Development of MW-level Ka-band Gyroklystrons

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on behalf of research teams of
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Electronic Engineering department, UESTC, Chengdu, China

Outlines

- Research groups (Strathclyde & UESTC)
- Motivation
- Principles of klystron and gyroklystron
- Simulation results
  - MIG gun
  - Cavity simulation

ABP group, Physics department, University of Strathclyde, Glasgow, UK

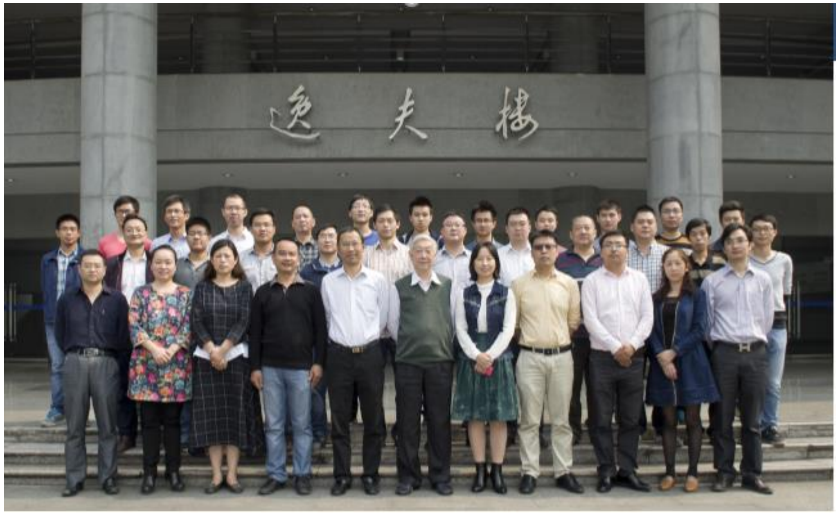
- Founded in 1978 by Prof. Alan Phelps
- **Group member**
  - 5 academic staff
  - 10 research staff
  - 6 PhD students
  - 1 technician

Successful high-power microwave sources built include FEL, CARM, gyrotron, gyro-TWA, BWO, Cherenkov maser & superradiant sources.

Accelerator relevant projects: DATA (dielectric and THz acceleration, CI), UK XFEL(Microwave Undulator, CI), MICE (Muon Ionisation Cooling Experiments, RAL), CompactLight project, WP4).

Present interests range from 200MHz to 1THz

High power millimetre wave technology group, Electronic Engineering department, University of Electronic Science and Technology of China, ChengDu, China

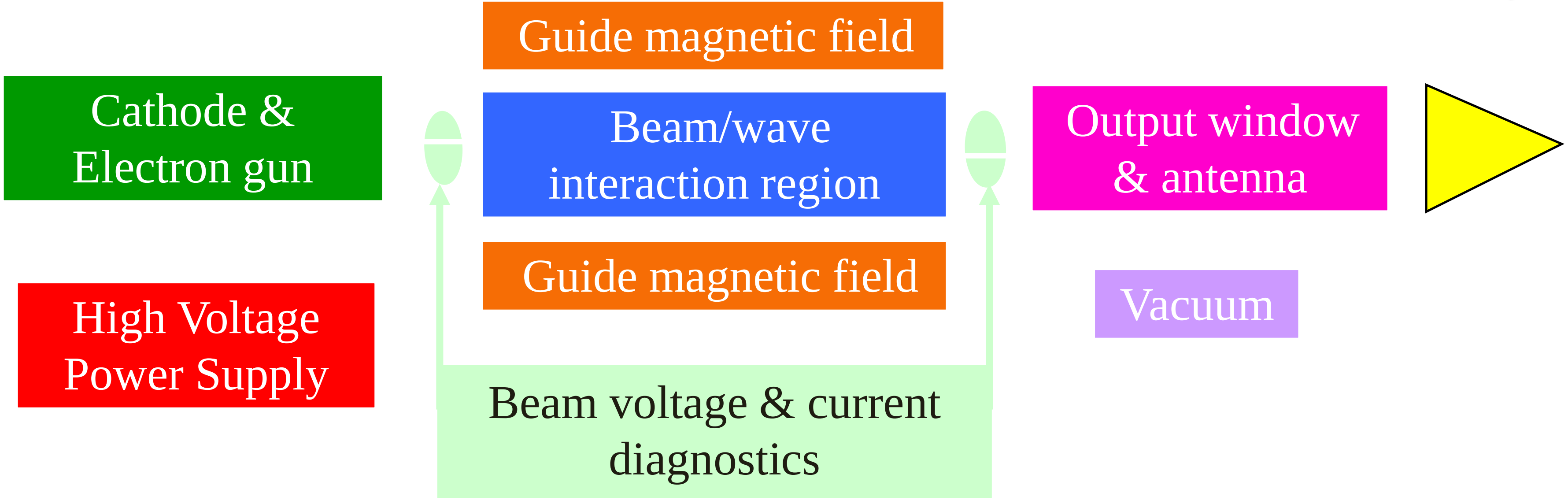


- Lead by Prof. Yong Luo
- **Group member**
  - 4 academic staff
  - 12 research staff
  - 11 PhD + 40 master students
  - 30 technicians

Research covers:

Millimeter and sub-millimeter high power microwave sources, including gyrotron, gyroklystron, gyro-TWT.
High efficiency, compact sources.
Reliability and stability testing.
Digital control and online diagnostics systems.
Modulation power supplies for vacuum electron devices.

