Generation of Pulsed High Magnetic Fields in a Small Laboratory

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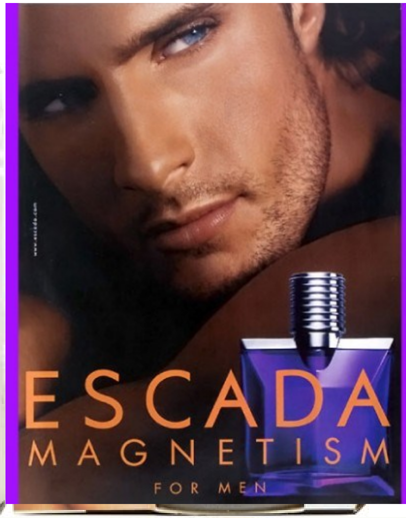
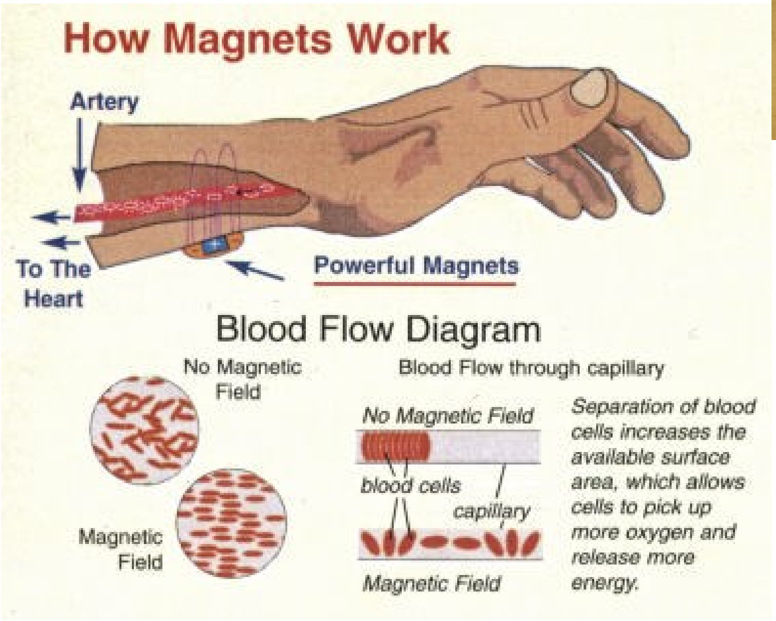
Friday, 22 May 2015

Magnets in Popular Imagination

- **Attractive**
- **Benign**
- **“Therapeutic”**





Separation of blood cells increases the available surface area, which allows cells to pick up more oxygen and release more energy.

Magnetic fields in classical physics

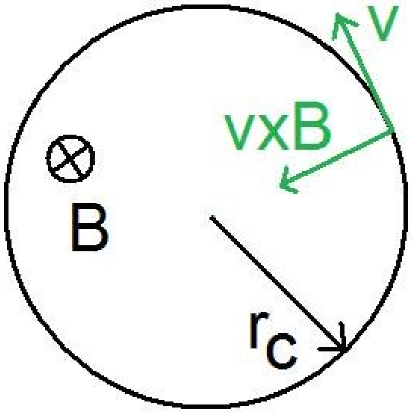
Magnetic fields

- Are a weak (relativistic?) effect due to moving charges
- Do no work, only bend trajectories (Lorentz force)
- Have no consequence on thermodynamic properties of classical systems

