ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-TUIAA01

TWENTY YEARS OF CRYOGENIC OPERATION OF THE FLASH SUPERCONDUCTING LINAC

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Abstract

The FLASH superconducting linac is in operation at DESY since more than 20 years. Many changes and upgrades took place to transform a test stand for single cryomodules to a successful free electron laser.

We summarize here the main steps of the FLASH history from the cryogenic point of view including the latest major upgrade that took place in 2022.

We also give an overview of cryomodule performances like cavity gradient and heat load measurements and their evolution over the time.

INTRODUCTION

FLASH [1, 2, 3, 4] is DESY's free-electron laser (FEL) user facility providing ultra-short femtosecond laser pulses in the XUV and soft-X ray wavelength range with unprecedented brilliance. FLASH is a high-gain FEL which achieves laser amplification and saturation within a single pass of a bunch of electrons through a long undulator.

The electron bunches are produced in a laser-driven photoinjector and accelerated by a superconducting linear accelerator. The superconducting techniques allows to accelerate thousands of bunches per second, which is not easily possible with other technologies.

At intermediate energies of 150 and 550 MeV the electron bunches are longitudinally compressed, thereby increasing the peak current from initially 50-80 A to 1- 2 kA, as required for the lasing process in the undulator. The beam is then accelerated to 1.35 GeV, passing through a collimation section to scrape of unwanted beam halo.

The beam then enters the undulators. The FEL radiation is produced by SASE (self-amplified spontaneous emission) process. The electrons interact with the undulator field in such a way, that so-called micro bunches are developed. These micro bunches radiate coherently and produce intense X-ray pulses. Finally, a dipole magnet deflects the electron beam into a dump, while the FEL radiation propagates to the experimental halls.

A SHORT HISTORY OF FLASH

FLASH emerged from the TESLA Test Facility (TTF) [5], an international effort to develop superconducting cavities and increase their deliverable accelerating gradient. In February 2000 for the first time worldwide, lasing has been achieved with a SASE FEL at a VUV wavelength of 109 nm. The facility has been substantially upgraded in 2002/2003 and became FLASH.

The commissioning of FLASH started in 2004 and the first lasing (32 nm) was achieved in January 2005. The FEL user operation started in summer 2005. In 2006, FLASH was operated with electron beam energies up to 700 MeV, providing photon wavelengths down to 13 nm. In 2007, the sixth accelerating module was installed, which increased the electron beam energy to 1 GeV, and decreased the achievable photon wavelength down to 6.5 nm. In 2009/2010, the accelerator has again been significantly upgraded being extended by a seventh accelerating module and by four superconducting cavities operating at 3.9 GHz to linearize the longitudinal electron beam phase space. The new configuration pushes the electron beam energy up to 1.25 GeV allowing lasing at 4.1 nm and thus entering into the water window.

In 2012, the construction of a second undulator beamline, FLASH2 has started and finished early 2014. The long trains of electron bunches of FLASH are split in two - such that one part serves the original FLASH1 beamline, the other part the new FLASH2 beamline, both with the 10 Hz repetition rate of the accelerator. This allows to almost double the test time available for scientific experiments.

During a nine-month shutdown in 2021/22, first part of a major upgrade of the overall facility, the FLASH linac was upgraded by replacing two accelerator modules by modern prototype modules of the type used in the European XFEL. They add features already present in most FLASH modules like double row piezo tuning, modern RF couplers, and a waveguide system optimized for better performance and highest energy gain. The new modules increase the energy gain by 100 MeV. A laser heater system has been set-up to reduce micro-instabilities in the electron beam. The second bunch compressor has now a new C-chicane design with a new matching section. The shutdown was also used for refurbishment work, especially for the cryogenic system.

OVERVIEW OF THE FLASH SUPERCODUCTING LINAC IN 2023

The SC linac consists of one 3.9 GHz cryomodule with four cavities and seven 1.3 GHz modules with eight TESLA type 9-cell cavities each, in red and yellow respectively in Figure 1. The linac is divided in three sections, injector (one accelerating module and the 3.9 GHz module), a first accelerating section with two 1.3 GHz cryomodules and a second section with the remaining 4 cryomodules; bunch compressors are installed between the different linac sections.

