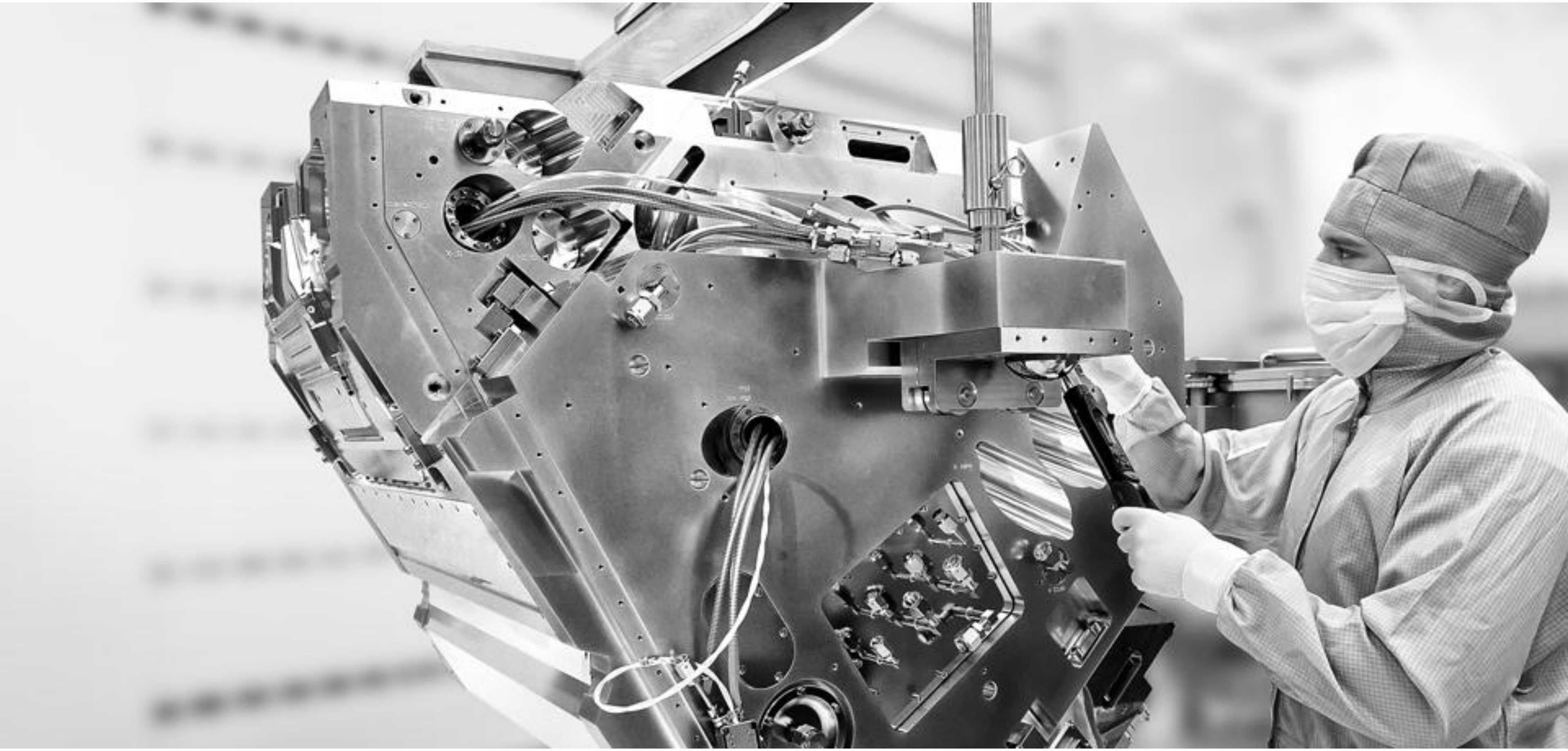
Concept study on an accelerator based source for 6.x nm lithography



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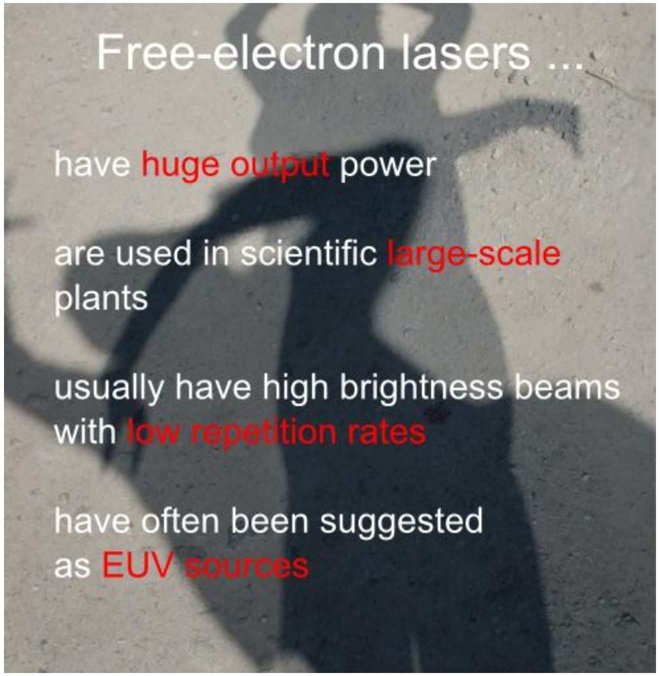
We would like to acknowledge fruitful discussion with E. A. Schneidmiller,
M. V. Yurkov, E. Saldin, H. Weise, et al. in earlier stages. DESY Hamburg

