The MIR* experiment: towards an in-vacuum detection of the Dynamical Casimir Effect

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on behalf of
the MIR collaboration

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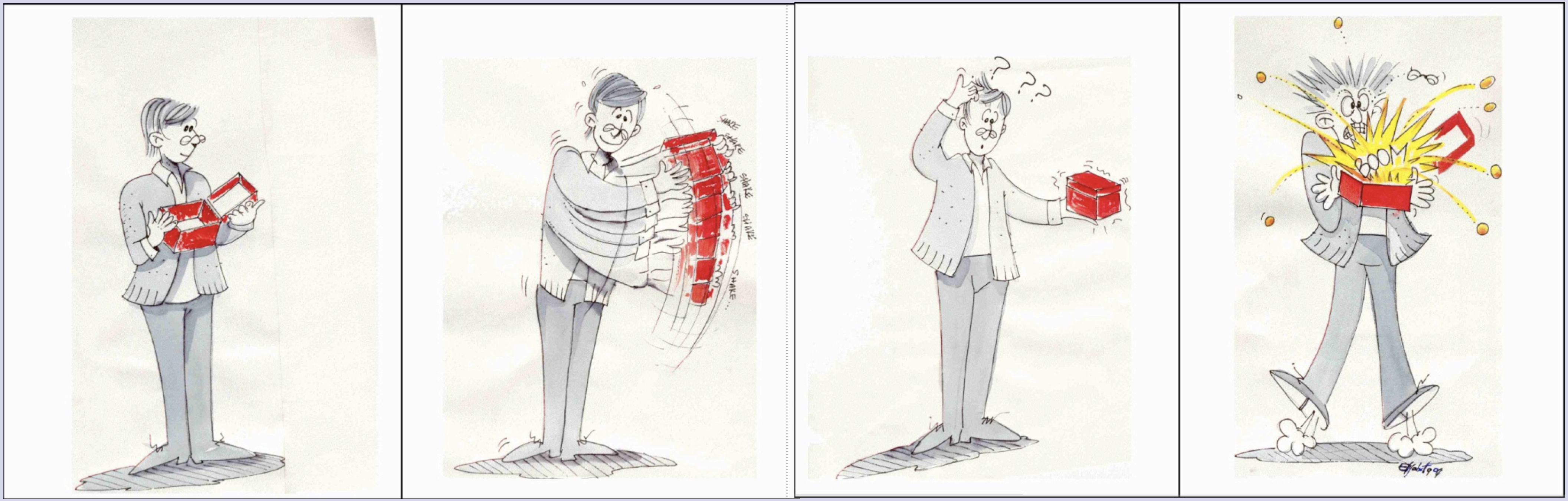
* Motion Induced Radiation

Outline



- Dynamical Casimir Effect
- Introduction to the MIR experimental scheme
- Optimization of the experimental parameters to maximize the gain
- Parametric excitation of a pre-charged field in the cavity
- Preliminary data analysis and discussion
- Perspectives and Conclusions

Dynamical Casimir effect

Due to dissipative effects against the quantum vacuum, non-uniformly accelerated boundaries should **emit real photons** with energies corresponding to the Fourier frequencies of the movement.

"Generation of particles pairs out of vacuum fluctuations via quantum squeezing induced by time-dependence of macroscopic boundary conditions"

Quantum theory of electromagnetic field in a variable-length one-dimensional cavity
Moore 1970, *J. Math. Phys.* **11**, 2679

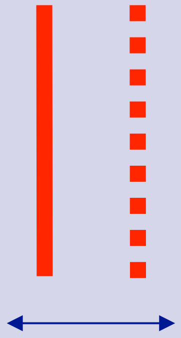
Radiation from a moving mirror in two dimensional space-time: conformal anomaly
Fulling and Davies 1976, *Proc. R. Soc. Lond. A* **348**, 393

$\langle N_{ph} \rangle \sim \Omega_m T \beta^2$

Motion Induced Radiation from a Vibrating Cavity
Lambrecht, Jaeckel, and Reynaud 1996, *Phys. Rev. Lett.* **77**, 615

Oscillating mirror
$\Omega_m / 2\pi \sim 10$ GHz
$T \sim 1$ s observation time
$\beta = v/c = 10^{-7}$
$\langle N_{ph} \rangle << 1$

effect is not detectable



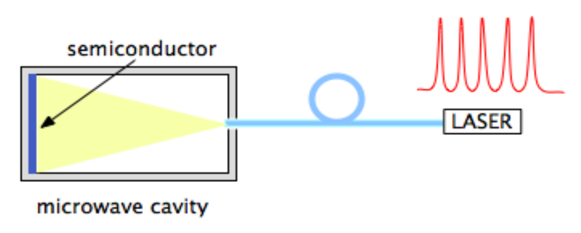
Resonating Cavities to increase the signal

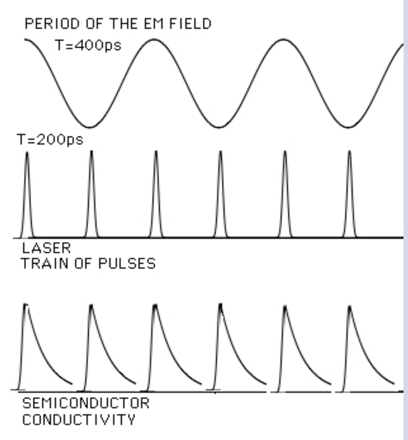
MIR experimental scheme - 1

MAIN INGREDIENTS

- Modulation of the surface conductivity of a semiconductor slab
- Parametric amplification inside a microwave cavity ($f_{rep} = 2f_0$)

A novel experimental approach for the detection of the dynamical Casimir effect
Braggio *et al*. 2005, *Europhys. Lett.* **70**, 754



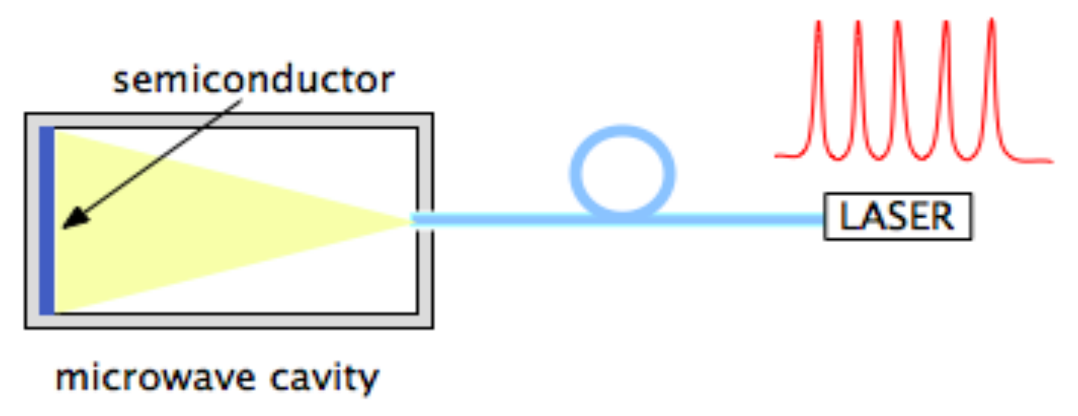


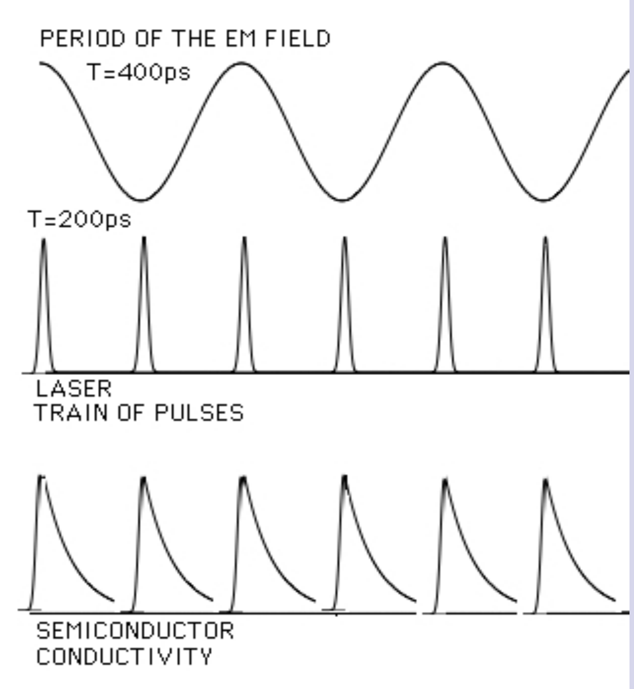
Accelerating reference frame for electromagnetic waves in a rapidly growing plasma: Unruh-Davies-De Witt radiation and the nonadiabatic Casimir effect
E. Yablonovitch 1989, *Phys. Rev. Lett.* **62**, 1742

Parametric excitation of vacuum by use of femtosecond pulses
Lozovik, Tsvetus, and Vinogradov 1995, *Physica Scripta* **52**, 184

Quantum phenomena in nonstationary media
Dodonov, Klimov, and Nikonov 1993, *Phys. Rev. A* **47**, 4422

MIR experimental scheme - 2





Requirements:

- RF cavity geometry: high stationary frequency shift, small illumination area, $f_0 \approx 2.5$ GHz, $Q_0 \approx 10^4$–10^6

- laser system: high frequency repetition rate ($f_{rep} \approx 5$ GHz, stability better than the cavity BW 1 kHz), tunable f_{rep}, ~10 ps pulse duration, $E_{\text{pulse}} \geq$ few microjoule, 780 – 820 nm output wavelength

- semiconductor: $d \approx 1$ mm thickness, high mobility (1 m^2/V s @ 4 K), recombination time of a few picoseconds

- low noise microwave receiver: sensitivity a few hundreds of 10^{-5} eV energy photons (i.e. 10^{-22} W/Hz)

Braggio *et al.* 2009, *NIM A* **603**, 451

Theory

V. V. Dodonov

Calculations with realistic MIR experimental conditions

Results: a significant amount of Dynamical Casimir photons (>10^3) can be produced in MIR experiment with feasible parameters

Calibration of the apparatus with a pre-charged field or with thermal photons

E_0 thermal or external field

$$N_{ph}(n) \propto E_0 e^{2|\chi_{\max}|F(A_0)n}$$

n number of pulses

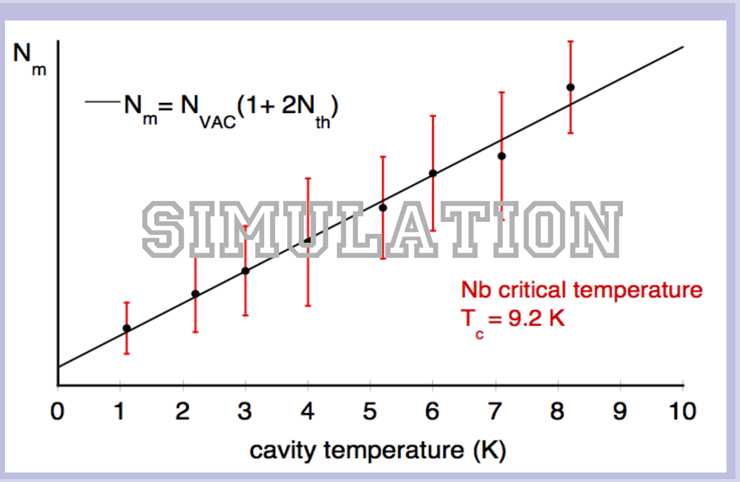
$F(A_0)$ gain coefficient

$|\chi_{\max}|$ increases with stationary frequency shift $\Delta f = f_{ill} - f_0$

