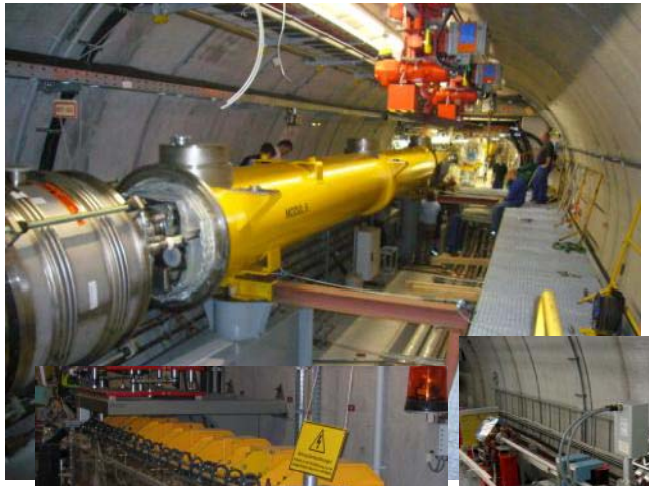
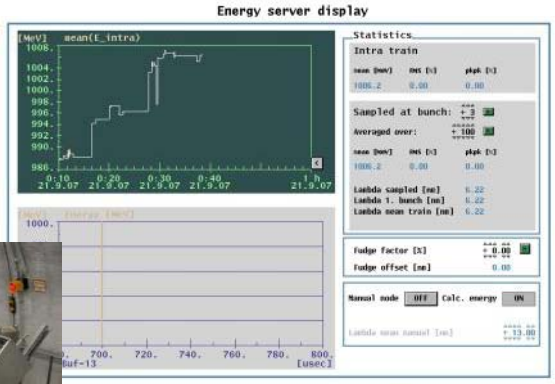
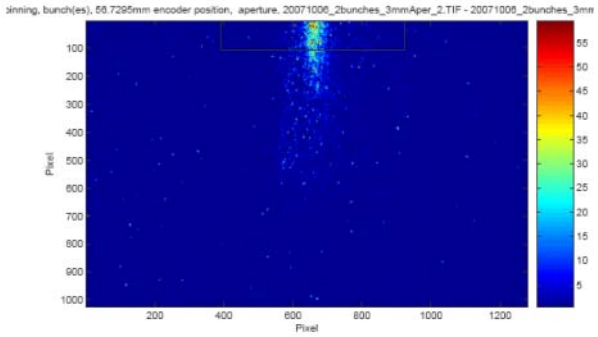
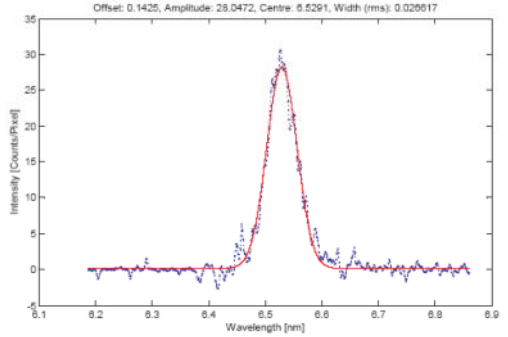
FLASH shutdown and commissioning 2007

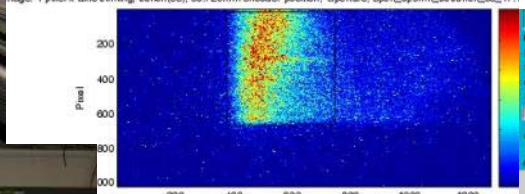
Katja Honkavaara

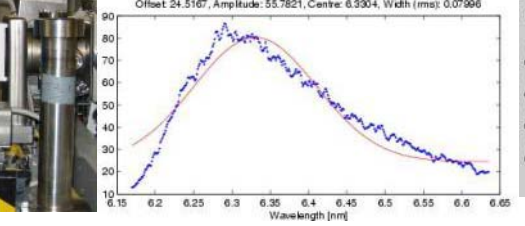


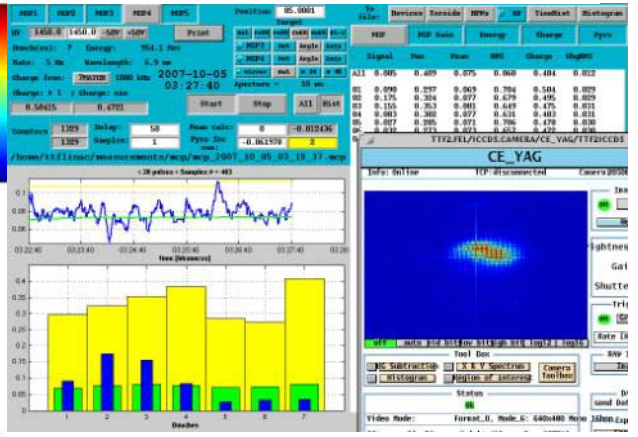












Design goals reached

FLASH
Free-Electron Laser
in Hamburg

DESY TELEGRAMM 21. September 2007

Design-Strahlenergie für FLASH erreicht!

Elektronenstrahl mit 6 Modulen erstmals auf 1 GeV beschleunigt

FLASH Reaches Design Beam Energy!

Electron beam accelerated to 1 GeV with 6 modules for the first time

Der Durchbruch passierte wieder in einer Nachtschicht, genauer am 21.9.2007, um 0:57 Uhr. Dieses Mal ging es um das Erreichen der geplanten maximalen Strahlenergie. „Ziel: Betrieb mit höchster Energie – Ergebnis: 1 GeV Energie !! Gemessenes Spektrum der spontanen Emission: ~ 6,3 nm", so der Eintrag im elektronischen Logbuch.

Während der letzten Wartungspause: Einbau des Beschleunigermoduls Nr. 6 in den FLASH-Tunnel.
During the last shutdown: installation of accelerator module no. 6 in the FLASH tunnel.

As usual, the breakthrough was achieved during a night shift, to be precise: on September 21 at 0:57 a.m. This time, the aim was to reach the planned maximum beam energy. "Goal: Operation to maximum energy—Achievements: 1 GeV!! Spectrum of spontaneous emission measured: ~ 6.3 nm," reads the entry in the electronic logbook.

Das Team im Kontrollraum beobachtete im Wellenlängenspektrum der im FLASH-Undulator spontan erzeugten Strahlung zum ersten Mal eine Überhöhung im Bereich von 6 Nanometern. Damit ist der Nachweis erbracht, dass alle sechs Beschleunigermodule – eins wurde in der vergangenen Wartungspause neu installiert, ein zweites ausgetauscht – funktionieren und die Elektronenpakete wie geplant auf eine Energie von 1 Giga-Elektronen-

For the first time, the team in the control room observed a peak around 6 nanometers in the wavelength spectrum of the spontaneous radiation generated in the FLASH undulator. This is the proof that all six accelerator modules—one of which was newly installed during the previous shutdown, a second one replaced—are working as planned and accelerating the electron bunches to an energy of 1 gigaelectronvolt (GeV). The measurement of

DESY TELEGRAMM 8. Oktober 2007

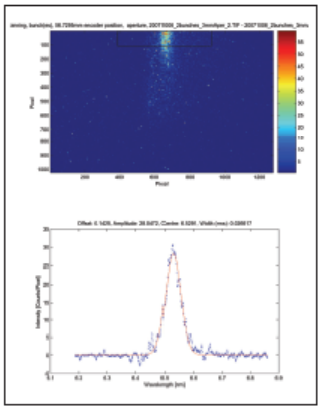
Wellenlängen-Weltrekord bei FLASH: 6,5 Nanometer!

Geplanter Designwert für die Laserblitze erzielt

Wavelength World Record at FLASH: 6.5 Nanometers!

