Validation of a Finite Element Simulation of a Downhole Perforating Gun String through Comparison with Data from a New Datalogging Sensor Sub

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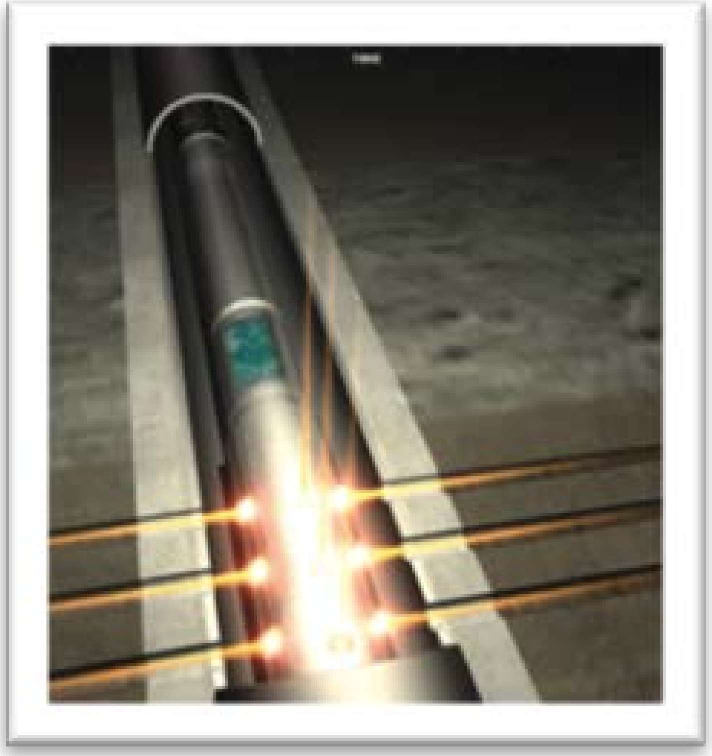
Timothy S. Glenn, Ph.D., Starboard
Marco Serra, Starboard
John P. Rodgers, Ph.D., P.E., Starboard
Gerald Craddock, Ph.D., Halliburton
Jim Wight, Halliburton

STARBOARD
INNOVATIONS, LLC.

Foreword on Well Perforating

- In cased oil wells, communication to the reservoir is restored by punching holes through the steel casing and concrete and into the rock formation.
- This perforation process involves detonating a string of shaped charges packaged in so-called “perforating guns”.
- Ideally, the incredible energy of all those high-explosive charges is directed toward jet formation and perforating.
- In reality, a large fraction of the explosive energy kicks off violent dynamics in the tool string and wellbore fluid.
- In most cases, the tool string remains in tact and is recovered, but costly failures can and do occur.

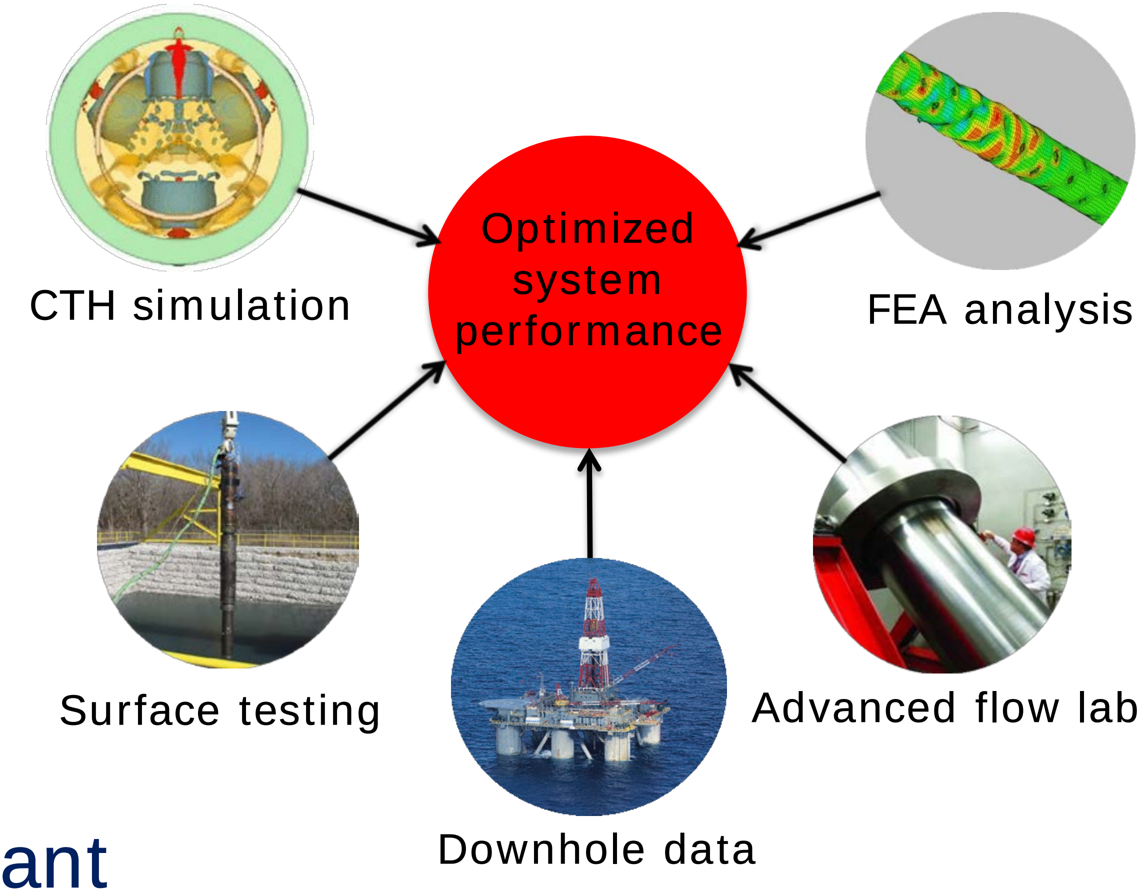
Introduction



- Current oil well designs are pushing the limits of downhole perforating guns.
- Scarcity and demand create pressure to increase gun capacity and performance in ever more challenging conditions.
- Traditional gun design approaches need improvement.
- Wellbore and gun string dynamics during the perforating event must be better understood to ensure reliability.
- A holistic approach involving advanced testing and modeling techniques is required.

