Overview of High-Brightness, High-Average-Current Photoinjectors for FELs

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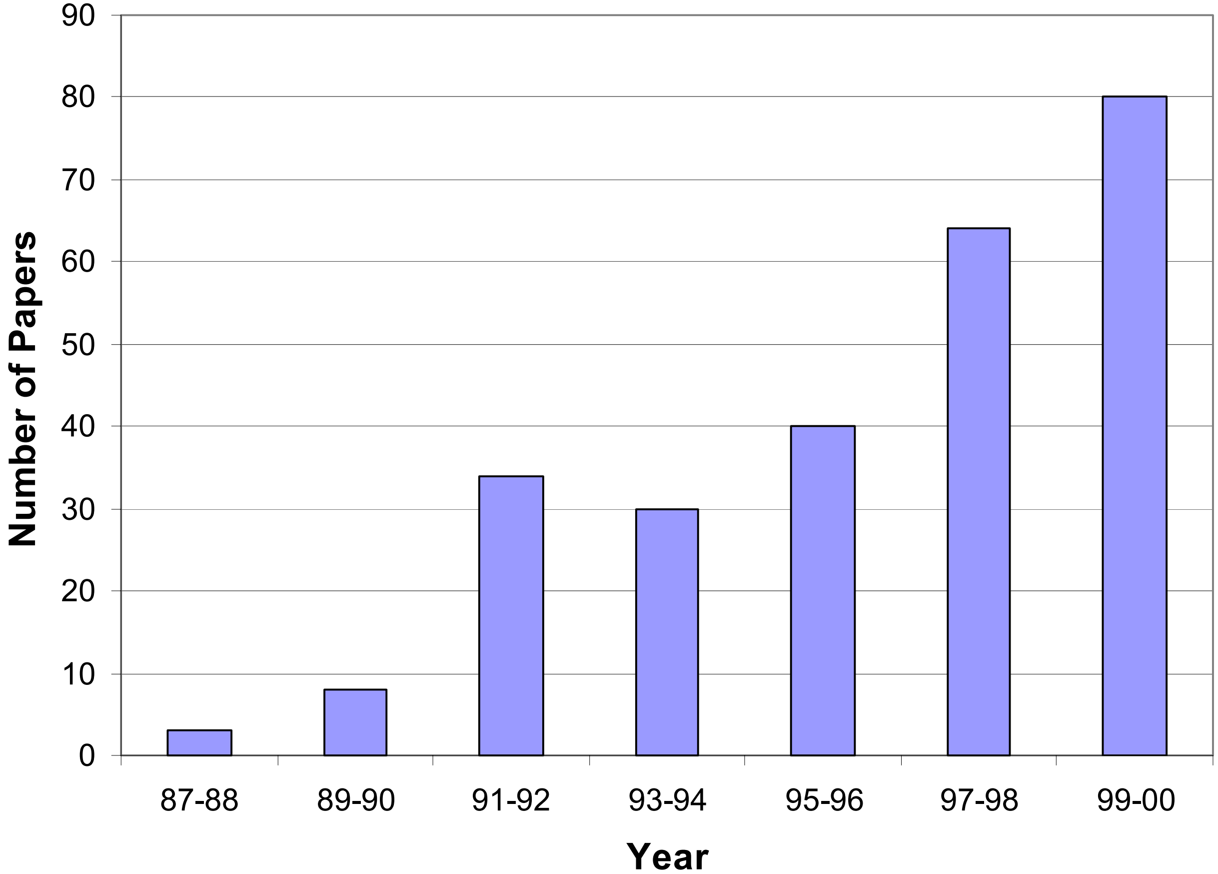
Number of Papers Published on Photoinjectors versus Year



P. G. O'Shea, *Proceedings of the 2nd ICFA Advanced Accelerator Workshop on The Physics of High Brightness Beams*, 1999.

Talk Scope

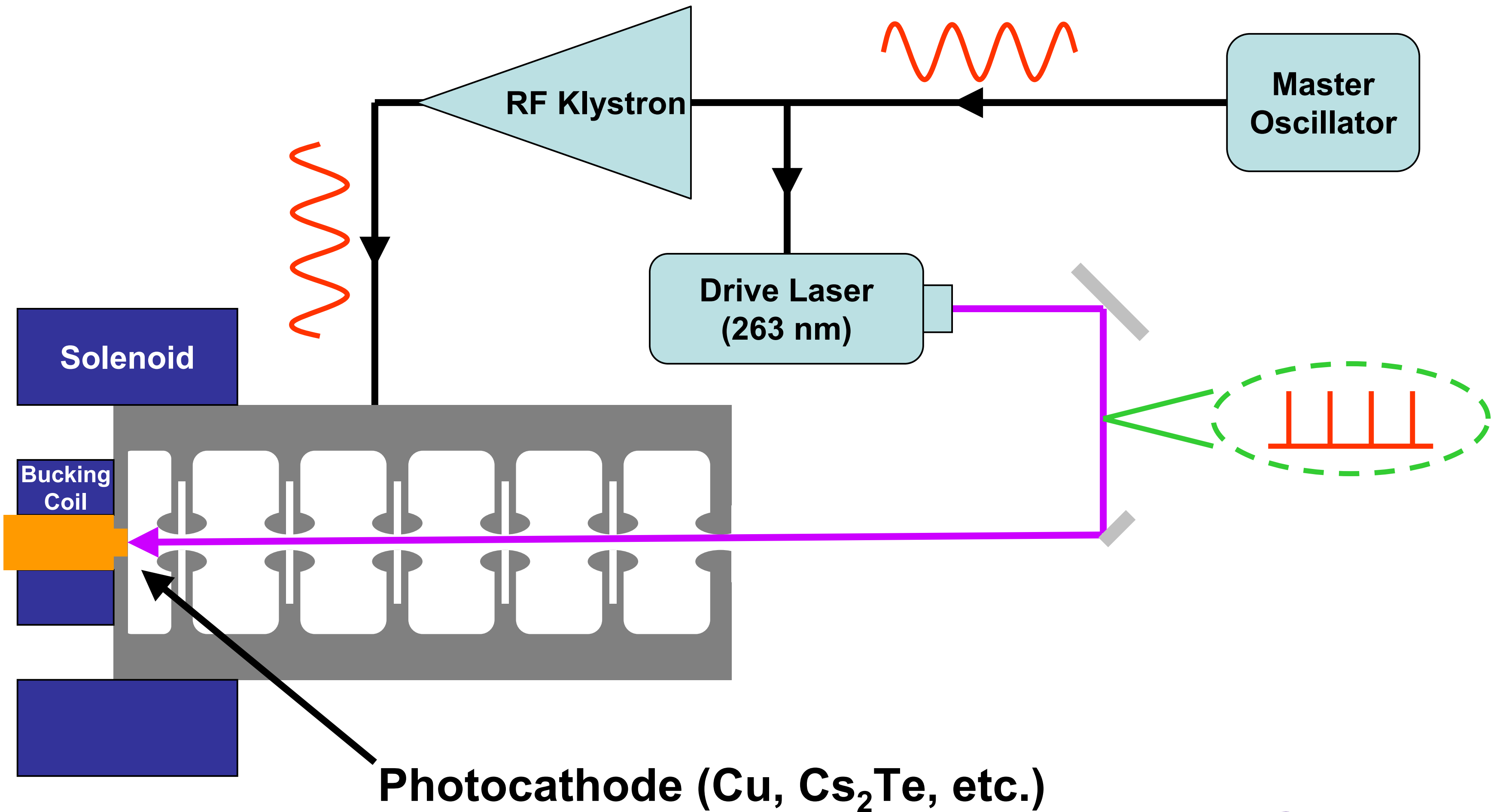
- High-brightness, high-average-current photoinjectors.

- High-average-current is defined as several mA (ultimate goal is ≥ 100 mA).

