Electron RF Injectors for Next Generation FELs

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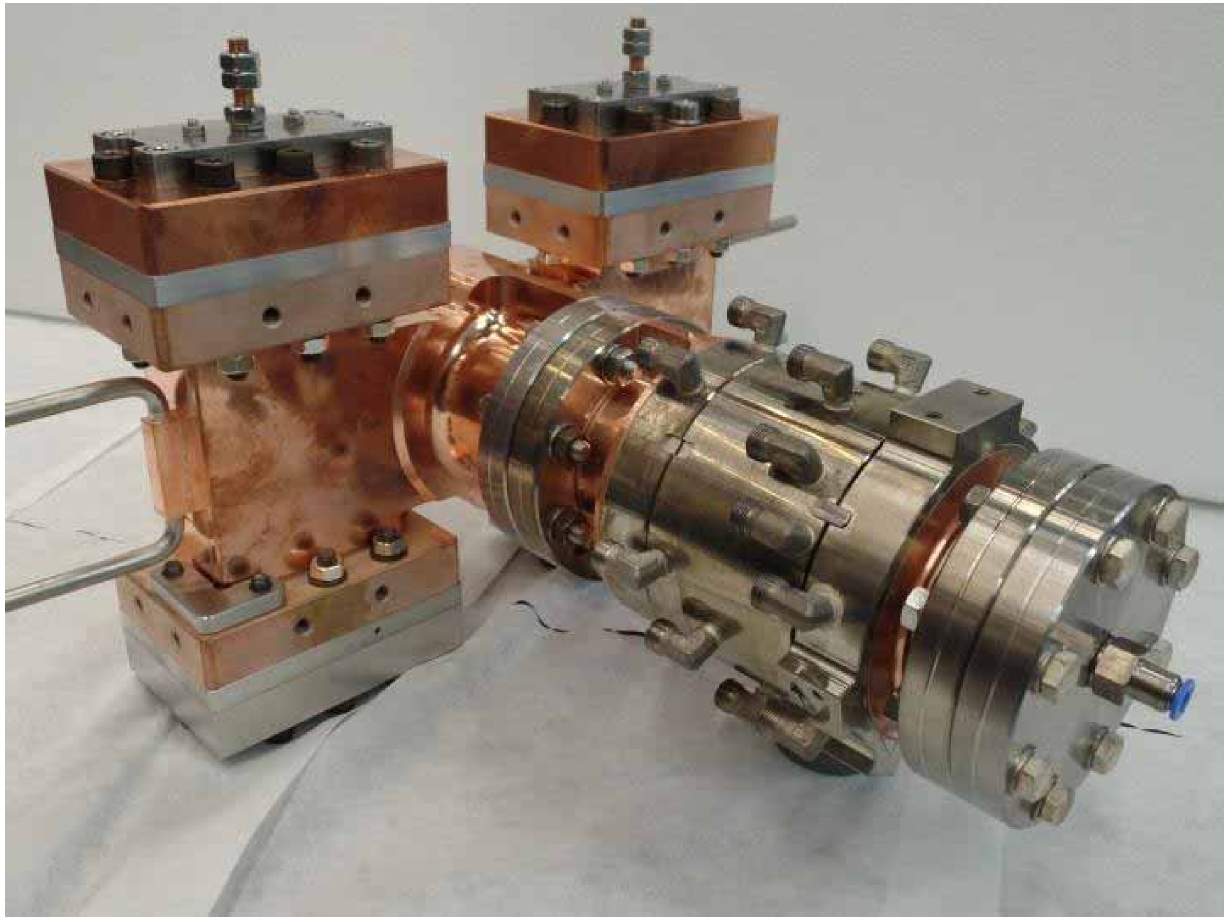
Lucerne, Switzerland

Outline

- Motivation
- Main constraints of the RF gun development
- RF guns of the operational FELs
- Modern trends on the RF gun development
- Normal conducting RF guns
- CW RF guns
- UK XFEL RF injector
- Conclusion



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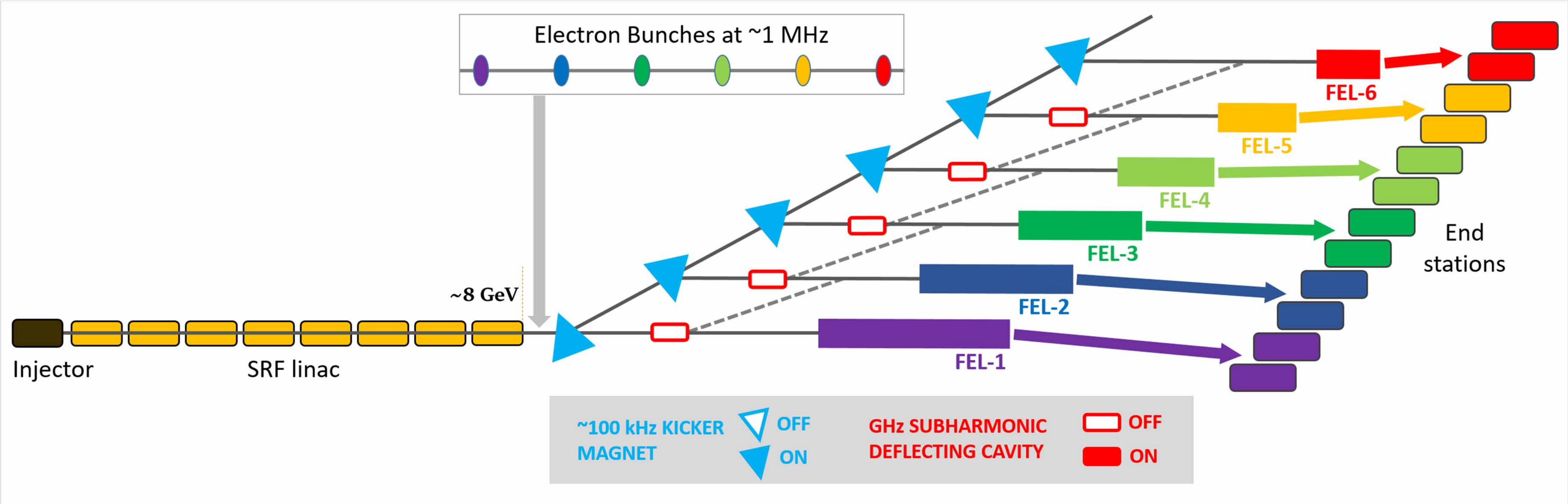
Concept of UK XFEL



