Millimeter-wave undulators for compact XFELs

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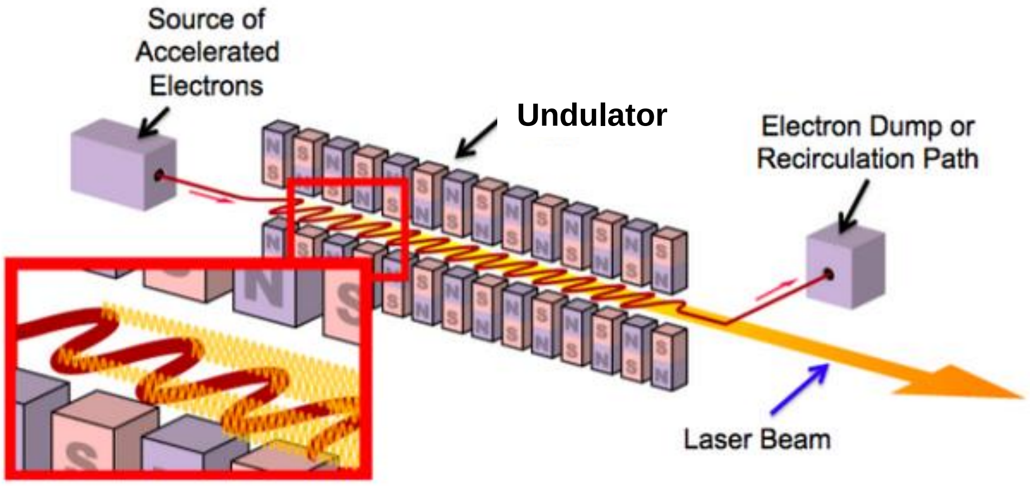
Free-electron Laser (FEL)



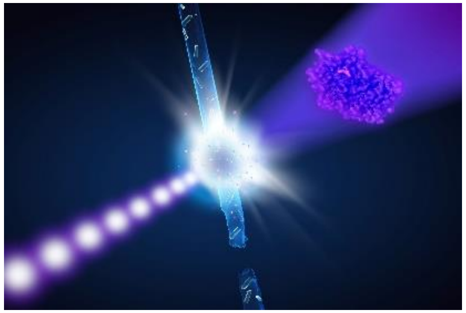
Wavelength of output radiation

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$K = \frac{|e|\lambda_u B_u}{2\pi mc} = 0.934 B_u[\mathrm{T}]\lambda_u[\mathrm{cm}]$$

Compact X-FEL relies on

- High-gradient accelerators
  - Traditional accelerators: higher frequency (X, Ka-band accelerators)
  - Novel accelerators: DLA, PWFA, LWFA
- Short wavelength undulator ($\lambda_u \downarrow$ enables $\gamma \downarrow$ for same f)



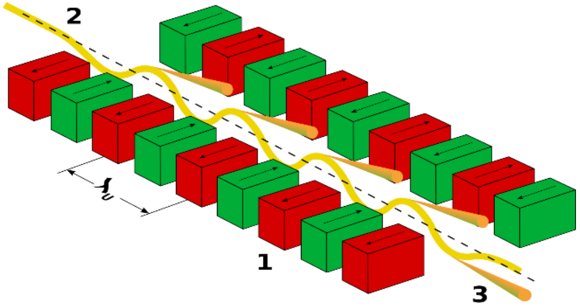
Uniqueness: Visualising ultrafast (fs) processes at the quantum scale (<1nm)

Timeliness: UK-XFEL science case made to STFC, UK in Oct. 2020 with UK XFEL CDR commissioned (2022 to 2025)

[1] Bolko Beutner, Introduction to Free Electron Lasers;
[2] P. G. O'Shea, Science, 292 (5523), pp. 1853-1858, 2001.
[3] A. Ghaith, Physics Reports 937(6), 2021;
[4] https://www.youtube.com/watch?v=-kdqVuJxkrs

