Advanced Light Source: The Science and Technology of Soft X-rays

Overview of the ALS

Industrial R&D at the ALS: Memristors

Basic R&D at the ALS: Skyrmions

A look to the future: ALS Upgrade

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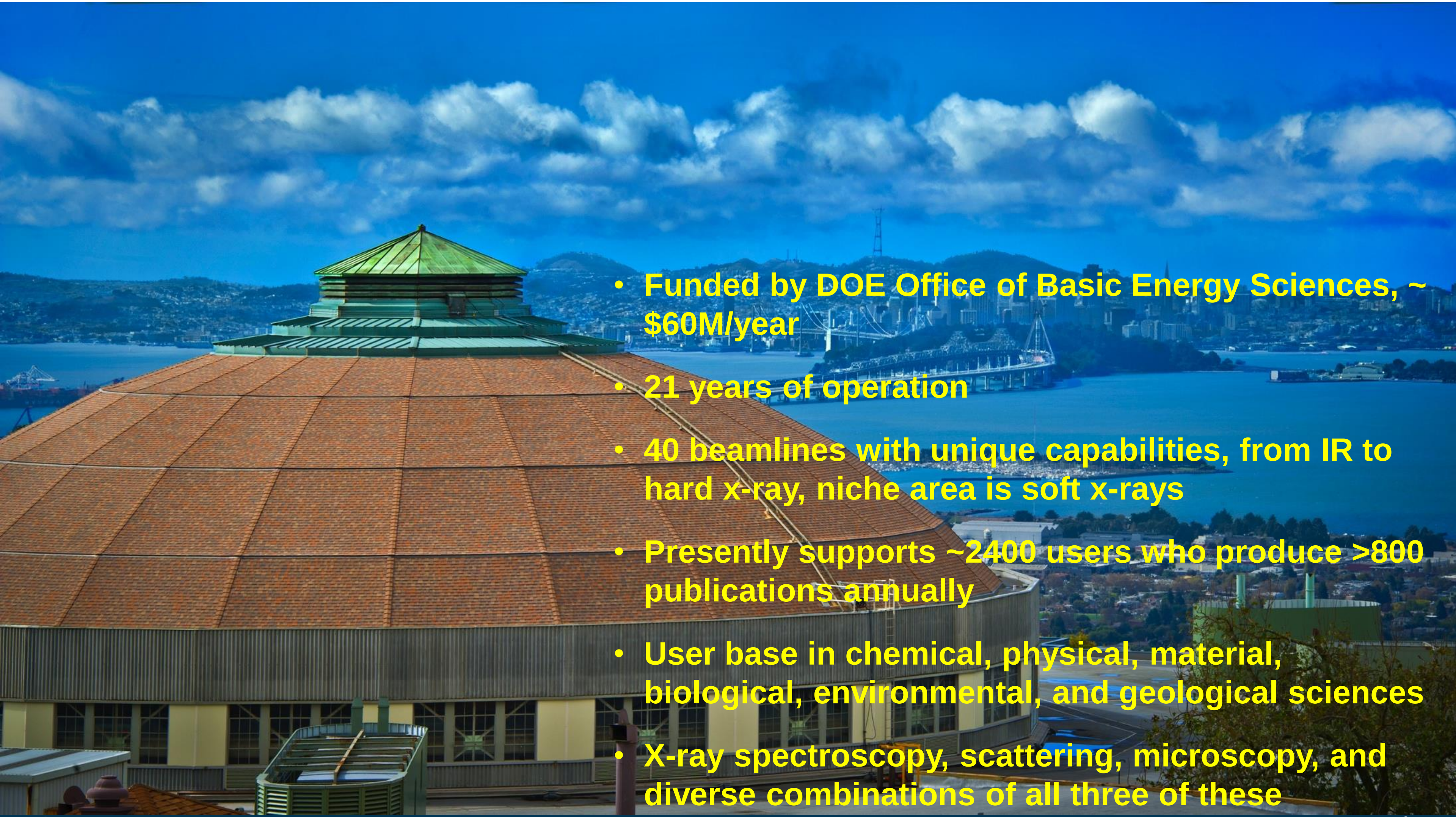
October 16, 2014

Overview of the Advanced Light Source

ALS mission is to *support users in doing outstanding science in a safe environment*

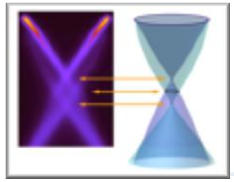


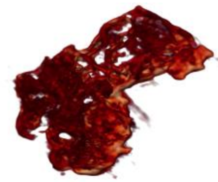
- **Funded by DOE Office of Basic Energy Sciences, ~ $60M/year**
- **21 years of operation**
- **40 beamlines with unique capabilities, from IR to hard x-ray, niche area is soft x-rays**
- **Presently supports ~2400 users who produce >800 publications annually**
- **User base in chemical, physical, material, biological, environmental, and geological sciences**
- **X-ray spectroscopy, scattering, microscopy, and diverse combinations of all three of these**

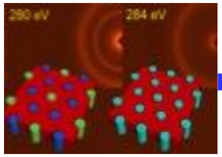
ALS Users Are Productive Across a Broad Range of High Impact Science and Critical Technologies

Hard materials: 5.3.2, 8.3.2, 10.3.2, 12.2.2, 12.3.2

Electronic textures: 4.0.3, 7.0.1, 10.0.1, 12.0.1

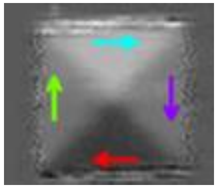


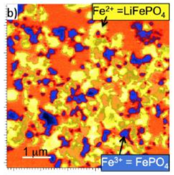




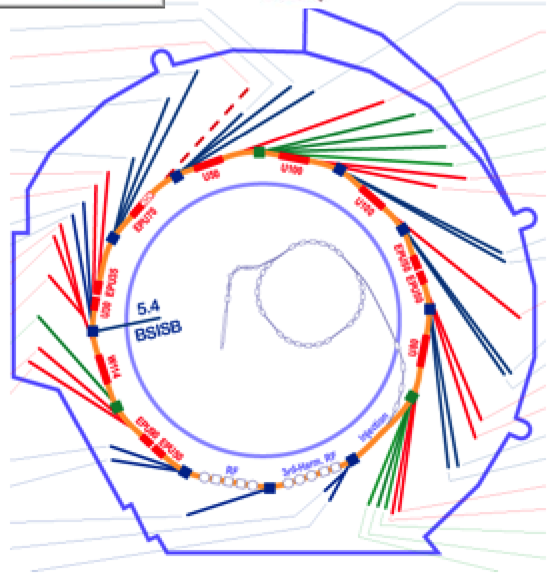
Polymers and resist materials: 5.3.2, 7.3.2, 11.0.1, 12.0.1

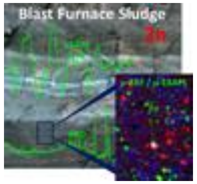
Magnetism: 4.0.2, 6.1.2, 11.0.1, 12.0.2





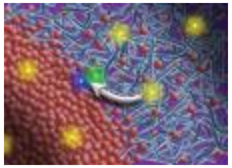
Electrochemical devices: 5.3.2, 9.3.1, 11.0.2