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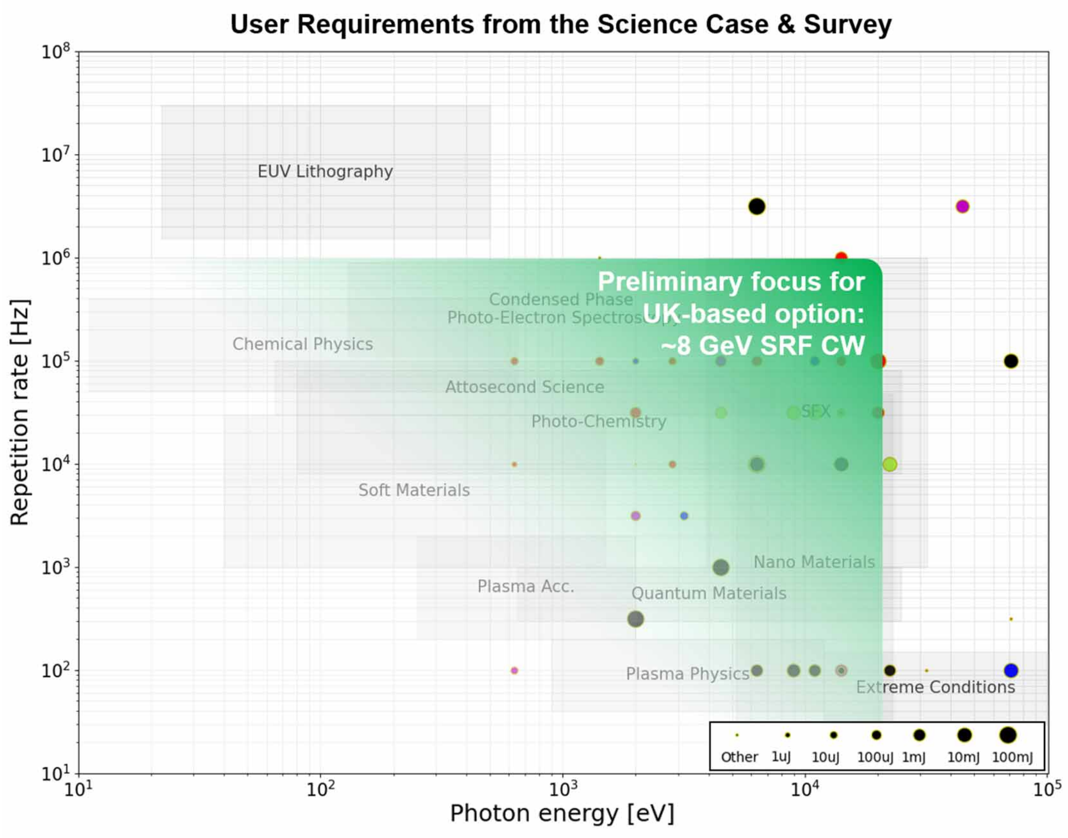
xfel.ac.uk

UK XFEL. General concept

- Transform-limited operation across the entire X-ray range (initial focus on 0.1 – 20 keV and 100 as – 100 fs).
- High efficiency facility, with a step change in the simultaneous operation of multiple end stations.
- Evenly spaced, high rep. rate pulses to match samples and detectors.
- Improved synchronisation/timing data with external lasers to < 1 fs.
- Widely separated multiple colour X-rays to at least one end station.
- Full array of synchronised sources: XUV-THz, e-beams, high power & high energy lasers at high rep. rate.



See also TU4P13 "An Introduction to the UK XFEL Conceptual Design and Options Analysis", D. Dunning *et al.*

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Typical requirements to the beams for next generation FELs

Wavelength of a photon with given energy is defined as:

$$\lambda = \frac{hc}{eU}$$

That gives 62 pm at U=20 keV (HXR) and 13.4 nm for U=100 eV (SXR)

For generation of photons with these energies by standard SASE schemes geometrical slice emittance of the electron beam at the entrance to the undulator may be estimated as:

$$\varepsilon = \frac{\lambda}{4\pi} \text{ or } \varepsilon_n = \frac{\beta\gamma\lambda}{4\pi}$$

$\varepsilon_n = 1.9\, mm \cdot mrad$ for generation of 100 eV photons with 1 GeV beam energy and

$\varepsilon_n = 0.078\, mm \cdot mrad$ for generation of 20 keV photons with 8 GeV beam

Bunch charge	100-300 pC	Peak current	3 kA
Bunch repetition rate	1+ MHz	RMS energy spread	$\leq 1.0 \cdot 10^{-4}$
Average current	0.3+ mA		

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Generation of the high brightness beams

- Before injection into the FEL undulator high brightness electron beam:
  - Emitted from photocathode with as low emittance as possible
  - Accelerated to MeV scale energy in the gun to preserve low emittance
  - Longitudinally compressed to the length, necessary for injection into the booster linac and accelerated to the energy of emittance dominated regime
  - Accelerated and compressed until required energy and length necessary for FEL generation
- We will consider first two stages of this process

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Electron emission in the RF gun

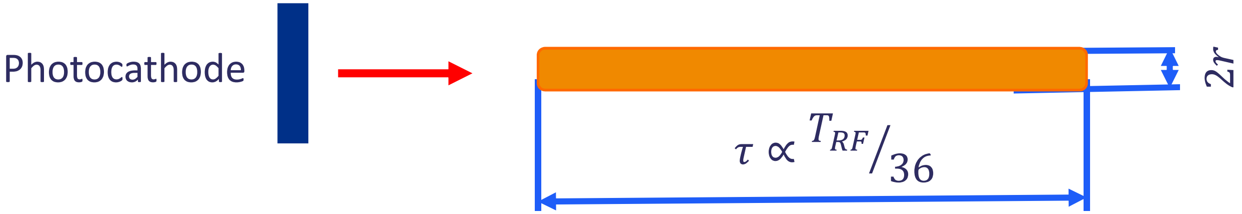
Emittance of the beam emitted from the photocathode in photoinjector is defined by laser beam transverse size and structure and Mean Transverse Energy (MTE) which is defined by property of the photocathode and laser pulse energy:

$$\varepsilon_{n,rms} \propto \frac{r}{2}\sqrt{\frac{MTE}{mc^2} + \frac{kT}{2mc^2}}$$

$$MTE = \frac{h\nu - \varphi_{eff}}{3}$$

at $h\nu - \varphi_{eff} \sim 1.0\ eV$, normalise RMS emittance at room temperature $\varepsilon_{n,rms} \sim 0.41r$

FEL injector typically operate with "cigar emission" when



For "cigar" emission $$r = \left(\frac{9Q}{\sqrt{2}\tau I_0}\right)^{2/3} \frac{mc^2}{eE_{emit}} \propto \frac{Q^{2/3}}{E_{emit}}$$

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

G. Shamuilov *et al.*, Appl. Phys. Lett. 113 204103 (2018)

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Photocathodes for RF photoinjectors

Material	Wavelength	Quantum Efficiency	Robustness	World Expertise	Application
High Work Function Metals (Cu, Mo, Nb)	UV	10^{-5}	High	High	NCRF high field guns
Te-based (Cs_2Te)	UV	0.05 – 0.1	Medium-High	High	NCRF high field guns
Low Work Function Metals (Mg)	UV	$10^{-4} – 10^{-3}$	??	Medium	Low Field SRF guns
Reduced Work Function Metal Oxides (MgO)	Blue	??	Medium-Low	Low	N/A
Sb-based (Cs_2KSb)	Green	0.05 – 0.1	Medium	High	Low/Medium field VHF/SRF guns
GaAs	IR-Green	0.001 – 0.4	Low	High	DC/Polarised guns