Design value for laser flashes reached

Zwei Wochen nach dem Erreichen der maximalen Strahlenergie von 1 Giga-elektronenvolt kam aus dem Kontrollraum die Meldung: „Am 4. Oktober haben wir in den Abendstunden zum ersten Mal bei FLASH das Lasen bei einer Wellenlängen von 7 Nanometern (nm) beobachtet." Schon 24 Stunden später gelang es dem FLASH-Team, den für die Anlage geplanten Designwert von 6,5 nm zu erzielen. Die in den sechs supraleitenden Modulen auf eine Energie von 986 Megaelektronenvolt beschleunigten Elektronenpakete zeigten bei ihrem Flug durch den Undulator nun auch bei dieser hohen Energie das gewünschte Verhalten: Ihre spontan



Plot und Zahlen für Experten:
Das Wellenlängenspektrum bei 6,5 nm. Zahl der Bunche: 2 - Apertur: 3 mm - Wellenlänge: 6,523 nm - Bandbreite: 0,0266 nm (rms)
Plot and numbers for experts:
the wavelength spectrum at 6.5 nm. Number of bunches: 2 - aperture: 3 mm - wavelength: 6.523 nm - bandwidth: 0.0266 nm (rms)

Two weeks after the maximum beam energy of 1 gigaelectronvolt was reached, the control room announced another milestone: "On the evening of October 4, we observed lasing at a wavelength of 7 nanometers (nm) at FLASH for the first time." Only 24 hours later, the FLASH team achieved the facility's design value of 6.5 nm. In FLASH, the electrons are accelerated to an energy of 986 megaelectronvolts in six superconducting modules. On their flight through the undulator, the electrons now demonstrated the desired behavior also at this high energy: the spontaneous radiation they emit amplified itself to form the desired free-electron laser radiation pulses (SASE-FEL).

Upgrade and commissioning of FLASH successful
thanks to hard work by the whole TTF/FLASH team

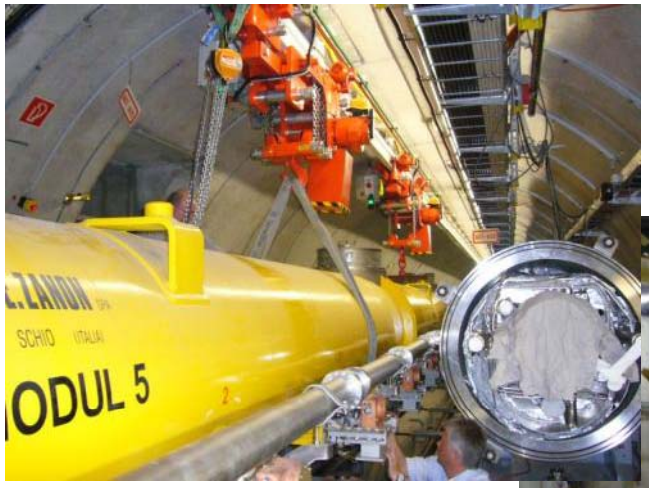
Shutdown April – June 2007

FLASH
Free-Electron Laser in Hamburg

- Shutdown started, as scheduled, March-26, 7 am
- Main hardware work
  - **Modules**
    - replacement of Module 3* by Module 7
    - repair of tuners of Module 5
    - install new Module 6 (including cabling and waveguides)
  - RF-stations
    - preparation of Kly / Mod 4 + waveguide distribution for operation of three modules by one RF-station (+LLRF)
    - pulsed power cables tests of Kly 5 in 'Anbau' and modulator in Hall 2
  - New design for the gun section
    - RF gun moved 30 cm downstream
  - Installation of optical replica synthesizer
  - Installation of IR undulator and beam line
  - Replacement of 4 OTR stations by OTR+WS stations
  - Change of D7ECOL dipole vacuum chamber
  - Installation of BPM to BC3 dispersive section
  - SR radiation port and THz diagnostics (BC3)
  - Photon diagnostics: New MCP detector
  - Second injector laser

Module transports

- Warm up: March-26 – April-2 (one week)
- Module 5 disconnected and transported (Apr-20) to the tuner repair
- Module 3* disconnected and transported out of the tunnel (May-11)
- Module 7 transported into the tunnel (May-15) → ACC3
- Module 6 transported into the tunnel (May-22)
- Repaired Module 5 transported into the tunnel (July-12)

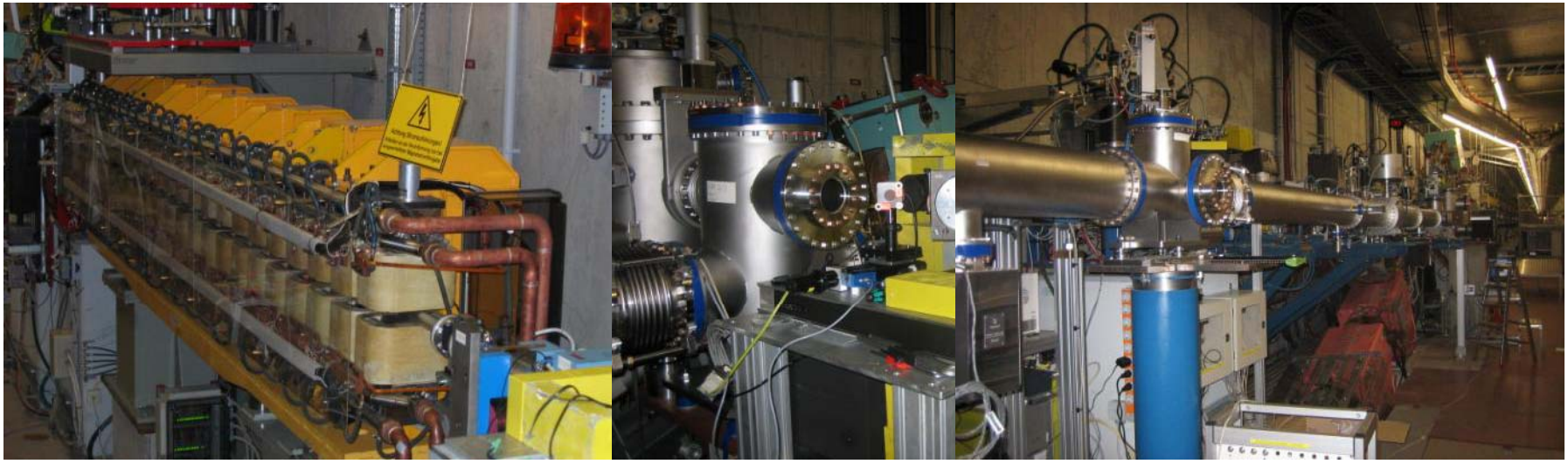


GUN section

- New design for the GUN section between RF gun and ACC1
  - new diagnostic cross (wakefields reduced, Teflon washers removed)
  - easier alignment of elements
  - RF gun on rails (similar to cathode system)
  - RF gun moved upstream by 30 cm
    → increased efficiency of the dark current collimator
    - place for a dark current kicker reserved (not yet installed)
  - work on the laser beamline
  - improved diagnostics
    - new camera set-ups: 2GUN and 3GUN with two optical magnifications, improved set-up of IDUMP
    - new camera (PCO) for on-line laser diagnostics

Infra-red undulator and beam line

- Infra-red undulator
  - IR undulator installed in the beam line between the last undulator module and the dump dipole
  - Motivation: pump and probe experiments, electron beam diagnostics
- Infra-red beam line
  - Beam-line, including diagnostics devices, installed to transport IR radiation to the experimental hall



First commissioning results → FLASH seminar 30.10.2007 (O.Grimm and M.Gensch)

