WP 5.4: Exotic Undulators

Microwave Undulator

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Microwave undulator (UK XFEL)

Liang Zhang, Strathclyde, Cockcroft Institute
PDRA, 1/04/2017 to 31/6/2019

Coherent wavelength is given by

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

λ_u is the period of the undulator
n is the harmonic number
K is rms undulator strength parameter
γ is the Lorentz-Fitzgerald relativistic factor

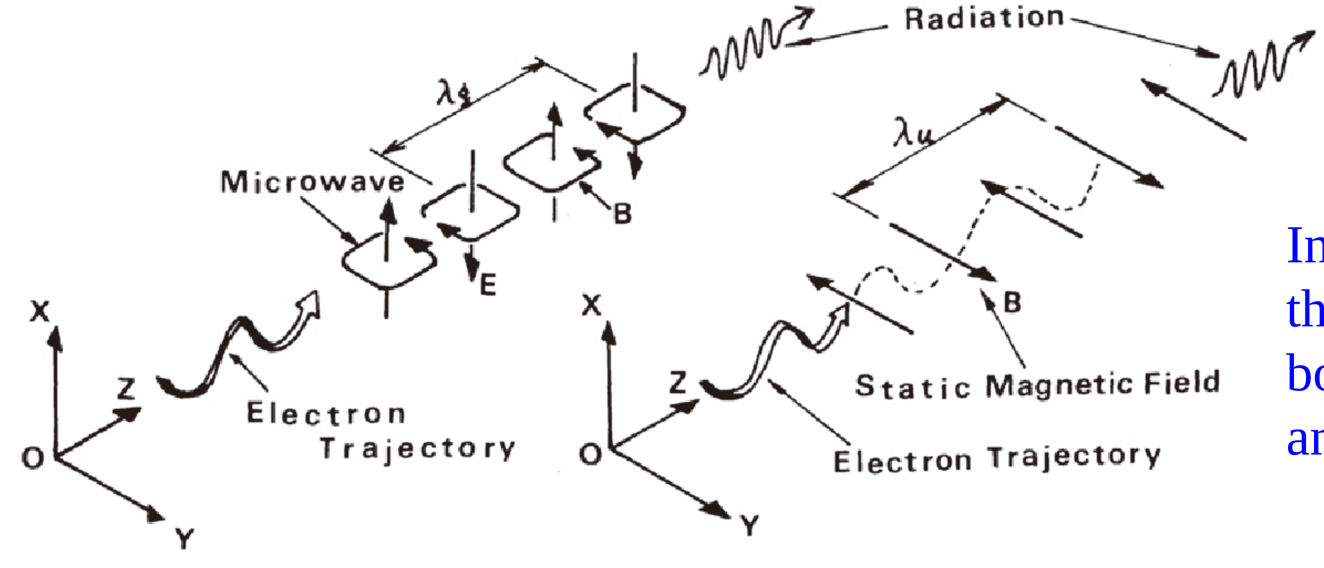
State of the art values are (e.g. PSI Swiss FEL)

$$\lambda_u = 15\text{mm} \qquad K = \frac{|e|\lambda_u B_0}{2\pi mc}$$

PSI undulator gap range can vary between 3mm and 6mm giving a tuning range for *K* of 1.8 to 1.0

Consequently for **λ** =0.1nm, ~10keV $\quad E \sim 6\text{GeV}$

Microwave undulator



(a) Microwave Undulator

(b) Magnetic Undulator

In microwave undulator, the electron bunch sees both the electric field and magnetic field.

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

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

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

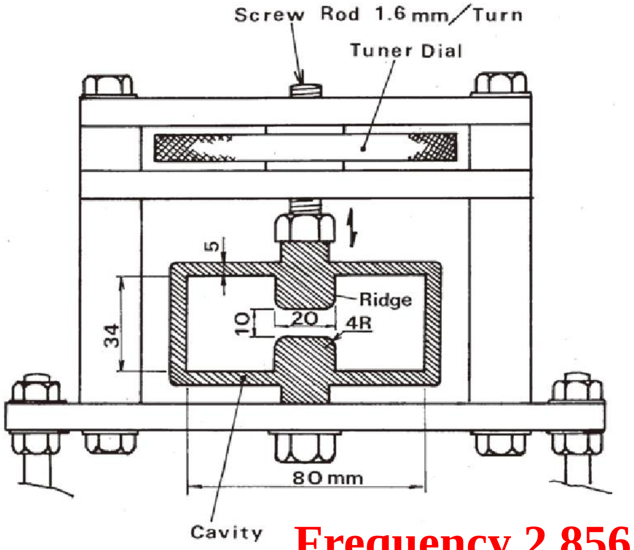
$B_z = B_0 sin(2\pi z/\lambda_u) = B_0 sin(k_u z)$

$F_x = e v_z B_y$

Advantages: (1) Fast dynamic control of polarization; (2) Easy to control the field strength by adjusting the input power; (3) Short wavelength; (4) Large aperture (cm vs mm); (5) Resilient to damage by radiation

Figure source: T. Shintake, Development of Microwave Undulator, 1983

Previous experiments



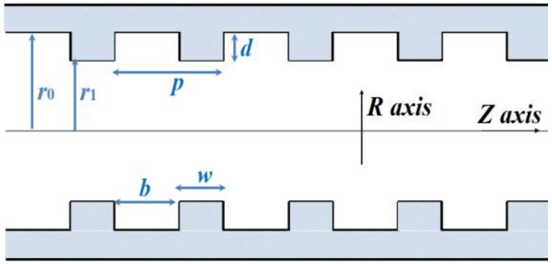
Frequency 2.856 GHz (1983)

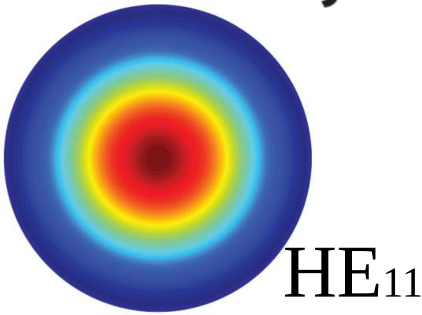
Table II. Measured cavity parameters.

