1.0 MW / 175 MHz Source for IFMIF: a study of alternatives

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Overview

1. IFMIF RF System
2. Conceptual design of an IOT
3. Conceptual design of a magnetron
4. Conclusions

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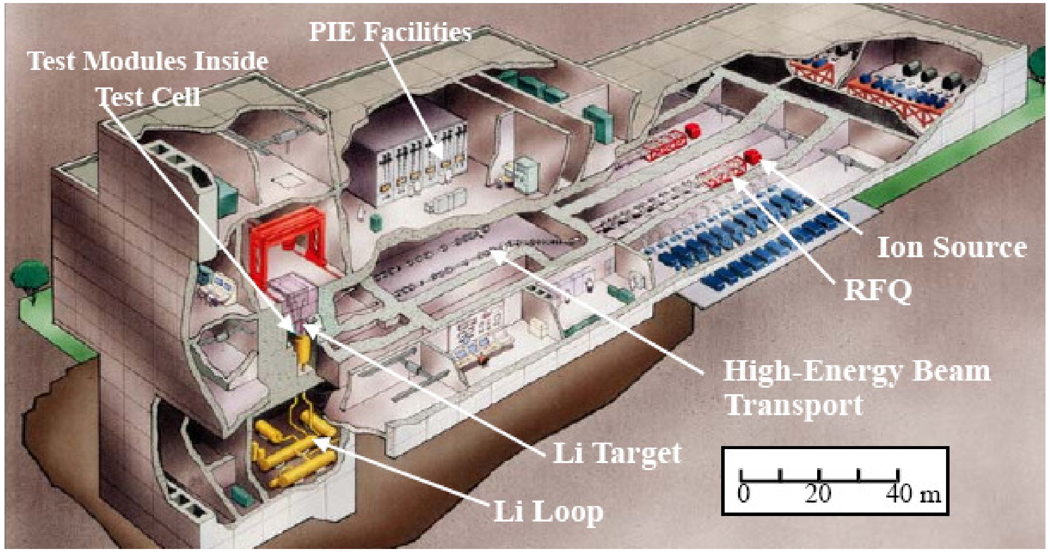
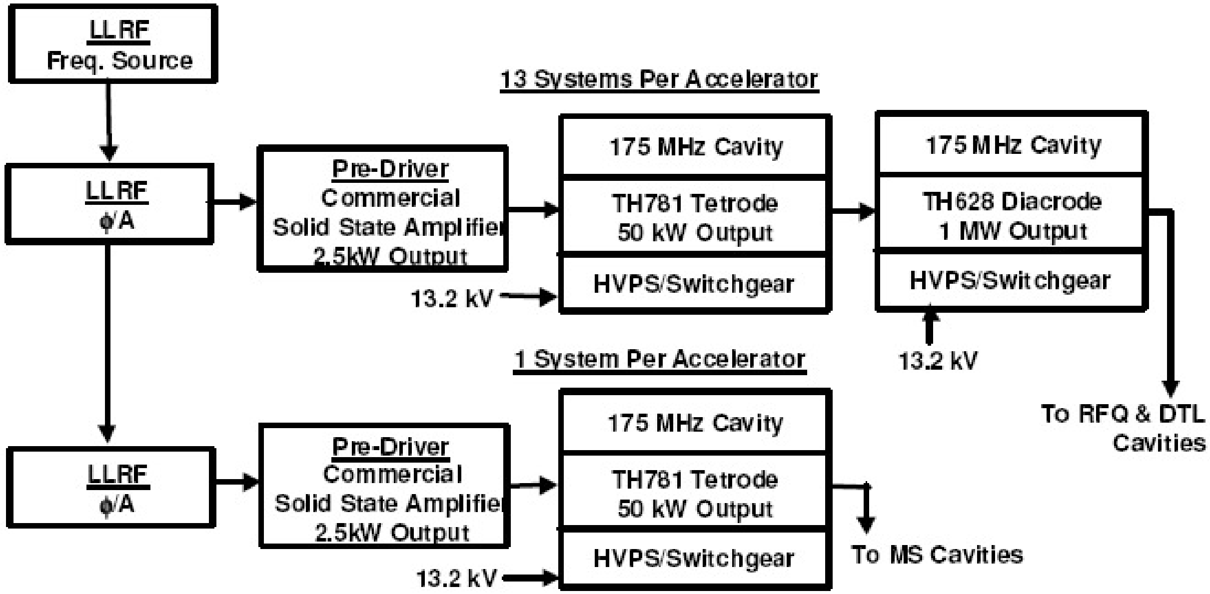
The International Fusion Materials Irradiation Facility

