The Future of X-ray FELs

Hans-H. Braun
Paul Scherrer Institut

3rd International Particle Accelerator Conference
New Orleans
May 20-25, 2012
+ many good posters on the subject
Recent developments
• X-ray FEL* user community
• R&D issues
• Near future of X-ray FELs
• Mid term Future
• Long term future

*Definition used:

X-ray FEL is a FEL with smallest $\lambda_{\text{photon}} < 5$ nm
Acknowledgements

Many thanks to

Paul Emma/LBNL
Bart Faatz/DESY
Katja Honkavaara/DESY
In Soo Ko/PAL
Subrata Nath/LANL
Jörg Rossbach/Univ. Hamburg
Siegfried Schreiber DESY
Michele Svandrlik/ELETTRA
Hitoshi Tanaka/Spring-8
Dong Wang/SINAP
and my colleagues at PSI

for providing information for this talk
The young history of X-ray FELs

Michele Svandrlík
TUOB03

2009

First Demonstration of Hard X-ray Self Seeding at LCLS

FERMI FEL:
80 – 4 nm SEEDED HGHG

2010

Paul Emma
WEYB02

First Lasing at 4.45 nm on June 6/7 (with 3rd harm.)

Hitoshi Tanaka
WEYB01

2011

10 June 2011

Announcement

SACLA Lased

2012
X-ray FEL users
• who are they?
• what instruments are they used to?

Life science
structural biology
Pharmacy

Atomic
physics

Solid state
physics

Synchrotron
light sources
\[ \Delta x \approx \text{Å} \]

Chemistry

Material
Science

X-ray FEL
\[ \Delta x \approx \text{Å} \; \& \; \Delta t \approx \text{fs} \]

Short pulse
lasers
\[ \Rightarrow \Delta t \approx \text{fs} \]
X-ray FEL allows for flash images on time scale of fastest chemical processes
FELs have the monopoly for intense coherent X-ray beam
World map of SR storage rings

Worldwide >50 synchrotron for photon science with ≈1000 user stations total

- wide range of applications in life science and material science
- attractive science portfolio of high brightness X-ray sources

Advantages X-FELs vs. synchrotron
- orders of magnitude higher peak brightness
- order of magnitude higher average brightness
- orders of magnitude better time resolution
- clean polarization and coherence

Difficulties X-FELs vs. SR storage rings
- much less integrated photon flux
- less beamlines/facility
- less stable beam conditions
- much higher cost per user station

vast scientific potential in uncharted territory
“New Science” session organized by Jochen Schneider/DESY

Every speaker was asked for a XFEL parameter-wishlist!

Monday, August 22

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker(s)</th>
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</thead>
<tbody>
<tr>
<td>13:00 ~ 15:00</td>
<td><strong>New Science</strong></td>
<td></td>
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<tr>
<td>13:00</td>
<td>Multi-photon processes and two-color studies in atomic and molecular systems</td>
<td>M. Meyer, European XFEL GmbH</td>
</tr>
<tr>
<td>13:30</td>
<td>Overview of Warm Dense Matter experiment at the FLASH and LCLS Free Electron Lasers</td>
<td>B. Nagler, SLAC</td>
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<tr>
<td>14:00</td>
<td>Femtosecond protein X-ray nanocrystallography</td>
<td>H. N. Chapman, DESY</td>
</tr>
<tr>
<td>14:30</td>
<td>XFEL interaction with correlated electron materials</td>
<td>H. A. Dürr, SLAC</td>
</tr>
</tbody>
</table>
FEL 2011

FEL parameter wish list for
Research on Atoms and Molecules
*Michael Meyer (European XFEL)*

- **i) Non-linear processes**
  - Direct processes: > 10^{15} W/cm^2
  - "short" pulses: < 10 fs
  - "long" pulses: 100 – 300 fs
  - Variable pulse duration & pulse energy

