Scouting in the Direction of an RF Gun for CEPC

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IHEP

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Motivation.

Ø Problem was found for the timing structure @Z

- According to the RF frequency of the Linac and rings, the timing system can't meet the requirements of physics design

f	SHB1	SHB2	Linac	DR	booster	collider
MHz	143	572	2860	650	1300	650

➢2*11*n=N*m2*m1*k

@Cai Meng

2020.07.17

- m1 = 11
- m2=3~5, 4
- N=4~6, 5

➢T_{beam}=1/fbm=N*m2*m1*0.34965ns

	frequency		Multiple	Preiod	
Common frequency	13	MHz	1	76.9231	ns
Two bunch	13	MHz	1	76.9231	ns
SHB1	143	MHz	11	6.9930	ns
SHB2	572	MHz	44	1.7483	ns
LINAC	2860	MHz	220	0.3497	ns
Booster	1300	MHz	100	0.7692	ns
Ring	650	MHz	50	1.5385	ns

- Requirement for bunch separation in collider (also in booster and Linac): 20ns~30ns

- Based on current design, the common frequency is 13MHz and the minimum bunch separation time is 76.92ns, which can't meet the requirements.

- If the SHB and thermionic electron gun are replaced by RF gun, the bunch separation time could be 7.692 * N (ns), so bunch separation in collider ring can be 23.08ns

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Requirement.

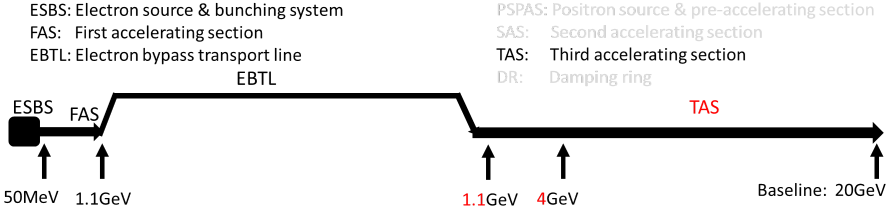

Figure 1. Electron ring lattice block diagram.(Courtesy of Meng Cai.)

Table: Requirement on the beam at the exit of ESBS.

Parameter	Symbol	Value	Unit
Bunch Charge	q	10	nC
Transverse Emittance	$\epsilon_\perp$	100	mm.mrad
Bunch Length	σ_t	3.3	ps
Bunch Energy	E_0	50	MeV

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Collection of Guns.

Facility	Type	Frequency [GHz]	Bunch Charge [nC]	Average Current [mA]	Gun Voltage [MV]	Cathode
Cornell (CBETA)	DC		1	65	0.75	Multi-alkalide
JAEA	DC		/	10	0.18	GaAs
KEK/cERL	DC		/	1.8	0.5	GaAs
JLab	DC		0.122	9.1	0.35	GaAs
Daresbury	DC		0.022	3.6	0.35	GaAs
CERN	NCRF	3	2.33	3.5	5	Cs2Te
FLASH	**NCRF**	**1.3**	**3**	**/**	**5**	**Cs2Te**
LCLS	NCRF	2.856	1	/	7	metal
LBNL(APEX)	NCRF	0.185	1	1	15	Multi-alkalide
LANL/AES	NCRF	0.7	/	/	/	/
ANL/AWA	**NCRF**	**1.3**	**100**	**/**	**8~14**	**Cs2Te**
Boeing	NCRF	0.433	7	32	5	Multi-alkalide
TsingHua	NCRF	2.856	0.5	/	50	Cu
HZDR	SRF	1.3	0.5	/	9.5	Cs2Te
HZB	SRF	1.3	/	/	/	/
UWM	SRF	0.1996	0.1	/	1	metal
NPS	SRF	0.5	/	/	/	/
BNL	SRF	0.112	2(max13)	0.15	1.2	Multi-alkalide
PKU	SRF	1.3	0.18	1	3.4	Cs2Te
What we want	TBD	TBD	10	0.001~0.002	50	TBD

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Gun Layout.

