Unit 18
Persistent currents and dynamic effects

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With significant re-use of material from the same unit lecture by Ezio Todesco, USPAS 2017

QUESTIONS

- Each conductor in a magnetic field tends to shield itself from the field – what happens for superconducting cables in a magnet ?
- Is there a dependence on ramp rate, and on the history of the magnet ?
- Are these effect large ? How can we remove them or live with them ?

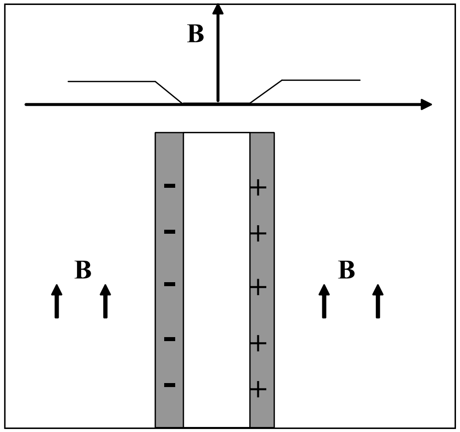
- These slides heavily rely on the lecture “Dynamic effects in superconducting magnets” by A. Jain at USPAS, Phoenix 2006, and on chapter 6 of Schmuser

CONTENTS

1. Persistent currents
2. Decay
3. Snap-back
4. Ramp effects

PERSISTENT CURRENTS: SUPERCONDUCTOR IN EXTERNAL FIELD

- Superconductor slab in external field
  - A superconductor tries to shield itself from a magnetic field
  - The shielding is made through currents that flow in each filament
  - These currents flow inside the superconductor and therefore have no resistance (persistent)

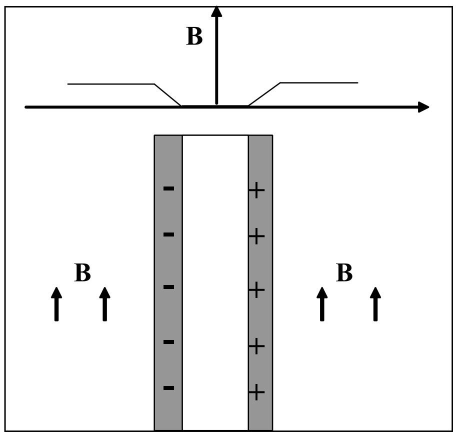


  - To maximize the shielded area, the persistent currents must have the largest possible current density, i.e. the critical current – which depends on the external field (critical state model)
  - These induced currents perturb the field harmonics

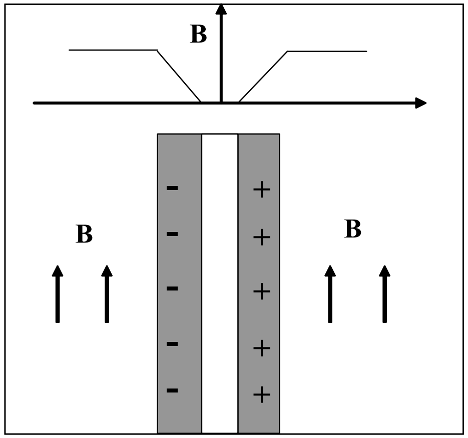
Reminder - superconductors in a changing field act to shield their interior - persistent currents

- Superconductor slab in external field

  - For low external fields, the critical current flows in the outer skin to generate a field opposite to the external one – inside the field is zero



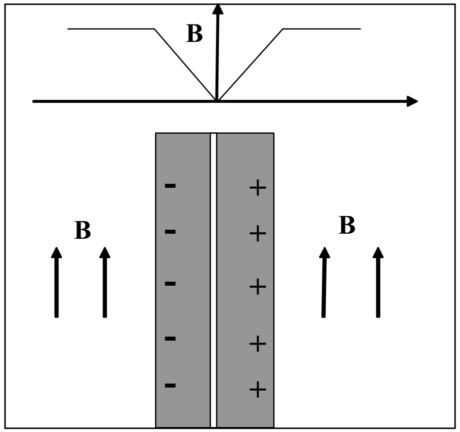
  - When the external field rises, the area filled with shielding currents increases



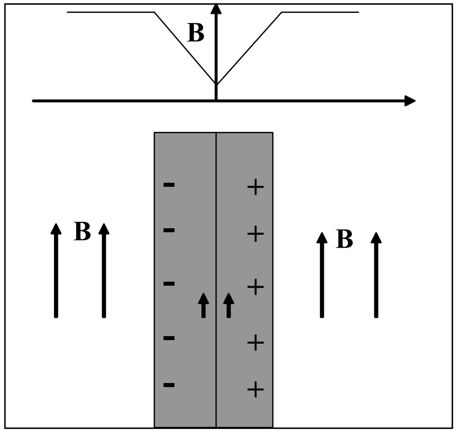
Reminder - superconductors in a changing field act to shield their interior - persistent currents

- Superconductor slab in external field

  - When the external field reaches a given value (penetration field), all the superconductor is filled with shielding currents



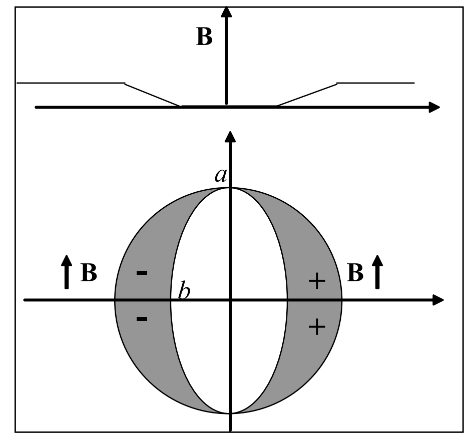
  - Beyond this value, the superconductor cannot do anything more to shield itself and a magnetic field is present inside it



