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From Gasoline to Ethanol Direct Injection Engines

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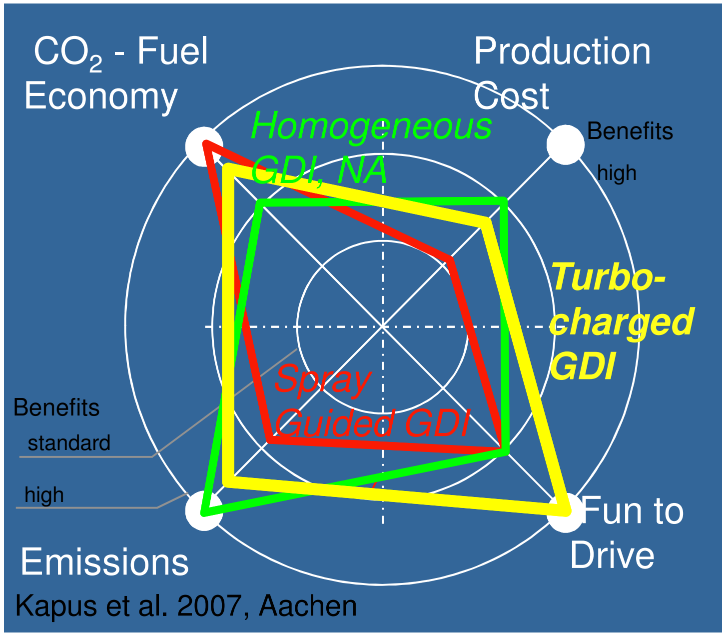
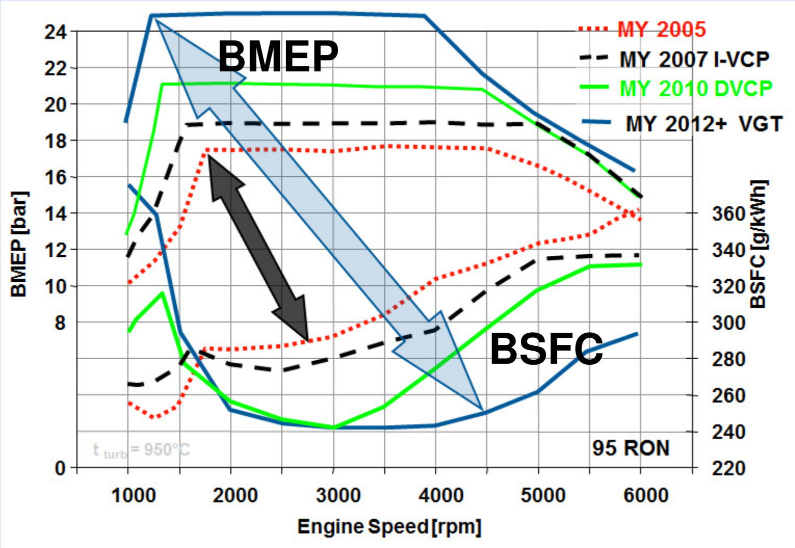
Development trend: Turbocharged GDI engine



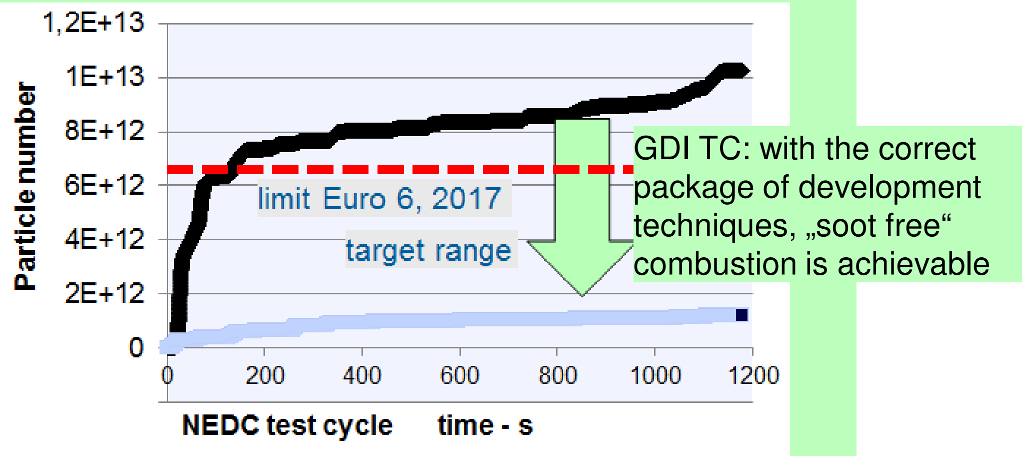
Why TC GDI has become today‘s development focus:

- high potential advantages in exploiting TC and GDI technologies
  - to meet customer expectations
  - to comply with legal requirements.
- we have learned to exploit such advantages with development techniques taylored to turbocharged gasoline direct injection combustion systems

Meeting drivers' expectations:
Performance development:
TC GDI shows continuous improvements



Meeting legal requirements:
Emissions development: the particle number (mostly soot) example for TC GDI



Gasoline DI is meeting customer expectations and complies with legal requirements

How would Ethanol DI change such diagrams?

Fuel features

		Gasoline	Ethanol
Chemical Formula	(-)	C_7H_{15}	C_2H_6O
Molecular Weight	(-)	99	46
Carbon Content	(%m)	84.9	52.2
Hydrogen Content	(%m)	15.1	13.0
Density Liquid at 20°	(kg/l)	0.740	0.790
Oxygen Content	(%m)	0	34.8
Lower Heating Value	(MJ/kg)	42.5	26.8
Heat of Evaporation	(kJ/MJ)	≈ 8.0	33.8
Octane Rating RON	(-)	95	>100
T evaporation	(°C)	25 - 210	78
Vapor pressure	(hPa)	60 - 90	17
Ignition temperature	(°C)	400	425

The Ethanol impact on combustion

Heating Value	inject 1,5 liter Ethanol for 1 liter Gasoline
Evaporation	Ethanol yields better charge cooling
	Ethanol has much higher risk at cold start
Octane number - RON	is a most attractive Ethanol feature

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Gasoline – Ethanol comparison:

Ethanol has promising as well as challenging features

1. How will such fuel features influence engine operation?
2. What does it need to exploit fuel advantages?
3. What is required to overcome the risks?

