

Exploiting Synergies in Neutron and X-ray Scattering for next generation spintronics technologies

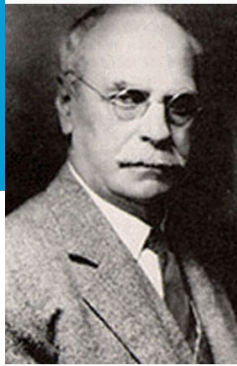
Dan Mannix
Science Days May 2024

Lead Scientist Heimdal Instrument ESS, Lund Sweden

Talk Outline



- (1) Spin Caloritronics: $Tb_3Fe_5O_{12}$ & $Gd_3Fe_5O_{12}$
- (2) Neutron Diffraction & Spectroscopy
- (3) X-ray Resonant Scattering: REXS & RIXS
- (4) X-ray Pump & Probe: Time resolved Diffraction
Phonon & Heat Dynamics (~1-100ps)



Hall Effect
1879

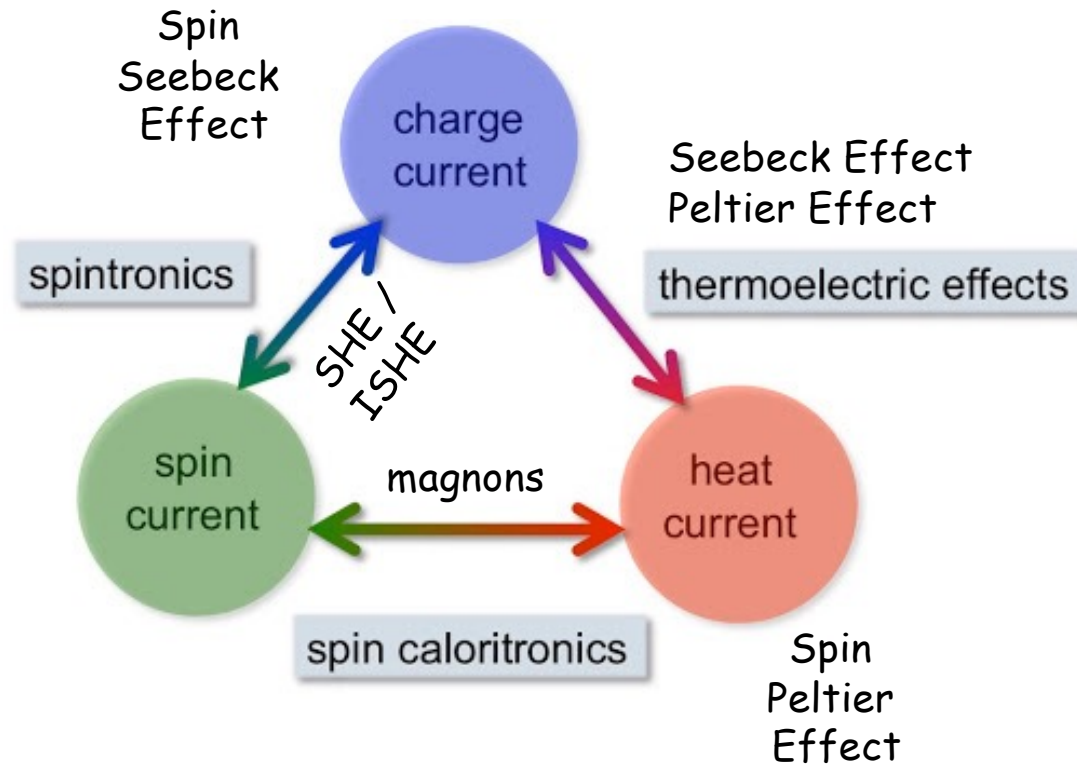
Spin Caloritronics ?

A New Spin on Old Physics



Interconversion of heat,
charge and spin currents

Spintronic + Thermoelectric
Functionality



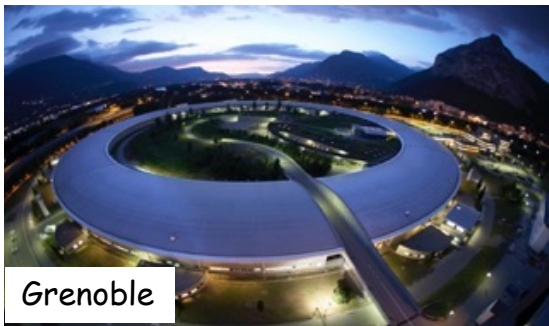
Seebeck Effect
1822



Peltier Effect
1834

European Flagship Science Facilities for Materials Research

ESRF-EBS 4th Generation Synchrotron:
 multibend achromat lattice
 ~200ps pulses. @0.35-350MHz
 10^{13} ph.s⁻¹
 Emittance 60 pm/rad - ~10nm beams

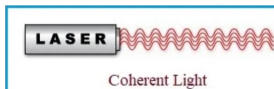


Grenoble



High Spatial Resolution

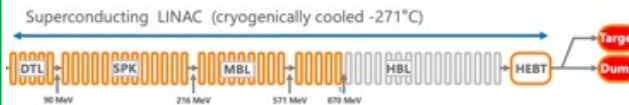
Also: MAX-IV Sweden
 APS-U USA ...



ESS:
 2GeV superconducting proton linac
 10^7 - 10^9 N.s⁻¹
 2.86ms pulsed neutrons 14Hz ~5MW



Lund



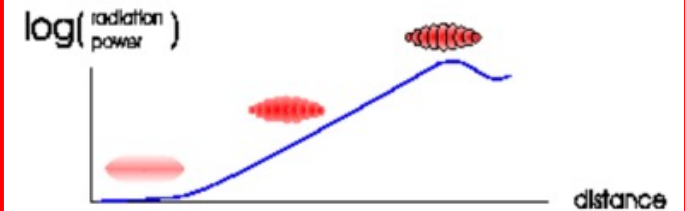
High Energy Resolution

Also: SNS USA
 J-parc Japan
 ILL - European Neutron Source

EuXFEL
 17.5GeV 3.4km superconducting linac
 10^9 ph. / 10fs
 600 x 10fs pulses per bunch @ 2.2MHz



