Accelerators and Magnets 2

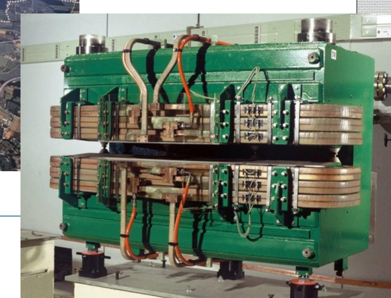
Volker Ziemann, FREIA

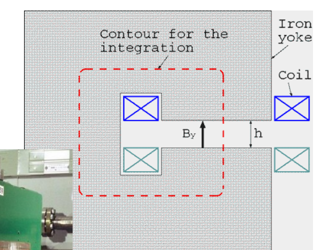
Last time:

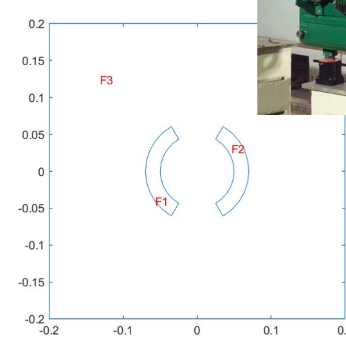
* Accelerators: LHC, MAX IV, ...
* Iron dominated magnets
* Superconducting magnets

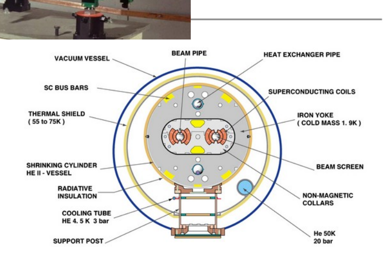
This time:

* Permanent magnets
* Magnetic measurements
* Alignment



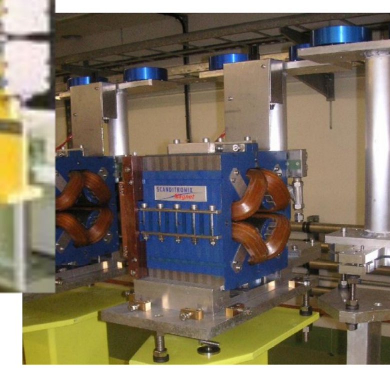


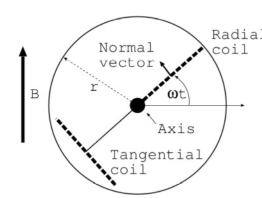


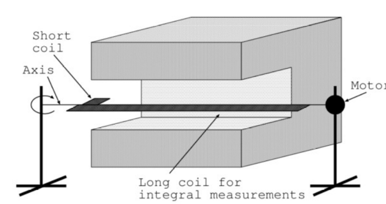


Today’s roadmap

- Remember the multipoles
- Permanent magnet
  - material
  - multipole magnets
  - undulators
  - solenoids
- Magnetic measurements
- Alignment of magnets

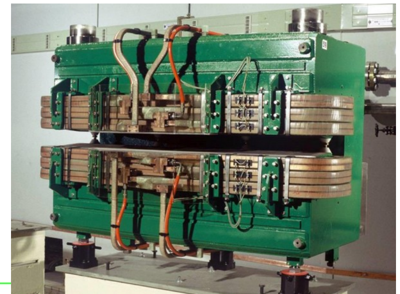


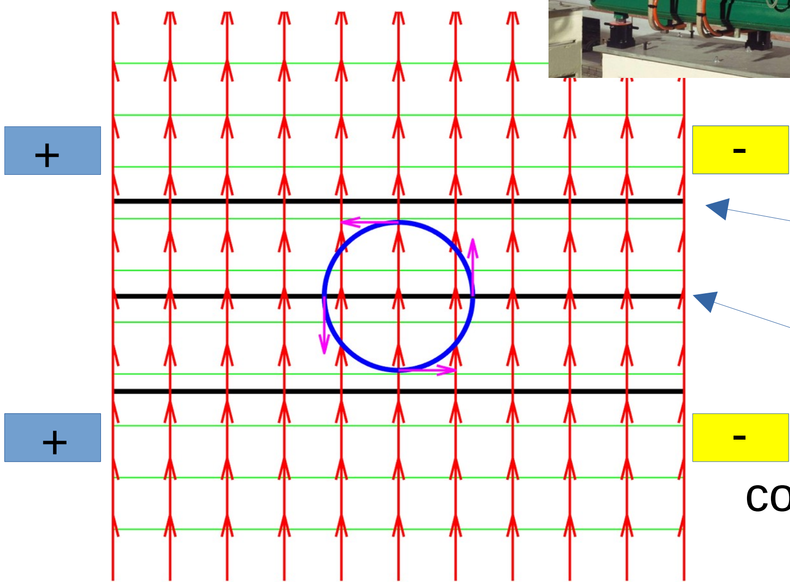




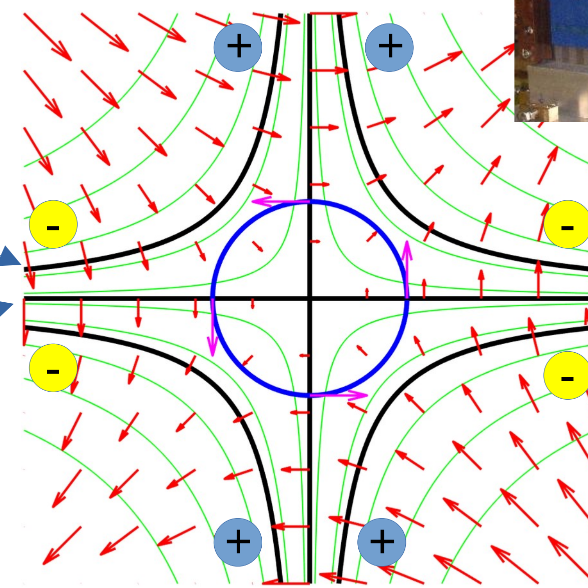
Multipole fields

Dipole





Quadrupole



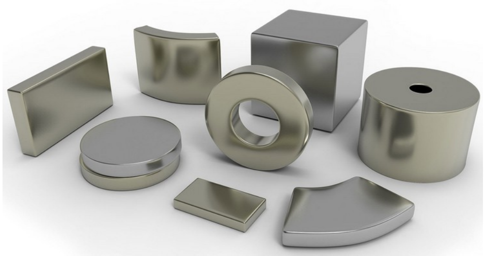
$$B_y + iB_x = B_0 \left(\frac{x+iy}{R_0} \right)^{m-1} = B_0 \left(\frac{r}{R_0} \right)^{m-1} e^{i(m-1)\phi}$$

m: magnitude $\sim r^{m-1}$, angle $\sim (m-1)\varphi$

m=tumble factor
(varvtal)

