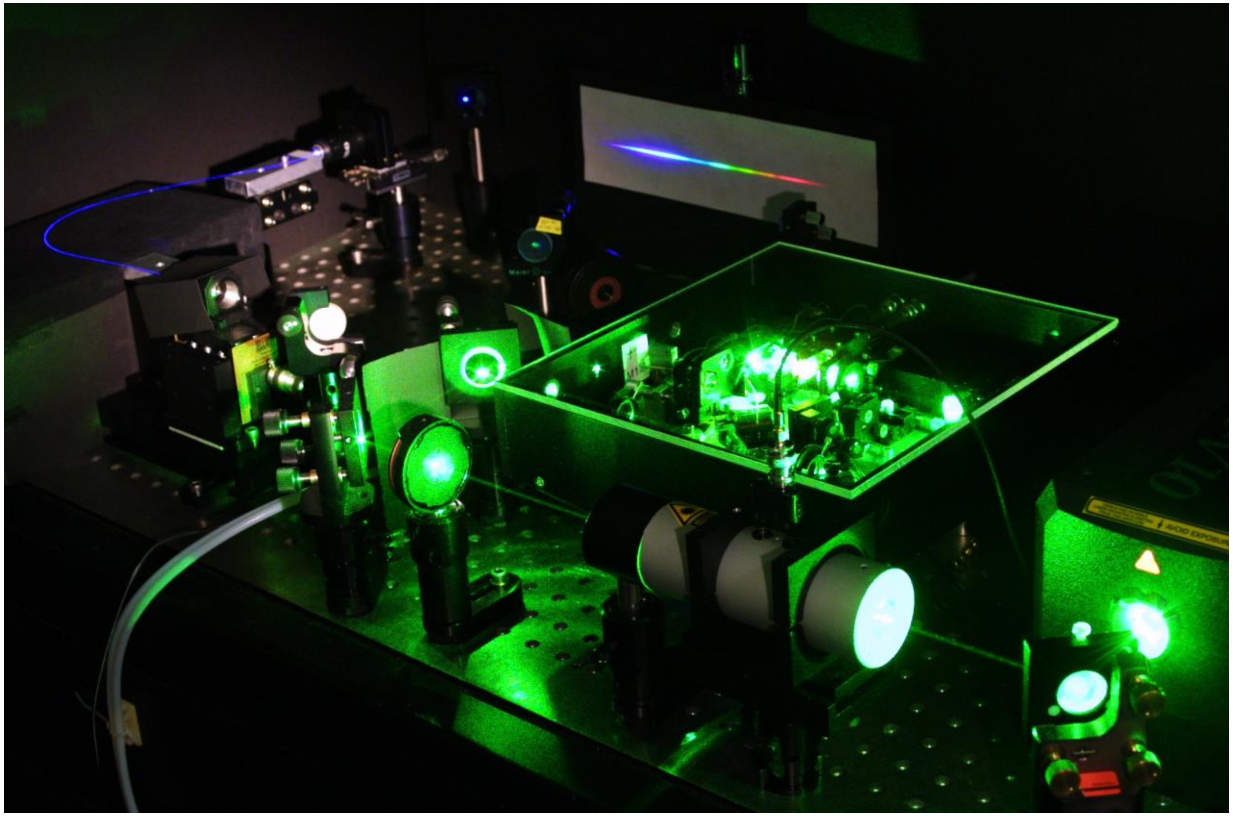
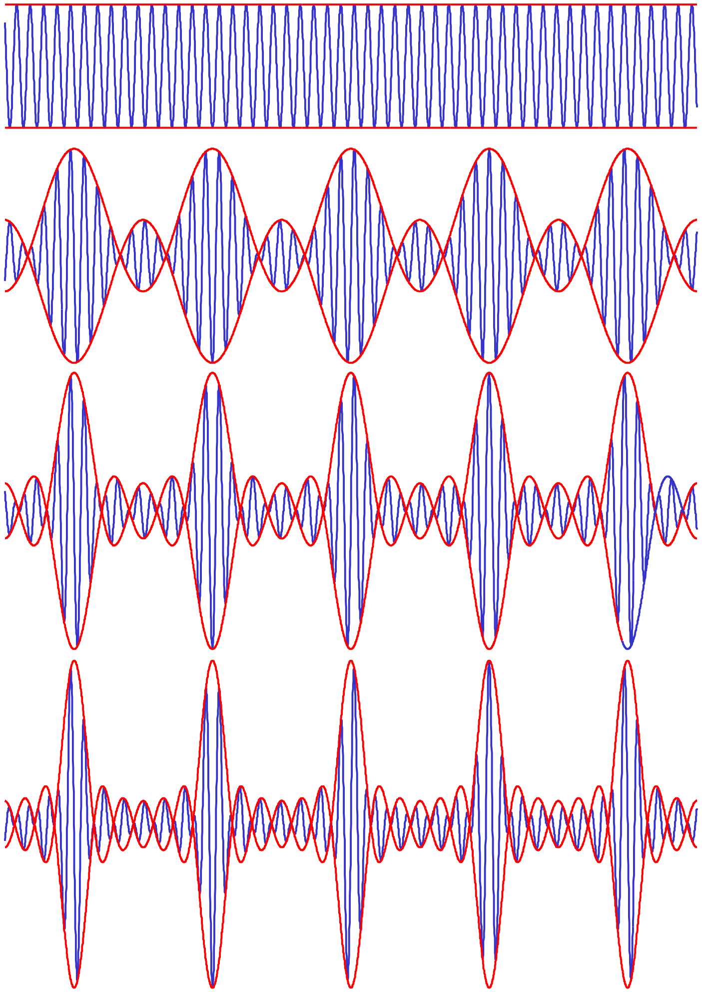
Measuring the Frequency of Light with Mode Locked Lasers



MPQ

Locking the Cavity Modes of a Laser



single mode :

3 modes :

5 modes :

7 modes :

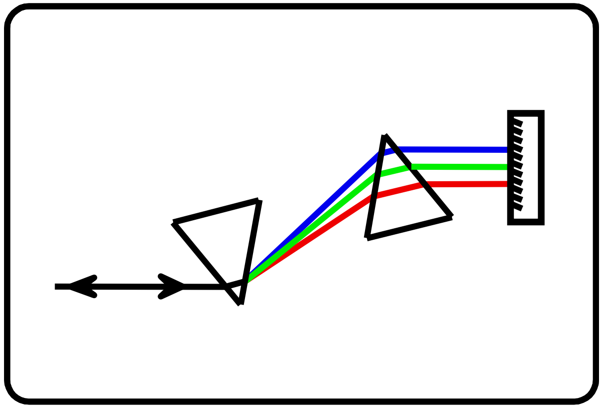
...

The Soliton Laser

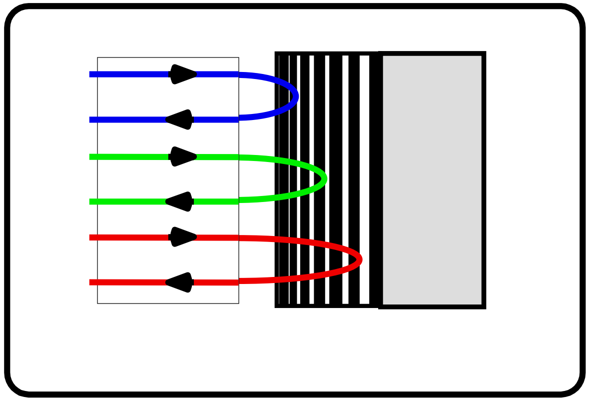
The effect of group velocity dispersion (GVD) and self phase modulation (SPM) on the puls reshaping cancel in a soliton.

- SPM: laser crystal $n(I) = n_0 + I(t)\, n_2$ with $n_2 > 0$
- GVD: prism pairs and/or chirped mirrors $d^2 1/dk^2 < 0$