Using the Bean model the field penetration can be estimated

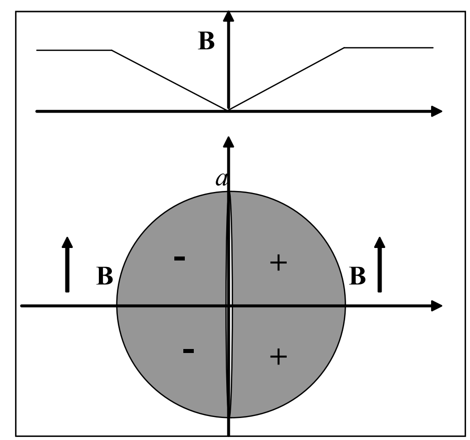
- Circular filament in external field
  - Hypothesis: currents flow in an elliptical shell (Bean model)
  - A bit of trigonometry gives the shielding condition determining b

$$B = \frac{2\mu_0 j_c a}{\pi}\left(1 - \frac{\alpha \cos\alpha}{\sin\alpha}\right) \qquad \cos\alpha = \frac{b}{a}$$



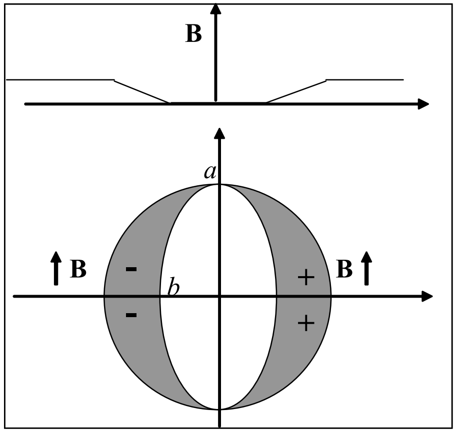
  - At full penetration one has b=0 and the magnetic field is the penetration field

$$B = B_{pf} \equiv \frac{2\mu_0 j_c a}{\pi}$$



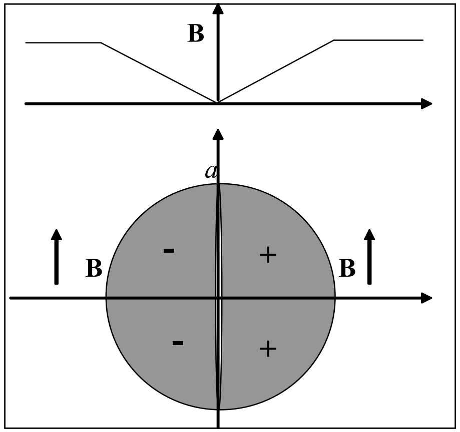
- Magnetization in a circular filament in external field
  - Magnetization estimate in the Bean model

$$M = \frac{2\mu_0 j_c}{\pi a^2} \int_{-a}^{a} dy \int_{b\sqrt{1-y^2/a^2}}^{\sqrt{a^2-y^2}} x dx = -\frac{4\mu_0 j_c a}{3\pi}\left(1-\frac{b^2}{a^2}\right)$$



  - At full penetration the magnetization is

$$M = M_{pf} = \frac{4\mu_0 j_c a}{3\pi}$$

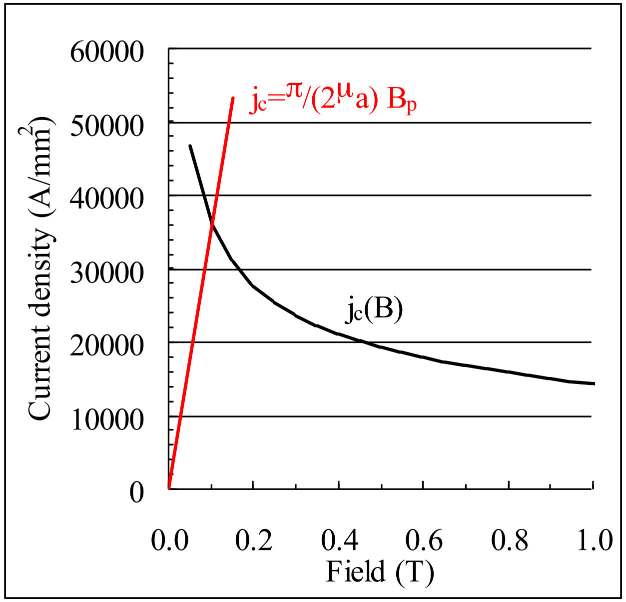


It does not take much field for the filaments to be penetrated

- Estimating penetration field
  - Critical current surface vs field
    use parameterization for low *j*
  - Critical current vs penetration field

  - Filament size is ~ 5-100 μm

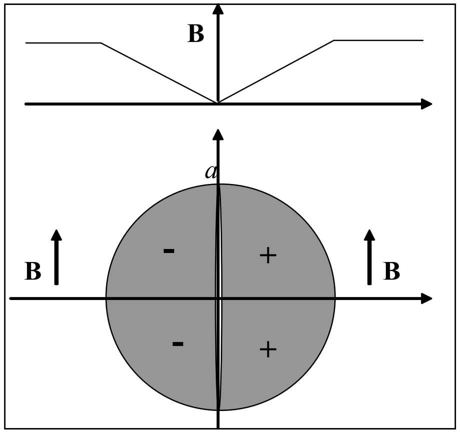
    (see Unit 4)

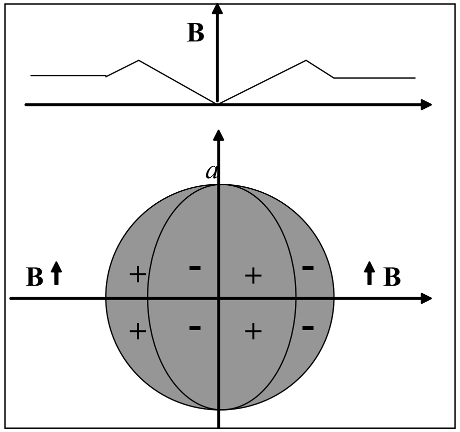


	Filament diameter (mm)	Temperature (K)	Critical current (A/mm^2)	Penetration field (T)
Tevatron dipole	0.009	4.2	25000	0.09
HERA dipole	0.015	4.2	21667	0.13
RHIC dipole	0.007	4.2	26786	0.08
LHC dipole	0.007	1.9	35714	0.10

