# WP5 Exotic Undulator,Tasks List

## David Zhu, Liang Zhang, Wenlong He, Adrian Cross

- Sub-Task 1 – Laser undulator design
- Sub-Task 2 – Plasma undulator design
- Sub-Task 3 – RF undulator design (ANSTO & Strathclyde)
  - RF undulator research overview
  - RF undulator physics
  - RF undulator design and numerical simulations
  - Feasibility evaluation of RF undulator for use in CompactLight
- Future Work

H2020 CompactLight, 19th -20th June 2018, Trieste, Italy

# Principle of FEL

Coherent wavelength is given by

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{k^2}{2}\right)$$

$\lambda_u$ is the period of the undulator

Typically best values are (e.g. Swiss FEL)

$$\lambda_u = 15\text{mm}$$

$$k = \frac{|e|\lambda_u B_0}{2\pi mc}$$

$k$ is the undulator strength parameter

Consequently for $\lambda$ =0.1nm

$$E \sim 6\text{GeV}$$

# Laser Driven Dielectric Undulator

- Proposed by T. Plettner in 2007
- Small period of 0.3 mm, k = 0.14
- Difficulties:
  - The beam should have small emittance
  - It is difficult to keep electric field in phase with the electron bunch

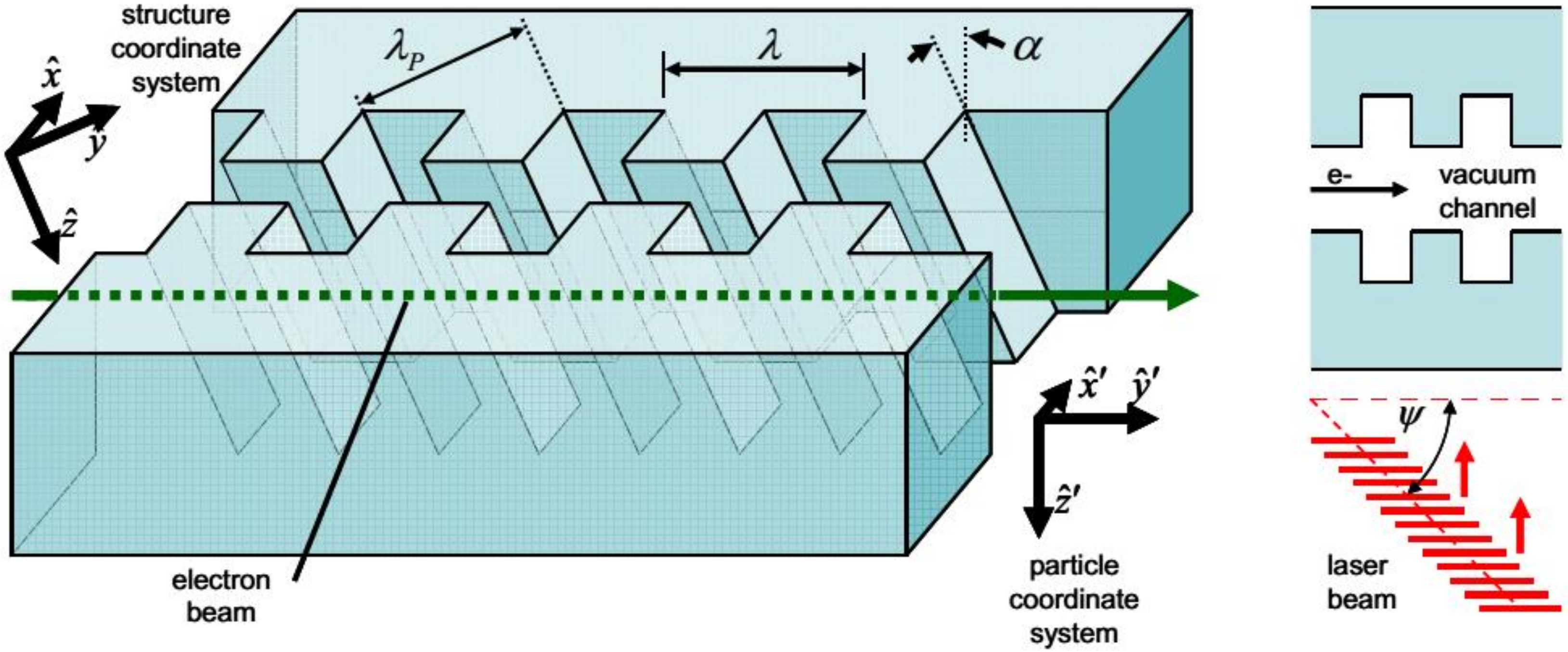


Figure source: T. Plettner and R. L. Byer, PRST-AB 11, 030704 (2008)

# Plasma Undulator

- J.W. Wang, C.B. Schroeder, R. Li, M. Zepf and S.G. Rykovanov, "Plasma channel undulator excited by high-order laser modes" Science Reports, 16884, (2017)
- Small period of ~1 mm, k = 0.44, Nos of periods 20
- Laser-created plasma undulator together with a laser-plasma electron accelerator (LPA), it is an open question whether these plasma undulators can be used as an FEL
    - Large radiation spread caused by varying values of undulator strength k
    - Strong focusing and hence large electron beam divergence
    - Electron trajectories are not independent of the injection positions
    - Stability of plasma undulator dependent on the laser and plasma stability

