High average current injectors for ERLs

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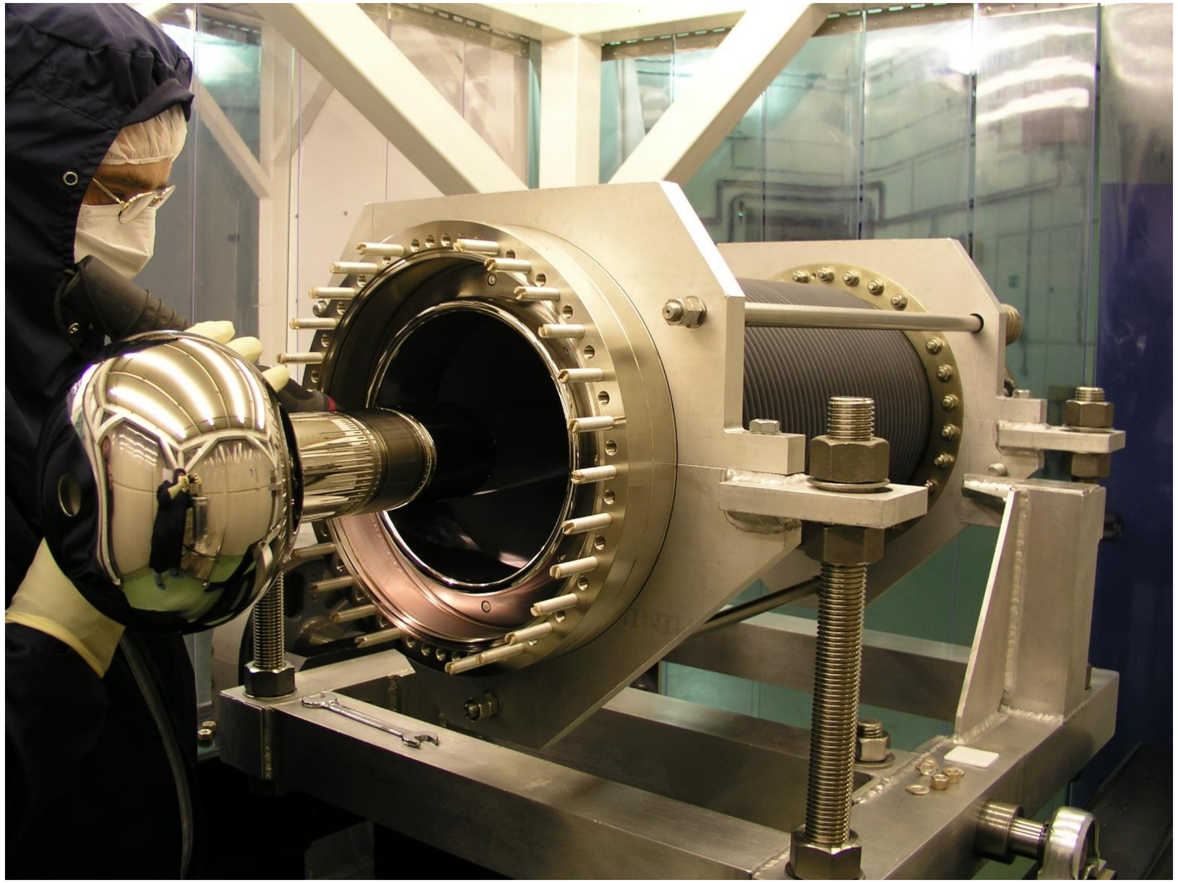
Outline

- Motivation
- Main constraints in design of high average current sources
- Current status in development of the ERL injectors
- Photocathode infrastructure
- Generation of polarised electrons
- Future perspectives
- Conclusion



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Motivation

- Energy Recovery Linear Accelerators (ERL) require injectors which deliver periodic sequence of electron bunches with different parameter range:
  - Bunch charge
  - Bunch repetition rate
  - Bunch length
  - Beam emittance
  - Beam energy spread
- Common for all the sources for future ERLs is relatively High Average Current – 100 mA range

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Source design constrains I. Technologies

- Minimum achievable emittance is limited by bunch charge and emission field on the photocathode and may be found as*:

$$I_{max} = \frac{Q}{\tau} = I_0 \frac{\sqrt{2}}{9} \left(\frac{eE_{emit} r}{mc^2} \right)^{3/2}, \varepsilon/r \propto \sqrt{\frac{h\nu - \varphi_{eff}}{mc^2}} \Rightarrow \varepsilon \propto Q^{2/3}/E_{emit}$$

- Maximum cathode electric field achievable in RF injectors directly linked with cavity frequency
  - Breakdown field limited by Kilpatrick criterion:

$$f(MHz) = 1.64 \cdot E_0 \left(MV/m \right)^2 \cdot e^{-8.5/E_0(MV/m)}$$

- Possible technologies providing CW operation
  - DC photoinjectors
  - Normal Conductive RF photoinjectors with a frequency not higher than about 200 MHz
  - Superconducting RF photoinjectorss
  - Thermionic injectors

* - D. Filippetto *et al.*, Phys. Rev. ST Accel. Beams 17, 024201 (2014)

