Study of the nonlinear magneto-optic effects in BBO

Jan Soubusta, Antonín Černoch, Jan Peřina Jr.

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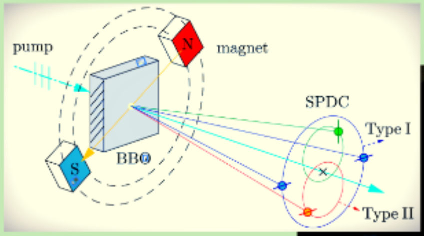
Czech Republic

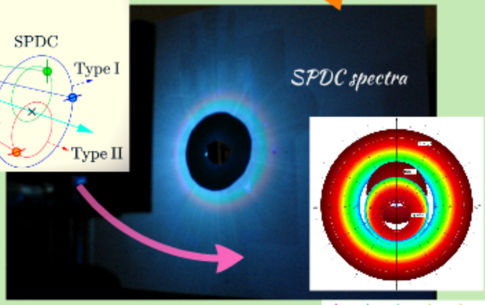
Outline

1. Introduction
2. nonlinear BBO crystals
   - Phase-matching conditions
   - SPDC spectra
3. Influence of magnetic field
   - Magnetic effective nonlinearity
4. Experimental results
5. Conclusions

1. Introduction

Typically used nonlinear (NL) processes
in classical optics: SHG, SFG, ...
in quantum optics: SPDC



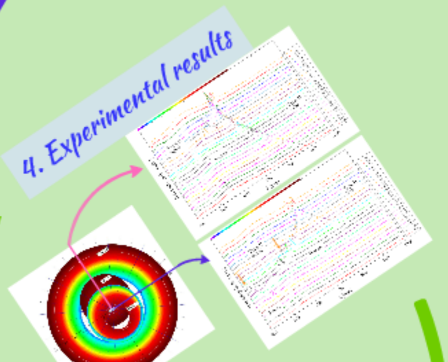


We pump BBO at 355 nm by **Paladin** picosecond laser.

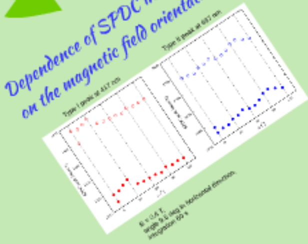
Degenerate SPDC is centered at 710 nm.

$1/\lambda_p = 1/\lambda_1 + 1/\lambda_2.$

4. Experimental results



Dependence of SPDC intensity on the magnetic field orientation



B = 0.4 T,
angle 9.5 deg in horizontal direction,
integration 60 s

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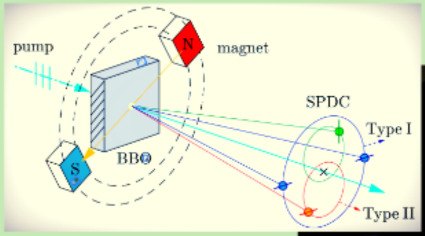
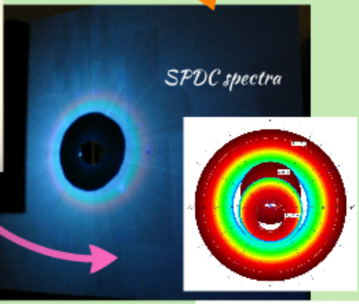


SPDC spectra



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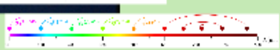
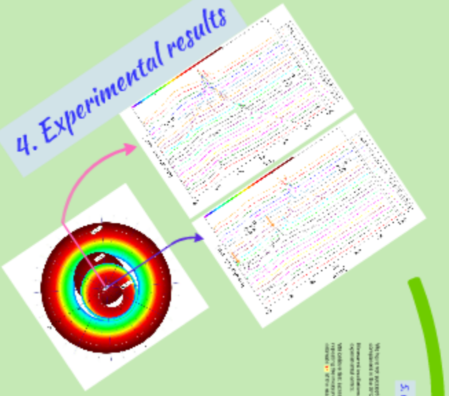
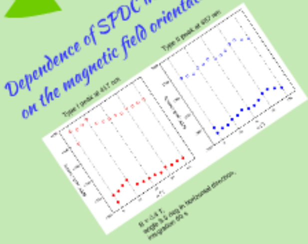


4. Experimental results



Dependence of SPDC intensity on the magnetic field orientation



B = 0.4 T,
angle 3.5 deg in horizontal direction,
integration 60 s

5. Conclusions

The End

Thank you for your attention !

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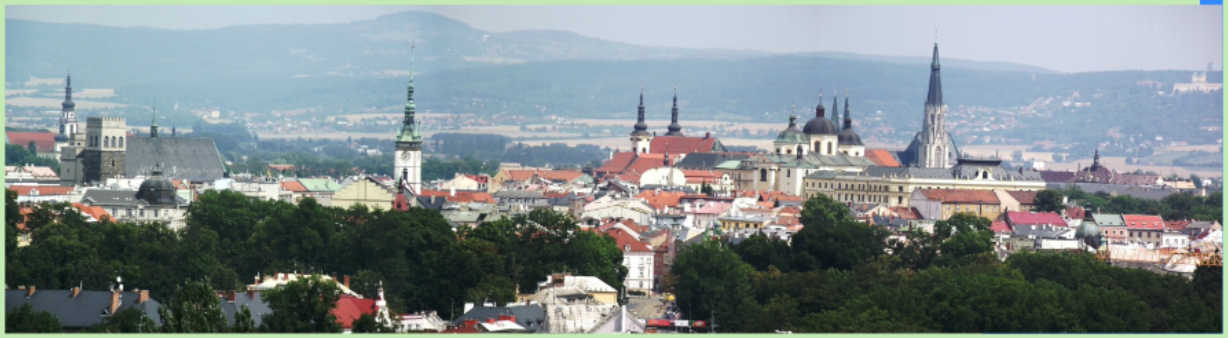

