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An ADVA Optical Networking Company

High performance optically-pumped cesium beam clock

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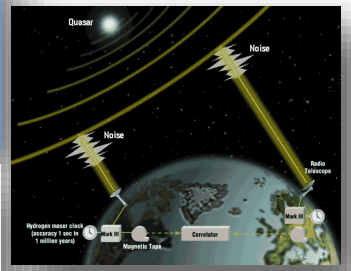
Outline

- Motivation and applications
- Cs clock: magnetic vs. optical
- Cs clock prototype development
- Conclusion

Identified markets

- **Telecommunication** network reference
  - Telecom operators, railways, utilities, …
- **Science**
  - Astronomy, nuclear and quantum physics, …
- **Metrology**
  - Time scale, fund. units measurement
- **Professional mobile radio**
  - Emergency, fire, police
- **Defense**
  - Secured telecom, inertial navigation
- **Space** (on-board and ground segments)
  - Satellite mission tracking, GNSS systems



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Available Cs clock commercial products

- **Long life magnetic** Cs clock
  - Stability : **2.7^{E}-11 $\tau^{-1/2}$, floor = 5^{E}-14**
  - Lifetime : **10 years**
  - Availability : commercial product
- **High performance magnetic** Cs clock
  - Stability : **8.5^{E}-12 $\tau^{-1/2}$, floor = 5^{E}-15**
  - Lifetime : **5 years**
  - vailability : commercial product
- **High perfermance and long life optical** Cs clock
  - Stability : **3.0^{E}-12 $\tau^{-1/2}$, floor = 5^{E}-15**
  - Lifetime : **10 years**
  - Availability : under development

Timing error prediction

$$\Delta T = T_o + (\Delta f/f) \cdot t + \tfrac{1}{2} D \cdot t^2 + \sigma_x(t)$$