Motivation

The demand

The shadowy existence



Many groups have suggested FELs as a possible high volume lithography source.

Motivation: demand for power and repetition rate

power

- resist sensitivity: 40 mJ / cm²
- optics transmission 3 x less compared to 13.5 nm

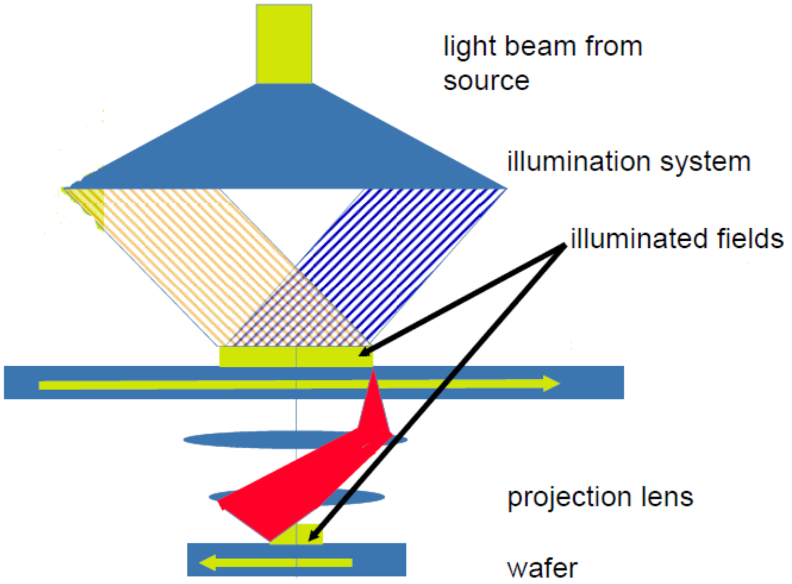
➢ approximately 5 x more energy needed than for a comparable system at 13.5

↓

1.5 kW average power

repetition rate

Mask and wafer are scanned synchronously across static light slit.



scanner / dose control

$$\text{repetition rate} = \underbrace{\frac{scan\ speed}{slit\ width}}_{\text{scanner}} * \underbrace{(number\ of\ pulses\ per\ slit)}_{\text{dose control}}$$

~ 250 kHz

The approach

Concept study done by FEL experts from Helmholtz-Zentrum Berlin.

- Design a free-electron laser which explicitly fulfills lithography demands.
- Preferably work with components which have been proven technical reliability in working facilities.

λ, central wavelength	nm	6.800 +/- 0.006	must	absolute value preliminary
λ-stability within 60 sec averaged over 5 msec	pm	0.34	must	dose control, exact value tbd
system bandwidth, $\Delta\lambda$	%	0.50	by design	sytem transmission bandwidth at waver level
average power within system bandwidth at 100 % dutycyle	kW	1.6	must	driving spec, the more the better
repetition rate	Hz	> 2.5 * 10^5	trade off	design range: 250 kHz – 10 MHz
spectral purity (out-of band, harmonics)		as high as possible		thermal loads
pulse duration		as long as possible		optics damage
brightness		as low as possible		optics damage

Agenda

1	FEL introduction
2	Main components and footprint of Litho-FEL
3	Litho-FEL in numbers: output and costs
4	Summary

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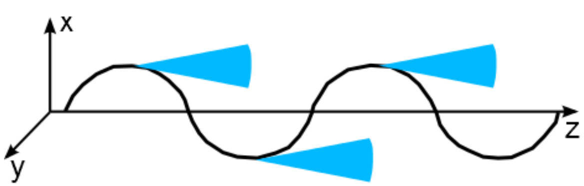
Undulator radiation

N_U alternating magnets force electron beam on sinusoidal trajectory.

Wiggler

$P \propto N$

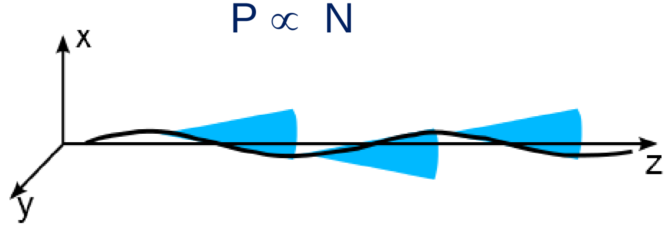


Cones of radiation do not overlap.