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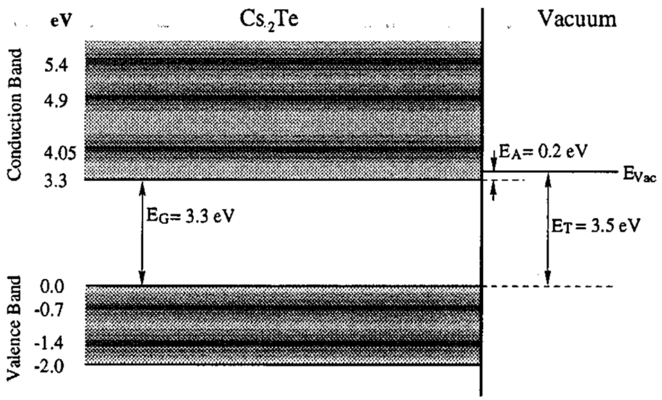
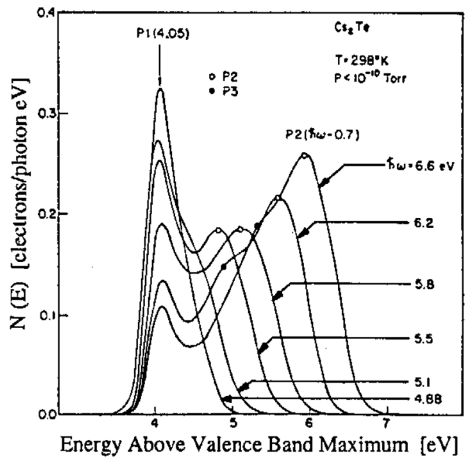
Photoemission from Cs_2Te – potential photocathode for CW XFELs





$$\varepsilon_{n,rms} = \frac{r}{2}\sqrt{\frac{2E_{kin}}{3m_0c^2}}$$

where

$$E_{kin} = E_f - E_G - E_A = 0.55\ eV$$

that gives

$$\varepsilon_{n,rms} = 0.85\sigma$$

Klaus Floettmann, “Notes on the thermal emittance of electrons emitted by Cesium-Telluride photo cathodes”, TESLA FEL-Report 1997-01

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Reduced Work Function Photocathodes: Ultra-thin Metal Oxide Films

Photocathode:

MgO on Ag(100)

- MgO film of around two monolayers reduced the WF by ~1 eV
- Spectral response shown up to 360 nm
  - 3rd harmonic of Nd:YVO_4 laser
- QE increase at 266 nm by a factor of eight

https://doi.org/10.1063/5.0124528

Courtesy L.B. Jones & Co

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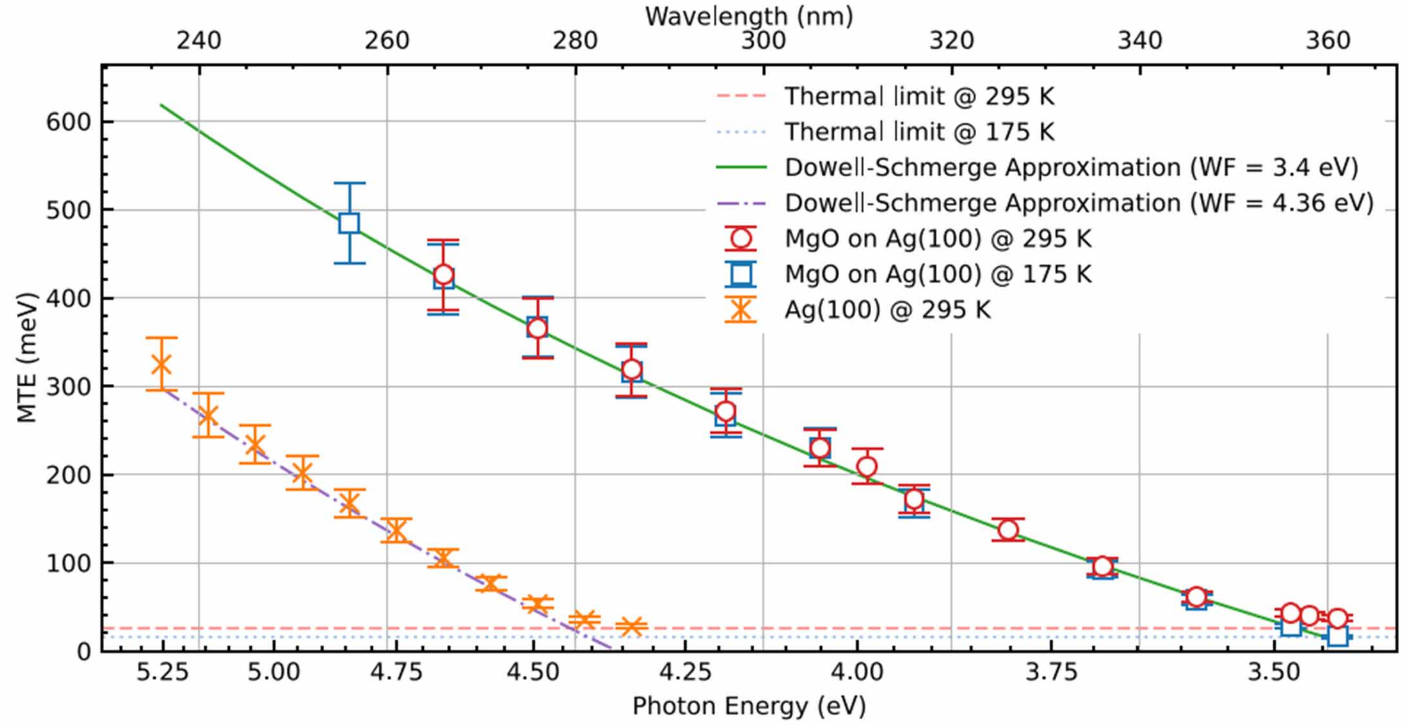
	WF [eV]	QE @ 266 nm
Ag(100)	4.36 ± 0.05	1.1×10^{-4}
MgO/Ag(100)	3.40 ± 0.10	9.2×10^{-4}



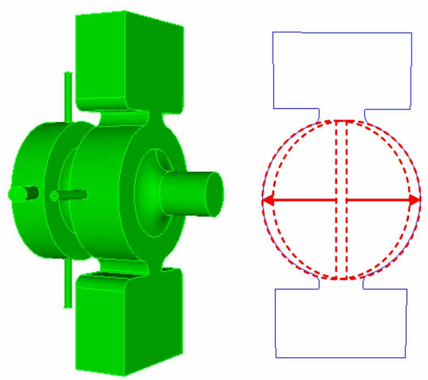
Beam acceleration in the gun

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

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

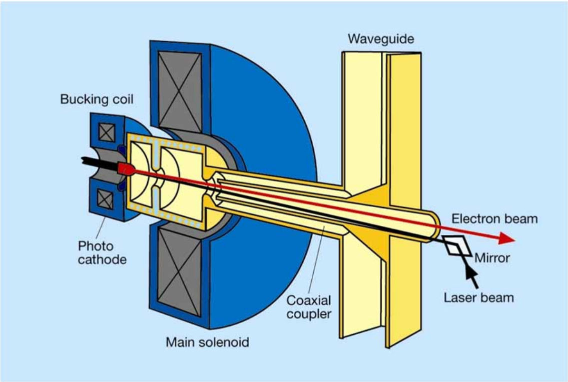
  - RF average and peak power dissipation
- Possible technologies for pulsed operation
  - High frequency (S-,C-,X- bands) NCRF guns
- Possible technologies for CW operation
  - DC photoinjectors
  - Normal Conductive RF photoinjectors with a frequency of about 200 MHz (VHF)
  - Superconducting RF photoinjectors
  - Thermionic injectors

