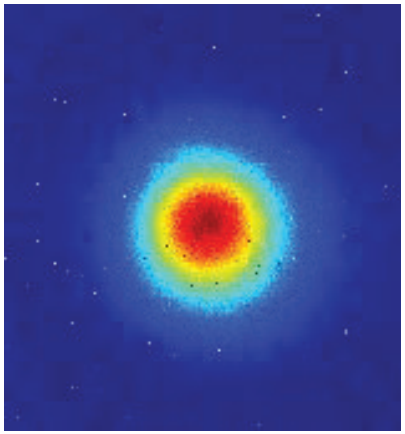
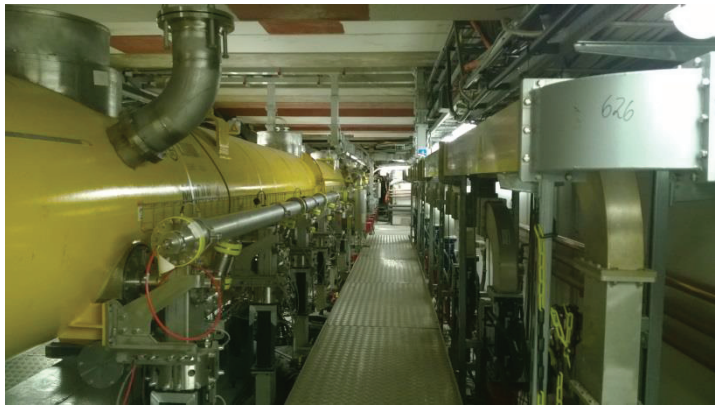
Optimizing of electron beam distribution at Eur. XFEL and FLASH.

FLASH.
Free-Electron Laser
in Hamburg

FLASH free-electron laser user facility at DESY



Bart Faatz



HELMHOLTZ
GEMEINSCHAFT

DESY

Outline.

FLASH.
Free-Electron Laser in Hamburg

- Layout/parameter FLASH.
- User wishes.
- Requirements on machine settings.
- Tests performed.
- User operation with multi-beamlines.
- Further developments.

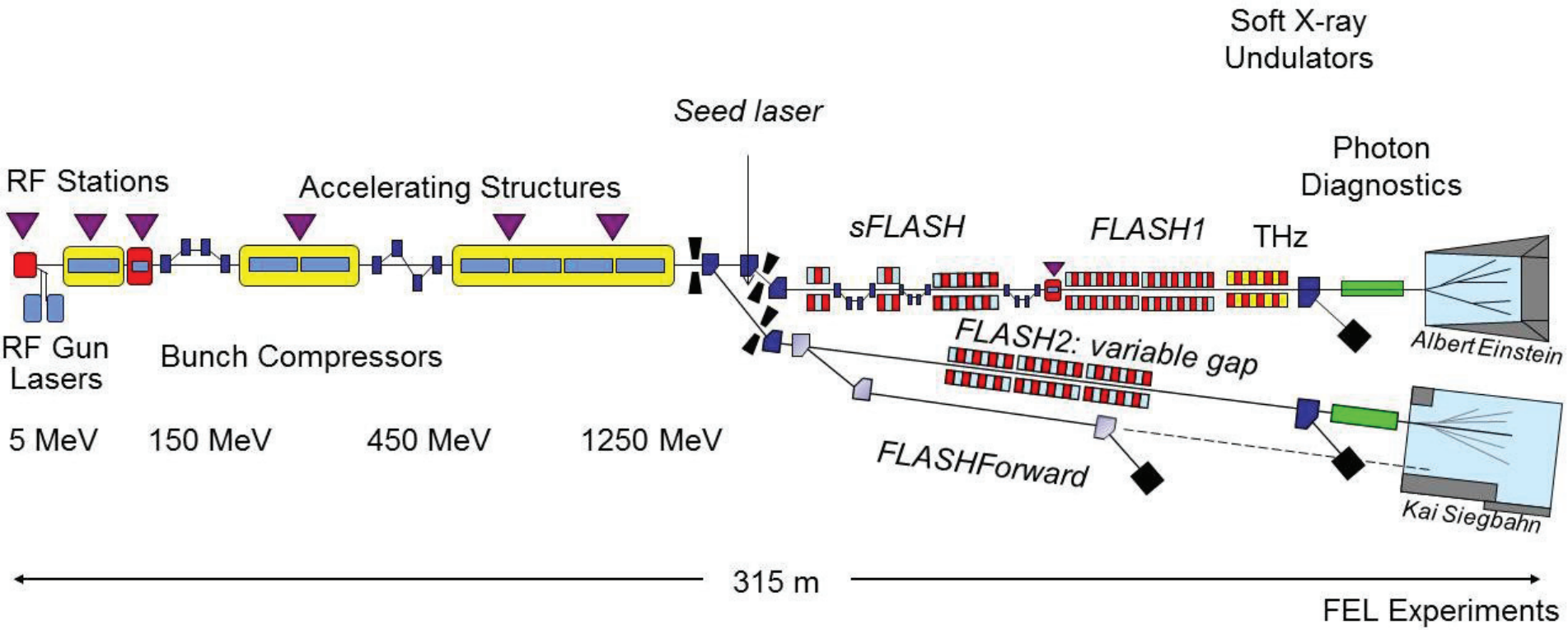
Possibilities at FLASH and Eur. XFEL are similar:

- *At Eur. XFEL, switching was foreseen from the start.*
- *At FLASH, the design was modified to allow for switching.*

Since FLASH is operating with two beamlines for several years, all parameters in this presentation are taken from FLASH.

Layout FLASH.

FLASH.
Free-Electron Laser in Hamburg



FLASH1 in user operation since 2005 (fixed gap undulator).

