X-ray spectropolarimeters and their application to Z-pinches

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Абстракт

- X-ray spectroscopy is a powerful tool to study high temperature plasma. This is almost routinely approach to estimate plasma parameters from relative intensities of He-like and H-like lines. There are enough reliable models to describe intensities of He-like lines so that comparison of experimental spectra with calculated one permits to extract plasma electron temperature and density. Other effects which should be taken into account in best accurate way are : optical density, presence of electromagnetic fields, collisional exchange between levels, etc.
- Experiments carried out on Z-pinches within last two decades have shown, that He-like lines are polarized. The reason for polarization is assumed to be the presence of electromagnetic field and/or electron beams. Today the general recommendation is: first to analyze the degree of polarization of lines used for diagnostics, then chose the model to be used for their analysis. Study of polarized emission of pulsed plasma is important to get information on the physical processes in plasma, on the application ranges of conventional diagnostics approaches, it open perspectives to create new type of diagnostics.
- Recently it was found that single hexagonal, trigonal or cubic crystal serves as polarimeter. Polarization analysis of pulsed irreproducible x-ray sources is usually carried out with two identical polarizers or with single crystal polarimeter. This paper describes the design of two types of spectropolarimeters, which are intended to diagnose polarization of X-ray lines. The example of their application is also presented.

Мотивация

- **Развить существующее направление рентгеновской спектроскопии – рентгеновскую поляризационную спектроскопию плазмы.**
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- **T. Fujimoto, H Sahara, G. Csanak and S. Grabbe, Atomic *States and Collision* Relaxation in Plasma Polarization *Spectroscopy: Axially Symmetric* Case, Research Report, NIFS-DATA Series, NIFS-DATA-38, Oct. 1996**
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- ***Analysis based on the Population-Alignment Collisional-Radiative model, inProceedings of the d US-Japan Plasma Polarization Spectroscopy Workshop,*Livermore, California June 18-21, 2001 (Edited by P. Beiersdorfer and T.**
- **Fujimoto), University of California Lawrence Livermore National LaboratoryReport UCRL-ID-146907, p.165**
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- **Baronova E.O., Gurey A.E., Dolgov A.N. Vikhrev V.V. et.al. X-ray line polarization measurements in Z-pinch discharge. Proc. of Eleventh Conference on UV and X-ray spectroscopy, Nagoya. 1995. P. 465-467.**
- **Baronova E.O., Jakubowski L., Sholin G.V. Application of X-ray polarization measurements to study plasma anisotropy in plasma focus machines// Plasma Physics and Controlled Fusion. 2003. V. 45. No 7. P. 1071-1077.**
- **Baronova E.O., Vikhrev V.V., Dolgov A.N..et.al. Investigation of polarization of line emission of multicharged ions in vacuum spark discharge // Plasma Physics reports.1998. V. 24. N1. P. 25.**

Публикации

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Baronova E.O., Stepanenko M.M.
Plasma Physics and Controlled Fusion. 2003. T. 45. № 7. C. 1113-1120.

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Volkov G.S., Zaitsev V.I., Lakhtyushko N.I., Fedulov M.V.
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CHARACTERIZING A POLARIZATION SPLITTING QUARTZ CRYSTAL
Wallace M.S., Presura R., Pereira N.R., Kastengren A.L.
В сборнике: ICOPS/BEAMS 2014 - 41st IEEE International Conference on Plasma Science and the 20th International Conference on High-Power Particle Beams. 41. 2015. C. 7012289.

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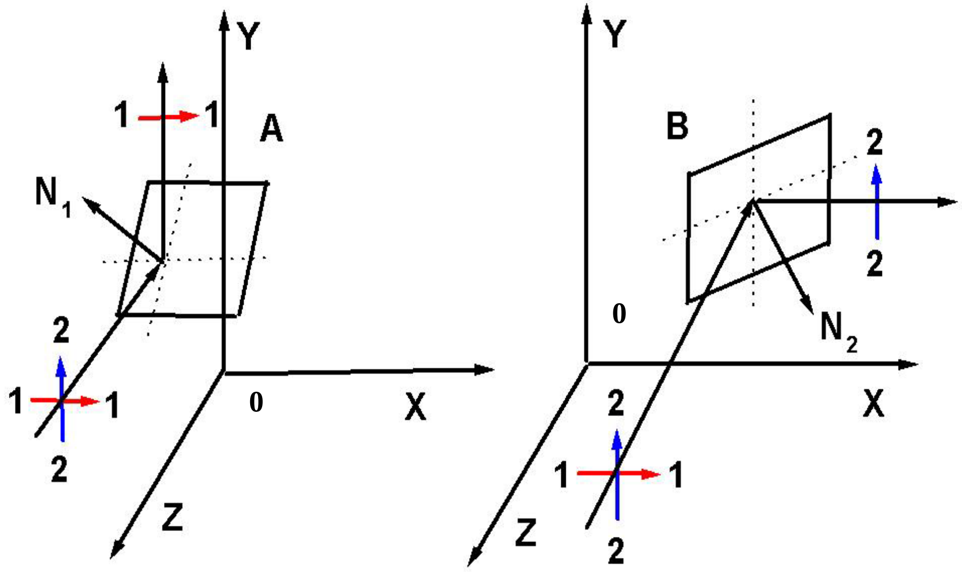
Wallace M.S., Presura R., Haque S., Pohl I., Lake P., Wu M.
Review of Scientific Instruments. 2020. T. 91. № 2. C. 023105.

The base for X-ray polarization analysis

- X-Ray polarization analysis is based on the diffraction properties of crystals, where the integral reflection coefficient P_D for symmetrical cut of ideal crystal is expressed as follows:
- $$P_D = (16/3\pi)(e^2/mc^2)(d^2/V)\, tg\theta_B K |F_{hkl}|$$
- where *e*, *m* –electron charge and mass, λ - wavelength, θ_B – Bragg angle, corresponding to condition $2d \sin\theta_B = k\lambda$, *d* – intermediate crystal distance, *k* – reflection order, F_{hkl} – atomic factor for hkl reflection, $V = 112\ A^3$ – volume of unit crystal cell, $K = (1+ |\cos 2\theta_B|)/2$ – polarization factor for naturally polarized rays. $K = ½$ for σ- component, $K = |\cos 2\theta_B|/2$ for π- component.
- if $\theta_B = 45°$ then only σ- component is reflected and crystal serves as polarizer.
- Polarimeter is a device, which separates two mutually perpendicular polarizations with equal effectiveness. A combination of two perpendicularly oriented identical polarizes is a polarimeter.