Heating Value	inject 1,5 liter Ethanol for 1 liter Gasoline
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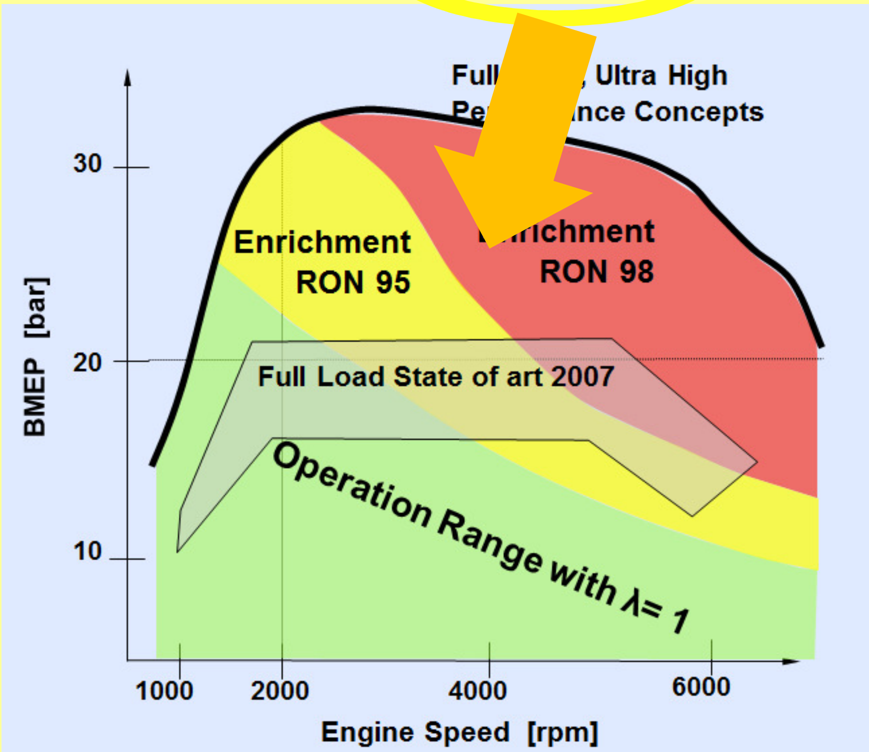


GDI high load operation:
the need for fuel enrichment is a
desaster for BSFC

Ethanol is most attractive in high load operation

- Charge cooling
- Octane number

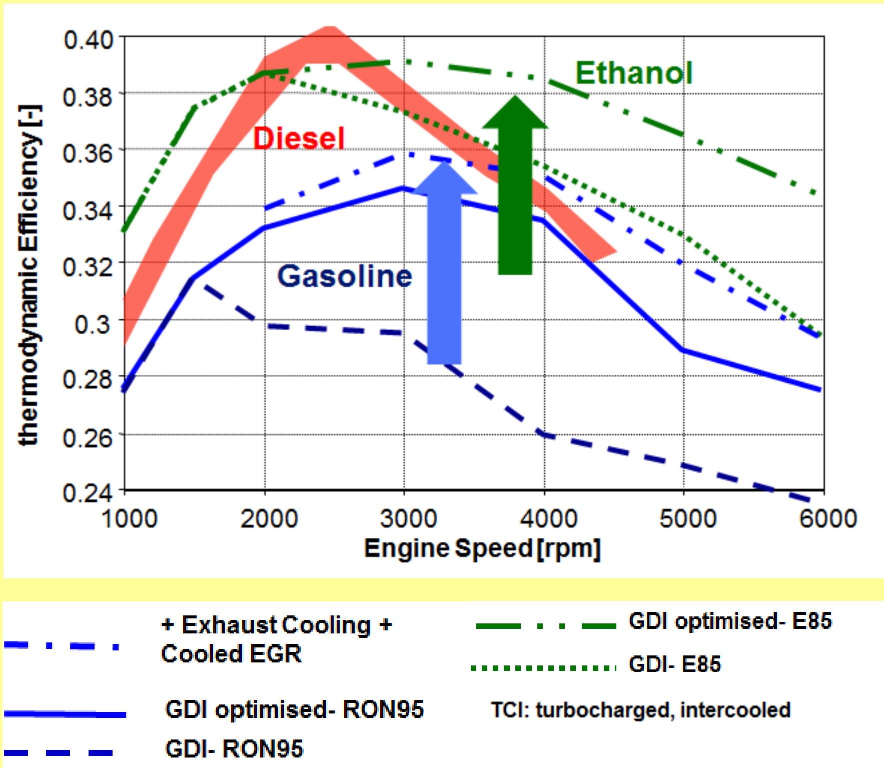
The risks

1. Handling 50% higher fuel flow needs specific attention in fuel injection development:
    - to meet the oil dilution risk
    - to tune spray – wall impingement events

2. Exploiting the RON advantage bears risks of high combustion chamber temperatures
    - spark plug, valve and piston durability
    - pre-ignition and irregular combustion
    - run-away knock

Full Load Efficiency with direct injection and turbocharging

Diesel - Gasoline – Ethanol (E85)



Ethanol is most attractive in high load operation

thermodynamic efficiency of a modern Ethanol engine (here on E85) is in good company with best Diesel engines

How to develop an Ethanol DI combustion system ?

Heating Value	inject 1,5 liter Ethanol for 1 liter Gasoline
Evaporation	Ethanol yields better charge cooling
	Ethanol has much higher risk at cold start
Octane number - RON	is a most attractive Ethanol feature

More fuel injected → more oil dilution

Fuel evaporation → is a big cold start issue

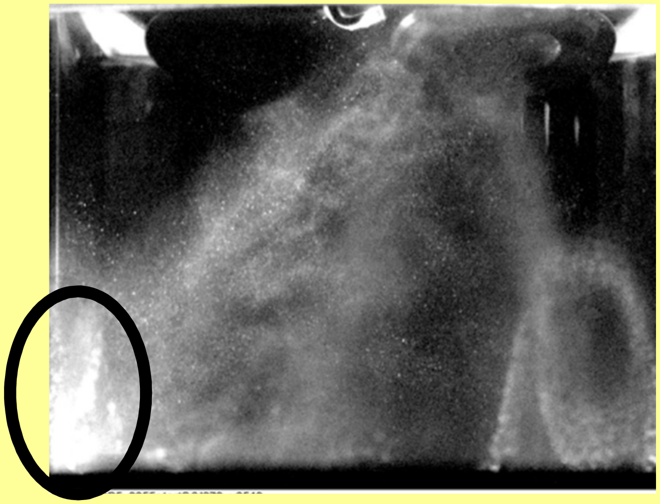
High RON → advanced spark timing yields lower exhaust gas temperature, but raises in-cylinder temperature

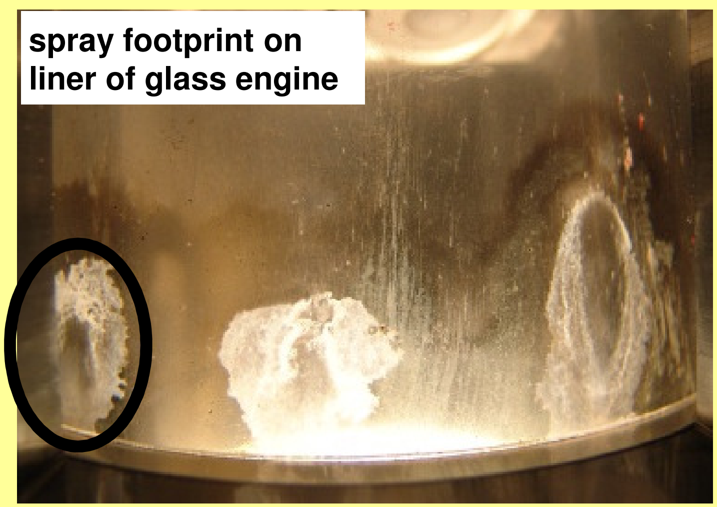
How to develop an Ethanol DI combustion system ?

