FLASH: Status & Upgrade. (MO3A5)

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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**
  - $\rightarrow$ Injector Upgrade (FLASH0)
    - $\longrightarrow$ Laser Heater
    - $\longrightarrow$ BC2
      - $\rightarrow$ partial compensation of long.-transv. correlations
  - $\rightarrow$ minor FLASH2 changes

- **The 2024/25 Shutdown** . . . a Staged Approach
  - $\rightarrow$ FLASH1 : external seeding + . . .
    - $\longrightarrow$ μBunching studies for seeding
  - $\rightarrow$ stage-FULL vs. stage-0

- **Summary / Outlook**

FLASH pre FLASH2020+.
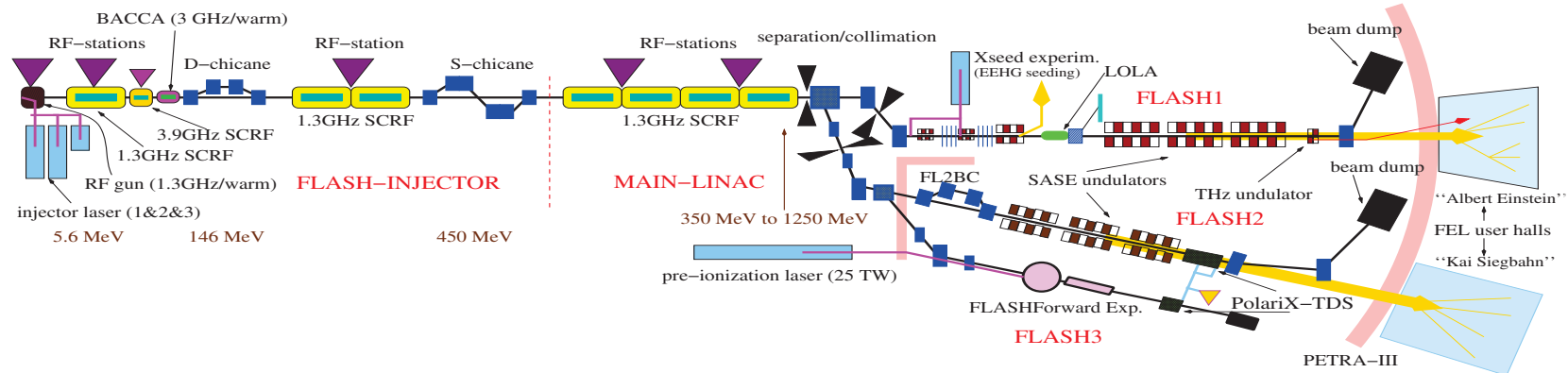
- superconducting free-electron laser w/ 2 FEL beamlines run simultaneously → for FEL user experiments

- injector/linac → FLASH0

- → switch-yard to
   - → FLASH1
   - → FLASH2

- *exclusively:* FLASH2↔ FLASH3

- FLASH3:
   plasma wake field acc. experi.
   FLASHForward>>

FLASH0 pre FLASH2020+.
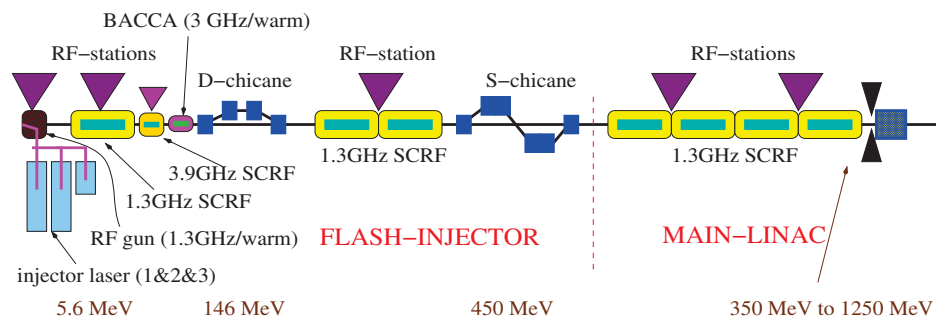
- injector/linac :
  $\rightarrow$ photo cathode RF gun $\sim$600 bu 1 MHz
  $\times$ 10 Hz

- 1st TESLA-type L-band module (**ACC1**):

- 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 TESLA-type L-band module
  (**ACC2** & **ACC3**)

- 2nd bunch compr. chicane
  (*now called* **FL0BC2**)

- "main linac" 4$\times$ (TESLA) L-band
  modules (**ACC4/5/6/7**)

