

# Development of a Regenerative Amplifier for the Coherent electron Cooling Proof of Principle Experiment (CeC-PoP) at RHIC

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## 1. Introduction/Motivation

The commercial laser from NuPhoton that was used for the Coherent-electron-Cooling Proof of Principle (CeC-PoP) experiment in the past runs could not meet the tight specifications needed to demonstrate coherent electron cooling due to nonlinear effects inherent to fiber lasers operating at high pulse peak powers.

Until recently a commercial Laser from NuPhoton was used, which consists of a Q-switched laser diode that produces a 27ns long pulse at 1064nm and 78kHz, a Mach-Zehnder electro optical modulator (MZ-EOM) and a chain of 3 fiber amplifiers.

The MZ-EOM is used to temporally shape the 27ns pulse to a 250-1000ps long flat top, which is then amplified to 2μJ. The output is then externally frequency-doubled to 1μJ of 532nm light.

The pulse peak power in the infrared (IR) amplification stages exceeds 8kW which leads to nonlinear effects that distort the temporal shape of the output pulse as shown in Figure 1.

*Figure 1  
Streak image of  
a green 400ps  
pulse at nominal  
energy out of the  
fiber laser (left)  
Projection of the  
streak image  
along the Y-Axis  
(right)*

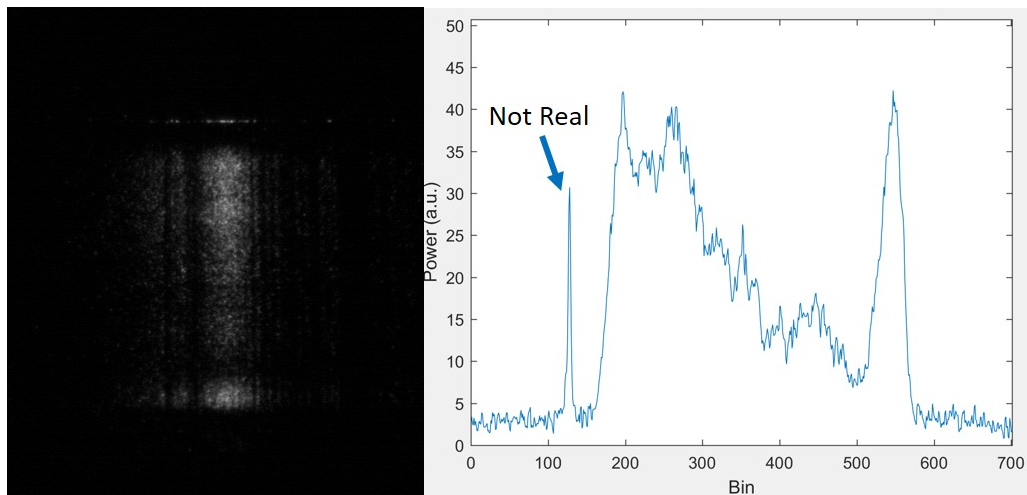


Figure 1 shows a streak camera measurement of the frequency-doubled laser pulses conducted with the fiber amplifiers of the NuPhoton laser operating at nominal power to produce 0.7μJ of 532nm light. Self-phase-modulation inside of the fiber amplifiers is seen to cause distortion of the temporal profile of the laser pulses.

The spike visible around Bin 125 is due to light leaking through the streak camera slit during relaxation of the streak tube.

In addition to nonlinear effects accumulating inside of the fiber amplifiers, an unstable temperature controller of one of the amplifier pump diodes in the NuPhoton laser led to average power fluctuations of >30% peak-to-peak.

To overcome these limitations, the Laser design was modified prior to the start of the 2018 RHIC run by introducing an additional amplifier stage that allows to take over the majority of the amplification process from the fiber amplifiers to keep the peak power in the fibers low and avoid the accumulation of nonlinear effects.

This approach allows for a reduction of the output power of the NuPhoton laser to about 5% of the nominal power level avoiding the accumulation of nonlinear effect and leaving 6mW of unstable IR seed power (See Figure 2) for a subsequent amplification stage.