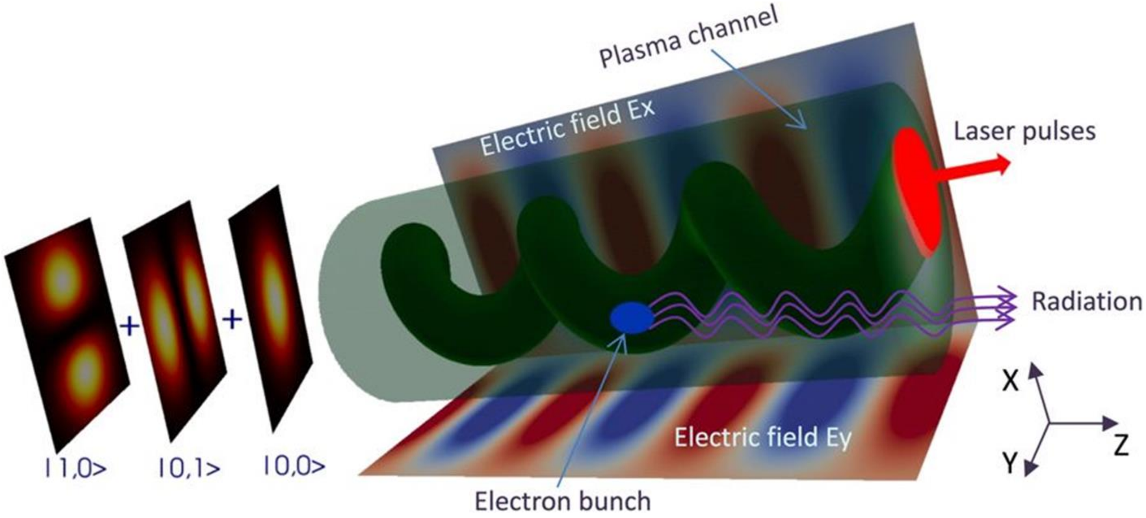


Figure source: J.W. Wang et al, Science Reports, 16884, (2017)

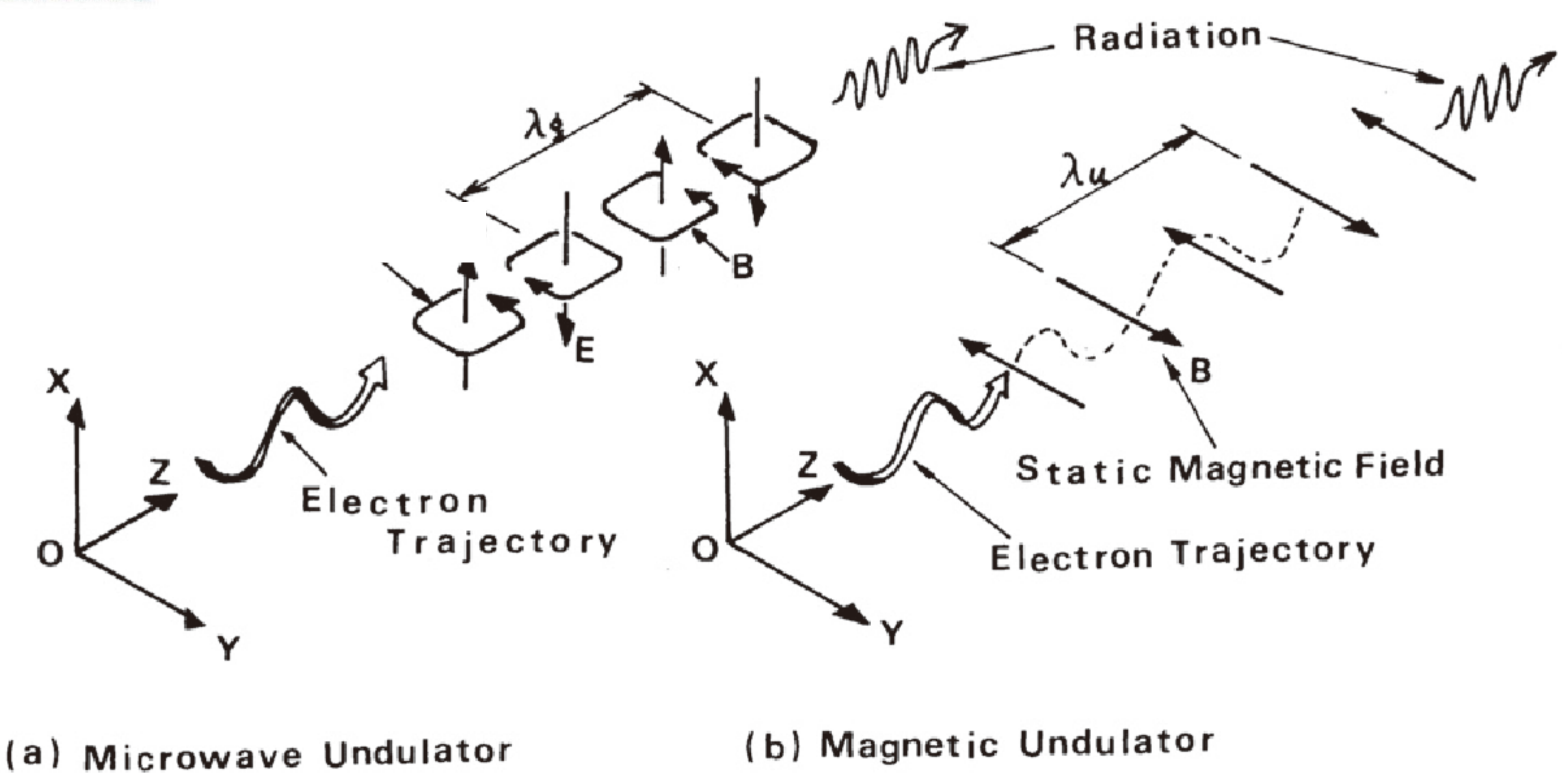
# Microwave undulator (UK XFEL)

