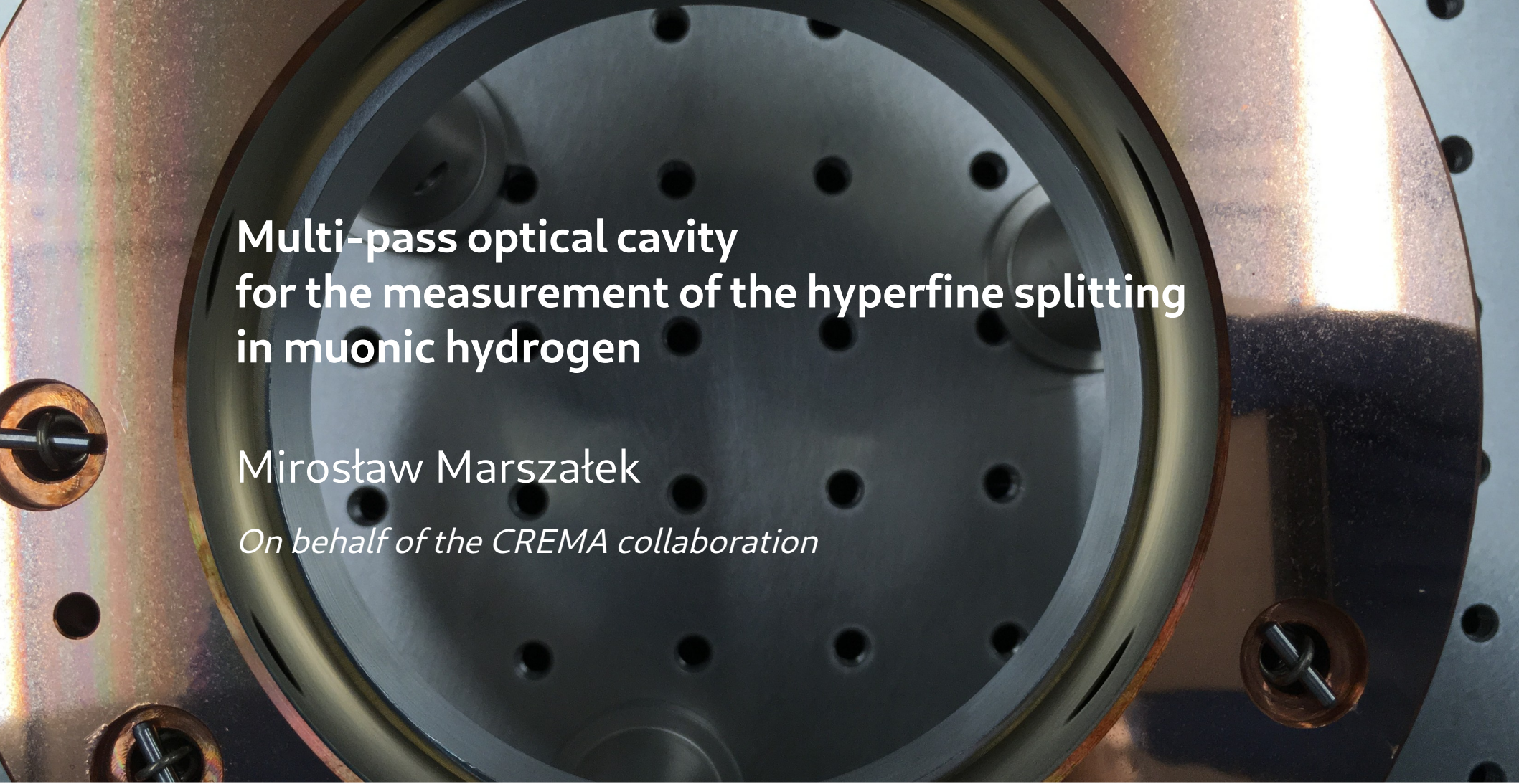


Multi-pass optical cavity for the measurement of the hyperfine splitting in muonic hydrogen

