Visualization of In-Cylinder Combustion R&D

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October 30, 2008

USCAR Directors Meeting

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U.S. Department of Energy

UChicago Argonne LLC

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Purpose of Work

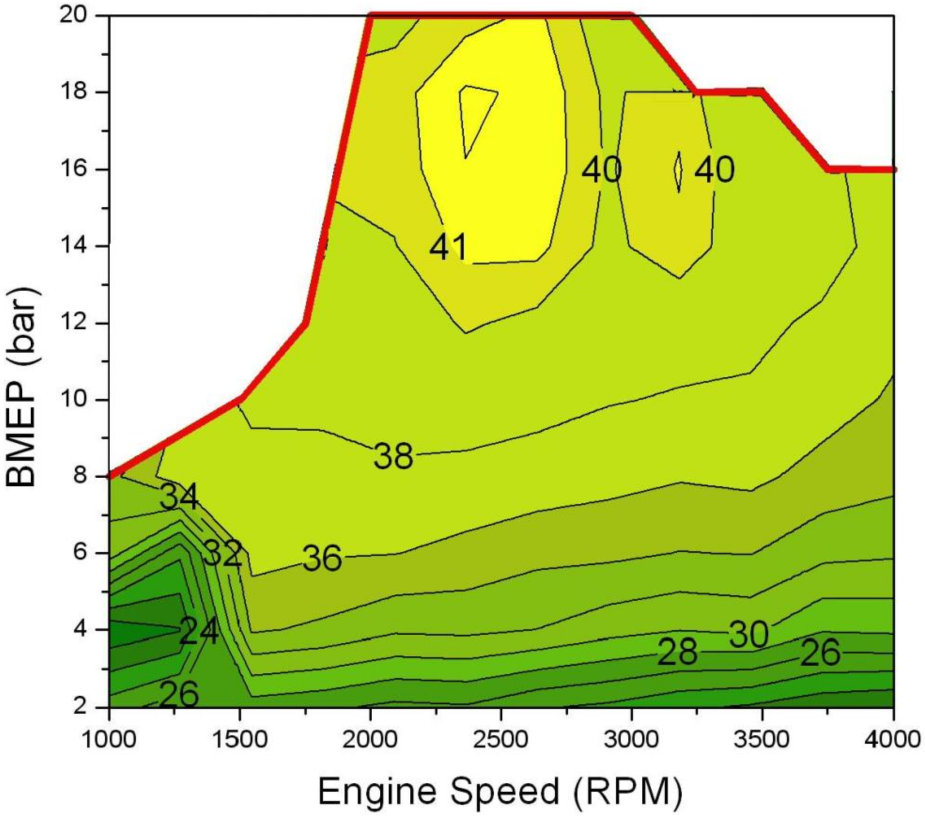
- Utilize in-cylinder combustion imaging to enable the implementation of low temperature combustion in a production automotive engine
- Integrate results with other national laboratories and industry
  - Using a common platform GM 1.9L TDI diesel engine
    - *SNL*
    - *UW-ERC*
    - *ORNL*
- Focus upon gasoline-like (low cetane) fuels
  - Opportunity to work with energy company using low octane (~60) fuel
- Maintain relatively high power densities (~10 bar BMEP) while retaining high efficiency and low emissions

Challenges to Automotive Powerplants

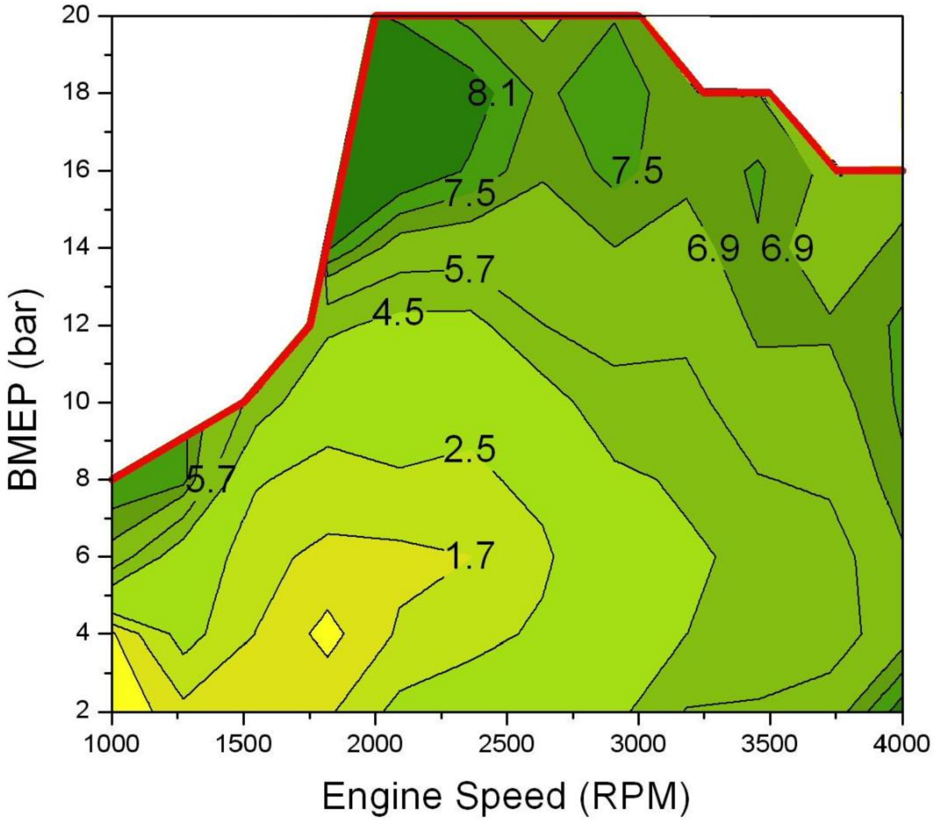
- Transportation powerplants need three characteristics for success
  - Power density
  - High efficiency
  - Low emissions
- “Low cost” not explicitly considered, but always in mind
- Most LTC concepts have been successful in generating high efficiency and low emissions – sacrificing power density (generally <5 bar BMEP)
  - MK, UNIBUS, etc
  - HCCI
  - HECC
- At 2.5 bar BMEP and 3000 RPM, a 1.9L engine produces 11.9 kW (15.9 bhp)
- Can a different trade-off be made that retains more power density?

BTE and NOx Performance of Argonne Engine

Brake Thermal Efficiency (%)



Brake Specific NOx (g/kW-hr)



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Specific Goals of this Project

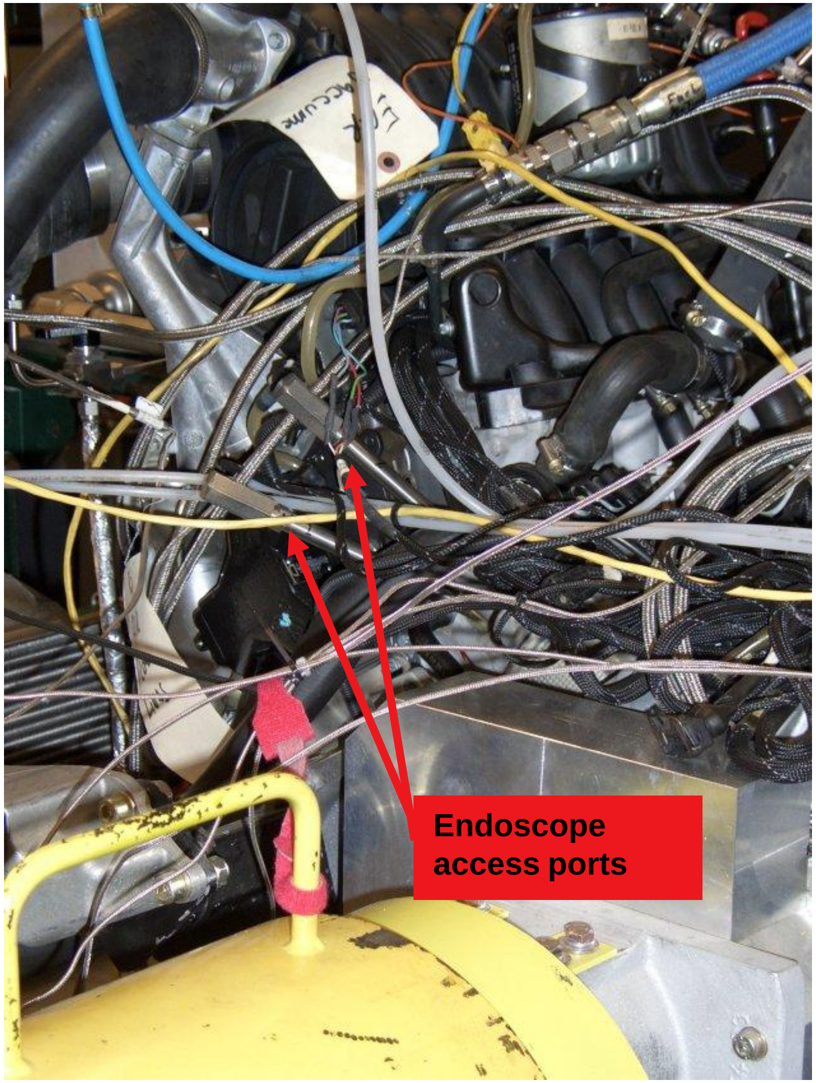
- Using a low cetane fuel, operate a modern automotive diesel engine whereby the ignition of the fuel occurs after the end of injection
  - Avoid diffusion flame and related soot/NOx problems
  - Avoid need of throttle to control power output
- Use advanced engine with great flexibility
  - High pressure diesel direct injection
  - Multiple injection per cycle capability
  - Variable EGR with advanced turbo
  - Swirl control
- Utilize advanced UV and visible light imaging to characterize combustion and operating regimes
  - Crank-angle resolution
  - Emission chemiluminescence for OH*, CH*
  - Absorption chemiluminescence for species concentration and combustion temperature
  - Soot radiation to detect any diffusion flame (if it exists)

Prior Argonne Work in This Area

- Hydrogen engine direct injection
  - Combustion imaging for OH*
  - OH* intensity related to NOx emissions
  - Combustion temperature using OH* spectroscopy
- Automotive diesel soot radiation imaging
  - 1999 version of Mercedes 1.7L TDI
  - SunDiesel comparison with standard diesel
  - Soot temperature and soot concentration with 2-color pyrometry
- 2-D imaging, combined with traditional performance and emissions measurements, provides a powerful tool to evaluate technologies

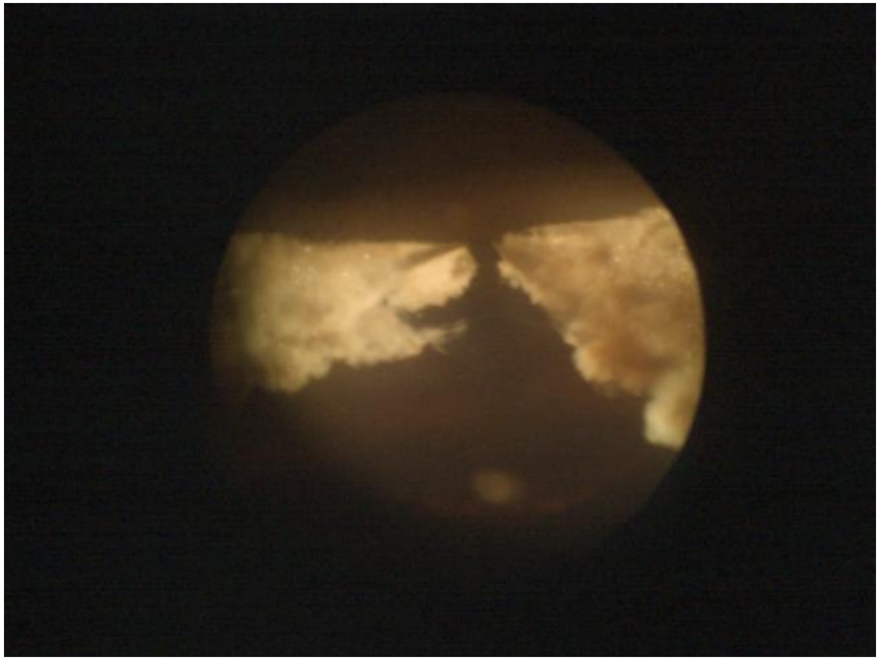
VisioScope™ used to study combustion of SunDiesel™ in a 4-cylinder, LD engine.