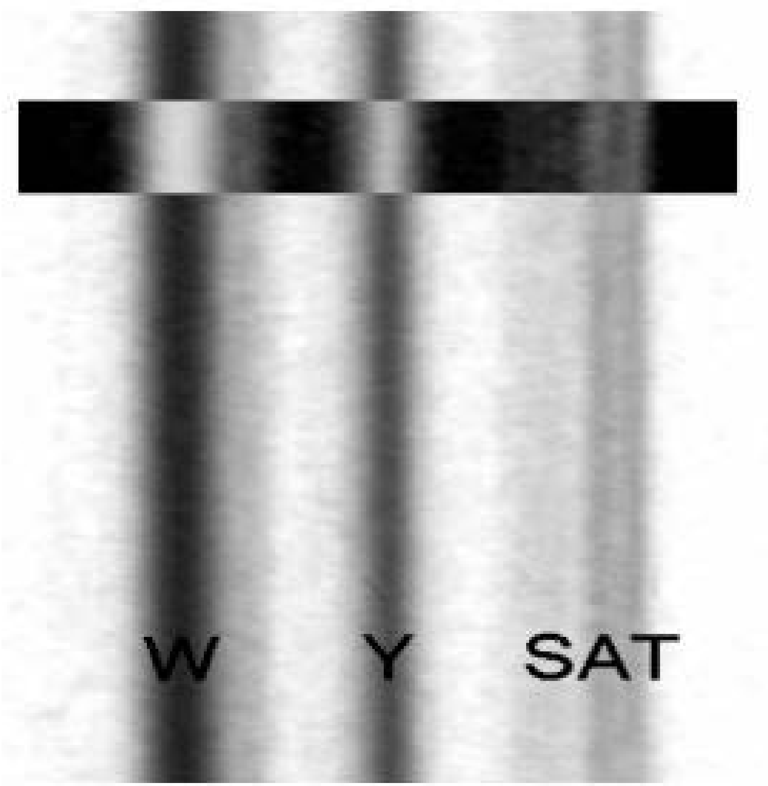
Scheme for X-ray polarization analysis

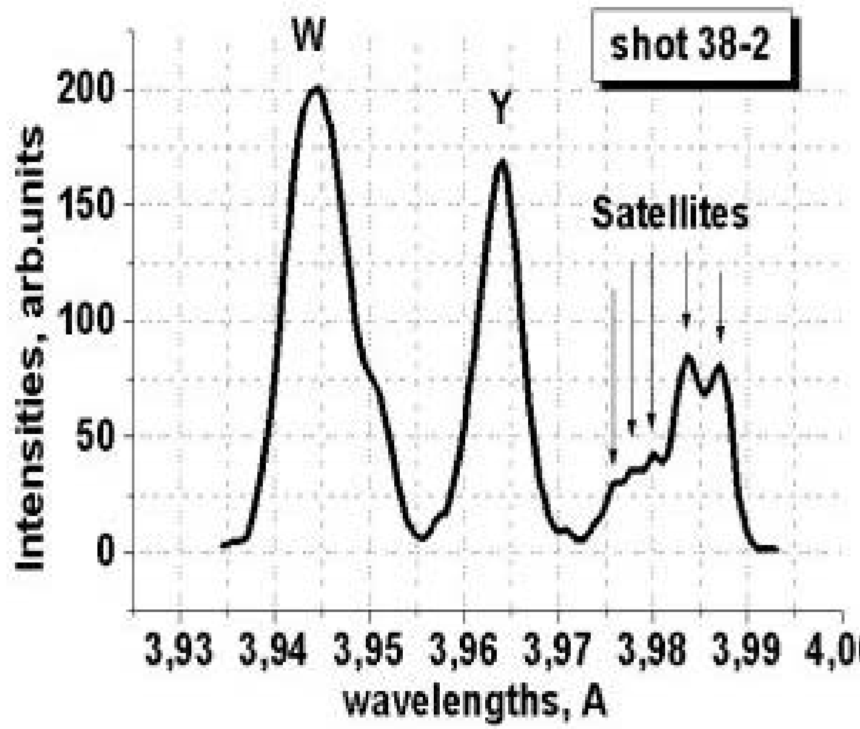


Polarization measurements can be done:

1. **single rotated crystal, which detects one polarization component, then rotated to 90º to detect second polarization component, works for stationary x-ray sources and pulsed sources with reproducible parameters.**
2. **Two identical crystals at θ_B =45°, oriented perpendicular to each other, looking to plasma from same direction**
3. **Single crystal polarimeter, based on hexagonal or cubic crystals**

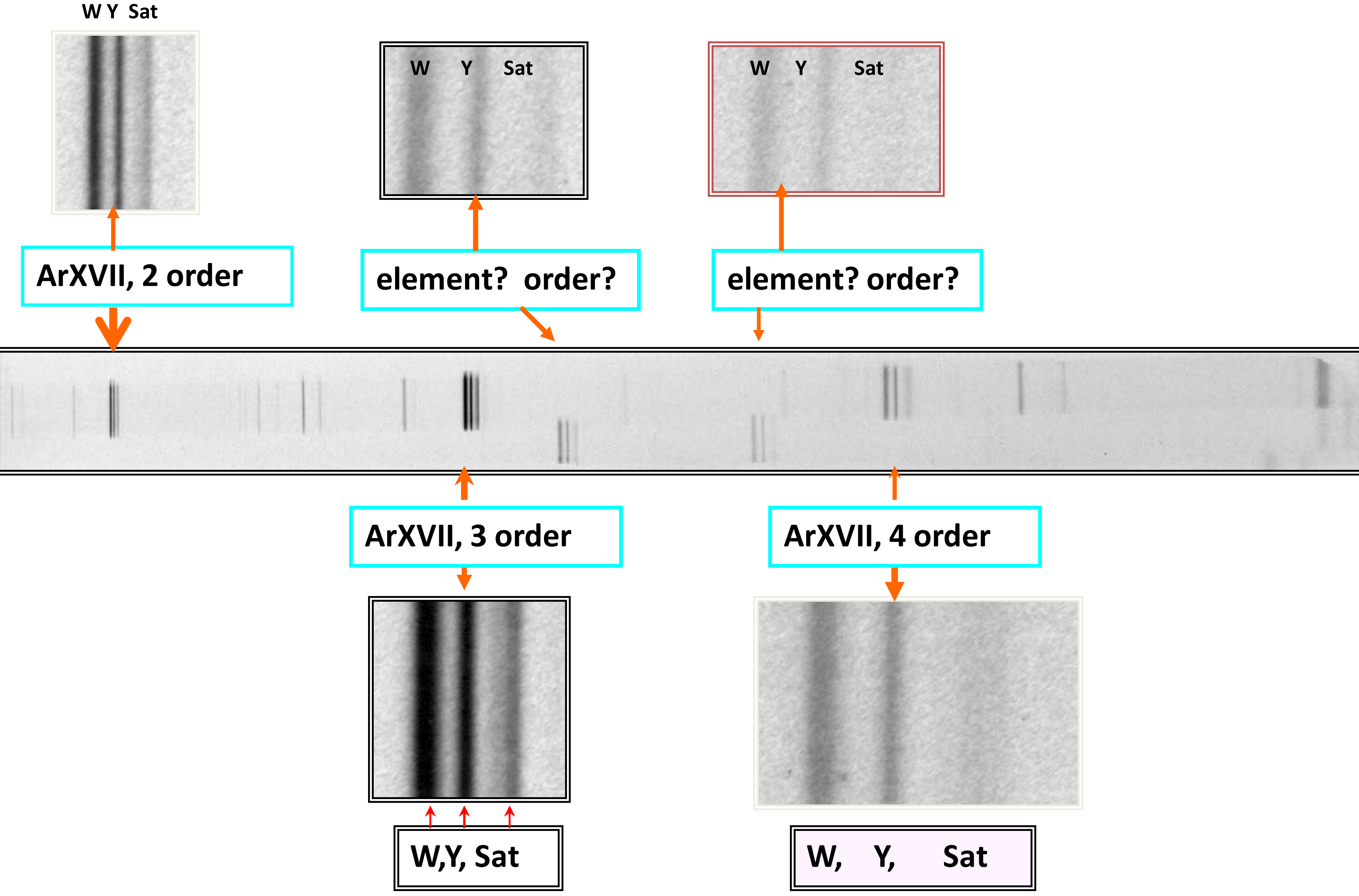
Typical He-like spectra, widely used to extract Te,Ne.
Maja plasma focus facility, Poland