Capabilities of Both groups



Cathode & Electron gun

High Voltage Power Supply

Guide magnetic field

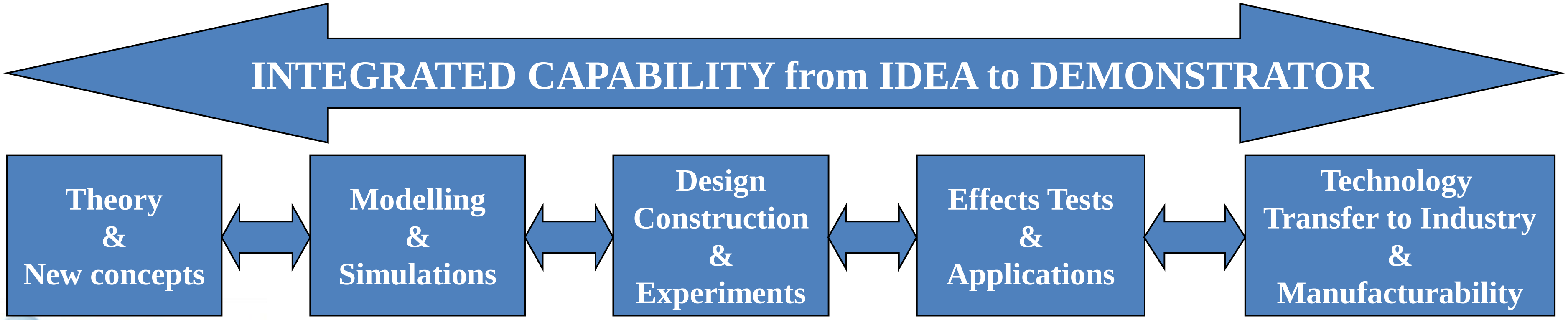
Beam/wave interaction region

Guide magnetic field

Beam voltage & current diagnostics

Output window & antenna

Vacuum



INTEGRATED CAPABILITY from IDEA to DEMONSTRATOR

Theory & New concepts

Modelling & Simulations

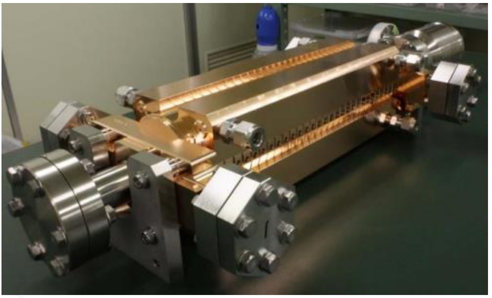
Design Construction & Experiments

Effects Tests & Applications

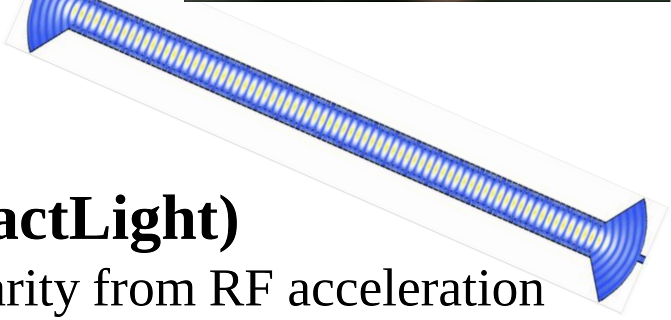
Technology Transfer to Industry & Manufacturability

Motivation

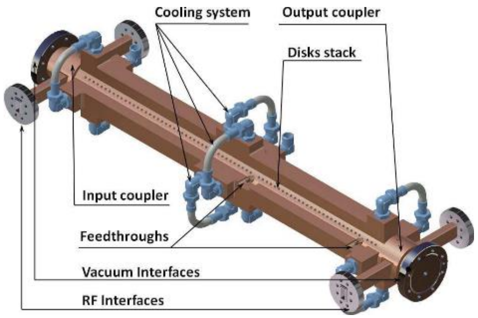
- **Accelerator (High acceleration gradient, CERN)**
  - Higher operating frequency
  - Higher breakdown limit



- **Microwave undulator (Design for UK-XFEL)**
  - Smaller period requires higher frequency
  - High power required (0.3 GeV/m ~ 1T).



- **Lineariser (Cockcroft Institute, CompactLight)**
  - Correct the longitudinal phase space non-linearity from RF acceleration
  - 3rd or 4th harmonic of X-band RF LINAC frequency

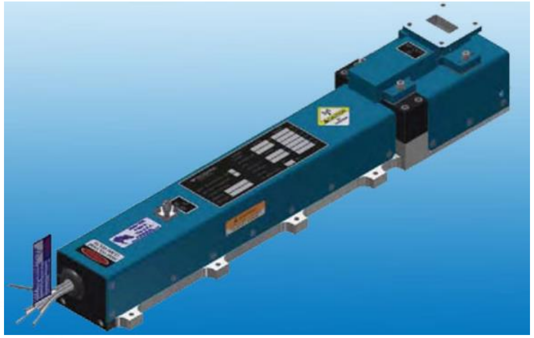


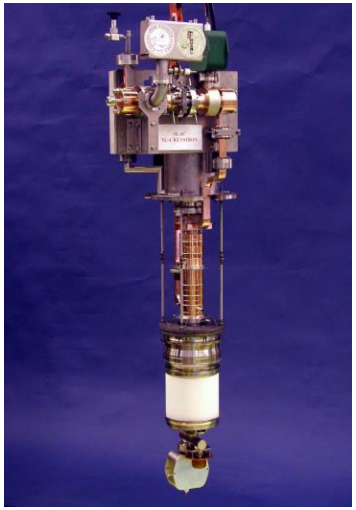
- **Design targets**
  - Gyroklystron (amplifier, narrow bandwidth)
  - 36 GHz and 48 GHz, 2 MW or 1.5MW output power.
  - Pulse duration 2 us, PRF 100 Hz.

Microwave sources

- Oscillators:
  - Backward wave oscillator (GW-level)
  - Gyrotron (ITER)
  - Magnetron (industry heating)

- Amplifiers:
  - TWT (wide bandwidth, lower gain, communications)
  - Klystron (narrow bandwidth, high gain for accelerators and radars)
  - Cyclotron Autoresonance Maser (CARM, high frequency)





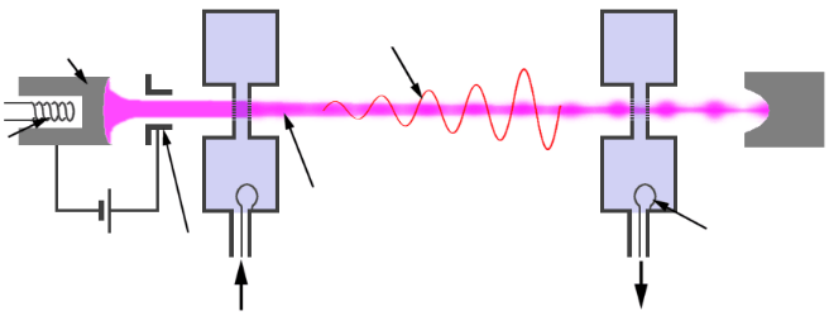
Commercial klystrons

S-band (3 GHz)
C-band (6 GHz)
X-band (~12 GHz)

