Appendix F: Milestones, changes in scope and concerns.
Compiled from quarterly reports to DoE NP office

Report Date: July 14, 2011
1. Developed and successfully tested RHIC ramp and store for the CeC experiment, measured all relevant parameter for Au-ion beam in the condition of the experiment;
2. Selected new base-line and back-up options for the accelerator;
3. Simulated beam dynamics for the base-line accelerator and for the back-up options of the gun;
4. Identified two 500 MHz cavities (free-of-charge, from former synchrotron facility at Daresbury lab, UK), which can be used for bunching electron beam in the present CeC accelerator scheme.
5. Selected the final lay-out of the CeC section;
6. Finalized the design of the helical undulator and ordered a 50-cm long prototype (using BNL LDRD funds)

Changes in the scope:
1. Our simulations demonstrated that using 200 kV CEBAF gun would create a significant challenge in achieving the required peak-current for the CeC experiment. It would require a significant and expensive low frequency multi-stage bunching system to compress the e-beam from 1-2 nsec down to 10 psec. Hence, this gun is considered as a back-up and its modification are excluded from
2. Since JLab team did not have resources to pursue beam dynamics studies of the CEBAF gun, Tech X redirected its resources to fill this gap. As the result Tech X focus was distracted from the main goal of developing start-to-end simulation package to the CeC PoP system. Part of this activity is shifted to FY12.

Details on, or further, issues/concerns (related to JLab's equipment)
Delays with making decision on the base-line design of the accelerator are the cause of the significant modifications of the equipment list and for a late start of placing purchasing orders. It may result in a need of extending a portion of equipment funds into FY12.

Report Date: October 14, 2011
1. Concluded the search and hired Dr. Igor Pinayev as the technical leader of the project. He started working start date is August 15, 2011;
2. Evaluated results of the RHIC ramp and store for the CeC experiment;
3. Developed layout of the accelerator and simulated beam dynamics;
4. Continue the process of transferring 500 MHz cavities. Working on MOU with Daresbury lab joining CeC collaboration; Daresbury group decided to officially join CeC collaboration.
5. Working on resource-loaded schedule for the cryo-system (using BNL PD funds)
6. Continued developing key analytical and simulation tools for predicting and improving the performance of the CeC cooler;

Details on, or further, issues/concerns
1. The alkali-antimonide photocathode has proven to be a robust cathode material, amenable to vacuum transport and relatively insensitive to back bombardment, capable of delivering high average current and high current density. Demonstrating 1 nC charge in a short bunch remains a challenge.

2. We are dedicating significant efforts to developing a resource-loaded schedule with plan to install the CeC equipment at the IP2 during 2013 RHIC shutdown, and starting commissioning the CeC accelerator at IP2 during Run 14.

Report Date: January 5, 2012

During this quarter we

- During this period we had received two 500 RF cavities
-

Fig. F.1. One of two 500 MHz room-temperature RF cavities arrived from Daresbury

And placed purchase orders on the following long-lead items:

- Cryo-module of 113 MHz gun (with NioWave)
- 113 MHz RF system (transmitter and circulator)
- 500 MHz RF system (transmitter and circulator)
- Design and placing purchases for CeC 4K and 2 K cryo-systems are in progress using BNL's PD funds
- Prototyping of the helical wiggler (supported by BNL's LDRD funds) proceeds close to the schedule and all components of the wiggler has been manufactured. Assembly of the prototype is in progress

Fig. F.2. Four magnet holders for the wiggler at BINP's workshop.

- Continue benchmark the simulation package against the exact analytical solutions

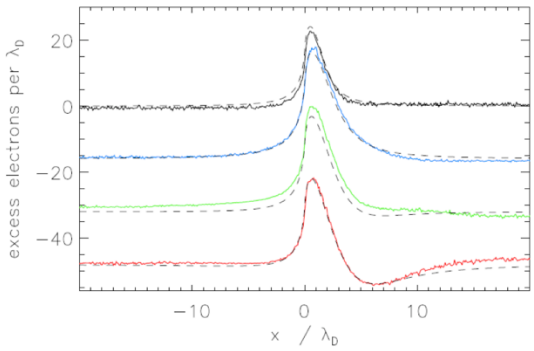


Fig. F.3.Comparison between VORPAL (Tech X) simulations and theory. Bell et al., Proc. 2010 PAC.

Report Date: April 9, 2012

- placed orders for the SRF gun cryogenic system
- started procurement of the driver laser
- successful design review of 113 MHz SRF gun (with Niowave)
- Tech X continued developing the start-to-end CeC simulation package and benchmarking it with analytical models developed at BNL
- JLab CeC team continued developing DC gun as a back-up option by testing first alkali-antimonide photocathode (grown at BNL) inside the 200 kV inverted photogun

From NP Quarterly Report CeC, April 2012, M. Poelker, JLab contribution

Main concern: Parmela simulations related to our DC high voltage gun fall-back option indicate bias voltage ~ 350kV or higher will be required to efficiently deliver 0.5nC bunches for CeC PoP.

Report Date: July 17, 2012

- Niowave is on schedule with modification of the 113 MHz SRF gun and the Critical Design Review has been successfully completed
- The $1.5M order for the 20 MeV 704 MHz 5-cell SRF cavity and its cryostat had been placed using C-AD AR&D funds, but funding by this project should cover the majority of the cost for this system in FY13 and FY14
- During RHIC Run 12 we have measured ion beam stability in conditions close to that for the CeC experiment.
- We started site preparation for the equipment installation in the 2 o'clock region

Main concern:

- The procurement of the driver laser was delayed due the absence of bid from a major vendor and funding reduction;
- Following negative assessment of the JLab DC gun prospects, we put on hold the developing of the DC photo-injector in JLab.

Report Date: September 30, 2012

- Placed RFP for the laser system
- Review the results of the wiggler prototyping: The wiggler prototype was assembled. Preliminary magnetic measurements had been made and results are satisfactory. A dedicated measuring system is under development and will be used for final measurements
- Vacuum pumping system for 2K heat exchanger had been purchased and is under construction. RFP for quiet 4K He heat exchanger has is in process. (BNL PD funds)
- Scheduled external CeC PoP Project review for December 4-5, 2012
- the cooling tower and the CeC water-cooling system were installed at IP2
- The area need for installation of the CeC SRF accelerator is fully cleaned and ready for installing of two 500 MHz RF cavities
- Procurement of the laser is on schedule and the delivery is expected in March 2013. No project delays are expected.
- Following RF equipment has been was purchased using the project funds and either received or will be received by the end of calendar year 2012:
    - directional coupler for the 113 MHz,
    - circulator for 500 MHz,
    - the 500 MHz transmitter,
    - circulator for 113 MHz,
    - the 113MHz amplifier

Changes in the scope:

The scope of the project did not change. We discovered that CeC PoP accelerator could be also used for important test of unique beam-beam effects in linac-ring collider as well as for test of bunch electron cooling planned for low energy RHIC program. These efforts, if pursued, will not affect the scope of the project and would be supported by funds independent from this project.

Brief summary of activity issues, concerns, successes:

1. The modifications of the CeC accelerator gun proceed as scheduled at Niowave. The gun manufacturing is expected to be completed in January 2013. Two tests of the 113 MHz gun will be held in November/December 2012 to validate the cavity performance and in January/February 2013 to verify the gun performance with the e-beam. These tests are a cost-effective beginning of the accelerator commissioning as well as part of the risk management aiming for the early detection of malfunctions. We placed an order for a solid-state laser with Q-switch suitable for the test.
2. JLab back-up gun development efforts supported by this project have been completed. No follow-up is planned.

Report Date: January 15, 2013

- continued acquisition of the equipment including RF cavities and gun, drive laser, and magnets.
- on December 4-5 2012, CeC PoP experiment went through the external review
- we received very positive report with a number of very good recommendations we plan to implement.

The scope of the project did not change.