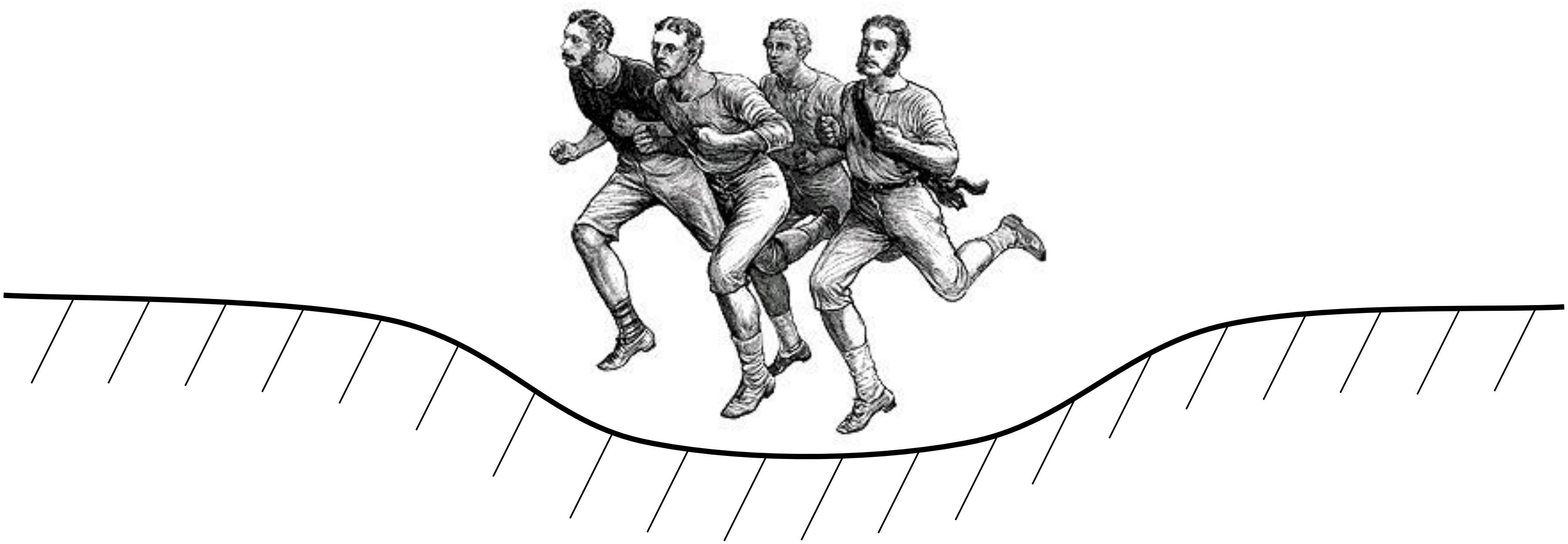
prism pair



chirped mirror

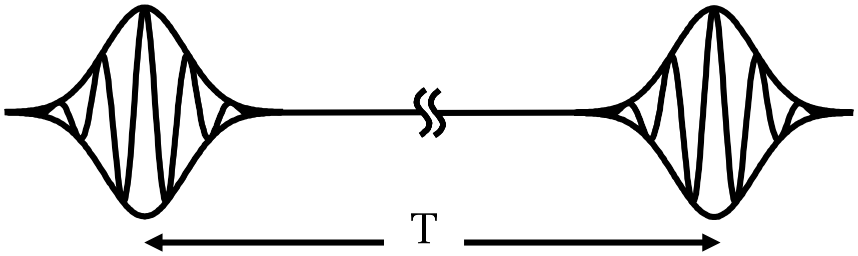


Mechanical Soliton: Runners on a Soft Surface

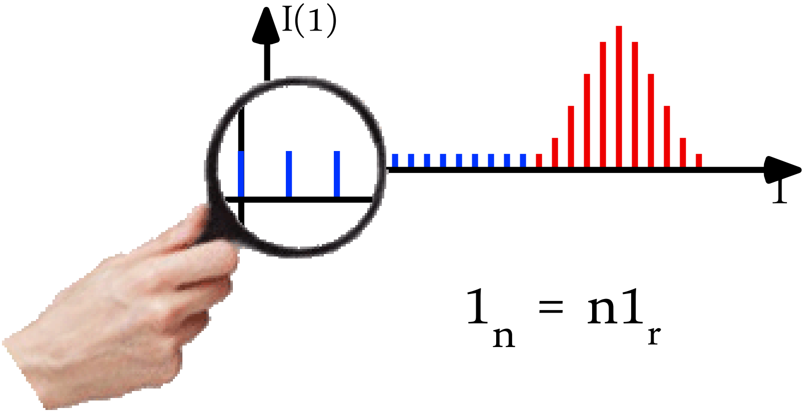


Carrier Envelope Phase of the Pulses

group velocity = phase velocity

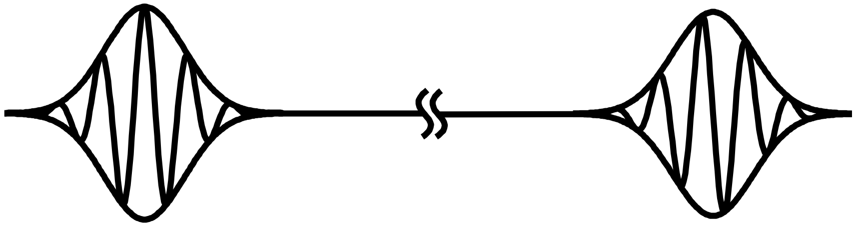


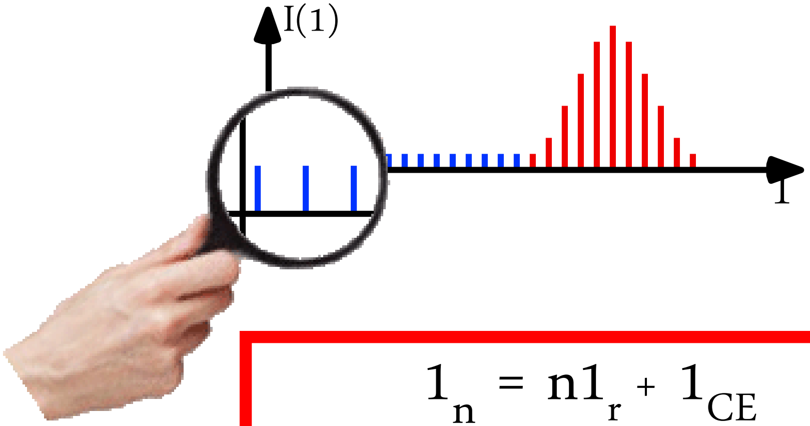
repetition rate: $1_r = 2\pi/T$



$$1_n = n1_r$$

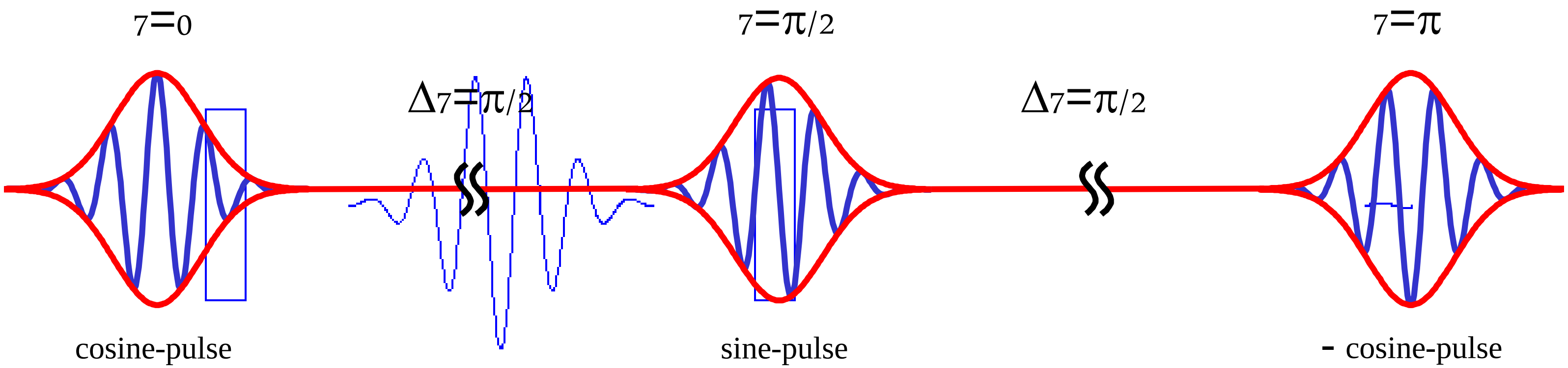
group velocity ≠ phase velocity





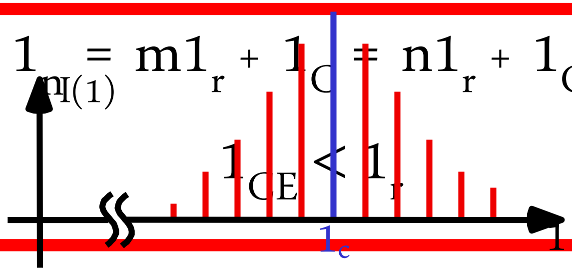
$$\boxed{1_n = n1_r + 1_{CE}}$$

Carrier Envelope Offset Frequency



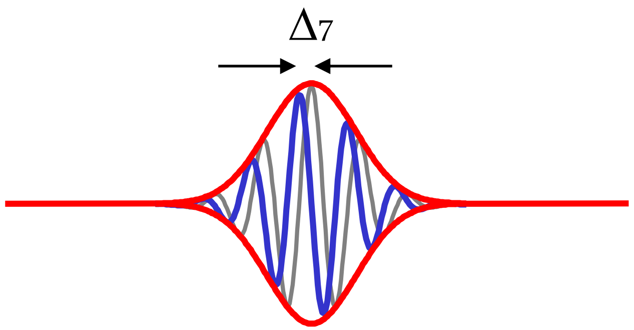
$$E(t) = A(t)\, e^{-i1_c t} = \sum_{m=-\infty}^{+\infty} A_m\, e^{-im1_r t\ -\ i1_c t}$$

