Accelerator Challenges at the European XFEL

Winfried Decking (DESY)

LBNL, May 5 2011

Outline

- Project Overview and Status
- New XFEL parameter range
- FEL performance and potential
- Beam distribution / Variable pulse properties
- Lattice Design
- Putting it all together – Project Organization

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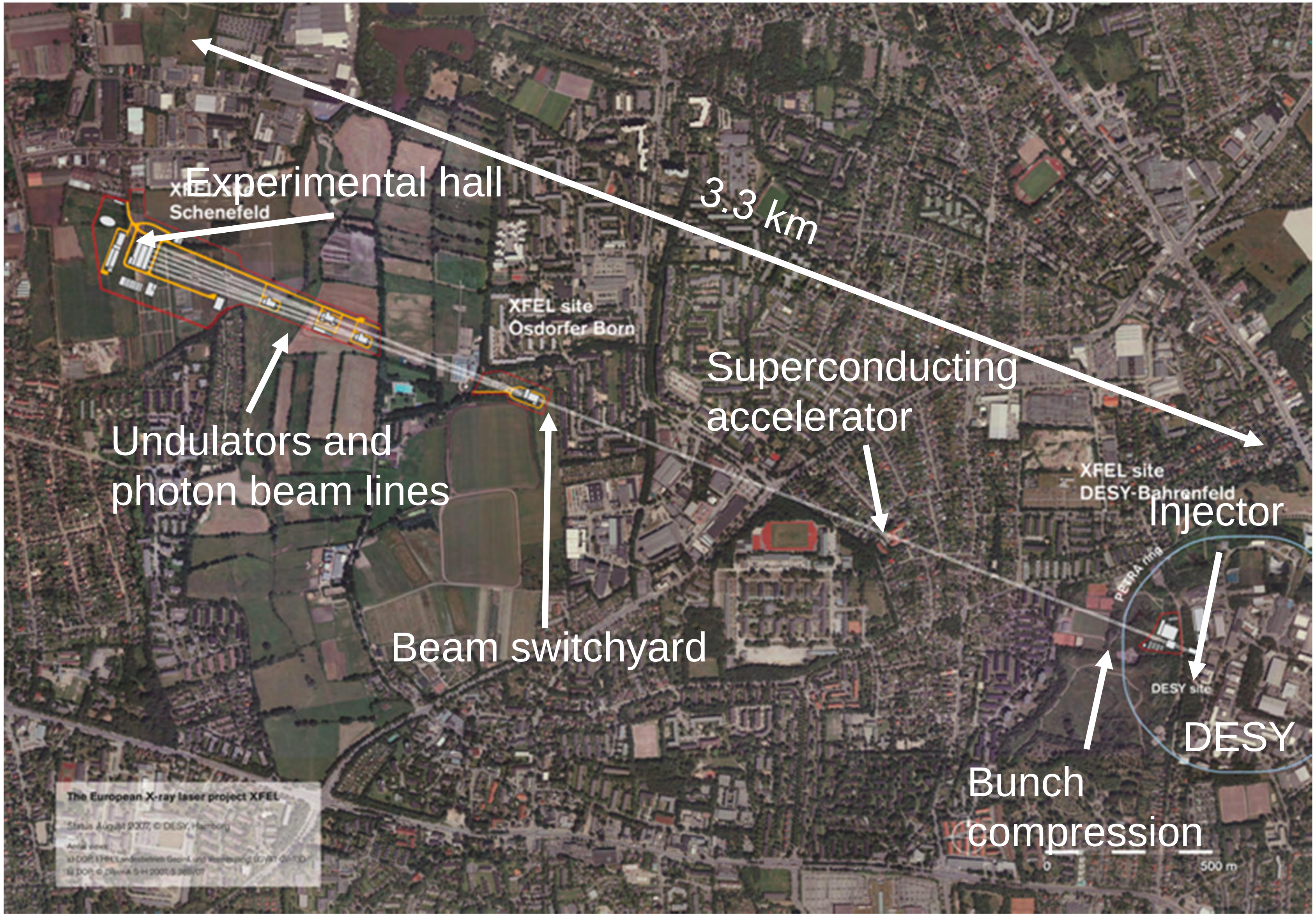
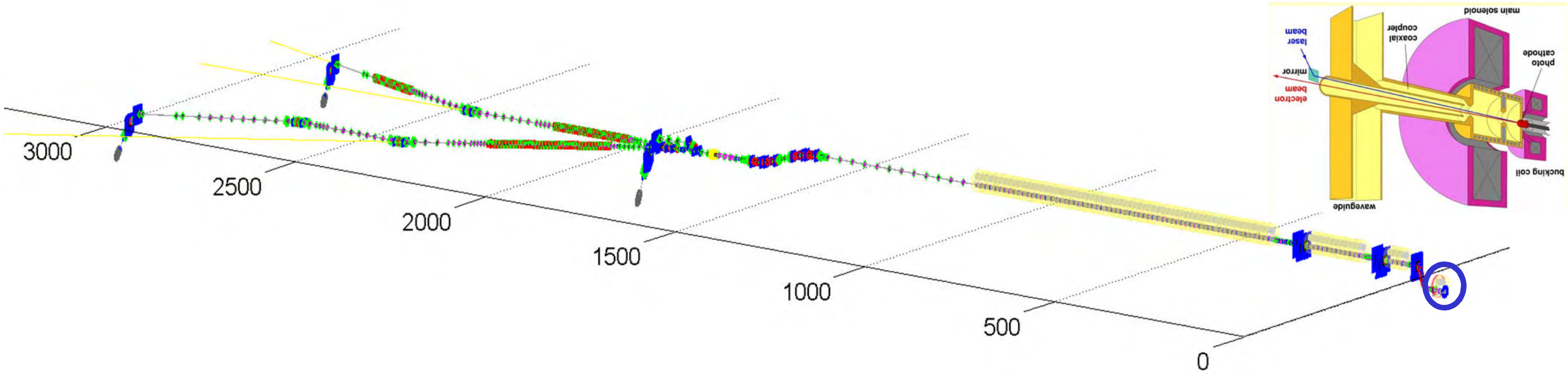
European XFEL in Hamburg



European XFEL - Injector



- Normal-conducting 1.3 GHz RF photo injector
- CsTe Cathode
- 4.5 MHz, 10 Hz Laser @ 260/1030 nm
- ε_n < 1μm at 1 nC
- Performance demonstrated at FLASH and PITZ

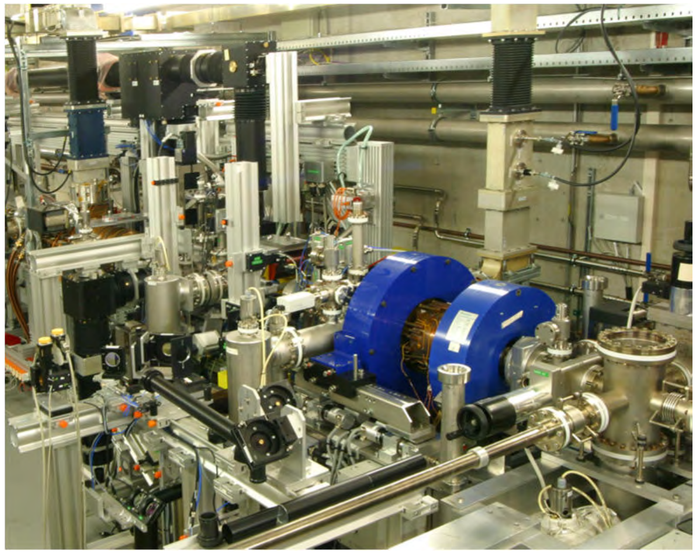
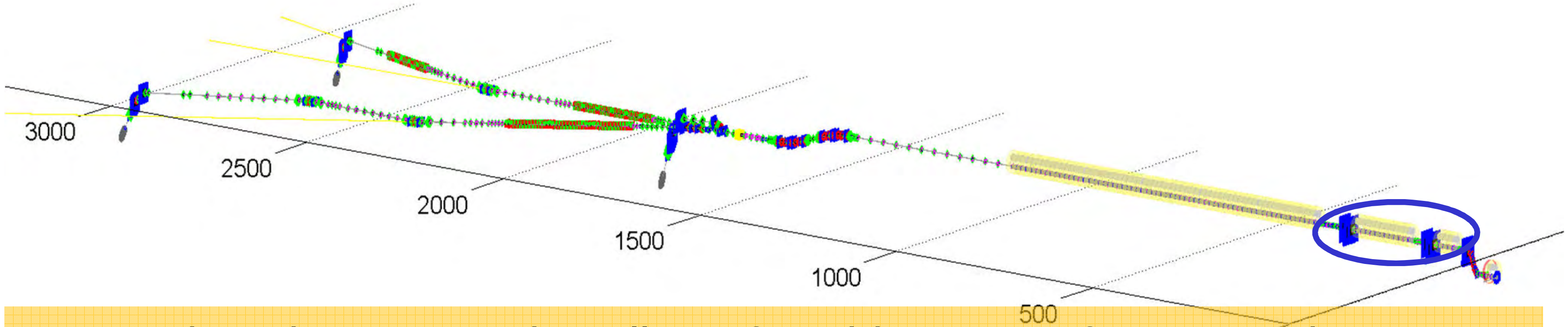
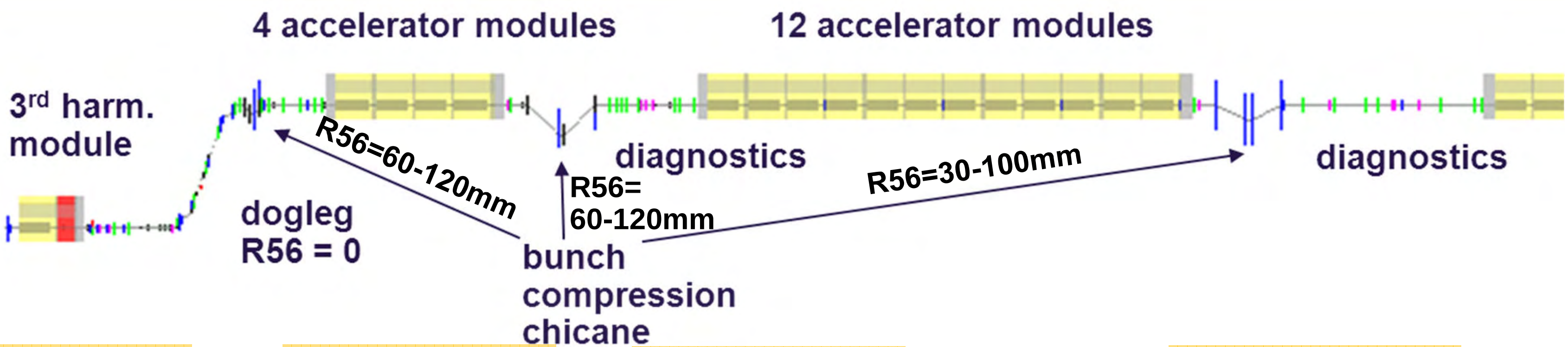


Photo Injector @ DESY Zeuthen

European XFEL – Bunch Compression



3 stage bunch compression allows for wide range of compression scenarios while minimizing sensitivities to RF-regulation imperfections and electron beam driven instabilities



σ_σ = 2 mm
I_{peak} = 50 A
σ_E = 0 %
E = 130 MeV

→

σ_σ = 1 mm
I_{peak} = 100 A
σ_E = 1.5 %
E = 130 MeV

→

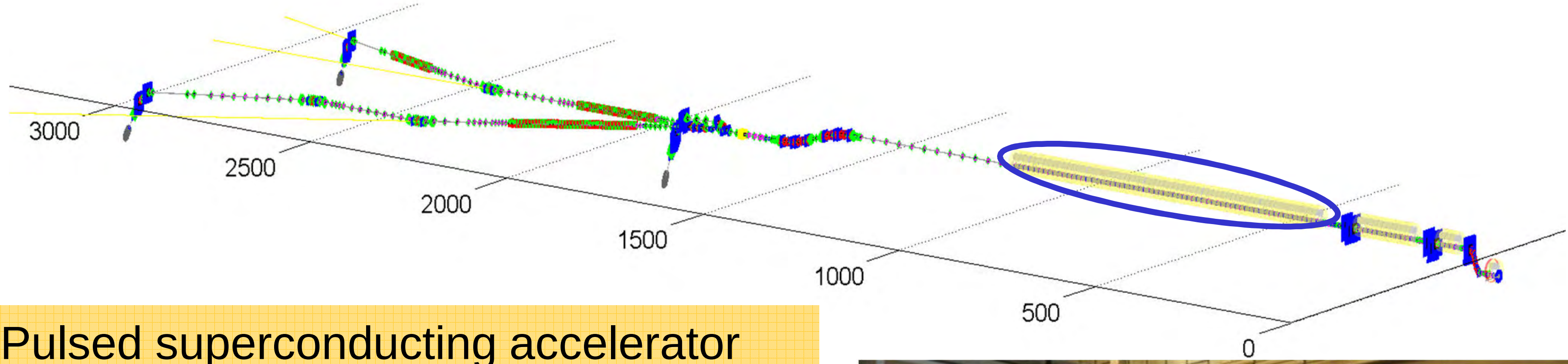
σ_σ = 0.1 mm
I_{peak} = 1 kA
σ_E = 1 %
E = 500 MeV

→

σ_σ = 0.02 mm
I_{peak} = 5 kA
σ_E = 0.3 %
E = 2000 MeV

→

European XFEL – Linear Accelerator



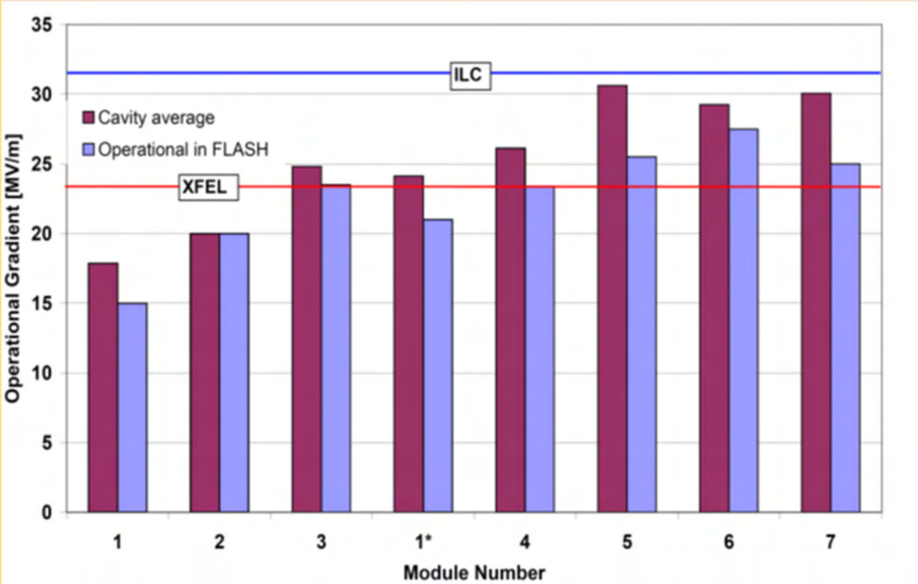
Pulsed superconducting accelerator

- 80 (100) TESLA type modules
- 20 (25) 5.2 MW RF stations
- 600 µs pulse width
- Up to 30 Hz repetition rate
- 24.3 (23.6) MV/m average accelerating gradient
- 14 (17.5) GeV final energy

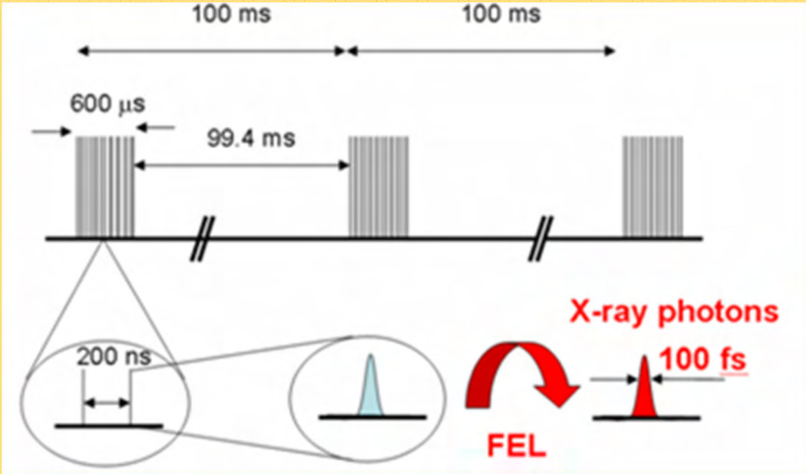
First XFEL prototype module (now installed in FLASH)

European XFEL – Linear Accelerator

Module Performance



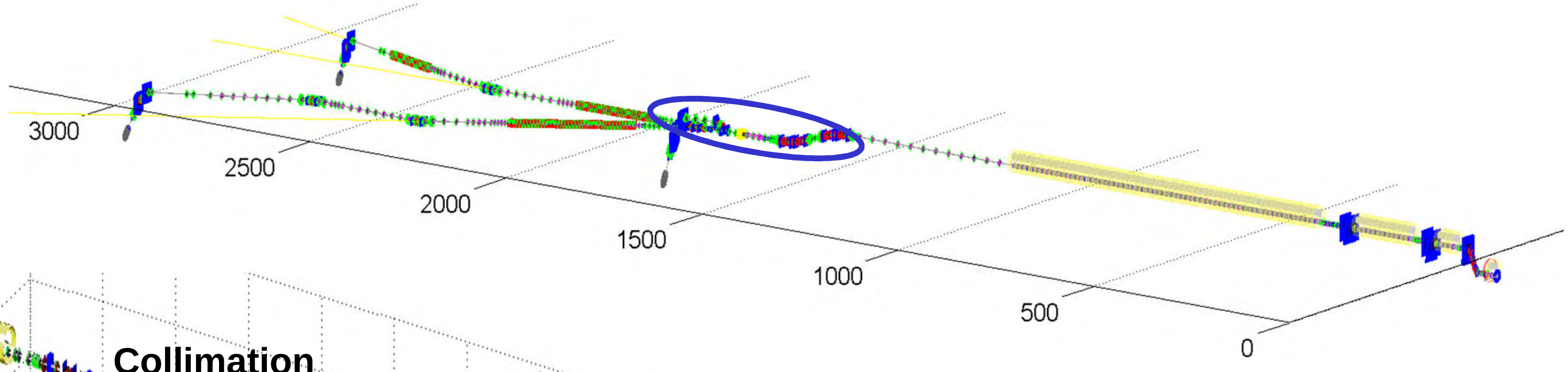
Time Structure

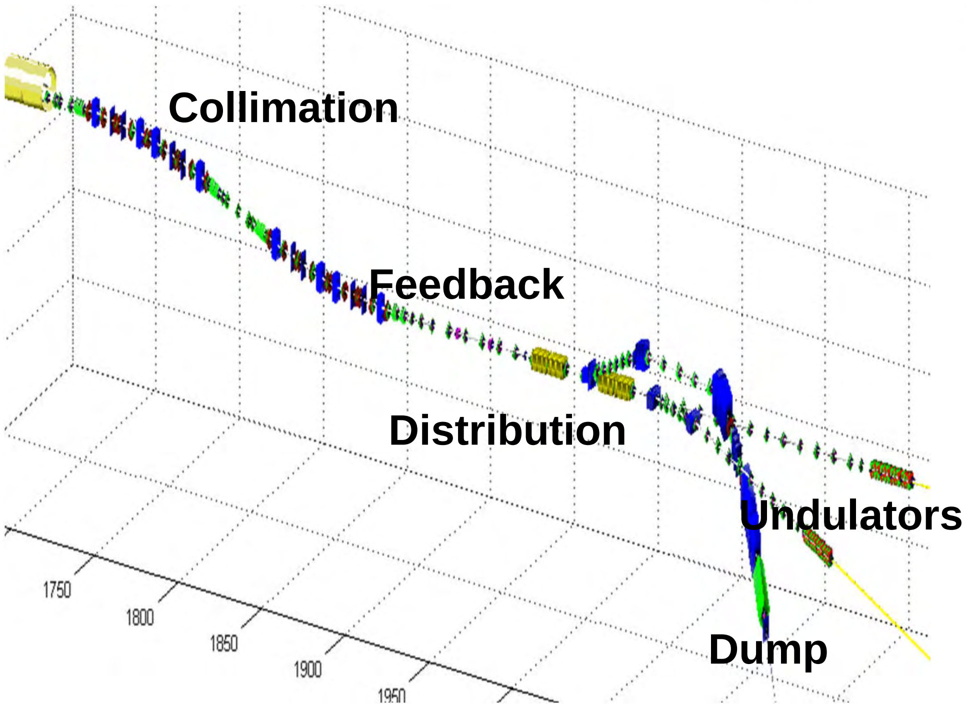


4.5 MHz frequency, 600 µs long bunch train bursts with 10 Hz repetition rate

Higher rep. rate possible on the expense of shorter pulses (average RF power limit)

