Waveguide DC Breaks with Optimized Impedance Matching Networks

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88-Inch Cyclotron Overview

Heavy Ions, Low Energy Protons, Microbeam

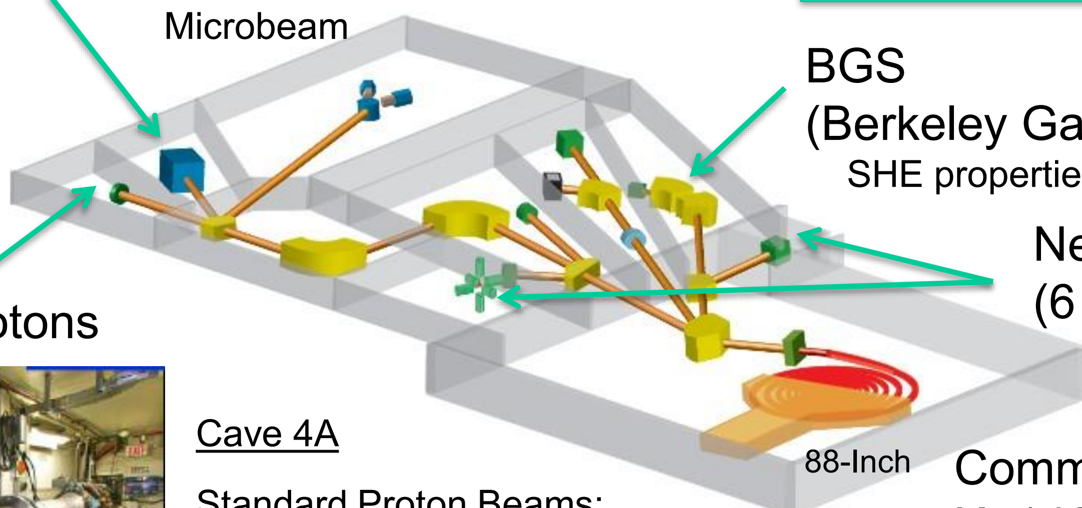
Cave 4B

Standard Cocktail Beams:
4.5, 10, 16, and 20 AMeV

Low Energy Protons:
1-10 MeV

One-stop facility for radiation effects testing*:
- Heavy Ions
- Light Ions
- Protons
- Low Energy Protons
- Neutrons
- Microbeams

Microbeam



BGS
(Berkeley Gas-filled Separator)
SHE properties

Neutrons
(6 to 30 MeV)
Cave 0

88-Inch

Commissioned in 1962
K=140, Accelerate H→U

Light Ions, Protons

Cave 4A

Standard Proton Beams:
13.5, 20, 30, 40, 50, 55 MeV

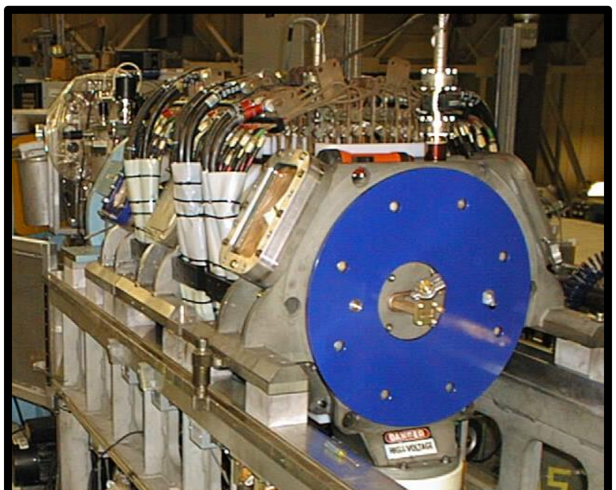
Light Ion Cocktails:
30 and 32.5 AMeV

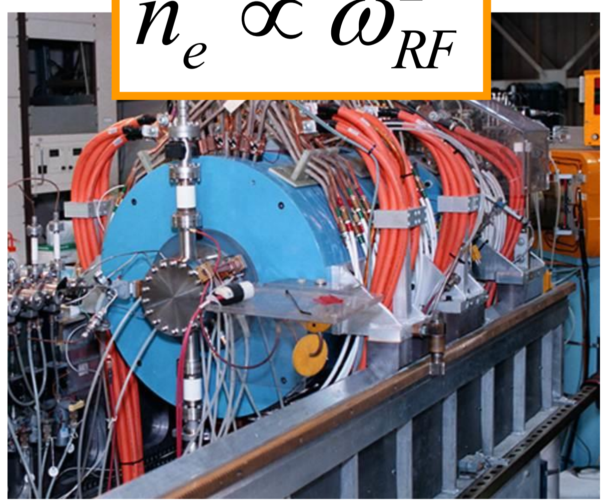
* M. Kireeff Covo et al., "The 88-Inch Cyclotron: A one-stop facility for electronics radiation and detector testing", Measurement 127 (2018) 580, https://doi.org/10.1016/j.measurement.2017.10.018.

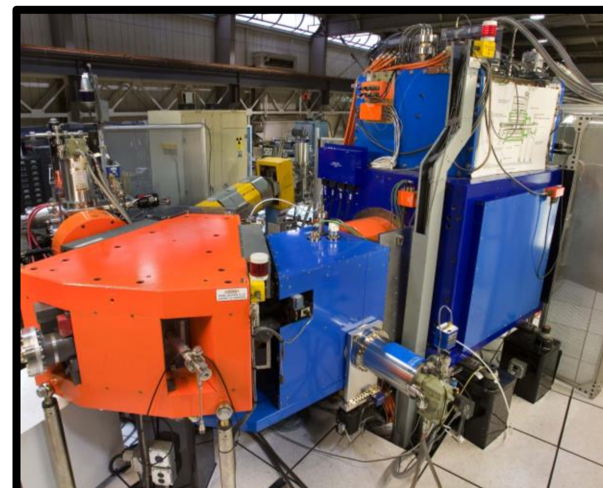
ECRIS Generations

ECR	AECR	VENUS
1983	1990, 1996 upgraded	2004, 2008 for operations
Max B-Field: 0.4 T	Max B-Field: 1.7 T	Max B-Field: 4.0 T (superconducting)
Freq: 6.4 GHz	Freq: 10.8-12.8*, 14 GHz	Freq: 18, 28 GHz
Max Power: 2.5 kW	Max Power: 5 kW	Max Power: 15 kW

$$n_e \propto \omega_{RF}^2$$







* M. Kireeff Covo et al, EEE Trans. on Plasma Sci. 39 (2011) 1455.