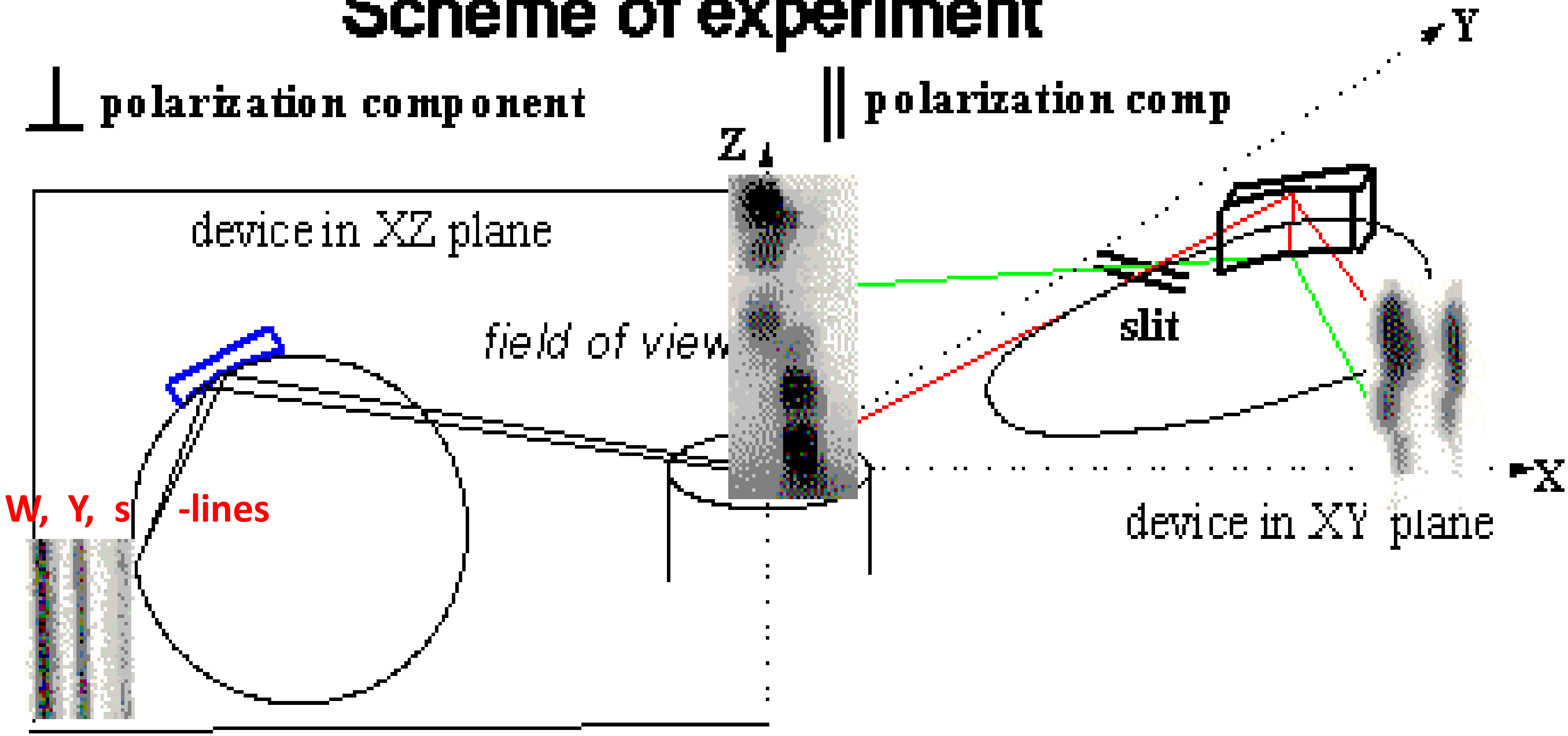
Time integrated spectra of ArXVII and its densitogram. I=500kA

ArXVII, ArXVIII in 2,3,4, orders of reflection, Angara, 4MA,
shot 2406.



Scheme of experiment

Poland, Maja machine,



1. field of view?
2. direction of optical axis?
3. Spectrum cannot be spatially resolved in Z direction

1. field of view is directly determined
2. direction of optical axis is determined
3. Spectrum is spatially resolved in Z direction

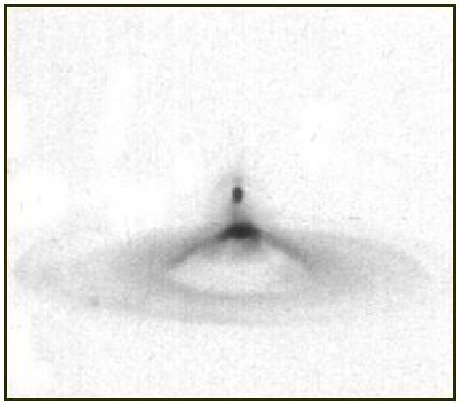
crystal sizes 8*15 mm^2

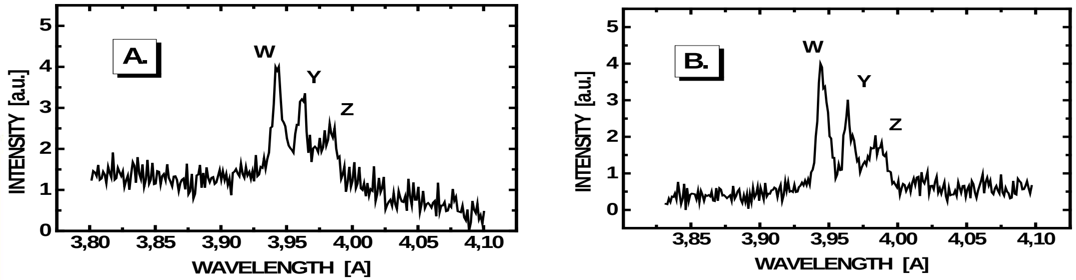
R=500 mm, FW_z=12 mm

reflection coefficient for different parts of crystal?

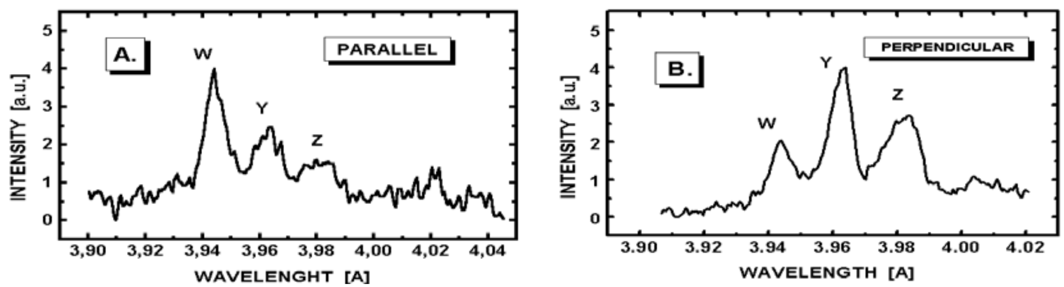
Experiments carried out on point-like source

Maya Facility, Poland, together with Dr. L.Yakubowski





Spectra of ArXVII, taken by two spectrometers A,B with dispersive plane parallel to the discharge axis.