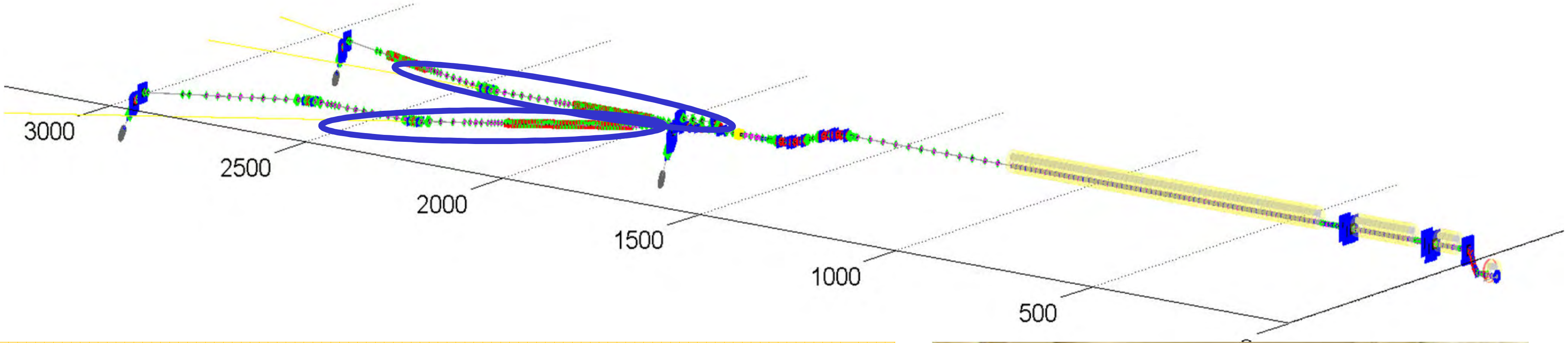
European XFEL – Collimation & Beam Distribution





- Collimation system for beam halo cleaning and emergency beam stop
- Transvers Intra-Bunch Feedback
- Flexible beam distribution system for quasi-simultaneous operation of two primary electron beam lines

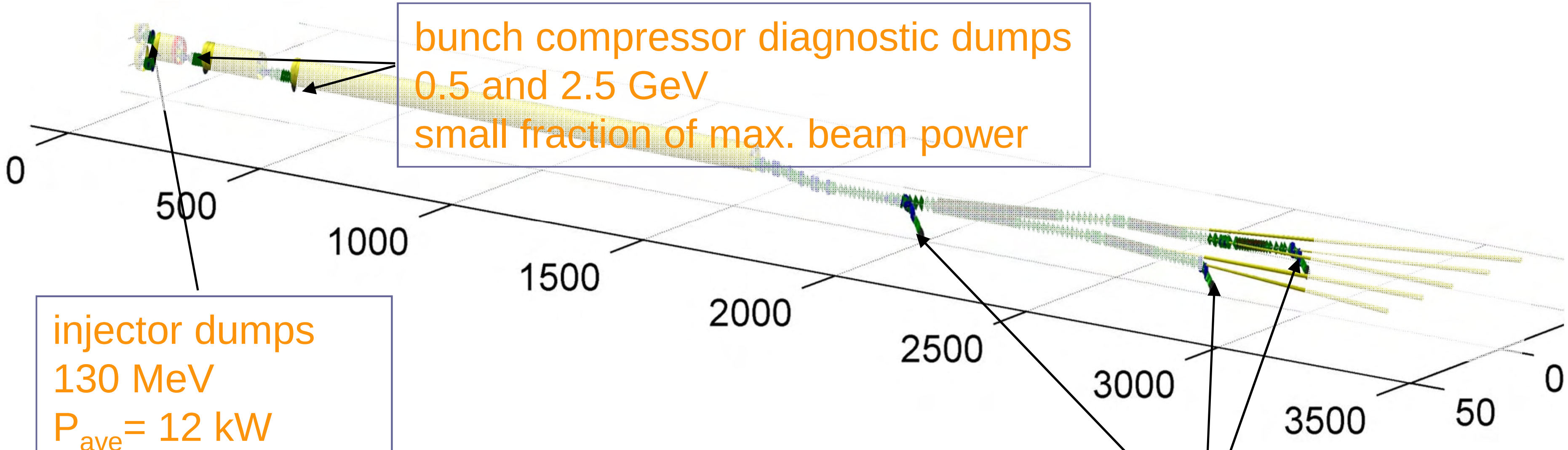
European XFEL – Undulators



- Five long undulator(-tunnel)s ensure saturation at <1 Å and leave room for more options and improvements
- Available straight section length 1500 m
- Initial total undulator length 455 m
- Out of vacuum, moveable gap (g_{min} = 10 mm) permanent magnet undulators with 40 resp. 68 mm period length

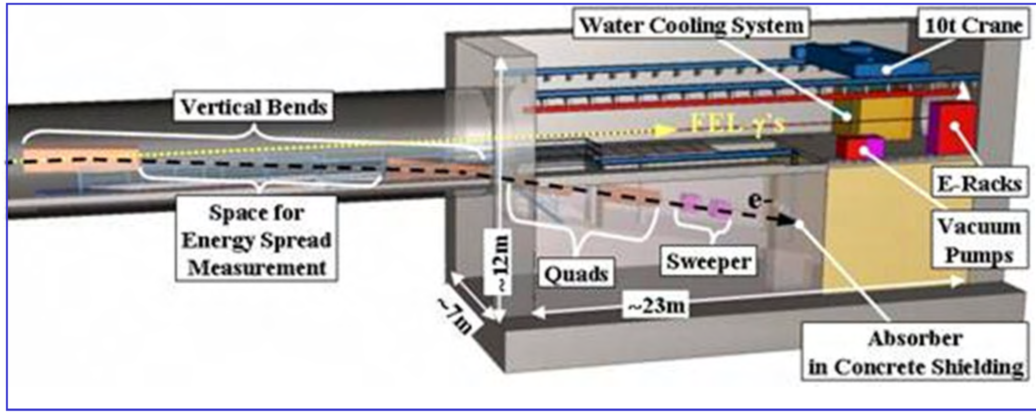
PETRA III undulator (XFEL prototype) in XFEL undulator measurement lab

Beam Dumps



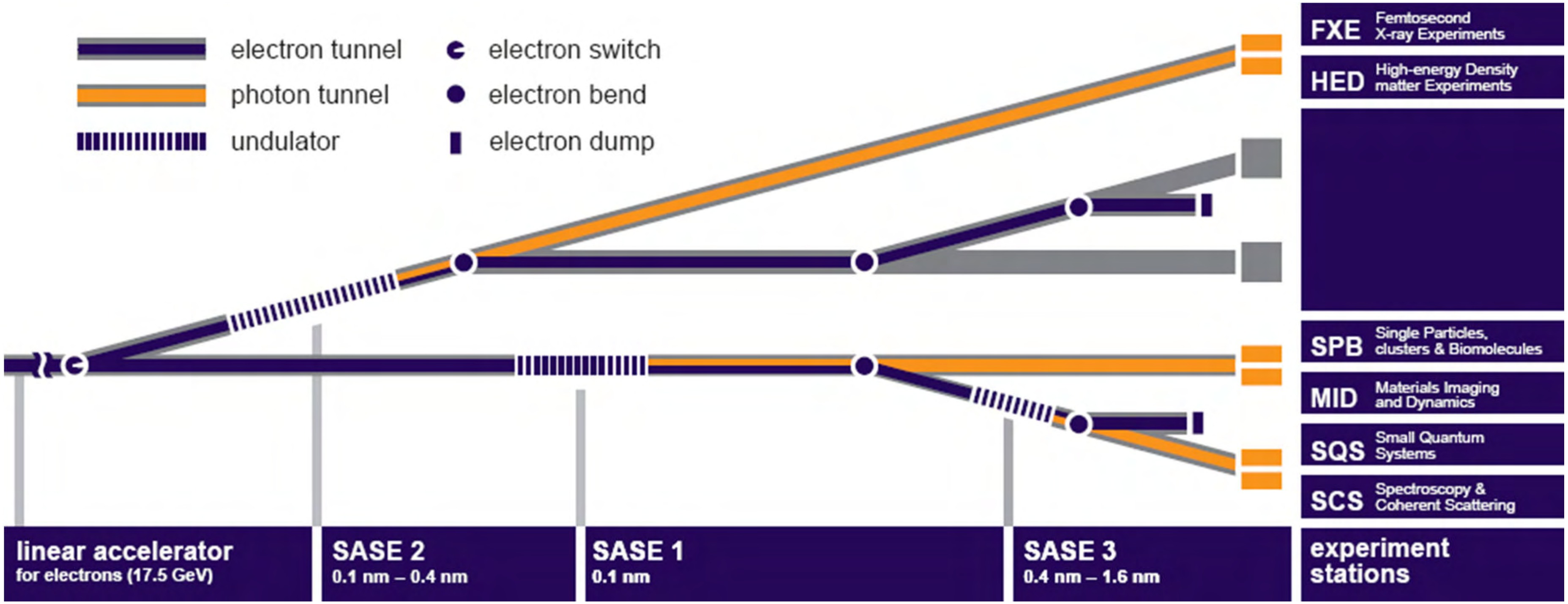
bunch compressor diagnostic dumps
0.5 and 2.5 GeV
small fraction of max. beam power

injector dumps
130 MeV
P_{ave}= 12 kW
max. beam power



main beam dumps
up to 25 GeV
P_{ave}= 300 kW
1/2 max beam power
beam magnified
slow sweep to distribute heat

Photon Systems: Beam Lines & Experiments

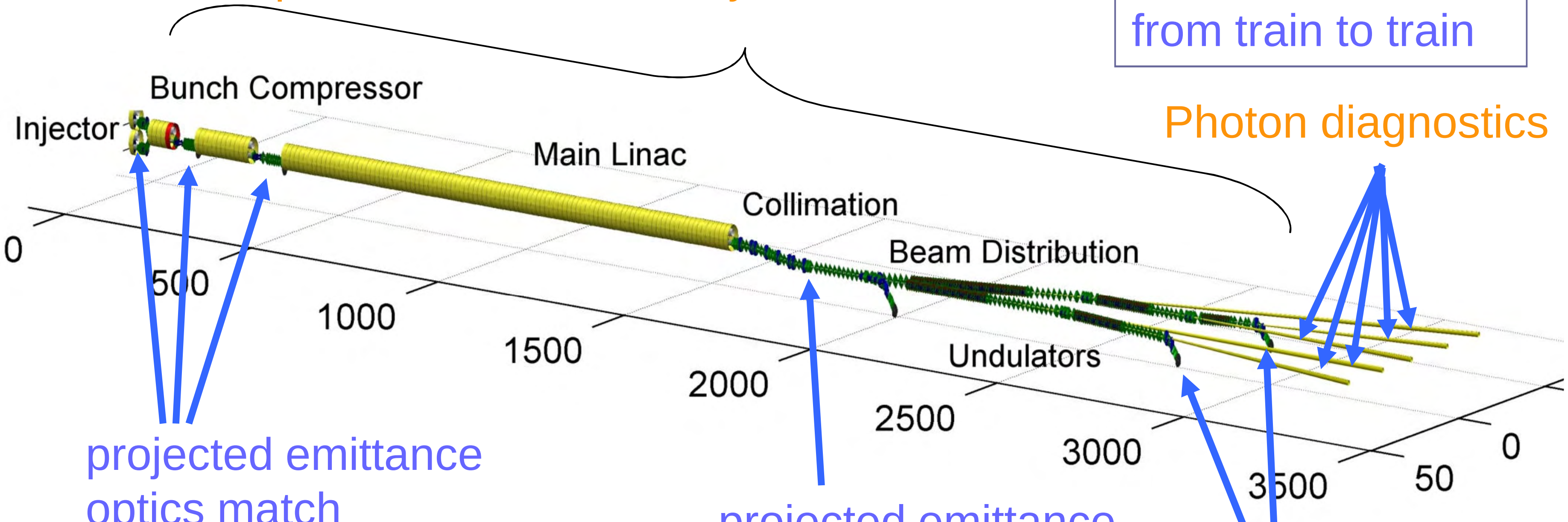


- 6 experiments fed from 3 SASE undulators in the start-up version
- Up po 15 experiments from 5 (SASE) undulators foreseen

Beam Diagnostics

within bunch
within bunch train
from train to train

beam position, beam intensity, beam losses



Photon diagnostics

projected emittance
optics match
energy
energy spread
rel. peak current
arrival time
slice emittance
long. bunch shape

projected emittance
optics match
energy
energy spread
rel. peak current
arrival time

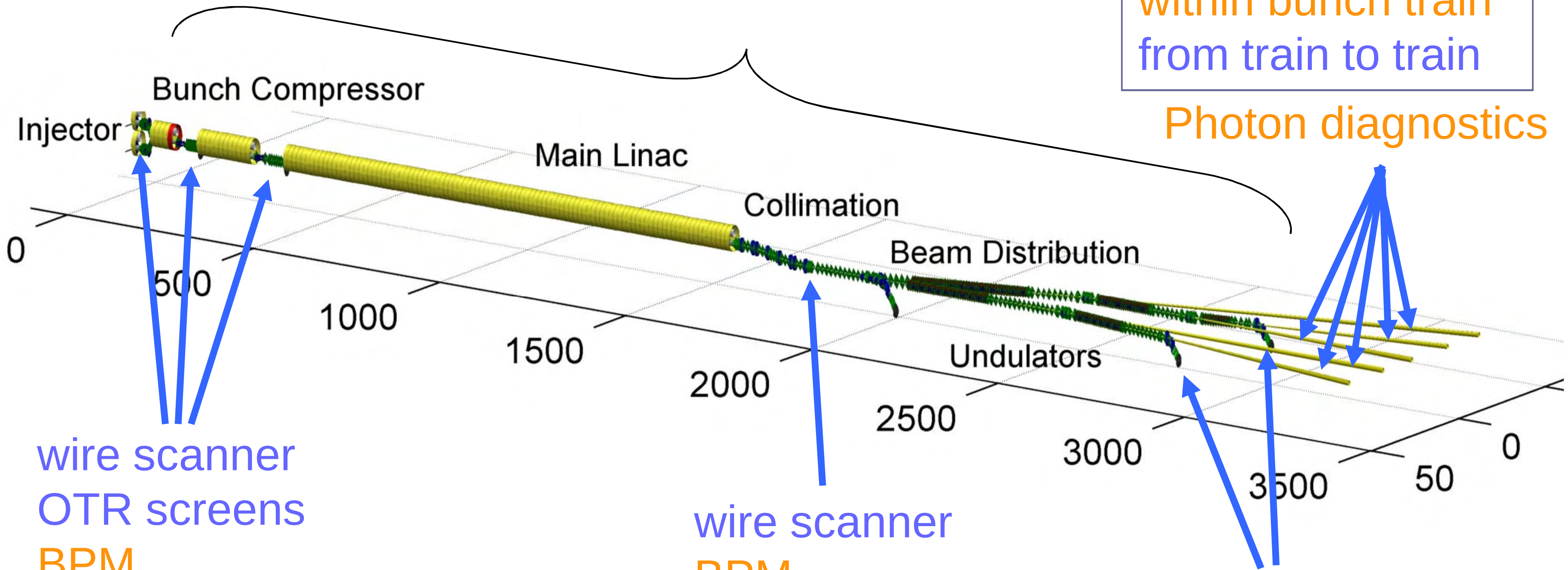
projected emittance

Beam Diagnostics

BPM, Toroids, Fibers, loss monitors, screens

within bunch
within bunch train
from train to train

Photon diagnostics



wire scanner
OTR screens
BPM
SR monitors
coherent diffraction radiation
transverse deflecting structure
electro-optical methods

wire scanner
BPM
SR monitors
coherent diffraction radiation
electro-optical methods

wire scanner

Project Milestones

June 2007: Official project start announced on basis of start version at 850M€/y2005 construction cost

Early 2009: Start of construction

30.11.2009: Signing of international state treaty which provides the basis for the foundation of the **European XFEL GmbH** in charge of the construction and operation of the XFEL facility

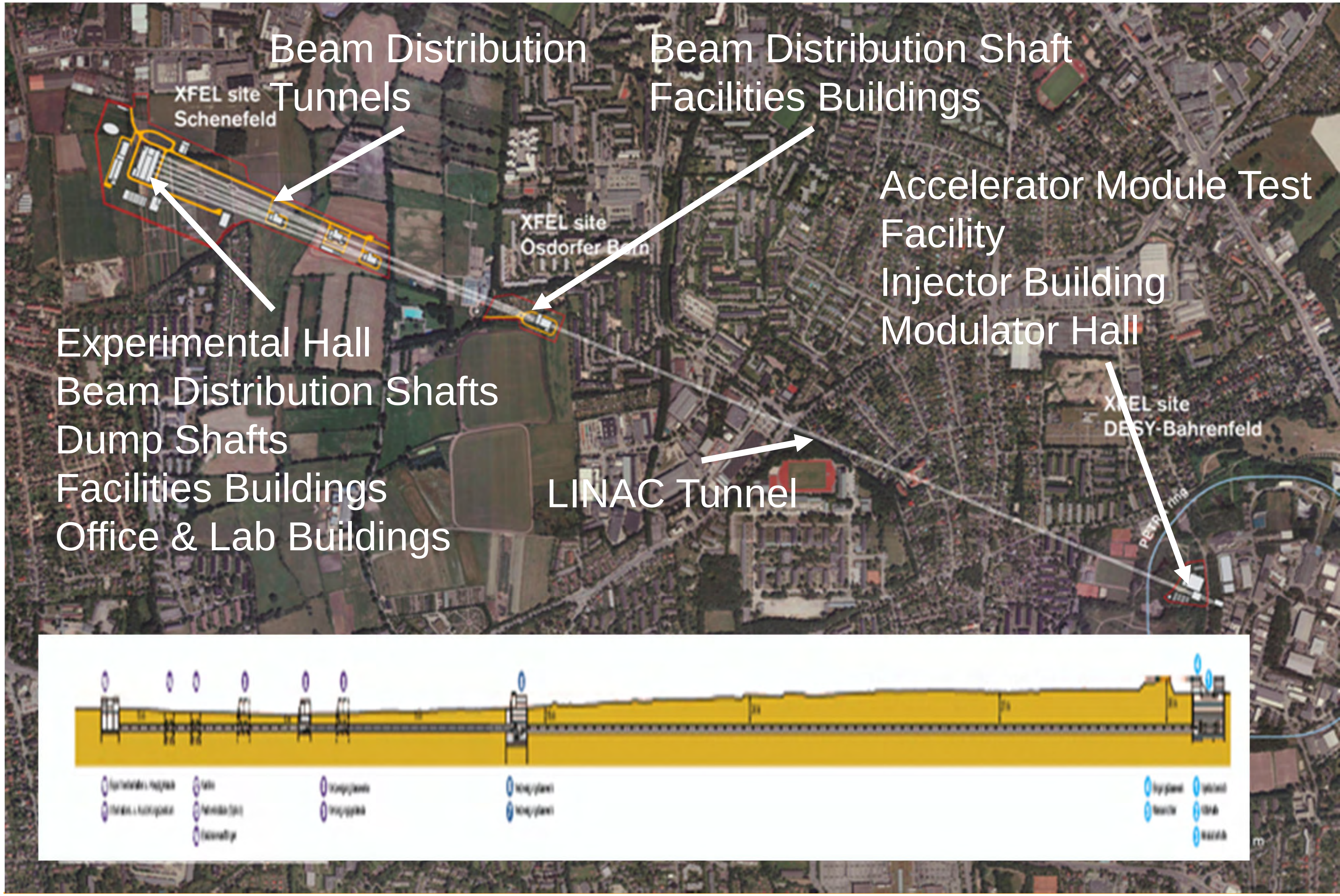
DESY leads the consortium that constructs the accelerator

