

## 3.9 GHz CAVITY MODULE FOR LINEAR BUNCH COMPRESSION AT FLASH

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### Abstract

3.9 GHz superconducting rf cavities have been developed at Fermilab as part of a DESY Fermilab collaboration. Four such 3.9 GHz cavities have been integrated into a module at Fermilab, shipped, and installed in the DESY FLASH XUV FEL at the downstream end of the 1.3 GHz injector module (ACC1). These cavities provide linearization correction to the sinusoidal accelerating field produced by the 1.3 GHz cavities in the injector module. This paper provides an overview of the cavity performance and discusses first operating experience at FLASH.

### INTRODUCTION

The 3rd harmonic module operating in decelerating phase in conjunction with the ACC1 module provides linearization of the rf acceleration field with time during the duration of the beam bunch. (ACC1-7 is the nomenclature for the seven 8 cavity modules in FLASH. See Fig. 5) This field linearization provides for much more controllable energy-time correlation of the bunch that is needed for subsequent bunch compression in downstream magnetic compressors and to prepare the beam for high peak current conditions needed for SASE lasing in the undulator section.

This paper will briefly summarize the development history and performance of the 3.9 GHz cavities. (See [1] this conference for more details on the cavities.) This paper will then describe the FLASH layout and recent upgrades made during the last shut down, the compression studies and simulations that have been performed at DESY, and discuss some of the commissioning results to date. The final section mentions future measurement programs and plans.

### 3.9 CAVITY PARAMETERS

The required voltage amplitude of the 3.9 GHz system can be determined from the accelerating voltage of the 1.3 GHz injector module (~160 MV) by asking that the 2nd derivatives with time or position  $s$  (relative to the bunch center) of the two systems cancel.

$$\frac{d^2}{ds^2} \left( A_{1.3} \cos\left(\frac{\omega_{1.3}}{c} s + \phi_{1.3}\right) + A_{3.9} \cos\left(\frac{\omega_{3.9}}{c} s + \phi_{3.9}\right) \right) = 0$$

$$\omega_{1.3}^2 A_{1.3} \cos\left(\frac{\omega_{1.3}}{c} s + \phi_{1.3}\right) + \omega_{3.9}^2 A_{3.9} \cos\left(\frac{\omega_{3.9}}{c} s + \phi_{3.9}\right) = 0$$

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Near crest at bunch center  $s=0$ ,

$$\frac{A_{3.9}}{A_{1.3}} = -\frac{\omega_{1.3}^2 \left( \frac{\cos \phi_{1.3}}{\cos \phi_{3.9}} \right)}{\omega_{3.9}^2} \approx \frac{1}{9} \quad (1)$$

$\phi_{3.9}$  is ~180 deg (decelerating mode) and  $s = -ct$ . The head of the bunch is at positive  $s$  and  $\phi_{1.3}$  must be positive for the energy of the bunch head to be lower than the tail for compression. The 3.9 GHz rf is operated near trough phase. Slightly more ACC39 voltage than a nominal 19 MV is desirable for compensation of other nonlinearities such as those from the compressors.

### Cavities

The 3.9 GHz cavities are to first order a scaled version of the TESLA 1.3 GHz cavities. They have 9 cells and an effective accelerating length of ~1/3 m. The gradient specification of 14 MV/m with four cavities in a module is sufficient to provide ~ -19 MeV beam energy change to meet the requirements of Eq 1. Though this gradient specification may seem low by today's standards, it should be remembered that these cavities are the first of their type and that the thermal heating is much higher at a specific gradient than with the 1.3 GHz cavities because of the surface resistance,  $R_{BCS}$ , scaling with  $f^2$ . More will be said on this below.

The cavities could not be an exact scaling of TESLA cavities, mainly because of the need to enlarge the beam tube and iris diameter in the end cells so as to have sufficient coupling to the input coupler. The coupler position in longitudinal  $z$  from the end cell could not be scaled exactly, but needed to be further away because of mechanical design constraints associated with the helium vessel and port flanges. The higher order mode (HOM) couplers could not be exactly scaled as well. They were the main source of technical difficulty. The 1/3 scale cavities are rather small and delicate compared with the much more substantial TESLA cavities. Fig. 1a shows a bare cavity, and Table 1 gives some of the relevant parameters.

