Title: Laser spectroscopy of muonic atoms and the proton radius puzzle

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Abstract: Laser spectroscopy of muonic hydrogen [1,2] yielded a proton rms charge radius which is 4% (or ~6 sigmas) smaller than the CODATA value [3]. This discrepancy is now called the "proton radius puzzle" [4].
Also the deuteron charge radius from muonic deuterium [5] is 6 sigmas smaller than the
CODATA value, but consistent with the smaller proton inside the deuteron.
These smaller charge radii, when combined with precision measurements of the 1S-2S transitions in regular (electronic) hydrogen [6] and deuterium [7], yield a 6 sigmas smaller value of the Rydberg constant [8], compared to the CODATA value.
In this talk I will report about a new measurement of the Rydberg constant from the 2S-4P transition in regular hydrogen performed in Garching [9], which supports the smaller, "muonic" value. More recently, however, a new measurement of the 1S-3S transition in Paris confirmed the larger proton radius [10].
Several new measurements, such as hydrogen from Toronto, elastic electron scattering at lower QÂ², and new results from electronic and muonic helium will help understand the proton radius puzzle.

Laser spectroscopy of muonic atoms: Charge radii and polarizabilities

The Proton Radius Puzzle and beyond

Randolf Pohl

Johannes Gutenberg-Universität Mainz
Institut für Physik, QUANTUM und Exzellenzcluster PRISMA+

before: Max-Planck Institute of Quantum Optics, Garching

Perimeter Inst.
Nov. 20, 2018

Outline

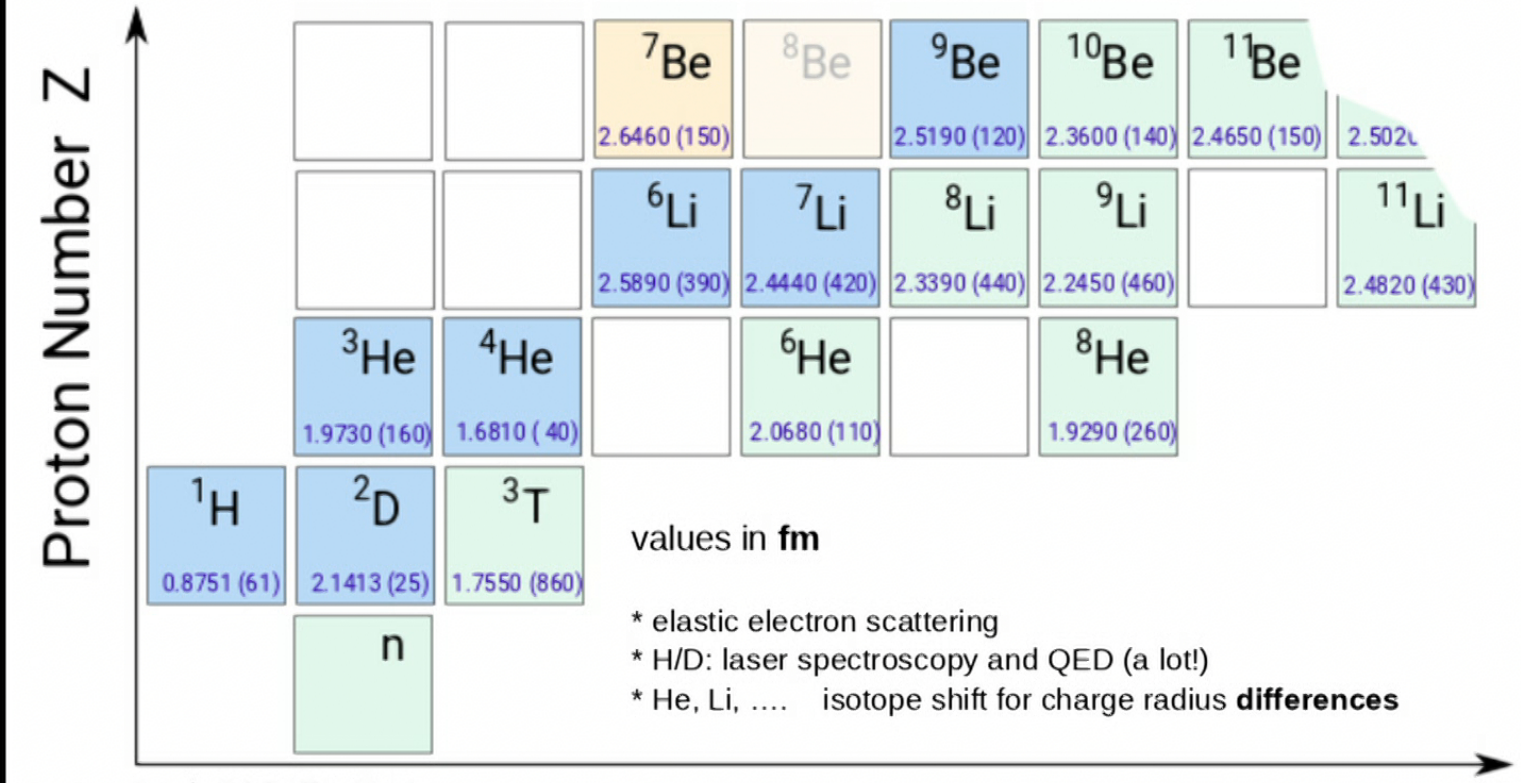
- Muonic atoms

  as a probe of nuclear physics (**charge radii**, magnetization radii, polarizabilities, …)
- The "Proton Radius Puzzle"
- Rydberg constant

  key parameter to check **atomic physics** part of the discrepancy
- Muonic helium
- Muonic future: Li, Be, T?

Nuclear rms charge radii

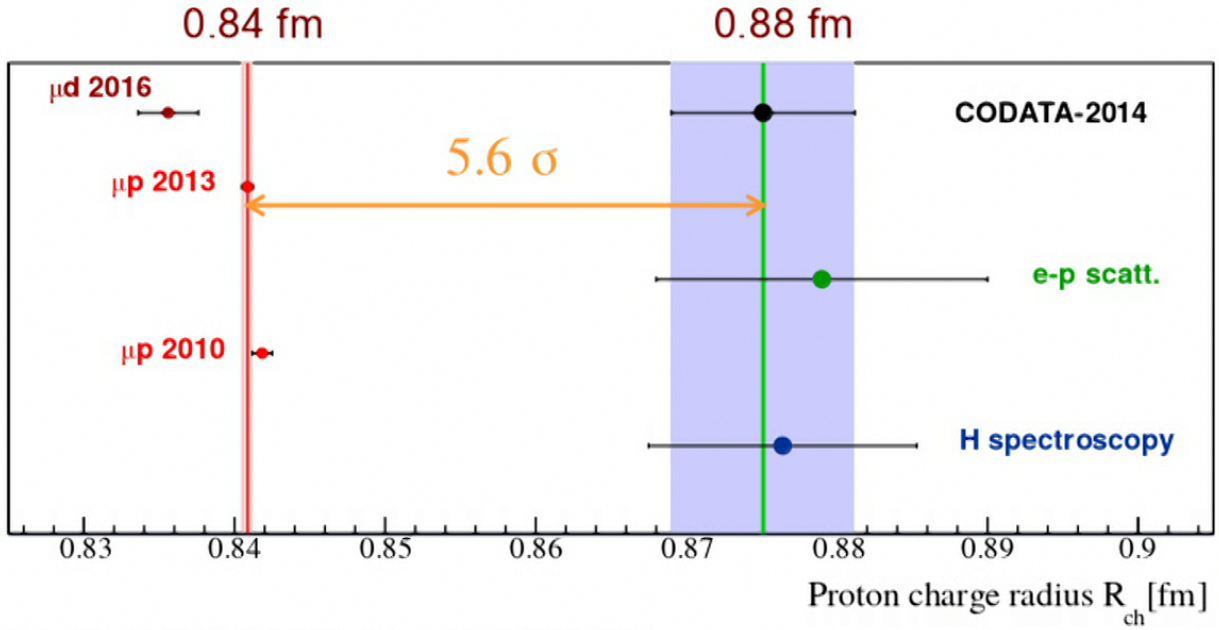
from measurements with **electrons**



sources: * p,d: CODATA-2014
* t: Amroun et al. (Saclay) , NPA 579, 596 (1994)
* ^{3,4}He: Sick, J.Phys.Chem.Ref Data 44, 031213 (2015)
* Angeli, At. Data Nucl. Data Tab. 99, 69 (2013)

The “Proton Radius Puzzle”

Measuring R_p using electrons: 0.88 fm (+- 0.7%)
using muons: 0.84 fm (+- 0.05%)



μd 2016: RP et al (CREMA Coll.) Science 353, 669 (2016)
μp 2013: A. Antognini, RP et al (CREMA Coll.) Science 339, 417 (2013)

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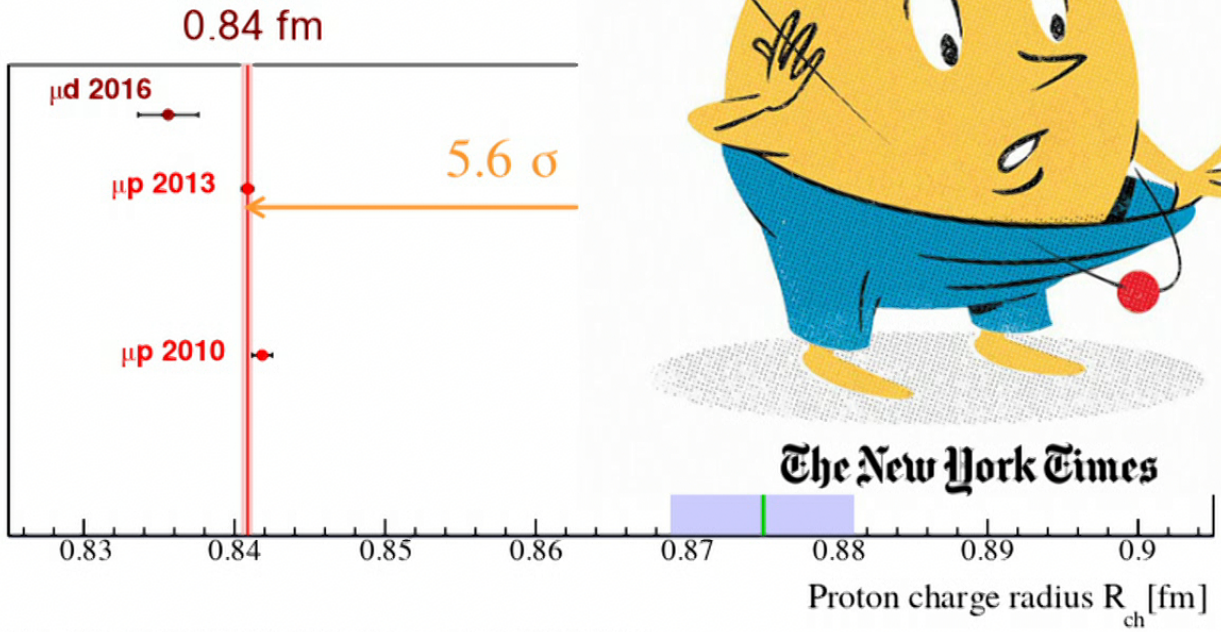

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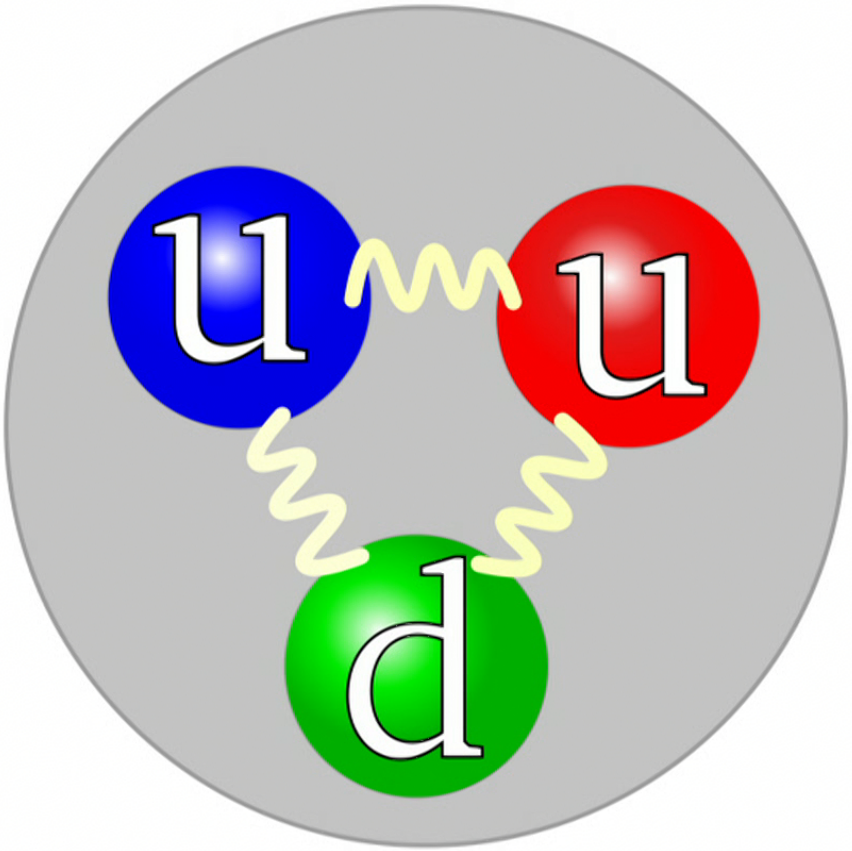
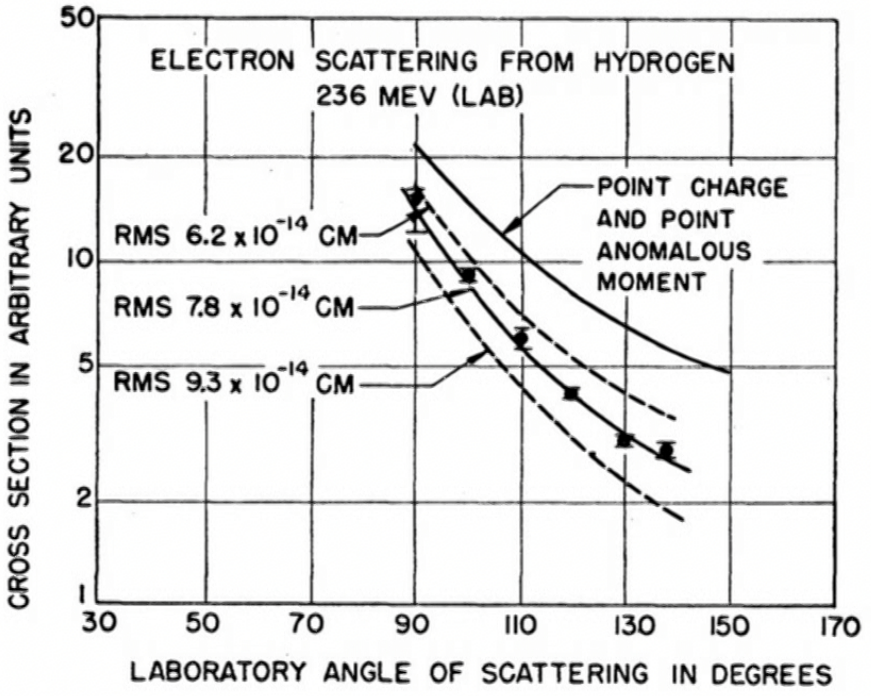
Proton – 3 Quarks



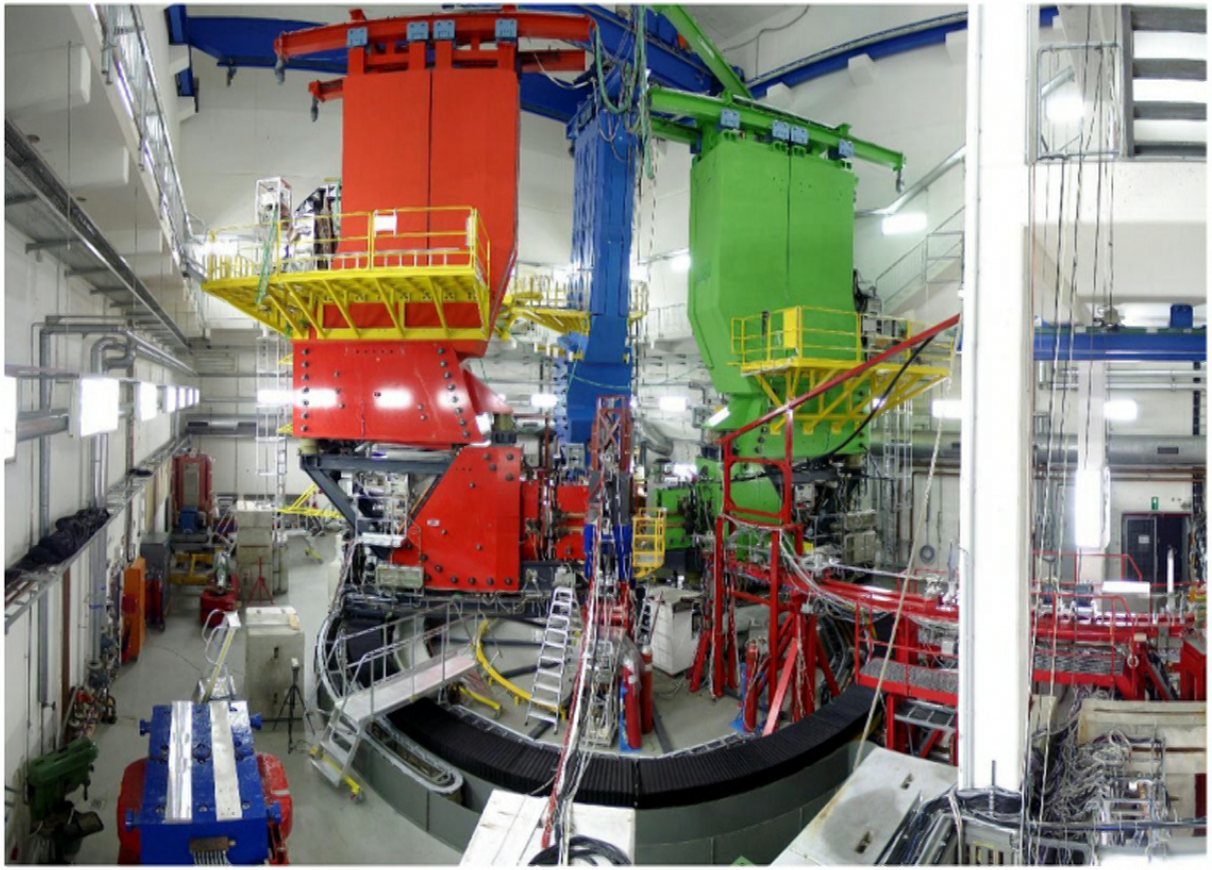
Robert Hofstadter – 1955

1915 – 1990

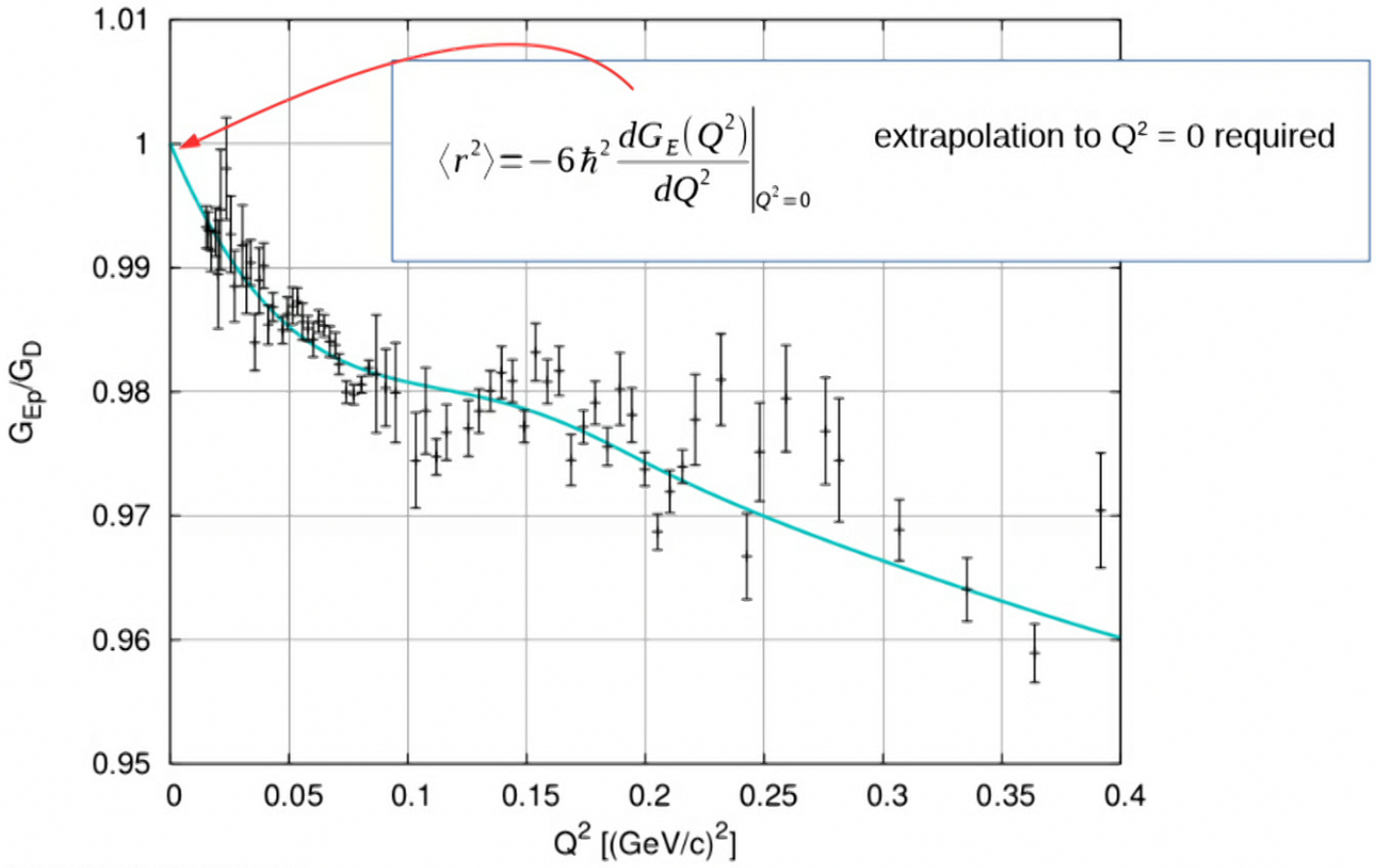


Phys. Rev. 102, 851 (1956)

Mainzer Microtron MAMI



Electron scattering - today

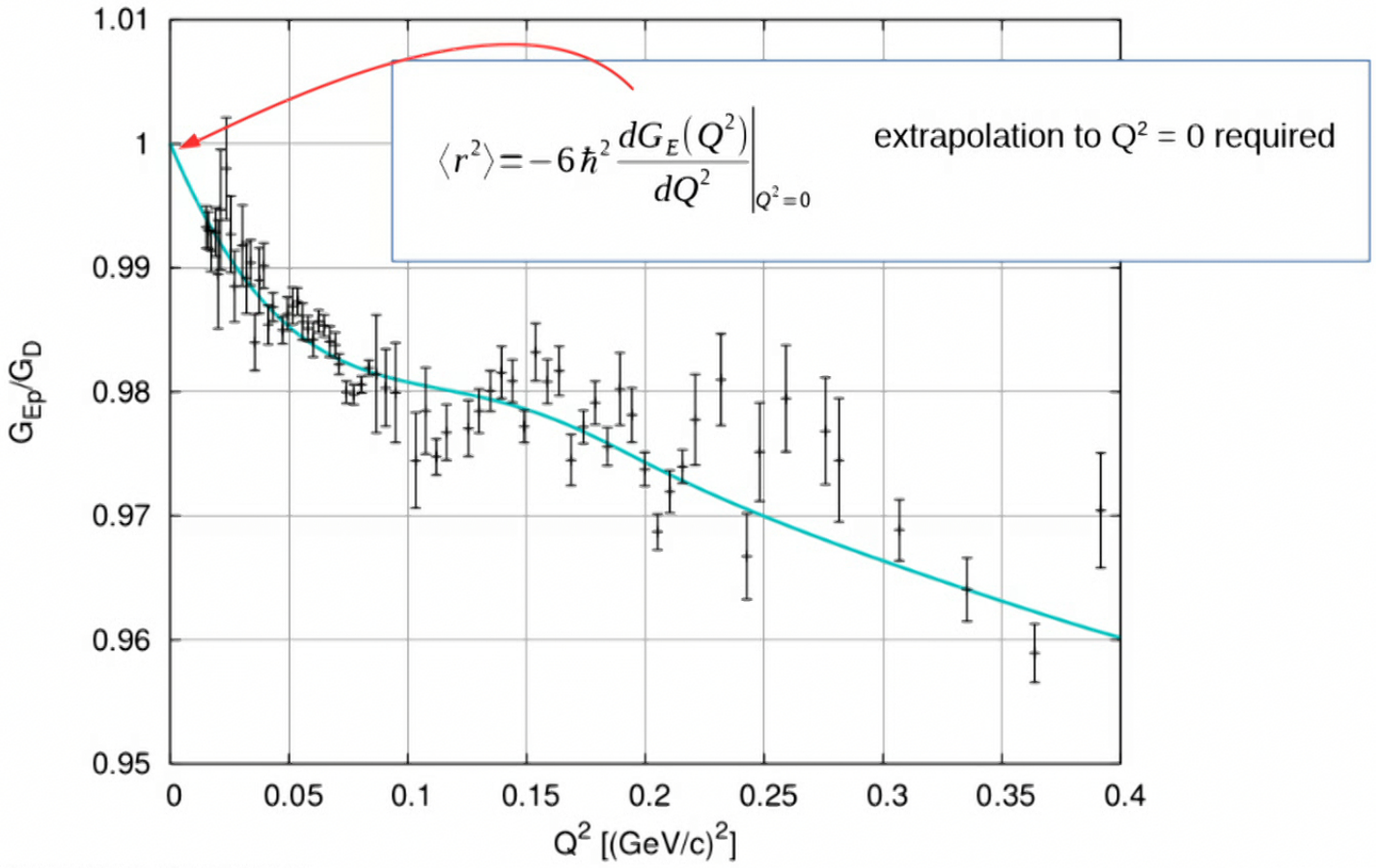


Mainz MAMI data 2010

Vanderhaeghen, Walcher: 1008.4225

Hydrogen

Electron scattering - today



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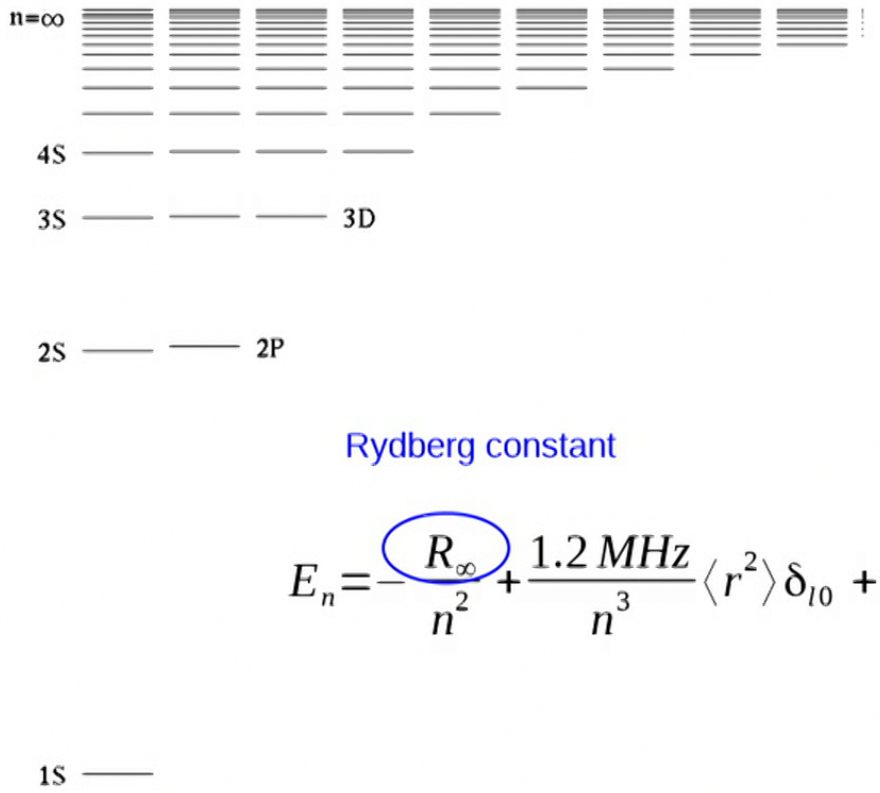
Energy levels of hydrogen



Rydberg constant

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

RP et al., Metrologia 54, L1 (2017)

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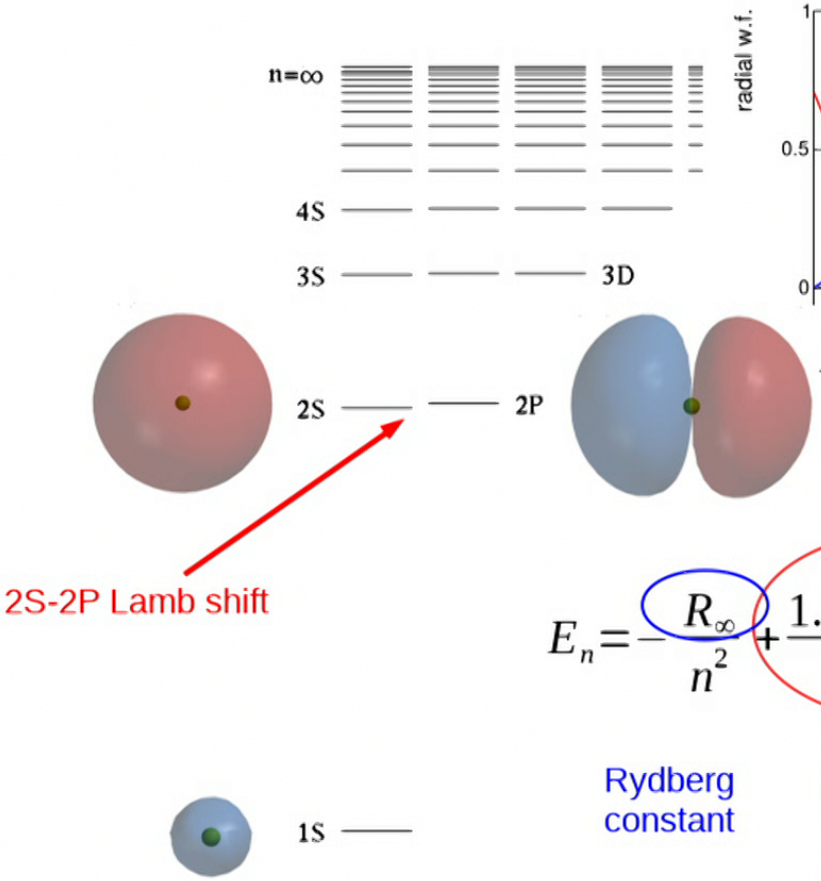
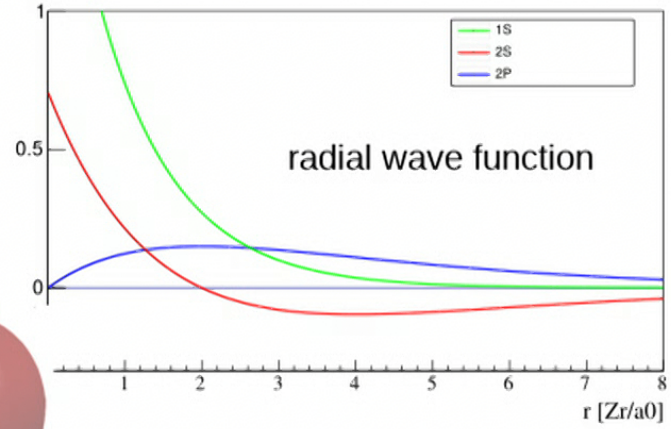




2S-2P Lamb shift

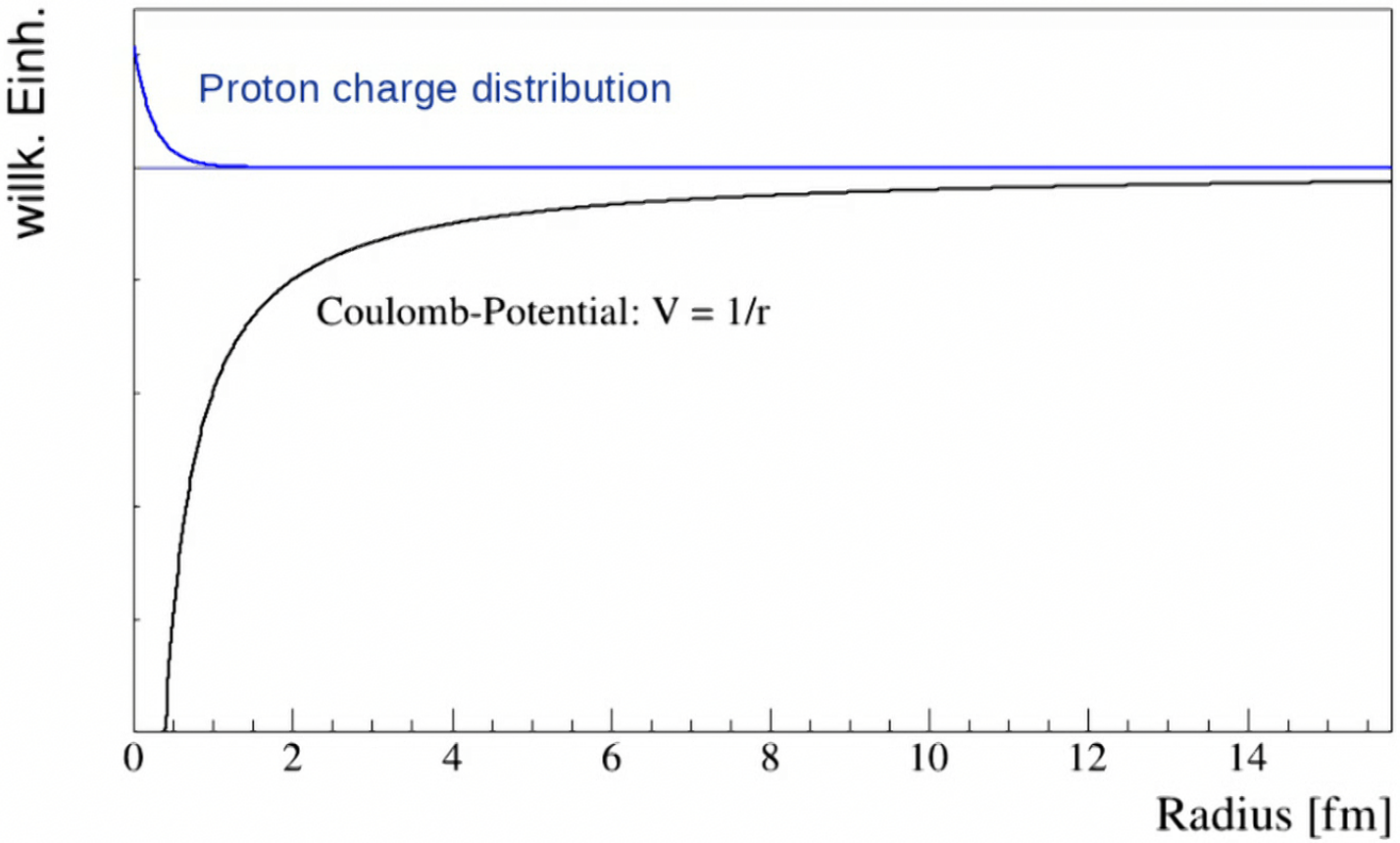
$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

Rydberg constant

finite size effect

RP et al., Metrologia 54, L1 (2017)

Proton radius and hydrogen



Muonic Hydrogen

A proton, orbited by a **negative muon.**

What is a Muon?

Carl David Anderson Seth Neddermeyer

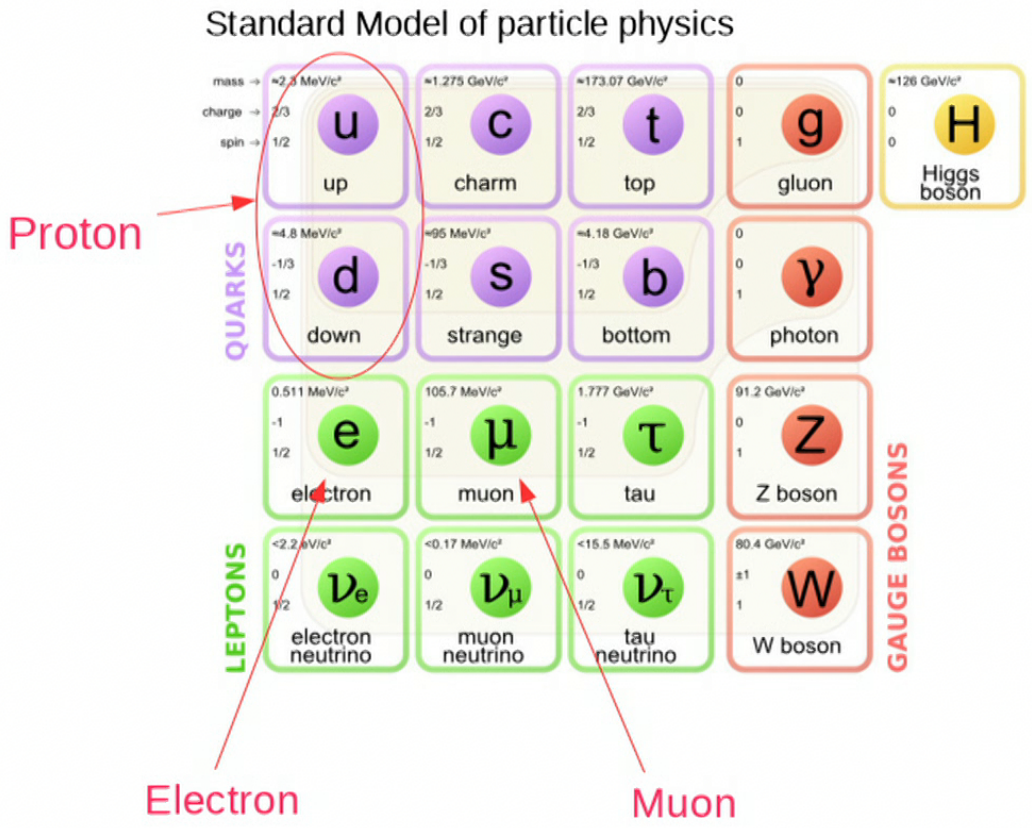
Nobel prize 1936
(for the Positron!)

Muons are **heavy electrons**:
200x the mass of an electron.

Discovered in 1936 by Carl D. Anderson and Seth Neddermeyer as part of the cosmic radiation.

Muon have a lifetime of 2 microseconds.
(millionths of a second).

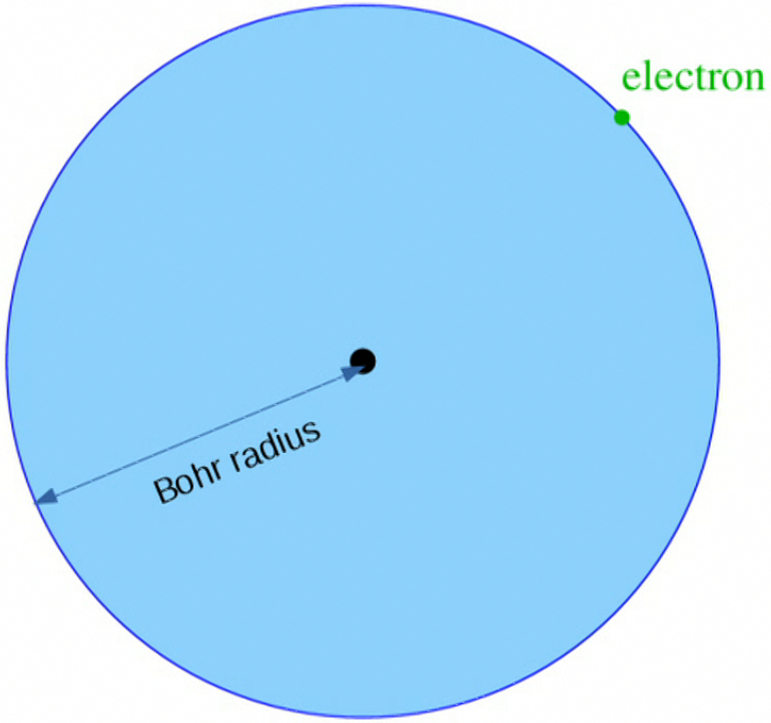
The Muon and its place in the Universe



Electronic and muonic atoms

Regular hydrogen:

Proton + Electron



Muonic hydrogen:

Proton + Muon

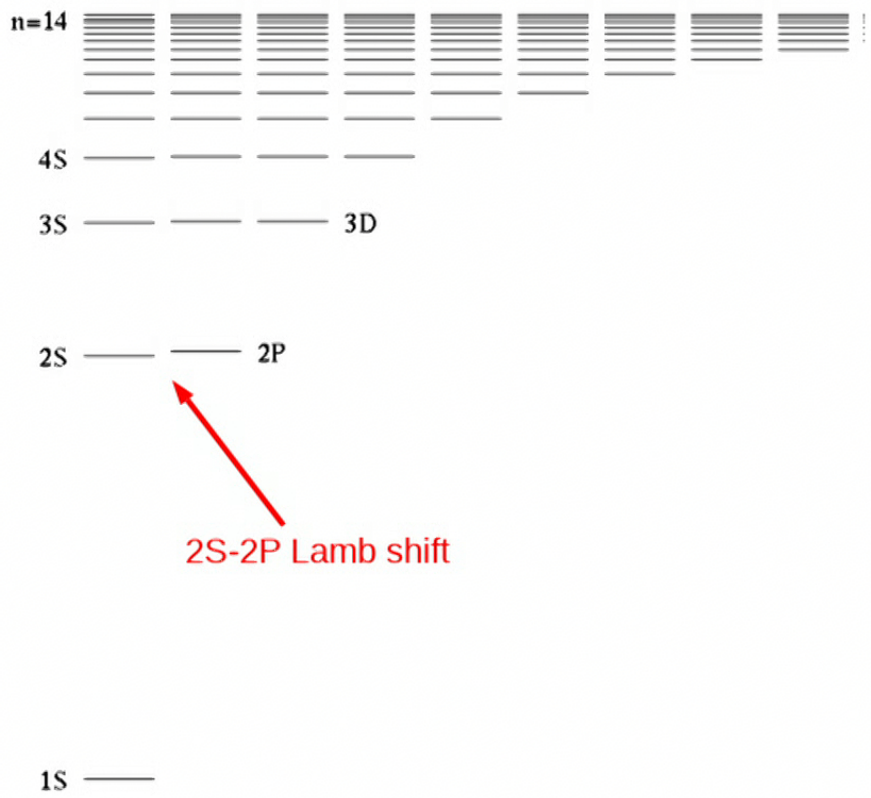
Muon **mass** = **200** * electron mass

Bohr **radius** = **1/200** of H

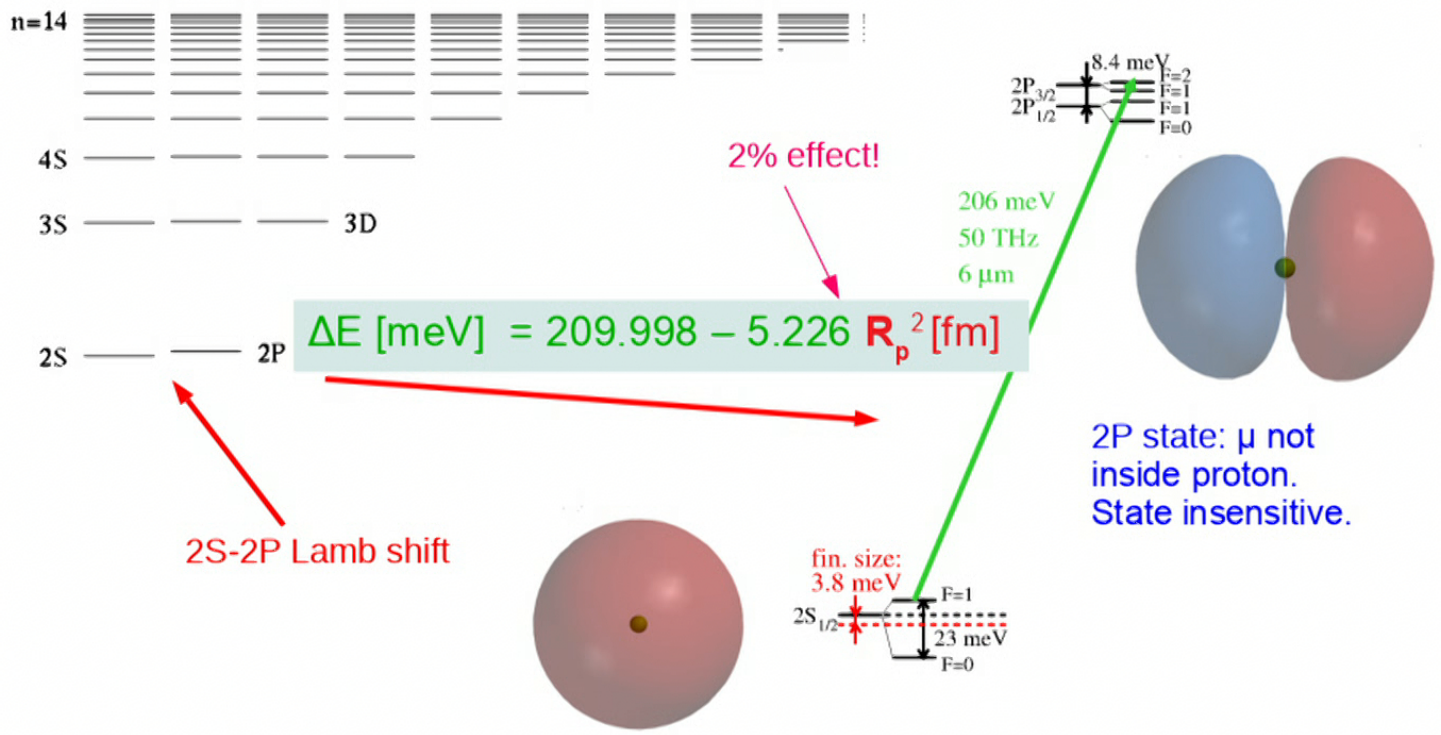
200^3 = a **few million times** more sensitive to proton size

Vastly not to scale!!

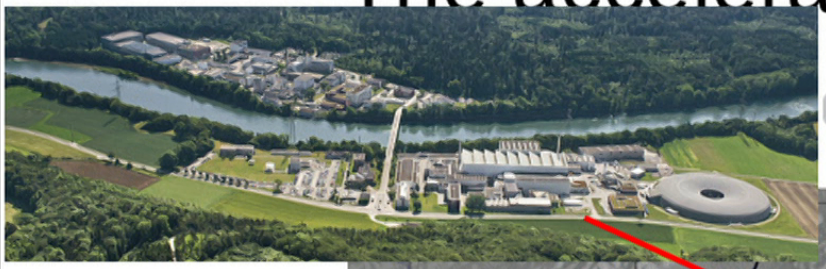
Muonic Hydrogen



Muonic Hydrogen

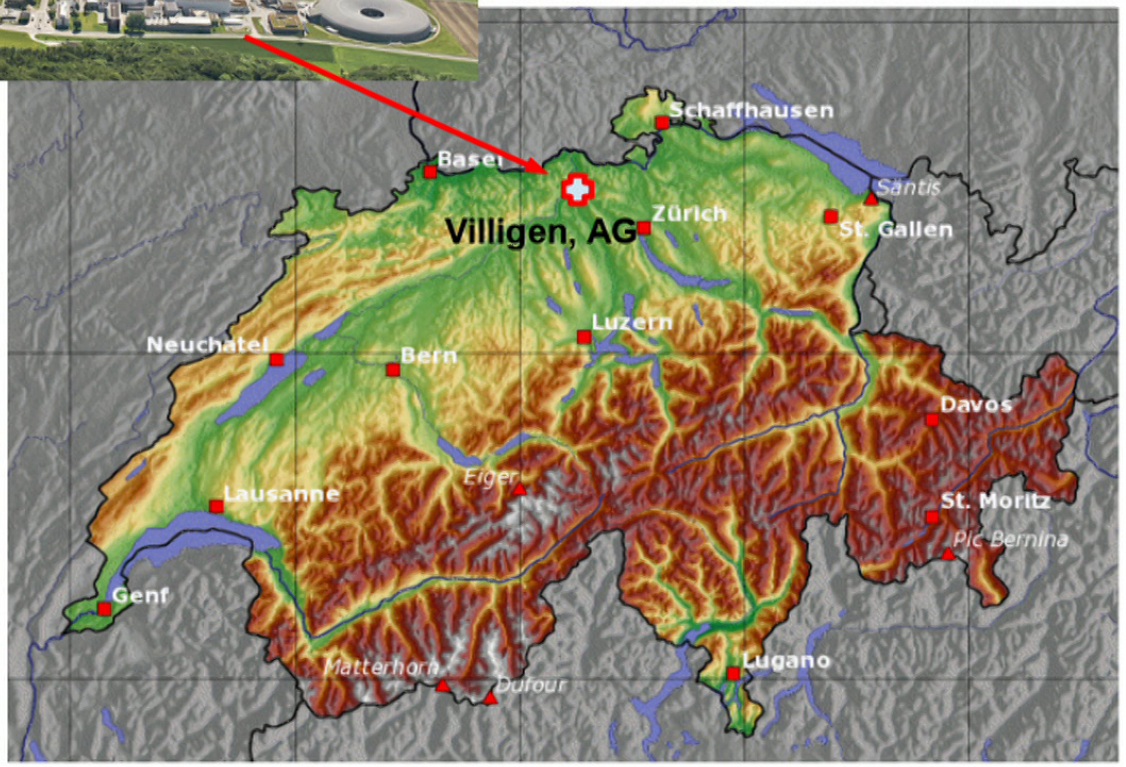


The accelerator at PSI

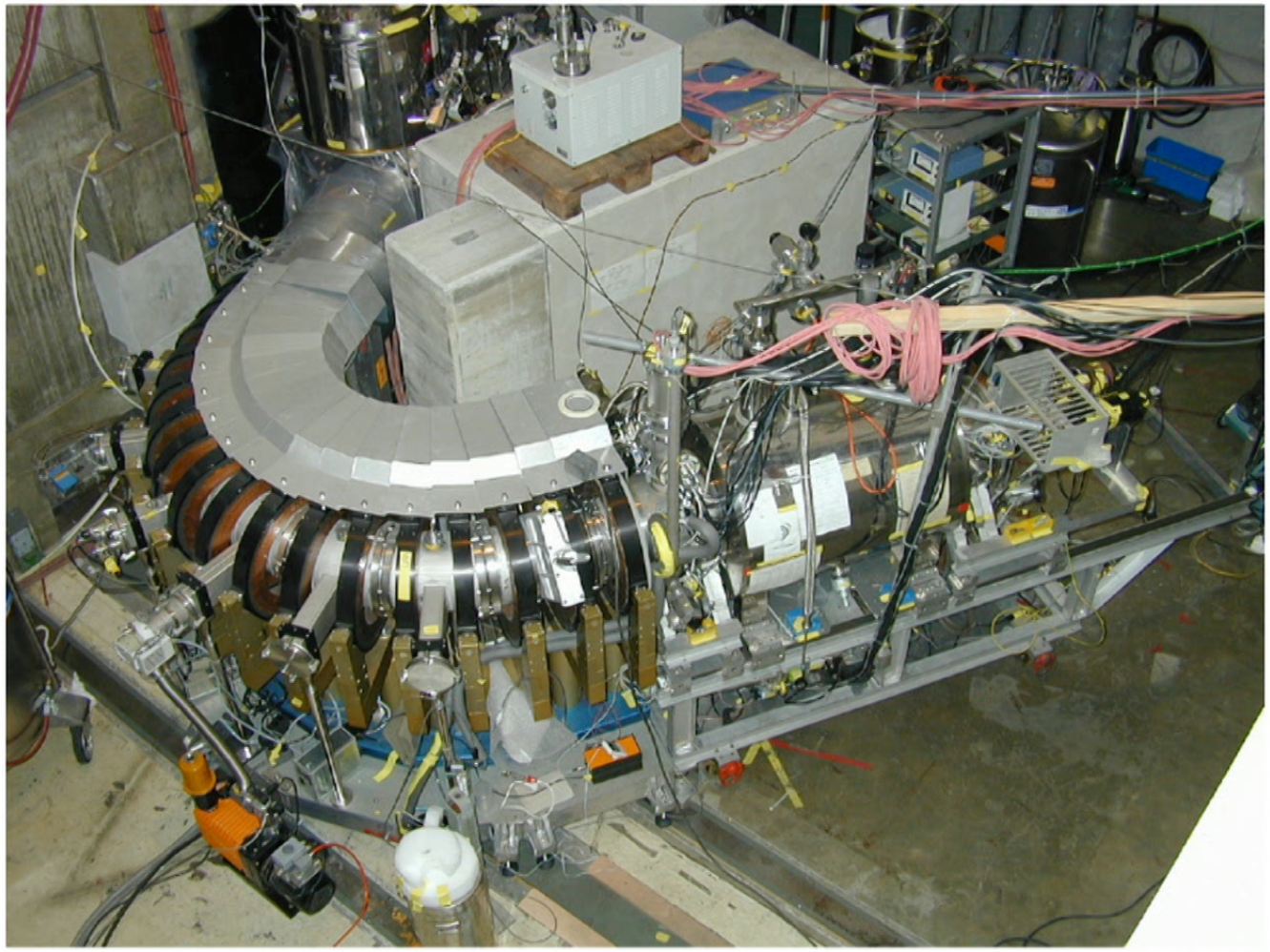


PAUL SCHERRER INSTITUT

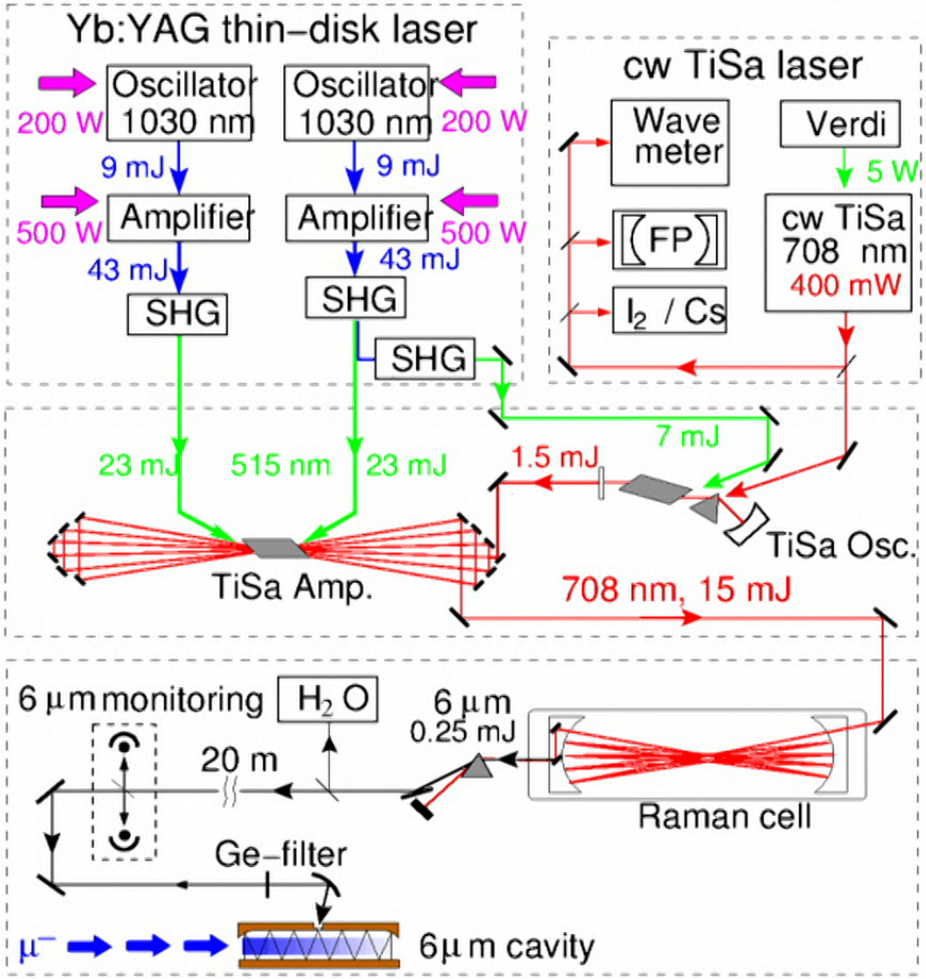
PSI



The muon beam line in πE5



The laser system



Yb:YAG Disk laser
→ fast response on µ

Frequency doubling (SHG)
→ green light to pump Ti:sapphire laser

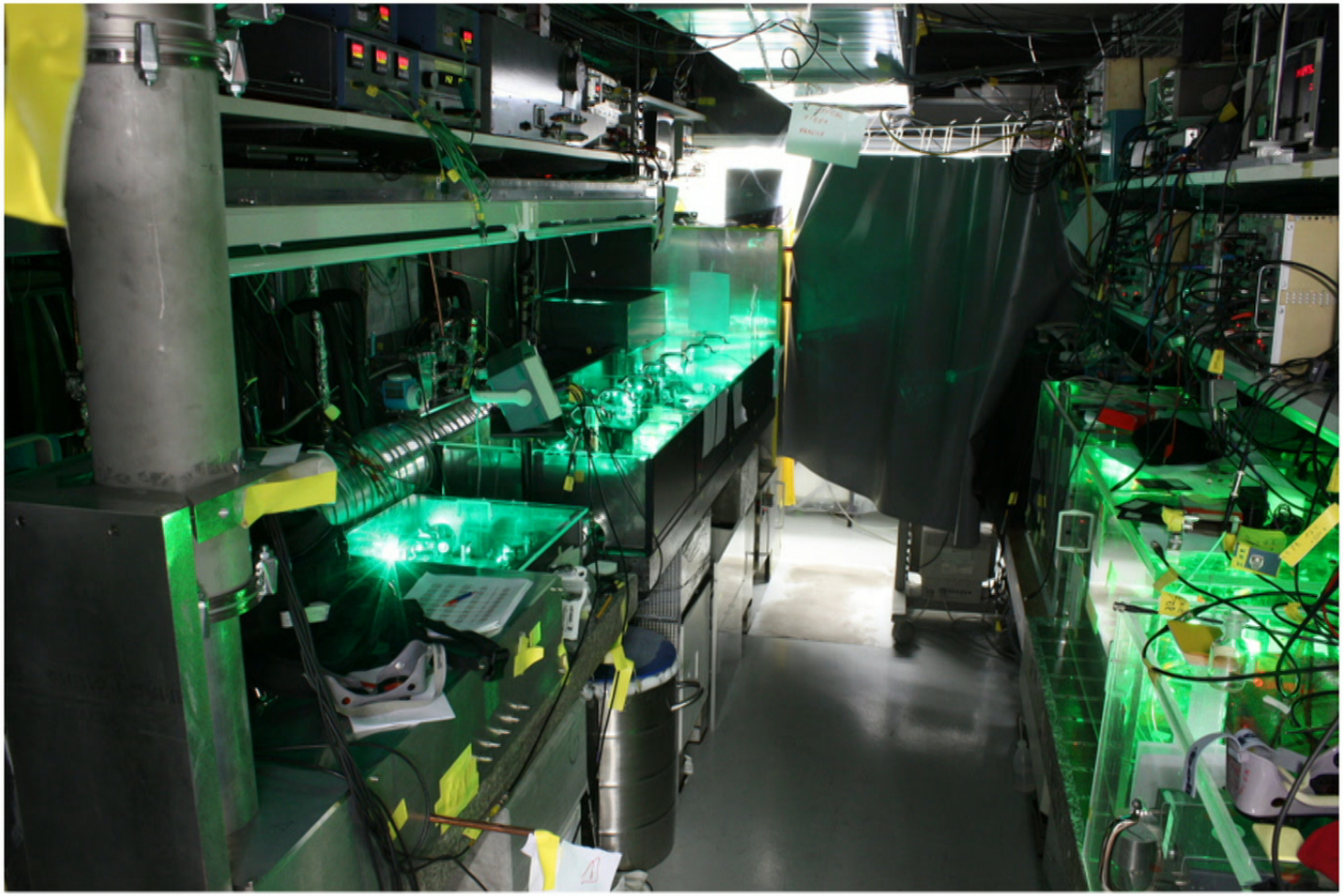
Ti:sapphire cw laser
→ determines laser frequency

Ti:sapphire MOPA
→ high pulse energy (15 mJ)