Optical replica synthesizer

- Installed in the section between the collimator and the undulator
- Motivation: measurement of longitudinal bunch profile with fs resolution
- Optical Replica set-up consists of
  - seed laser (outside tunnel in the new laser hut) and a laser beam line
  - two undulators + a chicane of four steerers
  - grenouille/FROG to translate electron bunch shape into optical pulse
  - diagnostics: two OTR stations + optical set-ups on optical tables

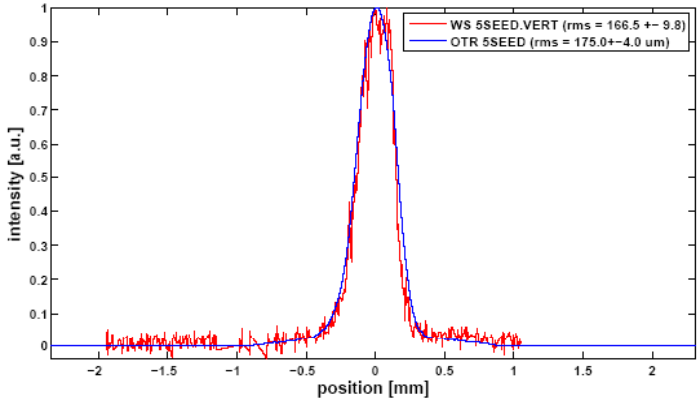
Vertical undulator VERONICA

Horizontal undulator HILDA

First commissioning results → FLASH seminar 20.11.2007 (V.Ziemann and G.Angelova)

WS+OTR Monitors

- 4 OTR monitors in the section between collimator and undulator replaced by OTR+WS monitors
  - motivation: non-destructive beam profile and emittance measurements in SEED section complementary to OTR measurements
  - wire scanners old devices from other accelerators at DESY
  - set-ups similar as in the DBC2 section
- Optical set-ups of OTR monitors re-aligned
- Commissioning of WS on-going
- First comparison measurement between OTR and WS profiles shows a good agreement



Commissioning July – August 2007

- Shutdown finished and the tunnel closed, as scheduled, Monday July-2, 2007
- Status in the beginning of July
  - most of the (large) installation work finished
  - vacuum + cryo work on the modules in the tunnel still on-going
  - module 5 not yet mounted into the tunnel
- Commissioning tasks
  - RF gun and GUN section
  - magnets
  - **accelerator modules** including RF and LLRF
  - establish stable electron beam operation through the linac before scheduled accelerator studies
  - establish lasing
  - reach design goals: 1 GeV beam energy and 6.5 nm lasing

RF-gun start-up

- During the shutdown: RF gun vented, mounted onto the rails, and moved 30 cm downstream
- Hardware installations in the GUN section finished in time
  → vacuum closed and pumped down by the end of June
- First RF to the gun in Monday July 2 (as scheduled)
- RF-conditioning smooth in the following two weeks (KW 27-28)
  - conditioning mainly during nights and weekends
- RF-gun conditioned up to 3.4 MW / 900 us
- First photo-electrons: July 6
  - after that conditioning and a work on the laser beam line continued
- Standard electron beam operation: July 23 →
- New laser system not ready in time → old laser used
  - problem: new timer modules introduced after the laser (successfully) installed
  - second laser and laser beam line need still to be commissioned

Commissioning of GUN section

- Diagnostics commissioned in July: camera set-ups, steerers, BPMs
- Beam based alignment of the RF gun
  - alignment of the laser beam on the cathode
  - several shifts scheduled for solenoid BBA in KW 31
    - due to a broken solenoid mover, could not be performed as planned
    - repair of the mover required several trials, including a change of the hardware (electronics) and help from experts (Zeuthen)
    - a system to measure the solenoid position is planned for the future
  - solenoid movers in operation (hardware + software) in Aug-10
    → solenoid BBA during a few shifts in the end of KW 32
    - due to the delay, experts and time not available for BBA as planned
  - alignment of laser on the cathode repeated in September
- Commissioning of the dark current collimator (September)
  - first results: collimator cuts remarkably the dark current
    - but: several corrections of the collimator position (horizontal and vertical) has been required to allow beam transport through the collimator with only small corrections by the gun section steerers

Results of recent Gun studies → FLASH seminar 06.11.2007 (J.-H.Han)

Commissioning of magnets

- 22 magnet power supplies exchanged during the shutdown → reduction of noise
  - mostly replacing chopper power supplies by Heidbrook supplies
- 10 complete working days in a block was requested by MKK for magnet tests
  - MST-test, interlock test, cable-magnet assignment, polarity checks, control adjustments
- Magnet commissioning suffered from the (delayed) work in the tunnel
  → requires 'Magnetstromfreigabe' → in conflict to work with an open tunnel
  → magnet tests shifted several times, and divided to several blocks
  → due to the reduced time: only the exchanged PS tested
- Magnet polarities checked with a hall probe in the tunnel
  - Polarity of a few (3-4) quadrupoles wrong → corrected
- Cold magnets of the new module 6 commissioned after the cool down
- Polarity of cold magnets, and those warm magnets not reachable with a hall probe: checked with beam
  - Polarity of Q9ACC5 and Q9ACC6 wrong → corrected
- Software, e.g. cycling procedure, updated to include the new/exchanged magnets and power supplies

Work on modules during July

- Status in July-2
  - all modules, expect Module 5, installed in the tunnel
  - cabling and waveguide installations of ACC6 on-going
- Module 5 finally installed end of KW 28 (July 12-13)
  - Conflict: Tunnel open during daytime to prepare module installation in several days in KW 27-28
    → scheduled magnet tests (MKK) shifted several times
    → scheduled reflected power tests (MHF-p) re-scheduled to August
- KW 29: Tunnel open, as scheduled, during daytime to complete hardware work on the modules: cryo and vacuum installations, waveguides, cabling, technical interlocks, rf-cable calibration
  - work could not be finished in KW 29 → KW 30 tunnel still open (daytime)
    → conflict with magnet tests
    → conflict with scheduled beam studies in the gun section (done during nights)

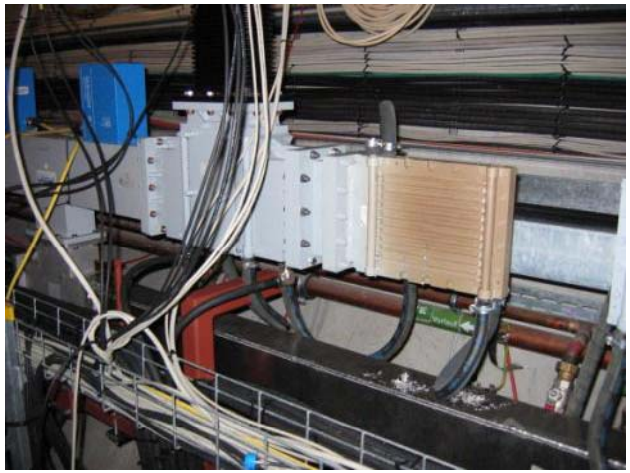
Hardware work on modules finished in Friday July-27
→ Ready for RF (warm coupler conditioning)

Warm coupler conditioning

- Couplers of the new modules (Module 6 and 7) conditioned at CMTS
  → warm coupler conditioning time in the linac much reduced
- Scheduled: short conditioning period before the cool down
  - to check that couplers are OK after the module transport
  - could be done only when the module hardware work finished in the tunnel
    → KW 31
- Conditioning of ACC4/5/6: Aug-1 to Aug-2 by MHF-SL (~ 30 hours)
  - Problem: See next slide
- Conditioning of ACC2/3: Aug-3 to Aug-6 by MHF-SL (~ 55 hours)
  - klystron 5 in Anbau and modulator in hall 2 (pulsed power cable)
    → personnel interlock test required (Aug-3 morning)
- Conditioning of ACC1: Aug-3 to Aug-5 by FLASH operators
  - nothing modified during the shutdown → conditioning 'by hand'