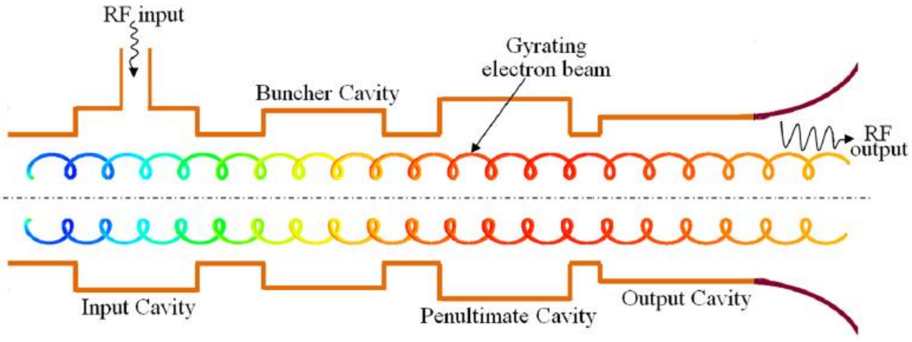
	SLAC **XL4,5**	**CPI** **8311A**	**Toshiba** **E3768B**
Frequency (GHz)	11.424	11.994	11.424
Beam Voltage (kV)	440	410	500
Beam Current (A)	350	310	270
Peak Power (MW)	50	50	75
RF Pulse width (us)	1.5 @ 60Hz	1.5	1.6
Gain (dB)	50	48	60
Efficiency	40%	40%	55%

Klystrons

- Conventional klystron
  - Bunching in axial direction, TM modes
  - Operating frequency determined by the cavity size, difficult to achieve high power at high frequency
  - High beam voltage, high frequency lead to small cavity gap.
  - To reduce the space charge effect and get higher power. (still small dimensions)
  - Multiple-beam klystron
  - Sheet-beam klystron
- Gyroklystron
  - Bunching in azimuthal direction. TE modes.
  - Lower axial velocity due to the beam alpha results in larger cavity size.
  - Operating frequency determined by the external magnetic field.
  - Open output cavity, high power capability.



klystron

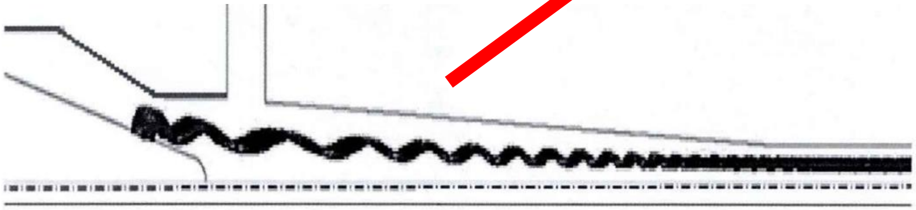


gyroklystron

Ka-band gyroklystron at UESTC

Low-power demonstration version

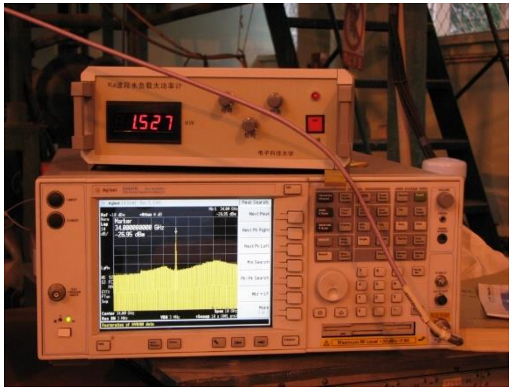
Output power (kW)	300
Beam voltage (kV)	68
Beam current (A)	11
Magnetic field (T)	1.32
Output frequency (GHz)	33.98
Drive power (W)	40
Gain (dB)	38.8
Efficiency	40%
Bandwidth (MHz)	280



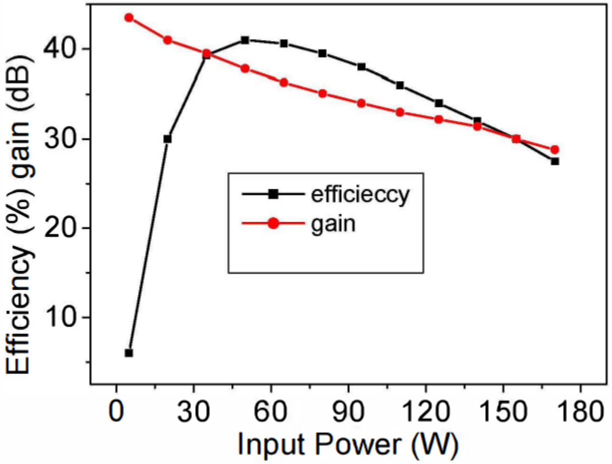
Dual-anode MIG gun.
Beam alpha 1.2
Magnetic field compression ratio 7.8

