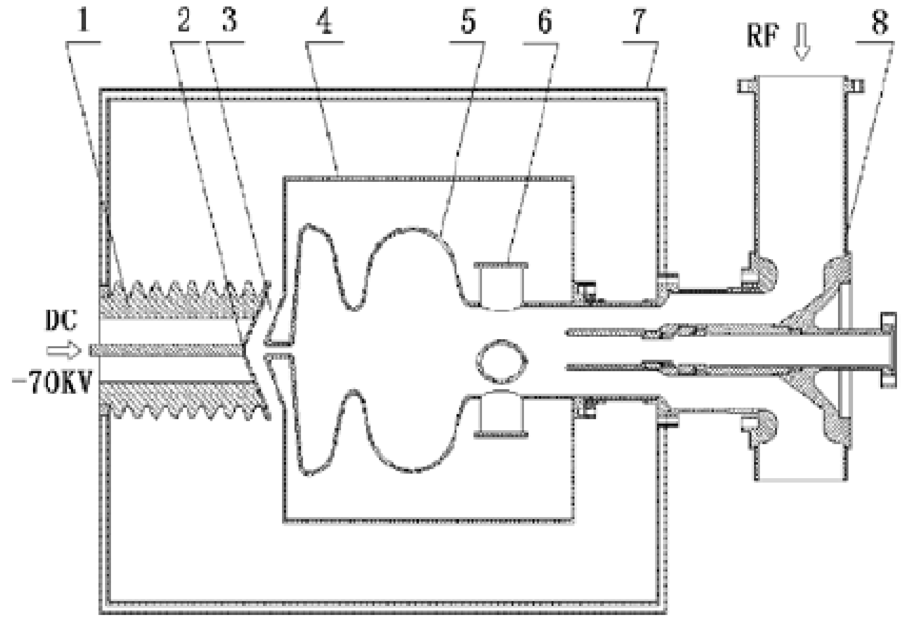
DC-SRF photoinjector—Idea

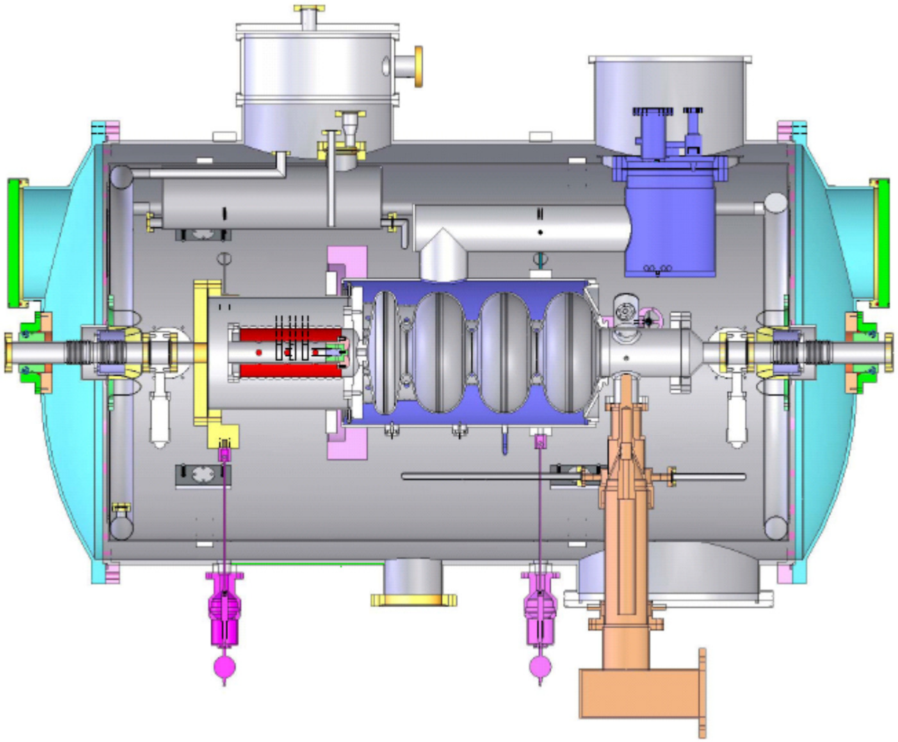
- First proposed in 2001 (K. Zhao et al., NIMA)
- Combine DC Pierce electrodes and SRF cavity

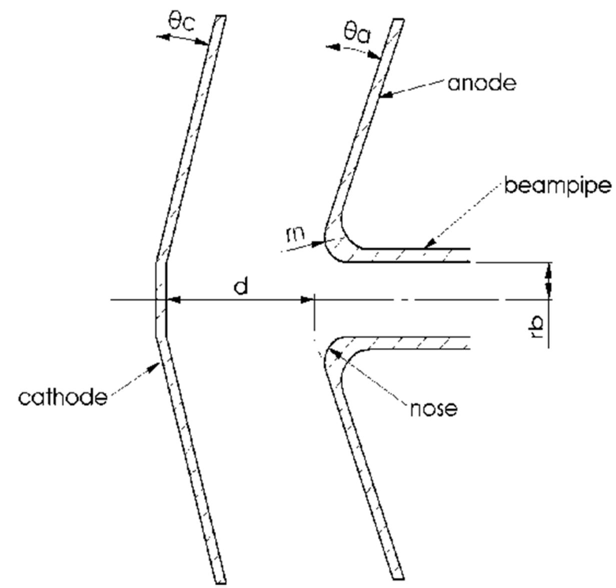


Advantages:

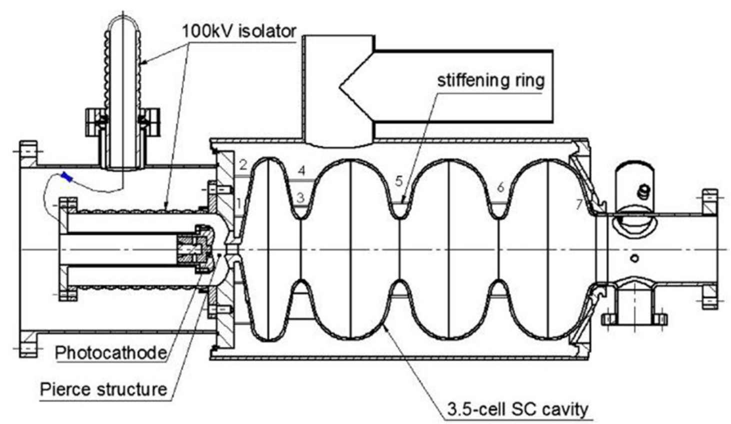
- Compatibility of normal conducting photocathode and SRF cavity is good;
- The structure is compact.