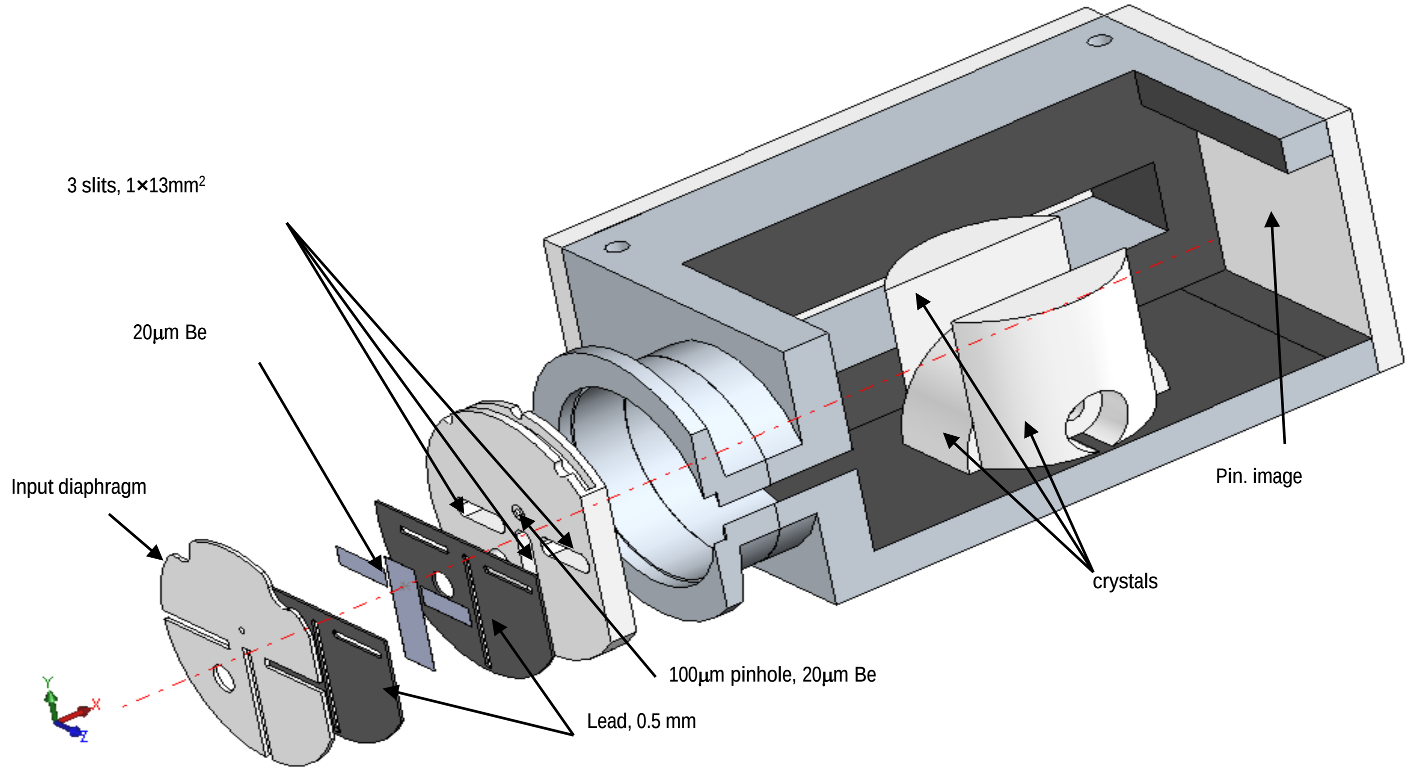


Spectra of ArXVII, taken by two spectrometers A,B with mutually perpendicular dispersive planes.

Conclusion: in z pinches with discharge current 150, 500 kA the relative intensities of Y , W lines were different for the two spectrometers, used in one the same experiment

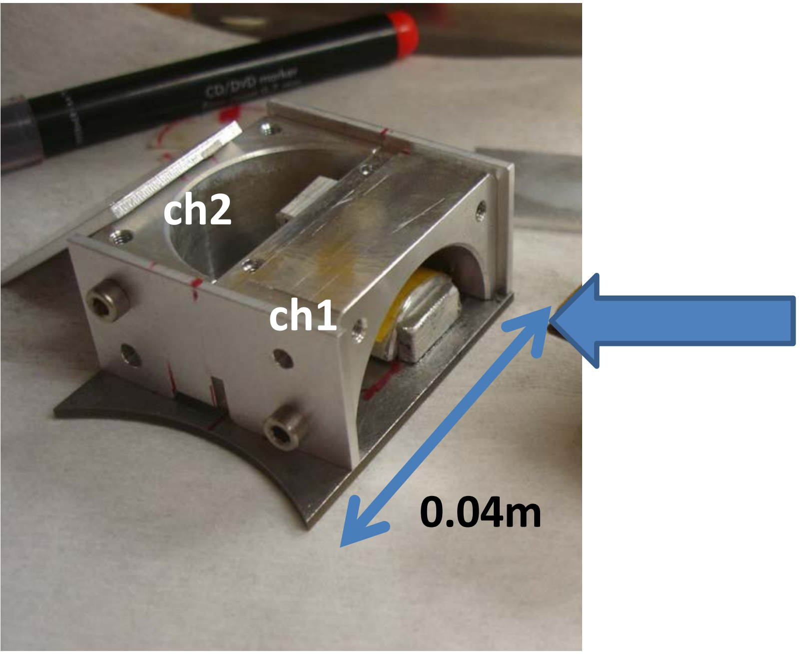
Two crystal spectropolarimeter

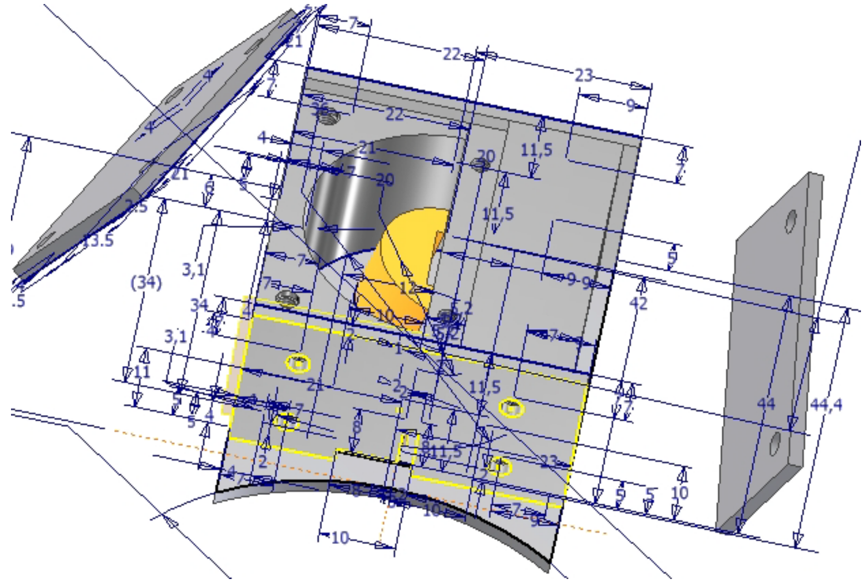
1. **Polarizers take spectra from same direction**
2. **Source size control**
3. **Mica crystals , λ=   for θB=45°**