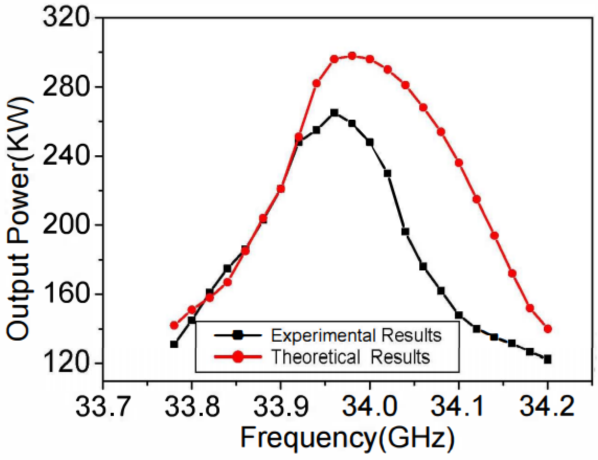
Ka-band gyroklystron at UESTC

Measurement setup
PRF 220 Hz



The TE01 output mode pattern captured on film

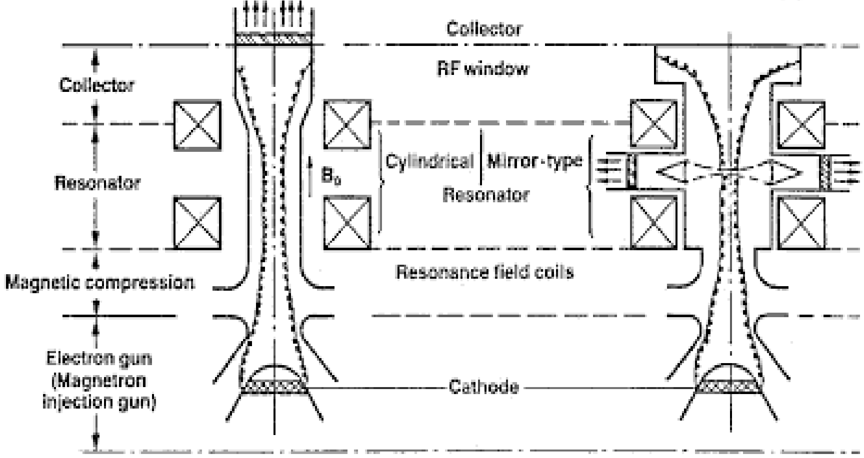


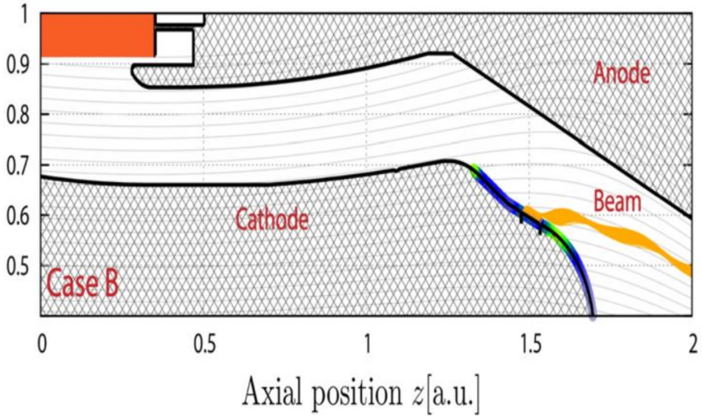


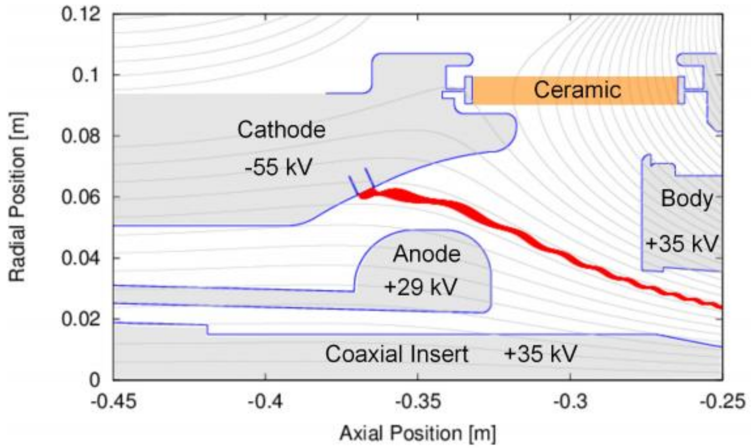
Successfully verified the design, further improvements on the electron gun and collector are required.

Improvements required

- From kW to MW
  - Higher beam voltage
  - Higher beam current
  - Energy recovery
  - Thermal stress
  - Quasi-optical mode converter





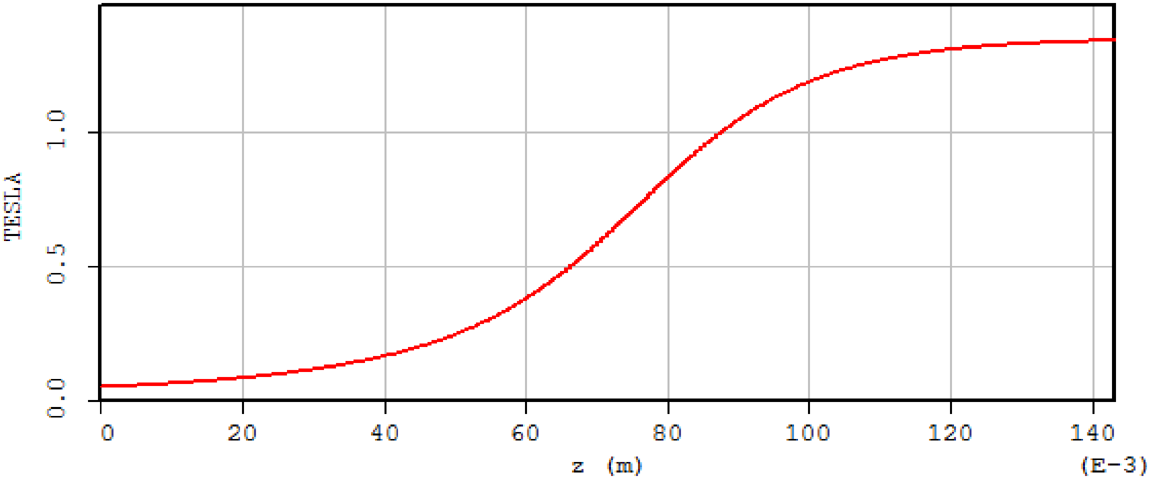


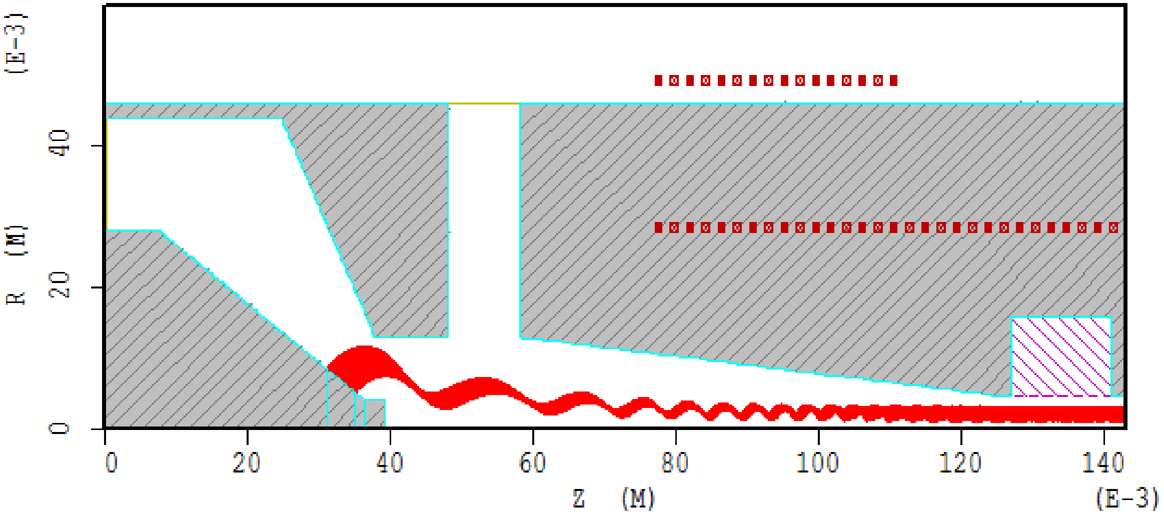
Configuration of MIG and IMIG. An example from KIT for 2MW coaxial-cavity gyrotron. Inverted MIG allows a larger emitter ring to have larger beam current.

