

SRF23 / Grand Rapids, MI, USA / 2023-06-27

The FLASH2020+ Upgrade Project. (TUIAA02)

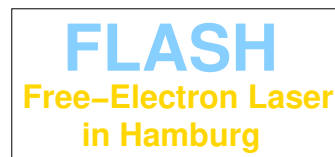
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for my co-authors:

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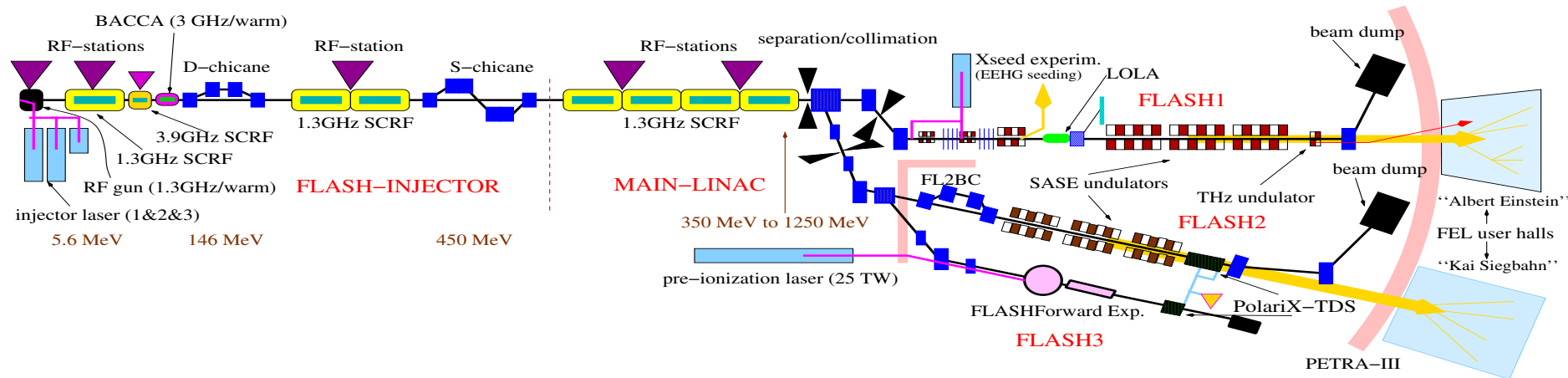
and for the complete FLASH- & FLASH2020+ -teams!



Content.

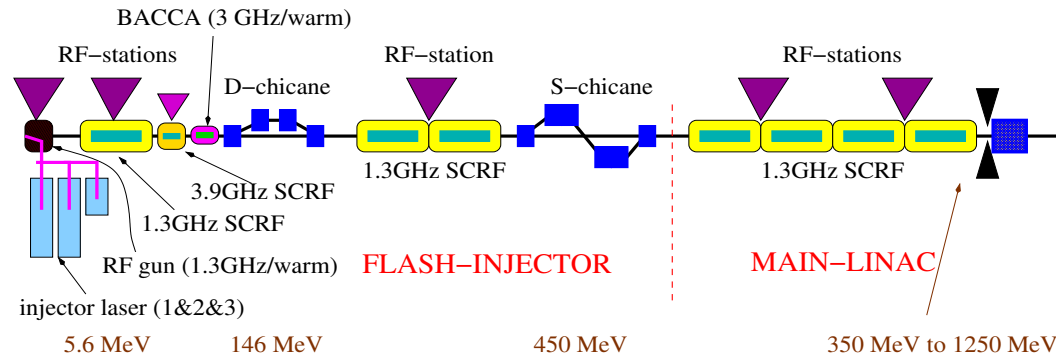
- **FLASH**
- **FLASH2020+**
- **The 2021/22 Shutdown**
 - Injector Upgrade (FLASH0)
 - **FLASH2** Upgrade
 - **Energy Upgrade** ⇒ **SRF**
- **The 2024/25 Shutdown . . . a Staged Approach**
 - ← interlude: what the hell is HGHG/EEHG?
 - **FLASH1** stage-FULL
 - stage-FULL vs. stage-0
- **Summary / Outlook**

FLASH pre FLASH2020+.



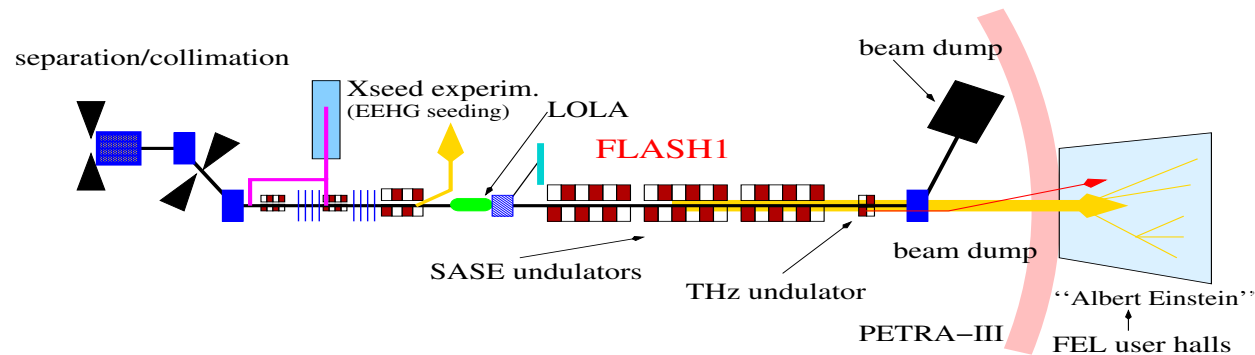
- superconducting free-electron laser w/ 2 FEL beamlines run simultaneously → for FEL user experiments
- injector/linac → FLASH0
- switch-yard to
 - FLASH1
 - FLASH2
- exclusively: FLASH2 ↔ FLASH3
- FLASH3:
 - plasma wake field acc. experi.
 - FLASHForward >>

FLASH0 pre FLASH2020+.



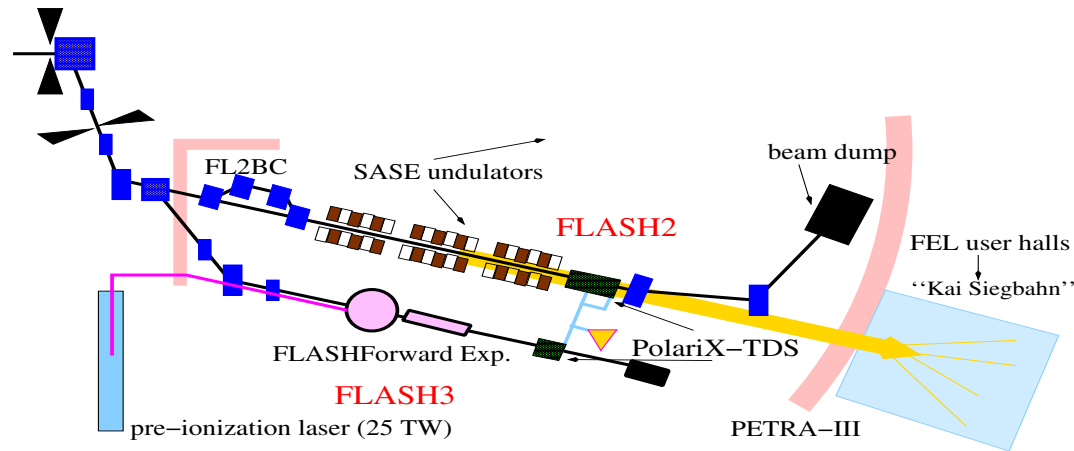
- injector/linac :
 - photo cathode RF gun ~ 600 bu 1 MHz $\times 10$ Hz
- 1st TTF-type L-band module (**ACC1**):
 - 8 nine-cell TESLA niobium cav.s + doublet magnet-pack
- SC 3.9 GHz linearizer
 - (4 scaled TESLA cav.s) (**ACC39**)
- NC 3.0 GHz long. feedback cavity (**BACCA**)
- 1st bunch compr. chicane (*now called **FL0BC1***)
- 2nd & 3rd TTF-type L-band module (**ACC2 & ACC3**)
- 2nd bunch compr. chicane (*now called **FL0BC2***)
- “main linac” 4 \times L-band modules (3 \times TTF + 1 \times XFEL-proto)

FLASH1 pre FLASH2020+.