Timing error

Initial timing calibration

Freq accuracy + Env. changes

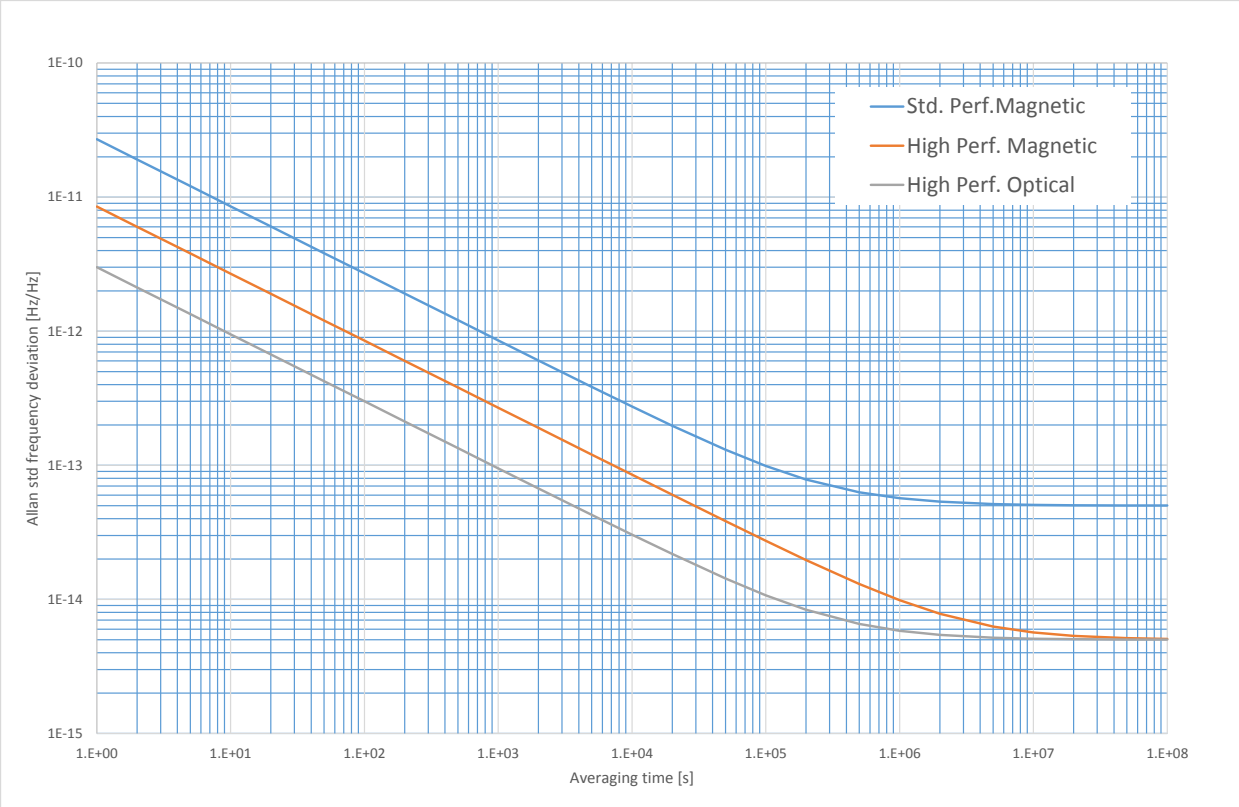
Freq linear drift

Noise timing error

$$\sigma_x(t) \cong \sigma_y(t) * t$$

- **T0** depends on timing reference, meas. resol. and noise
- **Accuracy** depends on reference accuracy, meas. resol. and noise, and **flicker frequency noise floor of the DUT**
- **Environmental sensitivities** are usually periodic variation of frequency, zero on average
- **Frequency drift** common in quartz and cell stds (Rb, maser), negl. for Cs
- **Intrinsic noise** sources **of the DUT (white and flicker FM)**

Frequency stability (ADEV)



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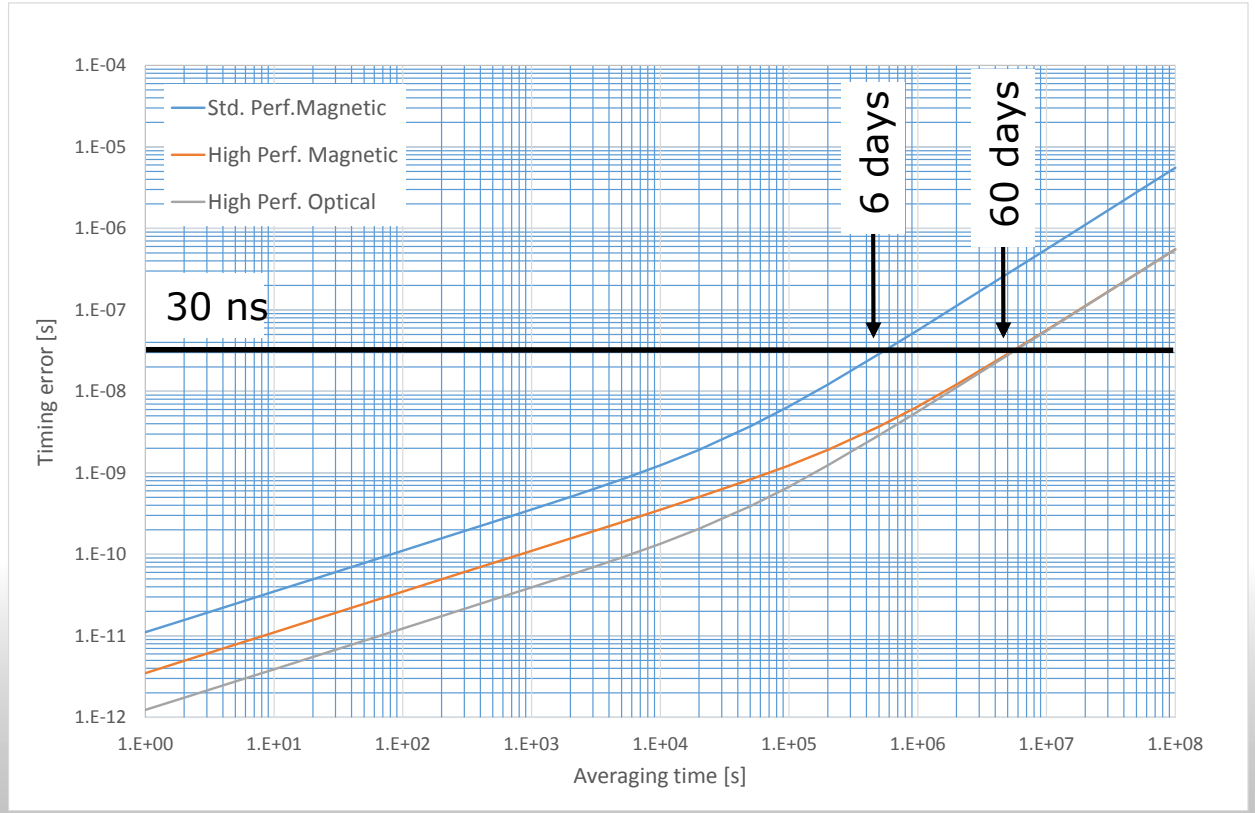
Timing error prediction



