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U.S. DEPARTMENT OF ENERGY

SRF gun – high current and polarized beam R&Ds

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C-AD MAC21
December 7-10, 2021

Outline

- Overview of CeC SRF gun upgrade in Run 21
- Beamline changes
- Laser updates
- Cathode development
- Diagnostics upgrades

What CeC gun demonstrated

- The CeC SRF gun generated electron bunches with very low normalized projected emittances (sub-μm at 1 nC) and charge per bunch exceeding 10 nC.
- The high QE room-t^o CsK_2Sb photocathodes operate for months in 1.25 MeV CW SRF gun without any significant degradation. We did not detect any degradation caused by generating CW electron beam
- CeC gun demonstrated capabilities of producing high quality electron beam and with new diagnostics installed measuring performance of CsK_2Sb, Na_2KSb and CsTe coated GaAS photocathodes, which is suitable for generating polarized electron beams

BNL’s tasks in SRF gun upgrade

Track 1, High current SRF electron gun: The focus of this research direction is to increase average current of unpolarized electron beam to 1 mA (maximum 3mA – ultimate goal) in the first two years (Phase I) of the project, and to 30 mA (maximum 100 mA -ultimate goal) during follow-up Phase II of the project.

- Main equipment: laser and diagnostics (DCCT)
- Main design – 100 kW FPC (FNAL)

Track 2, Polarized SRF electron gun: In contrast with Track I, this is completely new and untested direction in polarized electron gun R&D

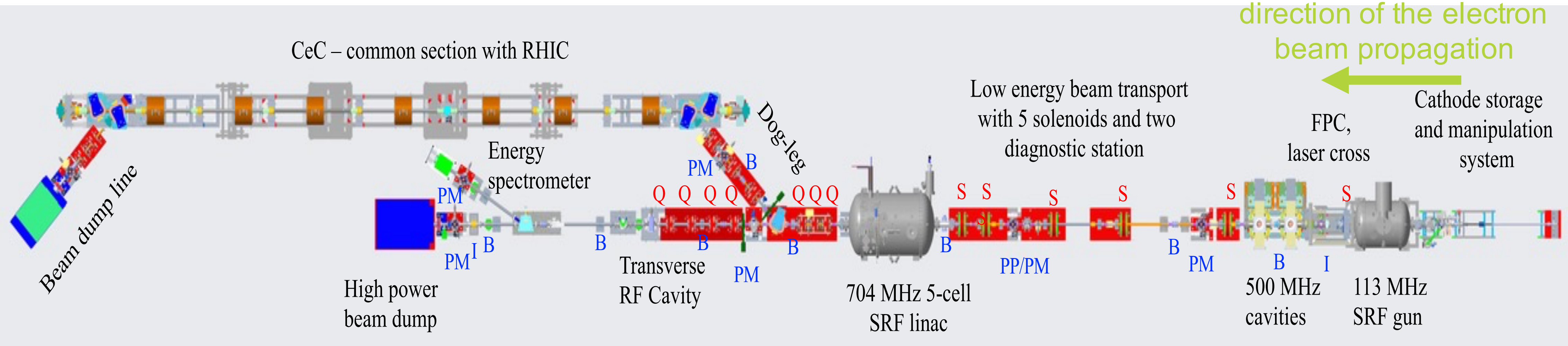
- Main equipment: polarimeter (JLAB), new UHV cathode transfer system, cathodes

Track 3, SRF electron gun performance restoration techniques: As any other SRF system, the SRF gun performance can degrade, for example from contamination or aging processes.

- Main design: plasma treatment for SRF gun (FNAL)
- Main experiment – He treatment at BNL

Preparation for the gun operation with 1-3 mA

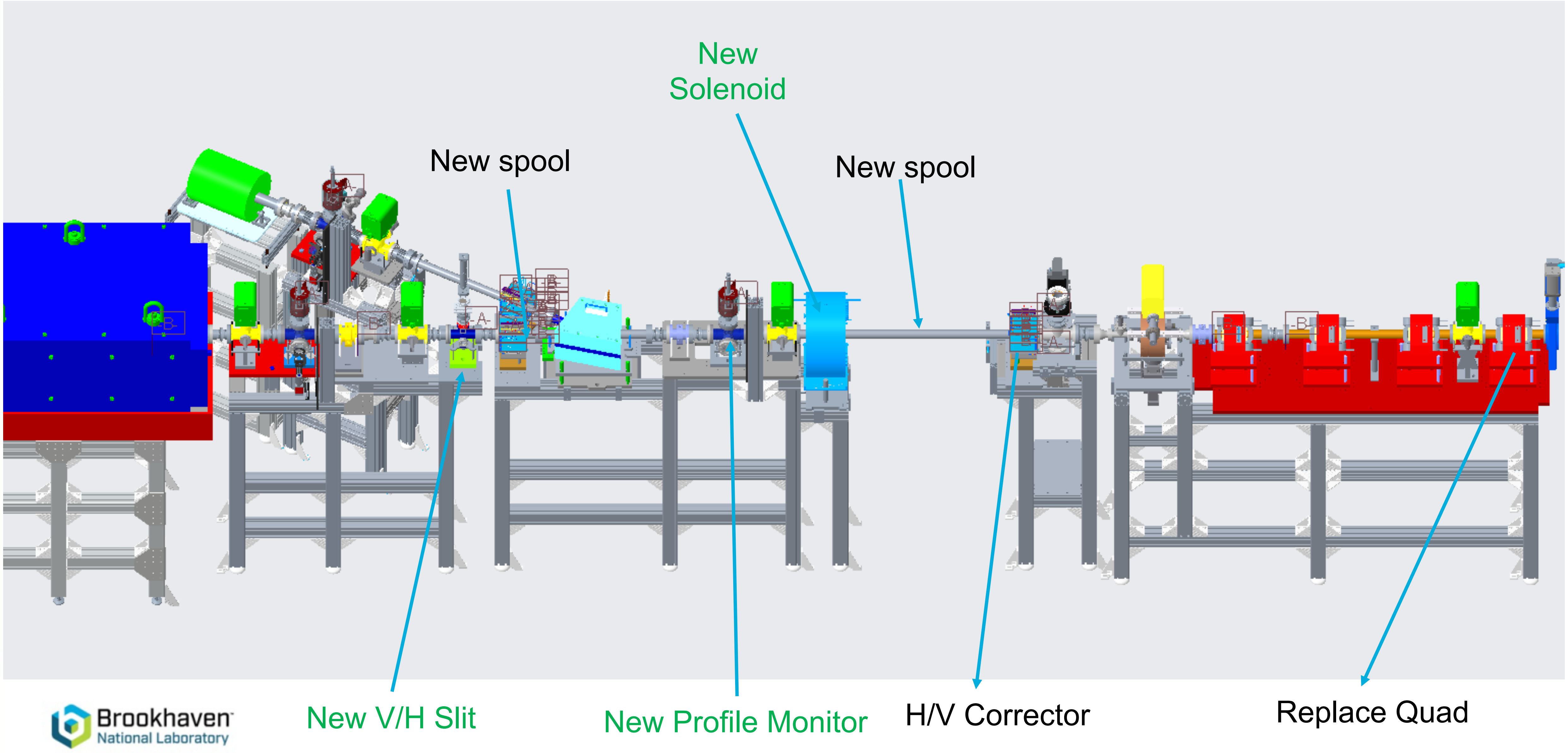
High current SRF gun experiment employs the existing Coherent electron Cooling (CeC) accelerator.



The system required the following modifications:

1. Additional focusing elements are necessary for a successful beam propagation – **new solenoid is installed**
2. Machine Protection System (MPS) requires adjustments to allow use of the bunching cavity and the 5-cell SRF accelerating cavity – **implementation is under way**
3. Additional diagnostic is required – **DCCT is installed**
4. Laser system upgrade is required – **under way, new high rep-rate seed laser is installed**

Diagnostics Beamline Upgrade – new solenoid installed



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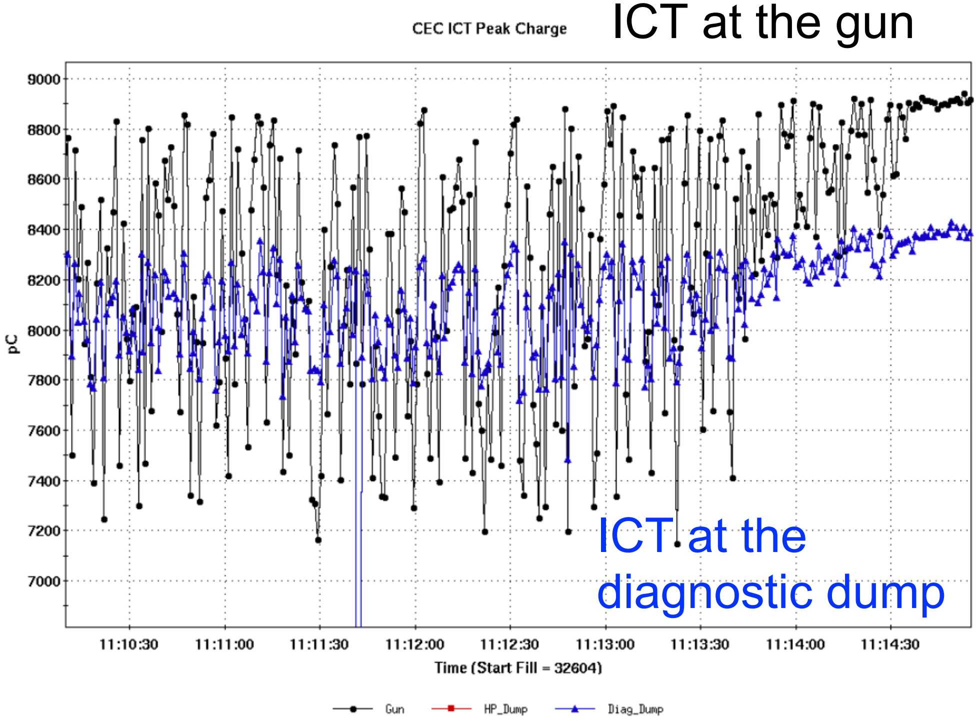
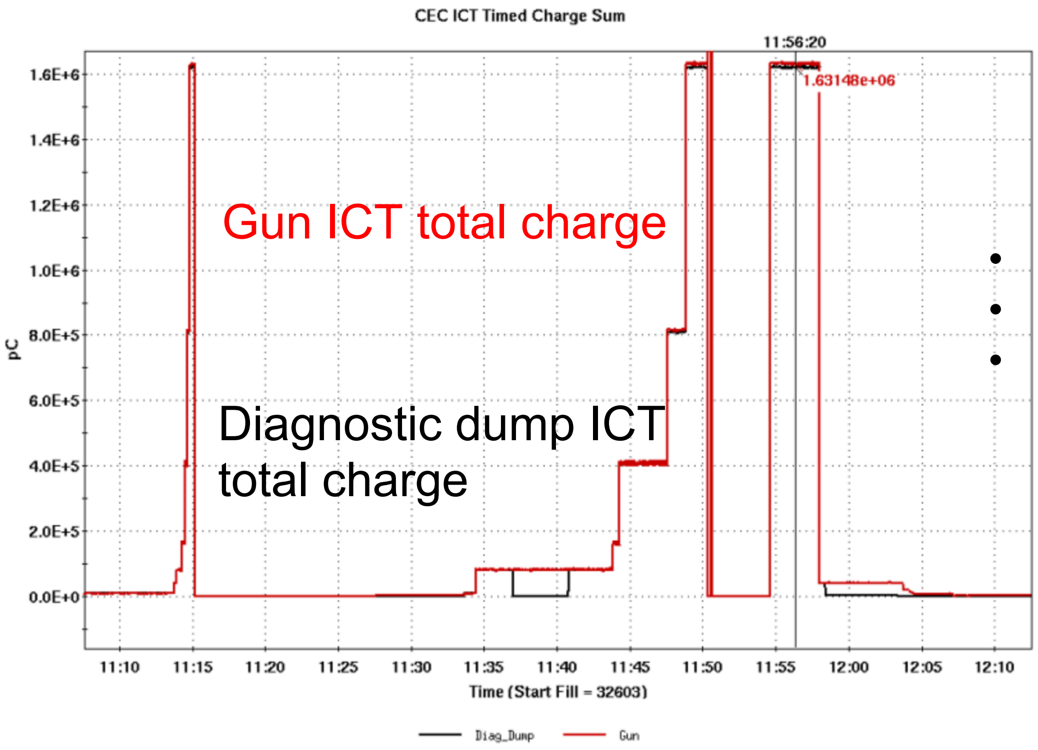
First attempt of high current operation (2021)





- 200 pulses
- 8 nC per pulse
- 1.6 uA beam current

1. We **demonstrated ultra high bunch charge (~ 8 nC)** with high transmission from the gun in run 21.
2. **MPS mode prohibited** us **from going further** up in total charge (with linac ~ 9 MV).
3. In run 22, a **new MPS mode will be implemented** to allow high current beam with linac running at lower voltages.

