433 MHz High Duty Photocathode RF Gun Experiments

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LANL

Gun Talk Outline

I. 433 MHz PhotoInjector Design Philosophy.

II. Review of 433 MHz RF Photocathode Gun Technology

- **A. Gun Design and Demonstrated Performance**
- **B. Cathode QE and Lifetime**
- **C. Drive Laser Performance**

III. Electron Beam Quality

- **A. Transverse Emittance**
- **B. Longitudinal Emittance**

IV. Summary and Conclusions

Historical Perspective

Motivation:

Design, build and test an RF photocathode gun capable of operating at high current and high duty factor for GBFEL.

Result:

A 1992 demonstration of a two-cell, 433 MHz photocathode gun at 32 mA of average current and 25% duty factor.

Photoinjector Design Philosophy

Use a CW low frequency photocathode gun to generate high charge (1-5 nC) and long (50 ps) micropulses.

Advantages:

- **Capable of CW operation**
- **High charge**
- **Long micropulses**

→ **Excellent Beam Quality at High Beam Current**

Disadvantage:

- **Cathode field limited to 25-30 MV/m**

Accelerate in Low frequency RF cavities.

Advantages:

- **Minimizes wakefields**
- **CW operation**

Disadvantage:

- **Accelerating gradient limited to 5 MV/m**

Linearize and compress to high peak current at 20 MeV.

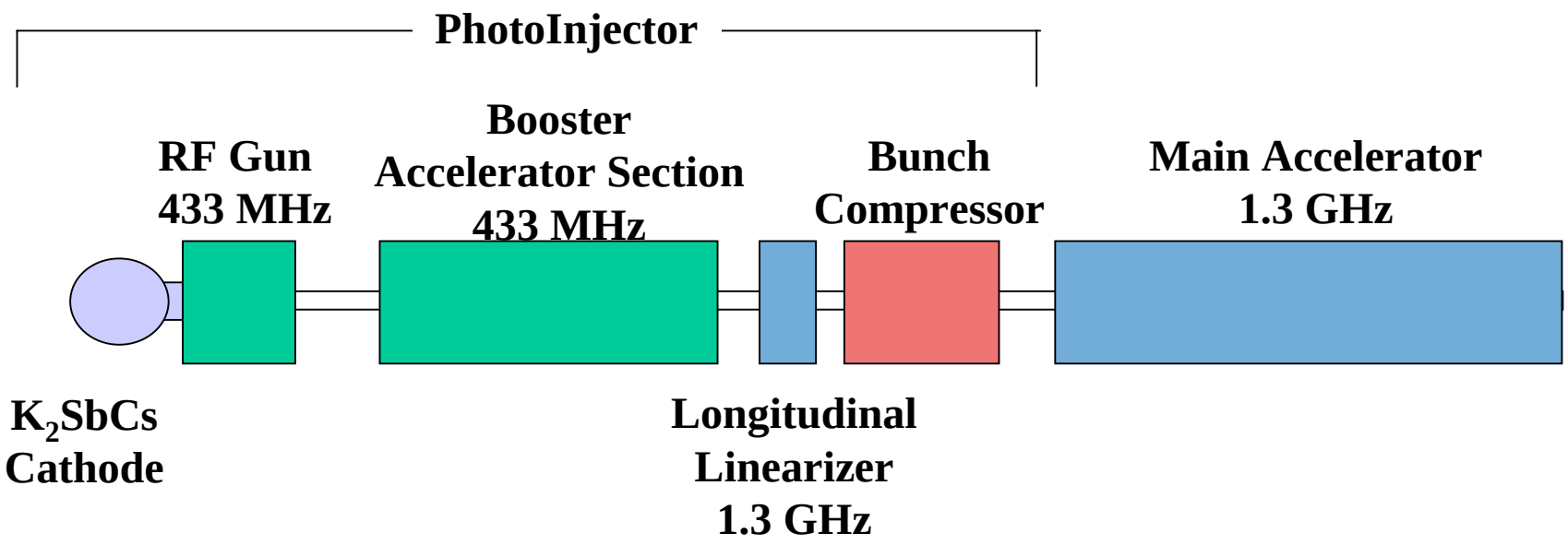
Advantages:

- **Linearizing improves compression**
- **Reduces space charge emittance growth**

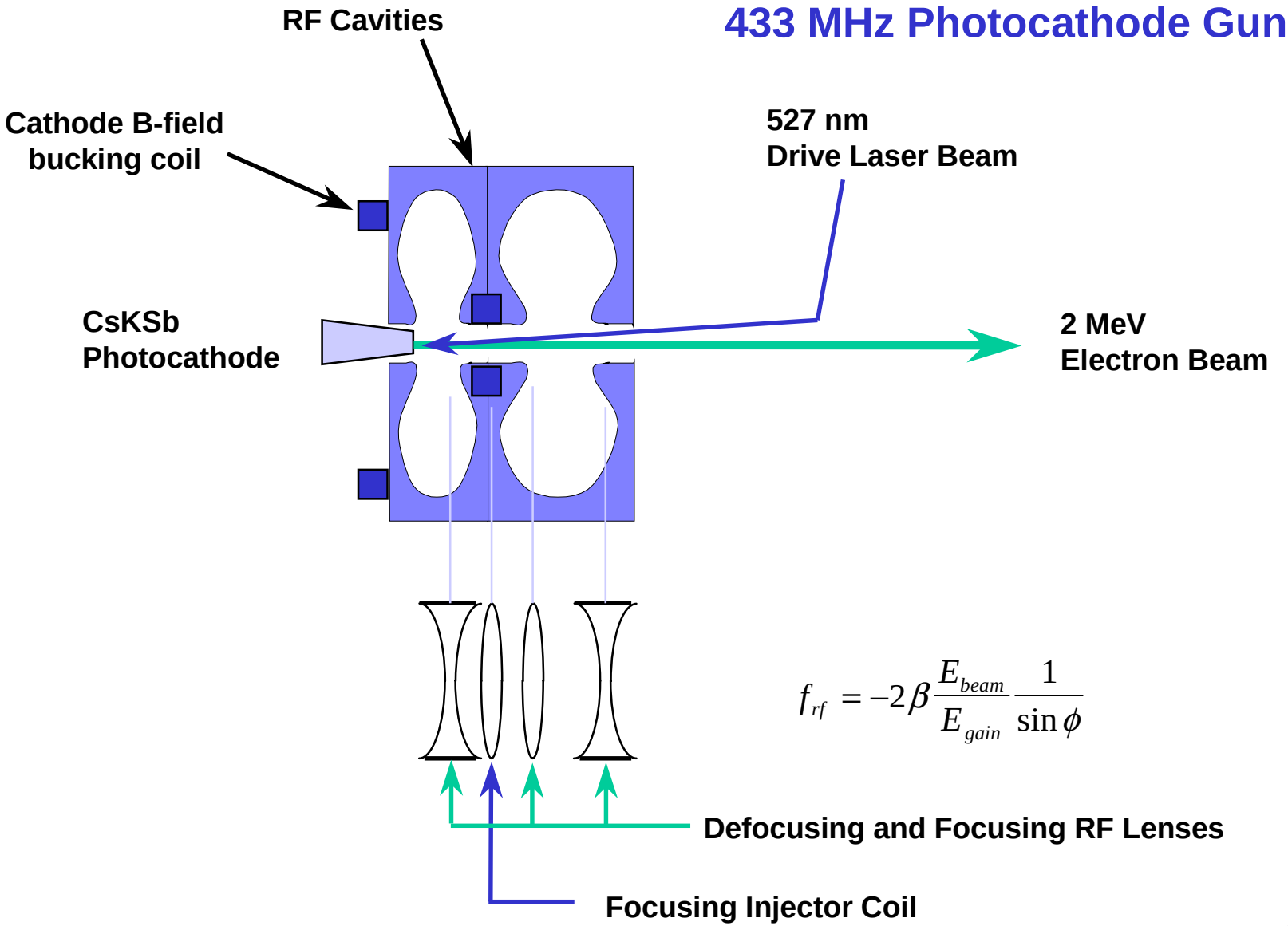
Disadvantage:

- **Emittance growth due to coherence synchrotron radiation**

Layout of the 433 MHz PhotoInjector

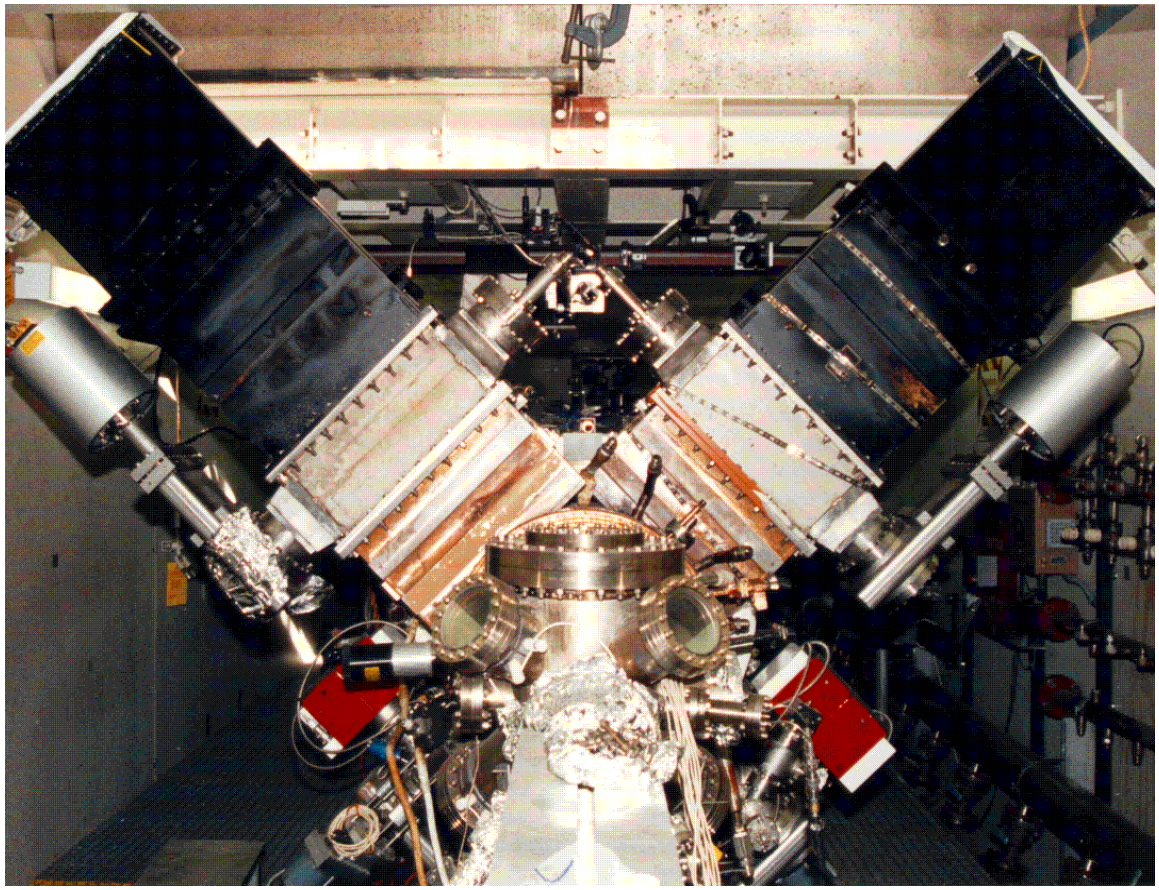


Electron Beam Optics of the 433 MHz Photocathode Gun



$$f_{rf} = -2\beta \frac{E_{beam}}{E_{gain}} \frac{1}{\sin\phi}$$

The Boeing 433 MHz RF Photocathode Gun



Demonstrated Performance of 433 MHz Photocathode Gun, 1992 H-D Test

Photocathode Performance:	
Photosensitive Material:	K_2CsSb Multialkali
Quantum Efficiency:	5% to 12%
Peak Current:	45 to 132 amperes
Cathode Lifetime:	1 to 10 hours
Angle of Incidence:	near normal incidence
Gun Parameters:	
Cathode Gradient:	26 MV/meter
Cavity Type:	Water-cooled copper
Number of cells:	4
RF Frequency:	433 $x10^6$ Hertz
Final Energy:	5 MeV(4-cells)
RF Power:	600 $x10^3$ Watts
Duty Factor:	25%, 30 Hertz and 8.3 ms
Laser Parameters:	
Micropulse Length:	53 ps, FWHM
Micropulse Frequency:	27 $x10^6$ Hertz
Macropulse Length:	10 ms
Macropulse frequency:	30 Hertz
Wavelength:	527 nm
Cathode Spot Size:	3-5 mm FWHM
Temporal and Transverse Distribution:	gaussian, gaussian
Micropulse Energy:	0.47 microjoule
Energy Stability:	1% to 5%
Pulse-to-pulse separation:	37 ns
Micropulse Frequency:	27 $x10^6$ Hertz
Gun Performance:	
Emittance (microns, RMS):	5 to 10 for 1 to 7 nCoulomb
Charge:	1 to 7 nCoulomb
Energy:	5 MeV
Energy Spread:	100 to 150 keV

RF Characteristics of 433 MHz Gun Cavities

Measured Values

Measured Gun Cavity RF Characteristics

Parameter		L1	L2	Units
frequency	f	433.33	433.33	MHz
shunt impedance	$R=V^2/P_c$	2.86	4.28	MΩ
coupling coefficient	β	3.1	3.1	

Operating Parameters for Existing Gun Cavities
External Coupling Coefficient β=3.1

Parameter		L1	L2	Units
nominal accelerating voltage	V	0.9	1.1	MV
wall loss power	P_c	285	285	kW
beam power @ I_{avg}=200 mA	P_b	180	220	kW
forward power required	P_k	515	545	kW
reflected power	P_r	50	40	kW

Optimized for 200 Milliamperes

Operating Parameters for PERL-Optimized Gun Cavities
External Coupling Coefficient β=2.0

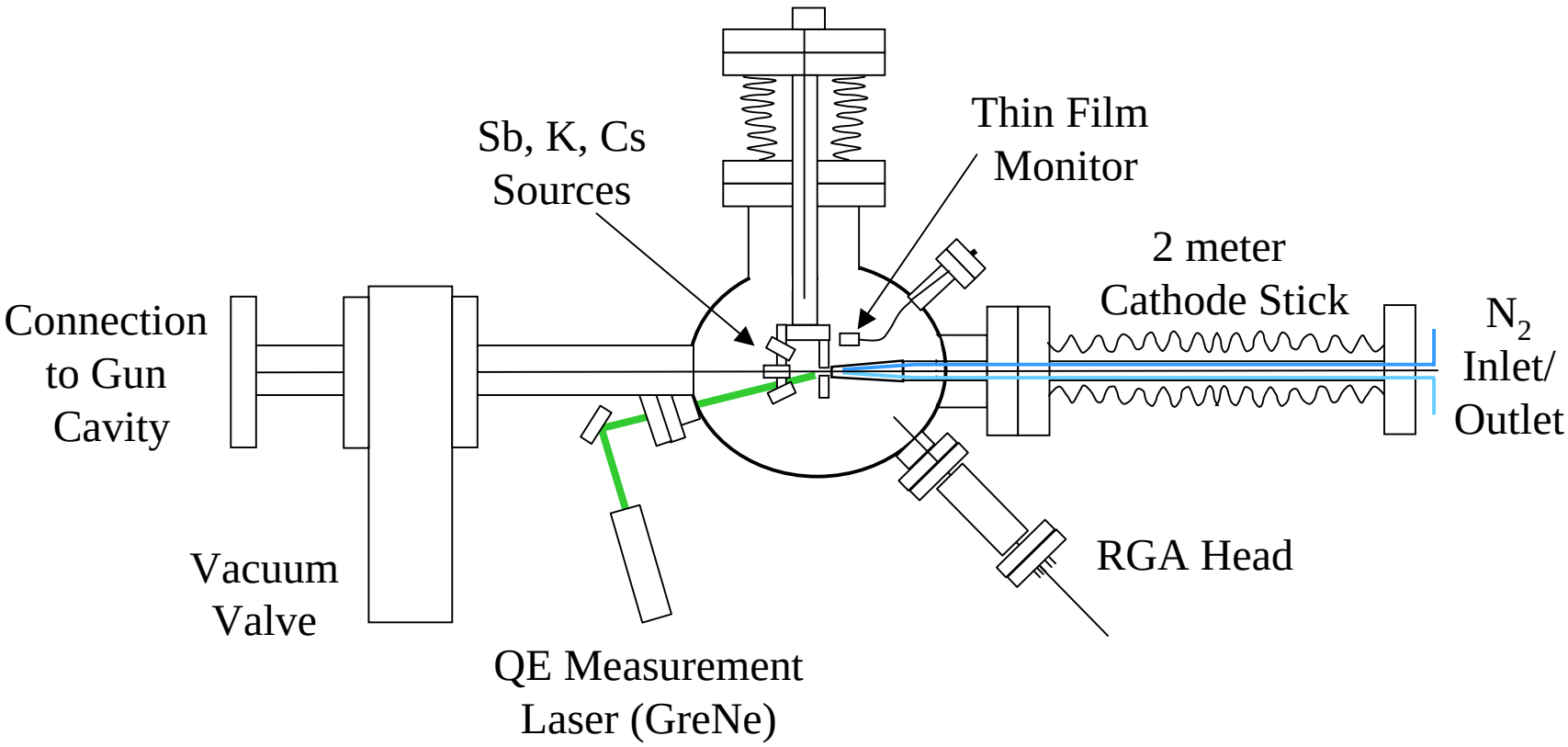
Parameter		L1	L2	Units
nominal accelerating voltage	V	0.9	1.1	MV
wall loss power	P_c	285	285	kW
beam power @ I_{avg}=200 mA	P_b	180	220	kW
forward power required	P_k	470	505	kW
reflected power	P_r	5	2	kW