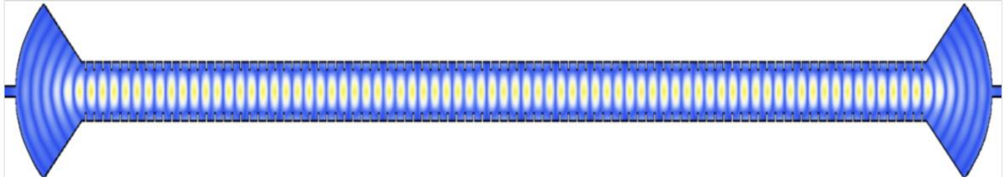
Quality factor	Q_1	7100
Transverse shunt impedance	R_1/Q_1	4.34×10^4 Ω/m
	R_1	308 MΩ/m
Guide wavelength	λ_g	115.56±0.78 mm
Undulator period	λ_u	55.01±0.19 mm

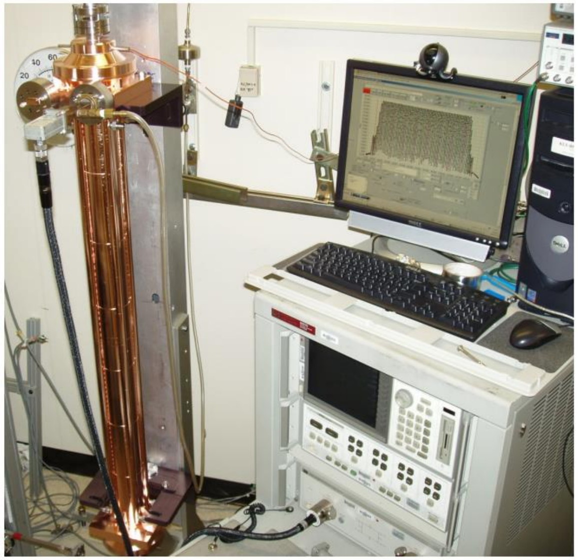
Table IV. Microwave and undulator parameters.

Microwave power	300 kW
Pulse duration	4 μsec
Repetition rate	10 pps
Peak electric field	12.8 MV/m
Equivalent magnetic field	430 Gauss
Undulator period	5.5 cm
K-parameter	0.24









Freq. = 11.424 GHz
K = 1 for 50 MW
Bu = 0.77 T
λu = 1.39 cm
Q = 91000 (meas.)
Q = 94000 (simu.)
Length = 1 meter
(PRL, 2014)

Demonstration experiment at NLCTA, SLAC

Cavity-type MU

(1) **Aiming at Ka-band (36 GHz), to achieve short undulator (~ 4.4 mm) period**

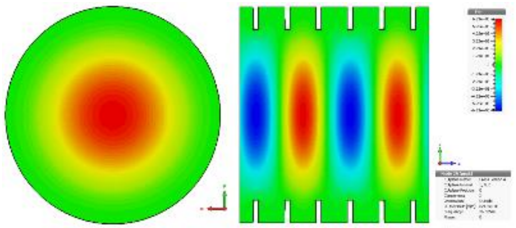
(2) **Low loss HE mode; High field at the cavity center.**

	State-of-the-art μ–wave undulator	**Record breaking μ–wave undulator**	**Dream μ–wave Undulator**
Period (mm)	13.9	13.9	4.4
Beam Aperture (mm)	5.0	5.0	5.0
Peak B Field (T)	0.92	1.62	2.0
K Parameter	1.2	2.1	0.82
Length (m)	4.0	1.0 - 4.0	1.0 – 4.0
Operating frequency (GHz)	11.424	11.424	36
Required microwave power (MW)	152	185 - 464	108 - 272
Required pulse length (us)	5.8	1.4 - 5.7	0.8 - 3.2

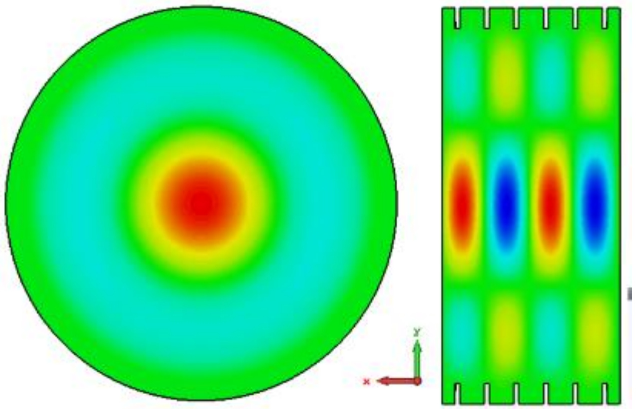
$P \propto L^{2/3}$ $T \propto L$

University of Strathclyde HPM source produced 65MW of power at 36GHz, I.V. Konoplev, A.W. Cross, et al, Appl. Phys. Letts., **92**, 211501, 2008