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Motivation for an Optical Cs clock

- **Improved performance (short and long-term stability)** for:
  - ePRTC applications (extended holdover period)
  - Metrology and time scales
  - Science (long-term stability of fundamental constants)
  - Inertial navigation (sub-marine, GNSS)

- **No compromise between lifetime and performance**
  - Same Cs reservoir capacity
  - Same Cs oven temperature
  - Same vacuum pumping capacity
  - Large improvement of Cs beam efficiency by laser optical pumping

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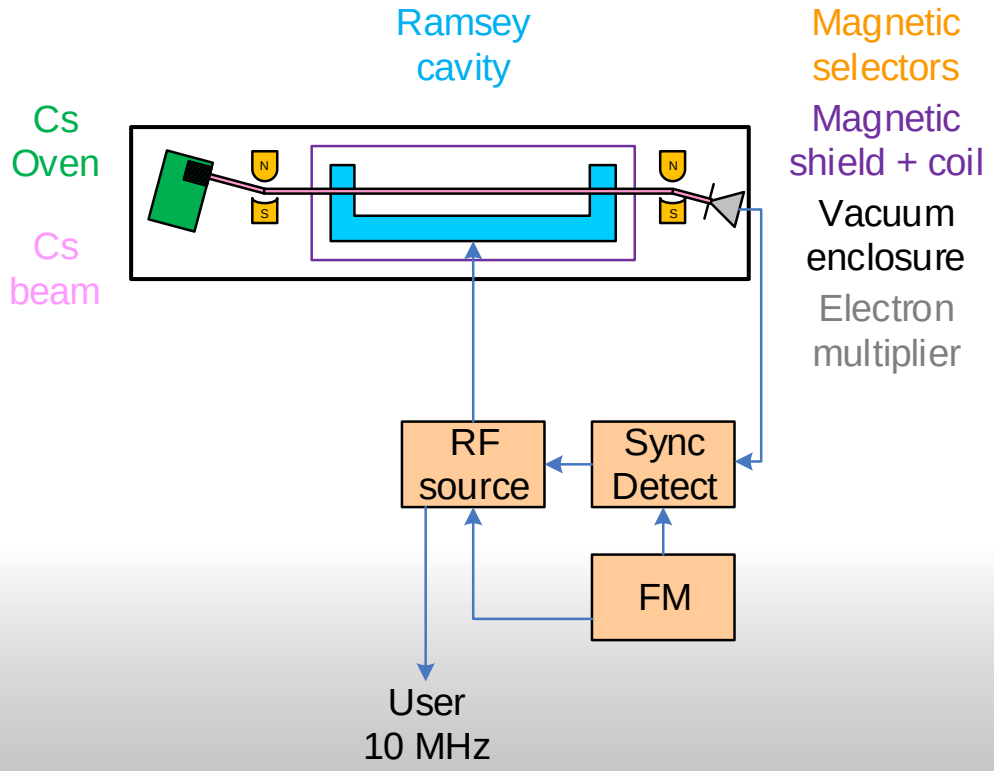
Magnetic Cesium clock operation



- **Cs beam** generated in the Cs oven (vacuum operation)
- Cs atoms state selection by **magnets**
- Cs clock frequency probing (9.192 GHz) in the **Ramsey cavity**
- Atoms detection and amplification by **electron multiplier** (vacuum)
- RF source servo loop using **atomic signal**