Figure 2  
Seed power  
recording over  
7hrs

$f_{rep}$ : 78kHz  
 $P_{Avg}$ : 6mW  
Energy: 77nJ  
stdDev: 1mW  
(16%)  
PV: 5mW  
(80%)

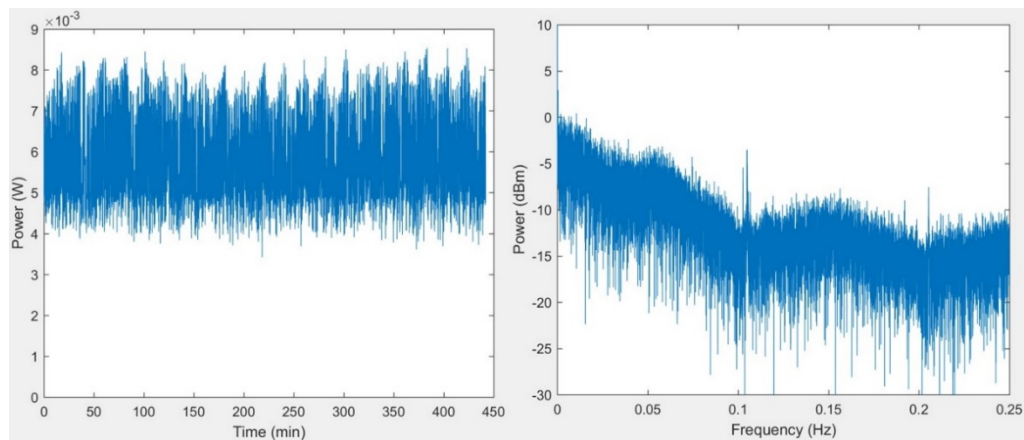


Figure 2 shows the power measurement of the NuPhoton seed laser output over 7 hours on the left and its frequency spectrum on the right. The periodic peaks in the power measurement occurring every 20 minutes are related to temperature fluctuations of  $0.5^{\circ}\text{C}$  in the laser support building 1002F caused by the climate control system. The strong peak at 0.1Hz on the right originates from a defective temperature controller regulating the temperature of one of the internal fiber amplifier pumps.

A solid state regenerative amplifier was developed as amplification stage subsequent to the NuPhoton laser. Due to its solid state nature, nonlinear effects distorting the temporal profile of the seed pulses are avoided. Also, the amplifier is driven in saturation with maximum energy extraction, which suppresses the fluctuations present in the seed beam.

A regenerative amplifier operates by trapping an optical seed pulse inside of a cavity by switching the intra-cavity Pockels Cell on or off. The seed pulse excites the eigen-mode of the cavity, which is amplified. After a predefined number of cavity roundtrips the Pockels Cell changes its state again to eject the amplified pulse out of the cavity. Regenerative amplifiers are regularly used for low repetition rate, direct amplification of ultra-fast laser pulses to the milli-joule level. The amplifier is designed to run 24/7 with full remote control, diagnostic, and self-protection capabilities. Design, construction and commissioning needed to be completed within 7 months to be available during RHIC Run2018.

## 2. Design

Due to spatial constraints on the optical table, a 90° bend design was chosen with a cavity length of 1m with the gain medium located in the center to support seed laser pulses of up to 1ns length (See Figure 3).

Figure 3  
Design of the regenerative amplifier model (Left)  
Schematic (Right)