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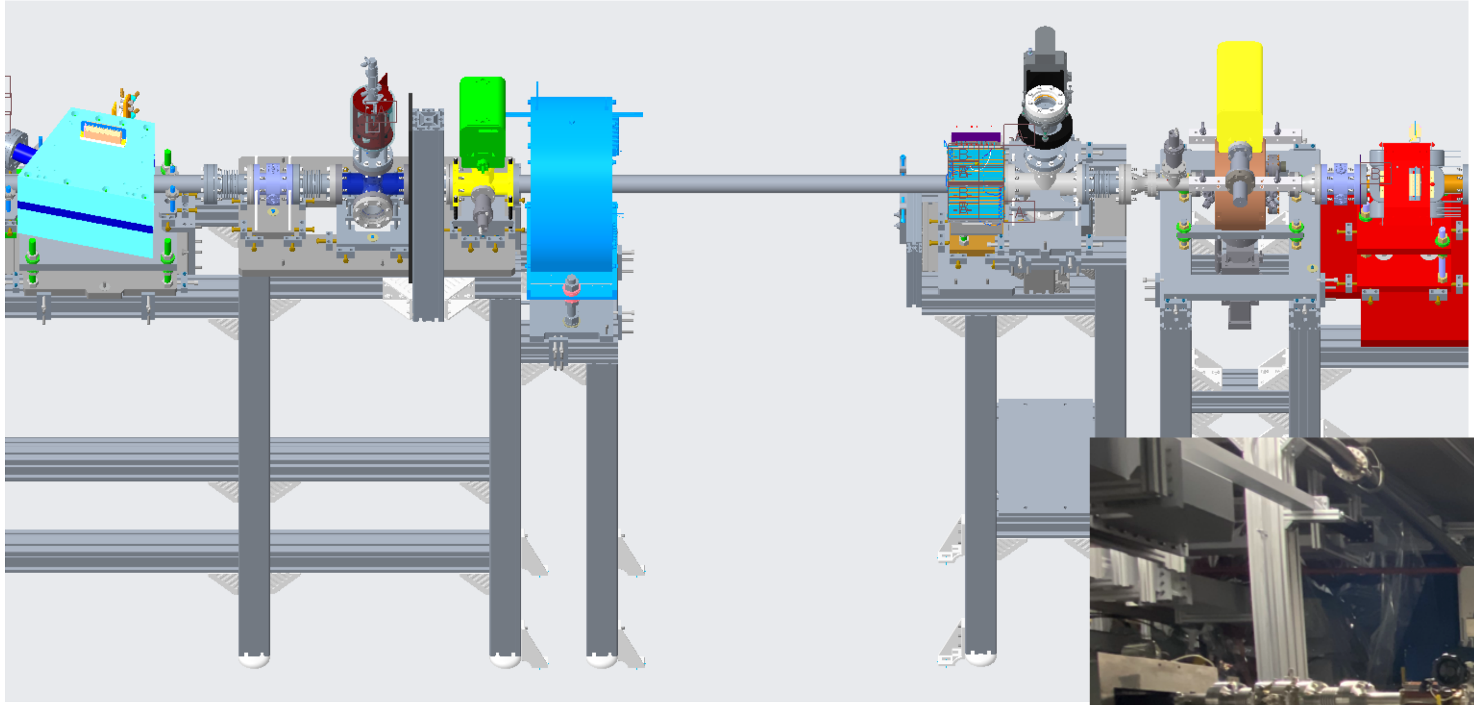
Profile Monitor and Solenoid

- Stand modification design completed
- Work in progress for relocation of H/V corrector and removal of Diamond detector stand
- Delay from vendor for profile monitor cross 10/05/21 – fabrication of new cross in house as backup



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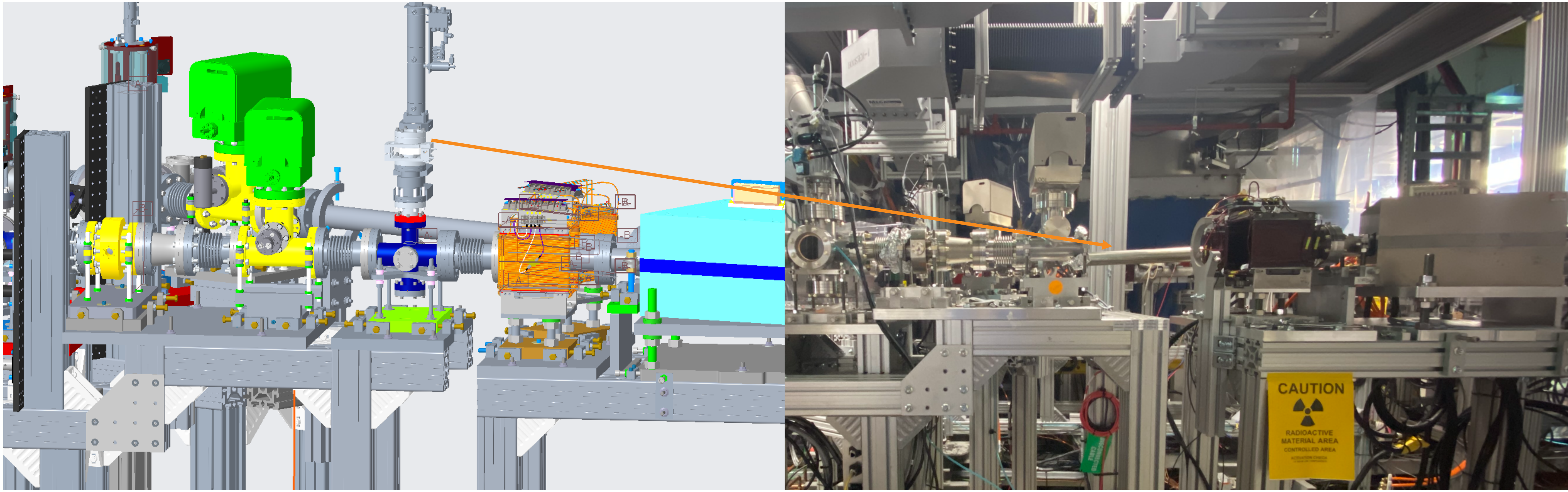
H/V Slit

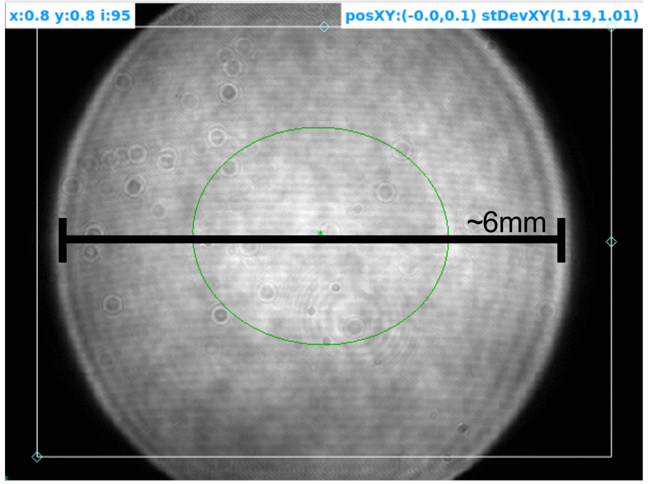
- Stand modification design completed
- Beamline vented and vacuum components removed
- BPM and ion pump relocated; survey to follow
- Delay from vendor for H/V Slit Custom cross 10/05/21



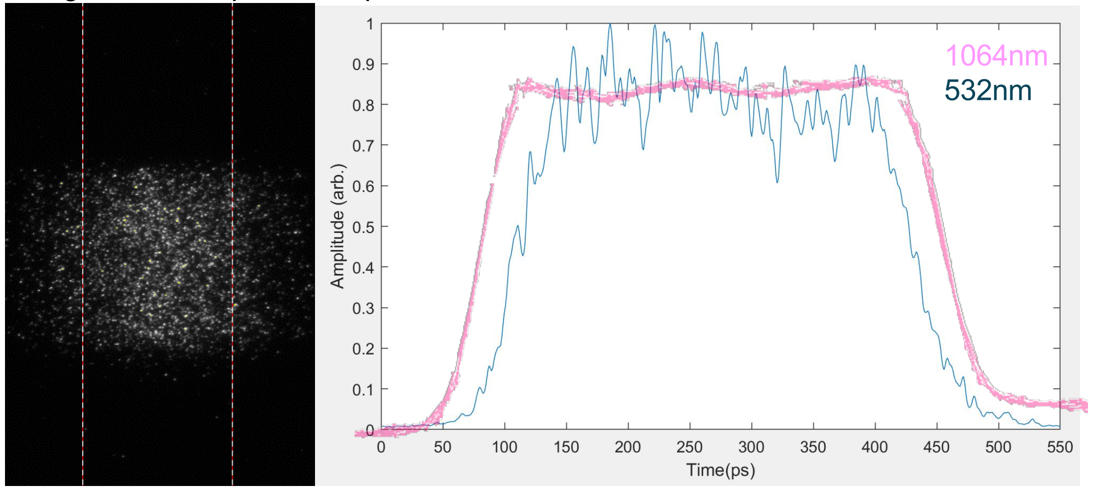
Laser Performance

Rep. Rate	78kHz
Pulse Energy 1064nm 532nm	 125µJ 85µJ
Pulse duration	125-1000ps
M^2	<1.05
Output stability 1064nm 532nm	rms 1% 2%
CoM stability Downstream of Aperture	<10µm rms

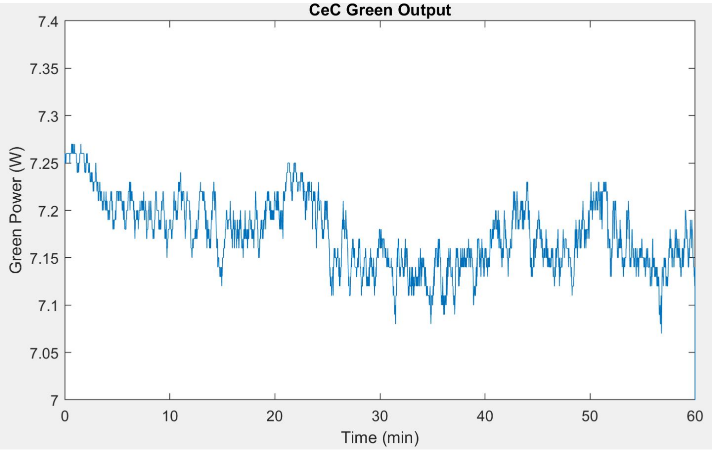
Transverse Profile imaged to the Cathode



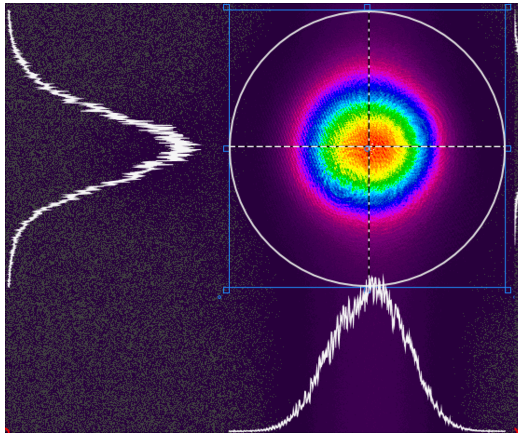
Longitudinal 375ps Flat-Top



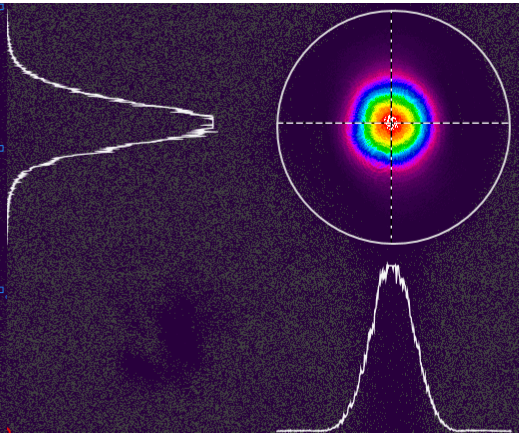
532nm Output Power



Transverse Profile 1064nm



Transverse Profile 532nm



Laser upgrade overview

Seed Laser → Regenerative Amplifier → NCPM SHG → AOM Pulse Picker → Intensity Control