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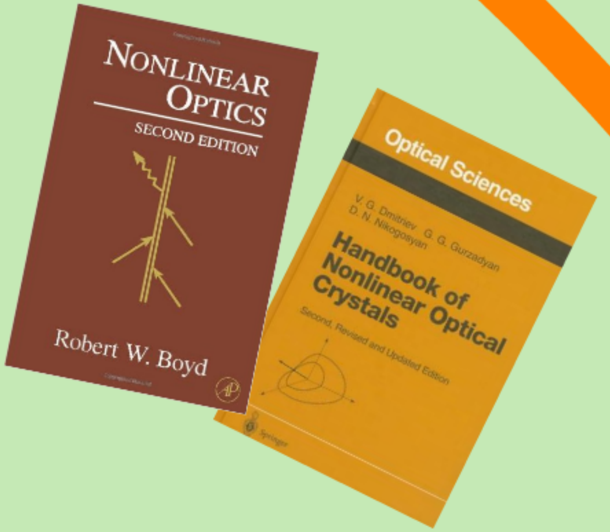
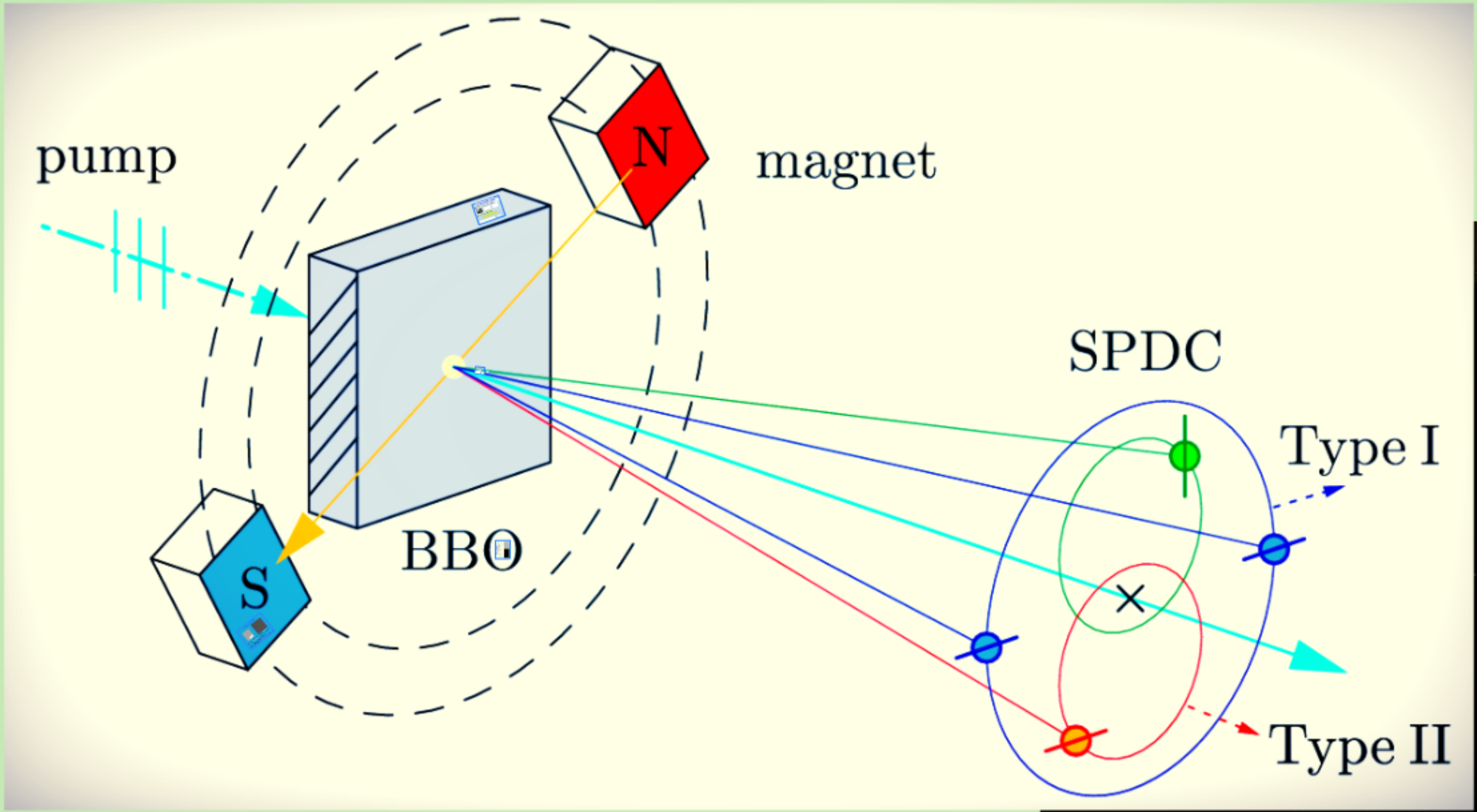
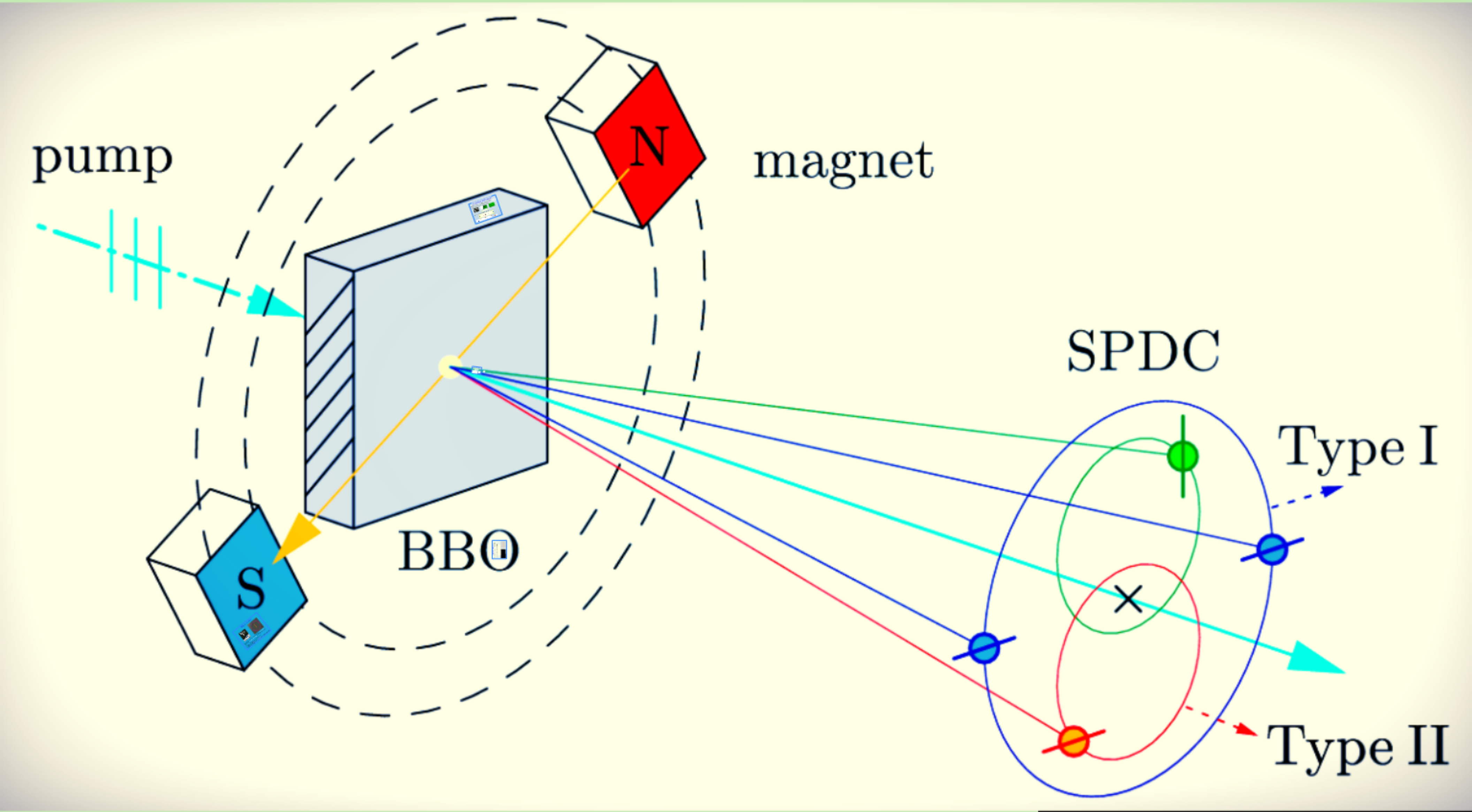


NONLINEAR OPTICS
SECOND EDITION
Robert W. Boyd

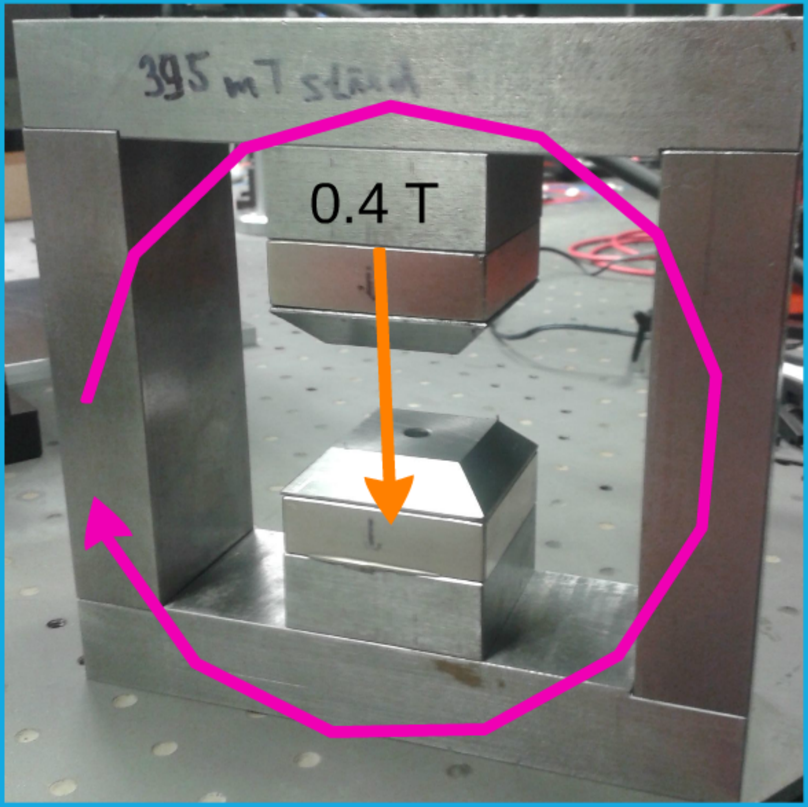
Optical Sciences
V. G. Dmitriev G. G. Gurzadyan D. N. Nikogosyan
Handbook of Nonlinear Optical Crystals
Second, Revised and Updated Edition
Springer



antum optics: SPDC



Why we do this?



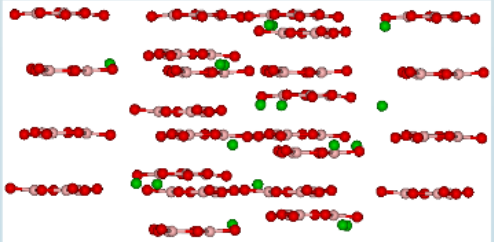
- Influence of magnetic field on NL processes was not tested yet.
- Mg. field can decrease the symmetry and can allow new processes.