Report Date: April 15, 2013

- Niowave conducted the second test of the 113 MHz gun using 2 kW amplifier we had procured for CeC PoP experiment. Multipacting was overcome by improving the coupling with cavity and utilizing the BNL's 2 kW amplifier. The maximum achieved accelerating voltage of 1 MV was limited by lack of the radiation shielding at Niowave test facility. All cryogenic parameters of the cavity and the cryostat were well within specs. Manufacturing of the 5-cell 704 MHz accelerator cavity progresses well. The cavity itself had been manufactured and will be shipped to BNL for vertical SRF testing.
- We tested a temporary pulsed UV laser and it is ready for use with the 113 MHz gun.
- Delivery of the main drive laser is expected in April 2013
- The laser room procurement is under way with expected delivery in August 2013.
- We successfully completed helical wiggler prototype and closed books on this LDRD project
- We started procurement process for FEL helical wigglers
- We continued procurement of solenoids and trim magnets for CeC beam transport

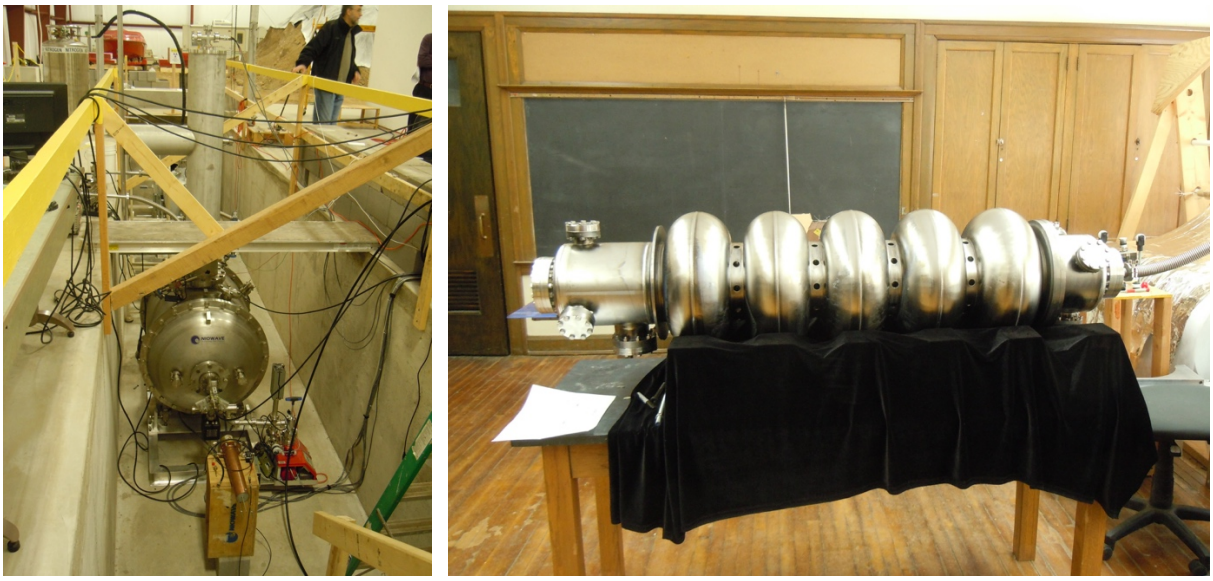
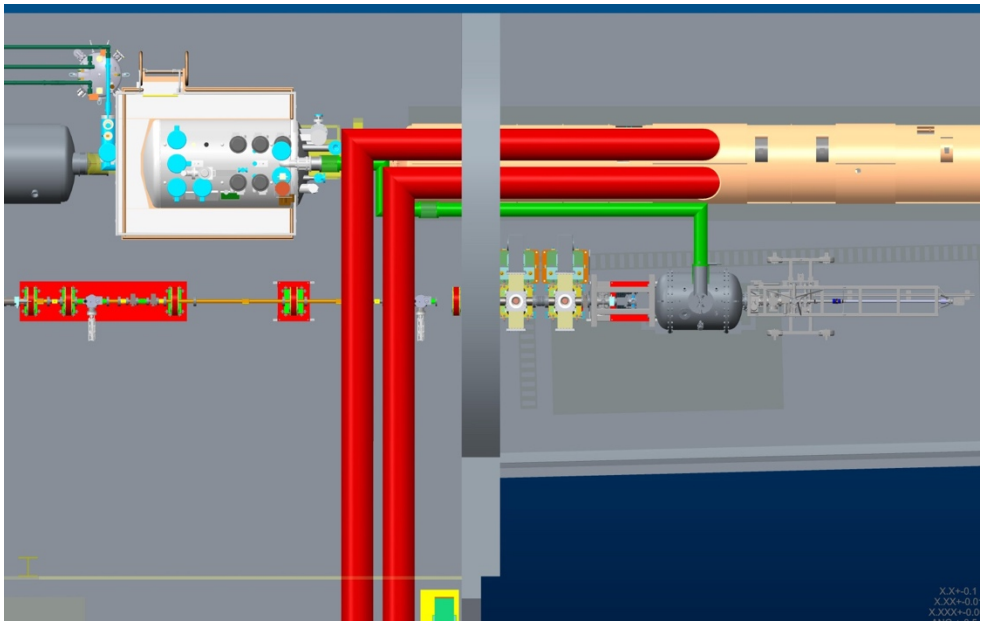


Fig. H.4. 113 MHz cavity in the trench during the test (left) and 704 MHz 5-cell accelerator cavity at Niowave after vacuum leak check.

Main concern:

1. We are started experiencing the lack of funds for equipment acquisition. It may cause delay in placing orders for long-term items (such as helical wiggler system) and result in delay of the commissioning of the CeC PoP.
2. All resources available from the BNL PD funds are already used for cryogenic system for CeC PoP experiment.
3. Both partial funding in FY13 (at about 50% of the amount requested by proposal with further reduction from $780K to $733K) as well as late availability of funds (e.g. we are still awaiting FY13 funds) have negative impact on our schedule and readiness for the installing and the commissioning of CeC systems.
4. To address these concerns we develop phase I commissioning plan for CeC accelerator



Fig, H.5. Layout of the phase I CeC PoP equipment at IP2: the 113 MHz SRF gun with cathode launcher, quiet He source, two 500 MHz cavities and the beam-line.

Report Date: July 12, 2013

- we started preparation for installation of the first phase (low energy part) of the CeC PoP accelerator. The security gate at IP2, which was interfering with the CeC PoP hardware, had been shifted 15-feet deeper into the RHIC tunnel. The floor has been prepared for installing the SRF 113 MHz gun and 500 MHz RF cavities.
- 4K He pump, required for the phase one of CeC accelerator, has been delivered and installed in Bldg. 1002.
- CeC PoP deionized water system is completed and fully operational.
- 50 kW 500 MHz transmitted had been successfully tested to full power with the dummy load. The coaxial line was installed extending from the transmitter to RHIC tunnel.
- Number of the cable trays for CeC PoP in Bldg. 1002 had been installed.
- Finished the manufacturer selection process and signed a contract for the production of the CeC PoP helical undulators.
- 704 MHz 5-cell niobium cavity has been manufactured by Niowave and passed inspection at BNL.

The scope of the project did not change, but we encountered some problems, which can cause delays. **Main concerns:**

- Because of reduced FY13 funding we discontinued simulation efforts at Tech X
- Delivery of the quiet helium source and vacuum jacket is delayed;
- The cathode launcher mechanism (made using SBU funds) was severely damaged during transportation in apparent track accident - we are making assessments of the impact on schedule and funding.
- Modest delay with manufacturing of fundamental power coupler, but it shouldn't affect the schedule.

Report Date: October 7, 2013

- Successful critical design reviews of the CeC helical wiggler system
- Successful preliminary design review of cryostat for 704 MHz SRF linac
- Both the 113 MHz SRF gun and 500 MHz RF cavities had been moved into the IP2 at RHIC and in the process of its final installation;
- We continued developing CeC infrastructure at Bldg. 1002 and at: trays, cryo-lines, electrical, cooling and cryogenic equipment
- The laser for CeC electron gun reached its specification at the manufacturer site
- All replacements parts for the cathode launcher, which was heavily damaged during its track accident. were received. The system was particle free cleaned, re-assembled and leak checked. Alignment and survey are in the process
- Diagnostics equipment for Phase I of CeC beam-line had been ordered using BNL's LDRD funds
- We placed the order for 704 MHz transmitter
- The 113 MHz SRF gun fundamental power coupler (FPC) is being manufactured
-

Fig. H.6. Left: The 113 MHz SRF gun and the 500 MHz RF cavities at 2 o'clock RHIC IP. Right: The CeC solenoids at the vendor facility

Main concerns:

- Supplementary funds of $677K were extremely timely and allowed us to order critical long-lead hardware for the CeC PoP experiment.
- One of our concerns is timely delivery of the helical wiggler system for its installation during RHIC shut-down in 2014. BINP will use their only precise CNC machining capable of handling 10-feet cassettes for helical undulators magnet arrays. BINP plans to manufacture first cassette in November 2013 to determine accurately the production time – then the delivery schedule will be re-assessed. We continue weekly teleconferences with BINP to monitor their progress.
- Second concern came with a month-long delay with delivery of the quiet helium source (manufactured by PHPK under contract using BNL PD funds).

The scope of the project did not change.

Report Date: January 13, 2014

- The 113 MHz RF gun and the 500 MHz cavities had been installed and surveyed at the IR2;
- The quiet helium source was installed in the IP2 at RHIC;
- Solenoids and low power beam dump shielding are installed;
- The trailer housing the drive laser was delivered;
- The clean rooms were installed on both sides of the 113 MHz gun;
- Cathode launcher has been moved into the RHIC tunnel;
- The production of the CeC helical wiggler system is on schedule.
    - The magnetic materials were delivered to Budker INP and the magnet holders (cassettes) for the first wiggler had been machined;
- The main drive laser for CeC electron gun was received;
- The vacuum jacket pipes for the liquid helium transfer from the quiet helium source to the gun are delivered.

Fig. H.7. Left: The CeC's quite helium source (top-right) is installed at IP2 above RHIC magnets. The photo was taken when the first of two LiHe transfer lines to 113 MHz gun is being installed. Right: The solenoids on their supports installed in the IP2.