End 2013: First beam in injector

End 2014: First beam in main linac

End 2015: Ready for users

Civil Construction

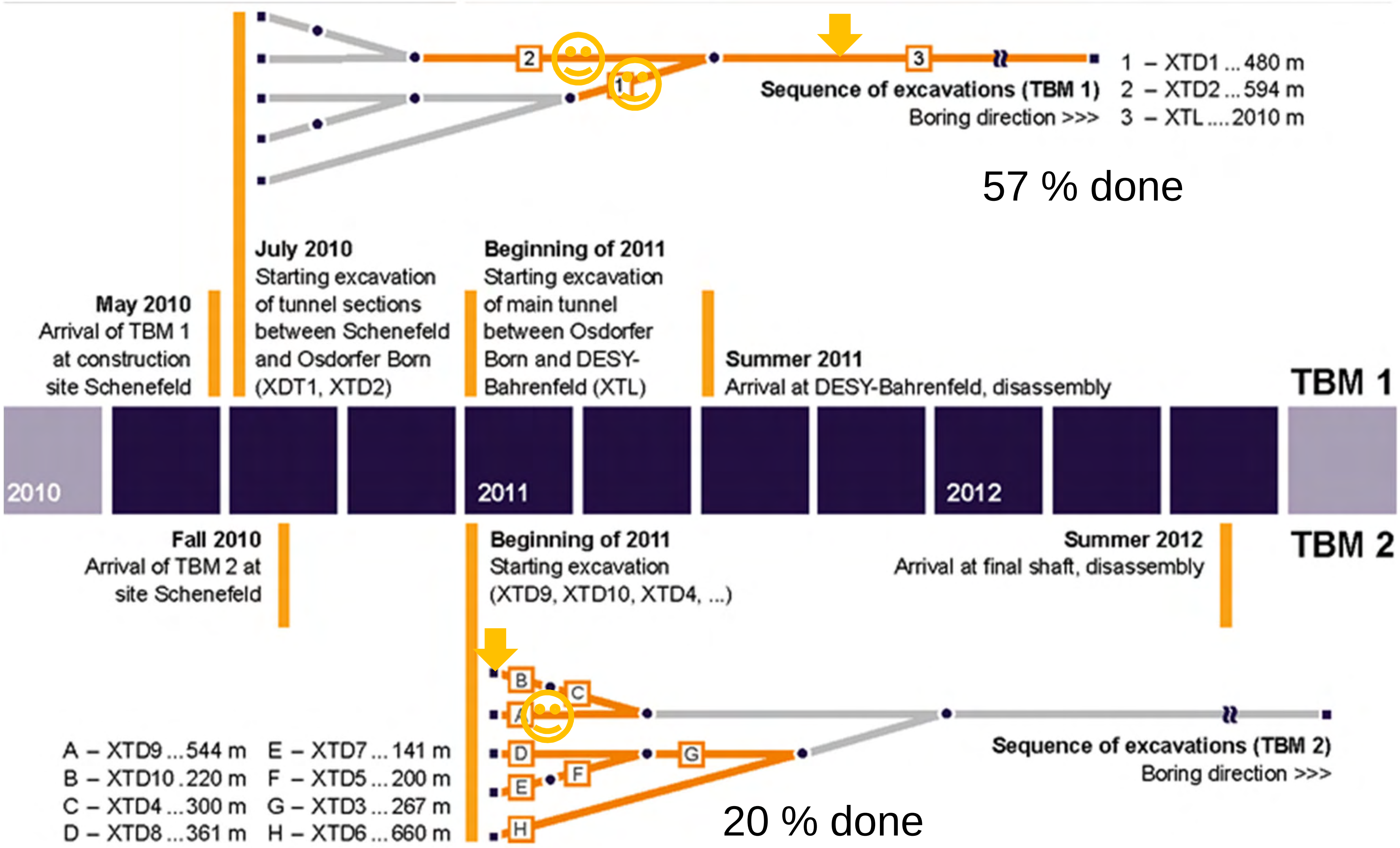


DESY Site

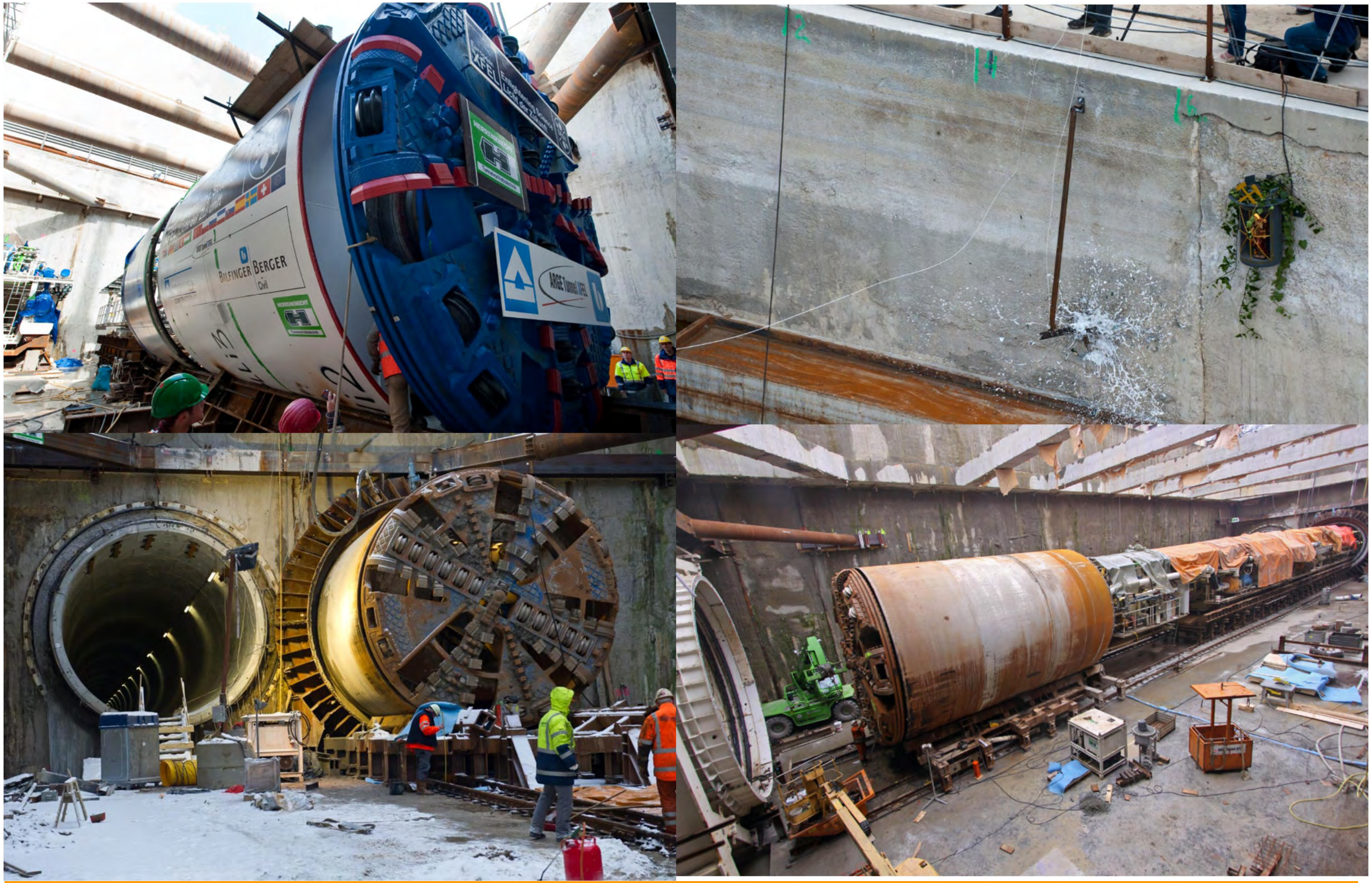
Injector Building – An Underground High Rise

Schenefeld Site

6 km of tunnel construction



Tunnel Construction



First Tunnel Ready – October 2010

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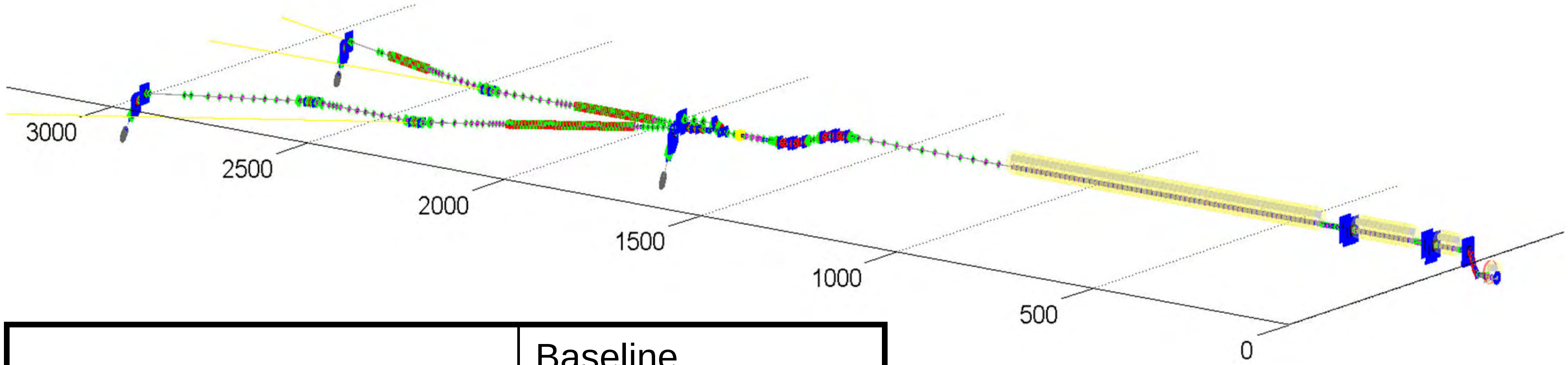
XFEL – Start-Up Version



	Baseline
Electron Energy	17.5 GeV
Bunch charge	1 nC
Peak current	5 kA
Slice emittance	< 1.4 mm mrad
Slice energy spread	1.5 MeV
Shortest SASE wavelength	0.1 nm
Pulse repetition rate	10 Hz
Bunches per pulse	3000

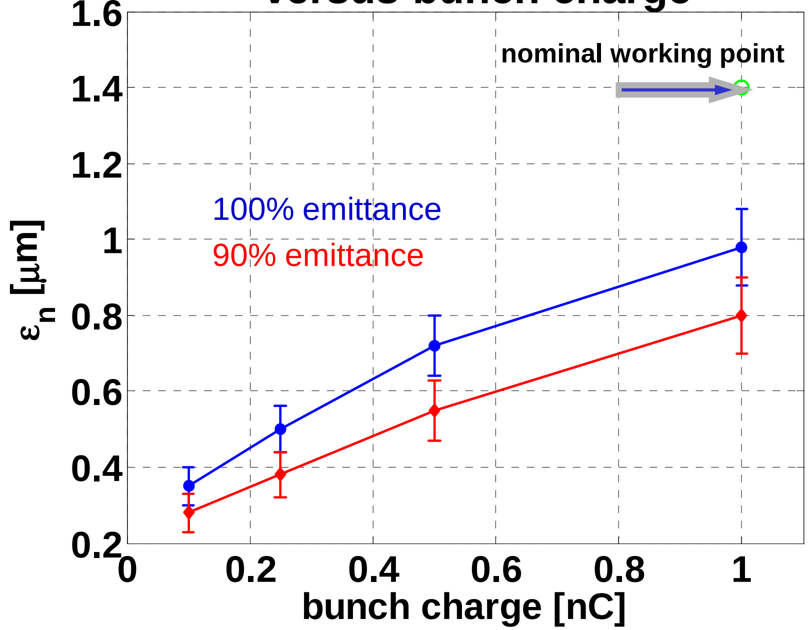
Improved Injector Performance & LCLS Lasing

- Remarkable success of LCLS both at nominal and 20 pC working point

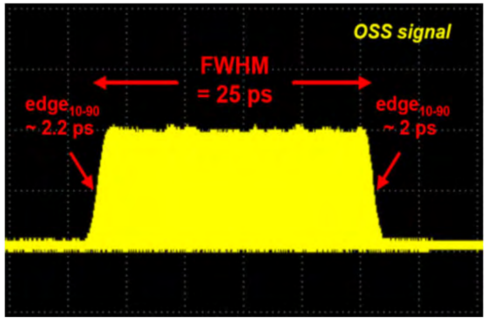
- Progress at PITZ

Photo Injector Test in Zeuthen

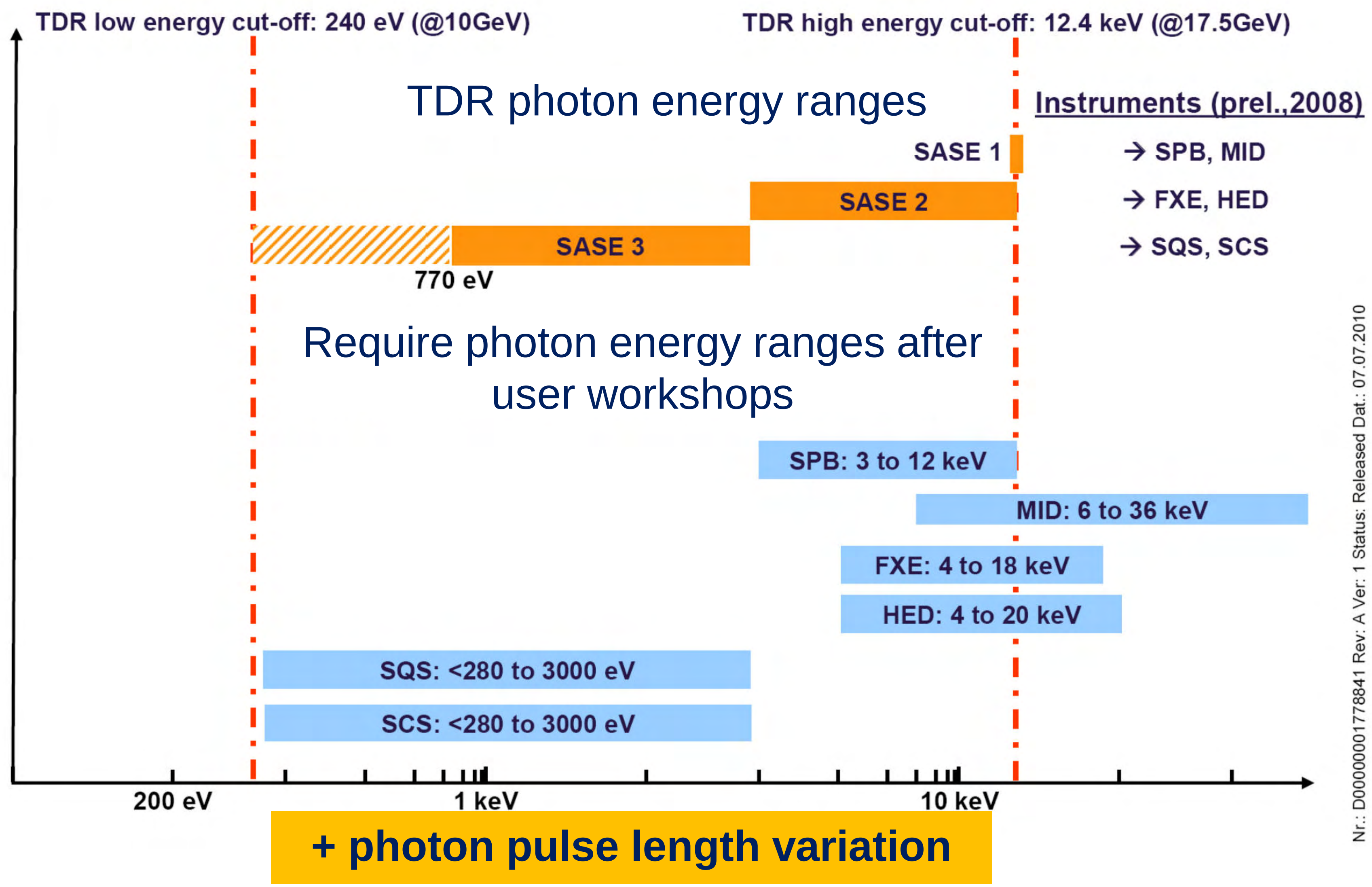
Measured projected emittance versus bunch charge



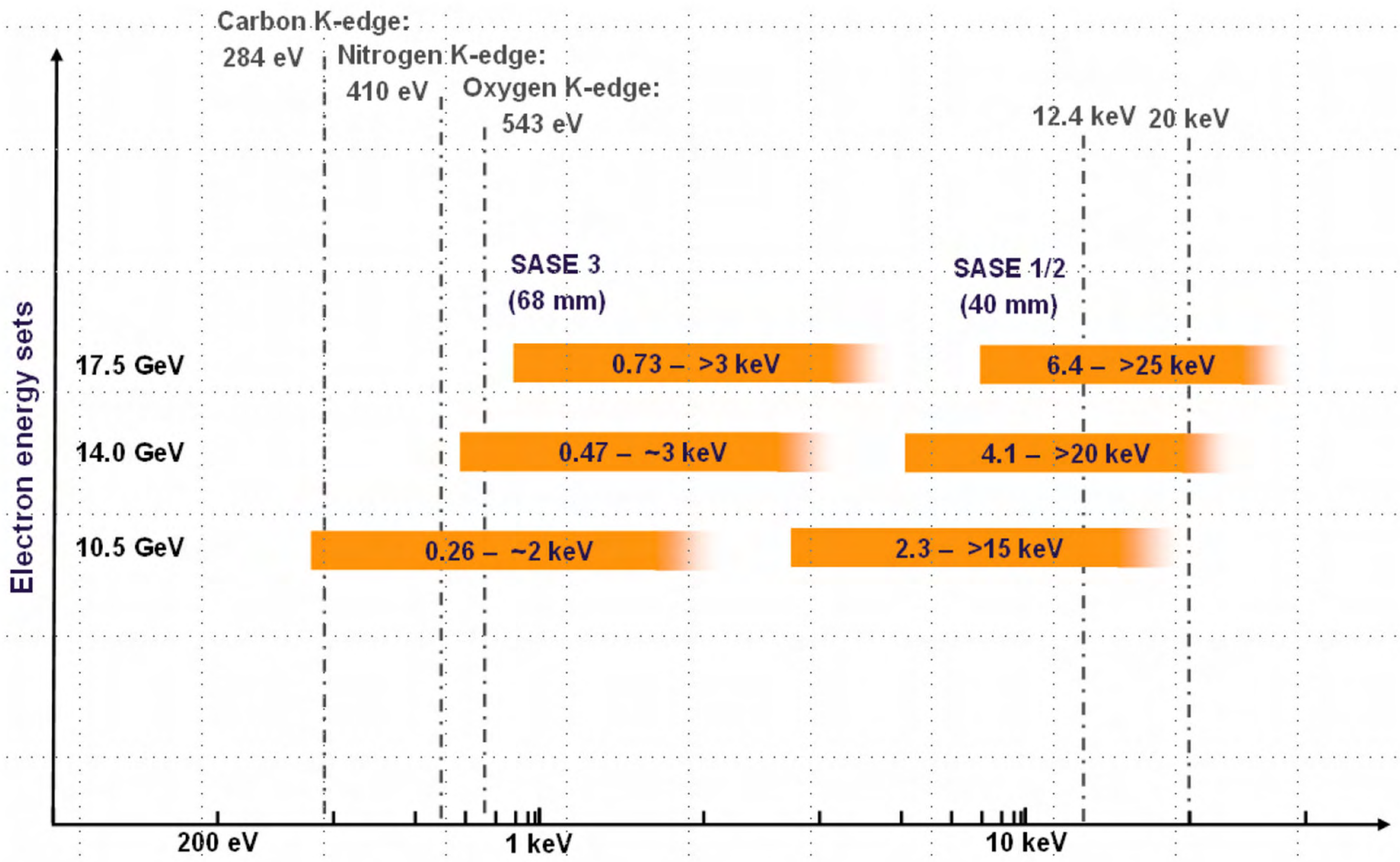
Flat-Top laser with sharp edges



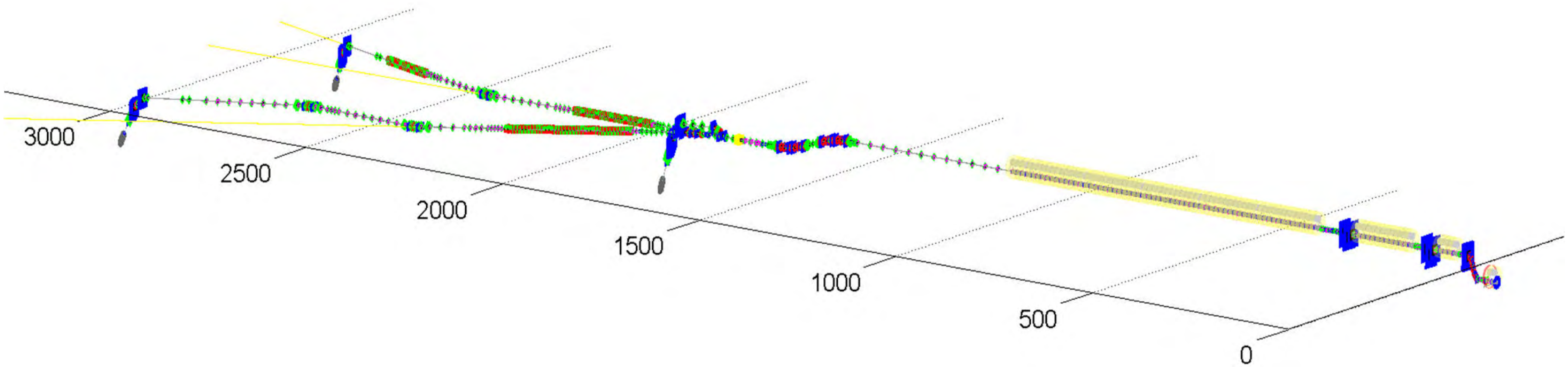
New Requirements from Users



New Photon Energy Ranges



XFEL – Start-Up Version



	Baseline	New Parameter Set
Electron Energy	17.5 GeV	10.5/14/17.5 GeV
Bunch charge	1 nC	0.02 - 1 nC
Peak current	5 kA	2 - 5 kA
Slice emittance	< 1.4 mm mrad	0.4 - 1.0 mm mrad
Slice energy spread	1.5 MeV	4 - 2 MeV
Shortest SASE wavelength	0.1 nm	0.05 nm
Pulse repetition rate	10 Hz	10 Hz
Bunches per pulse	3000	2700