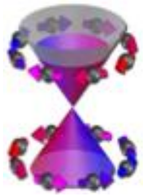




Environmental textures: 5.3.2, 10.3.2

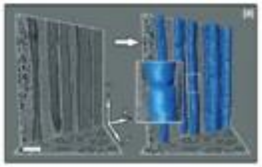
Organic PVs: 5.3.2, 7.3.3



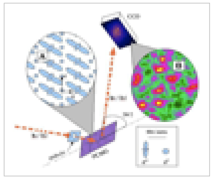


Spin textures: 10.0.1, 12.0.1

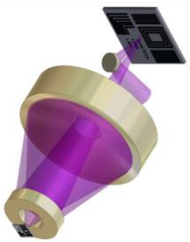
Cellular nanotomography: 2.1



Living tissues: 1.4, 5.4, 8.3.2



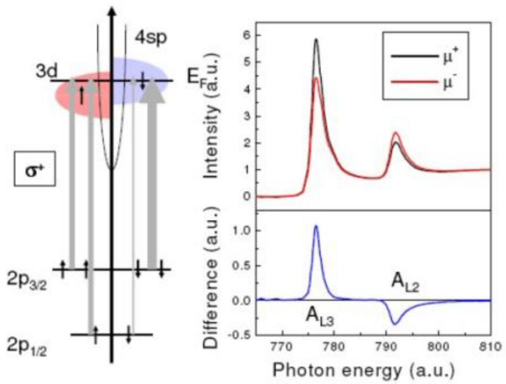
Orbital textures: 5.3.2, 12.0.2



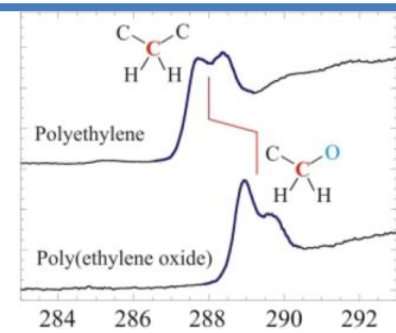
EUV technology: 6.3.1, 11.3.2, 12.0.1

Soft X-rays Enable Chemical, Electronic and Magnetic Imaging

3d transition metals



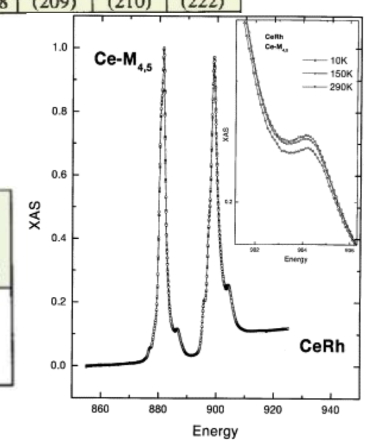
Light elements



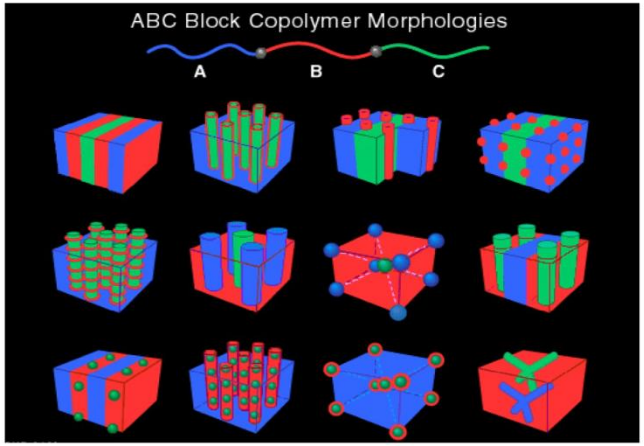
1 H 1.0079																	2 He 4.0026
3 Li 6.941	4 Be 9.012											5 B 10.811	6 C 12.011	7 N 14.007	8 O 16.00	9 F 19.00	10 Ne 20.179
11 Na 22.99	12 Mg 24.30											13 Al 26.98	14 Si 28.09	15 P 30.974	16 S 32.06	17 Cl 35.453	18 Ar 39.948
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.938	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.91	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57 *La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.2	77 Ir 192.2	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra 226.02	89 †Ac 227.03	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 § (269)	111 § (272)	112 § (277)						

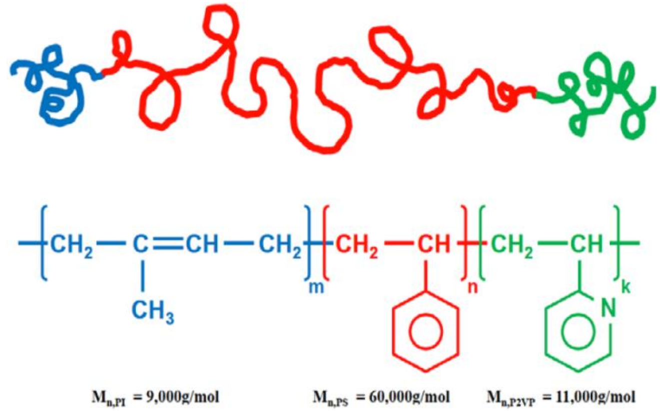
Rare earths

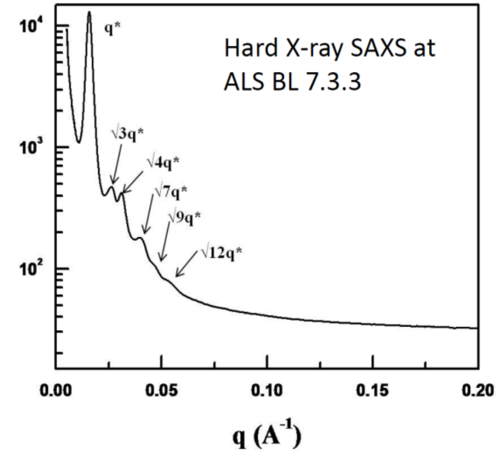
58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.97	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

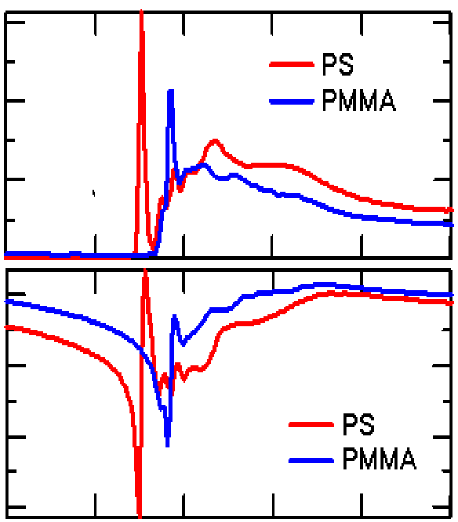


Chemically Sensitive Soft X-ray Scattering

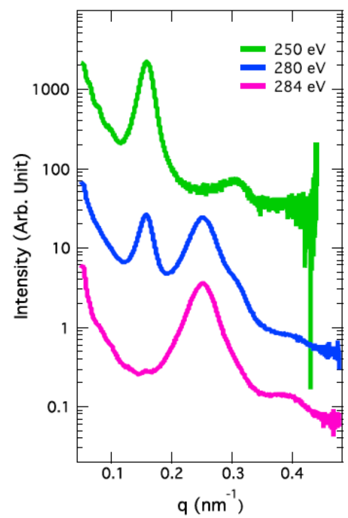


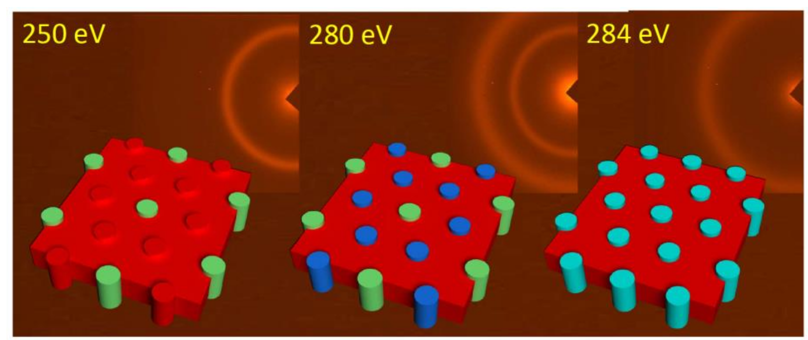






Photon Energy (ev)

