WP4: RF systems

- Sub-Task 4: Power sources for higher-harmonic systems, current goals/parameters, status

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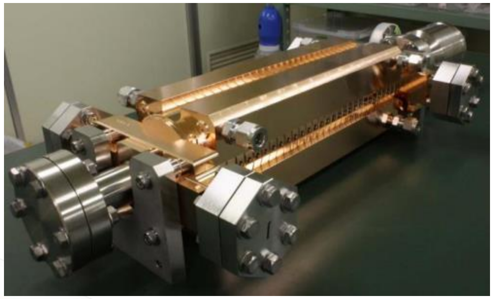
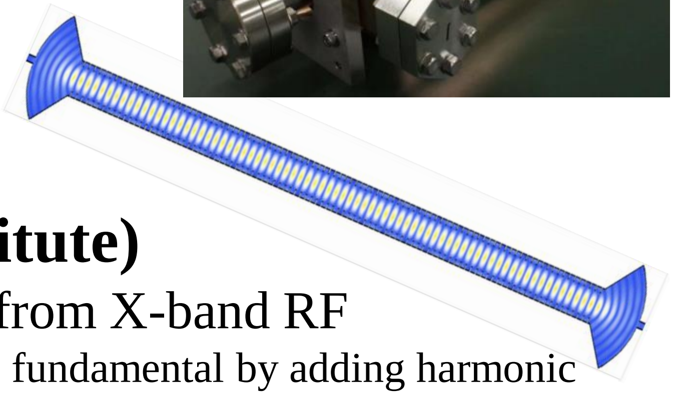
Outline

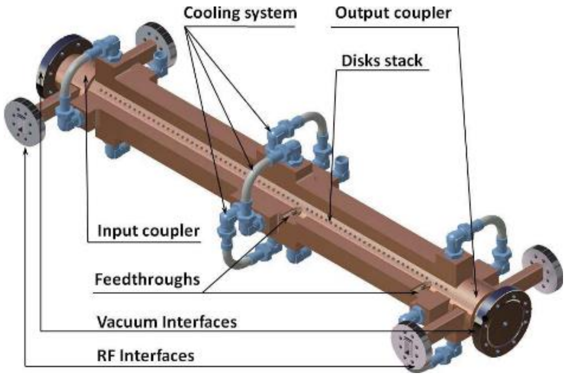
- Research groups (Strathclyde & UESTC)
- Motivation
- Principles of klystron and gyroklystron
- Simulation results
  - MIG gun
  - Cavity simulation
- 3rd harmonic Lineariser requirements

Motivation



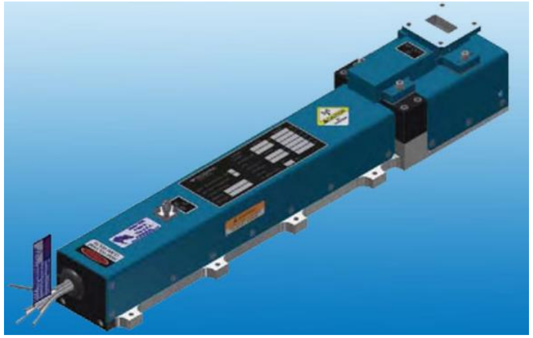


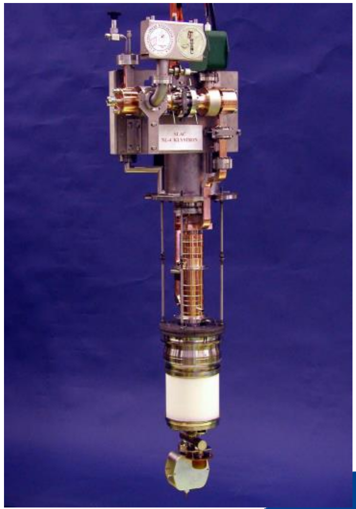
- **Accelerator (High acceleration gradient, CERN)**
  - Higher operating frequency
  - Breakdown limit
- **RF undulator (Proposed for UK-XFEL)**
  - Smaller period requires higher frequency
  - High power required
- **Lineariser (CompactLight, Cockcroft Institute)**
  - Correct the longitudinal phase space non-linearity from X-band RF
    - compensate for the curvature imposed on the bunch by the fundamental by adding harmonic
  - 3rd (36GHz) or 4th (48GHz) harmonic of X-band RF LINAC frequency
    - the higher the harmonic, the less amplitude (and thus RF power) required
- **Design targets**
  - Gyro-klystron (amplifier, narrow bandwidth)
  - 36 GHz, 2MW
    - 48 GHz, 1.5MW output power (Laurence Nix)
  - Pulse duration 2 us, PRF 100 Hz.