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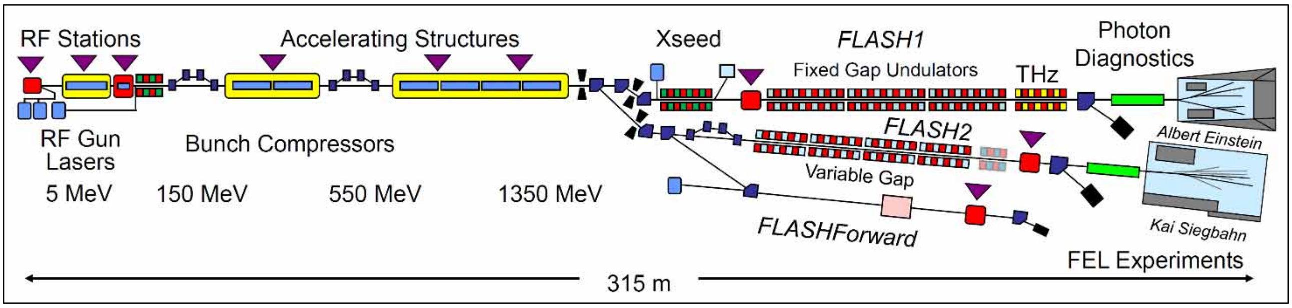

Figure 1: Schematic layout of FLASH in 2023 (not to scale), beam direction from left to right, length 315 m.

Three different generations of TTF cryomodules are installed in the FLASH accelerator: one older version (type II), with a bigger vacuum vessel diameter and the original cavity supporting structure, three type III TTF cryomodules (with, among other changes, a simplified supporting structure and a new 2-phase pipe design) and three XFEL prototype cryomodules (shorter and with minor modifications from the TTF type III ones). Many components are also not standardized among the different cryomodules, for example: type of tuner and piezo system, couplers (mainly TTF III couplers [6], but also one module with only XFEL couplers [7]), type of cavity and quadrupole (gas cooled at 4 K or immersed in liquid helium at 2 K) showing that the FLASH SC linac has been in constant evolution along its whole history.

Cavity Performances

Figure 2 shows the performances of the accelerating cavities once the cryomodules are installed in the FLASH linac.

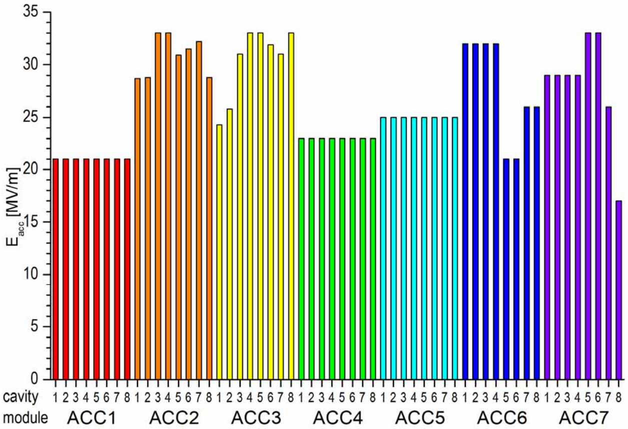

Figure 2: Cavity gradients in the FLASH linac at the end of 2022.

The newest cryomodules (ACC2, ACC3 and ACC7) have a modern waveguide system with so-called magic-T's which allows to adjust the RF power at each cavity, once their expected performances are known. ACC6 use a first prototype of such system.

ACC4 and ACC5 also have new wave guide systems installed during the last shutdown which allow adaptation of the RF power to the cavity properties, but the optimisation is still on going. ACC1 has an old system with less flexibility (the power is split in two, each part powering 4 cavities) but currently operates with the same RF power to all cavities, but has the advantage to have phase shifters for all single cavities – an important adjustment possibility for the first module after the RF-gun.

The average gradient available in the linac is about 84% of the maximum operating gradient measured during vertical tests. No gradient degradation has been observed at FLASH during operation.

CRYOGENIC SUPPLY AND DISTRIBUTION

The superconducting cryomodules are supplied with 4/5 K and 40/80 K helium from the FLASH cryoplant via various transfer lines and a sub-cooler box as shown in Figure 3.