Dynamical Casimir effect at finite temperature
Plunien, Schuetzhold, and Soff 2000, *Phys. Rev. Lett.* **84**, 1882

$$N_{th} = \frac{kT}{h\nu} = 8.5T$$

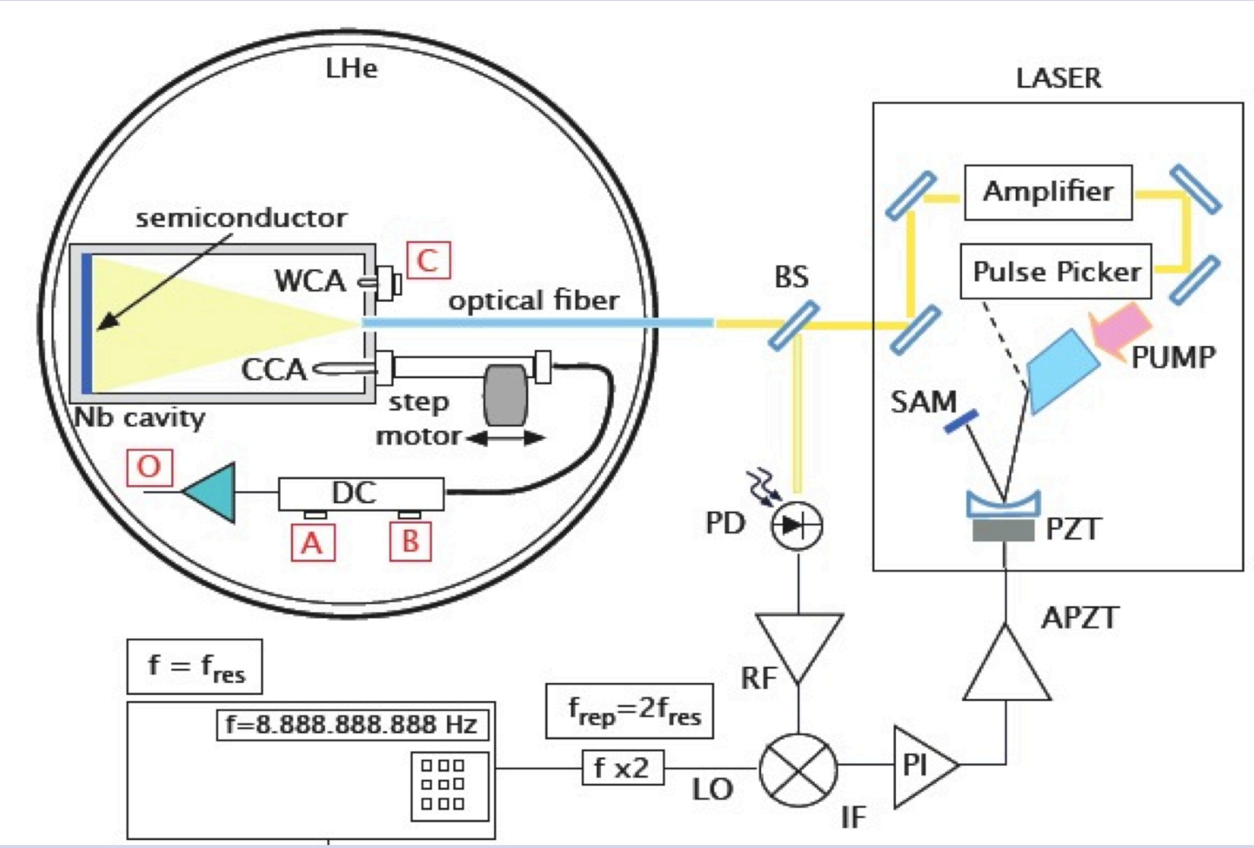
$$N^{meas} = G(1+2N_{th})$$



MIR experimental scheme - 3

30 l

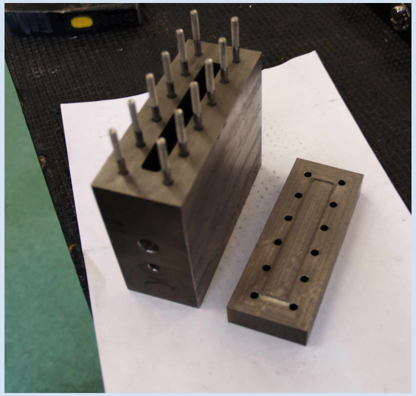
80 l LHe vessel, $T = (0.8 \div 9)$ K



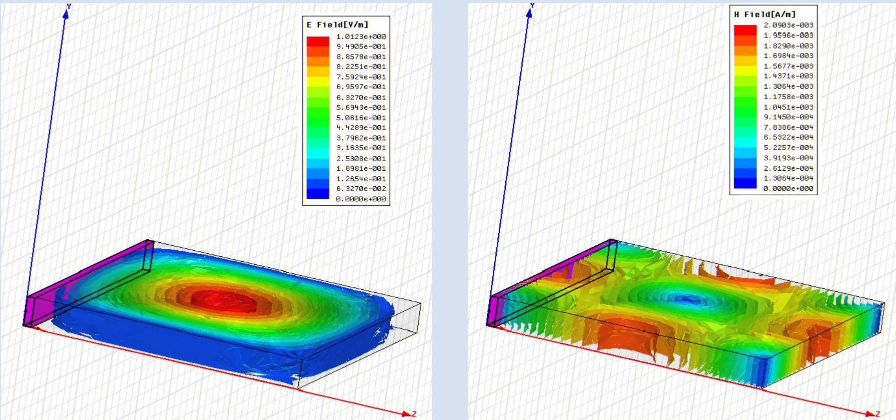
Microwave Cavity

Nb superconducting cavity

(80 x 90 x 9) mm^3



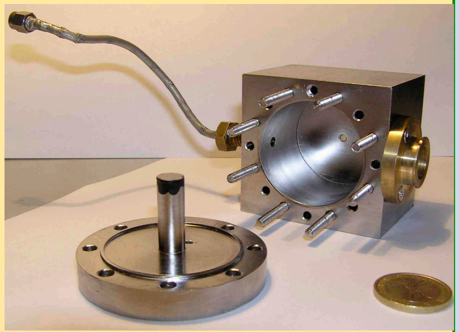
E, H field profiles



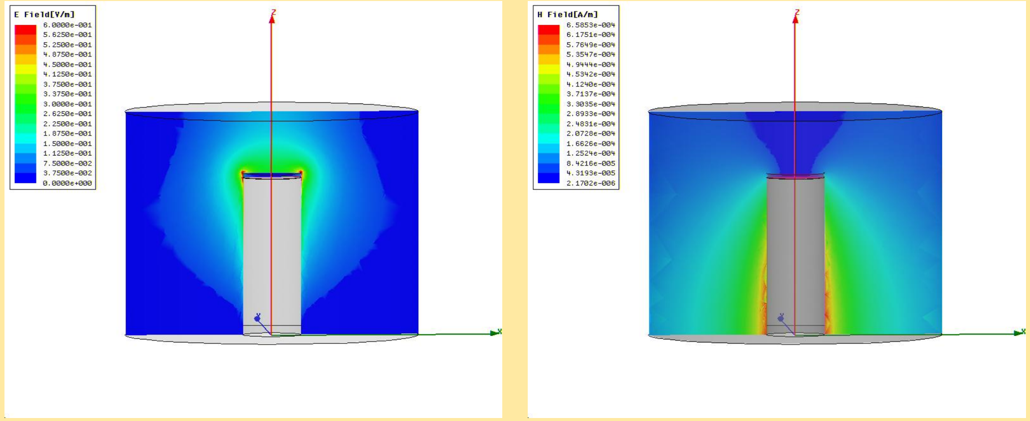
Cylindrical reentrant cavity

($\Phi_{\mathrm{cav}} = 42$ mm, $h = 34$ mm, $\Phi_{\mathrm{GaAs}} = 8$ mm, $d = 10$ mm)

1. Smaller amount of E_{pulse}
2. Simplified optical scheme for uniform illumination of the semiconductor



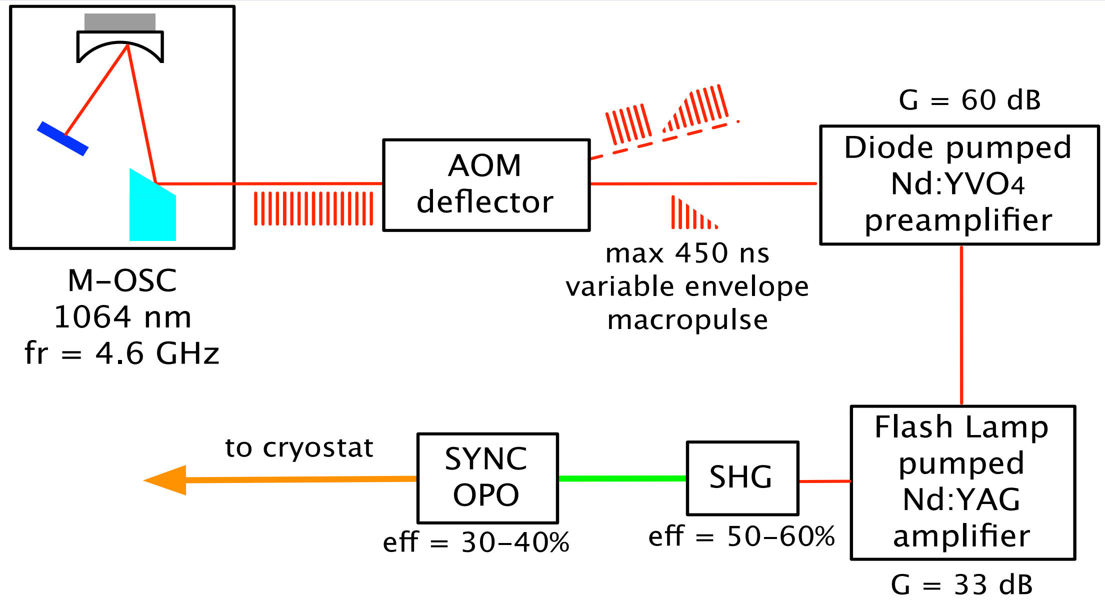
E, H field profiles



Note that:

- @ semiconductor position: $E \approx 0$ (rectangular cavity);
  $E = E_{\mathrm{max}}$ (cylindrical reentrant cavity)
- opposite sign of the frequency shift

Laser system - 1



M-OSC
1064 nm
fr = 4.6 GHz

AOM deflector

max 450 ns
variable envelope
macropulse

G = 60 dB

Diode pumped
Nd:YVO4
preamplifier

Flash Lamp
pumped
Nd:YAG
amplifier

G = 33 dB

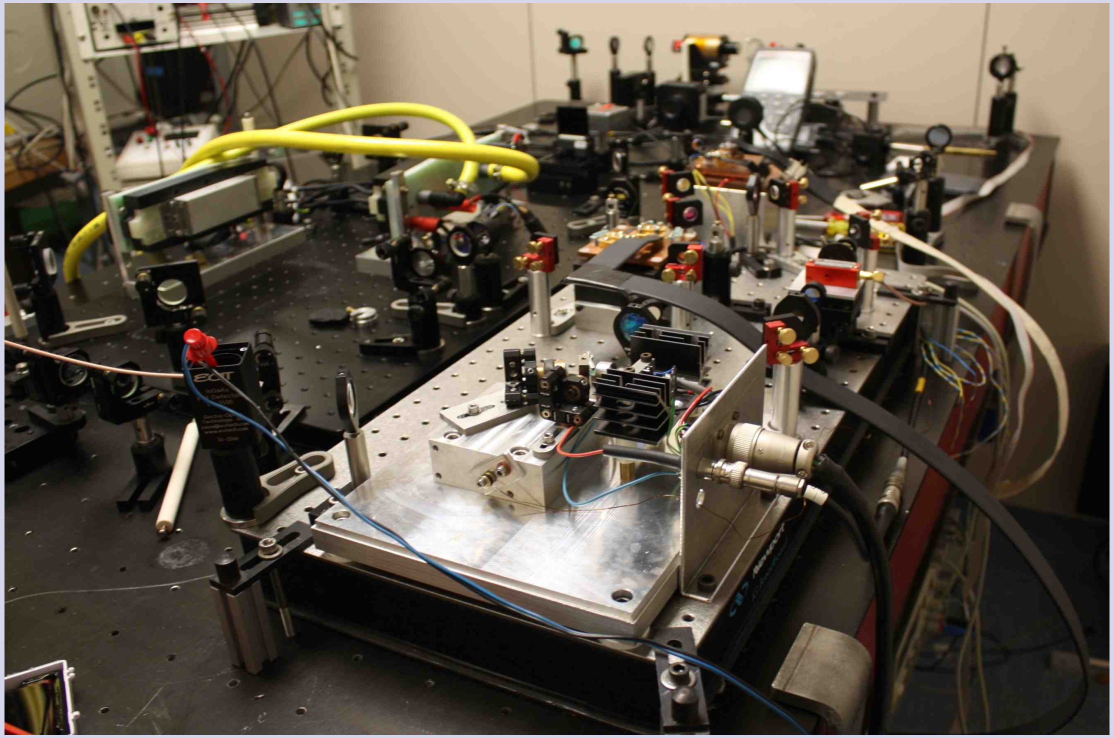
SHG

eff = 50–60%

SYNC
OPO

eff = 30–40%

to cryostat



$E_{\text{pulse}} \approx 10\ \mu\text{J}$;
since the average power of a CW mode-locked laser having this value of energy per pulse would be too high, we developed a laser delivering a macropulse of $\Delta T = 350 - 450$ ns duration (~ 2000 pulses).