Control the convection in stars : Sunspots

Technology: Tokomaks, synchrotrons,…

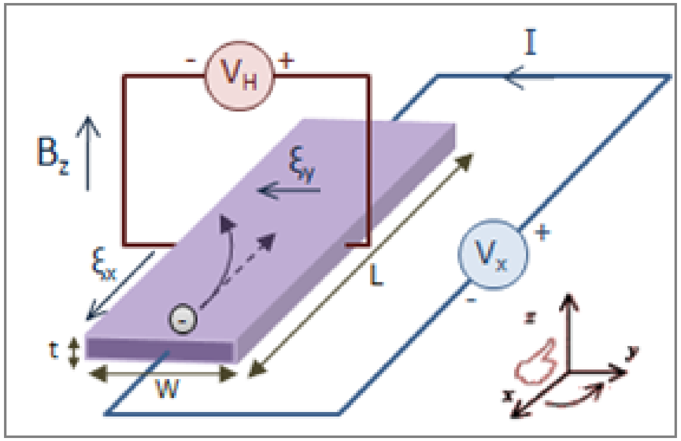
Cyclotron orbits



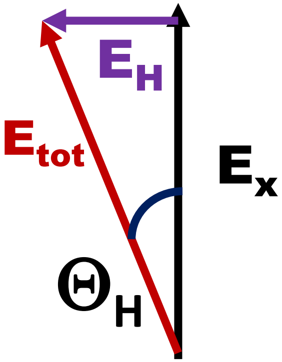
Magnetic fields in classical physics

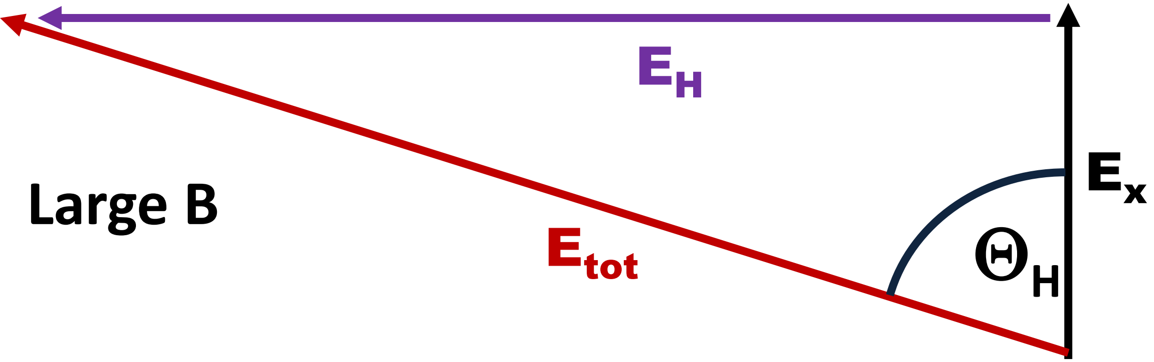
What is large?

Large magnetic field => Hall angle $\Theta_H \sim 90^{o}$



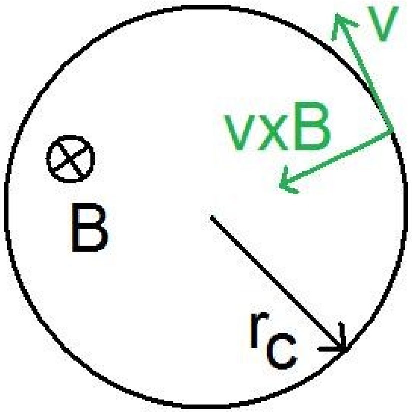
Small B





Large B

Motion is perpendicular to applied electric field

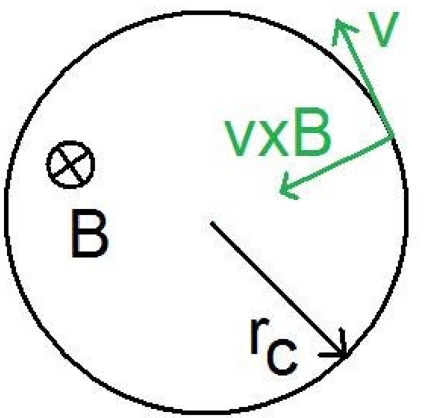


Tight cyclotron orbits

Magnetic fields in quantum physics

- Large magnetic fields have a profound effect on the energy levels and structure of atoms, molecules and even free electrons

Cyclotron orbits get quantized



$$l_B = \sqrt{\frac{\hbar}{eB}} \approx 25\text{ nm}\sqrt{1/B}$$

l_B only depends on fundamental constants

$\Rightarrow$ Electron in any material, atom or molecule is constrained to be restricted within this length

