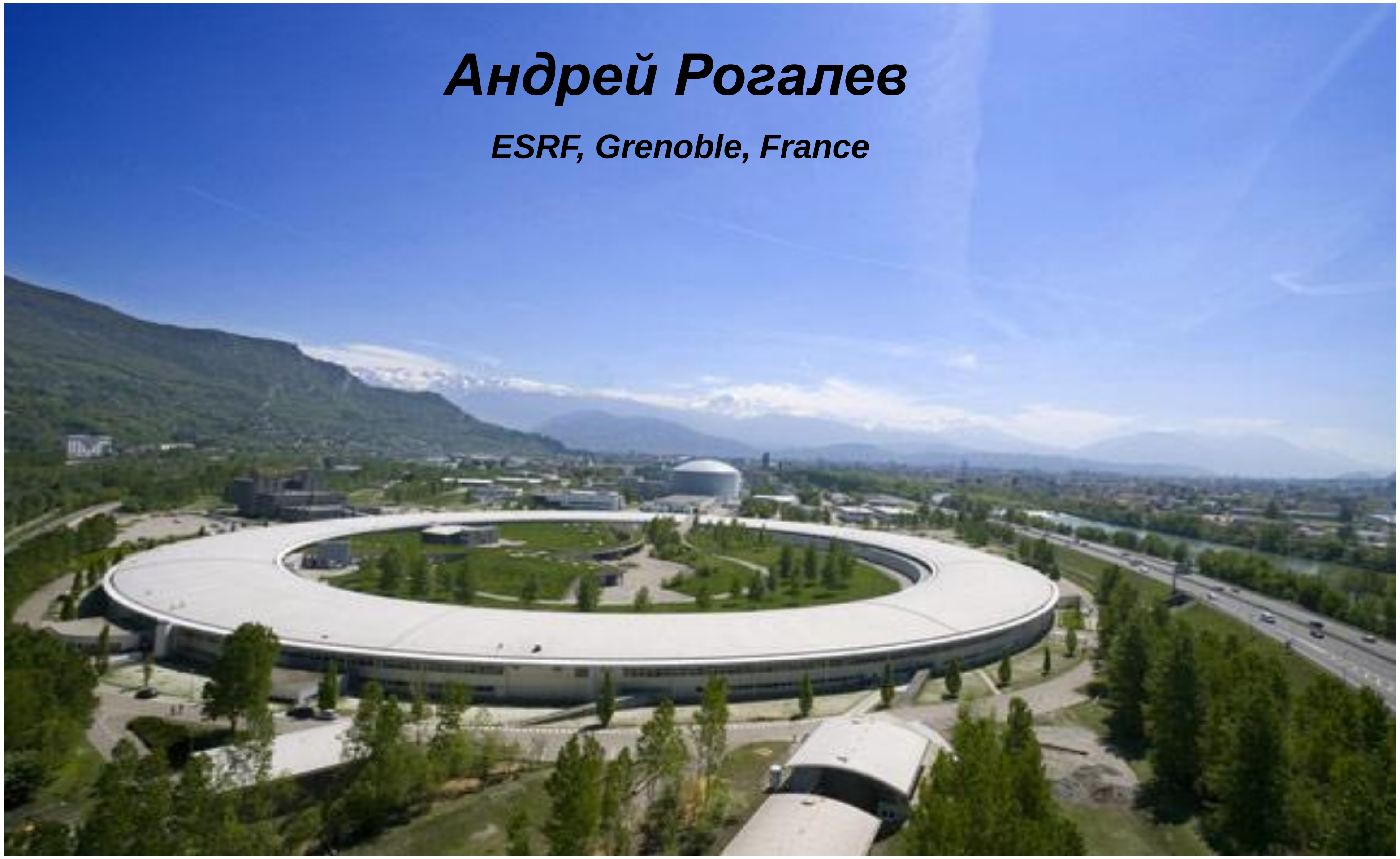
ESRF | The European Synchrotron

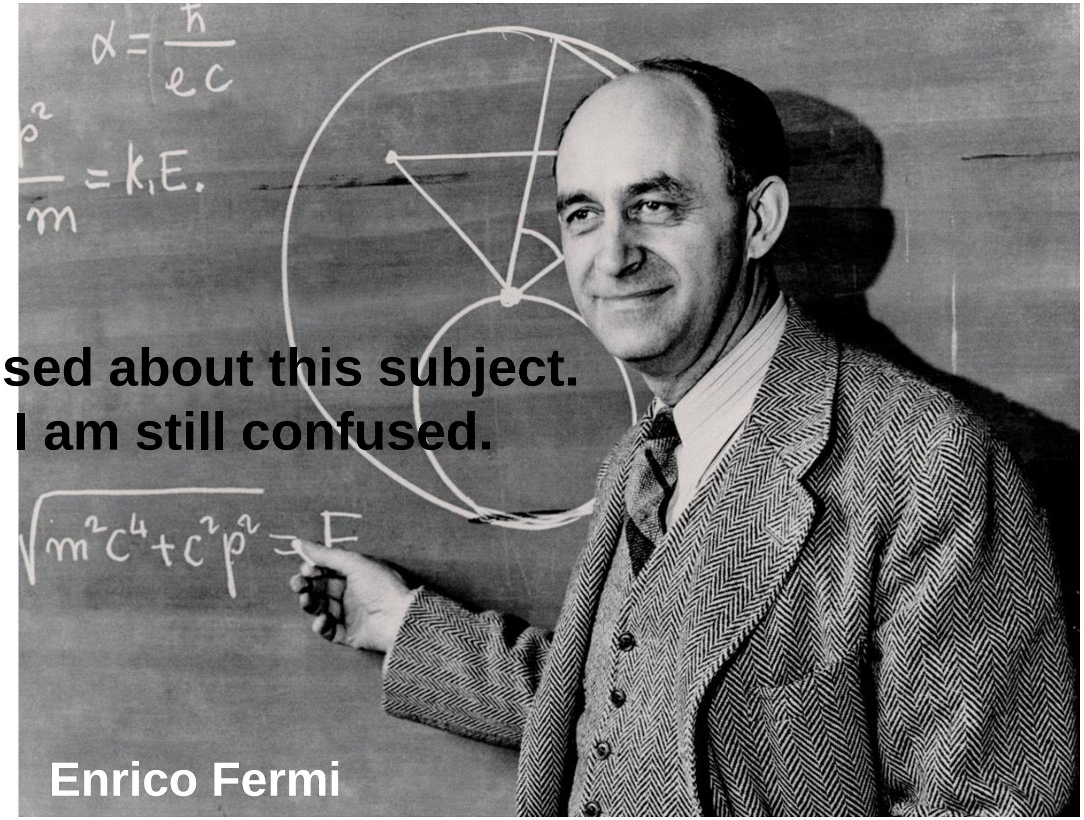
Синхротронное излучение и магнетизм: на пути к четвертому поколению.

Андрей Рогалев

ESRF, Grenoble, France

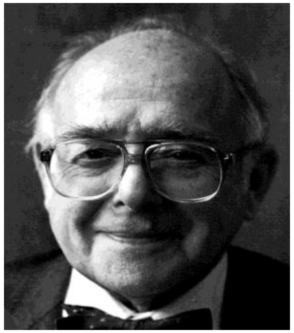


Never underestimate the joy people derive from hearing something they already know.


Enrico Fermi

Before I came here I was confused about this subject.
Having listened to your lecture I am still confused.
But on a higher level.

I hope it won’t take long !



Cliff Shull

1994
Nobel Prize
in Physics

Bert Brockhouse

Nobel Prize in Physics 1994: B. N. Brockhouse and C. G. Shull

Press release by the Royal Swedish Academy of Sciences:

"Neutrons are small magnets…… (that) can be used to study the relative orientations of the small atomic magnets. ….. *the X-ray method has been powerless and in this field of application neutron diffraction has since assumed an entirely dominant position.* It is hard to imagine modern research into magnetism without this aid."

Magnetic neutron diffraction is the leading and unbeaten experimental method …

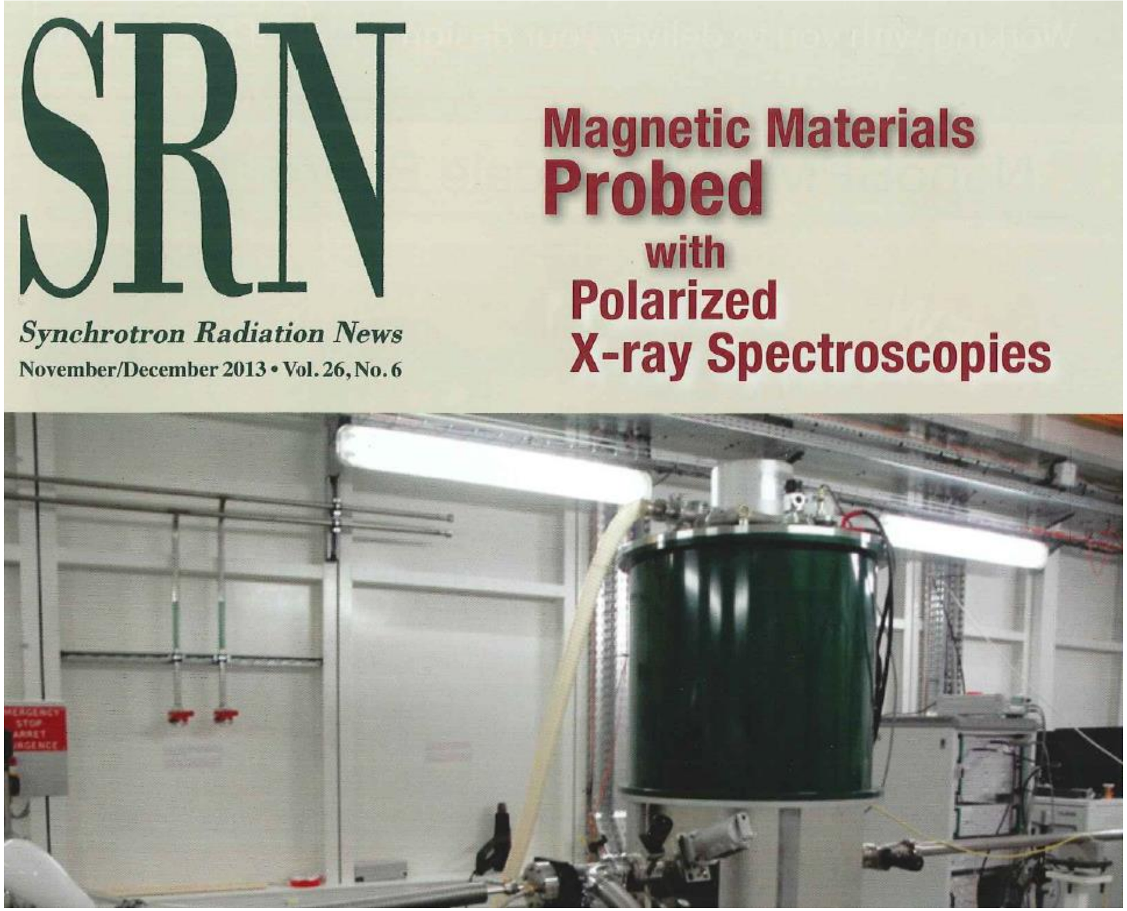
A. Gukasov in Book of abstract L School on Physics of condensed matter

The Agilent Technologies Europhysics Prize for outstanding achievement in condensed-matter physics in 2000:
P. Carra, G. Schütz and G. van der Laan

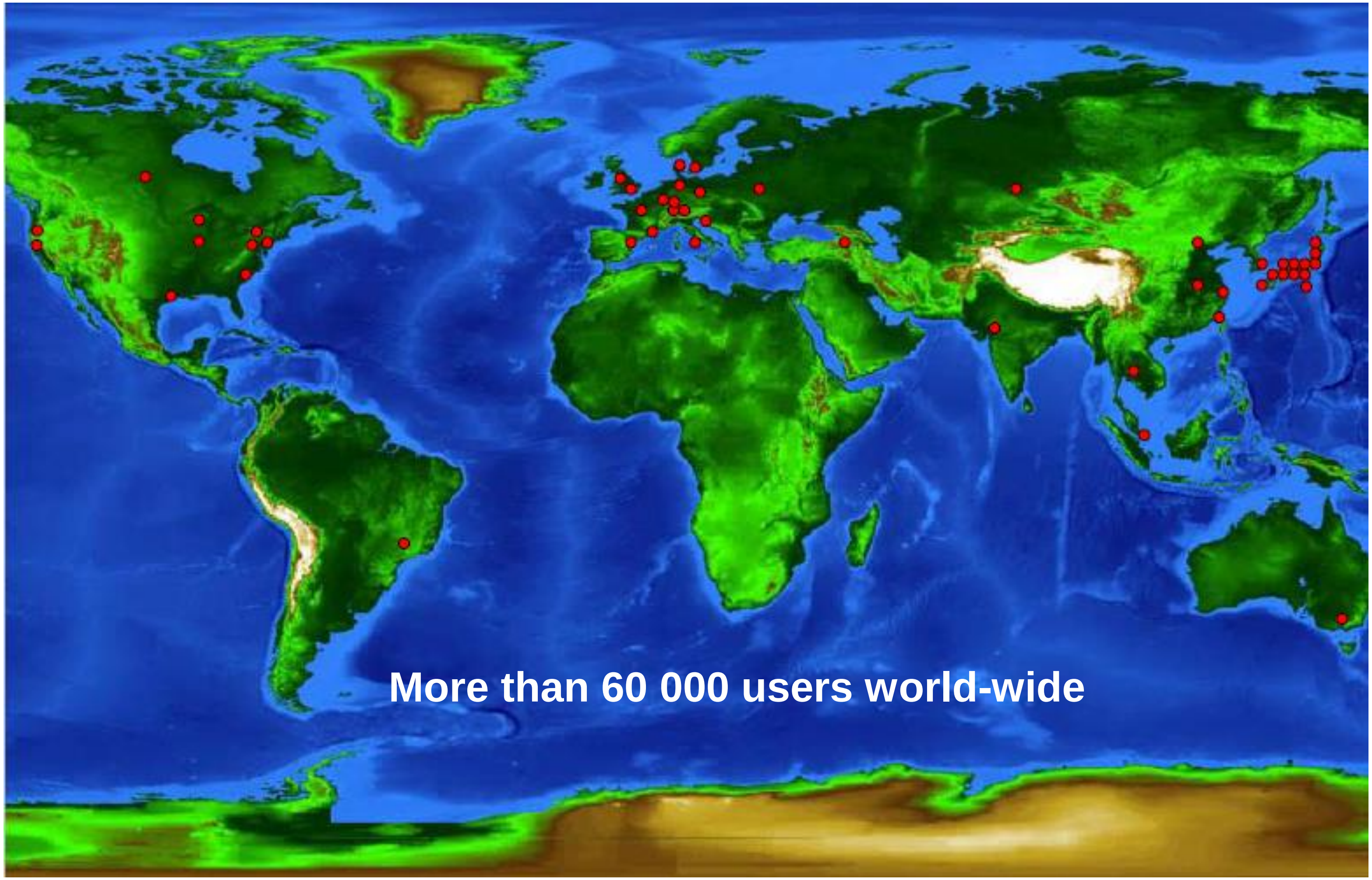
"for their pioneering work in establishing the field of magnetic X-ray dichroism. …it is possible to obtain information about the material that cannot be obtained with traditional measurements."

Nowadays:

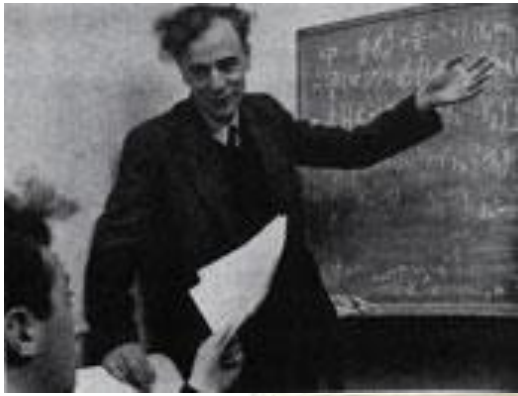
X-ray magnetic circular dichroism (XMCD) is considered to be one of the most important discoveries in the field of magnetism research in the last two decades. It is hard to imagine modern research into magnetism without the aid of synchrotron radiation.

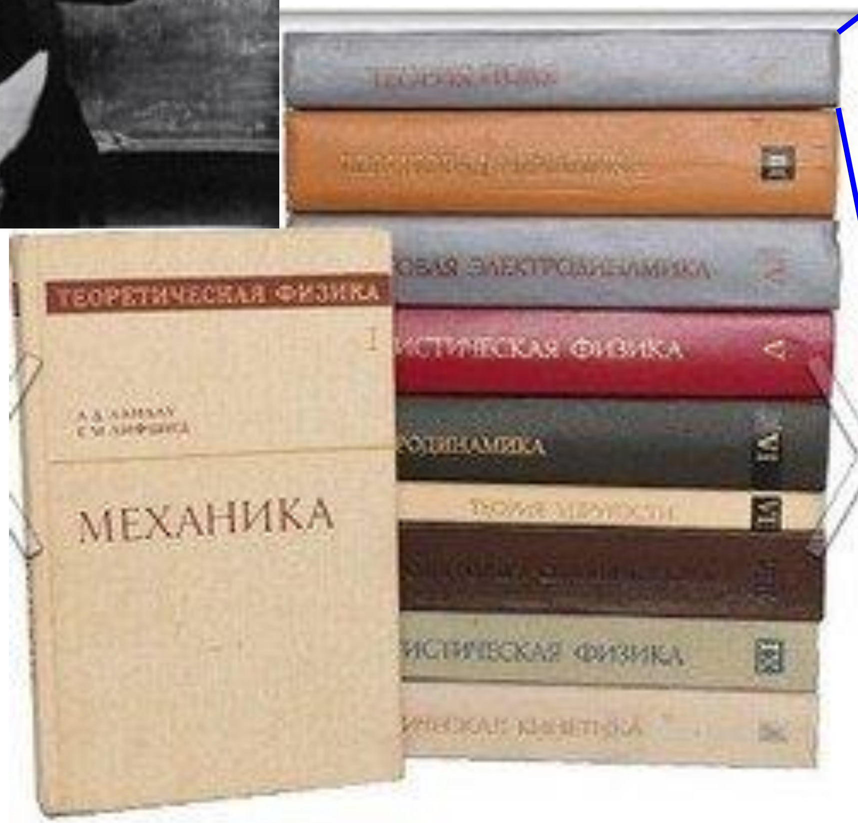


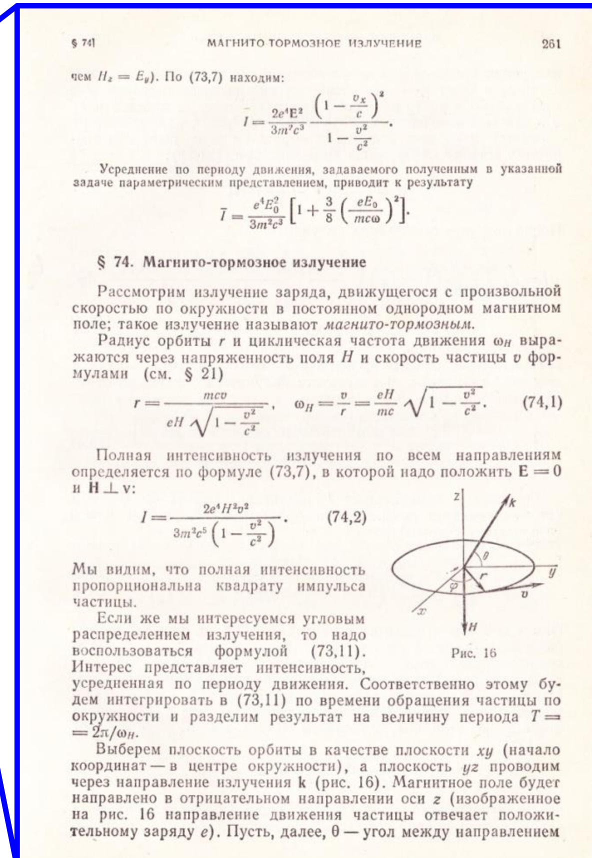
49 Synchrotron radiation facilities are running and 6 more are under construction



Landau and Lifshitz: Course of Theoretical Physics







§ 74] МАГНИТО-ТОРМОЗНОЕ ИЗЛУЧЕНИЕ 261

чем $H_z = E_y$). По (73,7) находим:

$$I = \frac{2e^4E^2}{3m^2c^3}\frac{\left(1-\frac{v_x}{c}\right)^2}{1-\frac{v^2}{c^2}}.$$

Усреднение по периоду движения, задаваемого полученным в указанной задаче параметрическим представлением, приводит к результату

$$\bar{I} = \frac{e^4E_0^2}{3m^2c^3}\left[1+\frac{3}{8}\left(\frac{eE_0}{mc\omega}\right)^2\right].$$

§ 74. Магнито-тормозное излучение

Рассмотрим излучение заряда, движущегося с произвольной скоростью по окружности в постоянном однородном магнитном поле; такое излучение называют *магнито-тормозным*.

Радиус орбиты r и циклическая частота движения ω_H выражаются через напряженность поля H и скорость частицы v формулами (см. § 21)

$$r = \frac{mcv}{eH\sqrt{1-\frac{v^2}{c^2}}}, \quad \omega_H = \frac{v}{r} = \frac{eH}{mc}\sqrt{1-\frac{v^2}{c^2}}. \qquad (74,1)$$

Полная интенсивность излучения по всем направлениям определяется по формуле (73,7), в которой надо положить $\mathbf{E} = 0$ и $\mathbf{H} \perp \mathbf{v}$:

$$I = \frac{2e^4H^2v^2}{3m^2c^5\left(1-\frac{v^2}{c^2}\right)}. \qquad (74,2)$$

Рис. 16

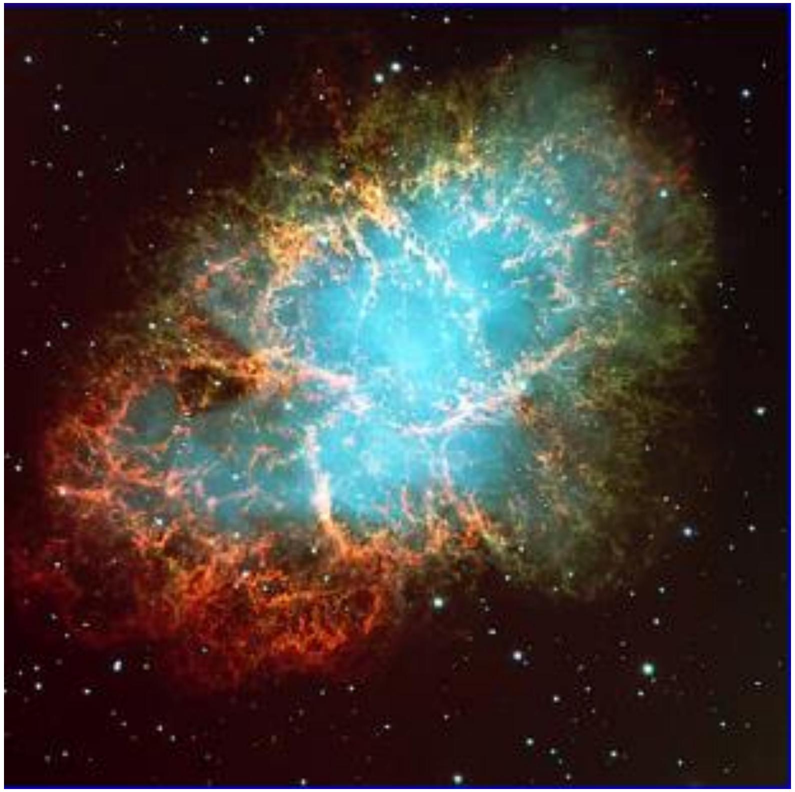
Мы видим, что полная интенсивность пропорциональна квадрату импульса частицы.

Если же мы интересуемся угловым распределением излучения, то надо воспользоваться формулой (73,11). Интерес представляет интенсивность, усредненная по периоду движения. Соответственно этому будем интегрировать в (73,11) по времени обращения частицы по окружности и разделим результат на величину периода $T = 2\pi/\omega_H$.