Microwave sources

- Oscillators:
  - Backward wave oscillator (GW-level)
  - Gyrotron (ITER)
  - Magnetron (industry heating)
- Amplifiers:
  - TWT (wide bandwidth, communications)
  - Klystron (narrow bandwidth, high gain for accelerators and radars), X-band
  - Gyrotron Klystrons, Ka-band (26.5 to 40)GHz & W-band (75 to 110)GHz
  - Cyclotron Autoresonance Maser (CARM, high frequency), G-band (140 to 220)GHz, Y-band (325 to 500) GHz





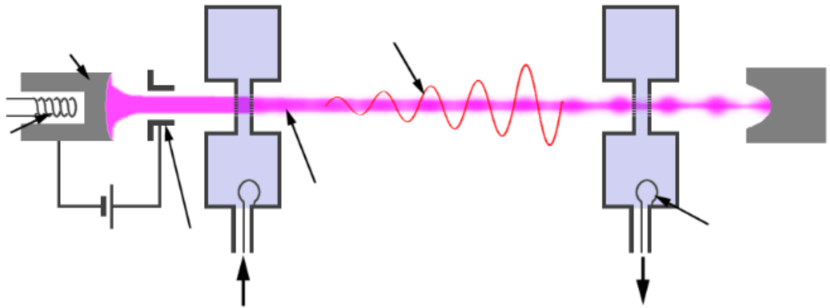
Commercial klystrons

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

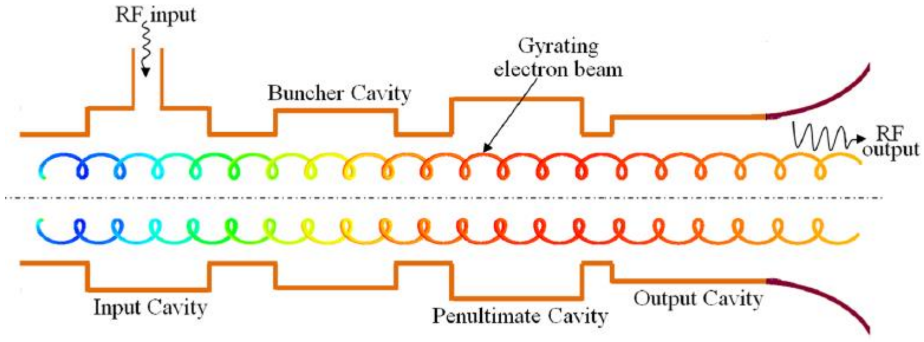
	SLAC XL4,5	**CPI 8311A**	**Toshiba E3768B**
Frequency (GHz)	11.424	11.994	11.424
Beam Voltage (kV)	440	410	500
Beam Current (A)	350	310	270
Peak Power (MW)	50	50	75
RF Pulse width (us)	1.5 @ 60Hz		1.6
Gain (dB)	50	48	60
Efficiency	40%	40%	55%

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 leads to small cavity gap
  - To reduce the space charge effect and get higher power (still small dimensions)
  - Multiple-beam klystron
  - Sheet-beam klystron
- Gyro-klystron
  - 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

