Research Progress at Strathclyde relevant to Accelerators

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Introduction

- Strathclyde research group overview
- SUPA
- Strathclyde research
  - High power microwave sources
  - Examples of modelling and experiments
- Conclusions

Strathclyde research group overview

500km

Strathclyde research group overview

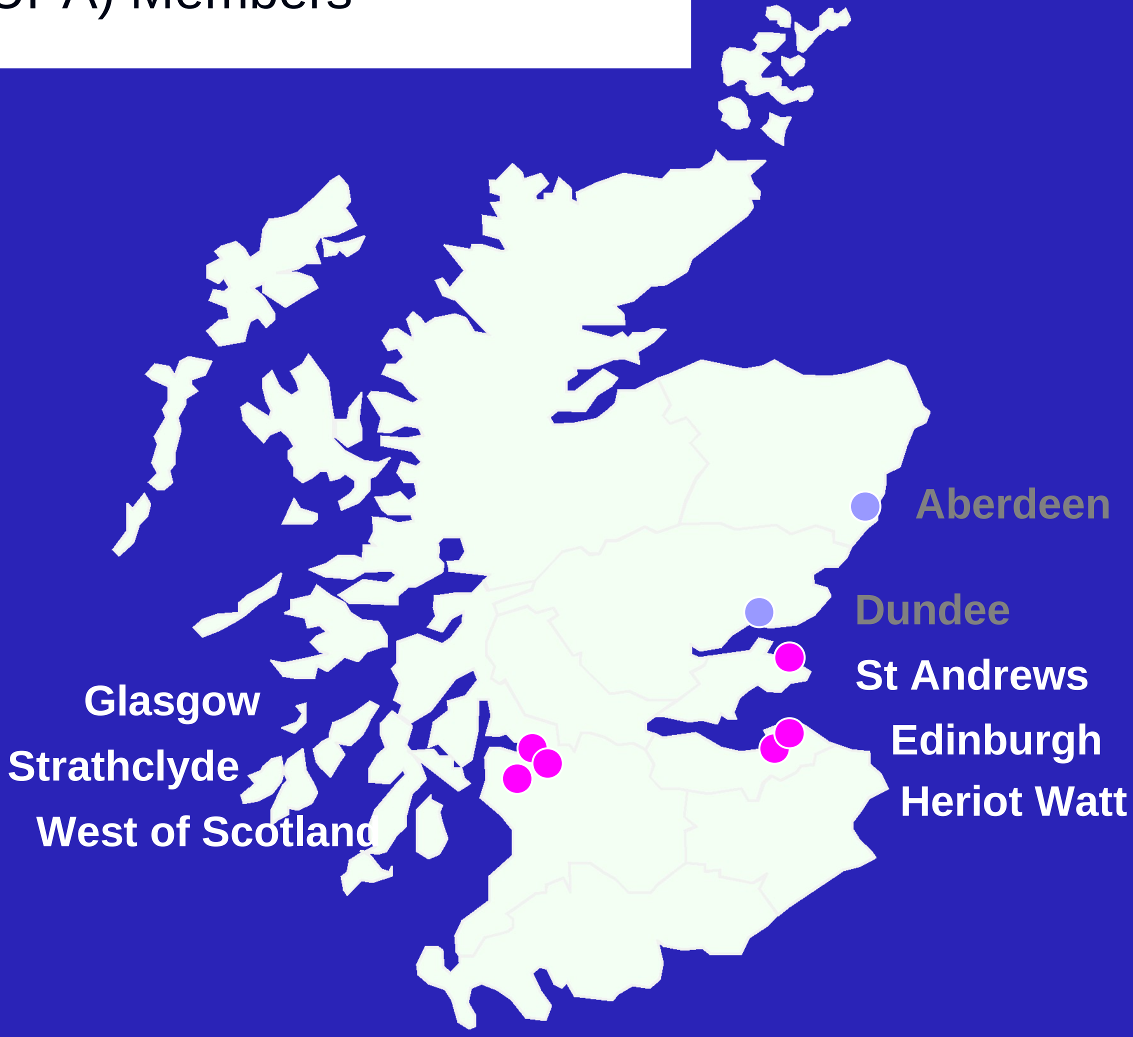
Physics Department

Strathclyde University Campus

Strathclyde research group overview

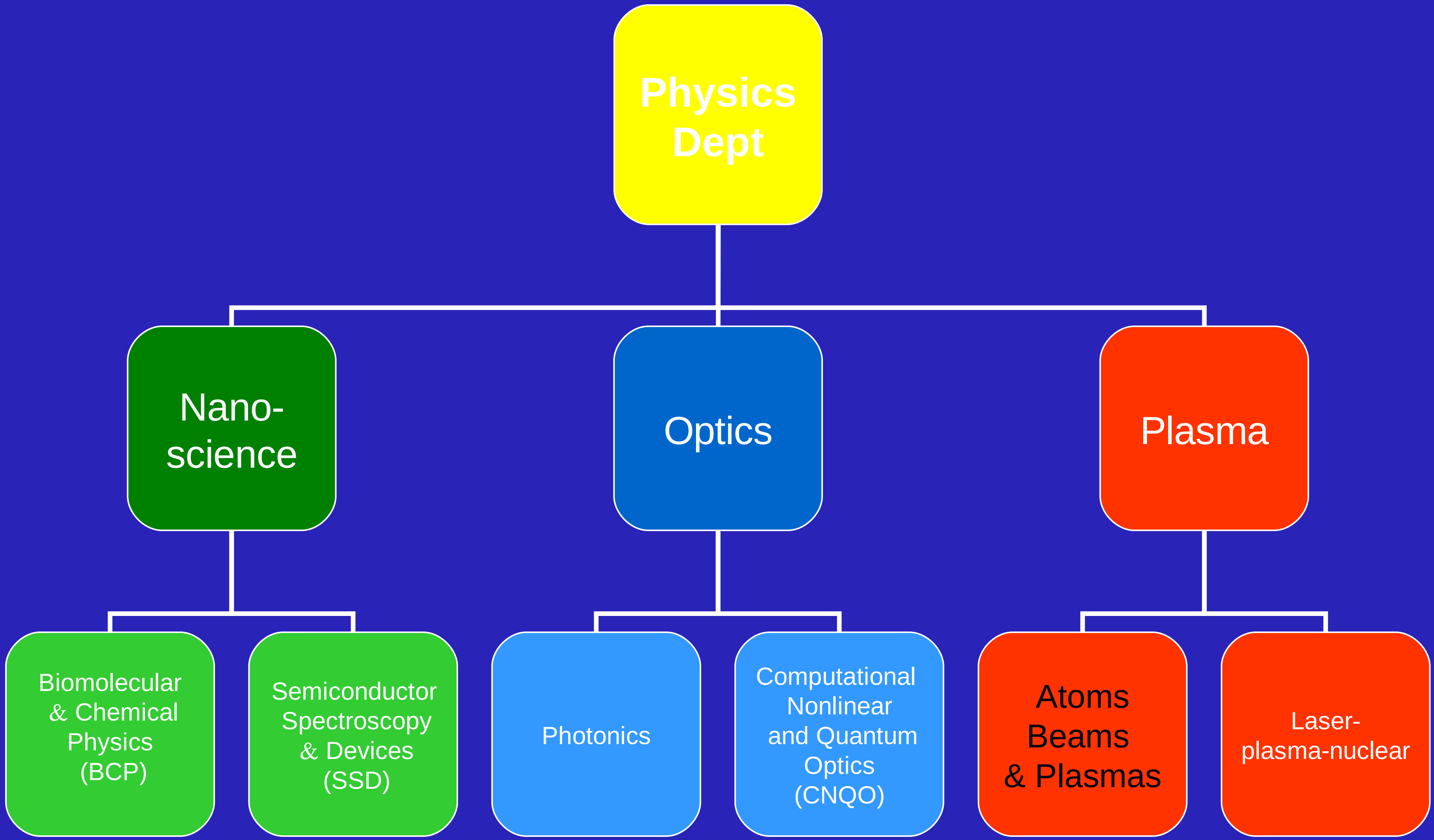
- University of Strathclyde ~ 17,000 students
- Physics Department one of 8 within SUPA
- SUPA graduate school ~ 400 PhD students
- Microwave & MM-wave research (~ 30 people)

Scottish Universities Physics Alliance (SUPA) Members



Research Themes in SUPA

- Nuclear and plasma physics
- Particle physics
- Condensed matter & materials
- Photonics
- Astronomy and astrophysics
- Physics applied to the life sciences
- Energy


Physics Dept
Nano-science
Optics
Plasma
Biomolecular & Chemical Physics (BCP)
Semiconductor Spectroscopy & Devices (SSD)
Photonics
Computational Nonlinear and Quantum Optics (CNQO)
Atoms Beams & Plasmas
Laser-plasma-nuclear

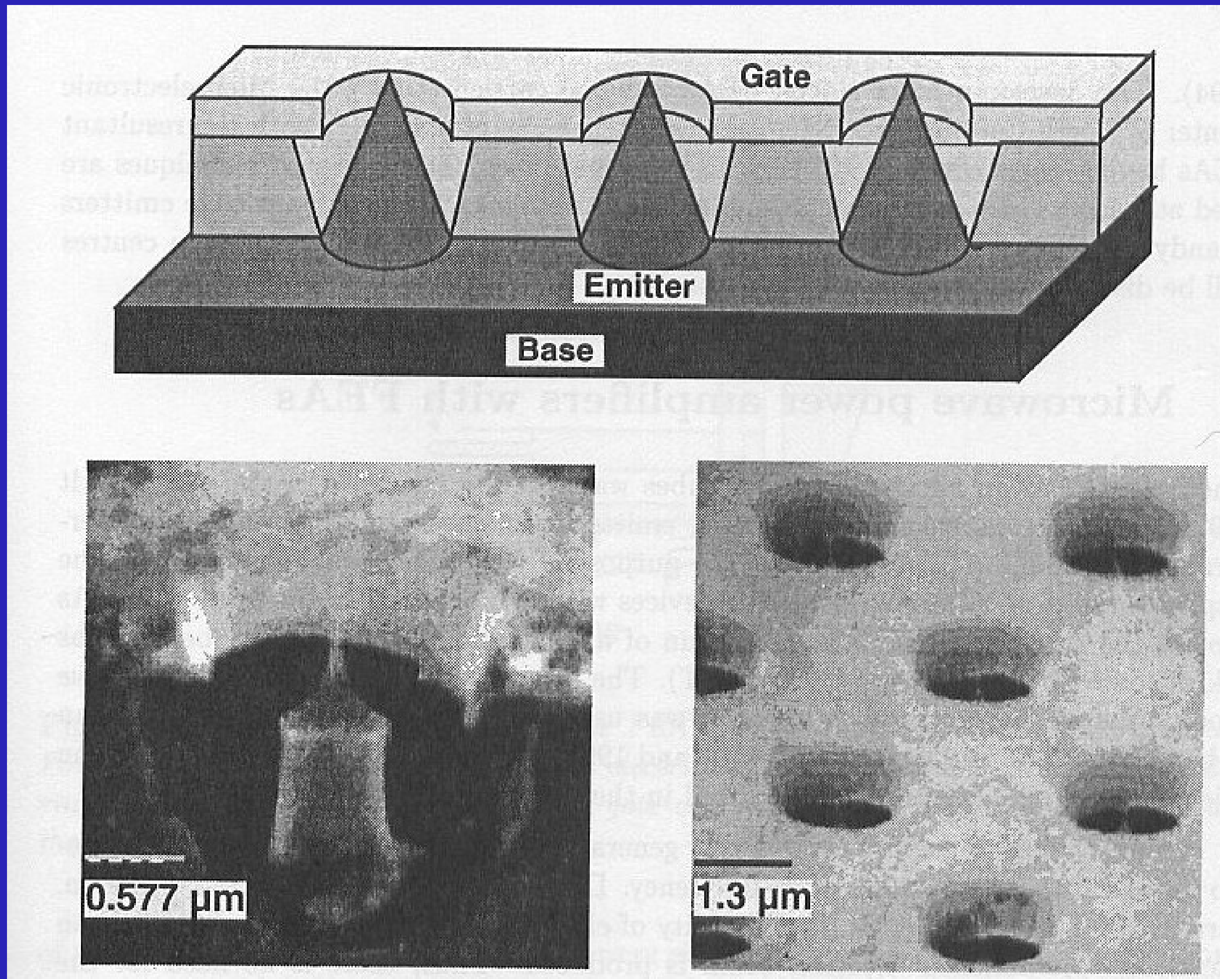
Strathclyde research group overview

- Cathodes
  - Field emission: FEA
  - Explosive/plasma flare: Metal & Velvet
  - Thermionic
  - Pseudospark
- Gun structures
  - Pierce, MIG, CUSP
- Coherent high power mm-wave generation
  - Slow wave: Dielectric Cherenkov, Cherenkov BWO
  - Fast wave: FEL, Gyrotron, CARM, Gyro-TWAs Gyro-BWOs, Superradiance (CRM & Cherenkov)

Examples of Strathclyde work on high power vacuum electronic mm-wave devices

- Modelling – using MAGIC, KARAT, SURETRAJ, OPERA, MICROWAVE STUDIO, COMSOL, VORPAL
- Electron beam research using thermionic, plasma flare, field emission array and pseudospark cathodes
- Design, construction and measuring output of high power mm-wave vacuum electronic devices. Includes research, design and construction of couplers, cavities, converters, collectors and windows
- (i) high power mm-wave diagnostics
  (ii) power supplies to drive the devices

Several different types of electron sources

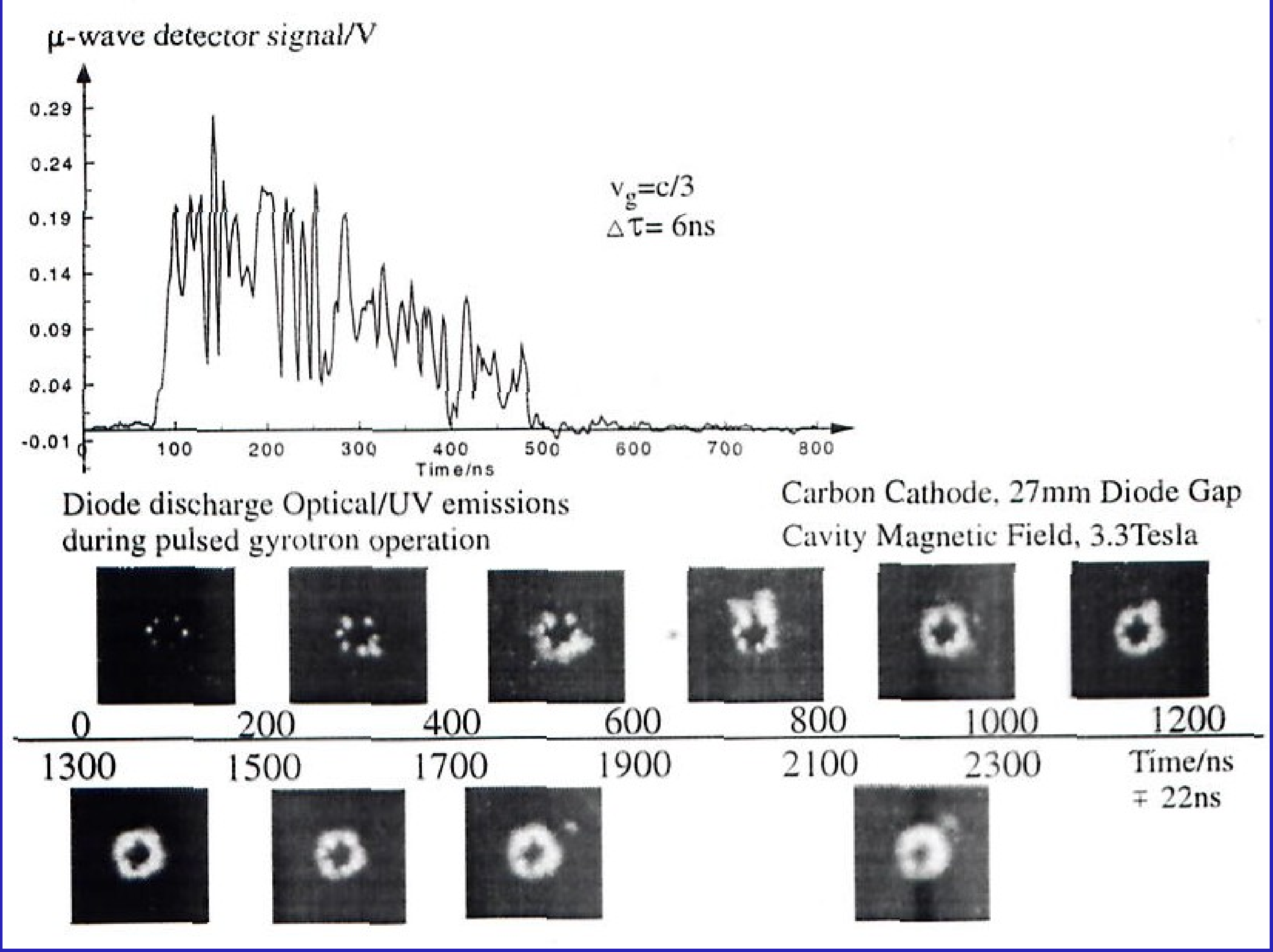


MM-wave gyrotron driven by a field emission array (FEA) electron gun

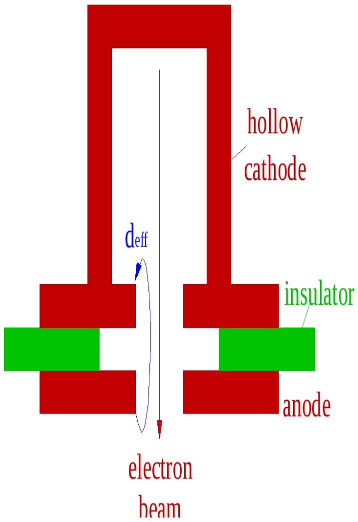
Physical Review Letters 77, 2320-2323, 1996