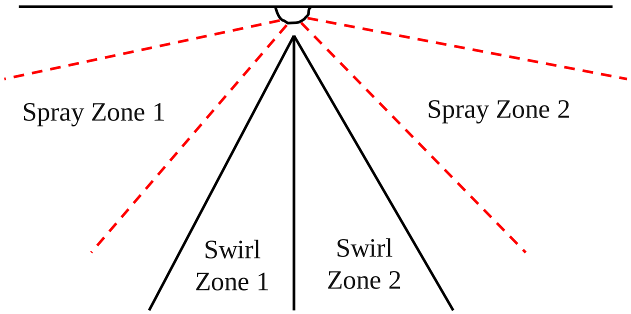
- Slight modification to engine provides access.
- Engine can be operated full speed/full load – all conditions.
  - 4000 RPM, 100% Load
- Other tools can be used simultaneously.
  - Emissions measurements
  - Pressure measurements
- Illumination capability is available (2nd access port).
  - Spray/mixture formation in pre-combustion phase
  - Part of next experiment matrix



Images obtained at 2500 RPM and 50% load.

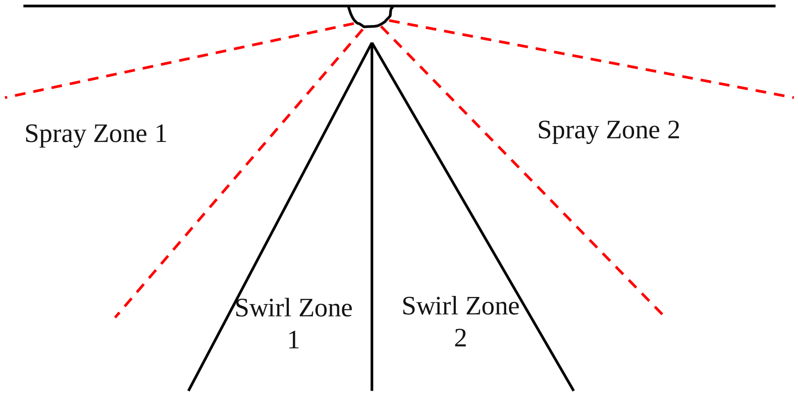
- Automotive “cruise” point
- Consistent test conditions
  - 705 bar injection pressure
  - 26.16 µs injection duration
  - Injection timing set at 3, 6, 9, and 12 deg BTDC
  - Allow load to “float” with timing change or fuel change
- Example of optical access shown
- Injector rotated to maintain window cleanliness



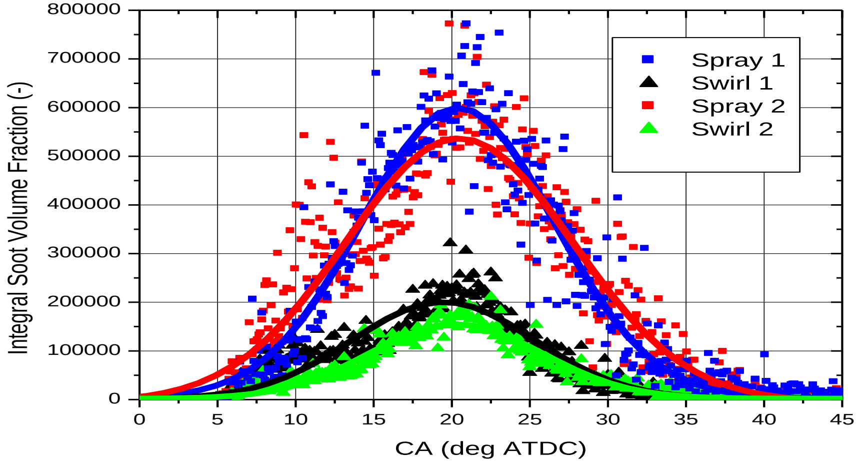


Digital image analysis sheds light upon soot mechanisms.

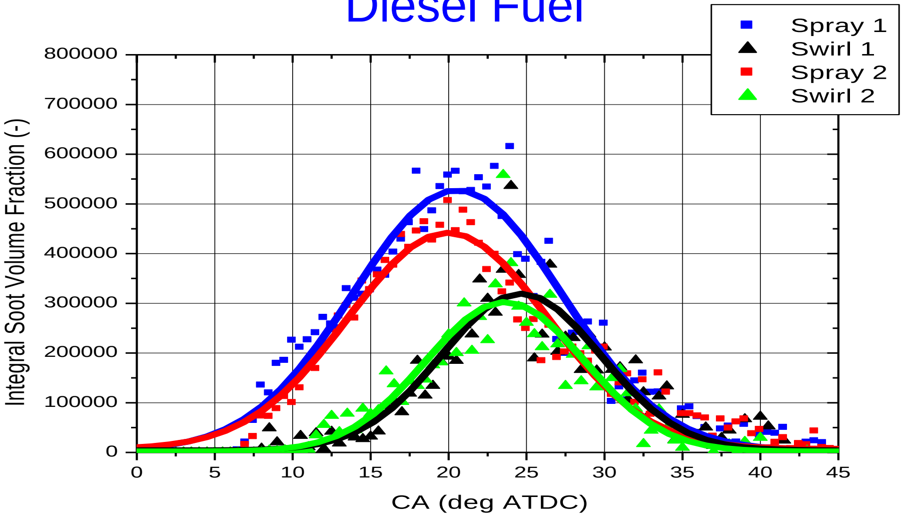
- 2-D details from imaging show where soot is formed/oxidized.
- Soot formation is actually higher for SunDiesel™ .
- Soot oxidation is more rapid for SunDiesel™ .
  - Different soot characteristics
    - *Low sulfur, low aromatic*
- ***Chemistry mechanisms and fluid mechanics are important for overall soot reduction!***



SunDiesel™



Diesel Fuel



Hydrogen engine application of UV optics

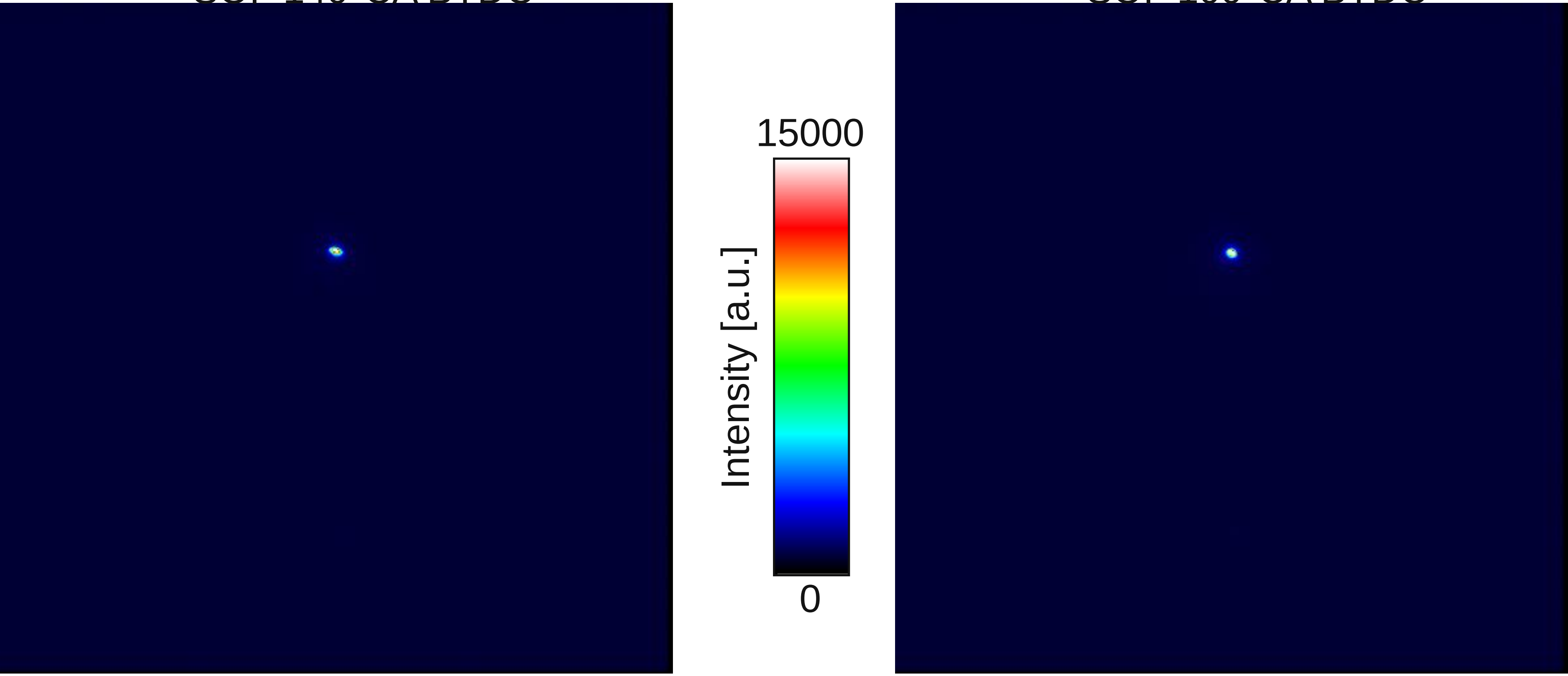
DI case comparing early injection (quasi-PFI) to later injection at global Φ=1.0