Over-heated circulator absorber

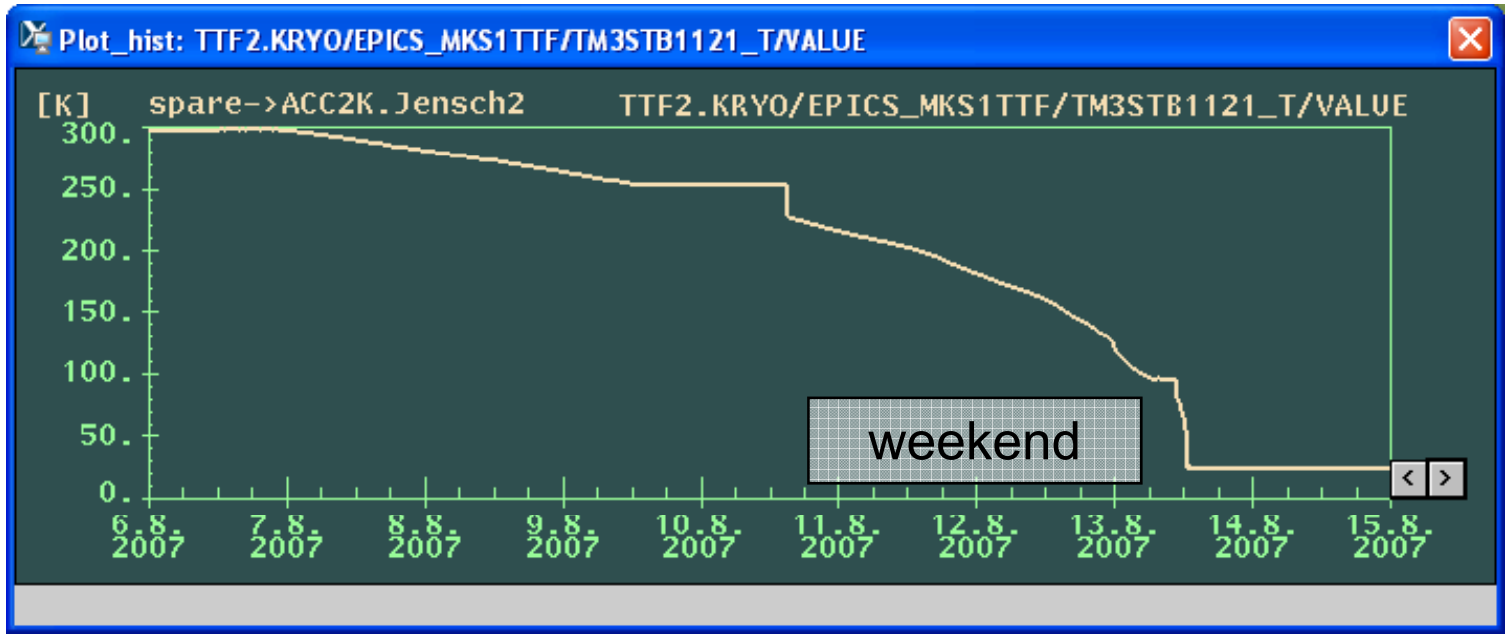
- ZZ in Aug-3 morning (for an other purpose): we found out that RF load (absorber) of ACC6 cavity 2 circulator has been over-heated
  - has happened during the coupler conditioning of ACC4/5/6
- Reason: Water cooling of ACC6 absorber was not running (valve closed); the lack of cooling was not detected by the technical interlock system, because the water interlock cable of the new module 6 was bridged
  → No interlock signal to the interlock box



- Absorber of ACC6/C2 circulator exchanged (Aug-3)
- Before continuing of the RF operation: water cooling and functionality of water interlocks of all the modules repaired and checked (Aug-3)

Module cool down

- Cool down started in Monday, Aug-6 at 3 pm
- Modules at 2 K in Tuesday, Aug-14 at 1 am
- Cool down: ~ 180 hours
  - almost factor of two longer than during the cool down in March 2004 (~ 100 hours)



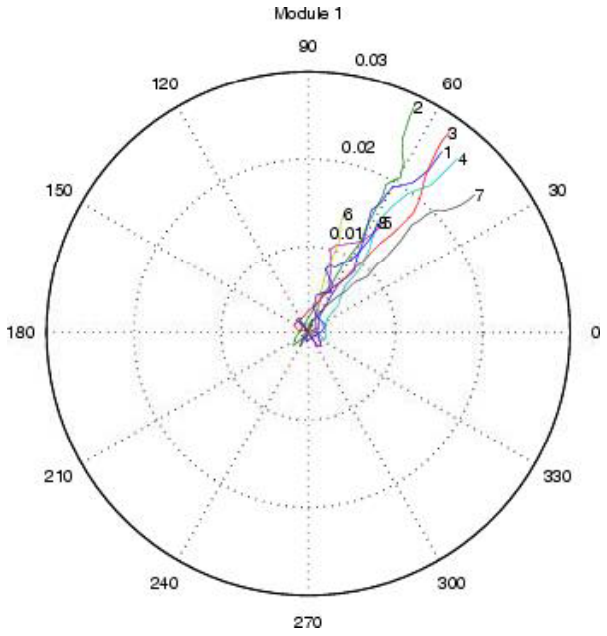
Cavity tuning

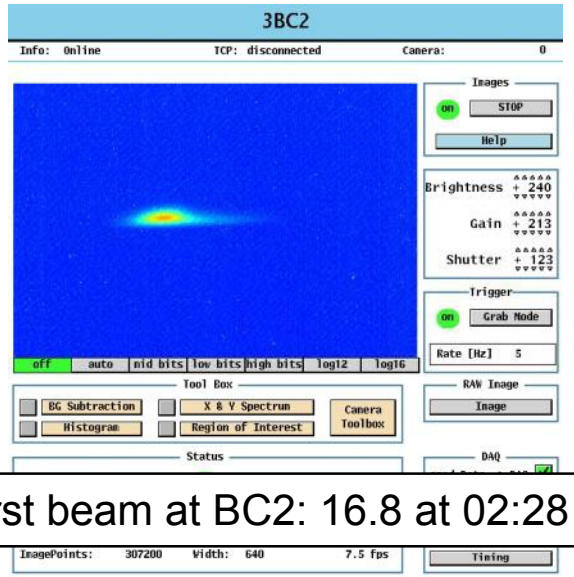
- Started: Tuesday Aug-14 morning (as soon as modules were cold)
- Frequency measurement of each cavity with a network-analyzer in the tunnel (except M6 which has cables out of the tunnel)
  → cavity tuning to resonance (1.3 GHz) and loaded Q-adjustment (Q=3E6)
- ACC1, ACC2, ACC3: Aug-14 and Aug-15 (daytime)
  - ACC1: C6 and C7 problem with tuner motors
    - C6 problem solved
    - motor of C7 has a short to ground inside the cryo module, and has to be driven by a potential free motor control
- ACC6: Aug-16 (daytime)
- ACC4 and ACC5: Friday Aug-17 until 9 pm
  - ACC5: Motors of C2,3,4,6,7 could not be started with their motor drivers
    - a special driver required to pulse for a short time a higher than usual current to give the motors an initial kick; after this, in all cases, the motors could be moved with their normal drivers to resonance
- Total time required for module hardware installations, cool down, conditioning, and cavity tuning underestimated
- Substantial amount of time saved by interleaving frequency tuning with RF and beam operation (phase adjustment, beam studies)

