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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Accelerator Challenges at the European XFEL – Winfried Decking, DESY
LBNL, May 5 2011
European XFEL - Injector

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

Photo Injector @ DESY Zeuthen
3 stage bunch compression allows for wide range of compression scenarios while minimizing sensitivities to RF-regulation imperfections and electron beam driven instabilities.
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)
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)
• 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
• 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 ($g_{\text{min}} = 10$ mm) permanent magnet undulators with 40 resp. 68 mm period length

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

- **Main Beam Dumps**: up to 25 GeV
  - $P_{ave} = 300$ kW
  - 1/2 max beam power
  - Beam magnified
  - Slow sweep to distribute heat

- **Injector Dumps**: 130 MeV
  - $P_{ave} = 12$ kW
  - Max. beam power

- **Bunch Compressor Diagnostic Dumps**: 0.5 and 2.5 GeV
  - Small fraction of max. beam power
Photon Systems: Beam Lines & Experiments

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

- Beam position, beam intensity, beam losses
- Photon diagnostics within bunch train from train to train
- Projected emittance, optics match, energy, energy spread, rel. peak current, arrival time, slice emittance, long. bunch shape
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

Accelerator Challenges at the European XFEL – Winfried Decking, DESY
LBNL, May 5 2011
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

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Injector Building – An Underground High Rise

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Schenefeld Site
6 km of tunnel construction

- 57% done
- 20% done
Tunnel Construction

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First Tunnel Ready – October 2010

Accelerator Challenges at the European XFEL – Winfried Decking, DESY
LBNL, May 5 2011
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• Beam distribution / Variable pulse properties
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• Putting it all together – Project Organization
### XFEL – Start-Up Version

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy</td>
<td>17.5 GeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>1 nC</td>
</tr>
<tr>
<td>Peak current</td>
<td>5 kA</td>
</tr>
<tr>
<td>Slice emittance</td>
<td>&lt; 1.4 mm mrad</td>
</tr>
<tr>
<td>Slice energy spread</td>
<td>1.5 MeV</td>
</tr>
<tr>
<td>Shortest SASE wavelength</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Bunches per pulse</td>
<td>3000</td>
</tr>
</tbody>
</table>
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

TDR photon energy ranges

TDR low energy cut-off: 240 eV (@10GeV)
TDR high energy cut-off: 12.4 keV (@17.5GeV)

Instruments (prel., 2008)
- SASE 1
  - SPB, MID
- SASE 2
  - FXE, HED
- SASE 3
  - SQS, SCS

Require photon energy ranges after user workshops

- SPB: 3 to 12 keV
- MID: 6 to 36 keV
- FXE: 4 to 18 keV
- HED: 4 to 20 keV

+ photon pulse length variation

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### Baseline vs. New Parameter Set

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>New Parameter Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy</td>
<td>17.5 GeV</td>
<td>10.5/14/17.5 GeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>1 nC</td>
<td>0.02 - 1 nC</td>
</tr>
<tr>
<td>Peak current</td>
<td>5 kA</td>
<td>2 - 5 kA</td>
</tr>
<tr>
<td>Slice emittance</td>
<td>&lt; 1.4 mm mrad</td>
<td>0.4 - 1.0 mm mrad</td>
</tr>
<tr>
<td>Slice energy spread</td>
<td>1.5 MeV</td>
<td>4 - 2 MeV</td>
</tr>
<tr>
<td>Shortest SASE wavelength</td>
<td>0.1 nm</td>
<td>0.05 nm</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Bunches per pulse</td>
<td>3000</td>
<td>2700</td>
</tr>
</tbody>
</table>
Establish new Working Point