Cavity design – HE_{11} / HE_{12}



HE11 mode



HE12 mode

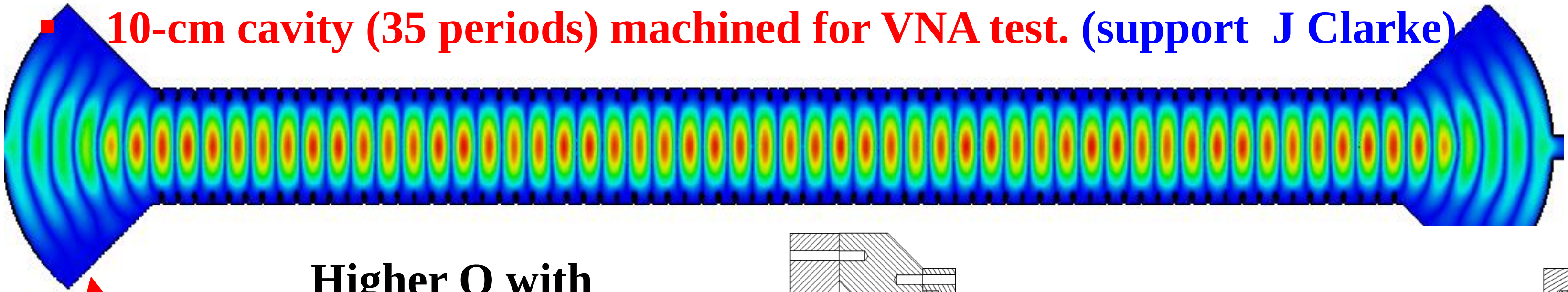
Dimensions calculated using theoretical equations

Operating mode	HE_{11}	HE_{12}
Operating frequency (GHz)	36	36
λ_0 **(mm)**	8.33	8.33
R_b **(mm)**	2.0	2.0
r_1 **(mm)**	$4R_b$=8.0	$9R_b$=18.0
depth $= \lambda_0/4$ **(mm)**	2.1	2.1
λ_g **(mm)**	9.06	9.12
$p = \lambda_g/3$ **(mm)**	3.00	3.02
s (mm)	0.5	0.5
$b = p -$ **s (mm)**	2.50	2.52
Q factor	94,344	187,073
Input power (MW)	50	50
Peak Ex on axis (V/m)	3.8E8	3.7E8
Peak E on wall (V/m)	7.3E6	9.5E6
B_u **(T)**	1.27	1.23
λ_u **(mm)**	4.34	4.35
K_u	0.52	0.50

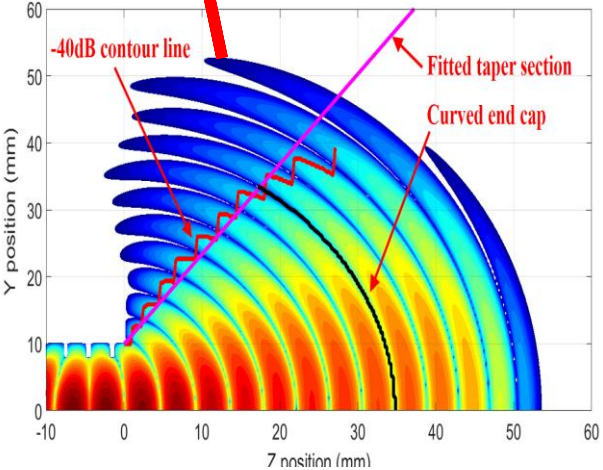
L. Zhang, W. He, J. Clarke, K. Ronald, A.D.R. Phelps and A.W. Cross, "Systematic study of the corrugated waveguide as a microwave undulator", Journal of Synchrotron Radiation, vol. 26, 2018

36 GHz corrugated cavity

- **Taper / Coupler design based on near field radiation pattern for 22-cm cavity (74 periods) (Maintain Q = 89648)**
- **An empirical formula was derived. (Allow scalable design)**
- **10-cm cavity (35 periods) machined for VNA test. (support J Clarke)**