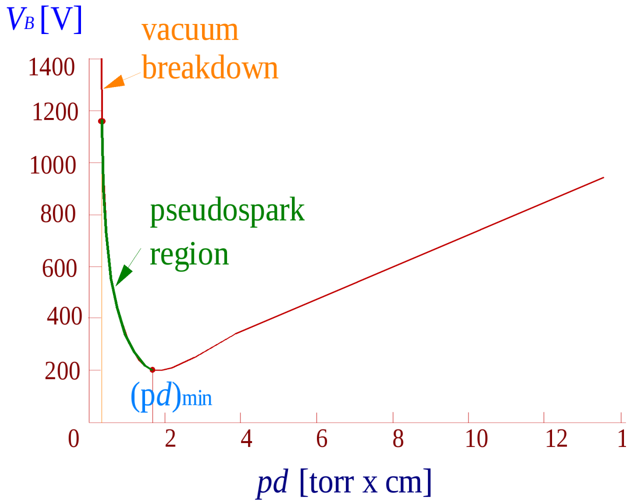
MM-wave gyrotron driven by a field emission array electron gun

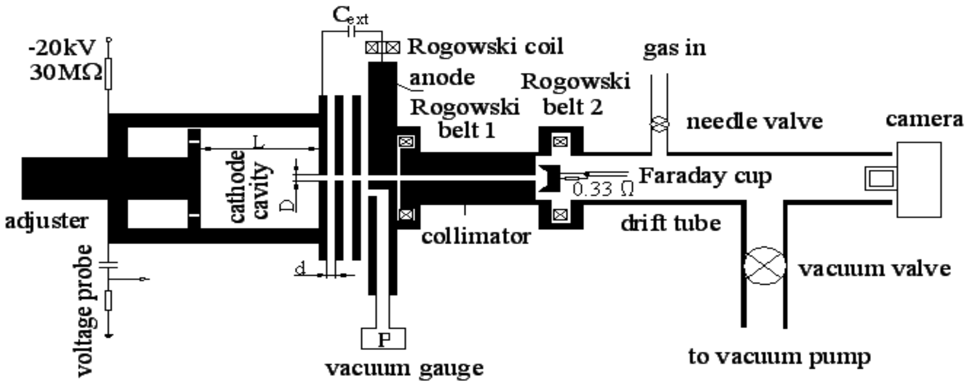
Plasma flare cathodes

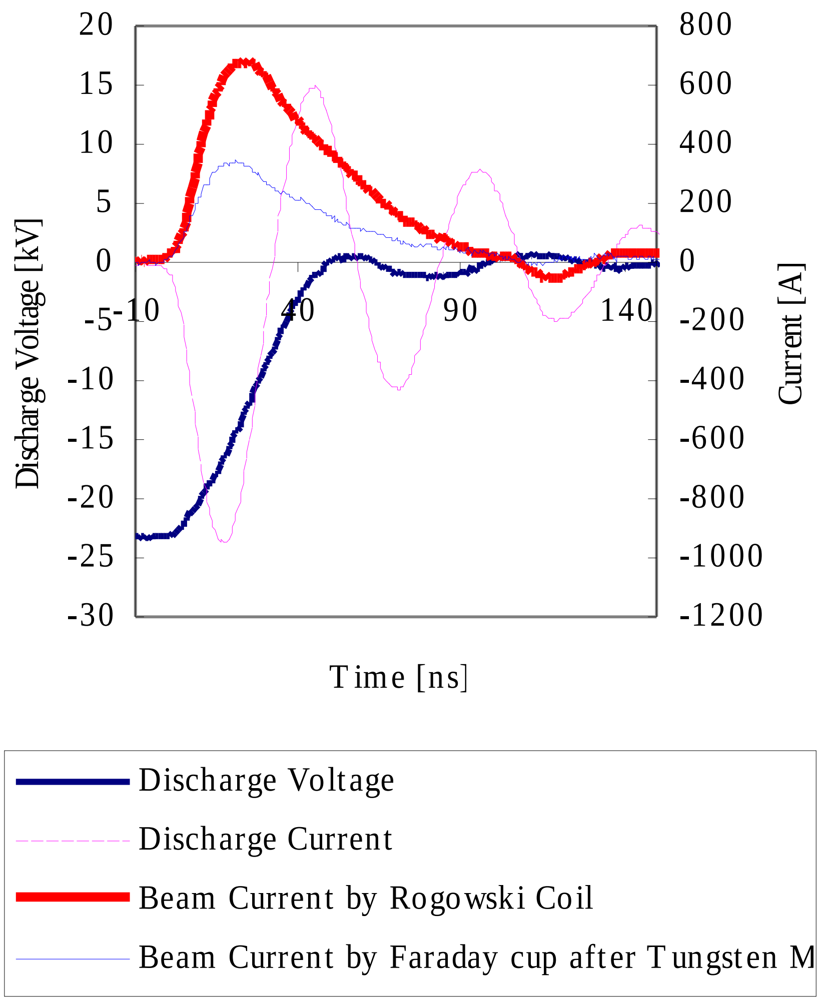


Mm-wave sources using a pseudospark generated electron beam

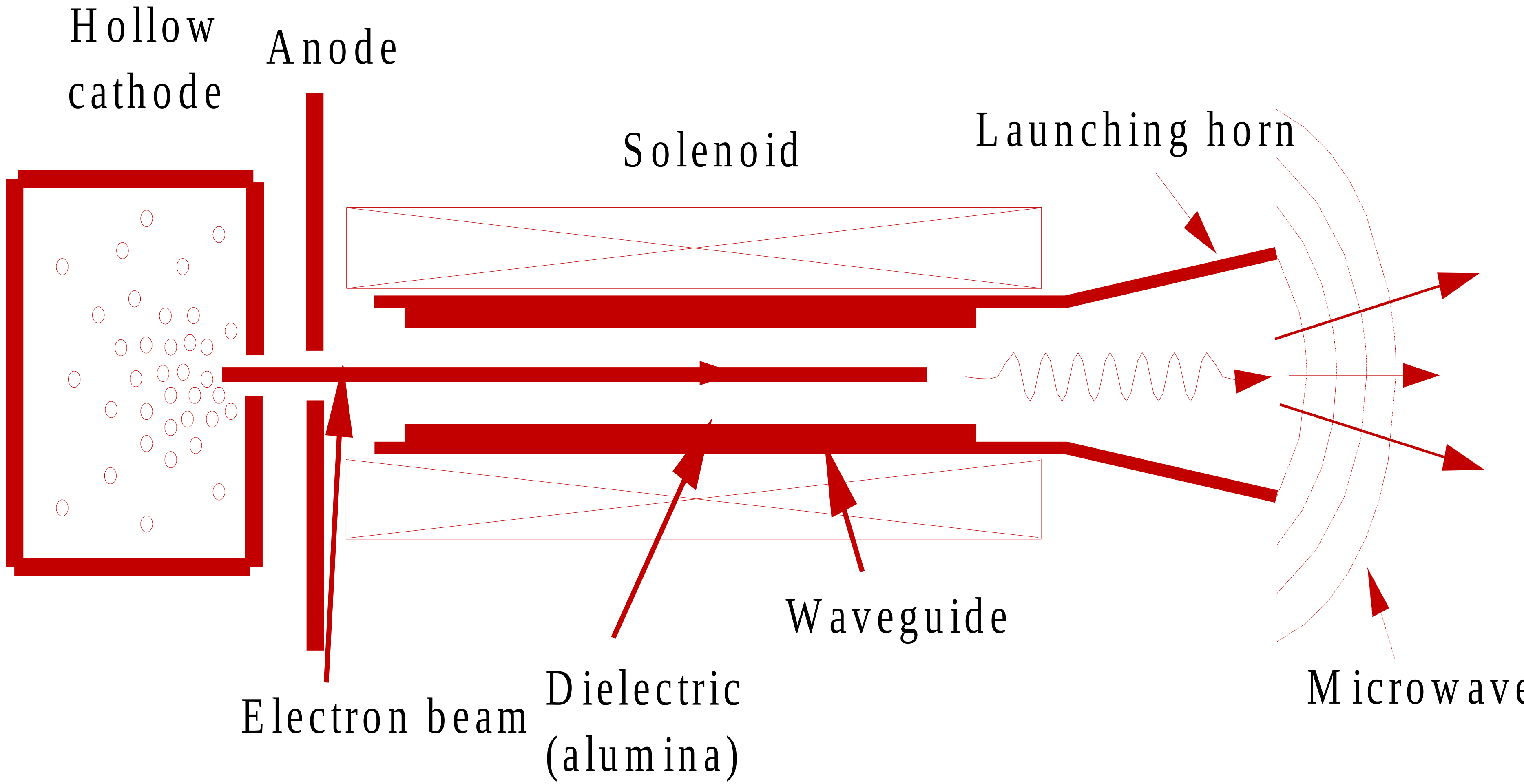


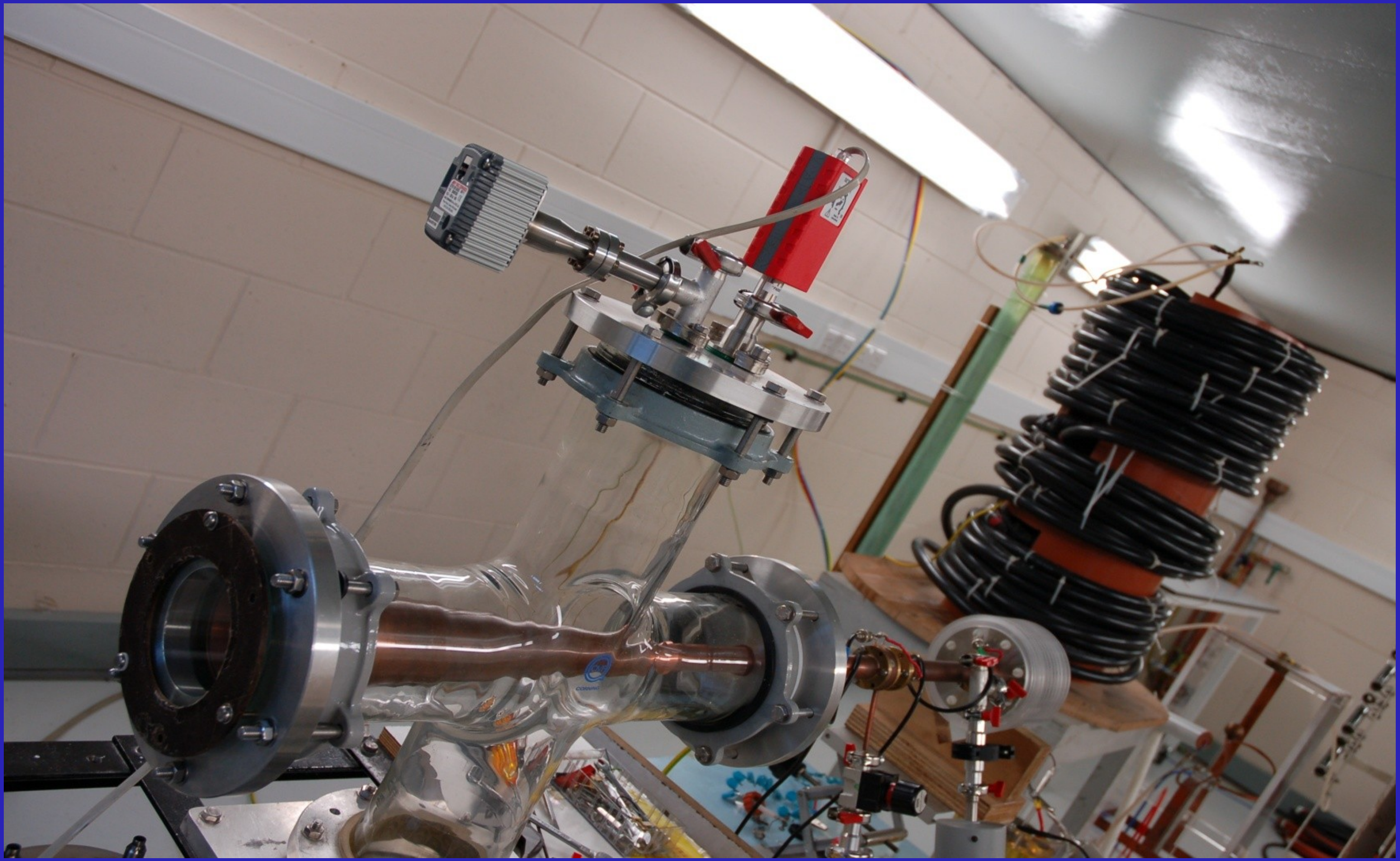






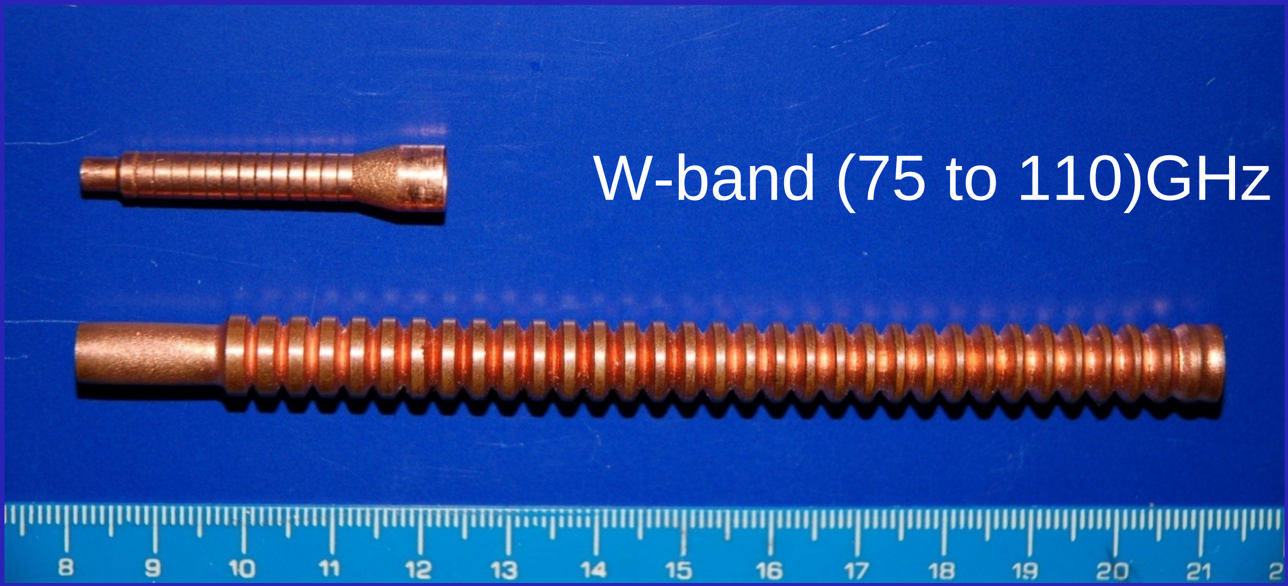
Cherenkov maser using high brightness electron beam from pseudospark source



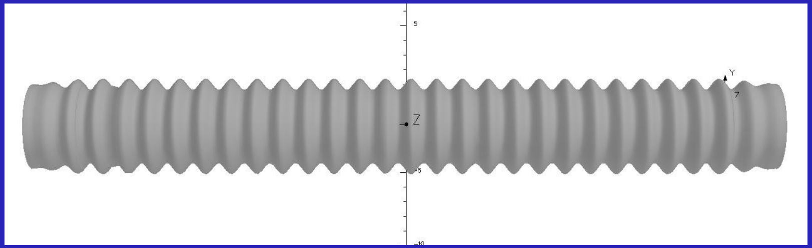


Experimental setup of the 14-gap PS
powered by a cable pulser
and beam-wave interaction investigation