Выберем плоскость орбиты в качестве плоскости xy (начало координат — в центре окружности), а плоскость yz проводим через направление излучения $\mathbf{k}$ (рис. 16). Магнитное поле будет направлено в отрицательном направлении оси z (изображенное на рис. 16 направление движения частицы отвечает положительному заряду e). Пусть, далее, θ — угол между направлением

Corresponding paragraph is entitled "Magnetic bremsstrahlung" ,
i.e. electromagnetic radiation due to the deceleration of a charged particle in magnetic field.

THE FIRST EVER RECORDED OBSERVATION



The Crab nebula is the expanding remains of a star that was seen to explode by Chinese astronomers in the year 1054 AD.
Hot excited gas emission (reddish) and bremsstrahlung (blueish) of high energy electrons in the magnetic field of the rapidly rotating neutron star.

PREDICTION OF SYNCHROTRON RADIATION

Доклады Академии Наук СССР
1944, Том XLIV, № 8

ФИЗИКА

Д. ИВАНЕНКО и И. ПОМЕРАНЧУК

О МАКСИМАЛЬНОЙ ЭНЕРГИИ, ДОСТИЖИМОЙ В БЕТАТРОНЕ

(Представлено академиком В. А. Фоком 27 III 1944)

Недавно Керстом (¹) был сконструирован новый прибор — бетатрон, с помощью которого уже удалось получить пучок электронов, имеющих энергию 20 MeV. Принцип действия бетатрона заключается в ускорении электронов вихревым электрическим полем, возникающим при изменении во времени магнитного поля, закручивающего электрон. В отличие от циклотрона, пригодность которого ограничена нерелятивистской областью, в бетатроне нет пределов для достижимых энергий из-за зависимости массы от скорости час

Однако следует указать на наличие другого обстоятел
приводящего к появлению предела энергий, которые могу
достигнуты в бетатроне. Такой причиной является тормозное
чение электронов в закручивающем их магнитном поле. Де
тельно, в магнитном поле электрон двигается ускоренно и, в
ветствии с классической электродинамикой, излучает эн
Легко видеть, что квантовые эффекты, ввиду больших ра
орбиты, не играют роли. Как указано одним из нас (²), эле
движущийся в магнитном поле с напряжением H, излучает на
ницу пути энергию, равную

$$-\frac{dE}{dx}=\frac{2}{3}\left(\frac{e^2}{mc^2}\right)^2\left(\frac{E}{mc^2}\right)^2\left(\frac{\vec{v}\,H}{c}\right)^2$$

(e — заряд, m — масса электрона, $\vec{v}$ — скорость, E — энергия.
выводе (1) предполагается, что $E \gg mc^2$). В бетатроне Кер
большей части пути $v \simeq c$ и перпендикулярно H; поэтому

$$-\frac{dE}{dx}=\frac{2}{3}r_0^2\left(\frac{EH}{mc^2}\right)^2 \qquad \left(r_0=\frac{e^2}{mc^2}\right).$$

Предельная энергия E_0 определится из условия, что (2)
равно энергии, приобретенной электроном в вихревом электрич
поле на единицу пути (³):

$$\frac{2}{3}r_0^2\left(\frac{E_0H}{mc^2}\right)^2=\frac{e\left|\frac{d\Phi}{dt}\right|}{2\pi R_0 c}=eR_0|\dot{H}|$$

(R_0 — радиус равновесной орбиты, Φ — поток индукции, $\dot{H}=$
Отсюда

$$E_0=mc^2\sqrt{\frac{3}{2}\frac{e}{c}\left|\frac{R_0\dot{H}}{r_0^2H^2}\right|}.$$

PHYSICAL REVIEW VOLUME 65, NUMBERS 11 AND 12 JUNE 1 AND 15, 1944

Letter to the Editor

PROMPT publication of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is the third of the month. Because of the late closing date for the section no proof can be shown to authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not in general exceed 600 words in length.

On the Maximal Energy Attainable in a Betatron

D. IWANENKO AND I. POMERANCHUK
Physical Institute of the Moscow State University, Moscow, and Physico-Technical Institute of the Academy of Sciences of the U. S. S. R., Leningrad, U. S. S. R.
May 18, 1944

BY means of a recently constructed induction accelerator-betatron, Kerst succeeded in obtaining electrons up to 20 Mev.[1] The principle of operation of the betatron is the acceleration of electrons by a tangential electric field produced by a changing magnetic flux, which is connected with the magnetic field keeping electrons on the orbit by a simple relation. In contrast to a cyclotron, whose applicability is essentially limited to the non-relativistic region on the ground of defocusing of orbits due to the change of mass at high energies, there is no such limitation for the betatron.

We may point out, however, that quite another circumstance would lead as well to the existence of a limitation for maximal energy attainable in a betatron. This is the radiation of electrons in the magnetic field. Indeed, electrons moving in a magnetic field will be accelerated and must radiate in accordance with the classical electrodynamics. One can easily see that quantum effects do not play here any important role as the dimension of the orbit is very great. As was shown by one of us[2] an electron moving in a magnetic field **H** radiates per unit of path the energy

$$-(dE/dX)=2/3(e^2/mc^2)^2(E/mc^2)^2[(\mathbf{V}/c)\mathbf{H}]^2 \qquad (1)$$

where e is the charge, m the mass, **V** the velocity, and E the energy of the electron; E is assumed much greater than mc^2.

In the betatron **V** is normal to H and practically for the whole path equal to c. Then we have

$$-(dE/dX)=2/3(e^2/mc^2)^2(EH/mc^2)^2. \qquad (2)$$

The limiting value of energy E_0 is to be determined from the condition that the radiated energy (2) will be equal to energy gained by the electron in the electric field produced by magnetic flux per unit of path:[3]

$$\frac{2}{3}r_0^2\left(\frac{E_0H}{mc^2}\right)^2=\frac{e|d\phi/dt|}{2\pi R_0c}=\frac{e}{c}R_0|\dot{H}| \qquad (3)$$

$$\dot{H}=dH/dt \qquad r_0=e^2/mc^2.$$

Here R_0 is the radius of the orbit, ϕ is the induction flux.[1]

Hence:

$$\frac{E_0}{mc^2}=\left(\frac{3eR_0}{2r_0^2c}\frac{\dot{H}}{H^2}\right)^{1/3}. \qquad (4)$$

Taking for H and E the values now being in use we get $E_0\approx 5\times 10^8$ ev, which is only five times as great as the energy which one expects to obtain in the betatron now under construction. From (4) one sees that E_0 is inversely proportional to the magnetic field applied and proportional to the square root of energy gained in the rotation electric field per unit of path. All this requires the using of smaller H or of higher frequencies with the purpose of getting higher limiting values of E_0.

The radiative dissipation of energy of electrons moving in a magnetic field must be also of importance for the discussion of the focusing of the electronic beam, as the energy of particles being accelerated will grow more slowly with the growth of H if the radiation is taken into account. This latter question may deserve a separate discussion.

[1] D. W. Kerst, Phys. Rev. **61**, 93 (1942).
[2] I. Pomeranchuk, J. Phys. **2**, 65 (1940).
[3] D. W. Kerst and R. Serber, Phys. Rev. **60**, 53 (1941).

G.E. SYNCHROTRON

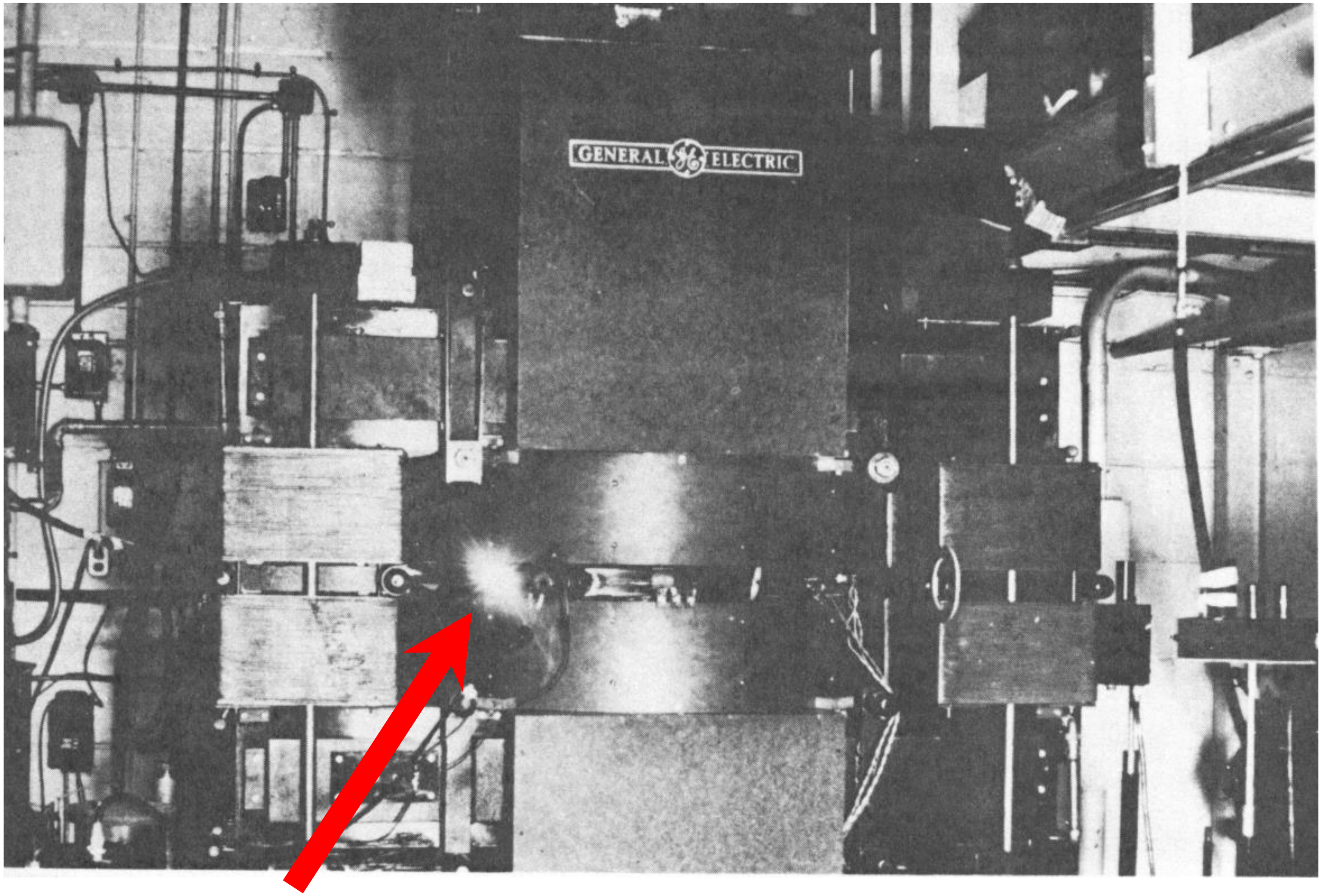
A5. Design of a 70-Mev Synchrotron. H. C. Pollock, R. V. Langmuir, F. R. Elder, J. P. Blewett, A. M. Gurewitsch and R. L. Watters, *General Electric Company.*—The synchrotron[1] under construction in the Research Laboratory of the General Electric Company is designed to operate with an equilibrium orbit 29.2 cm in radius. Peak fields of 8300 gauss at the orbit will permit acceleration of electrons to peak energies of 70 Mev. The magnet resembles a conventional betatron magnet except that the main core is replaced by a small core capable of carrying flux sufficient for betatron type acceleration up to about 5 or 6 Mev. At this point, the core begins to saturate and 163-Mc radiofrequency acceleration is initiated. The high frequency resonator is a quarter-wave coaxial structure whose inner and outer conductors are separated by the glass vacuum envelope. The inner and outer conductors of this resonator are thin films of silver which are divided by parallel scratches into narrow segments so that magnetic field distortions caused by eddy currents will be reduced to negligible proportions. Power is fed to this resonator from a master oscillator-power amplifier system. Timing and injection circuits will be discussed and tests on the various components of the machine will be described.

[1] V. Veksler, J. Phys. U.S.S.R. **9**, 153 (1945). E. M. McMillan, Phys. Rev. **68**, 143 (1945).

Group of Prof. H.C. Pollock builds 70-MeV synchro-cyclotron at the General Electric Co. at Schenectady, having transparent vacuum chamber to observe HV sparking, BUT

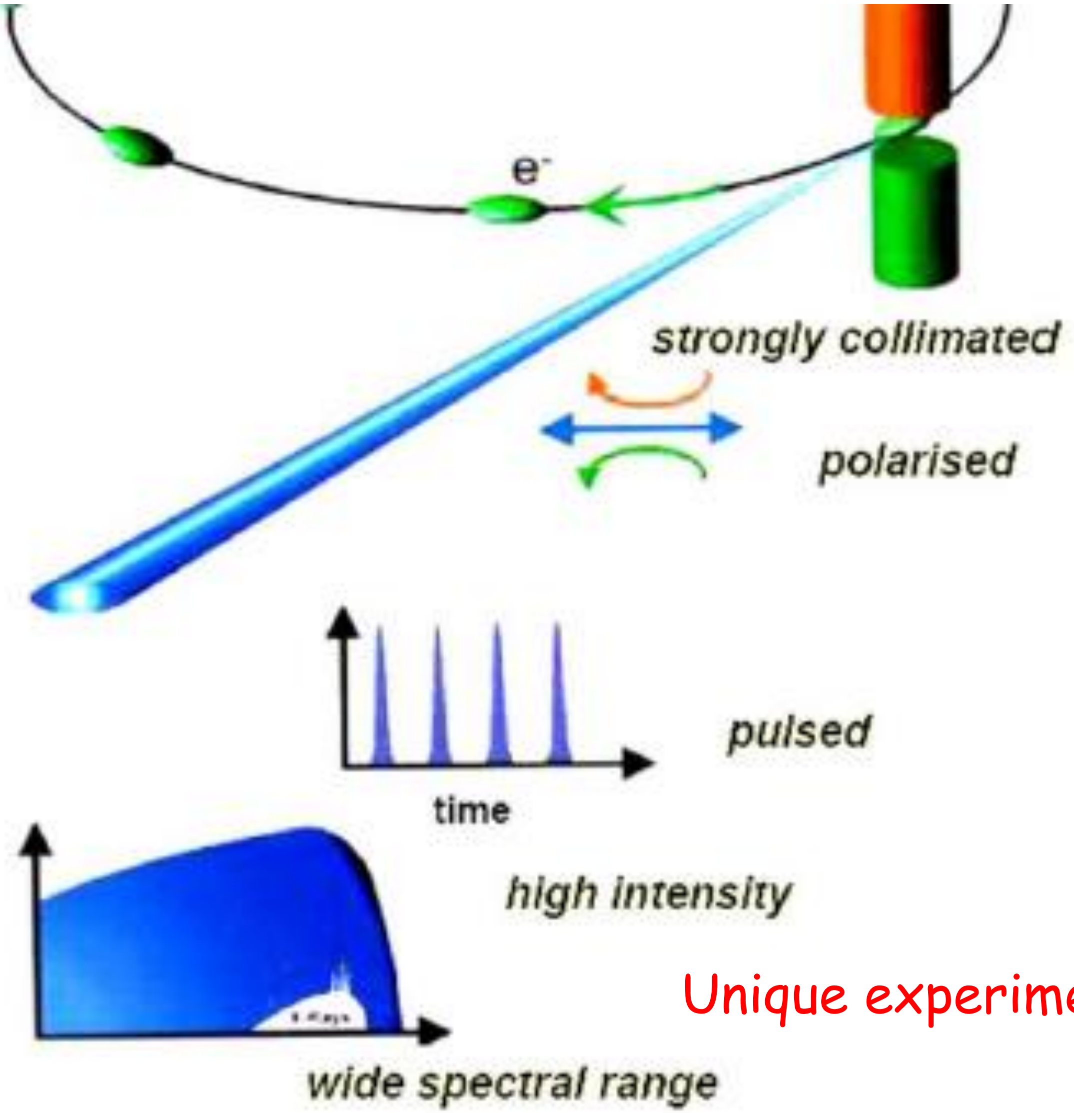
F.R. Elder, A.M. Gurewitsch, R.V. Langmuir, and H.C. Pollock, J. Appl. Phys. **18**, 810 (1947)
F.R. Elder, A.M. Gurewitsch, R.V. Langmuir, and H.C. Pollock, Phys. Rev. **74**, 52 (1947)

THE FIRST OBSERVATION OF SYNCHROTRON RADIATION



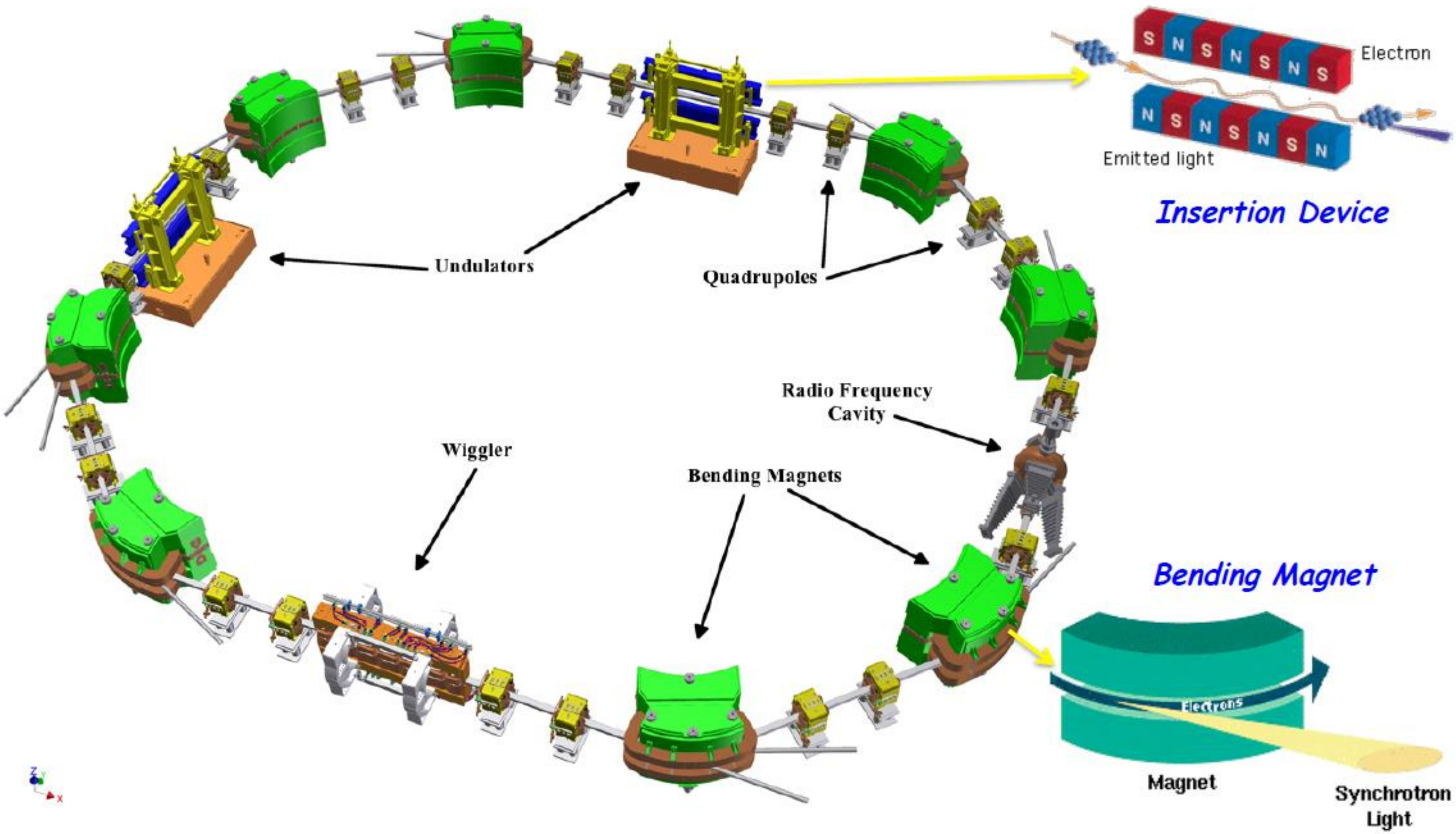
The 70 MeV synchrotron emitting light (24^{th} April 1947)

PROPERTIES OF SYNCHROTRON RADIATION FROM CYCLIC ACCELERATORS

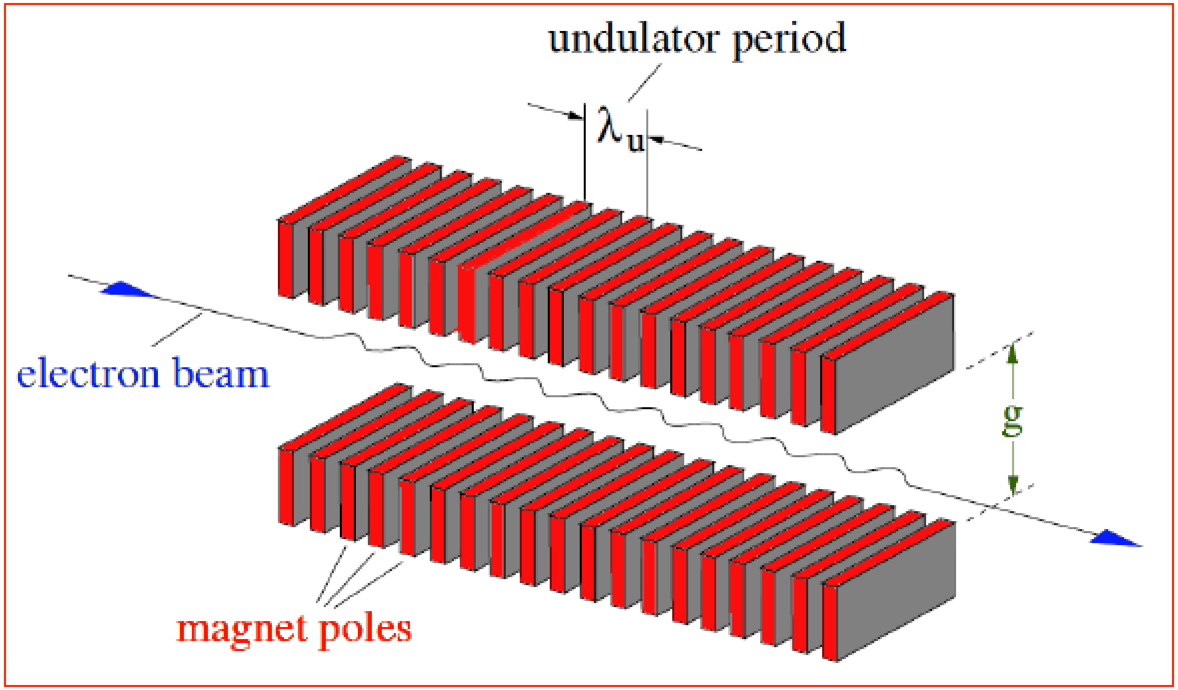


Unique experimental tool for X-ray physics

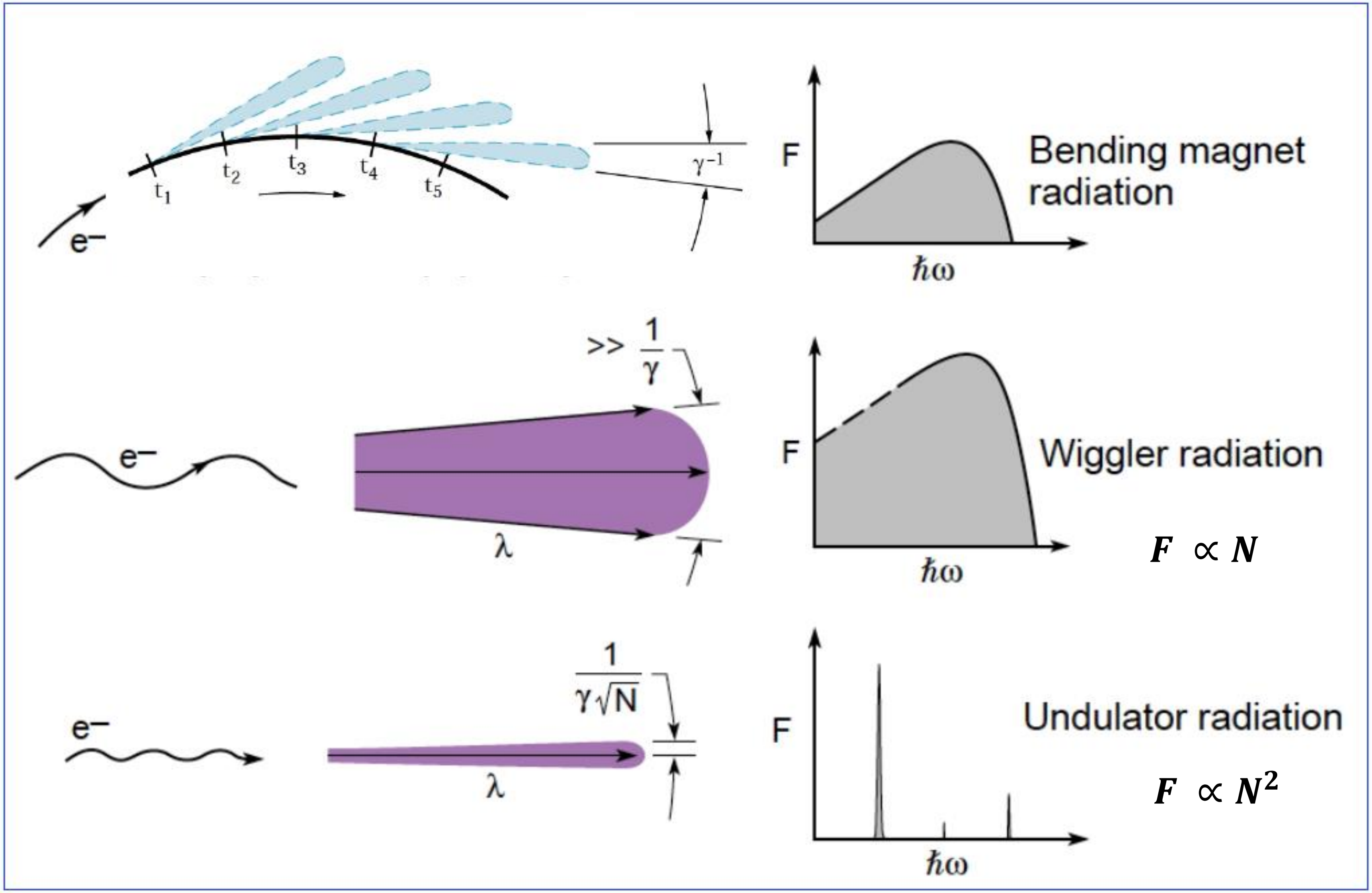
SYNCHROTRON RADIATION FACILITY

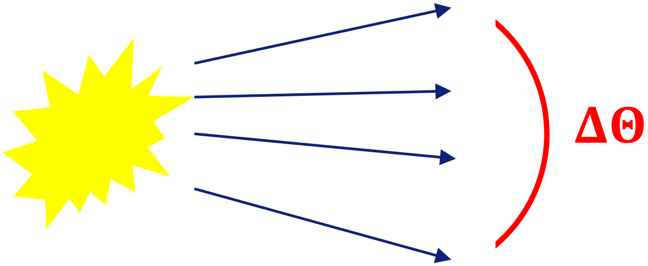


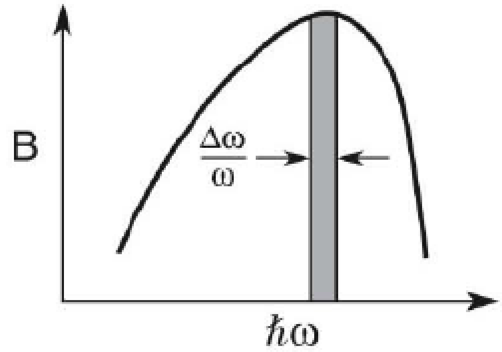
INSERTION DEVICES



Insertion devices (ID) are ***periodic arrays of magnetic poles*** with alternating field directions installed, in the straight sections of storage rings that force the particles to oscillate passing through the device.