RF guns of operational FELs

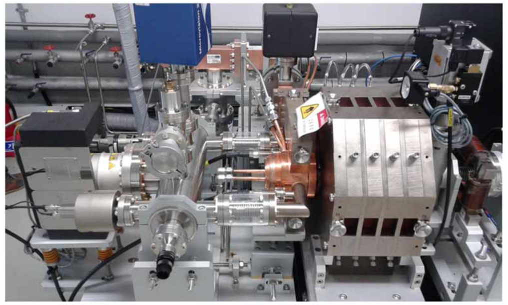


LCLS gun scheme

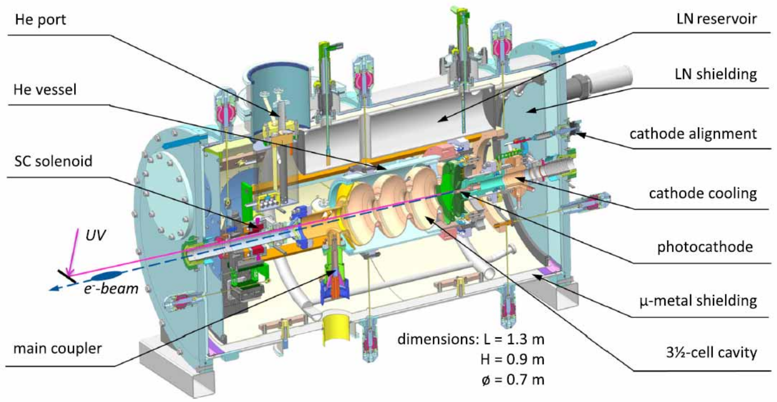
Facility	Technology	Number of cells	Operation mode	Bunch repetition rate, Hz	RF frequency, GHz	Cathode field, MV/m
LCLS	NCRF	1.6	Pulsed	120	2.856	115
SwissFEL	NCRF	2.6	Pulsed	100 (400)	2.856	100
PAL-FEL	NCRF	1.6	Pulsed	60	2.856	120
EuXFEL	NCRF	1.6	Train-Pulsed	10x2700	1.3	50-60
ELBE	SRF	3.5	CW	50000-250000	1.3	22



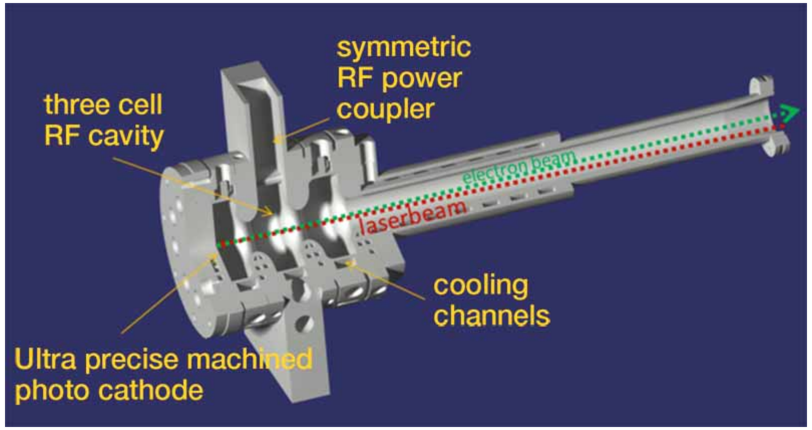
EUXFEL L-band gun



PAL-FEL gun



ELBE SRF gun



SwissFEL 2.6 cel gun

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Modern trends in the development of electron guns for XFELs

- Extra high cathode field high brightness pulsed photocathode guns
  - Increasing photocathode field as high as possible, typically higher than 120 MV/m
  - Development of the guns in S-, C- and X- bands
  - Cryogenic NCRF guns
  - Typically metal photocathodes
- High cathode field SRF CW photocathode guns
  - L-band TESLA type cavities
  - Operation at a field of 40-50 MV/m
  - Operation with low work function metal and/or Cs_2Te photocathodes
- Low cathode field CW SRF and NCRF photocathode gun
  - Operation at a cathode filed of 20-30 MV/m
  - Operation with low work function metal or alkali (Te and Sb) photocathode

Potential normalized slice emittance of the RF guns

Photocathode gun technology	Operation mode	Photoinjector operational frequency, MHz	Cathode field, MV/m	Emission pulse length, ps	Normalised beam emittance, nm·rad at bunch charge, pC**			
					20	50	100	300
DC*	CW	DC	10	149.34	28.1	51.8	82.3	171.1
Q-wave SRF	CW	112	20	248.02	10.0	18.5	29.3	61.0
Q-wavae NCRF	CW	186	20	149.34	14.1	25.9	41.1	85.6
Q-wave NCRF	CW	186	30	149.34	9.4	17.3	27.4	57.0
Q-wavae SRF	CW	217	30	128.01	10.4	19.1	30.4	63.2
L-band SRF	CW	1300	40	21.37	25.7	47.4	75.2	156.4
L-band NCRF	Train-pulsed	1300	60	21.37	17.1	31.6	50.1	104.3
S-band NCRF	Pulsed	3000	100	9.26	18.0	33.1	52.5	109.3
C-band NCRF	Pulsed	6000	200	4.63	14.3	26.3	41.7	86.7

* - injector with DC gun and 186 MHz buncher

** - injection at maximum field

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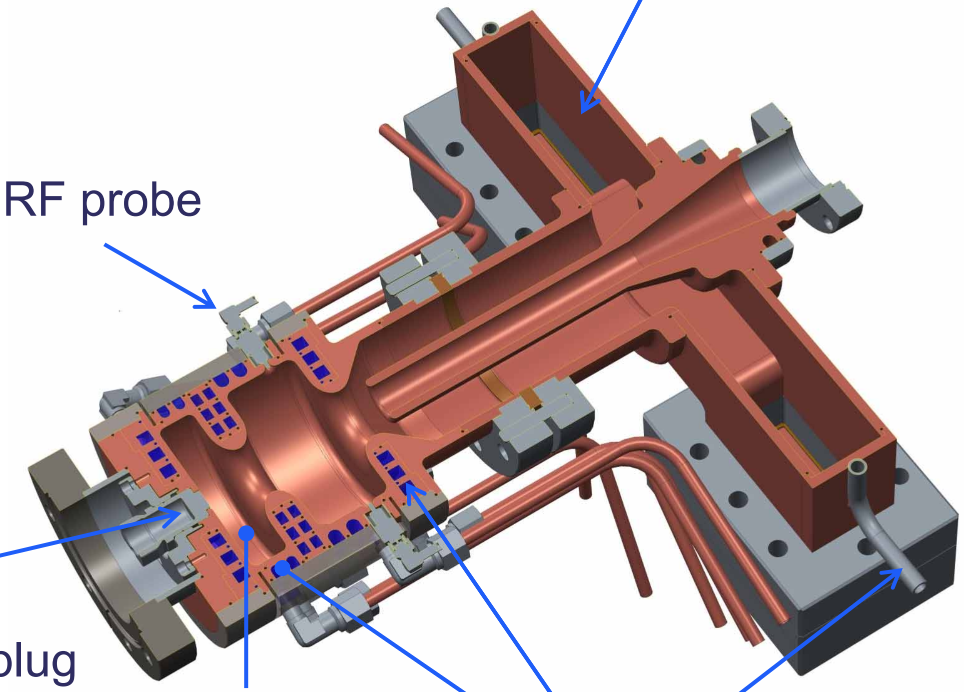
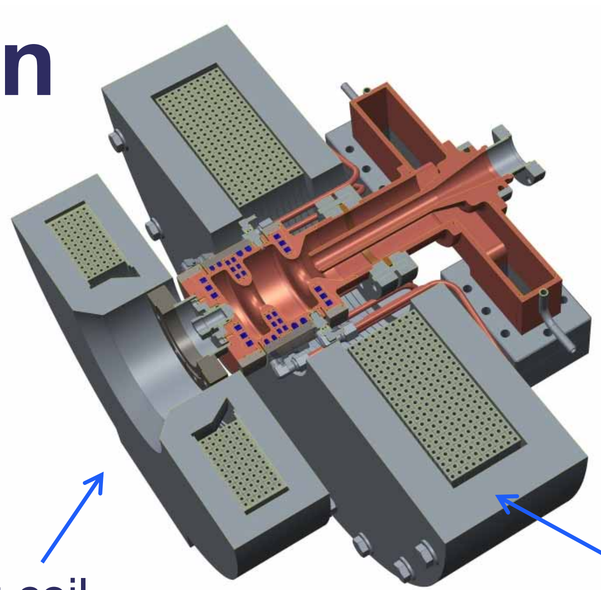
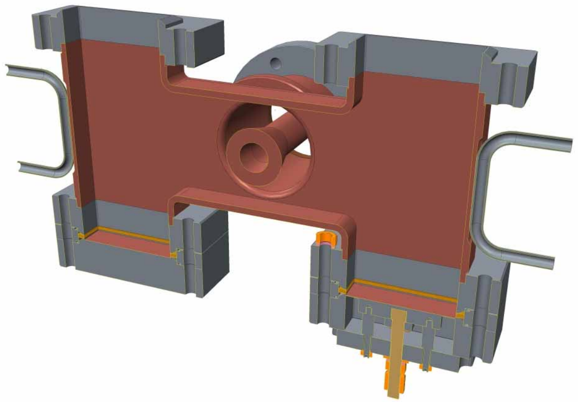
Daresbury 400 Hz High Repetition Rate Gun (HRRG)