Table 1: 9 Cell 3.9GHz Cavity Parameters

Gradient specification (MV/m)	14
Number of cavities in module	4
$E_{\text{peak}}/E_{\text{acc}}$	2.26
$B_{\text{peak}}/E_{\text{acc}}$ (mT/MV/m)	4.86
G1 (ohm) (=RsQ)	275
Active cavity length (m)	0.346
R/Q (ohm)	750
Module length beamvalve to bv (m)	2.535

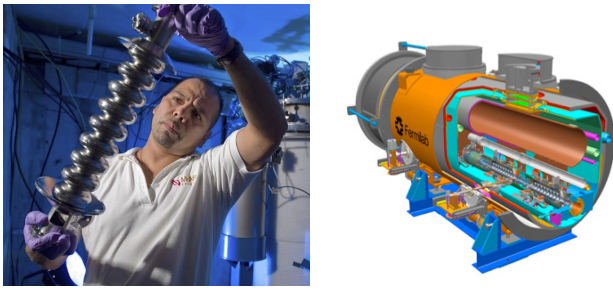


Figure 1: a) Bare 3.9 GHz cavity, b) Module solid model showing the very small cavities relative to the module.

### Module

The four cavities are mounted into a module that must connect directly to the downstream end of the injector module, ACC1. Because of these interface requirements and the very limited beam line z real estate, the input couplers are arranged on both sides of the beamline and the cavities appear dwarfed inside the module. The outside bellows of ACC1 and ACC39 modules were welded together because there was no space for the standard external bellows flanging. Fig. 1b shows the solid model of the ACC39 module with view of the cavities inside. [2]

### Higher Order Mode Couplers (HOMs)

The main technical difficulty in the development of the cavities was with the HOM couplers [3]. This caused considerable delay in the schedule and still remains a potential issue with two of the cavities in ACC39. The initial design with a two post “formteil F” (shaped part) based on the TESLA design showed strong multipacting in the HOM region. This was sufficient to actually crack the HOM F part during quasi-cw vertical test. The F shaped part was modified in some of the subsequent cavities by shortening the post extension into the beam tube and a new one post design was developed. See Fig. 2. Two of the cavities in ACC39 have the modified version and two have the new design. It has recently been discovered by tomographic imaging [1] that some of the spare cavities of the modified design also show formteil cracks, so that design is far from satisfactory in the long run. In horizontal cavity tests of the dressed cavities, both at the Fermilab Horizontal Test Stand (HTS) and at the DESY Cryo Module Test Bed (CMTB), one cavity showed quenching of the HOM antenna (the antenna that couples out the power, not the F part) at gradients above 18 MV/m. This cavity should be limited to gradients below this threshold. Even so the module as a whole should be capable of up to 25 MV of deceleration voltage.

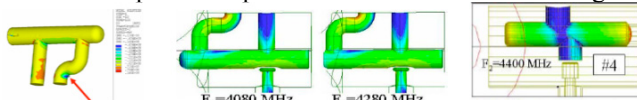


Figure 2: a) Finite element analysis showing high minus stress (arrow) at the crack fracture point. b), c) two post design and its modification, d) one post design.

### Thermal Analysis

It is expected that the rf surface resistance,  $R_s$ , of the 3.9 cavities should be considerably higher than for the 1.3 GHz cavities at the same peak surface magnetic field. This is because of the expected  $f^2$  scaling of the  $R_{BCS}$  and possible  $\sqrt{f}$  scaling of the residual resistance,  $R_{resid}$ , from external magnetic fields. It is very likely that 3.9 GHz cavities may be limited by “global thermal” heating runaway instability, whereas for 1.3 GHz cavities the rf peak magnetic field should approach the superconducting critical field  $B_c \sim 200$  mT well before global heating would have a significant impact on the cavity  $R_s$  or  $Q$ . [4]