Mirosław Marszałek

On behalf of the CREMA collaboration

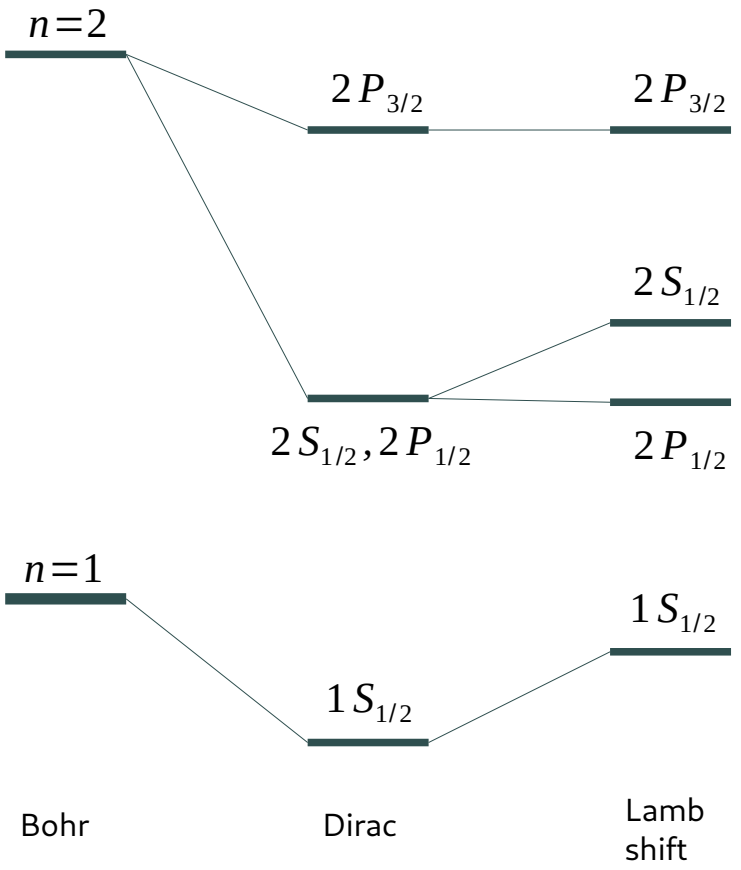
PAUL SCHERRER INSTITUT PSI

ETH zürich

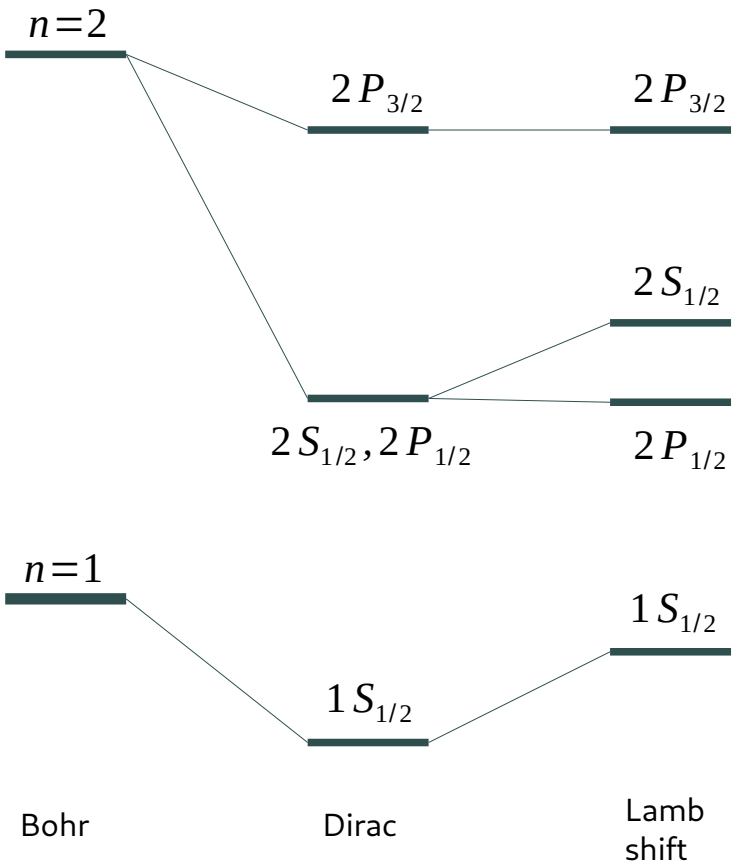
FNSNF

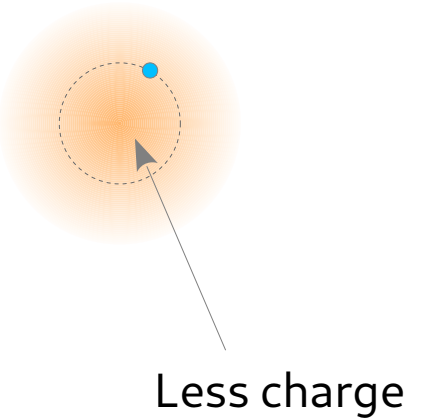
erc

The finite-size effect in hydrogen

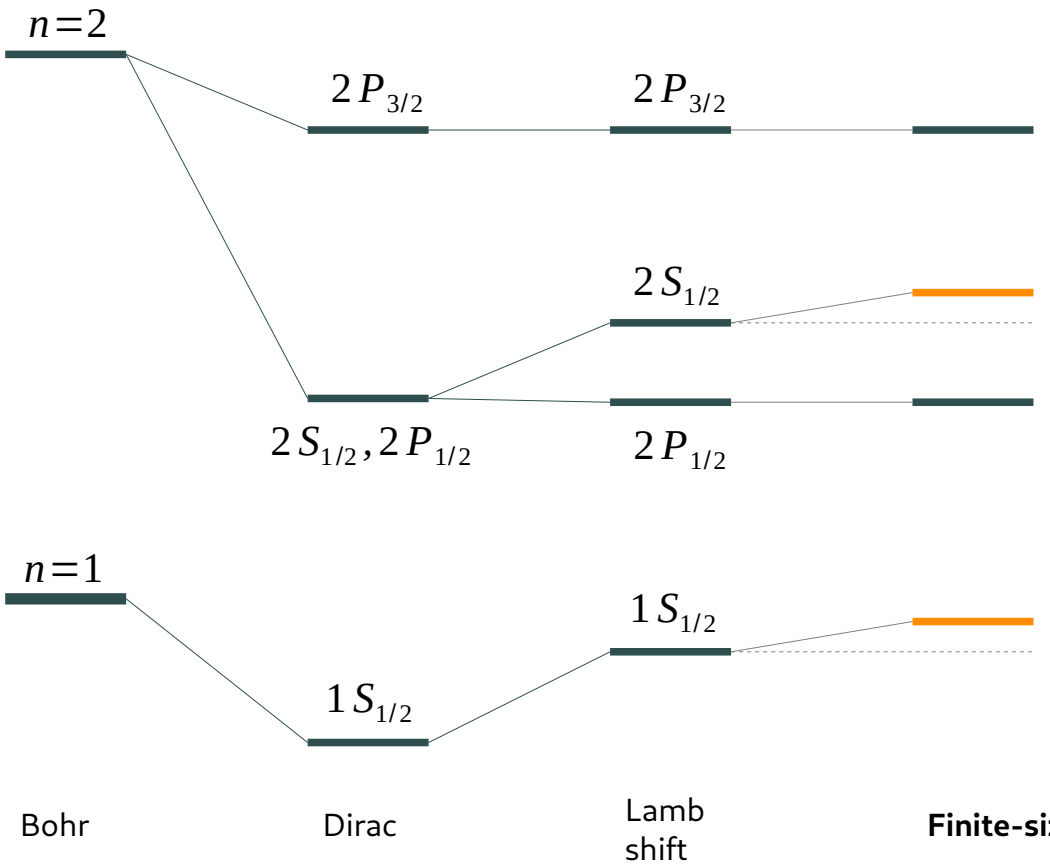


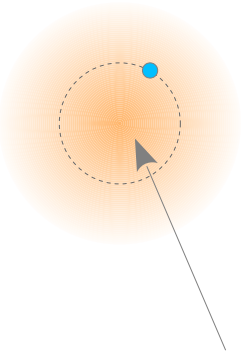
The finite-size effect in hydrogen





The finite-size effect in hydrogen



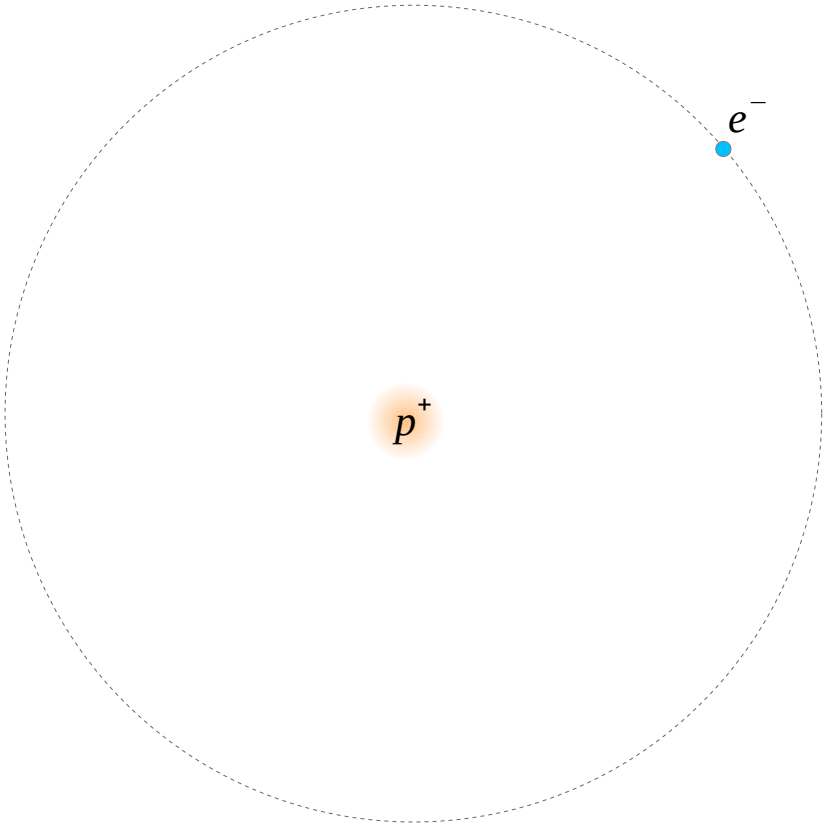


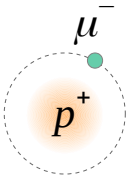
Less charge

$$\Delta E = \frac{2\pi\alpha}{3}\left|\Psi(0)\right|^2 R_E^2$$

$$= \frac{2(Z\alpha)^4}{3n^3} m_r^3 R_E^2$$

Muonic hydrogen



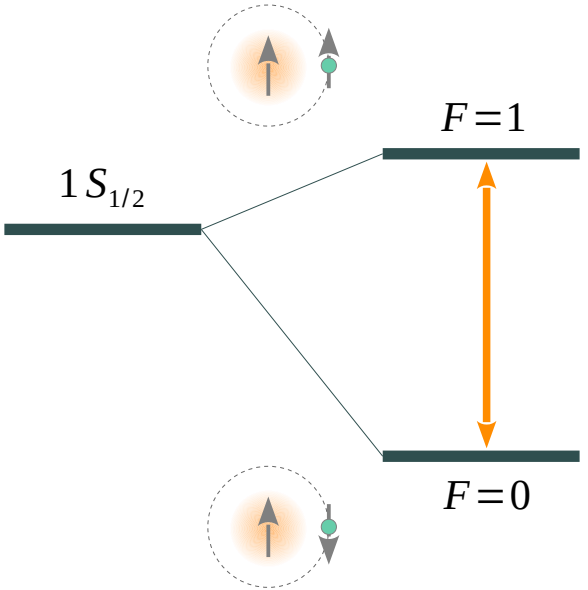


$$\Delta E \propto \left|\Psi(0)\right|^2 \propto m_r^3$$

$$m_\mu \approx 200\, m_e$$

$$\Delta E_\mu \sim 10^7 \Delta E_e$$

Hyperfine structure

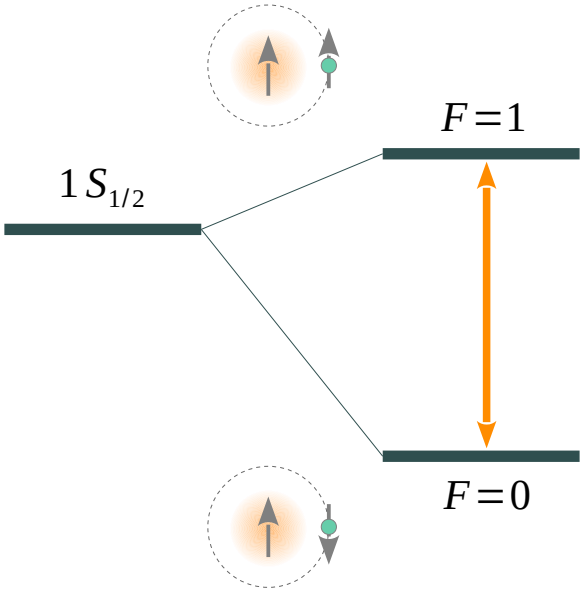


$$\Delta E_{\mathrm{hfs}} = E_{\mathrm{F}}\left(1+\Delta E_{\mathrm{QED}}+\Delta E_{\mathrm{TPE}}+\ldots\right)$$

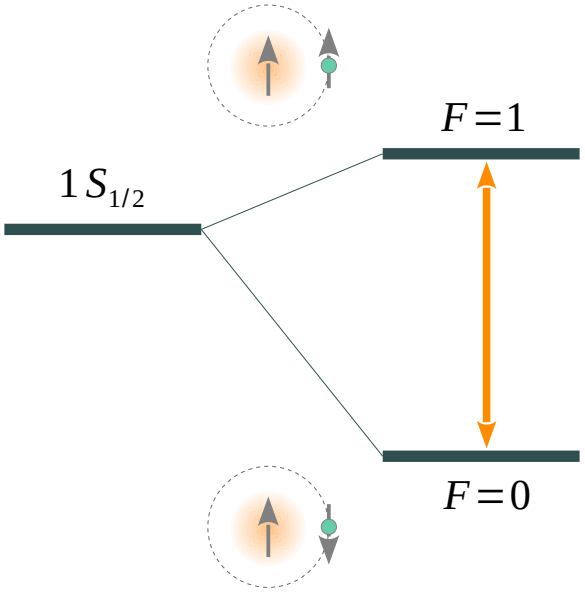
Hyperfine structure

$$E_F \propto \langle \mu_p \cdot \mu_\mu \rangle |\Psi(0)|^2$$

$$\Delta E_{hfs} = E_F (1 + \Delta E_{QED} + \Delta E_{TPE} + \ldots)$$



Hyperfine structure



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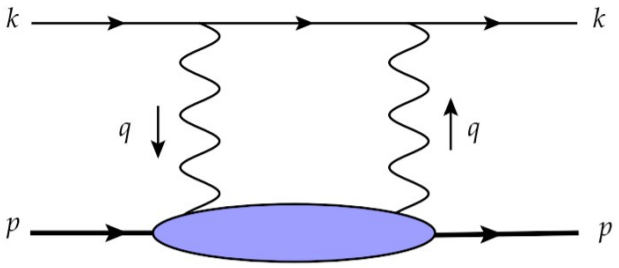
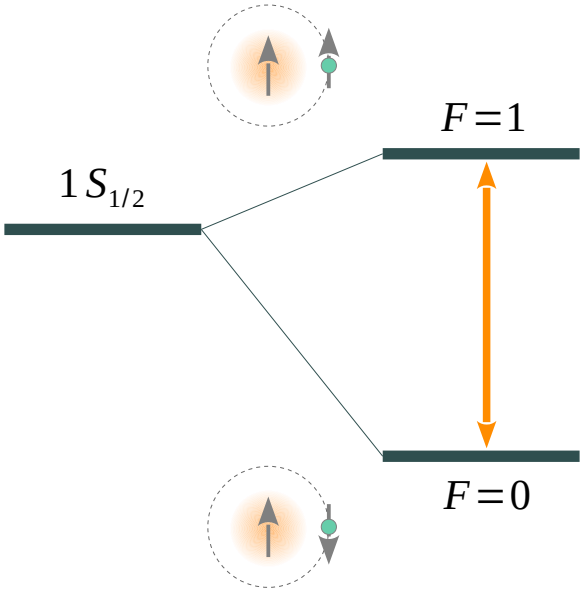
$$\Delta E_{hfs} = E_F (1 + \Delta E_{QED} + \Delta E_{TPE} + \dots)$$

$$\Delta E_{TPE} = \Delta E_Z + \Delta E_{recoil} + \Delta E_{pol}$$



Two-photon exchange

Hyperfine structure



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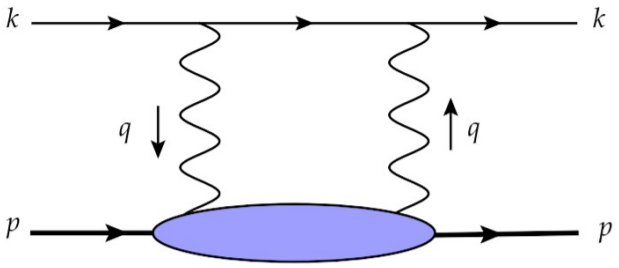
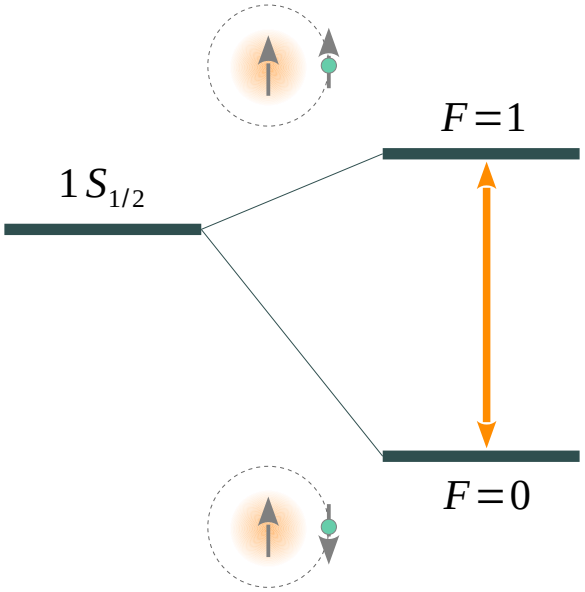
$$\Delta E_Z = -2 Z \alpha m_r R_Z$$