Data supplied by A.M. Vetter.
See also:
J.L. Warren, T.L. Buller and A.M. Vetter, "Design of MCTD Photoinjector Cavities", Proc. 1989 IEEE PAC, Vol I, pp.420-422. May 20-27, 1989, Chicago, Illinois,

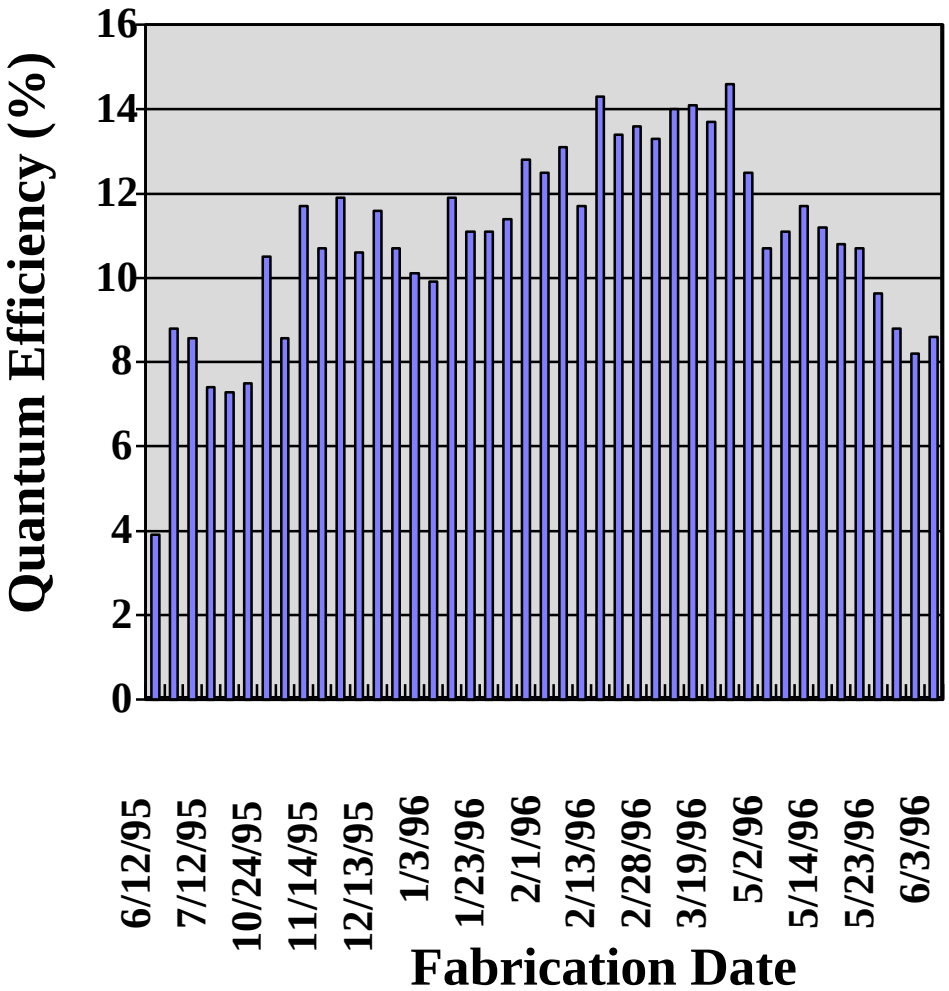
Types of Photocathodes

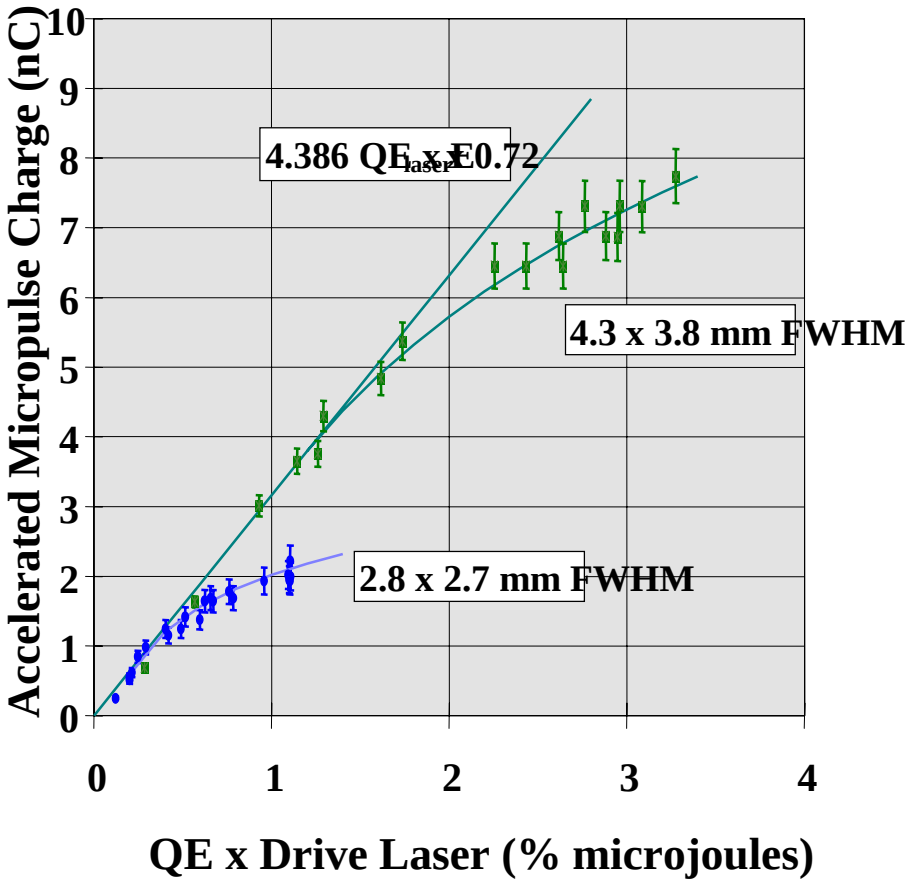
Material	QE Range	Drive Laser Wavelength	Cathode Fab.	Vacuum Req.	Drive Laser
Metal (Cu, Mo…)	~0.02-0.06%	260 nm, UV	None	10^{-7} T	Difficult
CsK_2Sb	10-14%	527 nm	Difficult	10^{-10} T	Moderate
CsTe	10-14%	260 nm	Easy	10^{-9} T	Moderate to Difficult
LaB_6	~0.1%	355 nm	Easy	10^{-7} T	Difficult
Ga As (Cs)	1-5%	527 nm	Moderate	10^{-11} T	Moderate