MIG-type electron gun

Emitter width L_s (mm)	5.23
Emitter average radius R_c (mm)	6.85
Anode angle φ_a (deg)	66.9
Current density J_s (A/cm^2)	20
Current I_0 (A)	**45**
Anode voltage V_0 (kV)	**95**
Modulating anode voltage V_m (kV)	38.5
Magnetic field @ gun exit B_0 (T)	1.34
Magnetic compression ratio f_m	10.5
Velocity ratio α	1.31
Transverse velocity spread $\Delta\beta_t$ (%)	2.31
Axial velocity spread $\Delta\beta_z$ (%)	4.09
Mean guiding center radius r_{g0} (mm)	2.25

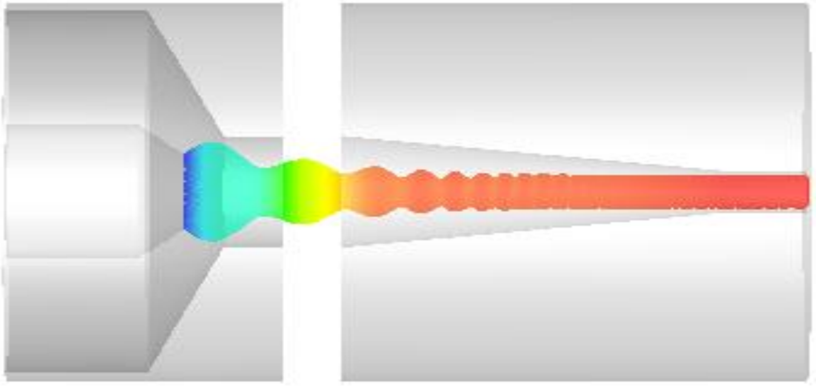
Magnetic field





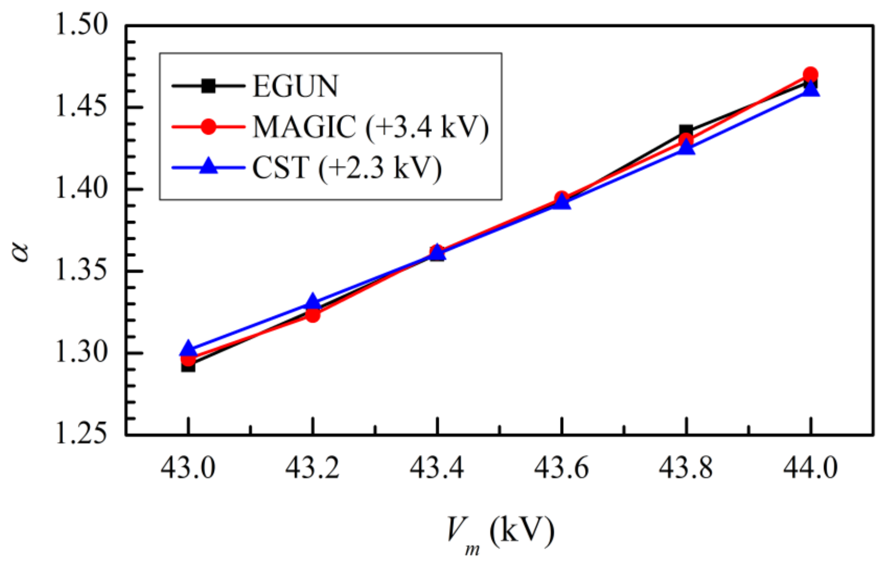
Beam trajectories

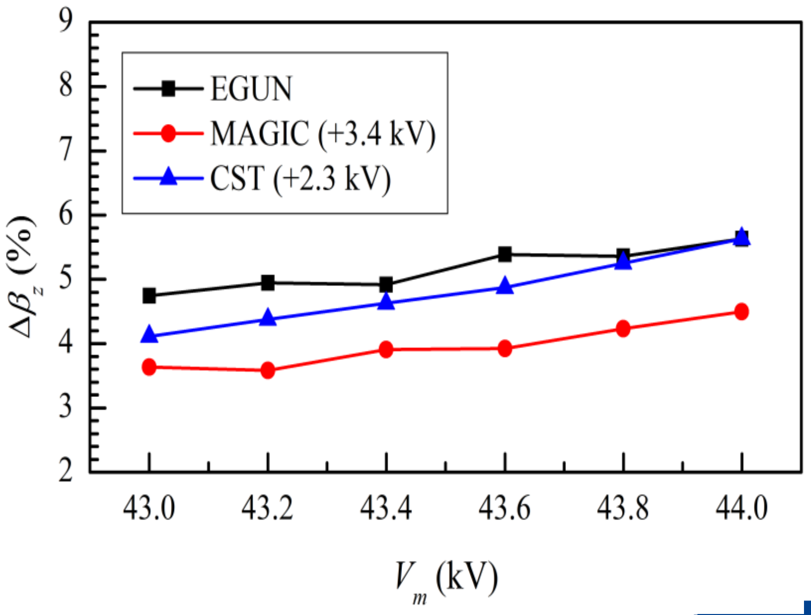
MIG-type electron gun



Simulated by Egun, MAGIC and CST PS.

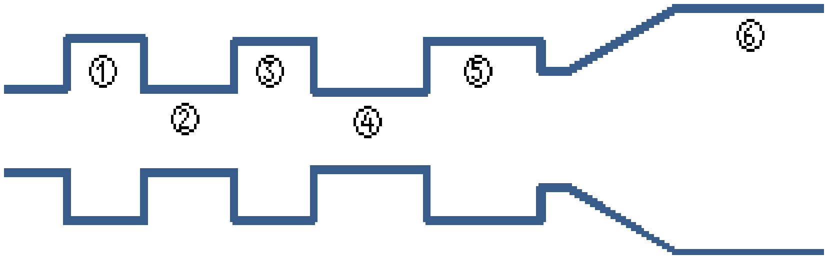
PARAMETERS	EGUN	MAGIC	CST
Velocity ratio α	1.32	1.32	1.32
Velocity ratio spread Δα (%)	7.99	5.74	7.12
Transverse velocity spread $\Delta\beta_t$ (%)	3.06	2.17	2.78
Guiding centre radius R_{g0} (mm)	2.36	2.42	2.41
Modulating anode voltage V_m (kV)	43.2	46.6	45.45