Main concerns:

- We are again running short of funds for the remaining hardware for CeC Phase II accelerator and waiting for the FY14/15 call for proposals.
- Timely delivery of the helical wiggler system for its installation during RHIC shutdown in 2014 stays one of our concerns. We continue weekly teleconferences with BINP to monitor their progress.
- Second long-lead item is 704 MHz SRF linac to be assembles at Niowave Inc. Vertical tests of two 5-cell SRF cavities for the linac (the best of two will be used for the linac) had been delayed until January 2014. Any further delays can affect timely manufacturing and installation. We are holding weekly tele-video-conferences with NioWave team.
- We have a serious delay with preparation and installation of vacuum system for the phase I of CeC. Lack of resources and competition with other RHIC projects such as e-Lenses, R&D ERL, 56 MHz SRF system, as well as with regular RHIC maintenance, made it impossible to prepare and install CeC Phase I vacuum chambers and pull all cables in IP2 as we planned. We are developing a contingency plan to install it during RHIC maintenance days.

The scope of the project did not change. In spite of complications, we continue pursuing the possibility of testing and operating the low energy part of CeC accelerator during the Run 14. We also allocated $50K for continuation of the Tech X efforts to continue simulations of CeC PoP beam-cooling

Report Date: April 7, 2014

Milestones:

1. All CeC Phase I equipment had been surveyed in its final location;
2. All necessary in-situ clean rooms had been assembled and installed;
3. The photocathode insertion and load-lock system had been baked in-situ and surveyed for installation into the 113 MHz gun;
4. The FPC and the laser–cross had been installed into 113 MHz gun;
5. Multiple scaffolds had been built to accommodate welding and in-situ assembly of the phase I equipment;
6. VJ pipes and the phase separator had been installation and their welding is in progress;
7. All phase I vacuum components had been particulate-free processed.
8. All cable trays had been installed
9. Vertical test of SBU 5-cell SRF cavities had been successfully completed with cavity demonstrating designed value (20 MV/m) accelerating gradient
10. BINP completed manufacturing of the high-precision cassettes for the first helical wiggler and started its assembly

Main concerns:

- ✓ While we had ordered all long-lead items (the 704 MHz linac and transmitter, helical FEL system), we already committed all available funds for the project. New funds are required (as indicated in our submitted proposal) to purchase the remaining equipment to complete and install the CeC system in 2014
- ✓ Stranded relations with Russia are our additional concern. Since our helical wiggler system is manufactured by Budker INP in Novosibirsk, Russia, we need to exchanged visits to ensure the successful completion of the system. Planned April 5-12, 2014 trip by Drs. Pinayev and Skaritka to BINP, Russia was canceled following DoE order. We expected delivery of the first wiggler in May 2014 followed by a visit to BNL by small team from Budker INP.
- ✓ Our main concern is to finish Phase I systems prior to the end of the RHIC run to allow the commissioning of the 113 MHz gun with the beam. Since RHIC operation started, CeC equipment located at IP2 can be accessed and operated on only during RHIC scheduled maintenance, with typical duration for 6-8 hours once in 2 weeks
- ✓ The contingency plan is to continue commissioning during the summer using a batch filling of the Li He. The used He will be recovered and stored for future use for RHIC
- ✓ There was a serious concern regarding compatibility of the CeC set-up at IP2 with RHIC plan to run asymmetric p-A collisions. The origin of this potential conflict is as follows: The aperture for CeC FEL wigglers. Which would be shared by the CeC electron and RHIC hadron beams, was approved 3 years ago. It is fully compatible with pp, AA and dA collisions in RHIC.

The scope of the project did not change. We are working towards commissioning of the Phase I of the CeC accelerator in FY14.

May 2014: Stony Brook University contributed major piece of equipment: the 704 MHz 5 cell SRF linac cavity manufactured by AES for project supported by DoE BES office to the CeC project. The less expensive, 704 MHz STF cavity made by Niowave was tested in the vertical test facility and was found to be inadequate. The AES built cavity for SBU, which satisfied our specifications, was shipped to Niowave for integration into the cryostat. This $1M contribution from Stony Brook University was critical for constriction of the CeC. Without this contribution the CeC project would be delayed at by one-to-two years.

Report Date: July 7, 2014

Milestones

- The cryogenic, RF and vacuum systems: cables pulled and terminated.
- The cathode insertion and load-lock system had been surveyed and installed into the 113 MHz gun; The gun is under vacuum and awaiting for the LHe system to start operations
- New water manifolds for the 500 MHz and 113 MHz cavities were installed
- Diagnostics equipment surveyed and installed.
- Request of an exception to allow the low power run of the injector in order to test beam generation in August –September, 2014 had been submitted;
- The first helical wiggler was assembled and pre-tuned.
- Cassettes for second helical wiggler were manufactured according to the schedule.

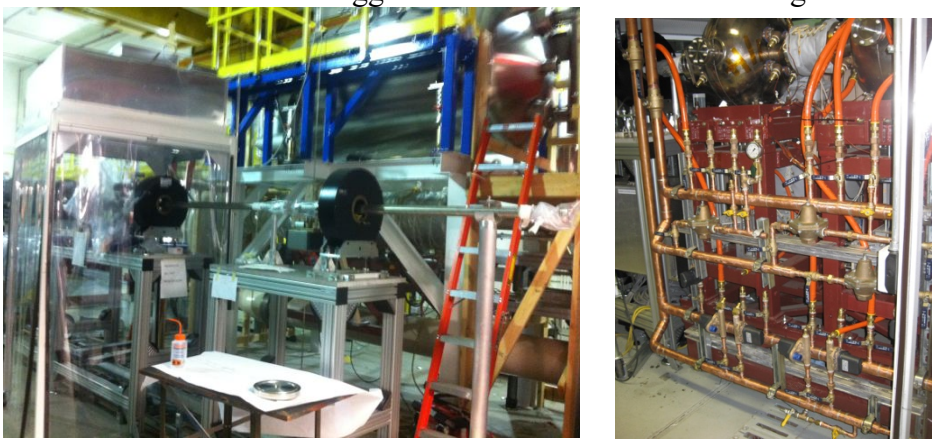


Fig. H.8. Left: Phase I (low energy) beamline with solenoids (black) and vacuum pipes during installation; Right: Water-cooling distribution system for 500 MHz (seen on the background) and 113 MHz system

Main concerns

- Funding level: we were informed that the project will receive in August 2014 $670K funding for FY14. This is at 35% level of our requested budget. As result we have to stop a number of purchases required for commissioning of Phase II. This can jeopardize commissioning of Phase II during RHIC Run 15, and furthermore, tests of the CEC during Run 16. We will do everything possible to continue commissioning and build-up of the system, but without additional funding in 2014 the progress will slow down significantly.
- A team of 8 experts from BINP plans to visit BNL for two weeks in August/September 2014 to set-up the magnetic measurements and tuning system for helical wigglers. Because of the strained relation with Russia, such visit requires a special permission from DoE. We had submitted request for such the exemption and waiting for the decision. If decision is negative,

there will be a major impact on the CeC PoP schedule and, potentially, the quality of the CeC FEL system.

- On technical side we are facing time pressure from the end of 2014 RHIC shutdown. The schedule for the vacuum vessel delivery and 704 MHz cavity integration is very tight and we do everything possible to ensure its installation before Run 15 starts. During CDR we found that the fundamental power coupler designed by Niowave has significant flaws. Contracting reliable vendor for FPC manufacturing, in this case Toshiba, require additional funds. Lack of funds might delay the project.

Report Date: October 7, 2014

- The welding of 4K He transfer lines is complete.
- The manifold is ordered with expected to be delivered in mid-October, 2014.
- Operation of the cathode exchange mechanism was successfully tested
- PASS area certification had been completed
- Vacuum system for the Phase I low power test is finished and leak checked
- First photocathodes for SRF gun with quantum efficiency of 9-10% were made
- The gas purge system for the water-cooling passes of the113 MHz gun parts exposed to cryogenic environment was successfully tested
- Niowave assembled the prototype of the tuner mechanism for the 704 MHz accelerating cavity
- Both 500 MHz RF cavity had been conditioned to the full power
- Budker INP started final tuning of the first helical wiggler
- Operation of machine protection system was verified during 500 MHz cavities tests.

