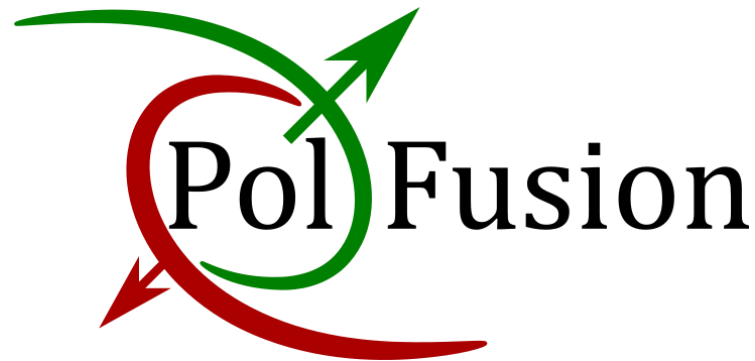
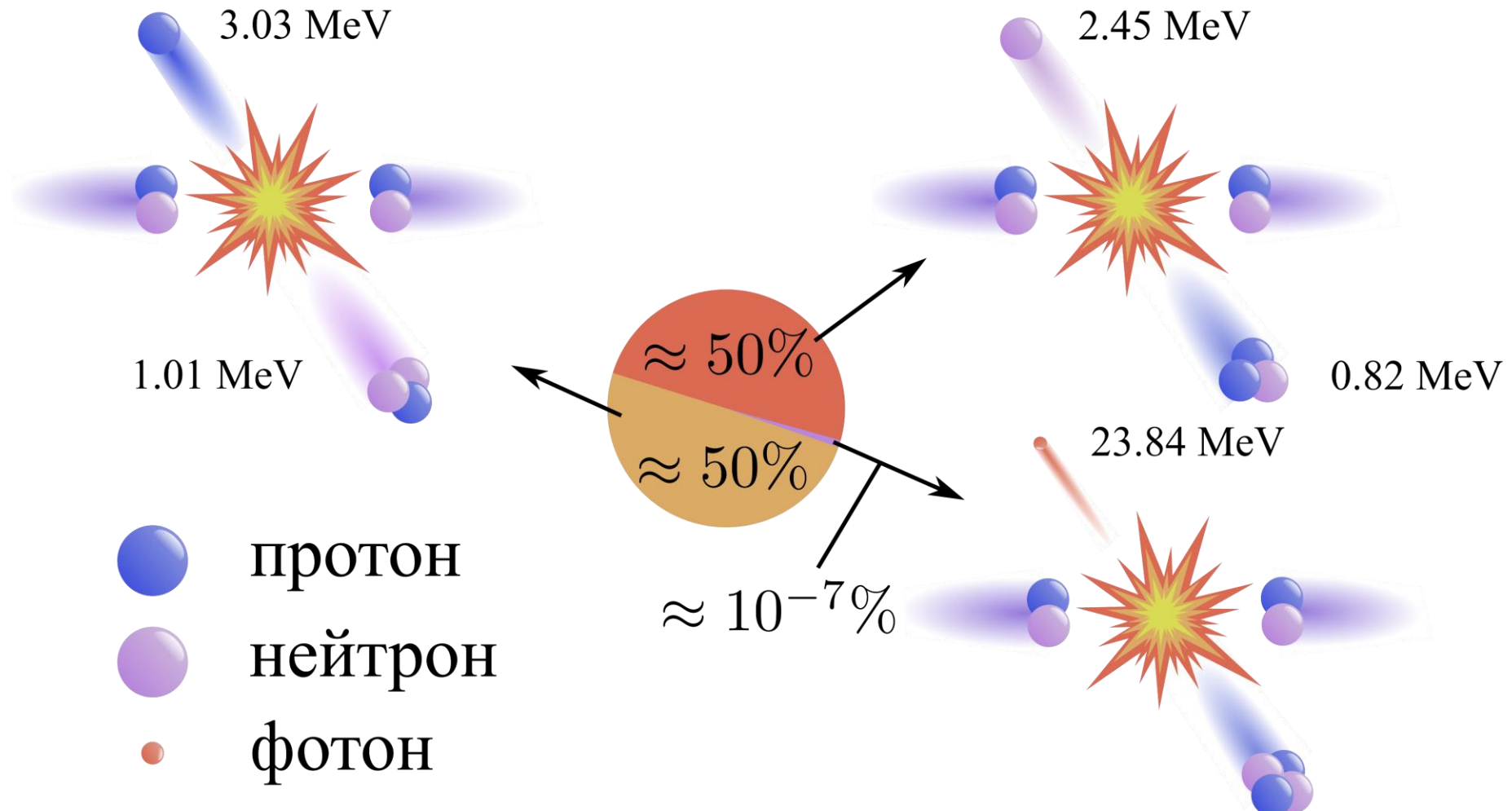
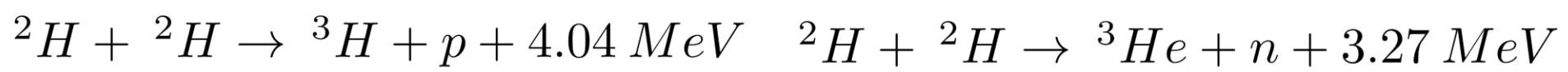





# Эксперимент PolFusion по исследованию термоядерной реакции синтеза поляризованных дейтронов.

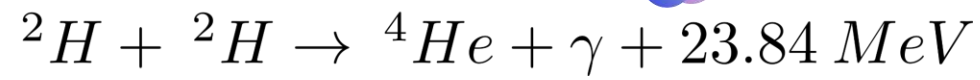


Иван Николаевич Соловьев

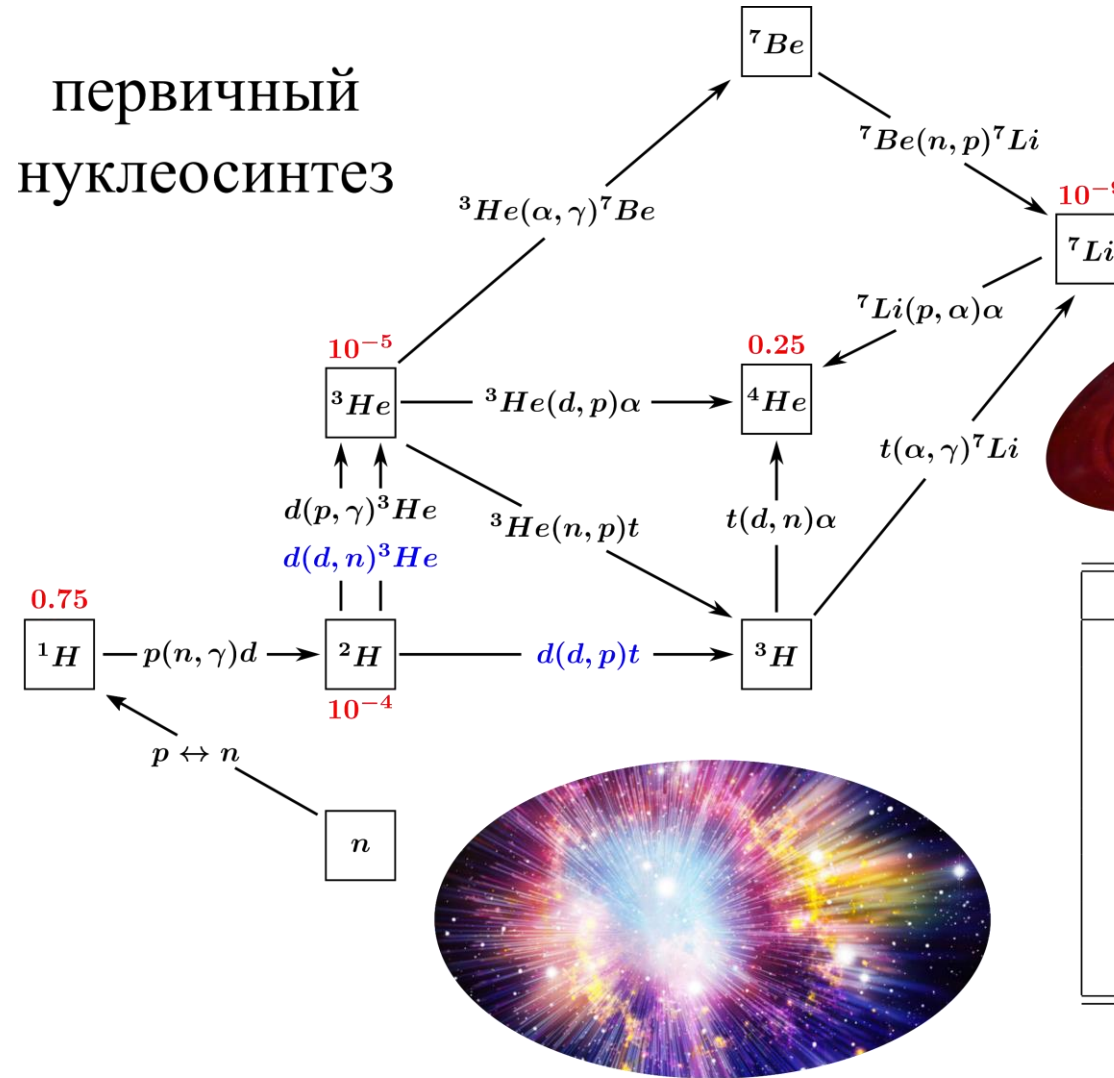
*научный сотрудник ЛКСТ ОФВЭ*



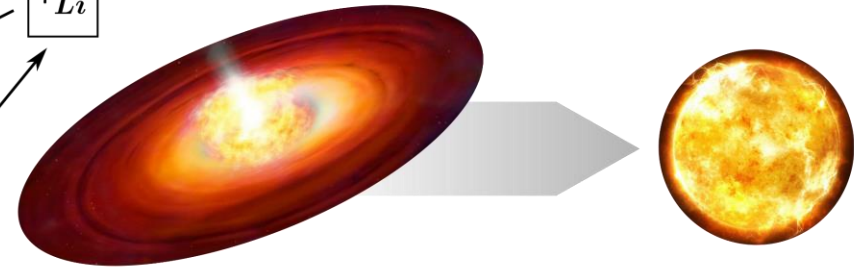
-  протон
-  нейтрон
-  фотон



## первичный нуклеосинтез



## Эволюция звёзд

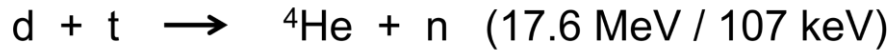


	$S(0), eV \times b$	$T, K$
$p(p, \nu e^+)d$	$4 \times 10^{-19}$	$10^7$
$^3\text{He}(p, \nu e^+)\alpha$	$8.6 \times 10^{-17}$	
$d(p, \gamma)^3\text{He}$	0.2	
$^3\text{He}(\alpha, \gamma)^7\text{Be}$	560	
$d(\alpha, \gamma)^6\text{Li}$	$2 \times 10^{-3}$	
$d(d, \gamma)\alpha$	$5.4 \times 10^{-3}$	
$d(d, n)^3\text{He}$	50000	$10^6$
$d(d, p)t$	56000	$10^6$

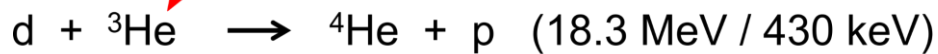
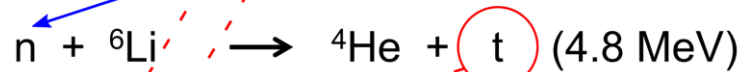
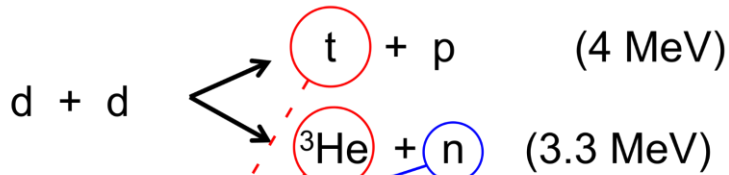
E. G. Adelberger et al., Rev. Mod. Phys. **83**, 195 (2011)

C. Angulo et al., Nuclear Physics A **656**, 3-183 (1999)

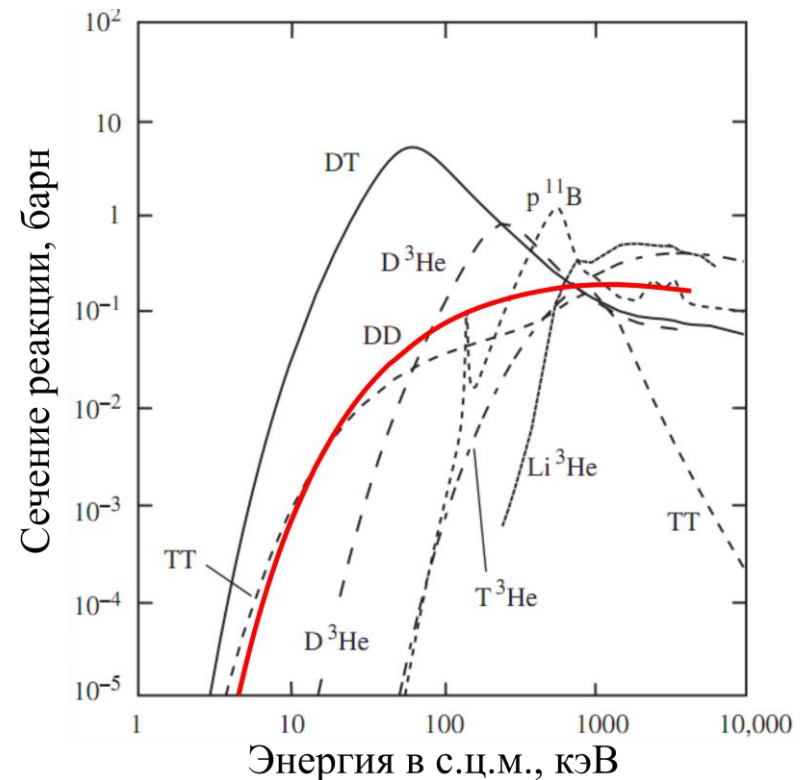
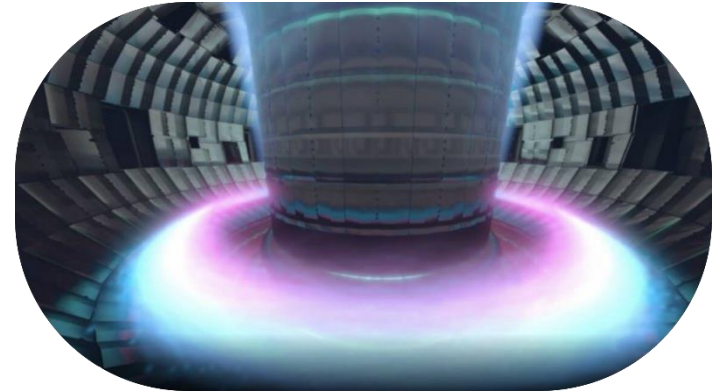
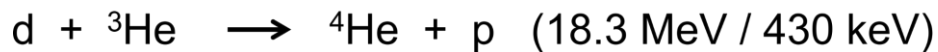
## 1 поколение:



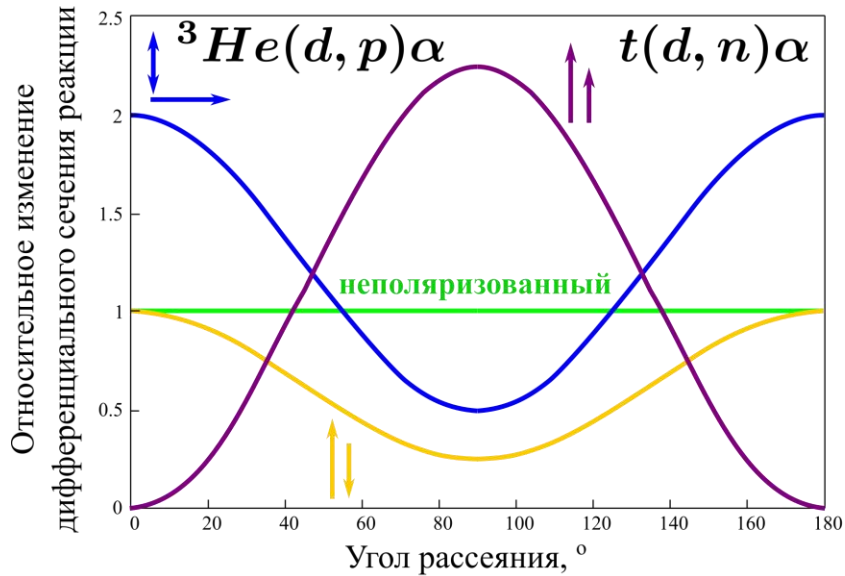
## 2 поколение:



## 3 поколение:



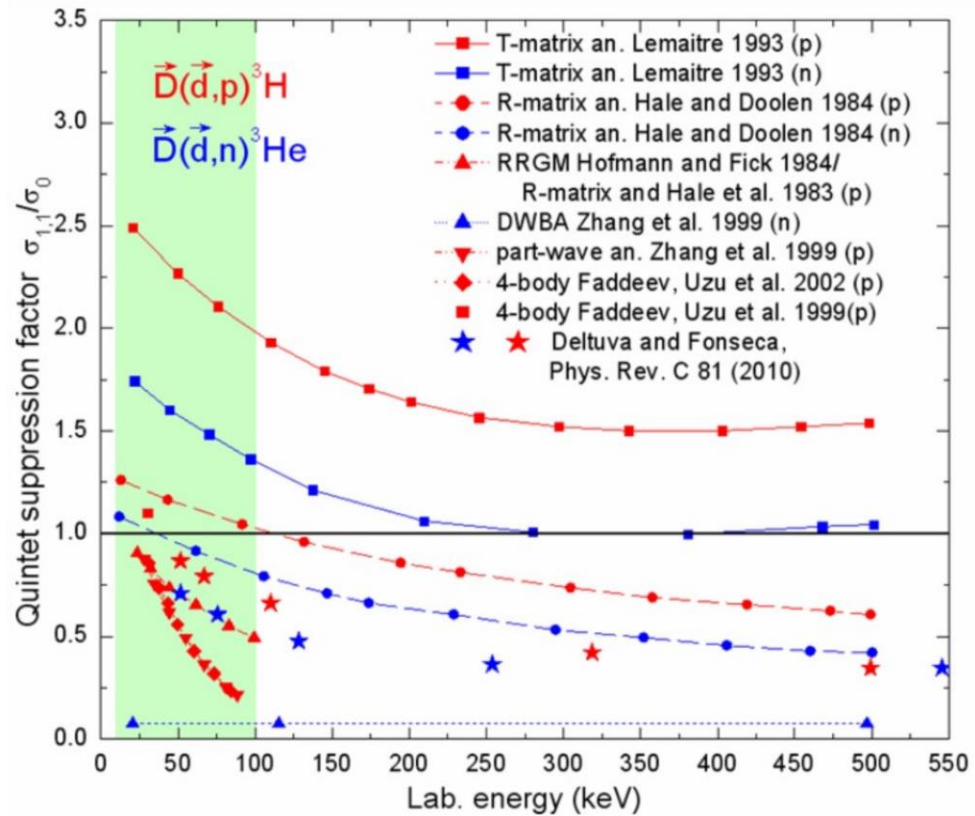
- Увеличение сечения реакции
- Контроль над направлением разлёта продуктов реакции
- Подавление нейтронного канала



Ch. Leemann et al., *Helv. Phys. Acta* **44**, 141 (1971)

R. Engels et al., *PoS SPIN 2018*, 176 (2019)

$$QSF = \frac{\sigma_{1,1}}{\sigma_0} \quad \sigma_0 = \frac{1}{9} \left( \underbrace{2\sigma_{1,1}}_{\text{Quintet}} + \underbrace{4\sigma_{1,0}}_{\text{Triplet}} + \underbrace{\sigma_{0,0} + 2\sigma_{1,-1}}_{\text{Singlet}} \right)$$



H. Paetz gen. Schieck *Nuclear physics with polarized particles* (Springer Verlag, Berlin, 2012); *Eur. Phys. J. A* **44**, (2010) 321; *Few-Body Syst.* **54** (2013) 2159

$$\sigma(\theta, \phi) = \sigma_0(\theta) \left( 1 + \sum_1^9 p_j^b A_j^b(\theta) + \sum_1^9 p_j^t A_j^t(\theta) + \sum_1^9 \sum_1^9 p_j^b p_k^t C_{j,k}(\theta) \right)$$

$$p_{l'} \sigma(\theta, \phi) = \sigma_0(\theta) \left( P_{l'}(\theta) + \sum_1^9 p_j K_j^{l'}(\theta) \right)$$

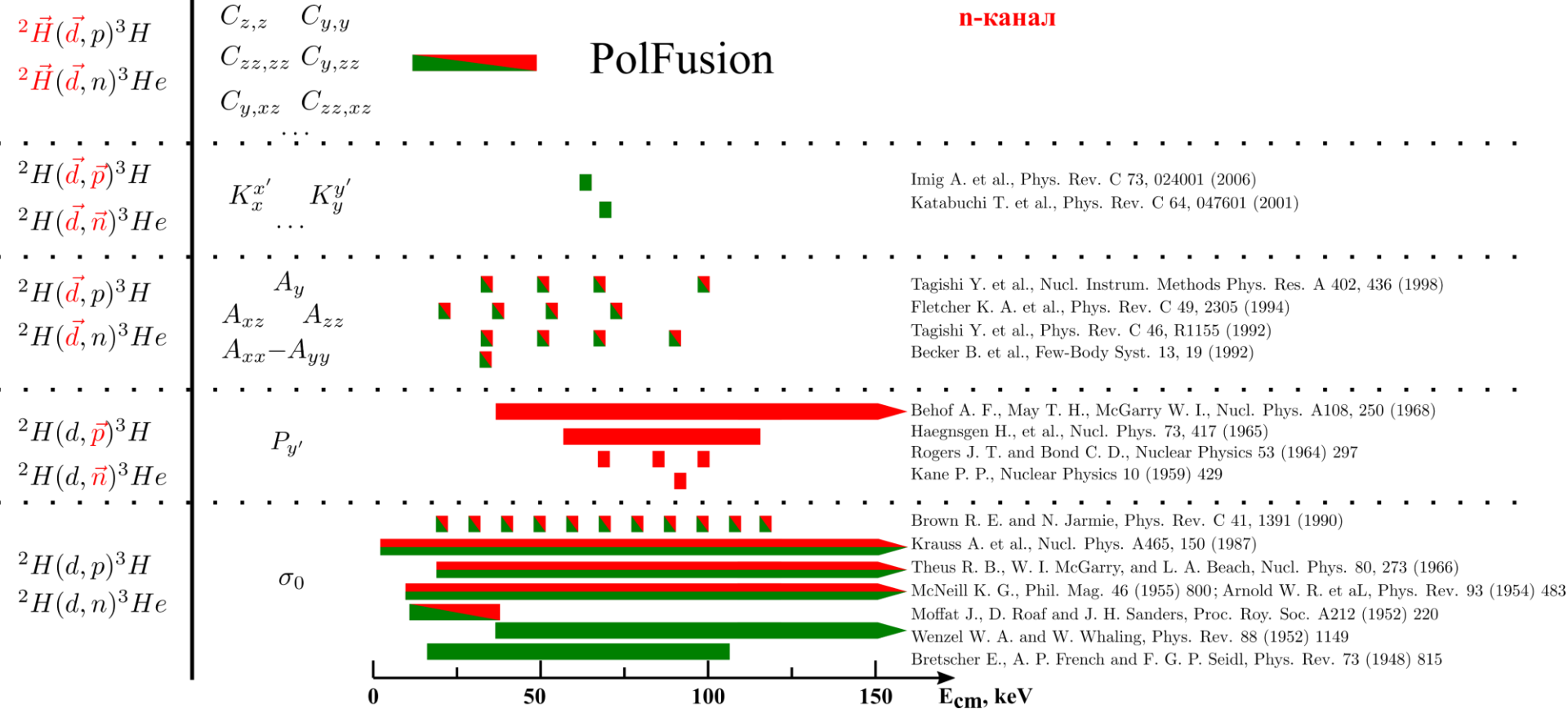
Gerald G. Ohlsen, Rep. Prog. Phys. **35**, 717 (1972)

**р-канал**

**п-канал**

Тип эксперимента

Наблюдаемые

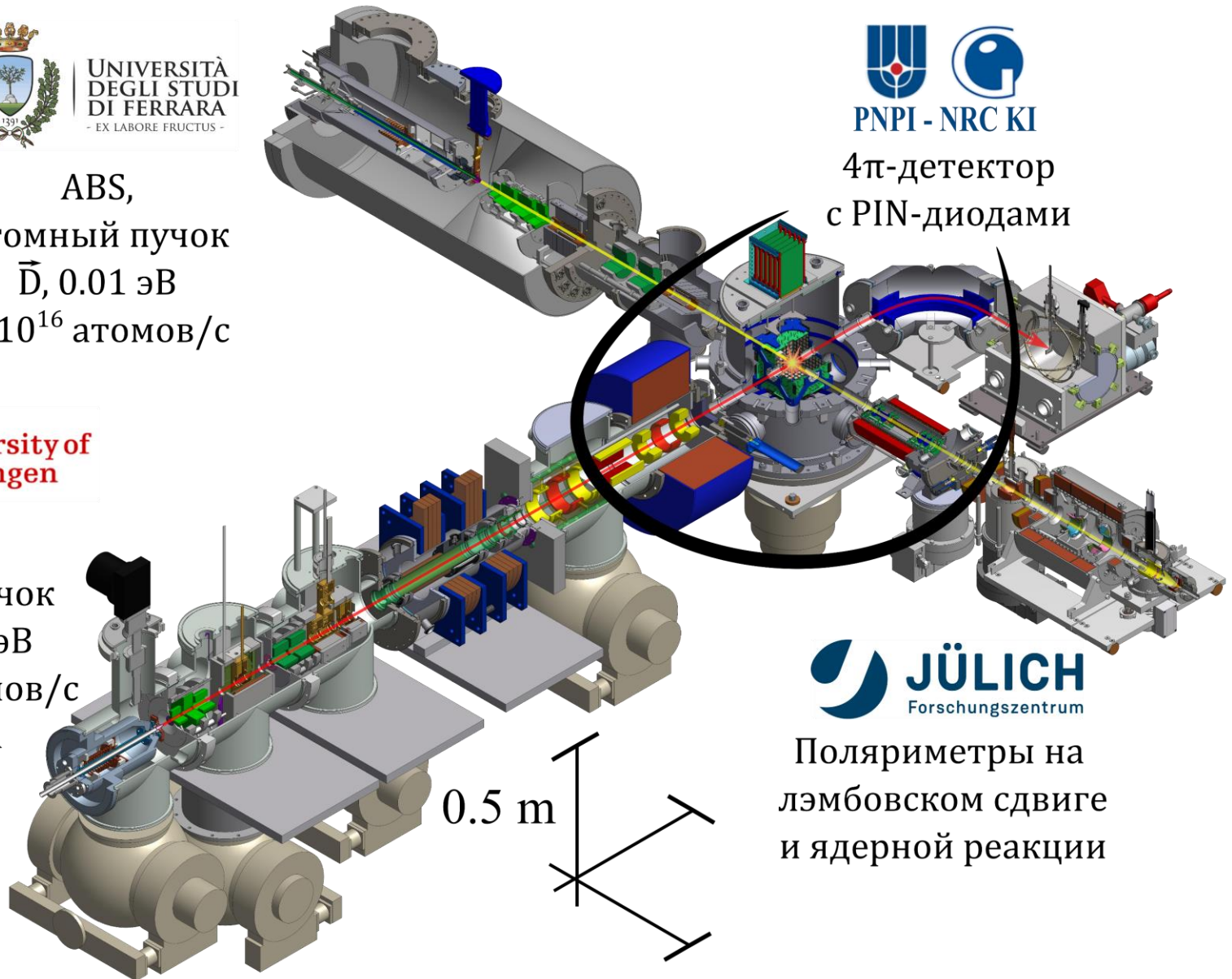




ABS,  
атомный пучок  
 $\bar{D}$ , 0.01 эВ  
 $4 \cdot 10^{16}$  атомов/с



POLIS,  
ионный пучок  
 $\bar{d}$ , 10-50 кэВ  
 $1.2 \cdot 10^{16}$  атомов/с  
>15 мкА