- **ii) Time-resolved experiments**
  - "Synchronization"
  - Pulse duration: < 10 fs (< 1 fs)
  - Temporal stability: > 10 fs

- **iii) "Complete" experiment repetition rate**
  - Coincidence techniques: > 1 kHz ("MHz")

- **iv) Soft X-ray regime**
  - "tunable"
  - C(1s) = 290 eV, N(1s) = 410 eV, O(1s) = 560 eV

- **v) Linear / circular polarization**
  - Dichroism

---

FEL 2011

FEL parameter wish list for
Matter in Extreme Conditions Research
*Bob Nagler (SLAC-LCLS)*

- **Short pulse lengths:**
  - Isochoric heating with inertial confinement
  - Beat hydrodynamic expansion (~10ps)
  - Beat electron-ion equilibration time (~1ps)
  - Beat inner shell recombination rate (1-100fs)
  - Beat electron-electron equilibration time (sub fs)

- **High Photon Flux**
  - High energy deposition, to increase heated sample size and temperatures (10^{13}-10^{14} photons)
  - Photon hungry probe techniques (10^{12}-10^{14} photons in small bandwidth 10^{-4} - 10^{-6})

- **Bandwidth**
  - Thomson scattering probe: 10^{-4} - 10^{-6}
  - X-ray absorption near edge spectroscopy: 1%-5%

- **Repetition rate**
  - 10Hz, limited by optical laser, target refresh rate

---

FEL 2011

FEL parameter wish list for
Macromolecular Single-Shot Coherent Imaging
*Henry N. Chapman (DESY-CFEL)*

- The key metric is photon power: Ideally ~10 TW
  - This gives about 10^{-20} W/cm^2 (with 1 micron focus, assuming beamline and focusing efficiency)
  - Only the first 10 to 30 fs of the pulse usefully contributes

- Wavelength range: 4 keV to 14 keV (to cover elemental edges from S to Se)
  - Also: 300-500 eV for water-window imaging of cells, viruses
  - Up to 30 keV for time-resolved imaging of nanoparticles

- Repetition rate: As high as possible
  - Need to match detector capabilities. 1 kHz repetition could be feasible

- Bandwidth: As high as possible
  - 1 to 10% bandwidth would allow structure determination with about 1% of the required pulses.
  - i.e. structure determined in <1000 shots

---

FEL 2011

FEL performance wish list for
Condensed Matter research
*especially correlated materials*
*Hermann Dürr (SLAC-Pulse/SIMES)*

- Femtosecond Two Color X-Ray Holography
  - Two independent colors (soft & hard x-rays) to probe-probe & pump-probe
  - 1-10 fs pulse length @ 1mJ
  - Polarization control
  - (self) seeding for reproducible pulses

- Transition metals; RE = rare earth elements
### X-ray FEL dream machine wish-list summary
from FEL’11 “New Science” session

<table>
<thead>
<tr>
<th>Shortest Pulse length</th>
<th>Max Peak Power</th>
<th>rep. rate</th>
<th>Polarisation control</th>
<th>band width</th>
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<tbody>
<tr>
<td>Research on Atoms and Molecules</td>
<td>&lt;10 fs</td>
<td>0.1 TW</td>
<td>&gt; 1 kHz</td>
<td>yes</td>
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<tr>
<td>Matter in extreme conditions</td>
<td>&lt;1 fs</td>
<td>1 TW</td>
<td>10 Hz</td>
<td>$10^{-3}$-$10^{-6}$</td>
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<tr>
<td>Macromolecular Single-Shot Coherent Imaging</td>
<td>10-30 fs</td>
<td>10 TW</td>
<td>1 kHz</td>
<td>$10^{-1}$-$10^{-2}$</td>
</tr>
<tr>
<td>Condensed Matter Research</td>
<td>1-10 fs</td>
<td>1 TW</td>
<td>yes</td>
<td>two color</td>
</tr>
</tbody>
</table>