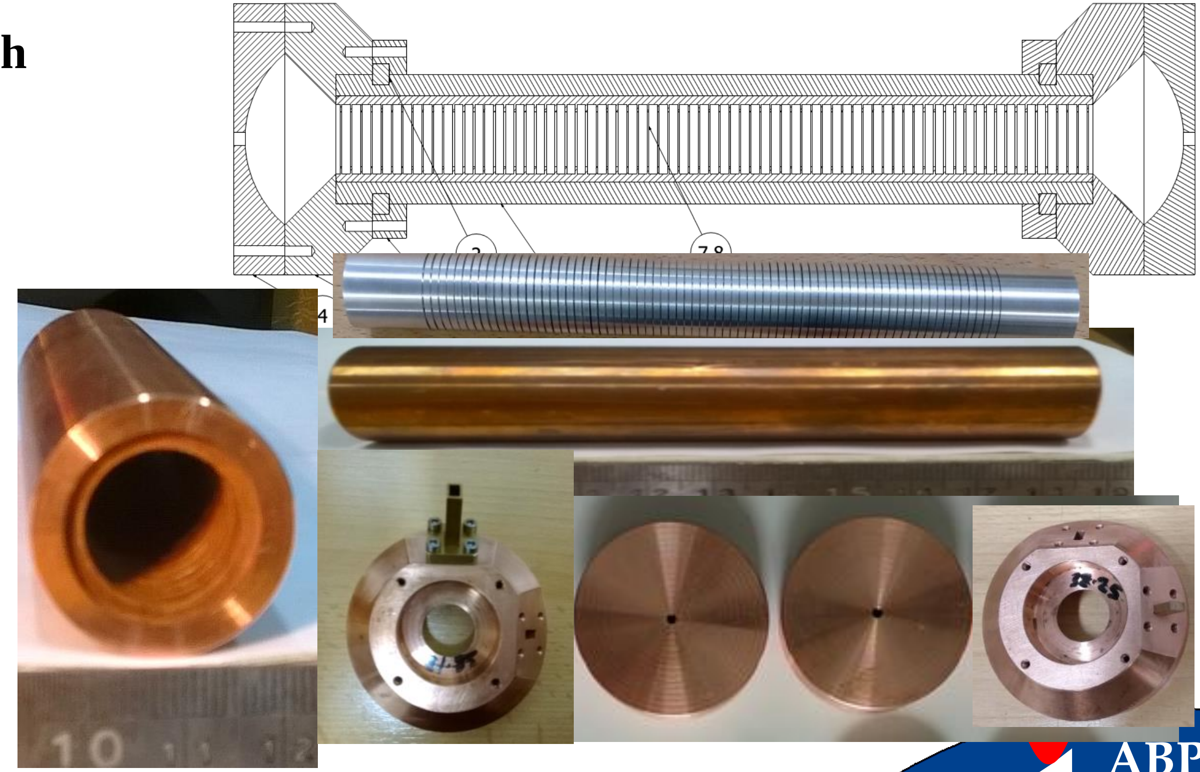


Higher Q with more periods

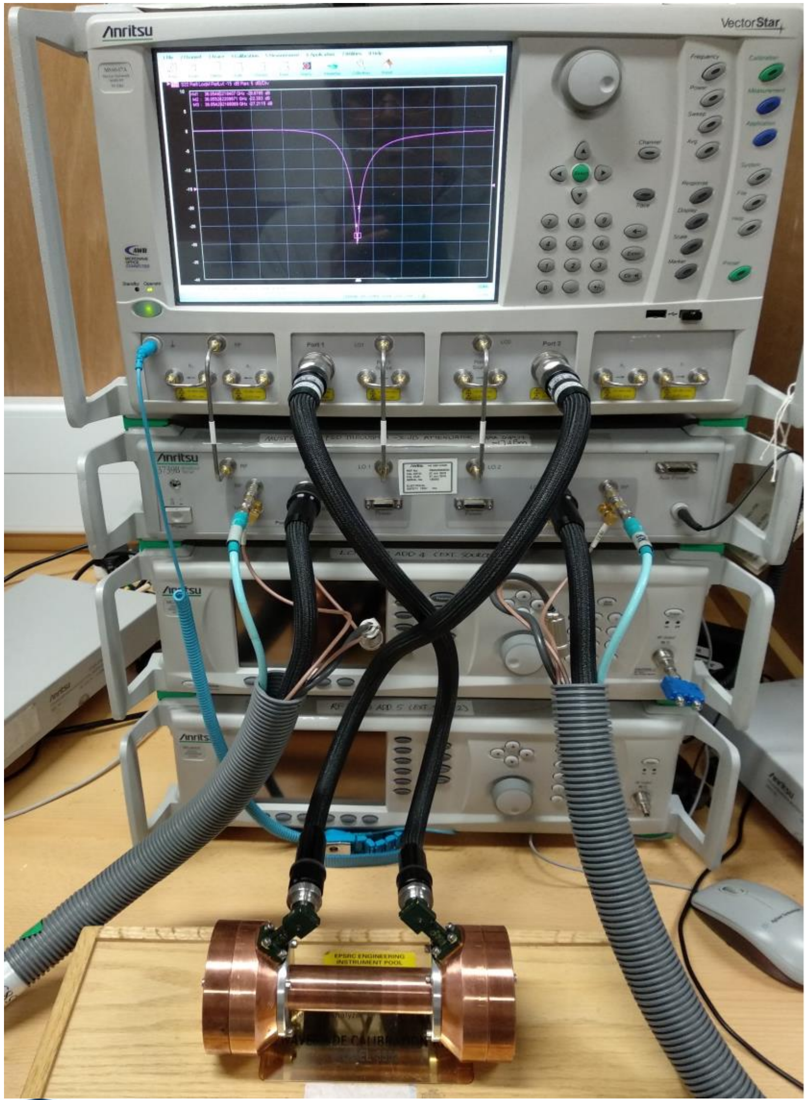


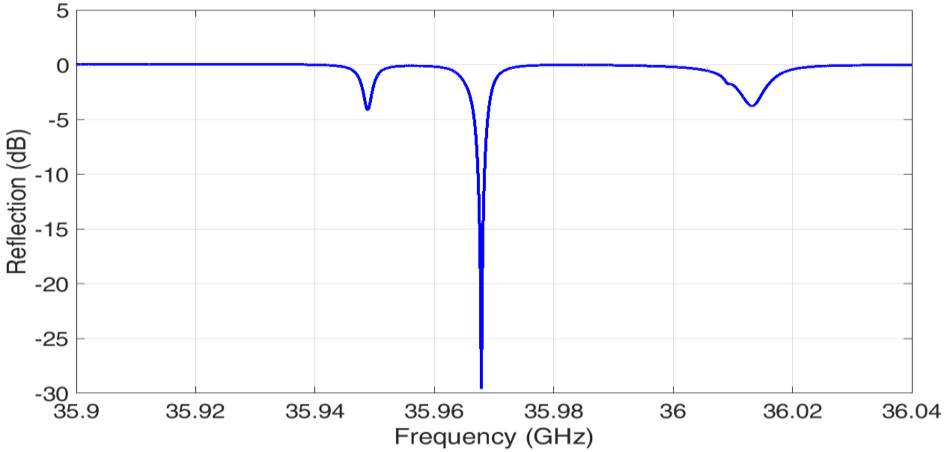
$$L(N) = \frac{\lambda}{2} N\left[1 + F(N)\frac{\lambda_g}{\lambda}\right]$$