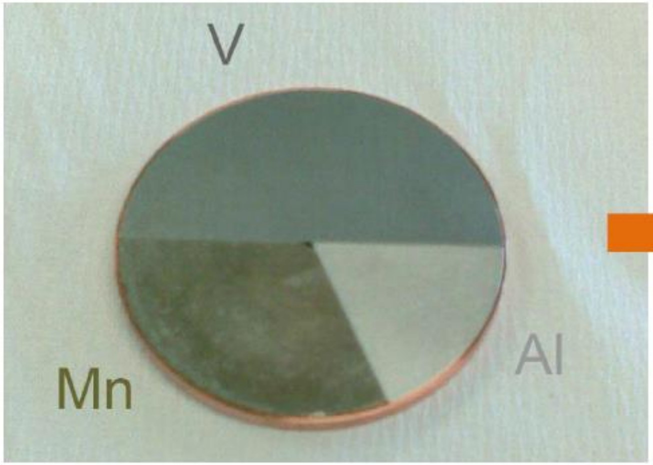


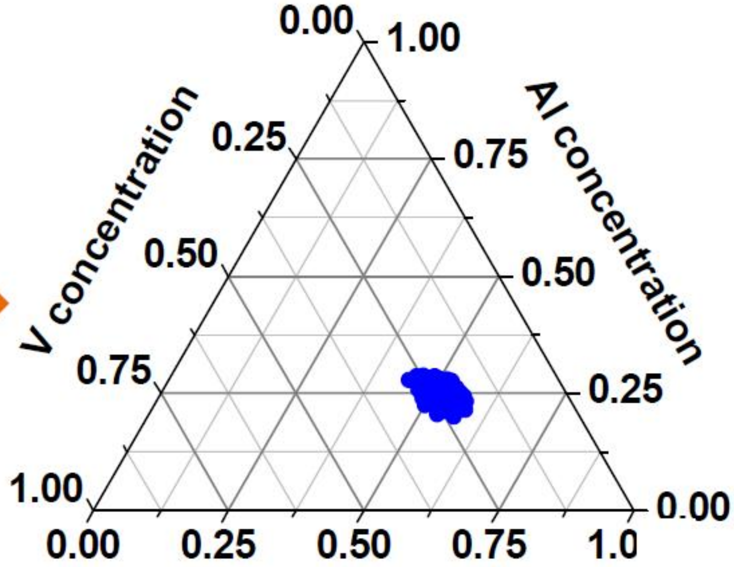


C. Wang et al., Nano Letters 2011

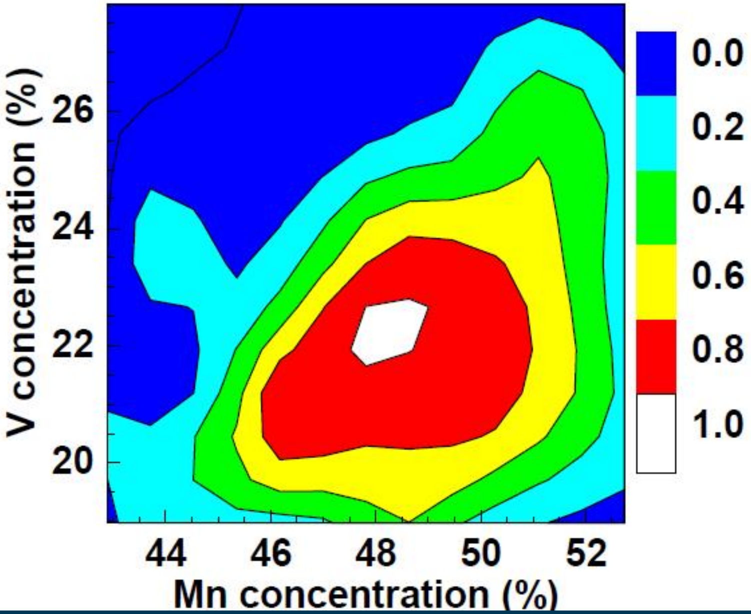
Materials Discovery: Magnetism in Heusler Alloys

$Mn_{2-\delta}V_{1+\delta}Al_{1+\delta}$ – Sputter Target





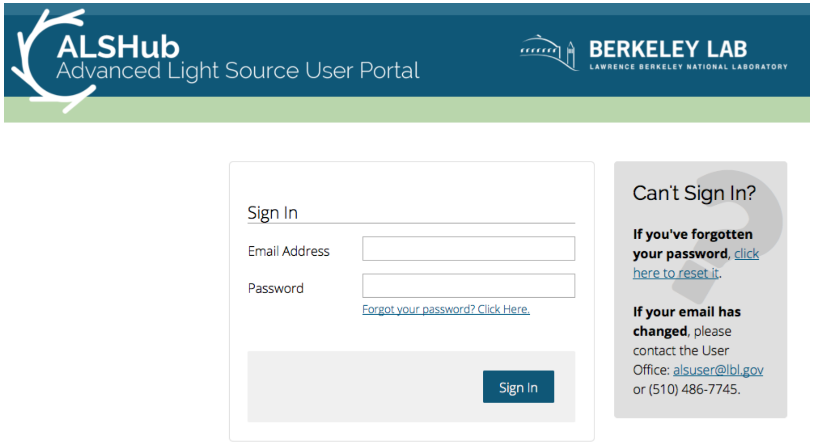
- Mn moment as function of composition (~200 XMCD spectra)
- Maximum moment for $Mn_{48.5}V_{22.5}Al_{29}$



Jan Schmalhorst, Daniel Ebke
Univ. Bielefeld, Germany

My Job: ALS Division Deputy for Science

(I sit around all day long and talk to smart people . . .)



Near-term 'planning'

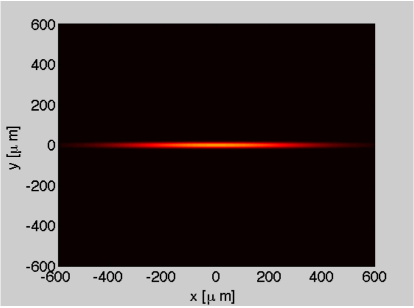
Advanced Light Source

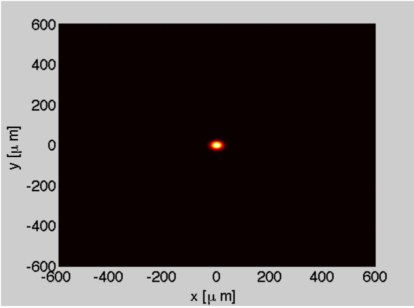
Strategic Plan

2014–18

Mid-term 'planning'

ALS Today → Diffraction-Limited ALS-U





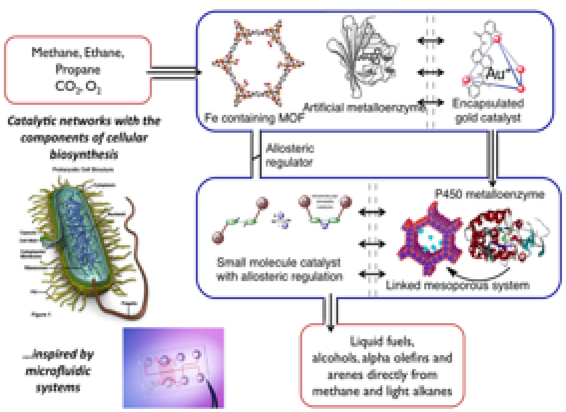
Long-term 'planning'

ALS and ALS-U Research Trends

Enabling directed chemistry

Designed nanostructure to control kinetics and optimize efficiency of diverse chemical systems

- Optimize electrodes of nano- and mesoscale structures for efficient energy conversion and storage
- Connect nanostructures in mesoscale functional networks for efficient and selective catalysis, electrocatalysis, and photocatalysis

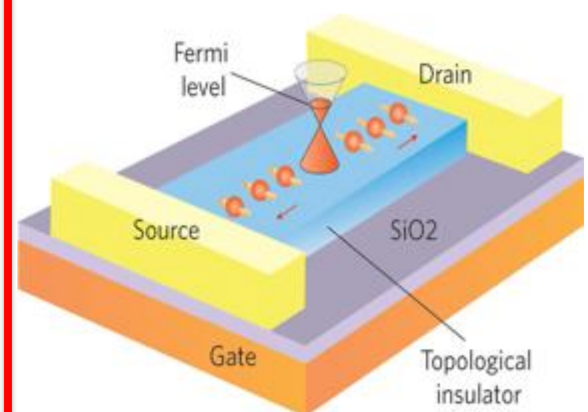


Toste/Hartwig, UC/LBNL

Materials to enabling human scale computing

New materials for controlling energy flow, and neural, quantum, and spintronic processing

- Map and optimize nanoscale spin currents and spin textures in operating spintronic structures
- Control emergent, strongly coupled excitations for low power applications
- Develop candidate materials and structures for neural processing

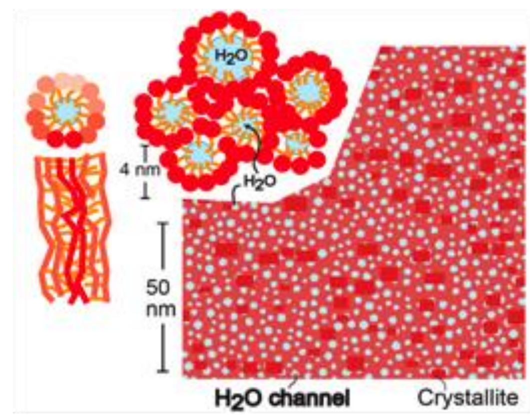


Xue, Nature Nano. **6**, 197–198 (2011)

Materials an chemistry to address global challenges

Material structures that rival the function of bio/enviro-systems

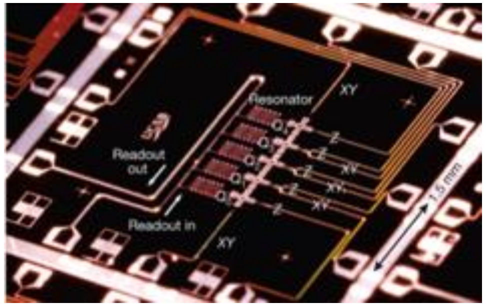
- Design nanoporous membranes with extreme chemical selectivity of a biological membrane
- Optimize porous materials for carbon capture and sequestration, environmental remediation, water purification