**state of the art**

| 1-100 fs | $\approx10$ GW | LCLS 120 Hz, FLASH 10x800 | only at FERMI | SASE $2\cdot10^{-3}$, seeded $5\cdot10^{-5}$ |

⇒ more power, shorter pulses, more pulses and more bandwidth control (chirp!)
X-ray FEL R&D Issues

Generic X-ray FEL*
*number of BC and undulator lines may vary

\[ \varepsilon_N < 1 \mu \text{m} \sqrt{q_B[nC]} \]

achieved with different injector technologies

- **LCLS:** S-band 1½ cell RF gun with Cu photo-cathode
- **PITZ:** L-band 1½ cell RF gun with Cs$_2$Te photo-cathode
- **SACLA:** Pulsed diode with thermionic CeB$_6$ cathode
- **SwissFEL:** S-band 2½ cell RF gun with Cu photo-cathode
- ...

open issues
  - low emittance for cw operation ⇒ *Fernando Sannibale, FRBBA01*
  - operational robustness
  - lower emittance always welcome
X-ray FEL R&D Issues cont.

**Generic X-ray FEL**
*number of BC and undulator lines may vary

- bunch compressors
- undulator line
- photon transport
- user stations

Theory of CSR and microbunching instability made enormous progress during last decade

LCLS has set the standard for most projects:
- laser heater to cure microbunching instability
- harmonic cavity for flat current profile
- long, small angle bunch compressors to minimize CSR emittance growth

Arguably biggest issue today is phase and amplitude stability of upstream RF
X-ray FEL R&D Issues cont.

**Generic X-ray FEL**
*number of BC and undulator lines may vary*

- bunch compressors
- undulator line
- photon transport
- user stations

Not a feasibility issue, but major factor for investment and operation cost

R&D topics
- A & $\varphi$ stability
- Reliable and cost effective RF sources
- Low power consumption for reasonable accelerating fields
Genealogy of X-ray FELs

SLC - 50GeV Linear collider
1989-1998

TESLA 500 GeV Linear collider
(preparation continues as ILC)

JLC-C 500 GeV Linear Collider
R&D project (abandoned 2004)

Present XFELs linac technology & parameters driven by particle physics ancestors
The LC Mantra of high gradient is not the key issues for X-ray FELs!

Make XFELs available for national labs and users
⇒ more economical solutions required without compromising scientific potential
Cost comparison linac technologies
or
Why doesn’t everybody build s.c. & c.w.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Linac investment cost w/o building</th>
<th>Typical gradients (excl. fill factor)</th>
<th>Electric consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsed n.c. with SLED</td>
<td>≈ 10 M€/GeV</td>
<td>20 MV/m (S-band)</td>
<td>≈ 0.5 MW/GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 MV/m (C-band)</td>
<td></td>
</tr>
<tr>
<td>Pulsed superconducting</td>
<td>≈ 20 M€/GeV</td>
<td>24 MV/m</td>
<td>≈ 0.5 MW/GeV</td>
</tr>
<tr>
<td>c.w. superconducting</td>
<td>≈ 30 M€/GeV</td>
<td>15 MV/m</td>
<td>≈ 5.0 MW/GeV</td>
</tr>
</tbody>
</table>

Beware!
This is not exact science!
Relative total capital and 10-year operational linac costs

Effect of increased energy cost on Eacc optimisation over 10 years

cost optimization s.c. linac in c.w. mode
from STFC-NLS design report
cost optimization pulsed n.c. linac for SwissFEL

Cost vs. gradient for S-band with 45 MW klystron,
S-band with 80MW klystron
and C-band with 50 MW klystron

Advantage of C-band is in real-estate needs and electricity consumption
SwissFEL C-Band Linac Module

¼ GeV in 9m with one klystron

Toshiba E37212
5.72 GHz, 50 MW, 3 μs, 100 Hz
with high T collector for heat recovery