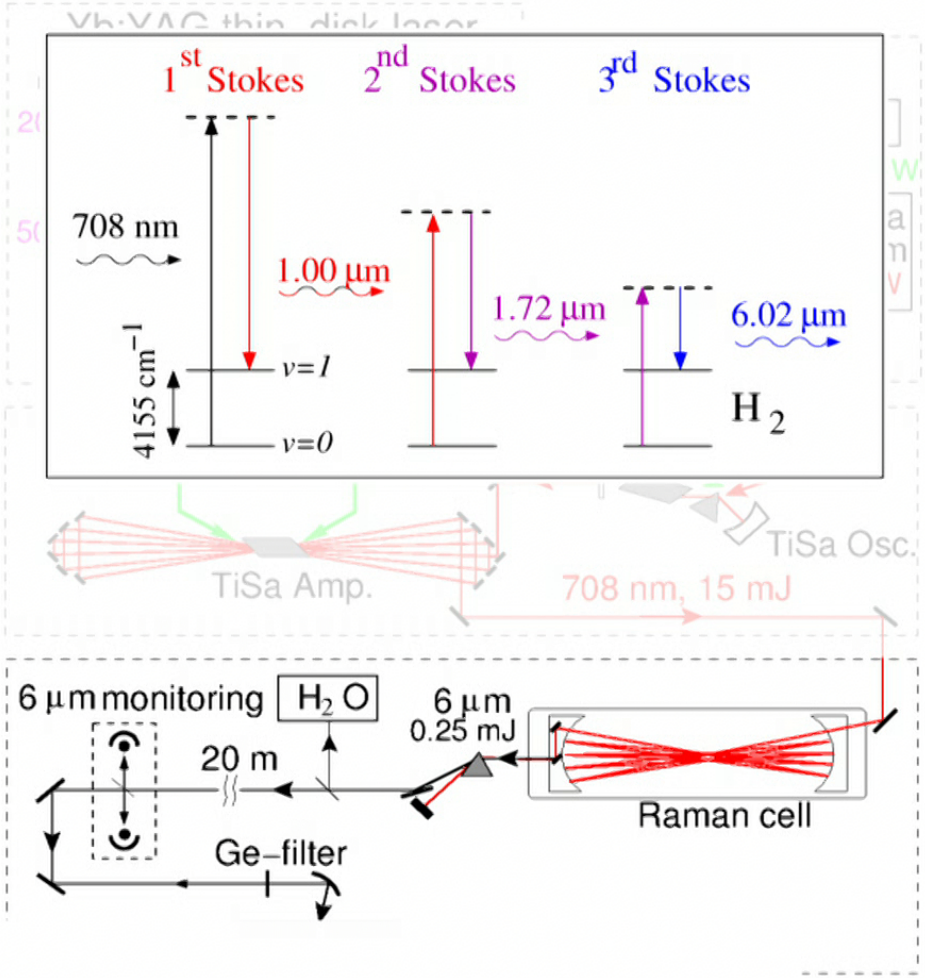
Raman cell
→ 3 sequential stimulated Raman Stokes shifts
Laser wave length → 6 µm

Target Cavity
→ Mirror system to fill the muon stop volume (H_2)

The laser hut at PSI



Laser system: Raman cell



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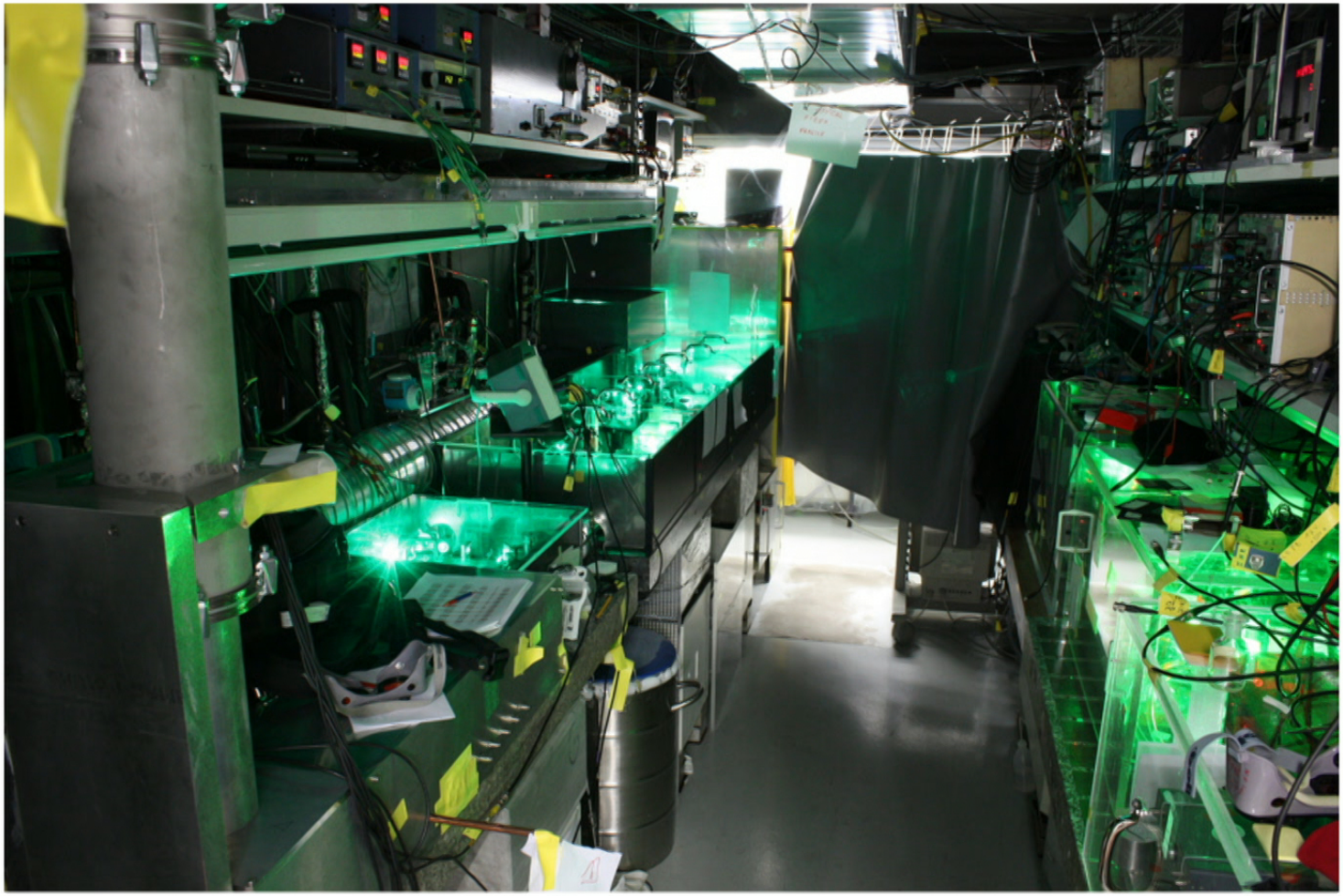
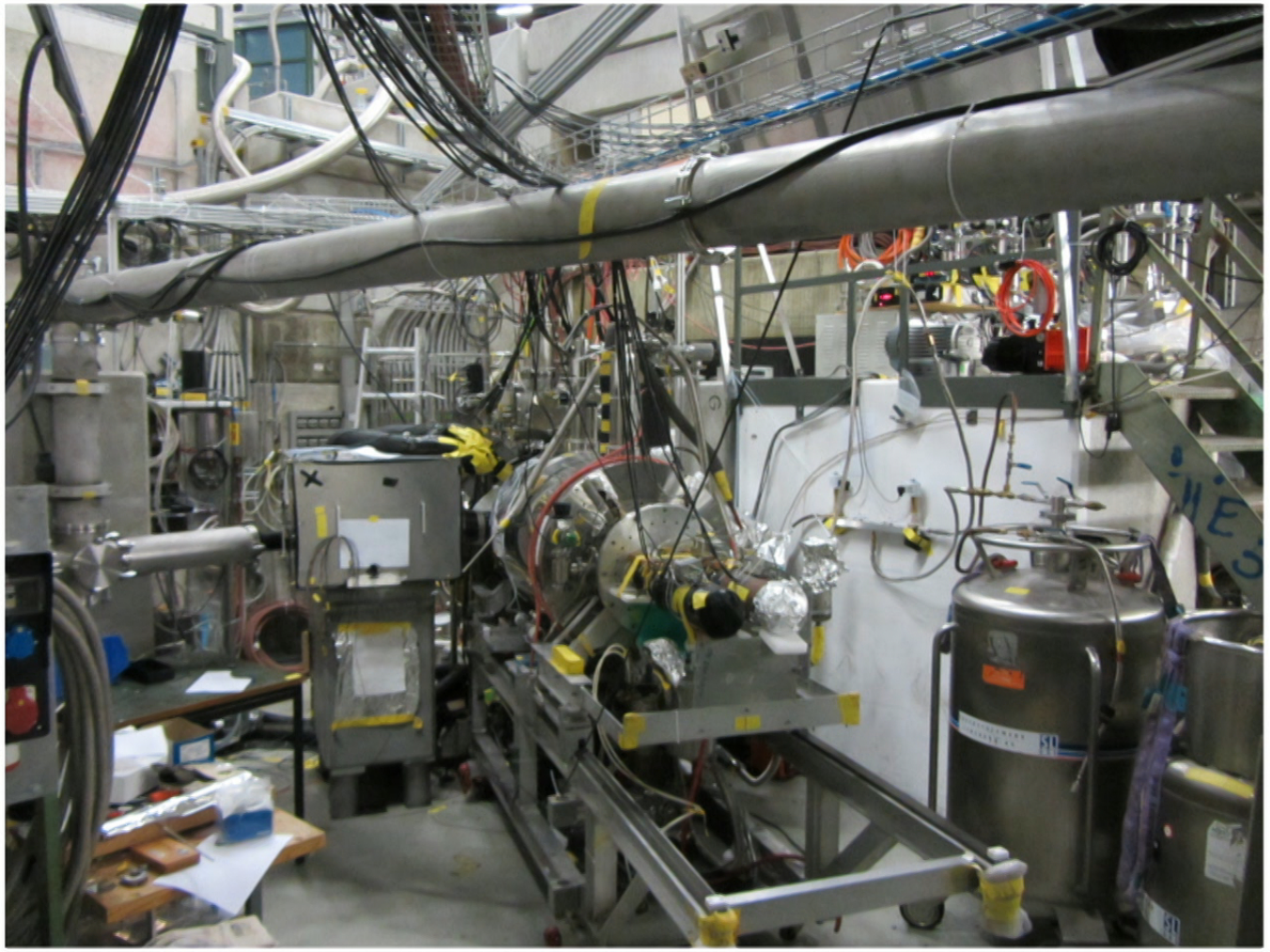
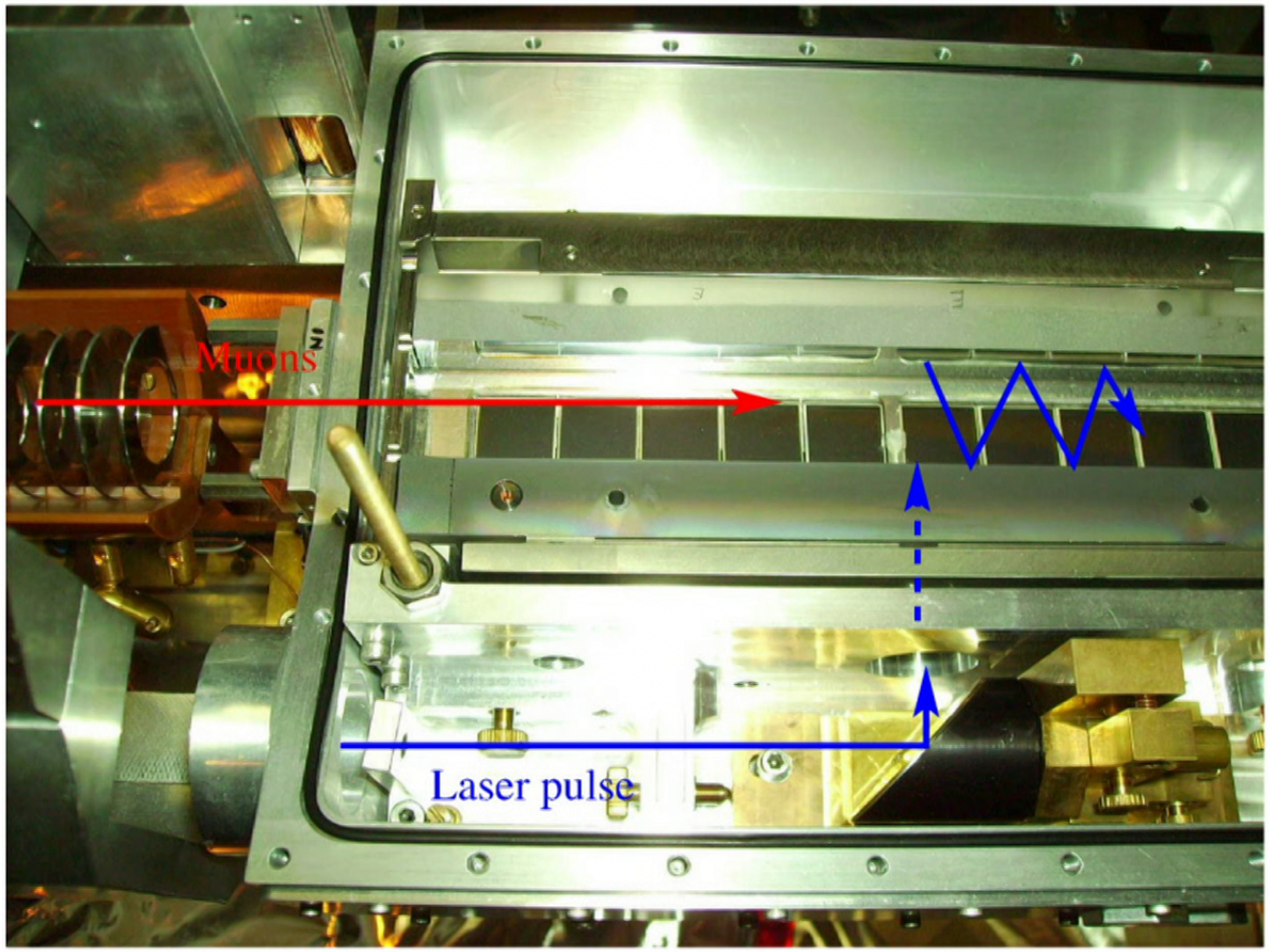
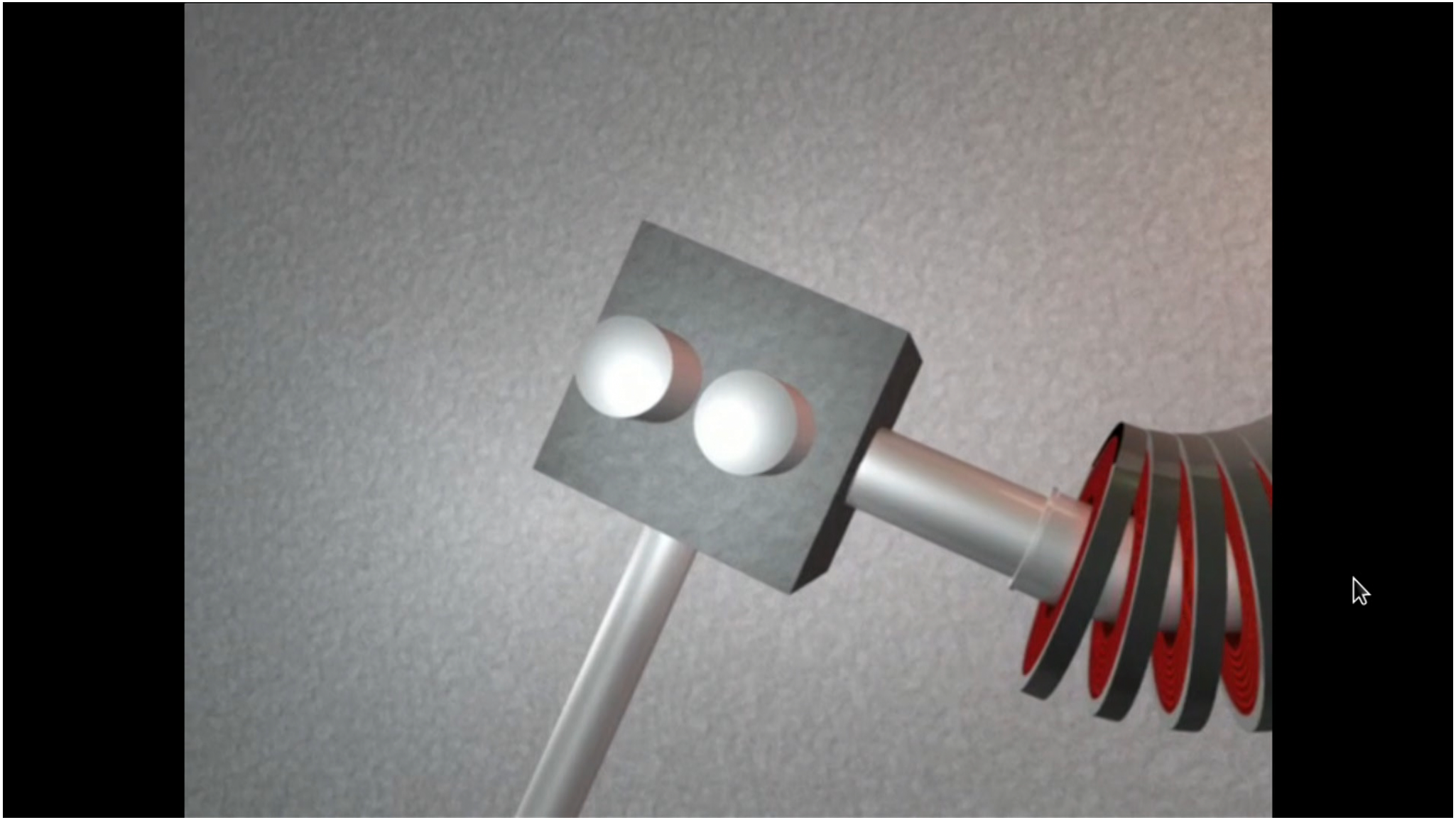