FLASH2 in user operation since 2016 (variable gap undulator).

FLASHForward R&D beamline for plasma-wakefield acceleration.

3 Injector lasers available of which normally 2 are used simulaneously.

DESY

Performance 2017.

FLASH.
Free-Electron Laser in Hamburg

FEL Radiation Parameters FL1 / FL2			
Wavelength range (fundamental)	4.2 – 51	4 – 90	nm
Average single pulse energy	1 – 500	1 – 1100	µJ
Pulse duration (FWHM)	< 30 – 200 fs		fs
Peak power (from av.)	1 – 5 GW		GW
Pulses per second	10 – 5000		
Spectral width (FWHM)	0.7 – 2 %	0.5 – 2 %	
Photons per pulse	$10^{11} – 10^{14}$		
Average Brilliance	$10^{17} – 10^{21}$		
Peak Brilliance	$10^{28} – 10^{31}$		

User wishes (machine side).

FLASH.
Free-Electron Laser in Hamburg

Variation in

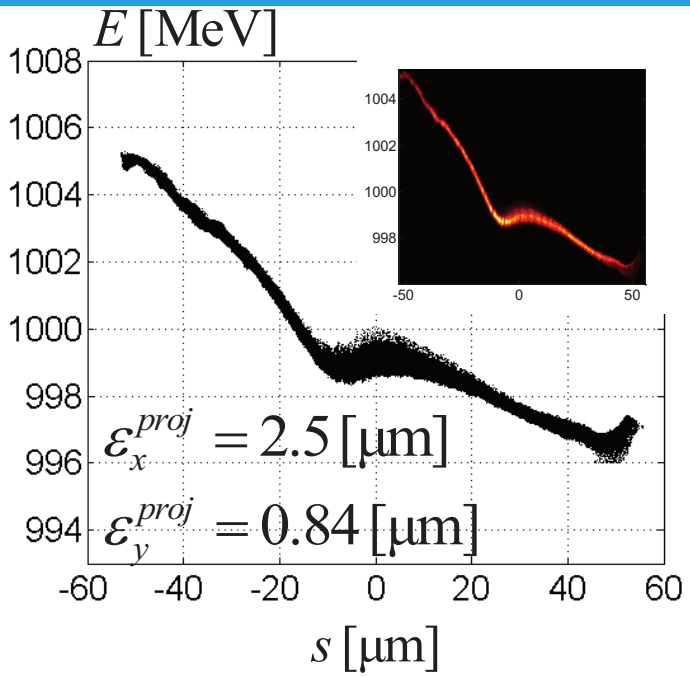
- Wavelength (including fast wavelength scans or several largely different wavelengths for one experiment).
- Pulse duration (bunch length) → different bunch charge .
- Pulse separation.
- Number of pulses.

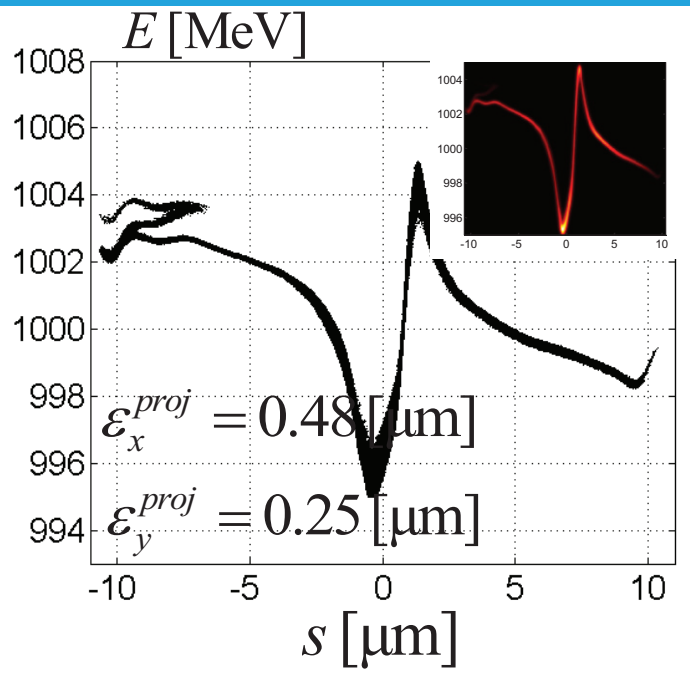
- Use variable gap undulators.
- Use two injector lasers.
- Do NOT reduce from 10 to 5 Hz with slow-switching.

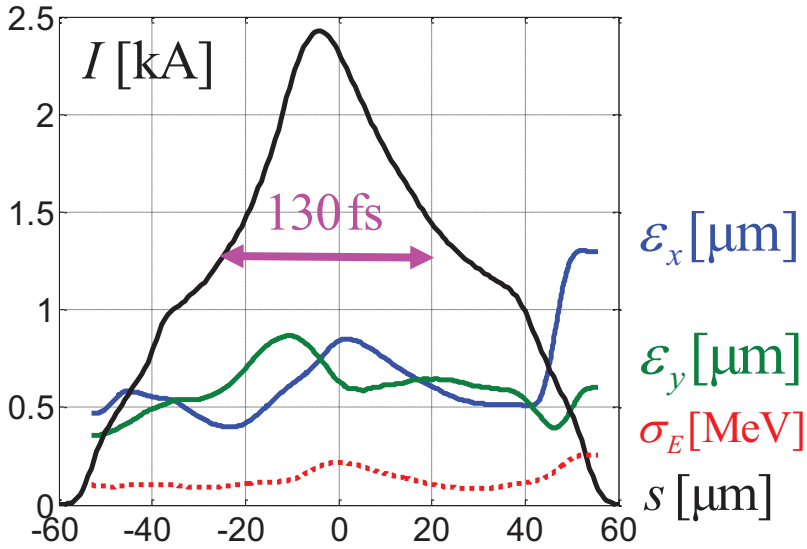
BIG CHALLENGE: different charges = different compression/injector settings.