RF System Configurations

1. The ion source is mounted on a high-voltage platform along with the RF system, which:
   - Requires a HV isolation transformer,
   - Limits access to the RF system for troubleshooting,
   - Increases the risk of damage to control electronics during breakdowns.

2. The RF System is maintained at ground potential, which:
   - Requires a HV DC break and a tuner for the disconinuity,
   - Allows access to the RF system for troubleshooting,
   - Protects control electronics from damage during breakdowns.

A DC break is a device designed to transmit RF signals with minimal losses and leakage, while simultaneously providing DC isolation from the ECR platform.

Types of Waveguide DC Breaks

1. Choke Flange

   It typically create a discontinuity in the waveguide through the insertion of dielectric.

2. Multi-layer

   It employs several layers of insulating materials between metal sections, each contributing to the overall dielectric strength of the system.

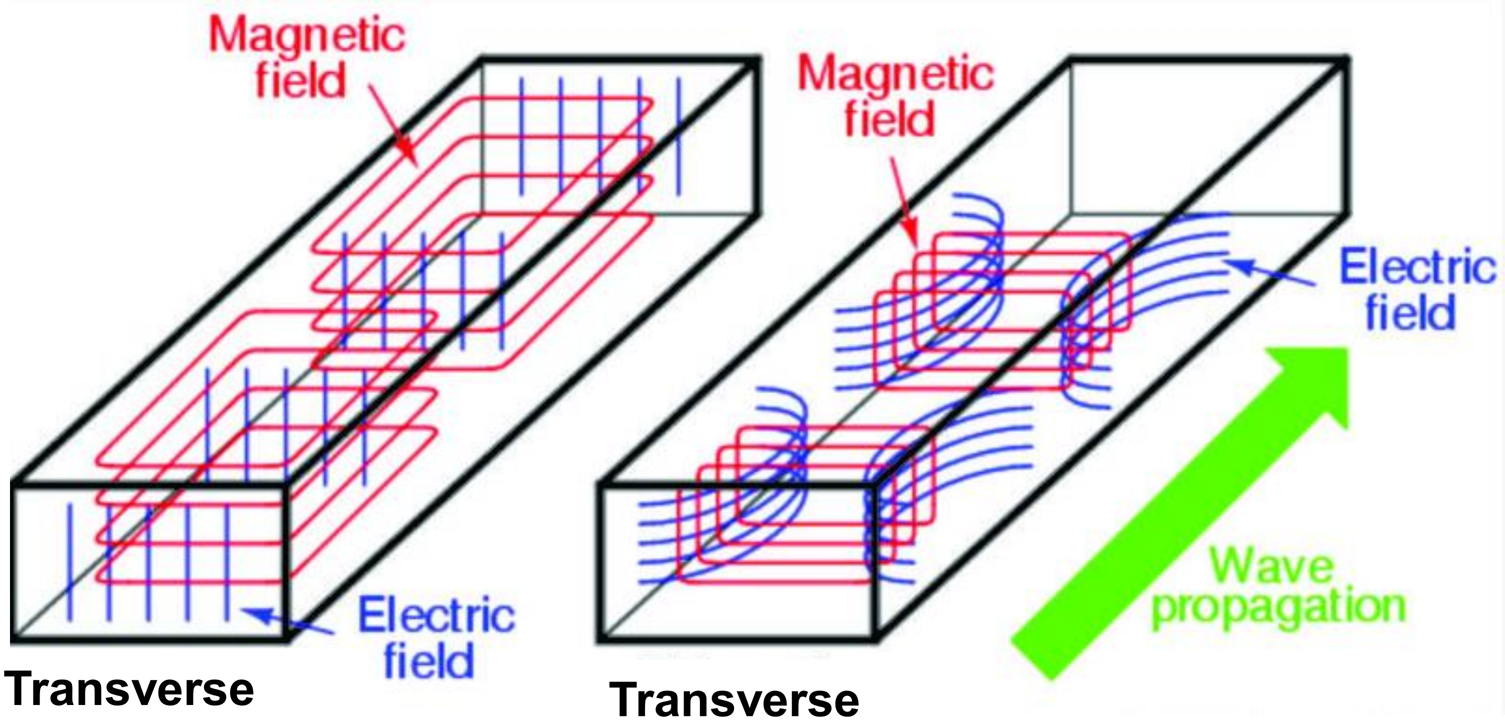
3. Woodpile

   It incorporates a woodpile crystal lattice made of dielectric materials to optimize the transition with minimal losses while ensuring isolation.

4. Tapered waveguide

   It use a tapered waveguide transition with mode conversion, followed by isolating the gap with low-loss dielectrics to maximize power transfer.

