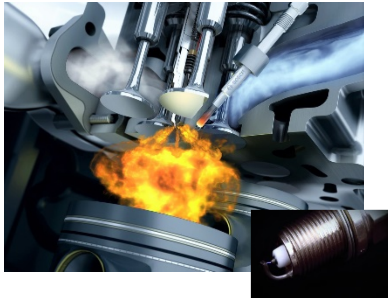
CFD modelling of the flame kernel growth process under highly diluted mixtures in SI engines



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NISSAN

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Outline

1) **Introduction**:

   motivation and *research engine description*

2) **Cold flow initialization**:

   application of *Polimi full-cycle methodology* for IC engines

3) **Spark-ignition (SI) combustion modelling**

   a) *Modelling approach*
   b) *Average cycle behavior* in a RANS context: *model setup and results*
   c) *First attempts* to predict *Cycle-To-Cycle Variability* (CCV) in a RANS context: *model setup and results*

4) **Conclusions and future developments**

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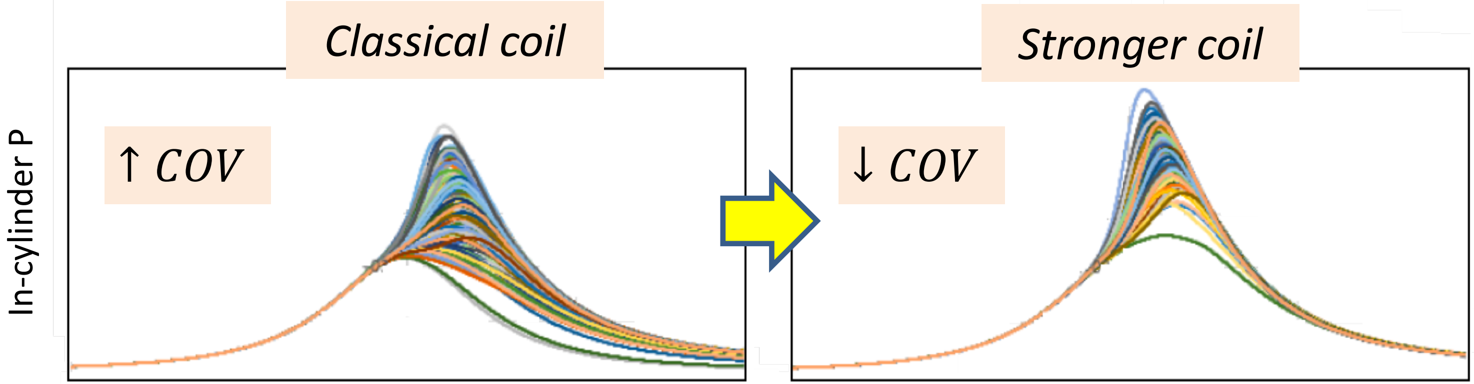
Introduction

Why is necessary to model in detail the ignition process?

- Last generation Spark-Ignition ICEs employed with premixed highly-diluted air-fuel mixtures

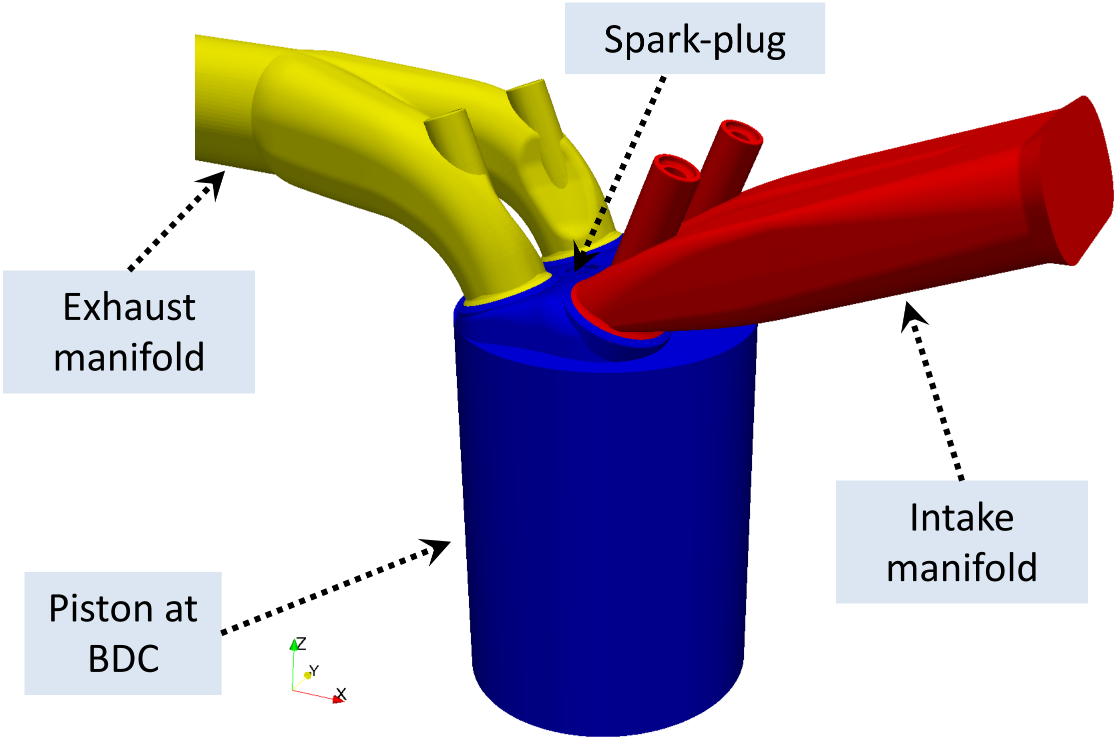
Air-fuel ratio $> \mathbf{25}$

- Experimental investigations shown significant effects of the ignition strategy



Introduction

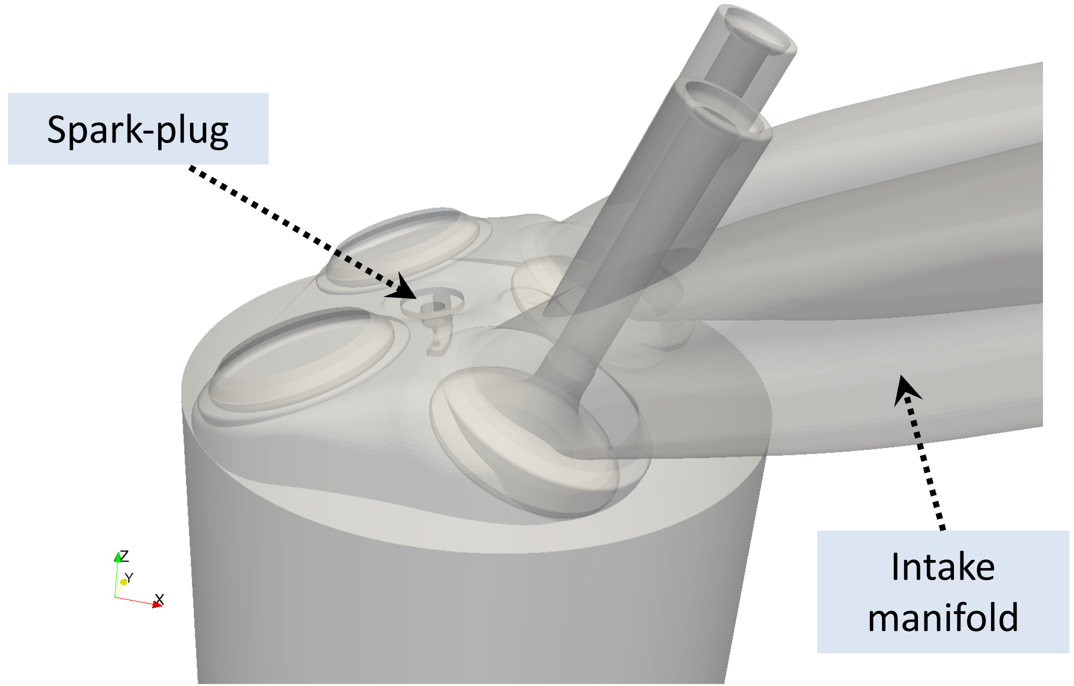
The investigated research engine



- 4 strokes optical SI research engine
- $C_8H_{18} - Air$ mixture
- Port-Fuel Injection (PFI)
- Compression Ratio $\approx$ 15
- Air-fuel ratio $>$ 25

Introduction

The investigated research engine



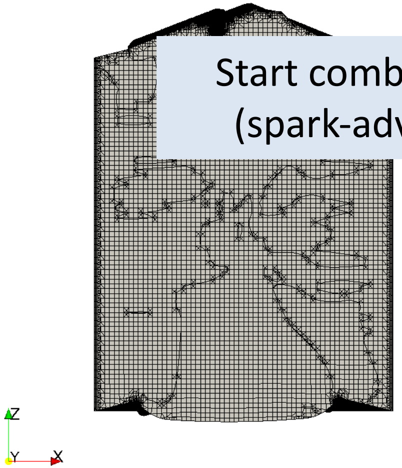
- 4 strokes optical SI research engine
- $C_8H_{18} - Air$ mixture
- Port-Fuel Injection (PFI)
- Compression Ratio $\approx$ 15
- Air-fuel ratio $>$ 25

Cold flow initialization

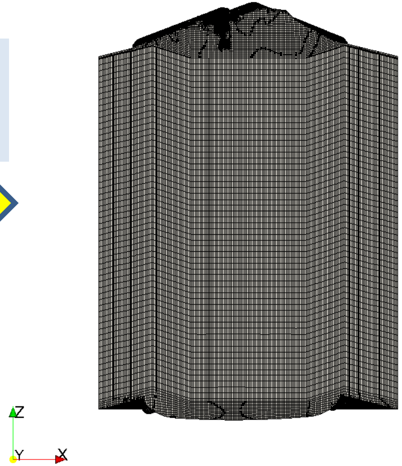
Polimi full-cycle methodology for ICEs: the *mesh generation process*

Deforming mesh

Layering mesh



Start combustion!
(spark-advance)



@ IVC

Deforming mesh

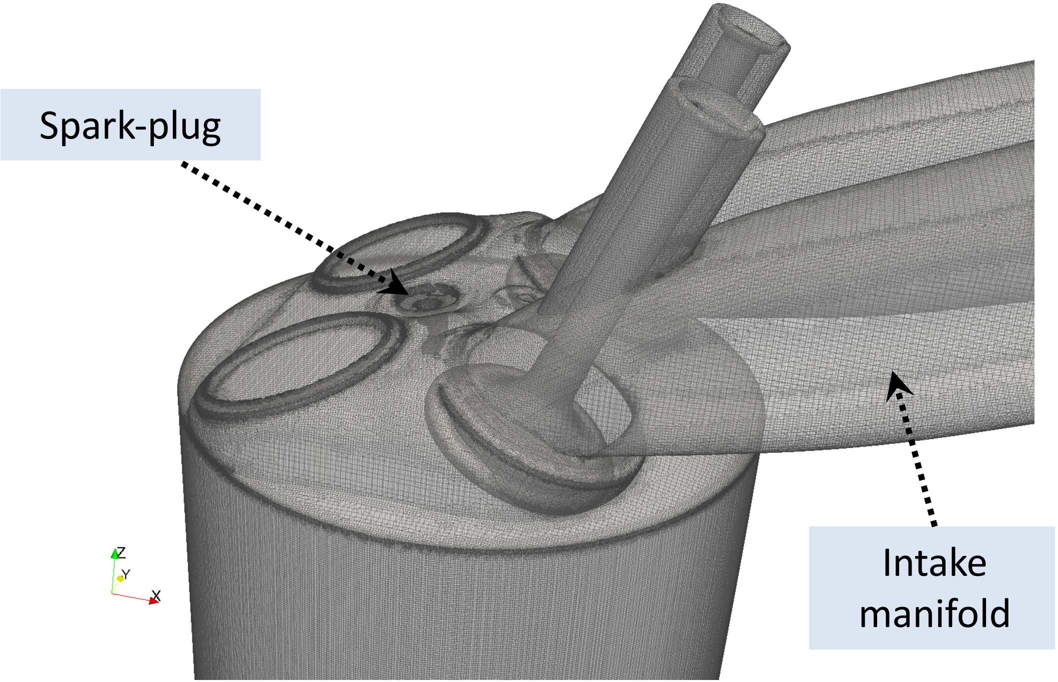
- Max cells n. ≈ 1 Mil 970 k
- Min cells n. ≈ 1 Mil 130 k