The FEL sub-cooler box supplies helium at different temperature levels not only to the FLASH cryomodules, but also to the CryoModule Test Bench (CMTB, a test bench for one complete cryomodule); two further connections are available at the box, but are at present not in use.

From the FEL sub-cooler a transfer line brings the helium to a distribution box in the tunnel, the so called "Fermi-box". Located in the FLASH tunnel and so called because provided by Fermilab in 1996 for the TESLA Test Facility, the Fermi-box contains the 4 K helium pot and the heat exchanger to sub-cool the 4 K helium that is delivered to the superconducting cavities.

The helium from the cryoplant is split in the Fermi-box between the injector cryomodules and the rest of the linac.

Three Joule-Thomson (JT) valves deliver the 2 K helium to the cavity strings: one JT valve for the two injector modules and two for the other two sections of the linac (respectively with two and four cryomodules). The third JT valve is needed due to the height difference of the 2-phase pipe between the XFEL type cryomodules (now installed at ACC2-ACC3) and the older transfer line that bypasses the second bunch compressor.

Isolation Vacuum

In the FLASH tunnel mechanical pump carts are connected to the isolation vacuum of the Fermi-box as well as the cryomodule groups. The pump carts consist mainly of a turbomolecular and a rotary vane pump as well as valves and passive vacuum gauges. The pump carts are remote

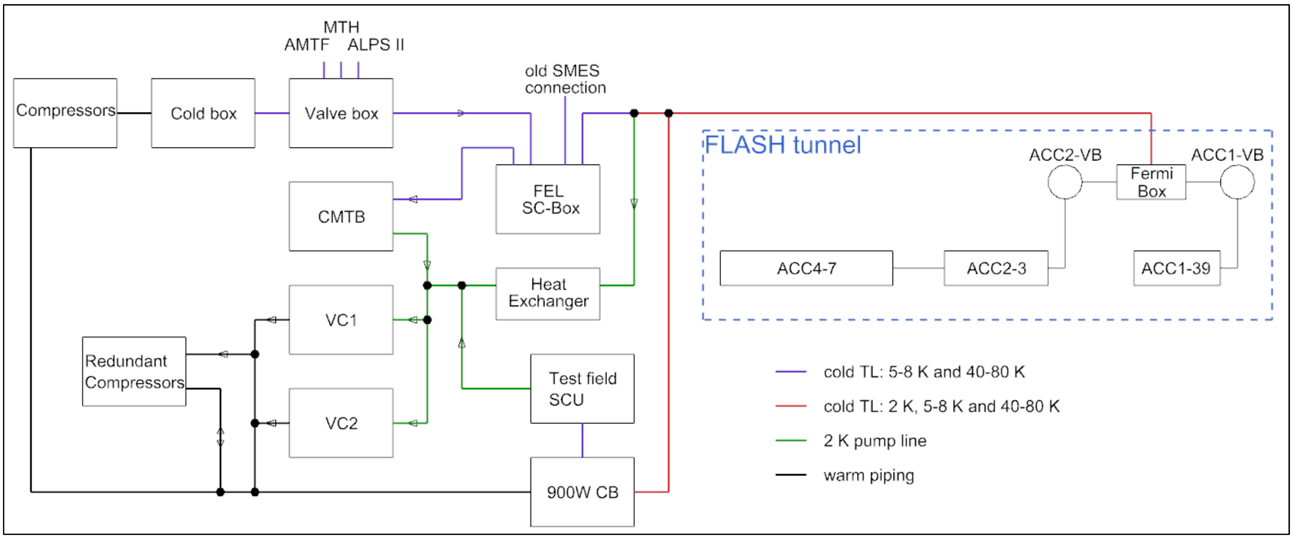

Figure 3: Schematic layout of FLASH cryogenic.

controllable but also operate self-sustaining in case of communication problems. Each module group is equipped with two pump carts for redundancy.

Vacuum barriers in the transfer lines to the Fermi-box, from the Fermi-box to the cryomodules and between the second and third cryomodule group are equipped with bypass lines including a bridge valve. These valves are usually closed but can be opened, depending on the pressure difference between the systems, in case of problems, e.g. failure of the pump cart connected to the Fermi-box.