Electromagnetic Waves Propagation

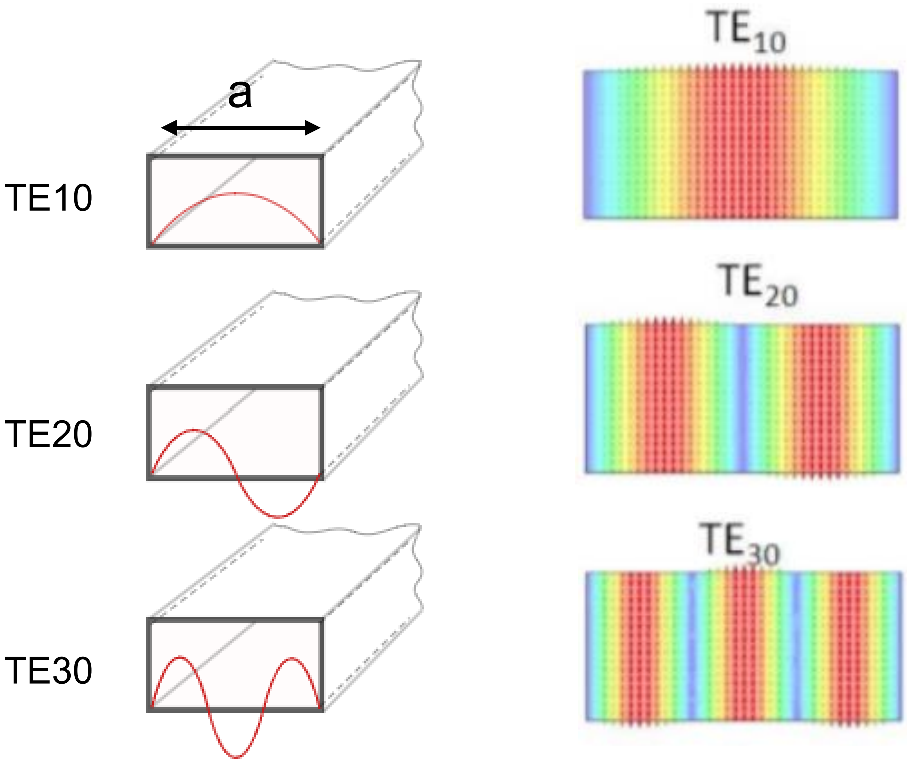


Transverse Electric Mode

Transverse Magnetic Mode

Waveguides provide low-loss transmission of high-frequency signals, offering high power handling, controlled propagation, and electromagnetic shielding.

Dominant Mode

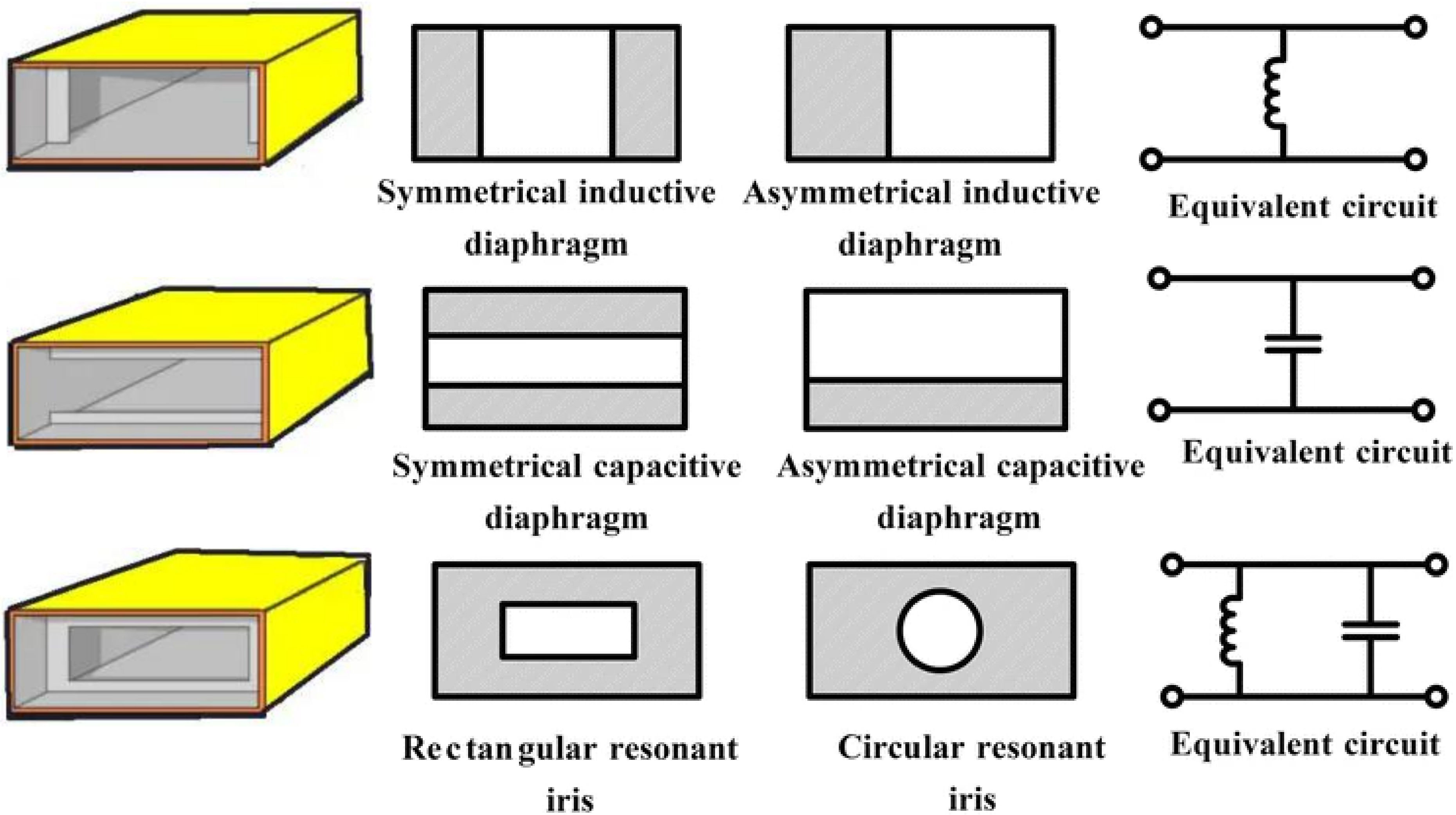


Rectangular waveguides primarily support the TE10 mode as the <u>dominant mode</u>, meaning it's the mode that propagates with the lowest cutoff frequency and losses.

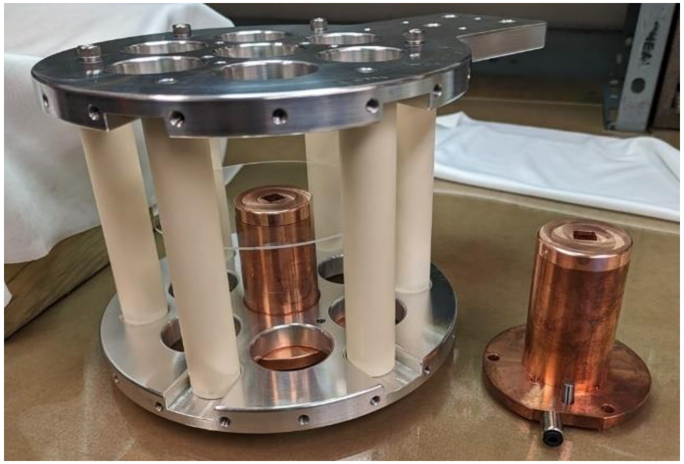
Cutoff Frequency for TE10 mode:

$$f_c = \frac{c}{2a}$$

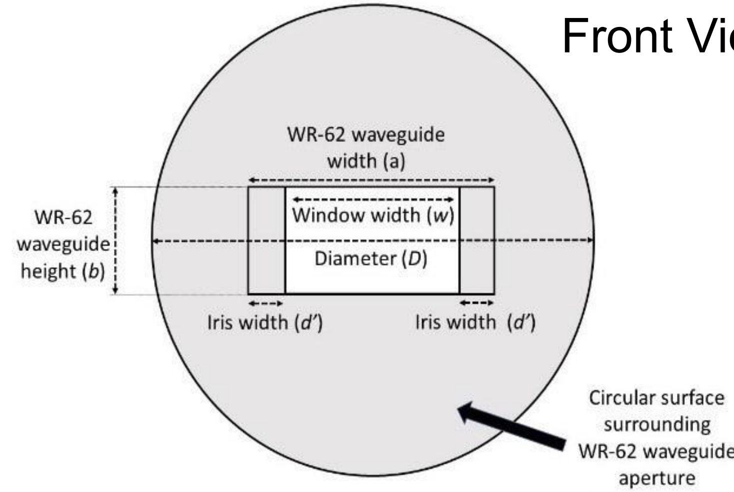
Equivalent Circuit for Waveguide Irises



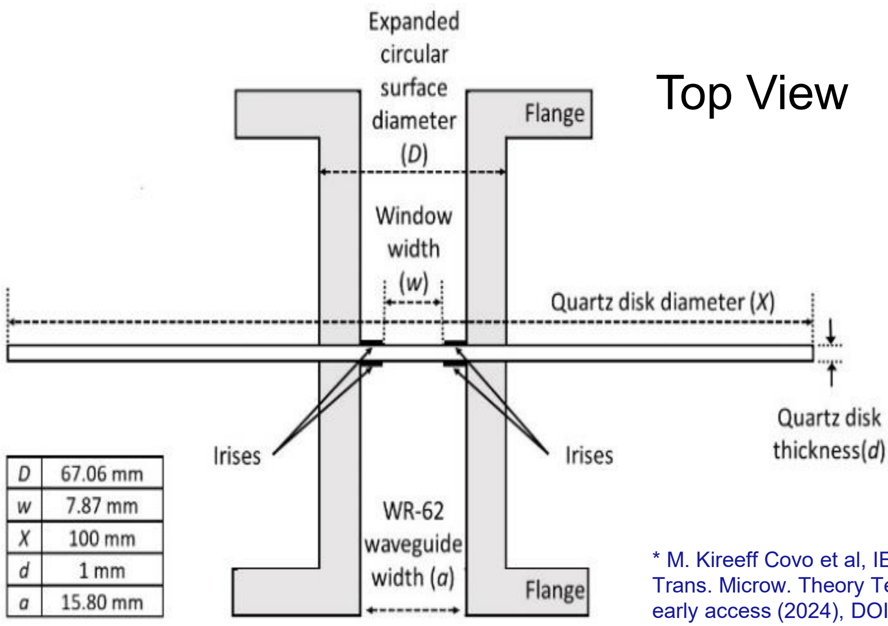
18 GHz HV DC Break (WR-62)*



Front View

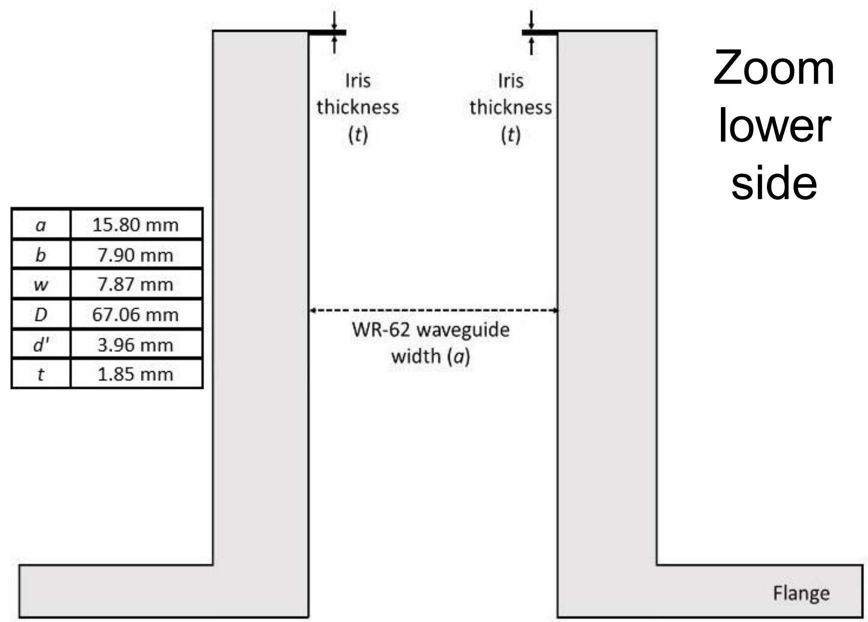


Top View



D	67.06 mm
w	7.87 mm
X	100 mm
d	1 mm
a	15.80 mm

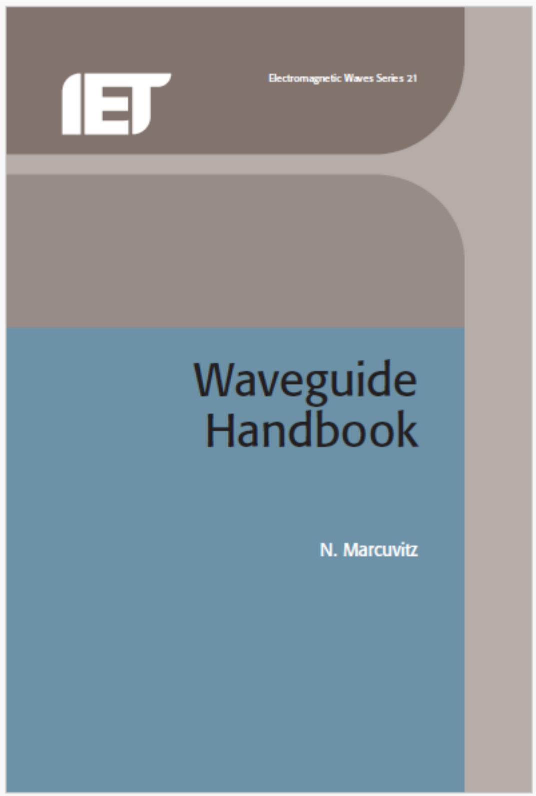
Zoom lower side



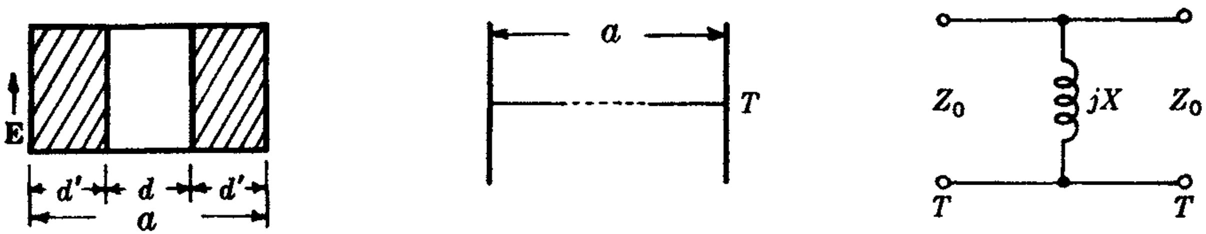
a	15.80 mm
b	7.90 mm
w	7.87 mm
D	67.06 mm
d'	3.96 mm
t	1.85 mm

* M. Kireeff Covo et al, IEEE Trans. Microw. Theory Tech., early access (2024), DOI: 10.1109/TMTT.2024.3409470.

Inductive Obstacles in Rectangular Waveguide



5·2. Inductive Obstacles and Windows in Rectangular Guide.—*a. Symmetrical Window.*—Symmetrical window formed by zero thickness obstacles with edges parallel to the electric field (H_{10}-mode in rectangular guide).



Cross sectional view   Top view   Equivalent circuit

FIG. 5·2-1.

Equivalent-circuit Parameters.—At the terminal plane T

$$\frac{X}{Z_0} = \frac{a}{\lambda_g}\tan^2\frac{\pi d}{2a}\left\{1 + \frac{3}{4}\left[\frac{1}{\sqrt{1-\left(\frac{2a}{3\lambda}\right)^2}} - 1\right]\sin^2\frac{\pi d}{a}\right.$$