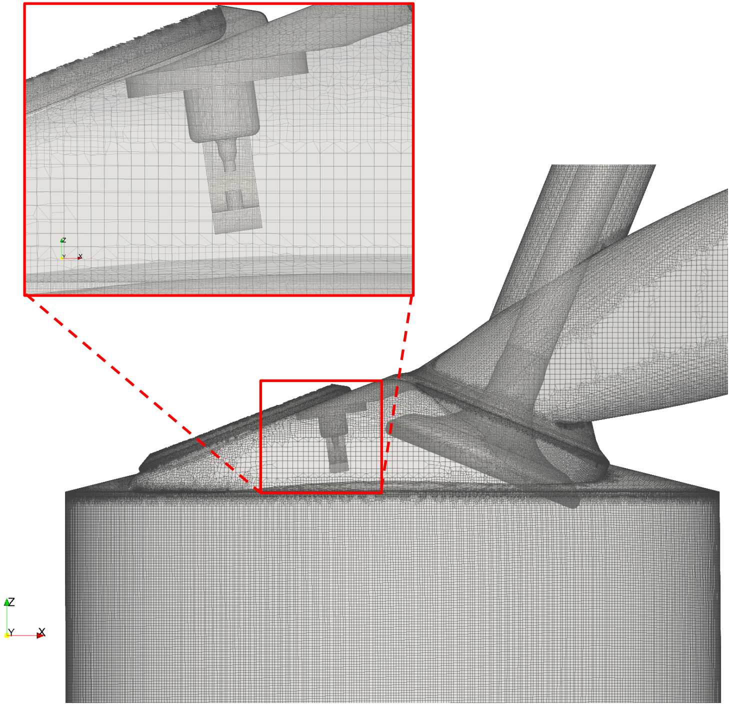
Layering mesh

- Max cells n. ≈ 2 Mil 190 k
- Min cells n. ≈ 910 k

Cold flow initialization

Polimi full-cycle methodology for ICEs: the *mesh generation process*





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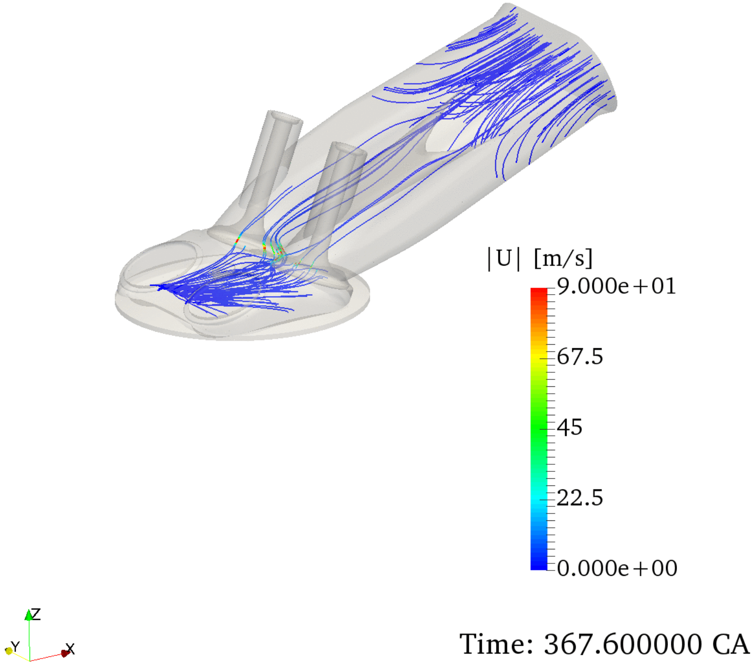
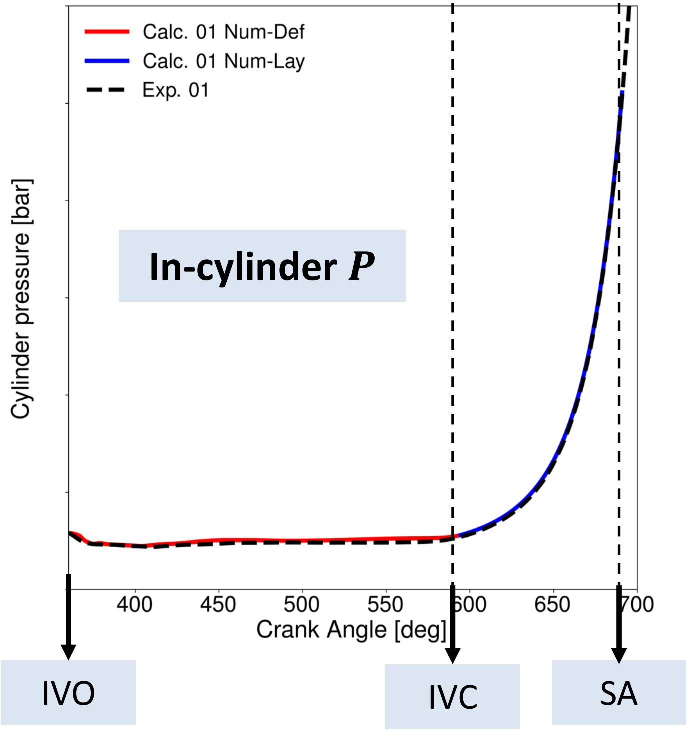
Cold flow initialization

Polimi full-cycle methodology for ICEs: *RANS numerical vs. experimental comparison*





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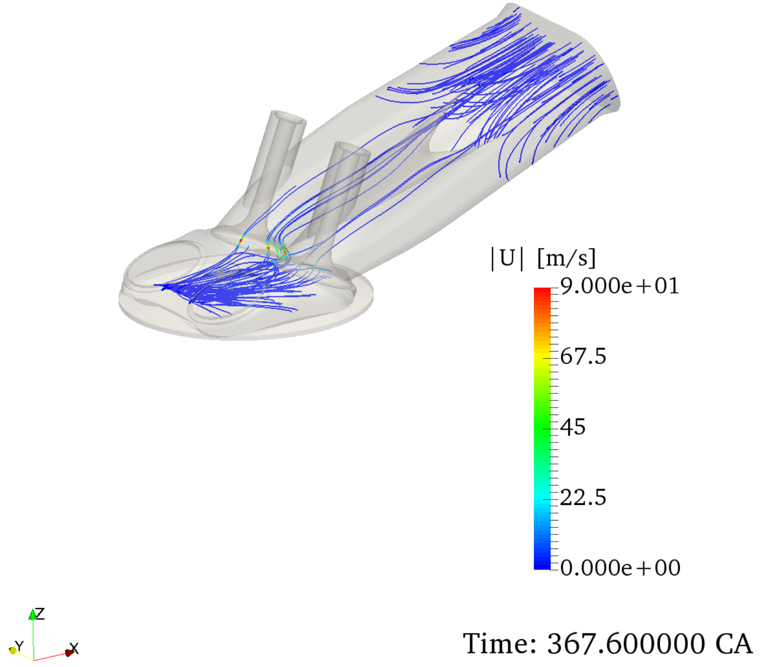
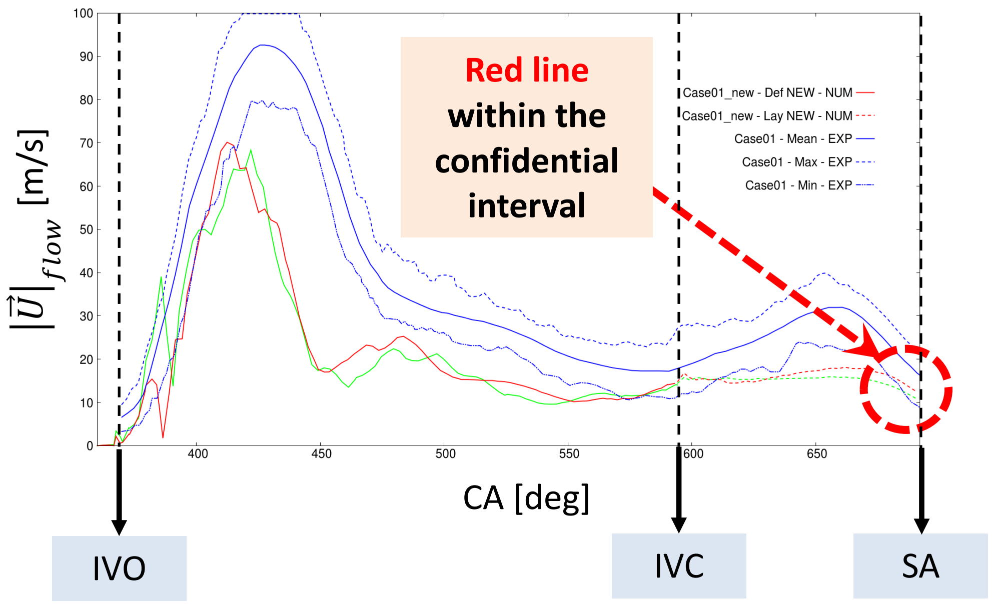
Cold flow initialization

Polimi full-cycle methodology for ICEs: *RANS numerical vs. experimental comparison*

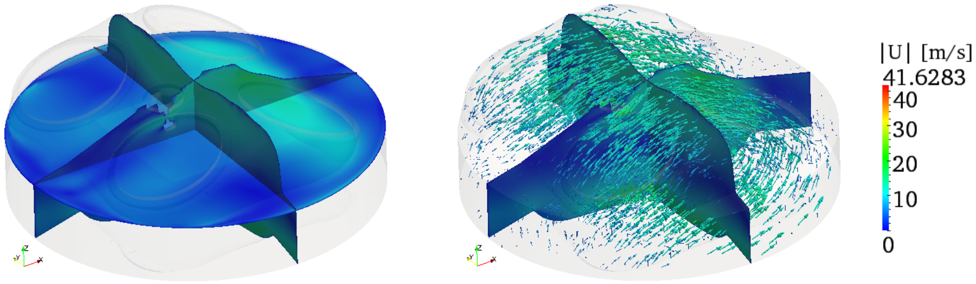


$|\vec{U}|_{flow}$ **at spark-gap center**

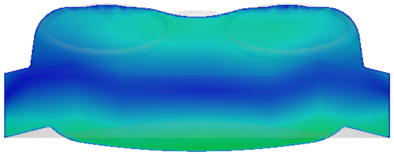


Cold flow initialization

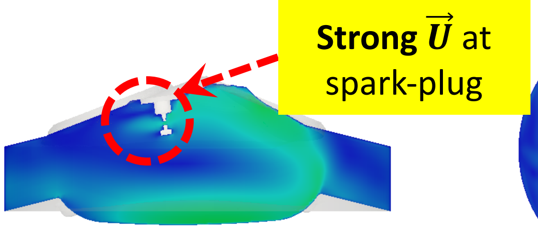
Polimi full-cycle methodology for ICEs: the *numerical $\vec{U}$ field at Spark-Advance*