DC-SRF photoinjector— 3.5-cell design





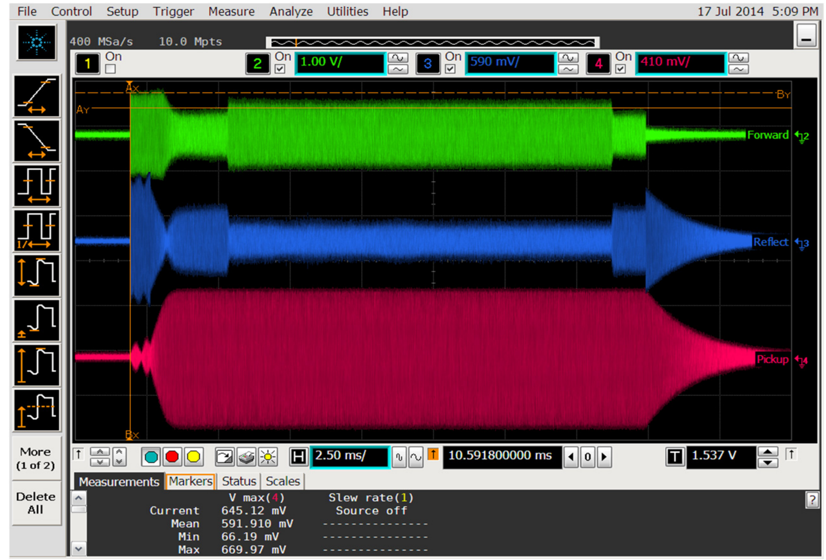
- 90 KV Pierce DC gun with Cs_2Te cathode matched with SRF cavity
- Operating at 2K

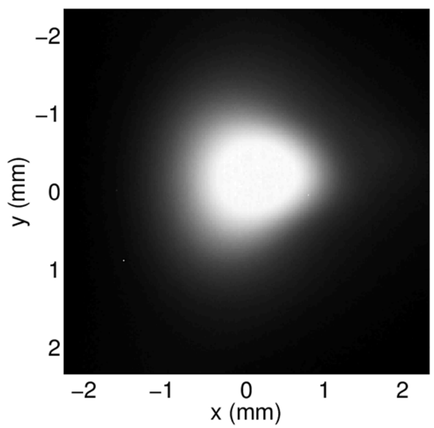


DC-SRF photoinjector— Installation

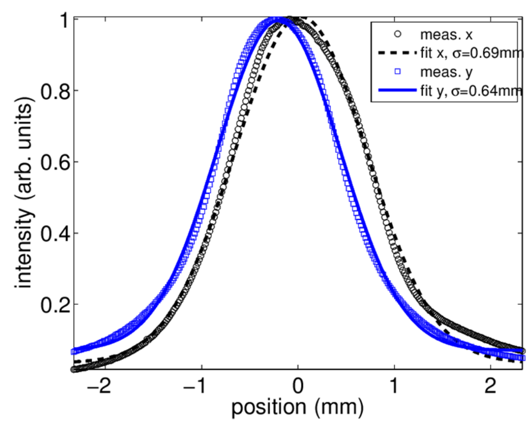
DC-SRF photoinjector— Commissioning

- avg. e-beam current ~ 1mA;
- e-beam energy ~3.4MeV;
- projected emittance ~ 1.5 mm-mrad (normalized rms, 100%);
- dark current < 1 nA