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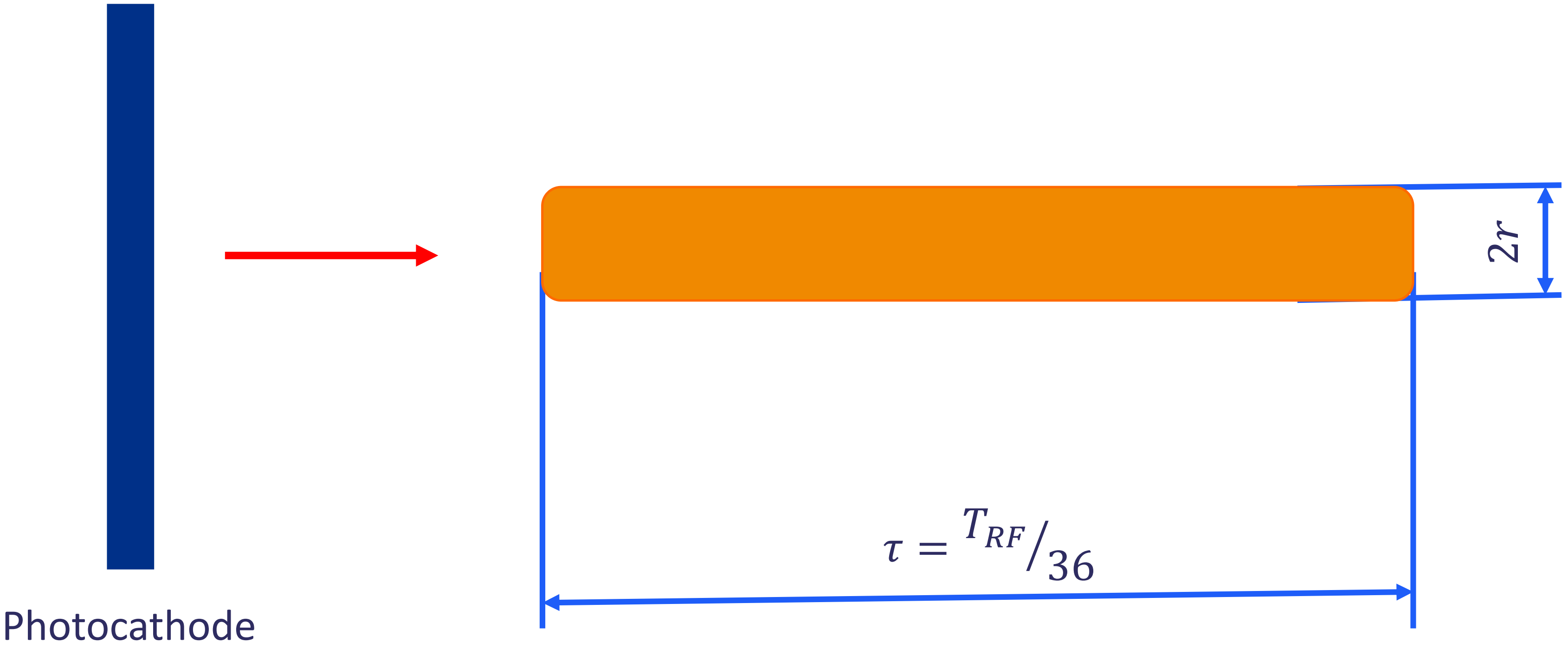
Optimal photoemission



For PERLE

$Q = 0.5\ nC$
$f = 800\ MHz$
$\tau = 35\ ps$
$I_{max} = 14.4\ A$
$E_0 = 5\ {}^{MV}/_{m}$
$E_{emit} = 5\ {}^{MV}/_{m}$
$r = 3.1\ mm$
$\varepsilon \sim 4.4\ mm \cdot mrad$

$$\varepsilon/r \propto \sqrt{\frac{h\nu - \varphi_{eff}}{mc^2}} \qquad I_{max} = \frac{Q}{\tau} = I_0 \frac{\sqrt{2}}{9}\left(\frac{eE_{emit}r}{mc^2}\right)^{3/2}$$

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Source design constrains II. Beam emission

- Charge delivered by photoinjector
  - Photocathode material and its Quantum Efficiency (QE) and lifetime
    - Level of operational vacuum required to provide acceptable photocathode lifetime for alkali photocathodes
  - Laser pulse parameters on the cathode
    - Spatial and temporal laser profile – pulse length and, as result, power density scales as $^{1}/_{f}$
    - Laser pulse energy
      - No problem for delivery by laser for Sb based photocathodes, may be an issue for Te based photocathodes
      - Laser pulse transport
        - Mirror damage due to high peak and average power density - no problem for alkali based photocathodes
- No problem for thermionic injector
- Minimum dark current

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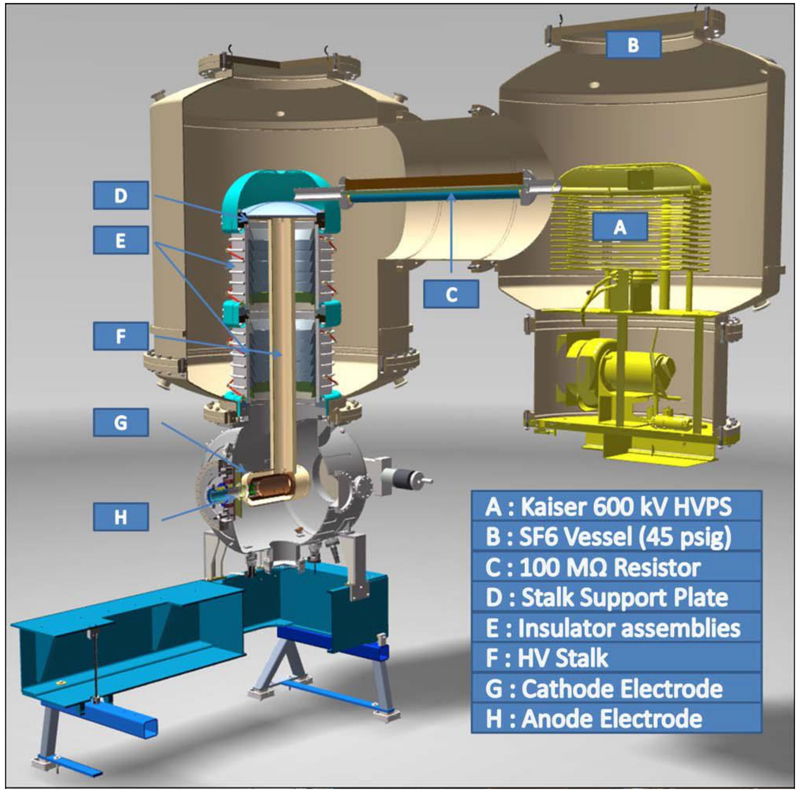
DC photocathode guns, Cornell