$$1_m = m1_r + 1_C = n1_r + 1_{CE}$$



Pulse-to-Pulse Carrier Envelope Phase Slippage

$$E(t) = \sum_{n=-\infty}^{+\infty} A_n e^{-in1_r t - i1_{CE} t}$$

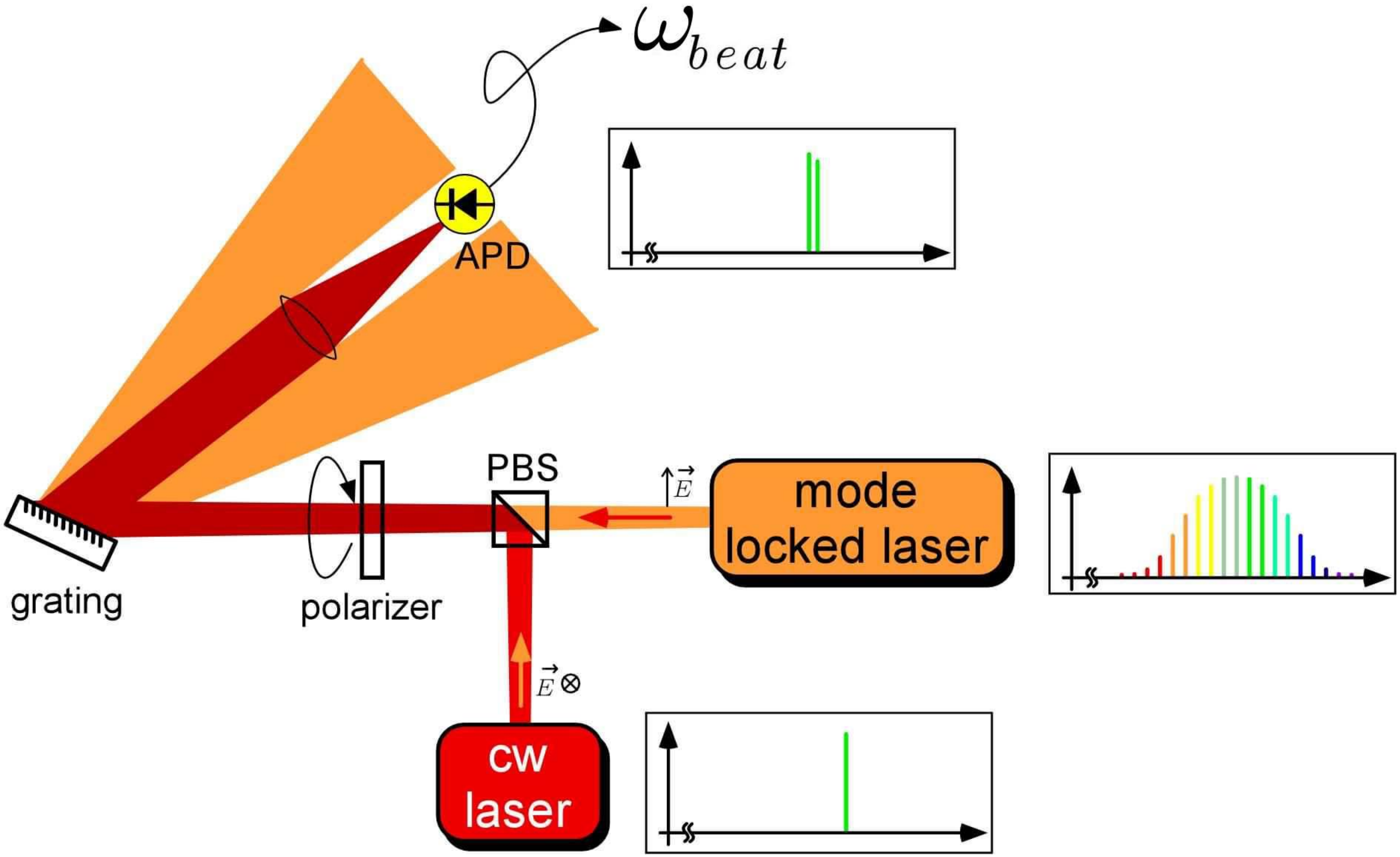


$$E(t+T) = \sum_{n=-\infty}^{+\infty} A_n e^{-in1_r t - in2\pi - i1_{CE} t - i2\pi 1_{CE}/1_r}$$

$$= E(t)\, e^{-i\Delta 7} \Rightarrow \boxed{\Delta 7 = 2\pi\, 1_{CE}/\, 1_r}$$

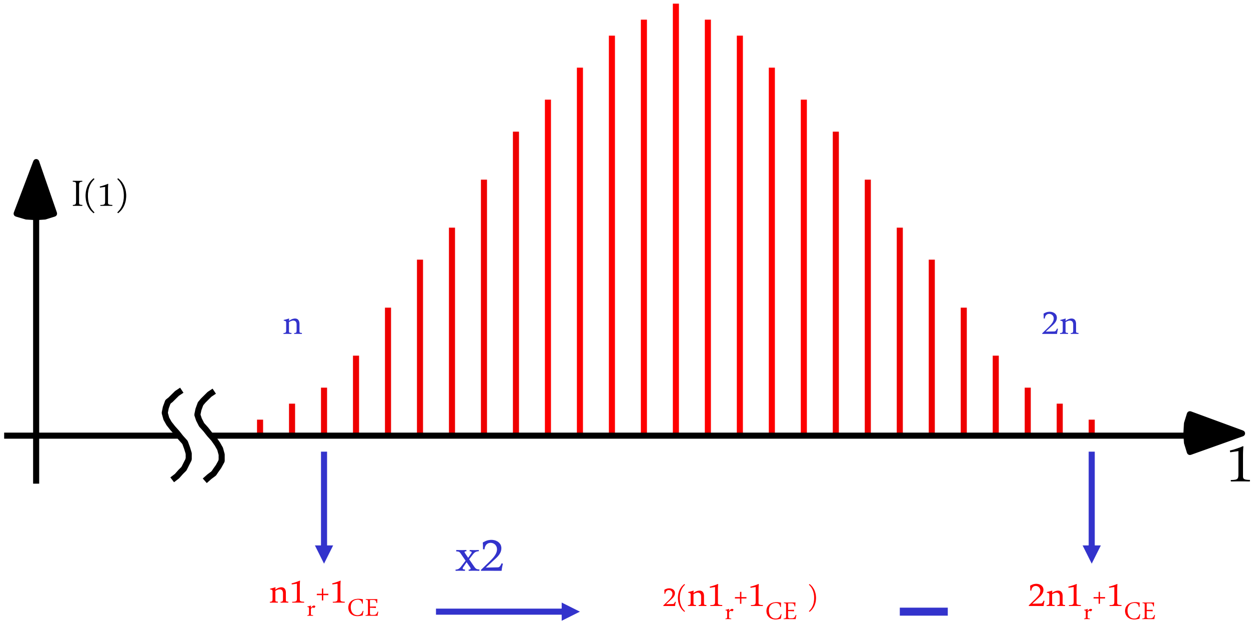
$$\boxed{1_{CE} = \Delta 7/T}$$

Selecting a Sinlge Mode from the Comb



Measuring the Carrier-Envelope Phase Slippage

it is simple to detect 1_{CE} of an octave wide frequency comb:



$$1_{CE} = 2(n1_r + 1_{CE}) - (2n1_r + 1_{CE})$$

Controlling the Frequency Comb

depends on the cavity length

$$1_n = n1_r + 1_{CE}$$

depends on the pump power

we can measure **and** control

$1_r = 2\pi/T$ **and** $1_{CE} = \Delta 7/T$

Optical Frequency Counter

locked to a Cs atomic clock

$$1_n = n1_r + 1_{CE}$$

every mode can be used for
optical frequency measurement

Optical Prescaler (Frequency Divider)

locked to an optical reference

locked to a fraction of 1_r

$$1_n = n1_r + 1_{CE} \qquad = (n + 1/k)\; 1_r$$

countable clock output

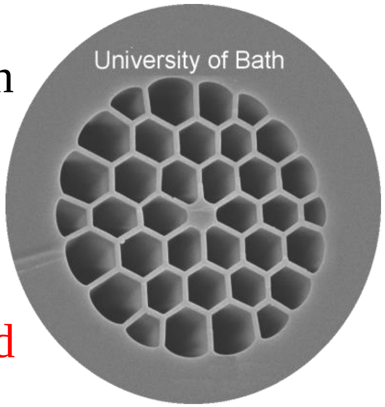
Generating an Octave Spanning Comb

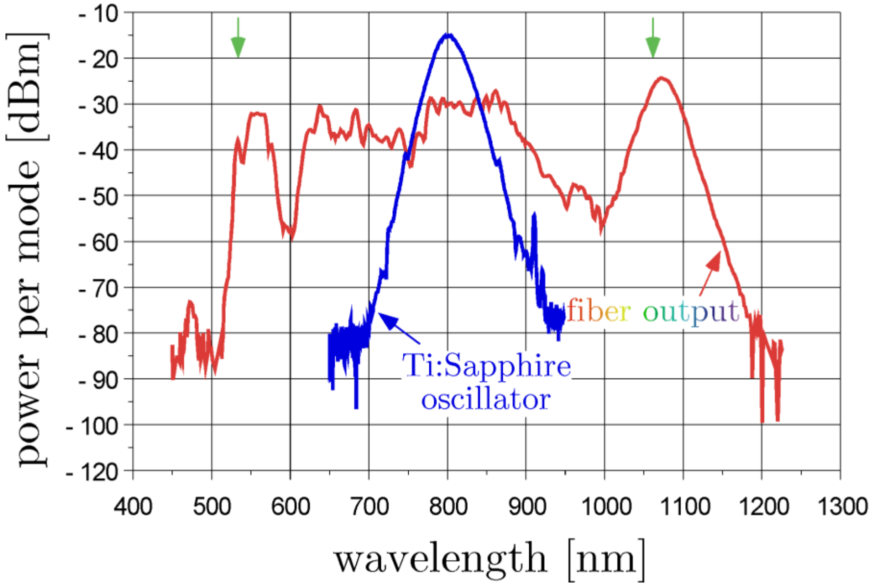
self phase modulation: $n(I) = n_0 + I(t)\, n_2$ with $I(t) \sim |A(t)|^2$

non-linear phase shift after propagating the length l: $\Phi_{NL}(t) = - I(t)\, n_2\, 1_c\, l/c$