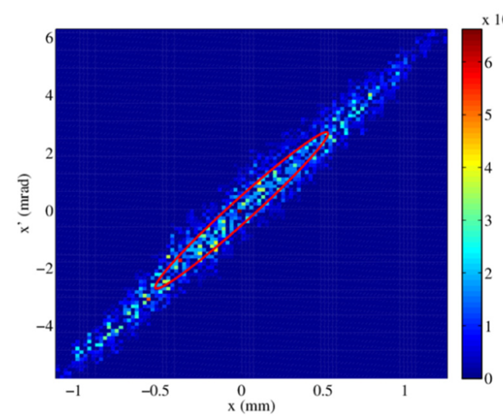




Trans. beam image



Trans. beam profile

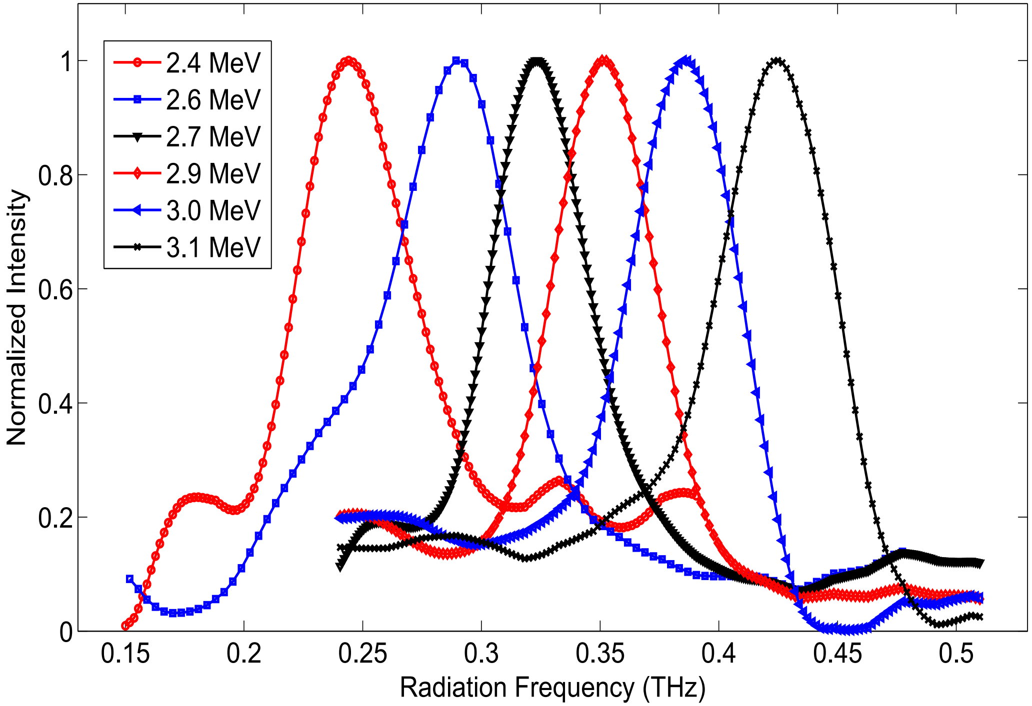


x phase space measured with scanning single slit

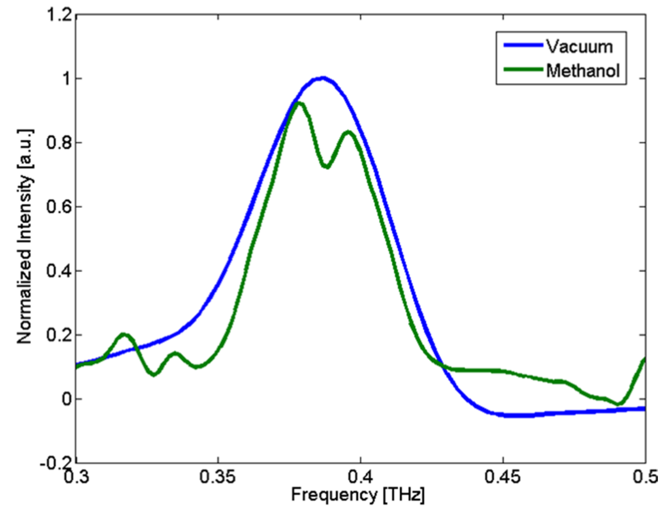
NIMA, 798, 117 (2015).

DC-SRF photoinjector— Operation

High rep-rate THz generation @ 3 MeV



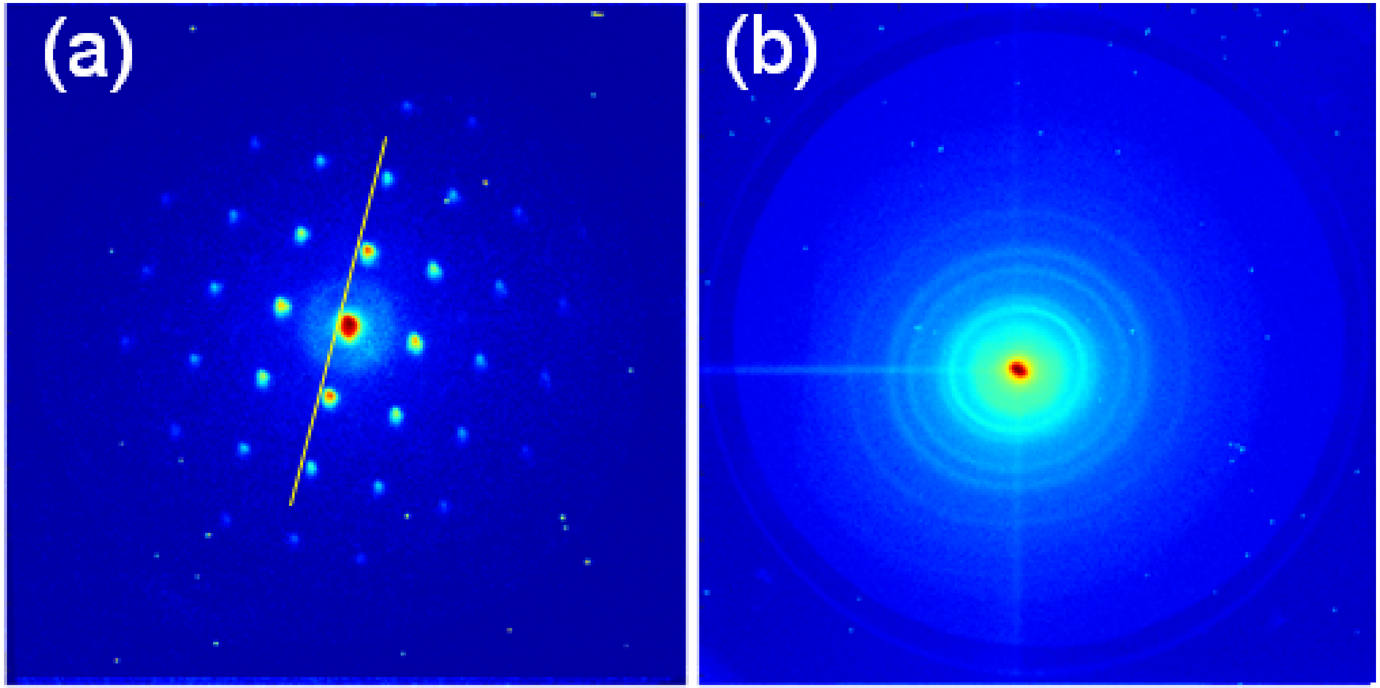
THz radiation spectrum with different electron beam energy. FWHM ~ 0.05 THz



Methanol absorption spectrum

NIMA, 820, 75 (2016).

DC-SRF photoinjector— Operation



MHz MeV UED

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]

Appl. Phys. Lett., 107, 224101 (2015).

DC-SRF photoinjector— Operation

Deliver beam to a 2×9-cell cryomodule for further acceleration

DC-SRF photoinjector— Characteristics

- DC-SRF gun has realized stable operation since 2014;
- Cavity degradation has not been observed after long time operation.