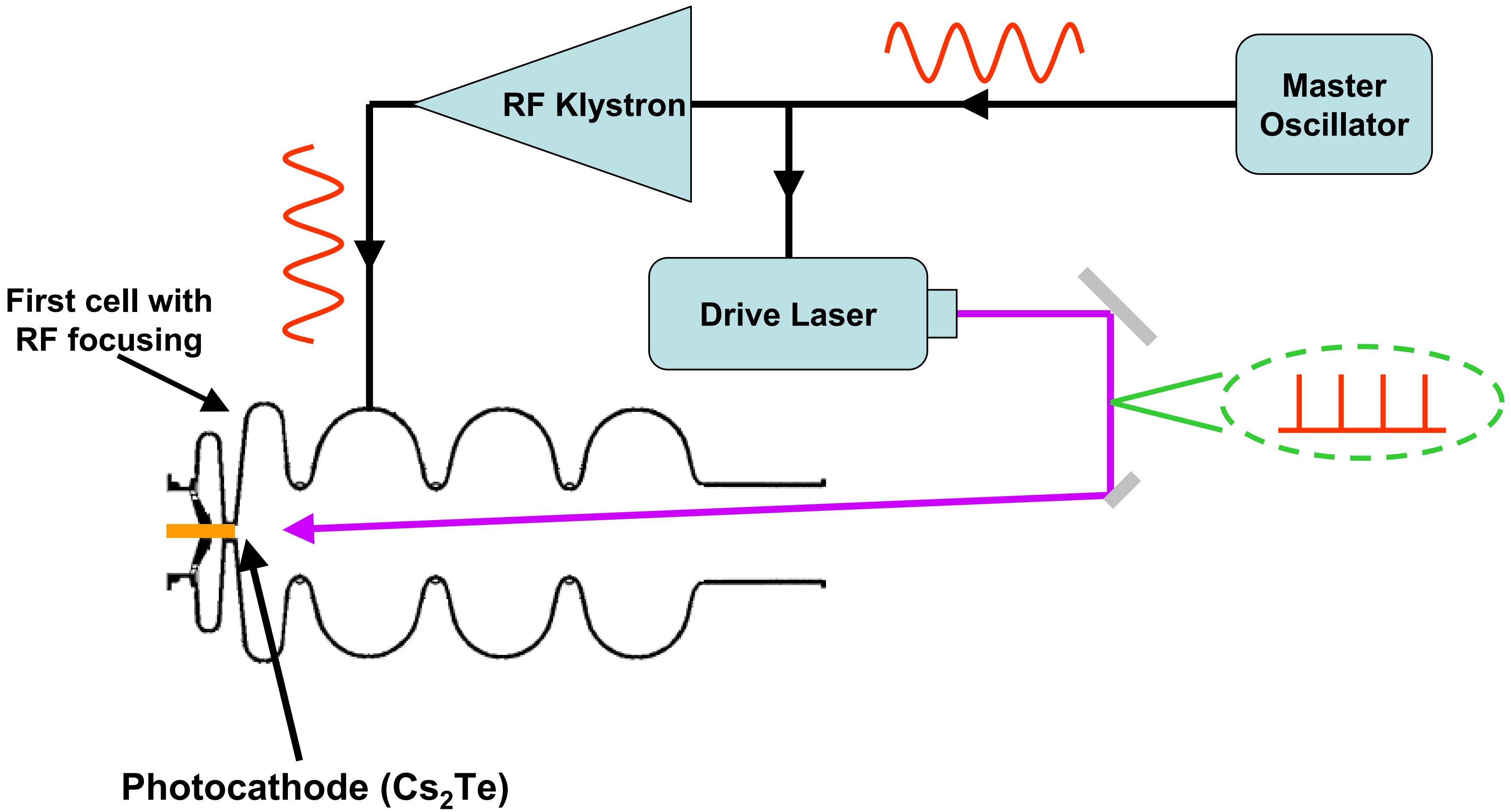
- Emphasis on normal conducting, RF photoinjectors.

