Considerations for Repetition Rate and Laser

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Jefferson Lab Professor

Presented to:
K-Long Review

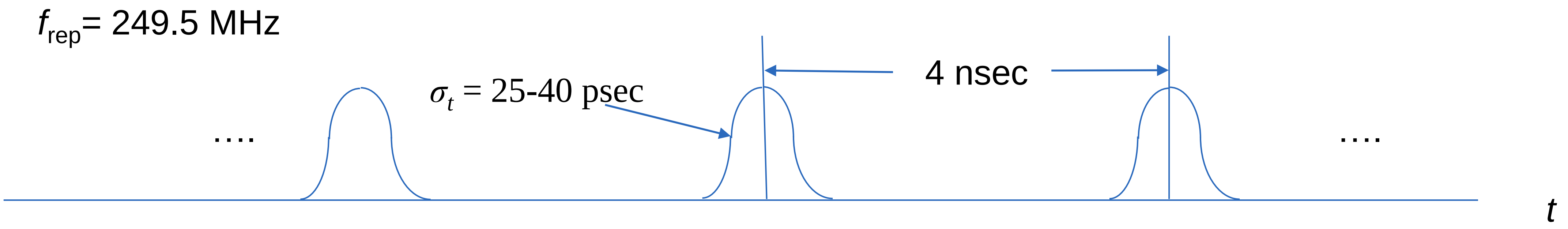
August 2, 2023

Outline

- CEBAF Beam
- K-Long Beam
  - Space Charge
  - Effect on Bunch Length
- Measurements at 130 kV
- Plans for 200 kV
  - Simulations
- K-Long Drive Laser
- LLRF
- Conclusions

CEBAF Beam

- Time structure off cathode for standard running to Hall D (4 Hall OPS)



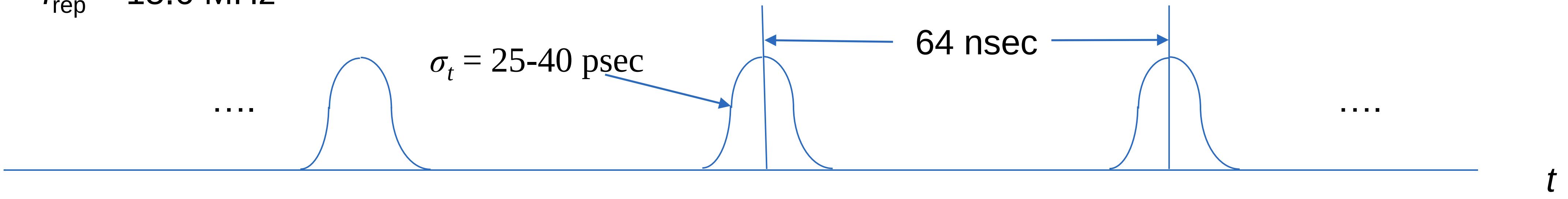
Average Current	Bunch Charge
1 μA	0.004 pC
5 μA	0.02 pC

- Time structure produced by CW pulsed laser structure illuminating photocathode

K-Long Beam Structure

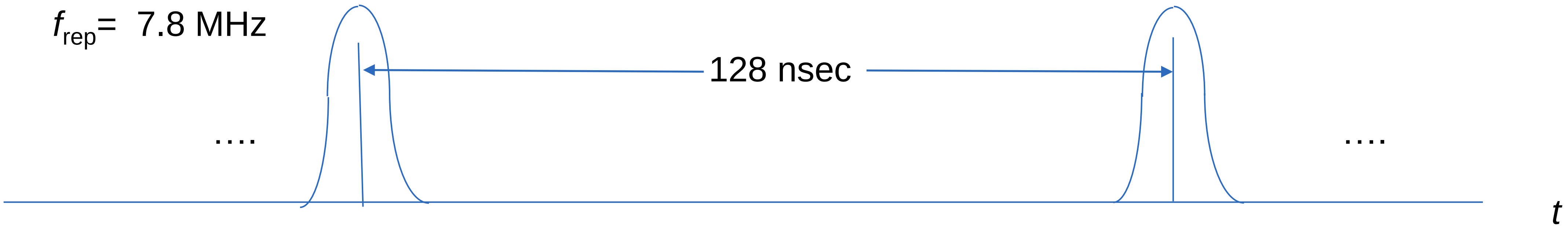
- Baseline

f_{rep}= 15.6 MHz



- 128 nsec

f_{rep}= 7.8 MHz



- Both 5 μA average current

Charge (Sunil Pokharel Annual Review; spokh003@odu.edu)

CEBAF K_L Beam Requirements

- CEBAF injector bunch currents and repetition rates for K_L experiment.

Current (μA)	Repetition Rate (MHz)	Sub-harmonic of 499 MHz	Bunch Charge (pC)	Equivalent 249.5 MHz current (μA)
2.5	15.59	32nd	0.16	40
2.5	7.80	64th	0.32	80
5.0	15.59	32nd	0.32	80 ← 64 ns baseline
5.0	7.80	64th	0.64	160 ← 128 ns goal
10.0	15.59	32nd	0.64	160 ← 128 ns 200 kV experiment

- With existing gun (130 kV), didn't achieve 0.64 pC from current laser, laser development is required to achieve bunch repetition rates.

- Power amplification is necessary for higher beam currents required

M. Amaryan, et al. arXiv:2008.08215v3 [nucl-ex] 4 Mar 2021

Space Charge

- Space charge forces are the Coulomb repulsive forces inside a region of charge accumulation.

- Space charge forces can degrade beam quality and cause instabilities resulting in emittance growth, energy spread, halo formation, particle losses and even can set up upper limit for beam current.

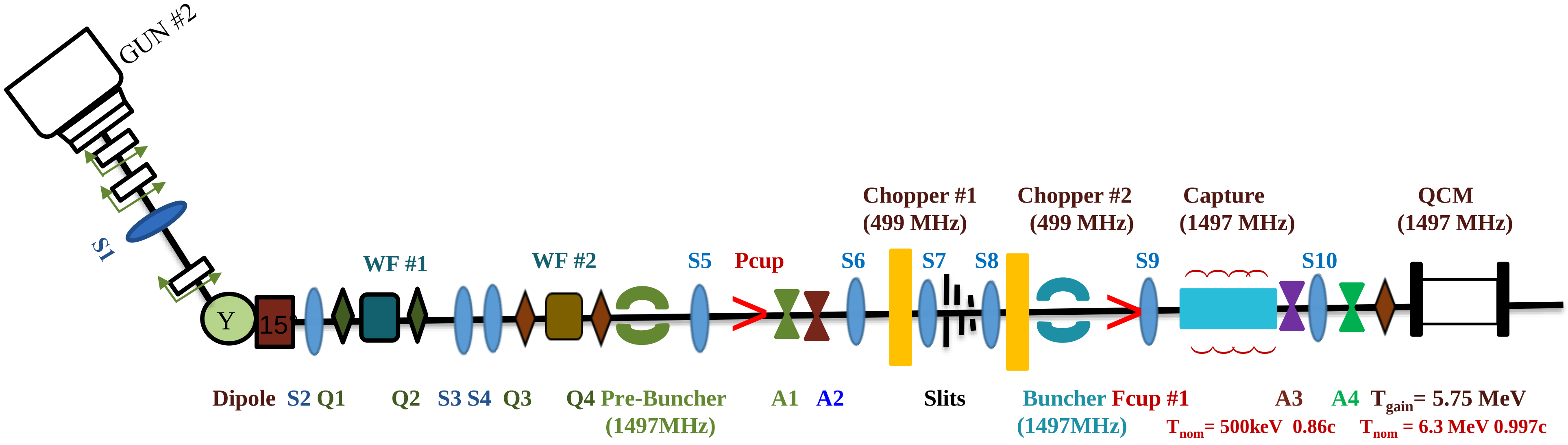
- For a Gaussian distribution, with $\sigma_x = \sigma_y = \sigma_r$

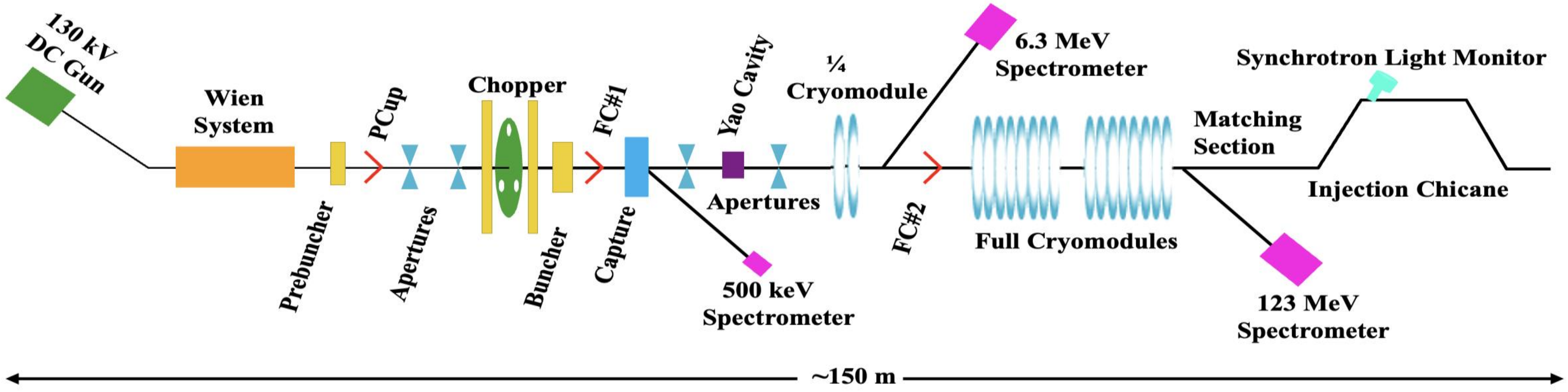
$$\rho(r,z) = \frac{q_0}{(2\pi)^{3/2}\sigma_z\sigma_r^2} . \exp(-\frac{z^2}{2\sigma_z^2})\exp(-\frac{r^2}{2\sigma_r^2})$$

$$F_r(r,z) = qE_r(1-\beta^2) = \frac{qq_0}{(2\pi)^{3/2}\epsilon_0\sigma_z\gamma^2} . \exp(-\frac{z^2}{2\sigma_z^2}) . \frac{1-\exp(-\frac{r^2}{2\sigma_r^2})}{r}$$