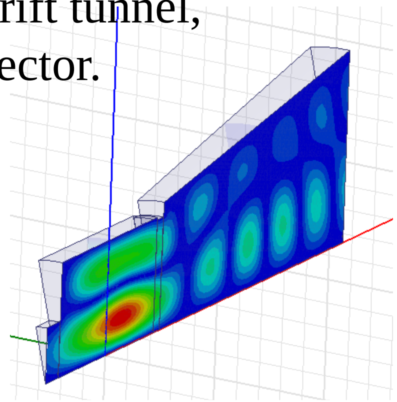


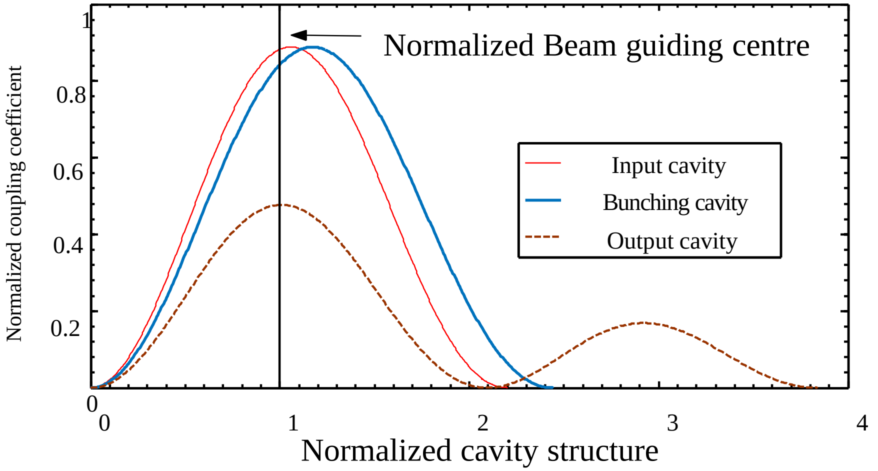
Simulation of the cavity

- Three-cavity structure
- The operating mode of input and buncher cavity are TE01. The mode of output cavity is TE02, to have larger power capability.



① input cavity, ② 1st drift tunnel,
③ bunching cavity, ④ 2nd drift tunnel,
⑤ output cavity and ⑥ collector.





The normalized coupling coefficient as the function of the normalized size of beam radius

Structure	F	Q
Cavity 1	35.25	52.6
Cavity 2	34.58	23.5
Cavity 3	35.79	78.6

Nonlinear simulation model

Beam-wave interaction

$$\frac{d\boldsymbol{p}}{dt} = -e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\frac{d\varepsilon}{dt} = e\boldsymbol{v} \cdot \boldsymbol{E}$$

The normalized motion equation

$$\frac{dp}{dz} + \frac{i\omega}{cu_z}\left(\gamma - \frac{\Omega_0}{\omega}\right)p = \frac{i\eta p}{2\Omega_0}\frac{dB_0}{dz} + \frac{i\eta}{2}\frac{\gamma}{u_{z0}}C_{mp}k_{mp}V_{\max}\left(\frac{f_{mp}(z)}{(\text{s-1})!}\right) \times J_{m-s}\left(k_{mp}R_e\right)\left(\frac{ck_{mp}p^*}{2\Omega_0}\right)^{s-1}$$

$$\frac{du_z}{dz} = -\left(\frac{\eta c u_t r_L}{u_z}\right)\frac{dB_0}{dz}$$

Ignore the axial momentum of the helical electron beam

$$\frac{dp}{dz} + \frac{i\omega}{cu_z}\left(\gamma - \frac{\Omega_0}{\omega}\right)p = \frac{i\eta}{2}\frac{\gamma}{u_{z0}}C_{mp}k_{mp}V_{\max}\left(\frac{f_{mp}(z)}{(\text{s-1})!}\right) \times J_{m-s}\left(k_{mp}R_e\right)\left(\frac{ck_{mp}p^*}{2\Omega_0}\right)^{s-1}$$

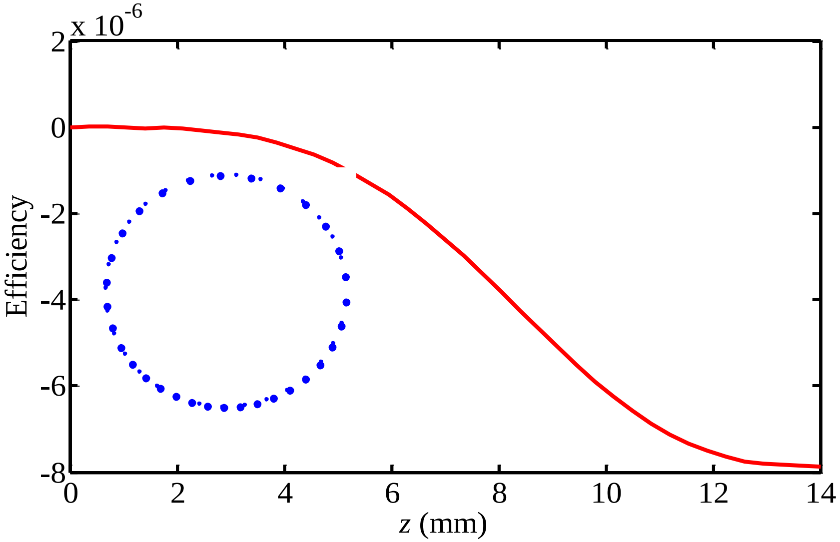
interaction efficiency

$$\eta = \frac{\langle\gamma_i\rangle - \langle\gamma_f\rangle}{\langle\gamma_i\rangle - 1} = \frac{\gamma_0 + 1}{2\gamma_0}\frac{\alpha_0^2}{\alpha_0^2 + 1}\eta_\perp$$

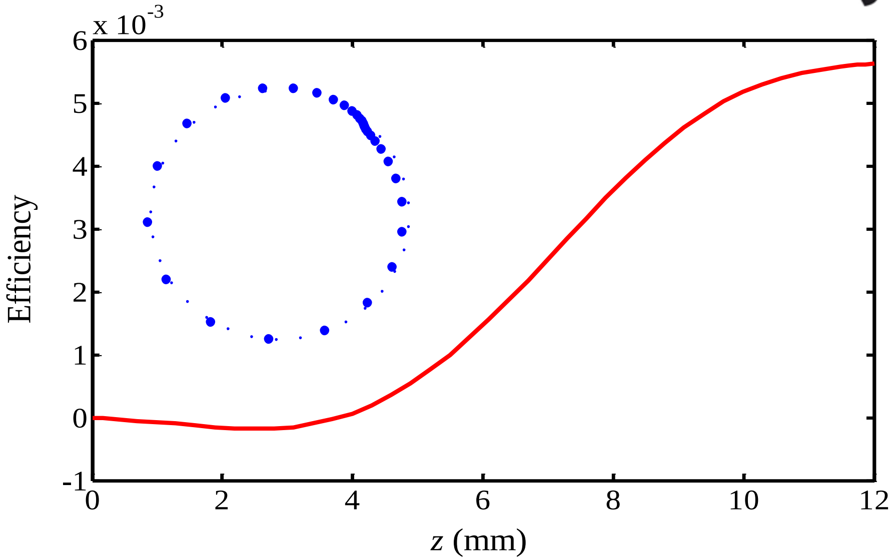
Fast and quickly estimate the interaction efficiency.

