WP5: Undulators

Microwave Undulator

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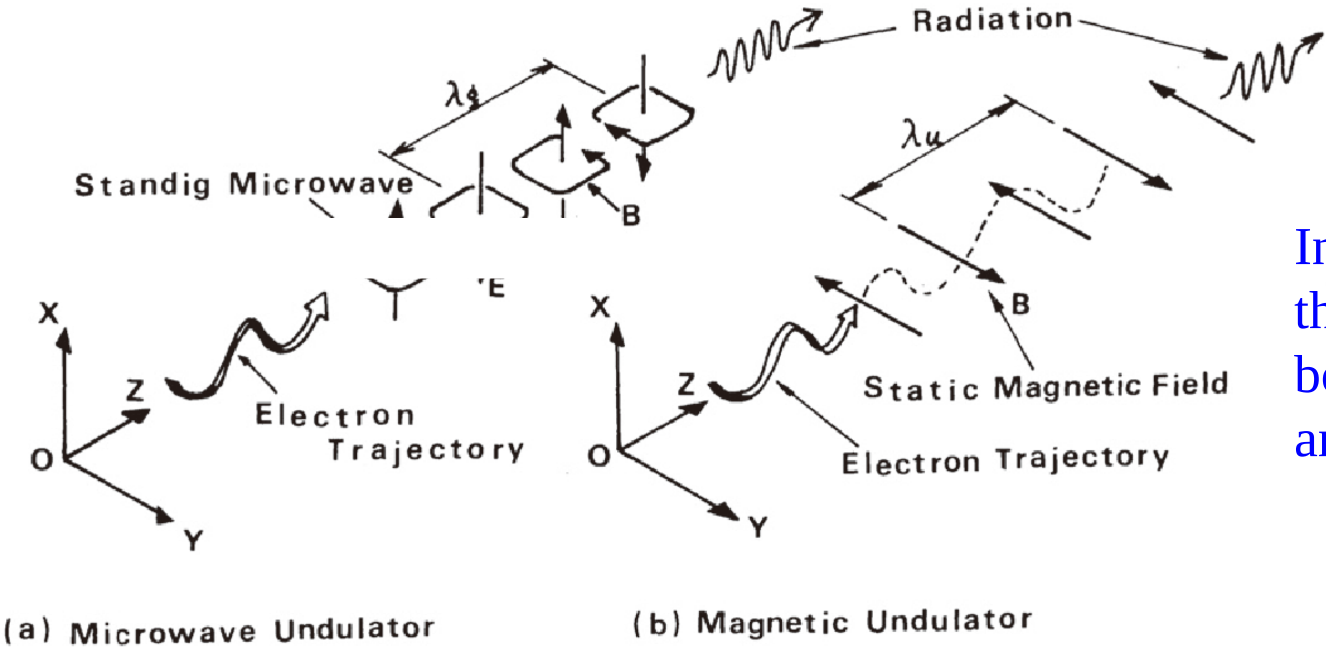
Microwave undulator



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

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

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

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

$B_y = B_0 sin(2\pi z/\lambda_u) = B_0 si\,n(k_u z)$

$F_x = e v_z B_z$

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) Less possibility of damage by radiation as compared with the use of permanent magnets

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

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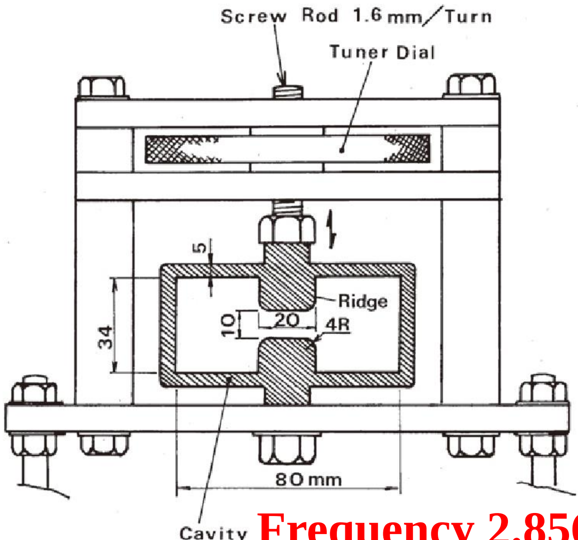
Previous experiments



