Optical design of 'shining light through wall’ experiments

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- light on right side of the wall oscillates into WISPs with probability $P$
- WISPs transvers through wall without attenuation
- WISPs oscillate on left side of wall back into light with probability $P'$
- photon to axion conversion probability
  \[
  P = \frac{1}{4} \frac{1}{\beta_a \sqrt{\epsilon}} (g_{\gamma\gamma} B_0 L)^2 \left( \frac{2}{qL} \sin \left( \frac{qL}{2} \right) \right)^2
  \]
- amplitude of WISPs field through wall $a = E_0 \sqrt{P}$
- amplitude of regenerated E-field on right side of wall $E_r = \sqrt{P'} a$
- regenerated photon/s on detector: $n \propto |E_r|^2 = P' P |E_0|^2$
**optical design goals**

- make regenerated EM field as large as possible \( (E_r = E_0 \sqrt{P P'}) \)
  - high power of light source (laser)
  - Fabry Perot resonator (optical cavity) on left side to enhance light field
- detect regenerated EM field with high sensitivity
  - light detection scheme with low dark noise
    - photon counting with low dark rate (CCD, transition edge detector)
    - optical heterodyne readout scheme to overcome dark noise of photodetector
- use optical recycling techniques to increase signal on detector
optical design - limitations

- “hard” physical limits
  - available aperture
  - available coatings (scatter loss)
  - limits set by environment (length and alignment fluctuations due to seismic, vibrations, ...)

- how much risk is acceptable
  - durability of coatings (intrinsic, cleanliness)
  - radius of curvature fabrication tolerances
  - cavity stabilization (g-factor, rms residuals)

- available resources
optical design process

design goals and limitations ⇒ top level design choices

go to next level of detail ...
optical design choices

- make regenerated EM field as large as possible \( (E_r = E_0 \sqrt{PP'}) \)
  - high power of light source (laser)
  - Fabry Perot resonator (optical cavity) on left side to enhance light field

\[ PB \geq 5000 \]
\[ \frac{dP_{\text{rms}}}{P} \leq 5\% \]

1064nm

laser

1064nm

\[ I \leq 1\text{MW/cm}^2 \]

exemplarily parameters of ALPS II design
35W laser system

- **Crystal:**
  3 x 3 x 10 mm\(^3\) Nd:YVO\(_4\)
  8 mm 0.3 % dot.
  2 mm undoped endcap

- **Pump diode:**
  808 nm, 45 W
  400 µm fiber diameter
  NA=0.22

- **Amplifier:**
  38 W for 2 W seed and 150 W pump

single-mode, single-frequency laser with high spatial purity are available

- 180W @ 1064nm
- 130W @ 532nm
Gaussian beam must fit to magnet aperture

$$\sqrt{2} \omega_0 \quad \text{beam waist } \omega_0$$

Rayleigh range $z_r$
radius of curvature of mirrors

optimization: minimal clipping losses at aperture
⇒ \( z_R = L \) (minimal beam radius on curved mirror)
radius of curvature of mirrors

radius of curvature of mirror must match wavefront curvature of desired gaussian beam:

\[ R(z) = z \left( 1 + \left( \frac{Z_r}{z} \right)^2 \right) \]

\[ z = z_r = L \quad \Rightarrow \quad R(z_r) = 2z_r = 2L \]

- higher order mode spacing

\[ \Delta f = \frac{1}{4} (n + m) \times FSR \]

\[ \Rightarrow \text{order 4 modes resonate at same length as } TEM_{0,0} \]

- this might cause problems in length and alignment control

- optimize for small aperture losses and no higher-order modes with low mode number close to \( TEM_{00} \) resonance
Mirror reflectivity

\[ PB_m \approx \frac{4T_{in}}{(T_{in} + T_{out} + A)^2} \]

\[ Finesse \ F = \frac{FSR}{FWHM} \approx \pi \ PB_m \]

- Mirror reflectivity needs to be optimized to get highest power buildup
- Goal: Impedance matched case
  \[ T_{in} = T_{out} + A \]
- Estimate of losses in cavity is an important design parameter
  - Scattering mirrors
  - Diffraction loss apertures
  - Absorption loss mirrors
- Durability of mirrors
ALPS II mirror reflectivity optimization

\[ r_{ap} : \text{radius of magnet aperture} \]
\[ d = \text{magnet length} \]
\[ PB_p = 5000 \]
\[ PB_r = 40000 \]
length and frequency fluctuations

frequency mismatch between one of the cavity resonance frequencies and laser frequency $\Delta \nu$ has to be small:
uncontrolled (free running) rms-mismatch $\Delta \nu_{\text{free}}^{\text{rms}}$ determines control loop range and lock-acquisition speed

remaining mismatch $\Delta \nu^{\text{rms}}$ with servo control determines power-buildup fluctuations
alignment control