FLASH1 pre FLASH2020+.
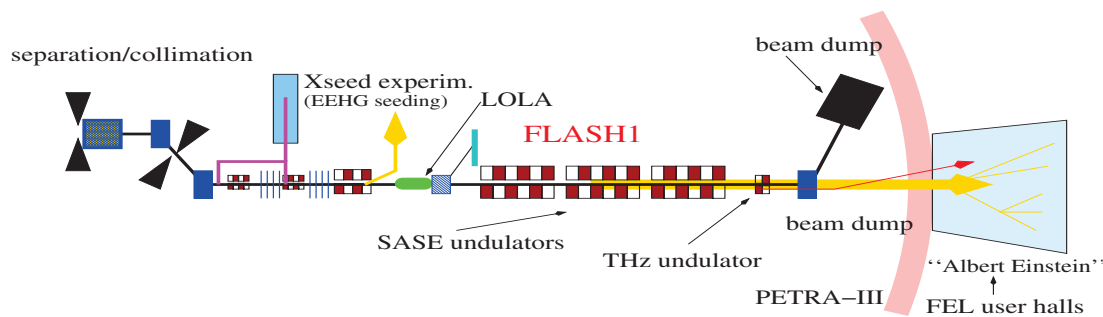
- E–collimation dogleg

- seeding experiment Xseed

- NC 2.865 GHz transverse deflect-
  ing structure (**LOLA**) from SLAC
  $\leftarrow$ longitudinal diagnostics

- main SASE (Self Amplification of Stimulated
  Emission) undulator $\leftarrow$ *fixed gap* :-(

- spent beam THz undulator
  (pump-probe experiments)

- tilted (x/y-coupled) dump line :-(

FLASH2 & FLASH3 pre FLASH2020+.
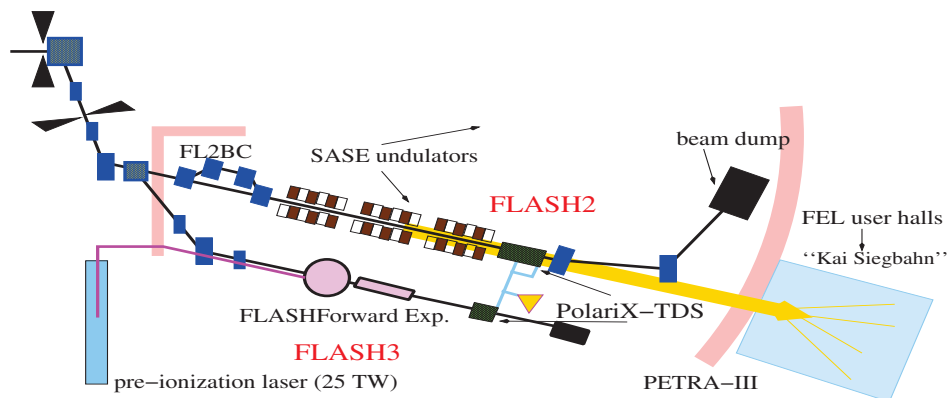
- switch-yard (FLASH0): kicker/septum w/ Lambertson (DC) septum