Two-photon exchange

Hyperfine structure



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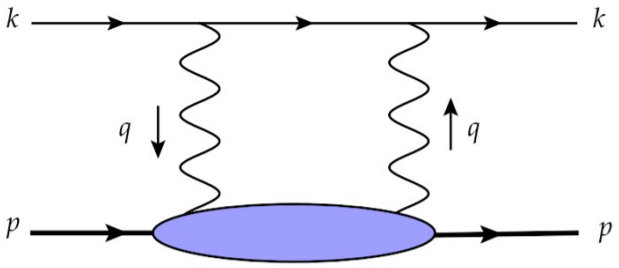
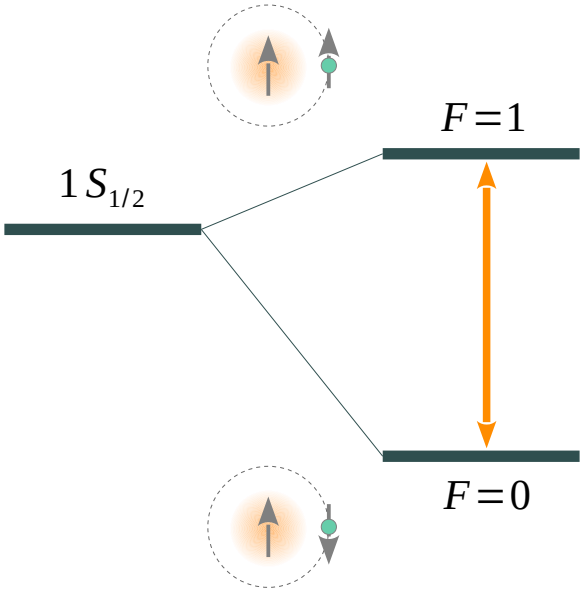
Zemach radius



Two-photon exchange

Hyperfine structure



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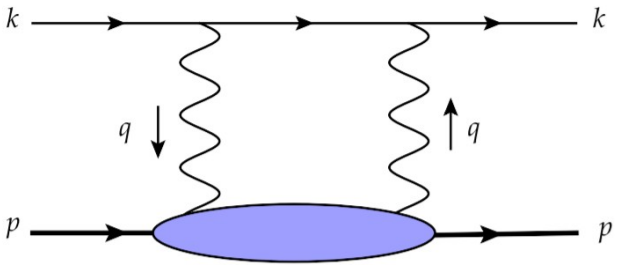
$$\Delta E_Z = -2 Z \alpha m_r R_Z$$

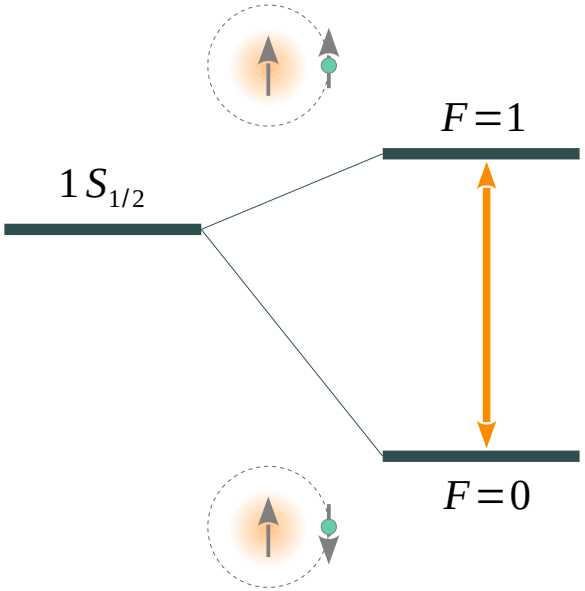
Zemach radius

$$R_Z = \int d^3\mathbf{r} |\mathbf{r}| \int d^3\mathbf{r}' \rho_E(\mathbf{r}-\mathbf{r}') \rho_M(\mathbf{r}')$$



Two-photon exchange

Hyperfine structure



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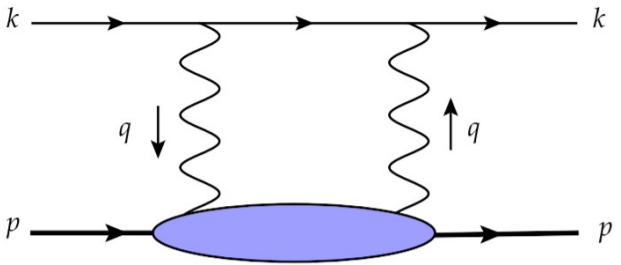
Zemach radius

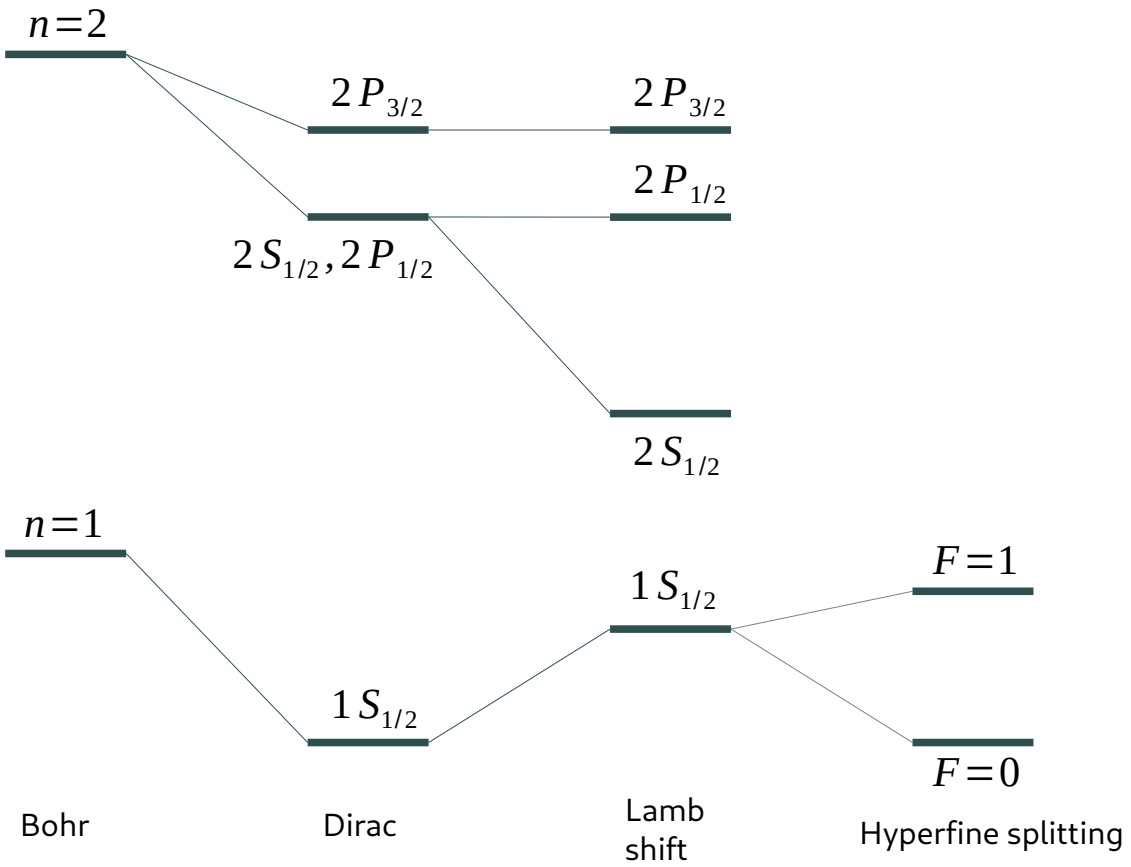


Two-photon exchange

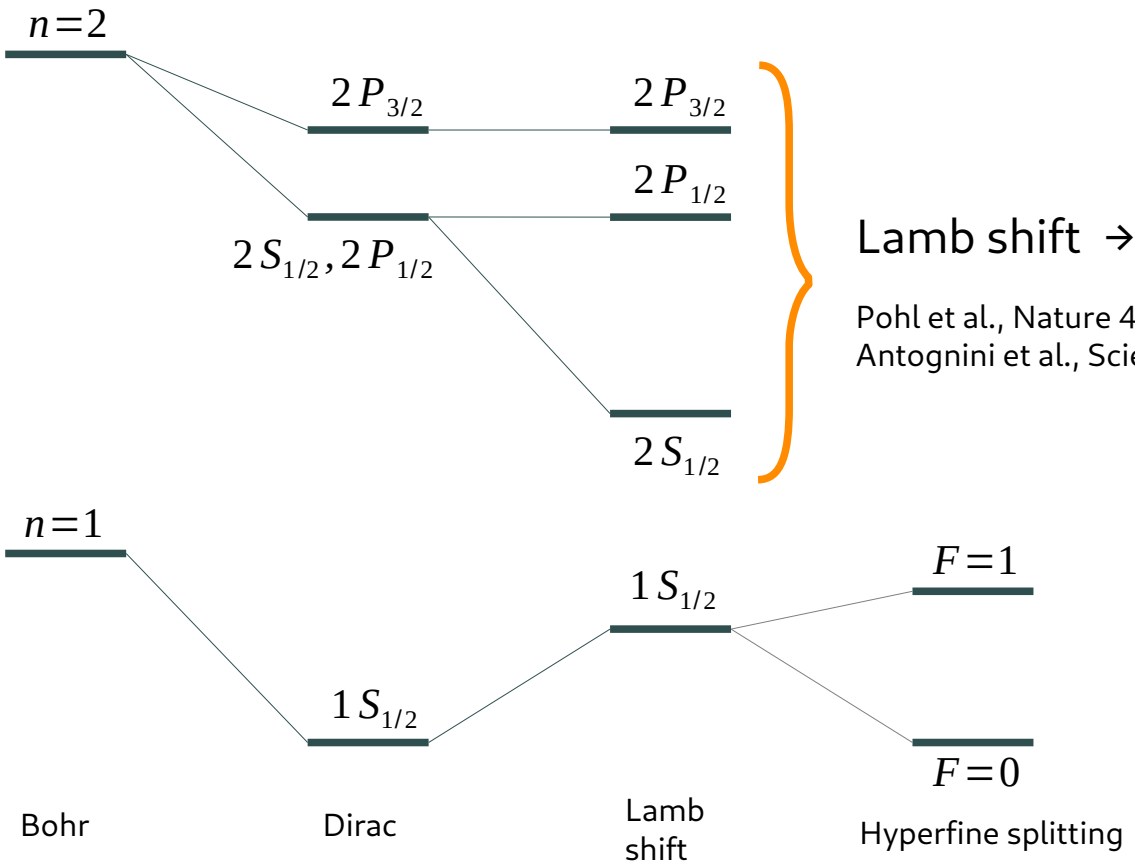
$$R_Z = \int d^3\mathbf{r} |\mathbf{r}| \int d^3\mathbf{r}' \rho_E(\mathbf{r}-\mathbf{r}') \rho_M(\mathbf{r}')$$

$$R_Z = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left(G_E(Q^2) \frac{G_M(Q^2)}{1+\kappa_p} - 1 \right)$$