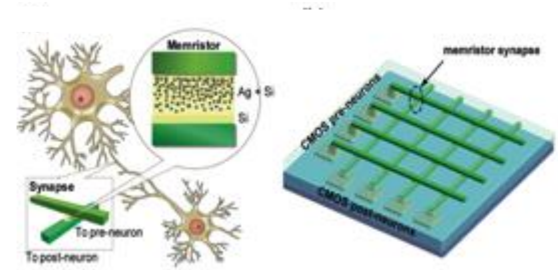
Schmitt-Rohr, Nature Mat. **7**, 75 (2008)

Materials for Computing at the Human Scale

Transformative material and device concepts for ultralow power future generation processing



Superconducting Q-bits

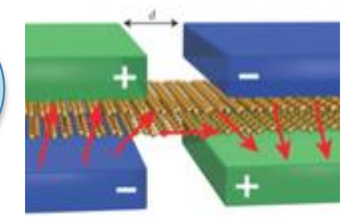


Neuromorphological processing

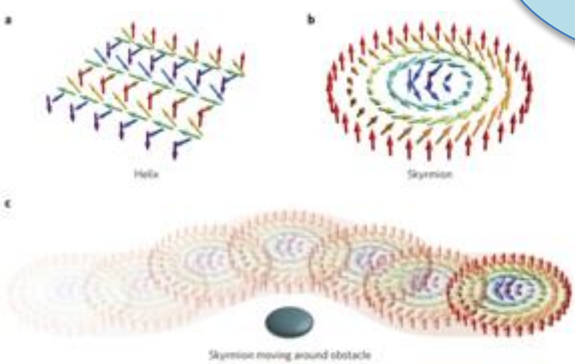
Composite Particles

Charges and orbitals

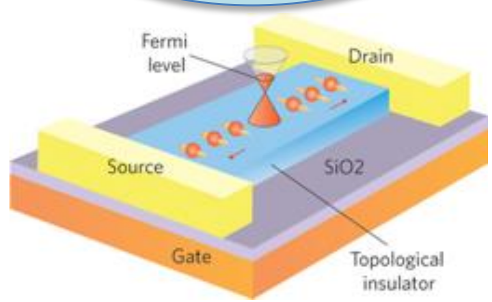
Spin currents and structures



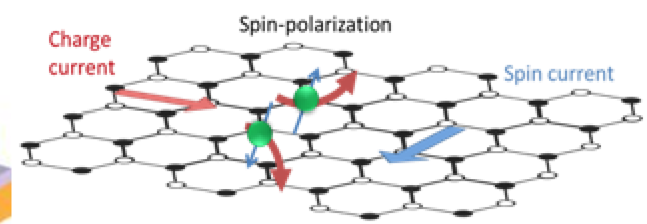
Graphene pseudo-spintronics



Classical and quantum processing with skyrmions

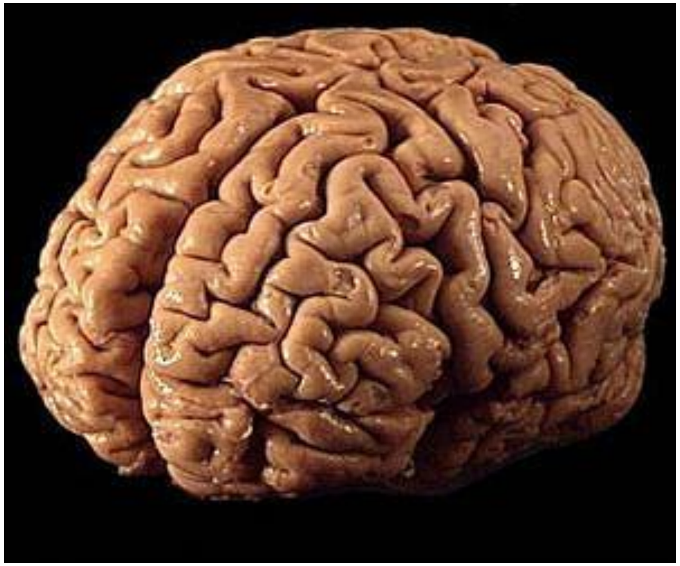


Spin currents and devices using topological insulators



Spin switching with currents

A Model in Power Efficient Computing



- ~20 W
- ~40 pFLOPS/sec
- ~100 Hz

- ~10^{11} neurons
- ~10^{14} synapses

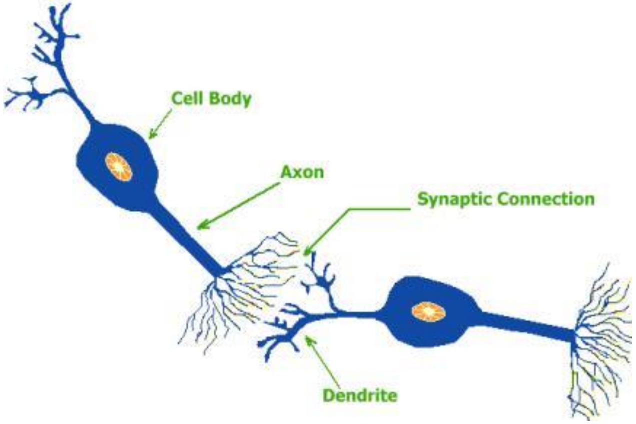
- Massively parallel
- Usually off – neurons spike
- 3D architecture with distributed memory

Many biological systems switch with energy near the Landauer limit kT ln(2) ~ 10^{-20} J

- - *even though they are immersed in a thermal bath which will drive fluctuations at the same energy scale*

- - *ingredients of the model are low frequency, low power, massive parallelism*

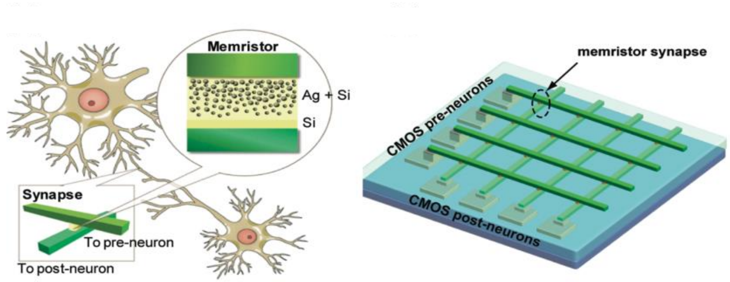
CMOS gates require ~10^5 kT to switch at present

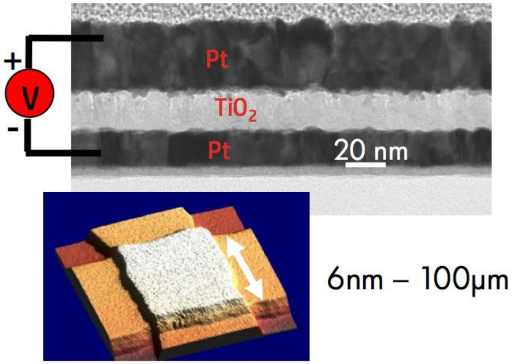


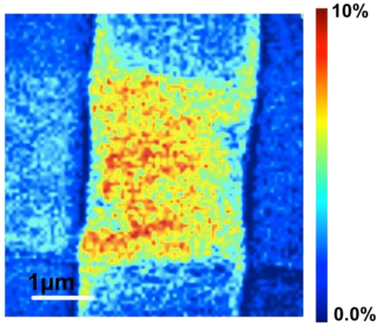
Biological Processing Element(s)

Low-hanging Fruit: Memristor Memory

(Stan Williams, et. al, HP Labs)



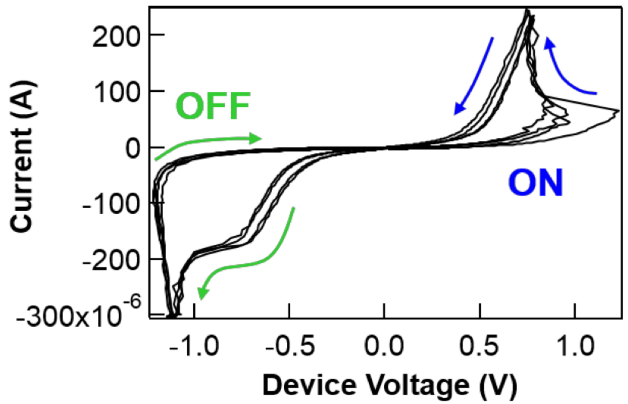




Memristor

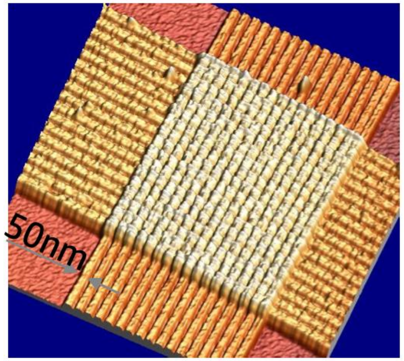
- - Resistance depends on current history
- - Resistance ~ strength of a synapse

2D map of oxidation states (ALS STXM)



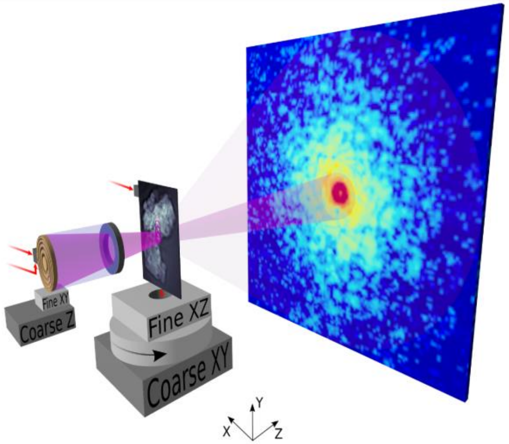
Memristor Crossbar Array

- Nonvolatile memory
- High density (30 nm -> 10 nm)
- Low switching energy (1 pJ)
- Fast (< 100 ps)
- Scalable in 3D (Tb cache?)