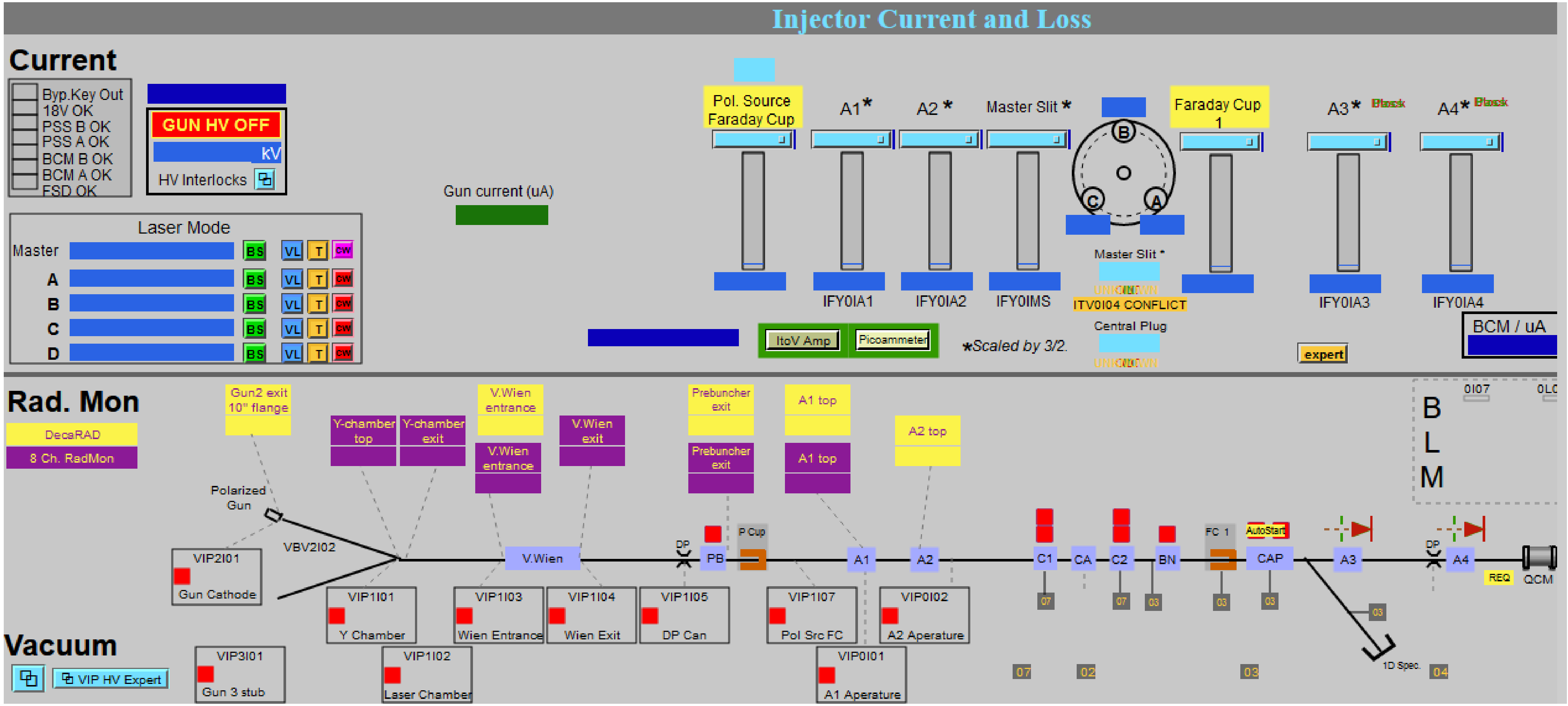
130 keV Beamline and Setup Details

CEBAF Injector Layout





Injector Tools for Measurements



Simulation Details (130 keV)

- General Particle Tracer (GPT) Simulations

- 130 kV gun
- 160 µA (0.64 pC, 128 ns) and 80 µA (0.32 pC, 64 ns) beam current at 250 MHz frequency.
- These are equivalent to 5 µA, 7.80 MHz and 15.59 MHz repetition rates

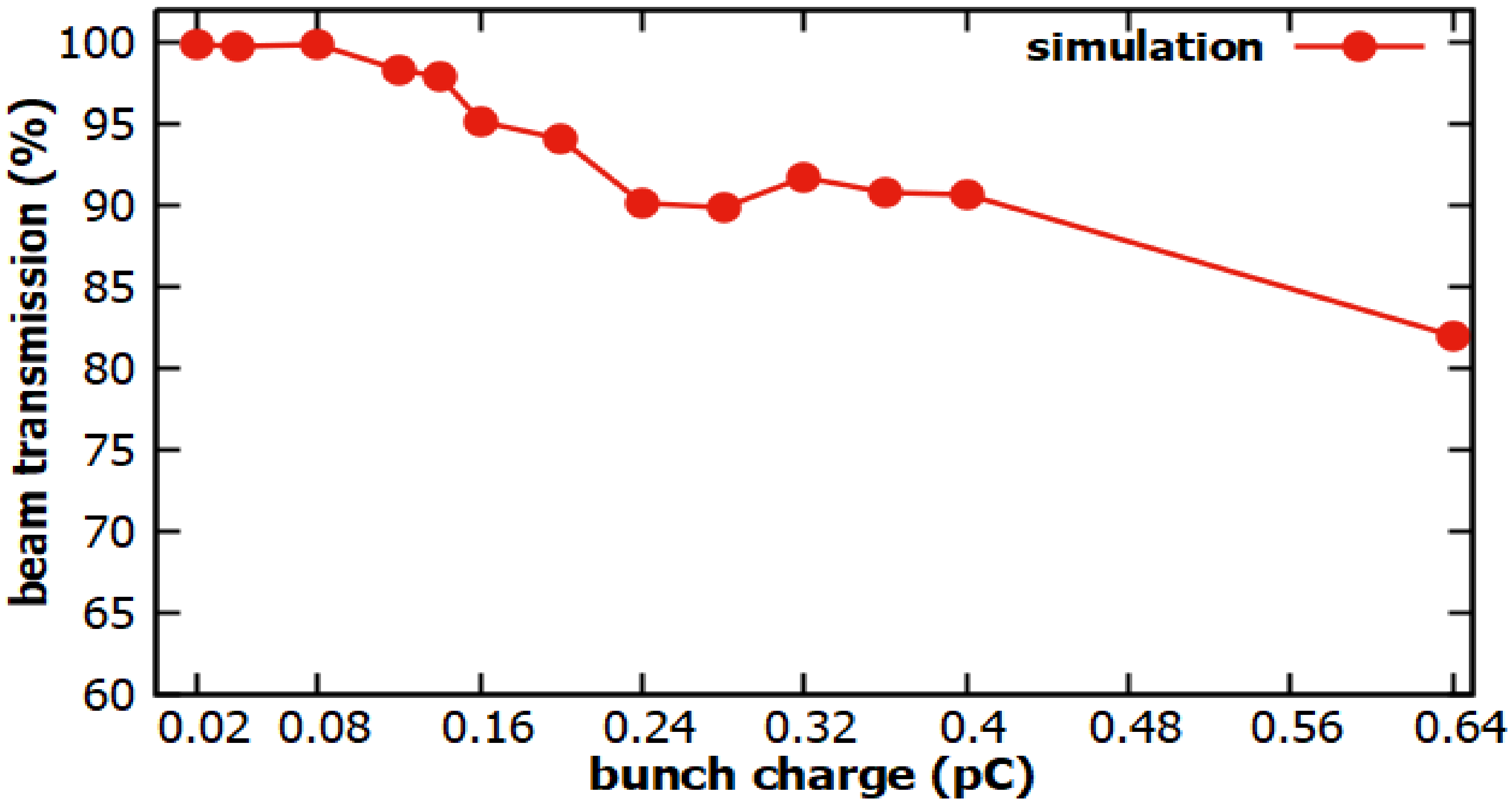
- Initial beam distributions
  - Gaussian beam, beam size (4 sigma) on cathode is X: 2.237 mm, Y: 2.093 mm
  - Laser pulse length 19.10 ps (FWHM=45ps)
  - The transverse thermal emittance,

$$\epsilon_{n,\perp} = \sigma_\perp \sqrt{\frac{\mathrm{MTE}}{mc^2}}$$

  - 0.1348 mm mrad for a mean transverse energy of 30.691 meV for the GaAs photocathode.
  - 10k macro-particles, using the space charge3Dmesh algorithm

I. V. Bazarov et al., Journal of Applied Physics 103, 054901 (2008)

Simulation Results (130 keV)

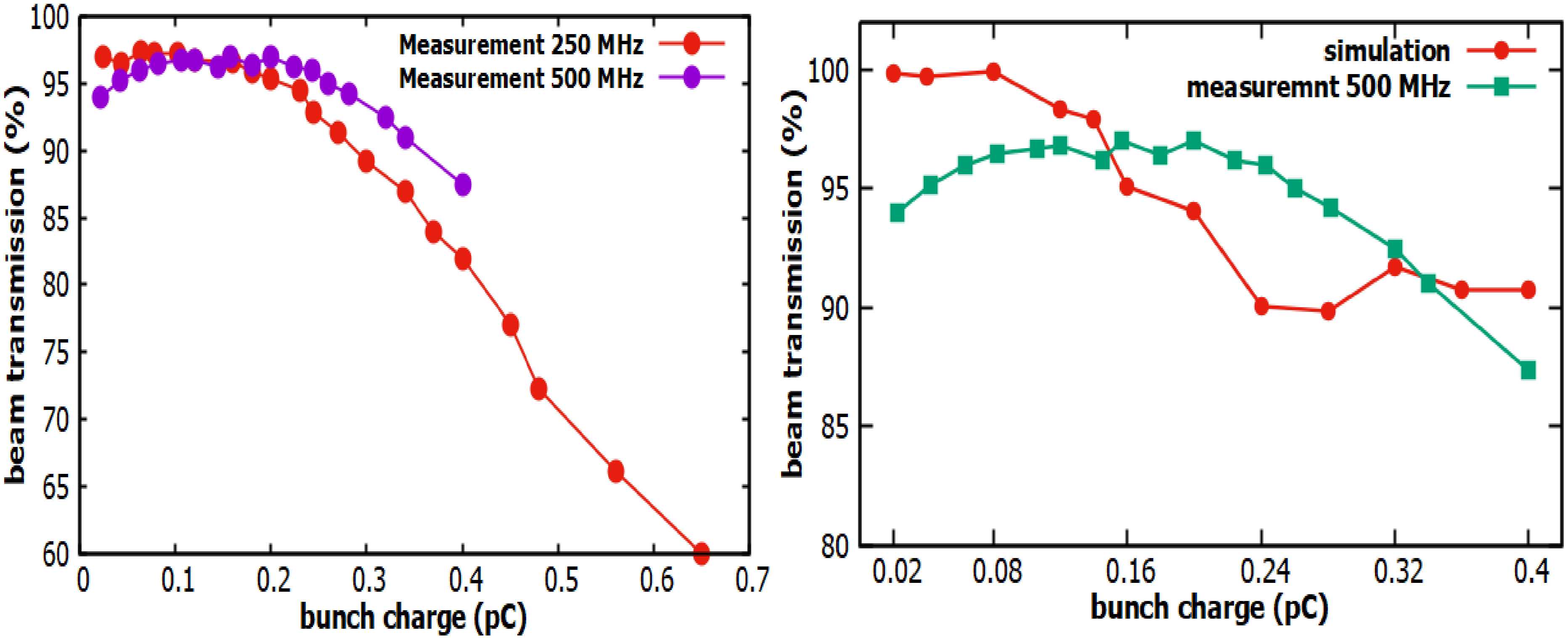


Beam transmission through the apertures A1 and A2 as a function of bunch charge.

S. Pokharel et al., 13th Int. Particle Acc. Conf., https://doi.org/10.18429/JACoW-IPAC2022-MOPOTK052

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Measurements and Simulation Results (130 keV)

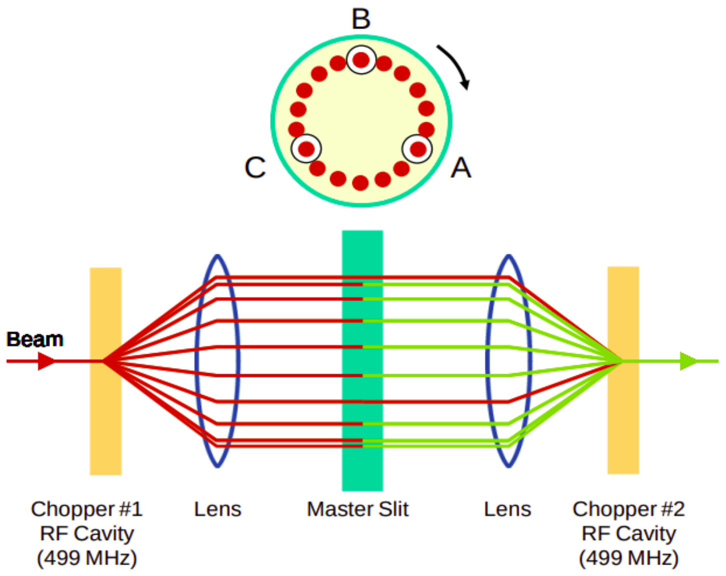


Beam transmission through the apertures A1 and A2 as a function of bunch charge.

