Facility Report – DESY –

Holger Schlarb, Group Leader MSK/DESY
GSI, Darmstadt, 16. October 2019

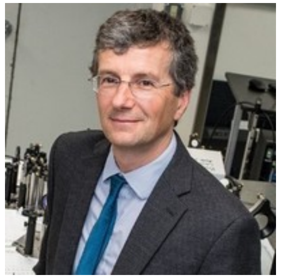
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES


European XFEL
X-Ray Free-Electron Laser
atomic structure & fs dynamics
of complex matter
CSSB
Centre for Structural Systems Biology
PETRA ext. East
REGAE
DESY II
PIA
SINBAD
LINAC II
CMTB
NanoLab
AMTF
MPI-SD
PETRA III
CFEL SCIENCE
PETRA ext. Nord
CUI THE HAMBURG CENTRE FOR ULTRAFAST IMAGING
Synchrotron radiation source (highest brilliance)
FLASH
VUV & soft-x-ray free-electron laser

DESY Accelerators & News

- **M-Director has changed:**

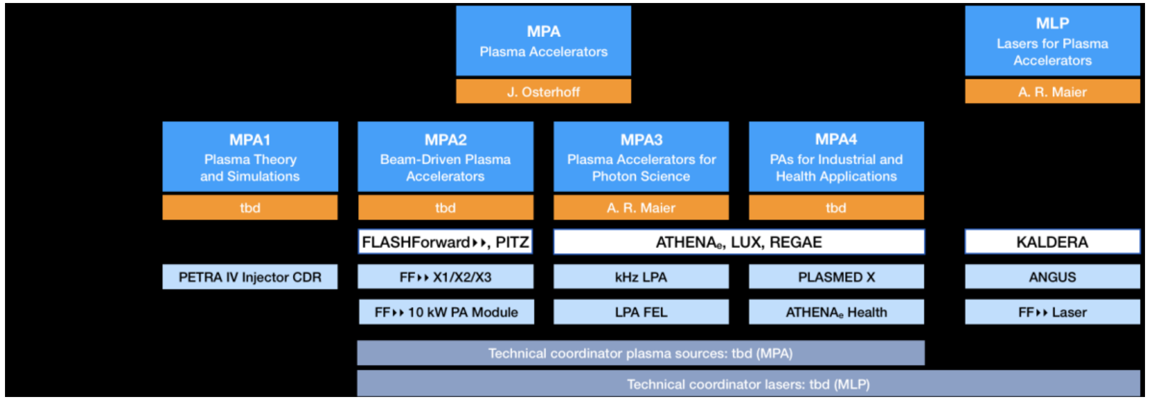
02/2019



Reinhard Brinkmann

Wim Leemans

- **Plasma Accelerator Group:**



~ kHz, ~ J
Class laser

- **Large conventional accelerator projects:**

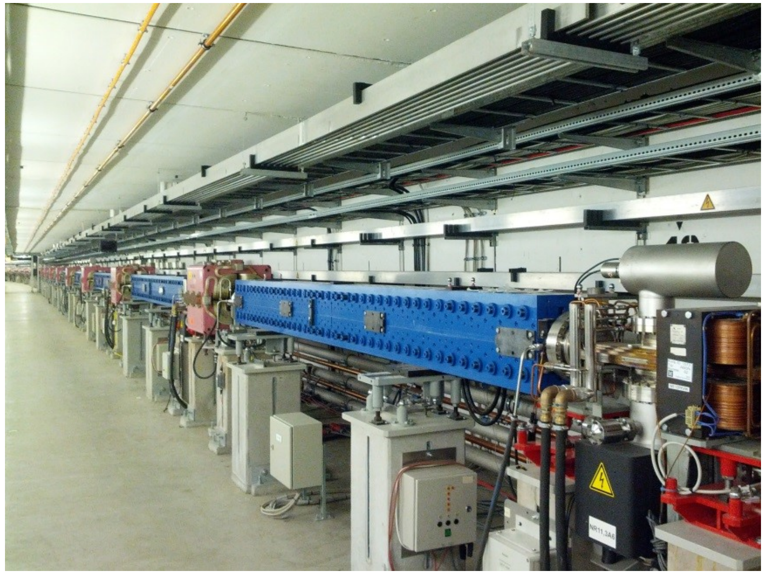
  - **FLASH2020+** 2020 (Und/Energy/Adv. FEL/Seeding/Synchr.)
  - **PETRAIV** 2025 (CDR compl.; MBA, x100 brilliance)
  - **EuXFEL-CW** >2030 (CW operation at EuXFEL)

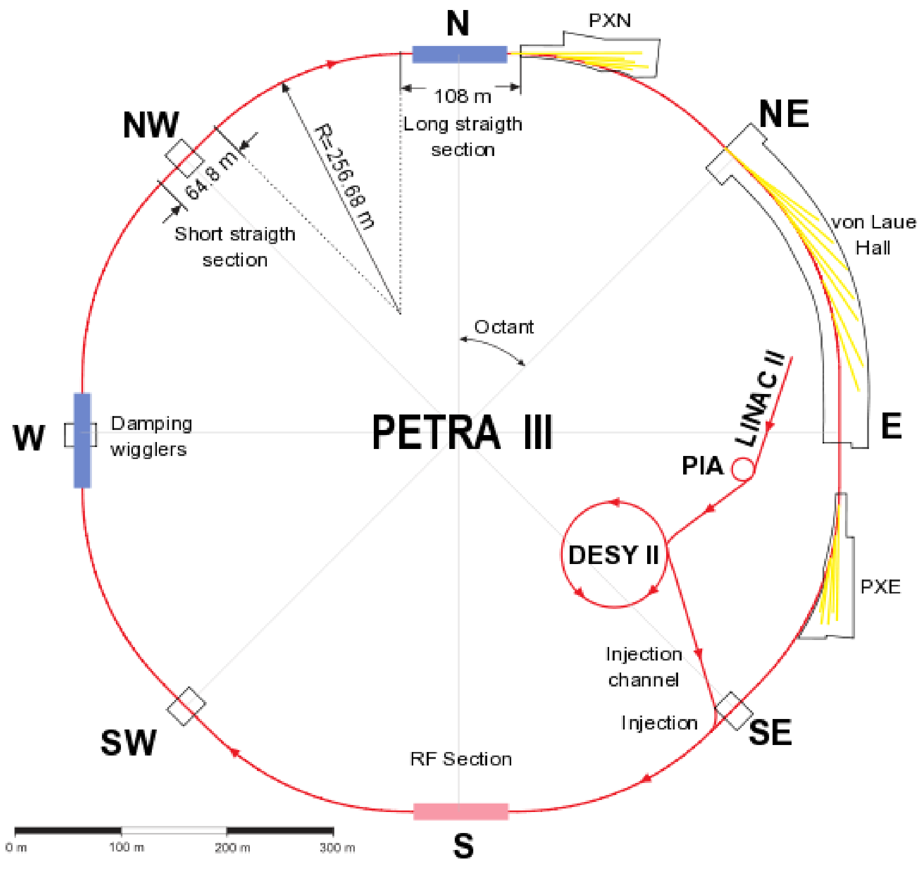
PETRA III / IV

PETRA III

Parameter	PETRA III	
Energy / GeV	6	
Circumference /m	2304	
Emittance (horz. / vert.) /nm	1.2 / 0.012	
Total current / mA	100	
Number of bunches	960	40
Bunch population / 10^{10}	0.5	12
Bunch separation / ns	8	192

Damping Wigglers: B ~ 1.5 T, λ = 0.2 m
2 x 10 x 4 m = 80 m
ε_x: 5 nm → 1.2 nm

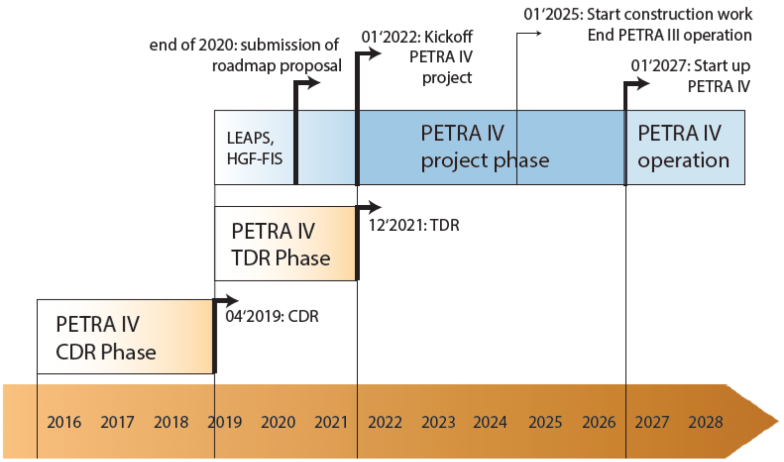


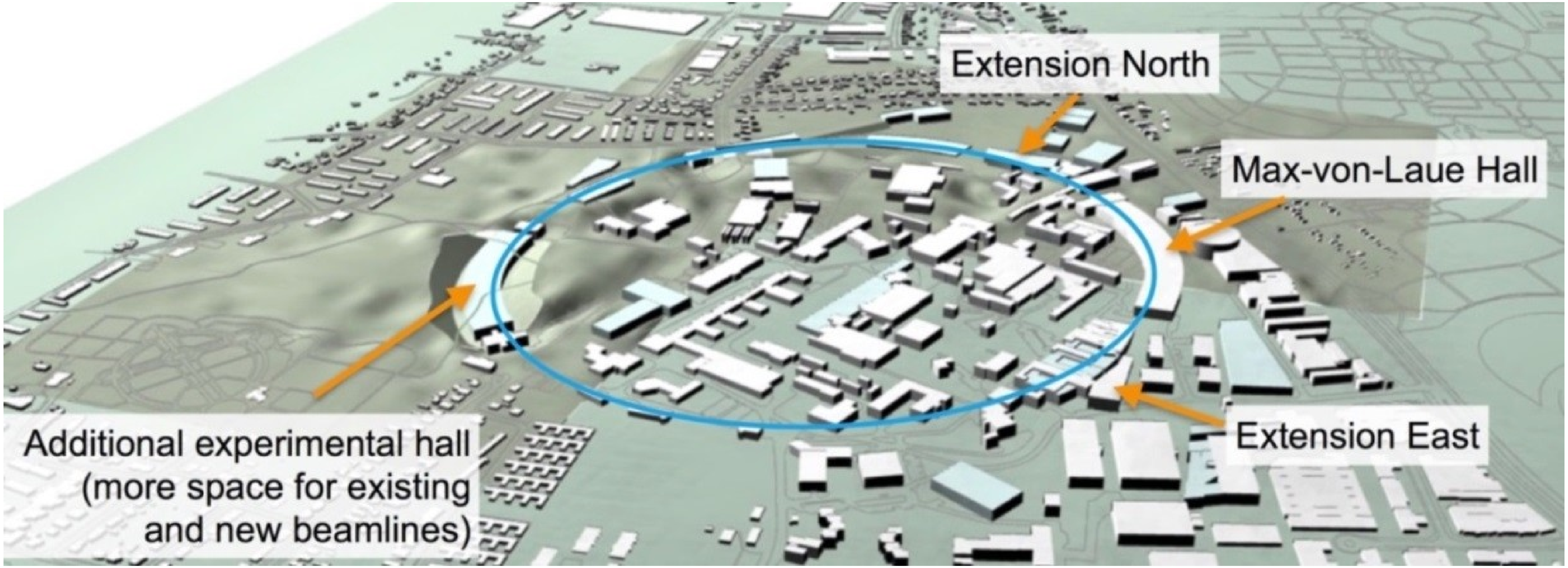


Dispersion correction in the wiggler sections:
$D_x <$ 18 mm, $D_y <$ 5 mm

PETRA IV

- CDR is ready for publishing
- TDR preparation has started
- Work package structure defined
- x 100 improved emittance in x/ diff. limit at 1 Å





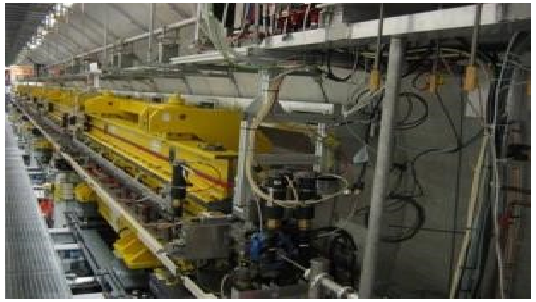
FLASH

FLASH Layout

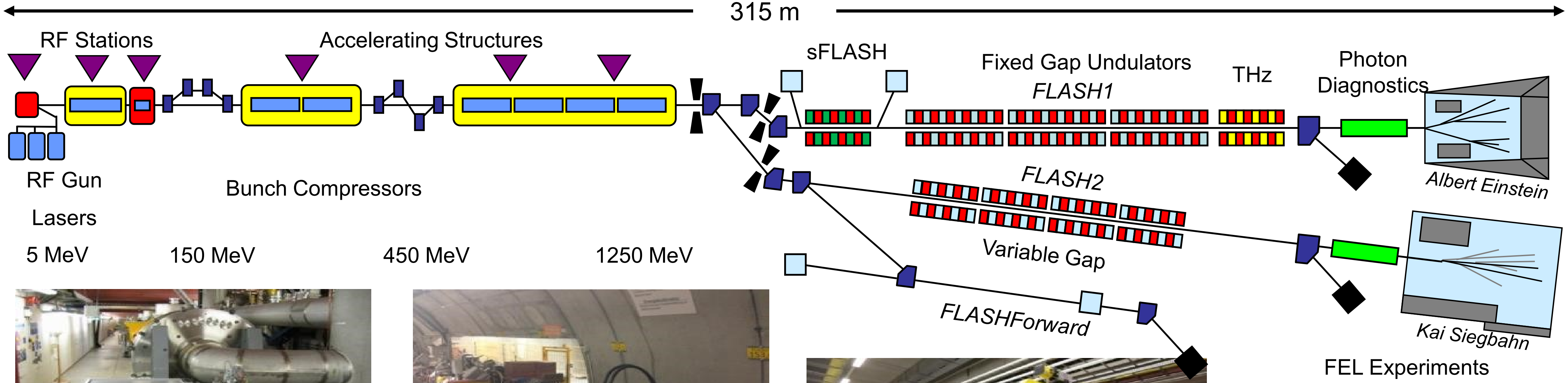
3rd harmonic sc module 3.9 GHz

TESLA type superconducting accelerating modules 1.3 GHz

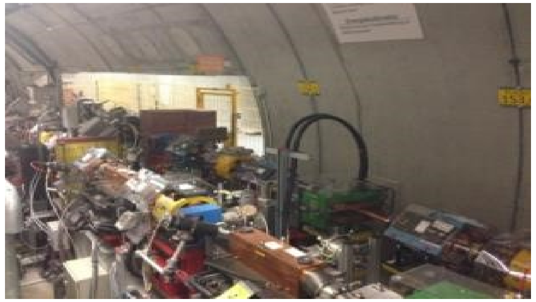
FLASH1 fixed gap undulators



FLASH1 Albert Einstein Hall



Normal conducting 1.3 GHz RF gun
Ce_2Te cathode / 3 injector lasers



Extraction to FLASH2

FLASH2 variable gap undulators

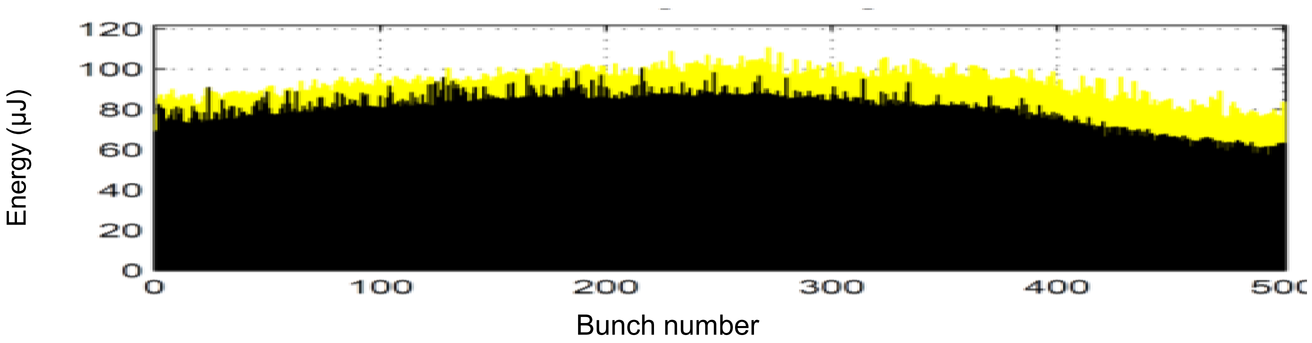
FLASH2 Kai Siegbahn Hall

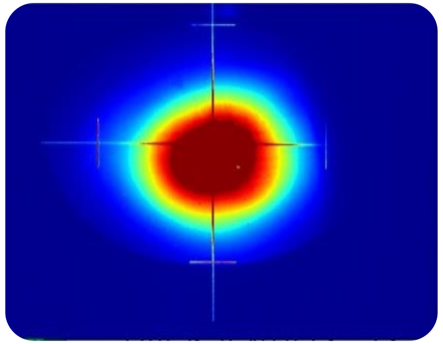
FLASH Parameters 2017 / 2018

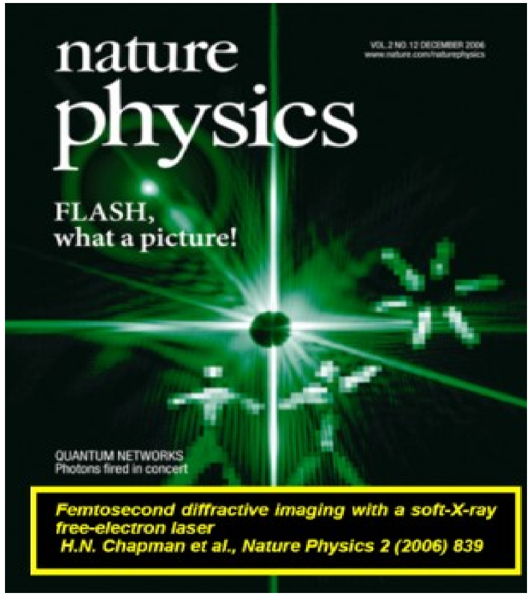
No changes in parameters

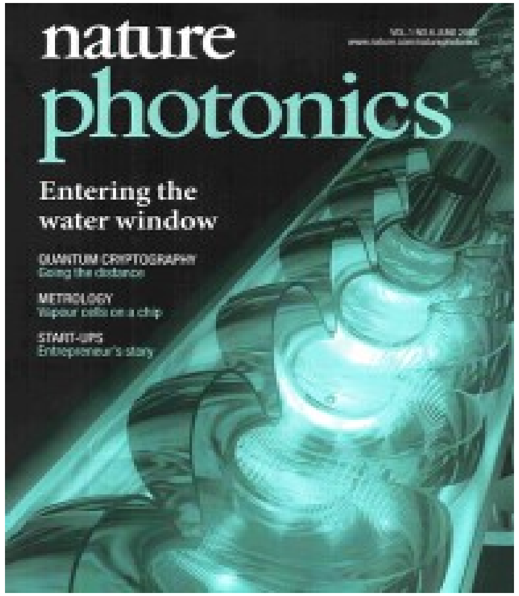
FEL Radiation Parameter FL1 / FL2	
Wavelength range (fundamental)	4.2 – 51 nm / 4 – 90 nm
Average single pulse energy	1 – 500 μJ / 1 – 1000 μJ
Pulse duration (FWHM)	< 30 – 200 fs
Peak power (from av.)	1 – 5 GW
Pulses per second	10 – 5000
Spectral width (FWHM)	0.7 – 2 % / 0.5 – 2 %
Photons per pulse	$10^{11} – 10^{14}$
Average Brilliance	$10^{17} – 10^{21}$ B*
Peak Brilliance	$10^{28} – 10^{31}$ B*

