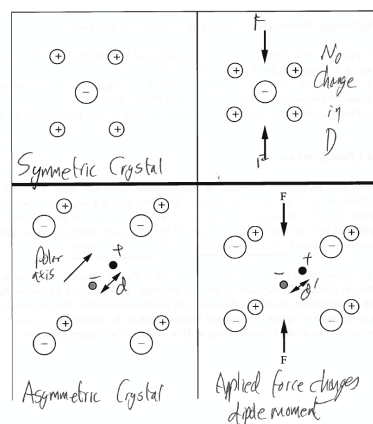


Q1

Part (a) of this question was well answered. In part (b) many candidates failed to note that the key point about a motion detector is the need to differentiate movement of a warm object across the field of view from overall changes in temperature of either the scene or the detector. A surprising number of candidates argued that the output from the two sides should be summed for more sensitivity rather than being connected in opposition to ensure that only changes affecting one side led to triggering. Candidates also failed to note that a pyroelectric sensor with a low emissivity coating could be used to compensate for temperature changes of the detector itself. The final, more mathematical, part (c) was reasonably well answered.

- a) Polarisation in a crystalline material arises from asymmetry. In a piezoelectric material the ions in the crystal structure are arranged such that a change in lattice parameter in one axis (uniaxial strain), such as would occur under uniaxial stress, results in separation of the centre of -ve and +ve charges leading to a net dipole moment. Pyroelectric materials have crystal structures with a permanent dipole so they must be asymmetric and strain will change the magnitude of the dipole. Consequently, all pyroelectric materials are piezoelectric. In the absence of a permanent dipole, however, a pyroelectric effect will not be seen.



The sketch above shows the behaviour of a piezoelectric crystal.

b) [This question relies on applying knowledge from the course to details of a practical application not explicitly covered in the course. Candidates can use what they have learnt to work through this nonetheless]

- i) Gold can be assumed to have a very low emissivity meaning any incident infra-red radiation is reflected away. Any pyroelectric voltage generated in this element can, therefore, be assumed to arise from changes in temperature at the detector. If the two elements are identical except for this factor it provides a way to null out such effects.
- ii) A single zone detector could be triggered by an overall change in the temperature of the scene that happened over a short time scale. If we compare the light falling on two different detectors with a lens arranged so as they are looking at different parts of the scene we can arrange for the detector to produce a voltage only if part of the scene changes temperatures, as would be expected from something moving across it.
- iii) The key point here is that the gold elements need to be arranged so as to produce an opposite polarity voltage from the active elements. Then the first pair of elements should be connected in

opposition to the second so that any stimulus producing equal responses on both sides is nulled. In this way only a change in incident IR radiation on one side of the detector will result in an input to the FET amplifier.

iv) If we thermally anchor the elements any heat arriving via infra-red radiation at the elements will drain away more quickly. This will reduce the thermal time constant and the overall responsivity of the detector in both current and voltage modes. However, it would increase the utility of the detector in sensing high frequency changes in incident IR. There is, therefore, an intrinsic trade off here. A detector designed for a burglar alarm is unlikely to want a large G_T however a detector optimised for high-speed response would.

c) i) ["Explain carefully" means that a bare derivation is not sufficient to gain full marks. An explanation of how the derivation works and the conceptual steps involved is required. This is not given in the notes in full and simply copying relevant sections will score poorly – a similar question for voltage responsivity is provided in the examples sheet.]

We are given the temperature difference equation and we need dT/dt for the element. If the temperature of the surroundings is assumed to not vary significantly on the timescale in question, we can make the assumption that $d\theta/dt$ is equal to dT/dt . We can therefore write an equation for dT/dt .

$$\frac{dT}{dt} = \frac{\eta W_0}{G_T + i\omega H} e^{i\omega t} = \frac{dT}{dt}$$

Having calculated that we can write an equation for the responsivity. We need to note that we need to take the modulus of what we have calculated to obtain a real, rather than complex, responsivity.

$$\frac{i_p}{W_0} = \frac{\eta W_0 A_p i\omega}{G_T + i\omega H} \quad \left| \frac{i_p}{W_0} \right| = \sqrt{\frac{\eta A_p i\omega}{G_T + i\omega H} \cdot \frac{\eta A_p -i\omega}{G_T - i\omega H}} = \frac{\eta A_p \omega}{\sqrt{G_T^2 + \omega^2 H^2}} = \frac{\eta A \omega}{G_T \sqrt{H\omega^2 \tau^2}}$$

