# Efficient Experimental Methods That Enable Control Of High Pressure Microwave Discharges

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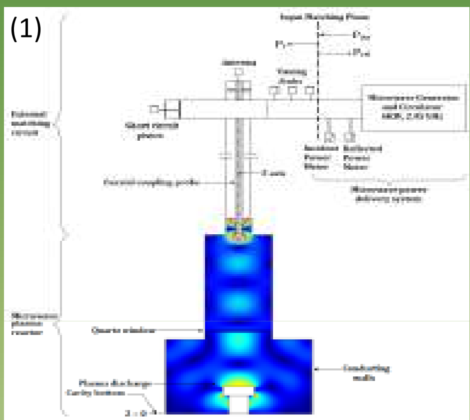
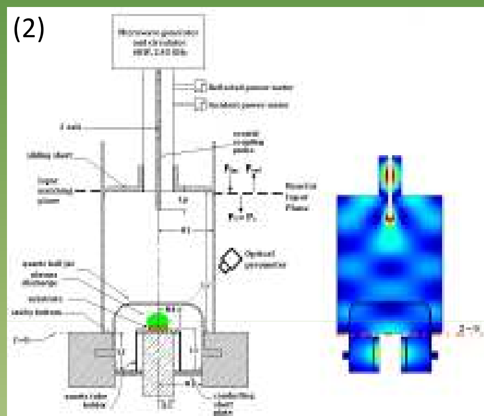
## Introduction:

Microwave Plasma-Assisted CVD method is a convenient mode of synthesizing SCDs. It is important to employ an electrically efficient process producing a stable plasma for the growth process.

## Experimental Details:

The main purpose of this research is to determine microwave coupling and operational efficiencies of microwave cavity plasma reactor used commercially for the synthesis of single crystal diamonds.




Operational Strategy:

- Adjust $L_p$ and $L_s$ to excite reactor cavity in a hybrid $TM_{013}/TEM_{001}$ mode
- Once plasma is formed, adjust $L_p$, $L_s$, L1 and L2 for optimum operating conditions
- Measure $T_s$, $P_{inc}$, $P_{ref}$, η with varying pressure, $Z_s$ and $L_s$ positions.

## Important reactor variables:

1. Microwave coupling efficiency into the reactor

   $\eta = (1 - (P_w + P_{ref})/P_{inc}) \times 100\%$

2. Overall microwave coupling efficiency into discharge

   $\eta_{coup} = (1 - (P_w + P_{ref} + P_{loss})/P_{inc}) \times 100\%$

   $= (1 - Q_L/Q_o) \times 100\%$ (for $P_w$, $P_{loss} = 0$)

3. Power coupled into discharge

   $P_{abs} = P_{inc} - P_{ref} - P_w - P_{loss}$

where, $P_w$ : any power lost in the external matching circuit

$P_{ref}$ : power reflected from input matching plane

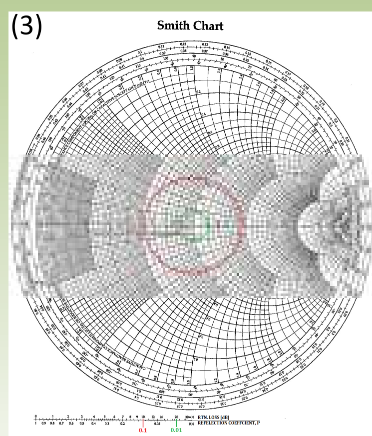
$P_{inc}$: incident power

$P_{loss}$: microwave power losses in cavity

$Q_0$: Empty cavity quality factor

$Q_L$: discharge loaded cavity quality factor

$P_{loss}$ is minimized by a well maintained cavity (high $Q_0$) and low $Q_L$



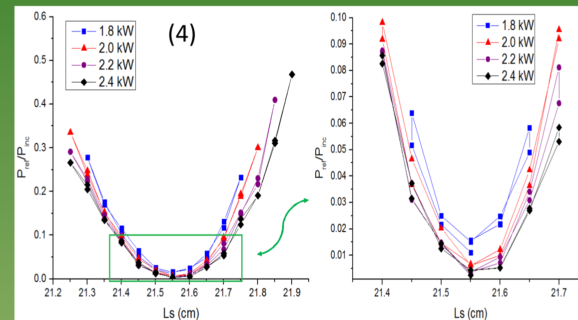

## Results:

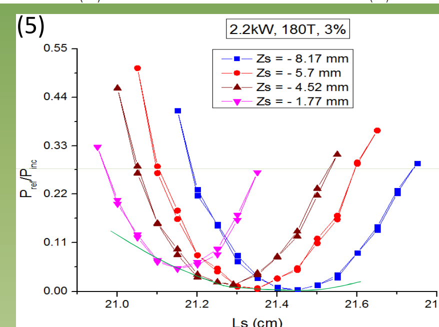
MSU reactor (fig.2) [1], has an internal matching configuration eliminating large microwave coupling power losses.

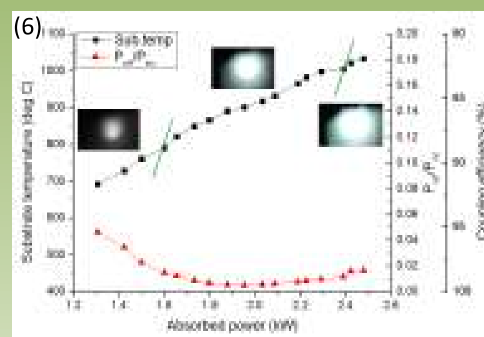
**(1)** Figs. 3,4 and 7 identify the "**best matched**" reactor position (η>98%) (green box/circle) at 180 Torr. For all SCD synthesis , $L_s$ = 21.55cm, η ~ 99%.

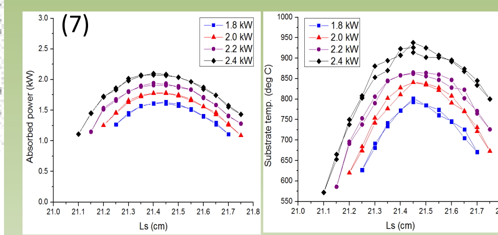
**(2)** Discharge boundary layer is modified when different substrate holders change $L_s$ and hence $Z_s$. Fig. 5 displays the effectiveness of in situ matching. η > 95% at best matched positions.

**(3)** Operational roadmap (fig.6) describes the safe and efficient operating regime of reactor. As pressure increases the plasma intensity and size increases.




## Conclusion:

Internally tunable microwave reactors reduce power and high coupling efficiencies (η>95%) are obtained over a wide pressure and power range providing flexibility in deposition conditions. This reactor is synthesizing commercial diamond with electrical efficiency of < 10 kW-h/carat [3]. The variable substrate position enables flexible process control and optimization.

## References:

[1] J. Asmussen et.al. US Patent 8,316,797 (2012) and 8,668,962 (2014)
[2] K.W. Hemawan et al. / Diamond & Related Materials 19 (2010) 1446–1452
[3] J. Lu et.al. Diamond and Relat. Mater. 37, 17-28 (2013 )

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