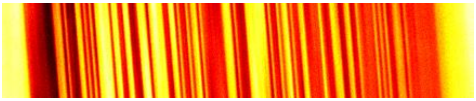


Chemical heterogeneity of the junction determines nonlinear behavior, switching energy, cycle life, etc.

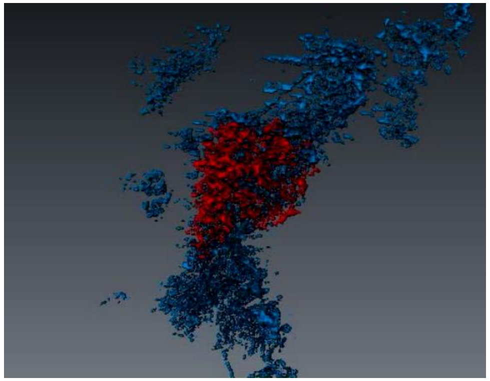
Chemical X-ray Microscopy to the Nanoscale



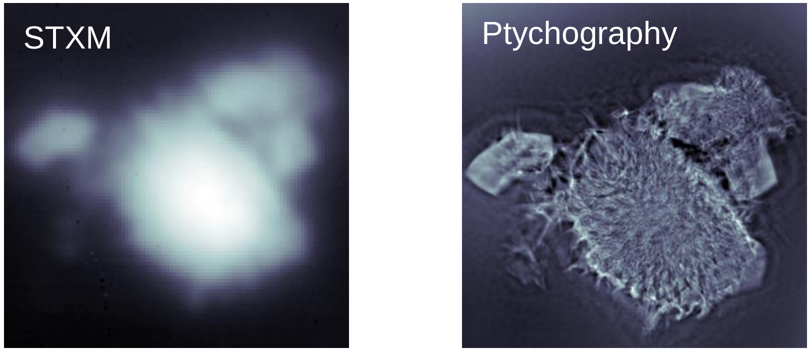
Diffractive imaging with ptychography



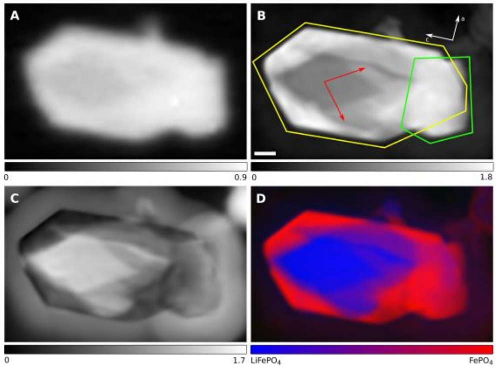
3 nm resolution on test objects



Sintered Zirconia in 3D



Resolving concrete chemistry



A. STXM @ 30 nm

B. Ptychography @10 nm: absorption

C. Ptychography@10 nm: phase

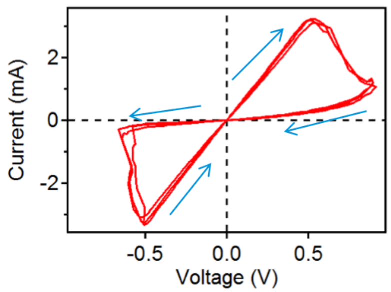
D. Chemical map@10 nm

Mapping battery oxidation states

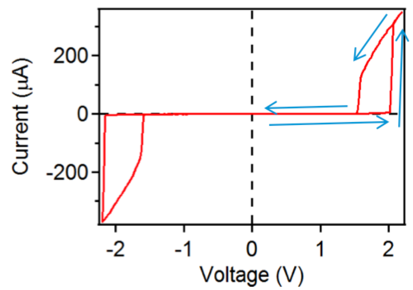
Memristor Networks: Neural-morphological processing

[Pickett, *et. al*., Nature Materials 12, 114–117 (2013)]

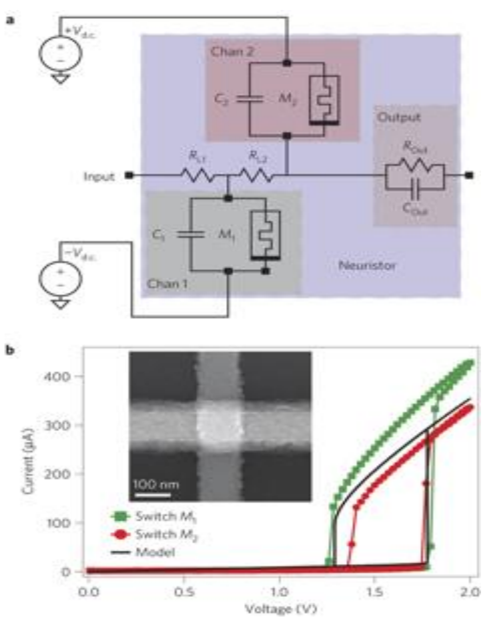
Nonvolatile memristor:
Emerging memory element



Volatile memristor:
Emerging processing element

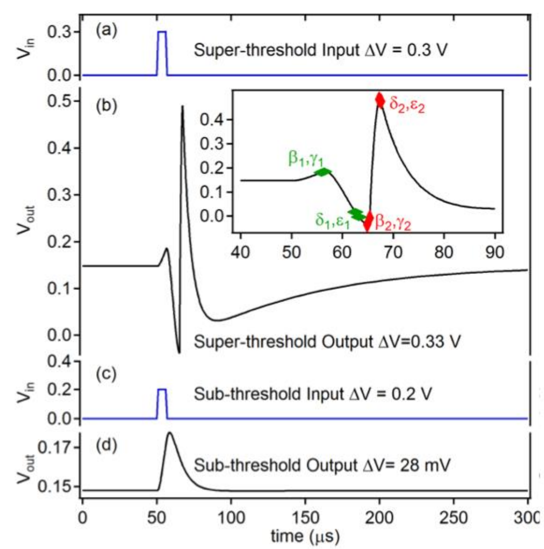


Chemical heterogeneity of the junction determines nonlinear behavior, switching energy, cycle life, etc.



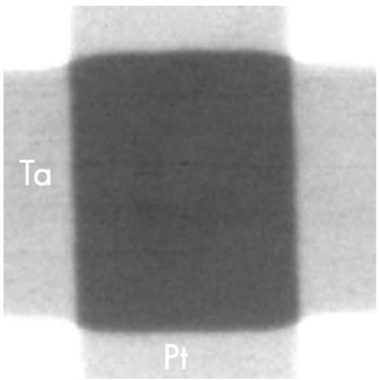
Memristive Neuristor:

- Two volatile memristors
- Two parallel capacitors
- All-or-nothing spiking

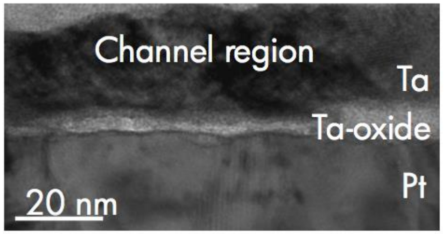


Adding Color to Optimize Memristor Junctions

Top view

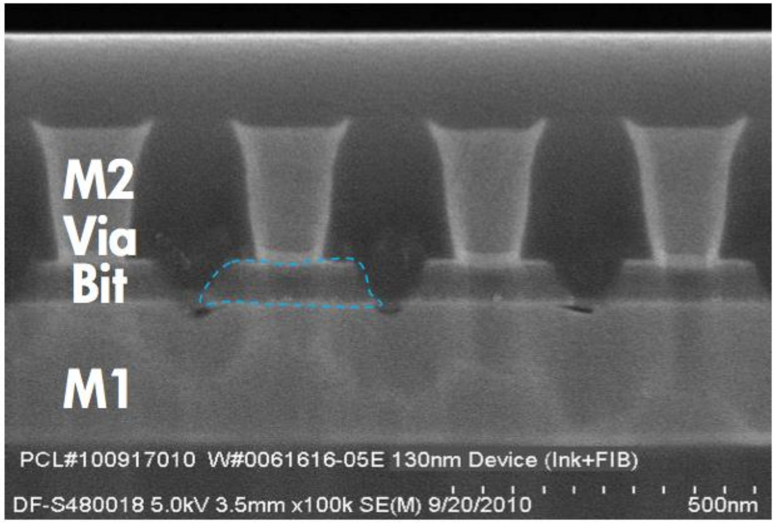


Cross-section

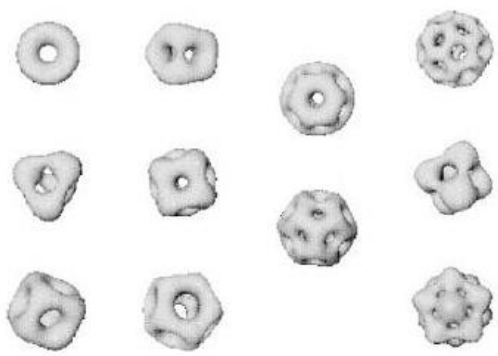


Full 3D mapping of chemical/structural/electronic properties with few nm resolution

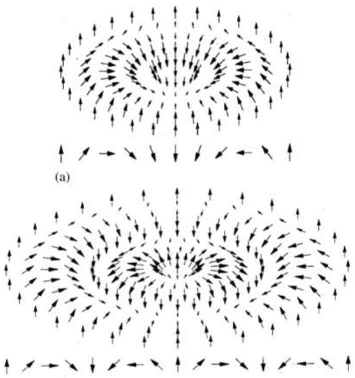
3D mapping of functioning device – junction, sidewalls, cycling lifetimes, etc,.



Changing Gears: Magnetic Skyrmions

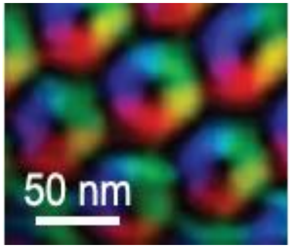


Tony Skyrme, 1962: *Topological Model of Baryons*



Skyrmions

Bogdanov, J. Mag. Magn. Materials 195, 182 (1999)



Skyrmion lattice

Seki et. al. Science ***336****, 198 (2012).*

What magnetic interactions conspire to cause magnetic skyrmions?

Micromagnetic Ginsberg-Landau free energy density

$$w = A\left(\nabla\vec{M}\right)^2 - \vec{M}\cdot\vec{H} - K\left(\vec{M}\cdot\hat{n}\right)^2 - \tfrac{1}{2}\vec{M}\cdot\vec{H}_m + w_D$$

Symmetric exchange: ferro- or ferri-magnetic

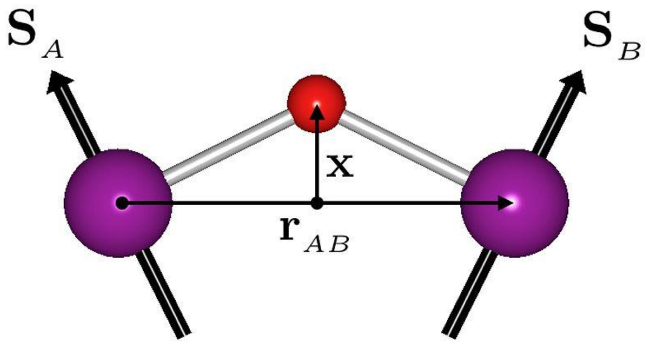
Zeeman energy: non-zero field

Perpendicular magnetic anisotropy (in films)

Demagnetizing (self) energy

Asymmetric exchange: Dzyaloshinskii–Moriya interaction

Dzyaloshinskii–Moriya Interaction



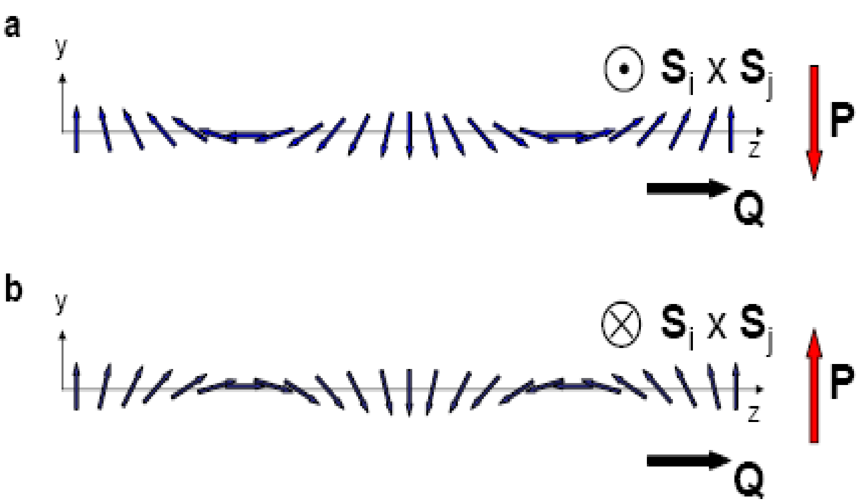
Exchange between neighboring spins

Symmetric (super)exchange (e.g., Heisenberg):

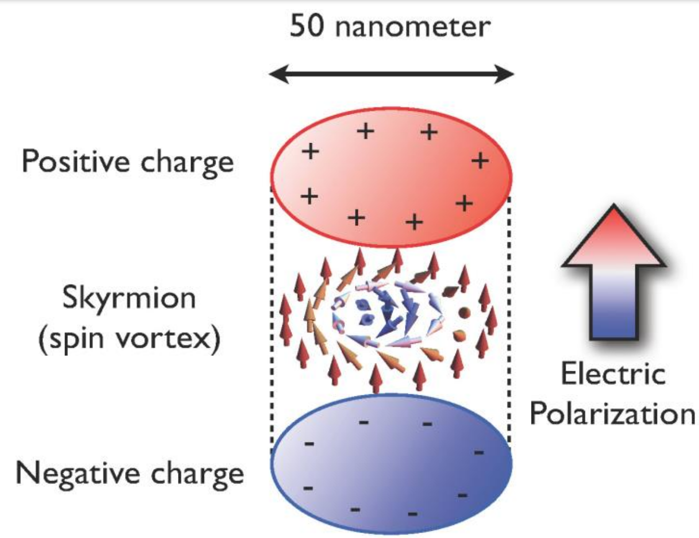
$$H_H = J\,\vec{S}_A \cdot \vec{S}_B$$

Asymmetric (super)exchange (e.g., DM via spin-orbit):

$$H_{DM} = \vec{D}_{DM} \cdot \vec{S}_A \times \vec{S}_B \qquad \vec{D}_{DM} \propto \vec{x} \times \vec{r}_{AB}$$

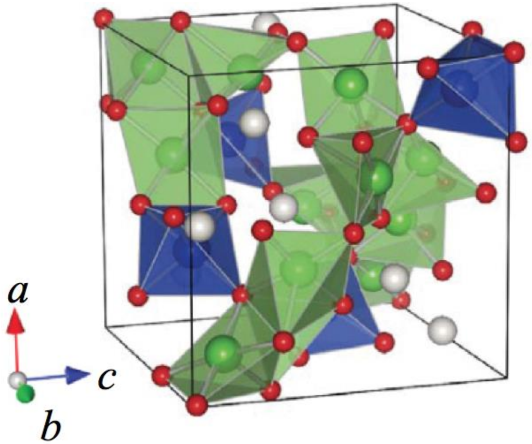


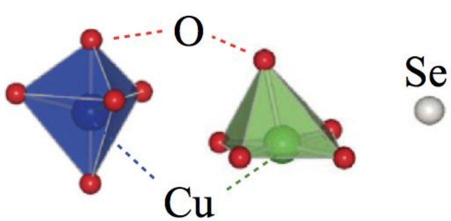
Spin-spirals in many materials with helicity set by the sign of D_{DM}



