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National Physical Laboratory

Optical cavity for ILC γ-γ collider: feasibility and development

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National Physical Laboratory (NPL)

--the UK's equivalent to NIST (USA), or PTB (Germany)

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NPL: Key Facts

- Located in **Teddington** --20 min. drive from Heathrow Airport
- **100+** years old
- Around **600 staff**
- Operated on behalf of the UK's Department of Trade and Industry by **NPL Management Ltd**, a wholly owned subsidiary of **SERCO plc**
- Projects run on commercial lines (**profit-and-loss** accounts) with full economic costings ("**FEC**") on infrastructure

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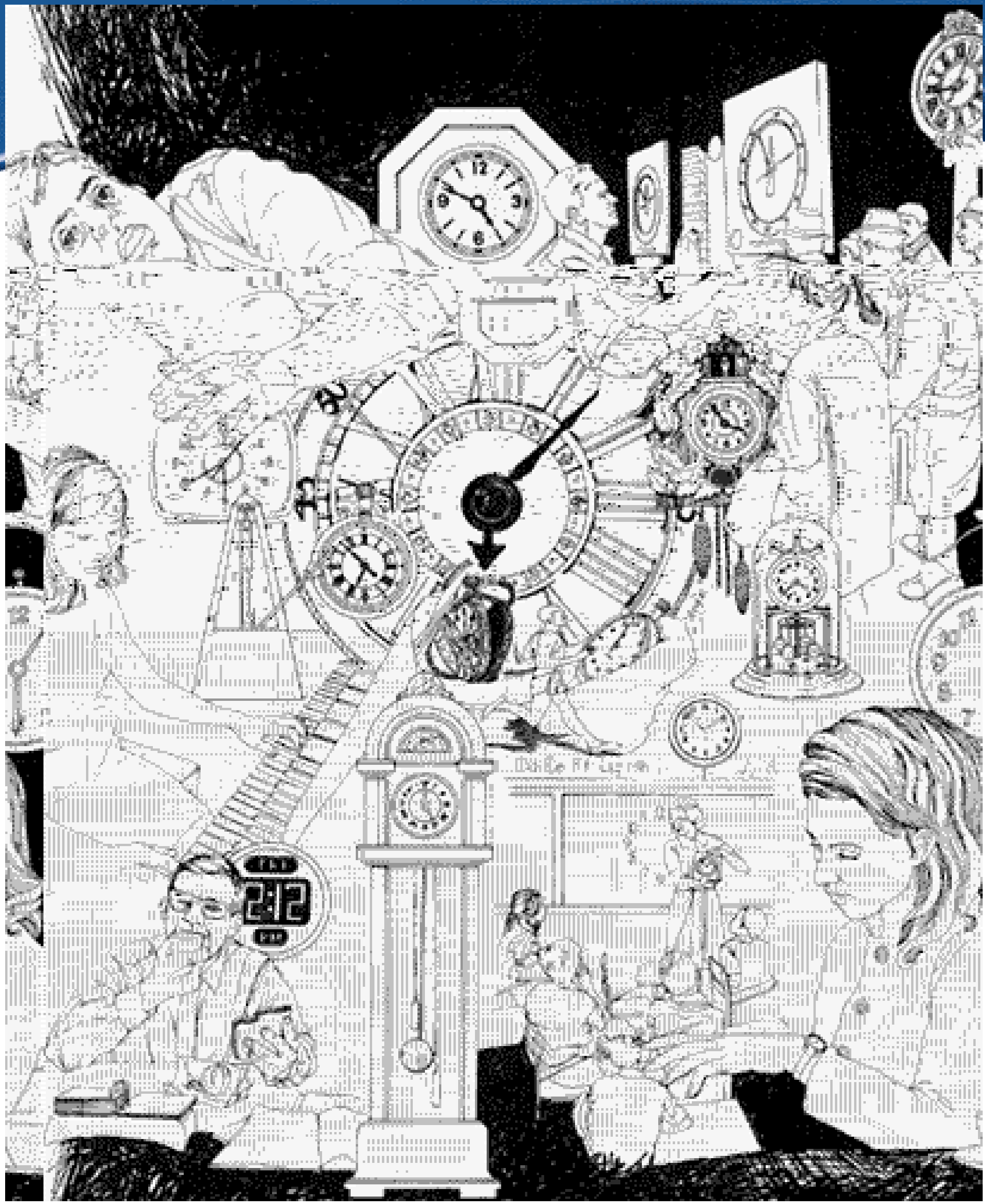
The art of (atomic) clock making ….

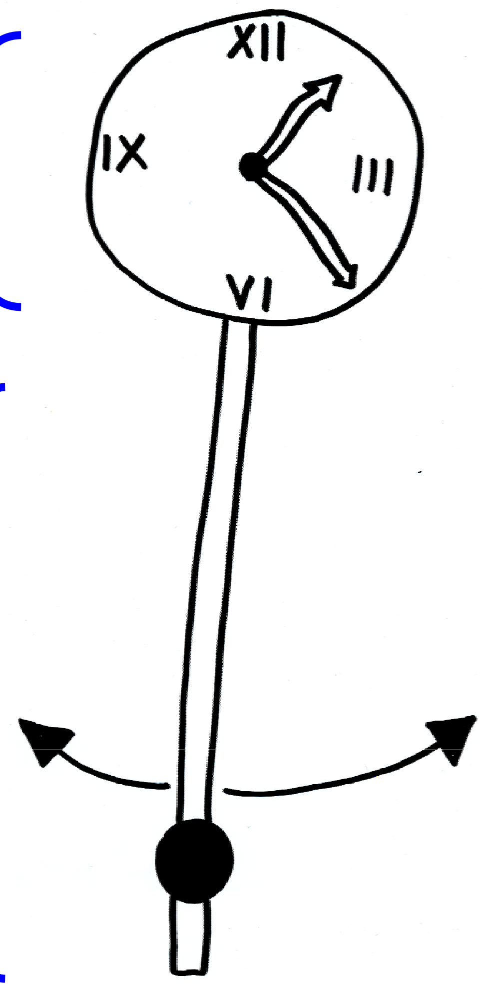


Courtesy NIST

Anatomy of a Clock (Why I am here!)