It is interesting to study the dependence of  $Q$  vs  $B_{peak}$  (or  $E_{acc}$ ) at 3.9 GHz in relation to  $Q$  slope and  $Q$  drop models that have been extensively worked on for 1.3 GHz frequency [4]. Simple 1D thermal models with thermal conductivity,  $\kappa$ , and Kapitza conductance,  $h$ , have been used to calculate predicted  $Q$  vs  $B_{peak}$  for the 3.9 GHz cavities [5]. Though  $\kappa$  and  $h$  are not known well, typically the model predicts higher  $Q$  slope, and maximum gradients at or below those that have been measured. Even using low field  $R_s$  values, the peak surface heating/cm<sup>2</sup> for 3.9 GHz cavities at 30 MV/m is 3 to 4 times that for 1.3 GHz cavities at 40 MV/m at 1.8 -2 K.

### Cavity Test Results

Fig. 3 shows the vertical test results of the ACC39 module cavities and that expected from a simple thermal model. Fig. 4 gives the measured gradients throughout their measurement history from vertical and horizontal tests at FNAL to Module test at DESY CMTB.

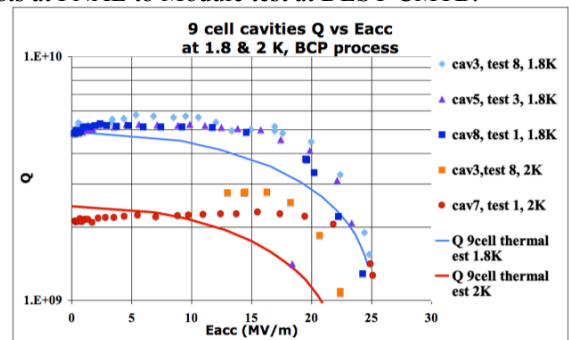


Figure 3: Vertical dewar bare cavity test results, and global thermal model estimate for 1.8 and 2 K helium.

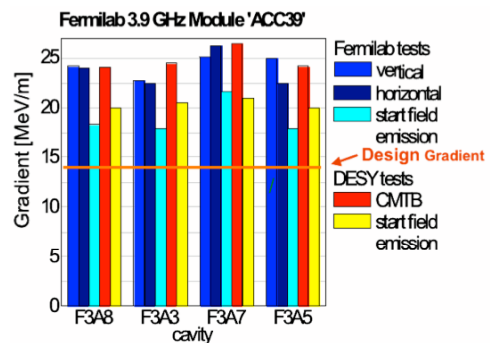


Figure 4: Achieved gradients throughout the test history.

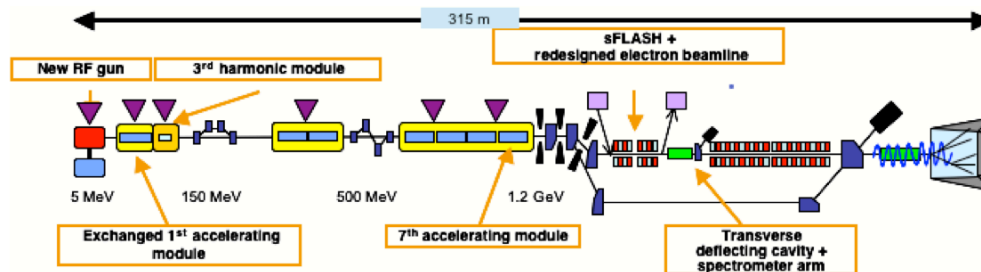


Figure 5: Layout of FLASH with new devices, installed during last shutdown, indicated.

## FLASH, COMPRESSION, AND COMMISSIONING OF ACC39

The FLASH free electron laser at DESY has recently been upgraded during the down time, Sept 09-Feb 10 [6]. Some of the major modifications have included installation of:

- A new injector gun, with lower dark current
- 2 new 1.3 GHz modules (rebuilt ACC1, new ACC7)
- The 3.9 GHz module, ACC39
- LOLA, deflecting cavity diagnostic system, at a new location, with new features
- The sFLASH experiment for high harmonic generation (HHG) laser seeding and a new undulator section

ACC7 is an XFEL prototype module and provides an energy gain of up to 240 MeV.

The present layout is shown in Fig. 5. The beam is accelerated off crest in ACC1 and linearized in the ACC39 module as discussed above. The beam bunch length is then compressed in a magnetic bunch compressor (BC2) before it is further accelerated off crest in ACC2/3 to a second compressor (BC3), and then accelerated to its final energy in modules ACC4-7.