Photocathode Fabrication Chamber

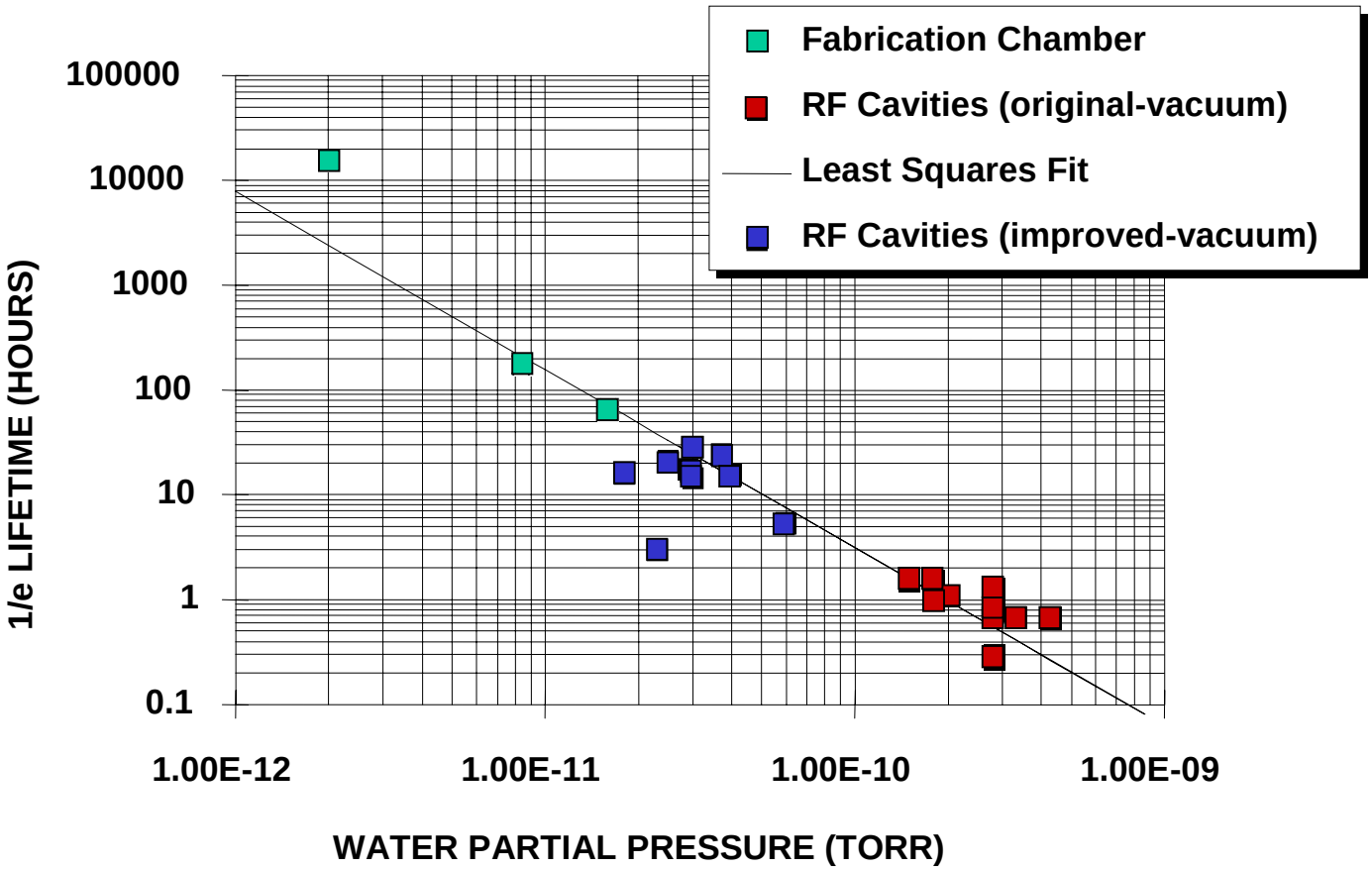


QE Fabrication History and Gun Space Charge Limits

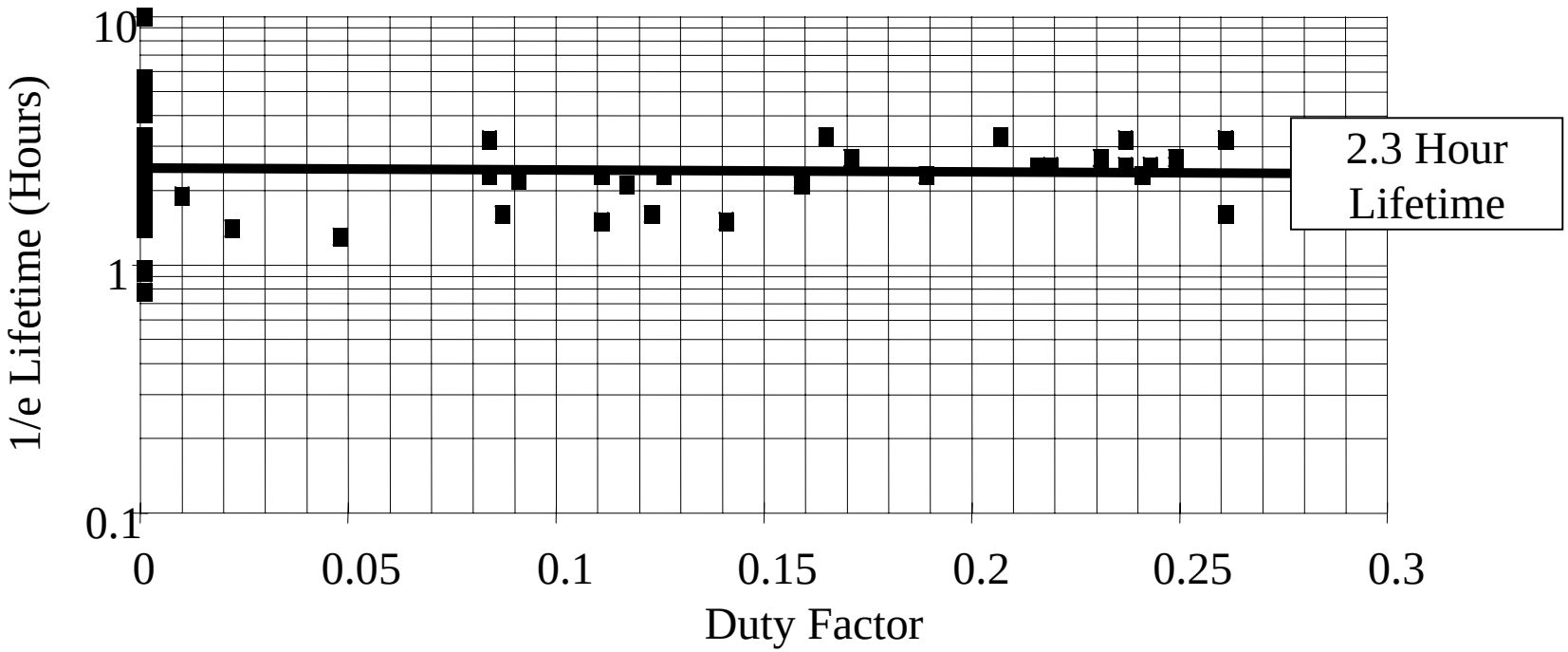




Cathode Lifetime Vs. H_2O Partial Pressure

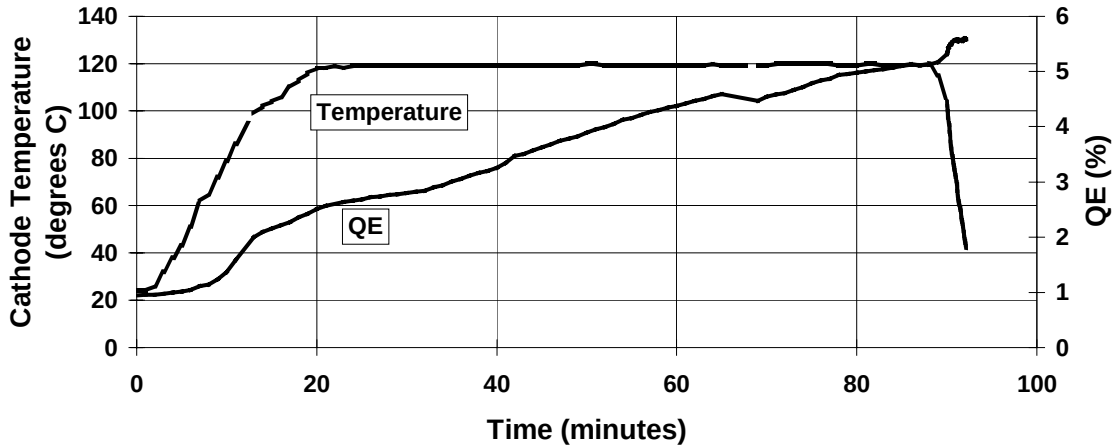


Photocathode 1/e Lifetime Vs. Duty Factor