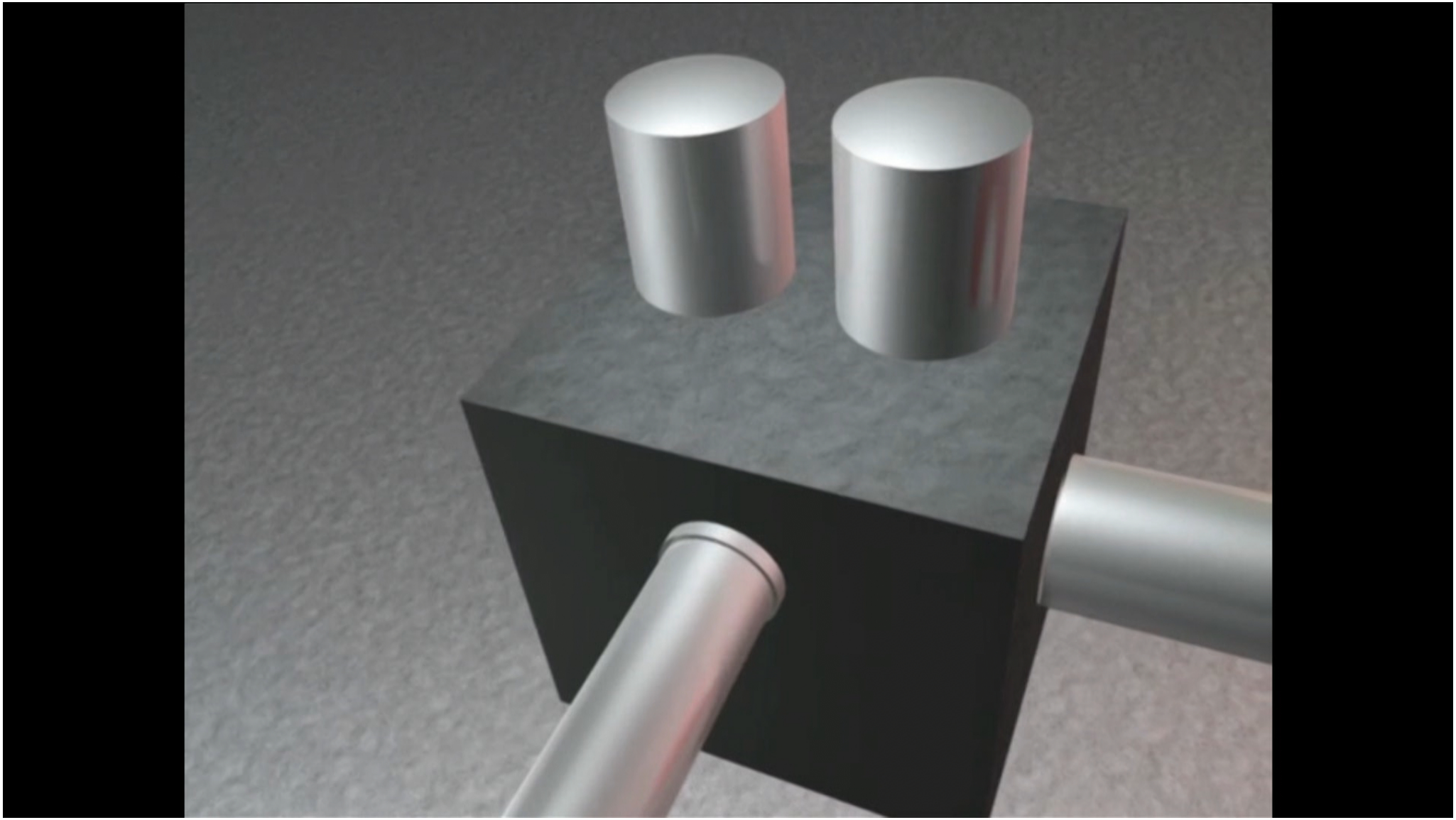
Laser beam line

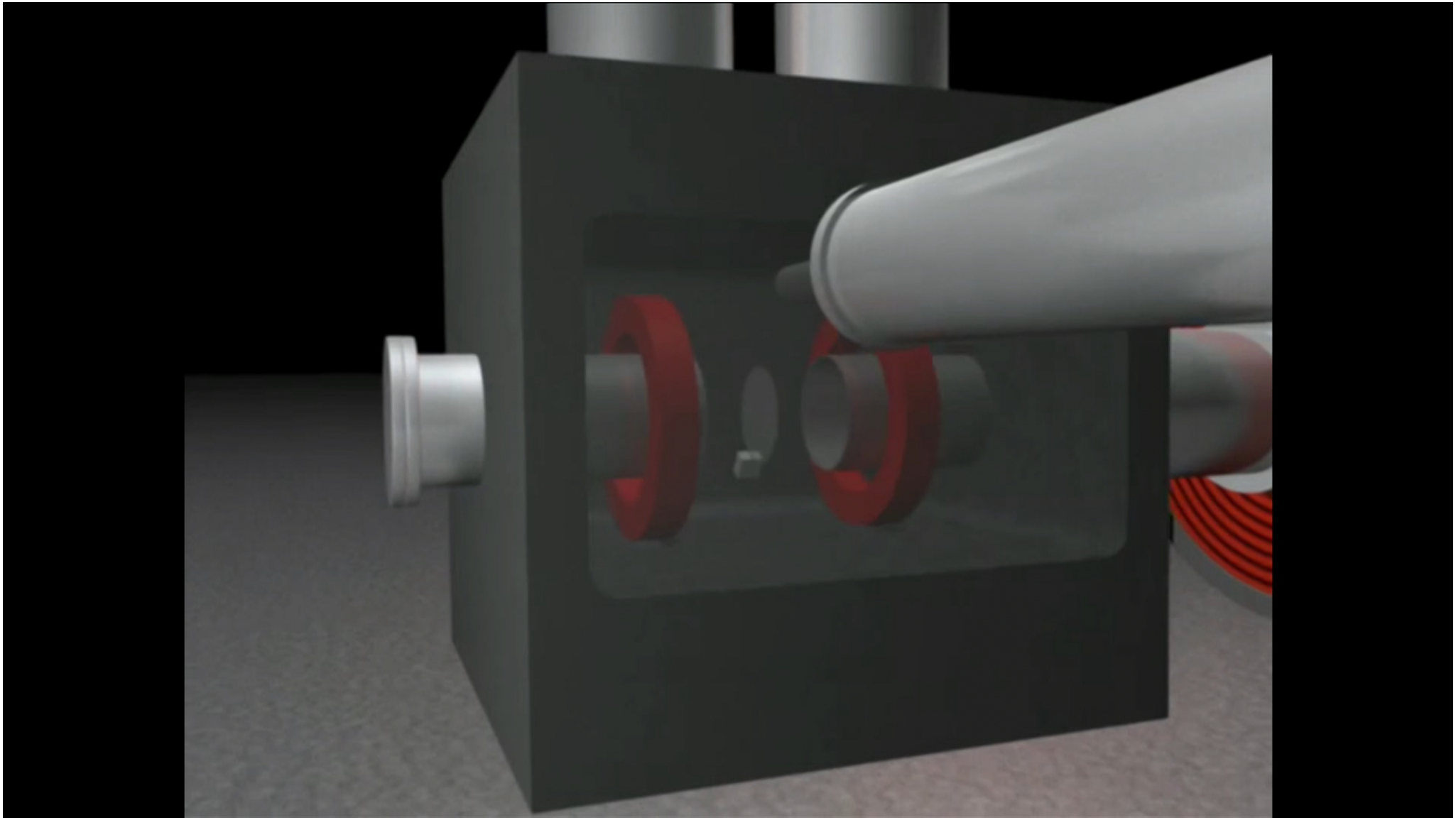


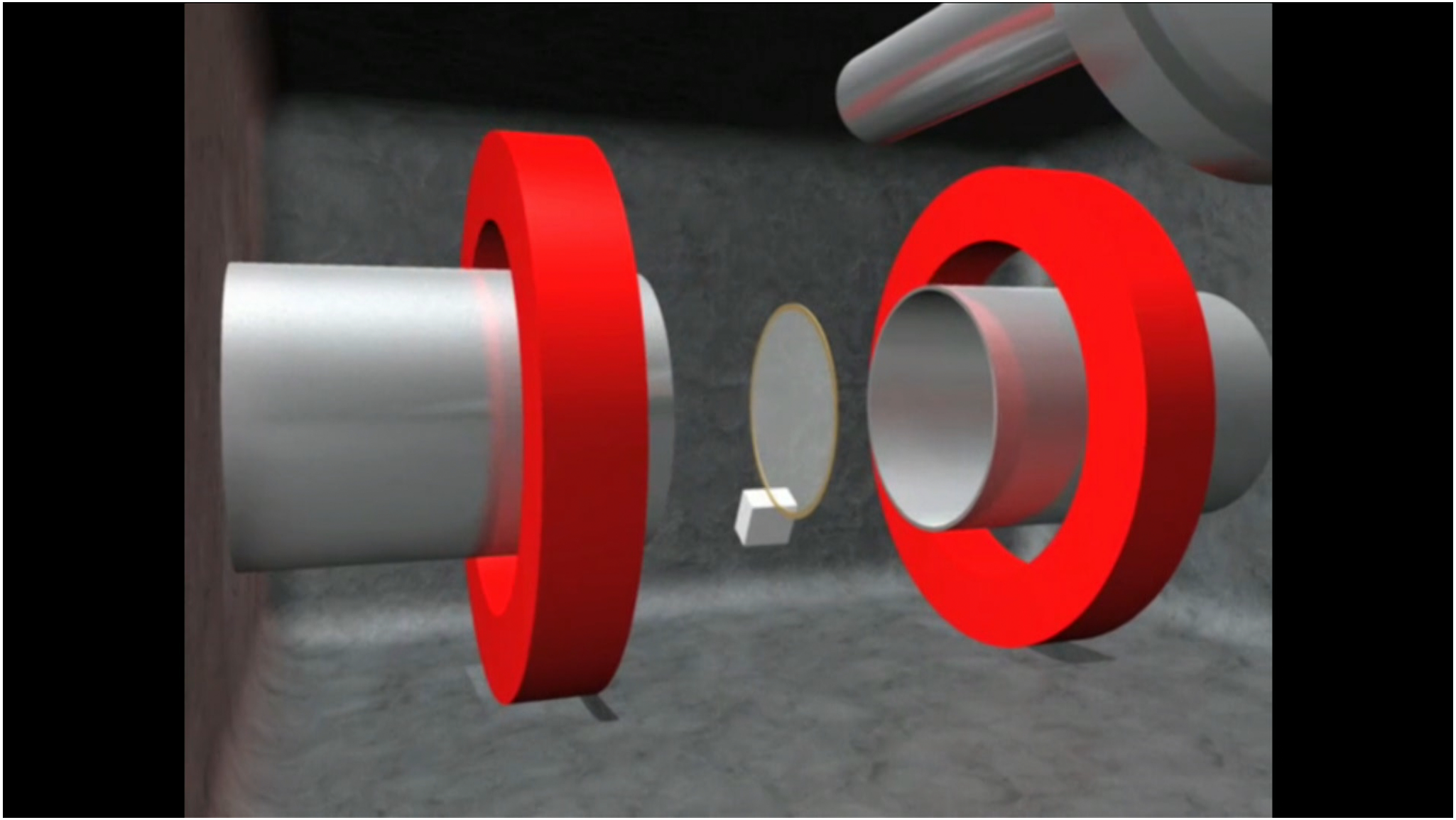
The hydrogen target

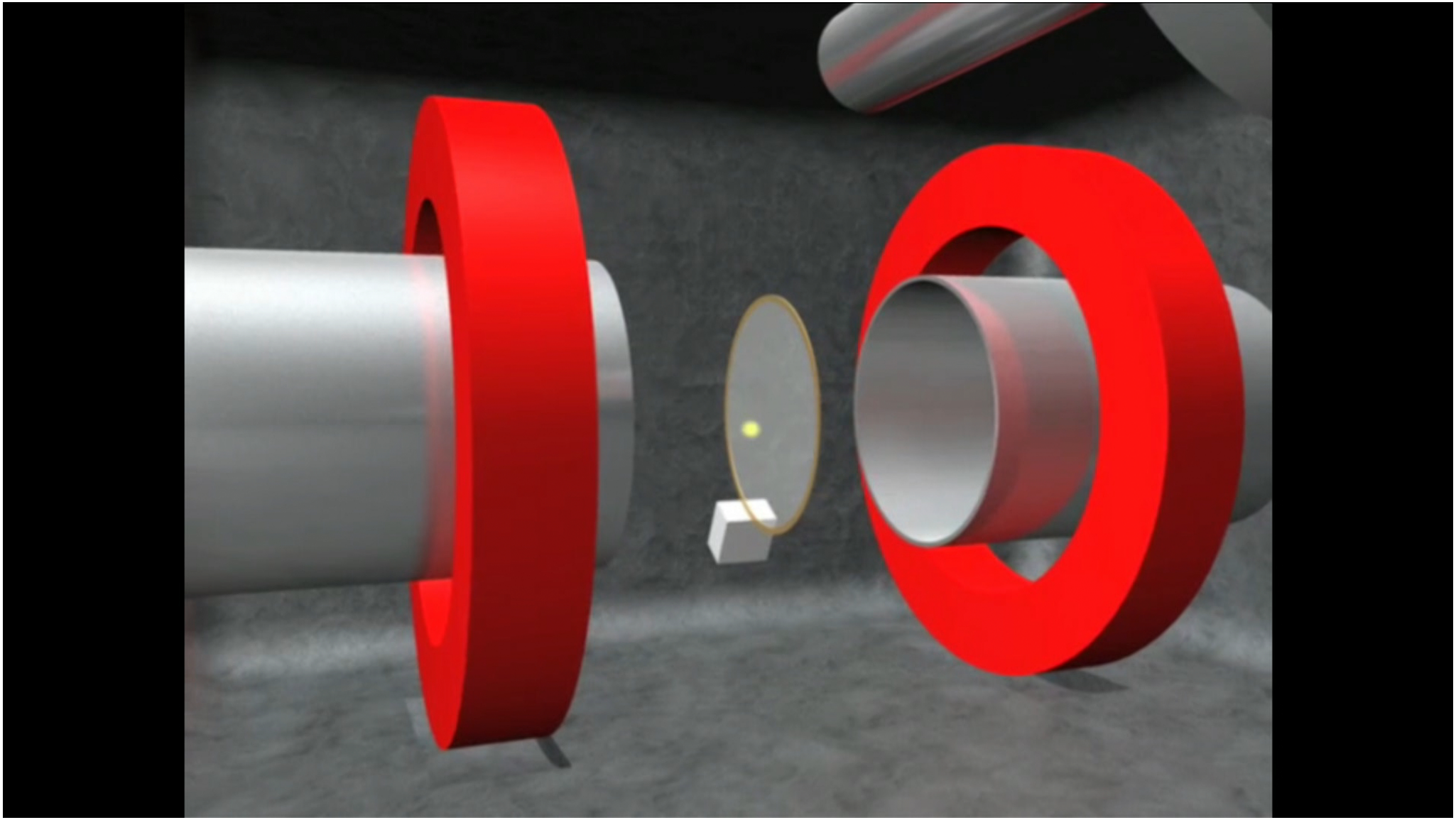


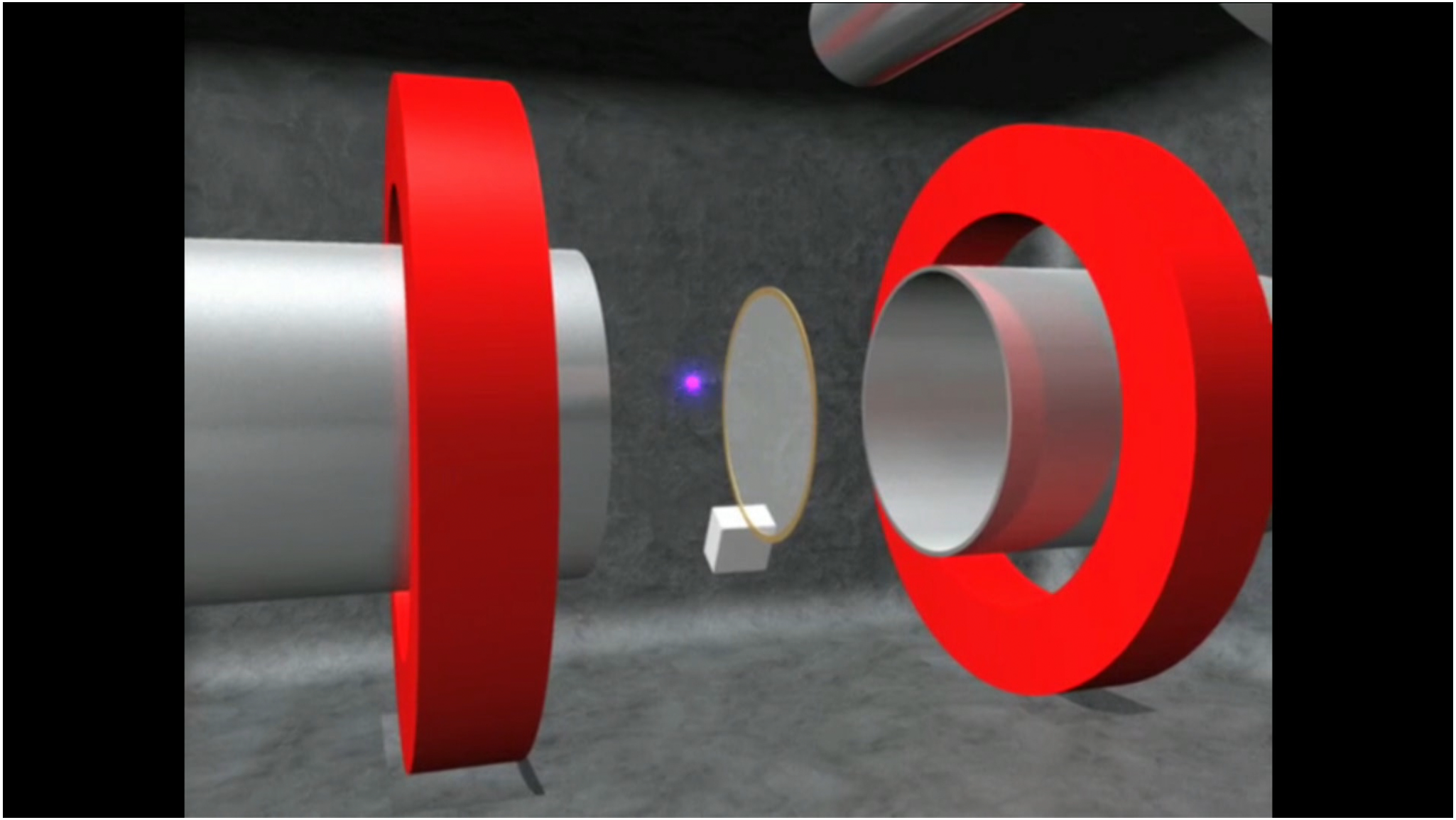


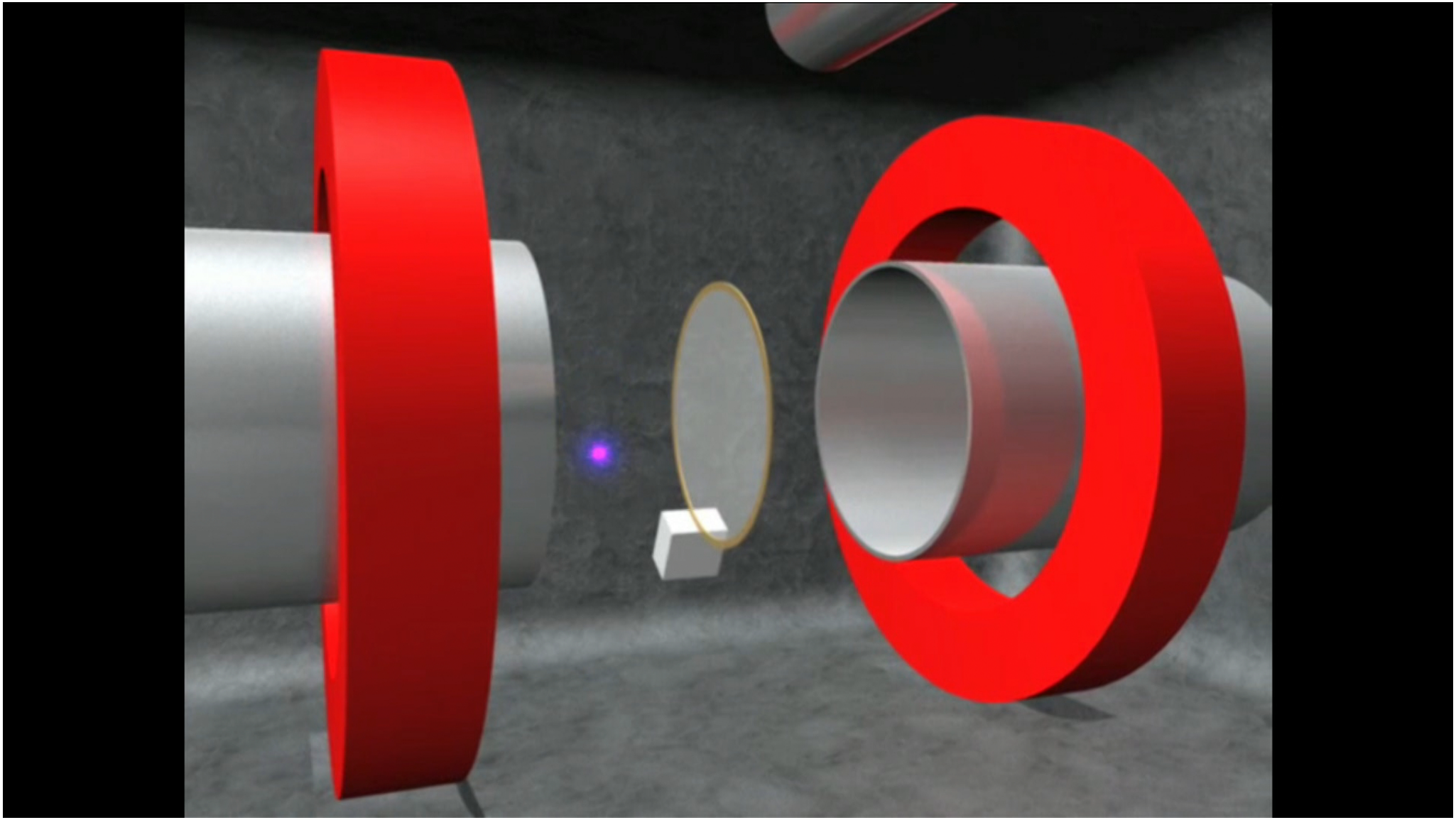


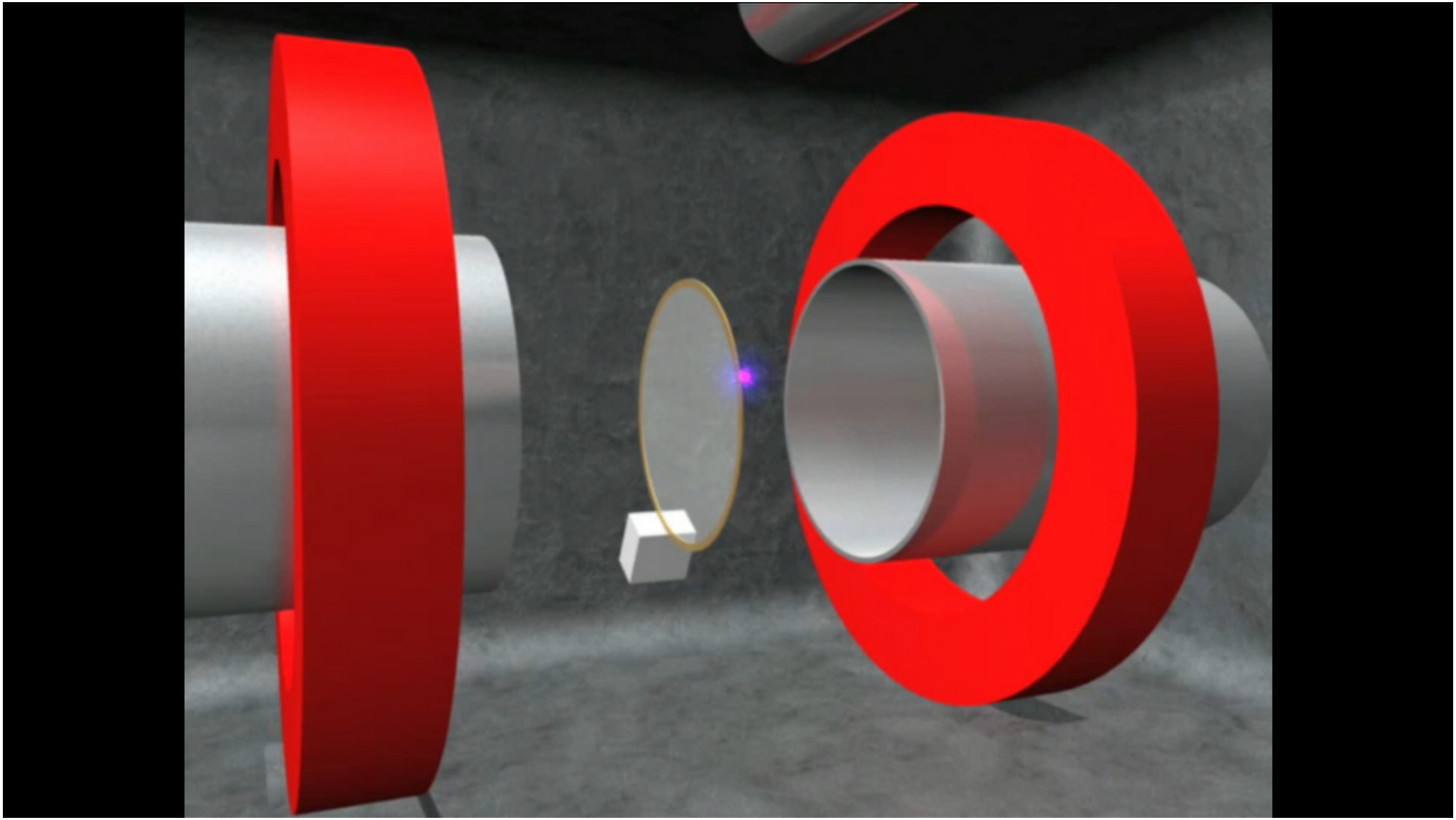


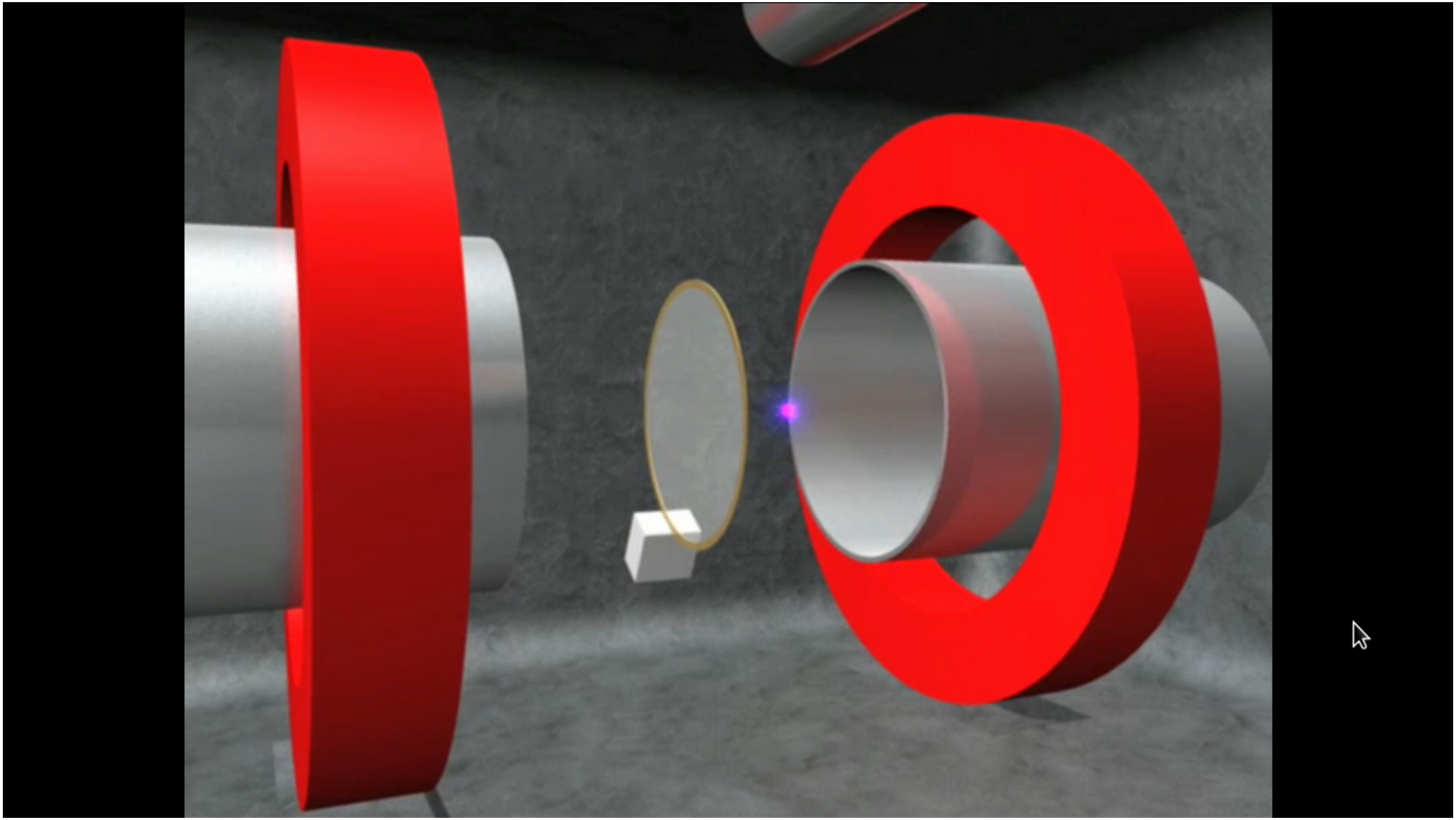


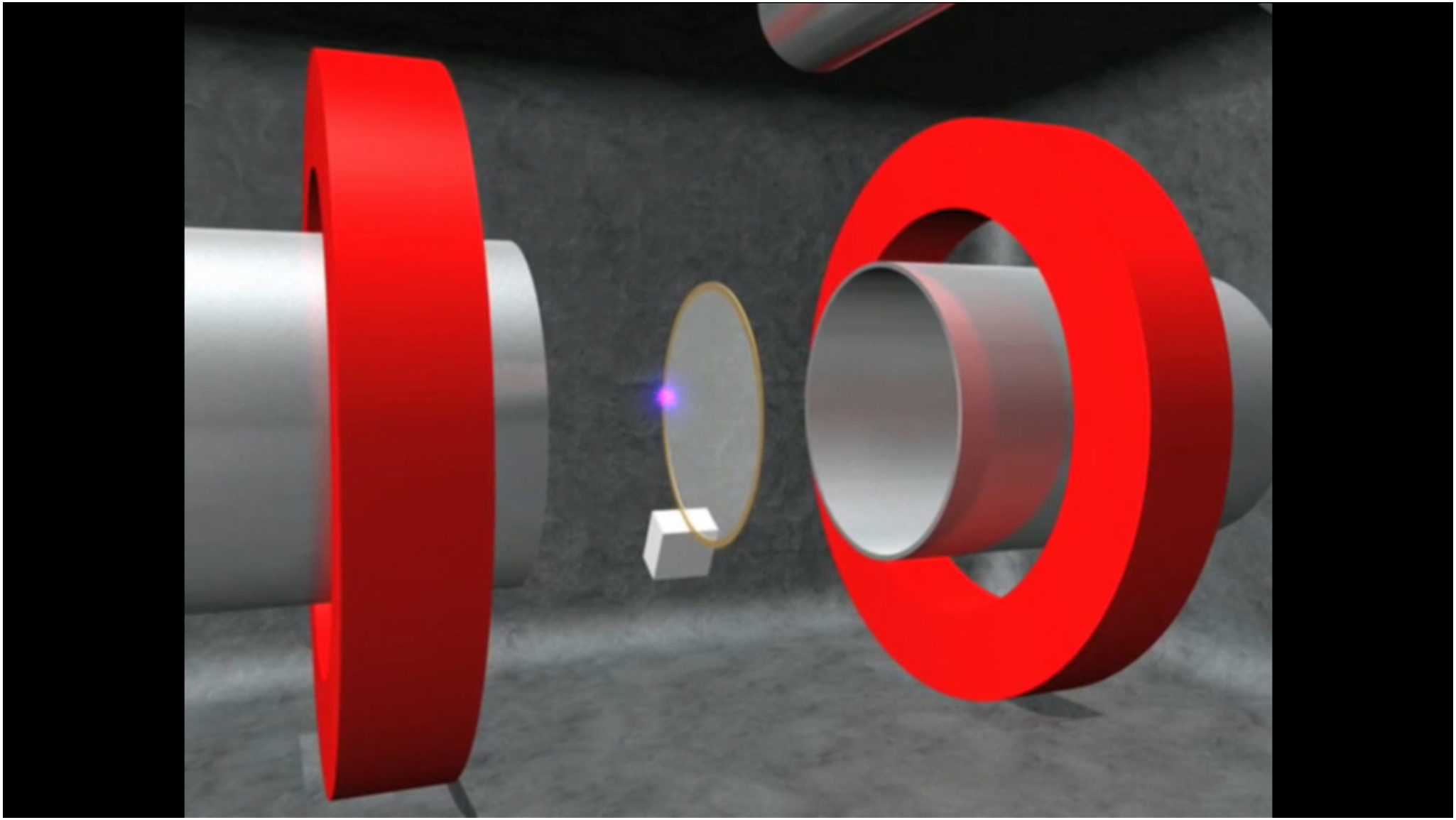


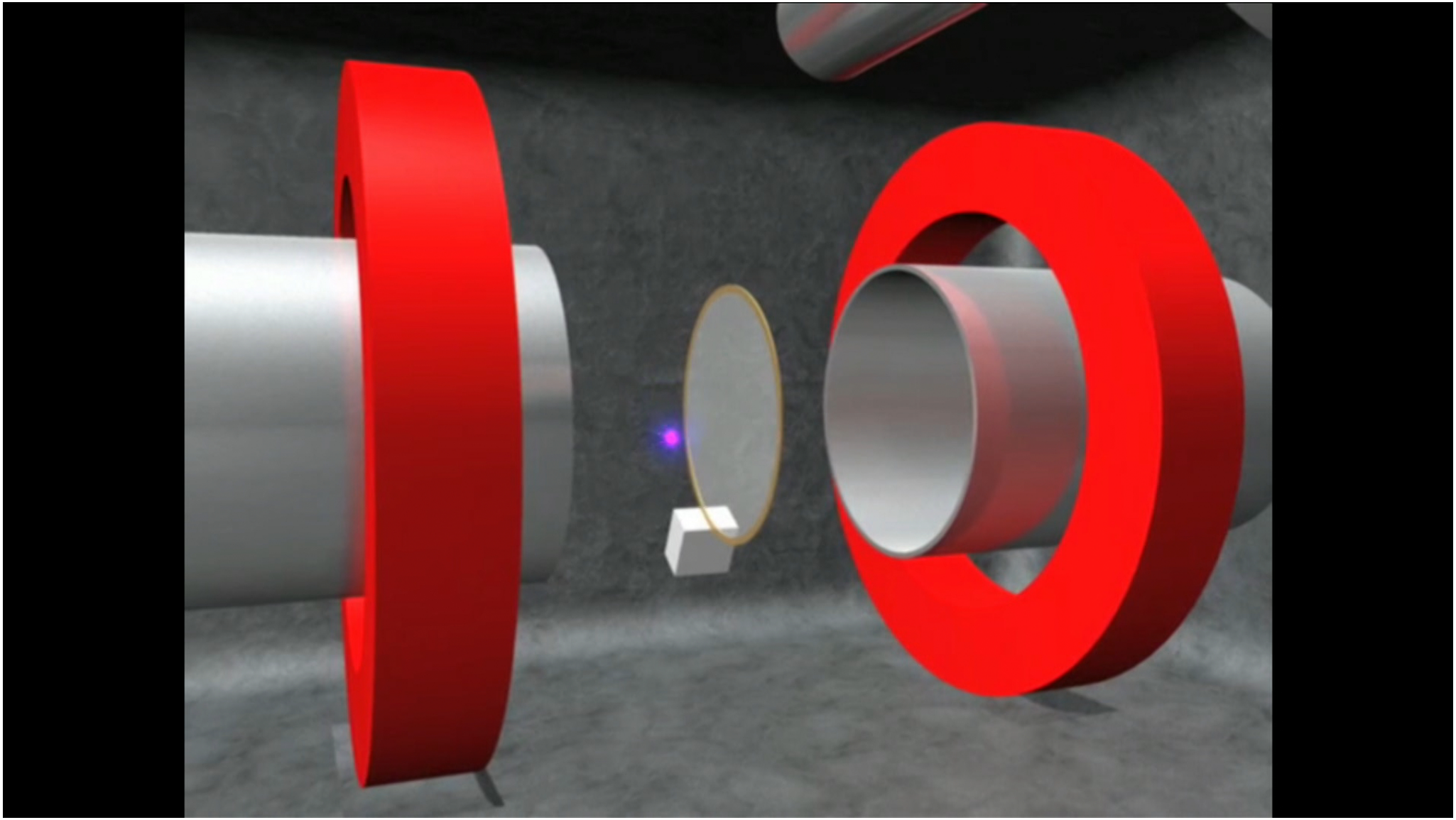


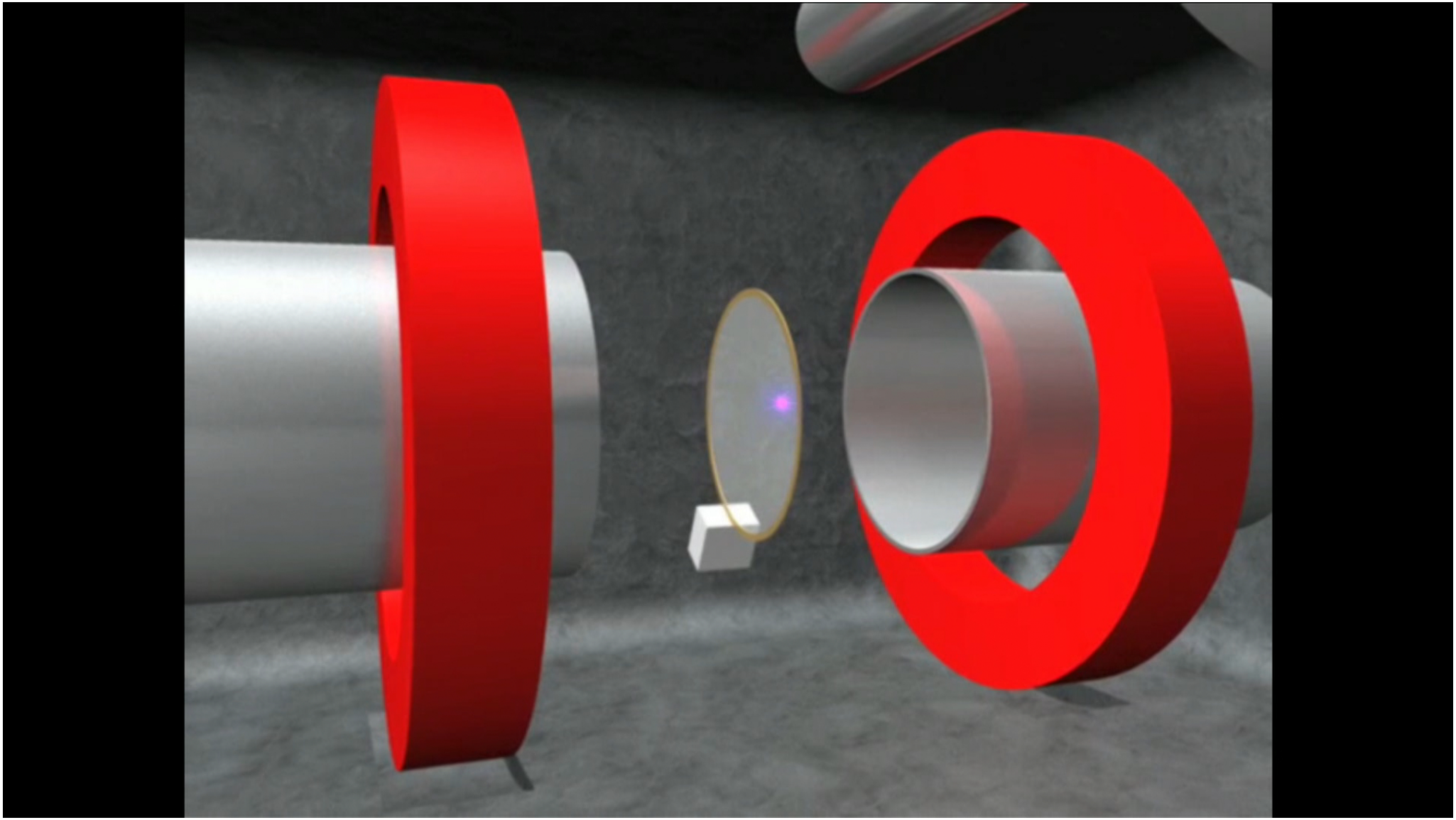


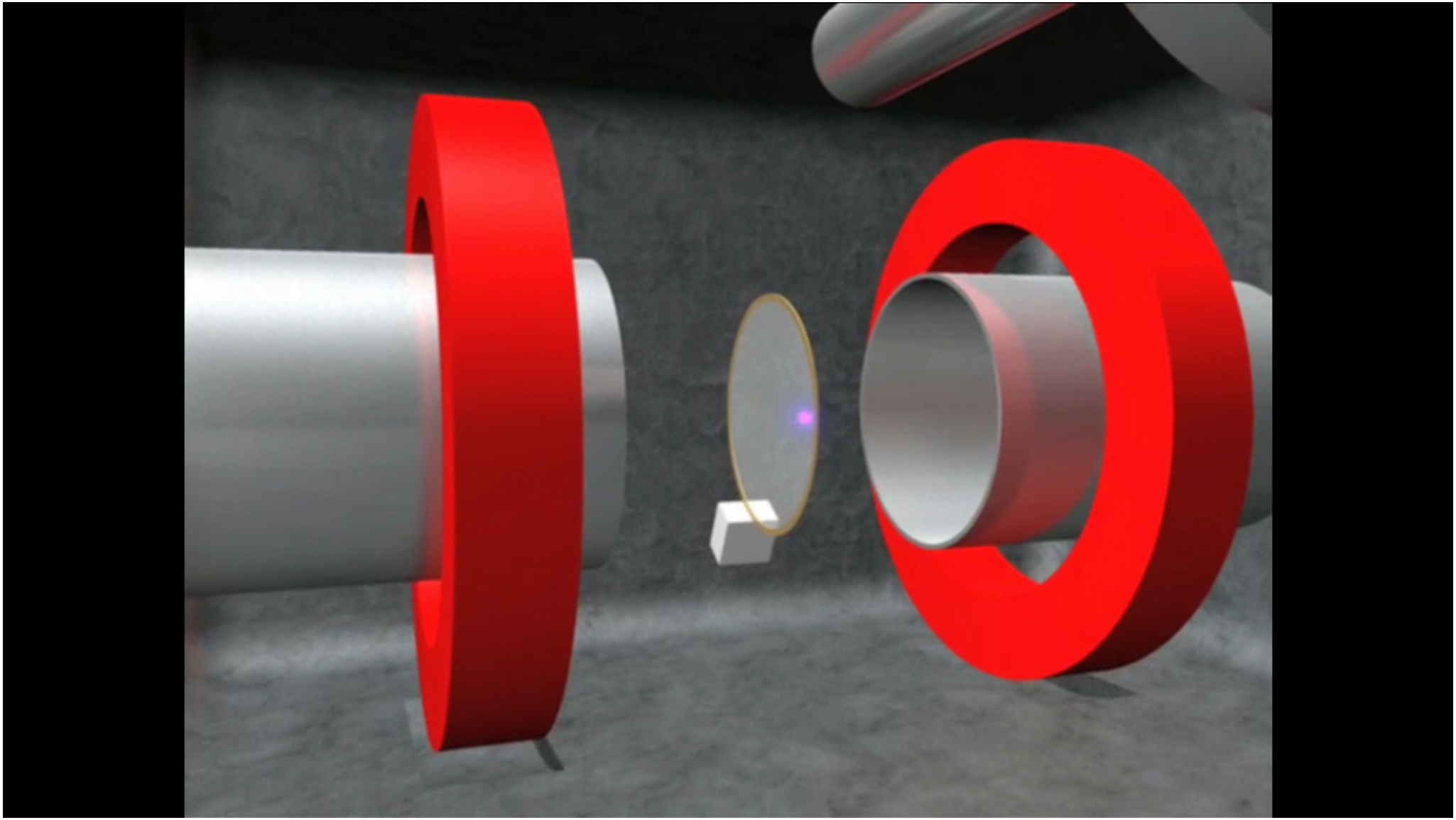


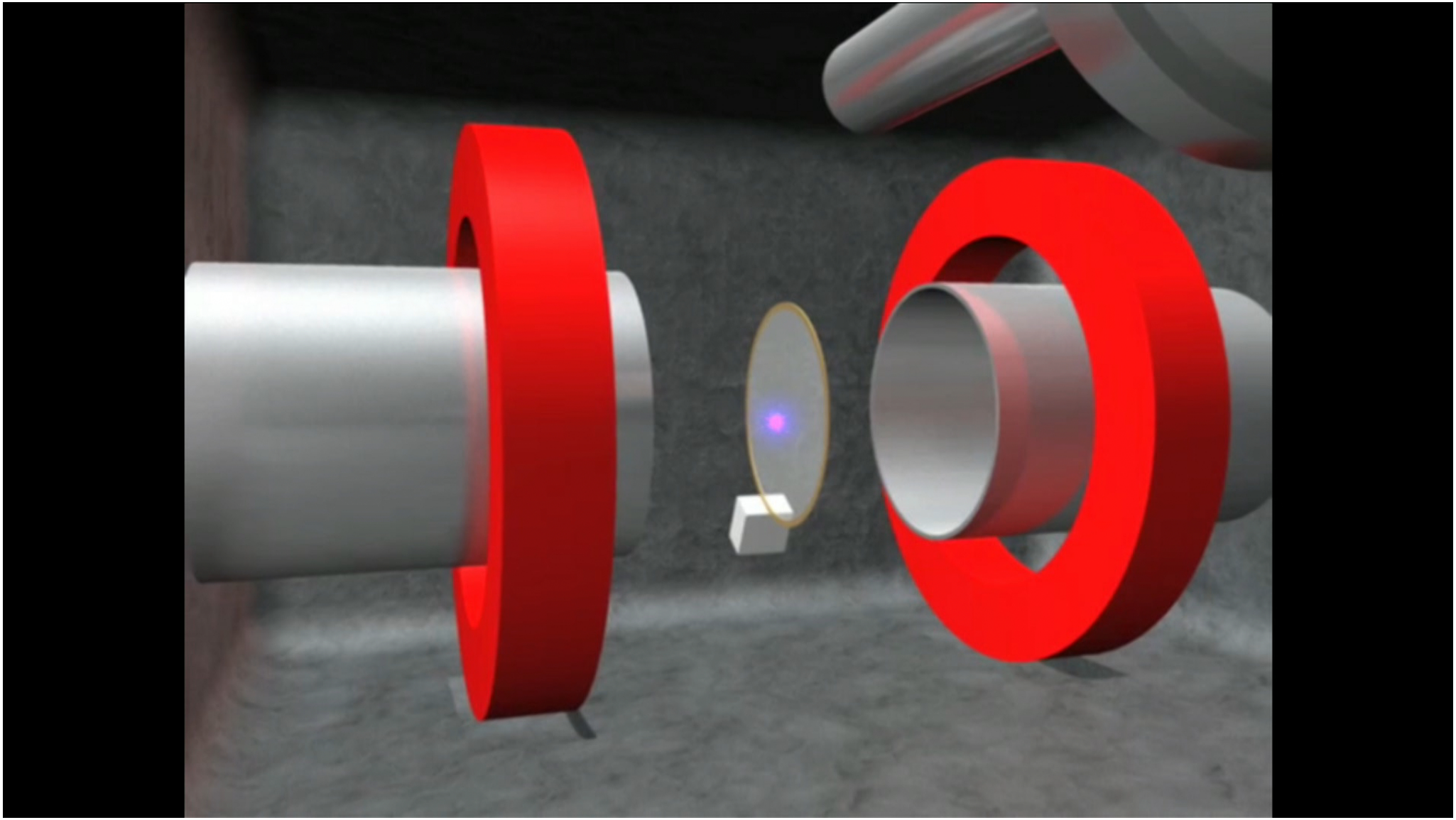


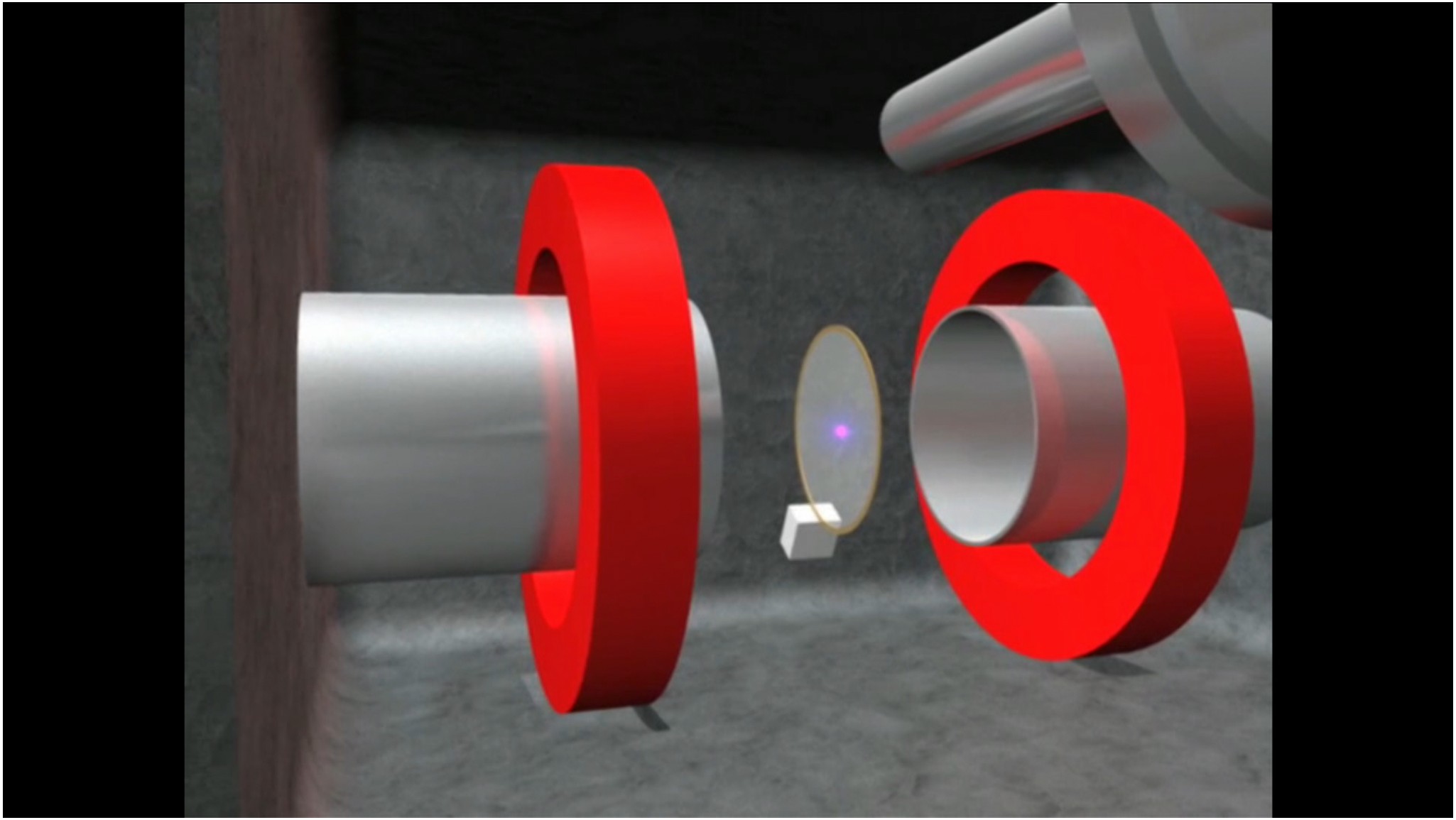


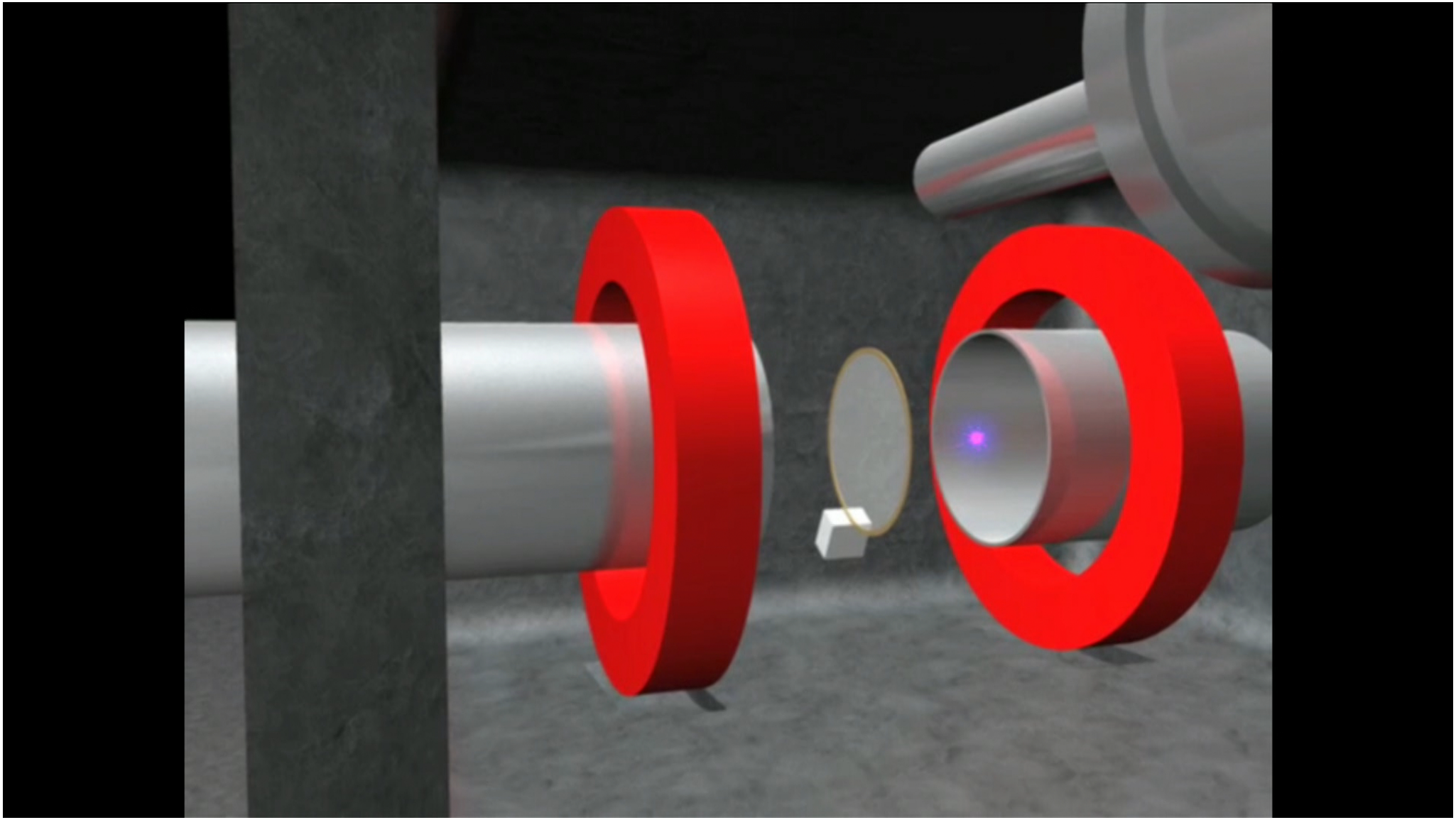


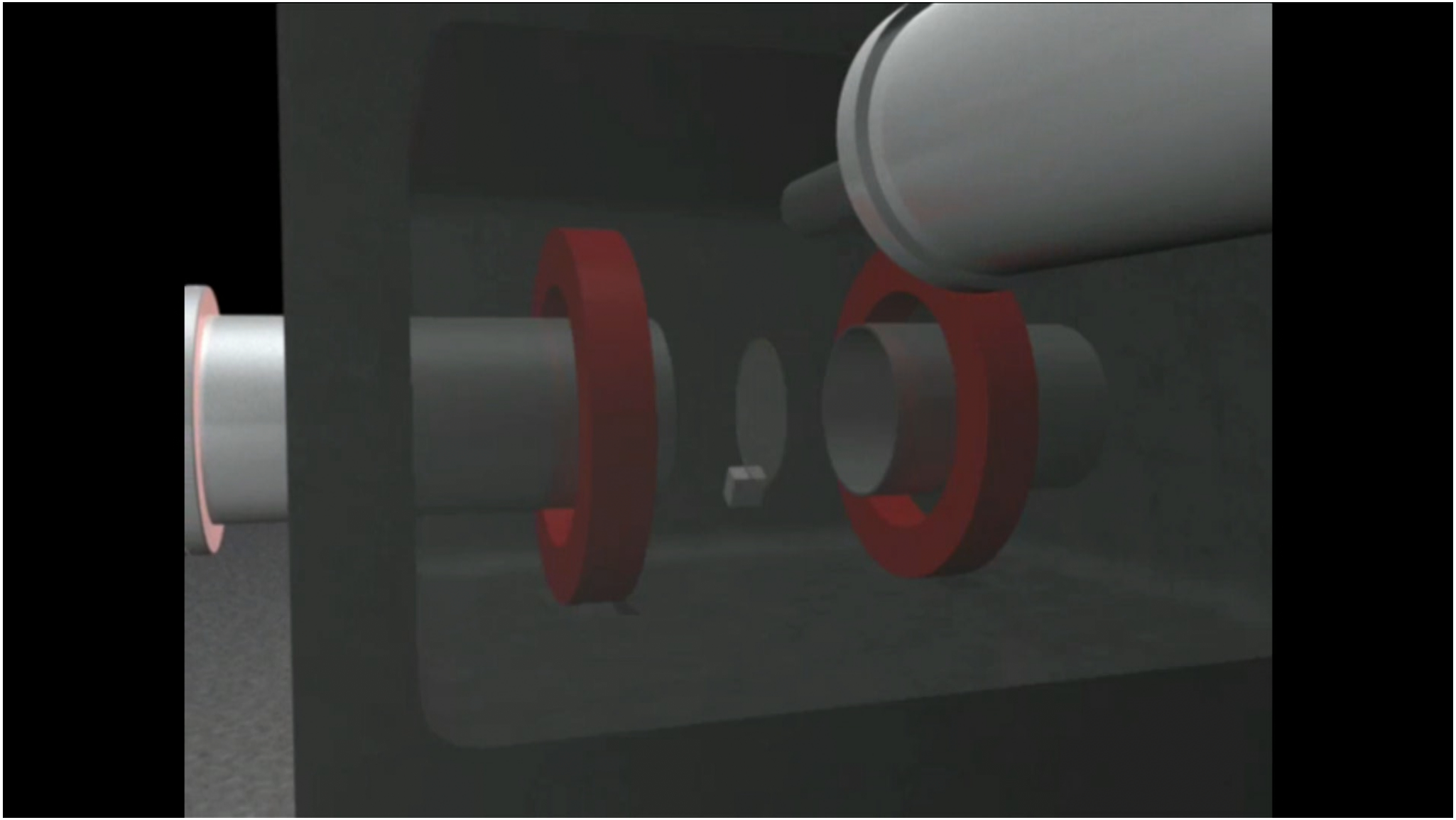


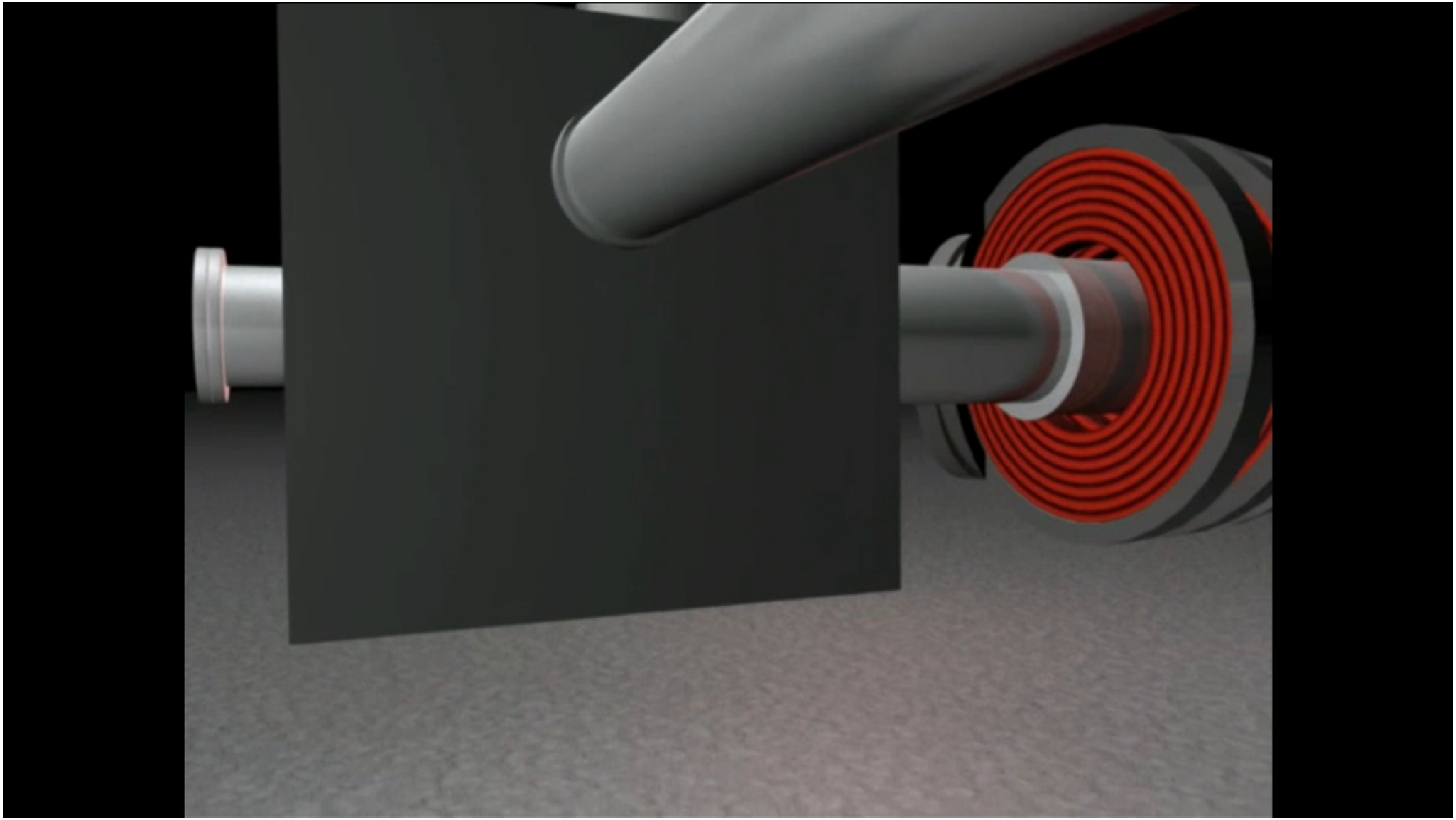


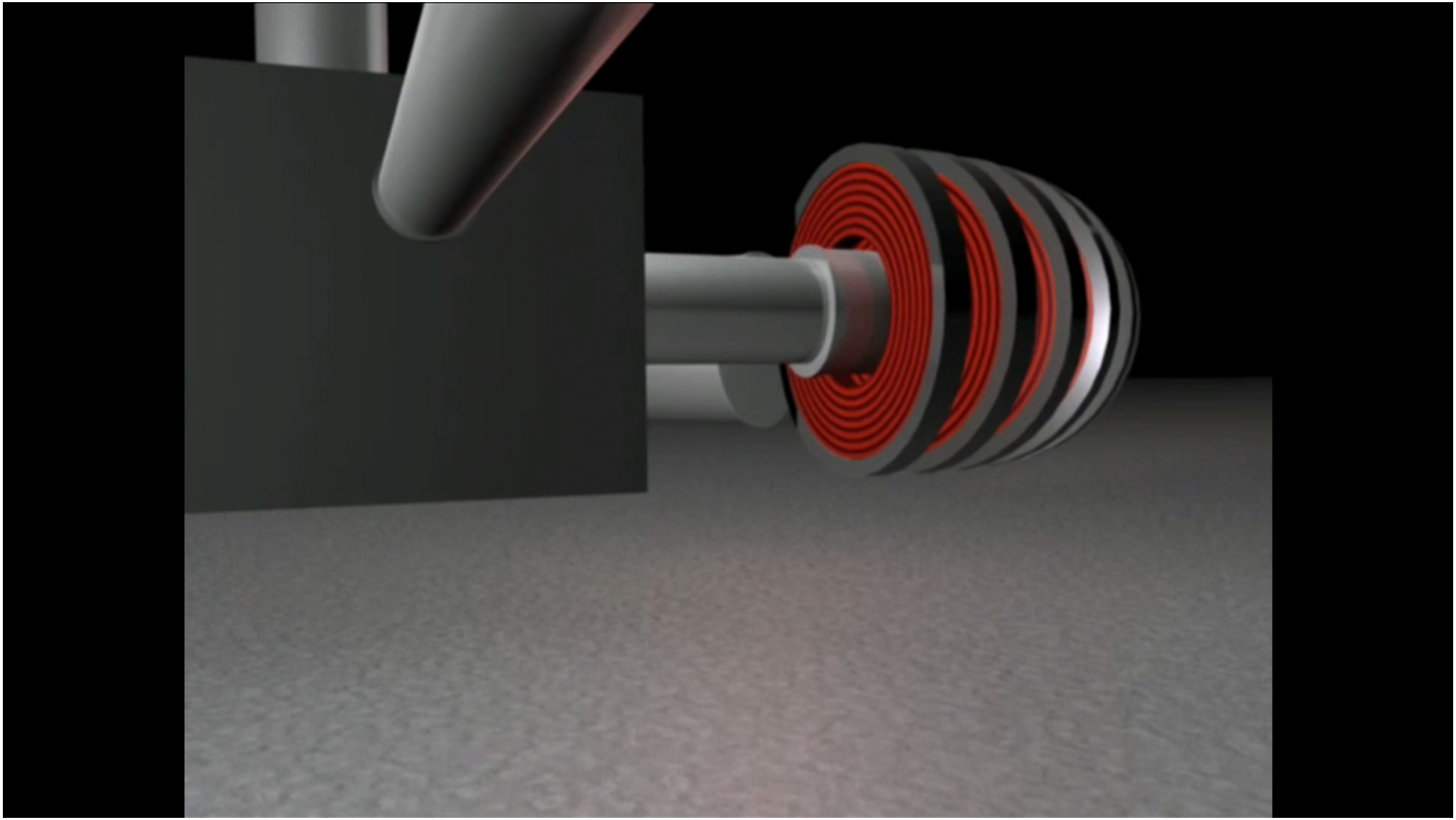


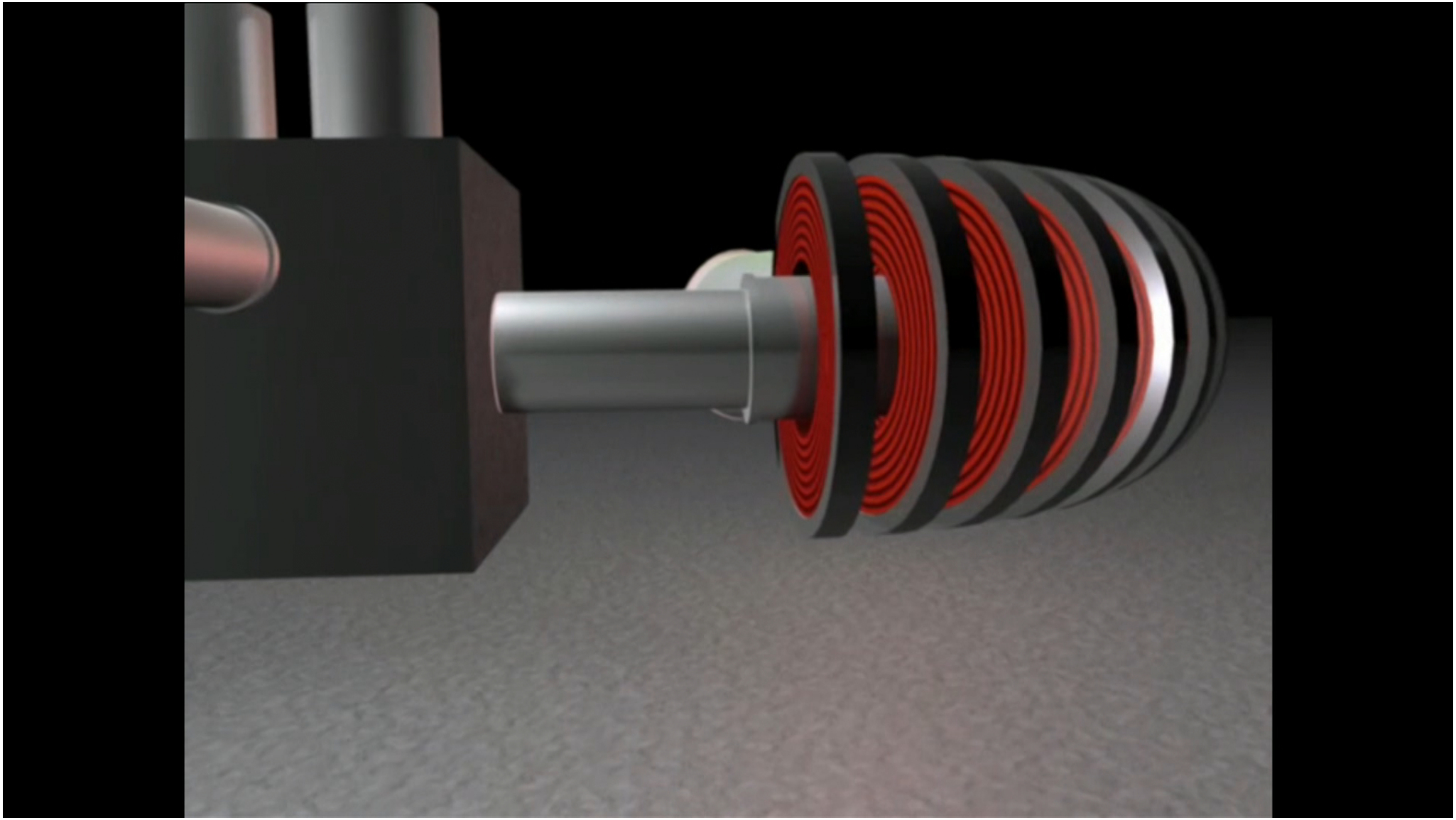


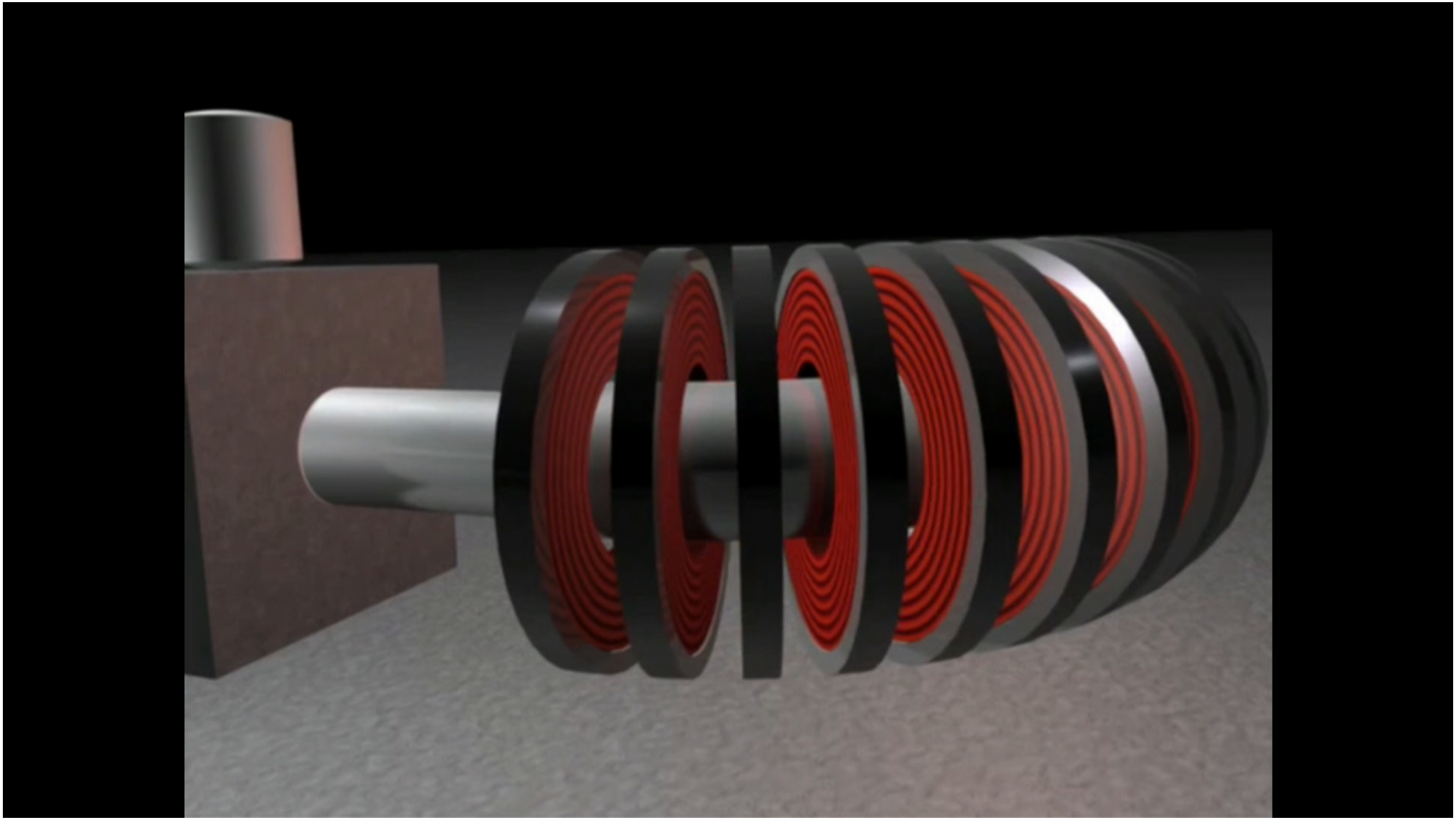


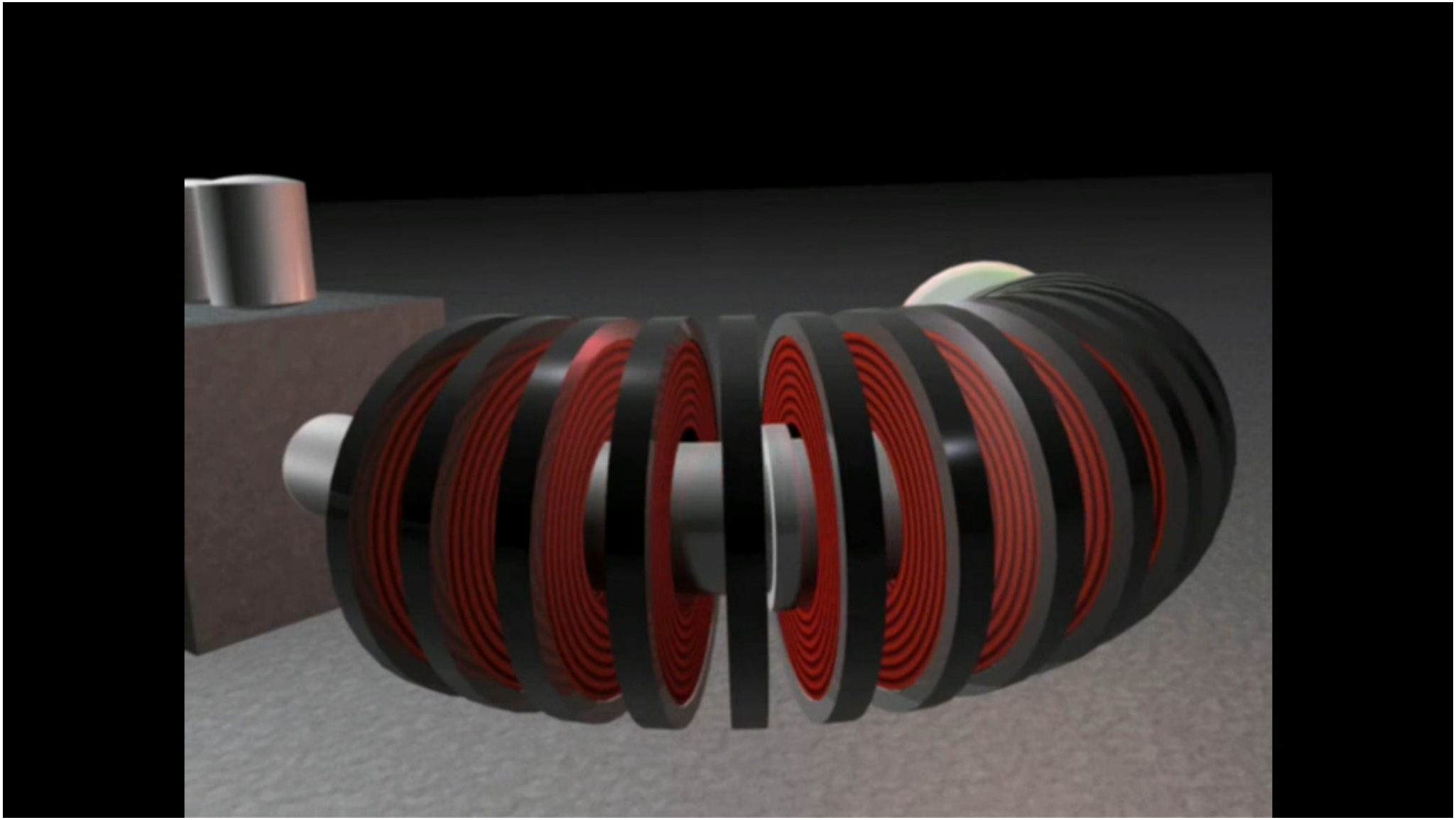


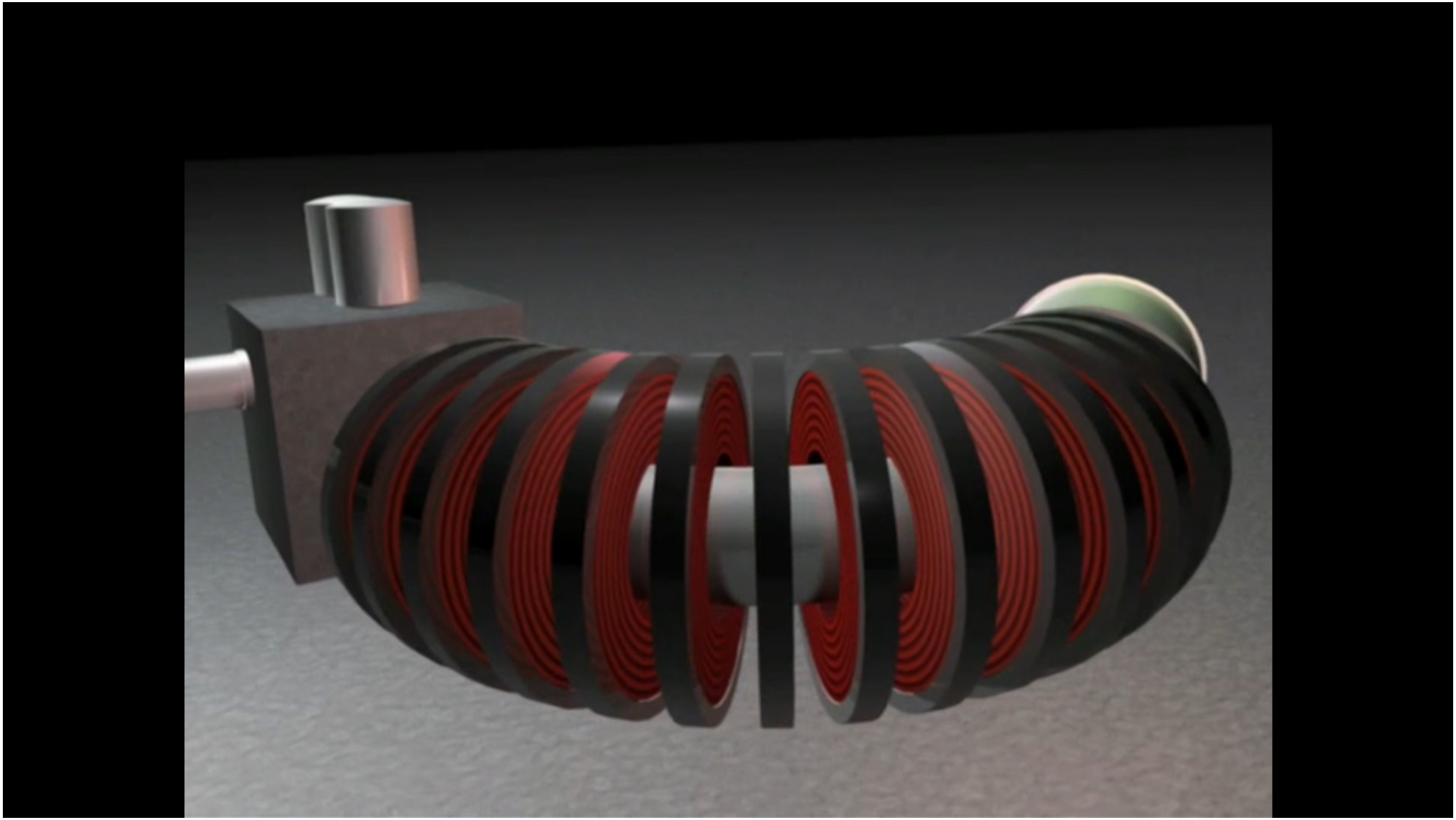


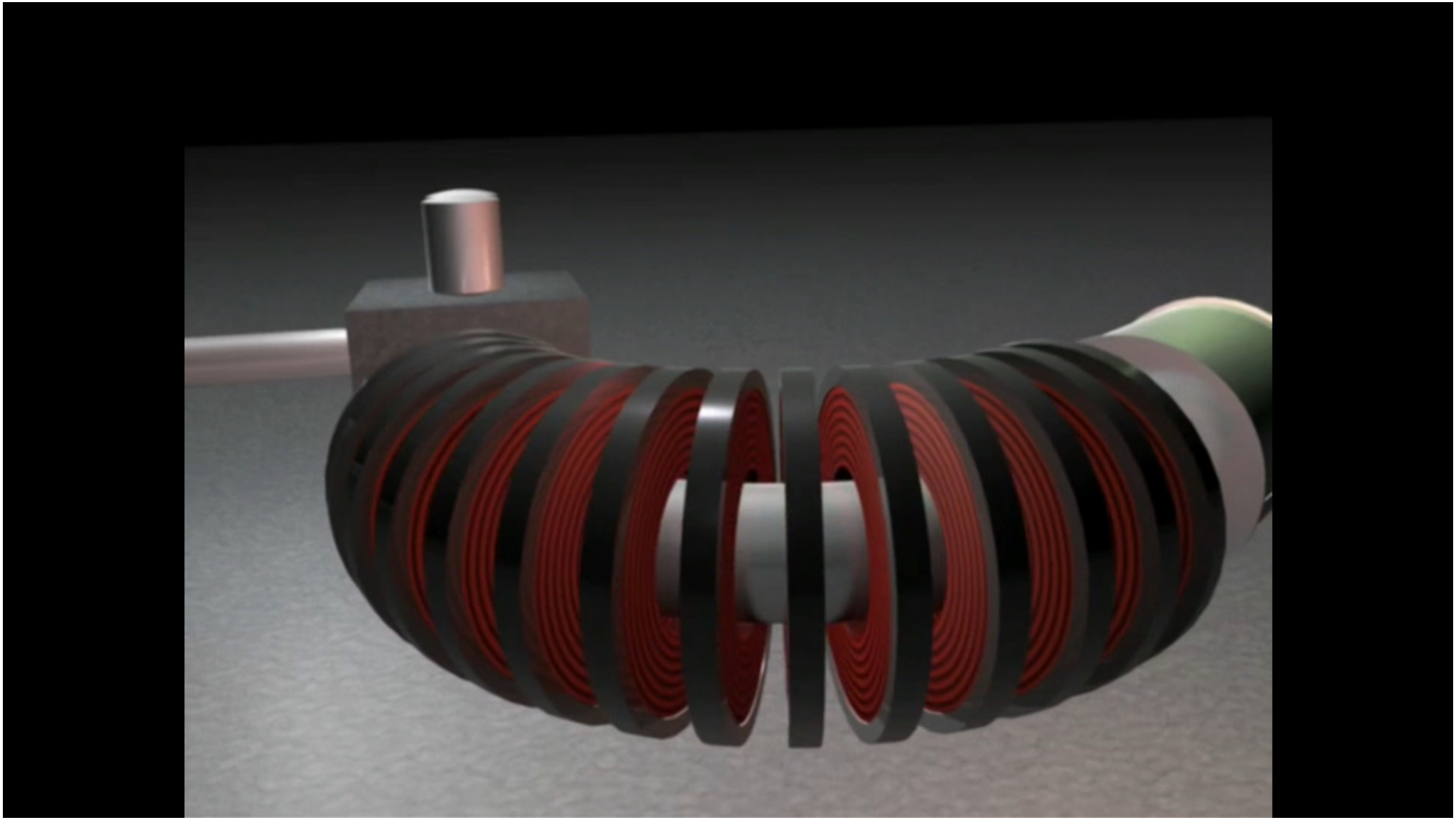


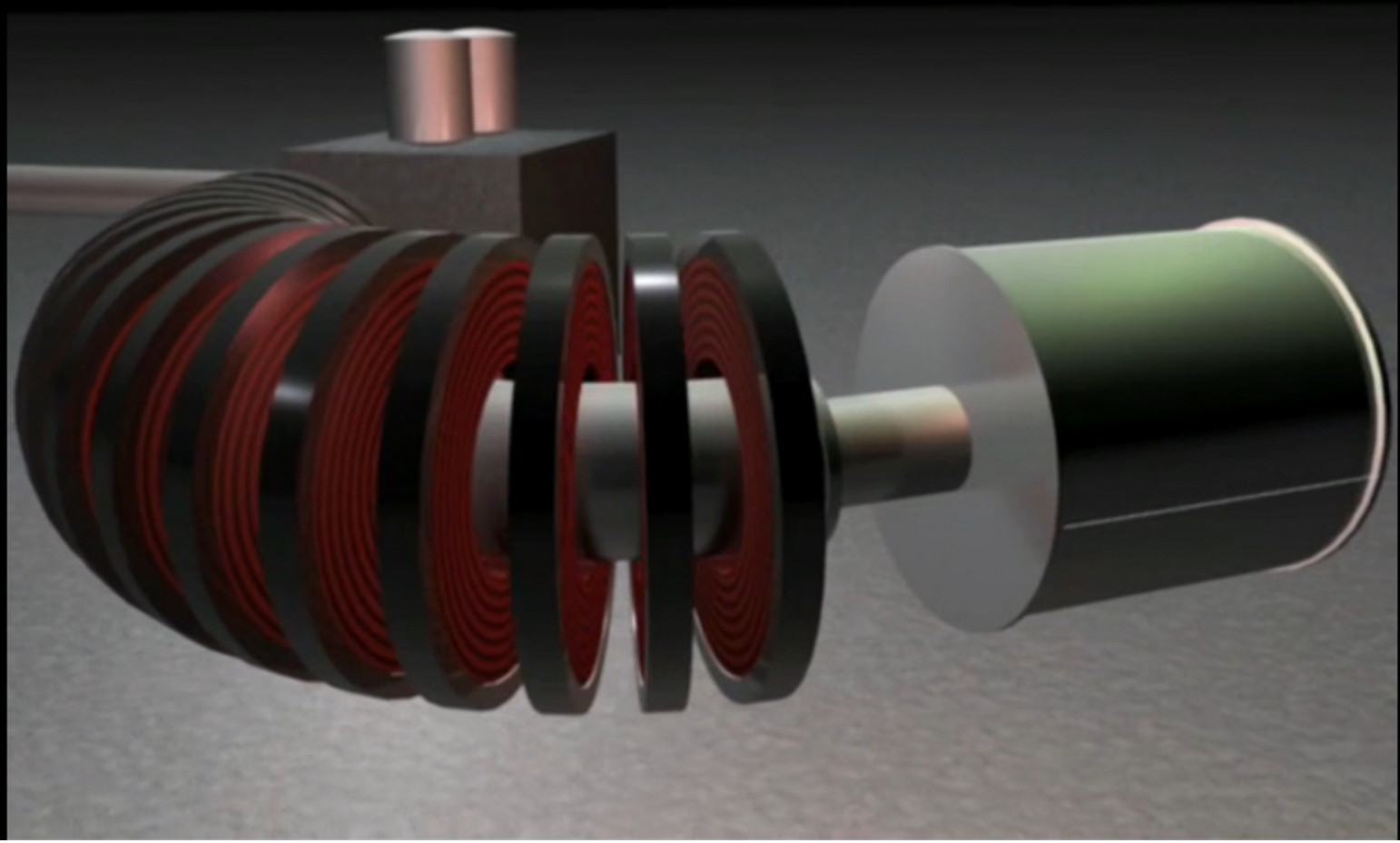


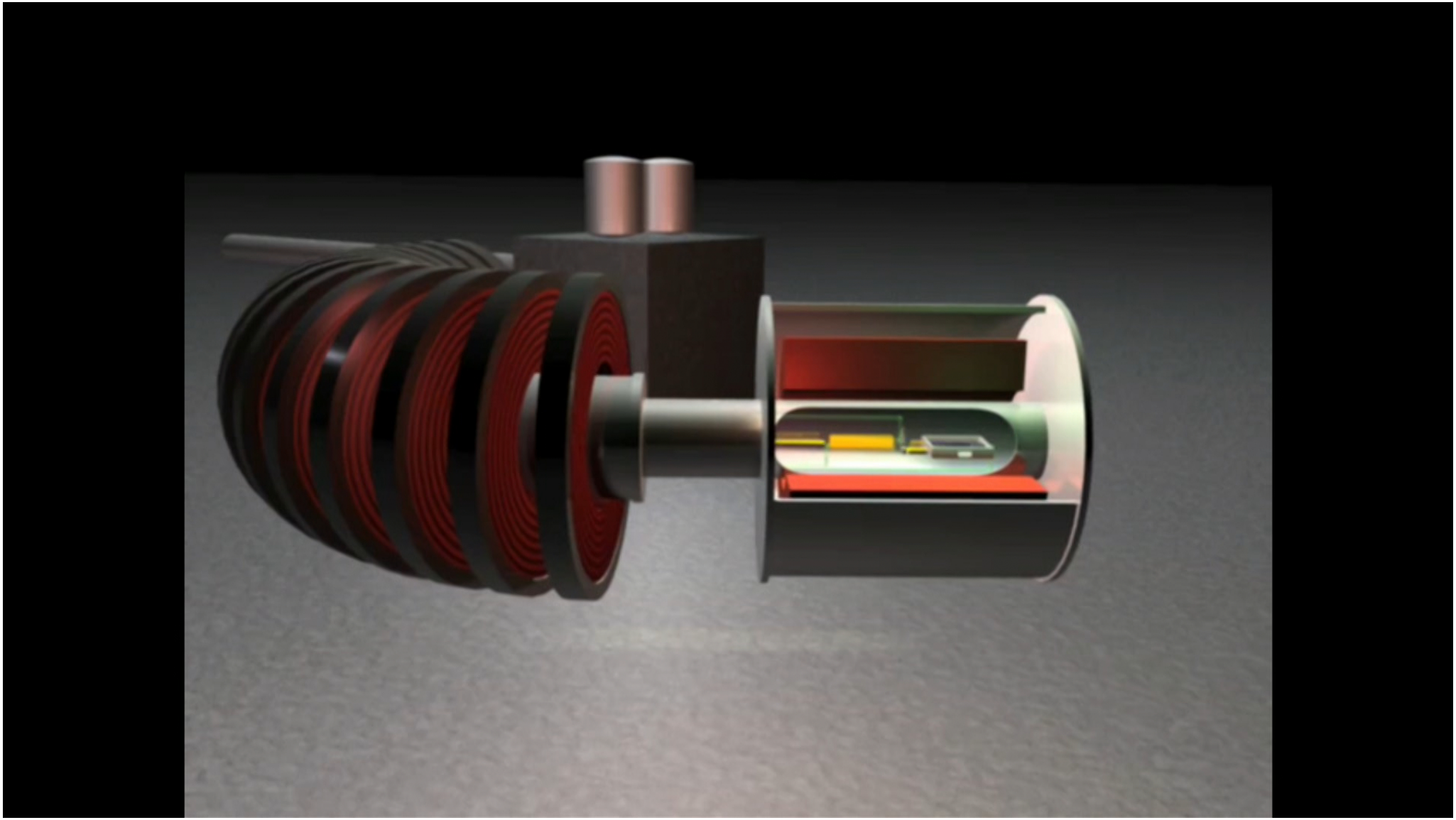