The compression that takes place at BC2 must be sufficient so that the rf curvature in modules ACC2 and ACC3 does not destroy the linearization of the beam from the injector. On the other hand it should not be so strong as to cause undue space charge or CSR effects while the beam is still at lower energy. BC3 then provides the final compression at an energy of about 500 MeV before the final acceleration of up to 1.2 GeV. Because of the long drift between BC3 and the undulators, longitudinal space charge can have a major effect on the energy variation along the bunch. Typical compression values are  $C1=9$ ,  $C2=9$  for a total of about 80.

The LOLA section [7], with its cavity supplied by SLAC, is critical to analyzing the beam compression. It has been moved to a location between the sFLASH section and the SASE undulators. It now has a dispersive dump line that allows for direct longitudinal phase space measurements. It also has a kicker and off axis recording system of bunch lengths that can be used parasitically for one bunch during multibunch SASE operation for users.

Upstream of the LOLA section is the sFLASH experiment section [8]. It is presently being commissioned. It relies on the 3rd harmonic linearization

of the bunch time structure in order to supply it with a long enough electron bunch (~100-200 fs) of uniform current amplitude. This is to provide for coincidence between the electron bunch and the seed laser pulse allowing for jitter between the two systems.

### *Development of the Compression Concept*

1. The original compression based on the energy time chirp being provided by just the 1.3 GHz rf systems (nonlinear energy chirp, “roll-over compression”) produces a very sharp peak current spike with a long tail. It was somewhat of a surprise that the slice energy spread from the injector was so small (few keV). This was the mode that FLASH has operated in up to now. (Fig. 6) Much of the electron bunch does not participate in the SASE lasing process. The lasing is very sensitive to rf settings (phase and amplitude) and it is difficult to tell just what part of the bunch is actually participating in the process.

2. With the 3rd harmonic rf system added, a more “linear compression” is possible with a linear energy chirp. Much more of the beam should be compressible into emittance suitable for lasing. The length of the electron bunch suitable for lasing should be adjustable with the chirp and compressors settings ( $R_{56}$ ). Just how short a lasing pulse can be provided is yet to be demonstrated.

3. Because of the better participation of the electrons and more uniform current in the compressed bunch, there is the possibility of reducing the bunch charge while maintaining saturation over much of the bunch and providing a better photon energy/bunch charge ratio. This will help lower beam losses and reduce effects of space charge and CSR.

4. The linear compression is a critical feature of the sFLASH seeded lasing as it should provide a reasonably uniform electron bunch current over a window to account for the possible arrival time jitter between electron bunches and seed laser.

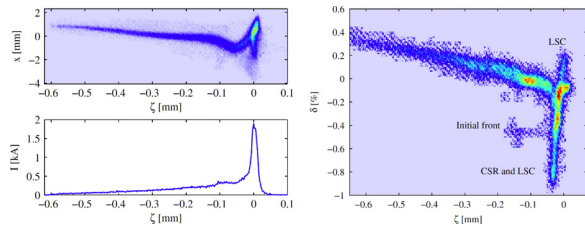


Figure 6: Longitudinal bunch structure before operation with 3<sup>rd</sup> harmonic module. a)  $x$  vs.  $z$ , b) projected current, c) reconstructed  $dp/p$  vs.  $z$  [9].

### Calculation and Simulations of Compression

I. Zagorodnov and M. Dohlus have analyzed the compression process and performed numerous analytical calculations and iterative simulation solutions including collective effects based on the analytically derived initial operating conditions [10,11].

Fig. 7 presents some of their work. Fig. 7a illustrates the difference in compression between “roll over” and “linear”. For linear, 1 nC gives 2.5 kA in a broad distribution, whereas for roll-over,  $\frac{1}{2}$  nC gives a narrow spike of  $\sim 1.5$  kA. The respective slice energy spreads are 120 keV and 200 keV. Fig. 7b shows the potential of going to very low bunch charges with linear compression and producing bunch lengths down to the  $\sim 10$  fs region.