Hamburg

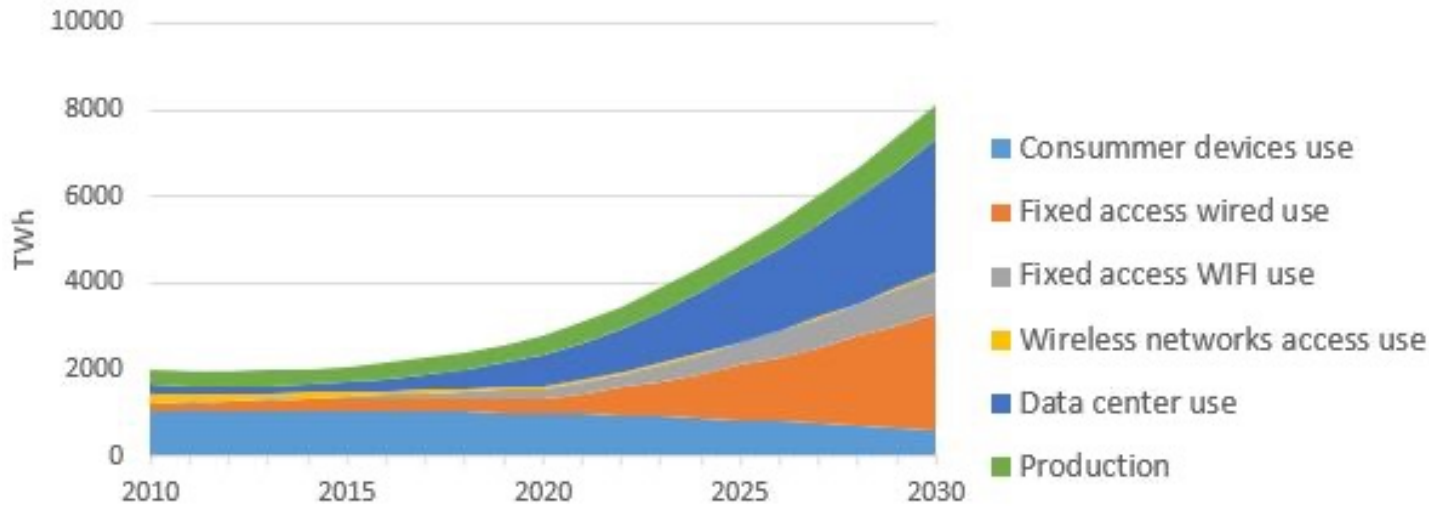


High time Resolution

Also: LCLS-II USA

The Digital Carbon Footprint

ICTs Power consumption 5-9% to Total electricity consumption



Tera= 10^{12}

Peta= 10^{15}



Article

New perspectives on internet electricity use in 2030

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Huawei Technologies Sweden AB, Kista, Sweden.; anders.andrae@huawei.com

Received: 24 April 2020; Accepted: 18 June 2020; Published: 30 June 2020.

Can we make the internet less power-thirsty?

8 hours ago



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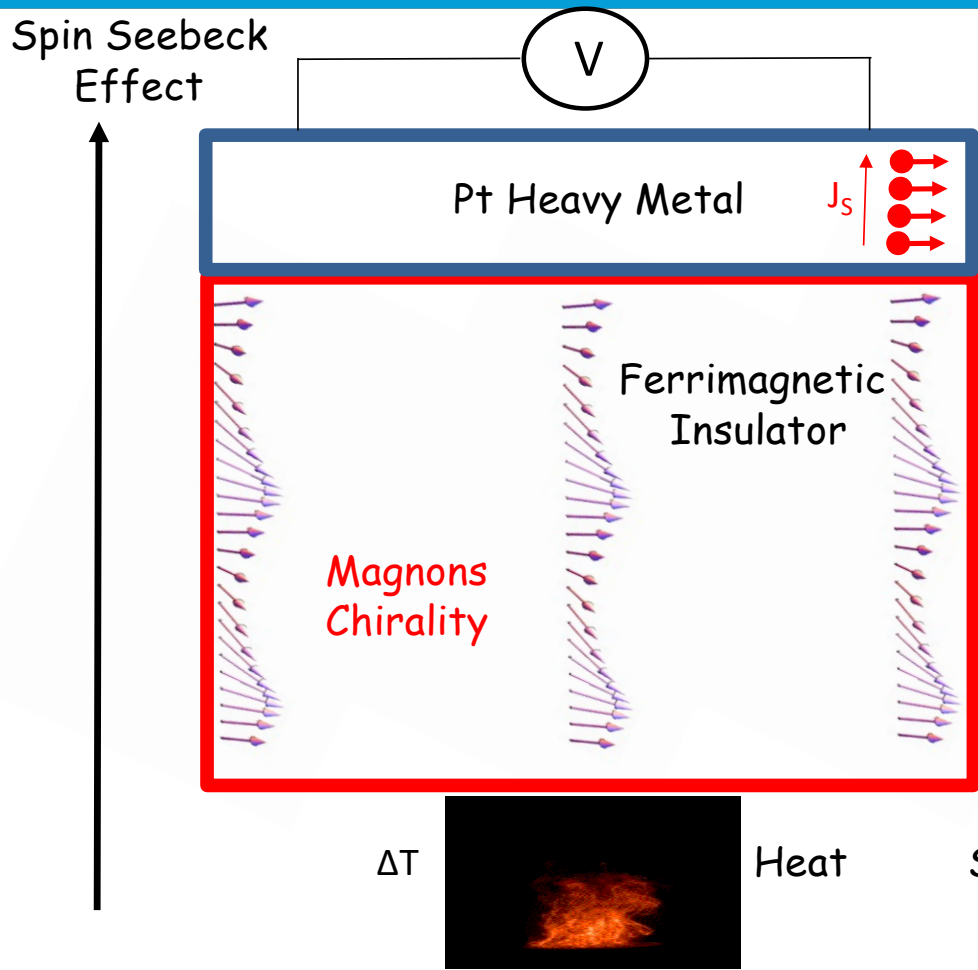
nature > news feature > article

NEWS FEATURE · 12 SEPTEMBER 2018 · CORRECTION 13 SEPTEMBER 2018

How to stop data centres from gobbling up the world's electricity

The energy-efficiency drive at the information factories that serve us Facebook, Google and Bitcoin.

Spin Caloritronics



Spin Caloritronics:

Devices: link heat current mediated by phonons to magnetic excitations mediated by magnons

Iron Garnet Family: Long Magnon lifetimes

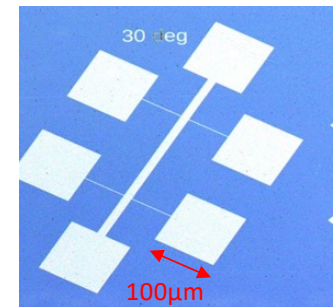
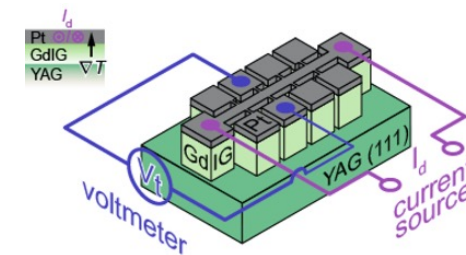
$Y_3Fe_5O_{12}$ (YIG / Pt)

$Tb_3Fe_5O_{12}$ (TbIG / Pt)

$Dy_3Fe_5O_{12}$ (DyIG / Pt)

$Gd_3Ge_5O_{12}$ (GdIG / Pt)