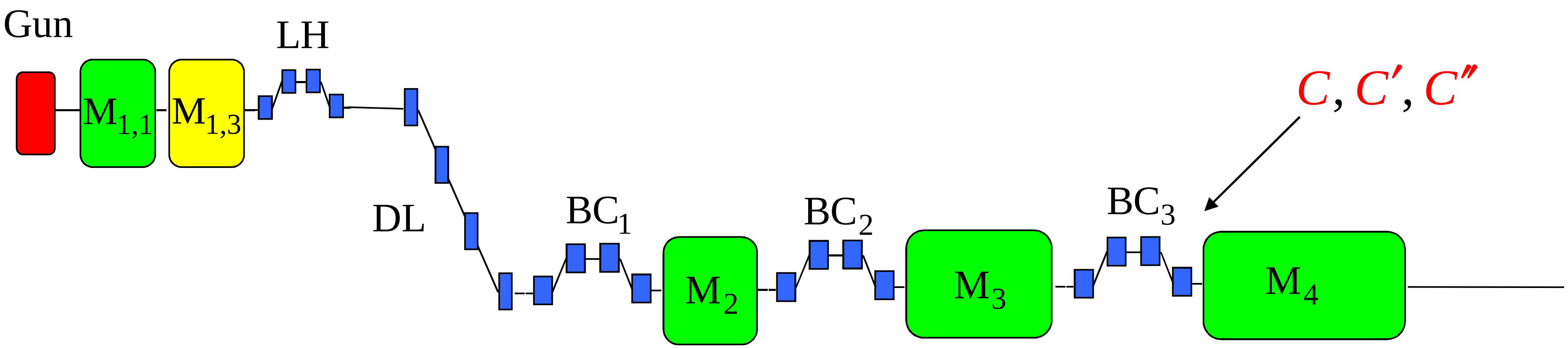
Establish new Working Point

Beam Parameters at GUN

Charge	nC	1	0.5	0.25	0.1	0.02	0.02	Optimized for shortest bunch length
Long. laser profile		Flat Top, 20 ps length, 2 ps rise time					Gaussian, 0.8 ps rms	
RMS laser spot size	mm	0.47	0.29	0.23	0.17	0.07	0.11	
Peak current	A	46.2	23.8	13.4	5.7	1.2	4.5	
Slice Emittance	µm	0.9	0.5	0.35	0.22	0.09	0.45	
Slice Energy Spread	keV	1	0.4	0.6	0.4	0.35	0.7	

Compression factor		120	220	380	830	1900
Peak Current	kA	5	5	5	5	4.5

Optimize BC Working Points



$E_1 = 130\,\text{MeV}$ $r_{56,1} = ?$ $C_1 = ?$

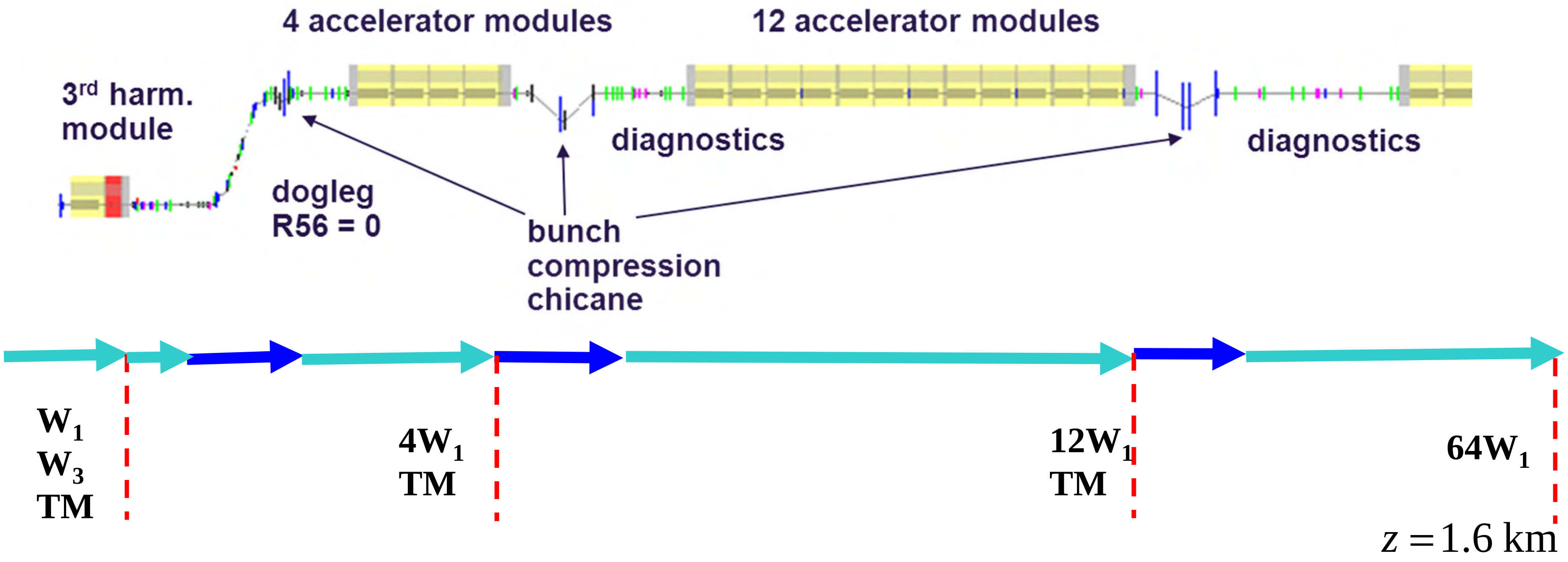
$E_2 = 700\,\text{MeV}$ $r_{56,2} = ?$ $C_2 = ?$

$E_3 = 2400\,\text{MeV}$ $r_{56,3} = ?$

- Optimize 11 macro parameters
- Criteria
  - Limit on energy chirp in dispersive sections
  - Symmetrize bunch current profile
  - Final energy chirp to compensate linac wakes
  - Optimize RF tolerance requirements

I. Zagorodnov, M. Dohlus, *A Semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects*, Physical Review STAB 14 (2011), 014403.

S2E Simulations – Full 3D Model



ASTRA (tracking with **3D space charge**)

CSRtrack (tracking through dipoles)

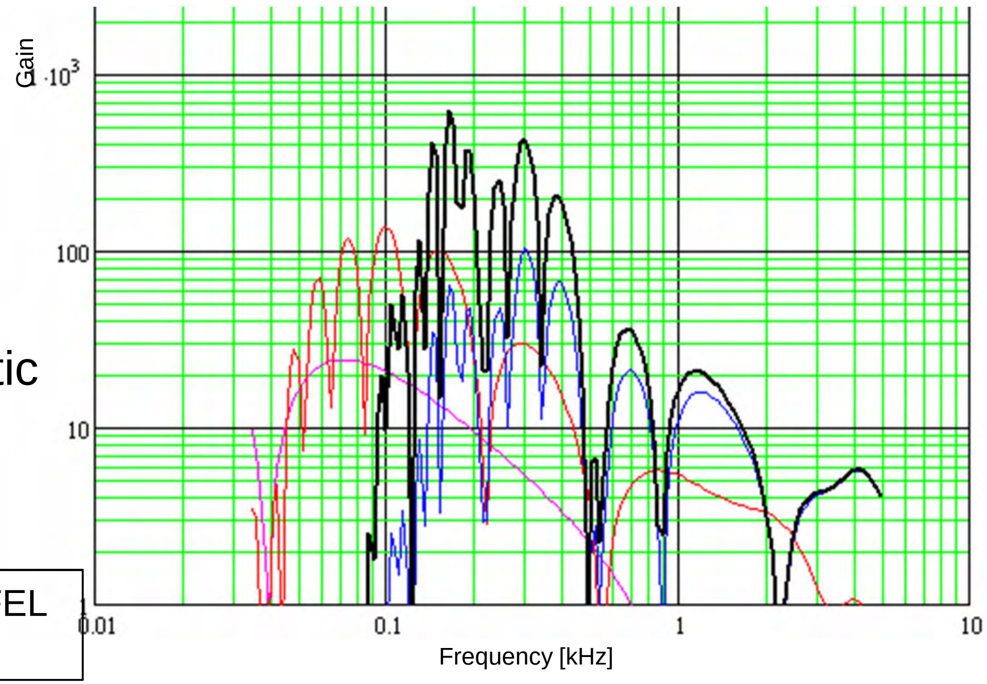
W1 -TESLA cryomodule wake
W3 - ACC39 wake
TM - transverse matching to the design optics

Micro-Bunching Instability

- Longitudinal space charge induced growth of initial current fluctuations
- Damping by large uncorrelated energy spread
- Smaller initial current -> smaller instability growth
- Laser heater scaled to provide same energy spread after final compression
- Keep final current ripple < 200 A => initial energy spread ≤ 20 KeV

Gain of initial density fluctuation

Example working point with realistic LH and 10 KeV energy spread



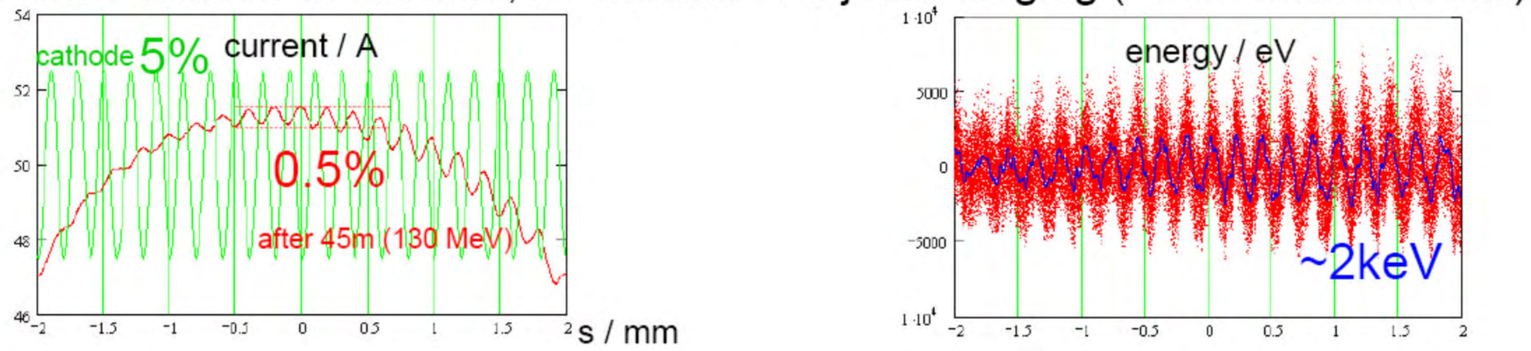
Microbunch amplification in the European XFEL
M. Dohlus et. al. DESY-TESLA-FEL-2009-02

Micro-Bunching Instability

- Longitudinal space charge washes out initial density ripple

ASTRA simulation:

5% modulation at cathode, $\lambda = 0.2\ \mathrm{mm} \rightarrow$ injector dogleg (~45m after cathode):



- Effect decreases with decreasing peak current
- Add uncorrelated energy spread to counteract instability

  => 2 final energy spread at 20 pC

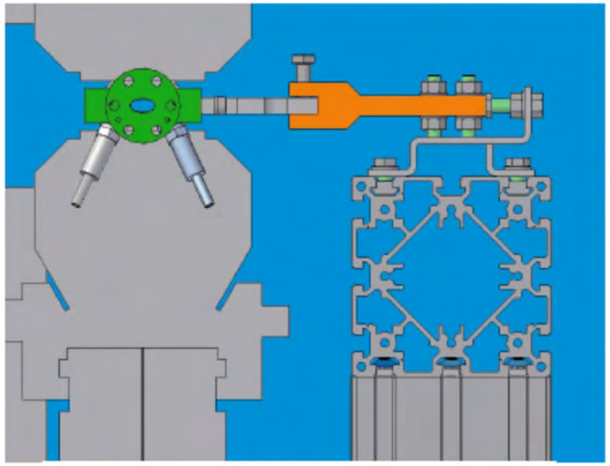
Beam Parameters at Undulator

- Uncorrelated energy spread increases due to compression
- Slice emittance degrades due to space-charge, CSR, and geometrical wakes

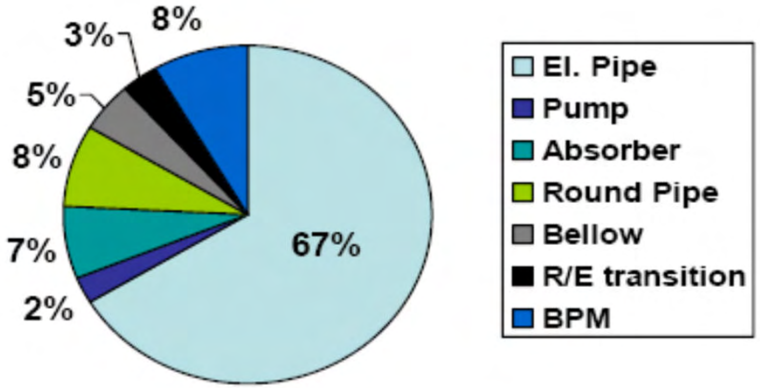
Charge	**nC**	**1**	**0.5**	**0.25**	**0.1**	**0.02**	
Compression factor		120	220	380	830	1900	
Slice Energy Spread	MeV	0.45	0.43	0.60	0.58	0.73	From S2E
Slice Energy Spread with LH	**MeV**	**2.0**	**2.2**	**2.5**	**2.9**	**4.1**	
Slice Emittance at Gun	µm	1	0.65	0.5	0.32	0.2	
Emittance Degradation	%	5.0	10.0	20.0	30.0	100.0	
Slice Emittance at Undulator		**0.97**	**0.70**	**0.60**	**0.39**	**0.32**	From S2E & Emittance Deg.

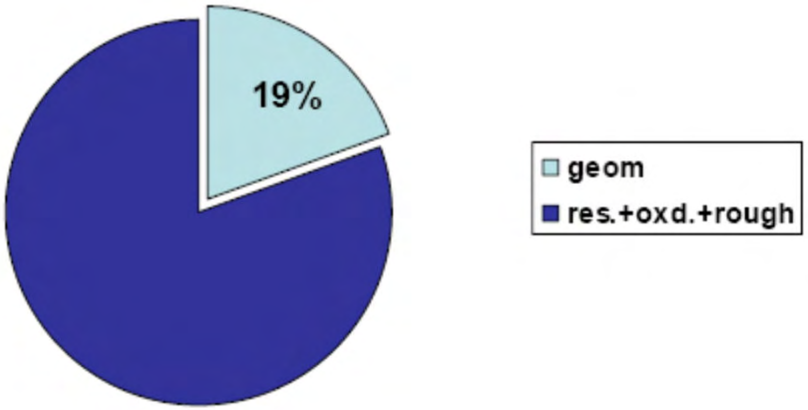
Impedance Budget - Undulator Vacuum System

- Undulator beam pipe 15 mm x 8.8 mm ellipsoid extruded Al



- Impedance Budget:
  – Criteria for max. roughness and oxide layer
    roughness [nm] + 50 x oxide layer [nm] < 500 nm

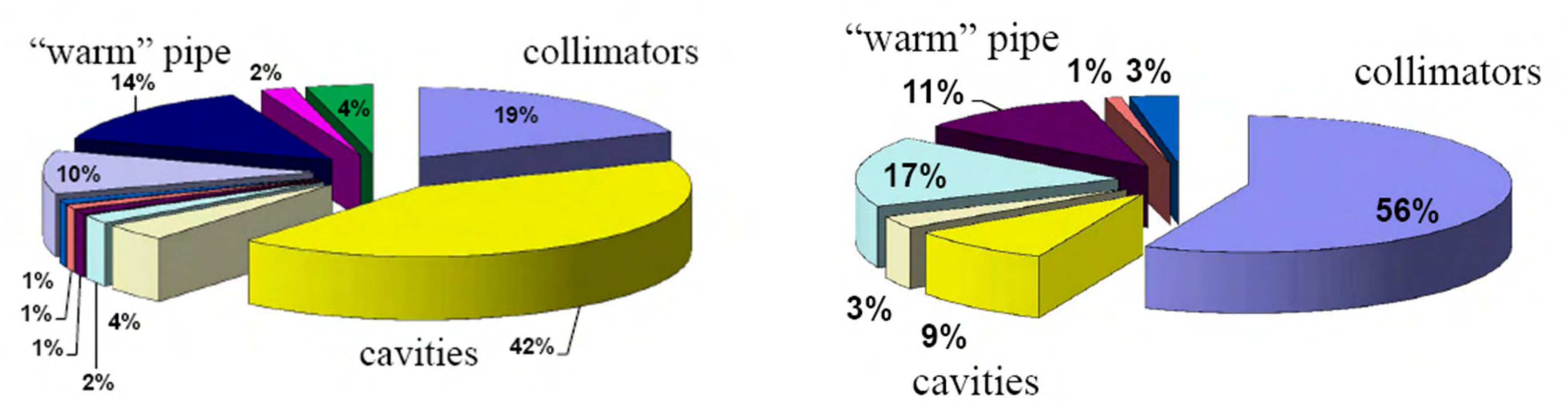




Impedance Budget – Other Components

All elements collected in impedance database

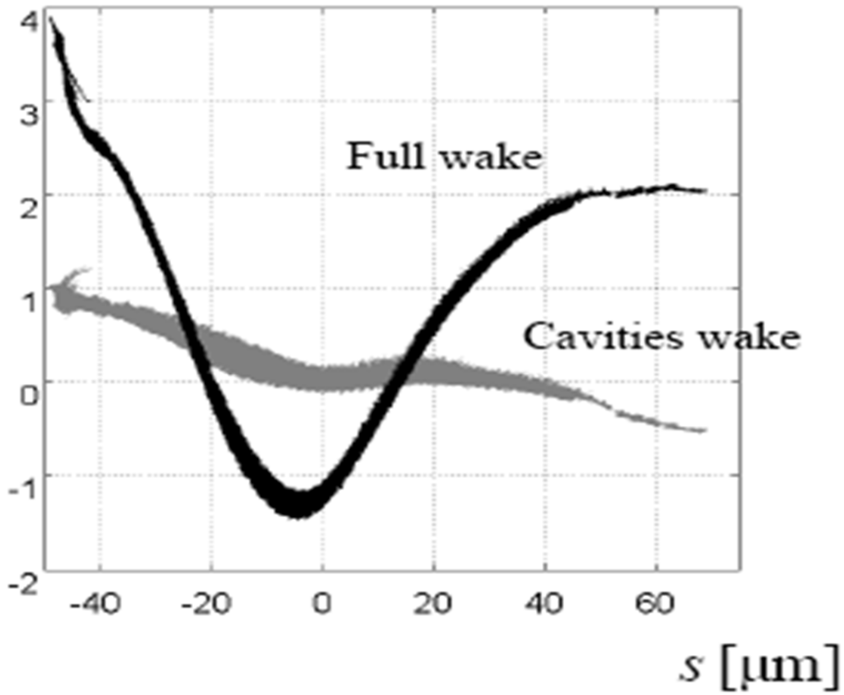
- wake field represented by Green's function
- convoluted with arbitrary bunch shape to obtain wake potential
- calculates energy loss and spread contribution