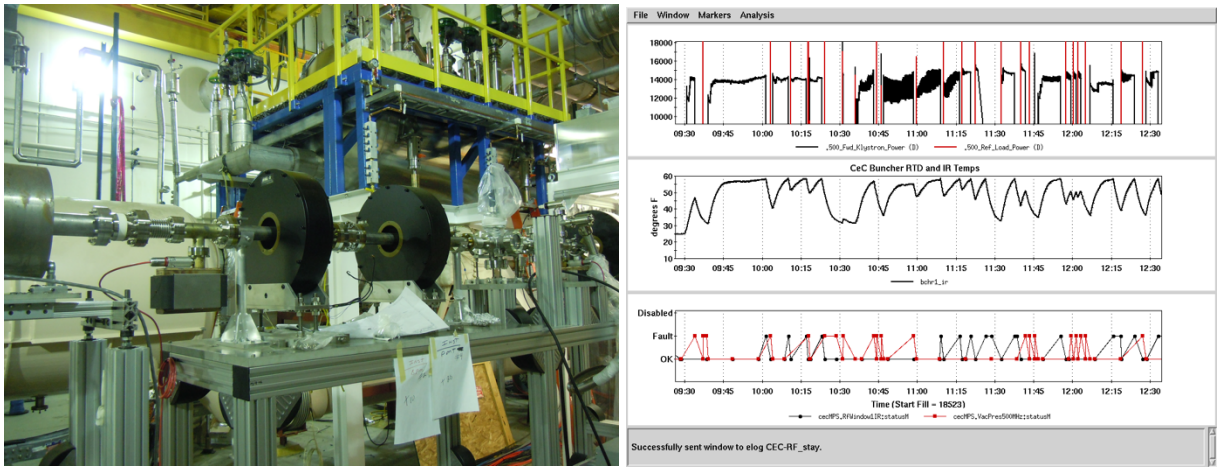


Fig. H.9. Left: View on the low power beam dump (on the left), ceramic break, two solenoids with beam position monitor in between, and profile monitor; Right: Graph from the conditioning of the first 500 MHz RF cavity. Top graphs forward (black) and reflected power (red).

<u>Main concerns:</u>

- The shortfall of funding (we were funded at about 35% level of the necessary funds to complete the project) did not allow us to proceed according to the original – technically driven – schedule. As the result, it is likely that we could not install equipment necessary for full energy CeC accelerator before the start of RHIC run in January 2015. We are running out of funds and will be unable to complete the project without additional funding. The project schedule had already slipped for one year.

Without additional funding we are facing a potential of slipping for two more years…. Hence, timely funding of this project is critical for its successful completion.
- The production of the 704 MHz accelerator cavity is will be likely delayed and we will be unavailable before the start on RHIC ring in January 2015.

Scope of project remains unchanged. The main CeC focus for the Run 15 will be on the testing and full characterization of the CeC injector and compression system. The photocathode performance and longevity will be one of our main priorities.

Report Date: January 5, 2015

Milestones

- 500 MHz RF cavities tested at design voltage.
- in October 27, 2014, we successfully cooled down the SRF gun to 4K using batched Li He, which was recycled for the use during RHIC He scrubbing.
- **We started conditioned the SRF gun and overcame multiple miltipacking zones (between 3 kV to 100s of kV). During the last day of the conditioning we demonstrated SRF gun voltage about 1.95 MV, which is just few percent shy of the designed value of 2 MV. This was achieved in a pulsed mode with from 10% to 25% duty factor.
- Low energy beamline with low power beam dump is installed.
- The first helical wiggler had been tuned and measured.

** Error in RF calibration was responsible for 1.95 MV reading – it fact it was only 1.6 MV

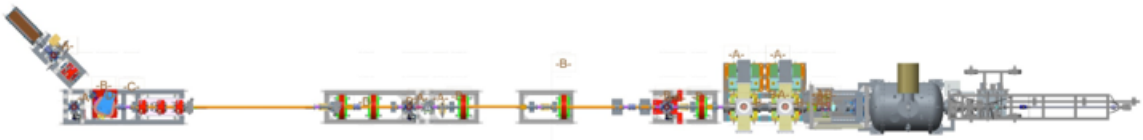


Fig. H.11. Layout of the CeC PoP system for tests during RHIC RUN 15.

Main concerns:

- As we stated in the previous report, we were funded at $670K level (35.3% of requested $1,896K) for FY14. A $5K was supplemented later. The $1.221M shortage of funds would not allow us to complete two main systems: the 704 MHz 20 MeV SRF linac and the helical wiggler system. The total shortage of funds for these two major purchase orders is $1,207,318.
- We continue modest progress with the 704 MHz SRF linac, which is currently at ANL undergoing the buffer chemical cleaning prior to the assembly into the cryostat at Niowave. If funds would become available (see section of concerns), the linac would be ready for delivery to BNL in April 2015 – it would require $740K of additional (uncommitted) funding.

The project scope did not change.

Report Date: March 27, 2015

Milestones

- Diagnostics equipment for low energy transport line is installed

- Control system developments is in progress. We can set and read most of parameters for magnets, RF, vacuum and machine protection system. Most of the values are logged into the database.
- CW operation of the 113 MHz gun was achieved with 1.2 MV. Further cavity condition will follow.
- Main drive laser installation in progress.
- Machine protection system is functional.
- Budker INP after initial delays with wiggler tuning is up to speed now and approaching the end of the tuning of the last helical wiggler
- Niowave have received an ASME code stamped vacuum vessel (major contract milestone) and proceeded to the integration of the cold mass

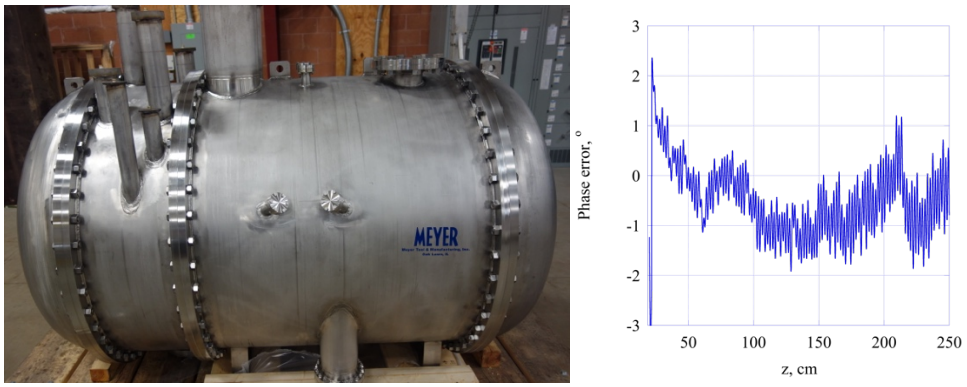


Fig. H.12. Left: ASME code vacuum vessel for the 704 MHz cavity. Right: Measured FEL phase errors in the second helical wiggler manufactured by BINP is well within specifications

Main concerns:

The availability of budget funds remains the main concern. We have used money from another source to pay for milestone in the Niowave contract on 704 MHz cavity, but we do not have funds for the next milestone payment. The same is valid for the helical wigglers. We need money as well for the further installation: vacuum system, supports, diagnostics equipment, control. The estimated short fall is around $1M.

RHIC run 15

During this RHIC run we continued installing, connecting and testing CeC equipment at RHIC IR2. This works was done in short 8-hour periods during bi-weekly RHIC maintenances. Still, even within this limited access time we had achieved significant progress.

Still the main focus and main challenge of the run was on commissioning the SRF electron gun. Trouble-shooting and commissioning this unique beyond-the-state-of-the-art system was a very challenging process.

We had established both the vacuum and RF voltage in the 113 MHz SRF gun necessary for initial electron beam test by the end of the 2014. During RHIC run we further improve the cavity performance by conditioning multipacting zones and using He treatment to burn-off the dark-current emitters. SRF gun cavity operated at 1.7 MV in CW mode and at 2 MV in the pulsed mode - sufficient for generating beam necessary for the CeC experiments. The level of the dark current from this gun was at a nano-ampere level.

A number of K_2CsSb photocathodes with high quantum efficiency (QE above 3%) were manufactured using custom molybdenum pucks as substrates. The cathode deposition system at Instrumentation Division (BNL) had being refurbished and supplied with fresh sources to achieve this performance. We manufactured a transport system with built in vacuum/NEG pump and QE monitoring system. It is used to store and transport up to three cathode pucks.

We experienced intermittent problem with cathode transfer and insertion system. This system provided by Stony Brook University had been severely damaged in a track accident, and later was rebuilt and refurbished. Multiple vacuum leaks and malfunctions in this system delayed commissioning of SRF gun – with limited RHIC accesses each vacuum failure resulted in 6 weeks delay. Vacuum in the transfer system was inferior for photo-cathodes survival and we improved it by installing NEG pumps.

