Argonne NATIONAL LABORATORY

Microwave Undulators and Beam Waveguides

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OUTLINE

- Basic elements of microwave undulators
- Beam waveguide as an undulator
- Major issues

EM Fields in a Waveguide in the TE_{01} Mode

$$E_y = E_0 \sin(k_x x)\, e^{-j\beta z}$$

$$H_x = (-\,E_0/Z_g) \sin(k_x x)\, e^{-j\beta z}$$

$$H_z = (j\, E_0/Z_g)\,(k_x/\beta) \cos(k_x x)\, e^{-j\beta z}$$

Where,

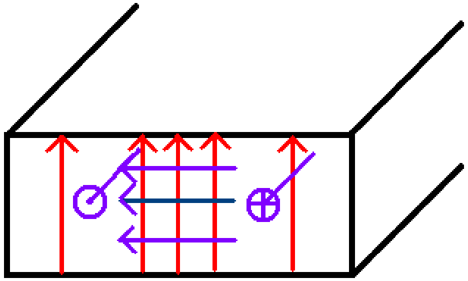
$$\omega = 2\pi f$$

$$k_x = \pi/w$$

w = width of WG

$$\omega^2 \mu_0 \quad \varepsilon_0 = (k_x)^2 + \beta^2$$

$$Z_g = [\omega\mu_0/\beta]$$



E-field in red
H-field in purple
copper walls in black

WAVEGUIDE CUTOFF FREQUENCY AND PHASE PROPAGATION VELOCITY

Cutoff frequency of waveguide below which wave won't propagate:

$$f_c = c/2w ,$$

w is the width of the waveguide and c the speed of light in a vacuum.

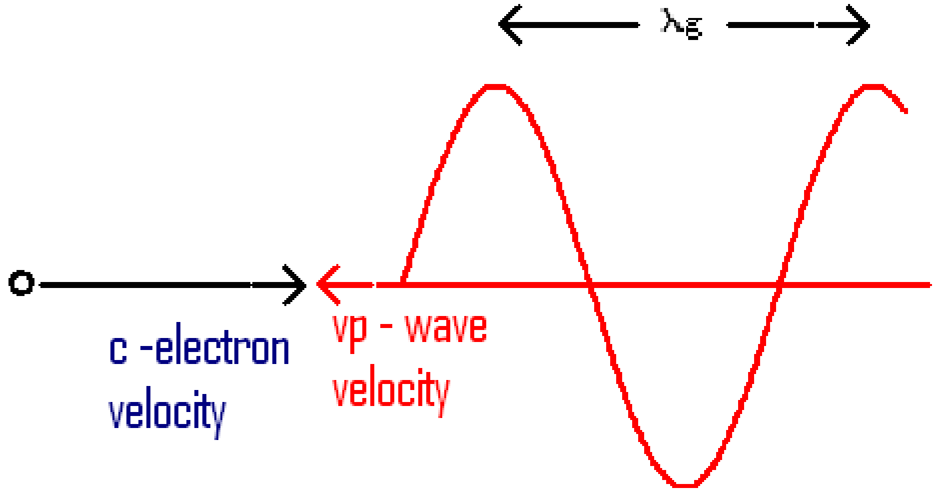
The velocity of the wave front in a vacuum is

$$v_p = c/[1 - (f_c/f)^2]^{1/2}$$

The wavelength of the propagating wave is

$$\lambda_p = v_g/f$$

ELECTRON LAUNCHED AGAINST A TRAVELING WAVE IN A WAVEGUIDE



VERTICAL FORCE ON ELECTRON MOVING IN DIRECTION OPPOSITE TO DIRECTION OF WAVE PROPAGATION AND EFFECTIVE UNDULATOR PERIOD

The time taken for an electron to travel from one wave crest to the next wave crest is

$T = \lambda_g / (c + v_g)$

The distance covered by the electron traveling at the speed of light in the time, T, is the effective undulator wavelength:

$\lambda_u = cT = \lambda_g / (1 + v_g/c)$

The vertical force on the electron at the crest of the wave is

$F_y = qc[E_0/c + \mu_0 E_0/Z_g] = qcB_u$

FORWARD POWER REQUIRED TO GENERATE UNDULATOR FIELD

$$P = (1/2)\int(\mathbf{E} \times \mathbf{H}) \cdot d\mathbf{A}$$

For a waveguide of width, w, and height, h, the power required from the microwave source is

$$P = (1/4)[(E_0^2)/Z_g]hw$$

EXAMPLE OF MICROWAVE UNDULATOR USING A STANDARD TE_{01} WAVEGUIDE

- From Kenneth Batchelor, Proceedings of the Linear Accelerator Conference, 1986

Waveguide Width	2.0 cm
Waveguide Height	1.0 cm
Operating Frequency	15 GHz
Undulator Length	1.0 m
λ_g	2.31 cm
λ_u	1.07 cm
Peak Electric Field Strength	15 MV/m
Microwave Power	3.99 MW*
Equivalent Undulator Field	0.466 T

*Batchelor's concept used a standing wave cavity, 1-m long with a 367-KW source

ISSUES RELATED TO MICROWAVE UNDULATORS

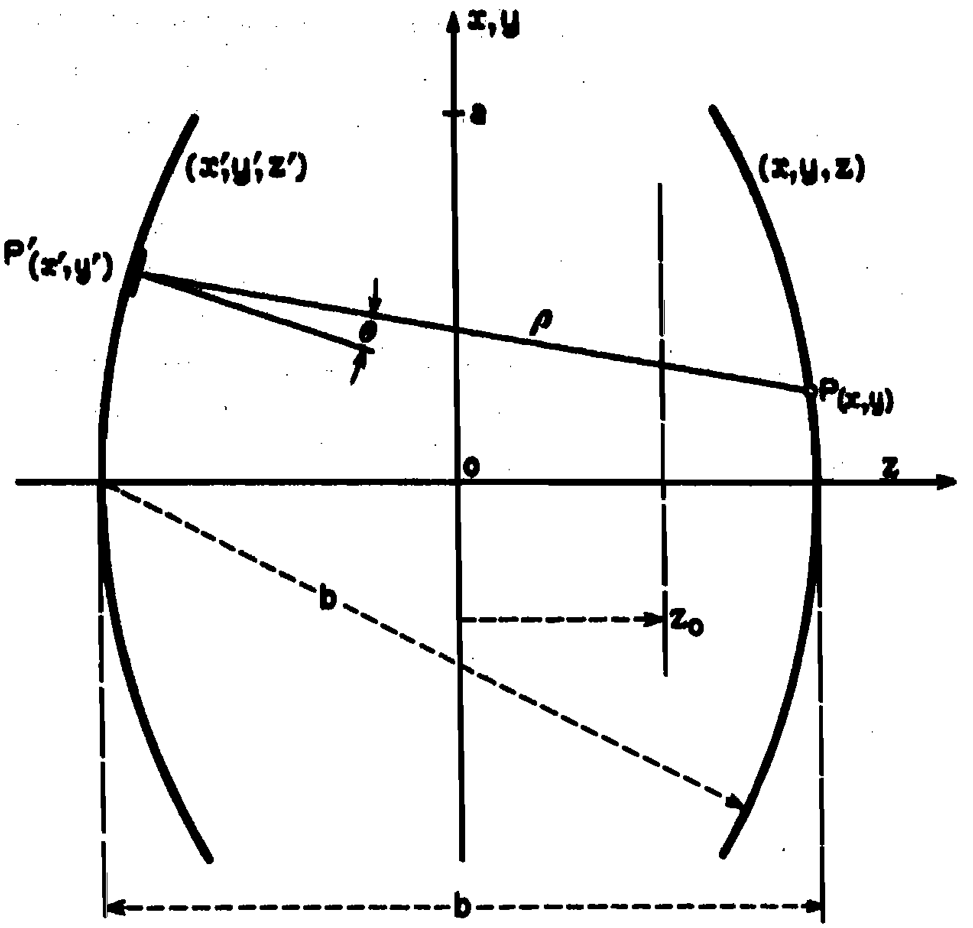
Aperture:

- Generally the waveguide dimensions for short period undulators are too small for storage rings when operating in a standard TE_{01} mode
- Wider aperture lowers the cutoff frequencies for lower TE_{0n} modes where n denotes $\sin(n\pi x/w)$. This requires stabilizing the guide against degenerate modes developing.

Microwave Power Source

- Power sources delivering tens of megawatts, even in pulsed mode, don't exist at frequencies around 20-30 GHz and above. Must resort to using a resonant system, such as a standing wave structure, having both forward and backward waves, leading to two radiation wavelengths. A standing wave structure can also have multiple modes, and different energy x-ray sources.
- The wider aperture requires more power for a given undulator strength.
- Operation in a resonant system, such as in the standing wave cavity, can interact with the circulating beam causing beam growth or instabilities.