3<sup>rd</sup> harm.  $\leftrightarrow$  roll-over

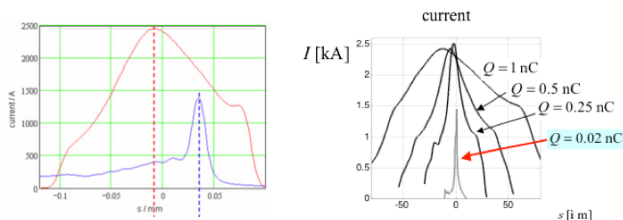


Figure 7: Simulations a) The comparison of current distribution for roll-over for 0.5 nC and linear for 1 nC. b) Current in the compressed beam as the charge is decreased and compression adjusted. [10,11]

### Results from Commissioning

Commissioning of FLASH [6] after the upgrade shutdown started in April-May and is ongoing. Accomplishments to date include:

- Lasing at 4.45 nm, single pulse bandwidth  $\sim 1/4\%$  rms and photon energies above 100  $\mu$ J, average 75  $\mu$ J with the 1.2 GeV beam and linear compression
- Lasing at a variety of wavelengths ( $\sim 13$ ,  $\sim 19$ ,  $\sim 26$  nm), with average photon energies achieved above 200  $\mu$ J at 19 and 13 nm
- Maximum photon pulse energy as high as 270  $\mu$ J at 19 nm
- Investigation of 2nd, 3rd, 5th harmonics
- Lasing with bunch charges from 0.1 to 1 nC
- Lasing of bunch trains of 130 bunches

Before the upgrade FLASH operated at up to 1 GeV, down to 6.5 nm, with pulse energies of up to 100  $\mu$ J and typically in the 20-40  $\mu$ J region [12].

Figure 8 shows the photon pulse energy for a 120 pulse bunch train. This picture was obtained without rf adaptive feed forward when there was considerable energy slope over the train ( $\sim 1\%$ ).

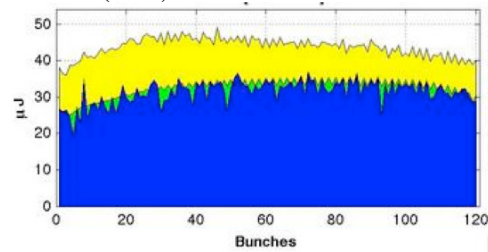


Figure 8: Photon bunch energy for 120 bunches; blue, last pulse, green running average, yellow, peak readings.

Since May during beam and photon beamline commissioning ACC39 has been in routine operation. S. Schreiber reported at FEL2010 [6]: “The radiation pulse energies are significantly larger and easier to tune compared to roll-over compression.” What is hard to quantify but very apparent to those familiar with previous operation is that stable SASE operation is much easier to achieve and maintain. Whereas previously, only experts could set up the SASE, now it can be done by those less experienced, and it takes less continuous tuning to maintain efficient lasing. This probably is due in a large part to the ACC39 module but also to the very substantial effort that has gone into the lrf systems improvements. [13, 14]

### Bunch Compression and LOLA Pictures

During the commissioning, some shifts have been dedicated to LOLA commissioning and to compression studies using LOLA. [7]

Measurements have been made to illustrate the linearization effect of the ACC39 module. These are illustrated in Fig. 9 where longitudinal phase space (LPS) measurements have been made in the LOLA dispersive section as a function of the voltage of the 3.9 GHz section while adjusting ACC1 to keep beam energy constant. The data is taken with ACC1 off crest ( $\sim 6$  degrees). This off crest setup is necessary in order to illustrate the linearization process with a partially compressed bunch that is not significantly distorted by the sinusoidal rf fields of the downstream accelerating modules. (On crest measurements would contain not only the rf curvature of the injector module, ACC1, but also those from ACC2-7 and would dominate over the effect of the 3.9 GHz system.) The top row in Fig. 9 clearly shows the linearization as ACC39 is turned up. The bottom left pane shows on crest beam without ACC39. Second and third from the left show overlay of off to linear, and  $s$  projection of the bunch as ACC39 is turned on. The two rightmost pictures in the bottom row show compression of a 0.4 nC bunch  $I_{\text{peak}}=1.6$  kA. Here the head of the bunch is to the left. The spike indicates that the compression is not yet optimized.

