Status and Perspectives of Photo Injector Developments for High Brightness Beams

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Motivation and Content

Realization depends on key parameters:

- Introduction**

- DC electron sources
- NC RF guns
- SC RF guns
- generic injector layout

- operation mode: pulsed or CW
 - single bunch charge
 - time structure of the beam
 - norm. transverse emittance
 - long. phase space allows further compression
- } average current

- Different Photo Injectors for Different Projects:**

- **high average current electron sources ($\langle A \rangle \geq 1$ mA)**

- DC guns from Cornell data sim.
- NC RF gun from Boeing data
- SC RF gun developments at Rossendorf data sim.
- DC, NC + SC RF gun developments from BNL, JLab, and LANL with AES data sim.

- **medium average current electron sources (1 mA $> \langle A \rangle > 1$ μ A)**

- NC RF gun at ELSA data
- NC RF gun for VUV-FEL and European XFEL data sim.
- NC and SC RF gun for BESSY sim.

- **low average current electron sources ($\langle A \rangle \leq 1$ μ A)**

- NC RF gun from SHI+FESTA data
- NC RF gun injector for SPARC sim.
- NC RF gun developments for LCLS sim.
- Waterbags and cold atoms from Eindhoven sim.
- some other developments [e.g. LEG at PSI (field emission cathode)] sim.

- Summary**

DC Photo Electron Guns

- Advantages

- good vacuum
 - NEA cathodes (GaAs),
 - low thermal emittance
- lots of operating experience

500-750 kV photo emission gun with preparation, cleaning, and load lock chambers

courtesy of Ch. Sinclair, Cornell

- Disadvantages

- low accelerating gradient at cathode
 - long bunches → buncher cavity
- low beam energy after the source → booster

- Advantages

- high accel. gradient at cathode + good space charge compensation → high bunch charge
- medium beam energy
- lots of operating experience, emittance record

- Disadvantages

- medium vacuum conditions
- water cooling limits average RF power → broad range of average currents (RF frequency)

SC RF Guns

- Advantages

- high RF duty cycle, CW
→ high av. beam power
- good vacuum condition
- medium beam energy

Courtesy of J. Teichert, FZR

- Disadvantages

- high accel. gradient at cathode, but limited space charge compensation → limited bunch charge
BUT: new developments are on the way
- limited operation experience

e.g. VUV-FEL injector:

Simulation of 'upgraded VUV-FEL'

ASTRA Simulation parameters:

Q = 1 nC

Laser	XYRMS	0.53	mm
	FWHM, Lt	20	ps
	rise time, rt	2	ps
	(thermal) LE	0.55	eV
MaxE	Gun	60	MV/m
	ACC1 (1st 1/2)	25.8	MV/m
	ACC1(2nd 1/2)	40	MV/m
Phi	Gun	-2.0	deg
	ACC1 (1st 1/2)	-15.3	deg
	ACC1(2nd 1/2)	-15.3	deg
Booster	(begin) z0	2.8	m
Solenoid	MaxB_main	-0.2253	T
	MaxB_buck	0.0112	T
	S_pos_main	0.276	m
ASTRA	particles	200k	
E-beam (z=20m)	Ek	128	MeV
	dp/p	1.45	%
	Xemit	0.81	mm mrd
	Zrms	1.85	mm

DC Guns @ JLab + Cornell

	JLab, exp. results
operation mode	
pulsed / CW	CW
single bunch charge	122 pC
single bunch rep rate	75 MHz
DC voltage / gap	350 kV / 10.57 cm
average current	9.1 mA
norm. trans. emittance (rms)	~ 8-10 mm mrad @ 10 MeV

DC Guns @ JLab + Cornell

	JLab, exp. results	Cornell, goal parameters	
operation mode		low charge	high charge
pulsed / CW	CW	CW	CW
single bunch charge	122 pC	77 pC	1 nC
single bunch rep rate	75 MHz	1300 MHz	1 – 10 MHz
DC voltage / gap	350 kV / 10.57 cm	~ 600 kV / 5 cm	~ 800 kV / 5 cm
average current	9.1 mA	100 mA	1 mA
norm. trans. emittance (rms)	~ 8-10 mm mrad @ 10 MeV	old: < 1 mm mrad, new: 0.1 mm mrad @ 13 MeV	new: ~ 1 mm mrad @ 13 MeV

old design for ERL-based X-ray source at Cornell:

see
I. Bazarov and C. Sinclair,
PAC2003, pp. 2062 - 2064

- 22 decision variables, incorporating all physical constraints (e.g. element field strengths and locations, SRF phases, transverse and longitudinal laser profiles, bunch charge, cathode thermal energy)
- ASTRA used for tracking
- optimization for 80 pC (max. av. brilliance) and 800 pC (high photon flux per pulse)