Operates with Na_2KSb photocathodes

Q (pC)	100% ϵ_n	95% ϵ_n	Core ϵ_n	Cathode ϵ_n
20	0.22 (0.24)	0.18 (0.19)	0.09 (0.08)	0.12 (0.11)
100	0.37 (0.39)	0.30 (0.32)	0.16 (0.16)	0.24 (0.23)
300	0.78 (0.78)	0.62 (0.60)	0.30 (0.28)	0.42 (0.41)
1000	2.3 (2.3)	1.6 (1.6)	0.56 (0.58)	0.59 (0.60)
2000	6.4 (5.4)	4.4 (4.0)	1.6 (1.3)	0.88 (0.90)

Operational parameters	
Conditioning voltage	500 kV
Operational voltage	400 kV
Operational current	70 mA

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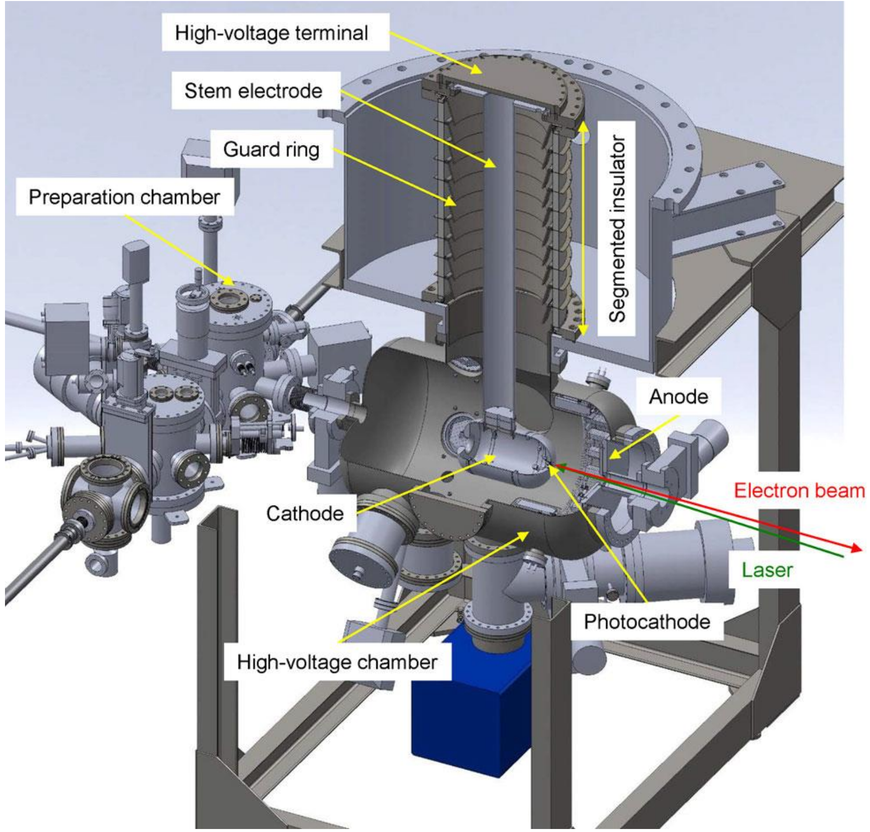
Rev. Sci. Instrum. **85**, 093306 (2014)

DOI: 10.1103/PhysRevSTAB.18.083401

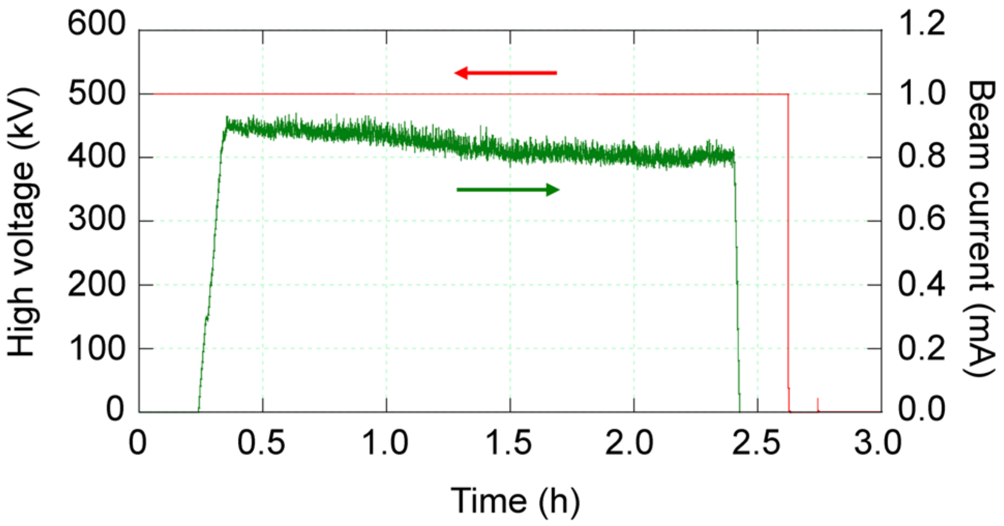
DC photocathode guns, cERL, KEK



DOI: 10.1103/PhysRevAccelBeams.22.053402

Operates with GaAs photocathodes

Parameter	Units	Value
Operation voltage	kV	350-500
Cathode field	MV/m	3-5
Average current	mA	Up to 75
Vacuum level	mbar	$<10^{-11}$