Maser **O**scillator **P**ower **A**mplifier – system

Seed laser:
- 50-750ps selectable Flat-Top Laser pulses, Rep. Rate 56.5MHz

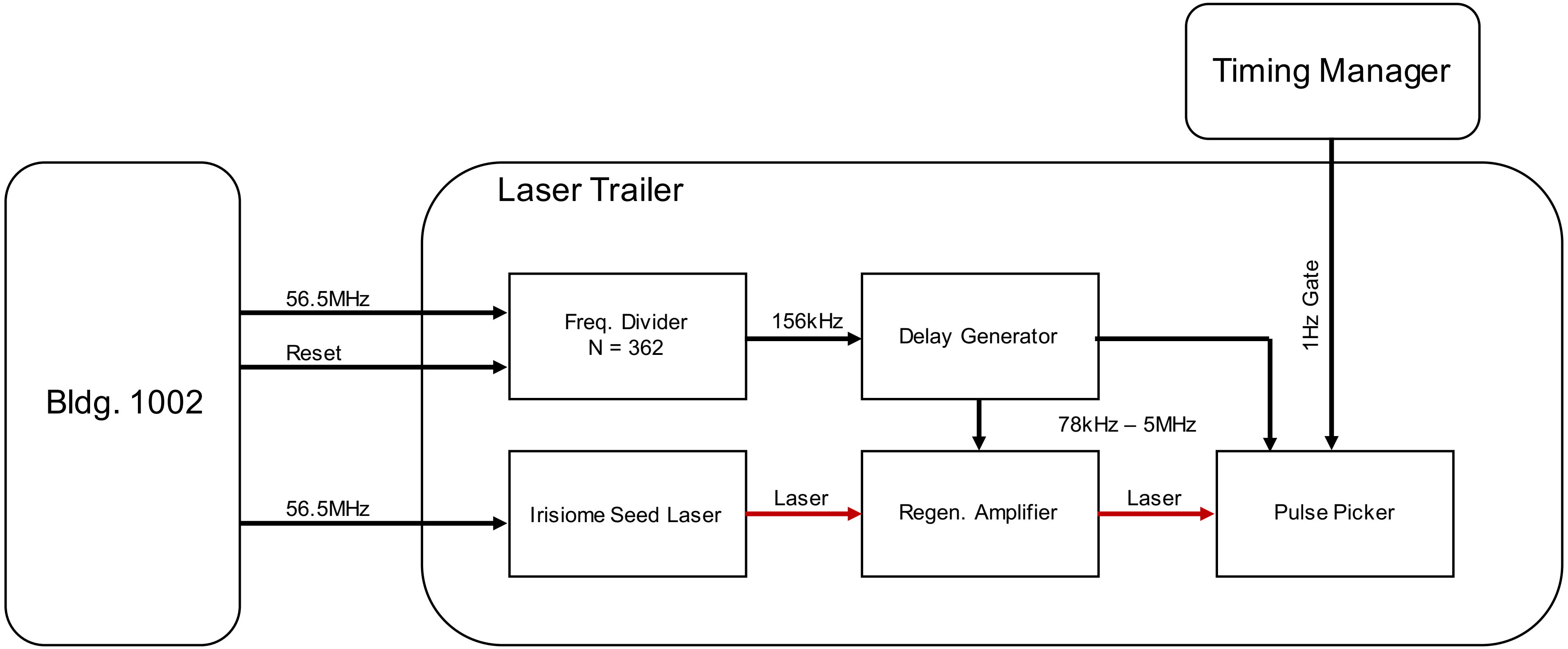
Regen:
- Single stage to final energy amplification + Pulse Picking to 78kHz, Max. rep. rate 5MHz
- Perfect transverse beam quality
- Solid State, linear amplifier

Non-**C**ritically-**P**hase-**M**atched **S**econd-**H**armonic-**G**eneration:
- Enables running at various power levels without adjusting the amplifier

AOM Pulse Picker:
- High Contrast optical switching up to 5MHz to pulse pick the amplified pulse stream

AOM based Intensity Feedback
- Self contained feedback loop to eliminate fast intensity modulations ~1kHz Bandwidth
- Complete the Gun Table camera modifications for gun table profile viewing
    - Replace scattering screen with fluorescent screen
- High Rep. Rate testing

Timing Diagramm

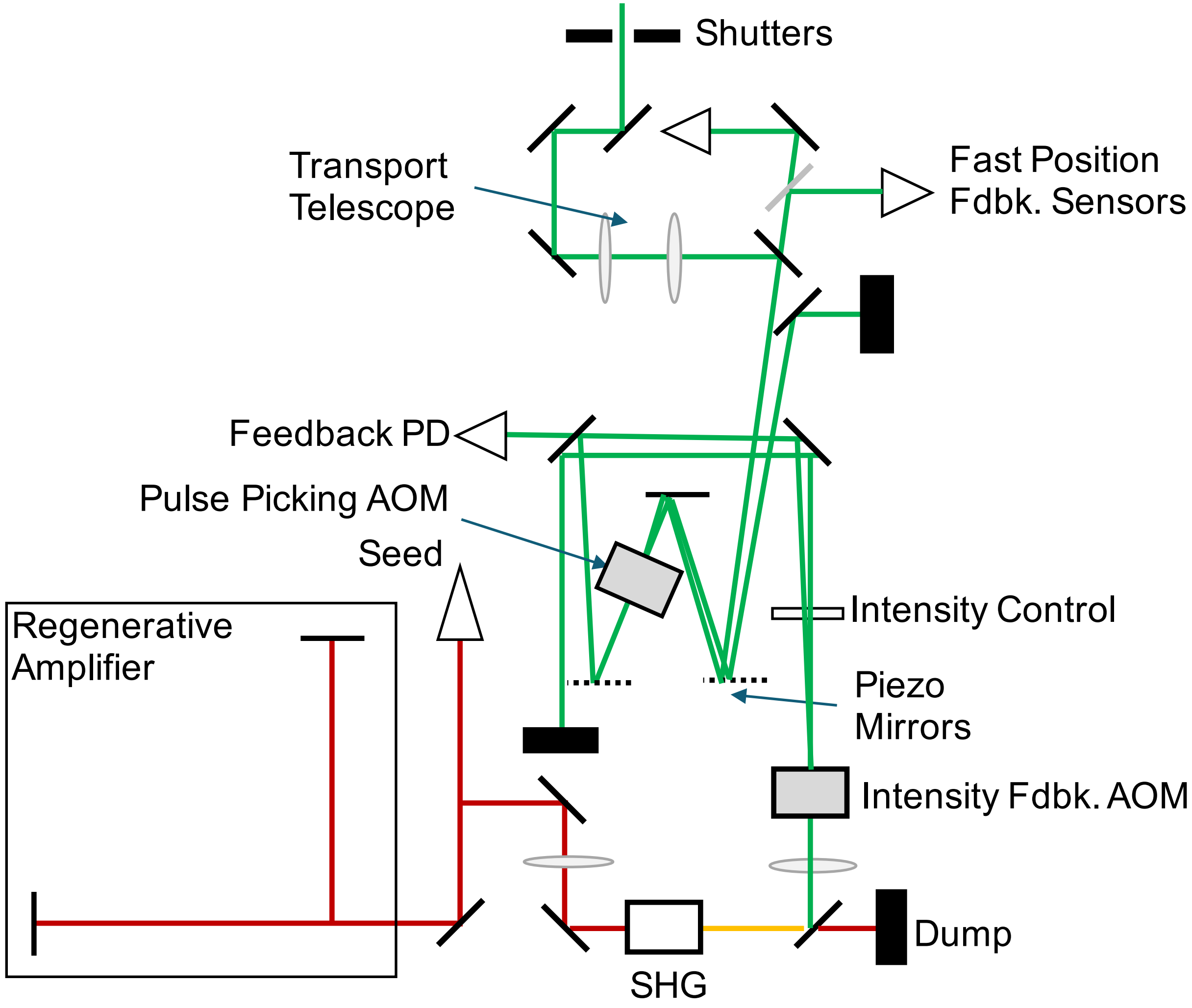


Laser Layout for Run22

- Exchange of IR Pockels Cell Pulse Picker with AOM to enable 0-100% duty cycle operation for high repetition rate operation (1-5MHz)

- Maintaining CW beam throughout the entire system to enable high bandwidth position and intensity feedbacks and limit thermal effects from repetition rate changes

- Addition of second AOM for fast intensity feedback
  - Still need to work out efficient noise detection method to reach 2kHz Fdbk. Bandwidth for operation at variable repetition rates (78kHz-5MHz)



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Expected Performance

	Unit	Min	Typ.	Max
Seed Wavelength			1064.2	
Output Wavelength	λ		532.1	
Bandwidth	nm		0.05	
Pulse duration (depends on Seed Option)	Ps	50	350	750
Pulse Shape (Identical to Seed)	-		Flat-Top	
Repetition Rate	kHz	10	78	5000
Average Power (532nm)	W	8	8	5
Pulse Energy	µJ	800	100	1
Charge equivalent after spatial shaping (1%QE)	nC	1600	200	2

Maximum available power at Gun FPCs

Power Amp max output (W)	4000	Tomco 4kW CW amplifier (113MHz)
Available power at FPCs (W)	3000	Transmission loss is 0.9 dB with an additional 0.3 dB from circulator and hybrid.
Power dissipation in FPCs (W)	1475	See table below from Cliff Brutus on calculation of losses
Total power to deliver to beam (W)	**1525**	We need to factor in loses for microphonics and beam loading compensation

Table 2: Distribution of RF power loses on the FPC

RF Power Loses	Value
On inner conductor hollow section	894.3 W
On inner conductor solid section	4.3 W
On bellows of outer conductor	554.6 W
On flange	21.9 W

Repetition rate and cavity frequencies (MHz) selection

Rep rate	Laser	Gun	Buncher	Linac
0.83703	56.91	112.99845	501.378	703.938
0.64942	56.5	112.99845	501.349	703.967
0.61748	56.8	112.99845	501.392	703.924
0.50900	56.5	112.99845	501.367	703.950
0.48917	56.75	112.99845	501.400	703.916
0.43294	56.72	112.99845	501.349	703.967

- New Laser installed for FY22 has f_center 56.5 MHz with 1MHz bandwidth
- Gun FPC_tuner coupling determines the frequency for operation

	Gun		Buncher		Linac
Tuner range (+/-) (MHz)	0.003		0.05		0.039
f_min (MHz)	112.9985		501.34		703.9
f_center (MHz)	113.0015		501.39		703.94
f_max (MHz)	113.0045		501.44		703.97

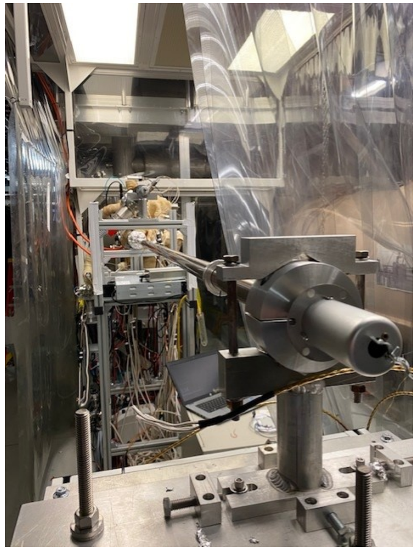
Preparation for polarized beam operation

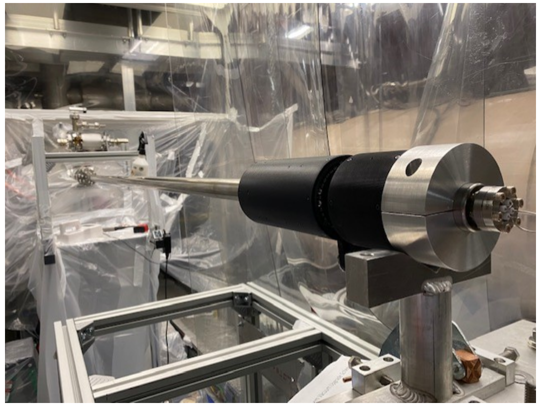
Goals:

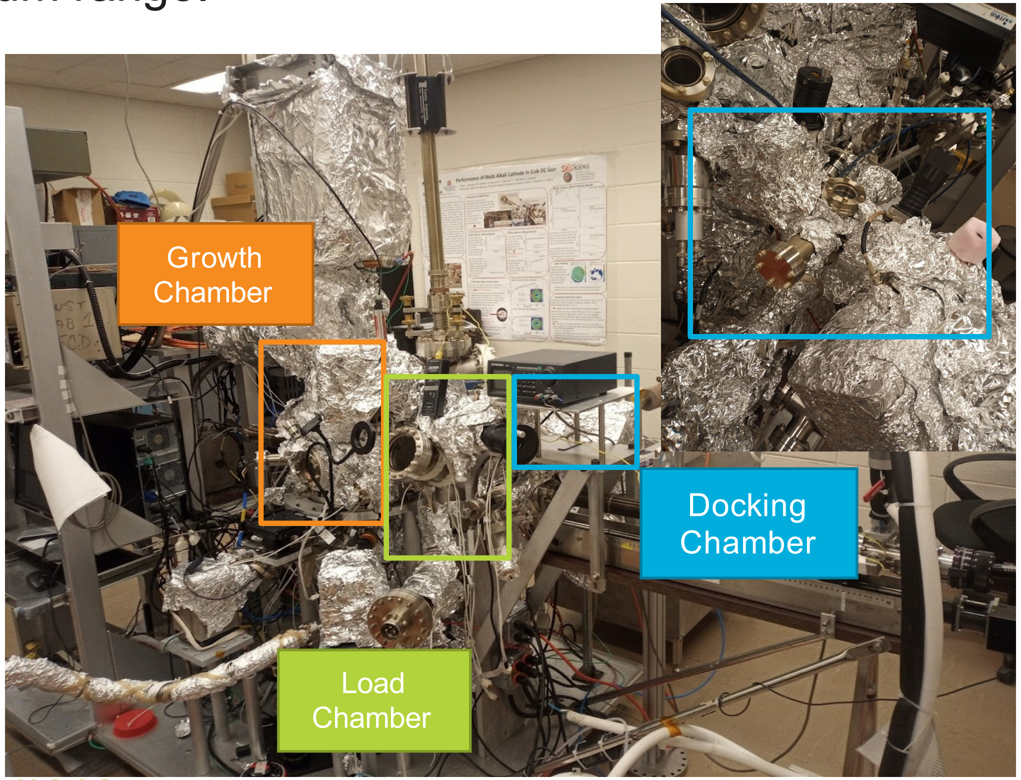
1. Upgrade cathode deposition and transport system for GaAs **– completed**
2. Introduce GaAs cathode into the SRF gun **– first tests will be performed at the end of CeC Run'22 (February-March 2022)**

New extreme vacuum cathode system:

Load lock and cathode transfer chambers achieved 10^{-12} Torr vacuum range.
This is about **100X better than the old system**.





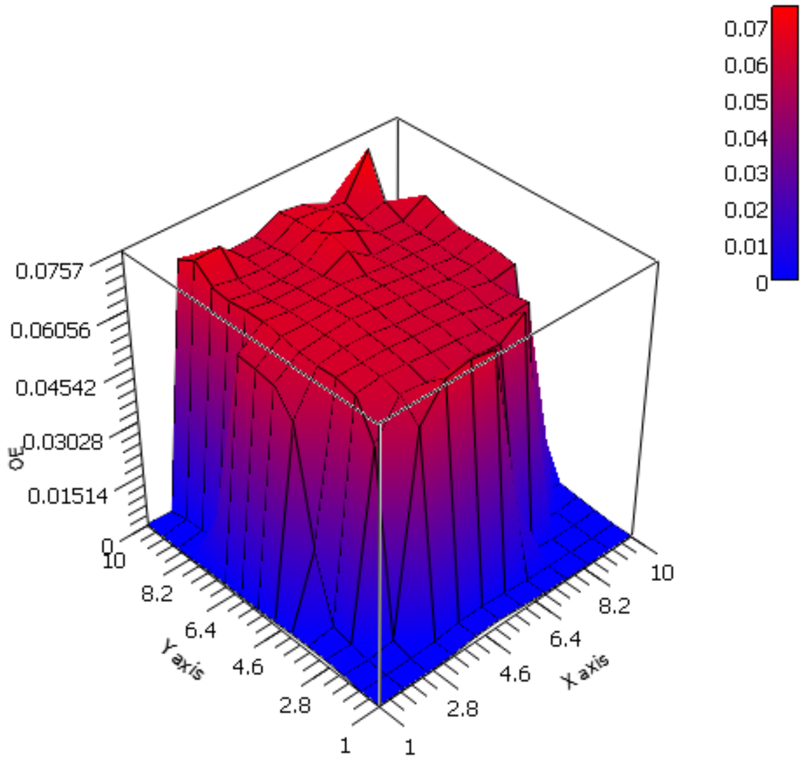


CeC cathode system upgrade:

- **Multiple clustered alkali sources;**
  - Sources for Na-K-Sb;
  - Growth in co-deposition;
  - Te and O_2 leak valve for GaAs;
  - Protective coatings;
- **Quantum efficiency 2D maps;**
- **New cathode magazine for 4 cathodes;**
- **New cathode manipulation system to mitigate particulate.**

QE 2D scan capability is included

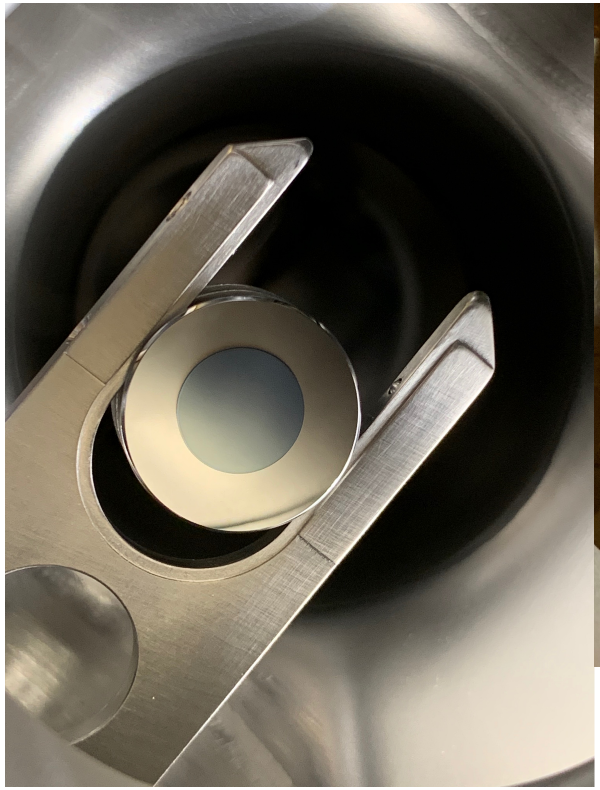
QE map of cathode #2 grown on 10/28/2021

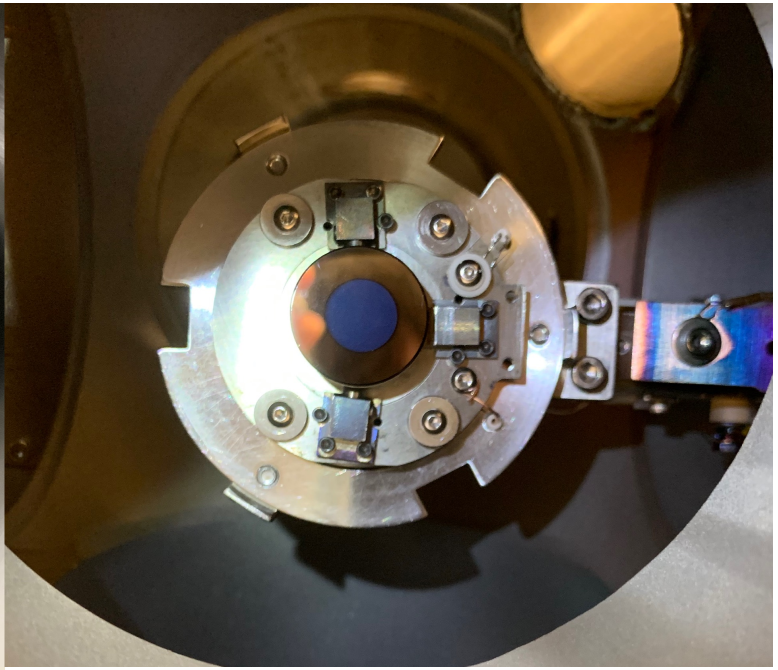


- Piezo motors are probably not the best choice due to their large backlash;
- looking to replace them with stepper motors;

3 cathodes for run 22 already delivered

- FY22 completing upgrade
  - installing the new sources;
  - Install components for GaAs;
    - O2 leak valve;
    - Te source;
    - NEG pumping module;
  - 3 cathode magazine for GaAs;
  - test stand integration;





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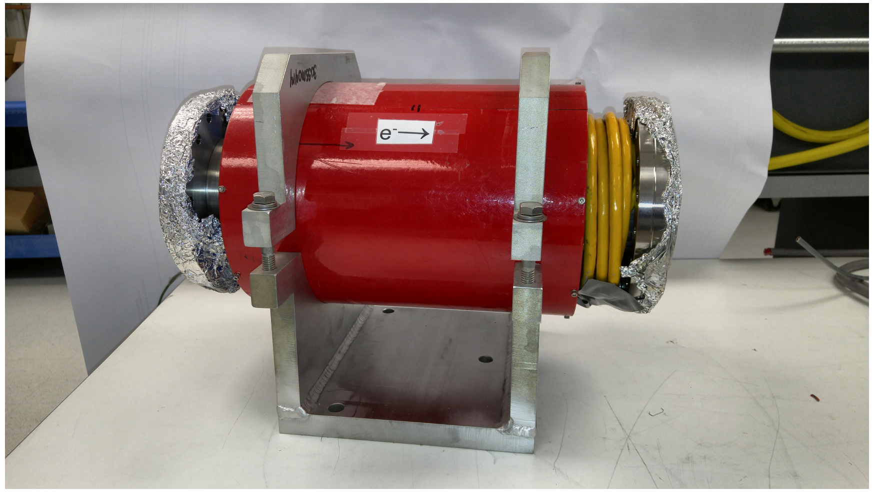
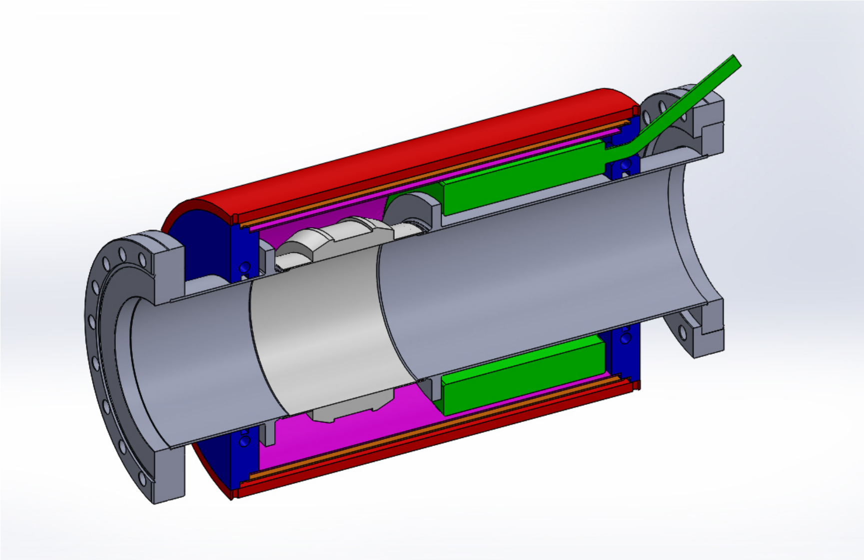
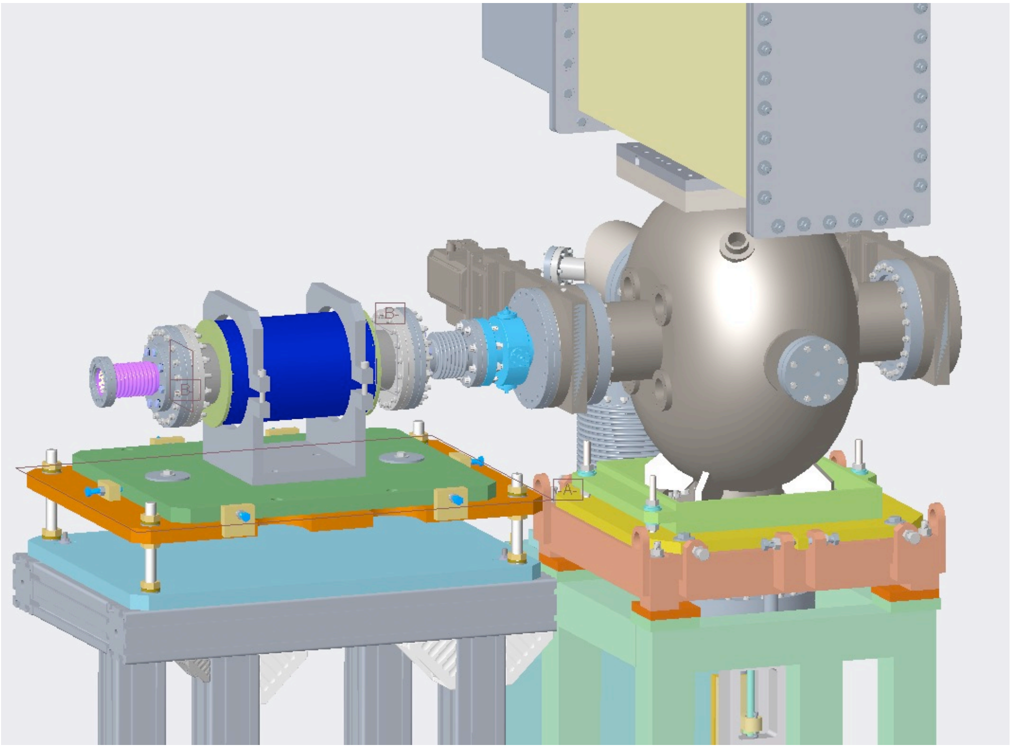
New diagnostics - DCCT