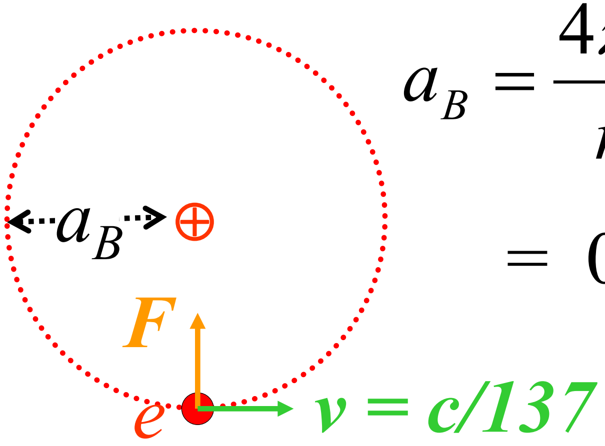
Magnetic field is large if l_B << other length scale of confinement (e.g., Bohr radius)

Coulomb *vs* magnetic confinement

Hydrogen atom

Free electron in a magnetic field

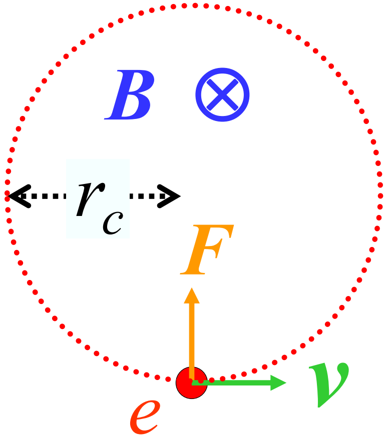
Bohr´s orbit



$$a_B = \frac{4\pi\,\varepsilon_0\,\hbar^2}{m_e\,e^2}$$

$$= 0.53\ \text{Å}$$

cyclotron orbit



$$r_c = \frac{m_e v}{eB}$$

$$l_B = \left(\frac{\hbar}{eB}\right)^{\frac{1}{2}}$$

Magnetic field is a tunable length scale

What is large?

Magnetic field is large if l_B << other length scale of confinement

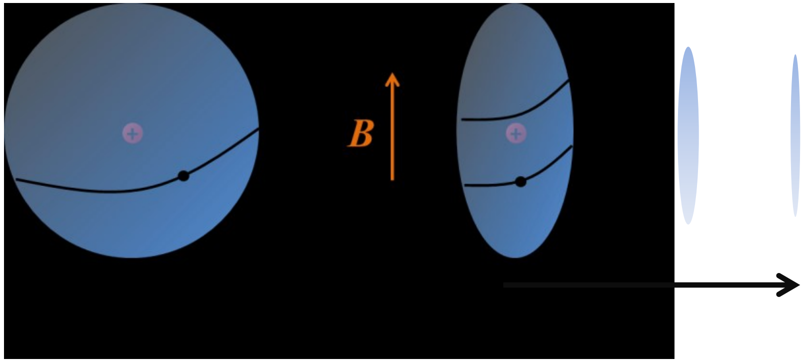
Hydrogen atom, Bohr radius $a_B \approx 0.05\, nm$

$$l_B = \sqrt{\frac{\hbar}{eB}} \approx 25\text{ nm}\sqrt{1/B}$$

=> $l_B \approx 2.5\, nm$ B=100 tesla

$l_B \approx 0.25\, nm$ B=10^4 tesla

$l_B \approx .025$ nm B=10^6 tesla

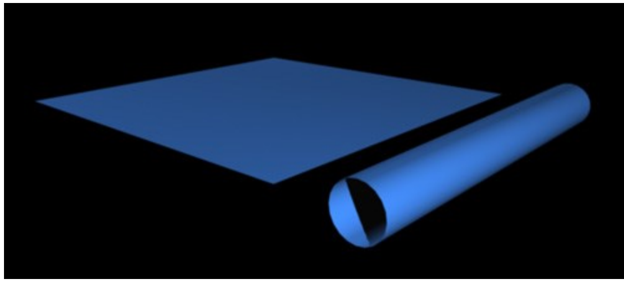


=> For hydrogen atom $l_B \approx a_B$ *at B* = 240 000 T

For B>> 10^6, the atom becomes one dimensional

What do these absurdly large numbers mean?