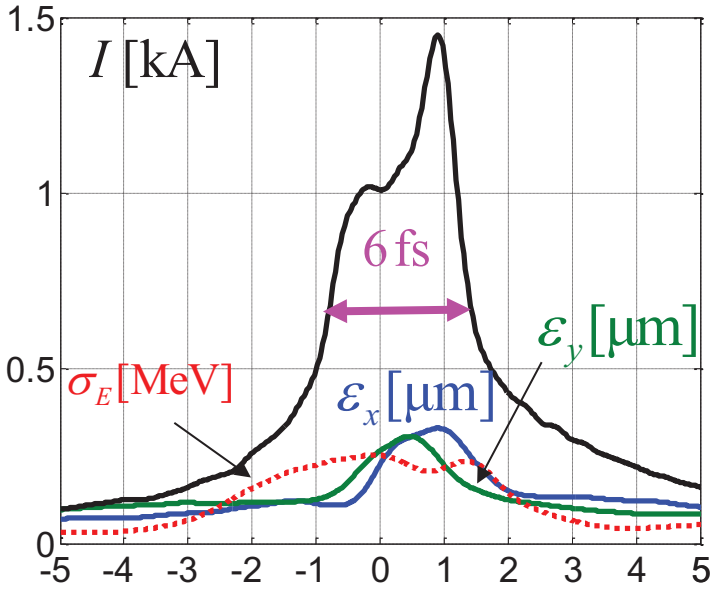
Different compression settings for 500 and 20 pC.

FLASH.
Free-Electron Laser in Hamburg







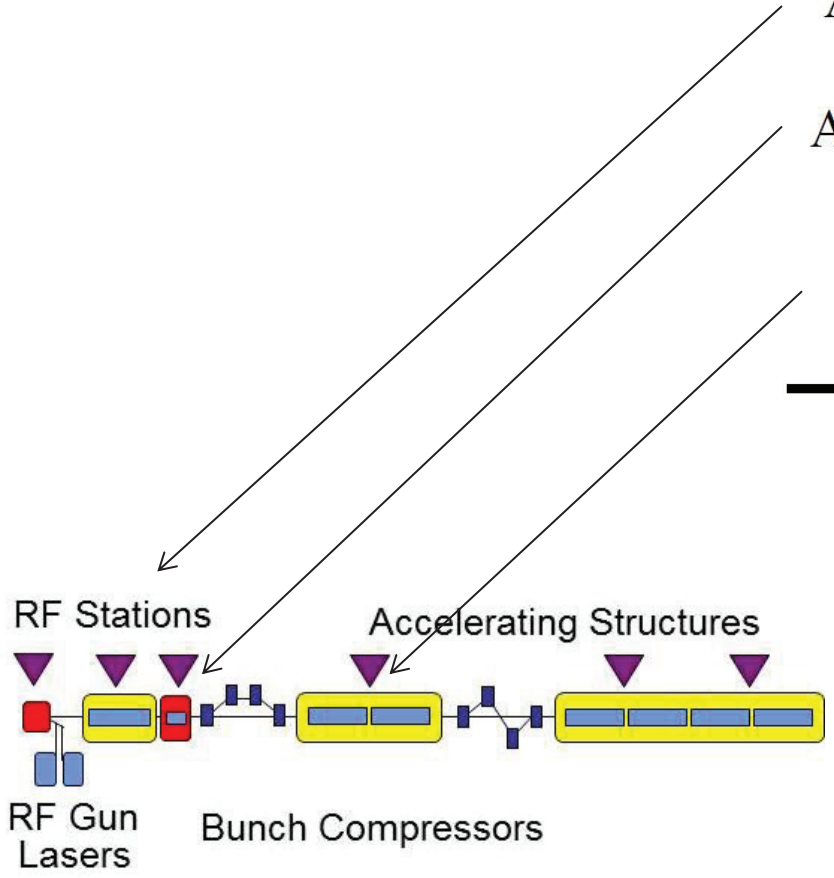


Courtesy: Igor Zagorodnov/Martin Dohlus

Requirements on machine RF (simulations).

FLASH.
Free-Electron Laser in Hamburg

q, nC		0.5	0.25	0.1	0.02
ACC1	$\|\Delta V\|/V$	0.004	0.0012	0.0003	0.00004
	$\|\Delta\varphi\|$, deg	0.025	0.013	0.007	0.0014
ACC39	$\|\Delta V\|/V$	0.01	0.0026	0.0008	0.00013
	$\|\Delta\varphi\|$, deg	0.061	0.033	0.02	0.004
ACC 2/3	$\|\Delta V\|/V$	0.0033	0.0026	0.0024	0.0016
	$\|\Delta\varphi\|$, deg	0.15	0.15	0.17	0.17



Optimized injector settings for each charge:

- Solenoid
- Spot on the cathode

Courtesy: Igor Zagorodnov/Martin Dohlus

DESY

Requirements on machine.