- E -collimation dogleg
- seeding experiment [Xseed](#)
- NC 2.865 GHz transverse deflecting structure (**LOLA**) from SLAC
← longitudinal diagnostics
- main SASE (Self Amplification of Stimulated Emission) undulator ← *fixed gap* :- (
- spent beam THz undulator (pump-probe experiments)
- tilted (x/y -coupled) dump line

FLASH2 & FLASH3 pre FLASH2020+.

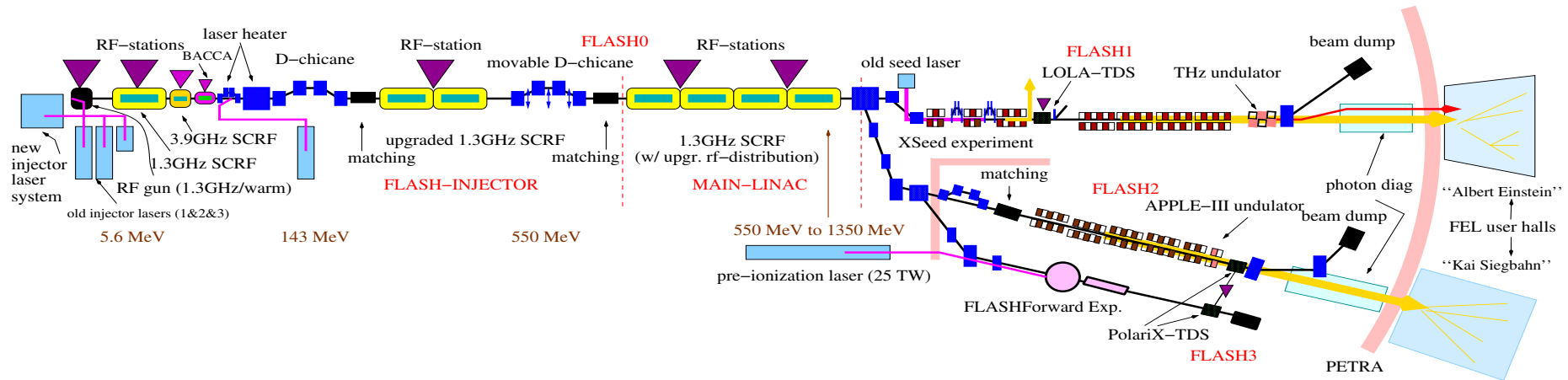


- switch-yard (FLASH0): kicker/septum w/ Lambertson (DC) septum
- complicated extraction arc (geometry!!!)
→ also extraction to FLASH3
- FLASH2's own post-acceleration, post-extraction bunch compressor (FL2BC)
- optics matching
- 12× planar variable gap undu.: SASE + advanced extensions: (harmonic-lasing-self-seeding, frequency doubler, etc.)
- 12.0 GHz PolariX TDS
- electron-photon separation + uncoupled dump line

FLASH2020+ : Motivation.

- FLASH ([SRF= high rep-rate] + soft X-ray + SASE)×2 beamlines should stay competitive for the next 10-20 years
 1. make lower photon wavelengths possible (“water window”)
 - ⇒ increase beam energy & afterburner-undulators
 - ← but keep the footprint!
 2. variable photon polarization ⇒ helical APPLE-III undulators
 - 3.a increase longitudinal photon pulse coherence ⇐ external seeding (HGHG/EEHG)
 - 3.b but keep THz output (⇐ pump-probe) → post compressor
 4. high quality beams require improved...
 - ... operability: transverse matching & reduce long.-2-transv. intra-bunch-corr.s & long. PS-diagnostics
 - ... better stability: ameliorate μ Bunching & remove intra-train orbit slopes

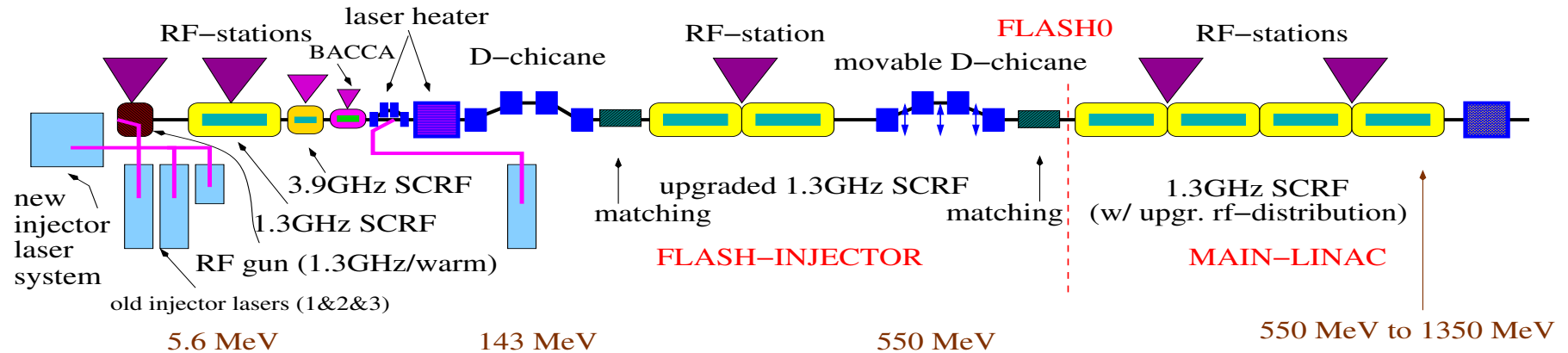
FLASH after the 2021/22 Shutdown.



- 2021/22:
only FLASH0 & FLASH2
- FLASH0: upgrade towards:
→ better beam quality/stability
→ higher final energy

- FLASH2: upgrade towards:
→ variable photon polarization
→ enhanced 3rd harmonics
← APPLE-III undulator
← prototype for
FLASH1 seed radiators

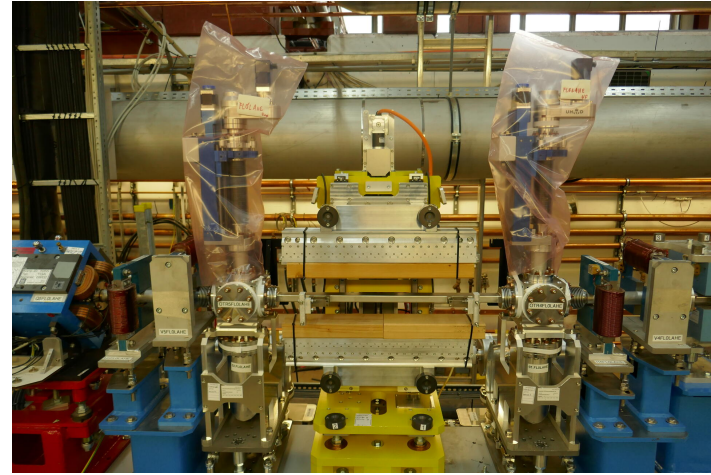
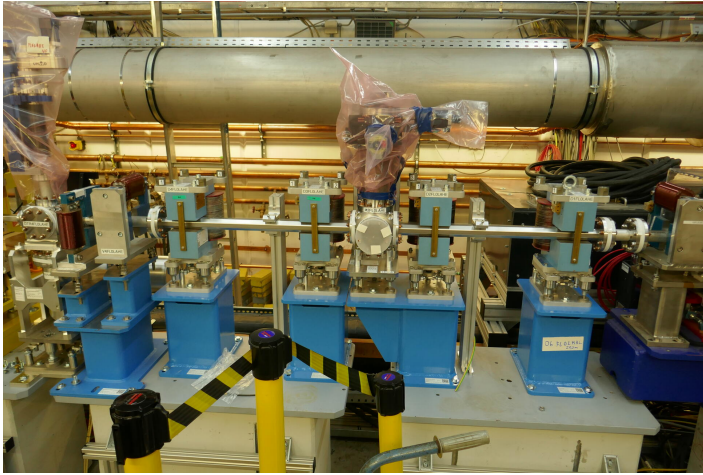
FLASH0 after the 2021/22 Shutdown.