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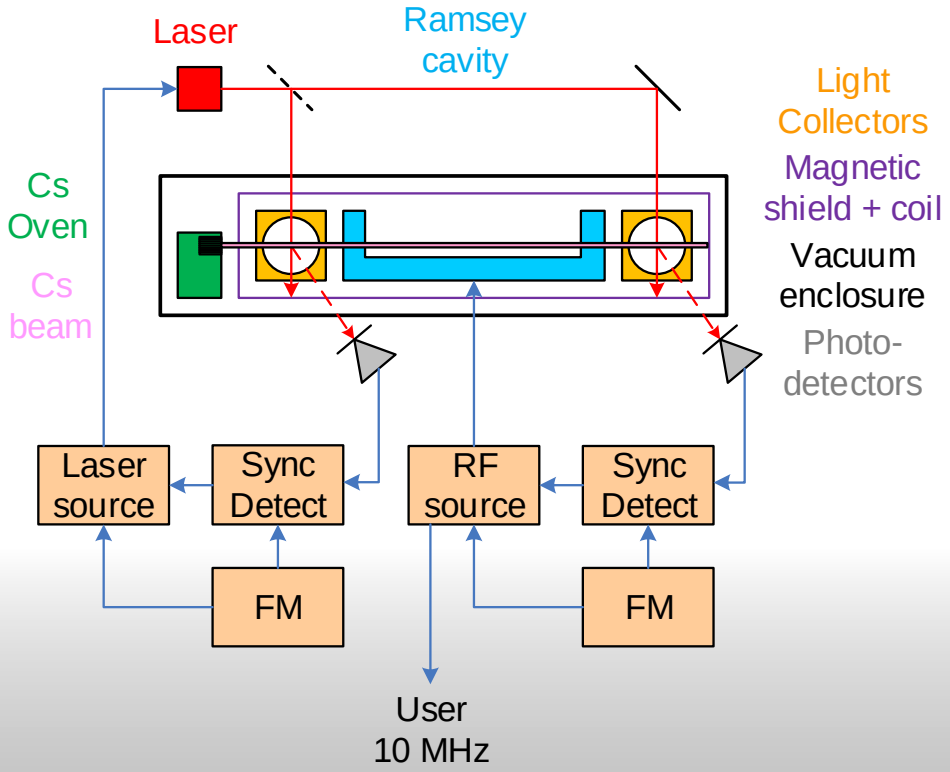
Optical Cesium clock operation



- **Cs beam** generated in the Cs oven (vacuum operation)
- Cs atoms state selection by **laser**
- Cs clock frequency probing (9.192 GHz) in the **Ramsey cavity**
- Atoms detection and amplification by **photodetector** (air)
- Laser and RF sources servo loops using **atomic signals**

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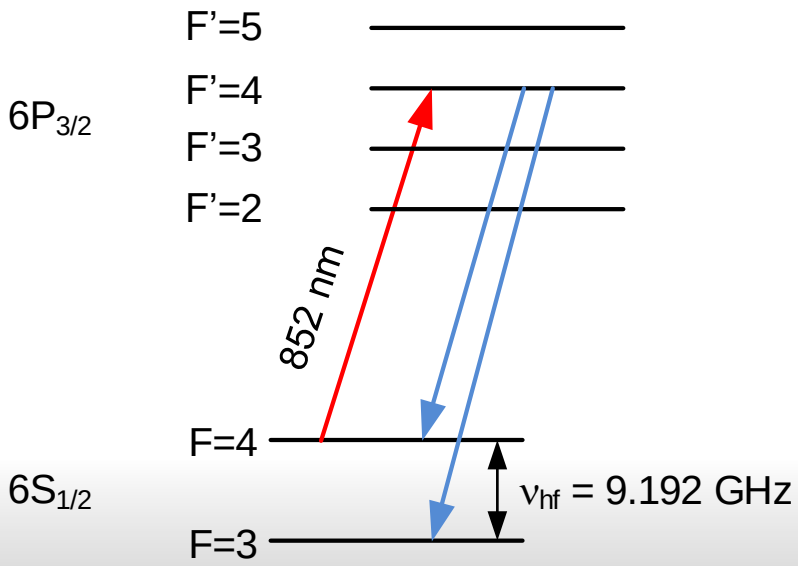
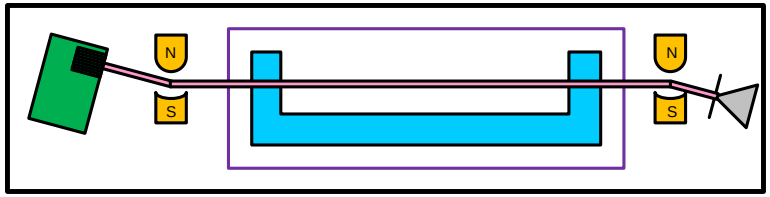
^{133}Cs atomic energy levels