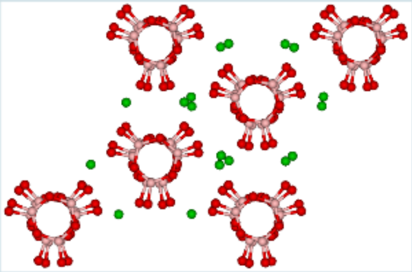
- We selected BBO crystals produced by **Eksma**.
- NL magneto-optic (MO) tensor is unknown
- Efficiency of the NL process should oscillate when rotating magnetic field.

2. Nonlinear BBO crystals

Artificially grown, discovered by Chinese in 1984 $(\beta\text{-BaB}_2\text{O}_4)$

BBO is negative uniaxial crystal - symmetry *3m* $n_e < n_o$





$$\vec{P}^{\mathrm{NL}} = \varepsilon_0 \overset{3\leftrightarrow}{\chi} : \vec{E}\vec{E}.$$

NL second order susceptibility reads

$$\overset{3\leftrightarrow}{\chi} = \left(\begin{array}{ccc|ccc} \cdot & \cdot & \cdot & \cdot & \chi_{31} & -\chi_{22} \\ -\chi_{22} & \chi_{22} & \cdot & \chi_{31} & \cdot & \cdot \\ \chi_{31} & \chi_{31} & \chi_{33} & \cdot & \cdot & \cdot \end{array} \right).$$

- $\chi_{22} = 2.2$ pm/V, $\chi_{31} = 0.08$ pm/V, χ_{33}– unknown,
- allowed processes: type 0, type I, type II

EKSMA OPTICS

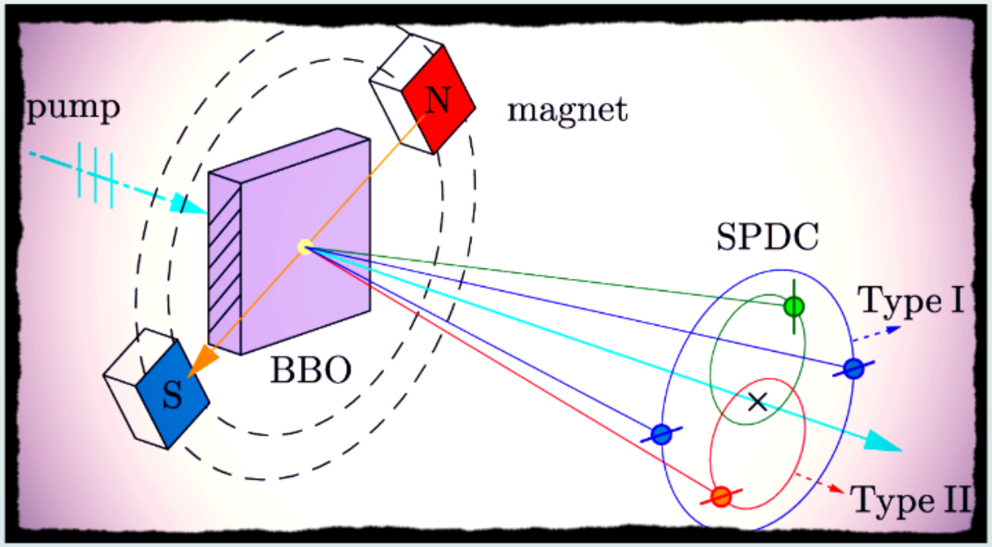
Effective nonlinearity

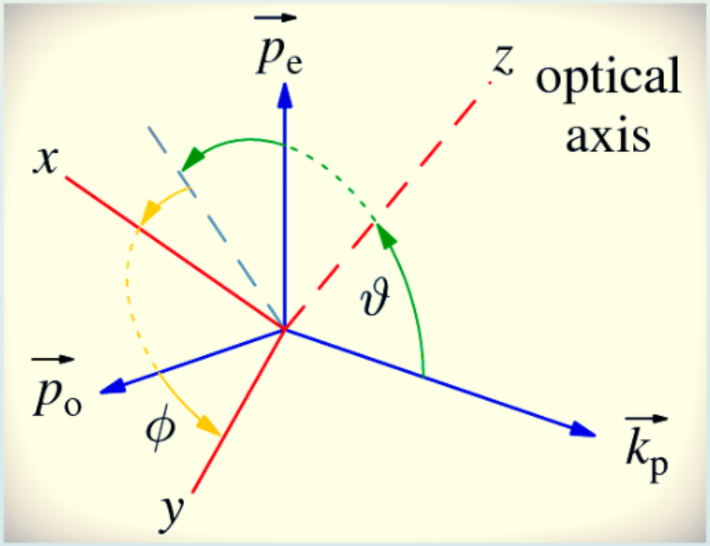
The effective NL coefficient is given by the experimental geometry

$$d_{\text{eff}}(\vec{p}_{\text{pump}} \to \vec{p}_{\text{signal}} + \vec{p}_{\text{idler}}) = \vec{p}_{\text{pump}} \cdot \overset{3\leftrightarrow}{\chi} \cdot E^{(2)}(\vec{p}_{\text{signal}}, \vec{p}_{\text{idler}}),$$

In bulk crystals only type I and type II interaction is allowed

$$\begin{aligned} \textbf{Type I}: \quad d_{\text{eff}}^{\text{I}} &= \vec{p}_{\text{e}} \cdot \overset{3\leftrightarrow}{\chi} \cdot E^{(2)}(\vec{p}_{\text{o}}, \vec{p}_{\text{o}}) \\ &= -\chi_{31} \sin\vartheta + \chi_{22} \cos\vartheta \sin(3\phi), \\ \textbf{Type II}: \quad d_{\text{eff}}^{\text{II}} &= \vec{p}_{\text{e}} \cdot \overset{3\leftrightarrow}{\chi} \cdot E^{(2)}(\vec{p}_{\text{o}}, \vec{p}_{\text{e}}) \\ &= \chi_{22} \cos^2\vartheta \cos(3\phi). \end{aligned}$$

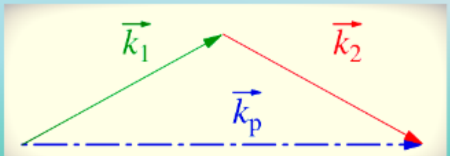




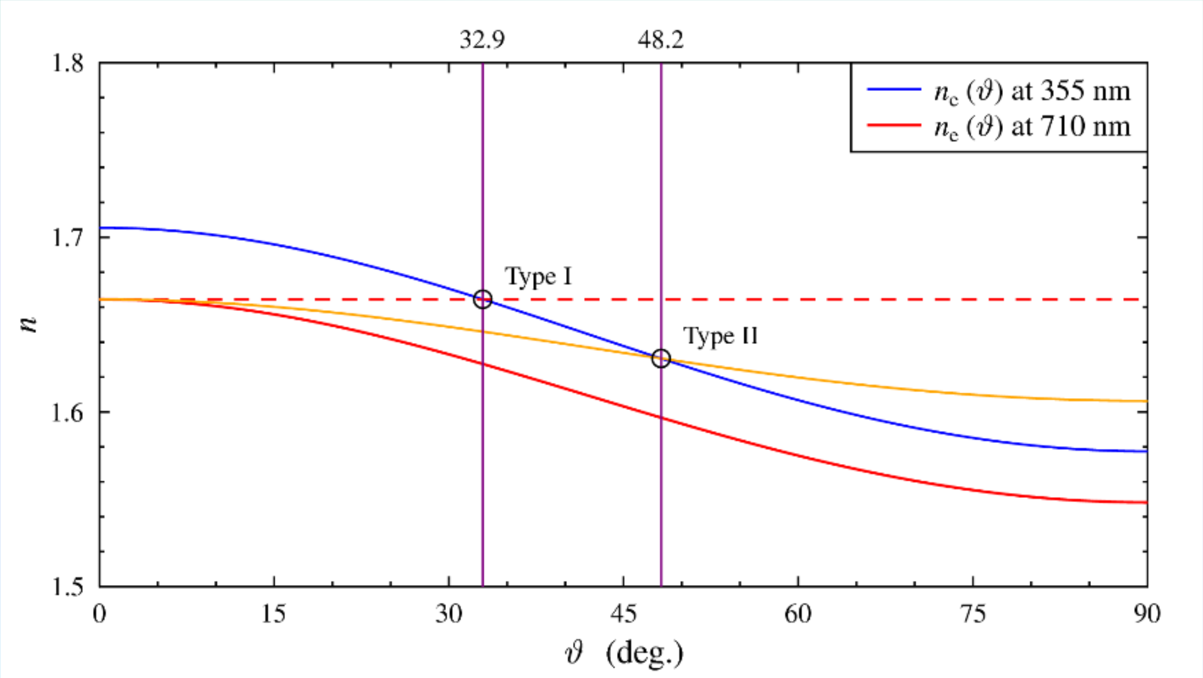
Phase-matching conditions

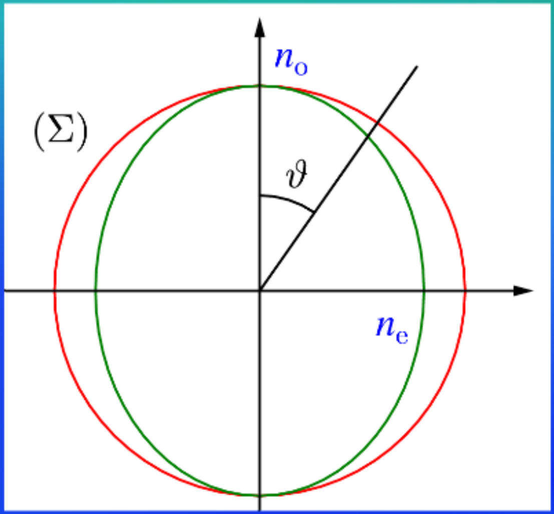
PM condition gives relation for refractive indexes:

$$k_{2\omega} < k_\omega + k_\omega \quad \Rightarrow \quad n(2\omega)\left(\frac{2\omega}{c}\right) < 2n(\omega)\left(\frac{\omega}{c}\right)$$

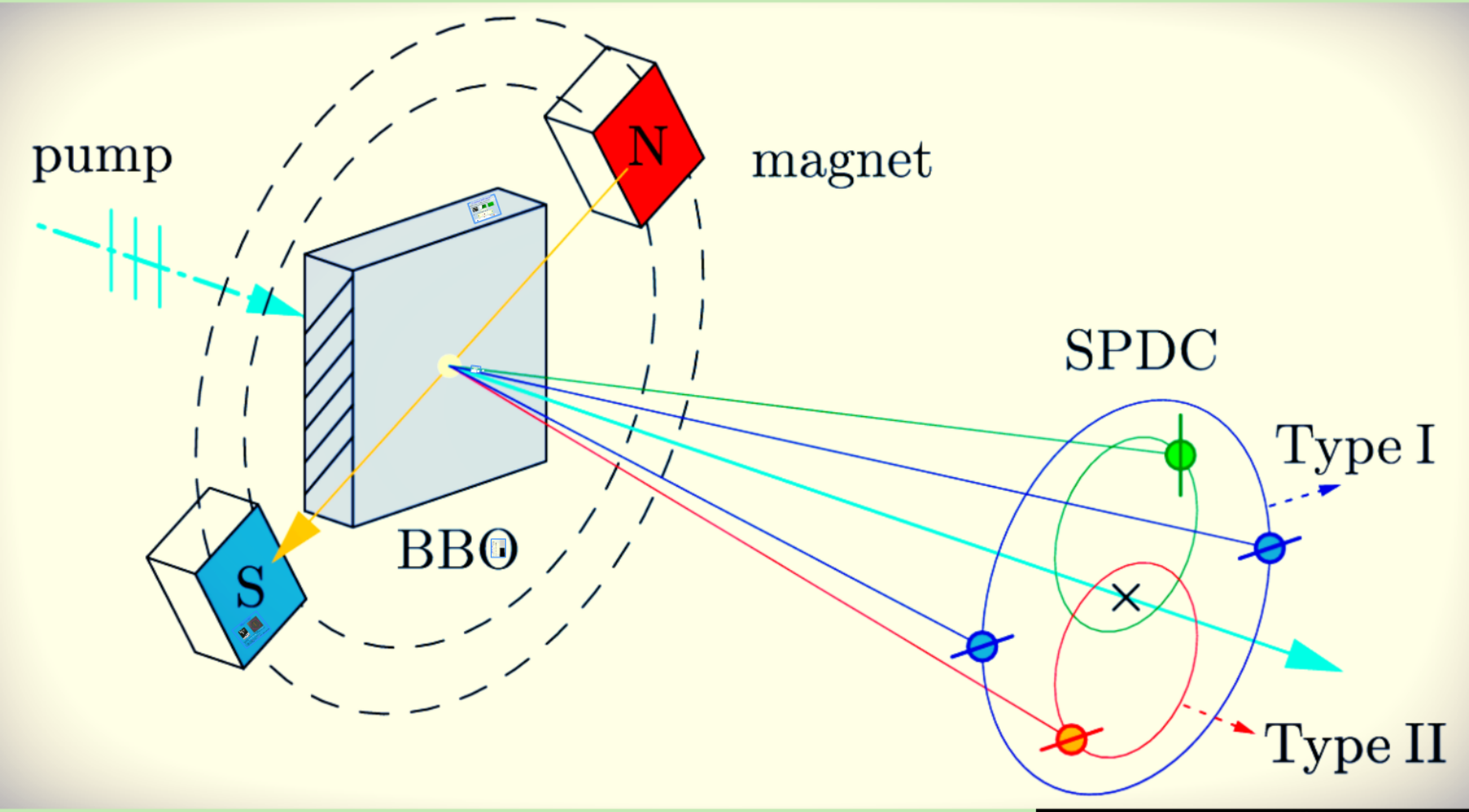


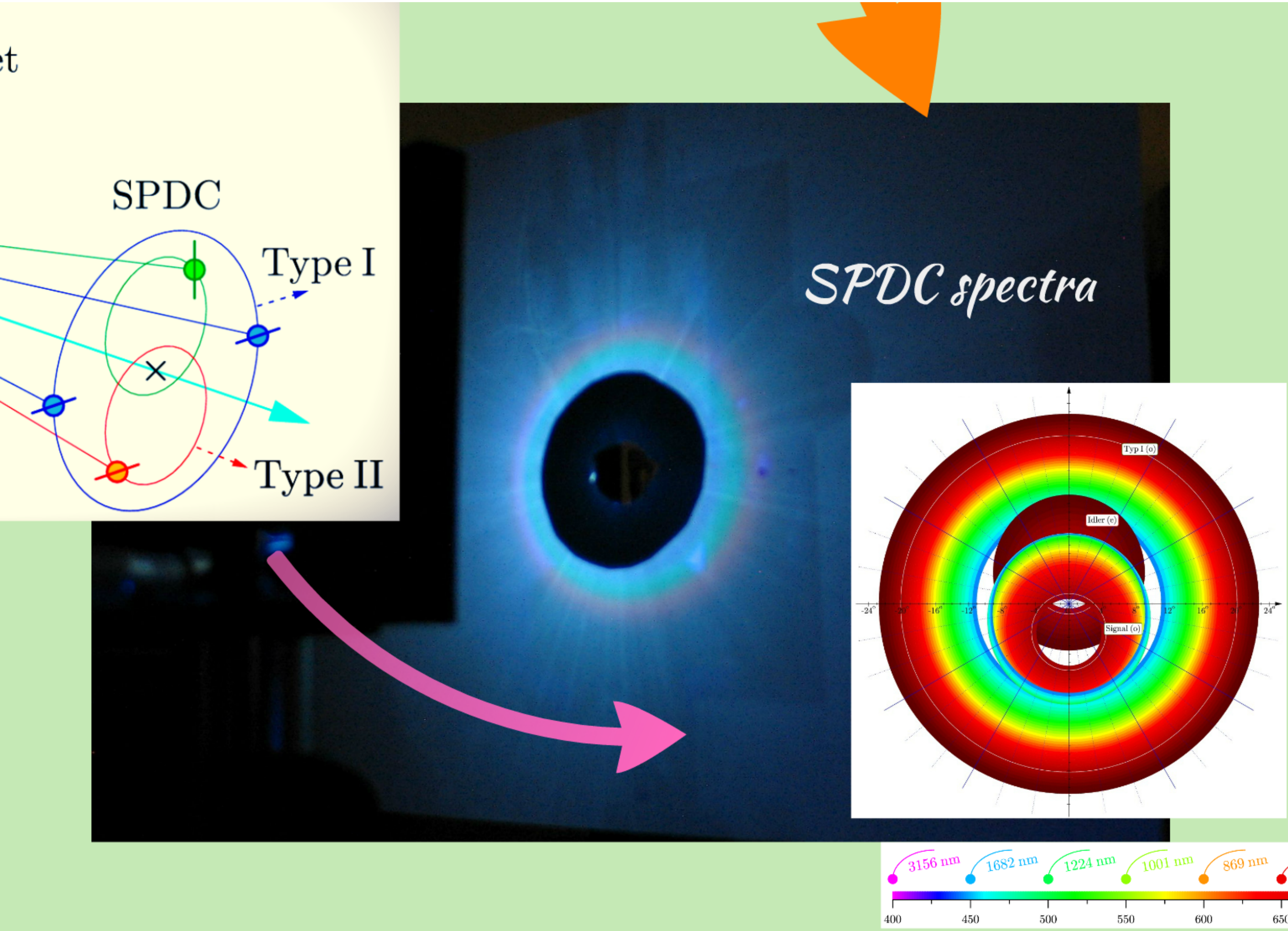
$$\begin{aligned} &\textbf{Type I}: && n_\mathrm{e}(2\omega) < n_\mathrm{o}(\omega), \\ &\textbf{Type II}: && n_\mathrm{e}(2\omega) < (n_\mathrm{e}(\omega) + n_\mathrm{o}(\omega))/2. \end{aligned}$$