Results for 800 pC:

opt. laser parameters:

1.6 mm rms spot size
17 ps rms pulse duration

Parameter	old design, PAC2003	This work	Units
Charge	80	80	pC
Laser spot size (rms)	0.6	0.3	mm
Laser pulse duration (rms)	20	11	ps
dc gun voltage	500	750	kV
Buncher voltage	116	126	kV
SRF cavity 1 gradient	9.8	5.5	MV/m
SRF cavities 2–5 gradient	7.2	10.6	MV/m
SRF cavity 1 phase	10	43	°
Solenoid 1 peak field	0.058	0.077	T
Solenoid 2 peak field	0.040	0.043	T
Solenoid 1 position	0.29	0.26	m
Solenoid 2 position	1.00	1.12	m
Buncher position	0.80	0.57	m
SRF cavity 1 position	1.80	1.90	m
Transverse emittance (rms)	0.82	0.14	mm mrad
Bunch length (rms)	0.80	0.78	mm
Longitudinal emittance (rms)	8.7	6.2	mm keV
Kinetic energy	10.6	12.6	MeV

Results for 80 pC

→ impressive results
for 80 and 800 pC

→ shows importance
and benefit of
multiv. optimization

Experimental Schedule:

- first electrons from gun in Dec. 2005
- mid 2006: laser for 1.3 GHz operation
- early 2008: injector cryomodule ready

- **possible problems, e.g.:**
 - temporal response of GaAs cathode might degrade temporal electron bunch profile at emission
 - desired gun voltage of 500-750 kV is above presently achieved values (→ geometry changes, coatings)
 - beam energy still low, needs proper matching of following accelerator
- possible source for polarized electrons (→ cathode + laser)

NC RF Gun @ Boeing

parameters measured in 1992:

pulsed / CW	pulsed
single bunch charge	1 – 7 nC
single bunch rep rate	27 MHz
length of bunch train	8.3 ms
bunch train rep rate	30 Hz
average current	6.7 – 47 mA
norm. trans. emittance (rms)	5 – 10 mm mrad @ 5 MeV
rf frequency	433 MHz

duty cycle: 25 %

RF power: **600 kW**

re-entrant design

→ 25 MV/m peak field @ cathode

record average current !!!

view from cathode side

gun type	½ cell gun results obtained
operation mode	
pulsed / CW	CW
single bunch charge	1-20 pC
single bunch rep rate	26 MHz
length of bunch train	-
bunch train rep rate	-
average current	≤ 130 μA
norm. trans. emittance (rms)	2.5 mm mrad @ 4 pC, 900 keV
rf frequency	1.3 GHz

- **NC Cs₂Te cathode in SC gun**
→ high QE → relax requirements on laser system
- no Q degradation observed over 7 weeks (5h/d)

gun type	3.4 cell gun, Goals	
operation mode	ELBE	high charge
pulsed / CW	CW	CW
single bunch charge	77 pC	1 nC
single bunch rep rate	13 MHz	1 MHz
average current	1 mA	1 mA
norm. trans. emittance (rms)	1.5 mm mrad @ 9.5 MeV	2.5 mm mrad @ 9.5 MeV
rf frequency	1.3 GHz	1.3 GHz

With magnetic mode:

$\Rightarrow \epsilon_n$ (1nC, 8.8MeV)
= **0.8-1.0 mm mrad**
dep. on B_{TE} phase
(no therm. emittance)

Status:

- two 3.4 cell guns tuned
- first beam autumn 2006

Source Developments with AES

gun type	1/2, SC, all Ni	1/2, SC, NC cath.	DC + SRF boost.	2 1/2, NC RF, CW
collabor. partners	BNL, data	BNL, design	JLab, design	LANL, design
pulsed / CW	the QE was measured to be	CW	CW	CW
single bunch charge / nC		1.42 / 10	0.133	1.0
single bunch rep rate / MHz		351.87 / 10	748.5	100
average current / mA		500 / 100	100	100
norm. trans. emittance (rms, geom. av.) / mm mrad	2 · 10 ⁻⁶ @266nm 1 · 10 ⁻⁵ @248nm	2.4 @ 2 MeV / 11.1 @ 3.2 MeV	1.2 @ 7.7 MeV	4 @ 2 MeV
rf frequency / MHz	1300	703.75	booster: 748.5	700

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- diamond amplifier cathode:

→ I. Ben-Zvi at Erice workshop

- more on SC photo injectors:

→ J. Sekutovicz at Erice workshop

→ J. Teichert at Nanobeams 2005

Emittances evolution for 1.4 nC bunch

- for ERL
- in final design
- first beam 2007

Source Developments with AES

gun type	1/2, SC, all Ni	1/2, SC, NC cath.	DC + SRF boost.	2 1/2, NC RF, CW
collabor. partners	BNL, data	BNL, design	JLab, design	LANL, design
pulsed / CW	the QE was measured to be $2 \cdot 10^{-6}$ @266nm $1 \cdot 10^{-5}$ @248nm	CW	CW	CW
single bunch charge / nC		1.42 / 10	0.133	1.0
single bunch rep rate / MHz		351.87 / 10	748.5	100
average current / mA		500 / 100	100	100
norm. trans. emittance (rms, geom. av.) / mm mrad		2.4 @ 2 MeV / 11.1 @ 3.2 MeV	1.2 @ 7.7 MeV	4 @ 2 MeV
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norm. trans. emittance (rms, geom. av.) / mm mrad		2.4 @ 2 MeV / 11.1 @ 3.2 MeV	1.2 @ 7.7 MeV	4 @ 2 MeV
rf frequency / MHz	1300	703.75	booster: 748.5	700

average power: $\leq$ **720 kW**

gun in fabrication,
high power test in 2006

Emittance from ELSA@CEA

pulsed / CW	pulsed
single bunch charge	1 – 3 nC
single bunch rep rate	72 MHz
length of bunch train	$\leq 140 \mu\text{s}$
bunch train rep rate	1 – 10 Hz
average current	$\leq 300 \mu\text{A}$
norm. trans. emittance (rms)	$\sim 1 - 1.5 \text{ mm mrad}$ @ 19 MeV
rf frequency	144 / 433 MHz

Goal parameters:	VUV-FEL	Europ. XFEL
pulsed / CW	pulsed	pulsed
single bunch charge	1 nC	1 nC
single bunch rep rate	1 – 9 MHz	5 MHz
length of bunch train	$\leq 800 \mu\text{s}$	$\leq 650 \mu\text{s}$
bunch train rep rate	1 – 10 Hz	10 Hz
average current	$\leq 72 \mu\text{A}$	$\leq 32.5 \mu\text{A}$
norm. trans. emittance (rms)	2 mm mrad @ 1 GeV	1.4 mm mrad @ 20 GeV
rf frequency	1.3 GHz	1.3 GHz

laser profiles:

FWHM $\approx 19\text{-}24 \text{ ps}$
rise/fall $\approx 7\text{-}9 \text{ ps}$

$\sigma_x = 0.57 \pm 0.02 \text{ mm}$
 $\sigma_y = 0.58 \pm 0.02 \text{ mm}$

Goal parameters:	VUV-FEL	Europ. XFEL
pulsed / CW	pulsed	pulsed
single bunch charge	1 nC	1 nC
single bunch rep rate	1 – 9 MHz	5 MHz
length of bunch train	$\leq 800 \mu\text{s}$	$\leq 650 \mu\text{s}$
bunch train rep rate	1 – 10 Hz	10 Hz
average current	$\leq 72 \mu\text{A}$	$\leq 32.5 \mu\text{A}$
norm. trans. emittance (rms)	2 mm mrad @ 1 GeV	1.4 mm mrad @ 20 GeV
rf frequency	1.3 GHz	1.3 GHz

long RF pulse:

long laser pulse train:

measured @ PITZ:

$p = 5.2 \text{ MeV/c}$

$Q = 1 \text{ nC}$

$\Phi = \Phi_m$

$I_{\text{buck}} = I_{\text{main}} * 0.075$

measured @ VUV-FEL:

$p = 127 \text{ MeV/c}$

$Q = 1 \text{ nC}$

- regularly obtain **2.1 mm mrad** (100% rms projected emittance)
- minimum **1.1 mm mrad** (90% rms projected emittance)

Thermal Emittance Measurements at PITZ:

cathode no. 43,
Nov.2004, QE ~ 3%

cathode no. 61,
Apr.2004, QE ~ 1%

ϵ_{th} depends on
individual cathode
and its surface
chemistry

$\rightarrow \epsilon_{\text{th}} = \epsilon_{\text{th}}(t)$

**$\rightarrow$ more cathode
studies needed !**

Upgrade of PITZ → PITZ2

- Goals:**
- reach XFEL requirements: **0.9 mm mrad @ 1 nC from injector:**
 - increase RF field on photo-cathode
 - improve laser system (mainly rise/fall time ≤ 2 ps)
 - study **emittance conservation principle:**
 - booster cavity (preliminary: TESLA booster, final: CDS booster)
 - new diagnostics beam line

Layout:

preliminary booster: TESLA prototype

in operation: gun + booster $\rightarrow$ 13.7 MeV/c

first **preliminary** emittance results
(not optimized yet !)

$p = 12.8 \text{ MeV/c}$, $Q = 1 \text{ nC}$,
 $\Phi_{\text{gun}} = \Phi_{\text{max}_p}$, $\Phi_{\text{booster}} = \Phi_{\text{min}_{dp}}$

Outlook:

- new gun cavity (#3) in Dec. 2005
- final booster in autumn 2006
- new laser system in spring 2007

BESSY FEL Injector Design

operation mode	phase 1, NC gun
pulsed / CW	pulsed
single bunch charge	2.5 nC
single bunch rep rate	333 kHz
length of bunch train	3 bunches
bunch train rep rate	1 kHz
average current	7.5 μA
norm. trans. emittance (rms), center slice at 2.3 GeV	1.5 mm mrad
rf frequency	1.3 GHz

NC gun:

- fabricated
- power test @ PITZ in 2006

BESSY FEL Injector Design

operation mode	phase 1, NC gun	phase 2, SC gun
pulsed / CW	pulsed	CW
single bunch charge	2.5 nC	2.5 nC
single bunch rep rate	333 kHz	> 25 kHz
length of bunch train	3 bunches	-
bunch train rep rate	1 kHz	-
average current	7.5 μA	> 62.5 μA
norm. trans. emittance (rms), center slice at 2.3 GeV	1.5 mm mrad	1.5 mm mrad
rf frequency	1.3 GHz	1.3 GHz

NC gun:

- fabricated
- power test @ PITZ in 2006

SC gun:

- 1.625 cell design available
- participate in FZR 3.4 cell tests

Emittance Record from SHI+FESTA

pulsed / CW	pulsed
single bunch charge	0.25 – 1.2 nC
single bunch rep rate	10 Hz
average current	2.5 – 12 nA
norm. horiz. emittance (rms)	~ 0.8 – 1.4 mm mrad @ 14 MeV

- 1.6 cell S-band gun (→ 4 MeV) + 70 cm SW linac (→ **14 MeV**)
- **Ti:Sapphire** laser system (→ **50 fs long pulses** at 800 nm) + **pulse shaping** (e.g. gratings + **liquid crystal** spatial light mod.)
- temporal shape of laser pulses: (x-ray streak camera, resolution: ~2 ps)

rise / decay
time: 1.5 ps,
limited by
streak cam.