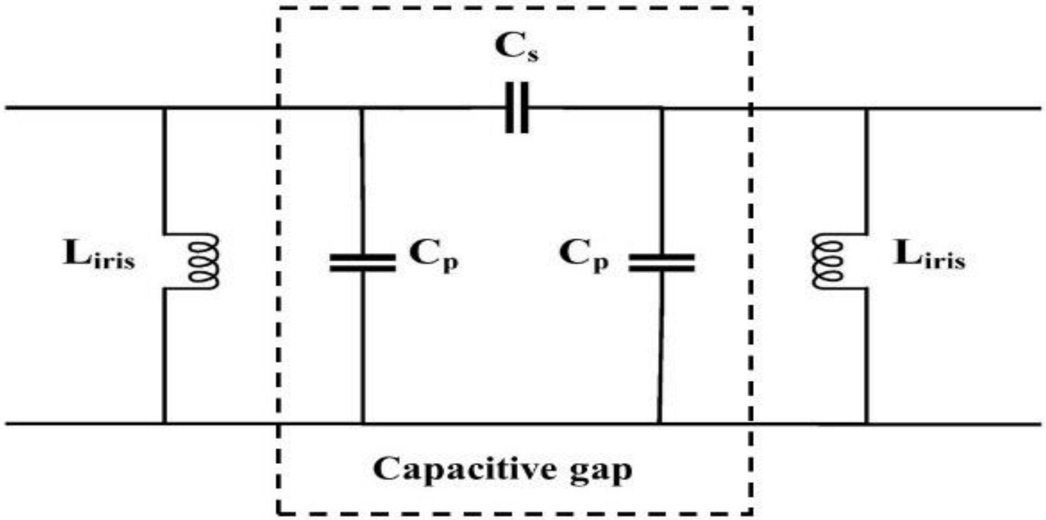
$$\left. + 2\left(\frac{a}{\lambda}\right)^2\left[1 - \frac{4}{\pi}\,\frac{E(\alpha) - \beta^2F(\alpha)}{\alpha^2}\cdot\frac{E(\beta) - \alpha^2F(\beta)}{\beta^2} - \frac{1}{12}\sin^2\frac{\pi d}{a}\right]\right\}, \quad (1a)$$

$$\frac{X}{Z_0} \approx \frac{a}{\lambda_g}\tan^2\frac{\pi d}{2a}\left[1 + \frac{1}{6}\left(\frac{\pi d}{\lambda}\right)^2\right], \qquad \frac{d}{a} \ll 1, \quad (1b)$$

$$\frac{X}{Z_0} \approx \frac{a}{\lambda_g}\cot^2\frac{\pi d'}{a}\left[1 + \frac{2}{3}\left(\frac{\pi d'}{\lambda}\right)^2\right], \qquad \frac{d'}{a} \ll 1, \quad (1c)$$

Equivalent Circuit*

$$C_s = \varepsilon_r \varepsilon_0 \frac{A}{d} = 1207 \text{ pF}$$



Marcuvitz's equation

$$\frac{X_L}{Z_0} \approx \frac{a}{\lambda_g} cot^2 \frac{\pi d'}{a} \left[1 + \frac{2}{3} \left(\frac{\pi d'}{\lambda} \right)^2 \right]$$

$$\frac{d'}{a} \ll 1$$

$L_{iris} \approx 4.29$ nH

$$f_r = \frac{1}{2\pi\sqrt{L_{iris} C_p}}$$

$\therefore C_p \approx 0.0182$ pF (18 GHz)