Total macropulse energy is a few tens of millijoules

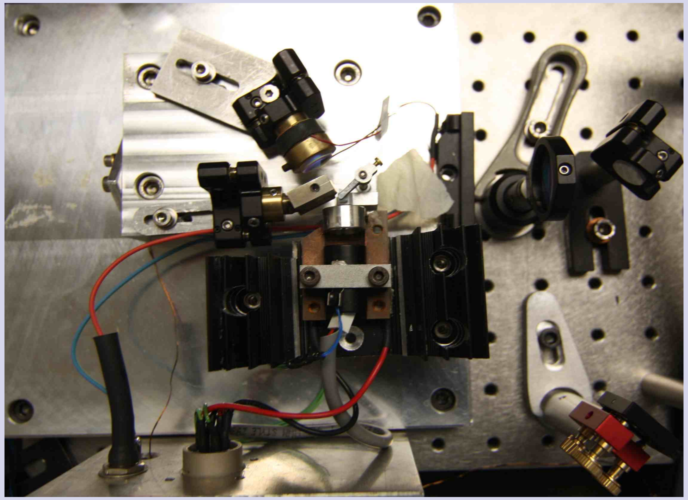
FINAL SPECS
- high frequency repetition rate ($f_{rep} \approx 5$ GHz, stability better than the cavity BW 1 kHz),
- tunable f_{rep},
- 10 ps pulses duration,
- $E_{\text{pulse}} \approx$ few microjoules,
- 780 – 820 nm output wavelength

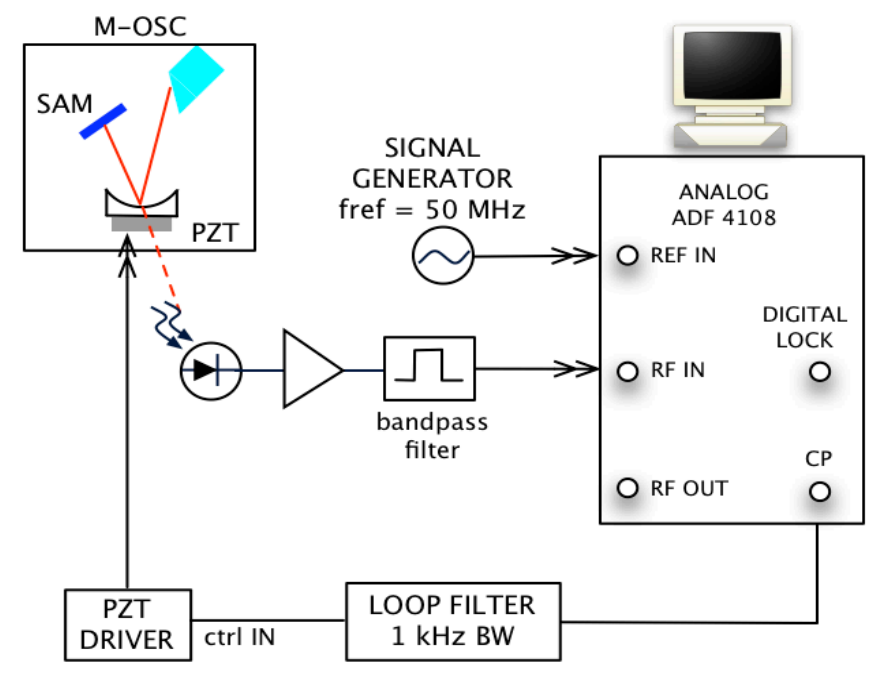
Agnesi *et al.*, *Optics Express* **13**, 5302 (2005)
Optics Express **14**, 9244 (2006)
Optics Express **16**, 15811 (2008)

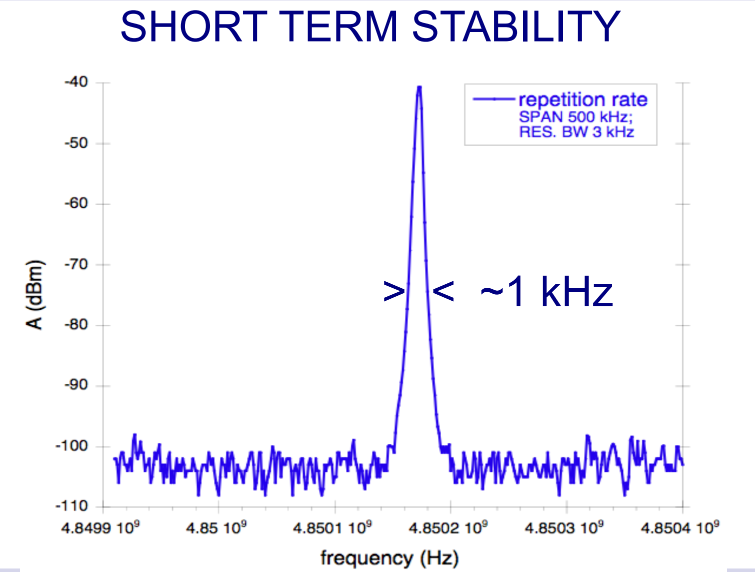
Laser system - 2

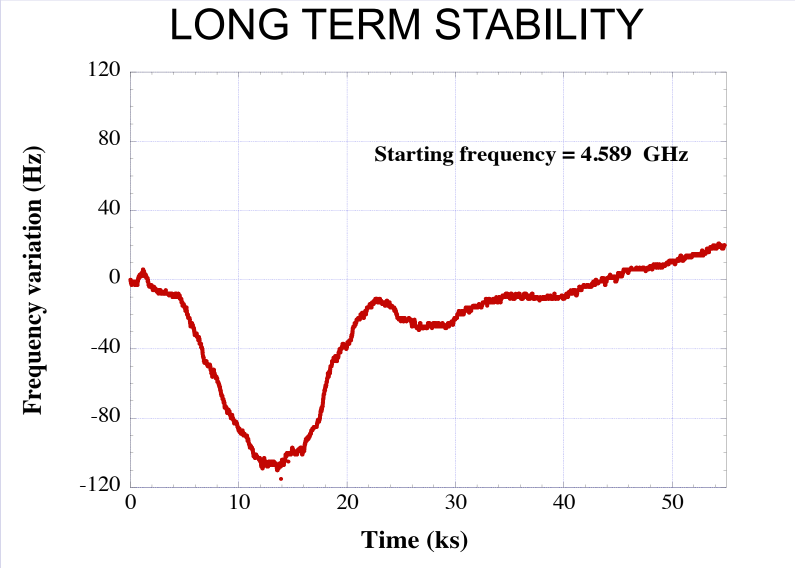
LASER repetition rate stability and tuning

Active control of the Master Oscillator length:
the feedback system locks the repetition frequency
of the laser to a reference microwave generator



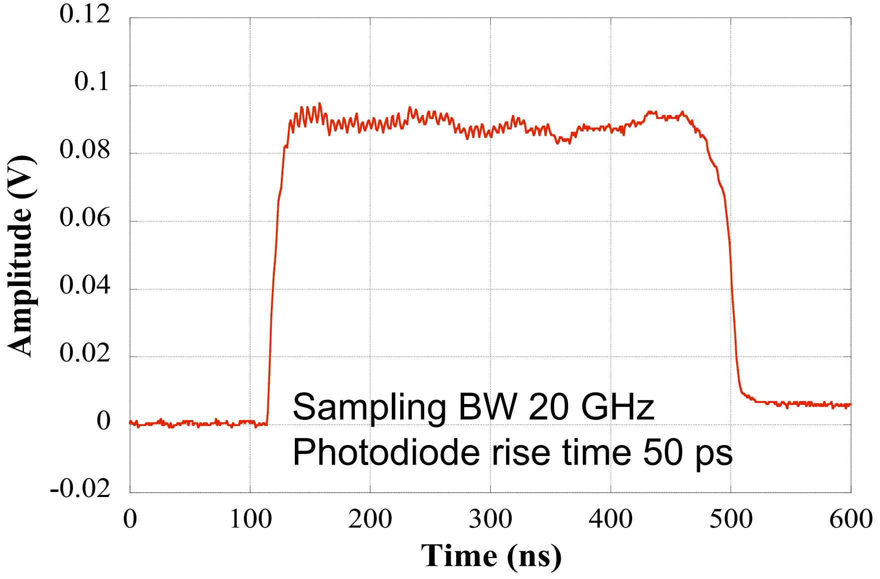



SHORT TERM STABILITY


LONG TERM STABILITY

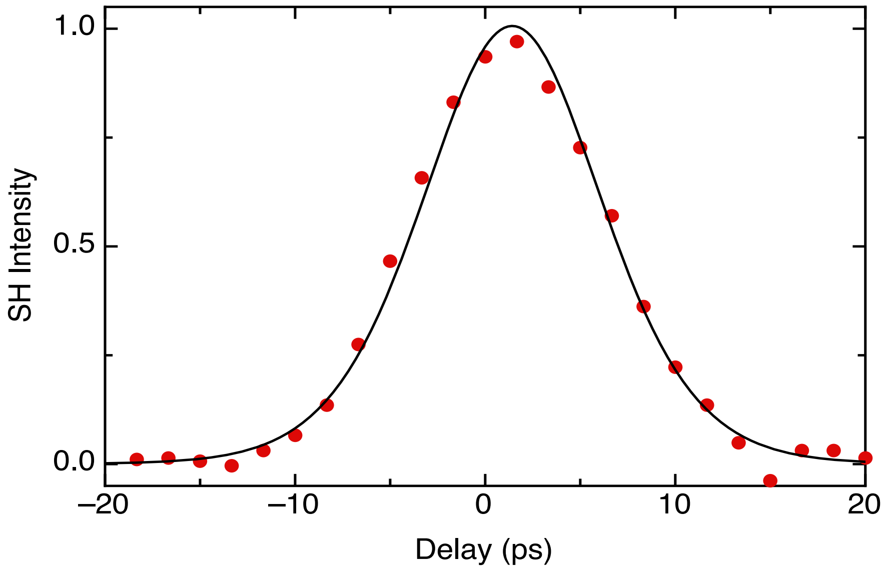
Laser system - 3

TRAIN OF PULSES

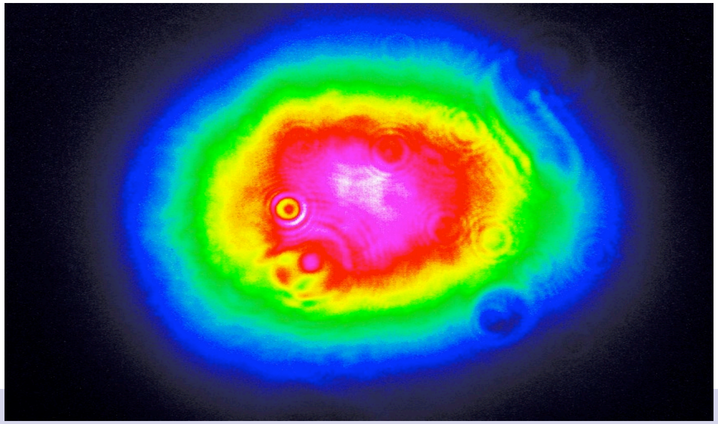


Sampling BW 20 GHz
Photodiode rise time 50 ps

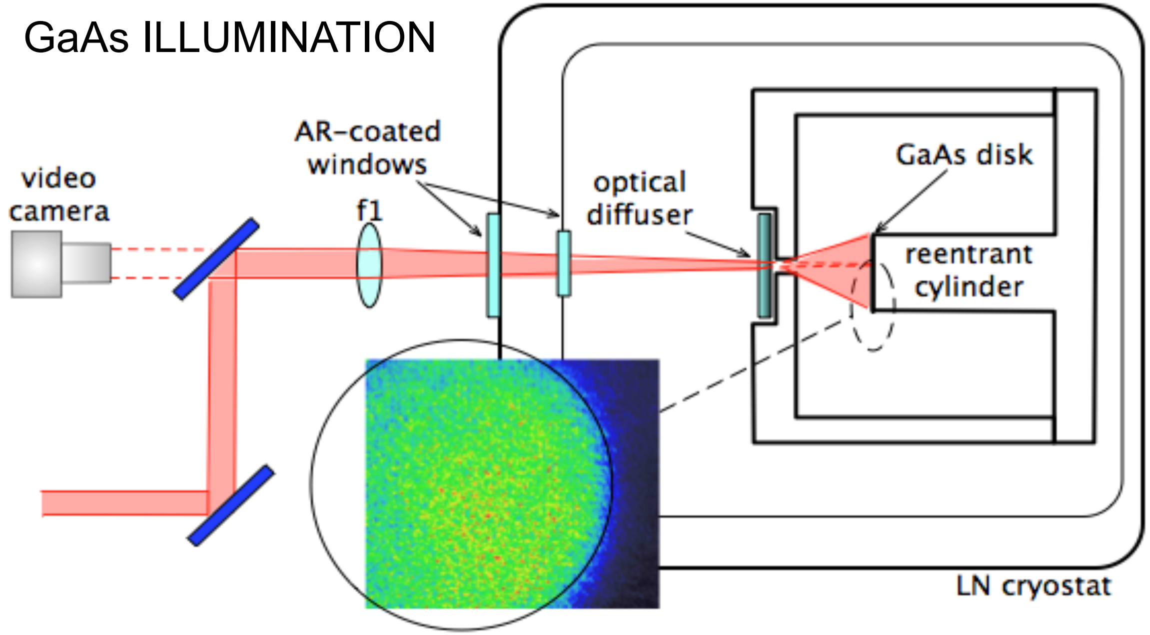
AUTOCORRELATION MEASUREMENT



BEAM PROFILE



GaAs ILLUMINATION



Semiconductor- 1

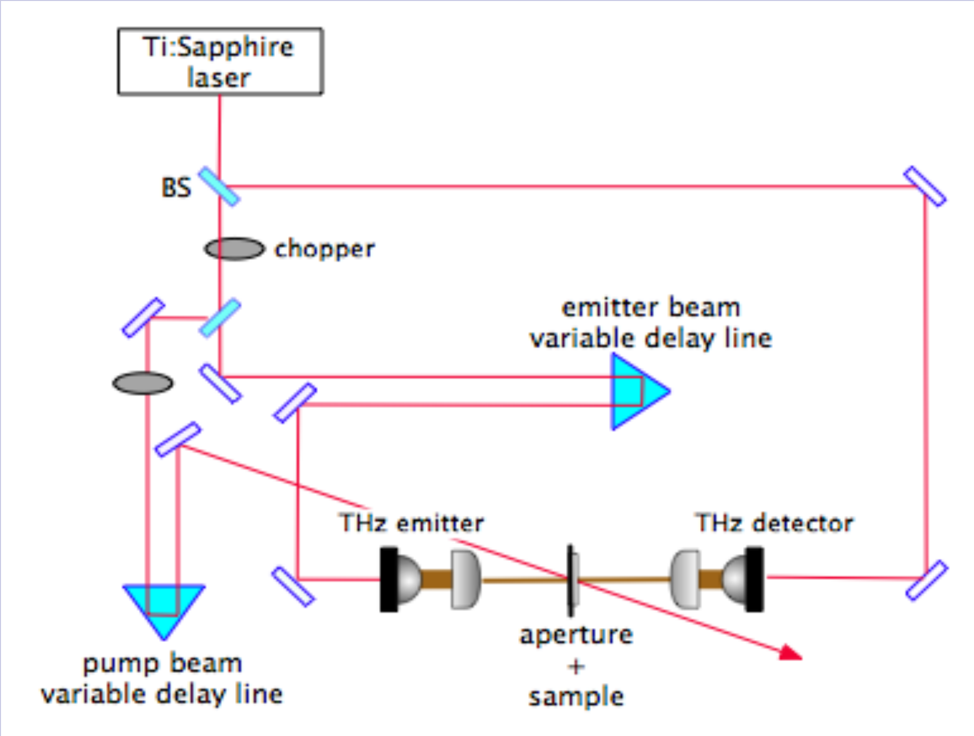
Requirements: high mobility (1 m^2/V s)
short recombination time (a few picosecons)