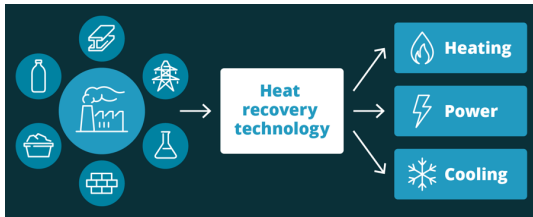
Prototype device structures



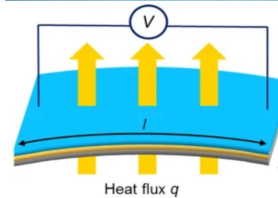
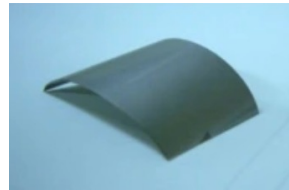
Neutron and X-ray Synergies for Advanced Spintronics Technologies

Magnons are (1) fast (ps) and (2) very low power consumption quasi-particles: YIG long magnon life-times

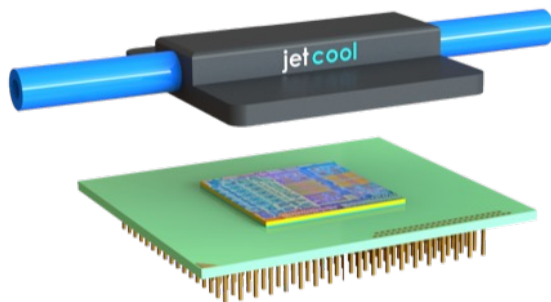
Waste Heat Recycling



A. Kirhara et al. *Sci Rep* 6, 23114 (2016)

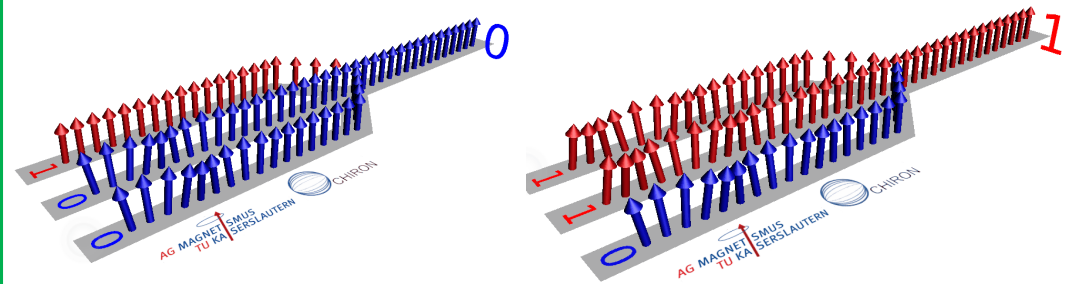


On Chip Cooling



Cooling function
+
Logic Function

Low power consumption electronics

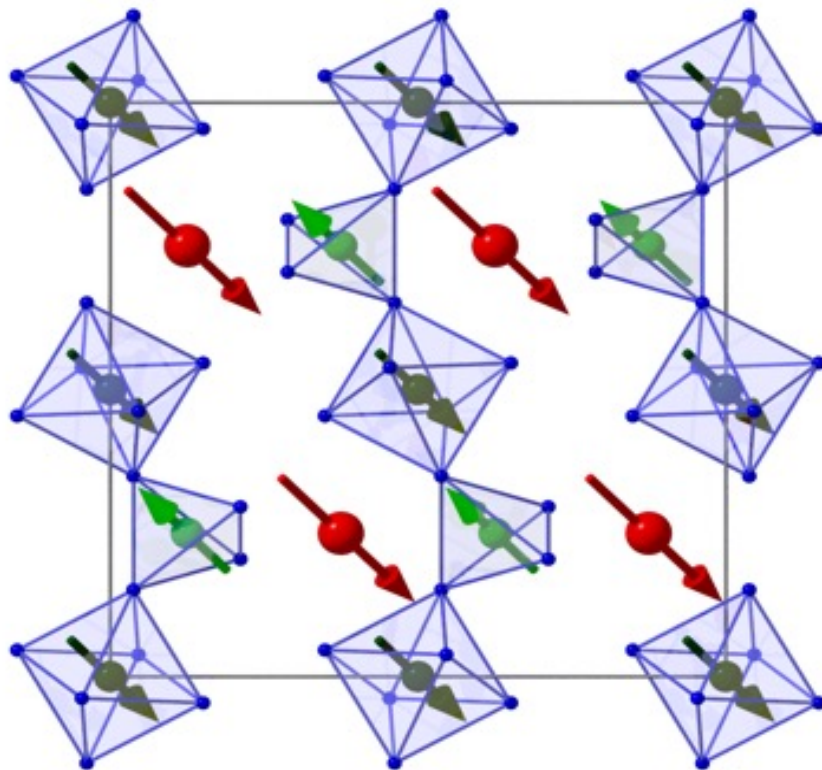


		Logic states							
Input	P ₁	0	0	0	1	0	1	1	1
	P ₂	0	0	1	0	1	1	0	1
	P ₃	0	1	0	0	1	0	1	1
O (O')		0	0	0	0	1	1	1	1
		Spin-wave phase		0	π				
		Logic state		0	1				

Re: Iron Garnets: $\text{Re}_3\text{Fe}_5\text{O}_{12}$

Re = Gd, Tb etc..

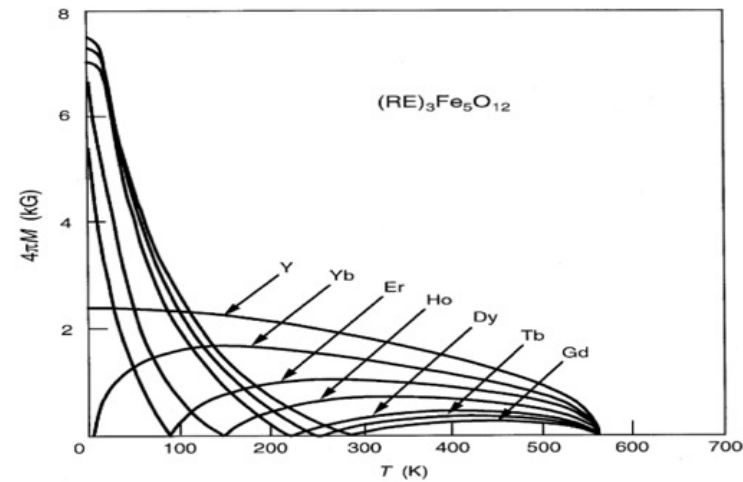
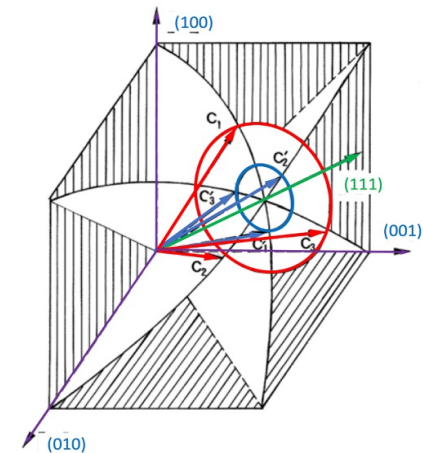
$\text{Gd}_3\text{Fe}_5\text{O}_{12}$