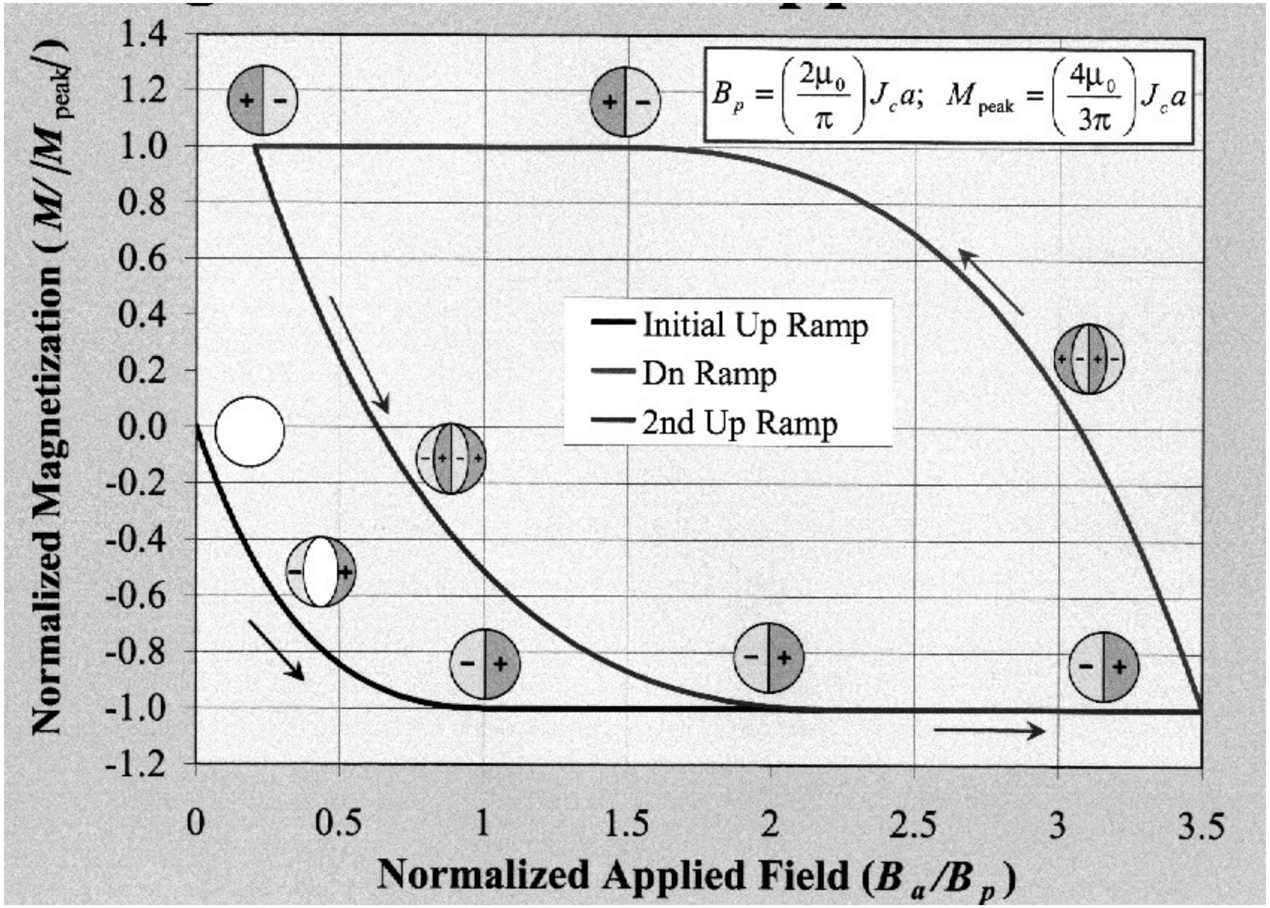
- The penetration field is in general rather low – at high field filaments are fully penetrated

- The phenomenology in a circular filament in external field ramping down
  - We reached the condition of full penetration
  - If now we ramp down, the external layer of the superconductor will have opposite current to continue the shielding
  - The shielding feature depend not only on the field but also on the previous fields: hysteresis effect