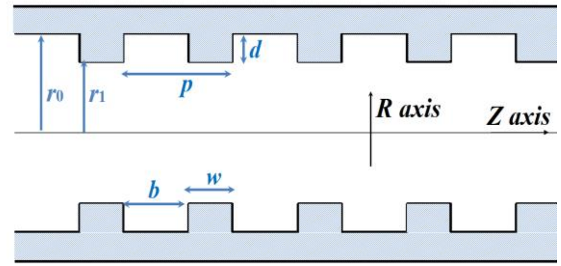
Frequency 2.856 GHz (1983)

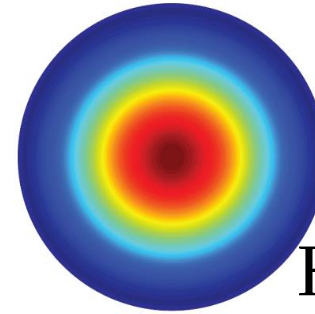
Table II. Measured cavity parameters.

Quality factor	Q_1	7100
Transverse shunt impedance	R_1/Q_1	$4.34 \times 10^4\ \Omega/\mathrm{m}$
	R_1	308 MΩ/m
Guide wavelength	λ_g	115.56 ± 0.78 mm
Undulator period	λ_u	55.01 ± 0.19 mm

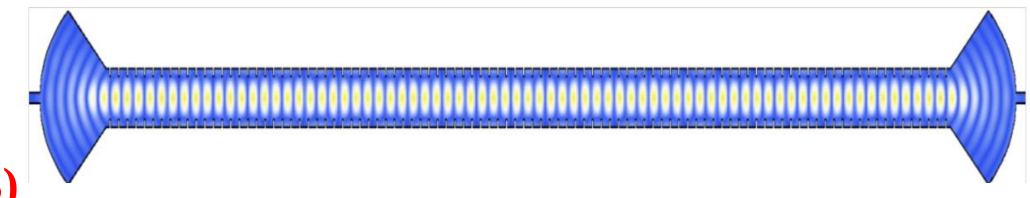
Table IV. Microwave and undulator parameters.

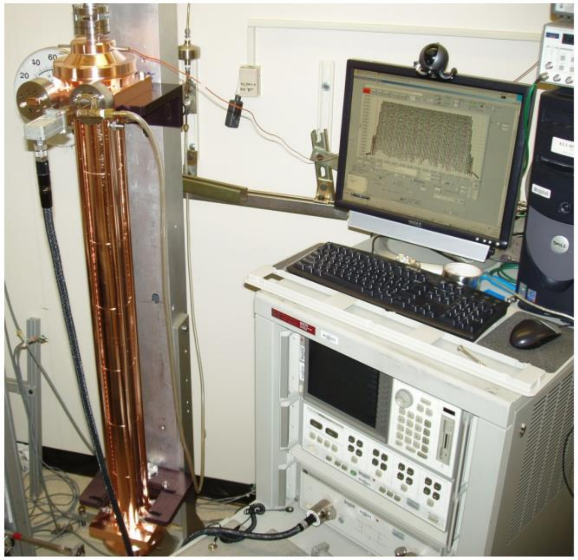
Microwave power	300 kW
Pulse duration	4 μsec
Repetition rate	10 pps
Peak electric field	12.8 MV/m
Equivalent magnetic field	430 Gauss
Undulator period	5.5 cm
K-parameter	0.24





HE$_{11}$





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

What we propose?