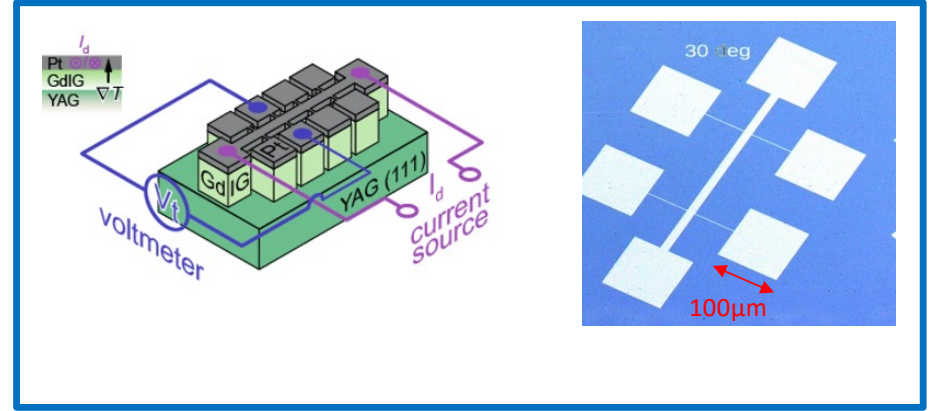
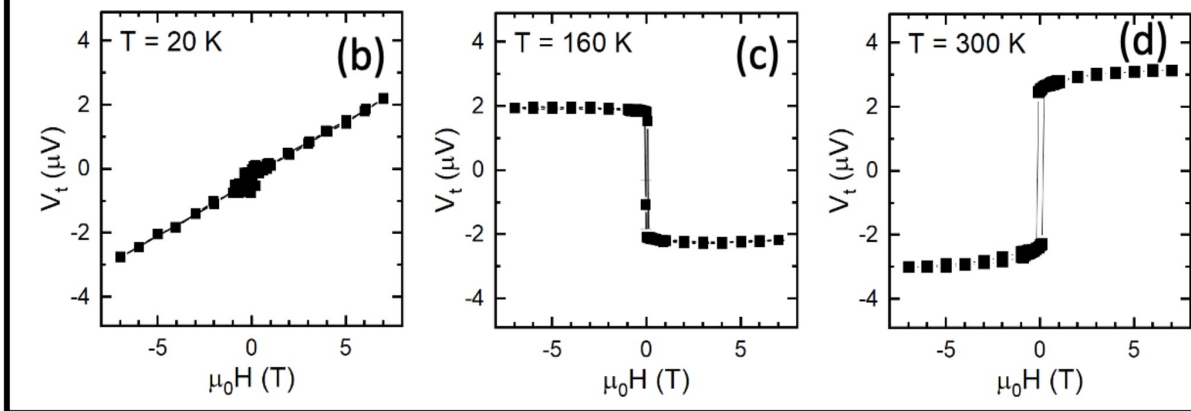
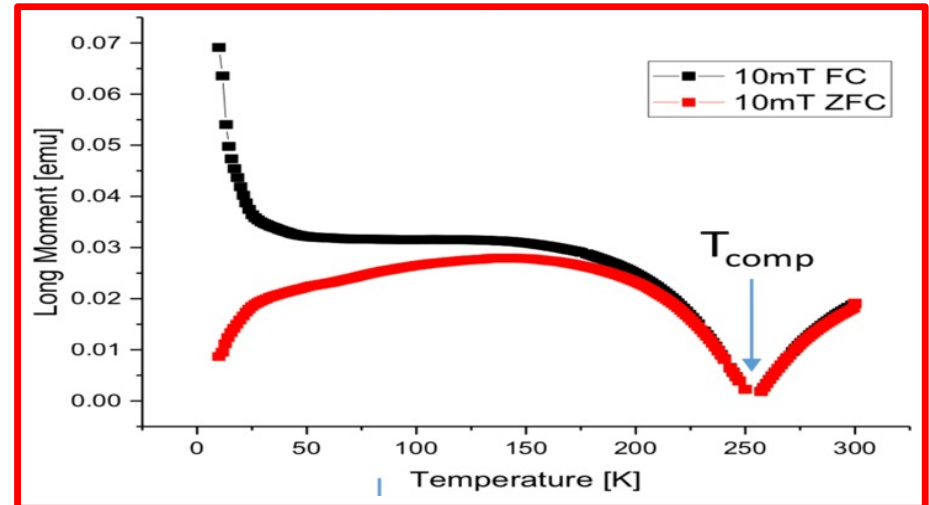
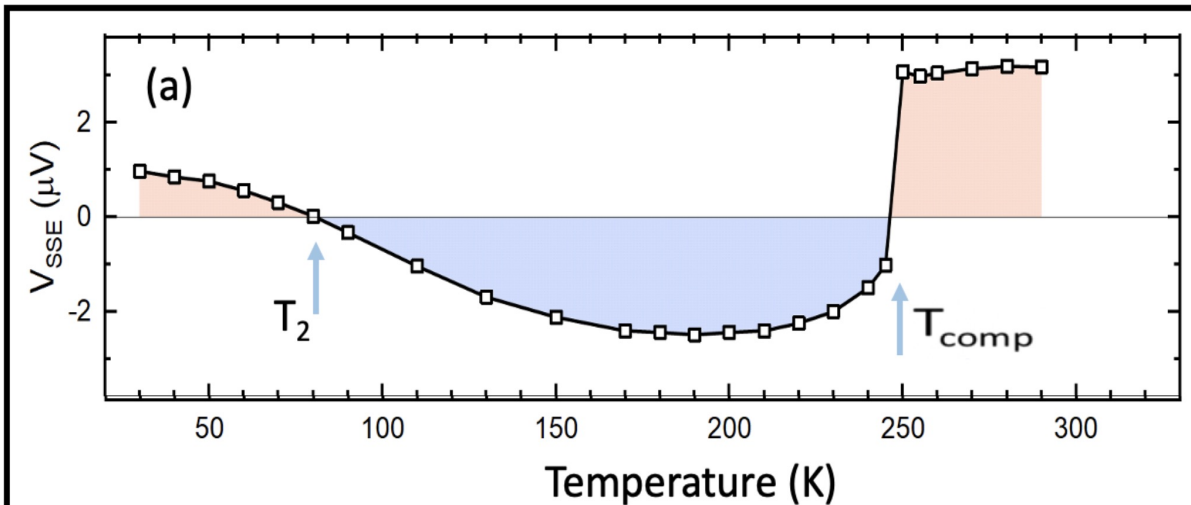
- Fe^{3+} Octahedral a-sites
- Fe^{3+} Tetrahedral d-sites
- RE^{3+} dodecahedral c-sites