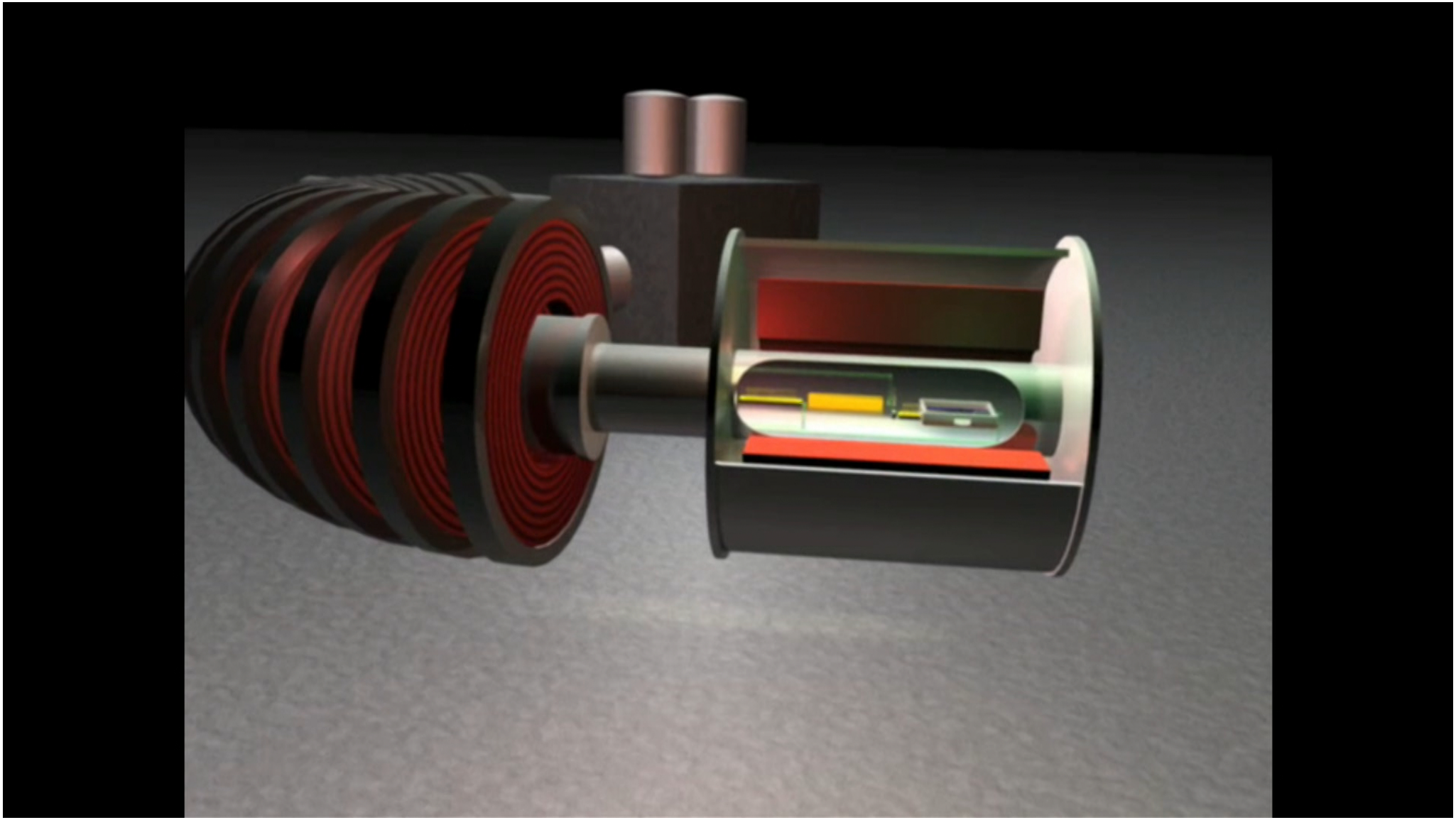


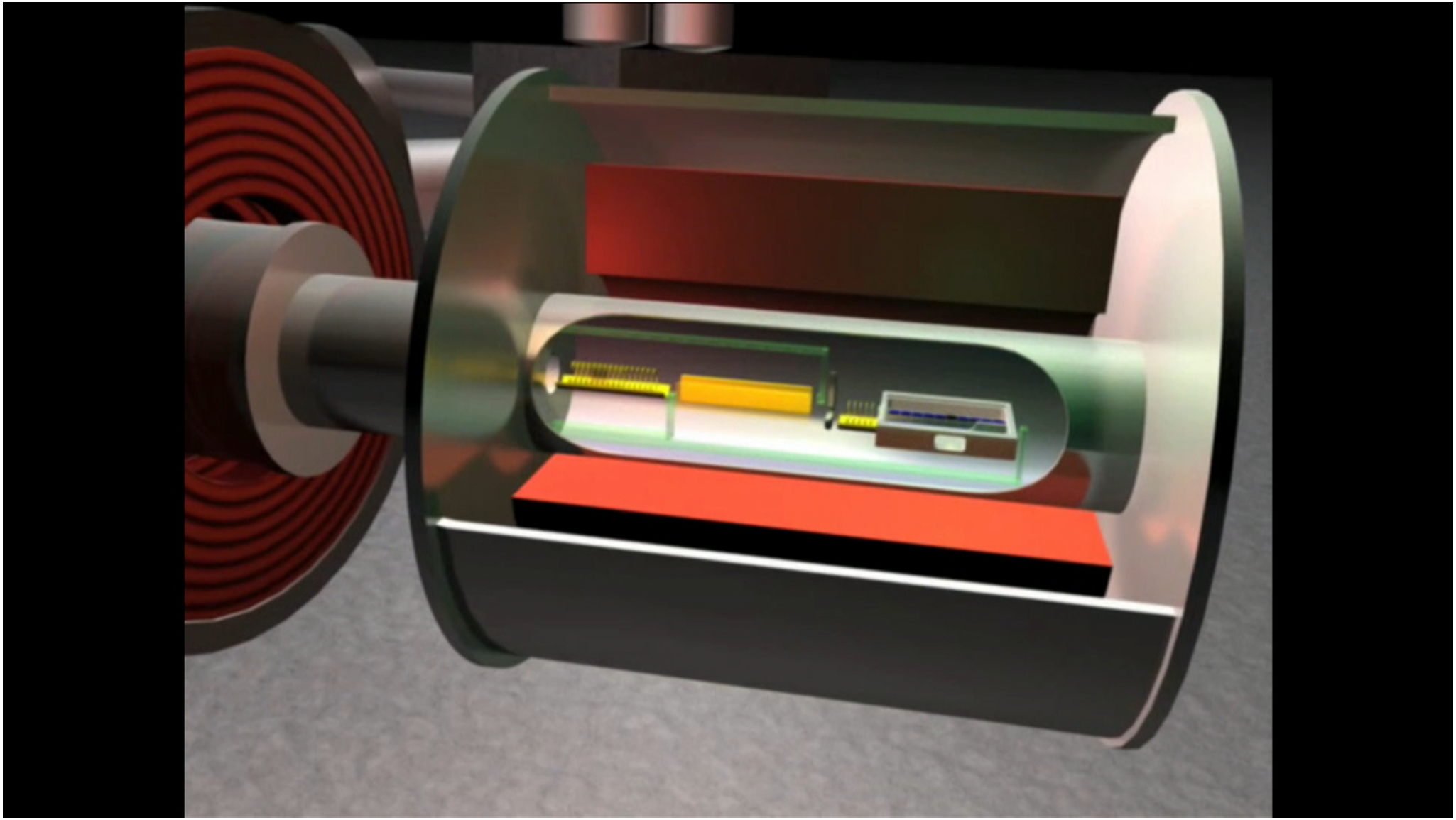


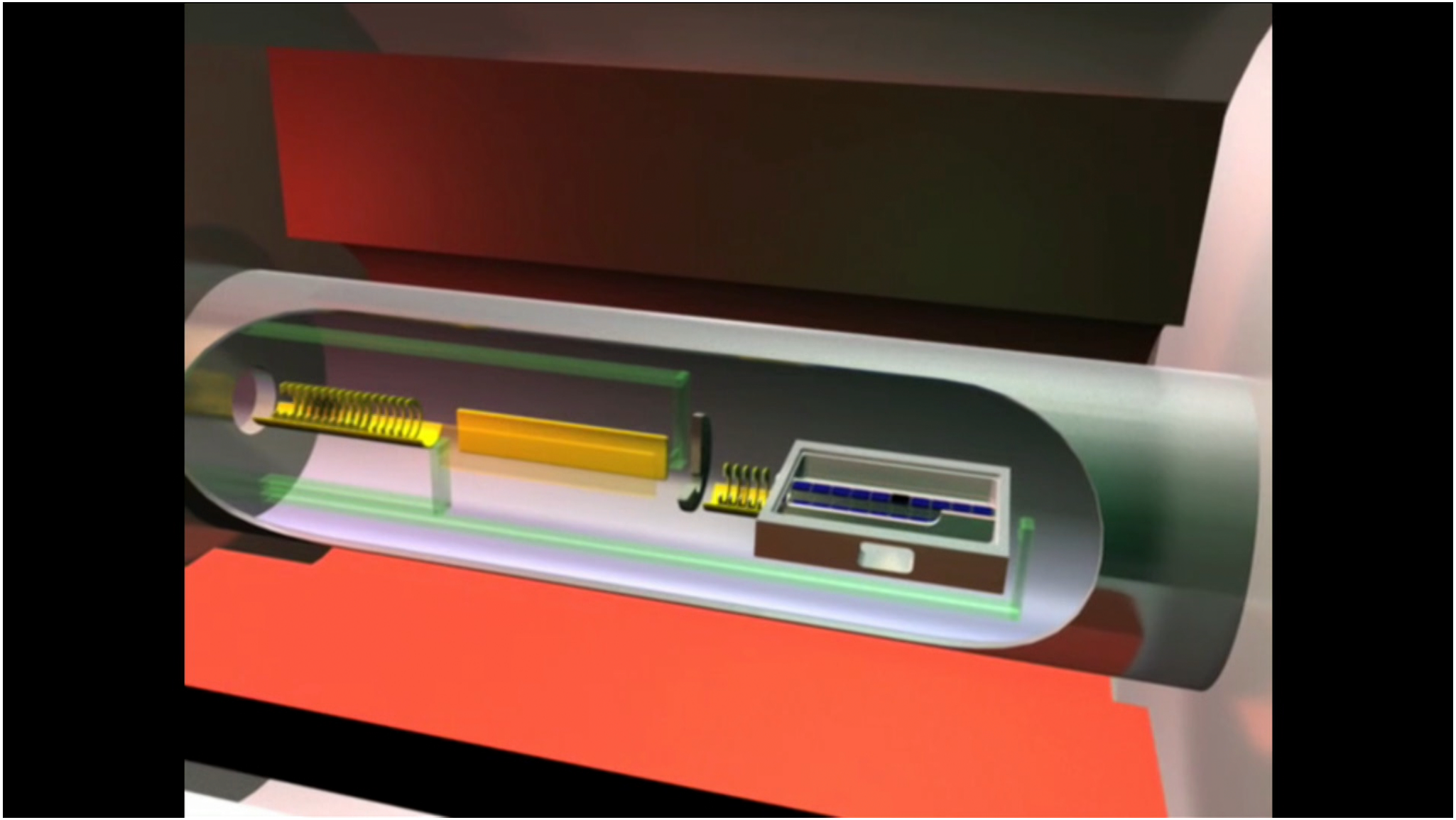


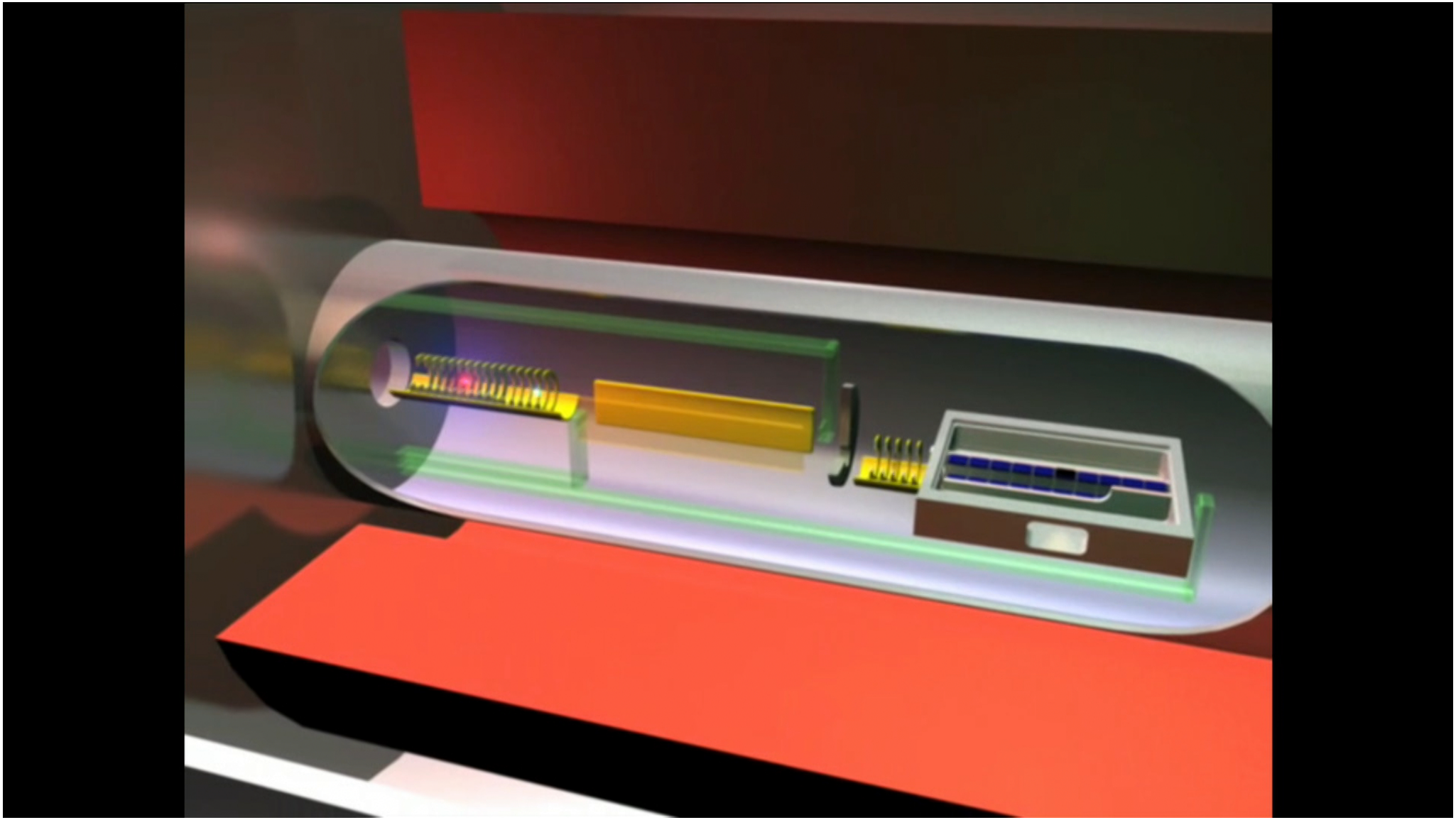


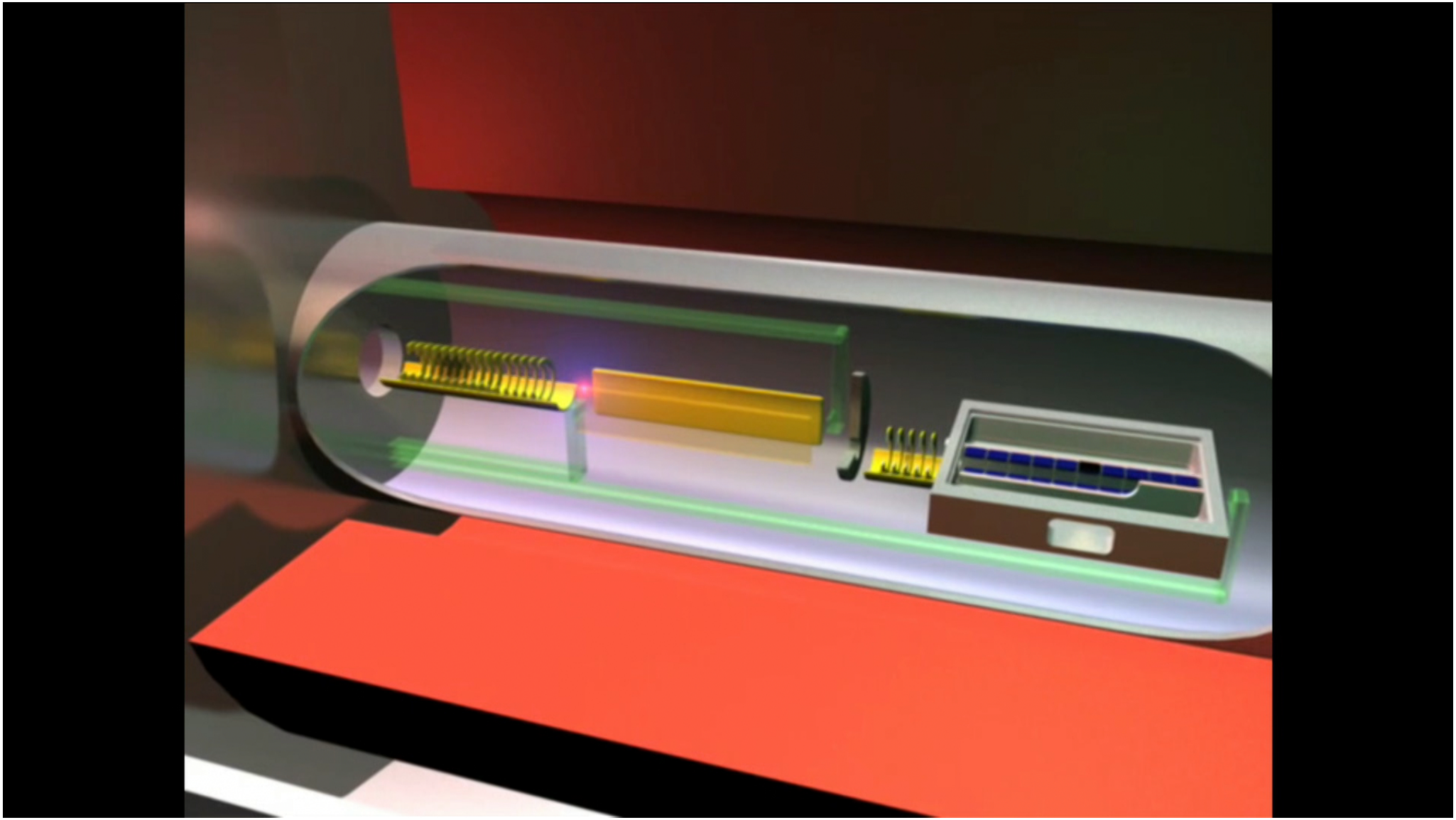


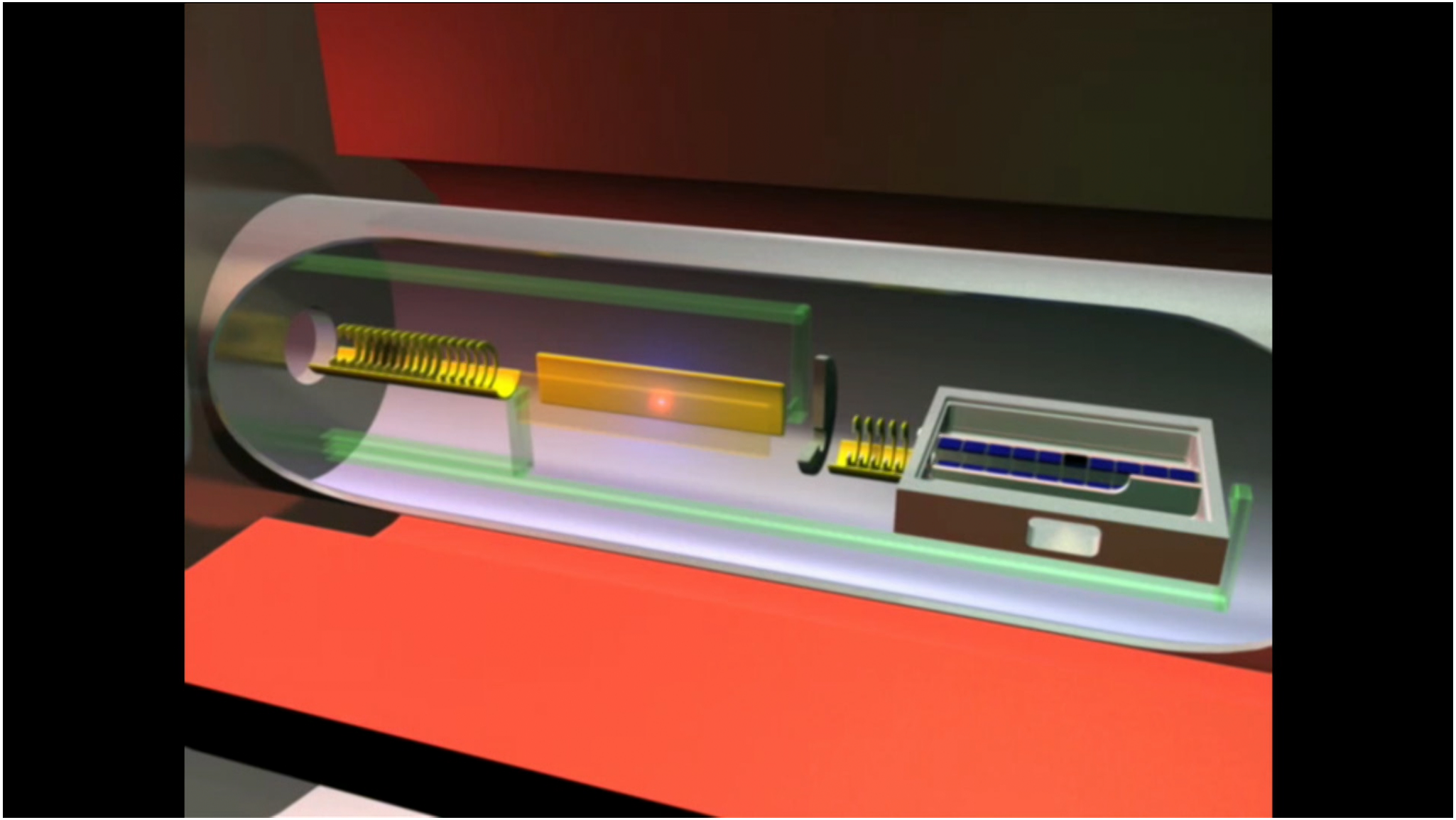


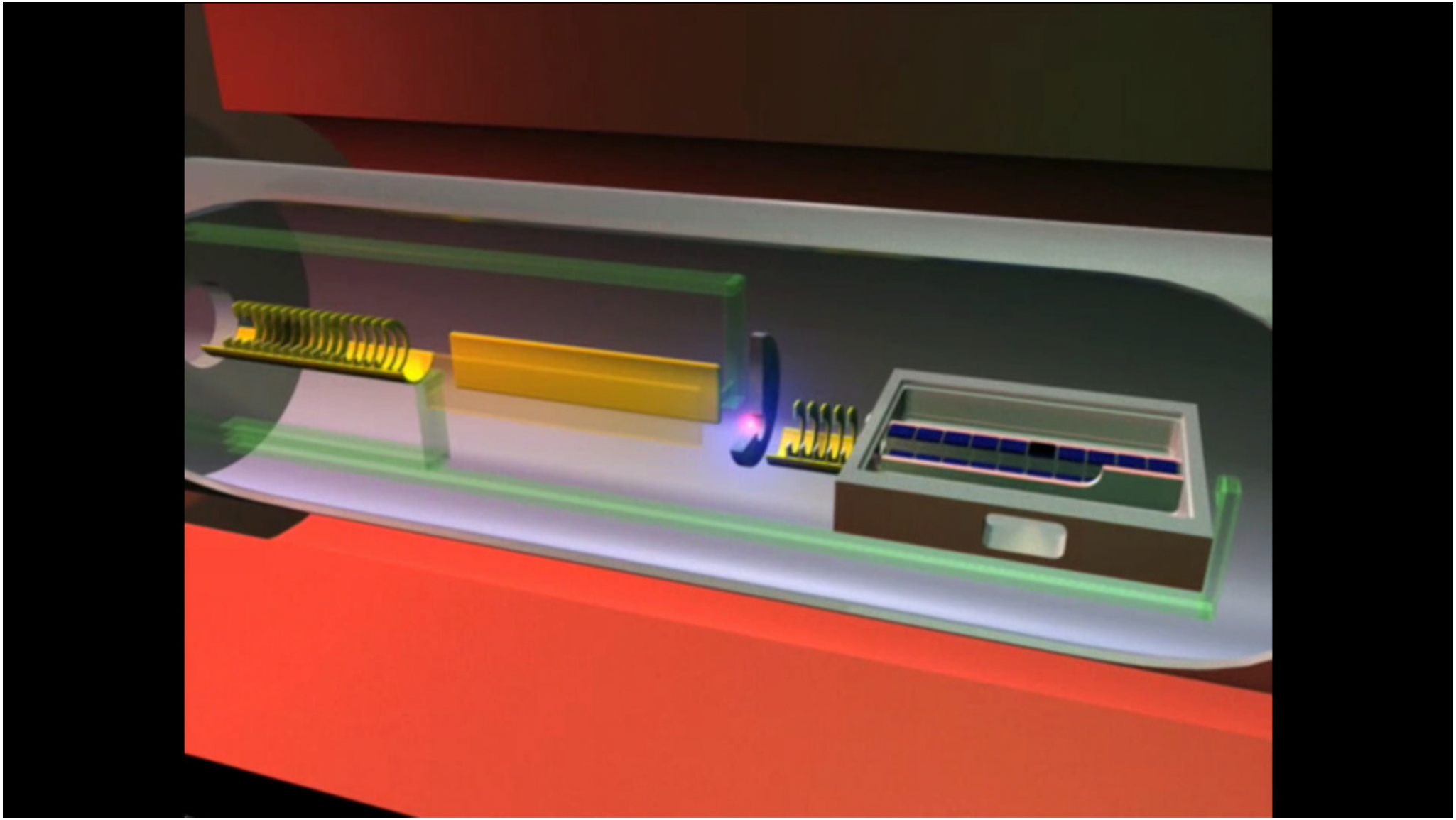


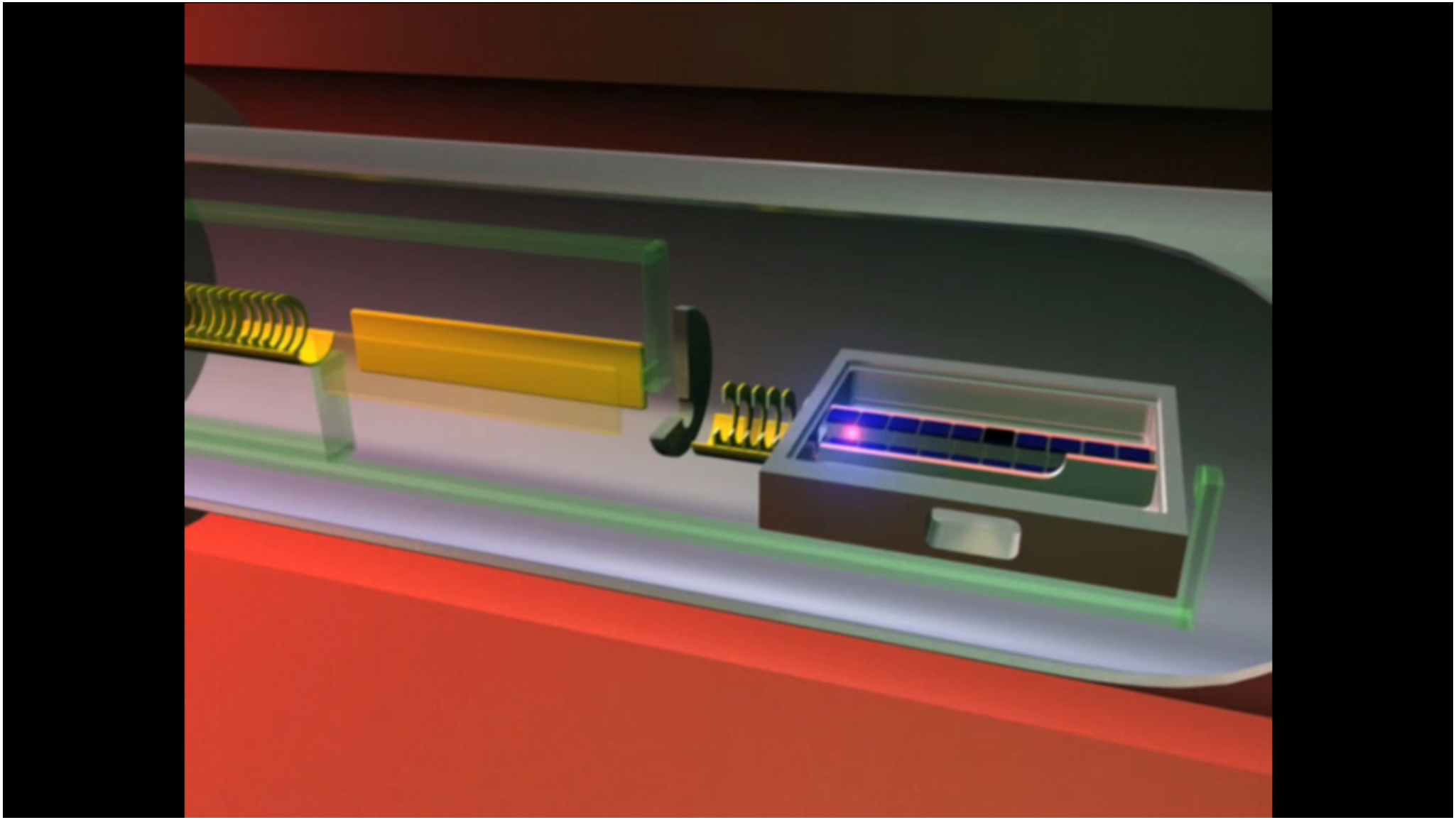


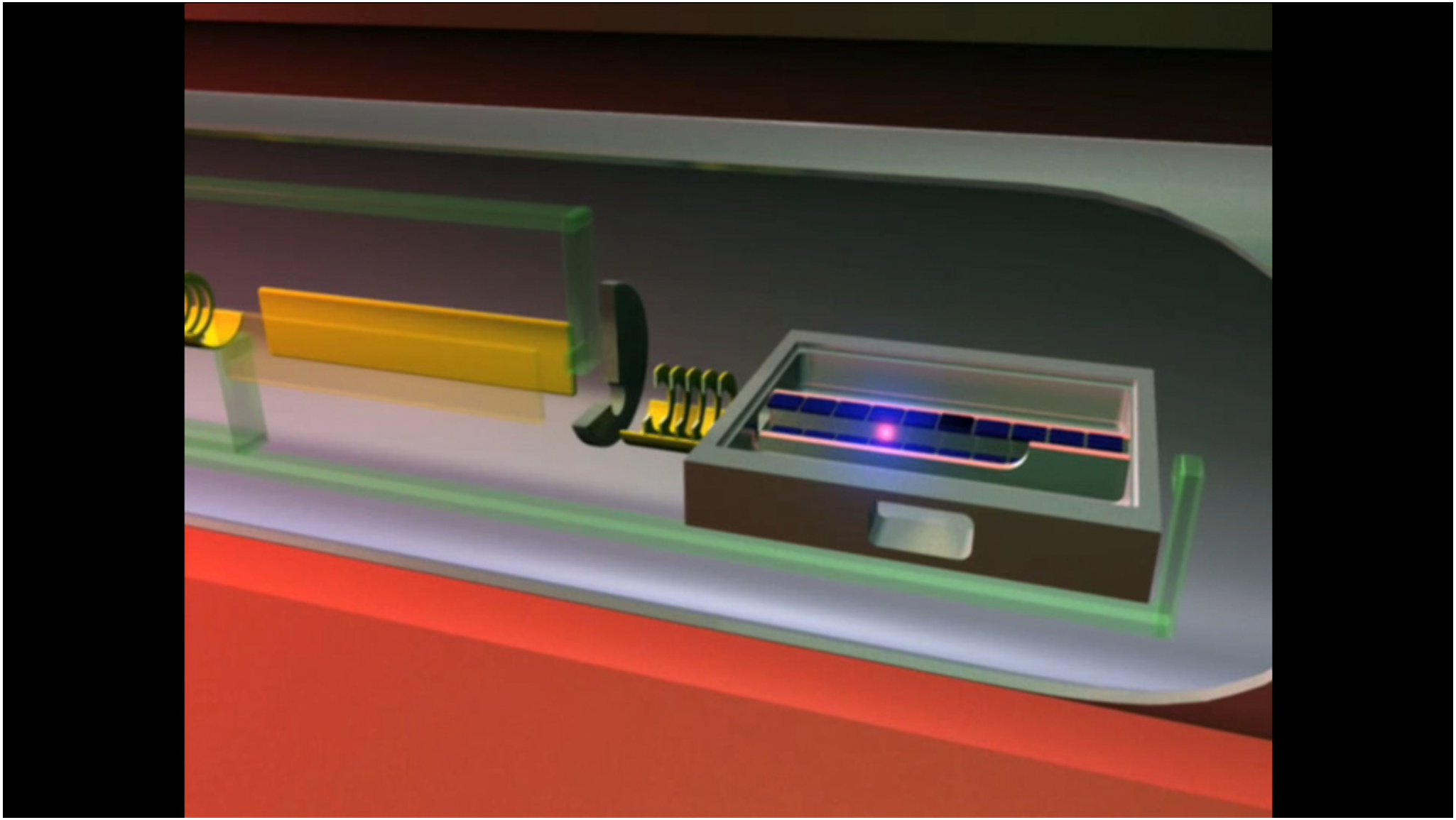


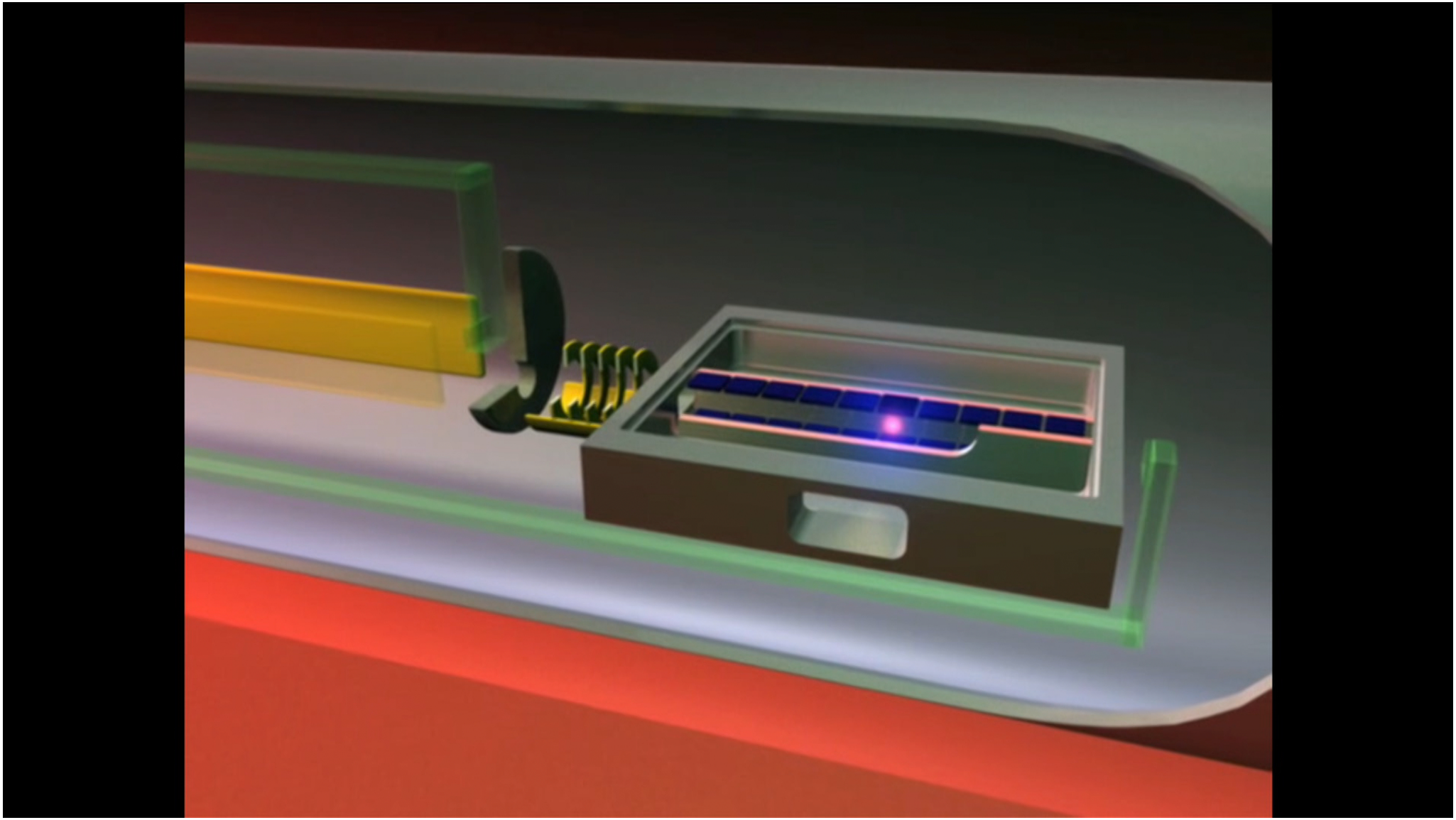


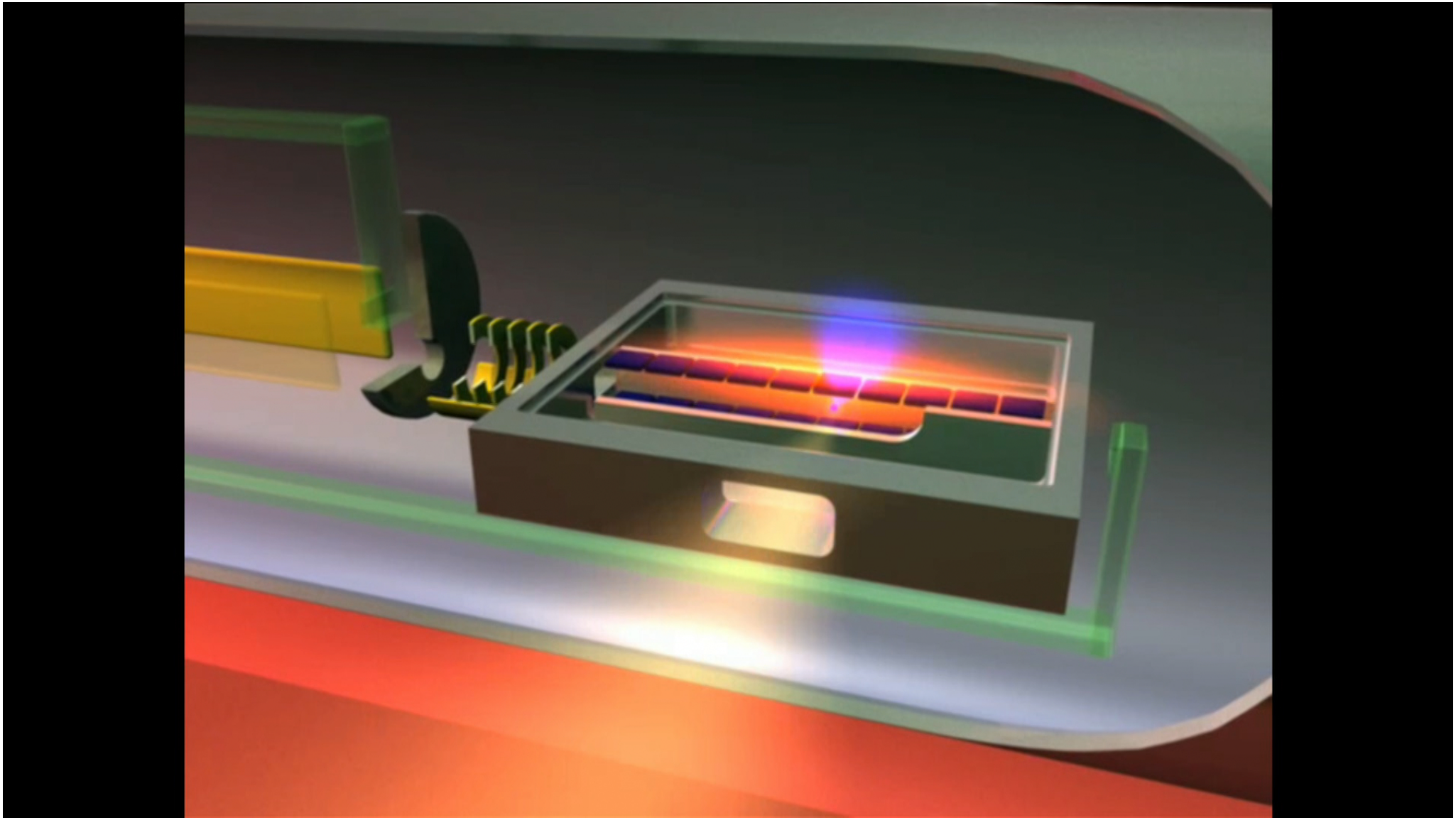


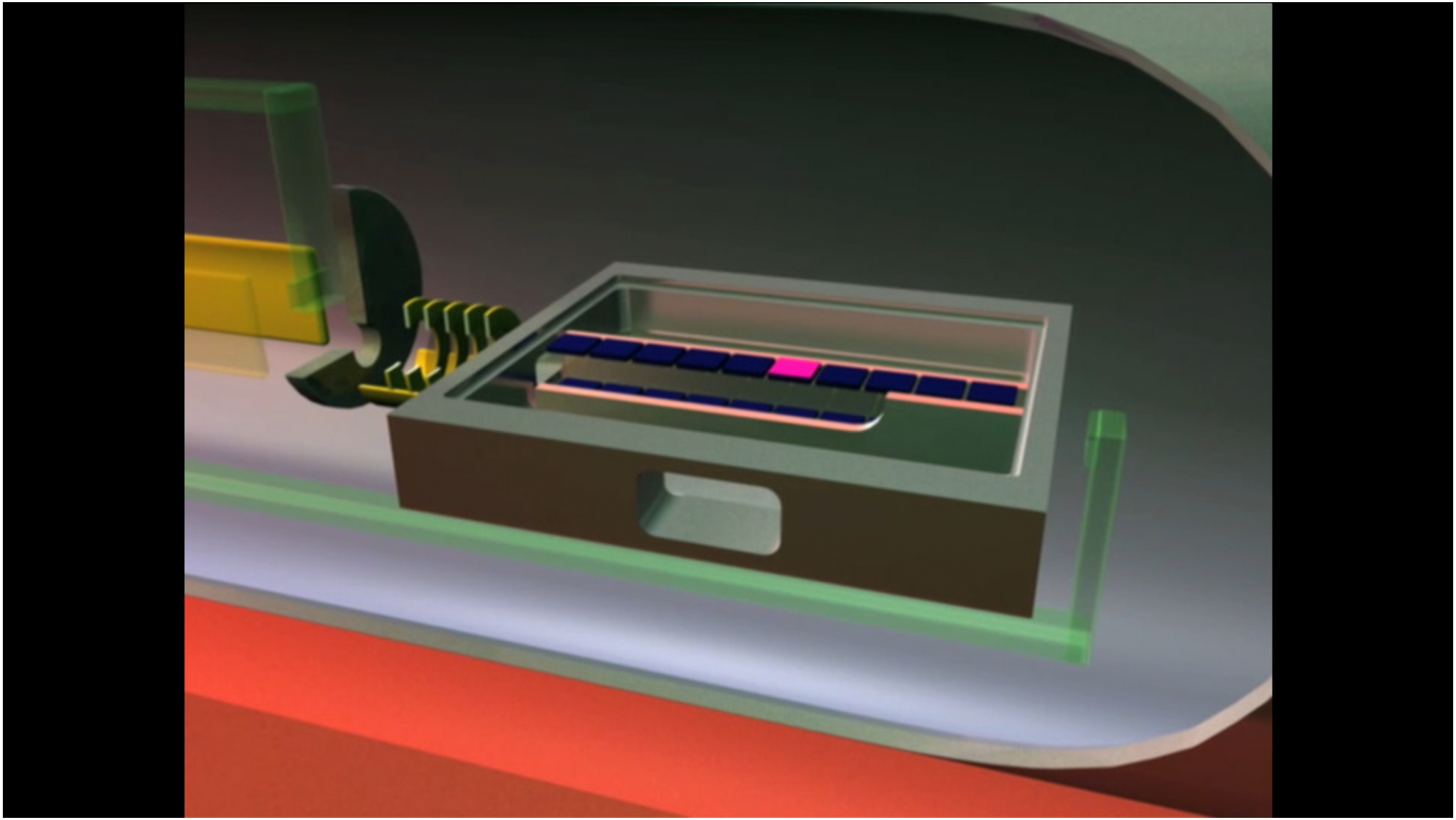






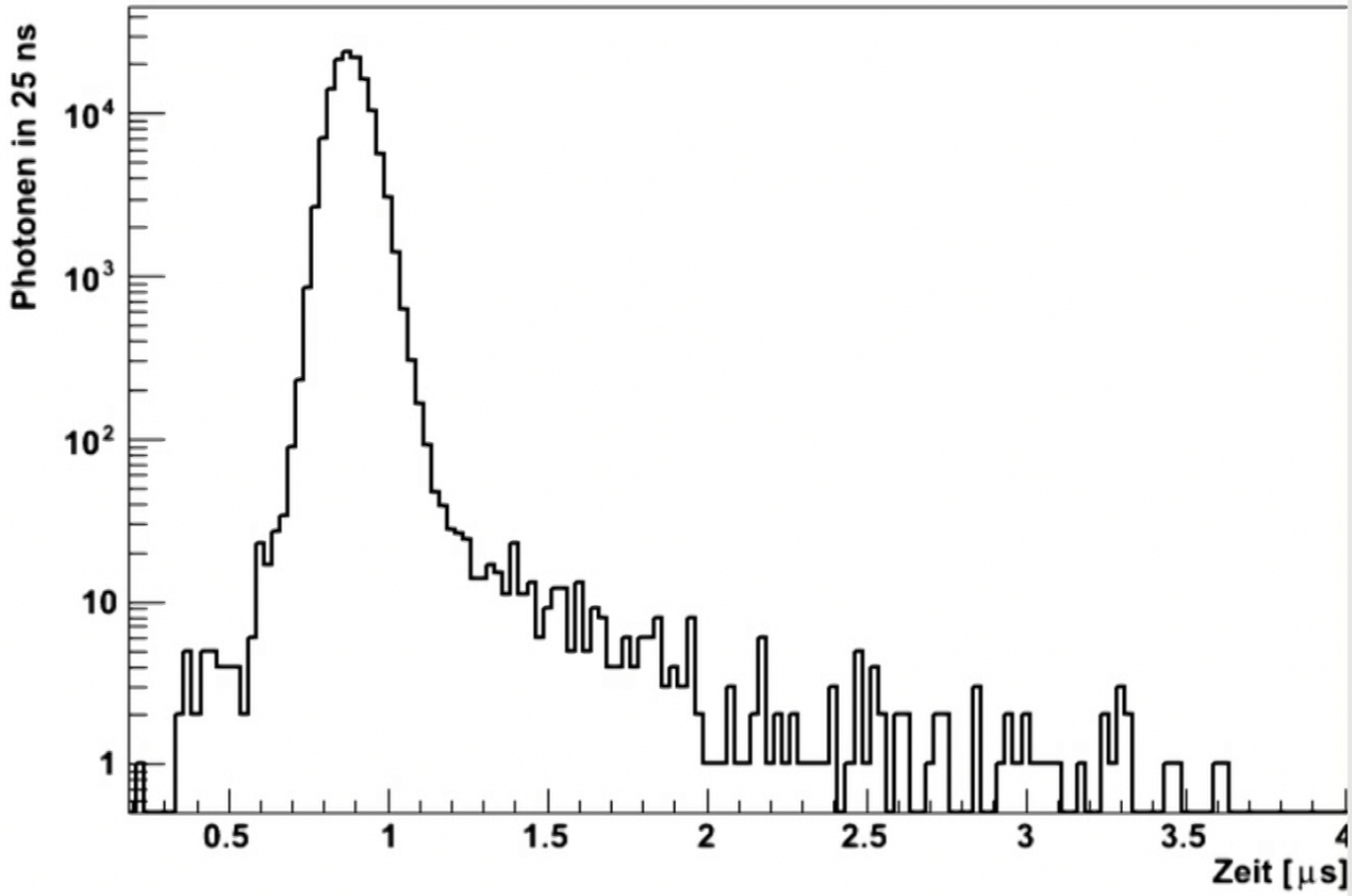




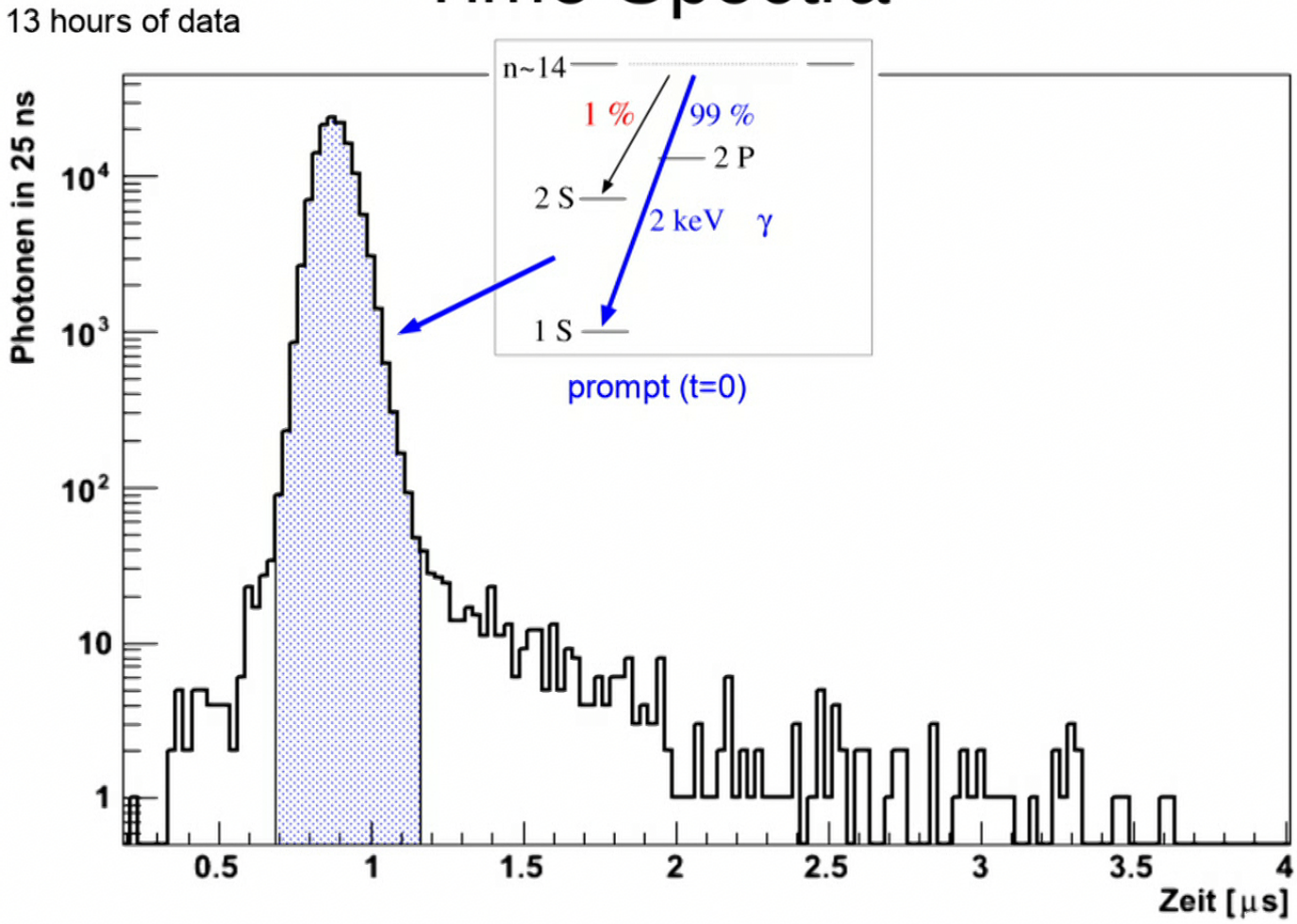


Time Spectra

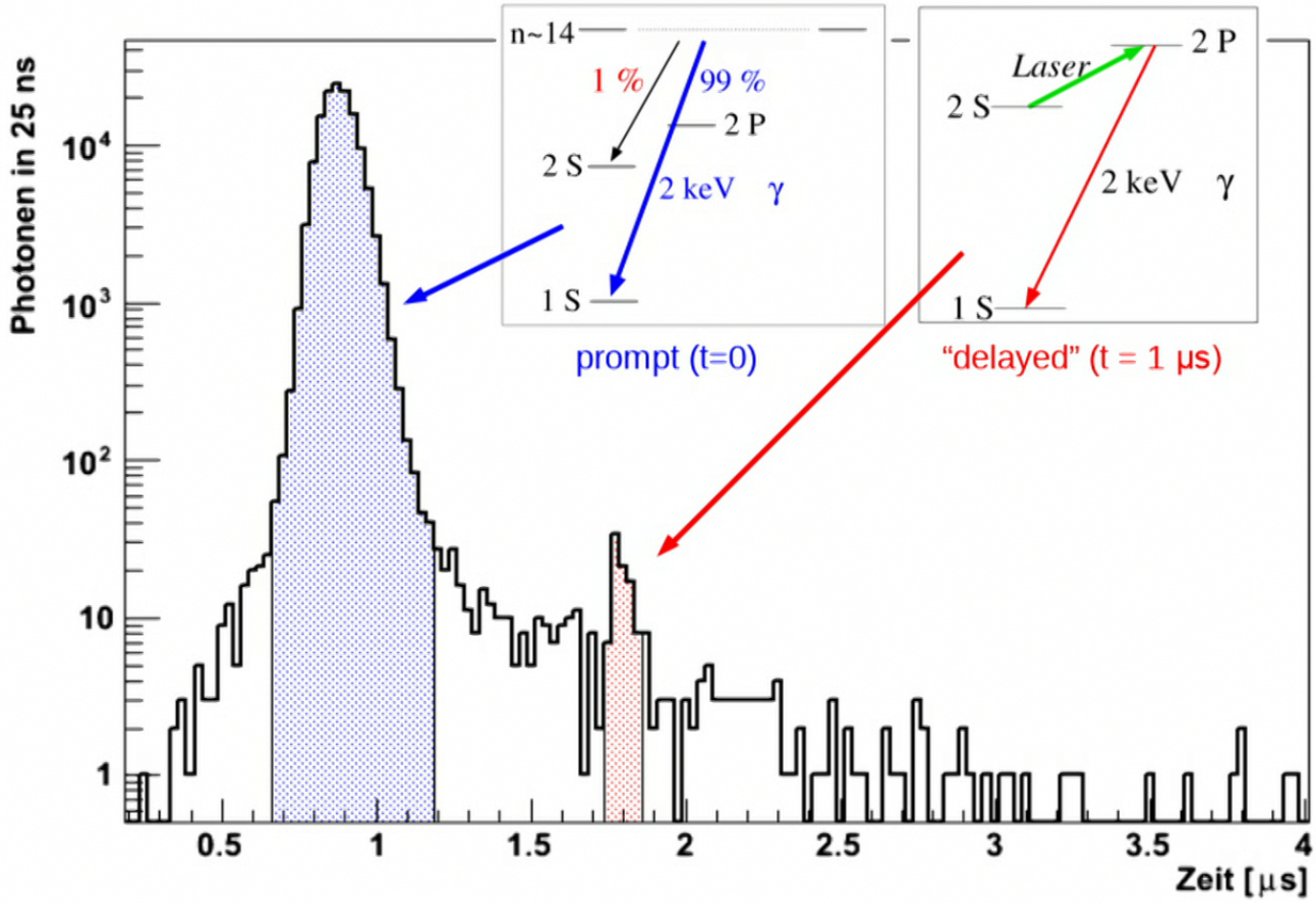
13 hours of data

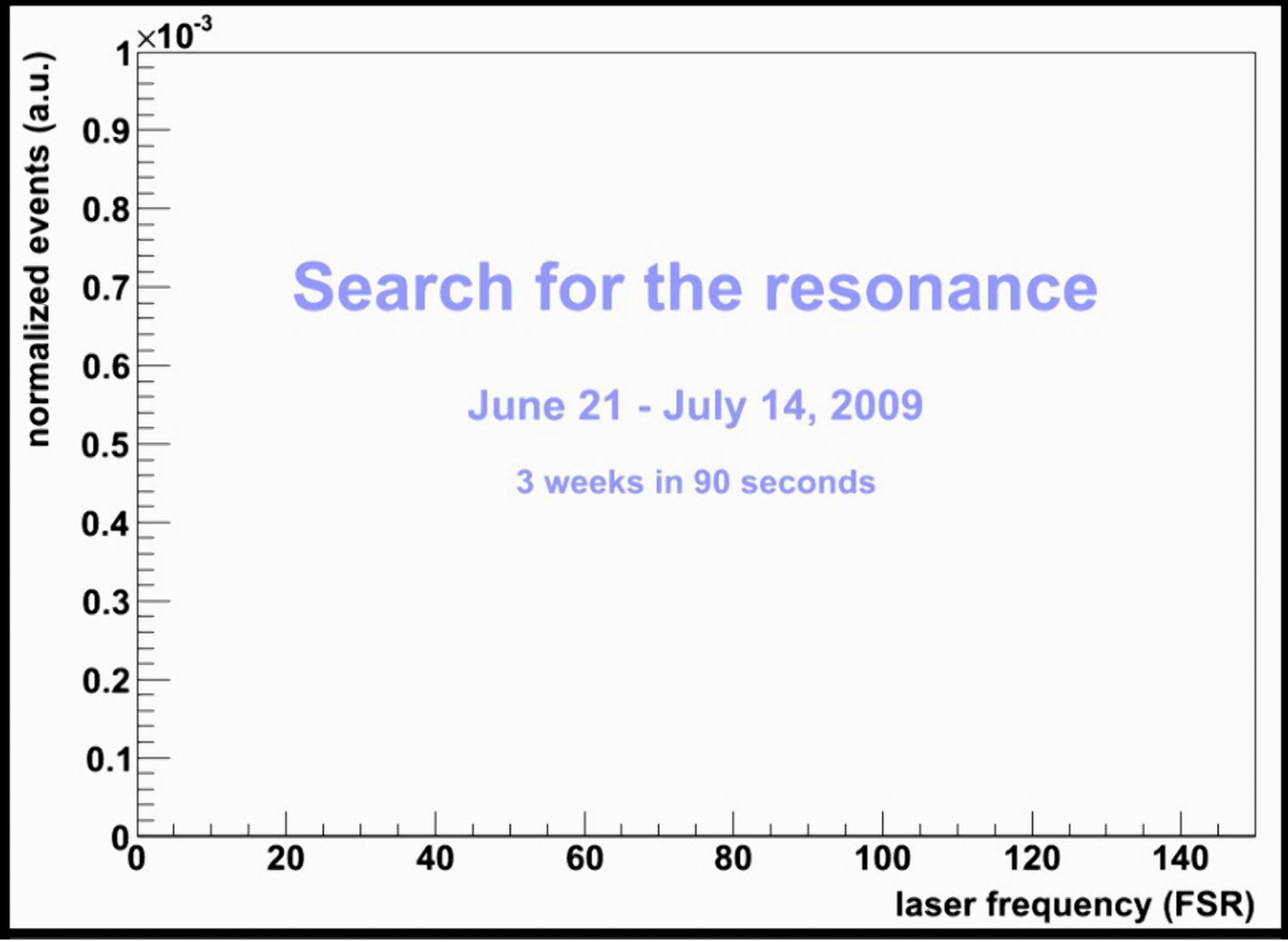


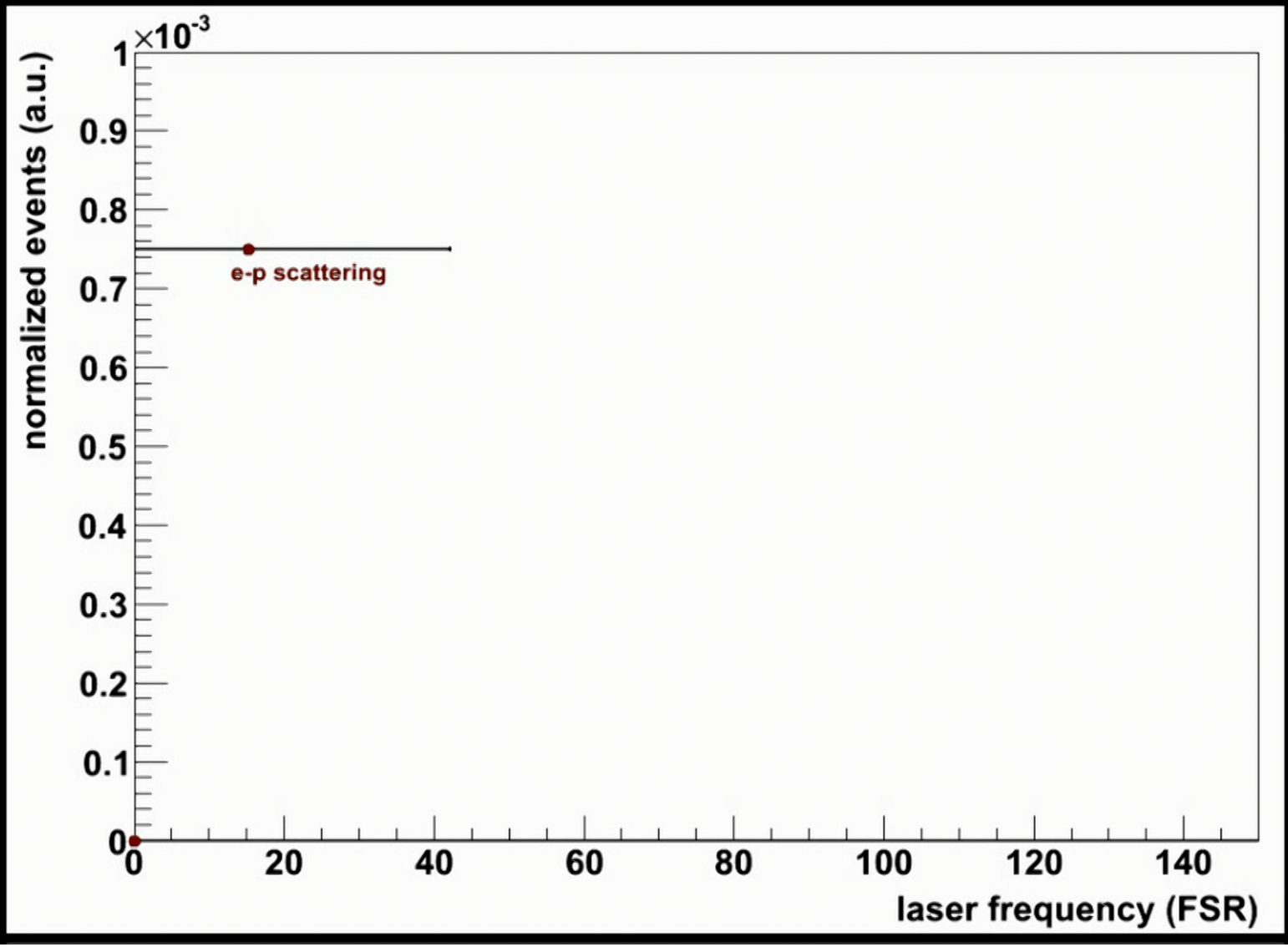
Time Spectra

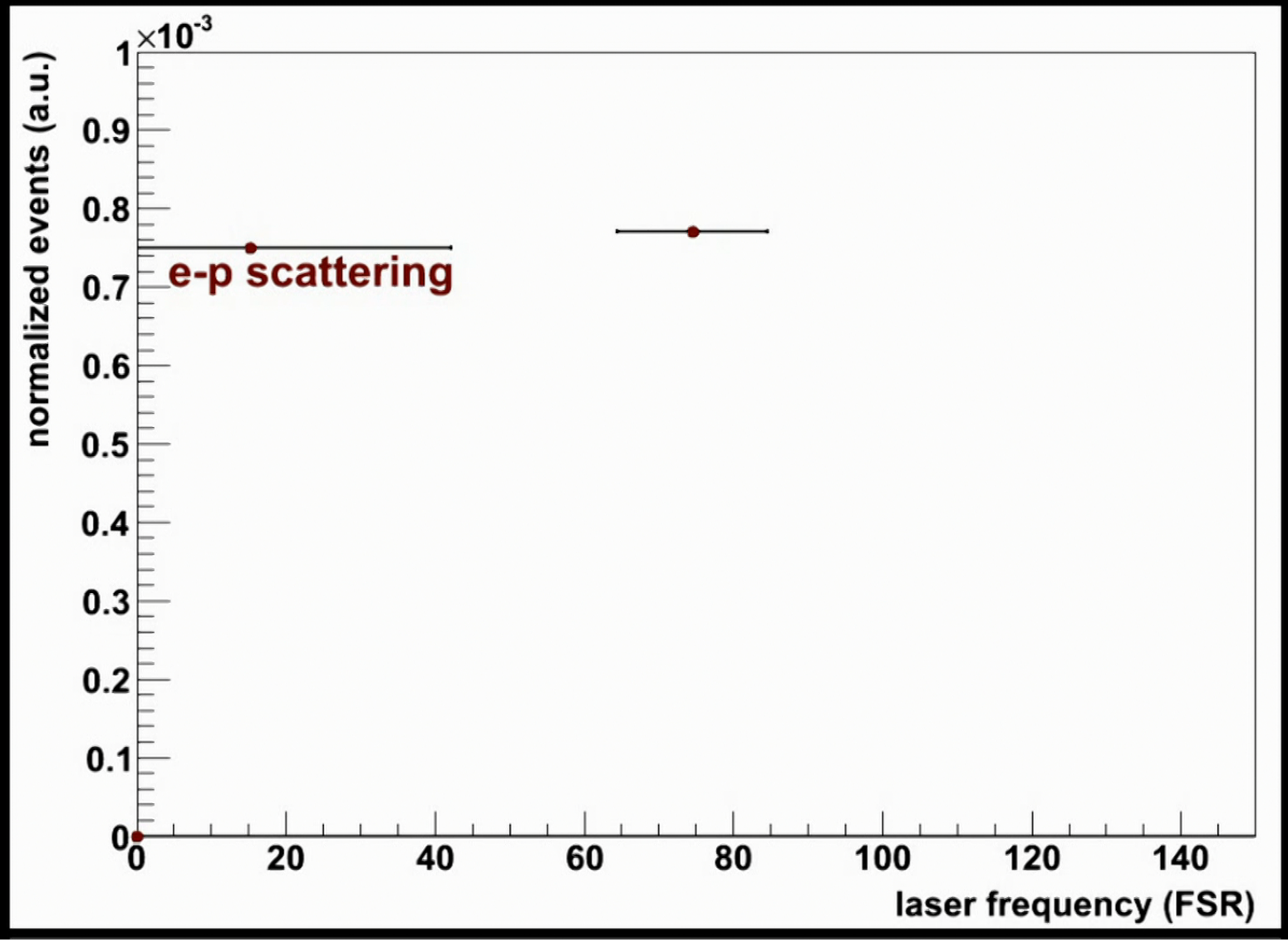


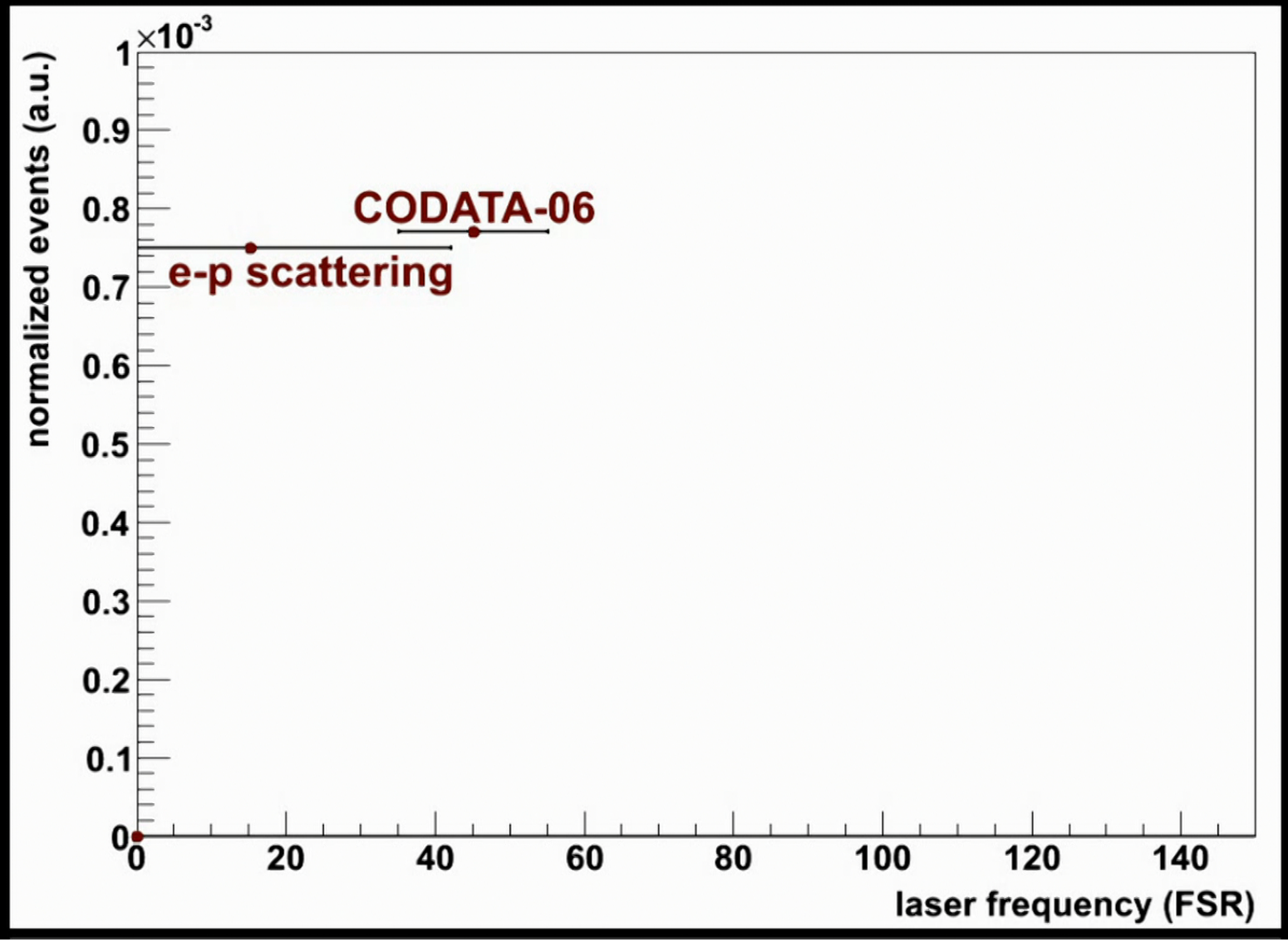
Time Spectra

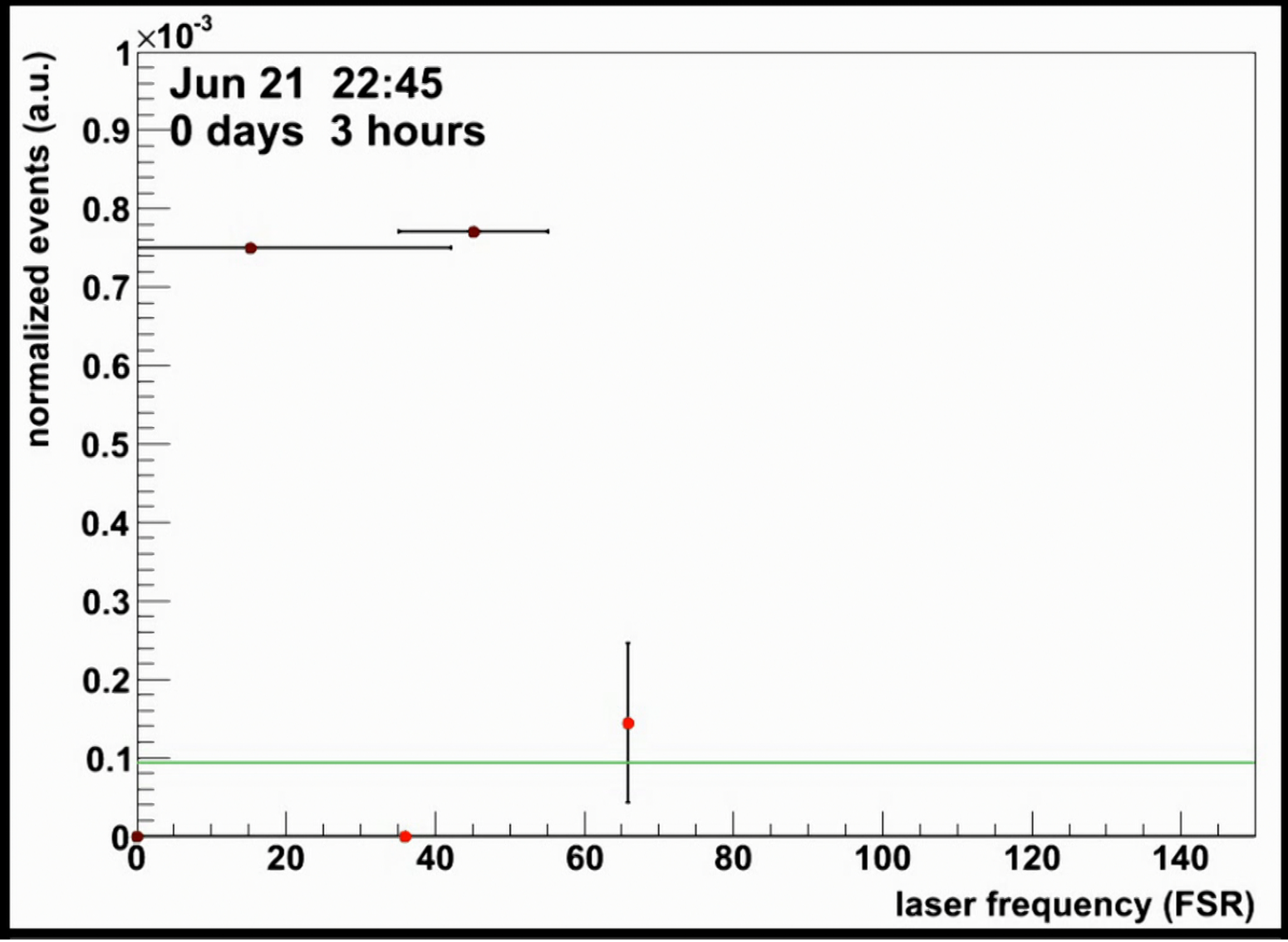


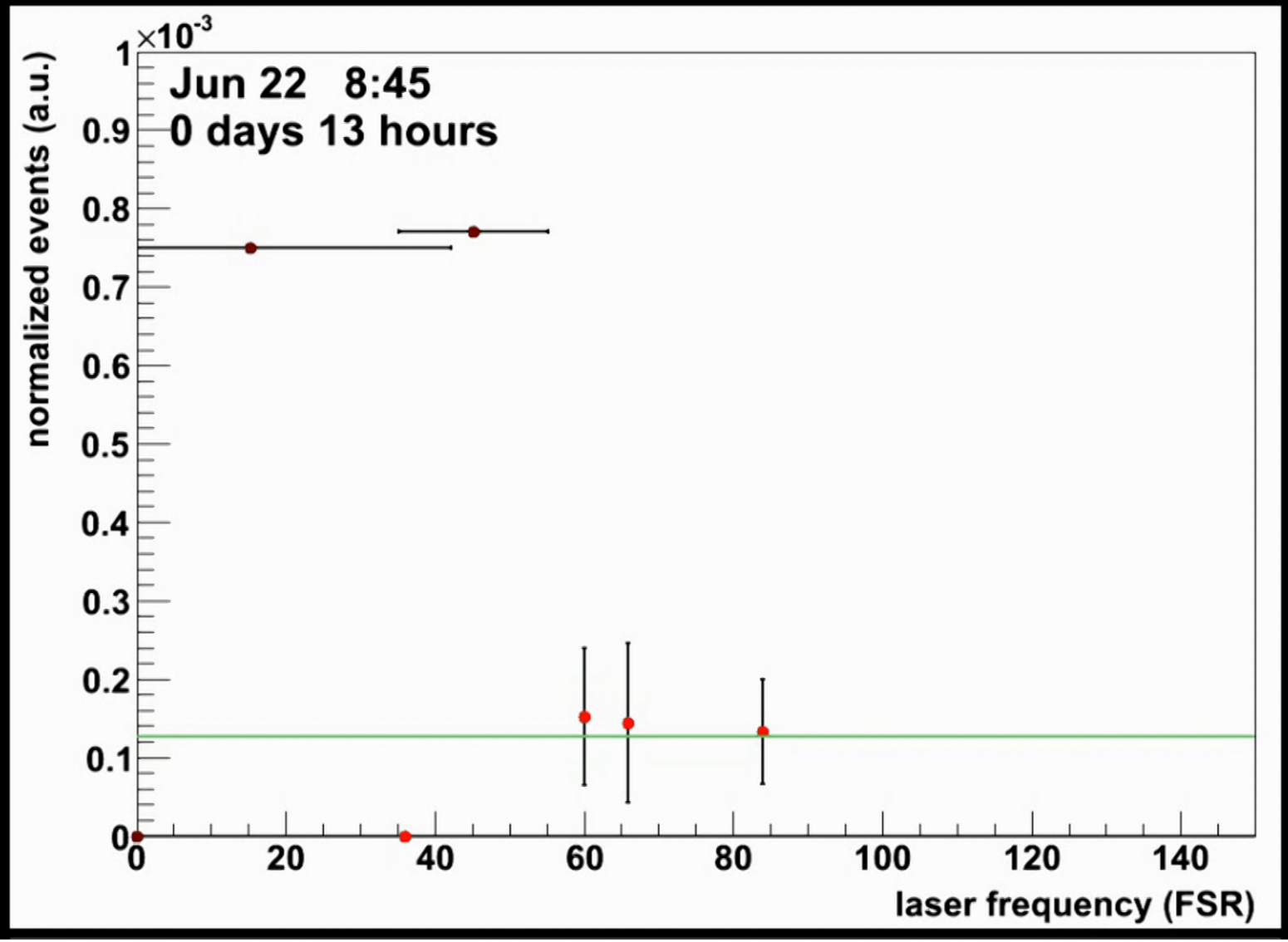

Search for the resonance
June 21 - July 14, 2009
3 weeks in 90 seconds
normalized events (a.u.)
×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