* photons/ s/ mrad²/ mm²/ 0.1%bw





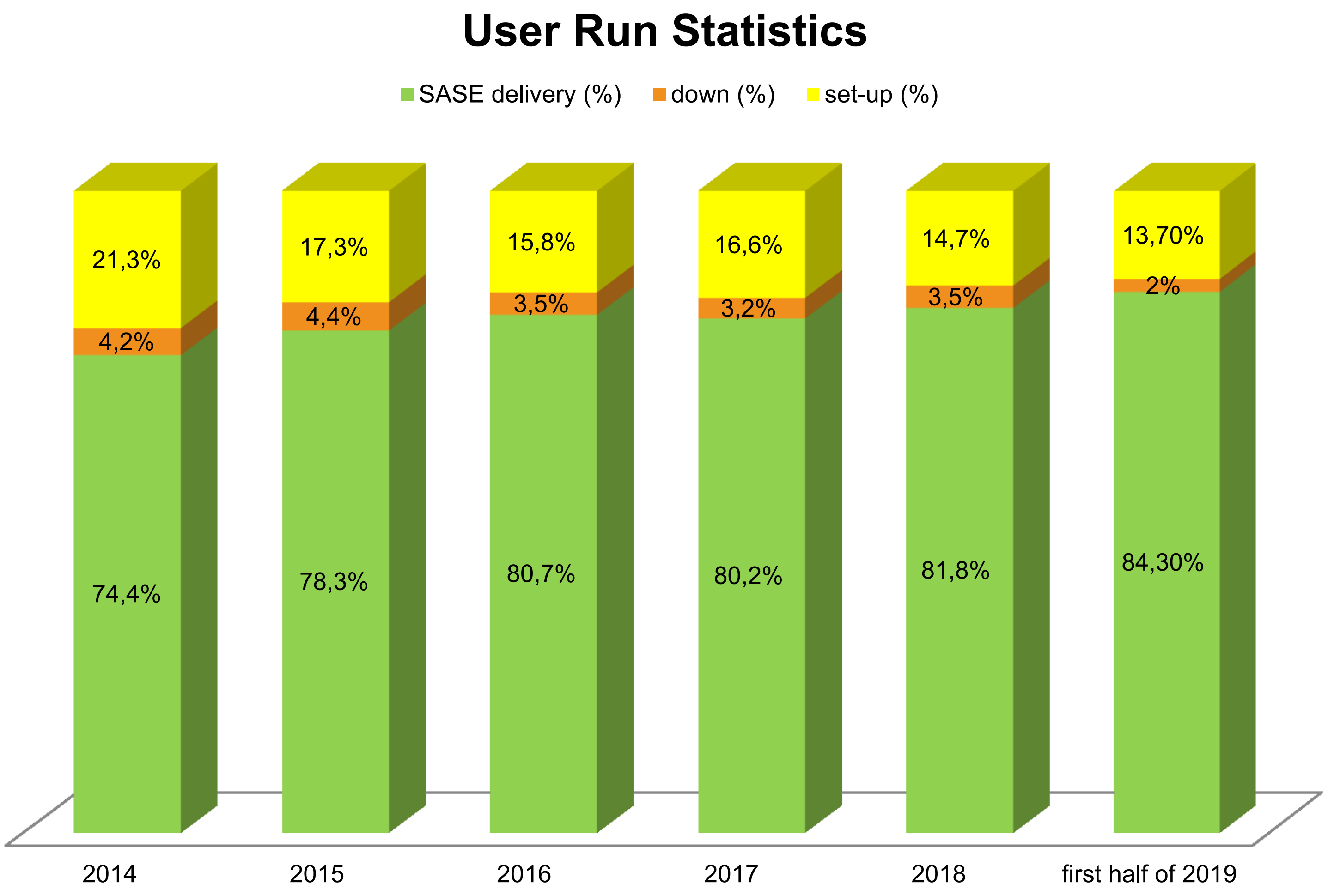


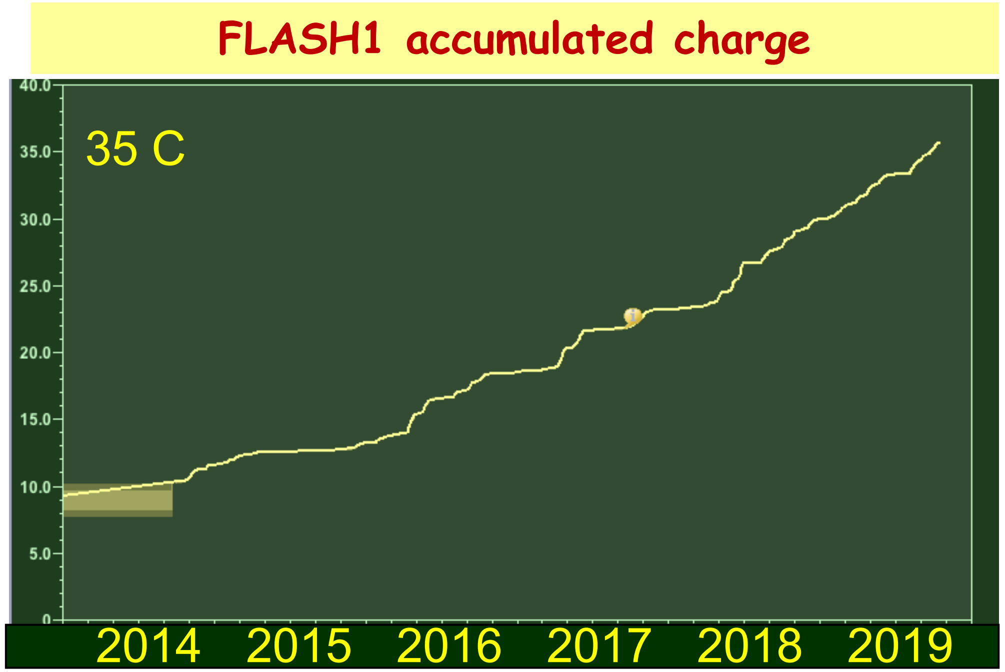


http://photon-science.desy.de/facilities/flash/publications/scientific_publications

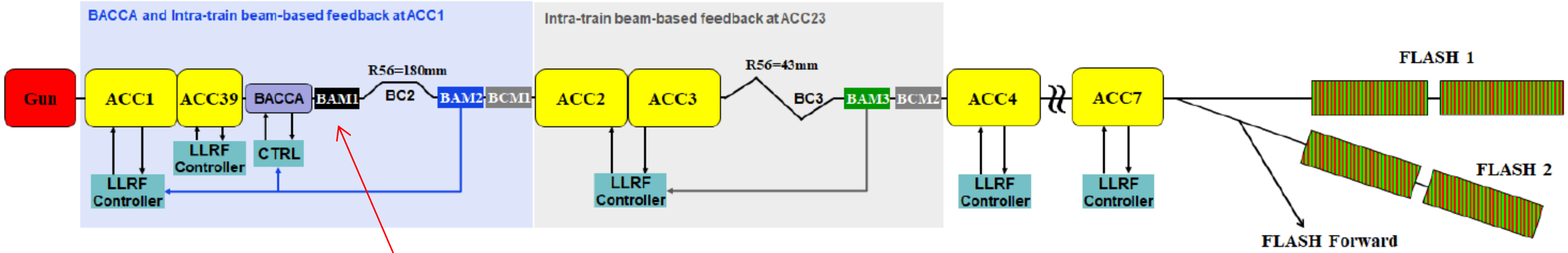
FLASH1 user run operation statistics 2014 - 2018

Slight decrease in tuning time over the years despite user experiments complexity and demands increase

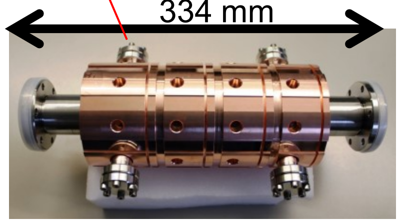




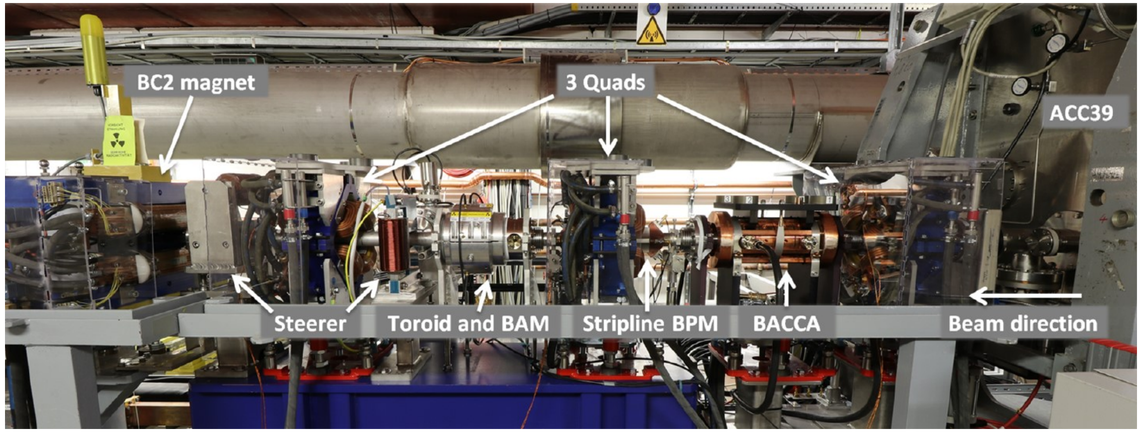
BACCA



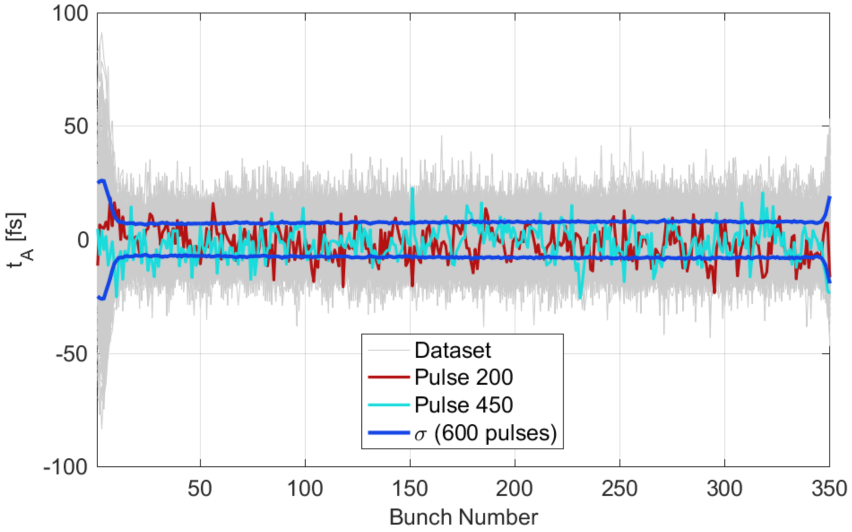
Fast arrival time stabilization towards 1 fs



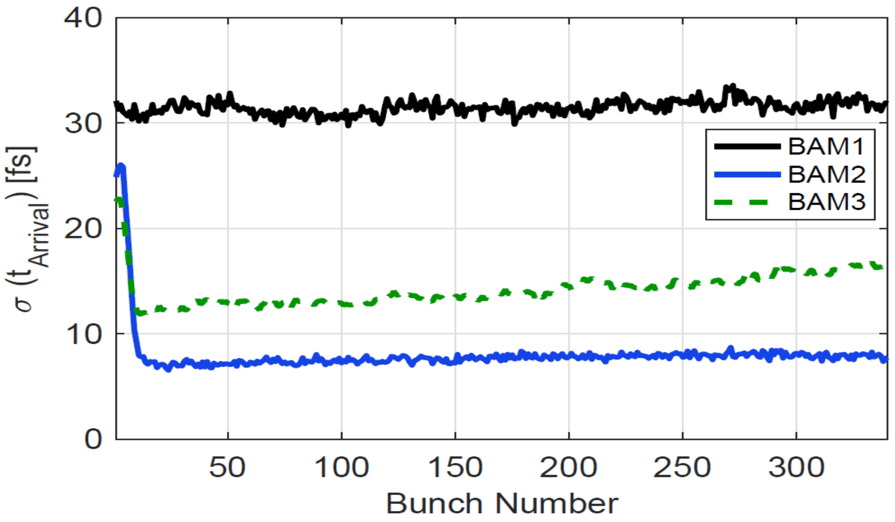
Courtesy: MSK, S. Pfeiffer, B. Lautenschlager et al.



- Normal conducting, S-band cavity “Bunch Arrival Corrector CAvity”(BACCA).
- Larger bandwidth to improve the arrival time stability below 5 fs
- Commissioning result: arrival time stability improved from 25 fs (rms) to 8.5 fs (rms)
- The steady state value of the arrival time stability is reached within the first 10 bunches (10 μs for 1 MHz).



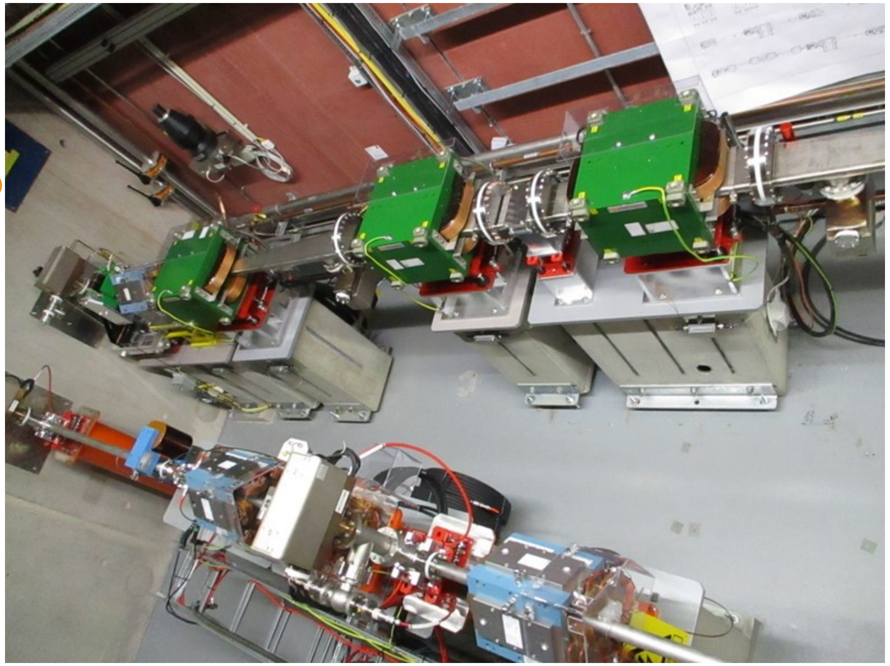
Mean free arrival time of the second BAM (BAM2).



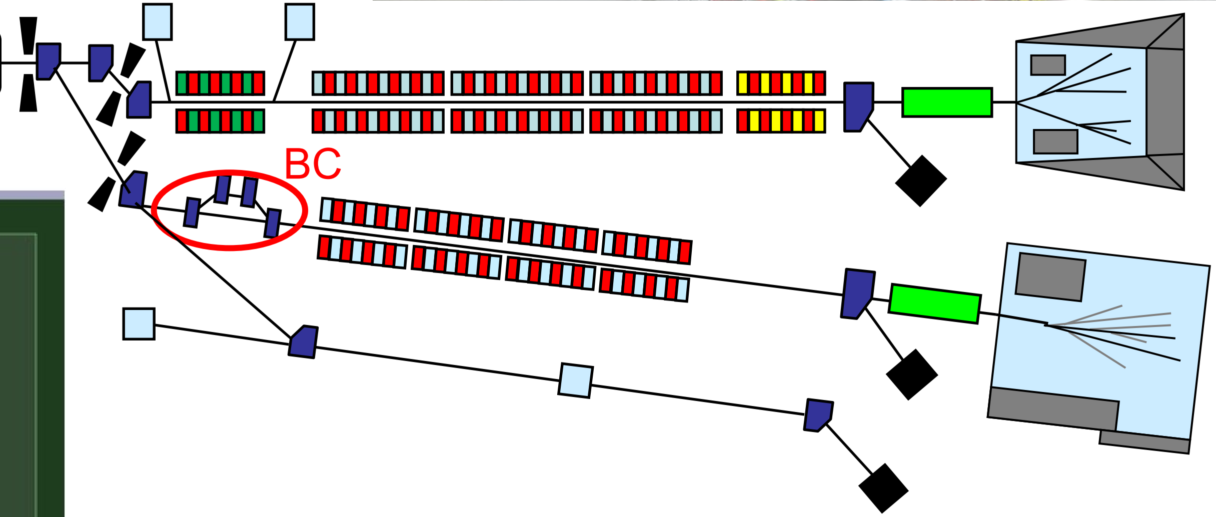
Standard deviation of the arrival time.