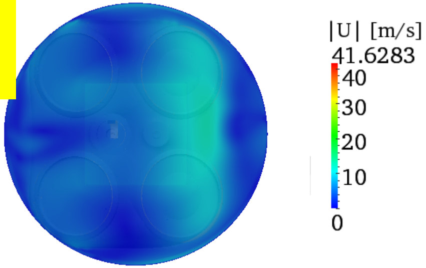
X-plane



Y-plane

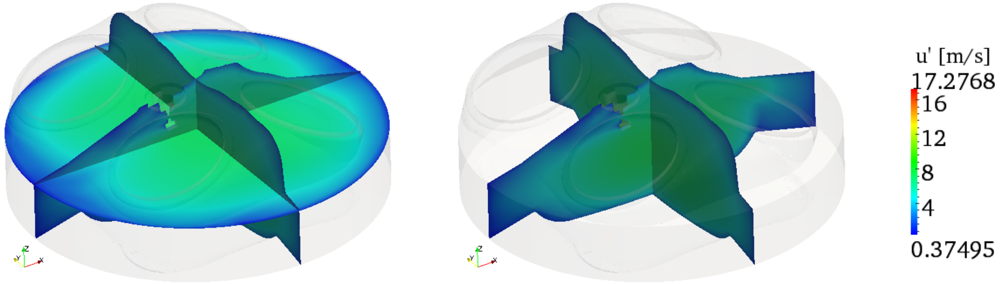


Z-plane



Cold flow initialization

Polimi full-cycle methodology for ICEs: the *numerical* u' *field at Spark-Advance*

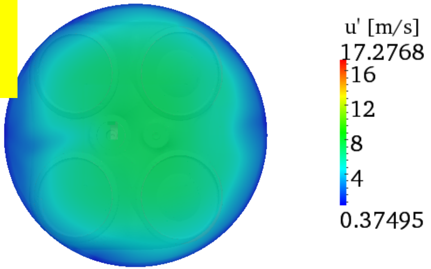


X-plane

Y-plane

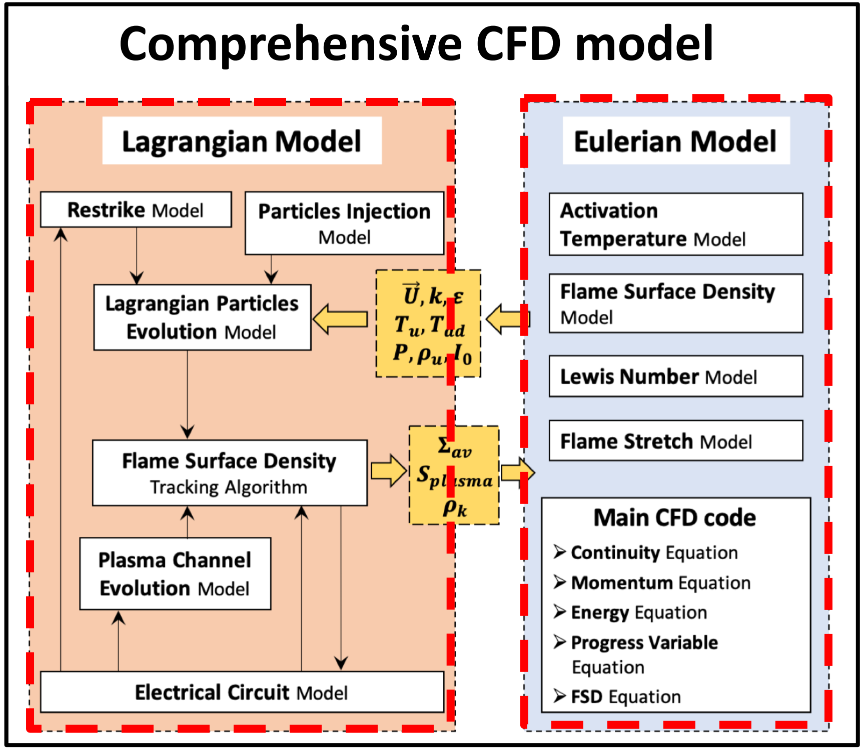
High u' at spark-plug

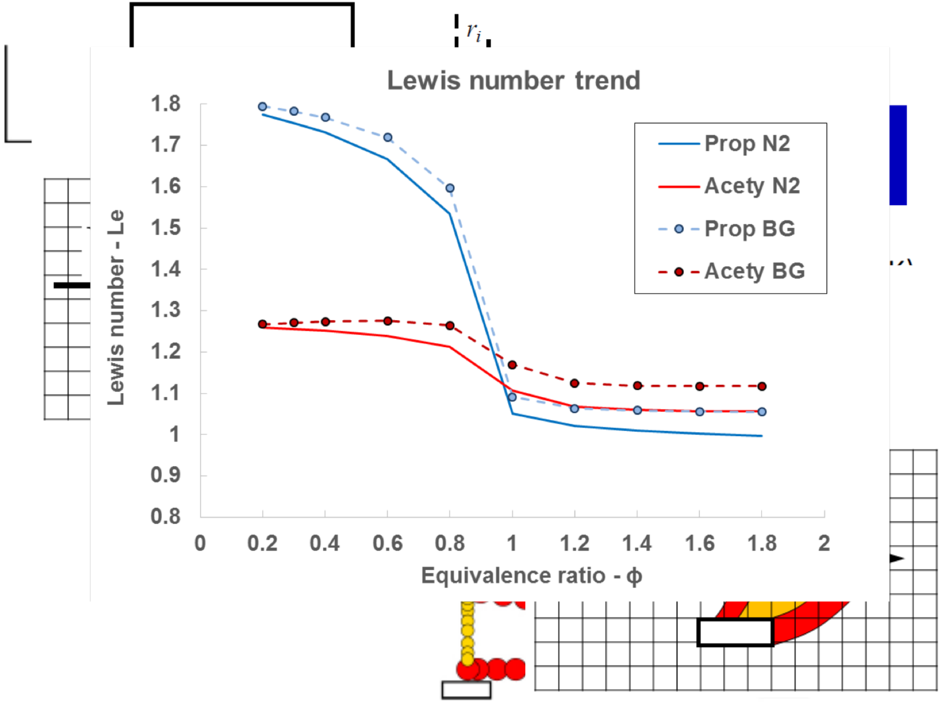
Z-plane



SI combustion modelling

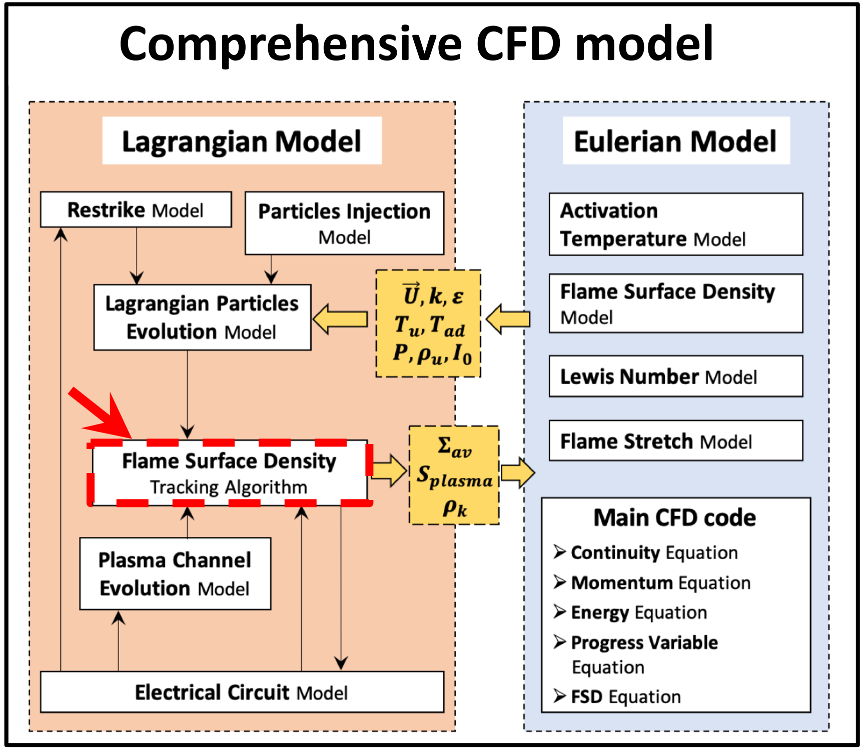
Modelling approach

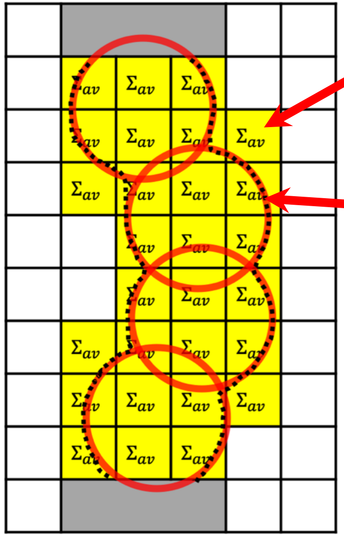




SI combustion modelling

Modelling approach





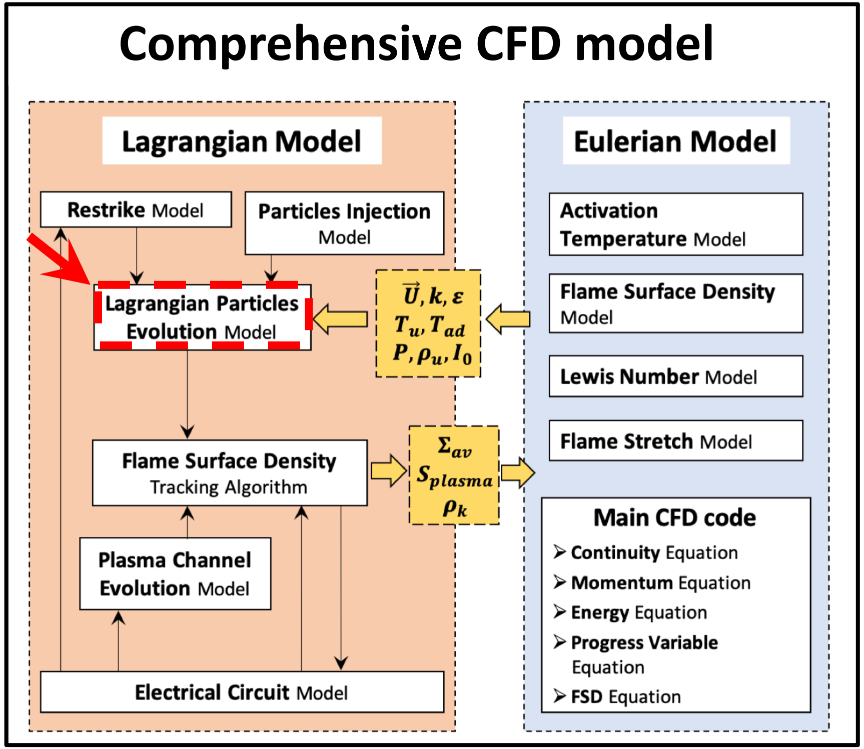
- **Detection of all cells "overlapped"** by the channel
- **Computation** of the "yellow" cells volume $V_{coupling}$
- Co… cal ch…

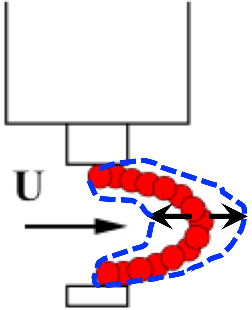
Suitable for parallel computations

- **Computation and allocation** of the average FSD as $\Sigma_{av} = A_{channel}/V_{coupling}$
- Similarly, S_{plasma} and ρ_k are **uniformly imposed to** $V_{coupling}$

SI combustion modelling

Modelling approach

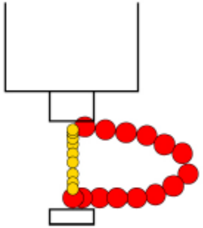




1) **Laminar**-only **stage included** into the Lagrangian framework

2) **If $d_{channel} < d_{tr-low}$: laminar-only flame** can be considered

3) **Flame stretch included into laminar flame evolution** (instability/quenching effects)



4) **At restrikes** (or at discharge end): **Lagrangian - Eulerian coupling maintained** according to laminar flame evolution

