EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Institute for Theoretical Physics

The case for measuring the gravitational field of the LHC beam

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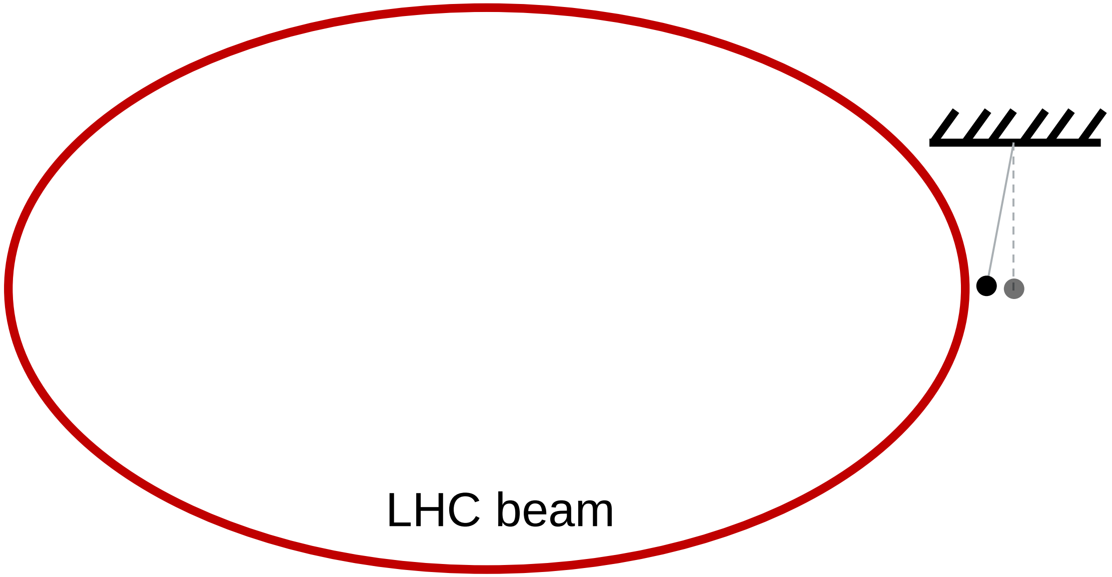
University of Southampton

Proposal

To measure the gravitational near field of the LHC proton beam



LHC beam

ultra-sensitive opto-mechanical acceleration sensor

1. The science case
2. Why LHC?
3. How?
4. Technical challenges
5. Links to other proposals

The science case

- Lab-scale test of GR in entirely new parameter regime
  - ultrarelativistic source of gravity (in the sense of special relativity)

$$T_{\mu\nu} \simeq \mathcal{E} \begin{pmatrix} \boxed{1} & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix}$$

- Non-relativistic sensor
  - sensitive to T_{00} component
  - Newtonian gravity, but source of gravity = almost pure kinetic energy rather than mass
  - $1/r$ decay of gravitational force rather than $1/r^2$
  - mm scale distance

- Tests of GR so far:
  - on astrophysical scales (planetary orbits, BH or NS mergers, grav. lensing)
  - gravitational redshift experiments
  - precision tests of equivalence principle
  - Yukawa-type deviations from 1/r potential on small distances (down to 56μm)?

… all with mass dominating as source

The science case

- Test alternative theories against experiment
  - e.g. Brans-Dicke theory
  - theories with free energy as source
  - in general, parametrized post-Newtonian theories, 10 parameters

- Medium- and long term perspectives:
  - cooling and squeezing of (ion?) beam => non-classical source of gravity?

Why LHC?