Liang Zhang[1,2], Wenlong He[1], Jim Clarke[2,3] & Adrian Cross[1,2]

[1]Department of Physics, SUPA, University of Strathclyde, Glasgow, G4 0NG, UK
[2]The Cockcroft Institute, Daresbury Laboratory, Warrington. WA4 4AD, UK
[3]Science and Technology Facilities Council, Daresbury Laboratory,
Warrington, WA4 4AD, U.K.

H2020 CompactLight, 19th -20th June 2018, Trieste, Italy

# Microwave undulator



$$E_x = E_0 \sin(2\pi z/\lambda_g) \cdot \sin(\omega t)$$
$$B_y = B_0 \cos(2\pi z/\lambda_g) \cdot \cos(\omega t)$$
$$F_x = -e(E_x - v_z B_z)$$

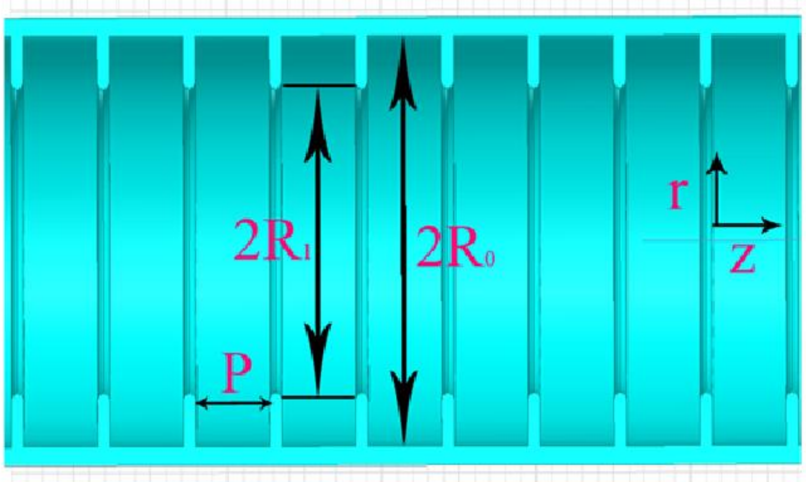
$$B_y = B_0 sin(2\pi z/\lambda_u) = B_0 sin(k_u z)$$
$$F_x = e v_z B_z$$

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

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

# Hybrid modes – HE$_n$ modes

- A corrugated waveguide has interesting feature of being able to generate a quasi-optical mode, which has very low loss. They have been widely used as mode converter horns or as high power gyrotron driven transmission line systems



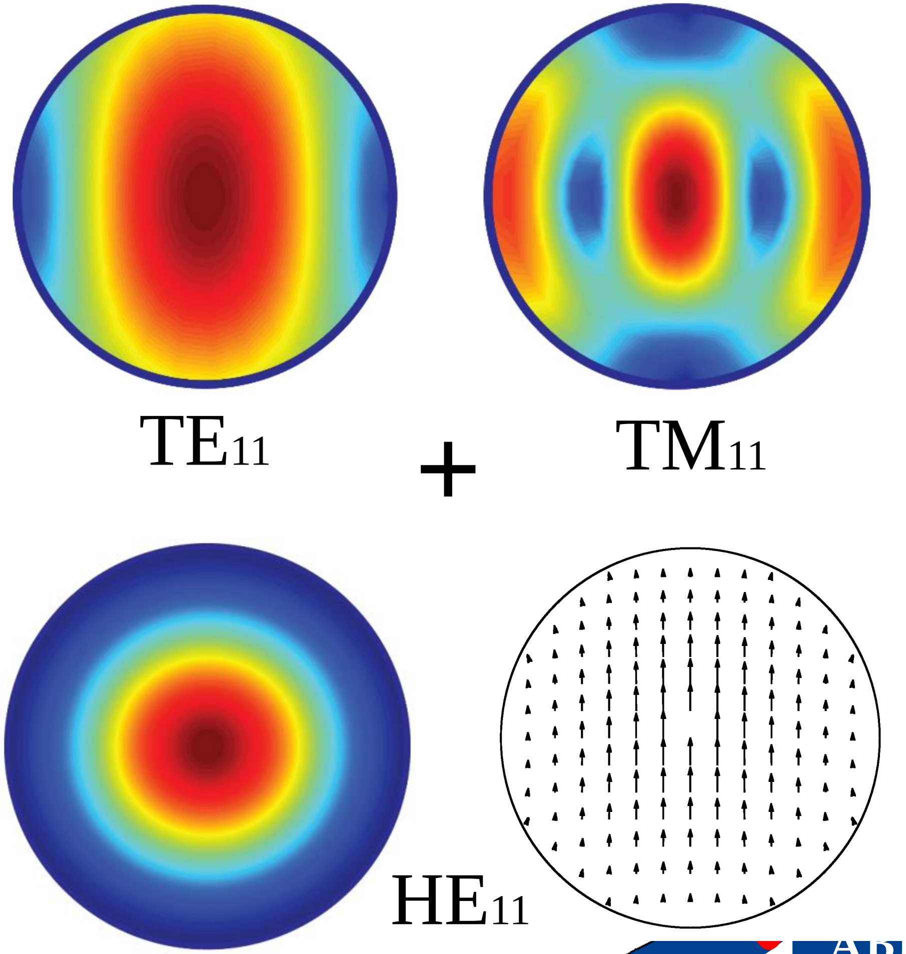
$$P \sim \frac{\lambda}{2} \qquad R_0 - R_1 \approx \frac{\lambda}{4}$$