5) **If $d_{channel} > d_{tr-high}$: fully turbulent flame only**

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SI combustion modelling

Average cycle behavior in a RANS context: model setup

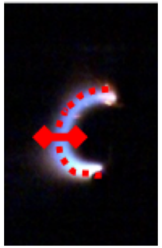
Target

- The impact of the electrical circuit: ***Case 01* vs. *Case 02***

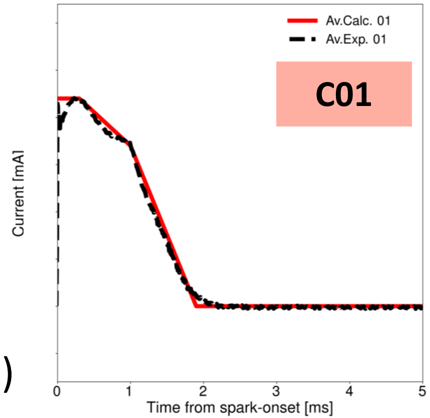
Case	Air/Fuel ratio	Coil features	Engine speed	Air mass
01	same (>25)	*constant + triangular*	same	same
02		*triangular*		

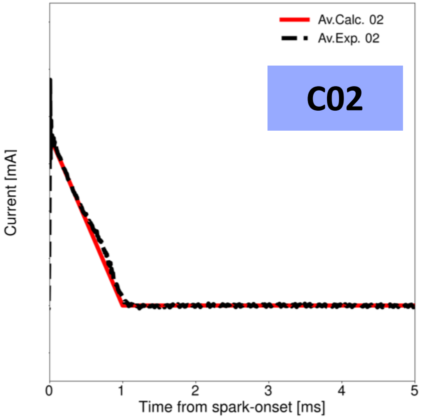
Lagrangian framework setup

- Breakdown Energy E_{bd} **estimated** according to the **initial Plasma Channel diameter** (thanks to available images).



- **Electrical circuit**: imposition of *the experimental average current trend* (over the available 200 cycles)

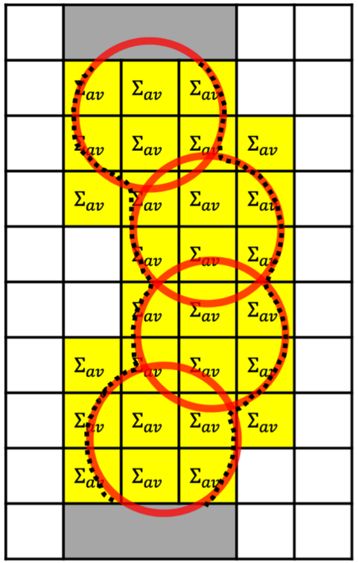




SI combustion modelling

Average cycle behavior in a RANS context: model setup

Lagrangian framework setup



➢ Evolution of each generated channel:

Until $d_{channel} < 2.5\ mm$ ⇒ **Laminar-only flame** (no Σ evolution)

$2.5 \leq d_{channel} < 5\ mm$ ⇒ **Laminar** (Lagrangian) **+ Turbulent** (Eulerian) **flame**

When $d_{channel} = 5\ mm$ ⇒ **Channel removal** (only turbulent Eulerian flame)

SI combustion modelling

Average cycle behavior in a RANS context: model setup

Eulerian framework setup

- Σ transport equation of the Coherent Flame Model (**CFM**) by *Choi and Huh*

$$\frac{\partial \rho \bar{\Sigma}}{\partial t} + \frac{\partial \rho \tilde{u}_i \bar{\Sigma}}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\frac{\mu}{Sc} + \frac{\mu_t}{Sc_t}\right)\frac{\partial \bar{\Sigma}}{\partial x_i}\right] + \rho P_{FSD}\bar{\Sigma} - \rho D_{FSD} + P_{Lagr}$$

Σ production

Σ destruction

Lagrangian coupling

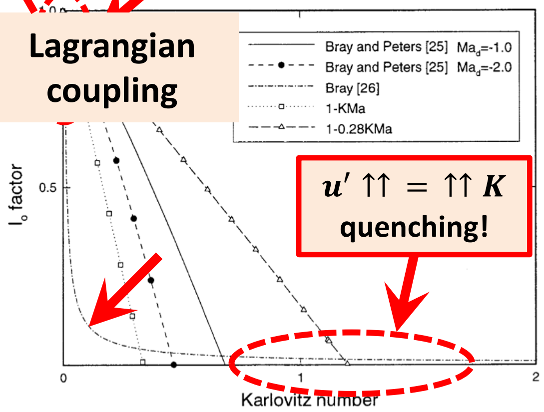
I_0 limited to 1 because $\approx$ laminar flames

$u' \downarrow\downarrow = K \downarrow\downarrow$
I_0 not defined!

- I_0 from *Bray correlation* with Choi-Huh Karlovitz number approximation

$$I_0 = \frac{0.117}{1+\tau} K^{-0.784}$$

$$K = \frac{\delta_l}{S_{l,0}}\left(\frac{1}{A}\frac{dA}{dt}\right) \propto \left(\frac{u'}{S_{l,0}}\right)^2 R_L^{-0.5}$$



$u' \uparrow\uparrow = \uparrow\uparrow K$
quenching!

The quenching effects generated by a **strong u' level** are considered on the flame front evolution by Bray model

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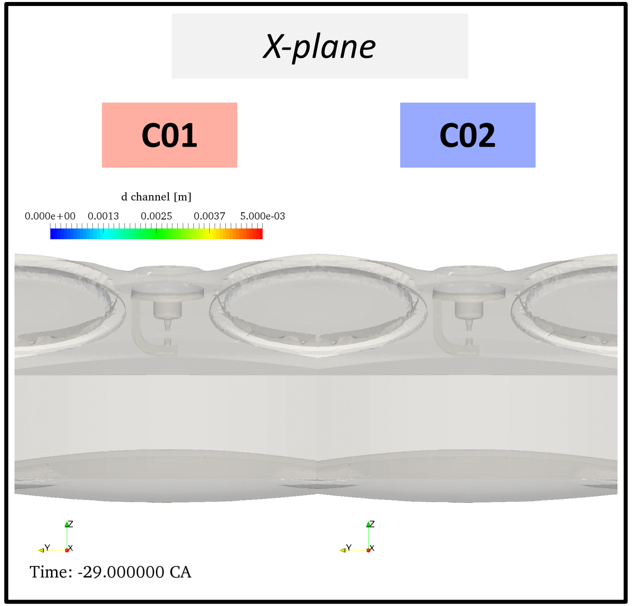
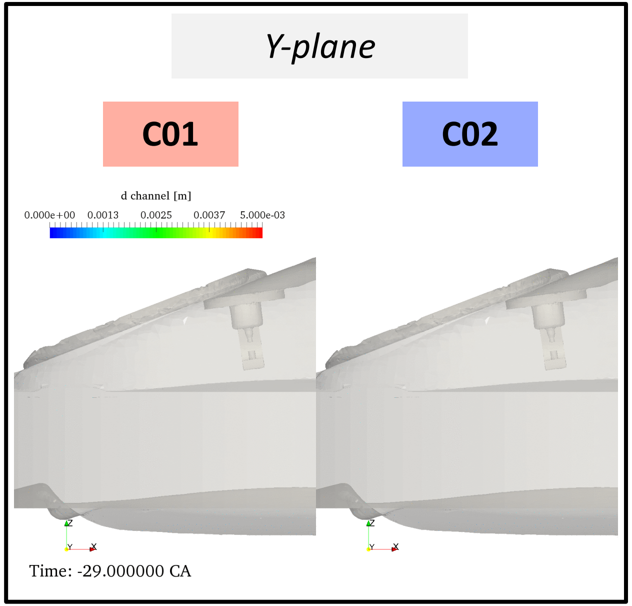
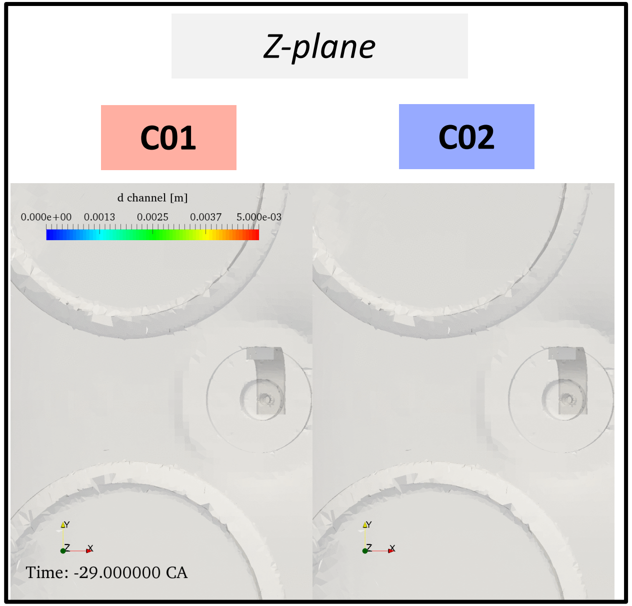
SI combustion modelling

Average cycle behavior in a RANS context: results – ignition process







Electrical arc + Flame iso-surface
@ $c = 0.2$

C02 combustion is **delayed with respect to C01**

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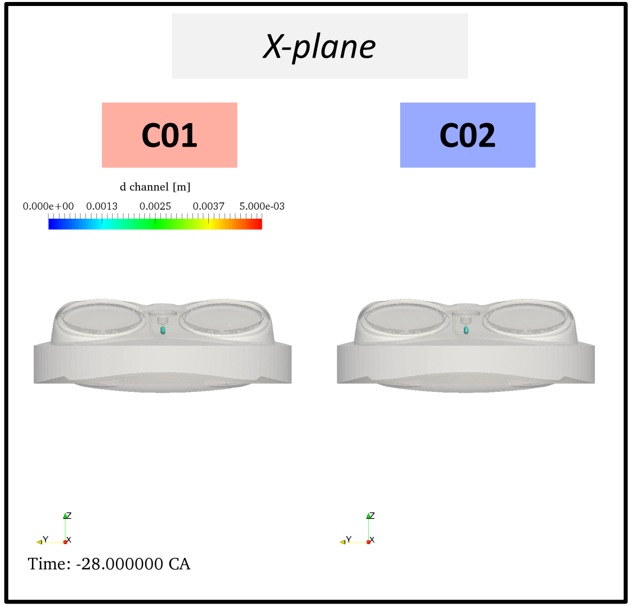
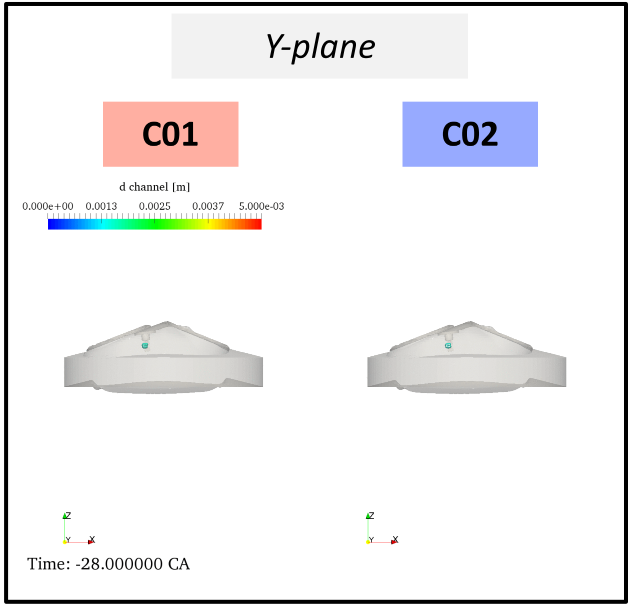
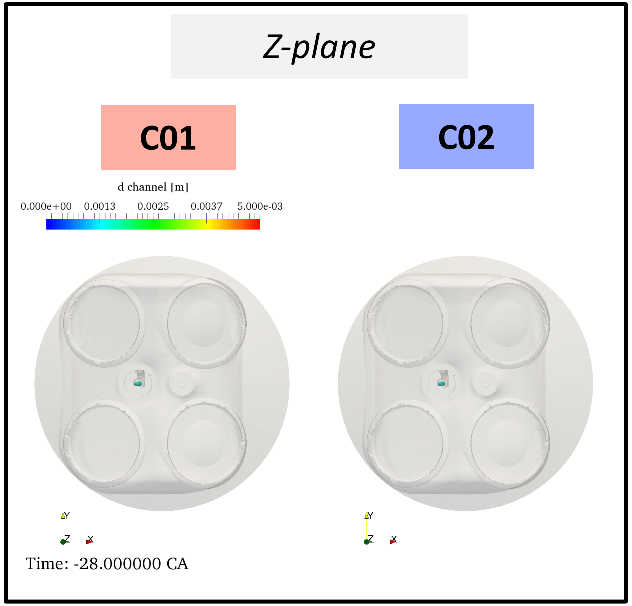
SI combustion modelling