BWO Interaction Region



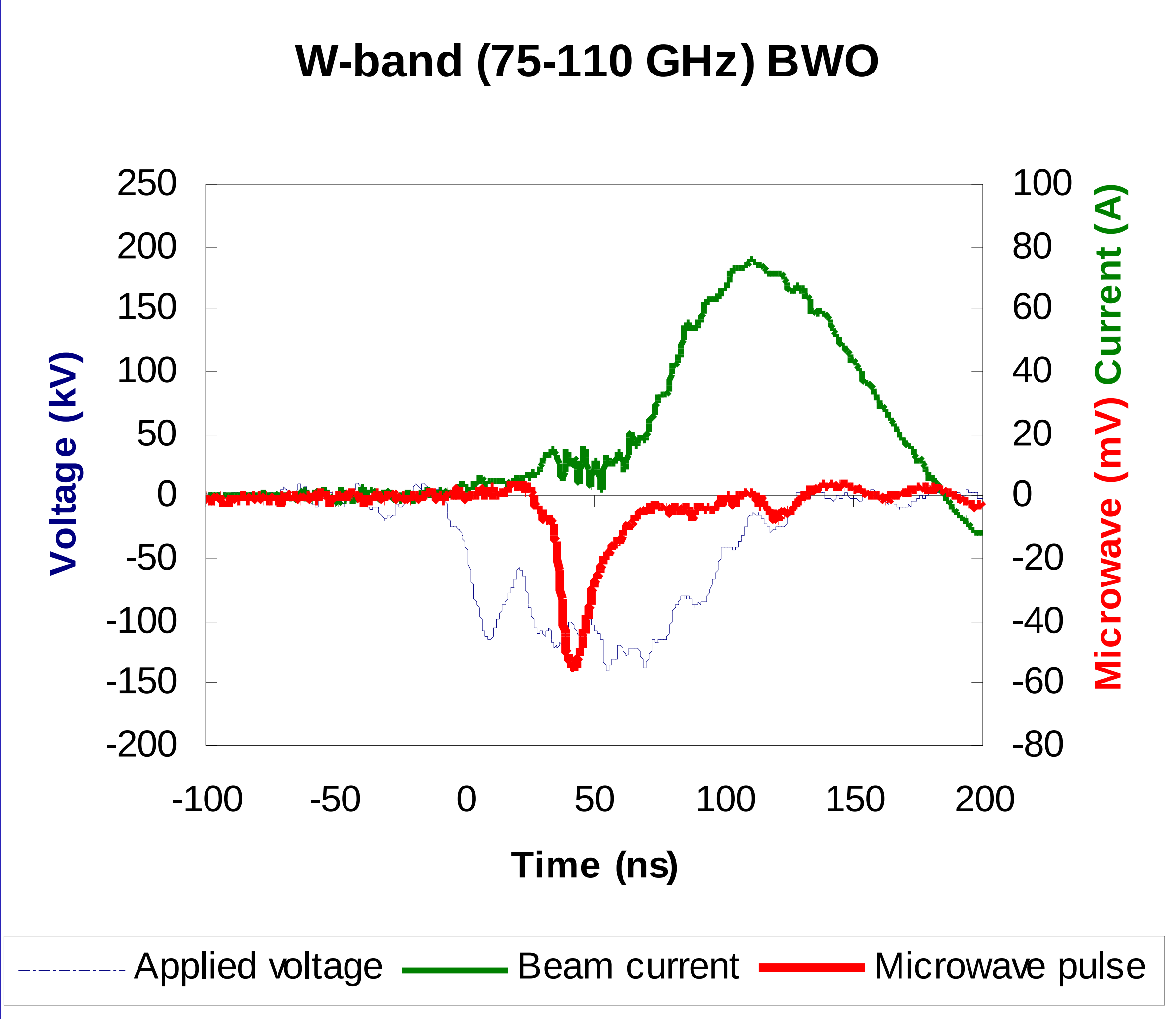
Ka-band
(26.5 to 40)GHz



W-band Aluminium positive former

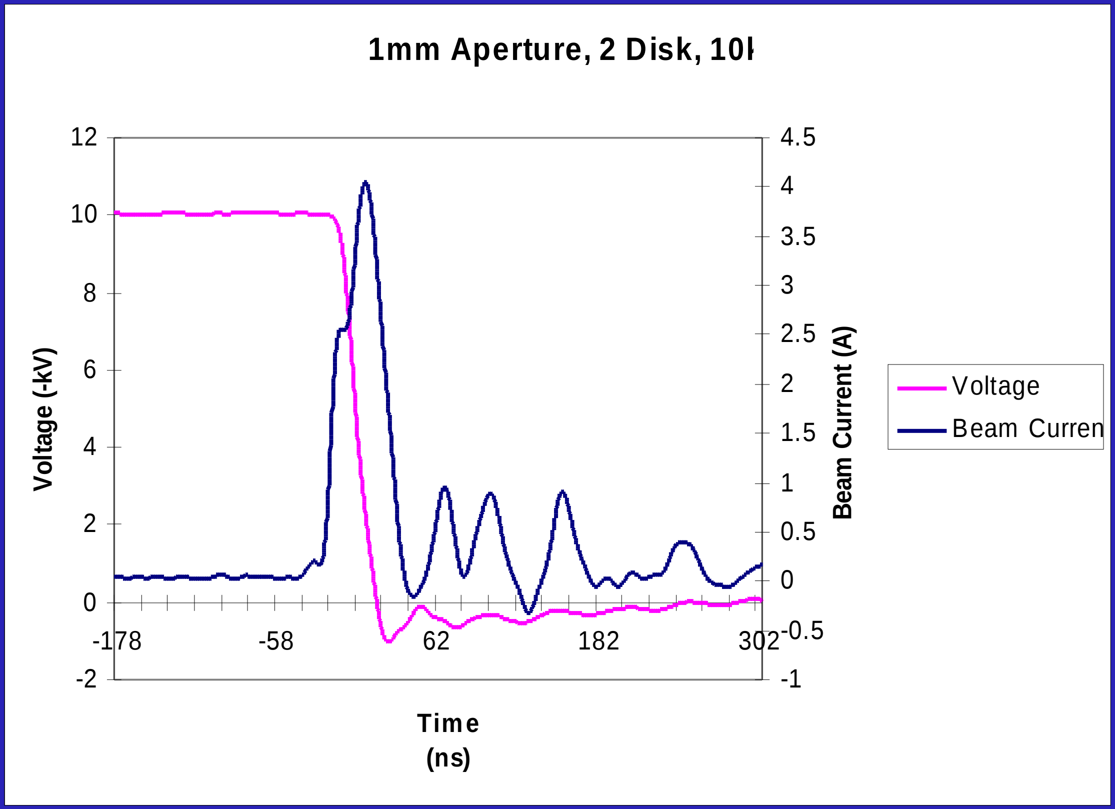
- Constructed in University Strathclyde
- Copper is deposited
- Aluminium dissolved in alkali solution

Advantages: a) compactness (table-top size);
b) simplicity (no B-field);
c) flexibility; d) PRF operation

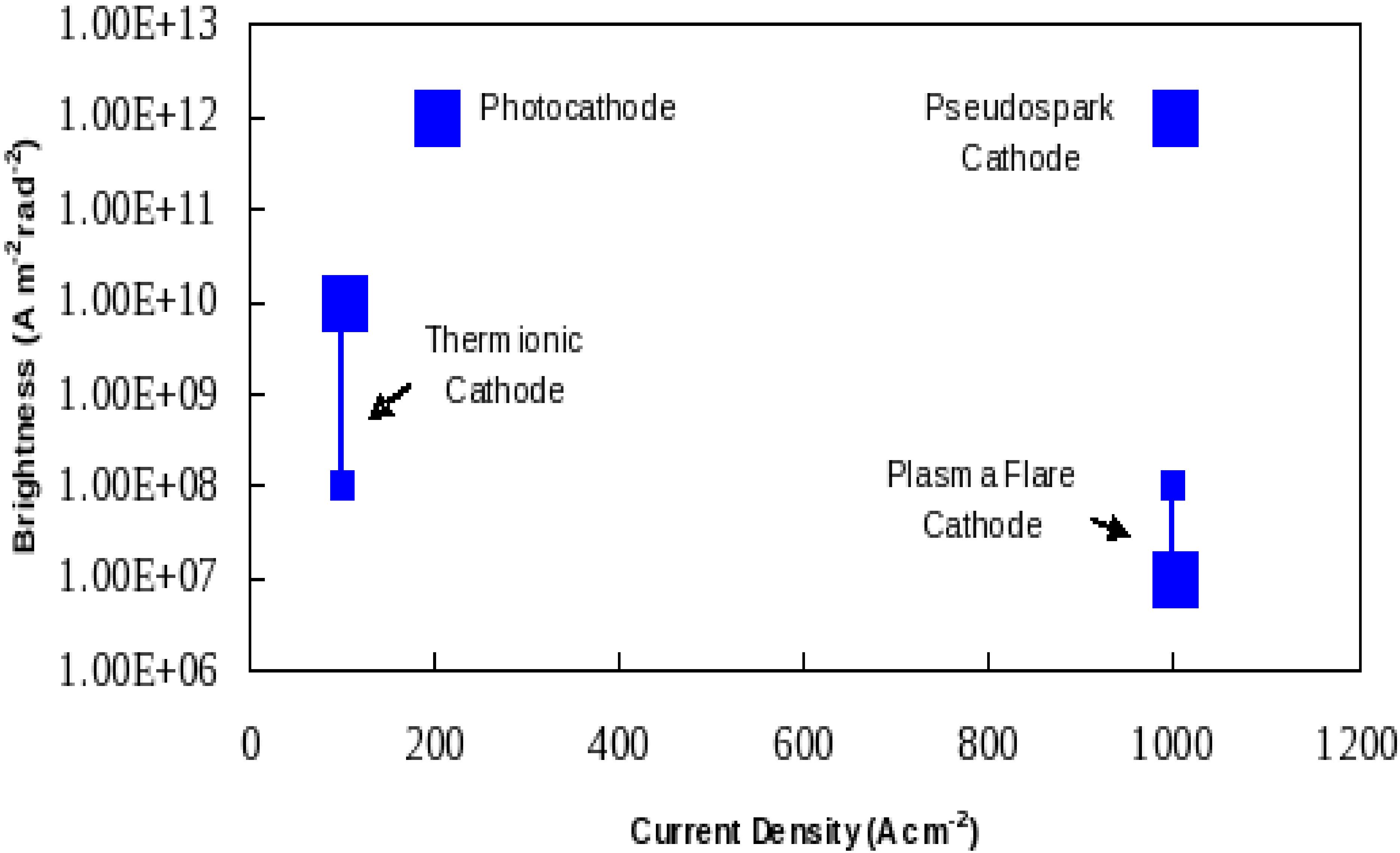


Time-correlated electron beam pulse (green)
microwave pulse (red)
and applied voltage pulse (blue)

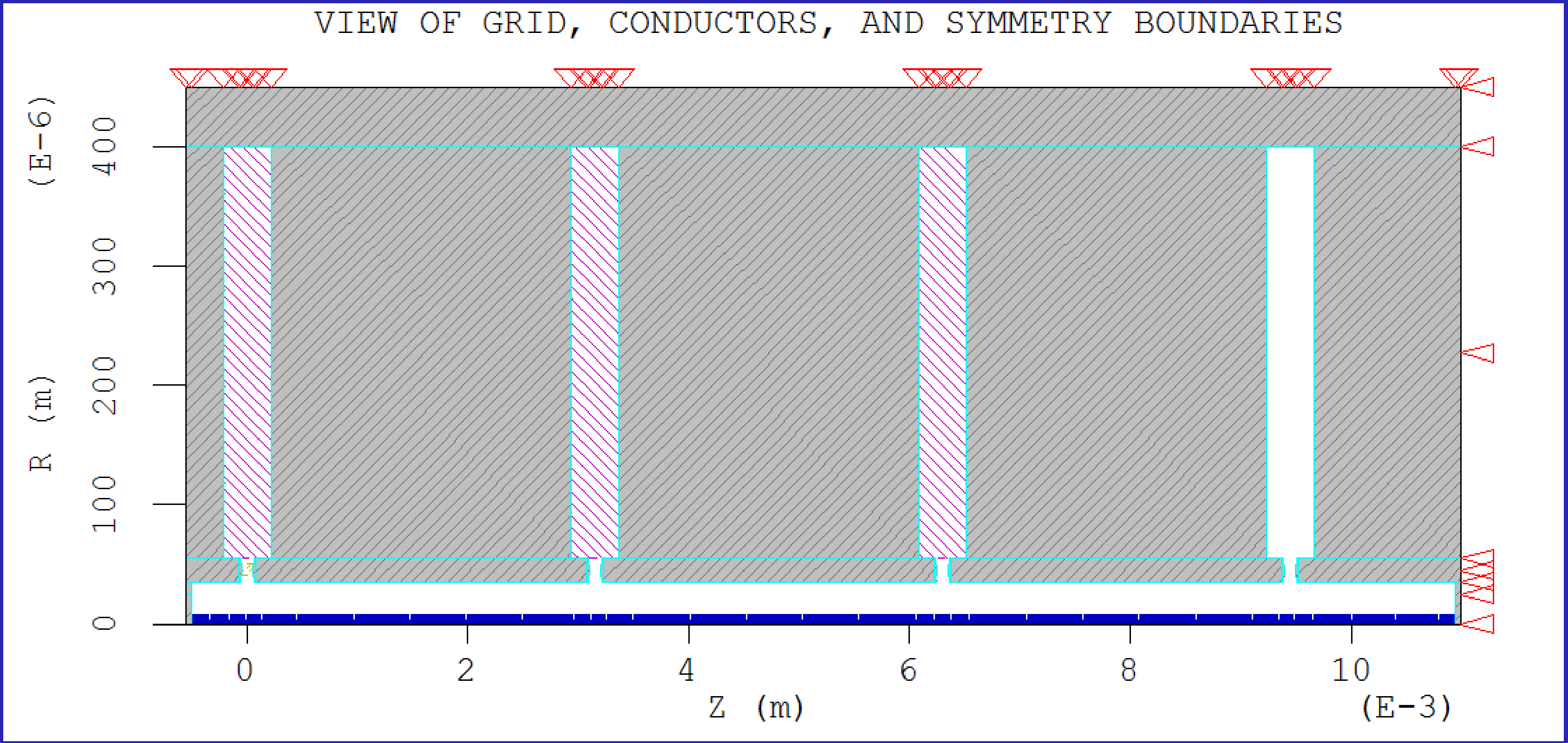
1 mm aperture single gap pseudospark beam measurements
Measured small size (1 mm) beam



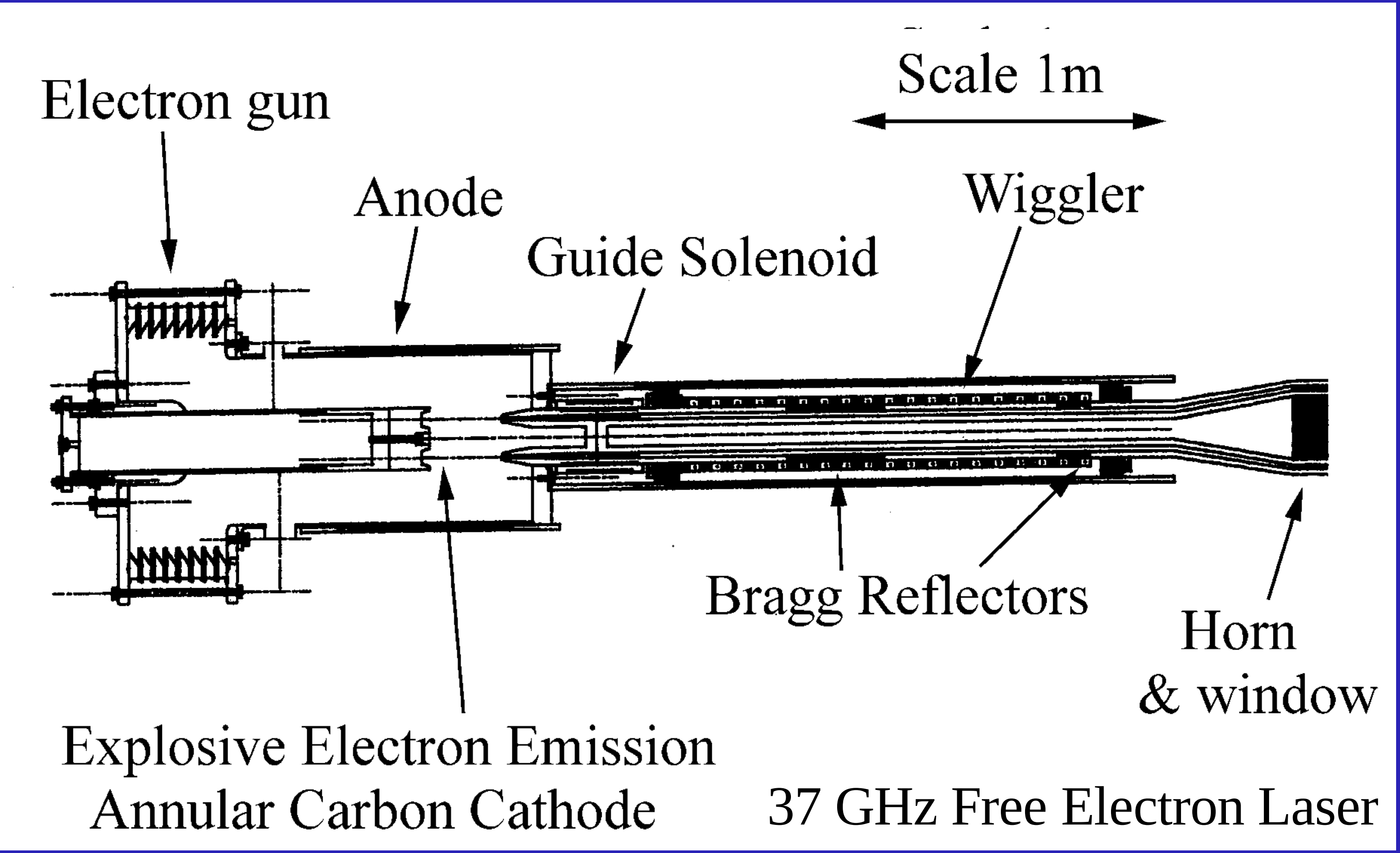
Comparison of four types of electron beam source