Typical parameters:

E_{acc}	8.5 MV/m
RMS pules length of UV laser	~6 ps
Operation mode	CW or Macropluse
Energy	3.4 MeV
average current	~1mA
Normalized transverse emittance (95%)	1.5 mm-mrad
Bunch charge	20-50pC
Energy spread	<1%
Bunch repetition rate	27MHz

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Knobs for reducing emittance

- DC voltage

  Current 50 kV (2.56 MV/m at cathode) ➔ 100 kV (5.12 MV/m at cathode)

- Drive laser

  Current free-running ➔ Shaping (Transversely truncated Gaussian, Longitudinally uniform)

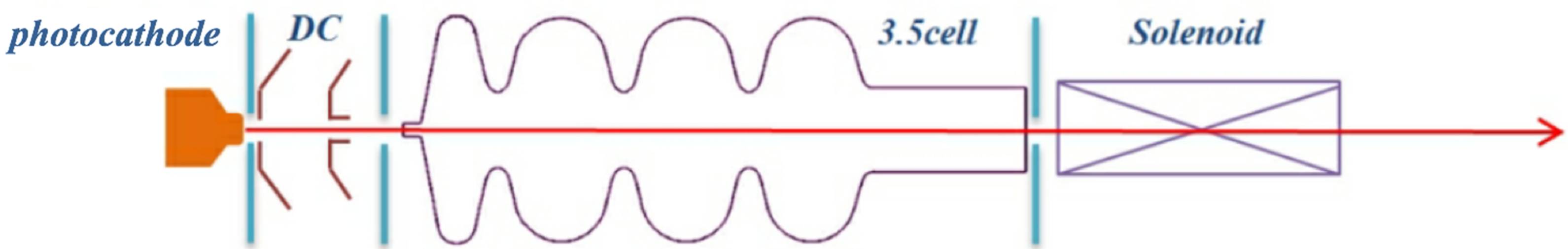
- Cathode

  Current Cs_2Te ($0.847\ \mu m/mm$)➔ K_2CsSb($0.56\ \mu m/mm$)

- Emittance compensation

  Further optimization of solenoid position

Genetic optimization for 3.5-cell injector



Model:

- DC + 3.5-cell SRF cavity + Solenoid
- Drive laser: Transversely truncated Gaussian

  Longitudinally uniform
- Bunch charge: 100 pC
- Photocathode : K_2CsSb cathode (at ~20K)

Tool:

Genetic optimizer: **MATLAB + ASTRA**

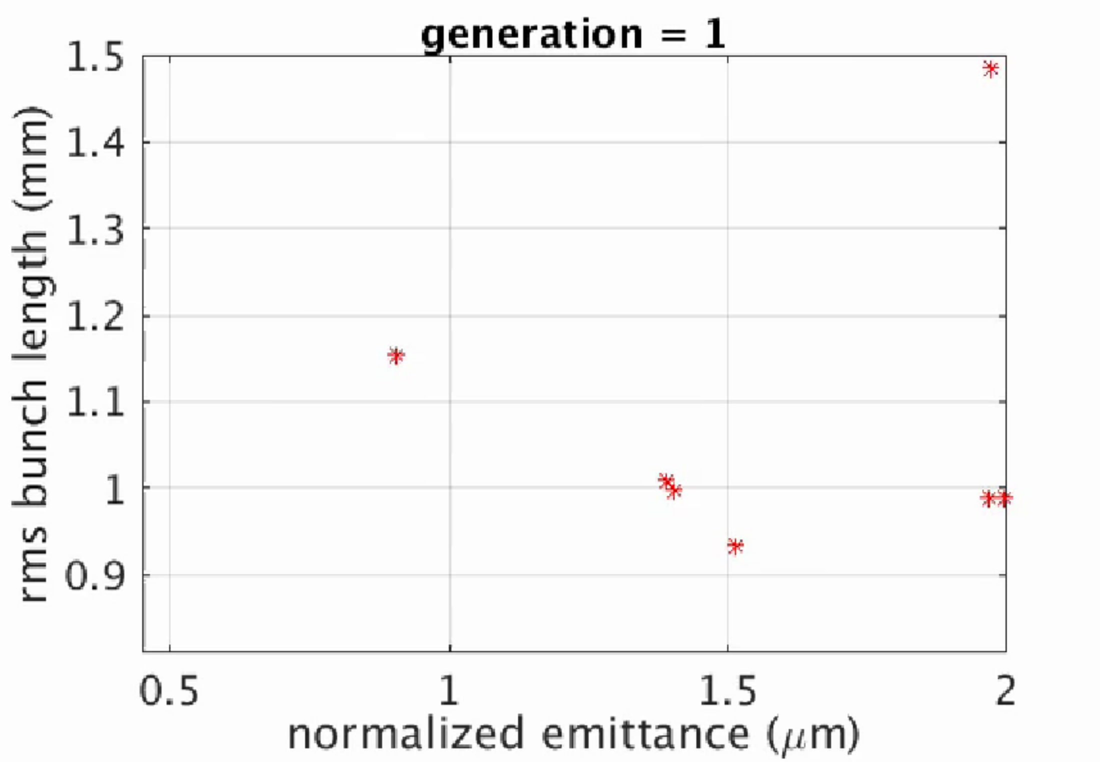
Searching range of parameters

Variables	Min	Max	Units
Laser pulse length	5	15	ps
Laser rms size	0.5	2	mm
3.5 cell Ez,max	12	25	MV/m
3.5 cell phase	-30	30	degree
Solenoid Bz,max	200	1500	Gs
Solenoid position	1	2	m

Issues:
thermal emittance, rf emittance, space charge emittance, rf focusing, emittance compensation

Compromise:
Laser rms size: thermal emittance vs space charge emittance;
Laser pulse length: rf emittance vs space charge emittance.