Permanent magnet material

- Magnets with large remanent field B_r
  - SmCo (B_r~1T), NdFe (B_r~1.4T)

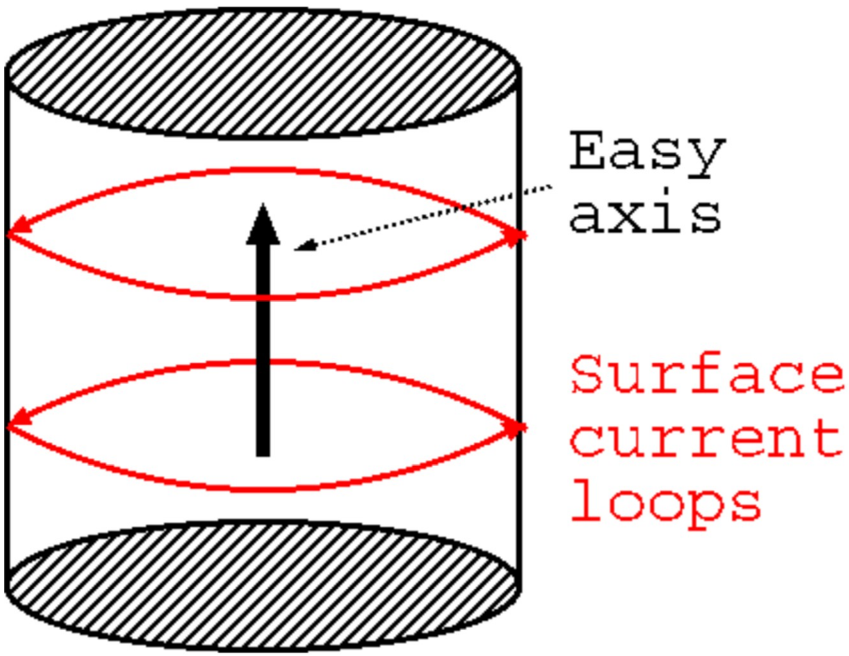


from: www.arnoldmagnetics.com

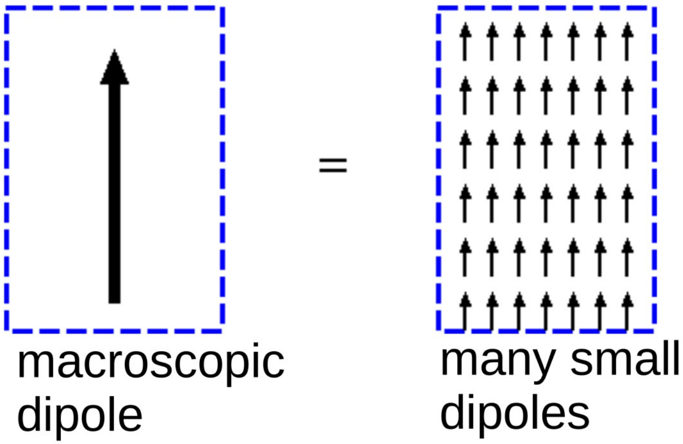
- Transparent to external magnetic fields
  - relative permeability μ_r~1

- Manufacture
  - Heat powder mixture to melt and rapidly cool
  - Grind to make powder, expose to strong field → aligns spins
  - *Sintering:* heat and compress
  - Expose to even stronger field (imprints field → easy axis)

How do they behave?



from: www.uge-one.com

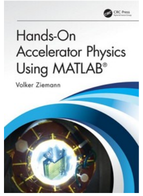


Like

* a **flux-pump** for field lines
* a **coil** around the surface carrying a very large current
* many many **small dipoles**, all aligned
* empty space (**transparent** to external magnetic fields)

Calculate field of several PM as the **superposition** of the individual fields.

PM dipoles

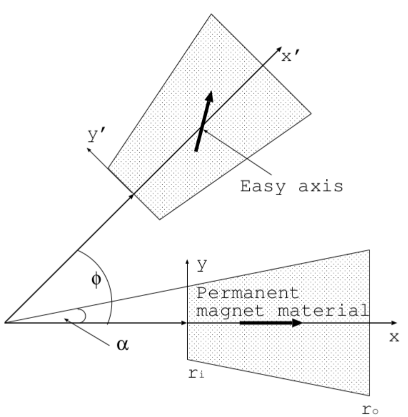


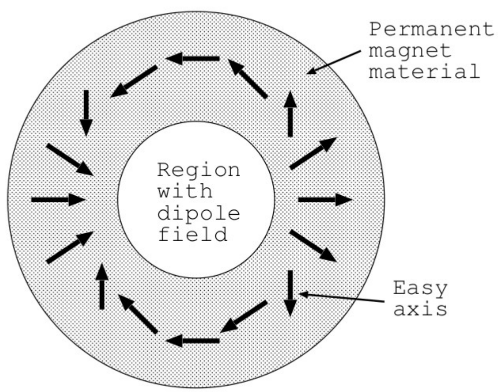
How much multipole does each small cube contribute?