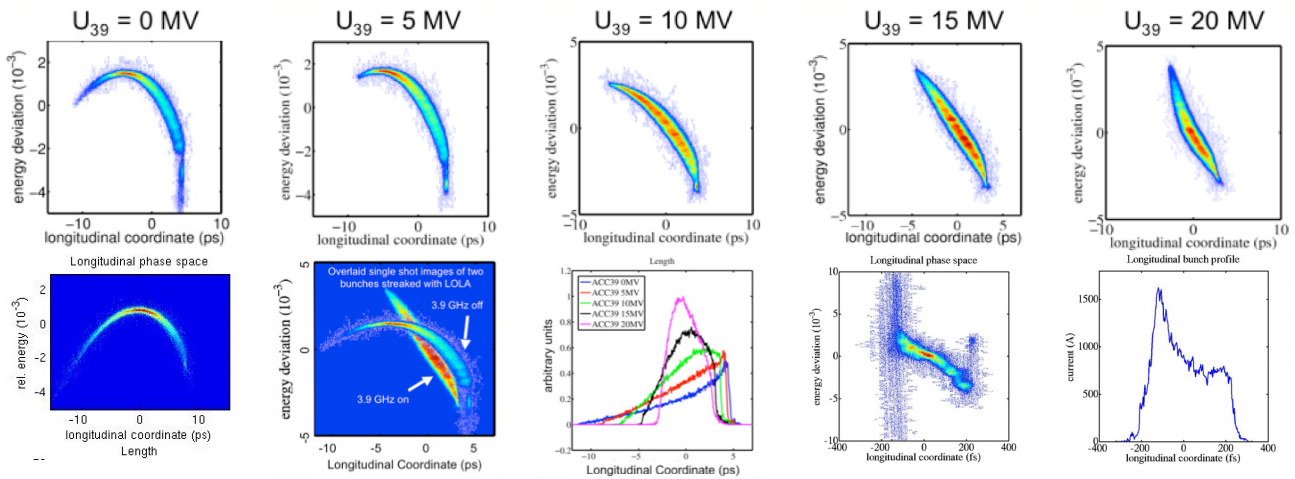


Figure 9: Top row- LOLA pictures,  $z$  vs.  $dp/p$  as ACC39 is turned up from 0 to 20 MV. Injector module ACC1 about 6 deg off crest. Bottom row (l to r) ACC1 on crest, ACC39=0; overlay of ACC39=0 and 15 MV; slice current projections; 0.4 nC bunch with greater compression, and its slice current projection. For the last two panes bunch head is to the left.

### Possible Impact of ACC39 on Beam

There is still considerable commissioning work to be done with the ACC39 module. As with any new cavity, high on the list is investigation of wake and HOM damping issues. With the 3.9 GHz cavities and their very much smaller aperture this will be a worry till the actual bunch charges and bunch trains up to 9 mA [14] have been shown. It is promising that commissioning has already operated with 130 bunches at 0.5 nC, but it is still far from the 9 mA goal. Efforts are underway to measure the single bunch emittance behind the injector as a function of beam position in ACC39. There is also a program to measure HOM mode spectra with beam position and determine the potential of HOM beam position monitors (BPM's) for the 3.9 GHz system [15].

### FUTURE EFFORTS AND CONCLUSIONS

In the near term there are still significant studies to do to understand and refine the compression conditions that best optimize both SASE and sFlash. There will be a push to understand just what part of the bunch provides SASE and how flat a bunch current pulse can be achieved. Effort will go into reduced charge operation and the tolerances of rf phase and amplitude will doubtless play major roll.

In the long term, XFEL plans to incorporate an eight-cavity 3.9 GHz module in the injector. This module will be provided by INFN. First tests of these cavities are planned for this fall.

In conclusion, the 3.9 GHz module appears to add significant capabilities to FLASH. The collaborative effort has been very successful.

### ACKNOWLEDGMENT

A tremendous number of people at Fermilab, JLab, and ANL have participated in the design, testing and construction of the module. It is impossible to do justice to them here other than to say that they should be proud of

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