R&D on a new material, starting from semi-insulating (SI) GaAs

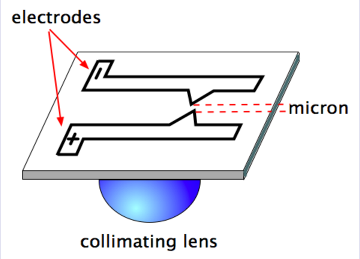
~~SI GaAs irradiated with thermal neutrons (Italy, USA)~~	Foulon *et al.* 2000, *J. Appl. Phys.* **88**, 3634
SI GaAs irradiated with Au, Br ions (Tandem accel. in LNL)	Mangeney *et al.* 2002, *Appl. Phys. Lett.* **80**, 4711
SI GaAs irradiated with 1-5 MeV protons (CN accel. in LNL)	Mangeney *et al.* 2000, *Appl. Phys. Lett.* **76**, 40

Measurement of the recombination time and mobility of the irradiated samples

Optical-pump terahertz-probe setup in SELITEC Vilnius, Lituania (prof Krotkus group)



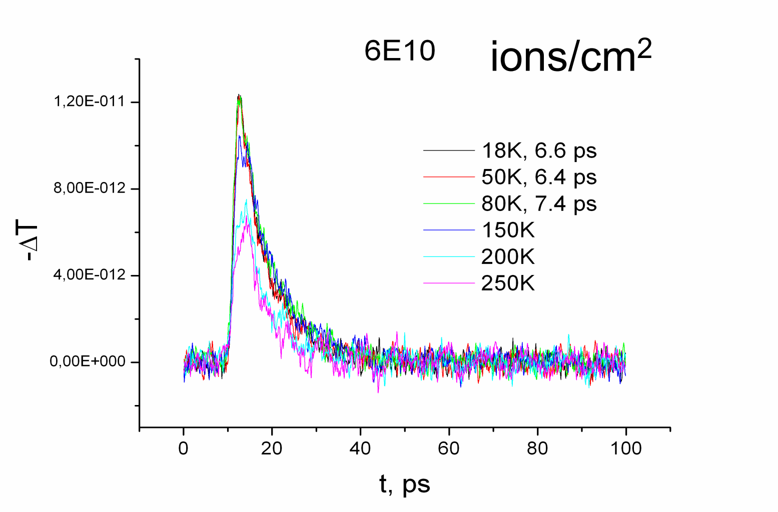
1. Same concentration of free carriers produced as in the plasma mirror ($n \approx 10^{17}$ cm^{-3});
2. Measurements are conducted at different temperatures in the range 300 – 10 K in a cryocooler



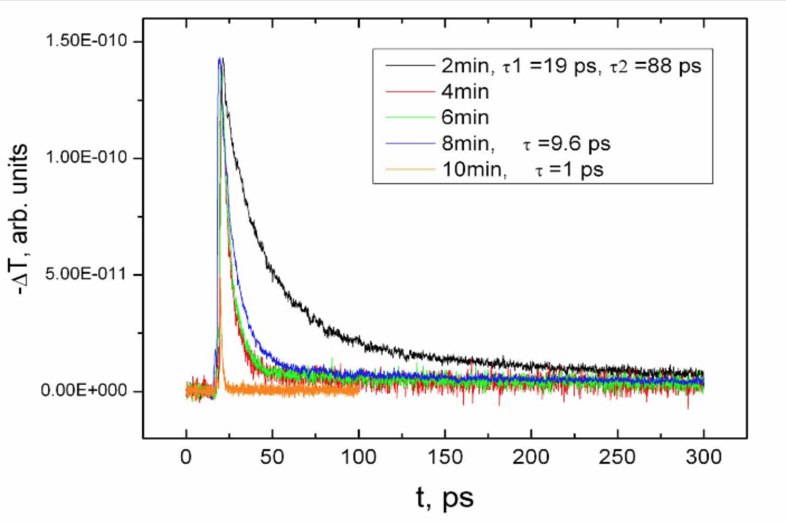
Semiconductor- 2

Measurements of mobility and recombination time with the optical-pump terahertz-probe setup: the terahertz transmission signal is connected to the variation of the GaAs conductivity

240 MeV Br^{14+} ions:
20 μm thickness of irradiated material
Recombination time at different temperatures



1 – 5 MeV protons:
100 μm thickness of irradiated material
Recombination time ad different irradiation doses

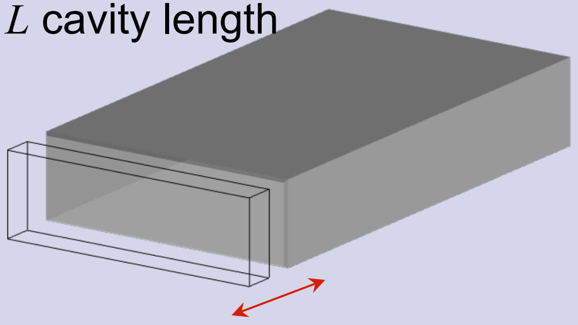


MOBILITY is inferred by comparison between the terahertz transmitted amplitude through the non-irradiated sample and the same sample after the irradiation procedure

After irradiation the mobility is 5 – 10% of the initial value (highest at 80 K). Still sufficient!

Stationary frequency shift - 1

The total number of produced photons depends exponentially on the frequency shift



L cavity length

d semiconductor thickness

$$N_{ph}(n) \propto E_0 e^{2|\chi_{\max}| F(A_0) n}$$

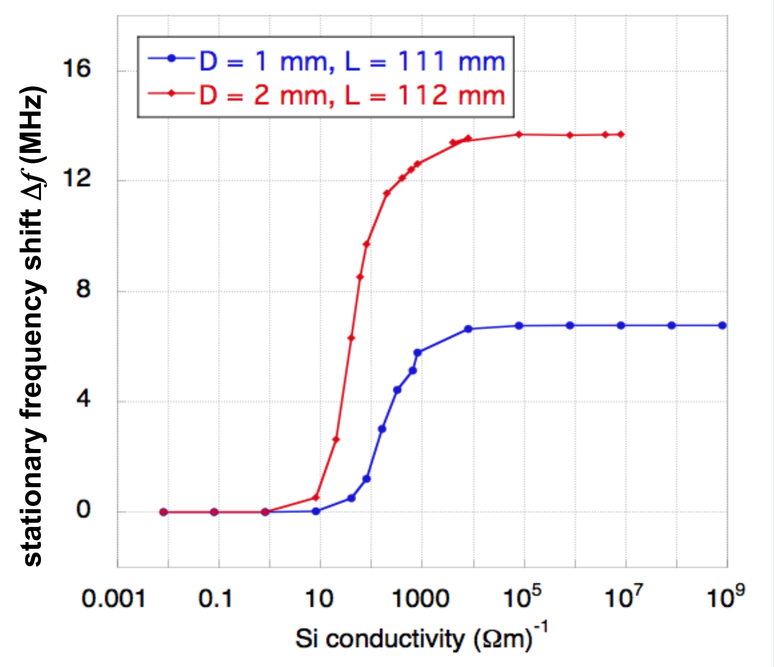
n number of pulses

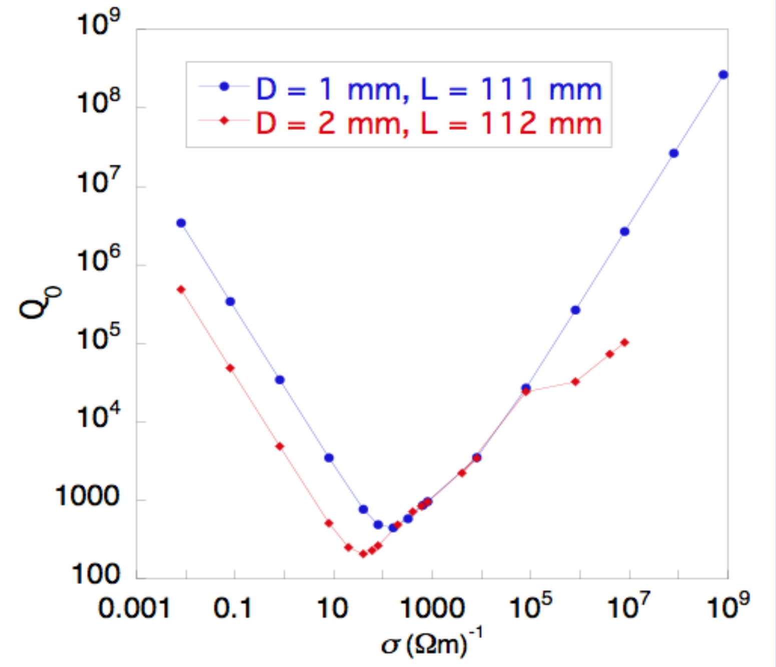
$F(A_0)$ gain coefficient

$|\chi_{\max}|$ increases with stationary frequency shift $\Delta f = f_{ill} - f_0$

$|\chi_{\max}| = 0.005 - 0.008$ for $d = 600\ \mu\text{m}$

Results obtained with Ansoft HFSS
(stationary boundary conditions, volume plasma)

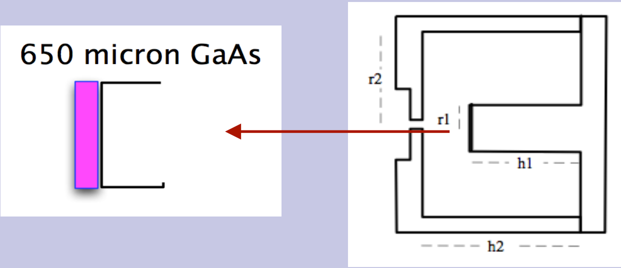




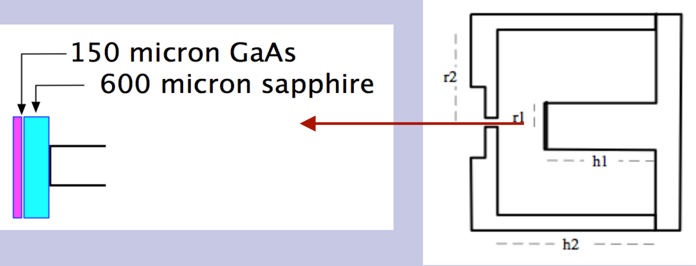
Stationary frequency shift - 2

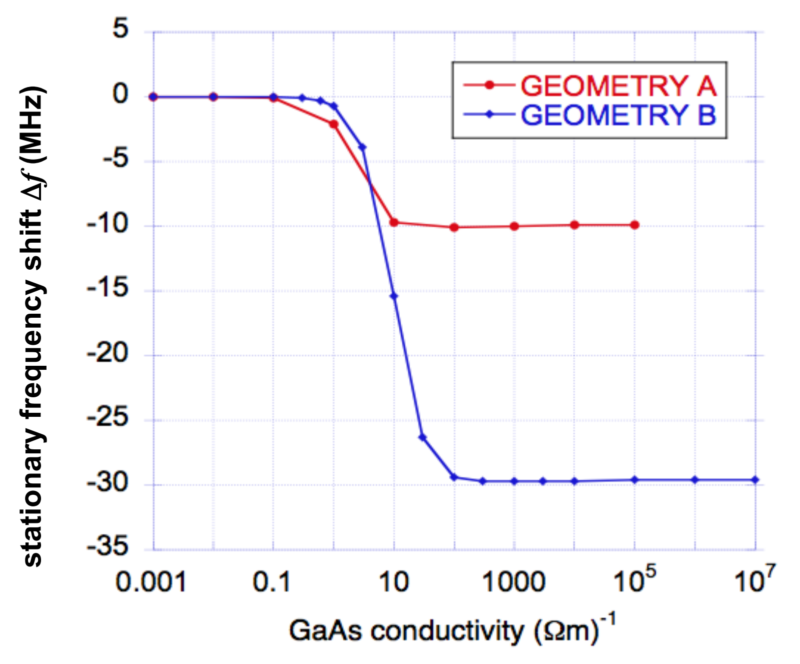
stationary frequency shift $\Delta f = f_{ill} - f_0$