- new injector laser system prepared
- new laser heater installed → space!
- ⇒ BC1 shifted downstream ← space!
- ⇒ matching section shrunk & modified to fulfill requirements
- ACC2 & ACC3: new high gradient modules

- redesign of FL0BC2: S-type → C-type → gain space for improved matching
- round chamber → quad/BPM/skew-quad packs *possible*
- movable chamber (+ inner dipoles) → keep variability for seeding (FL1) and SASE (FL2)

The FLASH0 Laser Heater.

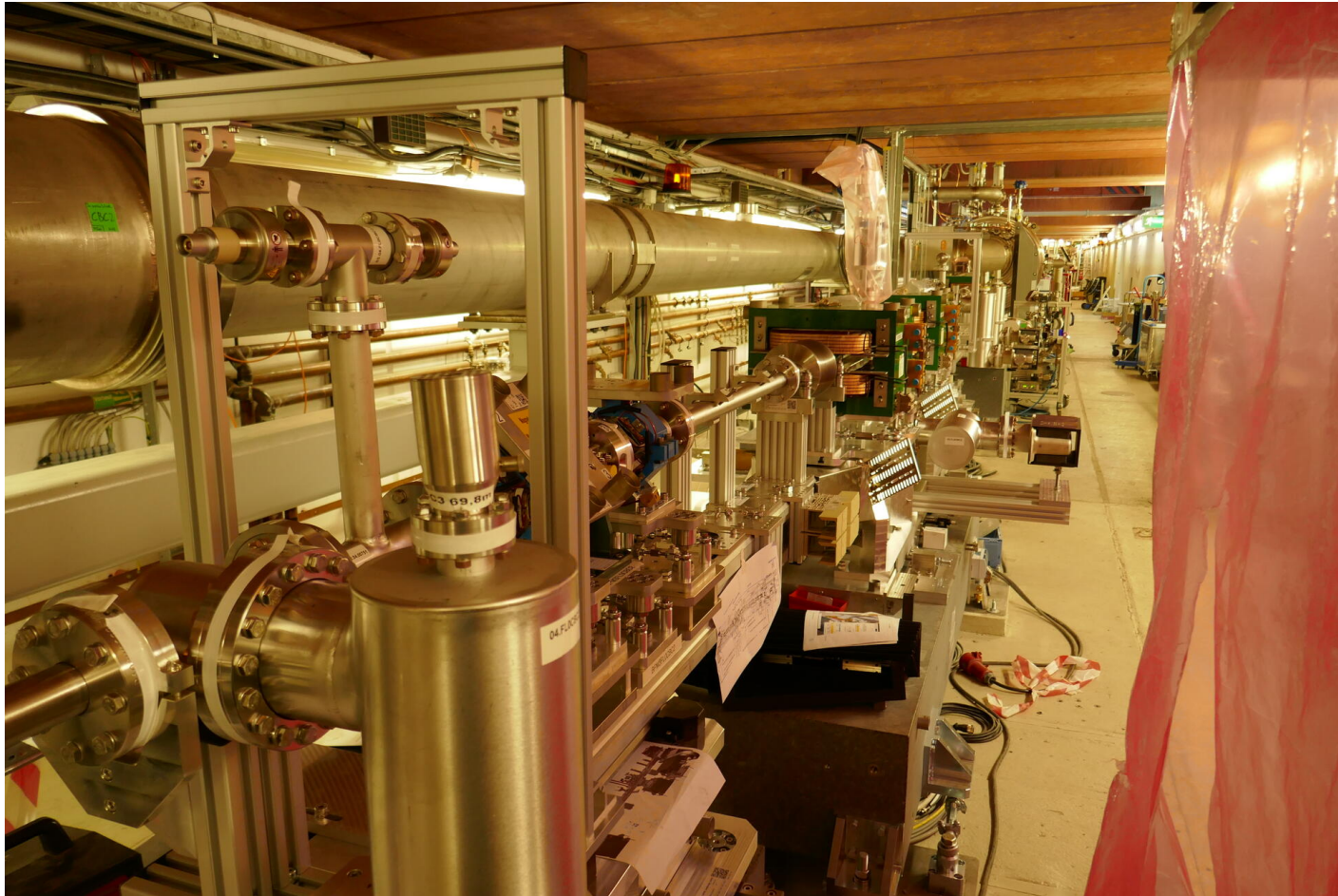


- (LEFT): incoupling chicane for LH laser
 - overlap bunch w/ laser (green) in undulator (RIGHT) \rightarrow E -modulation
 - BC1: strongly over-fold E -modulation \Rightarrow effectively incr. slice E -spread
 - Increased slice E -spread reduces the μ Bunching gain (+)
but it also reduces the FEL gain (-)
- \Rightarrow very sensitive knob for tuning
- Commissioning: overlap achieved & μ Bunching killed & SASE killed
but the sophisticated stuff is still coming!

FL0BC2 (1).

- replace old 6-dipole S-type chicane by new 4-dipole C-type chicane \Rightarrow space for matching
 - round vacuum chamber allows quad/BPM/skew-quad pack *around* the chamber
- \Rightarrow partial compensation of *systematic* longitudinal-to-transverse correlations inside the bunches
- \Leftarrow bunch has E -chirp, chicane has hor. dispersion \rightarrow head sees different kick through quad/skew-quad than tail
- but is impossible w/ std. flat chicane chamber !!!
 - make the chamber and the inner dipoles movable to enable change of deflection angle $\leftrightarrow M_{56}$

FL0BC2 (2).

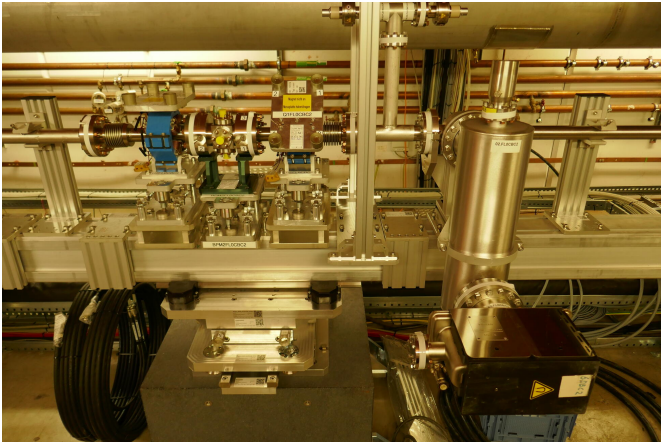


The new movable (0° — 6°) 2nd compression chicane w/ round chamber and quad/BPM/skew-quad packs for correcting intra-*bunch* longitudinal-to-transverse correlations.

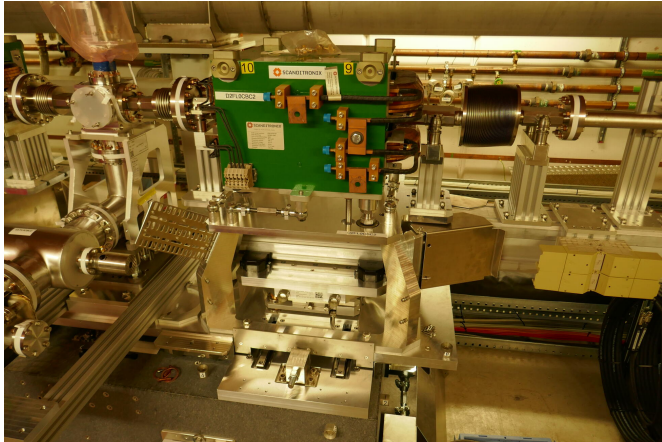
FL0BC2 (3).