First beam from the SRF gun: June 22-26, 2015

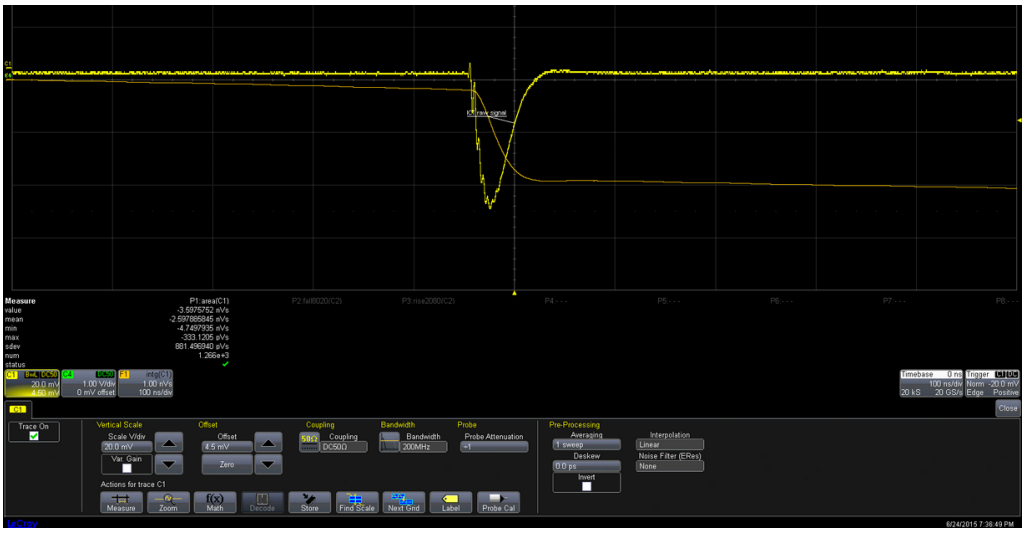


Fig. H.13. Oscilloscope trace of the signal from the integrating current transformer (ICT) with 3 nC charge per bunch laser-generated electron beam

Major milestone: May 9, 2014: DOE Approval for CeC SRF gun test

Department of Energy
Brookhaven Site Office
P.O. Box 5000
Upton, New York 11973

MAY - 9 2014

Ms. Gail Mattson
Brookhaven Science Associates, LLC
Brookhaven National Laboratory
Upton, New York 11973

Dear Ms. Mattson:

SUBJECT: APPROVAL OF THE ACCELERATOR EXEMPTION REQUEST FOR THE COHERENT ELECTRON COOLING INJECT DEVICE TEST

Reference: Letter from G. Mattson, BSA, to F. Crescenzo, SC-BHSO, Subject: Request of BHSO's Approval of the C-AD Exemption Request for "Coherent Electron Cooling Inject Device Test (CECI)"

The Department of Energy (DOE) Brookhaven Site Office (BHSO) has reviewed your request for a temporary exemption from the requirements of DOE O 420.2C, Safety of Accelerator Facilities, prior to performing low power testing of the CECI super-conducting RF electron gun and associated beam line components. Based on our review, low power testing of the CECI is approved and can commence under the limits established by the requirements specified in the Collider-Accelerator Department (CAD) Operations Procedure Manual (OPM) 2.5.2.2, Testing Safety Envelope Procedure for CECI Testing at Low Power, in RHIC, and the applicable requirements in the RHIC Accelerator Safety Envelope. The low power testing is expected to last for 7 months starting in June of 2014 and to be completed by December 31, 2014. Please notify this office, in writing, when the actual low power testing commences. BHSO will be monitoring the progress of the testing and tracking the expiration date of the exemption.

BHSO requires that CAD perform and submit a documented review of the Low Power Testing operations 3 months after its starting date. It must demonstrate that all controls, engineers and administration are in place and are functioning as described in the April 17, 2014 Unreviewed Safety Issue Analysis of the CECI Low Power Test and CAD OPM 2.5.2.2.

If you have any questions, please contact Patrick Sullivan, of my staff, at extension 4092.

Sincerely,

Frank Crescenzo
Site Manager

cc: R. Desmarais, SC-BHSO
R. Gordon, SC-BHSO
P. Sullivan, SC-BHSO
E. Lessard, BSA
V. Litvinenko, BSA
T. Roser, BSA
C. Schaefer, BSA

Report Date: July 7, 2015

Milestones

- **Demonstrating operation of 113 MHz SRF gun with 3 nC charge per bunch, 1.6 to 1.7 MeV energy in CW mode and above 2 MeV in pulsed mode.
- Production of high QE photocathodes for 113 MHz SRF gun.
- Budker INP finished tuning and measuring the last helical wiggler.
- All three wigglers and magnetic measurement equipment has arrived to BNL and are located in Bldg. 902
- Niowave finished the integration of the cold mass (704 MHz SRF linac) with pressure vessel of the linac cryo-module. They conducted the cold shock test.
- Completing the low energy transport beam line and its control system.

** Measurement error in RF calibration gave 15% overestimation of the beam energy

Report Date: September 30, 2015
Milestones

- Three FEL wigglers arrive to BNL
- Budker INP (Novosibirsk, Russia) team visited BNL July to set-up assembly, magnetic measurements and tuning systems for helical wigglers
- 704 MHz SRF linac cryomodule was completed and arrived to BNL
- Two helical wigglers are tuned to the specifications and installed at IP2
- All magnets for CeC PoP experiment had being measured.
- The SRF gun cathode exchange mechanism is modified to improve it robustness.
-

Fig, H.14 Left: The first helical wiggler installed in the RHIC tunnel; Left: 704 MHz SRF linac cryomodule arrived to BNL and moved to IP2

Main concerns:

- The main concern is insufficient funding of the project
- Timely delivery of the parts of the cryogenic system and a support platform

Report Date: January 12, 2016
Milestones

- Most of CeC equipment needed for commissioning is installed in RHIC IP2.
- We conducted IRR in December 2015 and planned ARR for March 2016
- All LI He cryogenic system is installed and connected to SRF cryostats

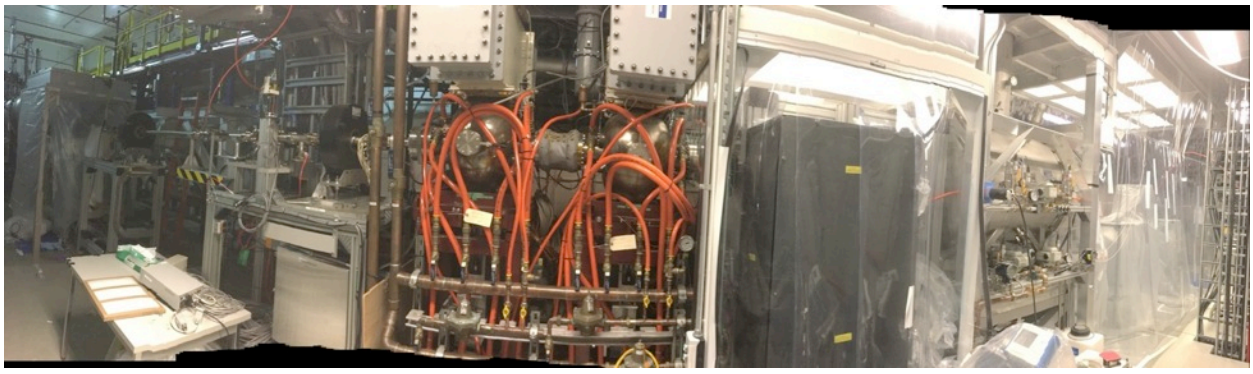


Fig. H.15. Assembled CeC accelerator system

Fig. H.16. Installed CeC section with three-wiggler FEL– common with RHIC

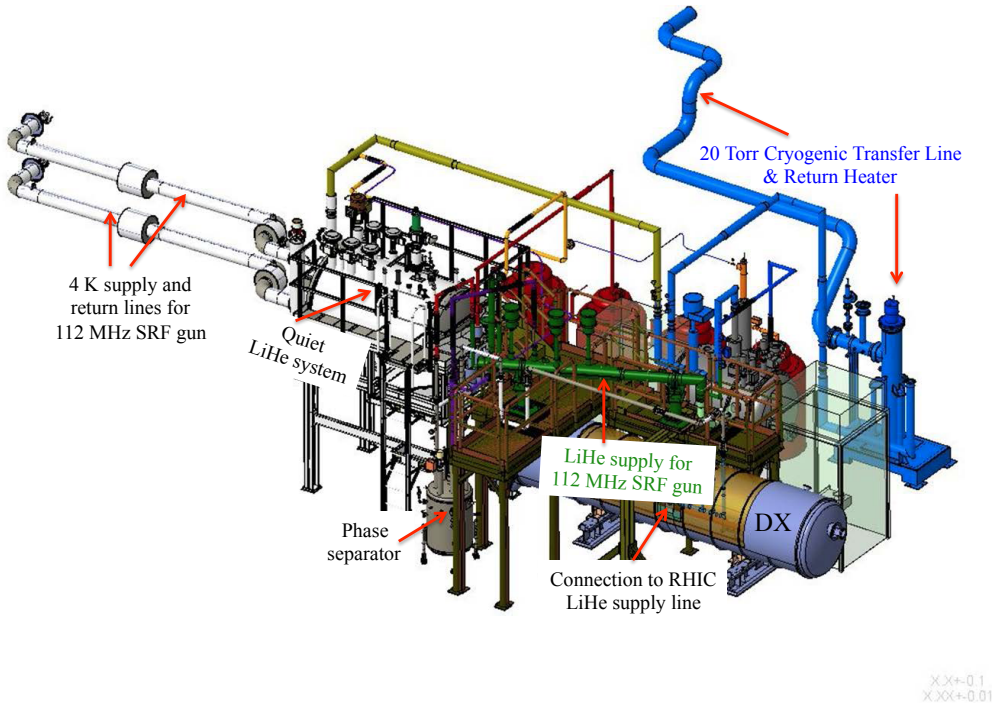


Fig. H.17 The 3D rendering of the CeC PoP experiment LiHe system

Main concerns:

- Our main concern is with availability of funds, which limit our ability to have completed set of necessary diagnostics and critical spare parts. We borrowed $300,000 and waiting for availability of funds. We will need about $0.8M to complete the CeC system and finish the program.
- On technical side, we discovered last Friday that some of the support structures inside 704 MHz SRF cryostat felled-off during transportation from Niowave to BNL. We are executing an ad-hoc plan to fix this problem before the start of the RHIC run.