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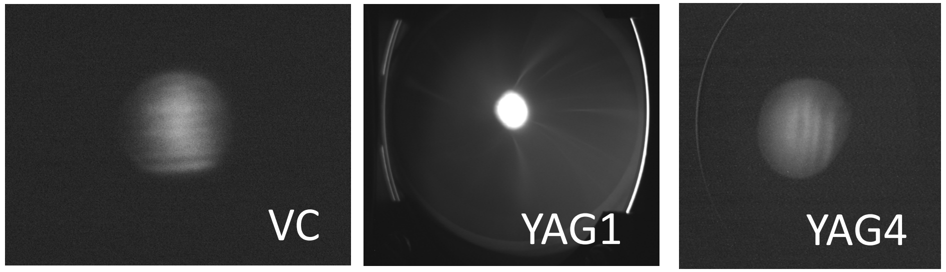
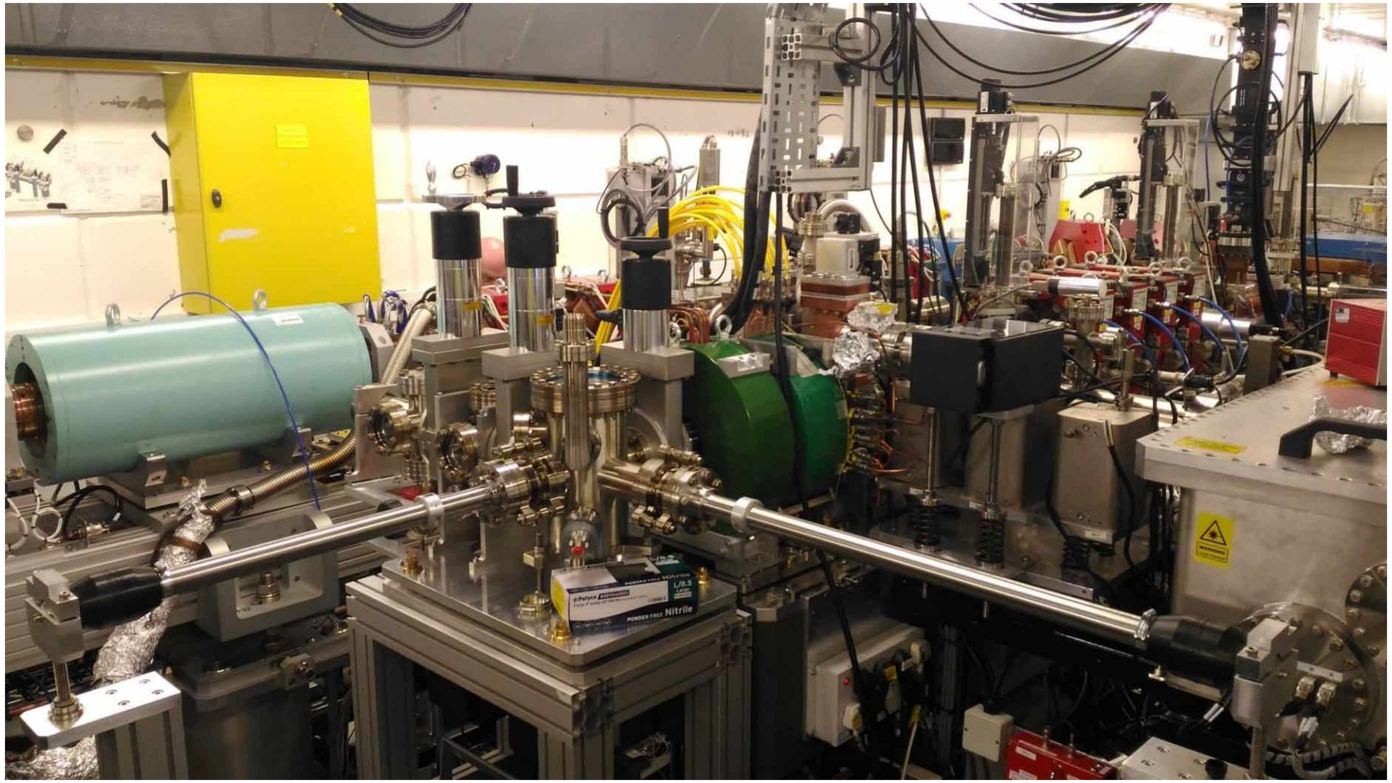
HRRG commissioning status

- HRRG has been recently commissioned at a field of 70 MV/m and demonstrated 100 pC bunches following with a repetition rate of 100 Hz.

- The beam was delivered by hybrid Cu-Mo photocathode with QE=$2.2 \cdot 10^{-4}$





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NCRF VHF photocathode guns

- Under development for LCLS-II and SHINE FELs.
- Most recent results have been presented in the presentations
  - MO3A1 – Dong Wang, “Progress on SHINE machine”
  - MO3A3 – Daniel Gonnella, “Status LCLS-II Superconducting linac” where first LCLS-II lasing was reported

Our congratulations to the LCLS-II team!!!

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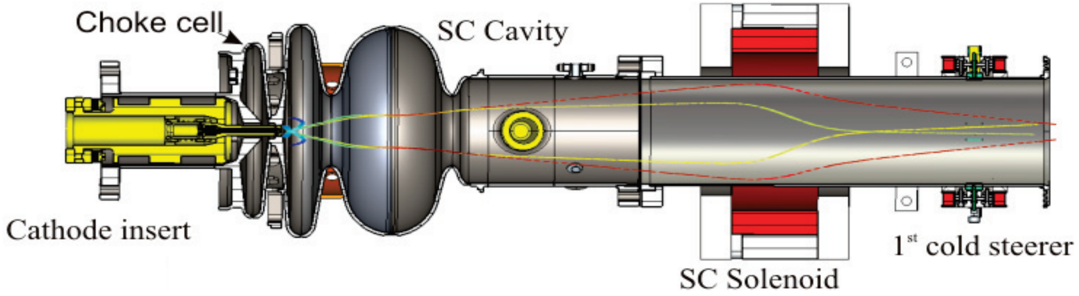
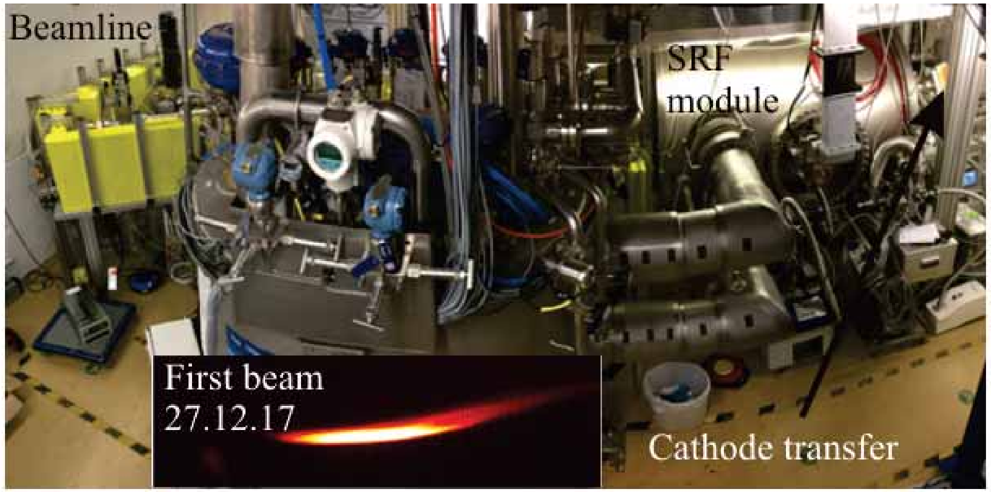
Rev. Sci. Instrum. **90**, 033304 (2019)