Approach

- For this effort, Starboard developed:
  - An advanced software package for simulating shock response to gun detonation
  - Methods and tools for testing perforating guns at the surface
  - A downhole logging tool to collect more relevant data than had previously been available



Optimized system performance

CTH simulation

FEA analysis

Surface testing

Advanced flow lab

Downhole data

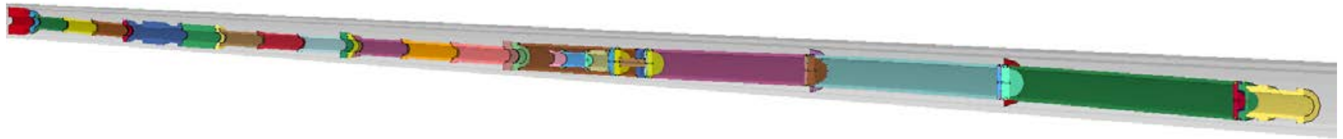
- Success required validating:
  - Model capability and accuracy
  - Sensor measurement quality and experiment repeatability

Agenda

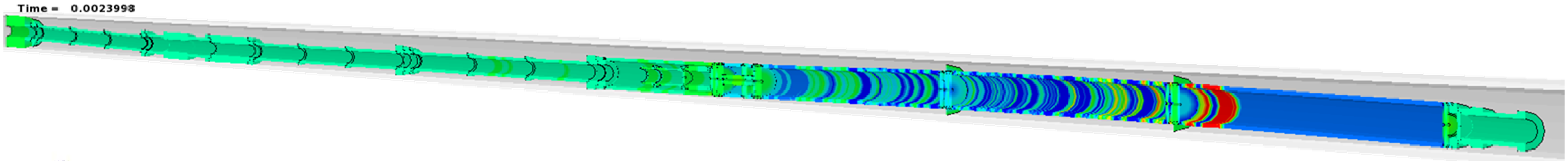
- Simulation software
- Instrumented surface testing
- Simulation software calibration
- Downhole logging tool, a.k.a. Shock Sensing Sub (SSS)
- Field trial and downhole data
- Simulation software validation
- Summary and conclusions

NOTE: Many details are vague to protect client's and customer's assets

Simulation Software



- FE-based software package
- Coupled fluid-structure transient simulation of the shock response of the BHA and wellbore to perforating gun string detonation
- Proprietary tool database and model generator/preprocessor
- End users without prior FEA experience can set up complex models quickly and reliably
- Commercial solver (routinely validated for accuracy, sensibleness)
- Proprietary scripts employed to evaluate failure criteria



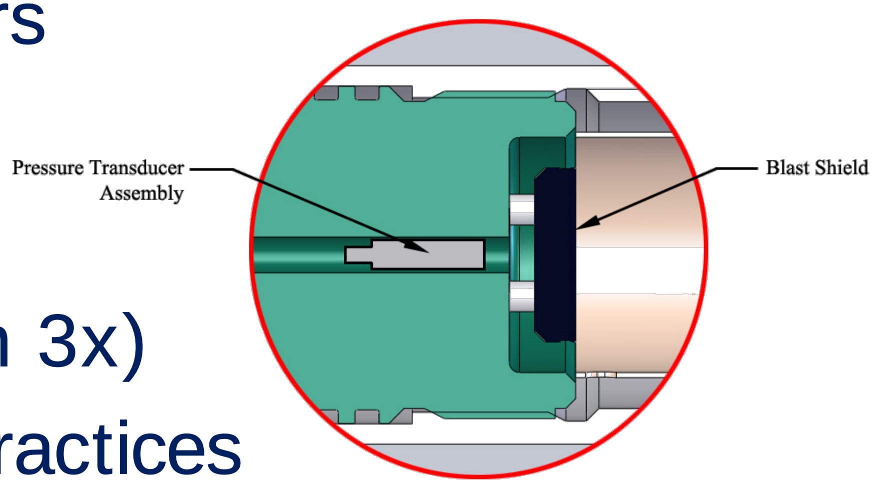
Simulation Software

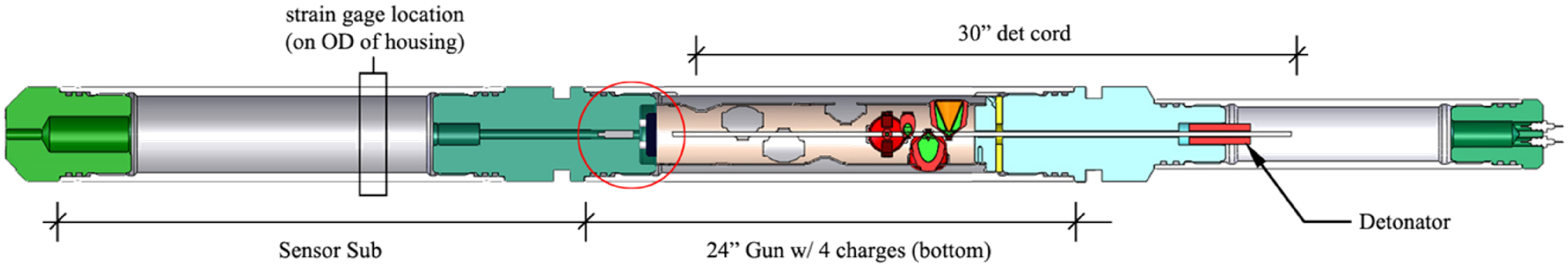
- Technical features include:
    - Realistic fidelity in three dimensions
    - Casing contact and friction
    - Multi-material fluid element formulation — mixing of gases, liquids, explosives
    - Nonlinear solid material models
    - Gravity and hydrostatic pressure initialization
    - Calibrated using surface test data (notably explosive parameters)

- Simulation output includes:
    - Complete set of solid and fluid DOFs and derived measures
    - 3-D visualization of dynamic loads and pressures, waves, mixing, etc.
    - Calculation of dynamic fracture risk

Instrumented Surface Testing

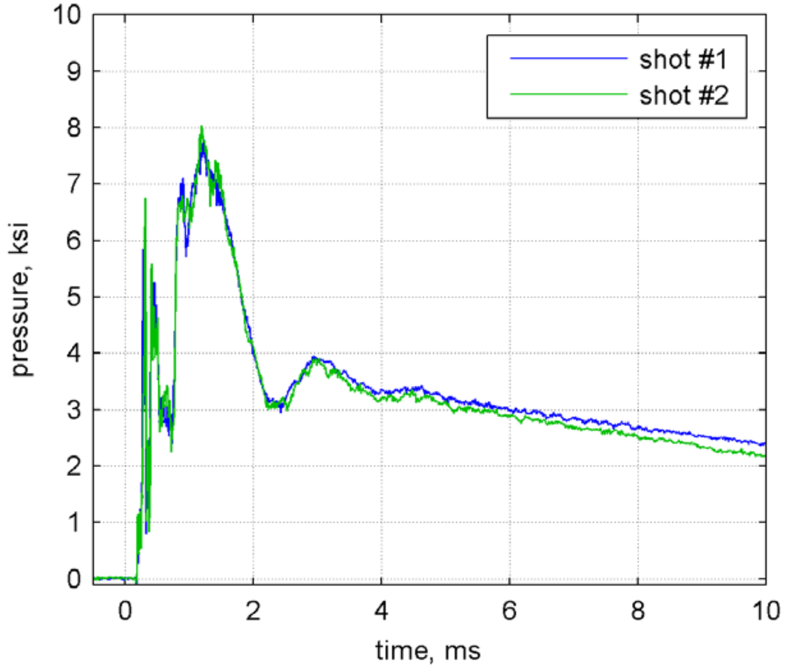
- Motivation
  - Measurement of gun internal pressure (prohibitive downhole)
  - Calibration of explosive model parameters
  - Parameter studies to isolate influences
  - Controlled and cost-effective
  - Verification of repeatability (each test run 3x)
  - Certification of sensors and integration practices