We have seen the hysteresis through the magnetization loop

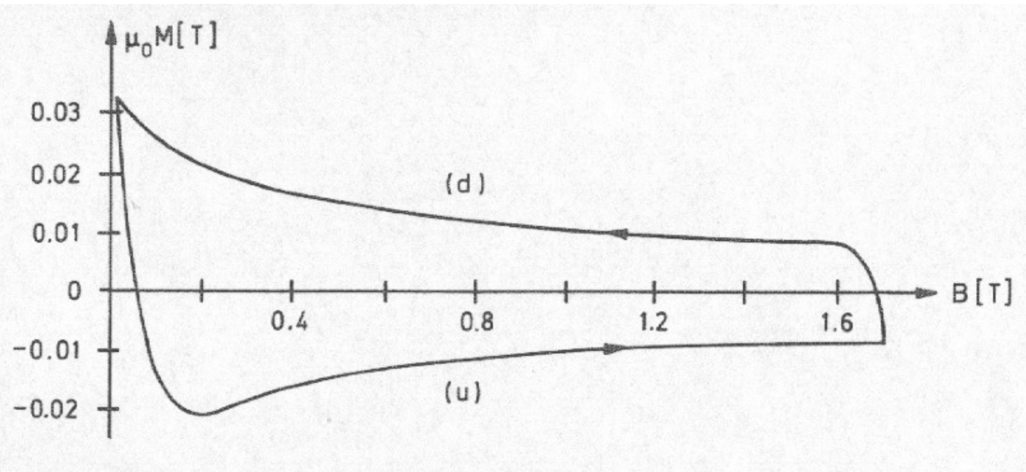


From A. Jain, USPAS 2007, Dynamic effects in superconducting magnets, pg. 18

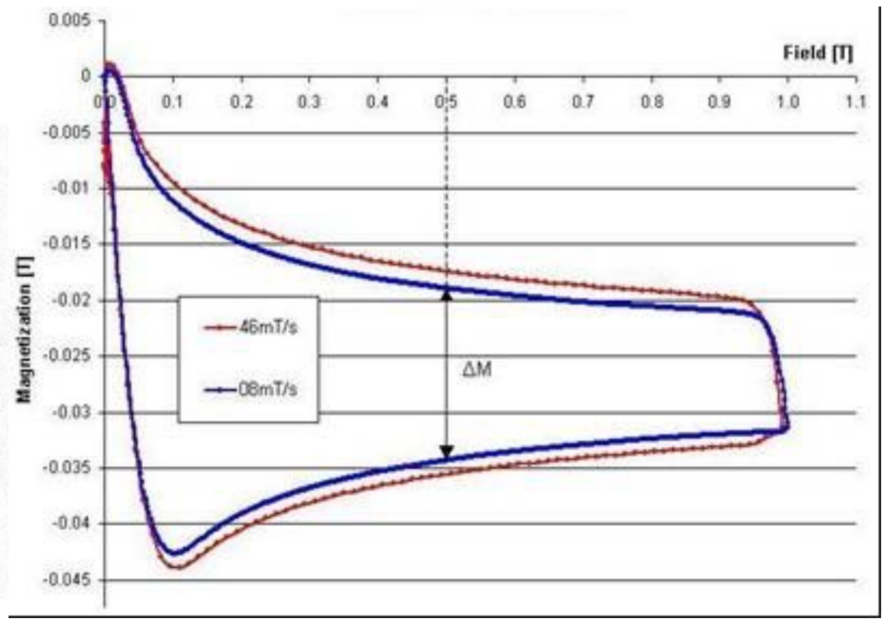
Recap

- Persistent currents depend on
  - External parameters: magnetic field and its previous values – but not on the rate of change of the field !
  - Filament parameter: size and geometry
  - Superconductor parameter: critical current
- Parametric dependence
  - For low external fields, the critical current is larger and therefore the persistent current and induced magnetization are larger
  - At large external fields the critical current becomes smaller and therefore the effect is smaller
- What happens in a magnet ?
  - Magnetic field in the coil has large variations in module and direction
  - Filament magnetization induces a perturbation in main field and harmonics
  - For larger fields, the harmonics are further reduced by the normalization

Measurements of magnetization of cables



Magnetization measurement in HERA cable
From P. Schmuser, pg. 85 Fig. 6.3



Magnetization measurement in LHC cable
Courtesy of L. Bottura et al.

How to use the model and data to compute the persistent currents and their effects

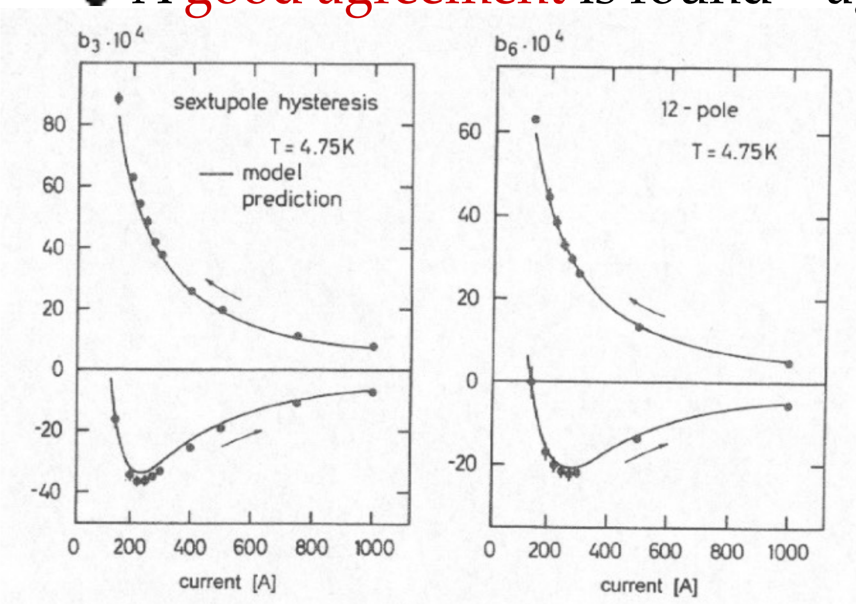
- A way to compute persistent currents
  - Calculate the field map in each strand of the coil (and its previous values)
  - Estimate the critical current vs field using measurements or a parameterization – note that values for low fields are very relevant
  - Compute the persistent currents of the filament using a geometrical model, and scale them to the strand
  - Scale the magnetization to take into account of

    the transport current – it must flow somewhere !

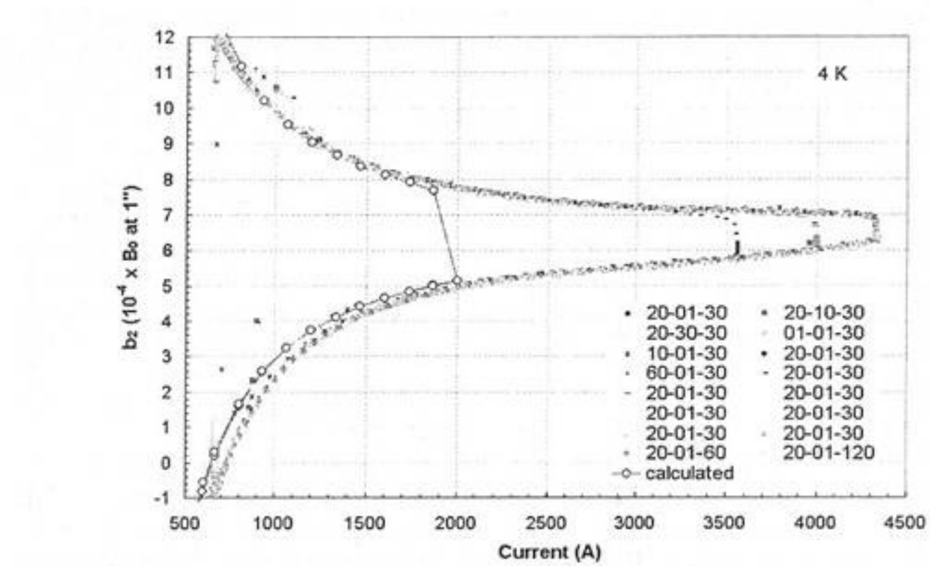
    Reduction factor is $1-\frac{j_t}{j_c}$
  - Evaluate the effect of these additional currents to the main field and to the field harmonics
  - Several codes can do this evaluation – Roxie, …

Example of calculation and comparison with measurements

- Comparison measurements vs model
  - A good agreement is found – agreement at ~90%



Persistent current measured vs computed in HERA dipoles and quadrupoles - From P. Schmuser, pg. 87 Fig. 6.5



Persistent current measured vs computed in Tevatron dipoles - From P. Bauer et al, FNAL TD-02-040 (2004)

- Spread of persistent current given by
  - Differences in the critical current
  - Differences in the filament geometry, deformed after cabling

So what can we do about it?