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC

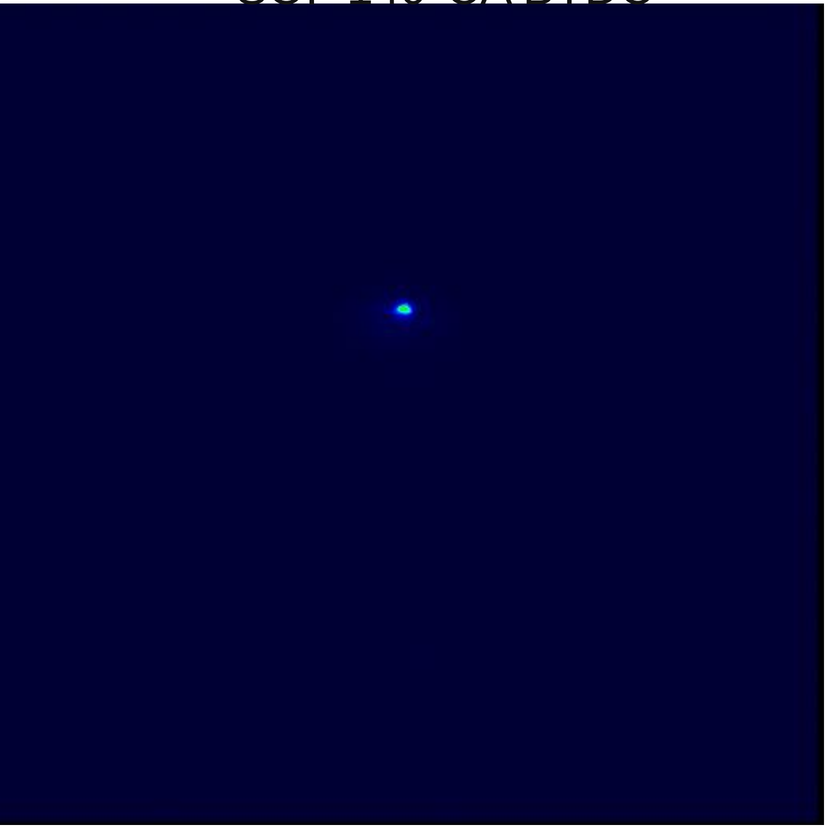


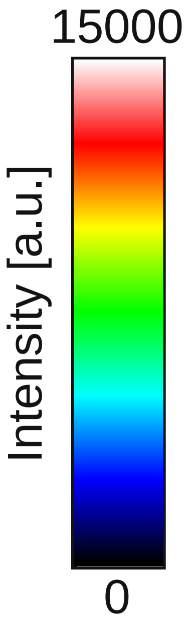
5°CA ATDC

2000 RPM Wide Open Throttle Φ=1

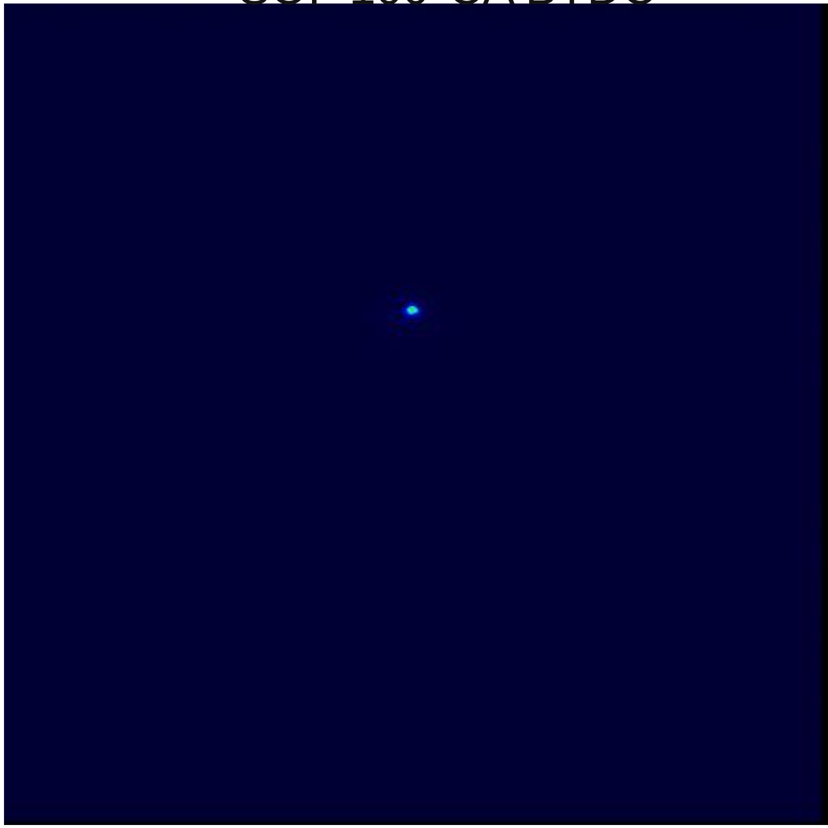
(Spark timing=5°CA ATDC)

SOI=140°CA BTDC





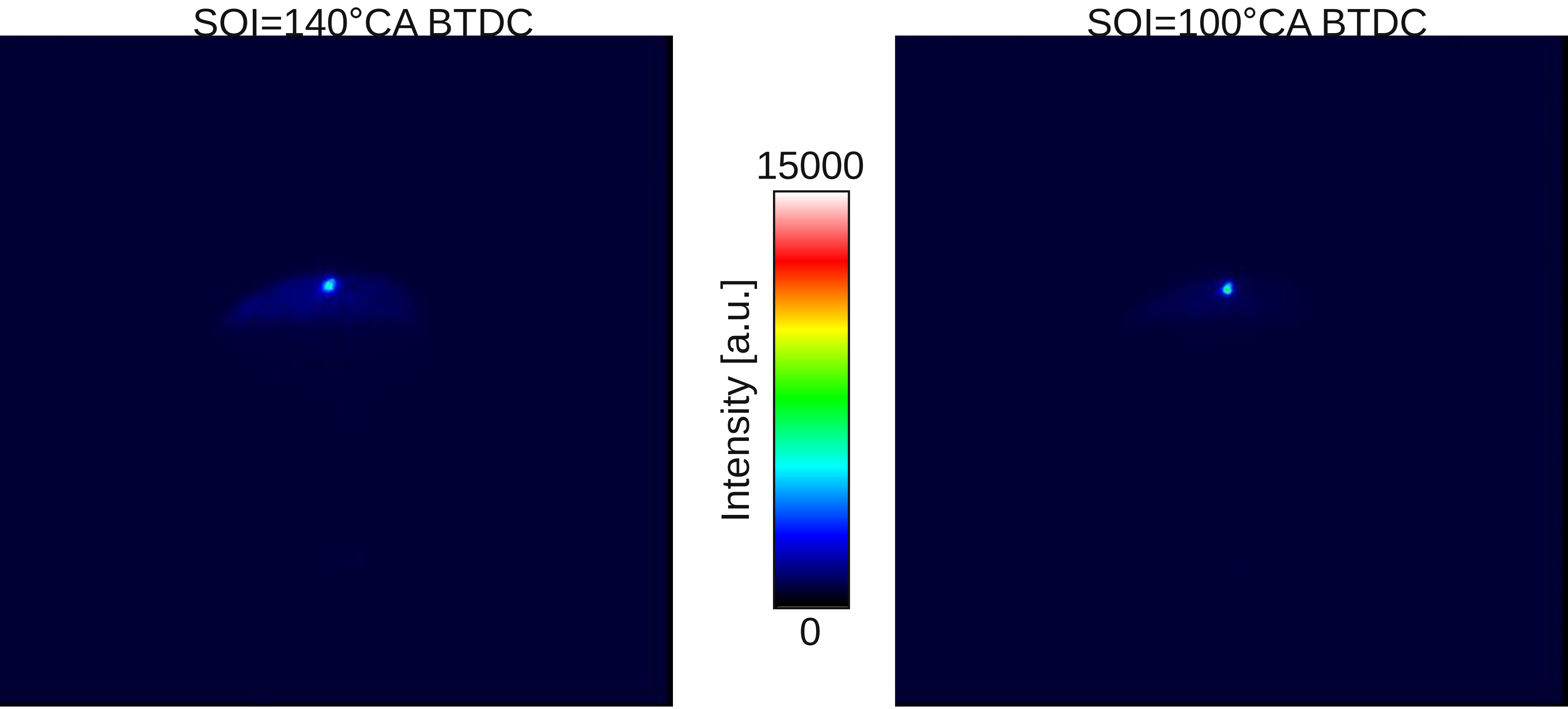
SOI=100°CA BTDC



7°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

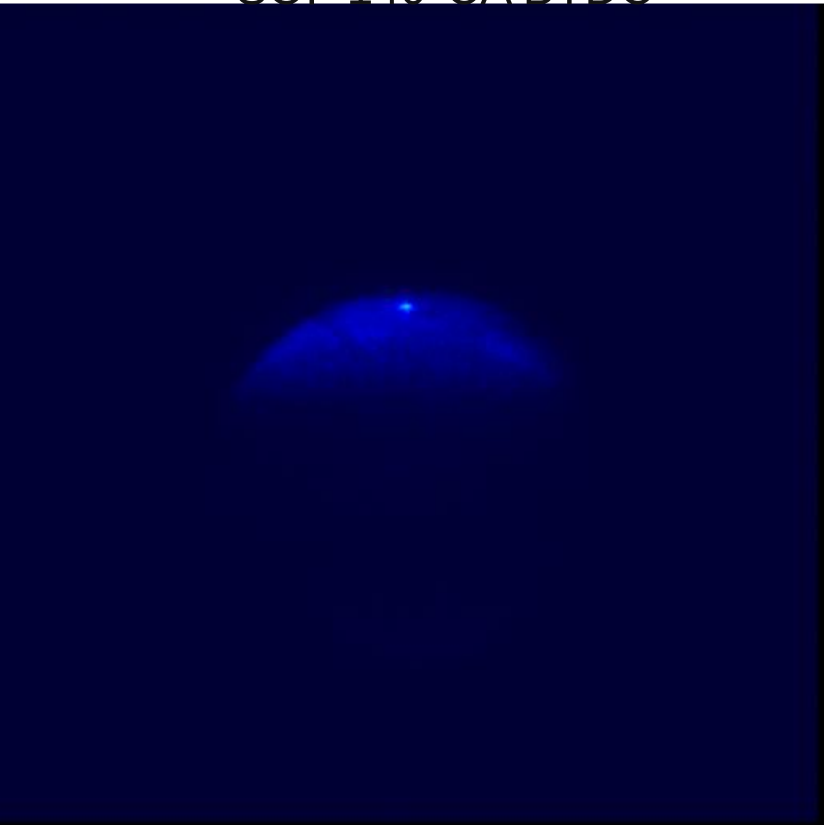


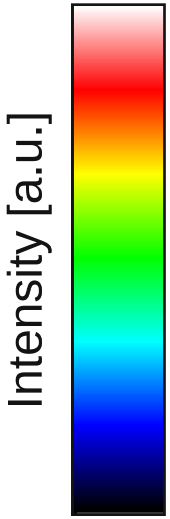
9°CA ATDC

2000 RPM Wide Open Throttle Φ=1

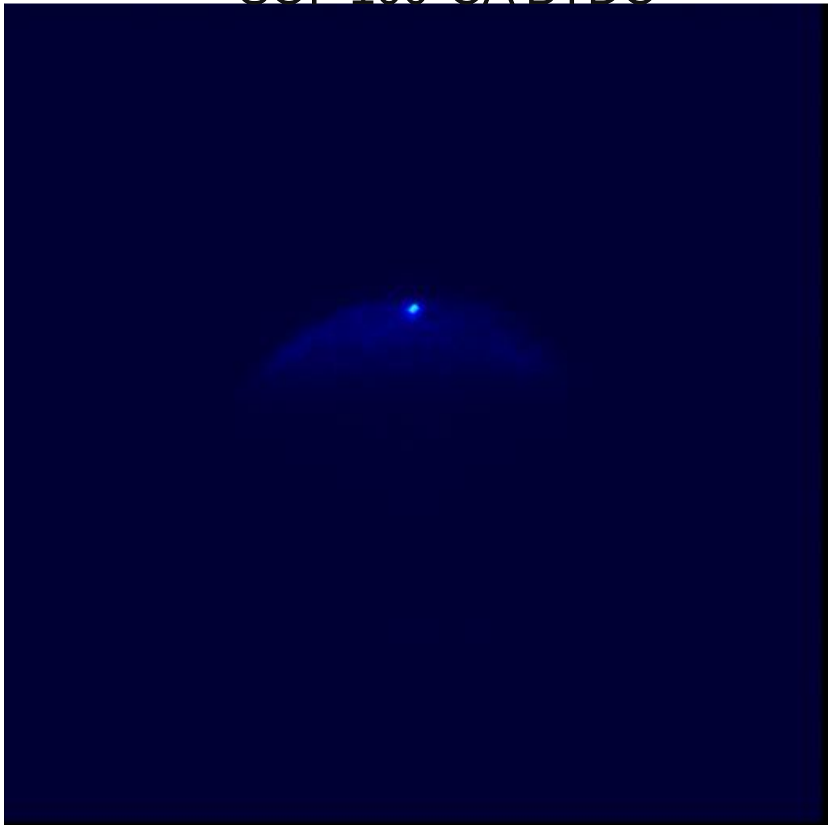
(Spark timing=5°CA ATDC)