Beam Parameters at GUN

<table>
<thead>
<tr>
<th>Charge</th>
<th>nC</th>
<th>1</th>
<th>0.5</th>
<th>0.25</th>
<th>0.1</th>
<th>0.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long. laser profile</td>
<td></td>
<td>Flat Top, 20 ps length, 2 ps rise time</td>
<td></td>
<td></td>
<td></td>
<td>Gaussian, 0.8 ps rms</td>
</tr>
<tr>
<td>RMS laser spot size</td>
<td>mm</td>
<td>0.47</td>
<td>0.29</td>
<td>0.23</td>
<td>0.17</td>
<td>0.07</td>
</tr>
<tr>
<td>Peak current</td>
<td>A</td>
<td>46.2</td>
<td>23.8</td>
<td>13.4</td>
<td>5.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Slice Emittance</td>
<td>µm</td>
<td>0.9</td>
<td>0.5</td>
<td>0.35</td>
<td>0.22</td>
<td>0.09</td>
</tr>
<tr>
<td>Slice Energy Spread</td>
<td>keV</td>
<td>1</td>
<td>0.4</td>
<td>0.6</td>
<td>0.4</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Optimized for shortest bunch length

<table>
<thead>
<tr>
<th>Compression factor</th>
<th>120</th>
<th>220</th>
<th>380</th>
<th>830</th>
<th>1900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Current</td>
<td>kA</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Optimize BC Working Points

- 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

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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, \( \lambda = 0.2 \text{ mm} \) → injector dogleg (\(~45\text{m after cathode})

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

\[ \Rightarrow 2 \text{ final energy spread at 20 pC} \]
Beam Parameters at Undulator

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

<table>
<thead>
<tr>
<th>Charge</th>
<th>nC</th>
<th>1</th>
<th>0.5</th>
<th>0.25</th>
<th>0.1</th>
<th>0.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression factor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>120</td>
<td>220</td>
<td>380</td>
<td>830</td>
<td>1900</td>
</tr>
<tr>
<td>Slice Energy Spread</td>
<td>MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.45</td>
<td>0.43</td>
<td>0.60</td>
<td>0.58</td>
<td>0.73</td>
</tr>
<tr>
<td>Slice Energy Spread with LH</td>
<td>MeV</td>
<td>2.0</td>
<td>2.2</td>
<td>2.5</td>
<td>2.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Slice Emittance at Gun</td>
<td>µm</td>
<td>1</td>
<td>0.65</td>
<td>0.5</td>
<td>0.32</td>
<td>0.2</td>
</tr>
<tr>
<td>Emittance Degradation</td>
<td>%</td>
<td>5.0</td>
<td>10.0</td>
<td>20.0</td>
<td>30.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Slice Emittance at Undulator</td>
<td></td>
<td>0.97</td>
<td>0.70</td>
<td>0.60</td>
<td>0.39</td>
<td>0.32</td>
</tr>
</tbody>
</table>

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
  
  \[ \text{roughness [nm]} + 50 \times \text{oxide layer [nm]} < 500 \text{ nm} \]
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
• 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

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• **FEL performance and potential**
  • Beam distribution / Variable pulse properties
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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)
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
**SASE 3 operation – Helical Afterburner (AFB)**

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.
• First order ok for $\lambda_r > 1\text{nm}$ (at $\varepsilon = 1.4 \text{ nm}$)
• For shorter wavelength higher order isochronicity needed, gets complicated and long

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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 and 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 bunch properties, 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**

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

**example:** pulser prototype measurement

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Pulse Pattern Creation cont.

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

- Energy variation within bunch train

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

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

$-10^{-3} / \mu s$

- And even bunch length variation within bunch train ??
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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 $1/10 \sigma$

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

Kick strength approx. 100-300 $\sigma$

$\Rightarrow$ rel. amplitude stability $< 1e^{-3}$ to $1e^{-4}$

Septum deflection approx. several 1000 $\sigma$

$\Rightarrow$ rel. amplitude stability $< 1e^{-5}$

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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

© V. Balandin, N. Golubeva, W. Decking, DESY
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

© F. Obier, J. Wortmann, W. Decking, DESY
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

- Measurement with beam shows strongly smeared out pulse shape?

\[ R_L = 25 \, \Omega \]
\[ C_L = 96 \times 2 \, \text{200} \mu \text{F} \]
\[ D_F = 3 \times \text{DSDI} 60-18 \text{A} \]
\[ C_{RF} = 30 \, n\text{F} \]
\[ R_{KC} = 25 \, \Omega \]
\[ L_K = 1.2 \, \mu \text{H} \]
\[ R_K = 1 \, \Omega \]

