Optimisation of FEL LINAC Accelerator Design to Minimize Total Lifetime Costs: RF Design Strategies

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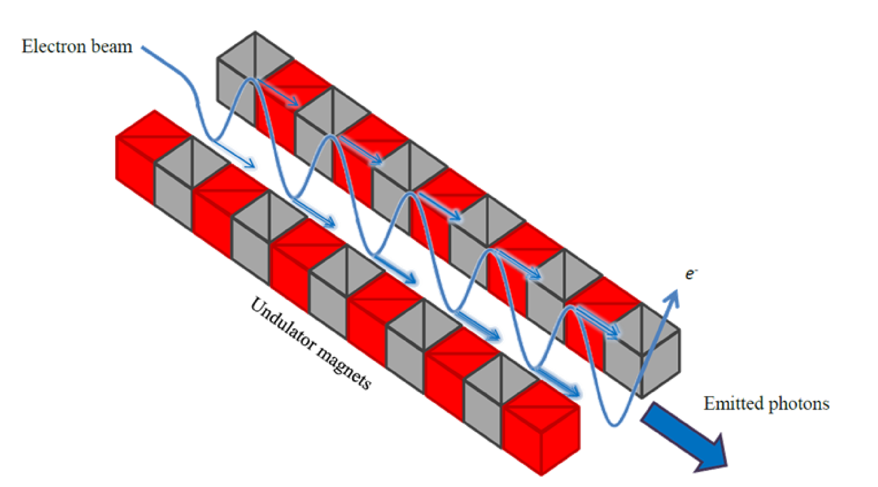
Abstract

This poster follows developments in the field of academic FELs, and presents information regarding novel technologies, specifically in the area of RF design strategy, that may be incorporated into future particle accelerator systems for academic and industrial applications, in order to minimize the necessary investment and operational costs. Two accelerator RF designs have come to prominence in LINACs of recent FEL projects: L-Band RF with superconducting cavities, and C-Band RF with normal conducting cavities. A major cost of L-Band FELs is the cryocooling system required to maintain the LINAC cavities at superconducting temperatures. However, accelerator designs may now use higher frequency C-Band, normal conducting RF cavities, with benefits of lower costs and reduced space for the LINAC. Careful RF design can provide entirely functional accelerators at greatly reduced cost. Our paper presents details of how such goals might be met, and estimates potential cost savings.

Free Electron Lasers



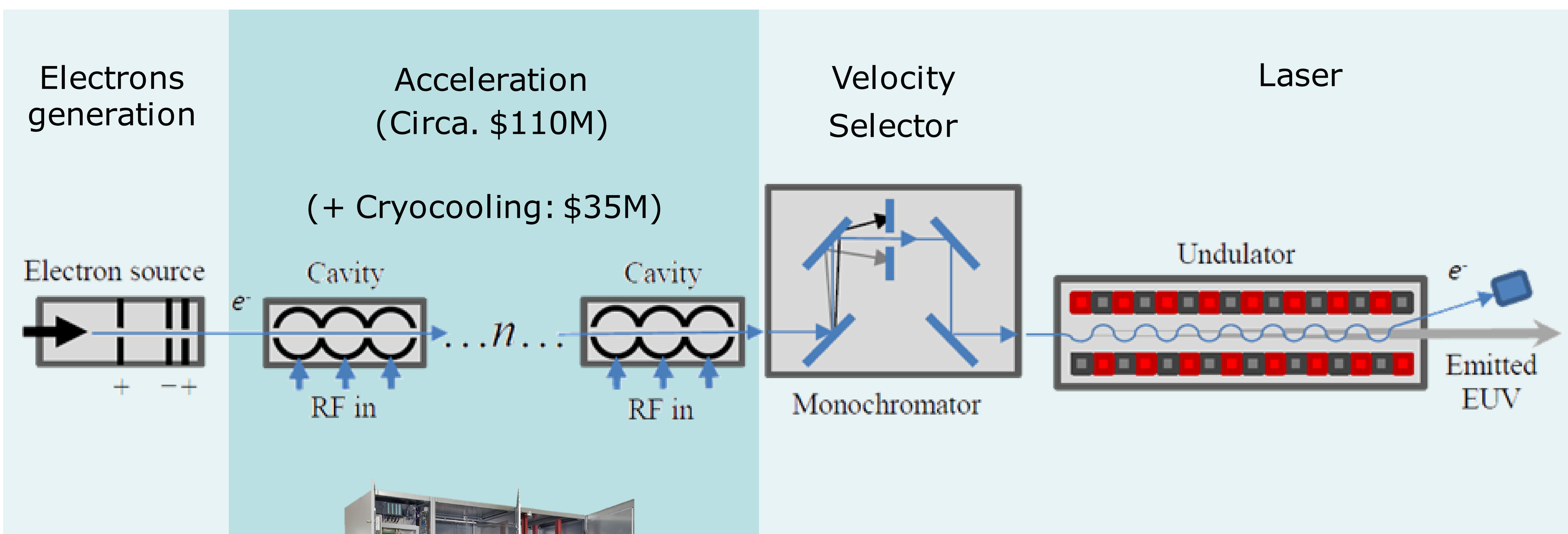
A Free Electron Laser (FEL) is a high intensity laser light source