Possible improvements:

(1) **Evaluate the possibility to operate at Ka-band, to achieve short wavelength operation**

(2) **Use a corrugated waveguide & further reduce the field at the wall (HE Hybrid mode)**

	State-of-the-art undulator	Record breaking undulator	Dream 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

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

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Corrugated waveguide design

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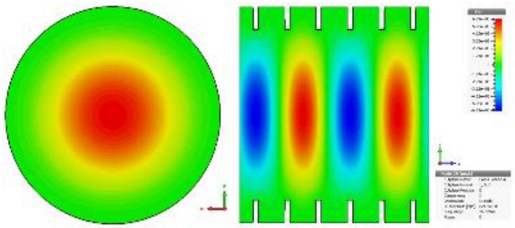
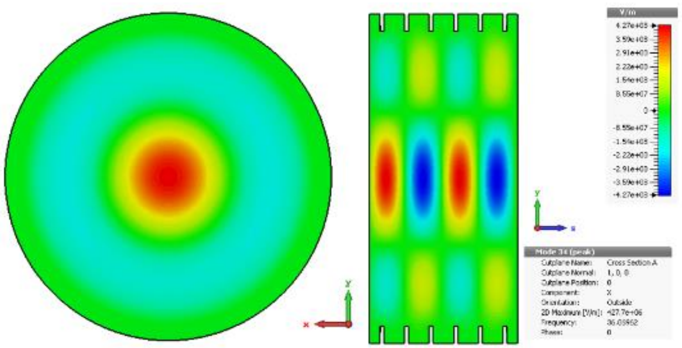


HE11 mode



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, 2019

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36 GHz corrugated cavity

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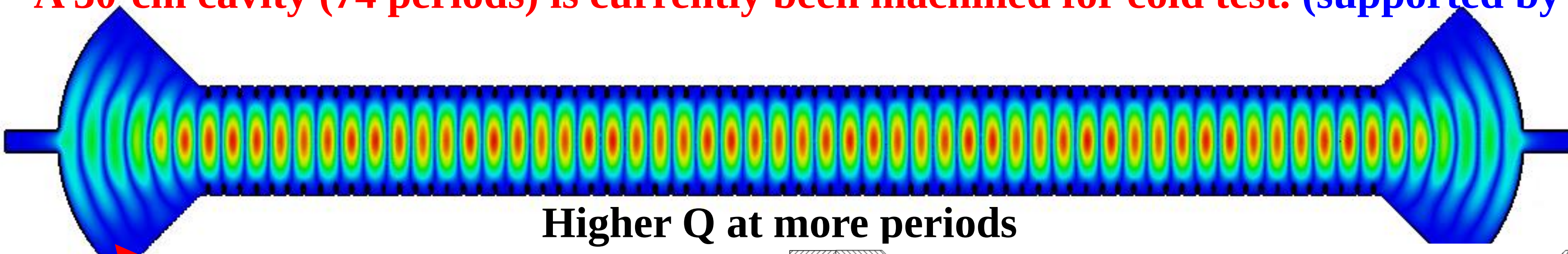
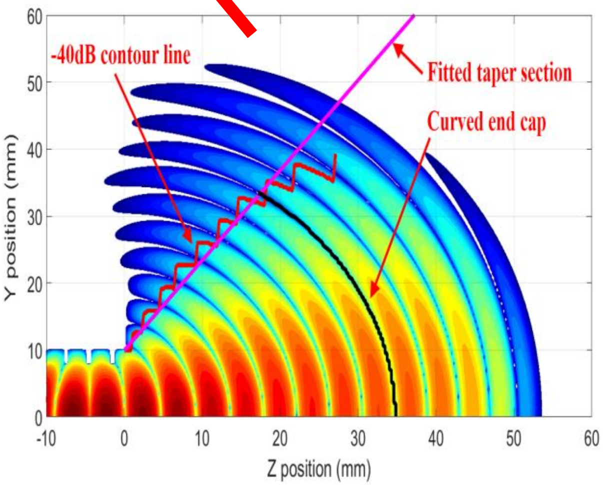
- **Taper / Coupler design based on near field radiation pattern. (Improved Q = 89648)**
- **An empirical formula was derived. (Allow scalable design)**
- **A 30-cm cavity (74 periods) is currently been machined for cold test. (supported by CI)**

