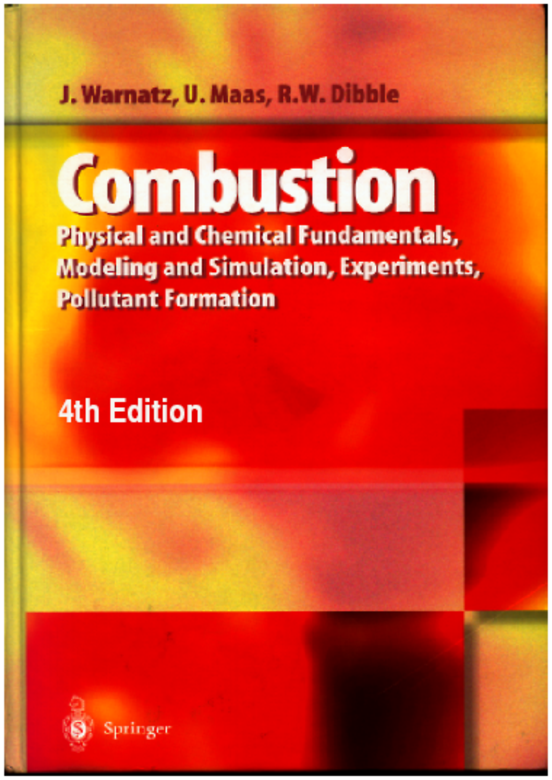
Please Bring Your "Out of the Box" Ideas to the High Pressure Combustion Workshop

High Pressure Combustion Workshop
At Argonne National Laboratories
Aug 2011

Robert W. Dibble UC Berkeley

Funded by DoE and KAUST

Buy This Book !



Out of the Box
The W number

All chemical reactions should get a permanent number that is Decimal. As new reactions are discovered, they can be assigned Numbers close to other reactions.

Thus $CO + OH \Rightarrow CO2 + H$ could be W 2.3

hypothetical new reaction

$CO + OOH \Rightarrow CO2 + OH$ could be W 2.3101 for example

W for Westbrook, Warnatz, Wolfrum, Woolbridge, Wolker
And Joe Micheals and Jim Miller (because "M" is "W" upside down

Out of the Box

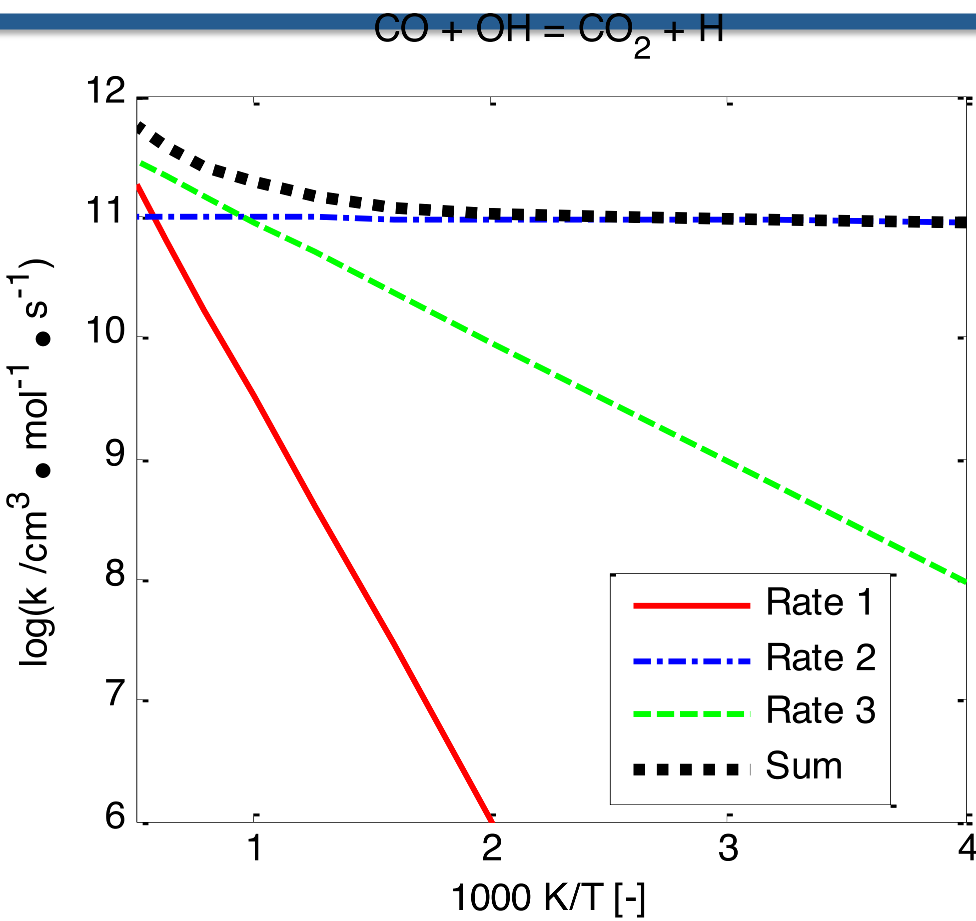
1….Rudy Marcus visits Berkeley
(Marcus is the "M" in RRKM)
He Lectures on
1…H2O(18) in ocean is different than H2O(18) in air

And

2…… CO + OH = CO2 + O "strange reaction"

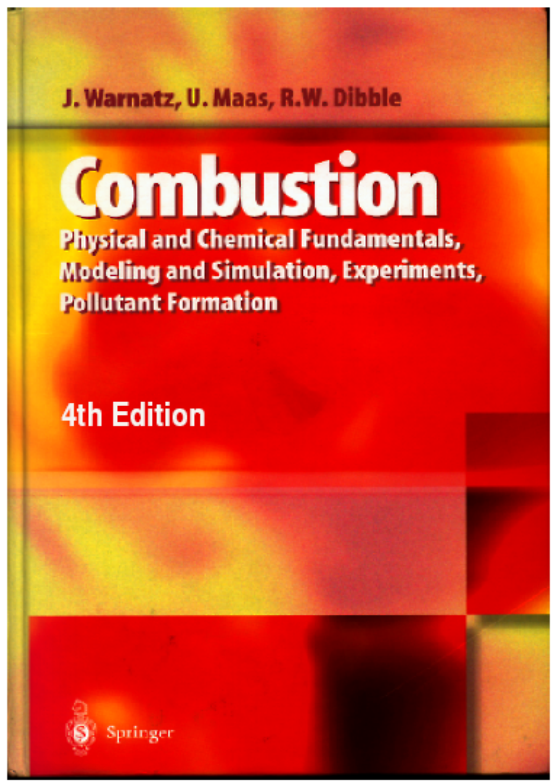
He was so excited about 1, that he never got to 2

Rate 2 governs at low temps; Rates 1 and 3 govern at high temperatures



					A_0 (cc/mol-s)	b	Ea (kJ/mol)
Rate 1	CO	+OH	$=CO_2$	+H	$1.00 \cdot 10^{13}$	0.0	66.9
Rate 2	CO	+OH	$=CO_2$	+H	$1.01 \cdot 10^{11}$	0.0	0.25
Rate 3	CO	+OH	$=CO_2$	+H	$9.03 \cdot 10^{11}$	0.0	19.1

Buy This Book !



REVIEW

1…Need to be hot, to have OH radicals,

OH needs to Burn out fuel *before*

OH can   burn out CO $CO + OH = CO_2 + H$

2…do not be too hot !

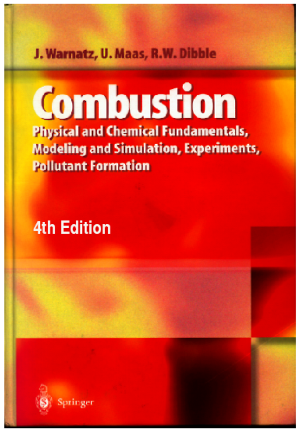
You will make NO

3…Do not be too cold !

need to be hot enough to have OH

to react with CO

4…buy the book !



Out of the Box

1….Downsizing is leading to turbocharging,
Thus higher pressures, thus more demand on
Spark electronics and electrodes. Advanced
Sparking systems are being explored

“1kg reduction of engine mass,
2kg reduction in vehicle mass “

Out of the Box (about 1970)

Rolls-Royce Diesel | Rolls-Royce.Edmunds.com

*www.**rolls-royce**.edmunds.com*

Rolls-Royce Research, Reviews & Latest Prices! Free Info.

▸

Search Results

The *Wankel* Rotary Engine: A History

*books.google.com*John B. Hege - 2006 - 174 pages - Google eBook - Preview

The work done by several companies to overcome these problems is described in detail, as are

More editions Add to My Library▼

Popular Science - Feb 1971 - Page 80

*books.google.com*Vol. 198, No. 2 - 162 pages - Magazine - Full view

A *Diesel Wankel* from *Rolls-Royce* By DAVID SCOTT / PS European Editot LJp to now, all *Wankel*

Add to My Library▼

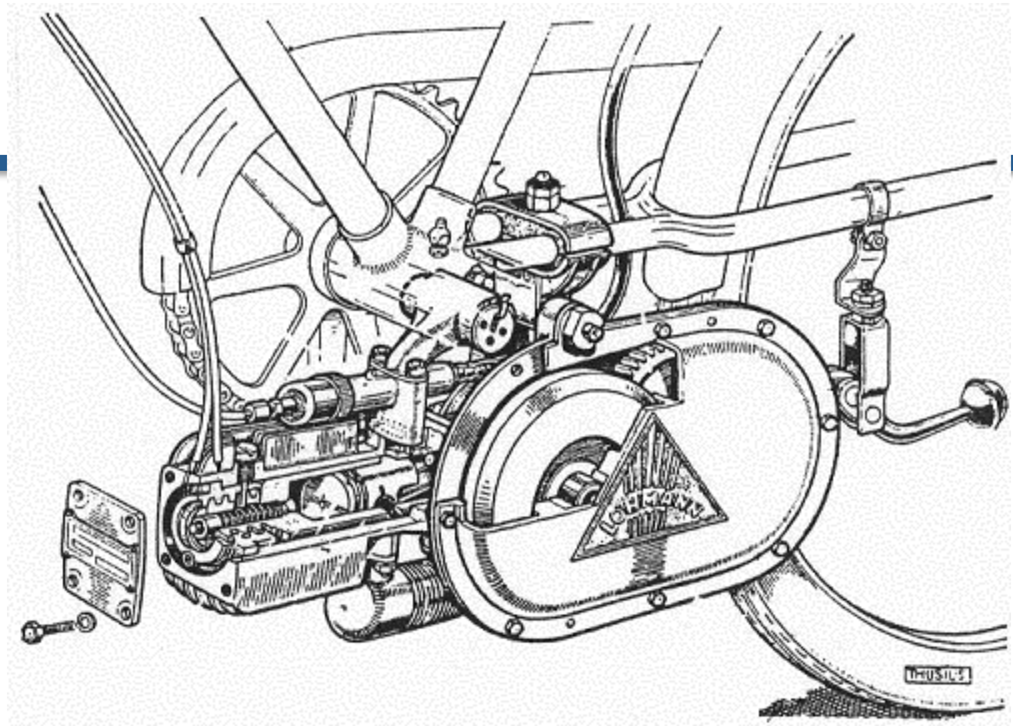
The rotor can take much more pressure,

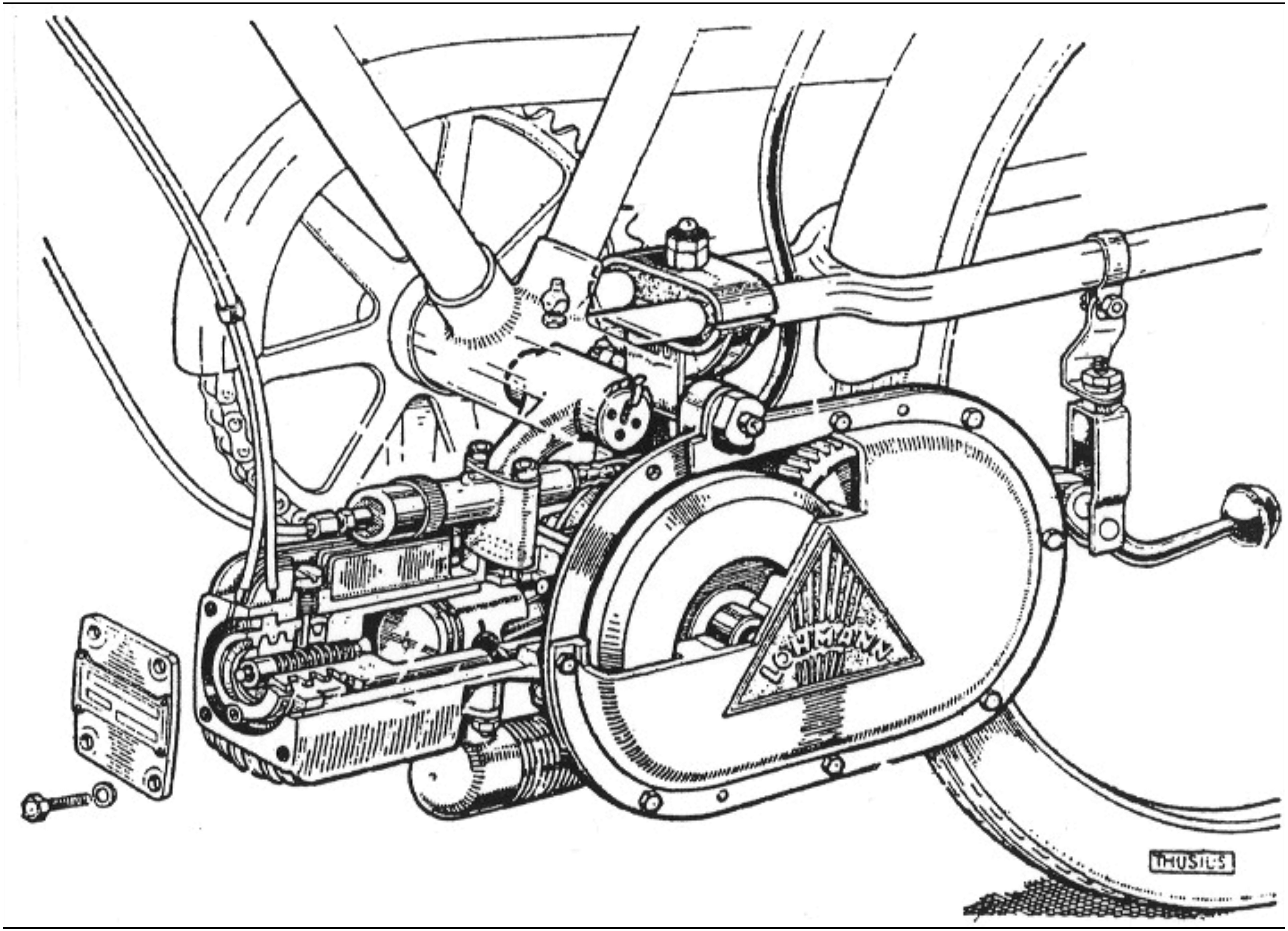
say 400 bar "Wankel boosting Wankel"

HCCI is not new !

Lohmann HCCI engine, ca 1952 (> 1949)
notice: no spark plug carbureted, 70$

ALL: find one (or earlier, bulb engines ca 1900.
Also, there are web sites; old farm machines




LOHMANN
THUSIUS

Out of the Box

The Argon Engine at Argonne Labs

Argon, mono atomic, with gamma=1.67
No vibrational or rotational degrees of freedom

Converting Chemical energy to vibrational energy
Is wasteful, thus,
nitrogen in engines is not optimal

The Argon Engine Project

H_2-O_2-Ar Internal Combustion Engine: the Mechanical Equivalent of a Fuel Cell

"We believe we can build the cleanest and most efficient engine in history (~50% and zero emissions) by optimizing the working medium (argon instead of nitrogen)"

Professors Dibble and Chen
Collaboration with Dr. Aceves at LLNL
UC Berkeley

April 1, 2008

Low temperature combustion requires high dilution levels - A challenge at high load