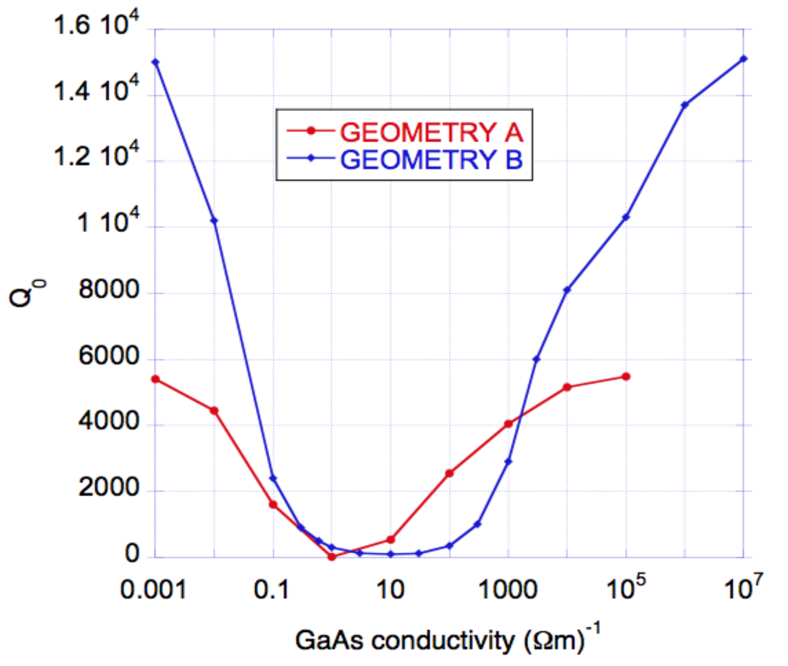
GEOMETRY A



GEOMETRY B

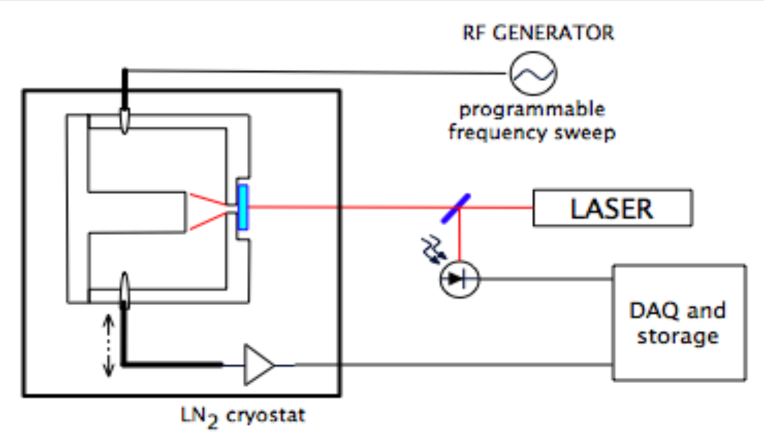






Stationary frequency shift - 3

Measuring the stationary frequency shift $\Delta f = f_{ill} - f_0$



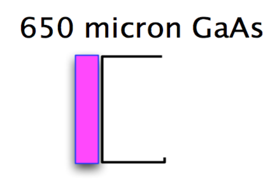
NON-IRRADIATED SEMICONDUCTOR

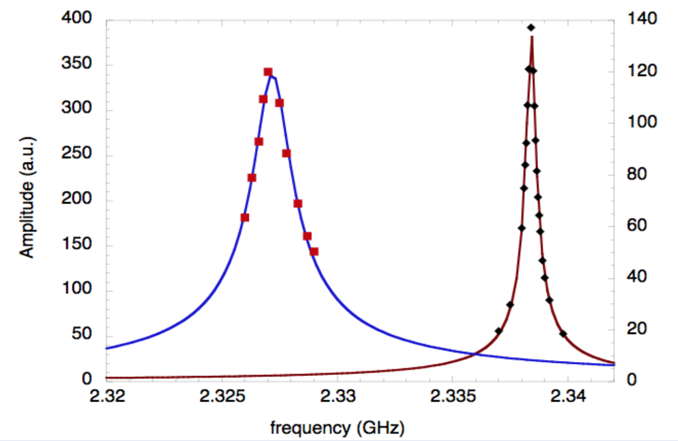
τ ≈ few nanoseconds @ $T = 290$ K

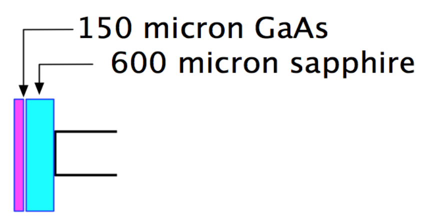
τ ≥ 100 µs @ $T = 77$ K

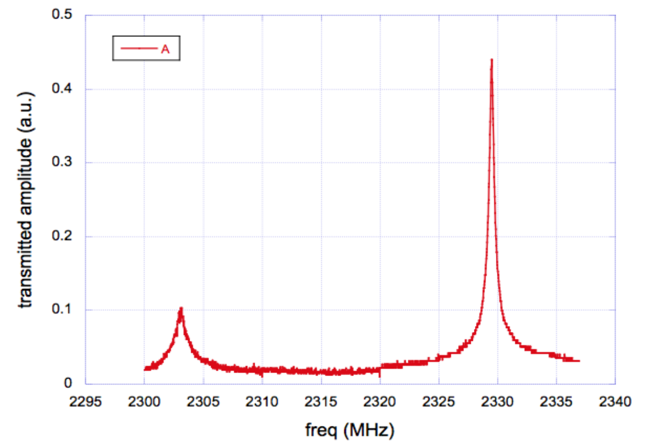
The free carrier plasma lasts for the whole duration of the macropulse ($\Delta t \approx 400$ ns).

$$\Gamma(\nu) = \frac{A\nu}{\sqrt{\left[\nu^2 - \nu_0^2 + \left(\frac{\nu_0}{2Q_0}\right)^2\right]^2 + \frac{\nu_0^2}{Q_0^2}}}$$









$f_{ill} = 2327.200 \pm 0.044$ MHz $Q_{ill} = 1500 \pm 100$
$f_0 = 2338.400 \pm 0.014$ MHz $Q_0 = 6200 \pm 100$
$\Delta f = f_{ill} - f_0 = -11$ MHz

$f_{ill} = 2303.08 \pm 0.05$ MHz $Q_{ill} = 2600 \pm 100$
$f_0 = 2329.50 \pm 0.05$ MHz $Q_0 = 8500 \pm 100$
$\Delta f = f_{ill} - f_0 = -26.4$ MHz

We obtain the same Δf foreseen by the simulations. In both cases there is a volume plasma

Stationary frequency shift - 4

In the previous measurement the free carriers are present in the overall GaAs volume. During the experiment we use instead a short $\tau \Rightarrow$ very thin film of photoexcited carriers

Thickness of the plasma is determined by absorption of light: $I = I_0 \exp(-\alpha x)$

at $T = 77$ K for $\lambda = (810 \pm 10)$ nm,
the absorption coefficient is $\alpha^{-1} \approx 1$ μm

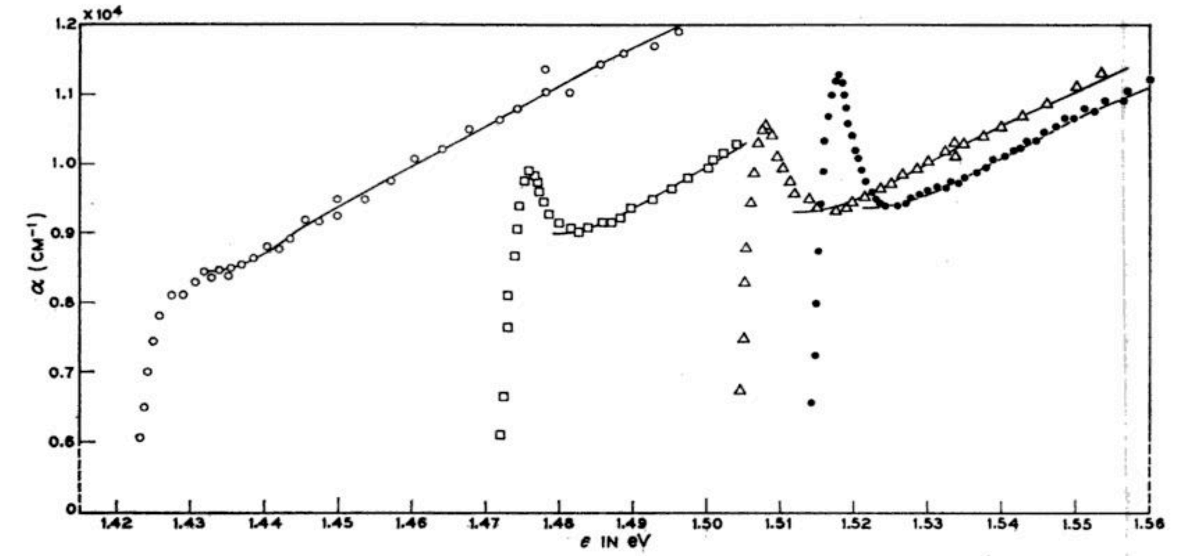
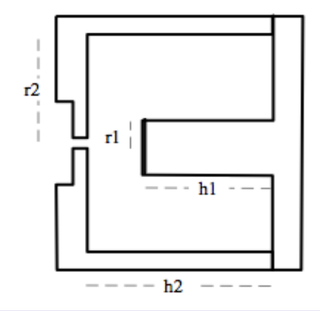
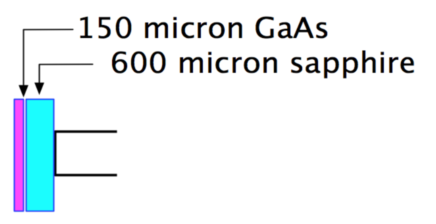


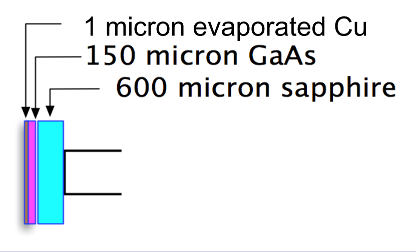
FIG 3 Exciton absorption in GaAs; ○ 294°K, □ 186°K, Δ90°K, ● 21°K.

Optical absorption of gallium arsenide between 0.6 and 2.75 eV
M. D. Sturge 1962, *Phys. Rev.* **127**, 768

Measurement with a thin metallic mirror:







$f_0 = 2.3285 \pm 0.1$ MHz
$Q_0 = 5000 \pm 100$

$f_{\mathrm{Cu}} = 2.3005 \pm 0.1$ MHz
$Q_0 = 5000 \pm 100$

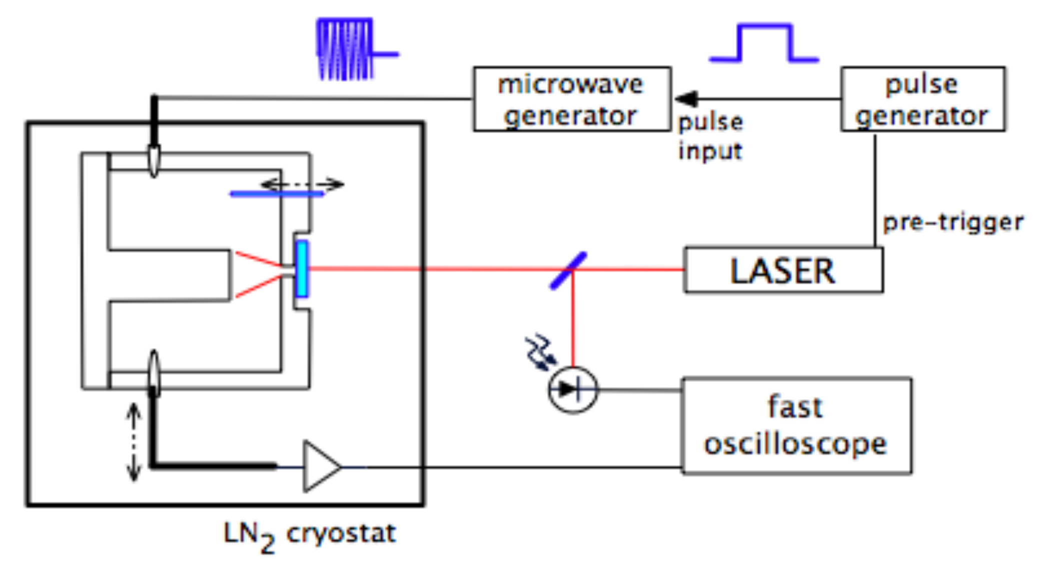
$\Rightarrow$ $\Delta f = f_{\mathrm{Cu}} - f_0 \approx 28$ MHz