Photoinjector examples

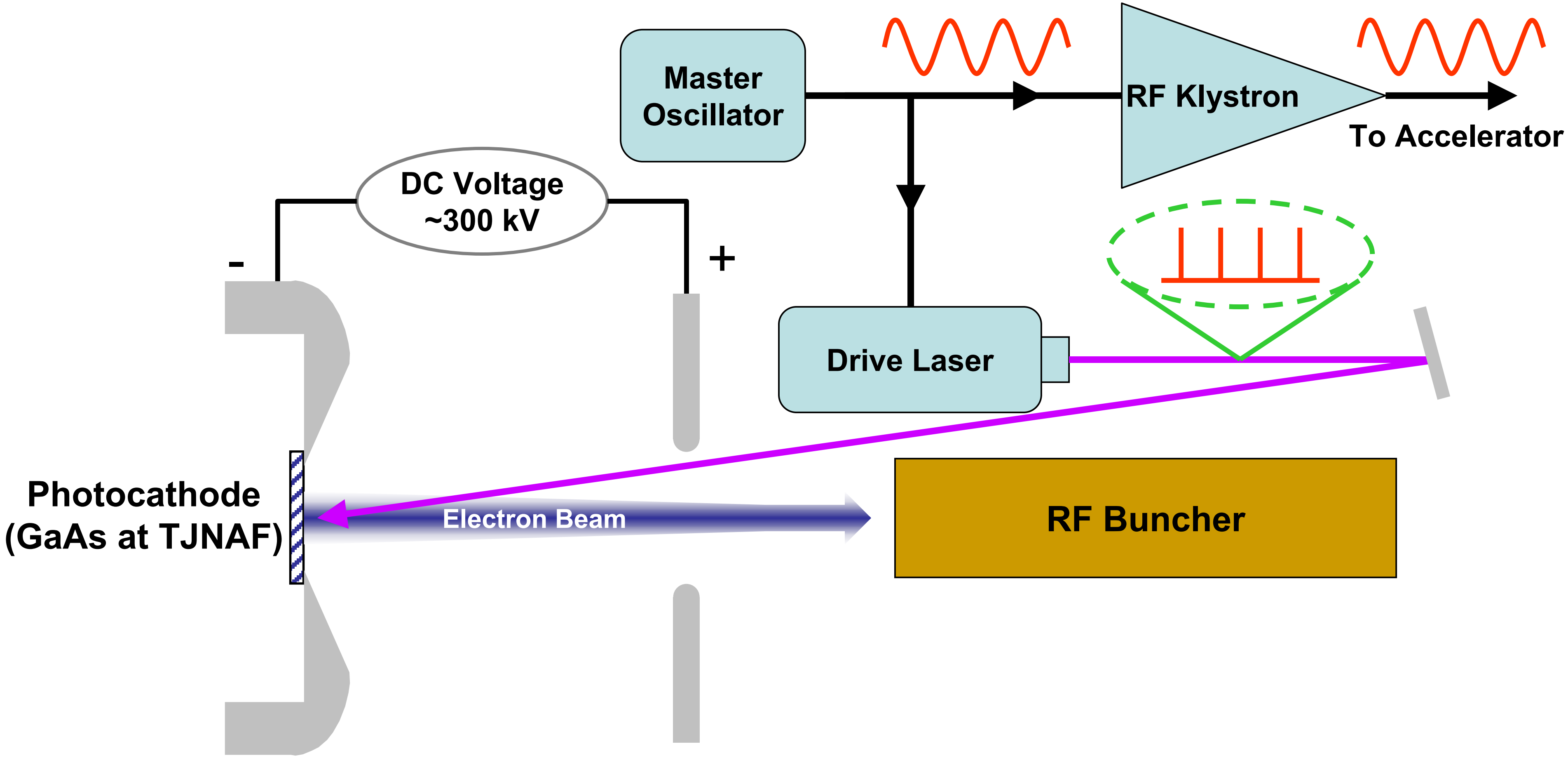
Normal Conducting RF Photoinjector



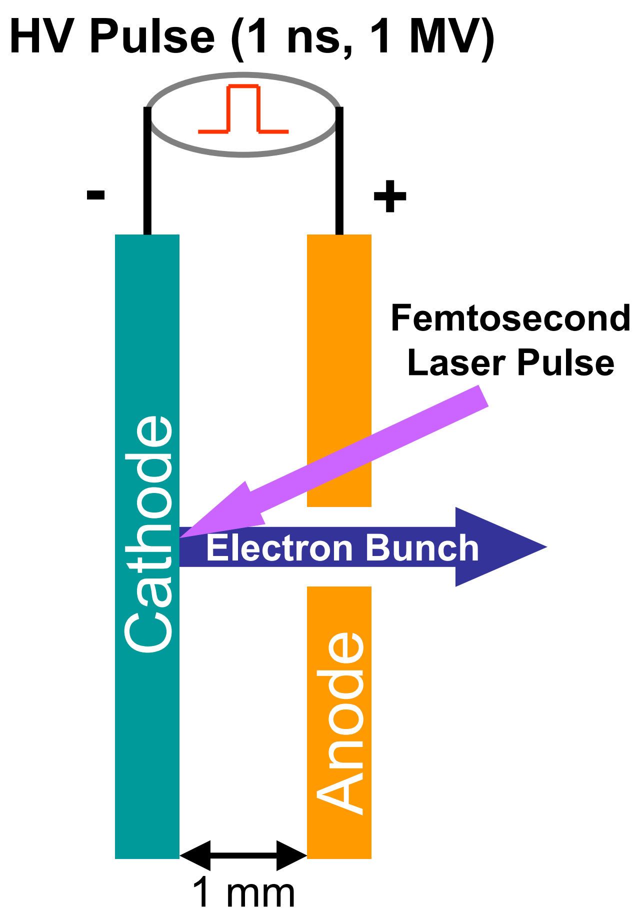
Superconducting RF Photoinjector



DC Photoinjector



High Voltage, Pulsed Photocathode Gun



- Pioneered by BNL
- Pulsed photocathode experiments at BNL and Eindoven University of Technology
- Copper cathode
- **1 GV/m accelerating gradient**
- 0.1 – 1 nC bunch charge
- 0.1 mm-mrad emittance at 0.1 nC
- 0.1 – 1 ps bunch length
- Goal is ultra-high brightness beam

Brief history of photoinjectors

Selected Highlights in the Photoinjector Timeline

1985: First photoinjector experiment at LANL.

1988: First FEL driven by a photo-injector at Stanford.
Theory of emittance compensation.

1989: First high-gradient S-band photoinjector at Brookhaven.

1991: First RF integrated photoinjector with emittance compensation at LANL.

1992: High duty factor, RF photoinjector experiment at Boeing.
First photocathode in a superconducting cavity at Wuppertal.

1993: LANL photoinjector driven FEL lases in the UV.

1996: First operation of DC photoinjector at TJNAF.

1997: Envelope analysis of emittance compensation.

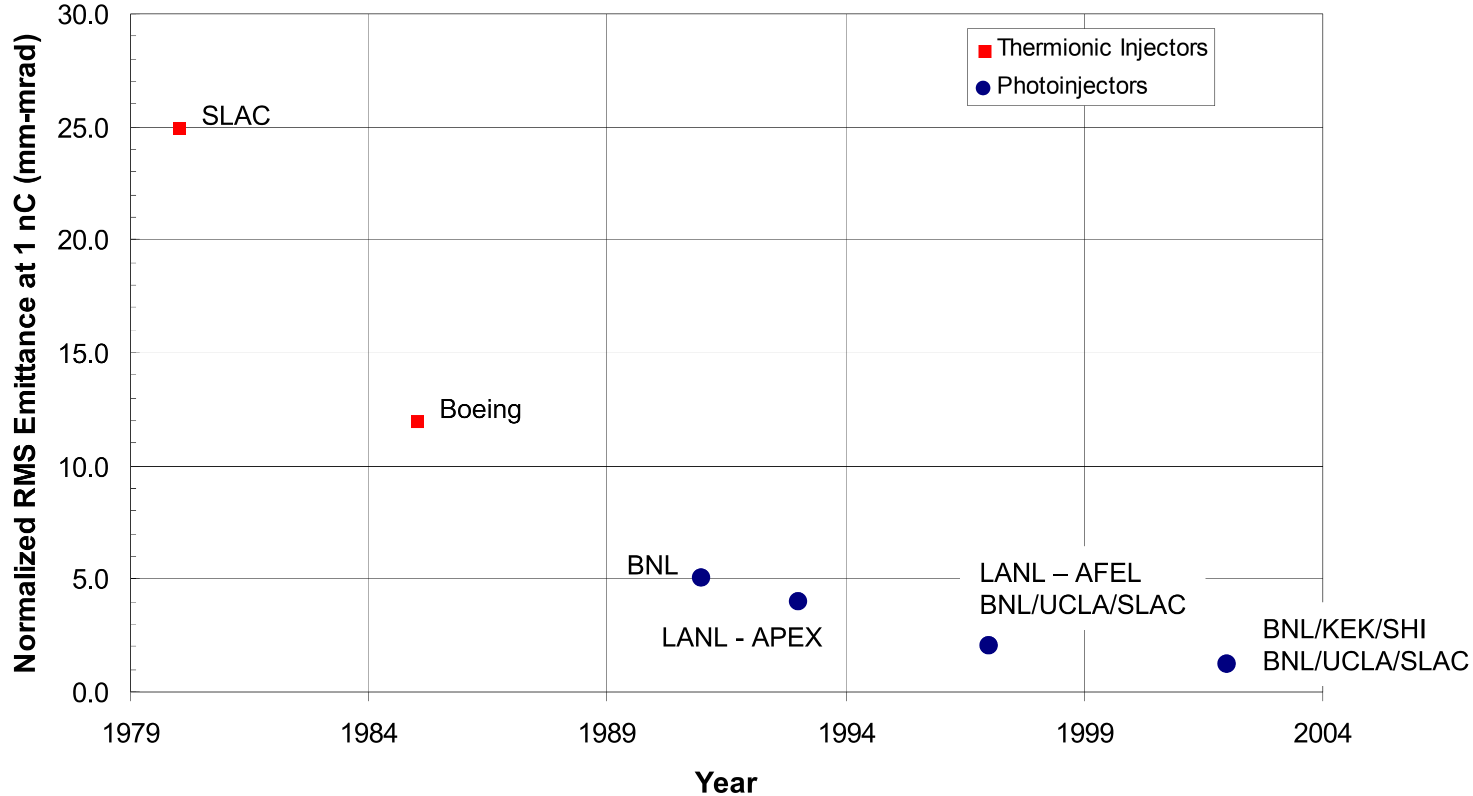
1999: TJNAF FEL demonstrates 1.72 kW average power, driven by DC photoinjector.

2002: First operation of a superconducting RF photoinjector at the Forschungszentrum Rossendor.

Photoinjectors Span a Wide Range of RF Frequencies and Applications

- Photoinjectors have been built and tested from 144 MHz (CEA) to 17 GHz (MIT).
- Photoinjectors have been designed at 90 GHz.
- Photoinjectors are used extensively as drivers for FELs. (primary motivator for photoinjector development)
- Photoinjectors have been used as drivers for electron beam driven plasma wakefield accelerator experiments.
- Photoinjectors are being considered as injectors for laser driven plasma wakefield accelerator schemes.
- It is hoped that photoinjectors can be used as the source for future colliders, replacing damping rings.

Our Ability to Mitigate Space Charge Induced Emittance Growth has Improved Over Time



P. G. O'Shea and L. Spentzouris, *Proceedings of the VIII Advanced Accelerator Concepts Workshop*, Baltimore, Maryland, July 1998.