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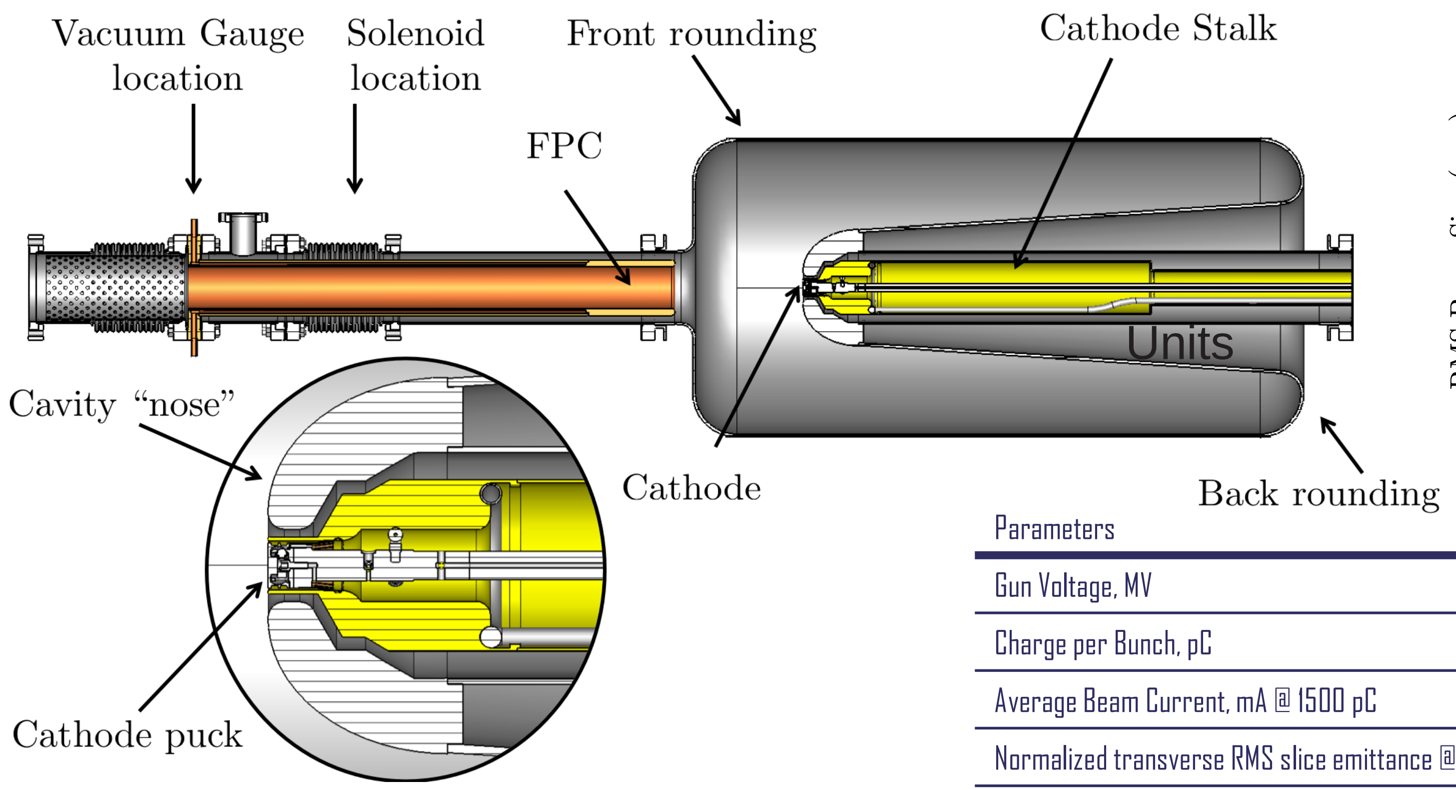
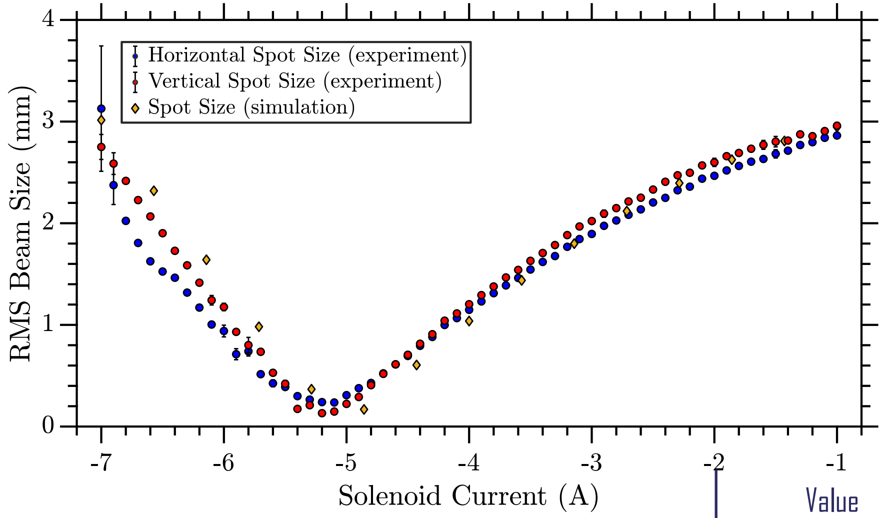
SRF Quarter Wave photocathode gun, BNL



Operates with Cs_2KSb photocathodes



DOI: 10.1103/PhysRevLett.124.244801

Parameters	Value
Gun Voltage, MV	1.25
Charge per Bunch, pC	100-20,000
Average Beam Current, mA @ 1500 pC	0.15
Normalized transverse RMS slice emittance @ 100 pC, mm-mrad	0.15
Normalized transverse RMS projected emittance @ 100 pC, mm-mrad	0.3
Longitudinal RMS slice emittance @ 100 pC, keV-ps	0.7
Quantum Efficiency, %	1-4