SOI=140°CA BTDC





SOI=100°CA BTDC



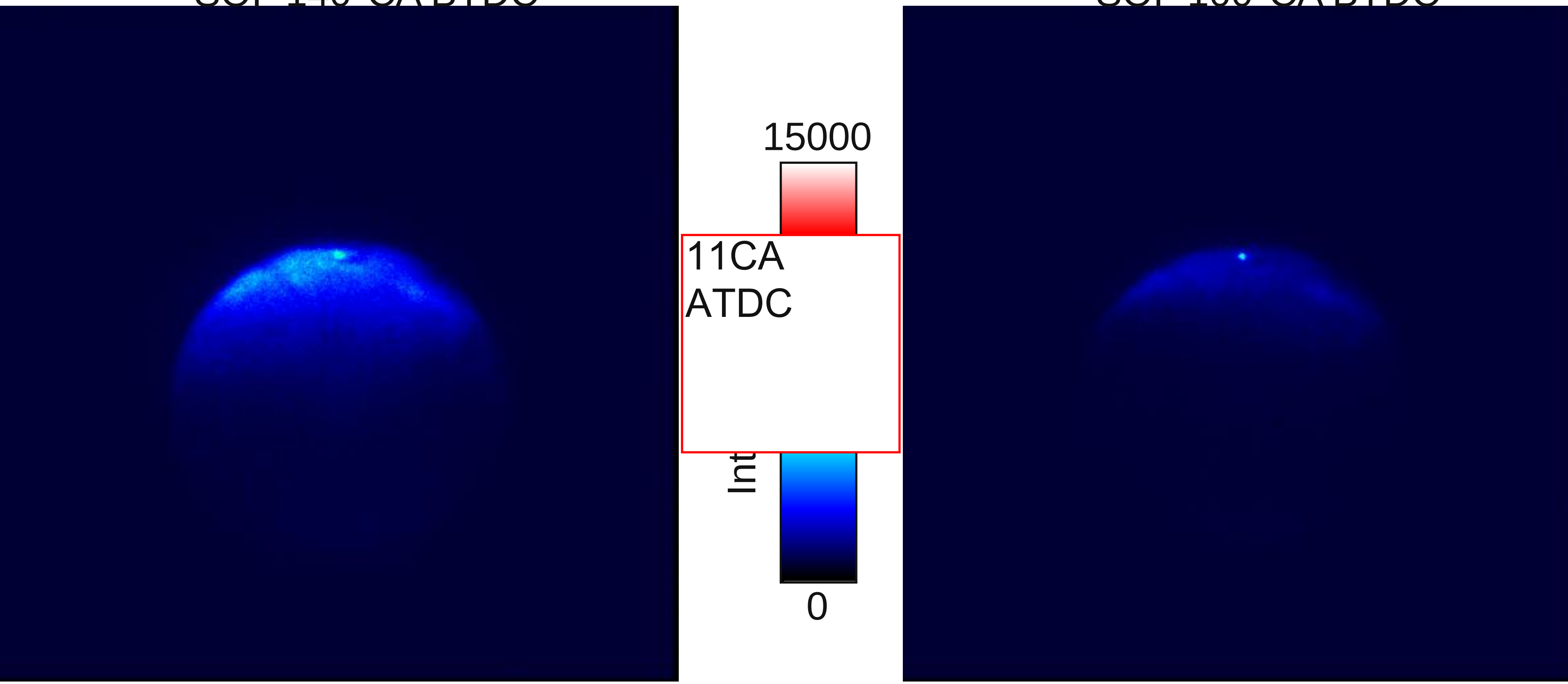
11°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

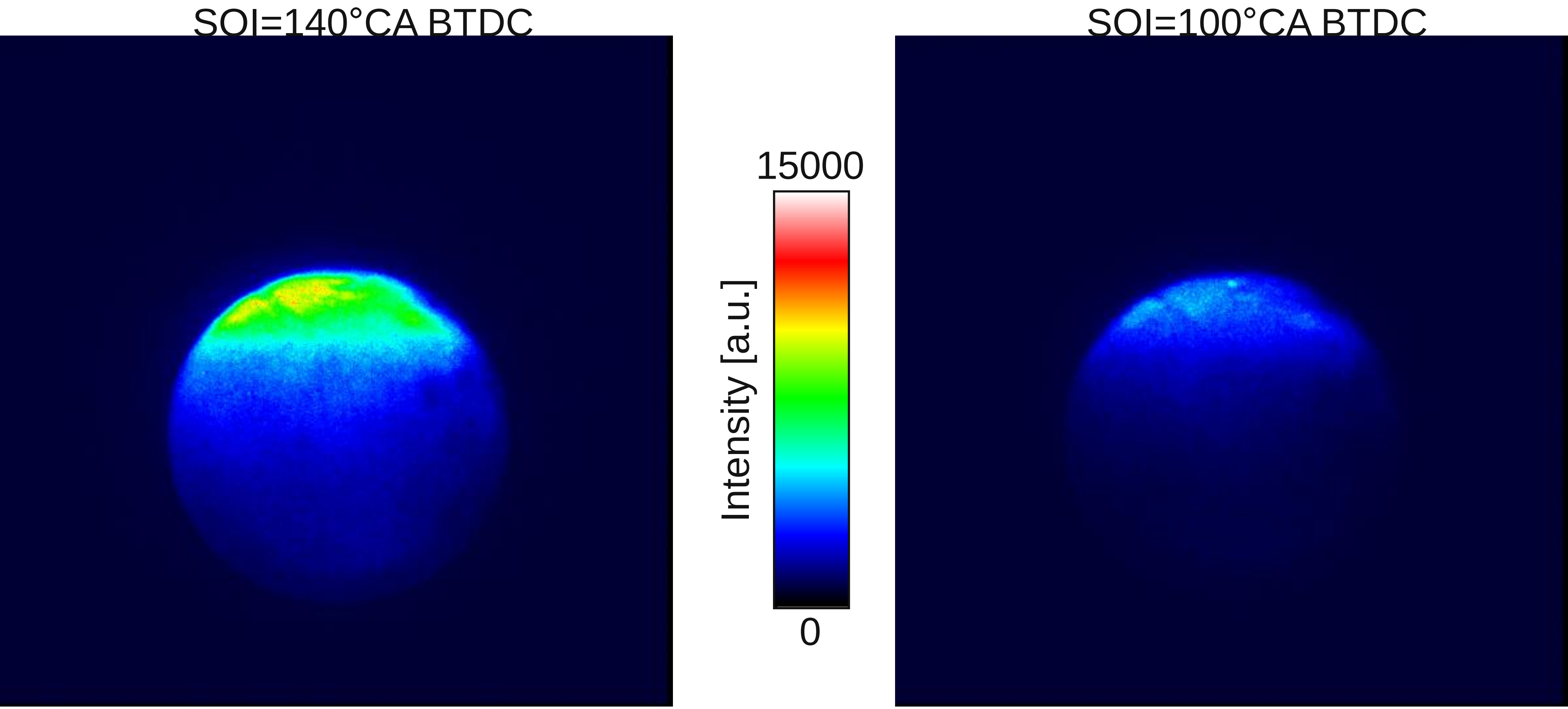
SOI=100°CA BTDC



13°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)



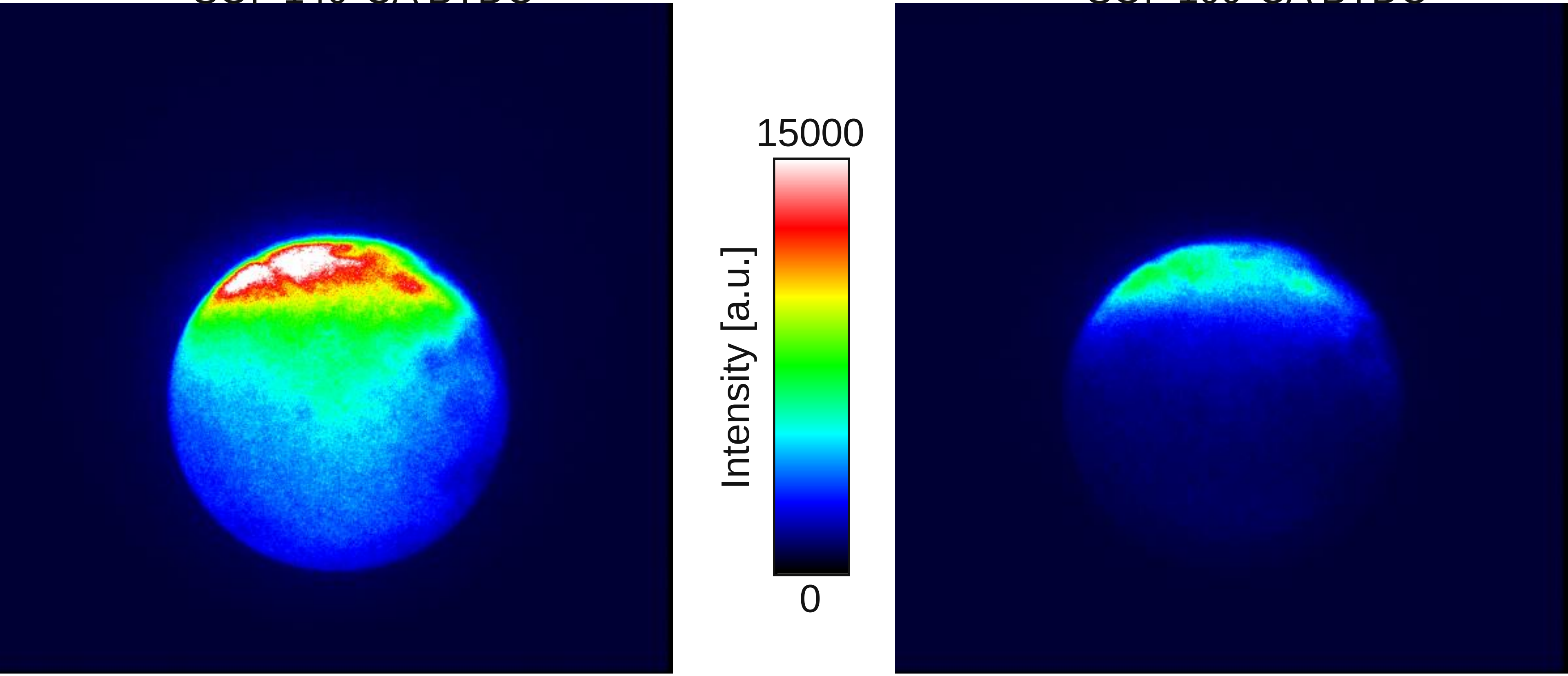
15°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



17°CA ATDC

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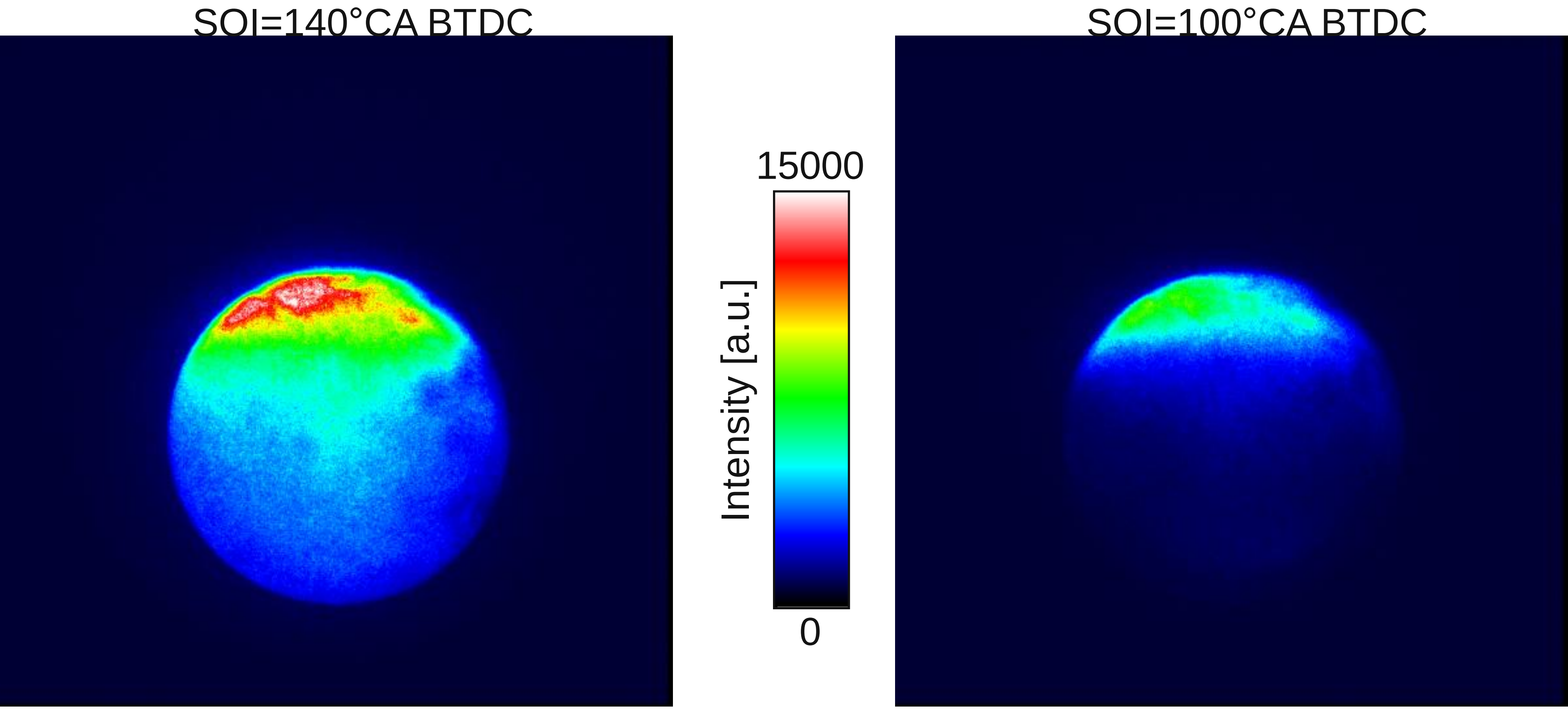
(Spark timing=5°CA ATDC)