t1
t2
t3
t4
t5
e−
γ-1
F
ħω
Bending magnet radiation
>> 1/γ
e−
λ
F
ħω
Wiggler radiation
$F \propto N$
1/γ√N
e−
λ
F
ħω
Undulator radiation
$F \propto N^2$





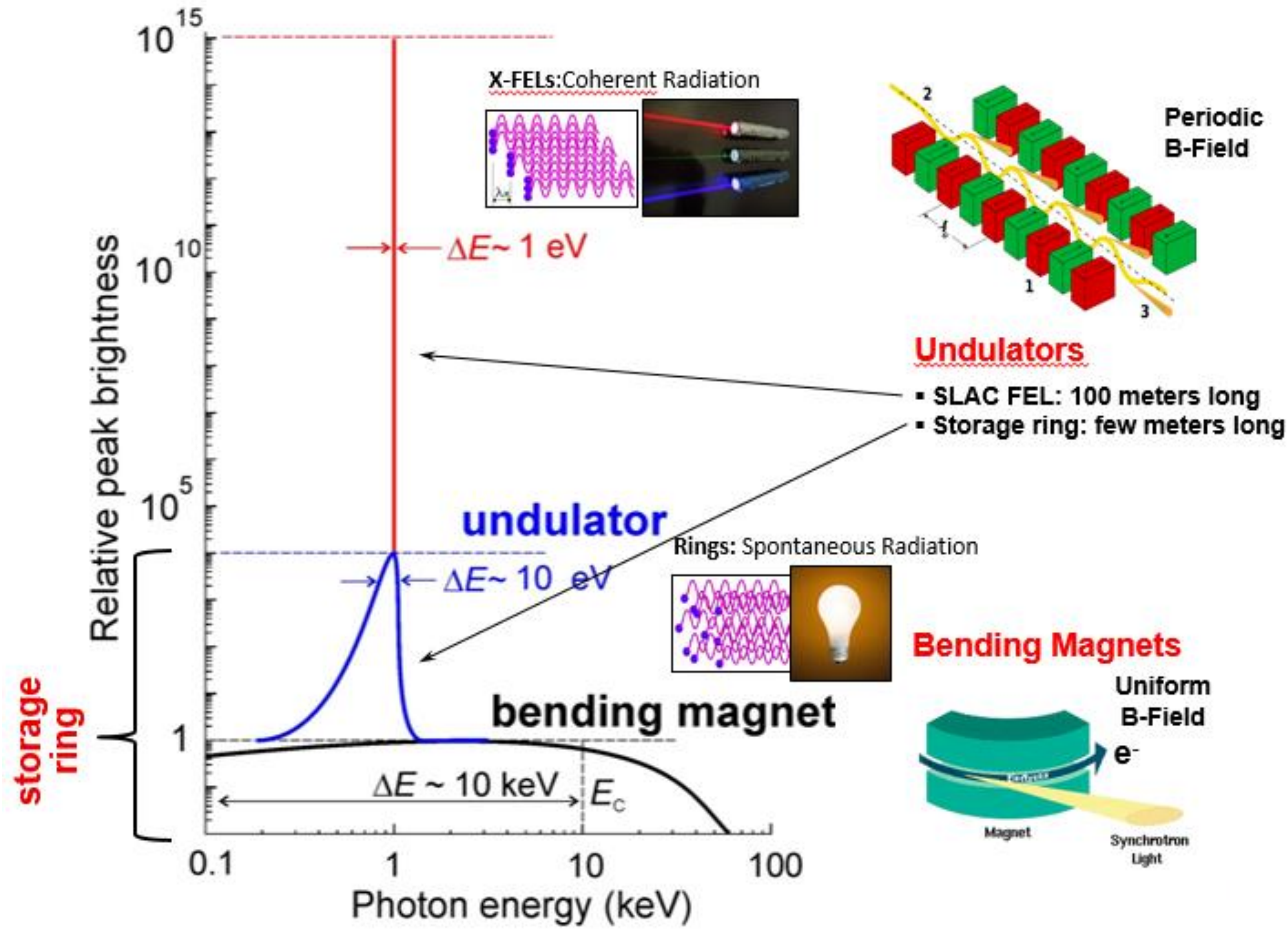
$$B = \frac{\textit{Photons in unit spectral range in unit time}}{(\textit{source size} \times \textit{divergence})^2}$$

Units: photons/s/mm^2/mrad^2/0.1%BW

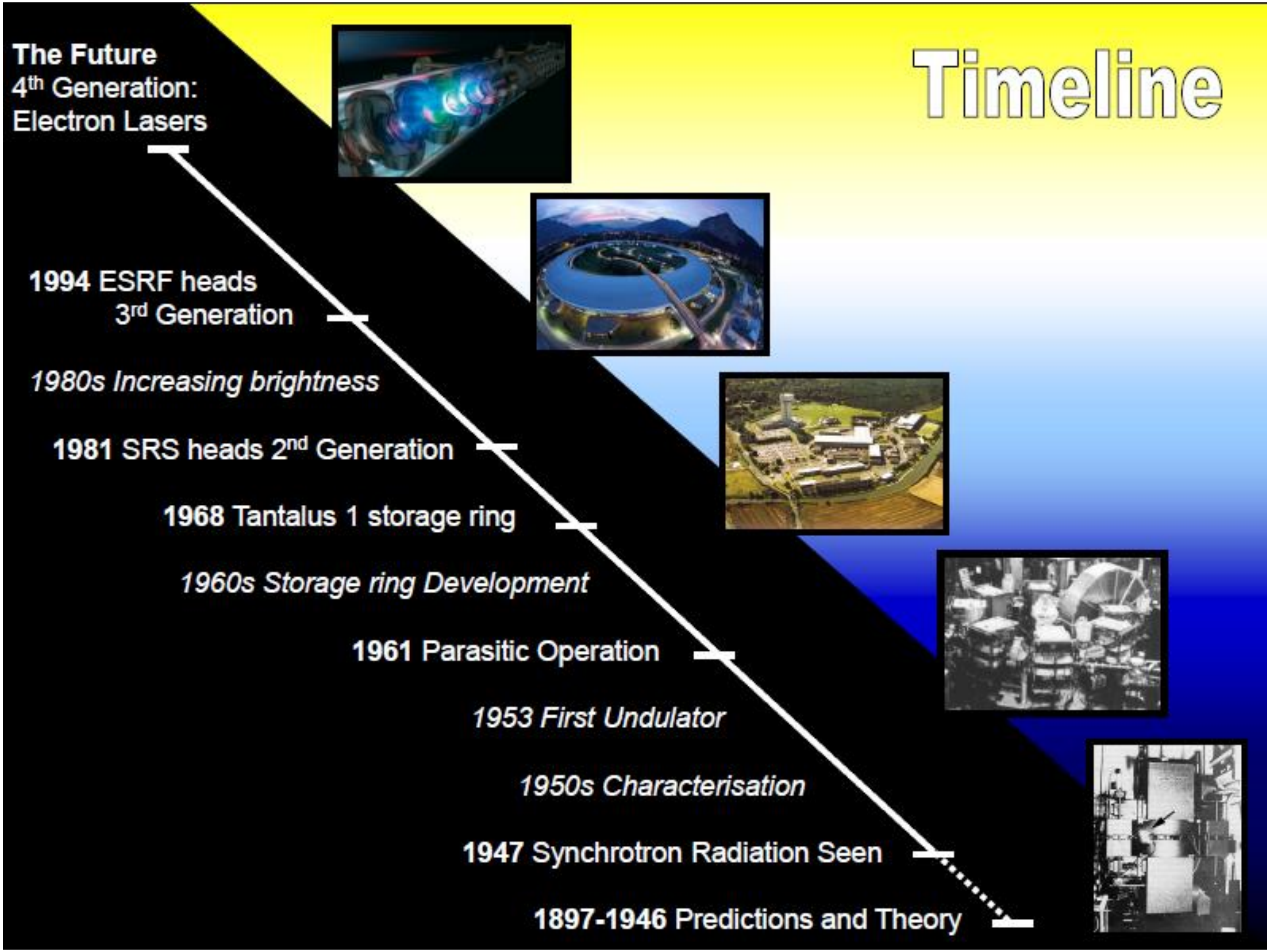
Brightness is at most conserved in an optical system: impossible to increase brightness given the source.

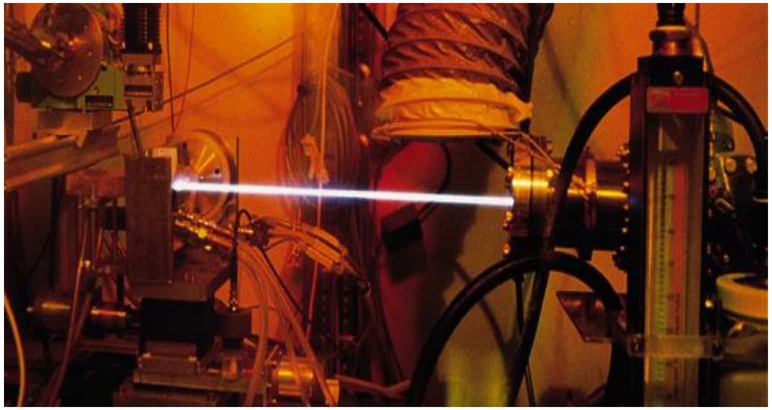
"Best optics is no optics"

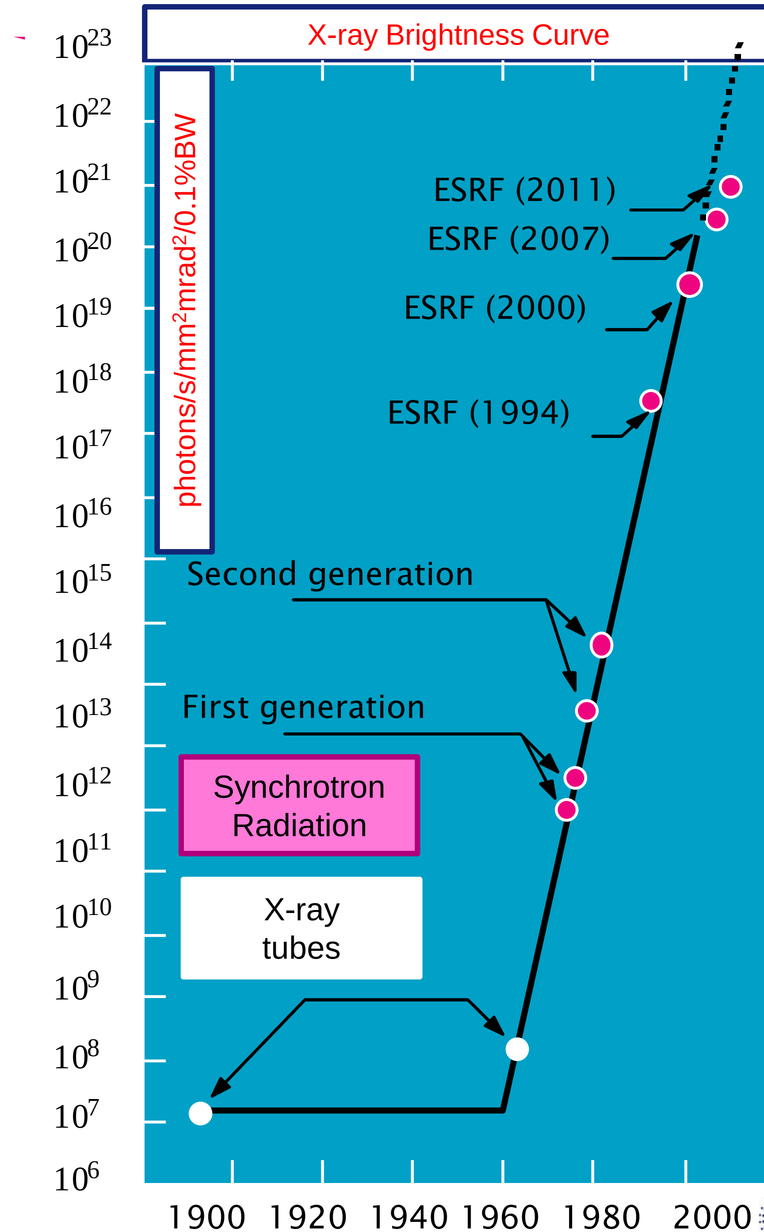
HOW BRIGHT IS SYNCHROTRON RADIATION SOURCE ?



SYNCHROTRON GENERATION TIMELINE







Short Wavelengths
- Comparable with atomic distances
- Bragg's diffraction

Energy resolution and tuning
- Core-hole electron transitions energies
- Element and orbital selectivity
- Inelastic scattering

Full control of polarisation
- Magnetic and electronic symmetries

Picosecond time structure
- Pump probe experiments
- Photon correlation spectroscopies

Strong collimation and coherence
- X-ray nanobeams

THIRD GENERATION SYNCHROTRON RADIATION FACILITIES

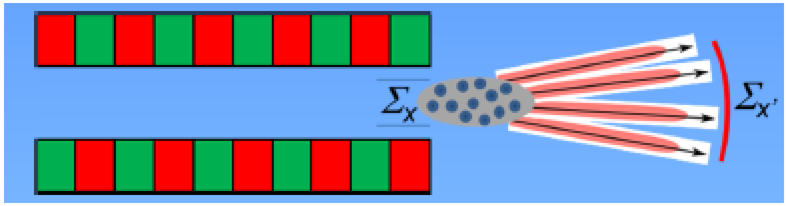
ESRF	6	GeV	France
ALS	1.9	GeV	USA
APS	7	GeV	USA
BESSY II	1.7	GeV	Germany
ELETTRA	2.0	GeV	Italy
SPring-8	8	GeV	Japan
MAX II	1.5	GeV	Sweden
SLS	2.4	GeV	Switzerland
PLS	2	GeV	Korea
SRRC	1.4	GeV	Taiwan
SSRL	3	GeV	USA
CLS	2.9	GeV	Canada
Soleil	2.5	GeV	France
Diamond	3	GeV	UK
Australian Light Source	3	GeV	Australia
Alba	2	GeV	Barcelona
SSRF	3.5	GeV	Shanghai
PETRA III	6	GeV	Hamburg

SHOPPING LIST FOR A BETTER SYNCHROTRON RADIATION SOURCE

- **Wavelength Range**
  - Determines science reach—atomic or electronic structure and dynamics
- **Brightness: Average and Peak**
  - Determines measurement sensitivity
- **Pulse Width**
  - fs pulses opens the window on ultrafast dynamics and ‘probe before destroy’ technology
- **Coherence**
  - Allows new techniques (e.g. coherent imaging)
  - Leads to high brightness of the beams
- **Stability**
  - Source stability in energy, position, time, intensity
- **Number of Undulators/Beamlines/Endstations**
  - Determines the number of users in parallel that can be accommodated and ultimately how much science gets delivered

UNDULATOR RADIATION BRIGHTNESS

- *Brightness convolution theorem:*



$$B = \frac{N_e F(\omega)}{2\pi^2 \Sigma_x \Sigma_y \Sigma_{x'} \Sigma_{y'}} \exp\left(-\frac{x^2}{2\Sigma_x^2} - \frac{y^2}{2\Sigma_y^2} - \frac{\phi_x^2}{2\Sigma_{x'}^2} - \frac{\phi_y^2}{2\Sigma_{y'}^2}\right)$$

$$\Sigma_{x,y}^2 \equiv \sigma_{x,y}^2 + \sigma_r^2 \qquad \Sigma_{x',y'}^2 \equiv \sigma_{x',y'}^2 + \sigma_{r'}^2 \qquad \sigma_r = \frac{\sqrt{2\lambda L_u}}{4\pi} \qquad \sigma_{r'} = \sqrt{\frac{\lambda}{2L_u}}$$

- *Electron beam emittance dominated regime:* $\epsilon_{x,y} = \sigma_{x,y}\sigma_{x'y'} \gg \frac{\lambda}{4\pi}$

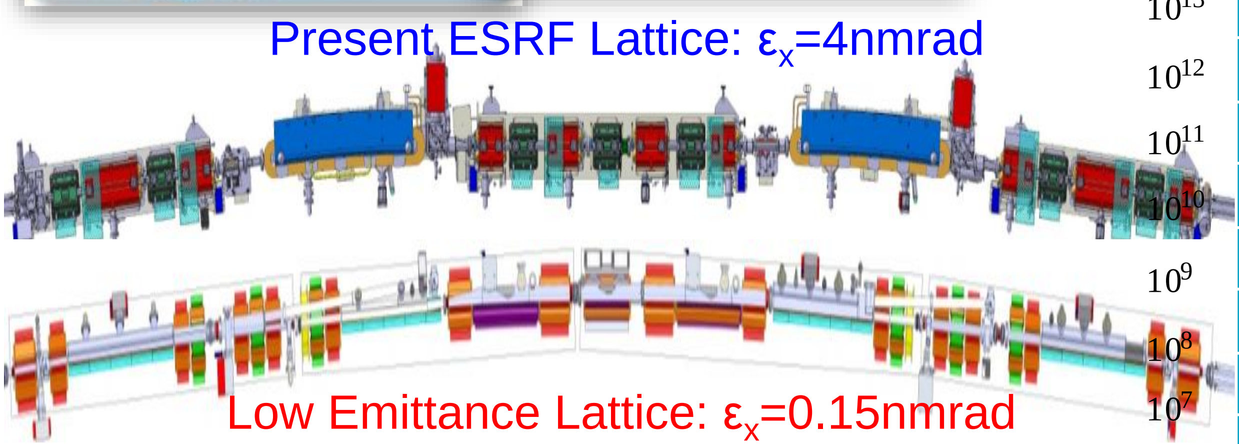
$$B = \frac{N_e F(\omega)}{2\pi^2 \sigma_x \sigma_y \sigma_{x'} \sigma_{y'}} = \frac{N_e F(\omega)}{2\pi^2 \epsilon_x \epsilon_y}$$

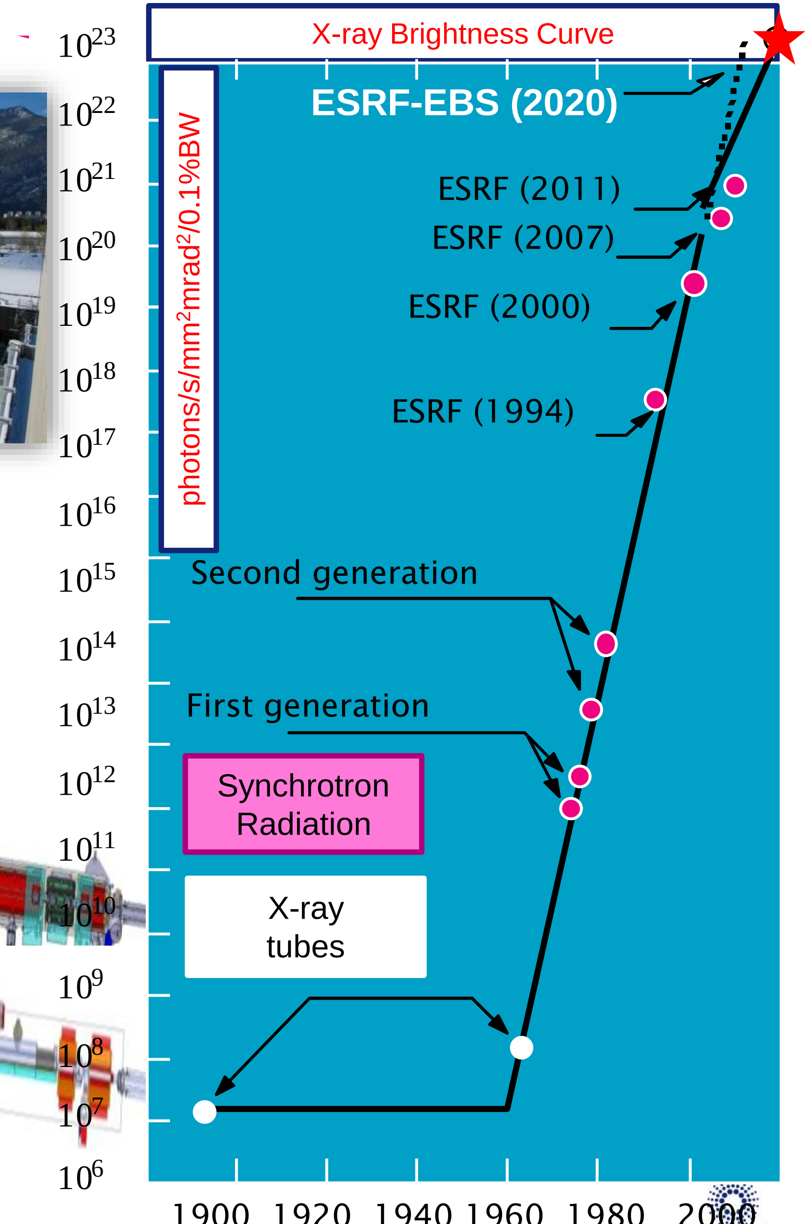
- *Radiation dominated regime:* $\epsilon_{x,y} \ll \frac{\lambda}{4\pi}$

$$B = \frac{N_e F(\omega)}{2\pi^2 \sigma_x \sigma_y \sigma_{x'} \sigma_{y'}} = \frac{N_e F(\omega)}{\left(\lambda/2\right)^2}$$