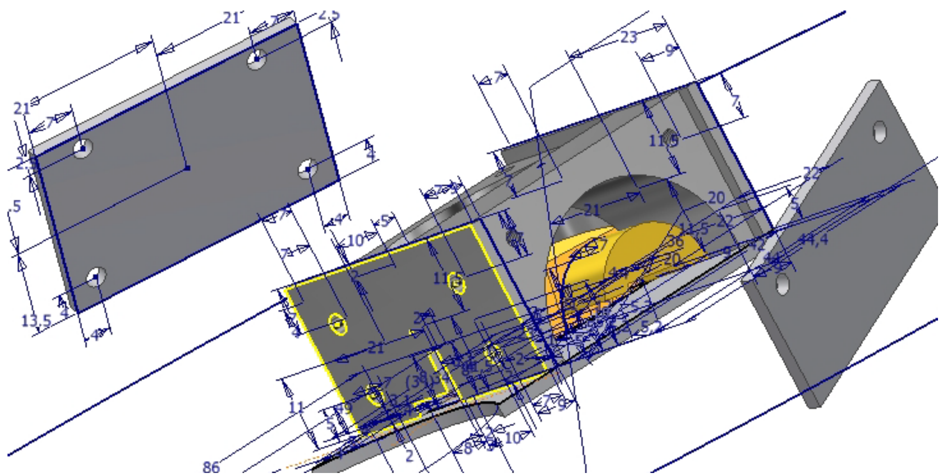


Four channel de Broglie spectropolarimeter`

Super compact two crystal spectropolarimeter

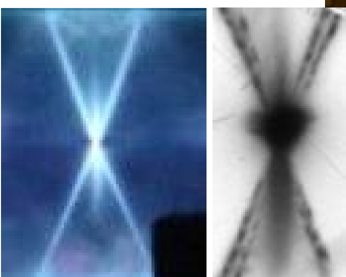


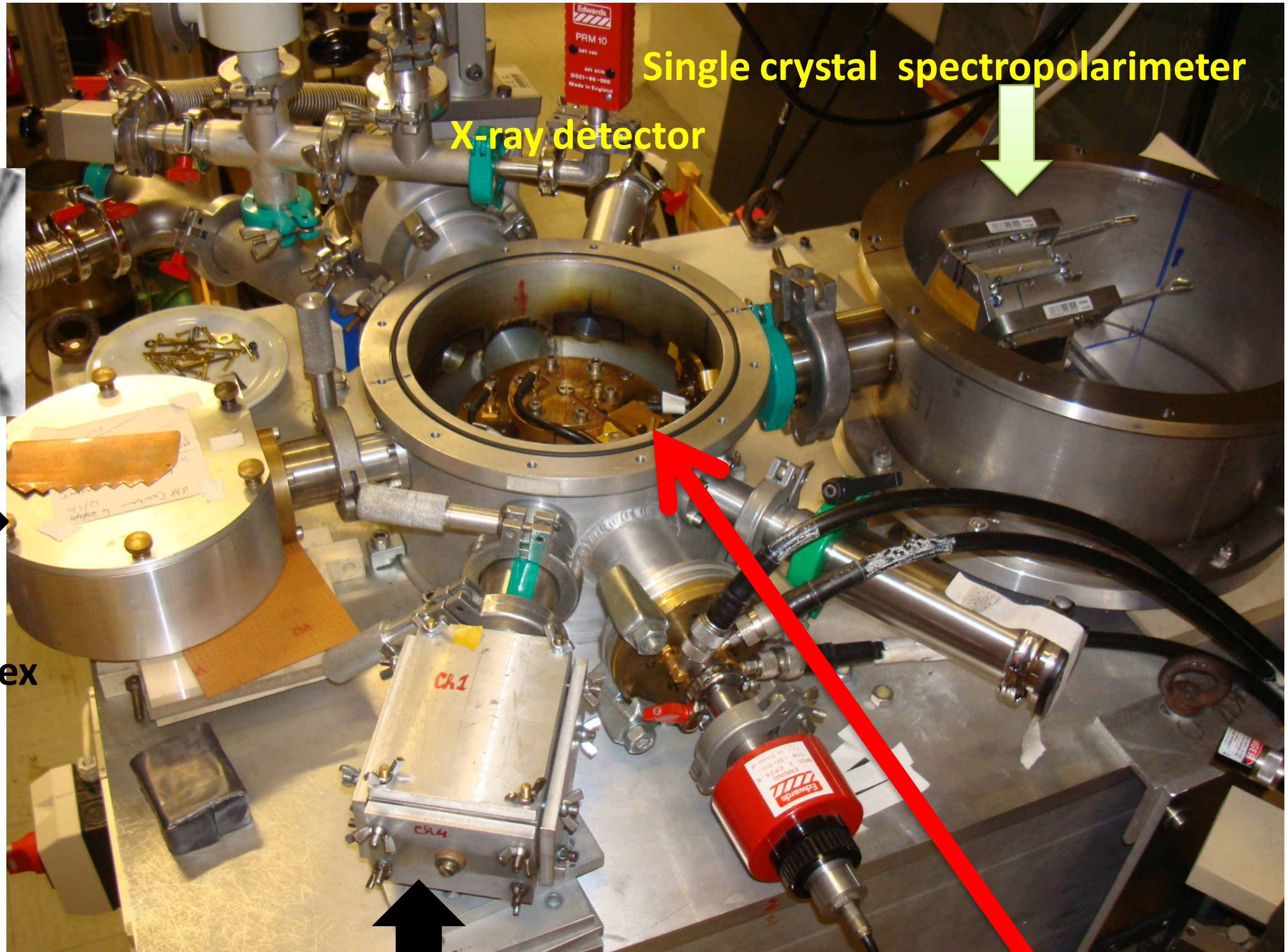




Drawings are done by “Inventor”

Positioning of spectrometers and polarimeters



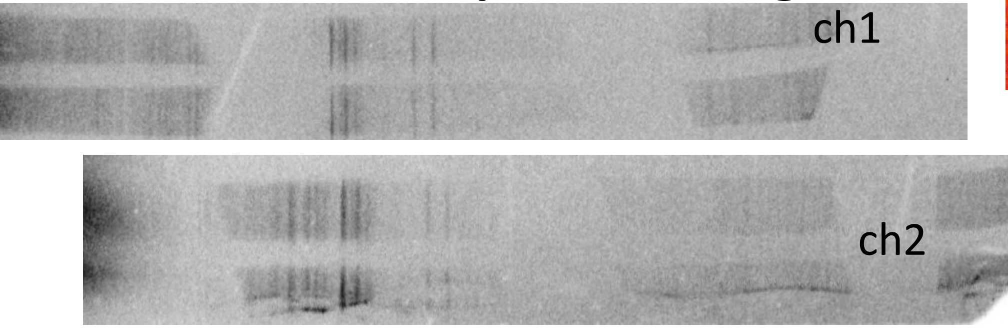


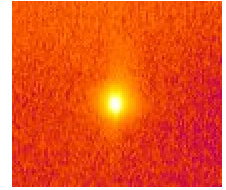
KAP R250 convex
spectrometer,
1 channel

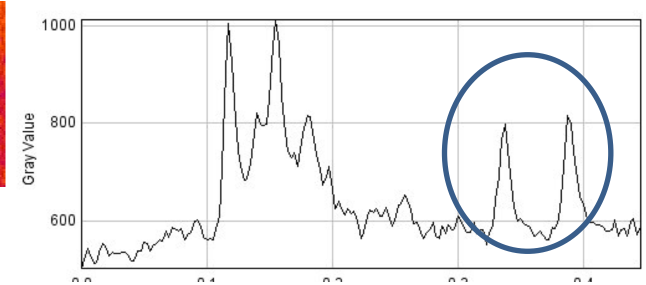
3 crystal spectropolarimeter
with pinhole, 4 channels