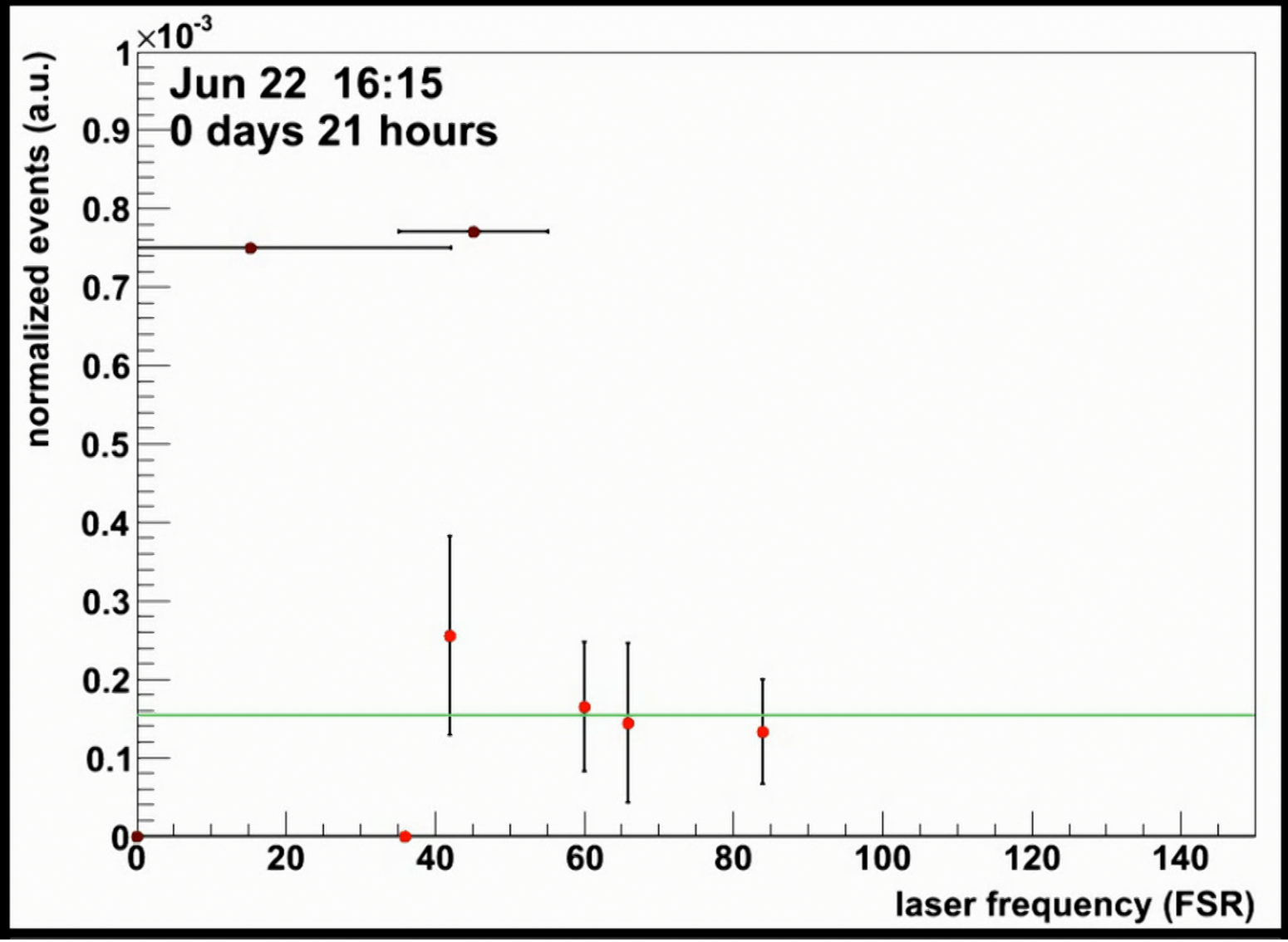

×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
normalized events (a.u.)
e-p scattering
0
20
40
60
80
100
120
140
laser frequency (FSR)

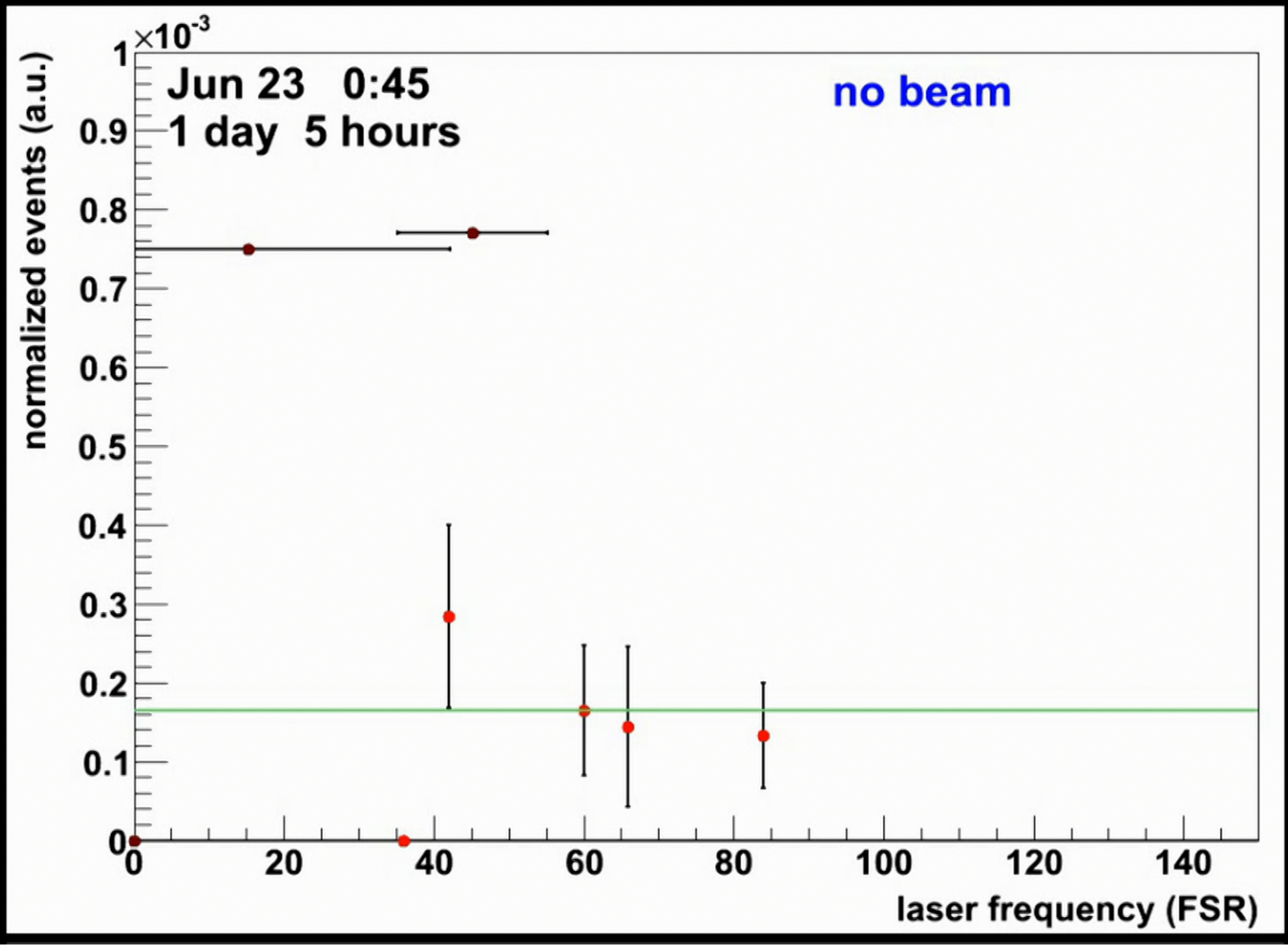

×10^-3
normalized events (a.u.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
e-p scattering
0
20
40
60
80
100
120
140
laser frequency (FSR)

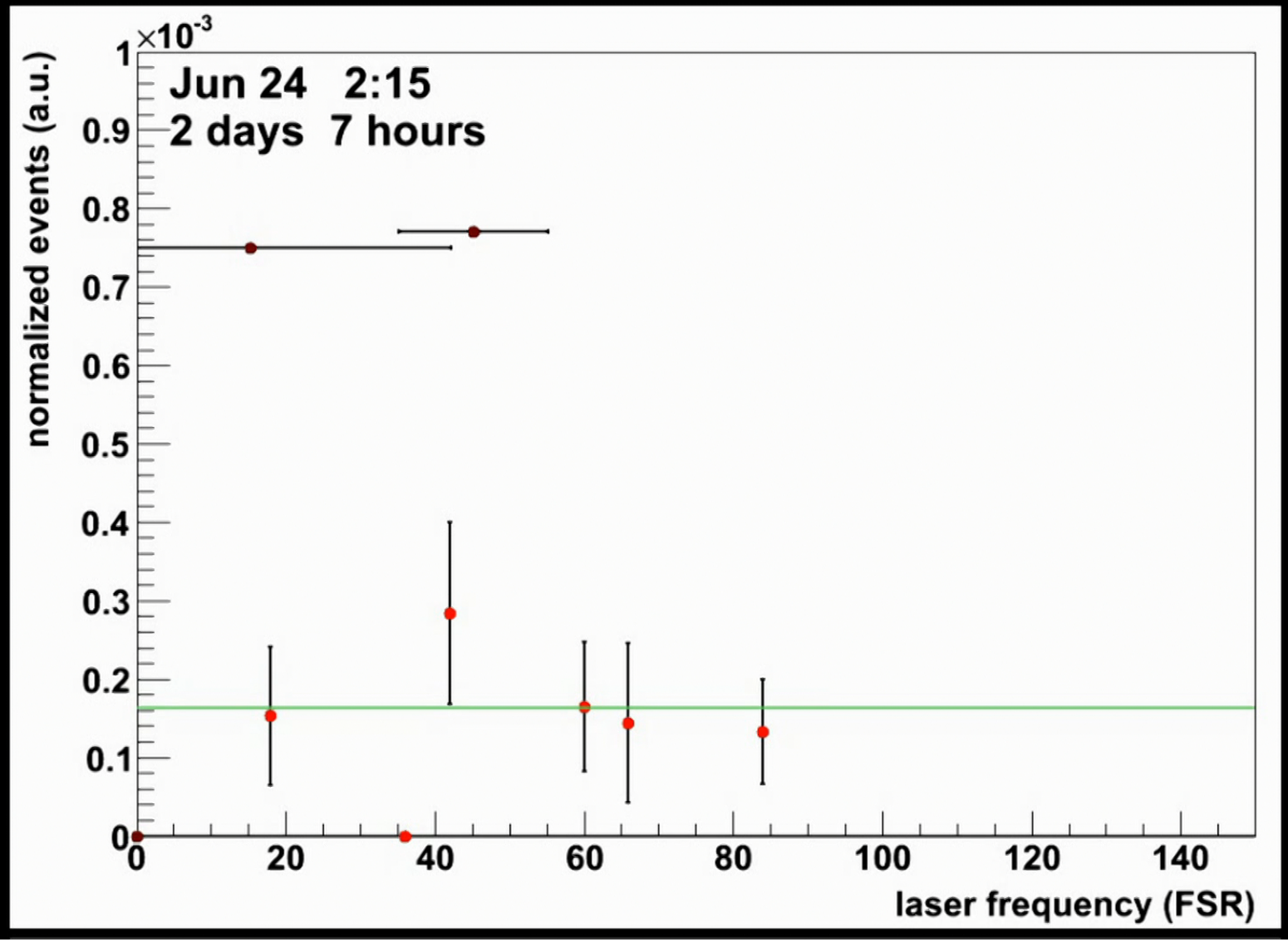

×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
normalized events (a.u.)
CODATA-06
e-p scattering
0
20
40
60
80
100
120
140
laser frequency (FSR)

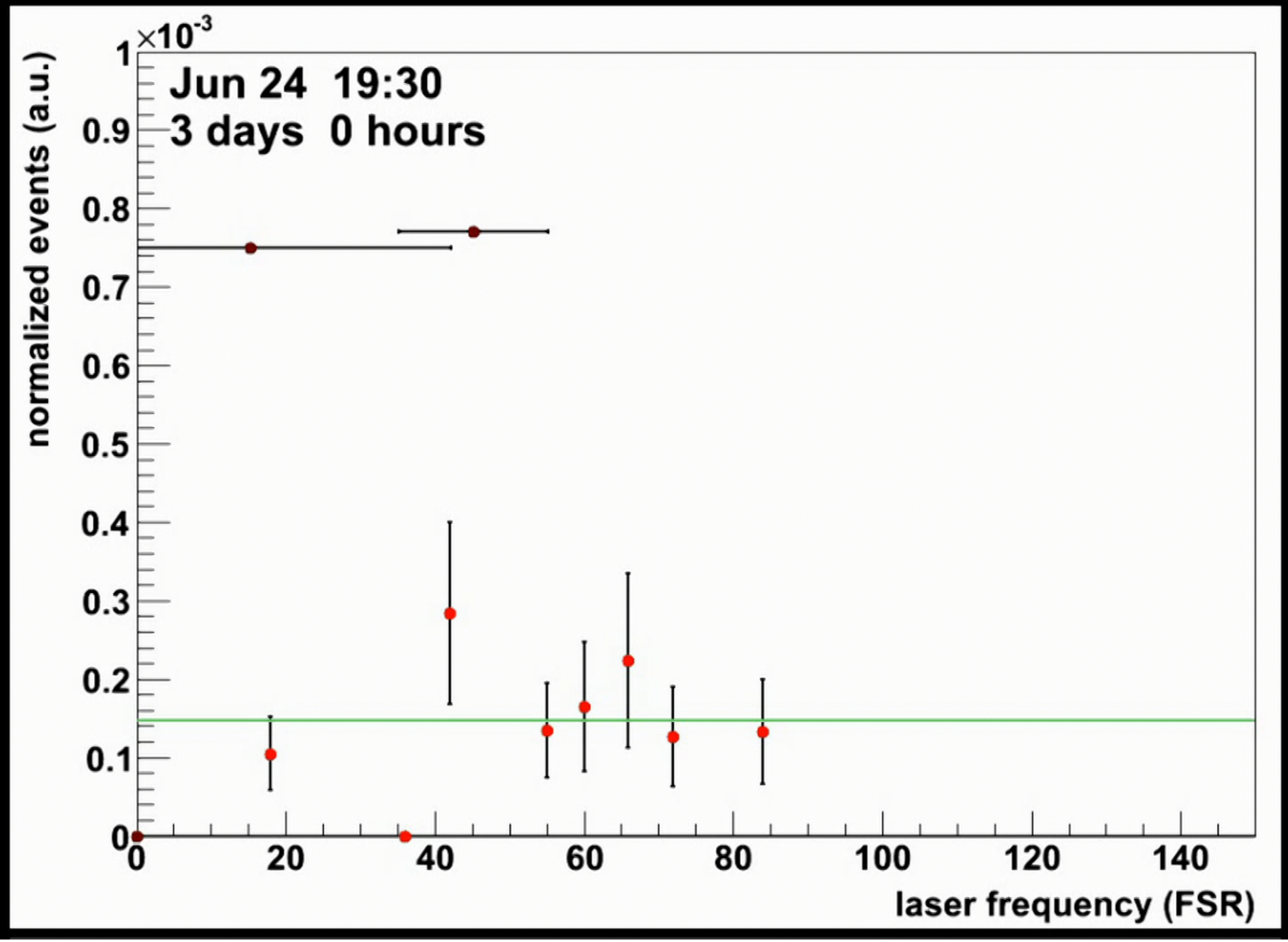

×10^-3
Jun 21 22:45
0 days 3 hours
normalized events (a.u.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

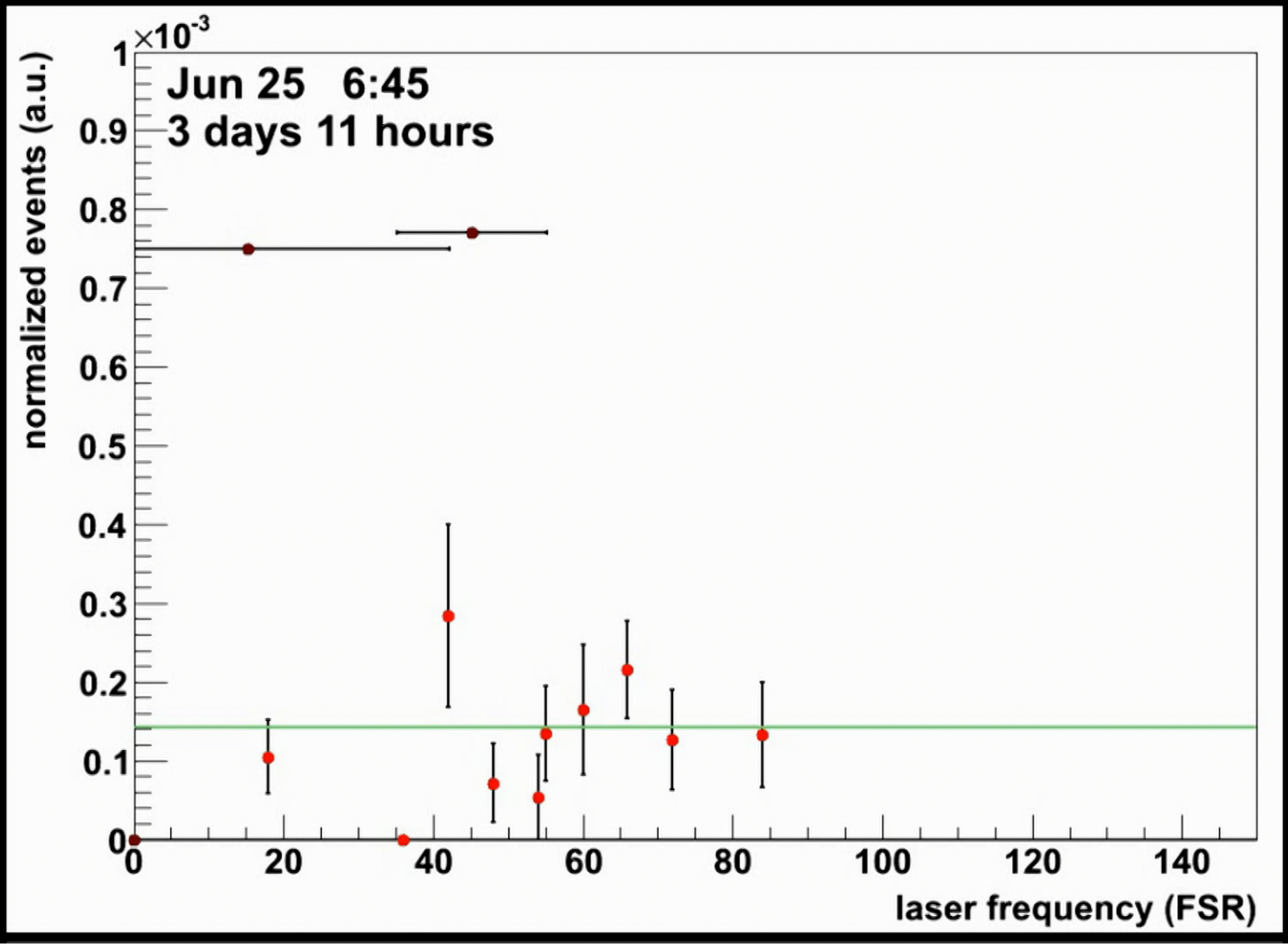

×10^-3
Jun 22 8:45
0 days 13 hours
normalized events (a.u.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

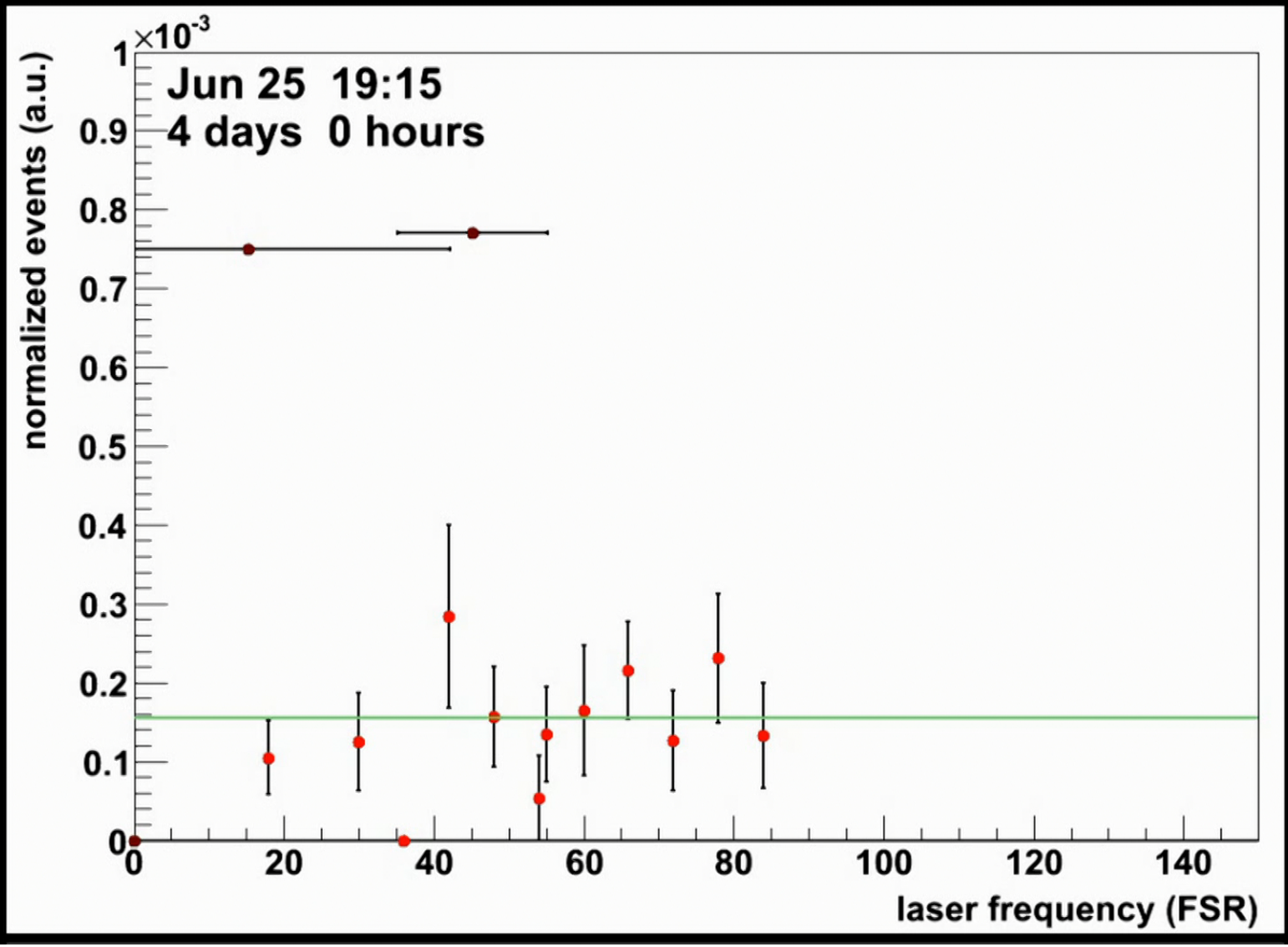

Jun 22 16:15
0 days 21 hours
normalized events (a.u.)
×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

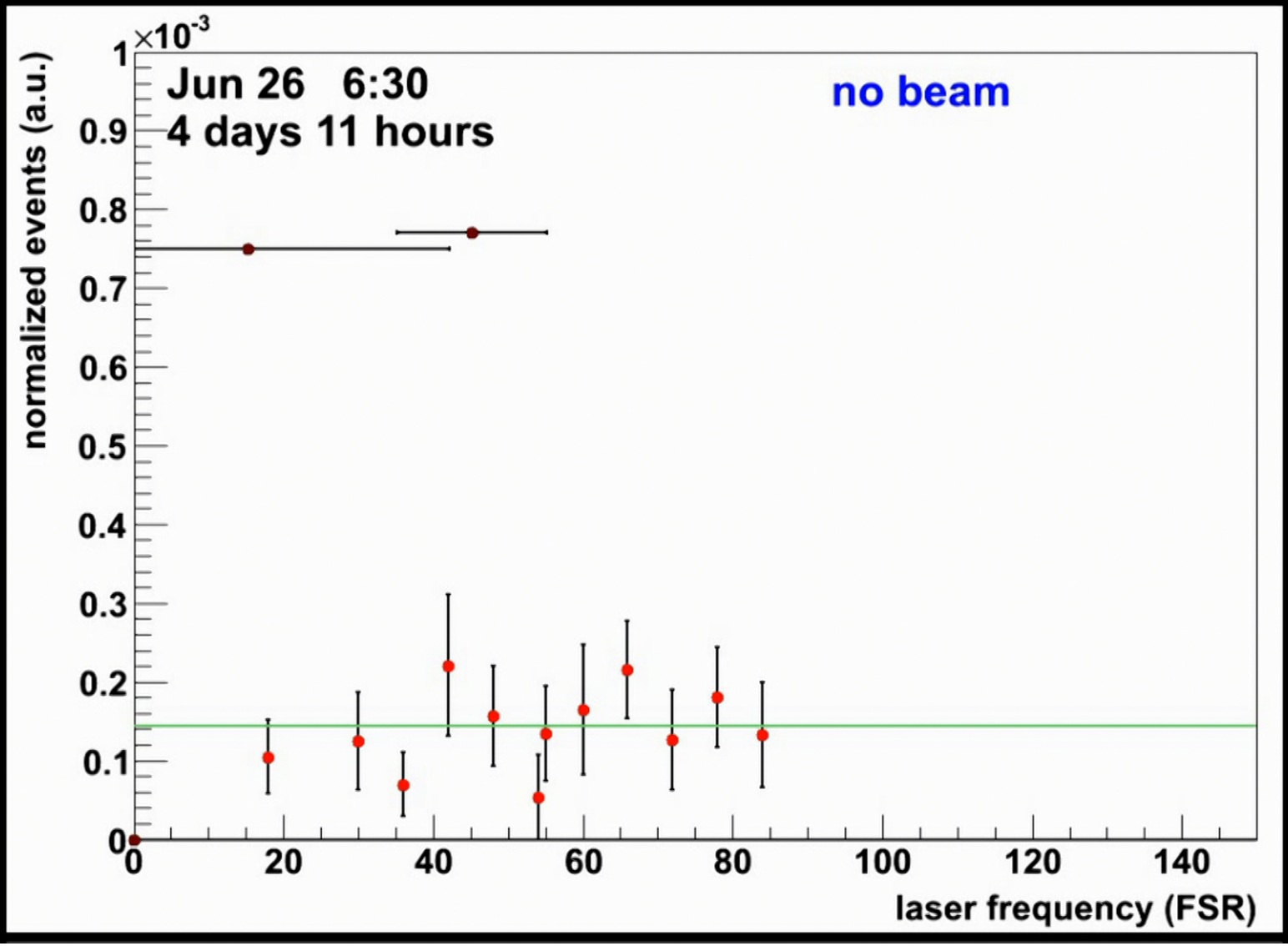

×10^-3
Jun 23 0:45
1 day 5 hours
no beam
normalized events (a.u.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

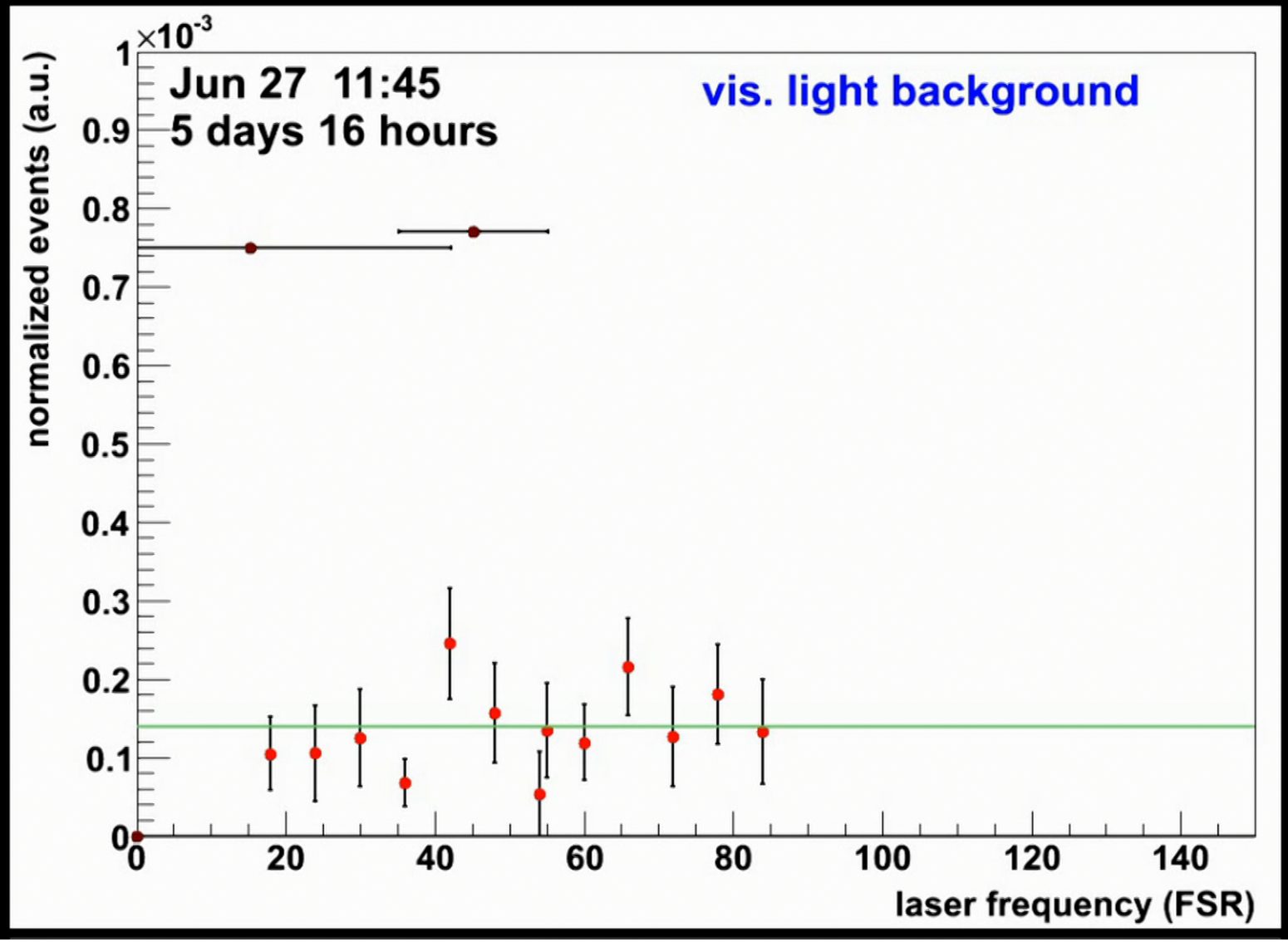

Jun 24 2:15
2 days 7 hours
normalized events (a.u.)
×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

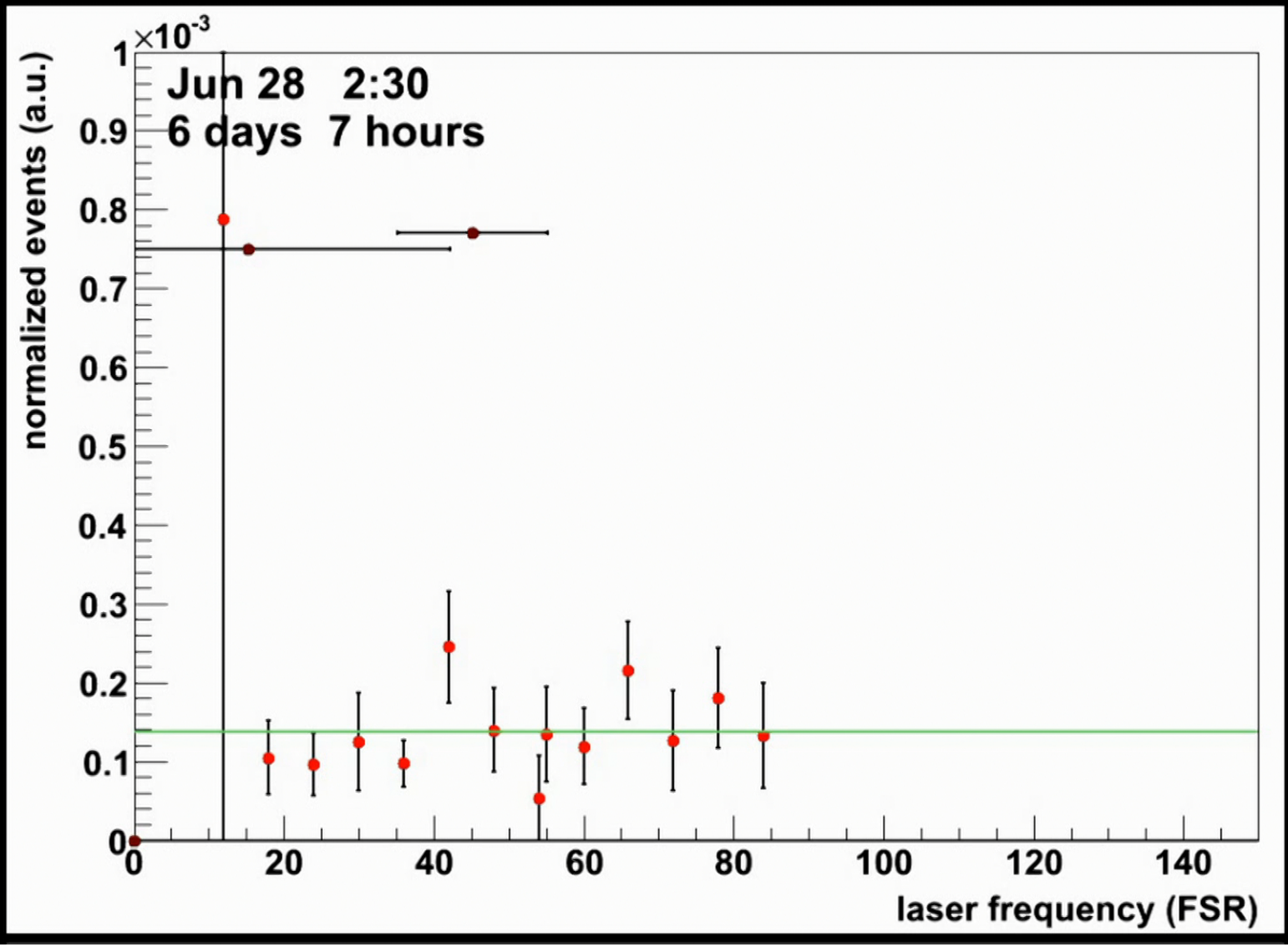

Jun 24 19:30
3 days 0 hours
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

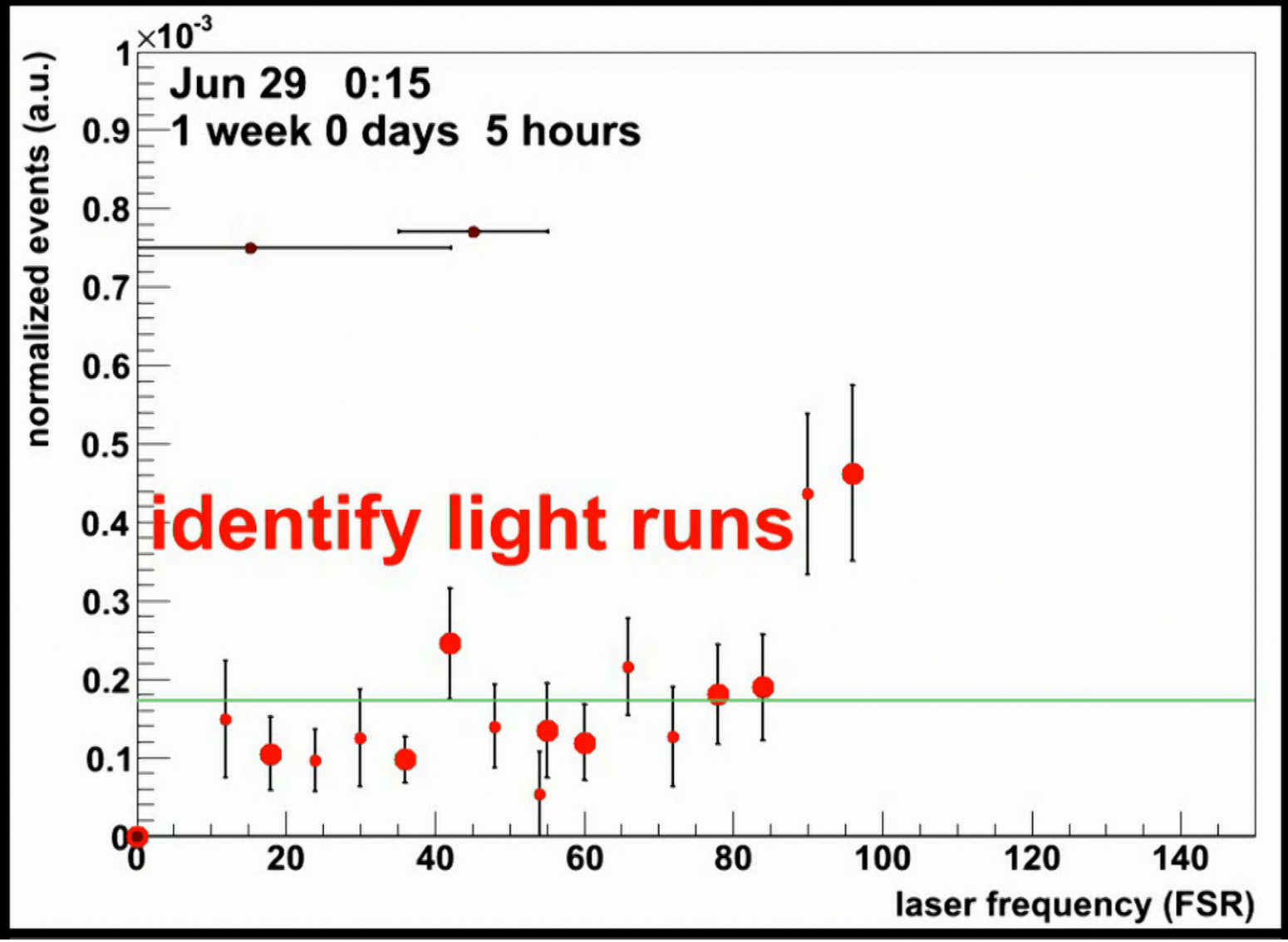

Jun 25 6:45
3 days 11 hours
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

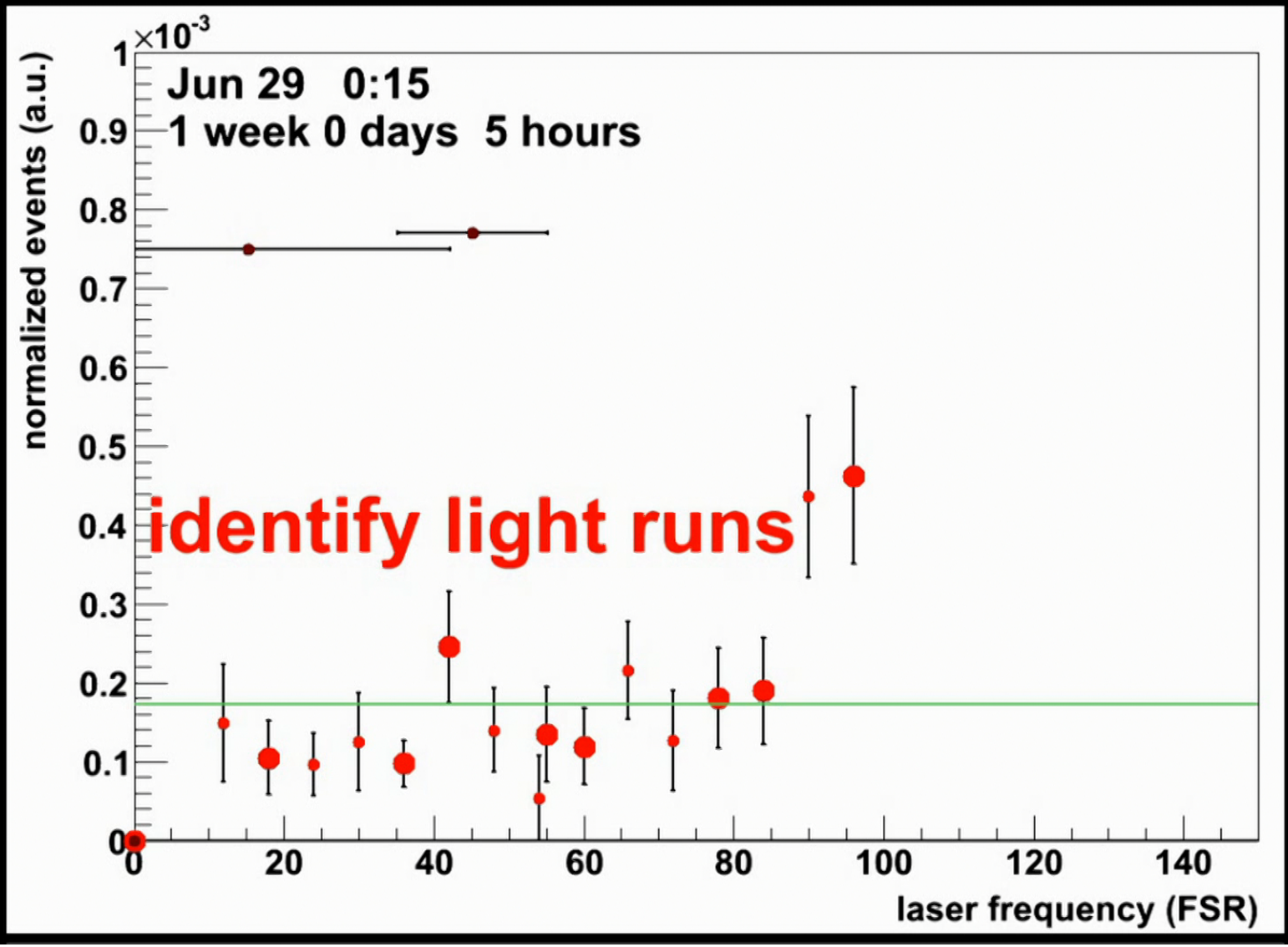

Jun 25 19:15
4 days 0 hours
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

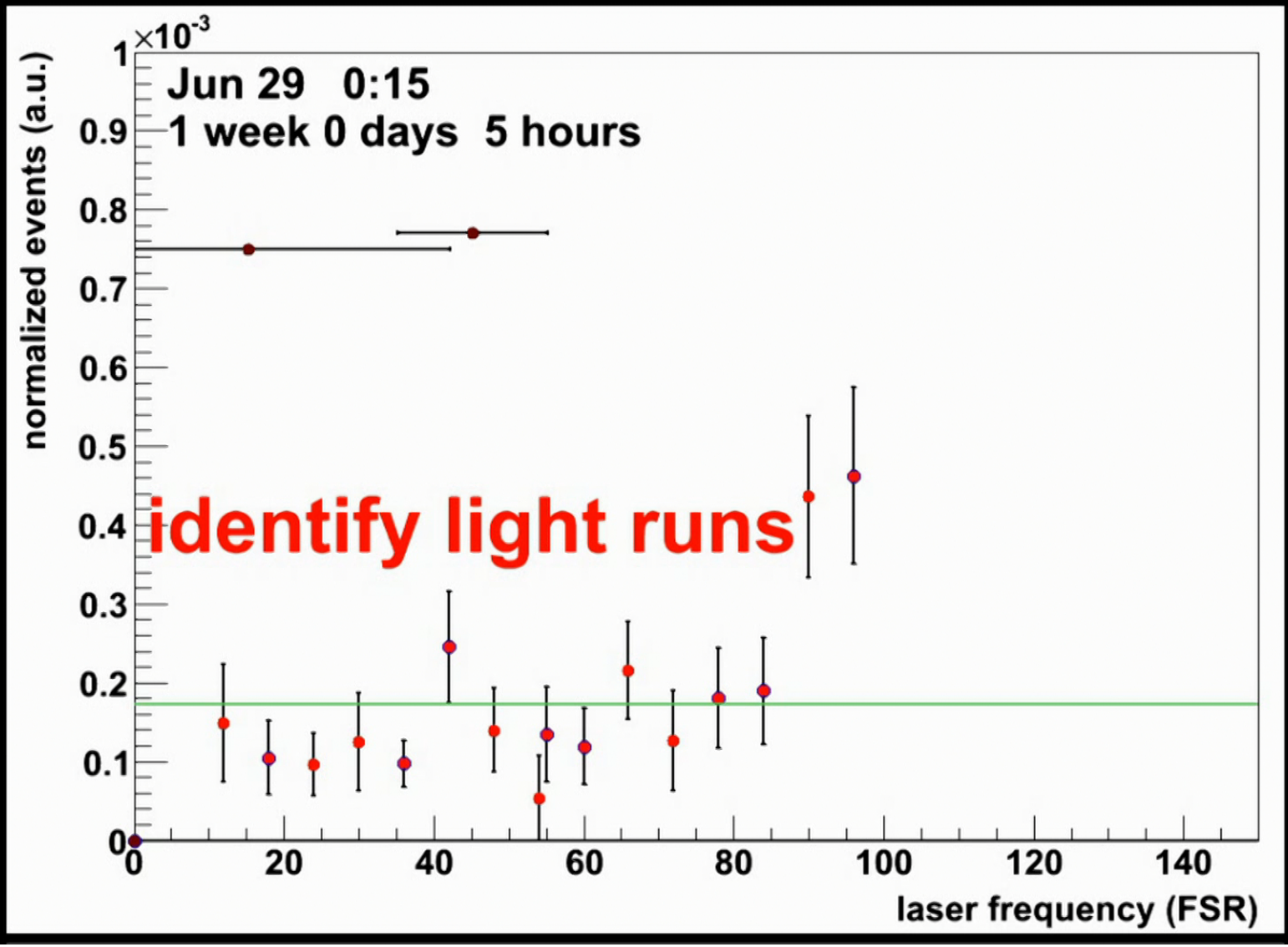

Jun 26 6:30
4 days 11 hours
no beam
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

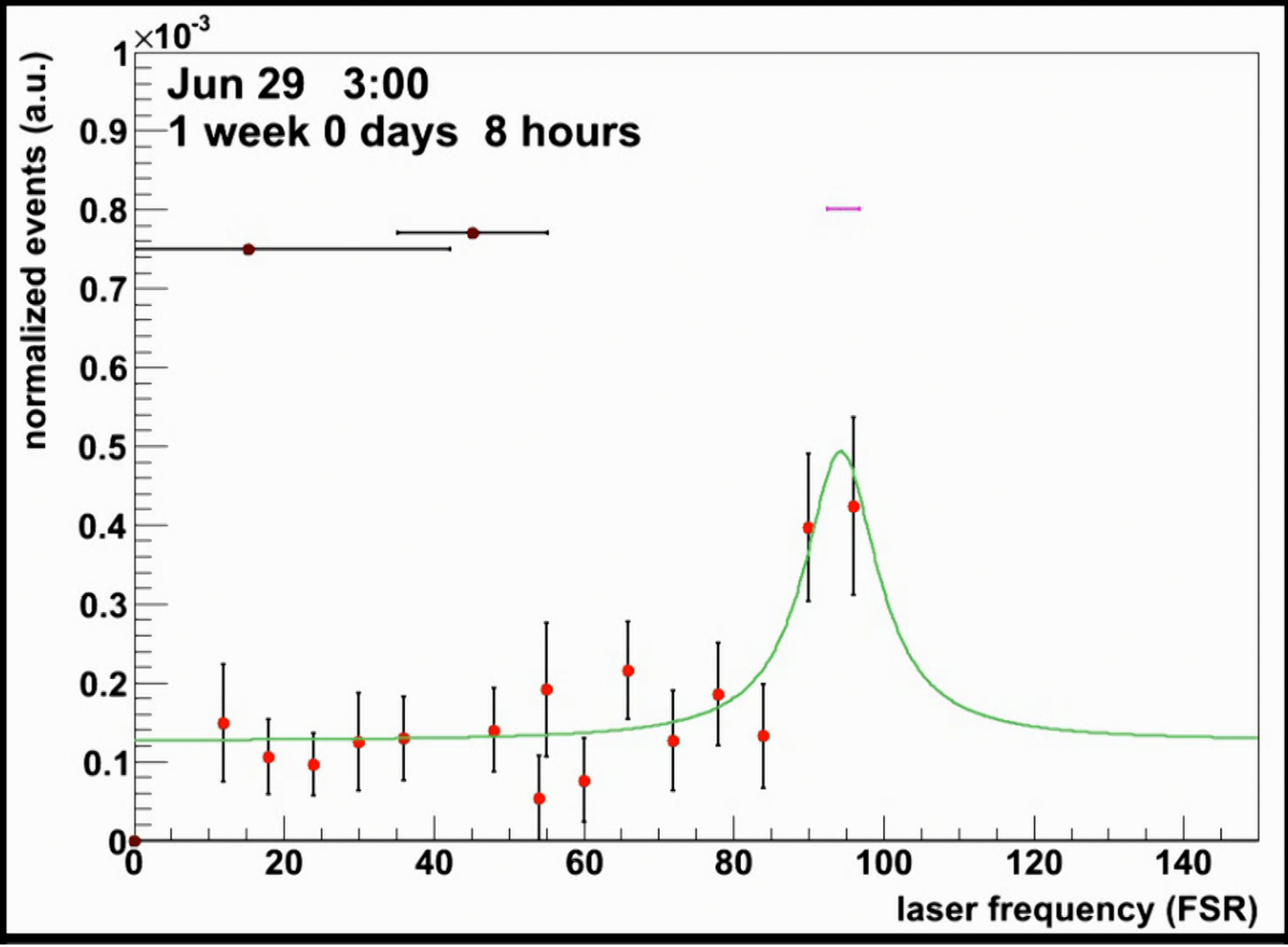

Jun 27 11:45
5 days 16 hours
vis. light background
normalized events (a.u.)
×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

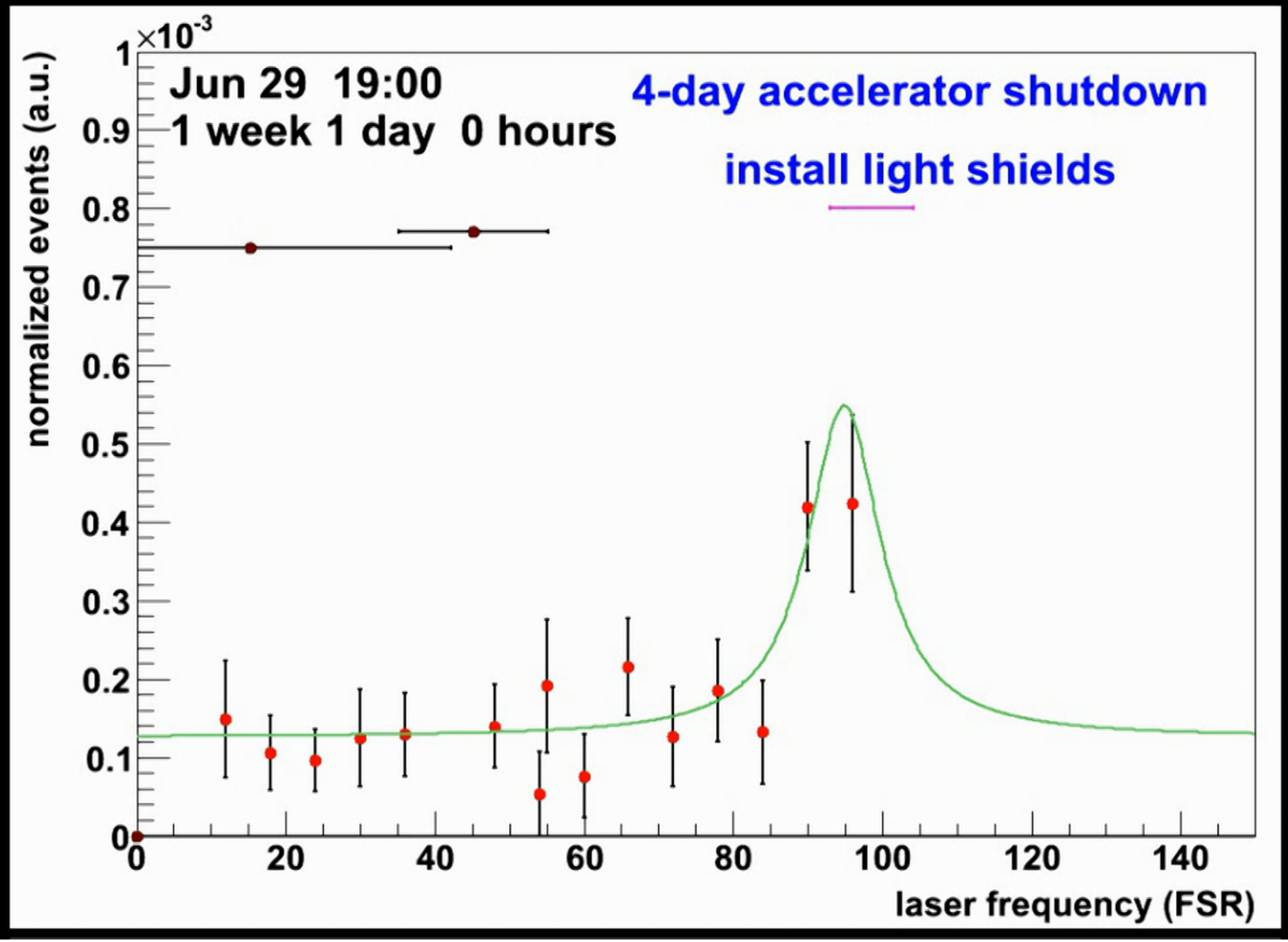

Jun 28 2:30
6 days 7 hours
normalized events (a.u.)
×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