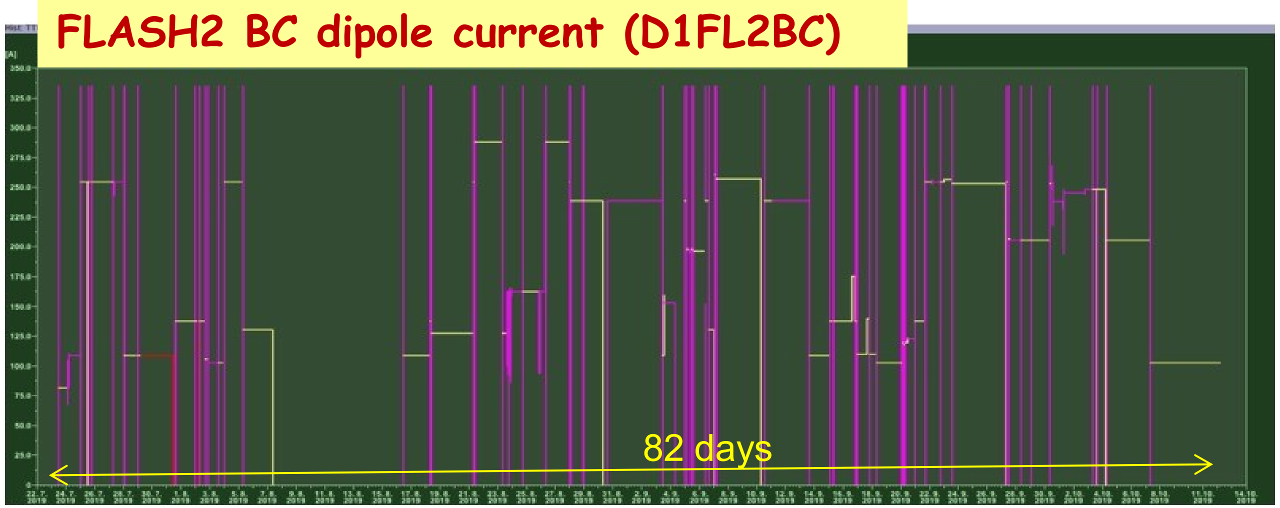
FLASH2 Bunch Compressor

Improves emittance, stability, flexibility, and short bunch generatio



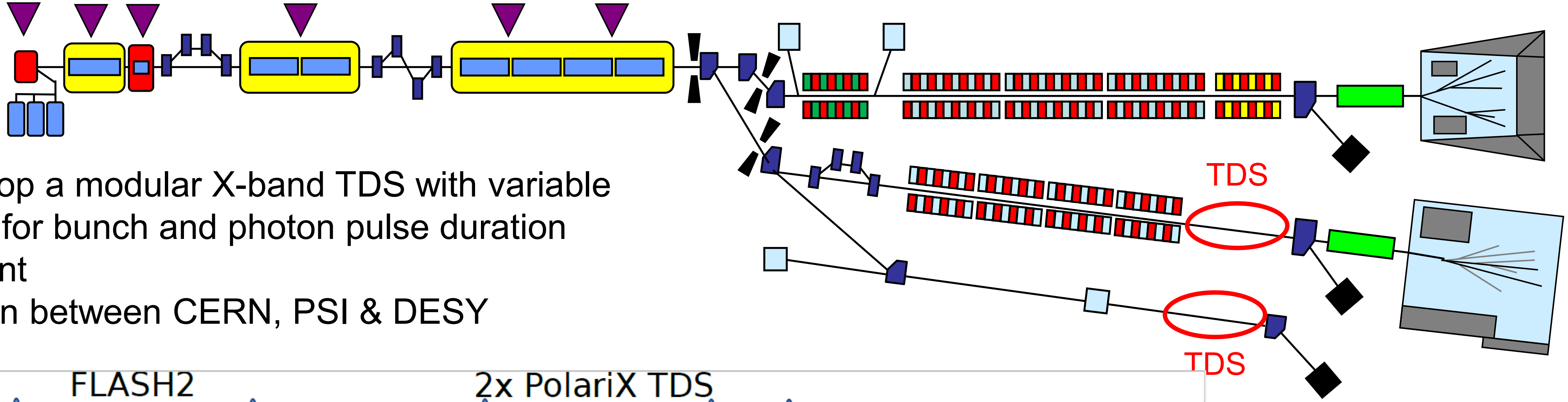
- Additional bunch compressor downstream extraction
  - Installed in June 2019, now routinely operated
  - Less compression at lower energies
  - Better control of CSR and space charge effects
  - Simulations show a significant improvement of beam properties



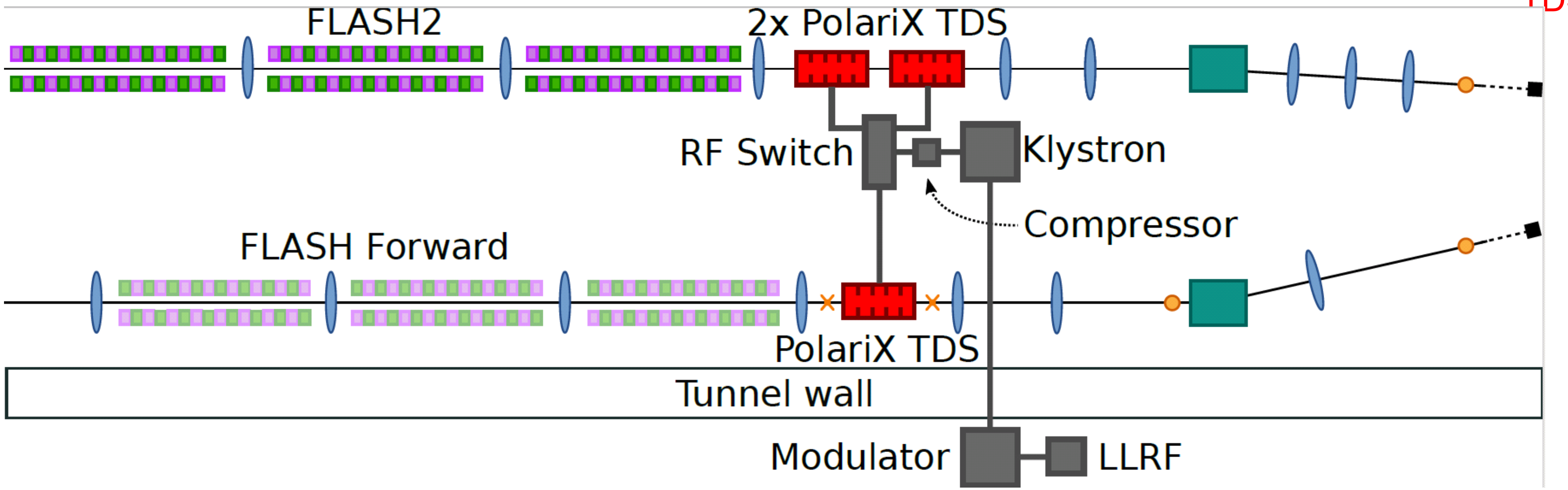


PolariX-TDS

Measures the longitudinal phase space with fs precision



- Goal: Develop a modular X-band TDS with variable polarization for bunch and photon pulse duration measurement
- Collaboration between CERN, PSI & DESY



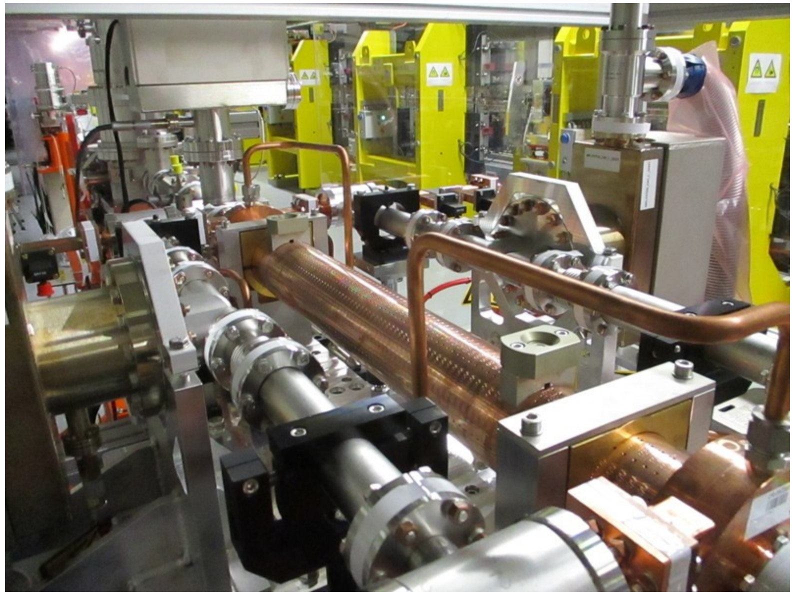
more details in poster M. Reukauff

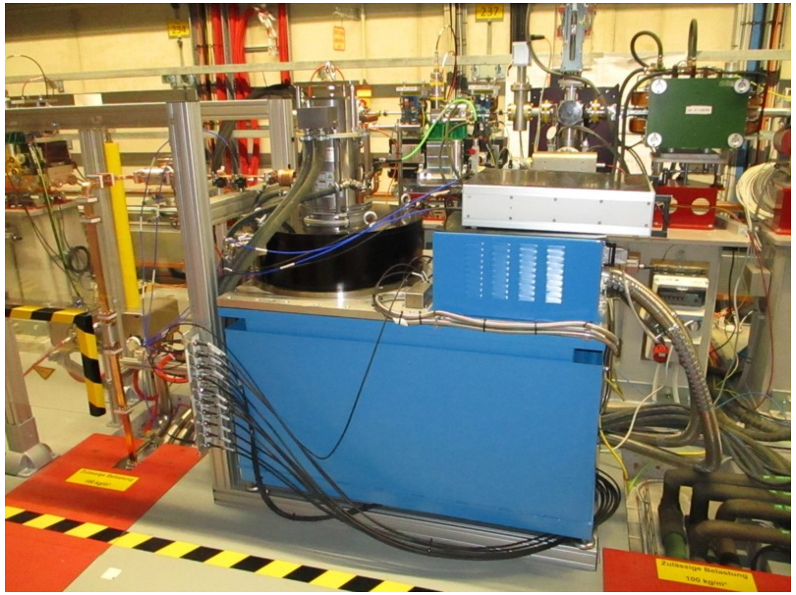
PolariX-TDS

FLASHForward

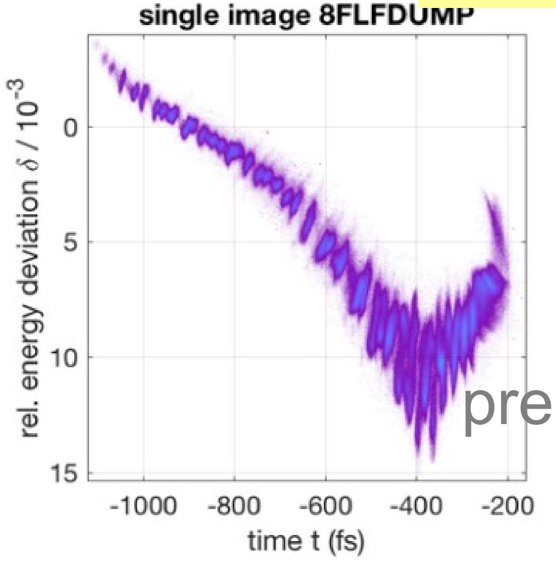
- Prototype has been installed in June 2019 in FLASHForward
- First measurements performed

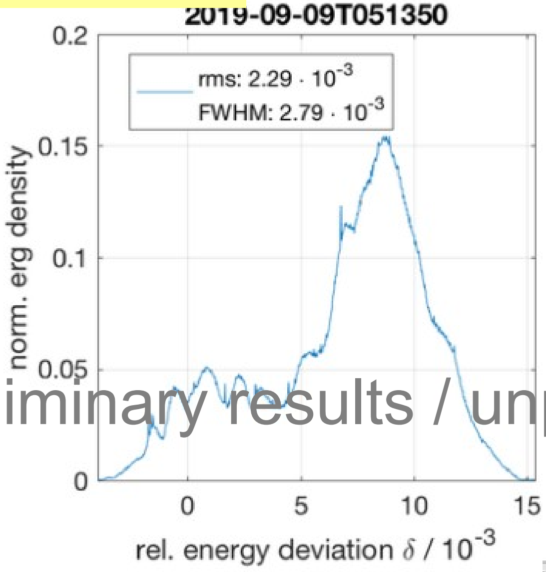
more details in poster M. Reukauff

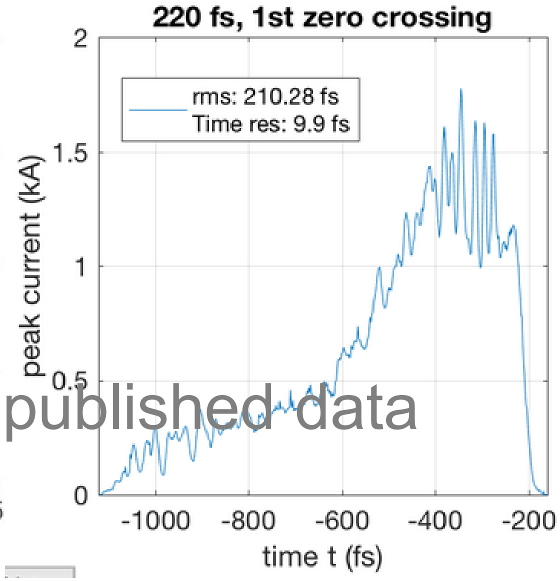




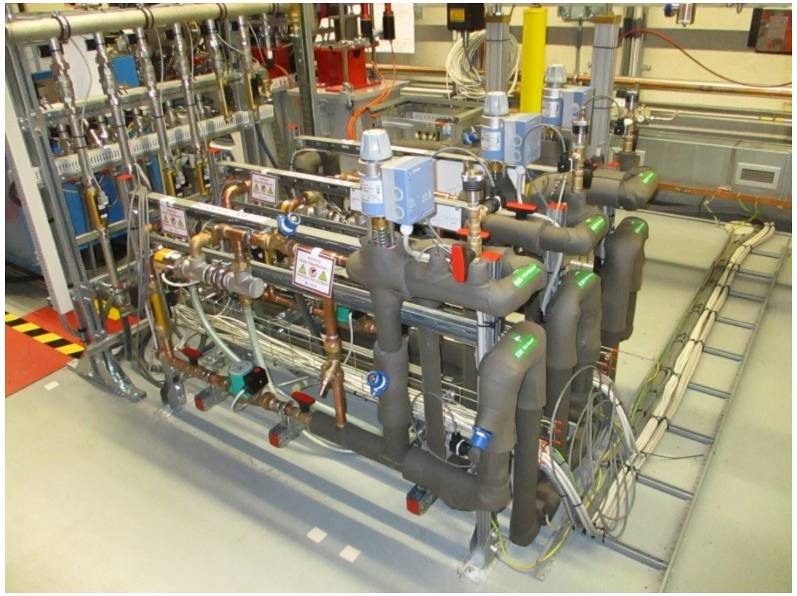
XTDS (FLF/FL2) station / klystron & klystron tank







preliminary results / unpublished data

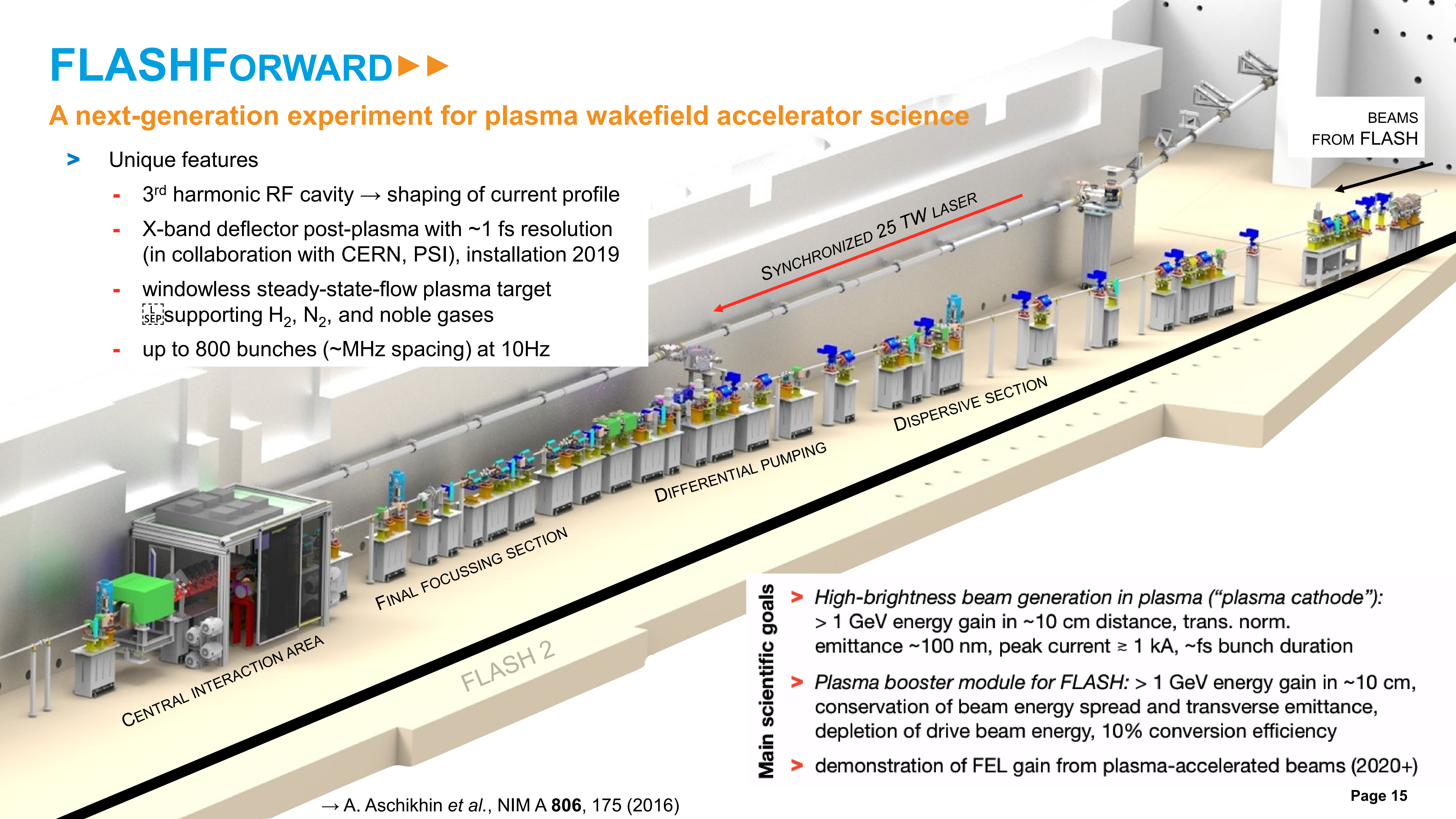


XTDS (FLF/FL2) station / cooler units

FLASHForward►►

A next-generation experiment for plasma wakefield accelerator science

- Unique features
  - 3^{rd} harmonic RF cavity → shaping of current profile
  - X-band deflector post-plasma with ~1 fs resolution (in collaboration with CERN, PSI), installation 2019
  - windowless steady-state-flow plasma target supporting H_2, N_2, and noble gases
  - up to 800 bunches (~MHz spacing) at 10Hz