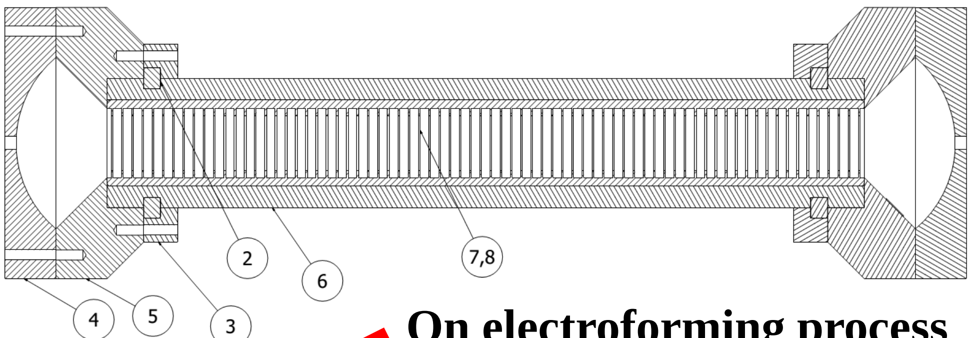


Higher Q at more periods

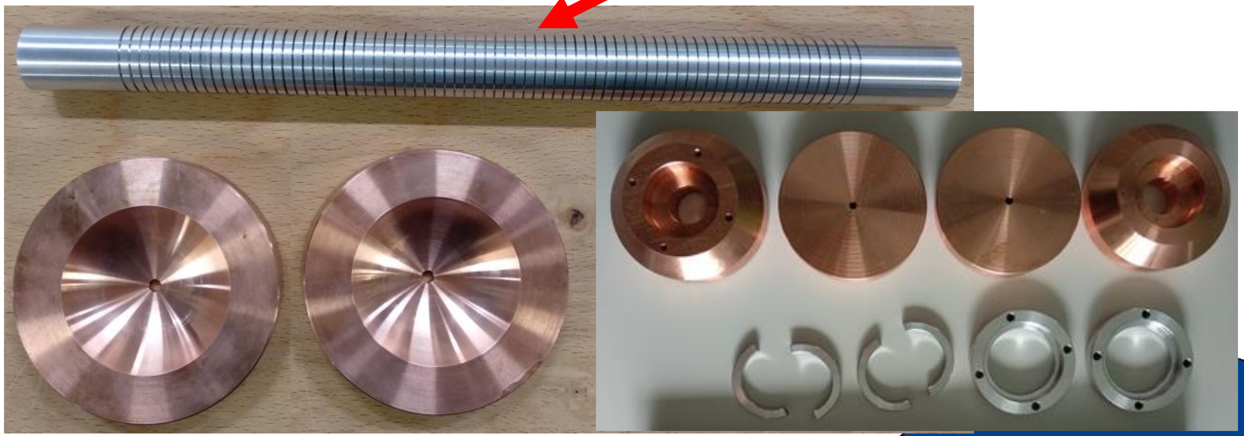


$$L(N) = \frac{\lambda}{2} N\left[1 + F(N)\frac{\lambda_g}{\lambda}\right]$$

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



On electroforming process



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Principle of “Flying” undulator

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

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

Backward 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.