Y. Yang, et al., *Journal of Applied Physics*, **92**, p. 1608, 2002

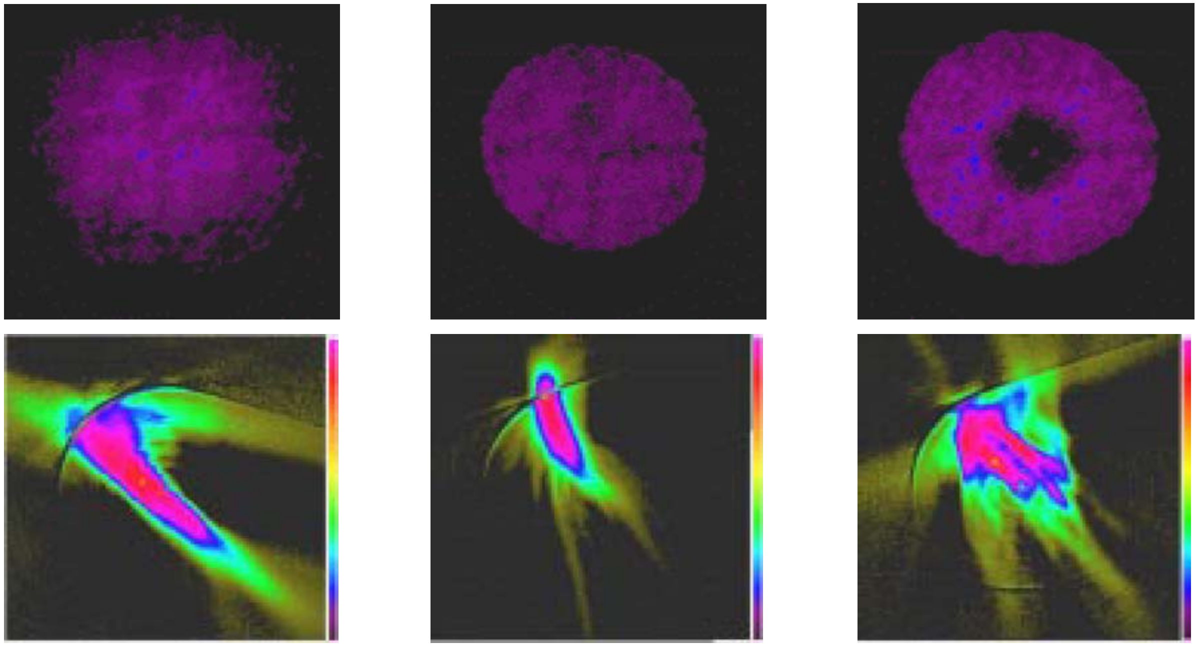
The Quality of Photoinjector Beams is Traceable to Our Ability to Shape the Drive Laser Pulse

Effect of transverse profile of drive laser pulse on beam phase space at the ATF (BNL)

Gaussian | "Flat Top" | Hollow

Laser Spot on Cathode

Resulting phase space from tomographic reconstruction

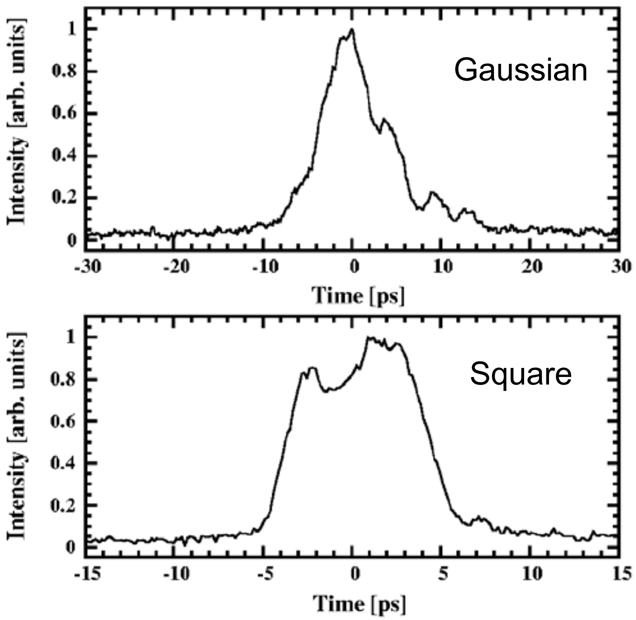


V. Yakimenko, M. Babzien, I. Ben-Zvi, R. Malone, and X. –J. Wang, *Proceedings of the 1998 European Particle Accelerator Conference*, Stockholm, Sweden, June 1998.

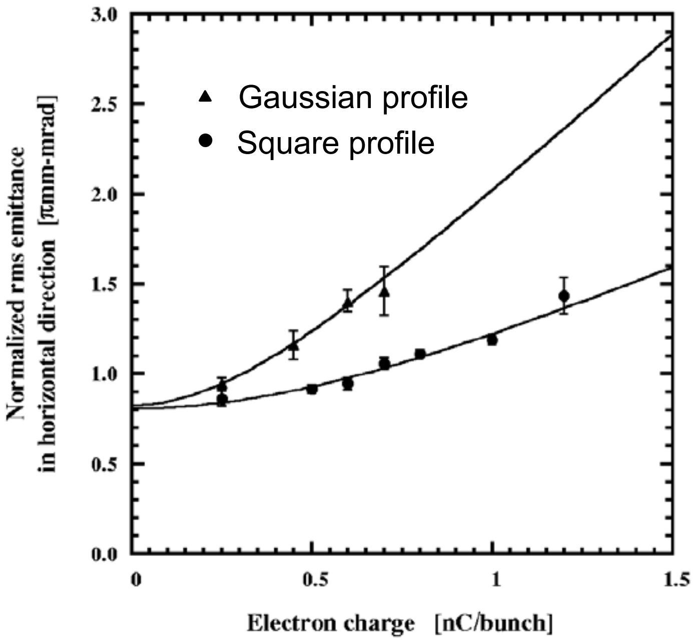
The Quality of Photoinjector Beams is Traceable to Our Ability to Shape the Drive Laser Pulse

Effect of temporal profile of drive laser pulse on beam emittance. BNL/KEK/SHI collaboration.