⇒ All N electrons radiate independently.

Undulator

$P \propto N$



Cones of radiation do overlap.

⇒ Interference effects of radiation from one electron.

⇒ Different electrons radiate independently an do not interfere.

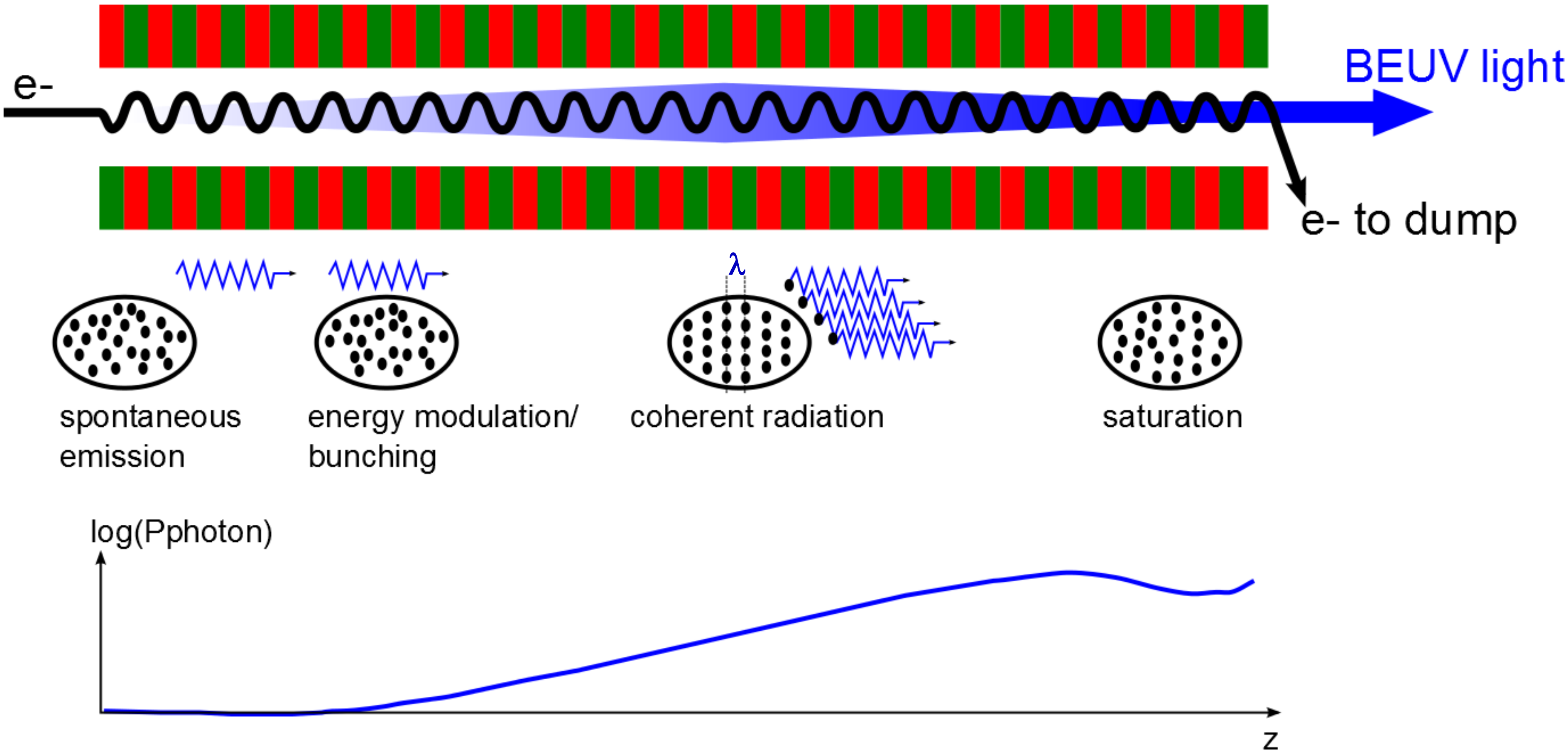
FEL

$P \propto N^2$

All N electrons in an electron pulse emit coherently.

⇒ Nonlinear dependence on the number of electrons.

FEL: coherent undulator radiation



To allow the process of micro-bunching the electron beam has to fulfill several prerequisites which can only be realized in a linear accelerator.