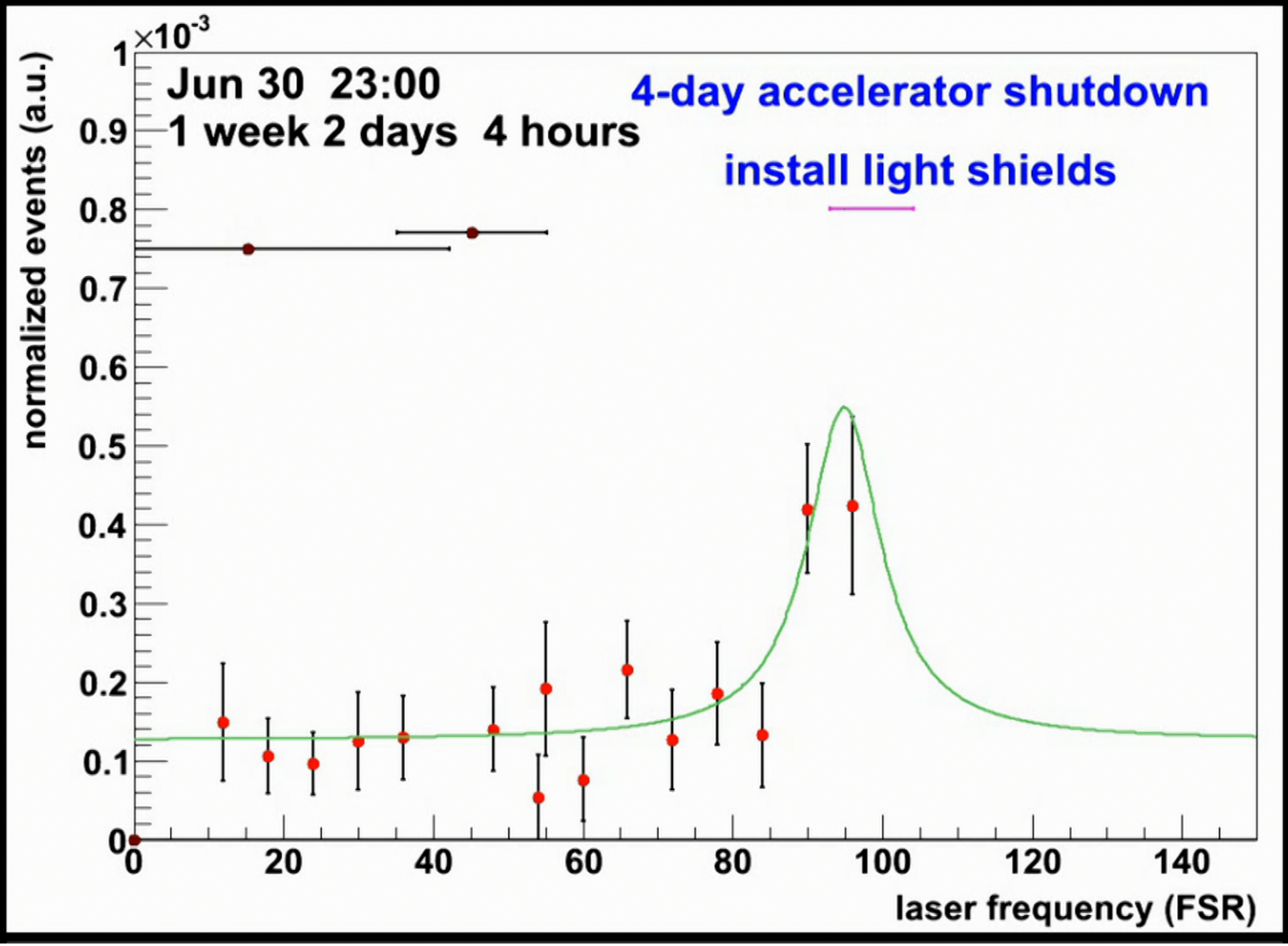

×10^-3
Jun 29 0:15
1 week 0 days 5 hours
normalized events (a.u.)
identify light runs
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

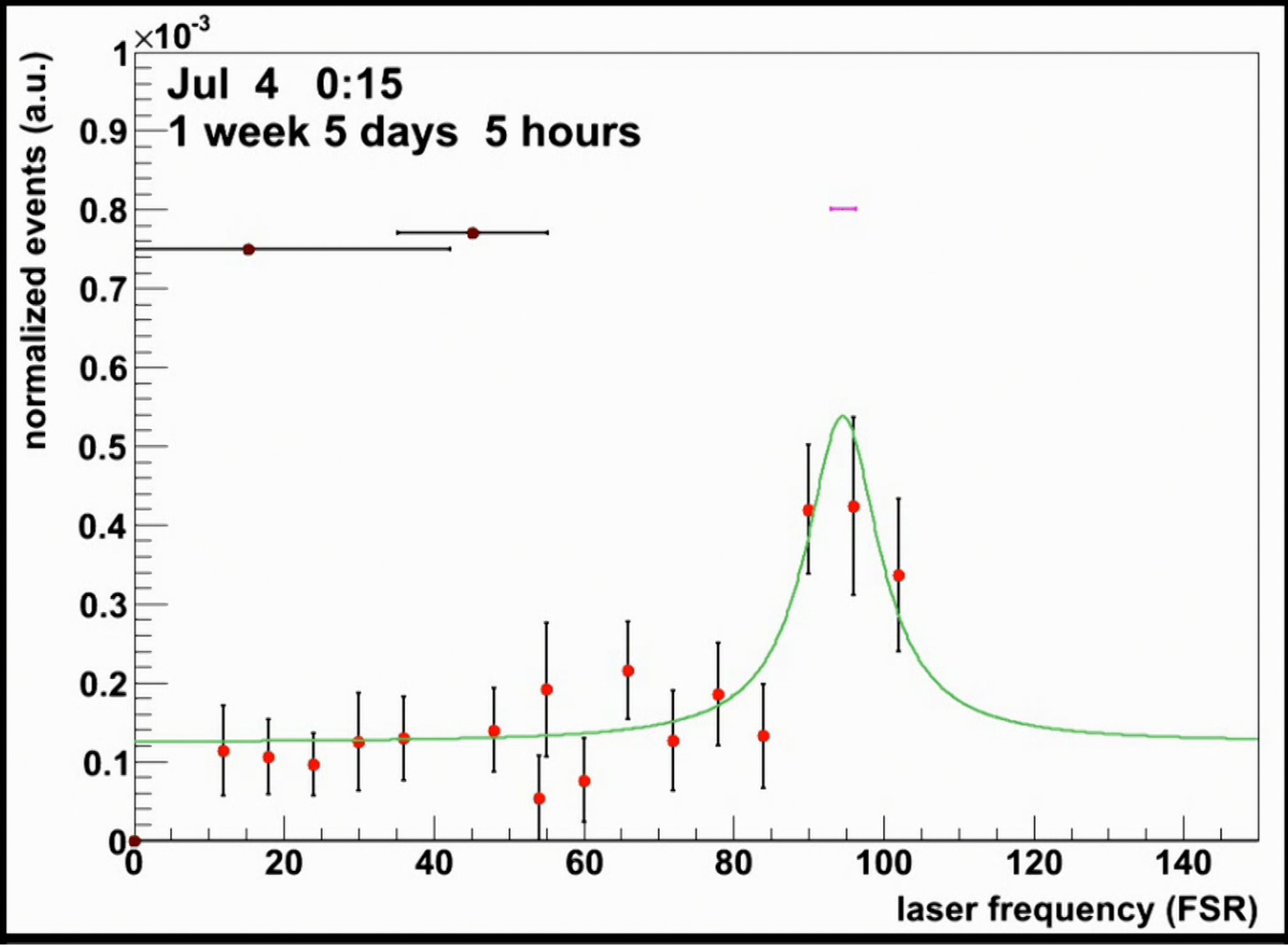

×10^-3
Jun 29 0:15
1 week 0 days 5 hours
normalized events (a.u.)
identify light runs
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

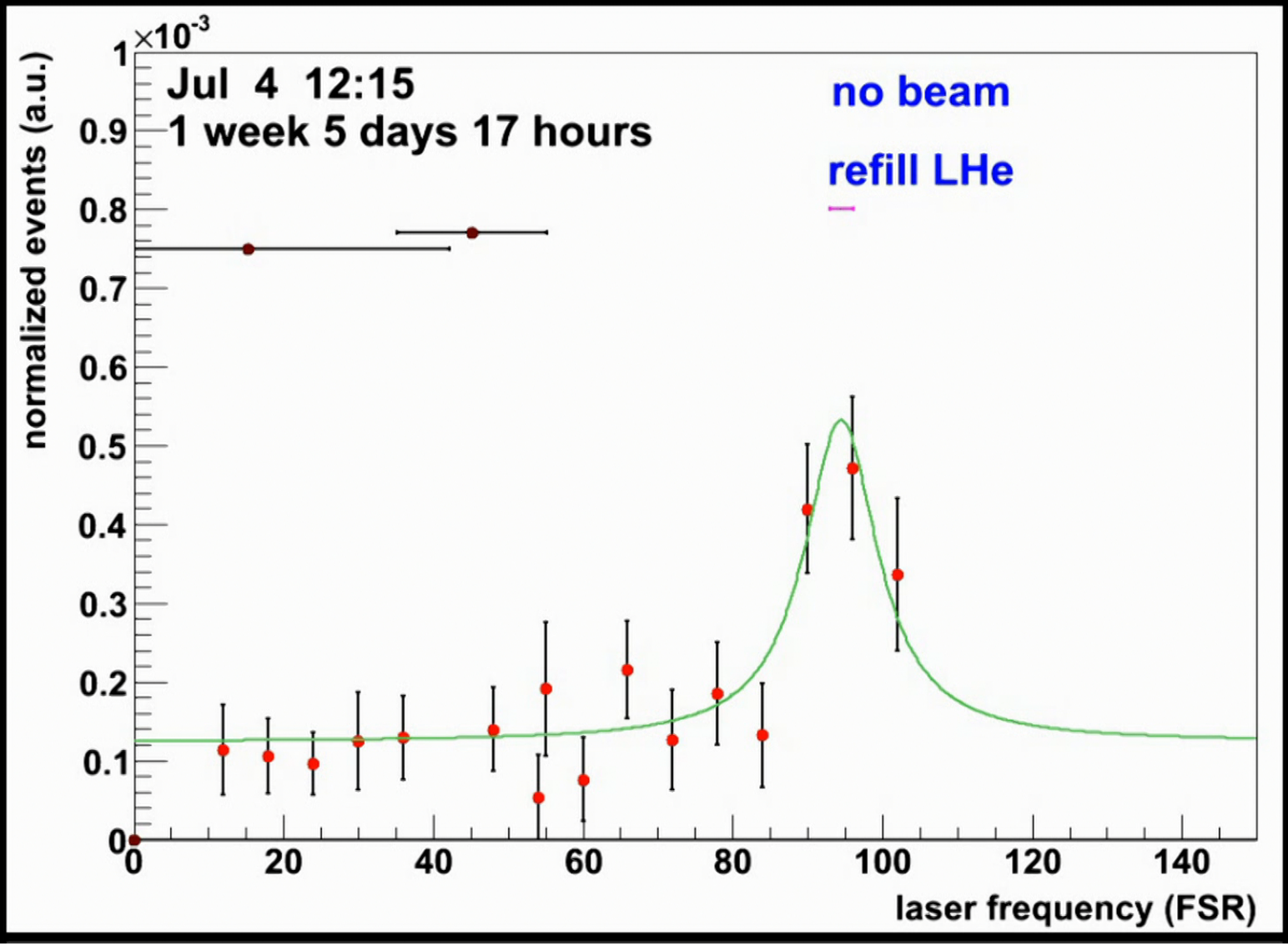

×10^-3
Jun 29 0:15
1 week 0 days 5 hours
normalized events (a.u.)
identify light runs
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

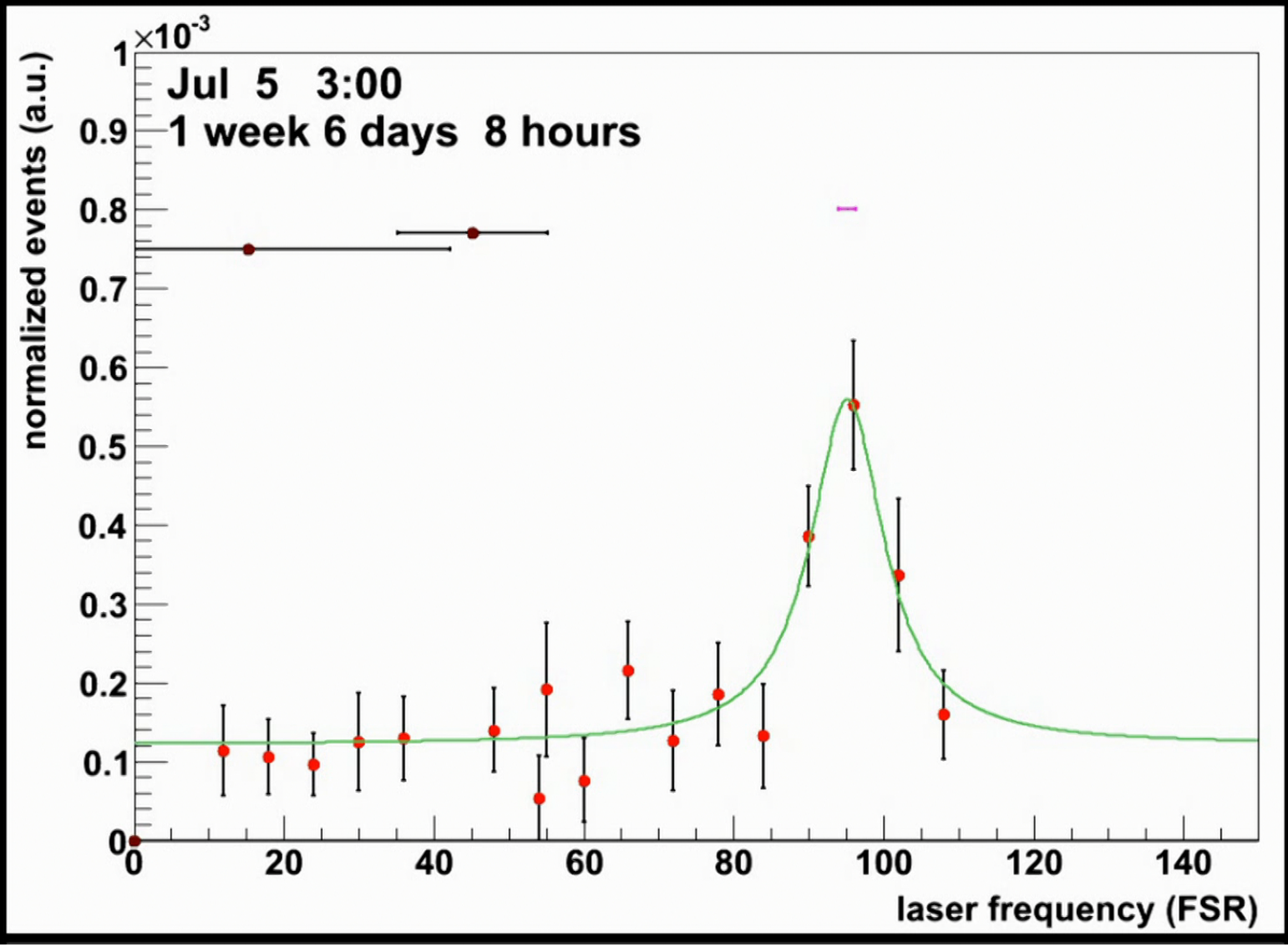

Jun 29 3:00
1 week 0 days 8 hours
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

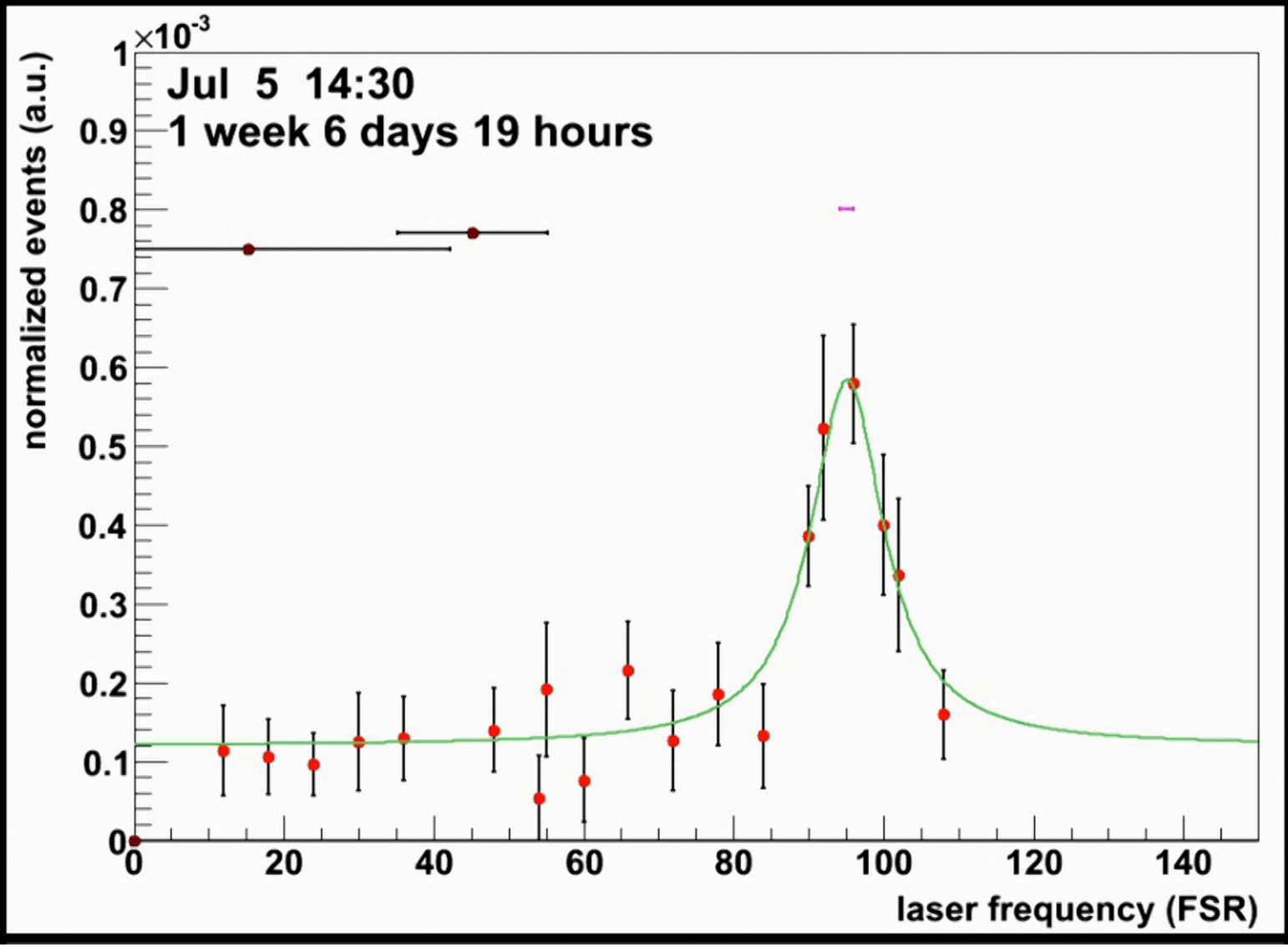

Jun 29 19:00
1 week 1 day 0 hours
4-day accelerator shutdown
install light shields
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

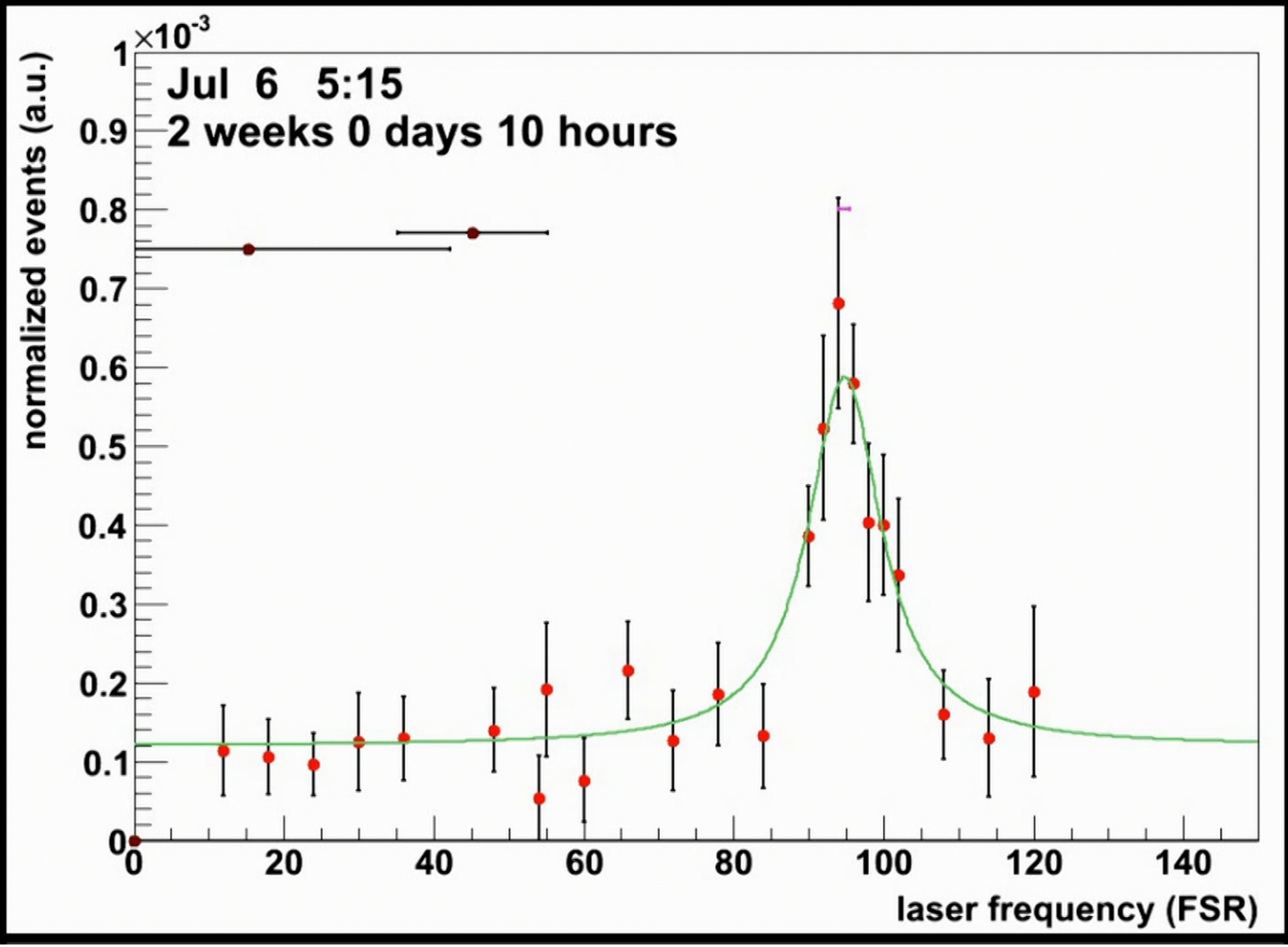

×10^-3
Jun 30 23:00
1 week 2 days 4 hours
4-day accelerator shutdown
install light shields
normalized events (a.u.)
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

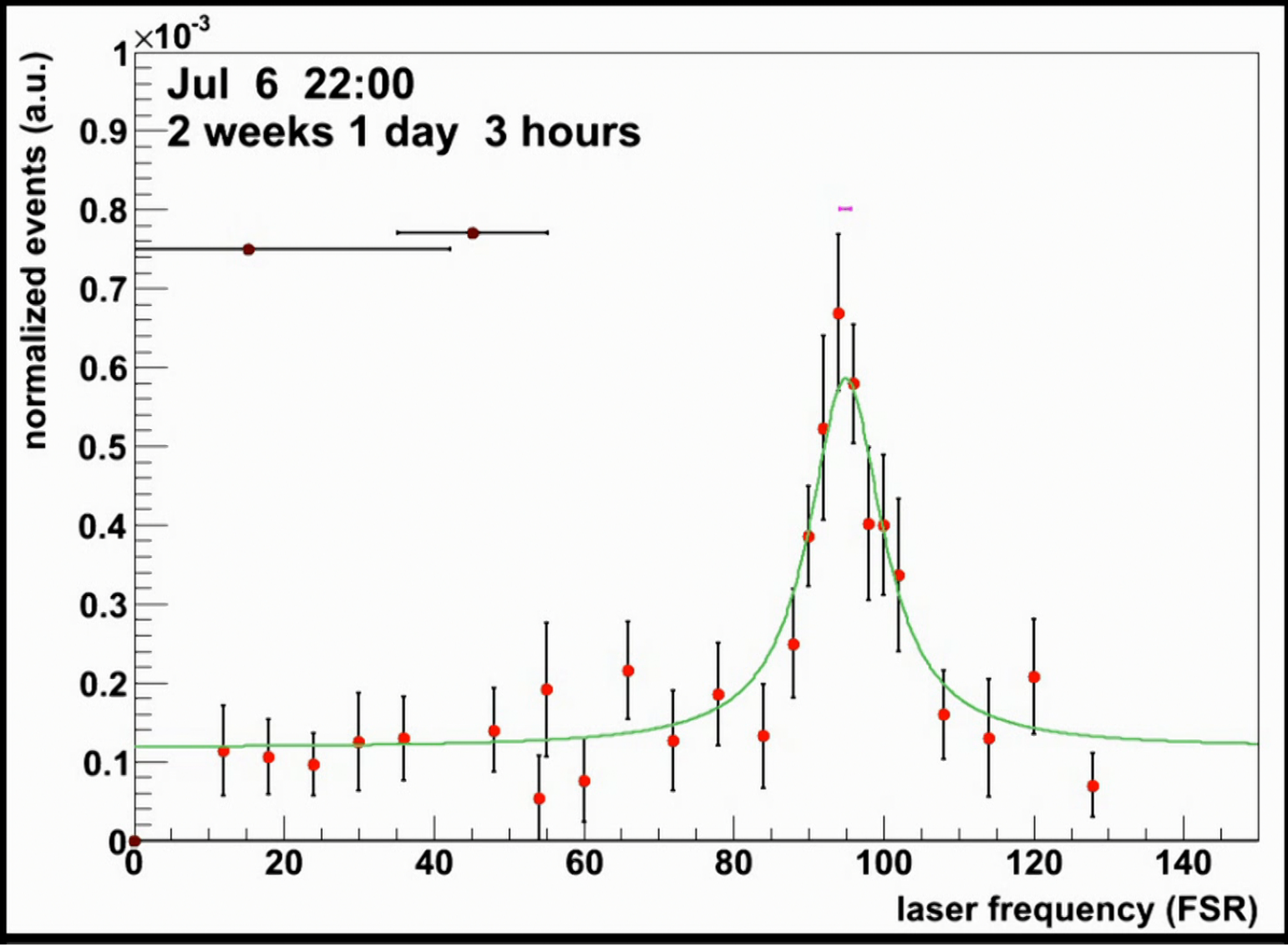

×10^-3
Jul 4 0:15
1 week 5 days 5 hours
normalized events (a.u.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

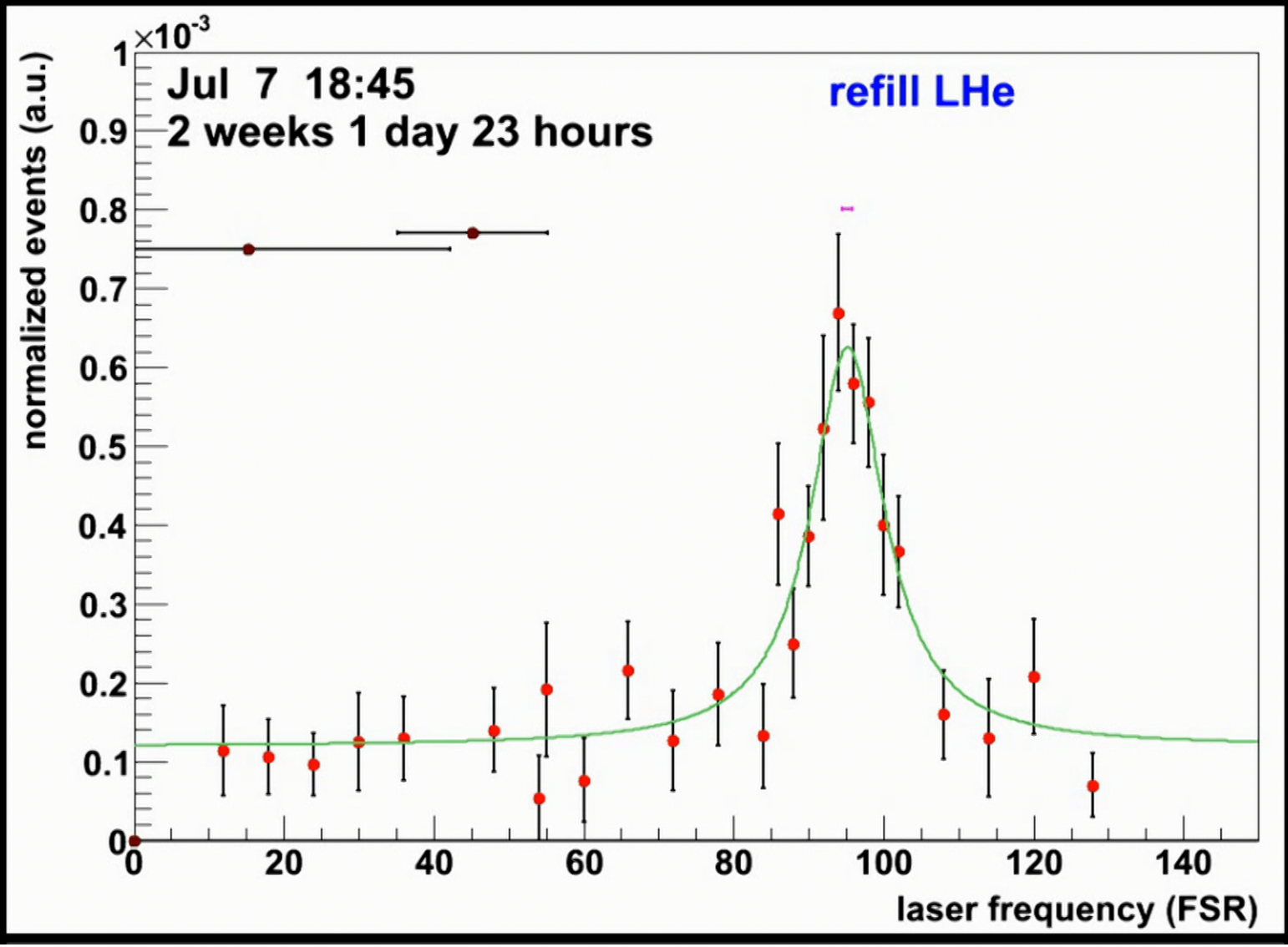

×10^-3
Jul 4 12:15
1 week 5 days 17 hours
no beam
refill LHe
normalized events (a.u.)
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

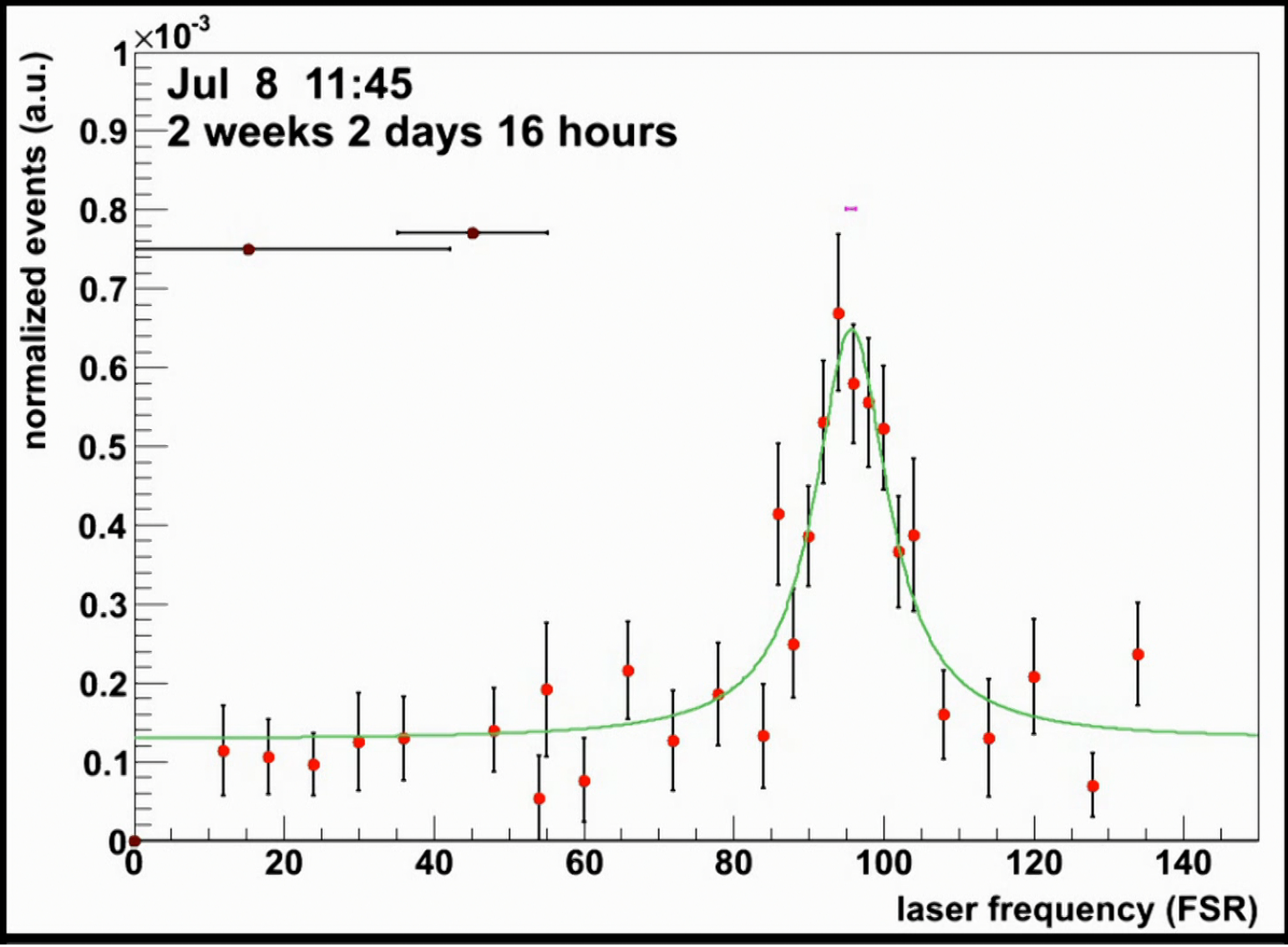

×10^-3
Jul 5 3:00
1 week 6 days 8 hours
normalized events (a.u.)
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

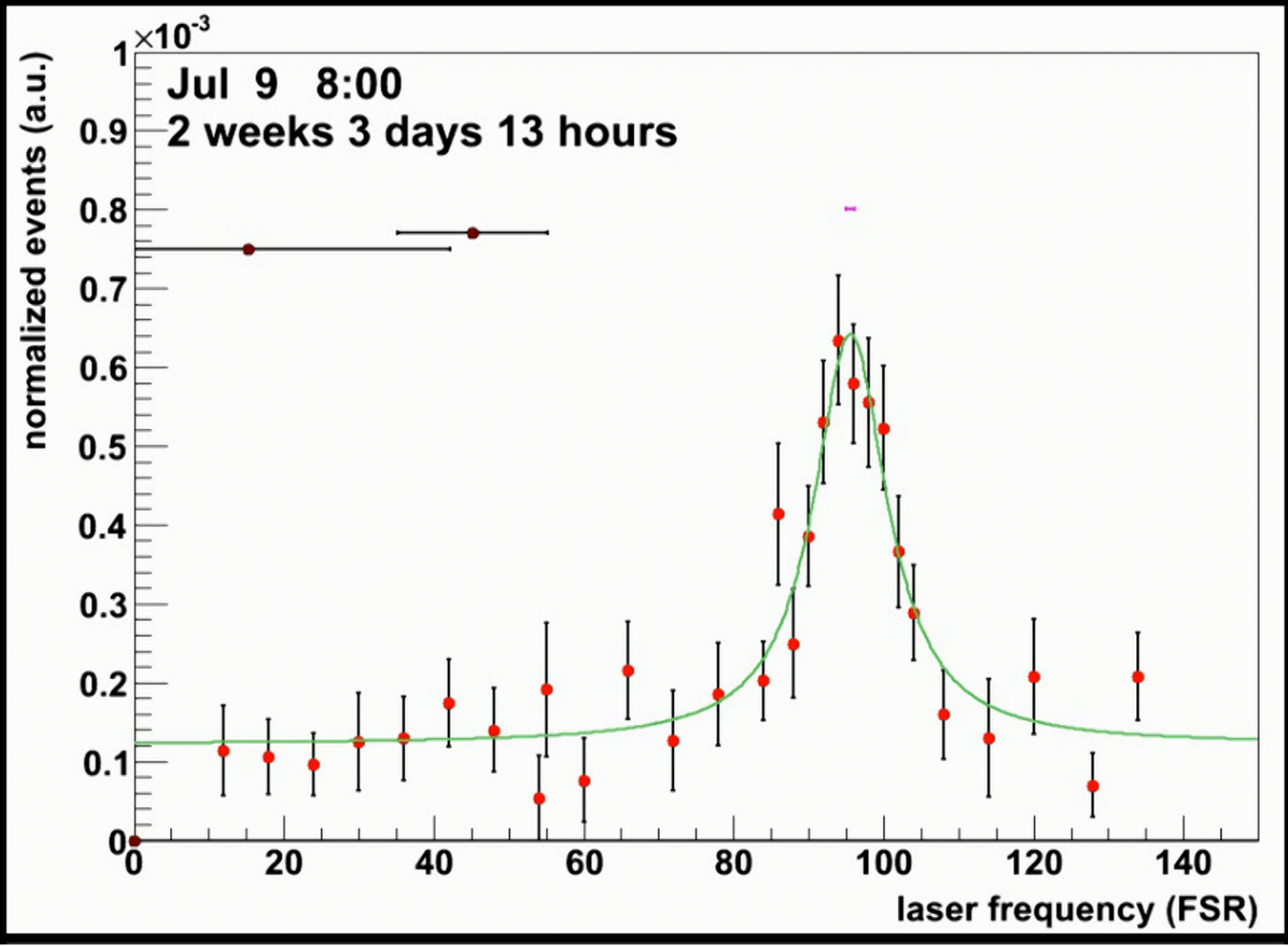

×10^-3
Jul 5 14:30
1 week 6 days 19 hours
normalized events (a.u.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

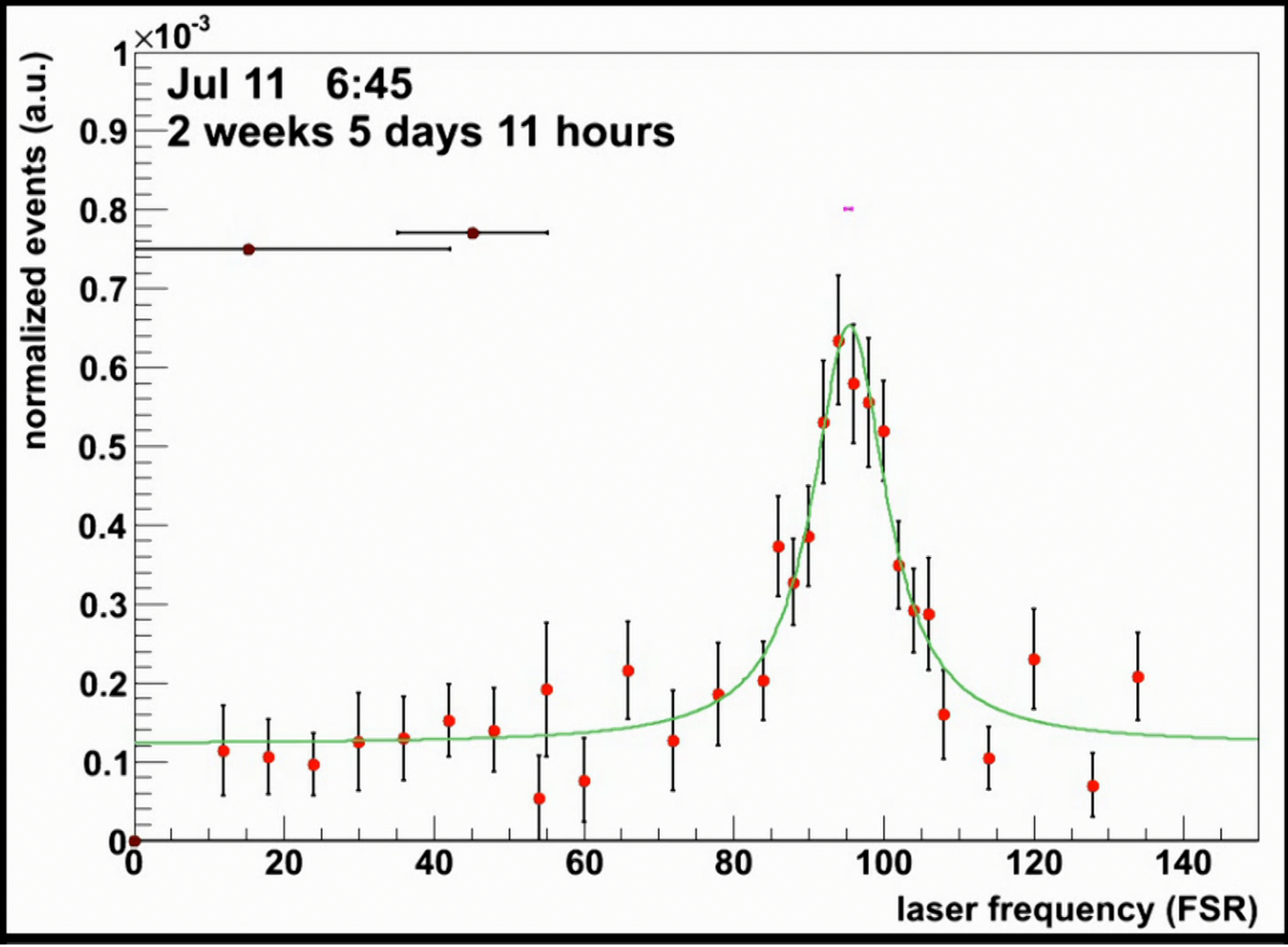

×10^-3
Jul 6 5:15
2 weeks 0 days 10 hours
normalized events (a.u.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

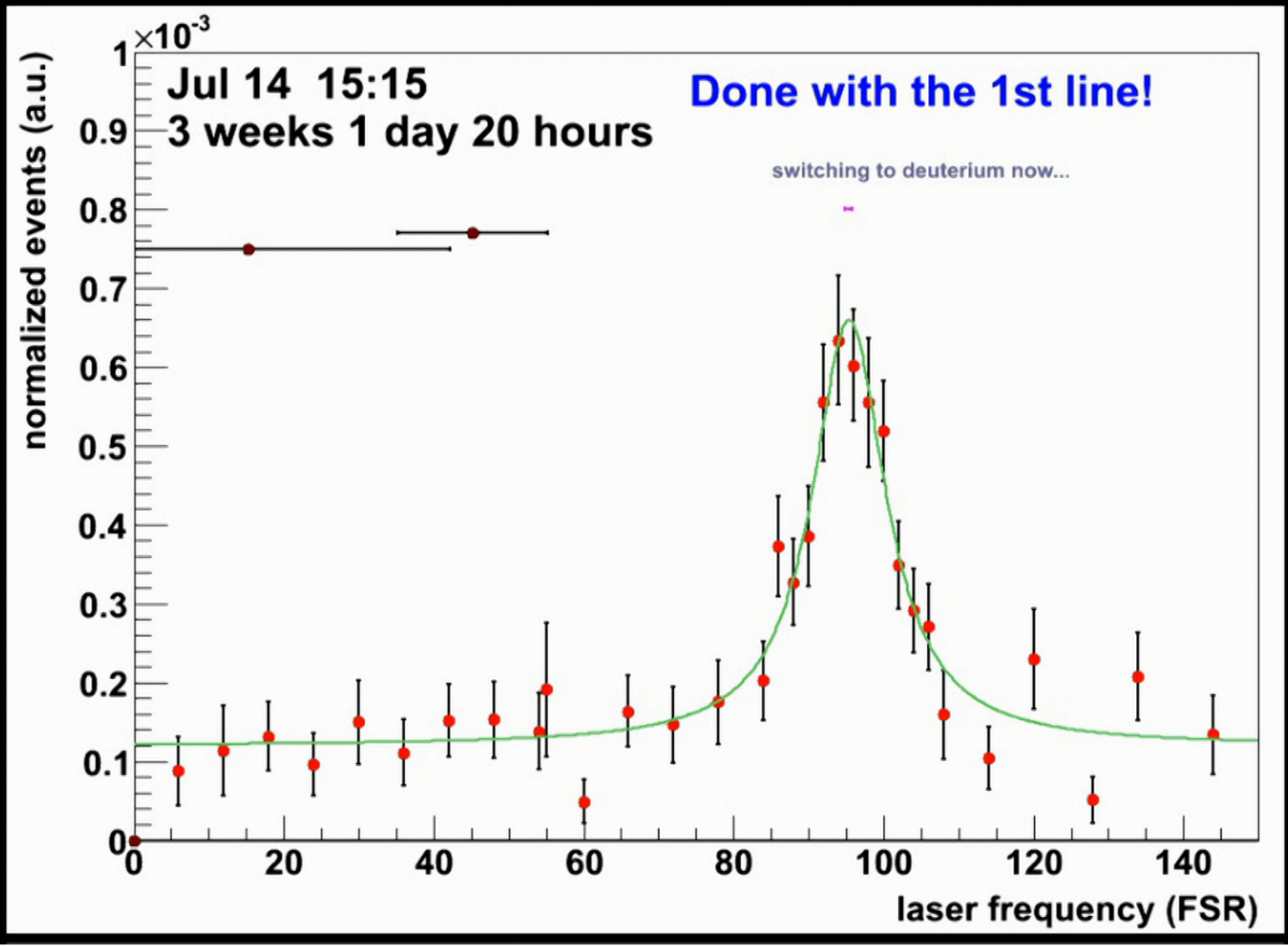

×10^-3
Jul 6 22:00
2 weeks 1 day 3 hours
normalized events (a.u.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)


Jul 7 18:45
2 weeks 1 day 23 hours
refill LHe
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

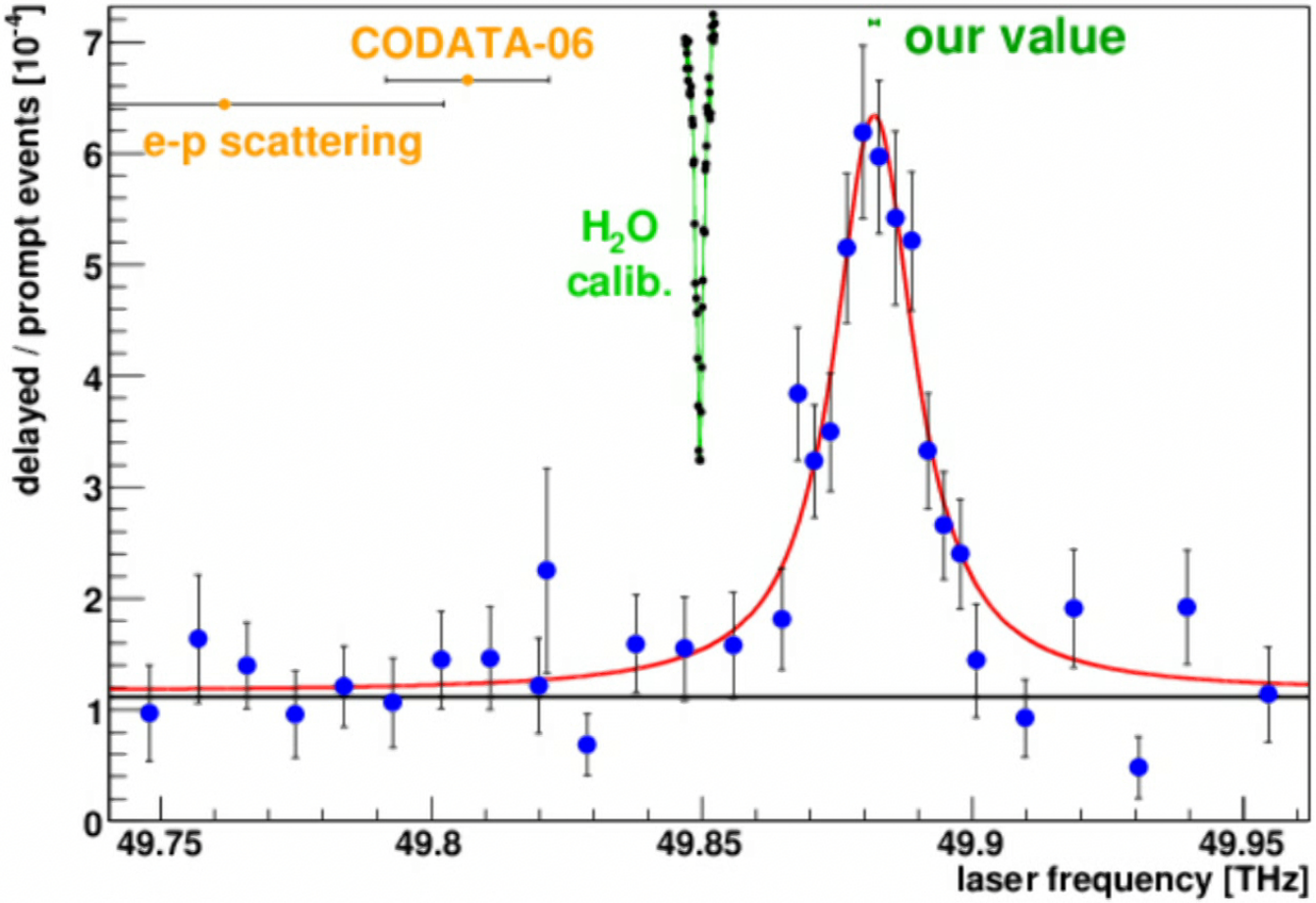

×10^-3
Jul 8 11:45
2 weeks 2 days 16 hours
normalized events (a.u.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)


Jul 9 8:00
2 weeks 3 days 13 hours
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140


Jul 11 6:45
2 weeks 5 days 11 hours
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

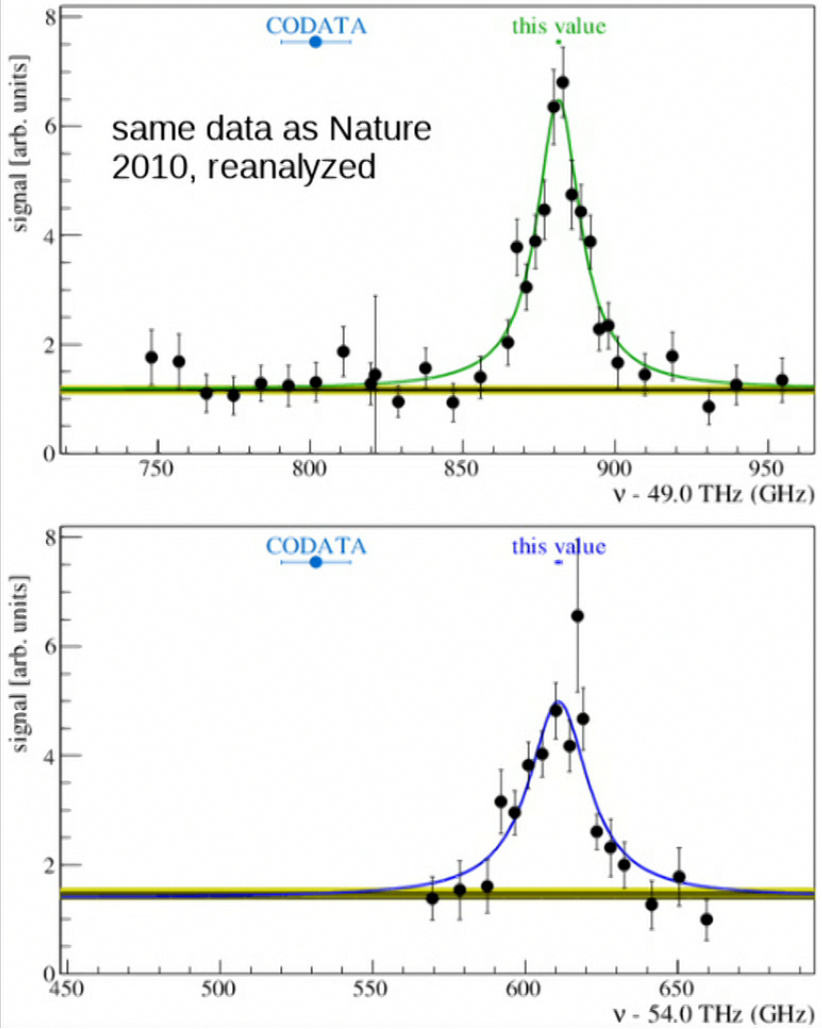

Jul 14 15:15
3 weeks 1 day 20 hours
Done with the 1st line!
switching to deuterium now...
normalized events (a.u.)
×10^-3
laser frequency (FSR)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

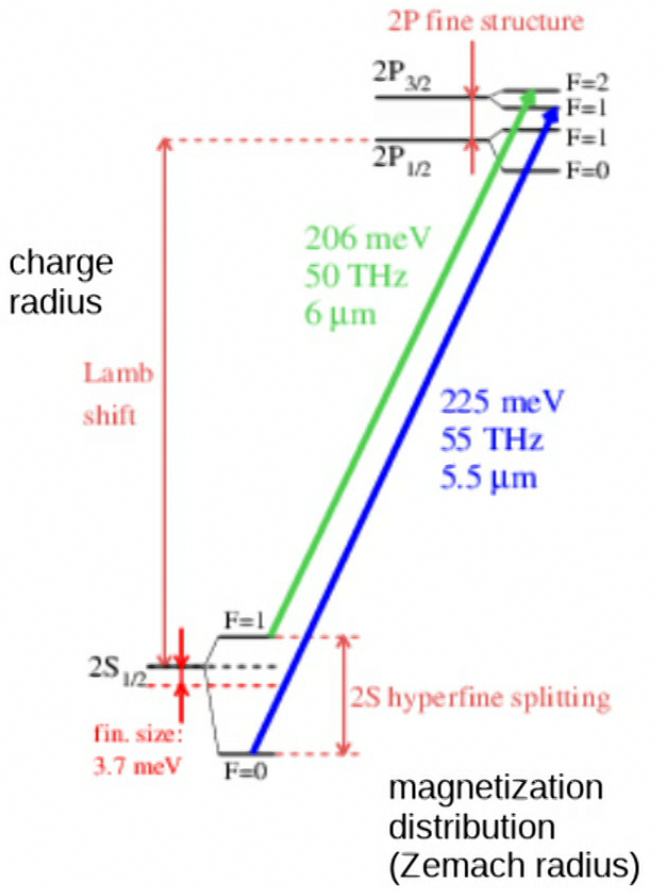
Resonance in muonic hydrogen



Pohl et al. (CREMA Coll.), Nature 466, 213 (2010)

2 transitions in muonic H





Antognini et al. (CREMA Coll.), Science 339, 417 (2013)

Theory in muonic H

$$\Delta E_{Lamb} = 206.0336\ (15)\ meV_{QED} + 0.0332\ (20)\ meV_{TPE} - 5.2275\ (10)\ meV/fm^2 * R_p^{\ 2}$$

Annals of Physics 331 (2013) 127–145

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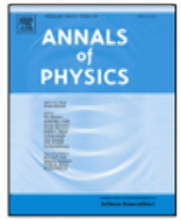


Theory of the 2S–2P Lamb shift and 2S hyperfine splitting in muonic hydrogen

Aldo Antognini [a,*], Franz Kottmann [a], François Biraben [b], Paul Indelicato [b], François Nez [b], Randolf Pohl [c]

[a] Institute for Particle Physics, ETH Zurich, 8093 Zurich, Switzerland
[b] Laboratoire Kastler Brossel, École Normale Supérieure, CNRS and Université P. et M. Curie, 75252 Paris, CEDEX 05, France
[c] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Our attempt to summarize all the original work by many theorists….

Theory I: “pure” QED

Table 1
All known radius-*independent* contributions to the Lamb shift in μp from different authors, and the one we selected. Values are in meV. The entry # in the first column refers to Table 1 in Ref. [13]. The "finite-size to relativistic recoil correction" (entry #18 in [13]), which depends on the proton structure, has been shifted to Table 2, together with the small terms #26 and #27, and the proton polarizability term #25. SE: self-energy, VP: vacuum polarization, LBL: light-by-light scattering, Rel: relativistic, NR: non-relativistic, RC: recoil correction.

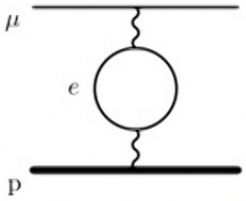
#	Contribution	Pachucki [10,11]	Nature [13]	Borie-v6 [79]	Indelicato [80]	Our choice	Ref.
1	NR one-loop electron VP (eVP)	205.0074					
2	Rel. corr. (Breit–Pauli)	0.0169[a]					
3	Rel. one-loop eVP		205.0282	205.0282	205.02821	205.02821	[80] Eq. (54)
19	Rel. RC to eVP, $\alpha(Z\alpha)^4$	(incl. in #2)[b]	−0.0041	−0.0041		−0.00208[c]	[77,78]
4	Two-loop eVP (Källén–Sabry)	1.5079	1.5081	1.5081	1.50810	1.50810	[80] Eq. (57)
5	One-loop eVP in 2-Coulomb lines $\alpha^2(Z\alpha)^5$	0.1509	0.1509	0.1507	0.15102	0.15102	[80] Eq. (60)
7	eVP corr. to Källén–Sabry	0.0023	0.00223	0.00223	0.00215	0.00215	[80] Eq. (62), [87]
6	NR three-loop eVP	0.0053	0.00529	0.00529		0.00529	[87,88]
9	Wichmann–Kroll, "1:3" LBL		−0.00103	−0.00102	−0.00102	−0.00102	[80] Eq. (64), [89]
10	Virtual Delbrück, "2:2" LBL		0.00135	0.00115		0.00115	[74,89]
New	"3:1" LBL			−0.00102		−0.00102	[89]
20	μSE and μVP	−0.6677	−0.66770	−0.66788	−0.66761	−0.66761	[80] Eqs. (72) + (76)
11	Muon SE corr. to eVP $\alpha^2(Z\alpha)^4$	−0.005(1)	−0.00500	−0.004924[d]		−0.00254	[85] Eq. (29a)[e]
12	eVP loop in self-energy $\alpha^2(Z\alpha)^4$	−0.001	−0.00150			[f]	[74,90–92]
21	Higher order corr. to μSE and μVP		−0.00169	−0.00171[g]		−0.00171	[86] Eq. (177)
13	Mixed eVP + μVP		0.00007	0.00007		0.00007	[74]
New	eVP and μVP in two Coulomb lines				0.00005	0.00005	[80] Eq. (78)
14	Hadronic VP $\alpha(Z\alpha)^4 m_r$	0.0113(3)	0.01077(38)	0.011(1)		0.01121(44)	[93–95]
15	Hadronic VP $\alpha(Z\alpha)^5 m_r$		0.000047			0.000047	[94,95]
16	Rad corr. to hadronic VP		−0.000015			−0.000015	[94,95]
17	Recoil corr.	0.0575	0.05750	0.0575	0.05747	0.05747	[80] Eq. (88)
22	Rel. RC $(Z\alpha)^5$	−0.045	−0.04497	−0.04497	−0.04497	−0.04497	[80] Eq. (88), [74]
23	Rel. RC $(Z\alpha)^6$	0.0003	0.00030		0.0002475	0.0002475	[80] Eq. (86)+Tab.II
New	Rad. (only eVP) RC $\alpha(Z\alpha)^5$					0.000136	[85] Eq. (64a)
24	Rad. RC $\alpha(Z\alpha)^n$ (proton SE)	−0.0099	−0.00960	−0.0100		−0.01080(100)	[43][h] [74]
	Sum	206.0312	206.02915	206.02862		206.03339(109)	

Antognini, RP at al., Ann. Phys. (N.Y.) 331, 127 (2013)

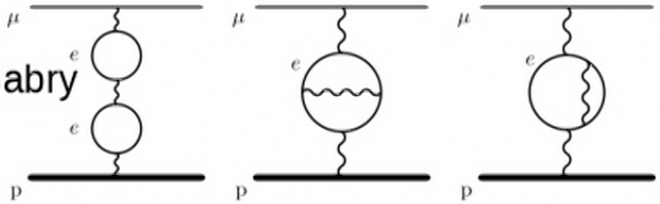
Theory in muonic H

ΔE_{Lamb} = 206.0336 (15) meV_{QED} + 0.0332 (20) meV_{TPE} – 5.2275 (10) $meV/fm^2 * R_p^2$

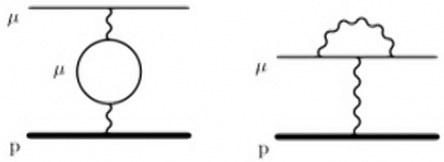
Uehling



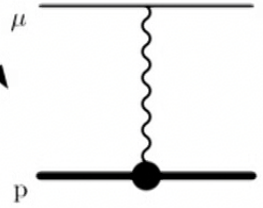
Källen-Sabry



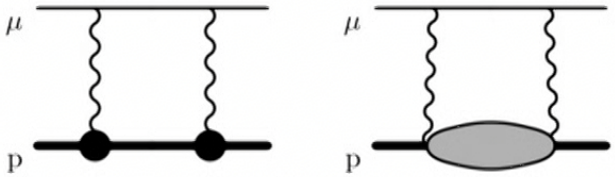
Muon SE+VP



and 20+ more….