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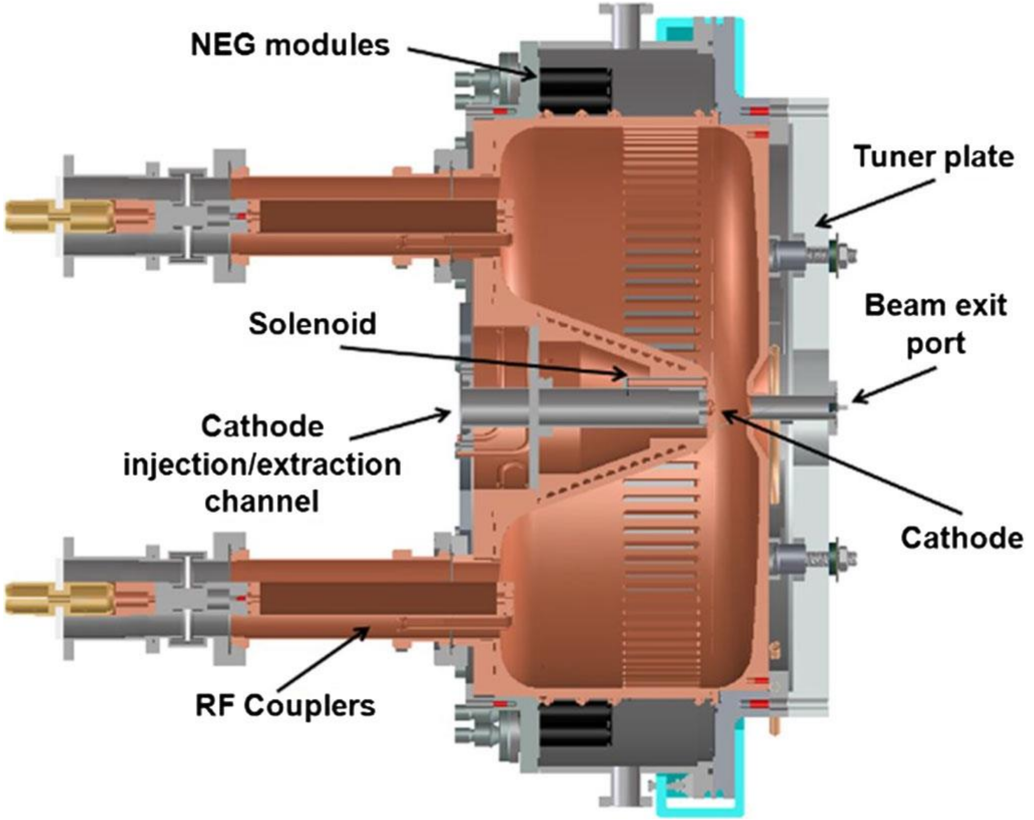
NCRF VHF photocathode guns, LBNL-SLAC

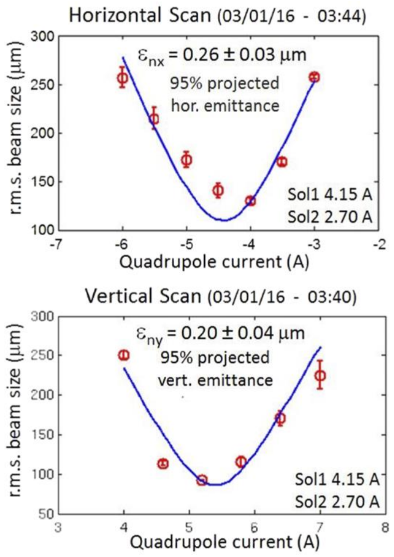
Operates with Cs_2Te or Cs_2KSb photocathodes

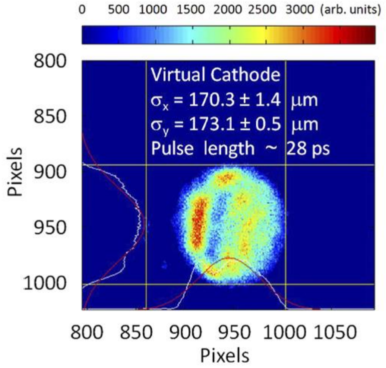


Rev. Sci. Instrum. **90**, 033304 (2019)

APEX Phase-II main parameters

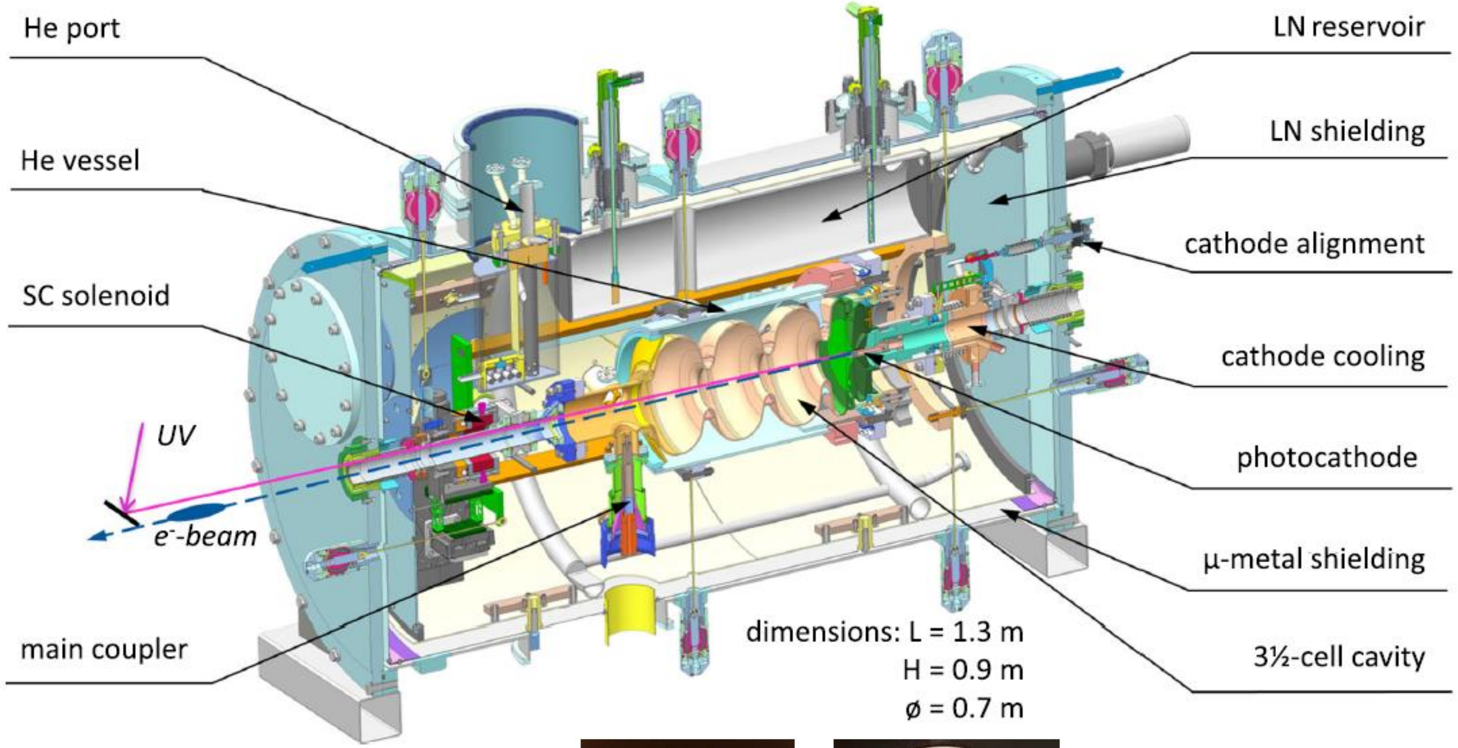
Gun frequency	185.714 MHz
Gun operation mode	CW
Max beam energy at gun exit	0.8 MeV
Nominal operational energy	0.75 MeV
Field at the cathode at 0.75 MeV	20 MV/m