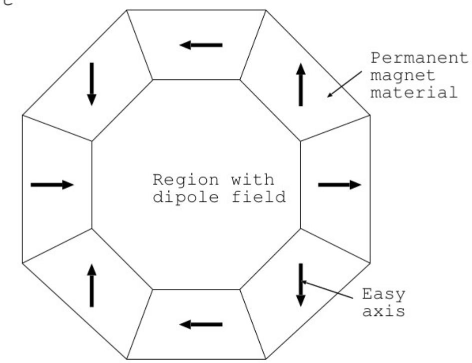
– integrate/sum over all small dipoles

$$\underline{B}^*(\hat{z}) = \sum_{m=0}^{\infty}\left[\frac{m+1}{2\pi}\int_\Omega \frac{\underline{B}_r}{z^{m+2}}\,dxdy\right]\hat{z}^m$$

Cubes are easier
to find than wedges
 - little more algebra
 with the integrals



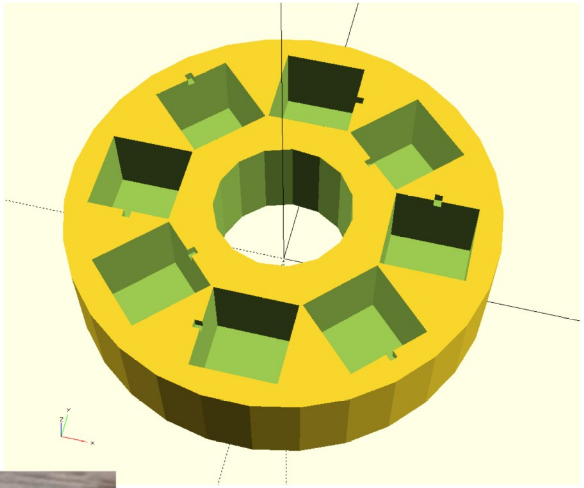


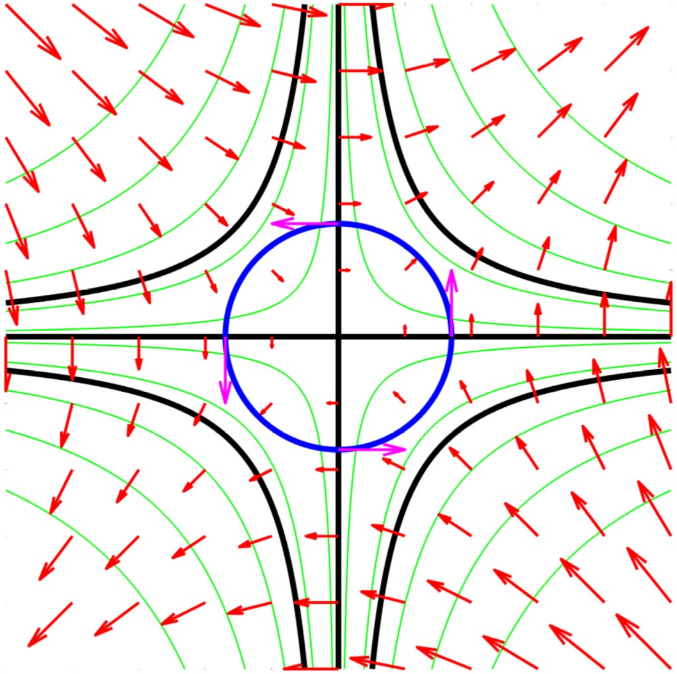


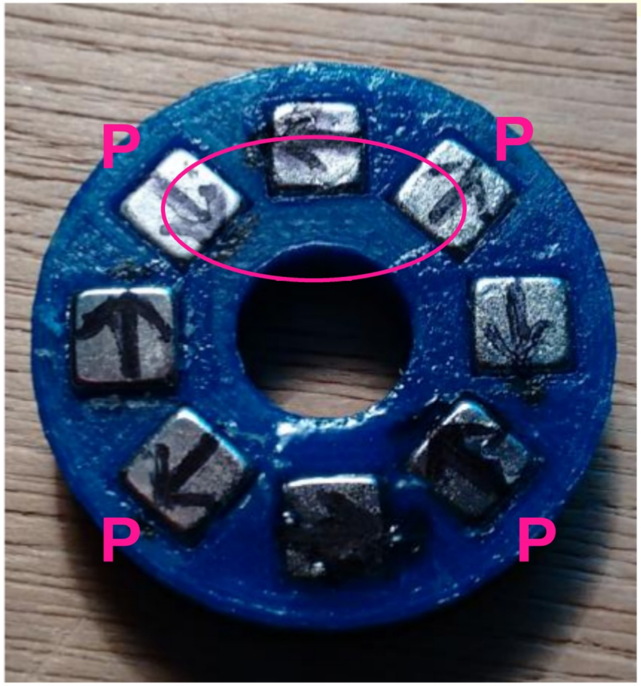
Magnetic field can be calculated
entirely analytically!
(continuous, wedges, cubes)

PM quadrupoles

Mark cubes and place with tumble factor m=2 in 3D printed frame







PM cubes pump flux lines around loops that create the field for the beam in the center.

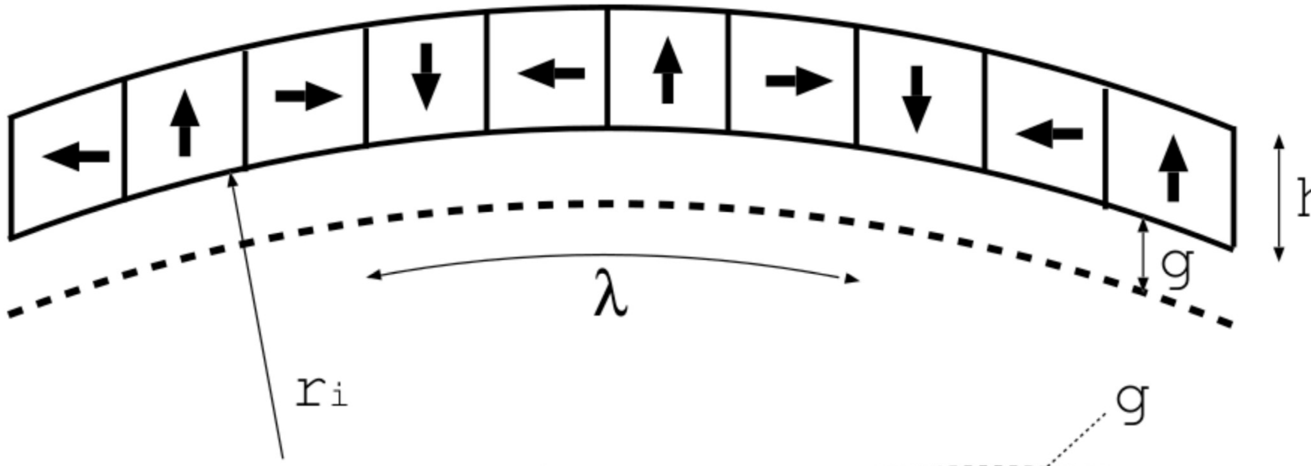
Also analytically calculated fields!