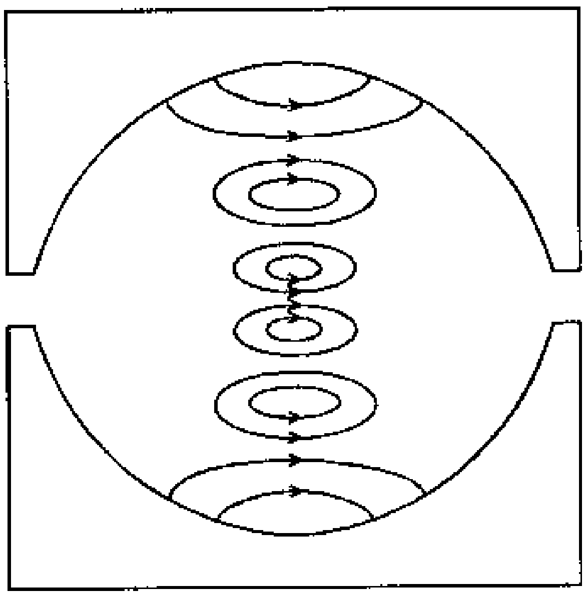
MICROWAVE BEAM WAVEGUIDE GEOMETRY



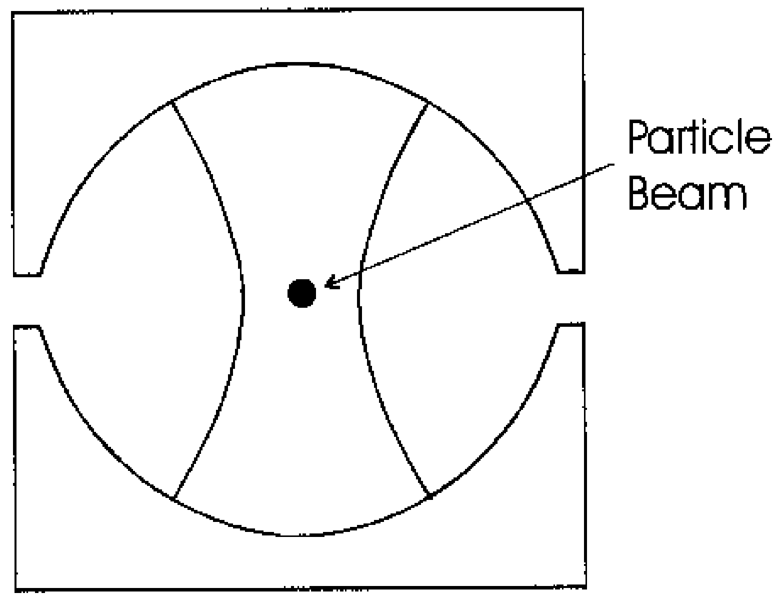
HISTORICAL REFERENCES TO BEAM WAVE-GUIDE DEVELOPMENT

- Beam waveguide concept proposed by Goubau and Schwering, “On the Guided Propagation of Electromagnetic Wave Beams”, IRE Transactions on Antennas and Propagation”, Vol. AP-9, May, 1961
- Modes and attenuation calculations were confirmed on a 9.5-GHz model section of a beam waveguide by Nakahara and Kurauchi, “Guided Beam Waves Between Parallel Concave Reflectors”, IEEE Transactions on Microwave Theory and Techniques, MTT-18, No. 2, February, 1967.

ELECTRIC FIELD PATTERNS FOR A BEAM WAVEGUIDE



Electric Field of TE_{mn} mode
m=5, n=0
(a)