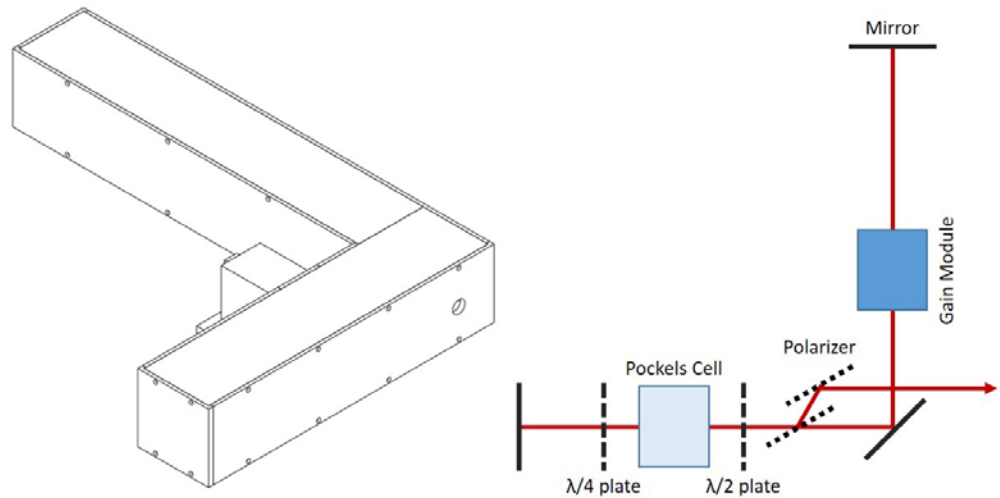


Figure 3 shows the isometric projection of the regenerative amplifier enclosure model on the left, which decouples the amplifier from periodic changes in the environment like the 20min cycle of the climate control in the laser support building. On the right a schematic of the amplifier cavity is shown, which consists of a 1m long optical cavity with flat end-mirrors (flat-flat cavity), a Pockels Cell for optical switching, an Nd:YAG rod based Gain module, polarizers, wave-plates and a bend mirror. The cavity is stabilized by the thermal lens induced by the pump radiation inside of the gain-rod.

To decouple the system from periodic environmental changes like changing temperature or humidity and protect against dust, an all-aluminum enclosure was designed and constructed to house the amplifier cavity. Also, to decouple the frequency-doubling stage subsequent to the amplifier, a 5mm long critically phase matched Potassium Titanyl Phosphate (KTP) crystal is used. Critical phase matching offers a wider temperature bandwidth than non-critical phase matching (or, temperature phase matching), but creates a slightly elliptical beam due to spatial walk-off caused by the non-coaxial propagation of the frequency-doubled and fundamental beams inside of the crystal. The ellipticity of the frequency-doubled beam is of no concern to the CeC PoP experiment and does not have to be corrected.

### 3. Commissioning

After completion of the design stage the cavity was set up in its final location in the laser support building. To characterize the optical cavity, the laser was operated as CW laser without operating the Pockels Cell.

Figure 4  
CW Cavity  
Characterization

Point of Operation

Current: 24A

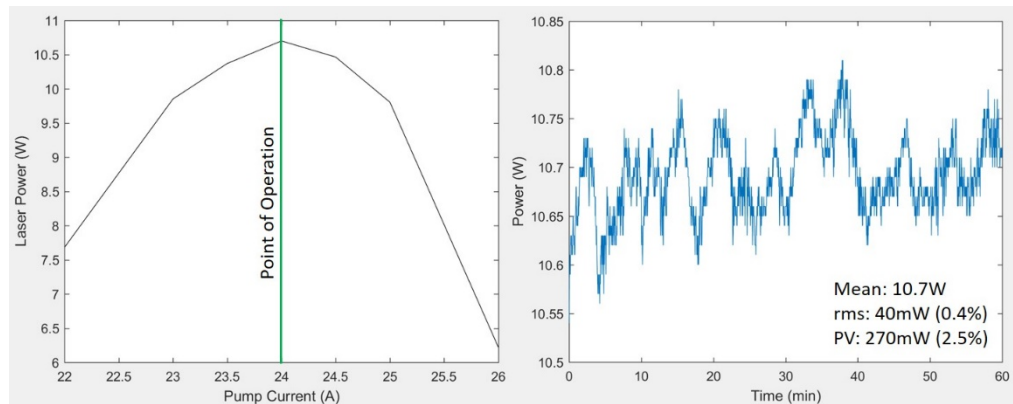


Figure 4 shows the optimization process of the cavity on the left. By changing the pump current of the gain module the thermal lens induced in the gain rod, which stabilizes the flat-flat cavity, is influenced directly. An average power measurement of the optimized cavity over 60 minutes is shown to the right.