BOC pulse compressor

4 x 2m C-band structures
In vacuum, variable gap undulators: for X-ray FELs pioneered by SACLA with $\lambda_U=18\text{ mm}$

Apple II undulators: for X-ray FELs pioneered by FERMI@ELETTRA

Open questions
- What is the smallest acceptable gap 4,3,2mm?
  - Decisive question for design of compact X-ray FELs
  - Tests at SACLA foreseen
- Shorter period PM undulators
- Improved PM materials
- Feasibility of short period sc undulators

Excellent undulator technology reviews in proceedings of FEL’11

J. Bahrdt, “Pushing the Limits of Permanent Magnet Short Period Undulators”
S. Prestemon et al., “Development of Superconducting Undulators”
U15 in-vacuum undulator for SwissFEL
X-ray FEL R&D Issues cont.

Generic X-ray FEL*
*number of BC and undulator lines may vary

bunch compressors

undulator line

photon transport

user stations

SASE or Seeding?
SASE principle

+ FEL amplifier without mirrors and without input signal ⇒ applicable for large wavelength range
Baseline operation mode for LCLS, SACLA and FLASH
- Individual time slices in the bunch radiate independently ⇒ spiky time structure, spectrum, intensity jitter by principle!
HHG seeding principle

**High Harmonic Generation in gases**

- **3 steps in HHG**
  1. Tunnel ionisation
  2. Acceleration in the laser field
  3. Recollision & emission of XUV photon

**HHG figure from** [http://www.newlightsource.org/events/presentations/open_meeting/Tisch.pdf](http://www.newlightsource.org/events/presentations/open_meeting/Tisch.pdf)
sFLASH seeding experiment at FLASH

- Experiment for direct HHG seeding in XUV range
- First seeding (38 nm) April-29, 2012

$\lambda_{\text{photon}} = 38\text{nm}$

Record for HHG seeding!

Courtesy
Katja Honkavara/DESY
HGHG principle

L.H. Yu, PRA 44, 5178 (1991)

slide courtesy Dong Wang SINAP
FEL-1 and FEL-2

- **Two FEL lines** will cover different spectral regions.
  - **FEL-1**, based on a single stage high gain harmonic generation scheme initialized by a UV laser, covers the spectral range from 80 nm down to 20 nm.
  - **FEL-2**, in order to be able to cover the wavelength range from 20 nm down to 4 nm starting from a seed laser in the UV, is based on a **double cascade** of high gain harmonic generation. A magnetic electron delay line is used in order to improve the FEL performance by using the fresh bunch technique.

Courtesy Michele Svandrlik/ELETTRA

\[ \lambda_{\text{photon}} = 20\text{nm} \]

*Record for HGHG seeding!*
EEHG principle

G. Stupakov, PRL 102, 074801 (2009)
First lasing of EEHG FEL at Shanghai SDUV

(3rd harmonic, 350nm, April 2011)

Gain curves of HGHG and EEHG

The EEHG radiation

Courtesy
Dong Wang/SINAP
Difficulties of seeding with external laser for short wavelength

1. External laser amplifier has $\lambda_{\text{photon}} \approx 1\mu$m
   Seeding FEL with $\lambda_{\text{photon}} = 1\text{nm}$ requires generation of harmonic 1000!

2. Spectral power of $e^-$ shot noise increases with $1/\lambda_{\text{photon}}$
   Seed signal power has to exceed shot noise, otherwise SASE radiation will dominate

figure from http://www.newlightsource.org/events/presentations/open_meeting/Tisch.pdf
First Demonstration of Hard X-ray Self Seeding at LCLS

SASE and Seeded spectra recorded on single shots. The left panels are SASE with 150 pC, 3kA peak current, un-seeded. The FWHM of the SASE spectrum is 0.2 % Bandwidth. The right panels are the seeded beam with the same electron beam parameters. The FWHM of the seeded beam is 0.5 eV (5x10^{-5} bandwidth).