- 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 μBunching & remove intra-train orbit slopes
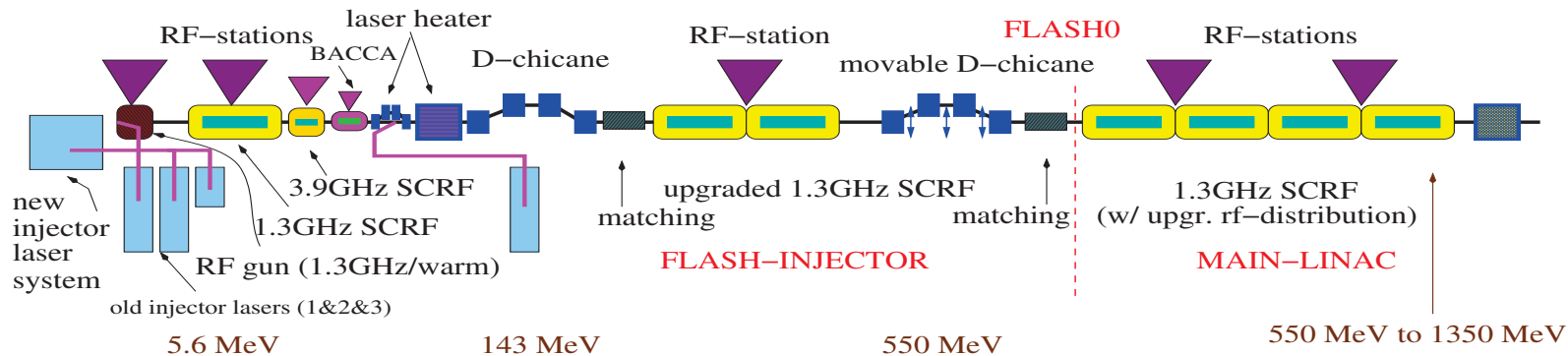
FLASH after the 2021/22 Shutdown.
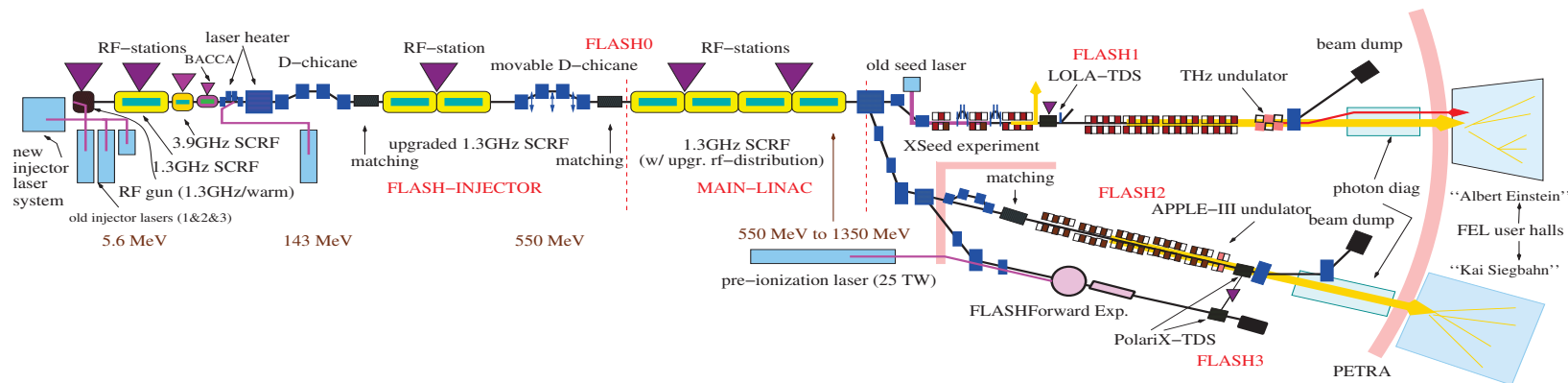
- 2021/22: changes:
  only in FLASH0 & FLASH2

- 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 simultaneously
 seeding (FL1) and SASE (FL2)

The FLASH0 Laser Heater.
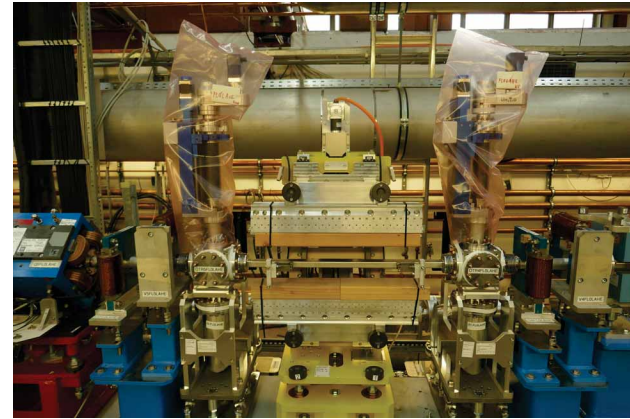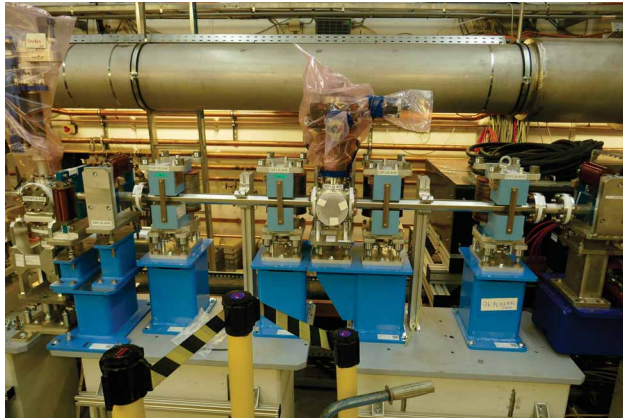
- (LEFT): incoupling chicane for LH laser

- overlap bunch w/ laser (green) in undulator (RIGHT)

- 1st BC-chicane (FL0BC1): strongly over-folds E-modulation

- Increased slice E-spread reduces the μBunching gain (+)
  but it also reduces the FEL gain (−)

⇒ very sensitive knob for tuning

- Commissioning: overlap achieved & μBunching killed & SASE killed
 but the sophisticated stuff is still coming!