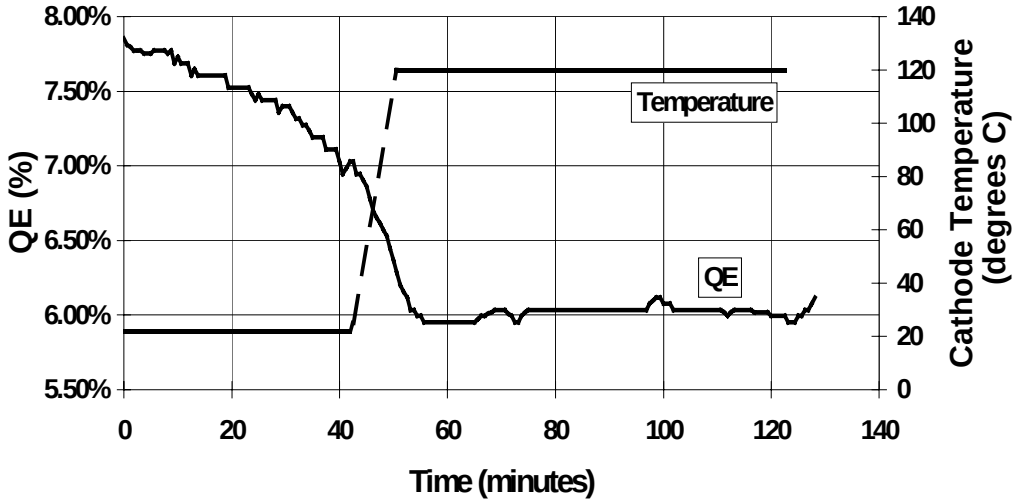


Cathode Rejuvenation
and
Improving Lifetime by Operating with Hot Cathode

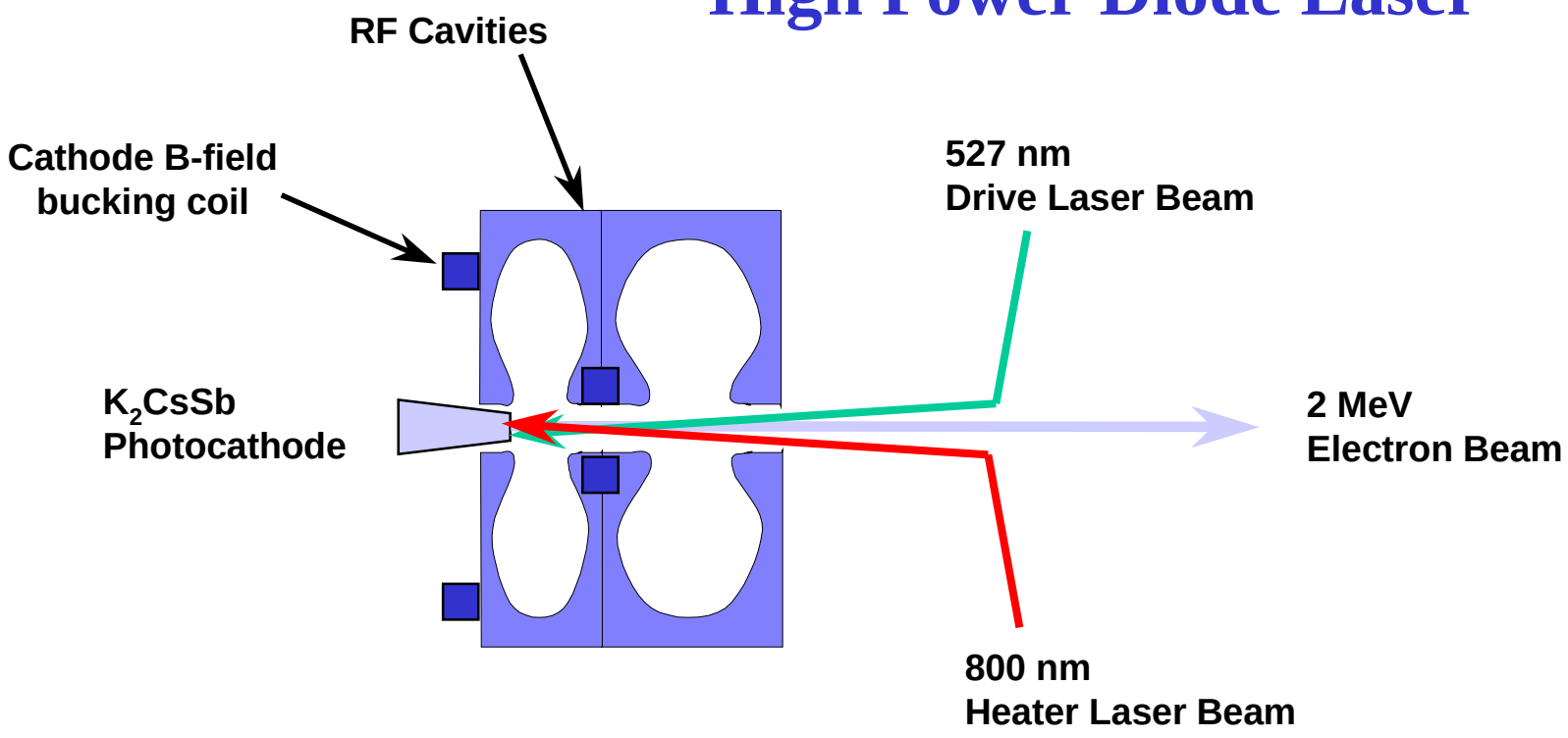
Rejuvenating a used K_2CsSb cathode by heating it to 120 degrees C. The quantum efficiency increases at the rate of 2.5% / hour