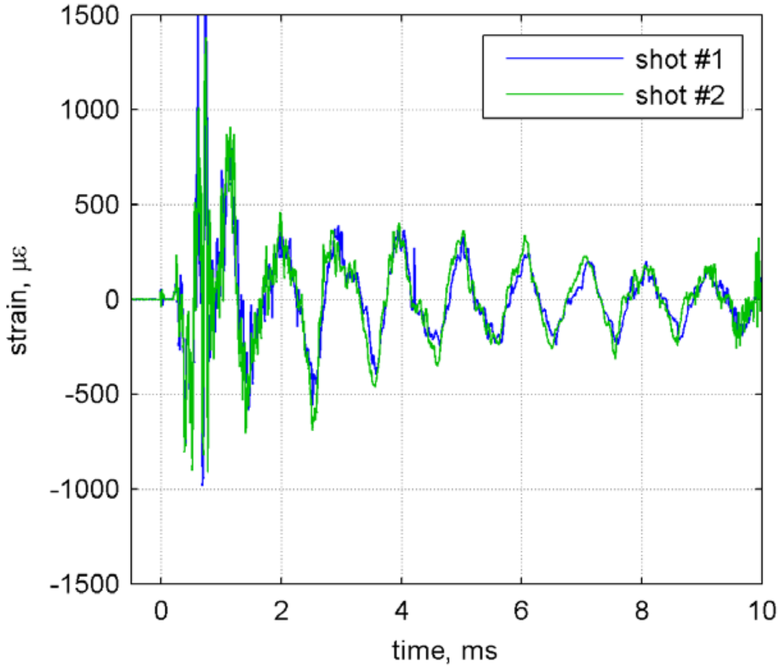




Instrumented Surface Testing

- Key observations
  - Excellent repeatability → limited uncertainty
  - Reliable measurement of gun internal pressure and average axial strain
  - Prominent features in pressure response facilitated separable parameter calibration

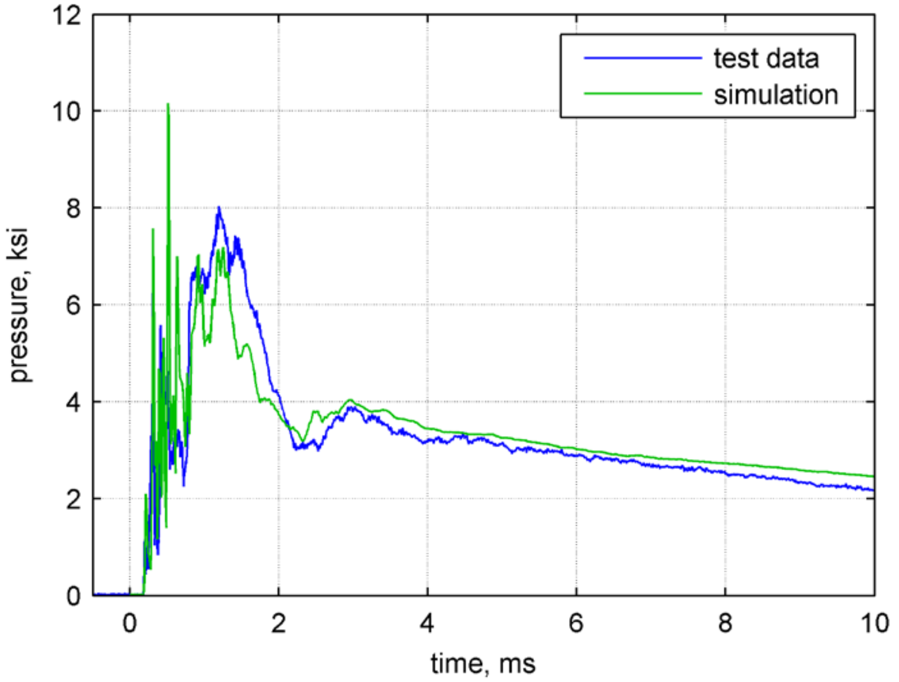


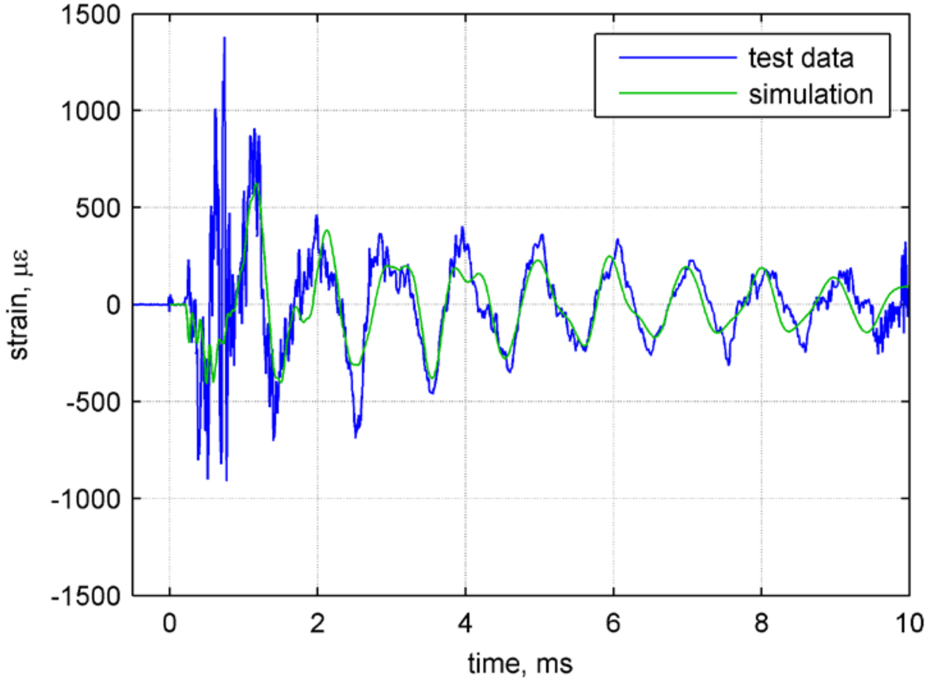


Simulation Software Calibration

- Approach
  - Modeled each surface test configuration.
  - Iterated on explosive model parameters to obtain best matching with each gun system.

- Results/Observations
  - Obtained remarkably good matching with data!
    - o Initial high-frequency pressure prediction attributed to model oversimplification, notably near sensor.
    - o Initial high-frequency strain data attributed to shock-induced triboelectric noise in wires.
  - Yielded set of consistent, calibrated model parameters for use in downhole simulations.