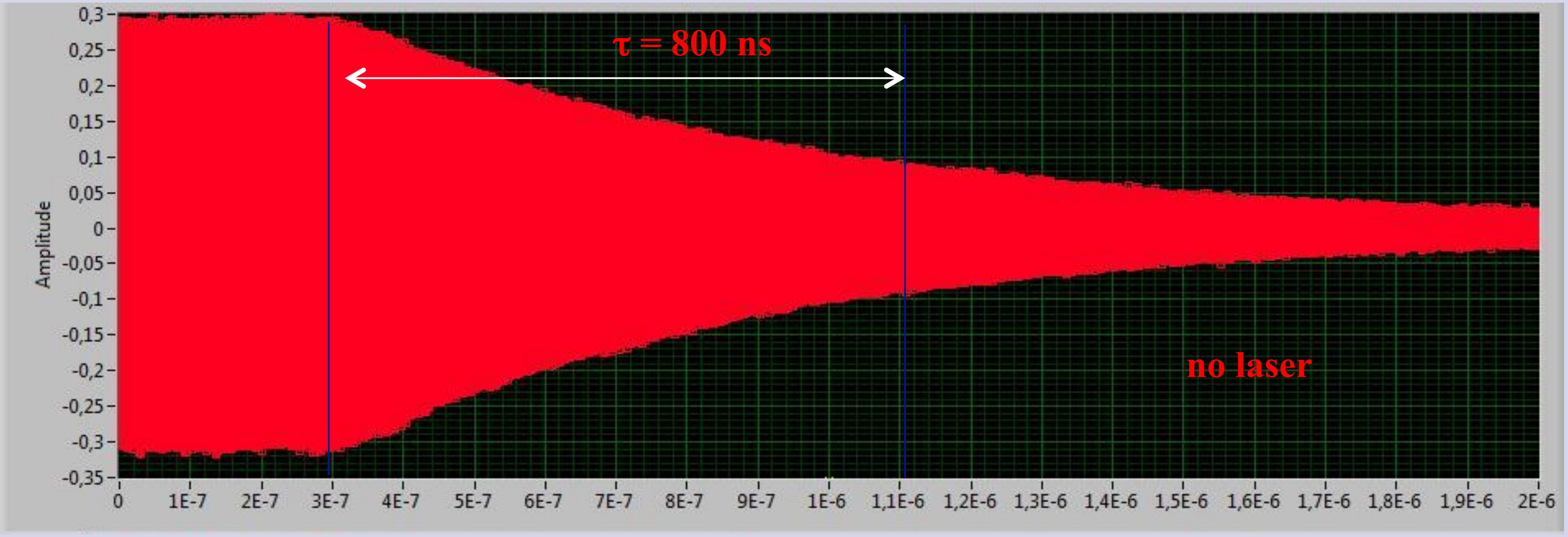
These measurements are not sufficient to characterize the “moving mirror”

Parametric excitation of an external field - 1

GAIN OF THE PARAMETRIC AMPLIFIER

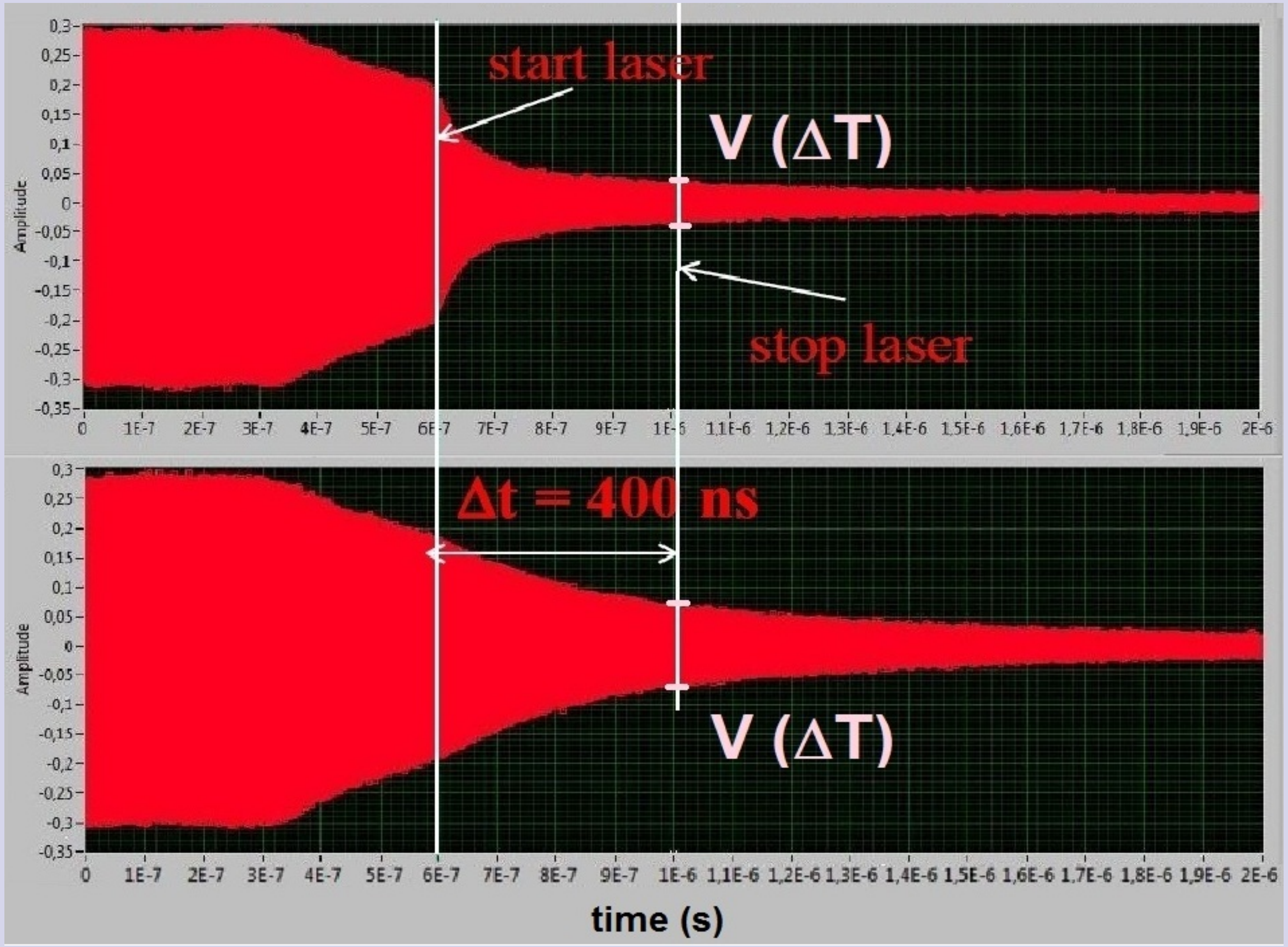
1. The cavity unperturbed mode f_0 is critically coupled to the transmission line; the cavity is pre-charged
2. the radiofrequency at the frequency f_0 of the unperturbed cavity is switched off and the EM field starts to decay with decay time τ_0 (free oscillations);

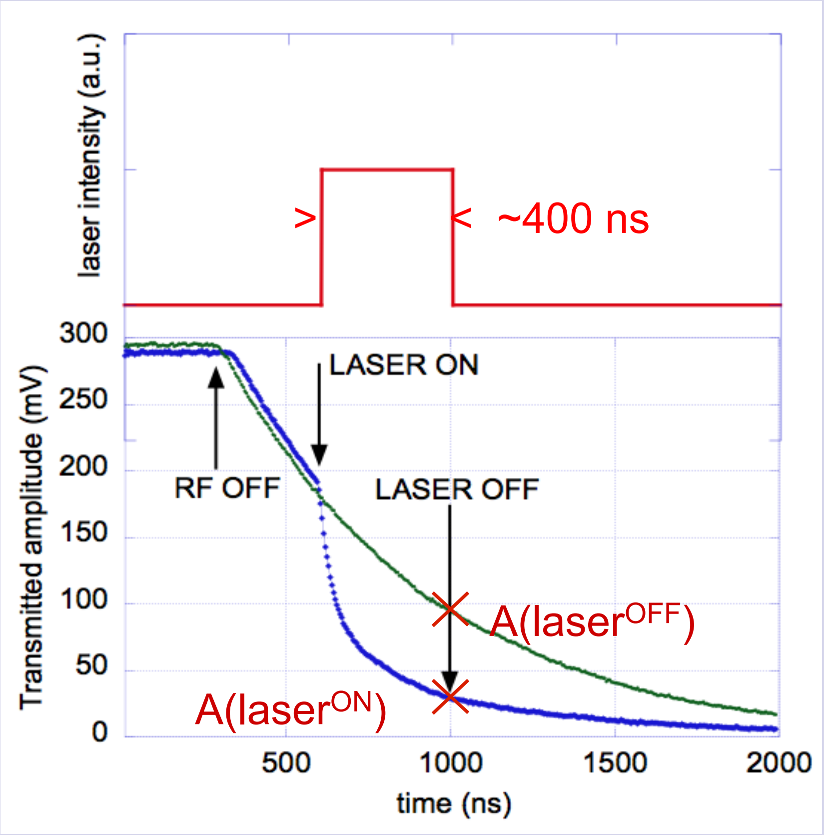




Parametric excitation of an external field - 2

3. ~100 ns after switching off the external generator, during the field decay, the laser train of pulses impinges on the semiconductor surface

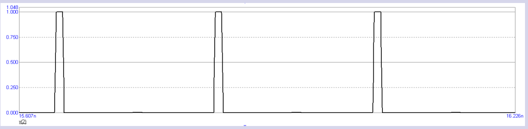


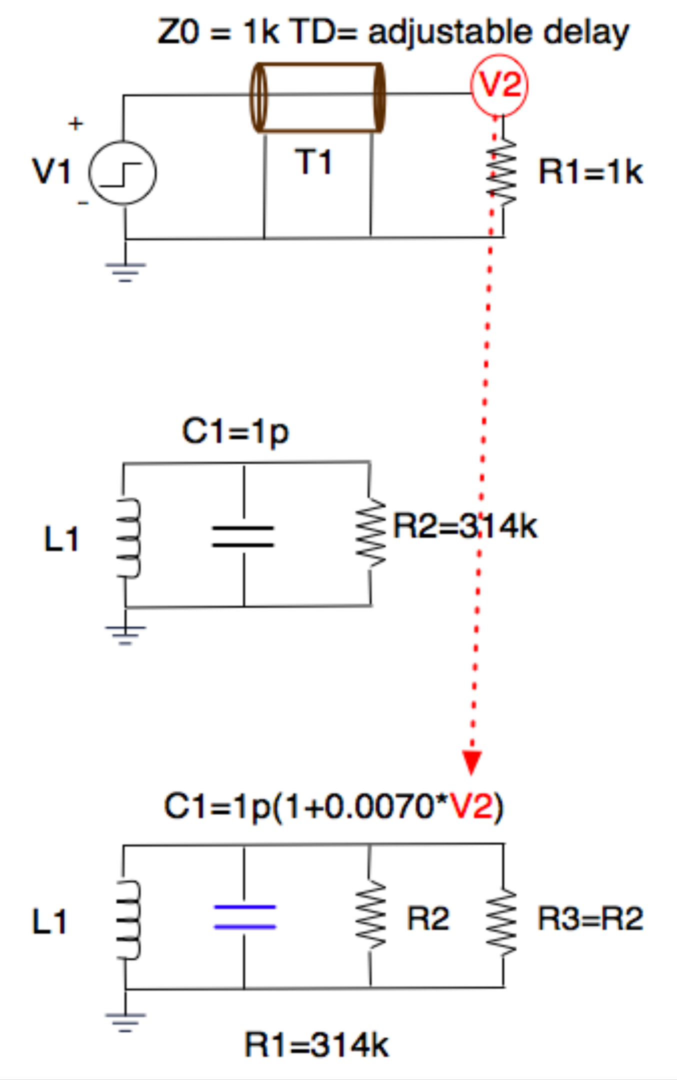


Amplification is never observed!

GAIN of the parametric amplifier = $A(\text{laser}^{ON})/A(\text{laser}^{OFF})$

Experiment simulation: RLC circuit - 1





pulse generator ⇔ train of pulses

- this circuit generates a voltage V2 which is then used to mathematically modify capacity C1
- Δt_{exc} excitation period
- temporal shape of the excitation (rise/decay time - duration)
- TD delay line to change the phase between the excitation and the free oscillations

RLC circuit ⇔ unperturbed cavity

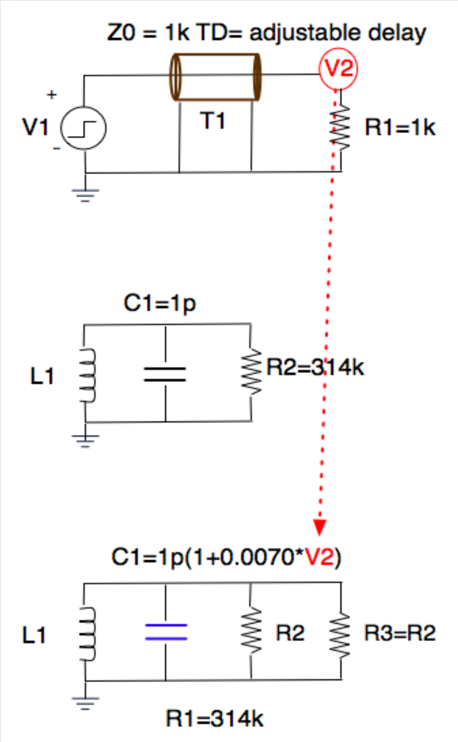
- $f_0=1/2\pi(LC)^{1/2}$ free oscillations frequency
- $Q_0 = R/\omega_0 L$ quality factor of the unperturbed cavity

RLC with variable capacitance ⇔ parametric excited cavity

- coefficient of V2 determines ΔC, corresponding to a frequency shift in the cavity $|\Delta f| = f\,\Delta C/2C$
- $Q_{\mathrm{exc}} = R_{\mathrm{parallel}}/\omega_0 L$ quality factor of the perturbed cavity

Experiment simulation: RLC circuit - 2

Transient analysis: evolution of an initial applied voltage level ⇔ pre-charged field