FL0BC2.

- replace old 6-dipole S-type chicane by new 4-dipole C-type chicane
  $\Rightarrow$ gain some 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

- movable chamber and the inner dipoles to enable change of deflection angle
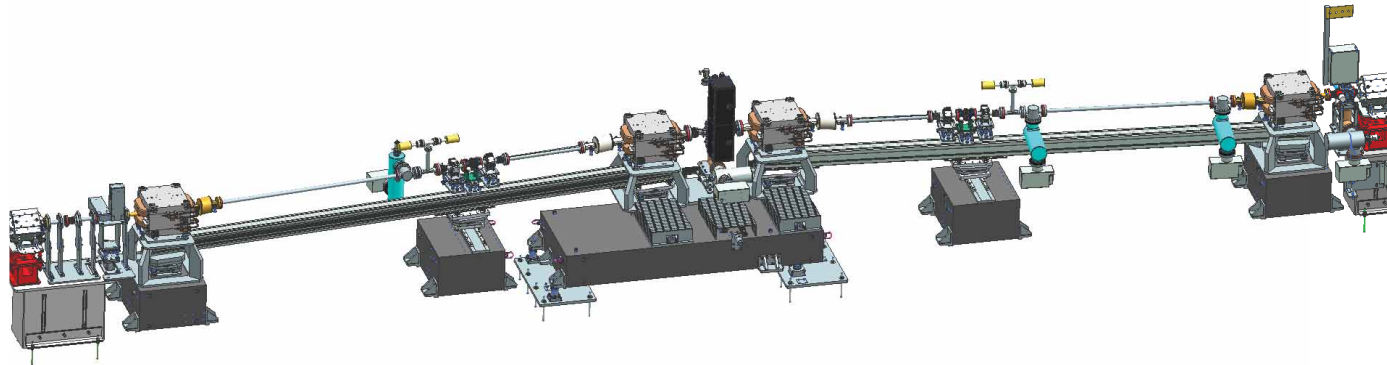
Compensating Long.–Transv. Correlation w/ FL0BC2.

- Idea by Guetg, Beutner, Prat, Reiche; Decker, Ding, Huang, Maxwell; (2015/16)

- $\langle \eta \rangle_\perp (\tau) := \int_{\mathbb{R}^5} \eta \Psi(\vec{z}_\perp, \eta, \tau) \, d^4 z_\perp \, d\eta$
  $\Rightarrow \langle \eta \rangle_\perp (\tau) = h\,\tau + O(\tau^2)$
  $\leftarrow$ bunch compression

- $\langle \vec{z}_\perp \rangle_\perp (\tau) := \int_{\mathbb{R}^5} \vec{z}_\perp \Psi(\vec{z}_\perp, \eta, \tau) d^4 z_\perp d\eta$
  $\Rightarrow \boxed{\langle \vec{z}_\perp \rangle_\perp (\tau) = \vec{\xi}\,\tau + O(\tau^2)}$