Forward wave

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

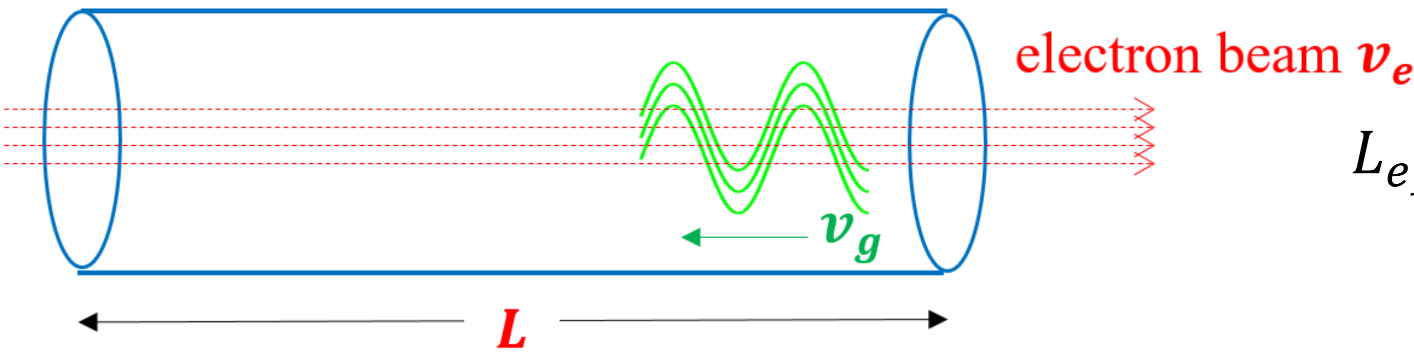
$$\frac{1}{\lambda_{uf}} = \frac{1}{\lambda_0} - \frac{1}{\lambda_g}$$

long wavelength.

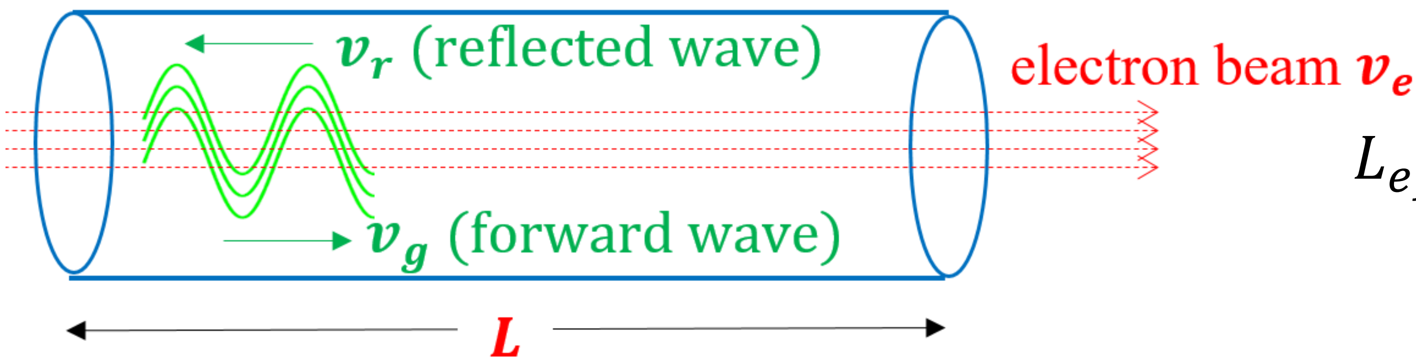
Usually λ_0 and λ_g are close values, therefore the backward wave is the dominant component. The impact of the forward wave can be minimized to operate the microwave undulator far away from the cutoff frequency.

“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.



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



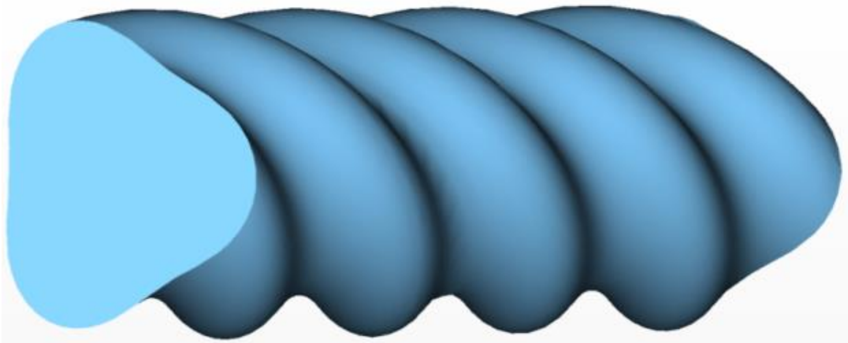
$$L_{eff} = \frac{v_{gr}\tau}{1 - v_{gr}/c}$$

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.