Important note: Discovery of the problem in the 704 MHz SRF cryostat turned out to be a very major problem: the inner part of cryostat had significant damage and integrity of LiHe system was damage. In short, the cryostat had to be opened and complex repairs have to be performed. Project was delayed by at least two months because of this major damage.

As was reconstructed during investigation of the problem, this major damage occurred during transportation from Niowave (Lansing, MI) to BNL. Track used for transportation of the SRF linac had to have shock absorbing suspension system, but it definitely was not operational. Studies of the accelerometer reading, which was attached to the crate during the transport) showed that the crate was exposed to exceedingly strong shocks. It was a second – but not the last - major damage to CeC equipment during the shipment.

Report Date: June 6, 2016, 2016

Milestones

- The entire CeC system had been installed and is currently under commissioning
- We conducted successful Accelerator Readiness Review for March 2016
- Three RF system operate both in phase-lock loop and in the synchronous modes
- The gun is fully operation and generates high quality electron beams. Maximum change per bunch is 4.6 nC
- The laser beam from the laser shack coupled to the 113 MHz SRF gun via an optical fiber

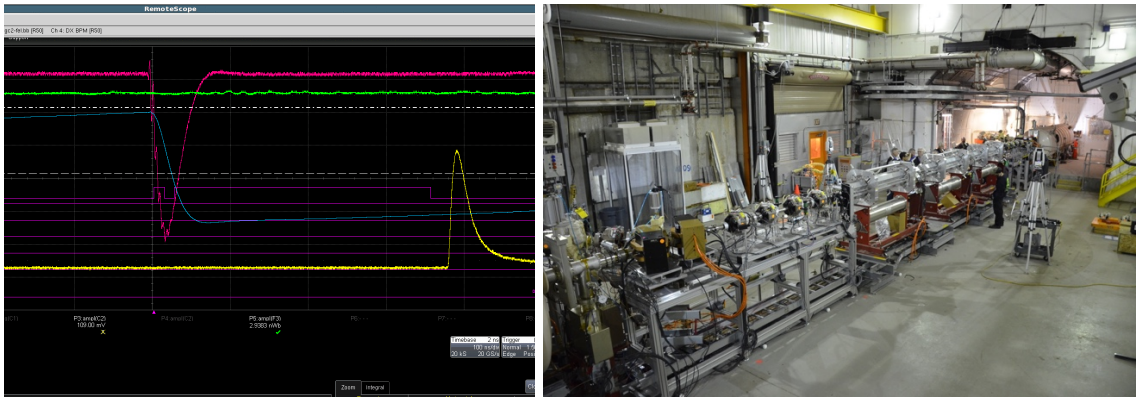


Fig. H.18. Left: A signal from ICT (red trace) and its integral (blue) corresponding to 4.6 nC per bunch. Yellow trace corresponds to a signal from photodiode sampling laser pulses. Right: Final alignment of the helical wigglers – RHIC maintenance, March 29, 2016.

Main concerns:

- The 704 MHz SRF linac is in place and is cryogenically connected to the quiet LiHe system. We have to remove to short sections of vacuum system next to the linac to conduct the repairs inside the cryostat created during shipment.
- The repairs with limited access into the cryostat are complicated, and results are not guaranteed. Best qualified technicians are performing this task.

Report Date: July 15, 2016

Milestones

- On March 8, 2016 the DoE office authorized low power (under 1 W of beam power) tests of the CeC accelerator
- We successfully finished repairs of 704 MHz linac cryostat
- We are commissioning of the CeC system and its beam diagnostics
- We generated electron bunches in the SRF with designed quality
- We propagated electron beam through the entire system

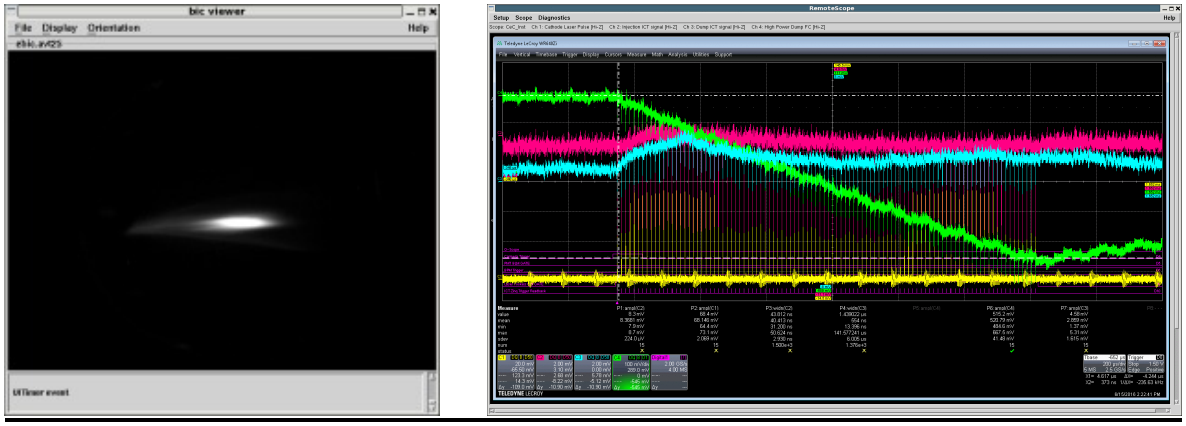


Fig. H.19 Left: Electron beam profile at YAG beam profile monitor in front of the high-power beam dump; Right: Scope trace (green) of 100 electron bunches reaching the high-power beam dump, serving as the Faraday cup.

Main concerns:

- The 704 MHz SRF linac accelerating voltage is limited to 9.6 MV in CW mode. This is unexpected result for SBU 5-cell cavity demonstrating 20 MV in VTF test.
- Investigation showed that poor SRF linac performance is the result one of the SRF cavity contamination. One of RF engineers opened vacuum flanges on the SRF linac cavity and exposed it to dirty air.
- We need to completely disassemble the cryostat, re-clean the cavity an dissemble it back
- We discovered that fiber cable used for delivering laser light from the laser shack to the SRF gun generates significant modulation in the laser pulse structure. Replacing it with larger core fiber cable did not solve the problem.

Report Date: October 21, 2016

Milestones

- We are addressing all conferences identified by the end of RHIC Run 16
- Contaminated 5-cell 704 MHz SRF cavity is extracted from the cryostat and send SRF for cleaning and treatment to ANL
- We are replacing high power Cu beam-dump with Al version, which would have significantly low level of residual radiation. The Cu beam-dump will be used in LEReC.
- All initial IR diagnostics is assembled on the optical table

Main concerns:

- Our main concerns is repairing 704 MHz SRF linac system to full performance
- Reliable LLRF system, multipacting in the SRF gun and strong SRF micro-phonics are also our concerns
- Other problem, such as lack of accelerator-based controls and limited diagnostics are important in determining the speed of the progress towards experimental demonstration, but not necessarily a final road-block towards the success
- We discovered that charging of the guns ICT ceramics causes semi-periodic e-beam orbit variation followed by sudden discharges.

Report Date: February 3, 2017
Milestones

- We refurbished the 704 MHz SRF linac and installed it back at CeC
- We replaced the gun ICT with new one having metallic insert
- We installed IR diagnostics
- We received first garage with improved design and placed and order for two more
- Aluminum high power dump is manufactured

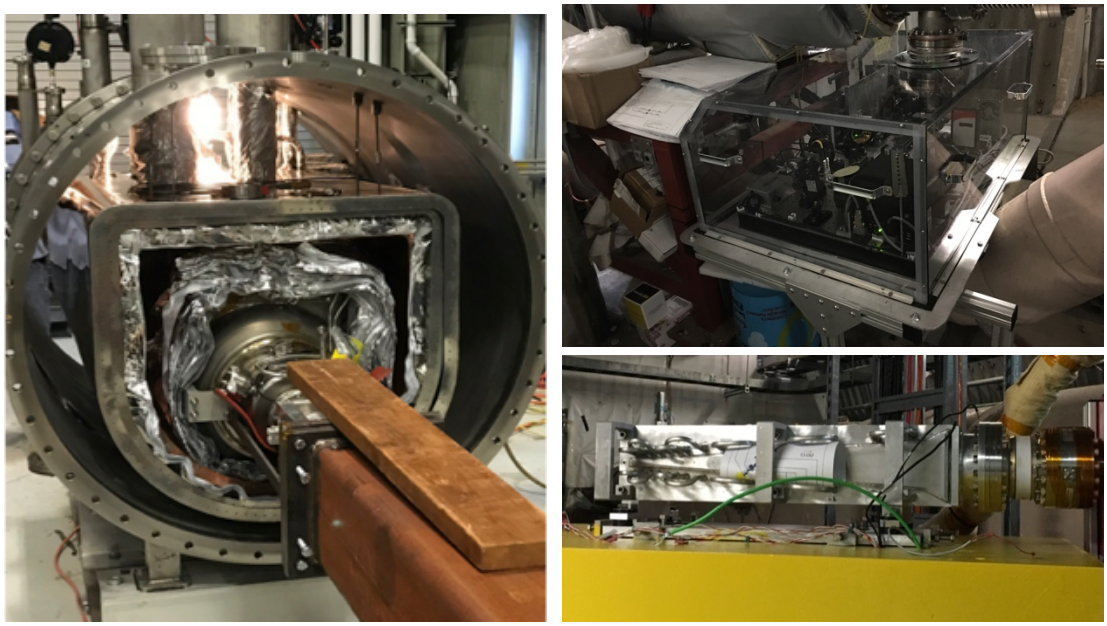


Fig. H.20 Left: Reassembly for the 704MHz linac cryostat at BNL; Right (top) – IR diagnostic box between DX and Do RHIC magnets; Right (bottom): All Al CEC beam-bump during installation.