Counter

Oscillator = Resonator + Sustaining Circuit



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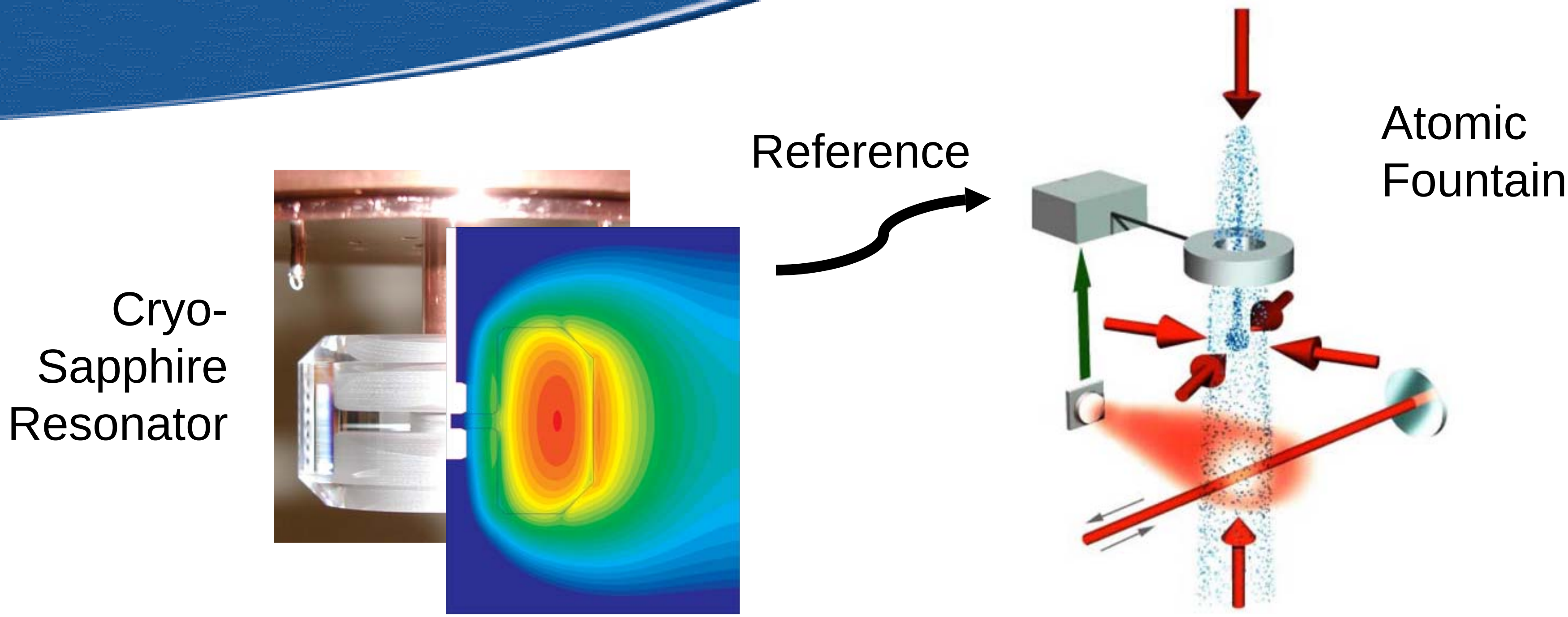
Ultrastable Oscillators for Microwave Atomic Frequency Standards (9.2 GHz)

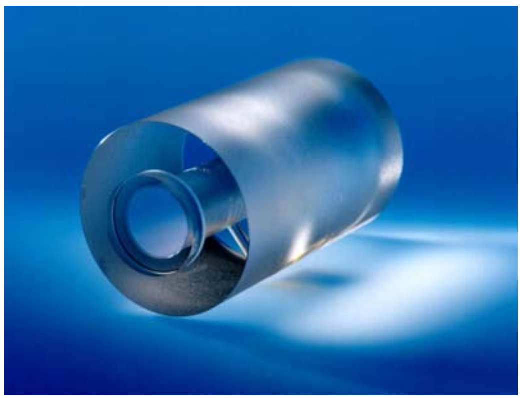


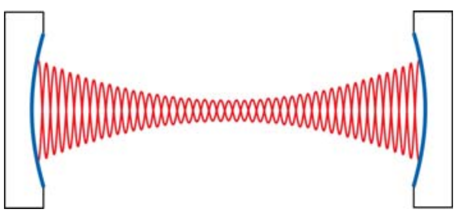
The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.