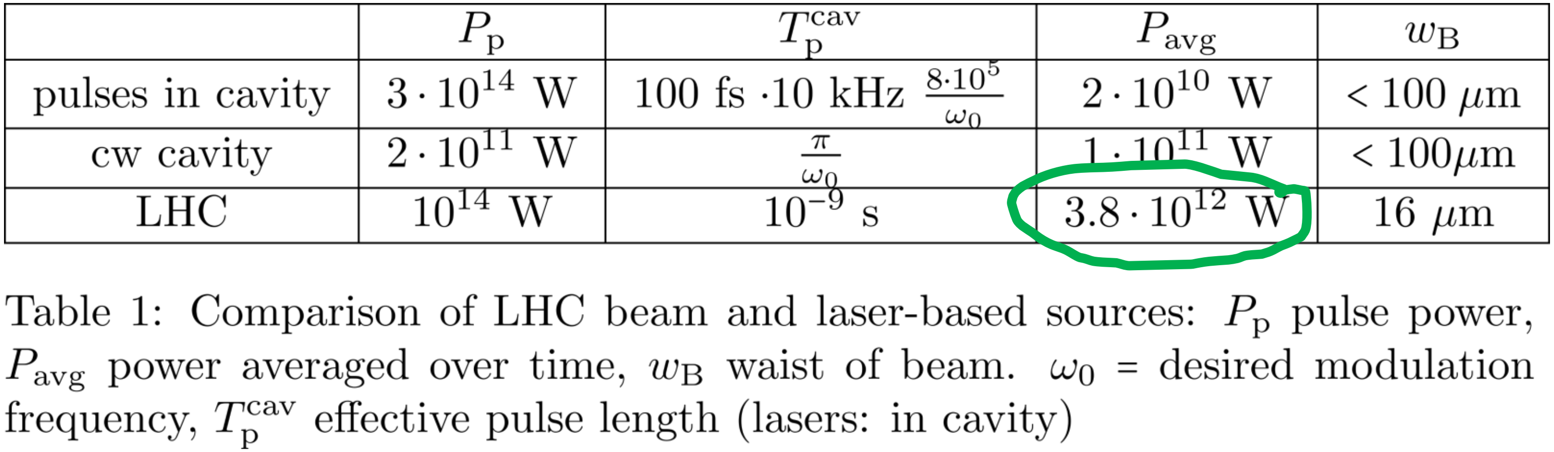
- Alternatives:
  - high power lasers (source = e.m. energy)
  - other accelerators

- What counts is average power and distance from beam:

Radial acceleration of non-relativistic probe mass:

$$a_\rho = -\frac{4GP_{\mathrm{av}}}{c^3}\frac{1}{\rho} \qquad \simeq -1.9\cdot 10^{-20}\,\mathrm{m/s^2}\ \text{at}\ \rho = 2\,\mathrm{mm}$$