At large ω , as we are told that period is small, we can write:

$$R_i = \frac{\eta A \omega P}{G_T \omega \tau^2} = \frac{\eta A P}{H}$$

The volume specific heat is simply $c = H/dA$ giving:

$$R_i = \frac{\eta P}{c d}$$

Which allows us to calculate current responsivity as required. In particular, we note that responsivity is inversely proportional to thickness.

ii) PVDF is easy to make as large thin films and is cheaper, but has inferior pyroelectric properties. We note here that the current responsivity as such does not depend on area, so simply making a larger area detector is not helpful. However, the voltage responsivity does, and most detectors

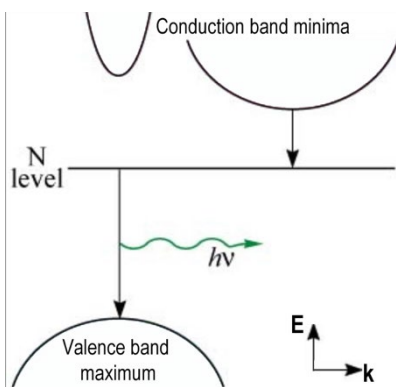
operate in voltage mode. So, if a large collection area can be used PVDF is advantageous (as in laser fluence detectors).

Turning to the specific situation here we can calculate the current responsivity of the LiTaO element as $1 * 230 \times 10^{-6} / 3.2 \times 10^6 * 40 \times 10^{-6} = 1.8 \times 10^{-6} \text{ A/W}$. To get the same current responsivity as the LiTaO element described, a PVDF element would need to be 5.77 microns thick. As PVDF is a plastic, producing such thin films is easy (unlike the challenging polishing required to produce thin ceramic elements). However, consideration would need to be given as to how to mount the thin film of plastic which, unlike a ceramic element, is not rigid. If the plastic is glued to a support then G_T is large which may be an issue, if used as a membrane issues of robustness may occur.

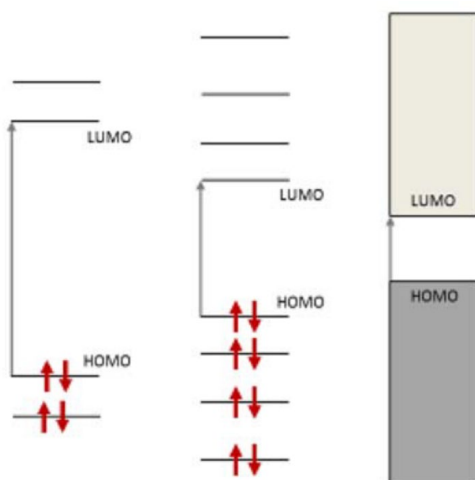
Q2

First part (a-b) generally well answered, although discussion sometimes lacked clarity, e.g. in (b)(iii). Some candidates confused by (a), i.e. application of Heisenberg uncertainty relationship to band diagram and the need for impurity addition. Answers to second part rather scattered, with some candidates trying to just fill in blocks from lecture notes rather than showing clear understanding and ability to connect across notes. Scores of undergraduate candidates to this question were all below 10, and rather disappointing.

a) GaP is indirect semiconductor, ie intrinsically not efficient at light emission. Efficient light emission is achieved by adding N impurity that enters P site. The impurity level sits in band gap below the conduction band minimum. Because it is spatially localised, its spread in momentum is large according to Heisenberg relation ($\Delta x \times \Delta p \geq \hbar/2$; see sketch). Carriers can hence radiatively recombine via the N level, as it can absorb the required momentum change (see energy and momentum conservation in sketch).



b) (i) Bandgap of PPV will decrease with increasing chain length. This can be rationalised by a “particle in box” model, as smaller chain length corresponds to larger confinement, hence larger energy gap. This is also analogous of transition from atomic levels to energy bands discussed for inorganic semiconductors like Si, where the energy levels split and broaden according to Pauli’s exclusion principle.