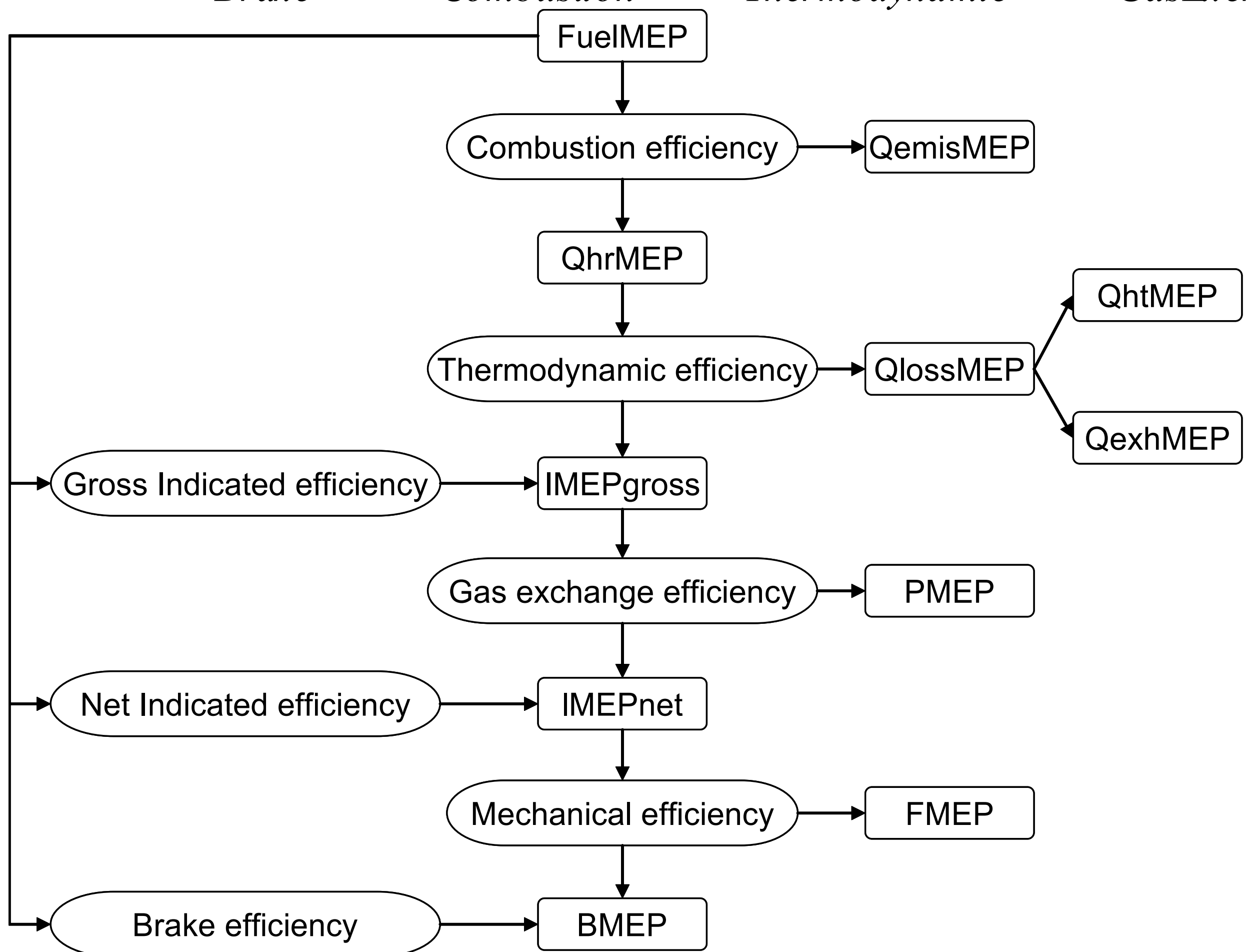
LUND UNIVERSITY

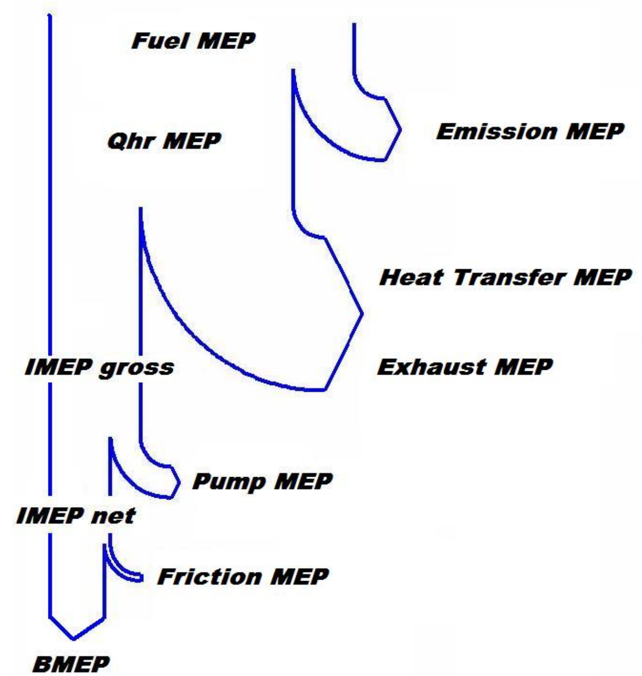
Prof. Bengt Johansson

Div. of Combustion Engines, Dept. of Energy Sciences

Energy flow in an IC engine

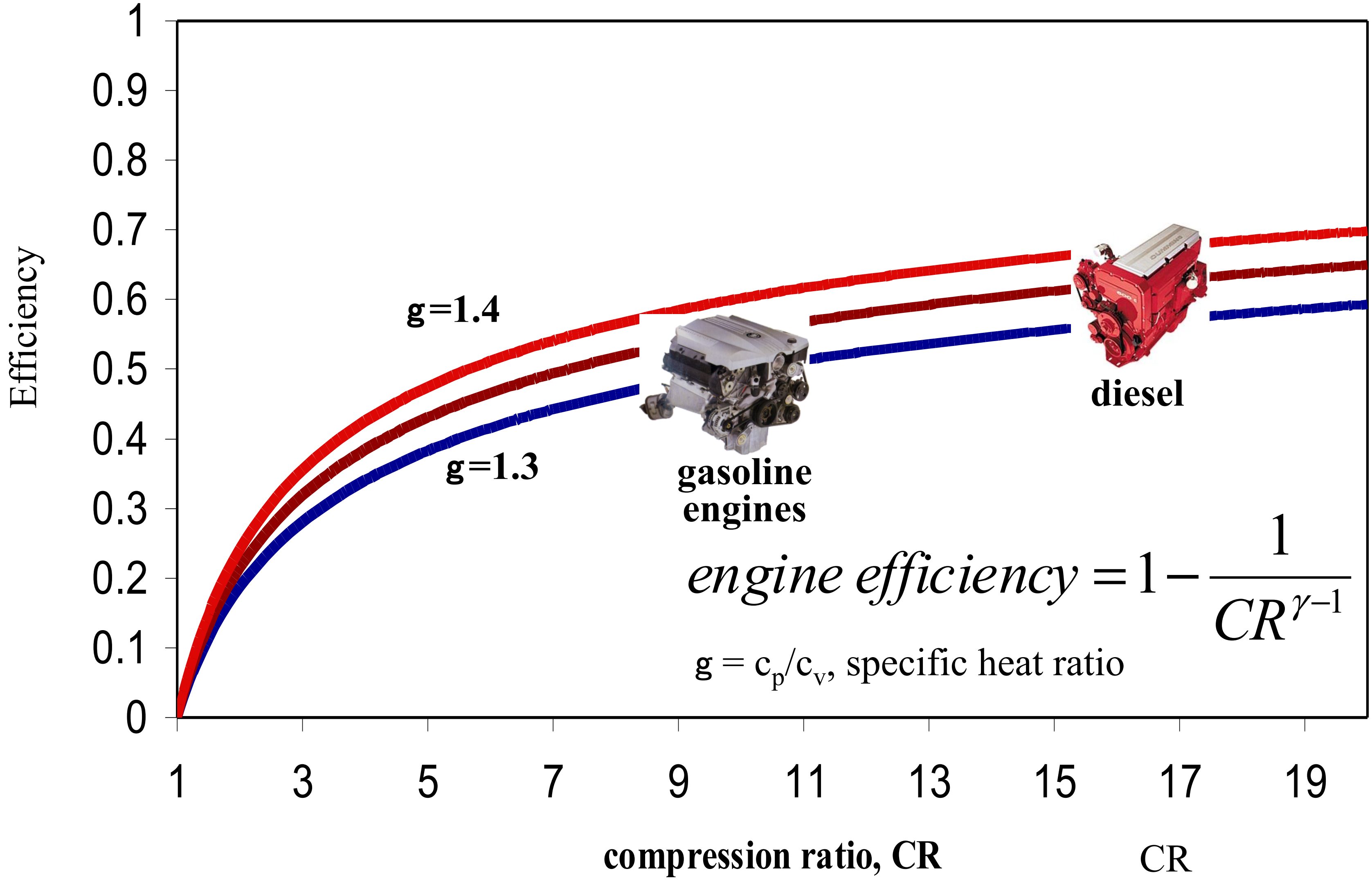
$$\eta_{Brake} = \eta_{Combustion} * \eta_{Thermodynamic} * \eta_{GasExchange} * \eta_{Mechanical}$$



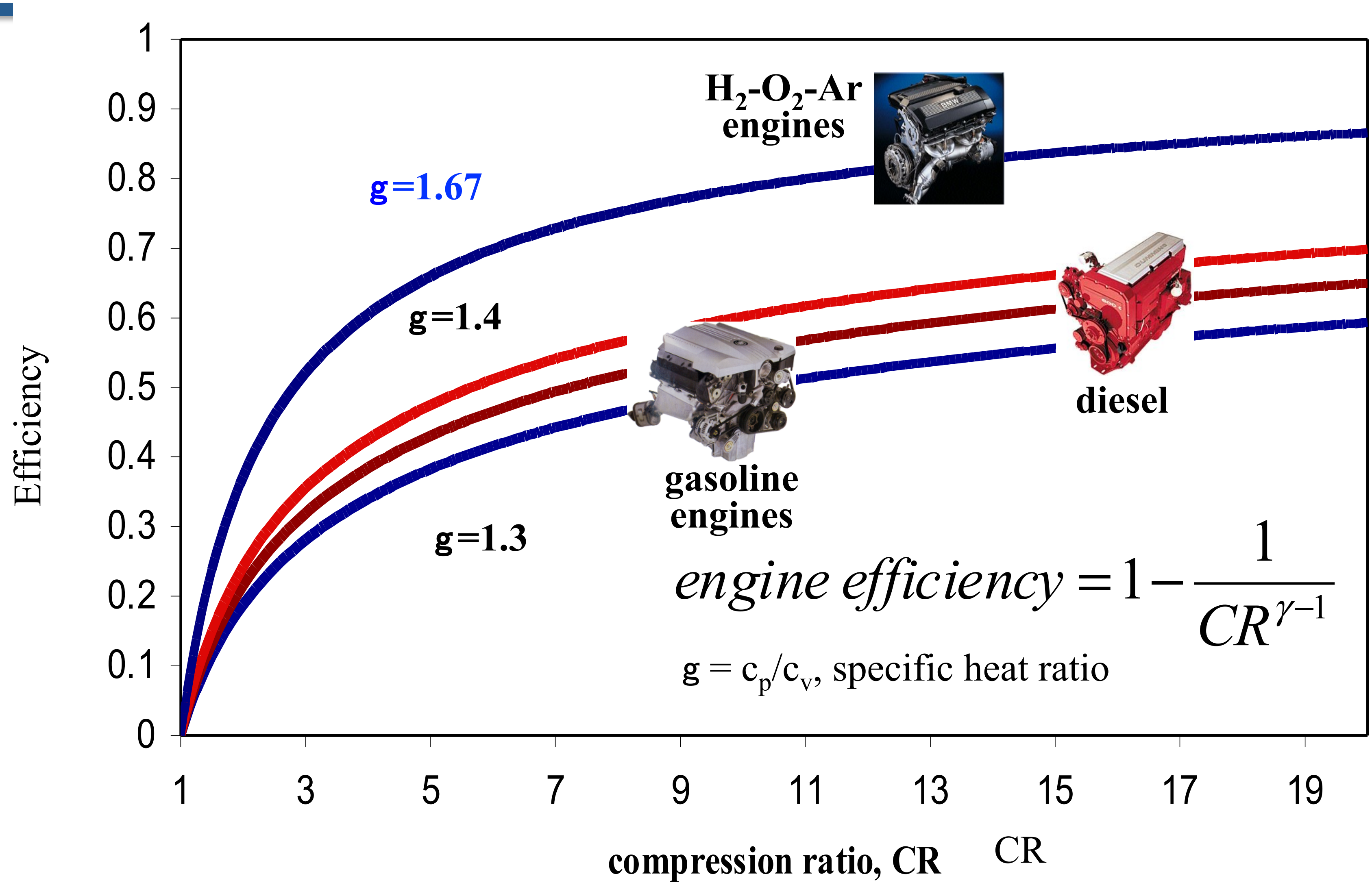


Slide from
Prof. Bengt Johansson

mixtures (specific heat ratio $c_p/c_v = \gamma <$ 1.4 for air, 1.67 for Argon)



by optimizing the working medium (argon instead of nitrogen)



H_2-O_2-Ar Internal Combustion Engine System:

The Mechanical Equivalent of a Fuel Cell

Salvador M. Aceves (LLNL)   Robert Dibble (UC Berkeley)

Next Steps

Stopped by Knock, Thus

Convert to Diesel Mode

Inhale Argon plus 10% hydrogen

Inject liquid : H2O2 or N2O or ?

Limits of MicroWave Assisted Combustion (mWASP) in Constant Volume Combustion Chamber

High Pressure Combustion Workshop
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B. Wolk, A DeFilippo, JY Chen, R Dibble (UC Berkeley)
A Nishiyama, Y Ikeda (Imagineering Inc.)

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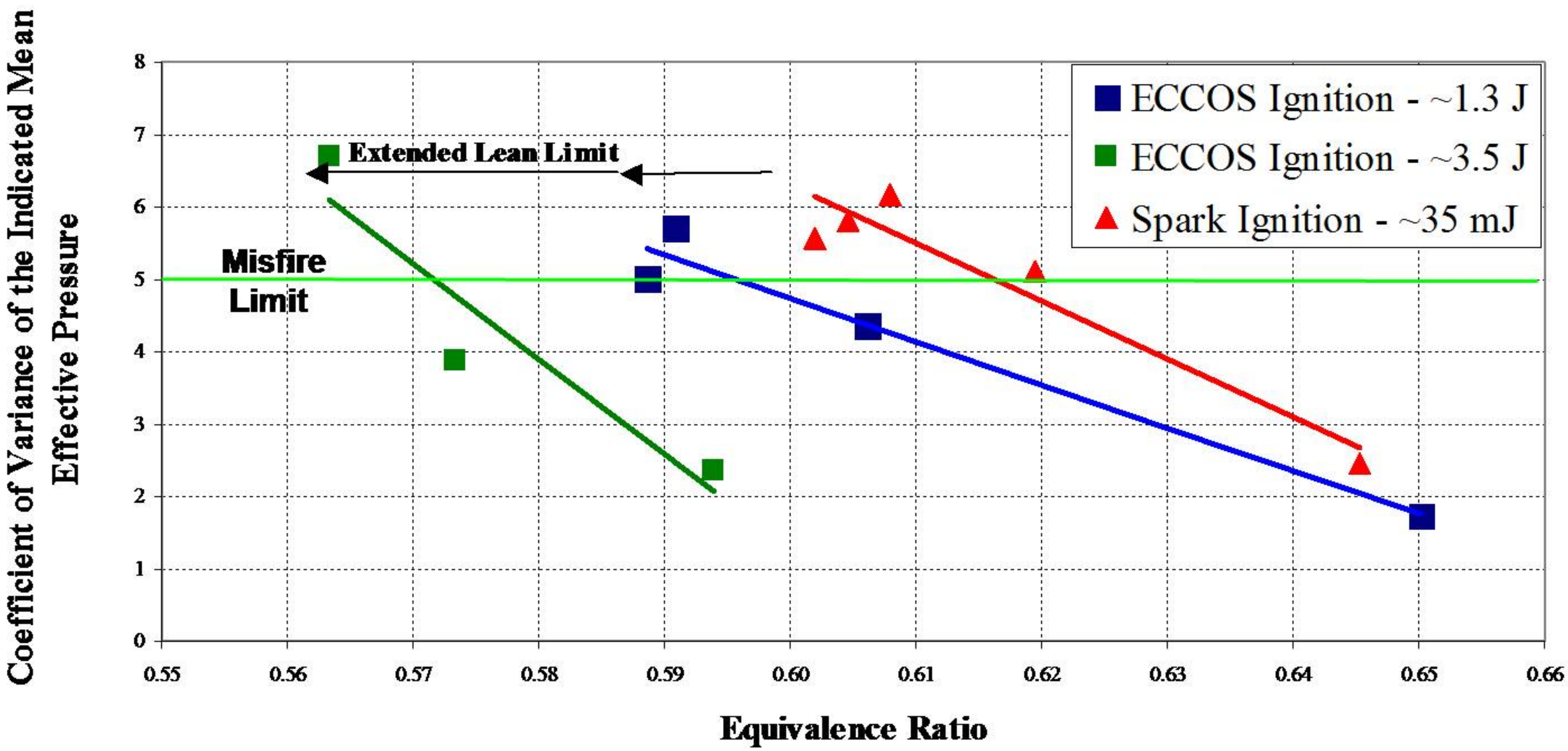
Research Into Spark Plugs is Electrifying Topic !

- **SwRI's DCO™ Ignition System tapped for R&D 100 Award**
- *For immediate release*
- Download this image
- San Antonio — June 22, 2011 — A novel ignition system for gasoline engines that creates a continuous spark of variable energy and duration has received a 2011 R&D 100 Award. R&D Magazine selected Southwest Research Institute's Dual Coil Offset (DCO™) Ignition System as one of the 100 most significant technological achievements of the past year.
- The DCO Ignition System is a continuous ignition system that uses two automotive-style ignition coils connected by a diode to create a continuous spark of variable duration in high-dilution engines. It has been shown to be more successful than other spark ignition systems in initiating combustion and allowing the engine to operate at high dilution rates. A high-dilution engine uses excess air or high levels of exhaust gas recirculation (EGR) to cool combustion temperatures, leading to cleaner emissions and less fuel consumption. It also lessens the potential for engine knock, which can lead to severe engine damage.

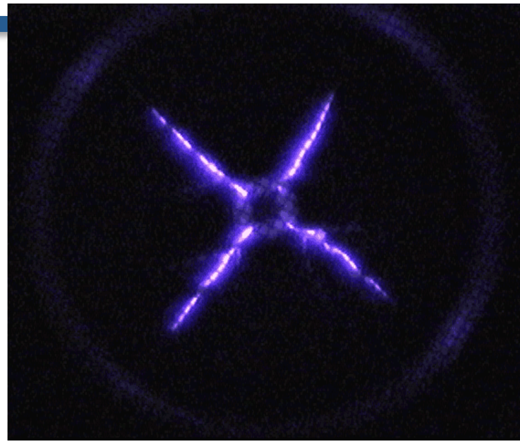
Electrically Controlled Combustion Optimization System (ECCOS)

Combustion Characteristics and Engine Performance

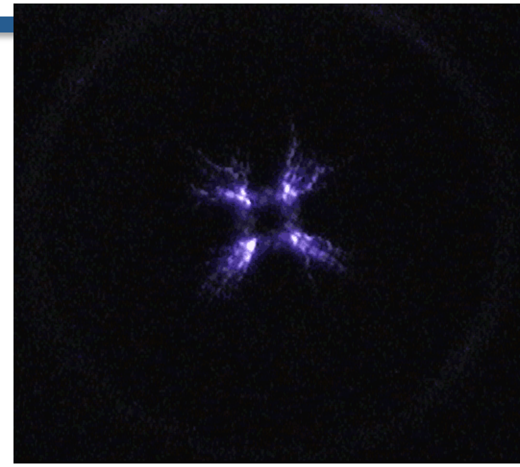
Lean Misfire Limit Comparison at 690 kPa BMEP



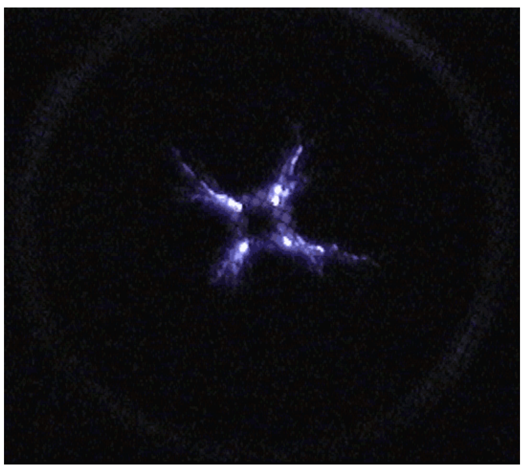
ECCOS Corona Discharge at Various Air Pressures



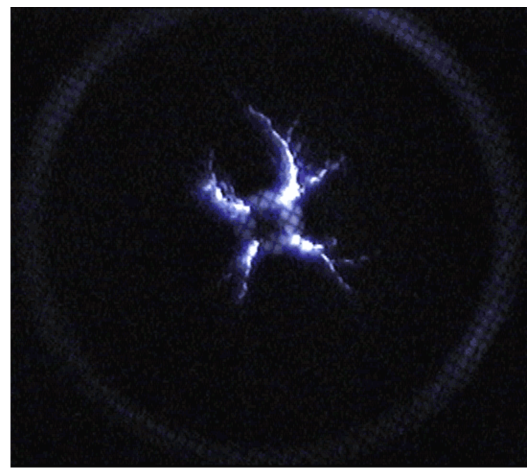
0 Bar, 200mj



6.9 Bar, 1600mj



13.8 Bar, 1800mj



20.7 Bar, 1700mj

Electrically Controlled Combustion Optimization System (ECCOS)

Combustion Characteristics and Engine Performance

Historical notes:
Isupport from California Energy Commission

about 2009
Bought out by Borg Warner
"Anticipating need for sparks at higher pressures, lean burn, higher EGR"

Out of the Box

1….Laser Spark Plug at Argonne Labs

MTZ: June 2006 p476
article by Spicher et al. from Karlsruhe

You will find the figures mentioned in this article in the German issue of MTZ 06|2006 beginning on page 476.