- Even with the finest filaments (~5 μm) the persistent current give several units in allowed multipoles at injection
  - How to cure this effect? Several strategies
- Change the hardware (not cheap …)
  - Of the cable: further reduce the filament size – feasible ?
  - Of the machine: reduce the energy range, i.e. increase the injection current
- Compensation
  - Design compensation: optimize coil geometry, such that harmonics are minimized at injection
    - Drawback: at high field harmonics will be not optimized, but the beam is smaller …
  - Active compensation through correction magnets (as in HERA, LHC)
  - Passive compensation through ferromagnetic shims or ferromagnetic cold bore

Decaying fields after stopping a ramp

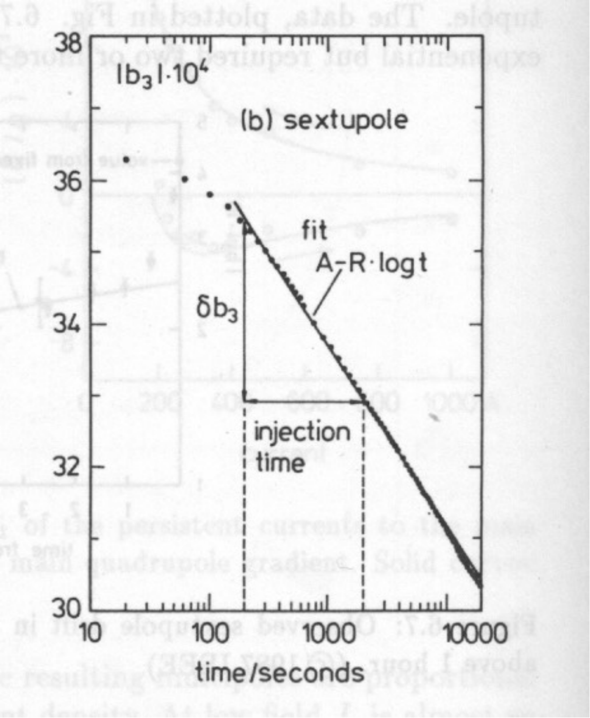
- Phenomenology
  - The injection of the beam is not instantaneous - takes ~ minutes
    - Tevatron: 30 minutes to 2 hours HERA: around 20 minutes
    - LHC: 20 minutes
  - During the injection the field is not constant and one observes a decay of main field and multipolar components ~ units
    - First observed in Tevatron in 1987

      [R. Hanft et al., Appl. Supercond. Conf. (1988), also in TM-1542]
  - Equations proposed to fit the decay
    - Logarithmic decay (HERA, Tevatron)

      $$b_3(t) = A - R \log t$$

    - Double exponential (RHIC, LHC)

      $$b_3(t) = A_1 \exp(t/t_1) + A_2 \exp(t/t_2)$$



Decay of b3 in HERA dipoles versus time, from Schmuser pg. 90, fig 6.8

Phenomena is real and must be understood

- Origins
  - Thermally activated flux creep inducing a decrease in the critical current density
    - It is temperature dependent
    - Produces a logarithmic decay
  - Boundary induced coupling currents
    - The strands carry different currents
    - Current redistribution can affect the magnetization due to the changes in the local field
  - There are indications that both mechanisms are involved in the decay of magnetization

One example: boundary-induced coupling currents

Markus Haverkamp Ph.D. thesis

- Can emanate from variations in the transverse contact resistances,
- or from variations in dB/dt across the cable
- Often systematic so can have significant impact on integrated multipoles
- Time constants long: 10-10^5s

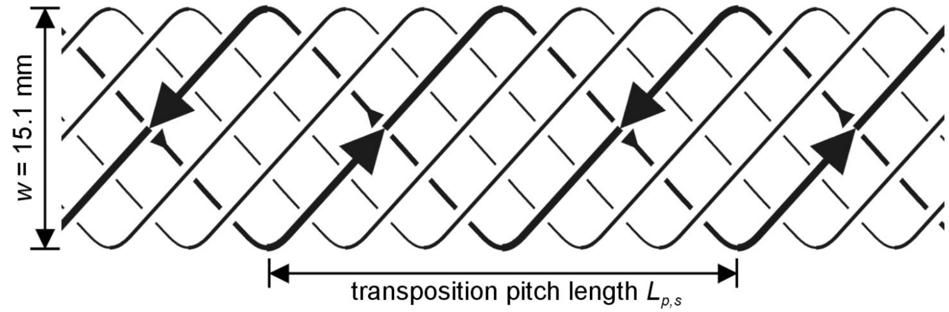


Figure 2.18 *Two strands in a Rutherford-type cable carry a current, flowing in a long loop.*