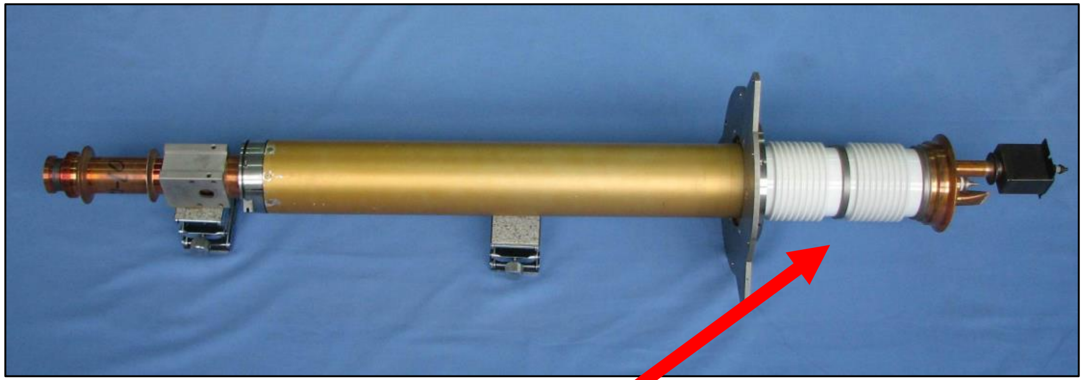


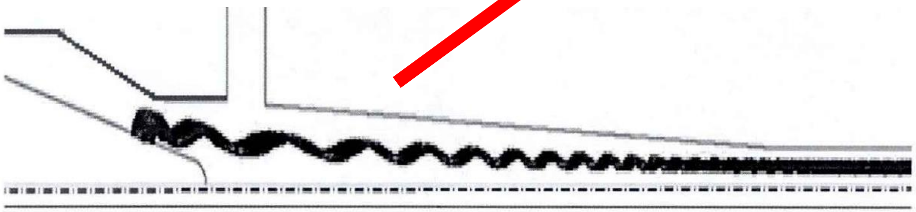
gyroklystron

Ka-band gyro-klystron at UESTC

Medium-power demonstration version

Output power (kW)	260
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

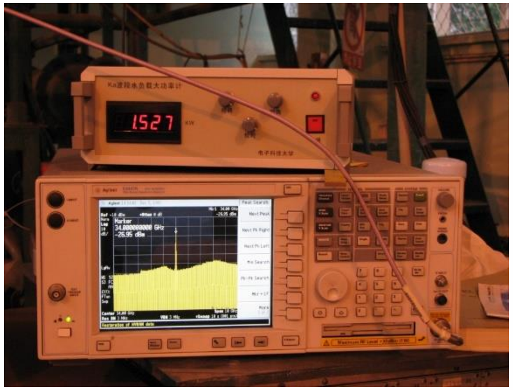




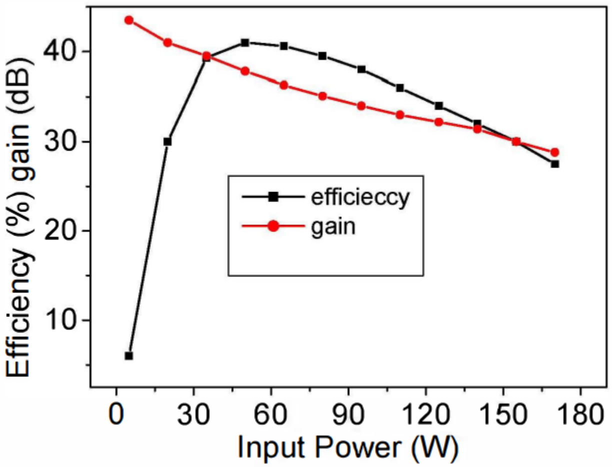
Dual-anode MIG gun.
Beam alpha 1.2
Magnetic field compression ratio 7.8