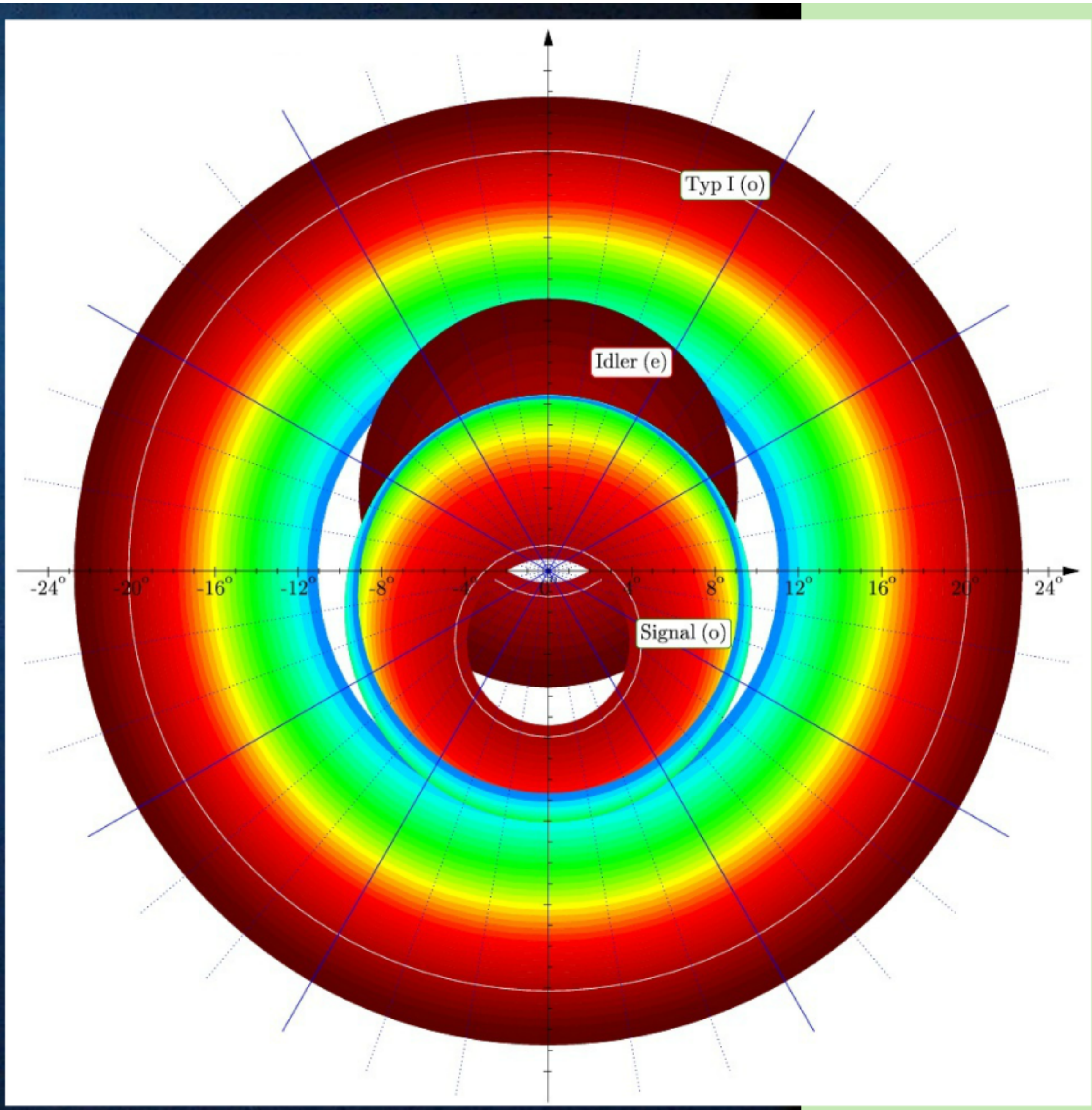




uantum optics: SPDC




et
SPDC
Type I
Type II
SPDC spectra
Typ I (o)
Idler (e)
Signal (o)
-24°
-20°
-16°
-12°
-8°
8°
12°
16°
20°
24°
3156 nm
1682 nm
1224 nm
1001 nm
869 nm
400
450
500
550
600
650



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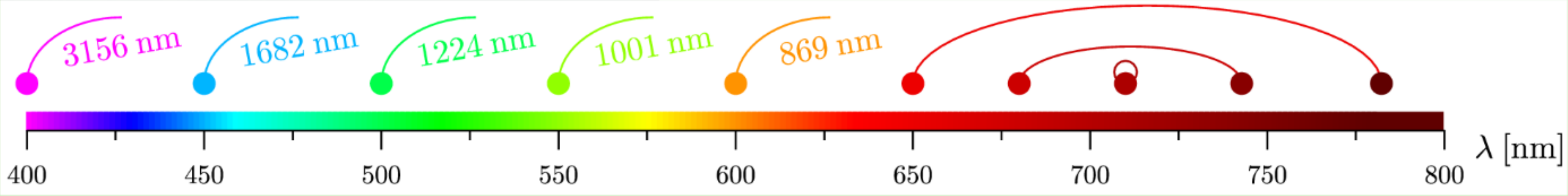

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3. Influence of magnetic field

We add linear dependence of the second order NL susceptibility on magnetization.

$$\vec{P}^{\mathrm{NL}} = \varepsilon_0 \overset{3\leftrightarrow}{\chi} : \vec{E}\vec{E}.$$

WITHOUT magnetic field

$$\overset{3\leftrightarrow}{\chi} = \left(\begin{array}{ccc|ccc} \cdot & \cdot & \cdot & \cdot & \chi_{31} & -\chi_{22} \\ -\chi_{22} & \chi_{22} & \cdot & \chi_{31} & \cdot & \cdot \\ \chi_{31} & \chi_{31} & \chi_{33} & \cdot & \cdot & \cdot \end{array}\right).$$

WITH magnetic field

$$\overset{3\leftrightarrow}{\chi} \rightarrow \overset{3\leftrightarrow}{\chi} + \overset{4\leftrightarrow}{\chi}^{M} \cdot \vec{M} = \overset{3\leftrightarrow}{\chi} + \sum_i \overset{3\leftrightarrow}{\chi}^{M}_{i}$$

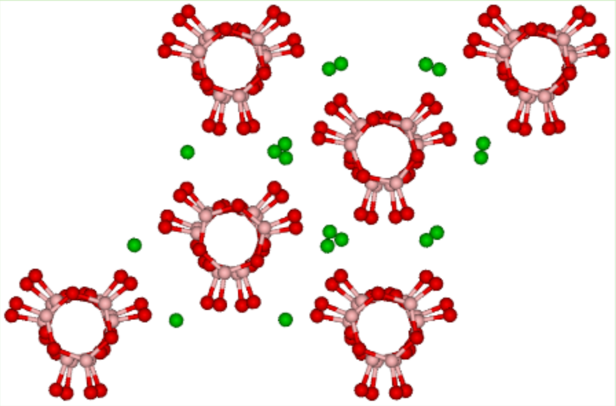
$$\overset{3\leftrightarrow}{\chi}^{M}_{x} = \left(\begin{array}{ccc|ccc} \cdot & \cdot & \cdot & \cdot & -\xi_{24} & \cdot \\ \xi_{22} & \xi_{22} & -\xi_{13} & \xi_{24} & \cdot & \cdot \\ \cdot & \cdot & \cdot & \xi_{34} & \cdot & \cdot \end{array}\right) M_x,$$