Mikrowellenbasiertes Zündprinzip
für Ottomotoren mit Direkteinspritzung
und strahlgeführtem Brennverfahren

Microwave-based Ignition Principle for Gasoline Engines with Direct Injection and Spray Guided Combustion System

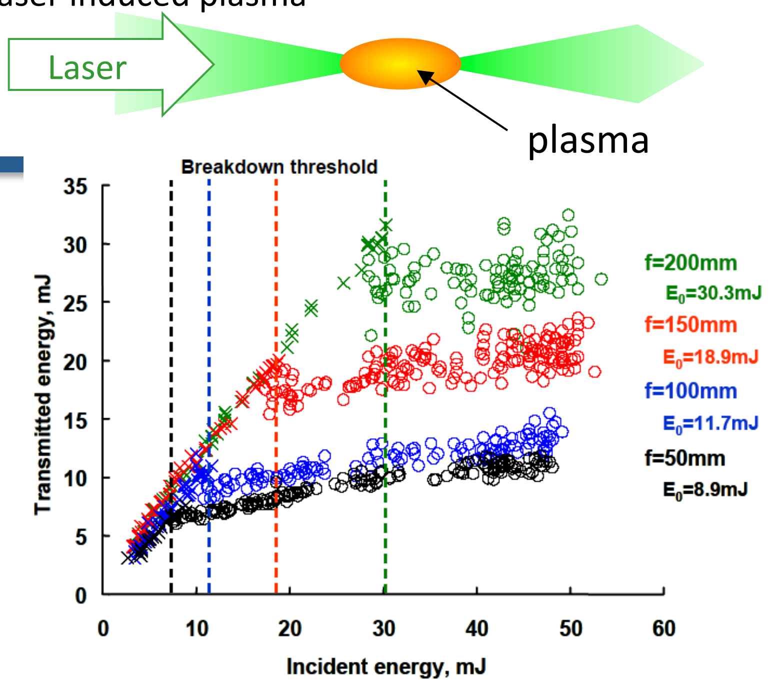
Engines with gasoline direct injection and spray guided combustion concept promise an increase in efficiency mainly due to the overall lean mixture and reduced pumping losses at part load. Thereby the requirements on the ignition system increase. Against this background a microwave-ignition principle was investigated at the Institute for Reciprocating Engines of the University of Karlsruhe (TH). The ignition plasma was visualised by a high speed photomultiplier camera.

Concept of new plasma generation technique

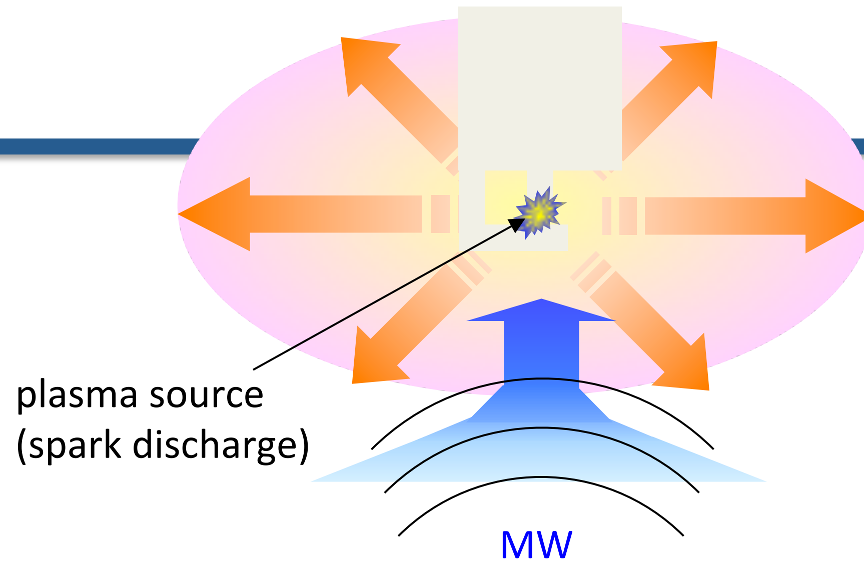
> Plasma absorb the light → Discharge of spark ignition absorb the microwave

> It is difficult to make stable cold pressure plasma in atmospheric, high pressure → Plasma is made by spark ignition before, microwave is used by pumping energy

Relation between incident energy and transmitted energy of laser induced plasma †



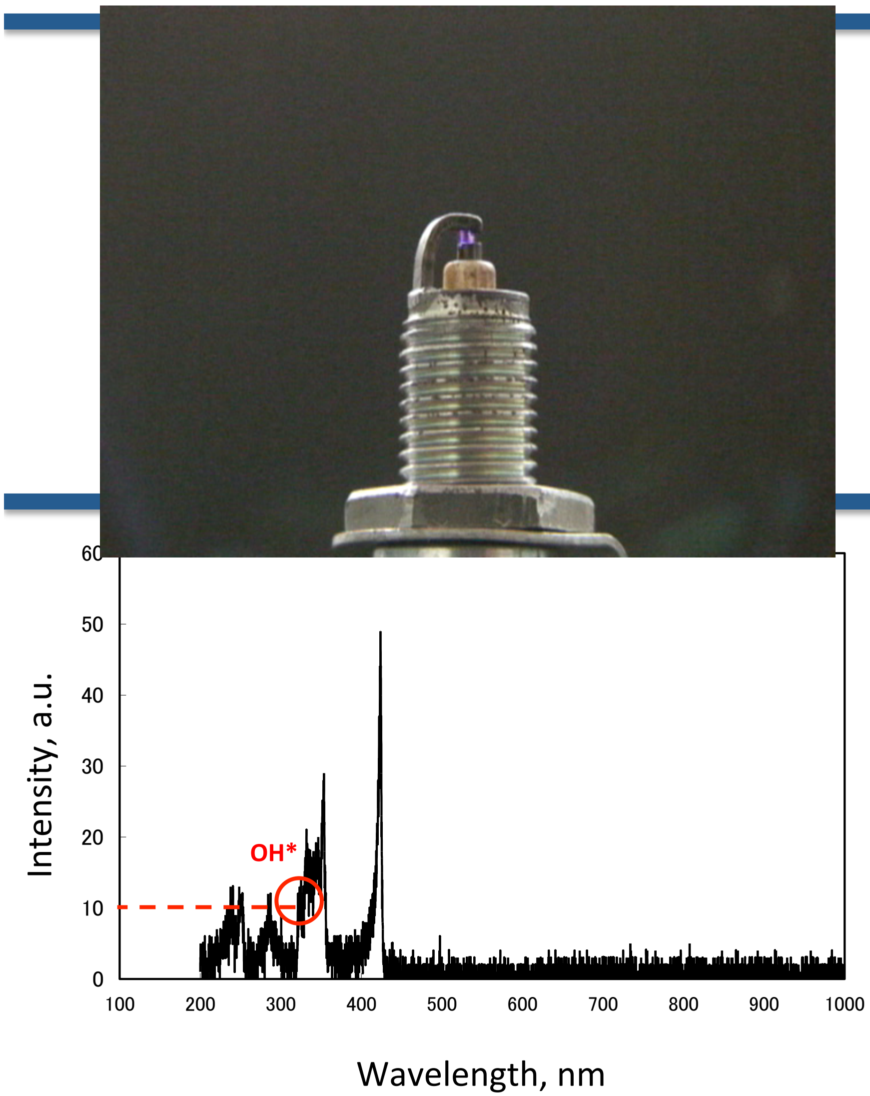
Small plasma source (spark) + Pumping (MW)



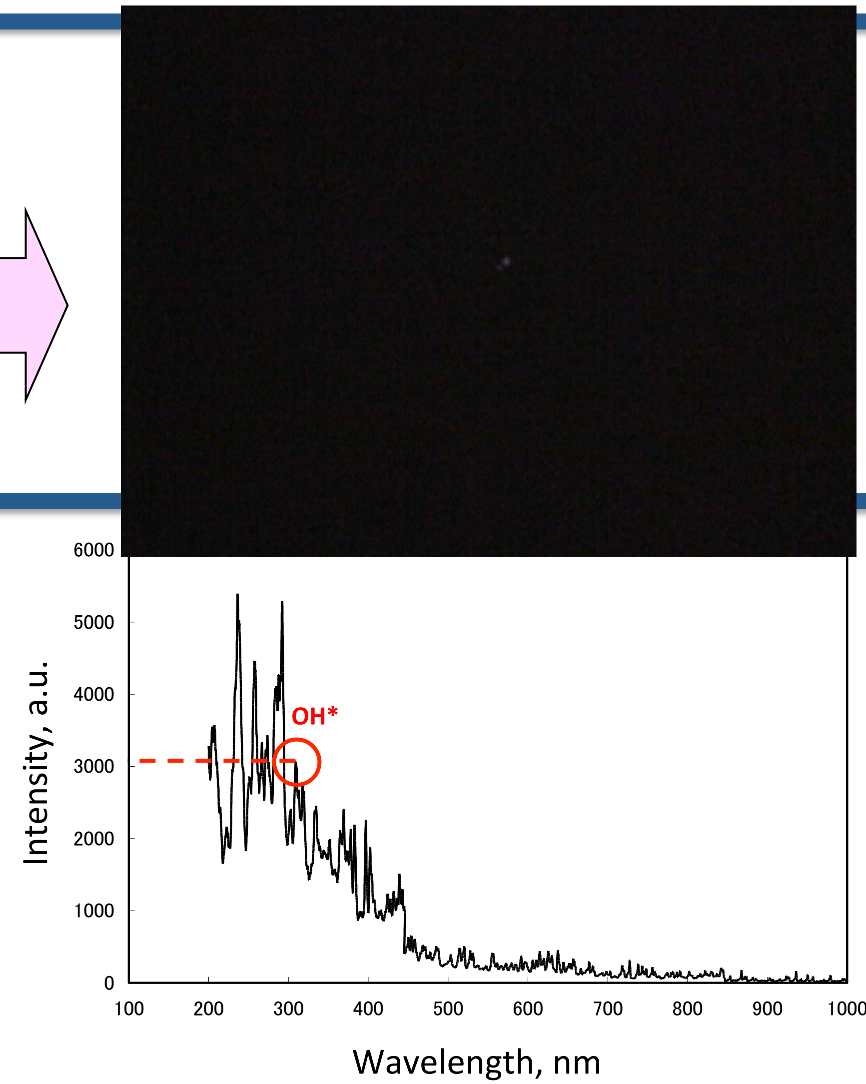
†Y. Ikeda, et. Al., 44th AIAA Aerospace Sciences Meeting and Exhibit, 9-12January 2006, Reno, Nevada, AIAA Paper No.2006-965, 2006.

Spark discharge → Microwave enhanced plasma

Spark plug for automobile



Microwave enhanced plasma



Development of antenna in spark plug

Prototype of spark plug having a microwave antenna

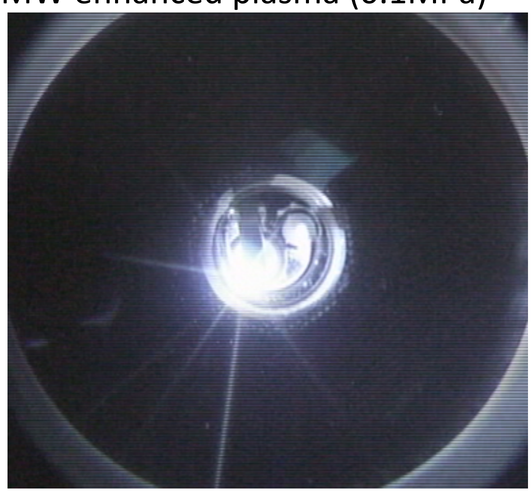
> In order to generate and sustain plasma in engine cylinder without changing exiting engine system, a microwave antenna was built into a spark plug.

> Antenna was made by tungsten wire having diameter of φ1mm.

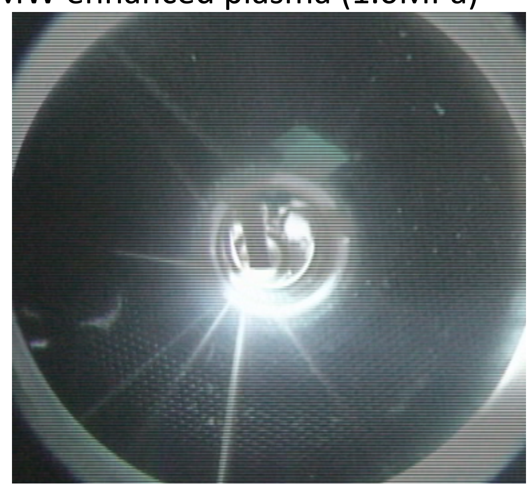
> Plasma was successfully generated elevated pressure condition of 1.0 MPa with the prototype spark plug.

Spark discharge (0.1MPa)

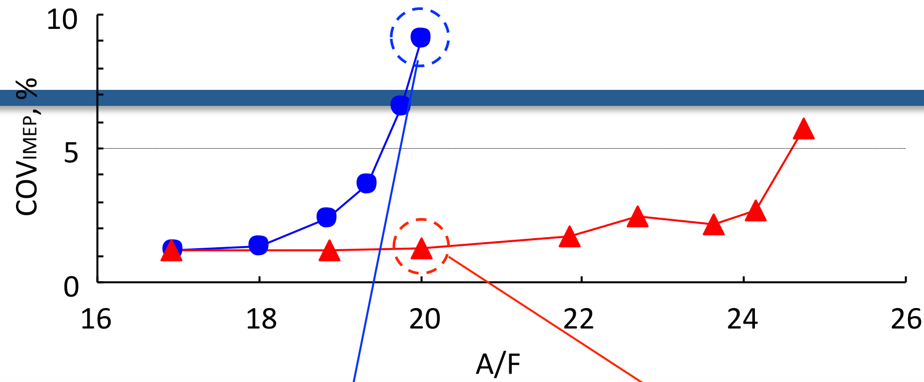
MW enhanced plasma (0.1MPa)



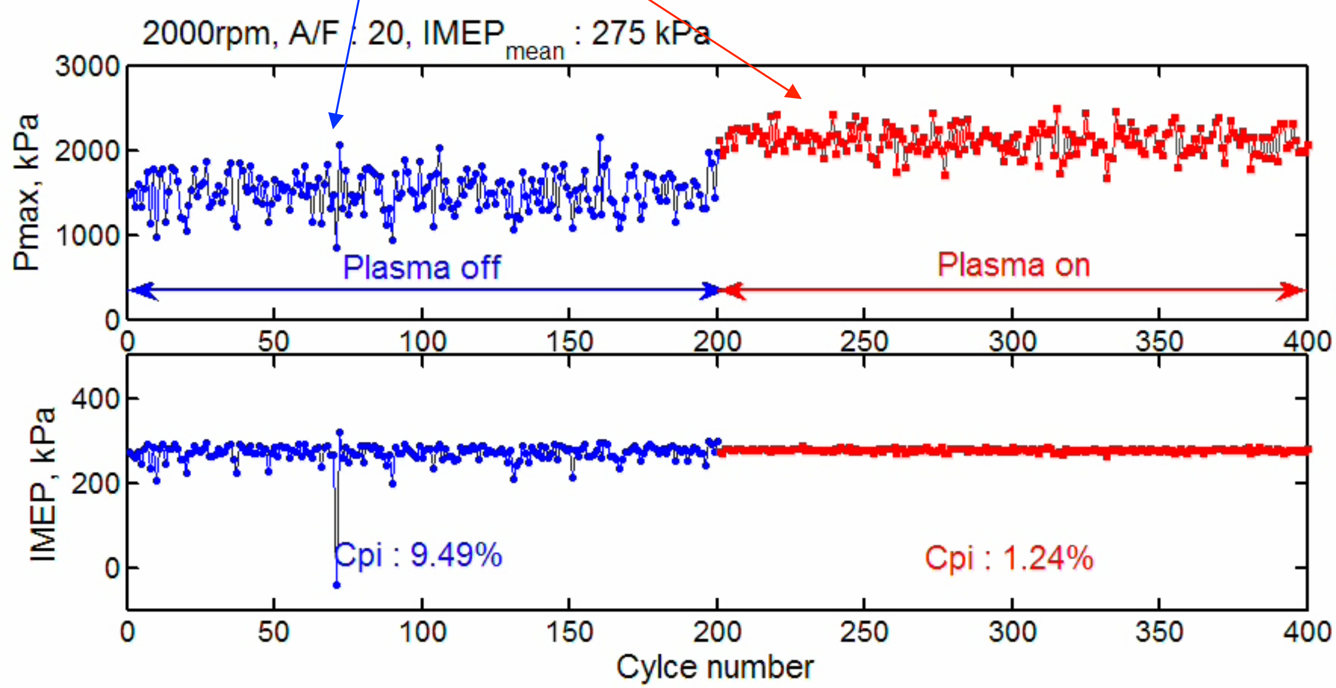
MW enhanced plasma (1.0MPa)