ACC1

- RF to ACC1: Aug-15 afternoon
  - first electron beam through BC2 only a few hours later
- Final LLRF adjustments of ACC1 in Aug-16 afternoon
  - fine tuning of cavities, adjustments of probe signal levels, measurements of loaded Q, cavity phase measurements with beam

ACC1 ready for standard beam operation: Thursday Aug-16 evening





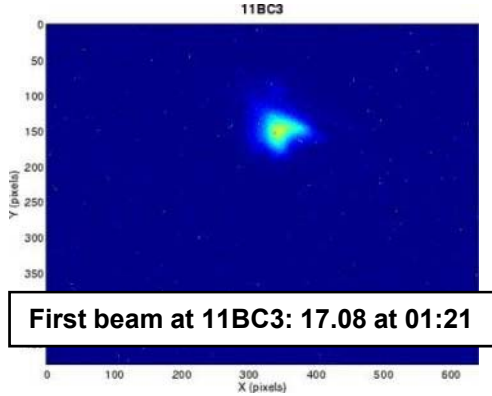
First beam at BC2: 16.8 at 02:28

Cold conditioning of ACC2/3

- Frequency measurements + cavity tuning of ACC2 and ACC3 finished Aug-15 afternoon
  → cold conditioning (15 hours)
  → LLRF and phase adjustments started Aug-16 evening (next slide)
- Measurement of power distribution between ACC2 and ACC3 (Aug-20)
  → discrepancy between the measured power and the probe signal
  → wrong calibration of the probe ACC3.C1 by factor of 2
  → ACC3 conditioned only up to 130 kW (probe used as a reference)
- Cold conditioning continued Aug 26-27 (28 hours)
- Conditioned up to the pulse length of 500 us (rise time) + 800 us (flat top) with the power level of **ACC2.C5: 102 kW**
  ACC3.C1: 210 kW

ACC2/3 phase and LLRF adjustments

- RF to ACC2 and ACC3: Aug-16 evening
  → measurement the phase between ACC2 and ACC3
  → ~ 90 deg phase difference between the modules
  → change of the waveguide length (in the tunnel) required
- Waveguide length changed (Aug-17 morning)
  → phases re-measured with the beam in the afternoon
  → difference ~ 180 deg: Correction to wrong direction!
- Waveguides re-corrected (Aug-18 morning)
  → phase measured in the evening → OK
- LLRF adjustments (phases of individual cavities, signal levels, loaded Qs) followed during the night

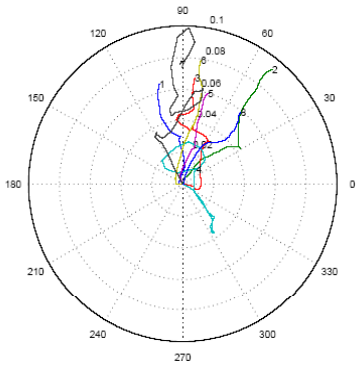


First beam at 11BC3: 17.08 at 01:21

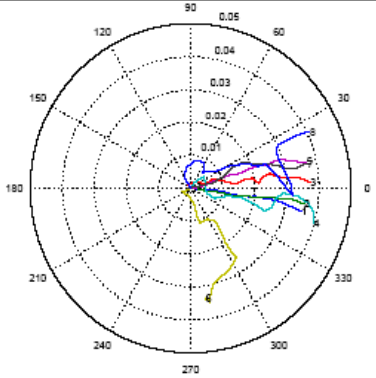
ACC2/3 ready for standard beam operation in Sunday Aug-19 morning
with full gradient after conditioning: Monday Aug-27

Phase adjustment ACC2/3

Initial situation: ~ 90 deg phase difference

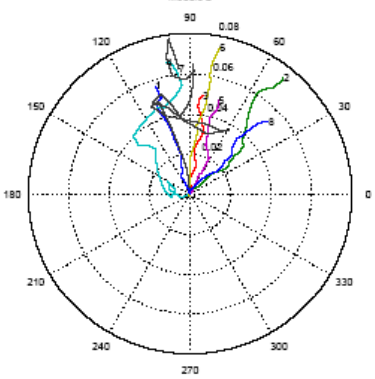


ACC2

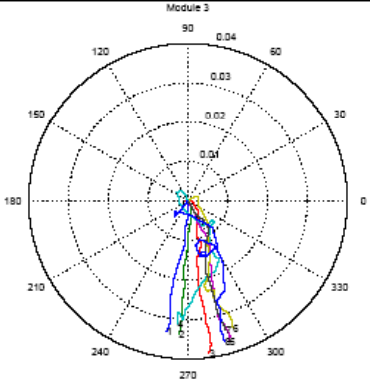


ACC3

After 1st iteration: ~ 180 deg phase difference

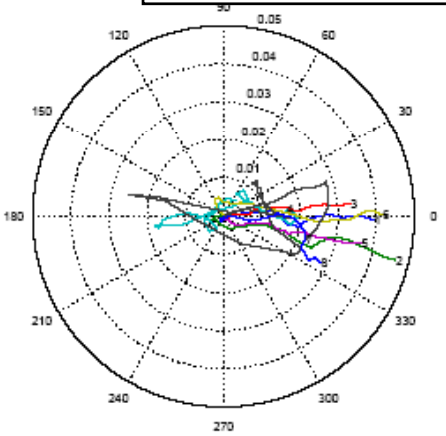


ACC2

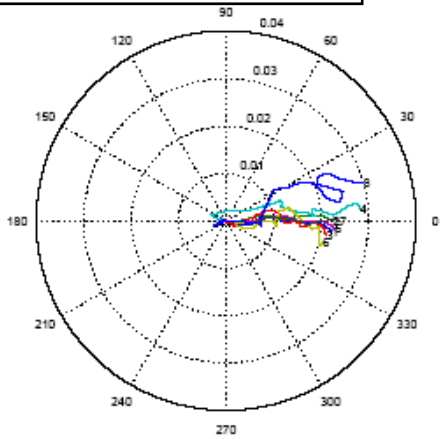


ACC3

After 2nd iteration and LLRF adjustments

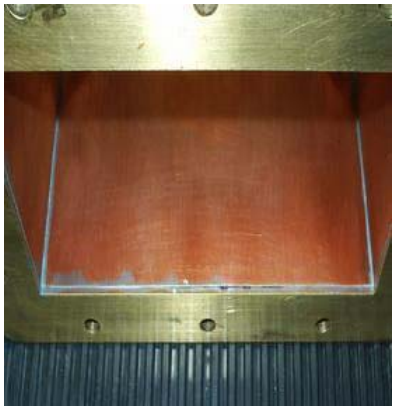


ACC2



ACC3

Cold conditioning ACC4/5/6



- Frequency measurement + cavity tuning of ACC4, ACC5, and ACC6 finished Aug-17 evening
  → cold conditioning until Aug-19 afternoon
  → conditioning stopped due to spark at C7 of ACC6
- Problem with the coupler C7 investigated in Aug-20
  → coupler waveguide disassembled: a broken solder connection between the waveguide flange and the body
  → coupler waveguide exchanged
- Cold conditioning of ACC4/5/6 continued in KW 34, when ever possible; completed parallel to ACC2/3 conditioning in Aug 26-27
- Total cold conditioning time of ACC4/5/6: ~ 76 hours
- Conditioned up to the pulse length of 500 us (rise time) + 800 us (flat top) with the power level of **ACC4.C1: 171 kW**
  ACC5.C2: 157 kW
  ACC6.C1: 357 kW