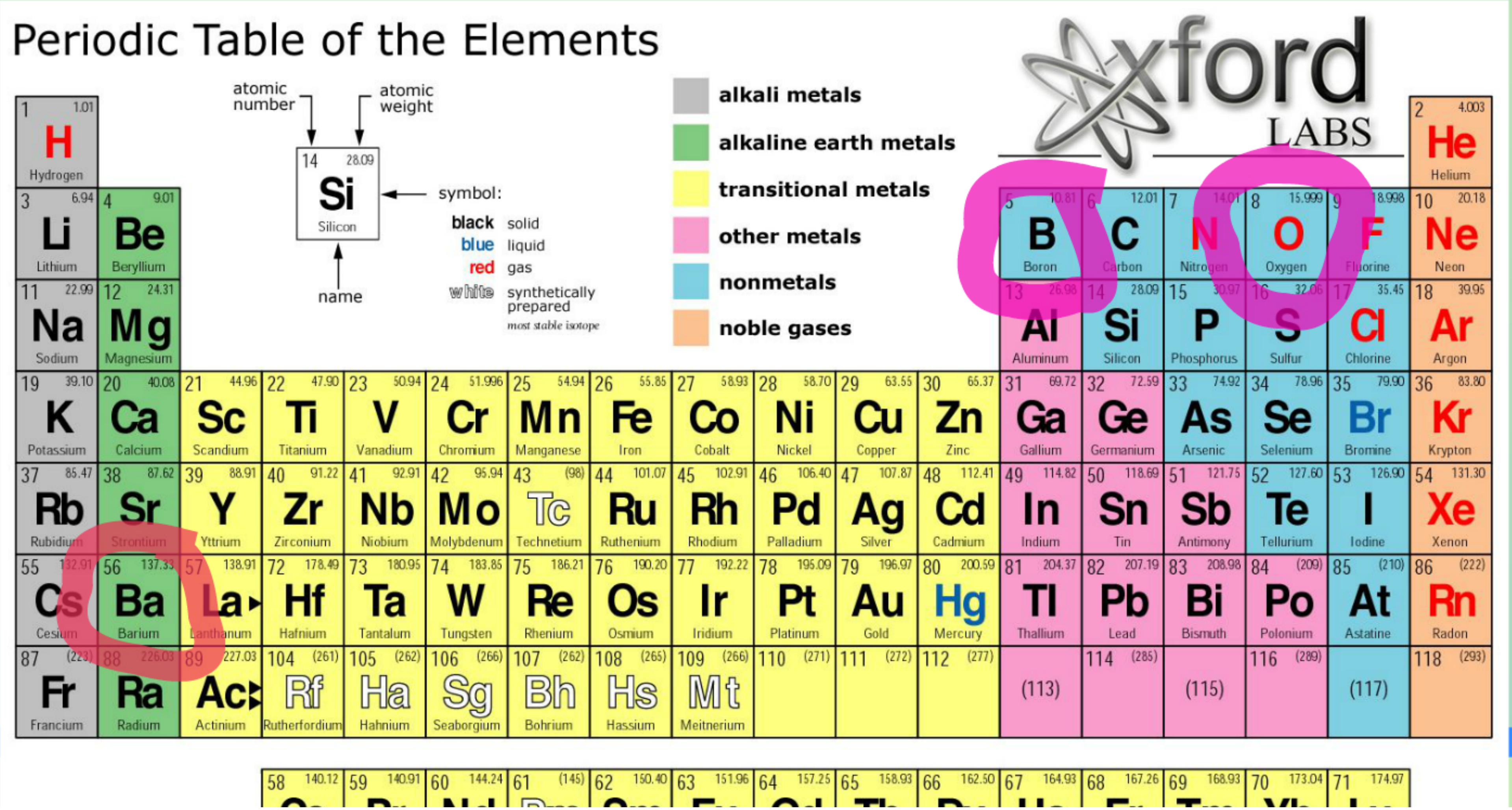
$$\overset{3\leftrightarrow}{\chi}^{M}_{y} = \left(\begin{array}{ccc|ccc} -\xi_{22} & -\xi_{22} & \xi_{13} & \xi_{24} & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \xi_{24} & \cdot \\ \cdot & \cdot & \cdot & \cdot & -\xi_{34} & \cdot \end{array}\right) M_y,$$

$$\overset{3\leftrightarrow}{\chi}^{M}_{z} = \left(\begin{array}{ccc|ccc} \cdot & \cdot & \cdot & \xi_{14} & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \xi_{14} & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{array}\right) M_z,$$

$$d_{\mathrm{eff}}(\vec{p}_{\mathrm{pump}} \rightarrow \vec{p}_{\mathrm{signal}} + \vec{p}_{\mathrm{idler}}) = \vec{p}_{\mathrm{pump}} \cdot \overset{3\leftrightarrow}{\chi} \cdot E^{(2)}(\vec{p}_{\mathrm{signal}}, \vec{p}_{\mathrm{idler}}),$$

$(\beta\text{-BaB}_2\text{O}_4)$





Periodic Table of the Elements

atomic number → 14 | atomic weight → 28.09 | symbol: Si | name: Silicon

symbol:
black solid
blue liquid
red gas
white synthetically prepared
most stable isotope

⬜ **alkali metals**
🟩 **alkaline earth metals**
🟨 **transitional metals**
🟪 **other metals**
🟦 **nonmetals**
🟧 **noble gases**

1 1.01 H Hydrogen																	2 4.003 He Helium
3 6.94 Li Lithium	4 9.01 Be Beryllium											5 10.81 B Boron	6 12.01 C Carbon	7 14.01 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Fluorine	10 20.18 Ne Neon
11 22.99 Na Sodium	12 24.31 Mg Magnesium											13 26.98 Al Aluminum	14 28.09 Si Silicon	15 30.97 P Phosphorus	16 32.06 S Sulfur	17 35.45 Cl Chlorine	18 39.95 Ar Argon
19 39.10 K Potassium	20 40.08 Ca Calcium	21 44.96 Sc Scandium	22 47.90 Ti Titanium	23 50.94 V Vanadium	24 51.996 Cr Chromium	25 54.94 Mn Manganese	26 55.85 Fe Iron	27 58.93 Co Cobalt	28 58.70 Ni Nickel	29 63.55 Cu Copper	30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.92 As Arsenic	34 78.96 Se Selenium	35 79.90 Br Bromine	36 83.80 Kr Krypton
37 85.47 Rb Rubidium	38 87.62 Sr Strontium	39 88.91 Y Yttrium	40 91.22 Zr Zirconium	41 92.91 Nb Niobium	42 95.94 Mo Molybdenum	43 (98) Tc Technetium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.40 Pd Palladium	47 107.87 Ag Silver	48 112.41 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium	53 126.90 I Iodine	54 131.30 Xe Xenon
55 132.91 Cs Cesium	56 137.33 Ba Barium	57 138.91 La ▸ Lanthanum	72 178.49 Hf Hafnium	73 180.95 Ta Tantalum	74 183.85 W Tungsten	75 186.21 Re Rhenium	76 190.20 Os Osmium	77 192.22 Ir Iridium	78 195.09 Pt Platinum	79 196.97 Au Gold	80 200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.98 Bi Bismuth	84 (209) Po Polonium	85 (210) At Astatine	86 (222) Rn Radon
87 (223) Fr Francium	88 226.03 Ra Radium	89 227.03 Ac ▸ Actinium	104 (261) Rf Rutherfordium	105 (262) Ha Hahnium	106 (266) Sg Seaborgium	107 (262) Bh Bohrium	108 (265) Hs Hassium	109 (266) Mt Meitnerium	110 (271)	111 (272)	112 (277)	(113)	114 (285)	(115)	116 (289)	(117)	118 (293)

58 140.12	59 140.91	60 144.24	61 (145)	62 150.40	63 151.96	64 157.25	65 158.93	66 162.50	67 164.93	68 167.26	69 168.93	70 173.04	71 174.97

Magnetic effective nonlinearity

Using Type II BBO crystal

- generates both processes
- Typically $\vartheta = 49.3°$, $\phi = 0°$
- Only horizontal magnetic field M_y will effect the susceptibility.
- $M_y = M \sin\alpha$, where α is measured from the vertical direction.

When rotating the magnetic field the efficiency of NL processes will oscillate with amplitude given by coefficient ξ_{22}.