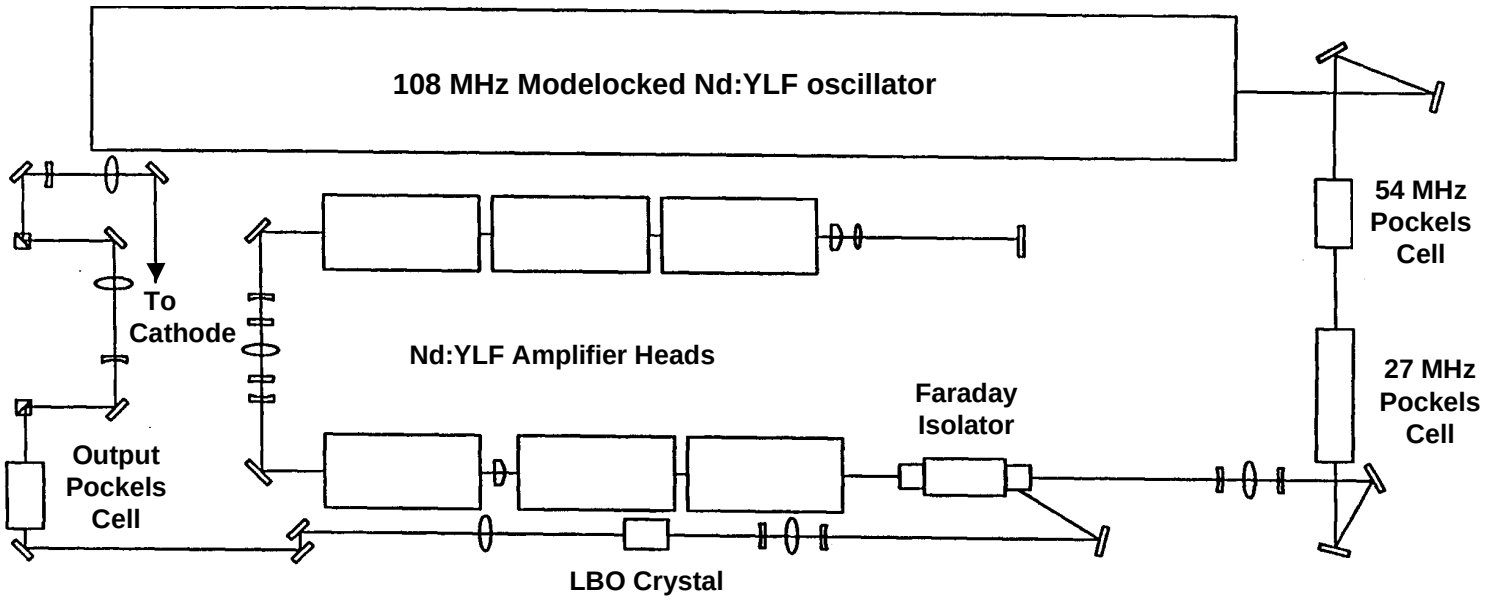
Photocathode quantum efficiency at elevated temperature in the RF cavity vacuum



Heating the Cathode With a High Power Diode Laser



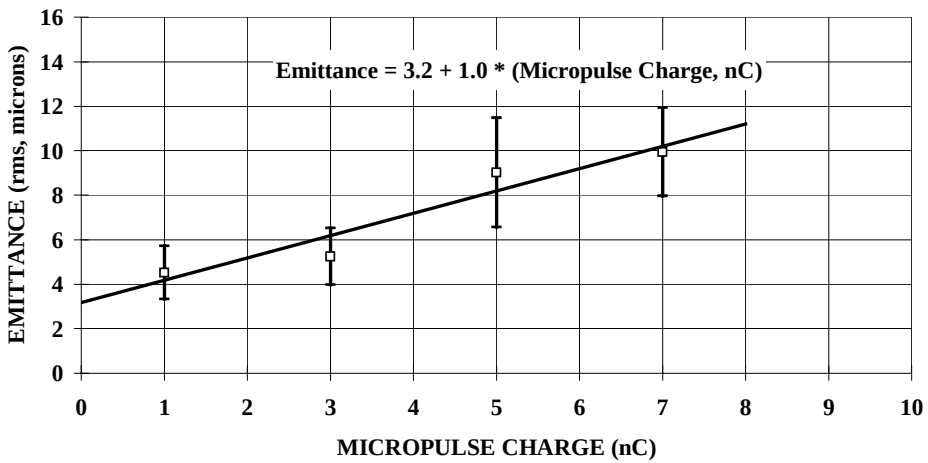
Drive Laser Configuration Used in 1992 High Duty Test



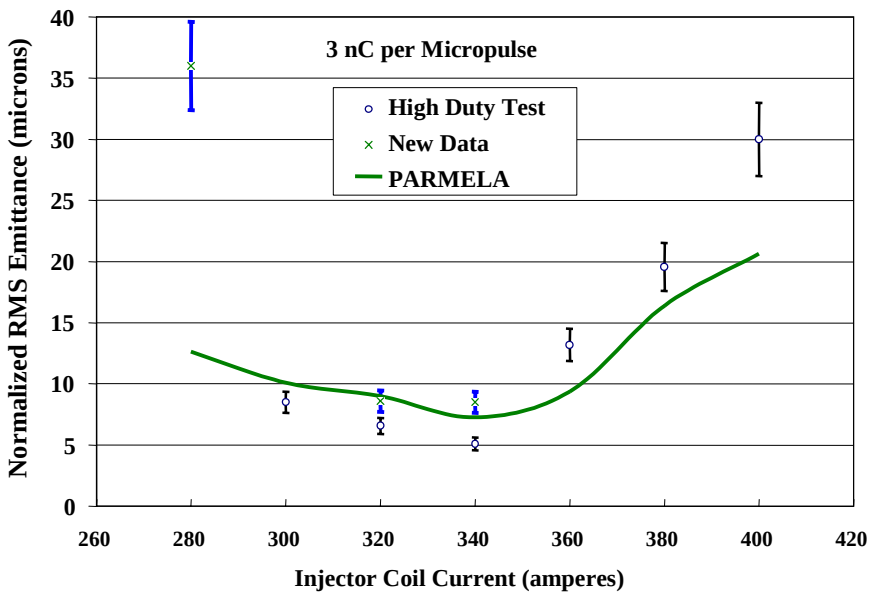
433 MHz Gun Transverse Beam Quality Measurements