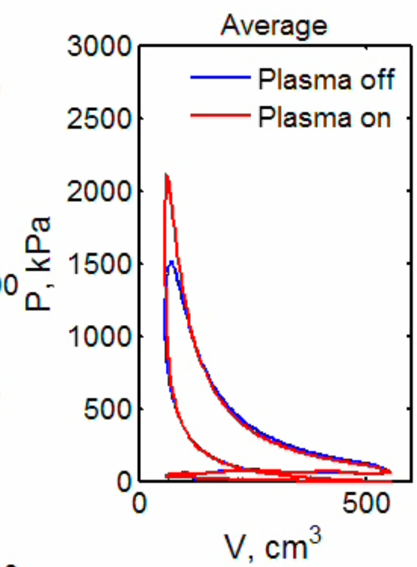


Effect of microwave ignition - Reduction of cyclic variations -



	Engine speed	A/F	MW	q_{ig} deg.BTDC	P_{max} kPa	IMEP kPa	Cpi %
	2000rpm	20	Off	48 (MBT)	1506	270.7	9.49
	2000rpm	20	On	56 (MBT)	2098	277.2	1.24

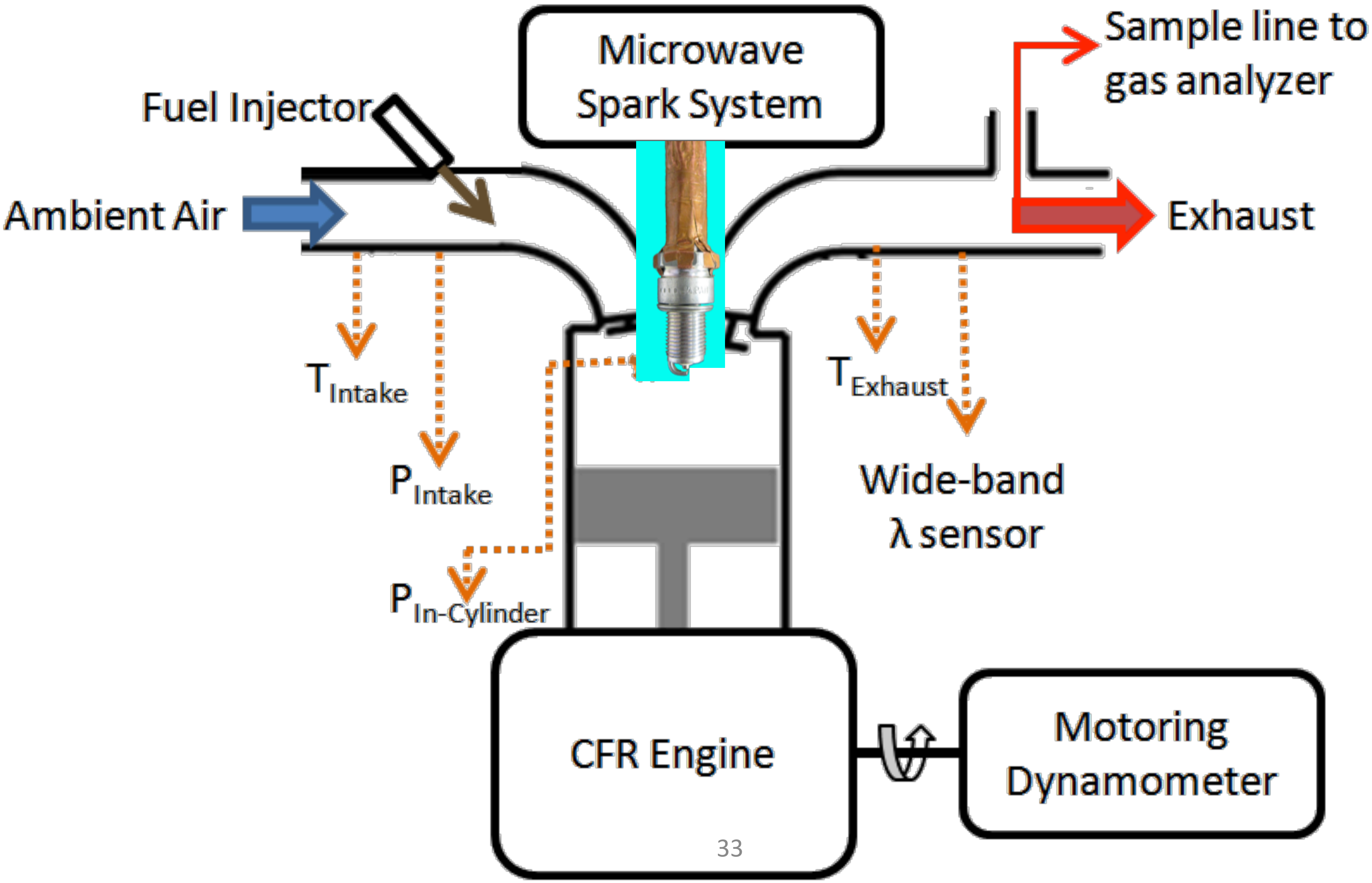




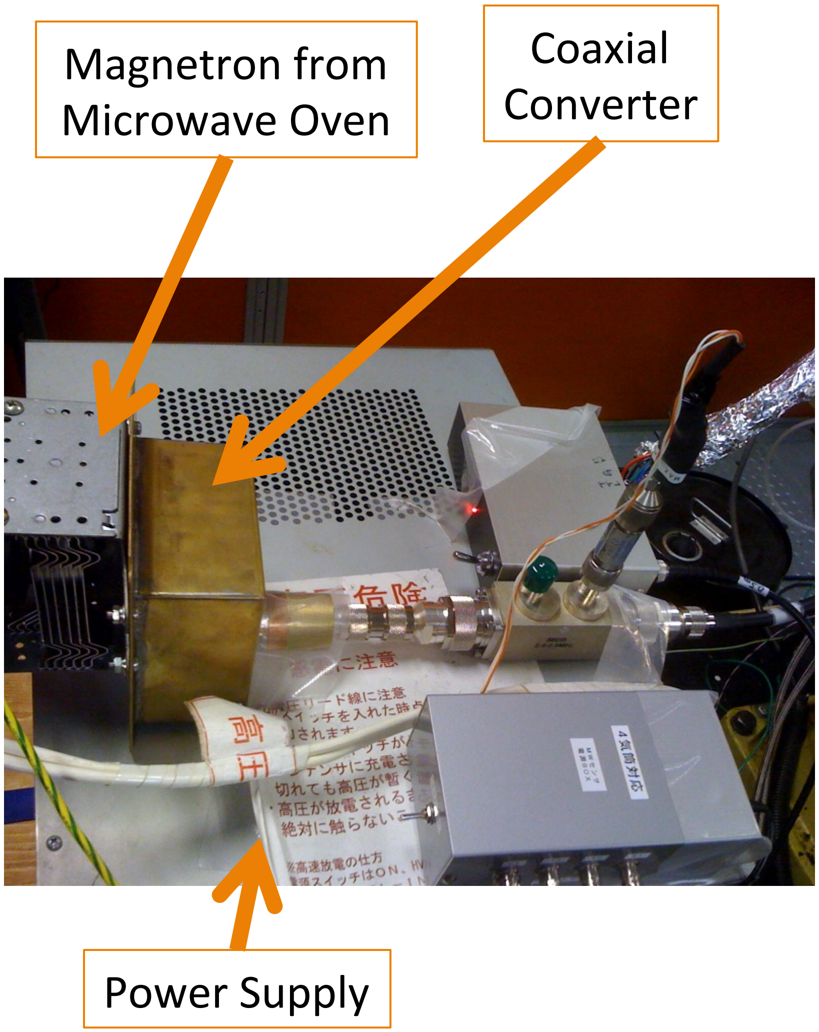
OK, several examples of novel sparks:
Now:
Internal Combustion Engine Operation with a microWave Assisted Spark Plug

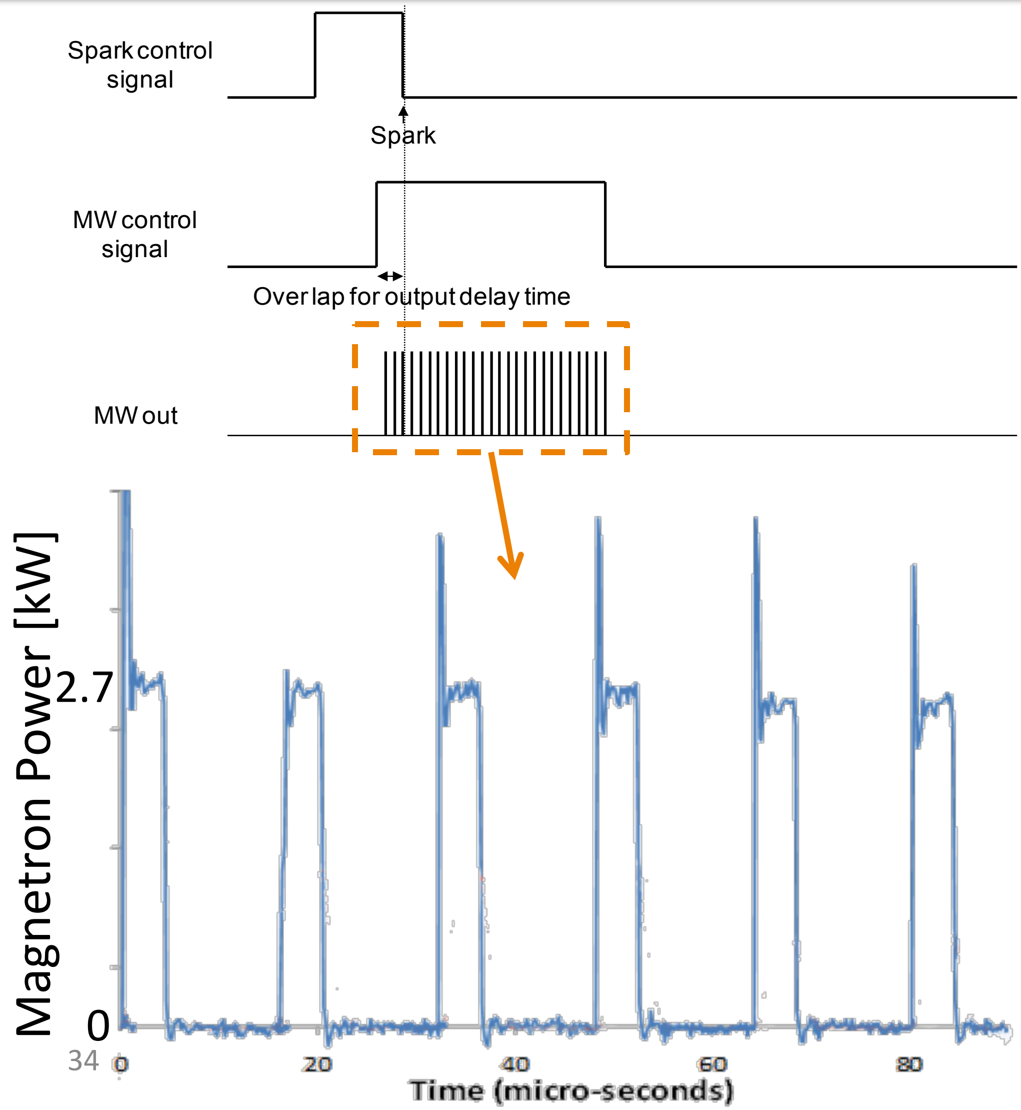
DeFilippo, Chen, and Dibble
University of California – Berkeley
Nishiyama and Ikeda
Imagineering, Kobe, Japan
Spring 2011meeting of DoE AEC at Sandia Livermore CA