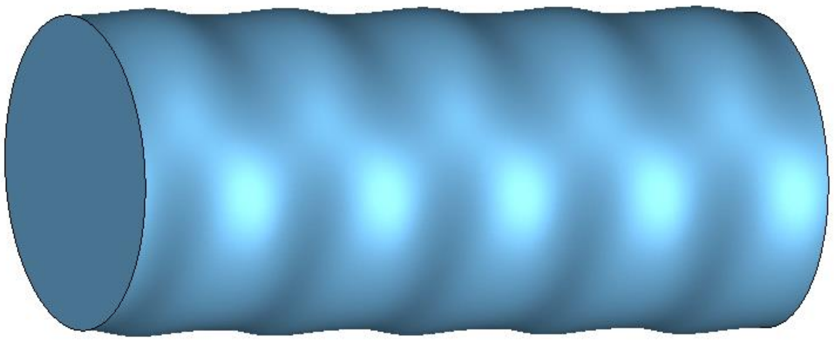
“Flying” undulator

“flying” undulator by helically corrugated waveguide



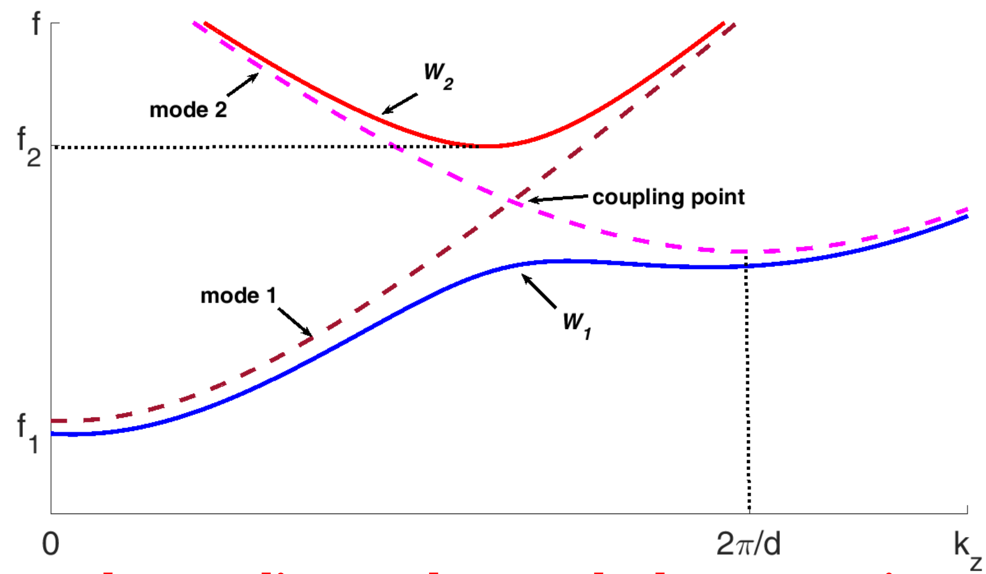
$$r(\theta,z) = R_0 + R_1 cos(m_B\theta + 2\pi z/d)$$