- The second of the two **DCCTs** that were used in ERL **has been rebuilt to have a larger aperture** than the original.
- It was **installed** in place of the second 500MHz cavity that was removed.



This DCCT will use an updated version of the electronics package that is designed to be more stable during thermal variations. This signal will then be processed with a spare channel in the existing Zynq system.



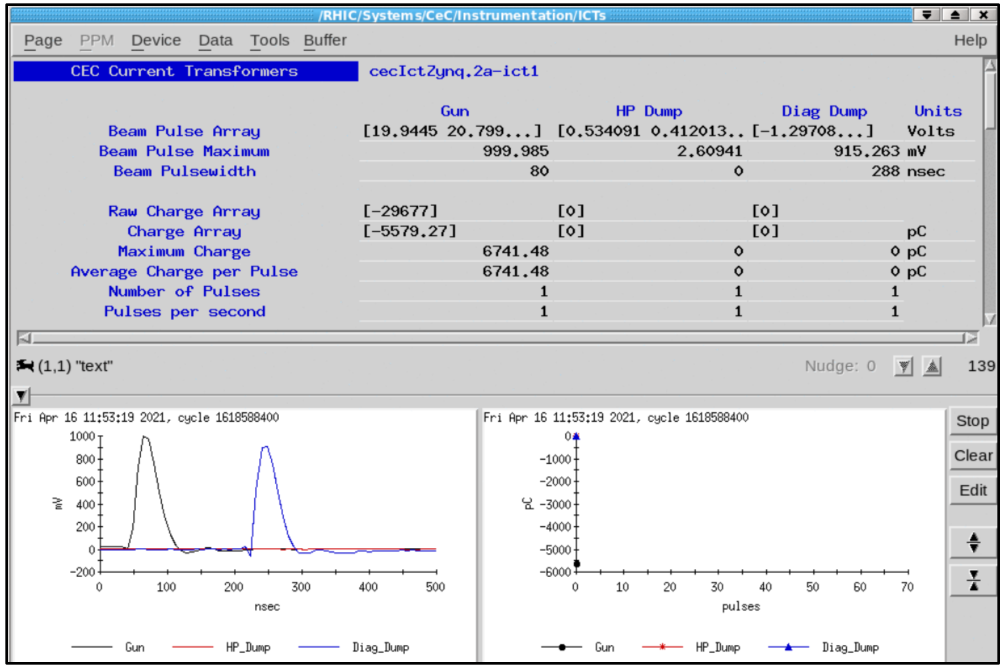
ICTs update

Higher repetition rate for Run 22

- Zynq firmware updated to process pulses at a rate of 1 MHz
- At the higher repetition rate, the pulses will start to run into each other causing a baseline to dip

Other updates

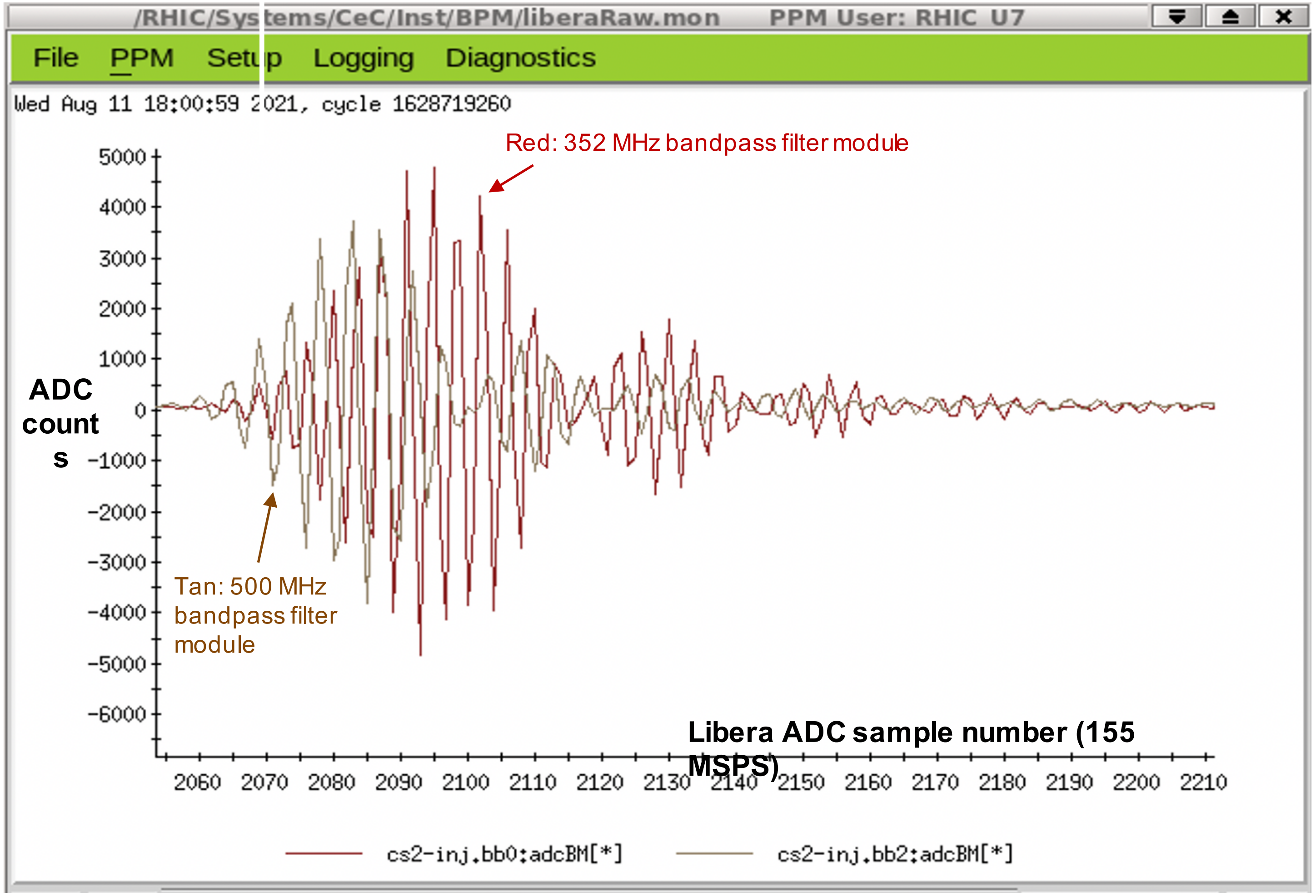
- Update to amplifier to allow for larger dynamic range in pulse intensity
- Updated amplifier design for improved common-mode noise filtering



BPMs CW operation

Bench-testing the following:

- 1 Hz single bunch noise and drift
- 78 kHz CW
- 1-5 MHz CW, including signal mixing with closely space bunches, especially the 352 MHz bandpass filter response
- Position measurements with different attenuator settings
- Setup for multi-bunch flavor and dense flavor, focusing on the following Libera parameters:
  - Num_of_bunches
  - data_averaging
  - spe_group_size



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CeC MPS Modifications for Run22

- Diamond detector was removed from the diagnostics beamline and corresponding limit switch was removed from the chain
- New profile monitor and slits were installed on the diagnostics beamline and corresponding limit switches were added to chain (no FPGA re-programming)
- One buncher cavity was removed and corresponding changes in the MPS were done
- Since space charge forces are significant we added option to deliver accelerated beam to the high-power dump in the diagnostics beam. For this purpose buncher cavity and linac are enabled (deflecting cavity is inhibited). Since the maximal power dump can take is 10 kW we added input from LLRF system that linac voltage is below the safe threshold.

Beam dynamics studies

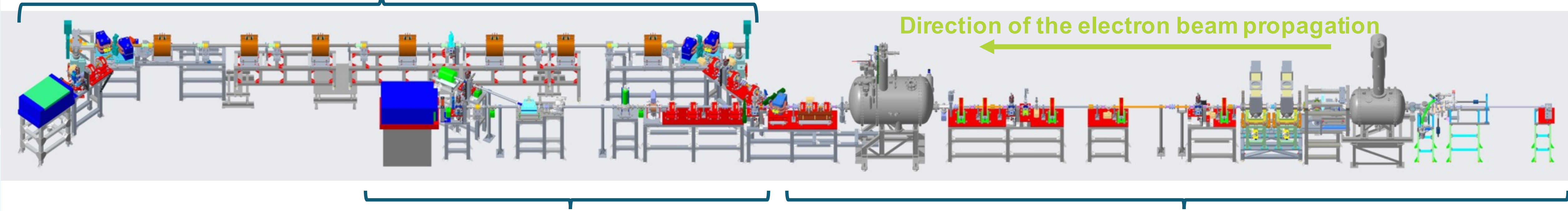
Desired beam parameters to deliver 1-3 mA

- Charge/bunch: 1.5-3.5 nC
- Operational repetition rate:
  - If using linac & buncher: 0.837 MHz
  - No linac & buncher: 2.974 MHz
- Higher current (3-10 mA) can be achieved by scaling up charge/bunch or repetition rate.

Operation without linac			
P [kW]	**I_{beam} [mA]**	**V_{gun} [MV]**	**Q_{bunch} [nC]**
2.5	1	1.35	0.34
f [MHz]	2	1.25	0.67
2.974	3	0.833	1.01
	4	0.625	1.34
	5	0.5	1.68

Operation with linac @ 3-6 MV			
P [kW]	**I_{beam} [mA]**	**V_{gun} [MV]**	**Q_{bunch} [nC]**
2.5	1	1.35	1.19
f [MHz]	2	1.25	2.39
0.837	3	0.833	3.58
	4	0.625	4.78
	5	0.5	5.97