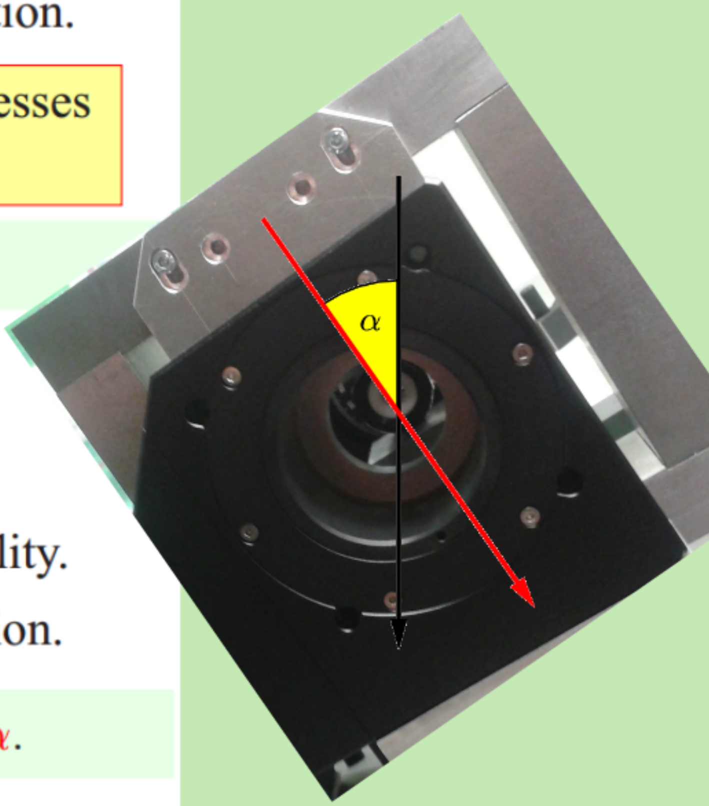
$$d_{\text{eff}}^{M,\text{II}\to\text{I}}(\alpha) = -\chi_{31}\sin\vartheta - \xi_{22}\cos\vartheta\, M\sin\alpha.$$

Using Type I BBO crystal

- Typically $\vartheta = 34.0°$, $\phi = 90°$
- Only horizontal magnetic field M_x will effect the susceptibility.
- $M_x = M \sin\alpha$, again α is measured from the vertical direction.

$$d_{\text{eff}}^{M,\text{I}\to\text{I}}(\alpha) = -\chi_{31}\sin\vartheta - \chi_{22}\cos\vartheta - \xi_{22}\cos\vartheta\, M\sin\alpha.$$

Type I SPDC intensity dependance on magnetic field is the same for all BBO crystals. Type II SPDC intensity dependance is more complex.



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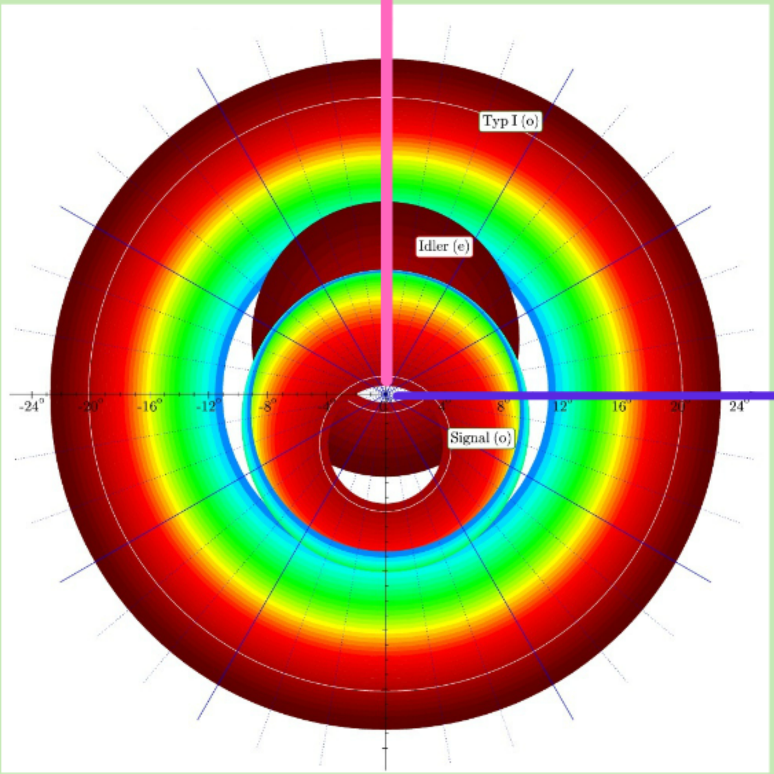
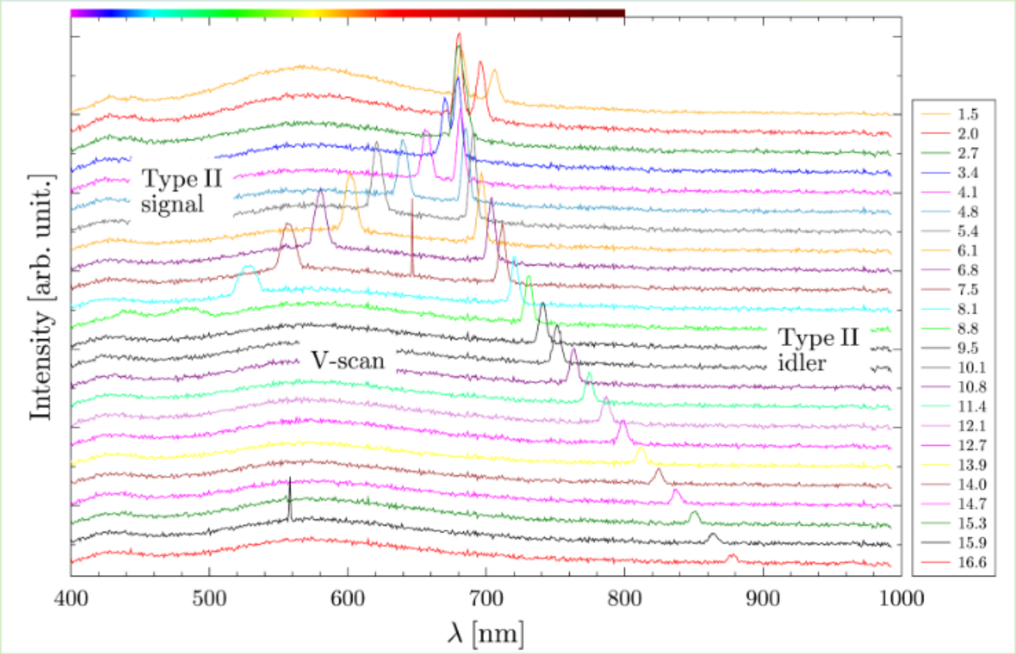
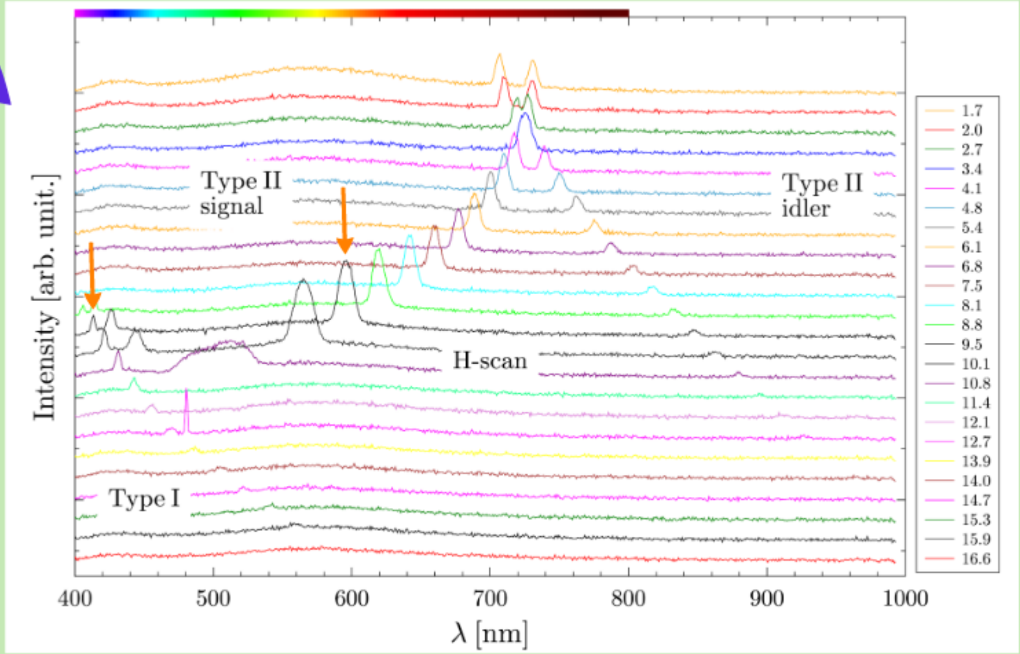
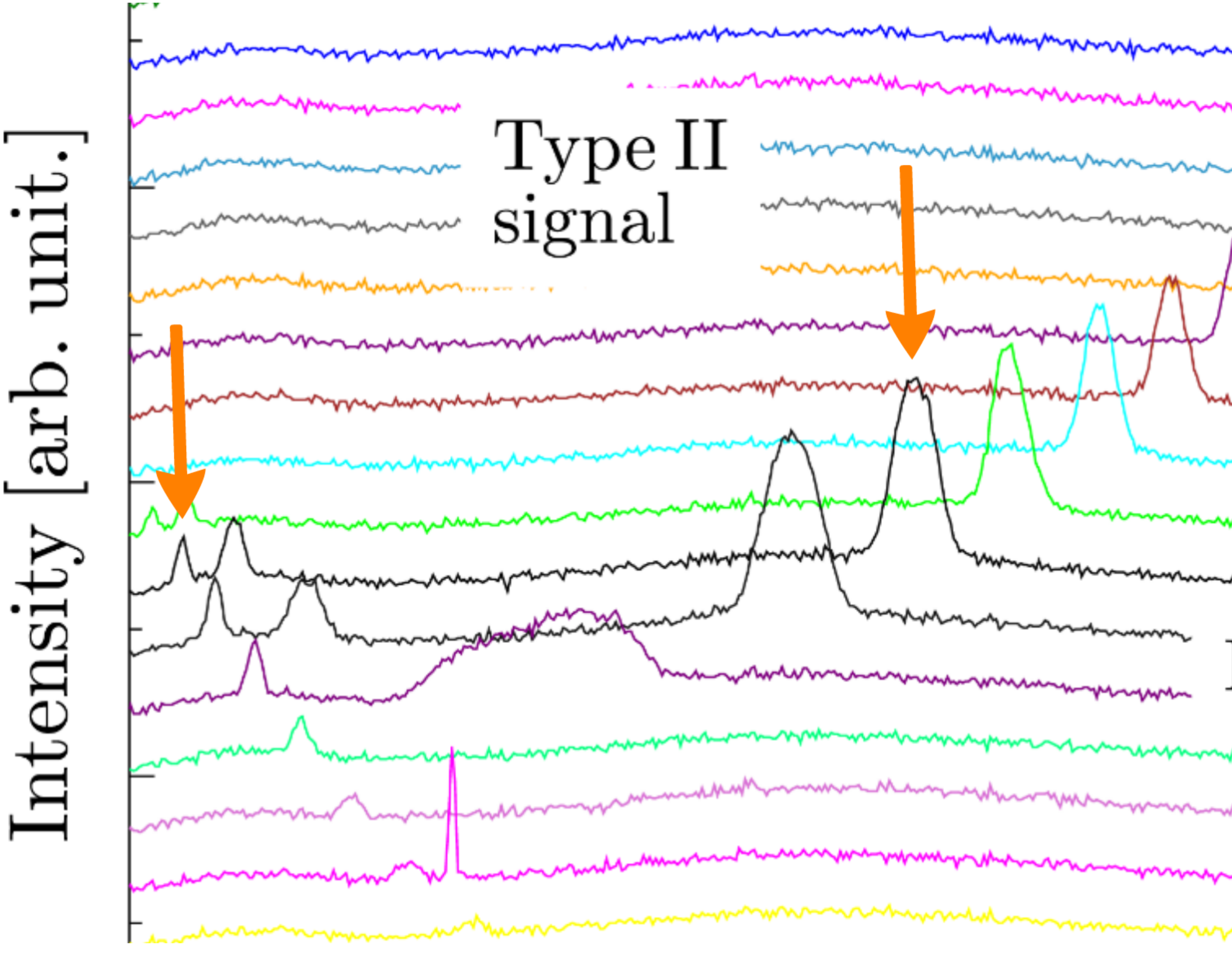
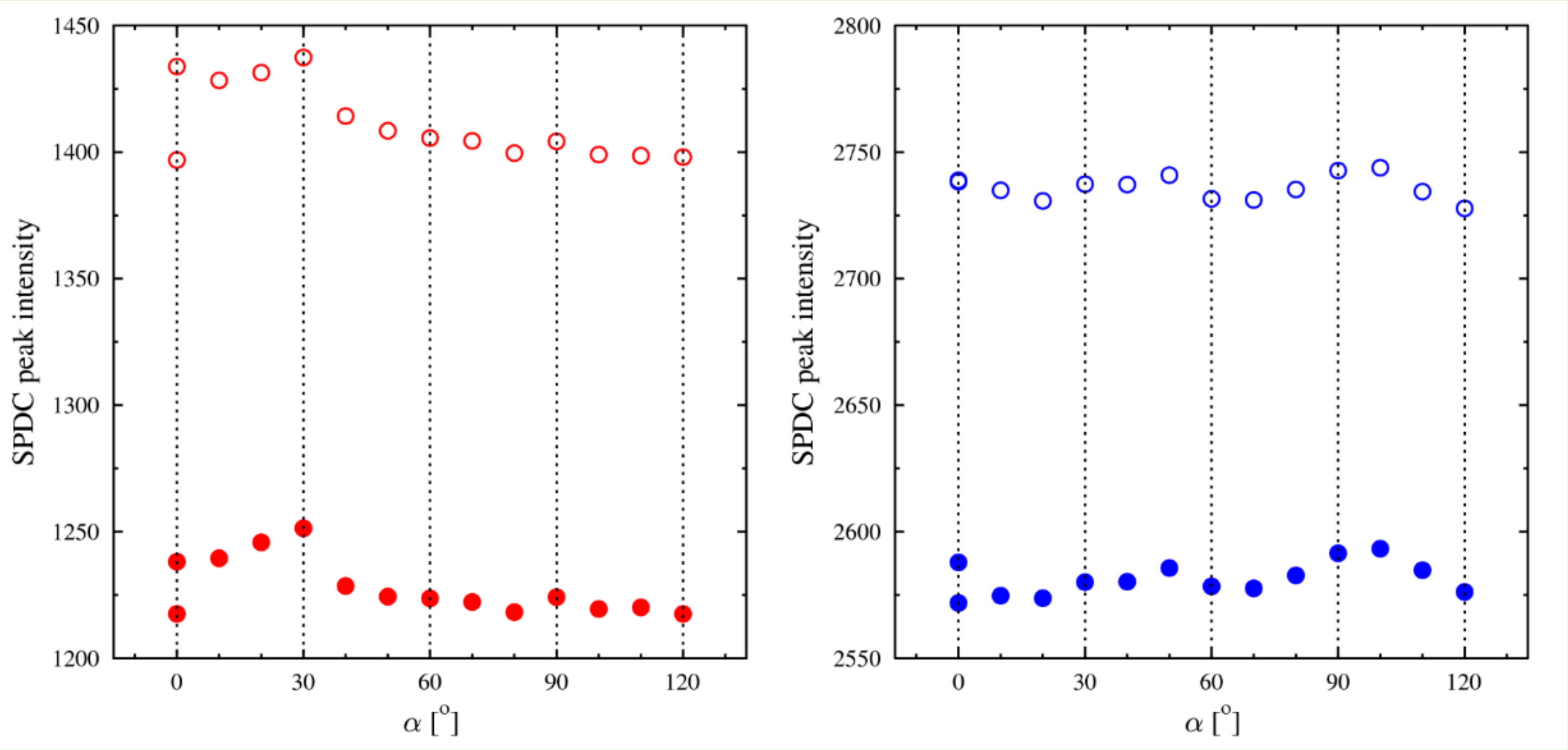