Spectroscopy of muonic hydrogen



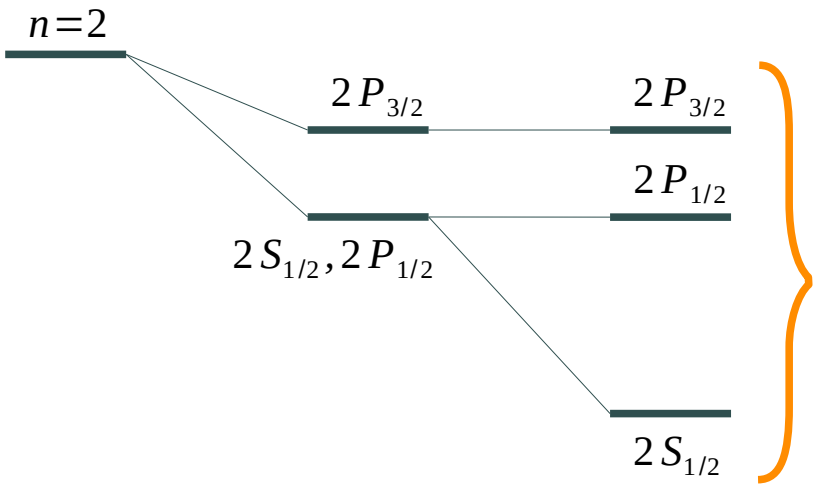
Spectroscopy of muonic hydrogen



Lamb shift → charge radius

Pohl et al., Nature 466, 213 **(2010)**
Antognini et al., Science 339, 417 **(2013)**

Spectroscopy of muonic hydrogen



Lamb shift → charge radius

Pohl et al., Nature 466, 213 **(2010)**
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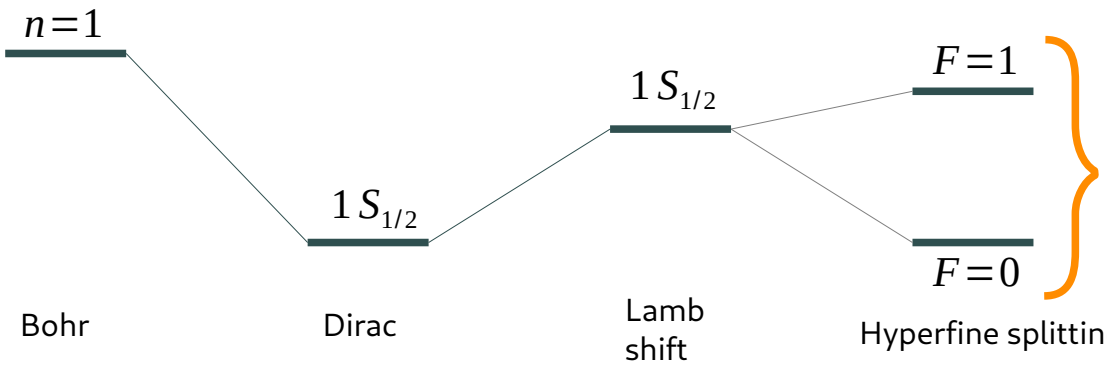


HFS → Zemach (magnetic) radius
In progress!

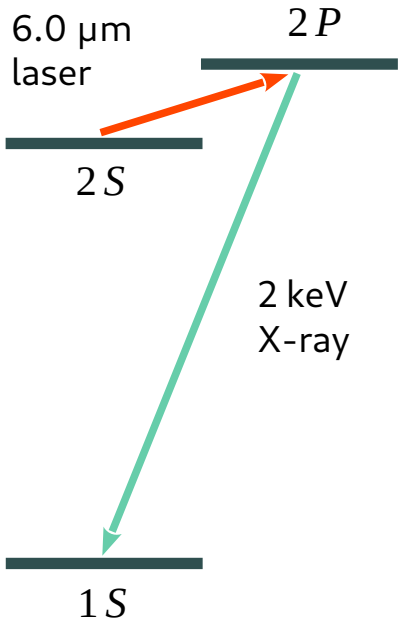
The HyperMu experiment

- **WHO:** The CREMA collaboration
- **WHERE:** The HIPA accelerator at PSI
- **WHAT:** The hyperfine splitting in muonic hydrogen at the the ppm level
- **WHY:** To gain insight into the nucleon structure


THERE

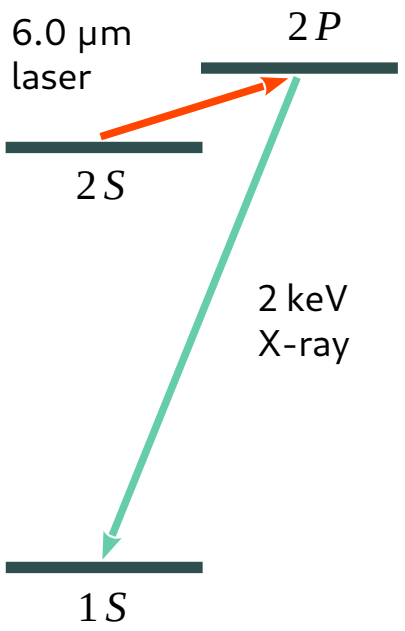
How do we measure this?

Lamb shift



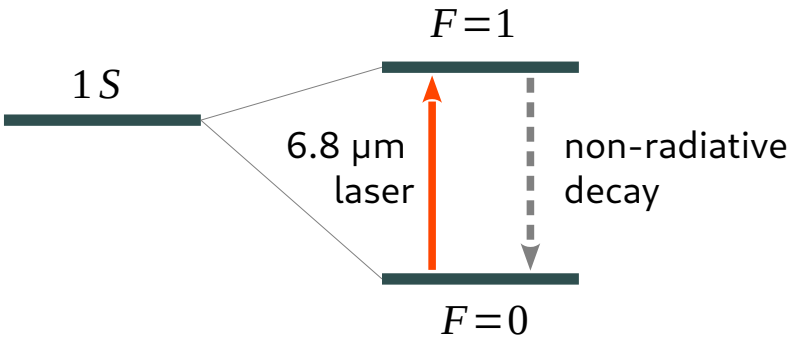
How do we measure this?