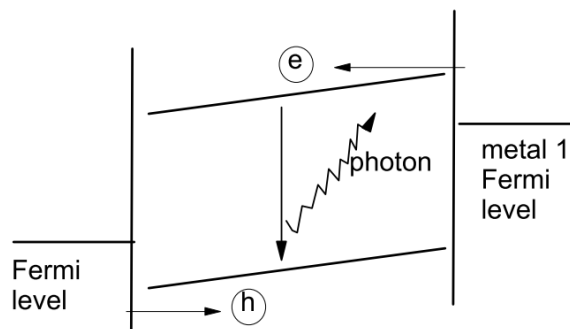
(ii) Exciton BE can be estimated with scaled hydrogenic model: $R = R_0 m^*/\epsilon_r^2$

where R_0 is the Rydberg unit of energy (13.6 eV). This gives $BE(\text{exciton}) \approx 0.34 \text{ eV}$

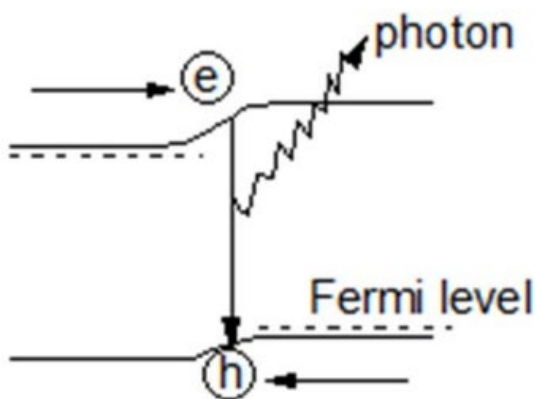
This is large exciton BE compared to standard inorganic semiconductors like Si, and means that much of the optoelectronic properties of such organic semiconductors are dominated by processes involving excitons.

(iii) As highlighted in (ii), for PPV the decay of excitons is key process, and thus unlike for inorganic semiconductors like GaP, simplest LED structure can be single layer device for PPV, whereas for GaP it's a p-n junction. More efficient LED devices can be formed via heterostructures, again bearing in mind the different device physics.

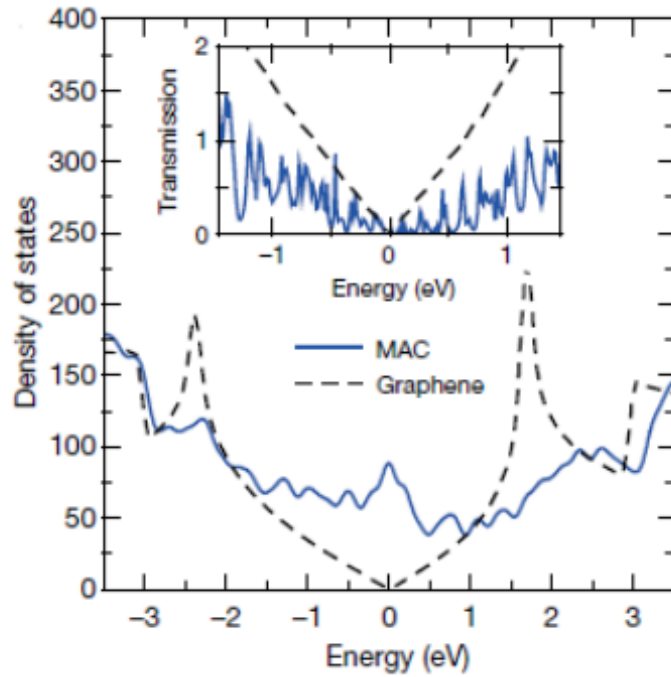
PPV:



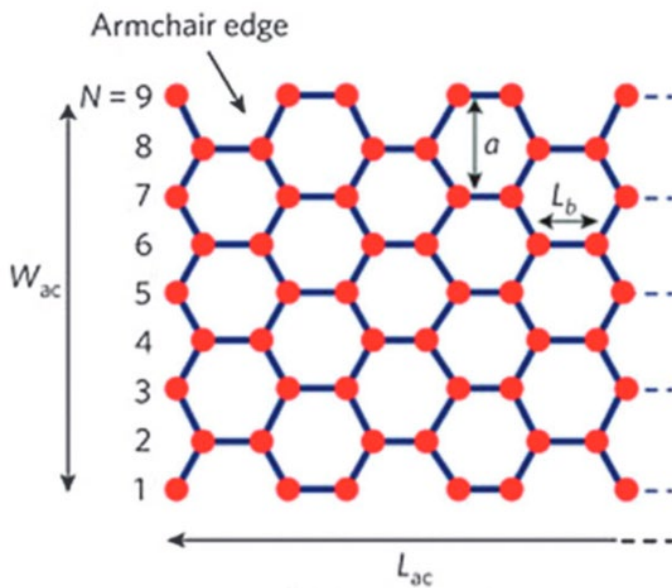
GaP:



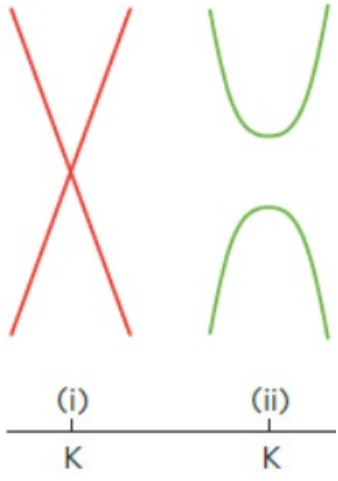
c) Graphene is a zero-band gap semiconductor with a linear E-k dispersion around the so called K-points. The disorder in monolayer sp²-bonded amorphous carbon (MAC) will introduce band flattening and localised states in the density of states (DOS). The V-shaped DOS of crystalline graphene around the Dirac point will be no longer present. The mobility of MAC will thus be very low, so its conductivity. MAC might be used as anti-corrosion layer in for instance magnetic device applications, or as ultra-thin electron microscopy support layer.



d) Armchair graphene nanoribbon (GNR) has “armchair” edge structure alike carbon nanotubes discussed in lectures.



While the detailed electronic structure of GNRs depends on their edge structure, a fundamental motivation is to open a band gap compared to gap-less graphene (see sketch). The size of the GNR band gap will scale inversely with their width (based on quantum confinement). This ability to tune electronic properties, like the band gap, makes GNR very interesting for nanoelectronics, alike carbon nanotubes.



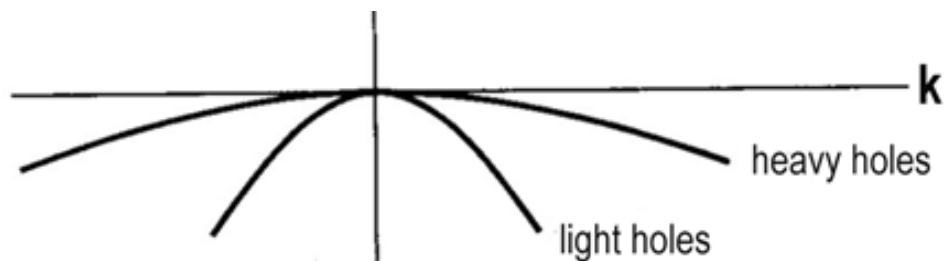
Q3

Part (a)(ii) well answered, while labelling in (i) not clear by some candidates. Parts (b)-(d) showed good basic understanding what hybrid perovskites are. Answers to part (e) varied from very fundamental derivation to scattered excerpts from lecture notes. Confinement argument generally understood, but some answers lacked detail such as confinement occurring for both electrons and holes.

a) i) The labelling of holes refers to the so-called effective mass, defined as the inverse of the band curvature:

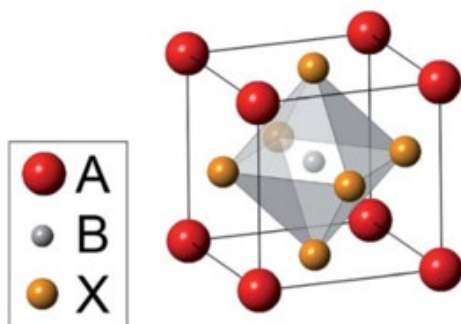
$$m^* = \hbar^2 \left(\frac{d^2 E}{dk^2} \right)^{-1}$$

A weaker curvature gives larger effective mass, see labelled sketch. Note that this refers to magnitude not sign (electron and hole effective masses have opposite sign).



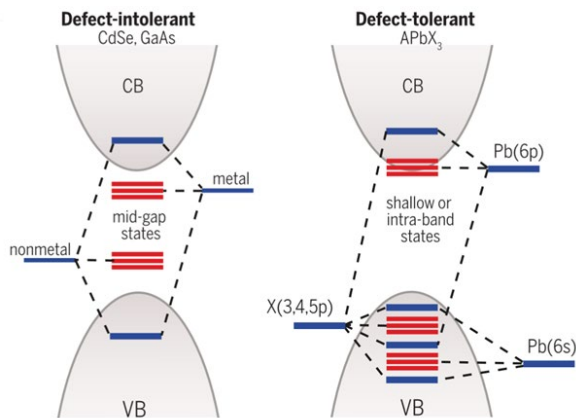
ii) A small m^* allows easy ionisation of dopants. Second, low m^* gives high mobility and high conductivity. The detailed band structure can vary with the thermal expansion/contraction of the lattice, so can the carrier concentration (and scattering) with T, hence the effective mass can be temperature dependent. Typically (for Si) m^* is found to increase with T.

b) MAPbI₃ has perovskite structure with formula ABX₃, where A = MA⁺, B = Pb²⁺ and X = I⁻. The structure consists of a 3D network of corner sharing BX₆ octahedra.