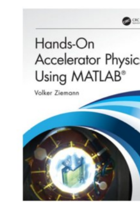
Hands-On Accelerator Physics Using MATLAB®
Volker Ziemann

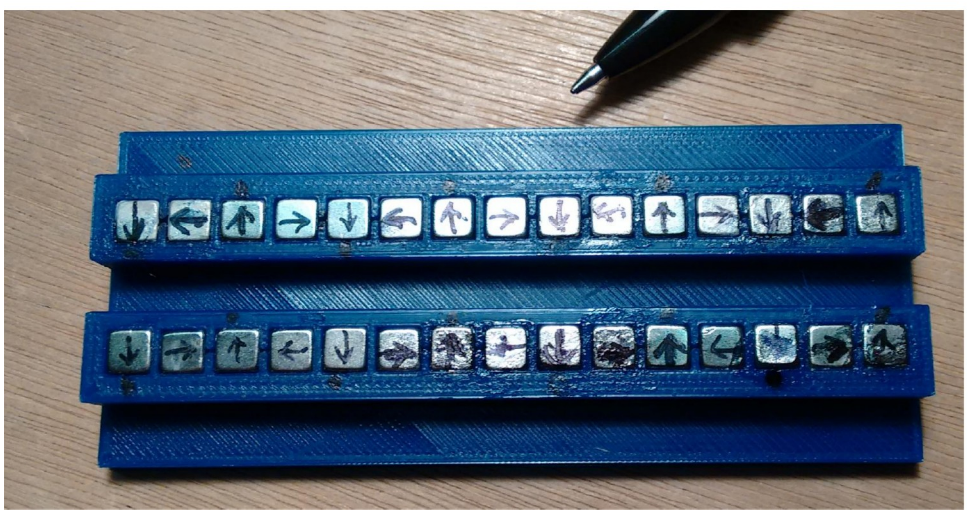
PM undulators

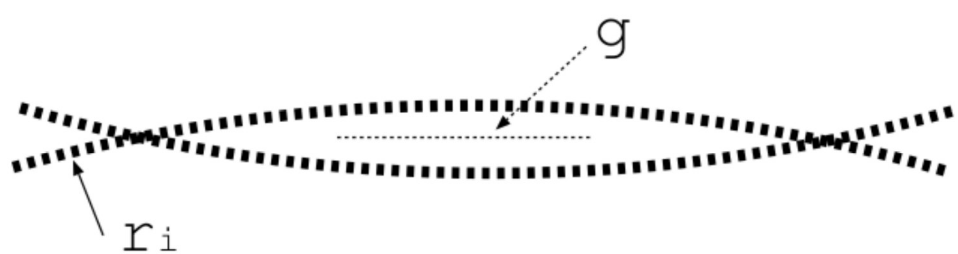
Speciality magnets to produce synchrotron radiation

Make assembly larger and larger, while maintaining the size of the cubes









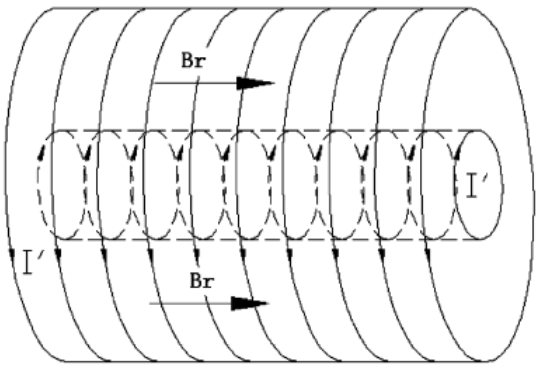
Derive magnetic field in gap entirely analytically from first principles

$$\underline{\hat{B}}^*(\hat{z}) \quad = i\underline{B}_r \frac{\sin(\pi/4)}{\pi/4}\left(1-e^{-2\pi h/\lambda}\right)e^{-2\pi g/\lambda}\cos(2\pi z/\lambda)$$