Average cycle behavior in a RANS context: results – complete combustion







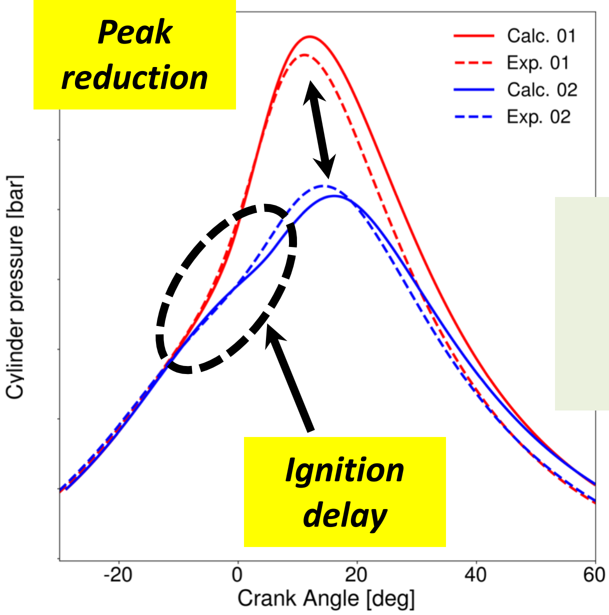
Electrical arc + Flame iso-surface
@ $c = 0.2$

C02 combustion is **delayed with respect to C01**

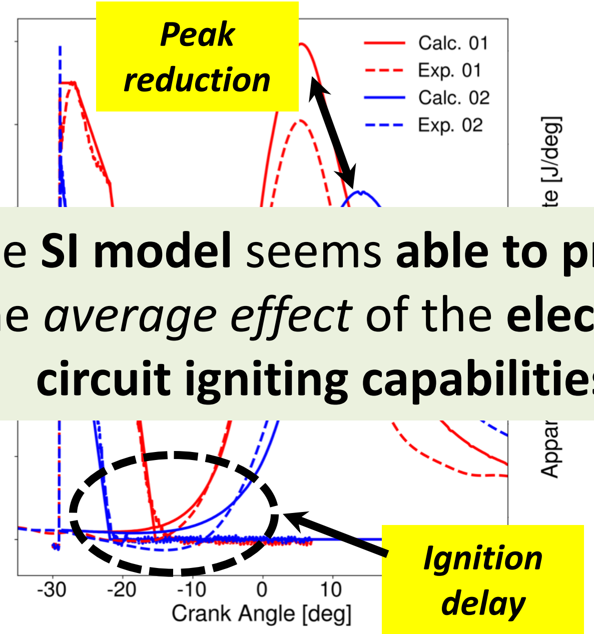
SI combustion modelling

Average cycle behavior in a RANS context: results

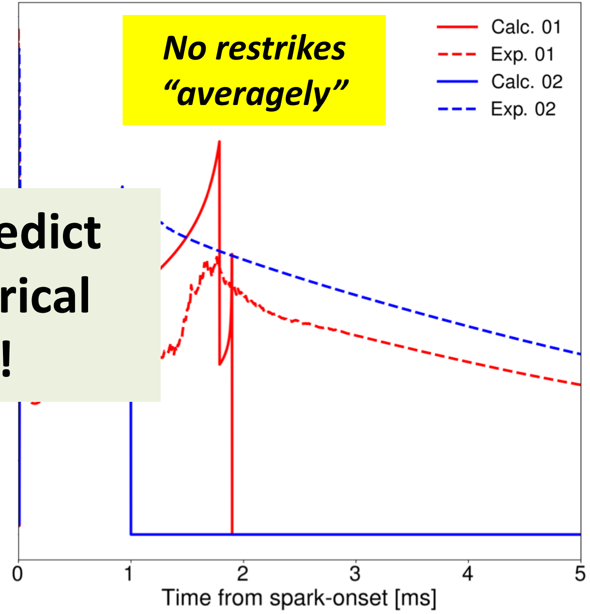
Pressure



AHRR and Current



Voltage



The **SI model** seems **able to predict** the *average effect* of the **electrical circuit igniting capabilities!**

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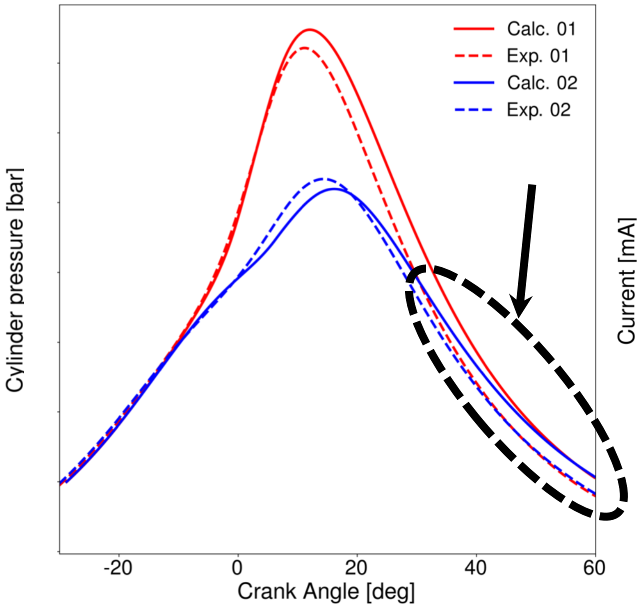
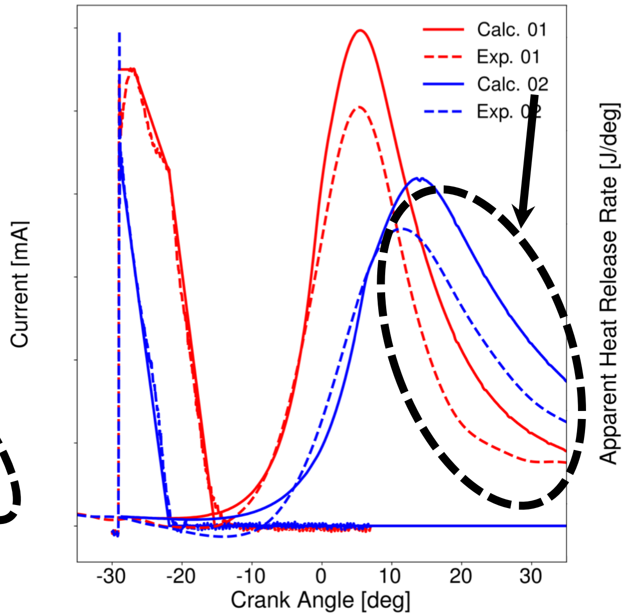
SI combustion modelling

Average cycle behavior in a RANS context: results

Pressure



AHRR and **Current**



End of combustion process

Numerical P and $AHRR$ ↑ than experimental ones

⇩

<u>Possible explanation</u>

Lack of crevices in the CFD domain

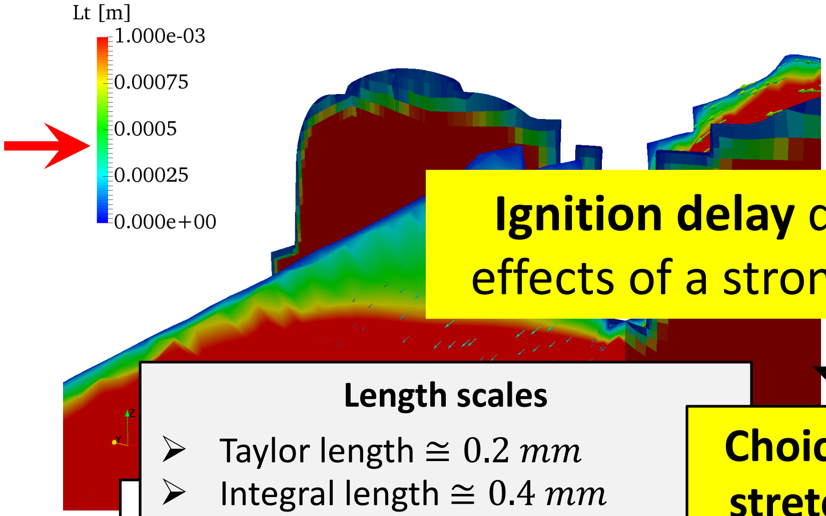
↓

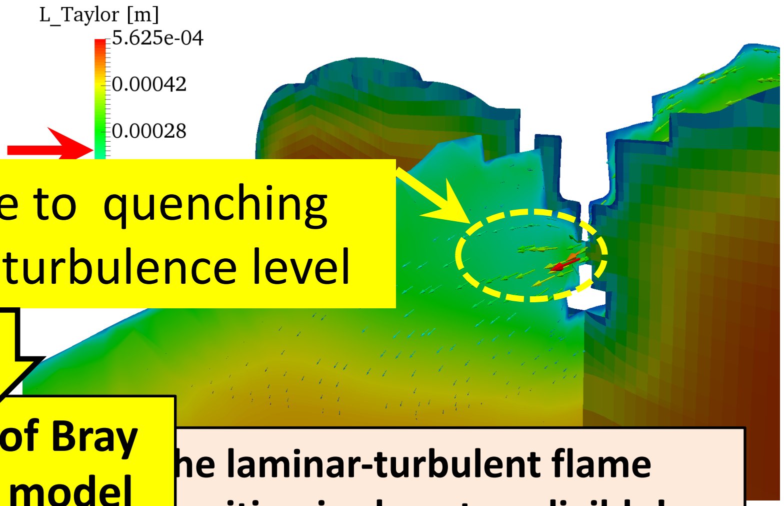
Flame burns completely the mixture when it approaches the engine walls (↑ $AHRR$)

SI combustion modelling

Average cycle behavior in a RANS context: results

Case 02 - *Classical coil*





Ignition delay due to quenching effects of a strong turbulence level

Length scales

- Taylor length $\cong 0.2\ mm$
- Integral length $\cong 0.4\ mm$
- **Channel radius** $\cong \mathbf{0.6\ mm}$

Choice of Bray stretch model

he laminar-turbulent flame ansition is almost negligible!