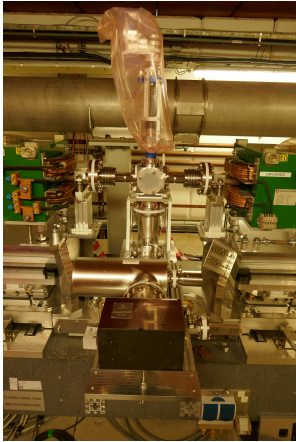
1st dipole



skew-quad → BPM → quad

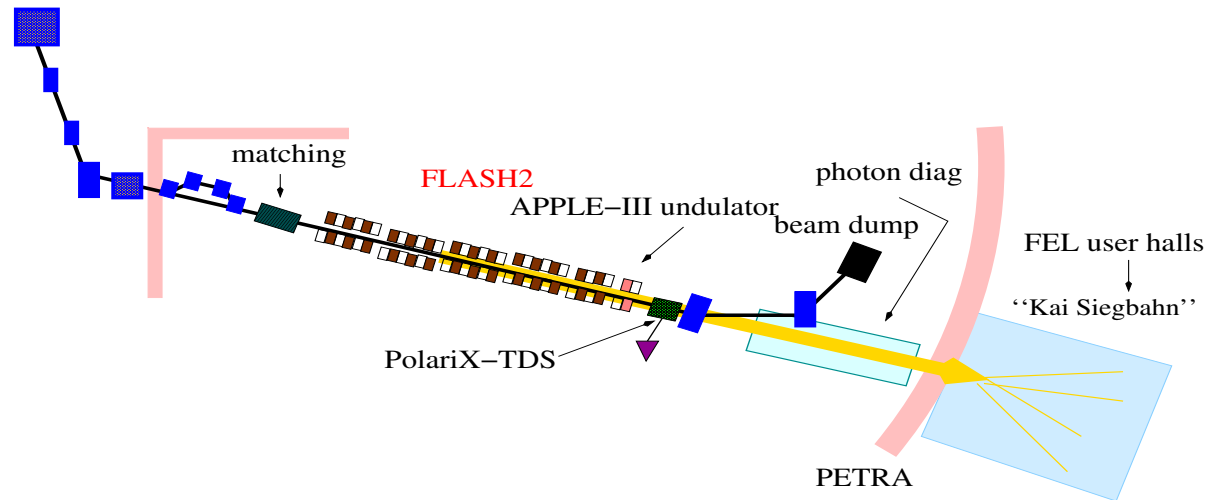


2nd dipole



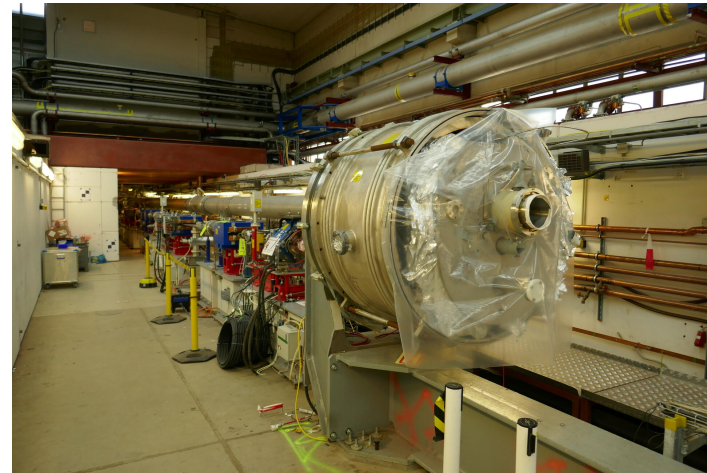
2nd dipole → screen chamber → 3rd dipole

FLASH2 after the 2021/22 Shutdown.



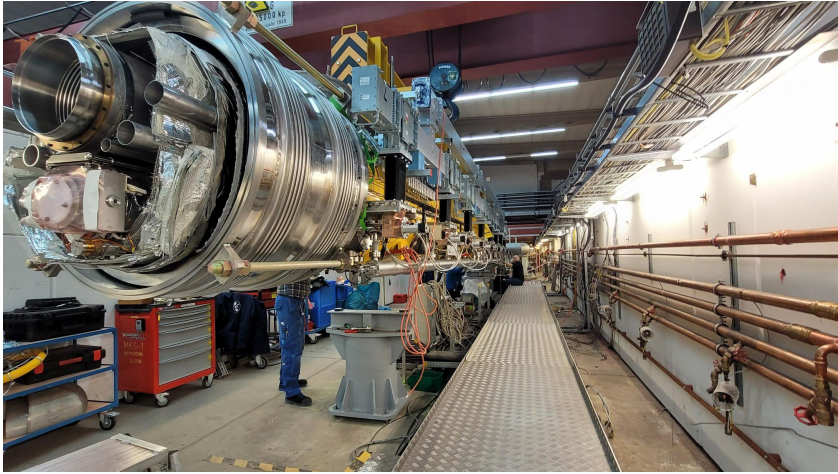
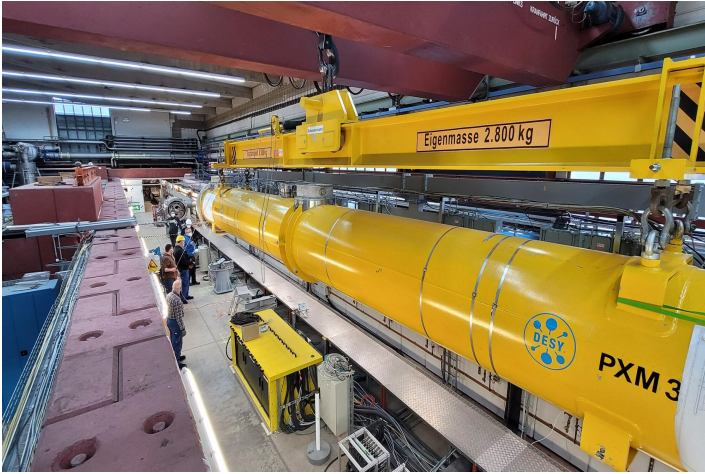
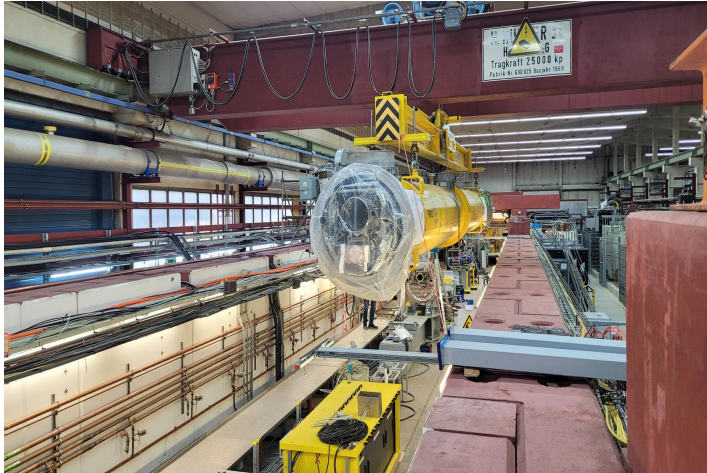
- last undulator ex-FL2SASE14 moved to FL2SASE2 (ex-FL2SEED7)
- space for afterburner undulator in ex-FL2SASE14 (now FL2BURN)
- beam diagnostics shifted upstream
- matching into undulator ⇒ new procedure
- APPLE-III 3rd harmonic a-burner ⇒ down to 1.3 nm & variable photon polarization
- **6 mm diameter** chamber already installed in FL2BURN
- parts for APPLE-III delayed: installation in fall 2023

The Energy Upgrade.