SRF L-band photocathode gun, HZB

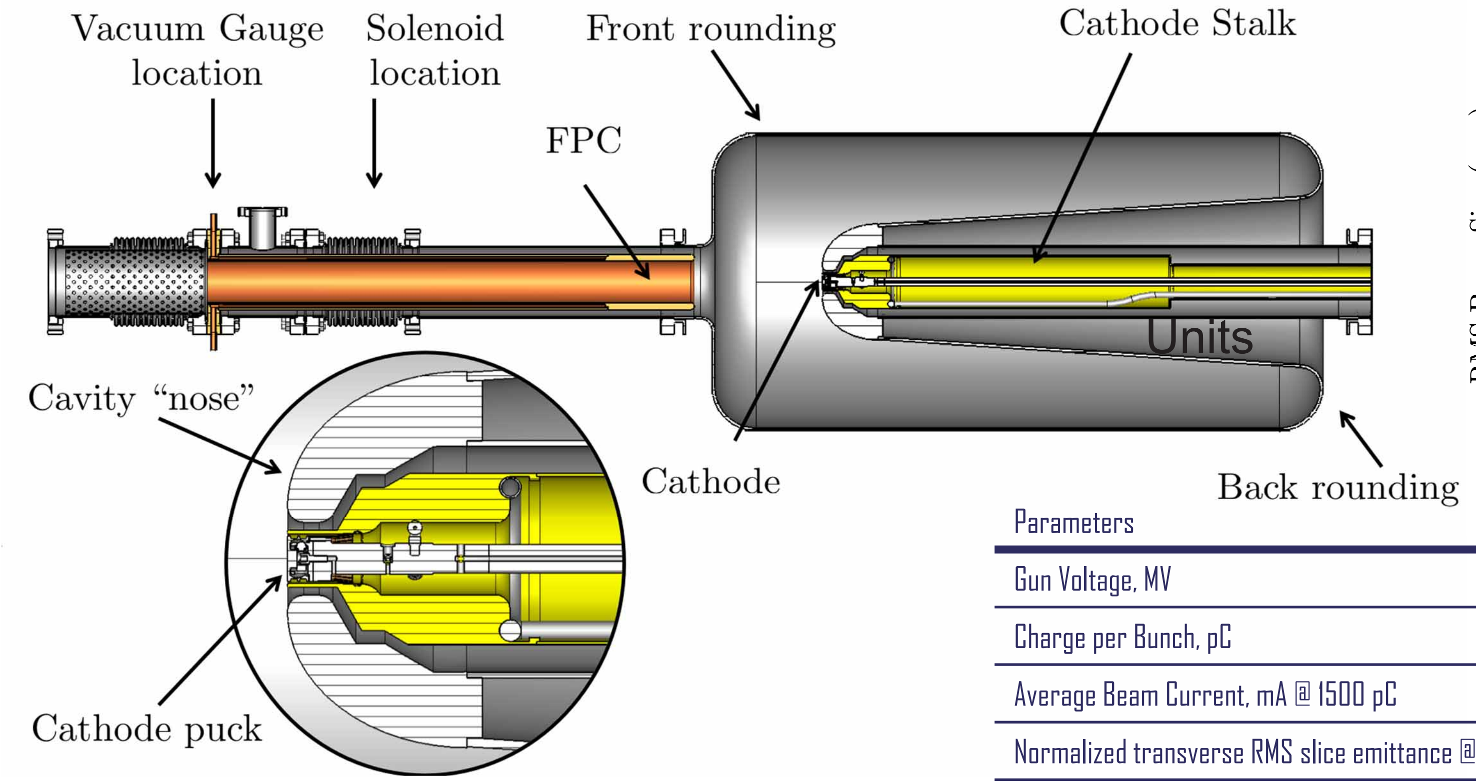




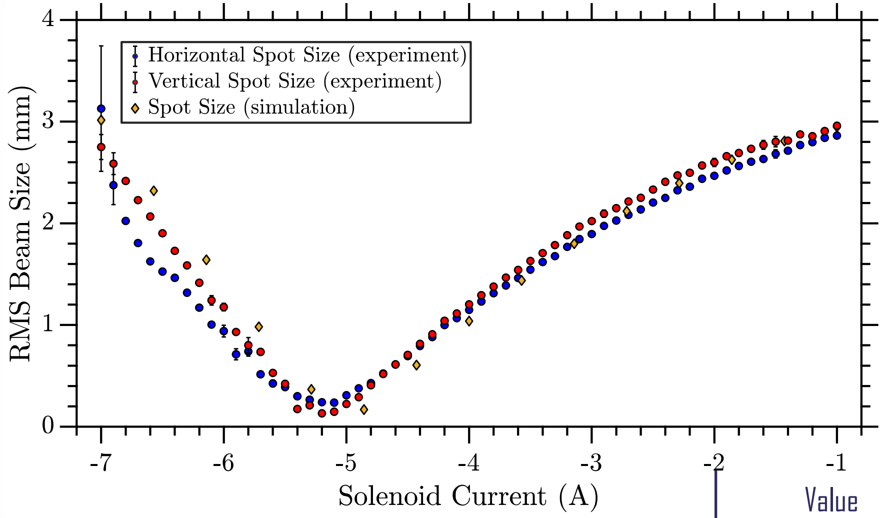
doi:10.18429/JACoW-IPAC2018-TUPML053

Cavities for operation with Cs_2KSb photocathodes

SRF Quarter Wave photocathode gun, BNL



Operates with Cs_2KSb photocathodes



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

DOI: 10.1103/PhysRevLett.124.244801

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Wisconsin SRF gun. Design

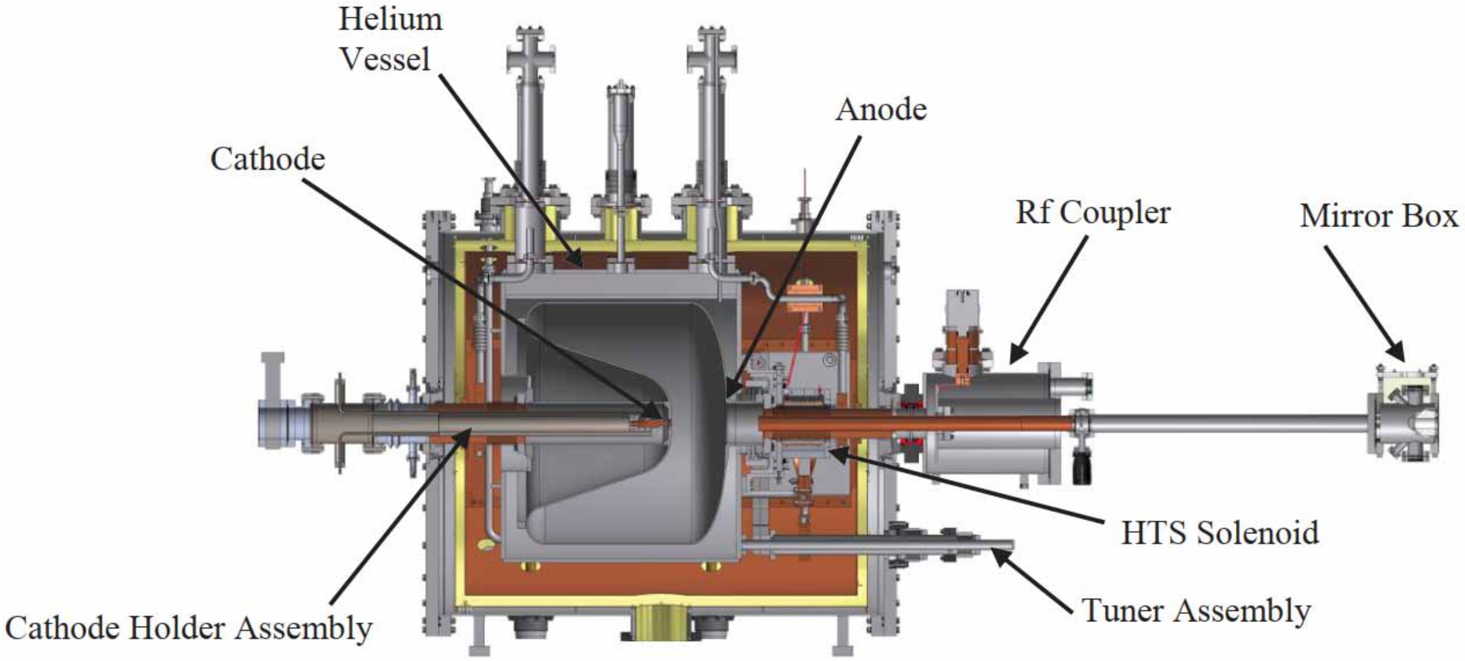
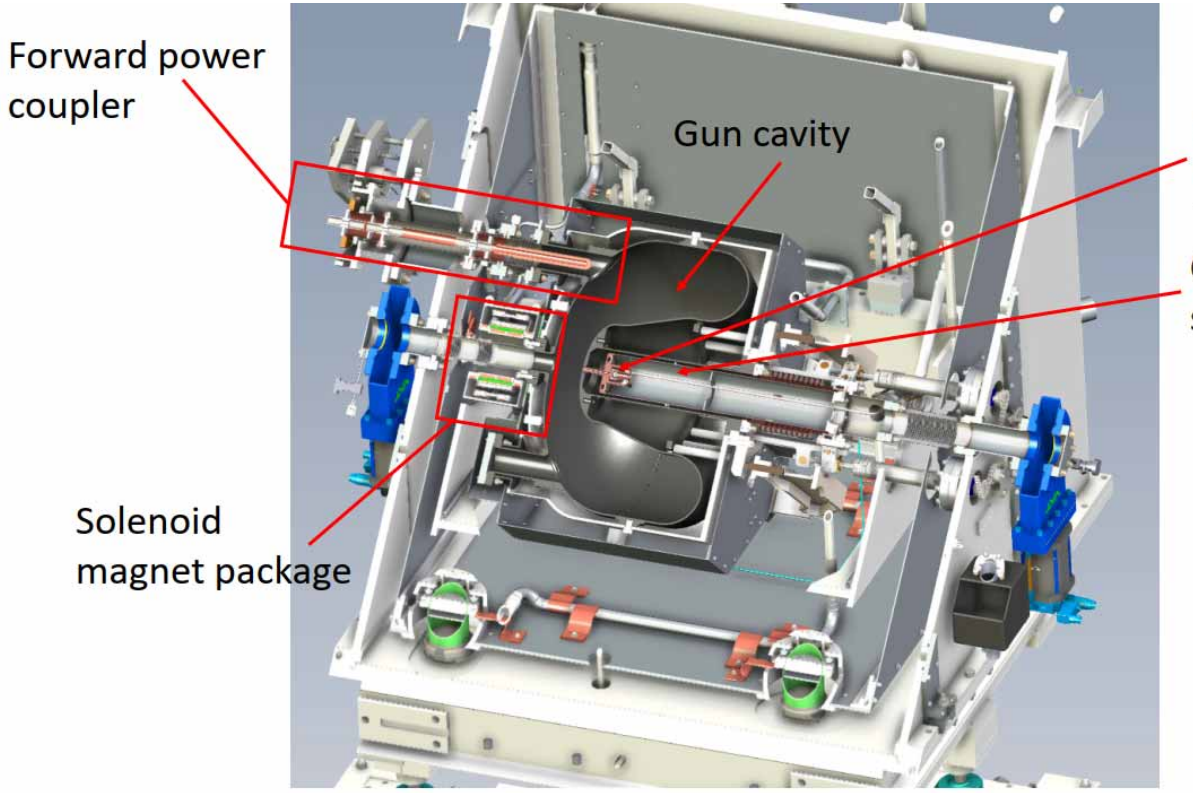


Table 1: Cavity Parameters