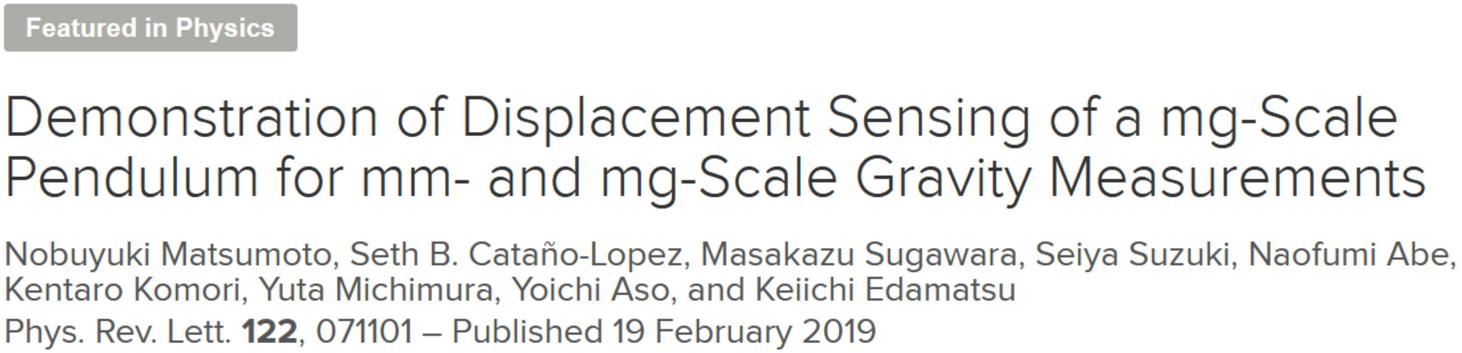
laser



	P_{p}	$T_{\mathrm{p}}^{\mathrm{cav}}$	P_{avg}	w_{B}
pulses in cavity	$3\cdot10^{14}$ W	100 fs ·10 kHz $\frac{8\cdot10^5}{\omega_0}$	$2\cdot10^{10}$ W	$< 100\ \mu$m
cw cavity	$2\cdot10^{11}$ W	$\frac{\pi}{\omega_0}$	$1\cdot10^{11}$ W	$< 100\mu$m
LHC	10^{14} W	10^{-9} s	$3.8\cdot10^{12}$ W	16 μm

Table 1: Comparison of LHC beam and laser-based sources: P_{p} pulse power, P_{avg} power averaged over time, w_{B} waist of beam. ω_0 = desired modulation frequency, $T_{\mathrm{p}}^{\mathrm{cav}}$ effective pulse length (lasers: in cavity)

Detectors: mg-scale, monolithic pendulum

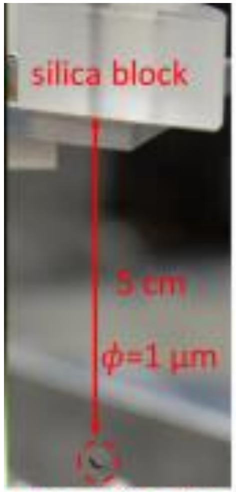


Featured in Physics

Demonstration of Displacement Sensing of a mg-Scale Pendulum for mm- and mg-Scale Gravity Measurements

Nobuyuki Matsumoto, Seth B. Cataño-Lopez, Masakazu Sugawara, Seiya Suzuki, Naofumi Abe, Kentaro Komori, Yuta Michimura, Yoichi Aso, and Keiichi Edamatsu

Phys. Rev. Lett. **122**, 071101 – Published 19 February 2019



7 mg silica disk

Catano-Lopez et al. 2020

- $Q_m = 10^5$, $\omega_m = 2\pi \times 4.4$ Hz, improved version with $Q_m = 2 \times 10^6$
- Optical spring => resonance frequency $400\ \mathrm{Hz} < \frac{\omega_0}{2\pi} < 1800\ \mathrm{Hz}$
  Feedback cooling compensates heating from optical spring, reduces Q
- Starting from room temperature, demonstrated
  $\omega_0 = 2\pi \cdot 280\,\mathrm{Hz} \qquad Q_{\mathrm{fb}} = 250 \qquad T_{\mathrm{fb}} \simeq \mathrm{mK}$
  Displacement sensitivity $3 \cdot 10^{-14}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$
- Expect displacement from LHC: ~ 10^{-24}m (distance 2mm, full resonant amplitude)
  But gain ~ 1000 from week-long measurement, ~1000 from nK cooling of pendulum mode in noise reduction

Optimization of pendulum setup

Total signal/noise ratio:

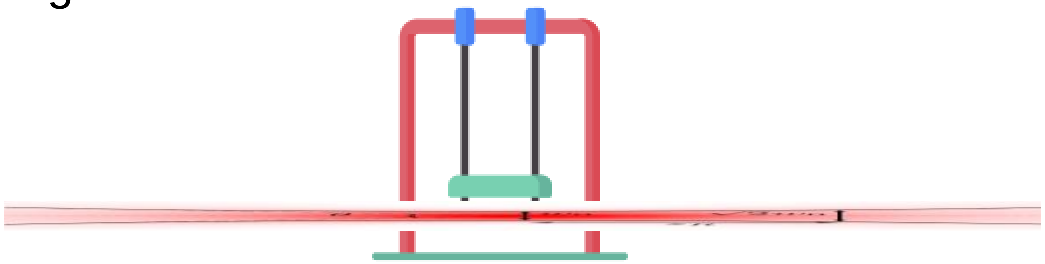
$$
\begin{aligned}
S/N &= x_{\mathrm{grav}}\left(1-\exp(-\omega_0(\tau_{\mathrm{tot}}-\tau_{\mathrm{m}})/(2Q_{\mathrm{fb}}))\right)\frac{\sqrt{\tau_{\mathrm{m}}}}{\sqrt{\bar{S}_{\mathrm{xx,tot}}}}\\
&\simeq 0.01\,\frac{\left(1-e^{((\tau_{\mathrm{m}}-\tau_{\mathrm{tot}})\frac{\omega_0}{2Q_{\mathrm{fb}}}}\right)\sqrt{Q_{\mathrm{fb}}\,m\,\tau_{\mathrm{m}}}}{\omega_0\sqrt{1+\coth\frac{4\cdot10^{-12}\omega_0}{T_{\mathrm{fb}}}}}
\end{aligned}
$$

- Thermal + quantum noise
- SI units for all quantities
- ρ_{min} = 100 μm from LHC beam line center

$\tau_{\mathrm{tot}} = \tau_{\mathrm{r}} + \tau_{\mathrm{m}}$ rise time + measurement time

cylindrical pendulum mass, up to 50cm long, max mass to maintain ρ_{min}

=> m = 33 mg for Si



Optimization

- Max S/N over τ_m, ω_0, Q_{fb}, T_{fb} with τ_{tot} =1 week, $1 \leq \omega_0 \leq 10^4$/s, $1 \leq Q_{fb} \leq 10^8$, 1 nK $\leq T_{fb}$

=> S/N ≈ 0.6

for $\tau_m = 3 \times 10^5$ s, $\omega_0 = 2\pi \times 0.16$Hz, T_{fb} = 1nK, $Q_{fb} = 1.2 \times 10^5$

relatively flat max, can accomodate technical constraints

- Futher improvements, but ρ_{min} = 2 mm :
  - High-luminosity LHC => factor 2 in average power
  - Tungsten as material of pendulum body (→ m=98 g)

=> S/N ≈ 6.1

Technical Challenges

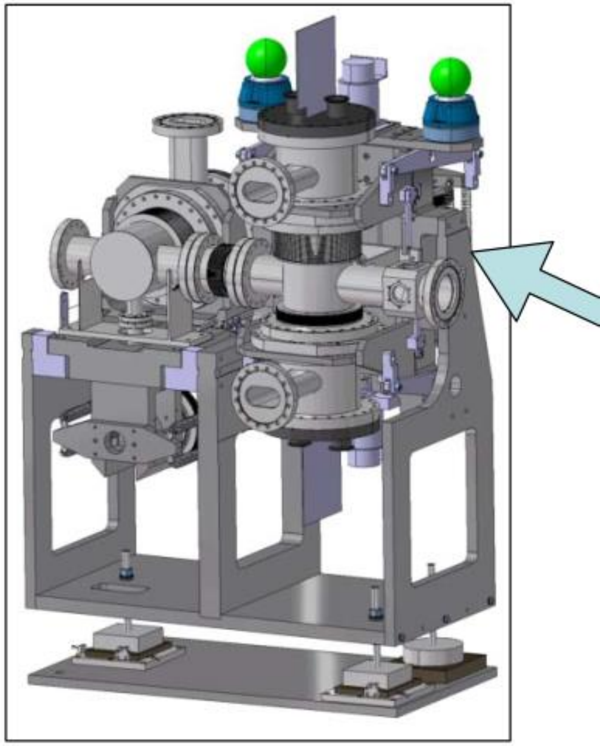
1. Getting close to beam
   - avoid beam exposure
   - Roman pot design (secondary vacuum chamber in main vacuum)
   - convex pendulum design?