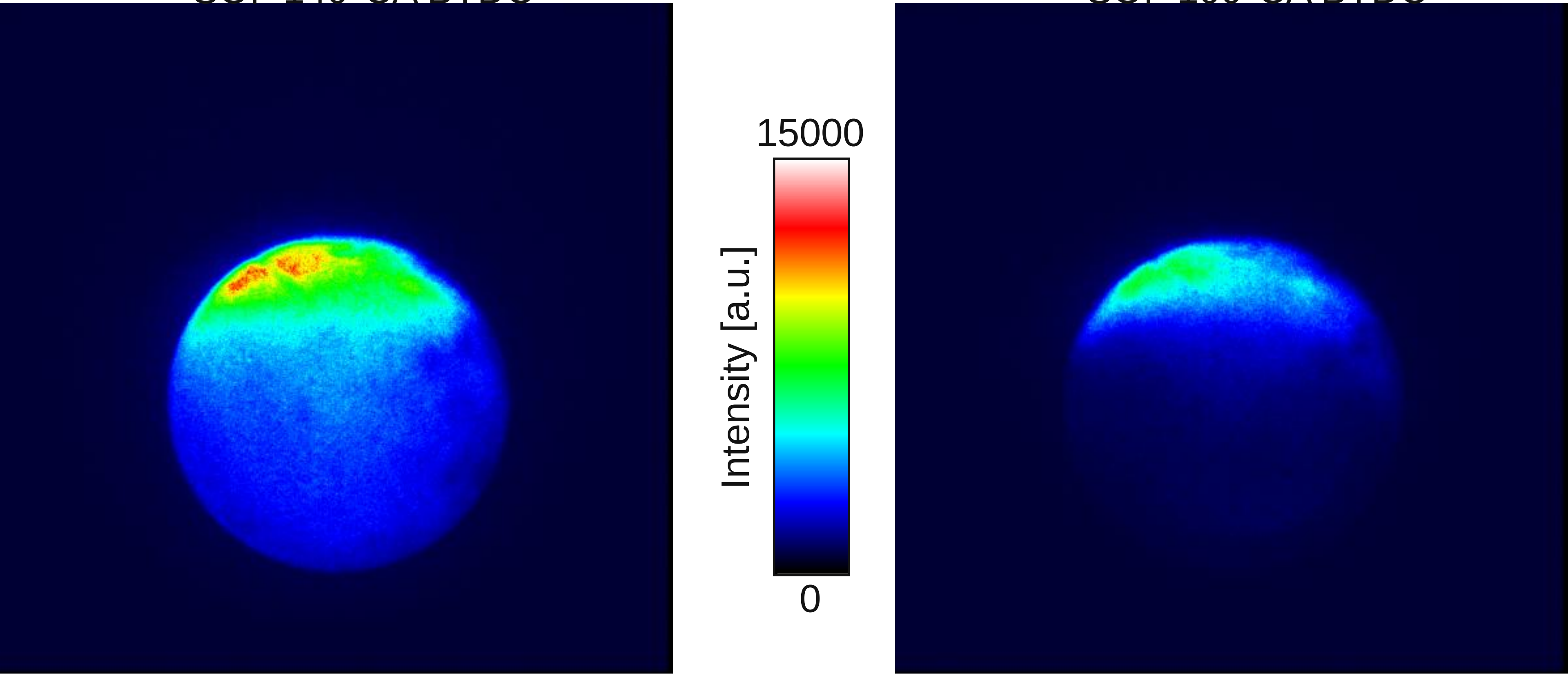
19°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



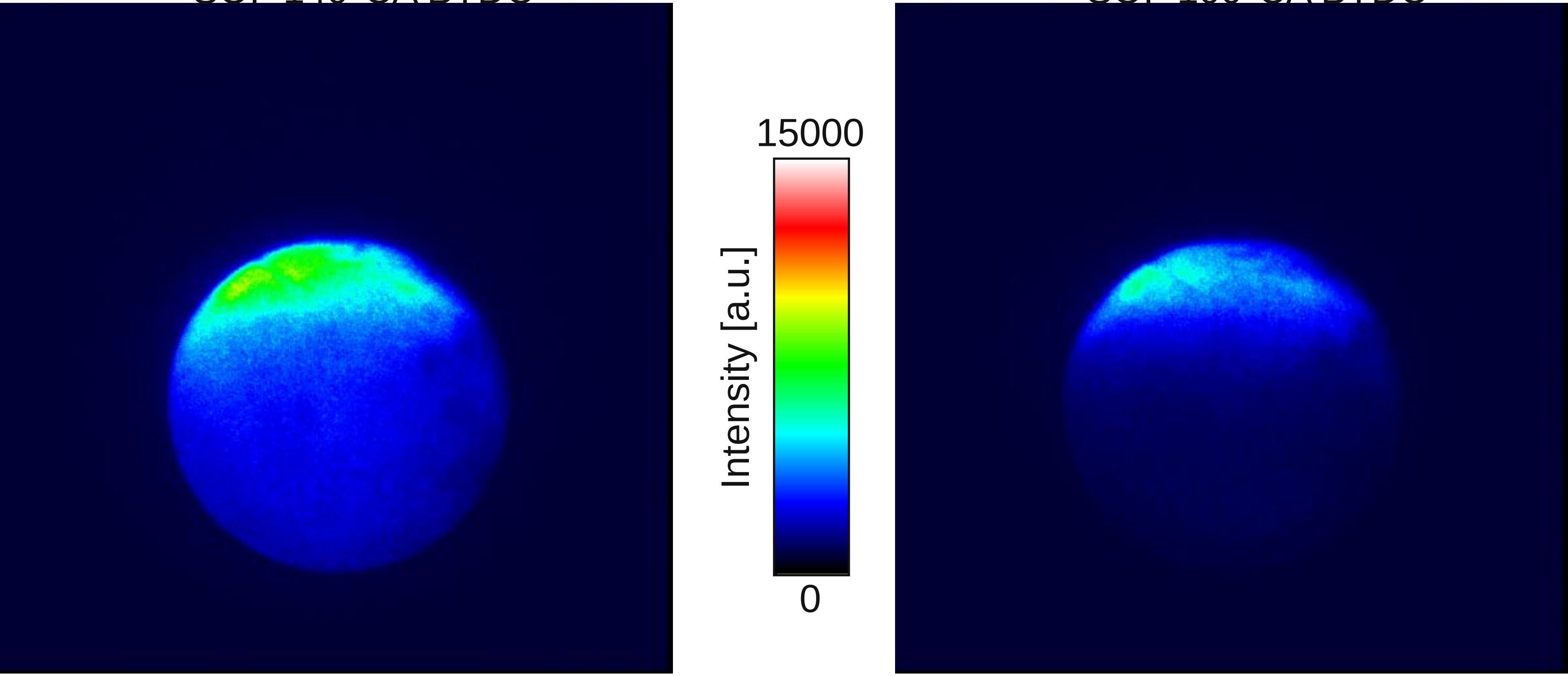
21°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



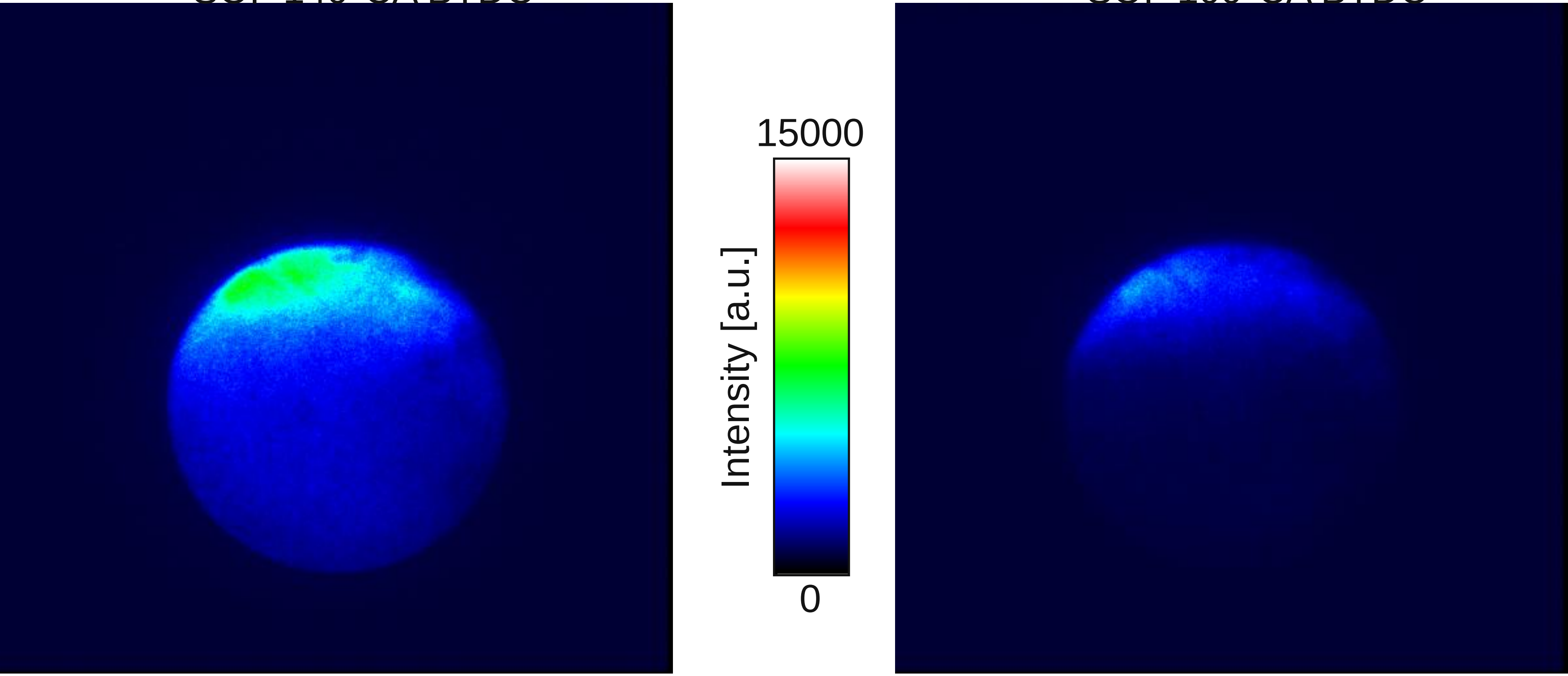
23°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