Parameter	Calc Value	Units
Temperature	4.2	K
Cavity Frequency	199.6	MHz
Unloaded Q (Q0), Nominal	3×10^9	
Surface electric field, Pk	53	MV/m
Integrated Electric Field	3.96	MeV
Dynamic heat loss at E_{PK}	39.2	Watts
Static Heat Loss at 4.2K	7.5	Watts

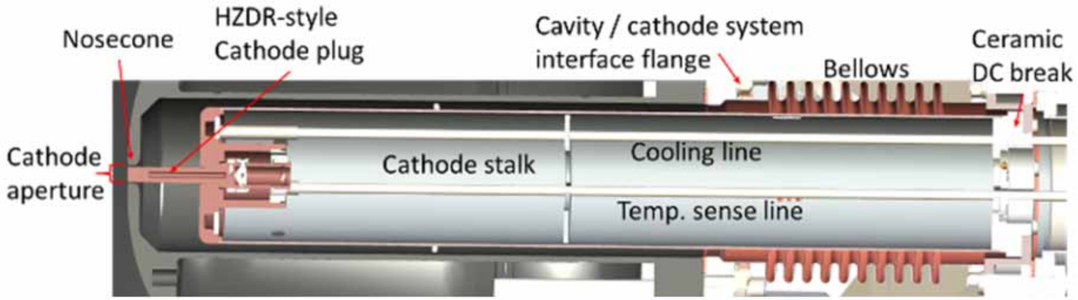
R. Legg et al. IPAC2012, MOPPP045

Quarter wave cavity SRF gun



Design parameters for the gun include:

- 187.5 MHz (1.3 GHz / 7)
- Field on cathode > 30 MV/m
- Beam energy > 1.6 MeV (kinetic)
- Cathode lifetime > 1 week (> 1 month target)
- Field emission / dark current < 10 nA @ E_{cath} = 30 MV/m