Figure 5  
CW Cavity  
Characterization

$M^2$  Measurement

Power: 10.7W  
 $M^2$ : 1.04

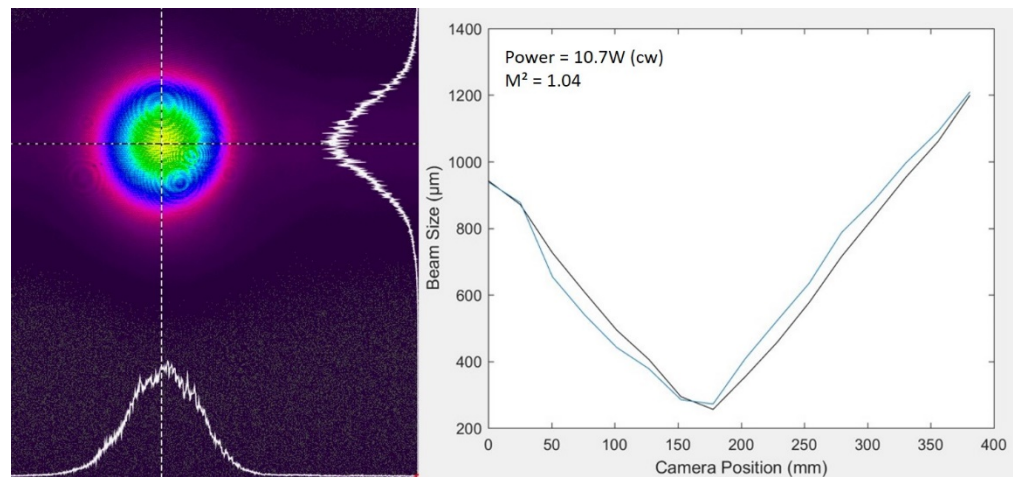


Figure 5 shows the output beam profile of the cavity on the left and the  $M^2$  measurement performed with a 200mm lens and a camera mounted on a guide rail to the right.

Once the CW operation optimization process was completed, the Regenerative Amplifier was seeded with the seed laser with properties shown in Figure 2 and the number of cavity roundtrips in the cavity was optimized for maximum energy extraction. Maximum energy extraction was demonstrated using 48 cavity roundtrips with a total output power of 9.2W (@78kHz)

Figure 6  
IR Power output  
recording over  
5hrs

$f_{rep}$ : 78kHz  
 $P_{Avg}$ : 9.2W  
Energy: 118 $\mu$ J  
stdDev: 70mW  
(0.8%)  
PV: 390mW  
(4.25%)

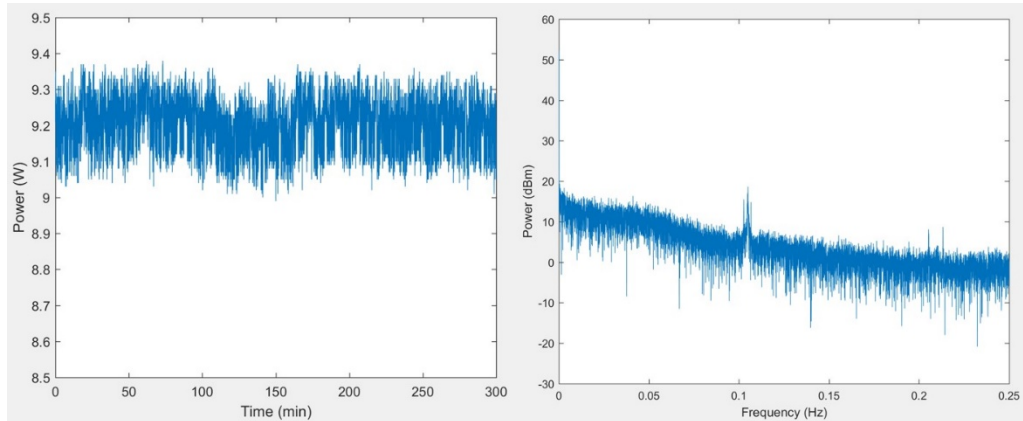


Figure 6 shows the 5 hour power measurement of the IR output of the regenerative amplifier on the left and the corresponding frequency spectrum on the right. The same peak at 0.1Hz that is visible in Figure 2 dominates the noise spectrum.