* M. Kireeff Covo et al, IEEE Trans. Microw. Theory Tech., early access (2024), DOI: 10.1109/TMTT.2024.3409470
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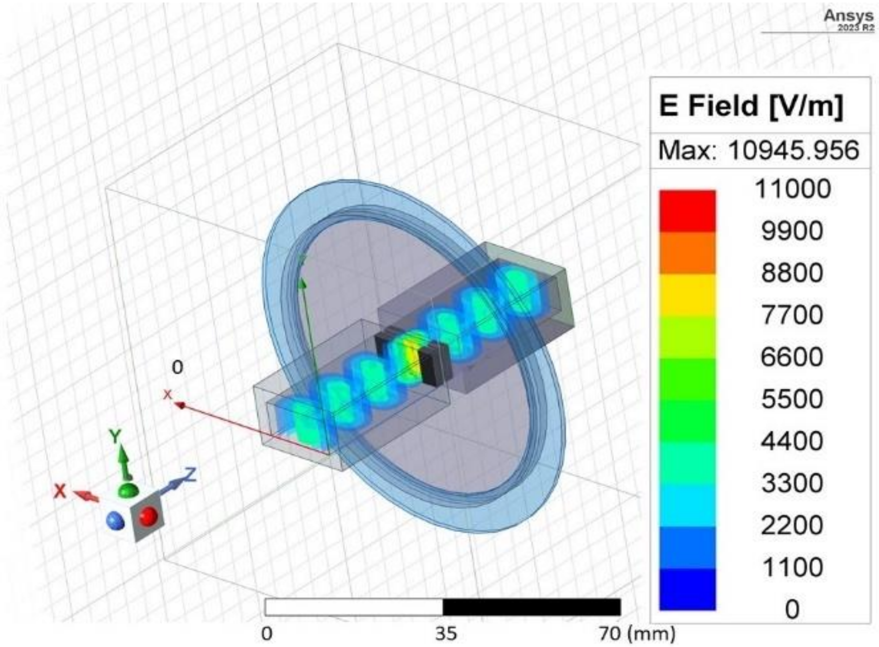
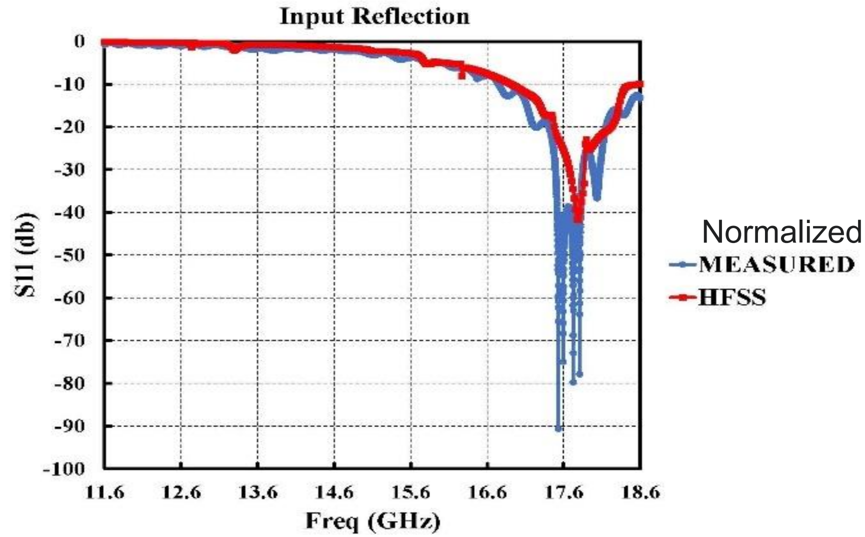
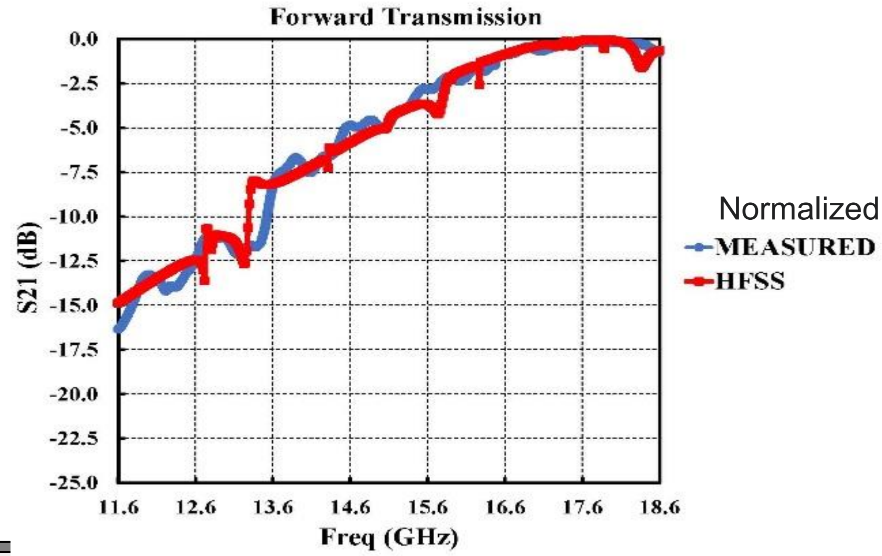
HFSS Simulation and Measurements*

HFSS (High-Frequency Structure Simulator)

- It uses 3D finite element method to solve Maxwell's equations, simulating electromagnetic fields in complex three-dimensional structures.