Active wide range gauges, consisting of a Pirani and cold cathode gauge, are connected to each isolation vacuum system, to monitor the pressure values.

THE FLASH CRYOPLANT

Origin and First Layout

Figure 4 shows the schematic of the FLASH cryoplant, which consists of one former HERA compressor unit and cold box that were operating at DESY to refrigerate the HERA accelerator between 1992 and 2007 [8].

A valve box and a sub-cooler box were installed in 1998 to connect FLASH (at the time still TTF) via the existing HERA distribution box to one of the existing cold boxes and compressor units. The valve box is directly connected to the HERA distribution box and supplies the FLASH sub-cooler box which foresees connections to FLASH and CMTB (CryoModule Test Bench).

Modifications

In 2010 a major modification took place after the shutdown of HERA: two compressor units and cold boxes, shown in Figure 5, were separated from the HERA distribution box and dedicated to the XFEL accelerator. Also, the AMTF (Accelerator Module Test Facility, new test facility with two vertical cryostats and three test benches for an entire XFEL cryomodule built at DESY to allow testing the series cavities and cryomodules for the XFEL accelerator [9]) was connected to the cryoplant in place of the Sud branch of the HERA cryogenic system.

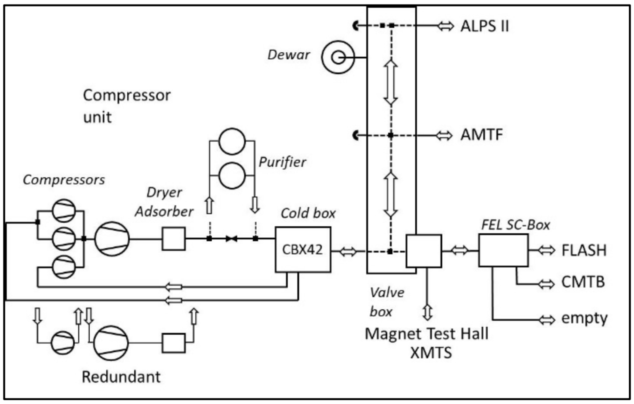

Figure 4: Layout of the FLASH cryoplant.

Figure 5: The cryoplant cold boxes.

Status in 2023

Since 2010 the FLASH cryoplant underwent various maintenance and upgrade interventions and in 2022 one additional user was connected to the cryoplant: the ALPS II [10] experiment is now cold and in operation, using 4 K and 40/80 K helium from the same cryoplant.

Capacity of the Cryoplant

The cryoplant can deliver up to 1000 g/s of helium at 18 bars. The low-pressure compressors have a power of 1.5 MW and the high-pressure ones reach 1.7 MW.

The cryoplant has a cooling power of 20 kW at 40/80 K, of 6.8 kW at 4.4 K and a liquefaction capacity of 20 g/s.

Since spring 2023 the FLASH cryoplant steadily supplies helium at 4 K and 40/80 K to the FLASH accelerator, two vertical cryostats and two horizontal test stands in the AMTF hall, one 1.3 GHz cryomodule at CMTB and 24 superconducting HERA magnets at the ALPS II experiment.

The cryogenic capacity of the cryoplant is reaching its limits and parallel cool down and warm up of different test benches is only possible to a limited extend. An accurate planning and careful operating are required from the cryogenic team to avoid instabilities and losses of helium.

A LINAC IN CONTINOUS EVOLUTION

The design of the FLASH cold accelerator has continuously undergone substantial changes during its history, as shown in Figure 6, on the contrary to many more recent superconducting linacs.

The accelerator started as a test facility for the injector with one single cavity, moved quickly to a complete cryomodule with eight superconducting cavities and is now a linac with a normal conducting RF-gun, one 3.9 GHz cryomodule with four cavities and seven 1.3 GHz modules with eight cavities each. The history of the FLASH accelerator represents the development of the SC RF technology in the first years of the new millennium.