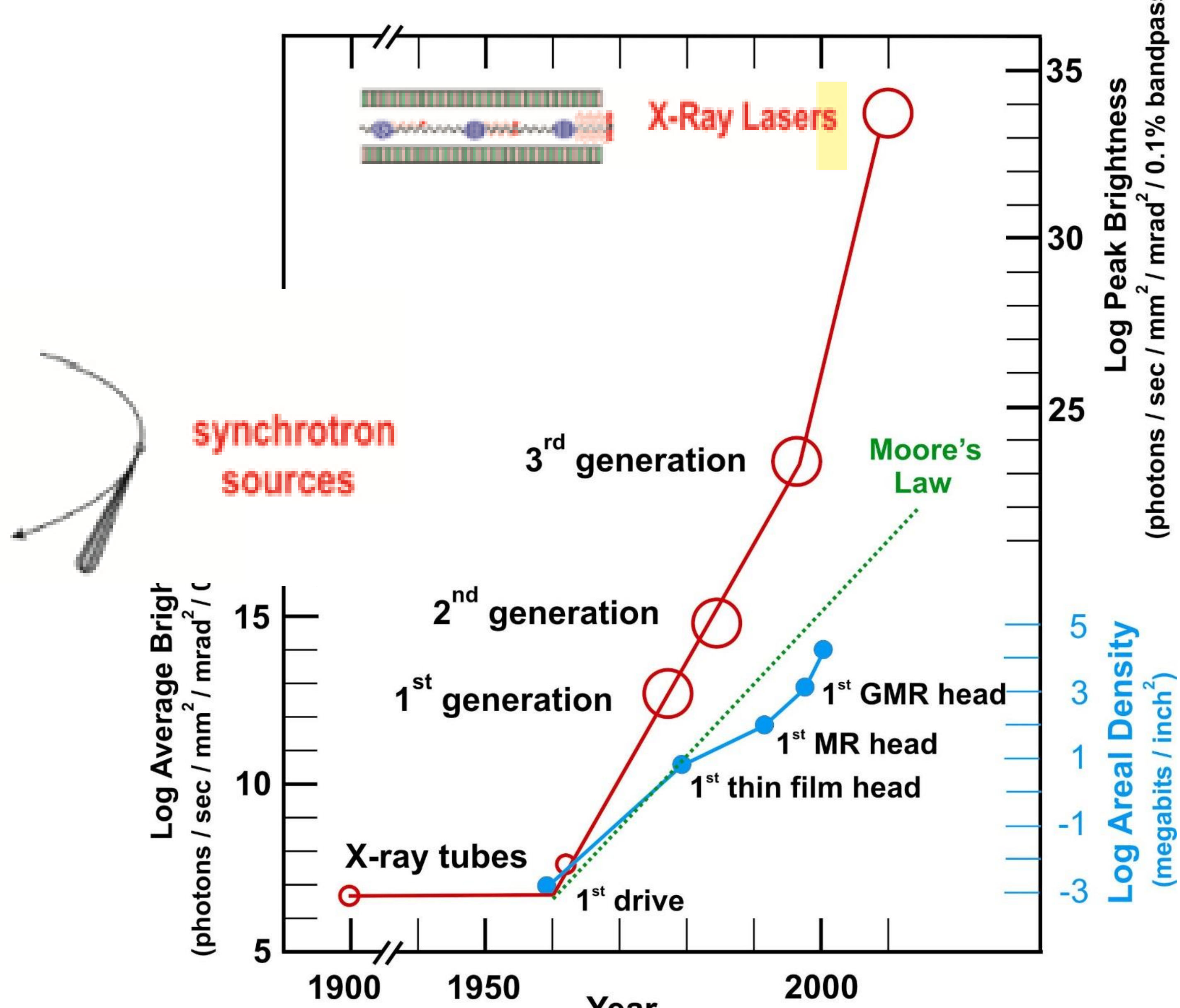
DIFFRACTION LIMITED SOURCE !!!

ESRF PUSH TOWARD HIGHER PERFORMANCES

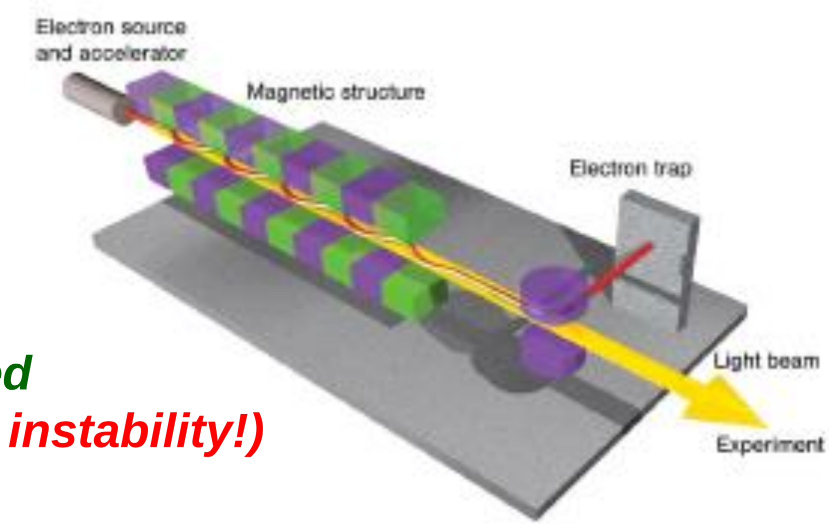




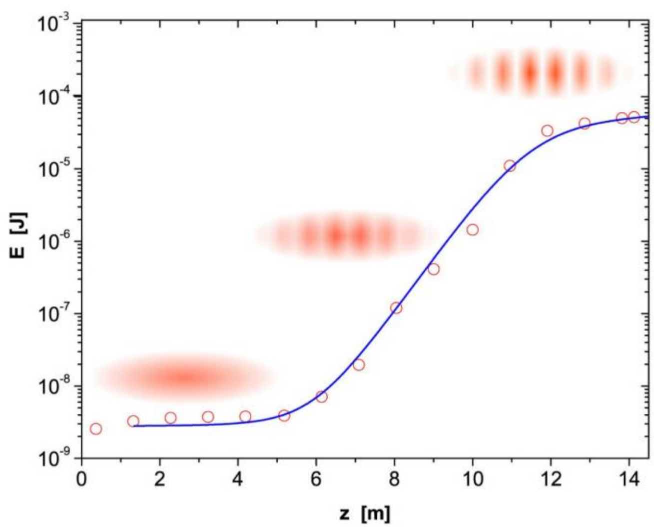
GROWTH OF X-RAY BRIGHTNESS AND MAGNETIC STORAGE DENSITY



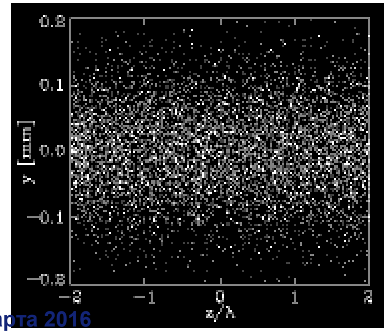
- ***Resonant interaction** of electrons with EM radiation in an undulator*
- ***Coherent radiation intensity ∝ N_e^2 due to beam microbunching*** *(N_e: # of e- involved ~10^6 to 10^9)*

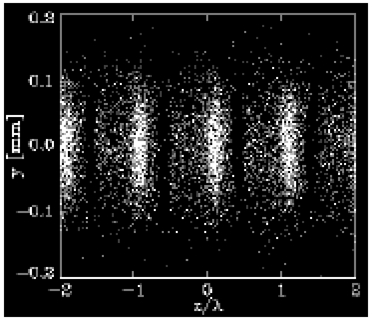


*At x-ray wavelengths, use **Self-Amplified Spontaneous Emission* (a wonderful instability!)** to reach high peak power*



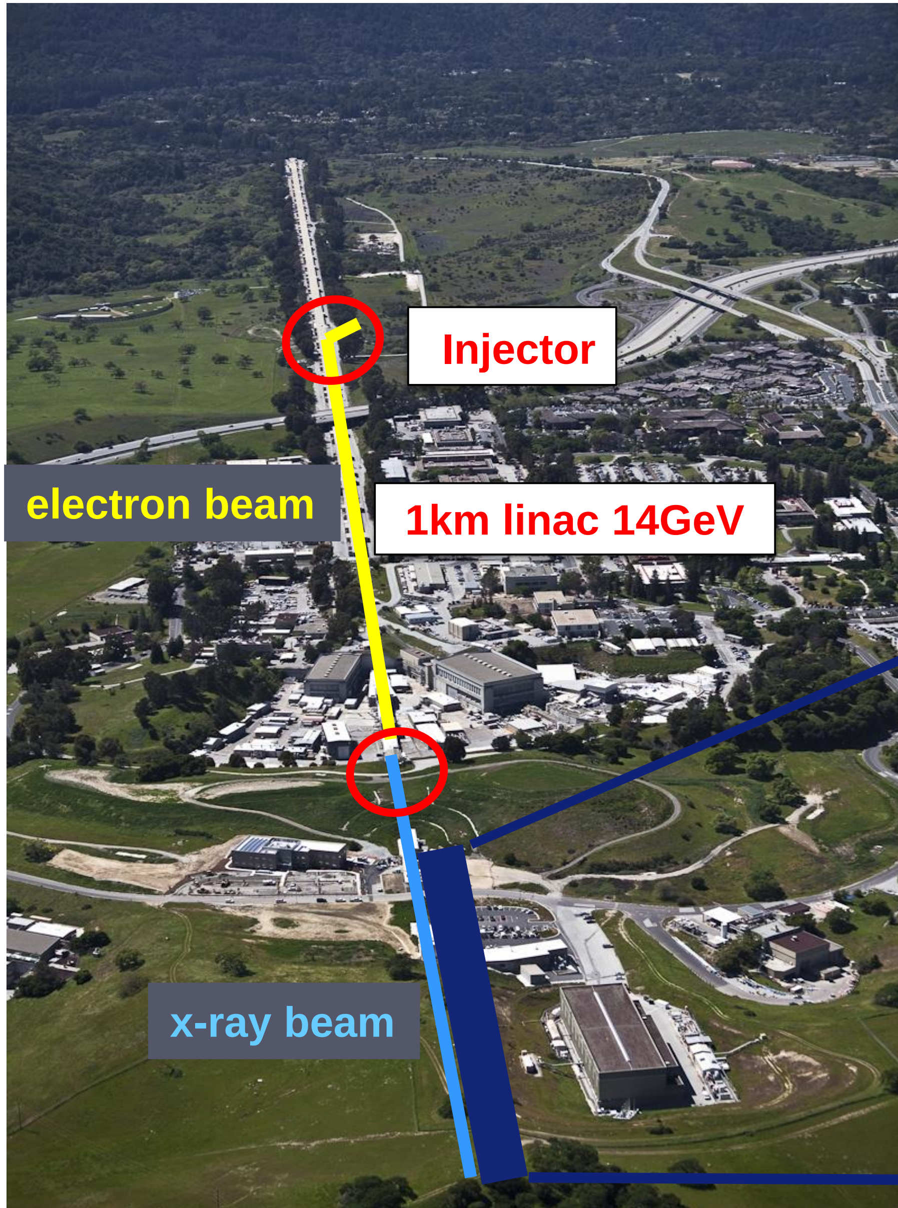
undulator entrance

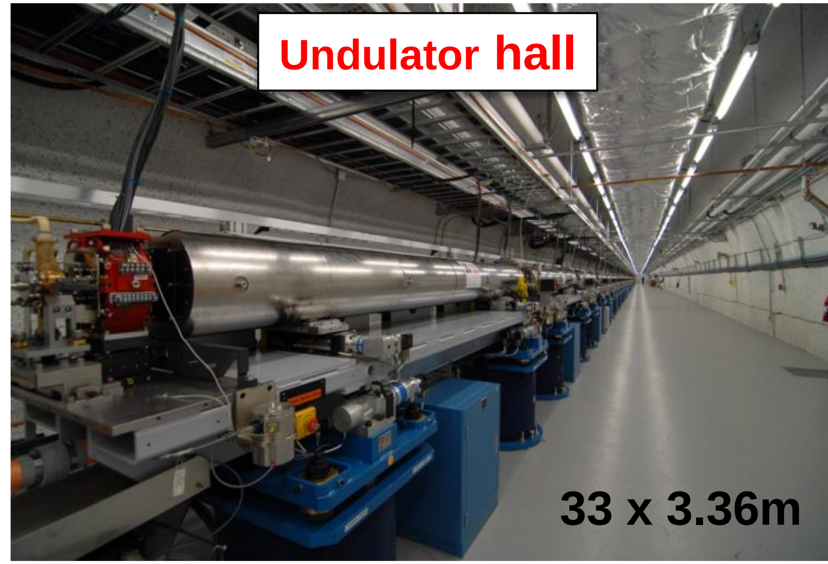


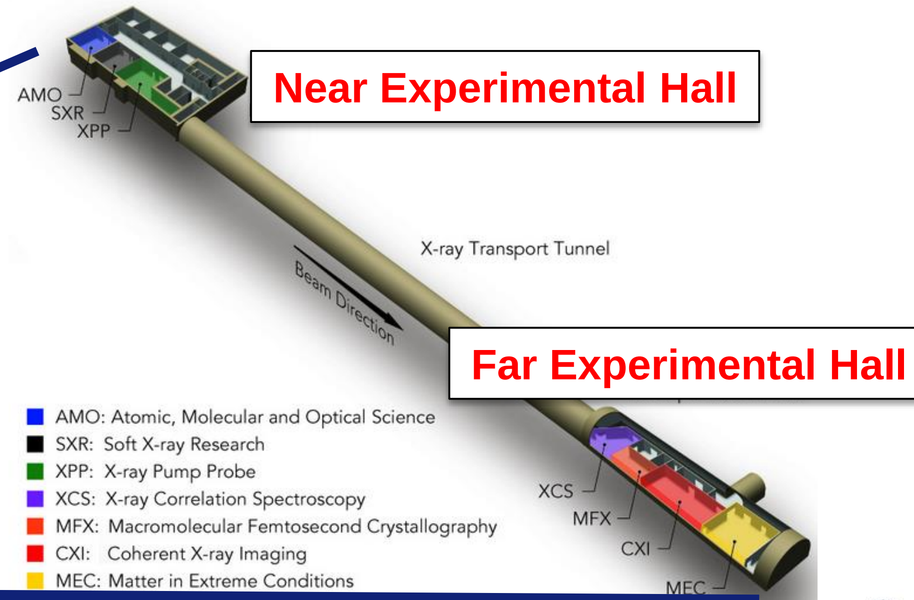


full saturation

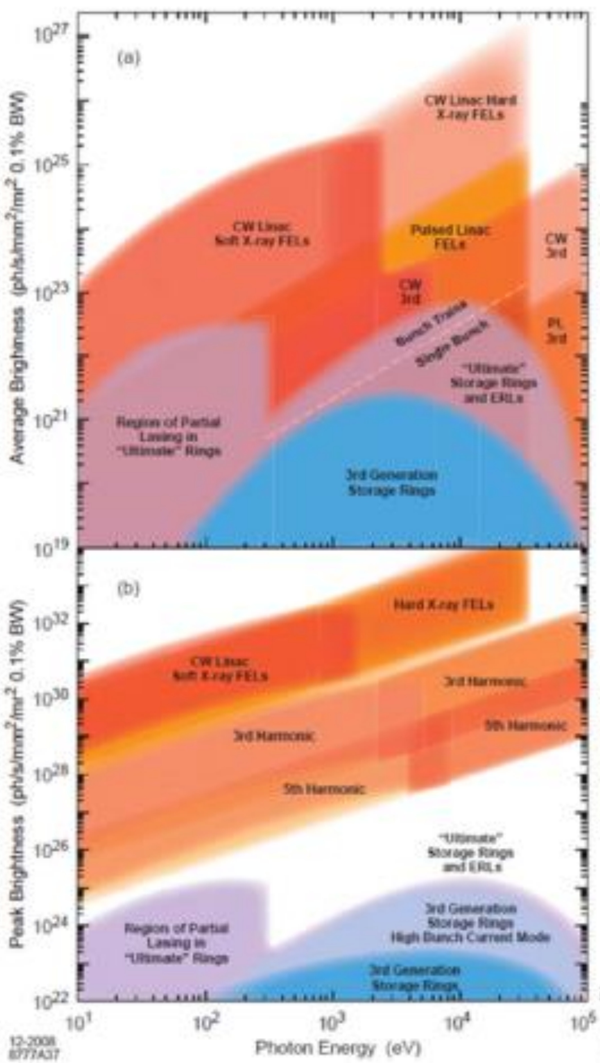
LCLS : THE FIRST X-RAY FREE ELECTRON LASER

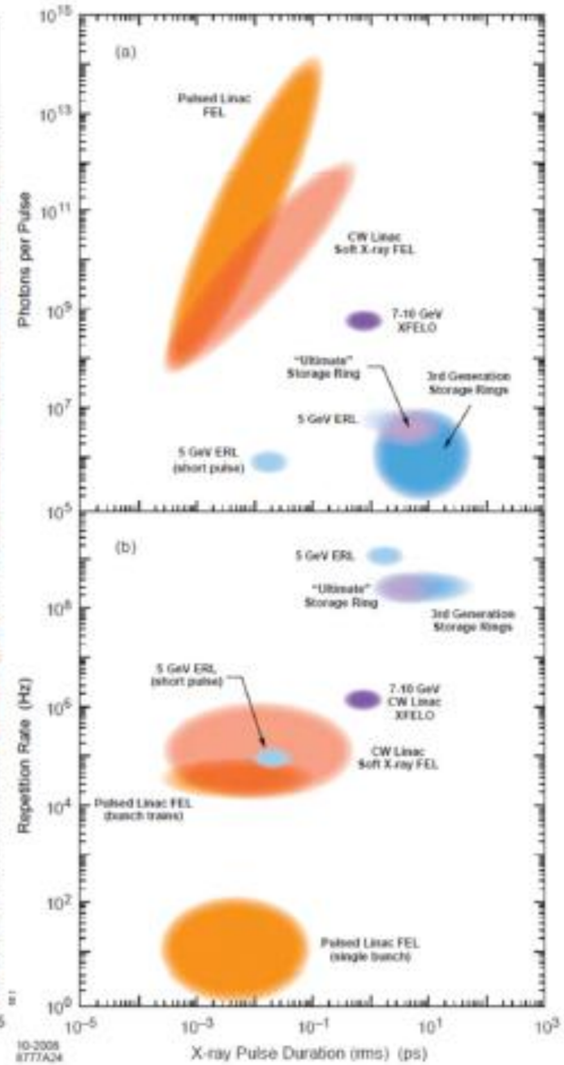


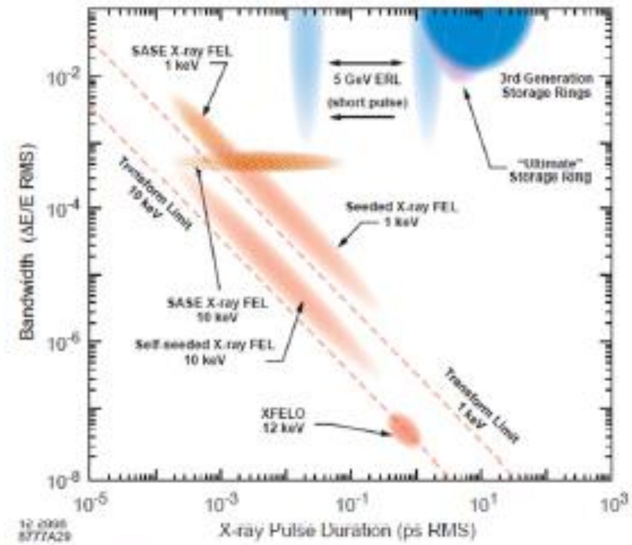




STORAGE RINGS ARE COMPLEMENTARY TO FELS







Specific properties of interest for USRs and any X-ray light source include:

- spectral brightness and flux (average and peak)
- coherent fraction and coherent flux
- beam size, divergence and pulse length
- pulse repetition rate and pulse train structure
- energy spectrum and energy spread
- spatial, temporal and spectral stability
- photon polarization

Storage rings typically are more stable (smaller parameter fluctuations)

BRIGHT SYNCHROTRON RADIATION SOURCES IN EUROPE

Current Status:

Several high performance hard-x-ray SR

ESRF, PETRA-3

Several high performance medium x-ray SR

BESSY, SLS, Soleil, Diamond

One ultimate medium x-ray SR

MAX-IV

Two soft x-ray FEL's

FLASH I & Fermi with1 undulator each

Near Future

Upgrade ESRF to 'EBS', expand PETRA-3

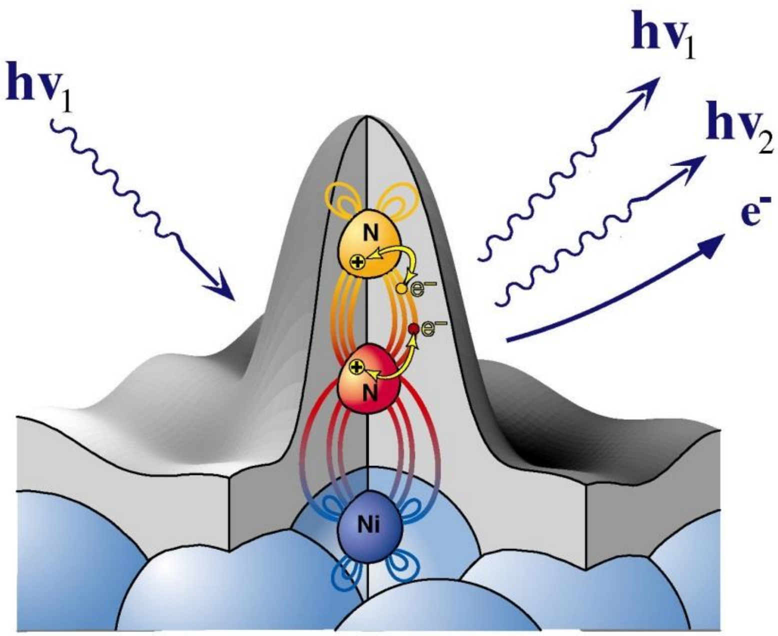
Expand FLASH I → FLASH II

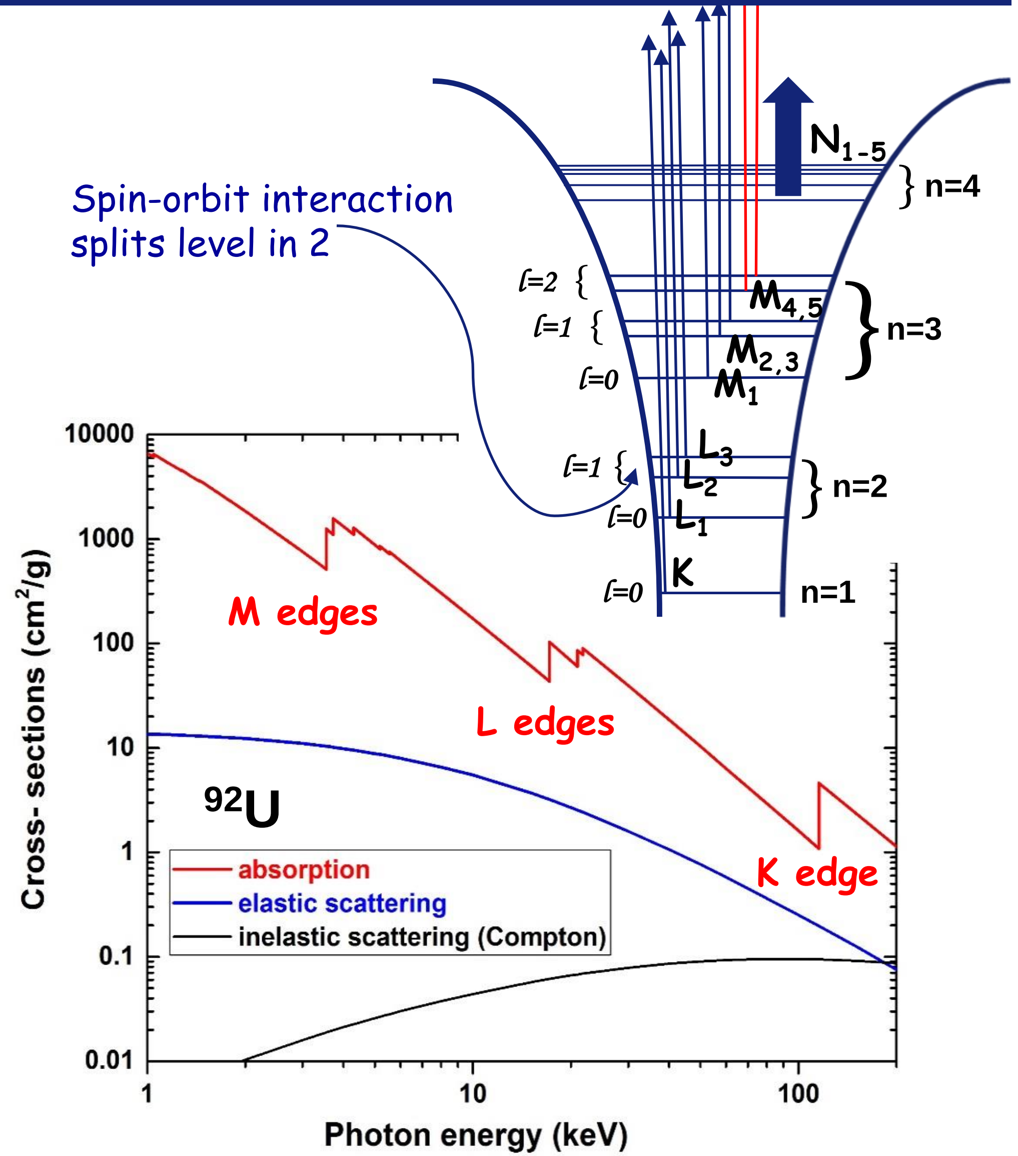
Two new hard x-ray FEL's:

XFEL: rep rate 3000 x 10; 6 undulators

SwissFEL: rep rate 100 Hz and 1 undulators

X-RAY INTERACTIONS WITH MATTER



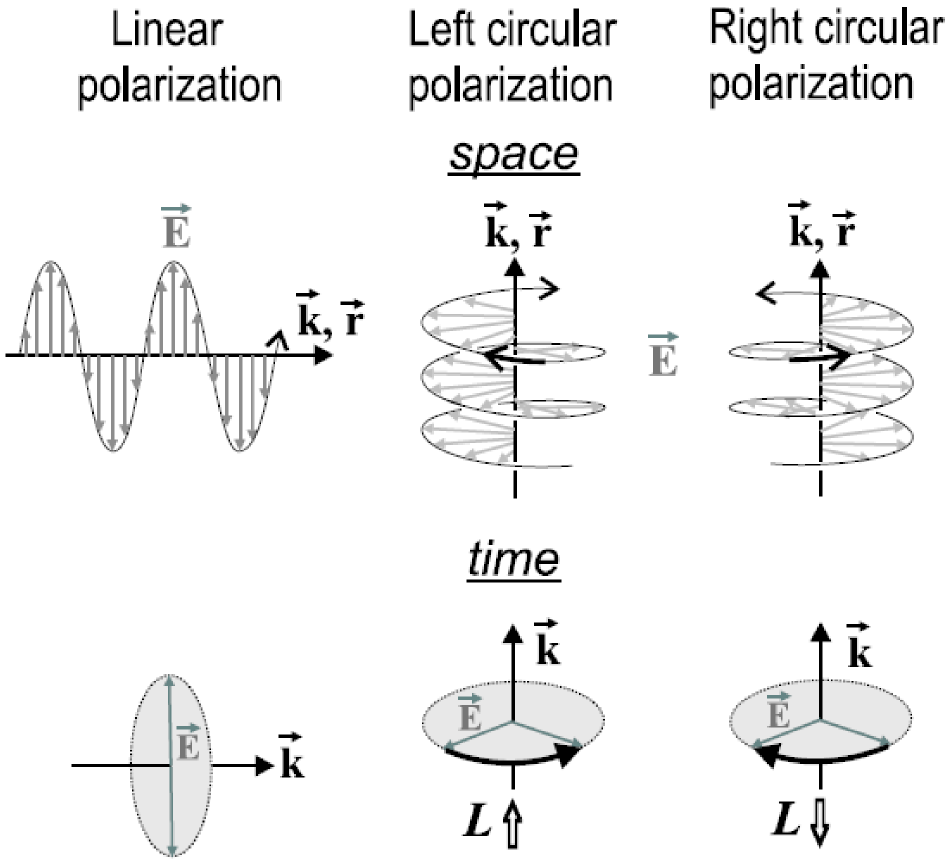


Photon could be

- absorbed (photoelectric effect
- elastically scattered
- inelastically scattered

For magnetism research, the key word - **POLARIZATION**

POLARIZATION OF LIGHT



Polarization vector $\boldsymbol{\epsilon} = \frac{\boldsymbol{E}}{E_0}$

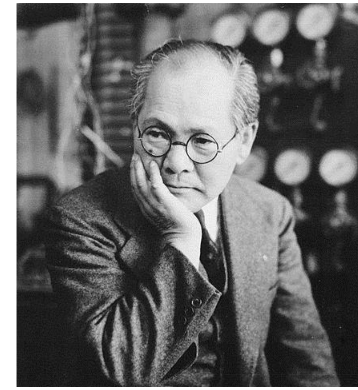
$\boldsymbol{k}$ // z

$\epsilon = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$ $\quad \epsilon = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \\ 0 \end{pmatrix}$ $\quad \epsilon = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -i \\ 0 \end{pmatrix}$

Note: the phase conventions are highly variable

Zeitschrift fur Physik, 52, 853-868 (1929)

On the scattering of radiation by free electrons according to the new relativistic quantum dynamics of Dirac



Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac.

Von **O. Klein** und **Y. Nishina** in Kopenhagen.

(Eingegangen am 30. Oktober 1928.)

Auf Grund der neuen, von Dirac entwickelten relativistischen Quantendynamik wird die Intensität der Comptonstreustrahlung berechnet. Das Resultat zeigt Abweichungen von den entsprechenden Dirac-Gordonschen Formeln, die von der zweiten Größenordnung hinsichtlich des Verhältnisses der Energie des primären Lichtquants zu der Ruheenergie des Elektrons sind.

interaction between photons and magnetic electrons is considered for the first time

$$\frac{d\sigma}{d\Omega} = \alpha^2 r_c^2 P(E_\gamma,\theta)^2[P(E_\gamma,\theta) + P(E_\gamma,\theta)^{-1} - 1 + \cos^2(\theta)]/2$$

$$P(E_\gamma,\theta) = \frac{1}{1 + (E_\gamma/m_e c^2)(1-\cos\theta)}$$

Magnetic Compton Scattering

When the X-rays are circularly polarized and the material object is a ferro- or ferromagnetic material, the Compton-scattered X-ray line shape is proportional to the scattering cross section,

$$\frac{d^2\sigma}{d\Omega d\omega} = C\,J(p_z) + C_{mag}\,P_c\,\mathbf{S}\cdot(\mathbf{k}\cos\theta + \mathbf{k}')\,J_{mag}(p_z)$$

where P_c is the degree of circular polarization of X-rays, **S** the spin direction, **k** (**k'**) the wavevector of incident (scattered) x-rays, θ the scattering angle. C and C_{mag} are constants.

$$\int J_{mag}(p_z)dp_z = \iiint n_{up}(\mathbf{p})dp_x dp_y dp_z - \iiint n_{down}(\mathbf{p})dp_x dp_y dp_z$$

$$= N_{up} - N_{down}$$

$$= \mu_{spin} \quad (\mu_B)$$

N. Sakai J. Appl. Crystallogr. 29 (1996), 81

THE FIRST HEROIC EXPERIMENT

VOLUME 37, NUMBER 6 PHYSICAL REVIEW LETTERS 9 AUGUST 1976

Compton Profile Due to Magnetic Electrons in Ferromagnetic Iron Measured with Circularly Polarized γ Rays

Nobuhiko Sakai and Kazuo Ôno
The Institute for Solid State Physics, The University of Tokyo, Roppongi, Minatoku, Tokyo, Japan
(Received 15 March 1976)

The Compton scattering of circularly polarized γ rays was used for studying the linear momentum distribution of electrons with unpaired spins in ferromagnetic iron metal. The observed Compton profile shows a broad minimum around zero momentum. The results are discussed in comparison with those calculated by Wakoh, Kubo, and Yamashita using the augmented-plane-wave method.

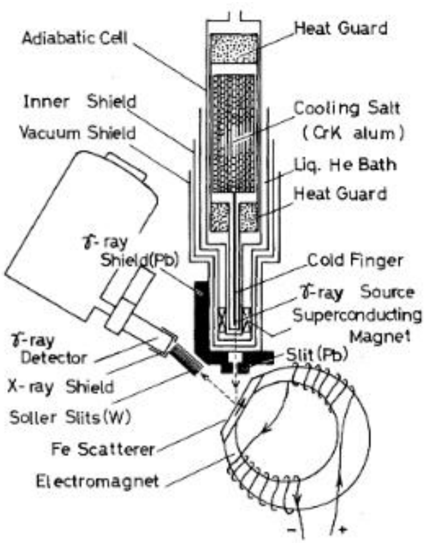


FIG. 1. Apparatus for measuring the Compton profiles by circularly polarized γ rays.

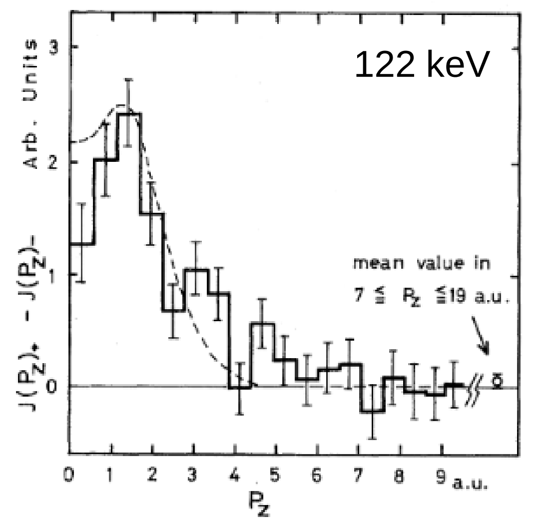
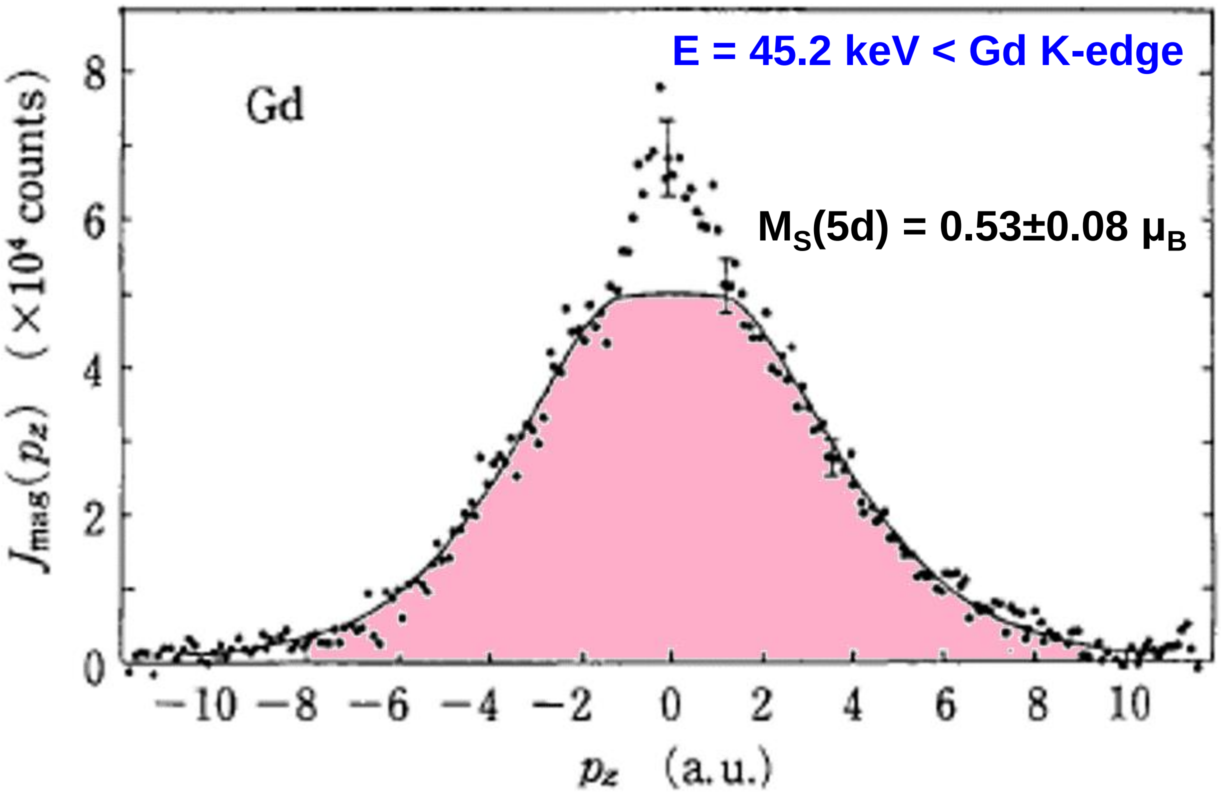


FIG. 4. Measured Compton profile, $J_+ - J_-$. The broken line is the profile calculated by Wakoh, Kubo, and Yamashita.

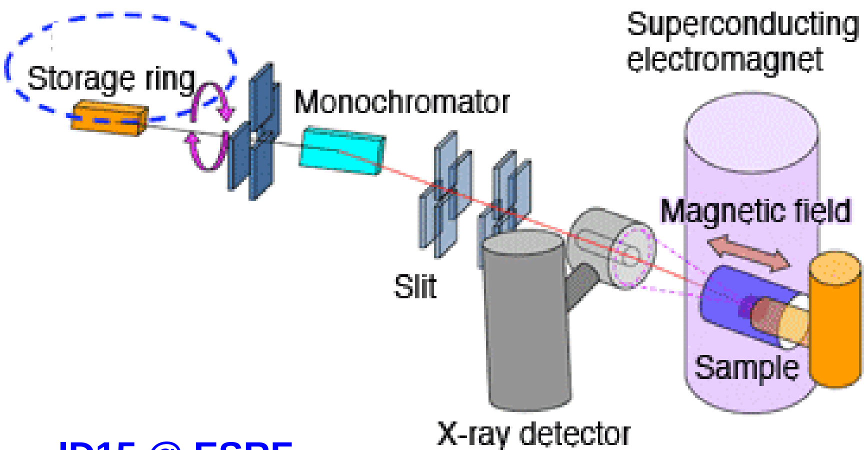
MAGNETIC COMPTON SCATTERING AT 2ND GENERATION SOURCES

$$I^+ - I^- = 2\, C_{mag}\, \mathrm{P}_c\, \mathbf{S} \cdot (\mathbf{k}\cos\theta + \mathbf{k}') \int \mathrm{J}_{mag}(\mathrm{p_z})d\mathrm{p_z}$$

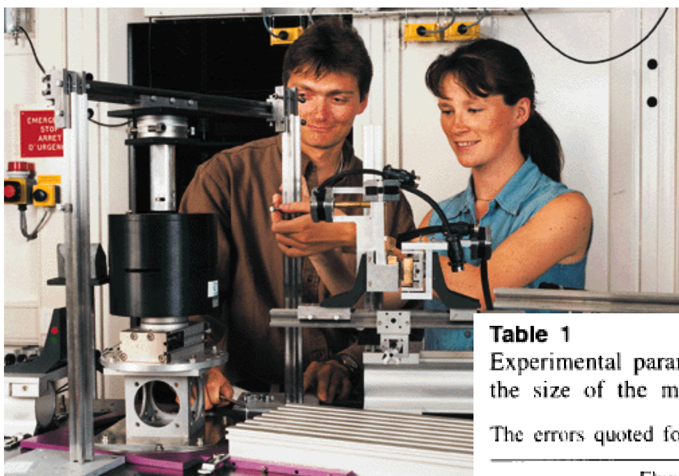
$$= 2\, C_{mag}\, \mathrm{P}_c\, \mathbf{S} \cdot (\mathbf{k}\cos\theta + \mathbf{k}')\, \mu_{spin}$$

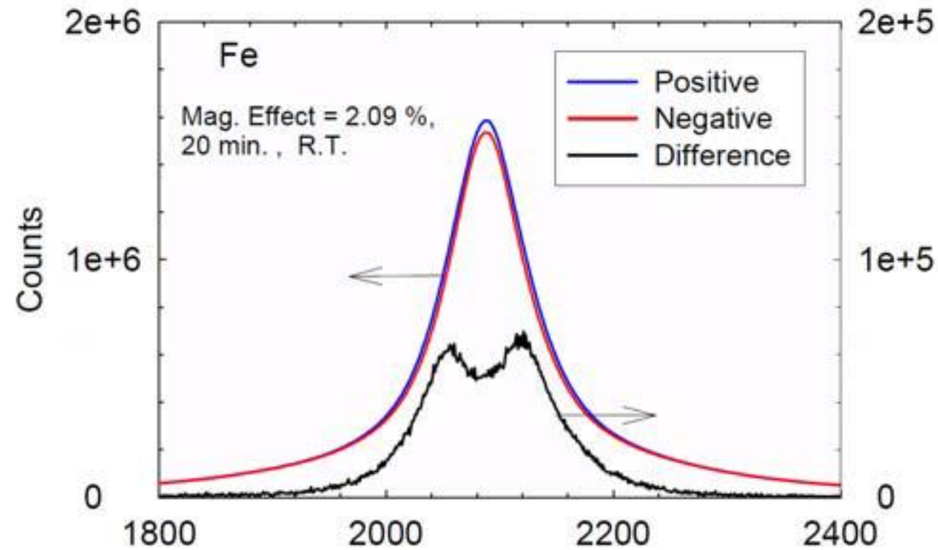


N.Sakai et al., J.Phys.Soc.Japan 60, 1201 (1991)



ID15 @ ESRF





J. Synchrotron Rad. (1997). **4**, 102–109

High-Energy Magnetic Compton Scattering from Iron

J. E. McCarthy,[a,b] M. J. Cooper,[b] P. K. Lawson,[b] D. N. Timms,[c] S. O. Manninen,[d] K. Hämäläinen[d] and P. Suortti[a]

[a]European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble CEDEX, France, [b]Department of Physics, University of Warwick, Coventry CV4 7AL, UK, [c]Division of Physics, University of Portsmouth, Portsmouth PO1 2DZ, UK, and [d]Department of Physics, PO Box 9, FIN-00014 University of Helsinki, Finland. E-mail: csmc@spec.warwick.ac.uk

Table 1
Experimental parameters for each incident energy, including incident flux, data-collection time, the scattered beam count rates and the size of the magnetic effect, R, as defined in the text.

The errors quoted for the predicted values of R are estimated from consideration of the uncertainties in P_i.

E_i (keV)	Flux at sample position (photons s^{-1})	Collection time (h)	Counts under Compton peak	Peak count rate into detector (counts s^{-1})	Polarization P_i (%)	Magnetic effect Observed (%)	Magnetic effect Predicted (%)
84.4	4×10^{10}	8	1×10^8	10 500	44	0.81 (1)	0.83 (5)
167.2	5×10^9	12.5	5×10^7	2300	51	1.45 (1)	1.61 (10)
256.0	5×10^8	13	4×10^6	23	51	1.99 (4)	2.10 (13)

PHYSICAL REVIEW B VOLUME 2, NUMBER 9 1 NOVEMBER 1970

Magnetic Scattering of X Rays from Electrons in Molecules and Solids

P. M. Platzman
Bell Telephone Laboratories, Murray Hill, New Jersey

and

N. Tzoar*
City College of the City University, New York City, New York
(Received 2 June 1970)

The scattering of moderately high-energy x rays from electrons in magnetic solids is analyzed. We show that (a) the incoherent Compton scattering of polarized x rays can be used to determine the spin-dependent momentum distribution function of electrons in ferromagnetic materials, and (b) the coherent Bragg scattering of unpolarized x rays can be used to determine the magnetic structure of antiferromagnetic solids below their transition temperature.

the geometry of the reciprocal lattice. Under typical conditions, however, R is approximately 10^{-6}.

Although R is a small quantity, it is a number which is definitely within the range of observation. The use of x rays to determine magnetic structures would be interesting in itself, but useful because of the fact that x-ray sources are easily available, whereas more conventional neutron piles are scarce.

Volume 39A, number 2 PHYSICS LETTERS 24 April 1972

OBSERVATION OF MAGNETIC SUPERLATTICE PEAKS BY X-RAY DIFFRACTION ON AN ANTIFERROMAGNETIC NiO CRYSTAL

F. De BERGEVIN and M. BRUNEL

Laboratoire de rayons-X, Cédex 166, 38–Grenoble-Gare, France

Received 14 February 1972

We observe on a NiO single crystal two superlattice X ray diffraction peaks, which disappear above the Néel point. Their intensities, 4×10^{-8} smaller than normal ones, agree with those evaluated from photon-electron spin interaction.

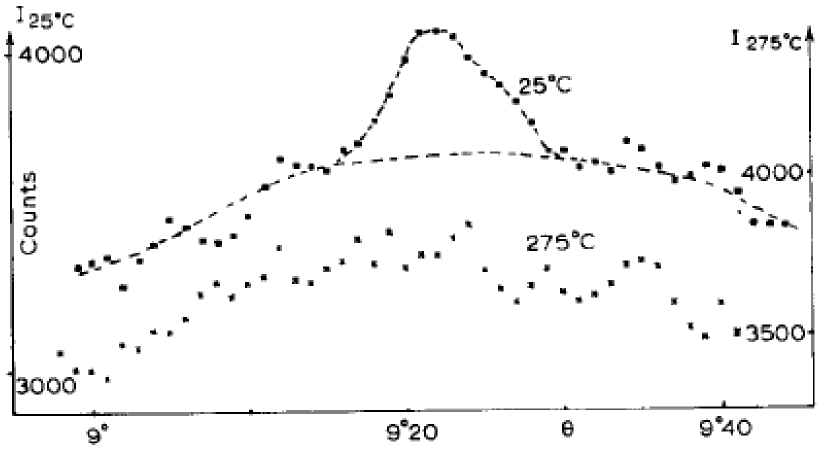


Fig. 1. Intensity $I_t(\theta)$ near the $(\frac{1}{2}\,\frac{1}{2}\,\frac{1}{2})$ position at $t = 25°$ C and 275° C in counts/225 min. The hump which cover the interval could be due to some impurity.

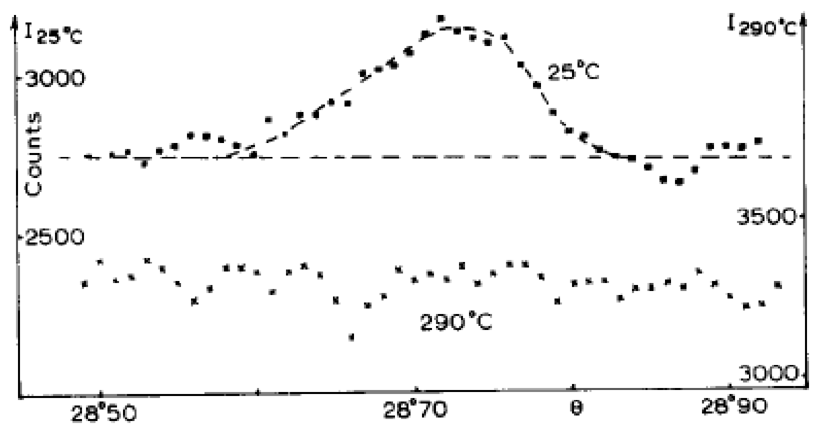
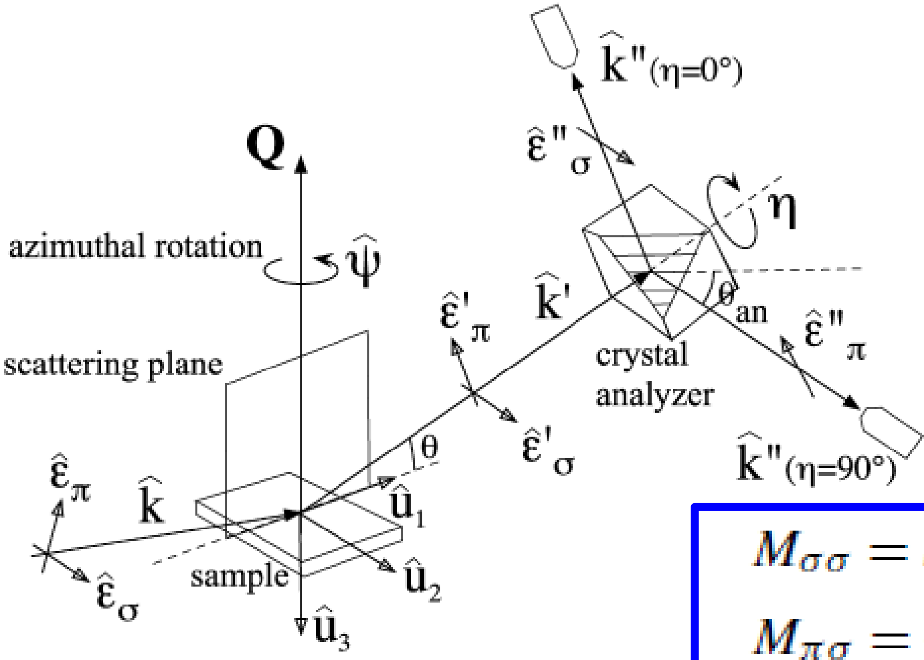


Fig. 2. Intensity $I_t(\theta)$ near the $(\frac{3}{2}\,\frac{3}{2}\,\frac{3}{2})$ position at $t = 25°$C and 290°C in counts/225 min.