An optimized case



Normalized emittance

$\epsilon_{nx} = 0.44\mu m$

$\frac{\epsilon_{thermal}}{\epsilon} = 69\%$

DC valtage: 100kV

Laser pulse length: 11.3 ps (rms)

Laser rms size @ 1.13 mm

Ez,max @ 23MV/m

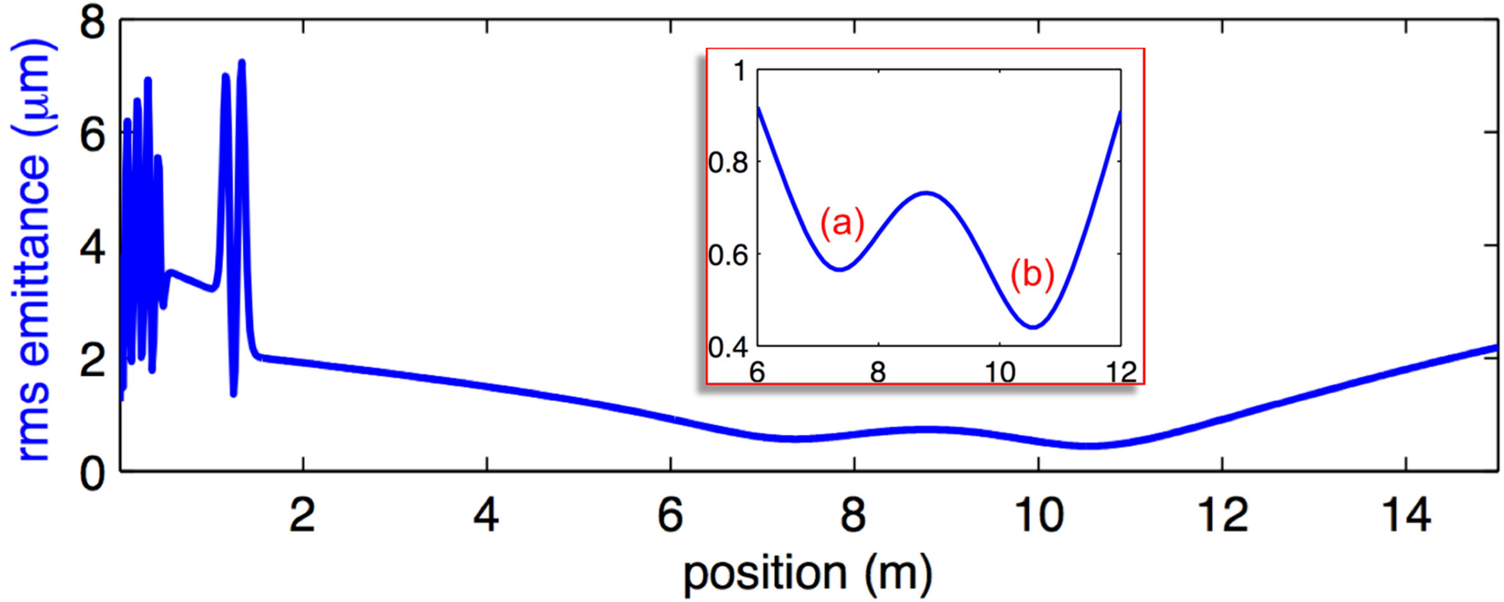
RF phase @ -17 deg

Solenoid B-field : 840 Gs

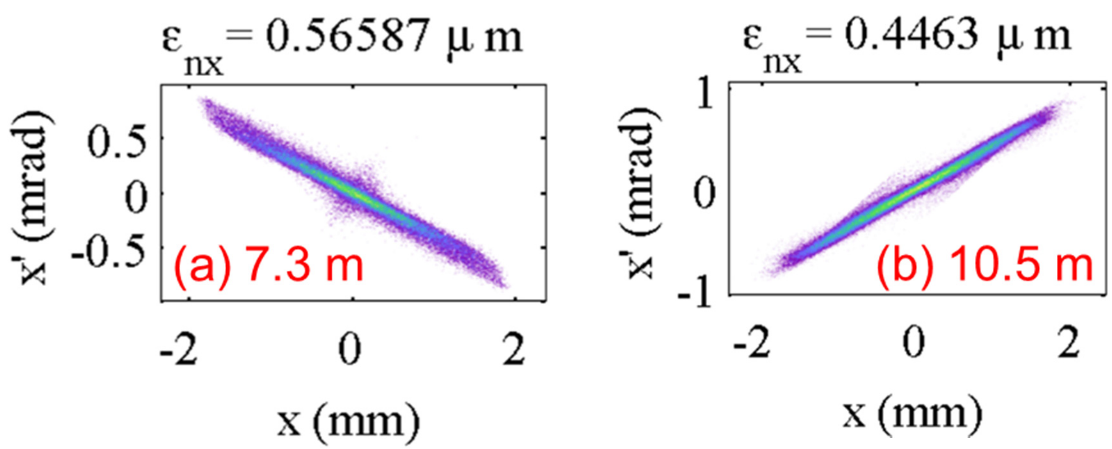
Solenoid position :1.25m

Note: 100% emittance used throughout this study
1k macroparticles used for fast optimization.
200k macroparticles used once optimized.

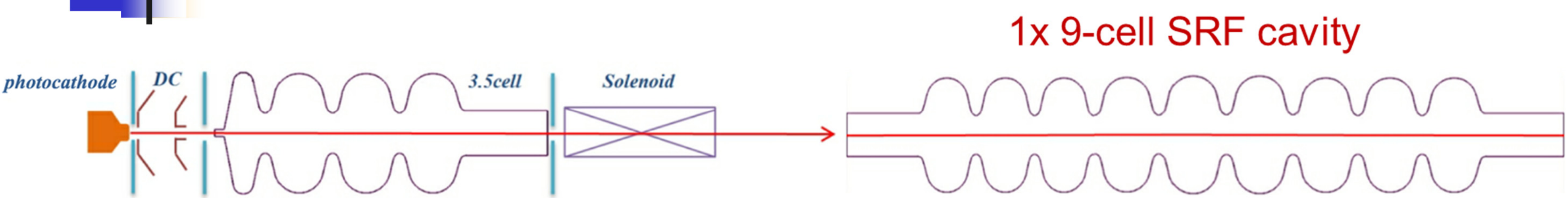
Emittance evolution for the optimized case