The lead halide cage primarily dictates bandgap. The material shows strong, tunable optical absorption over ~1.4-2.2eV range. It also shows good charge transport properties and can be deposited cheaply over large areas.

c) Unlike to GaAs, defect states of MAPbI₃ are thought to be shallow or to lie outside the bandgap. Hence they do not act as deleterious traps.



d) FA is larger cation, hence FAPbI₃ has larger lattice constant (see (b)). Lattice expansion means that bandgap decreases.

e) Starting with a 1D infinite potential well, the well must contain an integral multiple of half electronic wavelengths:

$$a = n \times \lambda / 2.$$

Using the de Broglie wavelength of the electron $\lambda = \frac{h}{p}$, and taking the electron energy as $E = p^2 / 2m$

gives:
$$E = \frac{\hbar^2 \pi^2}{2ma^2} n^2$$

Assuming the overall energy for 3D QD is simply the sum of the individual energies for each degree of freedom:

$$E_{well} = \frac{3\hbar^2 \pi^2}{m^* m_0 D^2} n^2$$

where m^* is the respective effective mass.

The band gap hence will change as

$$E_g(QD) = E_g(bulk) + E_{well}^*$$

where $E_{well}^* = E_{well}(e) + E_{well}(h)$ reflects the confinement of both electron and hole.

E_{well}^* is always a positive term, hence the band gap increases with decreasing QD diameter D , and thus optical emission will blue shift.

Q4

Candidates performed reasonably on part (a), although some lost marks by not discussing all requested elements. Part (b) was surprisingly poorly answered given it required only fairly broad-brush knowledge of the properties of different permanent magnet materials. Candidates answered (c) (i). Many were, however, unable to deduce in (c) (ii) that if the operating point of a magnet is near H_c that spontaneous demagnetisation is likely. In (c) (iii) many students failed to realise that peak (BH) is only obtained for $N=1/2$ where the material has a sufficiently high H_c . Many students claimed entirely unphysical BH products for cobalt steel that were larger than for Ferrite.

a) The key difference between a soft and hard magnetic material is magnetic coercivity. In a hard material this should be large to ensure that remanent magnetisation is retained. In a soft material, typically, we wish to minimise hysteresis losses so coercive field should be small. Hard materials are Alnico, NdFeB, SmCo, hard ferrites, etc. Soft materials are Si-Steel, iron, various grades of permalloys and soft ferrites.

In soft magnetic steels we typically thermally treat/anneal to obtain large grains, this minimises grain boundaries which obstruct the movement of domain walls and increase coercivity. In hard magnetic materials we typically wish to do the opposite and ensure small grain sizes to maximise the pinning of grain boundaries.

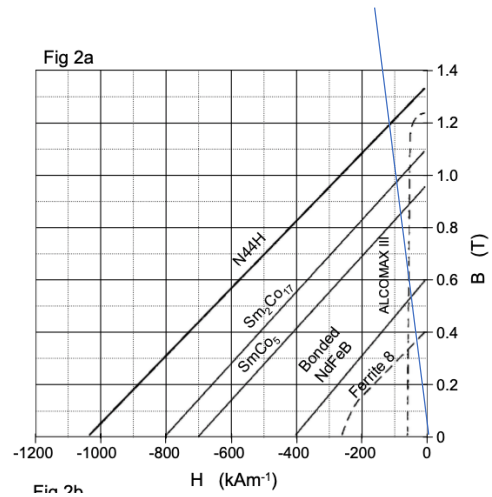
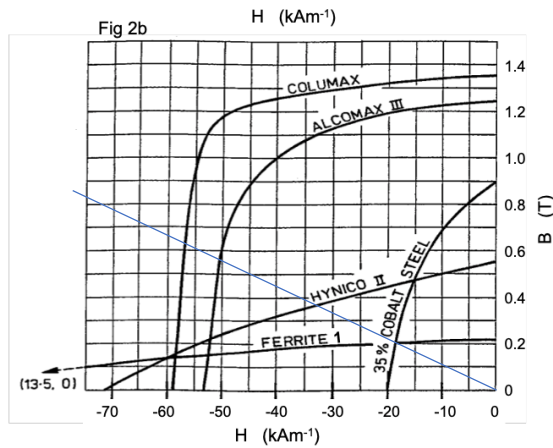
b) i) The configuration of the magnet suggests that it will spontaneously demagnetise without a keeper. This means the material cannot be a "super magnet" such as NdFeB or SmCo. This means Alnico, or a hard magnetic steel. The low field generated would tend to suggest a hard magnetic steel. Use in a toy would suggest cost is critical so cheap hard magnetic steel.