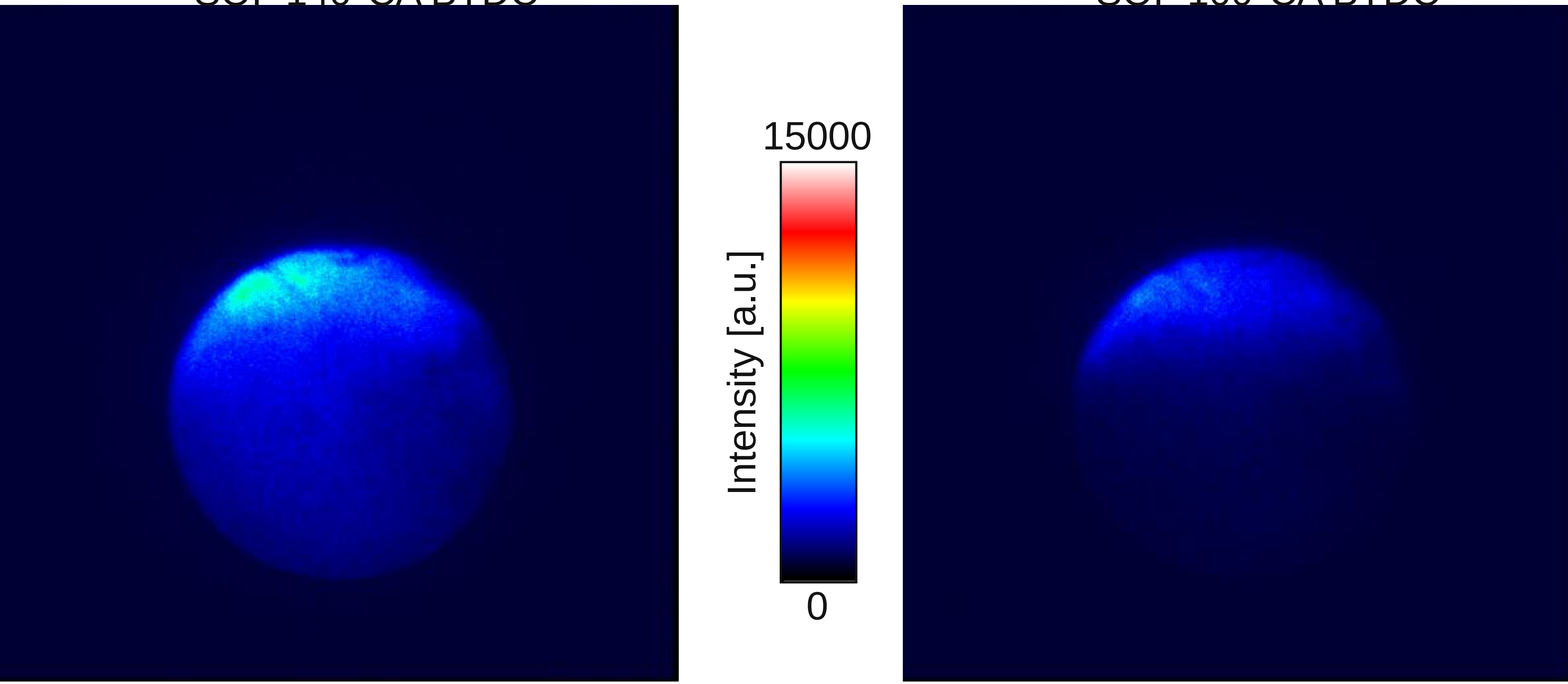
25°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

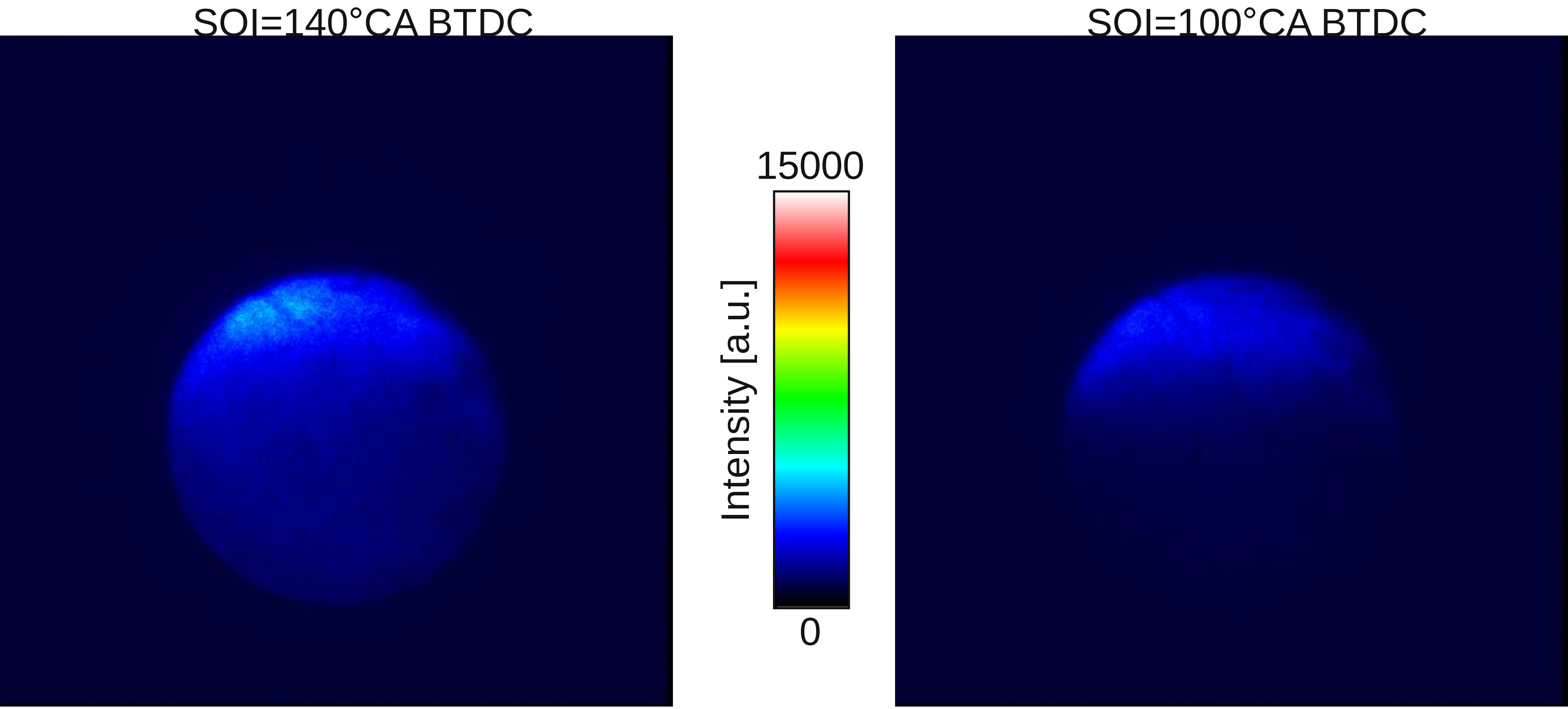
SOI=100°CA BTDC



27°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

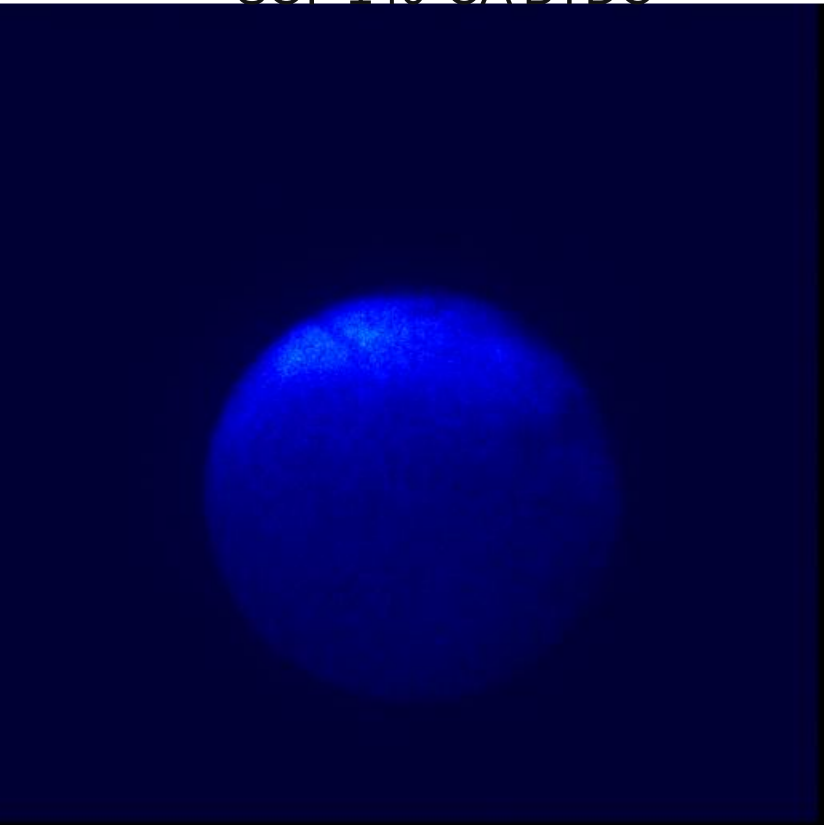


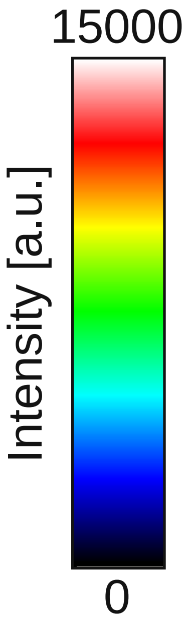
29°CA ATDC

2000 RPM Wide Open Throttle Φ=1

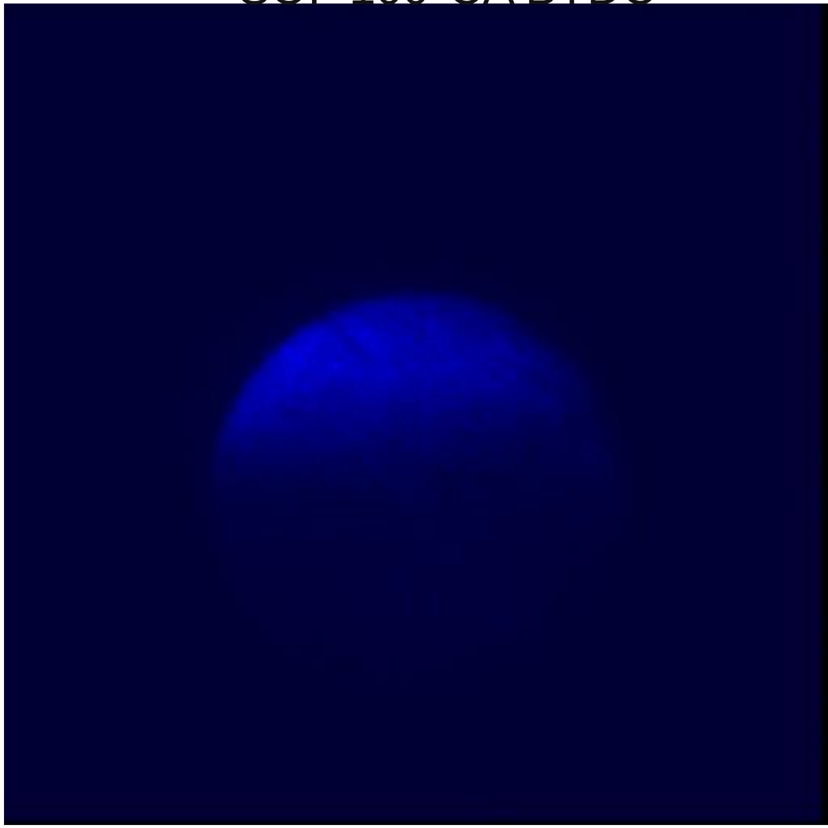
(Spark timing=5°CA ATDC)