- small alignment mismatch (lateral, diameter, ROC) as well as small alignment fluctuations

\[
P_B \approx \frac{4T_{in}}{(T_{in} + T_{out} + A)^2} \left( 1 + \left( \frac{\Delta \nu}{FWHM/2} \right)^2 \right) \left( 1 - \frac{\Delta \nu_{00}}{\nu_{00}^{opt}} \right)
\]

- active alignment control needs:
  - either high stability between position sensing photodiode or differential wavefront sensing
  - again range of actuator is an issue
  - no lock acquisition: error signal is valid once length control is in operation
matching of laser to generation cavity

- length / frequency control via Pound-Drever-Hall technique with appropriate actuators
- alignment control via split quadrant diodes (DC or heterodyne)
It works: ALPS1 experiment

- Circulating power: up to 1.4 kW at 532 nm
- Average over 55 h: 1.04 kW
- Factor 100 higher than pulsed systems

K. Ehret et al., NIM A, 612:83–96
optical design goals

- detect regenerated EM field with high sensitivity
  - use optical recycling techniques to increase power of regenerated light
- light detection scheme with low dark noise
  - photon counting with low dark rate (transition edge detector)
  - optical heterodyne readout scheme to overcome dark noise of photodetector

\[ N \leq 5 \times 10^{-3} / h \]

\[ \frac{dP_{rms}}{P} \leq 5\% \]

\[ \eta \geq 90\% \]

\[ P_{B equiv.} \geq 40000 \]

(exemplary parameters of ALPS II design)
requirements - regeneration side

- high cavity Finesse (high power buildup)
  - low diffraction loss by apertures (magnets)
  - low scattering (and absorption) of mirrors

- small $\Delta \nu := \nu_{\text{production}} - \nu_{\text{regeneration}}$
  - small length fluctuations of cavity
  - active length stabilization control loop with high bandwidth and sufficient range

- small spatial mismatch of regenerated EM field and cavity Eigenmode
  - small lateral and angular fluctuation of cavity Eigenmode (with respect to production cavity Eigenmode)
  - active stabilization of differential angular and lateral fluctuations (with high enough range and bandwidth)
- regenerated mode is identical to mode in generation cavity (photons have identical properties)
- match resonance frequency
- spatial mode matching
  - axial (two planar mirrors at distance)
  - lateral/angular (active control)
- without control beam hitting the detector (\( N \leq 10^{-3}/h \))
  - use control beam of different wavelength/polarization/spatial path
  - attenuate control beam by factor \( \alpha = 10^{19} \)
ALPSII solution: large \( \Delta \lambda \) and photon counting

- Mount central mirror of production cavity (PC) and regeneration cavity (RC) rigidly on base-plate.
- Use alignment markers rigidly mounted on base-plate to stabilize Eigenmodes of cavities to be co-linear.
fix production cavity mode

Stable baseplate
(placed on opt. table,
located inside vacuum)

HR 1064 nm

common axis for both cavities

Coated BS cube

dichroic mirror
(HR for green)

Quadrant-PD (1064 nm);
spatial ref. for lateral baseplate
position rel. to production mode
match SHG beam to regeneration cavity
lock and fix alignment of regeneration cavity
single photon detector
block all direct laser photons
ALPSII - special issues

- mirror show differential phase shifts for main and control beam
- low drift/fluctuations of components on central board
- central cavity mirrors need to be parallel $\alpha \leq 10 \mu rad$
- control beam must be attenuated by $\alpha = 10^{19}$
- free running rms motion low enough to allow for lock acquisition
- spectral density of free running mirror motion compatible with control loop parameters (actuator range, spectral gain shape)
small $\Delta \lambda$ and heterodyne detection

Müller et. al, Phys. Rev. D, 80 (2009)
small $\Delta \lambda$ and heterodyne detection

Müller et. al, Phys. Rev. D, 80 (2009)
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summary

- treat laser as gaussian beam
- optimize gaussian beam wrt magnet aperture
- choose mirror curvature for stable cavity operation and reasonable higher-order-mode spacing
- optimize mirror reflectivity
  - acceptable intensity (generation side only)
  - lock acquisition / available loop gain
- design length and alignment control for production and regeneration cavity
- choose control beam compatible with detection scheme

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