- Concept developed by Geloni, Kocharyan and Saldin, DESY 10-053 (2010).
- The mean seeded FEL power is 8 GW with a 2.5 GW SASE background at 8 keV for 40 pC bunch charge.
- Peak seeded power is in excess of 15 GW, comparable to SASE but with a spectral bandwidth reduction by the factor of 40.
- Next steps include system optimization of the LCLS undulator beamline including additional undulators which should increase seeded power and reduce intensity fluctuation.

Single shot pulse energy from the gas detectors with 40pC charge

- SLAC-Argonne-TISNCM Collaboration

Pulse energy

SASE FEL (U1-14: 56 m)
weak magnetic chicane at U15 (3.2 m long)
uniform undulator U16-25: 40 m
tapered undulator U26-33: 32 m
Seeding does not only improve bandwidth and longitudinal coherence but allows also for much better $e^{-}$ to photon conversion with tapering of undulator strength.
X-ray FEL facilities, the near future (until the end of this decade)

First beam parties, reserve date in your agenda

2012 FERMI FEL II, 4nm HGHG seeding cascade, circular polarization with Apple II
2013 FLASH II, second FEL undulator line with variable gap and seeding upgrade
2013 SX FEL based on SCSS in SACLAC undulator hall, Hitoshi Tanaka WEYB01
2015 European XFEL, HX FEL1, HX FEL2 and SX FEL3
2015 PAL XFEL HX and SX
2016 Shanghai SX FEL
2016 SwissFEL HX FEL
2017 LCLS II, HX and SX
2019 Shanghai HX FEL
2019 SwissFEL SX FEL

? NGLS
? MaRIE
FERMI FEL:
80 – 4 nm SEEDED HGHG

FEL I in operation (20-80 nm),
FEL II commissioning starting this year aiming for 4nm with cascaded HGHG seeding!
Talk Michele Svandrlik, TUOB03
FLASH II

- Separation FLASH and FLASH II behind last accelerator module
- Tunability of FLASH II by undulator gap change
- Extend user capacity with SASE and HHG seeding
- Use of existing infrastructure up to last accelerating module

<table>
<thead>
<tr>
<th>Electron Beam Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Beam Energy</td>
<td>0.5 – 1.25 GeV</td>
</tr>
<tr>
<td>Normalized Emittance</td>
<td>1.4 mm mrad</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>0.5 MeV</td>
</tr>
<tr>
<td>Peak Current</td>
<td>2.5 kA</td>
</tr>
<tr>
<td>Number of bunches/second</td>
<td>&lt;8000***</td>
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<table>
<thead>
<tr>
<th>Undulator Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Period</td>
<td>31.4 mm</td>
</tr>
<tr>
<td>Segment Length</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Number of Segments</td>
<td>&lt;12</td>
</tr>
<tr>
<td>Focusing</td>
<td>F0D0</td>
</tr>
<tr>
<td>Radiation</td>
<td></td>
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<tr>
<td>Wavelength SASE*</td>
<td>4-60 nm</td>
</tr>
<tr>
<td>Wavelength HHG*</td>
<td>10-40 nm</td>
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Start commissioning 2013

construction site
Largest X-ray FEL facility
27000 bunches/s in 3 FEL lines
17 GeV s.c. linac
Min. $\lambda_{\text{photon}} = 0.5\text{Å}$
Commissioning starts 2015
SwissFEL

1st phase
2013-16

Injector 0.36 GeV
Linac 1 2.0 GeV
Linac 2 3.0 GeV
Linac 3 3.0-5.8 GeV

0.36 GeV 2.0 GeV 3.0 GeV 3.0-5.8 GeV

2nd phase
2018-19?