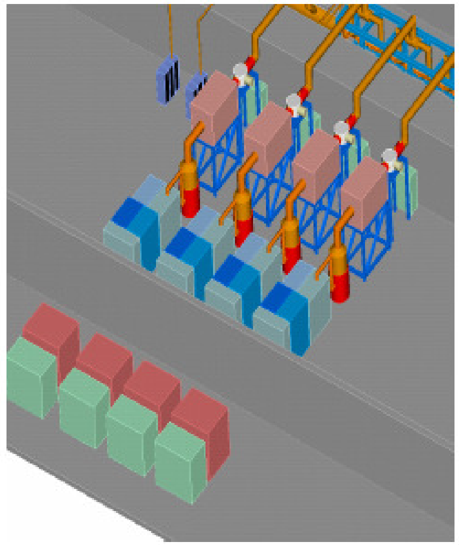


Accelerator reference design [1]

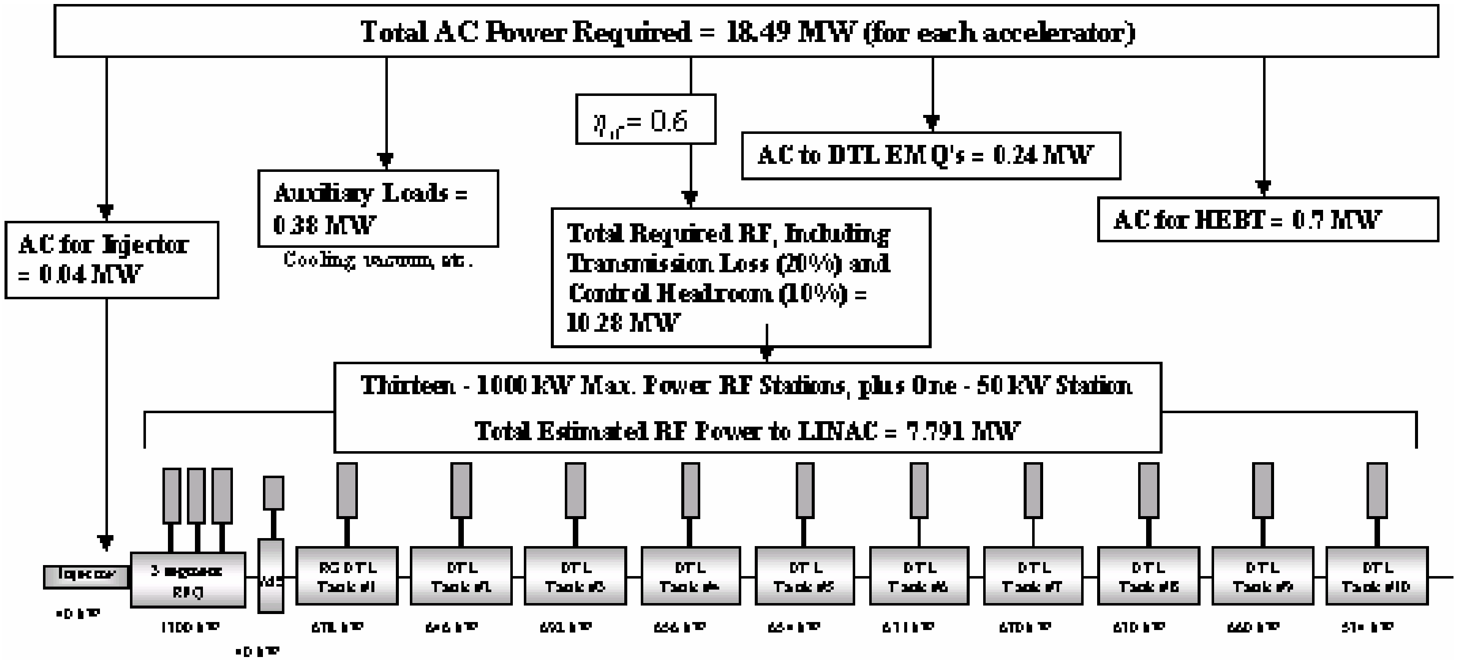
- Two CW 175 MHz linear accelerators
- 125 mA, 40 MeV deuteron beam.
- Conventional, room-temperature, RF linac

IFMIF RF power system conceptual design





IFMIF Power Requirements



Baseline RF Power Source

IFMIF RF Power Requirements		
Frequency	175 MHz	
Power	1.0 MW	
Duty	CW	Pulsed tune-up and start
Phase control	± 1 degree	Simultaneous
Amplitude control	± 1%	