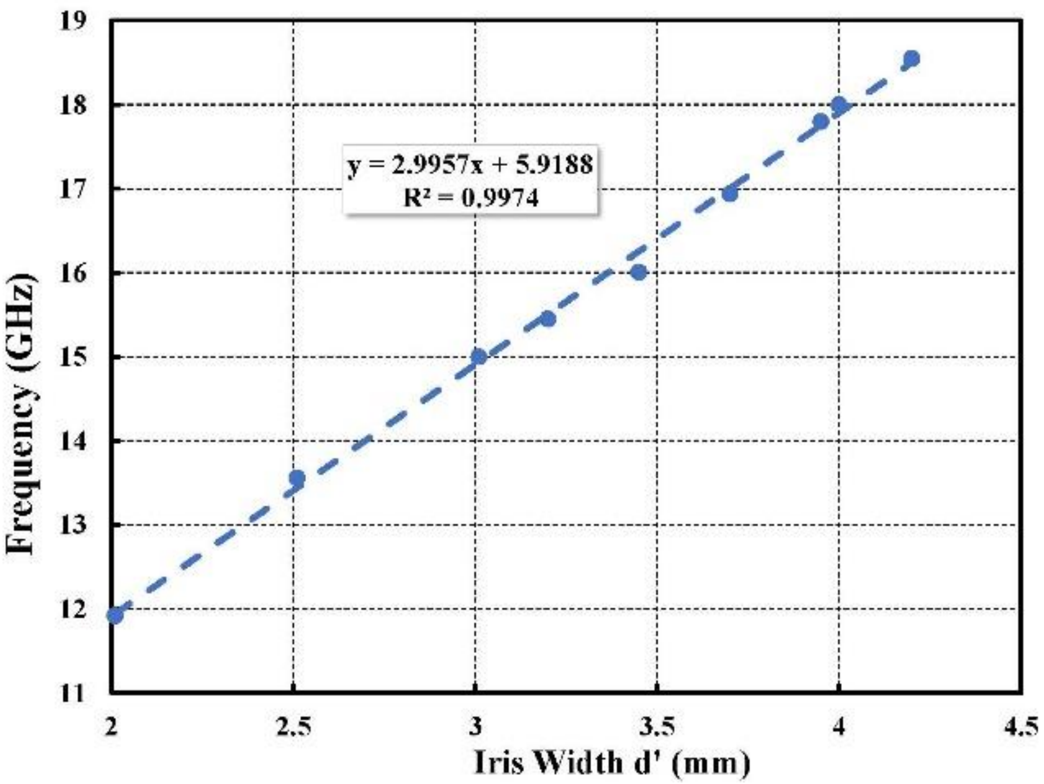




* M. Kireeff Covo et al, IEEE Trans. Microw. Theory Tech., early access (2024), DOI: 10.1109/TMTT.2024.3409470.

Frequency Optimization*

d' (mm)	f (GHz)	S_{11} (dB)	S_{21} (dB)
4.20	18.55	−37.61	−0.13
4.00	18.00	−41.35	−0.08
3.95	17.80	−41.27	−0.06
3.70	16.94	−53.20	−0.02
3.45	16.01	−34.91	−0.14
3.20	15.45	−25.56	−0.15
3.01	15.00	−36.17	−0.09
2.51	13.56	−22.34	−0.12
2.01	11.92	−52.84	−0.02



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$$f_r = \frac{1}{2\pi\sqrt{L_{iris}C_p}}$$

Considerations*

1. Child-Langmuir law

$$J = 1.72\mathcal{E}_0 \left(\frac{q}{m}\right)^{1/2} \frac{V^{3/2}}{d^2}$$

Space-Charge limited Flow

∴ Significant incentive to enhance the DC break to handle a higher extraction voltage V on the platform, as the total current density *J* scales with the extraction voltage *V* to the power of 3/2.

2. Dielectric thickness

Careful design is required to minimize microwave leakage due to the finite discontinuity between waveguides and dielectrics, and to reduce the insertion loss caused by the dielectric material from these custom components.

2. Dielectric RF energy loss (quartz)

$\alpha_d = 0.09106 \sqrt{\epsilon_r}\, f \tan\delta \;\, d\ (dB)$ ≈ 0.003 dB for 1 mm quartz

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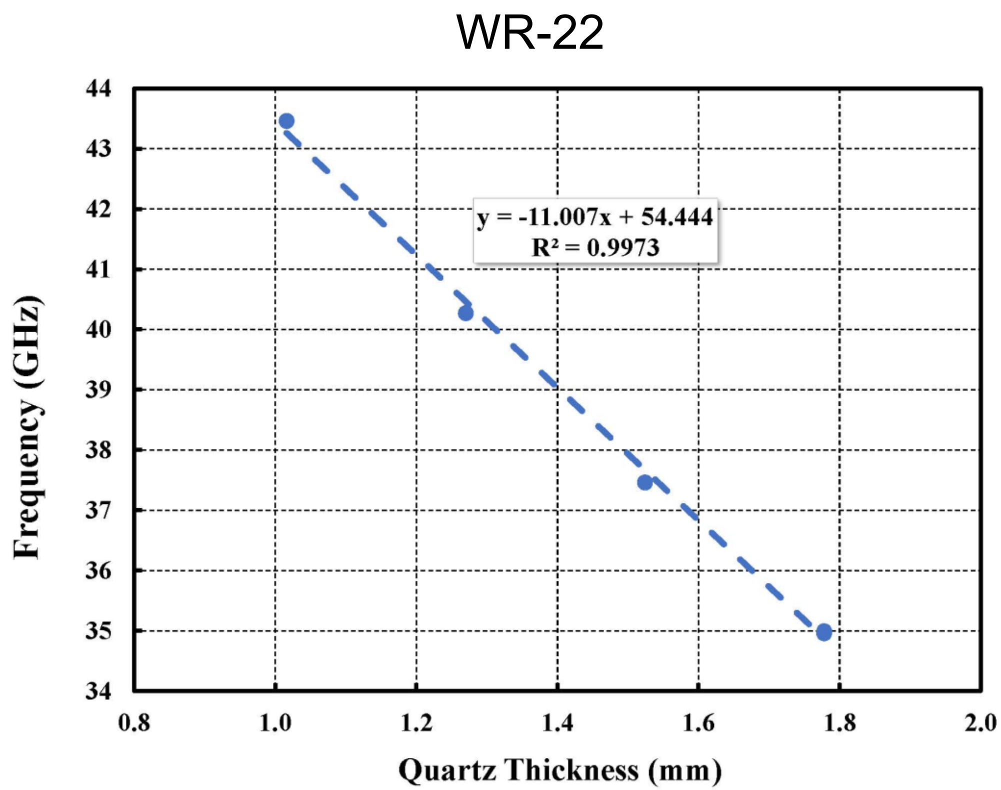
MARS-D Ion Source

The multi-frequency MARS-D ion source requires HV DC breaks that meet the following specifications:

- Isolation voltage: up to 45 kV;
- Transmitting power: 2 kW;
- Frequencies: 28, 35, and 45 GHz, using WR-34, WR-28, and WR-22 waveguides.