$$\vec{\mu}_{\text{Gd}} \parallel \vec{\mu}_{\text{Fe}} \parallel \{111\}$$

$\text{Tb}_3\text{Fe}_5\text{O}_{12}$

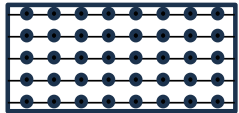


Tb₃Fe₅O₁₂ SSE & Magnetisation

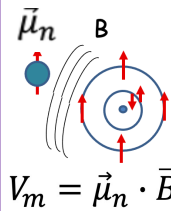


Structure

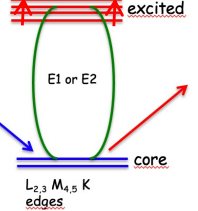
Crystal Structure



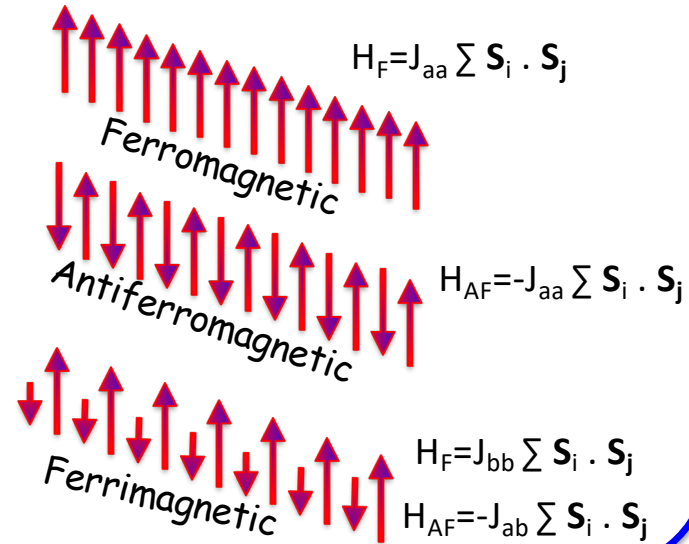
Neutrons



X-rays



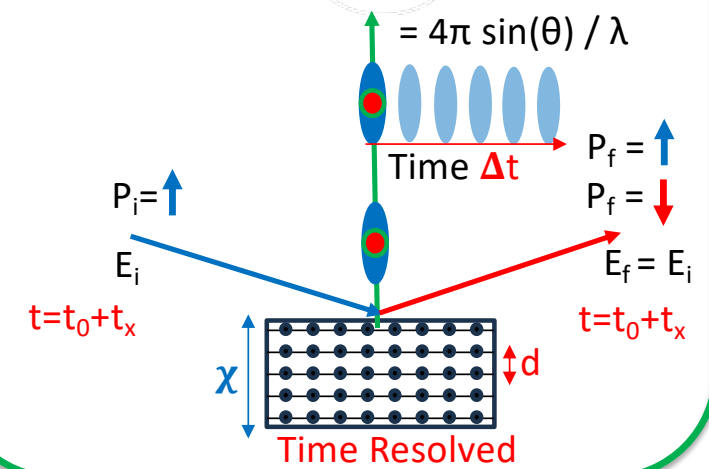
Magnetic Structure



Elastic Scattering

EUROPEAN SPALLATION SOURCE

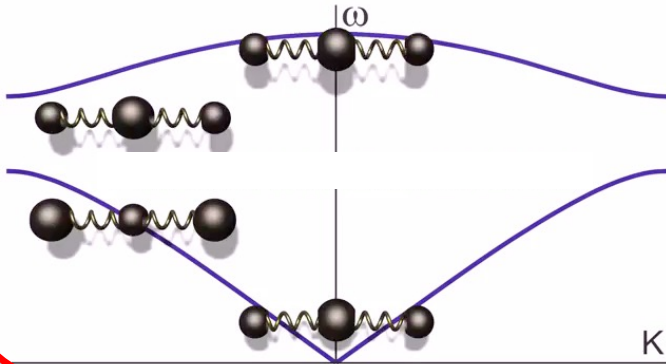
d=atomic distance



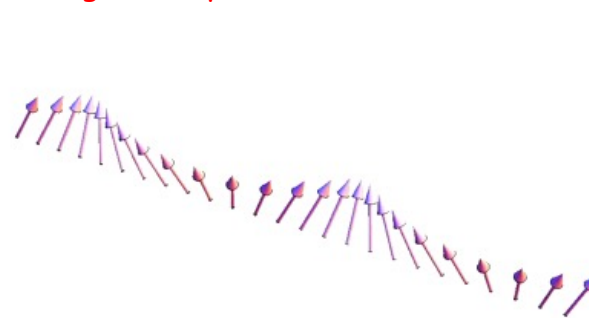
Dynamics

$V \approx 1000 \text{ m/s} = 10^{-9} \text{ m} / 10^{-12} \text{ s} = 1 \text{ nm} / \text{ps}$

Phonons: Sound Waves



Magnons: Spin-Waves

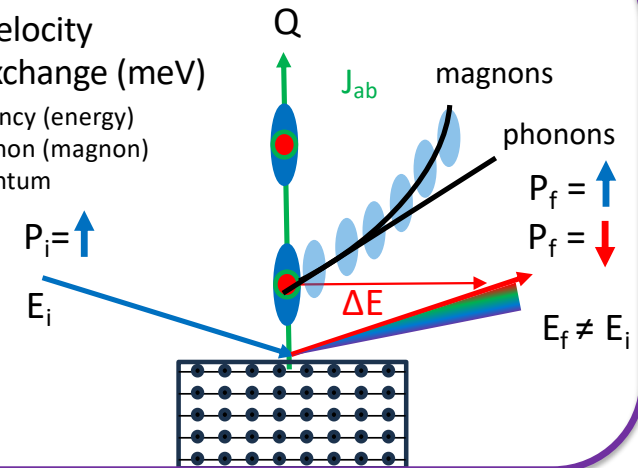


Inelastic Scattering

V=velocity

J=Exchange (meV)