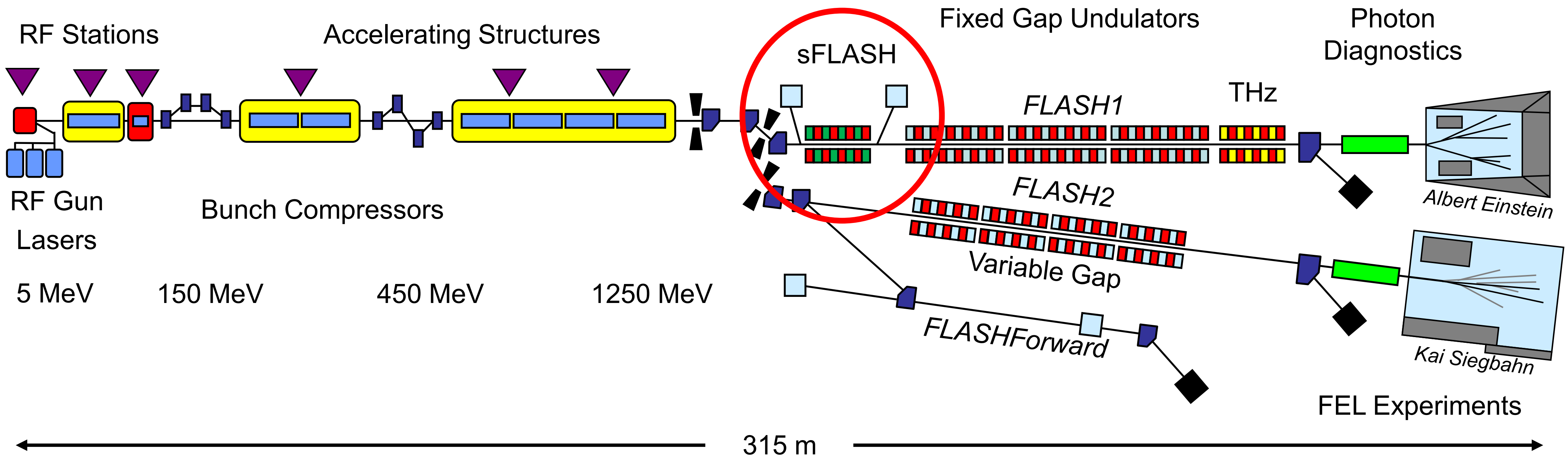
Main scientific goals

- *High-brightness beam generation in plasma ("plasma cathode"):* > 1 GeV energy gain in ~10 cm distance, trans. norm. emittance ~100 nm, peak current ≳ 1 kA, ~fs bunch duration
- *Plasma booster module for FLASH:* > 1 GeV energy gain in ~10 cm, conservation of beam energy spread and transverse emittance, depletion of drive beam energy, 10% conversion efficiency
- demonstration of FEL gain from plasma-accelerated beams (2020+)

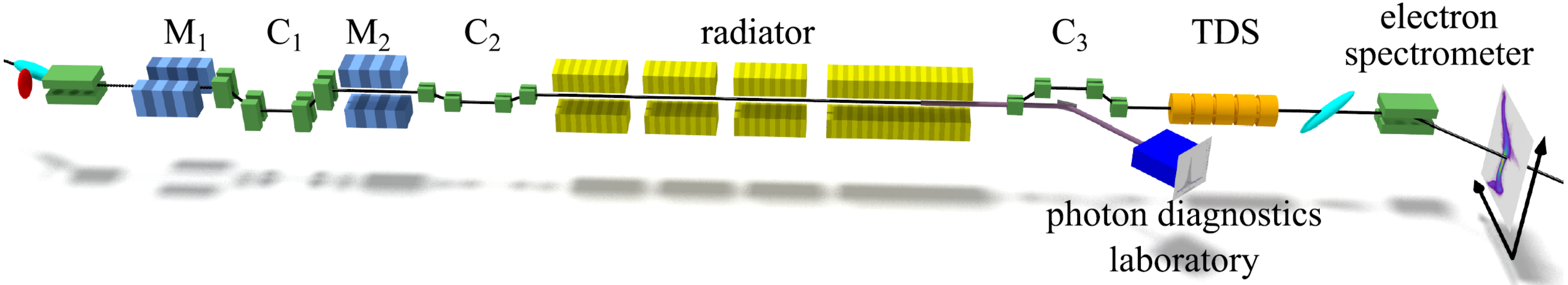
→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)

sFLASH – The Seeding Test Facility at FLASH

sFLASH as R&D experiment integrated into the FLASH user facility

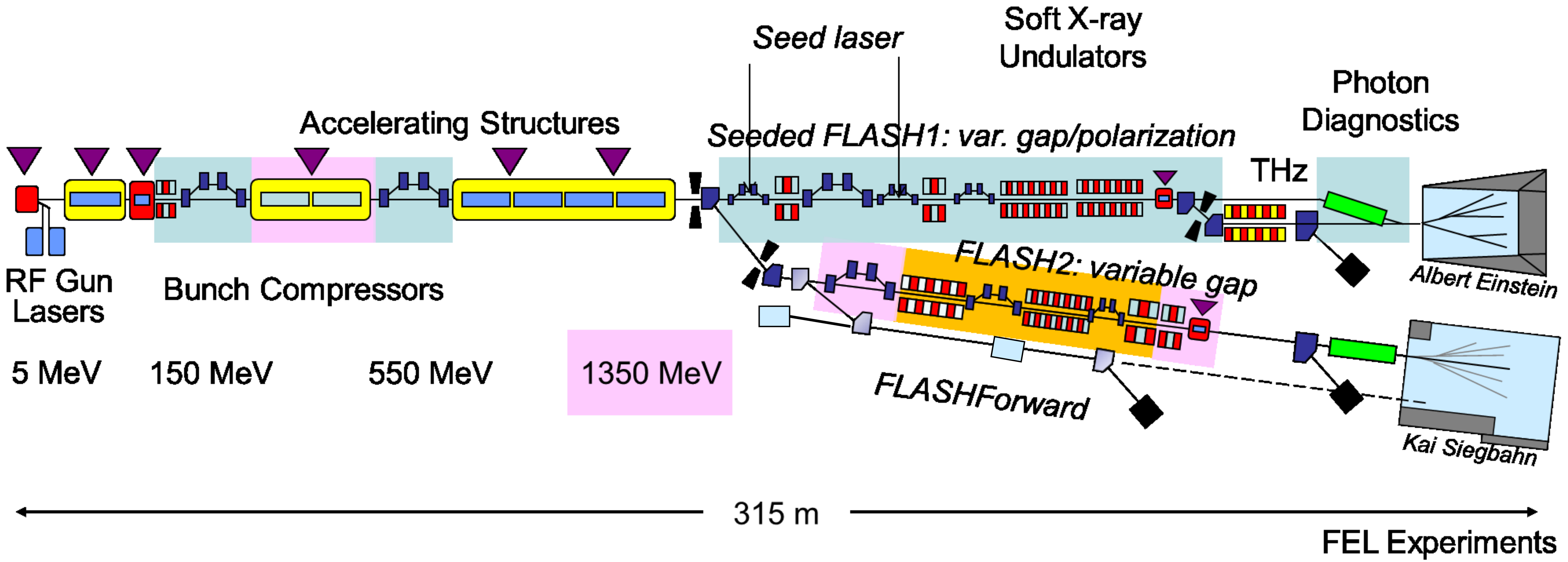


HGHG / EEHG Experiments + seed controls



CDR: Proposed Layout FLASH2020+

Towards a seeded high repetition rate XUV and soft X-ray FEL



Step 1
Energy upgrade
3rd BC (FLASH2)
TDS (FLASH2)
Injector Laser
Afterburner FLASH2

Step 2
Variable gap undulators (FLASH1)
Pump-Probe laser (FLASH1)

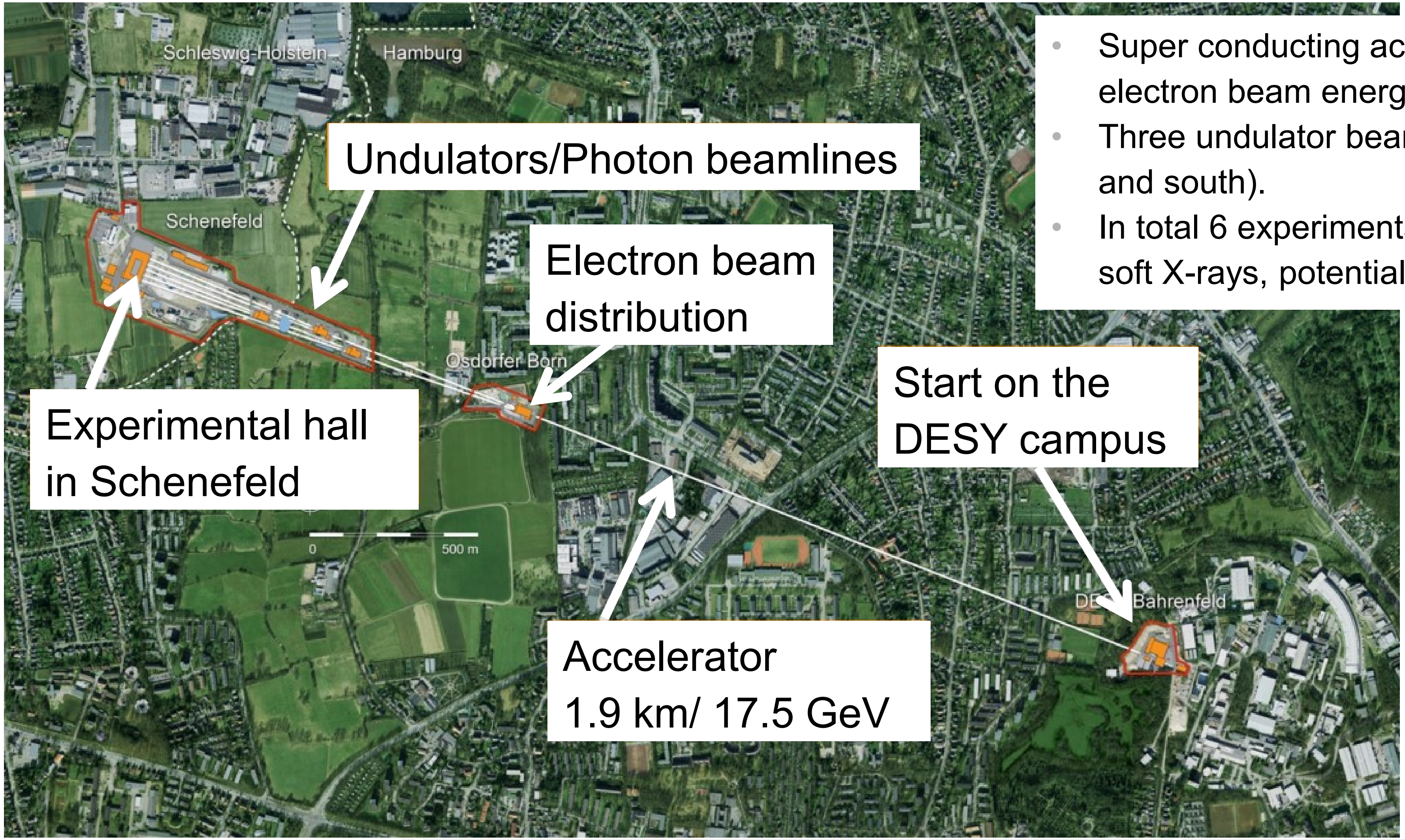
Laser heater in 1st BC
New 2nd bunch compressor (BC)

Step 3
High rep.rate seeding (FLASH1)
Photon diagnostics (FLASH1)

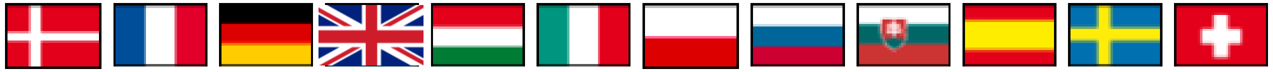
Step 4
New variable gap undulators + chicanes
for new lasing concepts (FLASH2)

European XFEL

The European XFEL between Hamburg Bahrenfeld and Schenefeld



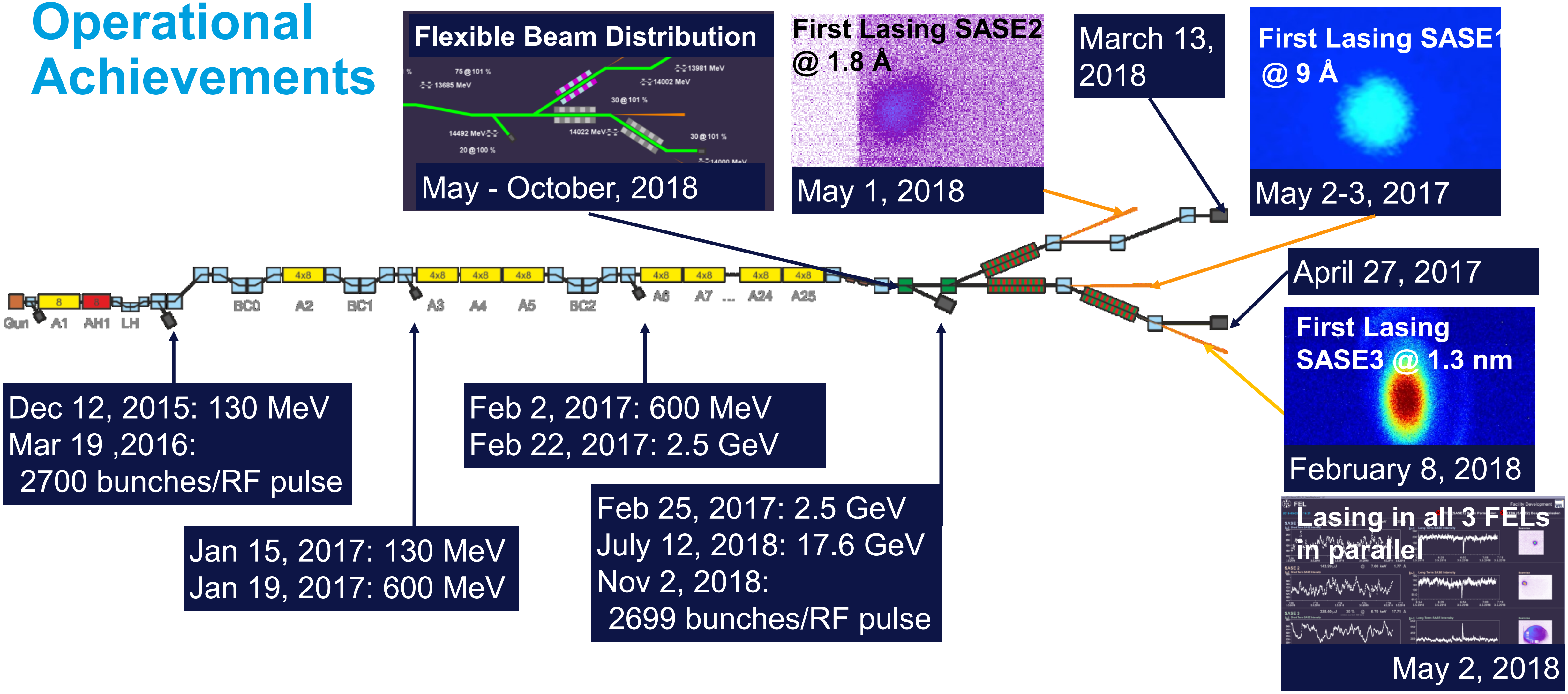
- Super conducting accelerator with up to 17.5 GeV electron beam energy.
- Three undulator beamlines in two branches (north and south).
- In total 6 experiments, 4 for hard X-rays and 2 for soft X-rays, potential for 2 more FELs



The longest superconducting linac in the world is in operation

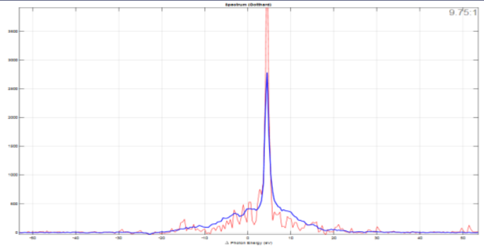
- 96 superconducting modules in a single cryostat in the main tunnel
- plus 2 injector modules
- RF components and electronics rack are located below the accelerator.

Operational Achievements



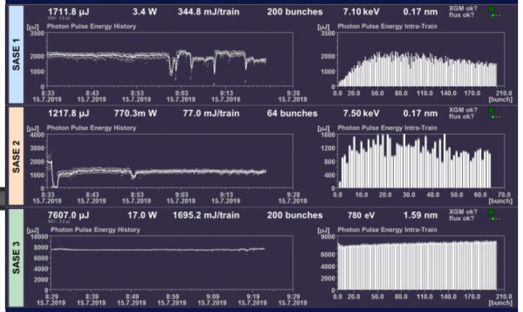
New since Spring 2019

SASE2 HXRSS @ 8 keV



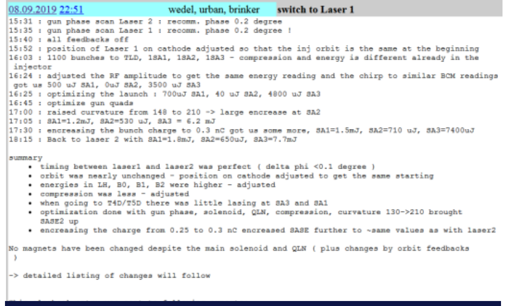
Sep 7, 2019

4.5 MHz User Operation



July 2019

Laser2 -> Laser1 -> Laser2



08.09.2019 22:51 wedel, urban, brinker **switch to Laser 1**

15:31 : gun phase scan Laser 2 : recomm. phase 0.2 degree
15:35 : gun phase scan Laser 1 : recomm. phase 0.2 degree !
15:40 : all feedbacks off
15:52 : position of Laser 1 on cathode adjusted so that the inj orbit is the same at the beginning
16:03 : 1100 bunches to TLD, 1SA1, 1SA2, 1SA3 - compression and energy is different already in the injector
16:24 : adjusted the RF amplitude to get the same energy reading and the chirp to similar BCM readings got us 500 uJ SA1, 0uJ SA2, 3500 uJ SA3
16:25 : optimizing the launch : 700uJ SA1, 40 uJ SA2, 4800 uJ SA3
16:45 : optimize gun quads
17:00 : raised curvature from 148 to 210 -> large encrease at SA2
17:05 : SA1=1.2mJ, SA2=530 uJ, SA3 = 6.2 mJ
17:30 : encreasing the bunch charge to 0.3 nC got us some more, SA1=1.5mJ, SA2=710 uJ, SA3=7400uJ
18:15 : Back to laser 2 with SA1=1.8mJ, SA2=650uJ, SA3=7.7mJ

summary

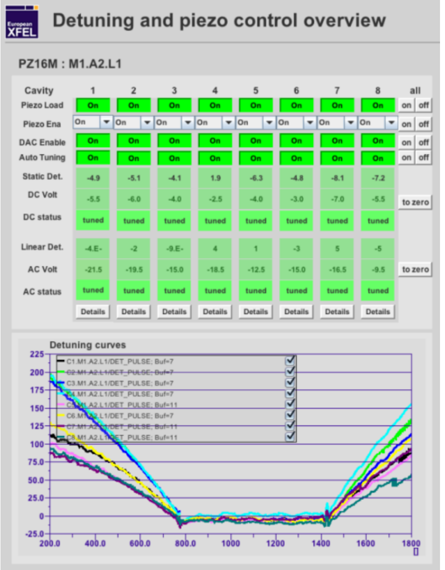
- timing between laser1 and laser2 was perfect (delta phi <0.1 degree)
- orbit was nearly unchanged - position on cathode adjusted to get the same starting
- energies in LH, B0, B1, B2 were higher - adjusted
- compression was less - adjusted
- when going to T4D/T5D there was little lasing at SA3 and SA1
- optimization done with gun phase, solenoid, QLN, compression, curvature 130->210 brought SASE2 up
- encreasing the charge from 0.25 to 0.3 nC encreased SASE further to ~same values as with laser2