Thales TH628 Diacrode®	
Frequency	200 MHz
RF Power	1.0 MW CW
DC Voltage	14.0 kV
DC Current	103 A
Operation	Class B
Anode efficiency	71.2%
RF Gain	12.98 dB

1000 Hours operation demonstrated with 98.7% availability

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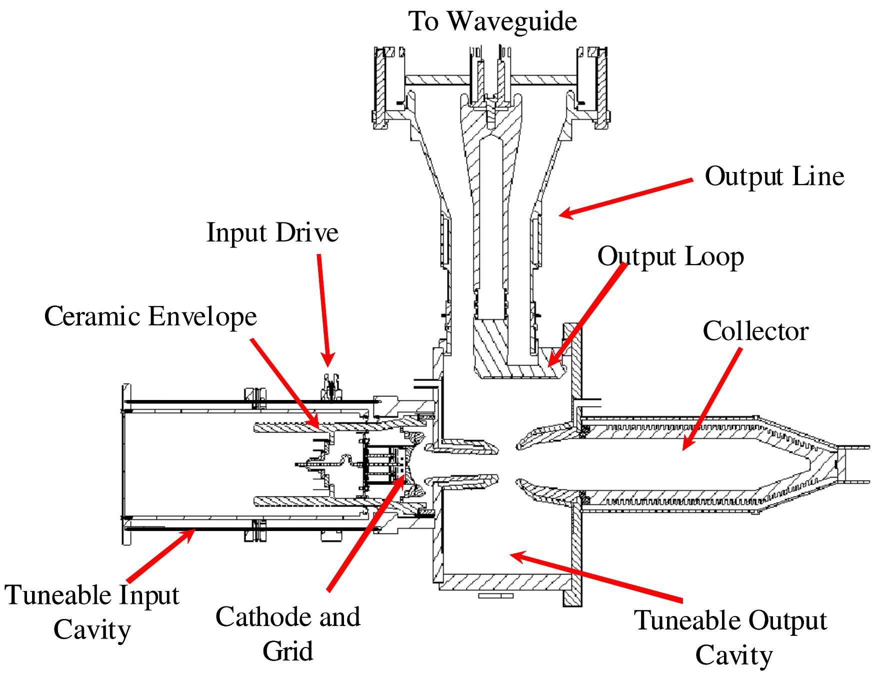
Inductive Output Tube (IOT)