FLASH.
Free-Electron Laser in Hamburg

- *Solenoid focusing cannot be adjusted: optimization by changing gun phase and amplitude*
  - *Automatically changes all (on-crest) phases downstream.*

Restriction at FLASH:

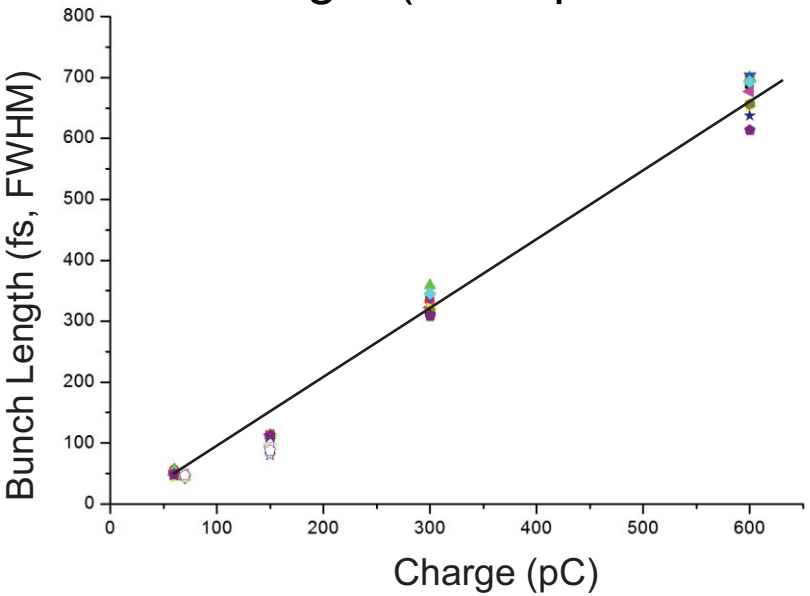
- *Laser spot on cathode cannot be changed (laser1 and laser2)*
  - *Limit on charge range that can be achieved.*
  - *Stability and beam quality an issue, especially at short wavelengths.*
- *Different injector lasers have different pulse duration.*

REMARK: for seeding or THz, there are in general different compression settings.

Tests performed at 0.7 GeV.

FLASH.
Free-Electron Laser in Hamburg

Bunch length (THz spectrometer) for different charges.



Charge	SASE (μJ)
70	31.3
150	113.9
320	180.7
660	202

Crucial were Gun phase and amplitude.

Charge (pC)	Gun ϕ	Gun ampl.	ACC1 ϕ	ACC1 ampl.	ACC39 ϕ	ACC39 ampl.	ACC23 ϕ	ACC23 ampl.	ACC45 ϕ	ACC45 ampl.
70	-4.7	3.98	1.1	160.8	-23.97	19.7	22.47	322.6	-6	223.6
150	-3.66	3.977	1.18	160.9	-23.98	19.7	22.52	322.6	-5	223.9
320	-0.6	3.977	0.98	160.9	-24.51	19.8	22.56	322.4	-1	222.8
660	-2.2	3.957	1.18	160.2	-24.36	19.1	23.39	323.4	-4	224.6

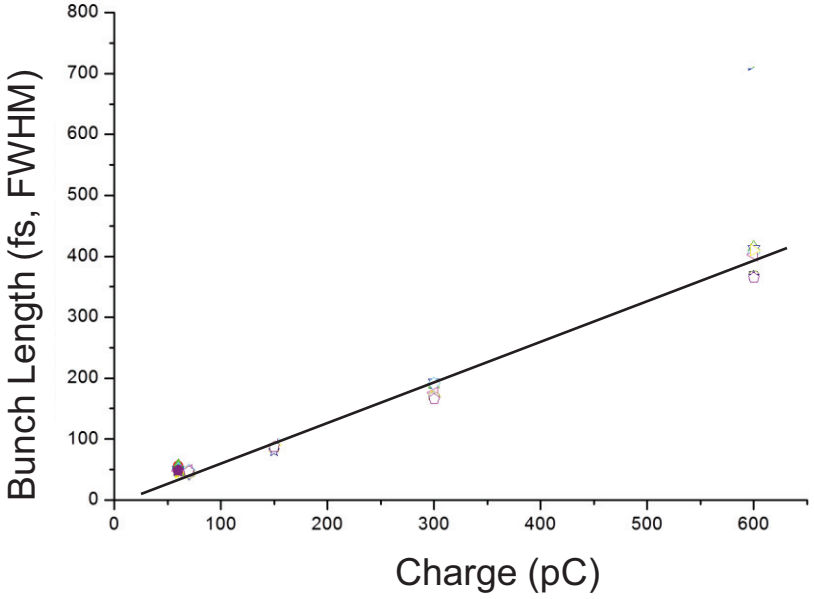
Courtesy: S. Ackermann/E. Hass

DESY

Tests performed at 1.1 GeV.

FLASH.
Free-Electron Laser in Hamburg

Bunch length (THz spectrometer) for different charges.



Charge	SASE (μJ)
80	31
150	68.4
300	98.3
630	117.8

Crucial were Gun phase and amplitude.