Example

FREE OSCILLATIONS

$f_0 = 2516.51$ MHz; $Q_0 = 5000$

MODULATION

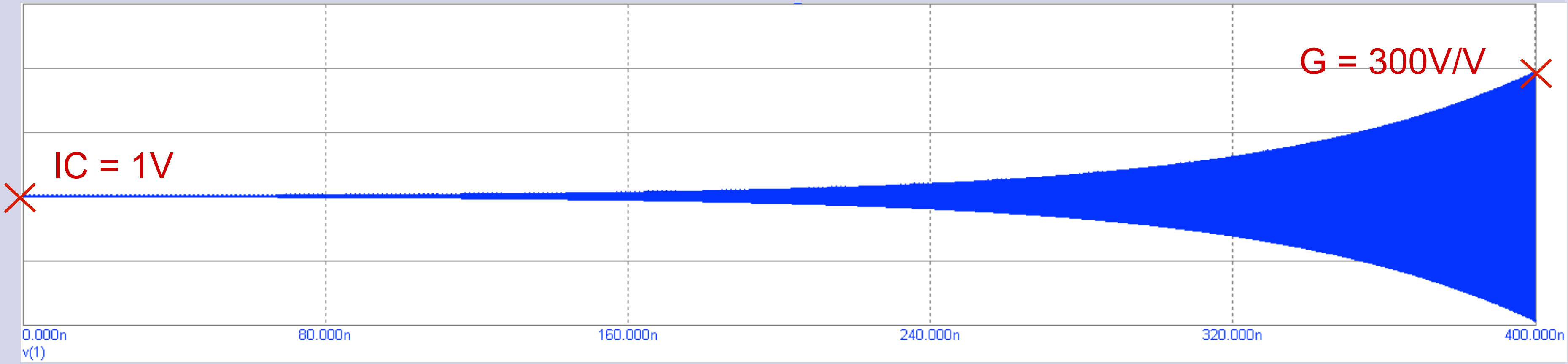
stationary frequency shift $\Delta f = 8.5$ MHz

2 ps rise time – 8 ps duration – 2 ps decay time

at parametric resonance

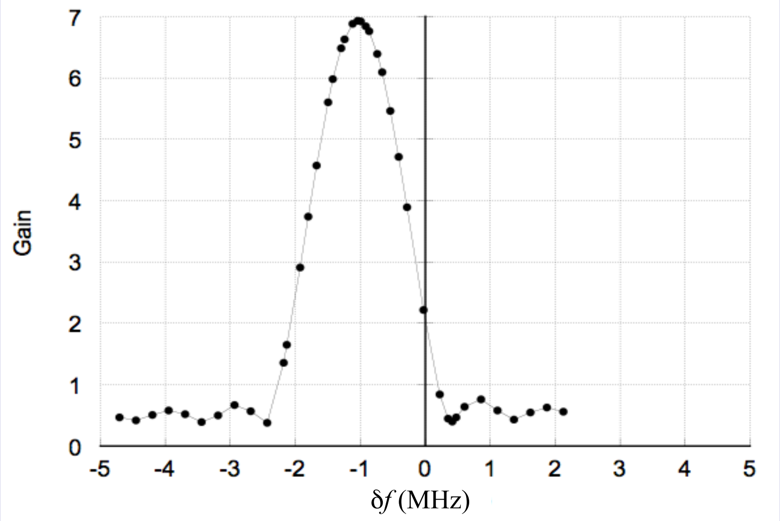
exponential growth of the field amplitude

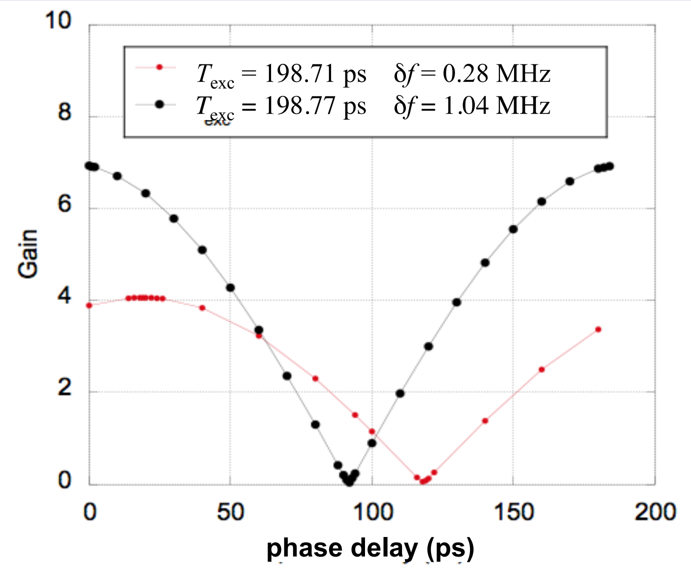
GAIN = ratio between the initial voltage and its amplitude after 400 ns

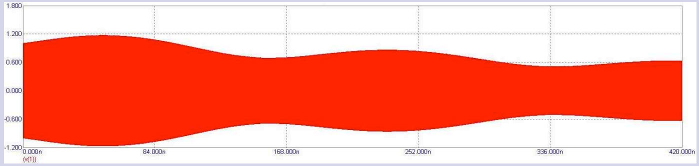


Experiment simulation: RLC circuit - 3

$\Delta t_{\mathrm{exc}} \approx 200$ ps







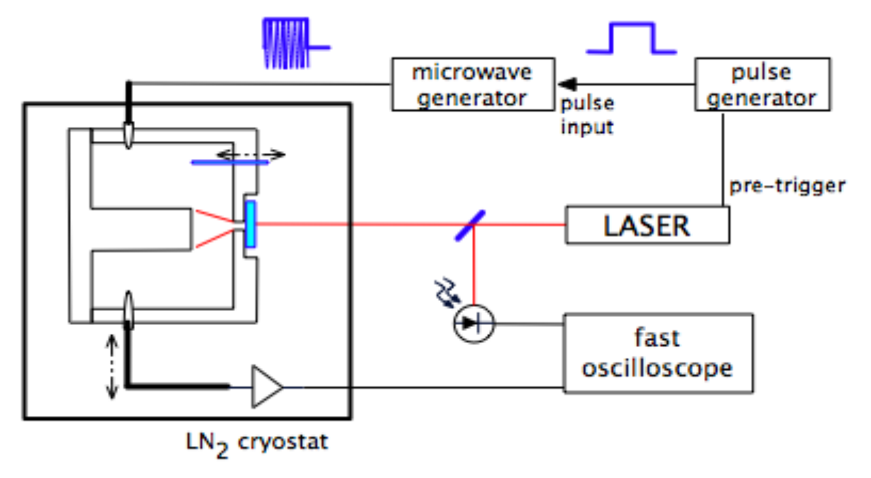
1. exponential growth at the parametric resonance; decaying oscillations when detuned
2. higher order maxima in the gain vs. δf plot are observed
3. the maximum of the amplification is found at $f_{\mathrm{rep}}=2\,f_0+\delta f$ (in our experiment the excitation is not a pure harmonic signal?);
4. If the phase between the excitation and the field in the cavity varies, at each laser shot a different gain is observed;

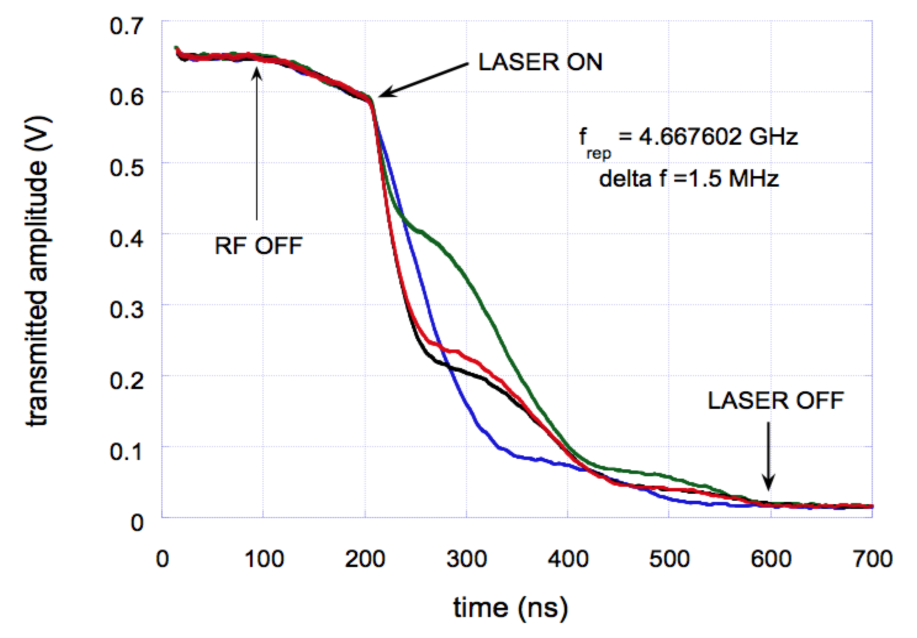
In agreement with V.V. Dodonov theoretical results

Parametric amplification of the classical field in cavities with photoexcited semiconductors, *Phys. Scr.* **T143**, 014009 (2011)

Parametric excitation of an external field - 3

Is our parametric amplifier characterized by a gain allowing the observation of the vacuum contribution? To test the apparatus and measure its gain we operate the cavity at 77 K.



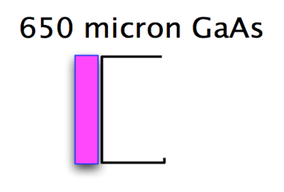


- The amplitude of the signal strongly depends on the phase

- The average value of the output amplitude (with respect to the input phase) and its standard deviation as functions of detuning from the resonance frequency show decaying oscillations.

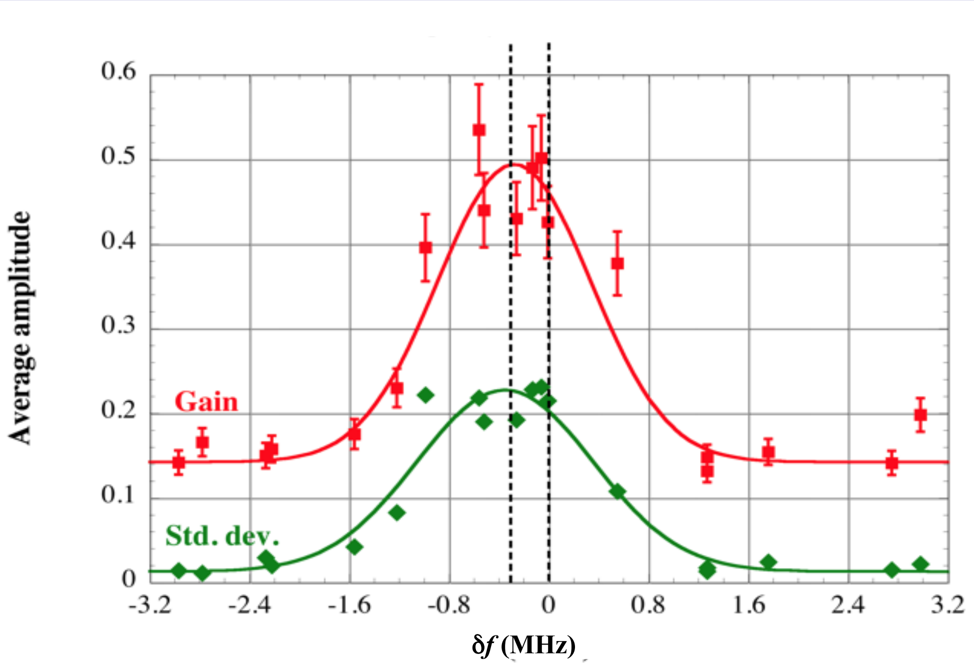
Parametric excitation of an external field - 4

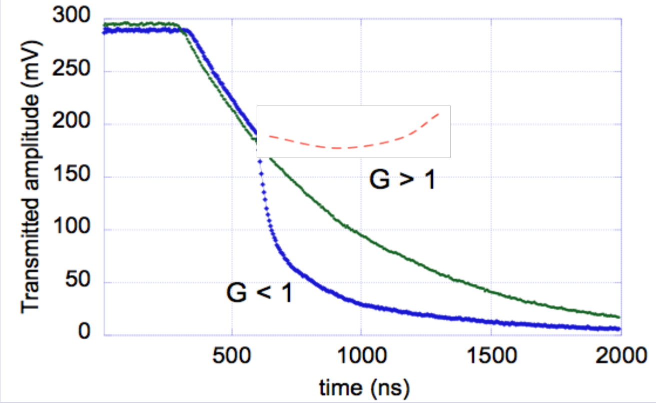
FIRST EXPERIMENTAL RESULTS



🙂 + Br ions-irradiated sample $\tau = 7.2$ ps

🙁 - stationary frequency shift $\Delta f \approx 11$ MHz
- tuning the cavity, laser f_{rep} fixed