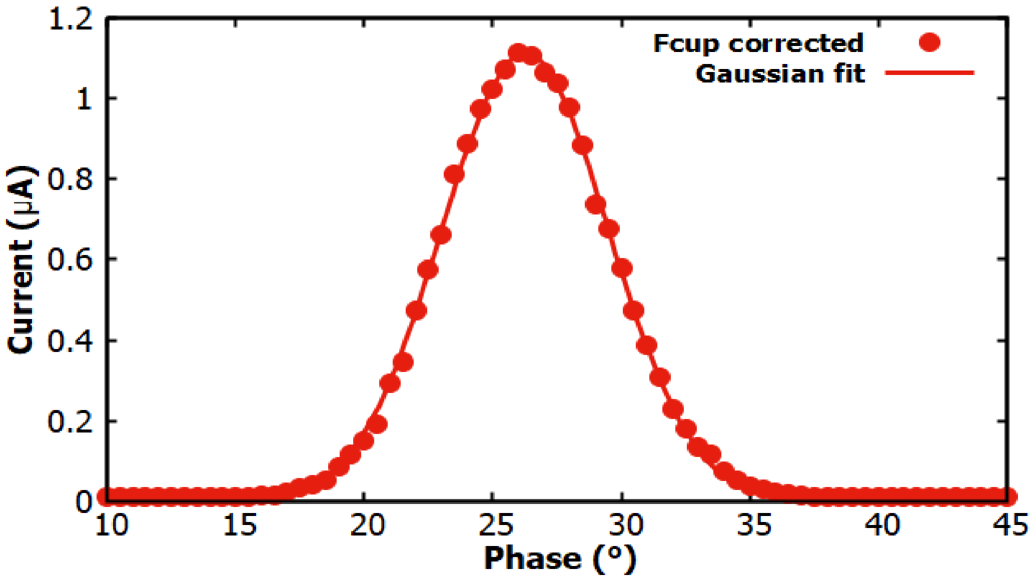
S. Pokharel et al., 13th Int. Particle Acc. Conf., https://doi.org/10.18429/JACoW-IPAC2022-MOPOTK052

Chopper Phase Scanning Technique

- Faraday Cup in conjunction with the chopper used for measuring bunch length
- Chopper selects a small fraction of the longitudinal phase
- Recording Faraday cup current as chopper phase is scanned, longitudinal profile obtained
- Measurements were performed for 249.5 MHz and 499 MHz frequencies



Three beam chopping system.



Chopper Scan for 2.5 μA beam at 249.5 MHz Prebuncher off.

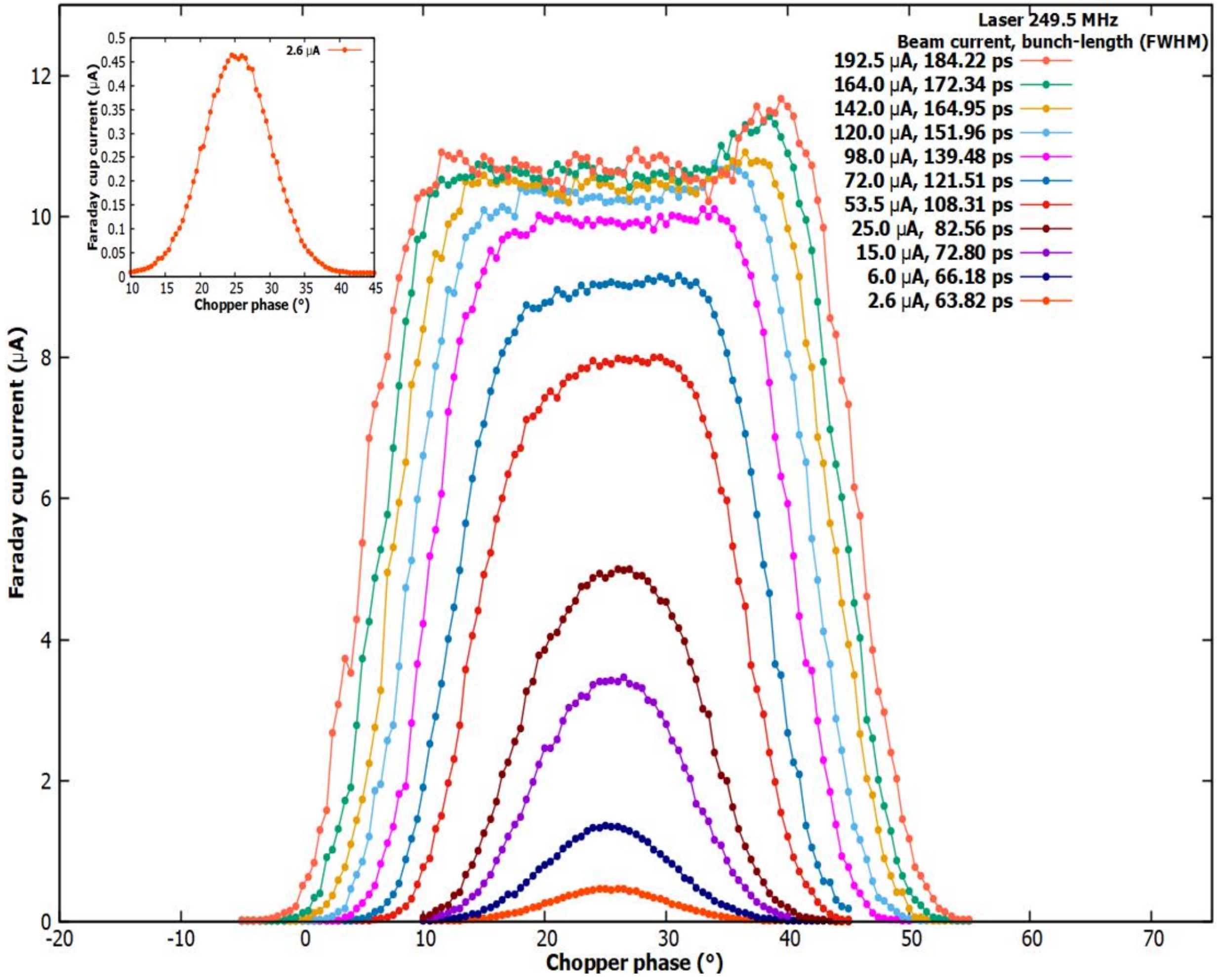
Simulation Details

- Particle distribution at cathode Gaussian
  - 2-200 μA, 10 k macroparticles
  - Laser pulse lengths 62.5 ps (FWHM) for 249.5 MHz, and 41.6 ps (FWHM) for 500 MHz drive lasers
  - beam dynamics simulations were conducted using two different 3D space charge solver schemes: spacecharge3D and spacecharge3Dmesh

Simulations using General particle Tracer (GPT)

Elements	Center Distance from the cathode (m)
Prebuncher	5.363
A1	6.48
A2	7.156
Choppers	7.60
Buncher	8.884
Faraday Cup#1	9.45
Capture	10.178
First 5-cell	12.426
Second 5-cell	13.185

Measurement Results (249.5 MHz)



Electron Bunch-length measurements at 249.5 MHz laser, beam size at cathode is 0.55 mm.

For low charge longitudinal profile,

$$f(x) = \frac{a}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

For high bunch charge longitudinal profile,

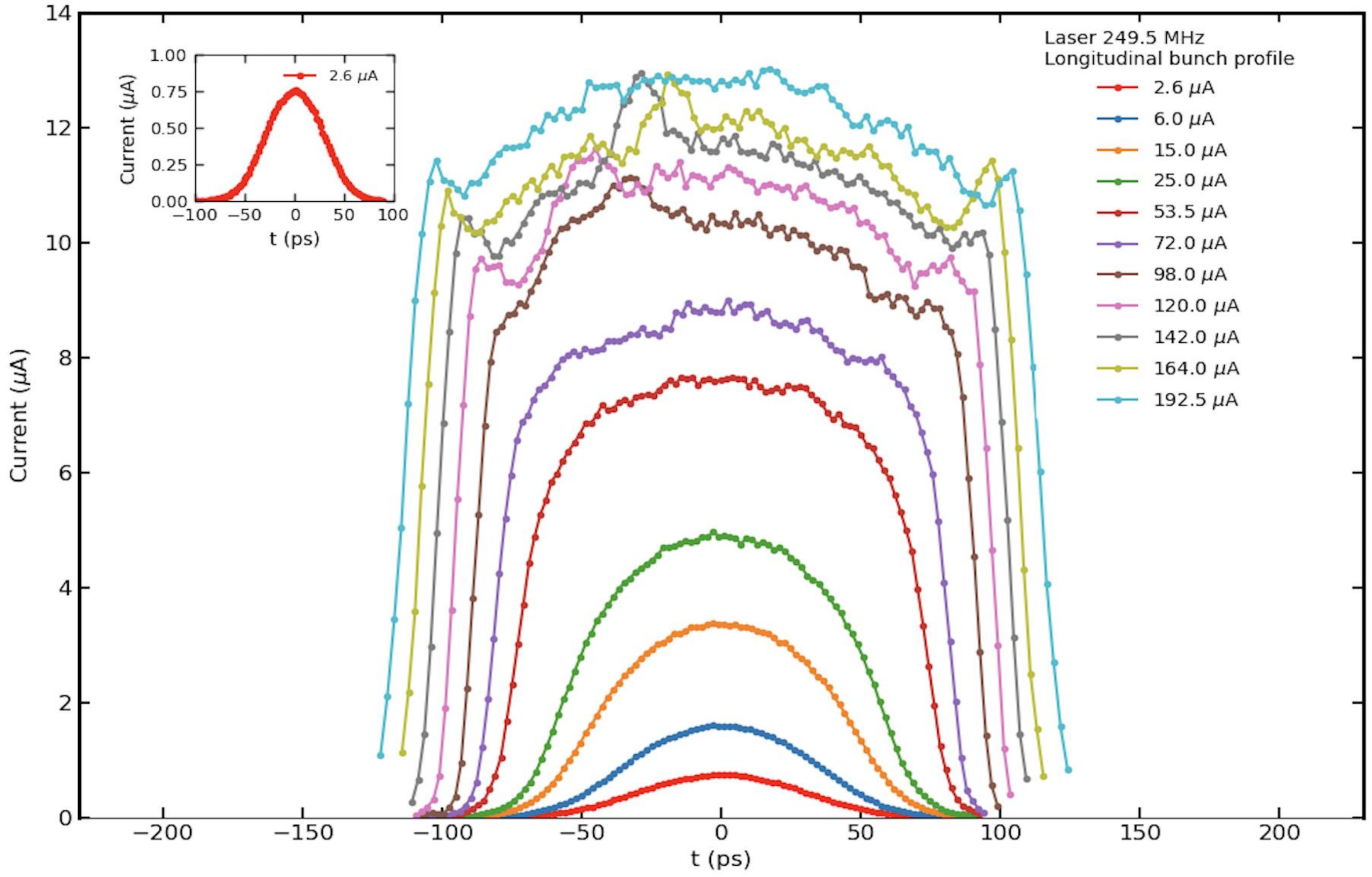
$$g(x) = \frac{A}{\sqrt{2\pi}\sigma_0}\exp\left(-\frac{(\mathrm{abs}(x-\mu))^N}{2\sigma_0^N}\right)$$

$$\sigma = \sigma_0\left(\frac{\pi}{2}\right)^{\frac{2}{N}-1}$$

σ_0 is the rms value of the Super-Gaussian distributions

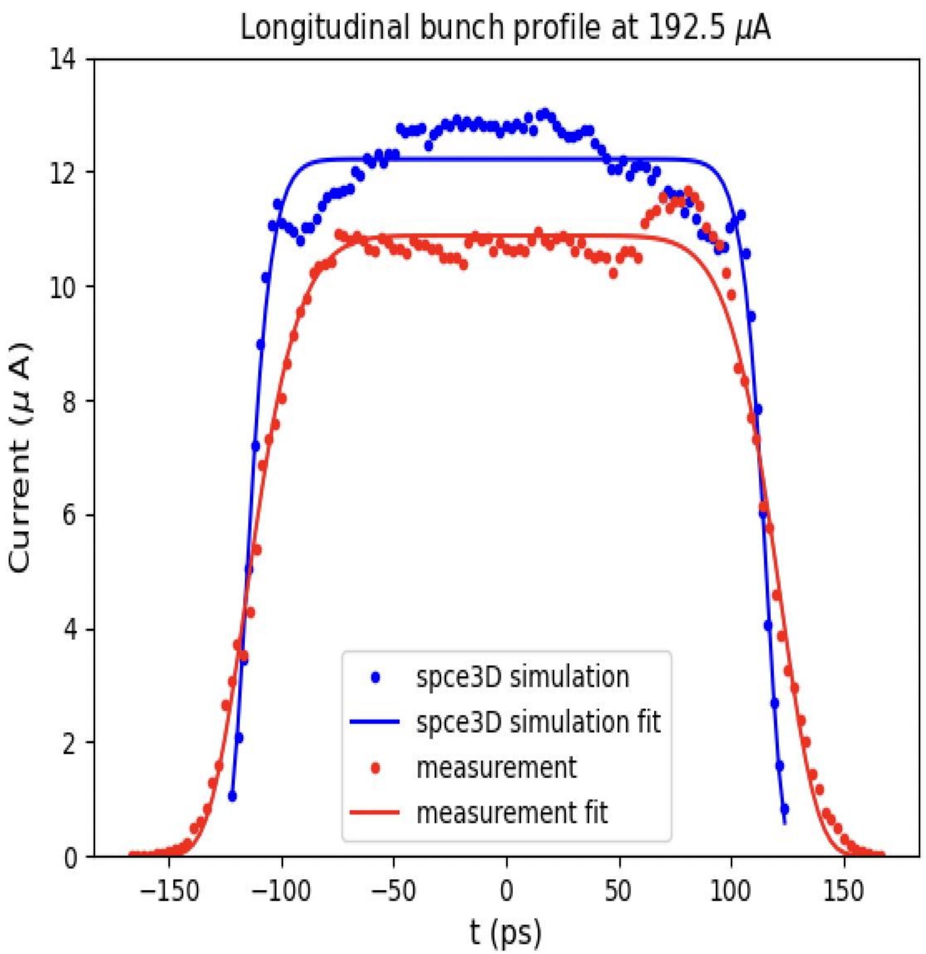
F.-J. Decker, AIP Conference Proceedings, Vol. 333 pp. 550–556 (1995)