Ultrastable Oscillators for Optical Atomic Frequency Standards: “Cavity-Stabilized Lasers”

Passive:

Optical cavity

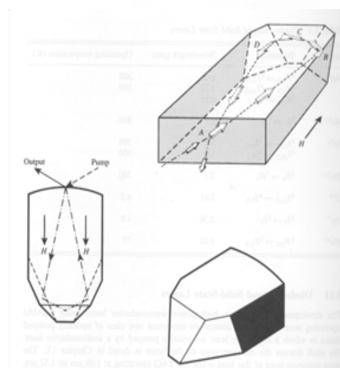




Lock

Active:

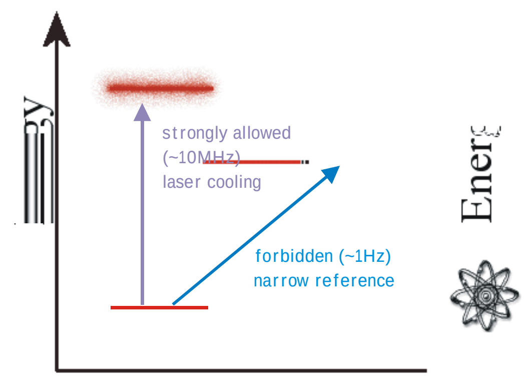
Voltage-tunable
CW probe laser



Reference
(“probe”)

Atomic:

Single trapped ion
($^{88}Sr^{+}$ or $^{171}Yb^{+}$)



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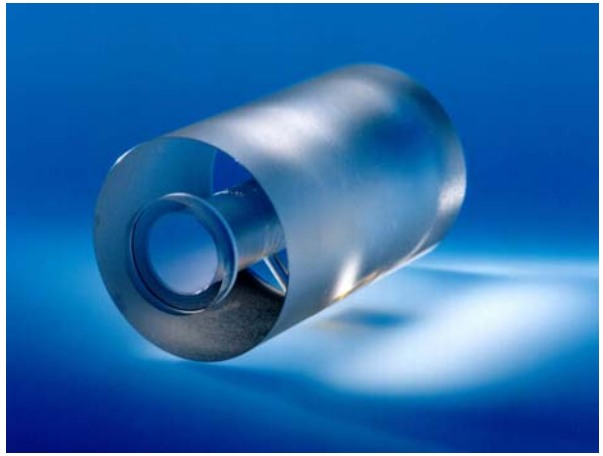
Optical Cavities ("Etalons"):

- Ultra-Low Expansion (ULE) Glass:



- Typical **length**: 10 cm

→Free spectral range ~ 1.5 GHz

- Typical **finesse**: 300,000

→ linewidth ~ 5 kHz

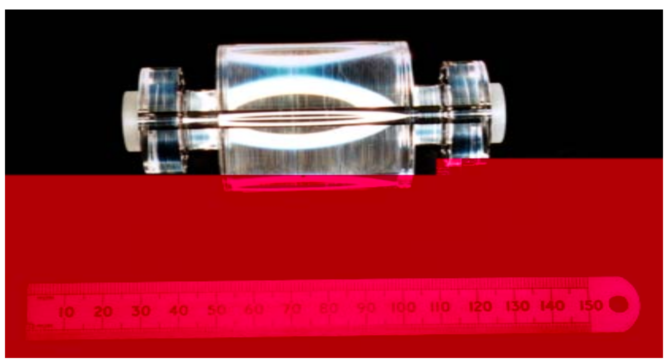
→ **power enhancement ~10^5**

[applied power (CW): 1 mW

intracavity power (CW): 100 W]

- Mirrors **optically contacted** to spacer

- Single-crystal Sapphire (cryogenic: ~4 K)