Lamb shift

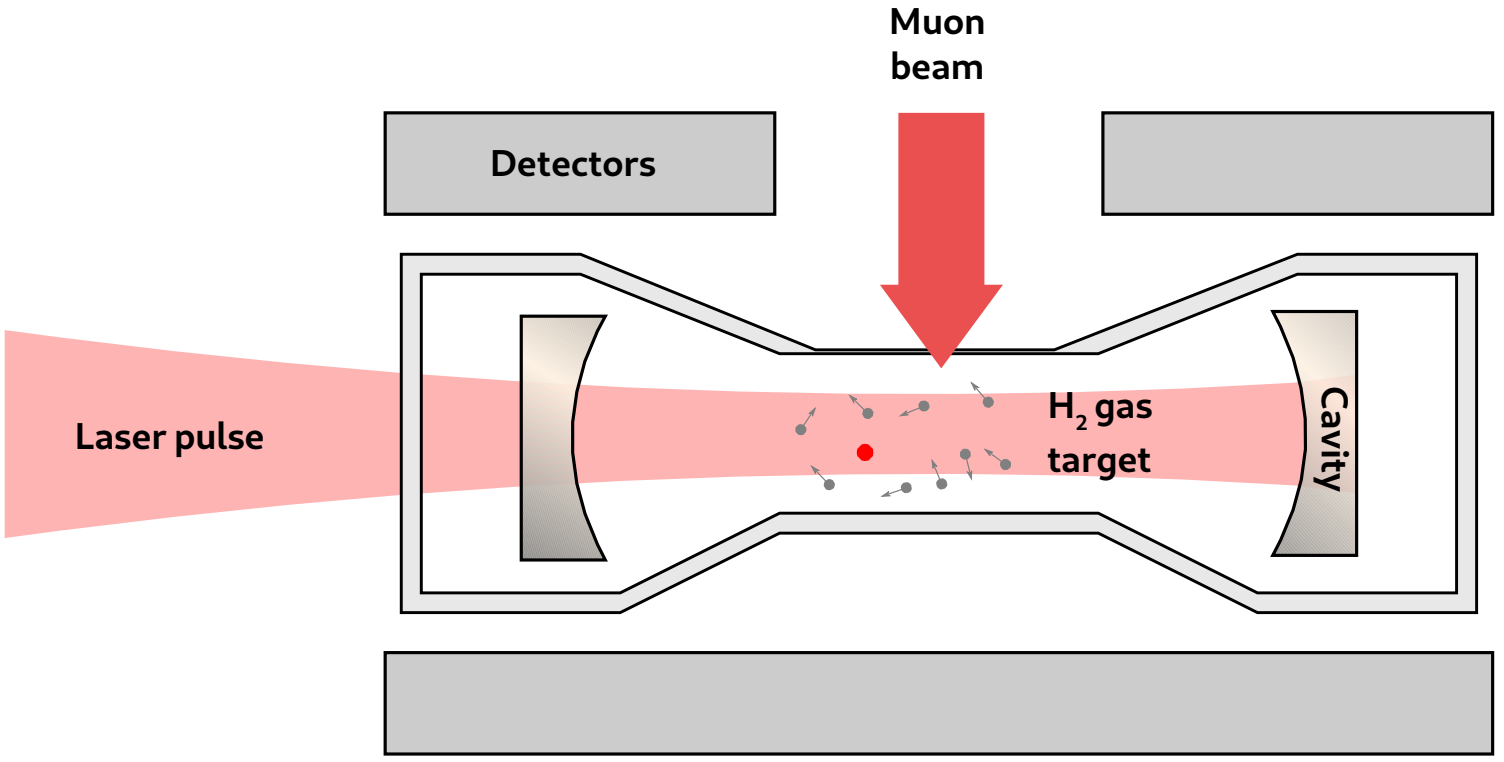


Hyperfine splitting

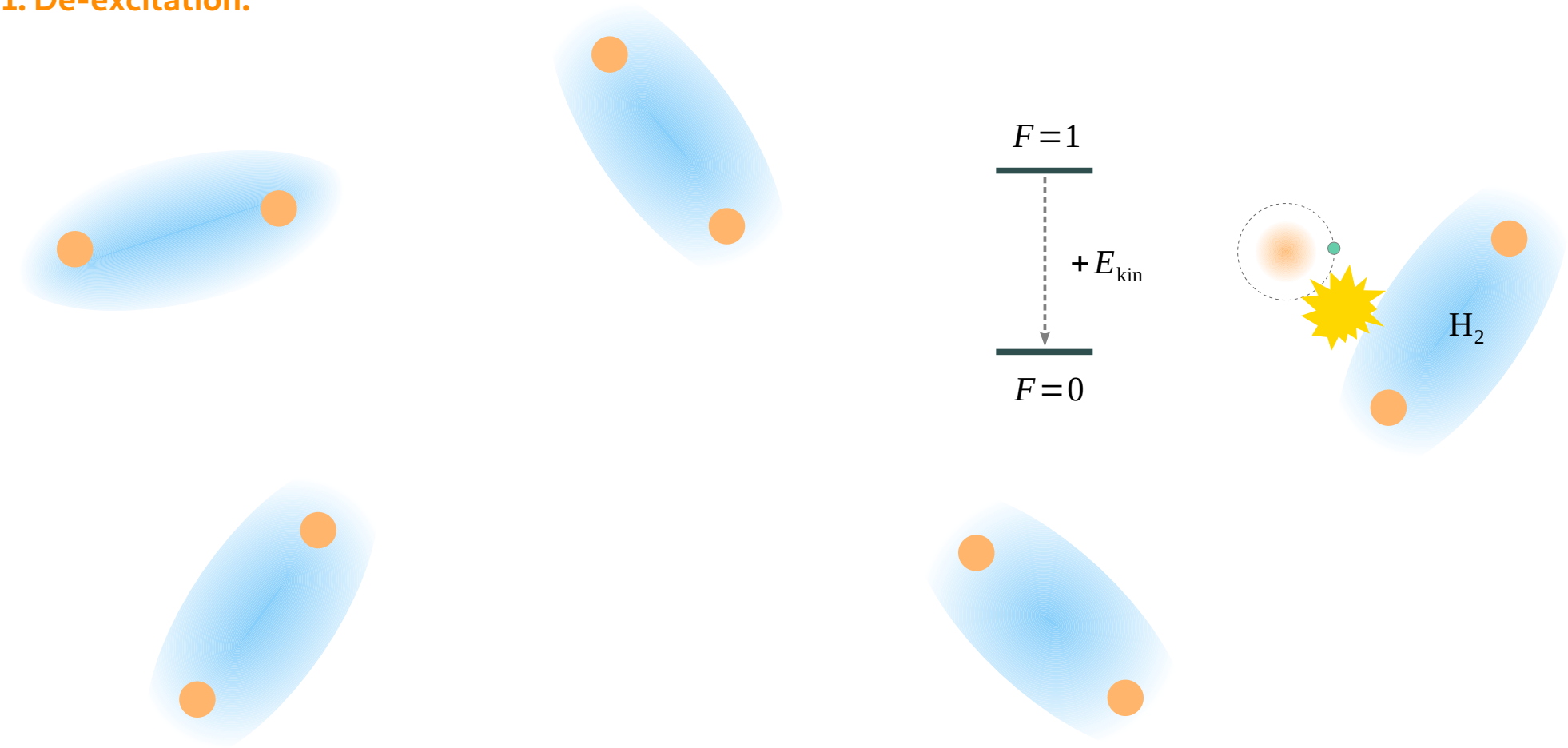
- Magnetic dipole transition
- No emitted photon



The apparatus

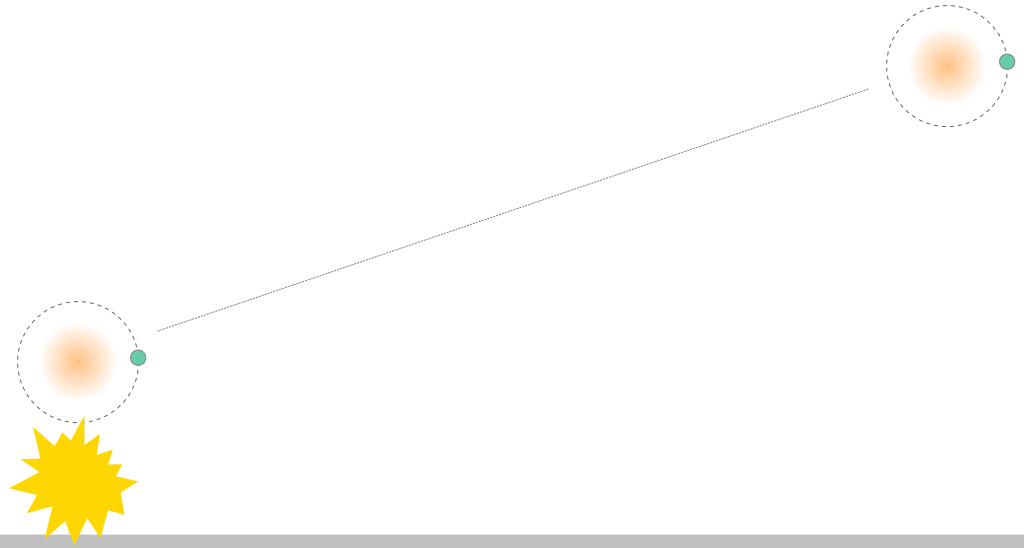


1. De-excitation.



1. De-excitation.

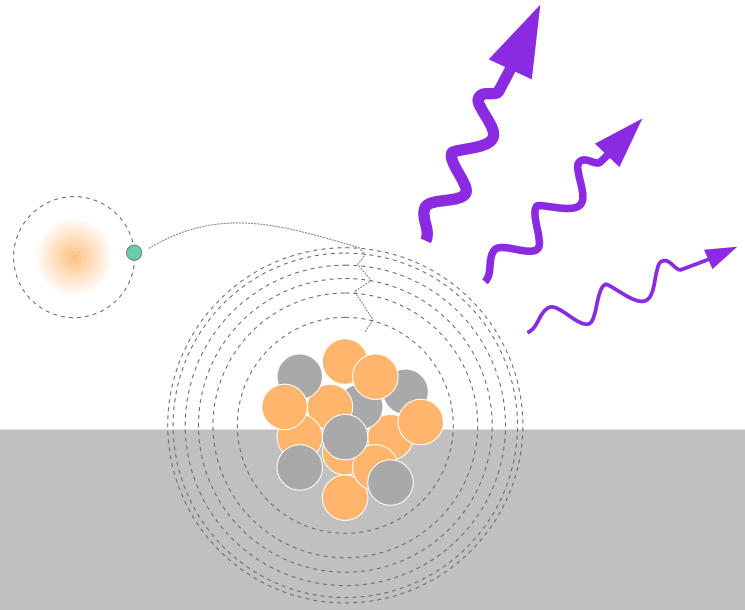
2. Collision with a wall.



1. De-excitation.

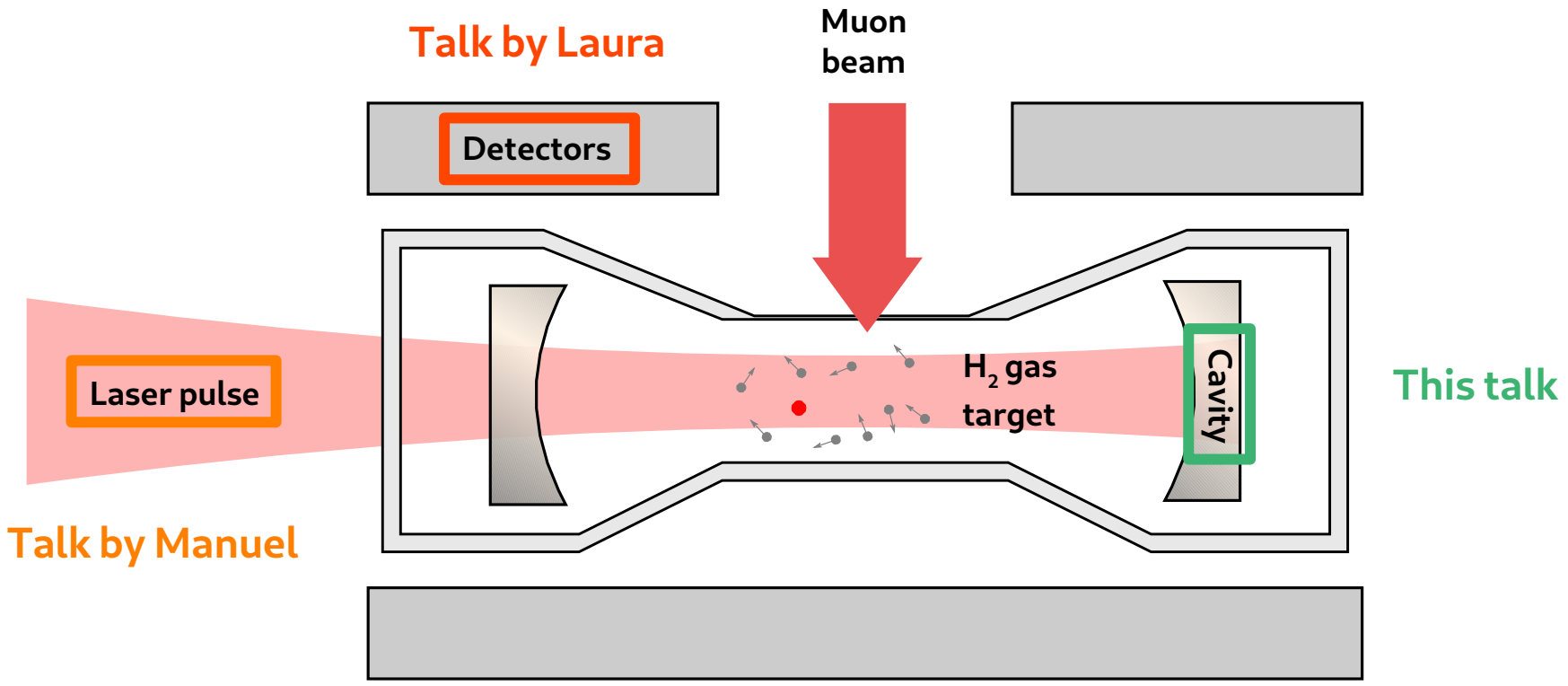
2. Collision with a wall.