The dominant mode is the HE$_{11}$, its field is:

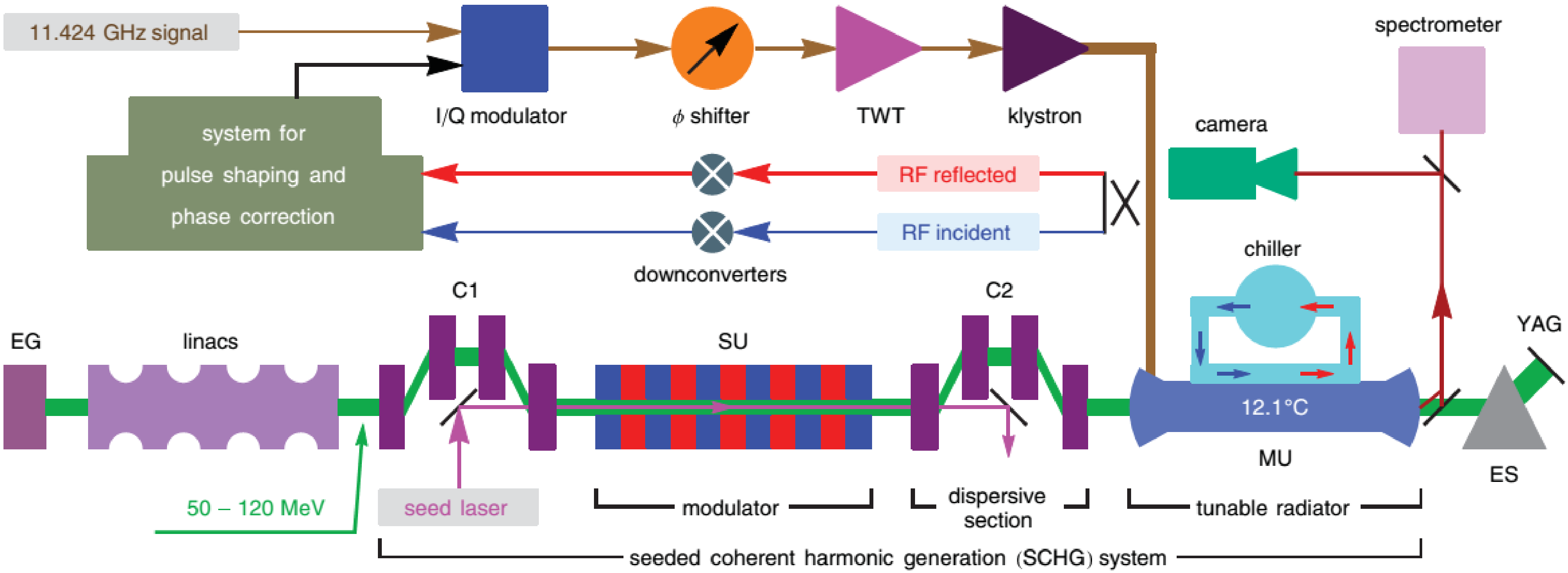
$$E_x = \frac{(X-Y)}{kr_1} A_2 J_2(k_c r)\sin(2\phi)$$