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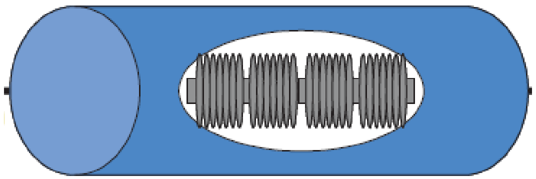
The accelerator



- Electrons are accelerated in superconducting cavities which are driven by a radio frequency.
- Our design:

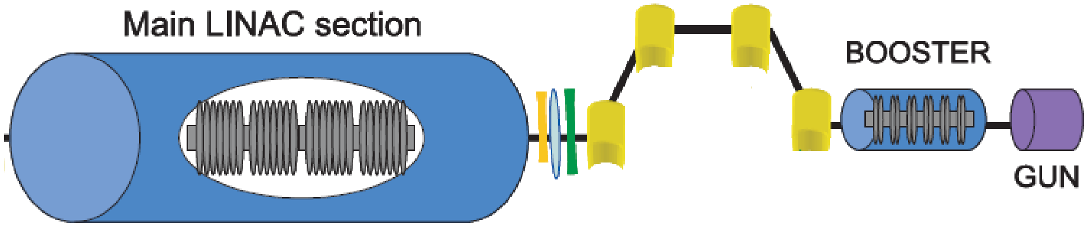
  Multi-cell L-Band SRF Modules with a gradient of about 17 MV / m (CW)
  e. g. Cornell-type 7-cell cavity modules.

  32 cavity modules in 4 cryogenic tanks, each tank of about 12 m.

N. Valles and M. Liepe, "DESIGNING MULTIPLE CAVITY CLASSES FOR THE MAIN LINAC OF CORNELL'S ERL ", in Proceedings of PAC 2011, New York, USA

S. Posen and M. Liepe,PHYS. REV. ST-AB, Volume 15, 022002 (2012)

The accelerator: injector

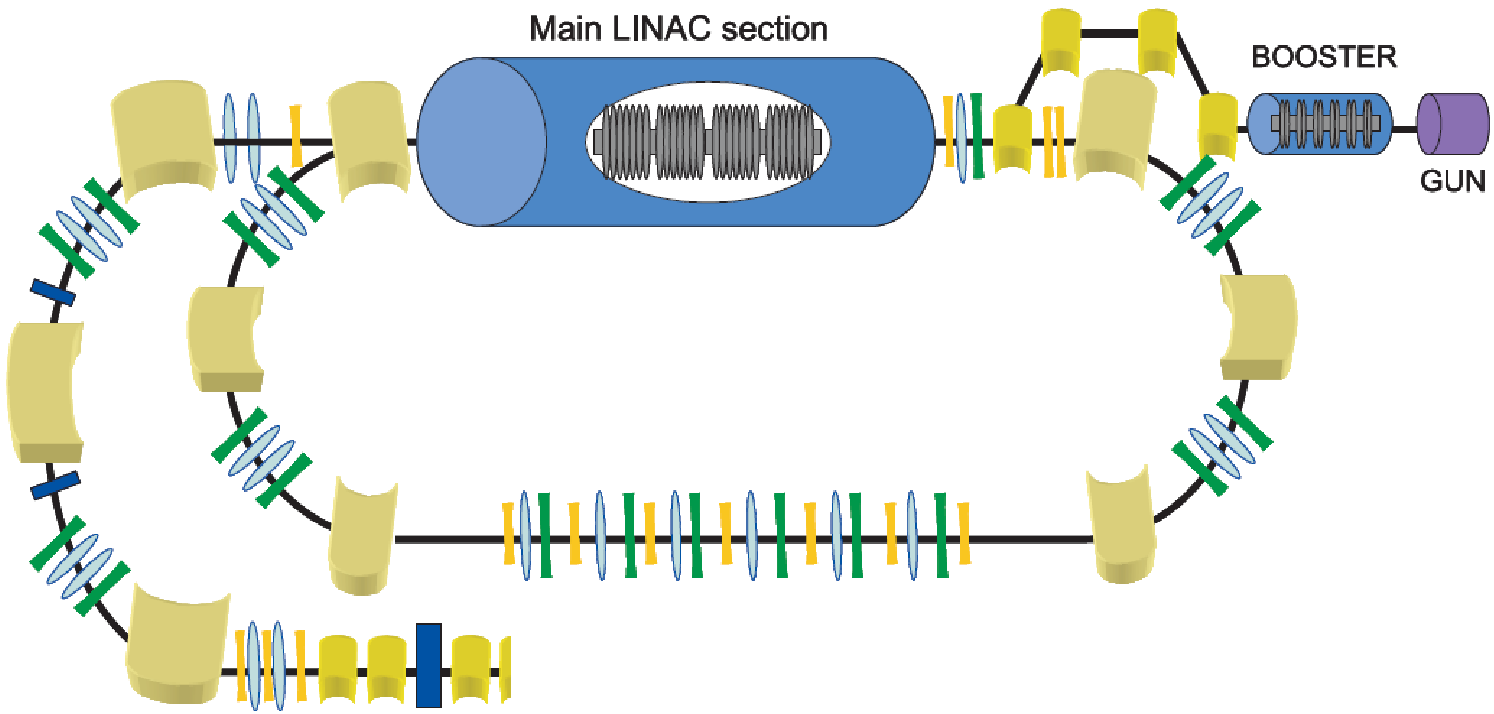


- Performance of a SASE FEL strongly depends on the quality of the electron beam.
- High-brightness electron injector is needed.
- Our design:
  - Cornell-type dc-photocathode gun or eventually the LBNL VHF gun.
  - 6 Cornell-type 2-cell cavities for the booster.
  - Transferline: merger of four-dipole C-shaped chicane.