From the TESLA Test Facility to FLASH

The first components of the TESLA Test Facility were assembled in 1996 to allow the cold testing of the injector with a one-cavity cryostat (the so called “capture cavity”, a contribution from Orsay and CEA Saclay). In the following years the test facility was extended at different times to allow the installation of two cryomodules with a bunch compressor in between. Two cryomodules of the first TTF generation were assembled at DESY and installed after the capture cavity cryostat like presented in Figure 6.

In 2003/2004 three further cryomodules and a second bunch compressor were installed. The third generation of TTF cryomodules was successfully tested in the second part of the linac, while the injector area was updated and the test facility became the FLASH FEL user facility in 2005.

FLASH Shutdowns in 2007 and 2009

The FLASH linac underwent a major upgrade in 2007 when an additional cryomodule was installed at the position ACC6, the cryomodule M5 at ACC5 was repaired (tuner motors exchanged) and the cryomodule at position ACC3 was replaced with M7.

A shutdown in 2009 allowed the installation of the seventh 1.3 GHz cryomodule at the end of the linac (position ACC7) and the 3.9 GHz cryomodule at the end of the injector. The 1.3 GHz cryomodule at ACC7 is the first XFEL prototype cryomodule installed at DESY. Thanks to the compatibility with the FLASH modules it was possible to install the XFEL cryomodule in the FLASH accelerator; the module demonstrated very good results and could undergo a long-time test (in 2023 the cryomodule is still in operation) with XFEL-like operating conditions.

Both shutdowns involved also the warm part of the linac, but this is not part of this paper.

At the end of the 2009 shutdown the FLASH accelerator reached the energy required to obtain photon wavelengths down to 4.1 nm and extend the experimental capabilities.

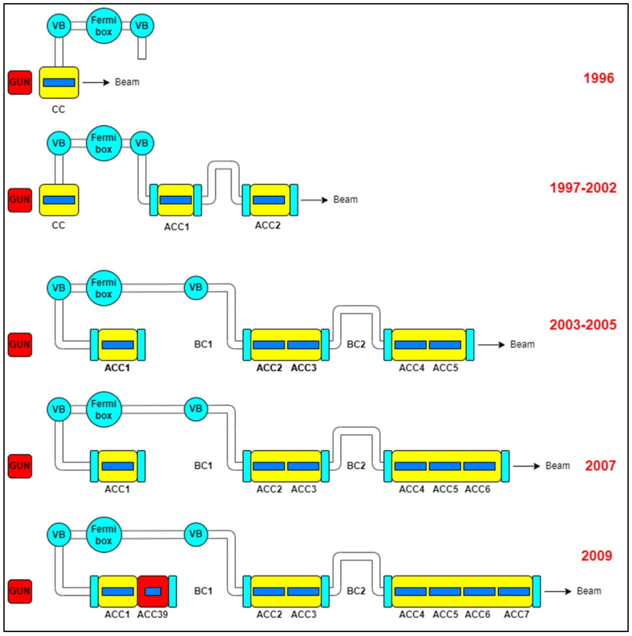

Figure 6: Overview of the TTF and FLASH cold linac layout over time.

THE 2022 SHUTDOWN

Scope of the Shutdown

FLASH underwent a further upgrade in 2022, which involved both the cold and the warm section of the facility [11]. The scope of the shutdown for the cold section was to increase the linac energy by 100 MeV exchanging with newer and better performing cryomodules the ACC2 and ACC3 modules, two old TTF type II cryomodules with not-state-of-the-art cavity performances and components. The decision was taken to refurbish the two remaining XFEL prototype cryomodules and replace some of the cavities to obtain two cryomodules with average gradients above 25 MV/m [12]. New end and feed caps and an additional 2 K JT valve were also needed to adapt the existing cryogenic distribution to the new cryomodule design (smaller vessel diameter, lower 2-phase pipe).

Preparation of PXM2.1 and PXM3.1

The two XFEL prototype cryomodules PXFEL2_1 and PXFEL3_2 where refurbished at DESY between 2020 and 2022 and became the FLASH cryomodules PXM2 and PXM3. The refurbishment required some not standard assembly operation: at PXM2 (then PXM2.1) some piezo and cable problems required special attention, while at PXM3 (then PXM3.1) a challenging operation took place to exchange a cold coupler part with a local clean room after it failed during the cold test at AMTF. Both modules were tested afterward at AMTF demonstrating good performances and where then approved for installation in the FLASH linac.