Methode: quad scan @ 14 MeV

(gaussian fit to background subtracted signal)

$$\varepsilon_n = \sqrt{(a' Q)^2 + b'^2}$$

	a'	$b' = \sqrt{\varepsilon_{rf}^2 + \varepsilon_{th}^2}$
	$\pi\text{mm-mrad/nC}$	$\pi\text{mm-mrad}$
Gaussian(9ps)	1.85 ± 0.13	0.83 ± 0.05
Square (9ps)	0.92 ± 0.05	0.81 ± 0.03

- transverse laser distributions: (@cathode)

For 1 nC:
 $\varepsilon_n \approx 1.2 \text{ mm mrad}$

gun type	1.6 cell gun from UCLA
design parameters:	
pulsed / CW	pulsed
single bunch charge	1.1 nC
single bunch rep rate	1-10 Hz
average current	1.1 – 11 nA
norm. trans. emittance (rms)	< 2 mm mrad @ 155 MeV
rf frequency	2.856 GHz

$Q=1.1$ nC, pulse length (FWHM) = 10 psec, rise time=1 psec

Max. slice
current=110 A

Current ≥ 100 A
in 54% beam

Projected
emittance= 0.75
mm mrad

gun type	1.6 cell gun from UCLA
design parameters:	
pulsed / CW	pulsed
single bunch charge	1.1 nC
single bunch rep rate	1-10 Hz
average current	1.1 – 11 nA
norm. trans. emittance (rms)	< 1 mm mrad @ 155 MeV
rf frequency	2.856 GHz

Tests @PITZ:

Status:

- E-meter tested at PITZ → back at Frascati
- full SPARC facility under installation
- first beam through E-meter at SPARC beginning of 2006

pulsed / CW	pulsed
single bunch charge	1.0 / 0.2 nC
single bunch rep rate	120 Hz
average current	120 / 24 nA
norm. trans. emittance (rms, slice)	1.0 / 0.8 mm mrad @ 135 MeV
rf frequency	2856 MHz

modified UCLA/BNL/SLAC 1.6 cell S-band gun:

- larger mode separation ($3.5 \rightarrow 15$ MHz)
 - larger iris radius, reduced iris surface field
 - dual rf feed, z coupling, racetrack shape
 - field probes in both cells
 - increased cooling channels
 - klystron pulse shaping $\rightarrow$ reduced dissipated power
- $\rightarrow$ improved emittance and stability**

In-Situ Hydrogen Beam Cleaning of Cathode Surface

Eindhoven: Waterbags + Cold Atoms

pulsed / CW	pulsed
single bunch charge	~ 10 pC
single bunch rep rate	1 kHz
average current	~ 10 nA
norm. emittance (rms)	~ 0.1 mm mrad

Status:

- first setup under installation
- results for 30 kV switching in 2006

- e.g.
- Argonne (e.g. planar focussing cathode → J. Lewellen @ FEL2005)
 - AES (11.4 GHz, symmetric, NC RF gun, design: ~1 mm mrad @ 1 nC, 10 nA)
 - [SPring8 (special thermal emission injector for SCSS) → T. Shintake @ Nanobeams2005]
 - [PSI (e.g. field emission cathode + diode acceleration + RF cavity)]

LEG @ PSI, design parameters:	
single bunch charge	0.2 nC
single bunch rep rate	10 Hz
average current	2 nA
norm. trans. emittance (rms)	< 0.1 mm mrad

**Double Gated
Field Emitter Arrays**
 $\varnothing < 1\text{mm}$, 50'000 Tips

FEA =
Large Beam Diameter
+ Low Divergence

Other Developments @

- e.g.
- Argonne (e.g. planar focussing cathode → J. Lewellen @ FEL2005)
 - AES (11.4 GHz, symmetric, NC RF gun, design: ~1 mm mrad @ 1 nC, 10 nA)
 - [SPring8 (special thermal emission injector for SCSS) → T. Shintake @ Nanobeams2005]
 - [PSI (e.g. field emission cathode + diode acceleration + RF cavity)]

LEG @ PSI, design parameters:	
single bunch charge	0.2 nC
single bunch rep rate	10 Hz
average current	2 nA
norm. trans. emittance (rms)	< 0.1 mm mrad

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Summary

- Lots of different developments with photoinjectors fill up a **large parameter space on beam quality, time structure** of the beam and **average current**.
- Simulations **predict very good performance of all three basic photo injector types** (plus hybrids).
- **Experimental progress** is visible: on subsystems (guns, laser, diagnostics) and on measured beam quality.
- P. O'Shea, ICFA workshop @ UCLA in 1999:
 ~ **“Get 1 μm @ 1 nC !!!”**
 → **still to be done experimentally !!!**
 → **ways to reach this are defined.**
- More research on **emission process** ($\rightarrow \epsilon_{\text{th}}$) gets important.