3. Detection.



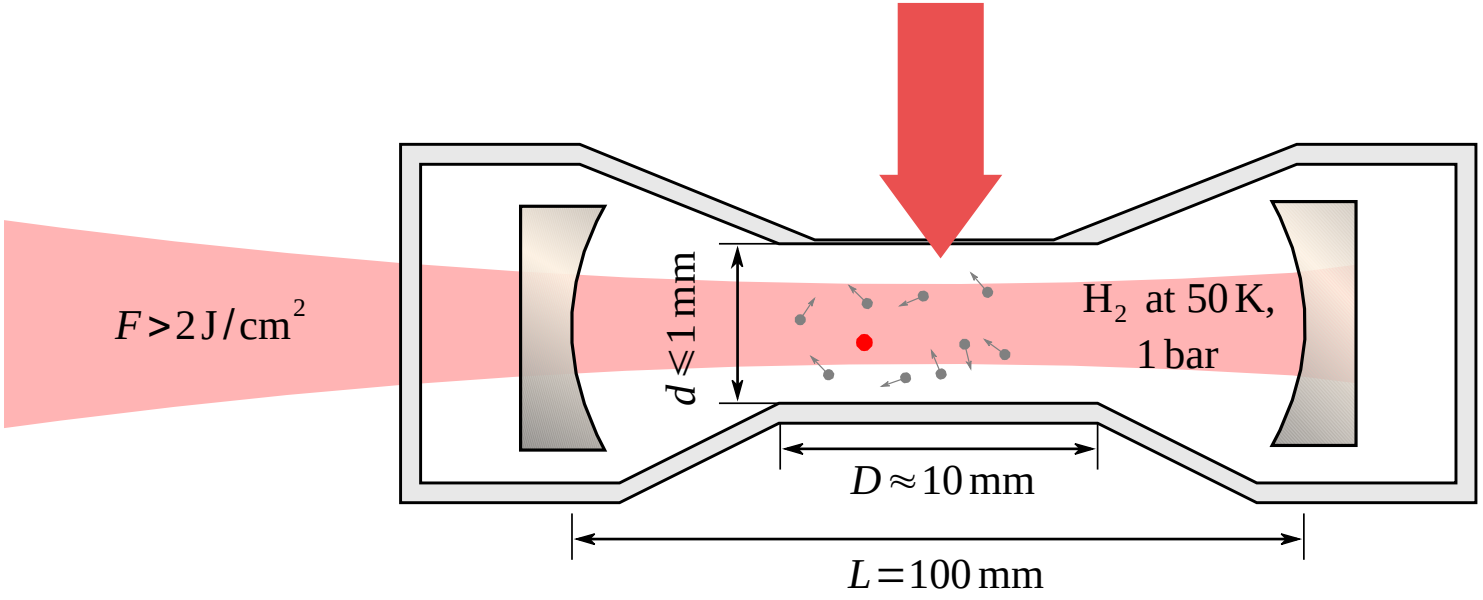
X-ray cascade
up to 10 MeV

The apparatus



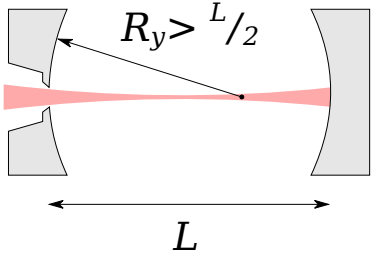
Requirements for the cavity

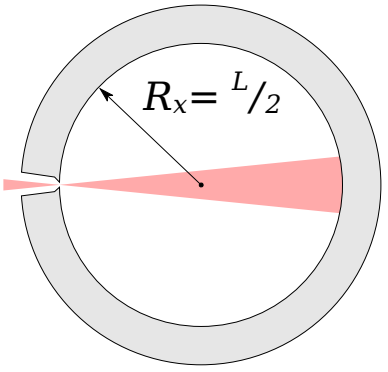
- Large illuminated volume
- >500 reflections
- Cryogenic temperatures

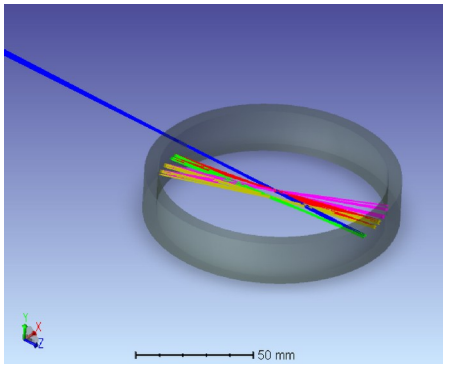


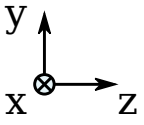
Cavity geometry

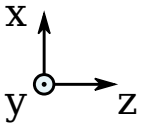
Closed toroidal surface











Cavity geometry

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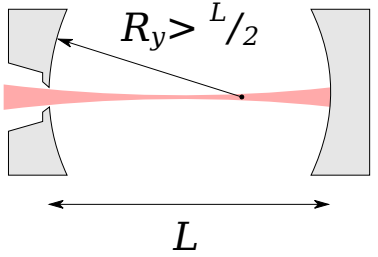
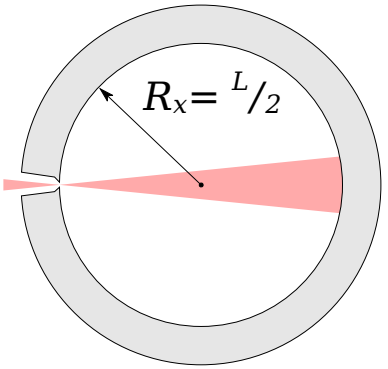
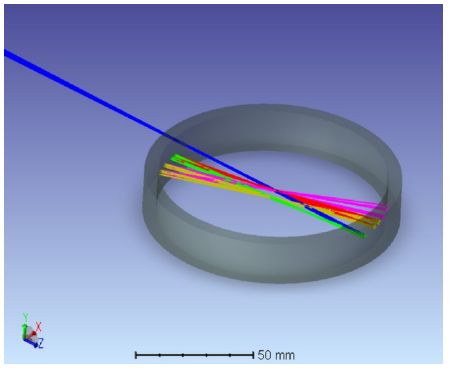
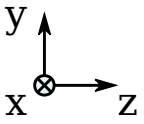
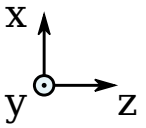