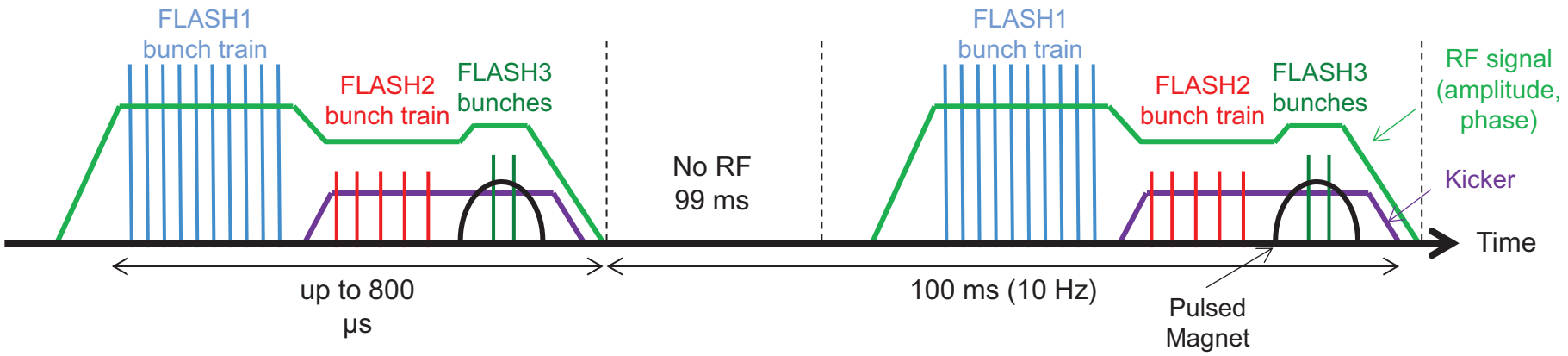
Charge (pC)	Gun ϕ	Gun ampl.	ACC1 ϕ	ACC1 ampl.	ACC39 ϕ	ACC39 ampl.	ACC23 ϕ	ACC23 ampl.	ACC45 ϕ	ACC45 ampl.	ACC67 ϕ	ACC67 ampl.
80	-5.2	3.873	1.16	160.5	-22.29	19.6	13.51	329.1	1.1	259.3	-0.07	345
150	0.1	3.886	1.27	160.4	-22.04	19.7	13.86	329	3.51	259.8	-0.37	344.9
300	-1.9	3.864	1.18	160.5	-22.47	19.6	14.26	329.6	2.5	259.8	-0.37	344.9
630	-2.13	3.862	1.01	161.1	-22.71	19.7	14.26	329.4	2.4	259.8	-0.44	345.7

Courtesy: S. Ackermann/E. Hass

DESY

Beamline switching (FLASH1, 2 and 3).

FLASH.
Free-Electron Laser in Hamburg



Requirements LLRF:

- **Small tunability of gradient or ACC45 and ACC67 for wavelength scans FLASH1**.
- Small tunability in phases of Gun, ACC1, ACC39 for variation in compression FLASH1,2 and 3.
- Allow for SASE in FLASH1 and seeding in FLASH2 or THz in FLASH1 and SASE in FLASH2.

Summary: Switch Times Needed

FLASH.
Free-Electron Laser in Hamburg

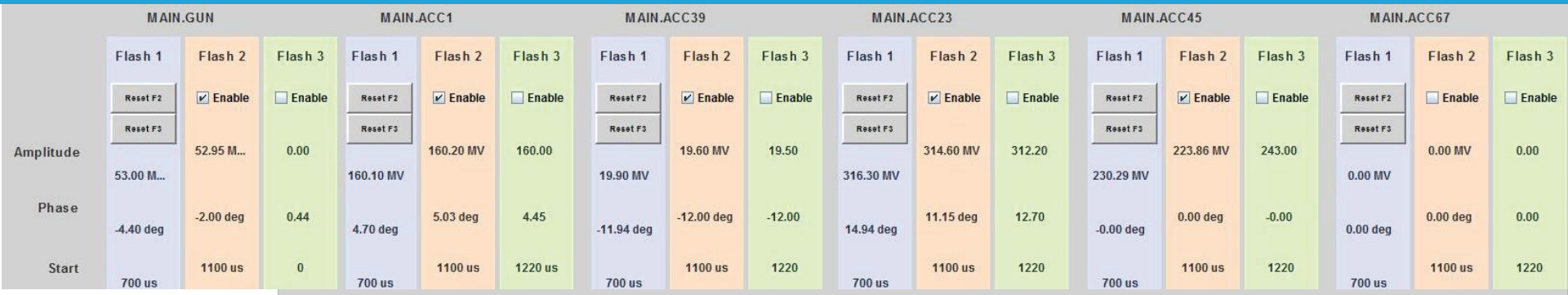
RF Station	Phase [deg.]	Amplitude [MV]	Transition time [µs]
GUN	+/-8	-0.1[MW]	50
ACC1	+/-2	+/-3	30
ACC39	+/-9	-3	60
ACC23	+/-3	-10	60
ACC45	+/-5	+/-15	100
ACC67	+/-5	+/-15	100

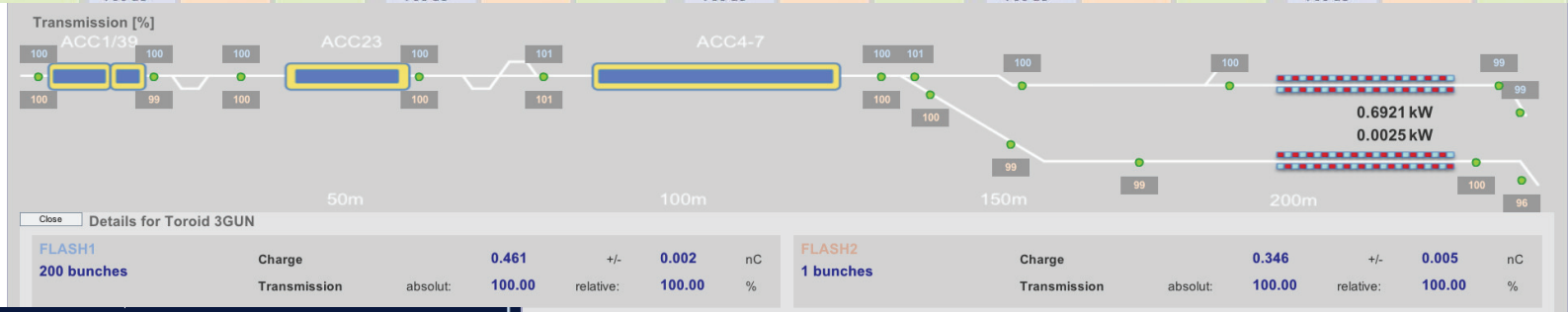
- **More tests needed for systematic setup.**