A microwave-assisted spark plug was tested on a CFR single-cylinder engine

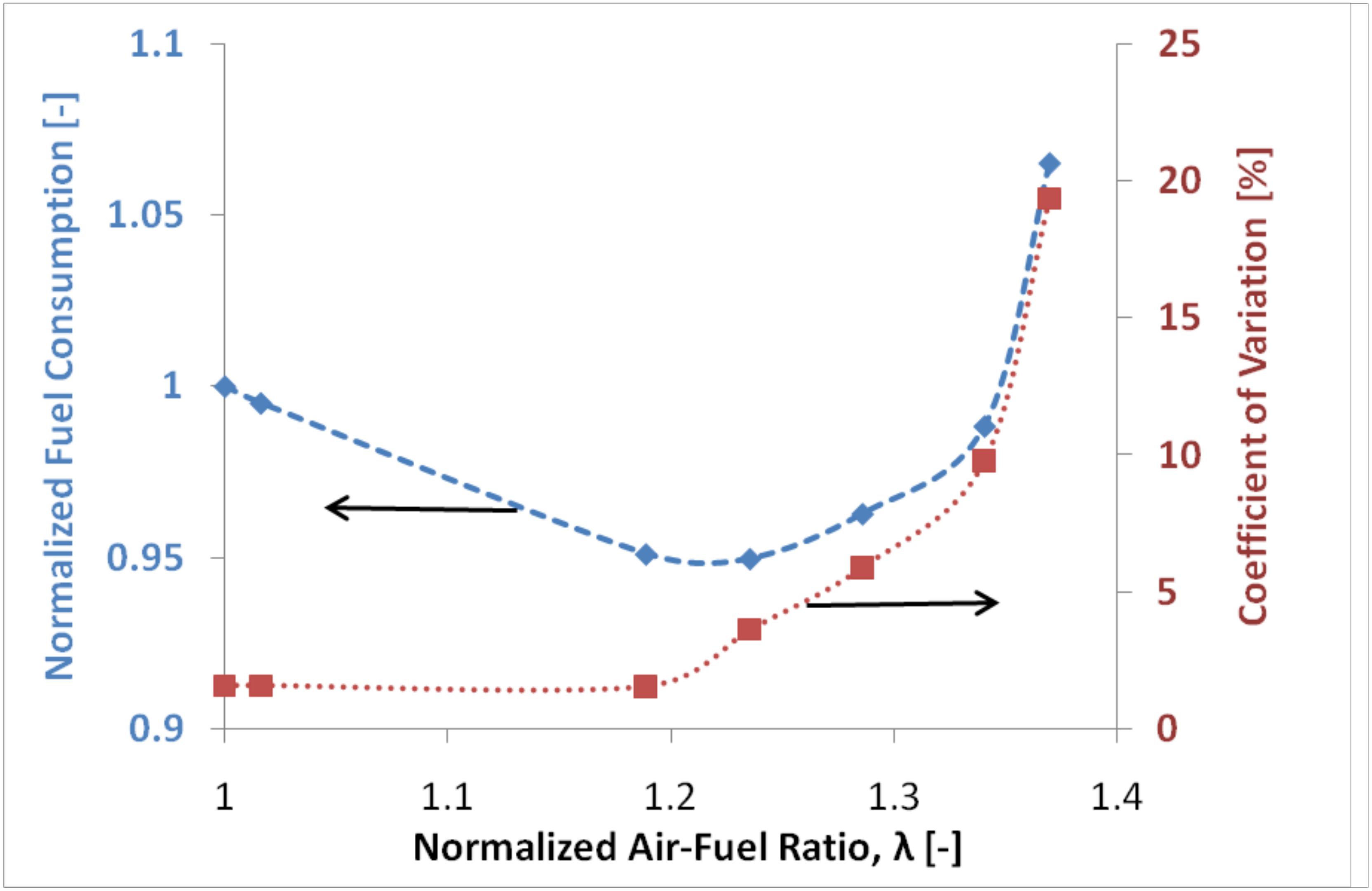


The microwave spark plug fires a regular spark and emits microwaves

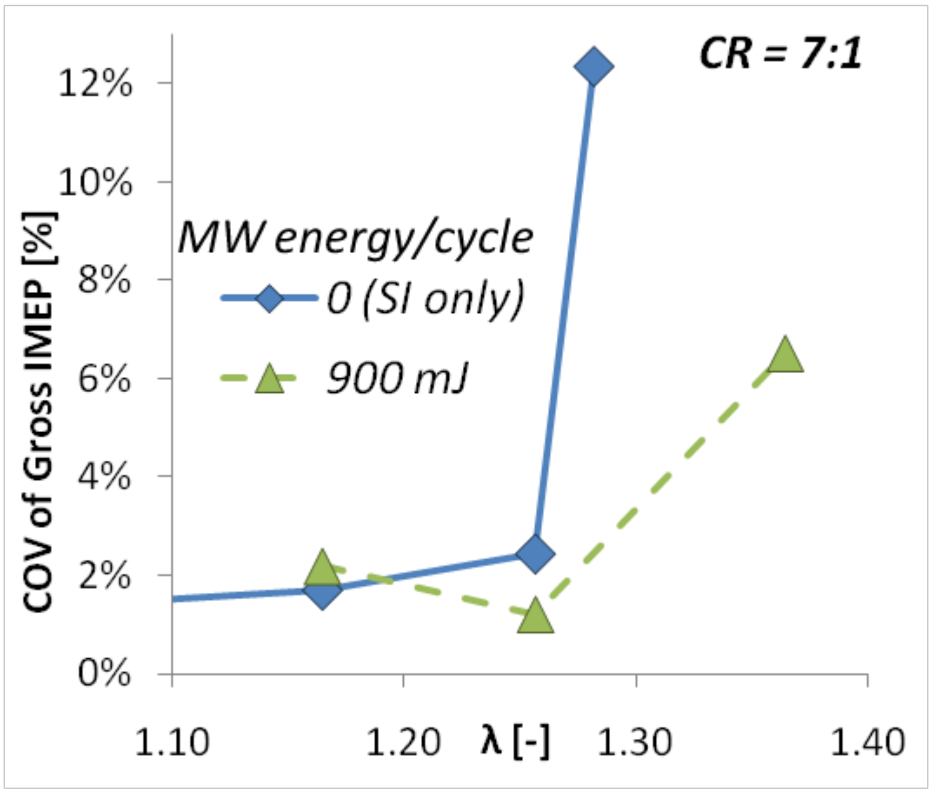


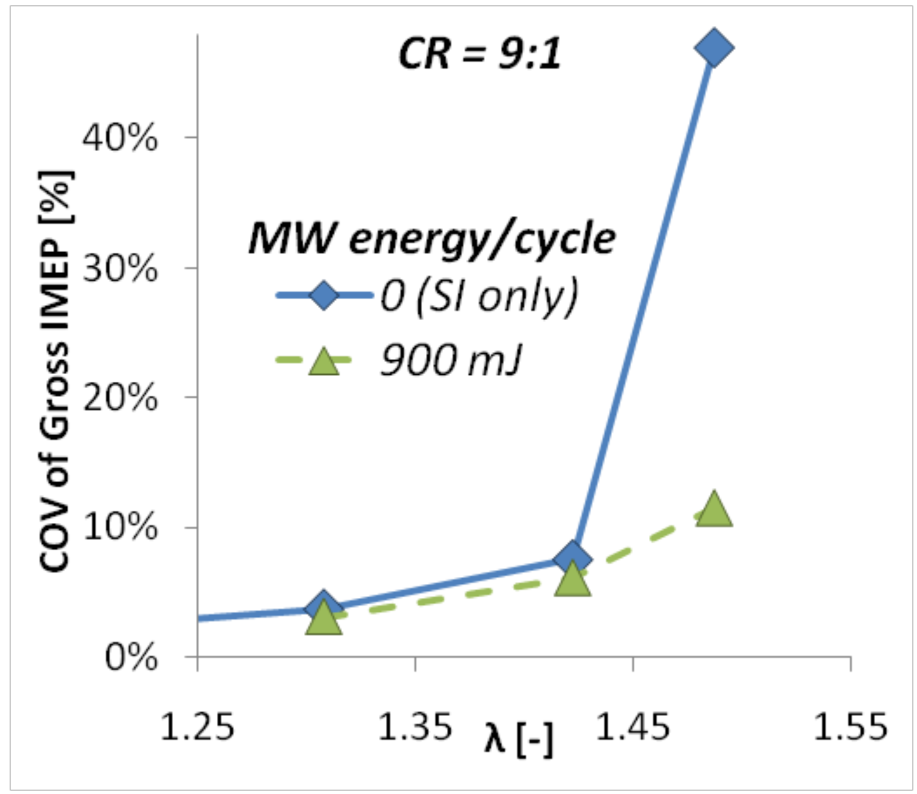


Lean combustion improves efficiency

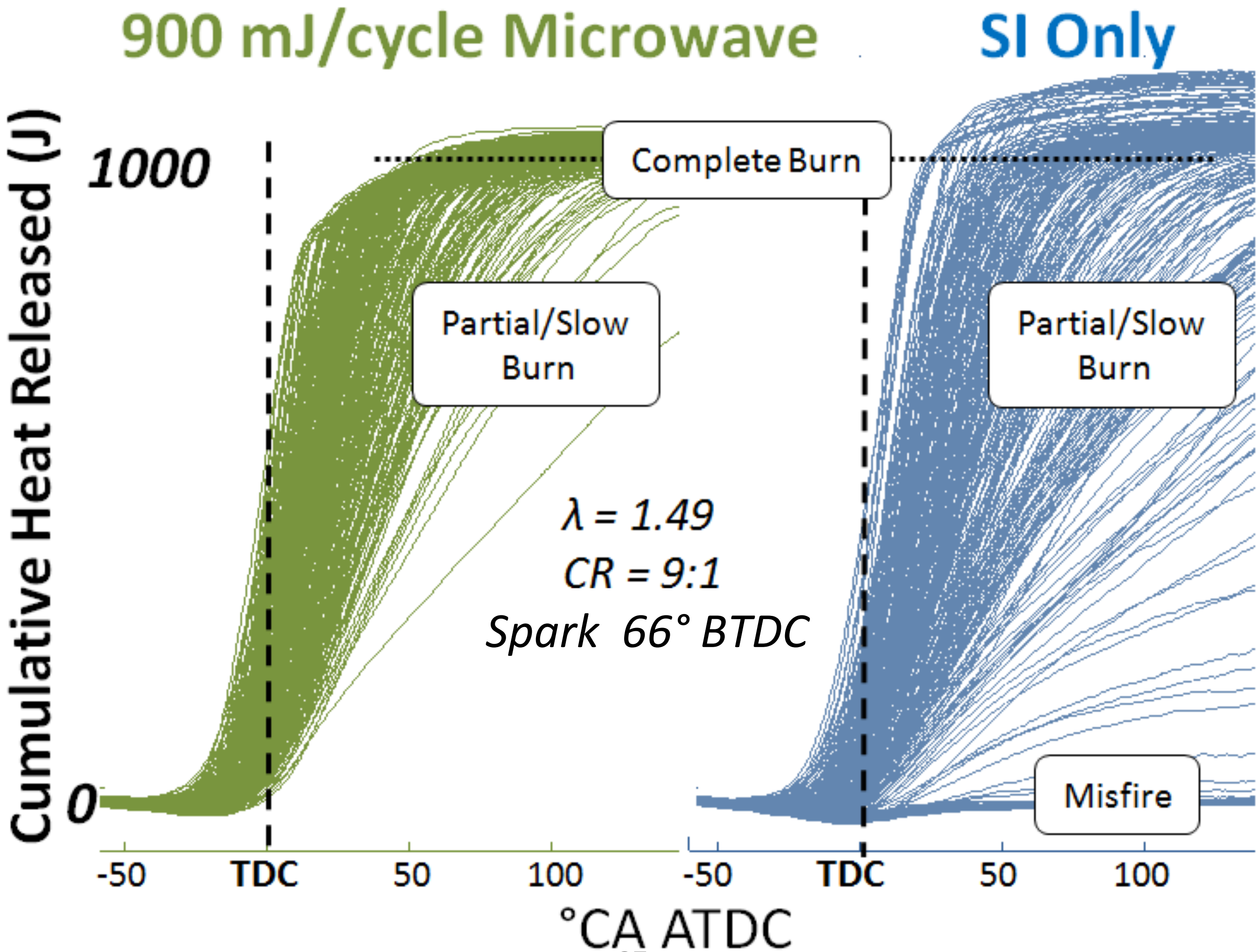


Microwave enhancement extends lean Limit

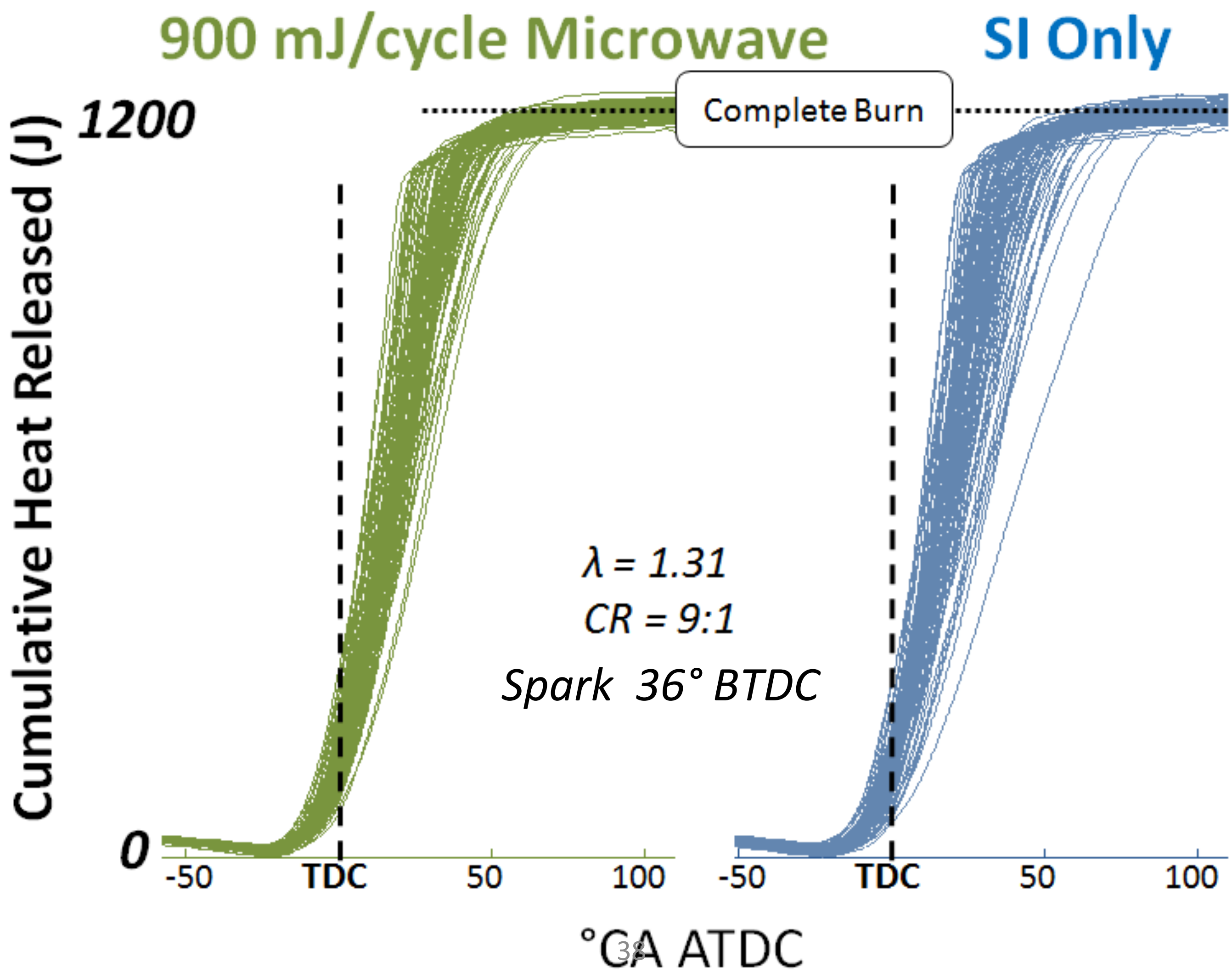




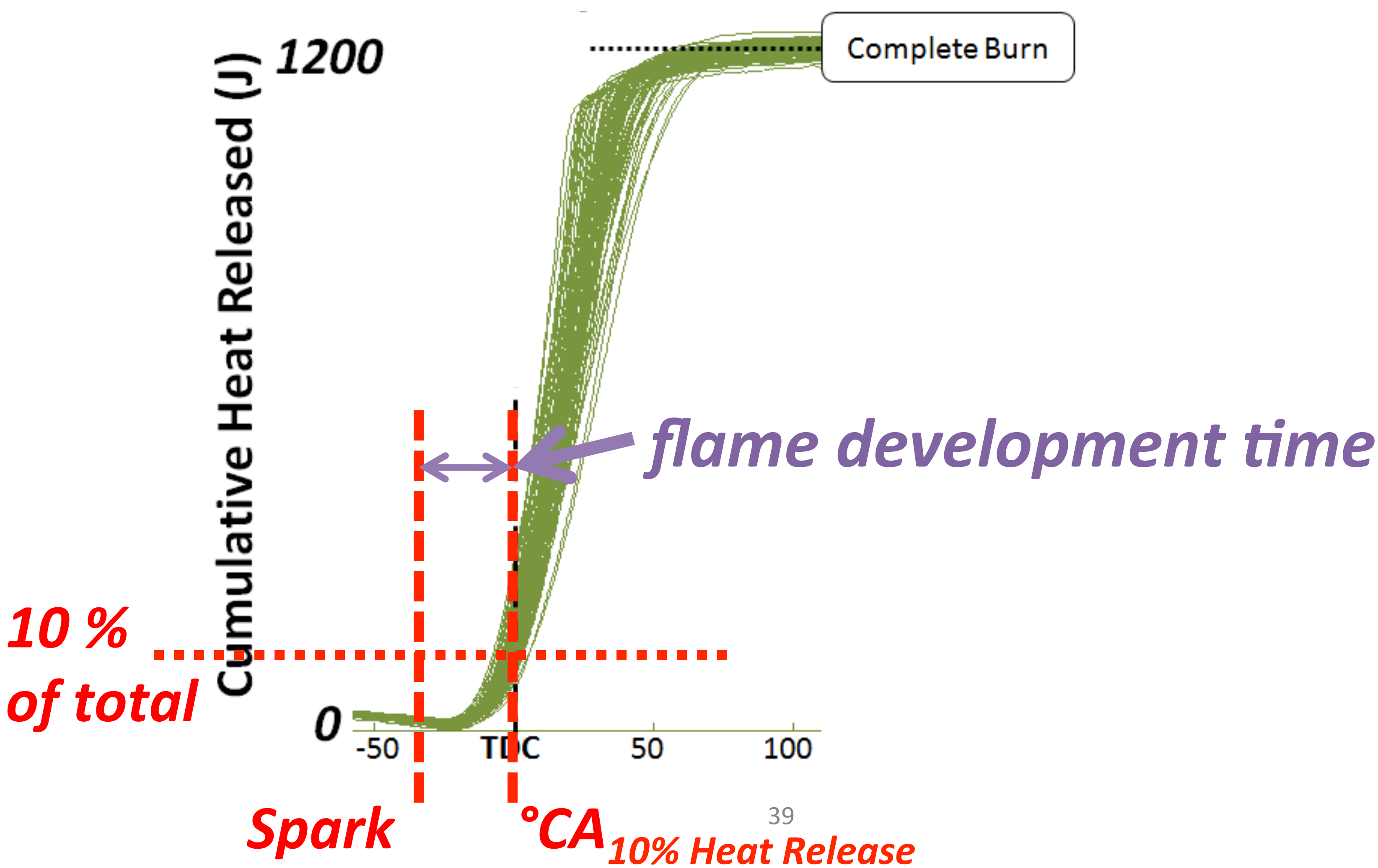
At lean conditions, microwaves reduces misfire and "partial-burn"



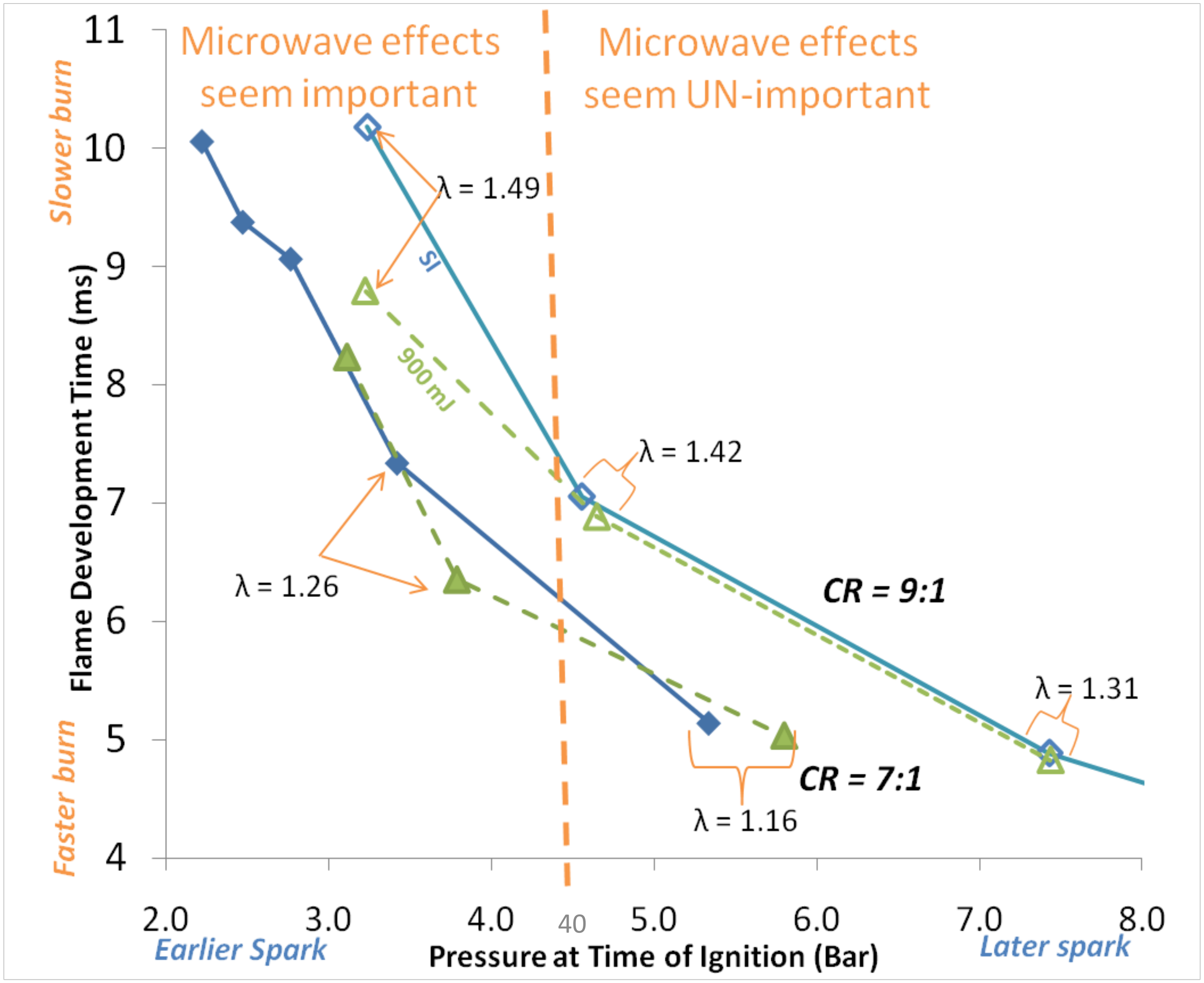
At stable conditions, combustion is unaffected by microwave enhancement



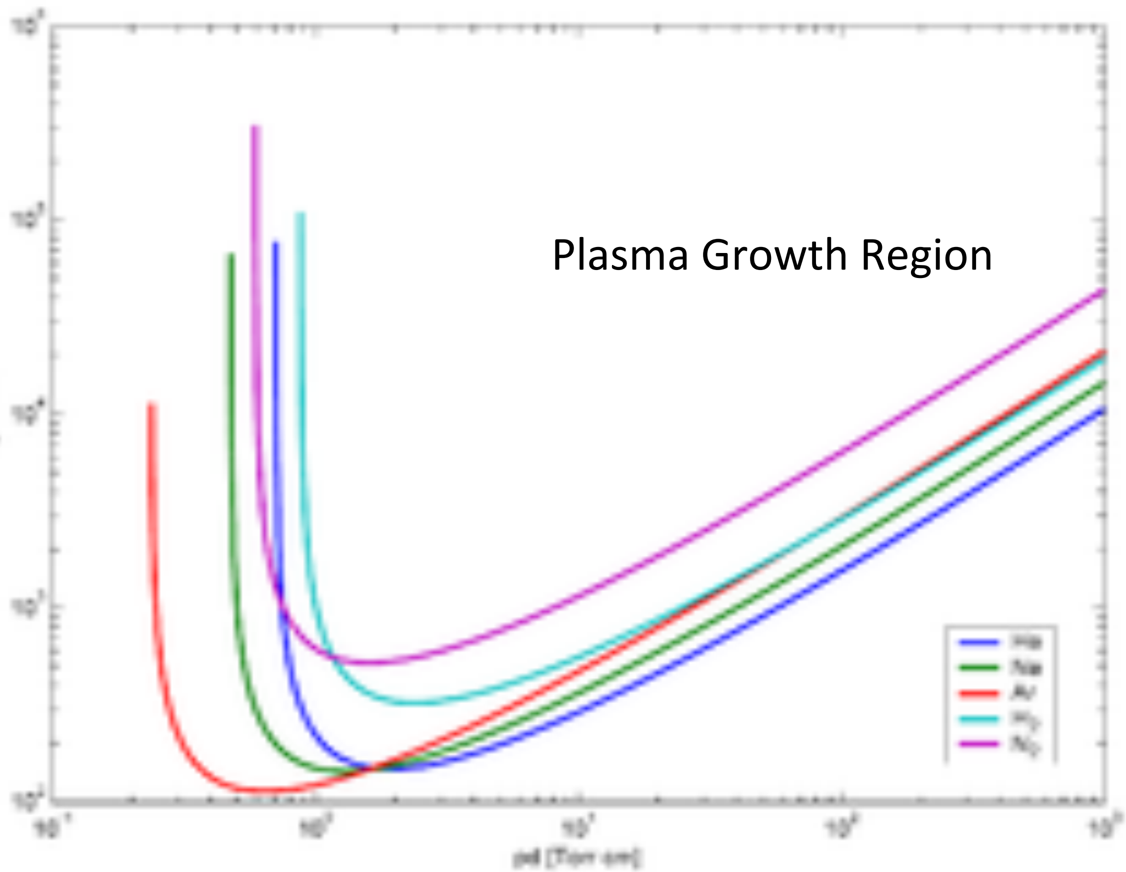
“Flame development time” is time from spark to 10% of cumulative heat release



Our mWASP is less effective at pressures higher than ~4.5 bar, why?