No magnets have been changed despite the main solenoid and QLN (plus changes by orbit feedbacks)

-> detailed listing of changes will follow

Sep 9, 2019

Cavity detuning control with piezo

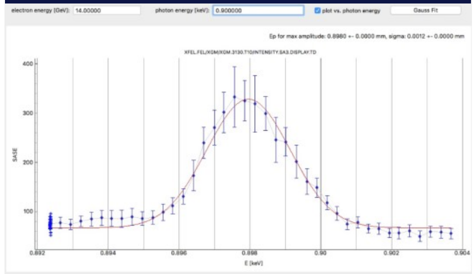


May-Sept, 2019

SASE1 lasing @ 20 keV

June 10, 2019

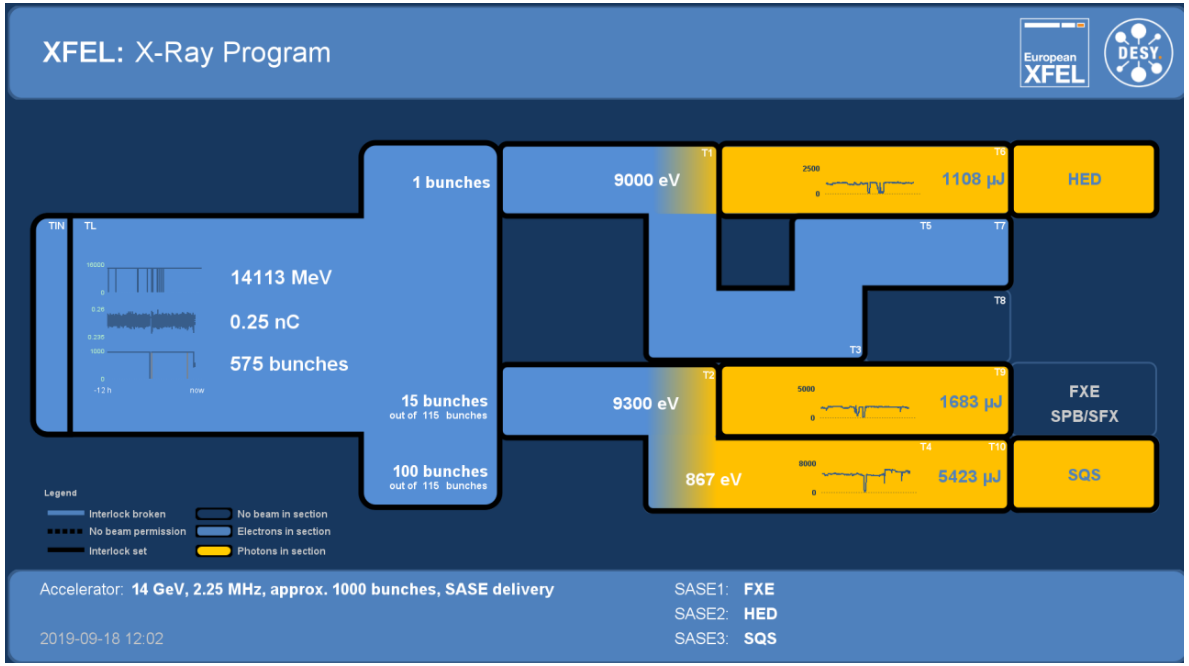
SASE3 5th harmonic lasing @ 4.5 keV



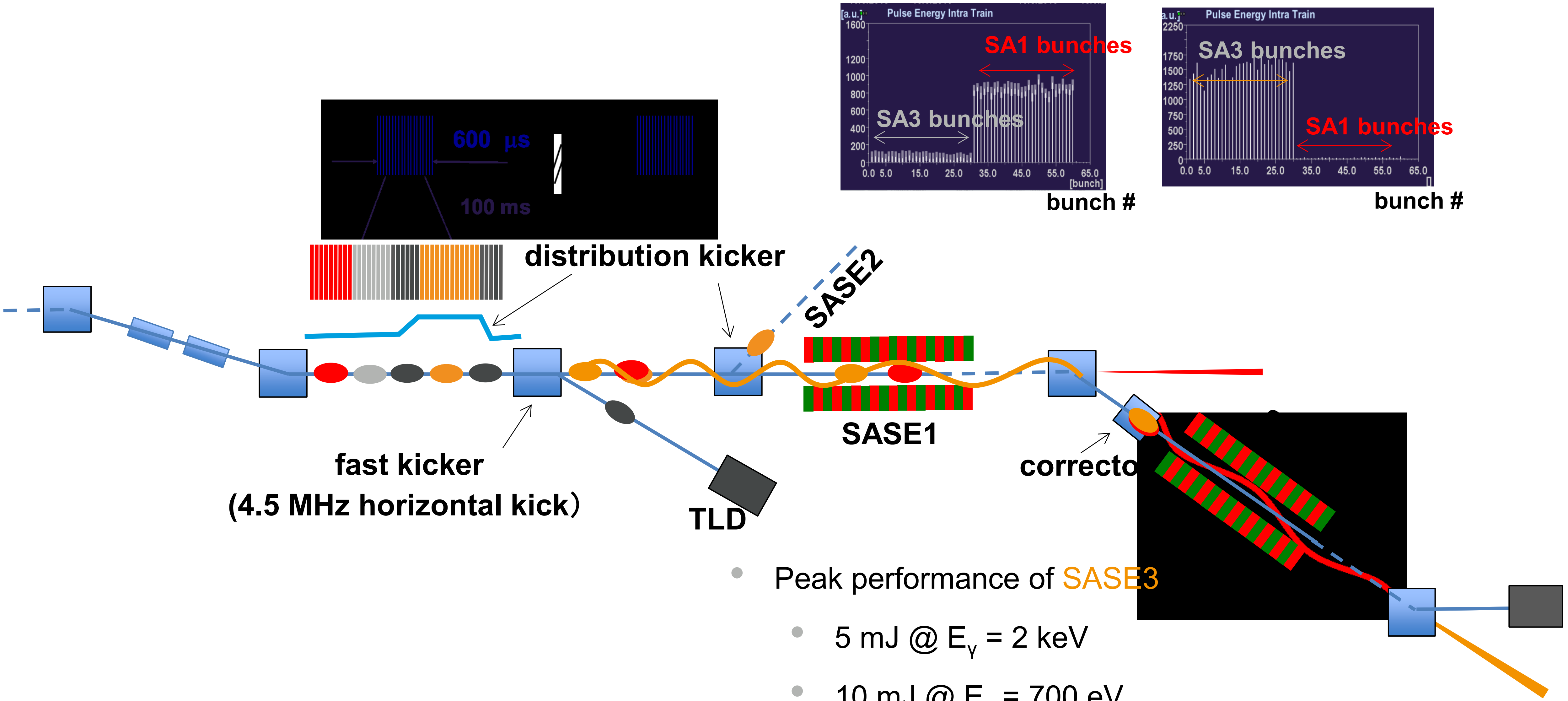
Aug 3, 2019

Accelerator Operation

- Standard working point **14 GeV**
- Maximum demonstrated energy 17.5 GeV
- Maximum energy 'out of the box' 16.5 GeV (without reserve station in L3)
- Bunch repetition 1.1 MHz, 2.25 MHz and 4.5 MHz
- Standard repetition rate changed **to 2.25 MHz**
- RF Flat-Top 550 – 600 µs, about 10% needed for feedbacks and SASE2/SASE1 transition
- **Very flexible bunch patterns** realized with distribution system

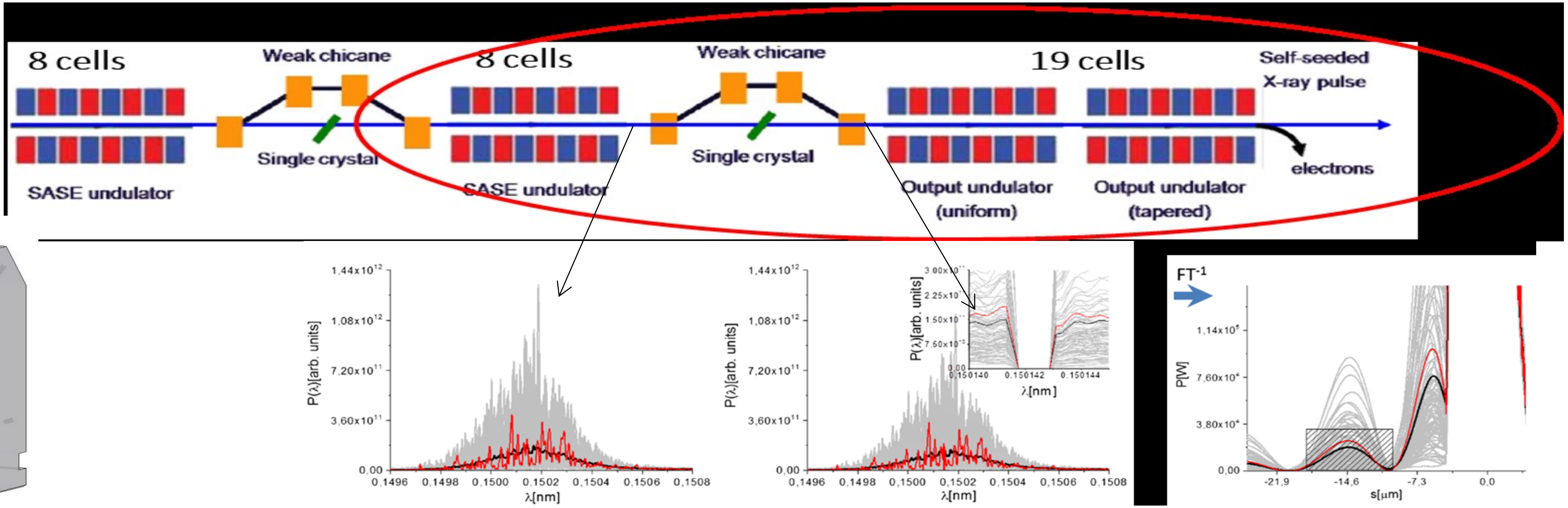


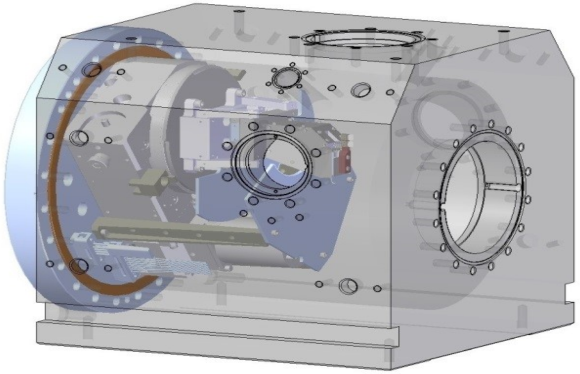
“Fresh bunch” lasing in SASE3

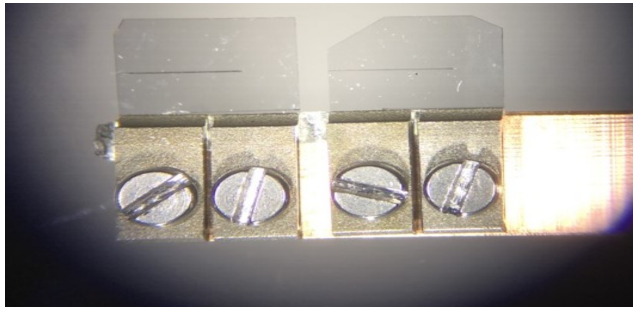


- Peak performance of SASE3
  - 5 mJ @ E_γ = 2 keV
  - 10 mJ @ E_γ = 700 eV

Self-Seeding Installation at SASE2

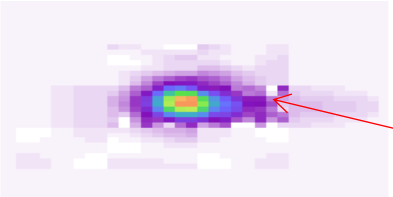


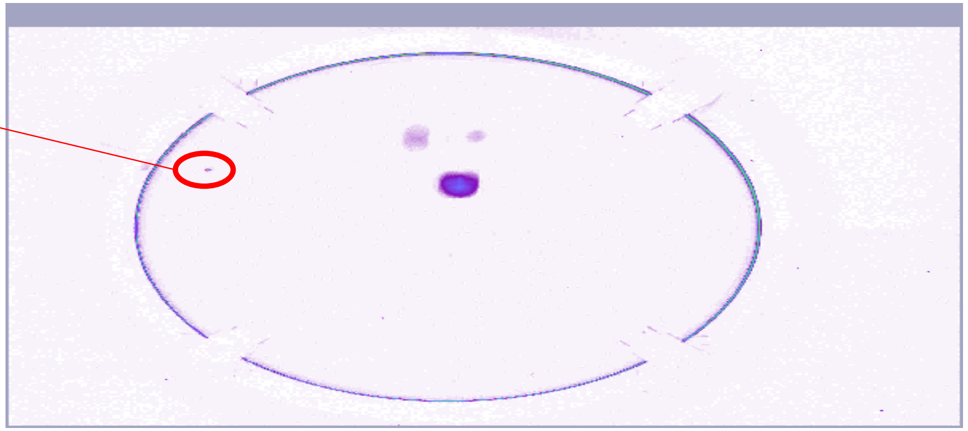


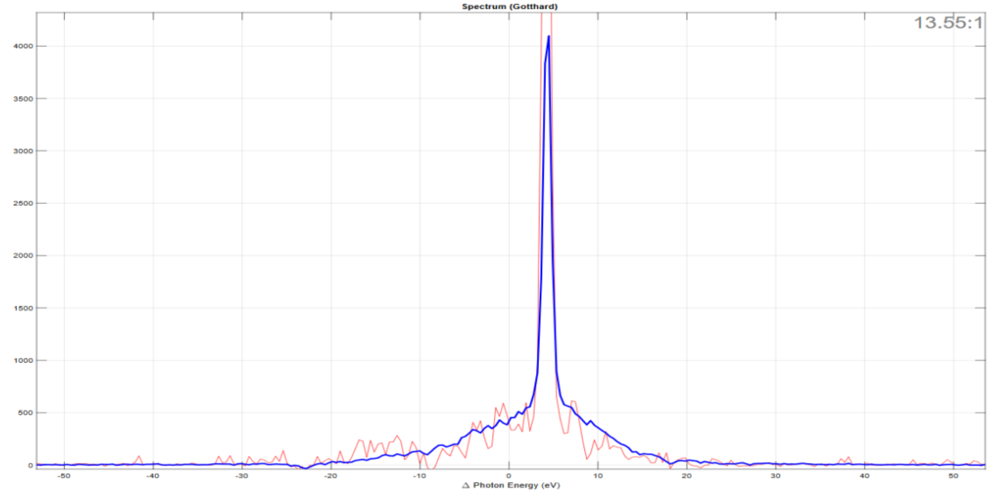


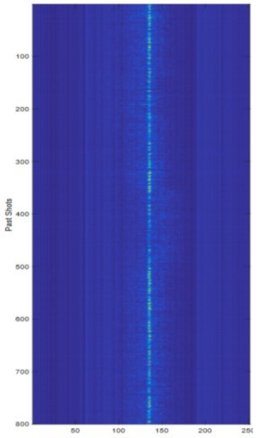
Self-seeding commissioning

- Reflection search:
  - Reflection (004), 100um, seen from 90deg camera
  - Pitch about 59deg
  - When reflection is observed, a notch is automatically formed in the spectrum









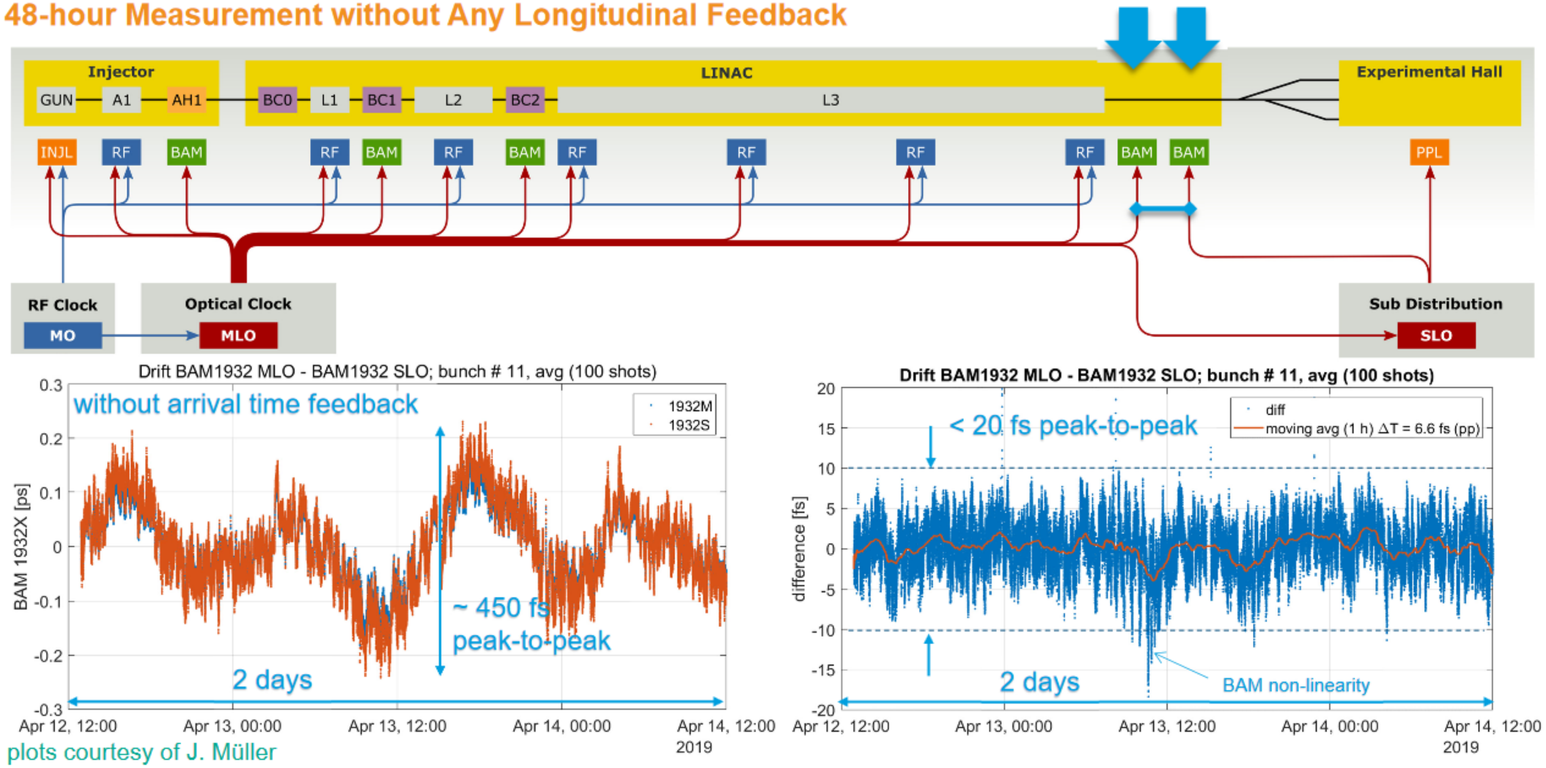
- Self-seeded pulses:
  - First observation of self-seeding at 8 keV in the linear regime
  - **microjoule-level pulses for now!**
  - An important milestone, but need lots of further development before SASE2 can be used in HXRSS mode