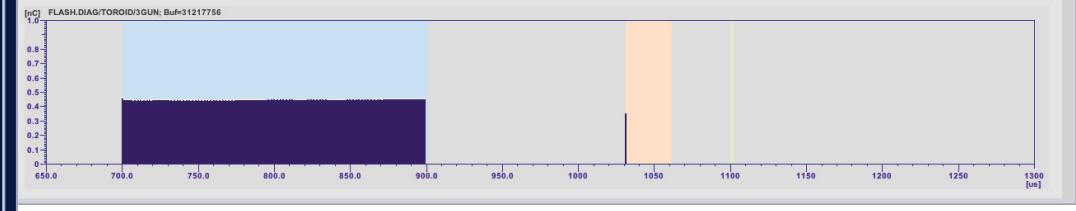
Courtesy: V. Ayvazyan

Enable simultaneous operation.

FLASH.
Free-Electron Laser in Hamburg





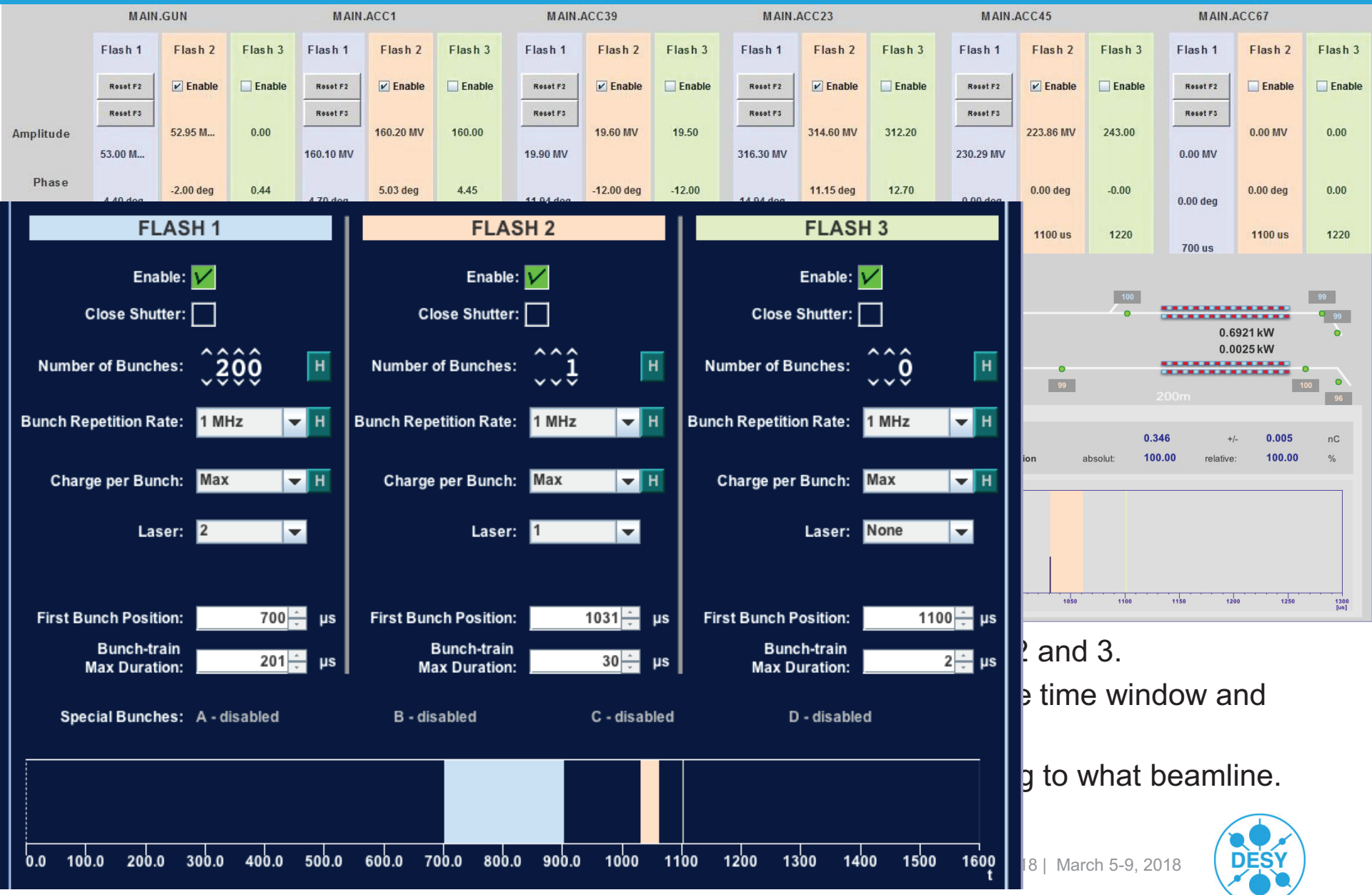


- Enable/disable FLASH1, 2 and 3.
- Define start time, available time window and rep.rate of each laser.
- Define which laser is going to what beamline.

DESY

Enable simultaneous operation.

FLASH.
Free-Electron Laser in Hamburg



2 and 3.

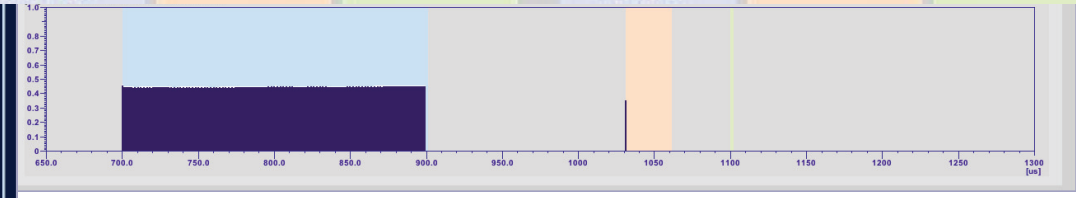
e time window and

g to what beamline.