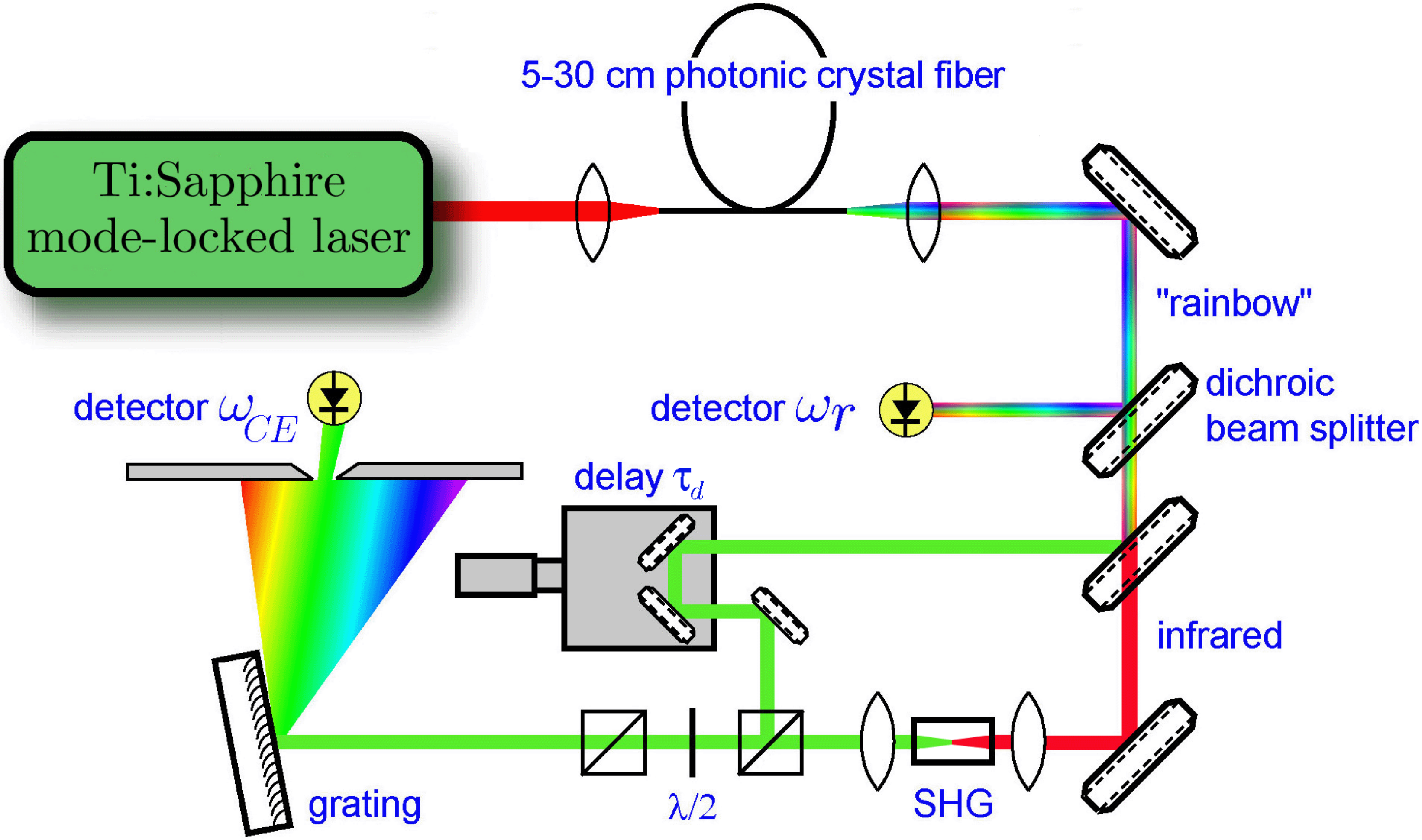
➡ extra frequencies: $\dot{\Phi}_{NL}(t) = - \dot{I}(t)\, n_2\, 1_c l/c$

William Wadsworth
Jonathan Knight
Tim Birks
Phillip Russell
U. of Bath England

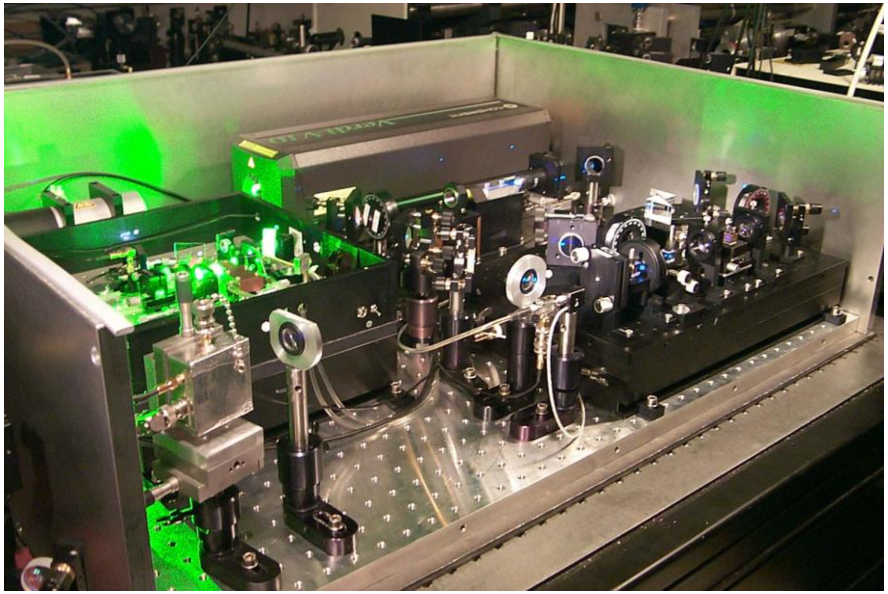




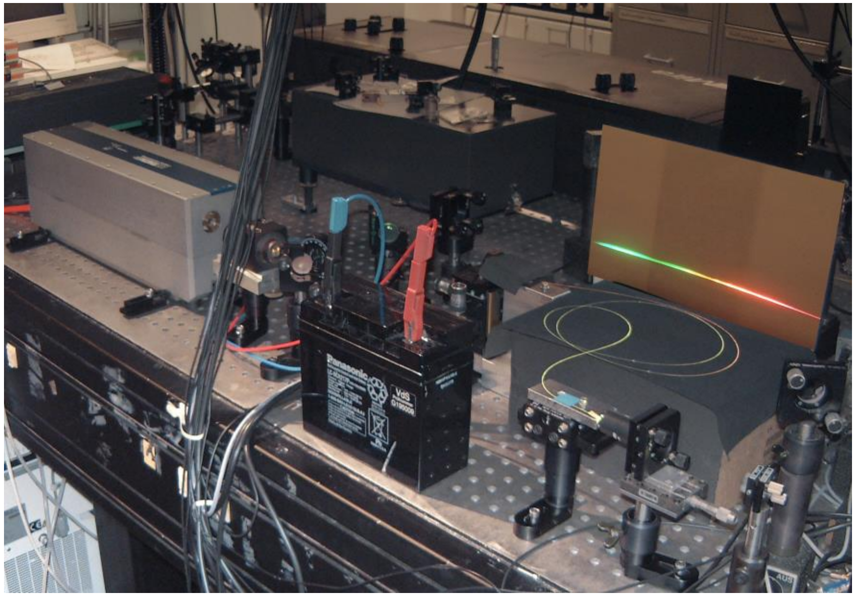
Self Referencing the Frequency Comb



Optical Synthesizer

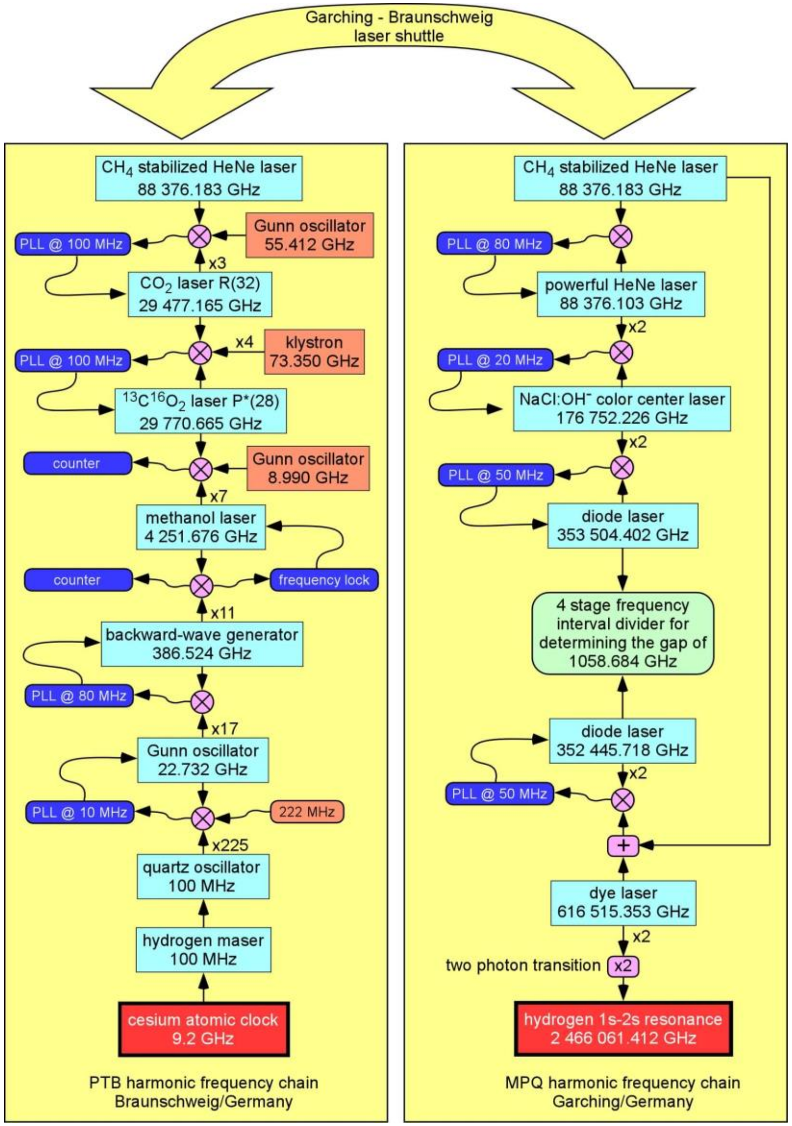


Based on a 650 MHz Ti:sapphire ring laser (GigaOptics).



Based on a Cr:LiSAF laser made at RTWH Aachen by P.Russbült, K.Gäbel and R.Poprave.