Such magnetic fields do exist in neutron stars and magnetars



Example of compactification*!

***Please see the beautiful article by ARP Rau (Am J. Phys. 1985)**

Magnetic field is a tunable length scale

The basic idea still works for smaller fields if the other confinement scale is larger

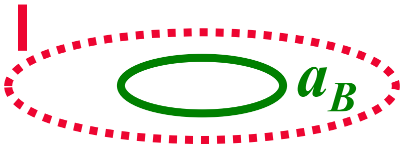
Example: Excitons in semiconductors, quantum dots

Magnetic length: $r_c = \left(\dfrac{\hbar}{eB}\right)^{\frac{1}{2}}$

a_B=Exciton Bohr radius

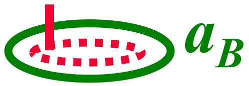
l_B is material independent!
10 nm ~ 13 Tesla
8 nm ~ 20 T
6 nm ~ 36 T

Low field



$$r_c > a_B/\sqrt{2}$$

High field



$$r_c < a_B/\sqrt{2}$$

Zero angular momentum bound states

Magnetic field reduces dimensions by two!

two dimensions + magnetic field
 => zero dimension
quantum well + magnetic field
 => quantum dots

Example: Quantum well laser

Laser characteristics are
 dramatically improved!

To some extent, this idea started the interest in quantum dots

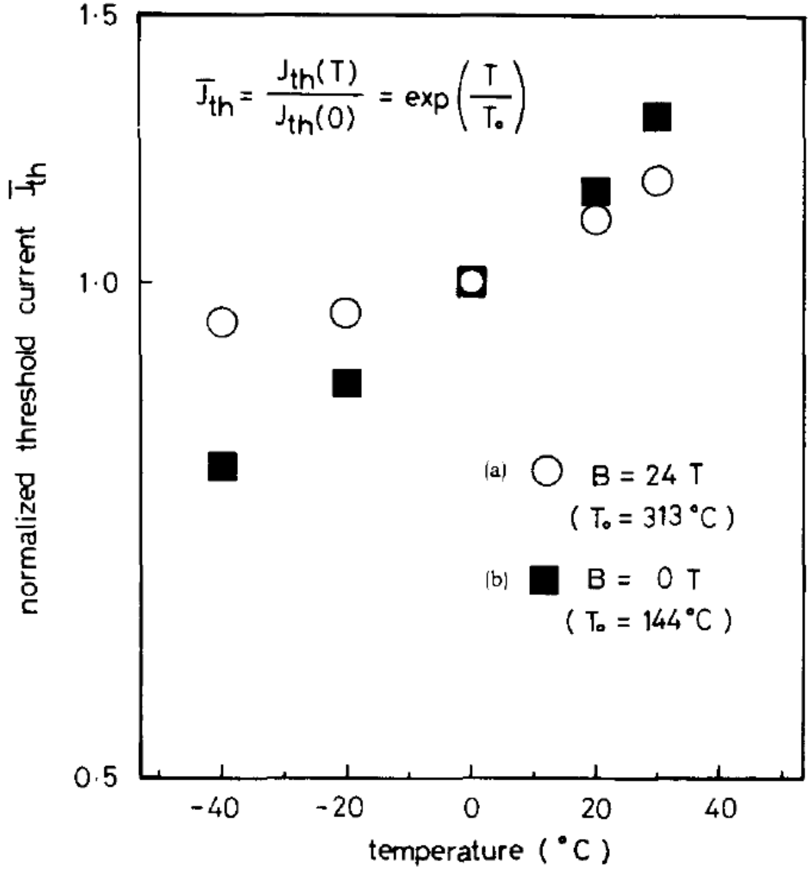
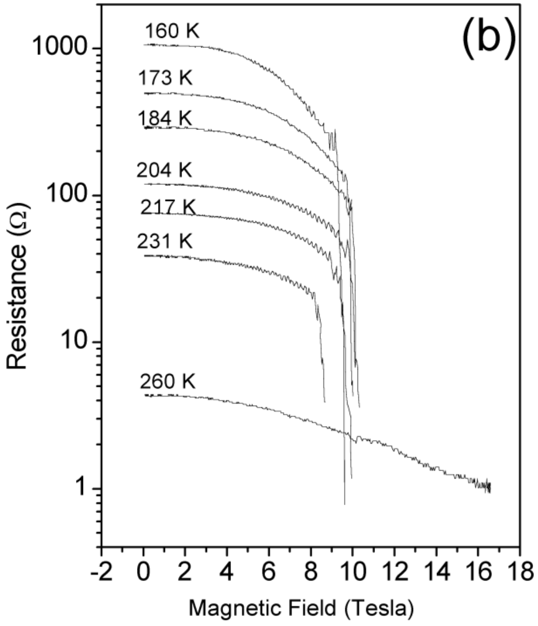