DESY

Enable simultaneous operation.

FLASH.
Free-Electron Laser in Hamburg



- Enable/disable FLASH1, 2 and 3.
- Define start time, available time window and rep.rate of each laser.
- Define which laser is going to what beamline.

DESY

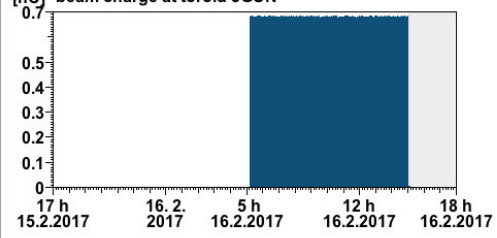
FL1 with SASE&THz, FL2 with short pulses SASE.

FLASH.
Free-Electron Laser in Hamburg

FLASH1.
Free-Electron Laser FLASH

Gruebel/Mueller, 20.8 nm+/- 0.10 nm, 1 bunch(es), 50-10

[nC] beam charge at toroid 3GUN

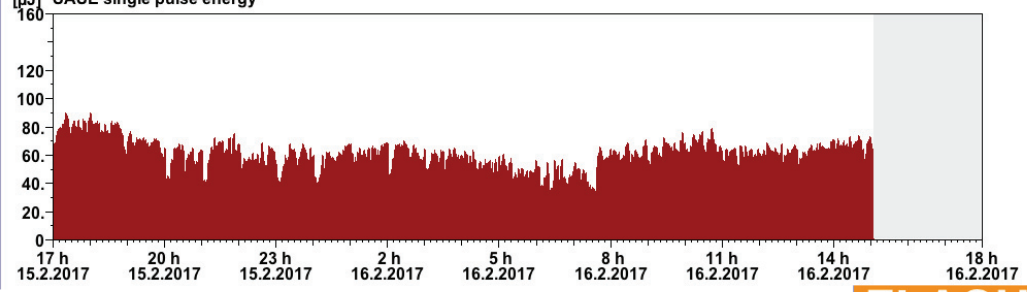


Bunches 1
Charge 0.68 nC
Rep.Rate 201 kHz

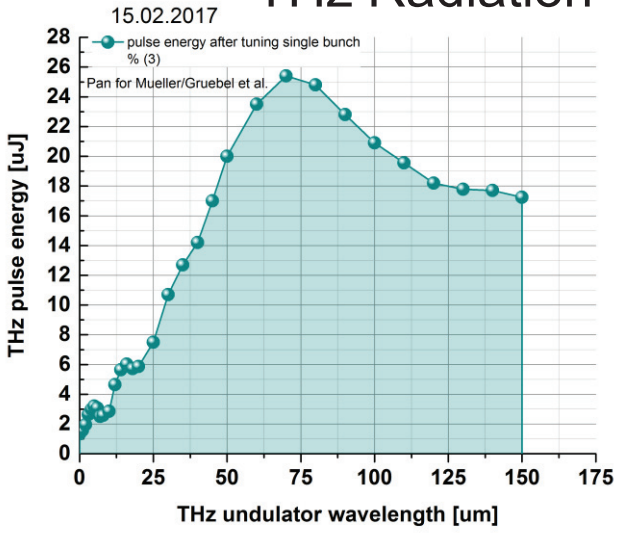
Beam En
Wavelen
SASE En

Ampl.	GUN	ACC1	ACC39	ACC2/3	ACC4/5	ACC6/7
	53.000 MV/m	159.99 MV	18.45 MV	308.02 MV	115.95 MV	0.00 MV
	53.000 MV/m	158.00 MV	19.60 MV	310.20 MV	111.78 MV	0.00 MV
Phase						
	-4.70 deg	4.92 deg	-10.42 deg	14.51 deg	1.00 deg	0.00 deg
	-1.50 deg	4.98 deg	-10.60 deg	10.53 deg	0.80 deg	0.00 deg

[µJ] SASE single pulse energy



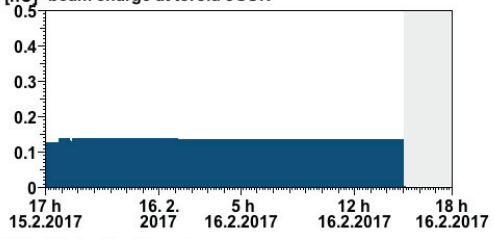
THz Radiation



FLASH2.
Free-Electron Laser FLASH

Rudenko, 51.7 nm+/- 0.30 nm, 35 bunch(es), 100kHz, < 50 fs, 20 µJ, FL26
SASE Delivery