Frequency (energy)
of phonon (magnon)
momentum

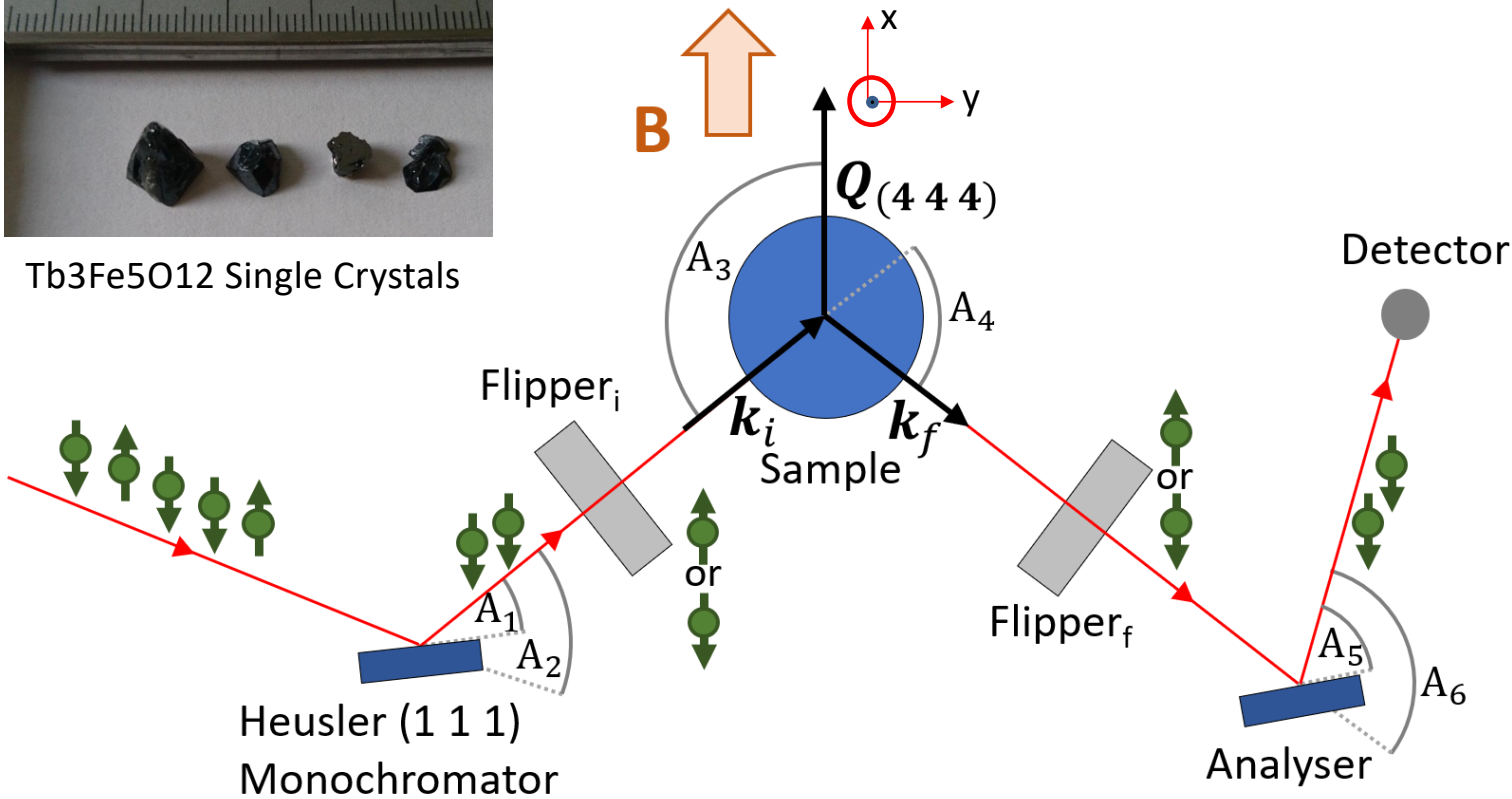


Polarised Inelastic Neutron Scattering (IN20)

Tb₃Fe₅O₁₂: Magnon Chirality



Tb₃Fe₅O₁₂ Single Crystals

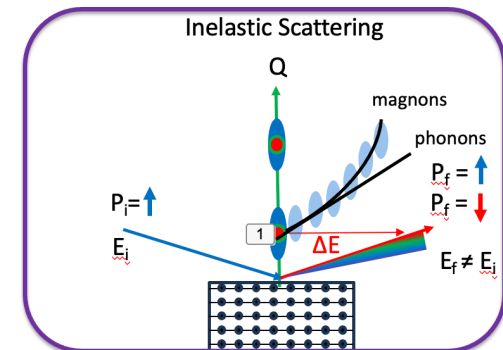


$$I_X^{\pm\pm} \propto |N|^2,$$

$$I_X^{\pm\mp} \propto |M_{\perp}|^2 \mp PM_{\text{ch}},$$

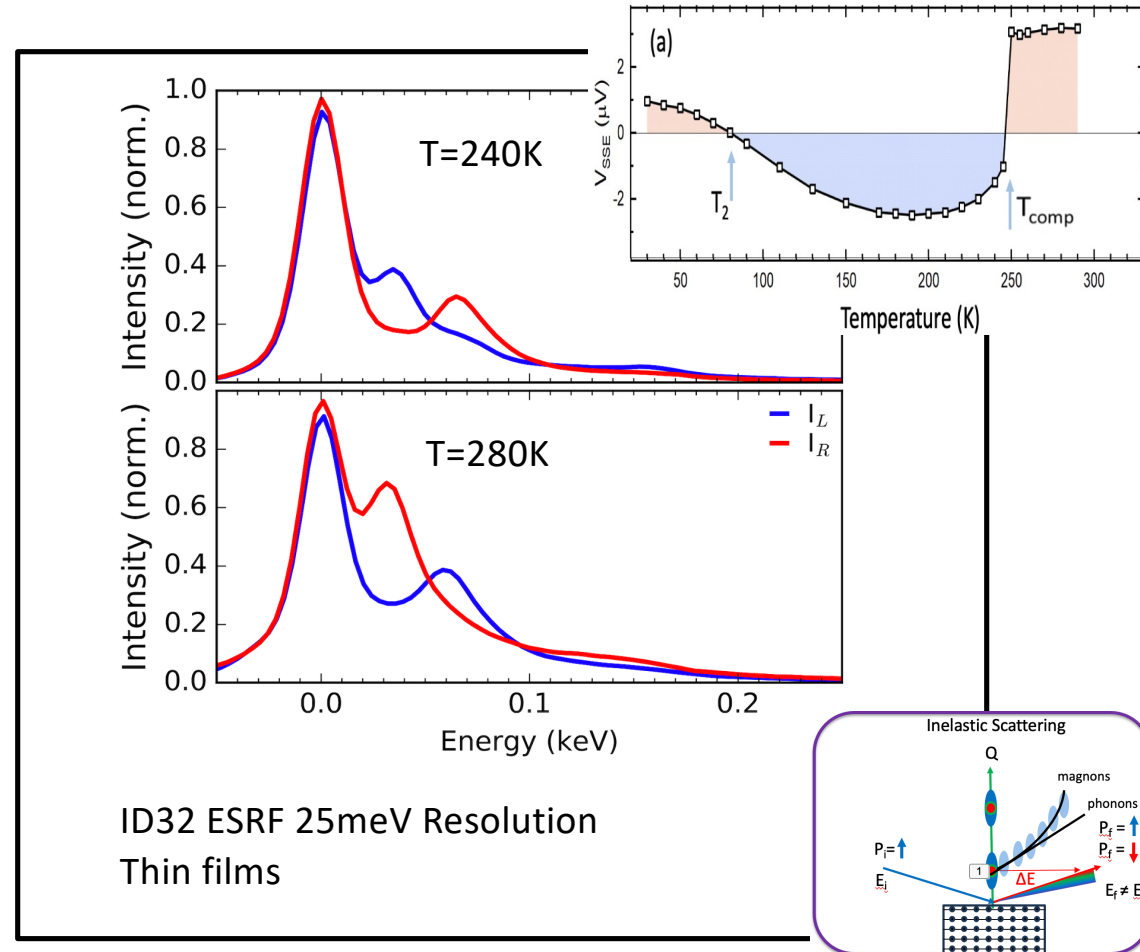
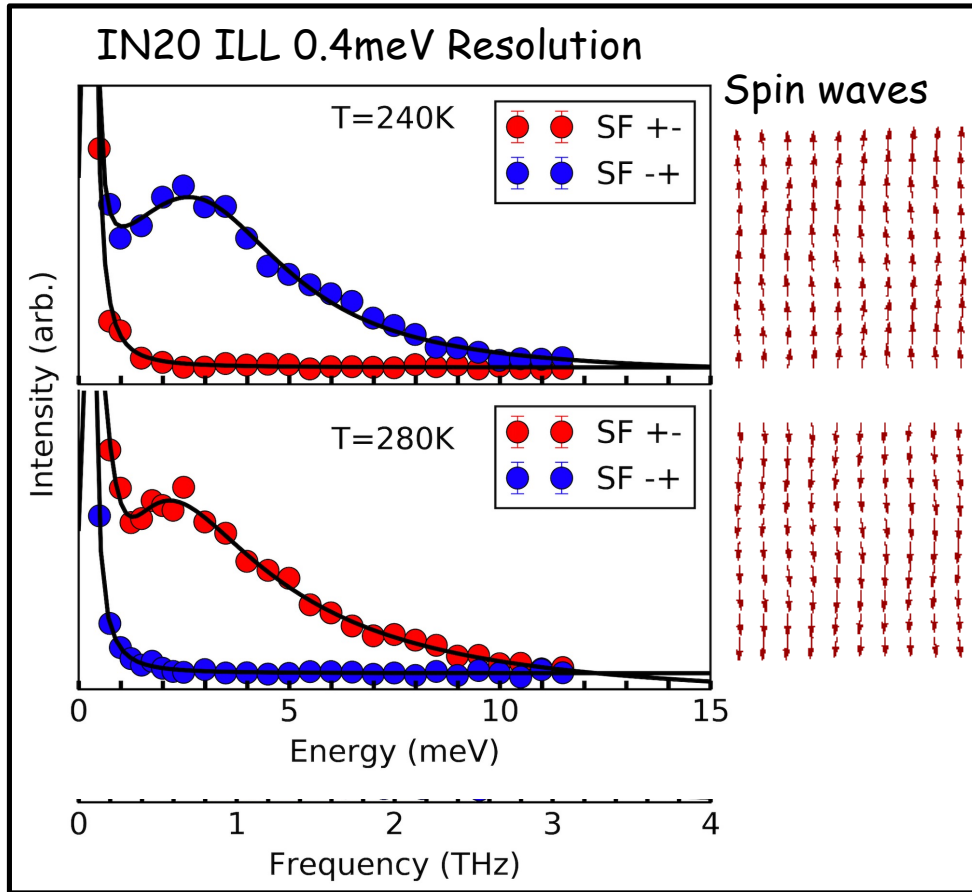
Magnon Chirality