Fuel features are the guide

What are specific development actions ?

Oil dilution, GDI examples





…is an issue in every GDI engine,
is a much larger issue when using Ethanol

The risk

- oil dilution with secondary lubrication risks
- loss local lubrication
- piston ring damage

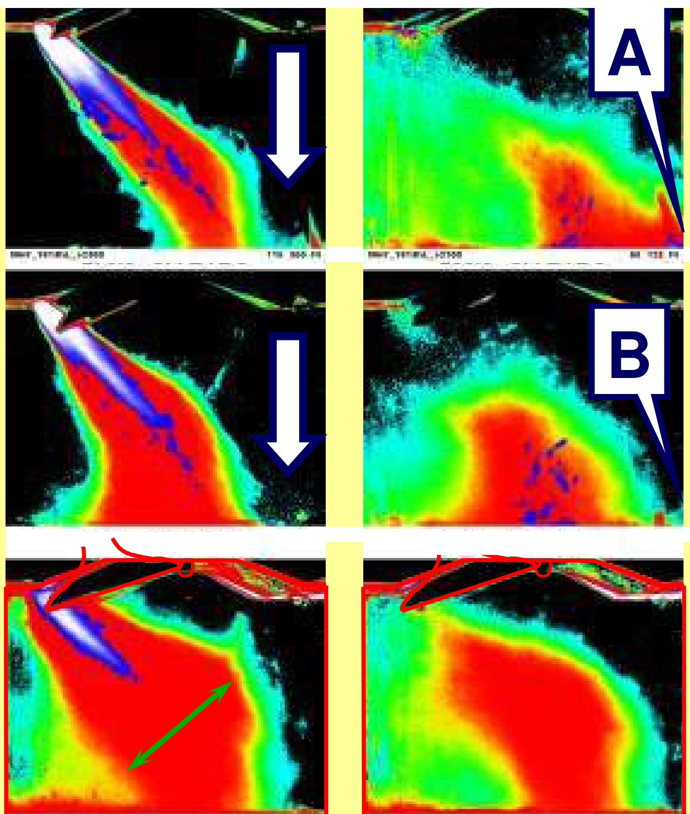
Handling 50% higher fuel flow with Ethanol injection

see film for wall wetting effects

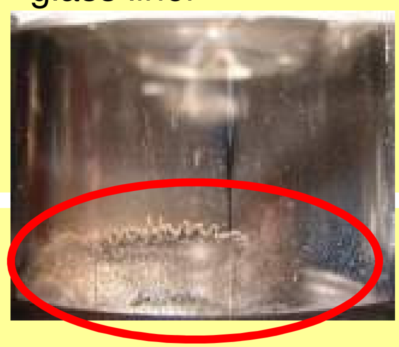
Oil dilution - improvement, GDI examples

50 70 deg CA ASOI

fuel spray and vapor in optical engine



spray footprint on glass liner



Improved spray width

No fuel liner impingement

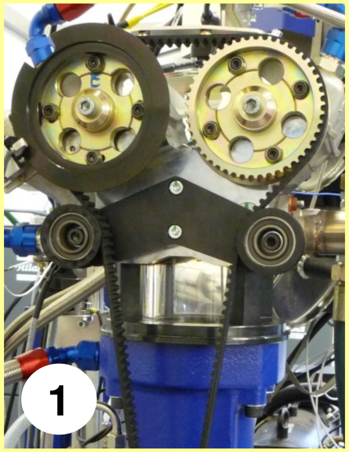
…is a much larger issue when using Ethanol

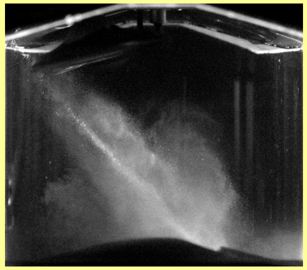
The recipe for improvement:

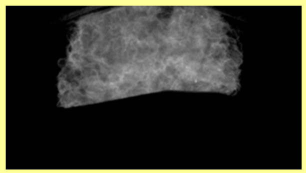
<u>injection system</u>:
select injector and injection parameters

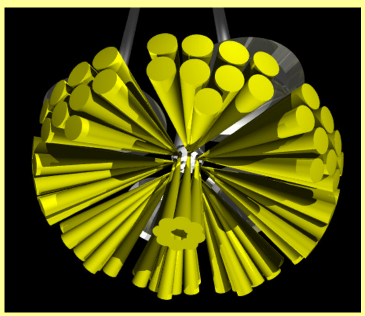
<u>intake ports – airflow</u>:
use in-cylinder flow as an air curtain to protect liner surface

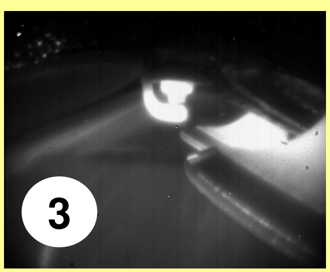
Combustion system development techniques for DI SI engines

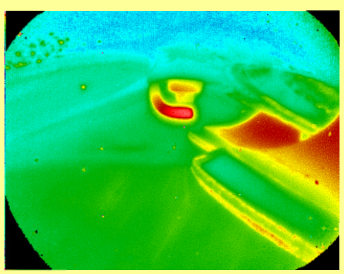












This presentation:
the tools we use in combustion system development

1. Use an optical engine to study mixture formation, ignition and combustion
   - at engine start
   - in catalyst heating mode
   - at low end torque

2. Use fiber optic sensor techniques to study high load combustion
   - knock
   - pre-ignition and irregular combustion
   - transient operation

3. Use thermal radiation techniques to study
   - spark plug temperature profiles
   - valve temperatures

The cold start risk

		Gasoline	Ethanol
Lower Heating Value	(MJ/kg)	42.5	[illegible]
Heat of Evaporation	(kJ/MJ)	≈ 8.0	33.8
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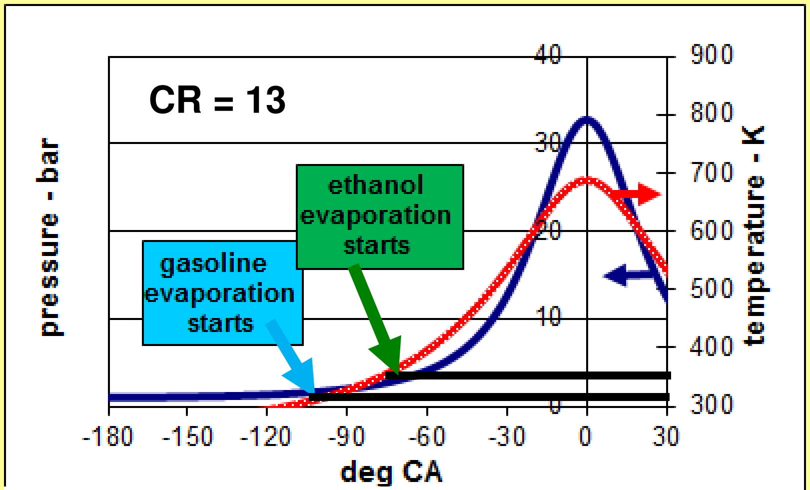


Graphic shows pressure and temperature traces at compression ratio = 13. Ethanol eaporation starts later in cycles and needs more heat to evaporate

our chances

- Compressed hot air is only heat source to evaporate Ethanol droplets
- Every droplet on cold combustion chamber wall is lost for ignition / combustion

Cold start:
Injection is key to success

What we want to happen

- inject small droplets
- they should float in air
- and evaporate in late compression cycle before ignition

How to operate an injector to accomplish such task?