- long.-to-transv. correlation
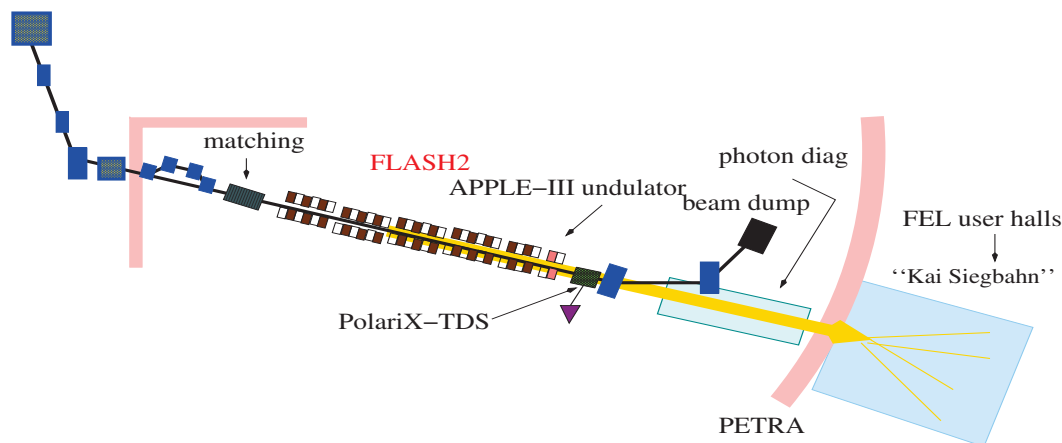 $\leftarrow$ compensate in chicane
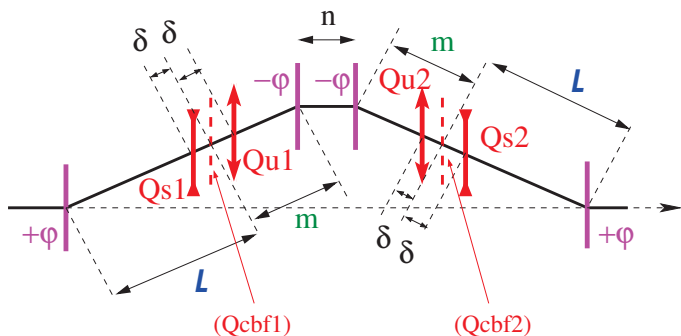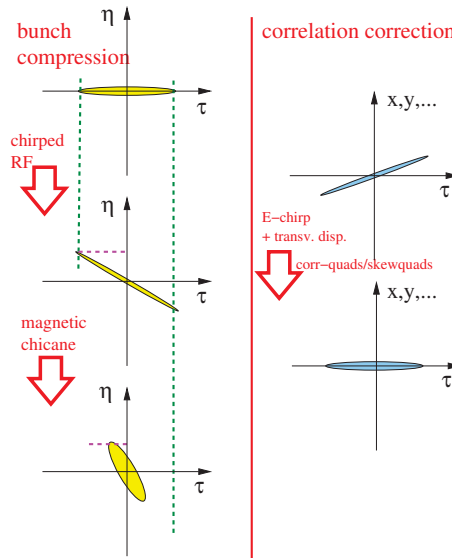
- thin lens model (IPAC21/TUPAB102)

- solve exactly for $\delta = 0$,
  then solve $O(\delta)$ f. $\delta > 0$

- gives quad/skew quad strengths
  for given correlation and E-chirp

 comes at a prize: disp$_\perp$ leaks & M_{56} modified

The Energy Upgrade.
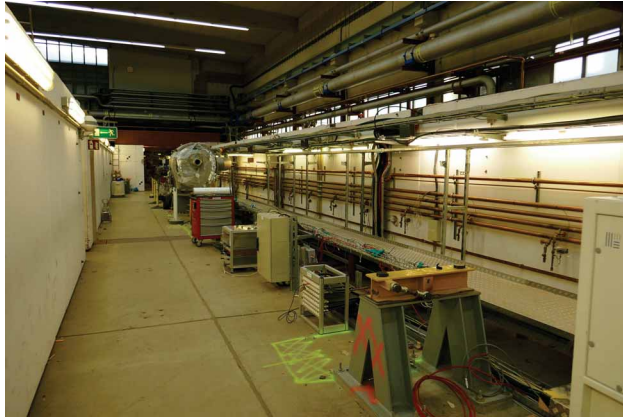
- pics: FLASH0
  $\rightarrow$ w/o old ACC2 & ACC3 in Jan. 2022 (left)
  $\leftarrow$the weakest modules in FLASH: beam energy at 2nd BC **was 450 MeV**
  $\rightarrow$ w/ the new ACC3 already placed on supports Feb. 2022 (right)

- replaced by **refurbished, XFEL-type modules PXM2.1 and PXM3.1**

- cav's new ACC2 : from 29MeV/m to 34MeV/m; cav's new ACC3 : from 24MeV/m to 34MeV/m

  + optimized power distribution through ACC23 wave guides

  $\Rightarrow$ E-gain of > 417 MeV possible even $25°$ off-crest

- great success**:** Beam energy at 2nd BC immediately up to 550 MeV,
  recently even **560 MeV** $\Rightarrow$ E-upgrade save to > 1300 MeV

FLASH2 after the 2021/22 Shutdown.

matching

FLASH2

APPLE–III undulator

photon diag

beam dump

FEL user halls

''Kai Siegbahn''

PolariX–TDS

PETRA

- last undulator ex-FL2SASE14 moved to FL2SASE2 (ex-FL2SEED7)

- space for afterburner undulator in ex-FL2SASE14 (now FL2BURN)

→ beam diagnostics shifted upstream & shorter

→ new matching into undulator

- 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 end of September?