- Stable **ground states** (F=3 and F=4)
- Switching between ground states F by **RF interaction 9.192 GHz**
- Unstable **excited states** (F'=2,3,4,5)
- Switching between ground states F and excited states F' by **laser interaction 852 nm** (or 351 THz)

Cesium clock: Magnetic vs. Optical



- Weak flux
  - Strong **velocity selection** (bent)
  - Magnetic deflection (**atoms kicked off**)
- Typical performances:
  - **2.7^{E}-11 $\tau^{-1/2}$**
  - 10 years
- **Stringent** alignment (bent beam)
- Critical component **under vacuum** (electron multiplier)

- High flux (x100)
  - **No velocity selection** (straight)
  - Optical pumping (**atoms reused**)
- Typical performances:
  - **2.7^{E}-12 $\tau^{-1/2}$**
  - 10 years
- **Relaxed** alignment (straight beam)
- Critical component **outside vacuum** (laser)

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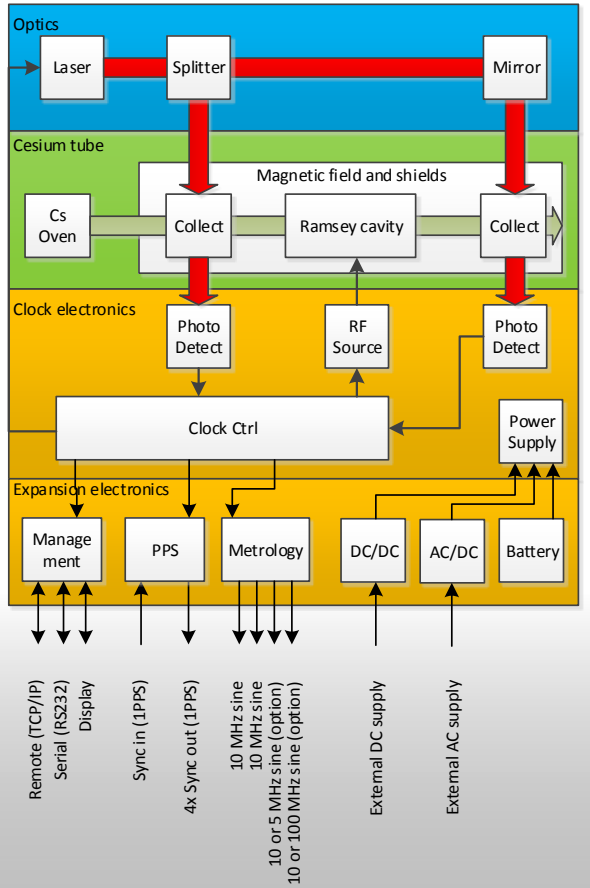
Clock functional bloc diagram



- Cs tube
  - Generate **Cs atomic beam** in ultra high vacuum enclosure
  - Electrical and optical feedthoughs for atomic signal generation
- Optics
  - Generate **2 optical beams** from **2 lasers modules** (cold redundancy)
- Electronics
  - **Cs core** for driving the Optics and the Cs tube
  - **External modules** for power supplies, management, signals outputs