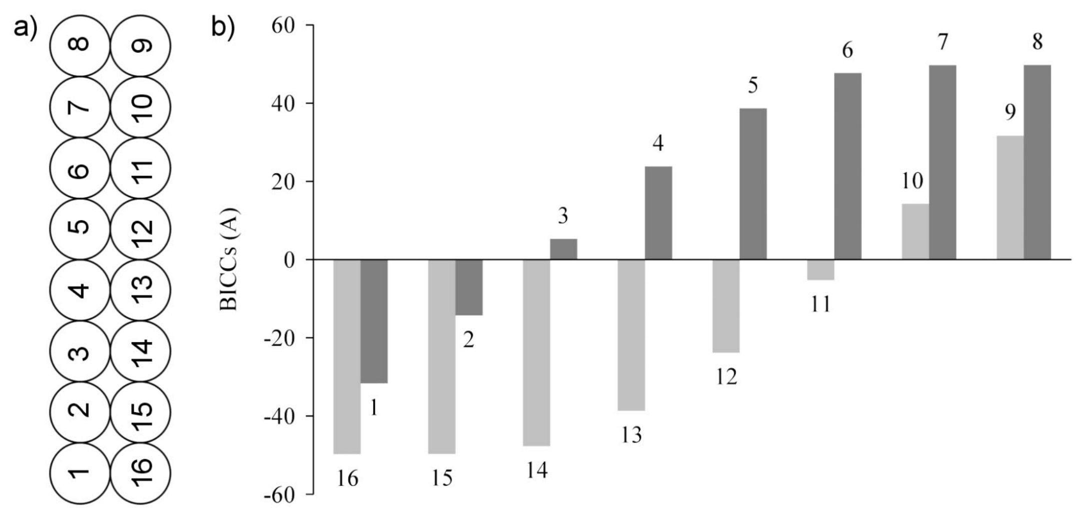
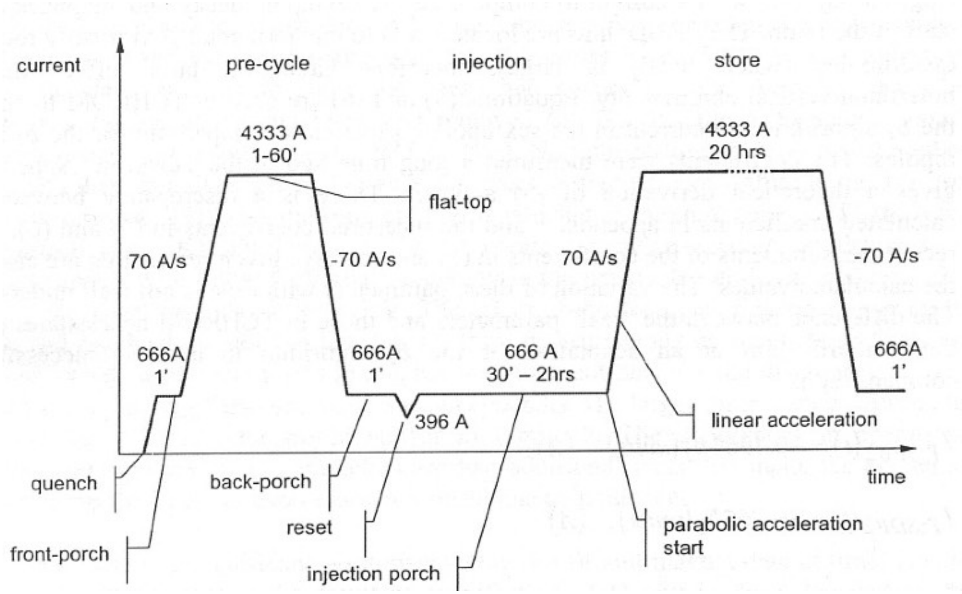


Figure 2.19 *a) Numbering of the strand positions in the cross section of a 16-strand Rutherford-type cable. b) Illustration of the BICC magnitude in a 16-strand cable at a certain z-position. The labels indicate the strand positions [55].*

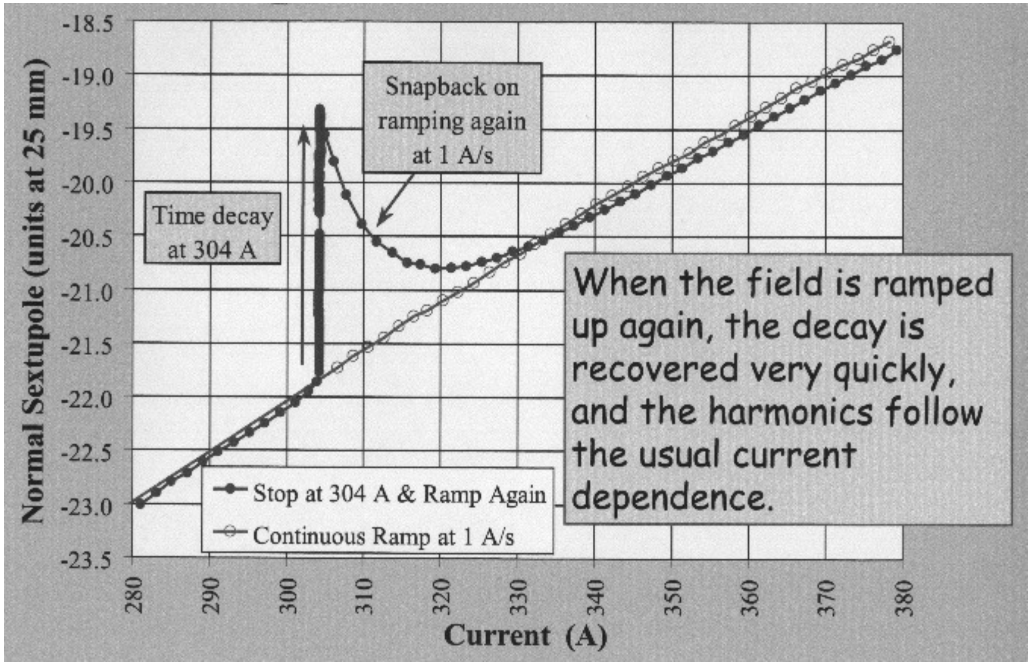
- Dependence on the previous history
  - The amplitude of the decay depends on the parameters of the previous cycles
    - Proportional to the flat-top current of the previous cycle
    - Decreases for longer back-porch
    - Saturates for flat-top duration longer than ~1 h



The cycle used for powering Tevatron dipoles, from P. Bauer et al, FNAL TD-02-040 (2004)