2. Cooling of detector:
   - cryostat (50mK) + electronic feedback cooling
   - optical spring

3. Shielding of e.m. forces from beam

4. Radioactive environment, beam halo
   -> first discussion with Stefano Redaelli

5. Beam modulation (~kHz)



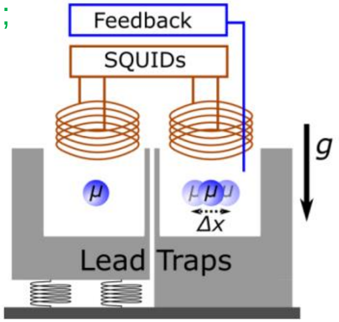
M. Orionno et al. EPAC 2006

Alternative detectors – connection to DRD5 / RDq technology developement

- Network of sensors
  - larger distance from beam, but many along the beam?
  - coherent averaging, S/N~ N_{sensor} DB, S. Popescu (2014); JME Fraisse, DB (2015) (+ new theory work ongoing with Maria M. Marchese, Stefan Nimmrichter, DB, D. Rätzel)
  - squeezed quantum noise ?
  - digital filtering, precisely known time-dependent signal?

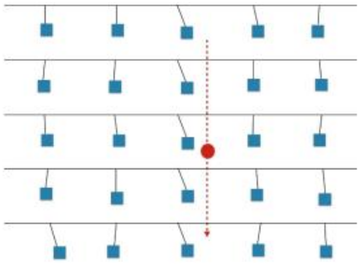
- Suspended (nano-?)magnets in superconducting trap Horizon 2020 project
  - projected acceleration sensitivity 10^{-14} g/Hz$^{1/2}$
  - UHV
  - superconducting electronics, SQUID read-out of displacements
  - natural electric field shielding, radiation protection ?

C. Timberlake et al. arXiv 2110.02263; A. Vinante, C. Timberlake, H. Ulbricht review (2022);



- Connection to wind-chime dark-matter detector

D. Carney et al. arXiv 1903.00492



Conclusion

- Measurement of gravitational near-field of LHC beam with optomechanical detector(s) appears to be possible in principle in near future.

- Would allow test of GR and alternative gravity theories in a completely new parameter regime on short distances in a lab experiment: kinetic energy as source!

- Substantial technological hurdles need to be overcome – let’s join forces !

- Long-term perspective: cooled and squeezed particle beam as quantum source of gravity
  - Felix Spengler, Dennis Rätzel, DB, New J. Phys. 24 (2022) 053021
  - Fabienne Schneiter, Dennis Rätzel, DB, Class. Quant. Grav. 35, 195007 (2018) and 36, 205007 (2019)

European Commission

Marie Sklodowska-Curie Action IF program –
Project-Name ”Phononic Quantum Sensors for Gravity”
(PhoQuS-G) – Grant-Number 832250