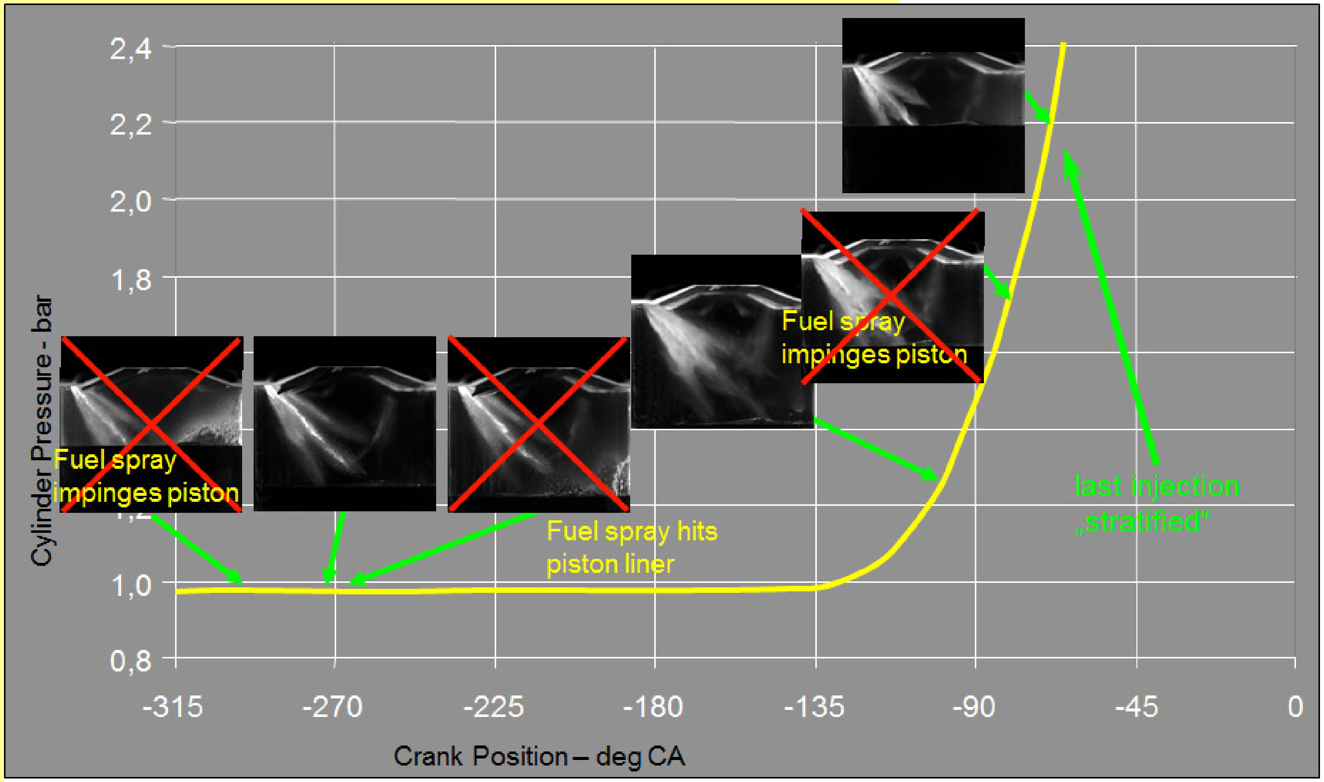
What we can do: we select -

- fuel rail pressure
- injection timing,
- duration and
- multiple injections

Seeing the fuel sprays is understanding the chances for best parameter selection

mixture formation

Cold Start in Transparent Engine at 20℃



What we want to happen

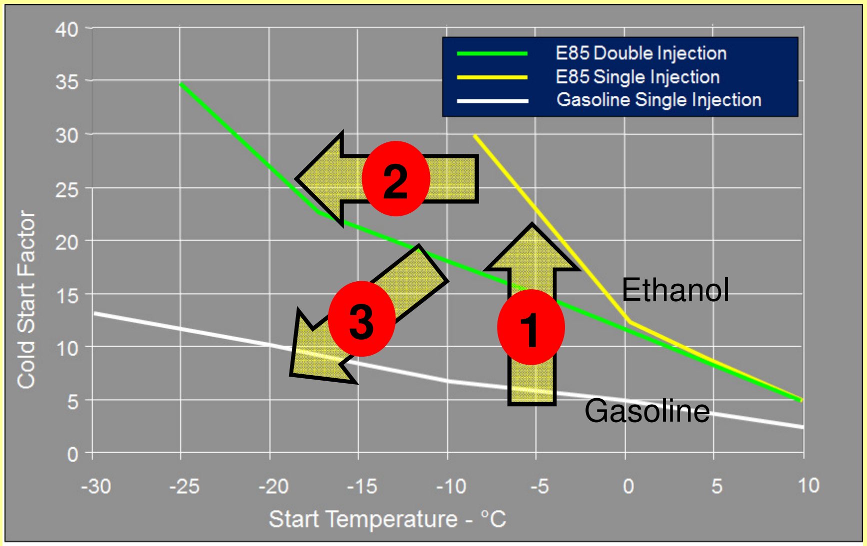
- inject small droplets
- they should float in air
- and evaporate in late compression cycle before ignition

What we can do

- inject for minimum wall impingement
- use late injection to exploit compression heat and stratification

mixture formation

Engine start tests with Gasoline and E85



1 the Ethanol disadvantage

2 improvement with double injection

3 My expectations: we exploit development chances with modern injectors

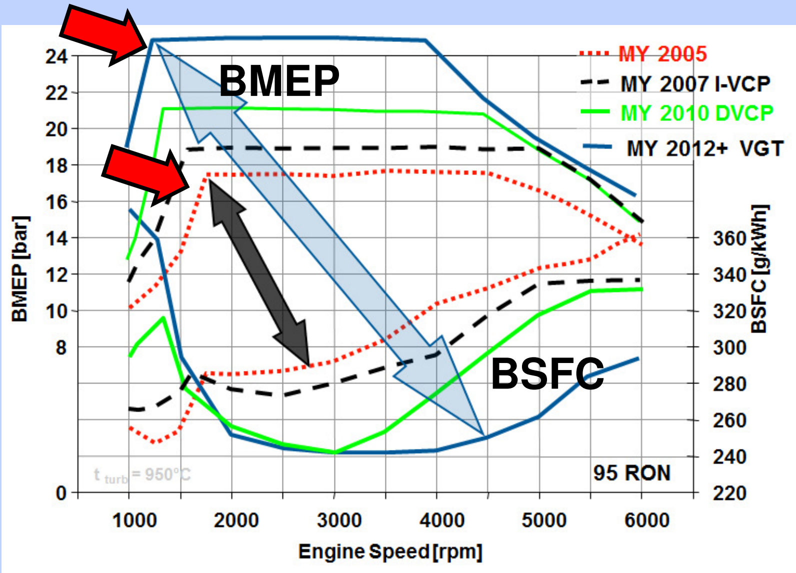
Cold start:

Direct injection offers features to make happen what we want to happen.