Common Section with RHIC



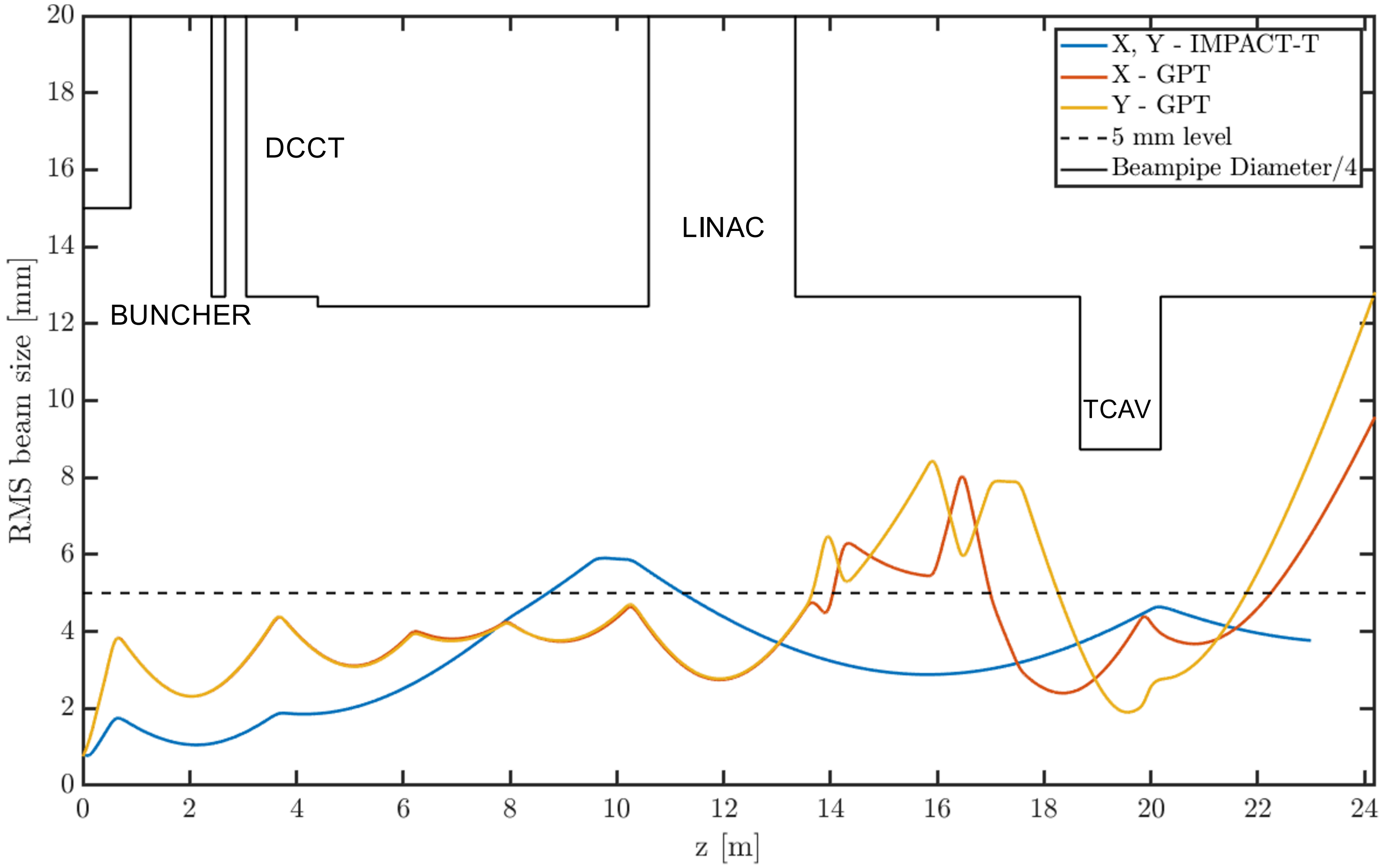
Time-Resolved Diagnostic Beamline (TRDBL)

Low Energy Beam Transport (LEBT)

Beam dynamics studies

Linac & buncher are OFF

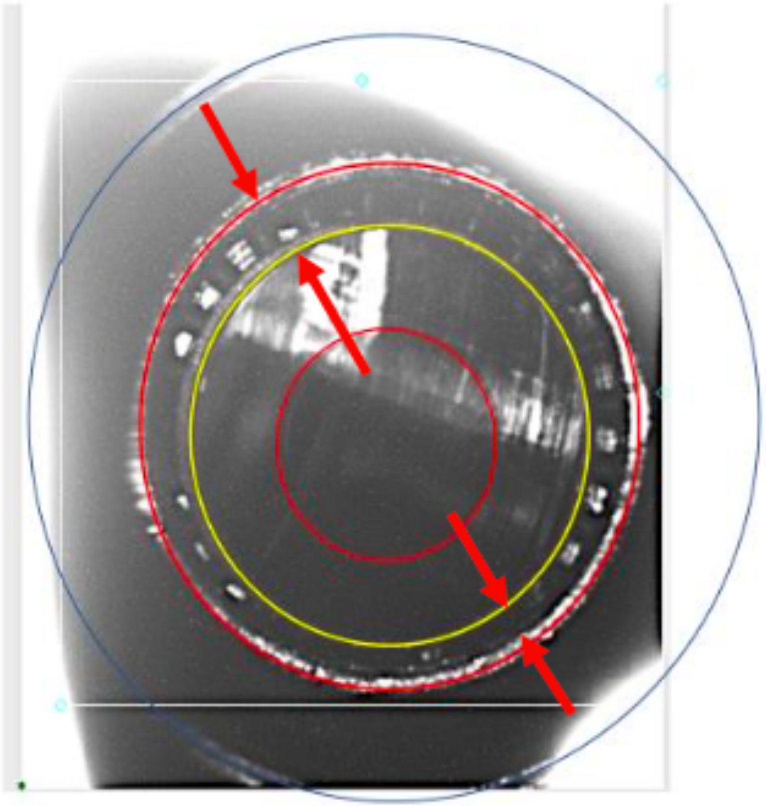
Parameter	Value
Bunch charge [nC]	1.5
Beam current @ 0.837 MHz [mA]	1.25
Laser pulse length [ps]	750
Gun voltage [kV]	833

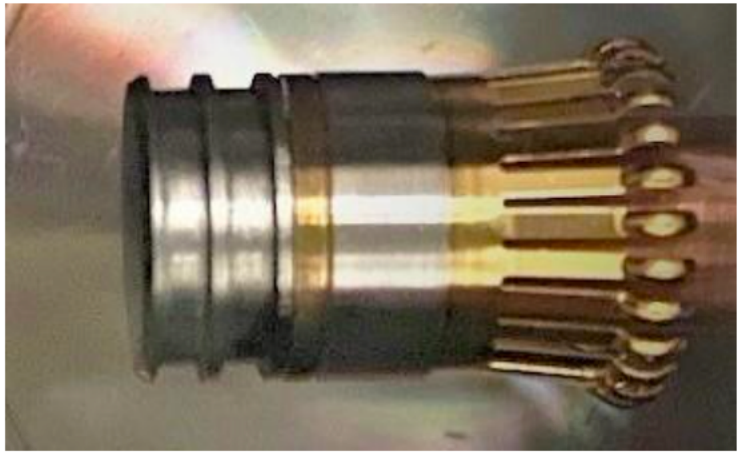


Practical experience with SRF gun treatment

Setback – damaged CeC cathode end effector

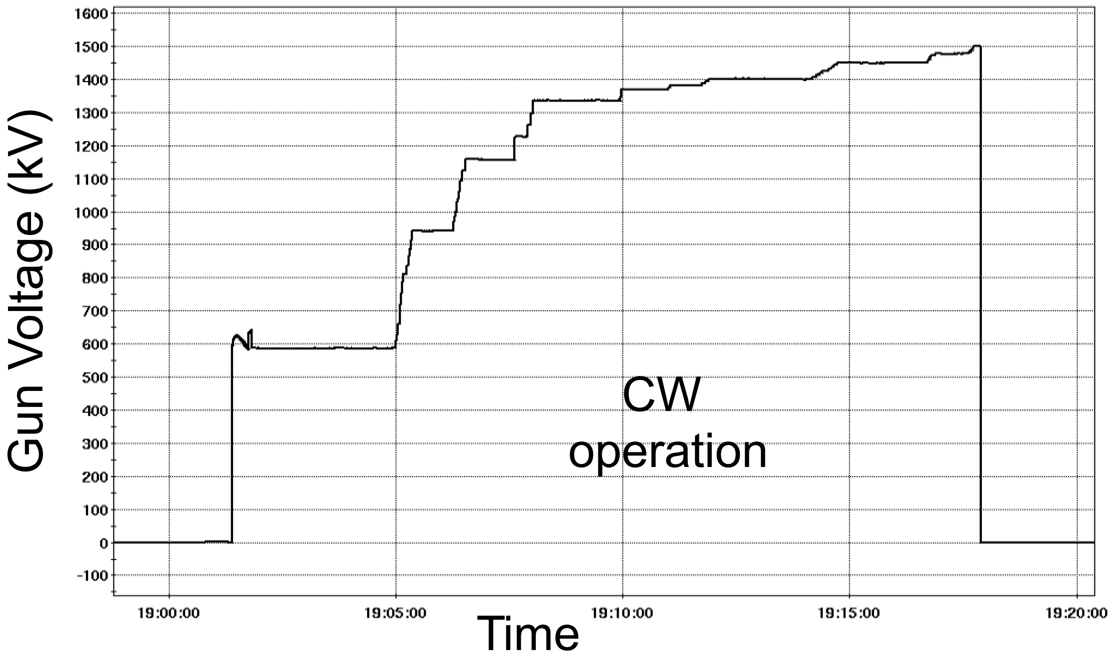
- In February 2021 SRF **gun showed significant performance degradation**
- Upon inspection, **damage** was found **to the cathode end effector within the gun**
- The damage cause significant contamination requiring an **immediate cavity treatment**

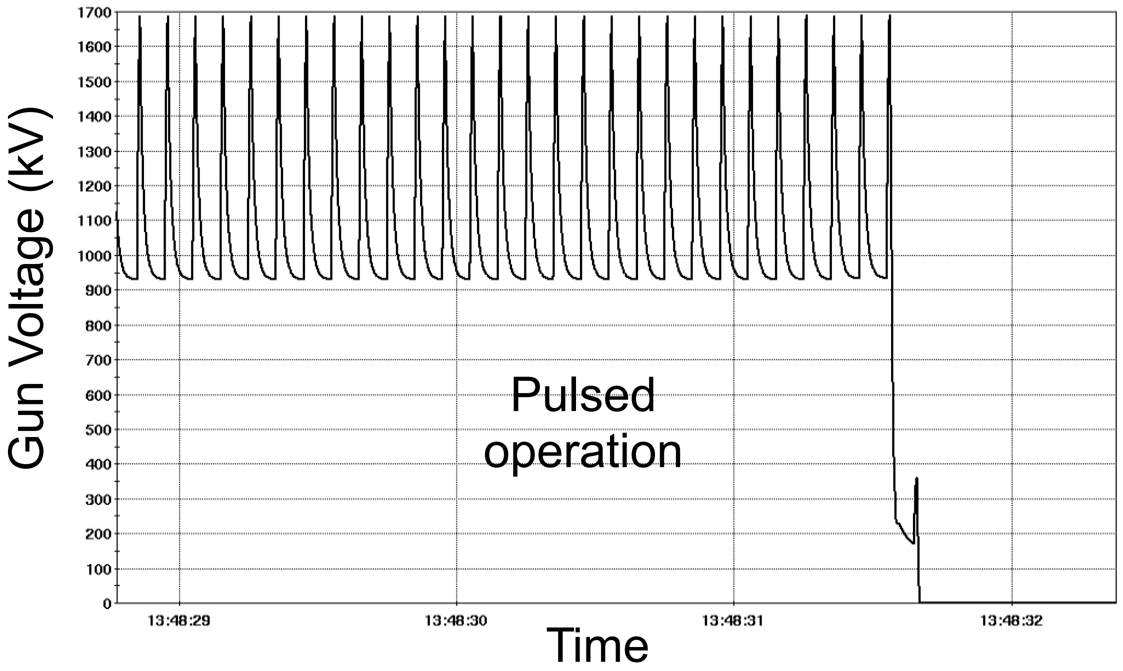




Practical experience with SRF gun treatment

- The maximum **CW voltage** achieved is **1.5 MV**. The **voltage is limited by** the **LiHe consumption** (max. available 8 g/sec).
- **Quench-like limit occurs at 1.7 MV.** This was done with a blank metal cathode and the cathode stalk in place (with recess ~ 8 mm).





After conditioning we managed to get **19.7 nC** per bunch with 500 ps pulses.

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Summary

- We practiced high current operation in Run 21 and obtained record high bunch charge, limitation being the MPS which will be updated in Run 22.

- Various components necessary for high current operation have been installed and tested.

- Beam dynamics simulations for the high current gun operation in February-March 2022 are nearing completion.

- We will pursue achieving 1 – 3 mA average beam current in Run 22 working in parallel with regular CeC operation.

Thank you for your audience!

Full author list

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Back up slides

2021 BNL spending is on track

ID #	Item/Task	Baseline Total Cost (AY$)	Costed & Committed (AY$)	Estimate To Complete (AY$)	Estimated Total Cost (AY$)
	Superconducting RF Electron Gun	361,200	195,108	166,092	361,200
	Totals:	361,200	195,108	166,092	361,200

	FY2021
a) Funds allocated	361,200
b) Actual costs to date	189,420
c) Uncosted commitments	5,688
d) Uncommitted funds (d=a-b-c)	166,092

Laser upgrades

The regenerative amplifier will be replaced by a fiber pre-amplifier and a solid state multipass main amplifier to generate ~30W of IR power @ 80MHz with tunable longitudinal flat-top pulses. The Seed laser, as well as most parts of the regenerative amplifier can be reused for this upgrade.