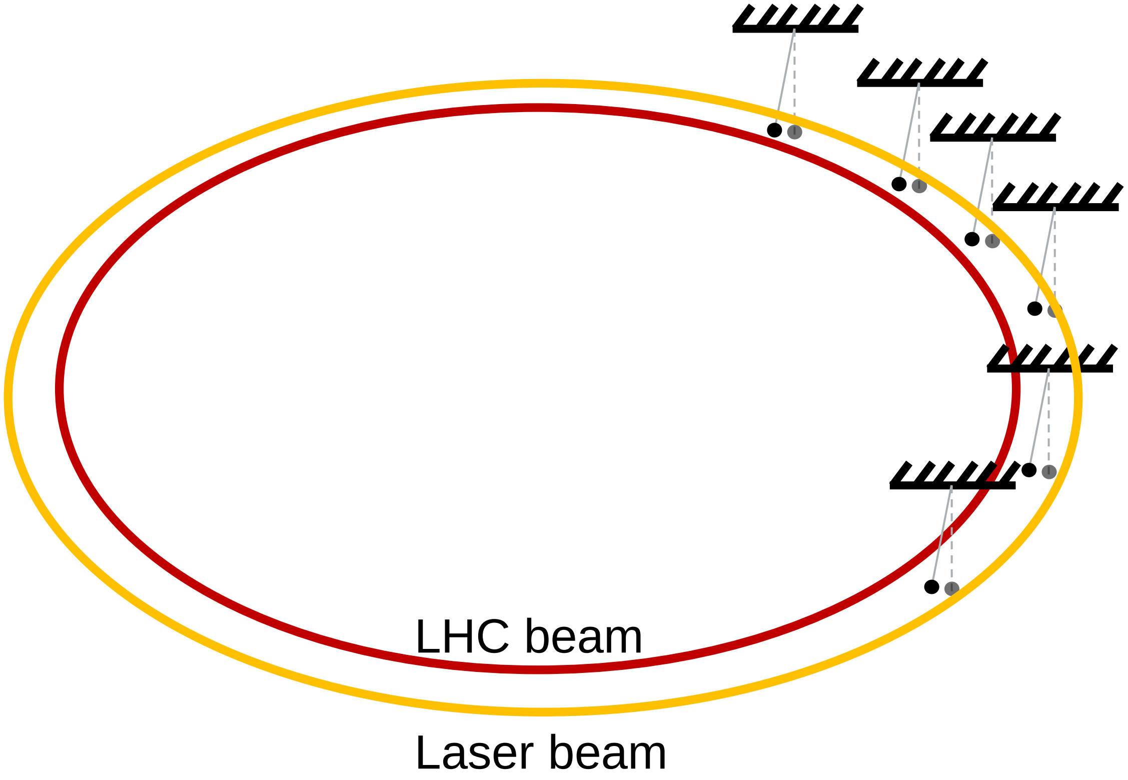
Alexander von Humboldt
Stiftung/Foundation

Feodor Lynen Research Fellowship

Backup

Coherent averaging

DB, S. Popescu (2014); JME Fraisse, DB (2015);



- Phase coherent addition of signal from N detectors by coupling to a common oscillator, e.g. mode of a ring laser.

- Expect S/N improvement ~ N rather than ~$N^{1/2}$

new theory work ongoing with Maria M. Marchese, Stefan Nimmrichter, DB, D. Rätzel

Sources 1: Modulated cw lasers + cavity

- Source high-power cw laser into high-finesse cavity

$$P_{\mathrm{cav}}^{\mathrm{max}} = \frac{2F}{\pi} P_{\mathrm{pump}}$$

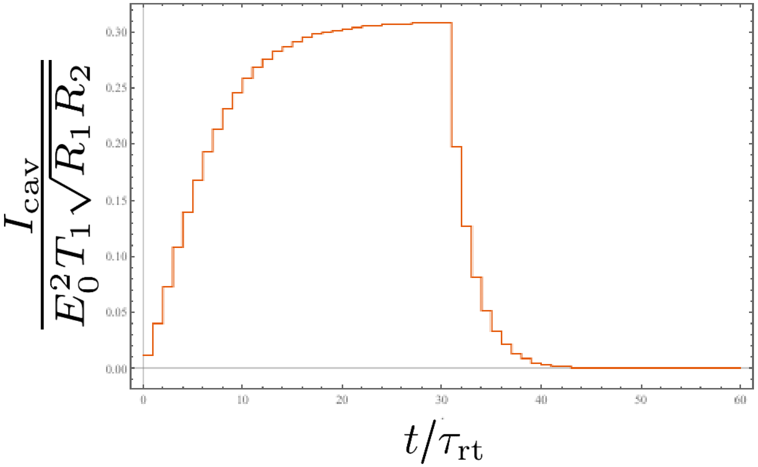
modulation period

loss time

$$\tau_{\mathrm{mod}} \gg \tau_{\mathrm{L}}$$

- Slow modulation => periodic build up and decay of circulating power in cavity

- Commercially available:
  - IR 500 kW cw multi-mode; F ~ 10^6 => P_{av} ~ 100 GW
  - 20 kW single mode => focus down to ~1μm waist