Simulation Results



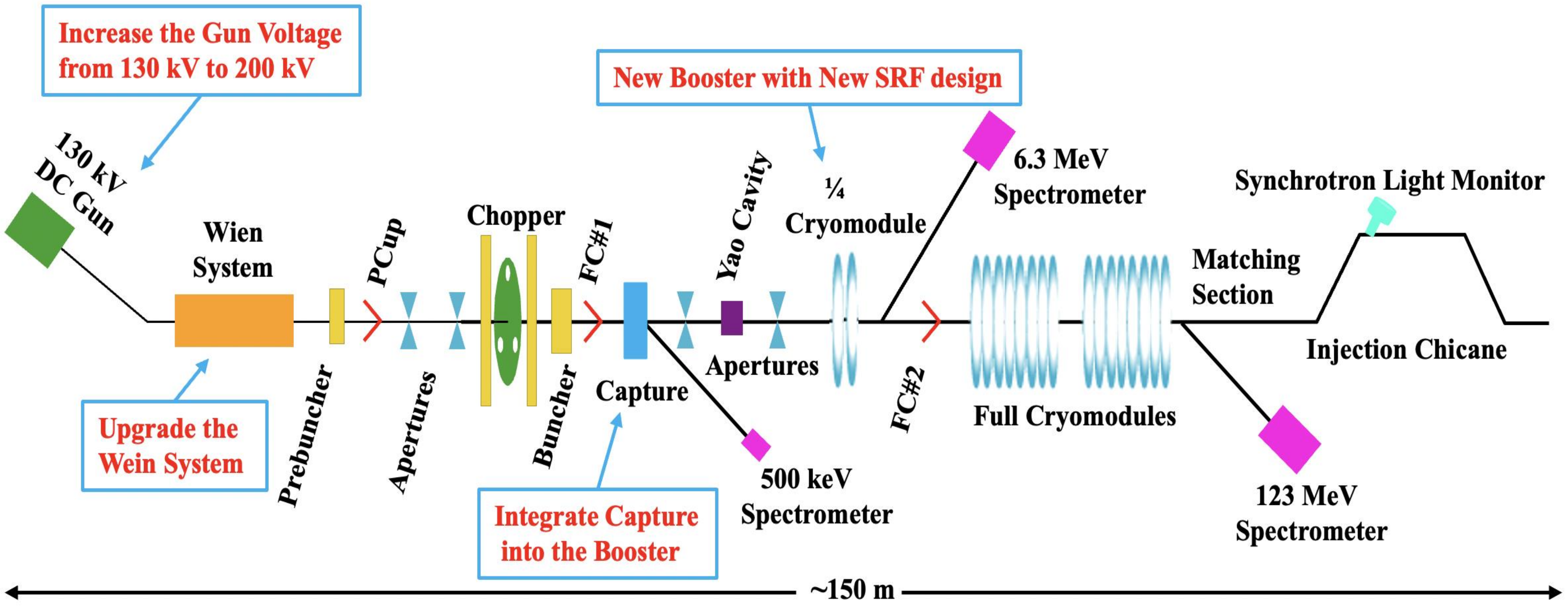
Electron Bunch-length measurements at 249.5 MHz laser at the location of chopper.

Comparison



Electron Bunch-length measurements at 249.5 MHz laser at the location of chopper.

Upgraded CEBAF Injector



Schematic of upgraded CEBAF Injector with areas of upgrades.

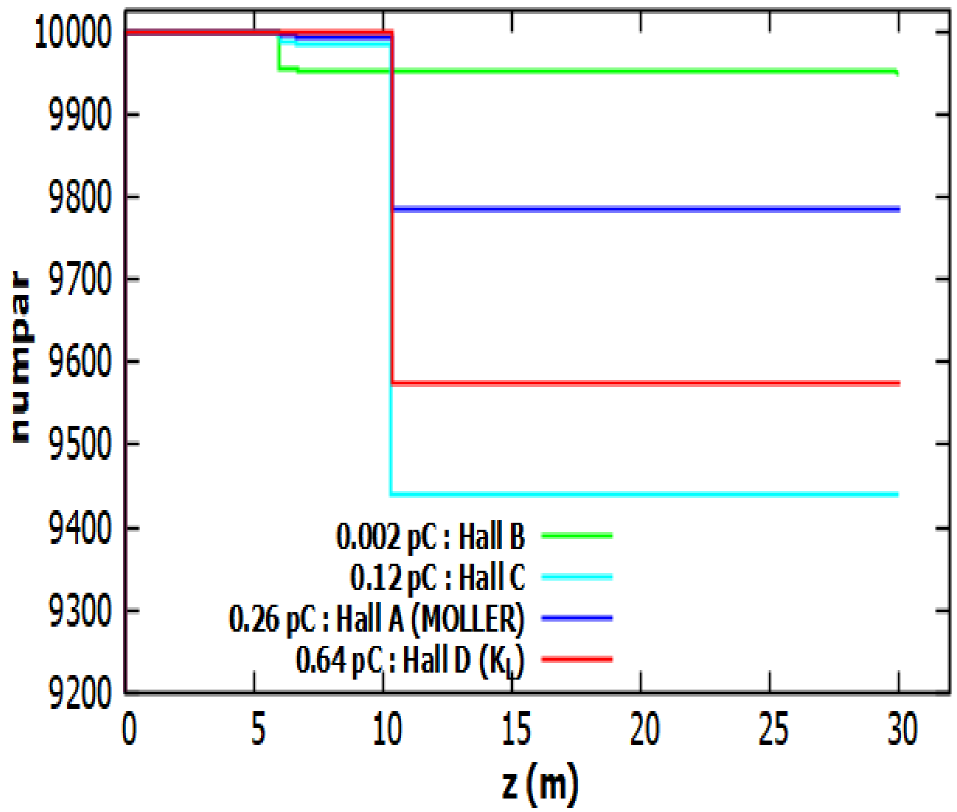
Injector Modelling

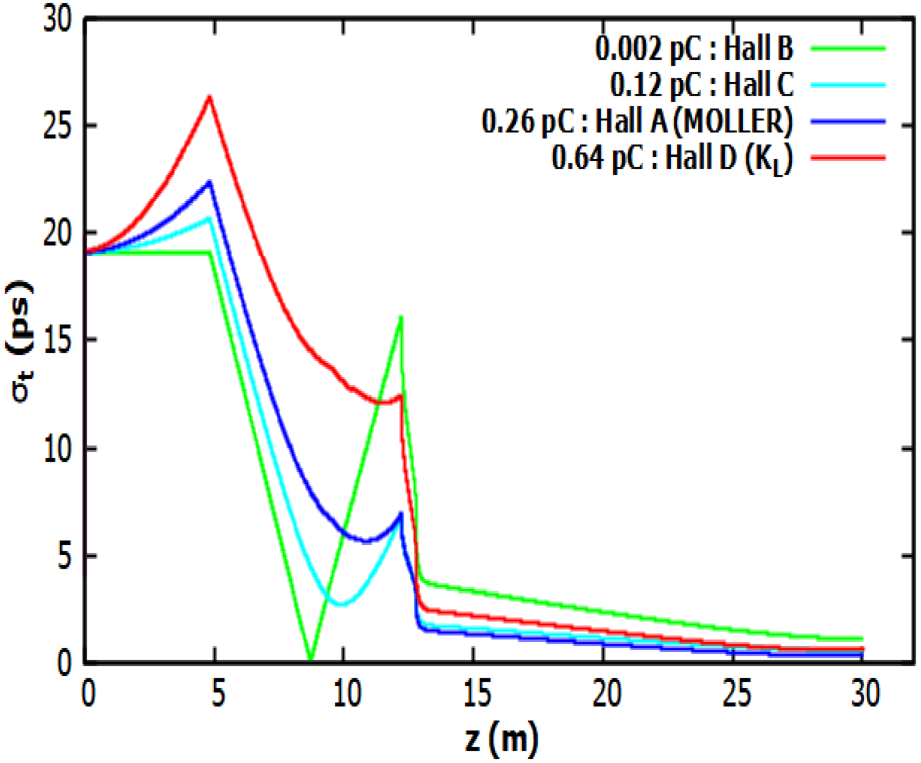
CEBAF INJECTOR MODEL FOR K-LONG BUNCH CHARGE AT 200 kV

- Performed using GDFMGO multi-objective global optimizer implemented in GPT.
- Optimizations were performed for K-Long bunch charge (0.64 pC), at 320 µA beam current, laser frequency of 499 MHz for 200 keV beams.
- Population size of 120 with 1000 generations was used for 120000 runs, resulting in 120 sets of optimal settings for magnetic elements and RF, with goal of achieving 99.9% beam transmission, $\epsilon_{n,x,y} \leq 0.25$ mm mrad, $\sigma_t \leq 0.5$ ps, kinetic energy 5.0 to 8.0 MeV upstream of the first full cryomodules.
- The number of macroparticles was 250, for 28 variables (magnetic elements and RF settings), 62 objectives, and constraints.

- Optima obtained from MGO were tested with increasing the number of macroparticles.
- Increase in macroparticles causes the degradation of beam characteristics.
- After optimization, one of the optimal solutions on the Pareto front was chosen for the injector's simulation of 10 k macroparticles.
- Optimal solution was selected based on the attainment of beam transmission greater than 90%, $\epsilon_{n,x,y} \leq 1.0$ mm mrad, $\sigma_t \leq 1.1$ ps.