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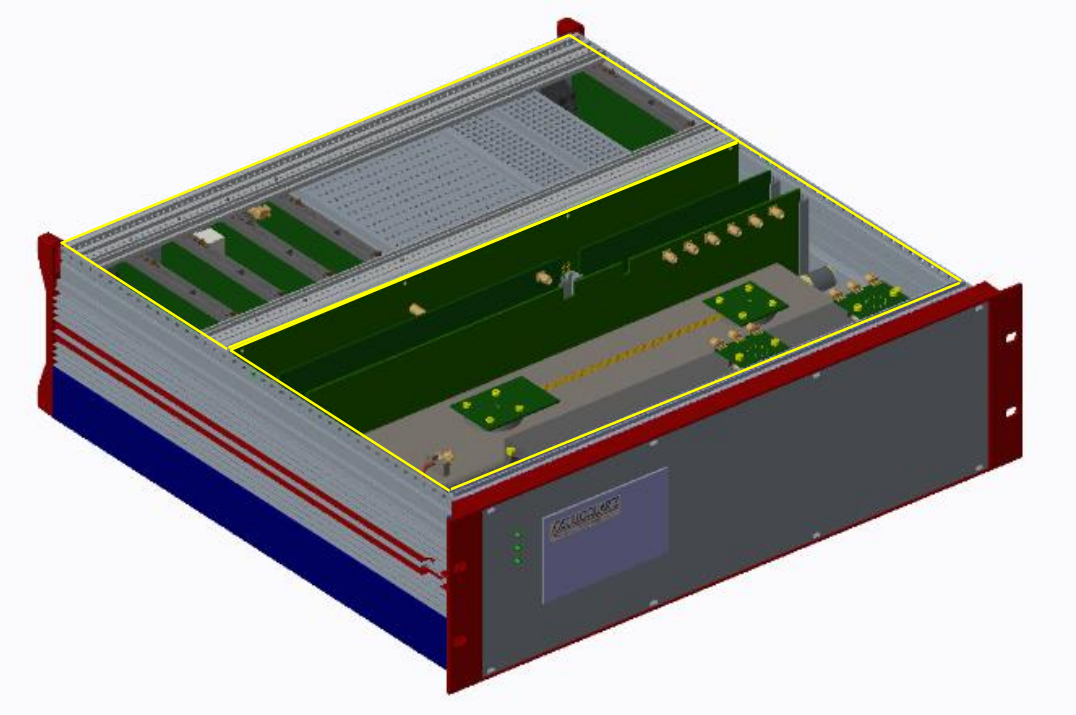
Cs clock design



- **19’’, 3U, 460 mm rack**
- **Cs core** is not customizable
- **Cs clock expansions** are customizable:
  - Sine waves outputs
  - 1PPS sync In/Out
  - Local & Remote management
  - Display
  - DC/AC power supplies
  - Internal battery