Aramis 0.1-0.7 nm
Athos 0.7-7 nm

Aramis
1-7 Å hard X-ray FEL for SASE with reservations for self seeded operation,
In-vacuum, planar undulators with variable gap.
User operation from 2017

Athos
7-70 Å soft X-ray FEL for SASE & self seeded operation.
APPLE II undulators with variable gap and full polarization control.
User operation from 2019
first beam foreseen for 2017
FEL Roadmap at SINAP

Shanghai Hard X-ray FEL

Soft X-ray Test (User) Facility

SDUV-FEL Test Bed
EEHG Cascaded HGHG + EEHG


courtesy of Dong Wang/SINAP
## Parameters of SXFEL

<table>
<thead>
<tr>
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<th>Test facility</th>
<th>User facility</th>
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<tbody>
<tr>
<td>Beam energy</td>
<td>840 MeV</td>
<td>1.3 GeV or higher</td>
</tr>
<tr>
<td>Beam energy spread</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>1~2mm-mrad</td>
<td>1~2mm-mrad</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>50~500pC</td>
<td>50~500pC</td>
</tr>
<tr>
<td>Linac structures</td>
<td>S-band + c-band</td>
<td>S-band + c-band</td>
</tr>
<tr>
<td>Seed laser wavelength</td>
<td>260nm+OPA</td>
<td>260nm+OPA</td>
</tr>
<tr>
<td>FEL output wavelength</td>
<td>8.8 nm</td>
<td>3.75 nm</td>
</tr>
<tr>
<td>FEL pulse duration</td>
<td>30 fs - 1ps</td>
<td>30 fs - 1ps</td>
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<tr>
<td>FEL scheme</td>
<td>Cascade HGHG</td>
<td>depends</td>
</tr>
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**Parameters of Compact XFEL**

<table>
<thead>
<tr>
<th><strong>Electron beam parameters</strong></th>
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<tbody>
<tr>
<td>Energy/GeV</td>
<td>6.4</td>
</tr>
<tr>
<td>Peak current/kA</td>
<td>3</td>
</tr>
<tr>
<td>Bunch charge/pC</td>
<td>250</td>
</tr>
<tr>
<td>Normalized slice emittance/mm-mrad</td>
<td>0.4</td>
</tr>
<tr>
<td>RMS slice energy spread</td>
<td>0.01%</td>
</tr>
<tr>
<td>Full bunch length/(fs)</td>
<td>100</td>
</tr>
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<table>
<thead>
<tr>
<th><strong>Undulator parameters</strong></th>
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<tbody>
<tr>
<td>Period/cm</td>
<td>1.6</td>
</tr>
<tr>
<td>Segment length/m</td>
<td>4.8</td>
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<tr>
<td>Full undulator length</td>
<td>70</td>
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<tr>
<td>Peak undulator field/T</td>
<td>0.93</td>
</tr>
<tr>
<td>K</td>
<td>1.4</td>
</tr>
<tr>
<td>Gap/mm</td>
<td>6</td>
</tr>
<tr>
<td>Average beta function/m</td>
<td>20</td>
</tr>
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</table>

**FEL parameters**

<table>
<thead>
<tr>
<th>Radiation wavelength/nm</th>
<th>0.1</th>
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<tbody>
<tr>
<td>(\rho)</td>
<td>3.41e-4</td>
</tr>
<tr>
<td>Peak coherent power/GW</td>
<td>10</td>
</tr>
<tr>
<td>Peak brightness/(\mu)</td>
<td>2e33</td>
</tr>
<tr>
<td>Pulse repetition rate (Max.)/Hz</td>
<td>60</td>
</tr>
<tr>
<td>3D gain length/m</td>
<td>2.156</td>
</tr>
<tr>
<td>Saturation length/m</td>
<td>50</td>
</tr>
</tbody>
</table>

**Graph**

- **x-axis**: Distance (m) from source to detector (z)
- **y-axis**: Intensity (P [W])