206 GHz four cavity klystron



Millimetre-wave free electron laser



Model and basic equations of 2D Bragg FEL

- The 2D Bragg corrugation of the waveguide surface can be defined as:

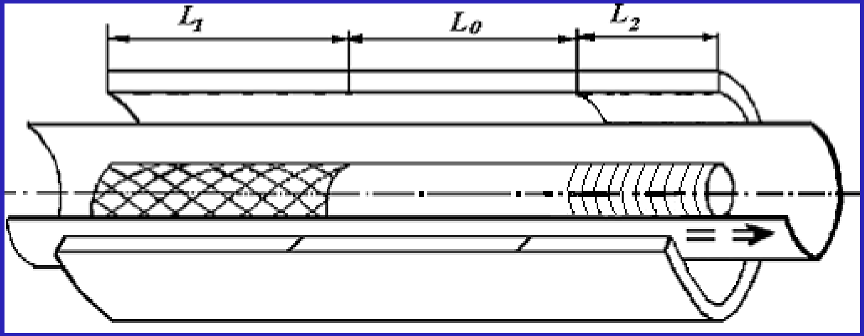
$$r(z,\varphi) = R_{in,out} + a_1 \cos(\bar{k}_z z)\cos(\bar{m}\varphi)$$

- EM field can be represented by four partial waves:

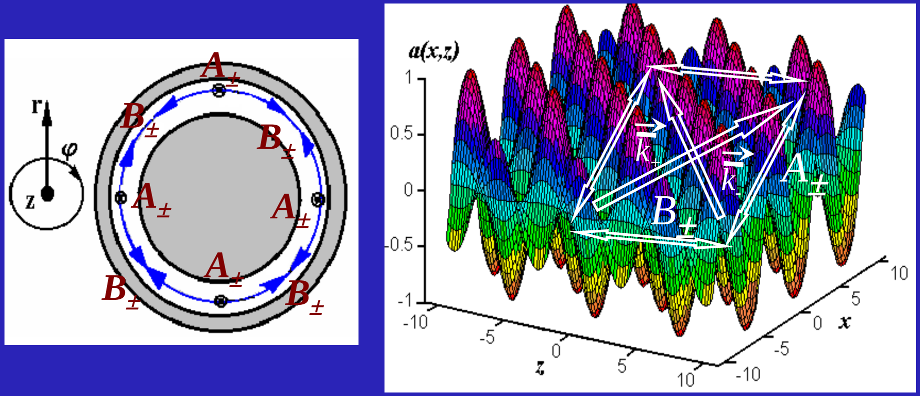
$$\vec{E} = \vec{A}_+ e^{-ik_z z} + \vec{A}_- e^{ik_z z} + \vec{B}_+ e^{-iM\varphi} + \vec{B}_- e^{iM\varphi}$$

M is the number of field variations along azimuthal co-ordinate φ. The partial waves $A_\pm$ propagate in $\pm$ *z* direction and $B_\pm$ are near cut-off waves. The waves are coupled on the corrugation if the following conditions are satisfied $k_z = k_z' \cong \bar{k}_z, \; |\bar{m}| = |M|$

- Schematic diagram of two-mirror 2D-1D FEM interaction region

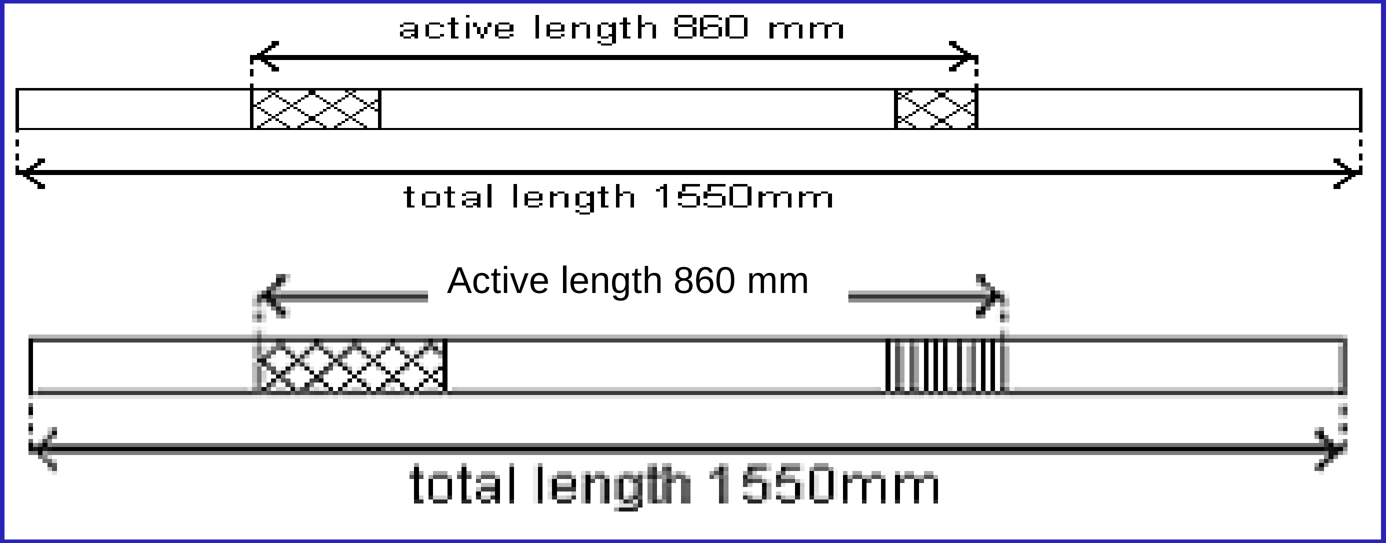


- Schematic diagram of 2D distributed feedback circle



Physical Review Letters <u>96</u>, art 035002, 2006

The FEL cavity configuration



(a) 2D-2D

(b) 2D-1D

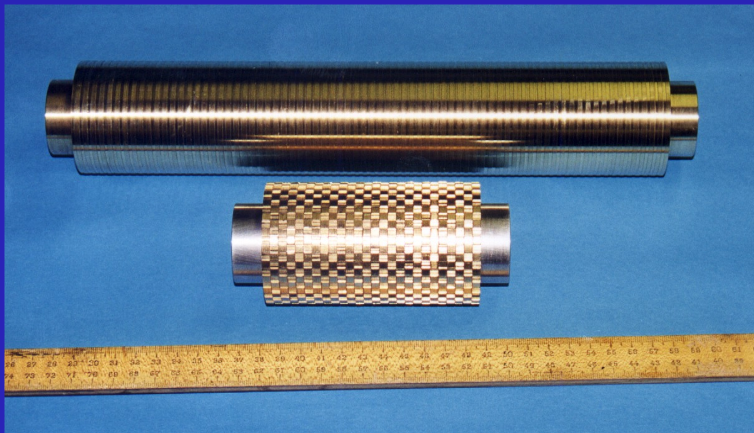
Schematic diagram of inner conductor with the corrugated structures

(a) 2D-2D

(b) 2D-1D

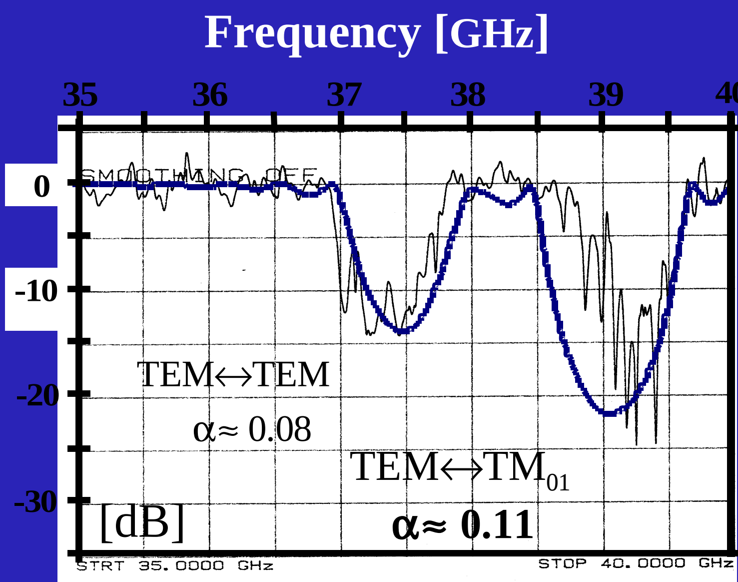
Photograph of inner conductor

Measurements of 1D and 2D Bragg structures

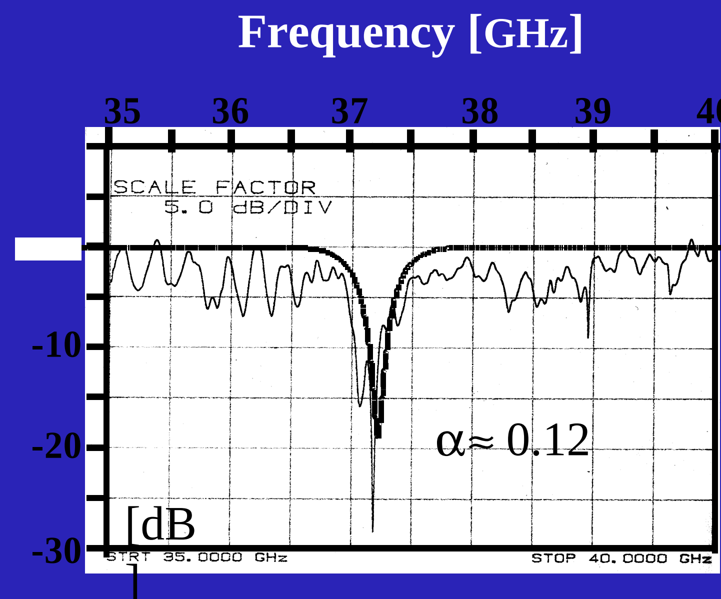


Co-axial 2D Bragg mirror

- constructed by machining square chessboard corrugations on the outer surface of the inner conductor

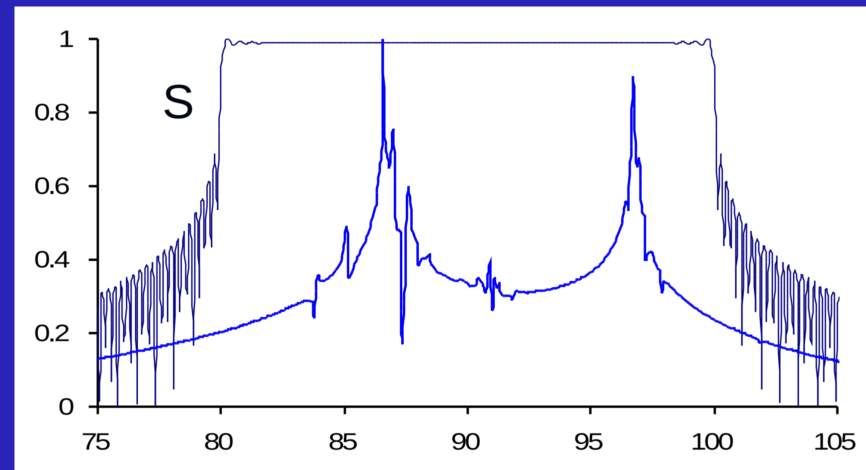


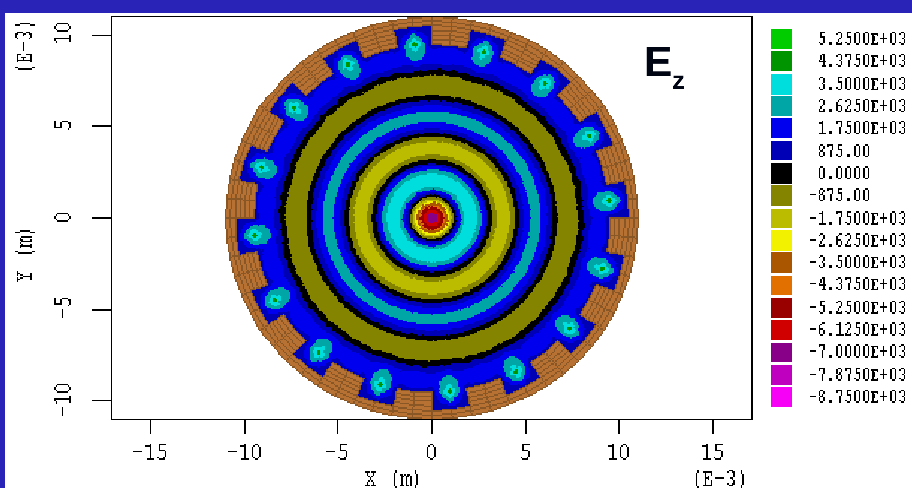
Millimetre wave transmission through the 1D Bragg structure of length l_z=30 cm

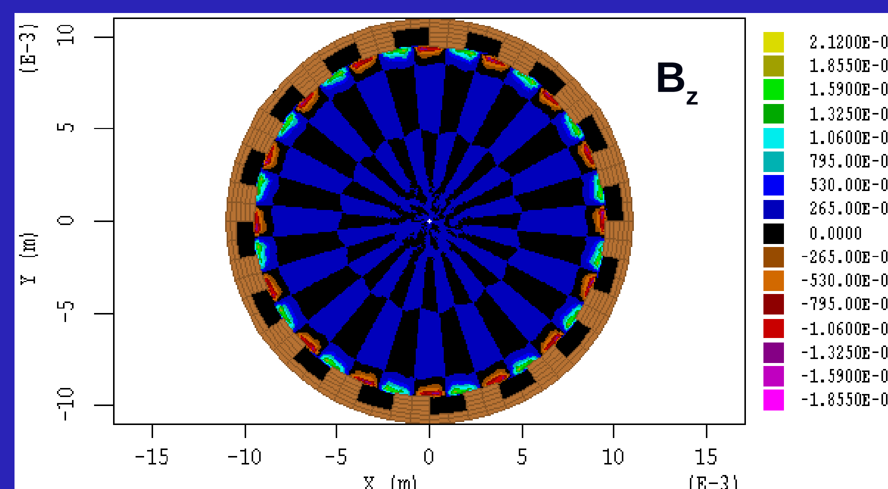


Millimetre wave transmission through the 2D Bragg structure of length l_z=4.8 cm

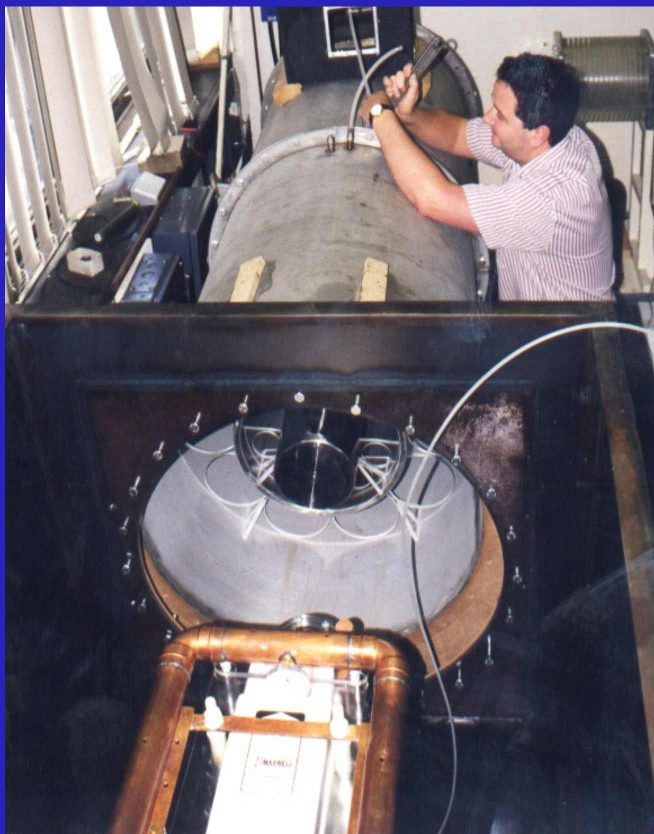
The spectra of a 7ns pump pulse at the input of the structure (thin line) and longitudinal electric fields (solid line) measured on the cavity's axis in the time frame (10ns – 30ns) having length 4.8 cm. The spikes are associated with cavity eigenmodes having radial indices *l*=6 and *l*=7. The contour plots of the longitudinal electric (E_z) and magnetic (B_z) components of the field inside the cavity observed using the 3D code MAGIC.