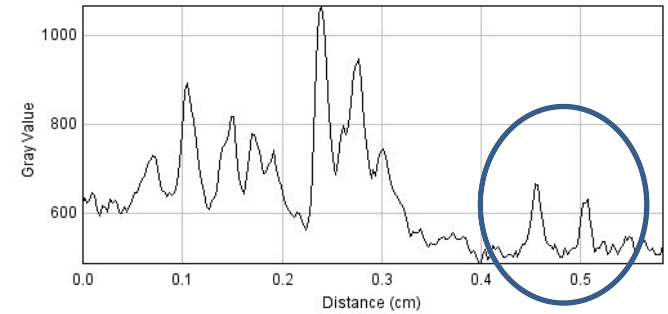
Mini 2 crystal spectropolarimeter
2 channels

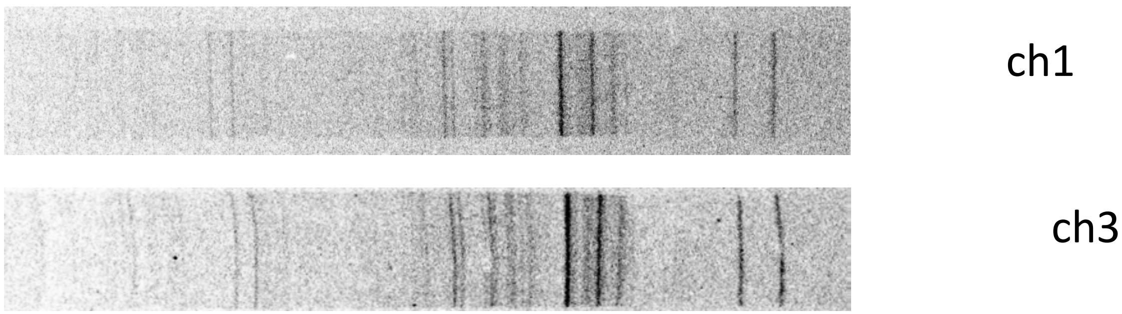
T140, Cu L-shell spectra in single shot

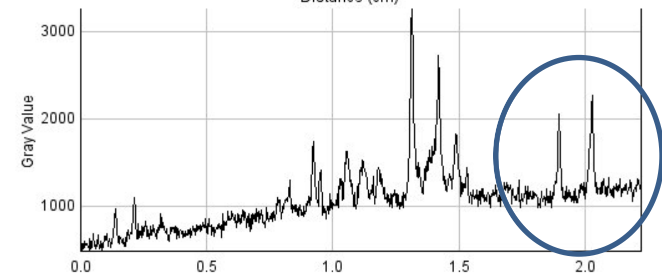


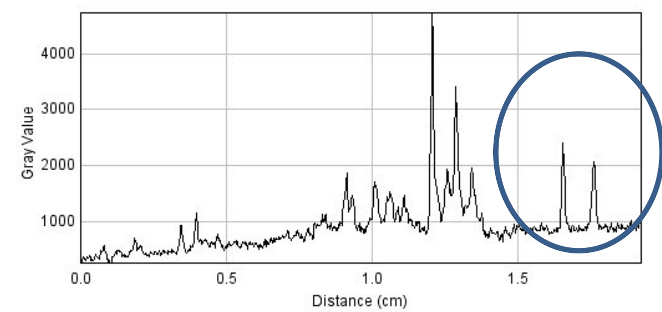


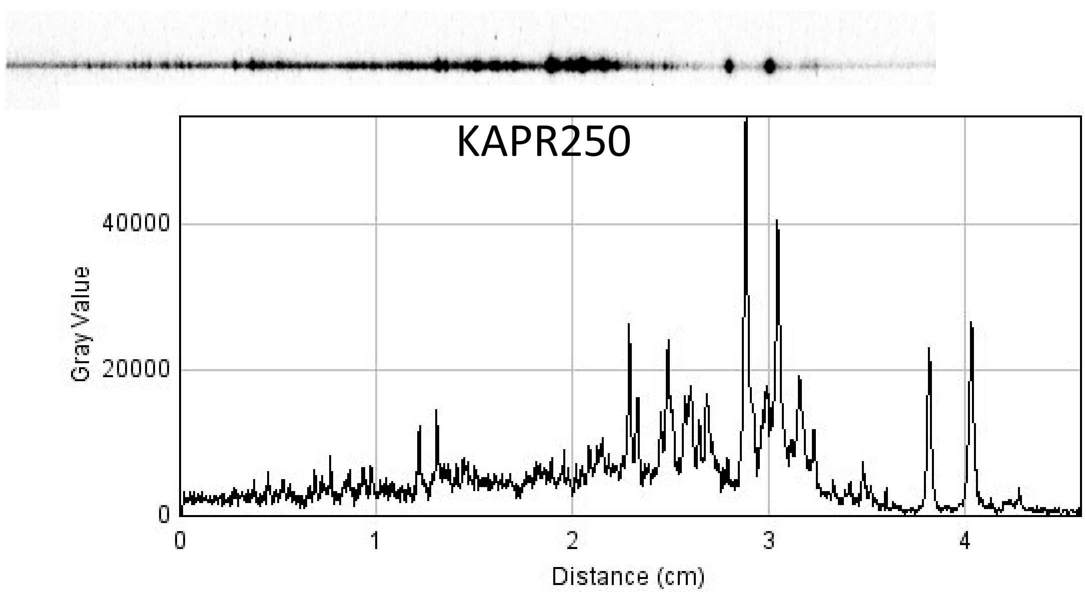






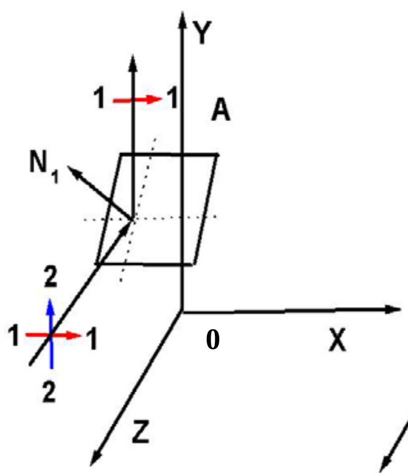


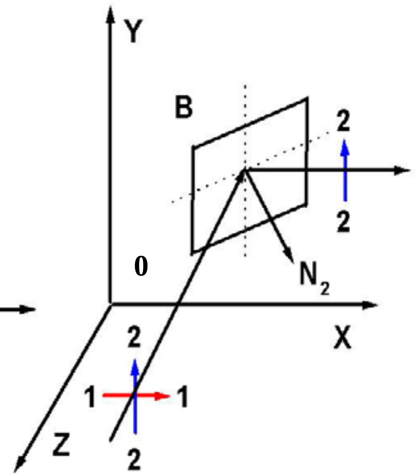


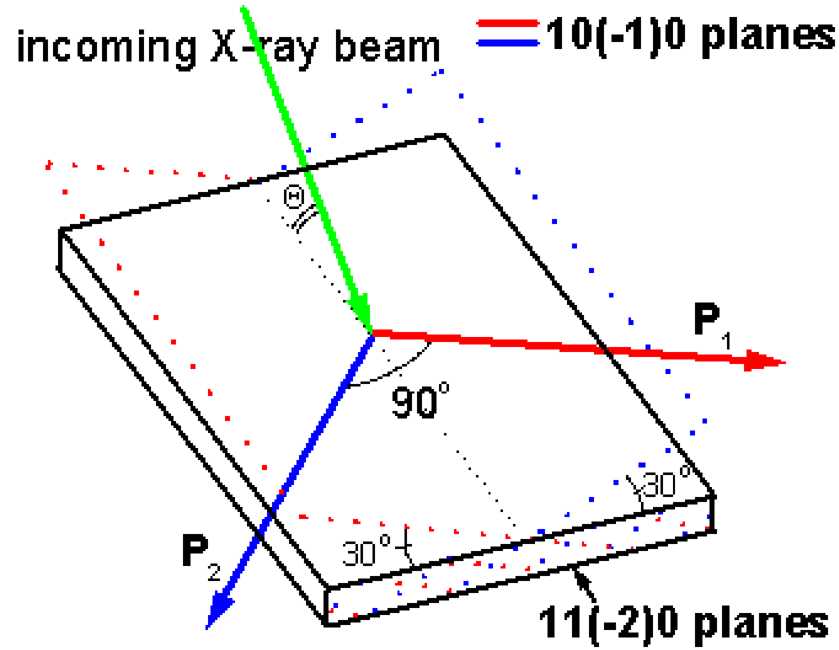


Однокристальный рентгеновский поляриметр

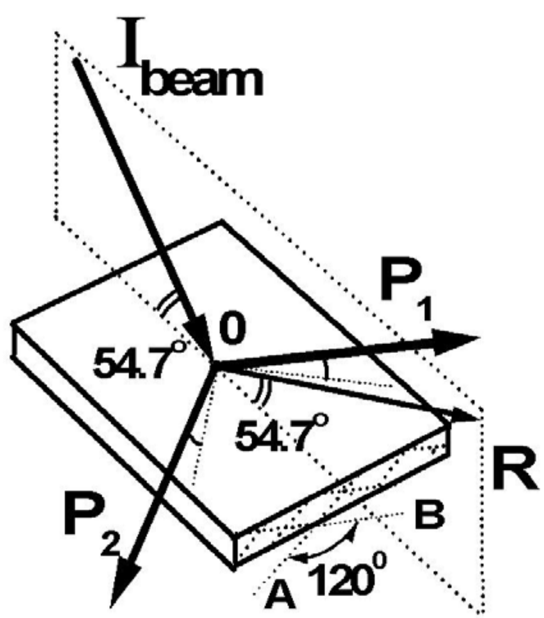
E.O.Baronova, M.M.Stepanenko, and A.M.Stepanenko, *Review of Scientific Instruments*, 79, 1-4, (2008).
Patent RRC KI № 2322684,Bul. №11,(20.4.2008).





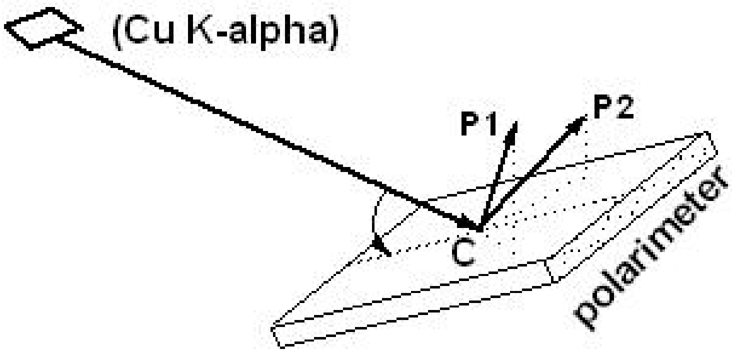


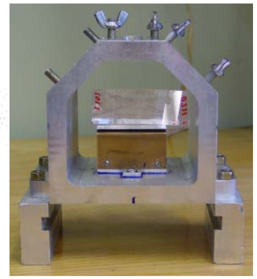
what is Θ? how to determine P_1, P_2 directions?