“double emittance minimum effect”
M. Ferrario, PRL 99, 234810(2007)

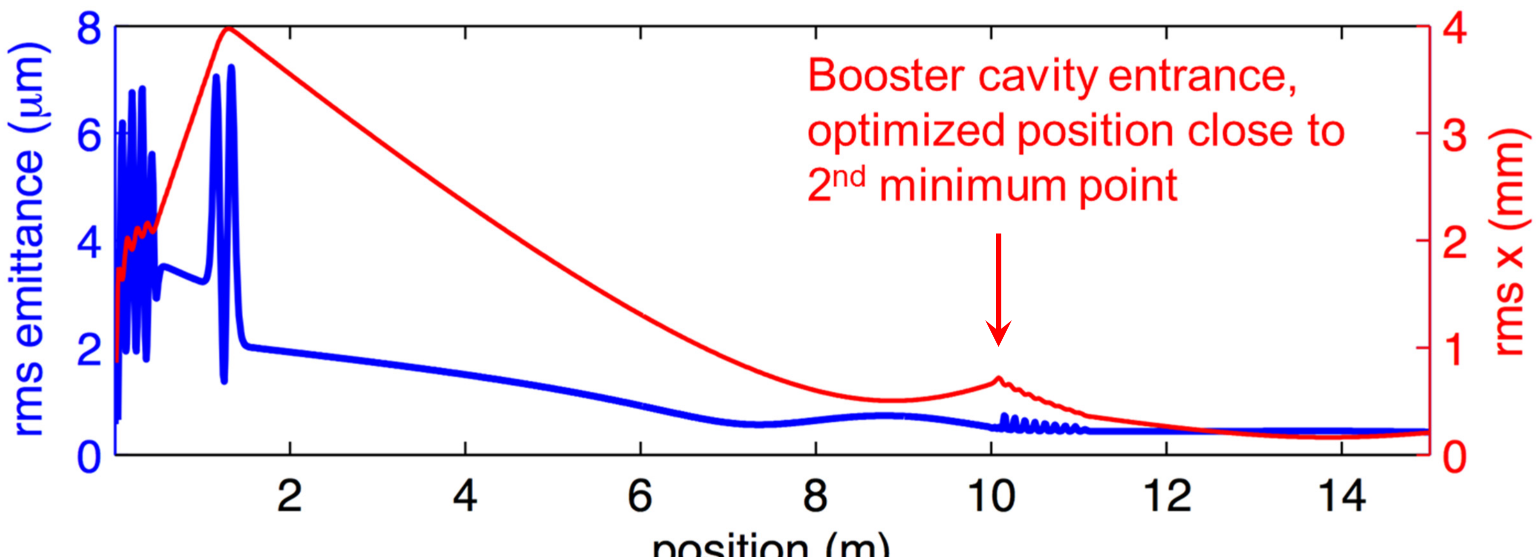


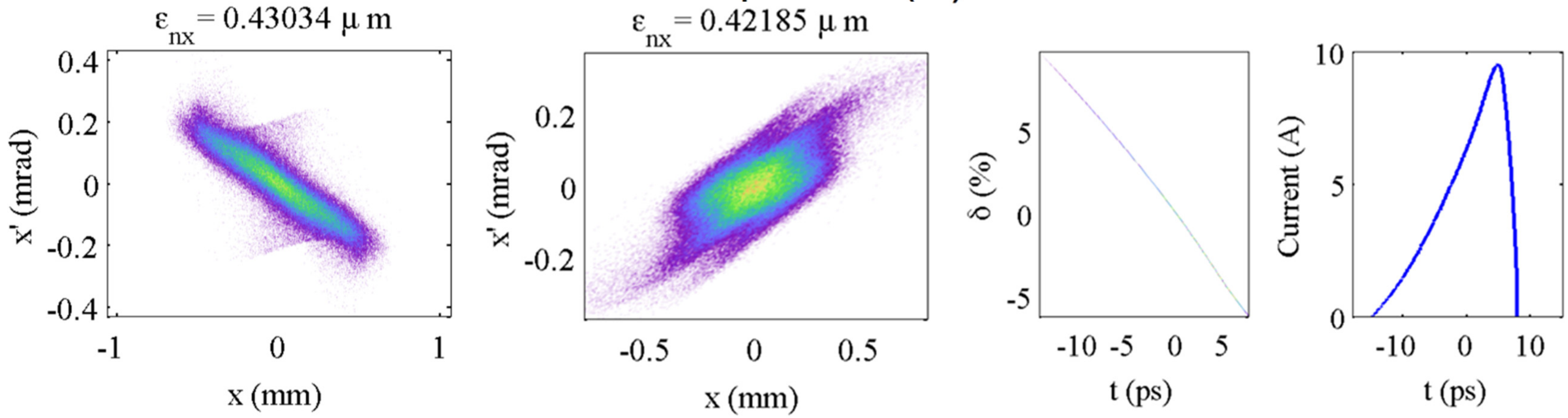
Freeze the emittance with booster cavity



- DC-SRF photoinjector with previously optimized parameters
- 1x9-cell TESLA-type cavity used to booster the electron energy
- Genetic optimization of booster cavity parameters (position, rf amplitude, rf phase)
- The position of 9-cell cavity was searched around the maximum emittance point between the two minimum (Ferrario point)

Emittance after booster cavity

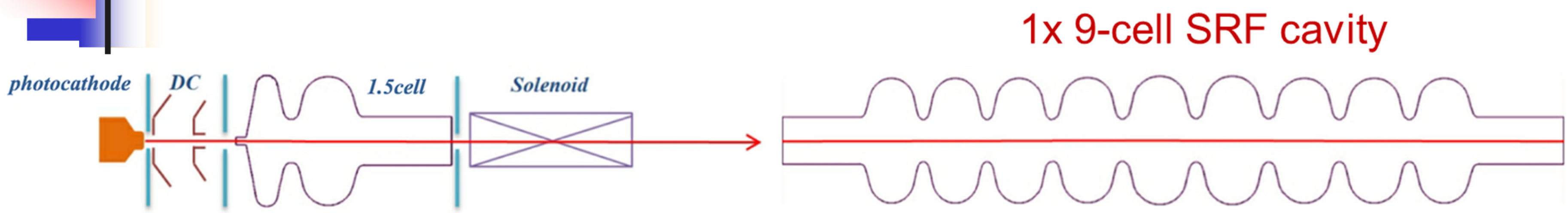




at 12 m

at 15 m

Preliminary simulation for 1.5-cell DC-SRF



DC + 1.5-cell SRF cavity + Solenoid

Benefit:

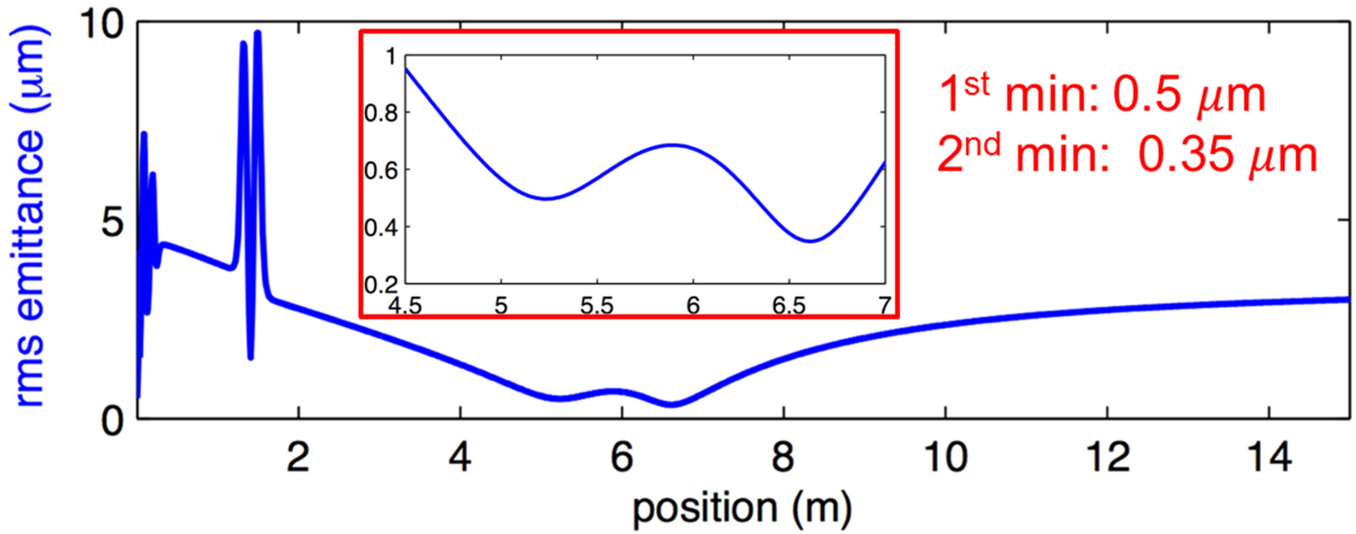
Reducing RF kick to electron slices

Parameters scanned:

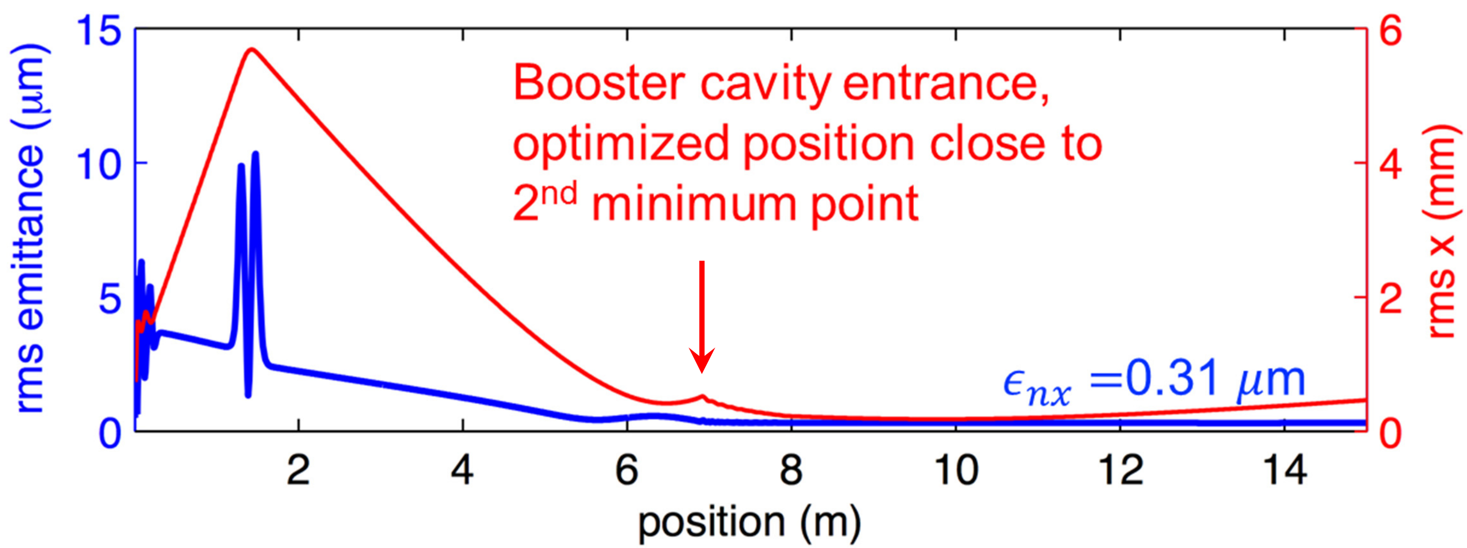
laser pulse length and rms size, 1.5-cell cavity field amplitude and phase, solenoid strength and position, 9-cell cavity position, field amplitude and phase.