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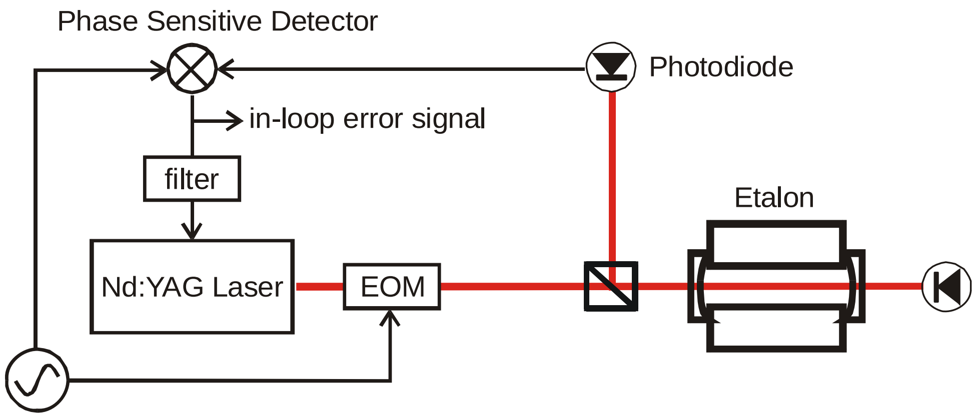
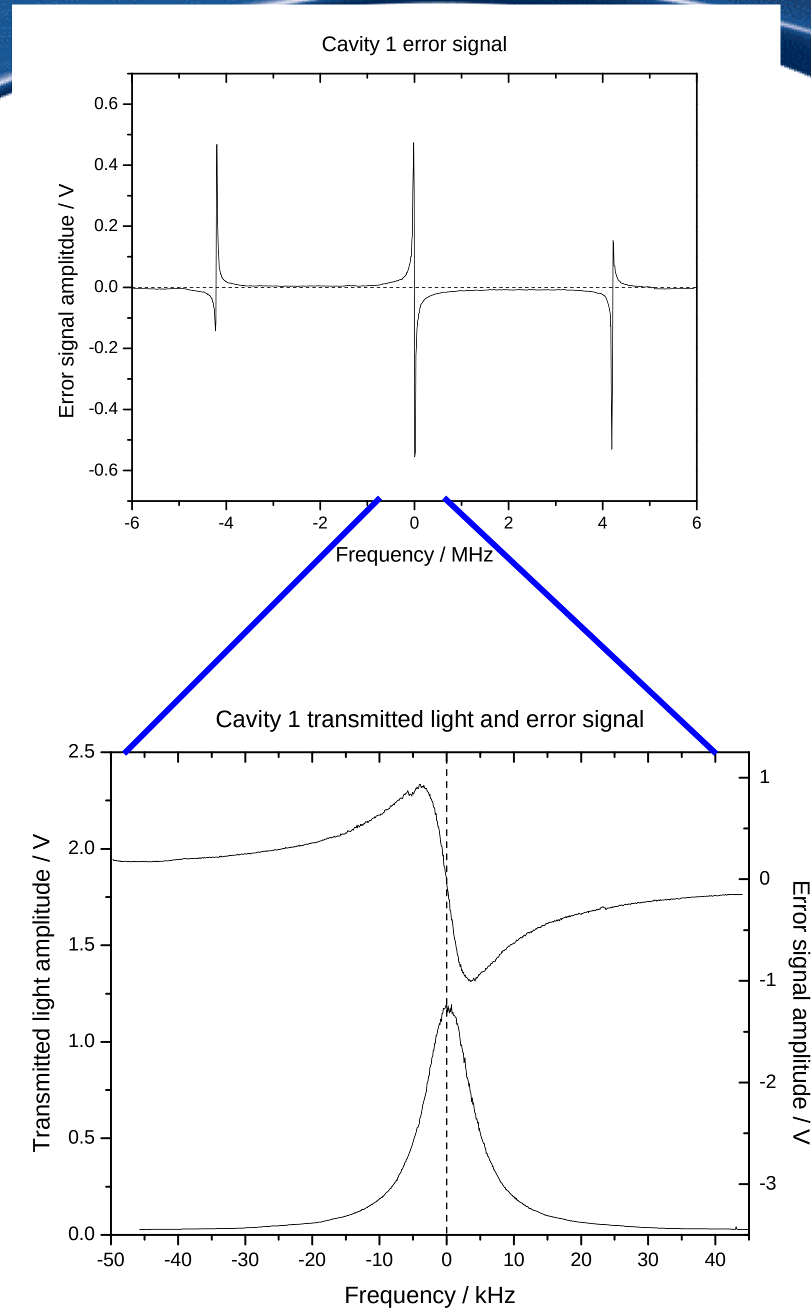
Pound-Drever-Hall Locking





Drever et al., *Appl. Phys. B,* **31**, 97 (1983)

- Typical sideband spacing 10 MHz
- Typical servo bandwidth 30 kHz

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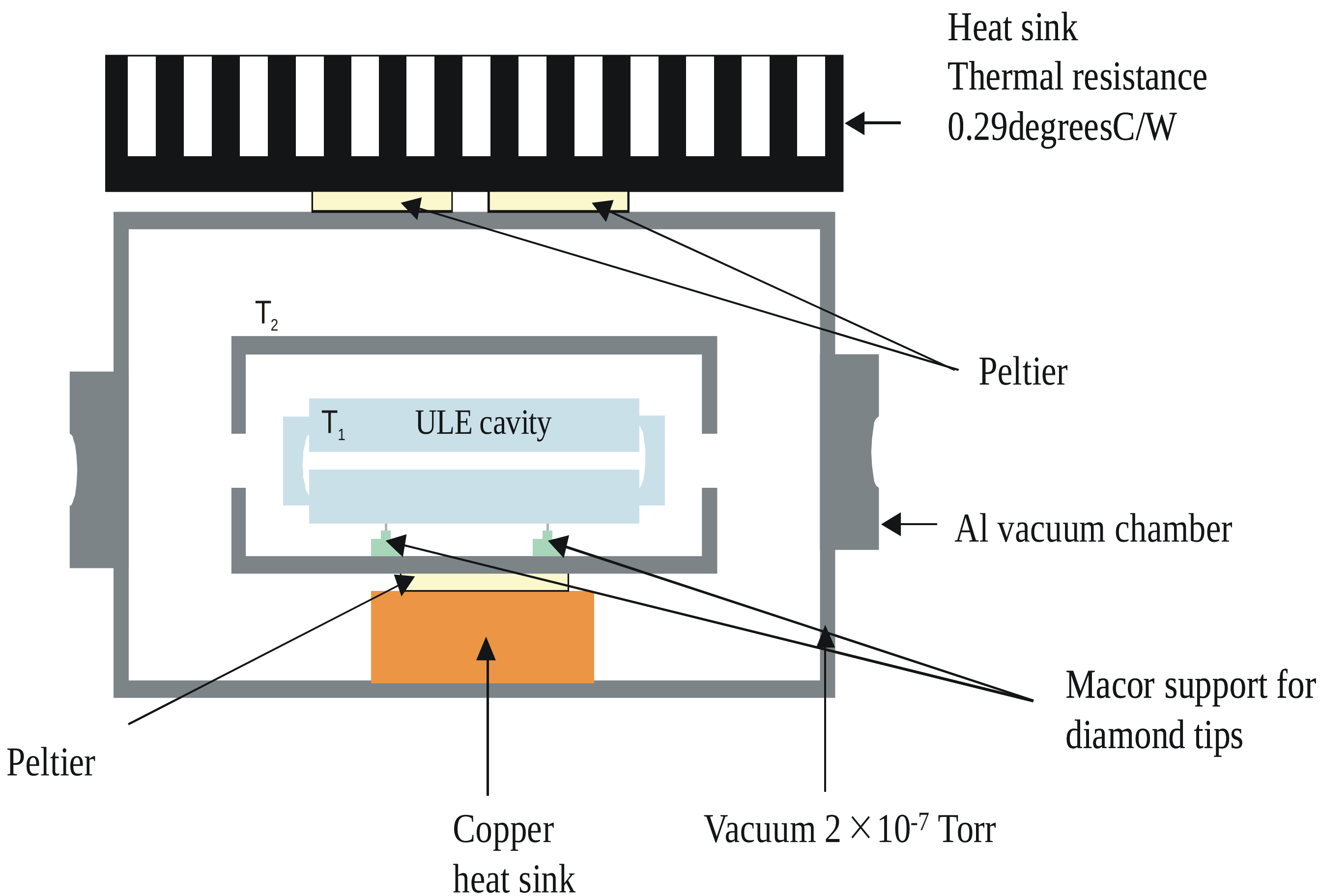
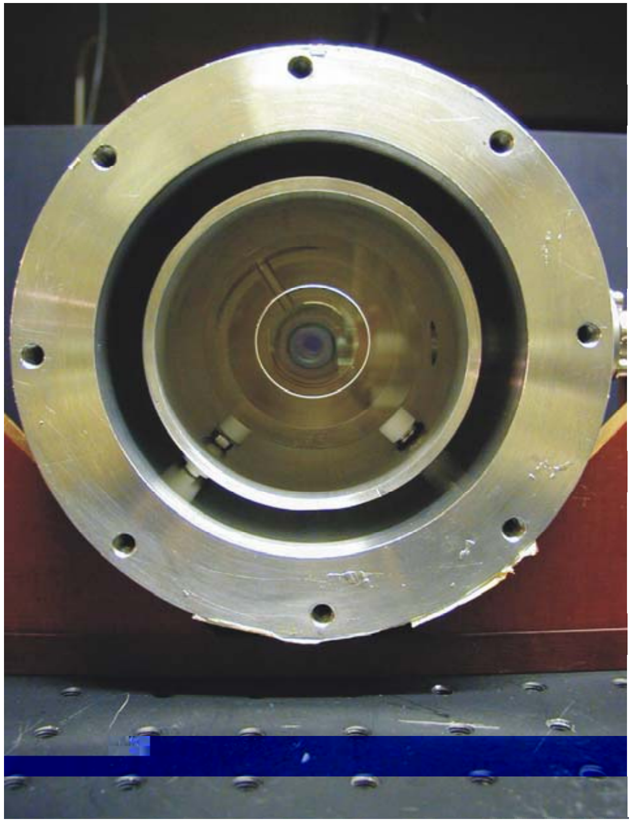
Temperature Control