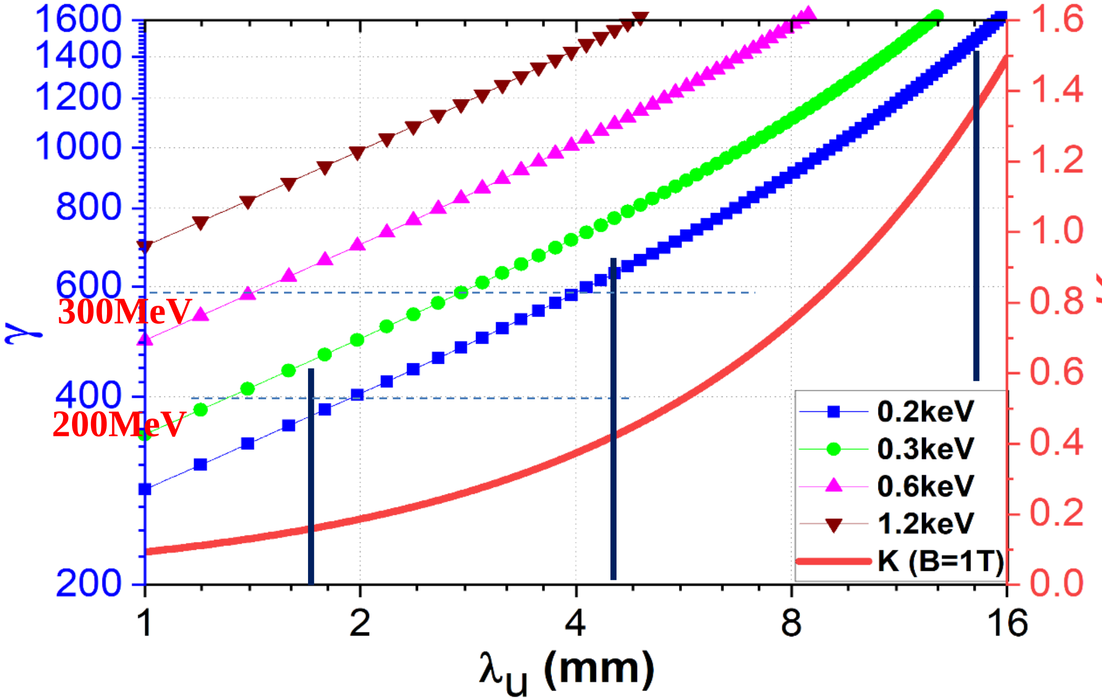
Undulators

- Permanent magnet undulators
- Cryogenic permanent magnet undulators
- Superconducting undulators
- Exotic undulators (Microwave undulator, Optical undulator)



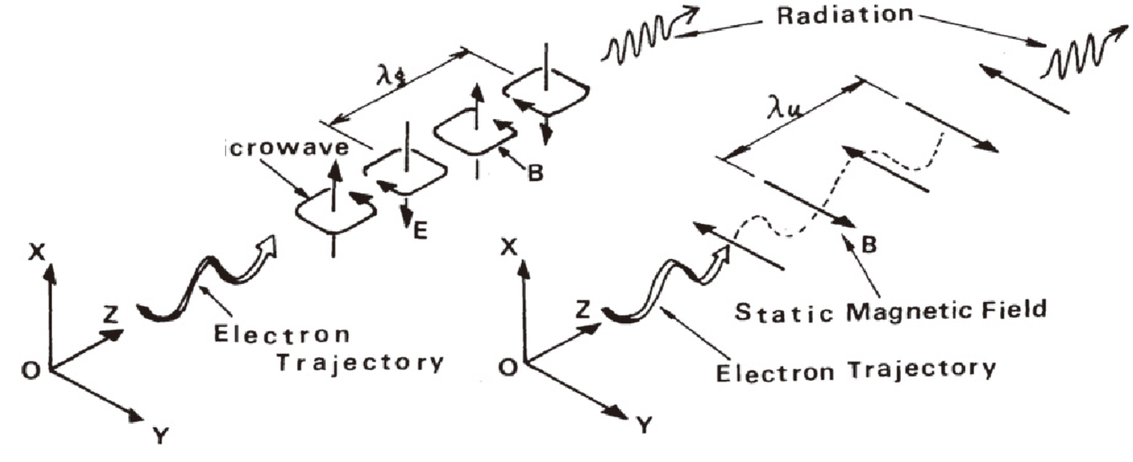
State-of-the-art PMU

	SwissFEL (Aramis)	Europe XFEL
Structure	Planar hybrid	Planar hybrid
Material	NdFeB	NdFeB
K	1.2	3.0
Period	15 mm	26 mm
Peak field	0.85 T	1.24 T
Gap type	Variable	Variable
Gap	4.7 mm	6 mm



1.7mm period allows for generating soft X-ray radiation using a 250 MeV beam.
Moderate K value for 1.7mm period MU mitigated by 588 periods per meter.

Microwave undulator (MU)



(a) Microwave Undulator (b) Magnetic Undulator

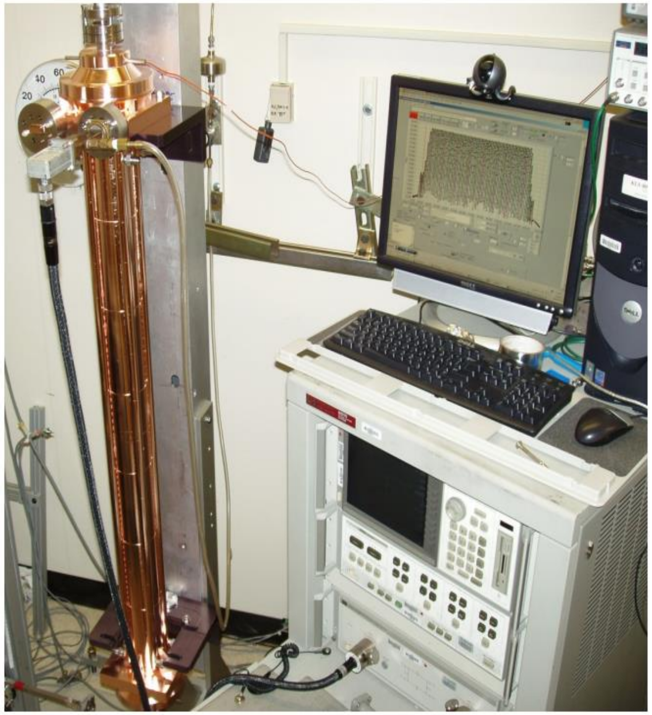
$\underline{E_x = E_0 \sin(2\pi z/\lambda_g) \cdot \sin(\omega t)}$