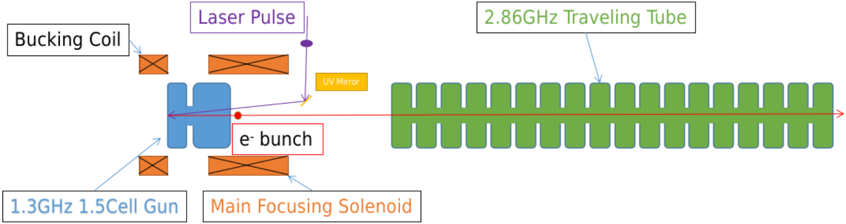


Table: Variables to scan.

Variable	Symbol
Max field of gun cavity	E_{gun}
Max field of the traveling tube	$E_{trav.}$
Phase of gun cavity	ϕ_{gun}
Phase of the traveling tube	$\phi_{trav.}$
Max field of first solenoid	B_{sol1}
Position of first solenoid	P_{sol1}

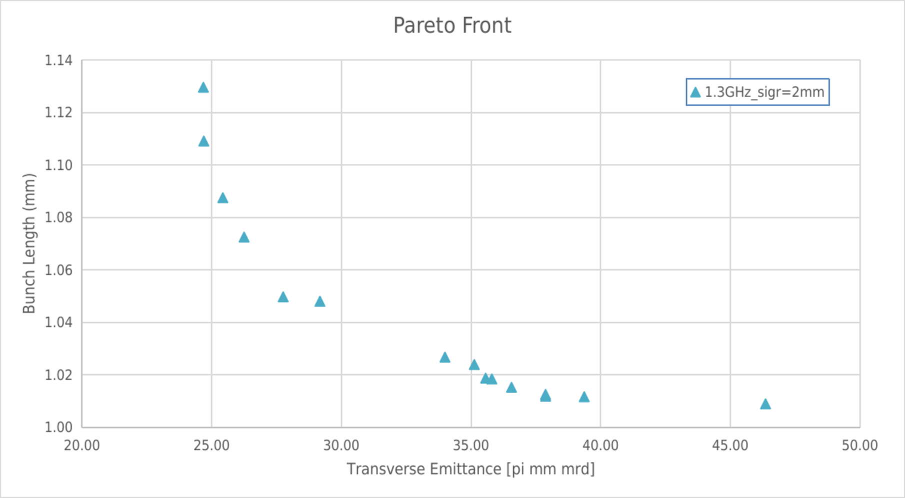
Table: Laser Parameters.

Parameter	Symbol	Value	Unit
Wavelength	λ	266	nm
Pulse Length	σ_t	2	ps
Transverse size	σ_r	2	mm

Tools used.

- Field Simulation: Superfish from LANL.
- Particle tracking with space charge and cathode effect(Schottky effect, mirror charge): ASTRA from DESY.
- Multi-Objective Multi-Parameter Optimization: Home made Python script pyMOGA.

Pareto Front



One of the point on the Pareto Front

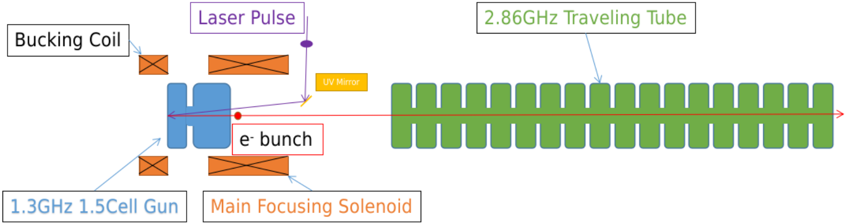


Table: Gun Parameters.

Parameter	Symbol	Value	Unit	Achievable
Gun Max E Field	E_{gun}	80	MV/m	Y
Gun phase*	ϕ_{gun}	-1.0	degree	Y
Sol. Starting Position	P_{sol1}	0.19	m	Y
Sol. Max B	B_{sol1}	0.33	T	Y
Sol. Int. B	$\int B^2 dz$	1.6e-2	$T^2 m$	Y
Trav. Tube Max E	$E_{Trav.}$	30	MV/m	Y
Trav. Tube Starting Point	$P_{Trav.}$	1.06	m	Y
Trav. Tube Phase	$\phi_{Trav.}$	-2.4	degree	Y

* cos convention, 0 degree gives max kick.