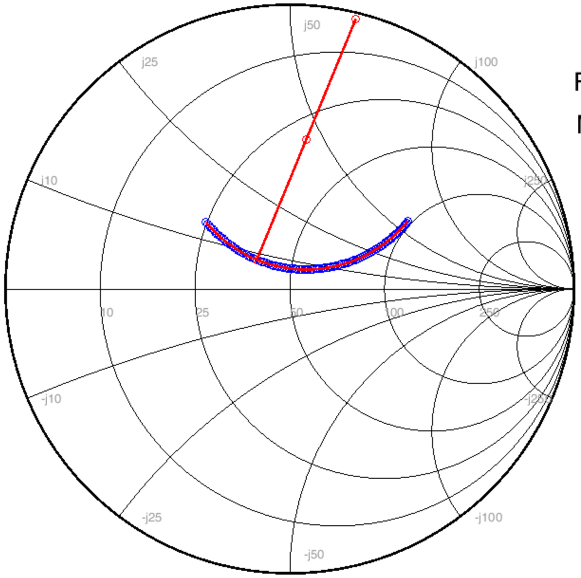
$$F(N) = 0.123e^{-0.213N} + 0.015$$



Measurement results







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Microwve Undulator.txt

Freq= 35.968 GHz

Q_0= 3.406e+04

Q_L= 1.046e+04

κ= 2.256

r_s= 0.51

~40% of the Q_0 compared with simulation due to:

- Surface roughness (need bright dip etching)
- Small gaps at the junctions (brazing)

Principle of “Flying” undulator

Rewrite the motion of the electrons in a cavity-type microwave undulator as

$$\frac{d\boldsymbol{p}_x}{dt} = \frac{eE_0}{2}\left(\frac{\varsigma}{Z_w}+1\right)\cos\left(\omega t+\frac{2\pi z}{\lambda_g}\right)+\frac{eE_0}{2}\left(\frac{\varsigma}{Z_w}-1\right)\cos\left(\omega t-\frac{2\pi z}{\lambda_g}\right)$$

Backward wave

Forward wave

$$B_{ub} = \frac{E_0}{2c}\left(\frac{\varsigma}{Z_w}+1\right)$$

$$\frac{1}{\lambda_{ub}} = \frac{1}{\lambda_0}+\frac{1}{\lambda_g}$$

short wavelength.

$$B_{uf} = \frac{E_0}{2c}\left(\frac{\varsigma}{Z_w}-1\right)$$

$$\frac{1}{\lambda_{uf}} = \frac{1}{\lambda_0}-\frac{1}{\lambda_g}$$

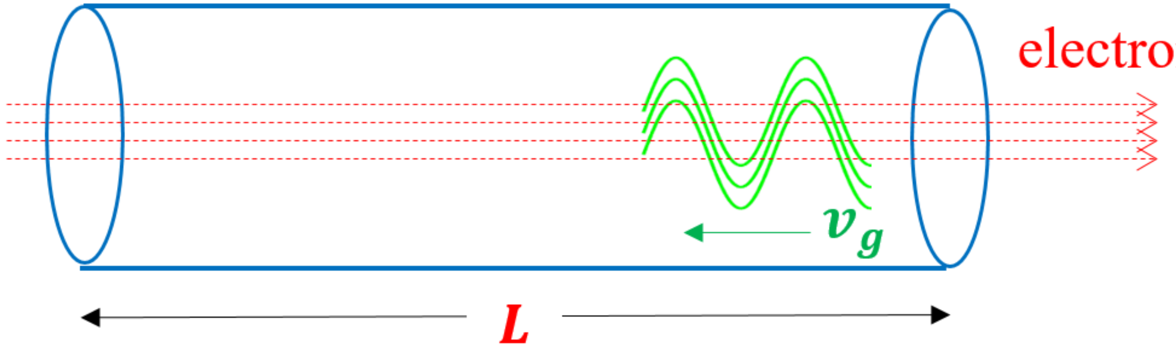
long wavelength.

Usually λ_0 and λ_g are close values, therefore the backward wave is the dominant component. The impact of the forward wave can be minimized to operate the microwave undulator far away from the cutoff frequency.

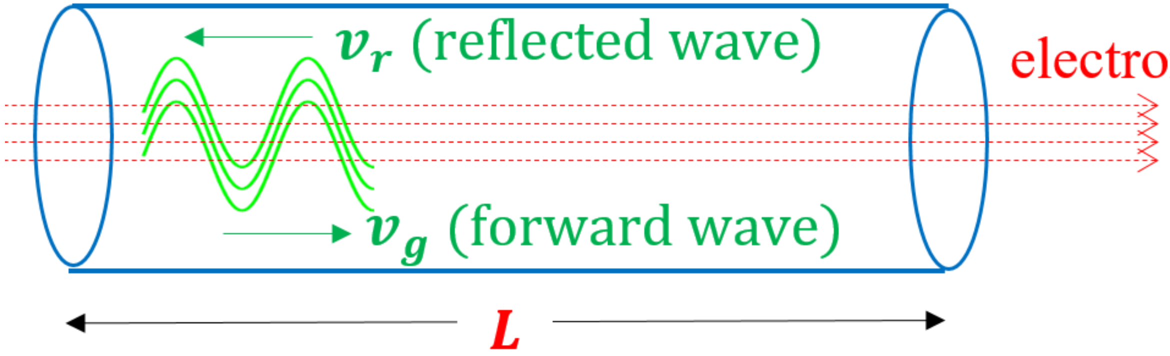
Funded by the European Union

“Flying” undulator

A waveguide can be used as a undulator instead of a cavity structure. The wave can co-propagate or counter-propagate with the electron beam.



$$L_{eff} = \frac{v_{gr}\tau}{1 + v_{gr}/c}$$



$$L_{eff} = \frac{v_{gr}\tau}{1 - v_{gr}/c}$$

A co-propagating wave with backward group velocity has longer effective interaction length.

[1] S. V. Kuzikov, et al., "Flying radio frequency undulator," Appl. Phys. Lett., vol. 105, no. 3, p. 033504, 2014.
[2] S. V. Kuzikov, et al., "Configurations for short period rf undulators," Phys. Rev. S.T., vol. 16, no. 7, p. 070701, 2013.