4π-детектор  
с PIN-диодами



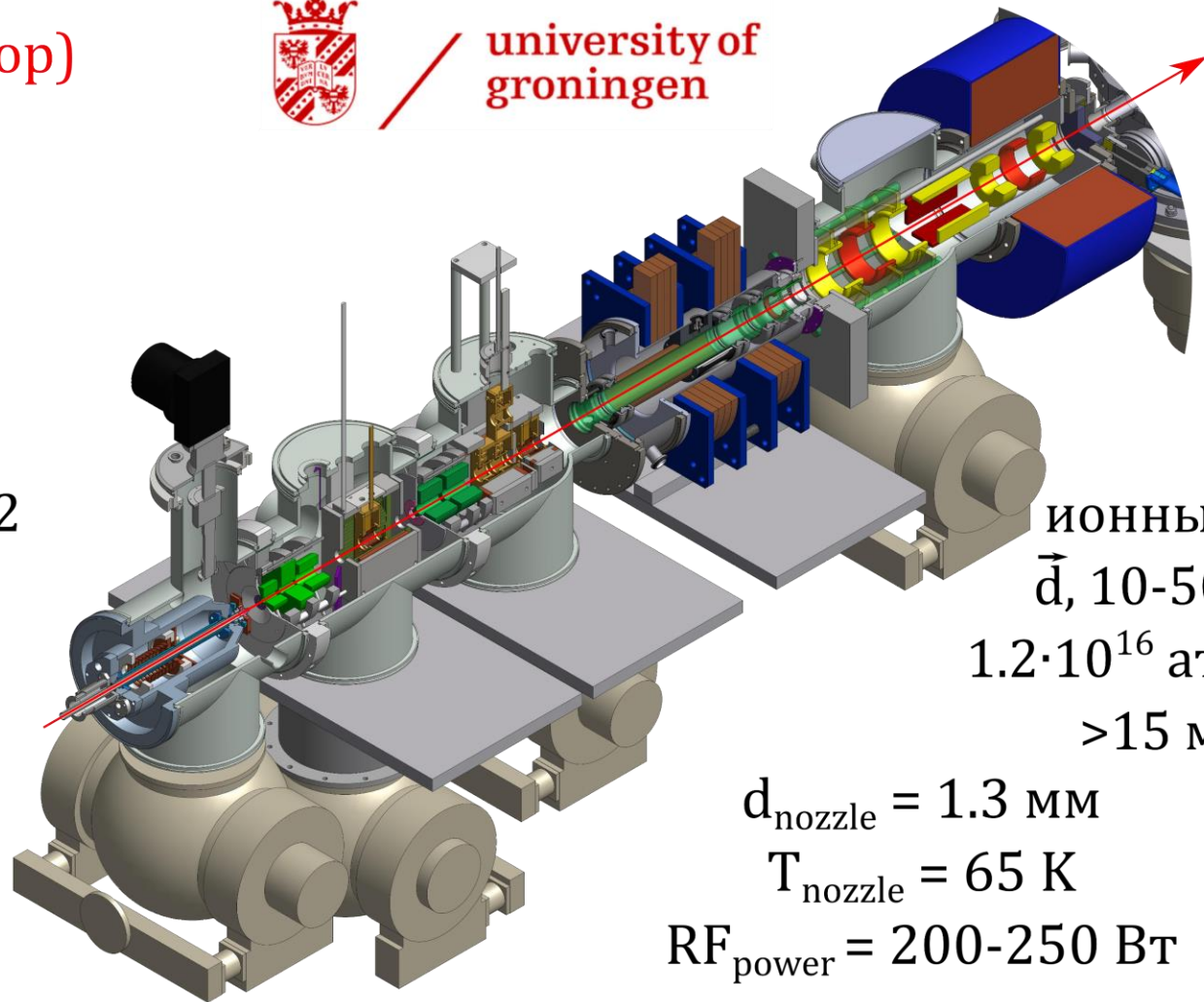
Поляриметры на  
лэмбовском сдвиге  
и ядерной реакции

$\rho_z$  (вектор)       $\rho_{zz}$  (тензор)

$\pm 2/3$	0
0	+1
0	-2
-1/3	$\pm 1$
+1/3	$\pm 1$
$\pm 1/3$	-1/2



university of  
groningen



ионный пучок  
 $\vec{d}$ , 10-50 кэВ  
 $1.2 \cdot 10^{16}$  атомов/с  
 $> 15$  мкА

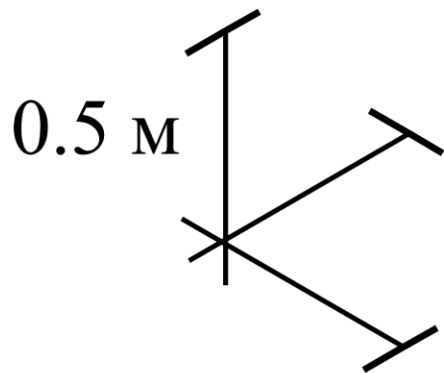
$$d_{\text{nozzle}} = 1.3 \text{ мм}$$

$$T_{\text{nozzle}} = 65 \text{ К}$$

$$RF_{\text{power}} = 200-250 \text{ Вт}$$

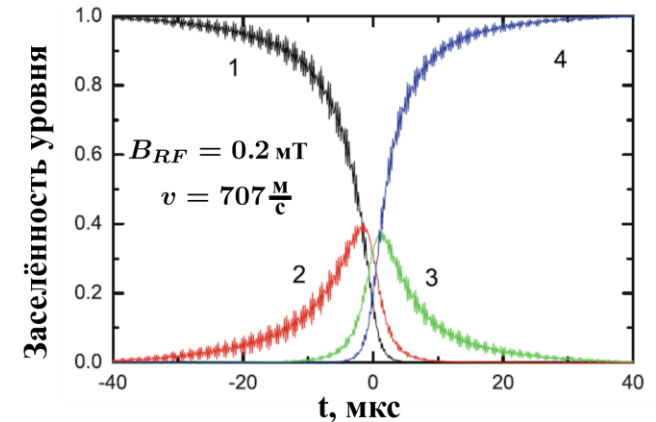
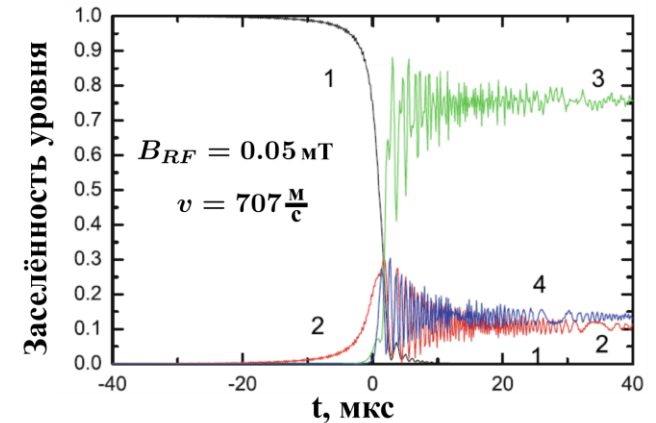
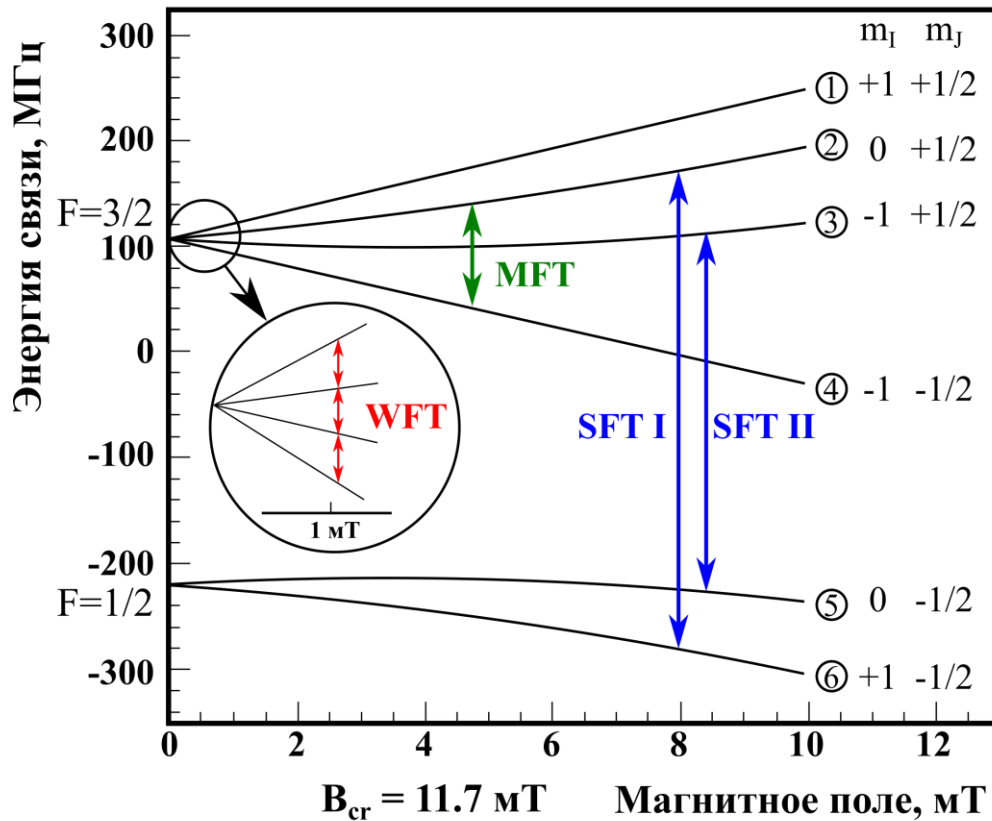
Поляризатор:

Sextupoles + WFT + Sextupoles + WFT + SFT1 (460 MHz) + SFT2 (350 MHz)





	WFT	MFT	SFT1	SFT2
$f, MHz$	8	25.4	460	350
$B_{RF}, mT$	0.2	0.1	0.2	0.2
$B_0, mT$	0.8	2.38/2.79/3.27	8	10
$\Delta B_0, mT$	0.2	0.2	0.7	0.7
$l_{RF}, mm$	40	69	40	40



$\rho_z$  (вектор)       $\rho_{zz}$  (тензор)

-2/3

0

0

+1

-1/3

+1

-1

+1

$\pm 1/2$

-1/2

атомный пучок  $d_{\text{nozzle}} = 2 \text{ мм}$

$\vec{D}$ , 0.01 эВ

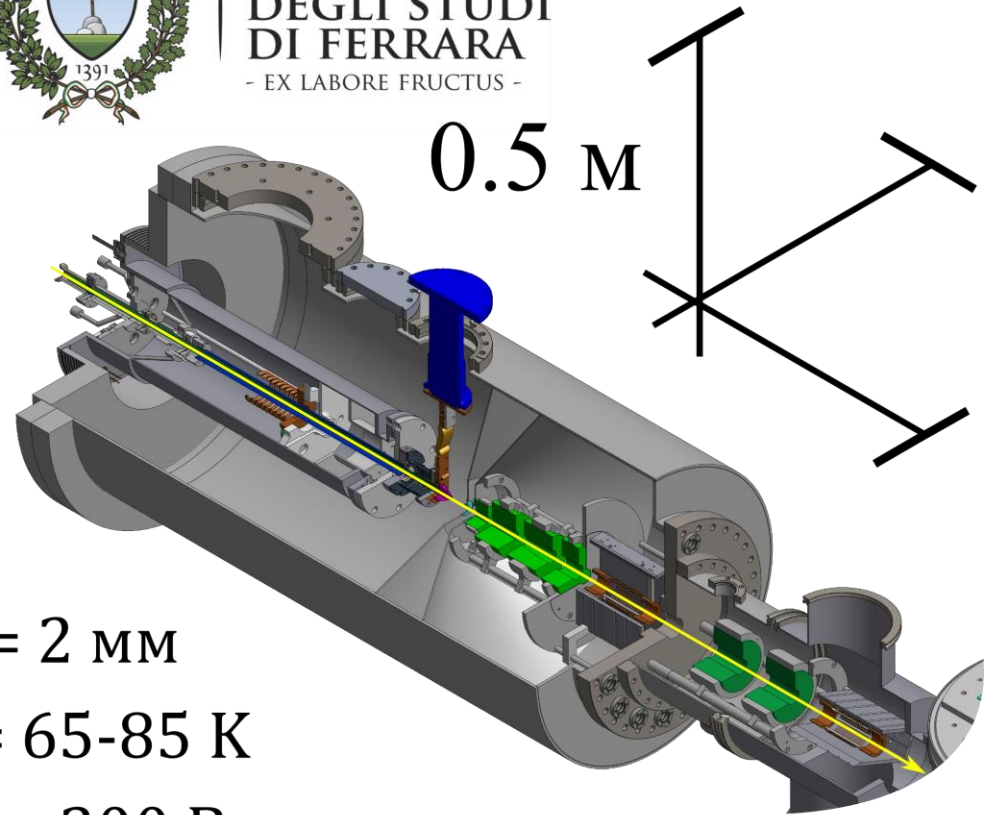
$T_{\text{nozzle}} = 65-85 \text{ К}$

$4 \cdot 10^{16}$  атомов/с  $RF_{\text{power}} = 300 \text{ Вт}$



UNIVERSITÀ  
DEGLI STUDI  
DI FERRARA  
- EX LABORE FRUCTUS -

0.5 м

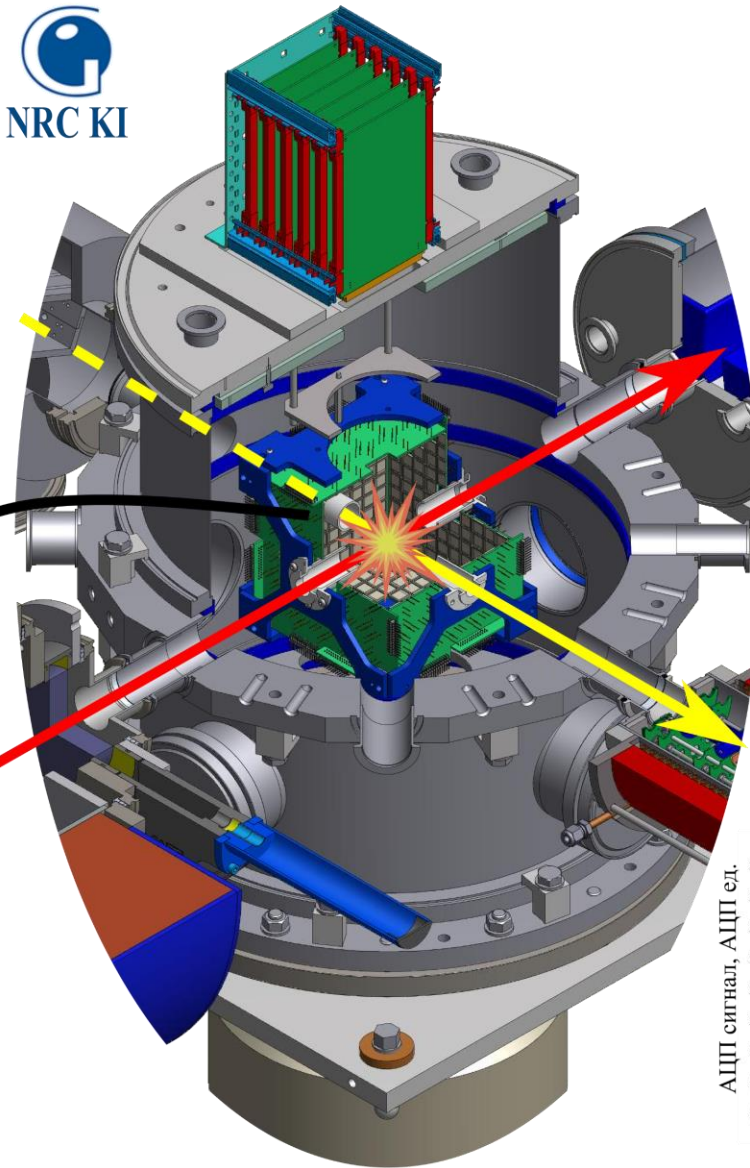


**Поляризатор:**

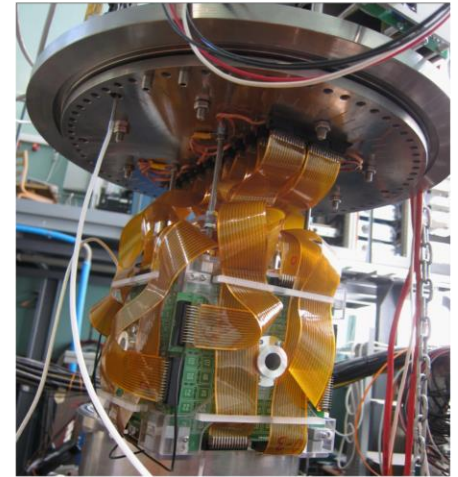
Sextupoles + MFT + Sextupoles + MFT



576 PIN диоды  
 Hamamatsu S3590-09  
 заряженные частицы:  
 0.2 - 4 MeV  
 с энергетическим  
 разрешением  
 < 50 keV

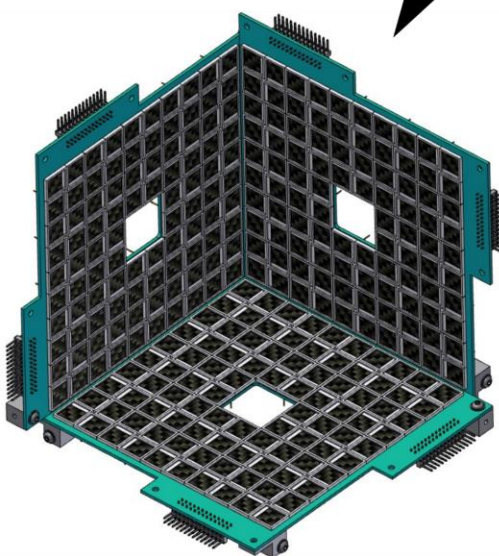
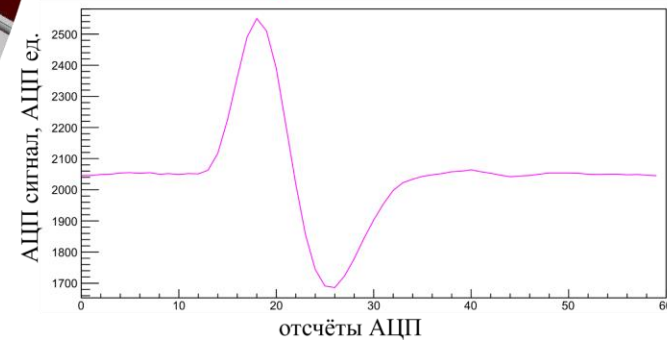