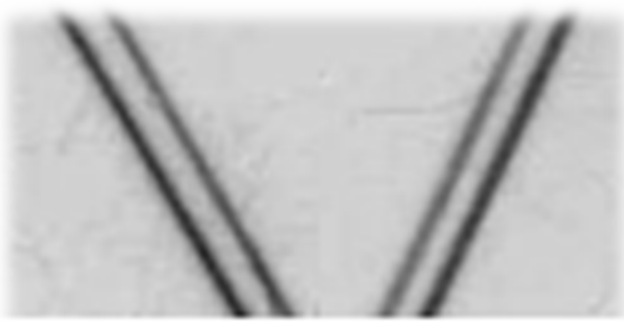
Поляриметр отражает обе компоненты поляризации, специально вырезанный кристалл может работать как поляриметр

Тестирование работы поляриметра на рентгеновской трубке

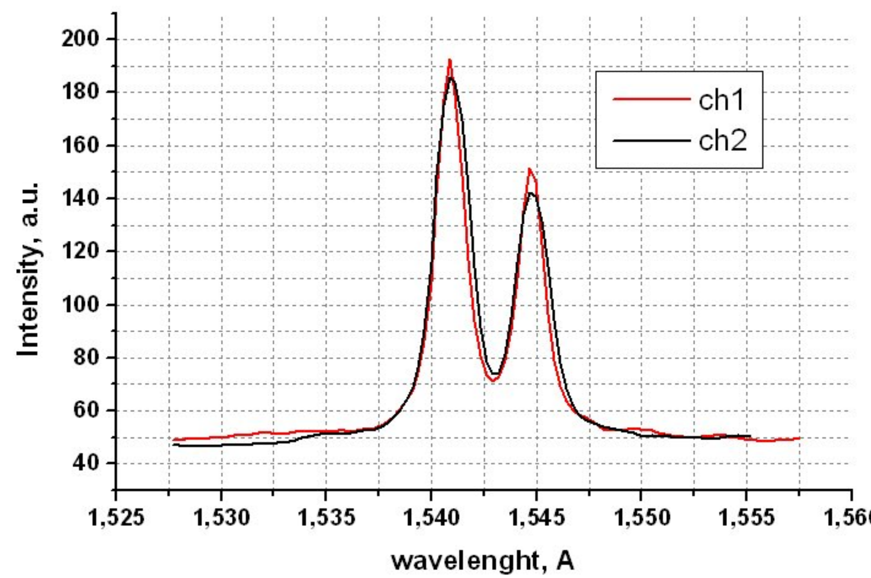




Использовалось К-альфа излучение меди в 4 порядке отражения от среза 10-10. Выделены две поляризованных компоненты из падающего излучения, с равными коэффициентами отражения.

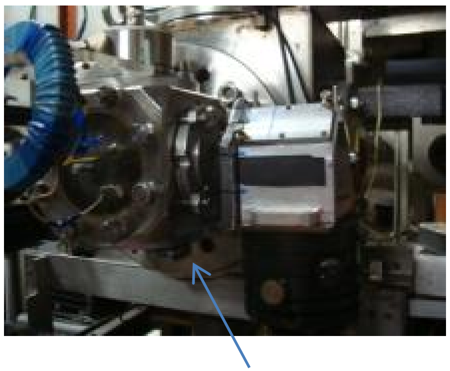


Перпендикулярно поляризованные компоненты К-альфа излучения меди

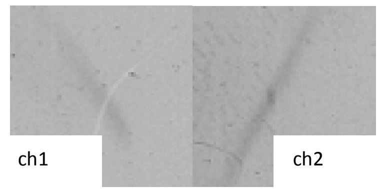


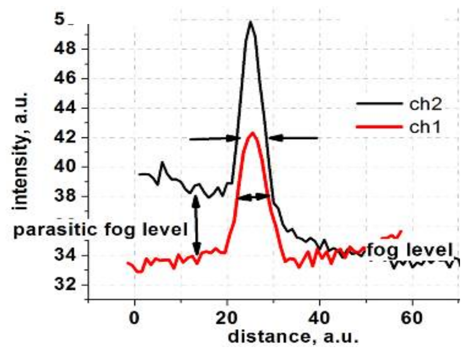
Напряжение 25 кВ, ток 20 мА, экспозиция 30 минут

Исследование поляризации характеристических К-альфа линий меди, эмитированных материалом анода на установке вакуумная искра.