Skyrmions in non-centrosymmetric materials – also with magnetoelectric effects

Chiral Skyrmions in Cu_2OSeO_3

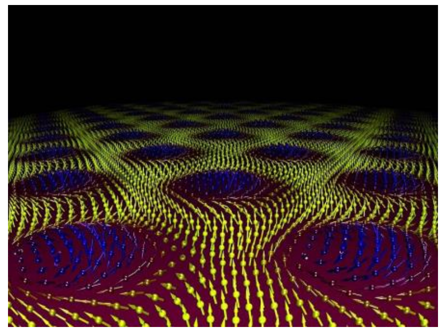


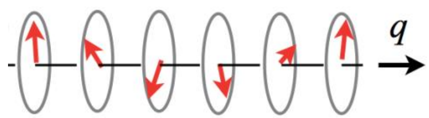


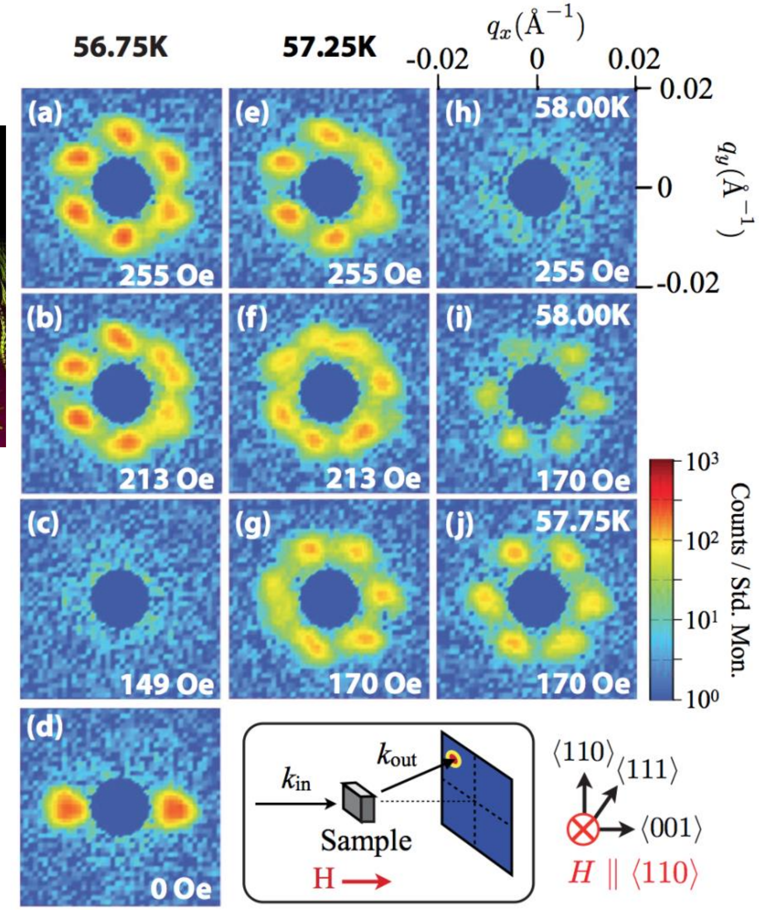
Cubic lattice

Ferrimagnetic

Non-centrosymmetric



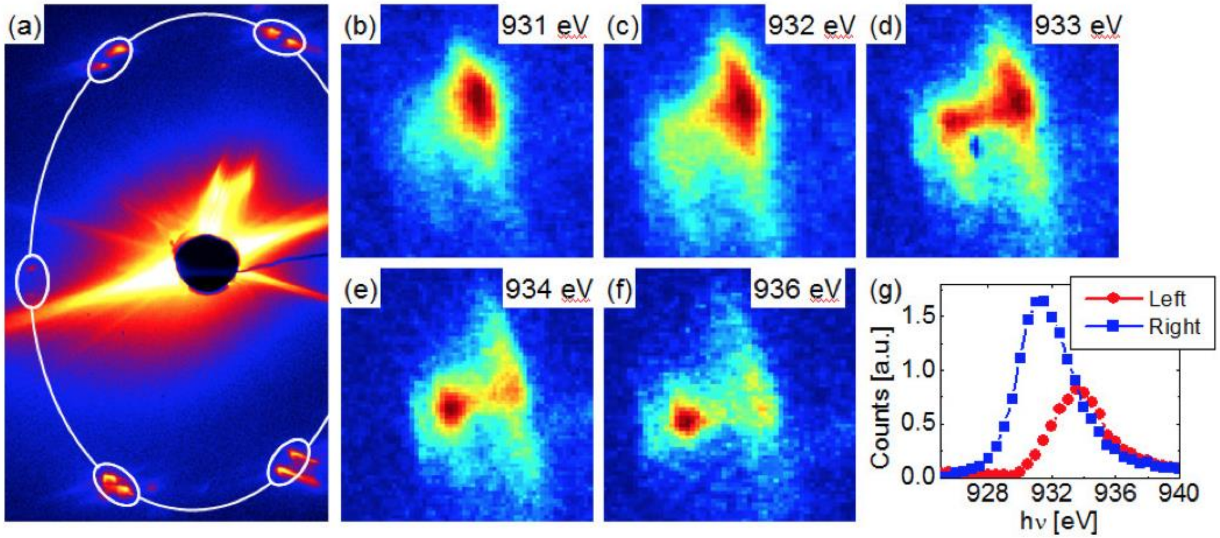




Neutron diffraction from spiral and skyrmion lattices

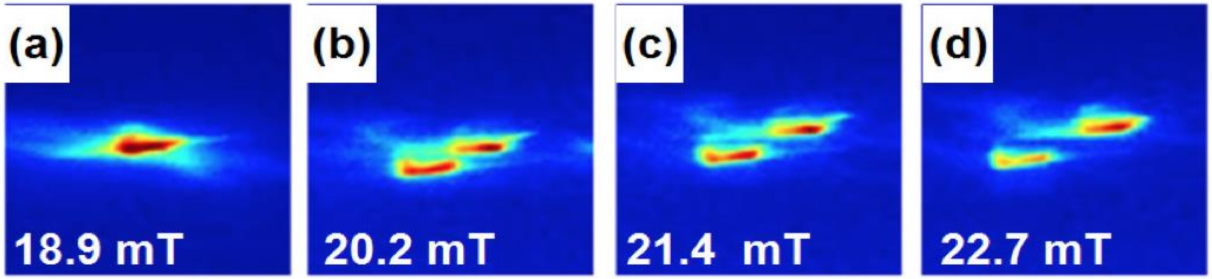
Seki, et. al., Phys. Rev. B **85**, 220406(R) (2012)

Split Skyrmion Phases in Cu_2OSeO_3



Skyrmion satellites split suggesting two phases

Different phases resonate at different energies and have different chemical character. . .



. . . and the splitting varies ~continuously with T and H

Rotational splitting is more robust than coupling to the lattice

We must be missing a term in the Hamiltonian. Ferrimagnetic?