R.L. Geng et al., "FABRICATION AND PERFORMANCE OF SUPERCONDUCTING RF CAVITIES FOR THE CORNELL ERL INJECTOR", Proceedings of PAC 2007, Albuquerque, New Mexico, USA

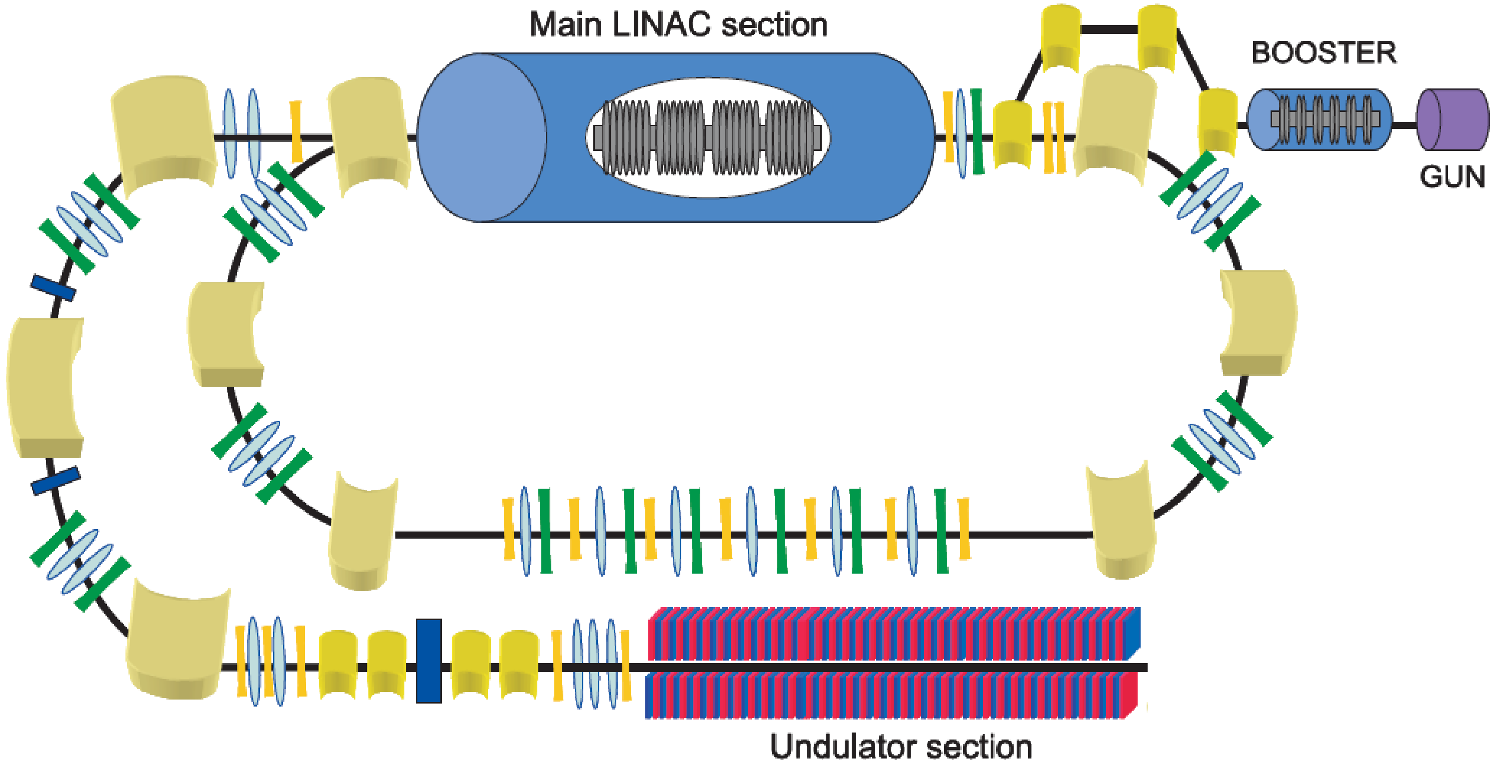
M.Liepe et al.,"The Cornell high-current ERL injector cryomodule", proceedings of SRF 2009, Berlin, Germany

The accelerator: recirculator



- To save costs and space the Main LINAC section is passed twice: recirculator
- The arcs are also used for beam shaping: compression, focussing, etc.