Phase I

Parameter	**Units**	**Value**	**Parameter**	**Units**	**Value**
Laser rep-rate, range	MHz	1 to 5	CsK_2Sb cathode QE	%	2 to 5
Laser wavelengths	nm	1064/532	Pulse profile		Beer- can
Pulse (flattop)	psec	50- 750	Jitter, RMS	psec	6
Pulse energy	nJ	1 -700	Charge per bunch	nC	1 - 2
Average power	W	6	Maximum average current	mA	≥10

Phase II

Parameter	**Units**	**Value**	**Parameter**	**Units**	**Value**
Laser rep-rate, range	MHz	56.5	CsK_2Sb cathode QE	%	2 to 5
Pulse (flattop)	psec	50- 750	Jitter, RMS	psec	6
Pulse energy	nJ	600	Charge per bunch	nC	up to 2
Average power at cathode	W	12	Maximum average current	mA	100

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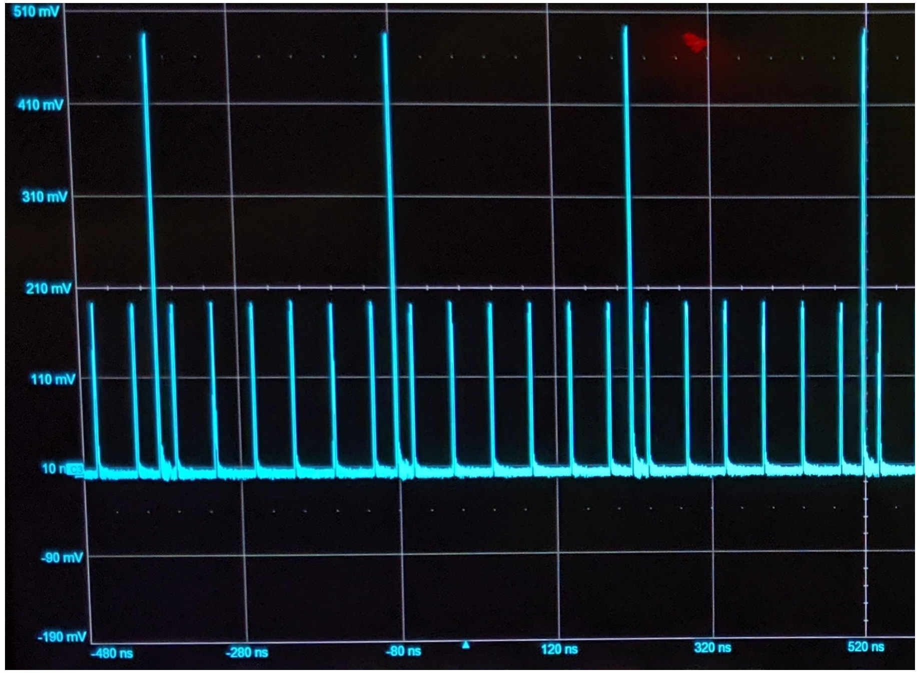
Demonstration of high rep. rate operation at SBU

Demonstrated rep rate: 3.33MHz (limited by Delay Generator timeout)
- Driver Rated for 5MHz (identical to the new CeC driver)

Output Power limited by Pockels Cell timing pattern: 6W
2.5MHz Operation does not suffer this issue: Power saturates at 14W

20MHz amplifier seed + 3.33MHz amplified Seed

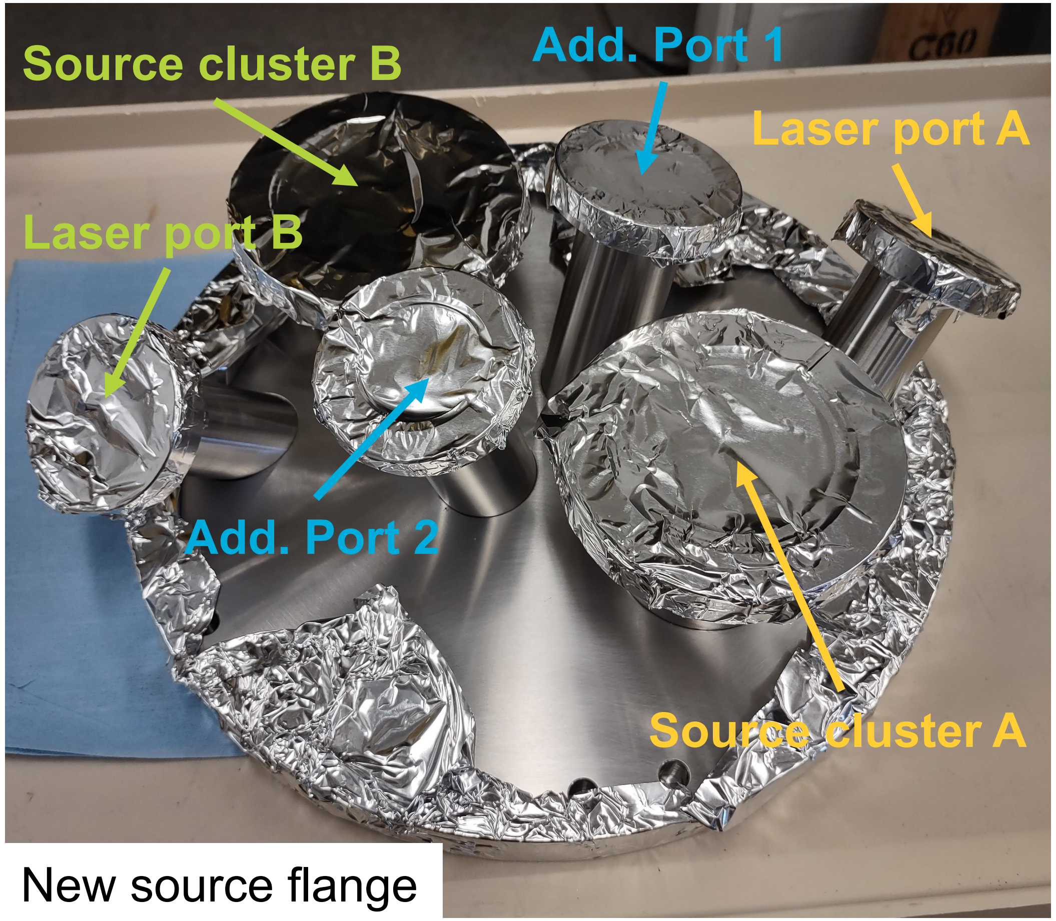


Longitudinal profile (2ns Flat-Top)

Main growth chamber

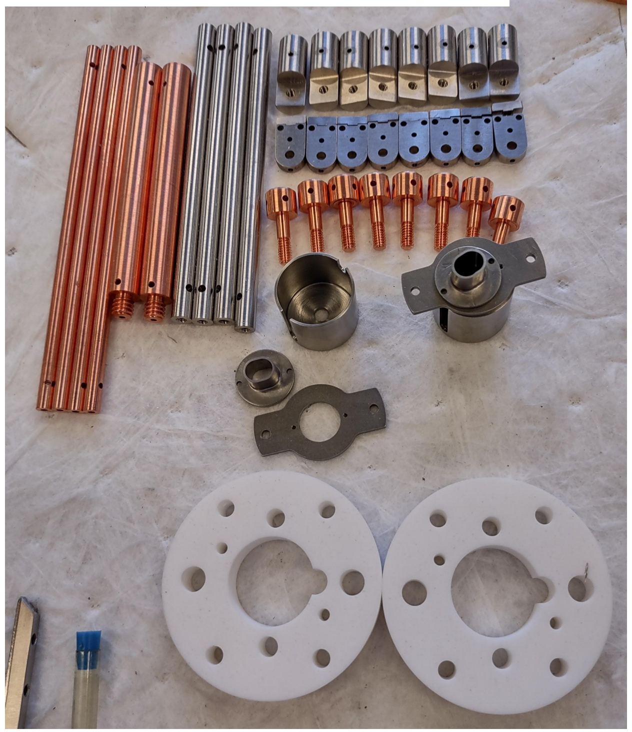
- Replace the main UHV chamber to allow
  - Hosting two cluster of sources (better alignment, co-deposition);
  - 2 additional port for future R&D on protective coatings;

New main chamber



New source flange

Clustered evaporators



Installation of the new evaporators assembly has been delayed to Dec 2021-Jan 2022 because of delays in the delivery of some required vacuum components.

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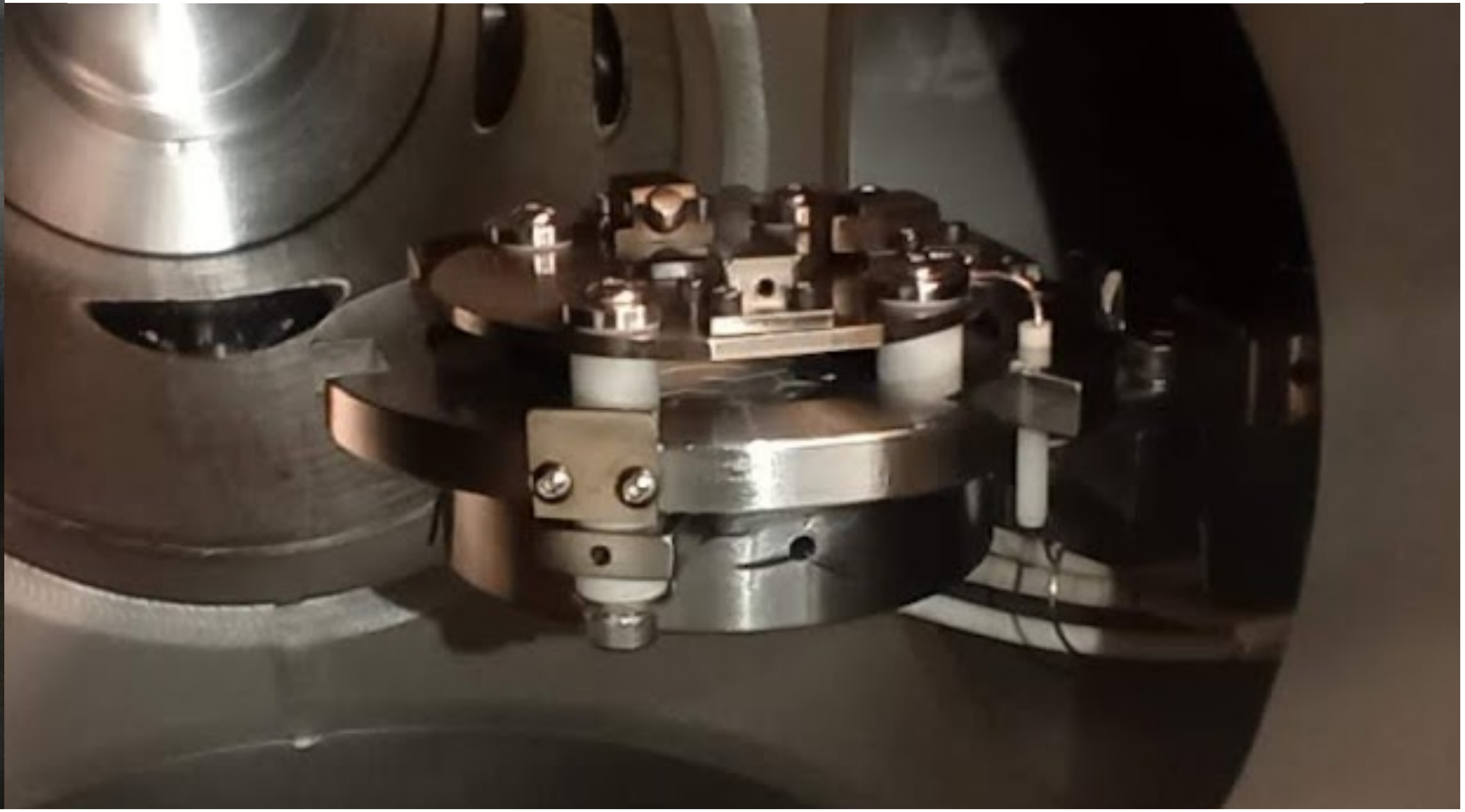
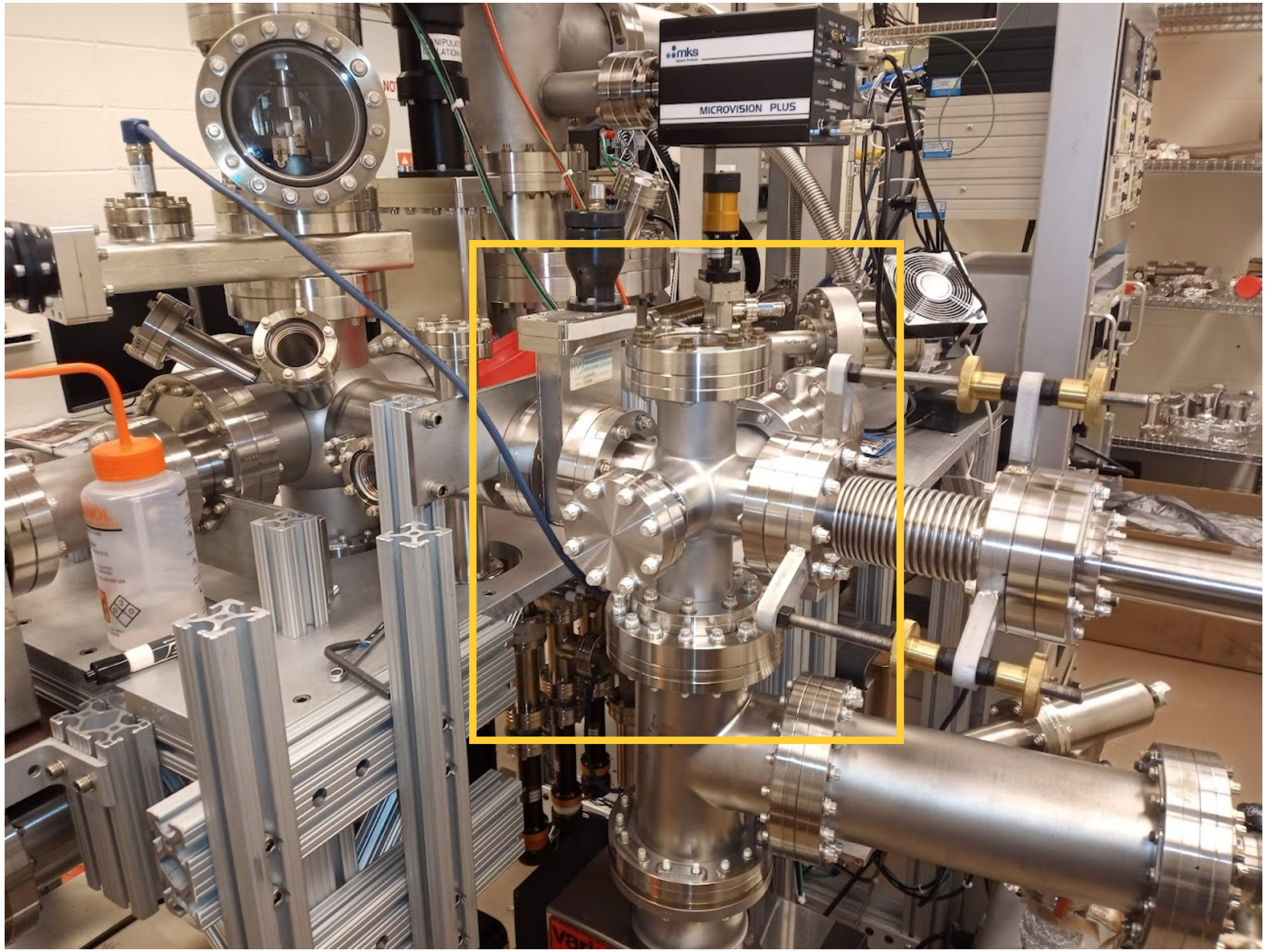
Sample heater and cathode mask