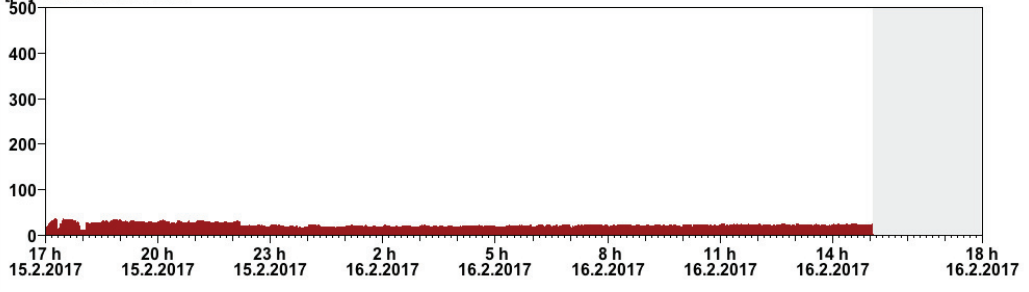
[nC] beam charge at toroid 3GUN



Bunches 10 Hz
30
Charge 0.14 nC
Rep.Rate 100 kHz

Beam Energy 560.3 MeV
Wavelength 53.1 nm
SASE Energy 23.9 µJ

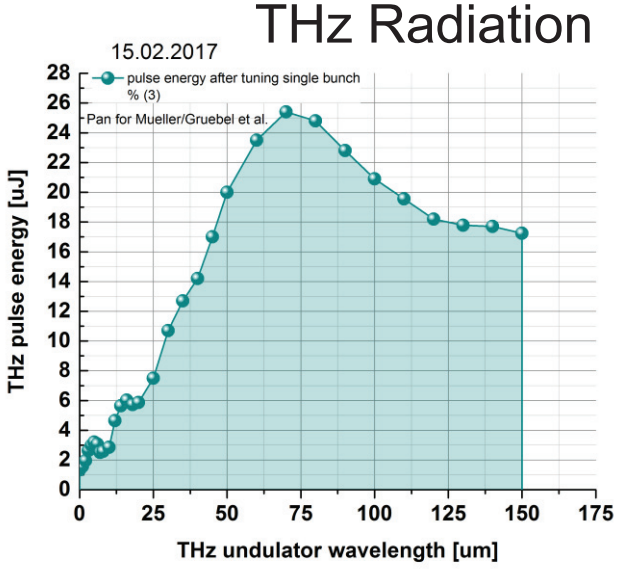
[µJ] Photonflux Tunnel



FL1 with SASE&THz, FL2 with short pulses SASE.

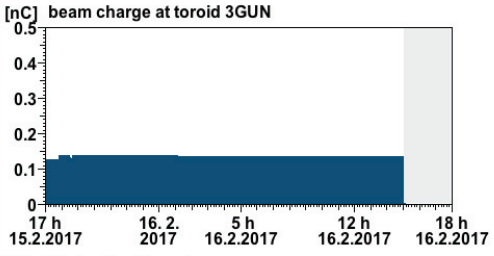
FLASH.
Free-Electron Laser in Hamburg

Ampl.	GUN	ACC1	ACC39	ACC2/3	ACC4/5	ACC6/7
	53.000 MV/m	159.99 MV	18.45 MV	308.02 MV	115.95 MV	0.00 MV
	53.000 MV/m	158.00 MV	19.60 MV	310.20 MV	111.78 MV	0.00 MV
Phase						
	-4.70 deg	4.92 deg	-10.42 deg	14.51 deg	1.00 deg	0.00 deg
	-1.50 deg	4.98 deg	-10.60 deg	10.53 deg	0.80 deg	0.00 deg



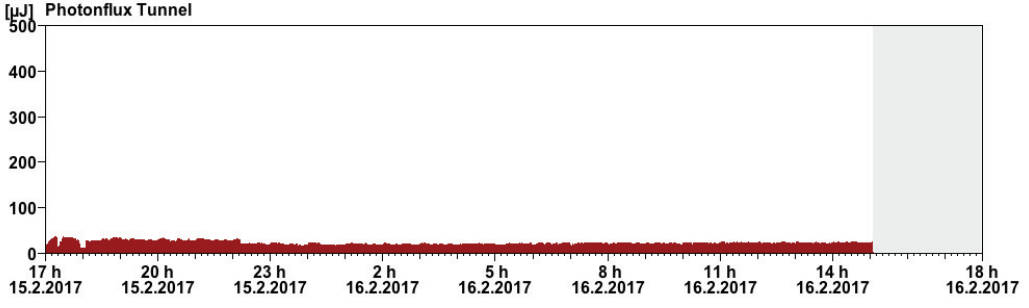
FLASH2.
Free-Electron Laser FLASH

Rudenko, 51.7 nm+/- 0.30 nm, 35 bunch(es), 100kHz, < 50 fs, 20 µJ, FL26
SASE Delivery



Bunches 10 Hz
30
Charge
0.14 nC
Rep.Rate
100 kHz

Beam Energy
560.3 MeV
Wavelength
53.1 nm
SASE Energy
23.9 µJ



sFLASH SASE and FLASHForward commissioning.

FLASH.
Free-Electron Laser in Hamburg

	R GUN	R ACC1	R ACC39	R ACC23	R ACC45	R ACC67
Flash 1	53.000 MV/m	160.080 MV	19.490 MV	312.000 MV	243.100 MV	0.000 MV
SP	0.000 H	160.08 H	19.49 H	304.00 H	243.10 H	0.00 H
old	0.000	160.080	19.490	312.000	242.100	0.000
RB	illegal property	160.063	19.483	312.002	242.075	0.000
Flash 1	-0.30 deg	4.36 deg	-12.00 deg	12.86 deg	1.70 deg	-0.00 deg
Phase	+0.44 H	+0.00 H	-0.00 H	+0.50 H	+6.00 H	+0.00 H
old	0.44	4.36	-12.00	12.86	1.70	-0.00
RB	illegal property	0.05	-0.04	0.54	5.97	0.00

Step in ACC23 gradient and phase (top and bottom picture are not corresponding, but within several minutes).

Transition time increased to 189 μs.

DESY

Simultaneous operation: further development.

FLASH.
Free-Electron Laser in Hamburg

Past: 50% users were single-bunch users, 50% were multi-bunch users.

Now: most users want multi-bunch.

Needed is a switching that gives both users long pulse trains

→ Switching RF from bunch to bunch.

→ Allow for both beam lines a rep.rate of 1 MHz.

Work in progress: Tests at <250 kHz at FLASH planned.

Thank you