PM solenoids

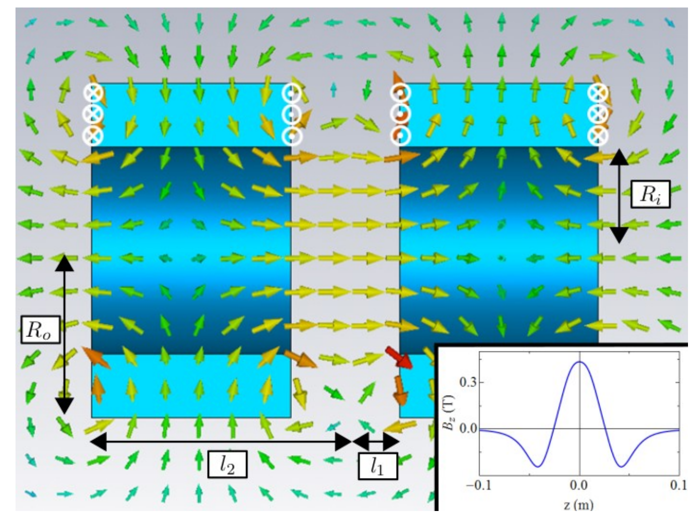
Axial magnets

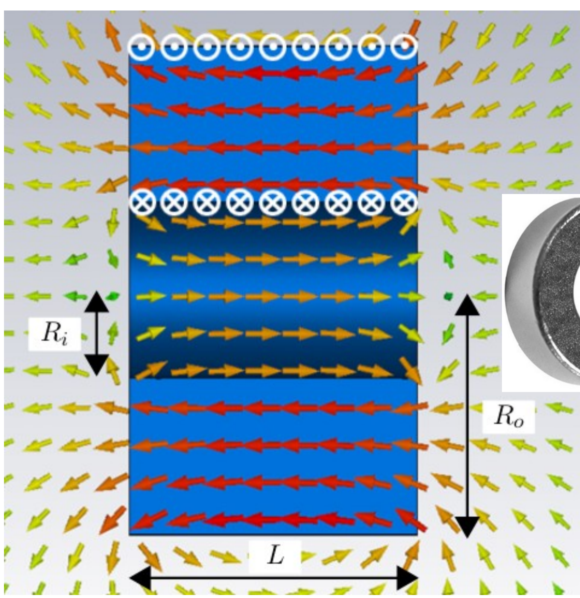
Radial magnets

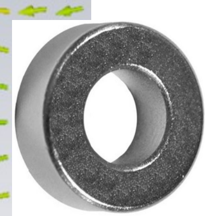


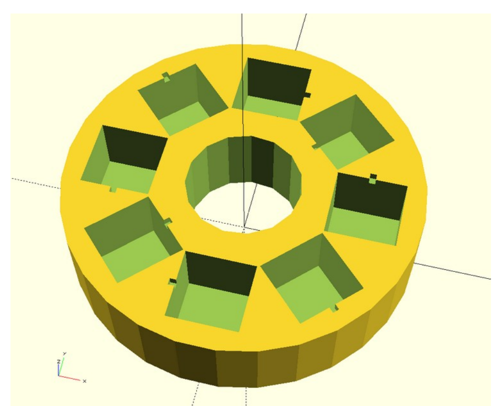
On-axis field can be calculated analytically (inner coil+outer coil)

$$B(z) = \frac{B_r}{2}\left[\left(\frac{z+l}{\sqrt{(z+l)^2+R_2^2}} - \frac{z-l}{\sqrt{(z-l)^2+R_2^2}}\right) - \left(\frac{z+l}{\sqrt{(z+l)^2+R_1^2}} - \frac{z-l}{\sqrt{(z-l)^2+R_1^2}}\right)\right]$$







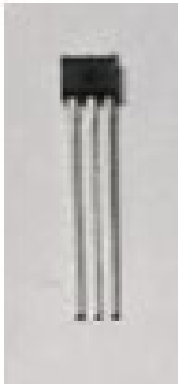


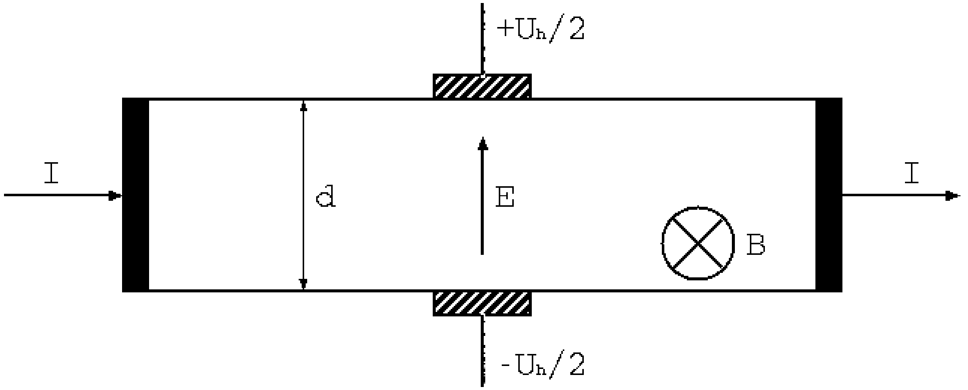
Radial magnets
- Easy axis points ‘inwards’

Axial magnets
- Easy axis points ‘forwards’

Magnetic measurements with a Hall sensor

- Magnetic field measurements
  - Pass current *I* through semi-conductor (left-to-right)
  - Perpendicular magnetic field *B* deflects charge carriers to upper and lower contacts
  - Charges accumulate and create electric field *E* to balance the magnetic deflection
  - $U_h=Ed$
  - A1324
    - V_c,GND, U_h
    - 50 mV/mT