Challenges of the Shutdown

An official pre-commissioning test with the authority would be requited after the shutdown to restart operation of the pressurized components after substantial modifications. This test would require the complete documentation of the older components (cavities and some piping) which is unfortunately no more available.

Therefore, the decision was taken to operate the superconducting linac, starting at the Fermi-box, at a reduced pressure, i.e. below 0.5 barg (limit of applicability of the European pressure directive) after the shutdown.

The operation of the 40/80 K thermal shield and the 5/8 K circuit with reduced maximum allowable pressure was never done before, therefore a test was performed in 2020 to verify its feasibility (see dedicated paragraph).

A lower maximum allowable pressure requires bigger relief valves which might become a space problem at some of the very small and compact components in the linac (feed and end caps or valve boxes). Therefore, a systematic analysis was performed on the components of the linac and an additional venting test (see dedicated paragraph) was done on a XFEL cryomodule to assess the required amount and dimension of the relief valves.

It was also decided to install a pneumatic loading system to all relief valves to make their opening pressure independent from the back-pressure (typically 0.3 bar) and help reclosing the valves just below the opening pressure in case of opening. The lower maximum allowable pressure drastically reduces the margin between operating pressure of the circuit and opening pressure of the relief valves and requires to significantly reduce the operating pressure after an accident, to allow for the relief valves to close completely.

Preliminary Tests

A first operation test was performed in January 2020 to verify the feasibility of the 0.5 bar operation. The maximum allowable pressure was reduced to 0.5 bar in all circuits, which meant an even lower operating pressure and therefore a small pressure difference along all the cold circuits of the linac.

All cavities where powered during the test to their operating gradients, one vertical cryostat in AMTF was warmed up and CMTB was warmed up and cooled down to verify the stability of the whole system (linac and cryoplant) in operating conditions and during transients.

The test was successful and showed that:

- the pressure of 1.5 bara was reached only in the starting phase of the test in the 40/80 K circuit, when the operating point was still being optimized;
- the pressure could be kept stable and below the maximum allowable value during the RF operation and with transient conditions at the test benches;
- the temperature of the 40/80 K shield and of the couplers increased at the beginning of the test, but quickly reached stable conditions at a higher temperature.

A second test was performed in summer 2020 to simulate a warm up and cool down cycle at lower pressure. The warm up took longer than a regular one with higher pressure due to the very limited pressure gradient along the 4 K circuit of the linac and the transfer lines (no valve was available to separate the linac from the transfer line to the sub-cooler). To mitigate this problem, it was decided to add a valve in the 4 K circuit to separate the transfer line piping (fully certified and operable at higher pressure) from the one of the cryomodules (which required the 0.5 bar operation).

Figure 7: The ACC3 end cap being manufactured at DESY before the 2022 shutdown.

Venting Test of an XFEL Cryomodule

Venting the isolation vacuum is considered the worst-case scenario in case of accident for this type of cryomodules. Therefore, a venting test (opening a pump port of the isolation vacuum) was performed in 2021 on an XFEL cryomodule at the CMTB to evaluate the heat flux to each cryogenic circuit and the effect of a venting accident on a string of cryomodules. The heat intake is a fundamental parameter to size relief valves.

A further consequence of the test was the reduction of the pump ports of the isolation vacuum at the cryomodules from DN100 to DN80.

More information about the venting test and a detailed paper will be published soon.

Main Activities During the Shutdown

The manufacturing and installation of two new end and feed caps, the installation of the ACC2 and ACC3 cryomodules and the modification of two existing caps and valve boxes were performed by the DESY cryogenic group. Figure 7 shows an example of the ACC3 end cap being manufactured at DESY.

The warm piping modifications where subcontracted to an external company under the supervision of the DESY

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-TUIAA01

cryogenic group, to keep the very tight schedule of the shutdown.

The modifications of the cryogenic infrastructure involved many other DESY groups (vacuum, transport, alignment, construction, only to mention some of them) and was performed in parallel to many other shutdown activities, like exchange of wave guides, upgrade of the control system, new cabling and similar.