- Tuneable frequency output
- High output power [1-2]
- Pulsed or continuous operation

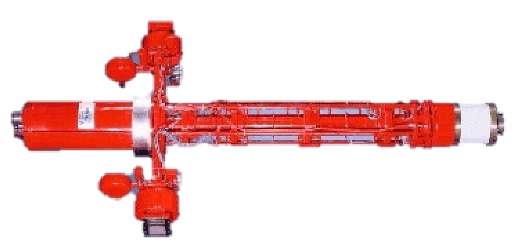
A FEL relies upon a principle of synchrotron radiation, whereby if a high-energy, relativistic charged particle is accelerated radially, photons are emitted to satisfy the physical principle of energy conservation. Thus, if an electron is passed into a magnetic field, it will be deflected by the field and will follow a curved path, releasing photons. Therefore an electron beam must be accelerated to high and precisely controlled velocities prior to entering the undulator stage of a FEL; a linear accelerator (LINAC) featuring an electron source and then subsequent accelerating cavities is required. From experience working with both the European FEL at DESY, and SwissFEL at PSI, the cost implications of the designs of these LINACs can be assessed.

Lessons from Euro XFEL and SwissFEL design

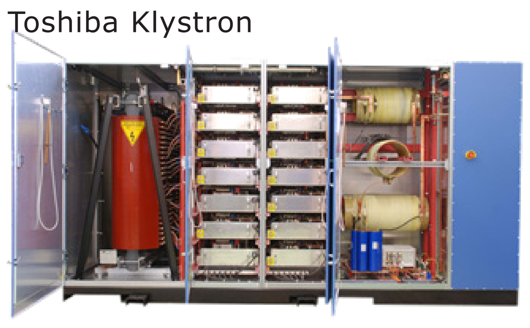
Recently, a FEL for industrial EUV semiconductor manufacturing applications was proposed [3], featuring solid state RF amplifiers and superconducting RF cavities:



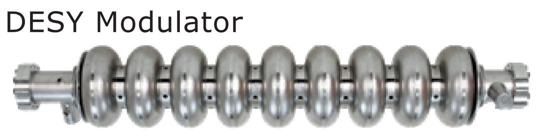
CapEx Estimate: $240M + Building/Infrastructure (2x FELs) [3] + Software/Electronics