$$E_y = A_1 J_0(k_c r) - \frac{(X-Y)}{kr_1} A_2 J_1(k_c r)\cos(2\phi)$$

In the balanced hybrid condition: $X = Y$



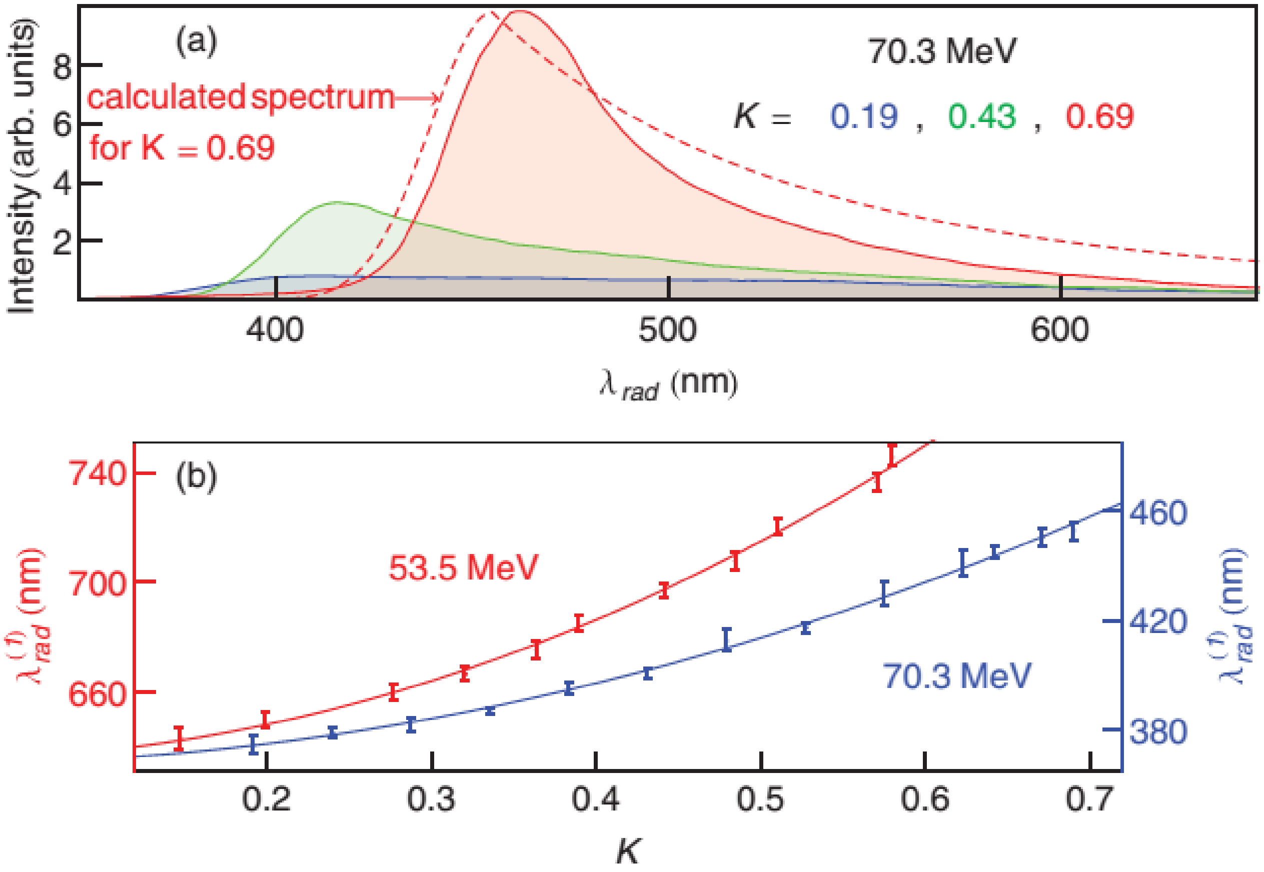
# Previous Experiments



Schematic layout of microwave undulator demonstration experiment at NLCTA, SLAC. EG: electron gun, C1: bypass chicane to introduce seed laser, SU: static undulator, C2: chicane used for spatial bunching when required, MU: microwave undulator, ES: energy spectrometer for electron beam, YAG: yttrium aluminum garnet screen.

Source: Sami Tantawi, Experimental Demonstration of a Tunable Microwave Undulator

# Experiment results



Demonstration of tunable undulator operation. (a) Spectra for various K. (b) Fundamental wavelength of on-axis radiation vs K for two beam energies. Each point with an error bar indicates a mean and standard deviation obtained from 10 to 100 data snapshots.

Source: Sami Tantawi, High-Field Short-Period Microwave Undulators

# What we propose?

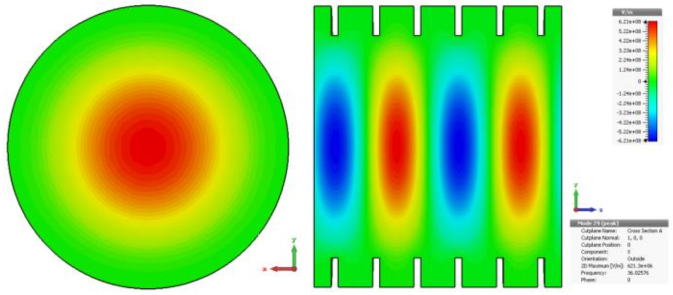
**Possible improvements:**

1. **Evaluate the possibility to operate at Ka-band, to achieve short wavelength operation**
2. **Possible to further improve the corrugated waveguide, and further reduce the field at the wall.**

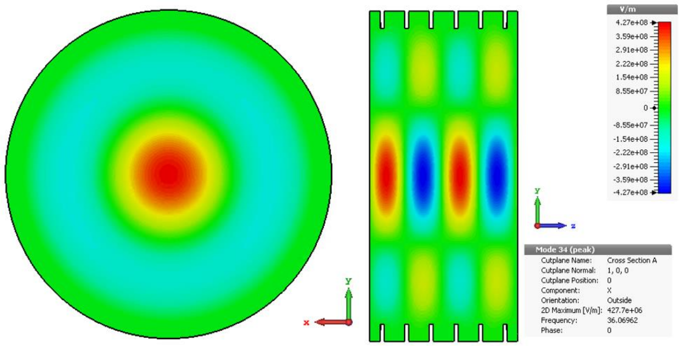
| | **State-of-the-art undulator** | **Record breaking undulator** | **Dream Undulator** |
|---|---|---|---|
| **Period (mm)** | 13.9 | 13.9 | 4.4 |
| **Beam Aperture (mm)** | 5.0 | 5.0 | 5.0 |
| **Peak B Field (T)** | 0.92 | 1.62 | 2.0 |
| **K Parameter** | 1.2 | 2.1 | 0.82 |
| **Length (m)** | 4.0 | 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 |