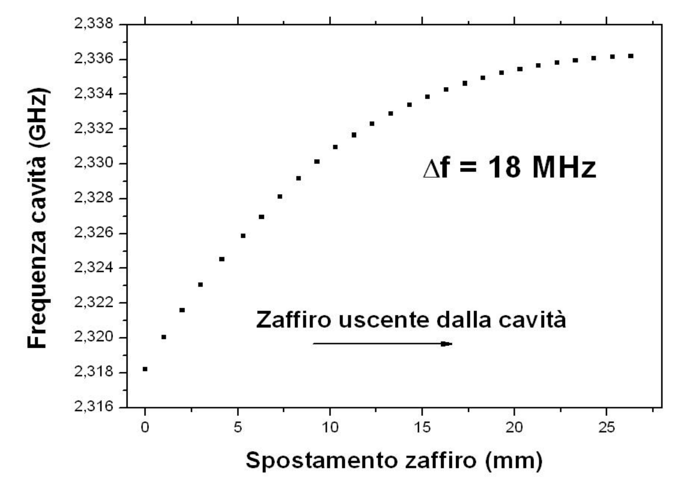
G = A(lasON)/A(lasOFF) < 1 ---> losses

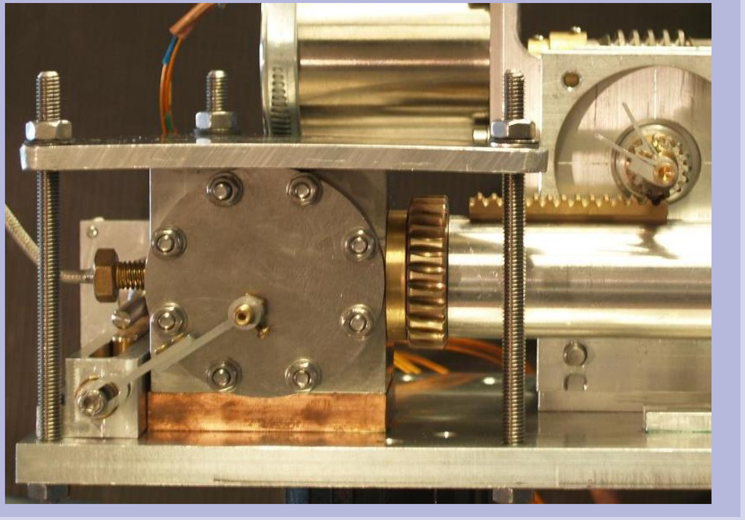
Maximal standard deviation is observed for the same resonance frequency as the average amplitude itself

Parametric excitation condition

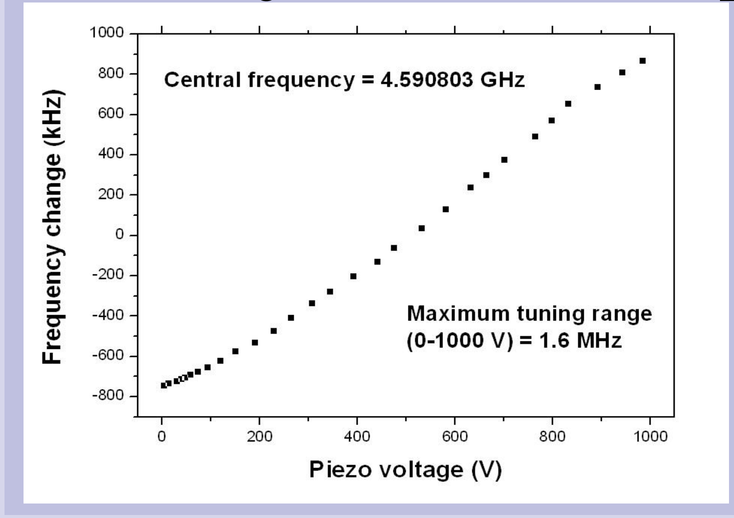
Matching the parametric resonance condition:

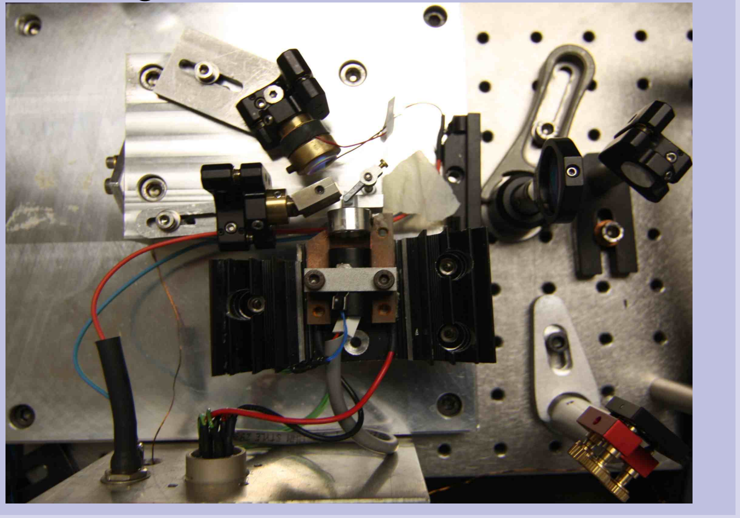
cavity tuning: a saffire rod changes the cavity resonance frequency





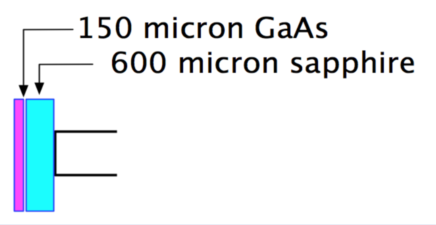
laser tuning: active control of the M_OSC length





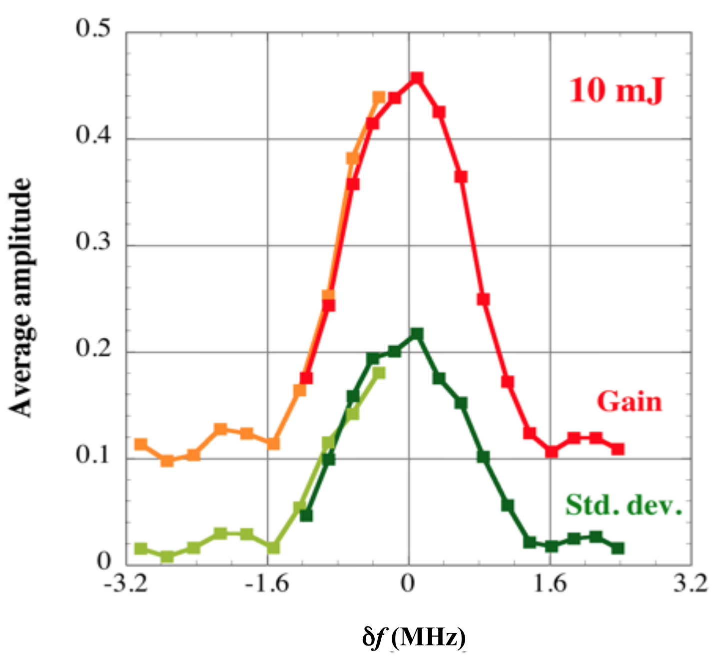
Parametric excitation of an external field - 4

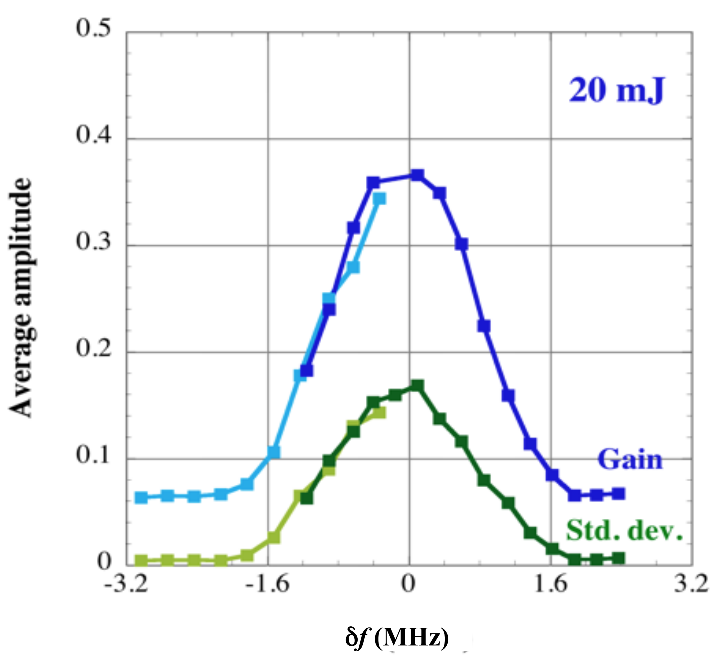
FURTHER EXPERIMENTAL RESULTS



☺ + frequency shift ≈ 28 MHz
+ sapphire substrate
+ mainly tuning the laser

☹ - proton-irradiated sample τ = 1 ps





The average value of the output amplitude and its standard deviation as functions of detuning from the resonance frequency show decaying oscillations.

Parametric excitation of an external field - 5

DATA ANALYSIS AND INTERPRETATION

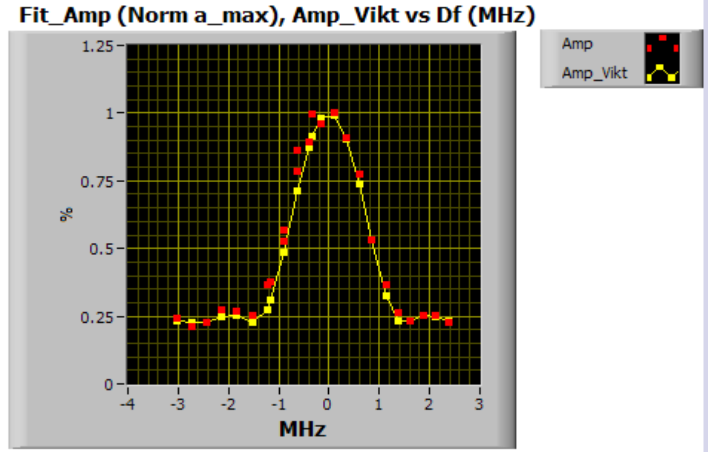
We fit the experimental curves with recent theoretical results obtained by V.V. Dodonov

$x(i) = (\delta(i_{Res}) - \delta(i))/((w/2 - \delta(i))|\delta(i_{Res})|/w/2)(1 - \delta(i_{Res})/w/2|))$

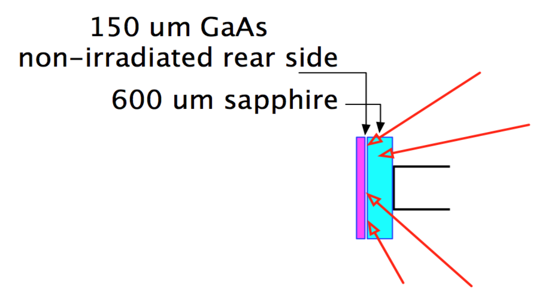
$\delta(i) = w/2 - w_o(i)$

$w_{Res}(i)/2 = w_o(i)/(1+\varphi/\pi)$ $\varphi = 2\pi\, w_o(i_{Res})|\chi|\,\tau$

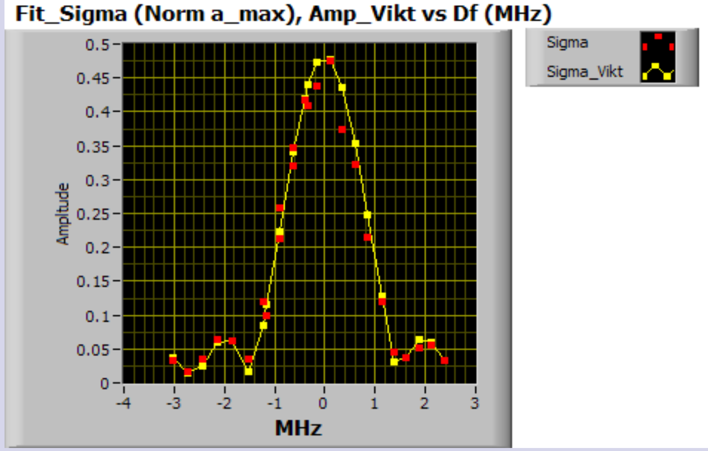
w is the laser frequency;
w_0 is the cavity frequency
φ phase, $|\chi|\,\tau$ depending on the semiconductor



LOSSES



Both the samples had no AR coating ⇒ more than 30% of the light is diffused in the cavity ⇒ continuous background of free carriers during the laser excitation



Coming soon

For a better understanding of the semiconductor

- Irradiation procedure – better control of the proton or ion beam
- Optical pump – terahertz probe setup in our laboratory
- Apply the antireflection coating to the “good” irradiated samples and repeat the gain measurement;
- Shaping of the laser pulse instead of tayloring the semiconductor recombination time

Conclusions and perspectives

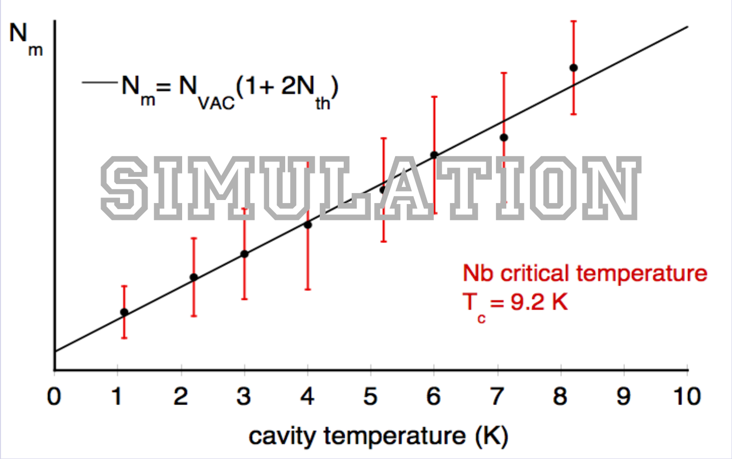
JSF Julian Schwinger Foundation

INFN

- The preliminary results of the parametric amplification of a classical field are coherent with theoretical predictions

- Once a G>1 amplification of a classical field is observed, the system is in principle ready to detect the quantum effect varying the cavity temperature in the range 0.8 K < T < T_c.

- Study of the thermal photons statistics



The MIR experiment:
towards an in-vacuum detection of the Dynamical Casimir Effect

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Dipartimento di Fisica, Università di Trieste, and INFN Sez. di Trieste

on behalf of
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