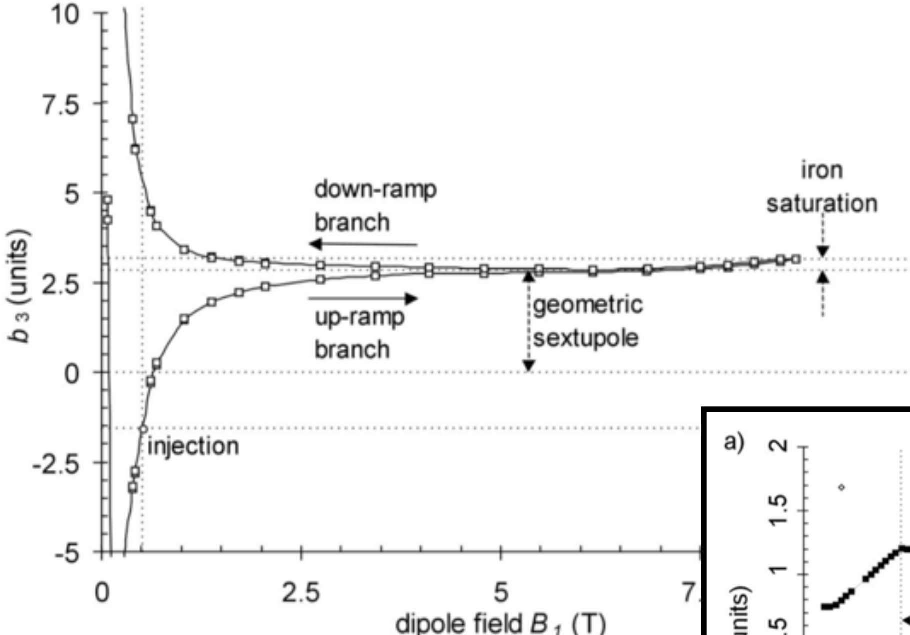
An example of impact of decay currents: snapback

- Phenomenology
  - At the end of the injection, the beam is accelerated and the field is ramped up
  - In that moment, the decay of persistent currents disappears and the previous values are recovered



Snapback phenomenology in RHIC dipoles, from A. Jain, USPAS 2006, « Dynamic effects and … », slide 27

Snapback has been studied in some detail



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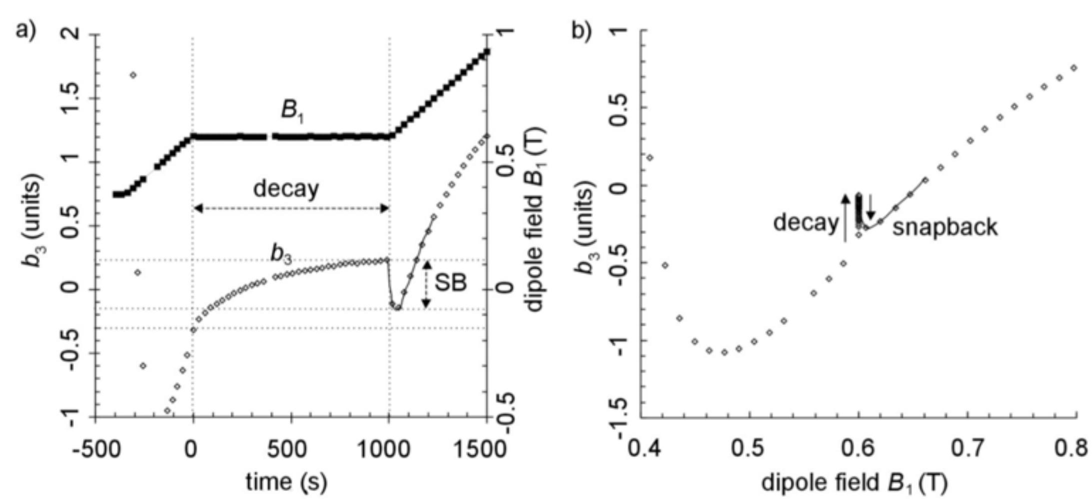


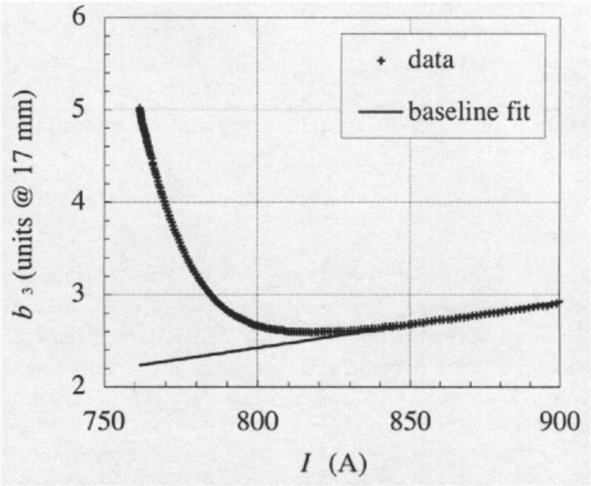
Figure 1.6 *a) The dipole field B_1 and the normal sextupole component b_3 are shown as a function of time. The injection field is reached at a time t = 0. The sextupole component decays during injection. After about 1000 s the magnet is ramped again. The snapback is clearly visible. b) The same measurement of b_3 is shown as a function of the dipole field, along the up-ramp branch of the hysteresis curve. The decay and snapback are indicated.*

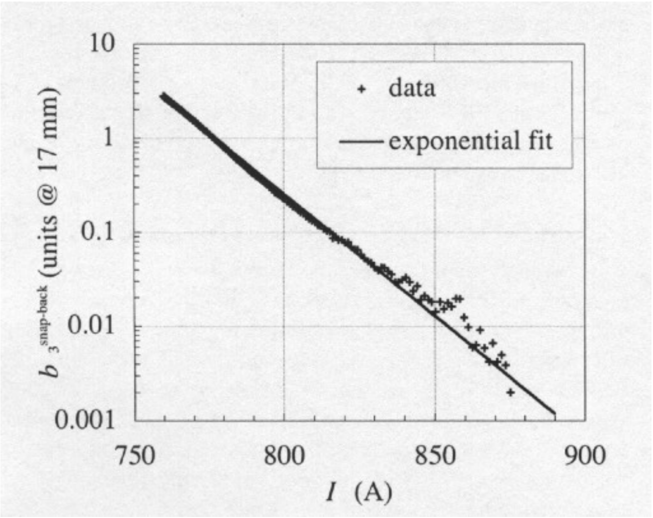
More data from CERN on snapback

- Snapback versus current
  - The snapback versus current (i.e. versus field, and versus time) dependence is exponential