Drive Laser Temporal Profile



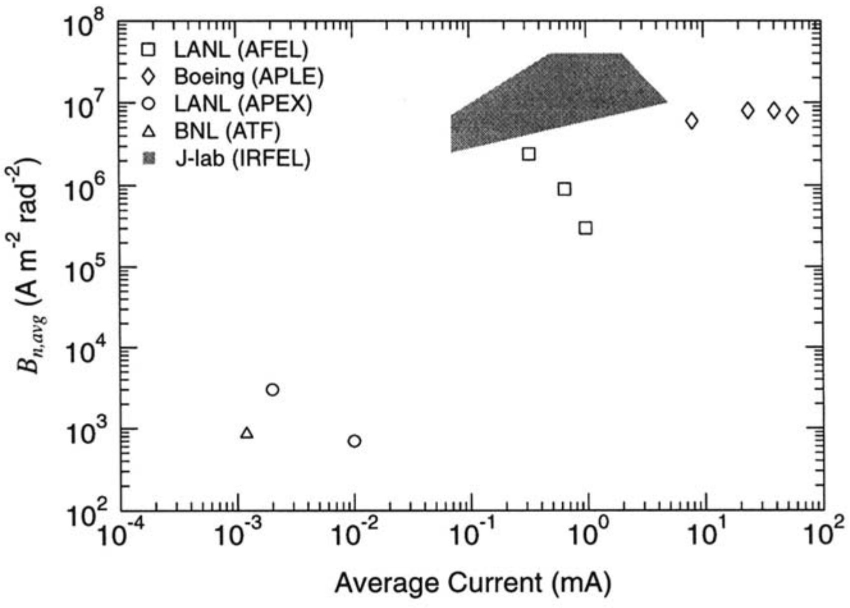
Emittance vs. Charge



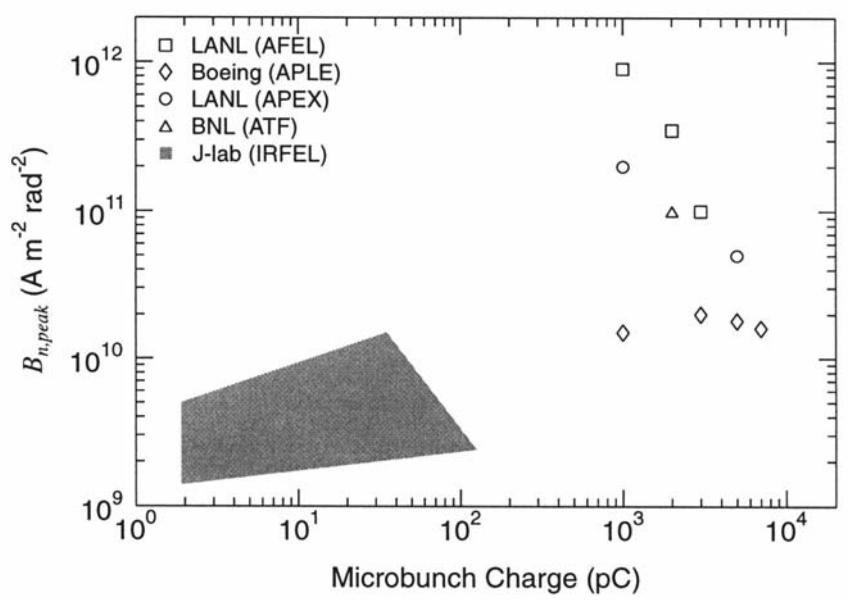
Y. Yang, et al., *Journal of Applied Physics*, **92**, p. 1608, 2002

Beam Brightness Comparison

Average Brightness vs. Current

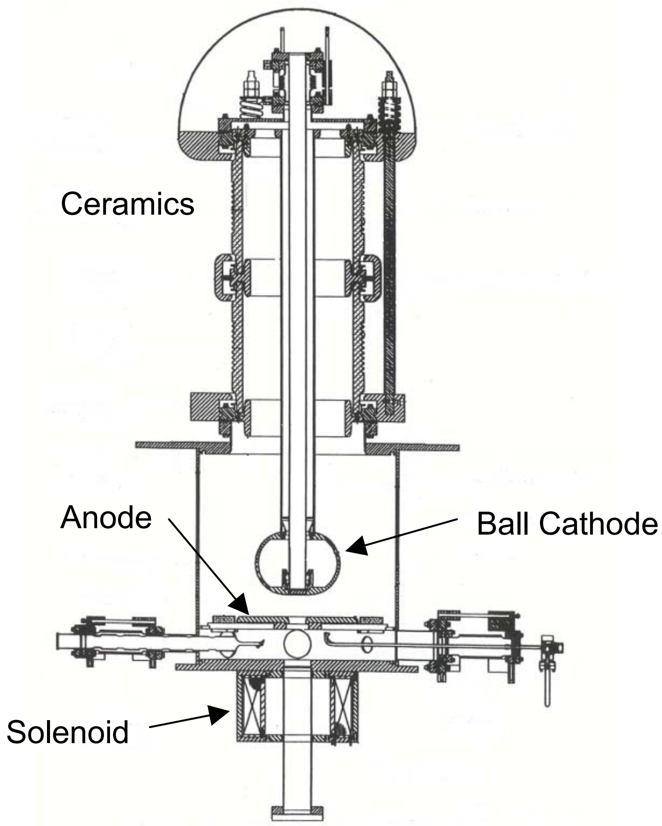


Peak Brightness vs. Charge



High-average-current DC photoinjectors

TJNAF High-Average-Current DC Photoinjector



Voltage	320 kV
Duty factor	CW
Charge per bunch	135 pC
Repetition rate	37.425 MHz
Average current	5 mA
Cathode	GaAs
1/e cathode lifetime	58 Hours
RMS emittance	25 mm-mrad
RMS temporal length (after bunching)	0.4 ps

- **Driver for FEL with output power in excess of 2.1 kW.**
- **Cathode lifetime limited by ion back bombardment.**
- **Voltage limited by field emission (design voltage 500 kV).**

T. Siggins, et al., *Nuclear Instruments and Methods A*, **475**, p. 549, 2001.

TJNAF/AES High-Average-Current DC Photoinjector: Future Possibilities

Gun voltage		500 kV
Average current		100 mA
Beam energy		10 MeV
Bunch charge	1 nC	2 nC
Transverse emittance	7.5 mm-mrad	10 mm-mrad
Longitudinal emittance	30 deg-keV	50 deg-keV
RMS bunch length	4 ps	5 ps

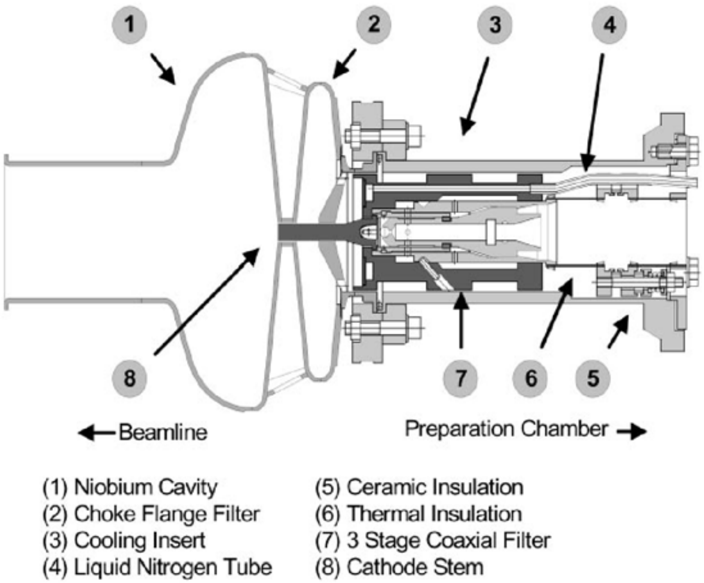
B. C. Yunn, *Proceedings of the 2001 Particle Accelerator Conference*, p. 2254, 2001.