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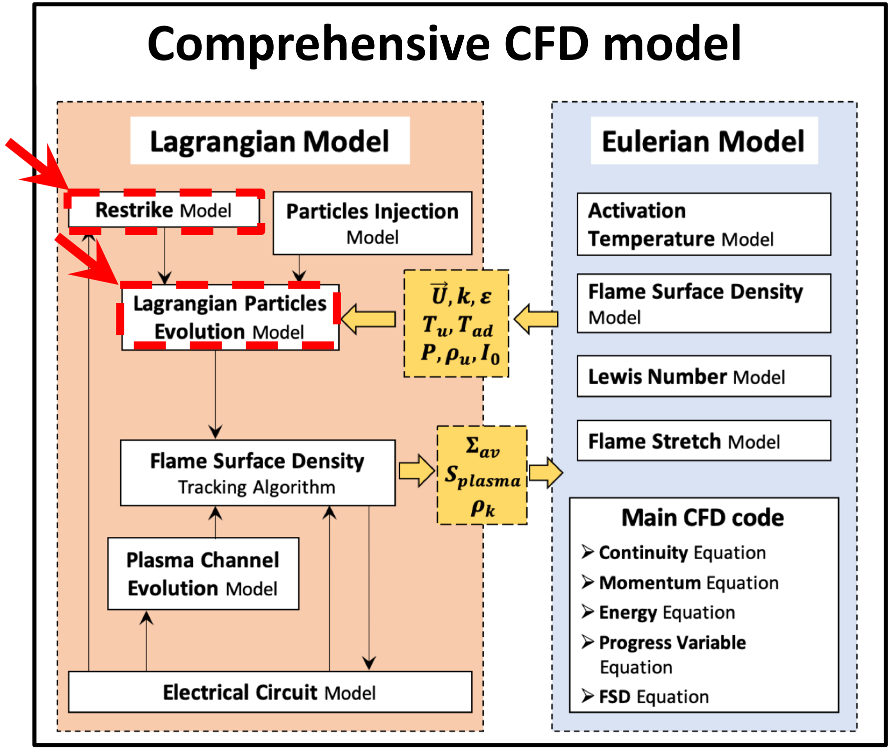
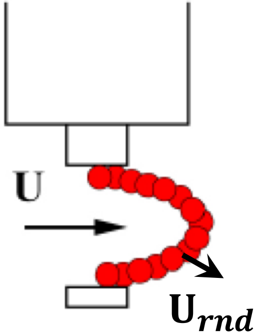
SI combustion modelling

First attempts to predict CCV in a RANS context: *model setup*



Model novelties

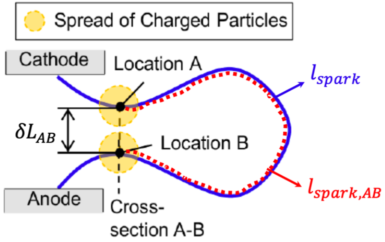


1) **"Near-DNS" Lagrangian channel evolution** starting from **RANS Eulerian fields**:

a) Initial random perturbation to $\vec{U}_{channel}$

b) Further particles evolution according to **Langevin model**

2) **Short circuit restrike modelling**



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SI combustion modelling

First attempts to predict CCV in a RANS context: *model setup*

Near-DNS Lagrangian channel evolution starting from **RANS Eulerian fields**

Target: predicting the CCV caused by the spark discharge

Approach:

a) At each discharge, an **initial perturbation** is applied **to channel particles velocity** (according to the u' features) to simulate a random variation of the velocity field with respect to average conditions

Perturbation = vector whose components are:

- Stochastic variables with a Gaussian distribution of 0 mean and u' standard deviation (because isotropic turbulence)
- Stochastically independent
- Features of perturbation:
  - a) **Same random vector for all particles** at same discharge event (hence **same direction** for all particles), to "simulate" a zero-divergence perturbation
  - b) **Standard deviation** equal to the **average u' of the particle**

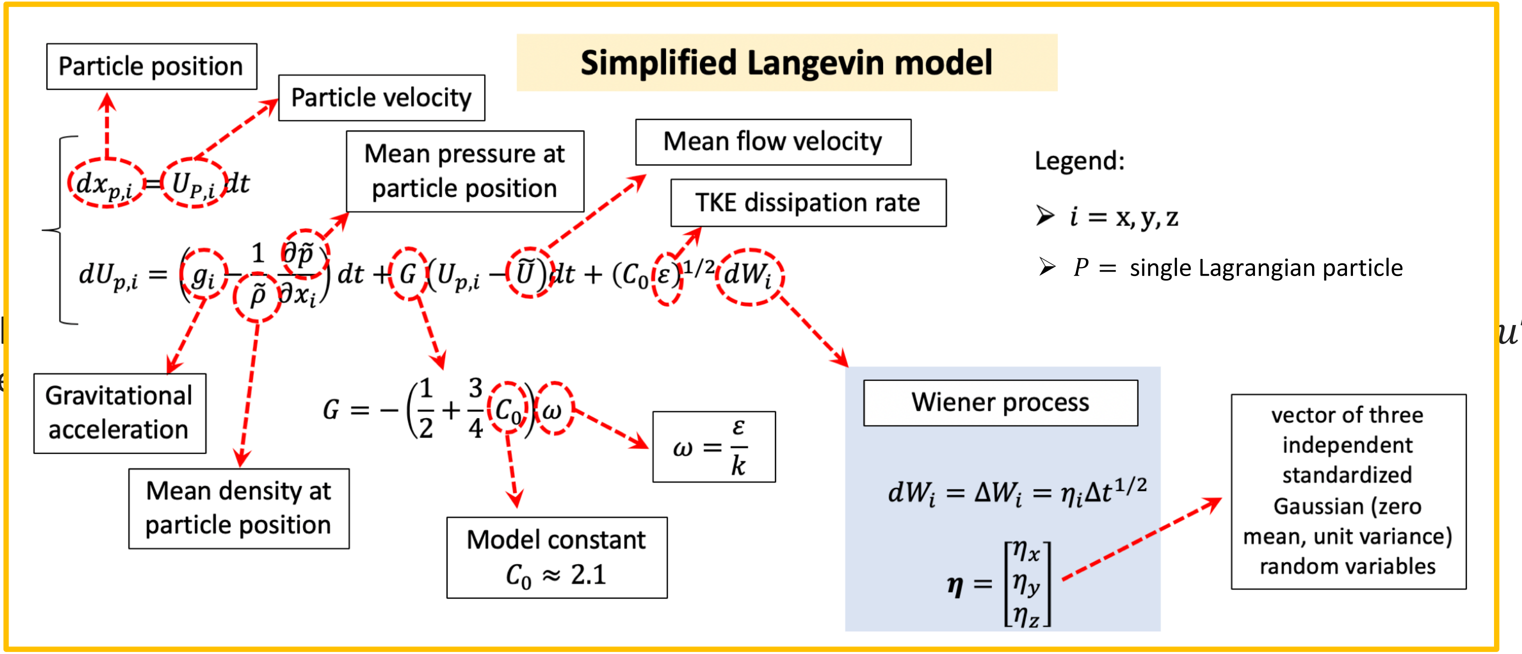
SI combustion modelling

First attempts to predict CCV in a RANS context: *model setup*

Near-DNS

Approach:

a) At eac … u'
feature



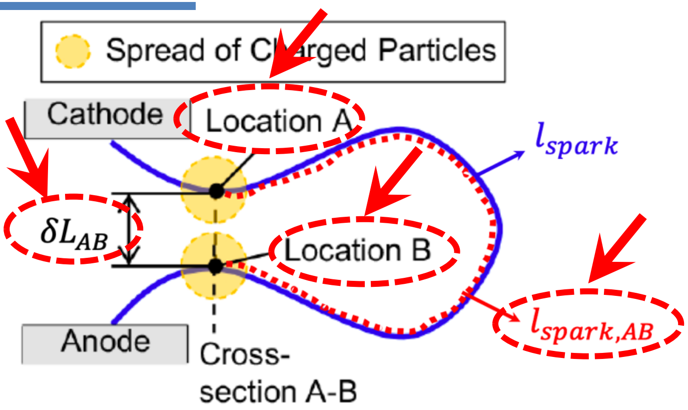
b) Then, **particle velocity evolves according to Simplified Langevin model**: the Wiener process features are added to the "old" velocity. Hence, the channel keeps memory of the initial perturbation.

SI combustion modelling

First attempts to predict CCV in a RANS context: *model setup*

Short circuit restrike modelling

Target: predicting “near-DNS” channel shortenings



Approach:

a) Two arbitrary positions ***A* and *B*** are **defined** along the plasma channel

b) The gas-column voltage fall, representing the **electrical resistance produced by the gas column**, is computed **between** positions **A and B** as:

$$V_{gc,AB}(t) = a_{gc} \frac{l_{spark,AB}(t)\, p^{c_{gc}}}{i_S^{b_{gc}}(t)}$$

c) The breakdown voltage fall, representing the **electrical resistance produced by the surrounding mixture**, is computed **between** positions **A and B** as:

$$V_{bd,AB}(t) = a + b\,\frac{p}{T_u} + c\,\frac{p}{T_u}\left(\delta L_{AB}(t)\right)^{n_1}$$

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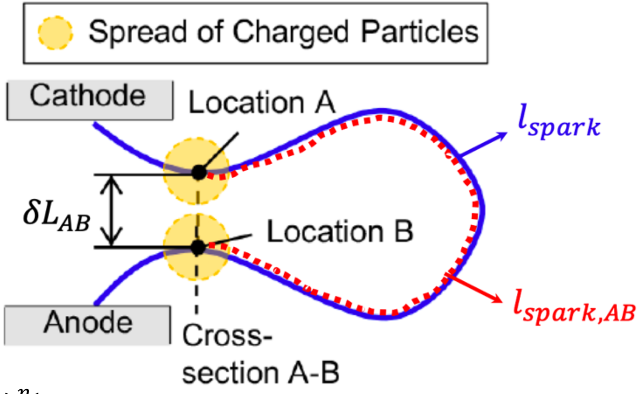
SI combustion modelling

First attempts to predict CCV in a RANS context: *model setup*

Short circuit restrike modelling

Target: predicting "near-DNS" channel shortenings



Approach:

d) At each time t value is checked:

$$a_{gc}\,\frac{l_{spark,AB}(t)\,p^{c_{gc}}}{i_S^{b_{gc}}(t)} \leftarrow V_{gc,AB}(t) > V_{bd,AB}(t) \rightarrow a + b\,\frac{p}{T_u} + c\,\frac{p}{T_u}\,\left(\delta L_{AB}(t)\right)^{n_1}$$

TRUE

Short circuit restrike!