The accelerator: undulator



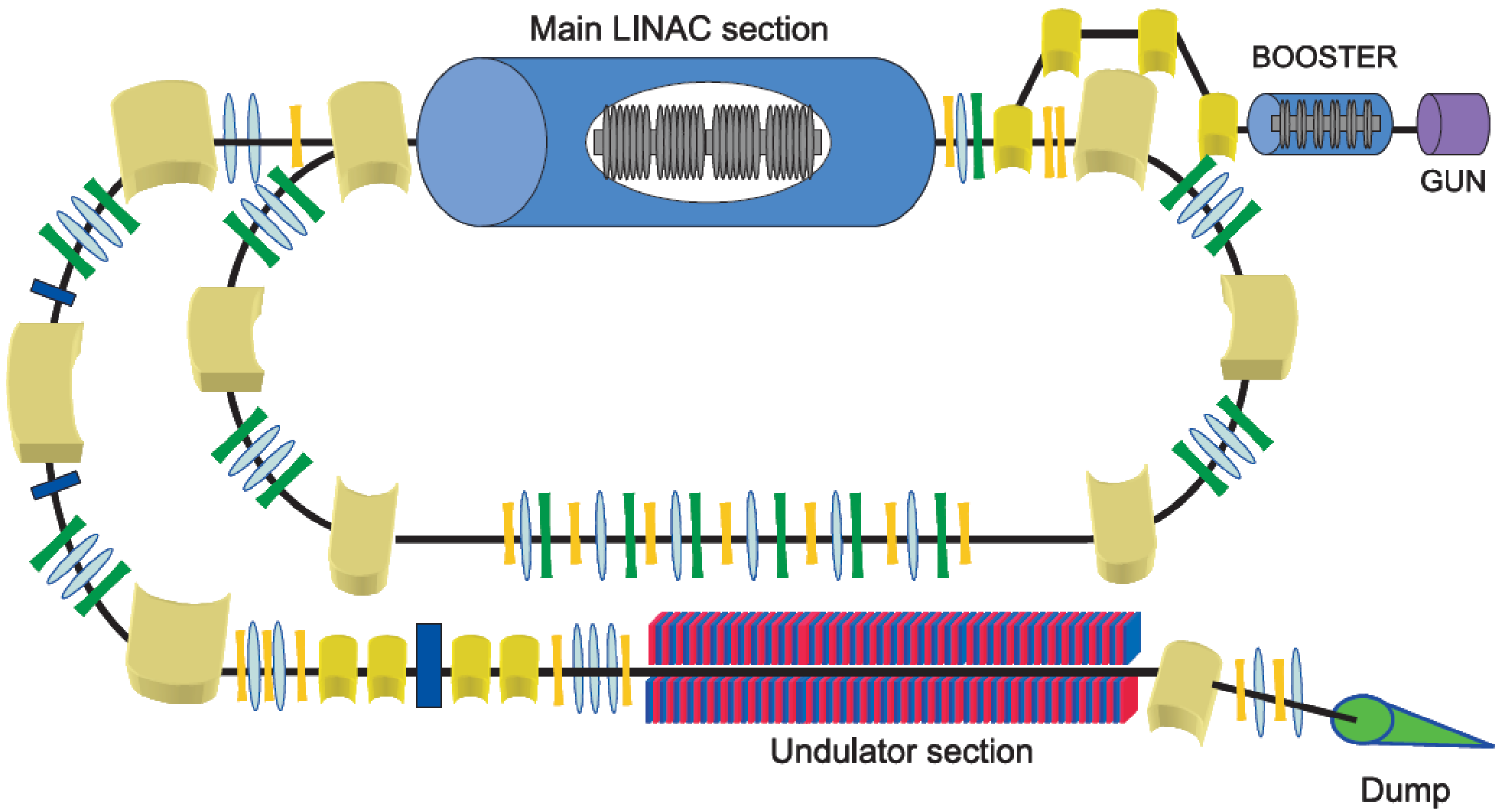
- 26 undulator modules, each 72 periods long (period 15 mm, gap 4.5 mm).
- In-vaccuum device cooled with liquid nitrogen.

T.Schmidt, S.Reiche, "UNDULATORS FOR THE SWISSFEL", in Proceedings of FEL 2009,Liverpool, UK