FIG. 3. Temperature dependence of threshold current J_{th} with and without magnetic field B (24 T). J_{th} is normalized by J_{th} at 0 °C, which is 52 mA at $B = 0$ and 54 mA at $B = 24$ T.

Arakawa and Sakaki, Appl. Phys. Lett (1982)

Magnetic Fields in Condensed Matter Physics

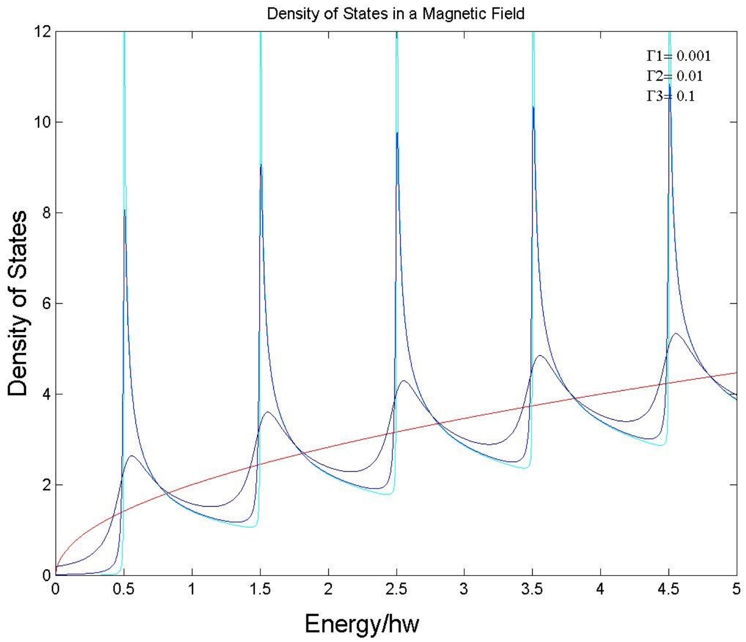
- Zeeman splitting (**NMR, ESR**)
- Magnetic Fields in **strongly-correlated materials** can tilt the balance between kinetic and potential energy, tune the interactions, add to molecular mean fields, suppress fluctuations, destroy superconductivity
- **Quantum Hall Physics**
- `**Fermiology**': Quantum oscillations
- **Transport coefficients**



Sudden 'melting' of the insulator state

Observing quantum effects

Quantized cyclotron orbits (Landau levels) change the energy spectrum even of free electrons