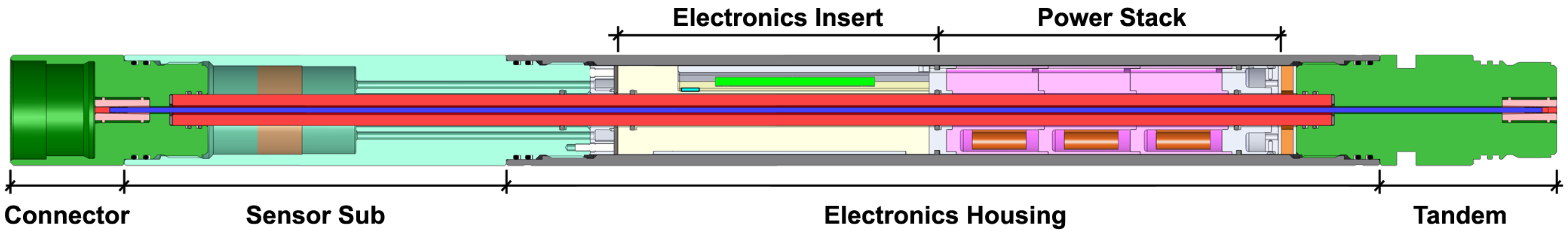
Shock Sensing Sub (SSS)

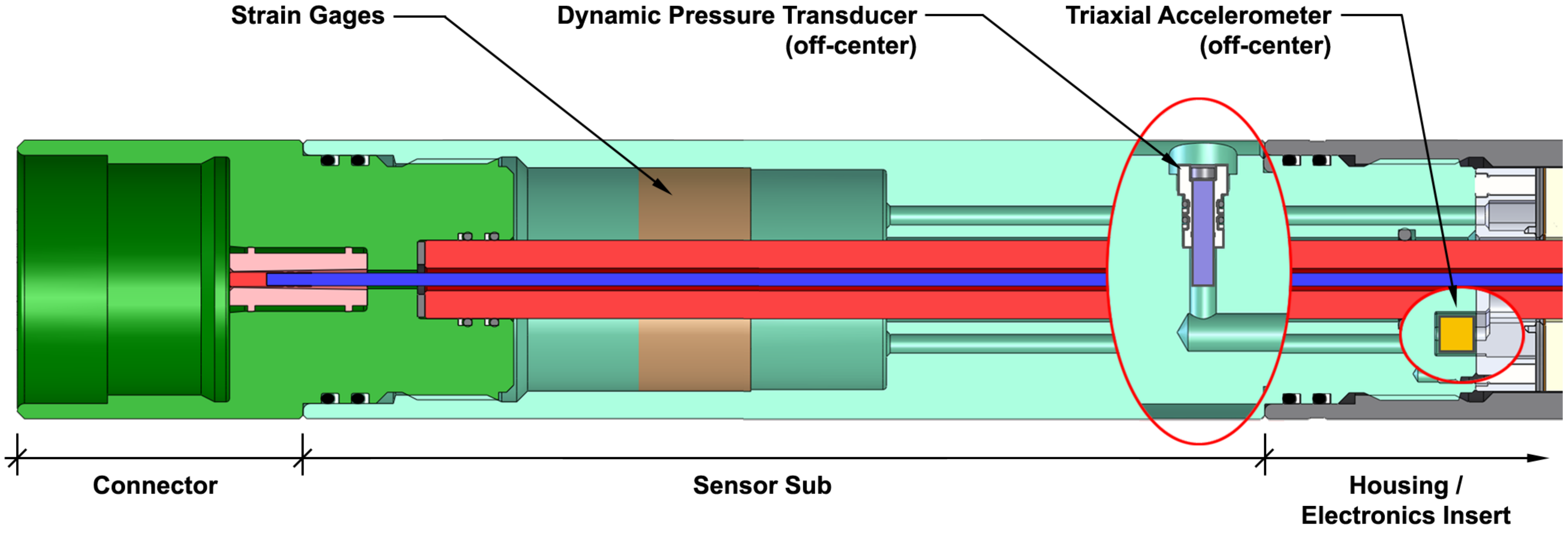
- Motivation
  - Simulation software would need to be validated against real downhole data
  - Existing loggers offered limited remote data
- Designed to...
  - provide add'l critical event data from directly within the perforation interval
  - be loaded like a gun and integrated into the gun string
  - increase confidence in measurements via collocation & redundancy of sensors
  - survive detonation event!

Specifications

Mechanical	
Diameter	4-5/8 in
Pressure rating	20,000 psi
Tensile rating	377,000 lbs
Connections	standard gun threads (pin x box)
Sensors	
Strain gages	3 axial, 3 hoop, 1 torsion
Pressure	Dynamic pressure, 100 ksi
Accelerometers	Triaxial, 60 kg
Temperature	RTD
Environmental	
Temperature rating	150 ºC
Logging	
Event Sampling Rate	100 kHz
Event Duration	1 sec
Event Records	10
Slow Sampling Rate	1/8 Hz before arming; 1 Hz after arming
Bandwidth	20 kHz
Resolution	12 bit
Run Duration	5 days

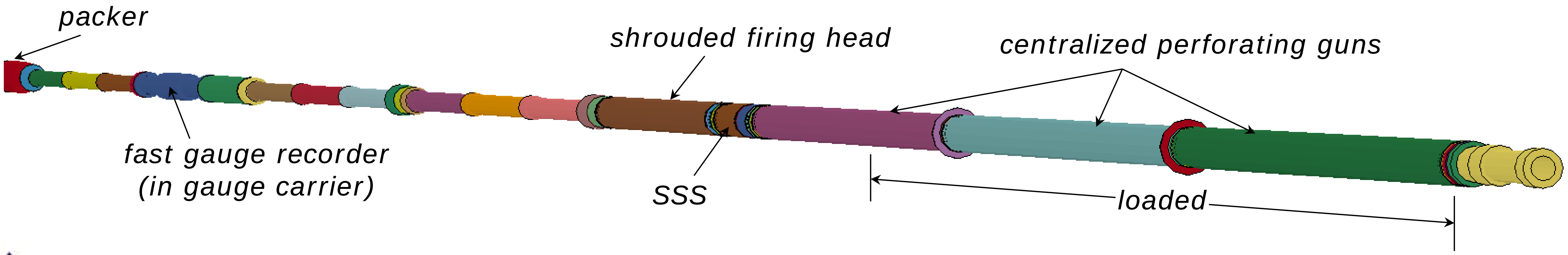
Shock Sensing Sub (SSS)