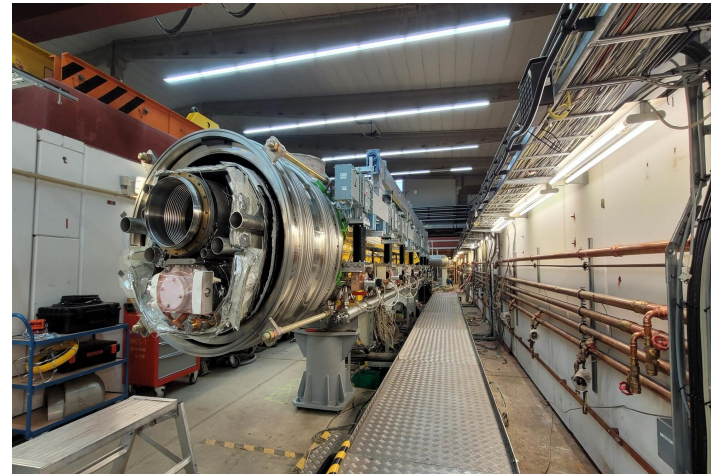
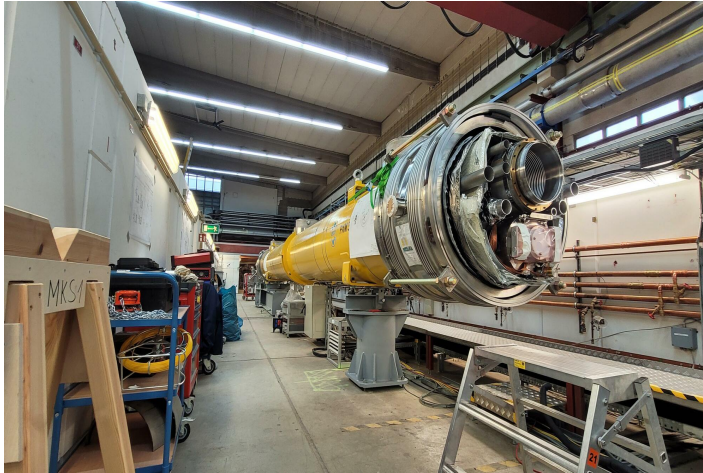


- pics: FLASH0 w/o old ACC2 & ACC3 in January 2022
←the weakest modules in FLASH: beam energy at 2nd BC **was 450 MeV**
- replaced by **refurbished, XFEL-type modules PXM2.1 and PXM3.1** ←
Serena's talk 20min ago
- cav's new ACC2 : from 29MeV/m to 34MeV/m
cav's new ACC2 : from 24MeV/m to 34MeV/m
+ optimized power distribution through ACC23 wave guides
- great success: Beam energy at 2nd BC **is 550 MeV**
measured w/ SASE via fixed gap undulator and high-res. spectrometer

ACC3 being Craned in.

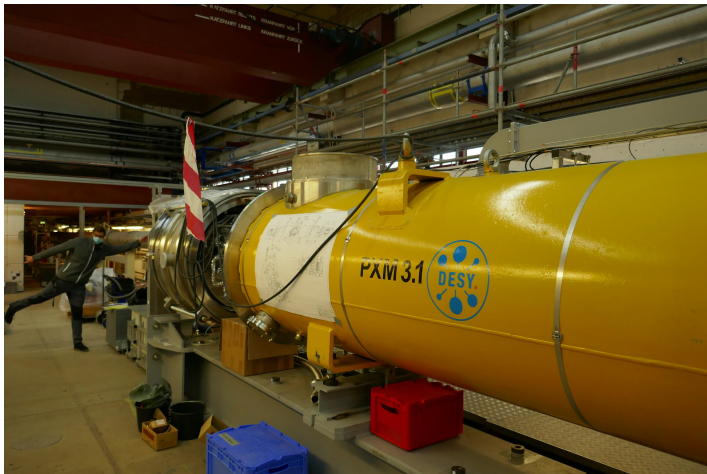
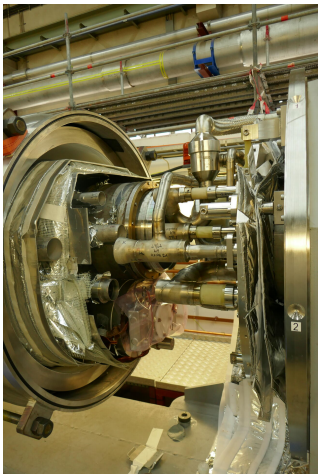
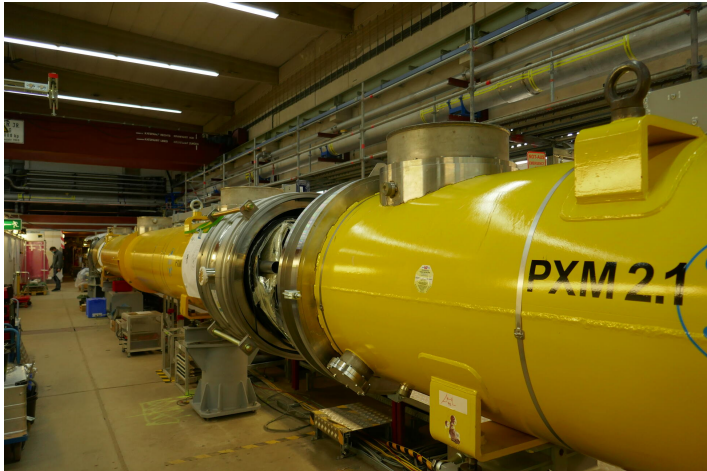
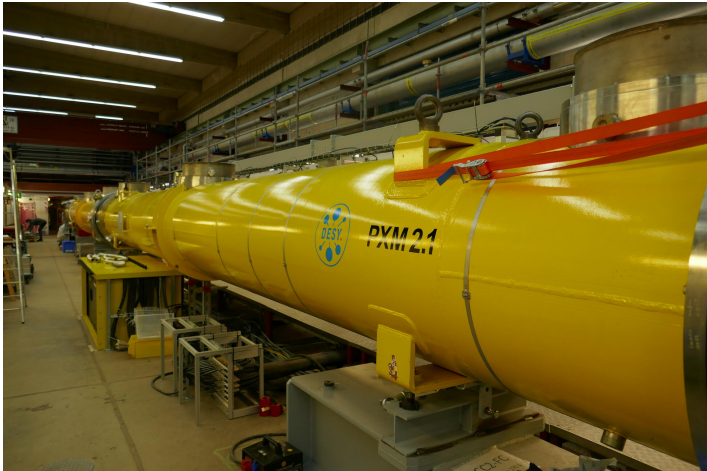


The Eagle has Landed.