Emittance measurements of 20 pC bunches generated by LBNL Cs_2KSb photocathode

SRF elliptical cavities photocathode gun, HZDR



Parameter	Value: Gun I	Value: Gun II
Type of cavity	Elliptical 3.5 cells	
Frequency	1.3 GHz	
Gun operation mode	cw	
Beam energy at gun exit	3.0 MeV	4.0 MeV
Acceleration gradient E_{acc}	6 MV/m	8 MV/m
Peak field on axis	16.2 MV/m	20.5 MV/m
Cathode field	7 MV/m	14.5 MV/m
dc bias at cathode	−5 kV	
Liquid He temperature	2 K	
Dynamic He load at max E_{acc}		10 W
Drive laser wave length	258 nm	
Photocathodes	Cs_2Te	Mg
Quantum efficiency	1%	0.1%–0.3%

Phys. Rev. Acc. Beams **24**, 033401

Mg (ps laser clean)
0.2-0.4 %

Cs_2Te on Cu plug
~ 1 %

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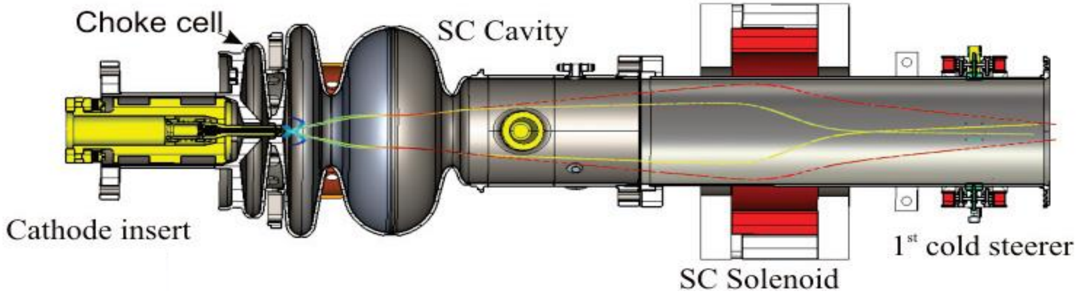
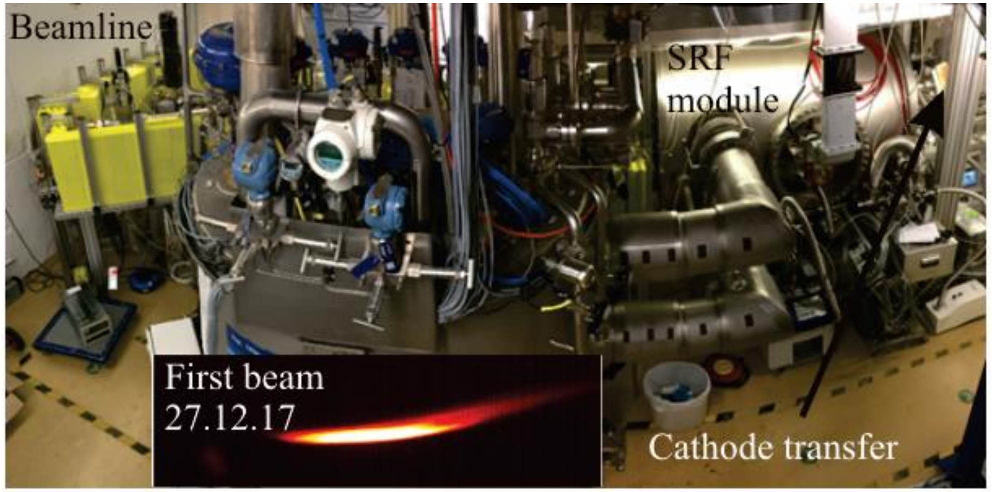
SRF elliptical cavities photocathode gun, HZB





Cavities for operation with Cs_2KSb photcathodes

doi:10.18429/JACoW-IPAC2018-TUPML053

Thermionic injectors

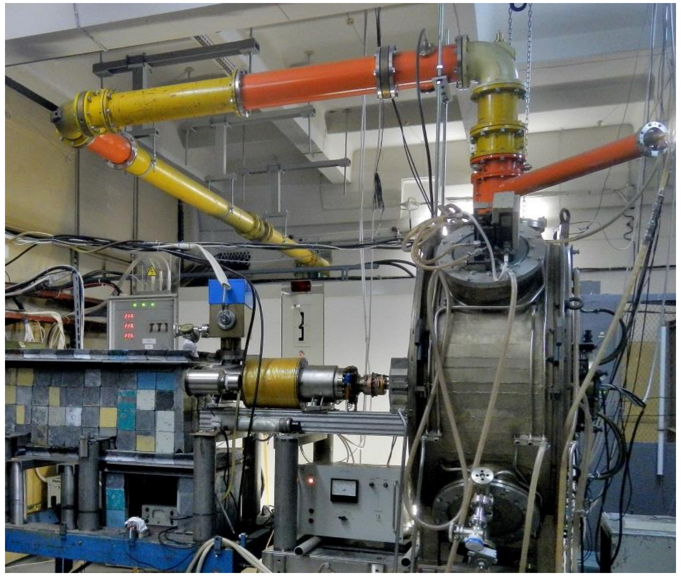
3 GHZ 600 mA grid modulated train pulsed thermionic gun of FLARE FEL