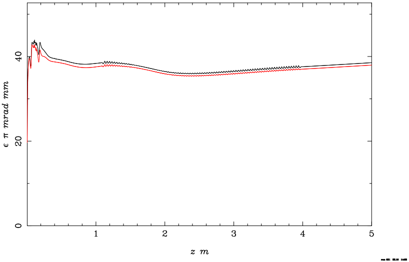
Achieved Beam Quality.

Table: Beam Quality.

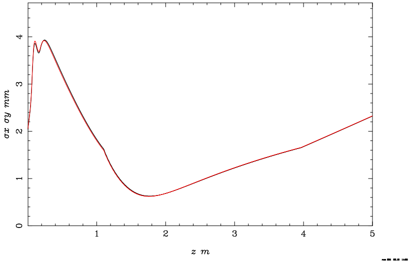
Parameter	Symbol	Value	Required	Unit
Trans. Emittance	ϵ_x	38.5	100	*mm.mrad*
RMS Bunch Length	σ_z	3.4	3.3	ps
Bunch Charge	q	10	10	nC
Bunch Energy	E_0	73	50	MeV

One of the point on the Pareto Front.

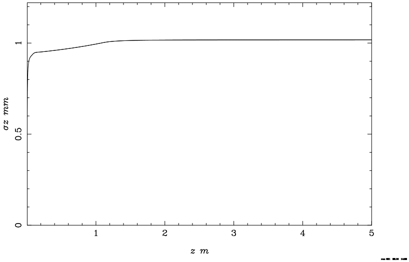
Transverse Emittance



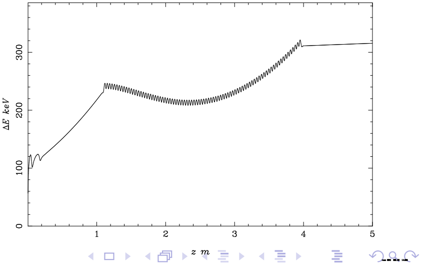
Beam Size



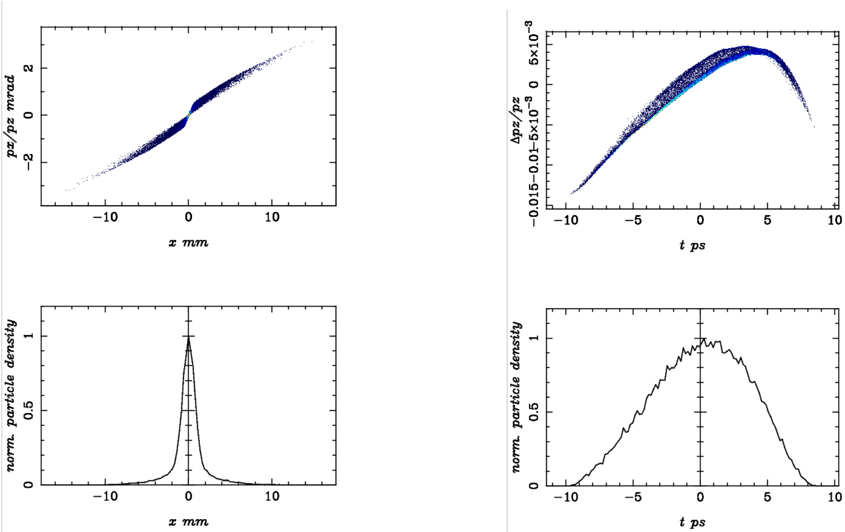
Bunch Length



rms Energy Spread



One of the point on the Pareto Front.(cont.)



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Cost Estimation.

Here is a coarse breakdown of the cost for the major components (R&D not included).

Table: Cost Estimation.

Component	Key Parameters	Cost [Million CNY]
Gun Cavity	L-band; $E_{cathode} > 100\,\mathrm{MV/m}$; $Q_0 > 2 \times 10^4$;	1
Gun PA	Rep. Rate : 100 Hz Peak power : 10 MW	6
Gun FPC	Average Power : 10 kW	1
Laser	Pulse energy : 1 uJ Pulse Length : 1 ps Rep. rate : 100 Hz	5
Subtotal		13

Risk factors

- Laser power density is high, might damage the cathode.
- Cathode charge life time under high bunch charge condition is still an open question.
- Dark current from the cavity could be higher than the photo-current.
- Beam loss due to nonlinear space charge effect.