These are well-resolved if

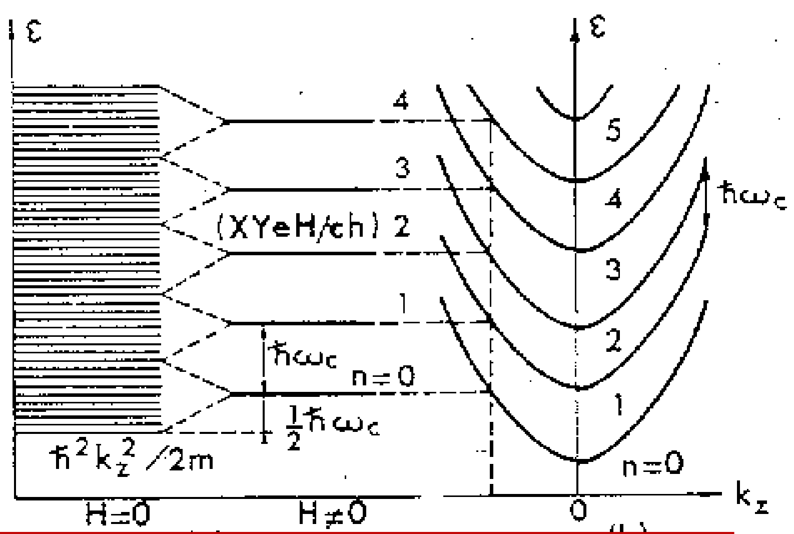
- at least one cyclotron orbit is completed before scattering
- thermal distribution of electrons does not average out the DoS structure
- electrons should obey Fermi statistics

Cyclotron energy $\gg$ thermal energy

=> $\hbar\omega >> k_B T$

Cyclotron frequency>> collision frequency

=> $\omega_c \tau >> 1$



Cyclotron energy ~ 1 Kelvin / Tesla

10 Tesla is a large field for many low temperature experiments

Often it is the B/T ratio that is important

Generation of high magnetic fields

1 Tesla is difficult to generate

Magnetic field in a infinite solenoid

$$B \approx \mu_0 n i \quad , \qquad \underline{\underline{\mu_0 \sim 10^{-6}\ \mathrm{N/A^2}}}$$

if,

no. turns /unit length , n ~ 1000

to generate 1 tesla

$$i \sim \frac{B}{\mu_0 n} \sim 1000 \ \text{Amps}$$

If coil resistance , R ~ 0.1 - 1 Ω

Power = $i^2 R \sim 10^5$-10^6 Watts/Tesla !

Iron cores: μ~1000, but saturate above ~ 1 tesla

Magnetic Field ~ Current

Heating ~ $(\text{current})^2$ x ~~resistance~~ x time

Minimize Resistance -> Superconducting magnets

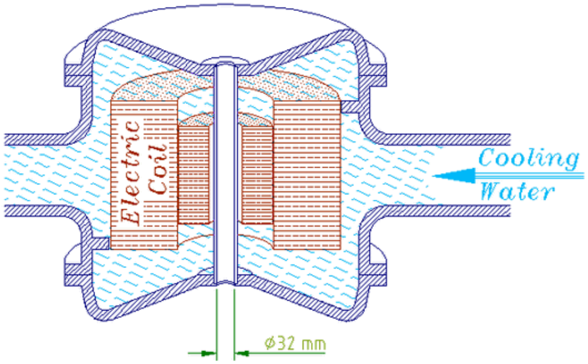
Superconducting magnets

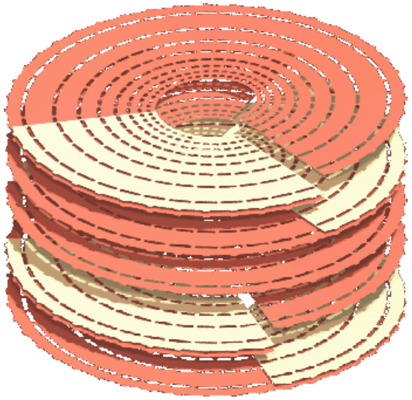
`Above ~ 18 tesla get prohibitively expensive (to buy and operate) and dangerous

`Max field ~ 22 tesla

Above 20 T, back to resistive magnets

- Enormous power ~20 MW (consumption of a small town)
- Large infrastructure ~ 1 per continent





Bitter discs or polyhelix

Peak Field ~ 35 tesla

(Resistive + superconducting) hybrid : 45 tesla

Florida (Grenoble and Nijmegen: under development)