Установка Зона 1. МИФИ
Вакуумная искра
I=200 kA,U=12-14kV





λ_1=1.5400 Å, λ_2 = 1.5404 Å
Расстояние от плазмы до кристалла -140 мм,
200 выстрелов,
разрешение $\delta\lambda/\lambda > 2*10^{-3}$

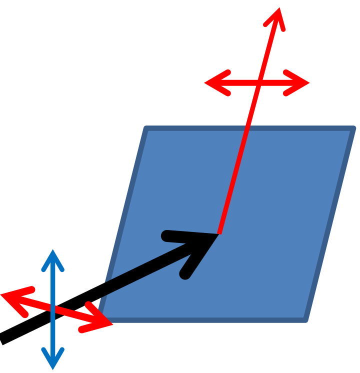
Сигналы в двух каналах поляриметра и их денситограммы.

Сигналы в двух каналах поляриметра не идентичны, что может свидетельствовать о наличии поляризации К- линий, эмитируемых под действием электронного пучка

Selection of polarized component in ideal (quartz, Si…) and mozaic(mica..) crystals

$$R_d=16/3/pi*e^2/m/c^2*d_{hkl}^2F_{hkl}/V*tgQ*(1+abs(cos2Q))/2*A_m;$$

$$R_d=16/3/pi*e^2/m/c^2*d_{hkl}^2F_{hkl}/V*tgQ*(1+cos^2 2Q)/2*A_m;$$

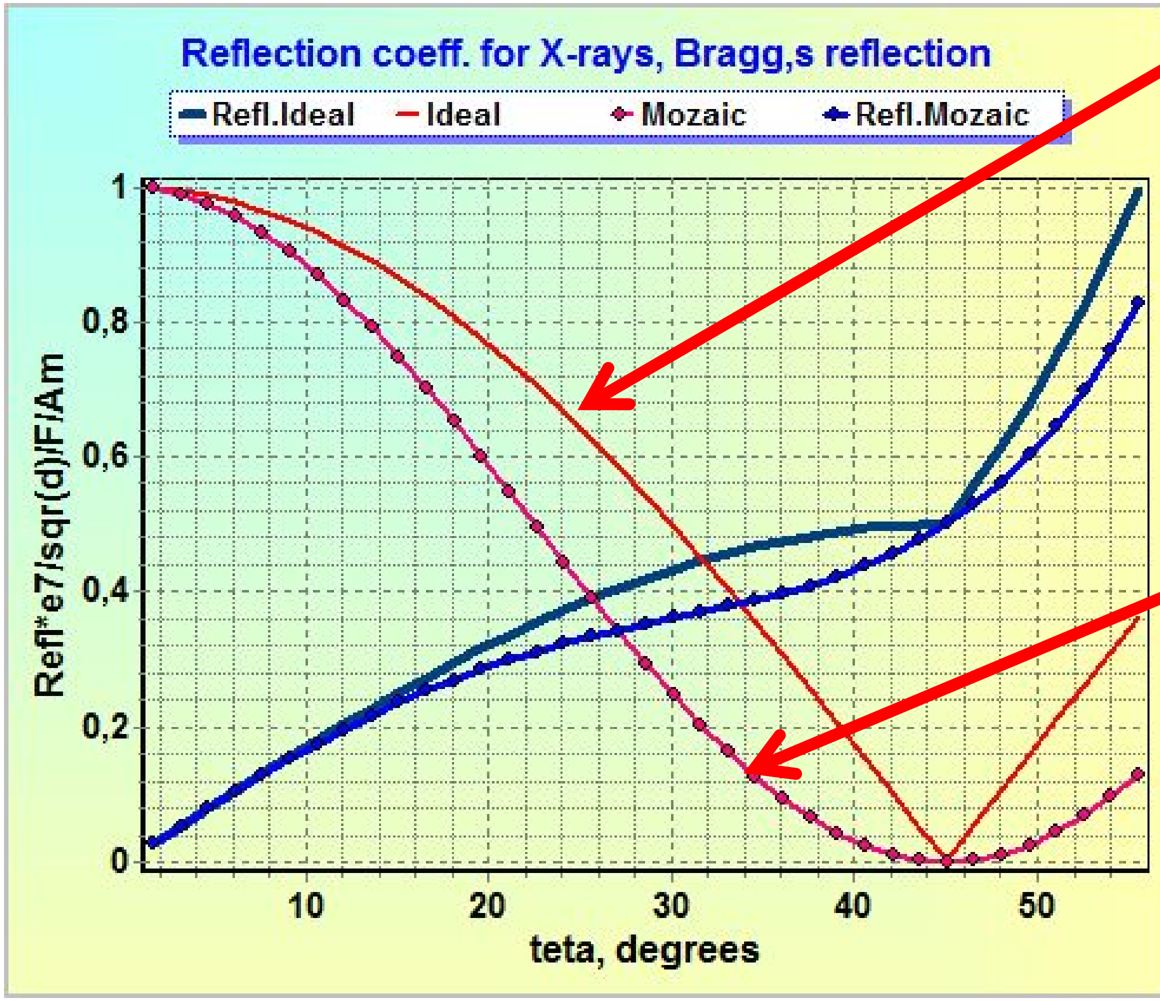


At 45 deg

Sigma- component

Pi-component

Ideal or mozaic crystals FOR SPECTROPOLARIMETRY?



Ideal crystals:
$I_{perp}/I_{par} = \cos 2Q$
flat quartz, does not need calibration, separates polarized component within 42-47 Bragg angle, bent quartz-??

Ideal Mozaic crystals
$I_{perp}/I_{par} = \cos^2 2Q$,
mica-mozaic crystal, needs calibration, separates polarized component within 37-53 Bragg angles

$R_d = 16/3/pi*e^2/m/c^2*d_{hkl}^2 F_{hkl}/V*tgQ*(1+abs(\cos 2Q))/2*A_m;$
$R_d = 16/3/pi*e^2/m/c^2*d_{hkl}^2 F_{hkl}/V*tgQ*(1+\cos^2 2Q)/2*A_m;$

Выводы

1. Рентгеновский поляризационный анализ является необходимым методом исследования параметров пинчевой плазмы

2. Двухкристальные и однокристальные рентгеновские спектрополяриметры доказали свою работоспособность в условиях их применения для реализации поляризационного анализа импульсных источников горячей плазмы малого размера.
3. Двухкристальный рентгеновский поляриметр обладает более широким диапазоном длин волн для осуществления поляризационного анализа и более простой настройкой в сравнении с однокристальным. Недостатком считается небольшое несовпадение углов зрения двух кристаллов и необходимость предварительной калибровки обеих каналов.
4. Однокристальный рентгеновский поляриметр - единственный прибор, в котором обе поляризационные компоненты выделяются с равной эффективностью и регистрируются с одного и того же направления на источник.