CRYOGENIC OPERATION

In this chapter we want to summarize different topics related to the cryogenic operation of the FLASH linac. First of all, we focus on the new operating mode (keeping the pressure in the linac below 0.5 bar), moving then to an overview of the heat loads of the linac at different temperature levels and to the pressure stability in the 2 K area.

Finally, we give an overview of the availability of the cryoplant in the last years.

Operation Below 0.5 bar

The operation of the FLASH cold linac with the new pressure limit is more sensitive to disturbances and a faster reaction time is needed to minimize negative consequences (for example helium losses) in case of problems.

The probability of losing helium in case of outages is higher with the lower opening pressure values of the relief valves and the reduced margin between operating pressure and opening of the valves (sometimes less than 100 mbar).

The recovery after an outage takes longer and more caution is needed to avoid opening the relief valves.

The whole system is also more sensitive and more caution is needed during transient operations in parallel systems (AMTF, ALPS II, CMTB).

Nevertheless, the first year of operation with the new pressure configuration was very successful (see for example pressure stability and cryoplant availability in the next paragraphs).

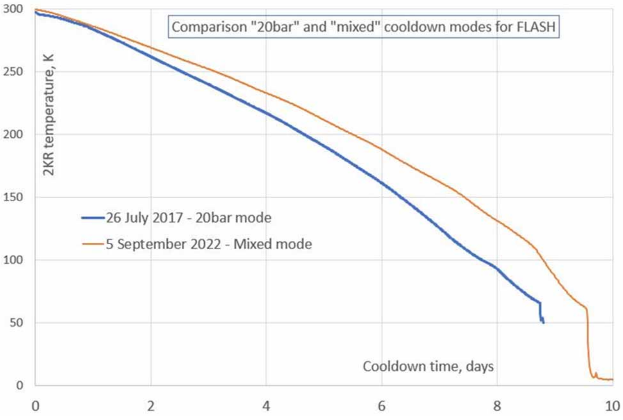

Figure 8: Overview of the cool down in 2022 and comparison with the latest cool down with higher pressure.

The first cool down with the new operating scheme took place in September 2022. The cool down to 4 K took circa 10 days and run smoothly over the whole temperature range. Some settings needed to be adjusted to the new configuration, for example the pressure of the warm gas mixing with the 4 K gas, but the overall operation took place without major issues. Figure 8 shows the comparison of the latest cool down with the previous one, performed at higher pressure levels. It is not clear if the difference of circa one day in the total duration is due to the different operating mode, or to slightly different boundary conditions (among others, the FEL sub-cooler was not pre-cooled in the 2022 cool down, while it was already at 4 K on 2017).

Heat Loads

The static heat loads are calculated for each circuit multiplying the helium flow with the enthalpy difference of the helium at the beginning and at the end of each circuit.

The 4/8 K circuit heat load data are unfortunately not available, since we operate the circuit with saturated helium and we do not know the quality of the fluid in the whole piping system. Depending on the percentage of liquid or gas, we would obtain different heat load values for the same input data.

Tables 1 and 2 show the heat load calculated for the thermal shield circuit at 40/80 K and for the cavity circuit at 2 K for the whole superconducting linac (starting at the Fermi-box). Both circuits include the eight linac cryomodules, three end and three feed caps, two small valve boxes and the transfer lines from the Fermi-box to the linac sections.

Table 1: Static Heat Load at 40/80 K

Time	RF energy (GeV)	P (bar)	Flow (g/s)	Heat load (W)
12/2018	0	11.8	15.4	796
12/2019	0	12.3	24.8	799
12/2020	0	12.8	16.8	888
12/2022	Varying	1.4	6.2	1051
12/2022	0	1.4	4.9	889
02/2023	Varying	1.4	9.5	1122
04/2023	0	1.4	8.9	1111

Table 2: Static Heat Load at 2 K

Time	RF energy (GeV)	P (bar)	Heat load (W)
12/2018	0	1.6	23
12/2019	0	1.6	35
12/2020	0	1.6	26
12/2022	0	1.4	28
04/2023	0	1.4	33

The 2 K heat loads are calculated using the warm flowmeters installed at the pump units VC1 or VC2, which are typically more accurate than cold ones. The enthalpy of the helium at the output of the circuit is a fixed value, corresponding to the enthalpy of helium at 2 K and 31 mbar.