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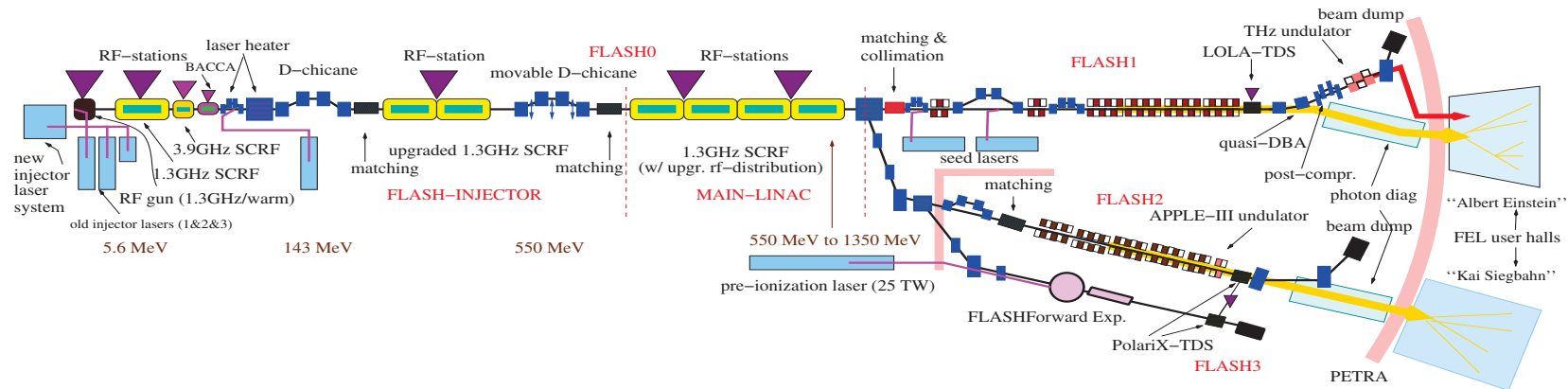
- 2024/25: only FLASH1

- the old FLASH1 will be completely removed

- FLASH1: upgrade towards:
  - → HGHG/EEHG seeding
  - → variable polarization
    (helical APPLE-III undulators)

→ disentangle photon beamline from dump line
  - → moved dump
  - → uncoupled dump line!

- 4 new chicanes: 3 for seeding
  & 1 as post-compressor for THz

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
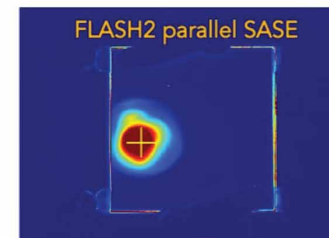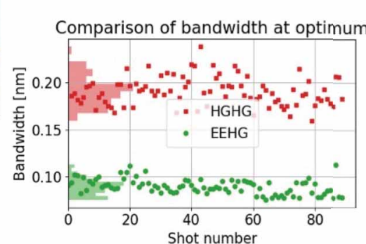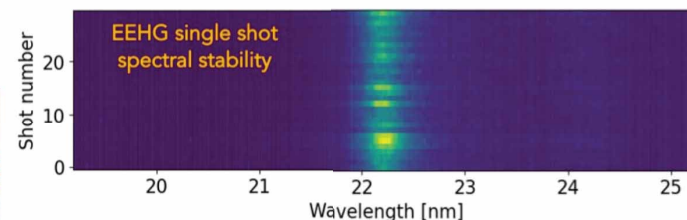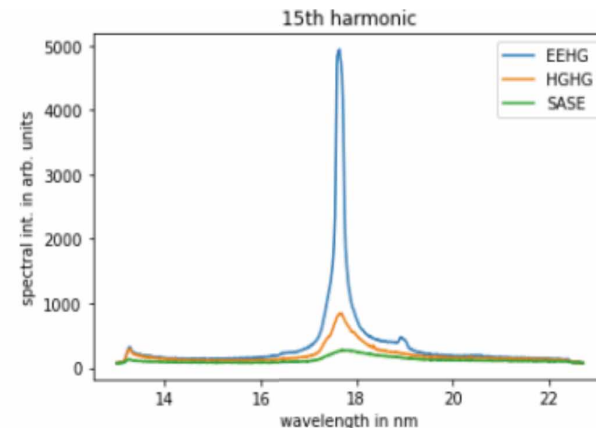
μ**Bunching Simulations using SelaV**$_{1D}$**.**

- LSC(+CSR) induced μbunching

- potentially degrades FEL performance

  not always:

  $\rightarrow$ SpaceChargeAmplifier!!!

  known to be more severe for external seeding

- **gain** mechanism well studied

  (Stupakov; Venturini; Shneid-miller, Saldin; Amstutz; . . .)