SOI=140°CA BTDC





SOI=100°CA BTDC

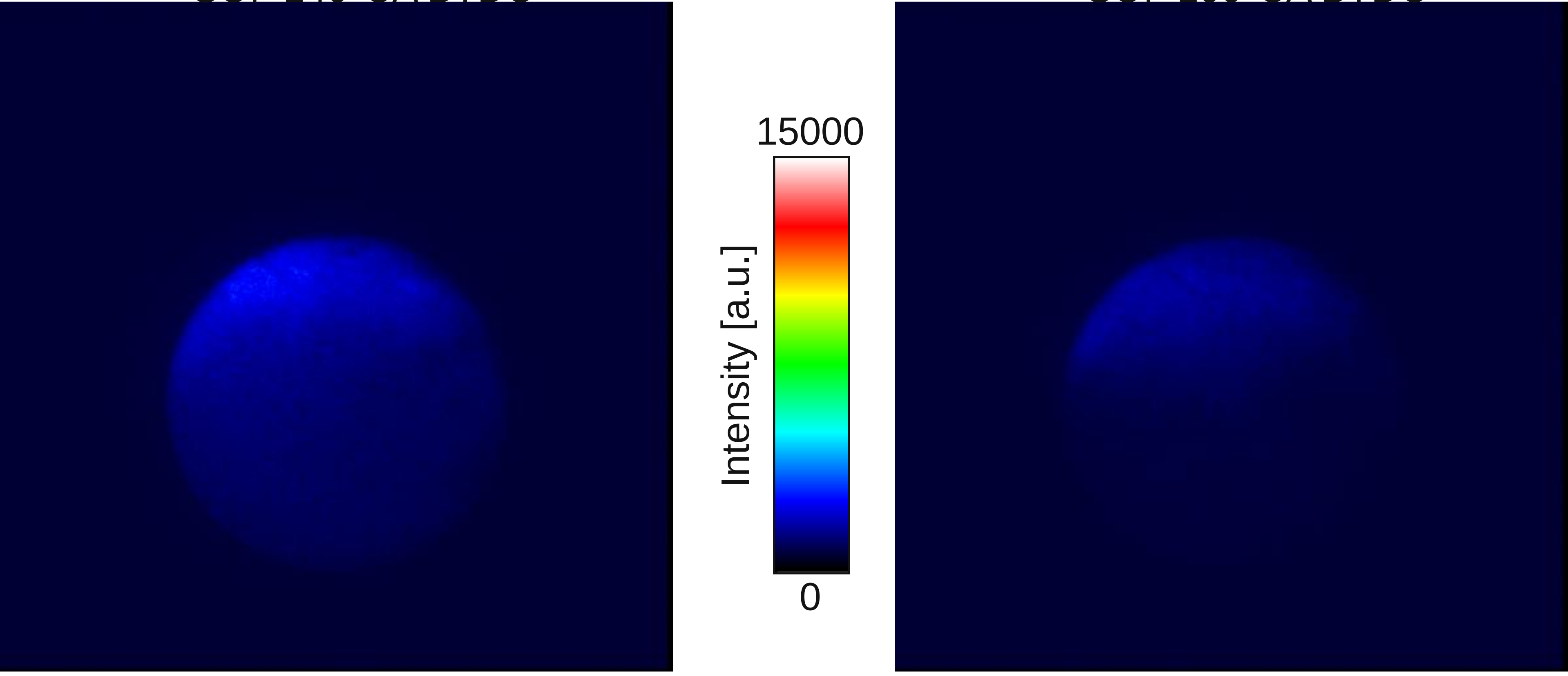


31°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC | SOI=100°CA BTDC



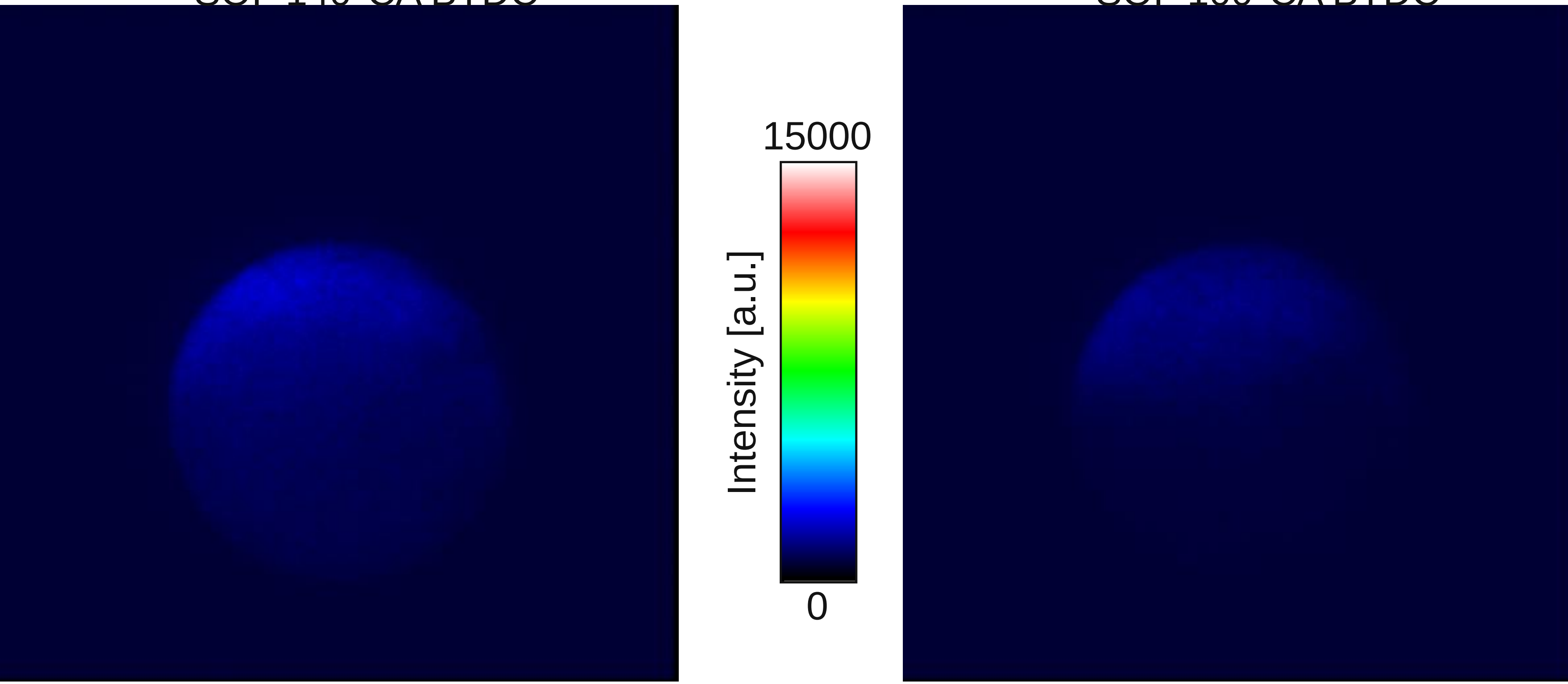
33°CA ATDC

2000 RPM Wide Open Throttle $\Phi=1$

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



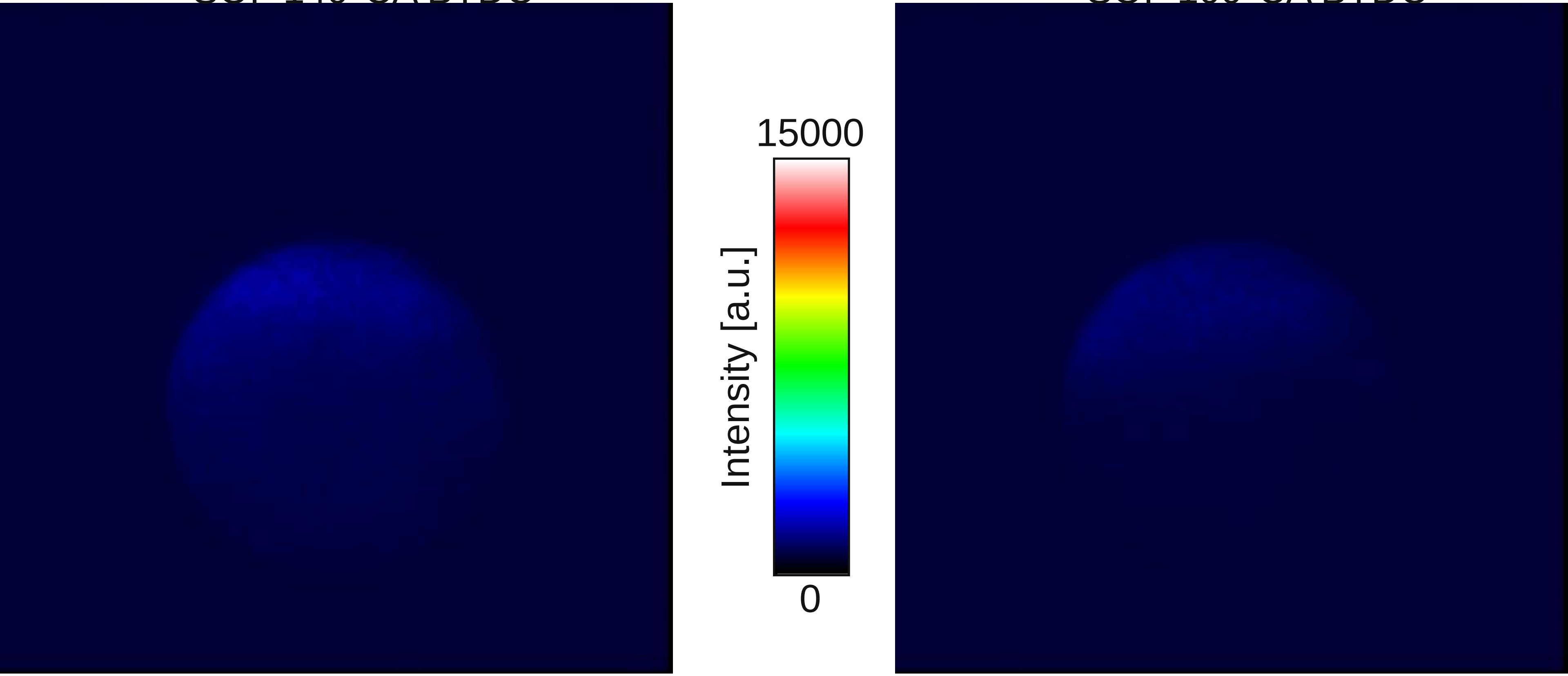
35°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



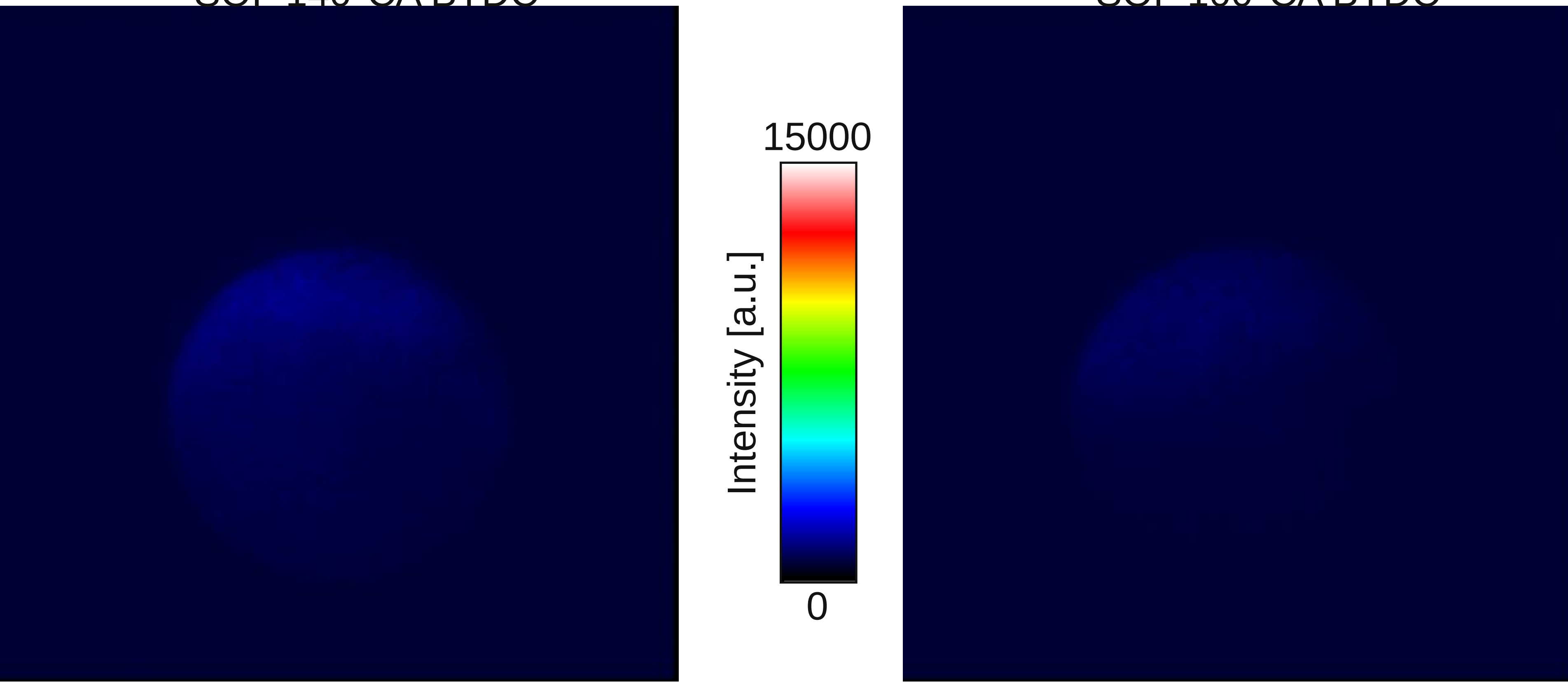
37°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