The 2 K heat load values look pretty stable among the years and we can calculate an average value since 2018 of circa 30 W. This value is consistent with typical heat load measurements on single cryomodules and transfer lines.

The 40/80 K heat load values are also consistent over time till we reach the new mode of operation with pressure values below 1.5 bara. Here we can notice that we measure higher heat load values for higher helium mass flows; this might be explained by the measurement inaccuracy of the cold flowmeter and / or the temperature sensors. The value around 1 kW is still a plausible one for a system like the FLASH cold linac.

Pressure Stability

The pressure stability is an important parameter to qualify the cryoplant. Unstable pressure in the 2 K area can cause detuning of the SRF cavities and make the linac operation difficult.

Typical requirements of pressure stability in SC linacs are less than one percent of the pressure value (circa 0.3 mbar in our case). At FLASH we demonstrated an average pressure stability better than ±0.1 mbar over many years. The value was not affected by the change to the 0.5 bar operation, as can be seen in Figure 9.

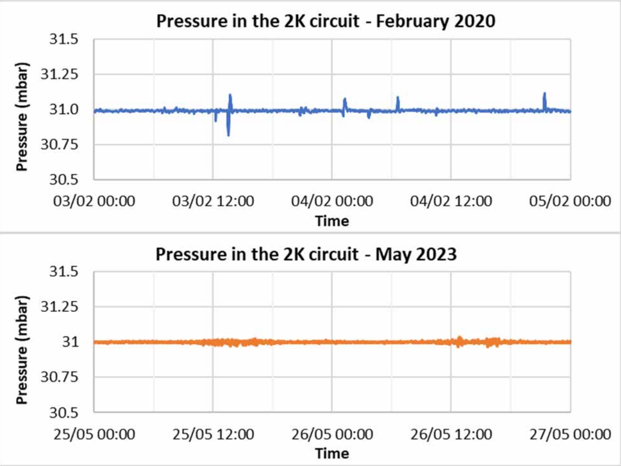

Figure 9: Typical pressure stability in the 2 K circuit before (up) and after (down) the 2022 shutdown.

Cryoplant Availability

The availability of the cryoplant is another key parameter for this type of infrastructure, having a direct impact on the accelerator uptime.

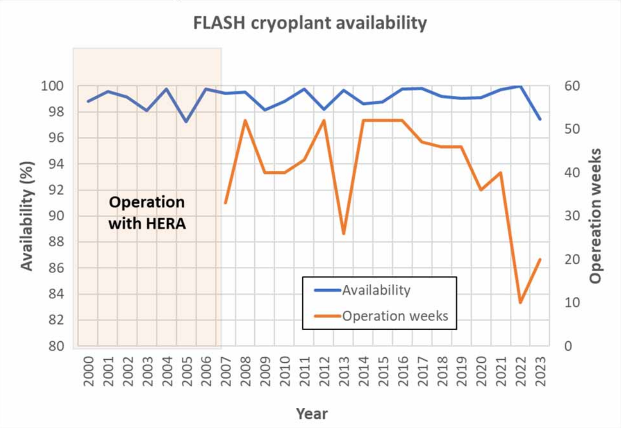

Figure 10: Availability (blue) and operating hours (orange) of the cryoplant.

The FLASH cryoplant demonstrated an average availability of more than 99% over more than 20 years of operation. Figure 10 shows the availability and the operating hours of the cryoplant since the year 2000. Typical sources of cryoplant failures are power outages, problems at the cooling water and faults at the compressor units.

SUMMARY

We presented here an overview of the cryogenic supply and distribution of the FLASH superconducting linac and a brief summary of its evolution in the last 20 years.

We also gave an overview of the activities of the cryogenic group during the latest shutdown of FLASH in 2022 which allowed an increase of the energy gain of 100 MeV.

Finally, we presented some relevant aspects related to the cryogenic operation of such a facility, like pressure stability, heat loads and availability of the cryoplant.

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