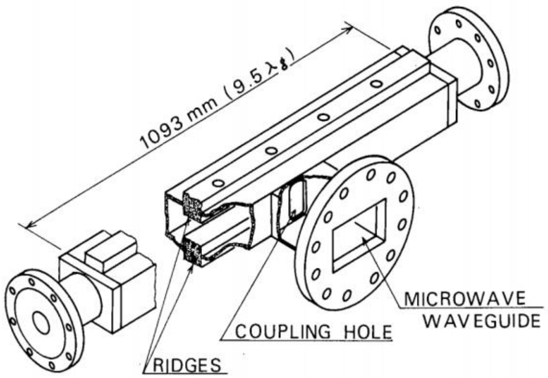
$B_y = B_0 \cos(2\pi z/\lambda_g) \cdot \cos(\omega t)$

$F_x = -e(E_x - v_z B_y)$

$B_z = B_0 sin(2\pi z/\lambda_u)$

$F_x = e v_z B_y$





NLP, Japan 1983: Frequency 2.856 GHz, Q 7100, λ_u 55.0 mm, K 0.24. Klystron power 300kW. λ 400nm @143MeV beam.

SLAC 2014: Frequency 11.424 GHz, Q 91000, λ_u 13.9 mm, K 0.69. Klystron power 50MW. Tunable radiation 400-600nm with 50 MeV to 70 MeV beam, and seeded coherent harmonic generation (SCHG) 160-240nm @ 120 MeV beam

[1] T. Shintake, Jpn. J. Appl. Phys. 22, 844, 1983.

[2] S. Tantawi, Phys. review letters 112, 164802, 2014.

Features of MMWU

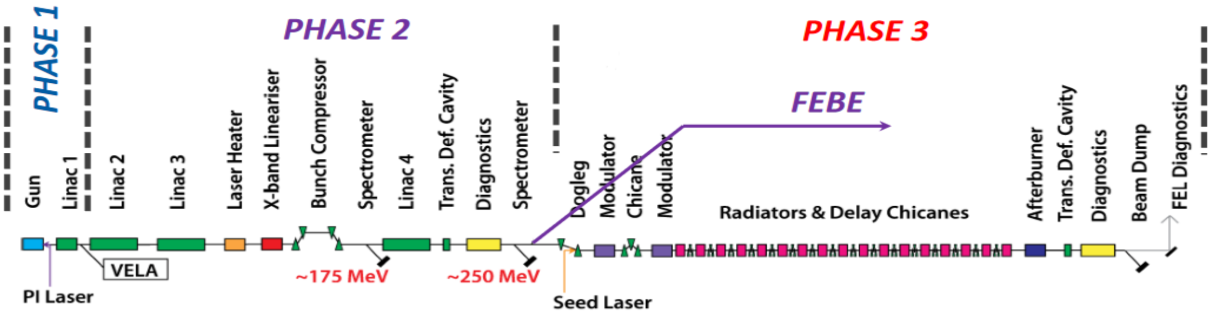
Features

- Shorter undulator period, lower beam energy;
- Large aperture to reduce wakefield;
- Fast control of polarization and magnetic field (electrical vs mechanical);
- Resilient to damage by radiation (copper vs rare-earth material).

Vision

- **Demonstrate soft X-ray radiation using the FEBE beam**

λ_u =1.7 mm @ 94 GHz;
K=0.13 @ 2.5MW drive power;
λ =3.57nm (348eV)@ 250MeV beam.



PHASE 1:
50 MeV, 100 pC at 10 Hz
ACHIEVED

PHASE 2:
250 MeV, BEING
PROCURED AND
ASSEMBLED

PHASE 3:
100 nm FEL
NOT YET FUNDED

[1] Deepa Angal-Kalinin, FEBE Users Group Meeting, 5th July 2022.

MU Research at UoS

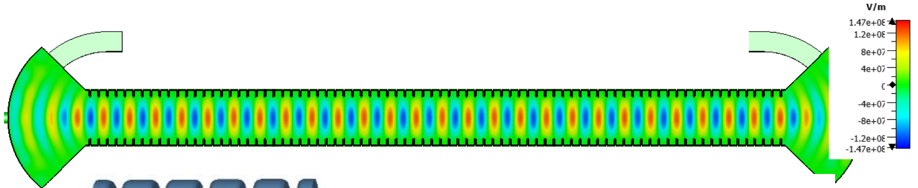
EM wave: traveling wave and standing wave

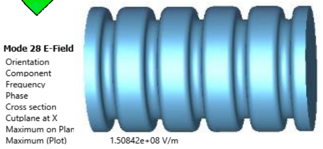
Requirements for the waveguide mode:

- $\varsigma \approx Z_w$, Overmoded waveguide
- Low loss, minimise field strength at wall
- Maximise B_u, maximise field strength at electron path
- TE-like mode ($E_z \approx 0$), maximise transverse field