1992 and 1994-1996 Test Results

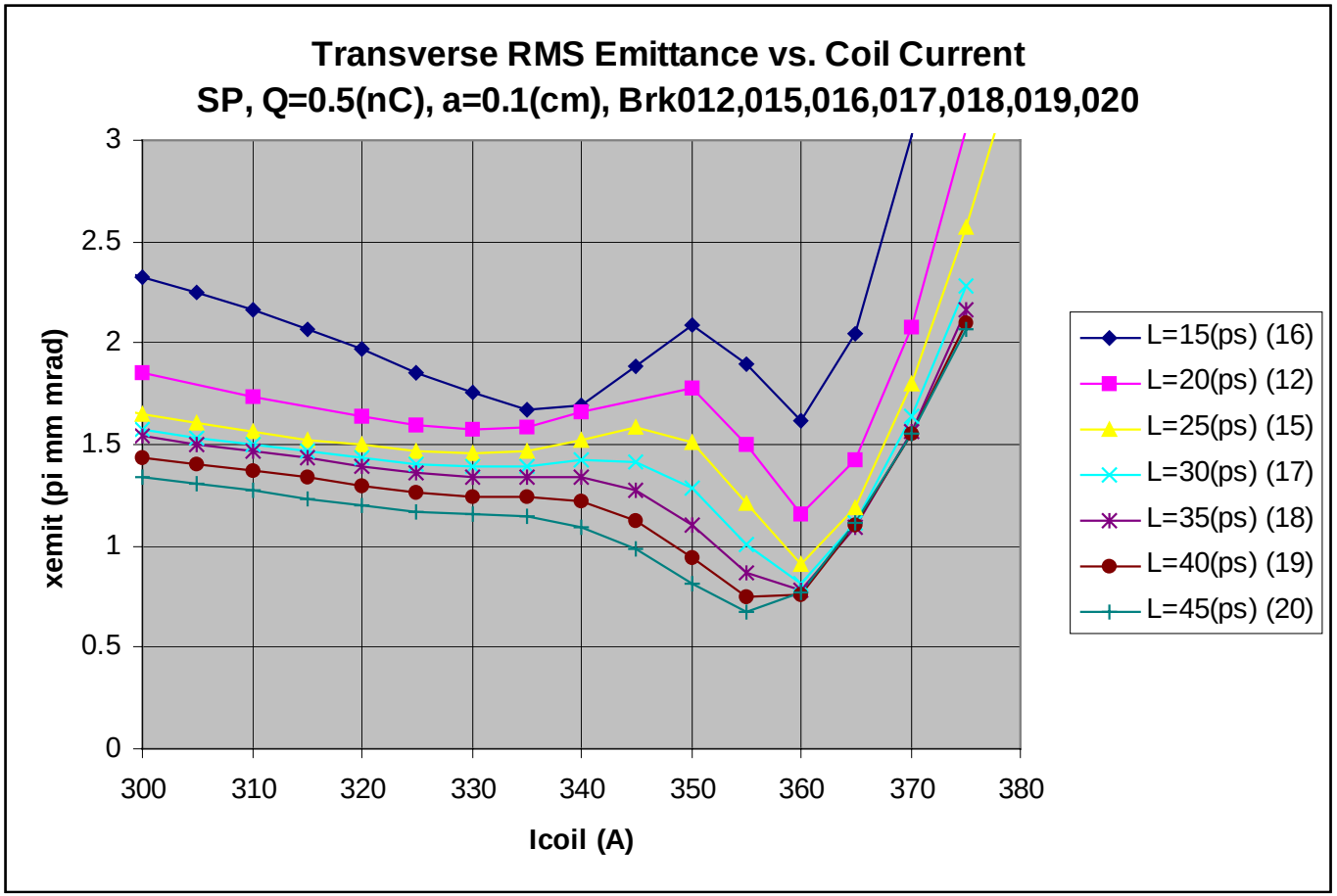
Gun Emittance Vs. Microbunch Charge



Beam Emittance at 3 nC Gaussian-Gaussian Distributions



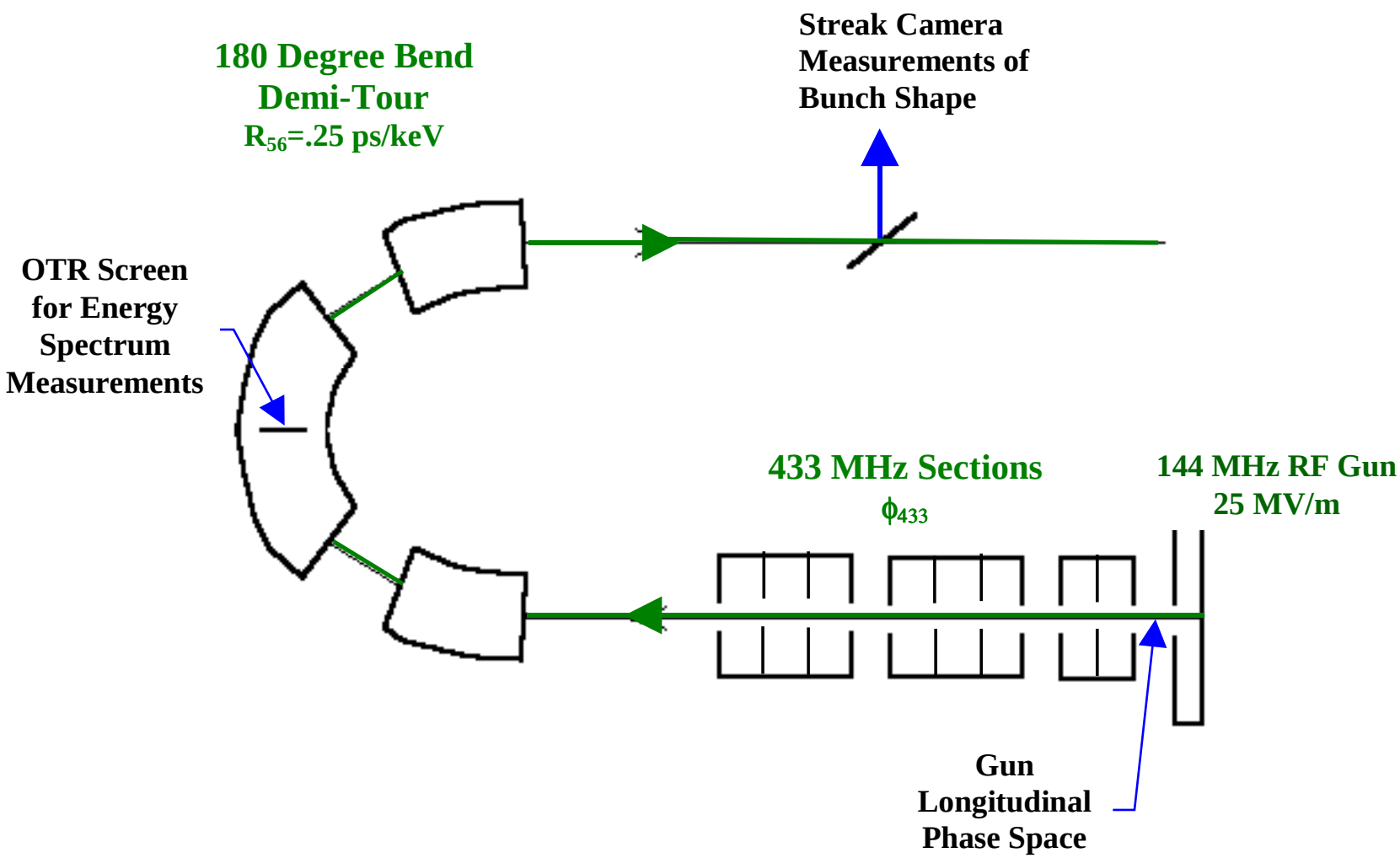
PARMELA_B Simulations at 0.5 nC



PARMELA_B calculations provided by B. Koltenbah, Boeing

Longitudinal Emittance

Components of the ELSA Accelerator Used to Make the Longitudinal Phase Space Measurements



Definition of Phase Space Parameters, Including Correlations

Longitudinal Beam Ellipse:

$$\gamma\Delta t^2 + 2\alpha\Delta t\Delta E + \beta\Delta E^2 = \frac{\varepsilon_\ell}{\pi}$$

Longitudinal Beam Matrix:

$$\tau = \begin{pmatrix} \tau_{11} & \tau_{12} \\ \tau_{12} & \tau_{22} \end{pmatrix} = \varepsilon_\ell \begin{pmatrix} \beta & \alpha \\ \alpha & \gamma \end{pmatrix}$$

$\sqrt{\tau_{11}}$ = **Uncorrelated Bunch Length**

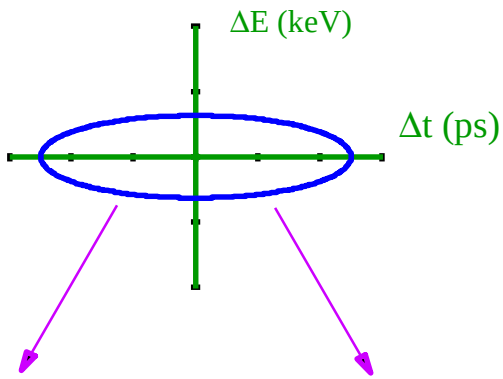
$\sqrt{\tau_{22}}$ = **Uncorrelated Energy Spread**

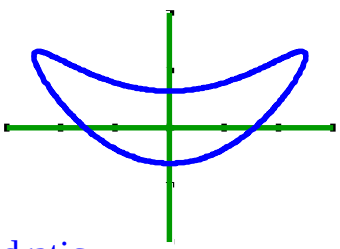
Include correlated emittance by distorting the ellipse boundary using quadratic and cubic terms:

$$\Delta E = -\frac{\alpha}{\beta}\Delta t \pm \sqrt{\left(\frac{\alpha}{\beta}\Delta t\right)^2 - \frac{\gamma\Delta t^2 - \frac{\varepsilon_\ell}{\pi}}{\beta}} + a\Delta t^2 + b\Delta t^3$$

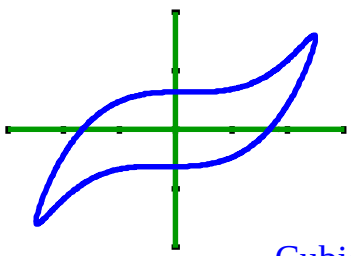
Distortions of the Longitudinal Phase Space Ellipse