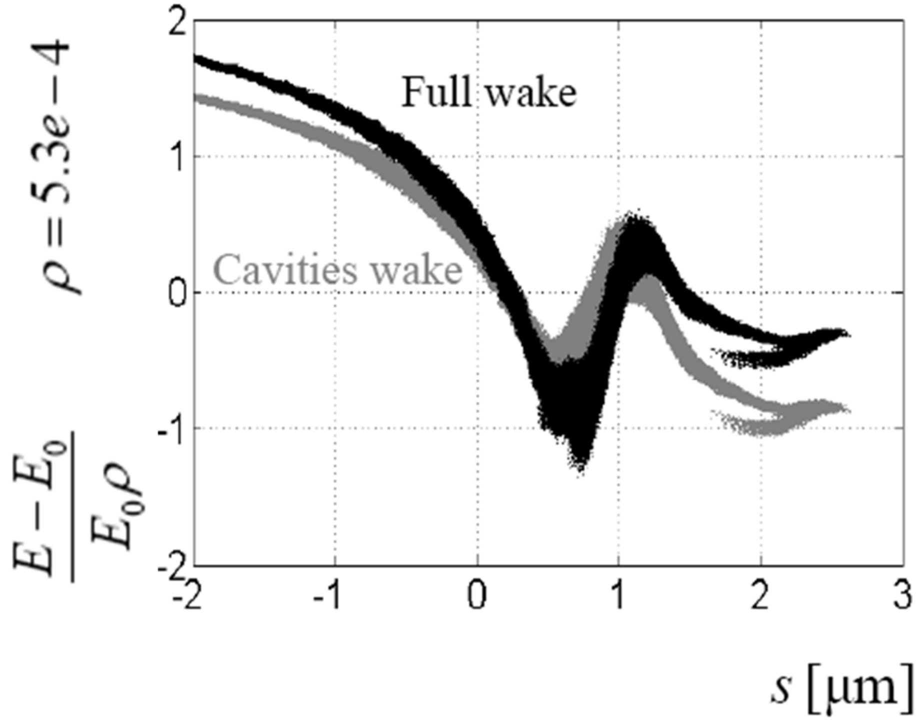
Impedance Budget Database, O. Zagorodnova,
http://www.desy.de/xfel-beam/data/talks/talks/zagorodnova_-_ibdb_20081103.pdf

Resulting Longitudinal Beam Profiles

1 nC



0.02 nC



- Conservative design of vacuum system
- Space charge wake dominates beam profile
- Effects on SASE can be mitigated by proper tapering of undulator for energy chirped beam

Longitudinal Impedance Budget and Simulations for XFEL, I. Zagorodnov, http://www.desy.de/xfel-beam/data/talks/files/Wakes_SASE.pdf

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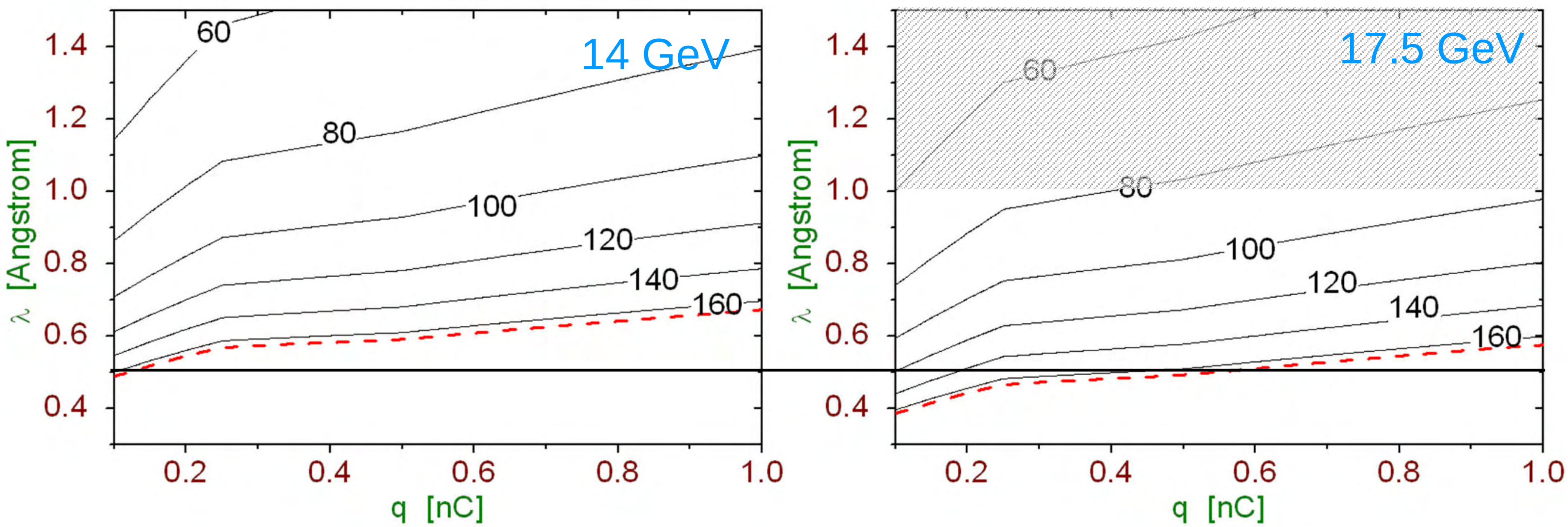
FEL performance at new parameter set

SASE 1/2 Saturation length

- Saturation = point with maximum brightness
- undulator with 165 m active length (now extended to 175)



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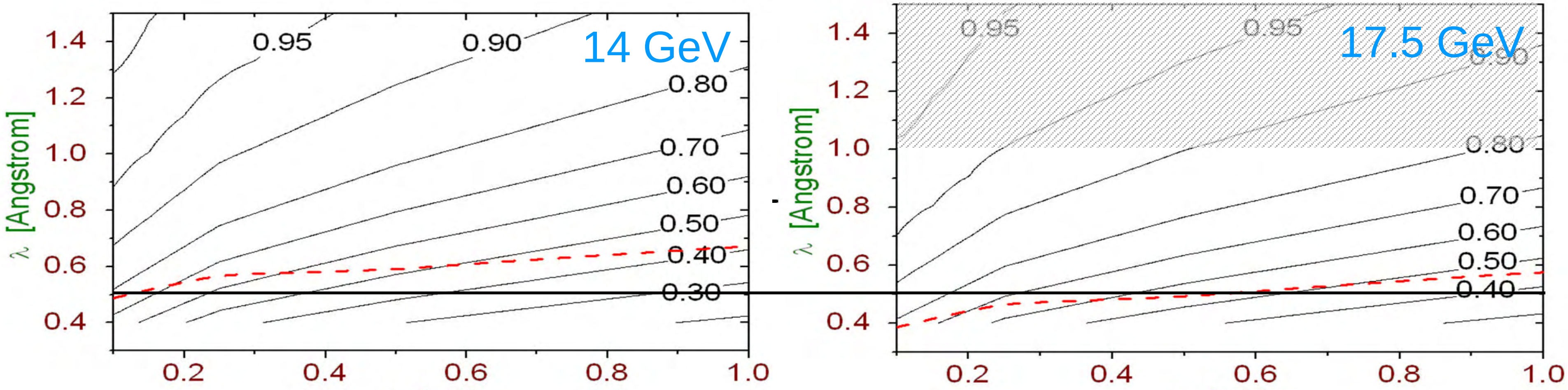
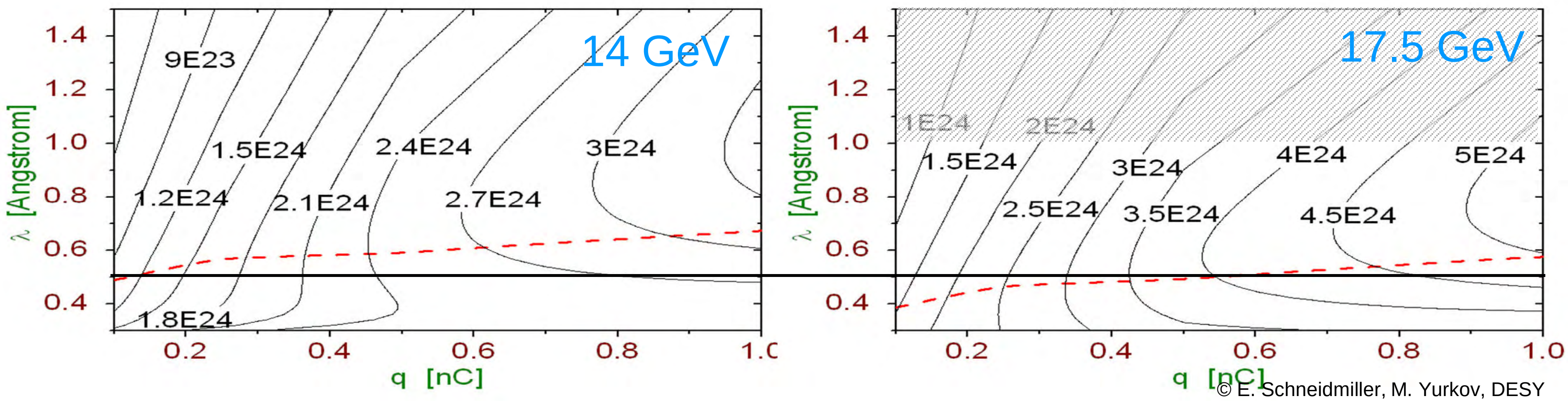
FEL performance at new parameter set

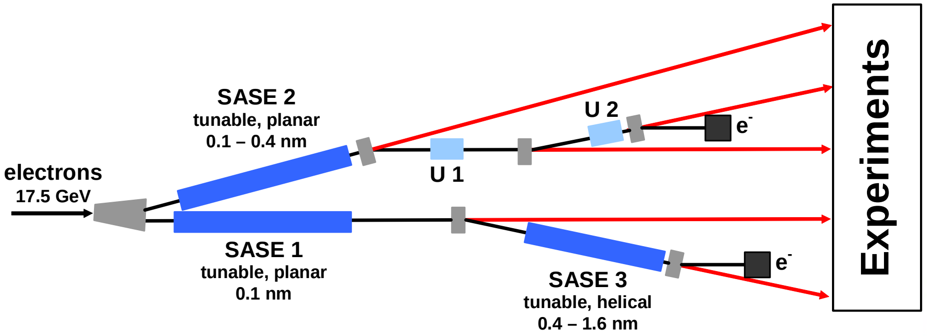
Coherence



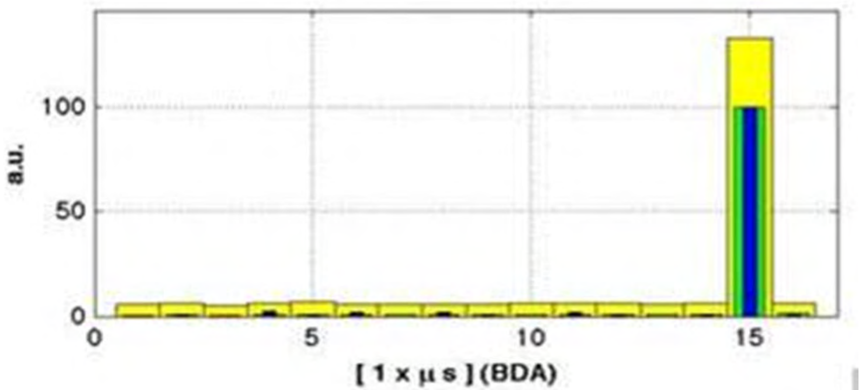
Average Brightness



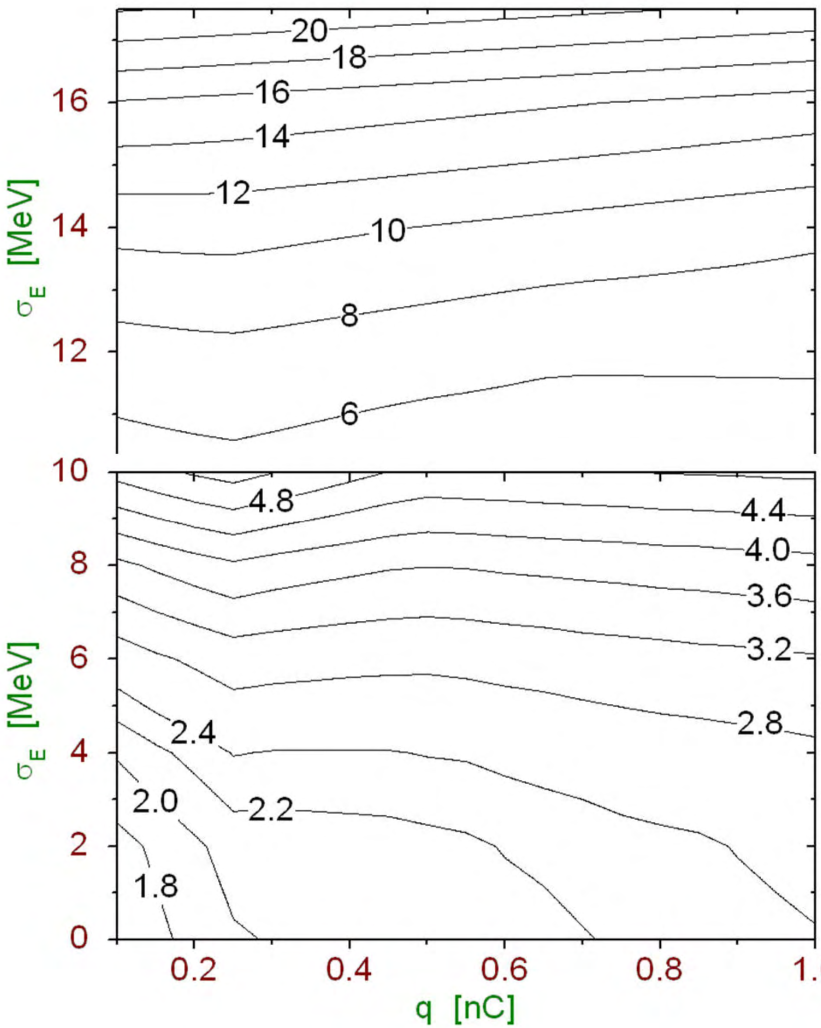
SASE 3 operation



- SASE 3 (k=0.5 – 3 keV) to be operated with ‘used’ bunches
- Energy spread induced by SASE1: less for higher charges and shorter wavelength
- Use ‘fresh’ bunch technique



minimum wavelength [Å] versus bunch charge and energy spread



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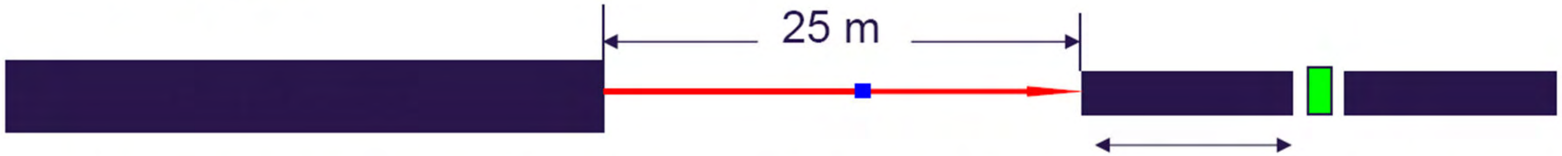
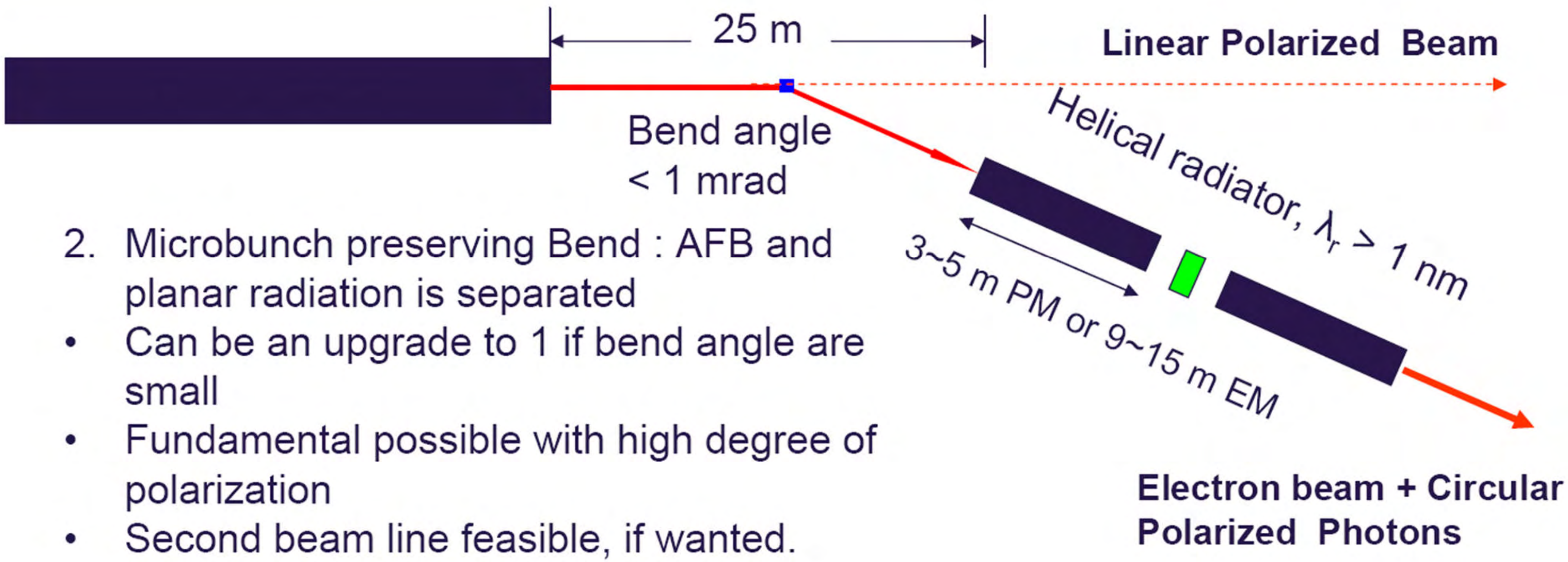
SASE 3 operation – Helical Afterburner (AFB)

Planar SASE 3

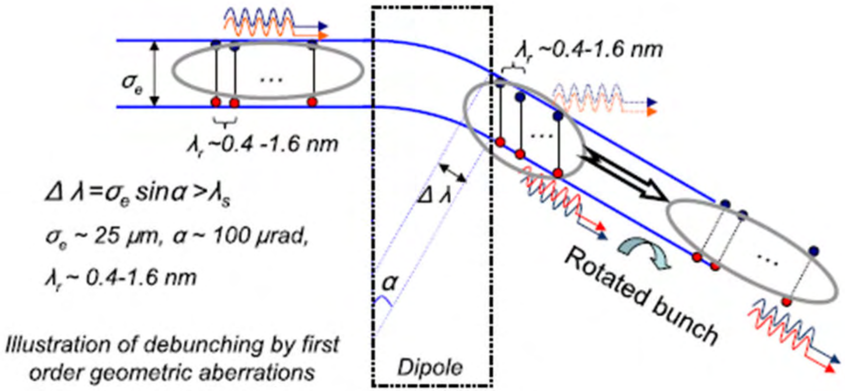


1. Straight: AFB radiation contaminated at fundamental with planar radiation AFB at 2ω, limits long wavelengths

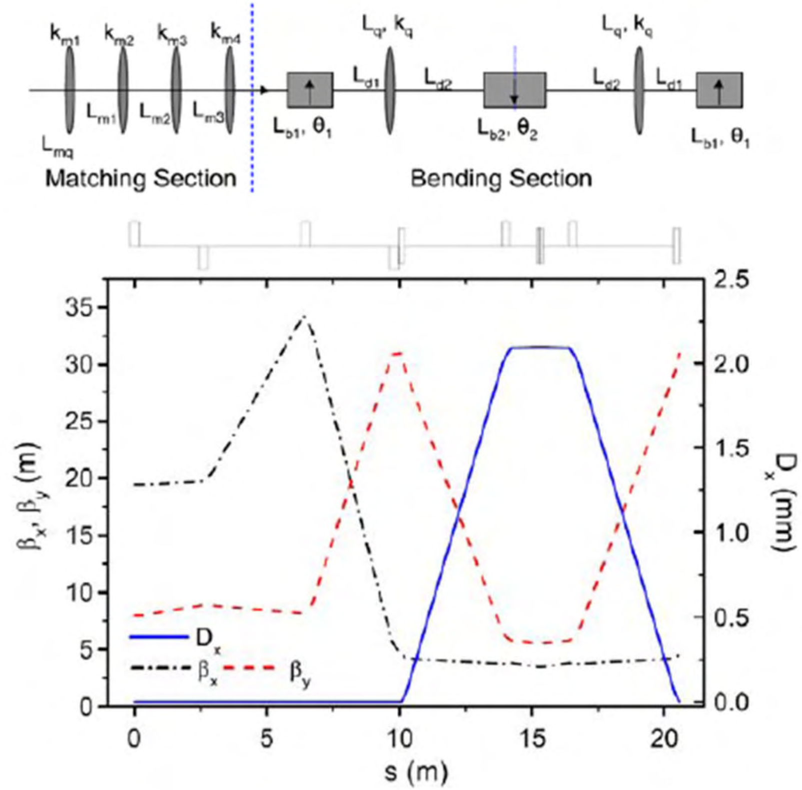


2. Microbunch preserving Bend : AFB and planar radiation is separated
   - Can be an upgrade to 1 if bend angle are small
   - Fundamental possible with high degree of polarization
   - Second beam line feasible, if wanted.