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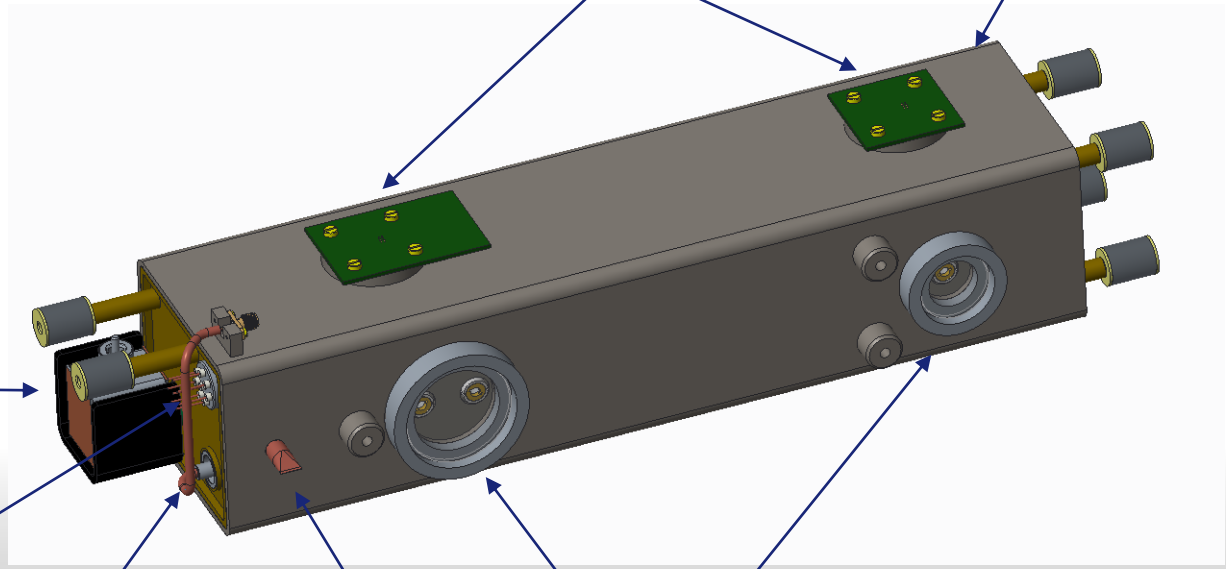
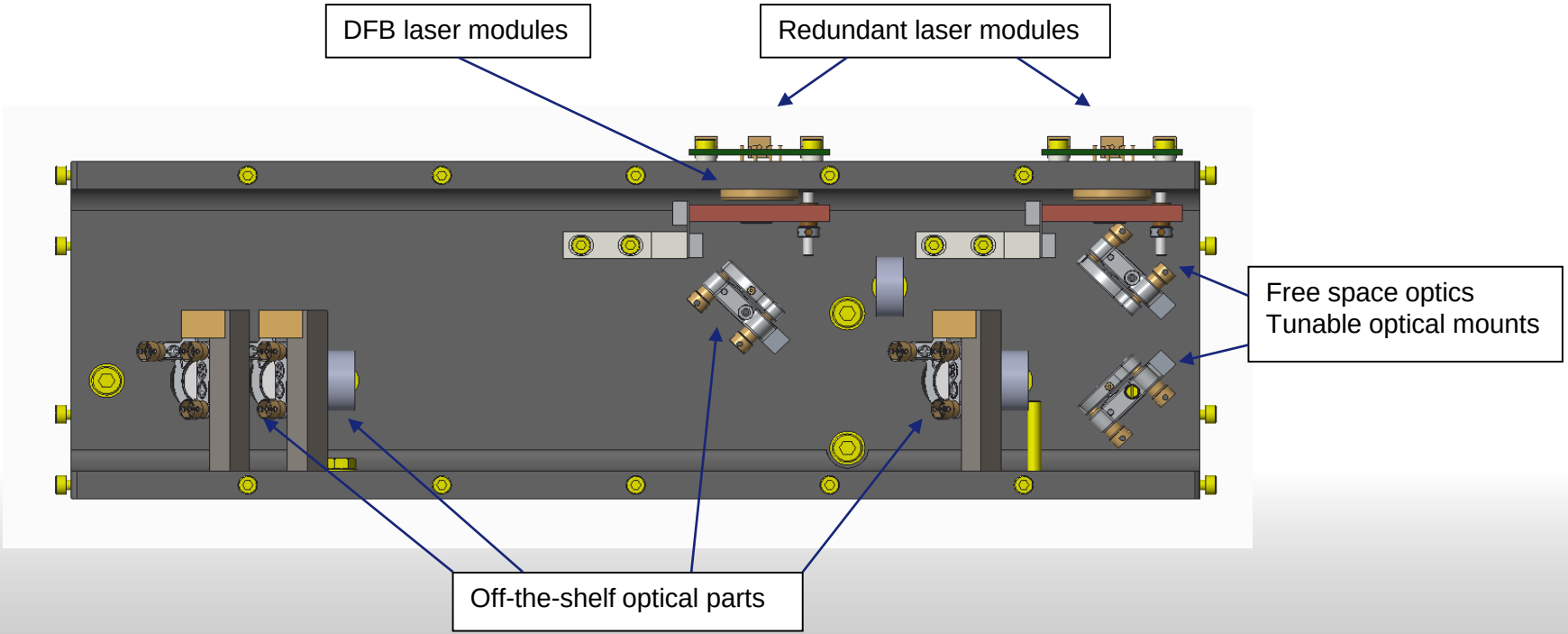
Cs tube design



Optics sub-system design



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Cs clock prototype

Laser frequency locking

- Laser current ramp (yellow)
- Atomic fluorescence signal (pink)
- FM demodulated atomic signal (green) used as **laser frequency error signal**
- Automatic **line identification algorithm**
- Automatic **laser frequency lock**