H. Bluem, A. M. M. Todd and G. R. Neil, *Proceedings of the 2001 Particle Accelerator Conference*, p. 92, 2001.

Superconducting RF photoinjectors

Forshungszentrum Rossendor Superconducting RF Photoinjector Tests

½ Cell Superconducting RF Photoinjector Test Gun

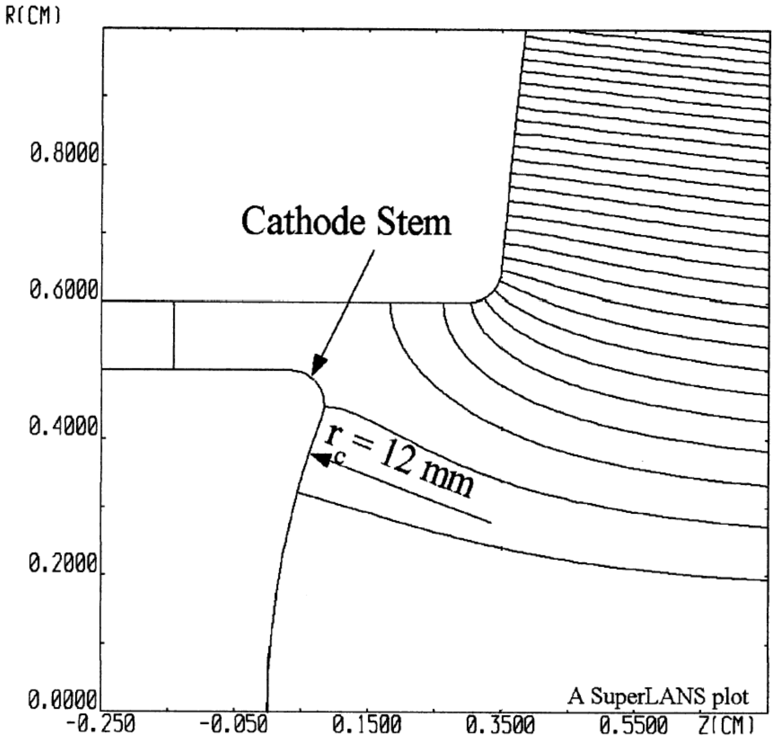


E. Barhels, et al., *Nuclear Instruments and Methods A*, **445**, p. 408, 2000.

H. Buttig, et al., *these proceedings.*

Superconducting RF Photoinjectors use RF Focusing for Emittance Compensation

Fields at Cathode



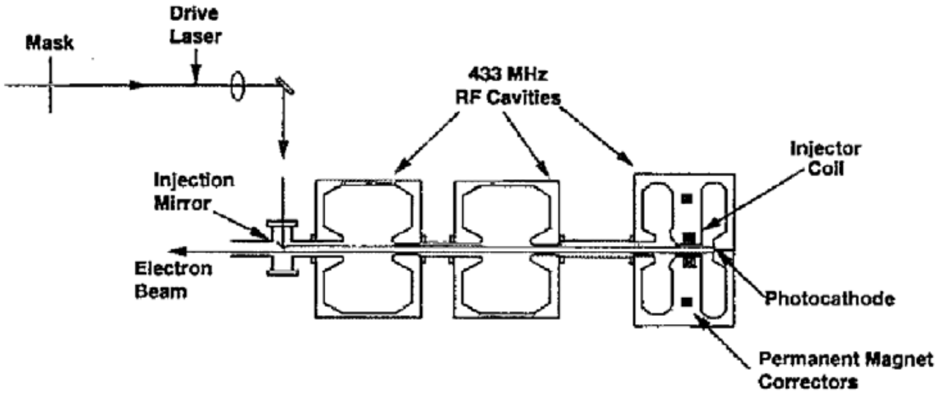
Results from PARMELA Simulations
(3 ½ Cell Injectors)

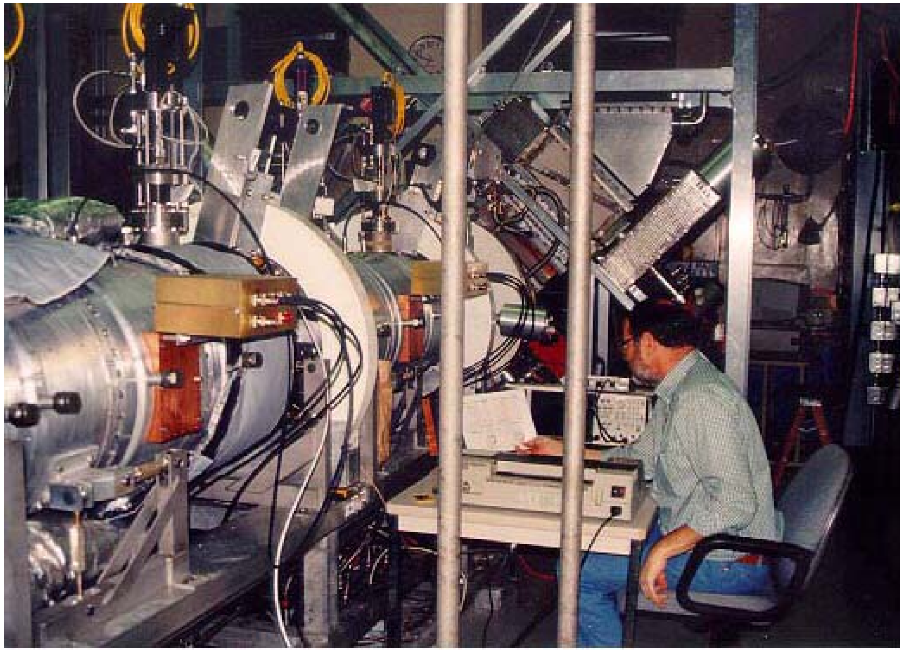
	1300 MHz Structure	650 MHz Structure
Average Gradient	25 MV/m	20 MV/m
Charge	1 nC	1 nC
RMS Emittance	2.2 mm mrad	1.36
RMS Length	1.7 mm	4.05 mm

D. Janssen and V. Volkov, *Nuclear Instruments and Methods A*, **452**, p.34, 2000.

Normal conducting RF photoinjectors

Boeing High-Average-Current Photoinjector





D. H. Dowell, et. al., *Applied Physics Letters*, **63**, p. 2035, 1993.

Boeing High-Average-Current Photoinjector Performance

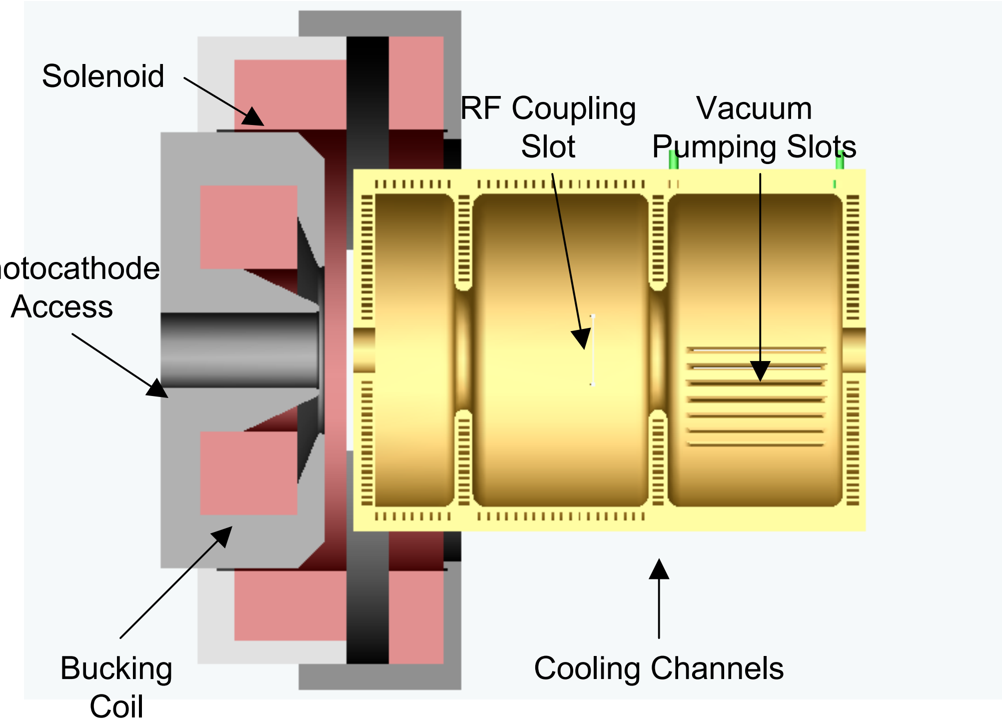
First operation	1992
Operation frequency	433 MHz
Cathode	K_2CsSb multialkali (5 – 10% efficient)
Cathode lifetime	1 – 10 hours
Gradient at cathode	26 MV/m
Duty factor	25%
Cavity type	Water cooled copper
Number of cells	4
Final energy	5 MeV
Average current	32 mA
Charge per micropulse	1 – 7 nC
RMS emittance	5 – 10 mm mrad
RMS bunch length	~ 20 ps
Energy spread	100 – 150 keV

D. H. Dowell, et. al., *Applied Physics Letters*, **63**, p. 2035, 1993.

Design of LANL/AES 700 MHz High-Average-Current RF Photoinjector

3D View

Cut Away View



S. S. Kurennoy, et al., *Poster WE-P-30.*

Power Dissipation in LANL/AES 700 MHz Photoinjector at $E_0 = 7$ MV/m

	Cold (1.9 Q Enhancement)	Warm
Peak power density (Watts/cm^2)	53	101
Average power density on outer walls (1/2 and center cells)	41	78
Average power density on outer walls (end cell)	34	65

S. S. Kurennoy, et al., *Poster WE-P-30.*

Required Performance of LANL/AES 700 MHz High-Average-Current RF Photoinjector

Frequency	700 MHz
Operation	CW
Average current	100 mA – 1 A
Energy after injector booster linac	> 5 MeV
Bunch charge	3 nC
RMS, normalized emittance	< 10 mm mrad
FWHM bunch length	8 ps
RMS energy spread	< 1%