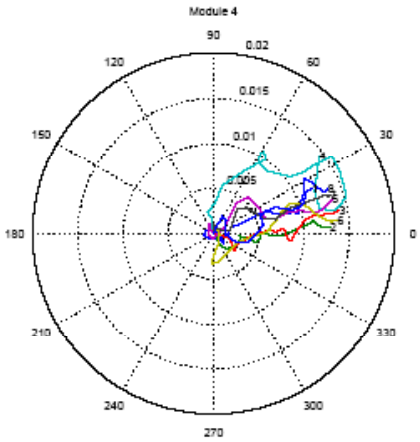
ACC4/5/6 phase and LLRF adjustments

- RF to ACC4, ACC5, and ACC6: Aug-20 evening
  → measurement of the phase between the modules
  → 120-150 deg difference between ACC4 and ACC5, phase of ACC4 and ACC6 almost equal
- Waveguide distribution (in the tunnel) corrected in Aug-21 morning
  → phases re-measured in the evening
  → phase difference between ACC4 and ACC5 ~ -130 deg; between ACC5 and ACC6 ~ +100 deg
- Waveguide distribution re-corrected in Aug-22 morning
  → phases re-measured in the evening
  → ~ 60 deg difference between ACC4 and ACC5/6; phase of ACC5 and ACC6 almost equal
- WG distribution corrected 3rd time in Aug-23 morning
  → phases measured in the afternoon
  → finally OK!
- Parallel to phase measurements: adjustments of phases of single cavities, signal levels, and loaded Qs

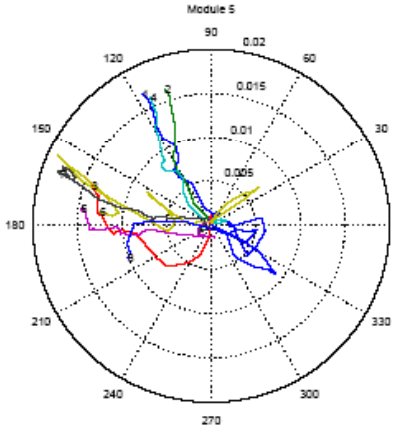
ACC4/5/6 ready for standard beam operation in Thursday Aug-23 midnight
with full gradient after conditioning: Monday Aug-27

Phase adjustment ACC4/5/6

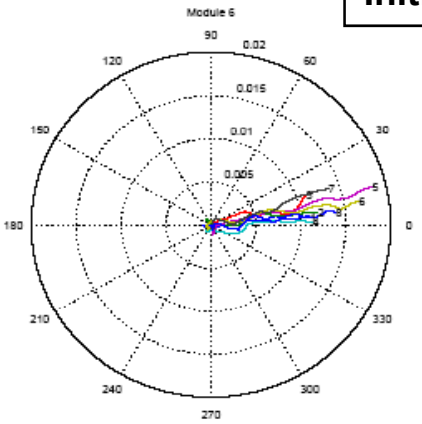
Initial situation



ACC4

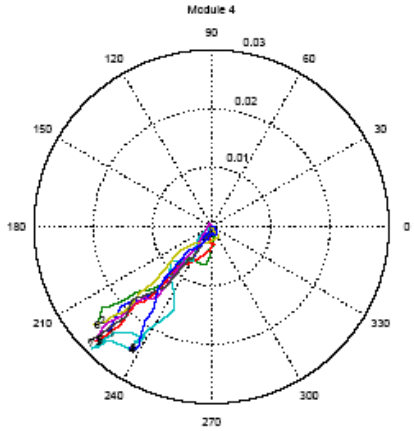


ACC5

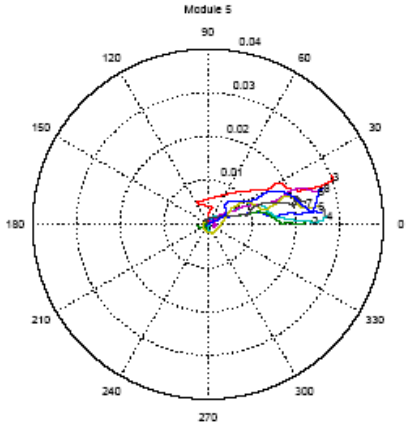


ACC6

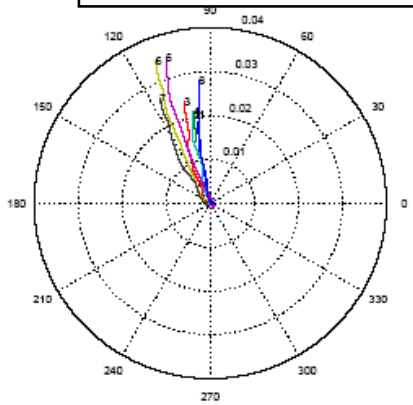
After first iteration



ACC4



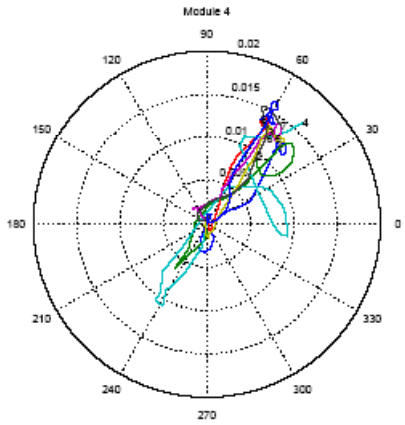
ACC5



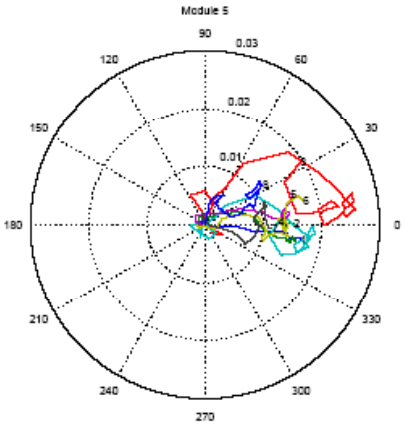
ACC6

Phase adjustment ACC4/5/6

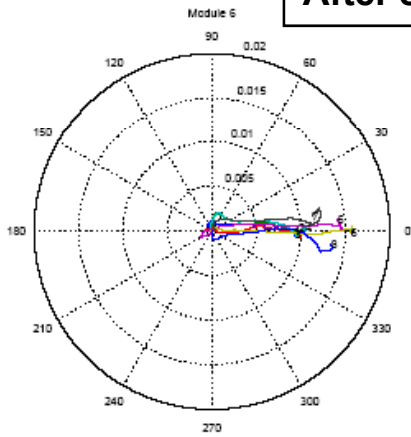
After second iteration



ACC4

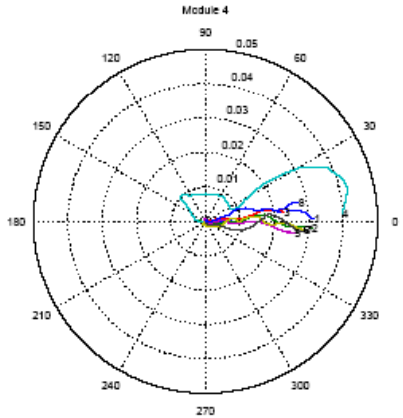


ACC5

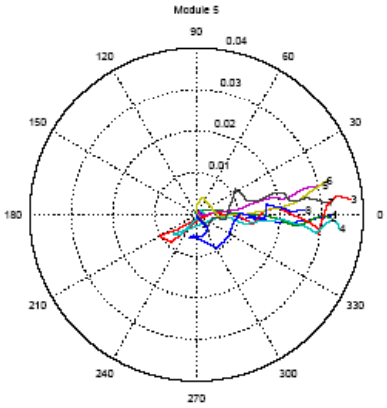


ACC6

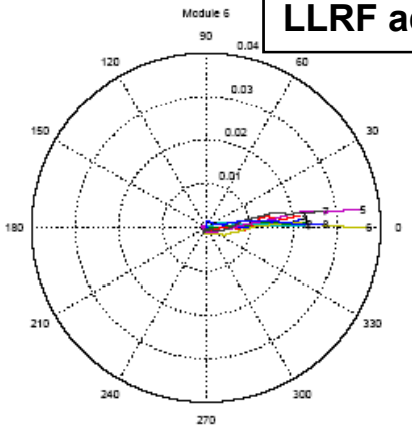
After third iteration and LLRF adjustments