Electron beam stability – longitudinal

- 12.9 fs RMS arrival time jitter across macro-pulse
- 12 fs RMS arrival time jitter macro-pulse to macro-pulse
- 450 fs peak-to-peak arrival time drift over 2 days

- < 20 fs peak-to-peak arrival time jitter after removing drifts
- timing tool campaigns →~25 fs RMS X-ray/optical timing jitter at SPB/SFX

48-hour Measurement without Any Longitudinal Feedback

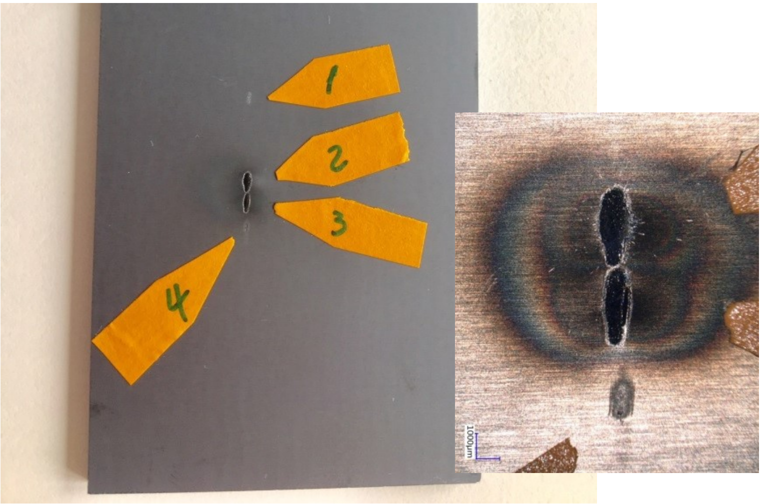


plots courtesy of J. Müller

more details talk J. Müller

Performance Rise and Future Expectations

Drilling Tests at SASE3 (08/2018)
(SCS, 700 eV, 300 x 4 mJx 10 Hz = 12 W)



Early 2018
~300 pulses/s/branch

Up to 2019 (today)

<4000 pulses/s/branch
SASE1/2: 0.8 – 8 W
SASE3: 30 W

…, 2020, …

Full performance:
27000 pulses/s
4.5 MHz
SASE1/2: 10..100W
SASE3: 300 W

(Accelerator) Parameter Space (as of Today)

Quantity	Unit	Project Goal	Achieved	Routine
electron energy	GeV	8 – 17.5	6 – 17.5	14
bunch repetition within pulse	MHz	Up to 4.5	Up to 4.5	1.13 - 4.5, plus subharmonics
bunch charge	pC	20 – 1000	100 – 500	250
max. beam power	kW	500 kW	80 kW	40 kW
undulators in operation (lasing)		SASE1-3	SASE1-3	SASE1-3
photon pulses / s / undulator		27000	5000	<3000
photon energy	keV	0.25-25	0.4-4.5; 5.8-20	0.6-2.2; 6 – 14
photon pulse intensity (SASE1) @ 14 GeV, 250 pC, 9.3 keV	mJ		2.5	2
photon pulse intensity (SASE3) @ 14 GeV, 250 pC, 600 – 900 eV	mJ		10	>5
photon pulse intensity SASE2 (@ 14 GeV, 250 pC, 9 keV	mJ		2.2	1.0

PITZ

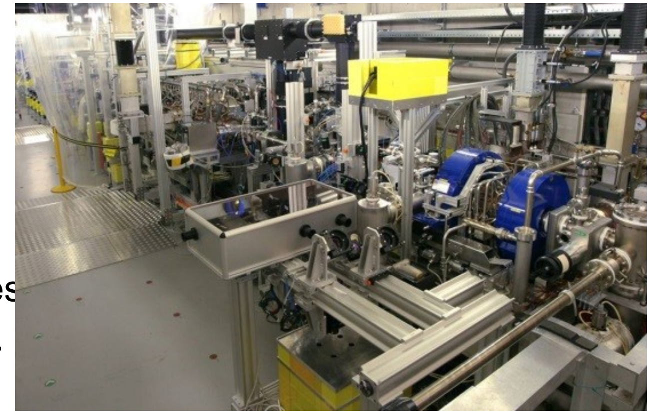
Photo Injector Test facility at DESY in Zeuthen (PITZ)

Main Goals:

- **provide optimized electron sources (minimum emittance) for FLASH and European XFEL**
- **do general accelerator R&D**

Research areas:

- basic photo injector R&D
- specific R&D for FLASH & European XFEL (for current facilities and future upgrades
  → e.g. CW upgrade of European XFEL)
- application of high brightness electron beams + general accelerator R&D for novel acceleration techniques
  → applications like **THz**, plasma acceleration, **UED**, …



PITZ highlights for ST3: ps and fs electron and photon beams

- THz SASE FEL for pump-probe experiments at European XFEL → poster
- Cathodes studies (Cs_2Te): various Te thickness, QE and thermal emittance → talk
- Frequency-detuning dependent RF coupler kick (simulations and experiment)
- Developments on CW injector: PITZ characterization at CW SRF gun gradients → poster
- Further improvements in the gun5 design (cathode area surface shape)
- Slice emittance measurements with TDS → poster
- Virtual Pepper-Pot Technique → poster
- Space-Charge Dominated Photoemission: slice emittance budget decomposition

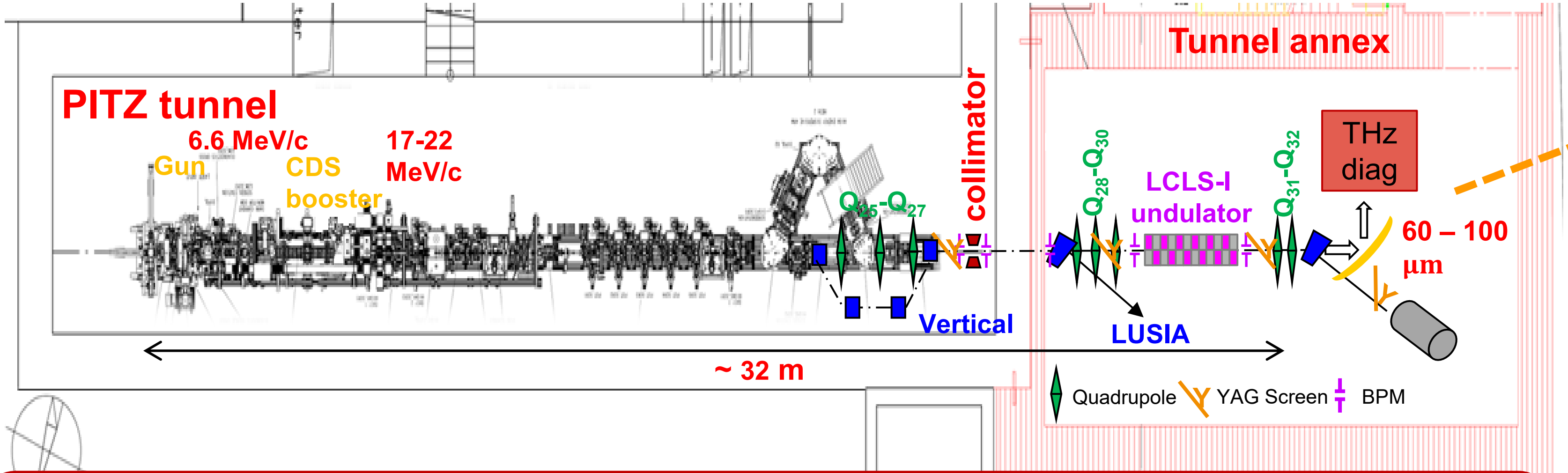
THz SASE FEL for pump-probe experiments at European XFEL

European XFEL (~3.4 km)

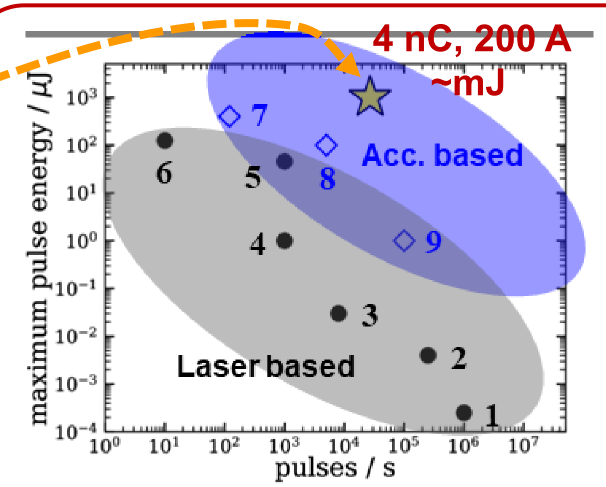
PITZ-like accelerator based THz source (~20 m)

X-ray
THz
Pump & probe

E.A. Schneidmiller, M.V. Yurkov, (DESY, Hamburg), M. Krasilnikov, F. Stephan, (DESY, Zeuthen), "Tunable IR/THz source for pump probe experiments at the European XFEL, Contribution to FEL 2012, Nara, Japan, August 2012



Motivation



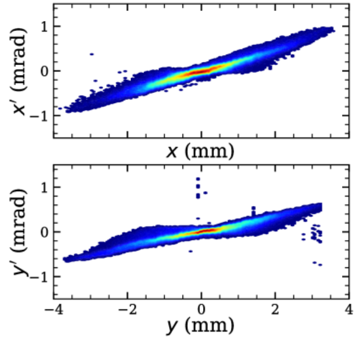
Pulse energy vs. rep.rate for modern THz sources

1,3,5,6: Optical rectification[1]
2: photoconductive antenna [1]
4: Two-color laser filamentation [2]
7: CTR (LCLS/FACET) [3]
8: UR (FLASH) [4]
9: UR (TELBE) [5]

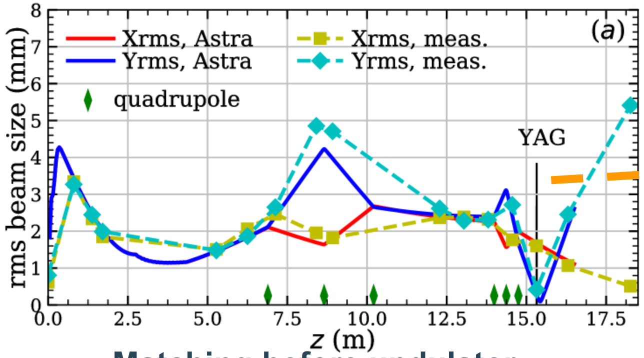
[1]B. Green, et al, Sci.Rep.V. 6, Article number: 22256 (2016)
[2]M. Gensch, Proceedings of FEL 2013, 474 (2013)
[3] T I Oh et al 2013 New J. Phys. 15 075002
[4]https://flash.desy.de/
[5]https://www.hzdr.de/db/Cms?pOid=34100&pNid=2609&pLang=en

Experiment with Gaussian photocathode laser

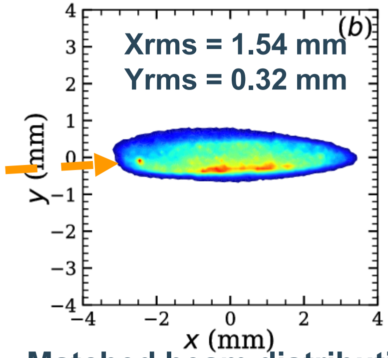
- Bunch charge 2.5 nC; peak current 153 A
- Best emittance: 4 mm mrad



Transverse phase space



Matching before undulator

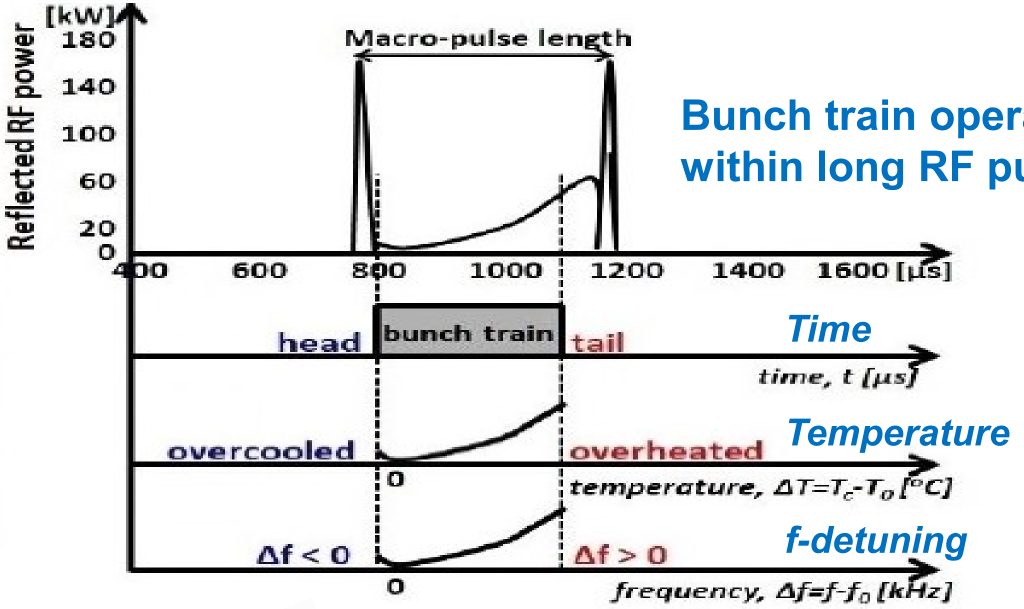


Matched beam distribution

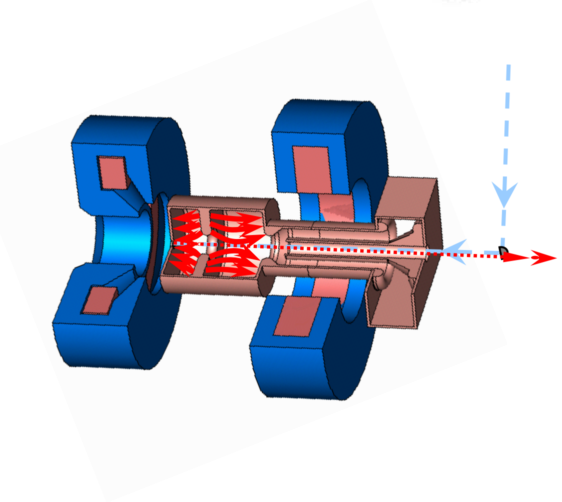
Frequency-detuning dependent RF coupler kick

Kick impacts on e- bunch train quality → FEL performance

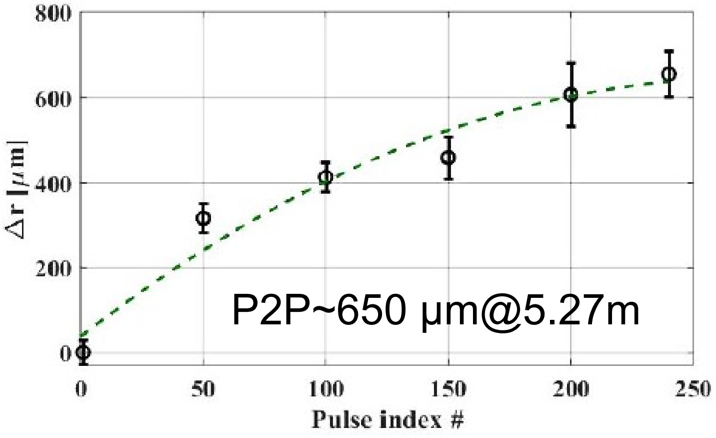
Y. Chen, THP007, FEL'19



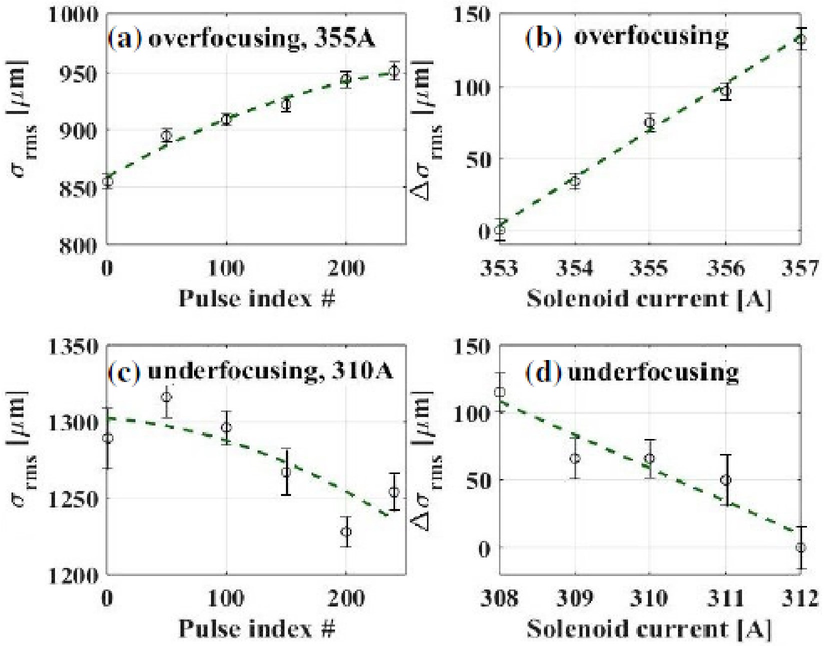
Bunch train operation within long RF pulse