Grid modulated cathode

Modulation cavity

Courtesy Lex van der Meer,
Radboud University, Nijmegen, NL

100 mA CW thermionic injector of Novosibirsk ERL on test beamline



Operation frequency 90 MHz
Pulse duration 1 ns
Beam energy 300 keV

Courtesy Oleg Shevchenko
BINP, RU

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Photocathodes for 100 mA photoinjectors

- Photocathodes which are of interest for HEP ERL’s
  - Sb-based “green” photocathodes such as Cs_3Sb, Cs_2KSb, Na_2KSb, CsNaKSb and others
  - Widely used in industry in PMT
  - Enough robust for operation with high average current
  - Laser systems are available
  - Technolohgy under development for accelerator applications
    - Optimisation of deposition procedure to obtain high QE
    - Lifetime at high average current
    - Operation at cryogenic temperature
    - Mean Transverse Energy
- GaAs based photocathode for delivery of polarised electrons
  - Very sensitive to operational vacuum and as result low charge lifetime in the range of 100’s C
  - Major efforts are concentrated on improving operational performance
- Cs_2Te photocathodes
  - Very robust. Operated at DESY FLASH for 2 years
  - High QE, but require UV laser which is not available for 100 mA range

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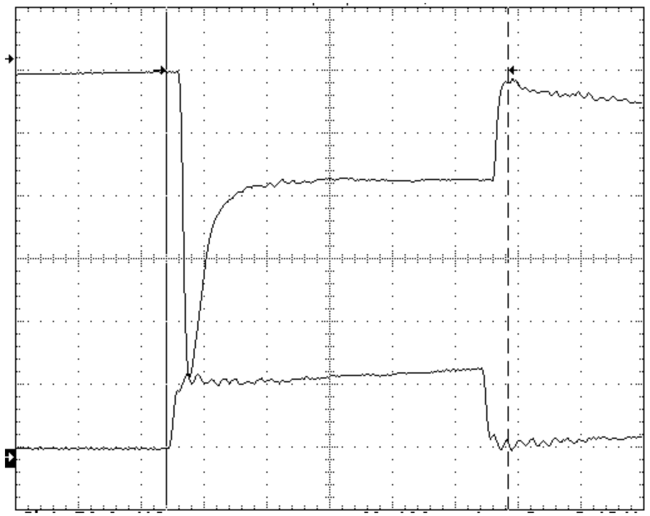
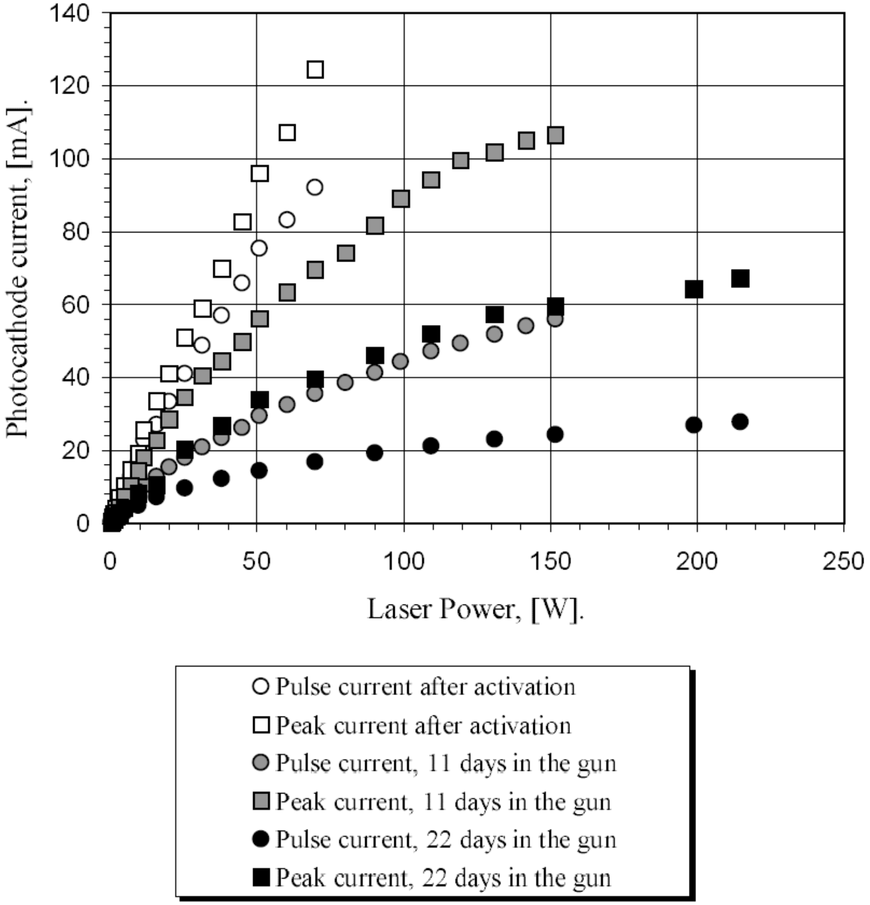
Generation of polarised electrons. Amsterdam Pulse Stretcher(AmPS), 1998





5 µs pulses with an amplitude of 120 mA of highly polarised beam has been demonstrated from 1.7 eV bandgap InGaAsP photocathode