The average power fluctuations visible in the seed power measurement in Figure 2 have been suppressed using the regenerative amplifier from 80% PV to 4.25% PV.

Due to the low power requirements of CeC (~1.5W Green) the conversion efficiency into green has been reduced artificially by placing the KTP crystal into a collimated section of the IR beam and detuning the polarization of the IR beam from the conversion plane. Optimized conversion efficiencies of 61% using a pair of cylindrical lenses have been observed with the 5mm KTP crystal. The crystal could be exchanged for a shorter one to reduce the ellipticity of the frequency-doubled beam if needed.



Figure 7  
Laser Beam Profile  
after frequency  
doubling  
Ellipticity due to  
walk-off is visible

$4\sigma_X$ : 948 $\mu\text{m}$   
 $4\sigma_Y$ : 880 $\mu\text{m}$

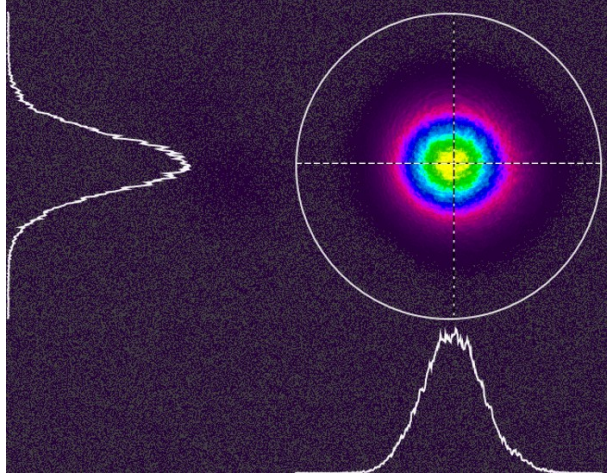


Figure 7 shows the beam profile of the frequency-doubled beam. The ellipticity caused by spatial walk-off in the critically phase matched KTP crystal is visible, but its extent is not of concern for the experiment and therefore not corrected.

Figure 8  
Parasitic Green  
Power  
measurement  
of diagnostic  
beam during  
operations

$P_{Avg}$ : 411mW  
stdDev: 7.3mW  
(1.8%)  
PV: 51mW  
(12.4%)

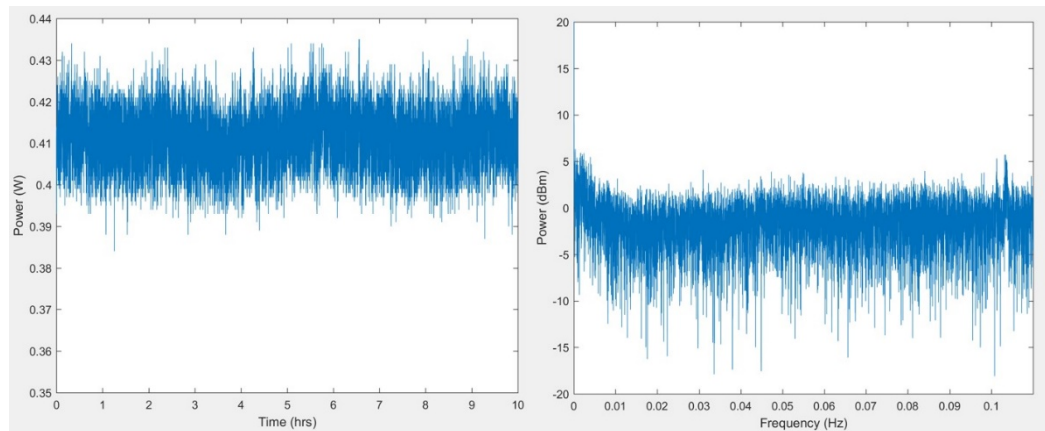


Figure 8 shows the power recording of part of the frequency-doubled light, which is split off from the main beam for diagnostic purposes on the left. The 0.1Hz peak originating in the NuPhoton laser is visible again in the corresponding frequency spectrum on the right. Due to the nature of frequency doubling being a second order nonlinear effect, an increase of the relative fluctuations by a factor of 2 with respect to the IR fluctuations is expected and measured.