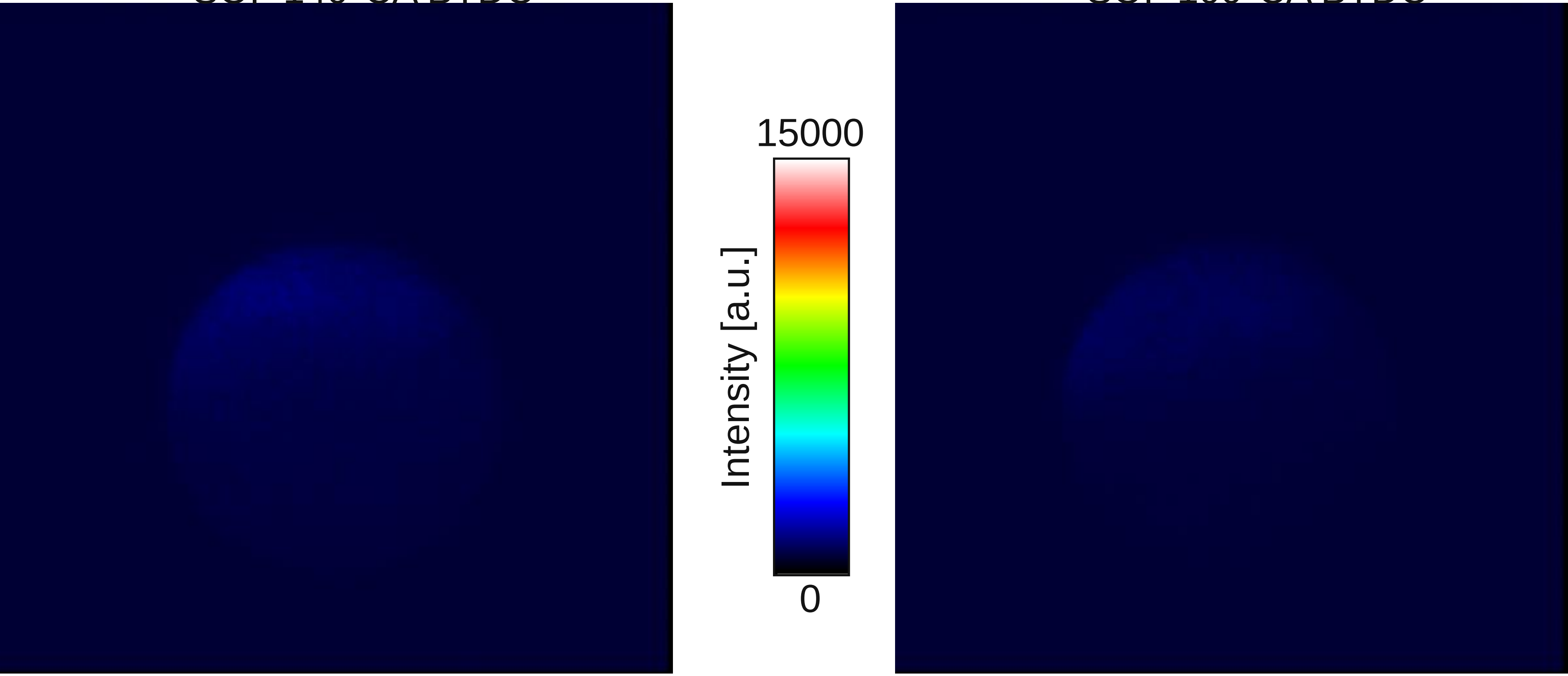
39°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



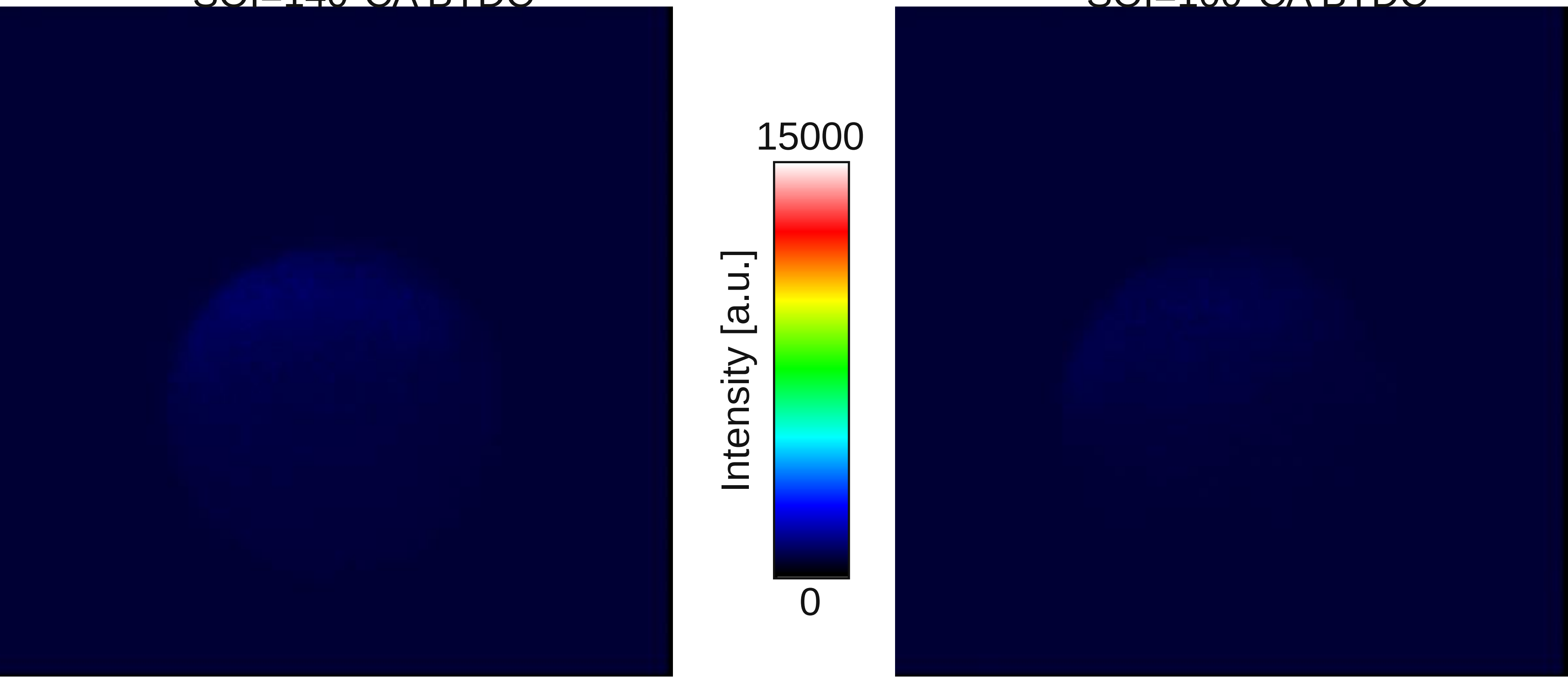
41°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



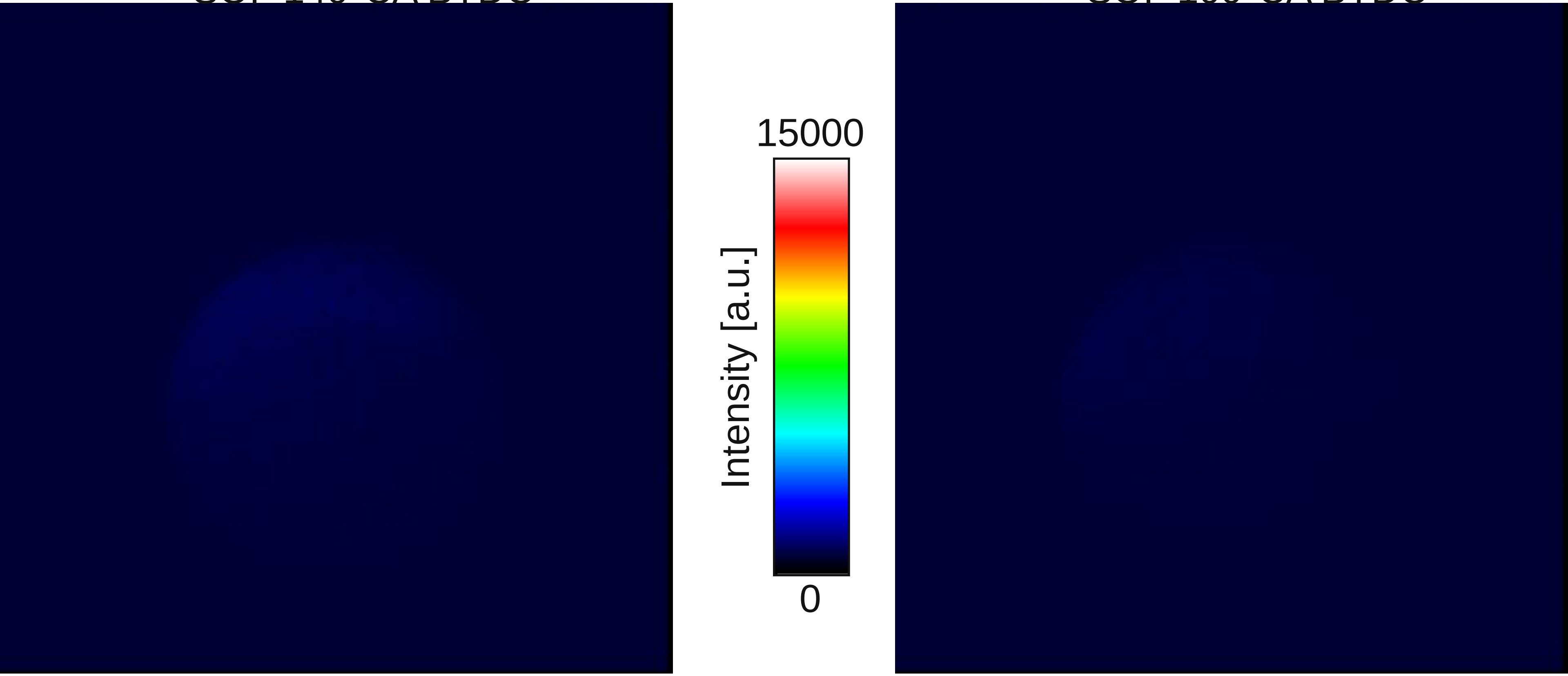
43°CA ATDC

2000 RPM Wide Open Throttle Φ=1

(Spark timing=5°CA ATDC)

SOI=140°CA BTDC

SOI=100°CA BTDC



45°CA ATDC

Summary

- Opportunity for high efficiency and low emissions over a variety of engine speeds exists with LTC concepts
- Low power density is a significant obstacle to marketplace acceptance for LTC
- Using in-cylinder combustion imaging in a production engine can enable advanced strategies for improved power density
- Engine test cell and instrumentation are functional
  - Baseline diesel data compares well with benchmark data
- Data will be relevant to industry using production engine with available fuels
- Install endoscopic hardware and open controller to enable LTC operation