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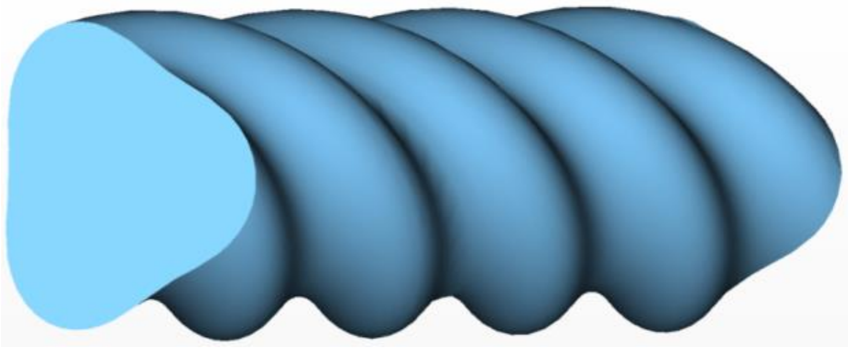
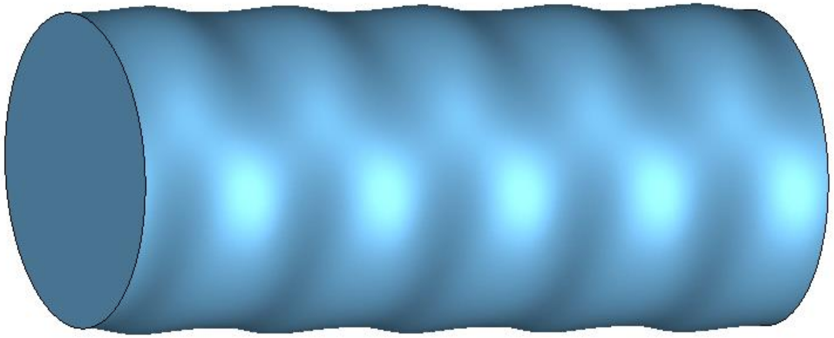
“Flying” undulator

“flying” undulator by helically corrugated waveguide



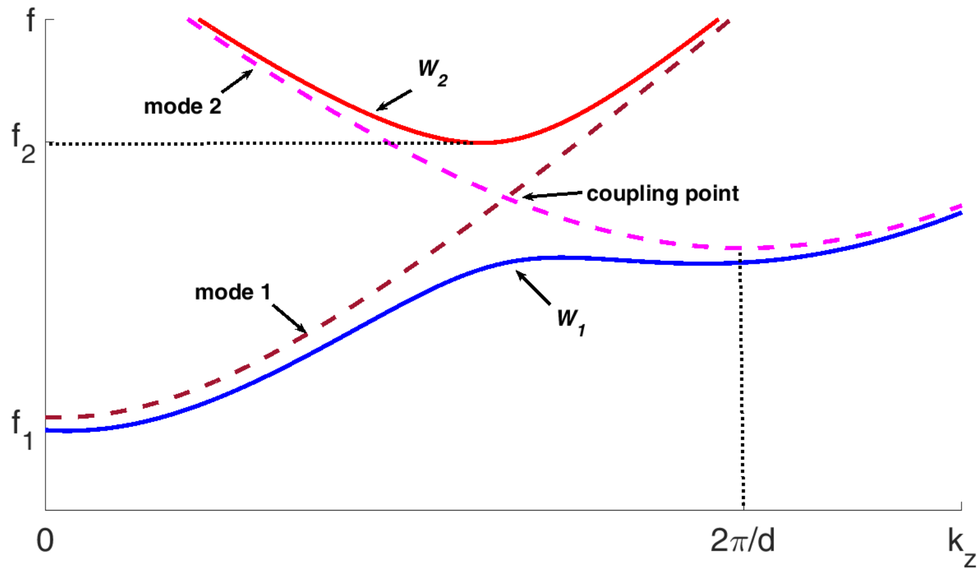
$$r(\theta,z) = R_0 + R_1 cos(m_B\theta + 2\pi z/d)$$

Circular polarization



$$r(\theta,z) = R_0 + R_2 cos(m_B\theta) cos\left(\frac{2\pi z}{d}\right)$$

Linear polarization



The coupling modes 1 and 2 have opposite directions of group velocities.

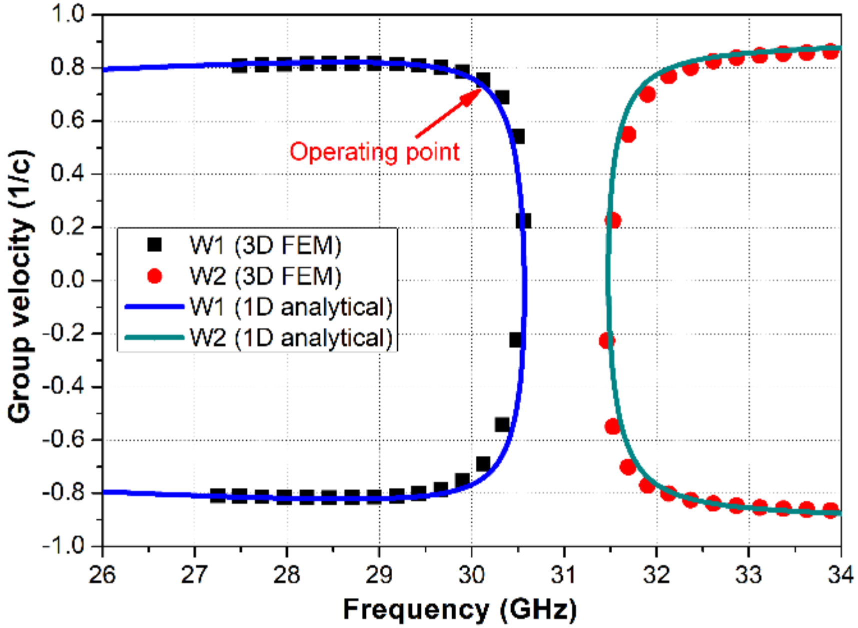
Cavity-type	Flying-type
energy per pulse (~200J)	energy per pulse (~1J)
High power, long pulse microwave source (50 MW, 2 us), PRF (~50Hz)	Ultra high power Short pulse microwave source (1 GW, 1 ns), high PRF 1kHz