Measured Intra-Train Orbit Change



Measured Intra-Train Size Change



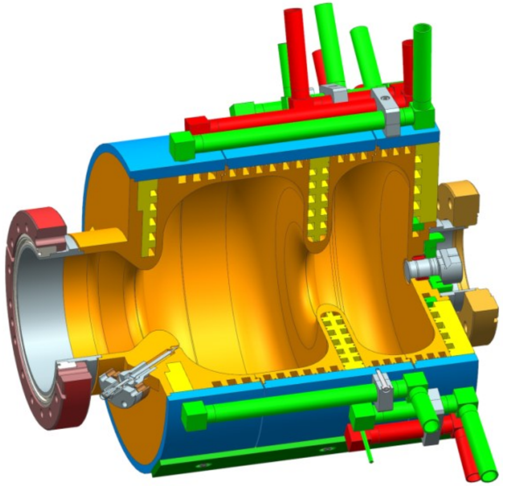
- Single bunch scan within RF pulse
- Low charge ~ 20 pC
- RF power ~5.7 MW
- Gun operated at MMMG
- Booster OFF
- Momentum flatness along train10^{-4}

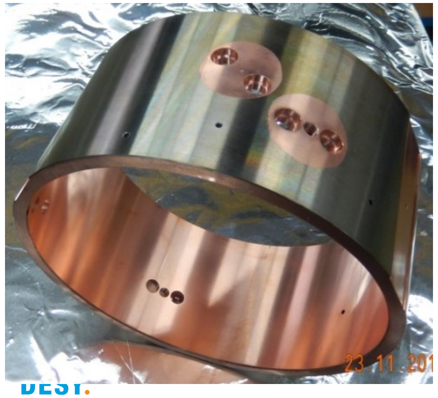
For a 240 µs bunch train,
→ measured P2P kick difference ~0.13 mrad
→ measured rms bunch size change in solenoid current: 2.7A (over focusing) and 2.3A (under focusing)

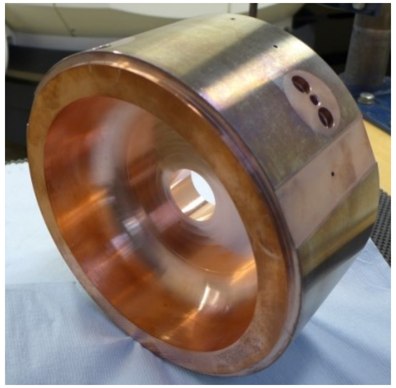
Gun5 and CW gun

In development

- **Gun 5 (pulsed) for FLASH & EuXFEL**
  - Extends the RF pulse from 650 us to 1 ms
  - Production is in progress

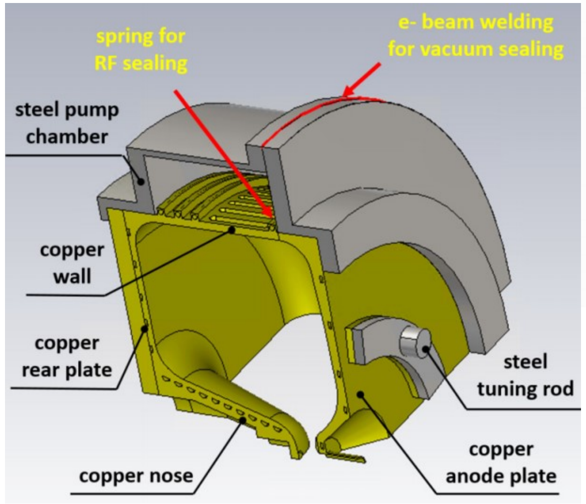


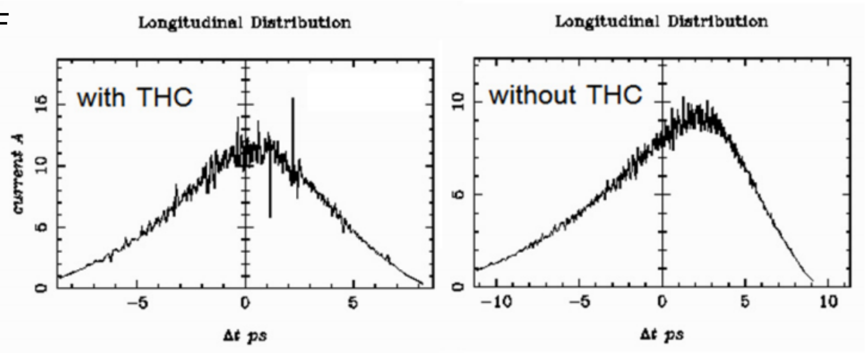


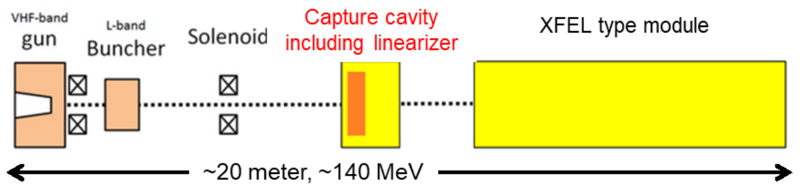


- **Normal conducting CW RF gun for Eu-XFEL**
  - A backup option for XFEL CW injector
  - A baseline physics design is almost done
  - 100 pC beam simulations show improvements over LCLS-II injector, 0.2 mm.mrad @ 10 A peak current
  - Adding a linearizer to capture cavity improves longitudinal beam distribution

Ecath ~28 MV/m, Vgun ~830 kV, ~100 kW RF







ARES@SINBAD

ARES is one of the Experiments located at SINBAD

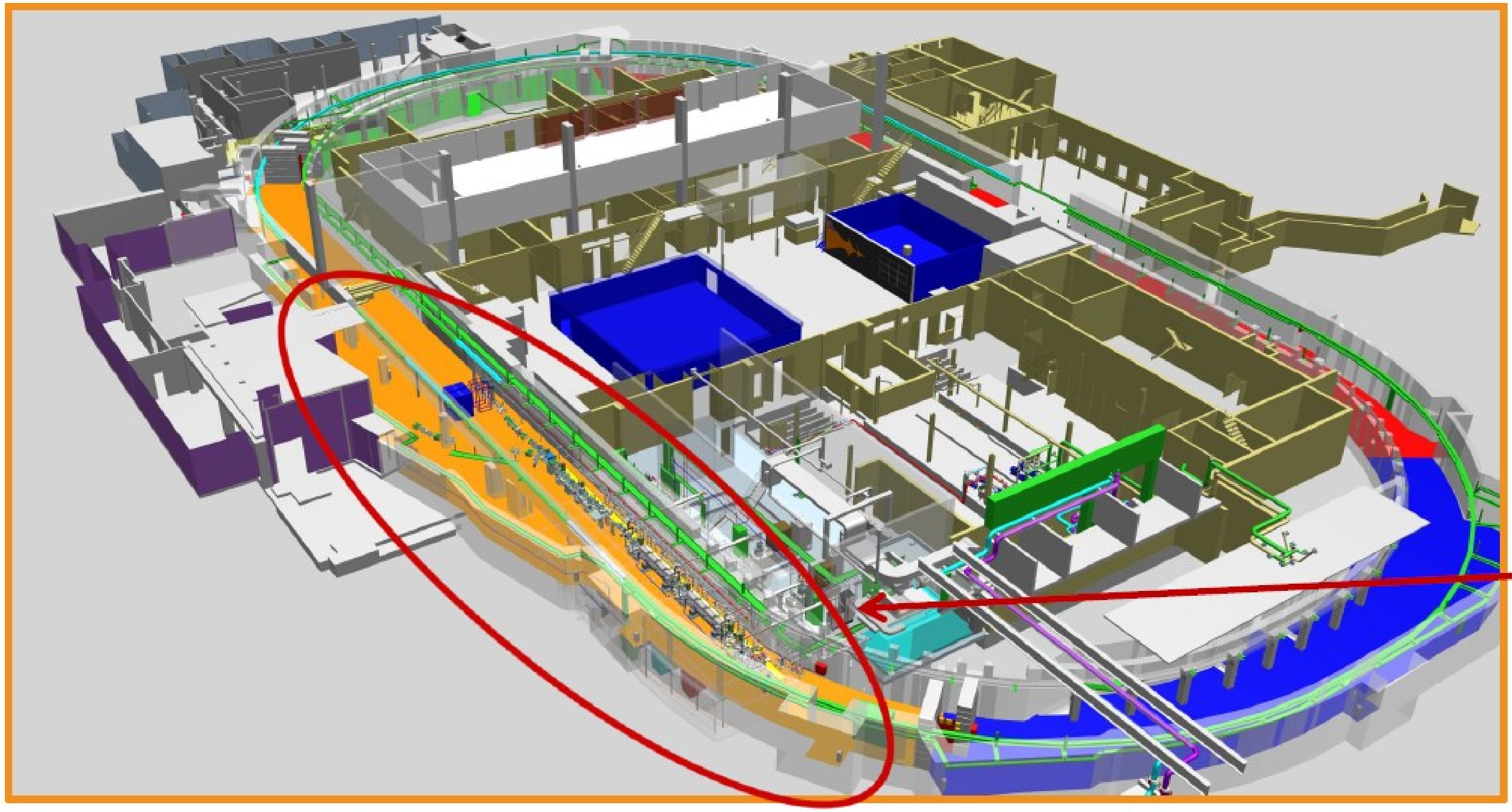
It is a conventional RF Photo-Injector for the Production of high Brightness fs electron Bunches with Energy > 100MeV

more details
F. Burkart

Dedicated acc. R&D facility for

(1) ultra-fast science R&D

(2) high gradient accelerator development



ARES Linac at SINBAD

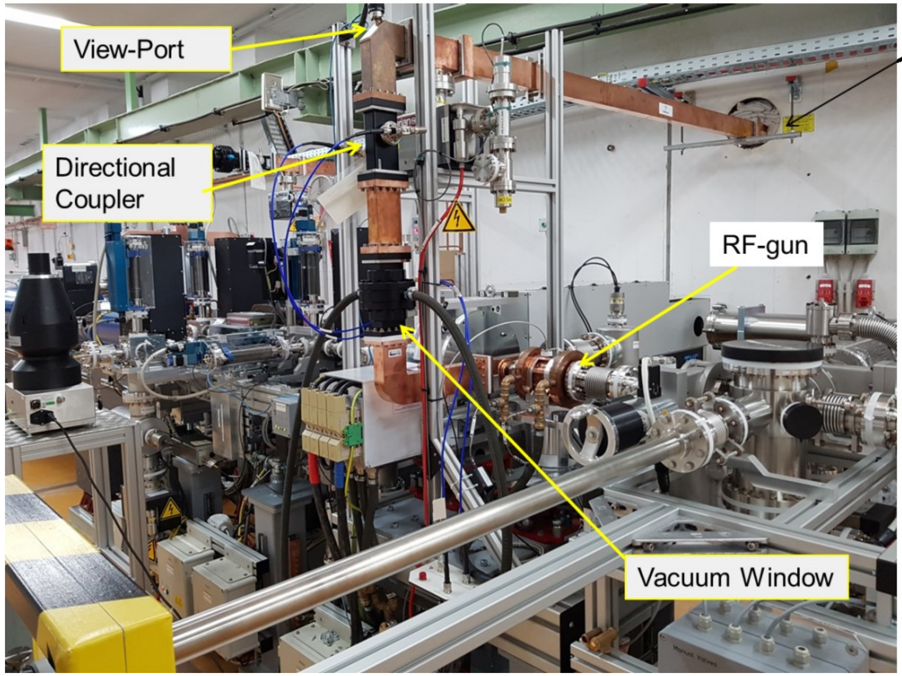
- Energy: 100 MeV
- Charge: 0.5 – 200 pC
- Bunch length: few fs - sub fs

SINBAD = Short Innovative Bunches and Accelerators at DESY

Courtesy: B. Marchetti

RF-Gun Conditioning

Encountered issues related to the waveguides system during commissioning…



To the klystron

RF-Layout in the RF-gun Area

Vacuum events during commissioning….

Courtesy: B. Marchetti

Black spots in bends… purely fabricated

Black spots in bends… purely fabricated

New vacuum window (**coated on both sides**),

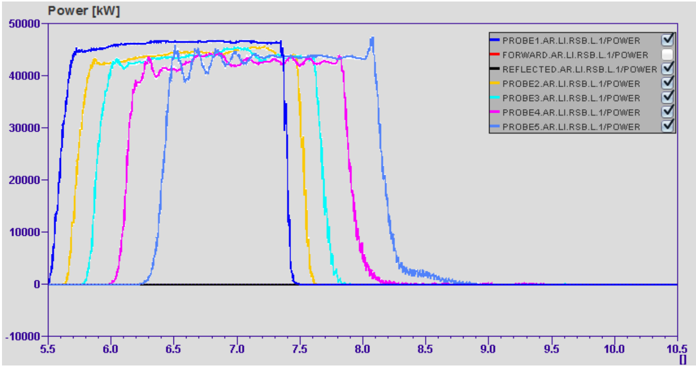
* forgotten coating on one side of the window by the company. We use same windows for the linac cavities.

Conditioning of the two linac structures started + + installation of remaining beamline

4th of July received the **safety approval for TWS**

Travelling-Wave Structure 1 (TWS1):

- Achieved **nominal peak power (45MW)** with **1.9 μs RF-pulse length** and **25Hz rep. rate** (sufficient for beam operation but limited by the vacuum window → same problem as for the RF-gun).



Travelling Wave Structure 2 (TWS2):

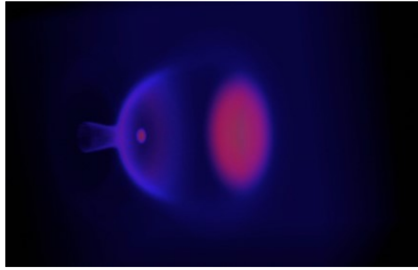
- Achieved **nominal peak power (45MW)** with **1.0 μs RF-pulse length** and **25Hz rep. rate**.

Courtesy: B. Marchetti

New Installations:

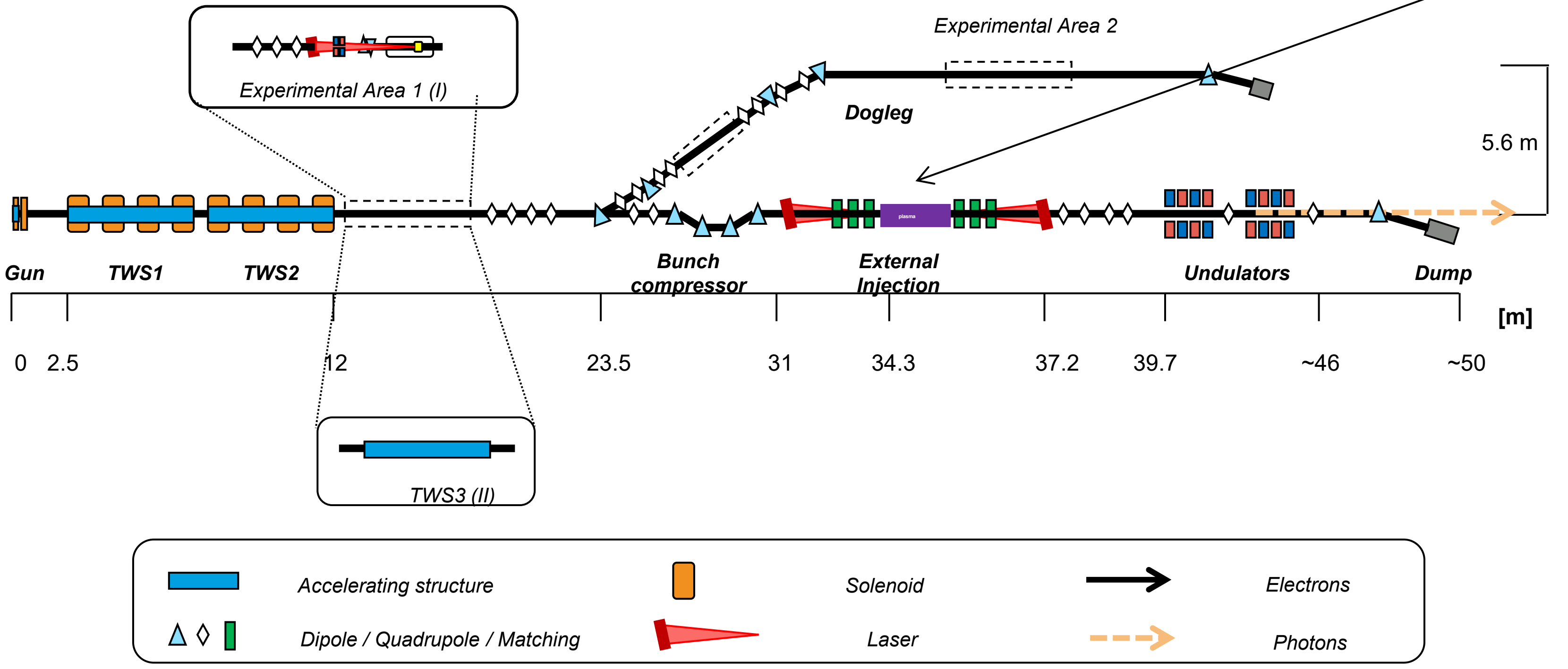
Diagnostics between the two travelling wave cavities, waveguides, beampipe up to end matching region, quadrupoles, steerers, high energy spectrometer…

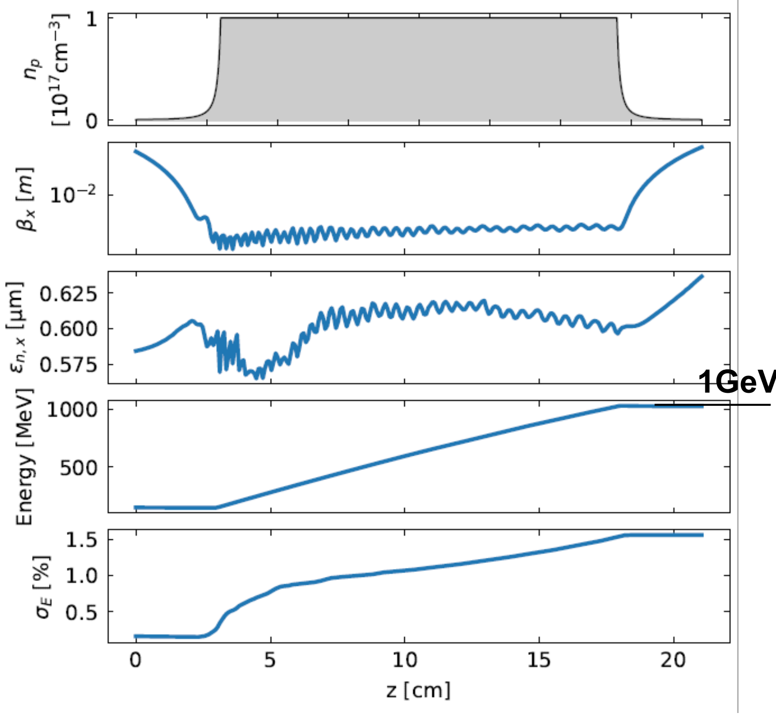
Update on the Simulations for ATHENAe



Iterations on start-to-end simulations for the **external injection** experiment are ongoing

- RF photo-injector provides a **well-know, well-characterized and well tunable electron**
- External injection of short electron bunches promises **excellent beam quality** (1 GeV, 0.2% energy spread, < 0.2 μm emittance).
- Unique possibilities for beam manipulation and synchronization
- Stepping stone to a **staged multi-GeV high performance** plasma accelerator.