$$\chi(\mathbf{q}, \omega) = \frac{I^{+-}(\mathbf{q}, \omega) - I^{-+}(\mathbf{q}, \omega)}{I^{+-}(\mathbf{q}, \omega) + I^{-+}(\mathbf{q}, \omega)}.$$

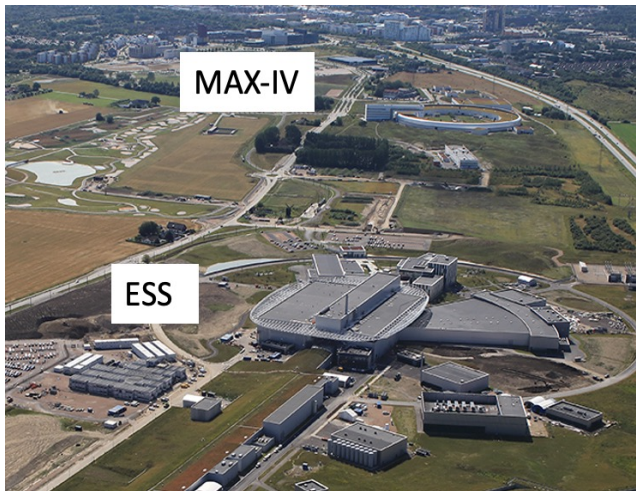
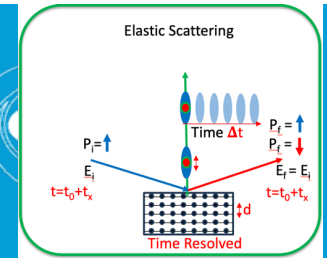




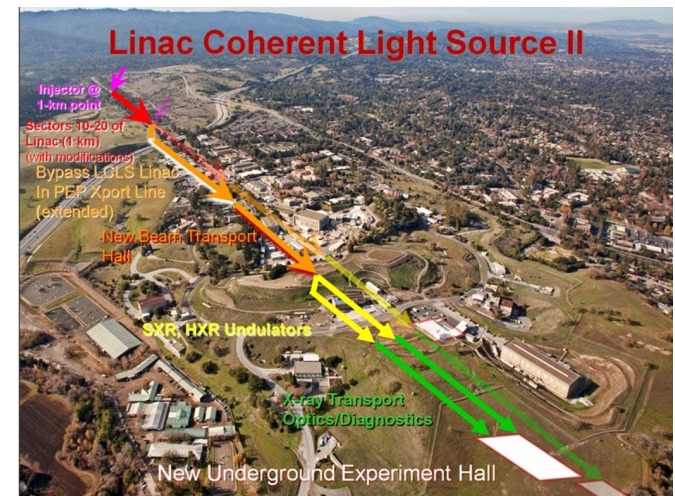
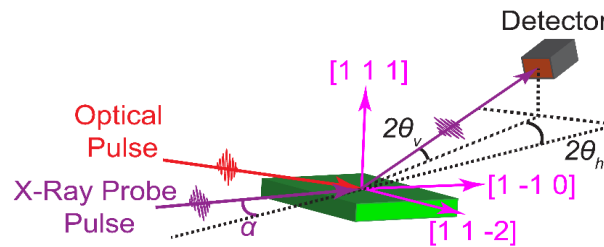
Magnon Chirality



X-Ray Pump - Probe: $Gd_3Fe_5O_{12}$ thin films

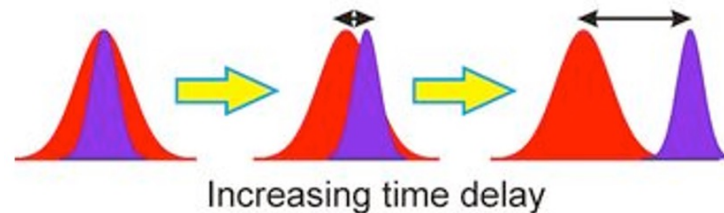


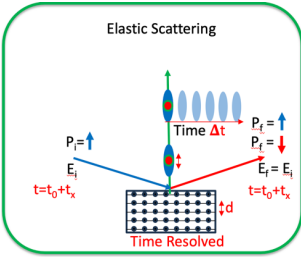
400nm Laser Pump
 ~ 50 fs pump pulses
 $1,3,5$ mJ cm^{-2}
 120Hz Rep. rate