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

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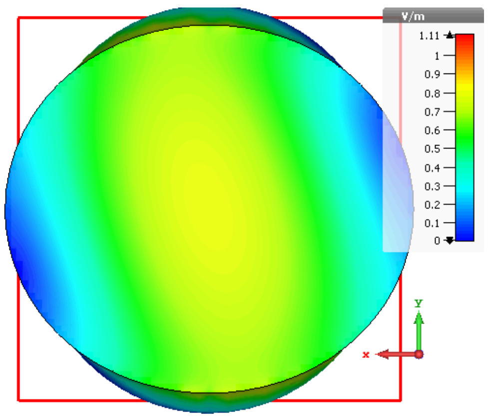
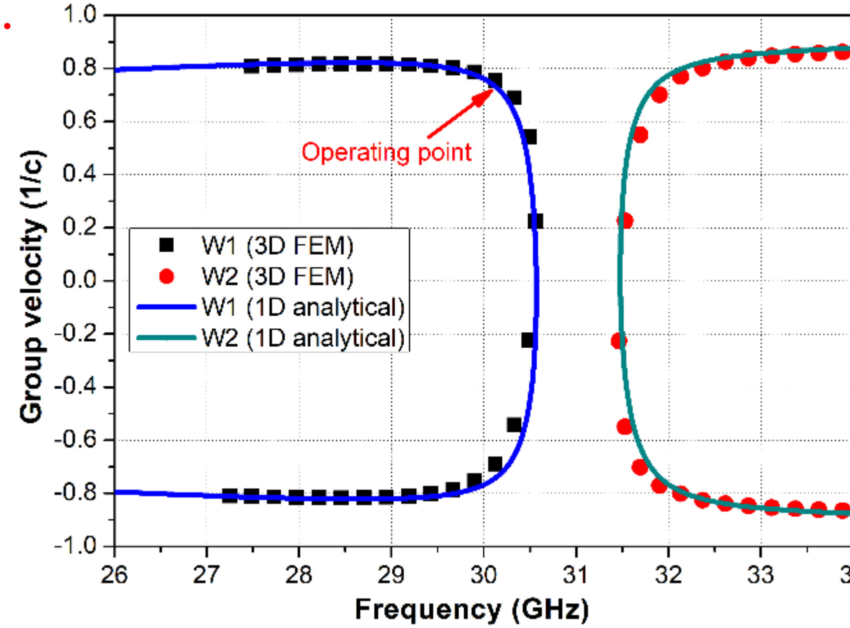
Design of “Flying” undulator

Operating mode: TE11 coupled with TE11 mode.
Operating frequency: 30.3 GHz

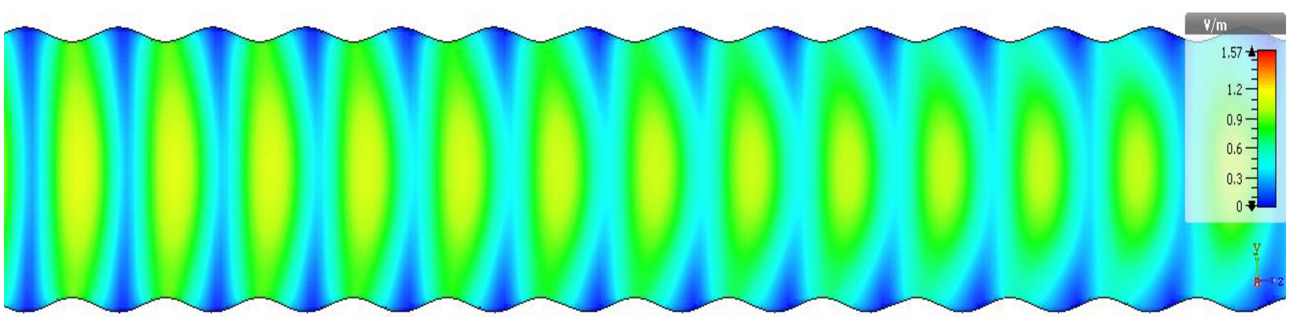
The dimensions are chosen from the dispersion relation of the operating mode.



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



$$v_g \approx 0.6c$$



1 GW input power:

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

It is possible to be driven by SR 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.

Conclusion & Future Work

- Two types microwave undulators have been investigated and designed.
- A cavity type microwave undulator is been machined and will be cold test in the future.
- David Zhu in ANSTO is now simulating the electron beam dynamics.
- The microwave undulators are on R&D stage, a proof-of-concept experiment will be proposed.

Acknowledgements

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