Figure 9  
Parasitic Green  
Power  
measurement  
during  
operations

$P_{Avg}$ : 415mW  
 $stdDev$ : 13.5mW  
(3.24%)  
 $PV$ : 65mW  
(15.6%)

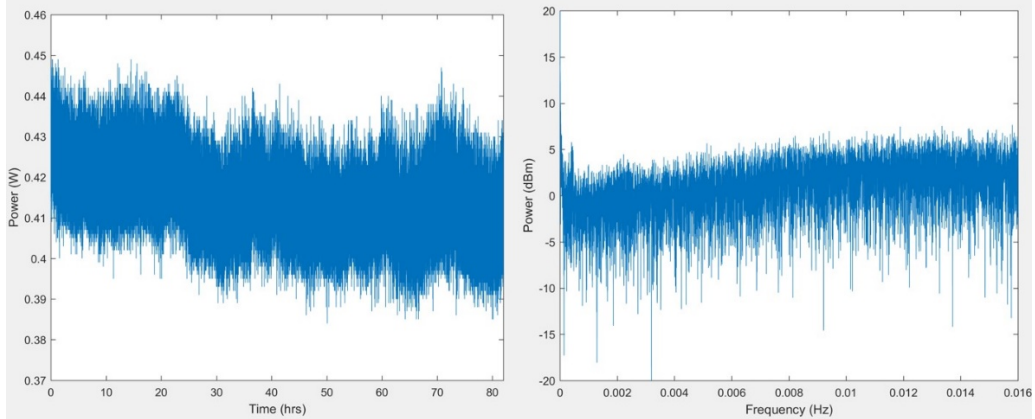


Figure 9 shows the power recording of the green diagnostic beam over the course of 3 days on the left and the corresponding frequency spectrum on the right. Again the power fluctuations are dominated by the residual power fluctuations of the seed laser penetrating the regenerative amplifier.

The temporal shape was measured again downstream of the regenerative amplifier show in Figure 10. The measurement shows a smoother longitudinal profile indicating the absence of the distortion caused by nonlinear effects with the original laser design. (Compare with Figure 1)

Figure 10  
Streak Image  
of green  $20\mu$   
400ps pulse  
using the  
Regenerative  
Amplifier

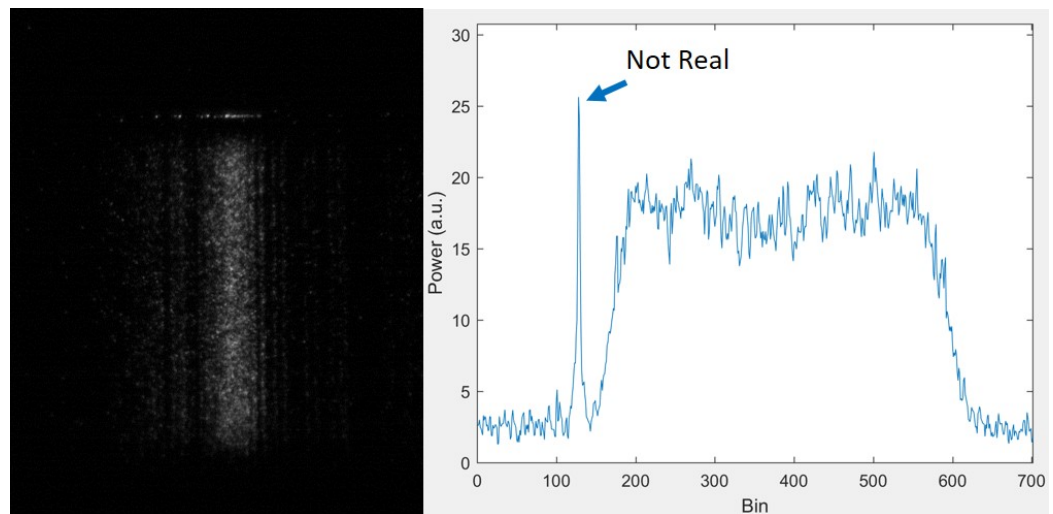


Figure 10 shows a streak camera measurement of the amplified and frequency-doubled 400ps laser pulse using the regenerative amplifier for amplification. The pulse retains its shape throughout the amplification process and does not experience nonlinear distortion.