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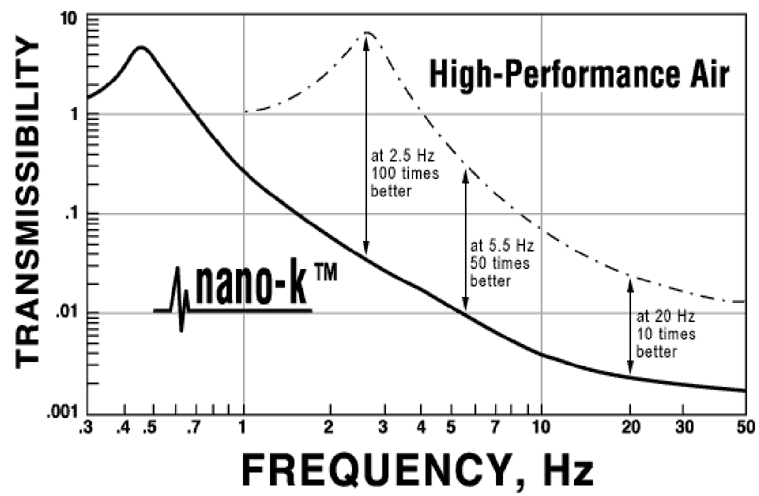
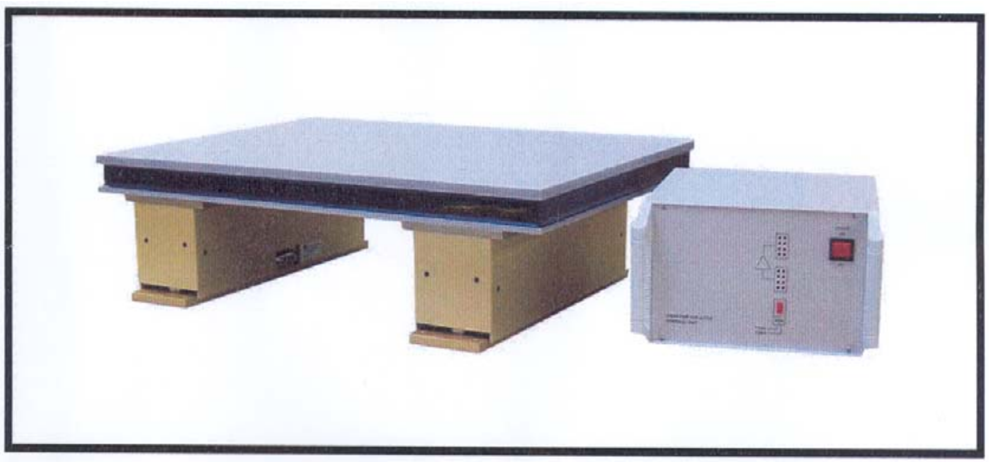
Cavity-Stabilized Laser: Optical Circuitry