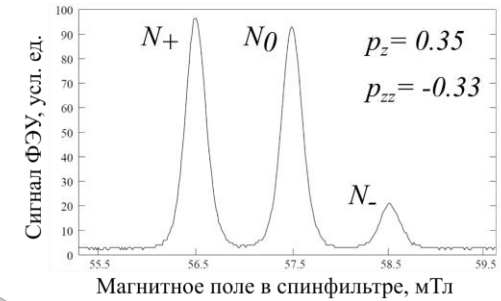
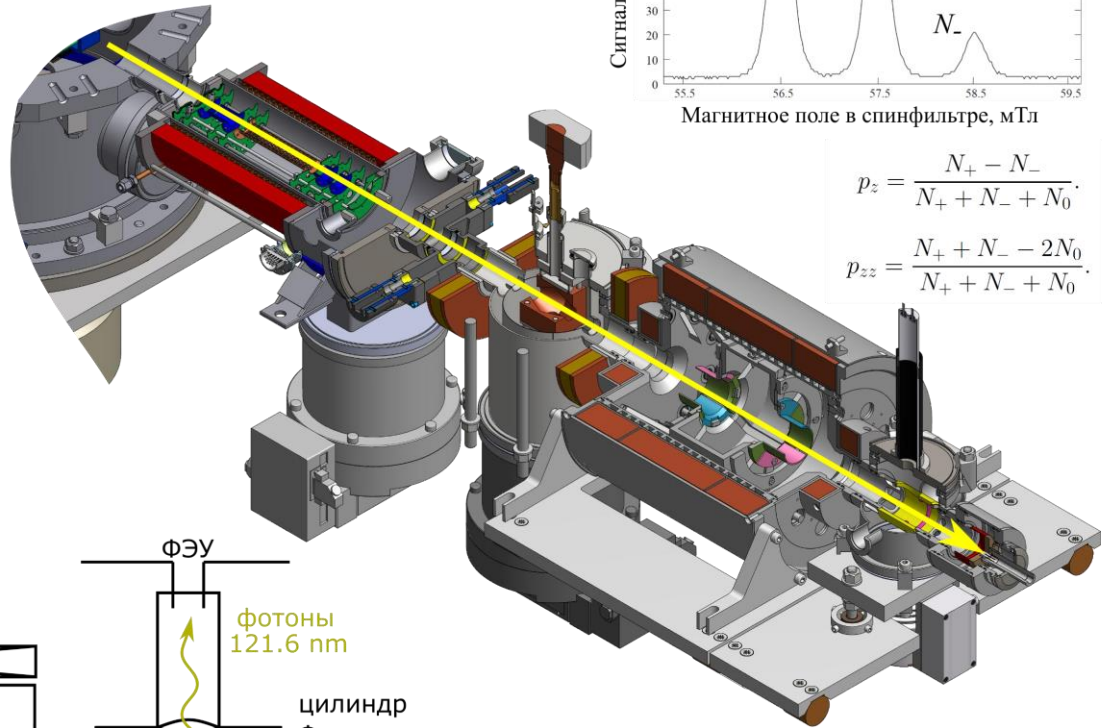
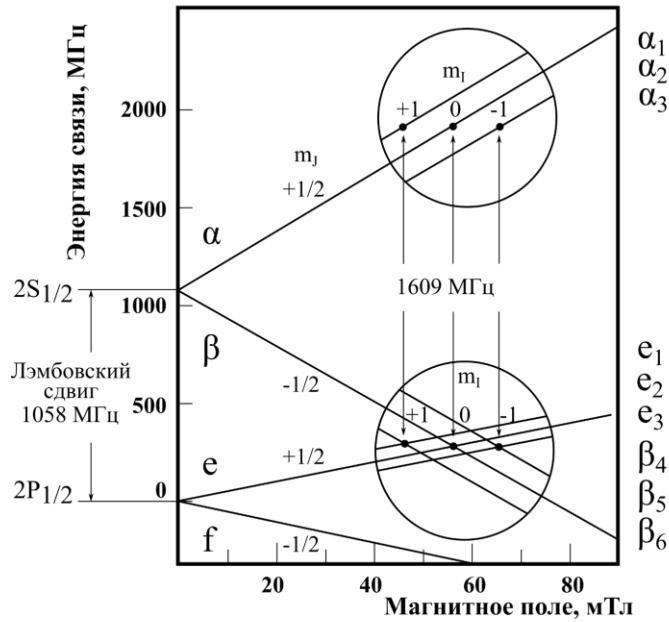
50% покрытие



10 нс точность записи  
 времени сигнала

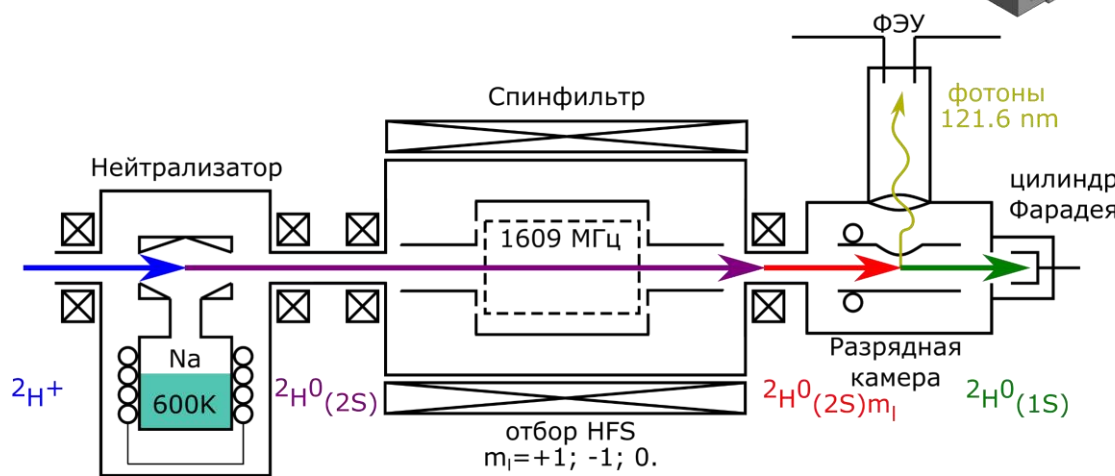
Форма сигнала:





$$p_z = \frac{N_+ - N_-}{N_+ + N_- + N_0}$$

$$p_{zz} = \frac{N_+ + N_- - 2N_0}{N_+ + N_- + N_0}$$





$$\frac{L - R}{L + R} = \frac{\frac{3}{2} P_{ZZ} \sin \beta A_y}{1 + \frac{1}{2} P_{ZZ} [\sin^2 \beta A_{yy} + \cos^2 \beta A_{zz}]}$$

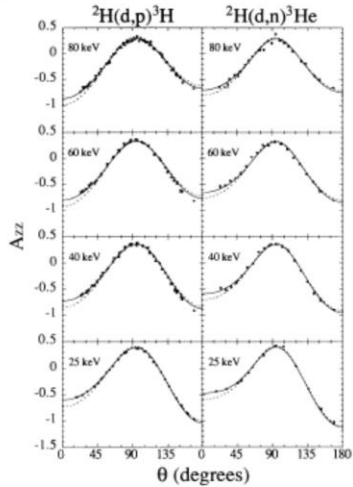
$$\frac{U - D}{U + D} = \frac{P_{ZZ} \sin \beta \cos \beta A_{xz}}{1 + \frac{1}{2} P_{ZZ} [\sin^2 \beta A_{xx} + \cos^2 \beta A_{zz}]}$$

$$\frac{2(L - R)}{L + R + U + D} = \frac{\frac{3}{2} P_{ZZ} \sin \beta A_y}{1 + \frac{1}{4} P_{ZZ} [3(\cos^2 \beta - 1) A_{zz}]}$$

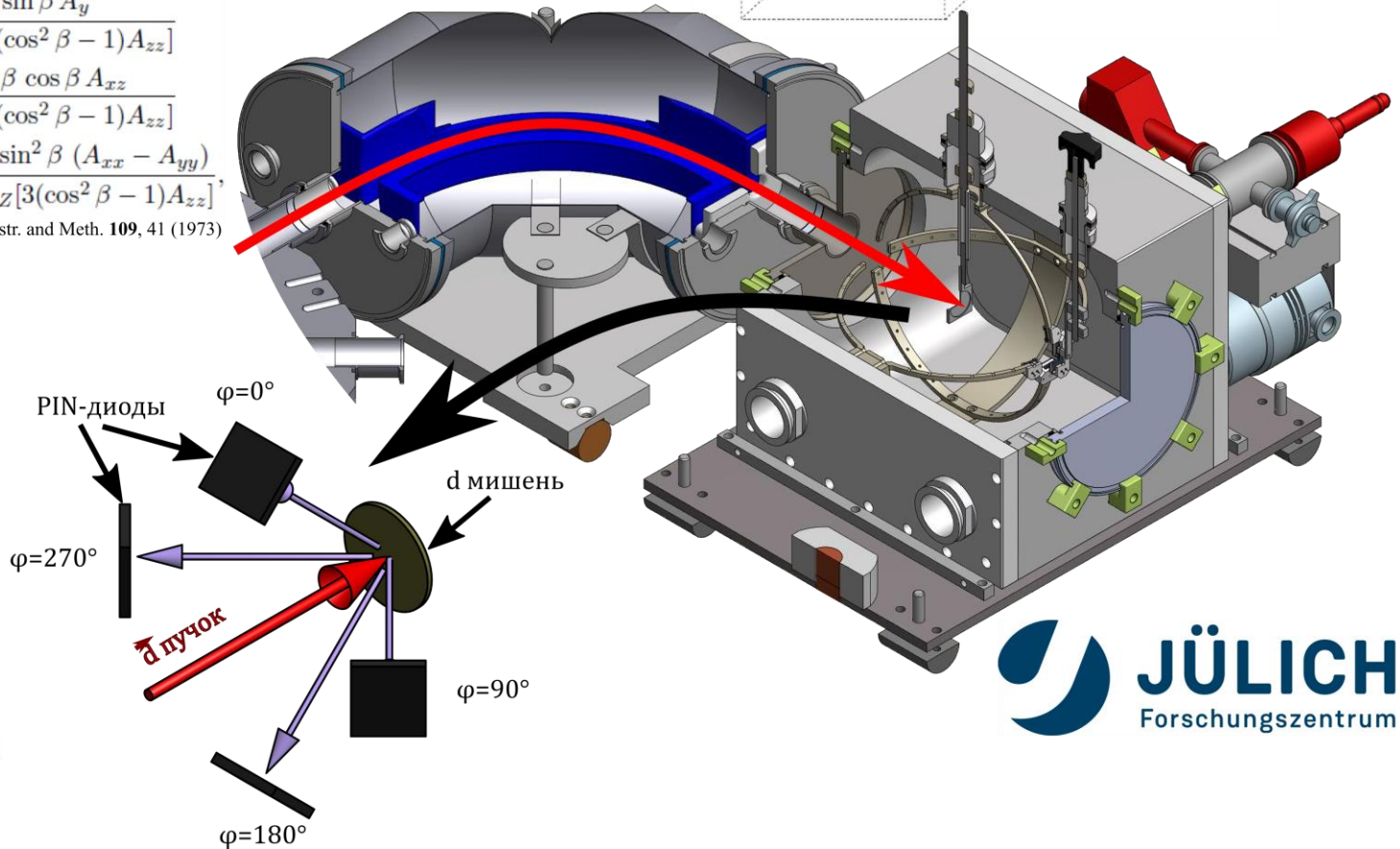
$$\frac{2(U - D)}{L + R + U + D} = \frac{P_{ZZ} \sin \beta \cos \beta A_{xz}}{1 + \frac{1}{4} P_{ZZ} [3(\cos^2 \beta - 1) A_{zz}]}$$

$$\frac{(L + R) - (U + D)}{L + R + U + D} = \frac{-\frac{1}{4} P_{ZZ} \sin^2 \beta (A_{xx} - A_{yy})}{1 + \frac{1}{4} P_{ZZ} [3(\cos^2 \beta - 1) A_{zz}]},$$

G.G. Ohlsen, P.W. Keaton, Jr., Nucl. Instr. and Meth. **109**, 41 (1973)



K. Fletcher, *et al.*, Phys. Rev. C **49**, 2305 (1994).



**Basel convention (1961):** Huber, P., Meyer, K.P. (eds.): Proceedings of the International Symposium on Polarization Phenomena of Nucleons. Helv. Phys. Acta Suppl. VI. Birkhäuser

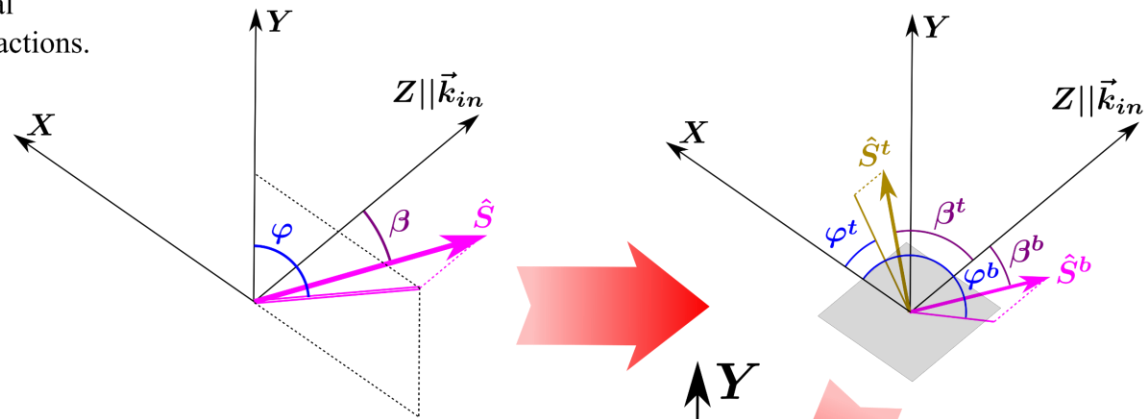
**Madison convention (1971):** Barschall, H.H.,

Haeberli, W. (eds.): Proceedings of the 3rd International Symposium on Polarization Phenomena in Nuclear Reactions.