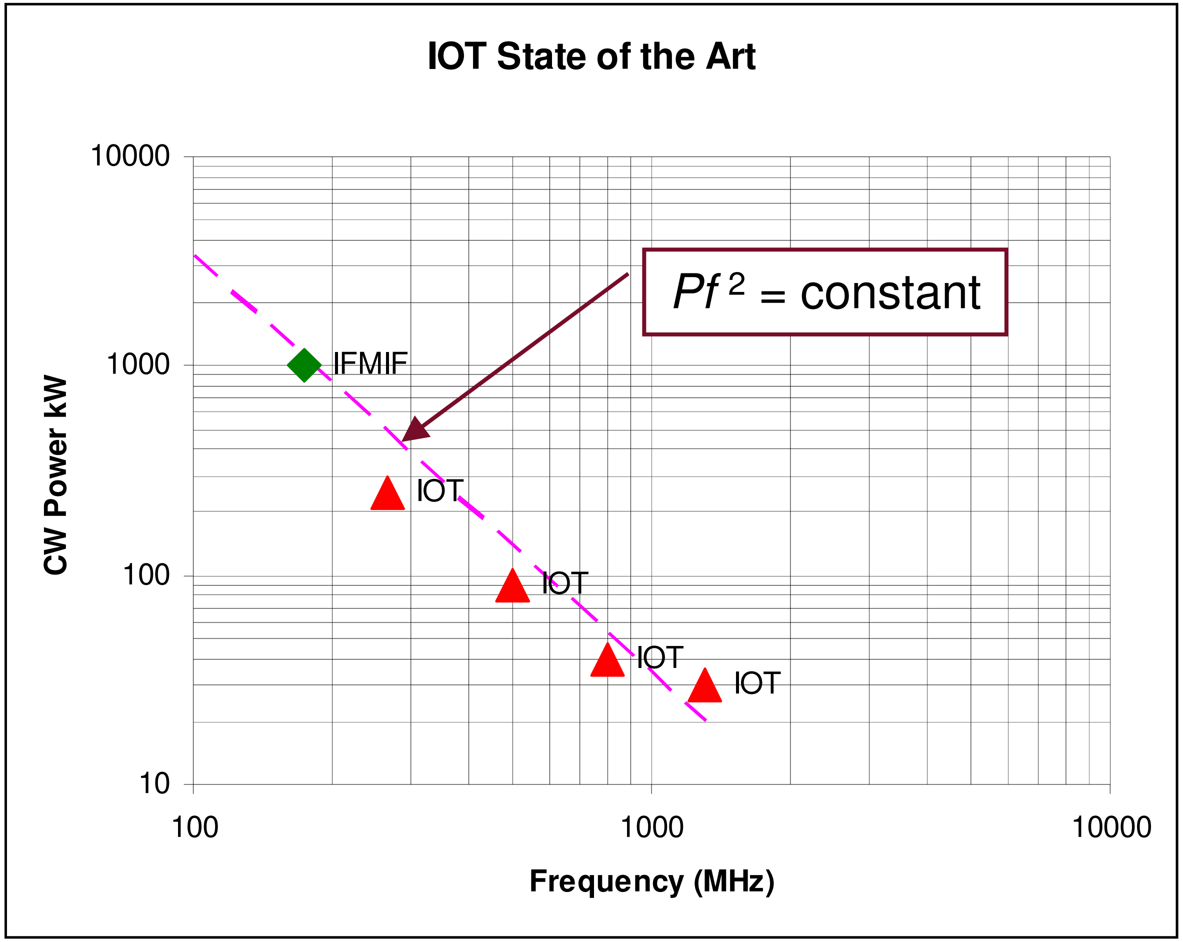


- Grid-modulated like a tetrode
- Operated in class AB or B for high efficiency
- All electrons have full EHT energy
- Compared with a tetrode
  - Lower current
  - Higher voltage
  - Higher gain

Inductive Output Tube (IOT)

IOT State of the Art [2], [3]			
Frequency	267 MHz	500 MHz	1300 MHz
RF Power	250 kW	90 kW	30 kW
DC Voltage	66 kV	37 kV	34 kV
DC Current	5.5 A	3.5 A	1.39 A
Efficiency	73 %	70 %	64 %
RF Gain	21 dB	22 dB	21 dB

IOT State of the Art



Conceptual Design of 175 MHz / 1.0 MW IOT

- P_{RF} = 1.0 MW; f = 175 MHz
- Assume efficiency: η = 65%
  - P_{DC} = 1.0 / 0.65 = 1.54 MW
- Assume peak current (Class B)
  - $I_{pk} = 3.6\ I_0$
- Assume peak perveance $I_{pk}/V^{3/2} = 2 \times 10^{-6}$
  - I_{pk} = 58A I_0 = 16.2A V_0 = 95 kV
- Assume peak cathode loading 1 A/cm^2
  - Cathode radius: r_c = 43 mm

Conceptual Design of 175 MHz / 1.0 MW IOT

- Electron velocity:
  - $u_0 = 1.6 \times 10^8$ m.sec^{-1}
- Electronic propagation constant:
  - $\beta_e = \omega/u_0 = 6.9$ m^{-1}
- Choose normalised beam radius: $\beta_e b = 0.06$
  - b = 8.6 mm
  - Drift tube radius: $a = 1.5 \times b = 13$mm
  - Area convergence: $(r_c / b)^2 = 25:1$
  - Brillouin field: $B_B = 0.045$T

Conceptual Design of 175 MHz / 1.0 MW IOT

- Typical gridded gun parameters
  - Grid transparency: 80%
  - Grid wire radius: 0.5 mm
  - Grid pitch: 5 mm
  - Amplification factor: 200
  - Grid voltage at cut-off: V_{g0} = -475V

Conceptual Design of 175 MHz / 1.0 MW IOT

- RF performance
  - Fundamental RF beam current: $I_1 = 0.5 \times I_{pk} = 29A$
  - RF grid voltage: $V_{g1} = 475$ V
  - RF input power: $P_{in} = 0.5 \times V_{g1} \times I_1 = 6.9kW$
  - Gain: 21.6dB