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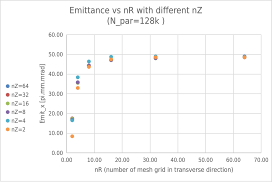
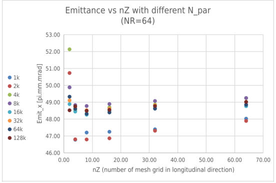
Summary

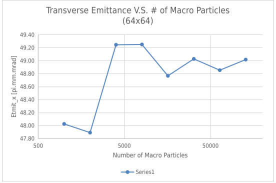
- Simulation shows that the 10 nC bunch from L-band RF gun is doable.
- There are existing examples (FLASH, ANL) that can produce beam with quality close to our requirement.
- Lots of practical hurdles.

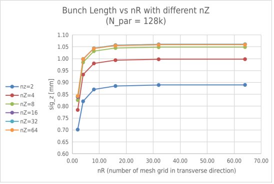
Thanks to the enlightening discussion with Shu Guan, Meng Cai, Li Xiaoping, Wang Dou, Qian Houjun, Xiang Rong, Wang Erdong, Xie Huamu, Wu Yuanhui.

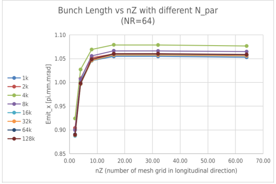
Convergence Study.

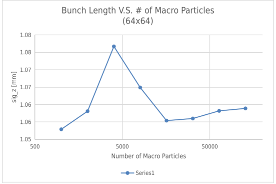












Convergence Study. (cont.)

Relative error of Eps_x (compare with 128k,64x64 case.) | Relative error sig_z (compared with 128k,64x64 case.)

N_par = 1k

nR\nZ	64	32	16	8	4	2	nR\nZ	64	32	16	8	4	2
64	2.020%	3.307%	3.605%	3.699%	4.566%	1.765%	64	0.567%	0.387%	0.387%	1.247%	5.260%	14.892%
32	2.699%	3.727%	4.568%	3.950%	4.394%	2.360%	32	0.756%	0.529%	0.491%	1.322%	5.336%	14.896%
16	4.841%	5.104%	5.614%	5.584%	4.972%	1.361%	16	1.284%	1.039%	1.020%	1.804%	5.979%	15.598%
8	9.833%	10.094%	10.607%	10.196%	8.462%	7.008%	8	2.267%	2.040%	2.030%	2.776%	7.015%	16.657%
4	22.455%	22.890%	23.363%	23.078%	19.556%	24.973%	4	4.911%	4.722%	4.769%	5.543%	9.754%	19.513%
2	55.605%	55.195%	56.083%	56.191%	55.209%	70.347%	2	15.965%	15.941%	16.210%	17.310%	21.201%	29.672%

N_par = 2k

nR\nZ	64	32	16	8	4	2	nR\nZ	64	32	16	8	4	2
64	2.293%	3.480%	4.394%	4.533%	4.517%	3.497%	64	0.076%	0.151%	0.094%	0.652%	4.741%	14.611%
32	3.138%	3.907%	4.637%	5.013%	3.941%	3.017%	32	0.132%	0.094%	0.047%	0.689%	4.797%	14.702%
16	4.941%	5.229%	5.894%	6.135%	4.392%	0.539%	16	0.416%	0.189%	0.255%	0.992%	5.175%	15.099%
8	9.952%	10.321%	10.631%	10.904%	8.930%	3.121%	8	1.369%	1.180%	1.247%	2.078%	6.172%	16.031%
4	24.114%	24.406%	24.526%	24.332%	21.299%	21.952%	4	4.335%	4.193%	4.372%	5.326%	9.432%	19.464%
2	58.514%	58.561%	59.029%	59.206%	58.567%	74.511%	2	16.741%	16.758%	17.017%	18.130%	22.104%	30.543%