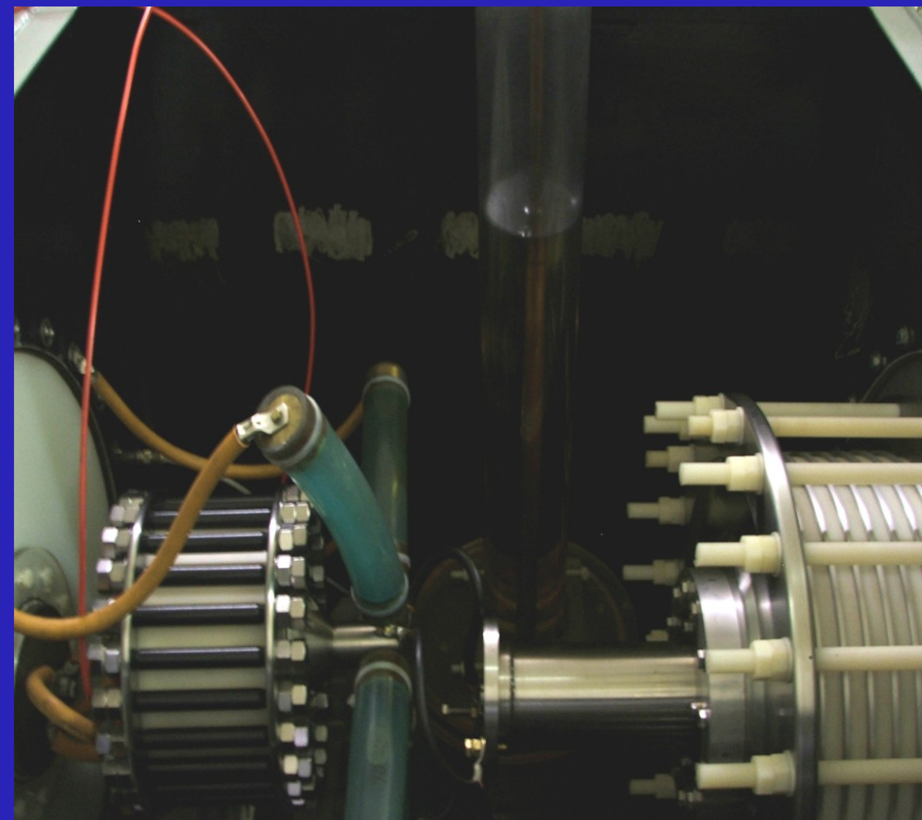




Pulsed power systems that drive the 600 MW electron beam

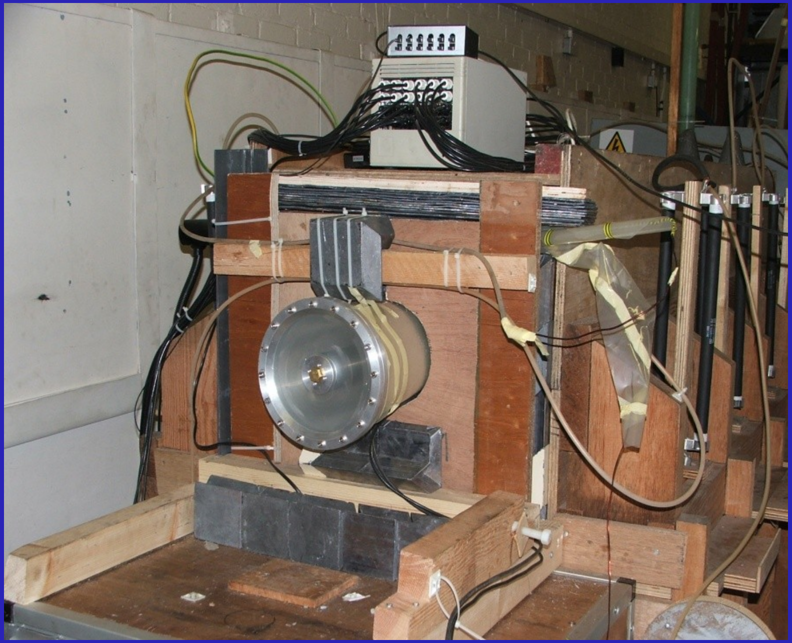


Assembly of the Marx pulsed power supply and the transmission line



Connection of the transmission line to the diode cathode via pressurised spark gap and matching resistors

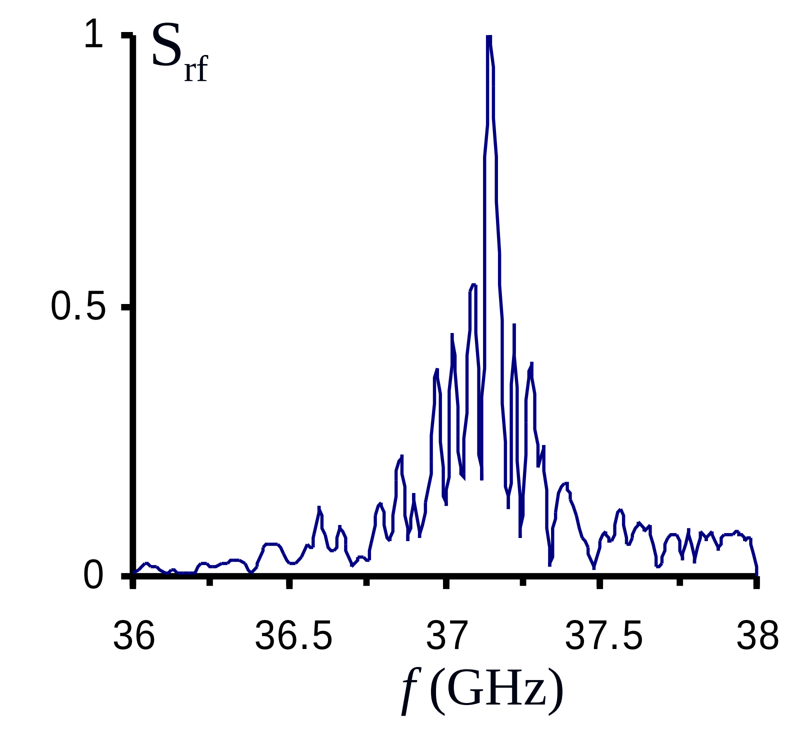
The FEL experiment



FEL apparatus to produce mm-waves

- co-axial output horn and Mylar window of diameter 0.2m
- matching resistors for capacitor bank powering solenoid
- ignitron switch and fibre optic controlled trigger unit
- solenoid of length 2.55m, diameter 0.3m with undulator inside
- 3D X-ray shielded enclosure

Heterodyne Frequency Diagnostics



Measured spectrum of the output radiation from the FEL
60 MW at 37.2 GHz

High power mm-wave amplifiers

- High power broadband mm-wave amplifiers are generally more difficult to achieve than the single frequency mm-wave oscillators

- A solution Strathclyde has been working on is the helical waveguide gyro-TWA (a type of gyro-TWT)

Use of dispersion graphs to design new RF sources

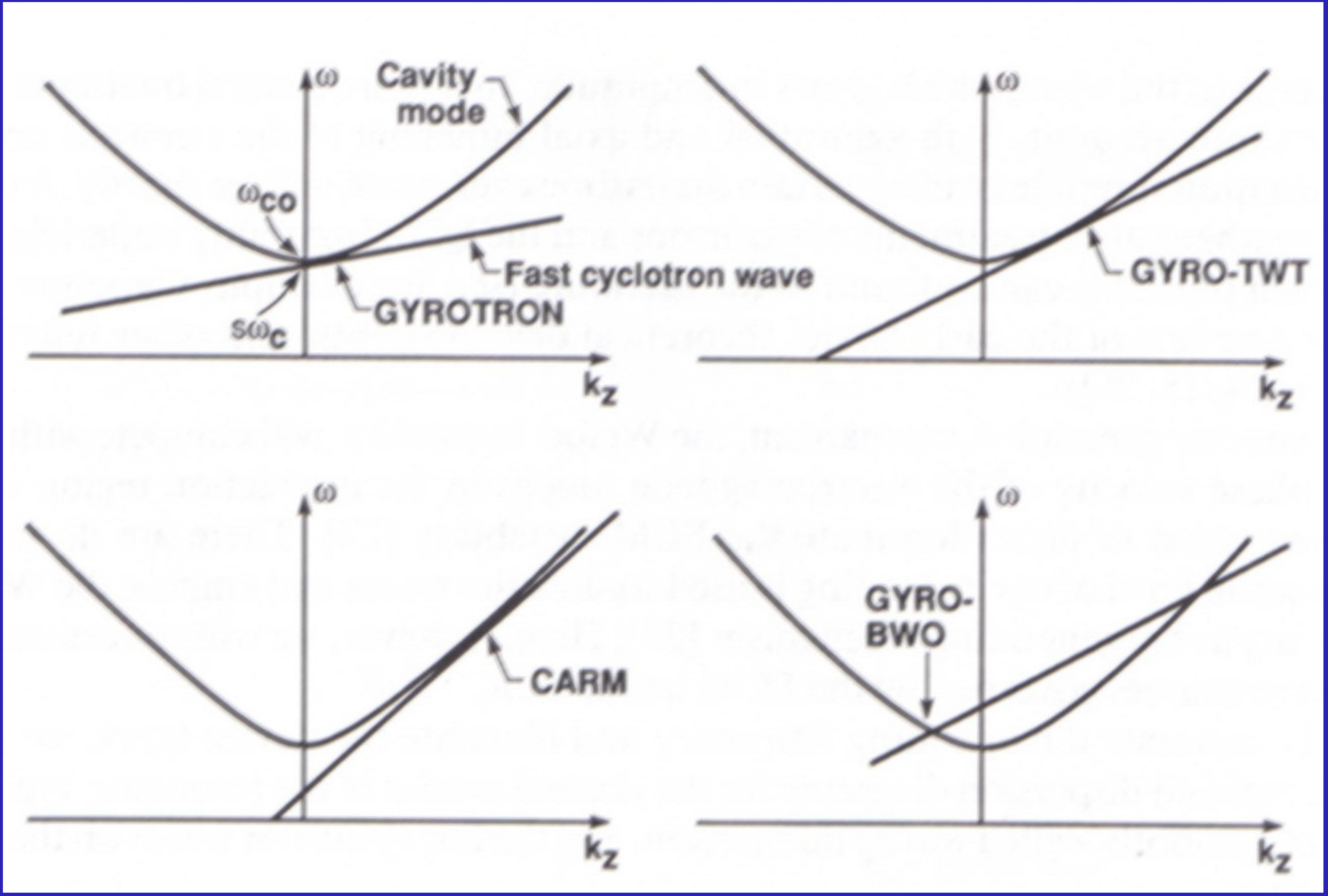
$$\omega^2 = \omega_{co}^2 + k_z^2 c^2$$

$$\omega = s\omega_c + k_z v_z$$

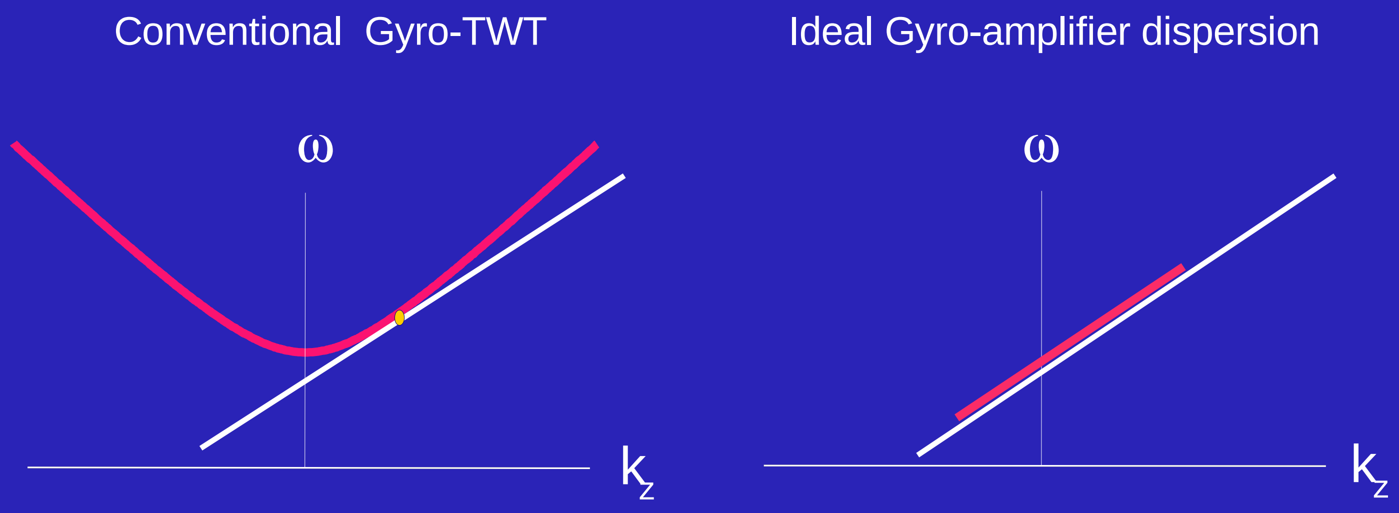
Where s is an integer, ω_c is the cyclotron frequency and ω_{co} is the cut-off frequency of the waveguide.

$$\text{where } \omega_c = \frac{eB}{\gamma m_e} \qquad \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$

Use of dispersion graphs to design new RF sources



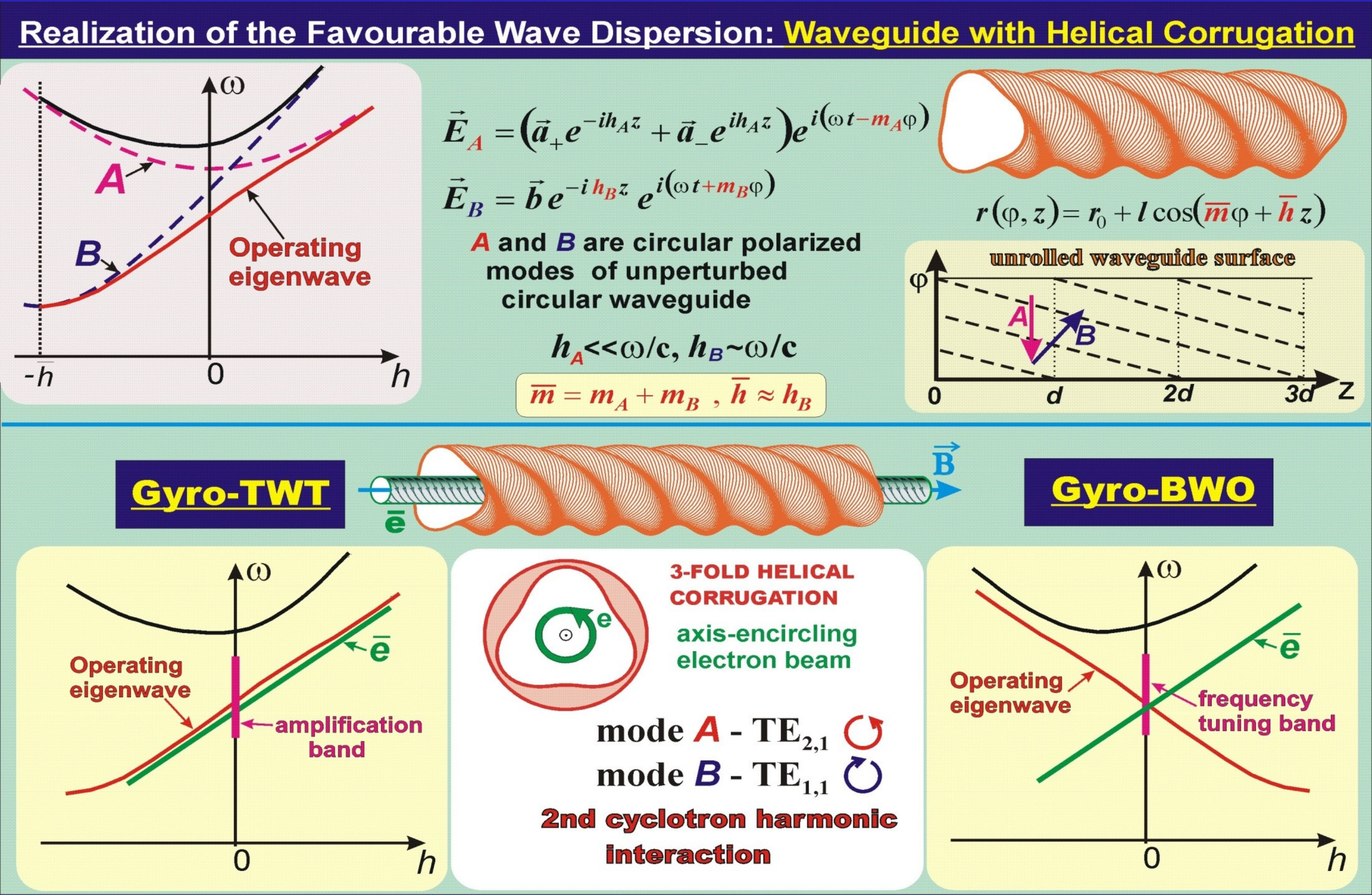
High power mm-wave amplifiers



Ideal dispersion can be realized by using a helically corrugated interaction waveguide