$$\tau_{\mathrm{p}}/\tau_{\mathrm{rt}} = 30, R_1 = R_2 = 0.8$$

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modulation period loss time

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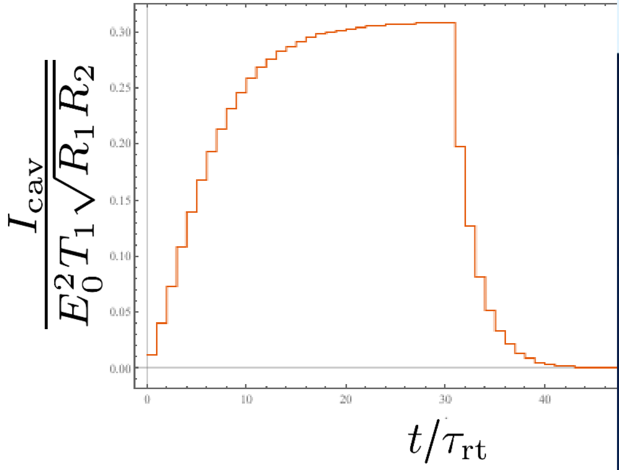
- Commercially available:
  - ➢ IR 500 kW cw multi-mode; F ~ 10^6 => P_{av} ~ 10^{11} W
  - ➢ 20 kW single mode => focus down to ~1μm waist
- m^2 size mirrors to avoid thermal damage, stabilize thermal modes?



YLS, 1-120+ kW

Ytterbium CW Laser Systeme

YLS Ytterbium Faserlasersysteme haben Leistungen von 1 bis 120 kW und arbeiten im CW oder moduliertem Betrieb von bis zu 5 kHz mit einem Steckdosenwirkungsgrad über 40 %. Die Leistung kann frei zwischen 10% - 100% der Nennleistung gewählt werden, ohne Änderung der Strahlqualität oder Strahleigenschaften. Daher eignen sich diese Laser ideal zum Schweißen, Bohren und Präzisionsschneiden. Es werden Bearbeitungsoptiken mit langer Brennweite für eine verbesserte Tiefenschärfe und minimale Verschmutzung der Schutzgläser verwendet. Die Laser können mit Faserlängen von bis zu 100 Metern und einer Vielzahl an Multi-Port Strahlschaltern, Strahlkopplern und Scannern ausgestattet werden.