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

# Corrugated waveguide design



HE11 mode

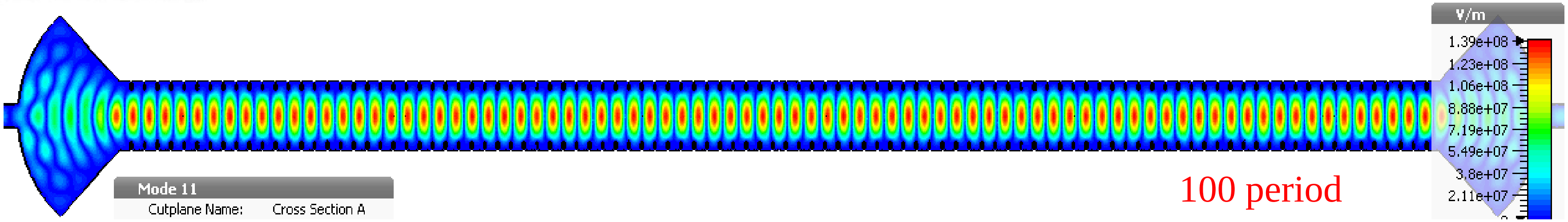


HE12 mode

| **Operating mode** | **$HE_{11}$** | **$HE_{12}$** |
|---|---|---|
| **Operating frequency (GHz)** | 36 | 36 |
| $\lambda_0$ **(mm)** | 8.33 | 8.33 |
| $R_b$ **(mm)** | 2.0 | 2.0 |
| $\boldsymbol{d_1}$ **(mm)** | $4R_b$=8.0 | $9R_b$=18.0 |
| depth $= \lambda_0/4$ **(mm)** | 2.1 | 2.1 |
| $\lambda_g$ **(mm)** | 9.06 | 9.12 |
| $p = \lambda_g/3$ **(mm)** | 3.00 | 3.02 |
| **w (mm)** | 0.5 | 0.5 |
| $b = p - w$ **(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 |
| $B_u$ **(T)** | 1.27 | 1.23 |

Dimensions estimated from theoretical calculation

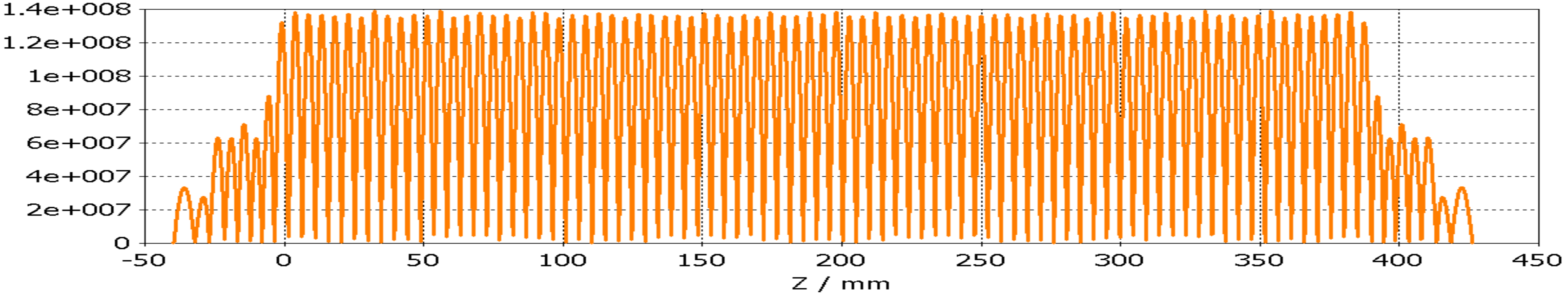
# 36 GHz corrugated cavity

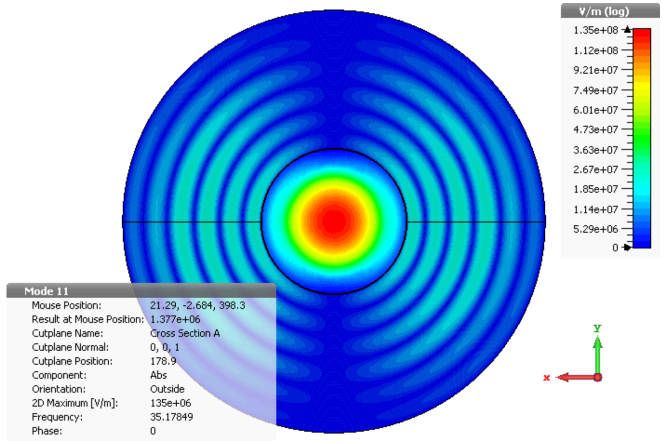


Mode 11

Cutplane Name: Cross Section A

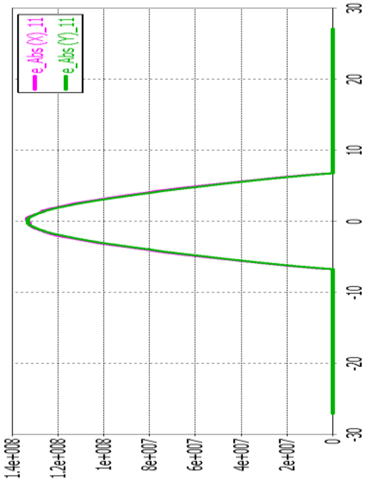
100 period





Mode 11

Mouse Position: 21.29, -2.684, 398.3
Result at Mouse Position: 1.377e+06
Cutplane Name: Cross Section A
Cutplane Normal: 0, 0, 1
Cutplane Position: 178.9
Component: Abs
Orientation: Outside
2D Maximum [V/m]: 135e+06
Frequency: 35.17849
Phase: 0