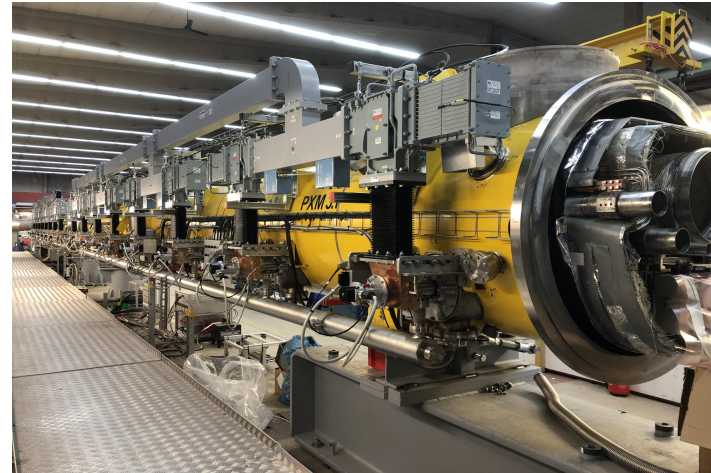
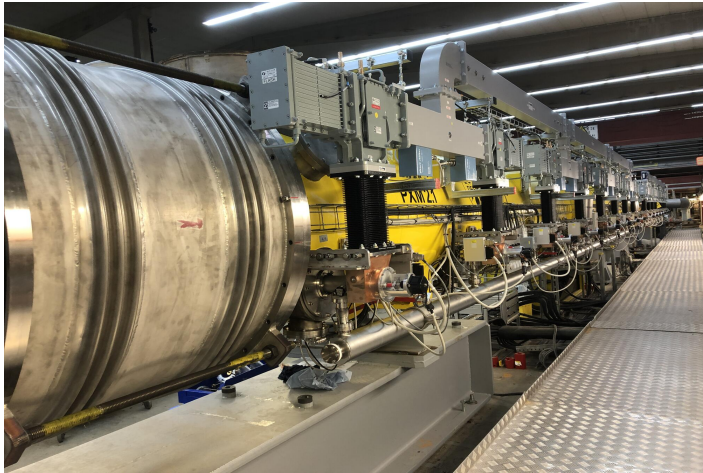


- 2022-02-24:
spectacular pictures. . .
- Everything went
extremely smooth
- my **unofficial** question is:
“Can we have more of these?” :-)

ACC3 & ACC3.

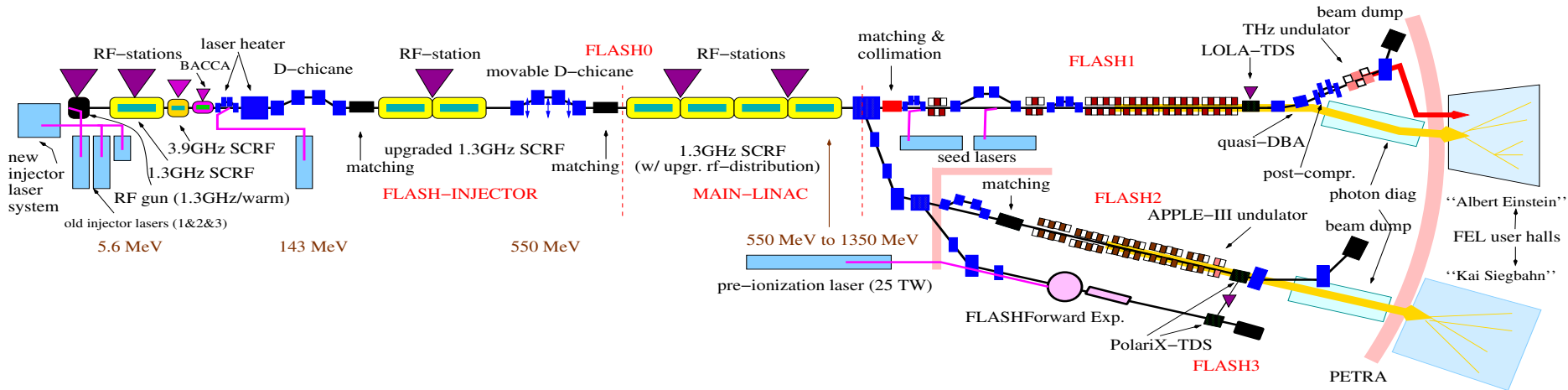


ACC2 & ACC3 Wave Guides.



- Also this went very well.
- Also planned / partly done for ACC4 & ACC5 → **work in progress**

FLASH after the 2024/25 Shutdown : Stage-FULL.



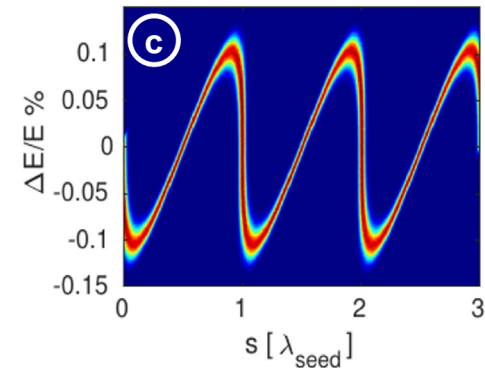
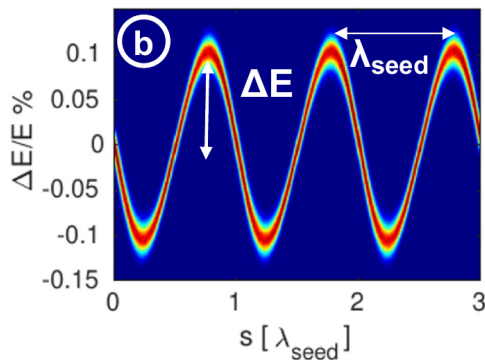
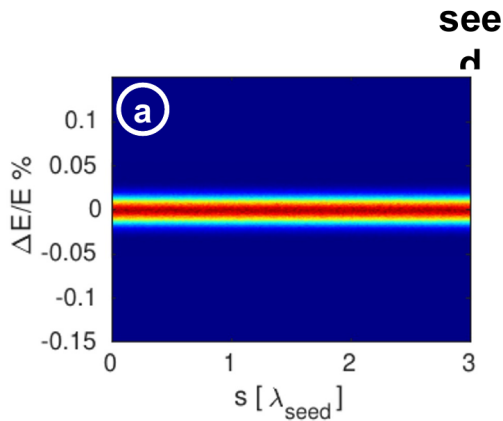
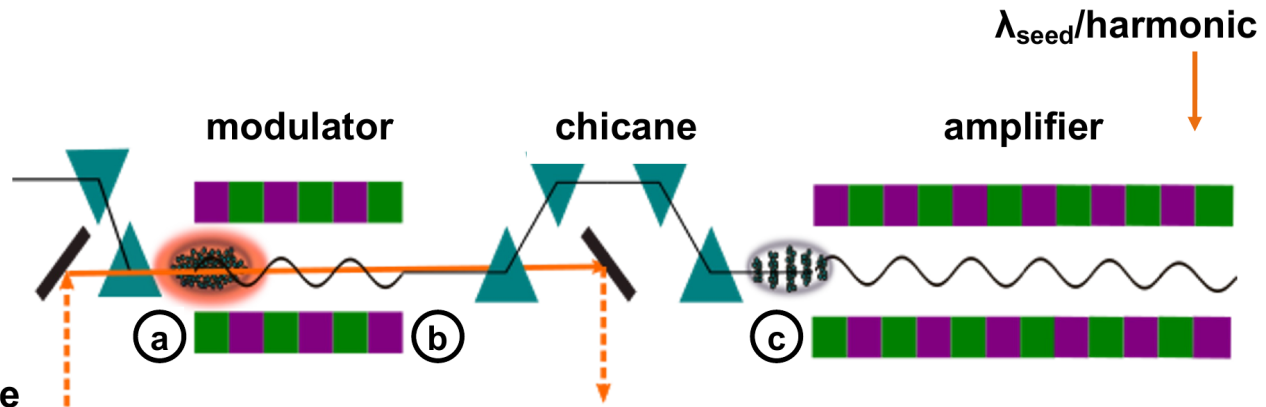
- 2024/25: only **FLASH1**
- the old **FLASH1** will be completely removed → disentangle photon beamline from dump line
→ moved dump
→ uncoupled dump line!
- **FLASH1**: upgrade towards:
 - HGHG/EEHG seeding
 - variable polarization (helical APPLE-III undulators)
- 3 new chicanes for seeding & 1 as post-compressor for THz(?)

Interlude : Seeding : HGHG.