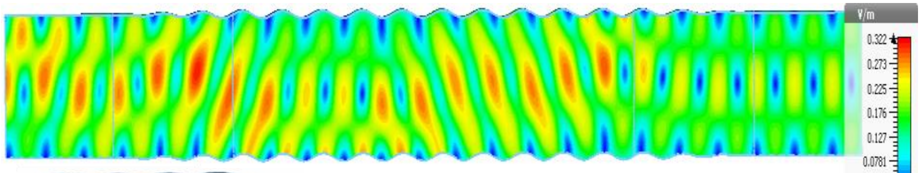
$$F_x = \frac{eE_0}{2}\left(\frac{\varsigma}{Z_{\mathrm{w}}}+1\right)\cos\left[2\pi z\left(\frac{1}{\lambda_0}+\frac{1}{\lambda_{\mathrm{g}}}\right)\right] + \frac{eE_0}{2}\left(\frac{\varsigma}{Z_{\mathrm{w}}}-1\right)\cos\left[2\pi z\left(\frac{1}{\lambda_0}-\frac{1}{\lambda_{\mathrm{g}}}\right)\right]$$

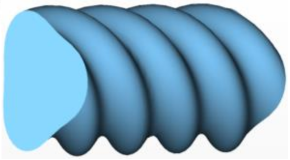
	Cavity-type undulator	Flying-type undulator
Microwave source	Medium power, long pulse microwave source, 30 MW, 2 μs	High power, short pulse microwave source, 800 MW, 10 ns
Field stability	Excellent	Tapered field due to loss
Phase accuracy	Excellent	Require phase locking





Cavity-type undulator based on the corrugated waveguide





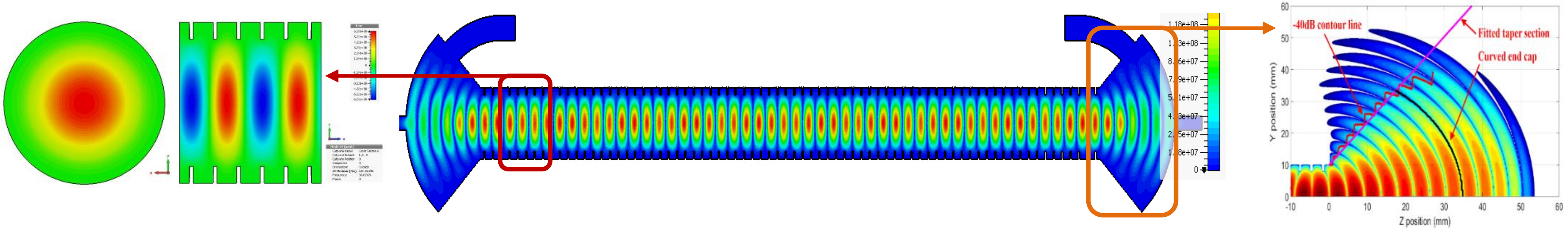
Flying-type undulator based on helically corrugated waveguide

[1] L. Zhang, W. He, J. Clarke, et. al, IEEE Trans. Electron Devices, 65(12), pp. 5499-5504, 2018

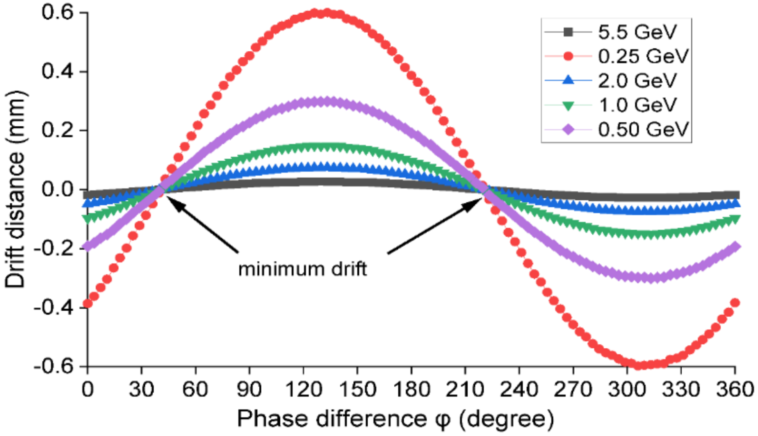
[2] L. Zhang, W. He, J. Clarke, et. al, Journal of Synchrotron Radiation, vol. 26, 2018

MU Research at UoS

- Design and optimize the undulator structure based on low-loss quasi-optical corrugated waveguide. Inner Diameter of 16.2mm, Length of 1m, *K* peak of 0.5 @50MW, 36GHz, 2μs pulse duration.
- Scalable (frequency and cavity length) design for the coupler structure
- Particle trajectory simulation in the MU