Determination of magnetic structure

Non resonant (far from the absorption edge) magnetic scattering
(extremely weak signal < 10^{-6})



M. Blume and D. Gibbs, PRB 37 (1988), 1779

$$M_{\sigma\sigma} = S_2 \sin 2\theta$$

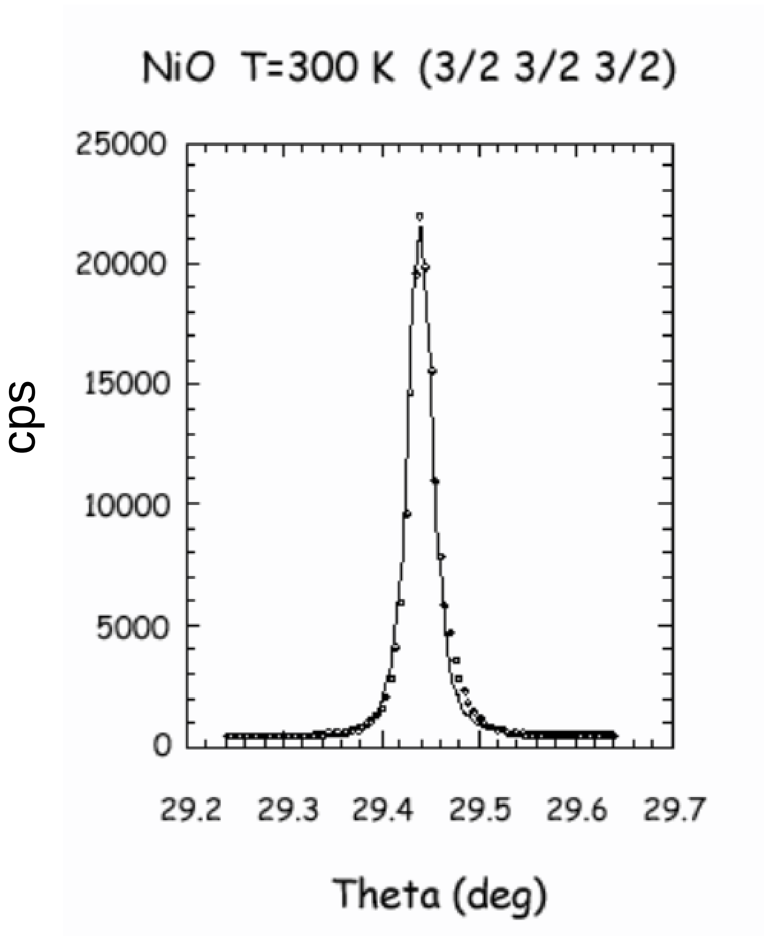
$$M_{\pi\sigma} = -2\sin^2\theta\left[(\cos\theta)(L_1+S_1) - S_3\sin\theta\right]$$

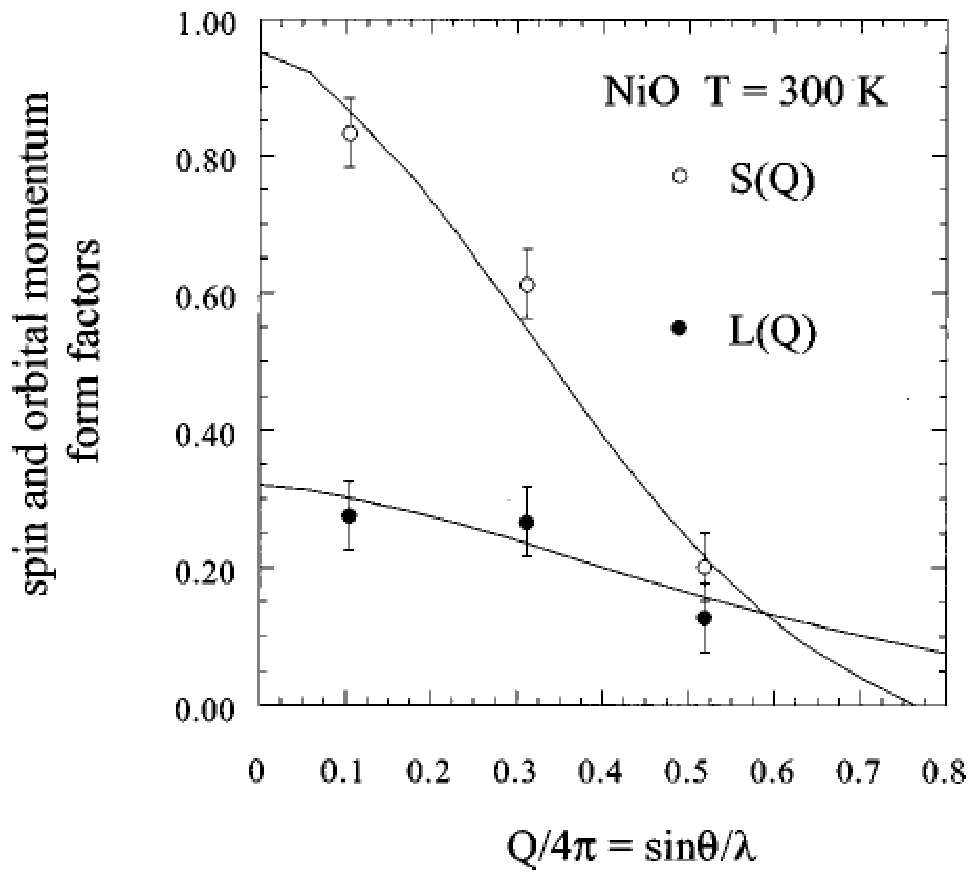
$$M_{\sigma\pi} = 2\sin^2\theta\left[\cos\theta(L_1+S_1) + S_3\sin\theta\right]$$

$$M_{\pi\pi} = \sin 2\theta\left[2L_2\sin^2\theta + S_2\right]$$

Determination of spin and orbital moment densities

MAGNETIC X-RAY SCATTERING

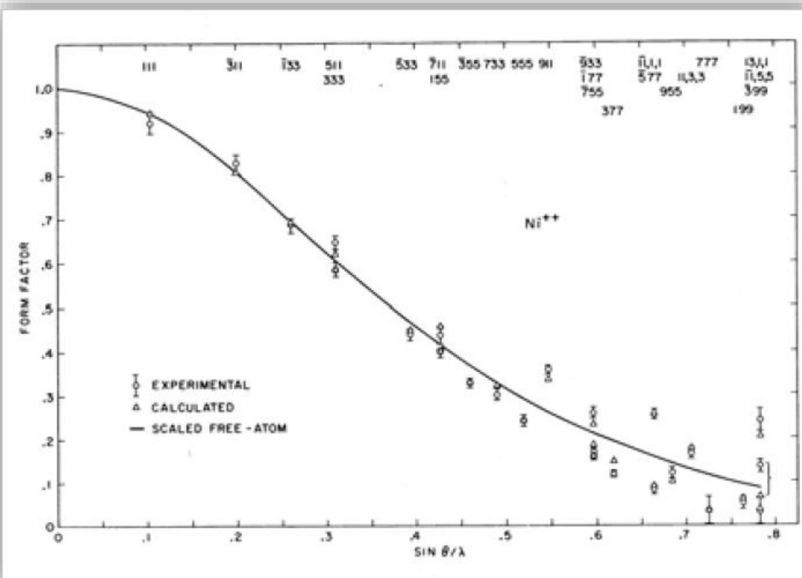




Magnetic form factor NiO

Scaling factor in Q space

H.A. Alperin PRL 6 (1961), 55



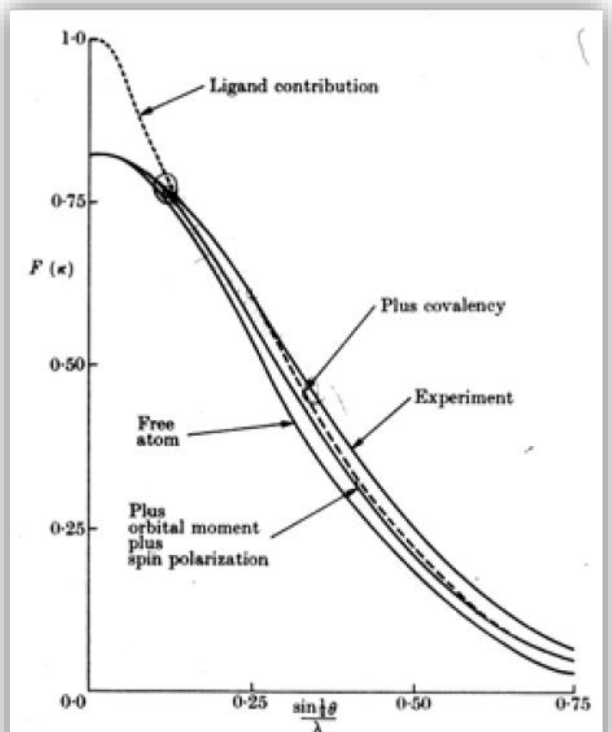


Fig. 7.27. Experimental and theoretical form factors for NiO.

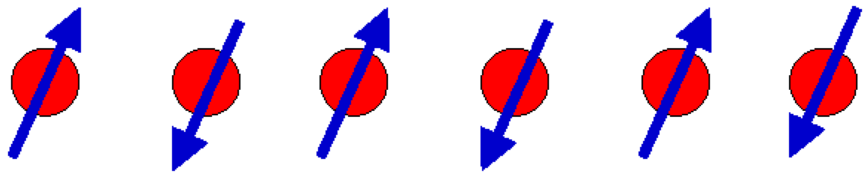
Inclusion of covalence and ligands

Orbital momentum contribution ?

W. Marshall and S.W. Lovesey
Theory of thermal neutron scattering.
Oxford University Press, 1971

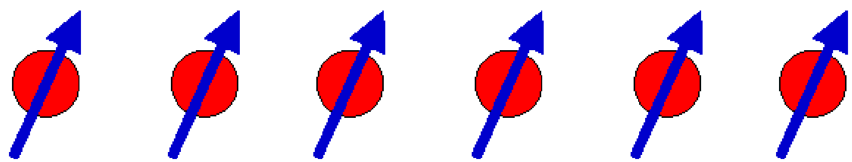
Antiferromagnet: magnetic periodicity = multiple of lattice periodicity

→ **additional magnetic reciprocal lattice vectors**



Ferromagnet: magnetic periodicity = lattice periodicity

→ **same reciprocal lattice vectors (intensity ~ 10^{-6})**



Interference between charge and magnetic scattering amplitude requires use of circularly polarized X-rays

M. Brunel and F. de Bergevin, Proc. ICM'73, Moscow

J. Phys.: Condens. Matter 5 (1993) L637–L642. Printed in the UK

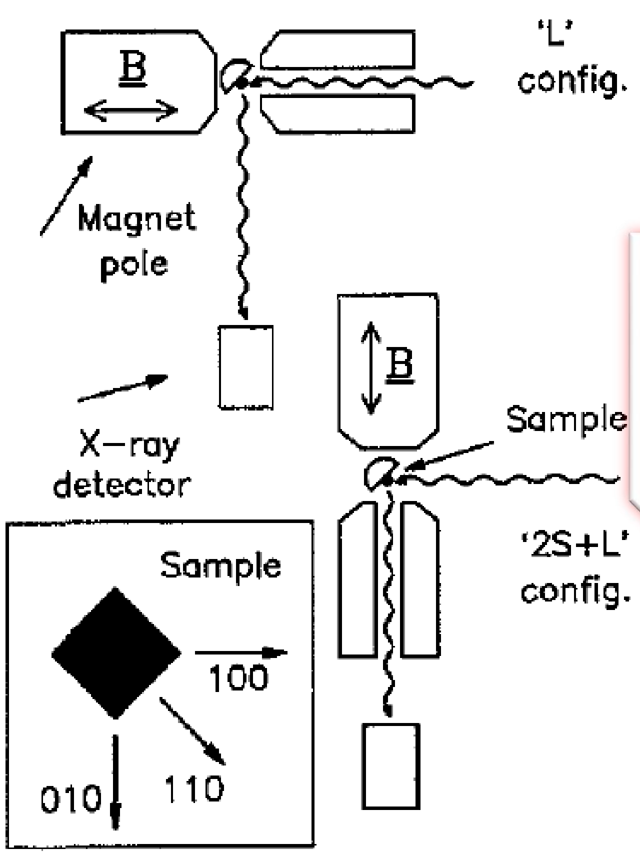
LETTER TO THE EDITOR

Spin and orbital magnetic x-ray diffraction in $HoFe_2$

S P Collins, D Laundy and G Y Guo
Daresbury Laboratory, Warrington WA4 4AD, UK

$$\frac{I_+ - I_-}{I_+ + I_-} = \frac{\hbar\omega}{mc^2} P_c \frac{L(Q)}{n(Q)}$$

$$\frac{I_+ - I_-}{I_+ + I_-} = \frac{\hbar\omega}{mc^2} P_c \frac{2S(Q) + L(Q)}{n(q)}$$



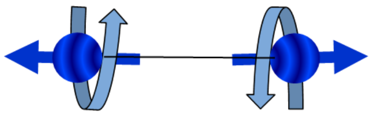
$\mu^S_{Ho} = 2.00 \pm 0.20\mu_B$	$\mu_{Ho} = 5.30 \pm 0.25\mu_B$
$\mu^L_{Ho} = 3.30 \pm 0.14\mu_B$	$\mu_{Fe} = -2.20 \pm 0.33\mu_B$
$\mu^S_{Fe} = -3.00 \pm 0.26\mu_B$	$S_{Ho}/L_{Ho} = 0.30 \pm 0.03$
$\mu^L_{Fe} = 0.80 \pm 0.19\mu_B$	$L_{Fe}/S_{Fe} = -0.53 \pm 0.14.$

To compare with polarized neutron diffraction:

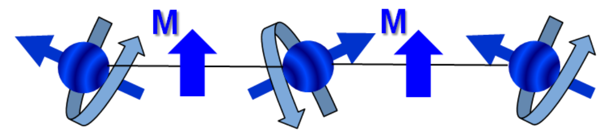
$$\mu_{Ho} = 6.3\ \mu_B \qquad \mu_{Fe} = -1.85\ \mu_B$$

DETERMINATION OF THE SIGN OF DZYALOSHINSKII-MORIYA

Collinear antiferromagnet | **Spin canted antiferromagnet**



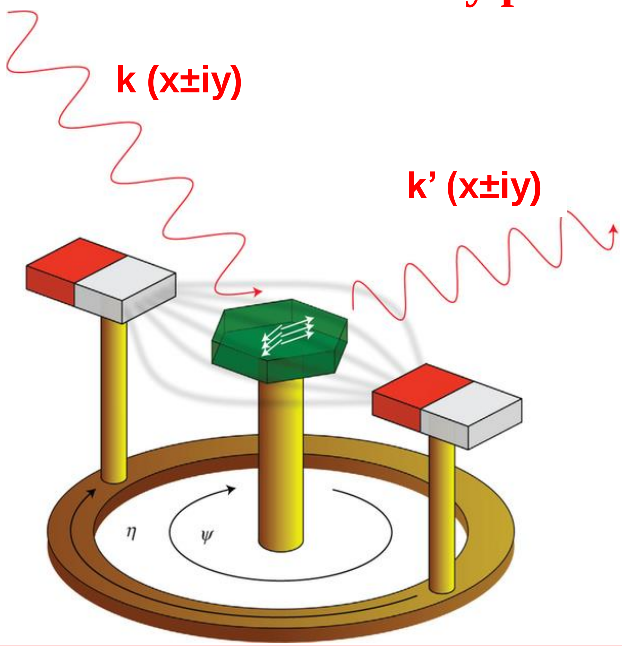
$$H_{DM} = \vec{D} \cdot (\vec{S}_i \times \vec{S}_j)$$



D = 0 | **D > 0** | **D < 0**

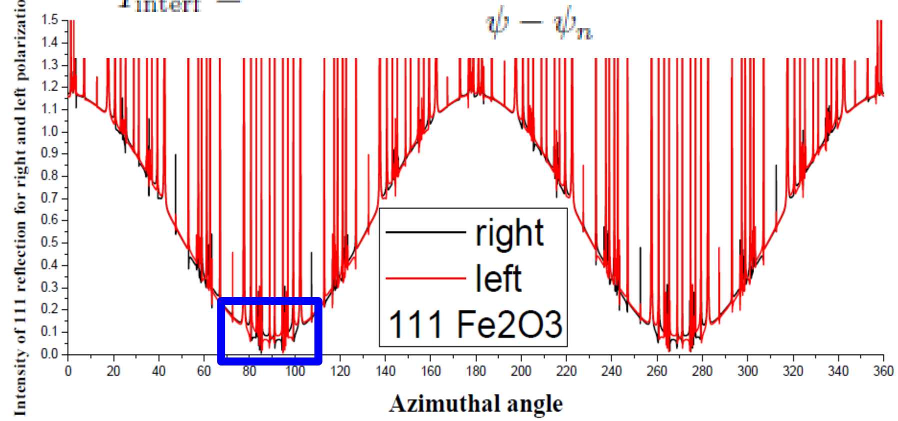
Dzyaloshinskii-Moriya interaction is at the origin of weak ferromagnetism, magnetoelectricity, multiferroicity, etc.

Interference of very weak non-resonant magnetic and multiple wave diffraction of circularly polarized X-rays measures the sign of DM



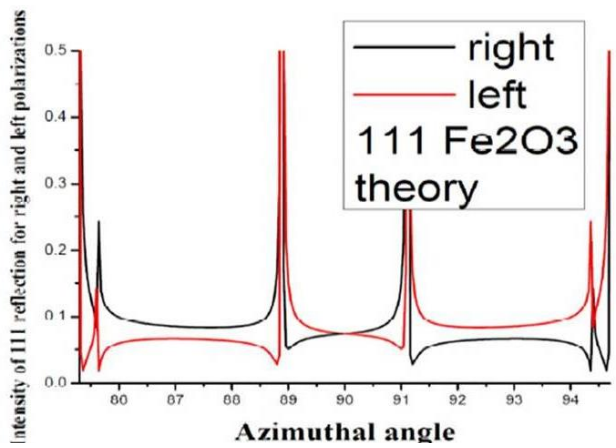
Calculated azimuthal dependence

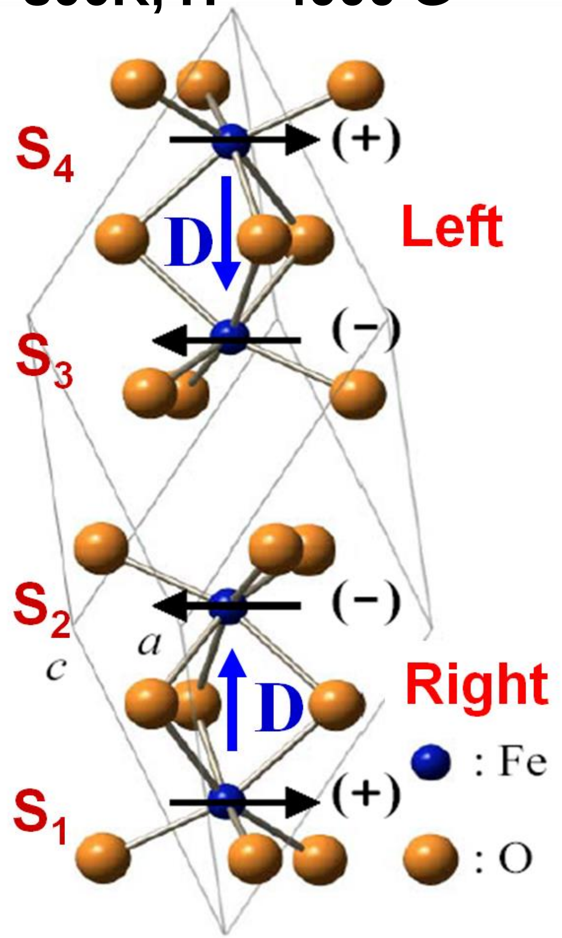
$$I_{\text{interf}} = \frac{A_n S_{\text{DM}} S_{\text{circ}} |f_{\sigma\sigma} + f_{\pi\pi}|_n \sin(\psi - \psi_H)}{\psi - \psi_n}$$



In coll. with V.E. Dmitrienko, F. de Bergevin, E.N. Ovchinnikova, J. Kokubun

Experiments have been performed on hematite Fe_2O_3 crystal :
$h\omega$ = 5.521 keV, Θ = 14.67°, T = 300K, H = 4000 G





The sign of Dzyaloshinskii-Moriya interaction in centrosymmetric crystals is determined by local chirality of their atomic structure

The first serious approach to the problem of absorption of circularly polarized X-rays

PHYSICAL REVIEW B VOLUME 12, NUMBER 11 1 DECEMBER 1975

Calculation of the M_{23} magneto-optical absorption spectrum of ferromagnetic nickel

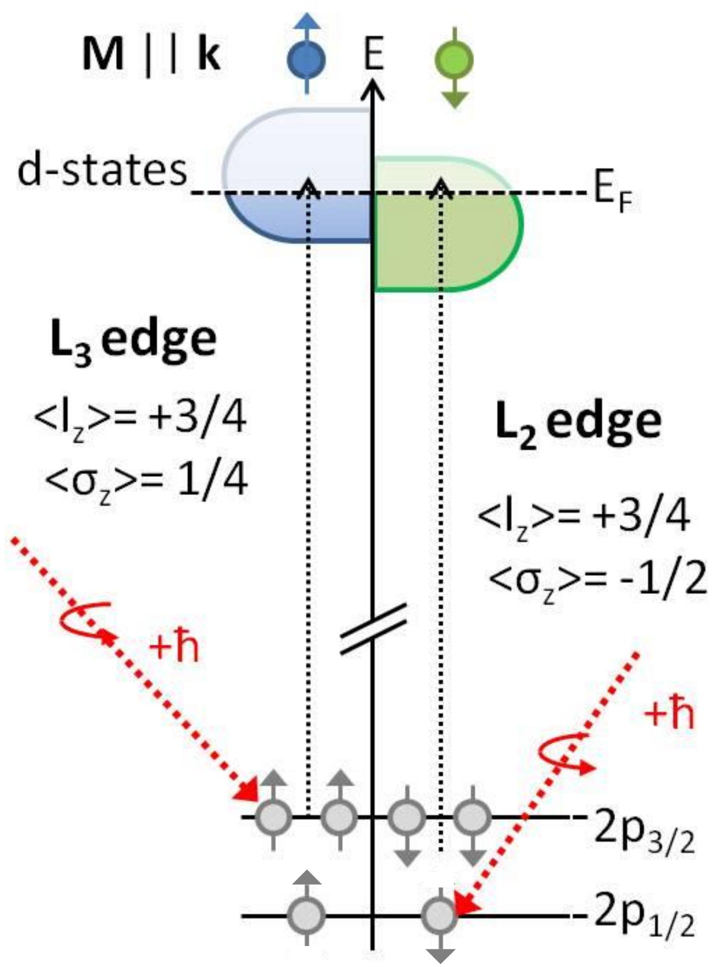
J. L. Erskine*
Department of Physics, University of Illinois, Urbana, Illinois 61801

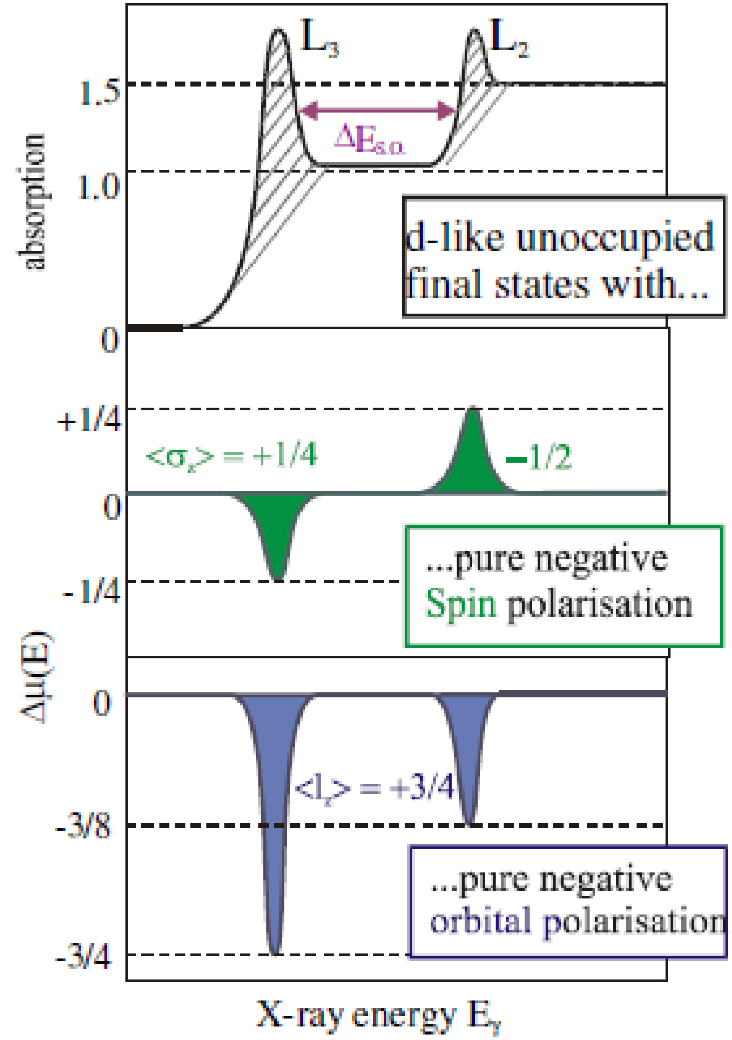
E. A. Stern†
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 28 April 1975)

The M_{23} magneto-optical absorption spectrum of ferromagnetic nickel is calculated using an approach similar to the component state-density method that has been successfully used in obtaining valence-band emission and absorption x-ray spectra of metals. The M_{23} magneto-optical effects result predominantly from spin-orbit splitting of the $3p$ core state in conjunction with the final d-state spin polarization. The calculated spectrum exhibits features that are directly related to electronic structure parameters including the $3p$ core spin-orbit splitting, and the unfilled d-band spin polarization. Temperature variations in the magneto-optical structure can be used to determine separately the exchange-splitting variation and spin-wave excitation contributions to the decrease in the magnetization. Experimental verification of these predictions should provide insight into the applicability of the Stoner model to ferromagnetic nickel and may be helpful in resolving some of the apparently conflicting results of other experimental probes of the spin polarization near the Fermi level in nickel.