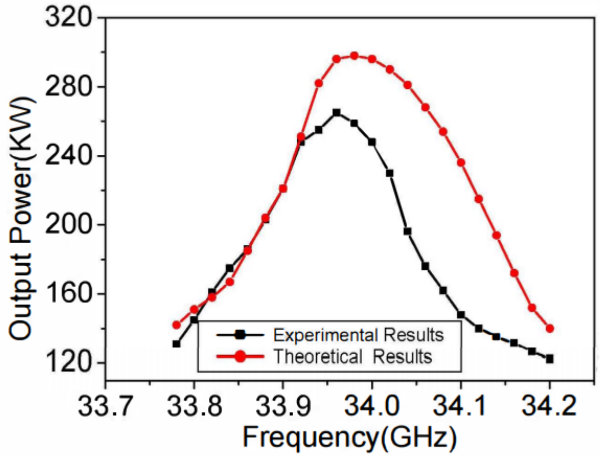
Ka-band gyroklystron at UESTC

Measurement setup
PRF 220 Hz



The TE01 output mode pattern captured on film



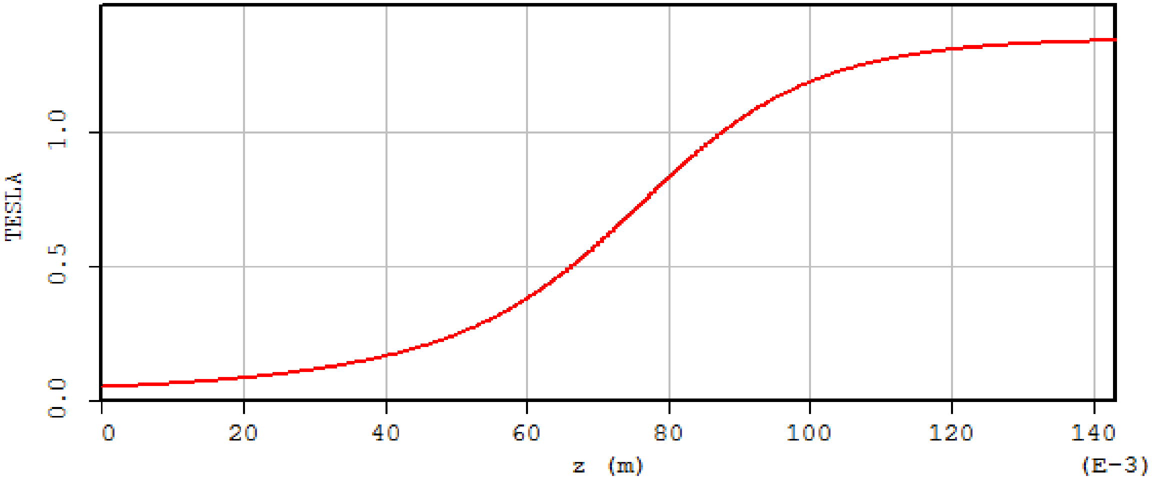


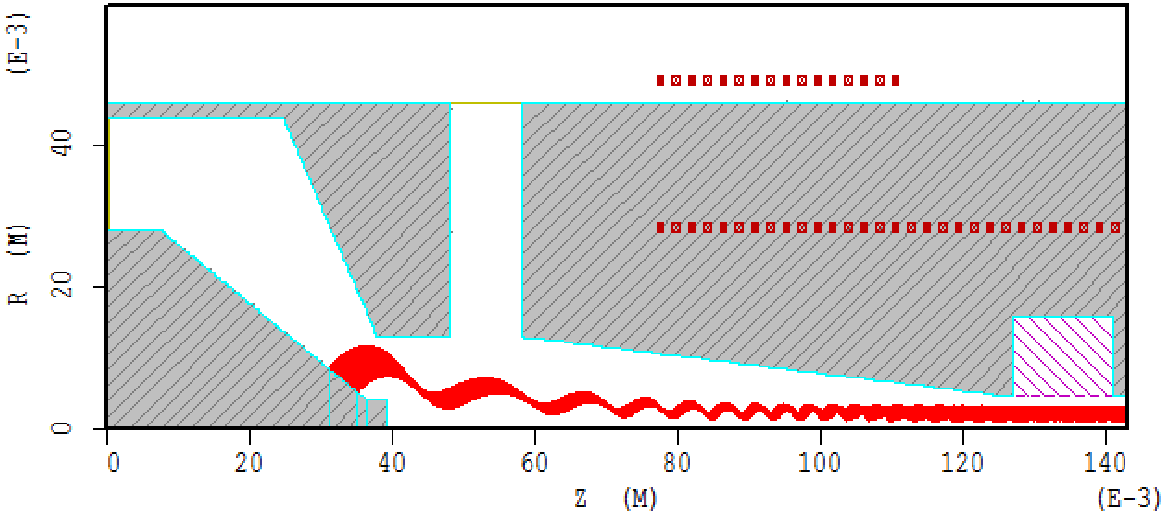
Successfully verified the design, further improvements on the electron gun and collector are required.