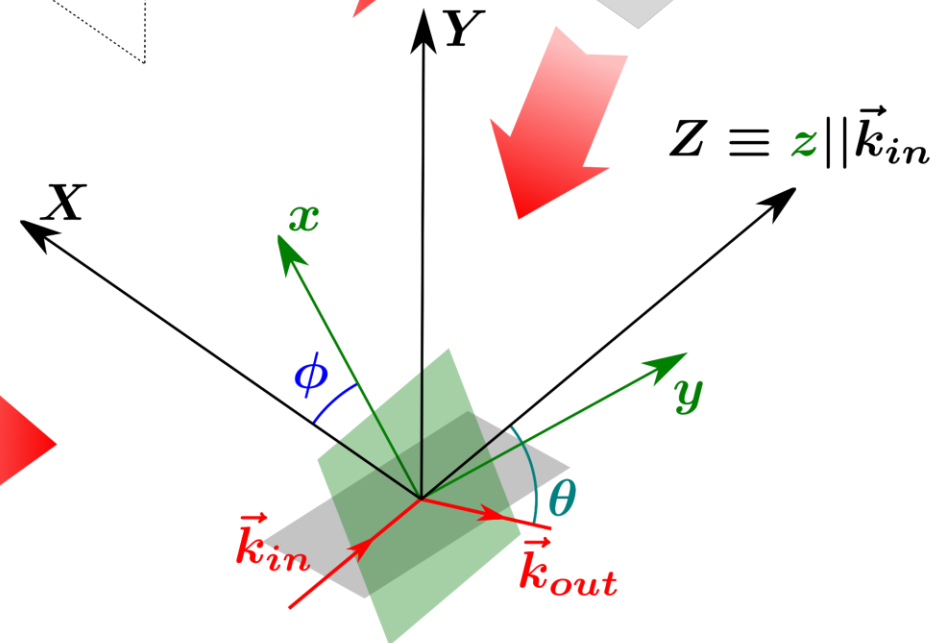
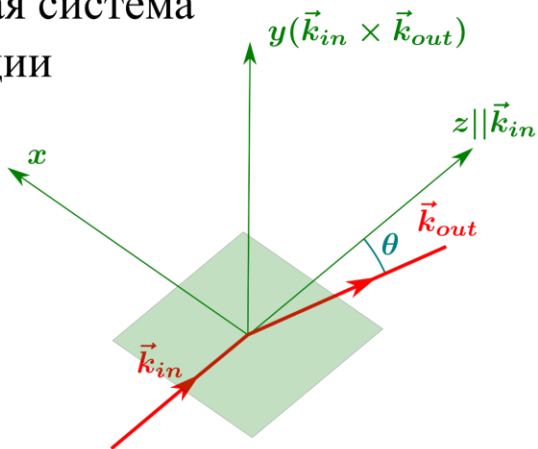
University of Wisconsin Press

Описание поляризации  
(фиксированная в пространстве  
координатная система)

$\vec{k}_{in}$	- МОМЕНТ ИМПУЛЬСА налетающей частицы
$\vec{k}_{out}$	- МОМЕНТ ИМПУЛЬСА вылетающей частицы
$\hat{S}^b, \hat{S}^t$	- ОСИ КВАНТОВАНИЯ пучка и мишени



Координатная система  
реакции



$$Y(\theta, \phi) = L \cdot \sigma(\theta, \phi)$$

$$\sigma(\theta, \phi) = \sigma_0(\theta) \left( 1 + \sum_1^9 p_j^b A_j^b(\theta) + \sum_1^9 p_j^t A_j^t(\theta) + \sum_1^9 \sum_1^9 p_j^b p_k^t C_{j,k}(\theta) \right)$$

Gerald G. Ohlsen, Rep. Prog. Phys. **35**, 717 (1972)

Знак поляризации: ( $L_{POLIS}, ABS$ )

$$L_{++} = L_{-+} = L_{+-} = L_{--}$$

$$\mathcal{A}^b(\theta, \phi) = \frac{(Y_{++} + Y_{+-}) - (Y_{-+} + Y_{--})}{Y_{++} + Y_{+-} + Y_{-+} + Y_{--}}$$

$$\mathcal{A}^t(\theta, \phi) = \frac{(Y_{++} + Y_{-+}) - (Y_{+-} + Y_{--})}{Y_{++} + Y_{+-} + Y_{-+} + Y_{--}}$$

$$\mathcal{A}^{b,t}(\theta, \phi) = \frac{(Y_{++} + Y_{--}) - (Y_{-+} + Y_{+-})}{Y_{++} + Y_{+-} + Y_{-+} + Y_{--}}$$

$$\beta^b = \beta^t = 0^\circ :$$

$$\sigma(\theta, \phi) = \sigma_0(\theta) \left[ 1 + \frac{1}{2} p_{ZZ}^b A_{zz}^b(\theta) + \frac{1}{2} p_{ZZ}^t A_{zz}^t(\theta) + \frac{9}{4} p_Z^b p_Z^t C_{z,z}(\theta) + \frac{1}{4} p_{ZZ}^b p_{ZZ}^t C_{zz,zz}(\theta) \right]$$

$$\mathcal{A}^b(\theta, \phi) = \frac{2|p_{ZZ}^b| A_{zz}^b(\theta)}{4+9C_{z,z}}$$

$$\mathcal{A}^t(\theta, \phi) = \frac{2|p_{ZZ}^t| A_{zz}^t(\theta)}{4+9C_{z,z}}$$

$$\mathcal{A}_Z^{b,t}(\theta, \phi) = \frac{9|p_Z^b| |p_Z^t| C_{z,z}(\theta)}{4+2p_{ZZ}^b A_{zz}^b(\theta) + 2p_{ZZ}^t A_{zz}^t(\theta) + p_{ZZ}^b p_{ZZ}^t C_{zz,zz}(\theta)}$$

$$\mathcal{A}_{ZZ}^{b,t}(\theta, \phi) = \frac{|p_{ZZ}^b| |p_{ZZ}^t| C_{zz,zz}}{4+9|p_Z^b| |p_Z^t| C_{z,z}}$$

$$p_Z^b = p_Z^t = \pm \frac{2}{3}$$

$$p_{ZZ}^b = p_{ZZ}^t = 0$$

$$\mathcal{A}_Z^{b,t}(\theta, \phi) = C_{z,z}$$

$$p_Z^b = p_Z^t = +\frac{1}{3}$$

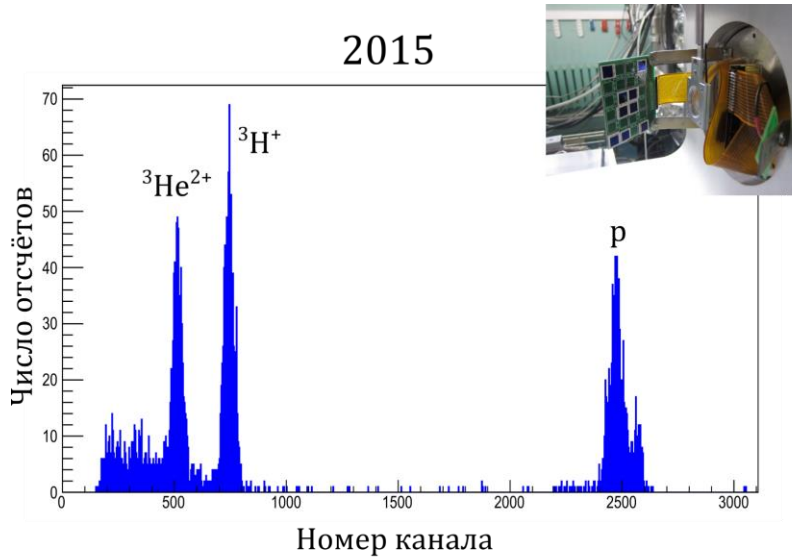
$$p_{ZZ}^b = p_{ZZ}^t = \pm 1$$

$$\mathcal{A}_{ZZ}^{b,t}(\theta, \phi) = \frac{C_{zz,zz}}{4+C_{z,z}}$$

$$\mathcal{A}_{ZZ}^b(\theta, \phi) = \frac{2A_{zz}^b(\theta)}{4+9C_{z,z}}$$

$$\mathcal{A}_{ZZ}^t(\theta, \phi) = \frac{2A_{zz}^t(\theta)}{4+9C_{z,z}}$$





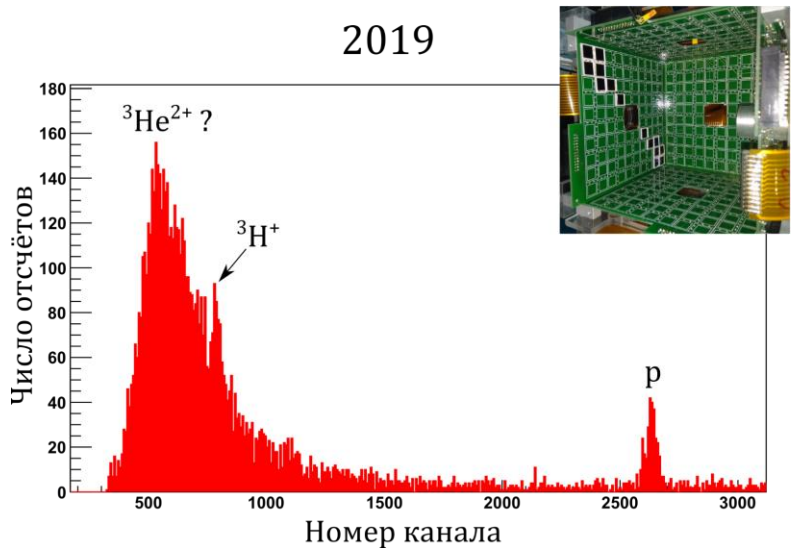
**Мишень:** дейтерированный полиметилметакрилат

**Плотность:**  $\sim 10^{17}$  атомов/см<sup>2</sup>

**Пучок:** 15 кэВ  $\sim$  5мкА

**Длительность:**  $\sim$  3 ч

**Цель:** оценка качества сигнала  
калибровка АЦП



**Мишень:** тяжёлая вода

**Плотность:**  $\sim 10^{12}$  атомов/см<sup>2</sup>

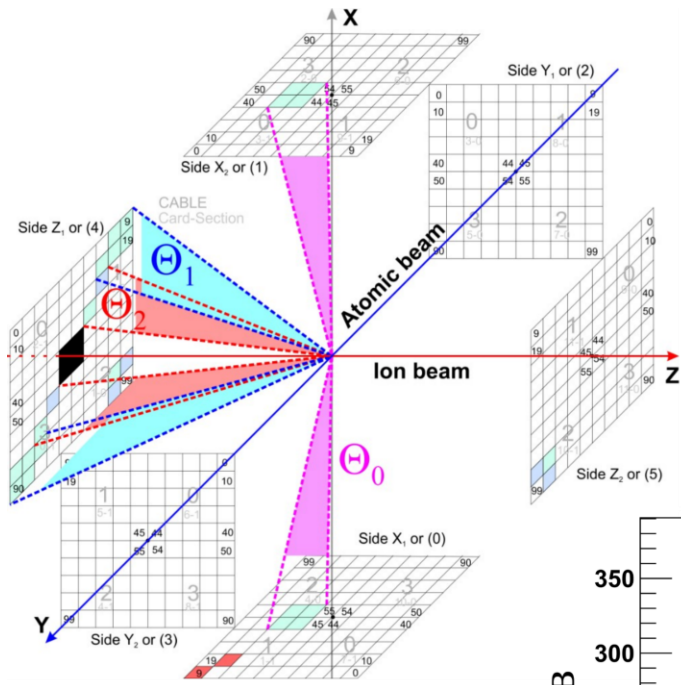
**Пучок:** 10 кэВ  $\sim$  10мкА

**Длительность:**  $\sim$  200 ч

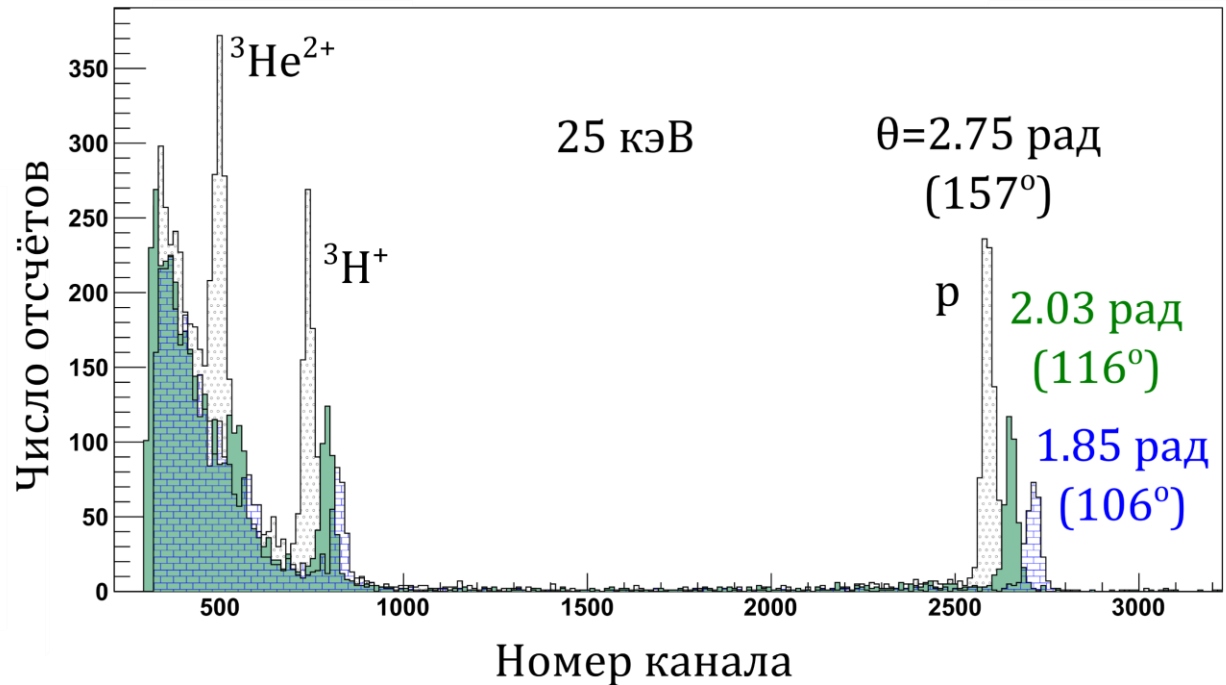
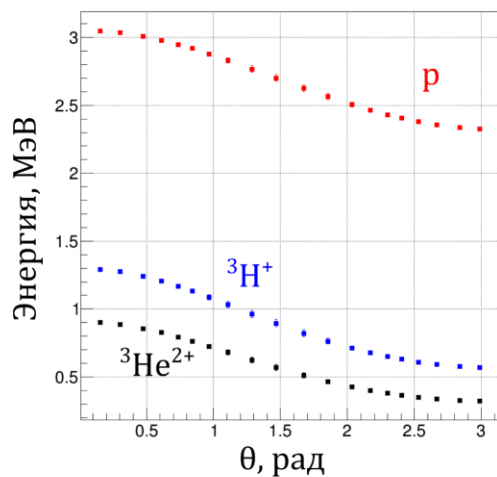
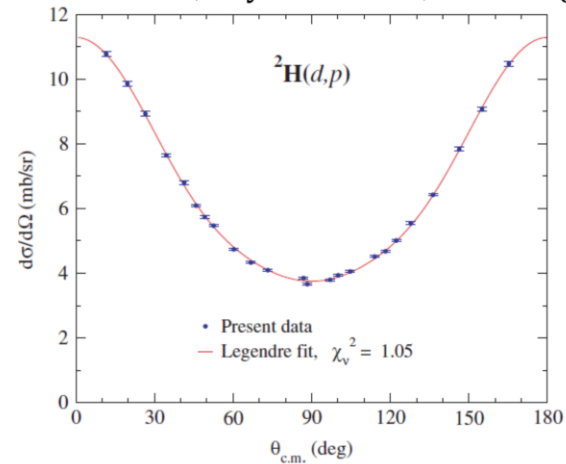
**Цель:** симуляция ABS  
оценка космического фона