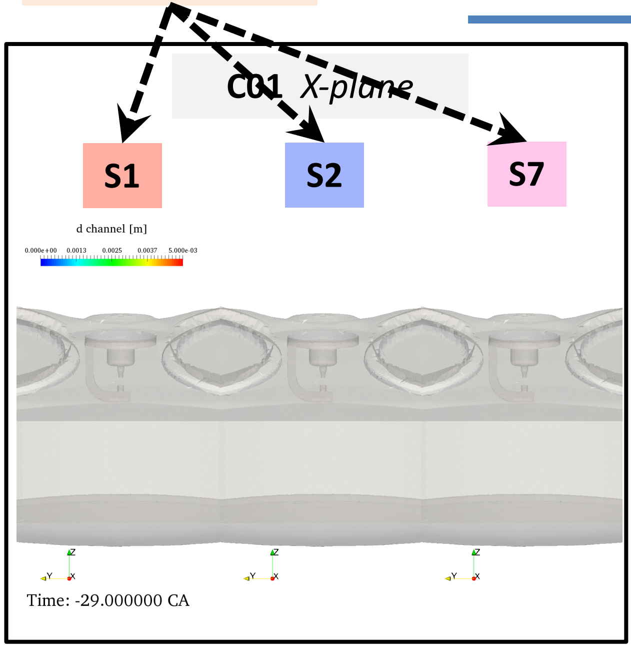
FALSE

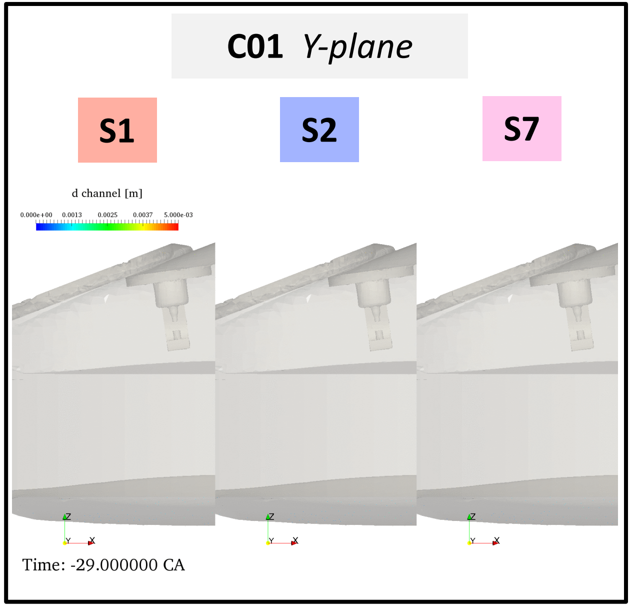
The existing arc is kept and evolved

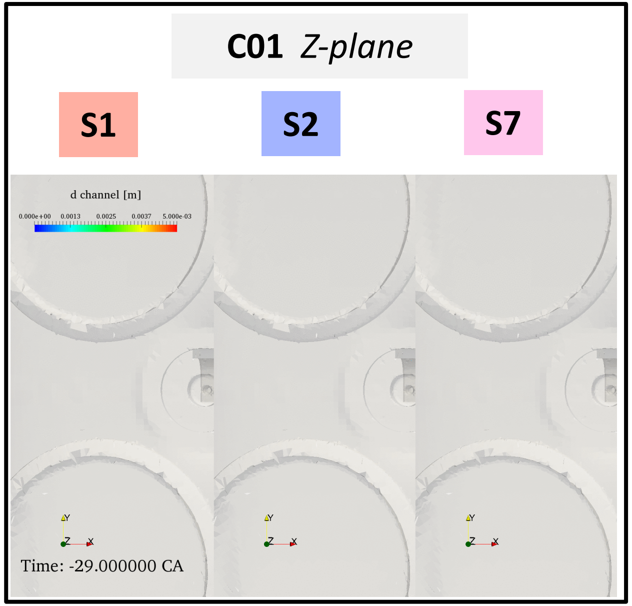
SI combustion modelling

First attempts to predict CCV in a RANS context: *results*

3 different $\vec{U}_{channel}$ perturbations





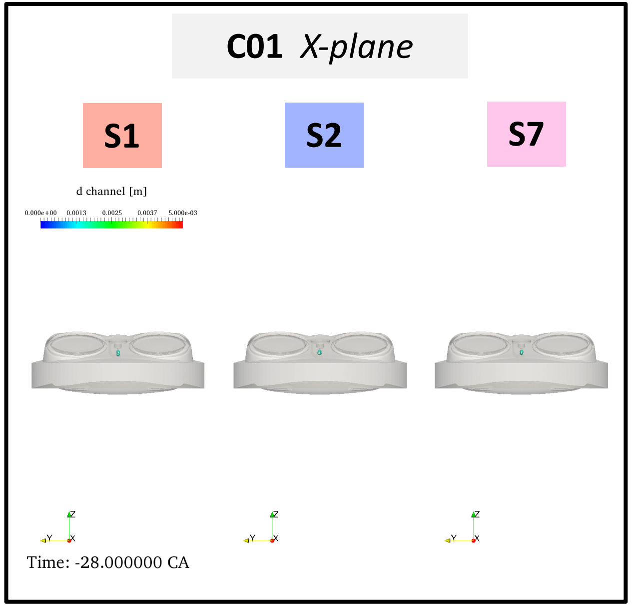


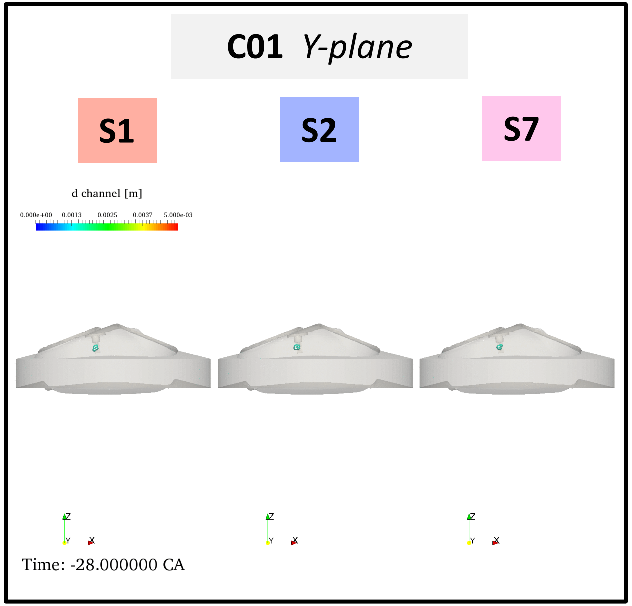
Electrical arc + Flame iso-surface @ $c = 0.2$

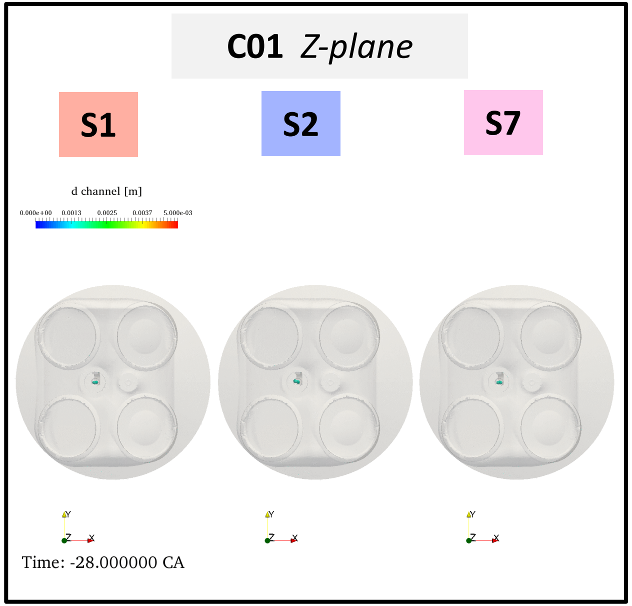
Each generated channel has a **unique behavior**, kept consistent with the average flow features

SI combustion modelling

First attempts to predict CCV in a RANS context: *results*







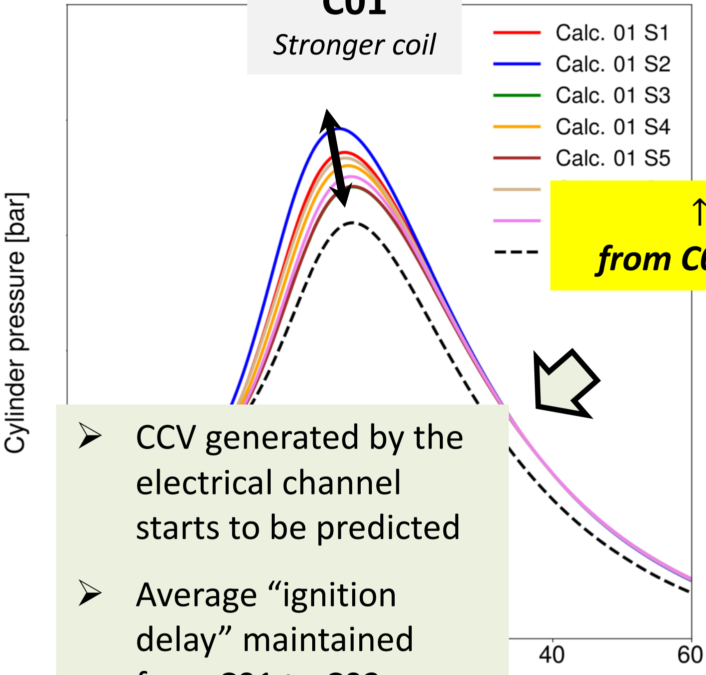
Electrical arc + Flame iso-surface $@\ c = 0.2$

The evolution of **each channel** influences the further **combustion development**

SI combustion modelling

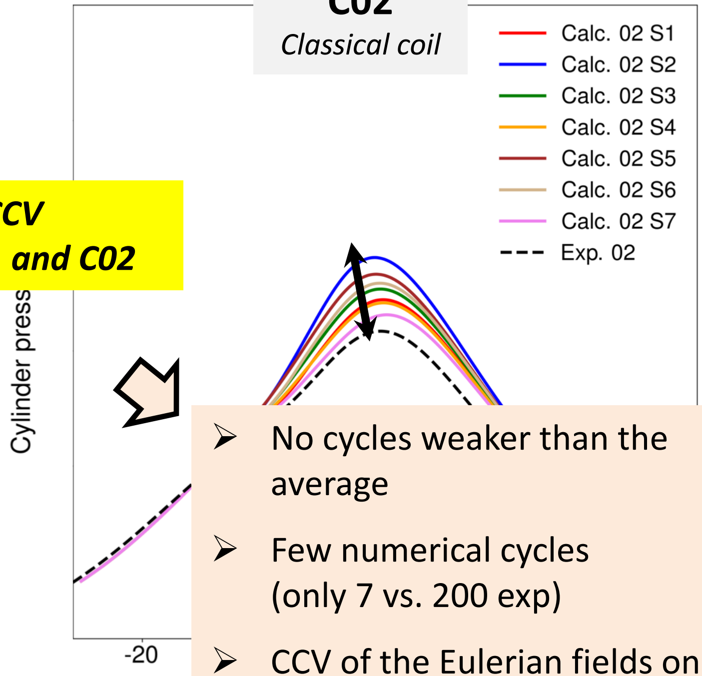
First attempts to predict CCV in a RANS context: *results*

C01
Stronger coil



↑ CCV
from C01 and C02

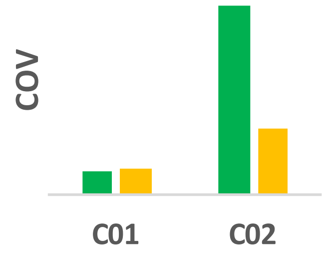
C02
Classical coil



- CCV generated by the electrical channel starts to be predicted
- Average "ignition delay" maintained from C01 to C02

- No cycles weaker than the average
- Few numerical cycles (only 7 vs. 200 exp)
- <u>CCV of the Eulerian fields on combustion not considered</u>

COV comparison



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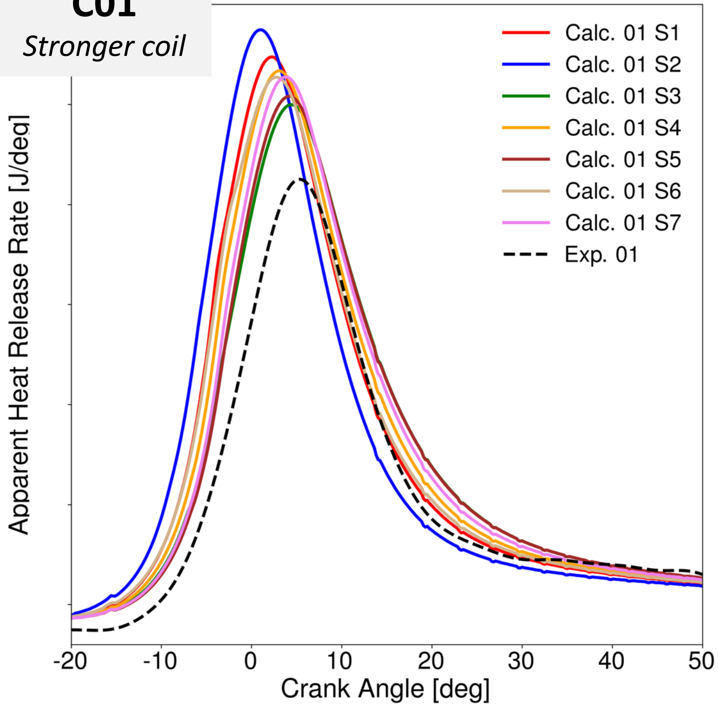
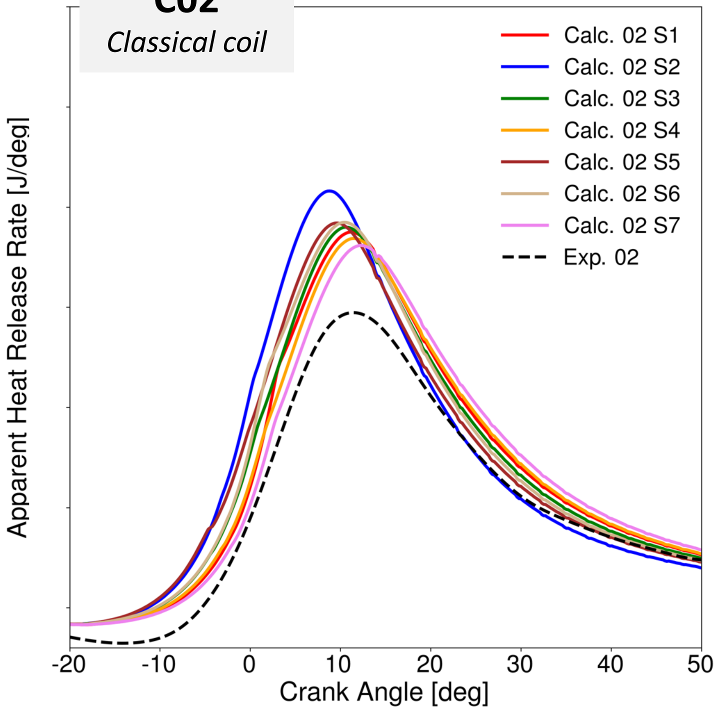
SI combustion modelling