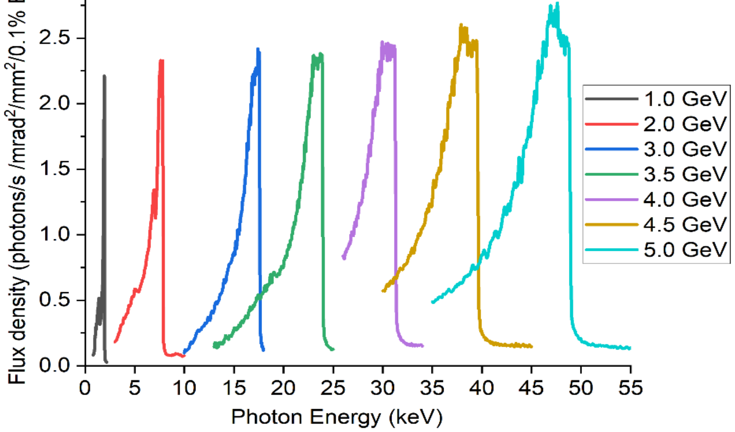


Designed from near-field radiation pattern



Zero drift distance by controlling injection phase

Small drift distance at higher beam energy (oscillator for beam energy > 1GeV)

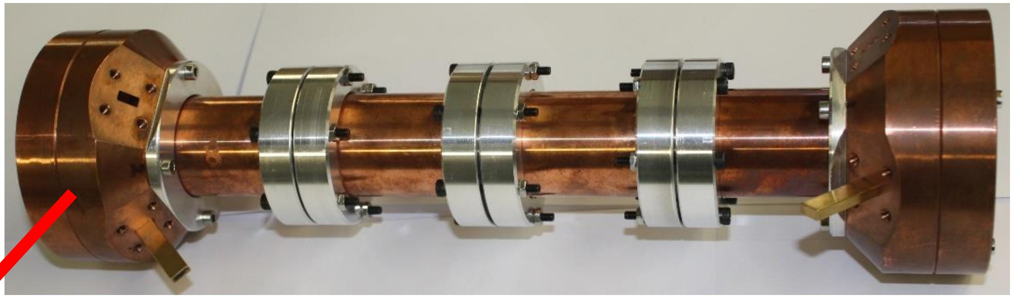


[1] L. Zhang, W. He, J. Clarke, et. al, IEEE Trans. Electron Dev., 66(10), p.4392-4397, 2019.
[2] L. Zhang, J. Clarke, C. Donaldson, et. al, Sci. Rep., 12, 7071, 2022.

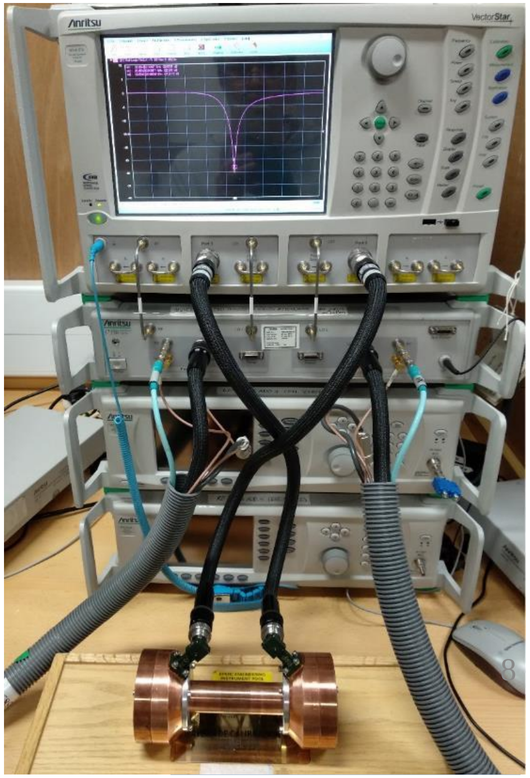
Manufacture of the MU

Evaluate the different methods of manufacture of a short section of MU and measure performance using a Vector Network Analyser (VNA).