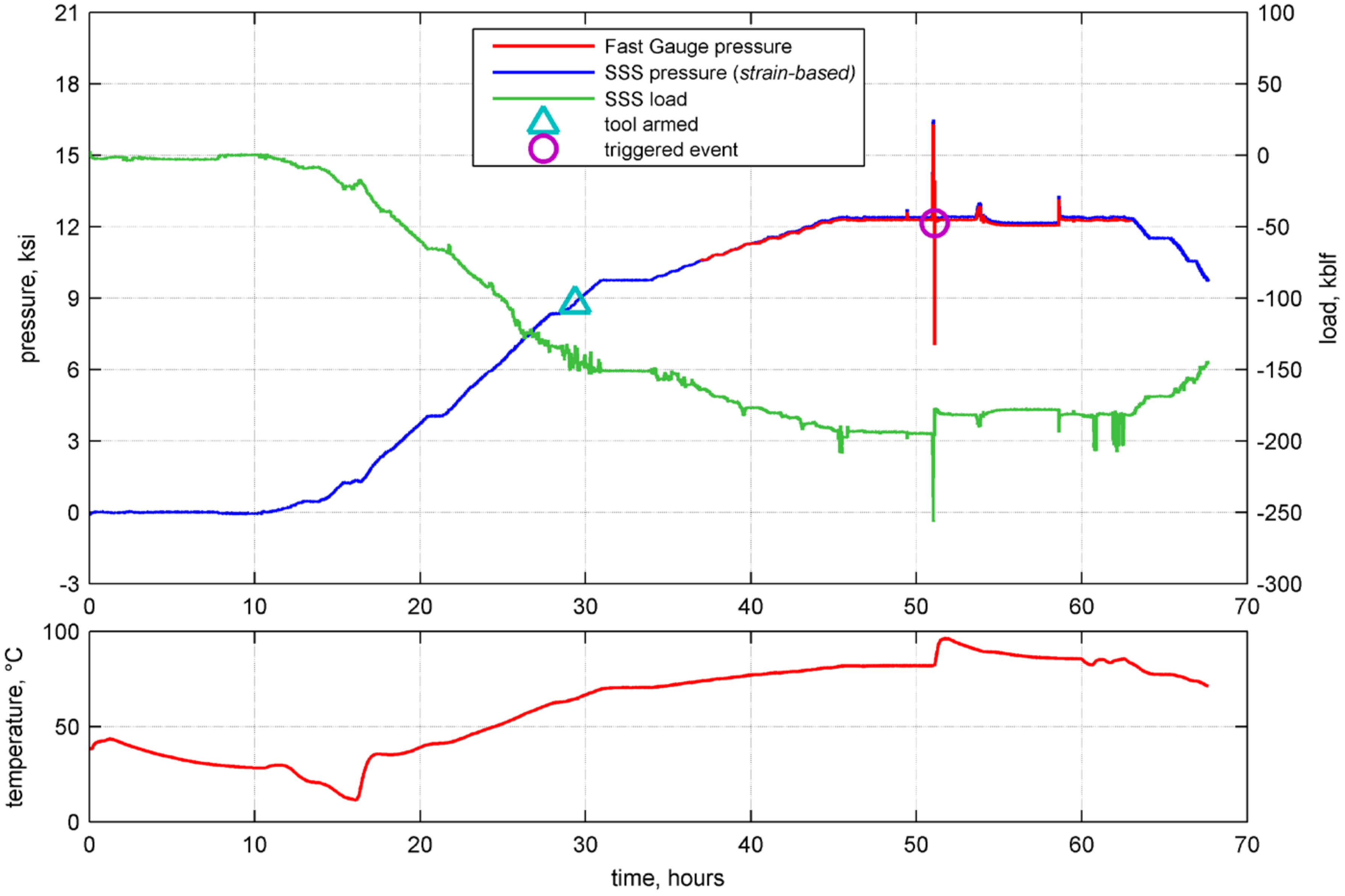
SSS Downhole Field Trial

- Job description
  - Gun system: 4-5/8”, 12 shots/ft using 28-g HMX SH LD charges
  - Perforation depth approximately 16,000 ft
  - Hydrostatic pressure 12,400 psi
  - Bottomhole temperature 190°F
  - Fast Gauge™ recorder 40 ft below the packer
  - Shock Sensing Sub placed between firing head and top gun



SSS Downhole Data

- 68 hours of low-speed data (1 SPS)
- Armed at 9,000-psi preset threshold
- Triggered on high-g detonation event
- 1 second of high-speed event data (100 kHz)