Emittance evolution

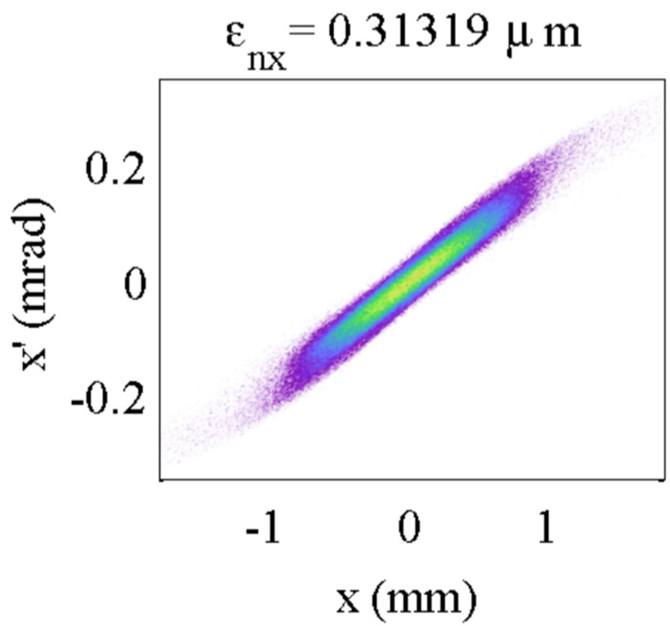
DC-SRF only

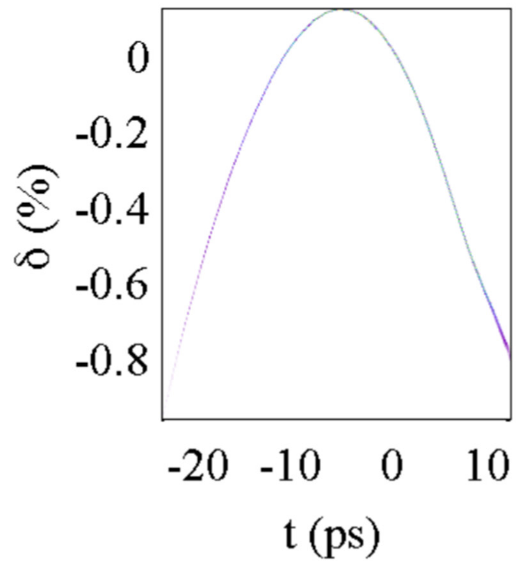


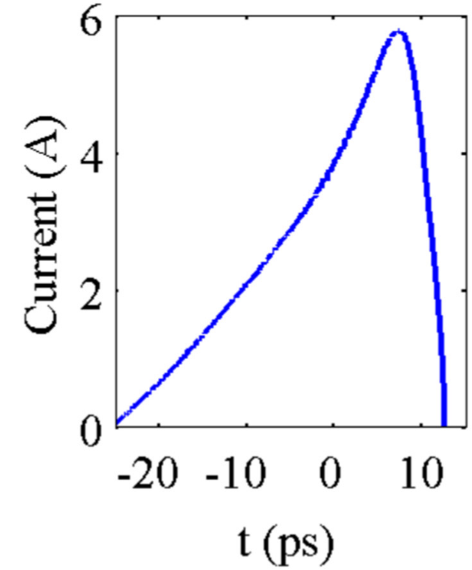
DC-SRF + 1x9-cell rf cavity

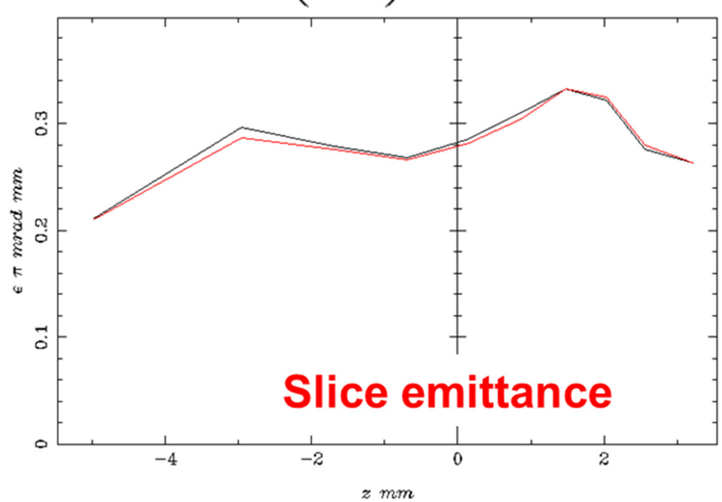


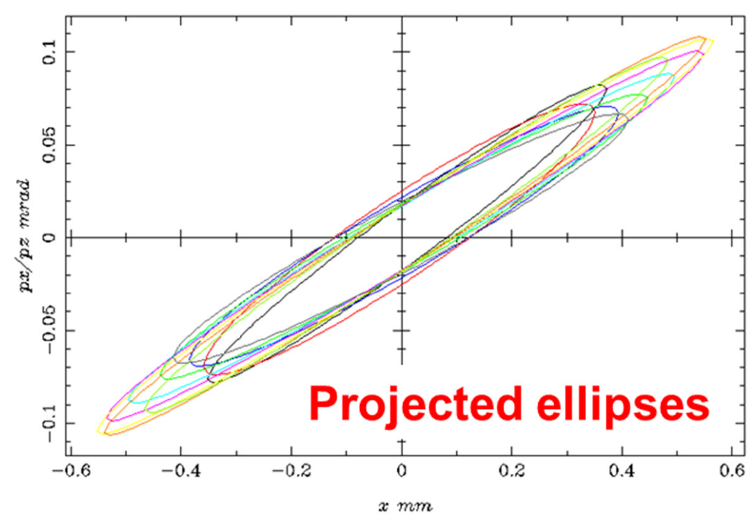
Optimized emittance at15m











Summary

- Stable operation of DC-SRF gun has been realized with average beam current of ~1mA;
- Beam emittance can be improved by increasing DC voltage, drive laser shaping, bi-alkali photocathode and emittance compensation;
- Simulation results are promising, emittance better than 0.5 μm could be achieved at 100 pC;
- Research on laser shaping, bi-alkali photocathode and structure optimizing of DC-SRF photoinjector are all in progress.

Thank you for your attention!