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

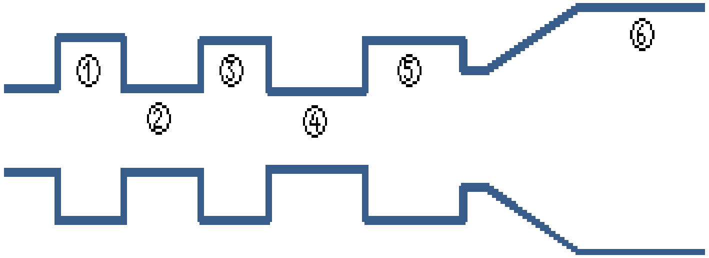




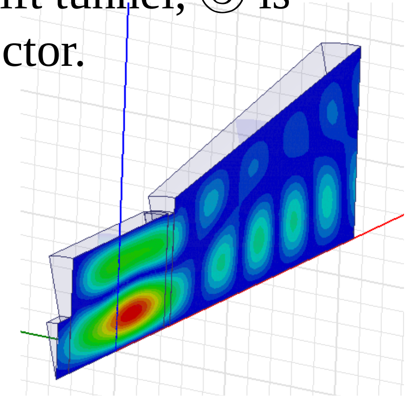
Beam trajectories

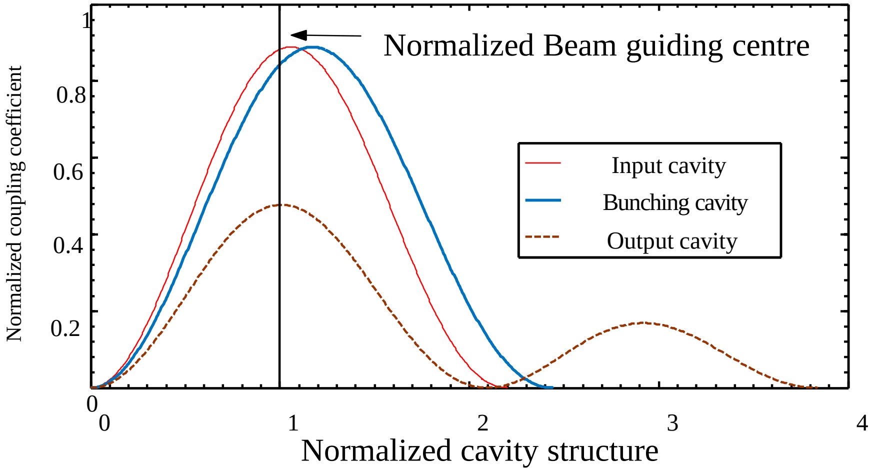
Simulation of the cavity

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

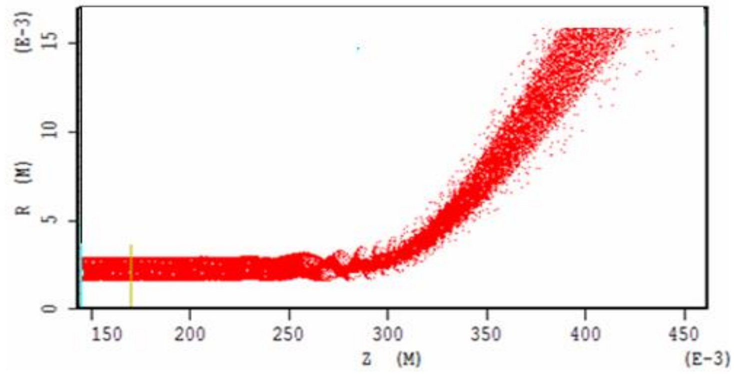


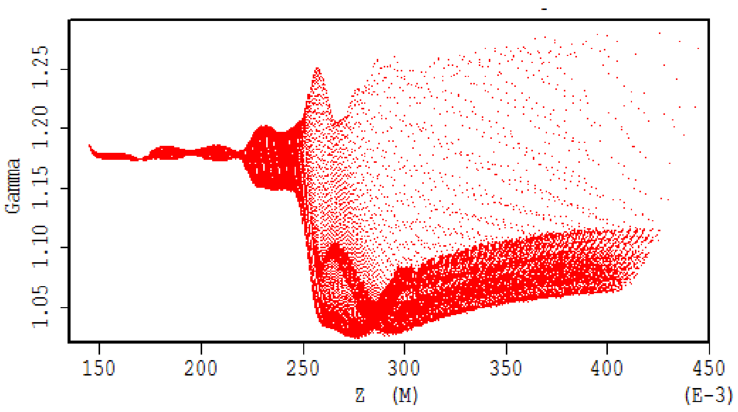


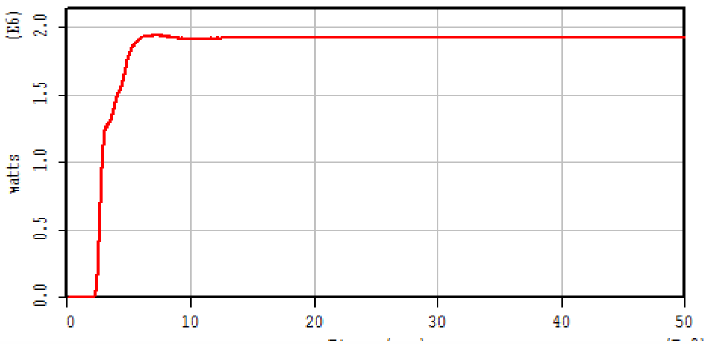
The normalized coupling coefficient as the function of the normalized size of beam radius

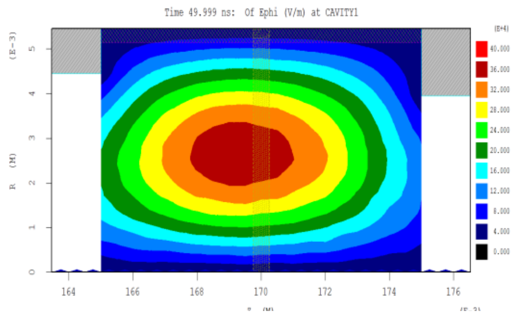
Structure	**F**	**Q**
Cavity 1	35.25	52.6
Cavity 2	34.58	23.5
Cavity 3	35.79	78.6

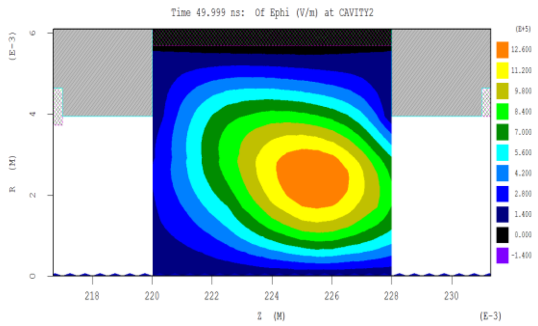
PIC simulations on the beam-wave interaction