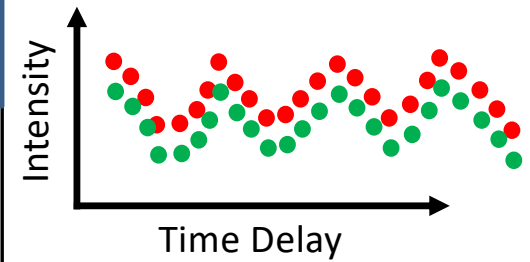
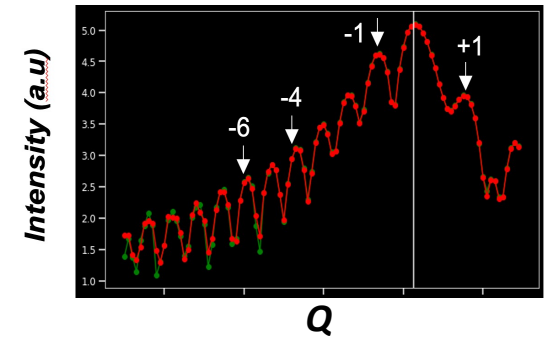
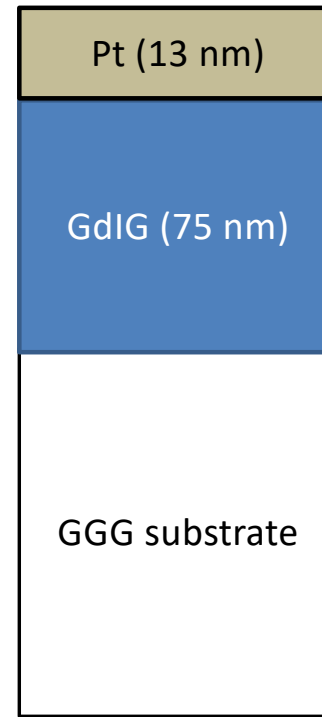
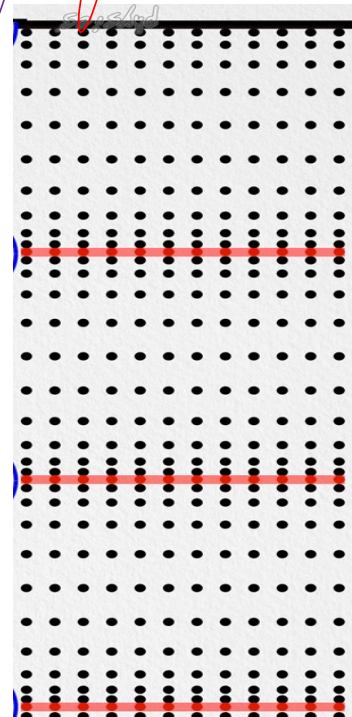
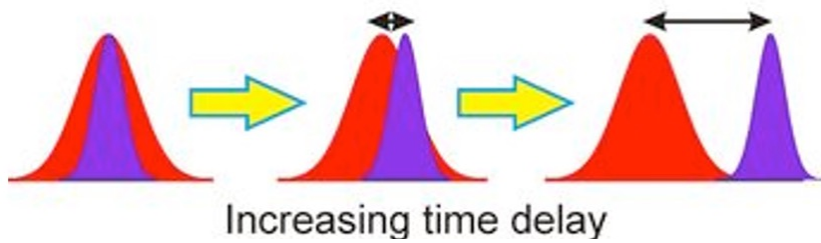
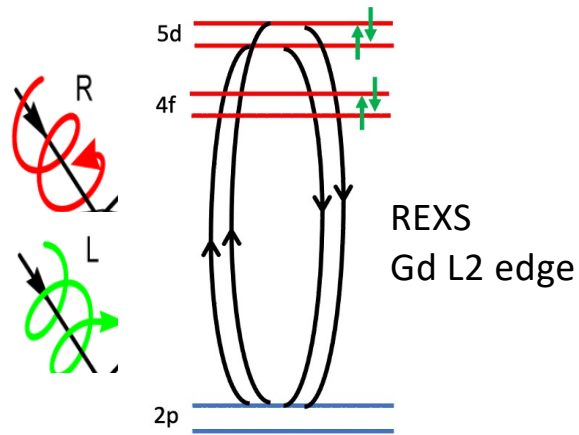
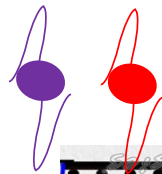
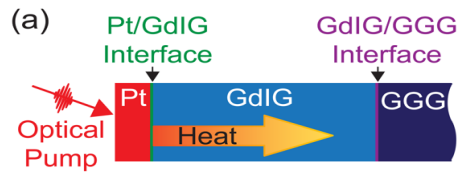
Femto-MAX Beamline: Max-IV
 100fs pulses. 10^4 Photons / pulse
 200fs time resolution
 10 Hz repetition rate

XPP: LCLS
 XFEL Pump Probe beamline
 ~ 10 fs pulse X-ray probe 10^9 Ph/pulse
 ~ 10 fs Resolution
 120Hz Rep. rate

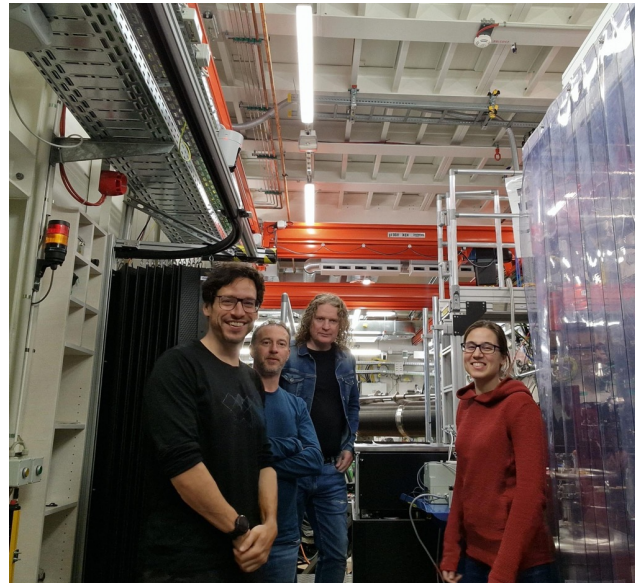




Pump-probe $Gd_3Fe_5O_{12}$



Eu-XFEL Magnetic Dynamics



Commissioning Expert & Proposal MAX-IV



MAX-IV

nanoMAX
SoftiMAX
FemtoMAX
DanMAX

Veritas
MAX-PEEM

Science **372**, 630–635 (2021)

Structural Dynamics
9, 045101 (2022)