**Timeline**

- **2010**
- **2011**
- **2012**
- **2013**
- **2014**
- **2015**
- **2016**
- **2017**
- **2018**
- **2019**
- **2020**
CW Soft X-Ray FEL Facility

NC-Gun (186 MHz)
- Seeded FELs
- SC RF
- High rep-rate

SRF L-Band Linac (1 MHz beam)
- SC undulators
- 1-MW beam power
- Fast switching

3-10 FELs (SASE, seeded, 2-color attosecond)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Beam Energy</td>
<td>2.4 GeV</td>
</tr>
<tr>
<td>FEL Wavelength Range</td>
<td>1 - 4.6 nm</td>
</tr>
<tr>
<td>Linac Beam Rate (CW)</td>
<td>1 MHz</td>
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<tr>
<td>Avg. Linac Current</td>
<td>0.3 mA</td>
</tr>
<tr>
<td>First Operation</td>
<td>2023</td>
</tr>
</tbody>
</table>
Proposed MaRIE 1.0 (Matter - Radiation Interactions in Extremes) will be an Accelerator user facility, leveraging LANSCE 0.8 – GeV proton accelerator adding to it an XFEL - a unique source of very hard, coherent, brilliant photons.

Pre-conceptual layout of the MaRIE 42-keV XFEL and 12-GeV electron linac. This layout has two L-band injectors operating at ½ the frequency of the main S-band linac. The linac is approximately 530 m long.

Pre-conceptual Design Parameters

<table>
<thead>
<tr>
<th>Energy</th>
<th>12 GeV</th>
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<tbody>
<tr>
<td>Linac frequency</td>
<td>3 GHz</td>
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<tr>
<td>Linac type</td>
<td>RT Cu</td>
</tr>
<tr>
<td>Cavity gradient</td>
<td>25* MV/m</td>
</tr>
<tr>
<td>Maximum beamline θ</td>
<td>4 degrees</td>
</tr>
<tr>
<td>Bunch compressor 1</td>
<td>6 m</td>
</tr>
<tr>
<td>Bunch compressor 2</td>
<td>22 m</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF pulse duration</td>
<td>1.5 µs</td>
</tr>
<tr>
<td>RF pulse rise time</td>
<td>0.8 µs</td>
</tr>
<tr>
<td>RF peak power</td>
<td>80 MW</td>
</tr>
<tr>
<td>RF Repetition rate</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Accelerator active length</td>
<td>480 m</td>
</tr>
<tr>
<td>Accelerator length from injector to linac end</td>
<td>528 m</td>
</tr>
</tbody>
</table>