Simulations with Optimized 200 keV Settings



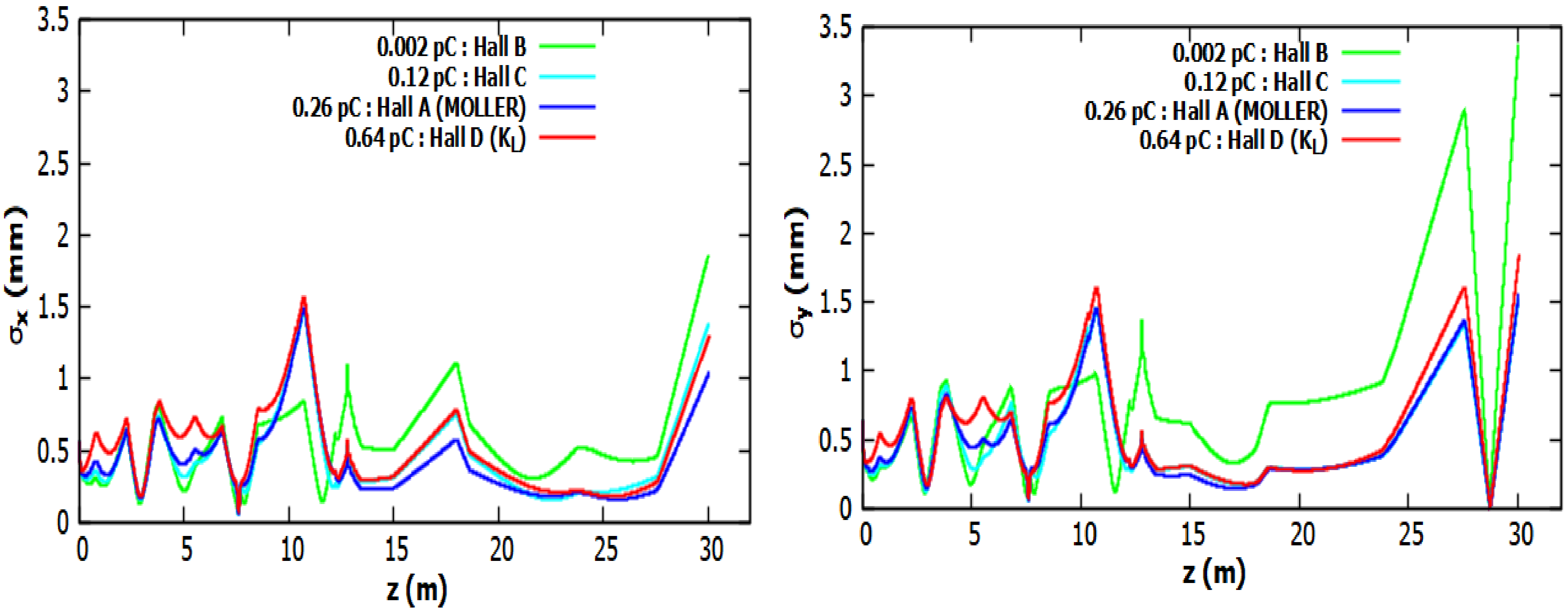


Transmission for various bunch charge specifications for the CEBAF four halls.

Evolution of bunch length along the beamline for various charges per bunch.

S. Pokharel et al., https://indico.jacow.org/event/41/contributions/2208/editing/paper

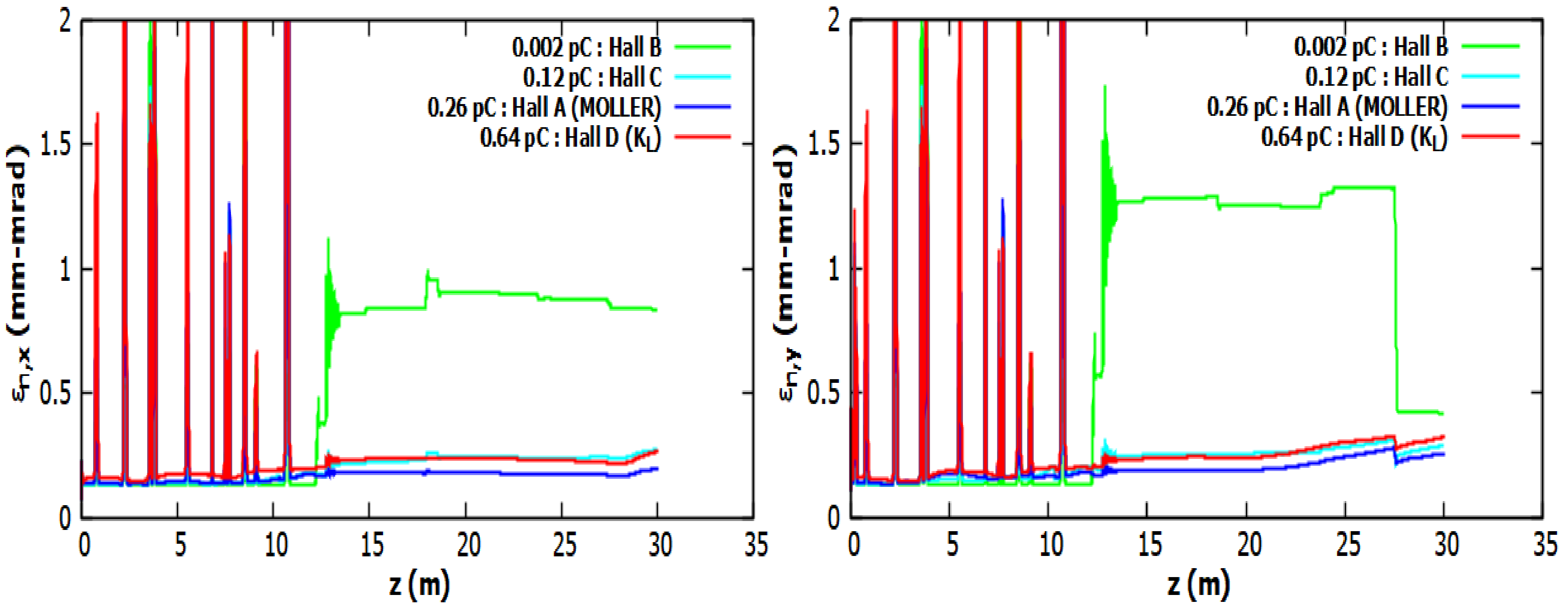
200 keV Simulations



Transverse horizontal and vertical beam sizes for different bunch charges.

S. Pokharel et al., https://indico.jacow.org/event/41/contributions/2208/editing/paper

200 keV Simulations



Transverse horizontal and vertical normalized emittances for different bunch charges.

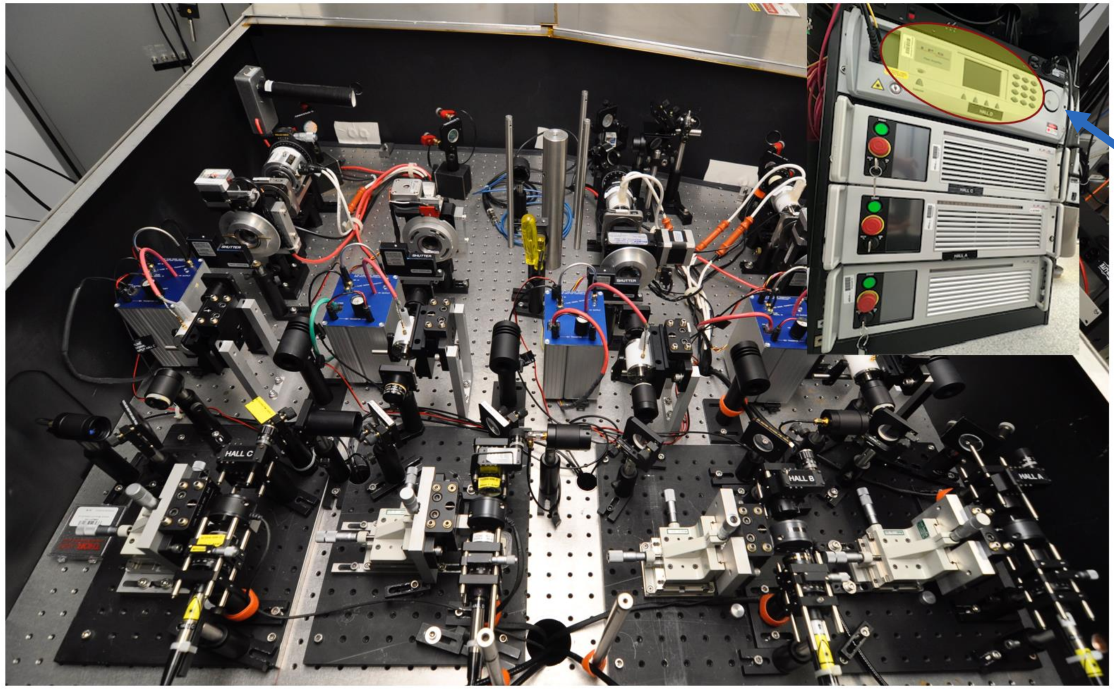
S. Pokharel et al., https://indico.jacow.org/event/41/contributions/2208/editing/paper

Drive Laser (Shukui Zhang <shukui@jlab.org>)

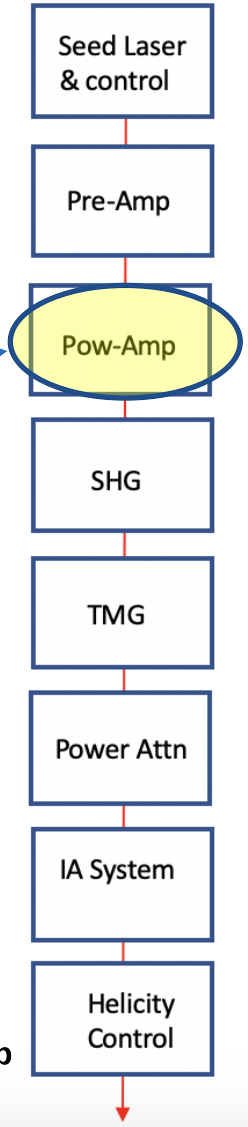
Parameters			Comment
Min Average Power (mW)	10	10	
Max Average Power (mW)	100	100	
Pulse Repetition Rate (MHz)	15.6	7.8	
Beam Spot Size (FWHM) (mm)	1.2~1.5	1.2~1.5	
Pulse Length (ps)	40~50	40~50	
Min e-Bunch charge (pC)*	0.32	0.64	*Based on 0.1% QE, 10 mW laser power
Min e-beam current (μA)*	5	5	

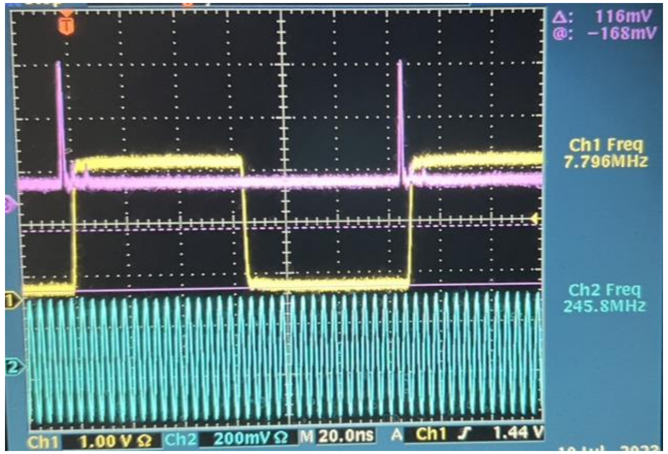
Photo of Drive Laser and New Parts

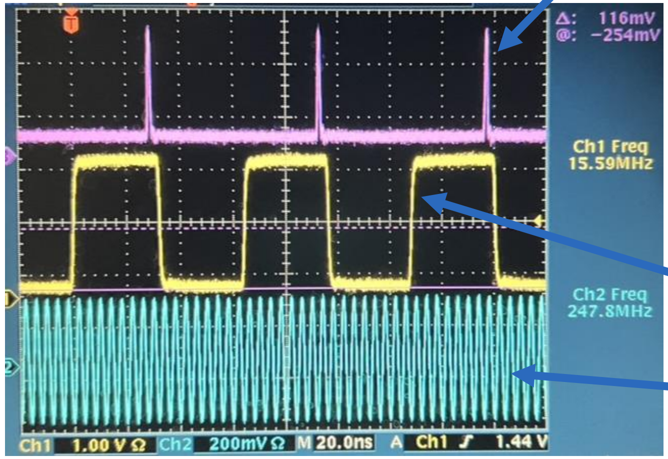
- <u>Technical scheme & key components</u>:
  - A new 1.5 µm Gain-switched seed
  - 15.6/7.8 MHz RF signal by dividing 249 MHz by 16/32
  - A new high pulse energy laser amplifier
  - Use Existing SHG for 780 nm & the rest of the hardware downstream in D laser beam path



