Research Progress at Strathclyde
relevant to Accelerators

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Introduction

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

View of the river clyde, Glasgow

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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

Aberdeen
Dundee
St Andrews
Edinburgh
Heriot Watt
Glasgow
Strathclyde
West of Scotland
Research Themes in SUPA

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

Diode discharge Optical/UV emissions during pulsed gyrotron operation

Carbon Cathode, 27mm Diode Gap Cavity Magnetic Field, 3.3 Tesla

$v_e = c/3$
$\Delta \tau = 6$ns
Mm-wave sources using a pseudospark generated electron beam

**Diagram Description:**
- **Left Panel:**
  - Hollow cathode
  - Insulator
  - Anode
  - Electron beam
  - Discharge gap
  - Diagram labeled with various components and connections.

- **Right Panel:**
  - Graph showing discharge voltage vs. time,
  - Graph showing discharge current vs. time,
  - Graph showing beam current by Rogowski coil vs. time,
  - Graph showing beam current by Faraday cup after Tungsten mesh vs. time.

**Graph Details:**
- **x-axis:** Time [ns]
- **y-axis:**
  - Discharge Voltage [kV]
  - Discharge Current [A]
  - Beam Current by Rogowski Coil [A]
  - Beam Current by Faraday cup after Tungsten Mesh [A]

**Additional Notes:**
- The pseudospark region and vacuum breakdown are indicated on the graph.
- The discharge gap is labeled as \((pd)_{min}\).
- The schematic diagram includes connections and labels for various components such as cathode, anode, vacuum gauge, and drift tube.
Cherenkov maser using high brightness electron beam from pseudospark source

Hollow cathode  Anode  Solenoid  Launching horn

Electron beam  Waveguide

Dielectric (alumina)
Experimental setup of the 14-gap PS powered by a cable pulser and beam-wave interaction investigation
BWO Interaction Region

W-band (75 to 110)GHz

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

1mm Aperture, 2 Disk, 10kV

[Graph showing voltage and beam current over time]
Comparison of four types of electron beam source

![Graph showing comparison of electron beam sources]
206 GHz four cavity klystron
Millimetre-wave free electron laser

Electron gun
Anode
Guide Solenoid
Wiggler
Bragg Reflectors
Horn & window
Explosive Electron Emission
Annular Carbon Cathode
37 GHz Free Electron Laser
Model and basic equations of 2D Bragg FEL

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

\[ r(z, \phi) = R_{in, out} + a_1 \cos(\bar{k}_z z) \cos(m \phi) \]

- EM field can be represented by four partial waves:

\[ E = A_\pm e^{-i k_z z} + A_\mp e^{i k_z z} + B_\pm e^{-i M \phi} + B_\mp e^{i M \phi} \]

\( M \) is the number of field variations along azimuthal co-ordinate \( \phi \). 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

\[ k_z = k'_z \cong \bar{k}_z, \quad |m| = |M| \]

Physical Review Letters 96, art 035002, 2006
The FEL cavity configuration

Schematic diagram of inner conductor with the corrugated structures

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

$$\alpha \approx 0.08$$

$$\alpha \approx 0.11$$

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

$$\alpha \approx 0.12$$
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, \( \omega_c \) is the cyclotron frequency and \( \omega_{co} \) is the cut-off frequency of the waveguide.

\[ \omega_c = \frac{eB}{\gamma m_e} \quad \gamma = (1 - \frac{v^2}{c^2})^{-1/2} \]
Use of dispersion graphs to design new RF sources
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

Realization of the Favourable Wave Dispersion: Waveguide with Helical Corrugation

\[ \tilde{E}_A = (\tilde{a}_+ e^{-i\hbar_A z} + \tilde{a}_- e^{i\hbar_A z}) e^{i(\omega t - m_A \phi)} \]

\[ \tilde{E}_B = b e^{-i\hbar_B z} e^{i(\omega t + m_B \phi)} \]

\( A \) and \( B \) are circular polarized modes of unperturbed circular waveguide

\( h_A \ll \omega/c, h_B \sim \omega/c \)

\( \overline{m} = m_A + m_B, \overline{h} \approx h_B \)

Gyro-TWT

Gyro-BWO

3-Fold Helical Corrugation

axis-encircling electron beam

mode A - TE\(_{2,1}\)

mode B - TE\(_{1,1}\)

2nd cyclotron harmonic interaction
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

![W-band Gyro-BWO Dispersion diagram](image1.png)

![W-band Gyro-TWA Dispersion Diagram](image2.png)
Predicted Performance

Gyro-BWO
- Centre freq. $\approx$ 94 GHz
- Tuning range $\approx$ 20%
- Maximum power $\approx$ 10 kW
- Efficiency $\approx$ 15%

Gyro-TWA
- Centre freq. $\approx$ 95 GHz
- Freq. bandwidth $\approx$ 10%
- Maximum power $\approx$ 10 kW
- Efficiency $\approx$ 15%
- Gain = 40 dB
390 GHz Harmonic Gyrotron

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

390 GHz 7th harmonic at TE_{71} mode

Growth rate at 7th harmonic resonance
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

Modes excited:
- $2^{nd}$ harmonic, $TE_{2,2}$ (37.5 GHz)
- $4^{th}$ harmonic, $TE_{4,3}$ (69.7 GHz & 75 GHz)

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

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

Advantages of depressed collector

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

\[ \eta_{\text{overall}} = \frac{P_{\text{output}}}{P_{\text{beam}} - P_{\text{collected}}} \]
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

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.
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.
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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