Not accurate enough.

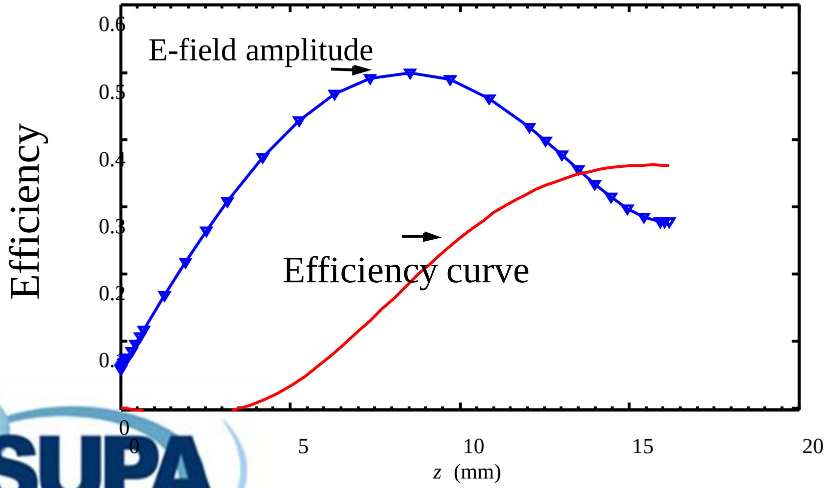
Nonlinear simulation results



Input cavity

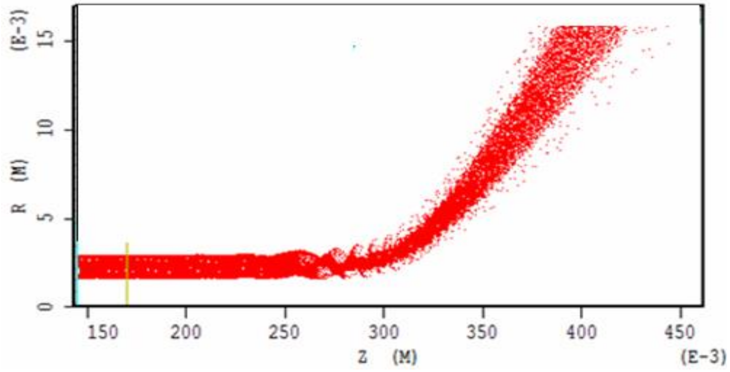


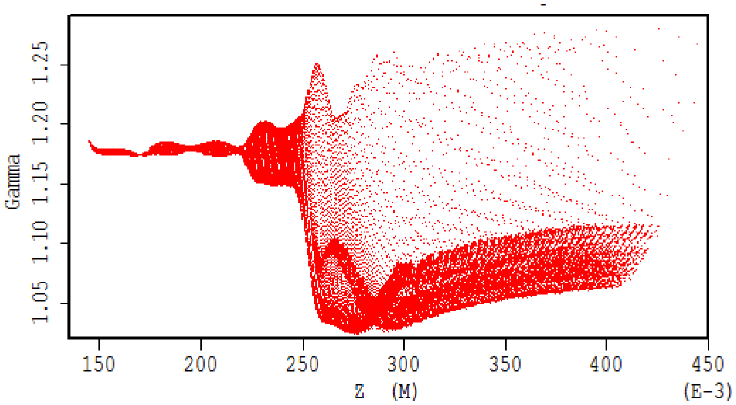
Middle cavity

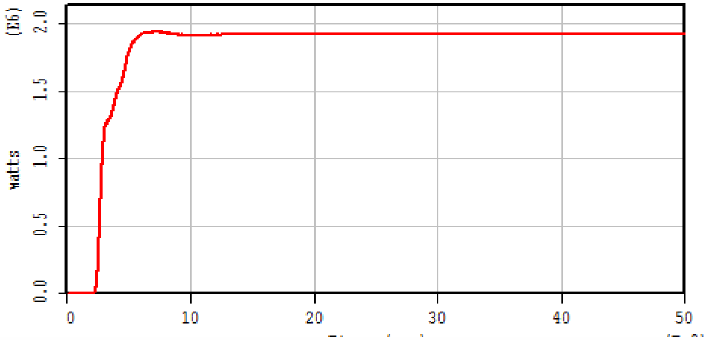


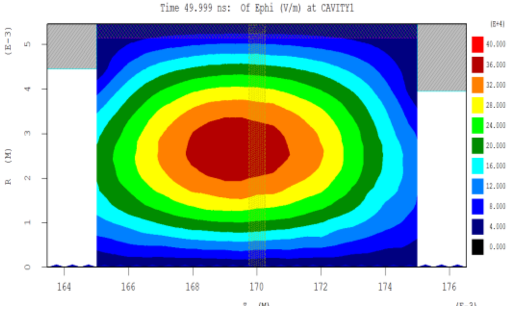
Output cavity

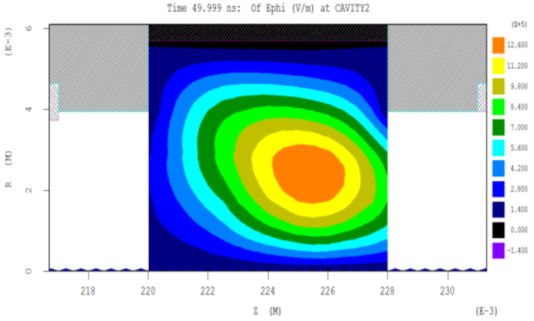
PIC simulations on the beam-wave interaction