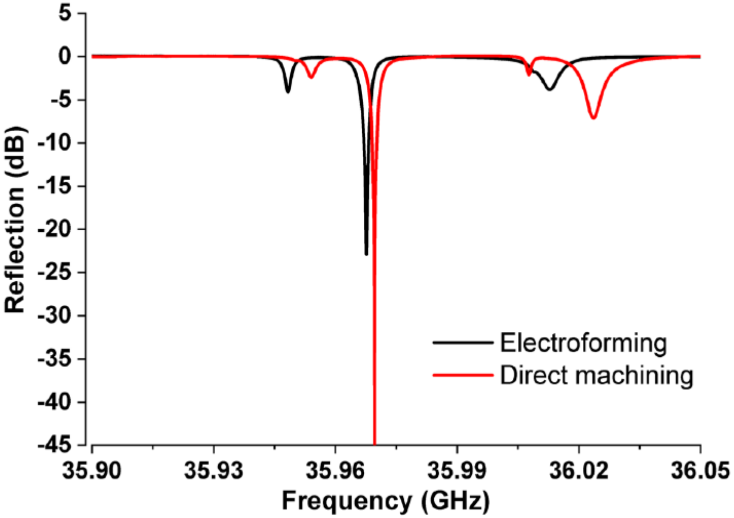
(1) Electroforming



(2) Directly machining

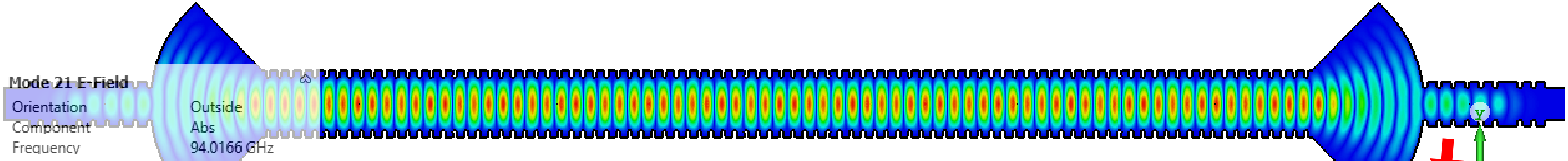


(3) 3D printing + plating



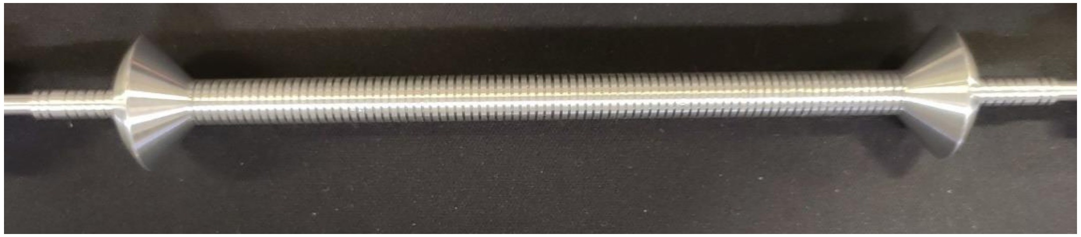
W-band MMMU

Frequency (GHz)	94.0	Q factor	47800
λ_0 in free space (mm)	3.19	Input power (MW)	2.5
Undulator period λ_u (mm)	1.72	Peak Ex on axis (V/m)	2.43E8
Waveguide radius (mm)	3.0	B_u (T)	0.81
Min. tunnel radius (mm)	1.80	Electric field at wall (V/m)	3.3E6
Corrugation period (mm)	1.38	K	0.13
Overall length (mm)	200	λ output (nm)	3.6nm (342eV)



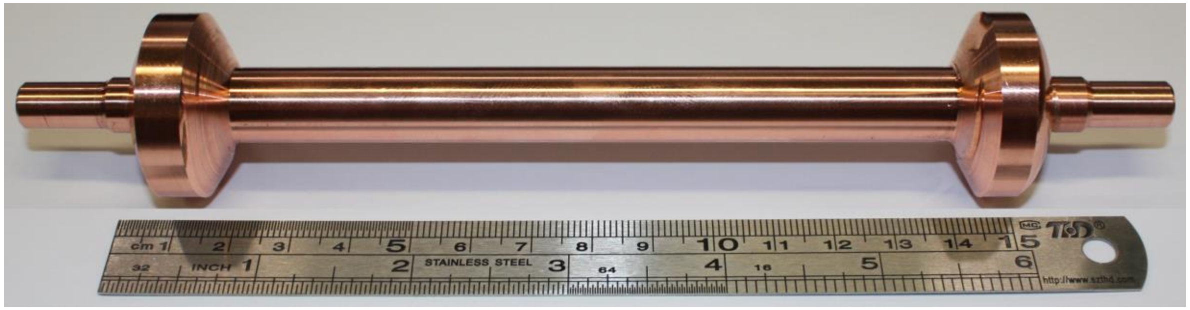
Mode 21 E-Field

Orientation	Outside
Component	Abs
Frequency	94.0166 GHz
Phase	0 °
Cross section	A
Cutplane at X	0.000 mm
Maximum on Plane (Plot)	5.7738e+08 V/m
Maximum (Plot)	5.79208e+08 V/m