ii) The physical description and indication of use at elevated temperatures would rule out NdFeB. The shape has a demagnetisation factor of 0.5 so the material must be a super-magnet. The only plausible candidate is SmCo₅. This is an expensive material but in a high-performance application that expense can be justified.

iii) The shape has a demagnetisation factor of 0.3 so it must be either NdFeB or SmCo₅. The application points to low cost being important and the physical description suggests a plated magnet. This strongly suggest NdFeB which is cheap, but performant. No need for high temperature operation.

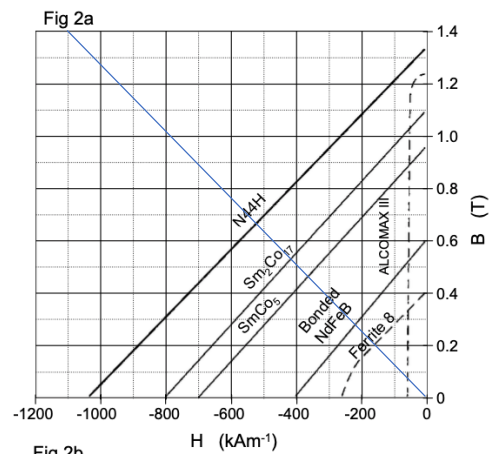
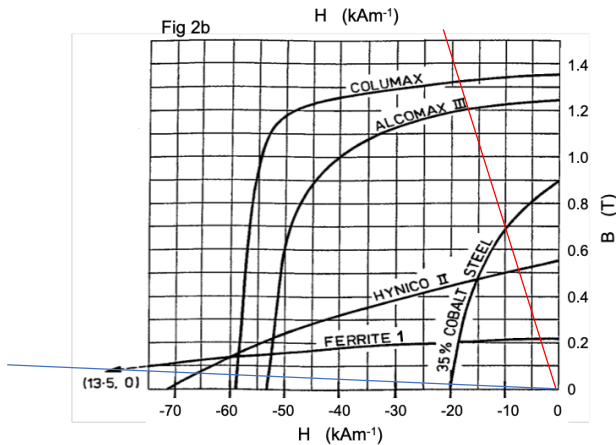
c) [These questions can be answered using the data book. Sketches/graphs are not required to be handed in – indeed data can be read off the plots using a ruler.]

i) As $B = \mu_0(M+H)$ and $H_d = -MN$ we can substitute so that $B = \mu_0 M(1-n)$ divide through to get B/H we obtain $B/H = \mu_0 (1-N / N)$. So our load line goes through 0,0 and (given N of 0.1) and $H=50 \text{ kAm}^{-1}$ $B=0.565$. We can then read off the plots 0.2 T for the Co-Steel and 0.37 T for the Ferrite 8.



ii) For the Ferrite we can see that the load line crosses the B - H loop well above H_c so this will not self-demagnetise. For the Co-Steel, however, we are operating close to H_c and thus we would expect this magnet to demagnetise.

iii) Students can either remember or quickly derive that $N=0.5$ maximises BH . However, the H_c needs to be large enough to allow this. At $H=50 \text{ kAm}^{-1}$ and $N=0.5$ $B = 0.0628 \text{ T}$ and at 500 kAm^{-1} $B=0.628 \text{ T}$ so we can plot the load lines. Clearly this is ok for the ferrite 8 and not for the Co-Steel.



For Ferrite 8 the intersection is at $B= 0.2 \text{ T}$ and 159 kAm^{-1} so the energy product is 31.8 kJ/m^3 which is correct for a high performance ferrite.

For Co-Steel at $N=0.5$ the effective B field is tiny as we have reached H_c , we need to think about a practical operating point before the BH characteristic “rolls over” – one suggestion is shown above. This is $B=0.7 \text{ T}$ and $H=10 \text{ kAm}^{-1}$ giving a BH of 7 kJ/m^3 which is about what we would expect..