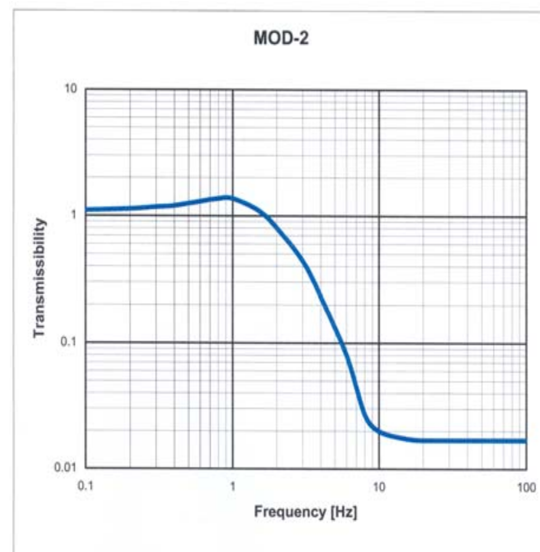
Vibration Reduction (Table-top Level)

Passive:



Active:





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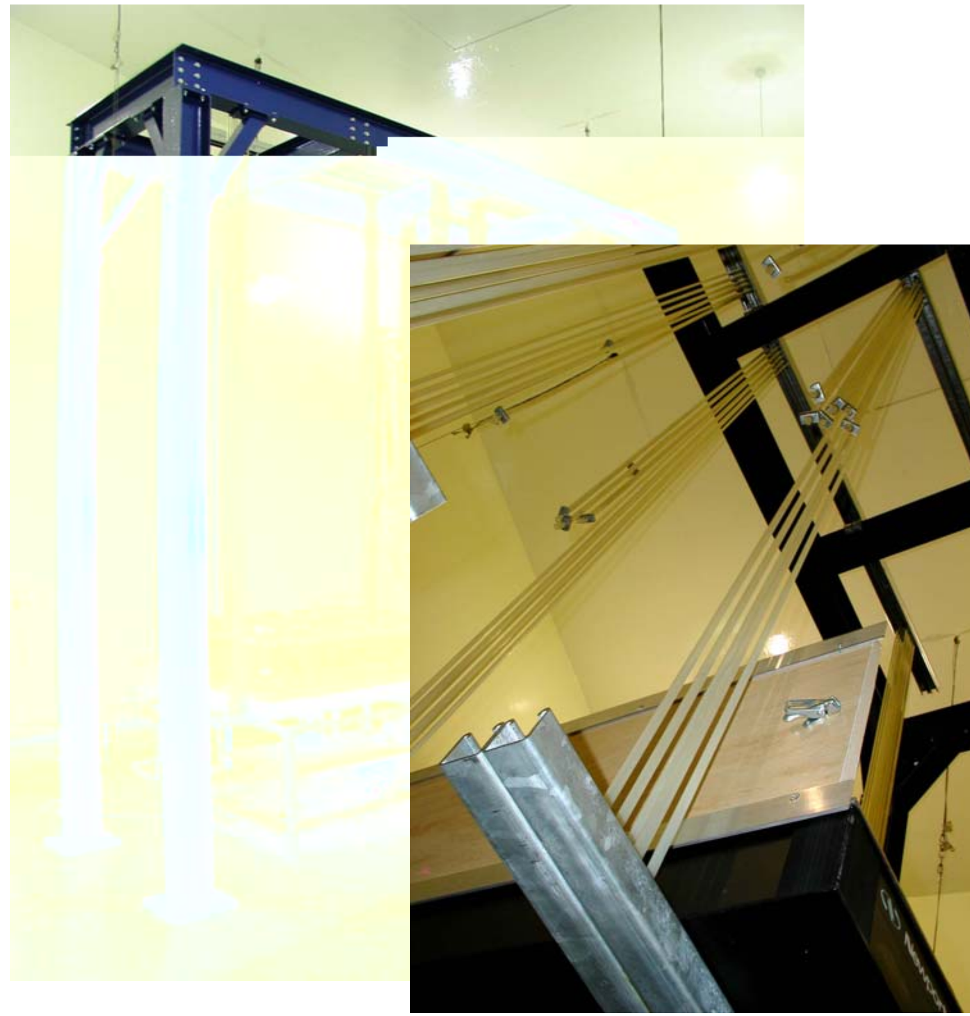
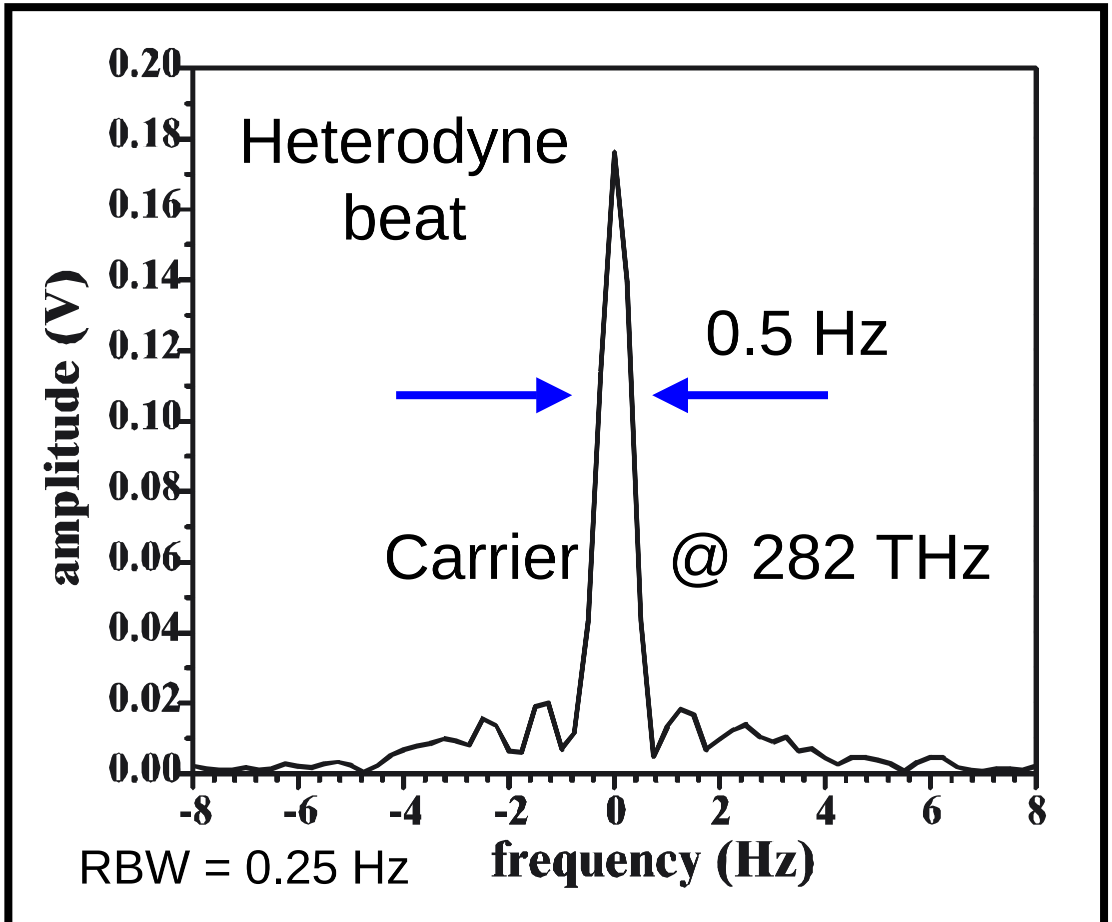
Mechanical and Acoustic Noise Isolation (Room Level)