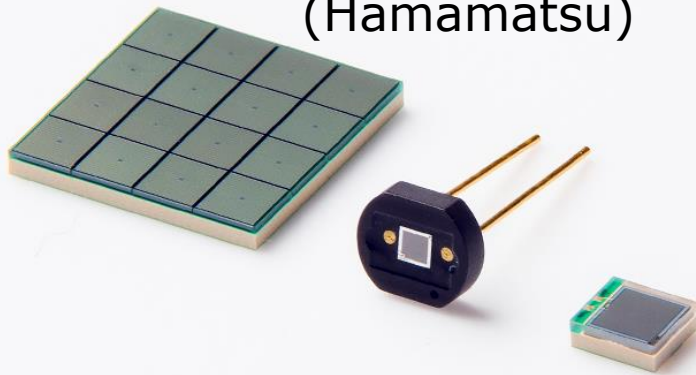
**Плотность мишени ABS:**  $2.7 \cdot 10^{11}$  атомов/см<sup>2</sup> при  $4 \cdot 10^{16}$  атомов/с



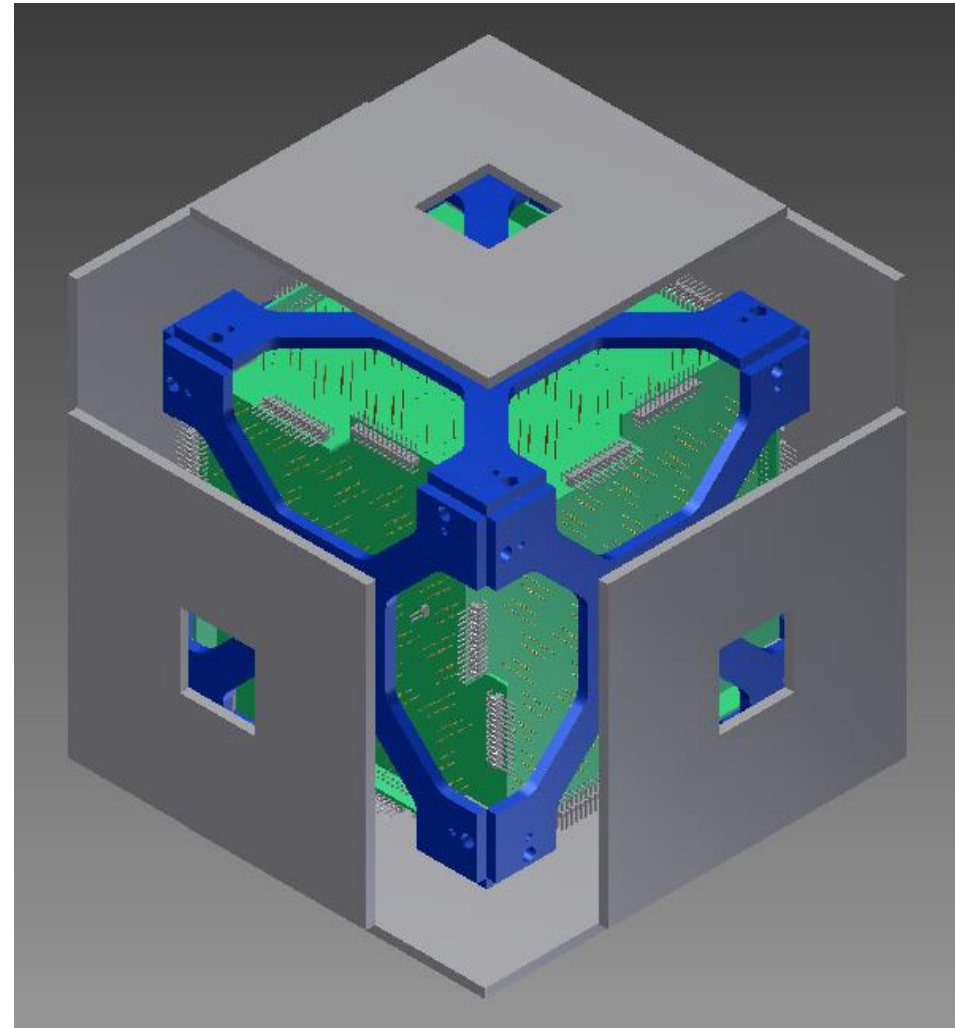
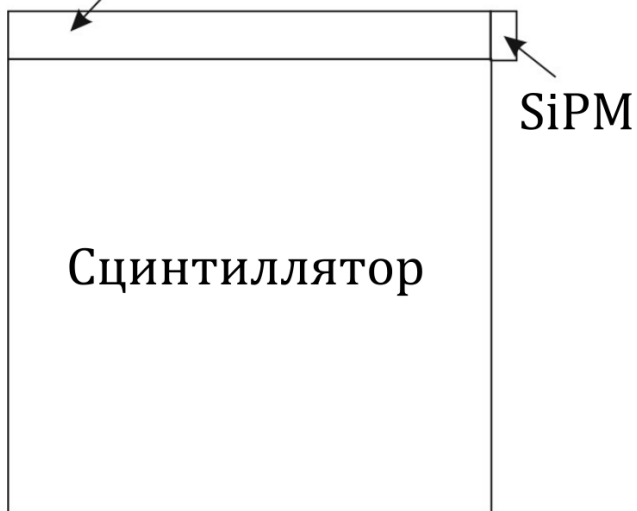
D.S. Leonard et al., Phys. Rev. C **73**, 045801 (2006).



MPPC S13360/S13362 series  
(Hamamatsu)



Элемент  
для сдвига частоты



## План на 2021 (первая половина)

- Запуск и отладка поляриметра на лэмбовском сдвиге
- Настройка RF ячеек POLIS
- Тестовый сеанс с поляризованным ионным пучком на паровой мишени

## План на 2021 (вторая половина)

- Разработка системы для регистрации космического фона
- Изготовление и установка SFT1 и SFT2 для ABS
- Настройка RF ячеек ABS
- Сеанс с неполяризованным ионным и неполяризованным атомарным пучками



---

Спасибо  
за  
внимание!

$$\sigma(\theta, \phi) = \sigma_0(\theta) \left( 1 + \sum_{j=1}^9 \bar{p}_j^b A_j^b(\theta) + \sum_{j=1}^9 \bar{p}_j^t A_j^t(\theta) + \sum_{j=1}^9 \sum_{k=1}^9 \bar{p}_j^b \bar{p}_k^t C_{j,k}(\theta) \right)$$

$$p_{l'} \sigma(\theta, \phi) = \sigma_0(\theta) \left( P_{l'}(\theta) + \sum_{j=1}^9 \bar{p}_j K_j^{l'}(\theta) \right)$$

$$\bar{p}_1 = \frac{3}{2} p_x$$

$$\bar{p}_2 = \frac{3}{2} p_y$$

$$\bar{p}_3 = \frac{3}{2} p_z$$

$$\bar{p}_4 = \frac{2}{3} p_{xy}$$

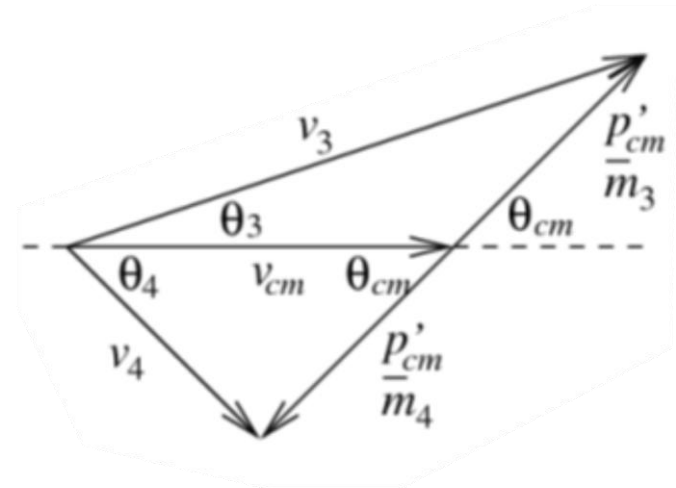
$$\bar{p}_5 = \frac{2}{3} p_{xz}$$

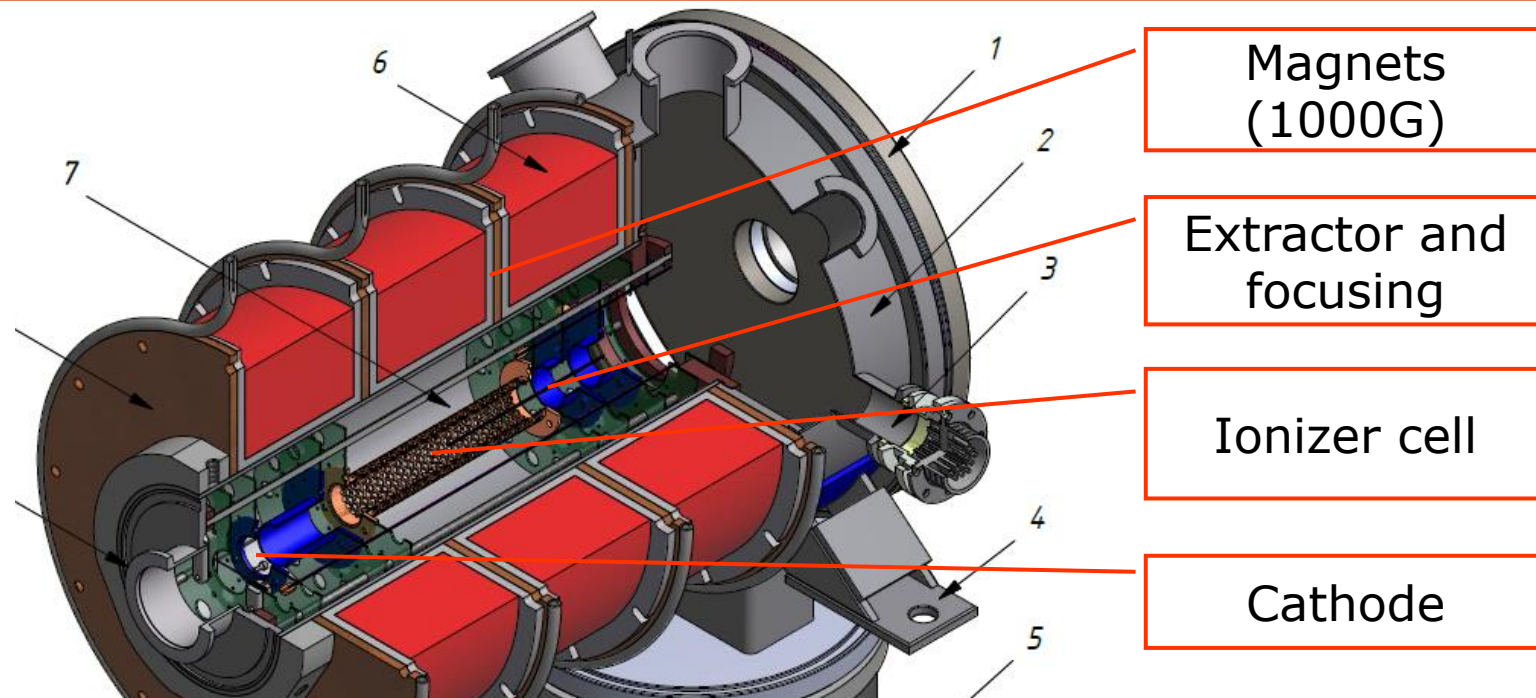
$$\bar{p}_6 = \frac{2}{3} p_{yz}$$

$$\bar{p}_7 = \frac{1}{3} p_{xx}$$

$$\bar{p}_8 = \frac{1}{3} p_{yy}$$

$$\bar{p}_9 = \frac{1}{3} p_{zz}$$



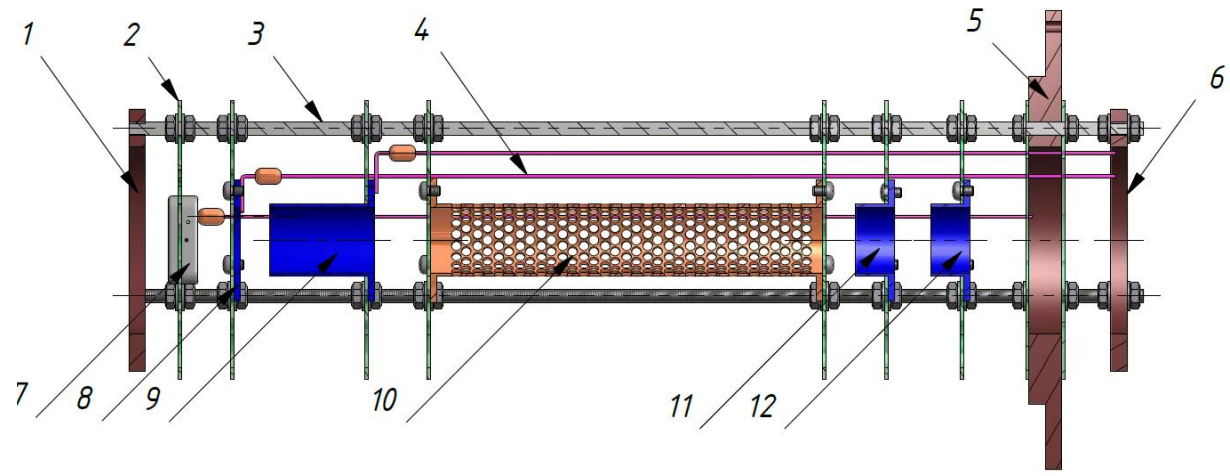
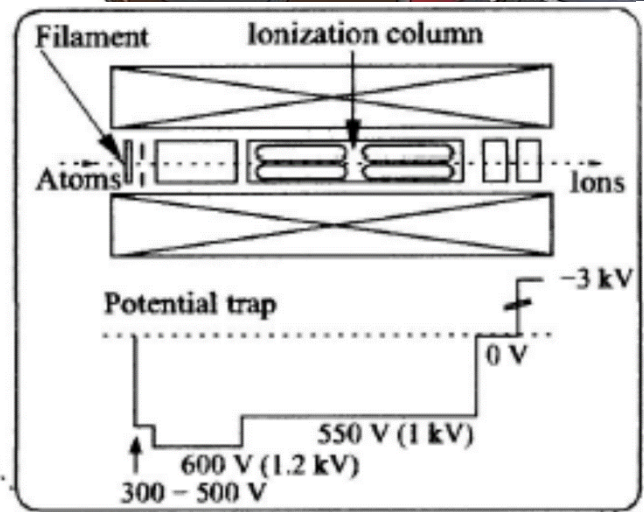