This needs efforts

- in enhancing injector spray formation capabilities
- understanding the fuel injection „windows of opportunity"

„low end torque“ at 1500 – 1800 rpm



mixture formation and combustion issues at low end torque: LSPI and knock

- fuel evaporation and homogenization at moderate airmotion – risk for oil dilution and wall film formation
- LSPI – low speed pre-ignition: low speed = long chemical induction time and high load = high wall temperature yield a
  - large time-temperature integral to drive chemical reactions
- LSPI chemical species risk from fuel, lube oil, deposits

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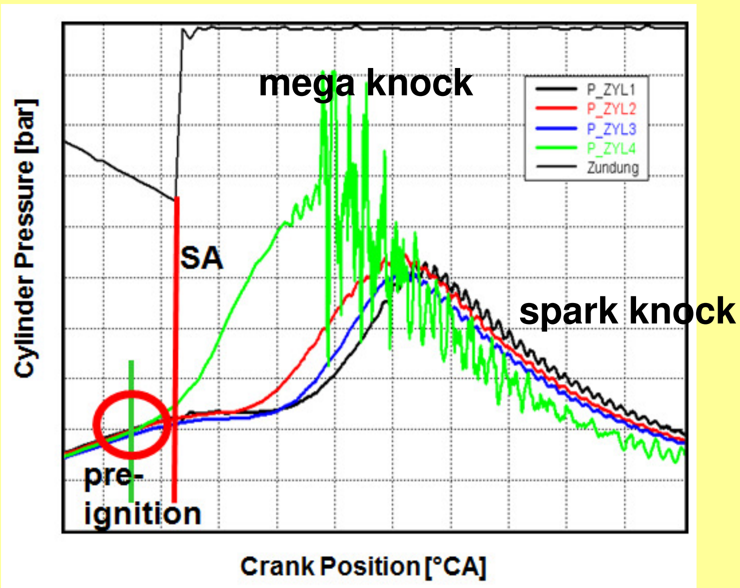
Low end torque for high dynamic response

Self ignition and irregular combustion events need special development efforts

- we use the optical engine to clarify and improve mixture formation topics at boosted full load injection
- we use fiber optic flame sensors in the normal multicylinder TC engine to minimize risk of irregular combustion

What is “irregular combustion” ?

LSPI - as any other irregular ignition event: if we know where it occurs, we may understand why it occurs



Pre-ignition: occurs spontaneously in one out of many cycles

Diagnostics task: find the location of such spontaneous ignition events

Analysis task: find the root cause of pre-ignition

Development task: find ways to avoid / minimize risk of pre-ignition

Low end torque – the LSPI risk

LSPI: low speed pre-ignition

To minimize / avoid pre-ignition it needs diagnostics and analysis in normal multicylinder engine operation.

We use fiber optic spark plug sensors to address this diagnostics task

Arrhenius:

$$\tau = A * p^{-n} * e^{\frac{B}{T}}$$

Livengood, Wu:

$$\int_{t_{IVC}}^{t_{IVC}+t_{SOC}} \frac{1}{\tau(s)} ds = 1$$

Igniting a mixture: the parameters of influence

A, B, n: chemical features

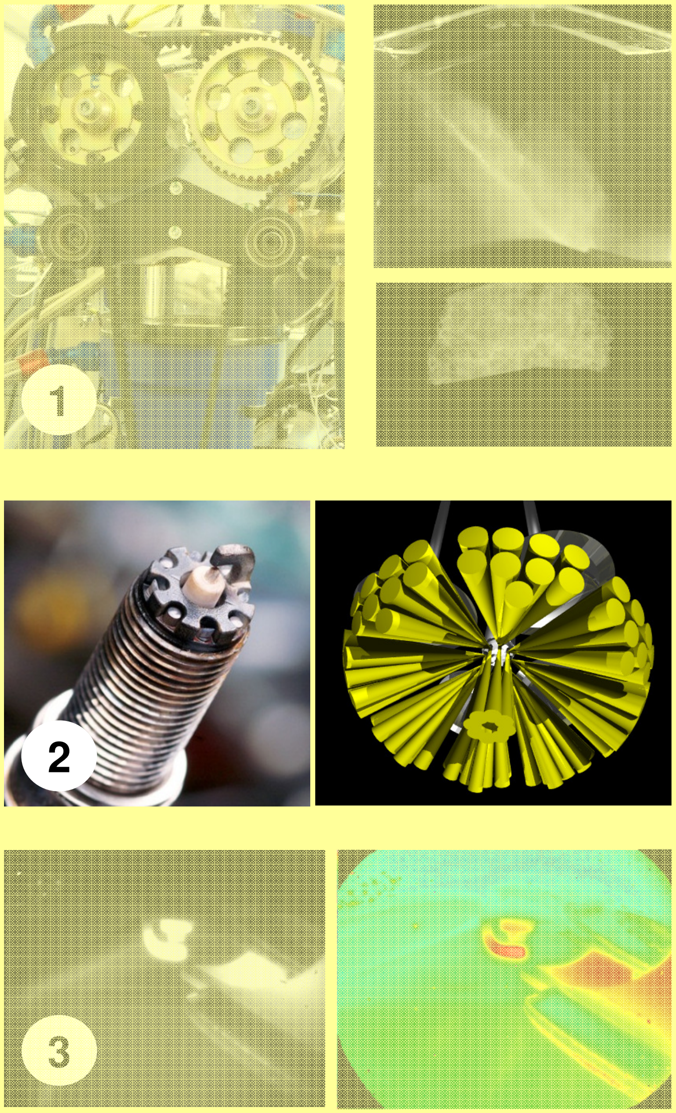
p, T: engine operation: boost, load

t_{SOC} ~ time to establish thermochemical chain reaction…is driving LSPI

t_{IVC} intake valve closure time

τ : ignition delay time

Combustion system development techniques for DI SI engines



LSPI is member of a large family of irregular combustion events

Focus 2: Irregular combustion

1. Use an optical engine to study mixture formation, ignition and combustion
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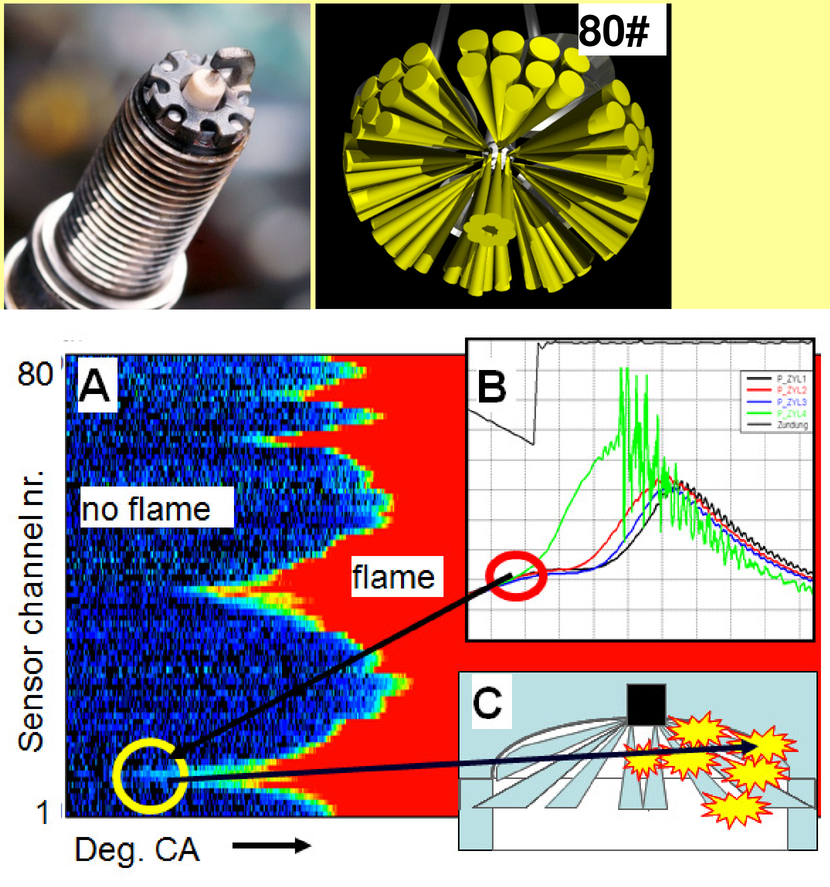
A fiber optic spark plug sensor for PI location diagnostics



A and B: flame and pressure signal of pre-ignition cycle.
C: locations of repeated PI events

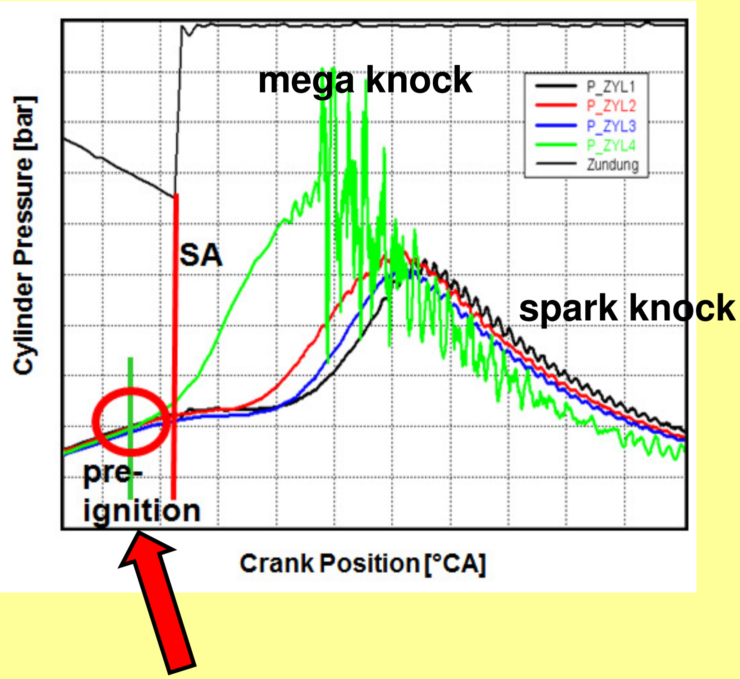
ptnss 2011

Low end torque – pre-ignition diagnostics with pressure and flame sensors

The spontaneous occurrance of PI events needs continuous signal recording and signal storage with trigger - on - event logics.

this brings us to the more general topic of irregular ignition / combustion events

Pre-ignition:
if we know where it occurs, we may understand why it occurs



hot spark plug ?
hot exhaust valves ?
hot piston ?
hot cylinder head surface ?

The high speed pre-ignition risk

HSPI: high speed pre-ignition

Ethanol Octane number allows spark timing to provide maximum torque with stoichiometric mixture even at high speed / high load operation.

This gives higher thermodynamic efficiency at the risk of higher combustion chamber temperature.

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Igniting a mixture: the parameters of influence
A, B, n: chemical features
p, T: engine operation: boost, load…is driving high speed PI
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Pre-ignition:
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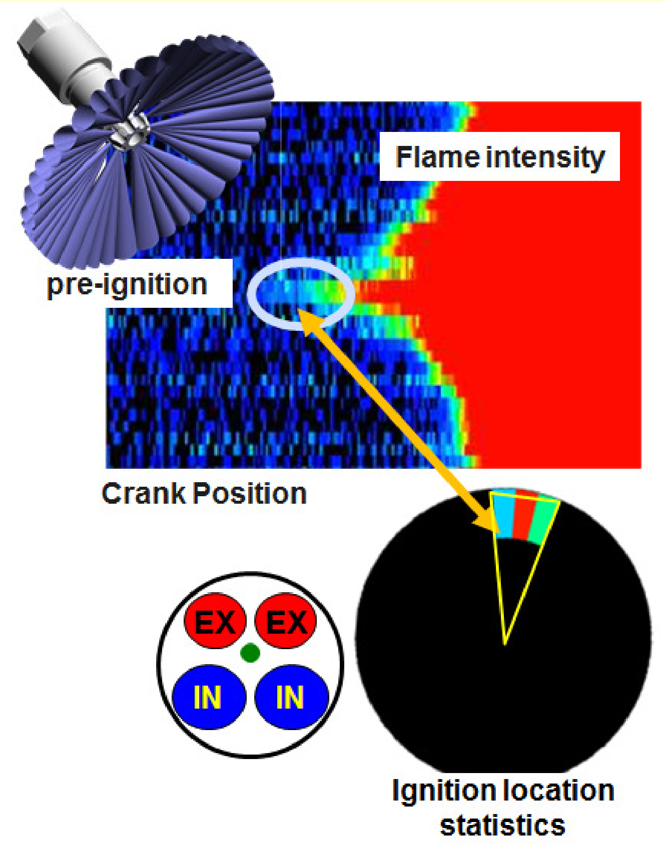