Intensity [arb. unit.]
Type II
signal

Dependence of SPDC intensity on the magnetic field orientation



Type I peak at 417 nm

Type II peak at 667 nm

B = 0.4 T,
angle 9.5 deg in horizontal direction,
integration 60 s

5. Conclusions

We have not succeeded to identify clear oscillating component in the SPDC peak intensity.

Measured oscillations are of the order of experimental errors.

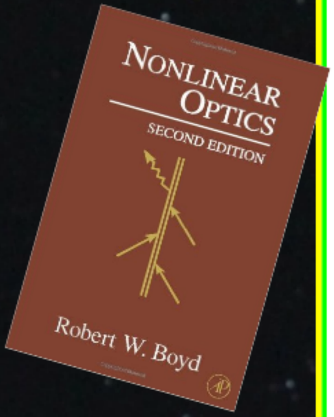
We believe that increasing the integration time and repeating the measurement we will succeed to estimate ξ_{22} of the magnetic NL susceptibility.;

The End

Thank you for your attention !

Acknowledgments

The authors acknowledge the project No. LO1305 of the Ministry of Education, Youth and Sports of the Czech Republic and the project 15-08971S of the Czech Science Foundation.



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[1] Boyd, R. W., [*Nonlinear Optics*], Academic Press, New York (2008, third edition).

[2] Dmitriev, V. G., Gurzadyan, G. G., and Nikogosyan, D. N., [*Handbook of Nonlinear Optical Crystals*], Springer, Heidelberg (1999, third edition).

[3] Nikogosyan, D. N., "Beta barium borate (BBO); A review of its properties and applications," *Appl. Phys. A* **52**, 359–368 (1991).

[4] "Nonlinear and Laser Crystals." http://eksmaoptics.com/nonlinear-and-laser-crystals/ (2013). [Online; accessed 5-September-2016].