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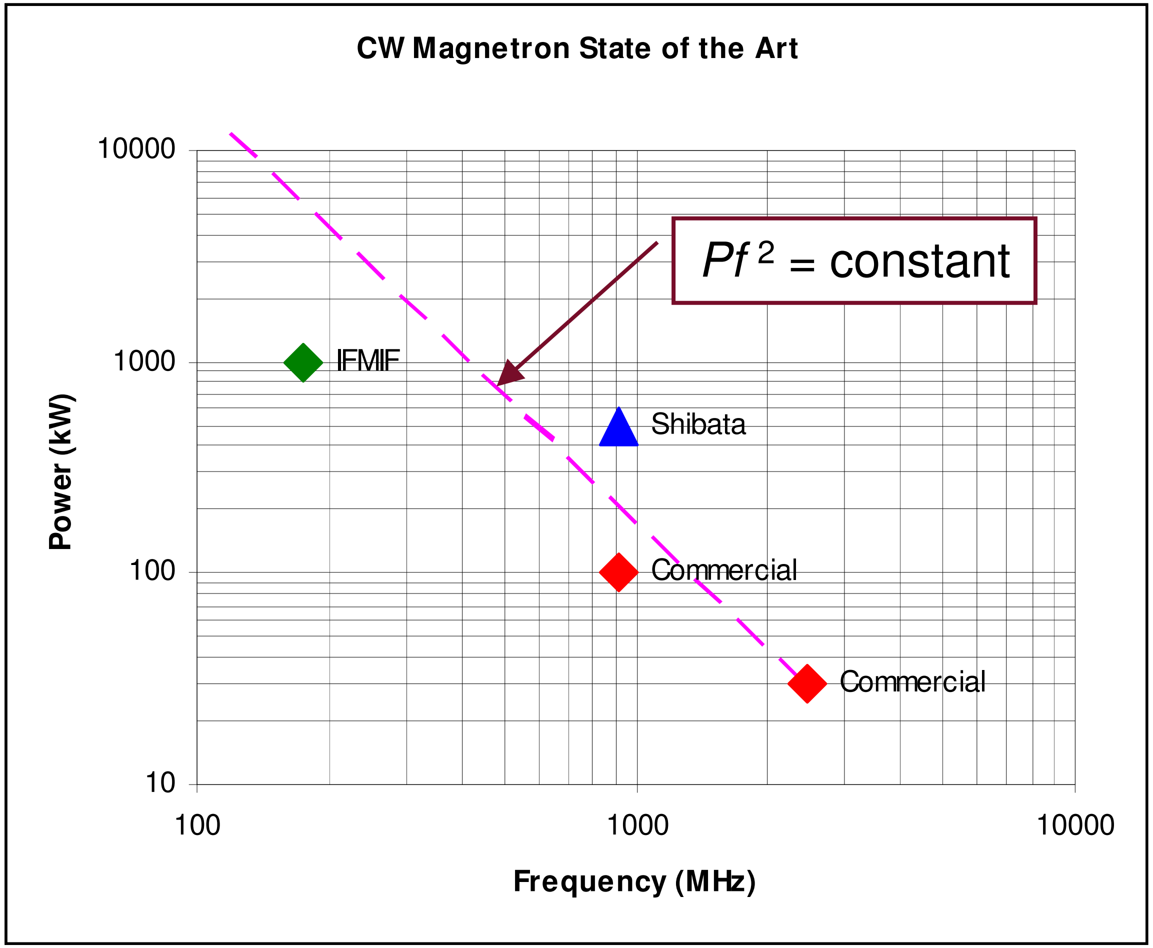
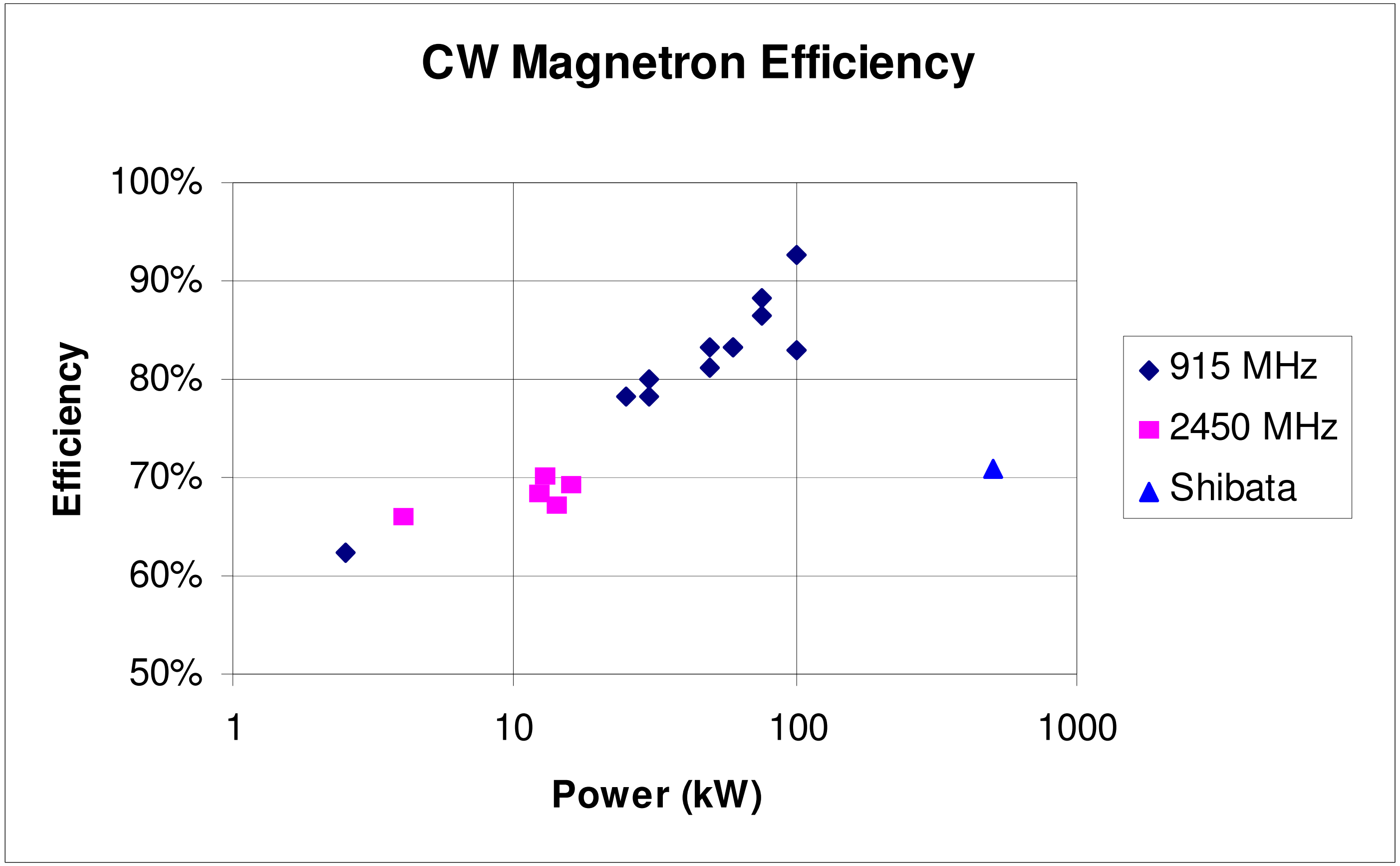
CW Magnetrons