Paschen Curve (1889)

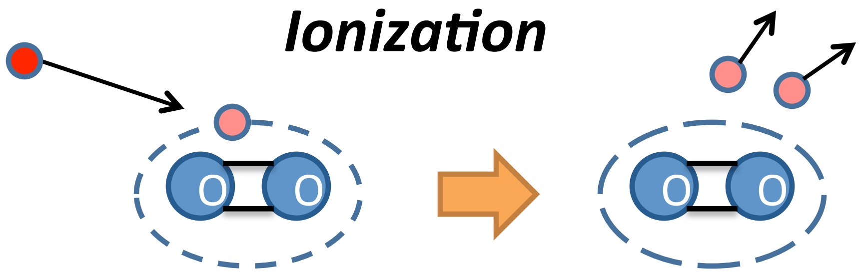


(Volts)

(Torr – cm)

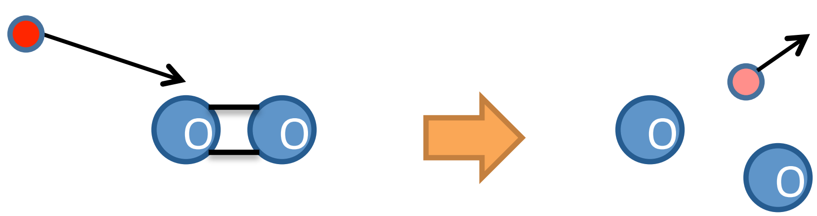
High-energy electrons ionize molecules and cause chemical reactions

Ionization

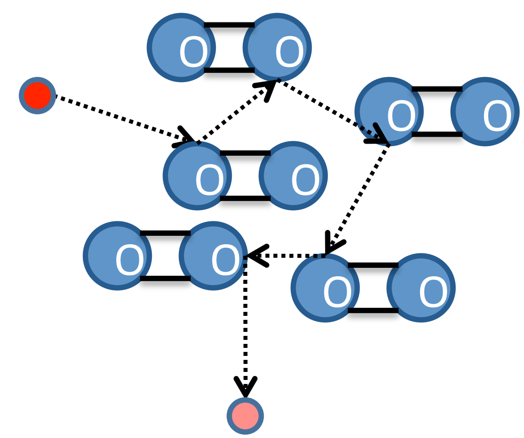


Included ions: CH_4^+, O_2^+, O^+, N_2^+, NO^+, O_2^-, CHO^+, CO_3^-, etc.

Dissociation

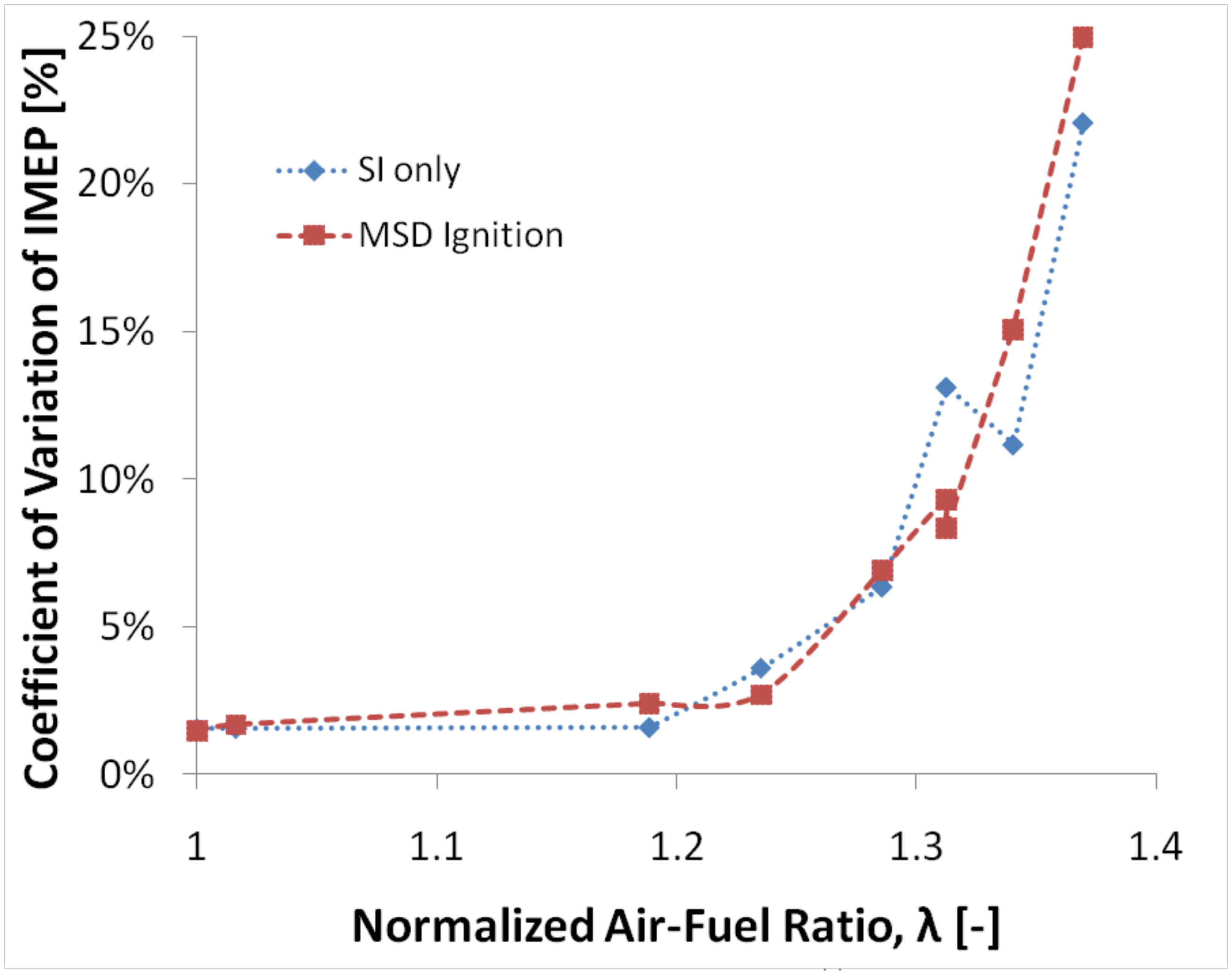


…but electrons lose energy through elastic collisions



Widely used Race Car Ignition System

The MSD ignition system did not outperform the standard spark plug



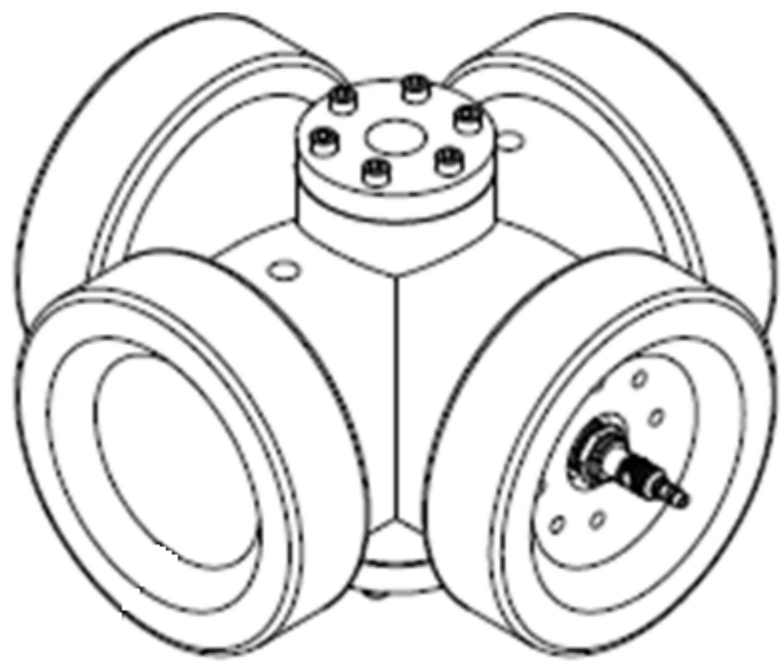
Conclusion:
Conventional spark plugs, with Multiple Spark Discharge " MSD "
Does not improve Ignition

Next steps:

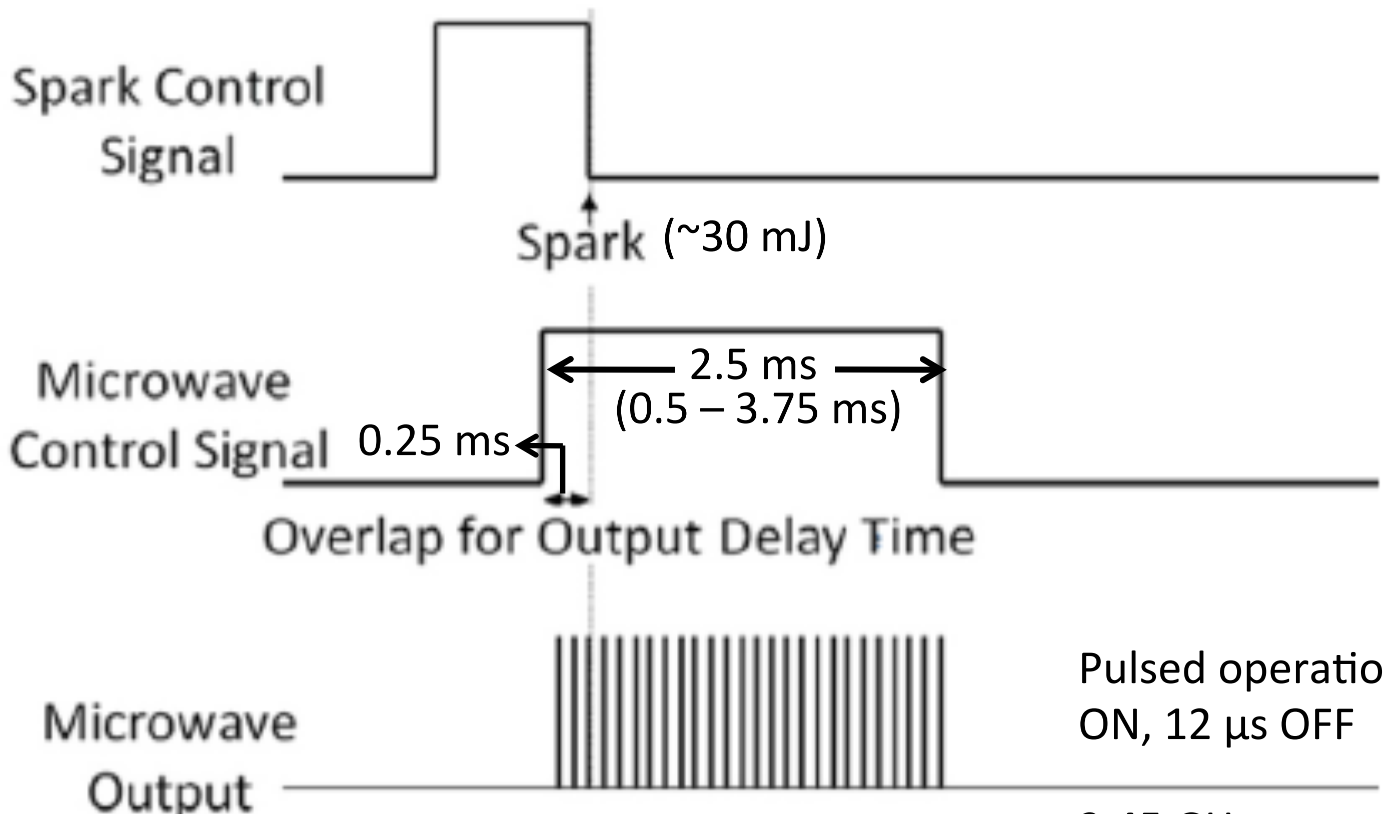
- Investigate pressure effects
  - Boosted pressure in CFR
  - Combustion Bomb
- Expand numerical modeling capabilities
  - Complete chemical mechanism
  - 3-D ignition simulation
- Upgrade microwave generator by factor of 10

Experiment Conditions and Metrics

- 1.6 L internal volume
- Premixed methane-air
- Flame Development Time (FDT)
  - Time from spark to 10% of total heat release
- Flame Rise Time (FRT)
  - Time from 10% to 90% of total heat release



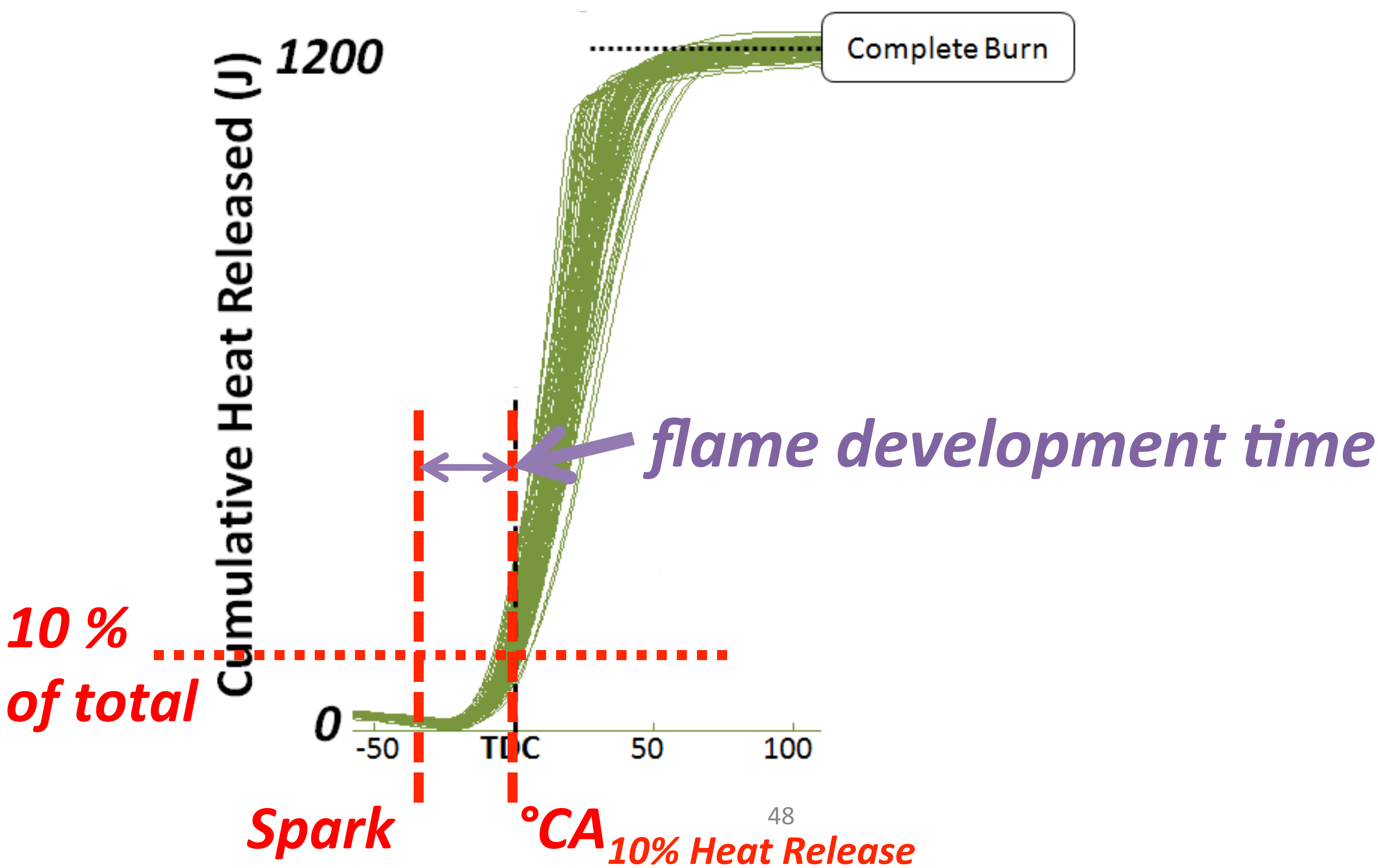
Timing Diagram for Spark Event and MW Emission