Initial geometry parameters:

Radius of the waveguide: 9.13 mm

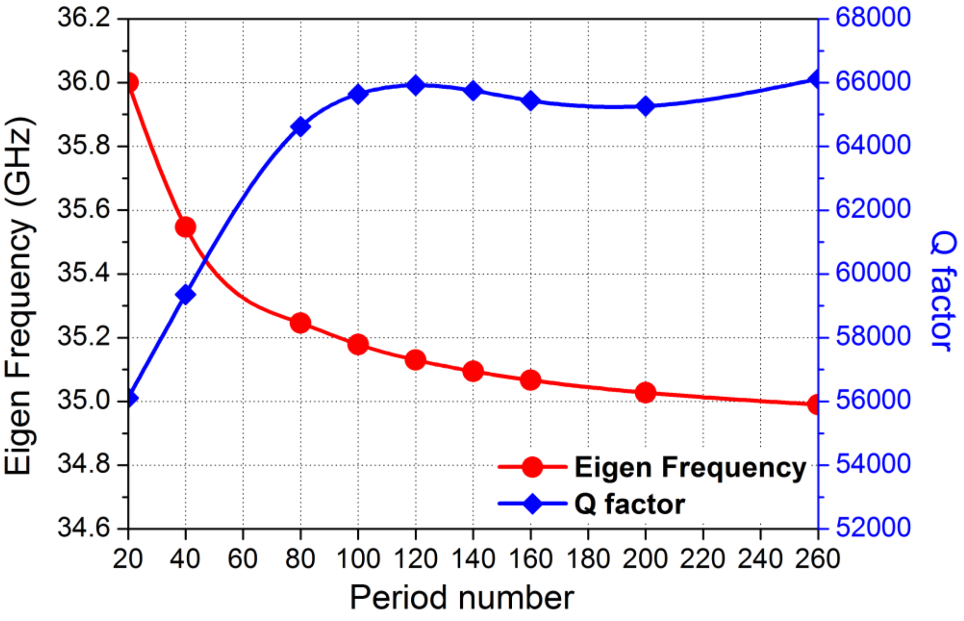
Period of the corrugation: 3.83 mm

Corrugation depth: 2.37 mm

Corrugation slot: 0.56 mm

Coupler radius: 35.55 mm

# 36 GHz corrugated cavity



The Q factors and eigenfrequencies changes with the period number (cavity length). However large period number leads to a long computing time and large memory requirements. Parameter scans were used to determine the final dimensions.

- University of Strathclyde HPM source produced 65MW of power at 36GHz (I.V. Konoplev, A.W. Cross, P. MacInnes, W. He et al, Appl. Phys. Letts., **92**, 211501, 2008)

Final parameters:

Radius of the waveguide: 8.88 mm

Period of the corrugation: 3.73 mm

Corrugation depth: 2.31 mm

Corrugation slot: 0.55 mm

Coupler radius: 34.56 mm

Period number: 100

Uniform field length: 1 meter

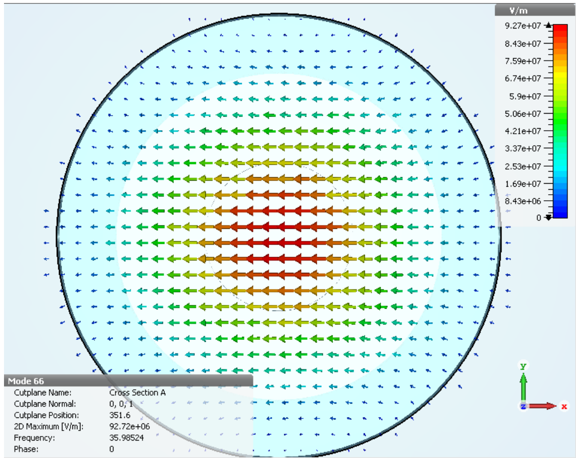
Resonance frequency: 35.2 GHz

Q factor: 66,000

Shunt impedance: 2.36E5

Peak field at the center: 0.926E8 V/m

@ input power of 55.9 MW

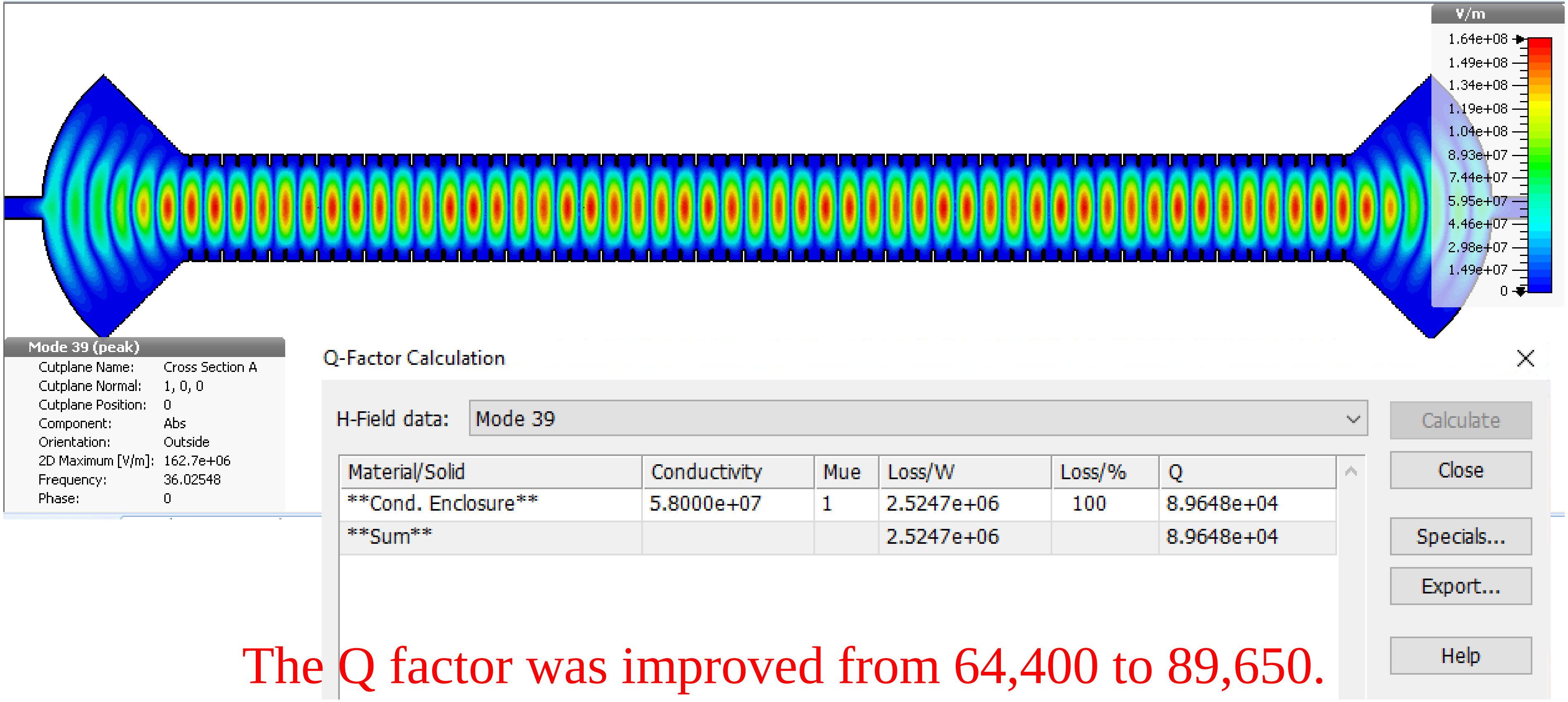


Mode 66

| | |
|---|---|
| Cutplane Name: | Cross Section A |
| Cutplane Normal: | 0, 0, 1 |
| Cutplane Position: | 351.6 |
| 2D Maximum [V/m]: | 92.72e+06 |
| Frequency: | 35.98524 |
| Phase: | 0 |

# Further improvement

To achieve higher Q factor. Parameter scanning of the coupler dimensions. It requires a lot of computing time as the structure is relatively large.



**Mode 39 (peak)**

| | |
|---|---|
| Cutplane Name: | Cross Section A |
| Cutplane Normal: | 1, 0, 0 |
| Cutplane Position: | 0 |
| Component: | Abs |
| Orientation: | Outside |
| 2D Maximum [V/m]: | 162.7e+06 |
| Frequency: | 36.02548 |
| Phase: | 0 |

**Q-Factor Calculation**

H-Field data: Mode 39

| Material/Solid | Conductivity | Mue | Loss/W | Loss/% | Q |
|---|---|---|---|---|---|
| **Cond. Enclosure** | 5.8000e+07 | 1 | 2.5247e+06 | 100 | 8.9648e+04 |
| **Sum** | | | 2.5247e+06 | | 8.9648e+04 |

The Q factor was improved from 64,400 to 89,650.
Nearly 40% improvement.

# Conclusion and Future Work:

- Simulations of electromagnetic wave fields setup in the cavity [Strathclyde]
- Electron beam dynamics simulations: ASTRA code [ANSTO]
- Photon radiation simulations: SPECTRA code and SIMPLEX code [ANSTO]
  - Need to know the electron beam parameters
- A 36 GHz microwave undulator conceptual design report
  - Manufacture a section of the 36GHz RF undulator in copper
  - Measurement of its reflection, transmission and losses using a Vector Network Analyser

# Acknowledgements

This work is supported by the European Commission Horizon 2020 Project "CompactLight" (777431-XLS), The support of the STFC UK (Cockcroft Institute Core Grant) is gratefully acknowledged

Thank you for your attention!

# Auxiliary Slide
# Electron beam parameters

| | |
|---|---|
| Beam Energy | 6 GeV |
| Bunch charge | < 250 pC |
| Energy Spread (rms) | 0.2% |
| Normalized horizontal emittance | < 1 mm mrad |
| Bunch length | 8μm |
| Max Bunch Repetition | 0.5GHz |
| Pulse length | 150ns |
| Number of bunches per pulse | 1 - 3 |
| Repetition rate | 50Hz (1000 Hz) |