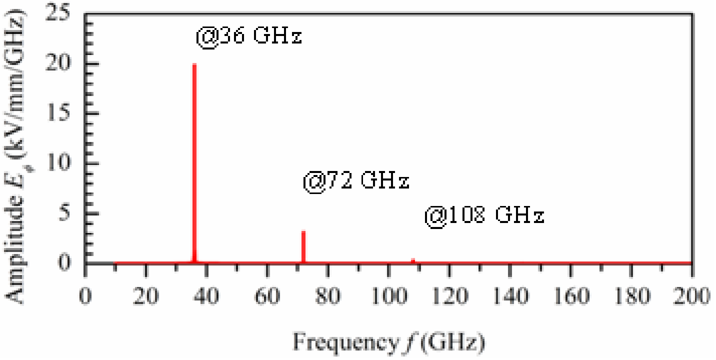


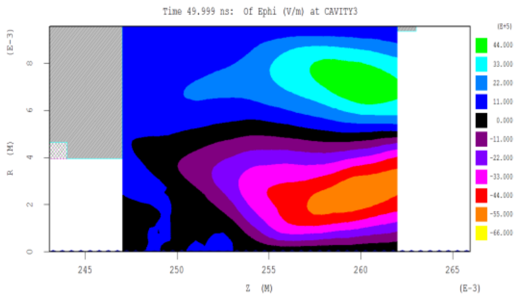


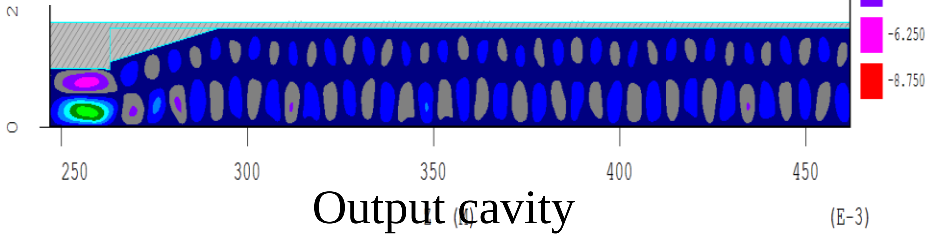






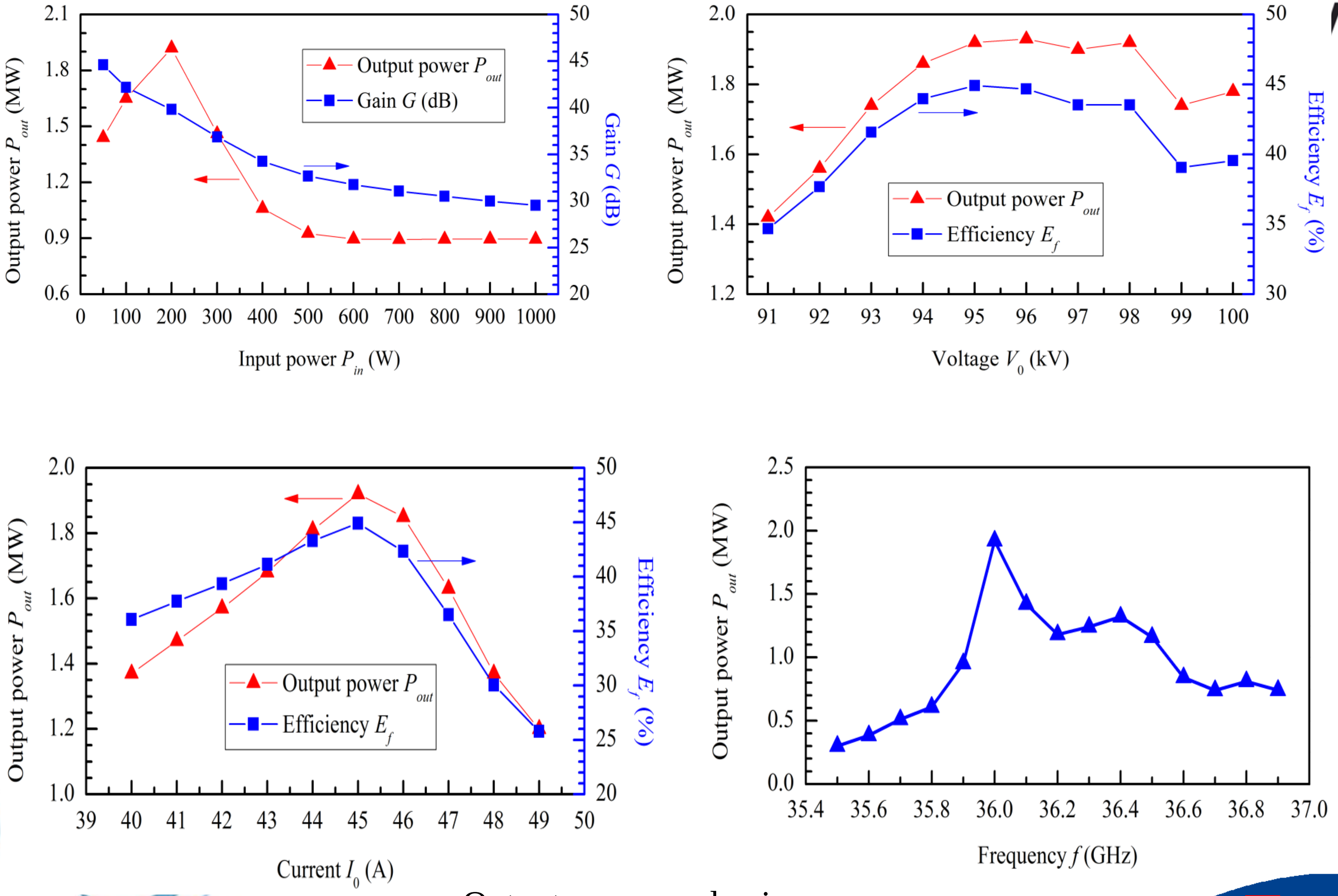






Output cavity

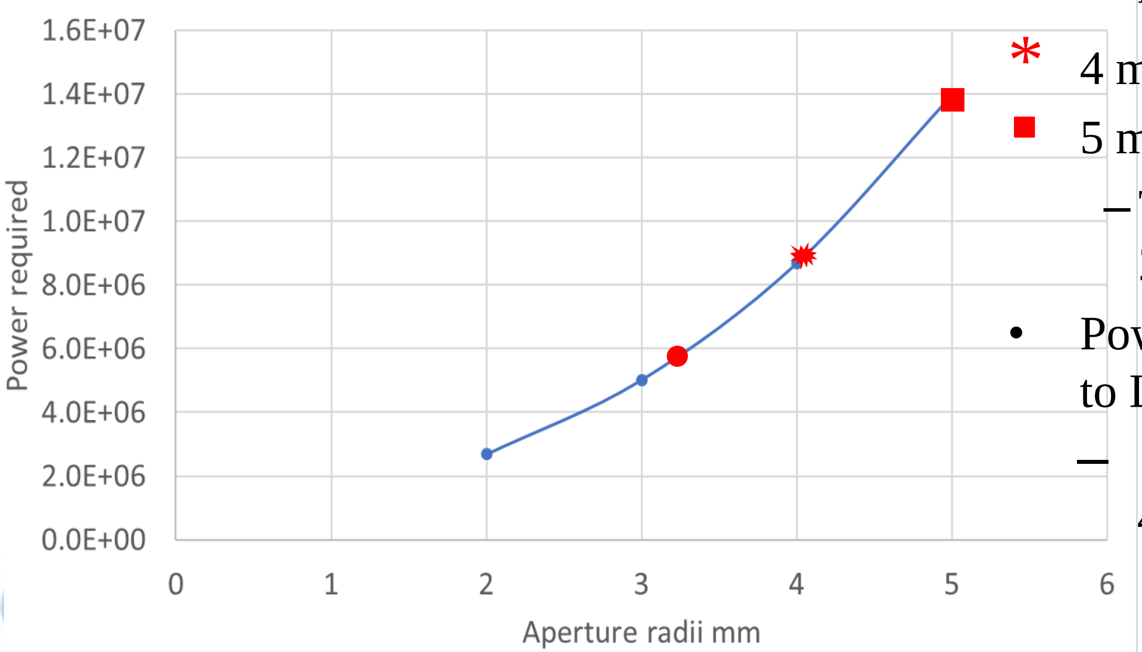
Gain curves in simulations



Output power and gain

36 GHz structure – WP3 (Dr. Graeme Burt) (Lancaster Univ)

- We have two options, either have a small aperture radiua (~3.2 mm), or try to design a large aperture structure. (Andrea looking at minimum aperture)
- Bruno (INFN) is focussing on a small aperture radius high gradient solution