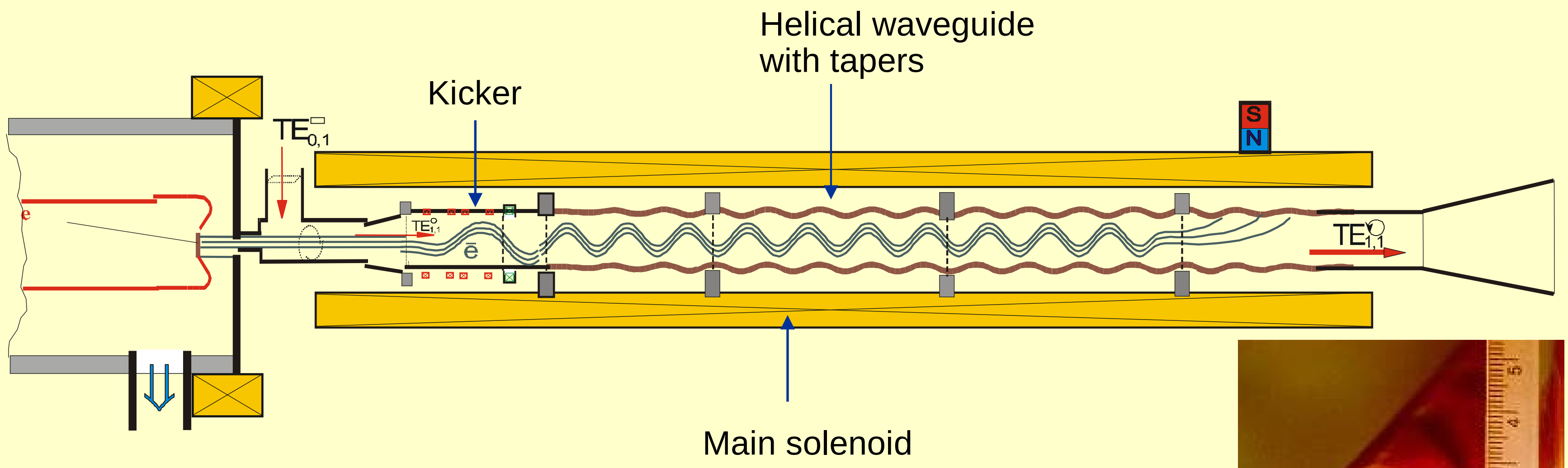
It changes the dispersion diagram such that an eigenwave of a constant group velocity (V_g=V_b) exists in the near-infinite phase velocity region (k_z=0) for a very wide frequency band.

Synthesis of Ideal mode to create new sources



High power mm-wave amplifiers

Gyro -TWA amplifier schematic

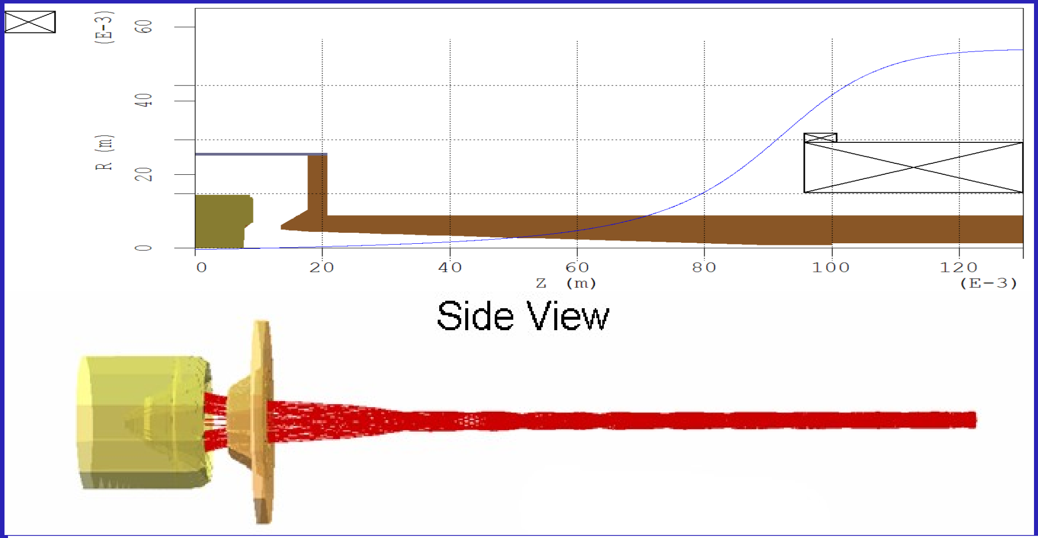


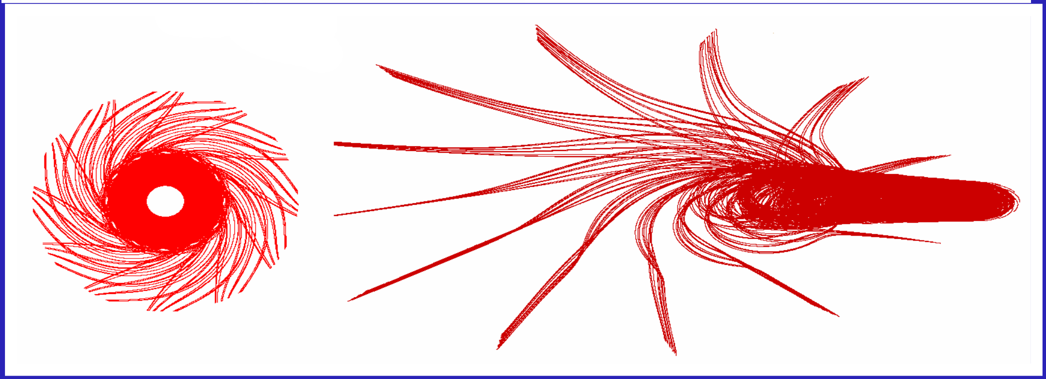
Physical Review Letters 81, 5680-5683, 1998
Physical Review Letters 84, 2746-2749, 2000
Physical Review Letters 92, art 118301, 2004

Modelling of a cusp gun for 390GHz gyrotron

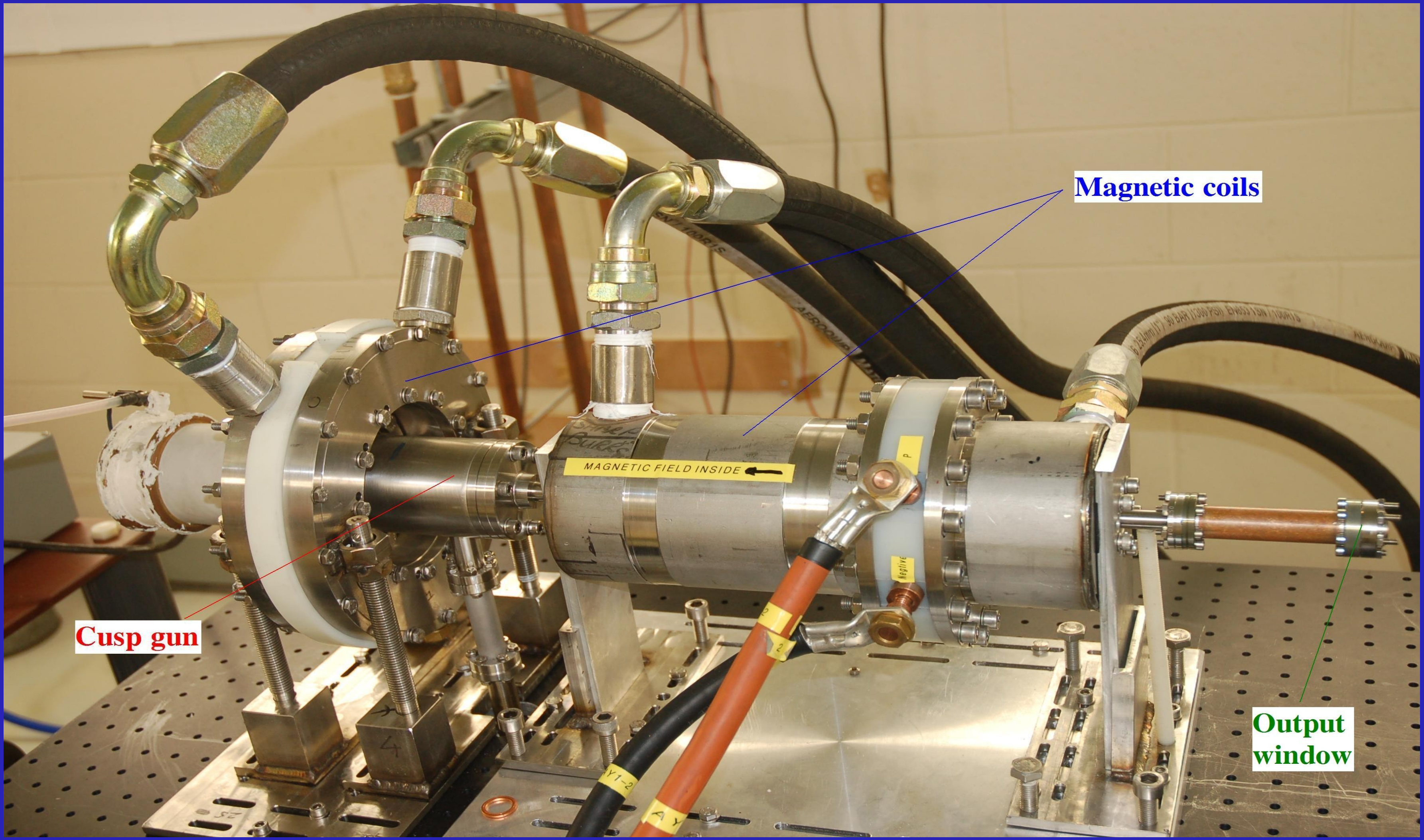
Cusp gun

- Axis-encircling, annular electron beam
- Better for energy recovery & mode selection
- Measurement agrees with simulation: 40kV 1.5A