Cavity-stabilized linewidth of laser source



- Laser linewidth (0.5 Hz) << cavity fringe width (10 kHz)
- Cavity length (10 cm) controlled to **1 part in 10^{15}**, *i.e.* **0.1 fm** !

Nd:YAG laser locked to **two** independent cavities on **separate** vibration isolation platforms.

S. Webster *et al*, Opt. Lett. **29**,1497 (2004)

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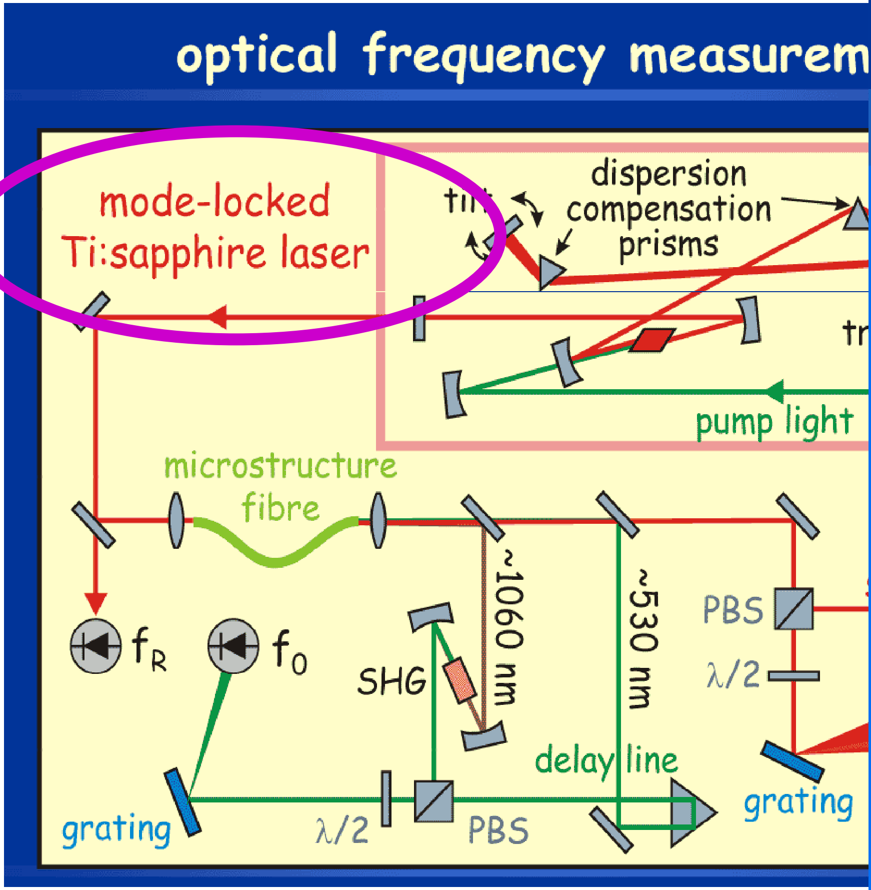
Pulsed lasers: Femtosecond Frequency Combs



- 88 MHz repetition rate
- comb span ~ 500 – 1100 nm
- H-maser/Cs fountain reference
- breadboard system; water cooling

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Feasibility of γ-γ Optical Cavity (as-proposed)

Comment by NPL laser jock:
"It's not just the cavity bit that scares me."