Main concerns:

- Our main concern is limited funds available for the project, which greatly limit our ability to have the completed set of necessary repairs, improvements and purchasing critical spare parts such as a spare laser. Currently there no funds available for this CeC project. All funds had been used in the FY16.
- One of the sacrifices caused by absence of sufficient funding – he full-scale simulations of CeC performance
- The performance of the 704 MHz SRF linac is of the main concern. There was additional accident with exposing the 704 MHz SRF linac to the atmosphere at BNL (caused by miscommunication between SRF group head and mechanical group). As the result, we had to repeat the cleaning of the cavity at ANL: both the buffer-chemical polishing (BCP) and high-pressure rinsing.
- SRF gun has multiple multipacting (MP) zones, which could affect QE of the photo-cathode. The new 4 kW transmitter (2X higher power) should allow us to pass the MP zones easier. We also installing an “oxygenation” unit, which should allow us to use pure oxygen to neutralize Cs deposited from the cathode onto the walls of SRF gun.

Report Date: April 27, 2017

Milestones

- 704 MHz SRF linac is commissioned and operating at 13.3 MV
- We propagated 14.6 MeV (low power) electron beam through the CeC system to high power dump.
- Cathodes in SRF gun are performing well
- Aluminum high power dump is installed

Important note: Confusing rumors that the linac is operating at design 20 MV voltage are incorrect. They were based on SRF group using incorrect calibration and listing these incorrect readings in eLogs. Measured beam energy showed that linac was delivering only 75% of these incorrectly reported "reported" numbers. Low than predicted linac voltage dramatically changed our plans for RHIC 17 run: in makes practically impossible to commission FEL and also caused a major shift of revolution frequency for a matched ion's energy

Main concerns:

- Our main concern is the funds availability for the project. We need funds for completion of the CeC beam diagnostics, which is definitely insufficient for effective commissioning
- According to the SRF experts, the CeC linac will be limited to CW RF voltage of 13.3 MV or below. The stated reason is that third the buffer-chemical polishing (BCP) opened a defect inside the cavity, which causes it to quench. As we reported, this cavity demonstrated 20 MV in VTF. According to the SRF group, there is no possibility to fix the cavity.
- With inferior linac voltage the FEL wavelength is 30 μm or longer. During this run the FEL commissioning will be blind-folded: the IR diagnostic has a vacuum window (installed after RHIC DX magnets) with cut-off at 16 μm. Since CeC FEL uses helical undulators, there is no third harmonic of radiation.
- Ion revolution frequency in RHIC at energy corresponding to the same relativistic factor as electron is out of the tuning range of our SRF gun. Hence, we decide to develop a mode when ion beam interacts with electron bunches every third turn.
- Additional concern is multipacting in SRF gun at about 40 kV level (first order multipacting in the rounding of the SRF gun), which is becoming progressively stronger. We understand very well where the multipacting (MP) is occurring, and suspect that Cs evaporating from SRF gun photocathode enhances SEY and the strength of the multipacting.

Report Date: August 2, 2017

Milestones

1. Beam parameters sufficient for CeC demonstration experiment were established
2. The CeC SRF accelerator is fully commissioned with beam energy up to15 MeV
3. Full power CW beam with low losses reliably propagated through the CeC system
4. Indication of interaction between electron and ion bunches is observed
5. Novel method of using solenoids for beam-based alignment is implemented
6. SRF gun and high QE photocathodes performance was excellent
7. We developed detailed plan for RHIC shut-down period

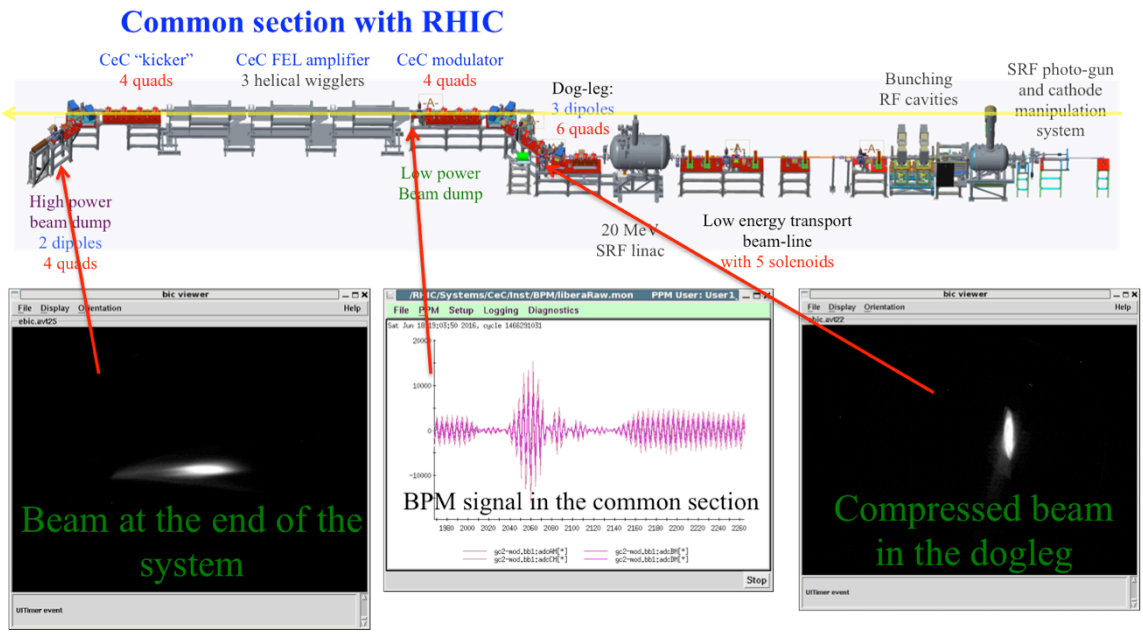


Fig. H.21. Typical operation of the CeC system during RHIC run 17: 1.56 MeV (total energy) 0.5 nC to 4 nC electron bunches are generated at SRF photo injector, energy-chirped in bunching cavities, compressed in low energy beam transport, accelerated to 14.7 MeV in the SRF linac and propagated through the achromatic dog-leg and CeC system (common with RHIC beams) to the high energy beam dump.

Table H.1. List of main CeC parameters

Parameter	Design	Actual	Comment
Species in RHIC	Au^{+79}, 40 GeV/u	Au^{+79} 26.5 GeV/u	To match e-beam
Particles/bucket	10^8 - 10^9	10^8 - 10^9	✓
Electron energy	21.95 MeV	**15 MeV**	**SRF linac quench**
Charge per e-bunch	0.5-5 nC	0.1- 4 nC	✓
Peak current	100 A	50 A	Sufficient for this energy
Pulse duration, psec	10-50	12	✓
Beam emittance, norm	<5 mm mrad	3 - 4 mm mrad	✓
FEL wavelength	13 μm	**30 μm**	**New IR diagnostics**
Rep-rate	78.17 kHz	26 kHz**	Temporary**
e-beam current	Up to 400 μA	40 μA	Temporary**
Electron beam power	< 10 kW	600 W	Temporary**

Main concerns:

- CeC operations during RHIC Run 17 was a real roller-coaster. CeC did not had sufficient engineering and technical support with many key systems. Two main impact came from the reduced linac voltage and very late availability of driver-laser for the SRF gun.
- Our main concern is availability of the engineering and technical staff during this shutdown when a major installation of LEReC equipment at IP2 will be undertaken.
- Technical concerns are related to building a stable and reliable laser for our SRF gun and stabilization of all three RF systems – the main focus in our CeC improvement plan.