Available Laser Parameters within the KALDERA frame: 100 TW, 3 J, 30 fs

Courtesy: B. Marchetti

more details F. Burkart

Thanks to

Siggi Schreiber, Rainer Wanzenberg, Barbara Marchetti, Jens Osterhoff, Frank Stephan, Winni Decking, Juliane Rönsch, and many more ….

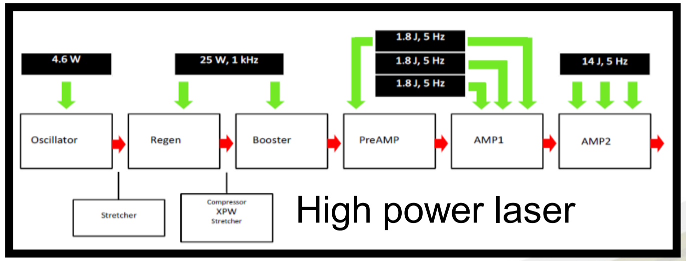
for material

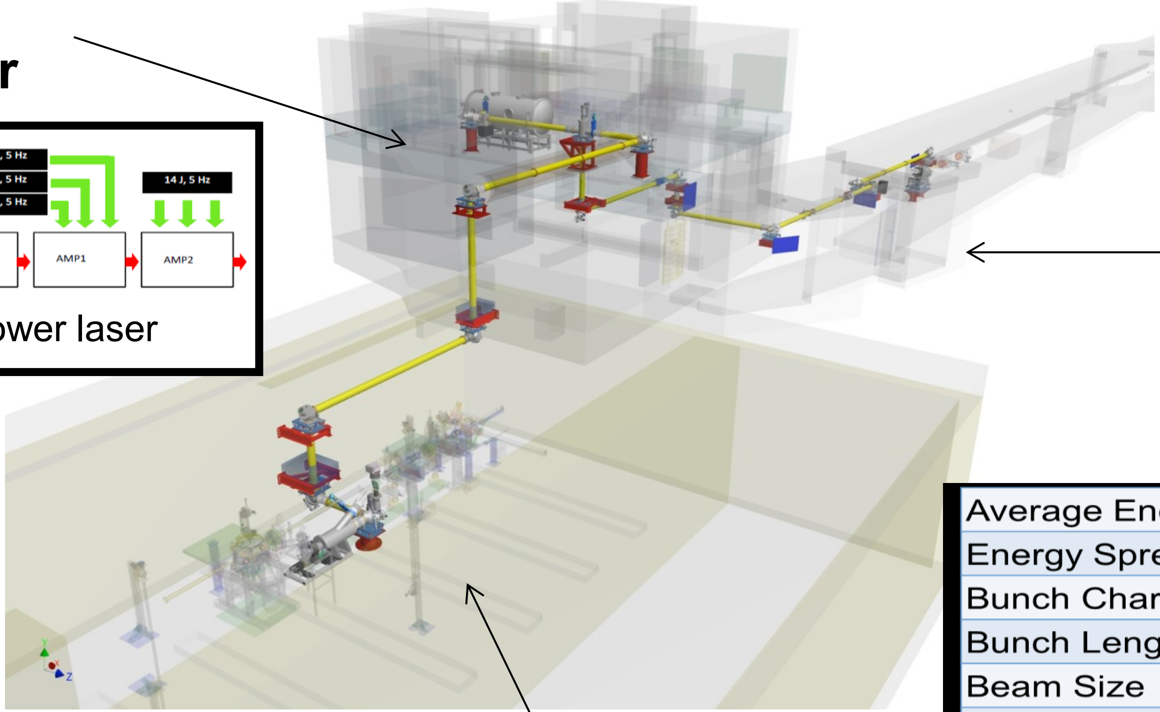
REGAE

REGAE — Relativistic Electron Gun for Atomic Exploration

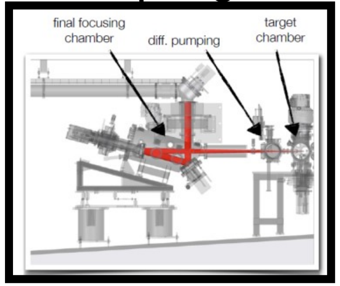
Latest developments

Angus:
200 TW laser





Incoupling

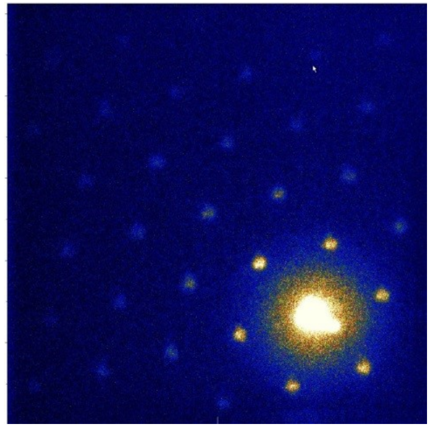


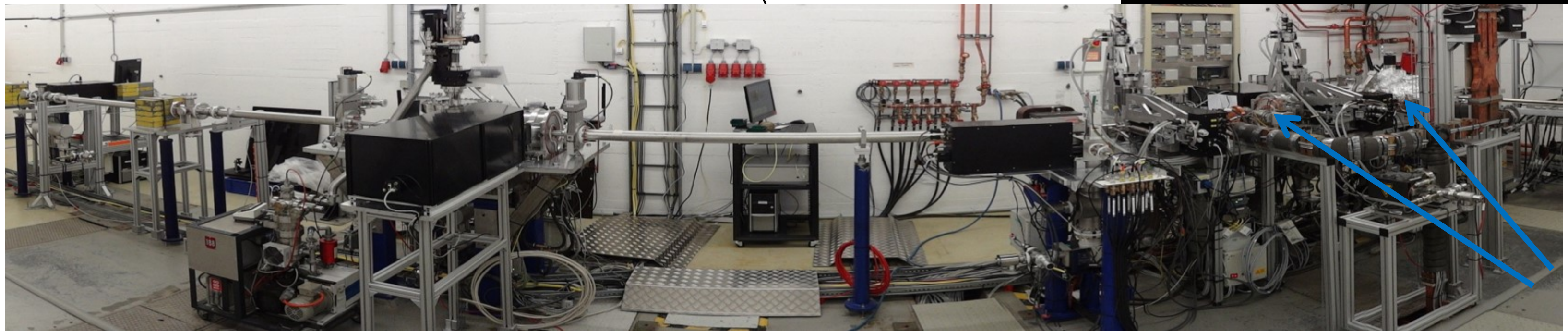
LUX → LPWA + Undulator

REGAE

Average Energy	5.6 MeV
Energy Spread	10 keV
Bunch Charge	100 fC
Bunch Length	<10 fs (rms)
Beam Size	600 μm (rms)
Transv. Emittance	0.03 π mm mrad

Ultra-fast electron diffraction (UED) pattern



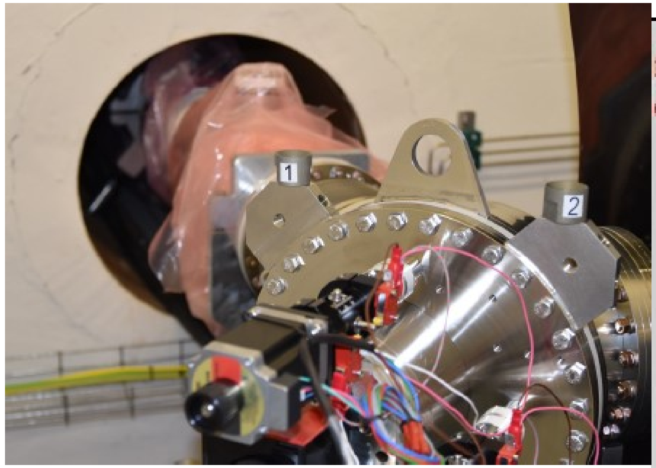


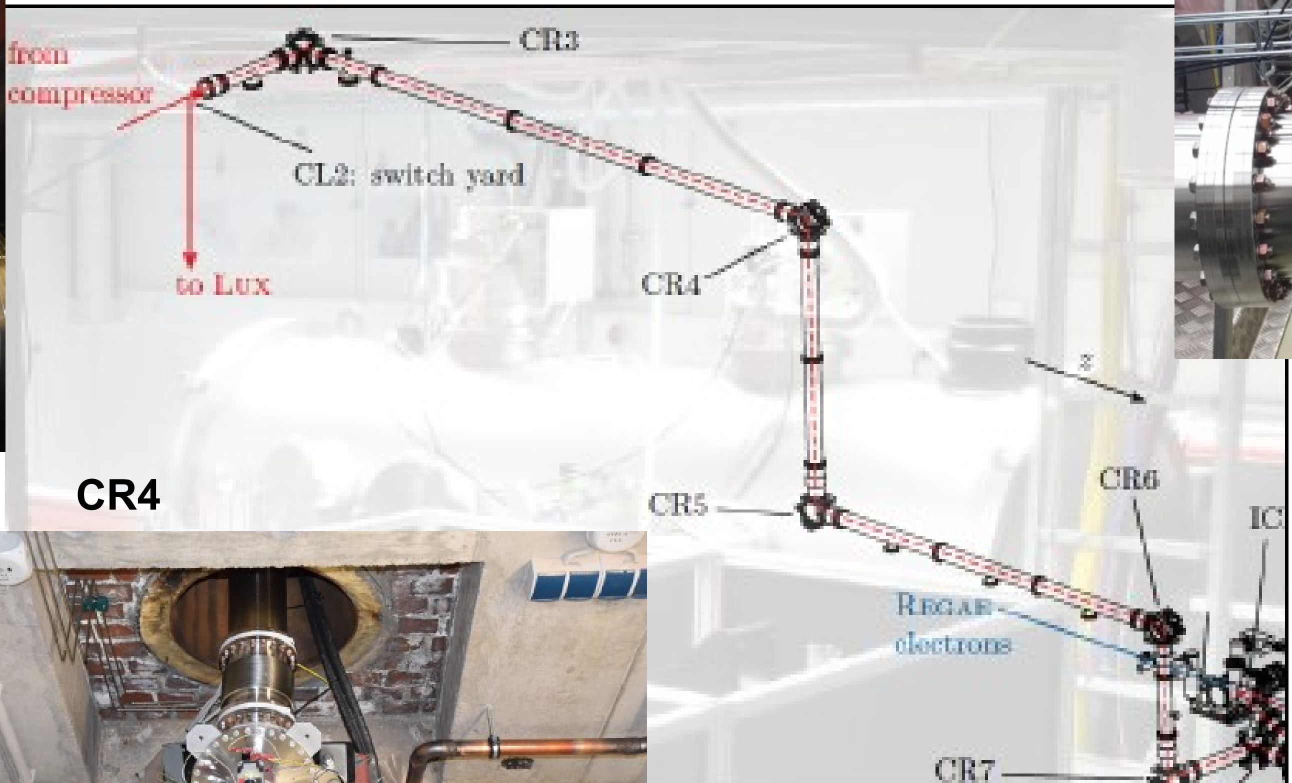
3 GHz RF gun & Buncher pulsed, 12.5 Hz, 5us

REGAE — Upgrade for external injection to probe LPWA

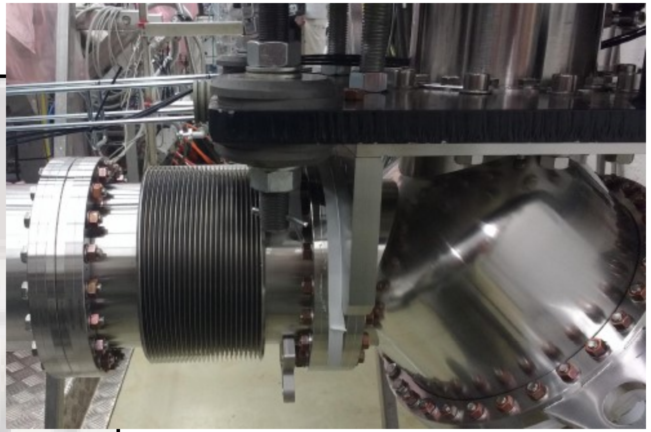
Latest developments: laser transport beam line ANGUS → REGAE ready

CR3

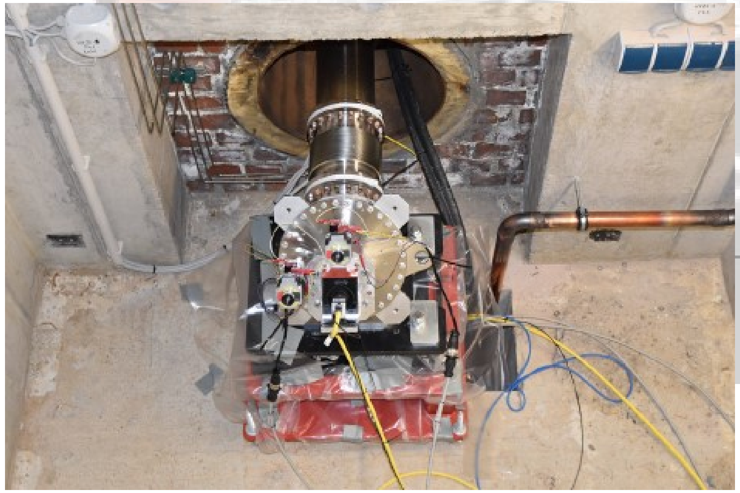




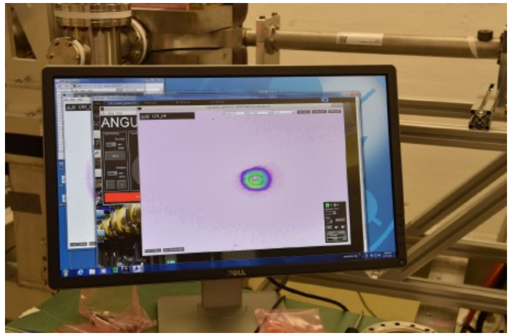
CR5-7



CR4

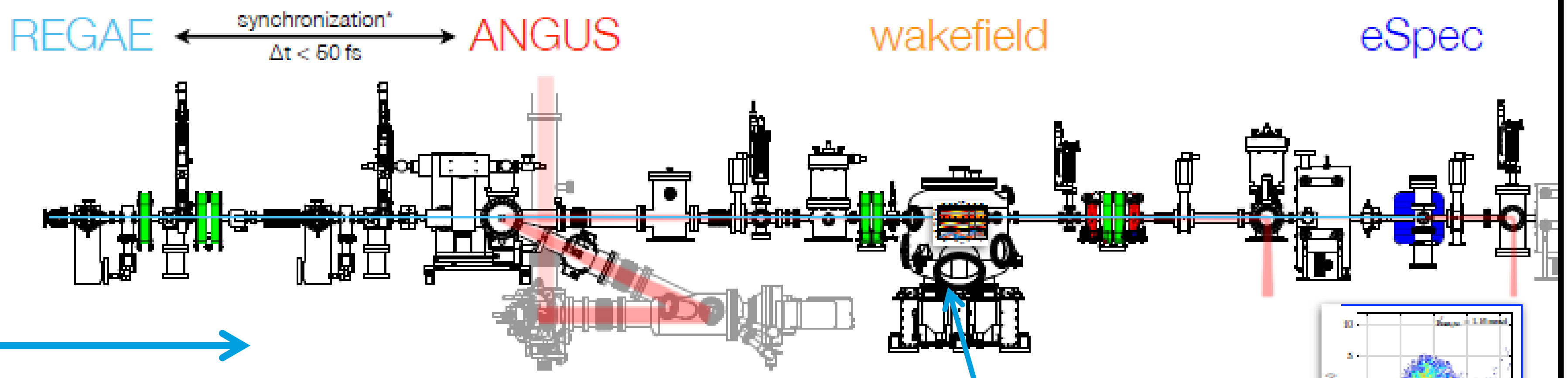


Controls..

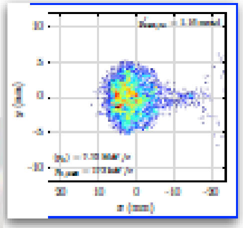


REGAE — Upgrade for external injection to probe LPWA

Latest developments: electron beam line ready for beam

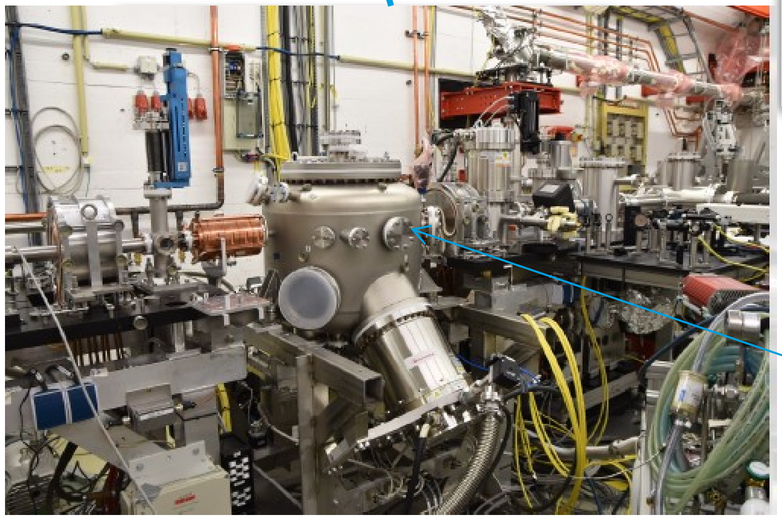


beam



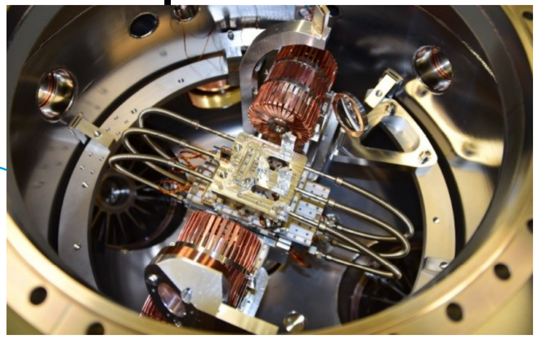
+ 2nd RF station for buncher (decoupling from gun)

+ transverse deflecting cavity (5 kW ampl. only)



Accommodates:

UED &
LWPA probing



➔ Tests start in Q4/2018