- **seed** mechanism mostly unclear $\rightarrow$ one thing is **shot noise**

- MP sim.: overestimating the intrinsic shot-noise

  $\rightarrow$ massive one-to-one simulations (extremely t-consuming!), **or:**

- SelaV$_{1D}$, based on backward tracking the PSD on **tree-grid** covering only the **support** of PSD

  semi-Lagrangian tracking / Method of Characteristics /Perron Frobenius Operators

  $\Rightarrow$ **w/ optimized compression WP and moderate LH amplitude $\rightarrow$ negligible**
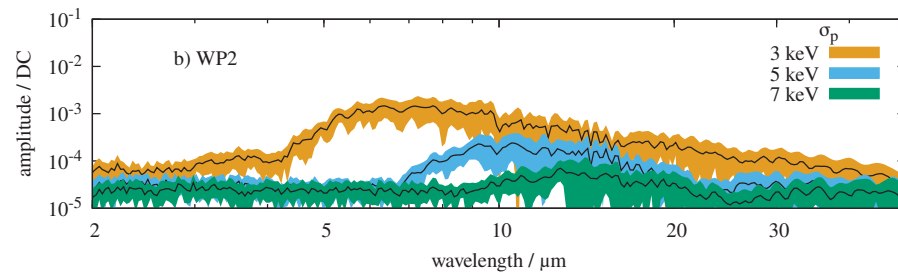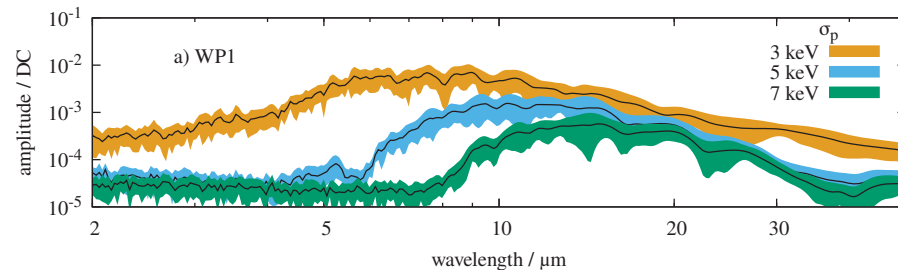
# FLASH1 after the 2024/25 Shutdown : Stage-FULL.
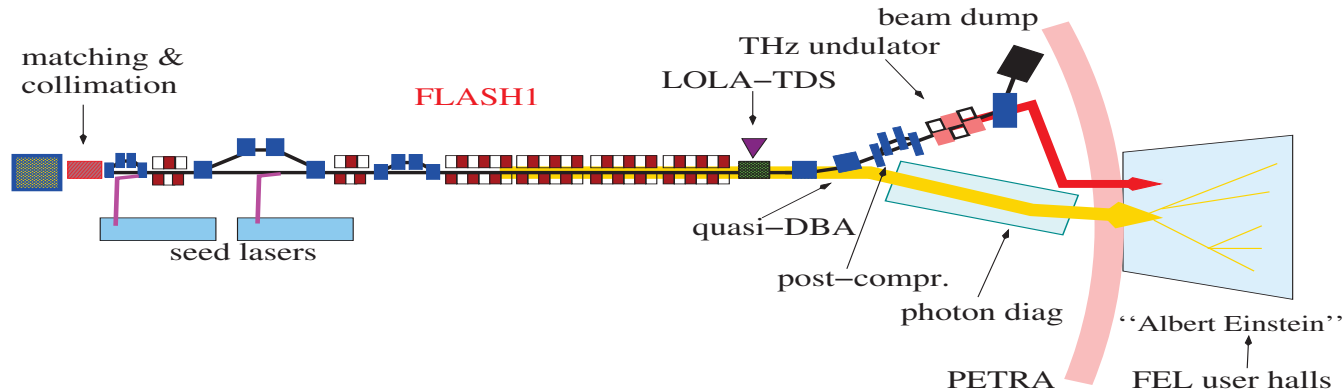
- incoupling of seed laser **L1**

- 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. . .