CW Magnetron State of the Art [4], [5], [6]			
Frequency	915 MHz	915 MHz	2450 MHz
RF Power	500 kW	100 kW	30 kW
DC Voltage	44 kV	18 kV	13 kV
DC Current	16 A	6.0 A	3.3 A
Efficiency	72.5 %	65 %	70 %
RF Gain	-	-	-

CW Magnetron State of the Art

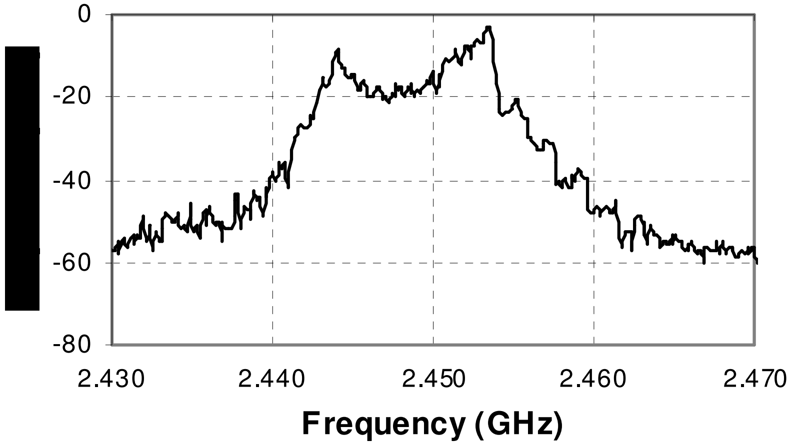


CW Magnetron Efficiency



Injection Locking

$$\frac{P_{inj}}{P_{RF}} = 4Q_L^2\left(\frac{\omega_i - \omega_0}{\omega_0}\right)^2$$



ω_0	magnetron frequency without injection
ω_i	injected frequency
Q_L	refers to the loaded magnetron. [7]