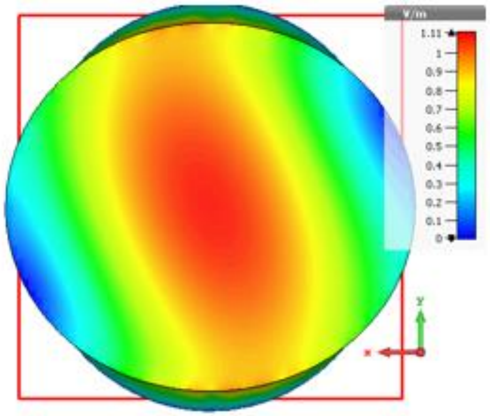
Design of “Flying” undulator

Operating mode: TE_{11} coupled with TE_{11} mode.

Operating frequency: 30.3 GHz

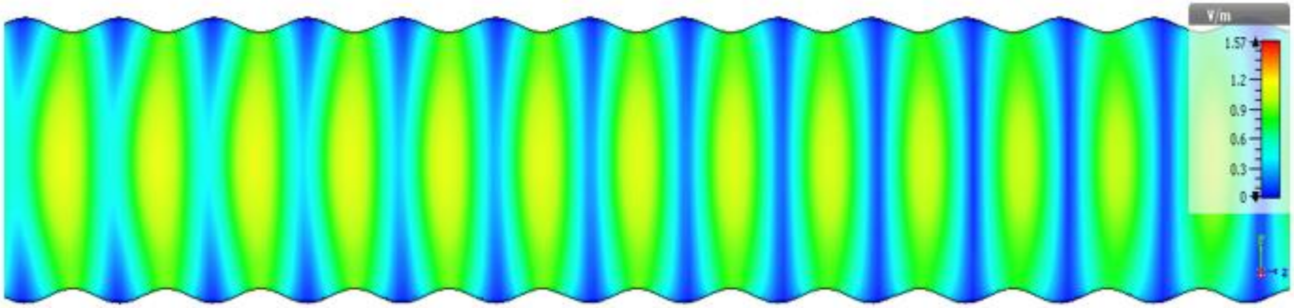
The dimensions are chosen from the dispersion relation of the operating mode.





$$R_0 = 5.8\ \mathrm{mm},$$
$$R_2 = 0.3\ \mathrm{mm},$$
$$d = 5.6\ \mathrm{mm}$$

$$v_g \approx 0.6c$$



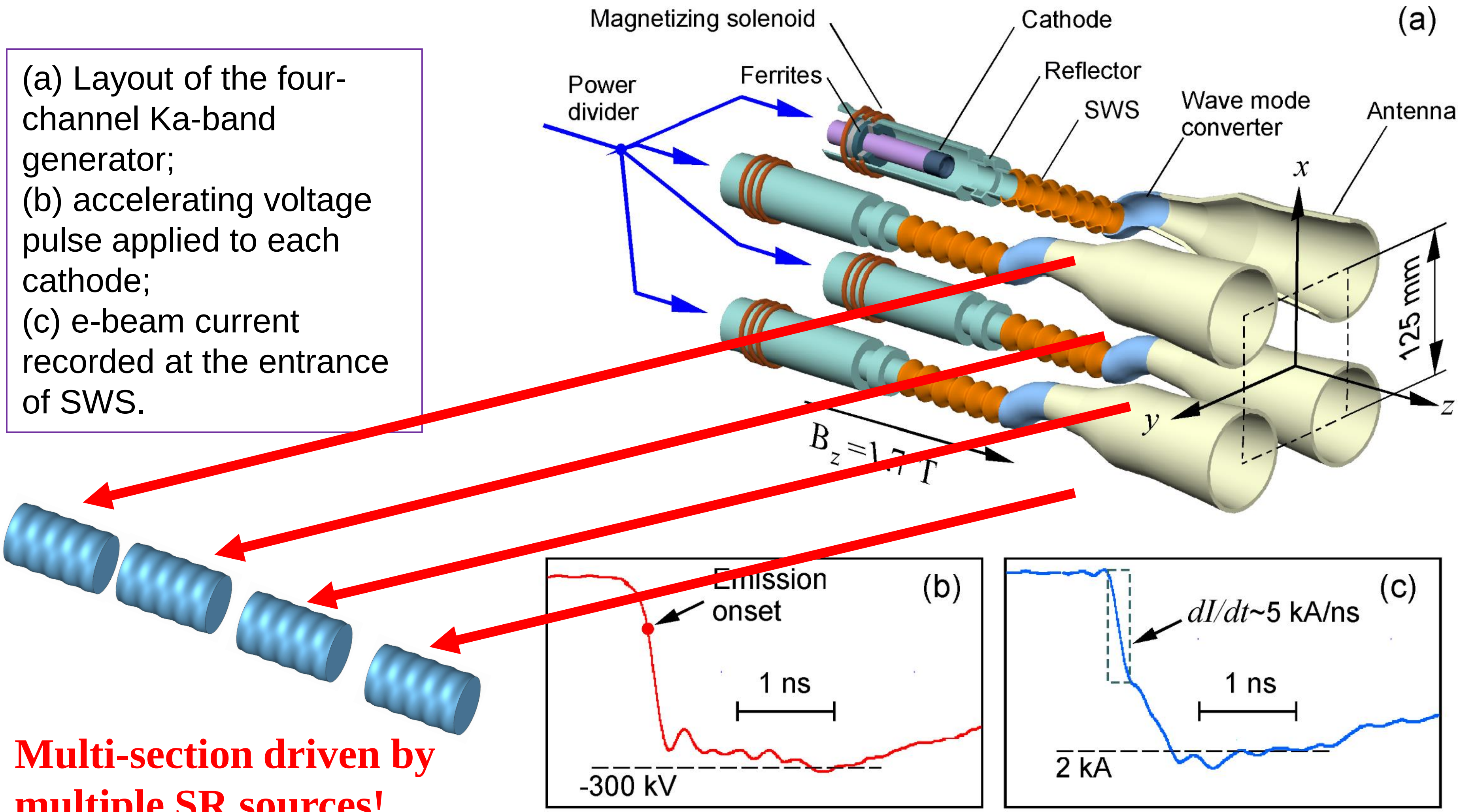
1 GW input power:

$$B_u = 0.3\mathrm{T}$$
$$\lambda_u = 4.95\ \mathrm{mm}$$
$$K = 0.14$$

Possible to be driven by Short pulse BWO (0.6 GW, Ka band)

L. Zhang, W. He, J. Clarke, K. Ronald, A. D. R. Phelps, and A. W. Cross, “Microwave undulator using a helically corrugated waveguide” *IEEE Trans. Electron Device*, vol. 65, no. 12, 2018.

- ☐ Principal scheme of four-channel Ka-band backward wave oscillator. (b) Accelerating voltage pulse applied to each cathode in the experiment. (c) Electron beam current recorded at the entrance of interaction space, corresponding to the cross-section z=3.5 cm

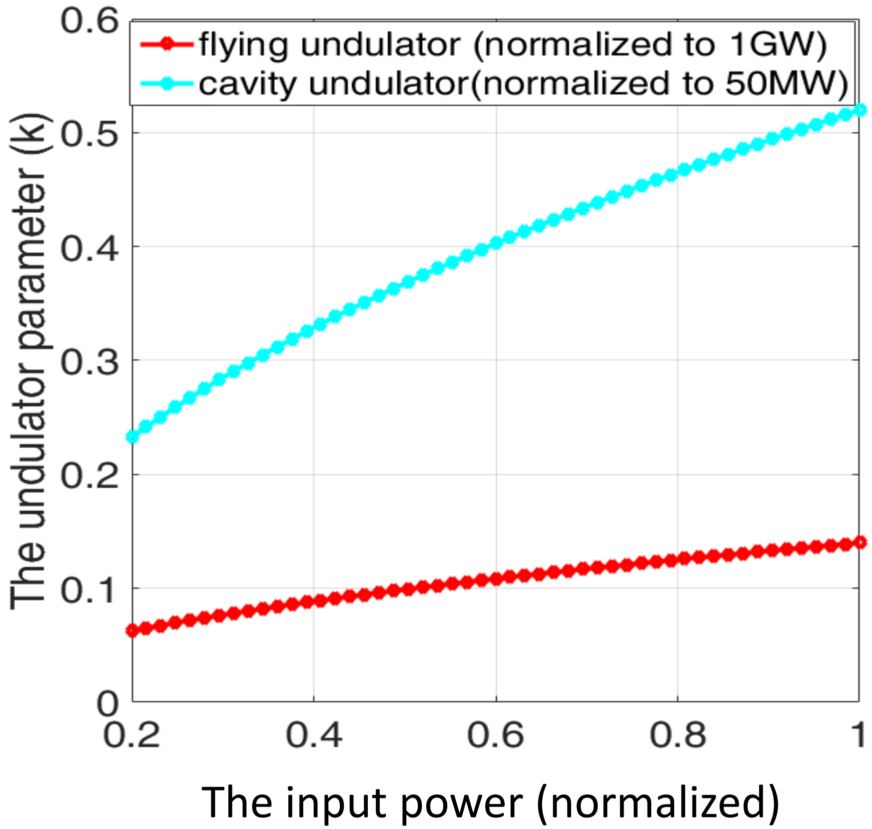


(a) Layout of the four-channel Ka-band generator;
(b) accelerating voltage pulse applied to each cathode;
(c) e-beam current recorded at the entrance of SWS.

Multi-section driven by multiple SR sources!

N. S. Ginzburg, A. W. Cross, et al, Phys. Rev. Lett., Phys. Rev. Lett. 115, 11, 12 p., 114802 (2015)

Summary



Microwave undulator

Advantage:

- Small undulator period (**~4.4mm**) enables high energy X-ray radiation
  - *K* peak value 0.5 for 50MW, 36GHz
  - *K* rms value 0.7 for 100MW, 36GHz

Challenges:

- Cavity undulator has a good undulator strength parameter *K* =0.5 for 50MW undulator of period **~4.4mm**
- Flying undulator has a lower undulator strength parameter *K*=0.14

	Cavity-type undulator	Flying-type undulator
Power supply	High energy per pulse (~200J)	Low energy per pulse (~1J)
Microwave source	High power, long pulse microwave source Co-axial Gyro-klystron or Magnicon (50 MW, 2 us), PRF (~50Hz)	Ultra high power Short pulse microwave source (1 GW, 1 ns), high PRF 1kHz

Conclusion & Future Work

- Two types microwave undulators have been investigated and designed.
- A cavity type microwave undulator has been machined and cold tested using Vector Network Analyser
  - Bead push-pull experiment, Louise Cowie, ASTeC, Daresbury
- Electron beam dynamics are being simulated
  - D. Zhu, Astra for beam dynamics and Spectra for photon output
  - N. Thompson & D. Dunning, ASTRA, Python, Genesis2
- Microwave undulators are at an R&D stage
  - a proof-of-concept experiment is proposed for Cockcroft core grant renewal (2021) using FEBE (0.2GeV or 1GeV) at Daresbury labs

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