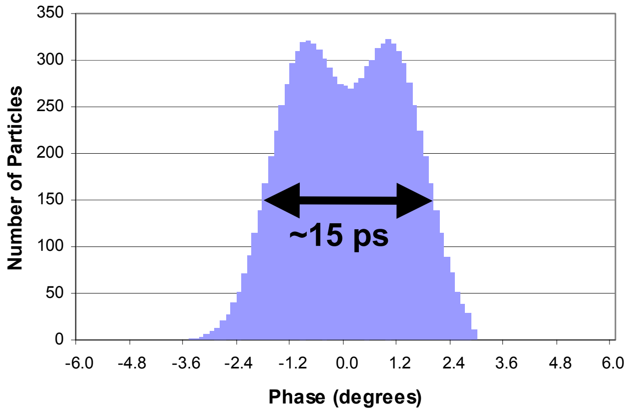
S. S. Kurennoy, et al., *Poster WE-P-30.*

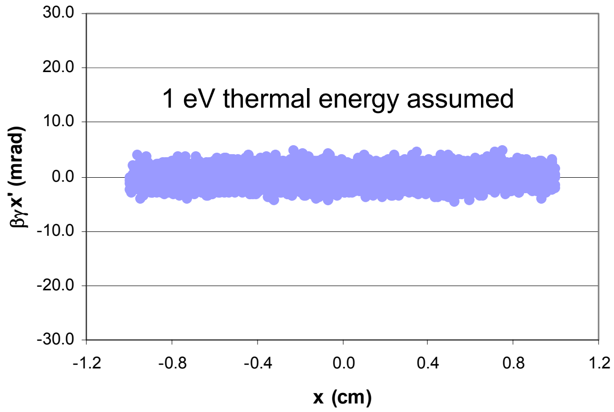
PARMELA Simulation of LANL/AES 700 MHz High-Average-Current Photoinjector at 3 nC

Longitudinal Distribution (1 degree ≈ 4 ps)

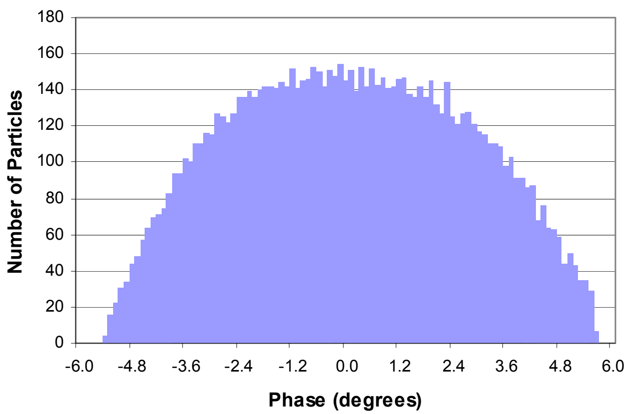
Transverse Phase Space

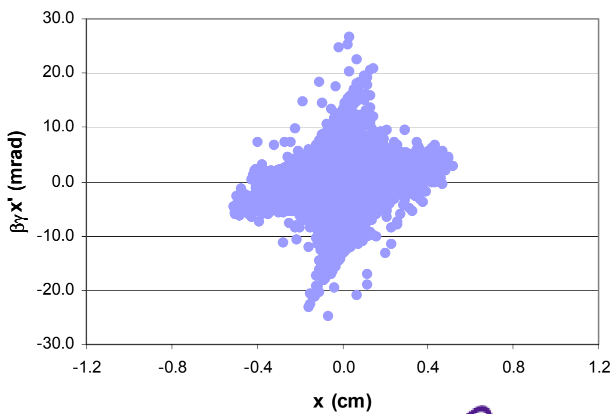
At Start



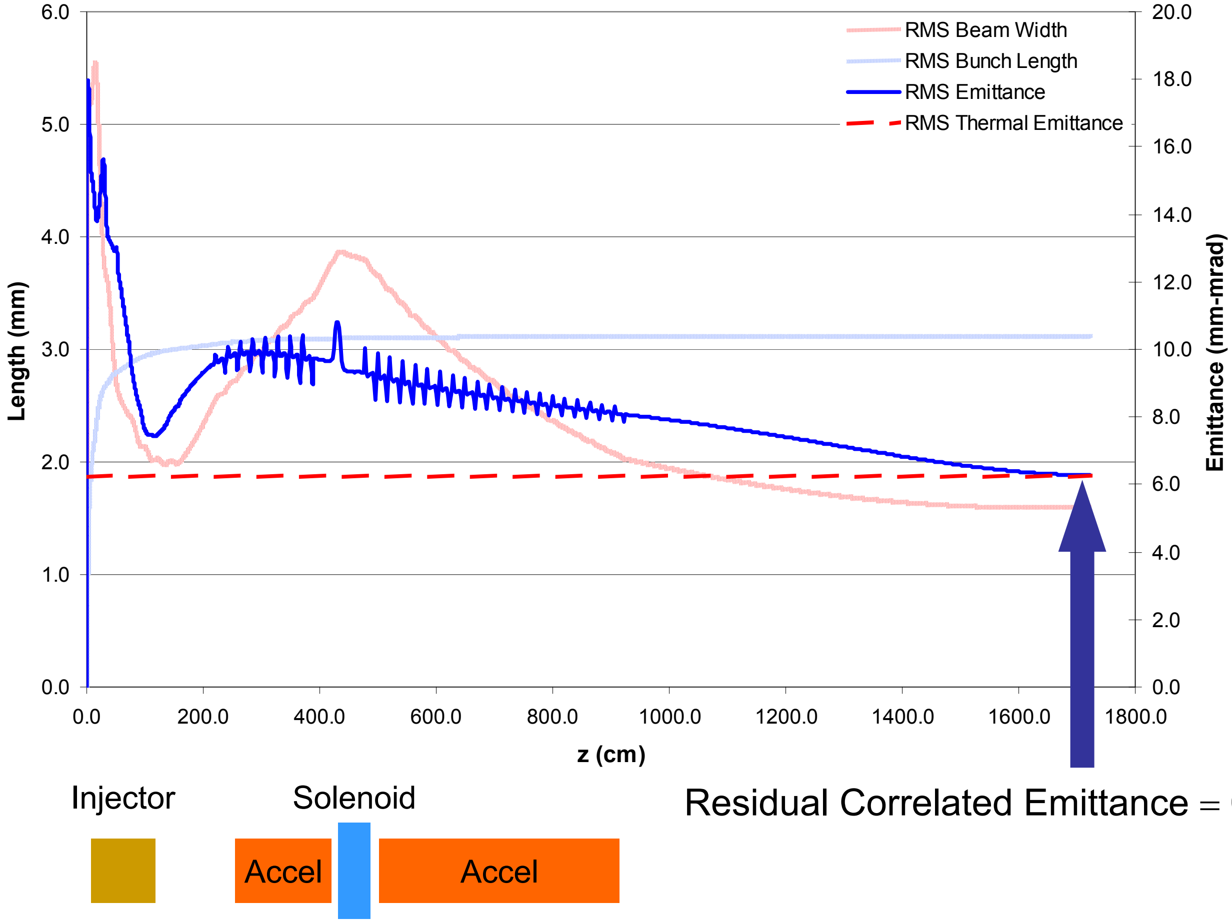


At End (24 MeV)





PARMELA Simulation of LANL/AES 700 MHz High-Average-Current Photoinjector at 3 nC



Residual Correlated Emittance = 0.63 mm mrad

Energy: 6 MeV 11 MeV 24 MeV

Comparison of Required Parameters to Simulation

	Required	Achieved in Simulation
Energy after injector booster linac	> 5 MeV	6 MeV
Bunch charge	3 nC	3 nC
RMS, normalized emittance	< 10 mm mrad	6.2 mm mrad
FWHM bunch length	8 ps	33 ps
Energy spread	< 1%	0.12%