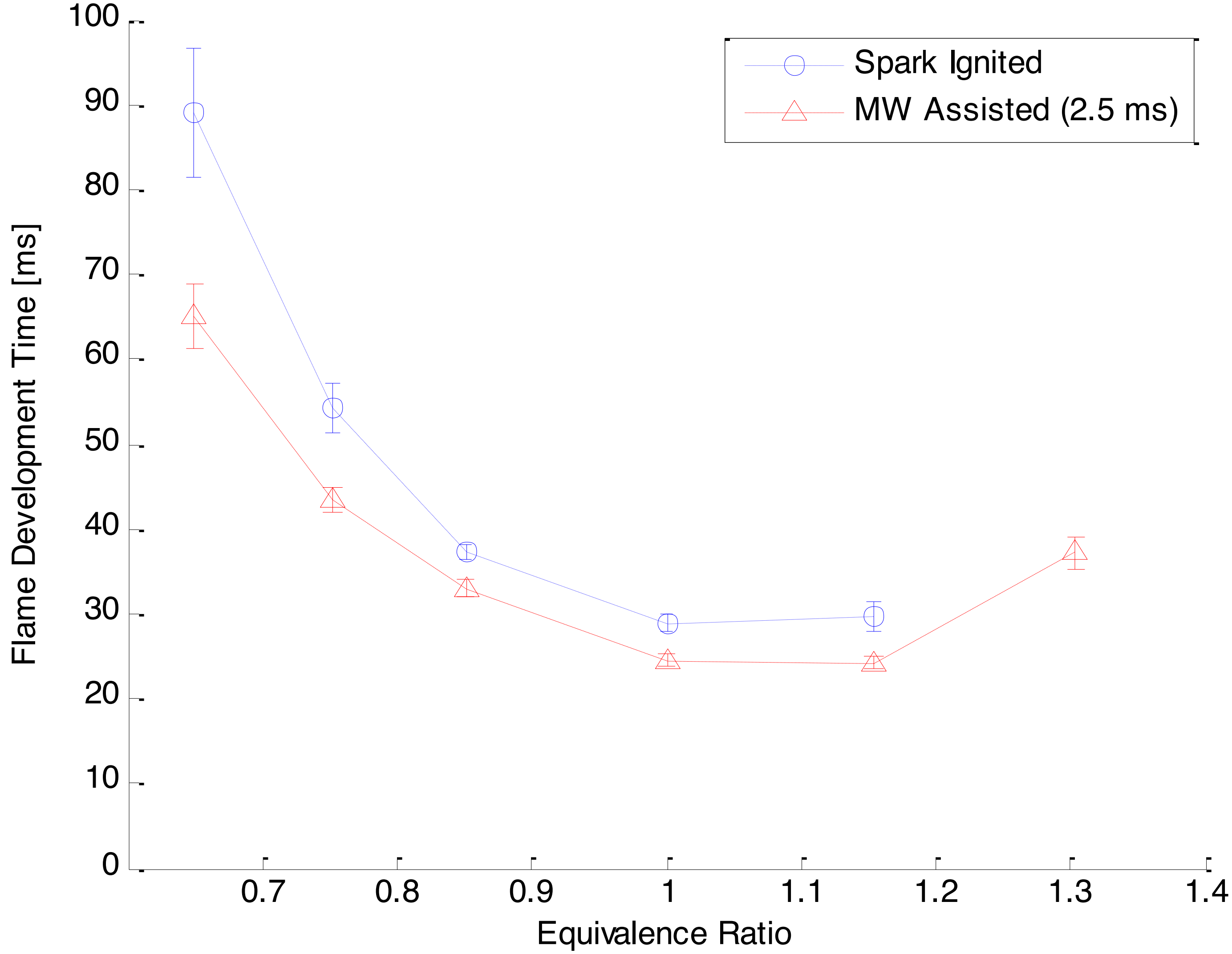
Pulsed operation: 4 µs ON, 12 µs OFF

2.45 GHz magnetron
500 W average power
2.6 kW peak power

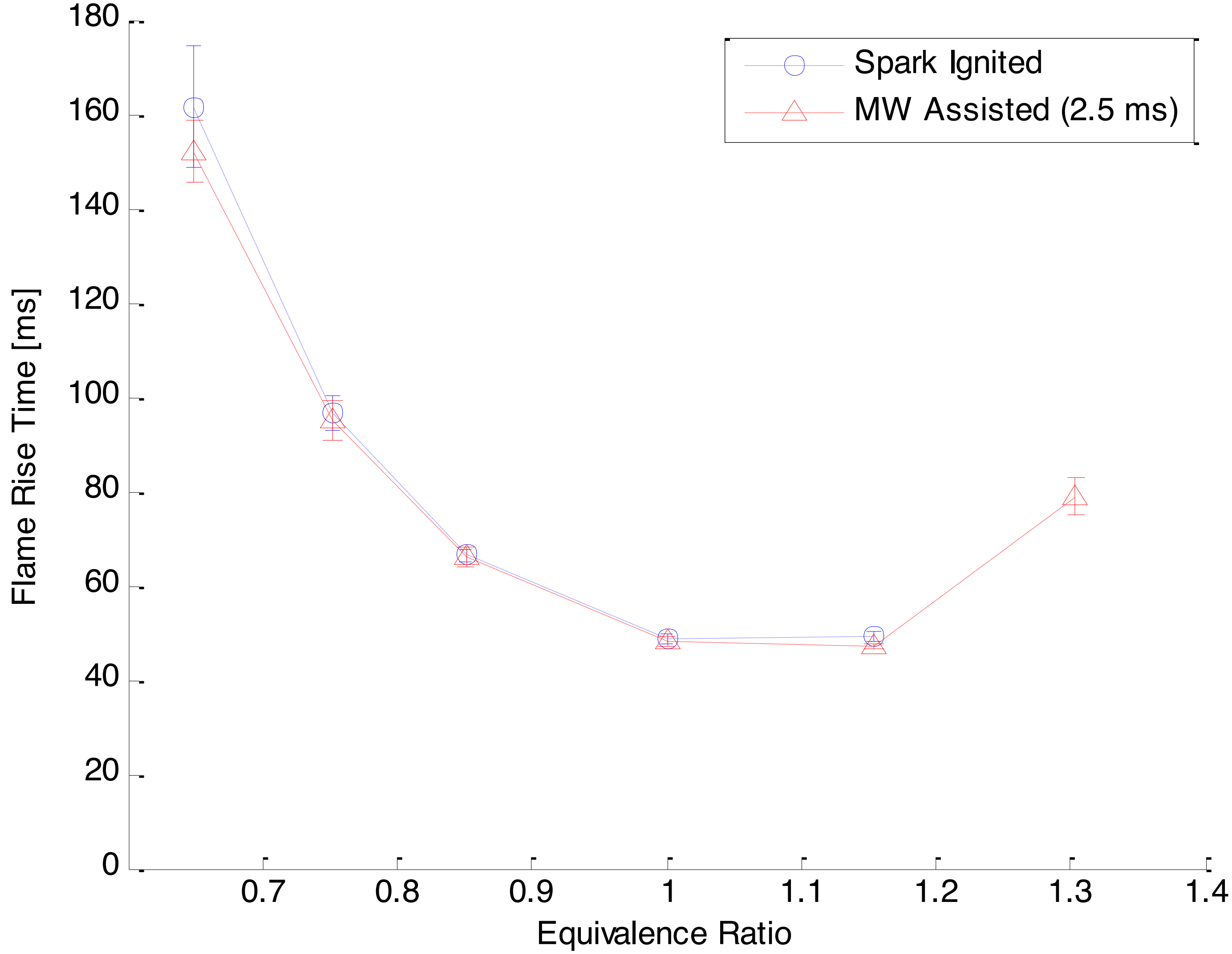
“Flame development time” is time from spark to 10% of cumulative heat release



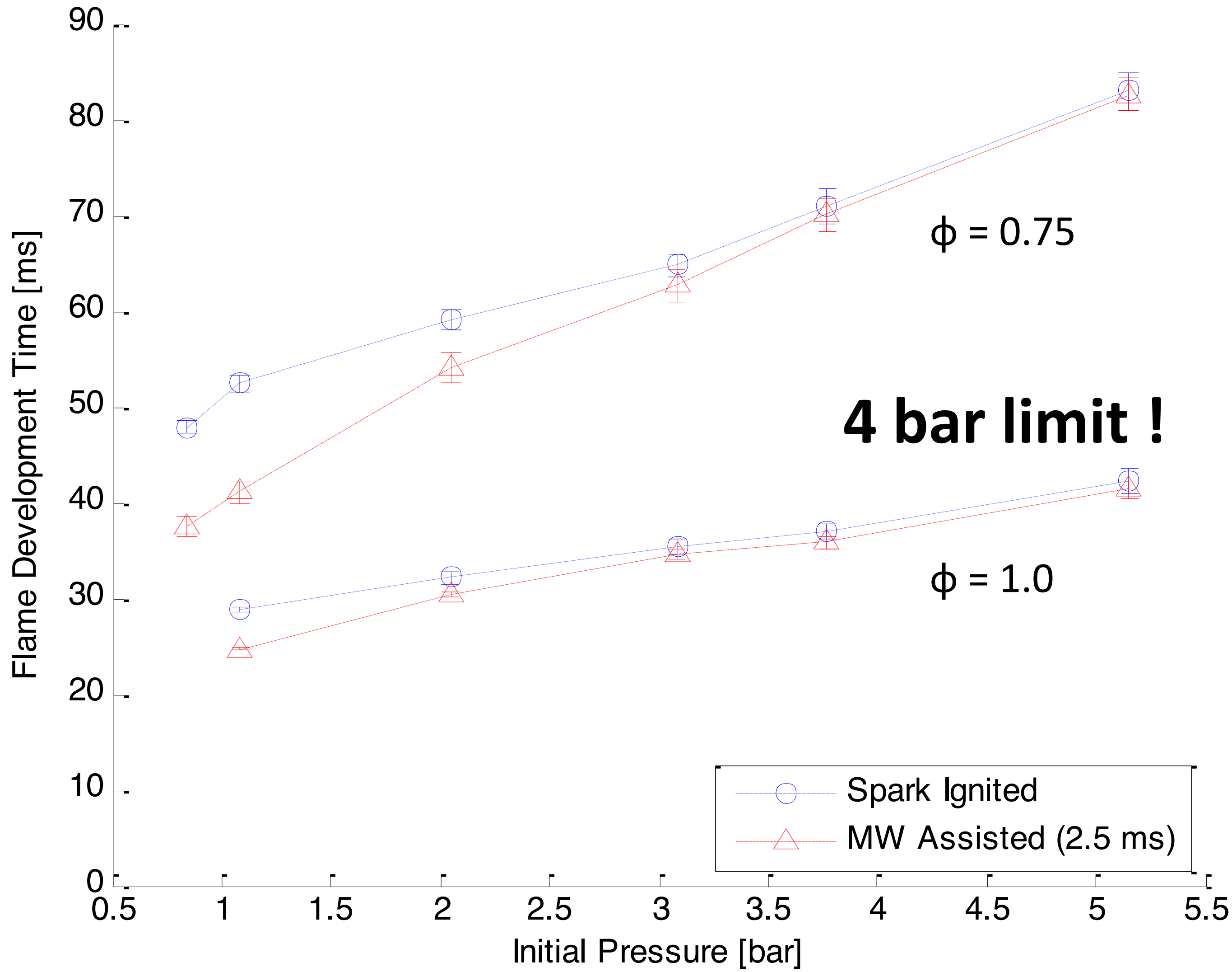
MW Decreases Flame Development Time (0-10%) for all Equivalence Ratios (1 bar)



Flame Rise Time (10-90%) Unaffected by mWASP for all Equivalence Ratios (1 bar)



mWASP Enhancement of FDT (0-10%) diminishes with Pressure



Boosted HCCI for High Power Output Using Ion Sensing for Ringing Detection

Robert Dibble
Samveg Saxena

University of California at Berkeley

Argonne National Laboratory

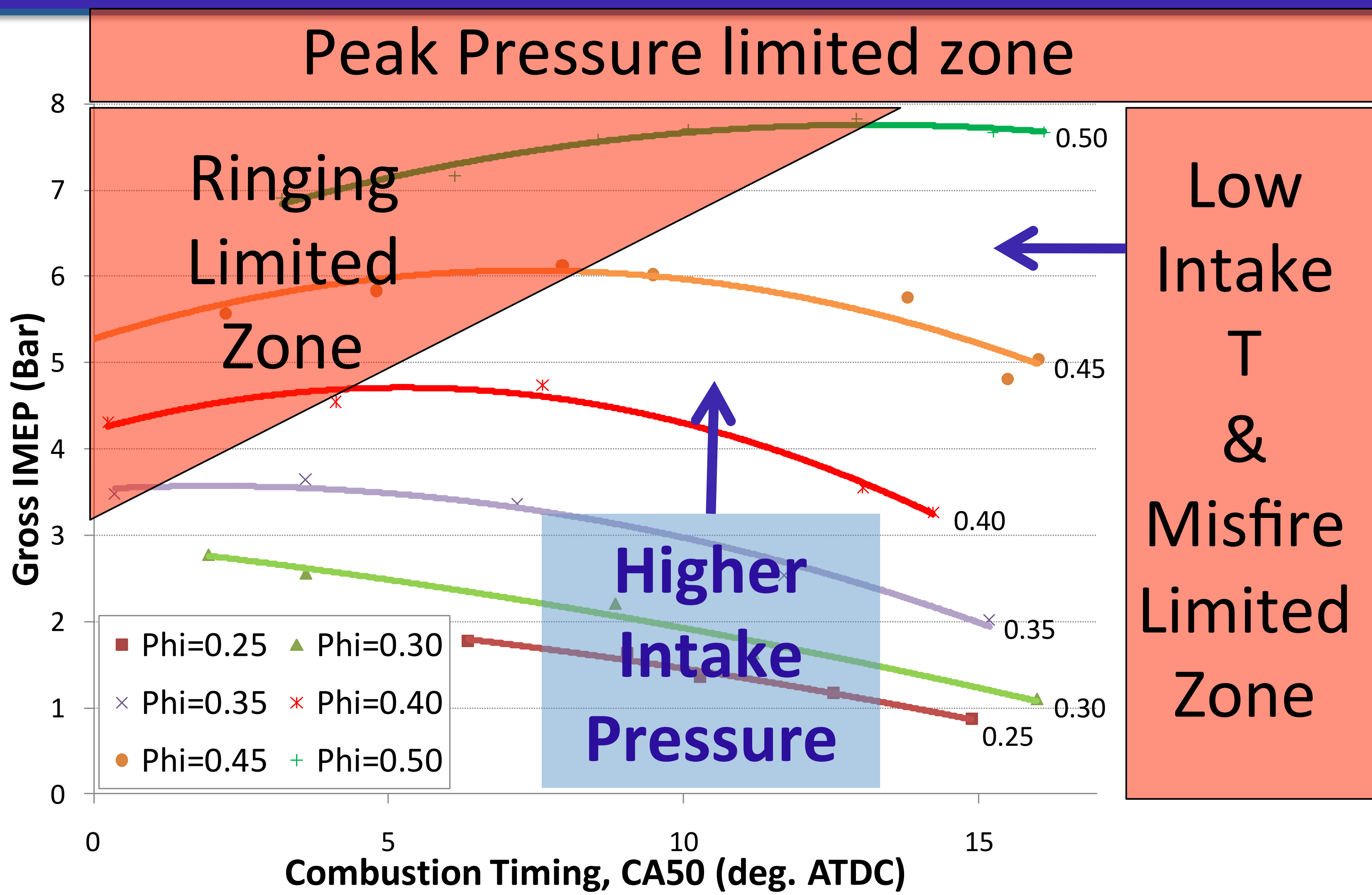
August 29, 2011

Transportation in the 1800s

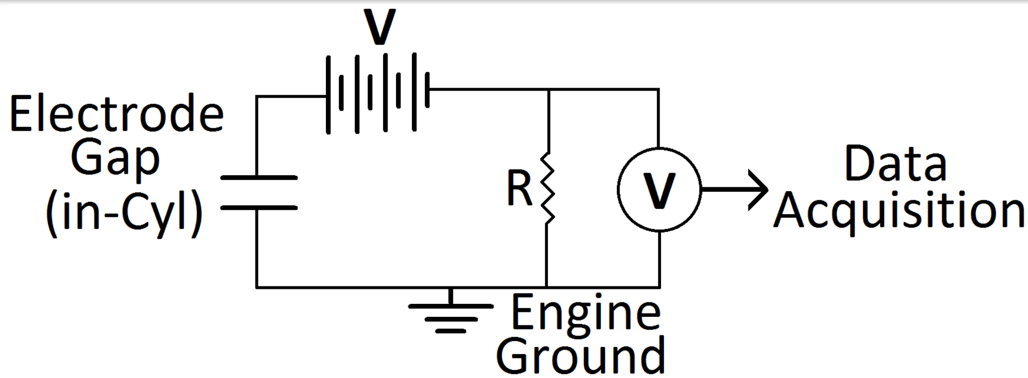
Source: www.histografica.com

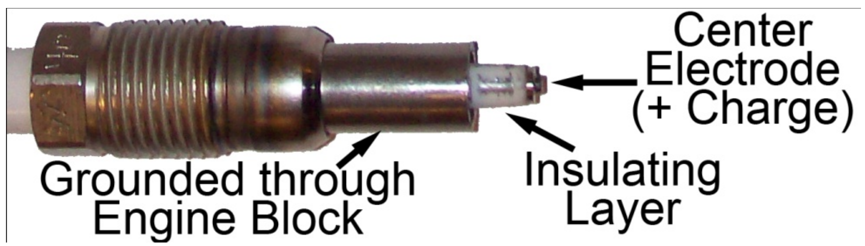
- Most vehicles had
- 1 HP
- Exhaust emissions 1000X higher than today's vehicles
- New jobs to deal with "exhaust"
- Lot's of noise, and a foul odor
- Growing horse-fuel takes up 1/3 of available cropland