hot spark plug ?
hot exhaust valves
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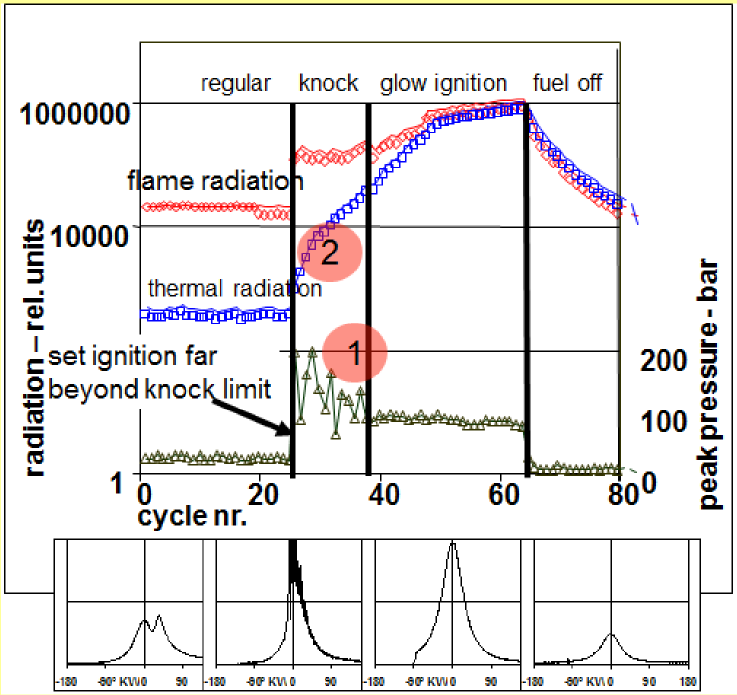
hot cylinder head surface ?

The high speed pre-ignition risk

Example shows one pre-ignition cycle with flame signal recorded with 40-channel VisioKnock spark plug sensor.

- Sensor channel identifies sector at which pre-ignition occurs.
- Collecting repeated PI events shows that PI always occurs within sector comprising exhaust valves.
- Recommended action: improve valve seat cooling, select cooled exhaust valves.

A runaway knock example in a GDI engine at a "thermal stress test"



1 Result for this operating point:
- engine needs >10 strong knock cycles to go into glow ignition

Result for engine testing:
- use SA (knock) versus time for thermal stress test
- use test bed watchdog to reduce testing risk
- use (partial) fuel cut to protect engine

2 - use thermal radiation signal to detect thermal runaway risk

The knock - runaway knock risk

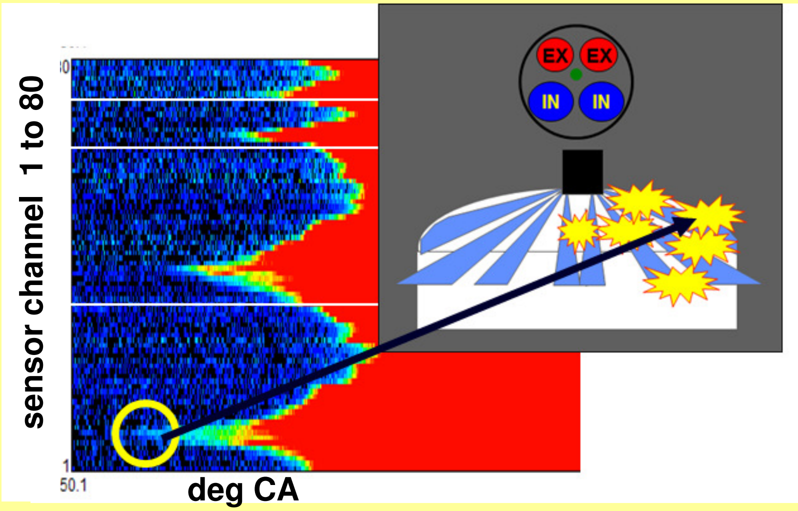
Ethanol Octane number allows spark timing to provide maximum torque with stoichiometric mixture even at high speed / high load operation.

This gives high thermodynamic efficiency at the cost of high combustion chamber temperature.

The consequence in case of „spark knock":

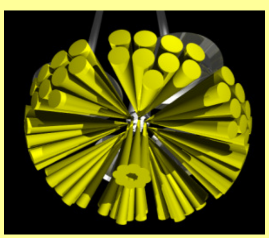
- knock introduces high heat flux through combustion chamber surface, this raises local surface temperature
- subsequent cycles may run into pre-ignition mode
- Stopping pre-ignition needs fuel cut

Pre-ignition:
if we know where it occurs, we may understand why it occurs



Signal analysis:
sector: is resolved with sensor channel
radial position: is reconstructed from flame speed and flame propagation interval

above data were recorded with 80# spark plug sensor



The chemical species risk

In addition to fuel – air mixture there is oil, oil vapor, EGR, and deposits inside the combustion chamber.

- chemical kinetics of such species can introduce PI
- glowing deposits and free moving hot deposit flakes can survive one exhaust stroke and ignite fresh charge before spark ignition

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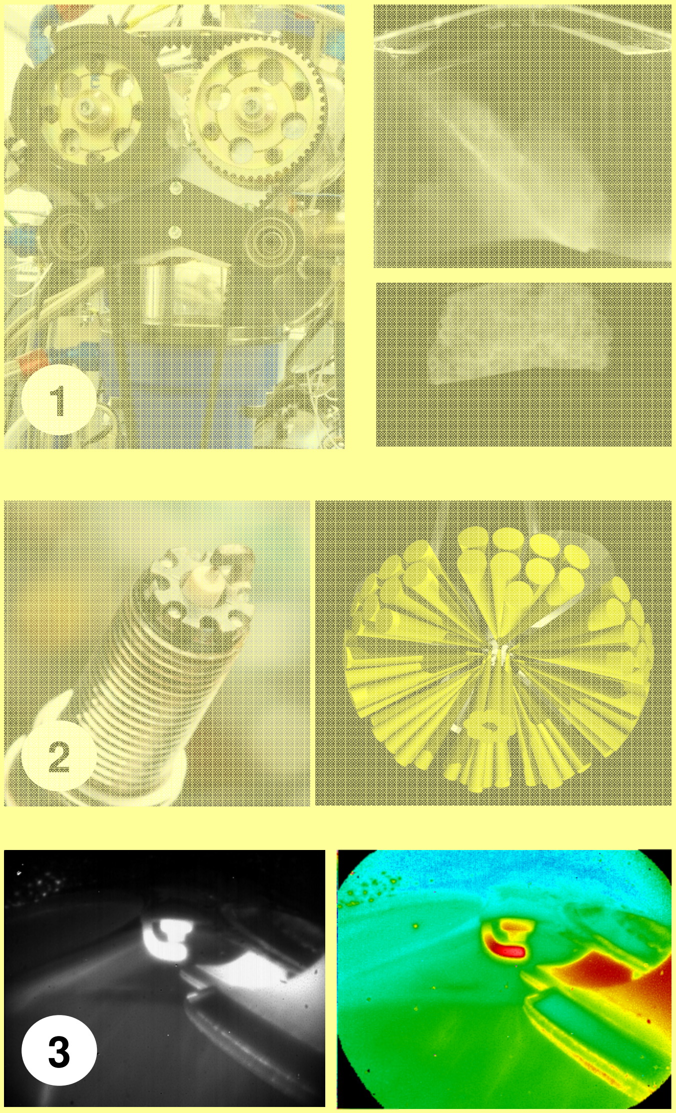
Combustion system development techniques for DI SI engines