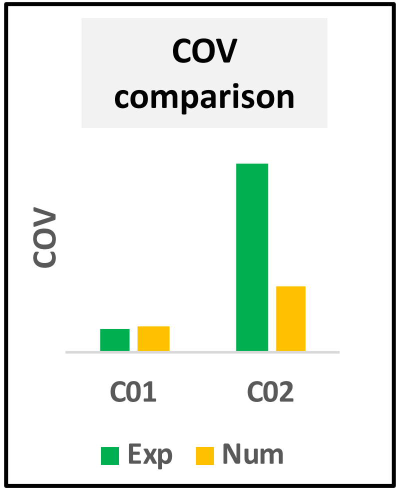
First attempts to predict CCV in a RANS context: *results*

C01
Stronger coil



C02
Classical coil

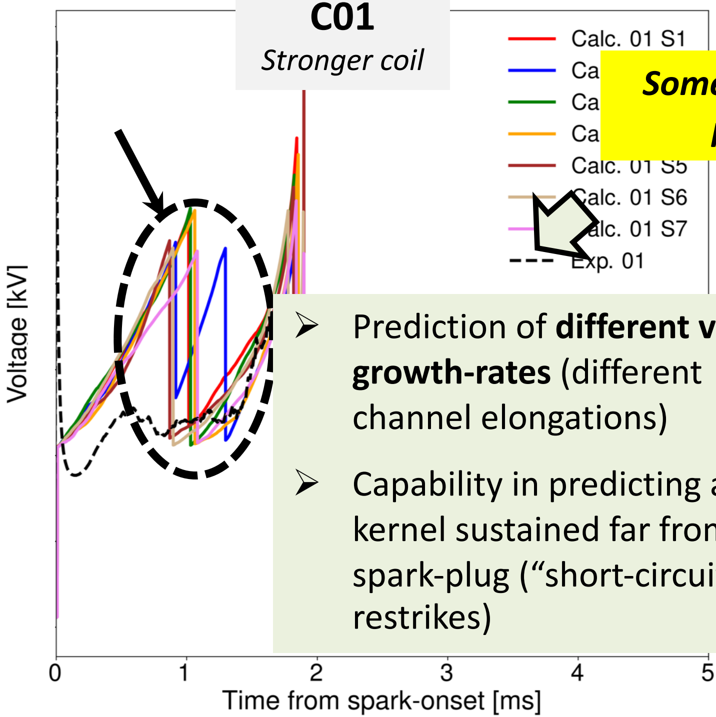




SI combustion modelling

First attempts to predict CCV in a RANS context: *results*

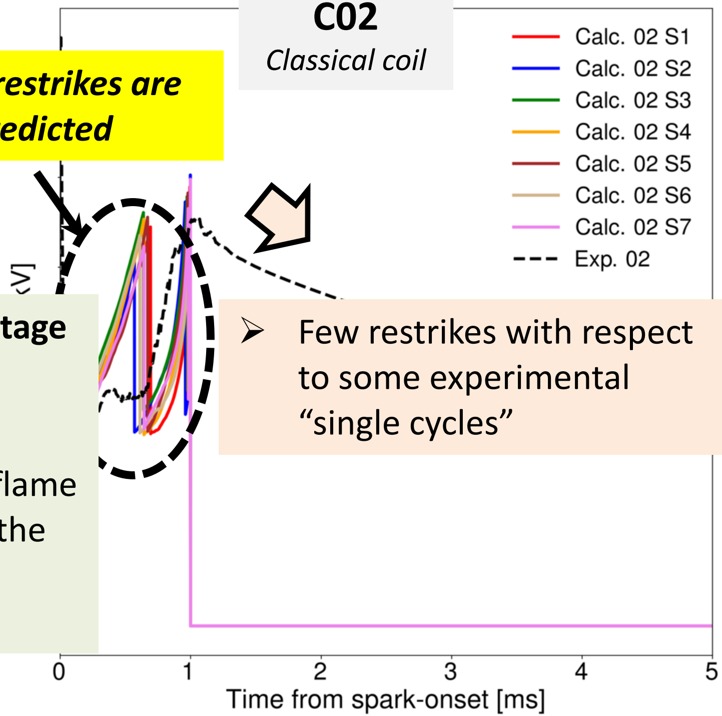
C01
Stronger coil



Some restrikes are predicted

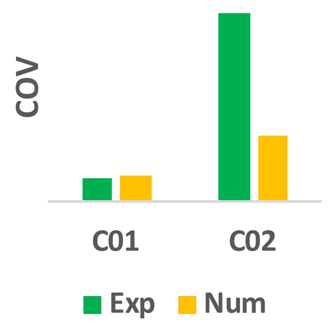
- Prediction of **different voltage growth-rates** (different channel elongations)
- Capability in predicting a flame kernel sustained far from the spark-plug ("short-circuit" restrikes)

C02
Classical coil



- Few restrikes with respect to some experimental "single cycles"

COV comparison



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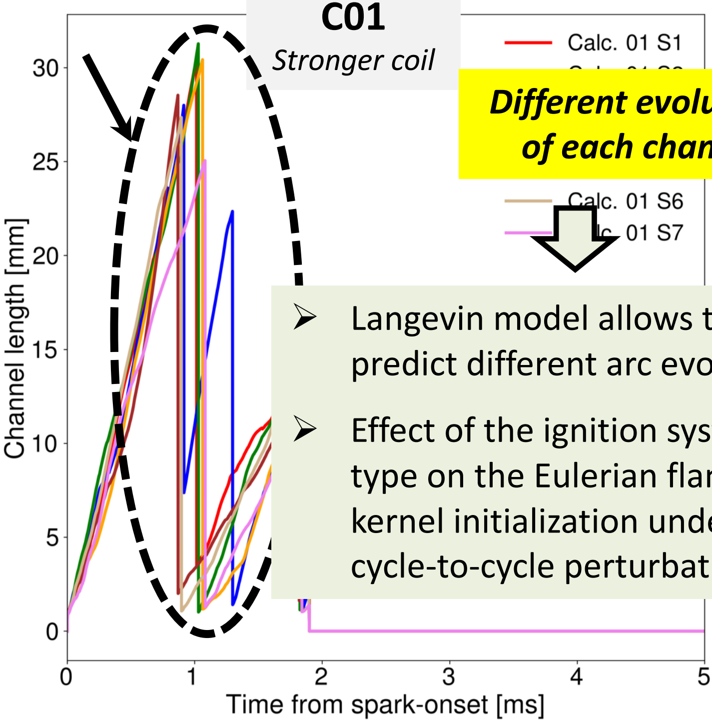
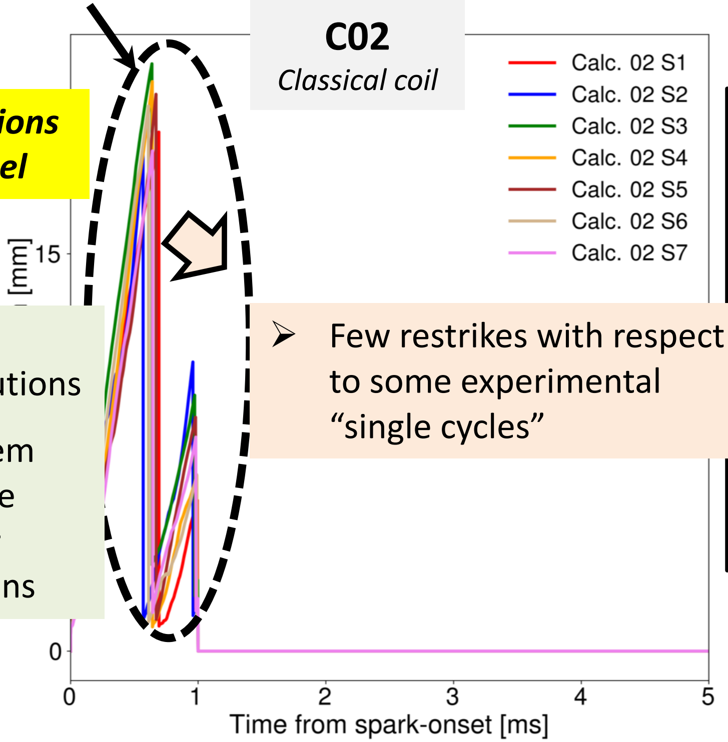
SI combustion modelling

First attempts to predict CCV in a RANS context: *results*

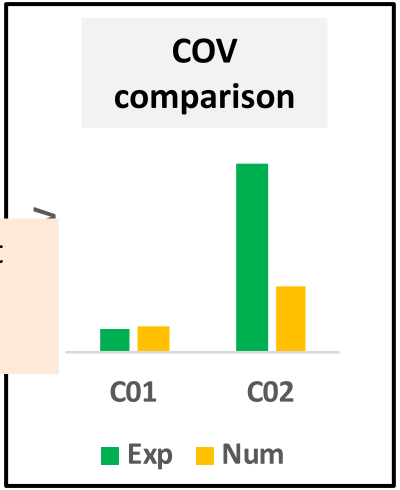


Different evolutions of each channel

- Langevin model allows to predict different arc evolutions
- Effect of the ignition system type on the Eulerian flame kernel initialization under cycle-to-cycle perturbations



- Few restrikes with respect to some experimental "single cycles"



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Conclusions

SI combustion engine modeling using the Open-FOAM® technology

- The **SI model** seems **able to predict** the *average effect* of the **electrical circuit igniting capabilities** of ultra lean fuel-air mixtures

- **Bray correlation for I_0** together with the $d_{channel}$ **threshold for turbulent combustion** seem fundamental to predict the stretch effects of a $\uparrow u'$ level on the early flame kernel development

- First attempts in **modelling the CCV caused by the ignition system** features with:

  a) a *RANS* approach for the Eulerian fields

  b) a "*near-DNS*" approach for the plasma channel evolution

  seem **promising**

Future developments

SI combustion engine modeling using the Open-FOAM® technology

- **Crevices addition to CFD domain**

Target: to improve the prediction of the final part of the average combustion process

- **Improve the calibration of “short-circuit” restrikes for predicting the channel-generated CCV**

Target: to better predict if the electrical circuit is able to sustain initial kernels far from the spark-plug or not (misfires, hence low pressure traces)

- **Simulation of more single cycles for predicting the channel-generated CCV**

Target: more statistically robust results

Thank you for your attention!

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Post-doc researcher

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