For a typical magnetron P_{inj} is about 10 dB below P_{RF}

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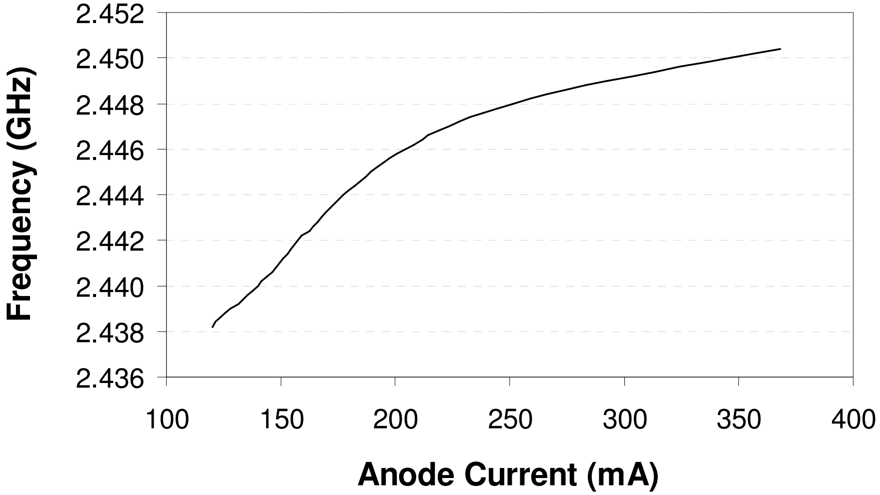
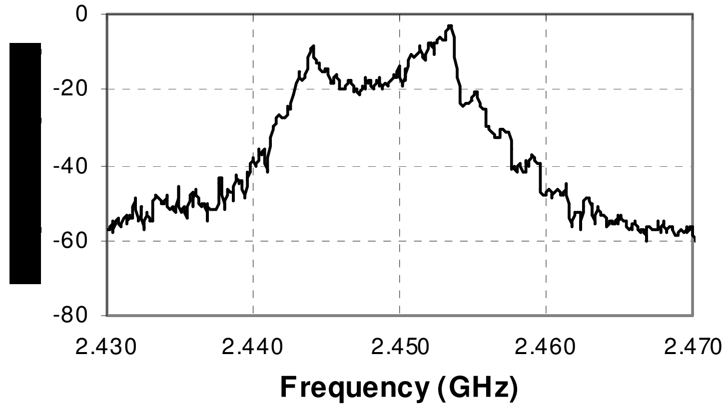
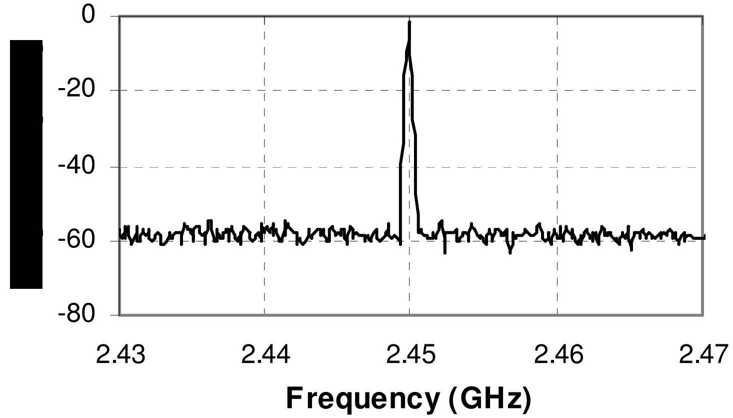
Magnetron Frequency Pushing