N_par = 4k

nR\nZ	64	32	16	8	4	2	nR\nZ	64	32	16	8	4	2
64	0.465%	0.314%	0.653%	1.085%	0.998%	6.363%	64	1.681%	1.879%	1.917%	0.982%	2.984%	12.716%
32	0.575%	1.024%	1.732%	1.767%	0.730%	5.963%	32	1.587%	1.785%	1.832%	0.897%	3.060%	12.727%
16	2.583%	2.807%	3.454%	3.819%	1.785%	4.329%	16	1.379%	1.587%	1.624%	0.661%	3.286%	12.979%
8	8.014%	8.397%	8.742%	8.775%	5.955%	3.813%	8	0.274%	0.463%	0.444%	0.567%	4.694%	14.564%
4	23.545%	23.680%	23.645%	23.400%	19.795%	25.797%	4	3.806%	3.711%	3.844%	4.835%	9.204%	19.508%
2	62.350%	62.546%	61.958%	62.876%	62.531%	78.206%	2	17.622%	17.671%	17.984%	19.099%	22.946%	31.184%

N_par = 8k

nR\nZ	64	32	16	8	4	2	nR\nZ	64	32	16	8	4	2
64	0.475%	0.114%	0.249%	0.488%	0.375%	1.769%	64	0.567%	0.699%	0.727%	0.293%	4.882%	15.049%
32	0.490%	0.712%	1.326%	1.173%	0.033%	1.096%	32	0.444%	0.567%	0.595%	0.434%	5.062%	15.232%
16	2.436%	2.807%	2.981%	3.107%	0.940%	1.506%	16	0.189%	0.312%	0.321%	0.708%	5.345%	15.549%
8	8.285%	8.342%	8.921%	9.021%	5.586%	9.303%	8	0.944%	0.822%	0.850%	1.983%	6.689%	16.995%
4	26.434%	26.419%	26.819%	26.513%	22.049%	32.232%	4	5.688%	5.653%	5.797%	7.037%	11.802%	22.525%
2	64.270%	64.414%	64.759%	65.300%	65.400%	82.162%	2	20.096%	20.162%	20.484%	21.705%	25.653%	33.611%

N_par = 16k

nR\nZ	64	32	16	8	4	2	nR\nZ	64	32	16	8	4	2
64	0.510%	0.730%	1.081%	1.538%	1.165%	0.263%	64	0.331%	0.170%	0.179%	1.247%	5.914%	16.172%
32	1.595%	1.716%	2.422%	2.256%	0.453%	1.024%	32	0.434%	0.274%	0.293%	1.369%	6.039%	16.287%
16	4.129%	4.439%	4.809%	4.923%	1.424%	4.376%	16	0.812%	0.661%	0.689%	1.785%	6.476%	16.757%
8	12.159%	12.094%	12.698%	12.783%	8.601%	14.715%	8	2.333%	2.229%	2.267%	3.438%	8.133%	18.469%
4	33.321%	33.399%	33.666%	33.193%	27.956%	41.202%	4	7.992%	7.960%	8.125%	9.337%	13.973%	24.440%
2	71.810%	72.083%	72.707%	73.124%	75.166%	88.319%	2	24.044%	24.138%	24.505%	25.679%	29.169%	35.851%

N_par = 32k

nR\nZ	64	32	16	8	4	2	nR\nZ	64	32	16	8	4	2
64	0.022%	0.406%	0.816%	0.998%	0.602%	0.192%	64	0.274%	0.113%	0.094%	1.180%	5.865%	16.023%
32	1.049%	1.326%	1.836%	1.559%	0.082%	0.312%	32	0.331%	0.179%	0.151%	1.247%	5.944%	16.104%
16	3.140%	3.489%	3.793%	3.448%	0.814%	2.103%	16	0.623%	0.472%	0.463%	1.558%	6.275%	16.507%
8	9.180%	9.242%	9.570%	9.266%	5.355%	10.180%	8	1.775%	1.653%	1.672%	2.814%	7.601%	17.928%
4	26.713%	26.654%	27.095%	26.366%	21.095%	32.752%	4	6.174%	6.112%	6.252%	7.496%	12.281%	22.909%
2	64.178%	64.547%	64.831%	64.877%	66.144%	82.189%	2	20.710%	20.779%	21.113%	22.330%	26.302%	34.145%