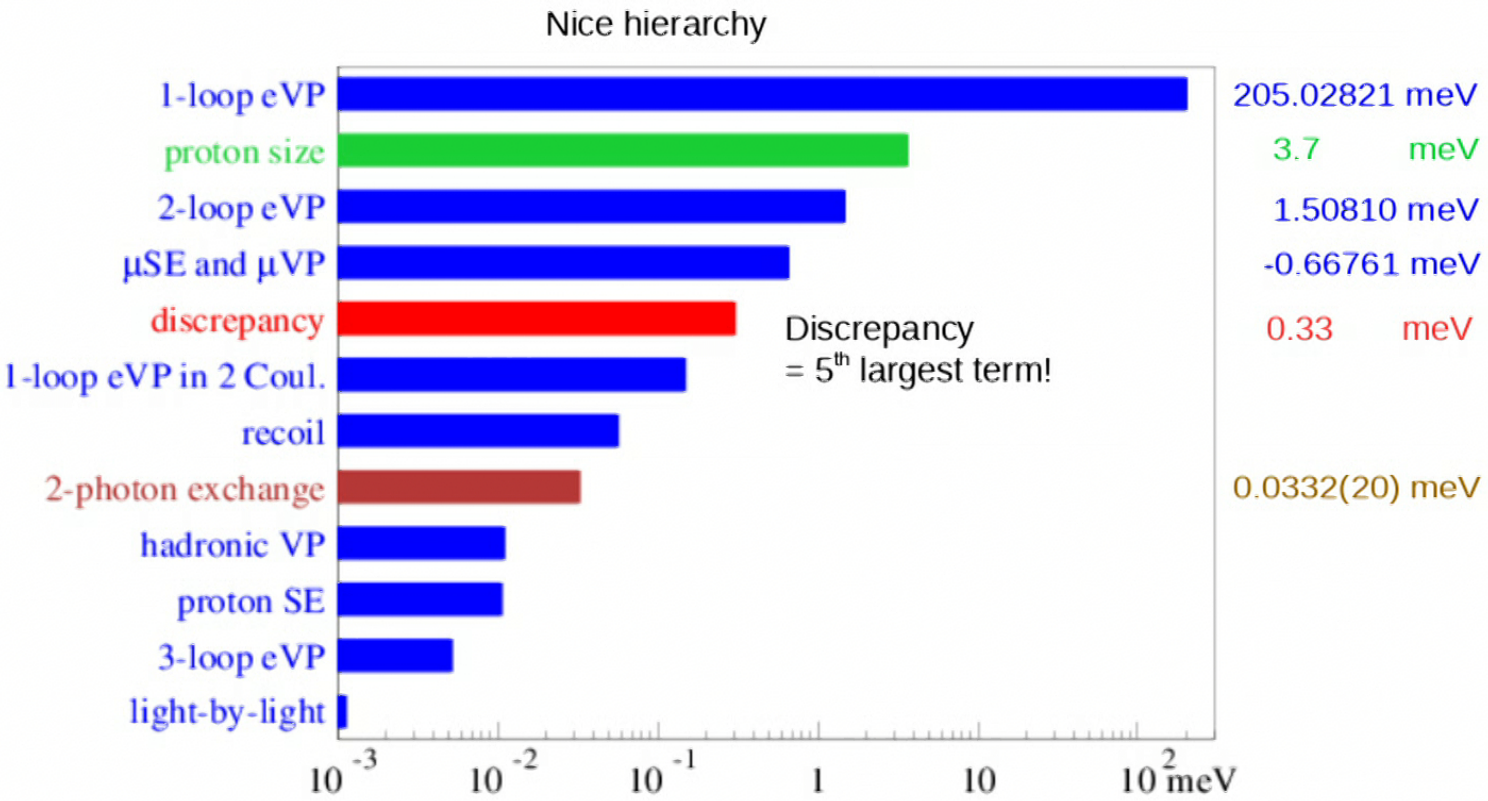
Proton form factor



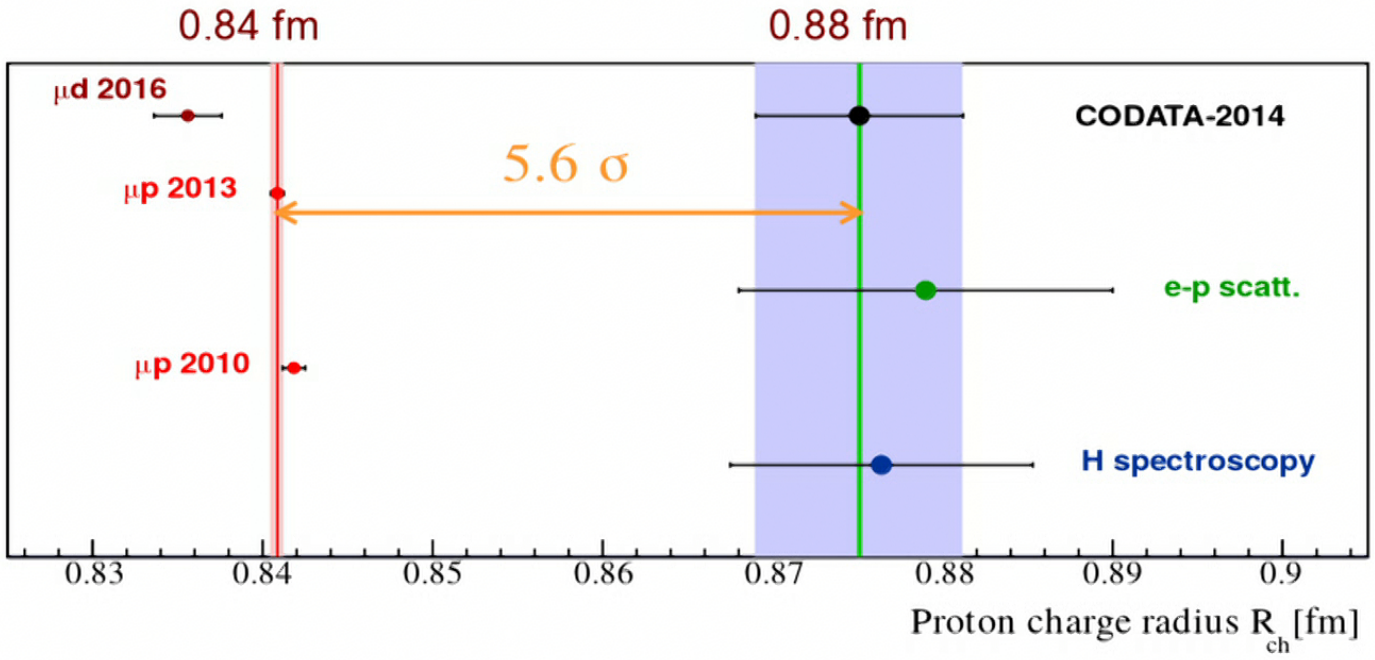
elastic and inelastic two-photon exchange
(Friar moment and polarizability)

Theory in muonic H

ΔE_{Lamb} = 206.0336 (15) meV$_{QED}$ + 0.0332 (20) meV$_{TPE}$ – 5.2275 (10) meV/fm^2 * R_p^2



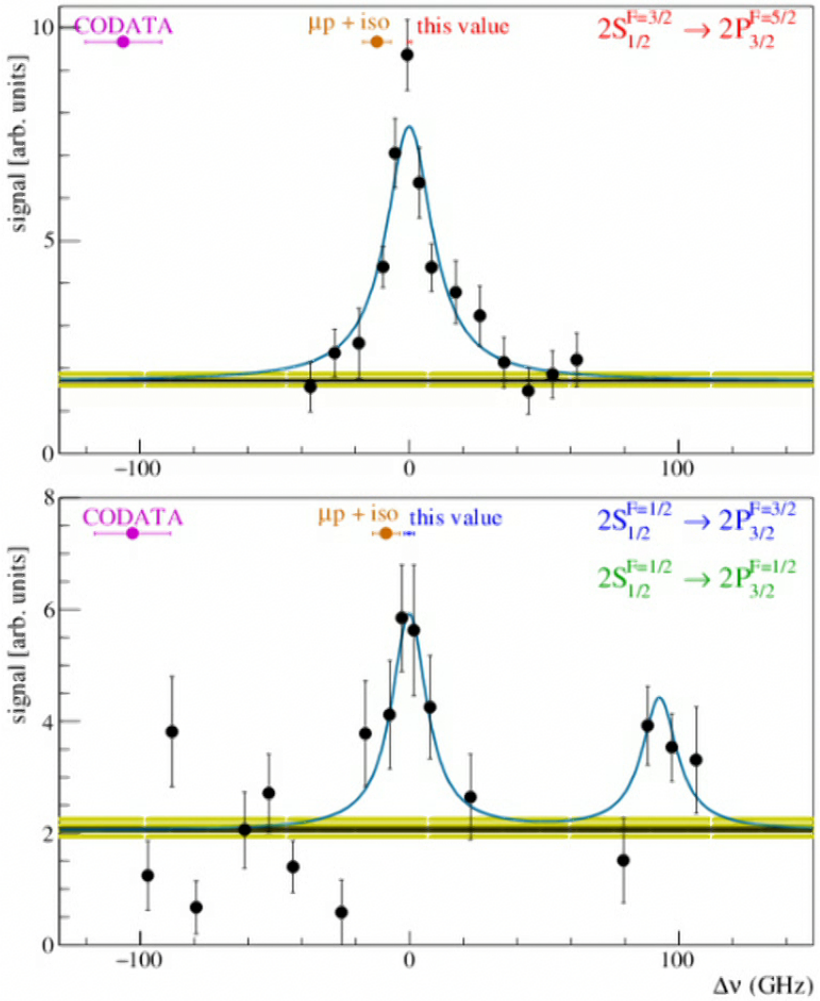
Muonic Hydrogen

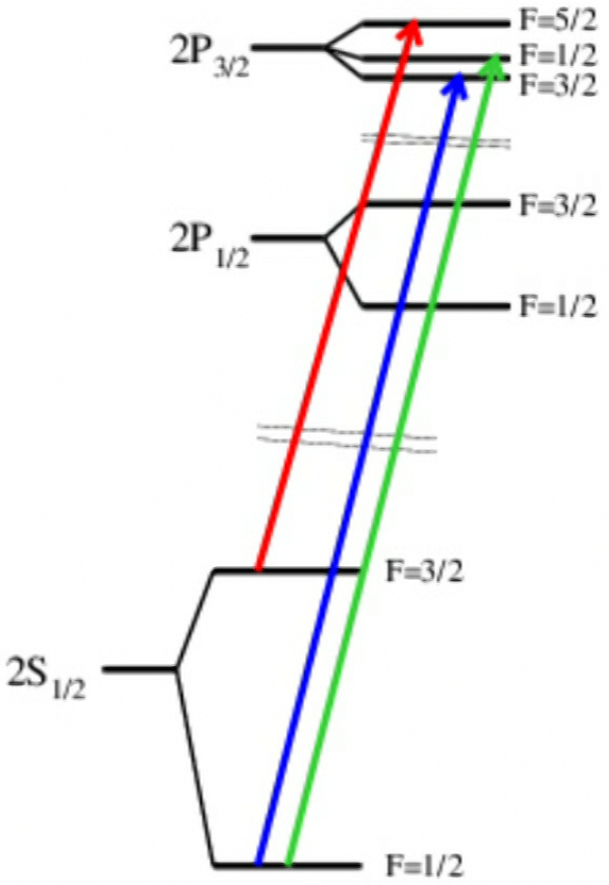


muonic hydrogen: 0.8409 ± 0.0004 fm
electronic hydrogen: 0.876 ± 0.008 fm
electron scattering 0.879 ± 0.011 fm

20x more precise

2.5 transitions in muonic D





Pohl et al. (CREMA Coll.), Science 353, 669 (2016)

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)\ meV_{QED} + 1.7150\ (\mathbf{230})\ meV_{TPE} - 6.1103\ (3)\ meV/fm^2 * \mathbf{R_d^2}$$

$$\Delta E^{\mu H}_{Lamb} = 206.0336\ (15)\ meV_{QED} + 0.0332\ (\ 20)\ meV_{TPE} - 5.2275\ (10)\ meV/fm^2 * \mathbf{R_p^2}$$

Annals of Physics 331 (2013) 127–145

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Theory of the 2S–2P Lamb shift and 2
splitting in muonic hydrogen

Aldo Antognini [a,*], Franz Kottmann [a], François
François Nez [b], Randolf Pohl [c]

[a] Institute for Particle Physics, ETH Zurich, 8093 Zurich, Switzerland
[b] Laboratoire Kastler Brossel, École Normale Supérieure, CNRS and Université P.
[c] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Annals of Physics 366 (2016) 168–196

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ELSEVIER

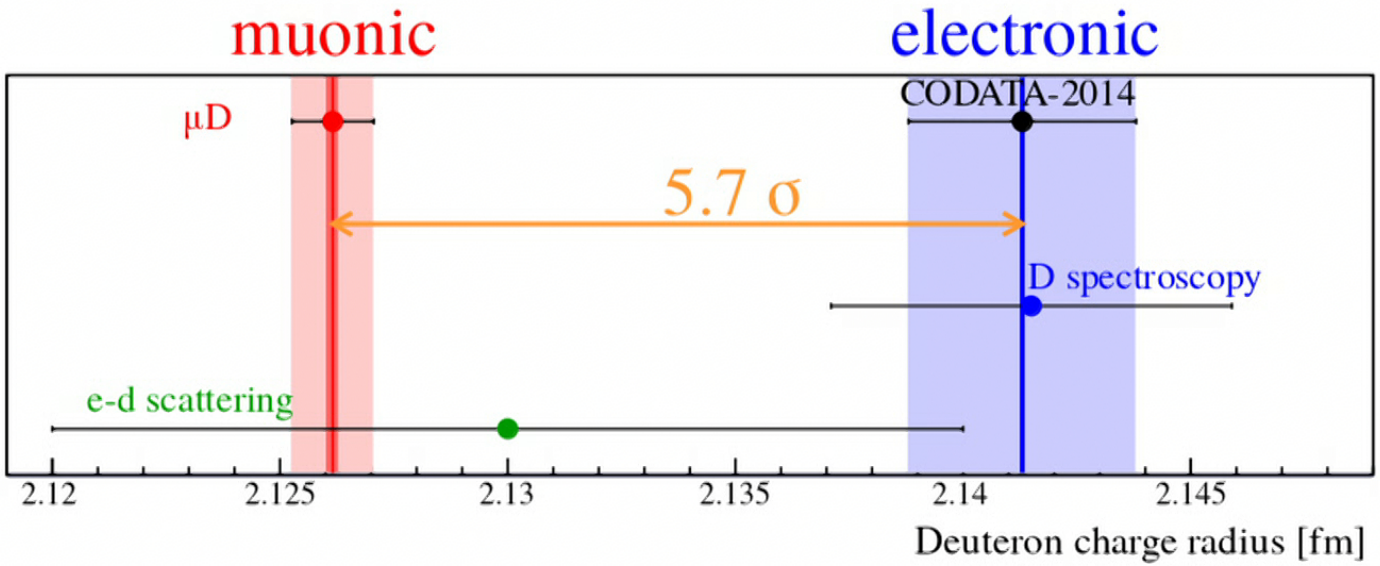
Theory of the $n = 2$ levels in muonic deuterium

Julian J. Krauth [a,*], Marc Diepold [a], Beatrice Franke [a],
Aldo Antognini [b,c], Franz Kottmann [b], Randolf Pohl [a]

Summarizes original work by: Bacca, Barnea, Birse, Borie, Carlson, Eides, Faustov, Friar, Gorchtein, Hernandez, Ivanov, Jentschura, Ji, Karshenboim, Korzinin, Krutov, Martynenko, McGovern, Nevo~Dinur, Pachucki, Shelyuto, Sick, Vanderhaeghen, et al.

Newer work: Pachucki et al., PRA 97, 062511 (2018), Hernandez et al., PLB 778, 377 (2018)

Muonic Deuterium



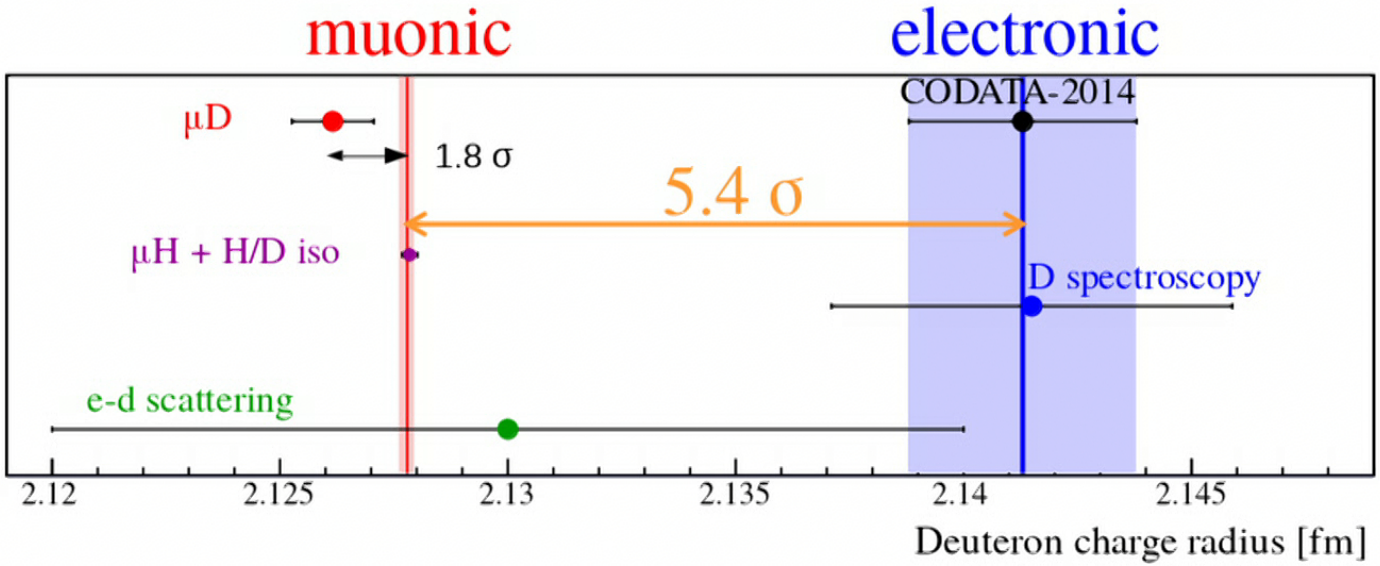
μD: 2.12616 $(13)_{exp}$ $(89)_{theo}$ fm (theo = nucl. polarizability)

CODATA-2014: 2.1**4**130 (250) fm

RP et al. (CREMA Coll.), Science 353, 559 (2016)

Krauth, RP at al., Ann. Phys. (N.Y.) 366, 168 (2016)
+ Pachucki et al., PRA 97, 062511 (2018)
+ Hernandez et al., PLB 778, 377 (2018)

Muonic Deuterium



μD: 2.12616 $(13)_{exp}$ $(89)_{theo}$ fm (theo = nucl. polarizability)

μH + H/D(1S-2S): 2.12785 (17) fm

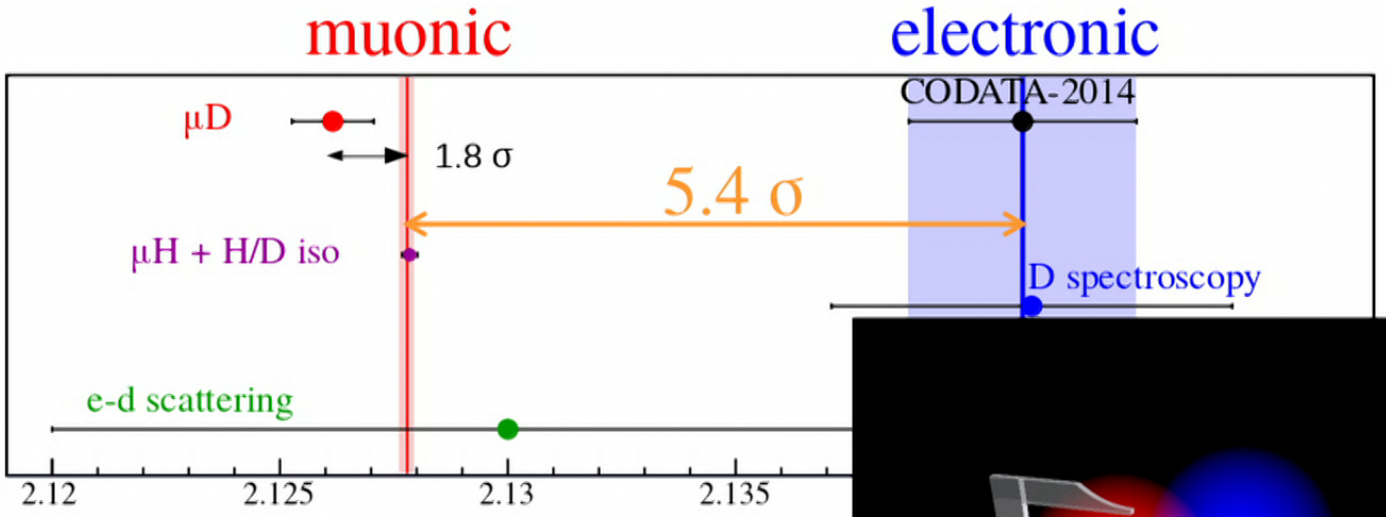
CODATA-2014: 2.14130 (250) fm

H/D 1S-2S isotope shift:
$r_d^2 - r_p^2 = 3.82070(31)$ fm²

Pachucki et al., PRA 97, 062511 (2018)

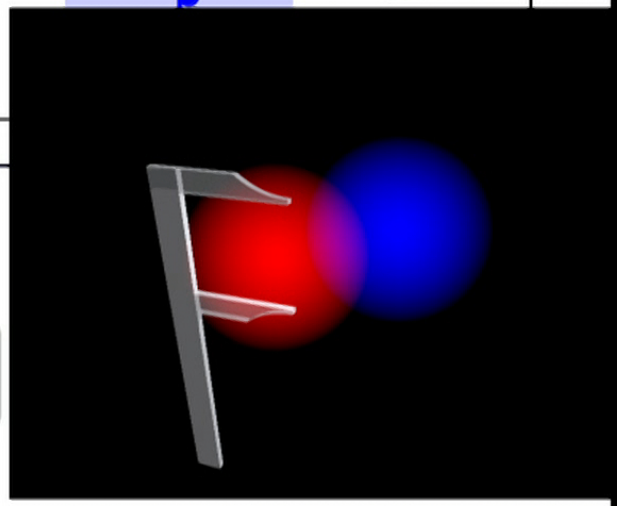
H/D 1S-2S. Parthey, RP et al. (MPQ Garching), PRL 104, 233001 (2010)
PRL 107, 203001 (2011)

Muonic Deuterium



Deuteron is CONSISTENTLY smaller!

$$R_d^2 = R^2_{struct} + R_p^2 + R_n^2 \ (+ DF)$$



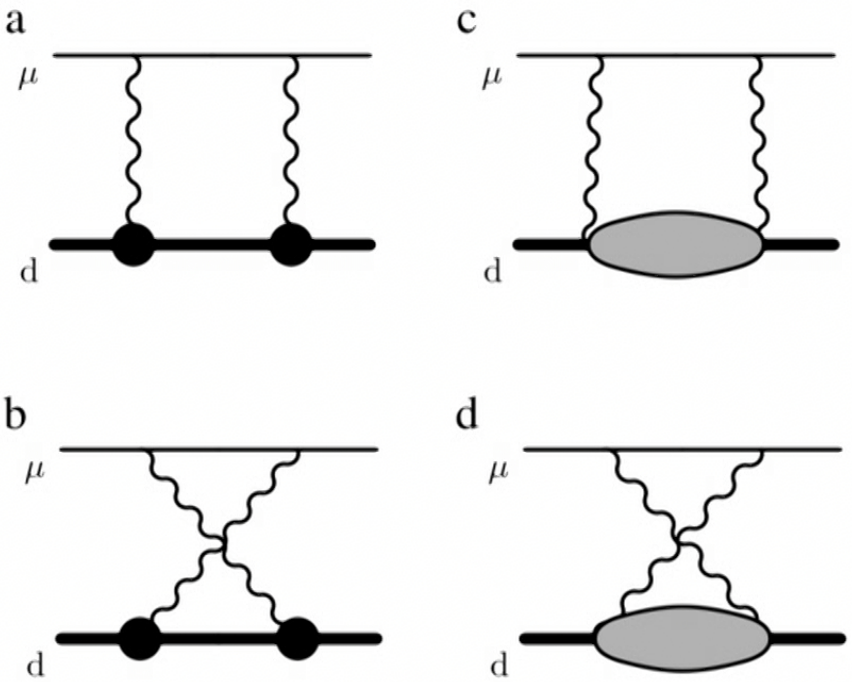
Pohl et al. (CREMA), Science 353, 669 (2016)

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)\ meV_{QED} + 1.7150\ (\mathbf{230})\ meV_{TPE} - 6.1103\ (3)\ meV/fm^2 * \mathbf{R_d^2}$$

Krauth, RP at al., Ann. Phys. (N.Y.) 366, 168 (2016)
+ Pachucki et al., PRA 97, 062511 (2018)
+ Hernandez et al., PLB 778, 377 (2018)

Two-photon nuclear structure contributions to the Lamb shift in muonic deuterium.



Theory in muonic D

$$\Delta E^{\mu D}_{\text{Lamb}} = 228.7854\ (13)\ \text{meV}_{\text{QED}} + 1.7150\ (\mathbf{230})\ \text{meV}_{\text{TPE}} - 6.1103\ (3)\ \text{meV/fm}^2 * R_d^{\,2}$$

Nuclear structure contributions to the Lamb shift in muonic deuterium.

Item	Contribution	Pachucki [55] AV18		Friar [60] ZRA		Hernandez *et al.* [58] AV18	N^{3}LO [†]		Pach.& Wienczek [65] AV18		Carlson *et al.* [64] data	Our choice value	source
	Source	1		2		3	4		5		6		
p1	Dipole	1.910	$\delta_0 E$	1.925	Leading C1	1.907	1.926	$\delta^{(0)}_{D1}$	1.910	$\delta_0 E$		1.9165 ± 0.0095	3-5
p2	Rel. corr. to p1, longitudinal part	−0.035	$\delta_R E$	−0.037	Subleading C1	−0.029	−0.030	$\delta^{(0)}_L$	−0.026	$\delta_R E$			
p3	Rel. corr. to p1, transverse part					0.012	0.013	$\delta^{(0)}_T$					
p4	Rel. corr. to p1, higher-order								0.004	$\delta_{HO} E$			
sum	Total rel. corr., p2+p3+p4	−0.035		−0.037		−0.017	−0.017		−0.022			−0.0195 ± 0.0025	3-5
p5	Coulomb distortion, leading	−0.255	$\delta_{C1} E$						−0.255	$\delta_{C1} E$			
p6	Coul. distortion, next order	−0.006	$\delta_{C2} E$						−0.006	$\delta_{C2} E$			
sum	Total Coulomb distortion, p5+p6	−0.261				−0.262	−0.264	$\delta^{(0)}_C$	−0.261			−0.2625 ± 0.0015	3-5
p7	El. monopole excitation	−0.045	$\delta_{Q0} E$	−0.042	C0	−0.042	−0.041	$\delta^{(2)}_{R2}$	−0.042	$\delta_{Q0} E$			
p8	El. dipole excitation	0.151	$\delta_{Q1} E$	0.137	Retarded C1	0.139	0.140	$\delta^{(2)}_{D1D3}$	0.139	$\delta_{Q1} E$			
p9	El. quadrupole excitation	−0.066	$\delta_{Q2} E$	−0.061	C2	−0.061	−0.061	$\delta^{(2)}_Q$	−0.061	$\delta_{Q2} E$			
sum	Tot. nuclear excitation, p7+p8+p9	0.040		0.034	C0 + ret-C1 + C2	0.036	0.038		0.036			0.0360 ± 0.0020	2-5
p10	Magnetic	−0.008 [◇a]	$\delta_M E$	−0.011	M1	−0.008	−0.007	$\delta^{(0)}_M$	−0.008	$\delta_M E$		−0.0090 ± 0.0020	2-5
SUM_1	Total nuclear (corrected)	1.646		1.648 [b]		1.656	1.676		1.655			1.6615 ± 0.0103	
p11	Finite nucleon size			0.021	Retarded C1 f.s.	0.020 [◇c]	0.021 [◇c]	$\delta^{(2)}_{NS}$	0.020	$\delta_{FS} E$			
p12	n p charge correlation			−0.023	pn correl. f.s.	−0.017	−0.017	$\delta^{(1)}_{np}$	−0.018	$\delta_{FZ} E$			
sum	p11+p12			−0.002		0.003	0.004		0.002			0.0010 ± 0.0030	2-5
p13	Proton elastic 3rd Zemach moment	0.043(3)	$\delta_P E$	0.030	$\langle r^3 \rangle^{pp}_{(2)}$				0.043(3)	$\delta_P E$		0.0289 ± 0.0015	Eq.(13) [d]
p14	Proton inelastic polarizab.					0.027(2)		δ^N_{pol} [64]			0.028(2) ΔE^{hadr}	0.0280 ± 0.0020	6
p15	Neutron inelastic polarizab.								0.016(8)	$\delta_N E$			
p16	Proton & neutron subtraction term											−0.0098 ± 0.0098	Eq.(15) [e]
sum	Nucleon TPE, p13+p14+p15+p16	0.043(3)		0.030		0.027(2)			0.059(9)			0.0471 ± 0.0101	[f]
SUM_2	Total nucleon contrib.	0.043(3)		0.028		0.030(2)			0.061(9)			0.0476 ± 0.0105	
	Sum, published	1.680(16)		1.941(19)		1.690(20)			1.717(20)		2.011(740)		
	Sum, corrected			1.697(19) [g]		1.714(20) [h]			1.707(20) [i]		1.748(740) [j]	**1.7096 ± 0.0147**	

Krauth, RP at al., Ann. Phys. (N.Y.) 366, 168 (2016)

+ Pachucki et al., PRA 97, 062511 (2018)
+ Hernandez et al., PLB 778, 377 (2018)

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)\ meV_{QED} + 1.7150\ (\mathbf{230})\ meV_{TPE} - 6.1103\ (3)\ meV/fm^2 * \mathbf{R_d^2}$$

ΔE_{TPE} (theo) = 1.7150 +- 0.0230 meV (Hernandez et al., 2018)

vs. **+- 0.0034 meV experimental uncertainty**

(1) **charge radius**, using **calculated TPE**

r_d (μD) = 2.12616 (13) $_{exp}$ (89) $_{theo}$ fm vs.

r_d (CODATA-14) = 2.1**4**130 (250) fm

(2) **polarizability**, using **charge radius from isotope shift**

ΔE_{TPE} (theo) = 1.7150 (230) meV vs.

ΔE_{TPE} (exp) = 1.7591 (59) meV 4x more accurate, 1.8σ

Krauth et al. (2016) + Pachucki et al. (2018) + Hernandez et al. (2018)

Theory in muonic He-3

$$\Delta E^{\mu^3He}_{Lamb} = 1644.4820(149)_{QED} + 15.3000(\mathbf{5200})_{TPE} - 103.5184(10) * R_h^2\ /fm^2 \quad [meV]$$

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)_{QED} + 1.7150(\ 230)_{TPE} - 6.1103\ (\ 3) * R_d^2\ /fm^2 \quad [meV]$$

$$\Delta E^{\mu H}_{Lamb} = 206.0336\ (15)_{QED} + 0.0332(\ \ 20)_{TPE} - 5.2275(10)\ * R_p^2\ /fm^2 \quad [meV]$$

Annals of Physics 366 (2016) 168–196

Eur. Phys. J. D (2017) 71: 341
DOI: 10.1140/epjd/e2017-80296-1

THE EUROPEAN PHYSICAL JOURNAL D

Topical Review

ELSEVIER

Theory of the $n = 2$ levels in muonic helium-3 ions

Beatrice Franke[1,2,a], Julian J. Krauth[1,3,b], Aldo Antognini[4,5], Marc Diepold[1], Franz Kottmann[4], and Randolf Pohl[3,1,c]

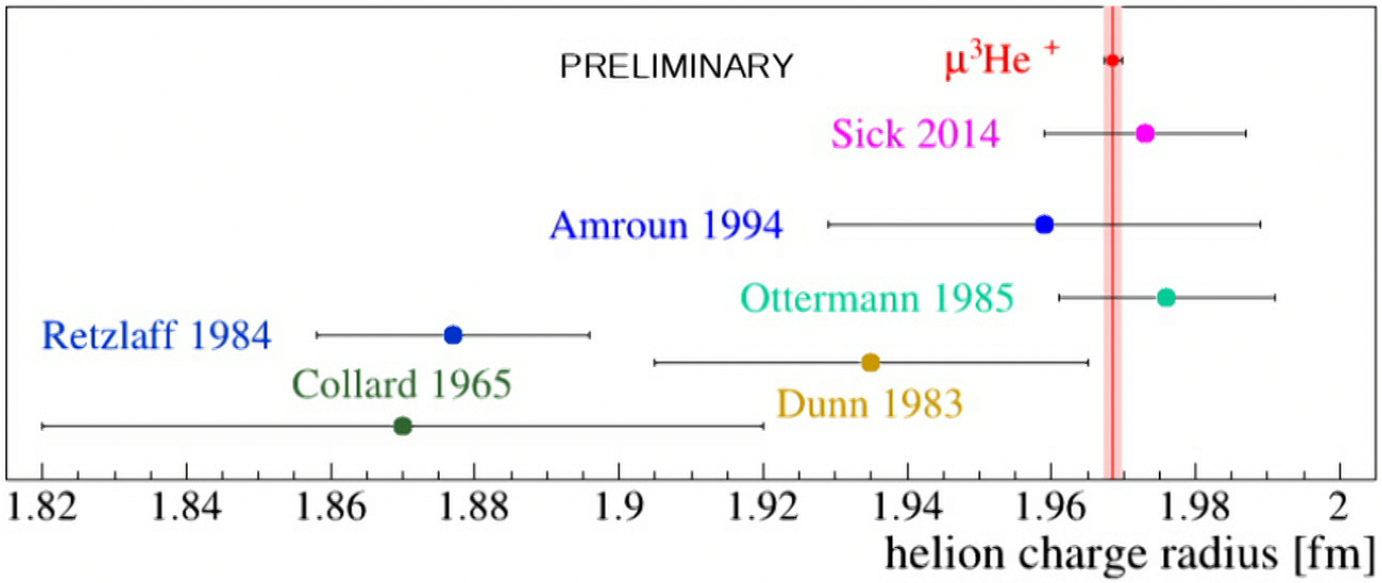
Theory of

Julian J. Krau
Aldo Antogn

[1] Max–Planck–Institut für Quantenoptik, 85748 Garching, Germany
[2] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada
[3] Johannes Gutenberg-Universität Mainz, QUANTUM, Institut für Physik & Exzellenzcluster PRISMA, 55099 Mainz, Germany
[4] Institute for Particle Physics and Astrophysics, ETH Zurich, 8093 Zurich, Switzerland
[5] Paul Scherrer Institute, 5232 Villigen, Switzerland

Three-photon contribution still missing (Pachucki et al., PRA 97, 052511 (2018))

Muonic Helium-3



prel. accuracy: exp +- 0.00012 fm, theo +- 0.00128 fm (nucl. polarizability)

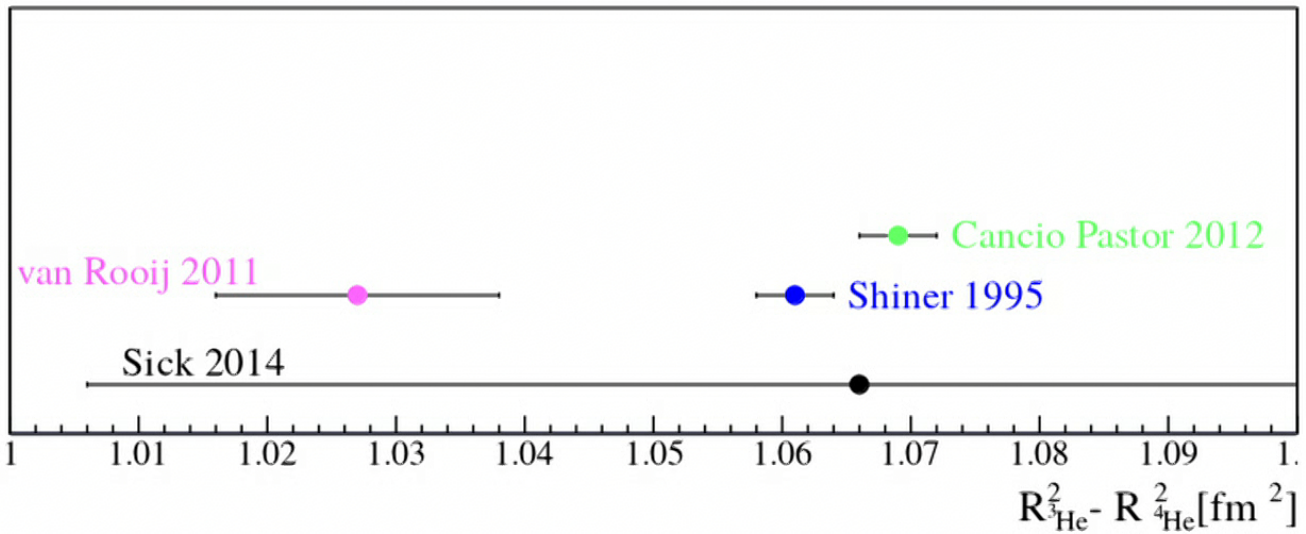
Theory: see Franke et al. EPJ D 71, 341 (2017) [1705.00352]

Muonic conclusions

- The proton radius is 0.84087 $(26)_{exp}$ $(29)_{theo}$ fm
- The deuteron radius is 2.12771 (22) fm
- both are **>5σ smaller** than CODATA values
- No discrepancy for the **absolute radii** of the helion and alpha particle
  (limited by e-scattering accuracy)
- **BUT: The helium isotope shift!!!**
- **(caveat: 3-photon, maybe more missing?)**

The ^{3}He – ^{4}He isotope shift

^{3}He / ^{4}He (squared) charge radius difference



Shiner et al., PRL 74, 3553 (1995)
vanRooij, Science 333, 196 (2011)
Cancio Pastor et al., PRL 108, 143001 (2012)

all evaluated with recent theory by Pachucki et al.

Sick, PRC 90, 064002 (2014)

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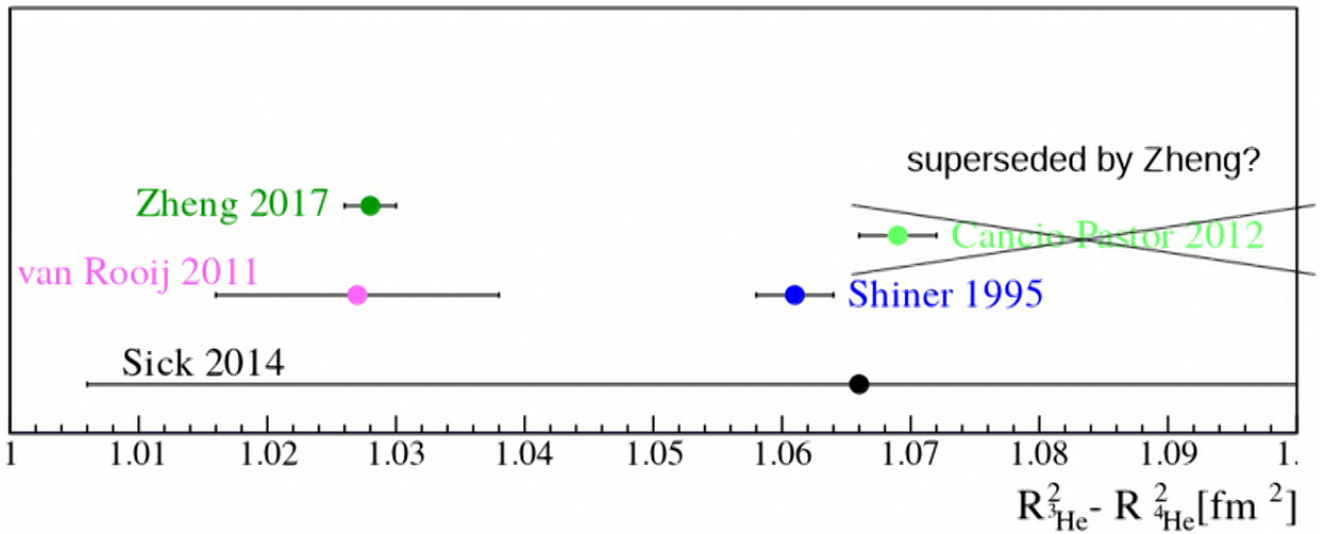

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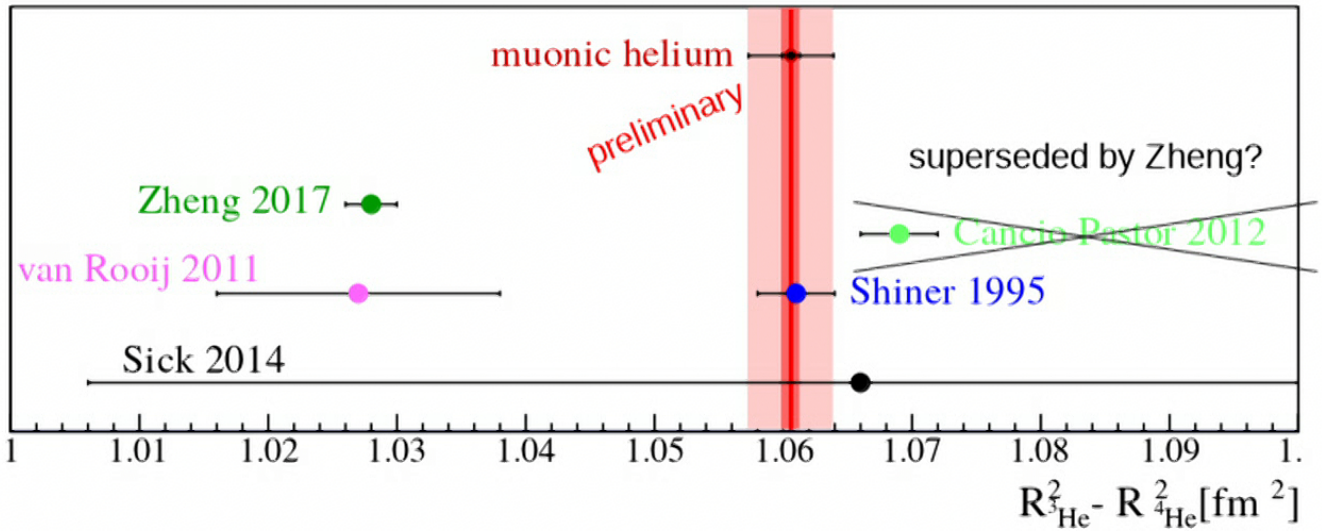


Another >5σ discrepancy?!

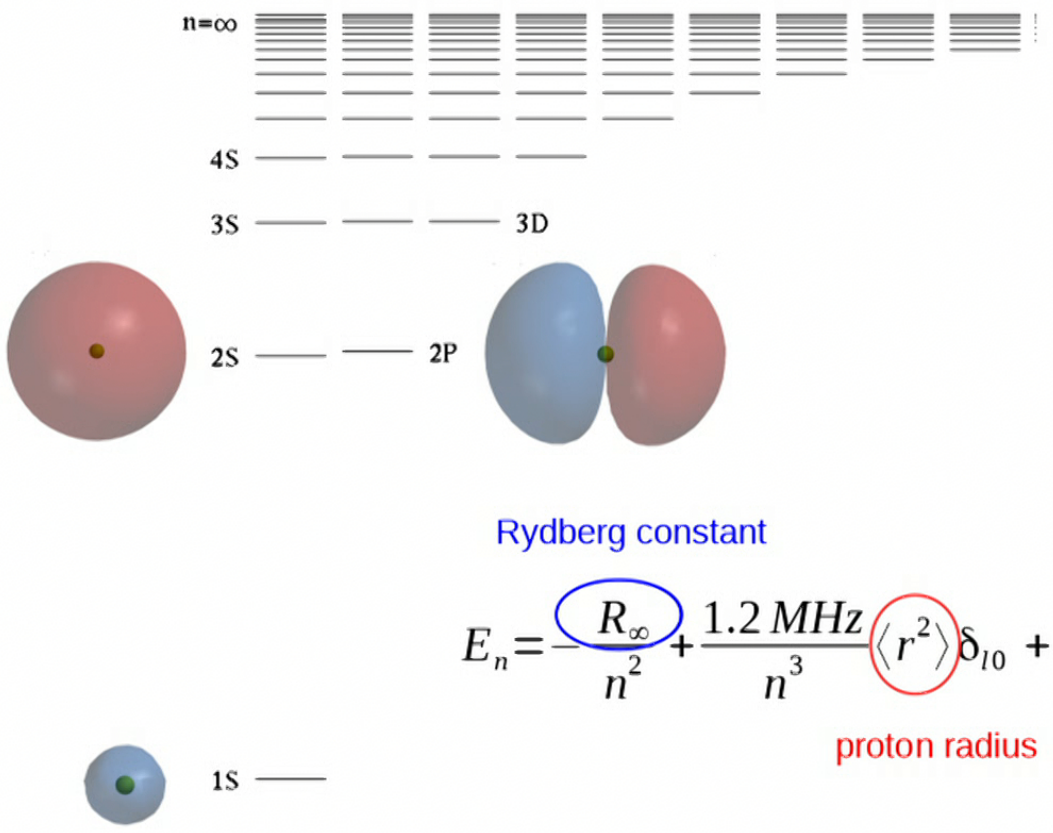
Part 2: The Rydberg constant

$$R_\infty = \frac{\alpha^2 m_e c}{2h}$$

- most accurately determined fundamental constant $u_r = 5.9 * 10^{-12}$
- corner stone of the CODATA LSA of fundamental constants
  links fine structure constant α, electron mass m_e, velocity of light c and Planck's constant *h*
- correlation coefficient with proton radius: 0.9891
  → The "proton radius puzzle" could be a "Rydberg puzzle"

- R_∞ is a "unit converter": atomic units → SI (Hertz)

Energy levels of hydrogen

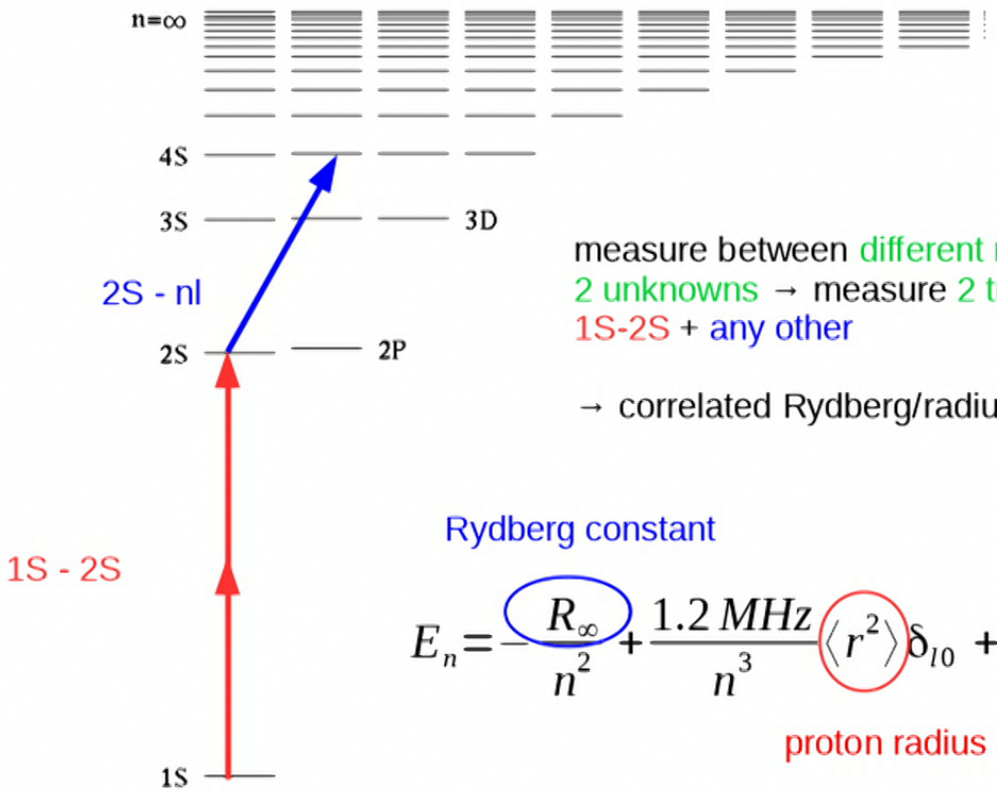


Rydberg constant

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

proton radius

Energy levels of hydrogen



measure between different **n**
2 unknowns → measure 2 transitions:
1S-2S + any other

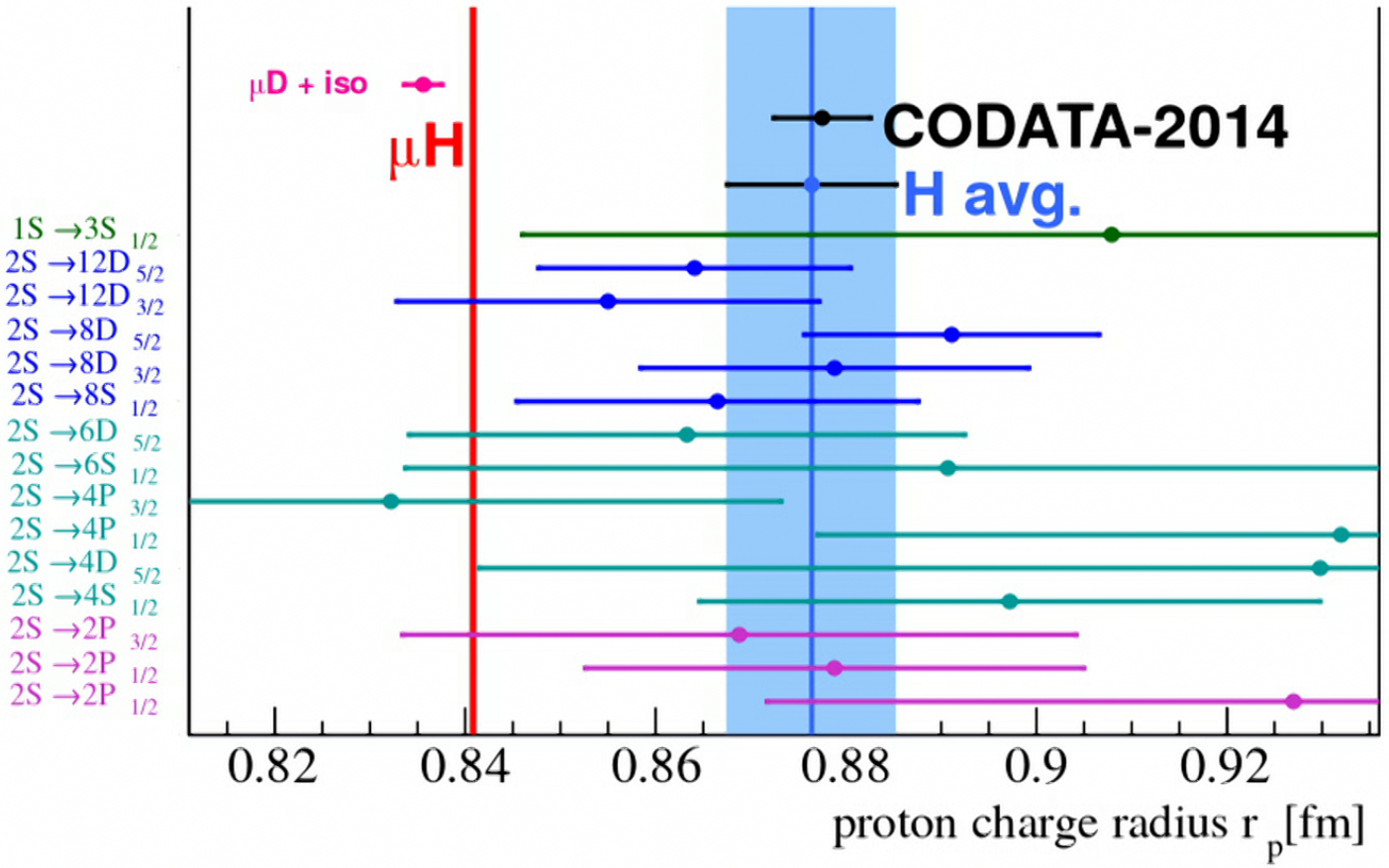
→ correlated Rydberg/radius pairs

Rydberg constant

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

proton radius

Rp from H spectroscopy



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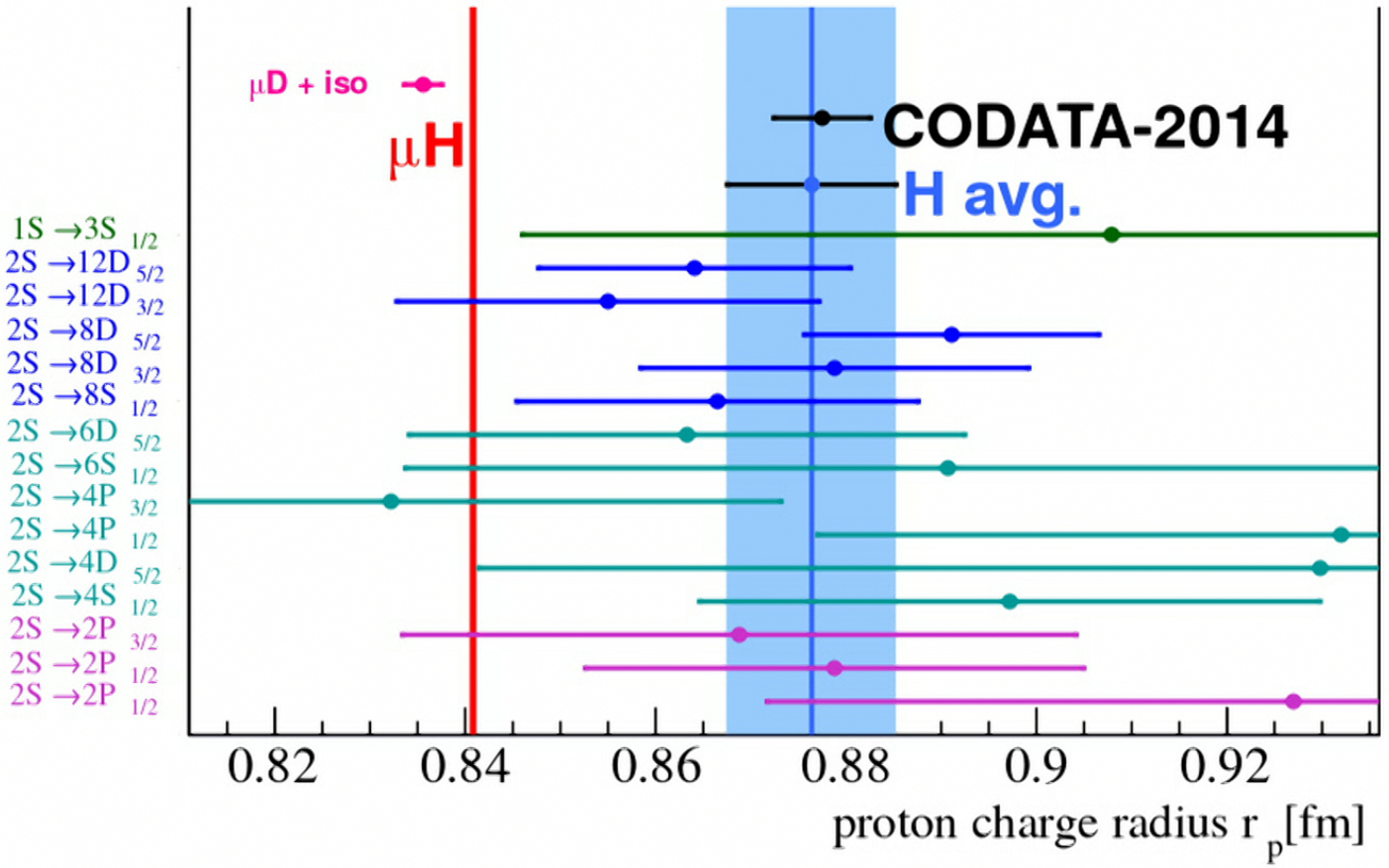
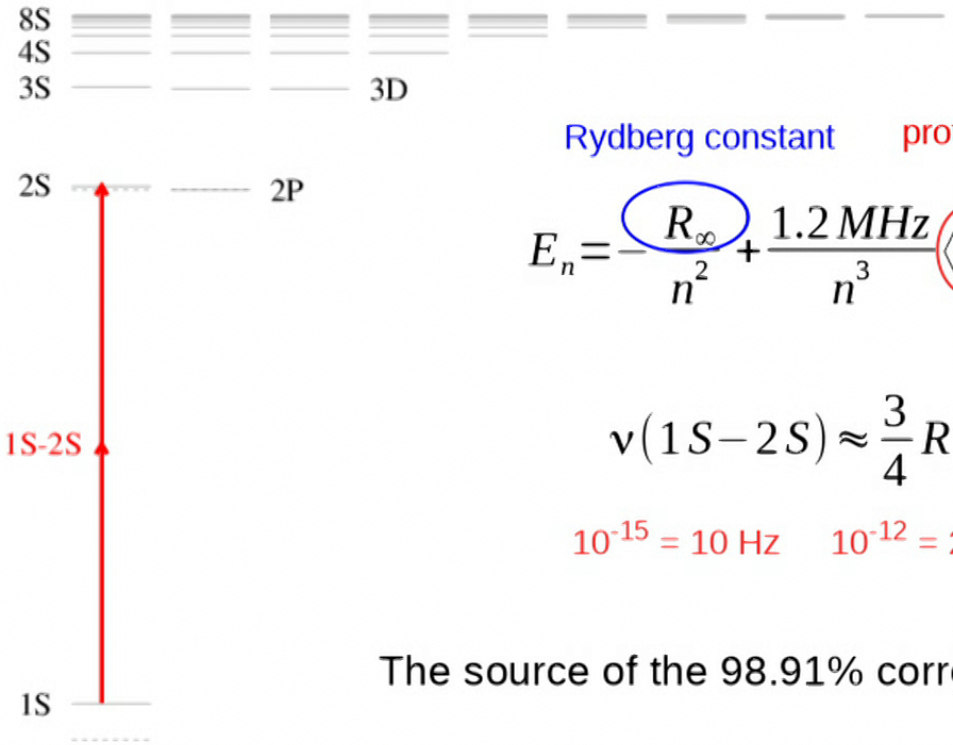


Correlation between R_∞ and R_p / R_d



Rydberg constant proton radius

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2 \rangle \delta_{l0} + \Delta(n,l,j)$$

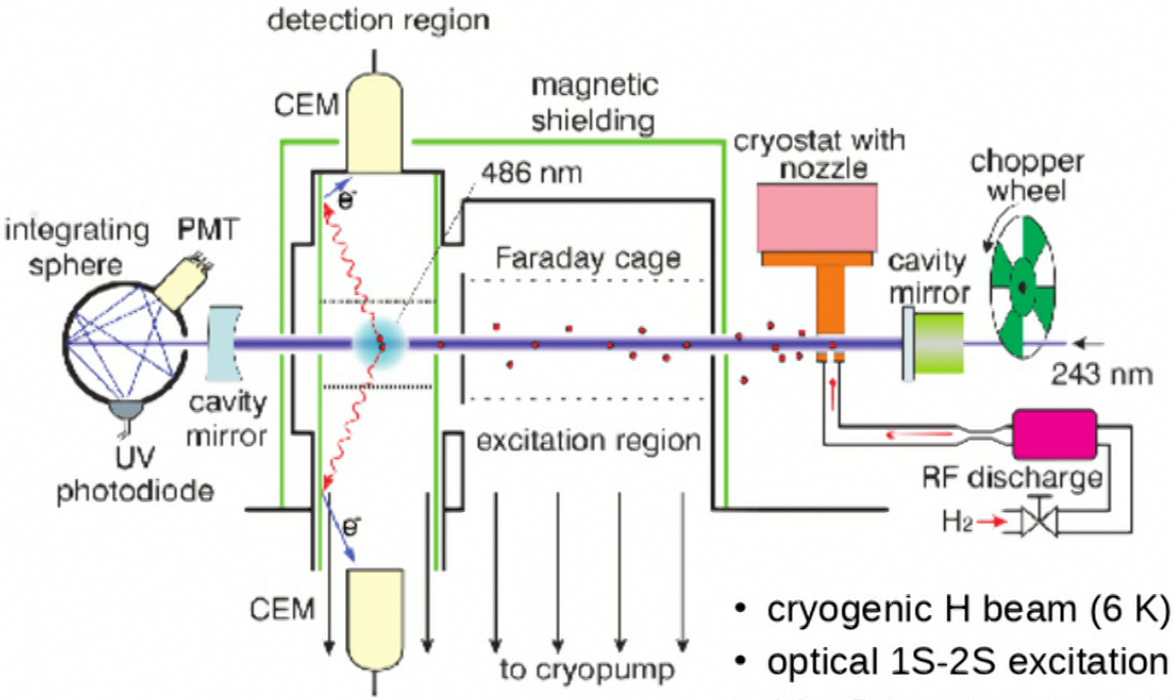
$$\nu(1S-2S) \approx \frac{3}{4}R_\infty - \frac{7}{8}E_{NS}$$