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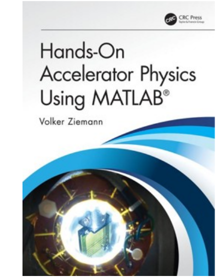
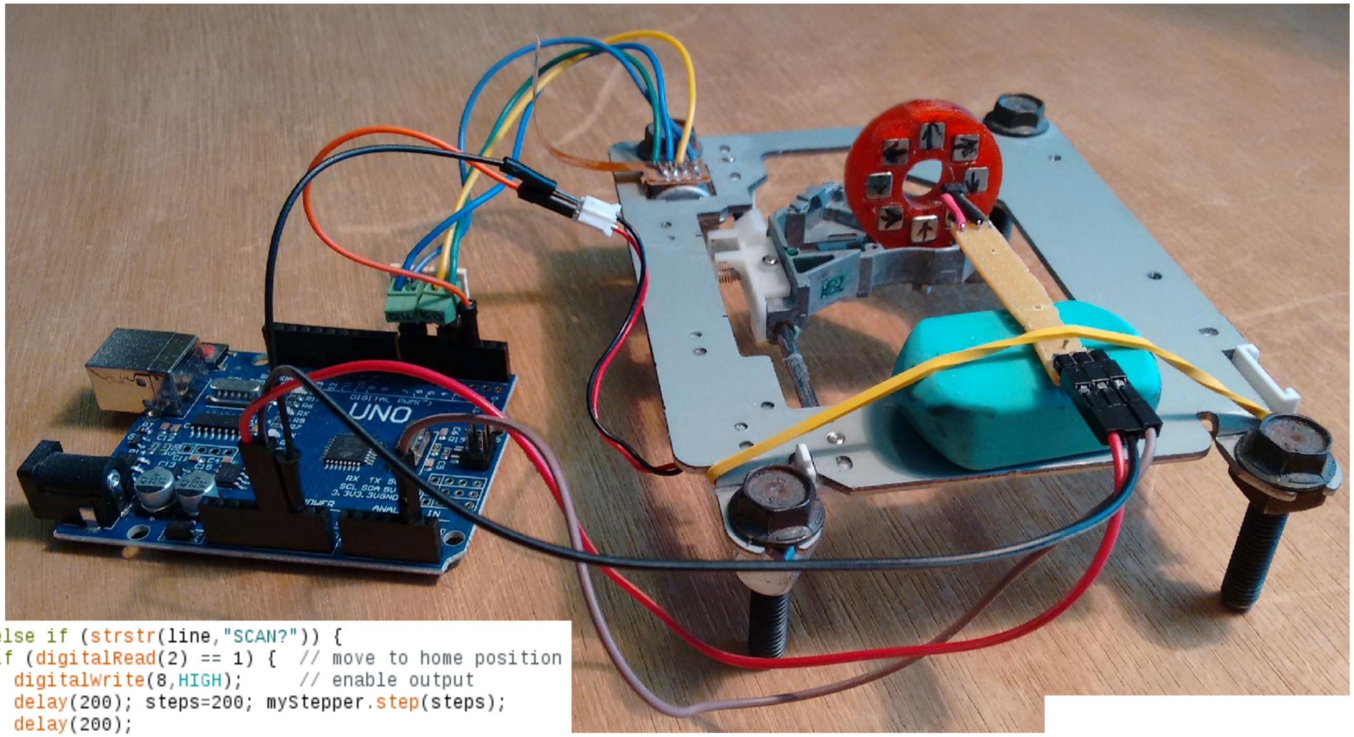


Measurement rig

(conceptual)



Frame from an old CD drive with stepper motor driven by an Arduino.

Control via RS-232 USB) from MATLAB

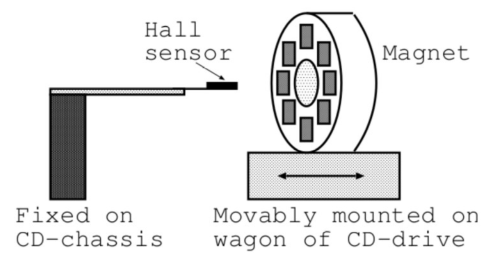
Software available from
https://www.crcpress.com/9781138589940

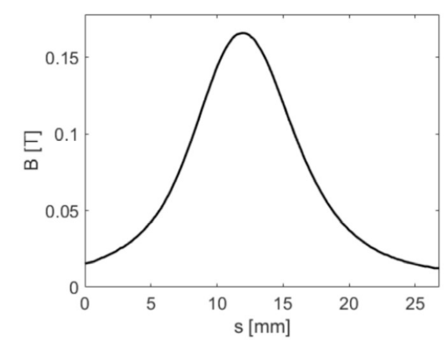
```
} else if (strstr(line,"SCAN?")) {
  if (digitalRead(2) == 1) {  // move to home position
    digitalWrite(8,HIGH);     // enable output
    delay(200); steps=200; myStepper.step(steps);
    delay(200);
  }
  Serial.println("SCAN");
  digitalWrite(3,HIGH);
  for (int i=0;i<150;i++) {
    steps=-1; myStepper.step(steps);
    delay(100);
    float B=1e-4*(5.0*analogRead(1)/1023-2.4)/1.3e-3;
    Serial.println(B,4);
  }
}
digitalWrite(3,LOW);
```

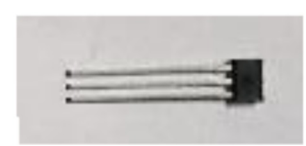
Arduino

MATLAB

```
fprintf(s,'SCAN?'); fscanf(s);      % read the "SCAN" echoed
Bfield=zeros(1,150);
for i=1:150                          % loop over the data points
  Bfield(i)=str2double(fscanf(s)); % string to double
end
xscale=0.18*(0:149);                 % 0.18 mm/motor step
plot(xscale,Bfield)
```