Laser amplifier to be replaced







Laser pulses

Low rep signal

249MHz Laser RF

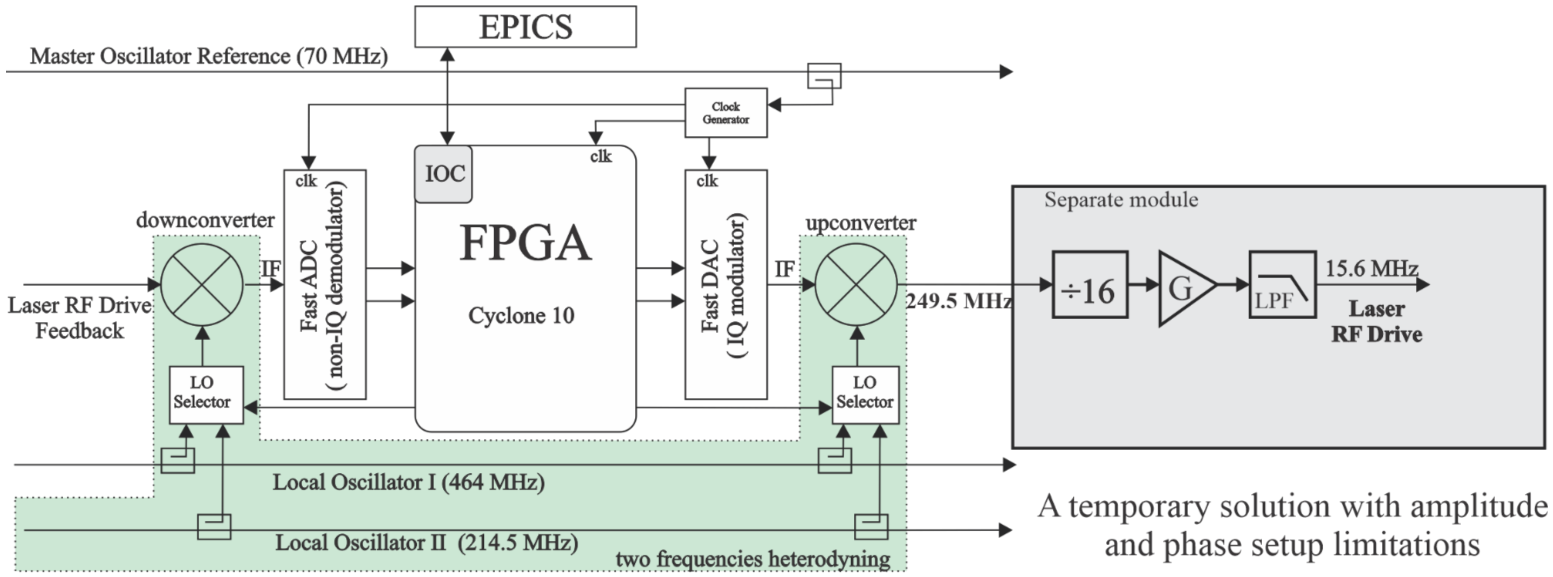
Possible Full System Test

- When available, experiment sending high charge beam to Hall D should be possible. Complete accelerator system test. Could add this to Sunil’s submitted test plan

LLRF (Tomasz Plawski <plawski@jlab.org>)

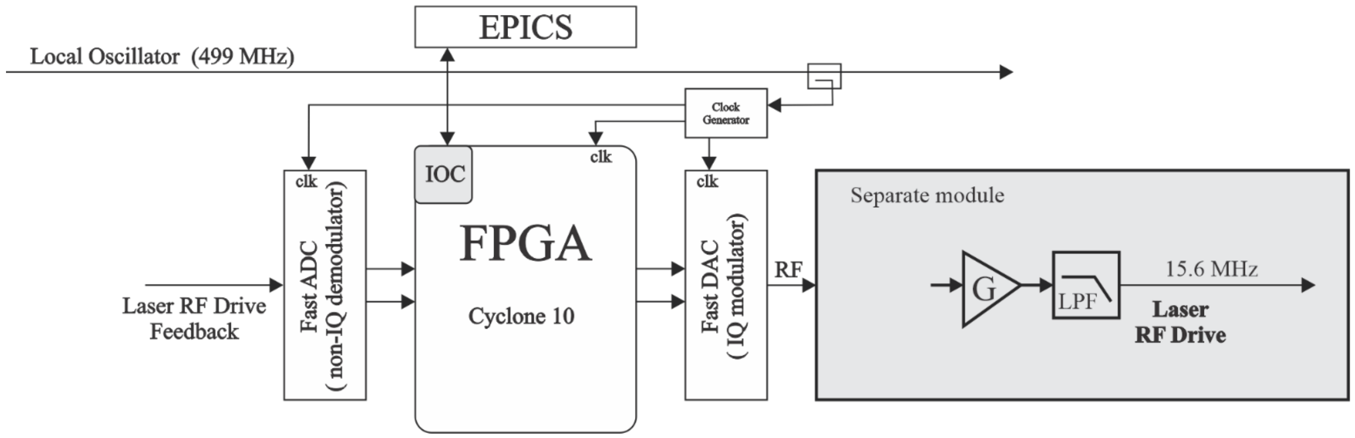
- Problem: 15.6 MHz Oscillation Phase Locked to Accelerator 1497 MHz
- The existing LLRF system can provide two frequencies: 499 MHz and 249.5 MHz. It utilizes the heterodyning concept, using two local oscillator signals locked to the accelerator's 499 MHz reference. This ensures that the drive signals are always locked to the variable frequency of the CEBAF accelerator.
- To add a low-frequency drive signal of 15.6 MHz, we are considering two techniques:
- Dividing the 249.5 MHz drive by 16. This is an easy and inexpensive solution, but it has a major drawback: the user cannot control the signal amplitude, and can only change the signal phase by +/- 11 degrees instead of +/- 180 degrees. (Temporary Solution)
- Designing a direct drive channel, which would provide full amplitude and phase control. This is more expensive in terms of component cost and labor, but it would allow for precise control of the drive signal via EPICS. (Longer Term)

LLRF (Tomasz Plawski <plawski@jlab.org>)



Temporary Solution

A temporary solution with amplitude and phase setup limitations



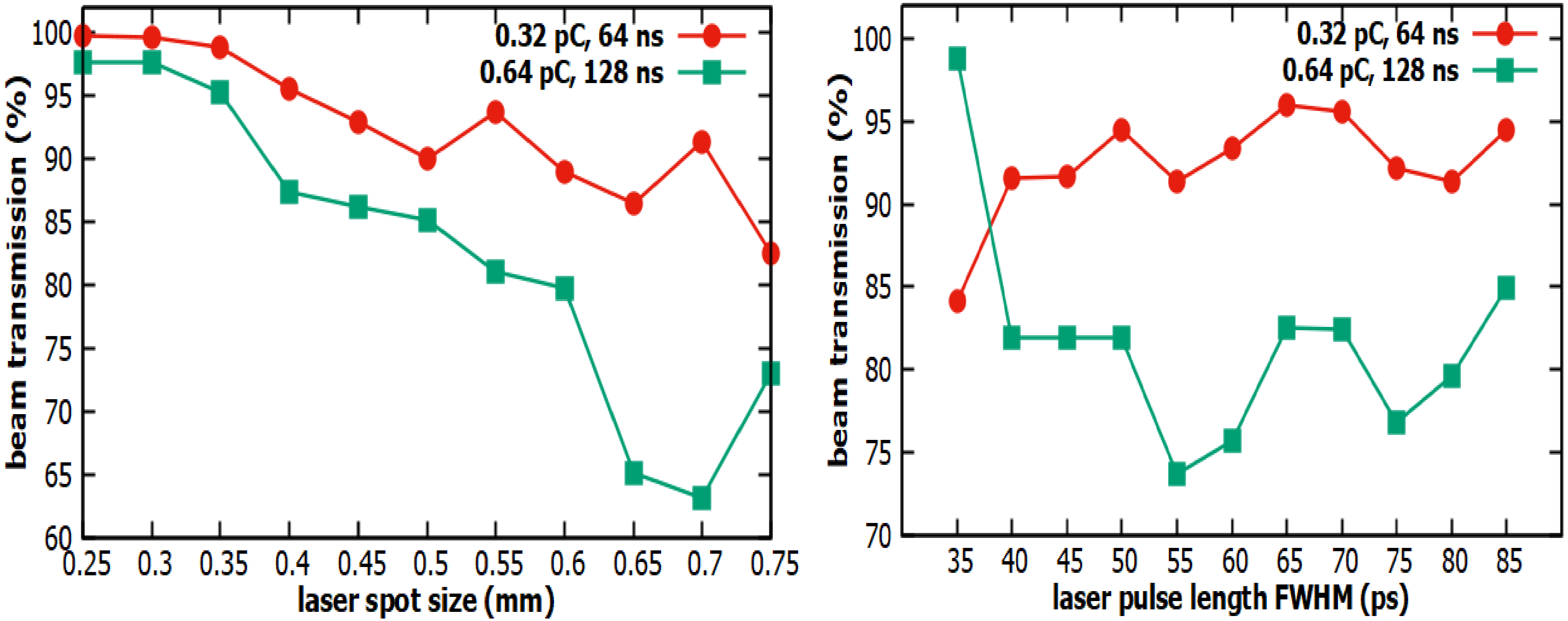
Long Term Solution

This solution is still in the conceptual design phase

Summary

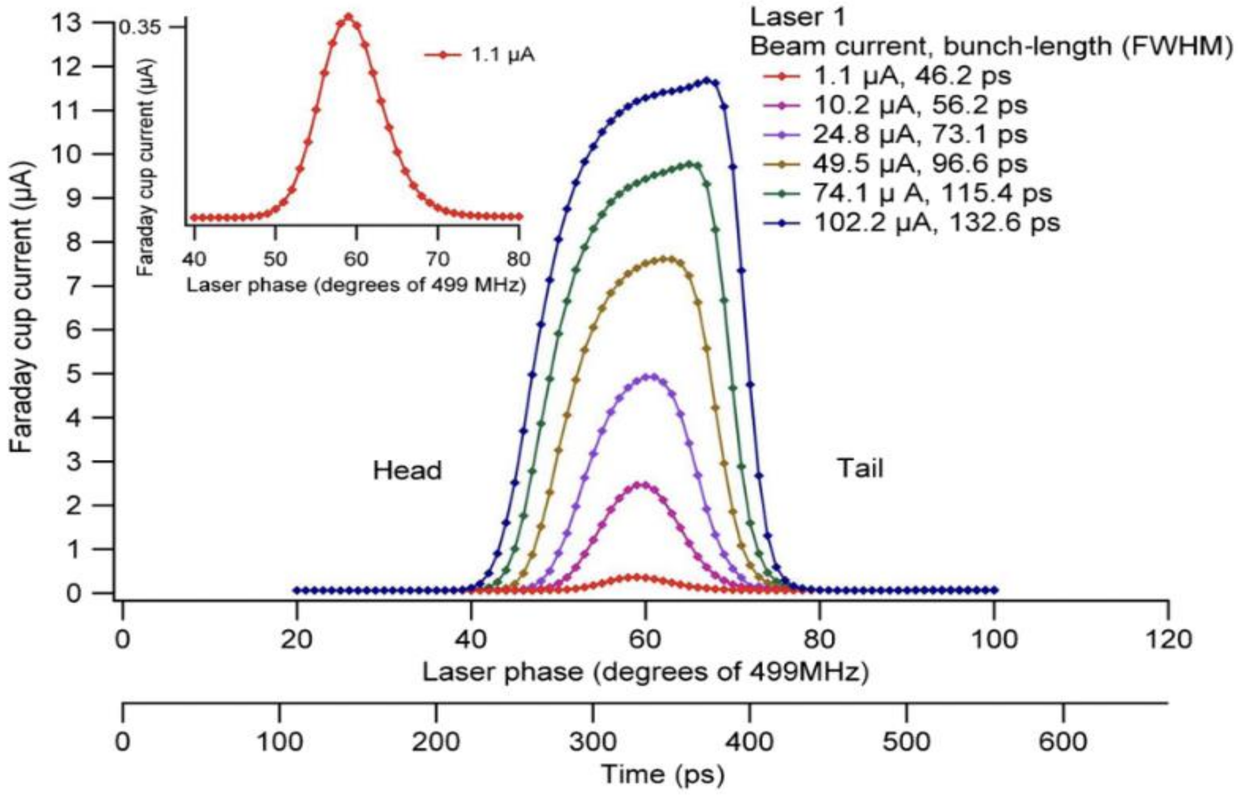
- Baseline K-Long beam has been produced and measured in the CEBAF injector at 130 keV. Beam quality seems good. Chopper scans of bunch length w/wo longitudinal bunching performed and agree with simulation expectations.
- A battery of simulations have been performed supporting operating at the injector upgraded energy of 200 keV. Simulations indicate good transmission and beam quality at twice baseline charge. At optimized settings for high charge, simultaneous operation with Halls A and C is indicated, with minor differences in the transverse beam optics.
- Laser supporting high charge running purchased. We are anxious to try it out.
- LLRF supporting baseline case will be available on installation.