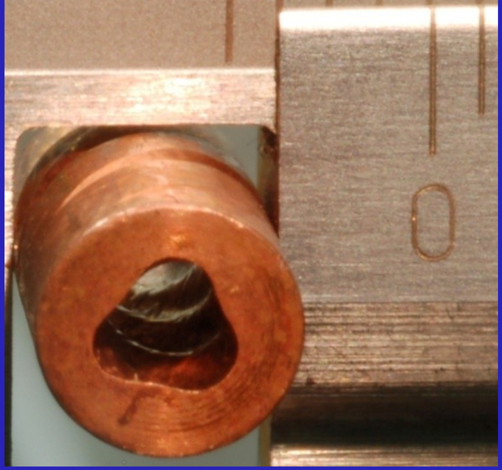


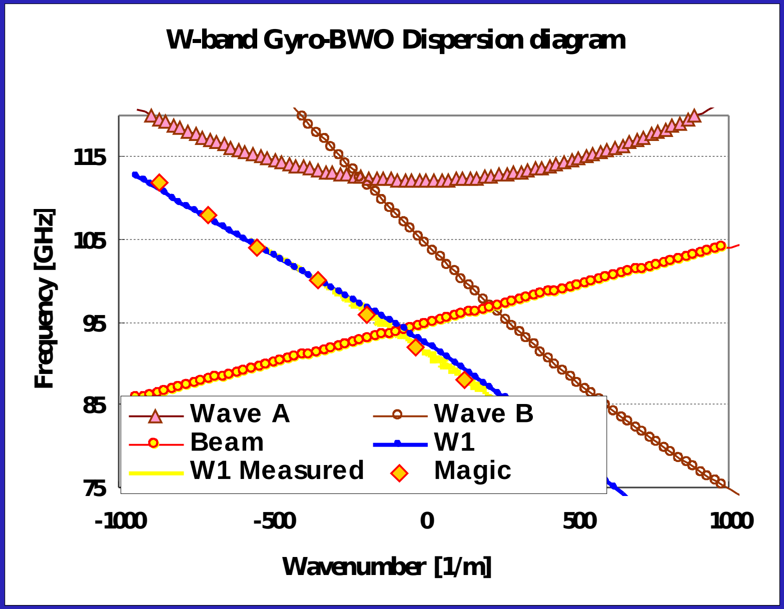
Wideband W-band gyro-device

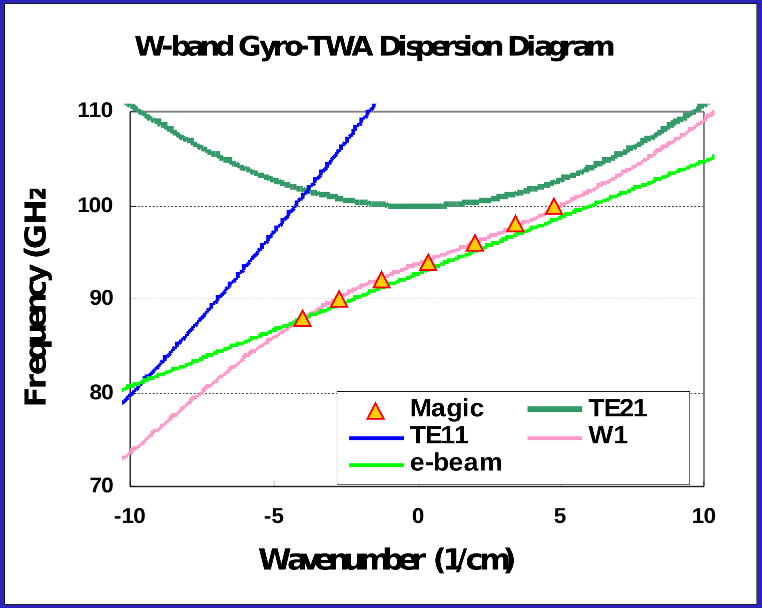


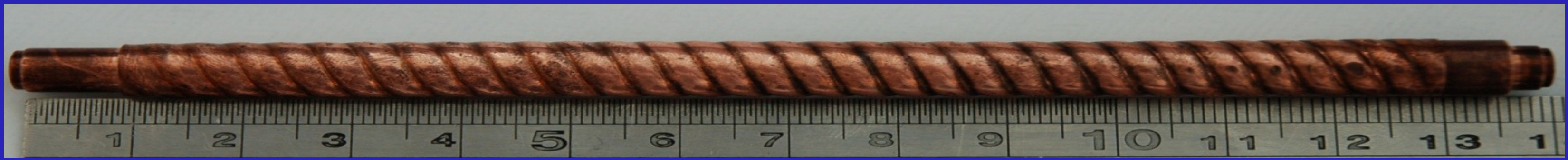
Helical interaction waveguide

- High power, high frequency, high efficiency
- Wide frequency band

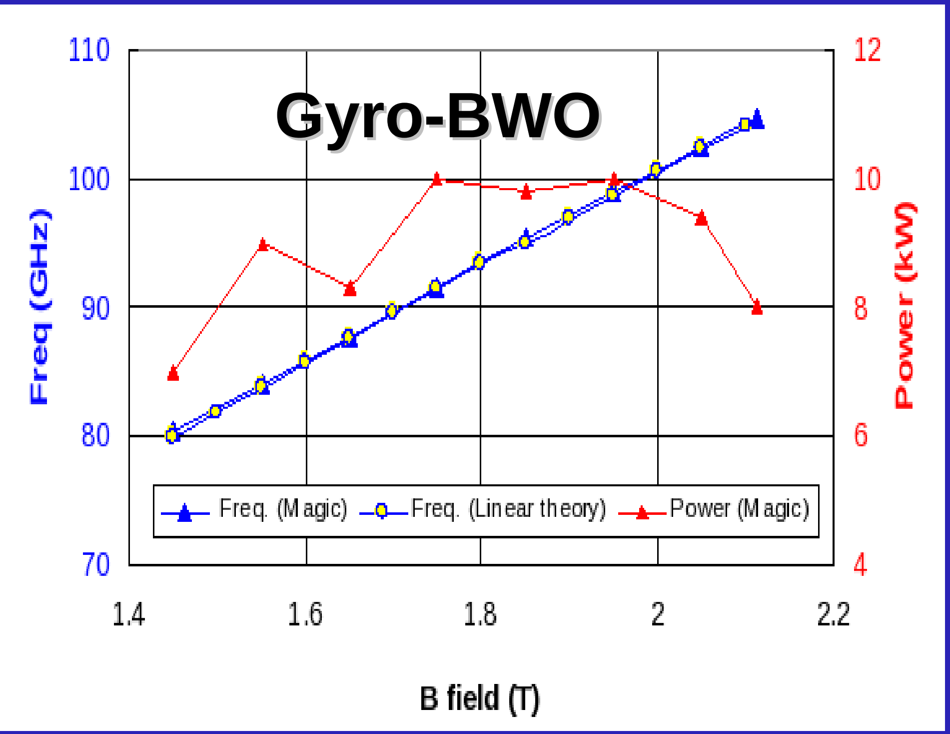


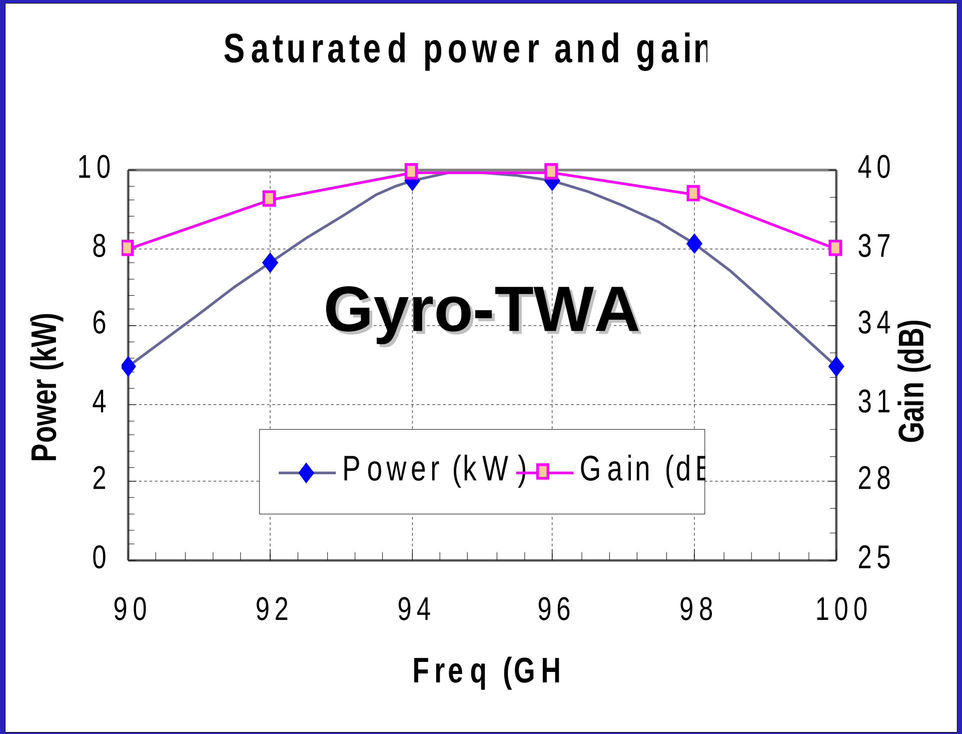






Predicted Performance



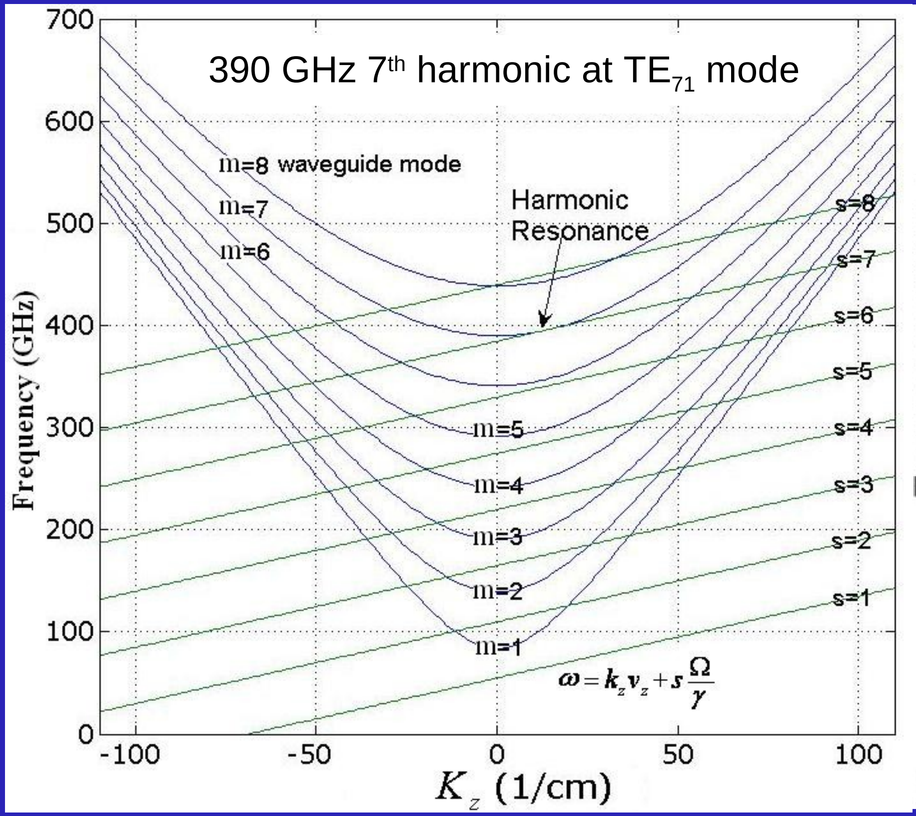


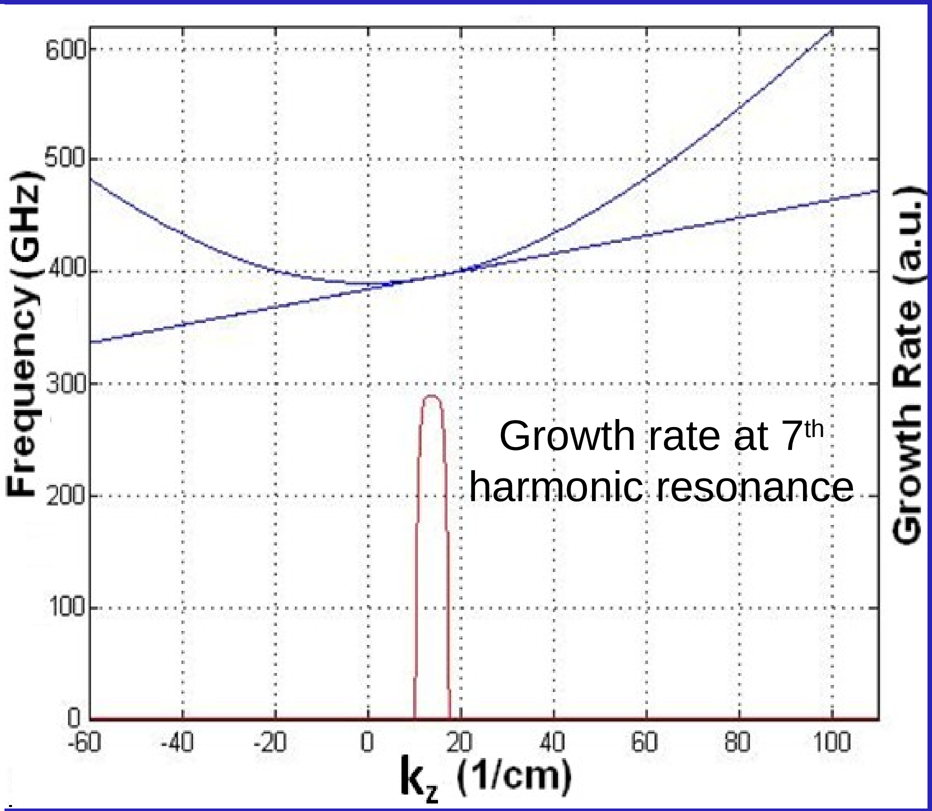
Centre freq. ≈ 94 GHz
Tuning range ≈ 20%
Maximum power ≈ 10 kW
Efficiency ≈ 15%

Centre freq. ≈ 95 GHz
Freq. bandwidth ≈ 10%
Maximum power ≈ 10 kW
Efficiency ≈ 15%
Gain = 40dB

390 GHz Harmonic Gyrotron

Design and simulation of a CW source based on a cusp gun and working at the 7th harmonic number

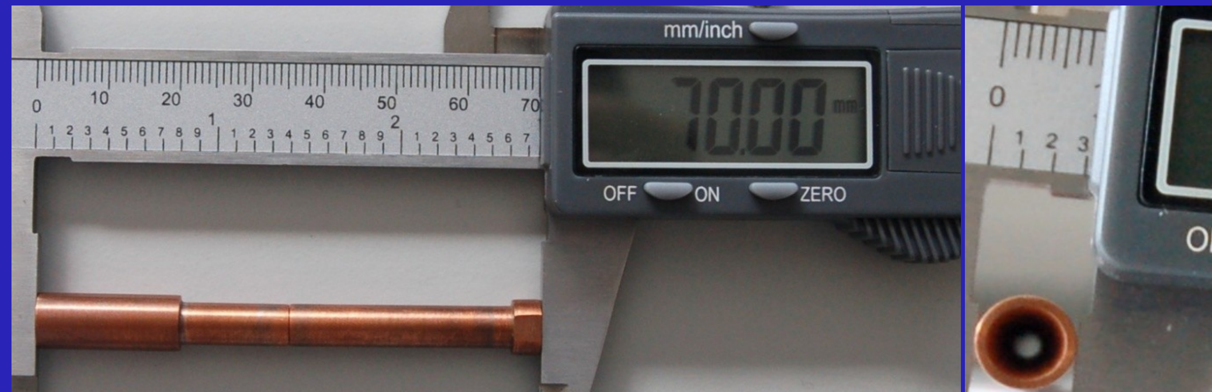




Cavity & Cold Test

Cavity designed

& manufactured



Cold tested with
300-500 GHz VNA

Average Losses:

Spark Erosion:
-0.5 dB

Drilled Cavity
-3.1 dB

Co-harmonic gyrotron using a novel corrugated cavity

Mean radius, r_0 = 8 mm

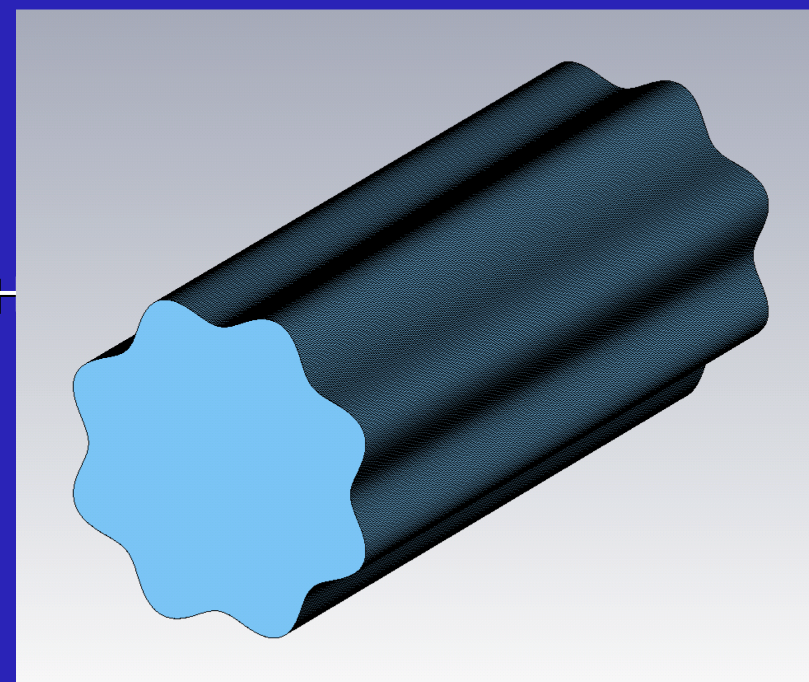
Corrugation depth, l = 0.7 mm

Length, L = 39 mm

$$r(\phi) = r_0 + l\sin(8\phi)$$

Modes excited:

- 2nd harmonic, $TE_{2,2}$ (37.5 GHz)
- 4th harmonic, $TE_{4,3}$ (69.7 GHz & 75 GH



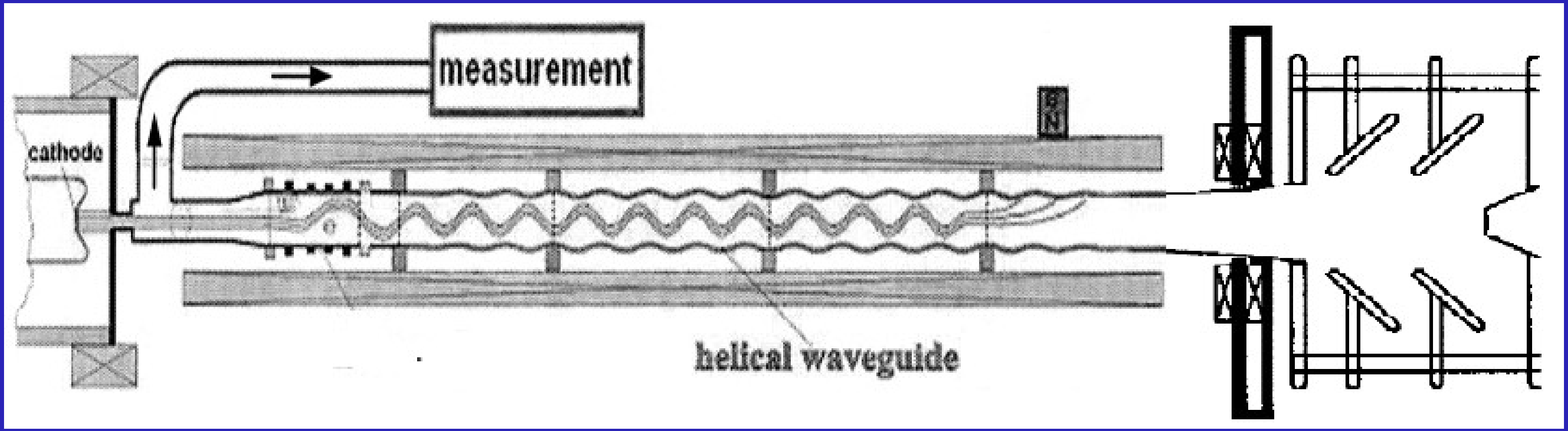
Suggested beam parameters:

- Beam voltage, 60 kV
- Beam current, 5 A
- Pitch angle, 45 degrees
- Magnetic field, 0.7 T
- Axis-encircling beam

Depressed collector research

Advantages of depressed collector

- Improve the overall tube efficiency
- Decrease cooling requirement
- Decrease x-ray emission



Depressed collector

$$\eta_{overall} = \frac{P_{output}}{P_{beam} - P_{collected}}$$

Depressed Collector Simulation

Simulation uses 3D PIC code MAGIC

Genetic algorithm used to optimize geometry

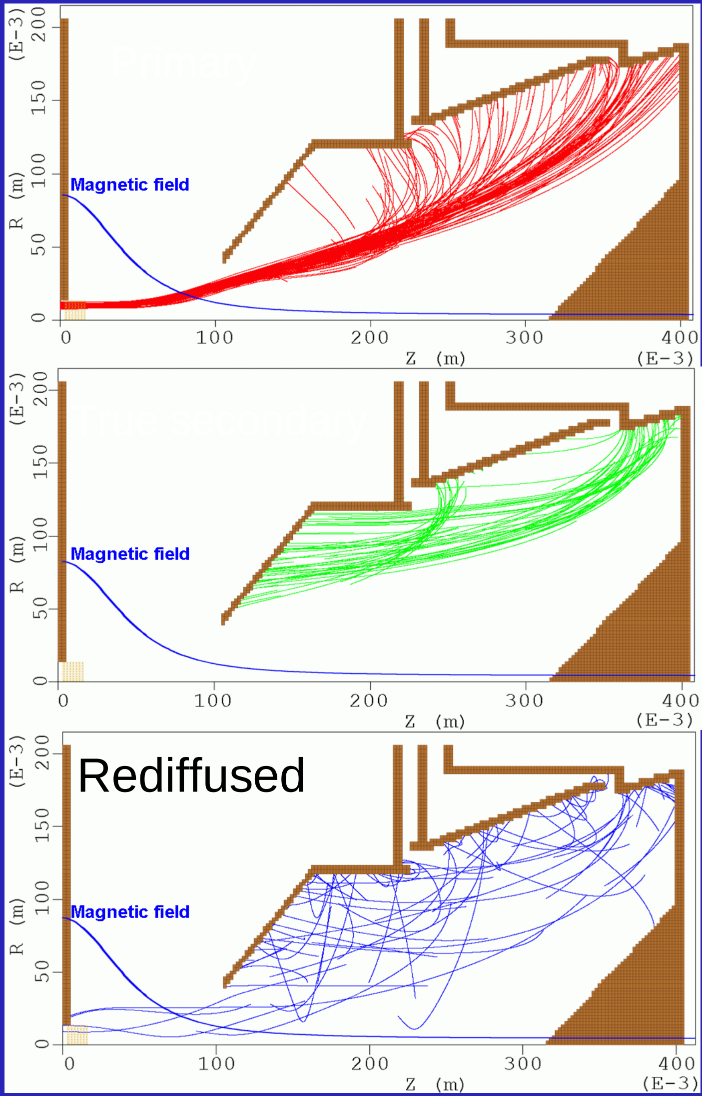
Effect of secondary electrons, including true secondary electrons and rediffused electrons