Two-step model

Exchange splitting of the valence band is driving the second step





Books by:

SIR OLIVER LODGE, F.R.S.

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ATOMS AND RAYS
MAKING OF MAN
MAN AND THE UNIVERSE
RAYMOND: OR LIFE AND DEATH
THE SURVIVAL OF MAN
REASON AND BELIEF
CHRISTOPHER
THE WAR AND AFTER
MODERN PROBLEMS

New York: George H. Doran Company

ATOMS AND RAYS

AN INTRODUCTION TO MODERN VIEWS ON ATOMIC STRUCTURE & RADIATION

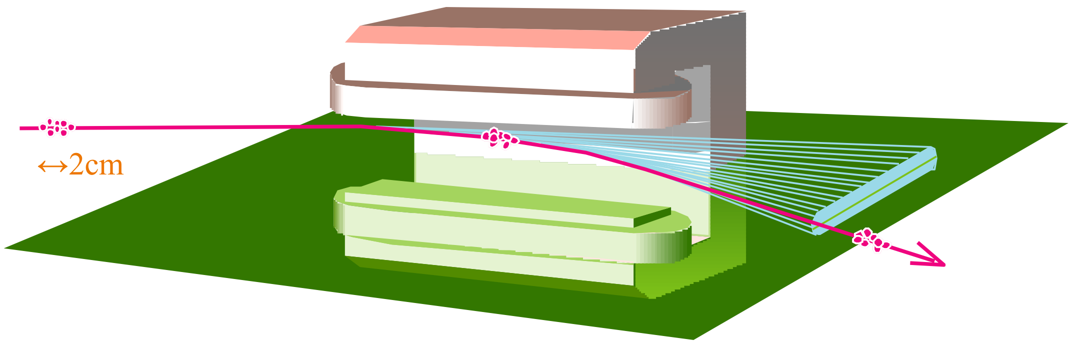
By SIR OLIVER LODGE, F.R.S.

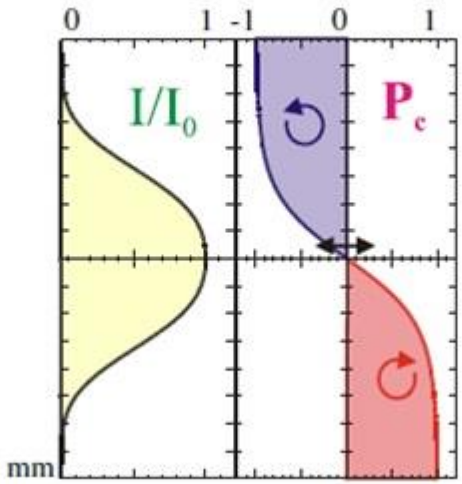
So it used to be thought that an atom must have a very complicated structure. And as my brilliant teacher of more than half a century ago, W. K. Clifford, used to say : an atom must be at least as complex as a grand piano. Or as someone has quite recently said : To try to make a model of an atom by studying its spectrum is like trying to make a model of a grand piano by listening to the noise it makes when thrown downstairs.

NEW YORK
GEORGE H. DORAN COMPANY

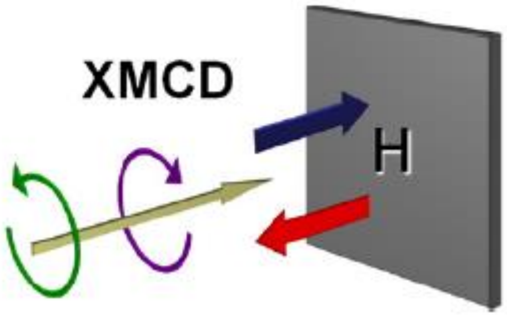
published in 1924

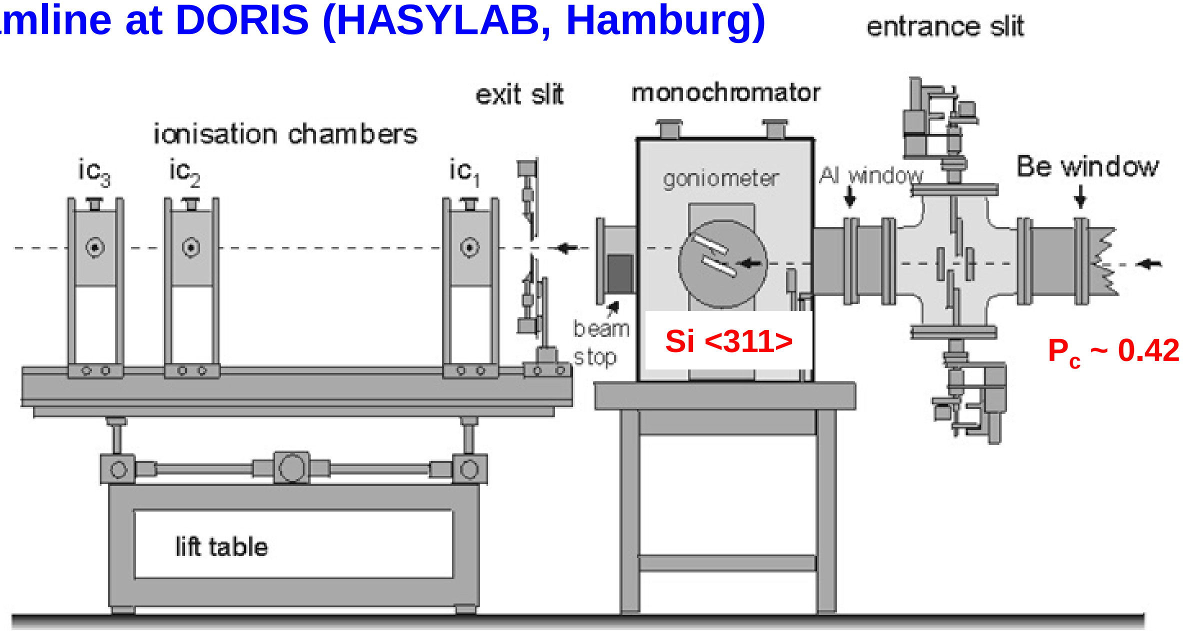
Synchrotron radiation from bending magnets





RÖMO beamline at DORIS (HASYLAB, Hamburg)





First experimental evidence

VOLUME 58, NUMBER 7 PHYSICAL REVIEW LETTERS 16 FEBRUARY 1987

Absorption of Circularly Polarized X Rays in Iron

G. Schütz, W. Wagner, W. Wilhelm, and P. Kienle[a]
Physik Department, Technische Universität München, D-8046 Garching, West Germany

R. Zeller
Institut für Festkörperforschung der Kernforschungsanlage Jülich, D-5175 Jülich, West Germany

and

R. Frahm and G. Materlik
Hamburger Synchrotronstrahlungslabor am Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg 52, West Germany
(Received 22 September 1986)

The transmission of synchrotron radiation through magnetized iron at energies above the K-absorption edge shows relative differences for right and left circular polarization of several times 10^{-4}. The observed spin dependence of the near-edge photoabsorption is proportional to the difference of the spin densities of the unoccupied bands. In the extended absorption region up to 200 eV above the Fermi level a small spin-dependent absorption is observed and thus is expected to give information on the magnetic neighborhood of the absorbing atom.

PACS numbers: 75.50.Bb, 75.10.Lp, 75.25.+z, 78.70.Dm

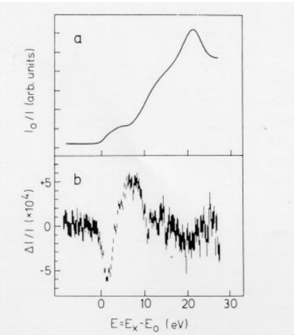


FIG. 1. (a) Absorption I_0/I of x rays as function of the energy E above the K edge of iron and (b) the difference of the transmission $\Delta I/I$ of x rays circularly polarized in and opposite to the direction of the spin of the magnetized d electrons.

XMCD is a new approach to study ferromagnetic system

RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 42, NUMBER 11 15 OCTOBER 1990-I

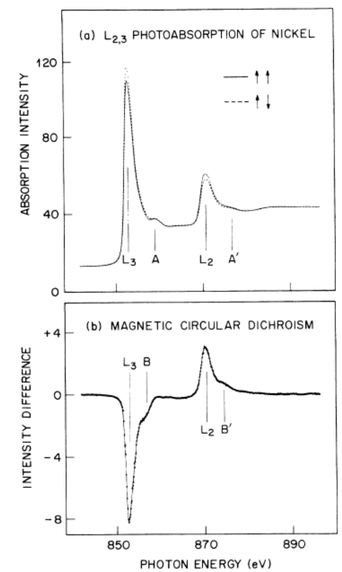
Rapid Communications

Rapid Communications are intended for the accelerated publication of important new results and are therefore given priority treatment both in the editorial office and in production. A Rapid Communication in **Physical Review B** *should be no longer than 4 printed pages and must be accompanied by an abstract. Page proofs are sent to authors.*

Soft-x-ray magnetic circular dichroism at the $L_{2,3}$ edges of nickel

C. T. Chen, F. Sette, Y. Ma, and S. Modesti
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 2 March 1990)

Magnetic circular dichroism (MCD) has been observed at the $L_{2,3}$ absorption edges of ferromagnetic nickel by use of circular-polarized soft-x-ray synchrotron radiation. The MCD intensity ratio between the L_2 and the L_3 edges is found to differ appreciably from that predicted by a simple exchange-split-valence-band model. Fine MCD features, imperceptible in the absorption spectra, are also observed and a tentative interpretation is given. This work, demonstrating the feasibility of MCD measurements in the soft-x-ray region, provides a new approach to study $3d$ and $4f$ ferromagnetic systems with their respective dipole-permitted $2p \to 3d$ and $3d \to 4f$ transitions.



Sum rules relate experimental XMCD spectra to the spin and orbital moments

VOLUME 68, NUMBER 12 PHYSICAL REVIEW LETTERS 23 MARCH 1992

X-Ray Circular Dichroism as a Probe of Orbital Magnetization

B. T. Thole,[1] Paolo Carra,[2] F. Sette,[2] and G. van der Laan[3]
[1]*Department of Chemical Physics, Materials Science Centre, University of Groningen, Nijenborgh 16, 9747 AG Groningen, The Netherlands*
[2]*European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble CEDEX, France*
[3]*Daresbury Laboratory, Science and Engineering Research Council, Warrington, WA4 4AD, United Kingdom*
(Received 2 December 1991)

A new magneto-optical sum rule is derived for circular magnetic dichroism in the x-ray region (CMXD). The integral of the CMXD signal over a given edge allows one to determine the ground-state expectation value of the orbital angular momentum. Applications are discussed to transition-metal and rare-earth magnetic systems.

Orbital sum rule

$$\int_{j^+ + j^-} (\mu^+ - \mu^-) = \frac{2l(l+1)}{l(l+1)+2-c(c+1)} \times C \times \langle L_z \rangle$$

Spin sum rule

$$\int_{j^+} (\mu^+ - \mu^-) - \frac{c+1}{c} \int_{j^-} (\mu^+ - \mu^-) = C \times [A\langle S_z \rangle + B\langle T_z \rangle]$$

VOLUME 70, NUMBER 5 PHYSICAL REVIEW LETTERS 1 FEBRUARY 1993

X-Ray Circular Dichroism and Local Magnetic Fields

Paolo Carra,[1] B. T. Thole,[1),(2] Massimo Altarelli,[1] and Xindong Wang[3]
[1]*European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble CEDEX, France*
[2]*Department of Chemical Physics, Materials Science Center, University of Groningen, Nijenborgh 16, 9747 AG Groningen, The Netherlands*
[3]*Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011*
(Received 13 July 1992)

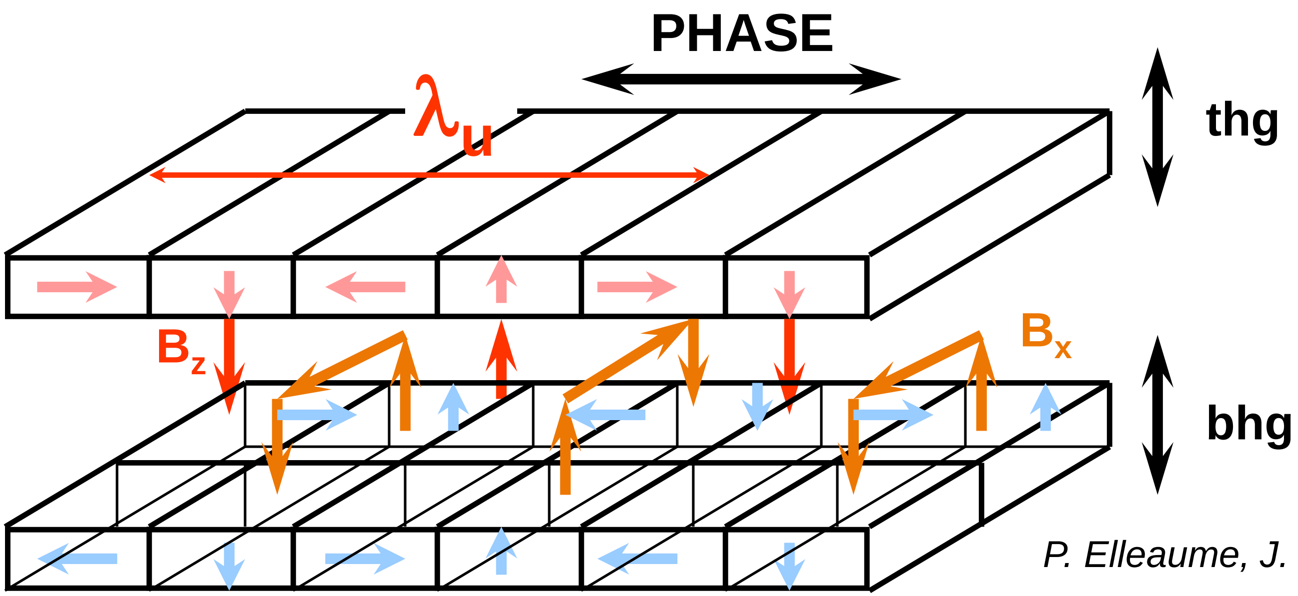
Sum rules are derived for the circular dichroic response of a core line (CMXD). They relate the intensity of the CMXD signal to the ground-state expectation value of the magnetic field operators (orbital, spin, and magnetic dipole) of the valence electrons. The results obtained are discussed and tested for transition metals and rare earths.

$$T = \sum_i (s_i - 3r_i(r_i \cdot s_i)/r_i^2)$$

$$C = \frac{1}{n_h} \int_{j^+ + j^-} (\mu^+ + \mu^- + \mu^0)$$ *- X-ray absorption cross section per hole;*

$$A = \frac{l(l+1) - 2 - c(c+1)}{3c}$$

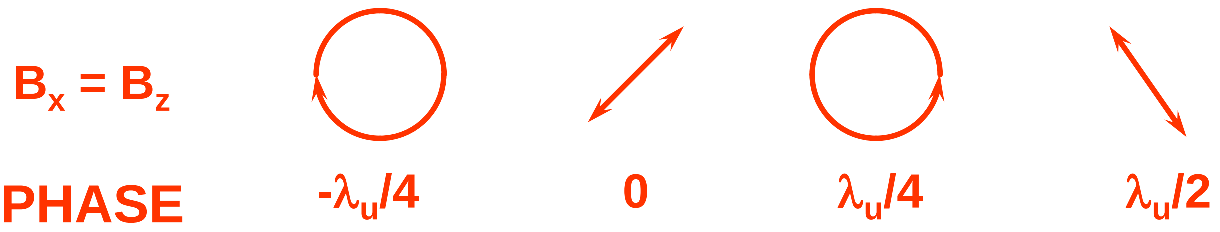
$$B = \frac{l(l+1)[l(l+1) + 2c(c+1) + 4] - 3c(c-1)^2(c+2)^2}{6c \cdot l(l+1)}$$



31 periods
λ_u = 52 mm

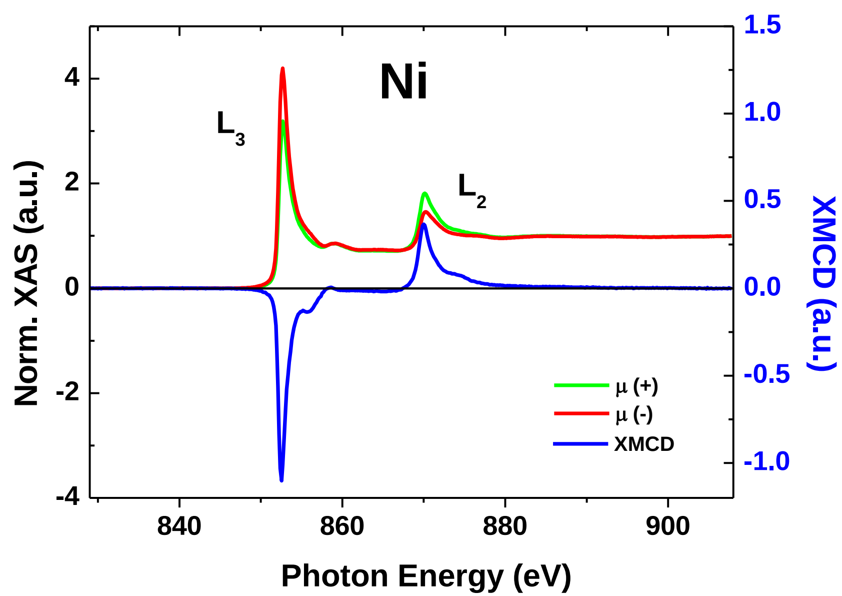
*P. Elleaume, J. of Syn. Rad., **1**, 19-26 (1994)*

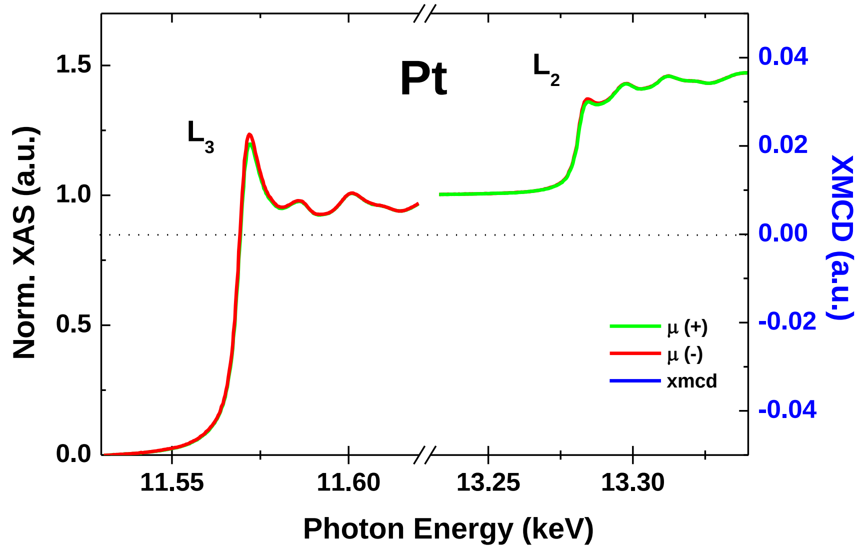
Full control of polarization: flipping time ~ 2 seconds