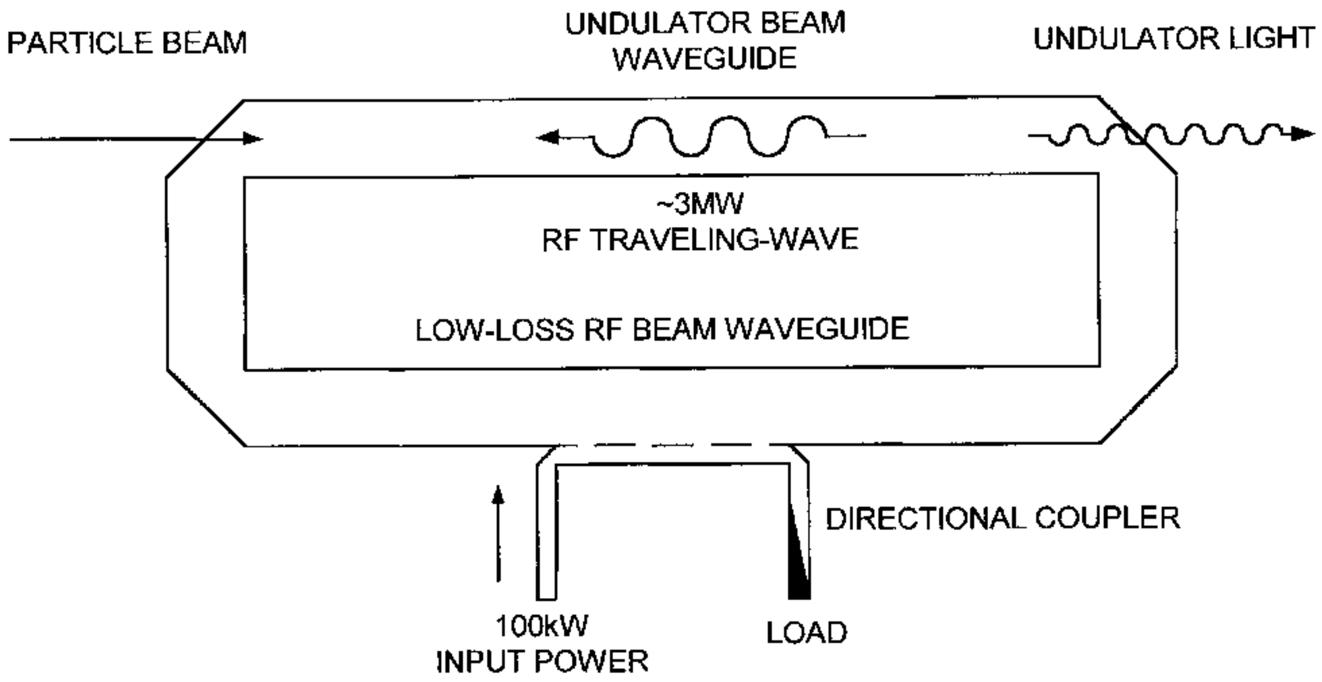


Gaussian RF Beam Envelope
(b)