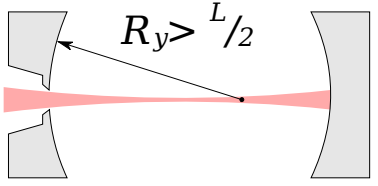


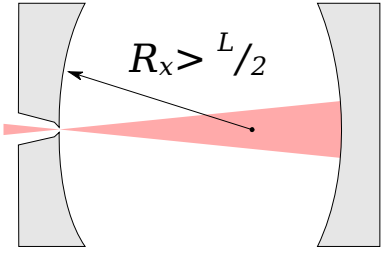


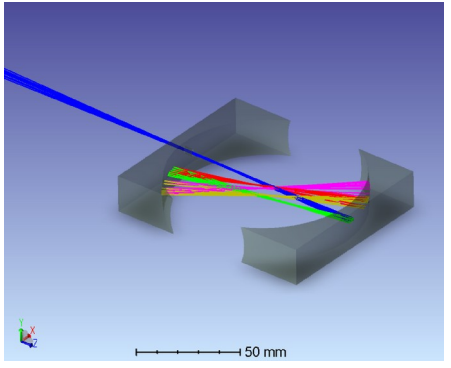




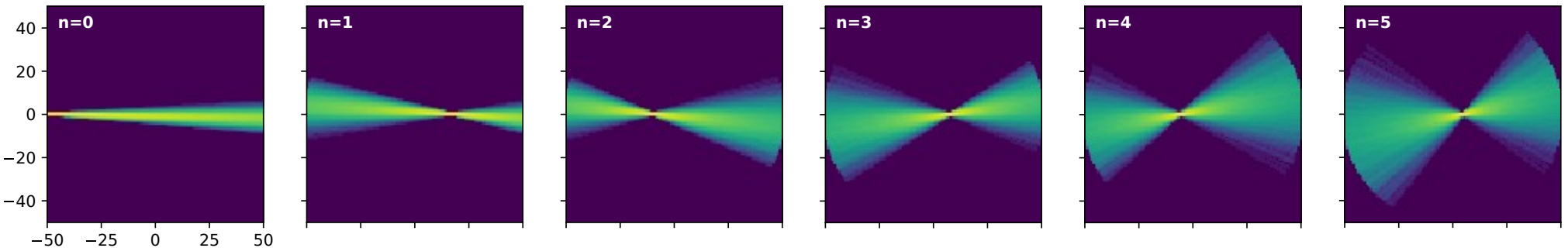
Two separate toric mirrors



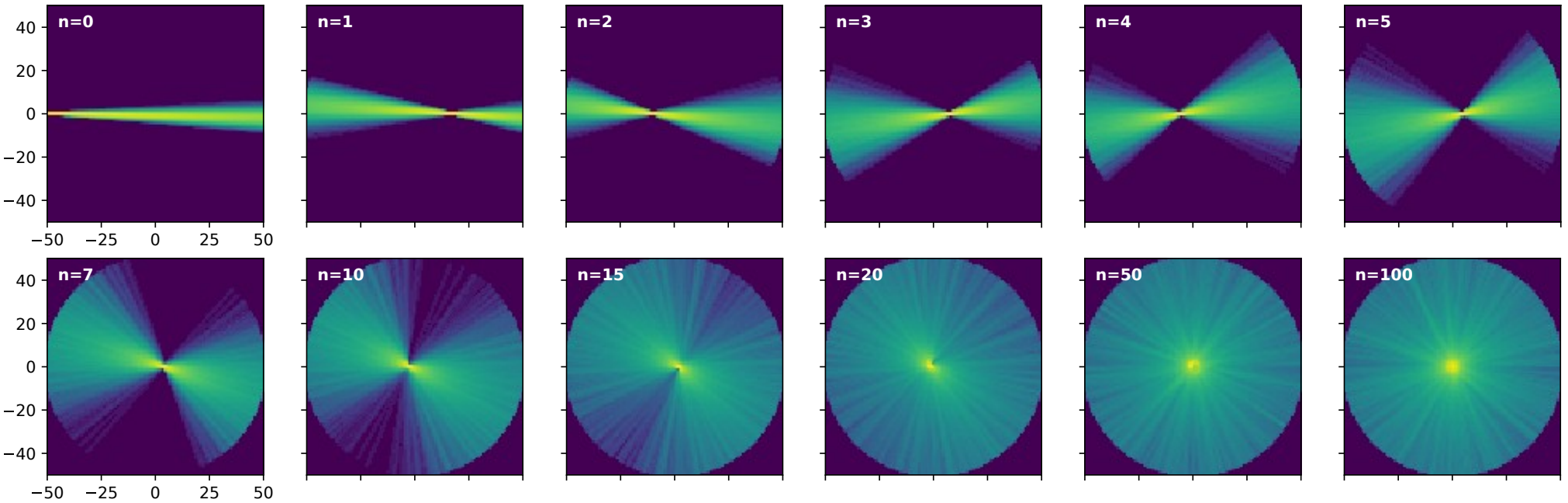




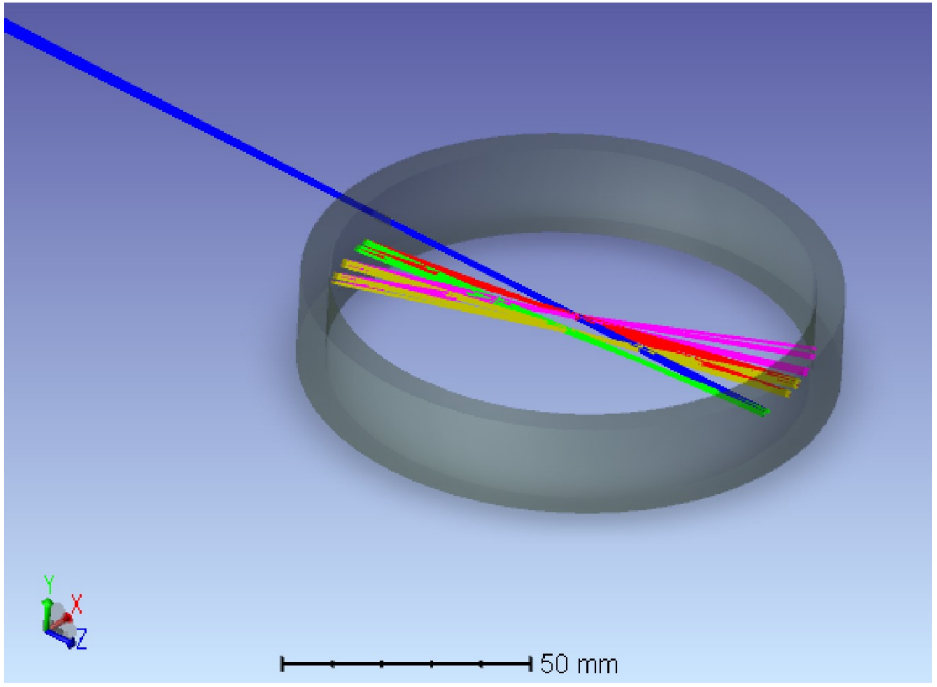
Ray tracing

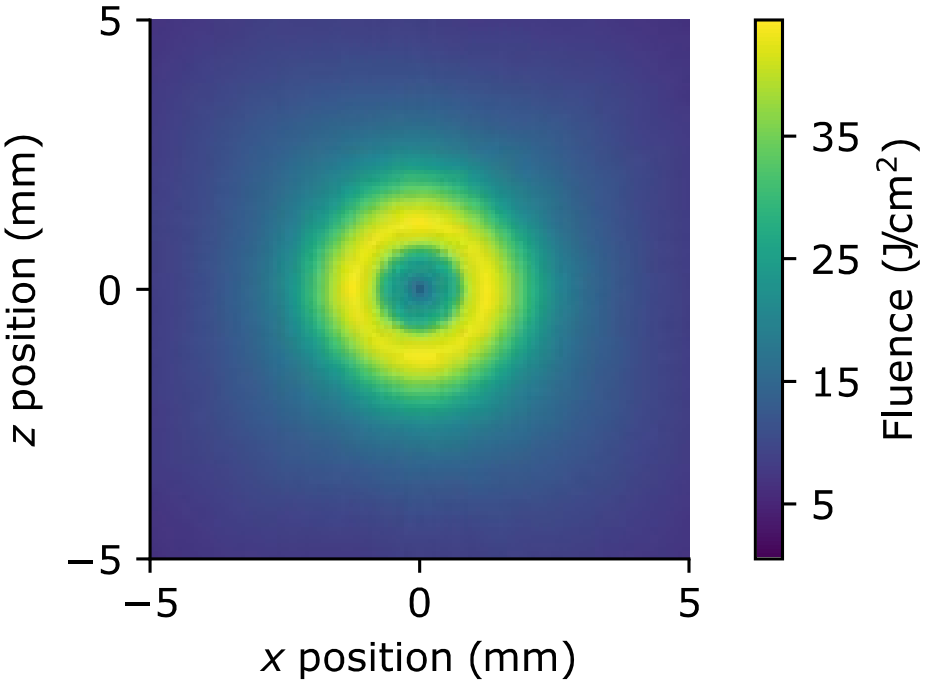


Ray tracing

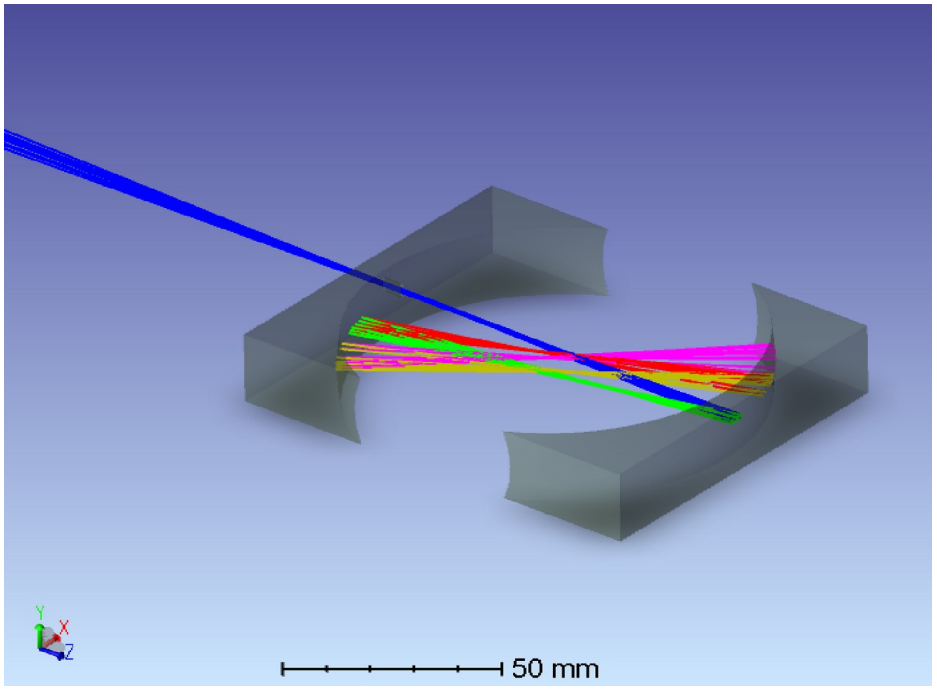


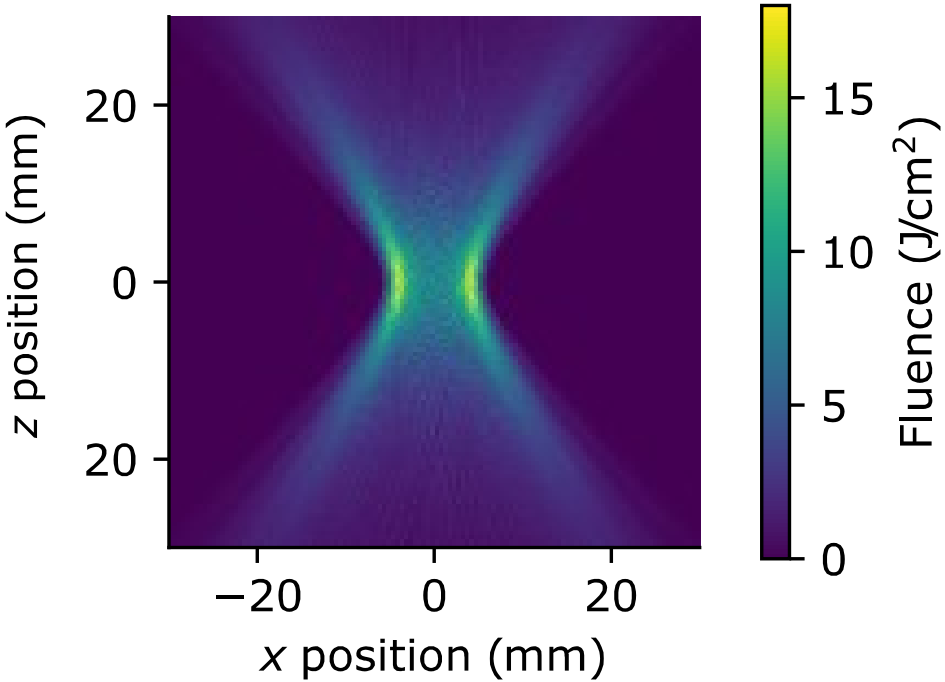
Fluence distributions



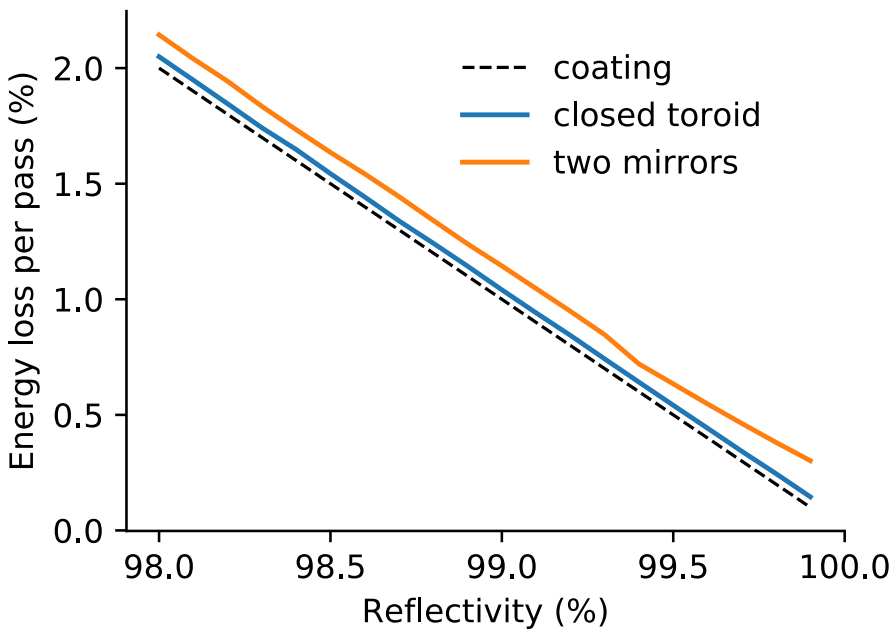


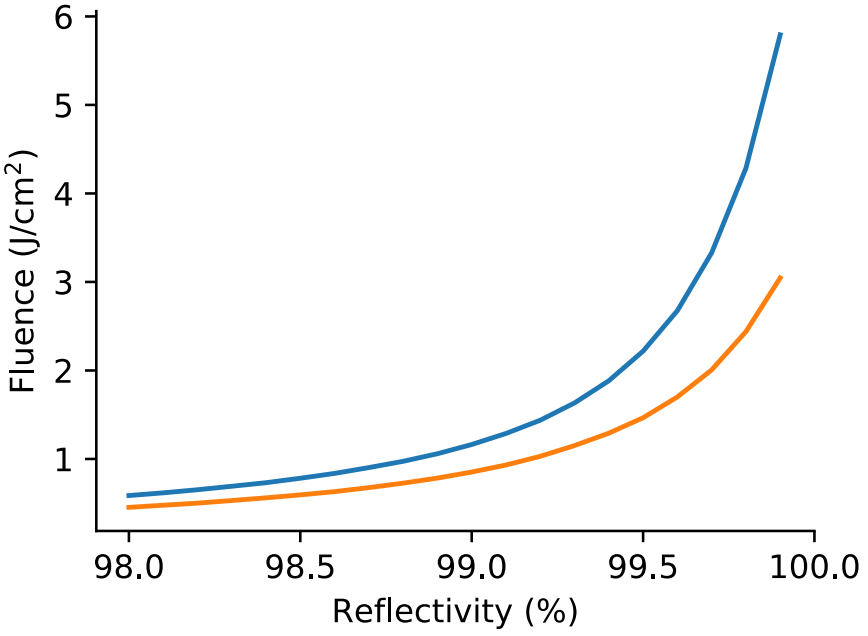
Fluence distributions





Performance of both designs





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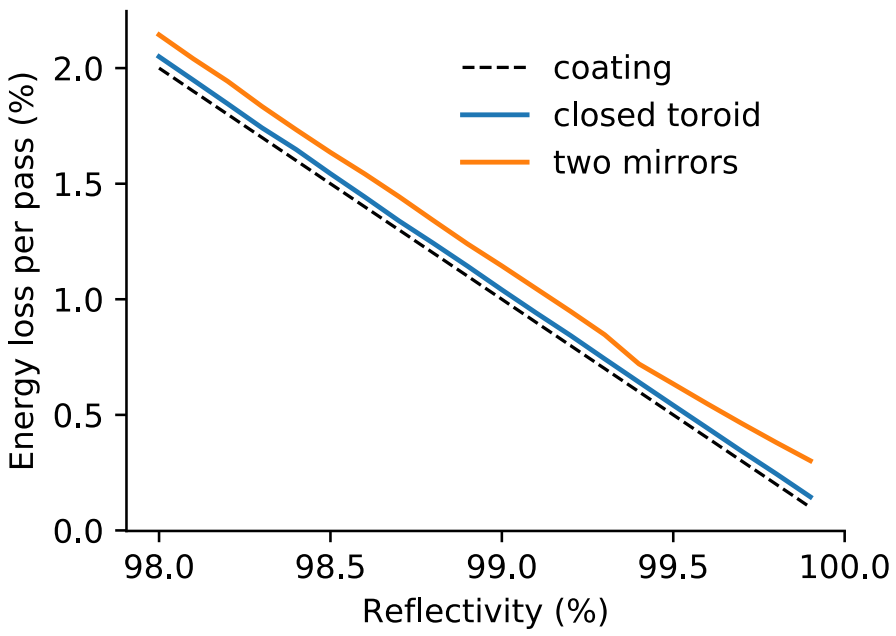