Harmonic Frequency Chains vs Optical Synthesizers



Garching - Braunschweig laser shuttle

CH_4 stabilized HeNe laser 88 376.183 GHz

PLL @ 100 MHz

Gunn oscillator 55.412 GHz

x3

CO_2 laser R(32) 29 477.165 GHz

x4

klystron 73.350 GHz

PLL @ 100 MHz

$^{13}C^{16}O_2$ laser P*(28) 29 770.665 GHz

counter

Gunn oscillator 8.990 GHz

x7

methanol laser 4 251.676 GHz

counter

frequency lock

x11

backward-wave generator 386.524 GHz

PLL @ 80 MHz

x17

Gunn oscillator 22.732 GHz

PLL @ 10 MHz

222 MHz

x225

quartz oscillator 100 MHz

hydrogen maser 100 MHz

cesium atomic clock 9.2 GHz

PTB harmonic frequency chain
Braunschweig/Germany

CH_4 stabilized HeNe laser 88 376.183 GHz

PLL @ 80 MHz

powerful HeNe laser 88 376.103 GHz

x2

PLL @ 20 MHz

NaCl:OH⁻ color center laser 176 752.226 GHz

x2

PLL @ 50 MHz

diode laser 353 504.402 GHz

4 stage frequency interval divider for determining the gap of 1058.684 GHz

diode laser 352 445.718 GHz

x2

PLL @ 50 MHz

+

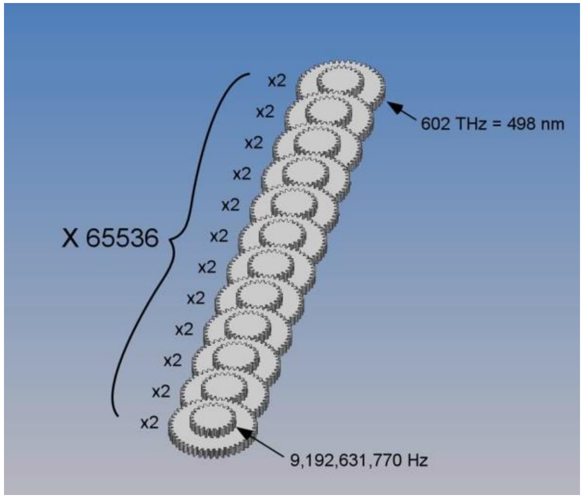
dye laser 616 515.353 GHz

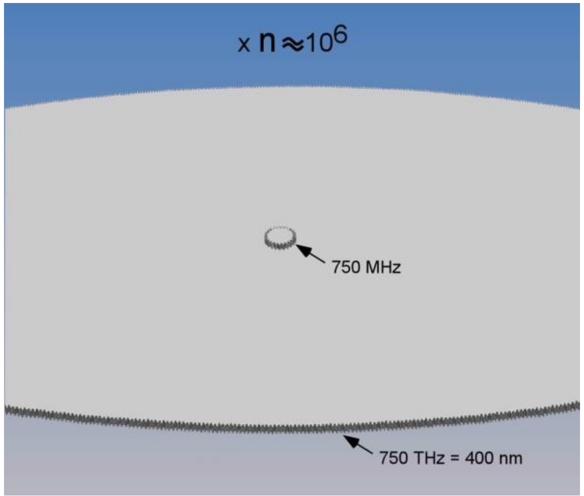
x2

two photon transition x2

hydrogen 1s-2s resonance 2 466 061.412 GHz

MPQ harmonic frequency chain
Garching/Germany

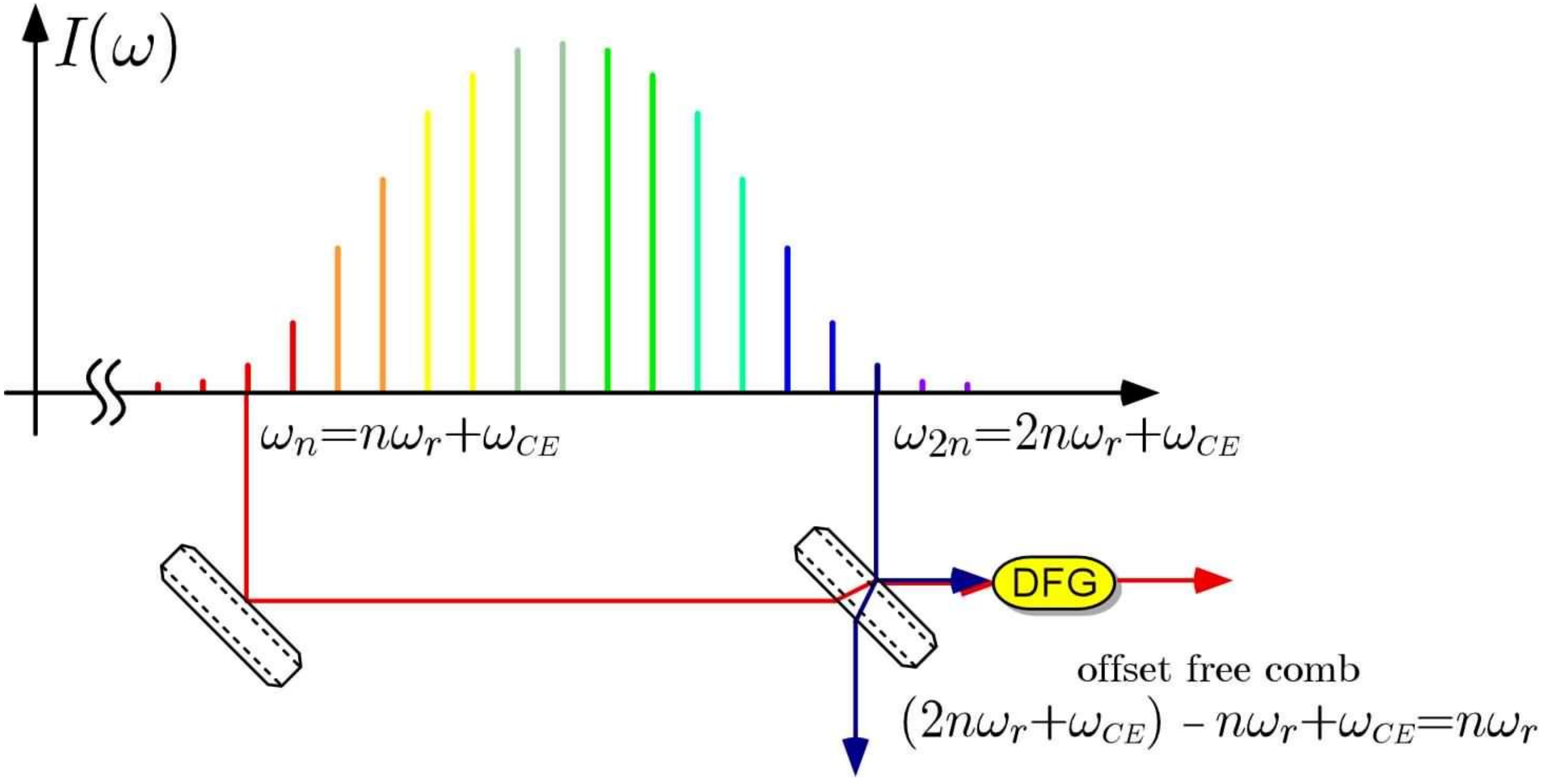




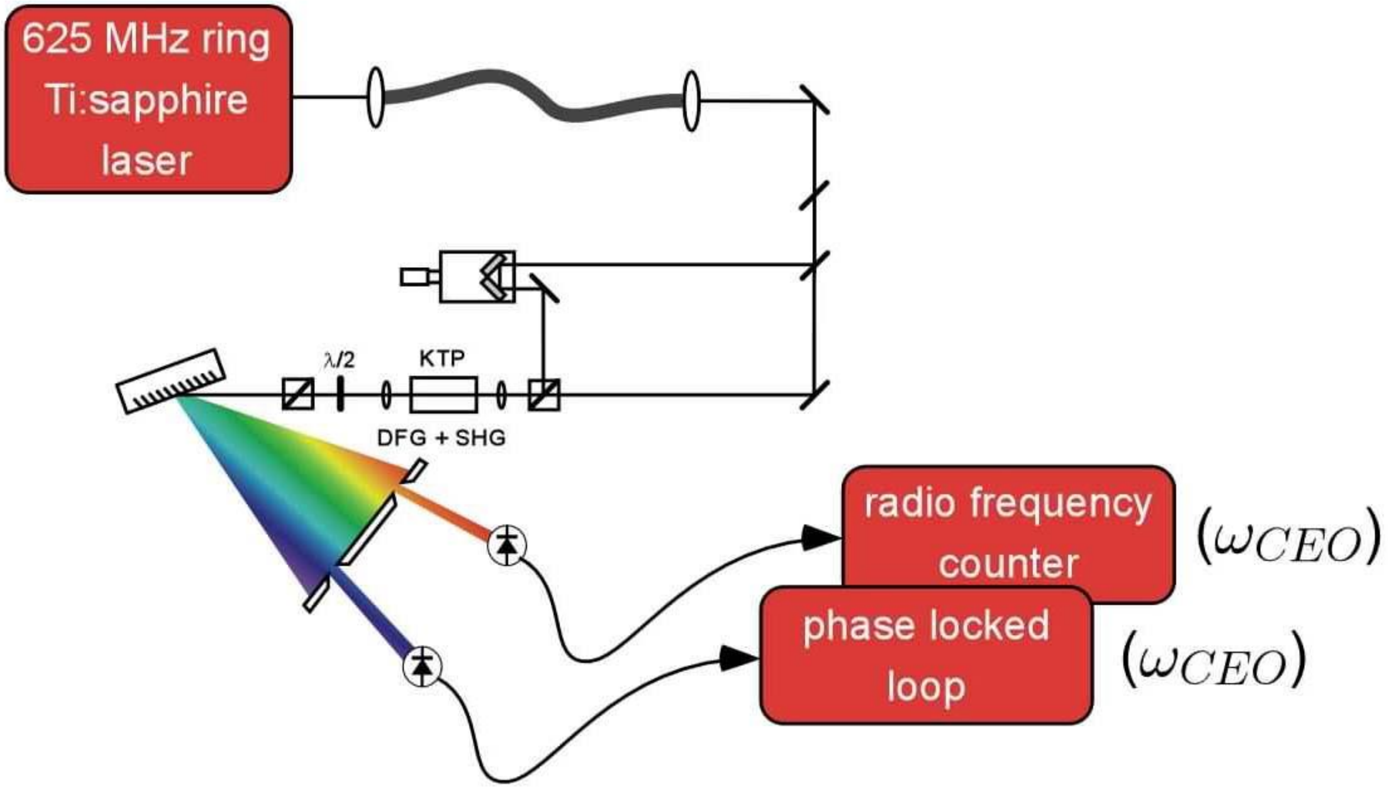
Adjusting the transmission ratio by selecting n:

$1_n = n1_r + 1_{CEO}$

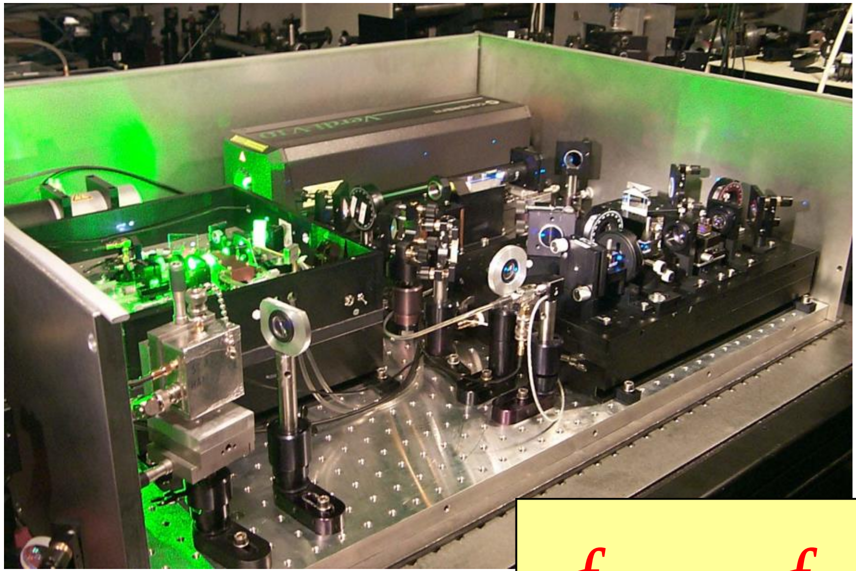
Self Differencing the Comb

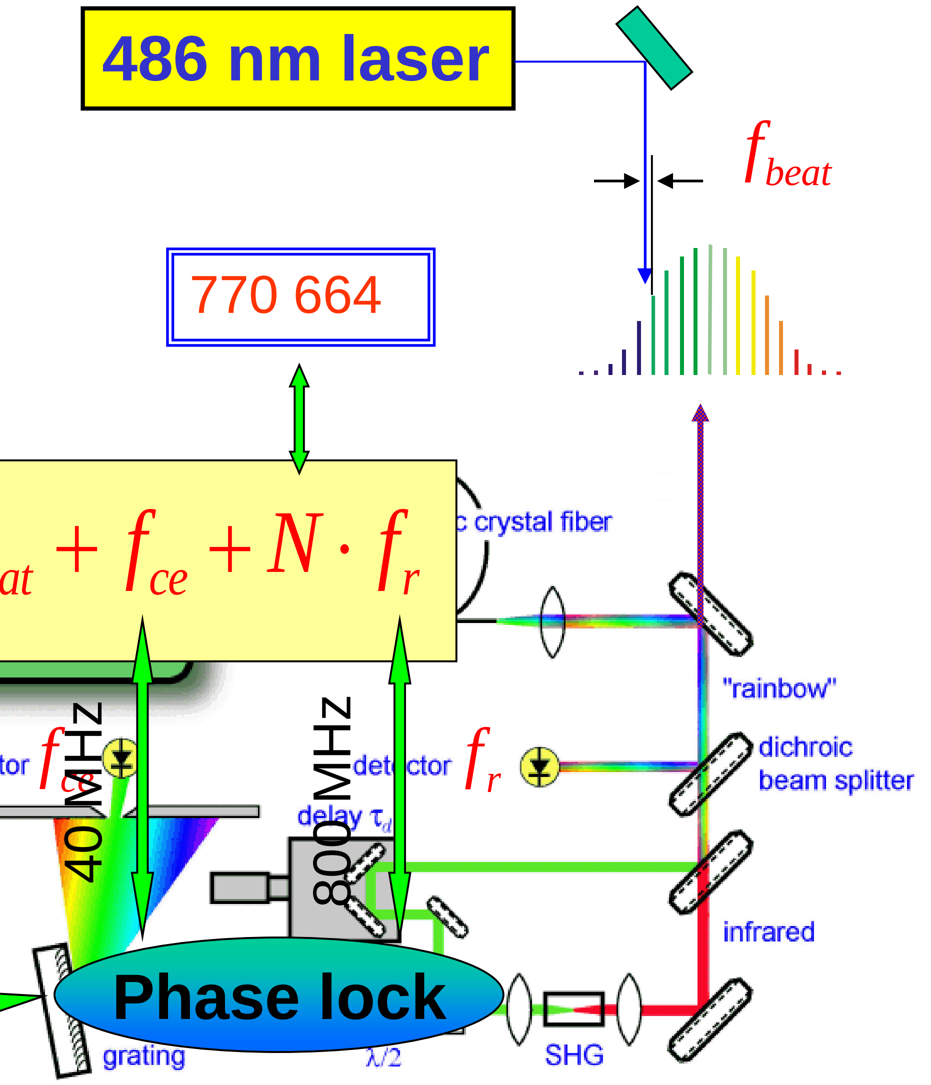


Testing the Self-Differenced Comb



Frequency Measurement





486 nm laser

770 664

$$f_{laser} = f_{beat} + f_{ce} + N \cdot f_r$$

40 MHz

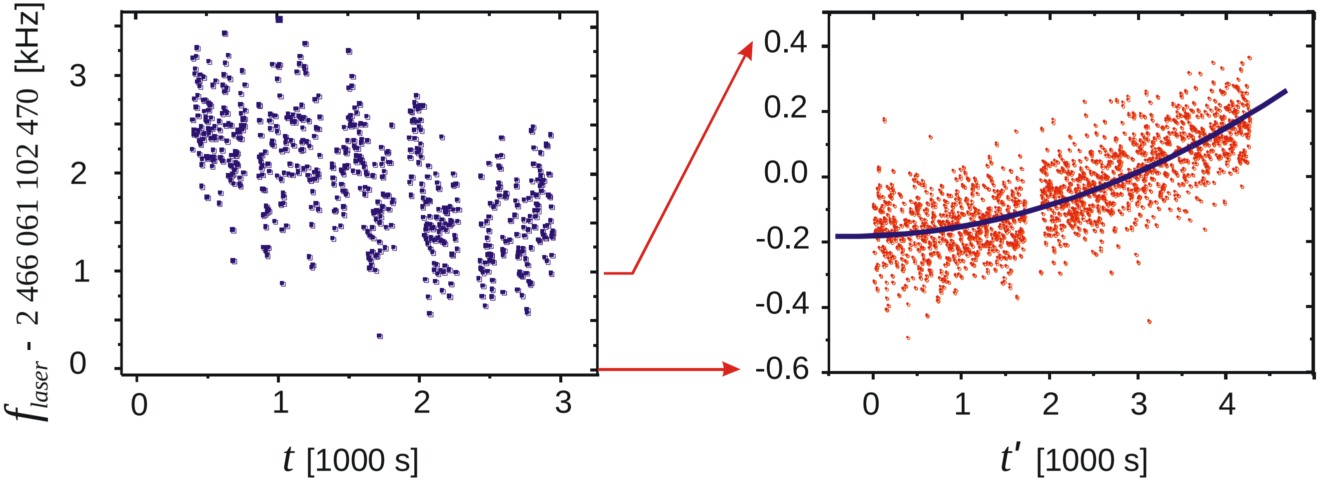
800 MHz

Phase lock

Primary Reference

Laser frequency measurement example

HP5701A clock



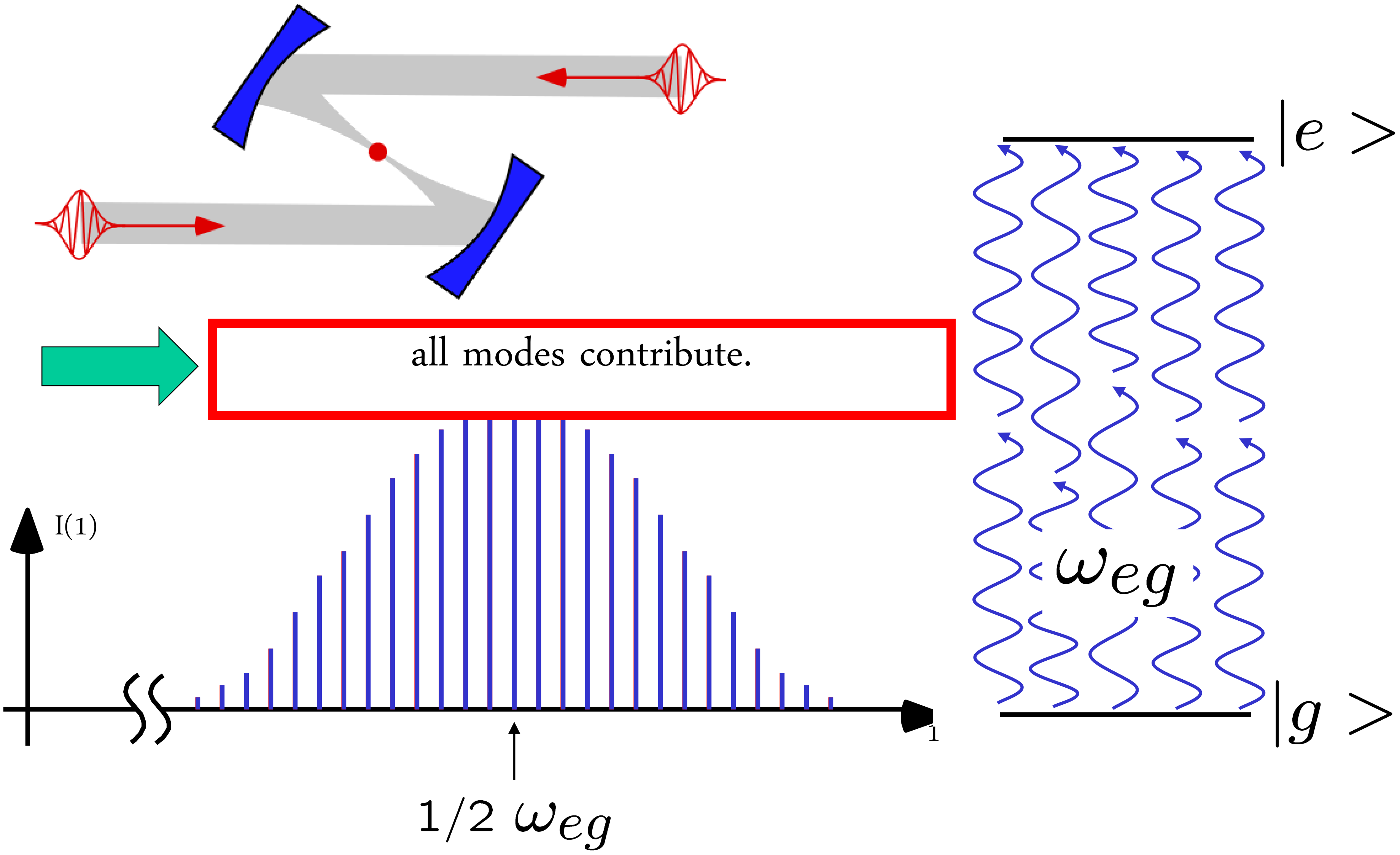
FOM

Other Applications

- Precission Spectroscopy

- Time Domain: Stabilization of the CE phase