Skyrmionic Information Processing

Opportunity

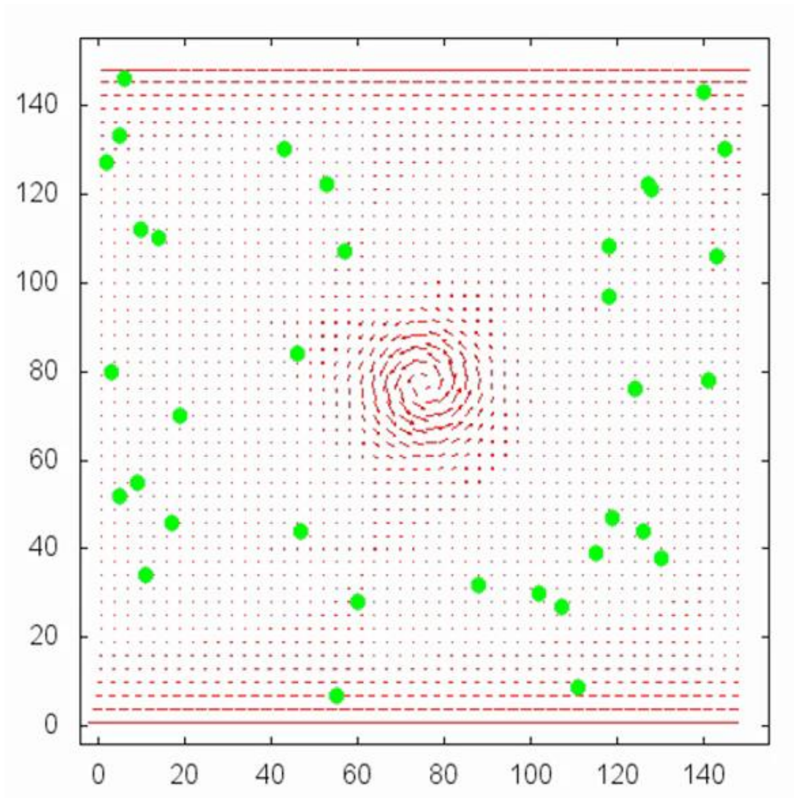
- E
  c
  r
- D
  p
  c

Chal

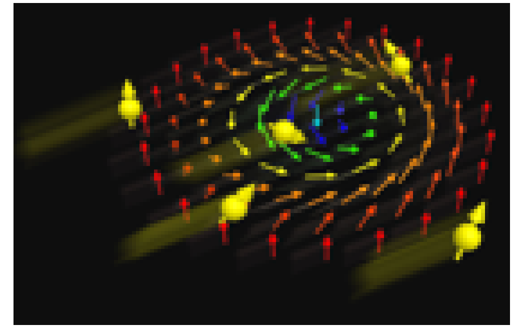
- I
  c
- F
  c

Soft

- k
  s
- N
  t
- F
  c
  freedom



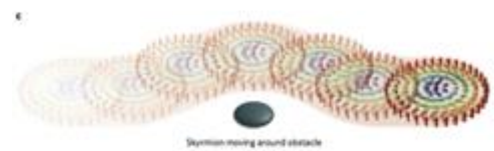
Skyrmion Motion
10.1038/nnano.2013.176



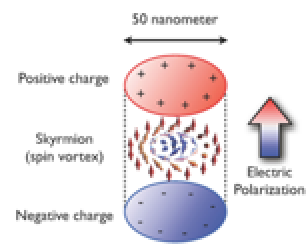
Skyrmions: Stable Topological Vortices

- - *Two quantum numbers – store information*

- - *Weak lattice coupling - low dissipation*

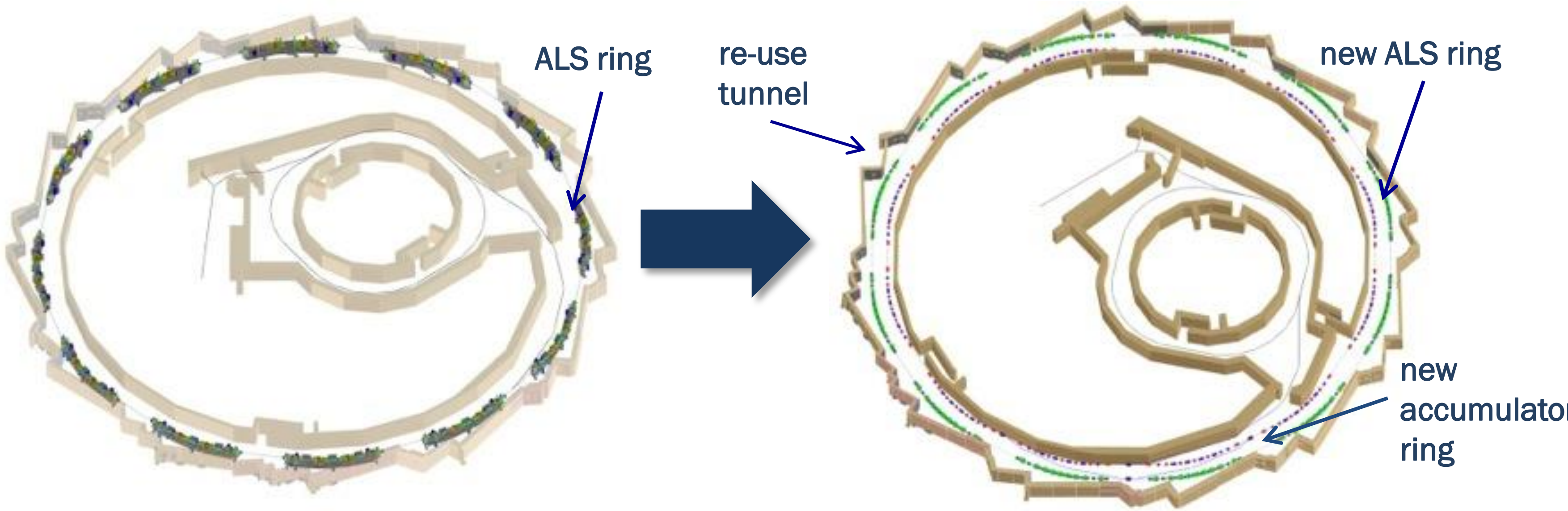


- - *Magnetoelectric – external field control*

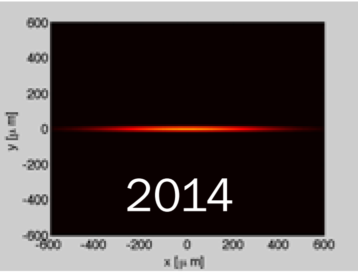


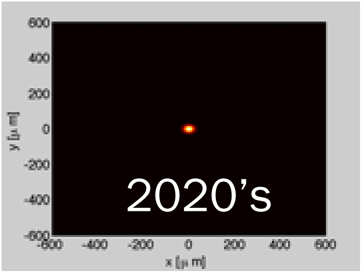
Candidate for low power classical and quantum information storage and processing

Scope of ALS-U



ALS today	ALS-U



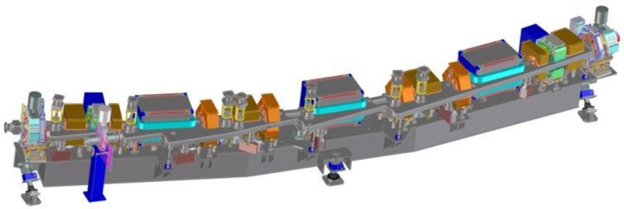


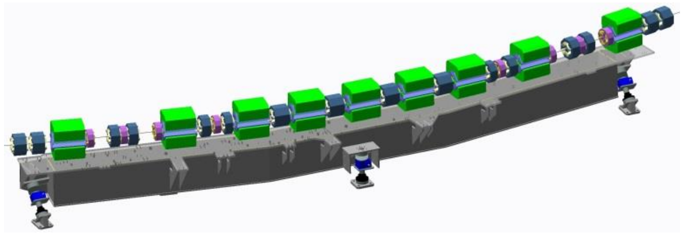
- New accumulator and storage ring based on multi-bend achromat lattice
- Re-use tunnel and beamlines

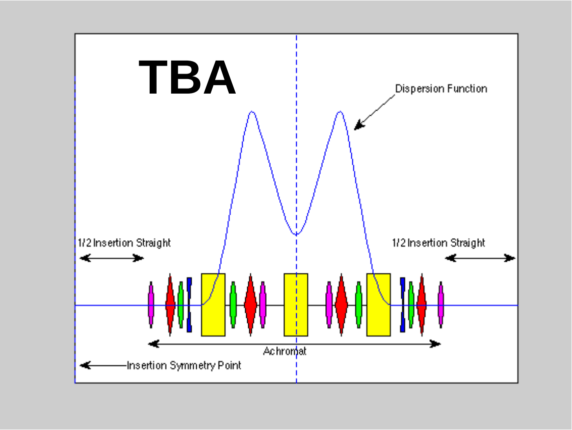
ALS-U will provide highest-power coherent soft x-rays from a synchrotron

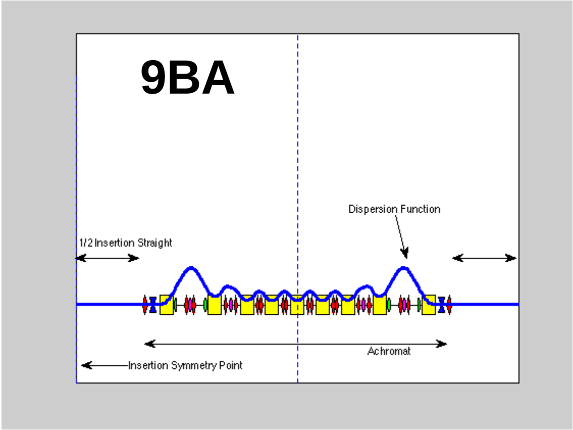
Multi-bend achromats pave way to the diffraction limit

Lattice design of ALS would evolve from a triple-bend achromats (TBA) to a multi-bend (9BA) achromat for ALS-II. Result is a large reduction in emittance









MBA: Strong Focusing and Low Dispersion

First used for MAX-IV.

$e_x = 2000\ \text{pm}\ @\ 1.9 GeV$

$e_x = 52\ \text{pm}\ @\ 2.0 GeV$

$$e_x = C_L \frac{E^2}{N_D^3}, \qquad e_x \mu \frac{E^2}{C^3}$$

C_L = lattice constant
N_D = # dipoles
C = Circumference

Some Parting Thoughts

DOE x-ray facilities have a large impact on diverse areas of science and technology, serving over 10,000 users/year

ALS fills an important soft x-ray niche that offers useful electronic, chemical, and magnetic contrast

Increasing source brightness combine spectroscopic contrast with imaging and time resolution and broadens the application areas

A planned upgrade of the ALS will provide intense, diffraction-limited soft x-ray beams that will continue these trends