Heat power density distribution on electrodes

Simulation of X-band Gyro-BWO and W-band Gyro-BWO

L. Zhang, et al, IEEE Trans. Plasma Sci., 37, 390-394, 2009

L. Zhang, et al, IEEE Trans. Plasma Sci., 37, 2328-2334, 2009



SUPA II project to apply plasma-based accelerators

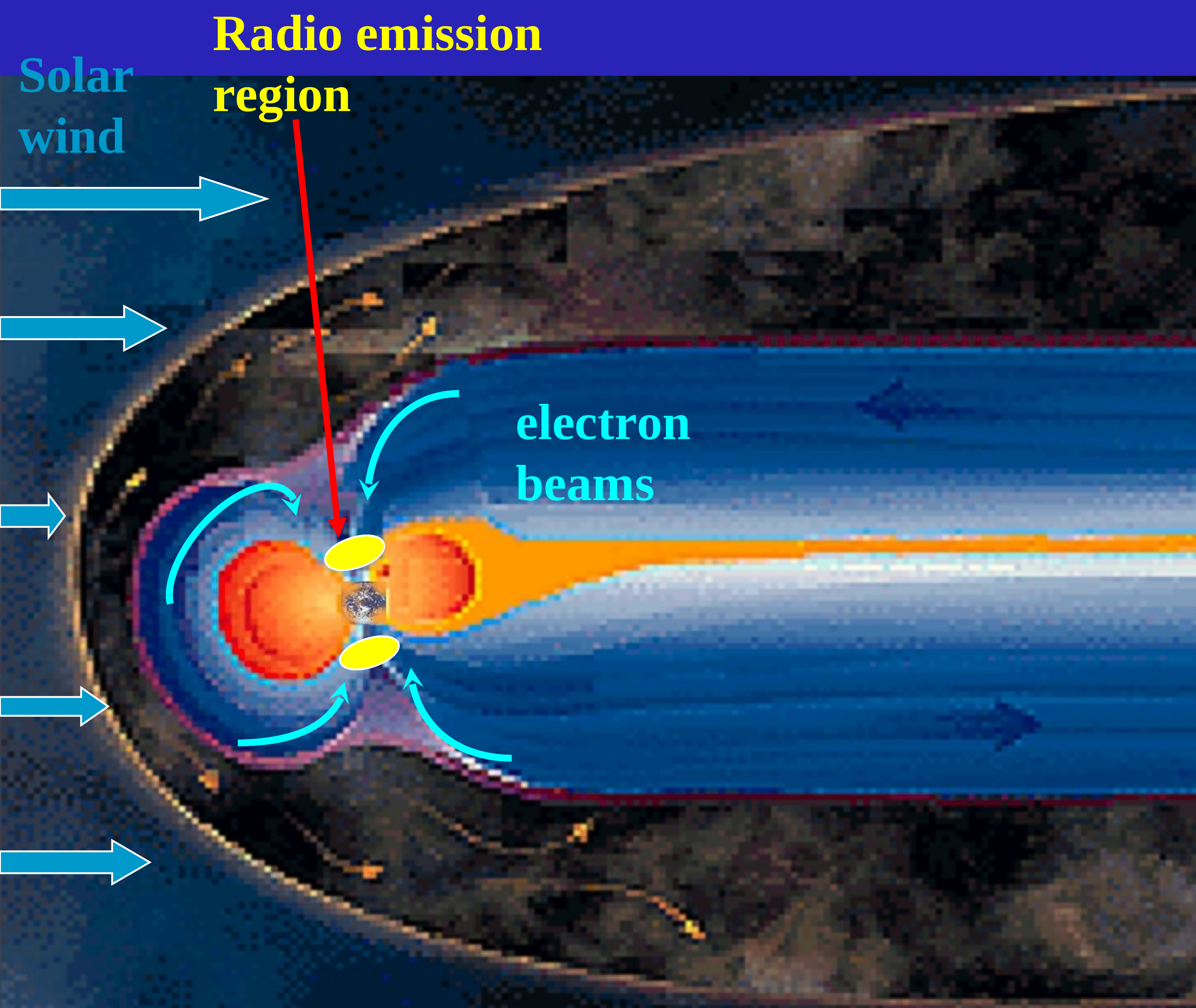
Auroral Kilometric Radiation - AKR

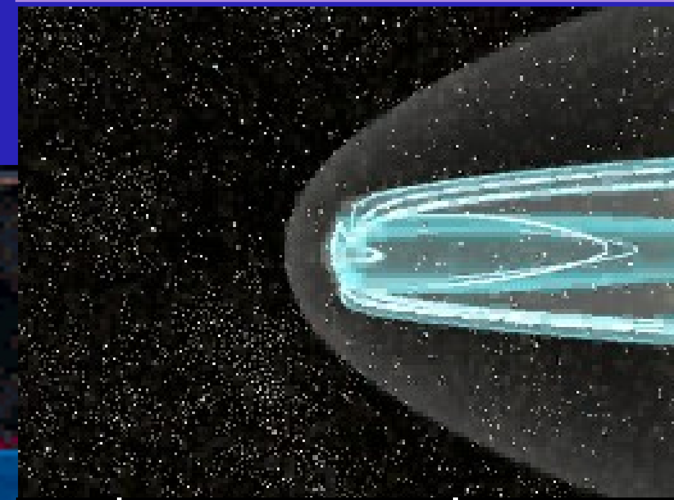
Aurora Borealis – Northern Lights

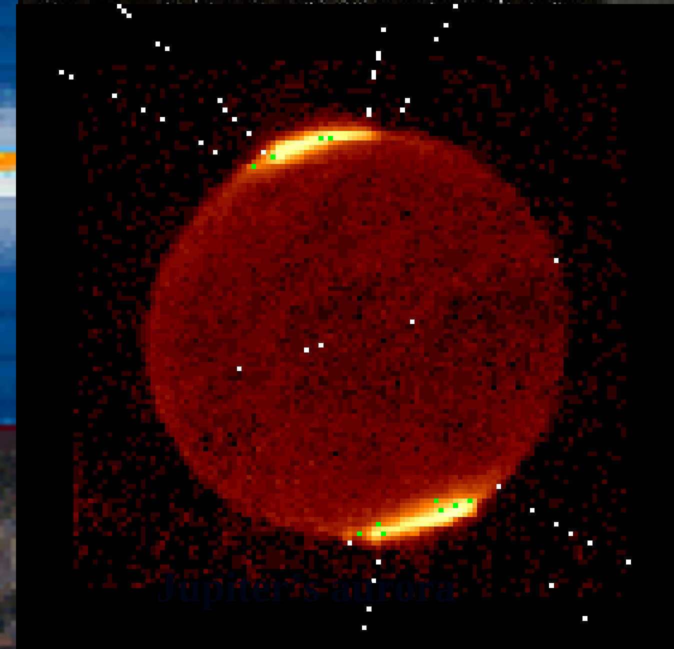
Planetary Magnetospheres

All solar system planets with strong magnetic fields (Jupiter, Saturn, Uranus, Neptune, and Earth) also produce intense radio emission – with frequencies close to the cyclotron frequency.

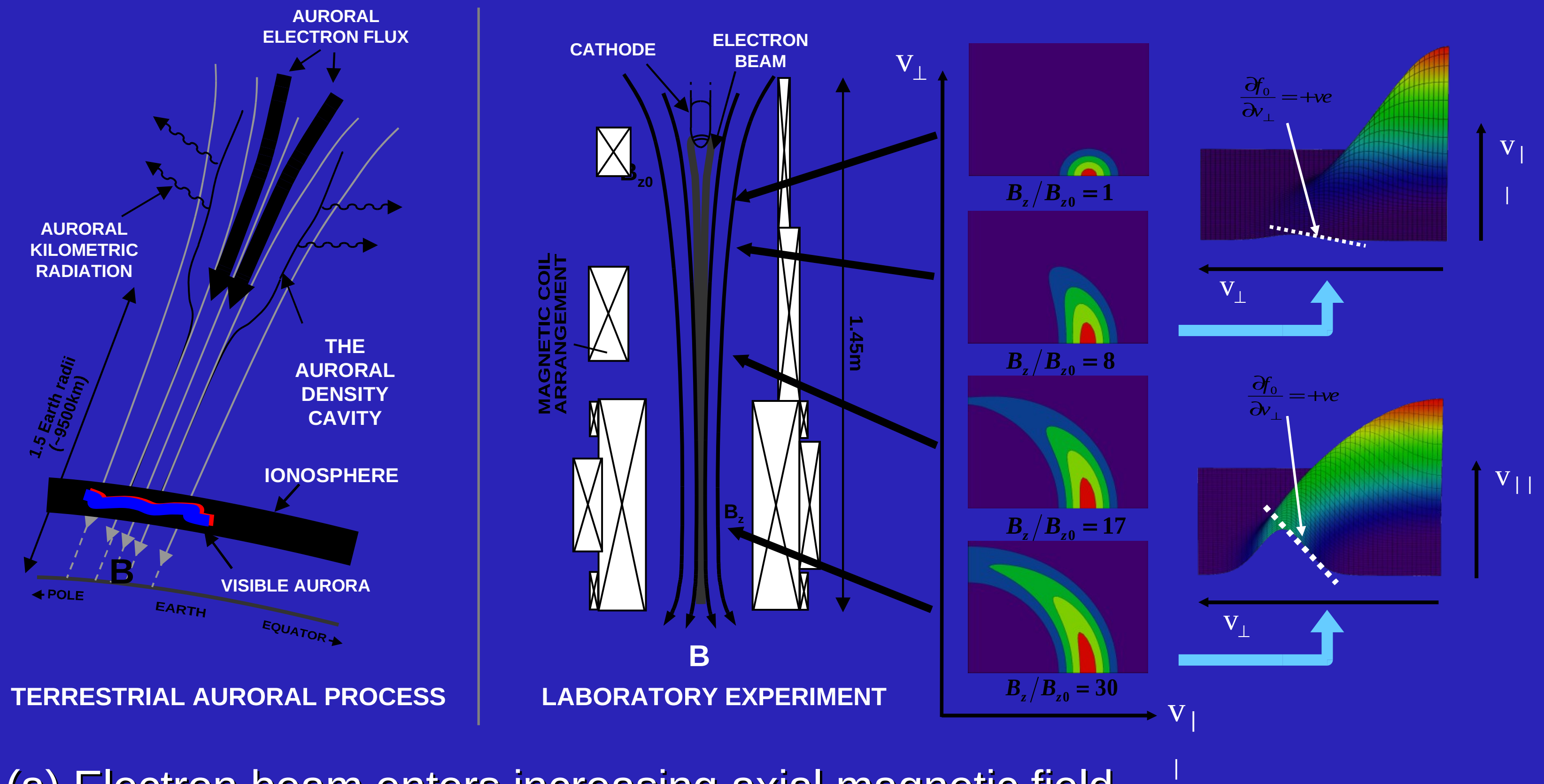


Planetary Aurora





Natural radiation sources – formation of an electron horseshoe distribution

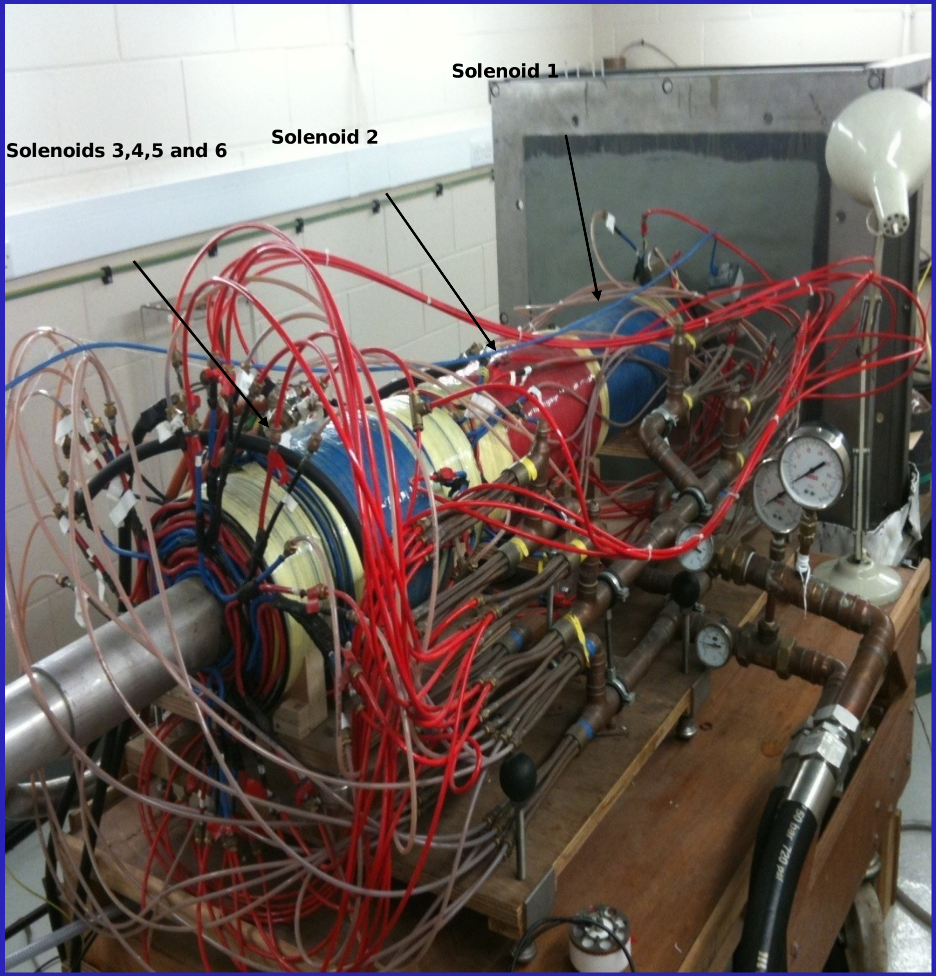


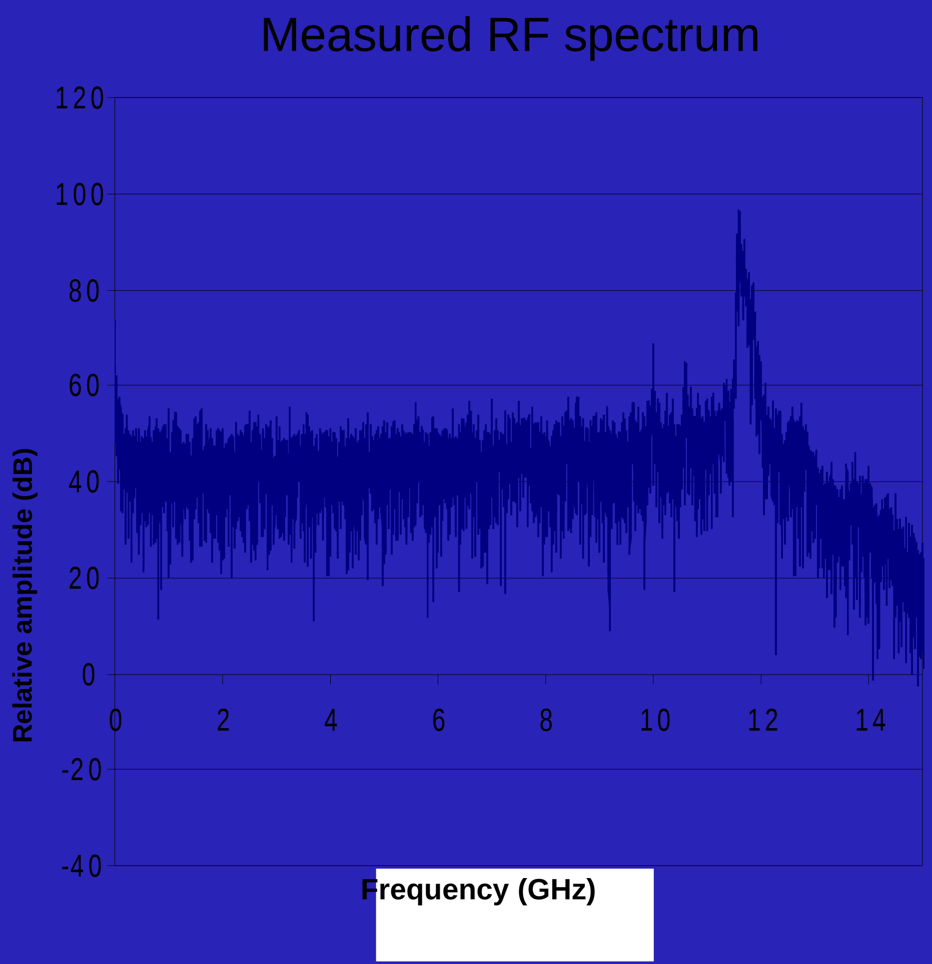
(a) Electron beam enters increasing axial magnetic field

(b) Electrons gain transverse velocity at the expense of axial velocity.

(c) Beam distribution function develops horseshoe-like profile.
- *positive gradient* in *transverse velocity* near the tip of the distribution.

AKR Strathclyde Laboratory Experiment





Conclusions

- Particle-wave interaction synergy of sources & accelerators
- High power mm-wave oscillators achieving MWs
- High power mm-wave amplifiers – novel solutions
- MM-wave research moving into THz range
- Microwave/RF ultra-high power sources ~1GHz
- Laser plasma accelerators for applications

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