Power supply

Semiconductor (IGBT)

Kicker-Magnet

Pulse current

Strip line

BPM reading

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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

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Collimation System

- Each arc consists of four 90° cells, constitutes a second-order achromat and is first-order isochronous.
- System can be tuned to a 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
  - $3\sigma$ ellipses with 0 and 1.5% energy deviation

- Collimator aperture radius to protect 3 mm (XFEL=4mm) undulator chamber
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- Putting it all together – Project Organization
European 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 kind
Accelerator Consortium Coordinator

Other In Kind Contributors
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Organigram for the XFEL Construction Project

Project Board (PB)
- Accelerator Consortium Coordinator – ACC
- Administrative Director of the XFEL GmbH – ADG
- Civil Construction Coordinator – CCC
- Cold Linac Coordinator – CLC
- Machine Layout Coordinators – MLC
- Photon Systems Coordinator – PSC
- Project Office Leader – POL
- Technical Coordinator – TC
- WP Representatives – WPRs
- XFEL Project Leader – XPL

Staff Functions
- Technical Coordination
- Project Office
- Change Management
- Safety & Health Coordination
- Communications
- Legal & Admin. Advice

WP-Group 1
- WP-01*: RF System
- WP-02*: Low Level RF
- WP-03*: Acc. Modules
- WP-04*: S.C. Cavities
- WP-05*: Power Couplers
- WP-06*: MCP Chopper
- WP-07*: Frequency Tuners
- WP-08*: Cold Vacuum
- WP-09*: (Cavity String Assembly)
- WP-11*: Cold Magnets
- WP-45*: 3.0 GHz System

WP-Group 2
- WP-12*: Warm Magnets
- WP-14*: Injector
- WP-15*: Bunch Compression
- WP-16*: Lattice
- WP-17*: Stand. Diagnostics
- WP-18*: Special Diagnostics
- WP-19*: Warm Vacuum
- WP-20*: Beam Dumps
- WP-21*: FEL Concepts

WP-Group 3
- WP-71*: Undulators
- WP-72*: Sim. of Photon Fields
- WP-74*: X-Ray Diagnostics
- WP-75*: Detector Development
- WP-76*: DAQ & Control
- WP-77*: Optical Lasers
- WP-78*: Sample Environment
- WP-81*: Scient. Instr. FXE
- WP-82*: Scient. Instr. HED
- WP-83*: Scient. Instr. MID
- WP-84*: Scient. Instr. SPB
- WP-85*: Scient. Instr. SQS
- WP-86*: Scient. Instr. SC5
- WP-87*: Scient. Instr. EFC
- WP-88*: Scient. Instr. EFC

WP-Group 4
- WP-28*: Acc. Controls
- WP-35*: Radiation Safety
- WP-36*: General Safety
- WP-37*: Personnel Interlock
- WP-38*: Tunnel Installation
- WP-39*: EMC
- WP-40*: IPS

WP-Group 5
- WP-10*: AMTF
- WP-13*: Cryogenics
- WP-32*: Survey & Alignment
- WP-33*: Utilities

WP-Group 6
- WP-31*: Site & Civil Constr.
- WP-41/42/43*: Site Lot 1-3
- WP-44*: Site Engineering
- WP-45*: AMTF Hall
- WP-47*: Lots 4-7, 9
- WP-48*: Lot 8

* Work Packages, which are covered by the Accelerator Construction Consortium

WP-monitoring by PB-member:
- CLC
- PSC
- CCC
- TC
- MLC

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16 Institutes Contributing to the accelerator
Example: Accelerator Modules

Vessel & cryostat
- IHEP/Beijing
- DESY
- CEA/Saclay
- INFN/Milano

RF power coupler
- DESY
- LAL/Orsay

Superferric magnet
- DESY
- CIEMAT/Madrid

BPM
- DESY
- CEA/Saclay
- PSI/Villigen

HOM absorber
- Soltan Inst/Swierk

Freq. tuner
- DESY
- INFN/Milano

s.c. cavities
- DESY
- INFN/Milano
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
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And thank you for your attention