External seeding

High gain harmonic generation

- Seed laser peak power tens to hundreds MW
- Typical wavelegh in the UV



- Bunching of electron beam at wavelength of seed laser
- Harmonics >20 have been demonstrated
- Efficiency decreases with increasing harmonic

$$\rightarrow b_h = \exp(-h^2 B^2 / 2) J_h(hAB)$$

$$B = kR_{56} \sigma_E / E$$

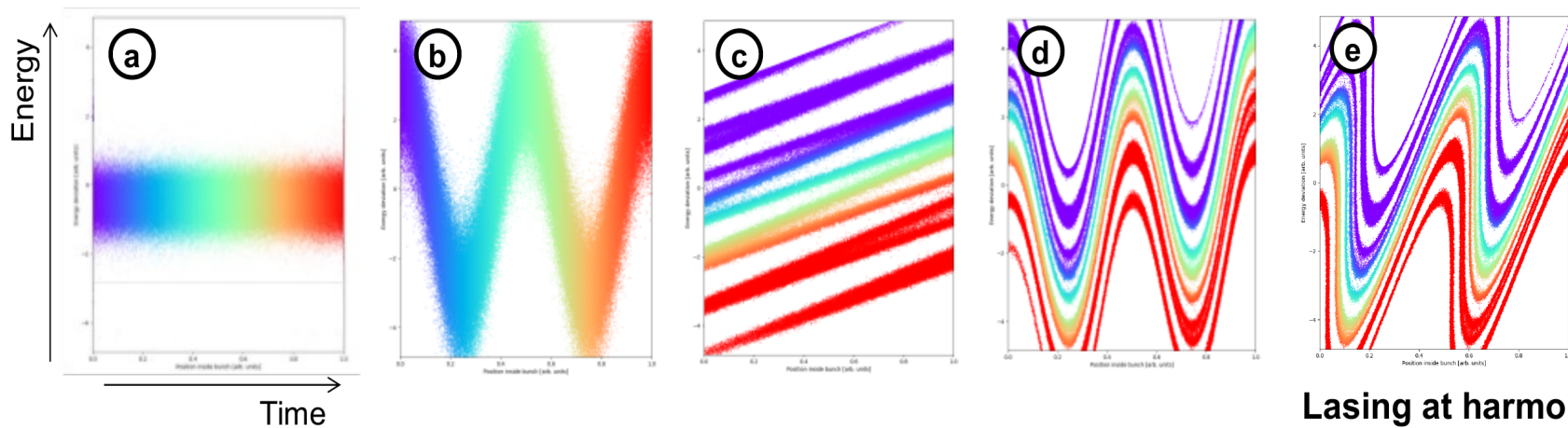
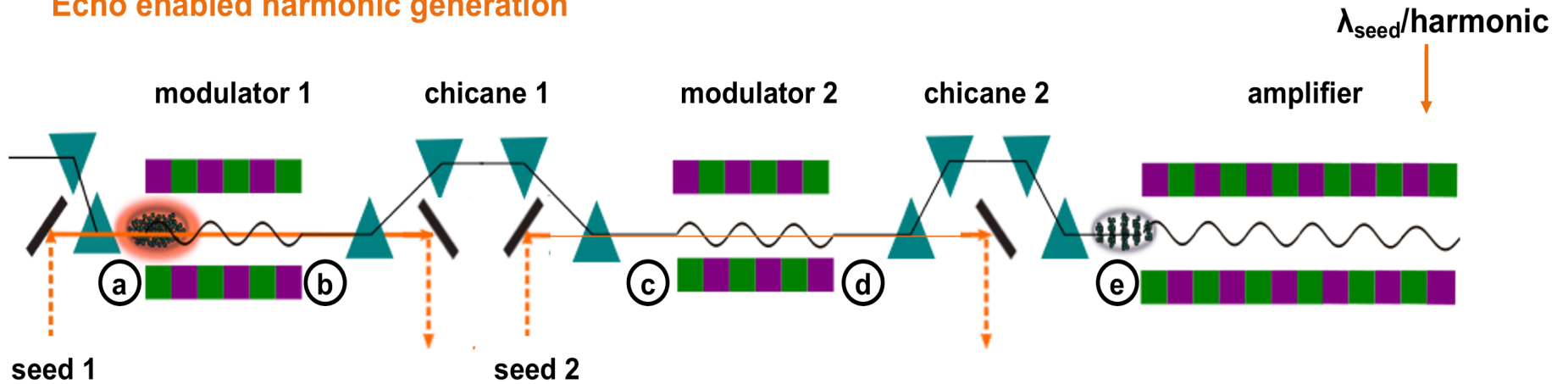
$$A = \Delta E / \sigma_E$$

How to allow conversion at higher harmonics?

Interlude : Seeding : EEHG.

External seeding

Echo enabled harmonic generation



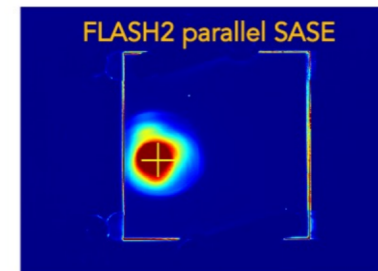
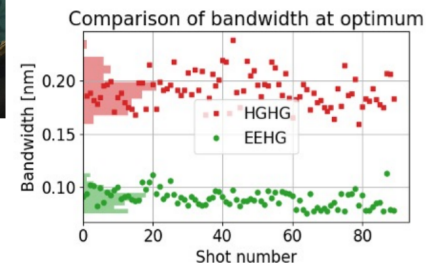
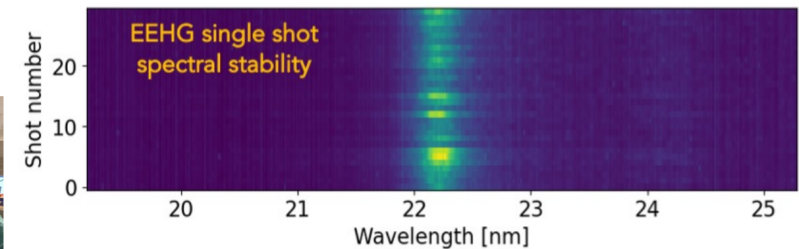
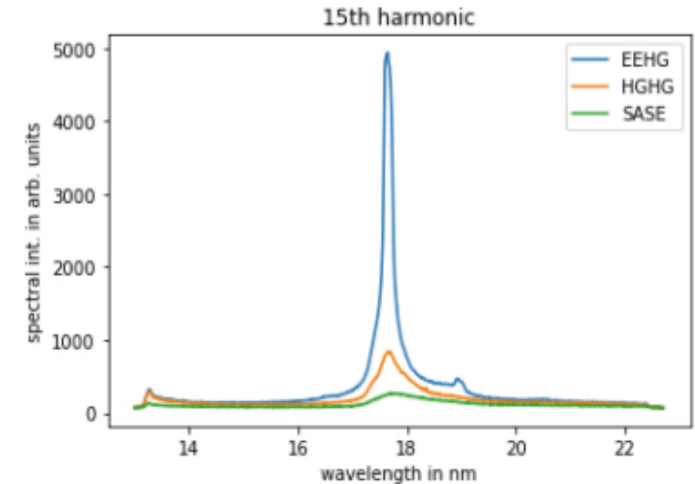
Lasing at harmonics >100 has been demonstrated

EEHG Seeding at Xseed Experiment in FLASH1.