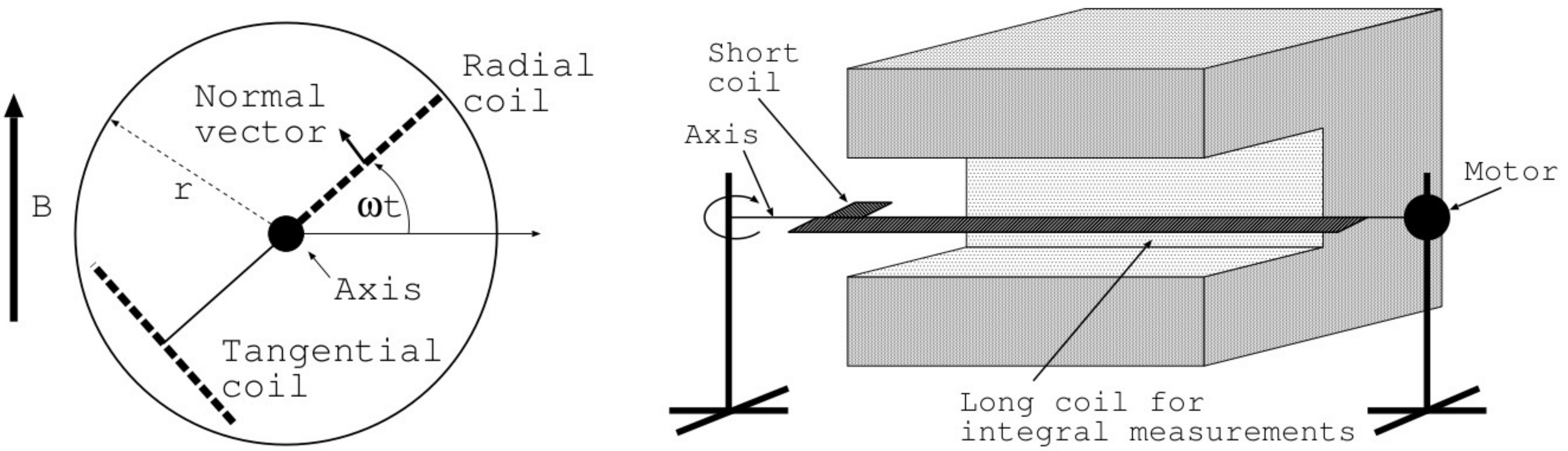






Magnet measurements with a rotating coil

- Rotating coil generates a voltage and the harmonics give the multipoles.



Works like a bicycle dynamo

Alignment

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- How do you do it?
  - Magnets on tables
  - Fiducialization to pods
  - Triangulation
- How well can you do it?
  - 0.2-0.3 mm OK
  - <0.1 mm increasingly more difficult
  - more difficult in large installations
- Sub-micron for linear colliders → beam-based

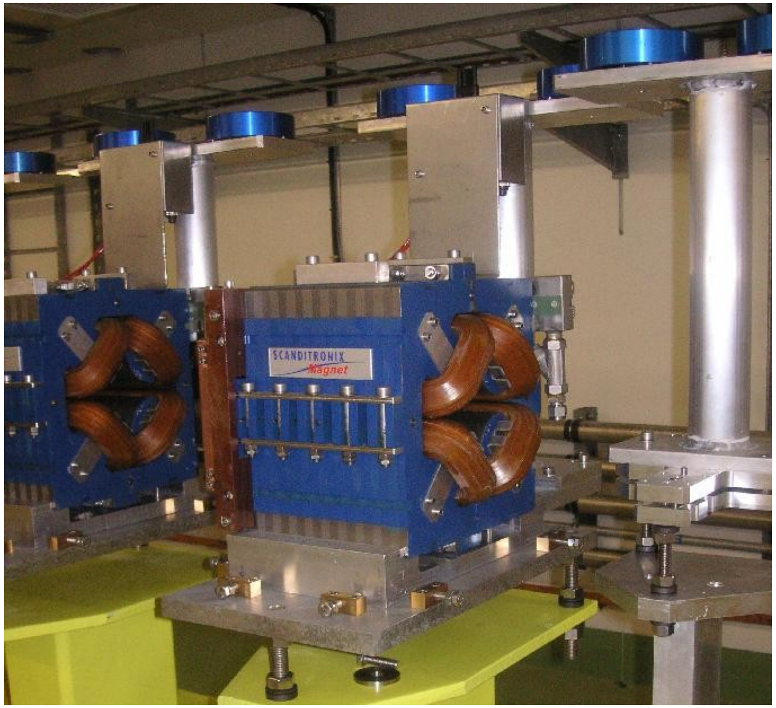
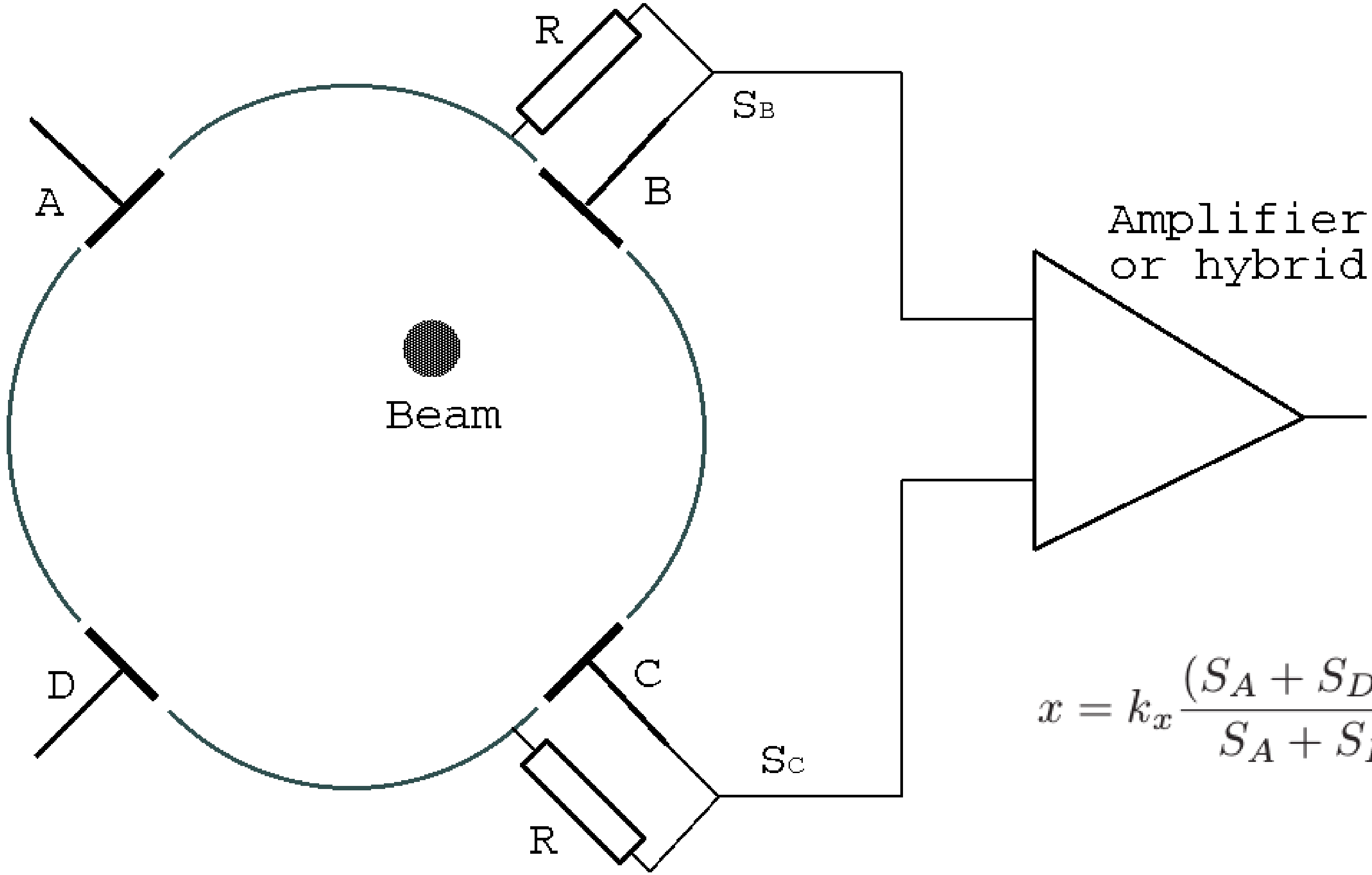