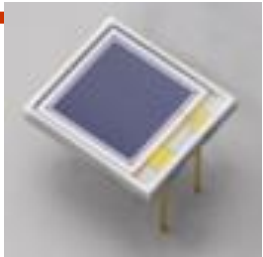
Magnets  
(1000G)

Extractor and  
focusing

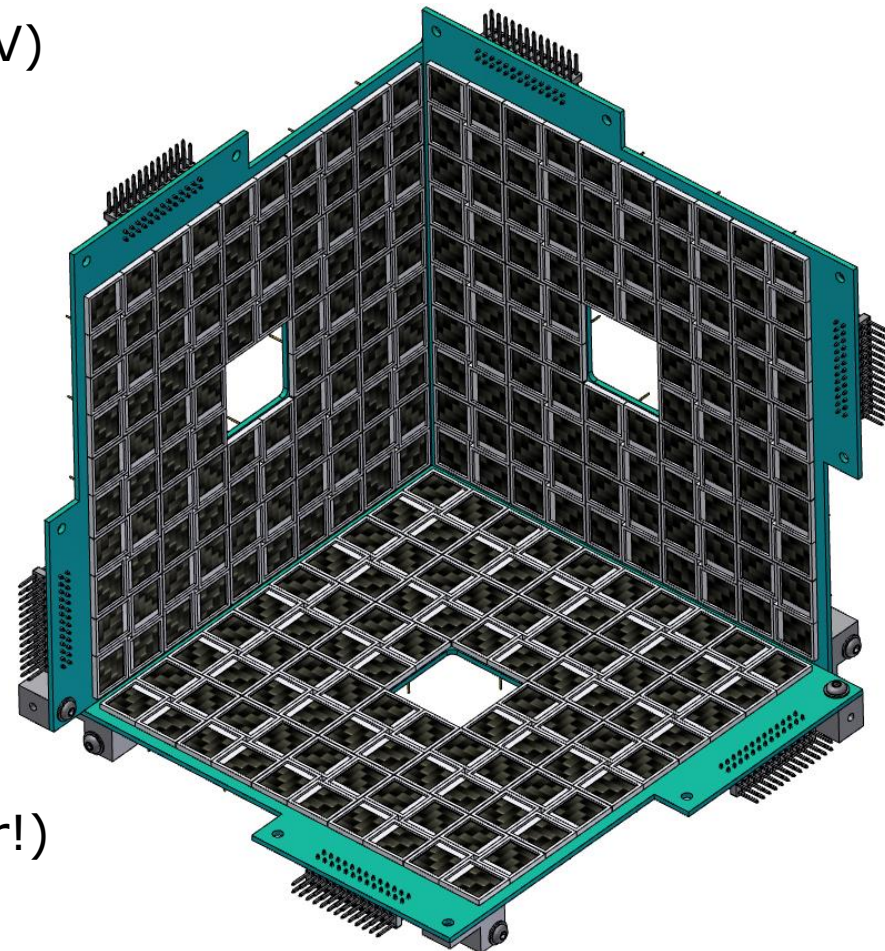
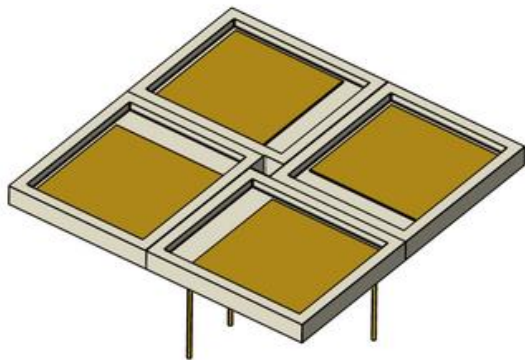
Ionizer cell

Cathode





- 4- $\pi$  detector with 51% filling
- 576 Hamamatsu PIN-diodes (S3590-09)
- PIN-diode active area: 1 cm<sup>2</sup>
- depleted layer: 300  $\mu$ m
- energy resolution: <50keV
- low reverse voltage ( $\leq$ 50V)



Square detector elements (4x4 diodes)  
Standard PCB assembly with  
spring through-hole mounting (no solder!)

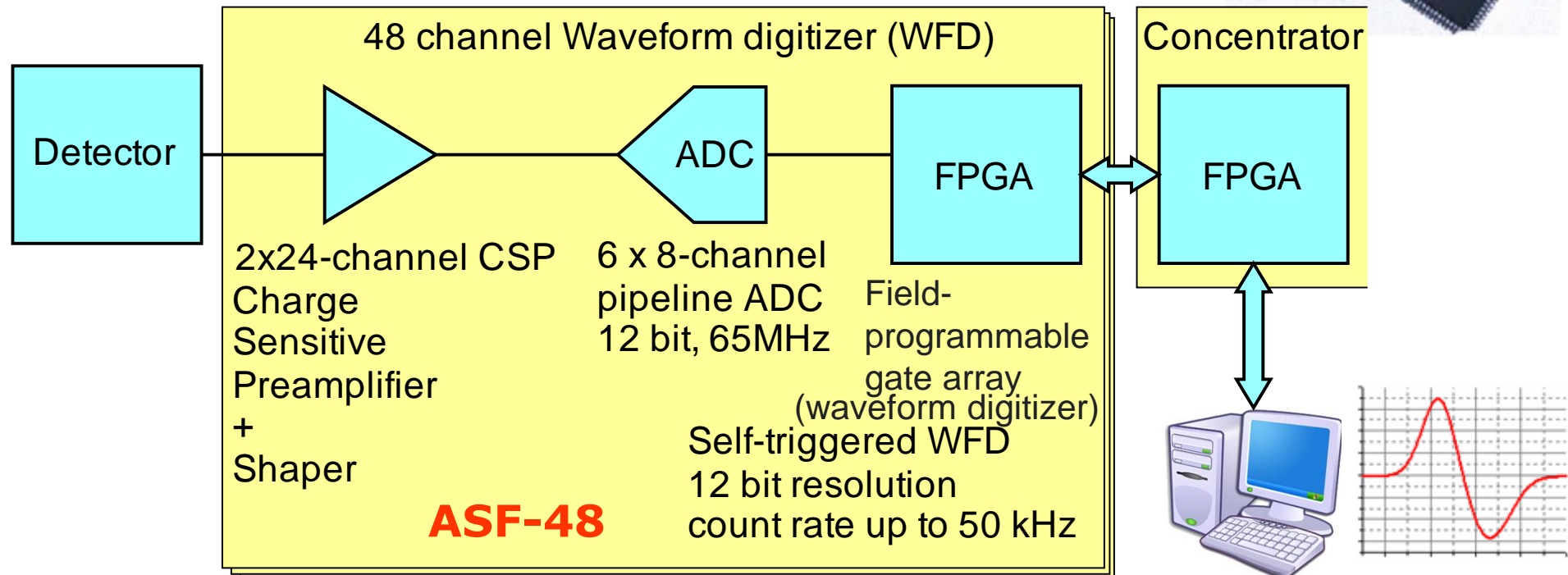


## Readout requirements:

- 600 channels
- Total count rate  $\leq 1\text{kHz}$
- Standard interface (Ethernet?)
- Event synchronization for coincidence trigger

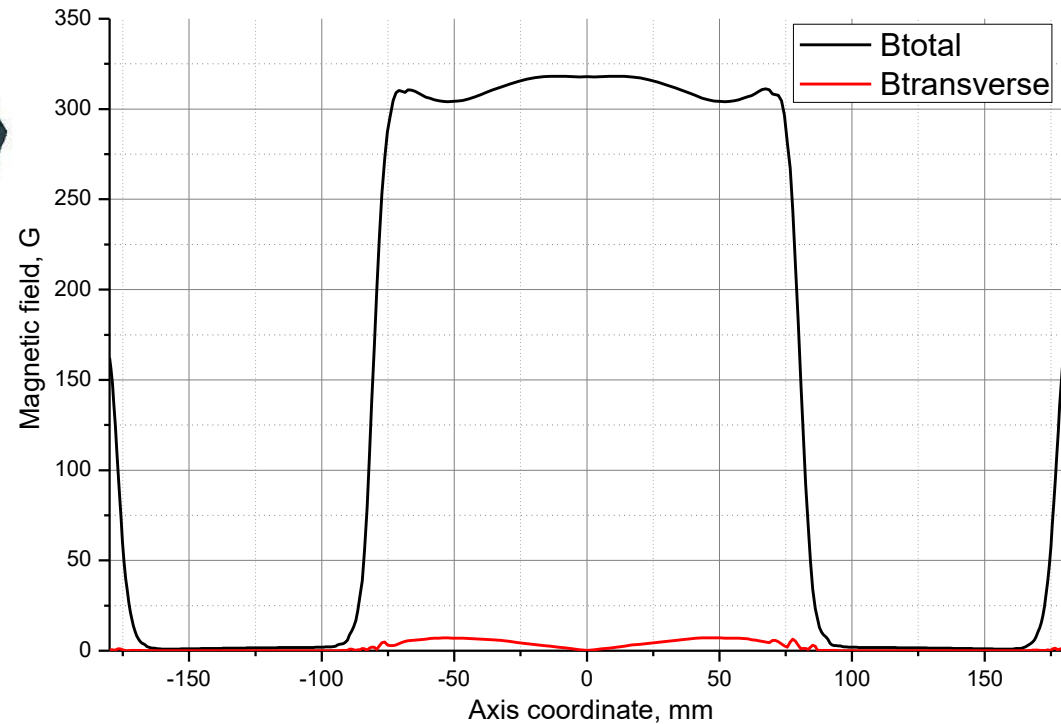
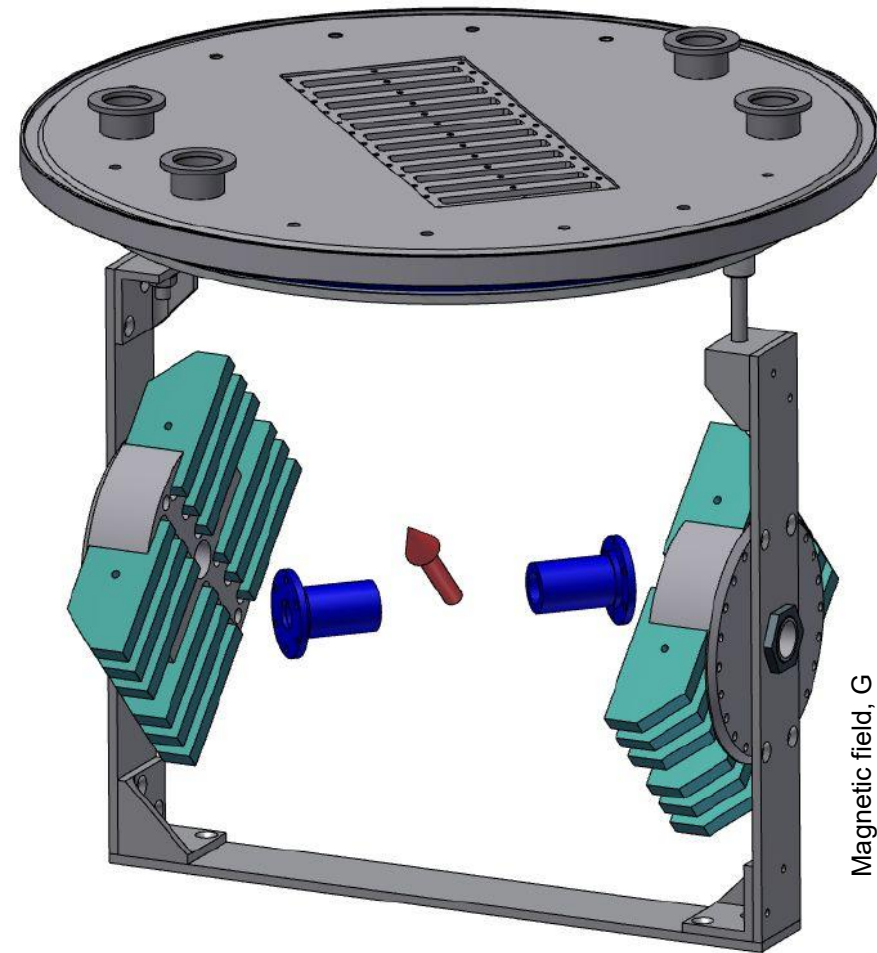
## CSP from ATLAS CSC [BNL]