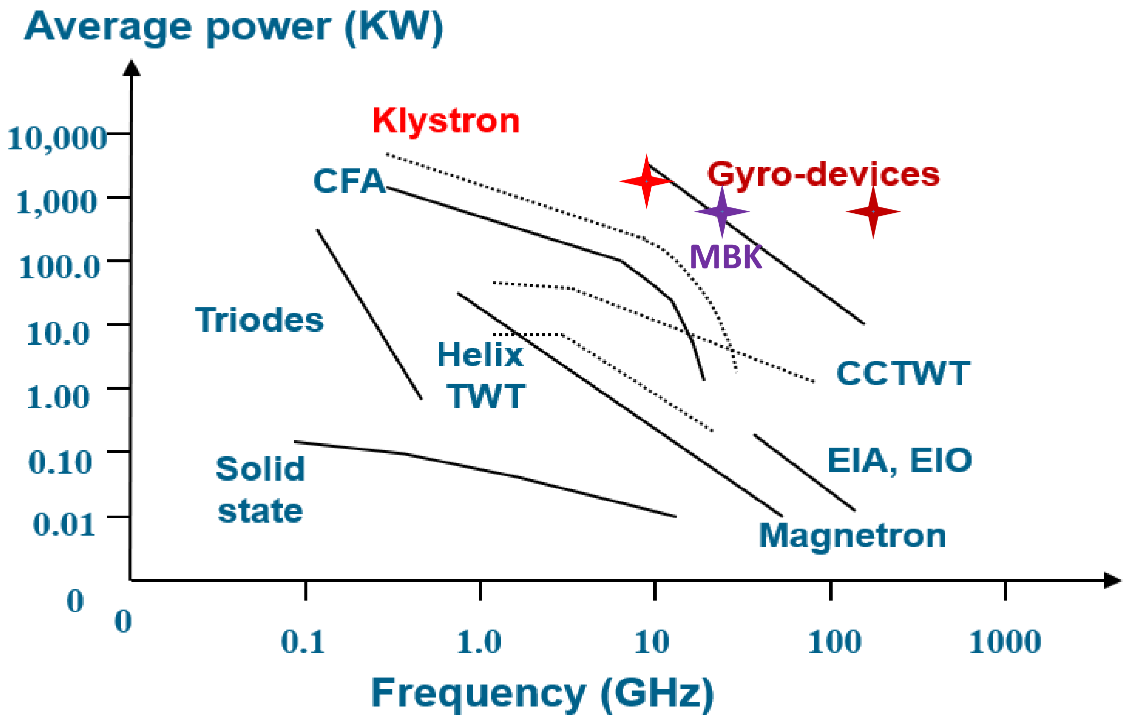
Bragg reflector to reduce the mm-wave power leakage and maintain large aperture.

With copper grown. Aluminium to be dissolve away.



[1] P. McElhinney, et. al, IEEE Trans. Electron Devices, 64(4), pp. 1763-1766, 2017.
[2] F. Toufexis, et. al, Phys. Rev. Accel. Beams, 22, 120701, 2019.

Driving sources

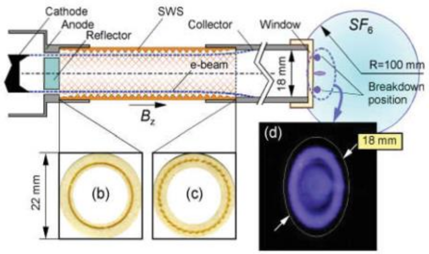


Frequency	Sources	Specifications
X-band	Klystron	11.424 GHz, 75 MW, 55%, SLAC
Ka-band	Gyro-klystron	30.0 GHz, 15 MW, 40%, IAP
	CARM	35.7 GHz, 30 MW, 10%, IAP
	Gyrotron	35.0 GHz, 250 MW, 10%, NRL
W-band	Gyrotron	94.4 GHz, 5.6 MW, 23%, pulsed mode, IAP
D-band	Gyrotron	170 GHz, 1 MW, 45%, CW, CPI, KIT, Japan, IAP
	CARM	250 GHz, 20 MW, 20%, NRL

SLAC
12GHz,
75 MW,
1.6 µs
@120 Hz,
Eff. 55%.

Japan
170GHz,
1 MW,
CW,
Eff. 45%.

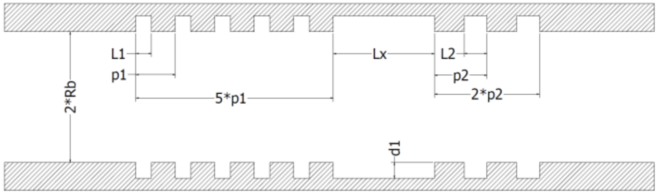
Strathclyde
90GHz, ~10 MW,
~150ns, single shot,
Eff. ~4%. (2D SWS)
60MW@36GHz

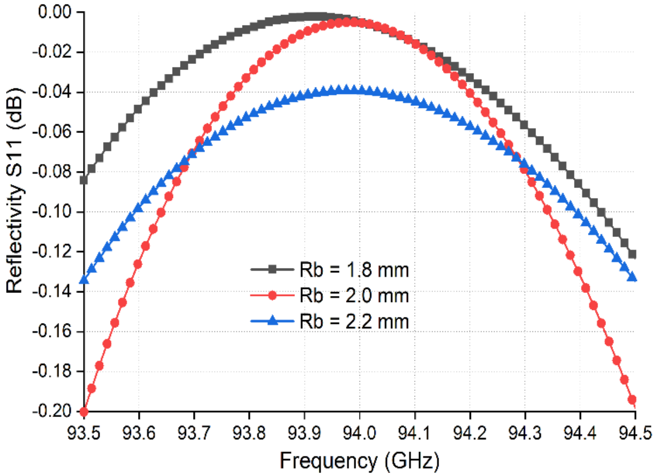


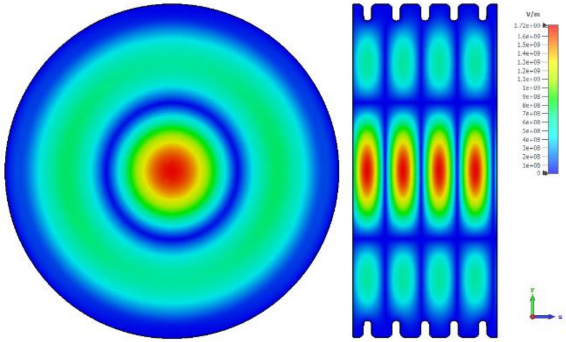
IAP, Russia
90GHz, 150MW,
~1ns, eff. 13%, IAP,
Russia