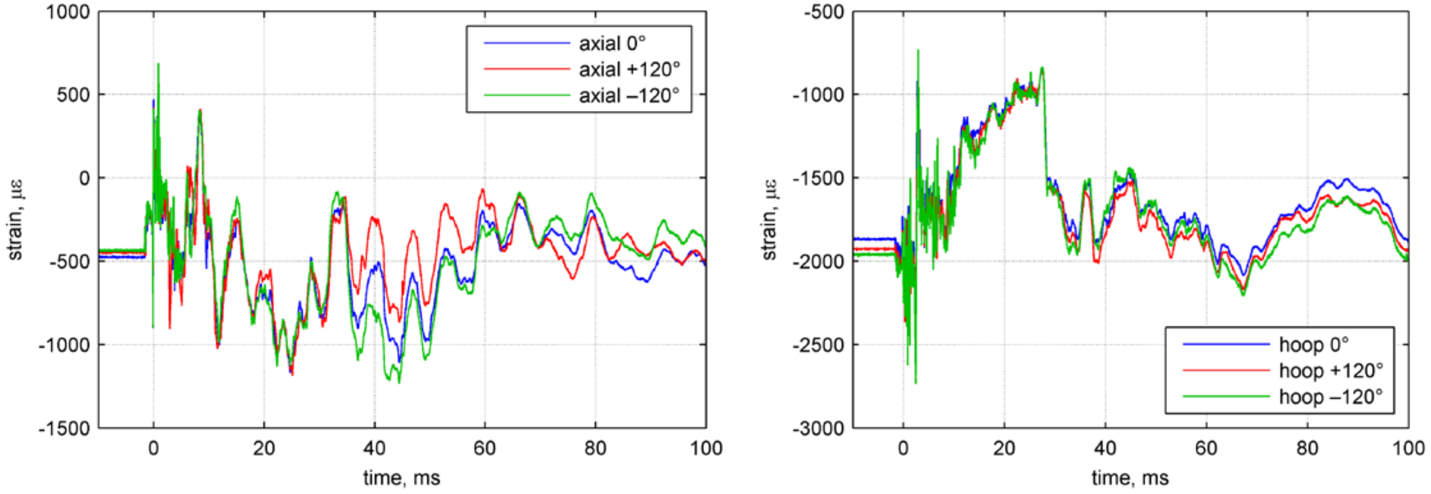


SSS Downhole Data

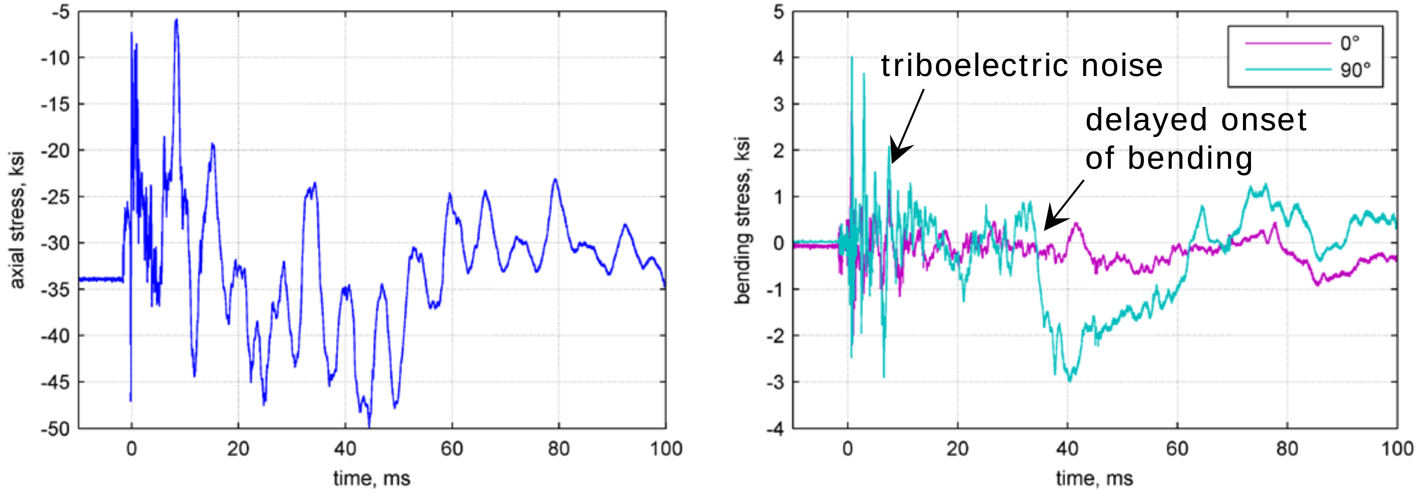
- Stresses calculated from strains
- Decomposed into avg axial stress and bending stresses then into axial load and bending moments
- Avg hoop stress provides another measure of pressure

- Notes on bending
    - Recognized by divergence of axial stresses
    - Delayed onset caused by difference in speed between dilatational and bending waves