Redesigned and modified to mitigate the particulate production from ceramics insulators



New docking chamber



A new docking chamber with a 3.375” port allows for a larger clearance around the magazine minimizing the chances of scraping and of particulate production;

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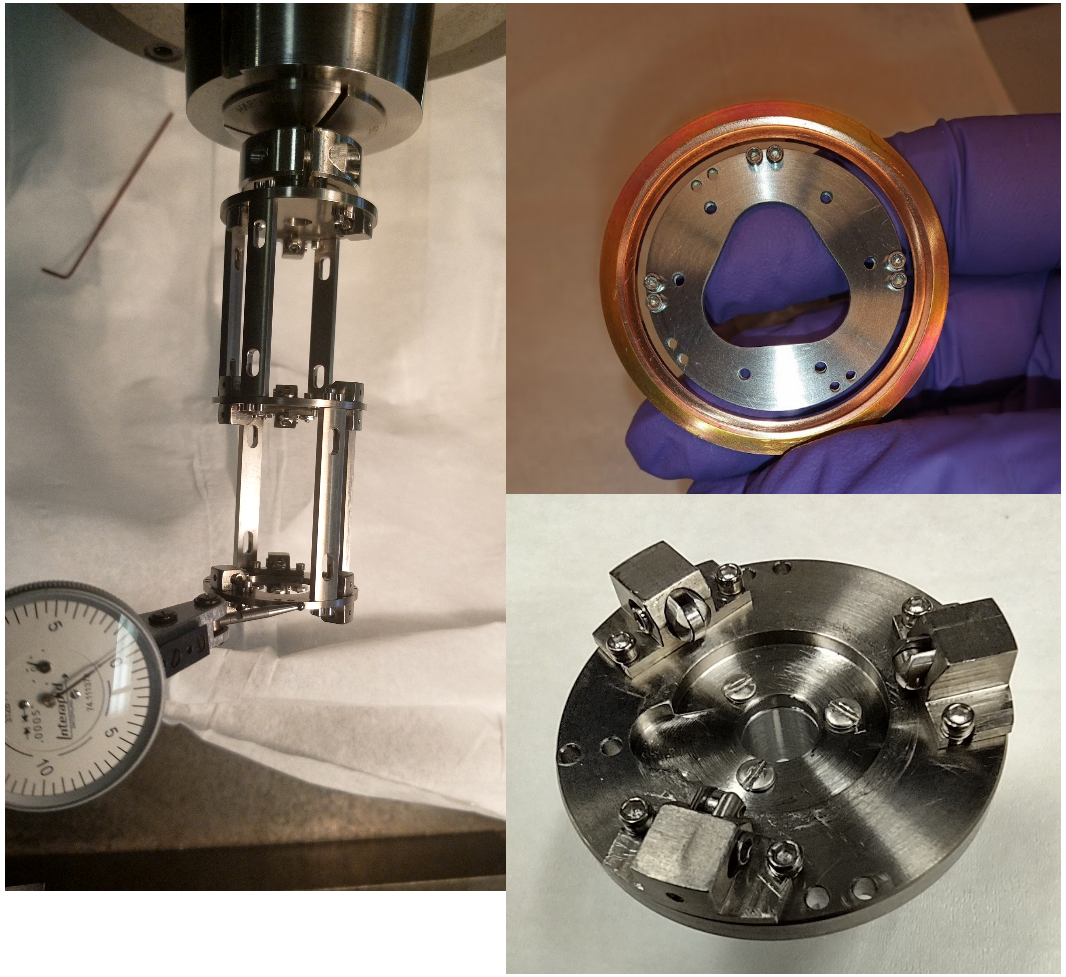
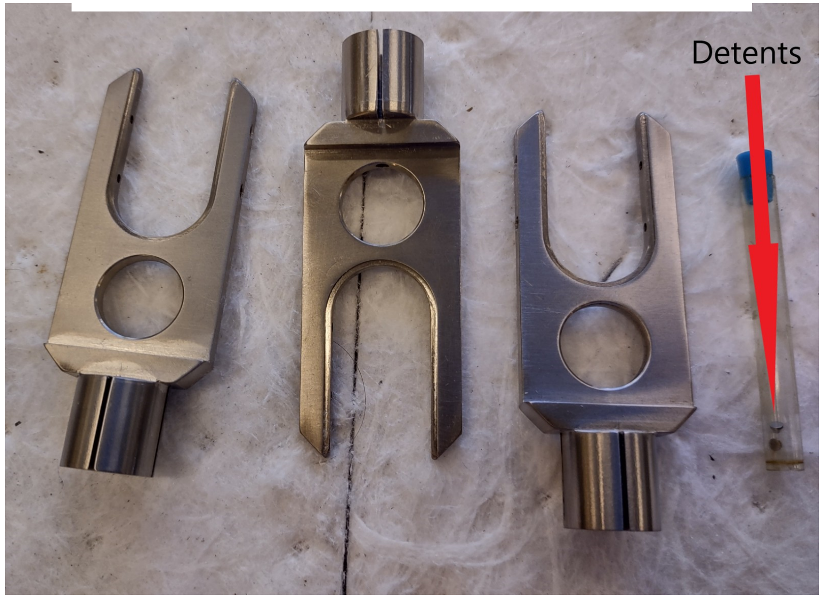
Cathode manipulation and transport

The magazine and forks used to manipulate the cathodes were redesigned to allow for a more rigid mechanical structure and increase the number of cathode that can be transported;



New magazine for up to 4 cathode transport

New forks with reduced width



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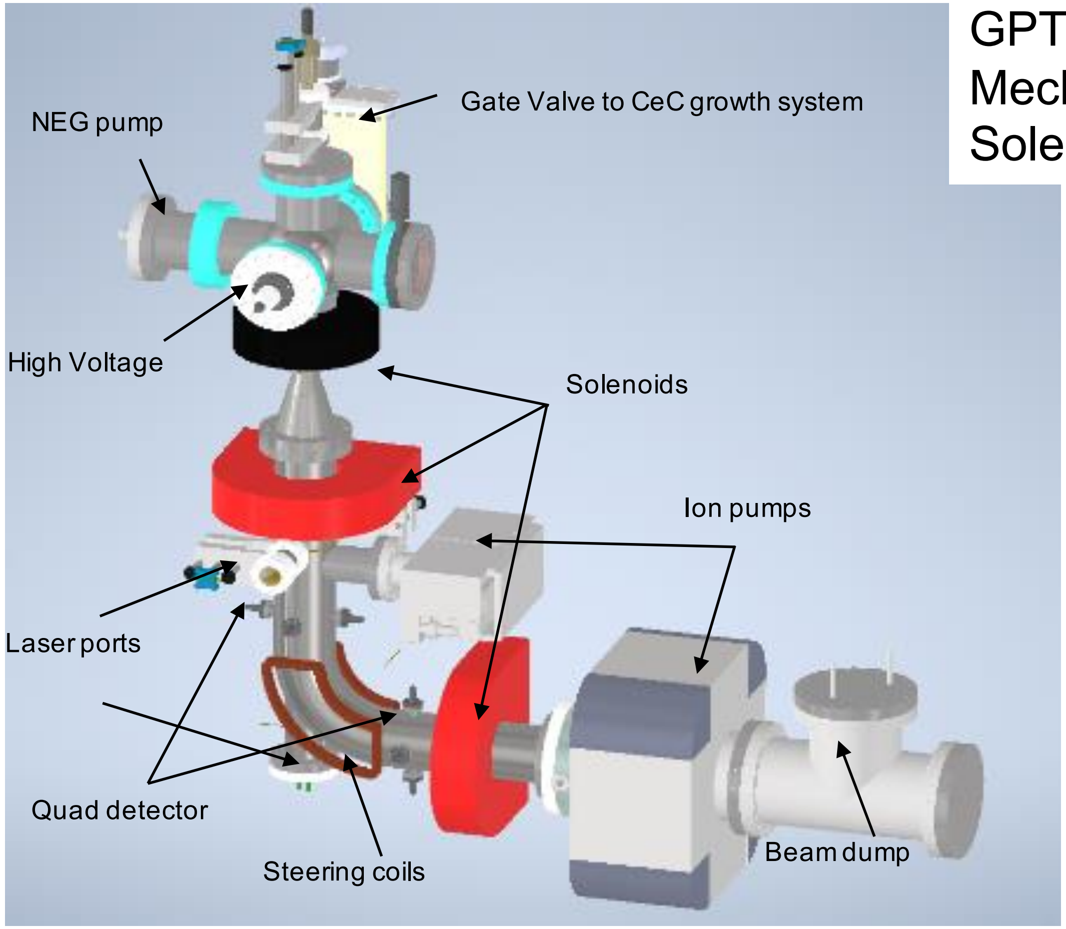
High current test stand (10 keV-100 mA)



Electrostatic design is completed
GPT simulation is completed
Mechanical design almost complet
Solenoid scan for measuring emittance