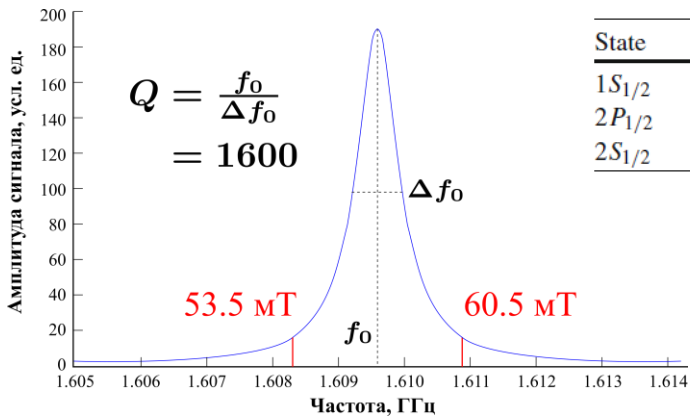
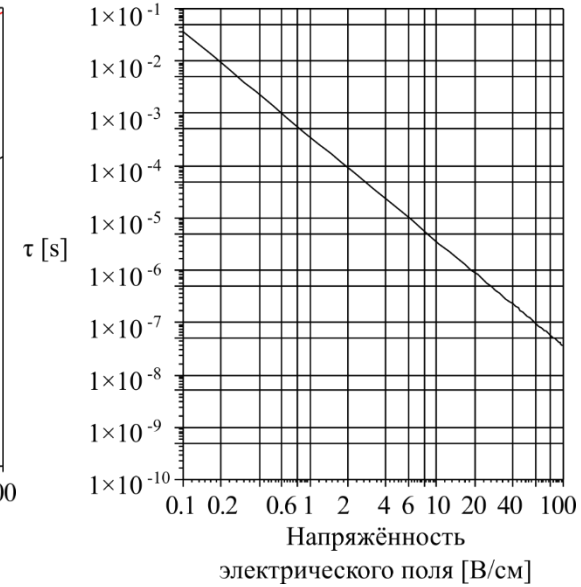
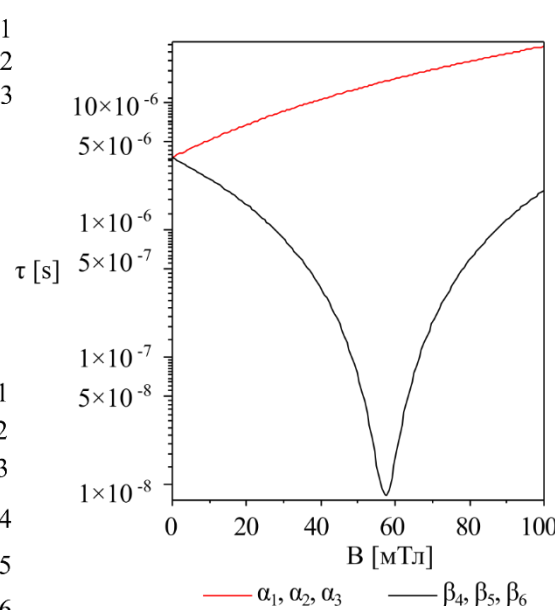
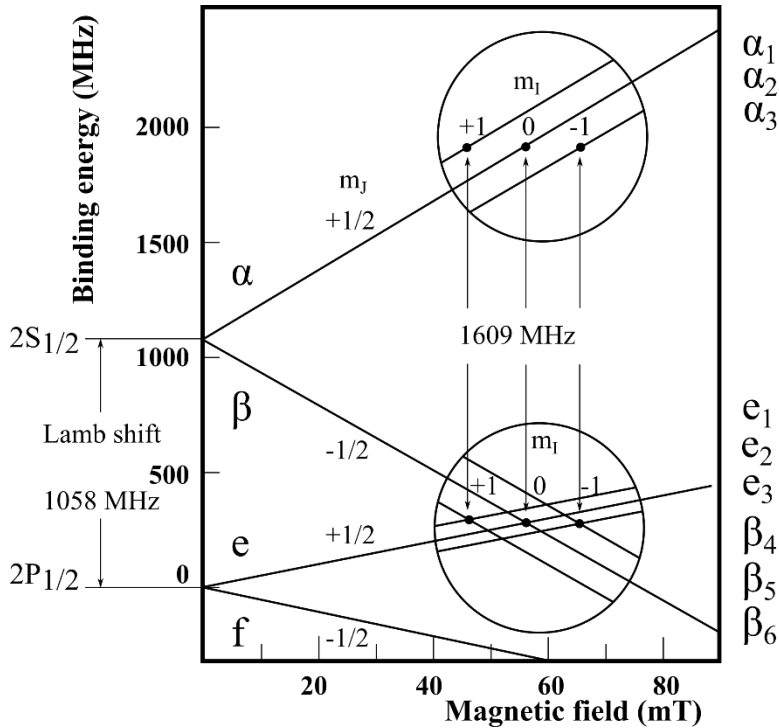
Junnarkar et al. IEEE Nuclear Science Symposium Conference Record (2005)



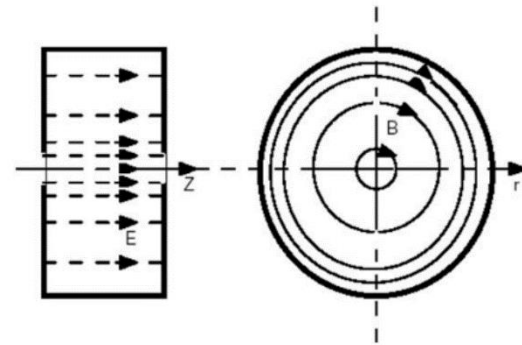
$$B = 300 \text{ G} = 2.5 B_c$$

Magnet field is generated by 24 permanent magnets with dimensions  $80 \times 40 \times 10 \text{ mm}^3$  with pole tip field of 1.25 T at the surface (NdFeB N40)





State	$B_{crit}$ (mT)	$\Delta W$ (MHz)
$1S_{1/2}$	11.7	327
$2P_{1/2}$	0.5	14
$2S_{1/2}$	1.5	41



$$\sigma(\theta, \phi) = \sigma_0 \left( 1 + \frac{3}{2} P_Z A_y(\theta) \cos \phi \sin \beta - P_{ZZ} A_{xz}(\theta) \sin \beta \cos \beta \sin \phi - \frac{1}{4} P_{ZZ} (A_{xx}(\theta) - A_{yy}(\theta)) \sin^2 \beta \cos 2\phi + \frac{1}{4} P_{ZZ} A_{zz}(\theta) (3 \cos^2 \beta - 1) \right).$$

G.G. Ohlsen, P.W. Keaton, Jr., Nucl. Instr. and Meth. **109**, 41 (1973).

$$\sigma_L = \sigma_0 \left( 1 + \frac{3}{2} P_Z A_y(\theta) \sin \beta + \frac{1}{2} P_{ZZ} (A_{yy}(\theta) \sin^2 \beta + A_{zz} \cos^2 \beta) \right),$$

$$\sigma_R = \sigma_0 \left( 1 - \frac{3}{2} P_Z A_y(\theta) \sin \beta + \frac{1}{2} P_{ZZ} (A_{yy}(\theta) \sin^2 \beta + A_{zz} \cos^2 \beta) \right),$$

$$\sigma_U = \sigma_0 \left( 1 + P_{ZZ} A_{xz}(\theta) \sin \beta \cos \beta + \frac{1}{2} P_{ZZ} (A_{xx}(\theta) \sin^2 \beta + A_{zz} \cos^2 \beta) \right),$$

$$\sigma_D = \sigma_0 \left( 1 + P_{ZZ} A_{xz}(\theta) \sin \beta + \frac{1}{2} P_{ZZ} (A_{yy}(\theta) \sin^2 \beta \cos \beta + A_{zz} \cos^2 \beta) \right).$$

$$L \propto \sigma_L$$

$$R \propto \sigma_R$$

$$U \propto \sigma_U$$

$$D \propto \sigma_D.$$

$$R = \frac{R_{polarized}}{R_{unpolarized}}.$$



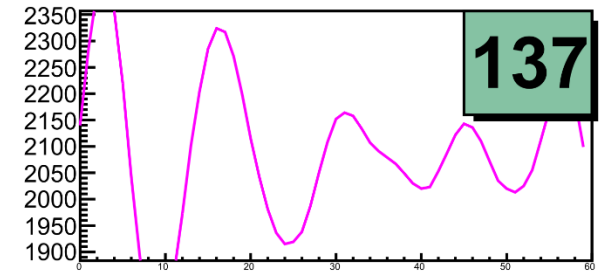
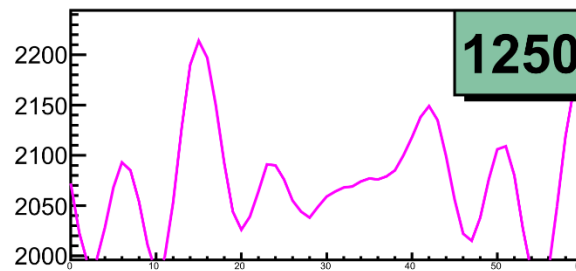
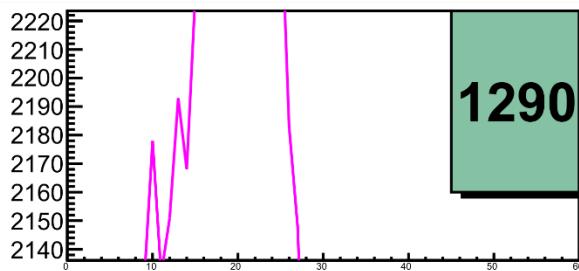
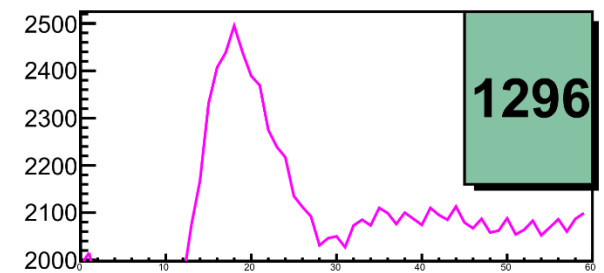
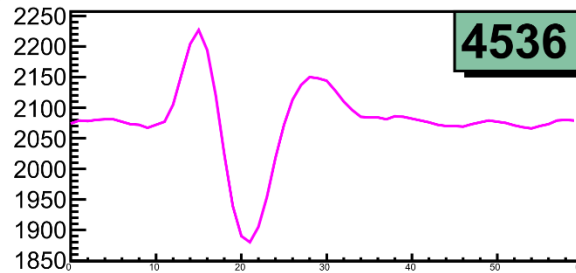
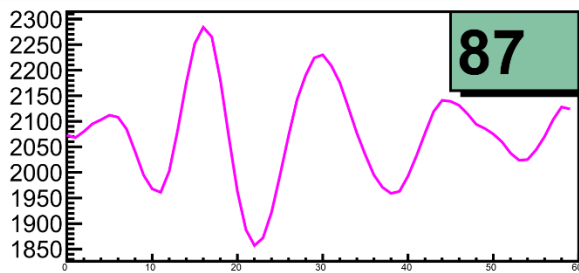
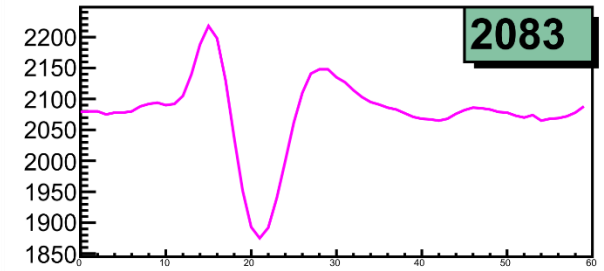
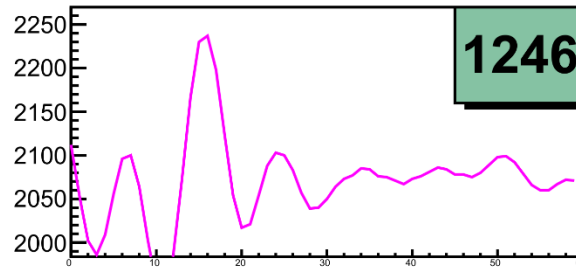
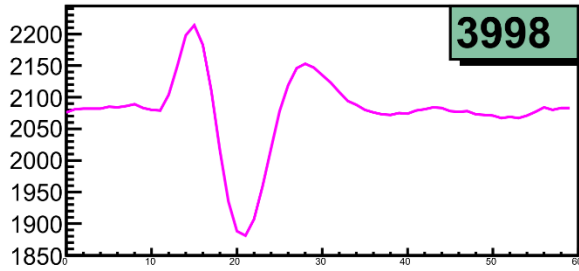
$$\epsilon_1 \equiv \frac{L - R}{L + R} = \frac{\frac{3}{2} P_Z \sin \beta A_y}{1 + \frac{1}{2} P_{ZZ} [\sin^2 \beta A_{yy} + \cos^2 \beta A_{zz}]}$$

$$\epsilon_2 \equiv \frac{U - D}{U + D} = \frac{P_{ZZ} \sin \beta \cos \beta A_{xz}}{1 + \frac{1}{2} P_{ZZ} [\sin^2 \beta A_{xx} + \cos^2 \beta A_{zz}]}$$

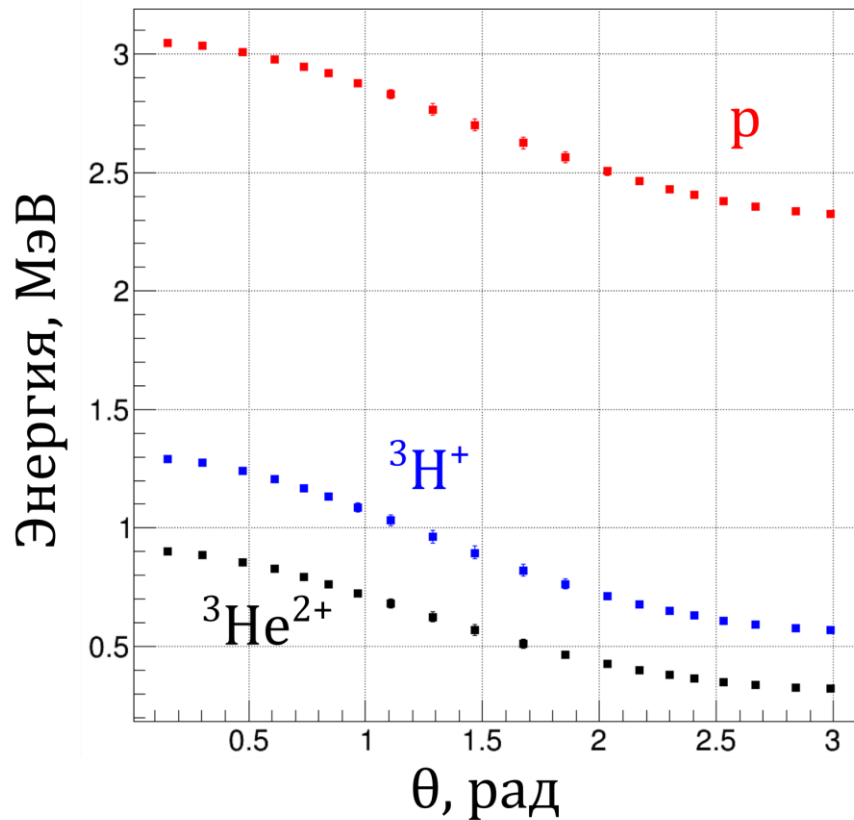
$$\epsilon_3 \equiv \frac{2(L - R)}{L + R + U + D} = \frac{\frac{3}{2} P_Z \sin \beta A_y}{1 + \frac{1}{4} P_{ZZ} [3(\cos^2 \beta - 1) A_{zz}]}$$

$$\epsilon_4 \equiv \frac{2(U - D)}{L + R + U + D} = \frac{P_{ZZ} \sin \beta \cos \beta A_{xz}}{1 + \frac{1}{4} P_{ZZ} [3(\cos^2 \beta - 1) A_{zz}]}$$

$$\epsilon_5 \equiv \frac{(L + R) - (U + D)}{L + R + U + D} = \frac{-\frac{1}{4} P_{ZZ} \sin^2 \beta (A_{xx} - A_{yy})}{1 + \frac{1}{4} P_{ZZ} [3(\cos^2 \beta - 1) A_{zz}]},$$







На основе формул из [Г.А.Борисов, Р.Д.Васильев, В.Ф.Шевченко  
Кинематические таблицы ядерных реакций d,n и p,n  
Издательство стандартов, Москва 1974]