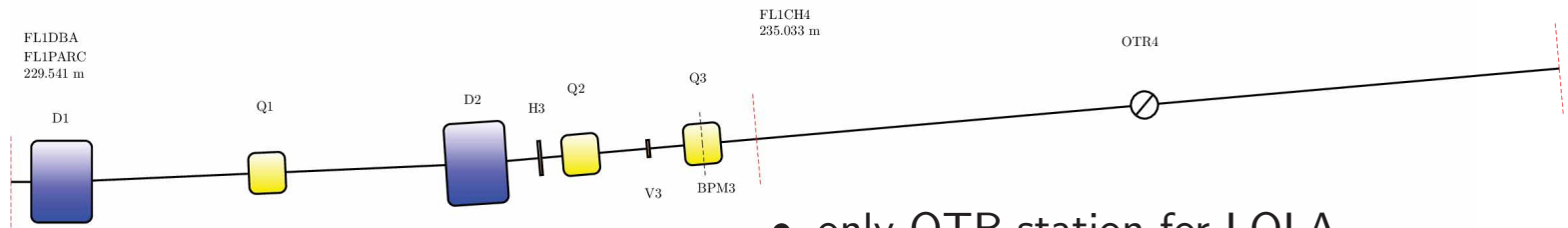# FLASH1 FL1RADI Stage-FULL (top) vs. Stage-0 (bott.).
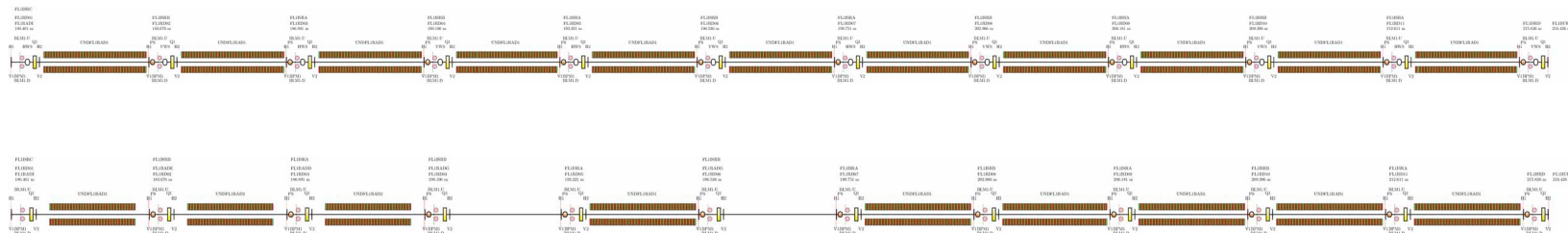
- **6 instead of 11 APPLE-III** undulators

- **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.).
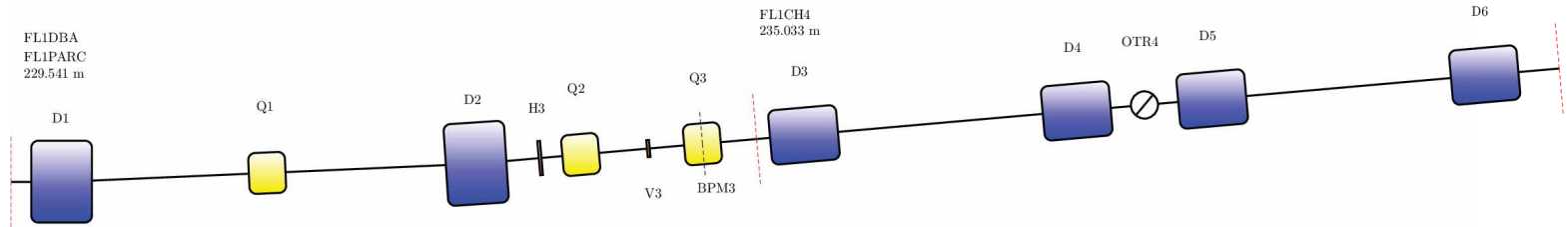
- **No post-compression chicane FL1CH4**

- 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)

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 $\sim$ 5000 bu/sec.

- 1st upgrade shutdown (2021/22) went well:
  user-run after quick beam commissioning.
  $\rightarrow$ Commissioning still ongoing whenever there's time. . .

- E-upgrade: two new very nice high-gradient modules for ACC2&3
  $\Rightarrow$ 100-110 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 be design of stage-0.

- Seeded operation still uncompromised goal of stage-0.

- We are looking forward to the shutdown in 2024/25!

Thank you for Listening!