The spike visible around Bin 125 is due to light leaking through the streak camera slit during relaxation of the streak tube.

Figure 11  
Regenerative  
amplifier Setup  
in the laser  
support  
building  
(1002F) at the  
2o'clock sector  
of RHIC

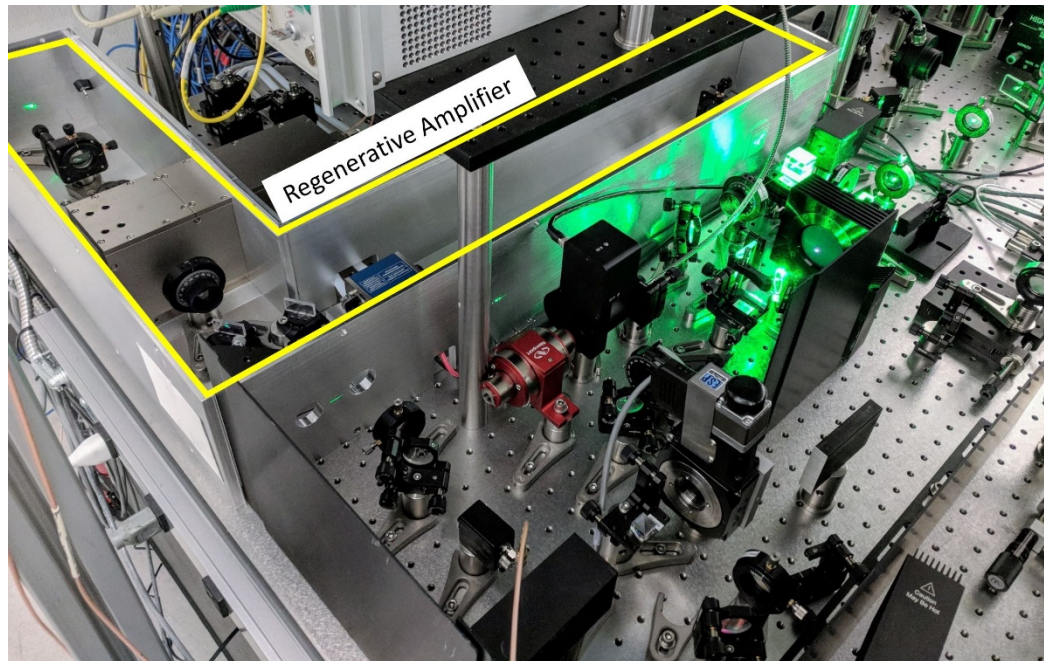


Figure 11 shows the amplifier setup in the Laser support building (1002F). The NuPhoton laser is located above the regenerative amplifier. The new laser design using the regenerative amplifier provides green power well in excess of the CeC PoP design requirements.

#### 4. Summary

A Regenerative amplifier was proposed and developed to overcome the limitations of the fiber laser used for the CeC PoP experiment. The amplifier was successfully commissioned during the first week of March 2018, delayed by 2 months due to a failure of the NuPhoton seed laser which was sent to the vendor for repair, missing the goal to finish commissioning before the start of RHIC run2018 by 1 month.

The upgraded laser for the CeC PoP experiment is now fully remote controlled and operates on demand, 24/7. The laser system is interlock-protected by an additional new in-house designed laser protection system with measured inputs from various system temperatures and coolant flows. In addition multiple power sensors and status information from chillers and Power supplies are continuously logged at a 1Hz rate with data available to all users through the C-AD control system.

The regenerative amplifier has successfully avoided the accumulation of nonlinear effects that caused the distortion of the temporal pulse profile which is crucial for CeC operations. In addition, the power fluctuations of the seed laser have been significantly mitigated by using the regenerative amplifier. Furthermore, the resulting excess power produced by the amplifier offers two additional advantages. First, the high available power allows for electron beam generation at a lower photocathode quantum efficiency. Secondly, the higher power allows for producing a significantly more uniform transverse intensity distribution on the photocathode due to overfilling of the aperture imaged onto the photocathode.