J. Bahrdt, "Pushing the Limits of Short Period Permanent Magnet Undulators", in Proceedings of FEL 2011, Shanghai, China

G. Ingold et al., AIP Conf. Proc. 879, 388 (2007); doi: 10.1063/1.2436081

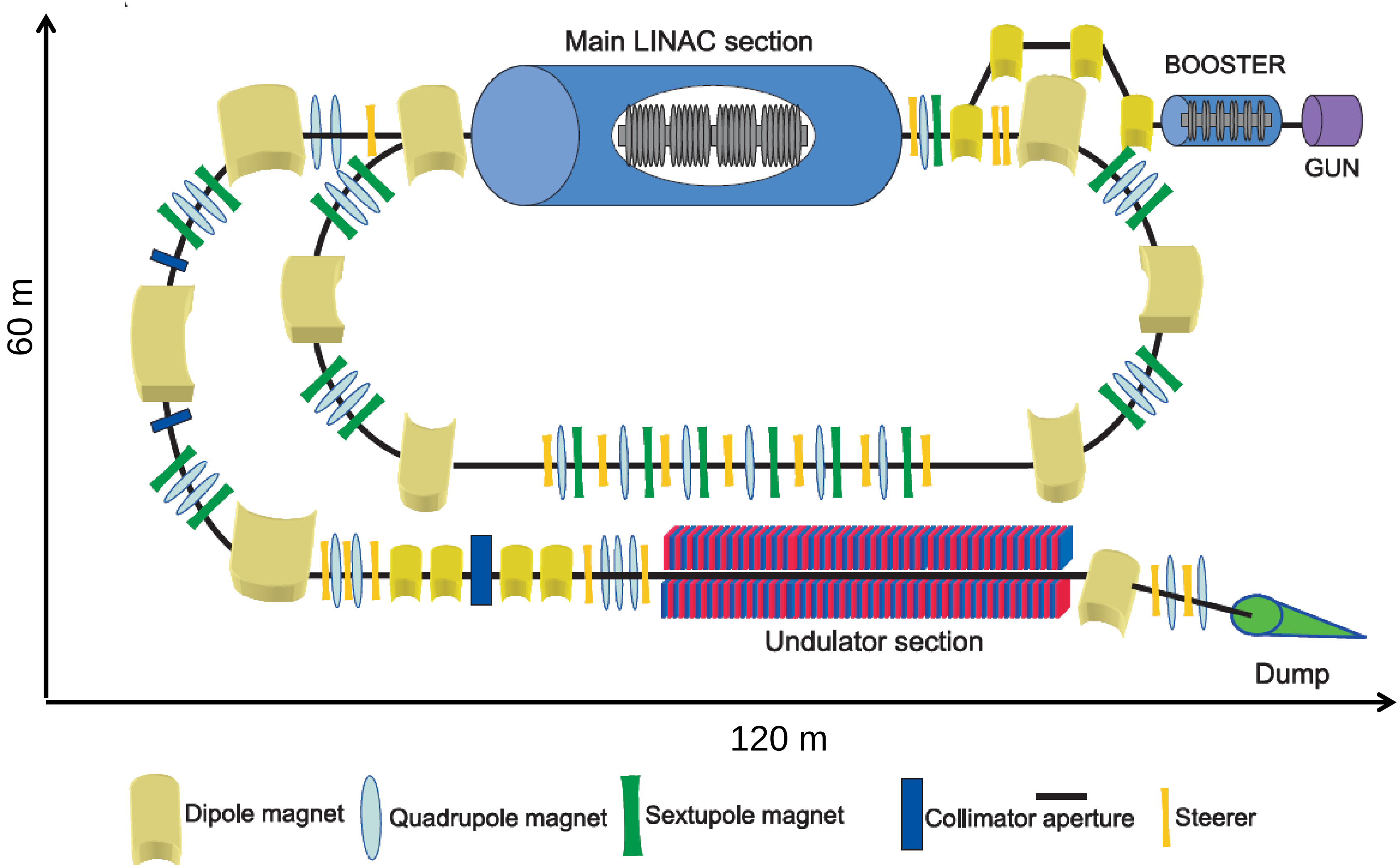
The accelerator: dump



- After the SASE process in the undulator the electron beam can not be reused.
- Dump: a water based dump of the type which is in use for many years at SLAC.

R. Appleby et al., "The International Linear Collider beam dumps", SLAC-PUB-11638, January 2006

The accelerator: dump



The accelerator: dump

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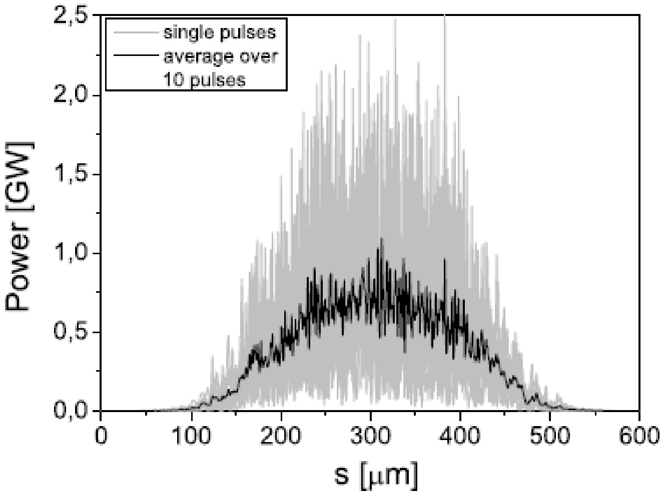
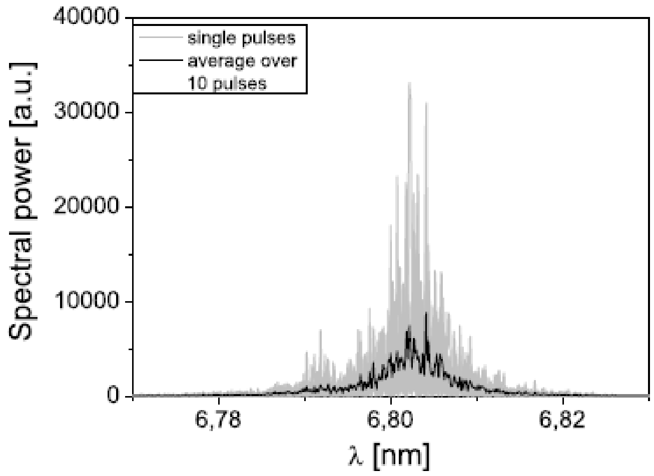
SASE-FEL for Litho: Output