Report Date: October 5, 2017

Milestones

5. We fixed energies of the electron and ion beams to γ=28.5
6. RF frequency of the SRF gun was tuned to match revolution frequency of 26.5 GeV
7. An SVD diamond window transparent in full IR range was installed for IR diagnostics
8. Helicity of the third wiggler was fixed

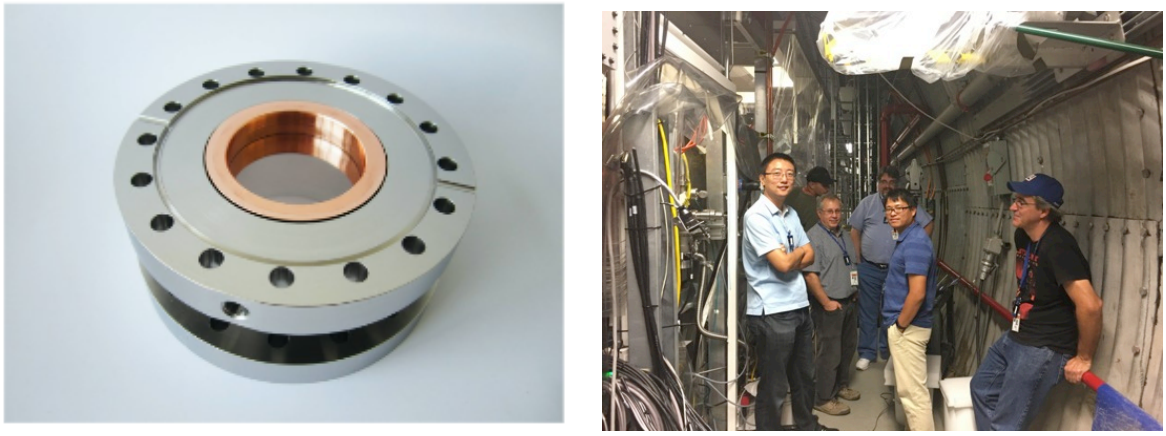


Fig. H.22. Left: SVD diamond window; Right: retuning of the SRF gun frequency to a harmonic of 2.6.5 GeV/u Au ions revolution frequency

Main concerns:

- The same as in previous report.

Report Date: January 15, 2018

Milestones

1. The fiber laser amplifier was replaced with regenerative amplifier
2. Operational ICT was installed at the beam dump
3. IR diagnostics was upgraded to be sensitive at 30 um

Main concerns:

- Dedicated time for LEReC commissioning and CeC is starting soon – our success during this RHIC run strongly depends on readiness of the systems

- Technical concerns are related to building a stable and reliable laser for our SRF gun and stabilization of all three RF systems – the main focus in our CeC improvement plan.
- The seed laser failed and was shipped to the vendor for repairs. Regenerative amplifier is not commissioned - all this can significantly delay start of CeC.

Report Date: April 17, 2018

Milestones

1. The fiber laser amplifier has been replaced with the regenerative amplifier by March 28
2. Compressed electron beam had been propagated though the CeC system
3. IR diagnostics has been commissioned and is operational
4. Partial (two layers out of three) magnetic shielding was installed on the DX and D0 magnets adjacent to CeC low energy transport beam-line
5. High quality beam has been established an propagated through the CeC system

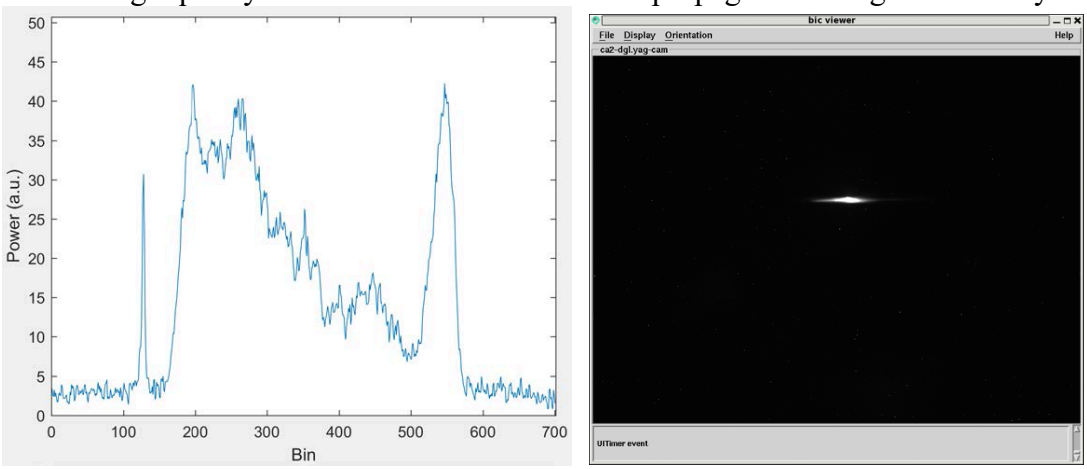


Fig. H. 23. Left: Laser pulse structure measured by streak camera: the laser pulses are clearly out of specification and contain a lot of the internal structure; Right: Image of 14.5 MeV 600 pC compressed electron bunch at YAG profile monitor located in the dog-leg. Horizontal dispersion in the location is 0.7 m and RMS energy spread is less than 0.1%

Main concerns:

- Month and a half of dedicated CeC time had been lost because the laser for the SRF gun was not operational. First useful laser beam from NuPhoton laser was given to us only on March 1, when the dedicated time without RHIC beam was over.
- In March we re-commissioned the CeC accelerator system with old, unstable and poorly perfuming NuPhoton laser. Its poor and out-of-specifications performance was confirmed using streak-camera borrowed from ATF
- Very late availability of the laser system greatly reduced our chances for successful experiment
- We also concerned by the laser amplitude stability and its large time jitter. The absence of a spare laser source to use as input to the regenerative amplifier is our major concern;
- We also concerned about a possibility of radiation damage from RHIC beam losses of the CeC FEL permanent magnet wigglers;
- Single-point vulnerability is also our concern, but we do not have funds for spares

Since the 6 weeks of the dedicated time for the Ce was lost by unavailability of the driver-laser and next four weeks were impaired by late commissioning of the regenerative amplifier, we switch to aggressive and risky plan. We have two an a half month with two remaining week of dedicated RHIC time. The plan is:

- April – compress the beam to 70-100 A peak current demonstrate FEL amplification.
- 2 days of dedicated time to evaluate the FEL gain and to establish CW lasing
- First half of May
    a. establish interaction between electron and ion beams.
    b. 2-3 days of dedicated time to align beam relativistic factors and to fix the energy of CeC accelerator
- Second half of May – establish interaction between electron and ion beams.
    a. 2-3 days of dedicated time to observe amplification of the signal imprinted by hadrons and
    b. potentially first signal of CeC process
- June 1-17 – Optimizing the CeC accelerator parameters and CeC experiments.
    a. 7 days of dedicated CeC time.

Report Date: July, 2018

Milestones

- We achieved only one milestone: FEL amplifier was commissioned and operated both in the pulsed and the CW mode - world's first CW SASE FEL
- We had achieved all deign (KPP) parameters with the electron beam
- We synchronized in time and overlapped in space electron and ion beams, and observed their interaction
- Two other milestones had not been reached:
    - demonstrating imprint of the ion signature into the electron beam and
    - CeC cooling of ion beam

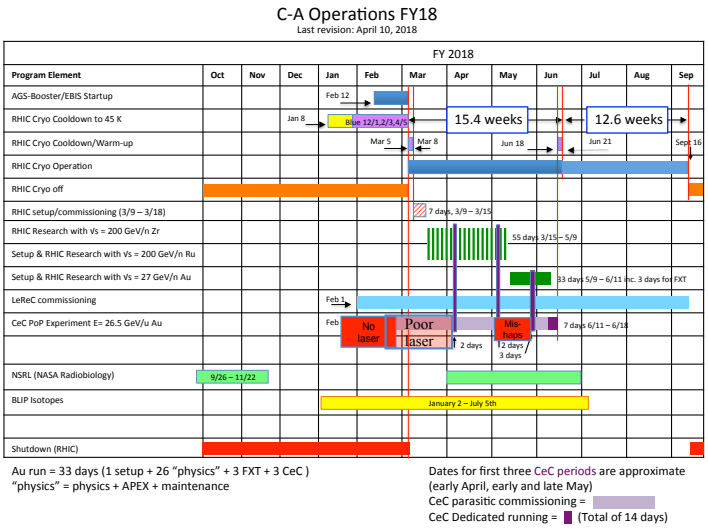


Fig. H.24. Illustration to CeC operation during regular RHIC run 18. CeC was allocated 14 days of dedicated RHIC time, of which approximately 9 days were used.

Low availability ~ 30% of the CeC system, especially the laser, was a major factor slowing down the CeC experiment. In addition, a number of configuration changes – outside control reach and without the awareness by the CeC group - resulted in major damage to the CeC experimental program additional loss of 4 weeks of operation in May and June. The CeC team was exhausted chasing the problem created by these configuration changes. Lost time and efforts, both February -March and May-June, had a major impact on our ability to progress toward the ultimate goal of demonstrating cooling.

Main concerns:

- The reason behind our inability to observe ion imprint into the e-beam is not understood and need to be investigates

Report Date: October 18, 2018

Milestones

- We determined the cause explaining our experimental results of the ion imprint studies: excessive noise in the electron beam caused by plasma-cascade instability
- We either eliminated or prove extremely unlikely other possible scenarios

On hardware side of the process – the common section of the CeC system, including FEL, had been removed in preparation for installation of large aperture vacuum pipe suitable for low energy RHIC and LEReC operations. The CeC accelerator, its dog-led and the beam dump section remain intact.

Fig. H. 25. All CeC equipment, including the modulator, FEL and the kicker, has been removed from the common section at IP2. Only quadrupole support stands and cable trays remain on place.