SASE 3 – Helical Afterburner



First order isochronous bend ~ **1000 μrad**



- First order ok for λ_r>1nm (at ε =1.4 nm)
- For shorter wavelength higher order isochronicity needed, gets complicated and long

Y. Li, W. Decking, B. Faatz, J. Pflueger, Phys. Rev. STAB 13, 080705 (2010)

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- Putting it all together – Project Organization

Serving multiple users

- Storage rings have 30+ beam lines with >MHz pulse repetition rates
- FELs serve one user at a time with the driver linac repetition (or pulse) rate

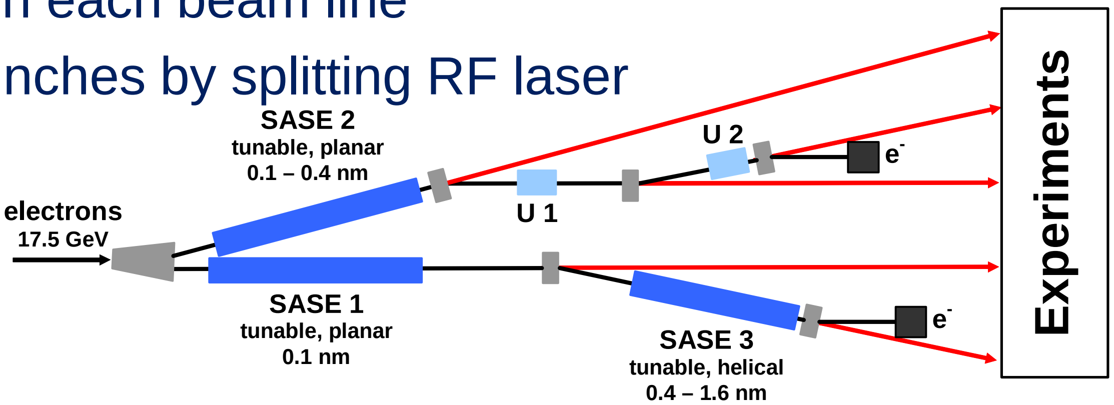
  (exception: use spent beam to drive another FEL, usually only possible for soft x-rays with less demanding beam quality requirements, example European XFEL)

- Nevertheless many user stations are desirable
  - to allow for experiment set-up
  - to make efficient use of many pulse linacs

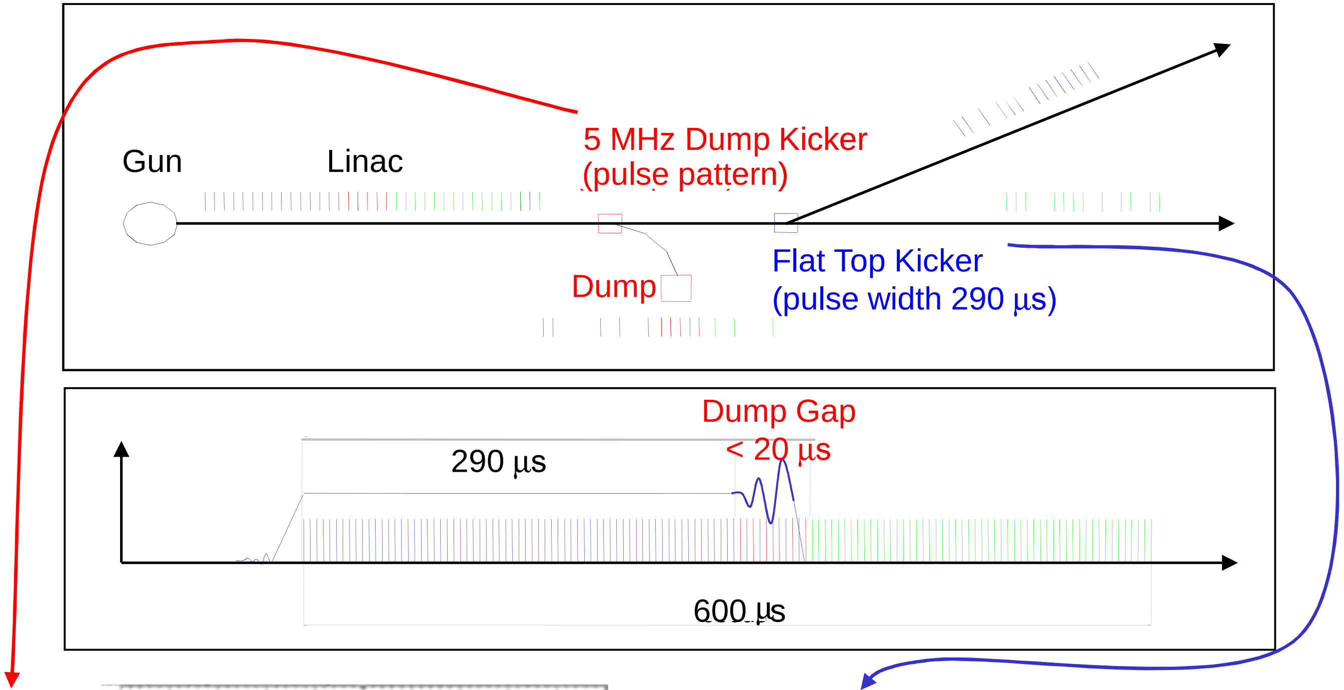
Beam Distribution into multiple beam lines

- Assumption: linac an laser is most stable with constant bunch pattern/beam loading
- Pulse switching is done with fast kickers
- **Both beam lines will have same bunch properties**

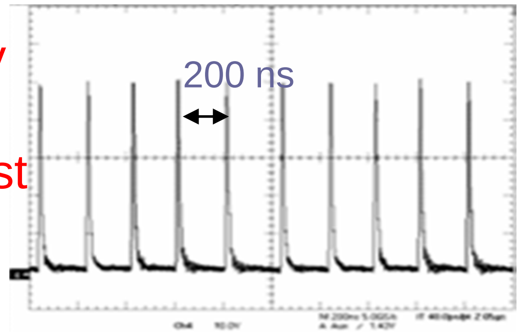
  (this is the challenge for the future: provide different bucnh propoerties, i.e. bunch length etc. within bunch train)
- Options:
  - All pulses in one beam line (max. beam power 300 kW !)
  - One split per pulse into two beam lines
  - Arbitrary patterns in each beam line
  - Closely spaced bunches by splitting RF laser



Pulse Pattern Creation

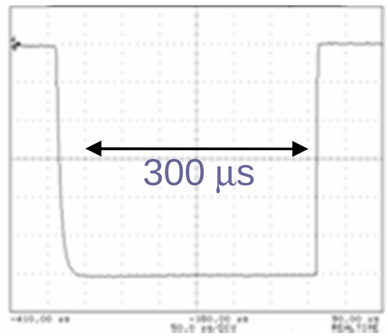


- low accuracy (>1 %)
- 4.5 MHz burst operation



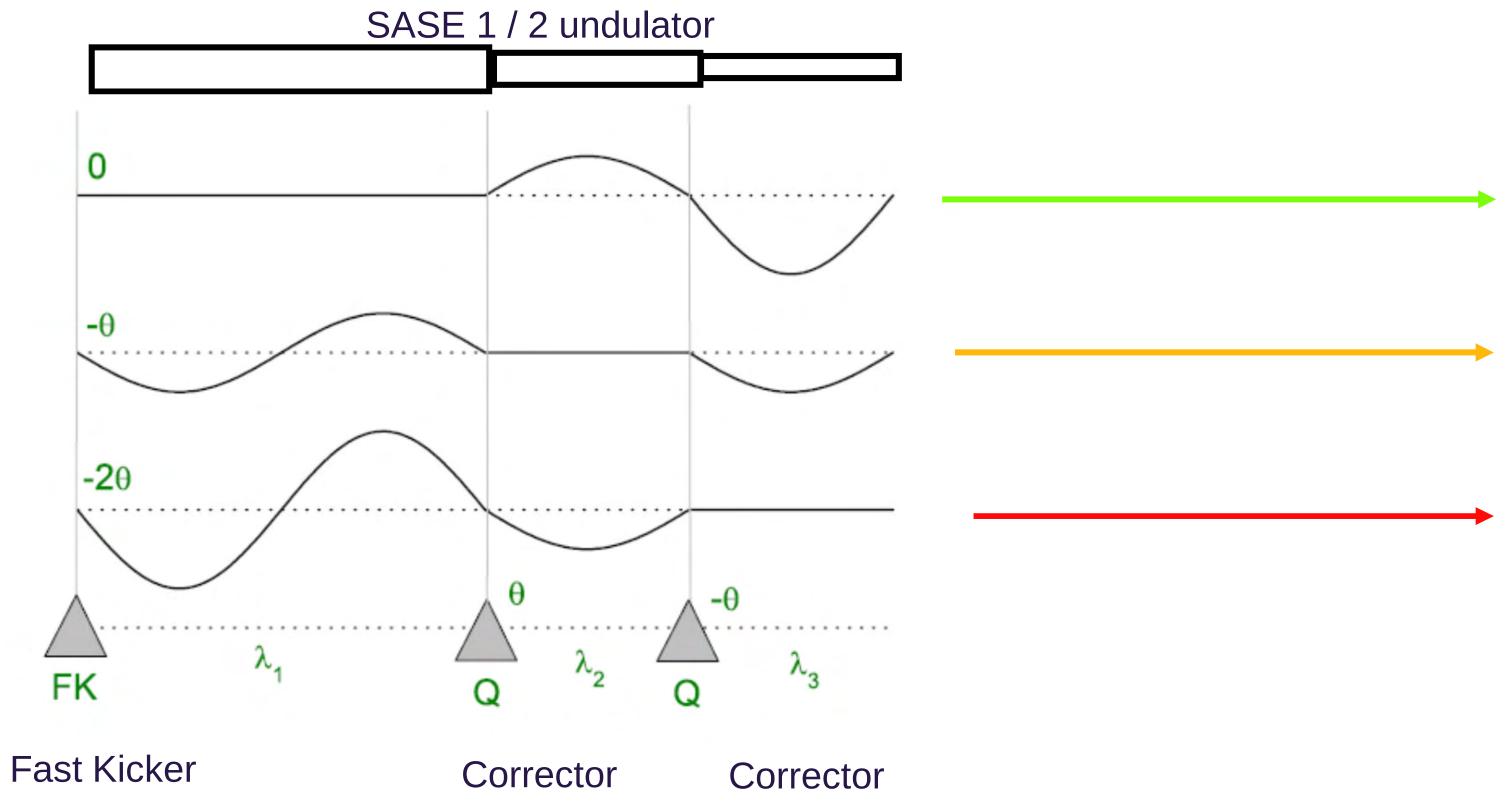
example:
pulser prototype measurement

- high accuracy (< 0.01 %)
- 10 Hz operation



example:
pulser prototype measurement

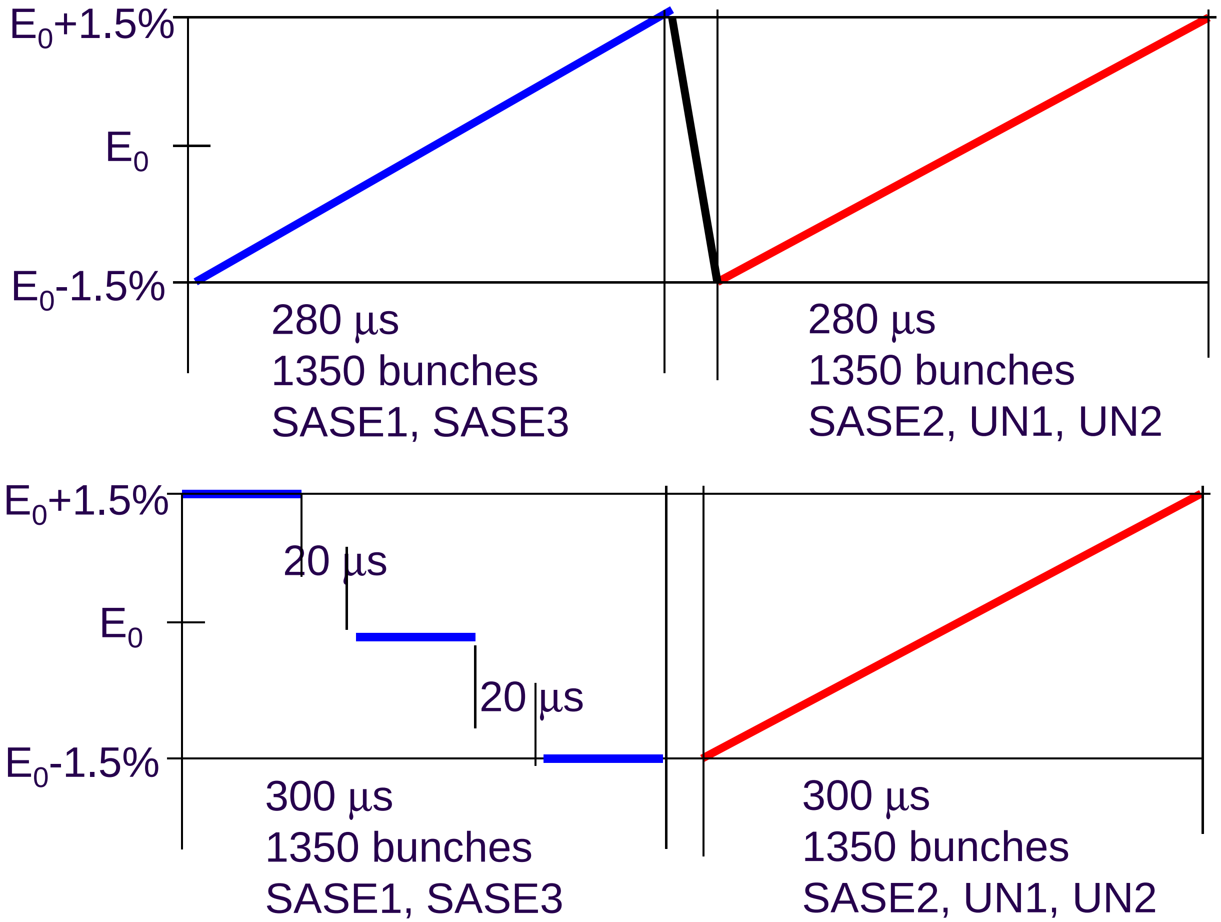
Pulse Pattern Creation cont.



- Reasonable in one undulator only if $L_{und}>L_{sat}$
- Bunch to bunch switching possible
- Separate beam lines ($\theta \approx 10\ \mu$rad) possible ?
- 'De-coupled' operation of SASE1 and SASE3

More Pulse Variations

- Energy variation within bunch train



$\Delta E/E_{max} = 3\ \%$

$\Delta E/E = +\ 10^{-4} / \mu s$
$\quad\quad\quad\ \ -\ 10^{-3} / \mu s$

- **And even bunch length variation within bunch train ???**

Outline

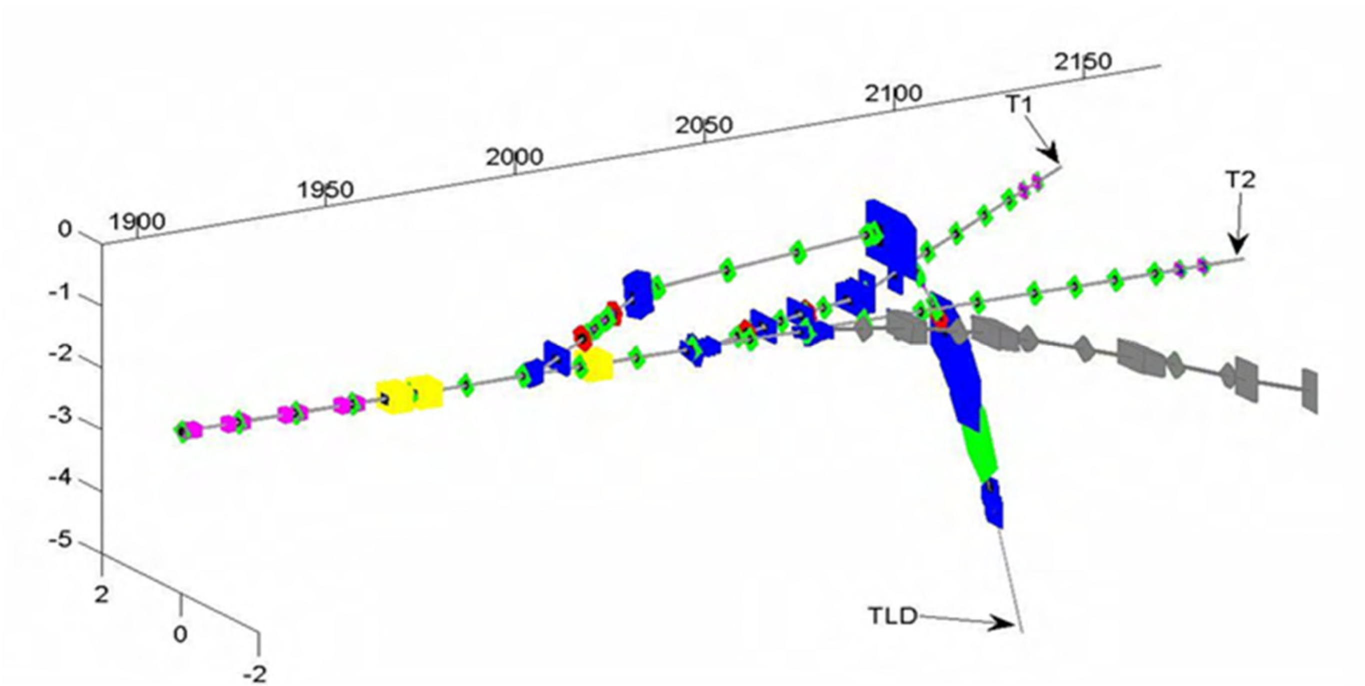
- Project Overview and Status
- New XFEL parameter range
- FEL performance and potential
- Beam distribution / Variable pulse properties
- Lattice Design
- Putting it all together – Project Organization

Optics Design

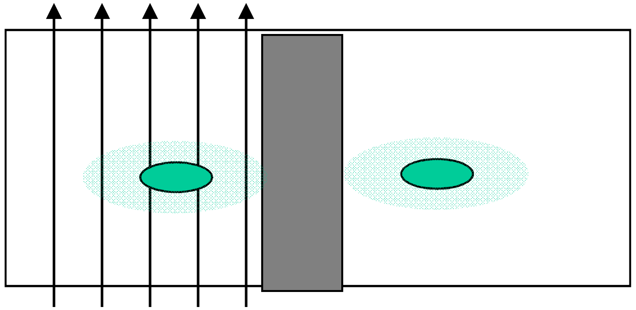
- Beam transport for large energy spread/chirp or energy variations along bunch train => achromatic (R_{16} ,R_{26} etc. =0)
- Maintain (or even fine tune) compression for energy chirped bunches (left over from previous compression, longitudinal space charge, wakes) => isochronous, or tunable R_{56}
- Minimize CSR induced energy spread increase => minimize total bending angle
- Minimize CSR induced transverse emittance growth => optimize beam optics in and in between bends
- Prevent additional micro-bunching instability gain => isochronous, or tunable R_{56},optimize beam optics
- Energy collimation => decouple dispersion and beta function, provide large dispersion to maximize collimation apertures
- Match all geometric and engineering constraints
- Match all geometric and engineering constrains
- Robust and easy tune able