courtesy of Subrata Nath/LANL
<table>
<thead>
<tr>
<th></th>
<th>LCLS</th>
<th>LCLS II</th>
<th>Eu-XFEL</th>
<th>SACLA</th>
<th>FLASH</th>
<th>FLASH II</th>
<th>FERMI</th>
<th>SwissFEL</th>
<th>PAL XFEL</th>
<th>Shanghai XFEL</th>
<th>NGLS</th>
<th>MaRIE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shortest wavelength</strong>&lt;br&gt;Å</td>
<td>1.5</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>40</td>
<td>40</td>
<td>1</td>
<td>(0.6)</td>
<td>1</td>
<td>10</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td><strong>Undulator type</strong>&lt;br&gt;hard X-ray.</td>
<td>Fixed gap</td>
<td>Variable gap</td>
<td>Variable gap</td>
<td>In-vacuum Var. gap</td>
<td>n.a.</td>
<td>n.a.</td>
<td>In-vacuum var. gap</td>
<td>Variable gap</td>
<td>Variable gap</td>
<td>n.a.</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td><strong>Injector</strong>&lt;br&gt;S-band RF gun</td>
<td>S-band RF gun</td>
<td>L-band RF gun</td>
<td>Pulsed Diode</td>
<td>L-band RF gun</td>
<td>L-band RF gun</td>
<td>S-band RF gun</td>
<td>S-band RF gun</td>
<td>S-band RF gun</td>
<td>S-band RF gun</td>
<td>S-band RF gun</td>
<td>VHF c.w. RF Gun</td>
<td>?</td>
</tr>
<tr>
<td><strong>Cathode</strong>&lt;br&gt;</td>
<td>Cu</td>
<td>Cu</td>
<td>Cs₂Te</td>
<td>CeB₆ (thermionic)</td>
<td>Cs₂Te</td>
<td>Cs₂Te</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
<td>K₂CsSb</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td><strong>Main linac technology</strong>&lt;br&gt;pulsed</td>
<td>n.c.</td>
<td>n.c.</td>
<td>s.c.</td>
<td>s.c.</td>
<td>s.c.</td>
<td>n.c.</td>
<td>n.c.</td>
<td>n.c.</td>
<td>n.c.</td>
<td>s.c.</td>
<td>n.c.</td>
<td>n.c.</td>
</tr>
<tr>
<td><strong>RF frequency</strong>&lt;br&gt;S-band</td>
<td>S-band</td>
<td>L-band</td>
<td>C-band</td>
<td>L-band</td>
<td>L-band</td>
<td>S-band</td>
<td>S-band</td>
<td>S-band</td>
<td>L-band</td>
<td>S-band</td>
<td>L-band</td>
<td>S-band</td>
</tr>
<tr>
<td><strong>RF Rep. rate</strong>&lt;br&gt;Hz</td>
<td>120</td>
<td>120</td>
<td>10</td>
<td>60</td>
<td>10</td>
<td>10</td>
<td>10-50</td>
<td>100</td>
<td>60</td>
<td>60</td>
<td>n.a.</td>
<td>60</td>
</tr>
<tr>
<td><strong>FEL pulses/RF pulse</strong>&lt;br&gt;</td>
<td>1</td>
<td>1</td>
<td>2700</td>
<td>1</td>
<td>2700</td>
<td>2700</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1 MHz c.w.</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td><strong>max. bunch charge</strong>&lt;br&gt;nC</td>
<td>0.25</td>
<td>0.25</td>
<td>1</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>max. electron energy</strong>&lt;br&gt;GeV</td>
<td>13.6</td>
<td>14</td>
<td>17.5</td>
<td>8</td>
<td>1.2</td>
<td>1.2</td>
<td>1.5</td>
<td>5.8</td>
<td>10</td>
<td>6.4</td>
<td>2.4</td>
<td>12</td>
</tr>
<tr>
<td><strong>No. RF stations</strong>&lt;br&gt;</td>
<td>81</td>
<td>81</td>
<td>29</td>
<td>69</td>
<td>15</td>
<td>34</td>
<td>49</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td></td>
<td></td>
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<tr>
<td><strong>Approx. facility length</strong>&lt;br&gt;km</td>
<td>1.7</td>
<td>1.7</td>
<td>3.4</td>
<td>0.8</td>
<td>0.32</td>
<td>0.32</td>
<td>0.5</td>
<td>0.7</td>
<td>1.1</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>
No. X-ray FELs worldwide
(undulator lines with $\lambda_{\text{photon}} < 50\text{Å}$)

slope $\approx 16$ XFELs/decade
or
$\approx 8$ facilities/decade
X-ray FEL’s Mid Term Future

see also Wim Leemans, WEIC03

courtesy Florian Grüner
Some benefits from bandwidth and collimation properties of diffraction limited coherent X-ray beams

• Energy problem solved (see left)

• World communication network backbone based on 100 beam XFEL links with 10 Zettabyte/s

• Near light velocity space probe powered by XFEL beam from ground station on their way to Sirius

• Novel “Black&Decker iFEL” drill, cut, welding tool revolutionizes quality of do-it-yourself products
Thank you for your attention!

Thanks to the IPAC organizers for choosing this great place!