Main worries and doubts:

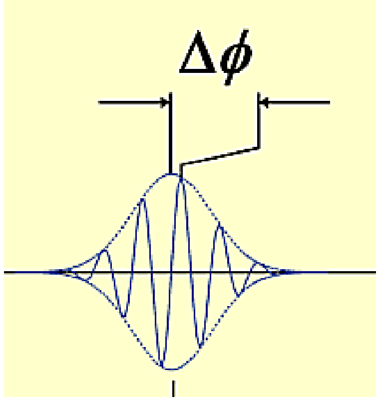
- **Big, complex** project [→ appropriate management (quality system) and tasking/contractualization (specifications, design reviews, …)]

- **Mechanical** infrastructure (impact on alignment/stability) –not defined

- **Pulsed, high-power effects** not experienced with low-power CW systems: radiation pressure, thermal heating, mirror damage –unknown territory for NPL

- **Dynamics** of cavity (mirrors/adaptive optics): degrees of freedom, servo bandwidths, accommodation of pulse-train duty cycle –little/no experience with multi-dimensional **adaptive optics**

Outstanding Questions (Selected)

- **Carrier-envelope offset phase** of optical pulse:  ?

- Quantification of **mechanical noise/drift** to be defeated by locking servos

- Locking/mode-matching with **mode degeneracy** of near-concentric cavity

- (Sufficiently low-loss) **adaptive optics** for pulsed high-power operation

- Quantification of **mirror damage** (thresholds, MTBFs, …)

- **Division of functionality/authority** between drive laser, optical cavity, and accelerator beam: tunable/steerable laser or movable cavity mirrors or transversally shifted accelerator beam?

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Stephen Webster's thoughts on g-g collider cavity I

[1] Cavity stability

Does the cavity geometry necessarily have to be near concentric? Can this requirement be relaxed? I agree that this will make locking difficult, apart from the stability issue. Can one get close enough to degeneracy such that there is a single (albeit broad) unresolved line?

[4] Feedback

General question: what is being locked to what? If the e-beam really is immutable, ultimately, one has to lock the cavity to the e-beam – both in position and in synchronism with the pulses/packets. How does one obtain a discriminant for this(these) lock(s)? To what extent can one rely on the passive stability of the support structure whatever form this may take? Are adaptive optics really necessary? – concede that this is probably the case if one has to actuate one of the massive mirrors.

Is adaptive optics compatible with highish (~1000) finesse?

[5] Hardware

Parabolic mirrors required: adds to difficulty and expense of manufacture.

I agree that the issue of maintaining polarisation – on which the scattering rate is highly dependent – and birefringence of the optical elements has been overlooked, and may be a major issue.

The Badalek report suggests the use of protective (and removable) glass plates in front of the mirrors to shield them against electrons and gamma radiation. –Circular polarization precludes orienting these plates at Brewsters angle (w.r.t. to *both* directiond of polarization).

This will have consequences for the finesse/cavity loading. Long-term exposure damage is a worry.

[6] Drive laser

The specification for the laser power/system required is unclear. General point: surely one should aim for as high a finesse as possible in order to minimise the power required of the seed laser. A range of figures for build-up/finesse are assumed at various points.

Trade-off between finesse, damage threshold and "speed" (low-dispersion) of mirrors …

Way forward I

Network (to relevant knowledge/expertise to **fill** existing **holes)**:

- Quantitative knowledge of **pulsed-power effects**
- Realistic specification for **drive laser** (M^2 etc)
- Existing, relevant designs of **adaptive optics**

Survey:

- Know thine enemy --specification and/or **measurement of** cavities' likely mechanical/acoustic/thermal/gaseous/particulate **environment**

Simulate:

- Linear model for cavities' in-loop **dynamical response** to pertubations (beyond quasistatic approach w.r.t. photo-mechanical shock)

→ **Modularization and interfaces ("white paper"):** Overall design and compatible, individual **specifications** for drive laser, optical cavity and accelerator beam

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Way Forward II ("Experimental Test-Beds")

- Damage testing of mirror samples

- CW drive laser with length adjustable cavity (close to concentricity): longitudinal lock, basic transverse beam-pointing (low bandwidth), quantify mode matching and cavity build-up

- Migrate to mode-locked drive laser: dispersion correction, temporal profilometry (e.g. "FROG")

- Incorporate spatial profilometry (i.e. mode-waist imaging) and adaptive optics (high bandwidth)

- Scale model of complete system

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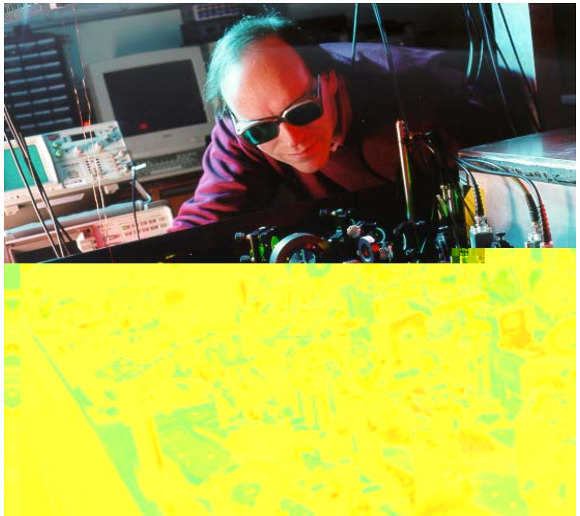
NPL Participation



• Staff with relevant skills and existing capabilities/facilities in optical metrology and cavity-stabilized lasers

But:

• Alignment required with NPL's core business: "Measurement Science"

• UK domestic issue: funding "wall" between DTI and EPSRC/PPARC

• Timing: most projects at NPL formulated within 3-year research programmes

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