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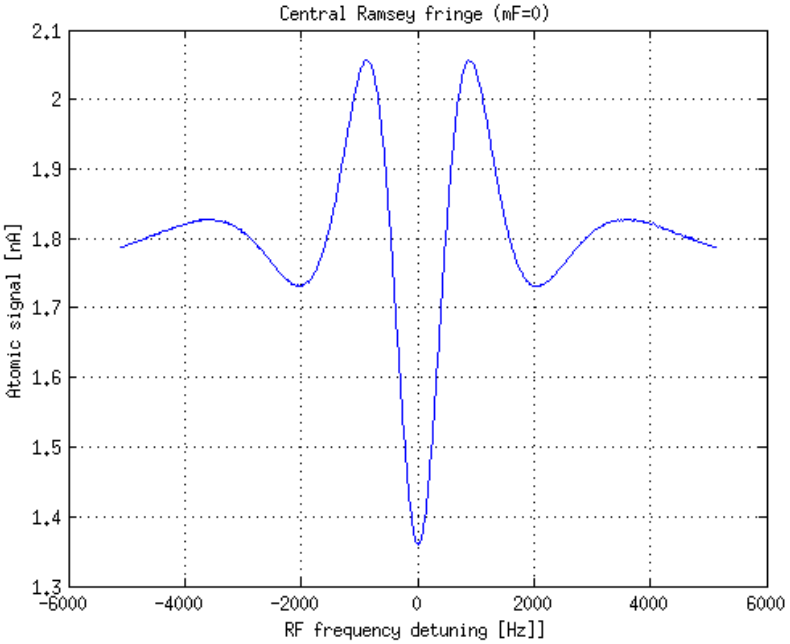
Ramsey fringe



- Atomic **RF frequency discrimination signal**
- **Inverted fringe** (minimum amplitude at resonance)
- Fringe amplitude
  - **700 pA**
- Signal/Noise
  - **18’500 $Hz^{1/2}$**
- Fringe linewidth
  - 740 Hz
- Atomic quality factor
  - **$12.4^{E}6$**

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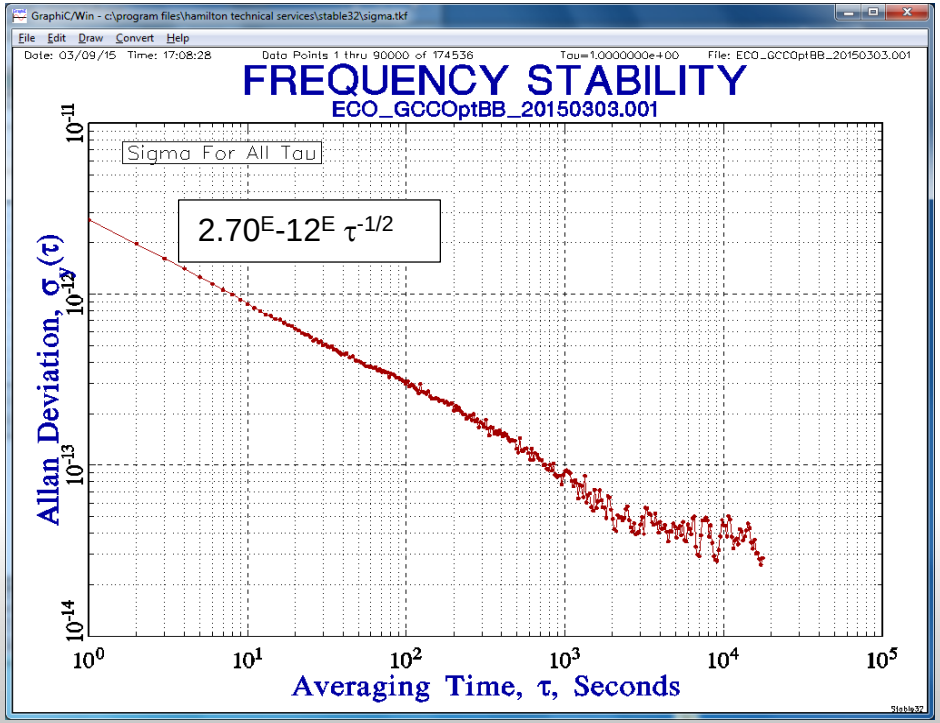
Short-term frequency stability



- Measured Allan deviation
  - **2.7^{E}-12 $\tau^{-1/2}$**
- Theoretical prediction
  - **2.4^{E}-12 $\tau^{-1/2}$**
  - Proves proper clock tuning parameters
- Performance limitations
  - Short-term: **Spurious light**
  - Long-term: **Single servo loop** in operation (OCXO)

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Conclusion

- Development of the world best commercial Cs beam clock
  - **Laser** optical pumping technology inside
  - **10x better** frequency stability (<3E-12 $\tau^{-1/2}$)
  - **Long lifetime** (10 years), no compromise with performance
- Standard 19” rack, 3U high, 460 mm deep
  - Management: serial, remote, display
  - Signals: 5, 10, 100 MHz, 1 PPS

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Thank You