Strain Measurements



Decomposed Stresses

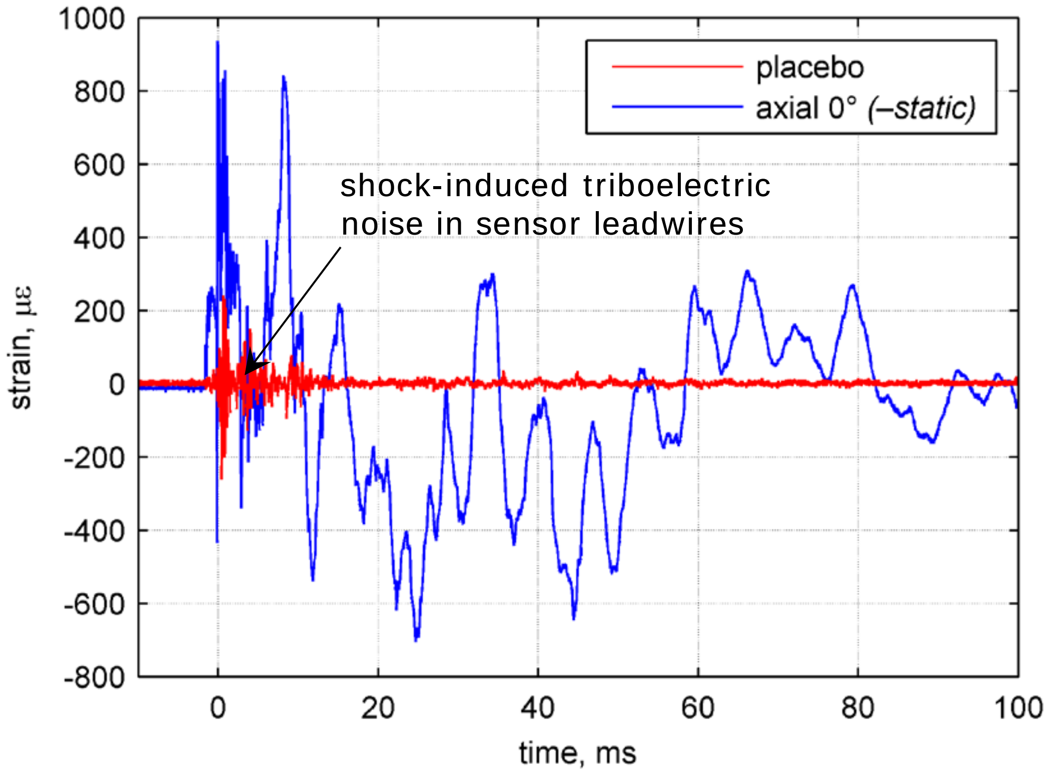


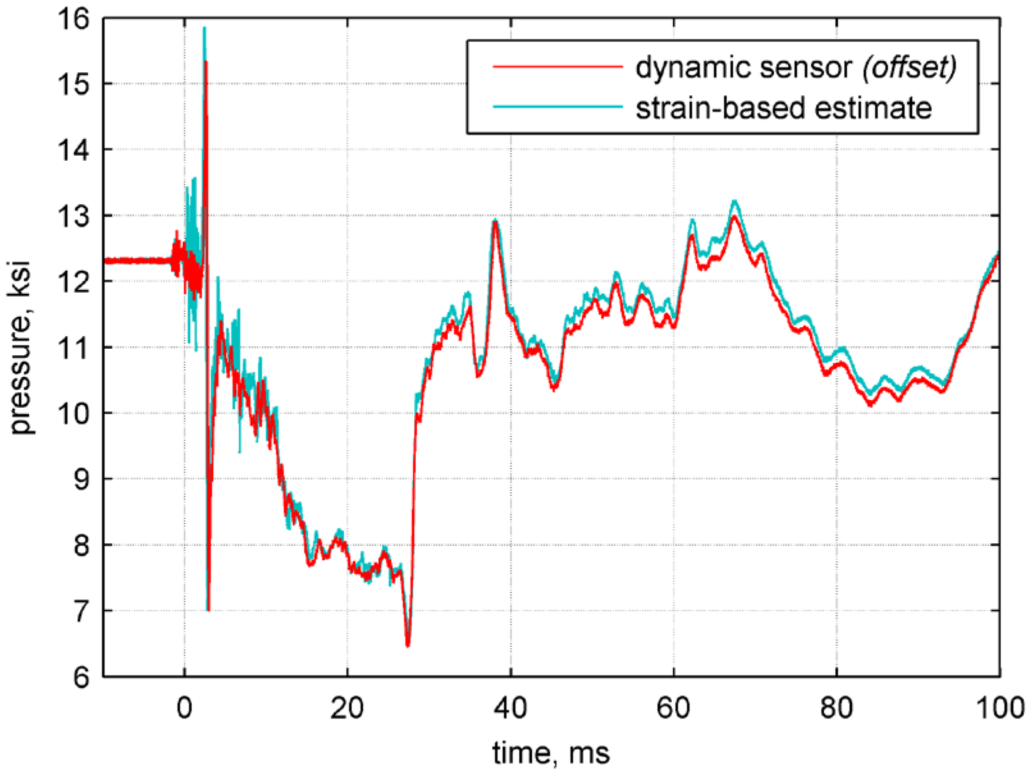
triboelectric noise

delayed onset of bending

SSS Downhole Data — Validation

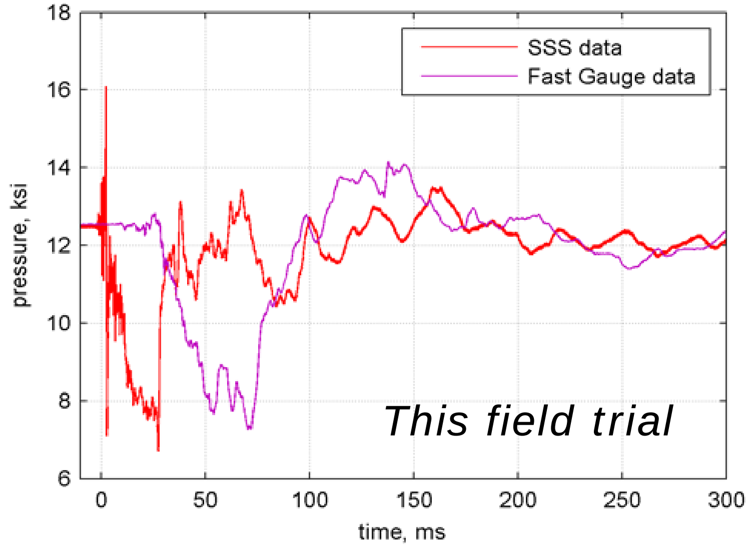
- Triboelectric noise contribution characterized by “placebo” strain sensor
- Excellent correlation between dynamic pressure transducer and strain-based calculation — validates strain accuracy, sub body as transducer



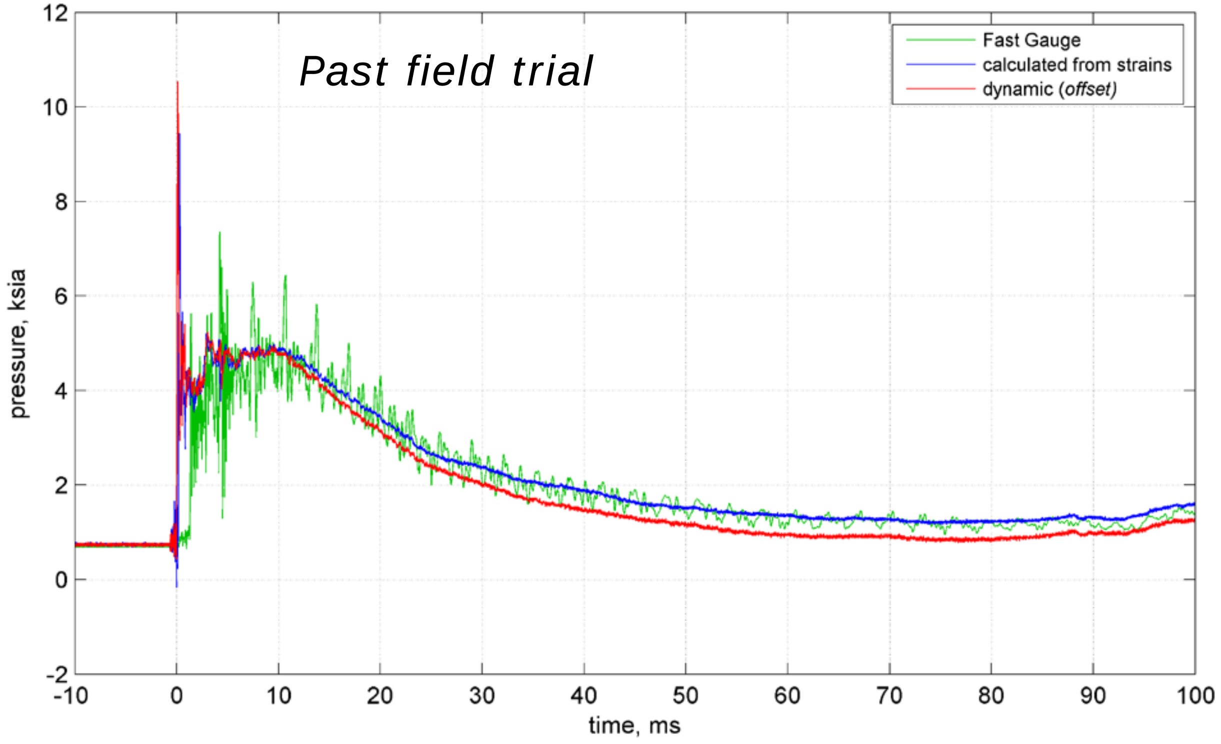


SSS Downhole Data — Validation

- Validation of pressure measurement against accepted tool (Fast Gauge)
  - Customer assurance
  - Limited comparison in this field trial due to physical separation
  - Collocation in past field trial provided direct comparison, opportunity to expose concern with accepted tool’s dynamic response (port dynamics)