Doing Spectroscopy with the Comb

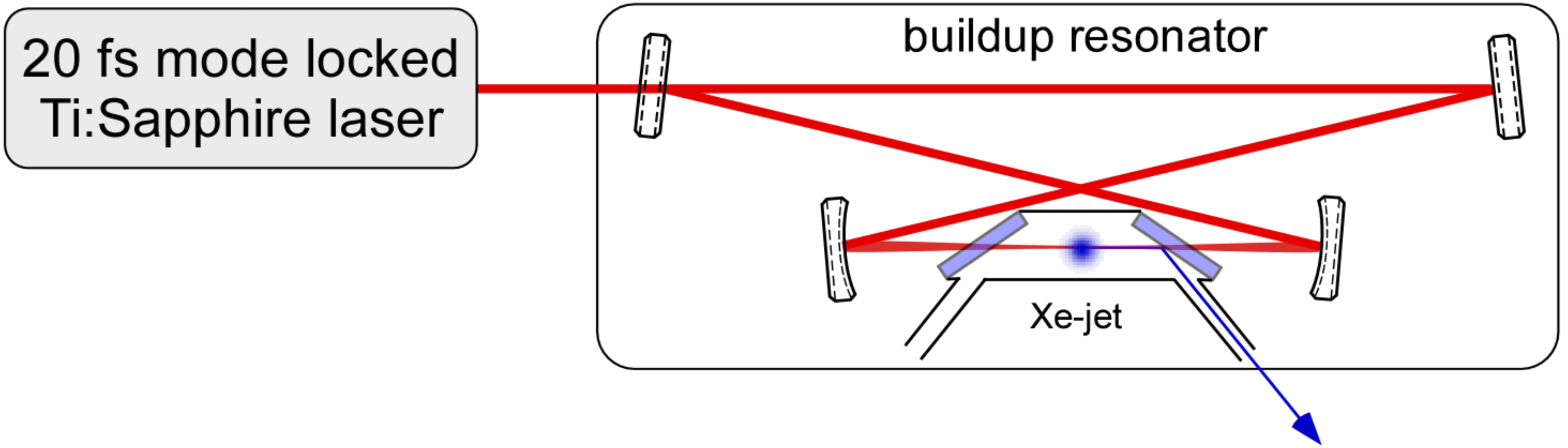


all modes contribute.

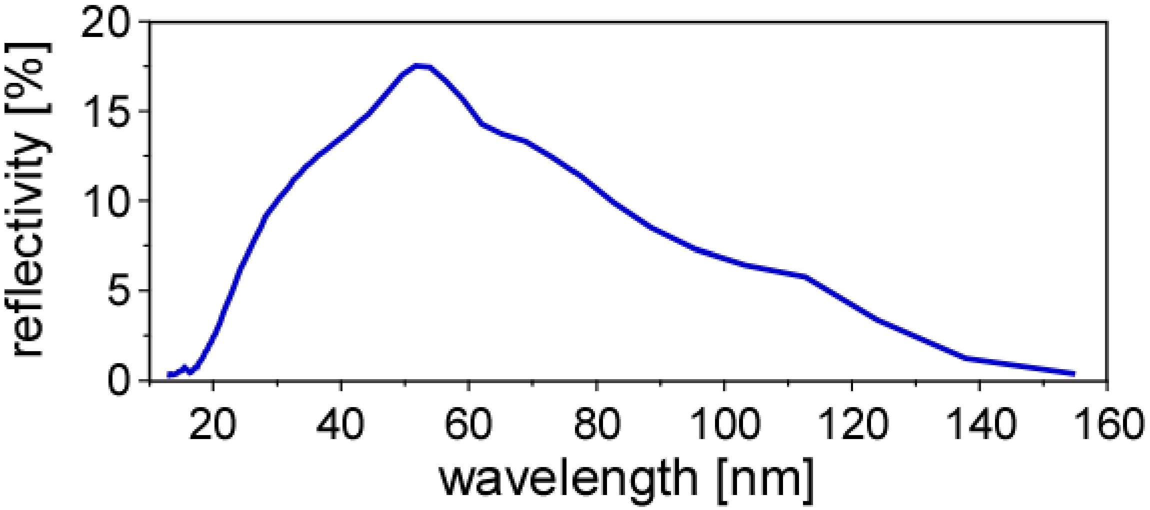
Pionieered by: Ye.V.Baklanov, V.P.Chebotayev, Appl. Phys 12, 97 (1977) and M.J.Snadden, A.S.Bell, E.Riis, A.I.Ferguson, Opt. Comm. 125, 70 (1996)

HHGs with 114 MHz Repetition Rate

focal spot ~5.3 μm 1/e diameter~5.5 x 10^{13} W/cm²

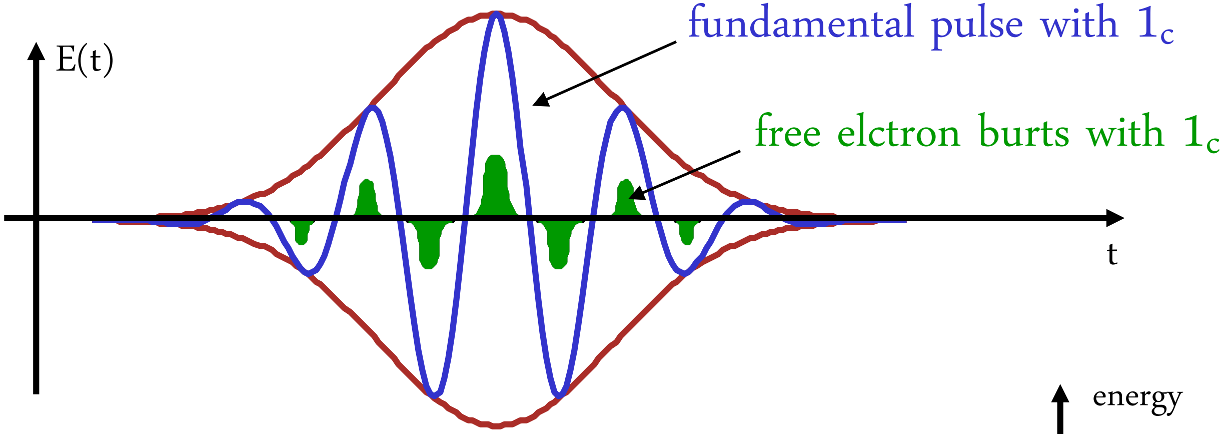


XUV output



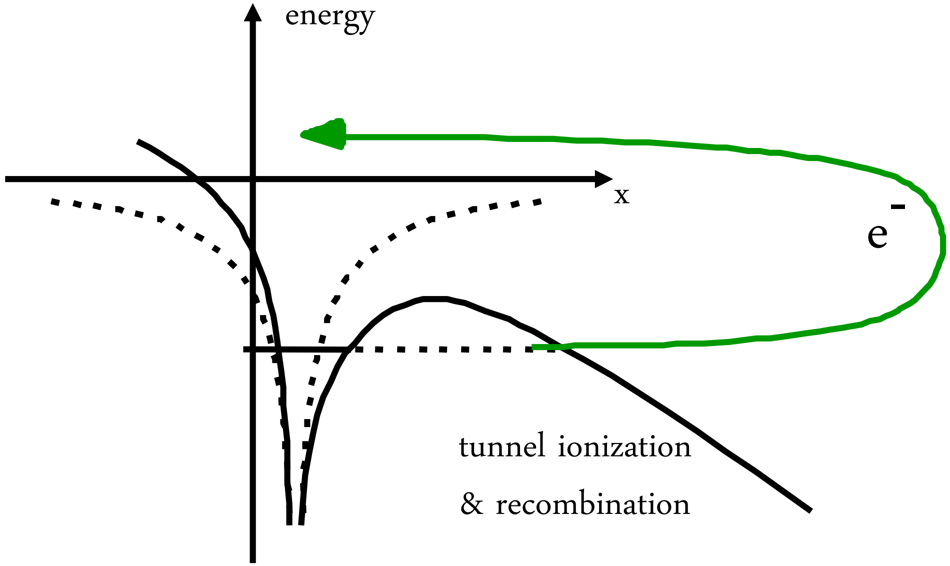
Nature 436, 234 (2005) & PRL Phys. Rev. Lett. 94, 193201 (2005)