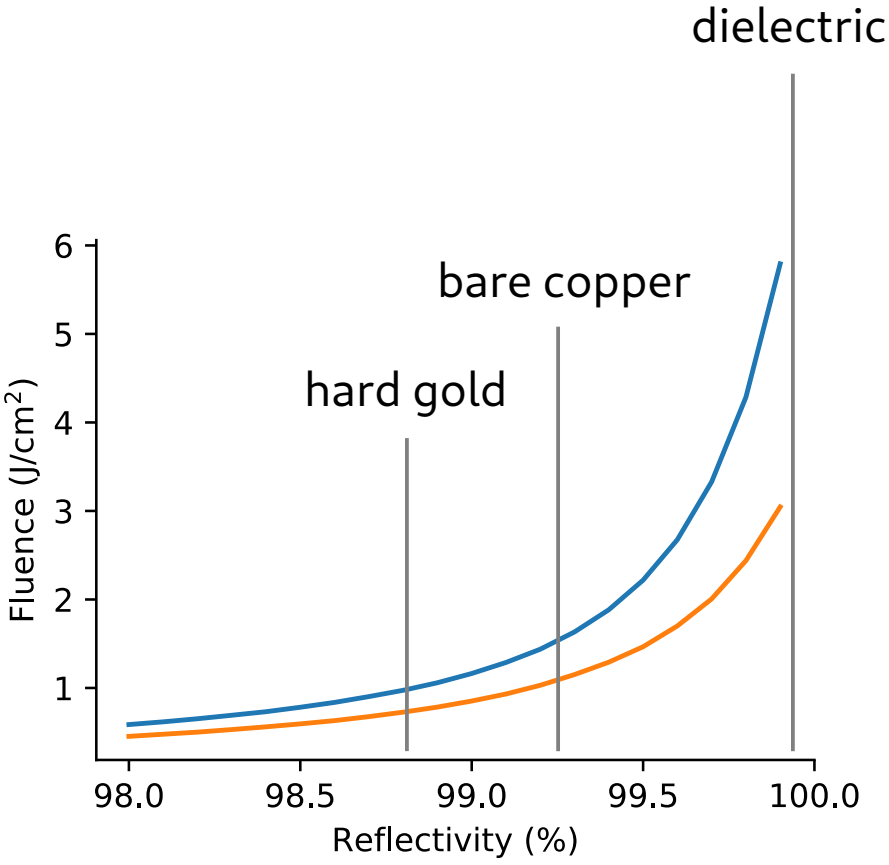

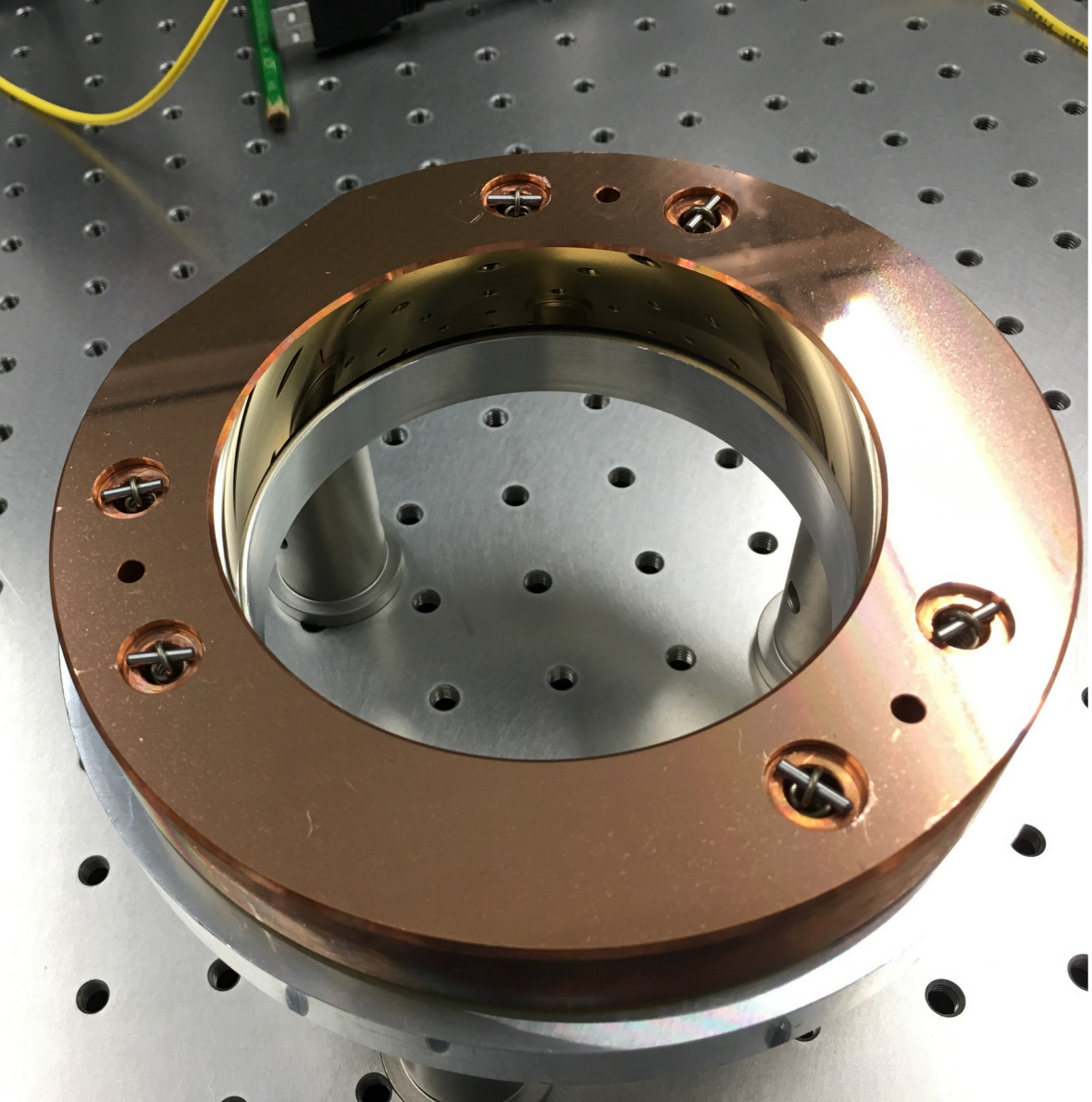

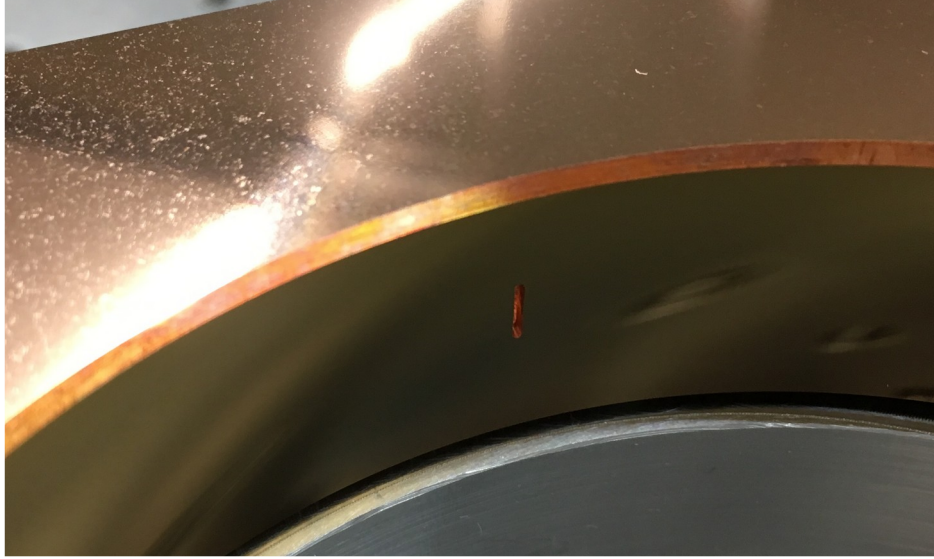

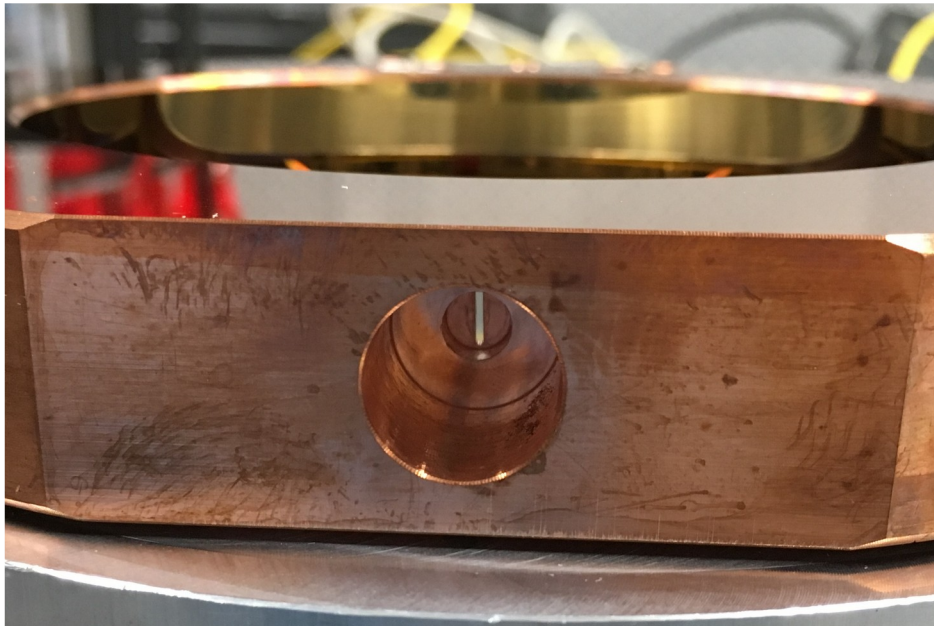

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Thank you!