ACC4



ACC5

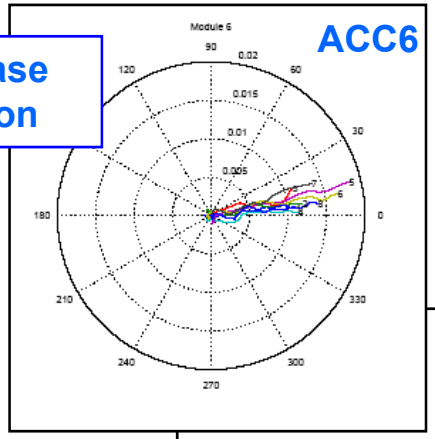


ACC6

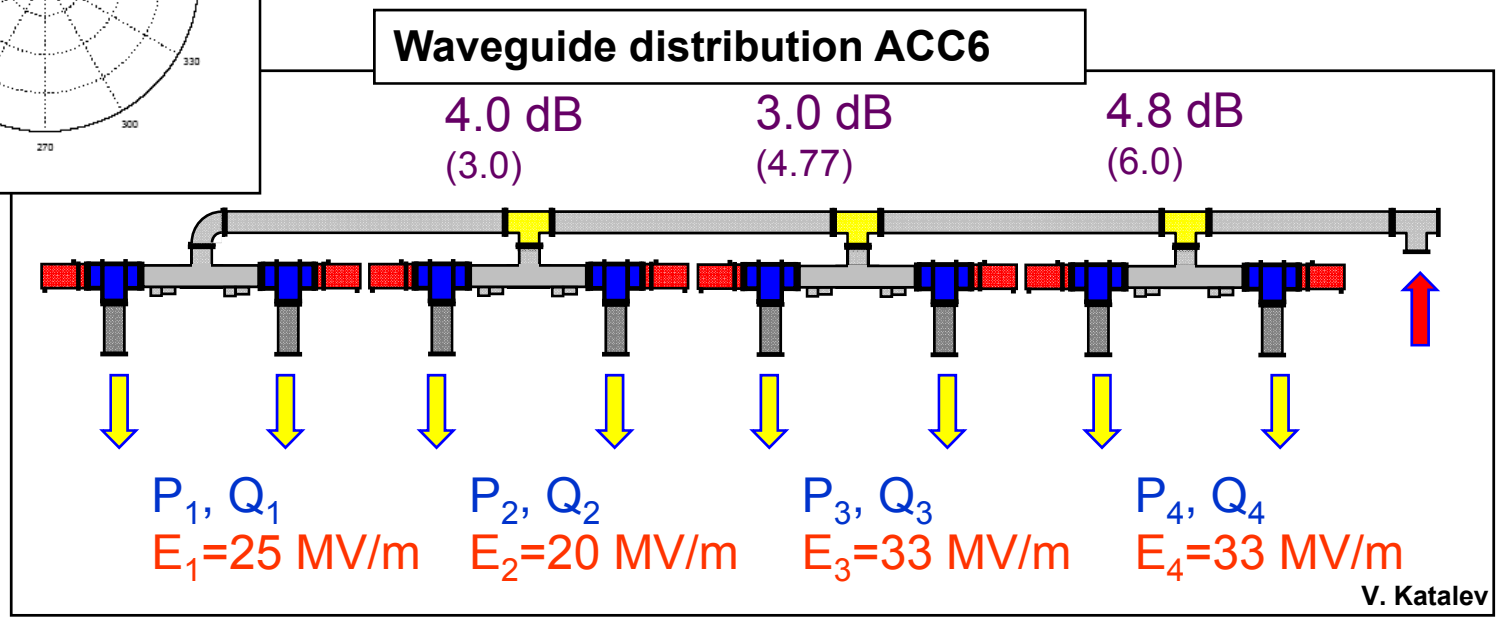
New waveguide distribution ACC6

- A new waveguide distribution system used for ACC6
  → foreseen for XFEL
- System pre-adjusted in Hall 2
- Power distribution and phase distribution for the individual cavities almost perfect

Initial phase distribution



Waveguide distribution ACC6

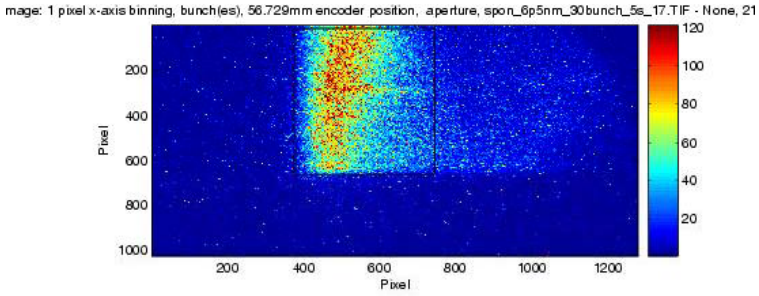


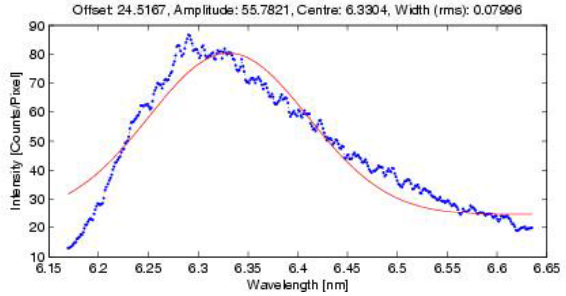
Electron beam operation

- First beam at BC2: Aug-16 at 02:30 am
  - only a few hours after the first RF to ACC1
- First beam at BC3: Aug-17 at 01:20 am
  - only a few hours after first RF to ACC2 and ACC3
- First beam to dump via by-pass (~750 MeV): Aug- 22 at 23:50 through undulator (50% transmission): Aug-23 at 06:30 am
  - adjustments of ACC4/5/6 phase and LLRF settings were still on-going
- 800 MeV through undulator (full transmission): Aug-24 at 05:20 am
  - only few hours after the final LLRF adjustments of module ACC4/5/6
- Beam operation through the linac established just in time for the scheduled accelerator studies (Aug-27 →)
  - **Collaborators could performed their studies as scheduled**

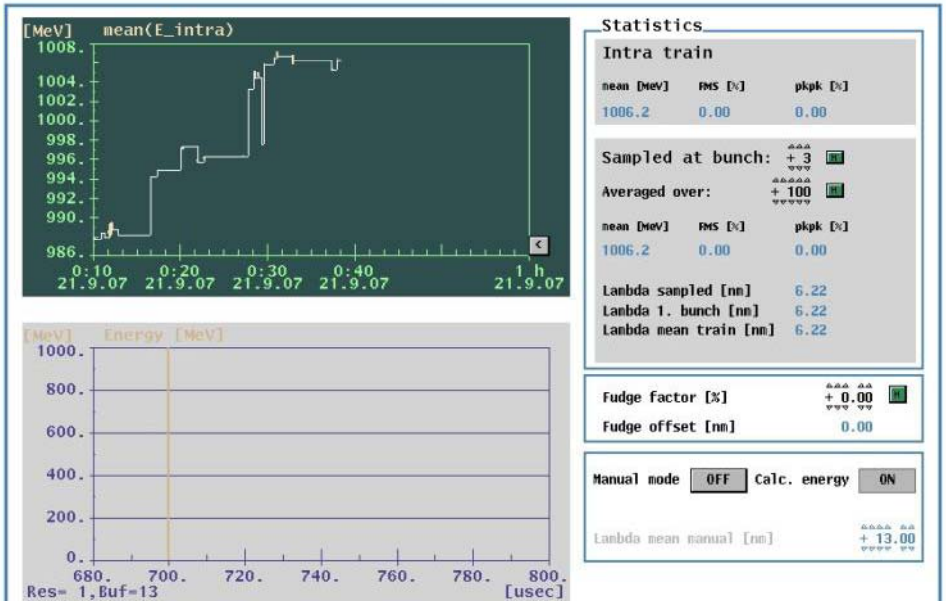
Maximum beam energy

- ~ 970 MeV electron beam through the undulator to the dump: Sep-9 evening
- 1 GeV beam energy reached for the first time in the night Sep-18/19
- 1 GeV energy confirmed by measuring the spectrum of the spontaneous radiation: Sep-21 at 2 am
- Note: to reach 1 GeV, modules are tuned individually to their limits