Simulation Results (130 kV gun)



Beam transmission as a function of laser spot size and pulse length.

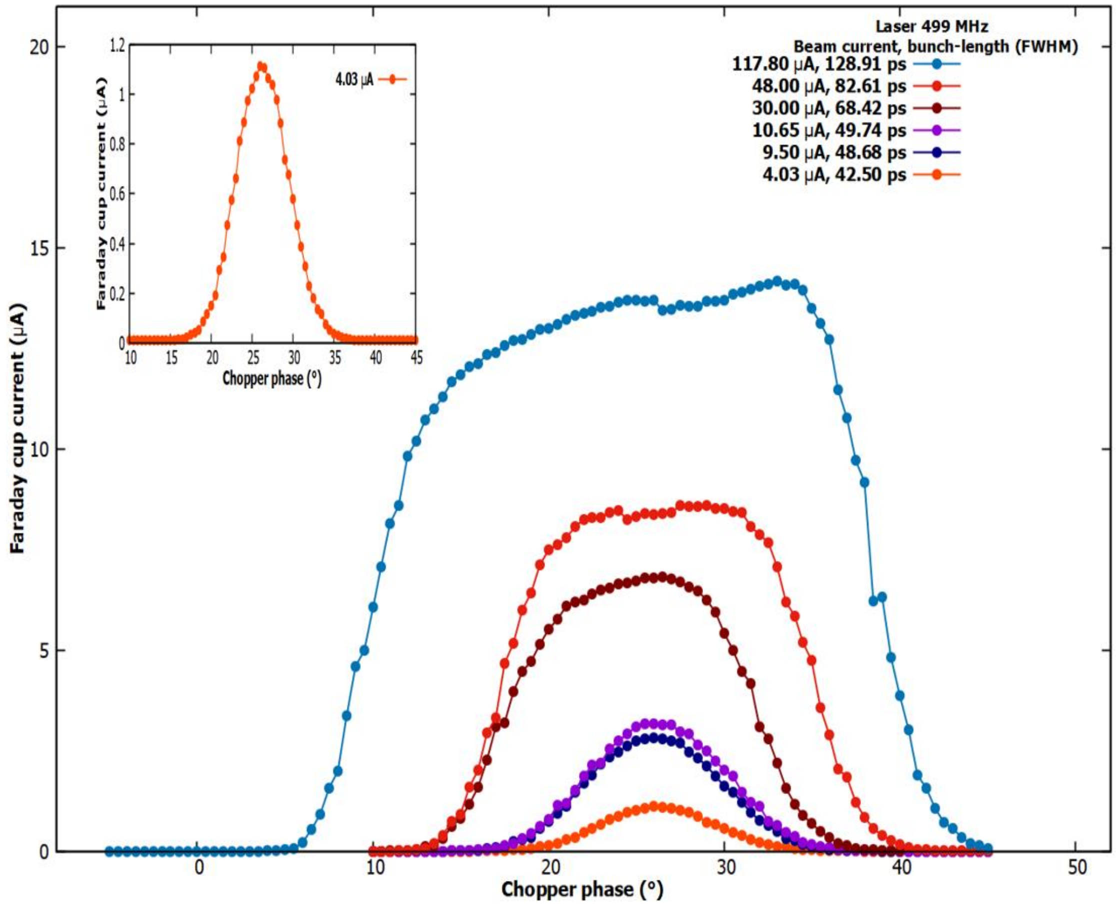
S. Pokharel et al., 13th Int. Particle Acc. Conf.,
https://doi.org/10.18429/JACoW-IPAC2022-MOPOTK052



Electron Bunch-length measurements at 249.5 MHz laser, beamsize at the cathode is 0.25 mm.

B. Roberts et al., Phys. Rev. Accel. 19, 7 052801 (2016).

Measurement Results



Electron Bunch-length measurements at 499 MHz laser.

For low charge longitudinal profile,

$$f(x) = \frac{a}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

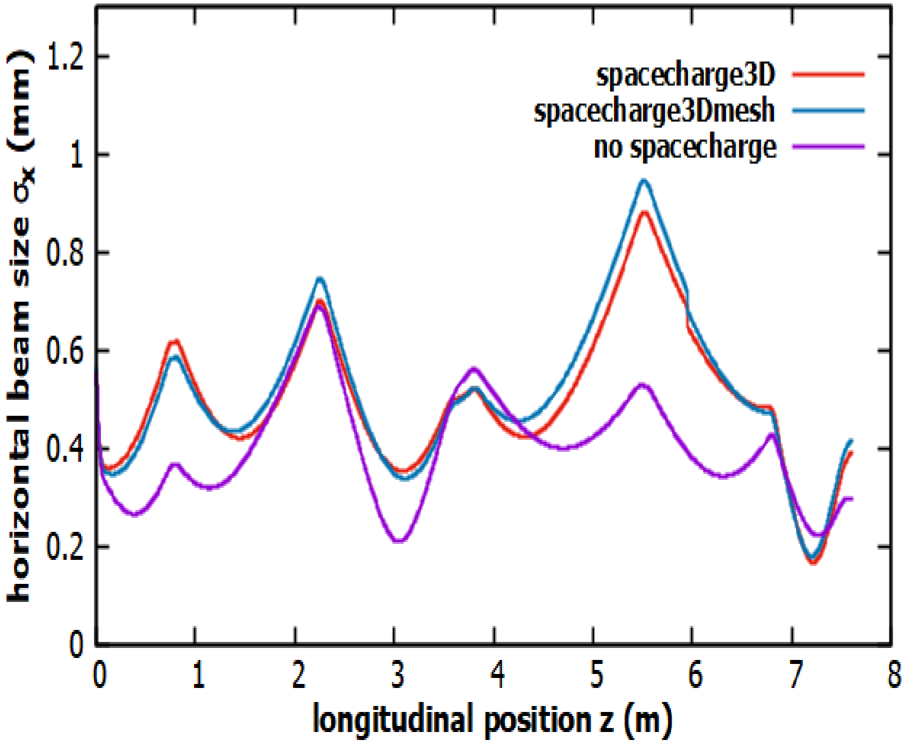
For high bunch charge longitudinal profile,

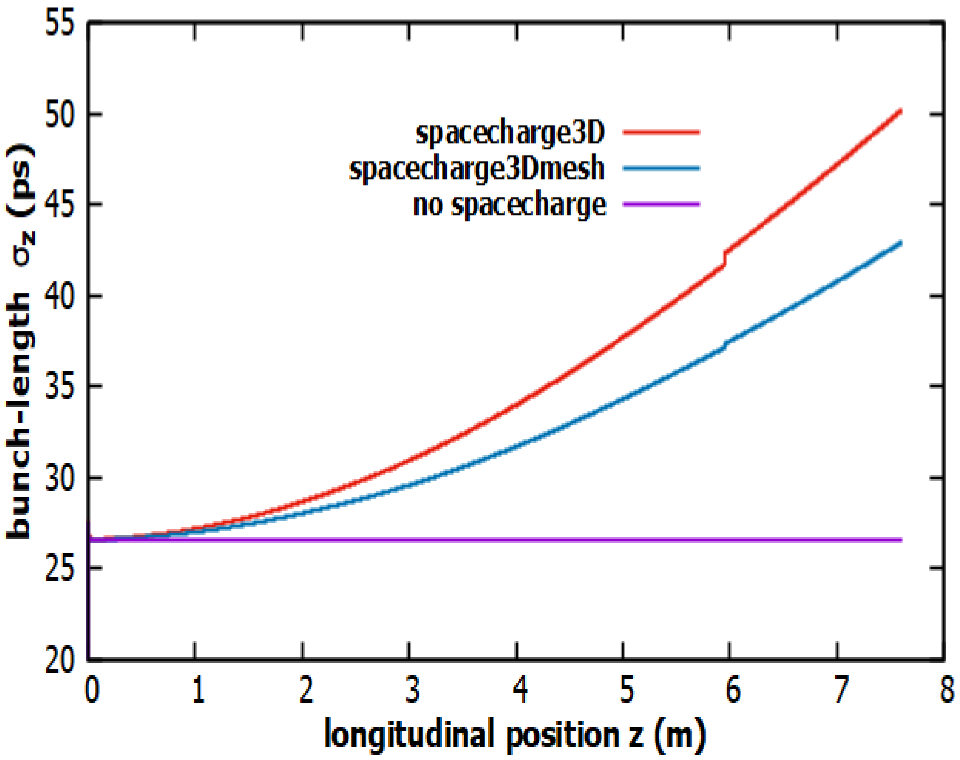
$$g(x) = \frac{A}{\sqrt{2\pi}\sigma_0} \exp\left(-\frac{(\mathrm{abs}(x-\mu))^N}{2\sigma_0^N}\right)$$