$$b_3^{sb} = \Delta b_3^{sb} \exp\left(- \frac{I - I_{inj}}{\Delta I} \right)$$

  - The snapback takes place in a few seconds – very fast phenomena





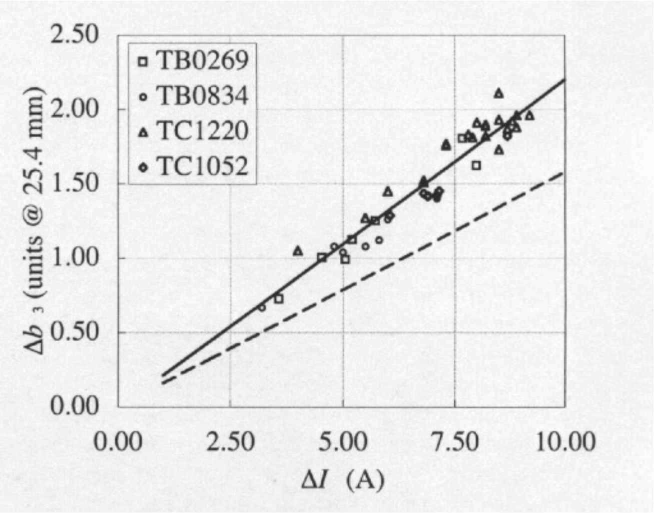
Snapback in b3 versus time, LHC main dipoles, from L. Bottura et al, IEEE Trans. Appl. Supercond. **15 (2005)** 1217-20.

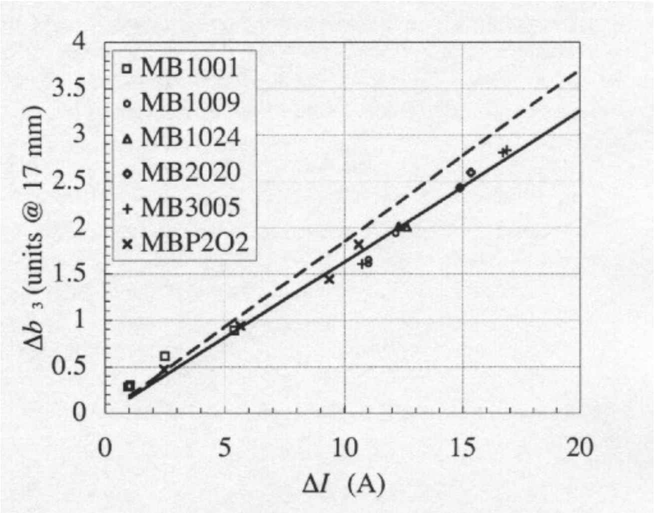
Comparison between Tevatron and CERN experience

- Snapback versus current

$$b_3^{sb} = \Delta b_3^{sb} \exp\left(-\frac{I - I_{inj}}{\Delta I}\right)$$

  - Two parameters: amplitude (the same of the decay) and "time" constant ΔI
    - Measurements show that they are proportional $\Delta b_3^{sb} \propto \Delta I$
    - The constant depends on the magnet design
    - One can justify this proportionality through a model

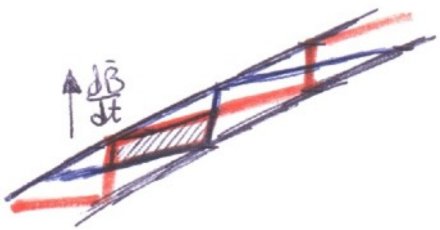




Linear relation between snapback constants for Tevatron (right) and LHC (left) dipoles
from L. Bottura et al, IEEE Trans. Appl. Supercond. **15 (2005)** 1217-20.

Effects induced during ramping

- The ramping of the magnet induces a variation of the flux with time in loops made by strands
  - This variable flux can induce currents which are
    - Proportional to the ramp rate
    - Proportional to the area of the loop
    - Inversely proportional to the inter-strand cross-contact resistance
  - These currents may perturb the field homogeneity for high ramp rates
  - A cure: increase the inter-strand resistance by special coating
  - For example, in the LHC dipoles the ramp rate is 10 A/s, the inter-strand resistance is > 15-40 μΩ, and the impact on field quality is negligible



- Another effect can come from flux variation in loops made by filaments - coupling currents

CONCLUSIONS

- Persistent currents
  - The mechanism
    - The conductor shields itself from the external magnetic field → this generates shielding currents inside the conductor → field perturbation
  - Features
    - Contribution is very relevant at injection, disappears at high field
    - Contribution on allowed harmonics, proportional to filament size, gets worse with large energy sweep
    - Contribution depends on the previous values of the magnetic field, but not on the rate of magnetic field change (hysteretic phenomena)
  - Reliable models can predict the persistent currents
  - Corrections
    - Passive correction with ferromagnetic shims
    - Smaller filament, smaller energy sweep
    - Active correction with corrector magnets

CONCLUSIONS

- Decay
  - The mechanism
    - When the field is constant (this happens at injection energy) the magnetization decays with time due to different mechanisms
      - Flux creep
      - Boundary induced coupling currents
  - Features
    - Scale time is ~100 s
    - Semi-empirical fits with exponential or logarithms are used
    - Contribution depends on the previous history, including the rate of magnetic field change (dynamic effect)
  - No quantitative predictions available
  - Corrections
    - Phenomena are slow, corrector magnets are used to compensate on the fly

CONCLUSIONS

- Snapback
  - The mechanism
    - When the field is ramped up again, all the decay of persistent currents is wiped out and the previous state is recovered
  - Features
    - Scale time is ~1 s
    - Fit with exponential, based on heuristic model, are used
    - The amplitude of the snapback and the time constant are proportional – can be justified with an heuristic model
  - Corrections
    - Phenomena are fast, they cannot be corrected on the fly but correction curves should be implemented based on measurements

REFERENCES

- General
  - M. N. Wilson, Ch. ?
  - Schmuser, Ch. 6 and 7
  - L. Bottura, “Field dynamics in superconducting magnets for particle accelerators”, CERN 98-05 (1998).
  - Classes given by A. Jain at USPAS 2006, Unit 7
  - Ph. D. thesis of A. Verweij
- Decay and snap-back
  - L. Bottura et al, IEEE Trans. Appl. Supercond. **15 (2005)** 1217-20
  - N. Sammut Ph. D. thesis on the LHC magnets
  - Several works by P. Bauer et al carried out in 2000-2005 at FNAL on Tevatron
  - Complete references on the works on Hera can be found in Schuser book