Undistorted Phase Space
$\tau_{12} = 0$
$a = 0, \; b = 0$



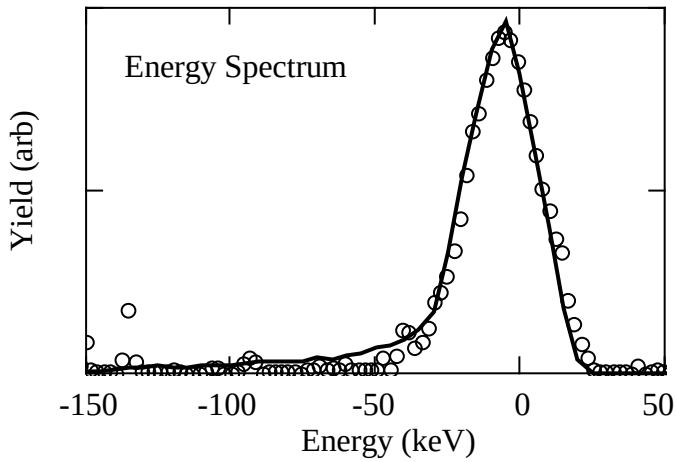


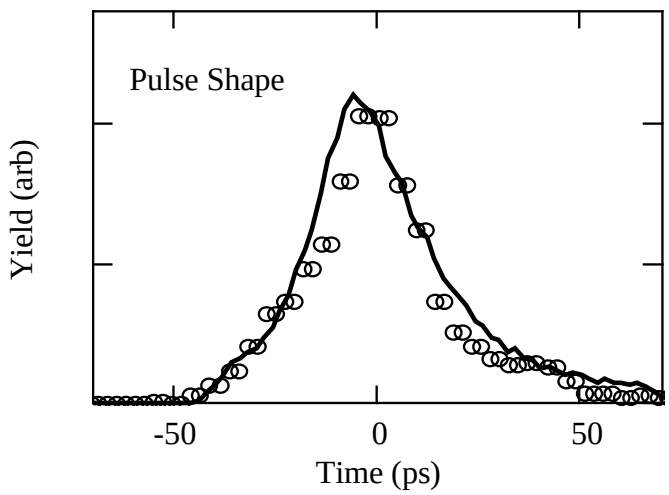
Quadratic
Distortion
$\tau_{12} = 0$
$a > 0, \; b = 0$



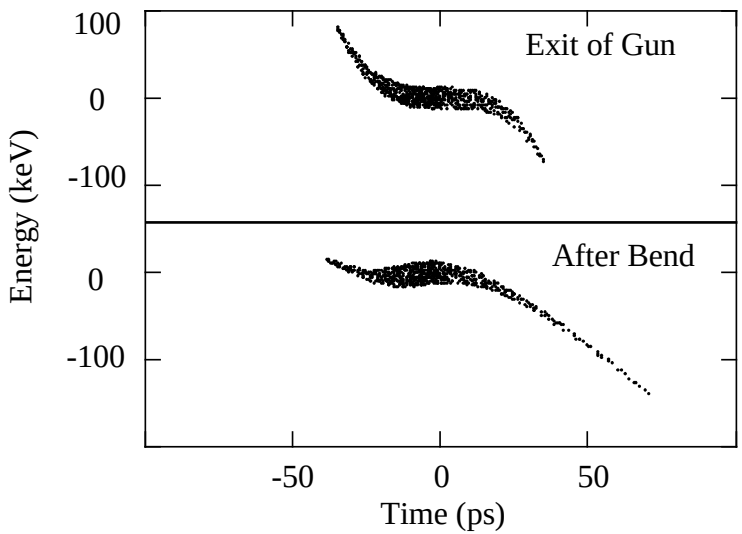
Cubic
Distortion
$\tau_{12} = 0$
$a = 0, \; b > 0$

Fits to 1 nC per Microbunch Data



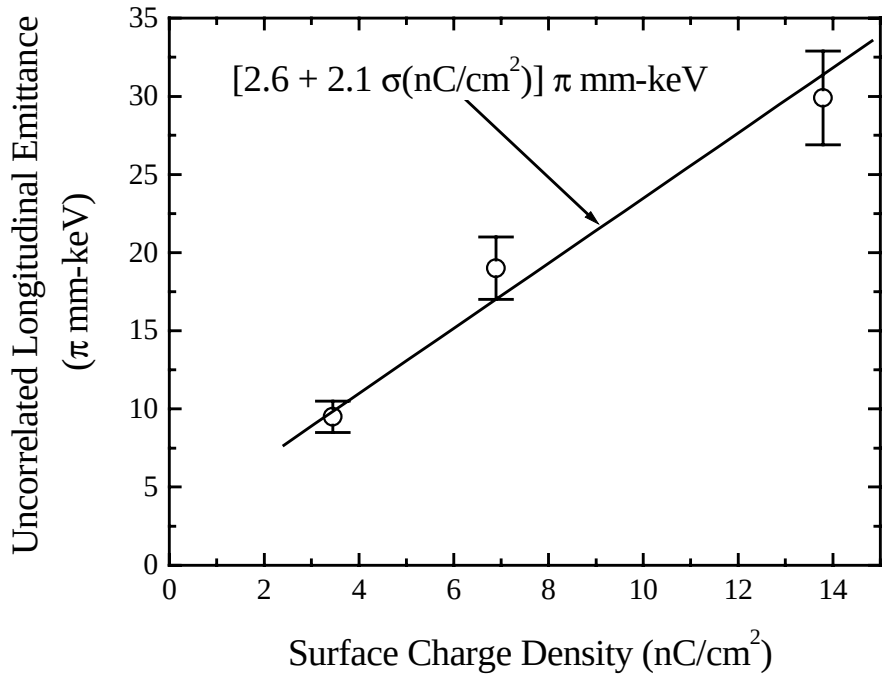


Longitudinal Phase Space Distributions Obtained from the Data Analysis

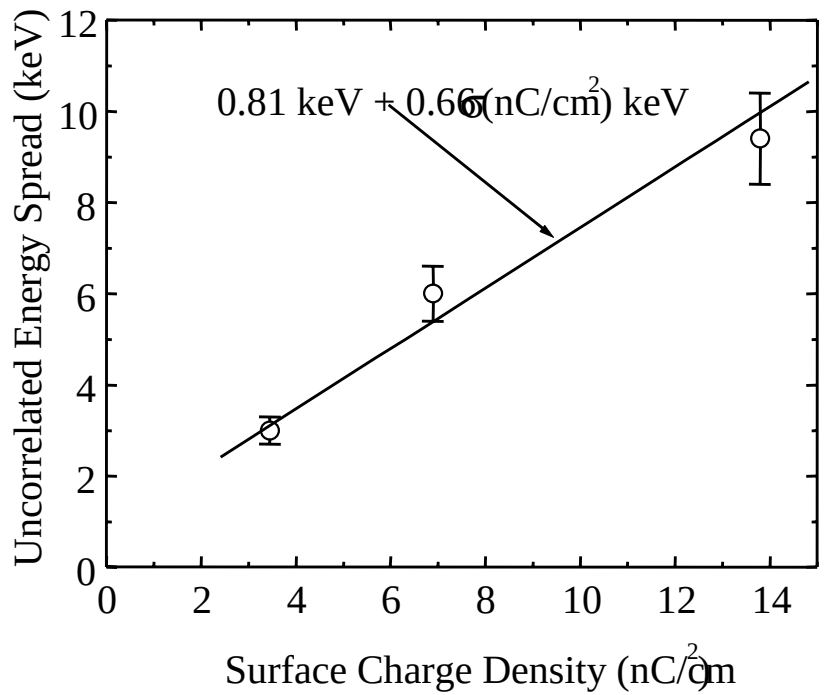


Ref: S. Joly et al.,...

The Uncorrelated Emittance Grows Linearly with Surface Charge Densities Below the Space Charge Limit



In These Experiments Most of the Emittance Growth Was due to Increased Energy Spread



Pulse length a constant 11 ps(rms)

10 nC/cm² corresponds to 11 MV/m

Ref: D.H. Dowell et al., PAC97.

Summary and Conclusions

433 MHz PhotoIjnector Design Philosophy/Approach:
Gun, Booster, Linearizer and Compressor

433 MHz Gun has Demonstrated Most of the PERL Requirements:
Duty Factor
Beam Quality:
Transverse and Longitudinal Emittance

Problems and Unfinished Business:
Cathode Lifetime
Cathode Fabrication
Drive Laser
RF Design and Controls
Experimental Verification of Low Emittance at 0.5 nC
Start-to-End Simulations
CSR Experiments