- Aperture design aim is to achieve 8 MV in 25 cm, with a 4 MW input power hence we need Rs/L > 64 Mohm/m (ignore output power lost, see next slide)
- For a 3.2 mm aperture radius
  - ~2MW, 36GHz Gyro-klystron with
  - SLED type compression could be used to increase peak power by factor of ~2.5 (5MW)



Power required for a 5pi/6 mode with recirculation

✱ 4 mm aperture radius needs 8.7 MW,25cm

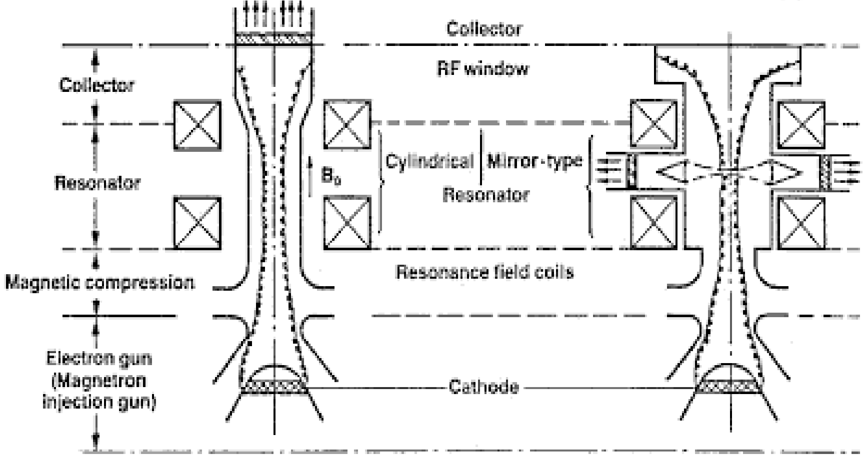
■ 5 mm aperture radius need 14 MW

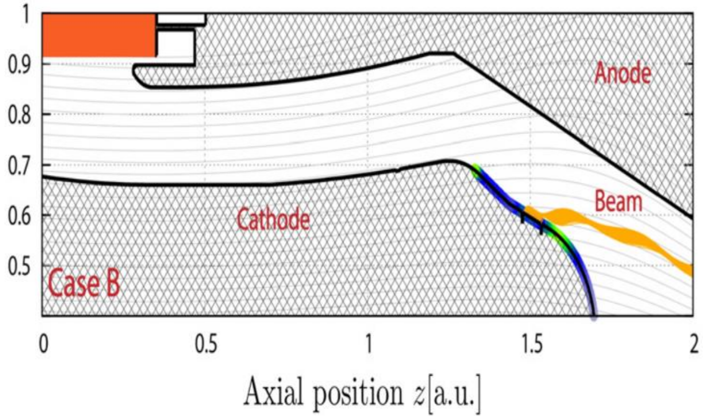
- This would require a higher power, 20MW, 36GHz, co-axial gyro-klystron