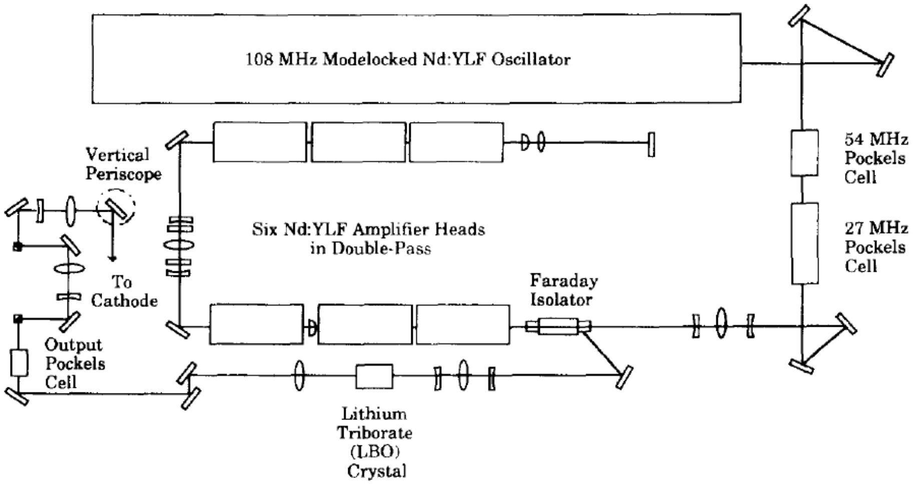
Drive lasers

Laser Power Requirements at Three Common Drive Laser Wavelengths for 100 mA Beam

$$\text{Laser Power} = \frac{1}{\lambda QE}\frac{hc}{q_e}$$

Harmonic	Wavelength	Assumed Cathode QE	Average Power (100 mA Beam)
2ω	527 nm	1%	24 W
3ω	351 nm	1%	35 W
4ω	263 nm	1%	47 W

Boeing High-Average-Current Photoinjector Drive Laser



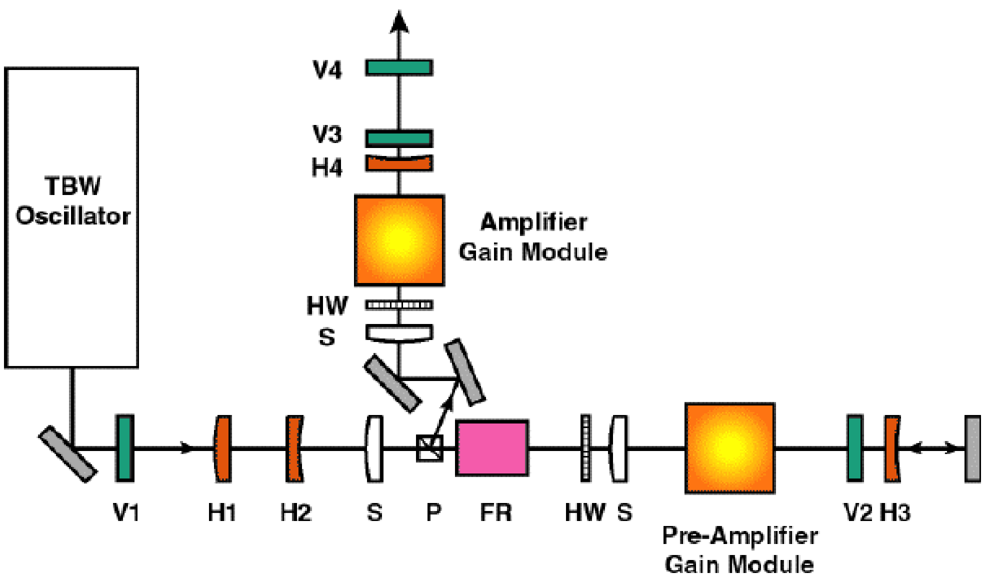
$I = 32\text{ mA} \Rightarrow QE = 2.35\%$

$I = 100\text{ mA} \Rightarrow QE = 7.36\%$

Location	Efficiency or gain	Micropulse energy [μJ]	Rep. Rate [MHz]	Ave. power during macropulse [W]	Duty factor [%]	Net average power [W]
Oscillator output @ 1053 nm		0.185	108	20	100	20.0
Entrance to amplifier chain	0.8	0.148	27	4	30	1.2
Exit of amplifier chain	12	1.776	27	48	30	14.4
After LBO doubler @ 537 nm	0.5	0.888	27	24	30	7.2
After output pockels cell	0.81	0.719	27	19.5	25	4.9
At photocathode	0.65	0.468	27	12.7	25	3.2

D. H. Dowell, S. Z. Bethel and K. D. Friddell, *Nuclear Instruments and Methods A*, **356**, p. 167, 1995.

Possibility of CW UV Laser for High-Average-Current Operation



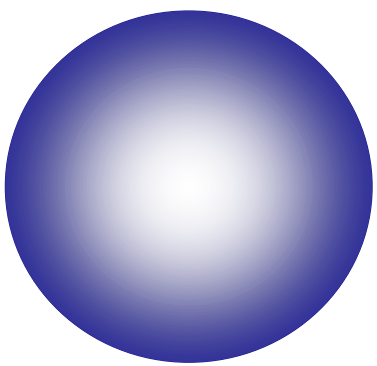
Seed laser	SESAM-mode-locked
Pulse rate	100 MHz
Seed laser CW power	0.7 W
Pulse length	4.5 ps
CW power at 1047 nm	15.7 W
CW power at 524 nm (Type I LBO crystal)	8.8 W
CW power at 262 nm (Type I, critically phase matched, CLBO crystal)	2.9 W

Power in the UV can be increased to ~12 W. (private communication)

K. J. Snell, D. Lee, K. F. Wall and P. F. Moulton, *Topical Meeting on Advanced Solid-State Laser*, Davos, Switzerland, February 2000.

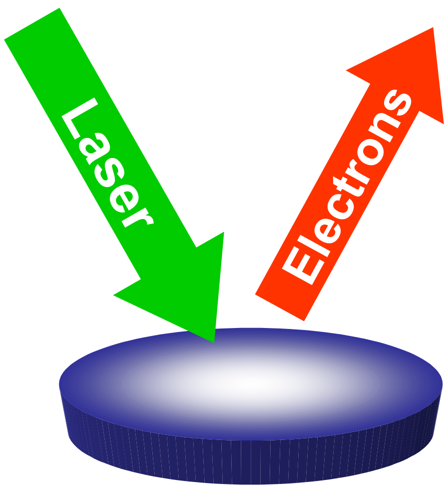
Photocathodes

What is the Perfect Photocathode?



Easy to fabricate.

Can be used as coaster…



…and still get 10% QE.

Desired Photocathode Requirements

- QE ~ 10 %.
- Operation at visible wavelengths.
- Low thermal energy (<< 1 eV).
- Excellent vacuum tolerance. (Less important for DC and superconducting guns.)
- Prompt emission. (Less important for DC gun.)
- Long lifetimes (> 1 month).

Properties of Selected Photocathodes

Material	λ [nm]	QE [%]	Lifetime	Temporal Response	Vacuum Tolerance	Drive Laser Power at 100 mA [W]
K_2CsSb (multialkali)	527	8	4 hr	prompt	Poor	2.9
Cs_2Te with CsBr coating	263	5	> 100 hr	prompt	very good	9.4
GaAs	527	5	58 hr	< 40 ps	moderate	4.7
Cu	266	0.05	> 1 year	prompt	excellent	933
Mg	266	0.3	> 1 year	prompt	excellent	155

- Existing photocathodes will probably work for high-average-current machines.
- "Magical" photocathode still eludes us.

Summary

Summary

•100 mA photoinjectors using normal conducting RF and DC technology can be built now.

•Superconducting RF photoinjectors are not yet ready, but maybe in the near future?

•High-average-power drive lasers are accessible at visible wavelengths, and possibly in the UV.

•We need better photocathodes.