10^{-15} = 10 Hz 10^{-12} = 20 kHz

The source of the 98.91% correlation of R_∞ and R_p

1S-2S: Parthey, RP et al., PRL 107, 203001 (2011)

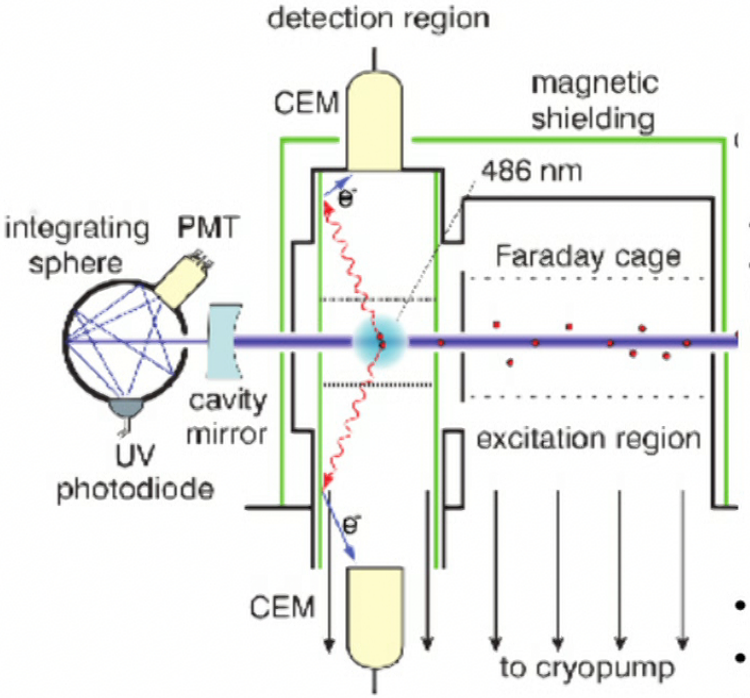
Garching H(2S-4P)

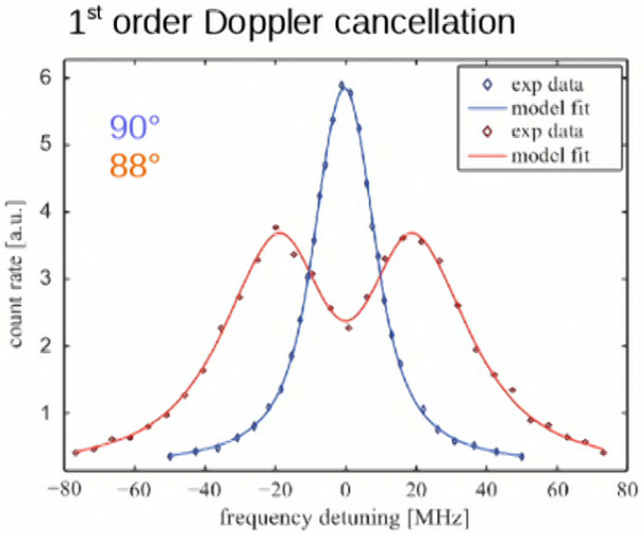


- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, F=0)
- 2S-4P transition is 1-photon: retroreflector
- split line to 10^{-4} !!!
- 2.3 kHz vs. 9 kHz PRP
- large systematics

Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

Garching H(2S-4P)





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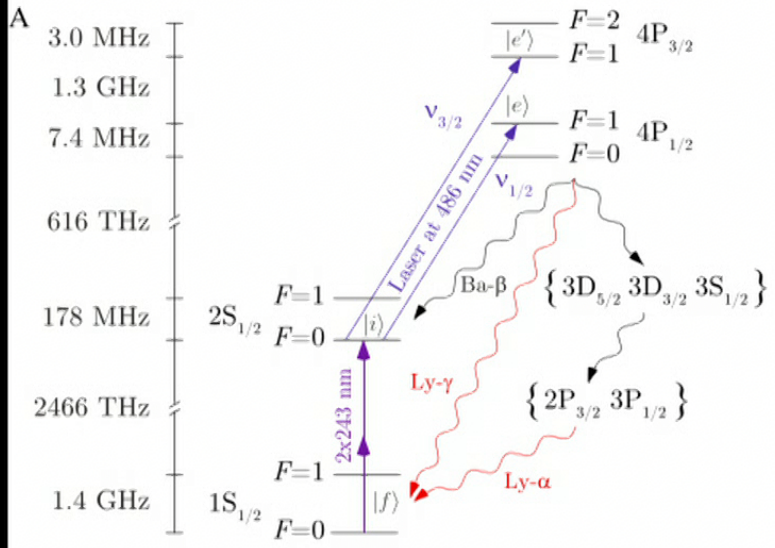
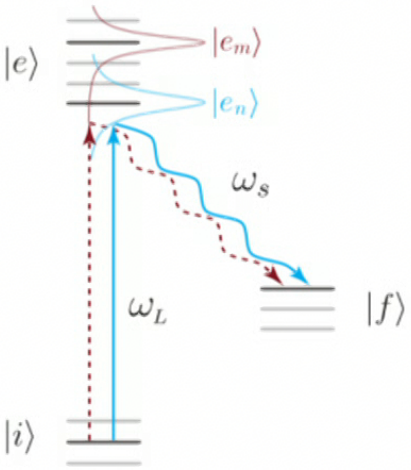
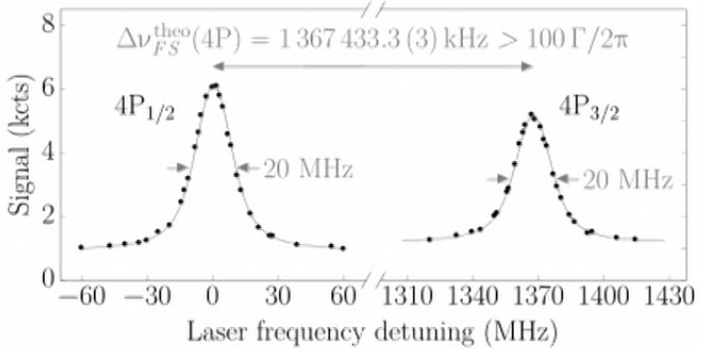
Quantum interference shifts





B



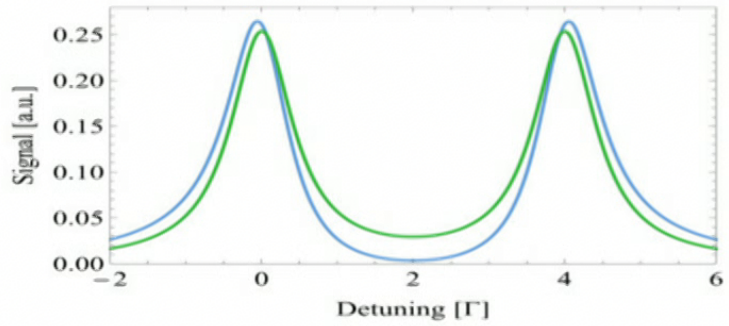
$$P(\omega) \propto \left| \frac{(\vec{d}_1 \vec{E}_0)\vec{d}_1}{\omega_1 - \omega_L + i\gamma_1/2} + \frac{(\vec{d}_2 \vec{E}_0)\vec{d}_2 e^{i\Delta\Phi}}{\omega_2 - \omega_L + i\gamma_2/2} \right|^2$$

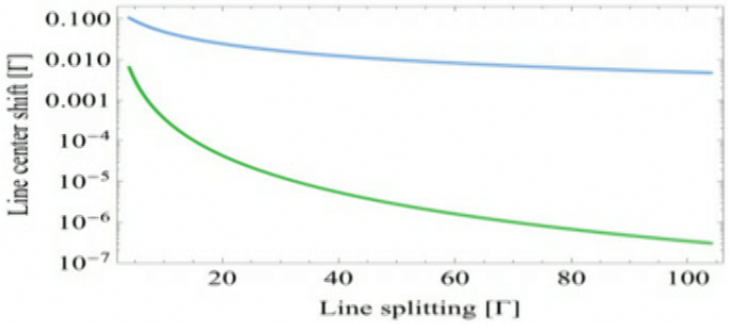
= Lorentzian(1) + Lorentzian(2)

+ cross-term (QI)

see
Horbatsch, Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011); PRA 86 040501 (2012)
Sansonetti et al., PRL 107, 021001 (2011)
Brown et al., PRA 87, 032504 (2013)

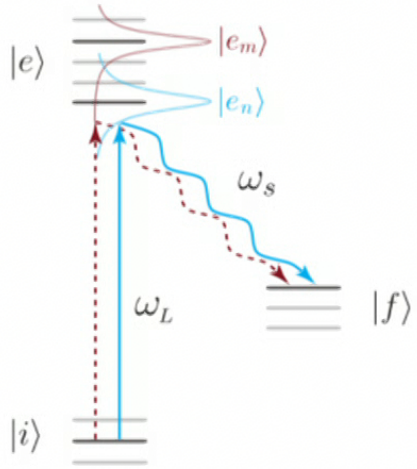
Quantum interference shifts





Fitting this with 2 Lorentzians creates

line shifts



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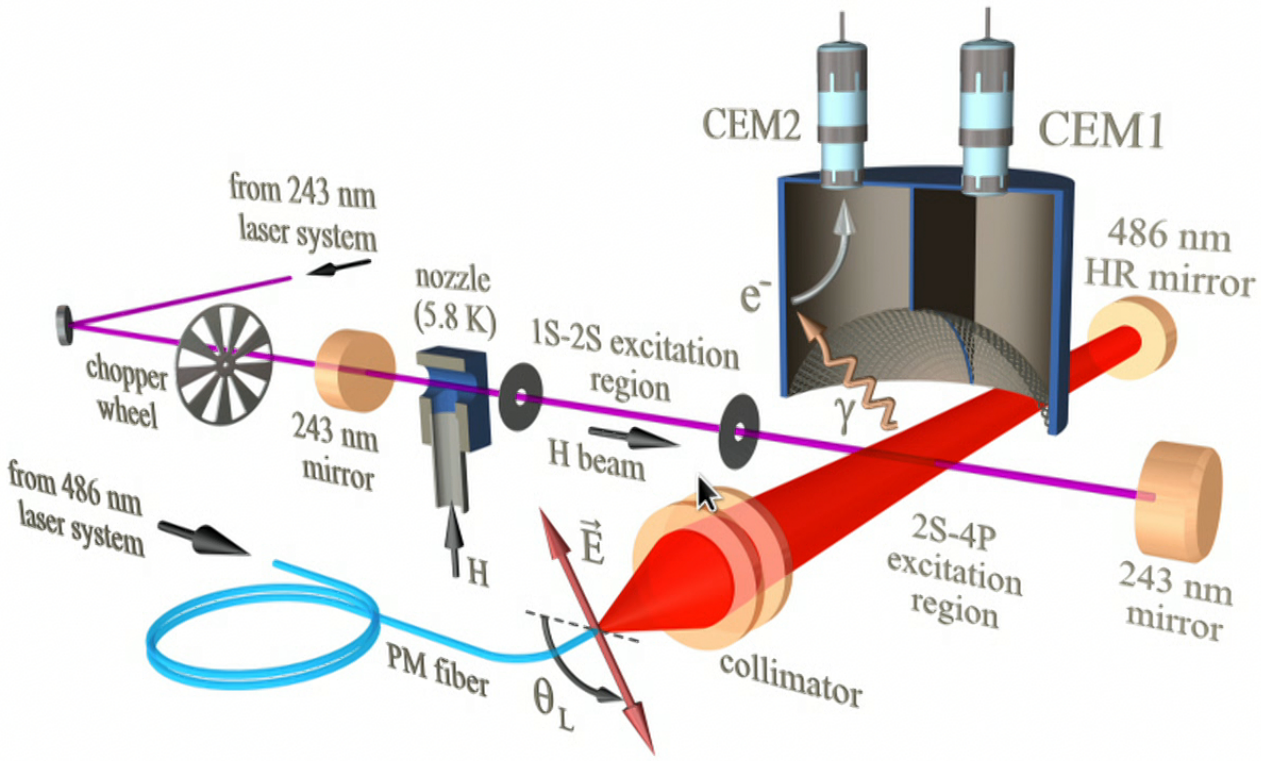
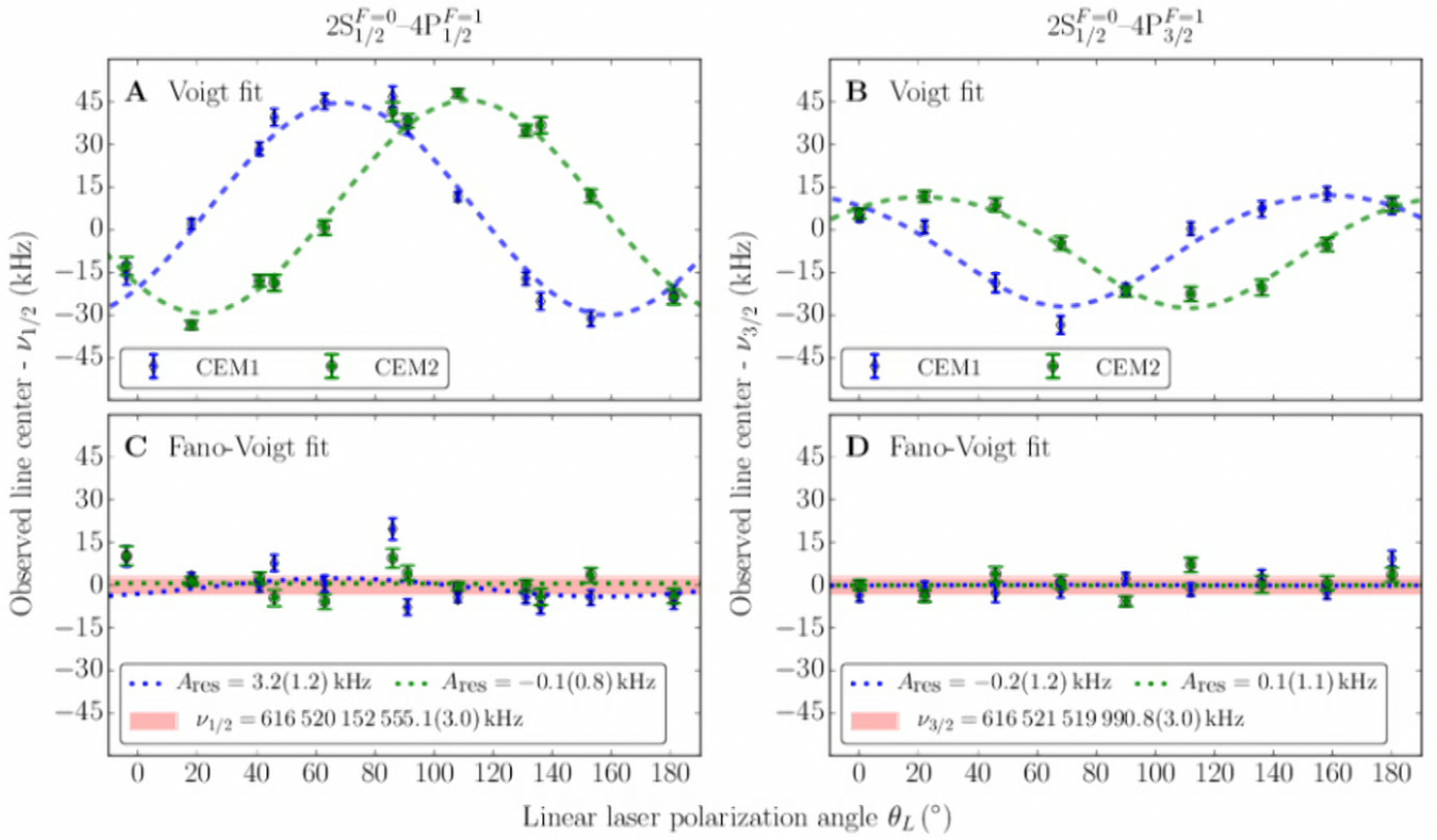
Studying QI in 2S-4P

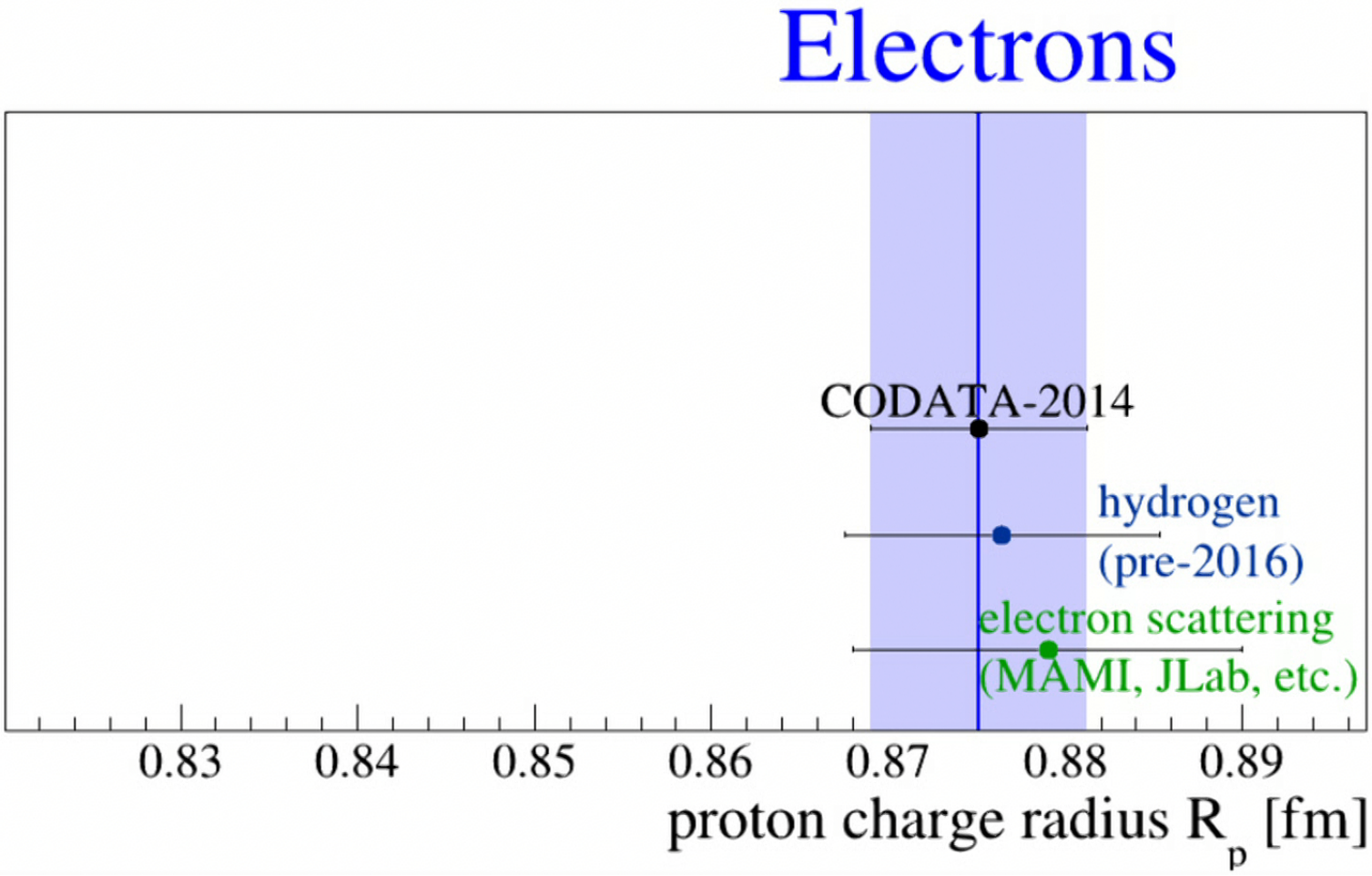


QI in hydrogen ($\Delta = 100\ \Gamma$)

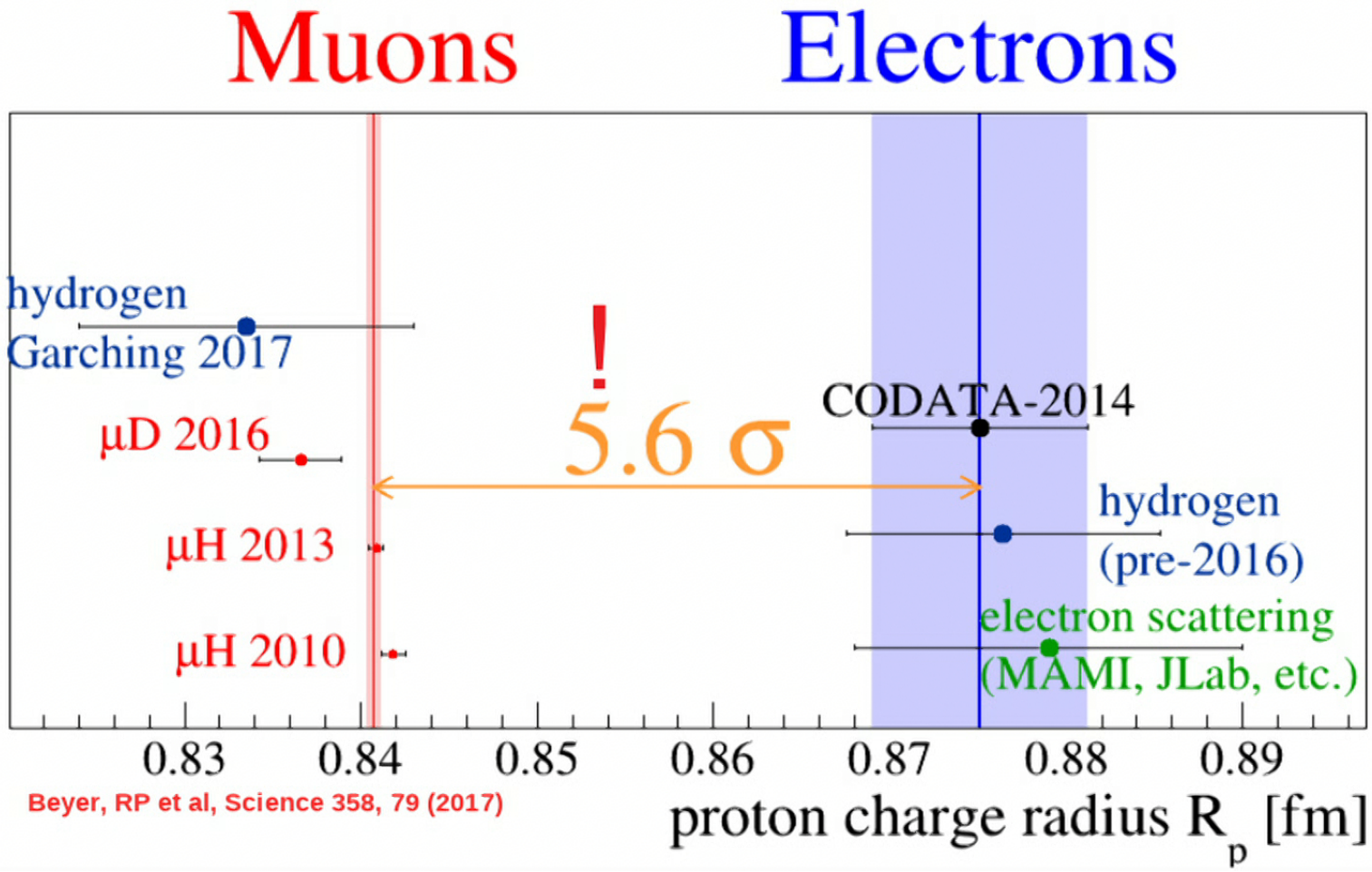


Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

The “old” measurements



New Measurements



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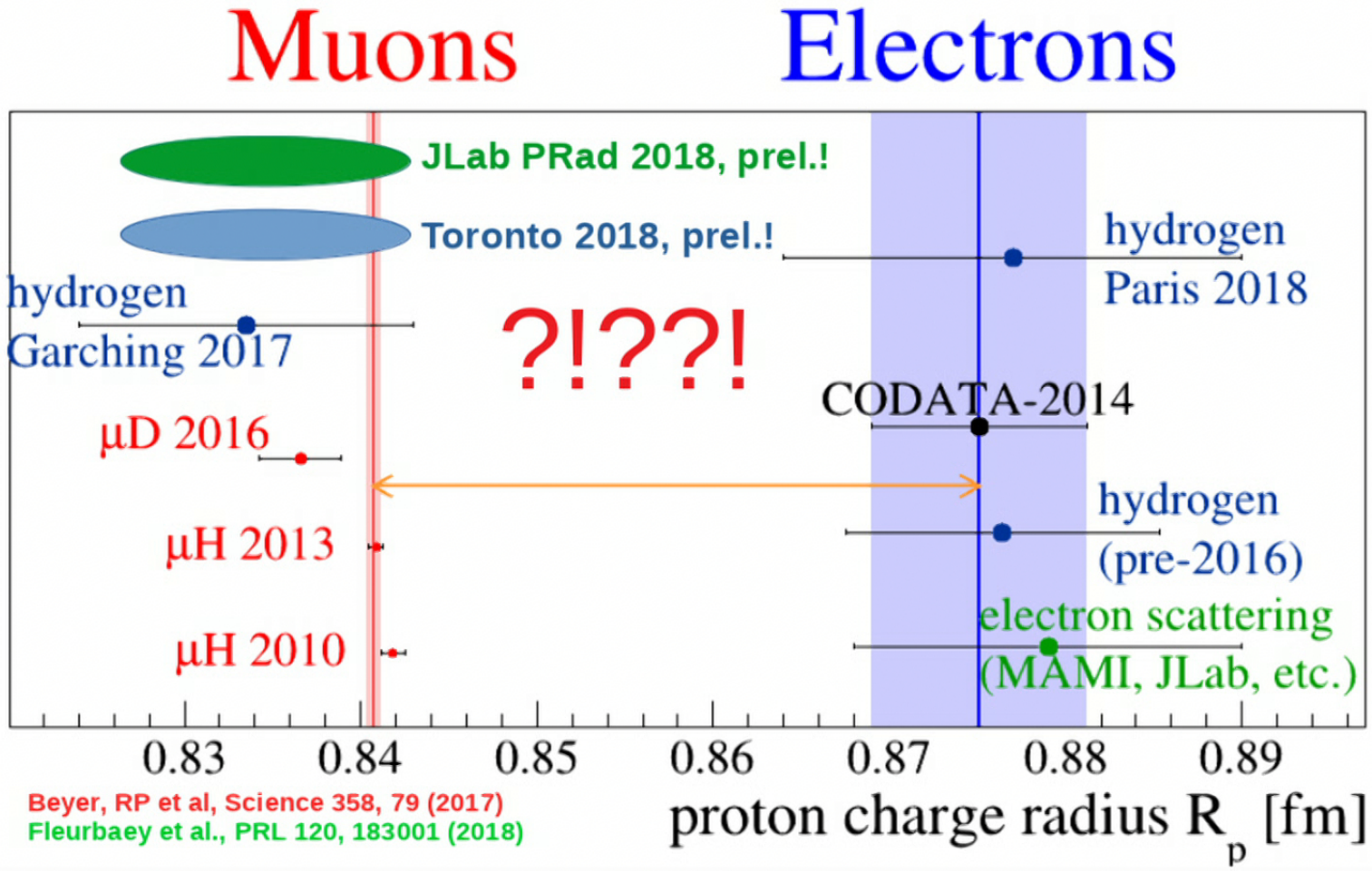
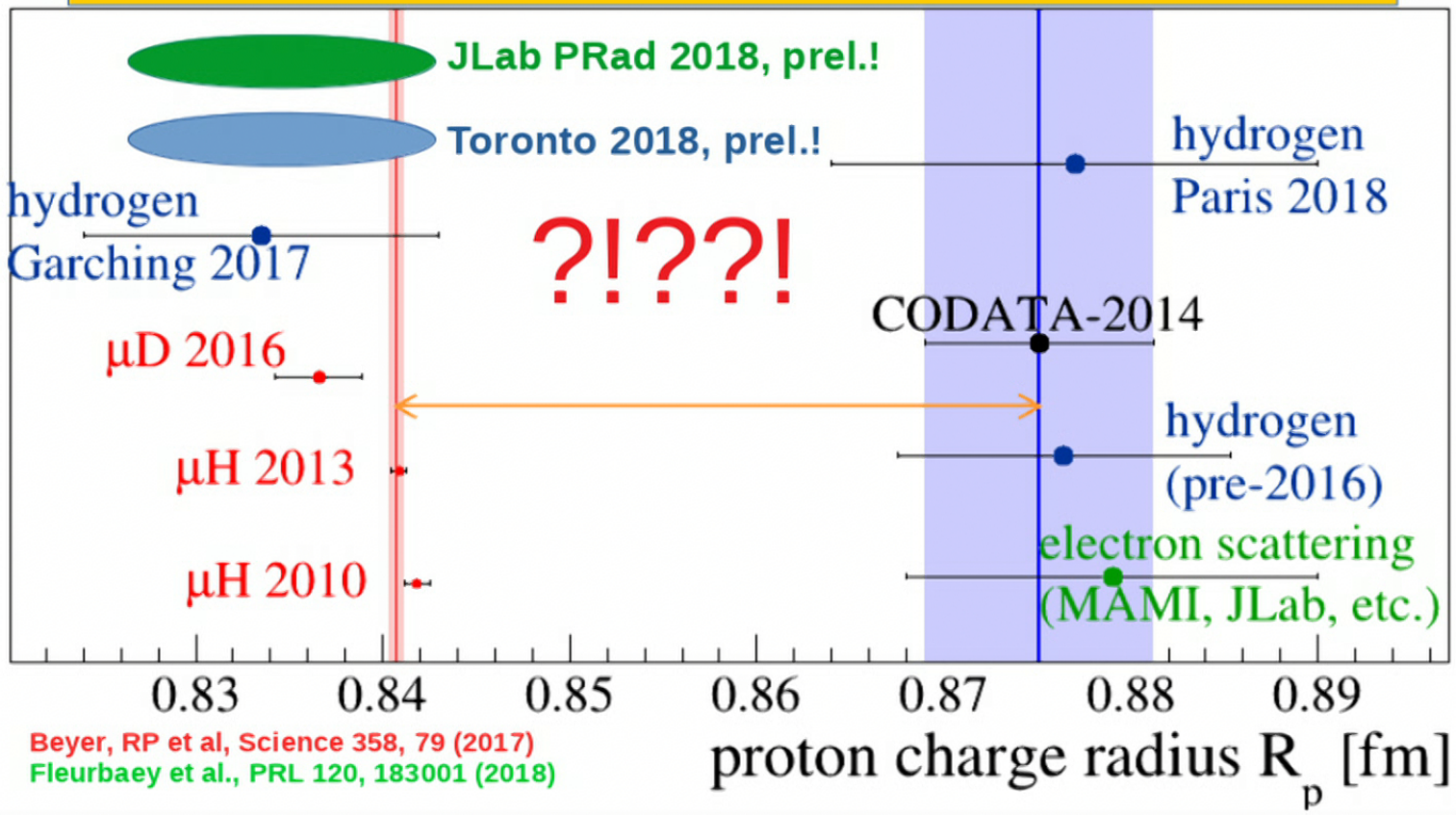


Beyer, RP et al, Science 358, 79 (2017)
Fleurbaey et al., PRL 120, 183001 (2018)

We have a “Rydberg problem” AND a scattering problem?!?!?!

→ need even more data!



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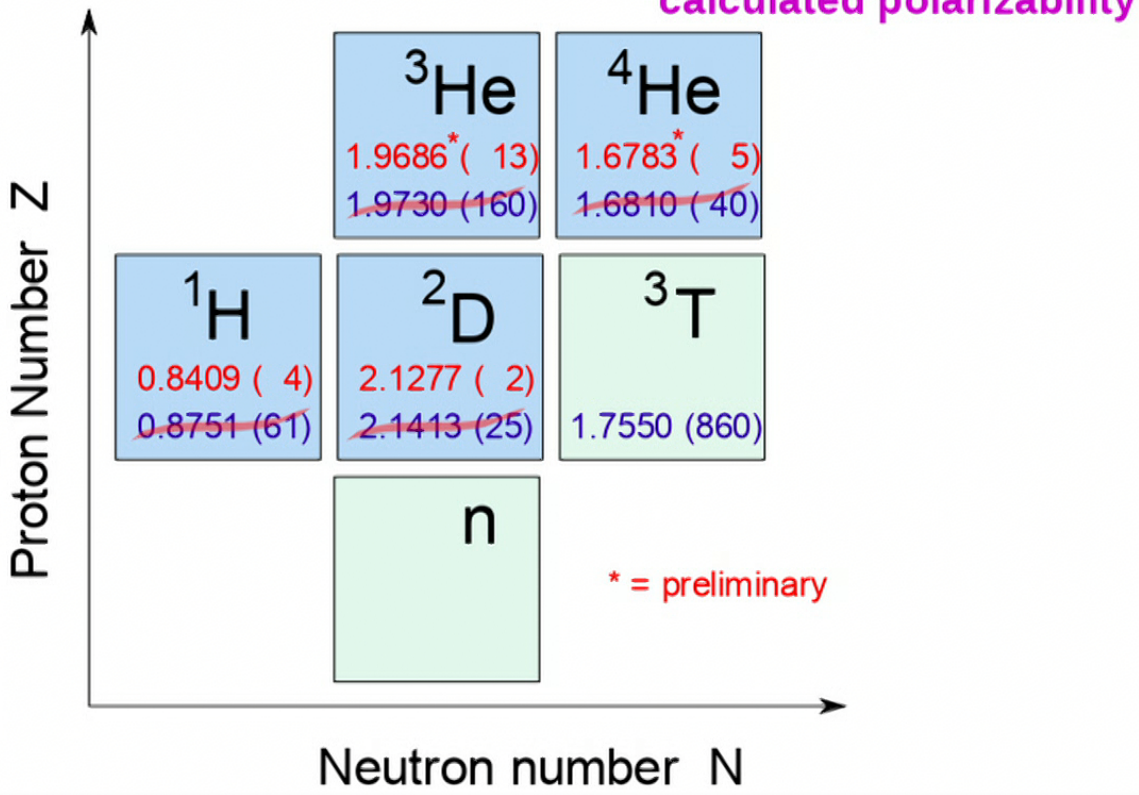
Conclusions

Muonic atoms / ions provide:

- **10x more accurate charge radii**, when combined with **calculated polarizability**



Conclusions

Muonic atoms / ions provide:

- **10x more accurate charge radii**, when combined with **calculated polarizability**

- few times more accurate **nuclear polarizability**, when combined with **charge radius from regular atoms**

Muonic atoms are a novel tool for proton and new-nucleon properties!

Conclusions

Proton radius situation:

- smaller radii from muonic **hydrogen** and **deuterium** imply a smaller Rydberg constant
- new H(2S-4P) gives a smaller proton radius
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- H(2S – 6P, 8P, 9P, …) and D(2S-nl) underway in Garching and Colorado
- H(1S – 3S, 4S, ..) underway in Paris and Garching
- H(2S-2P) (Hessels @ Toronto)
- Muonium at PSI, J-PARC
- Positronium (Cassidy @ UCL, Crivelli @ ETH)
- He^+(1S-2S) underway in Garching (Udem) and Amsterdam (Eikema)
- HD^+, H_2, etc. in Amsterdam (Ubachs @ Amsterdam) and Paris (Hilico, Karr @ Paris)
- He (Vassen @ Amsterdam), Li^+ (Udem @ Garching)
- HCI, e.g. H-like Ne (Tan @ NIST)
- Rydberg-atoms, e.g. Rb (Raithel @ Ann Arbor)
- new low-Q^2 electron scattering at MAMI, JLab, MESA
- muon scattering: MUSE @ PSI, COMPASS @ CERN

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Compare Rydberg values to test QED and SM

Up next: Hyperfine structure in μp

The 21 cm line in hydrogen (1S hyperfine splitting) has been **measured** to 12 digits (0.001 Hz) in 1971:

$$\nu_{exp} = 1\,420\,405.\,751\,766\,7 \pm 0.000\,001\ \text{kHz}$$

Essen et al., Nature 229, 110 (1971)

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QED test is limited to 6 digits (800 Hz) because of proton structure effects:

$$\nu_{theo} = 1\,420\,403.\,1 \pm 0.6_{\text{proton size}} \pm 0.4_{\text{polarizability}}\ \text{kHz}$$

Eides et al., Springer Tracts 222, 217 (2007)

Proton Zemach radius

HFS depends on “Zemach” radius:

$$\Delta E = -2(Z\alpha) m \langle r \rangle_{(2)} E_F$$

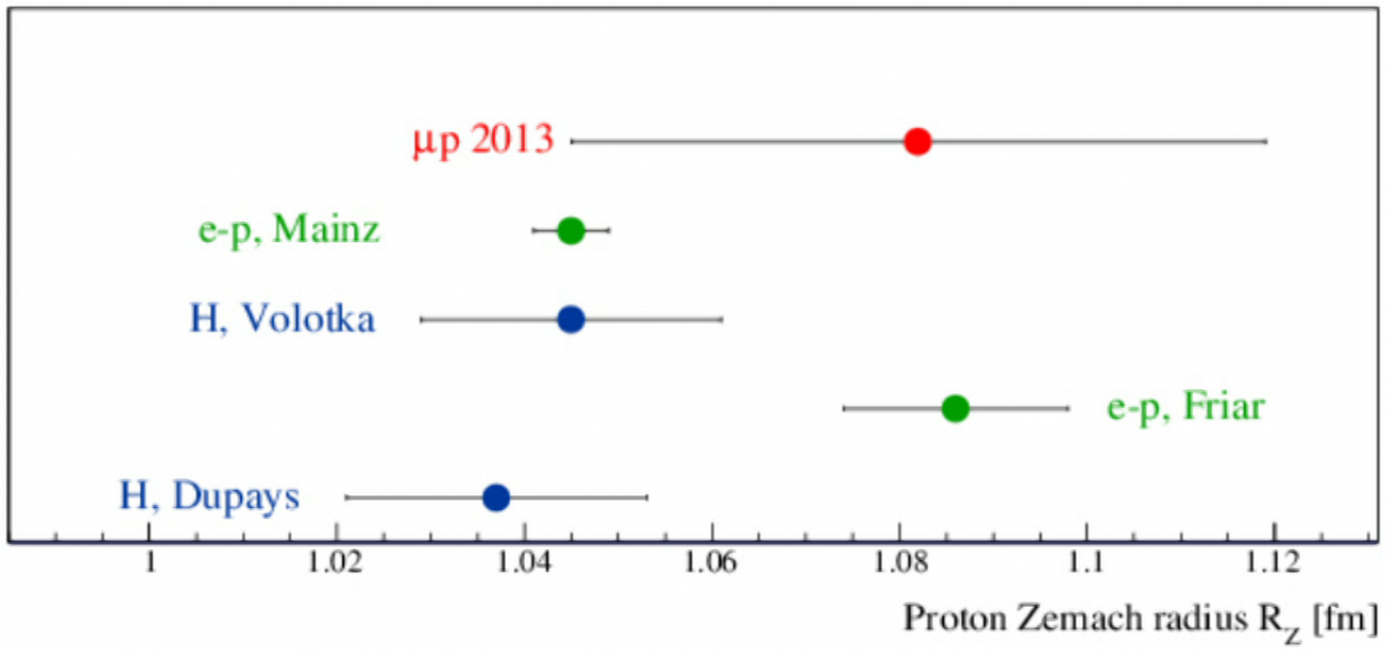
$$\langle r \rangle_{(2)} = \int d^3 r \, d^3 r' \rho_E(r) \rho_M(r') |r - r'|$$

Zemach, Phys. Rev. 104, 1771 (1956)

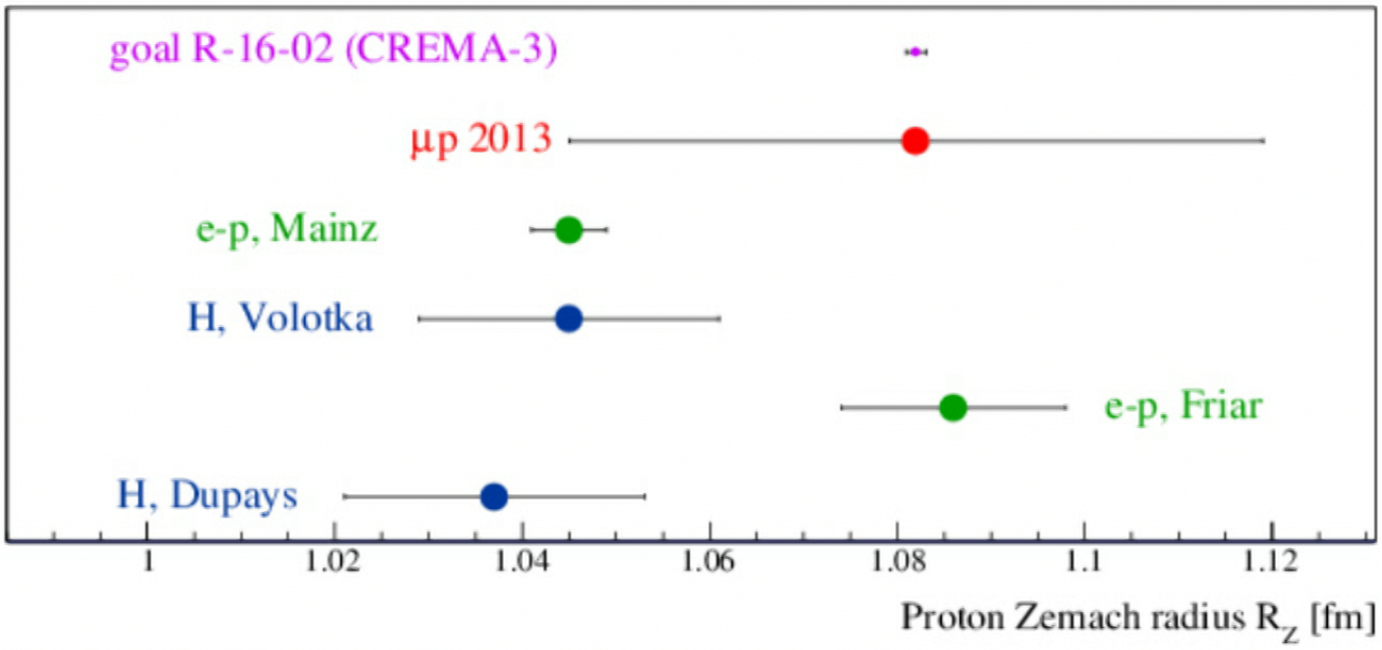
Form factors and momentum space

$$\Delta E = \frac{8(Z\alpha) m}{\pi n^3} E_F \int_0^\infty \frac{dk}{k^2} \left[\frac{G_E(-k^2) G_M(-k^2)}{1+\kappa} \right]$$

Proton Zemach radius from μp



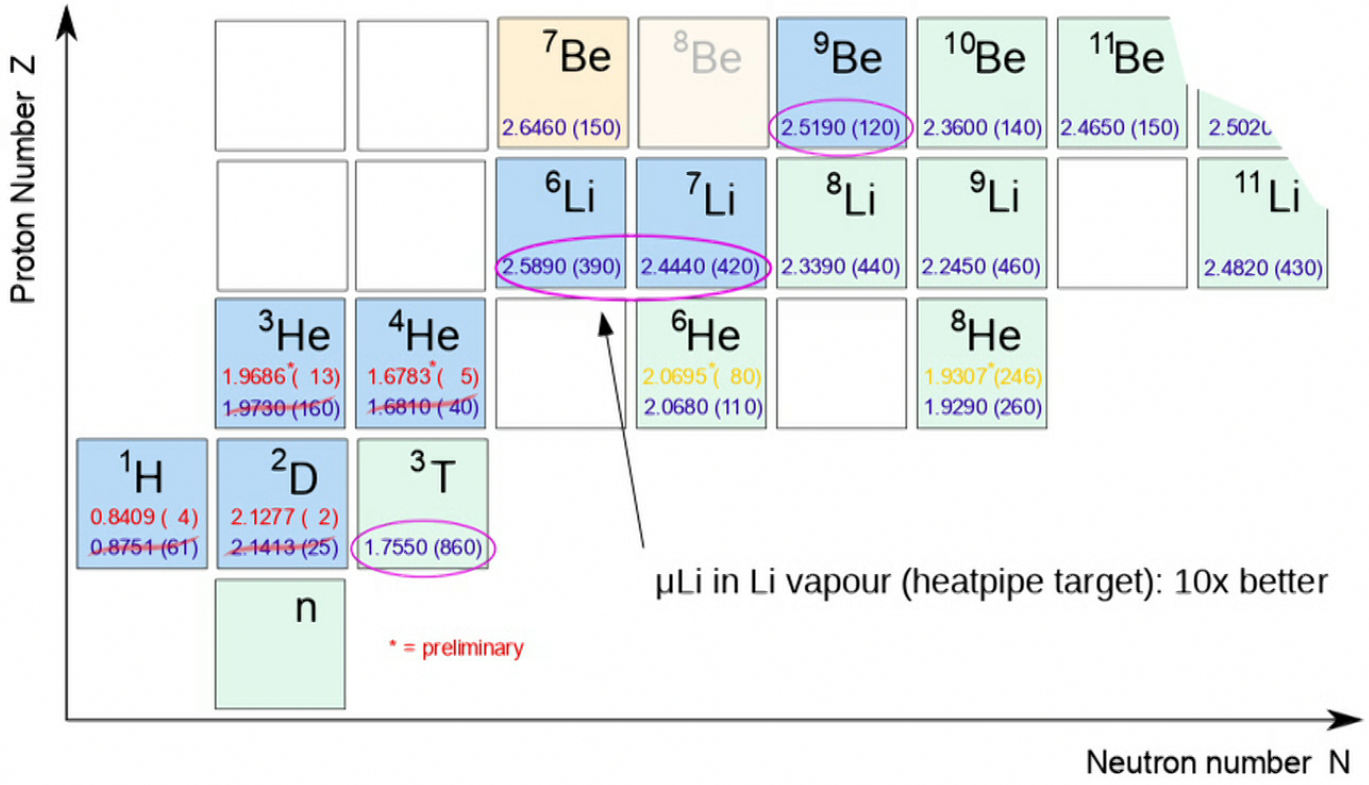
Proton Zemach radius from μp



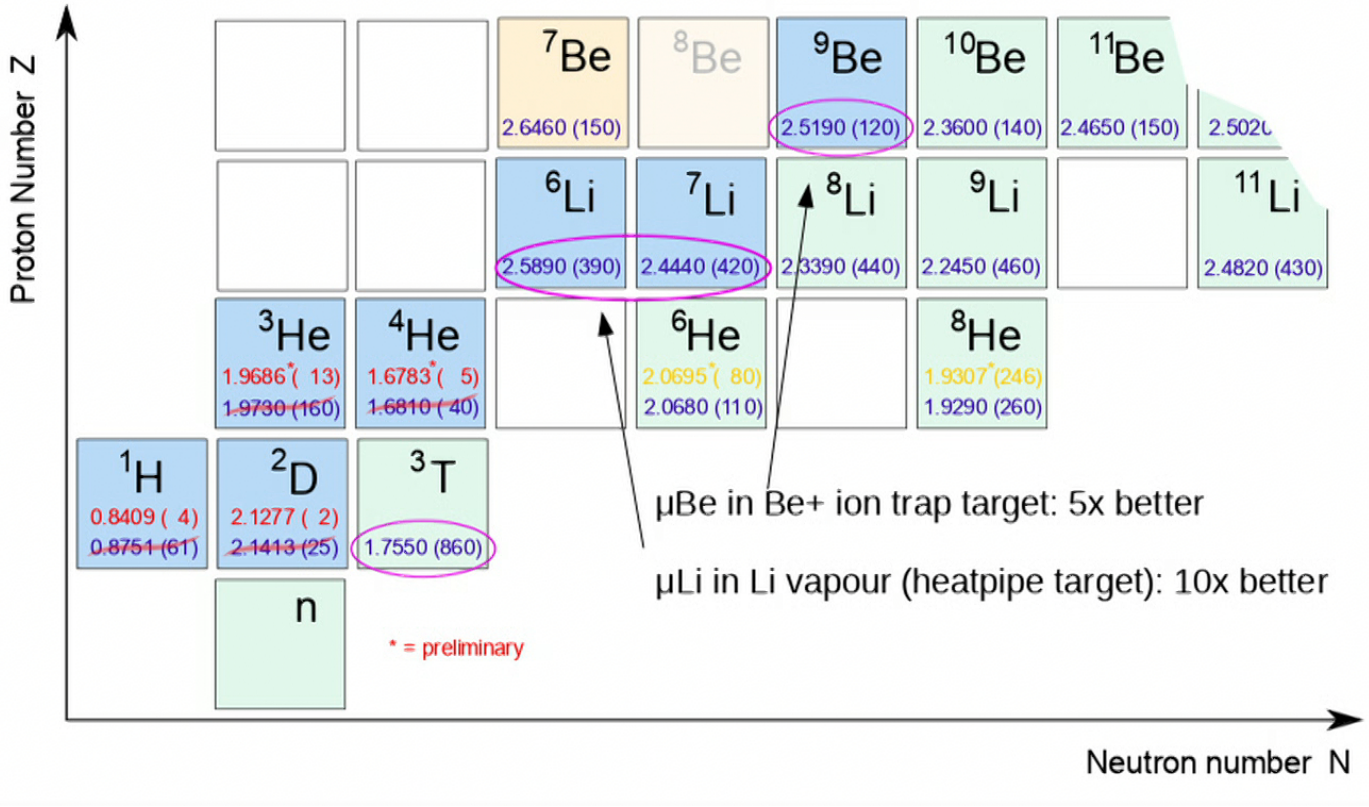
PSI Exp. R-16-02: Antognini, RP et al. (CREMA-3 / HyperMu)

see e.g. Schmidt, RP et al., arXiv 1808.07240

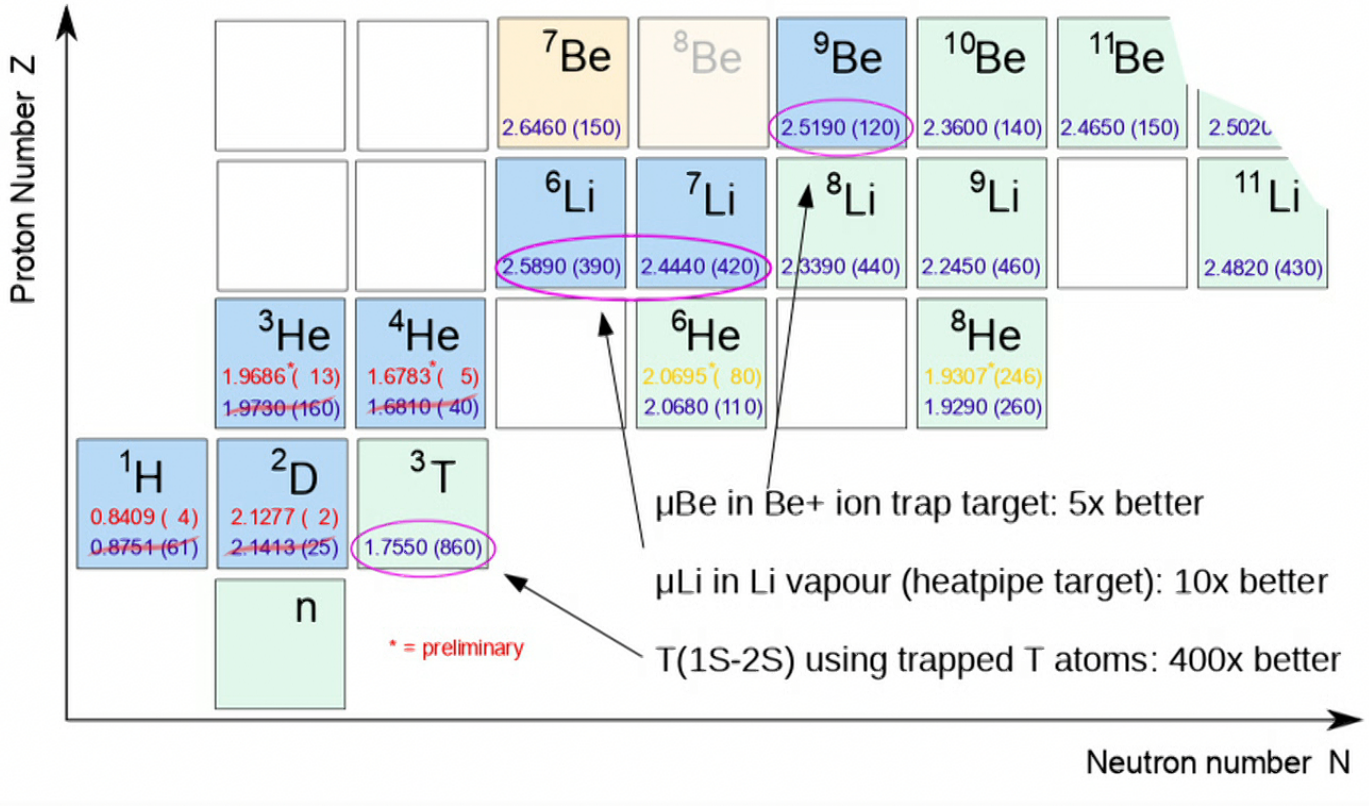
Charge radii: The future

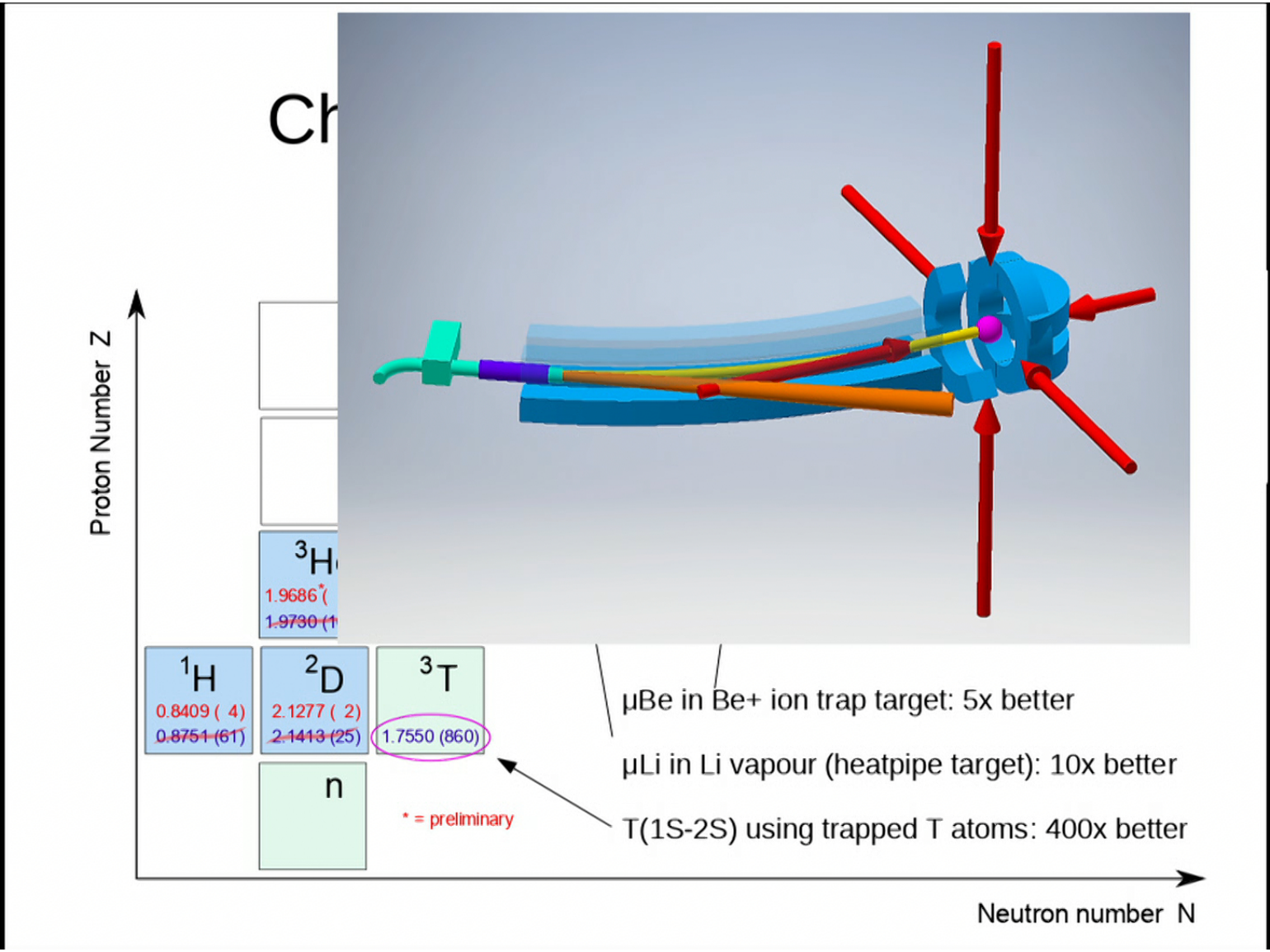


Charge radii: The future



Charge radii: The future




Ch
Proton Number Z
Neutron number N
^{3}H
1.9686*(
1.9730 (1
^{1}H
0.8409 (4)
0.8751 (61)
^{2}D
2.1277 (2)
2.1413 (25)
^{3}T
1.7550 (860)
n
* = preliminary
μBe in Be+ ion trap target: 5x better
μLi in Li vapour (heatpipe target): 10x better
T(1S-2S) using trapped T atoms: 400x better

Thanks a lot for your attention

The Garching Hydrogen Team:

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Thanks a lot for your attention

My new Mainz group:

Jan Haack, Merten Heppener, Rishi Horn, Ahmed Ouf, Stefan Schmidt, Gregor Schwendler, Lukas Schumacher, Andreas Wieltsch, Marcel Willig

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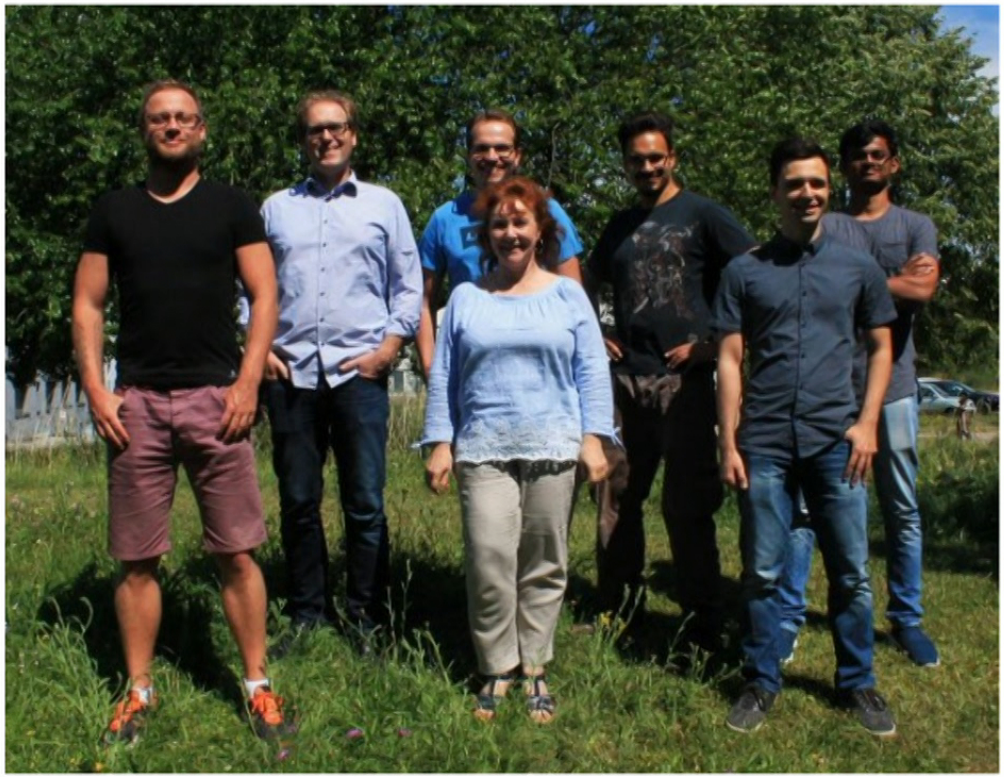
Group at JGU Mainz



“old” picture from summer 2018, now + 1 PhD, +1 MSc, +2 BSc

Charge radii: The future