Effects from Increasing the Isolation

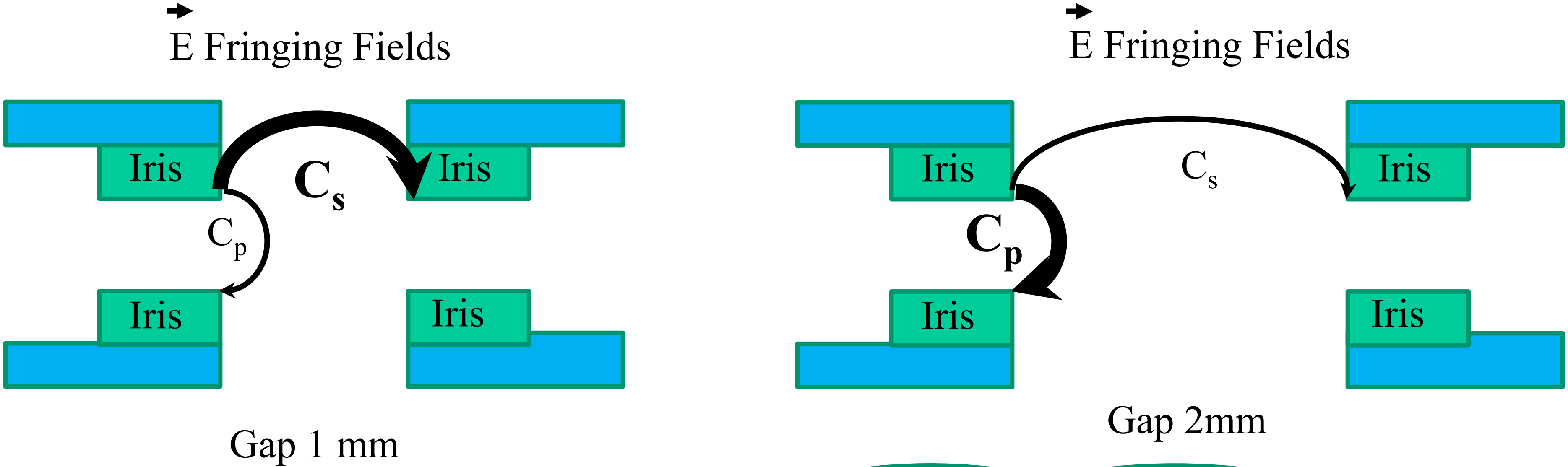


∴ Increasing the quartz thickness decreases the resonant frequency f_r, as it leads to an increase in the shunt capacitance C_p. Simultaneously, the RF leakage also increases.

$$f_r = \frac{1}{2\pi\sqrt{L_{iris}C_p}}$$

Waveguide DC Break with Increased DC Isolation

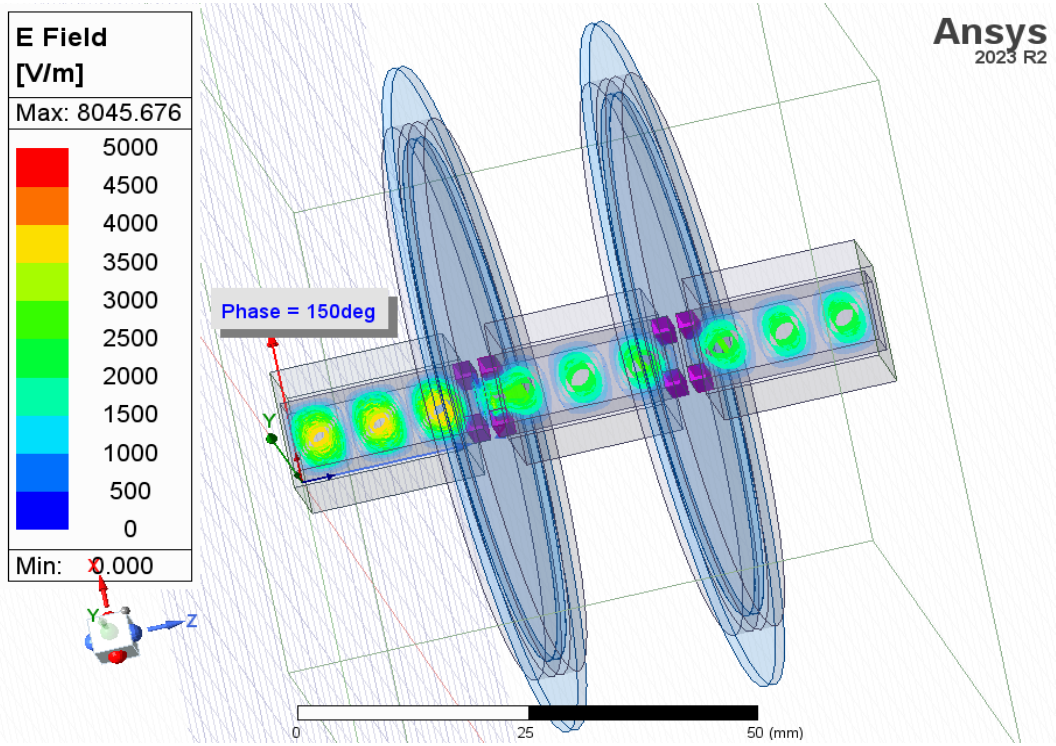
WR-34 22.00 to 33 GHz   Dim: 0.34 [8.636] 0.17 [4.318] for used in 28 GHz
WR-28 26.50 to 40 GHz   Dim: 0.28 [7.112] 0.14 [3.556] for 35 GHz
WR-22 33.00 to 50 GHz   Dim: 0.224 [5.6896] 0.112 [2.8448] for 45 GHz.



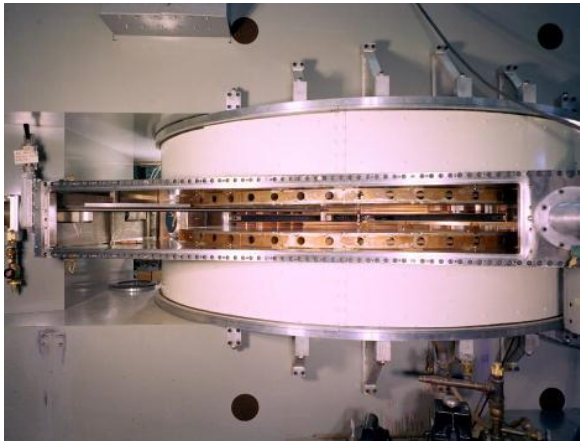
As the gap between open-ended waveguides increases, the fringe electric fields intensify at the open-ended edges, increasing the shunt capacitance C_p and raising the risk of losses and RF leakage.

Inductive Iris Aperture New Configuration

Waveguide	W (mm)	f (GHz)	S11 (dB)	S21 (dB)
WR34	4.32	28	−39.21	−0.06
WR28	3.20	35	−37.97	-0.04
WR22	2.23	45	-24.30	-0.03



88-Inch Cyclotron



Thanks!!!!
Please visit us at
http://cyclotron.lbl.gov