Toshiba Klystron



DESY Modulator

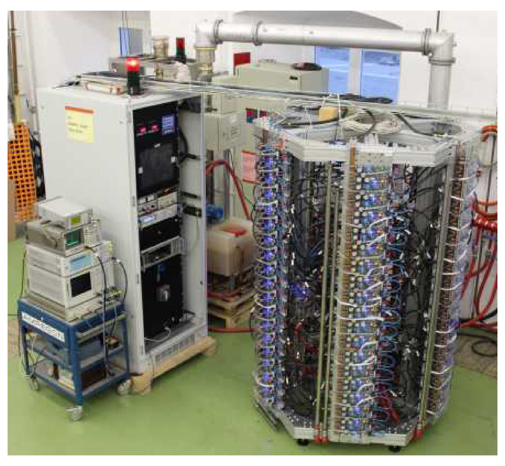


Resonant Cavity

Superconducting cavity = Niobium
Normally-conducting cavity = Copper

	Euro X-FEL	SwissFEL
# Klystrons	26	26
Costs	Circa. €5.2M	Circa. €5.9M
# Modulators + Transformers	26	26
Costs	Circa. €17.4M	Circa. €15.7M
# Cavities	104x Superconducting	104x Normally conducting
Costs	Circa. €97.5M	Circa. €21.8M
Total Costs	Circa. €120.1M	Circa. €43.4M
% relative to Euro XFEL	100%	36%

Solid State vs. Tube Technology



Solid State

PROS	CONS
• Highly reliable	• Low efficiency at high frequencies (>1 GHz)
• Low maintenance	• Pulsed output power limited to max. CW power
• Cheap spares	
• Similar price to tube amplifiers	

Tube

PROS	CONS
• High efficiency at high frequencies (>1 GHz)	• Limited tube lifetime
• Capable of being «overdriven» to MW outputs when pulsed	• Spare tubes are expensive
• Mature technology	• Single critical component?

Are Tubes a Single Critical Component?

Tubes have been used for decades in critical applications:

- Air Traffic Control / Air Defence Radars, 1960s – 1990s
- Domestic Television Broadcasts, 1950s – 1990s

These applications demand highly reliable operation. Good system design can provide redundancy guaranteeing uninterrupted operation.

Are Tubes Expensive?

Comparison of LINAC costs for
Proposed 1.3 GHz Superconducting/CW/SS solution: $100M (+ $35M cryocooling)
Alternate Normally-conducting/Pulsed/Tube solution: $45M (no cryocooling)

- High frequency tube solution saves $55M LINAC costs (mainly cavities)…
- …and $35M for cryocooling
- Tubes circa $250k each when bought in bulk (1-off, 2-3x price?)
- $90M saving = 360x replacement klystron tubes!

Assuming LINAC requires 10 RF stations, each tube amplifiers could have double redundancy, and still replace all tubes every 18 months for the (assumed) 20 year operational FEL/LINAC lifetime and still be $2.5M cheaper!

Future CapEx Savings

Proposed Criteria [3]	CapEx Estimate	Alternative	Revised CapEx Estimate
Building & Facilities	$50M	None proposed, (although 5.7 GHz LINAC has smaller footprint)	$50M
Electronics & Software	$20M	None proposed	$20M
RF Amplifier 1.3 GHz, Solid State, CW (35% efficient)	$100M	5.7 GHz, Tube, Pulsed (65% efficient)	$45M (Assuming 45% of superconducting LINAC costs)
RF Cavities Superconducting Niobium Cavities		Normally-conducting Copper Cavities	
Cryocooling 1 kW Cryoplant for 4K operation	$35M	None required. Standard water cooling	<<$1M
Installation & Commissioning	$10M	None proposed	$10M
FEL Undulator & Optics	$25M	None proposed	$25M
Totals	**$240M**		**<$151M**

Conclusion

Using superconducting RF cavities in particle accelerators also requires expensive cryocooling systems which, together, account for significant proportion of accelerator cost. If normally conducting cavities can be incorporated into RF design strategy of future accelerators, significant savings can be made, by removing the need for cryocooling, and by enabling higher frequency operation. Since solid state amplifiers are not yet available for high power, efficient, pulsed operation, tube amplifiers are the primary choice for use with normally conducting cavities. These allow construction of accelerator systems at a fraction of the cost of superconducting systems with solid state RF amplifiers. Good RF design can negate the reliability concerns associated with tubes.

References

[1] J Feldhaus, Journal of Physics B: Atomic, Molecular and Optical Physics, 43 (19) 194002 (2010)
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[3] E. R. Hosler et al., "Considerations for a free-electron laser-based extreme-ultraviolet lithography program", Proc. SPIE 9244 (2015) [9422-0D]