Photo: R. Ruber, CTF3-TBTS

Beam Position Monitor



$$x = k_x \frac{(S_A + S_D) - (S_B + S_C)}{S_A + S_B + S_C + S_D}$$

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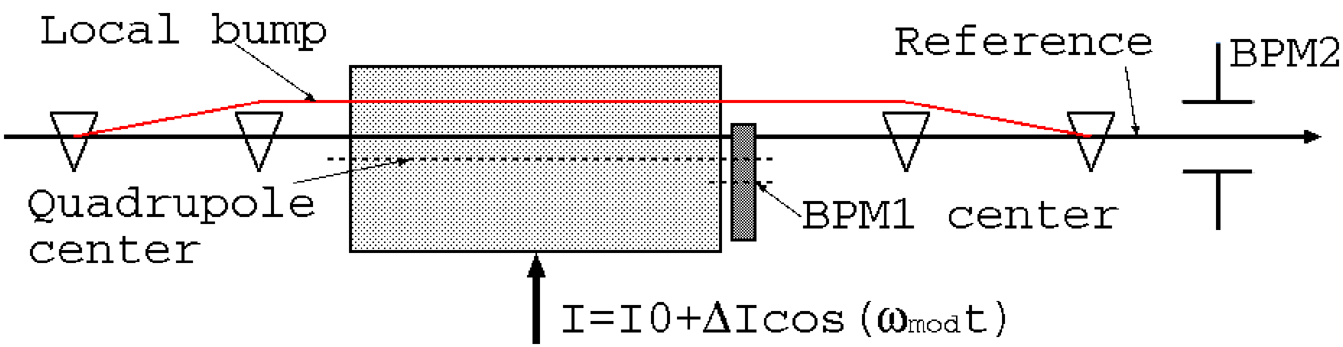
Find offsets with K-modulation

- BPM+Quadrupole are often mounted on the same support



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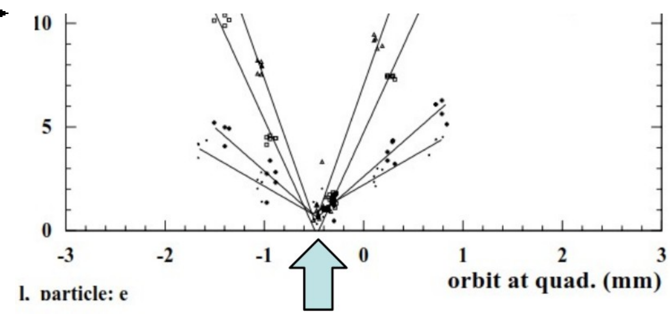
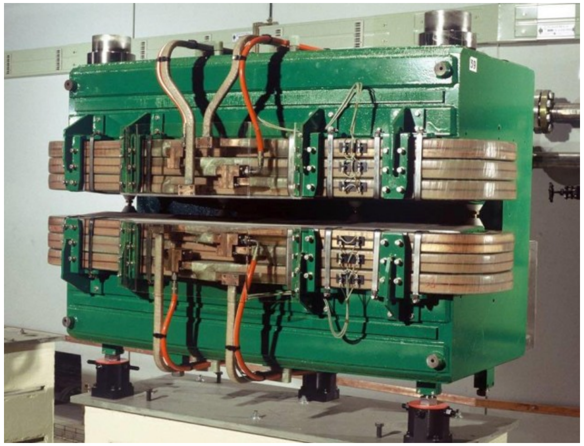
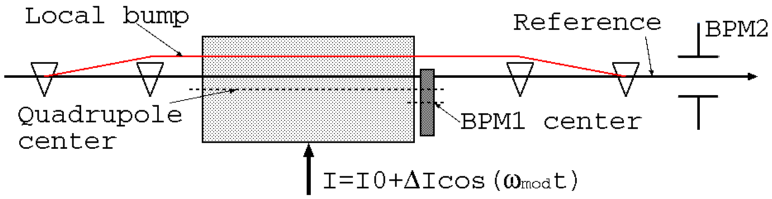


- Modulate focal length *f* of quadrupole
  - Kick from quadrupole $\Theta = x_{offset}/f(\omega)$ is also modulated
  - Observe on BPM2 and minimize signal by moving beam with a bump → quadrupole center
  - Reading of BPM1 gives BPM1 offset rel. to quadrupole

Summary

- Accelerators
- Iron-dominated magnets
- Current-dominated magnets
- Permanent magnets
- Magnetic measurements
- Alignment

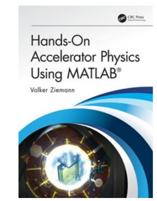




More fun courses...

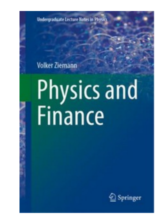
...*brought to you by **FREIA***

- 1FA330: Accelerator physics and Technology



- 1FA362: Permanent magnets

- 1FA348: Accelerators and Detectors (MJ++)
- 1FA361: Physics and Finance



- 1FA589: Optics and Photonics (VG)
- 1FA349: Sensor to Report