High Harmonics Generation (HHG)



fundamental pulse with 1_c

free elctron burts with 1_c

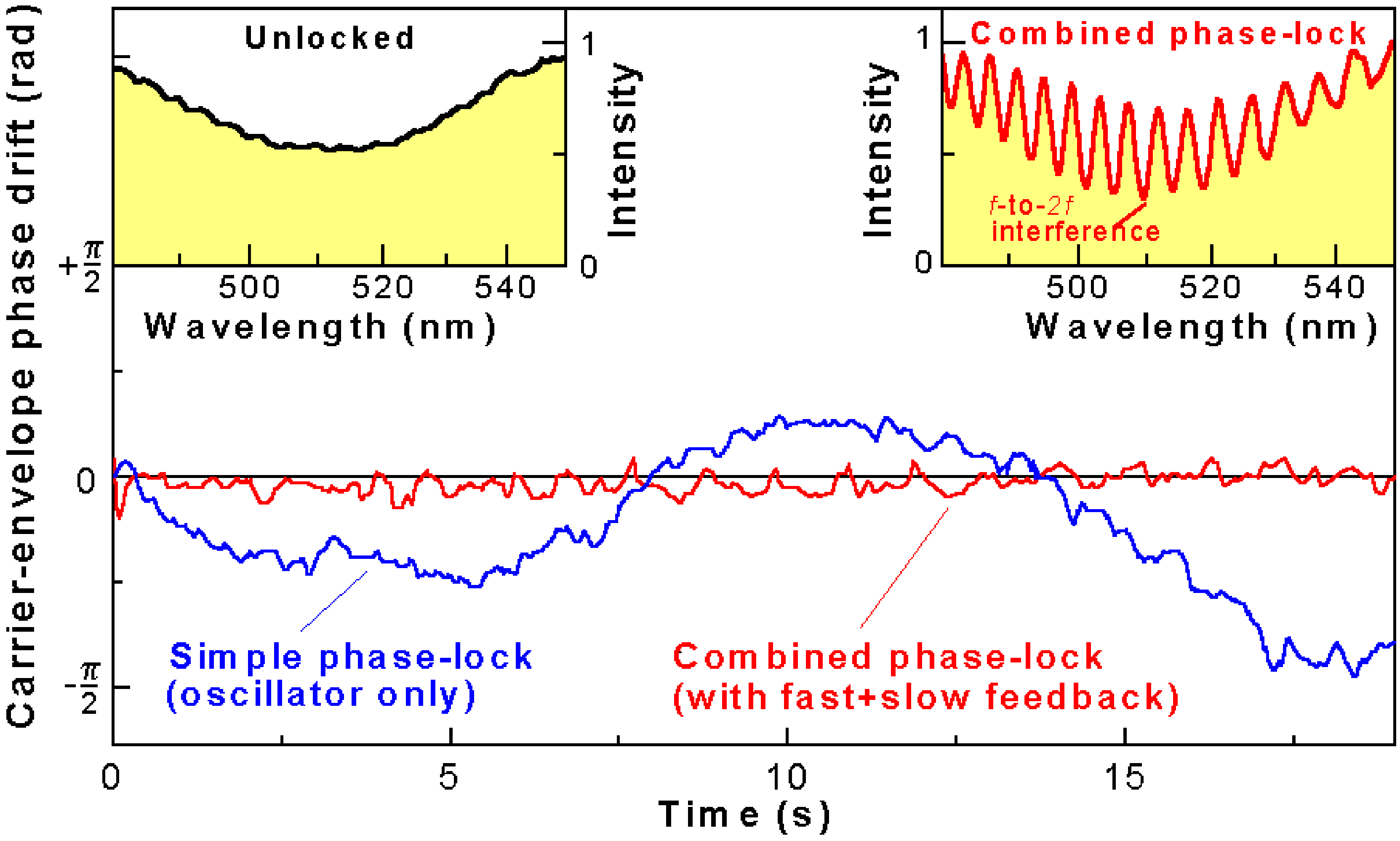


tunnel ionization

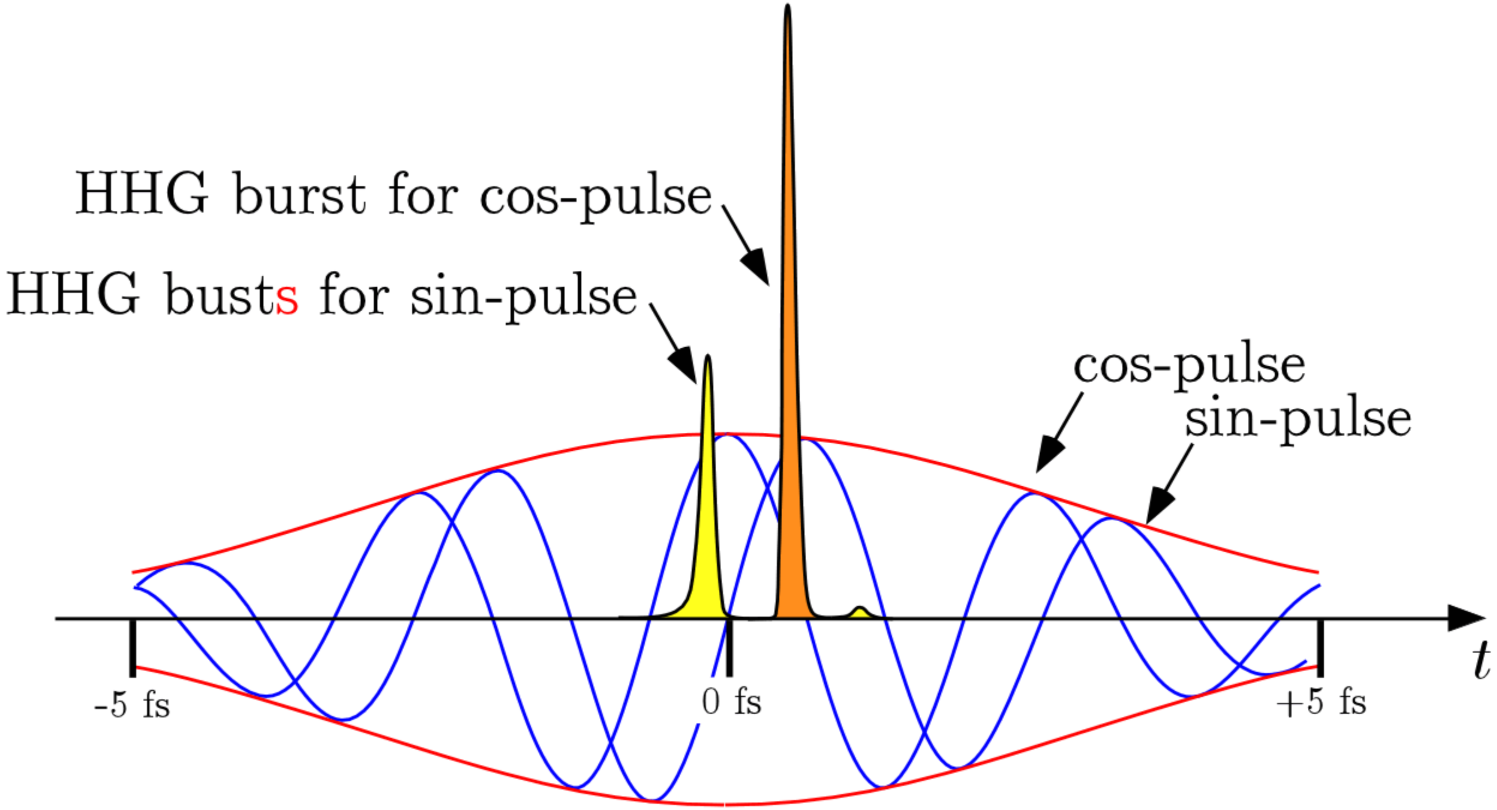
& recombination

- free electrons emit HHG´s
- only odd orders created
- HHG vanish for smal elliptic polarization
- very short pulses make HHG´s merge

Stabilzing the CE Phase of Intense Pulses



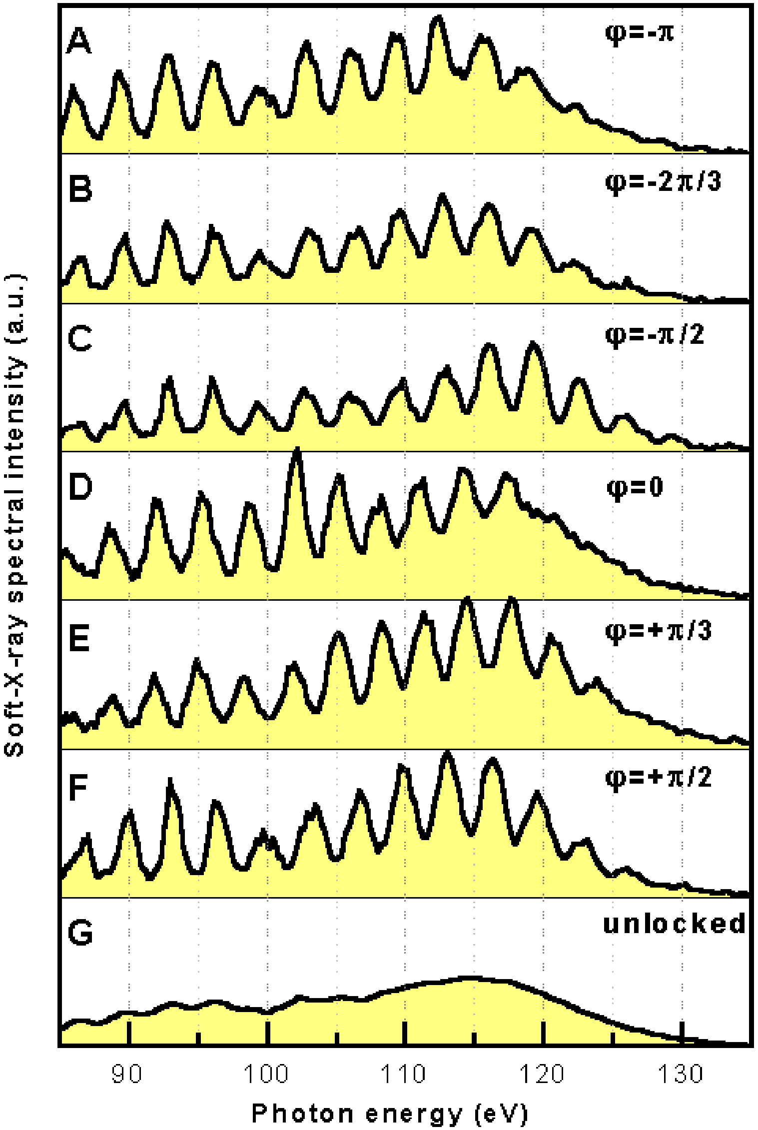
Phase Sensitive High Harmonic Generation



calculated HHG intensity @ 3.2nm

Phys. Rev. Lett. 85, 740 (2000)

Phase Sensitive High Harmonic Generation



sin drive

cos drive