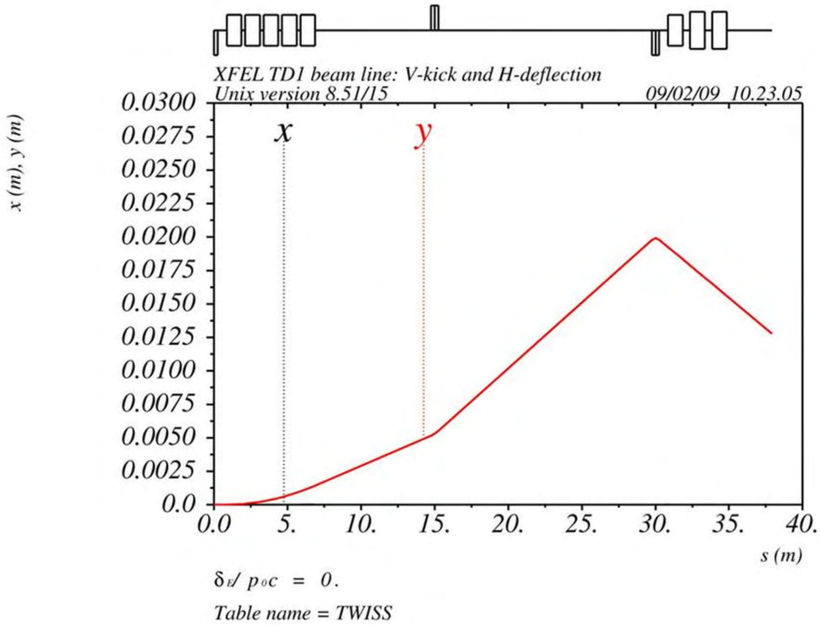
Beam Switch Yard

- Kicker-Septum Scheme
- Stable flat-top kicker distributes between beam lines
- Fast burst kicker deflects into dump for arbitrary bunch pattern and emergency beam abort
- Linac operates with constant beam loading



Kicker Septum Scheme





Challenging stability goal of 1/10 σ

$$\frac{\Delta\Theta}{\Theta} = n_{jitter} \bigg/ \left(2m_{collimation} + \frac{x_{septum}}{\sigma_{x,septum}}\right)$$

Kick strength approx. 100-300 σ

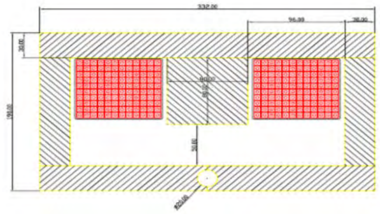
=> rel. amplitude stability < 1e-3 to 1e-4

Septum deflection approx. several 1000 σ

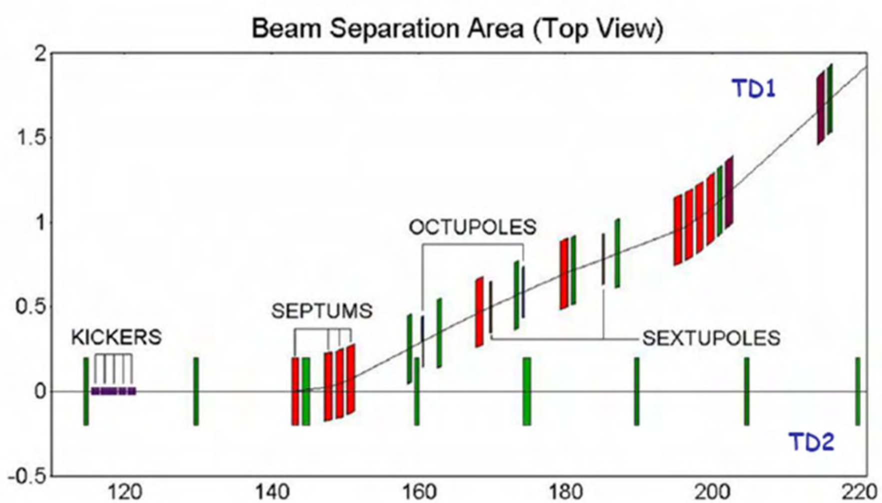
=> rel. amplitude stability < 1e-5

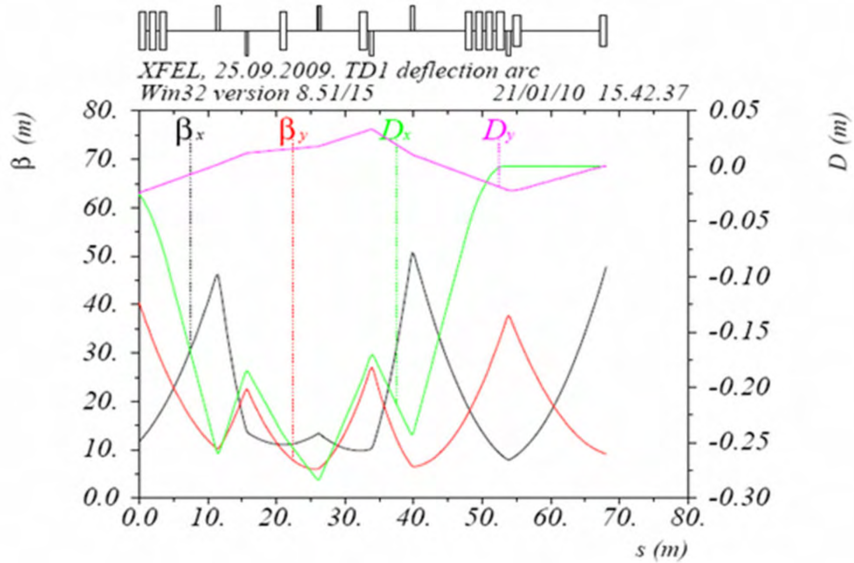
Switch yard cont.

Horizontal deflecting Lambertson DC septum (requires vertical kick)



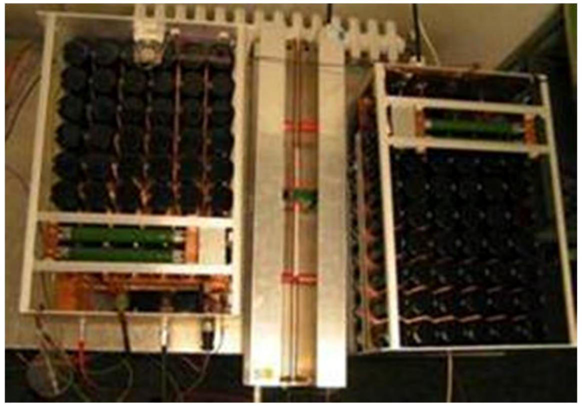
- Simultaneous horizontal and vertical dispersion
- Tilted Lambertson septum compensates common downstream quad
- Tilted sextupoles and octupoles control chromatic aberrations (DE/E=3%)
- Reverse bends for first order isochronicity





Kicker/Pulser Developments

- ‘Slow’ flat top pulser
  - Capacitor discharge bank
  - Regulated charging current
  - 10 Hz, 1 ms pulse width, 10 μs rise/fall
  - < 3e-4 pulse amplitude stability

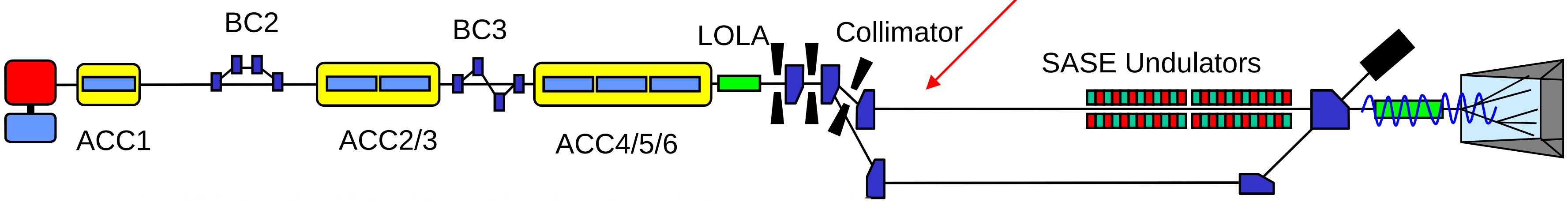


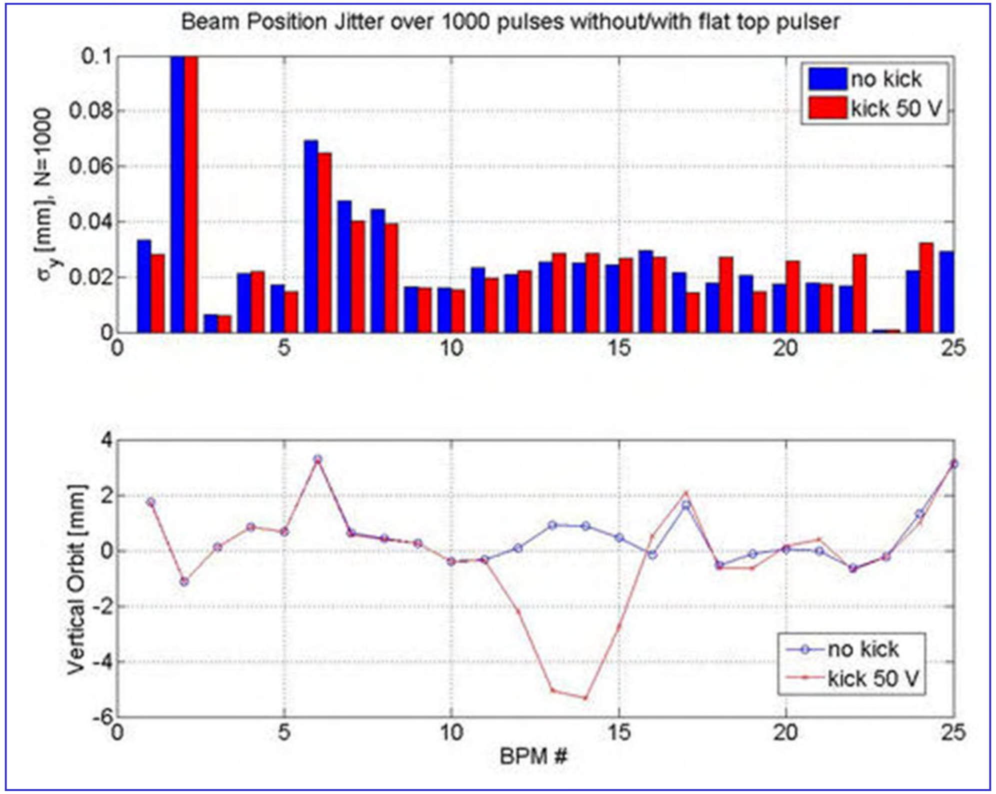
- ‘Fast’ single bunch kicker
  - Company development (still going on)
  - 4.5 MHz, < 100 ns rise/fall
  - <1e-2 pulse amplitude stability
  - <3e-4 after pulse ripple

Pulser measurements – all ok

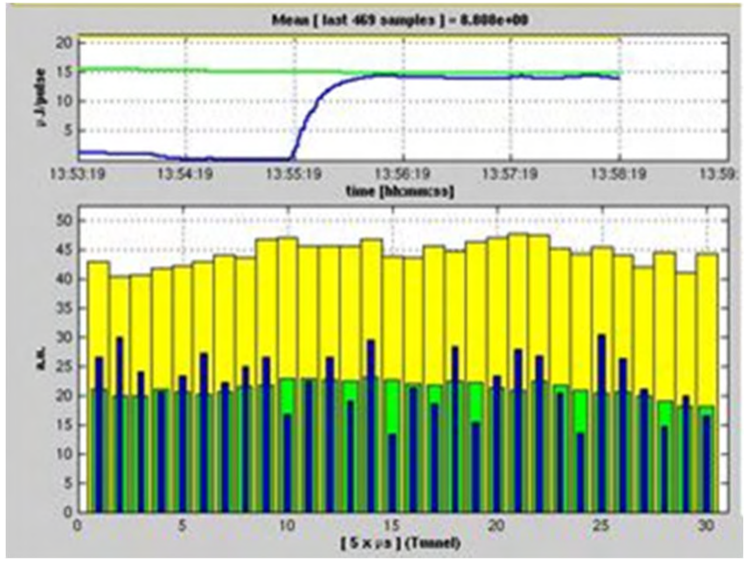
FLASH Measurement

installed on one of the FB kickers
closed bump with 2 downstream VSTEERERS



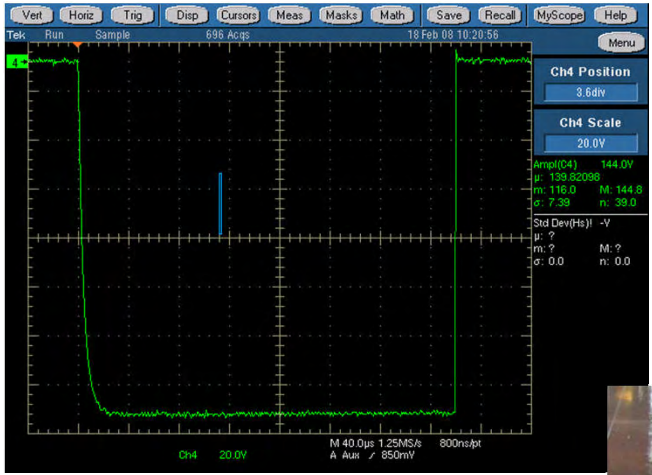


maintains SASE

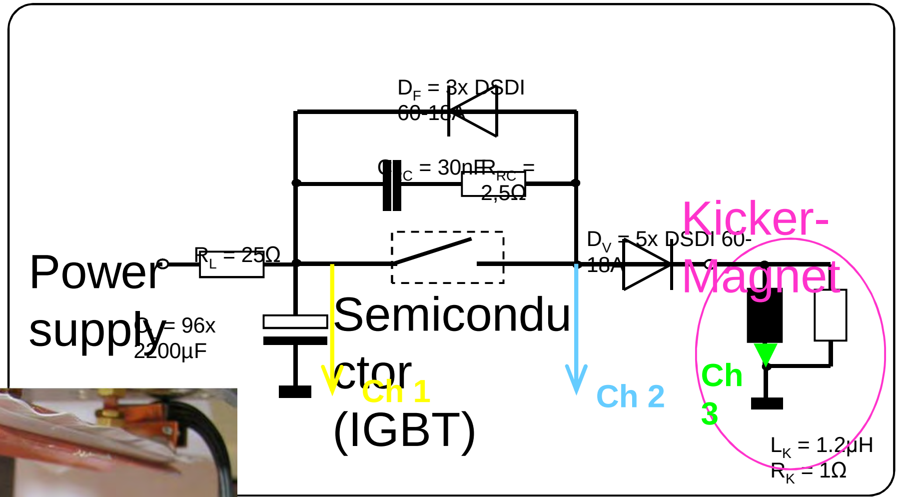


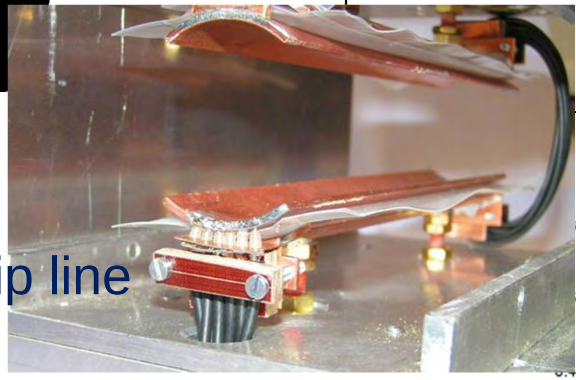
Actual SASE power over 30 bunches in RF pulse (blue, green average, yellow maximum)

Pulser measurements – or not

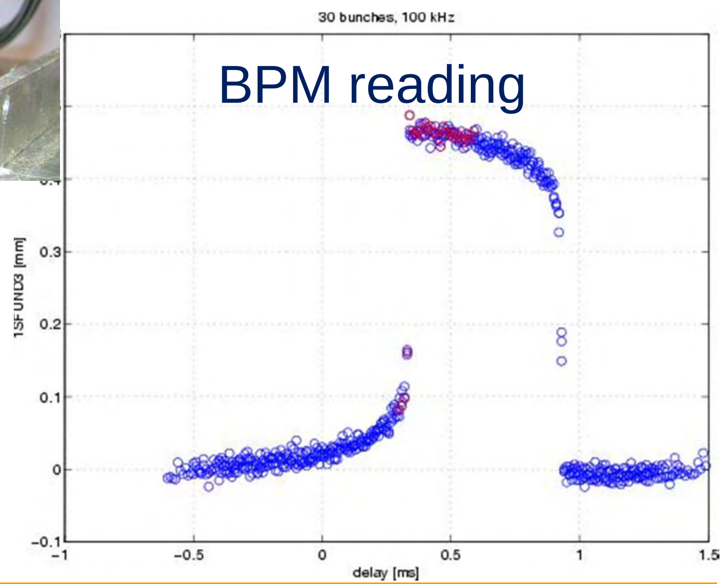


Pulse current





Strip line

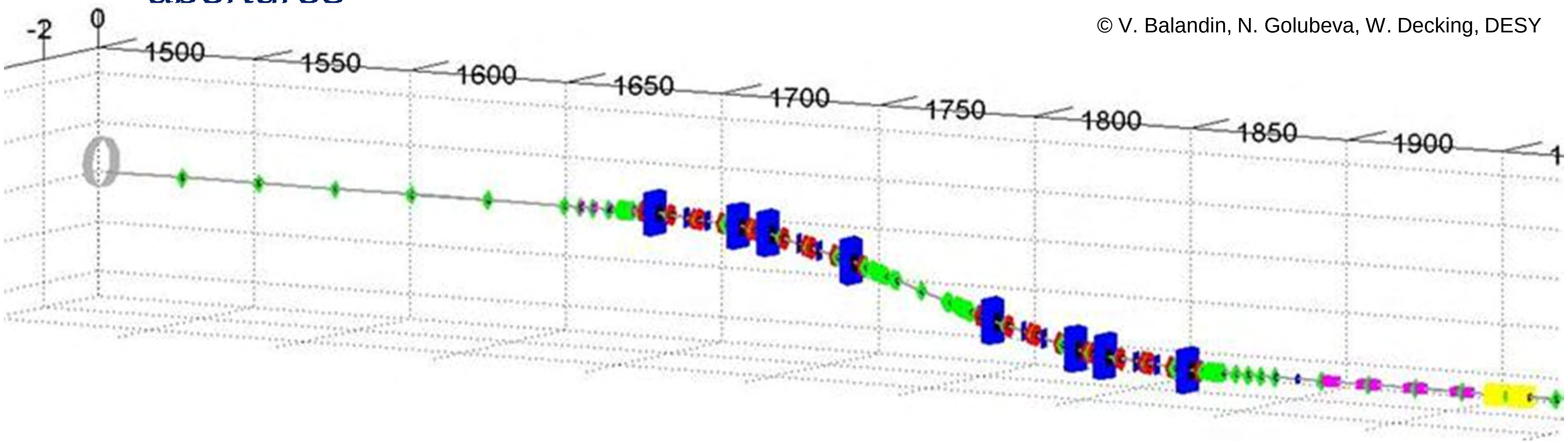


BPM reading

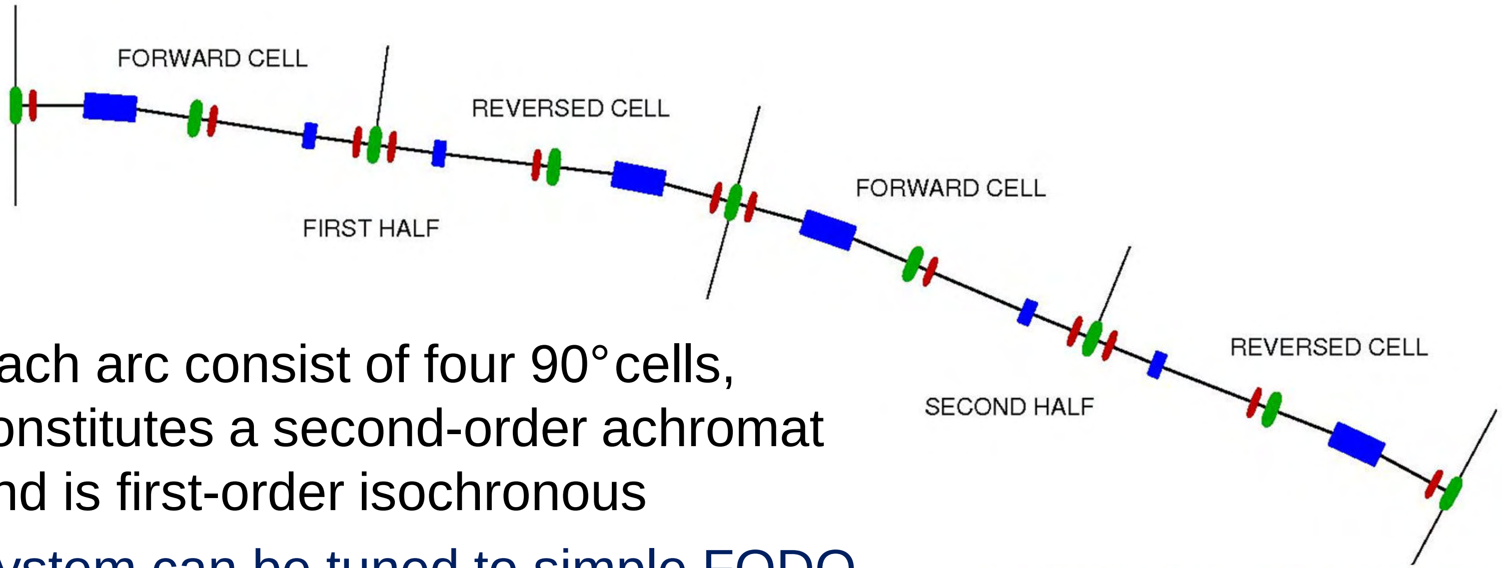
- Measurement with beam shows strongly smeared out pulse shape?