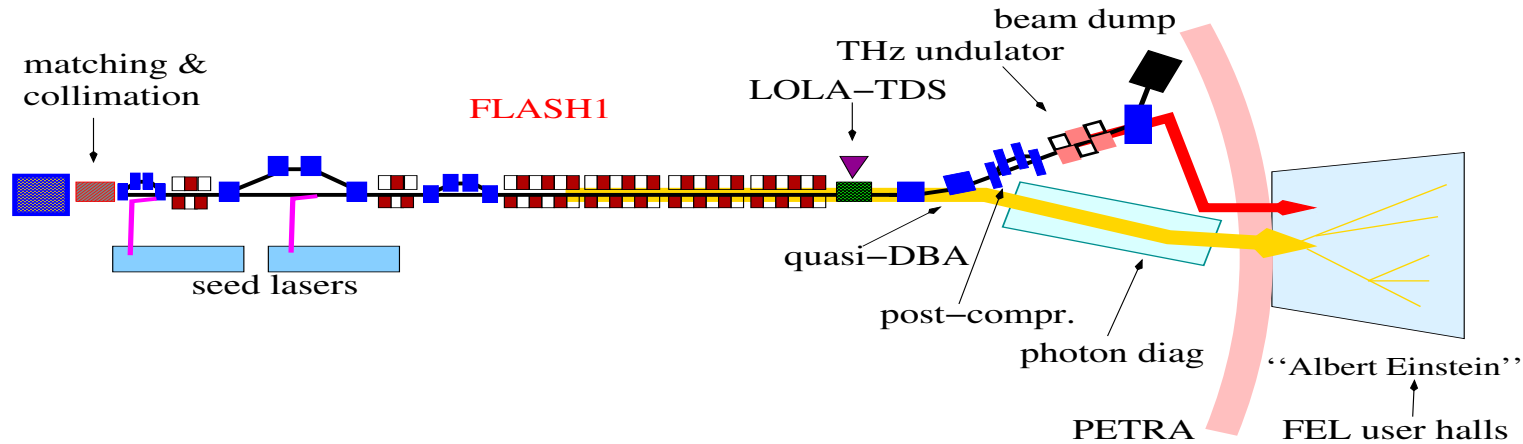
A major success: EEHG at FLASH

Worldwide unique: parallel operation of EEHG and SASE

- Initial EEHG setup looking at 12th harmonic took 3 full days!
 - Characterizing 12th harmonic
- Complete re-setup in only 4 hours
 - Characterizing harmonics 9, 12, 15 and 17
- Successful seeding of 2nd bunch
 - mimicking bunchtrain operation → full train to come
- Parallel SASE operation at FLASH2 with 30 bunches above 100uJ at 30 nm
- **A major team effort!**
 - Expertise vital for future seeded FLASH1
- Continued experiments offer unique chance
 - Shorten commissioning time
 - Develop tools and procedures

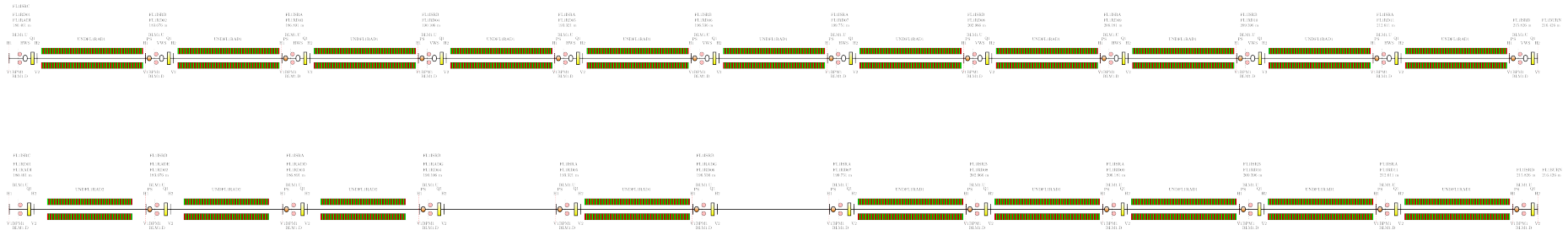


FLASH1 after the 2024/25 Shutdown : Stage-FULL.



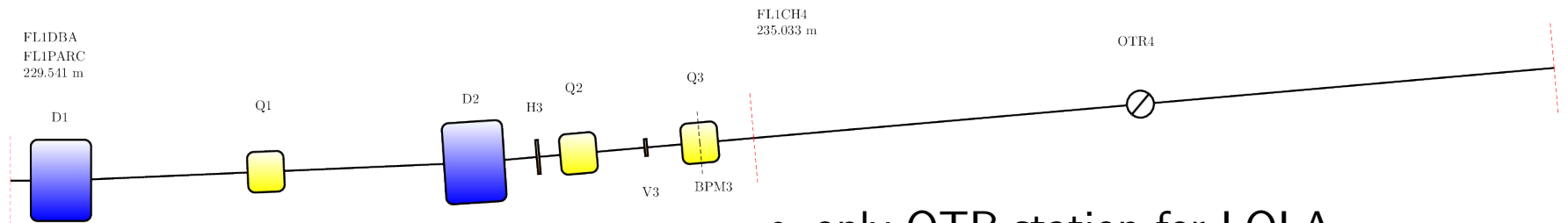
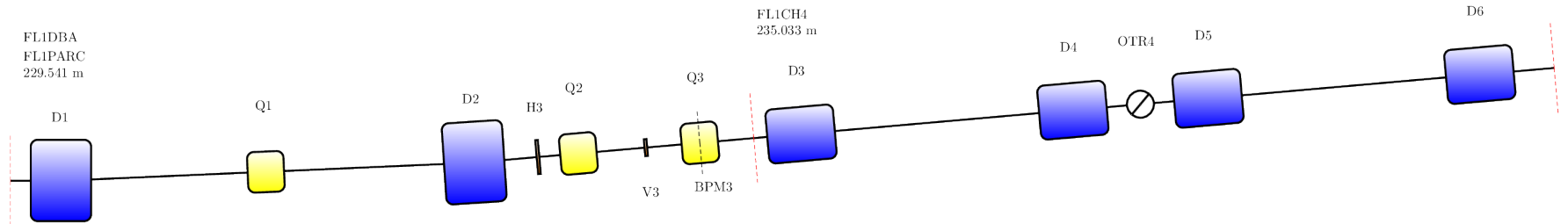
- incoupling of seed laser **L1**
- 1st modulator
- over-folding chicane
(+ out-coupling **L1** + incoupling **L2**)
- 2nd modulator
- bunching chicane (+ out-coupling **L2**)
- seed radiators:
variable polarization APPLE-III
- new location of LOLA
- quasi-DBA (5°) & post-compressor
chicane & THz radiator
- new dump line
- **but then...** the staged approach...

FLASH1 FL1RADI Stage-FULL (top) vs. Stage-0 (bott.).



- **6 instead of 11 APPLE-III** undulators
- **replace 3 of 5 w/ Xseed, P2N-type undulators** as bunchers
- **leave 2 of 5 empty** (FODO-layout is kept)
- **No wire scanners** / only WS-chambers
- otherwise : **intersections stay as designed**

FLASH1 FL1PARC Stage-FULL (top) vs. Stage-0 (bott.).



- **No post-compression chicane FL1CH4**
- i.e. **No post-compression for THz undulator**
- only OTR station for LOLA
- x -dispersion from messing with quasi-DBA \Rightarrow parasitic use = **bunch length only** (full long. PS only in destructive mode)

FLASH1 FL1RADT Stage-FULL (top) vs. Stage-0 (bott.).



- **No dedicated BAM**
 - **No dedicated BCM**
- ← not needed **w/o FL1CH4**

- **No coherent THz transition radiator** (target)
- maybe: install the BAM/BCM/CTR vacuum chambers already in 2024/25 shutdown

Summary & Outlook.

- FLASH is undergoing a substantial upgrade/refurbishment program (**FLASH2020+**).
- **If we're quick**, then FLASH will be the only seeded soft X-ray FEL capable of ~ 5000 bu/sec.
- 1st upgrade shutdown (2021/22) went well: user-run after quick beam commissioning.
→ Commissioning still ongoing whenever there's time...
- *E*-upgrade: two new very nice high-gradient modules for ACC2&3
⇒ 100 MeV more at end of the injector (FL0BC2)
- 2nd upgrade shutdown being prepared. Everything within schedule.
- However, in 2024/25 only reduced version possible = "stage-0".
- Full upgradability to "stage-FULL" is guaranteed by design of stage-0.
- Seeded operation still uncompromised goal of stage-0.
- We are looking forward to the shutdown in 2024/25!