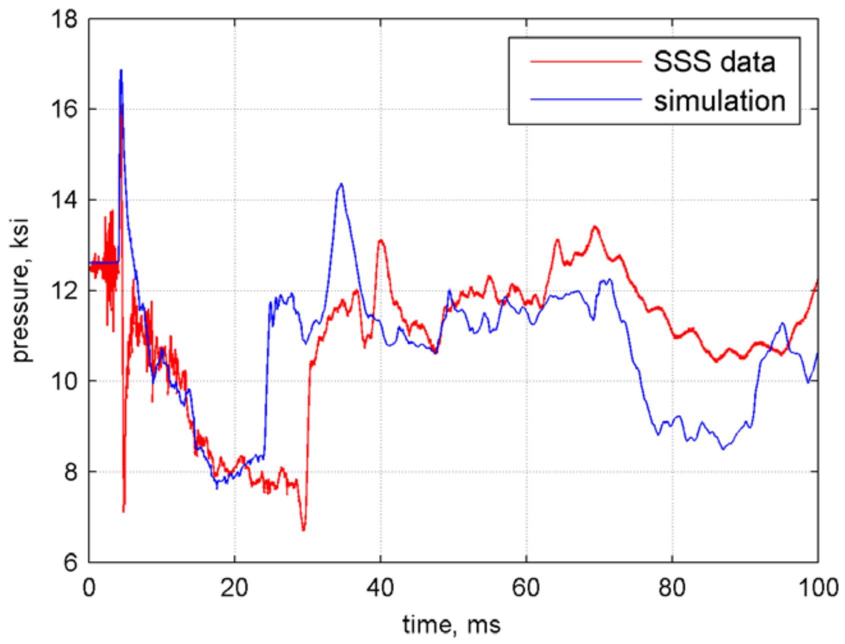
This field trial

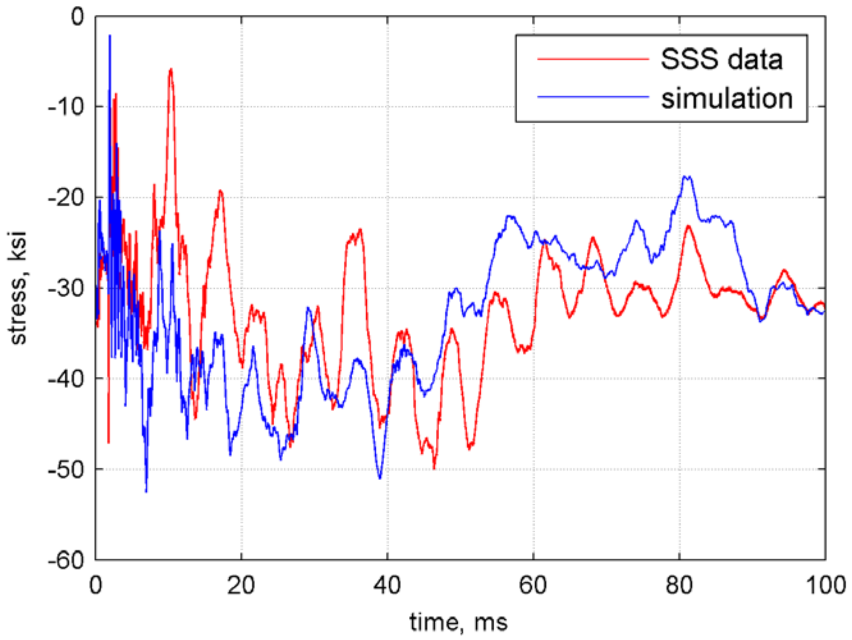


Past field trial

Simulation Software Validation

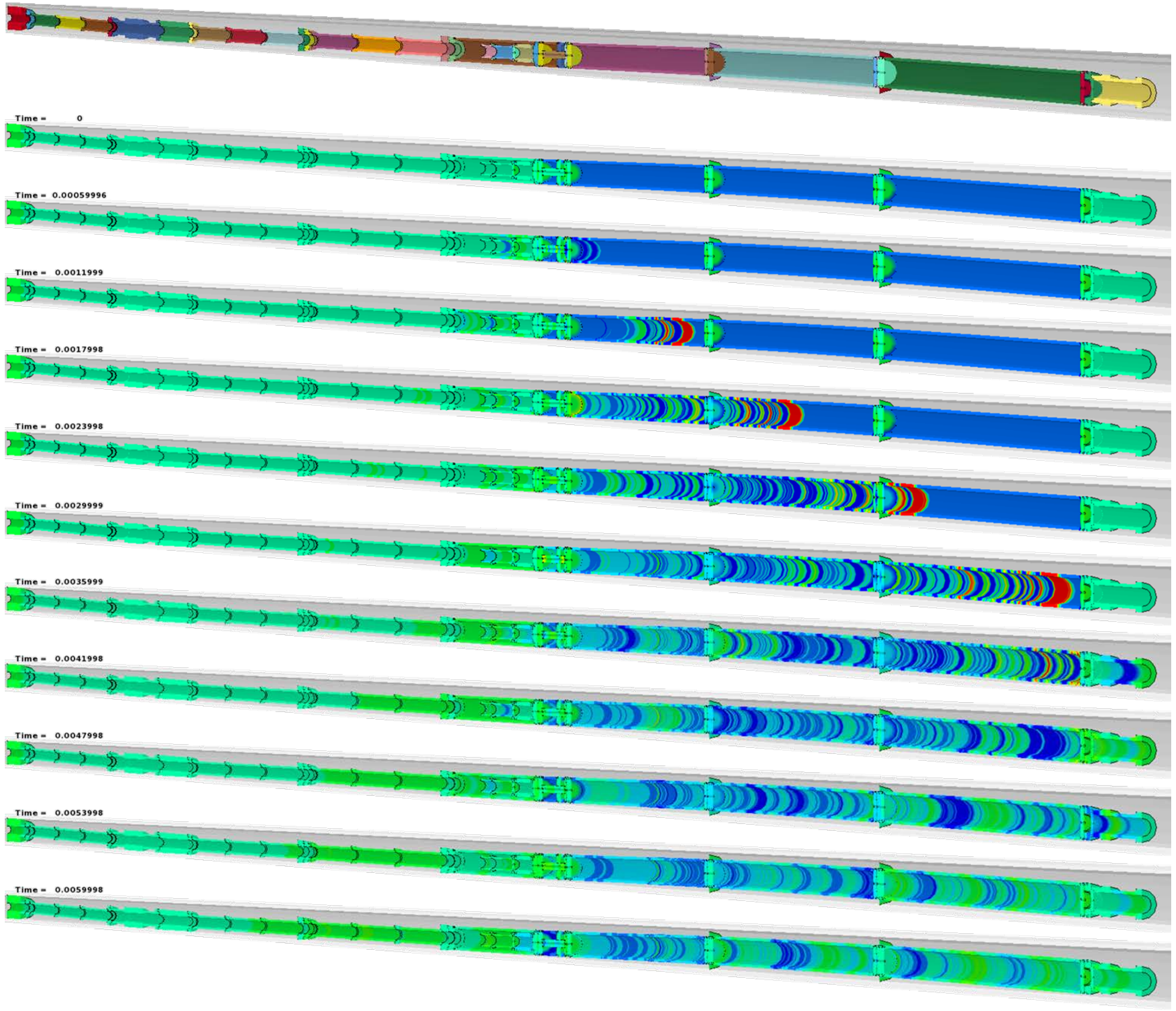
- Modeled the SSS downhole field trial
- Obtained critical parameters from the calibrated surface test model of this specific gun system
- Qualitative model-data comparison
  - Wellbore pressure at SSS (above guns)
    - Improved prediction of underbalance amplitude & duration
    - Excellent capture of principal events and dynamics
  - Stress in SSS
    - Accurate capture of system frequencies
    - Good prediction of overall stress levels
- Explored Dynamic Time Warping and metrics for quantitative assessment





Downhole Simulation

- Visualization
  - Axial stress contours overlaid on deformed geometry
  - Blue compression, red tension
  - Snapshots at 0.6-ms intervals
  - Tension spike behind detonation front → potential failure concern
  - Reflections at every significant structural transition make it increasingly difficult to follow individual wave packets
  - Animations are invaluable for identifying features in trace data



Summary & Conclusions

- Understanding of wellbore and gun string dynamics has vastly improved with the successful development of:
  - An advanced software package for simulating the perforating event with superior capability and accuracy compared to previously used simulation tools
  - A downhole logging tool that collects more relevant data
- Calibration of critical model parameters was facilitated by new methods and tools for testing perforating guns at the surface, notably the measure of internal gun pressure.
- These tools have benefited failure investigations and will advance gun system and job design approaches.
- Confidence in these tools ultimately relied on demonstrating:
  - Sensor measurement quality
  - Experiment repeatability (to limit uncertainty of the actual response)
  - Strong model-data correlation

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