In a pure circular mode NO emission of high order harmonics on axis

ELEMENT SELECTIVITY OF XMCD

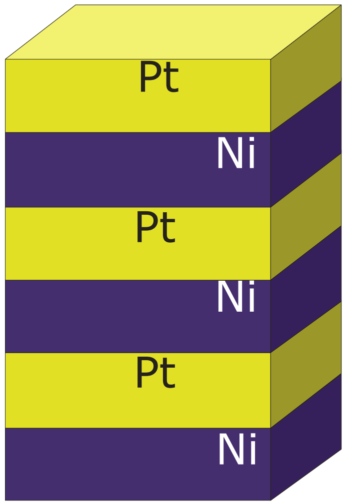




Ni_2 / Pt_2 multilayer

T ~ 10K

H = ± 5 T

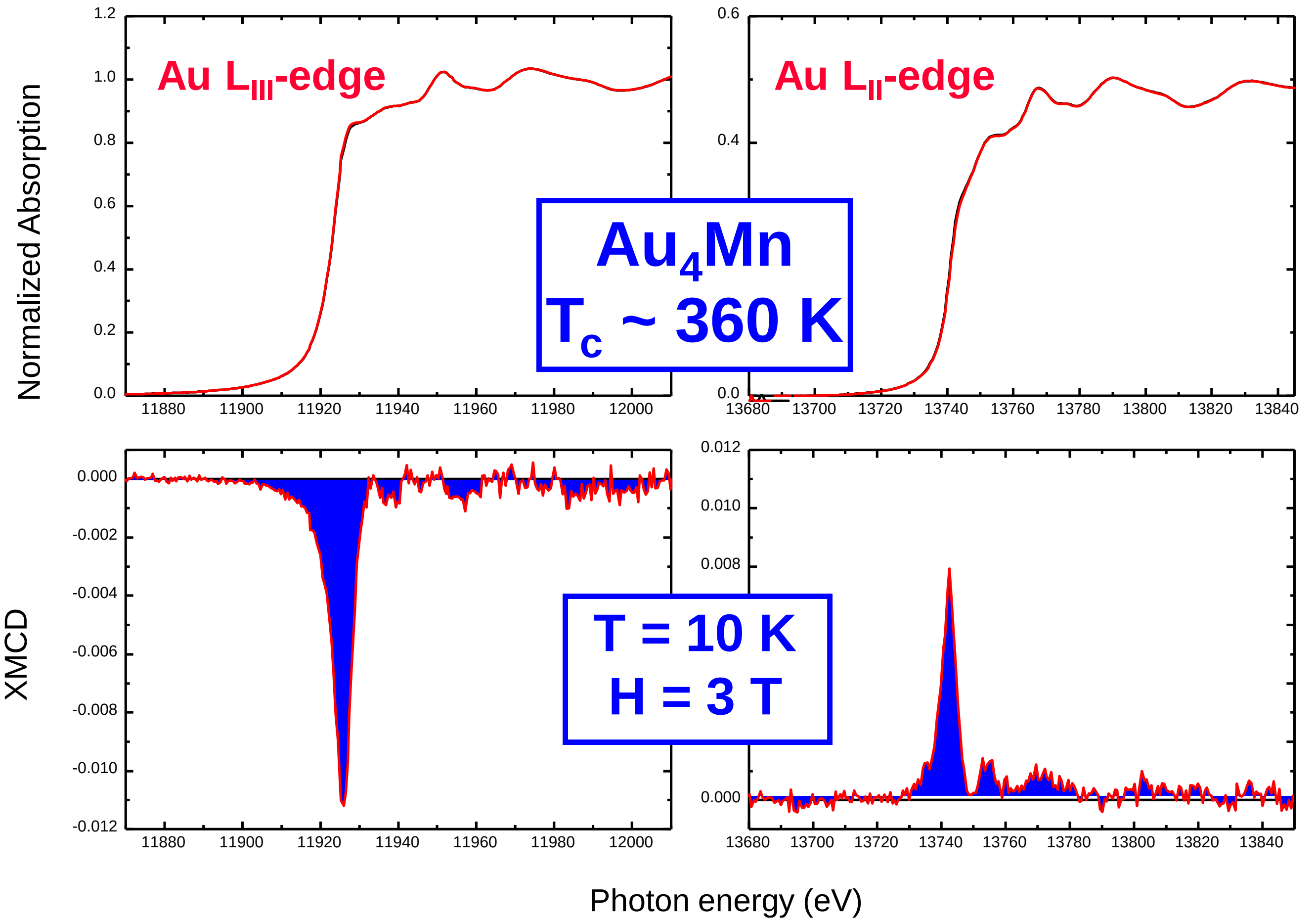


RESULTS

- **Ni magnetic moments:**
  - μ_S^{3d}=0.35 μ_B/atom
  - μ_L^{3d}=0.038 μ_B/atom
- **Pt induced magnetic moments:**
  - μ_S^{5d}=0.14 μ_B/atom
  - μ_L^{5d}=0.03μ_B/atom

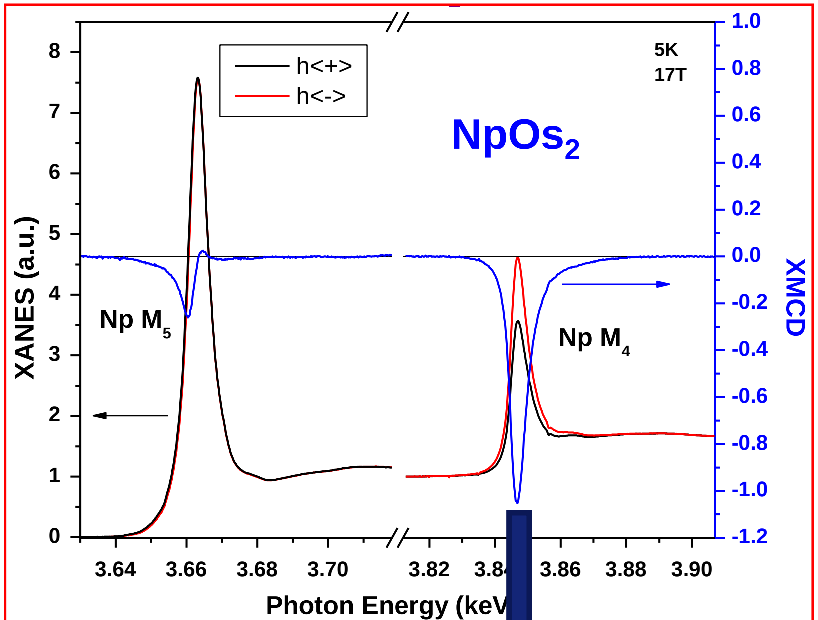
F. Wilhelm et al., Phys. Rev. Lett., 85, 413 (2000)

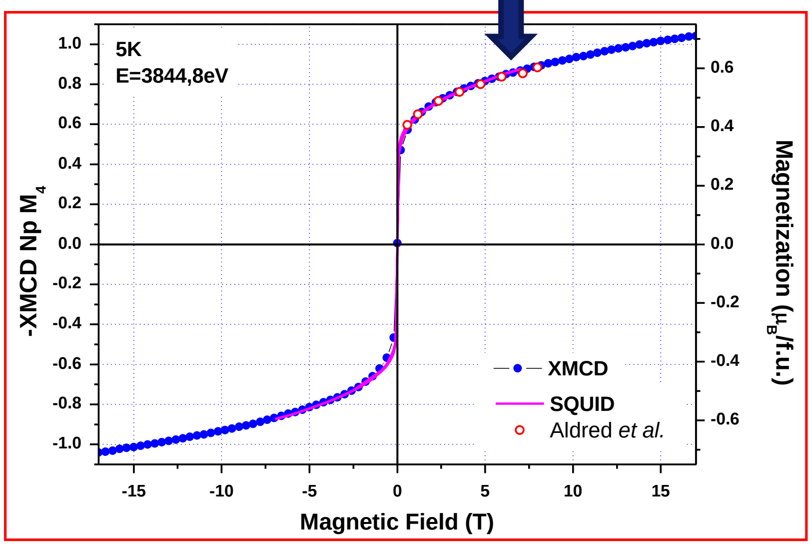
SENSITIVITY OF XMCD



$\langle S_z \rangle = 0.0353(5)\mu_B$ $\langle L_z \rangle = 0.0054(5)\mu_B$ (per Au atom)

To compare with $4.15\mu_B$ per Mn atom





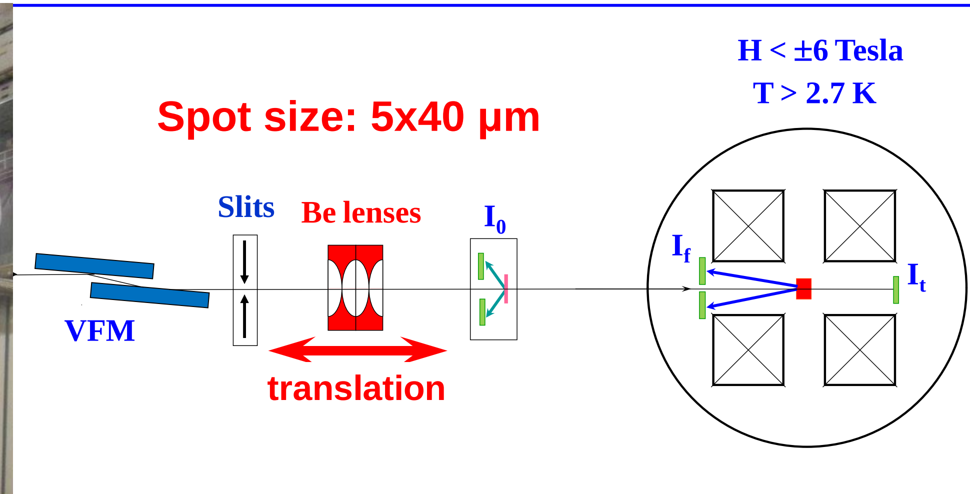
H < ± 17 Tesla, T > 2.0 K

Typical sample size
0.65mm X 0.80mmx0.12mm

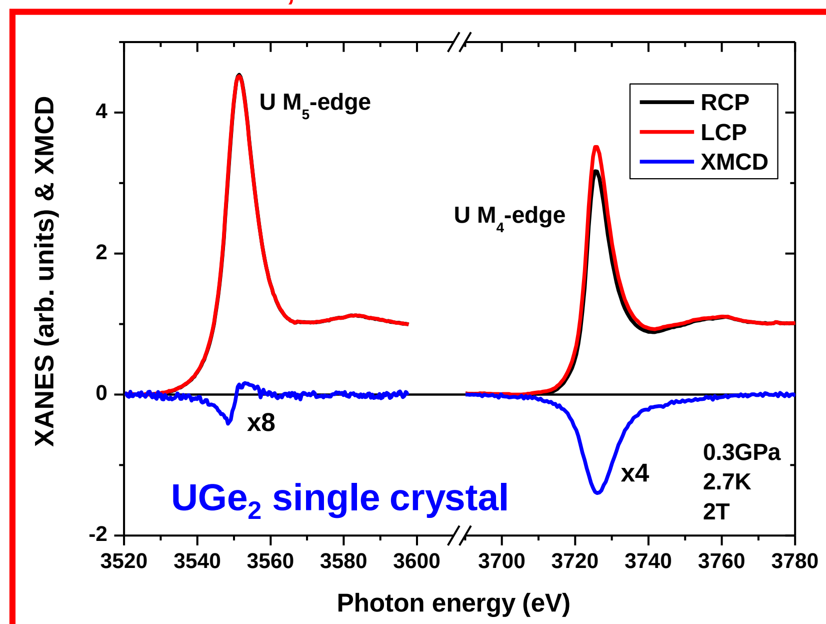
Aldred et al., PRB10, 1011(1974) *Wilhelm et al., PRB 88, 024424 (2013)*

XMCD UNDER HIGH PRESSURE

High pressure XMCD end station



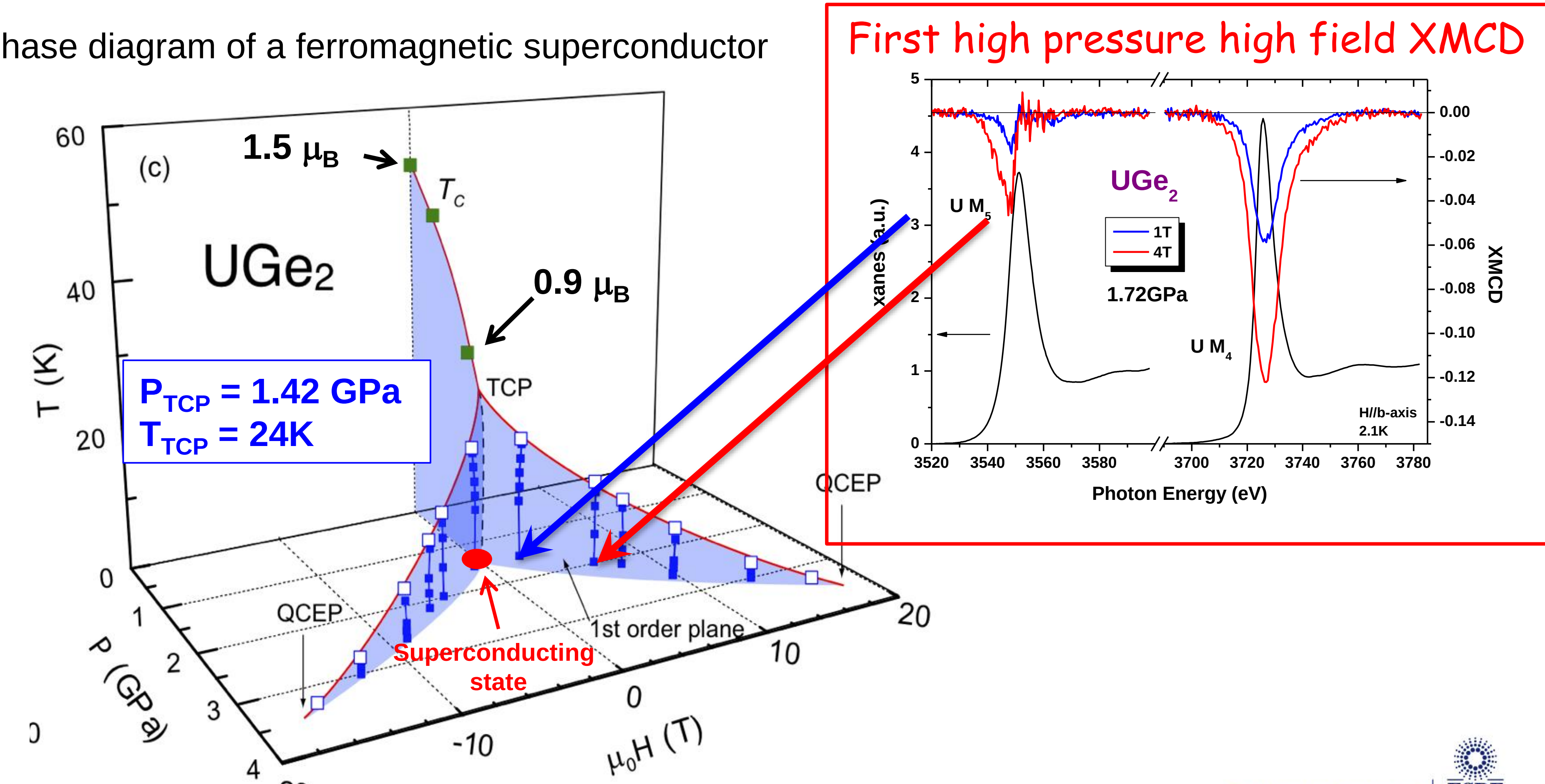
First U $M_{4,5}$ XMCD under pressure



Study of electronic and magnetic structure of matter under multiple extreme conditions of high magnetic and/or electric fields, very low temperature and high pressure.

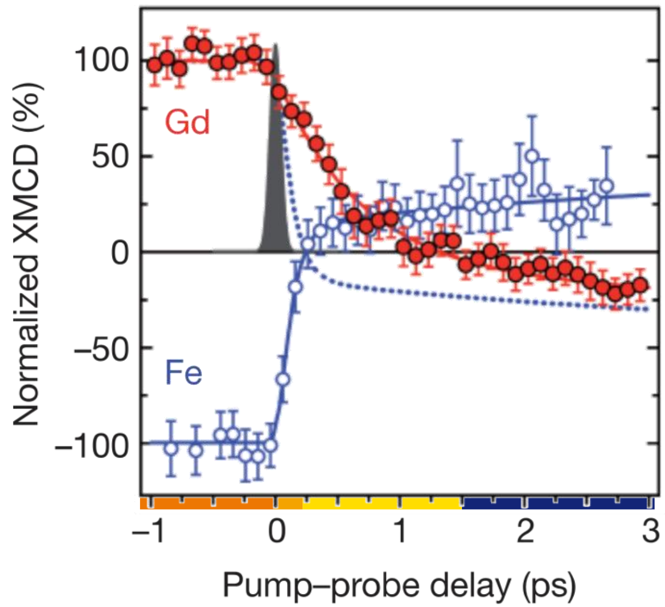
Phase diagram of a ferromagnetic superconductor

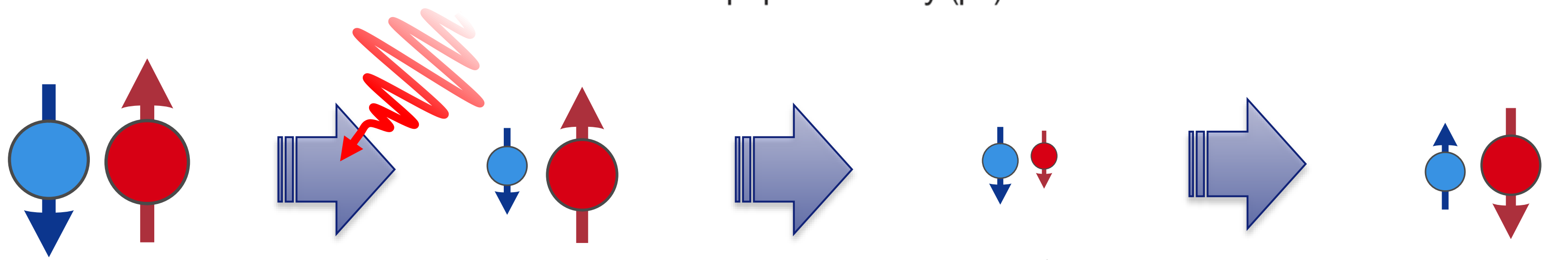
First high pressure high field XMCD



FIRST ELEMENT SELECTIVE XMCD DYNAMICS AT FEL

Element-resolved dynamics.





Initial State

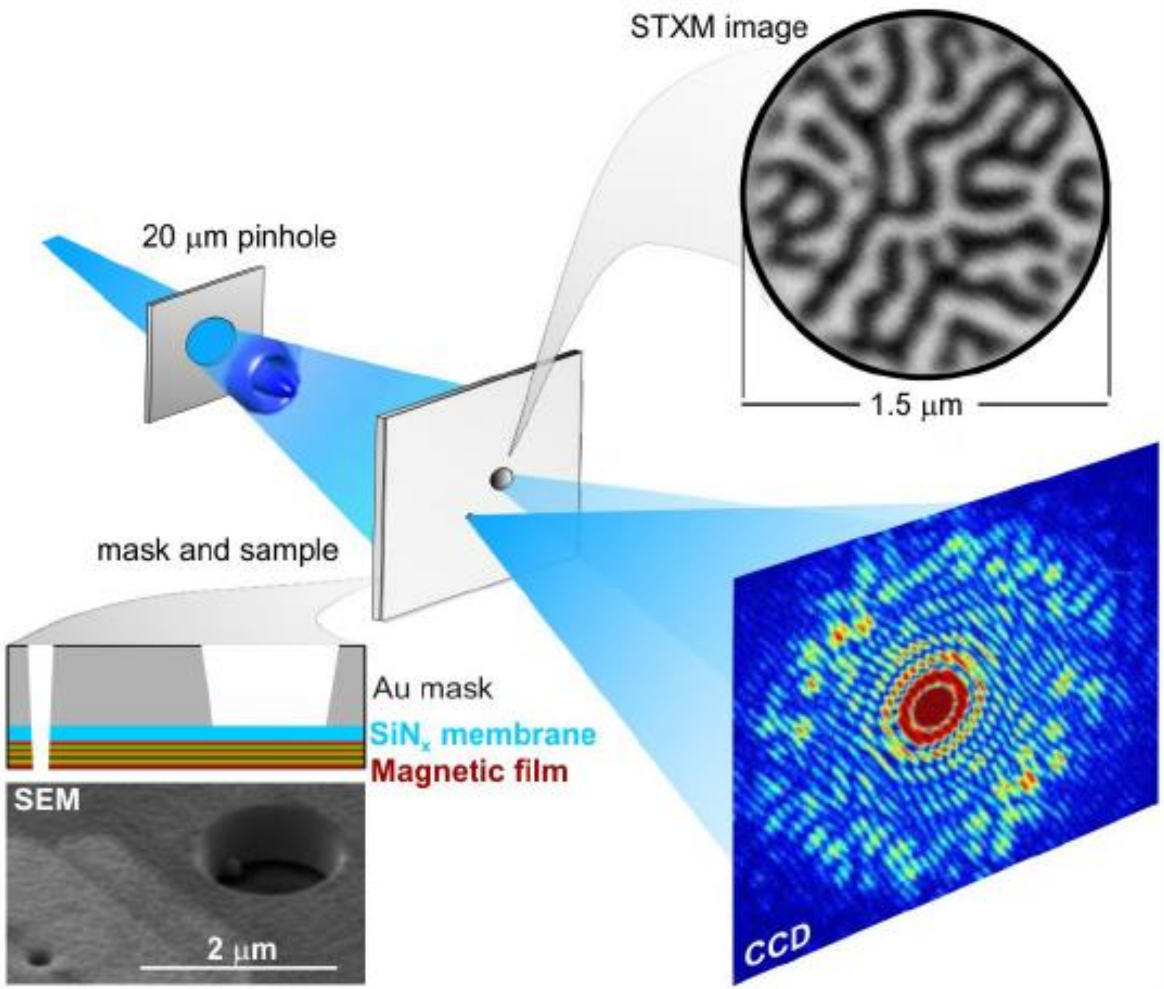
Different demagnetization times

Transient ferromagnetic-like state

Reversal of the sublattices

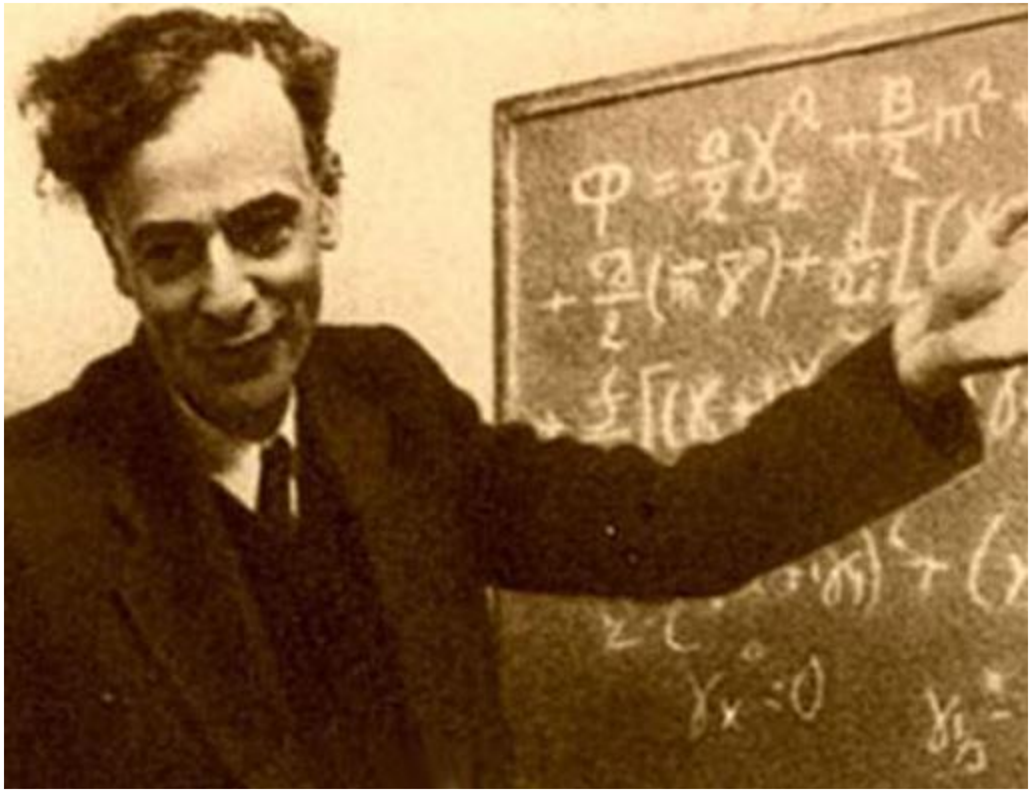
Radu *et al. Nature*, **472**, 205-208 (2011).

Lensless imaging of magnetic nanostructures by x-ray holography



S. Eisebitt, J. Lüning, W.F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt & J. Stöhr / *Nature*, 16 Dec 2004

LenslessImagingF1.ai



"This work contains many things which are new and interesting. Unfortunately, everything that is new is not interesting, and everything which is interesting, is not new."

L.D. Landau

X-ray scattering and spectroscopy offer unique possibilities to study magnetic materials

- Spin density profile using high energy X-ray magnetic Compton scattering

- Magnetic structure of an antiferromagnet using non-resonant magnetic diffraction with unpolarised X-rays

- Polarization analysis of non-resonant magnetic diffraction gives access to spin and orbital magnetization densities in an antiferromagnet

- Determination of spin and orbital magnetization in ferromagnets using diffraction of circularly polarized X-rays

- Spin and orbital magnetic moments with element and orbital selectivities in ferro- ferri- and paramagnets can be determined using X-ray Magnetic Circular Dichroism

- X-ray Resonant Magnetic Scattering allows one to study magnetization profile across a multilayer

Thank you for your patience and your attention !