The Limits Constraining HCCI Power Output



Ion Sensing in HCCI Engines





Ion sensors detect electrons from chemi-ionization reactions

$$CH + O \rightarrow CHO^{+} + e^{-}$$

$$CHO^{+} + H_2O \rightarrow H_3O^{+} + CO$$

Ion sensing vs. Pressure sensing

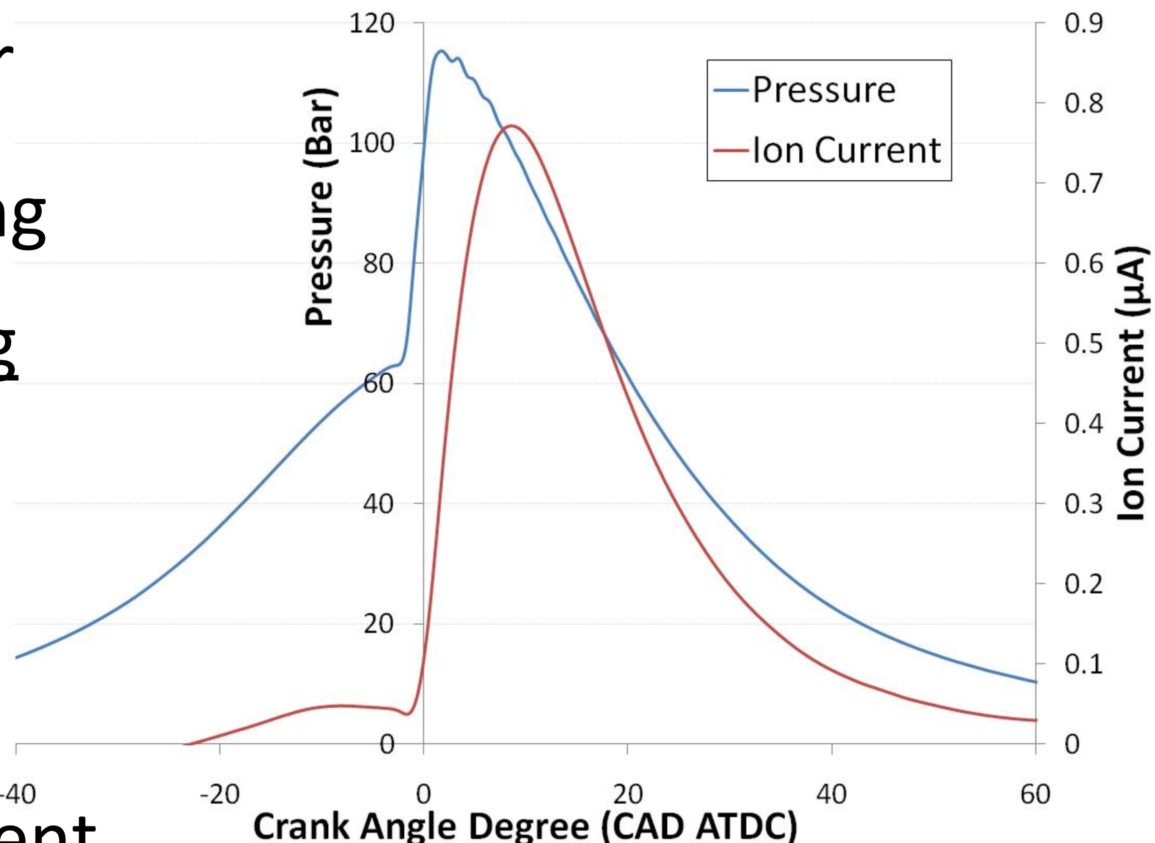
Require a sensor for detecting combustion timing

<u>Pressure Sensing</u>

- Global measurement
- Expensive

<u>Ion Sensing</u>

- Local measurement
- Inexpensive



Ion Sensing ineffective at low φ, but useful for ringing

- Ion sensors can effectively detect combustion timing in HCCI for control

- Ineffective at low equivalence ratio, where there is a low concentration of ionized species
  - Saxena, et al. Increasing signal-to-noise ratio of sparkplug ion sensors…, 33rd International Combustion Symposium

- Ringing occurs at higher equivalence ratios - Ion signal useful for detecting ringing
  - Saxena, et al. Characterization of HCCI ringing behavior using ion sensors, accepted for 2011 SAE Powertrains, Fuels, Lubricants Meeting - SAE 2011-01-1777

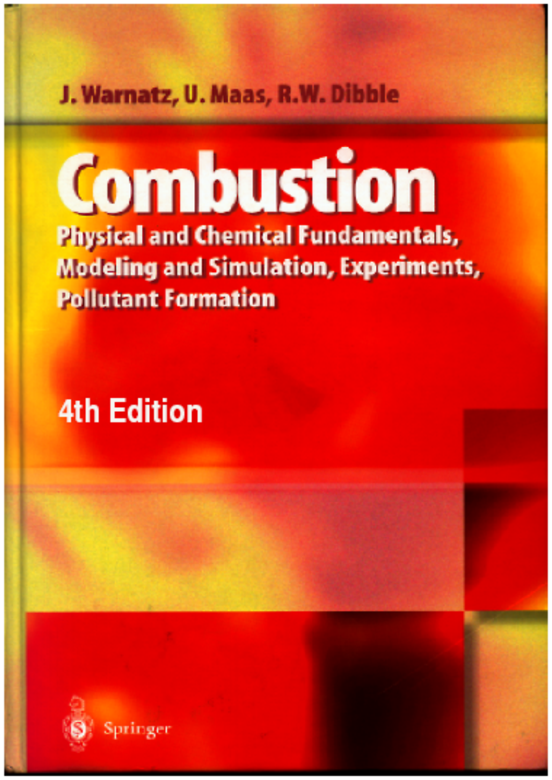
Please Bring Your “Out of the Box” Ideas to the High Pressure Combustion Workshop

High Pressure Combustion Workshop
At Argonne National Laboratories
Aug 2011

Robert W. Dibble UC Berkeley

Funded by DoE and KAUST

Buy This Book !



REVIEW

1…Need to be hot, to have OH radicals,

OH needs to Burn out fuel *before*

OH can burn out CO $CO + OH = CO_2 + H$

2…do not be too hot !

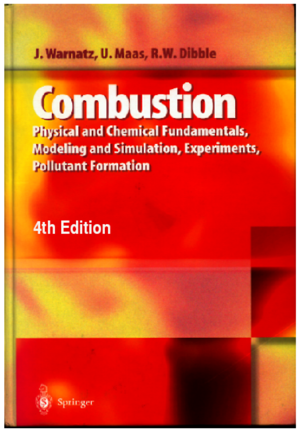
You will make NO

3…Do not be too cold !

need to be hot enough to have OH

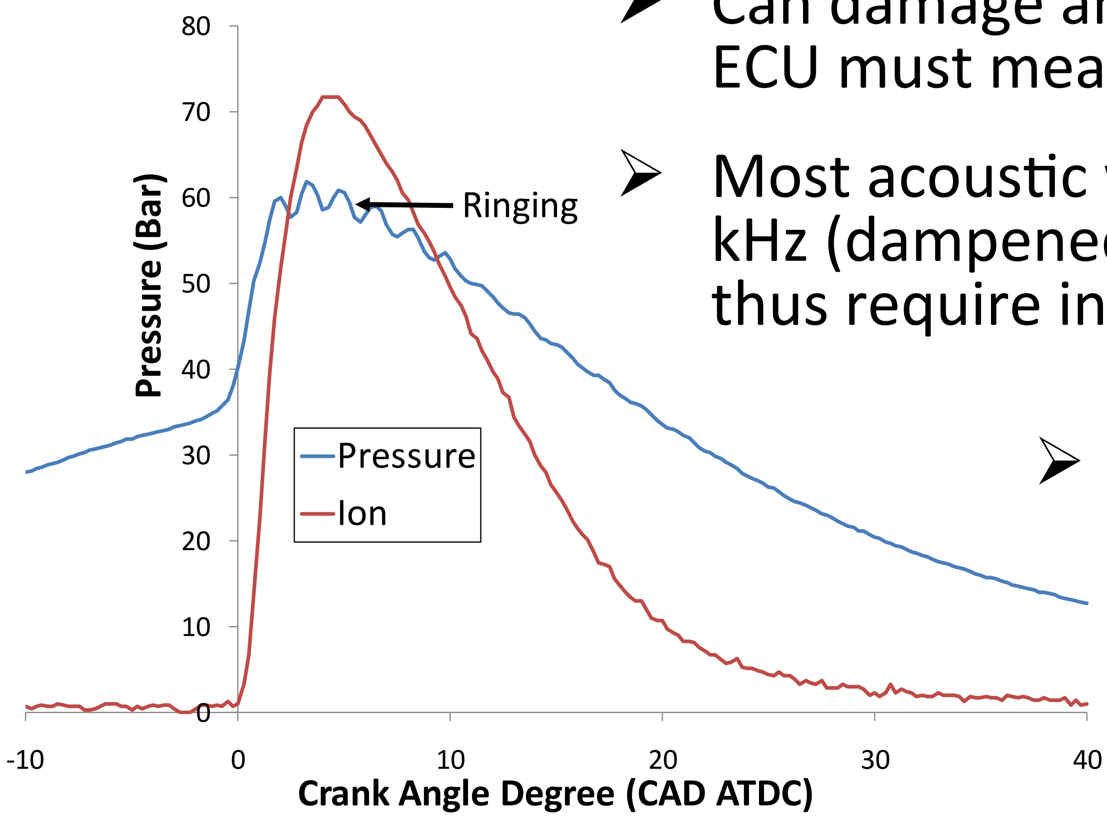
to react with CO

4…buy the book !



Require effective sensing to avoid ringing damage to an engine

- Ringing – pressure waves coinciding with excessive heat release rates



- Can damage an engine over time – ECU must measure ringing intensity
- Most acoustic wave energy near 5 to 6 kHz (dampened by cylinder block/lining, thus require in-cylinder sensor)
- Pressure pulsations can be order of magnitude larger than knocking

Ringing Intensity vs. Ion Ringing Intensity

Ringing Intensity

$$RI \approx \frac{1}{2\gamma} \frac{\left(\beta \frac{dP}{dt}_{\max}\right)^2}{P_{\max}} \sqrt{\gamma R T_{\max}}$$

J.A. Eng
SAE 2002-01-2859

Requires expensive in-cylinder P sensing

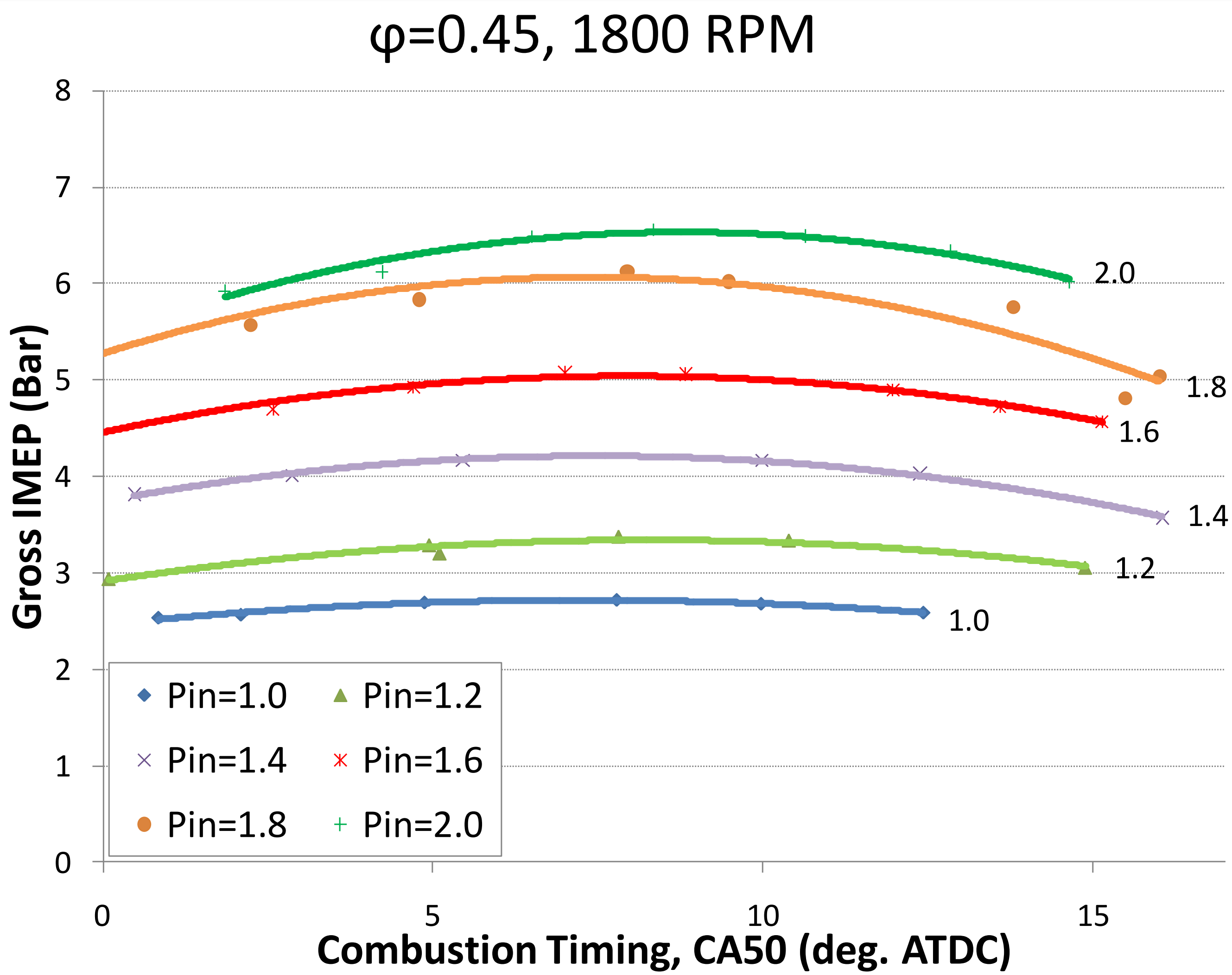
Ion Ringing Intensity

$$\text{Ion RI} \approx \frac{\alpha \cdot \left(\frac{P_{in}}{P_{atm}} \cdot \frac{d\text{Ion}}{dt}_{\max}\right)^2}{\sqrt{Ion_{\max}}}$$

S. Saxena
SAE 2011-01-1777

No in-cylinder P required

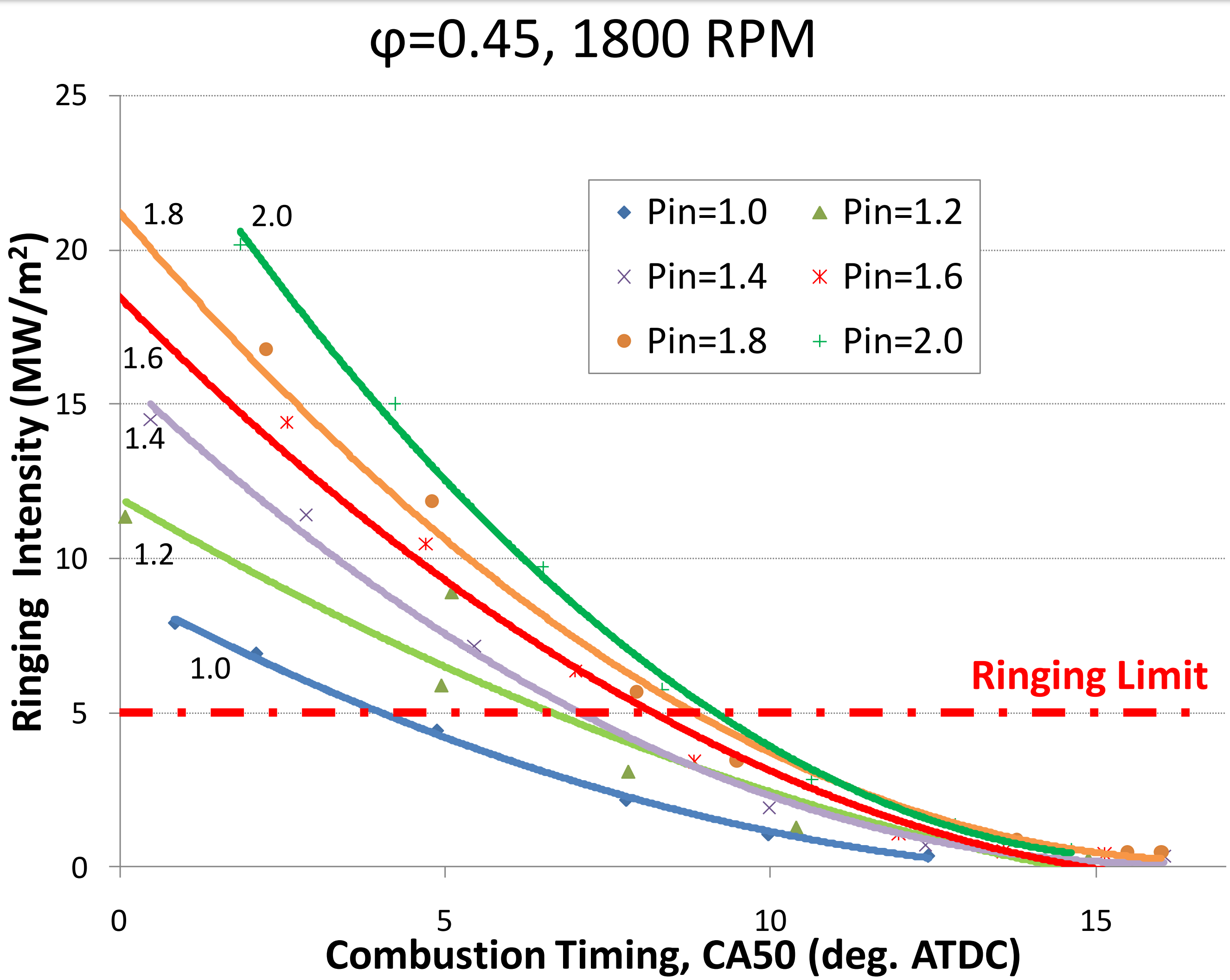
Power output increases with higher P_{in}, max at intermediate CA50



Overall Trends:

- IMEP increases with higher P_{in}
- IMEP is highest at intermediate CA50s

Ringing becomes a more significant constraint at higher P_{in}



Overall Trends:

- Ringing decreases with lower P_{in}
- Ringing decreases with delayed CA50

Out of the Box