N_par = 64k

nR\nZ	64	32	16	8	4	2	nR\nZ	64	32	16	8	4	2
64	0.333%	0.812%	1.271%	1.426%	0.828%	0.637%	64	0.066%	0.085%	0.094%	0.992%	5.727%	15.871%
32	1.406%	1.732%	2.277%	2.140%	0.112%	0.122%	32	0.123%	0.038%	0.047%	1.039%	5.797%	15.932%
16	3.305%	3.640%	4.086%	4.019%	1.040%	1.591%	16	0.416%	0.255%	0.255%	1.369%	6.122%	16.303%
8	9.450%	9.566%	10.003%	9.784%	5.361%	10.107%	8	1.558%	1.435%	1.464%	2.588%	7.445%	17.705%
4	26.505%	26.836%	27.127%	26.546%	21.142%	32.483%	4	5.840%	5.777%	5.914%	7.146%	12.029%	22.607%
2	63.598%	63.531%	63.576%	64.525%	65.133%	81.957%	2	20.355%	20.420%	20.758%	21.978%	25.961%	33.794%

N_par = 128k

nR\nZ	64	32	16	8	4	2	nR\nZ	64	32	16	8	4	2
64	0.000%	0.496%	0.957%	1.067%	0.528%	1.006%	64	0.000%	0.151%	0.161%	0.954%	5.754%	15.974%
32	1.281%	1.324%	2.107%	1.905%	0.016%	0.922%	32	0.057%	0.104%	0.113%	1.001%	5.799%	16.020%
16	3.246%	3.546%	4.025%	3.915%	0.469%	3.132%	16	0.359%	0.198%	0.198%	1.332%	6.157%	16.417%
8	9.366%	9.491%	9.856%	9.803%	5.298%	10.929%	8	1.520%	1.398%	1.426%	2.569%	7.443%	17.782%
4	26.893%	27.186%	27.456%	26.868%	21.686%	32.729%	4	5.736%	5.662%	5.804%	7.025%	11.884%	22.491%
2	64.529%	64.214%	64.653%	65.616%	66.236%	82.778%	2	20.391%	20.453%	20.782%	21.993%	25.922%	33.734%

Reference

- B. Dunham, et al. "Record high-average current from a high-brightness photoinjector," Applied Physics Letters,102.3 (2013): 034105. T. Nishitani, et al., "JAEA photocathode DC-gun for an ERL injector," in Proc. FEL2006, p. 319 (2006).
- R. Nagai, et al., "High-voltage testing of a 500-kV dc photocathode electron gun," Review of Scientific Instruments, 81.3 (2010): 033304.
- C. Hernandez-Garcia, et al., "A high average current DC GaAs photocathode gun for ERLs and FELs," in Proc PAC'05, Knoxville, TN, USA, May 2005, paper WPAP050, pp. 3117-3119.
- S. L. Smith, et al., "The status of the Daresbury energy recovery linac prototype," in Proc. PAC'07, Albuquerque,NM, USA, May 2007, paper TUPMN083, pp. 1103-1105.
- THE PHIN PHOTOINJECTOR FOR THE CTF3 DRIVE BEAM R. Losito, M. Vogt, et al., "Status of the free-electron laser FLASH at DESY," in Proc. IPAC'11, San Sebastián, Spain, Septem- ber 2011, paper THPC081, pp. 3080-3082.
- R. Alley, et al., "The design for the LCLS RF photoinjec- tor," NIM, A 429.1 (1999): 324-331.
- F. Sannibale, et al., "Advanced photoinjector experiment photogun commissioning results," Phys. Rev. ST Accel.Beams 15.10 (2012): 103501.
- D. Nguyen, "Development of High-average-current RF Injectors," in Proc. FEL'08, Gyeongju, Korea. August 2008, paper THCAU02, pp. 511-516.
- D.H. Dowell et al., Applied Physics Letters, 63, 2035 (1993).
- A. Arnold, et al., Nuclear Instrum. Methods, A 593.1 (2008): 57-62.
- A. Neumann et al., “CW Superconducting RF Photoinjec-tor Development for Energy Recovery Linacs,”in Proc.LINAC10, Tsukuba, Japan, September 2010, paper THP112, pp. 998-1000.
- J. Bisognano, et al., “Wisconsin SRF Electron Gun Commissioning,” in Proc. NAPAC'13, Pasadena, CA USA,September 2013, paper TUPMA19, pp. 622-624.
- Long lifetime of bialkali photocathodes operating in high gradient superconducting radio frequency gun
- K. Liu, et al., talk at SRF2015, FRAA05