Collimation System

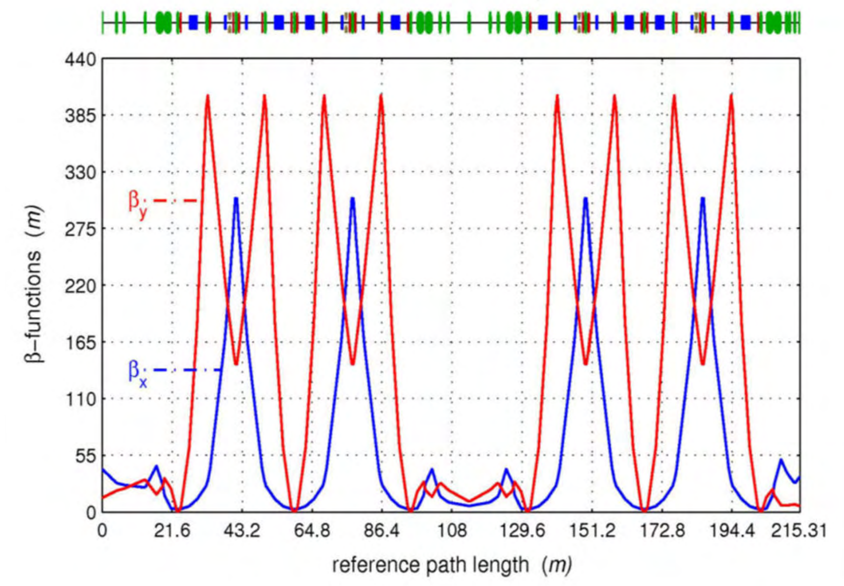
- Hardware protection for miss-steered beam
  - Beam size large enough (> 80 μm) to withstand impact of 100 bunches in TiAl collimators
- Beam Halo collimation
  - Combined energy and betatron collimation required proper adjustment of dispersion and betatron function ratio
- Large energy bandwidth and tune able R56
  - arc consists of four 90 deg FODOS in mirror symmetry
  - reverse bends for R56 tune ability
  - Sextupoles improve energy bandwidth and allow larger collimator apertures



Collimation System

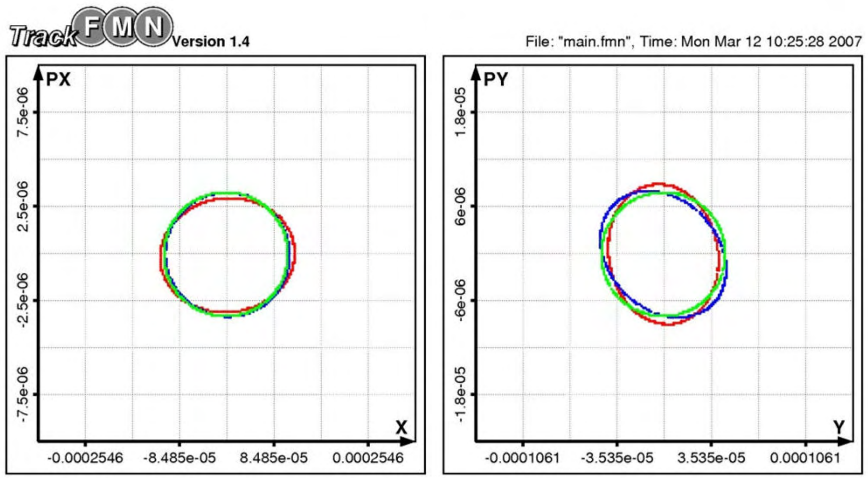


- Each arc consist of four 90° cells, constitutes a second-order achromat and is first-order isochronous
- System can be tuned to simple FODO channel for commissioning or diagnostics purposes
- Beta-function value can be varied to tune energy and betatron collimation depth independently
- Primary collimators with three different apertures foreseen

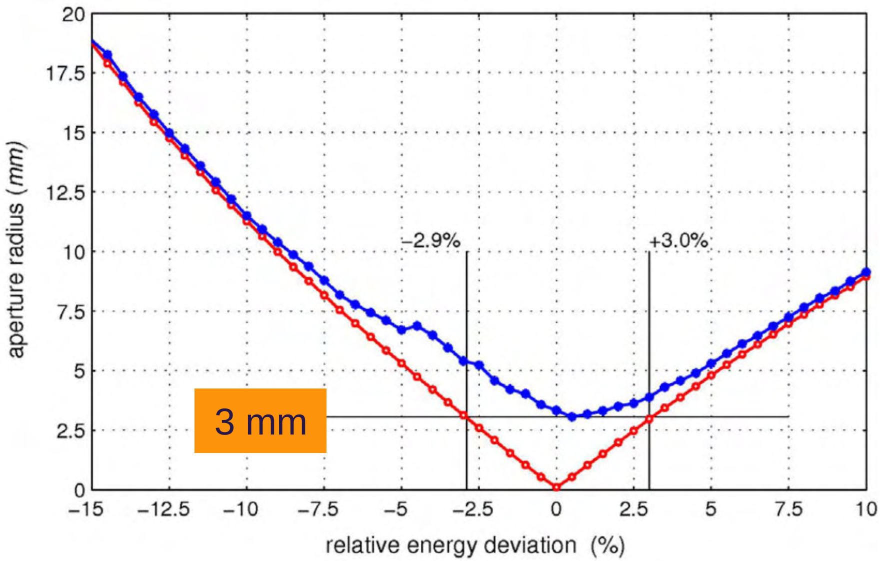


Collimation System

- Optimized Sextupole Scheme
  - 3 σ ellipses with 0 and 1.5% energy deviation



- Collimator aperture radius to protect 3 mm (XFEL=4mm) undulator chamber



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XFEL Organization

European XFEL GmbH

Shareholders: Institution or Agencies from 11 European Countries

Council

Management Board

Entrusted the construction and operation of the European XFEL

Advisory Bodies:

SAC, MAC, AFC, IKRC, ACB

Accelerator Consortium

Coordinator DESY

16 Institutes that construct the European XFEL accelerator by contributing in kin

Accelerator Consortium Coordinator

Other In Kind Contributors

XFEL Construction Project Structure

XFEL Construction Project Board

Accelerator Consortium Coordinator

- **Cold Linac Coordinator**
- **Machine Layout Coordination**

European XFEL GmbH Management

- **Photon Systems Coordinator**
- **Machine Layout Coordination**

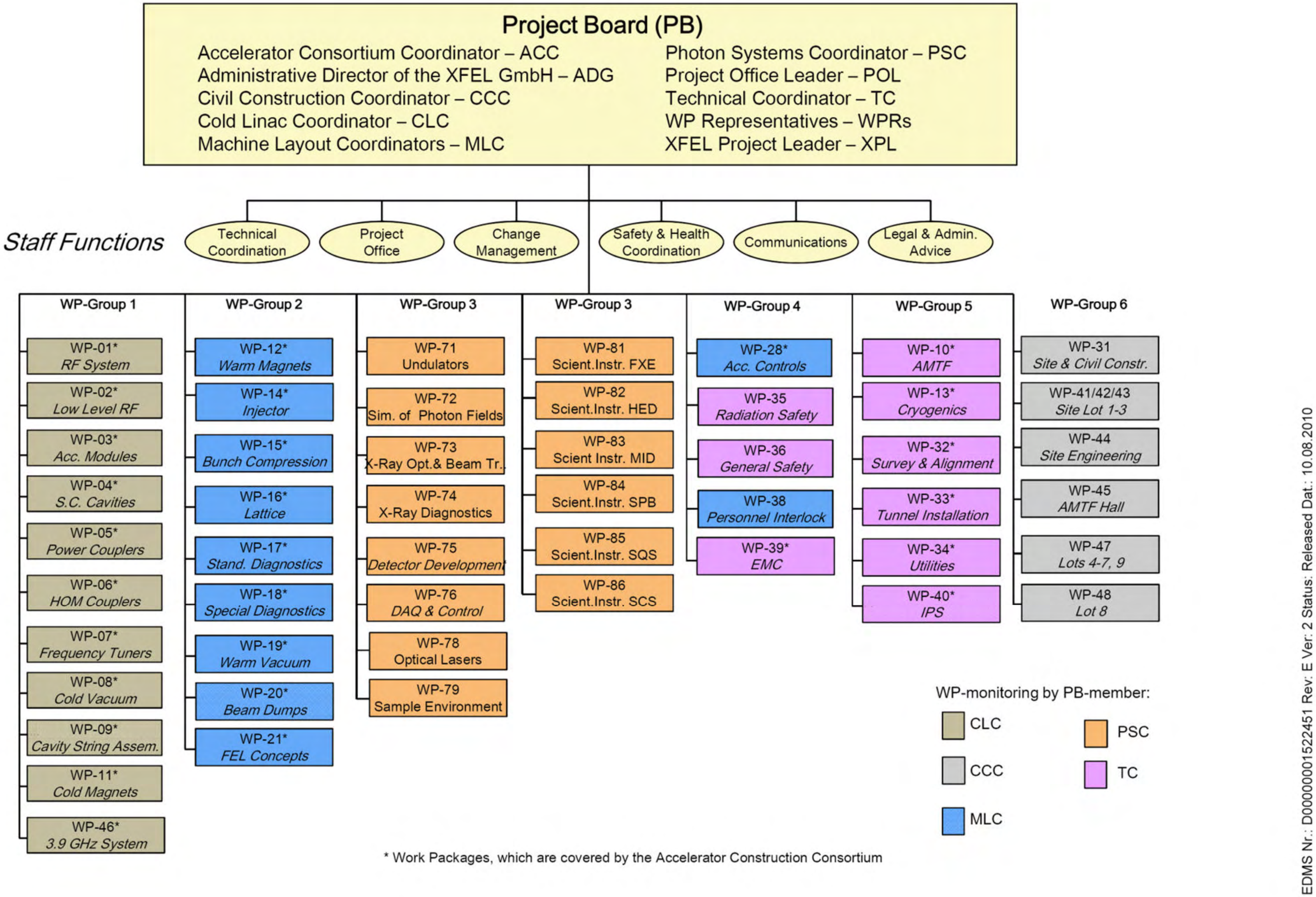
- **Technical Coordination**
- **Project Office**

Accelerator Related Work Packages

Common Work Packages

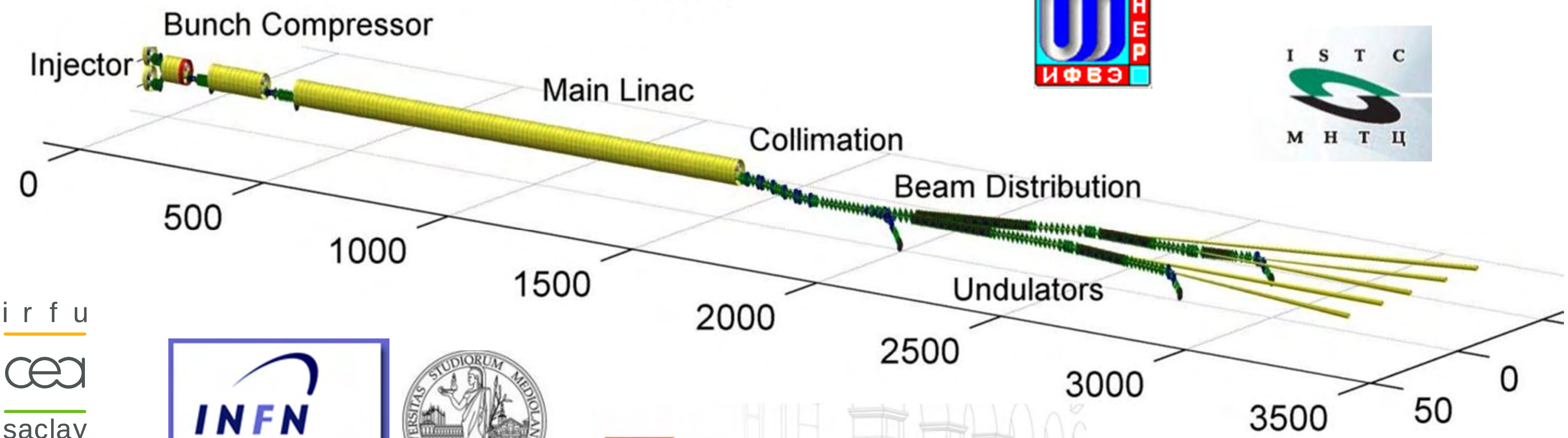
Photon System Work Packagaes

Organigram for the XFEL Construction Project



16 Institutes Contributing to the accelerator

DESY
HELMHOLTZ | ASSOCIATION
UPPSALA UNIVERSITET



IHEP
ИФВЭ
I S T C
М Н Т Ц
irfu
cea
saclay
INFN Istituto Nazionale di Fisica Nucleare
Wrocław University of Technology
PAUL SCHERRER INSTITUT PSI
MINISTERIO DE EDUCACIÓN Y CIENCIA
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
cnrs
In2p3
Stockholm University
Institute of High Energy Physics
Chinese Academy of Sciences

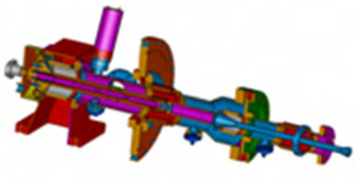
Example: Accelerator Modules

Vessel & cryostat

- IHEP/Beijing
- DESY
- CEA/Saclay
- INFN/Milano

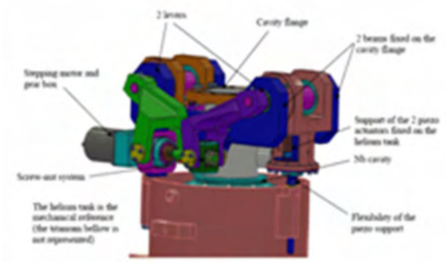
RF power coupler

- DESY
- LAL/Orsay



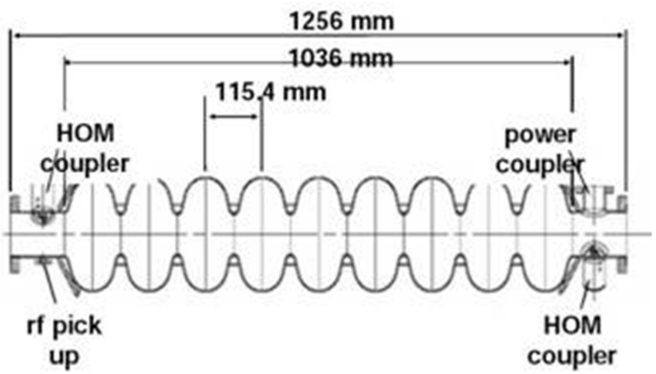
Superferric magnet

- DESY
- CIEMAT/Madrid



Freq. tuner

- DESY
- INFN/Milano



s.c. cavities

BPM

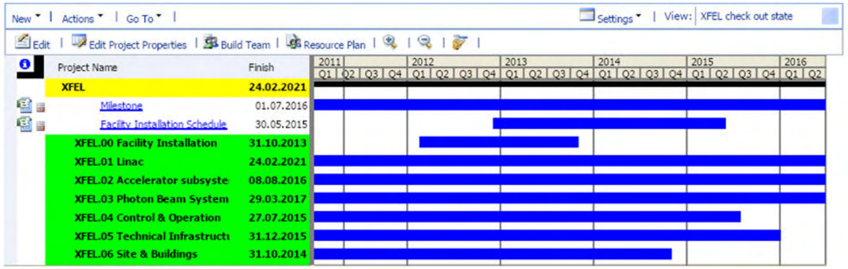
- DESY
- CEA/Saclay
- PSI/Villigen

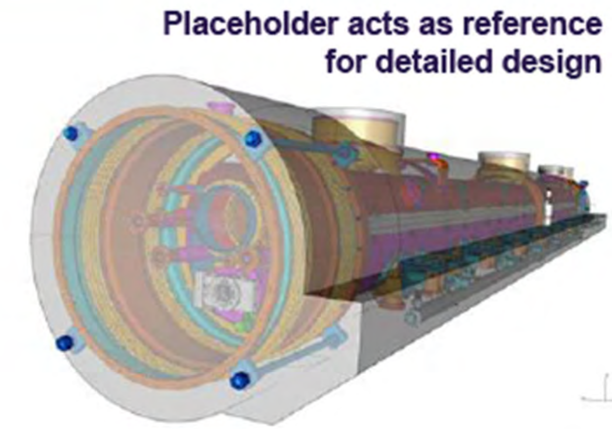
HOM absorber

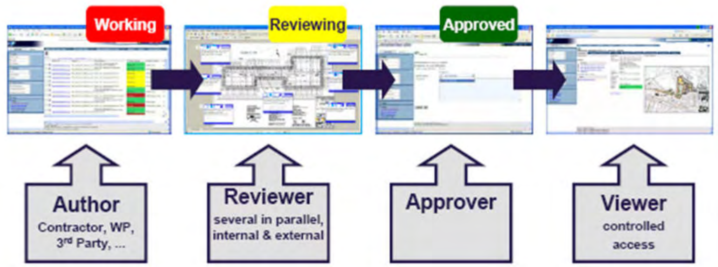
- Soltan Inst/Swierk

Project Planning

- All activities linked via a MSPE-plan
  - Connecting through linked milestones
  - Update at least quarterly
- Integration through 3D master model
  - Exchange of various CAD formats and integration into IDEAS master model
- Process (reviewing, documentation, …) established in EDMS







Summary

- European XFEL posses technical, scientific and organizational challenge
- Goal is to be competitive in 2015 (when others have been operating for years)
- Main challenge ahead is to cope with the ever-growing but still largely unknown wishes of the multiple user community
- The design is robust, flexible and (hopefully) conservative enough

Thanks

To my colleagues, there results are presented in this talk

DESY FEL Beam Dynamics Team: Vladimir Balandin, Bolko Beutner, Martin Dohlus, Nina Golubeva, Evgeny Kot, Torsten Limberg, Sasha Meykopff, Eduard Prat, Matthias Scholz, Igor Zagorodnov, Olga Zagorodnova

FLASH Crew: Bart Faatz, Katja Honkavaraa, Siggi Schreiber, Mathias Vogt

FEL Physics: Gianlucca Geloni, Jörg Rossbach, Evgeny Saldin, Evgeny Schneidmiller, Michail Yurkov

XFEL Coordination Team: Reinhard Brinkmann,Thomas Hott, Hans Weise, Riko Wichmann

Undulator: Joachim Pflueger, Yuhui Li

Injector: Klaus Floettmann

Diagnostics and LLRF: Christopher Gerth, Dirk Nölle, Holger Schlarb

Kicker: Frank Obier, Jens Wortmann

And many others

And thank you for your attention