Peak Power [MW]	2000-2500
Pulse power [MW]	280
Pulse duration (fwhm) [fs]	2000
pulse energy [mJ]	0.5664
Rep. rate [MHz]	3
Ave. pulse power [kW]	1.7
Relative bandwidth [%]	0.1
Rad. Size (rms) [μm]	175
Rad. diff. angle (rms) [μrad]	20

simulation: pulse power



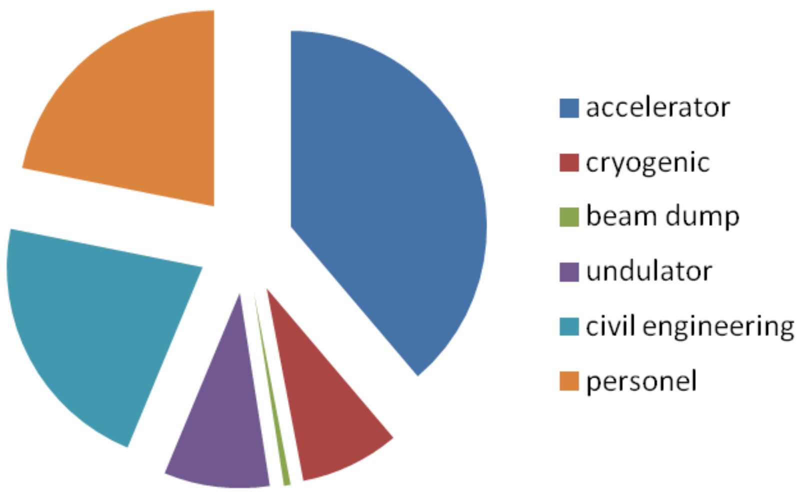
simulation: spectral distribution of power

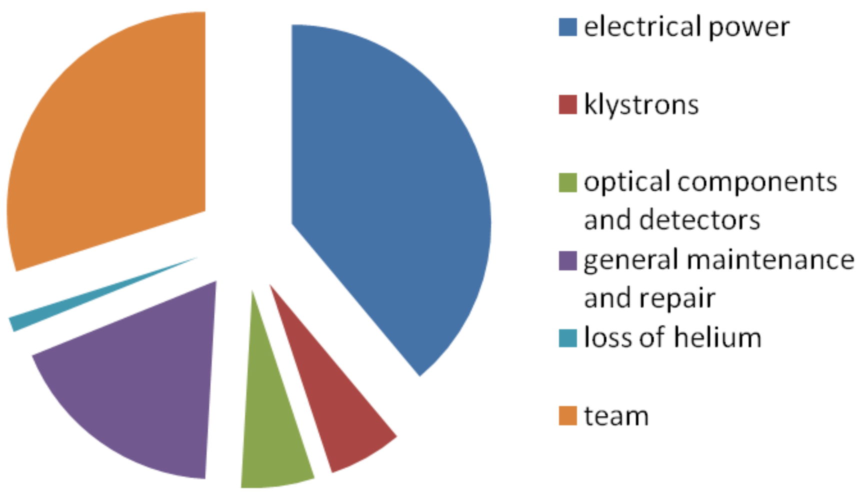


SASE-FEL for Litho: costs

facility costs of about 200 M€

operation costs of about 20 M€ / year





tentative estimation from concept study, no technical design report

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Pro and contra

Pro:

- Big output power.
- Most of the generated light is in-band.
- Small etendue.
- No debris.

Contra:

- Big footprint and technical complexity.
- Very high brilliance beam: life-time issues of the optics have to be solved.

Summary

- A SASE-FEL is feasible for high power lithography source.
- Average output power @ 6.7 nm of 1.7 kW.
- Repetition rate of 3 MHz.
- The design is optimized for robustness. Only components which have already proven the technical reliability in existing facilities or at least in laboratories have been utilized.
- A tentative estimation of building and operational costs on basis of the concept study has been presented.

We make it visible.