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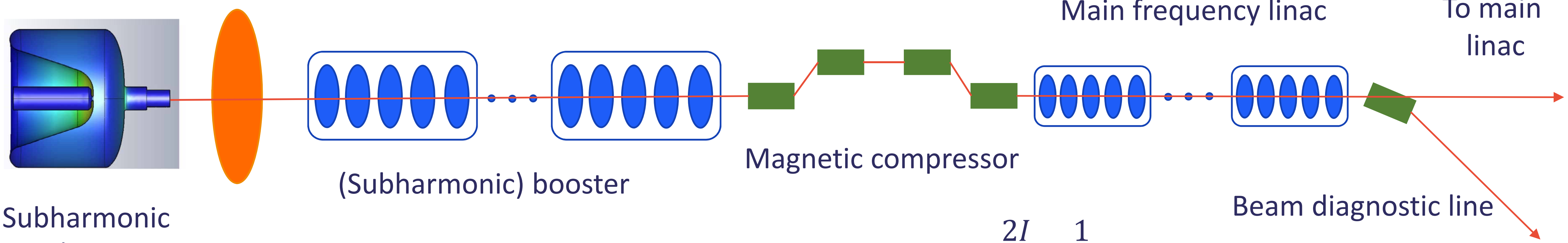
J.W. Lewellen, NAPAC2022, WEPA03

Concept of UK XFEL Low Energy Beamline



$$\gamma = \frac{2I}{I_A} \cdot \frac{1}{\gamma' \varepsilon_n}$$

For $I = 15\,A, \varepsilon_n = 0.078\,mm \cdot mrad\ and\ \gamma' = 39\ ^{1}/_{m}\ (20\ ^{MeV}/_{m})$

$$\gamma = 580, E = 296\,MeV$$

Some RF linearization and laser heater may be required

See also TU4P12 “Injection into XFELS, a review of trends and challenges”, Can Davut *et al.*

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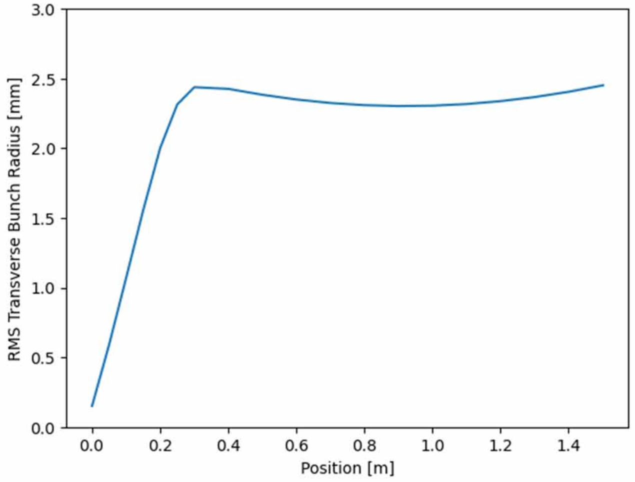
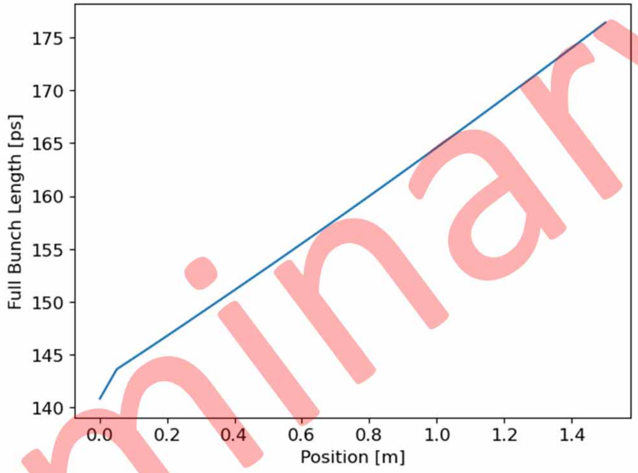
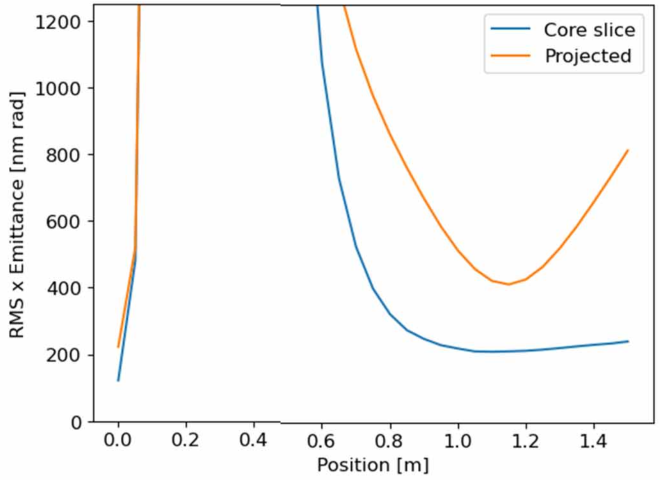
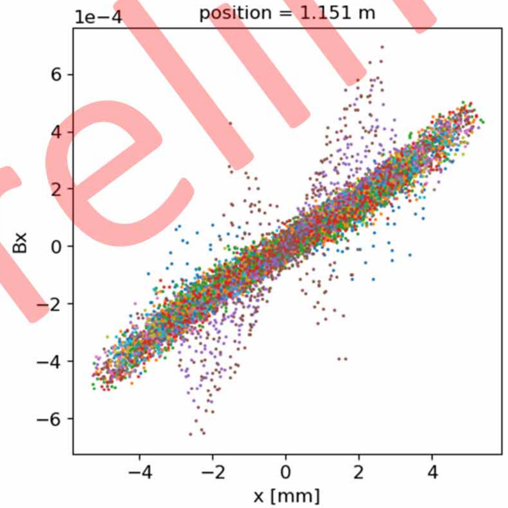
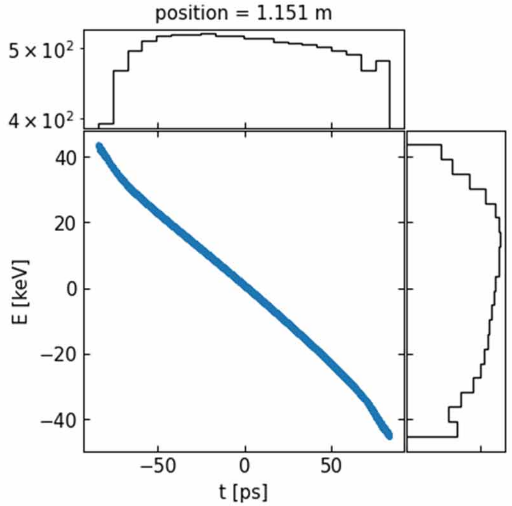
GPT simulation of 300 pC beam in the 30 MV/m 186 MHz VHF gun











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Courtesy Suzanna Percival

Conclusions

- New XFELs projects are dedicated for generation of photons with an energy of 20keV and higher that requires extra high brightness electron beams to limit energy of the drive linacs
- Some of the project including UKXFEL also require repetition rate of the photon pulses of 1 MHz and higher
- Existing injector technologies do not allow to meet these two requirements simultaneously. So photoinjector R&D should be concentrated on two directions:
- Development of extra high brightness high field photocathode guns for operation in pulsed mode
- Development of high brightness high repetition rate injector for operation in CW mode. That may be reached by two ways
  - Development of high frequency medium field SRF photocathode guns. That requires
    - Design of RF cavities and photocathode infrastructure
    - Development of low dark current photocathodes which are able to operate in SRF gun environment and deliver mA scale average current
  - Development of NCRF and/or SRF VHF low field photocathode guns
    - In case of use SRF cavities resolve the same photocathode problem as for high frequency SRF guns
    - Development of the emittance preserving compression technologies which would allow for delivering high brightness beam into the main drive linac

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