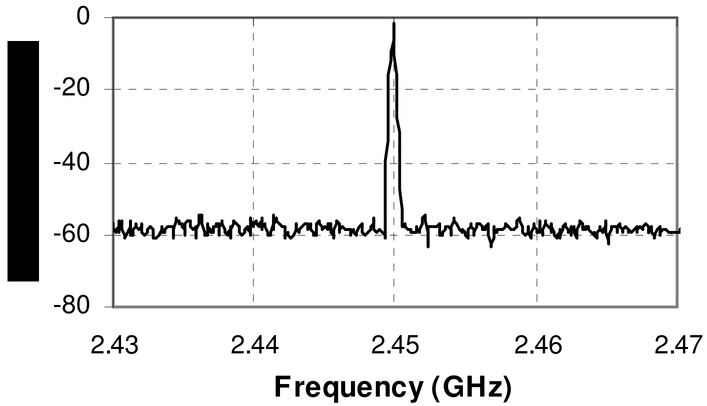


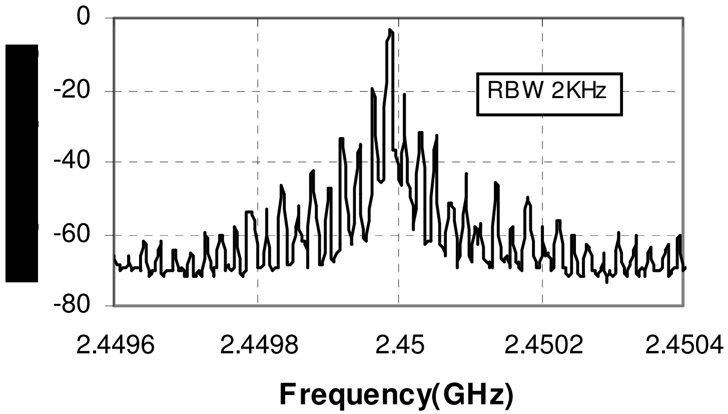


- Frequency depends on the anode current
- Switched-mode power supply in a phase-locked loop stabilises the frequency by controlling the current [8], [9]

Accurate control of a ‘cooker’ magnetron

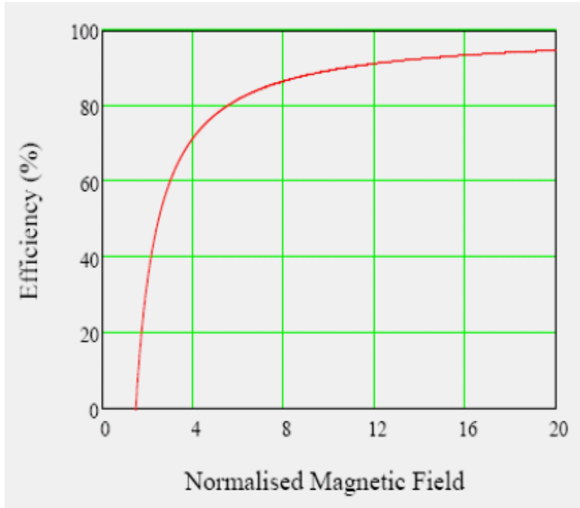
- Frequency is stabilised with a phase-locked loop
- Injection locking is then possible with much lower injected power
- Phase locked to better than 1º with injected power – 37dB
- 90º PSK modulation demonstrated at 2 MHz
- Magnetron responds to 90º phase shift in ~200 nsec
- It might be possible to use controlled magnetrons to power an accelerator





Conceptual Design of 175 MHz / 1.0 MW Magnetron

- P_{RF} = 1.0 MW; f = 175 MHz
- Assume efficiency: η = 85%
  - P_{DC} = 1.0 / 0.65 = 1.2 MW
- Assume impedance V_0/I_0 = 3.0 kΩ
  - V_0 = 60 kV I_0 = 20A
- Use a high normalised magnetic field to achieve the target efficiency



Conceptual Design of 175 MHz / 1.0 MW Magnetron

Design criteria:

- Cathode loading < 1.0 A/cm^2
- Cathode height << λ_0
- Anode vane tip temperature < 600 K
- Product EV_a < 1000 kV^2/mm

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Conceptual Design of 175 MHz / 1.0 MW Magnetron

Leading Dimensions	
Cathode radius	8.3 cm
Number of anode cavities	10
Anode vane tip radius	13.1 cm
Anode height	17.1 cm
Anode outer radius	55.9 cm

Conceptual Design of 175 MHz / 1.0 MW Magnetron

Electromagnet specification		Flux density	0.043 T
Inside radius	60 cm	Voltage	14 V
Outside radius	70 cm	Current	24 A
Height	26 cm	Power	340 W
Current density	1 A/mm^2	Resistance	0.57 Ω
Number of turns (tape)	400	Self inductance	0.94 H
RF power change by 1% in 100 msec requires $\Delta V = 24V$			

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Comparison of Sources

	Diacrode	**IOT**	**Magnetron**
Anode voltage	14 kV	95 kV	60 kV
Anode current	103 A	16.2 A	20 A
Efficiency	71%	65% (>75% with a multi-element depressed collector	85 %
Gain	13 dB	23 dB	> 30 dB
Drive power	50 kW	5 kW	< 1 kW
Cooling	Anode	Collector	Anode and (probably) cathode
Electromagnet	No	Yes	Yes

IOT Development

- Possible with current technology
- Would require 2 - 3 years R&D
- Issues
  - Mechanical stability of control grid
  - Multi-element depressed collector design
  - Demonstration of life and reliability

Magnetron development

- Appears to be possible
- Would require 4 – 5 years R&D
- Issues
  - Cathode choice for long life
  - Development of switched mode power supply
  - Demonstration of simultaneous control of amplitude and phase stability
  - Demonstration of lifetime and reliability

References

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