$$\sigma = \sigma_0 \left(\frac{\pi}{2}\right)^{\frac{2}{N}-1}$$

σ_0 is the rms value of the Super-Gaussian distributions

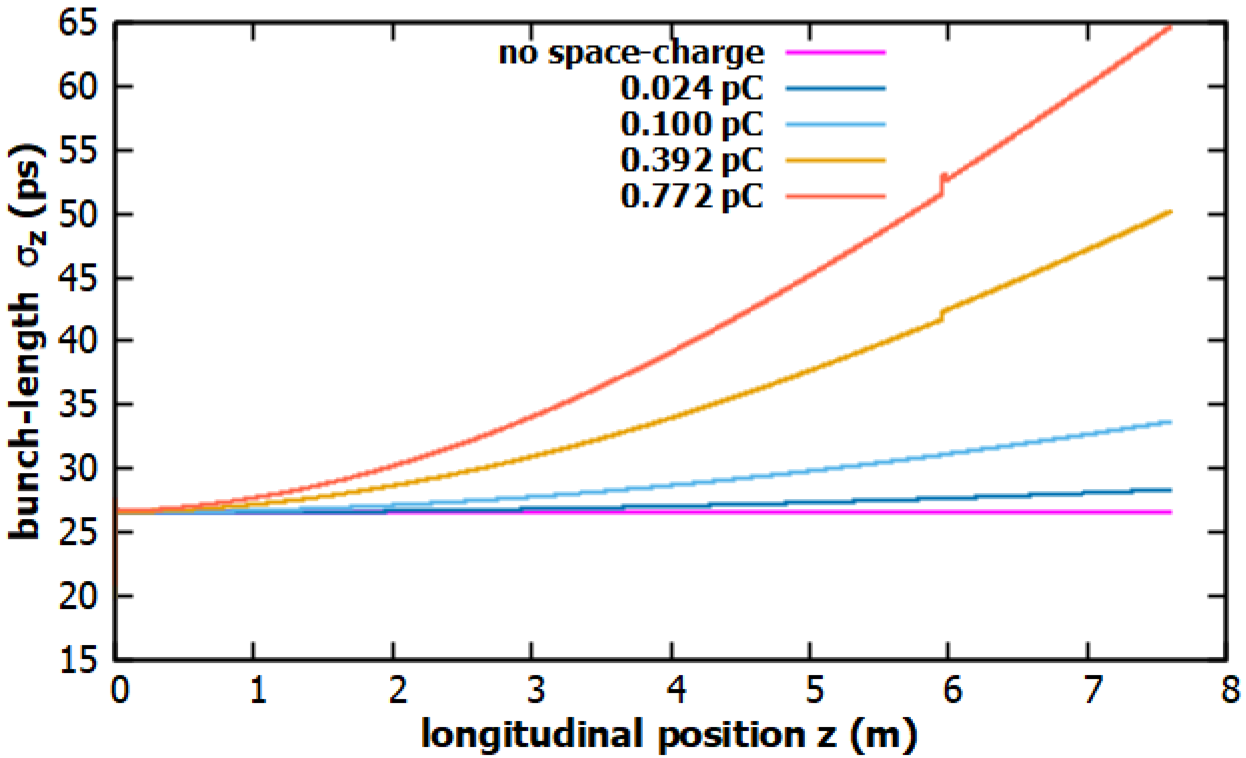
Simulation Results





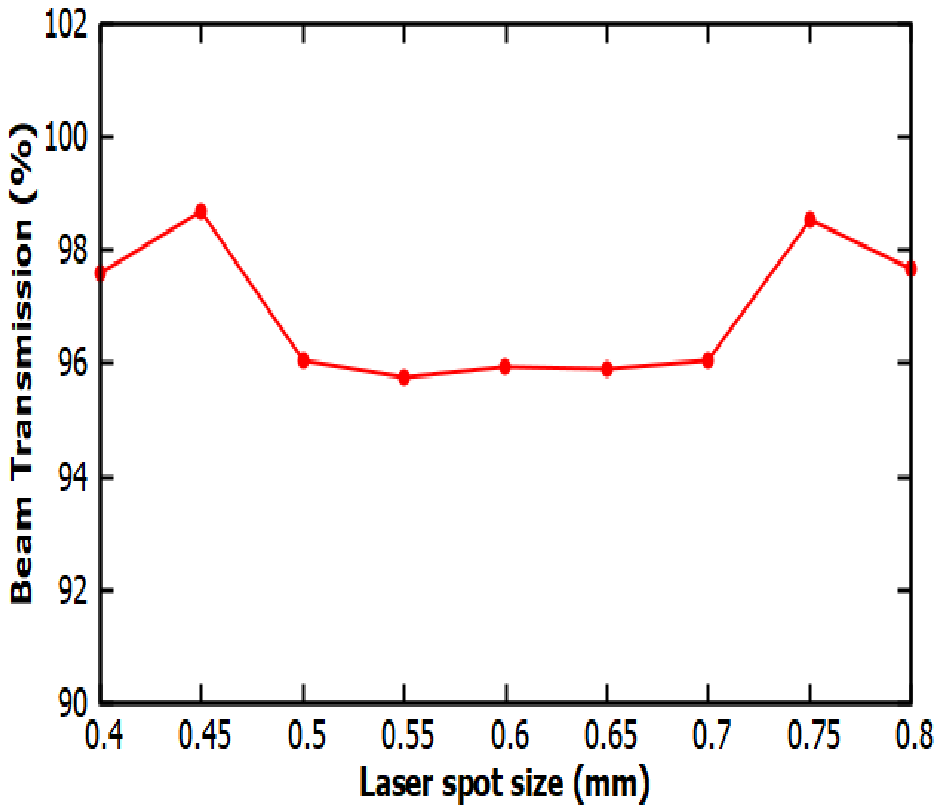
Horizontal (left) and longitudinal (right) rms beam sizes as a function of distance from the photocathode for different space-charge schemes for 100µA beam current (0.40 pC bunch charge) using the laser at 249.5 MHz. The location of chopper is 7.60 m from the cathode.

Simulation Results

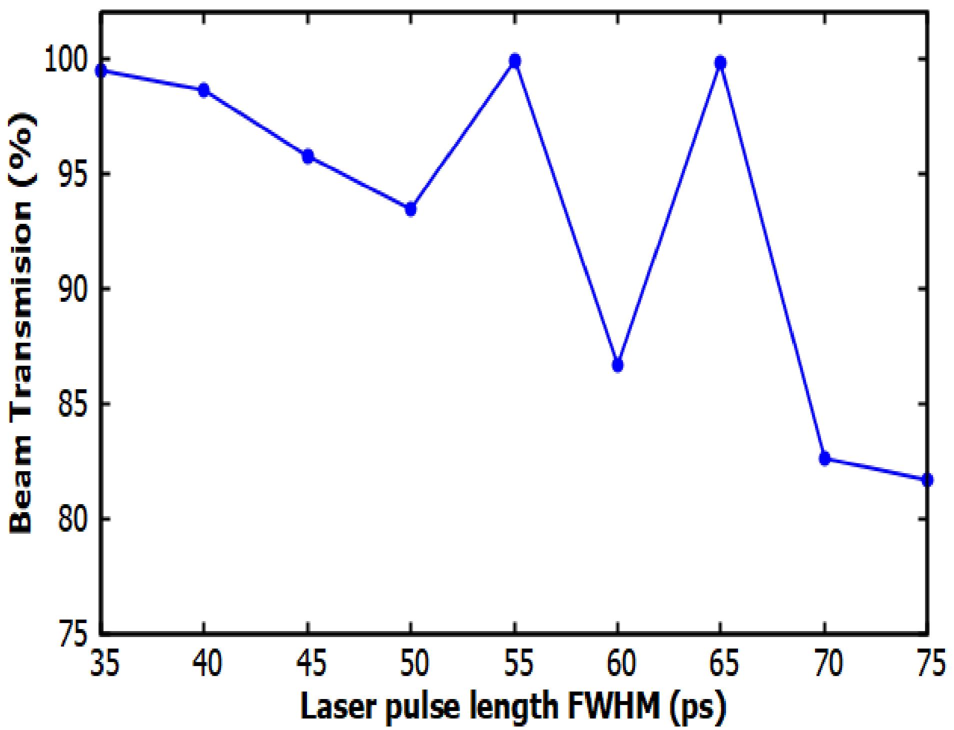


Longitudinal rms beam sizes as a function of distance from the photocathode for spacecharge3D scheme for various bunch charges using the laser at 249.5 MHz.

Simulation Results at 200 kV



Beam transmission vs. laser spot size at cathode for K-Long bunch charge.



Beam transmission vs. laser pulse length at cathode for K-Long bunch charge.

S. Pokharel et al., https://indico.jacow.org/event/41/contributions/2208/editing/paper

Summary and Outlook

- CEBAF Upgraded Injector Model for K_L experiment (130 kV gun), high and low bunch charge beam is simulated
- The laser pulse lengths and laser spot sizes are varied
- We found that maximum bunch charge from the gun (0.4 pC) and it is about 12% loss at 499 MHz and in good agreement with the simulations.
- For 250 MHz drive frequency the bunch charge from the gun (0.64 pC), but the losses in the apertures are high, about 39%.
- Bunch length is measured at 130 KV using GPT simulations and the Chopper phase scanning technique for various charge/bunch or beam currents at the CEBAF injector.
- The longitudinal profile at the chopper for low charge per bunch and with Prebuncher on are the Gaussian but for high charge beam without pre-buncher on are Super Gaussian

Conference Paper/ Poster Presentation and Participation

ODU

- KLF Collaboration Meeting, May 27, 2022, CEBAF Injector for KL Beam Conditions
- Attended IPAC'22, June 12-17, 2022, Bangkok, Thailand, and presented Posters:
  - CEBAF Injector Model for KL Beam Conditions
  - Modeling a Nb3Sn cryounit in GPT at UITF
- Attended NAPAC'22, Albuquerque NM, August 7-12, 2022, TEDPAC@NAPAC and contributed oral presentation
  - Bunch Length Measurements at the CEBAF Injector at 130 kV
- PPB - December 14, 2022, CEBAF Injector for different voltage beams using two 5-cell cavities
- Winter 2023 USPAS Session, January 23 - February 3, 2023, Houston, TX, Measurement and Control of Charged Particle Beams, Michiko Minty, and Frank Zimmermann
- Data Science Boot Camp 2023, ODU, May 8-13, 2023.

Conference Proceedings and Publications

ODU

- S. Pokharel, A S Hofler, G A krafft, “Modeling a Nb_3Sn cryounit in GPT at UITF” J. Phys.: Conf. Ser. 2420 012054, doi:10.1088/1742-6596/2420/1/012054
- S Pokharel et al, “CEBAF Injector Model for K_L Beam Conditions”, 13th Int. Particle Acc. Conf., https://doi.org/10.18429/JACoW-IPAC2022-MOPOTK052
- S Pokharel et al, “Bunch Length Measurements at the CEBAF Injector at 130 kV”, 5th North American Particle Accel. Conf., https://doi:10.18429/JACoW-NAPAC2022-FRXD6
- S Pokharel et al, “CEBAF Injector Model for K-Long bunch charge at 200 kV”, 14th Int. Particle Acc. Conf., #526 WEPL054 (accepted for publications)

Ongoing Work

- Submitted the first three chapters of thesis
- Made a beam test plan for K-Long with Hall D new laser
- GPT Optimization of the upgraded Injector with Wien System ON
- Journal Paper Manuscript preparation
- Tech note preparation
- JLUO Poster

Evolution of bunch length of beam through the CEBAF injector

S. Pokharel,[1,*] G. A. Krafft,[1,†] A. S. Hofler,[2] R. Kazimi,[2] M. Bruker,[2] J. Grames,[2] and S. Zhang[2]

[1] *Center for Accelerator Science, Old Dominion University, Norfolk, Virginia, 23529, USA*

[2] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA.*

(Dated: March 14, 2023)

An invasive chopper phase scanning technique was used at a frequency of 499 MHz to evaluate the temporal characteristics of spin-polarized electron bunches produced by a 130 kV DC high-voltage photogun at the Continuous Electron Beam Accelerator Facility (CEBAF) injector. The bunches were created at laser drive frequencies of 249.5 MHz and 499 MHz, and ranged in width from 25 to 185 picoseconds (full width at half maximum, FWHM). In addition, beam dynamics simulations were conducted using two different three-dimensional (3D) space charge solver schemes, namely, spacecharge3D and spacecharge3Dmesh, along the CEBAF injector beamline from the gun to the chopper. The noninvasive measurements were compared to the predictions from particle tracking simulations using General Particle Tracer (GPT).

I. INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) injector at Jefferson Laboratory provides a beam to the main accelerator, which consists of two recirculating linacs operating at 1497 MHz, connected by beam transport arcs. The beam is delivered to each experimental hall at 499 MHz, one-third of the linac frequency. The CEBAF polarized electron source creates spin-polarized electron beams using a DC high-voltage photogun. The electron beam originates within the pho-

a process called photoemission. In this process, a high-intensity laser pulse is used to eject electrons from a metal cathode, which are then accelerated by an electric field towards the rest of the accelerator. The prebuncher cavity is used to provide some initial bunching of the electron beam when the current is high. The chopper system is used to chop the beam into short pulses corresponding to a different experimental halls. The buncher cavity is where the main bunching of the electron beam occurs. The capture cavity then accelerates the compressed beam to an energy of 500 keV. The first two superconducting

Bunch Length and Buncher Voltage Calculation at UITF

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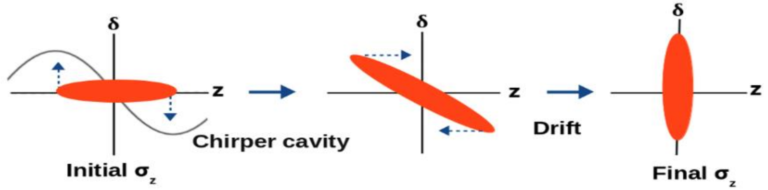
Abstract

In this note, we discuss the evolution of longitudinal phase space and bunch length compression of a non-relativistic electron beam using the beamline layout of the Upgraded Injector Test Facility (UITF) at Jefferson Lab. Also, we calculated the buncher voltage for a 200 keV electron beam.

Bunch Length Compressor/Buncher

An RF cavity is used to introduce a velocity difference between the particles of an electron bunch. The bunching RF cavity is a single-cell copper structure [1] that operates at zero crossing of the RF phase. At zero crossing, the tail particles will receive an added energy while the head particles will receive an energy decrease. After traversing a drift, the bunch length is decreased; and the bunch is compressed.

Ballistic compression is carried out by chirping an electron bunch in a chirper cavity (RF cavity) at zero crossing, followed by a drift where slow electrons at the head move back with respect to the centroid and fast electrons at the tail catch up with the centroid as shown in Fig. 1.



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