Ongoing work

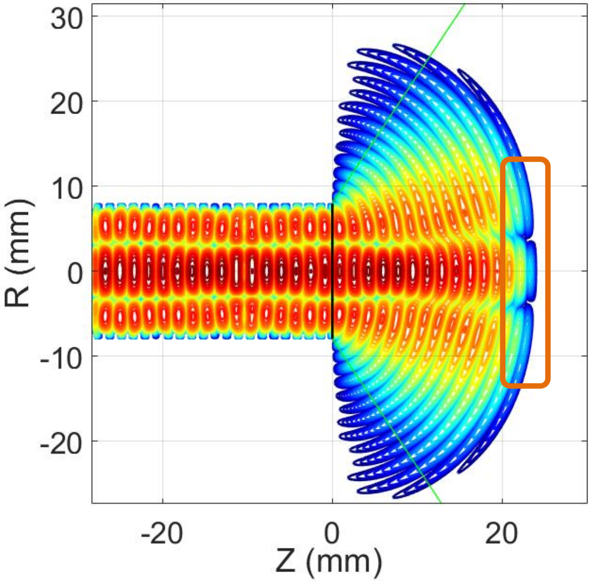
- Step tuning the undulator period based on longitudinal mode index $\mathrm{HE}_{1,1,N}$
  - Broadband Bragg reflector
  - Broadband/multi-frequency drive sources (5% bandwidth)
- Higher order mode HE_{12}
  - Larger radius (2.5 times)
  - Lower field strength at the wall (4 times reduction)
  - Complicated coupler structure





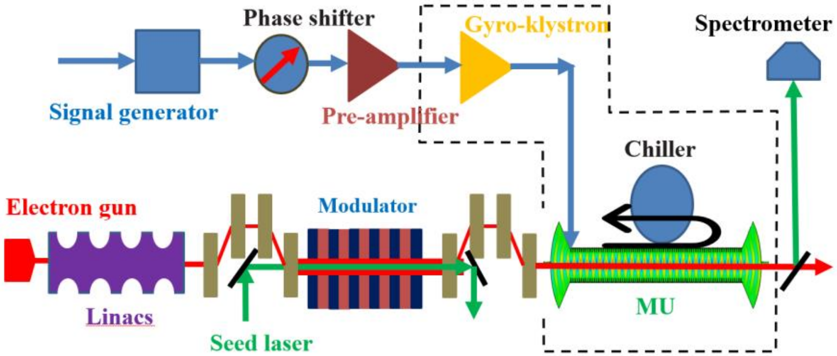


HE_{12} mode

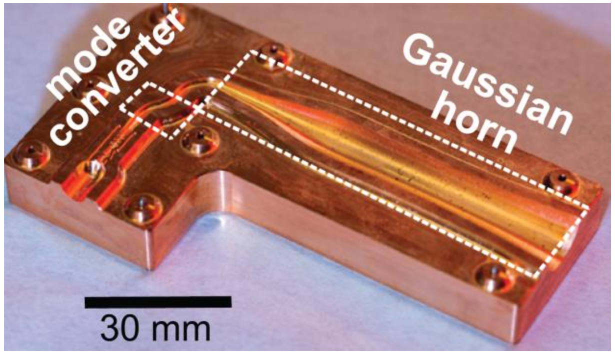


Conclusion

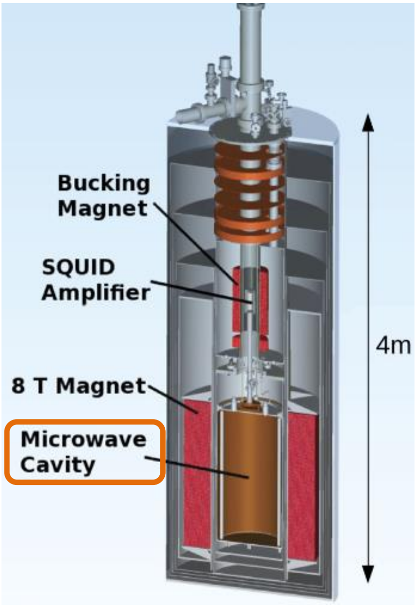
- Millimetre-wave undulator enables
  - X-FELs using the 250MeV FEBE beam at Daresbury Lab
  - The MW-level millimetre-wave source developed for the MU can be used for high-gradient accelerator research
  - Enhances the search for axion-like-particles (ALPs) by increasing the event rate of the detection system



X-FEL radiation with FEBE



mm-wave/THz acceleration



axion detection

[1] E. Nanni, SLAC, HG 2021.
[2] G. Linde, IEEE Trans. Aerospace and Electronic Systems, 44(3), pp. 1102-1117, 2008.
[3] M. A. K. Othman, et. al, Appl. Phys. Lett. 117, 073502 (2020).
[4] L.M. Capparelli, Physics of the Dark Universe, 12 (37-44), 2016.

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Thank you for attention!

I’d be happy to answer any questions