This presentation

Focus 3: in-cylinder temperatures

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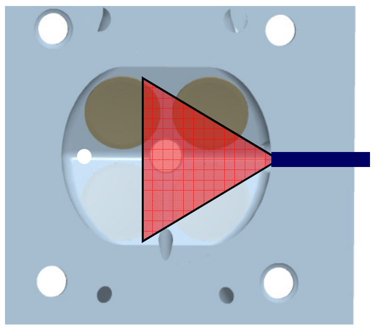
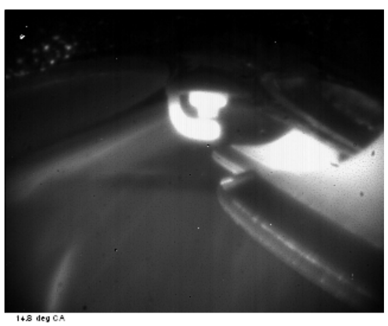
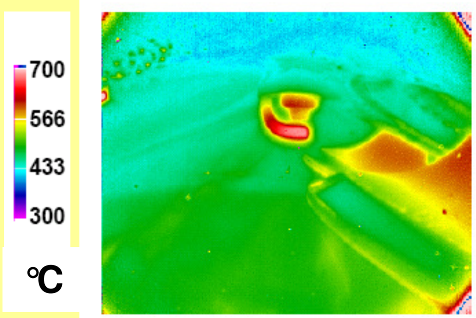
Combustion system development techniques for DI SI engines



Endoscope access into combustion chamber, IR sensitive camera



thermal image of hot combustion chamber surfaces



calibrated temperature field

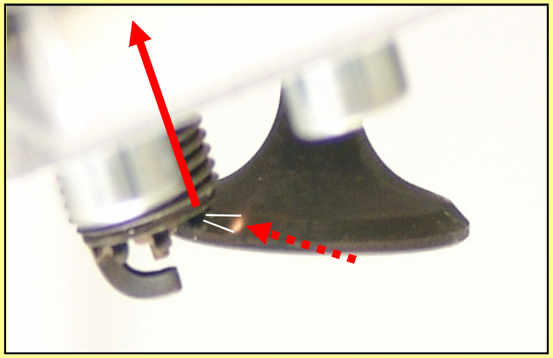
„Single shot“ thermal imaging

Example shows gasoline engine thermal images. Temperatures in Ethanol engines are even more critical with risk of thermal pre-ignition or thermal damage of components.

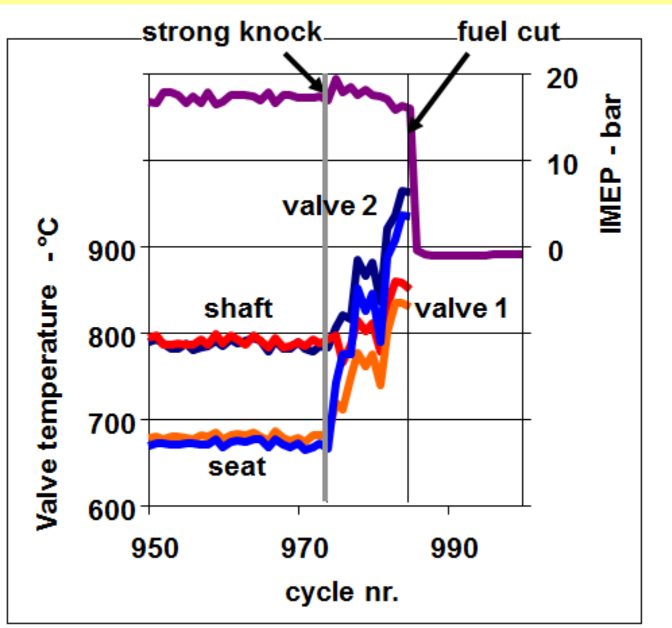
Thermal imaging with endoscope, IR camera and temperature calibration techniques provides variants analysis in normal engine operation.

Combustion system development techniques for DI SI engines

in-cylinder temperatures



access to valves with fiber optic spark plug sensors



example shows valve temperature response to knocking combustion cycles in GDI engine

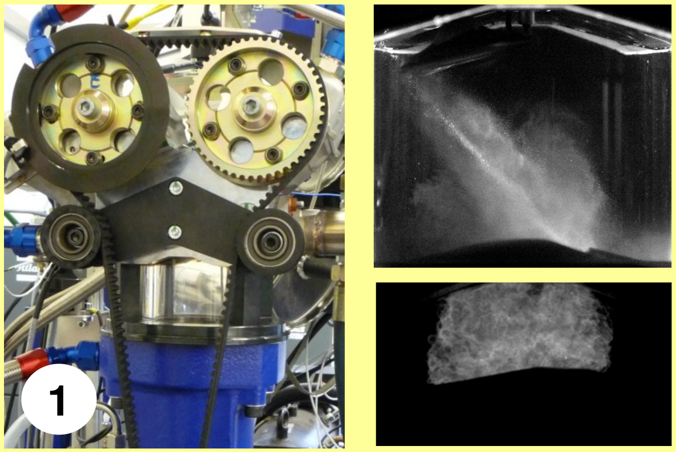
Continuous, cycle and crank angle resolved thermal radiation measurement

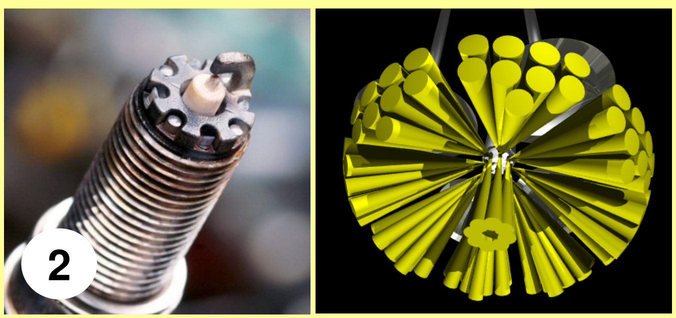
.

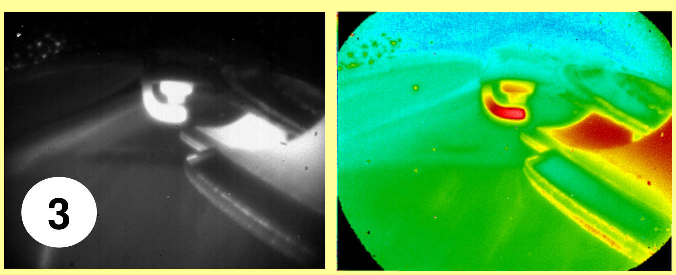
Thermal risk analysis at load transients needs continuous signal recording:

- Fiber optic spark plug sensors access thermal radiation, IR sensitive photo diodes (PD) record radiation signals.
- Signal calibration is achieved with specific calibration device

From Gasoline to Ethanol Direct Injection Engines







Summary

1. Fuel features guide and dictate Ethanol engine development efforts

2. Direct injection together with turbocharging appears to best handle fuel obstacles and exploit fuel benefits

3. GDI development methods are well applicable to Ethanol engines across the entire load, speed and temperature range of a modern engine

From Gasoline to Ethanol Direct Injection Engines

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