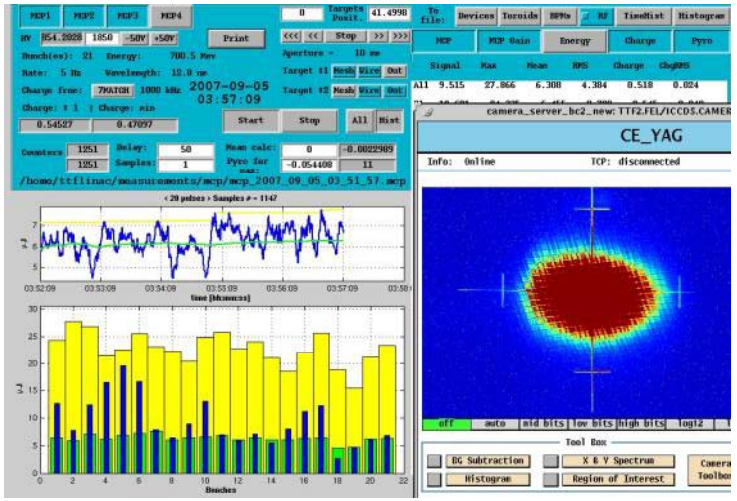


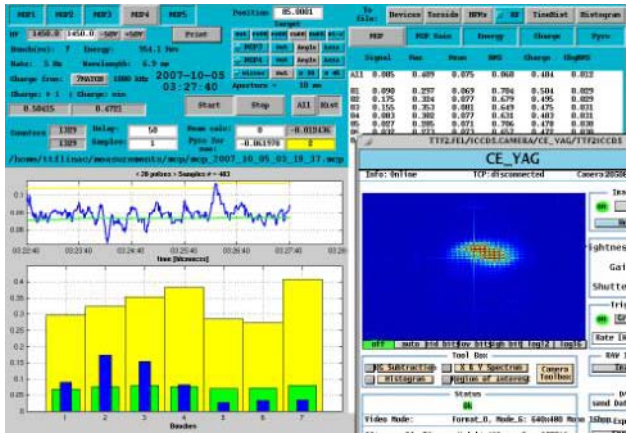
Energy server display

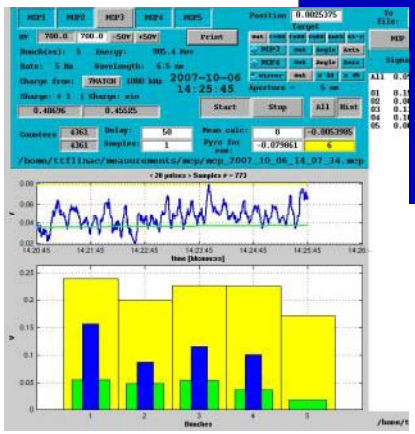


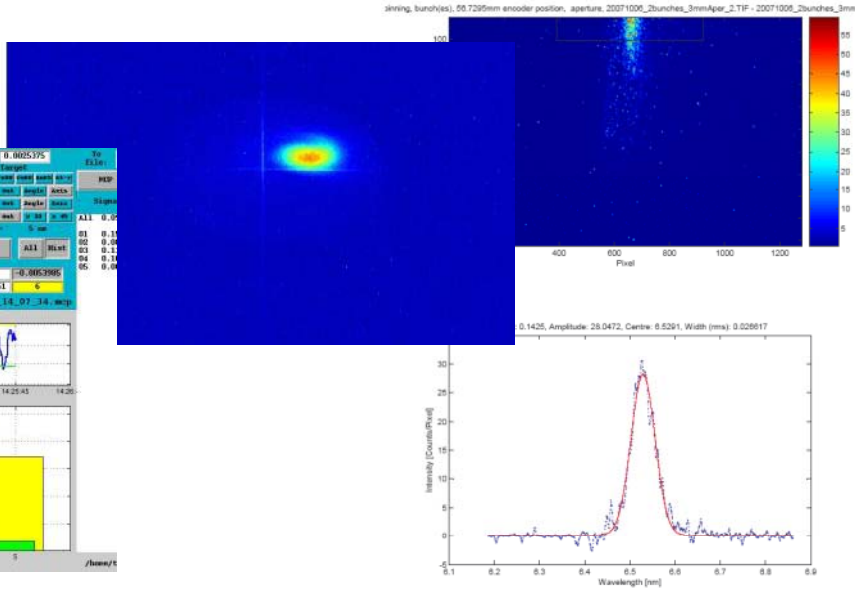
SASE

- First trial to establish lasing after the shutdown (Sep-4/5) successful
  → Lasing at ~13.5 nm (~6 uJ average) established within two shifts
- One week, starting Oct-2 after the maintenance, scheduled for lasing at the shortest possible wavelength
  → lasing at 6.9 nm Oct-4 evening
  → lasing at 6.5 nm Oct-5 afternoon
  - Level ~ 1 uJ (detectors not yet calibrated)









Summary

- Operation of FLASH successfully established after the shutdown
- Design goals of 1 GeV beam energy and lasing with 6.5 nm reached
- Start-up of electron beam operation delayed (only) by ~ 10 days in respect to the schedule in the beginning of the shutdown
  - delay mainly because more time than expected required for work on modules
- Commissioning time used effectively, especially during KW 33-34
  - Morning shift: frequency measurements + cavity tuning (KW33)
    or correction of the wave guide length between modules (KW 33/34)
  - Afternoon shift: RF to modules, phase measurements + LLRF adjustments
  - Night shift: electron beam operation
- Accelerator and FEL studies started as scheduled in Aug-27
- Due to the start-up delay, not enough time for machine studies before scheduled accelerator studies
  - optimization injector set-up, diagnostics commissioning, beam optics, SASE
  - required rescheduling of these tasks to September – October

    ⟶ establishing lasing and maximum beam energy during contingency shifts

    ⟶ lasing at 6.5 nm rescheduled to KW 40

    ⟶ beam optics studies in KW 41-42

FLASH schedule

- KW 42: Lasing with long bunch trains
- KW 43-44: Miscellaneous studies
  - Optical replica, IR undulator, LLRF, BPM, BAM, beam tilt, BBA, intra bunch train feedback, energy server, change of wavelength
  - Establishment of SASE operation for beam line commissioning
- KW 45-47: Photon beam line commissioning
  - Stable SASE operation required
- KW 48-51: FEL user experiments
- KW 52-1: Maintenance
- KW 2-6: Accelerator and FEL studies
  - Submit your beam time requests before Nov-12, 2007
- KW 7-10: FEL user experiments
- KW 11-13: FEL studies
- KW 14-17: FEL user experiments
- KW 18-20: Maintenance