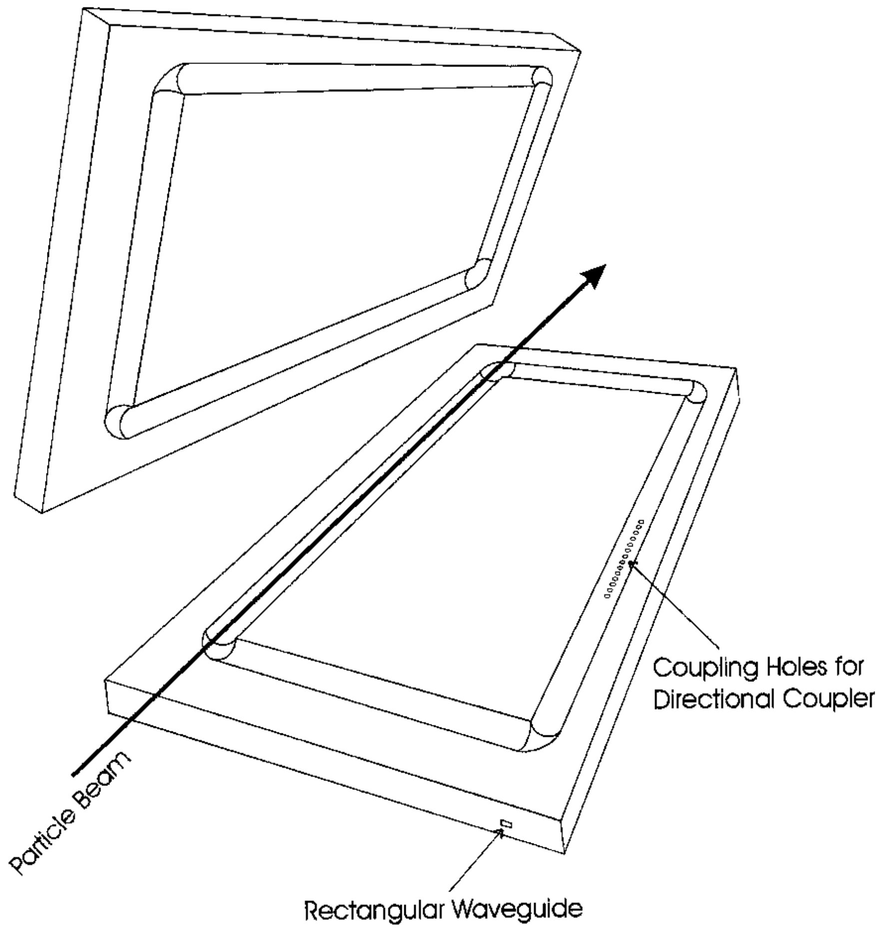
POTENTIAL ADVANTAGES OF A BEAM WAVEGUIDE AS AN UNDULATOR

- The aperture better matches the beam requirements
- Because the microwave field is higher near the center of the structure and lower near the walls, the microwave power required for a given deflecting field is less than a standard TE_{0n} waveguide.
- The heat load is distributed over a larger area making the cooling easier.

SCHEMATIC VIEW OF A MICROWAVE BEAM WAVEGUIDE UNDULATOR IN A RESONANT RING CONFIGURATION



PROPOSED CONCEPT FOR CONSTRUCTION OF A BEAM WAVEGUIDE/RING RESONATOR UNDULATOR



PARAMETERS FOR A BEAM WAVEGUIDE MICROWAVE UNDULATOR

Operating frequency	34 GHz
Operating mode	TE_{70}
Reflector focal length	6.0 cm
Distance between deflectors	10.0 cm
Length of beam waveguide	1.8 m
Directional coupler coupling	-15 dB
Undulator period	0.45 cm
Equivalent undulator field, 625 KW	0.25 T

From Elliptical Beam Waveguide program by Y. W. Kang currently at SNS, Oak Ridge National Laboratory

BRIGHTNESS OF 115-KeV X-RAYS FROM A MICROWAVE BEAM WAVEGUIDE UNDULATOR WITH λ_u = 0.45 cm*

B [Tesla]	Peak Brightness [Photons/(mm-mrad)^2 /sec/0.1%BW]
0.125	6×10^{16}
0.25	2×10^{17}
0.5	1×10^{18}

A superconducting undulator with a 1.6-cm period, 2.4-m long, and a maximum 1.3-T B_u , can deliver a brightness of about 6×10^{16} and achieve continuous tuning from about 10-KeV.

* Based on APS beam parameters:
7-GeV,100-ma, σ_x = 0.342-mm, σ_y = 0.091-mm, σ'_x = 24-μrad, σ'_y = 9-μrad

FIELD TOLERANCES FOR X-RAY BRILLIANCE CALCULATIONS

- A $\pm$2-mm region exists over which the field variation is within 0.5%.
- The vertical region over which the field variation is 0.5% is $\pm$1.8-mm.
- The field variation over the 1.8-m length in the electron beam direction is better than 0.1%.

MICROWAVE POWER SOURCE CONSIDERATIONS

- CPI Communication &Power Industries has designed a CW gyro-klystron that can deliver 400-KW near the desired frequency and they have a catalog tube that operates at 28-GHz and 200-KW CW (VGA8000)
- Toshiba offers a 28-GHz, 500KW CW gyrotron (E3955SU)
- These power tubes might not have the stability required for an undulator.

R&D ISSUES RELATED TO THE MICROWAVE BEAM WAVEGUIDE UNDULATOR

- For the ring resonator to achieve high power gain as predicted, corner reflectors must efficiently transmit the wave in forward direction around the ring with very small leakage and reflection.
- Tolerances need to be analyzed.
- Higher Order and Lower Order Modes can be excited in the structure and they need to be analyzed in detail to see how effectively they can be extracted and damped through the gaps between the reflecting guide sheets.
- Beam interaction with the microwave beam waveguide needs to be studied in detail.

Summary

- Microwave waveguides can in principle be used for undulators with periods less than 1-cm that are capable of generating x-rays greater than 100-110 KeV on the first harmonic.
- However, the present level of development is not more than at the concept stage, and considerable R&D would be needed to establish their full capability.
- 1.2 to 1.6-cm period superconducting undulator working on the 5th harmonic would be able to achieve most, if not all, of what a microwave undulator can do. However, a superconducting undulator of this capability will also need significant R&D.