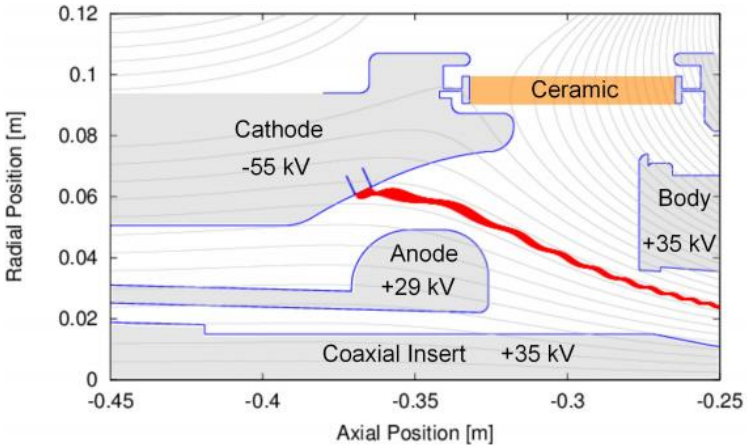
- Power required is inversely proportional to Length
  - For 50cm, 4 mm aperture radius need 4.4MW

Improvements required

- From ~MW to 60 MW
  - Higher beam voltage (440kV)
  - Higher beam current (350A)
  - Energy recovery
  - Thermal stress
  - Quasi-optical mode converter



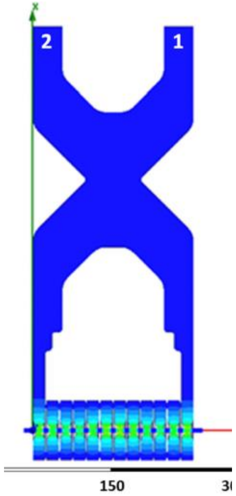


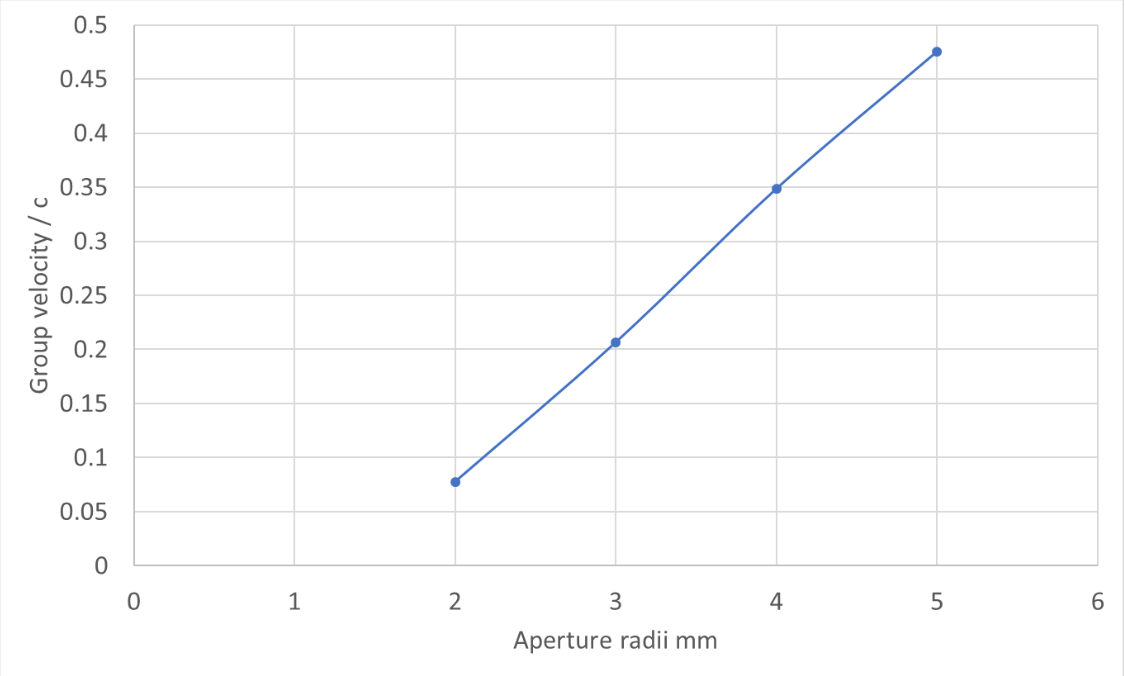


Configuration of MIG and IMIG. An example from KIT for 2MW coaxial-cavity gyrotron. Inverted MIG allows a larger emitter ring to have larger beam current.

Group Velocity Issue – WP3 (Dr. G. Burt)

- The other issue is large aperture means high group velocity and hence a high output power (needs more power). Options to solve this are
  - Use a standing wave structure (needs a circulator, not sure if a MW Ka band circulator exists, probably rules out pulse compression)
  - Recirculate the output power back into the input (CERN has done this before with structure shown at the bottom of slide)
    - ☐ At 45% of c and 3dB attenuation is 2.5 m so 10 passes required, filling time is ~5ns per pass, probably can fill in 150ns
  - Use the TM_{020} mode which can have low group velocity with large aperture but has a low impedance
  - Use a phase advance closer to pi (7pi/8) and a re-entrant cavity to slow vg





Acknowledgement

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Thank you for your attention!

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