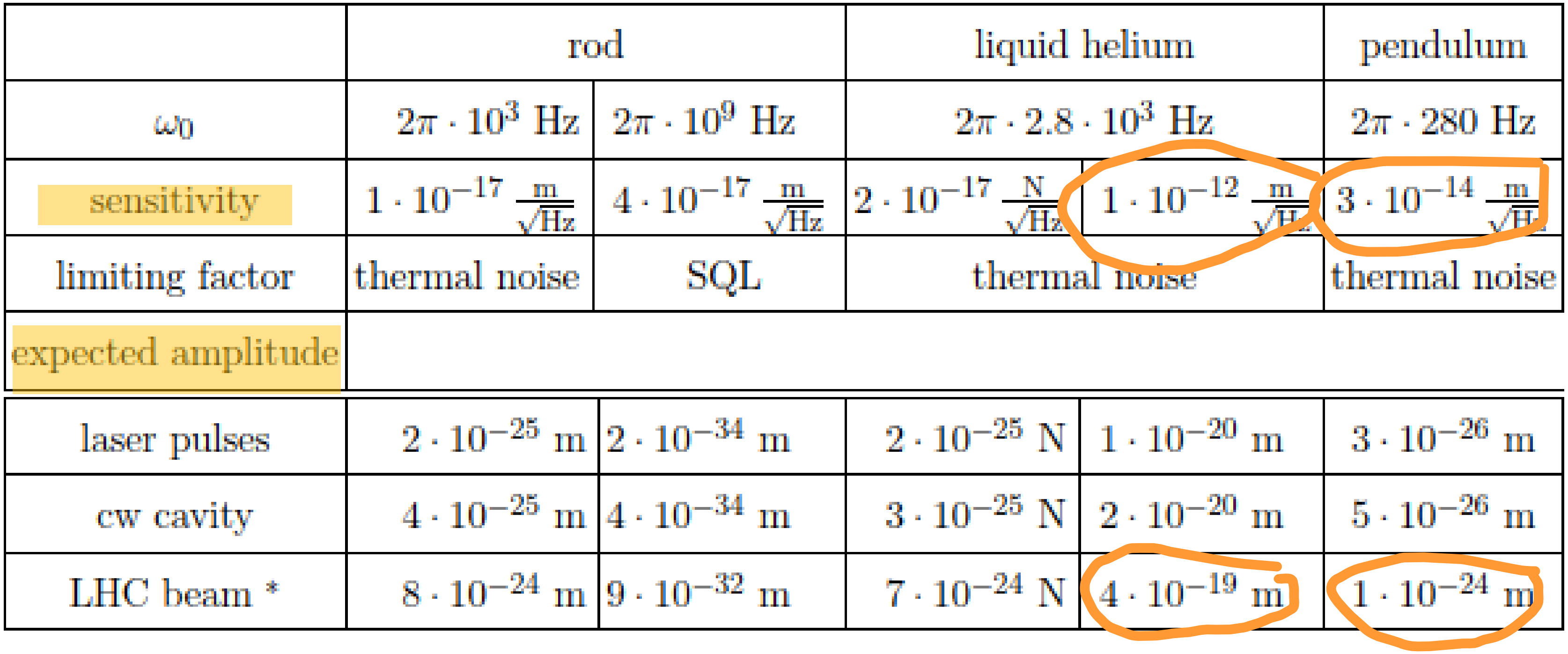
Sources 2: LHC particle beam

- 6.5 TeV energy per proton
  - ⇒ rest mass negligible
  - ⇒ almost idential energy-momentum tensor as light beam

- 2808 bunches with ~10^{11} protons each over ring of 26,659 m length
  - ⇒ bunch rate 31.2Mhz
  - ⇒ lower frequencies via modulation?

- Pav ~ 10^{12} W, beam waist 16 μm

Signals versus sensitivities



	rod		liquid helium		pendulum
ω_0	$2\pi \cdot 10^3$ Hz	$2\pi \cdot 10^9$ Hz	$2\pi \cdot 2.8 \cdot 10^3$ Hz		$2\pi \cdot 280$ Hz
sensitivity	$1 \cdot 10^{-17} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$	$4 \cdot 10^{-17} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$	$2 \cdot 10^{-17} \frac{\mathrm{N}}{\sqrt{\mathrm{Hz}}}$	$1 \cdot 10^{-12} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$	$3 \cdot 10^{-14} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$
limiting factor	thermal noise	SQL	thermal noise		thermal noise
expected amplitude					
laser pulses	$2 \cdot 10^{-25}$ m	$2 \cdot 10^{-34}$ m	$2 \cdot 10^{-25}$ N	$1 \cdot 10^{-20}$ m	$3 \cdot 10^{-26}$ m
cw cavity	$4 \cdot 10^{-25}$ m	$4 \cdot 10^{-34}$ m	$3 \cdot 10^{-25}$ N	$2 \cdot 10^{-20}$ m	$5 \cdot 10^{-26}$ m
LHC beam *	$8 \cdot 10^{-24}$ m	$9 \cdot 10^{-32}$ m	$7 \cdot 10^{-24}$ N	$4 \cdot 10^{-19}$ m	$1 \cdot 10^{-24}$ m

* assumption of modulation of LHC beam while maintaining average power

- Full resonant amplitudes, require long build-up times for large Q
- T=5mK for thermal noise, 2mm distance for pendulum

- What can help: long integration time, lower *T*, get closer to beam