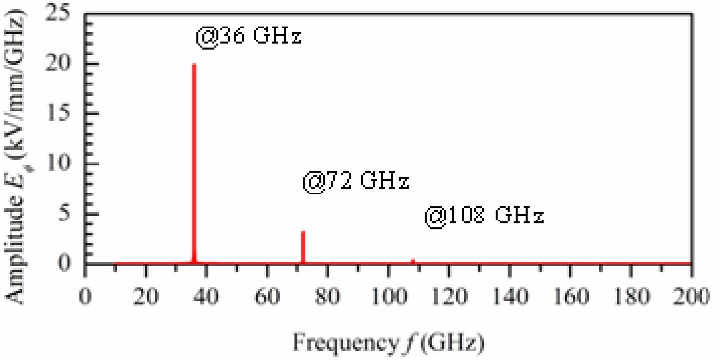


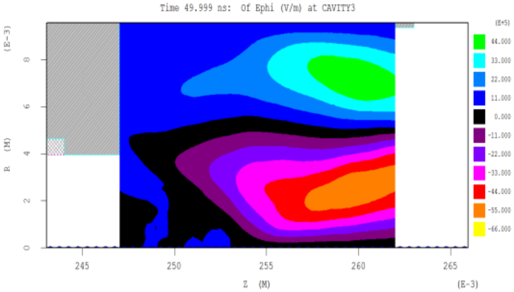


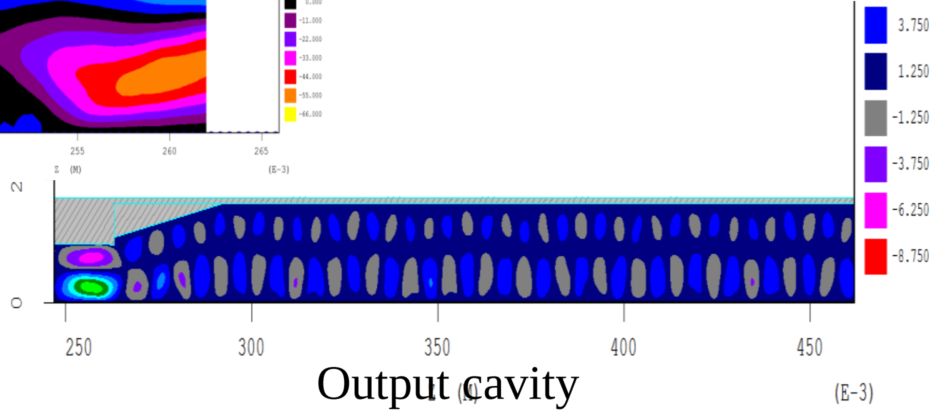






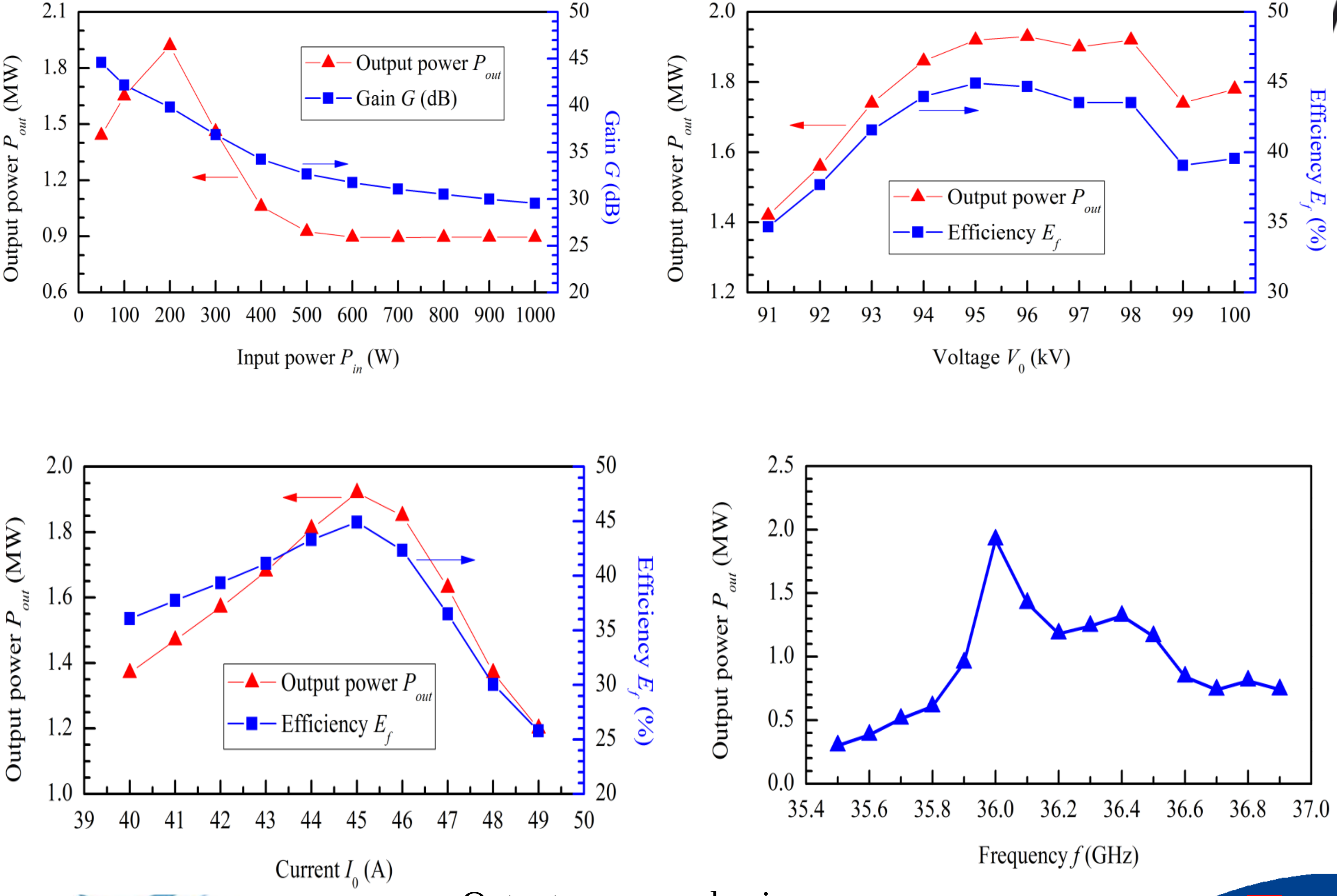






Output cavity

Gain curves in simulations



Output power and gain

Acknowledgement

- This work is supported by the European Commission Horizon 2020 Project Compact light (777431-XLS), and the State Scholarship Fund from the China Scholarship Council.

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