B.L. Militsyn, ISBN 90-386-0777-6, 1998

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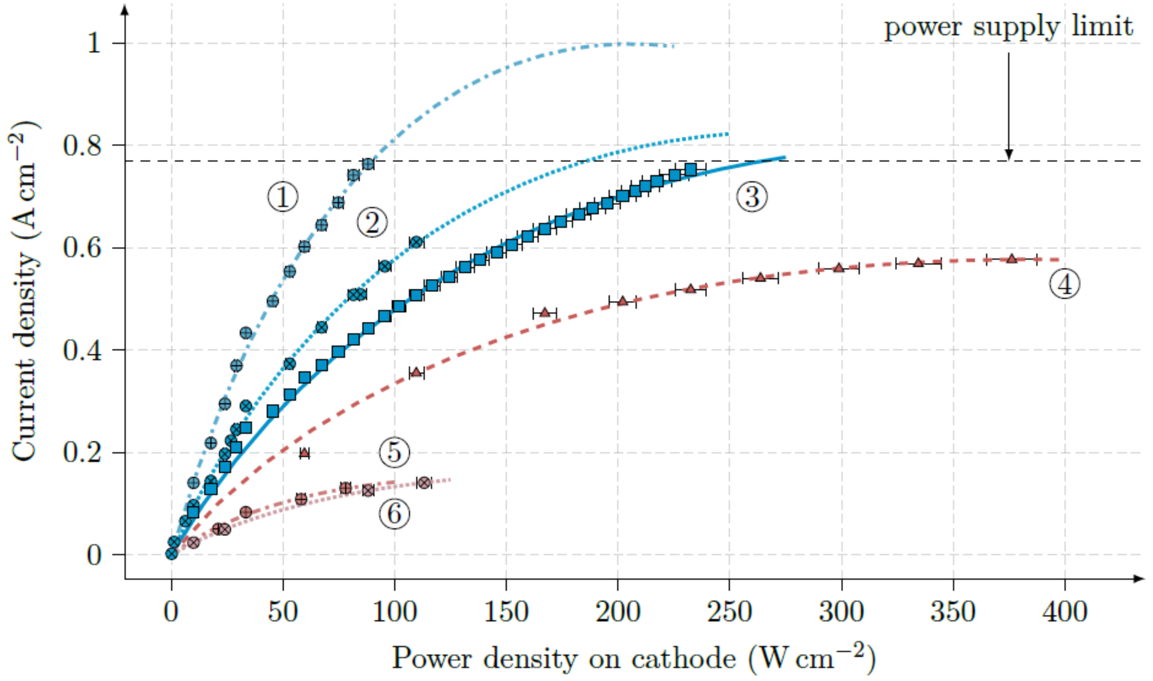
Generation of polarised electrons, UoM, 2019

S. Friederich *et al* 2019 *J. Phys.: Conf. Ser.* **1350** 012045



No.	QE_0	$E_0/\tilde{\chi}$	E_0 (meV)	j_p (A cm^{-2})
①	2.40 %	37 %	26	0.58
②	1.55 %	34 %	24	0.39
③	1.15 %	35 %	25	0.41
④	0.85 %	30 %	21	0.20
⑤	0.50 %	40 %	28	0.11
⑥	0.39 %	39 %	28	0.10

10 mA current, limited by HV power supply, has been demonstrated from bulk GaAs photocathode in 400 µs pulses

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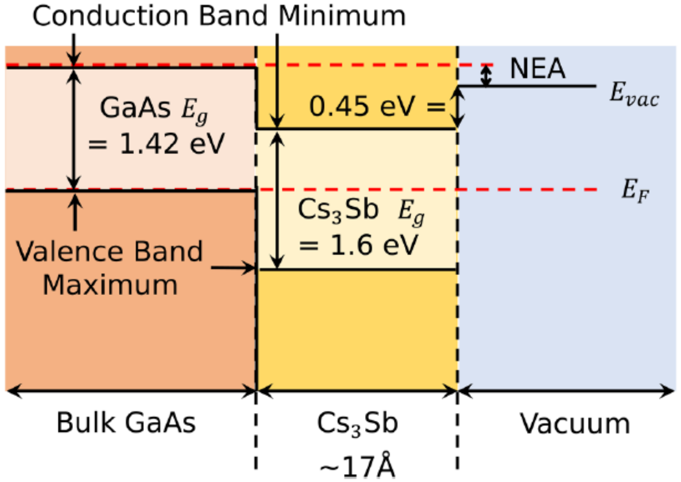
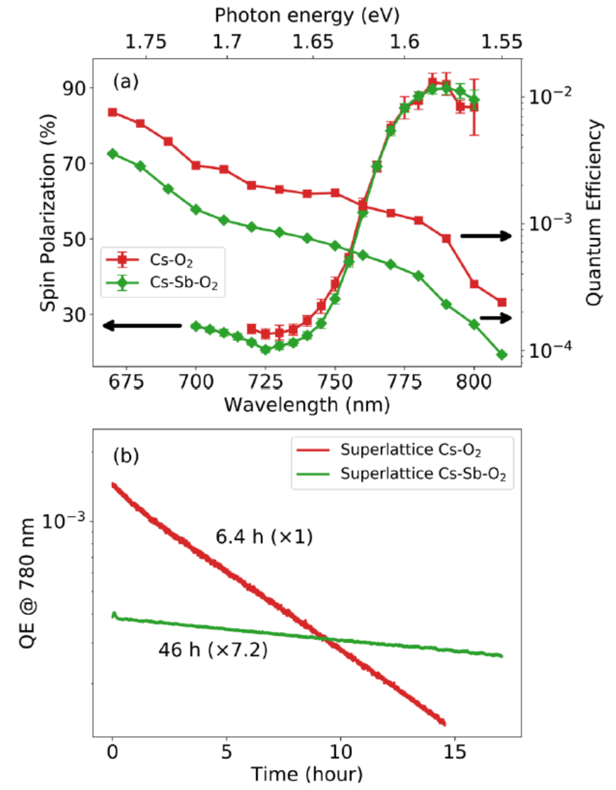
Improvement of GaAs operational performance

- Operational performance of GaAs photocathodes depends on means of their activation – reducing work function. Earlier following procedures were used:
  - Cs – photocurrent generation
  - Cs-O – activation to NEA state
  - Cs-NF_3 – slightly better operational performance, but don't used due to SHE restrictions
- New activation procedures have been developed

Activation with Cs_3Sb



Activation with alkali metals:



J.Appl.Phys. 127, 124901 (2020)

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Conclusion

- DC photocathode guns operated with Sb-based photocathode and thermionic guns can demonstrate at the moment unpolarised current of as high as 100 mA
- Potential to reach this current also have photocathode guns equipped with Sb photocathodes
  - QWR SRF gun
  - QWR NCRF gun
  - Elliptical cavity SRF gun
- There is no operational injector which can demonstrate 100 mA of polarised current, it's limited by photocathode lifetime
- Potential to deliver this current, in case of success of the program on improving GaAs lifetime by activation with Cs-alkali metal layer,
  - DC photocathode guns
  - SRF photocathode guns

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