- Florida 45 T hybrid magnet requires 33 MW to operate and more than 15,000 litres of water every minute for cooling the resistive part
- Precision coil design and assembly (hot spots/stress) ~1 million dollars

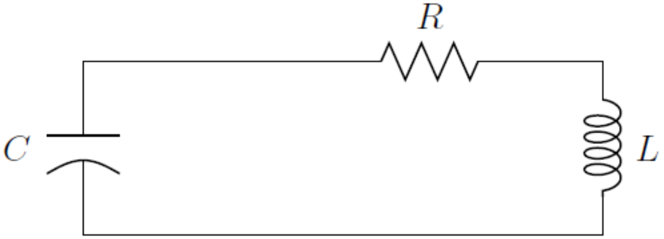
Magnetic Field ~ Current
Heating ~ (current)^2 x resistance x ~~time~~

Or

Minimize Time -> Pulsed Magnets

Pass a large current for a few milliseconds

Pulsed Magnet = Capacitive Discharge Circuit
Like a Camera Flash

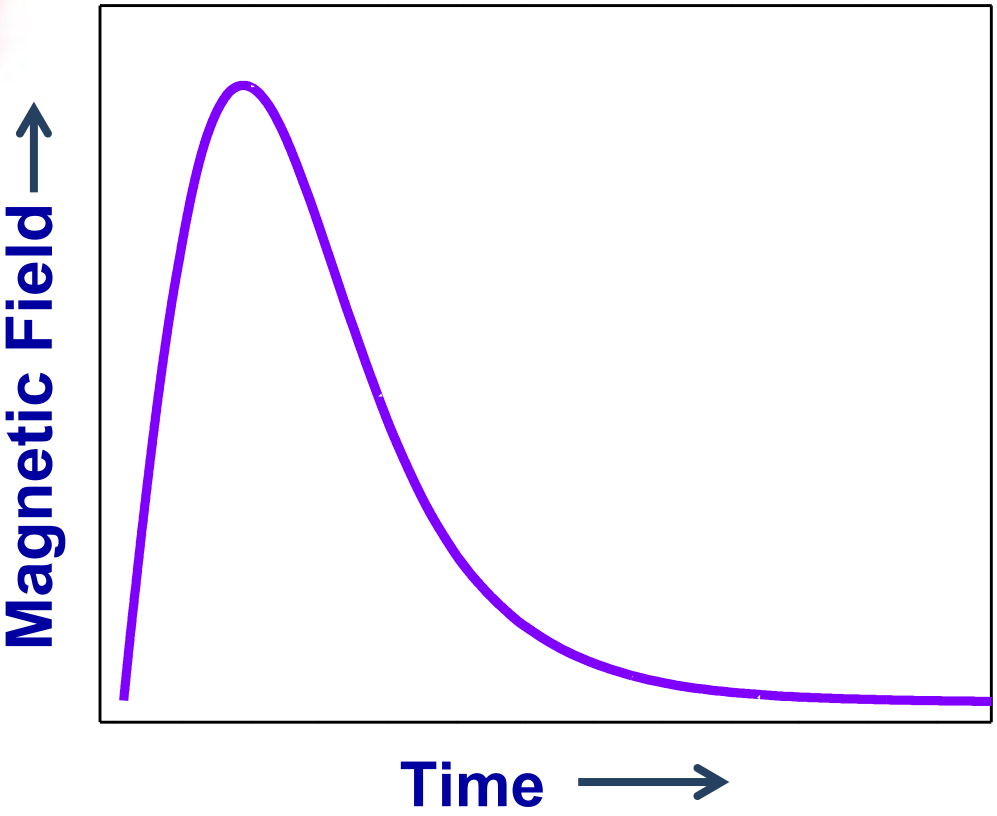


LCR circuit

A Basic Pulsed Magnet

1. Capacitor bank
2. Solenoid Coil
3. HV Power supply
4. Switch

Figure Courtesy: Michael Davidson, NHMFL .



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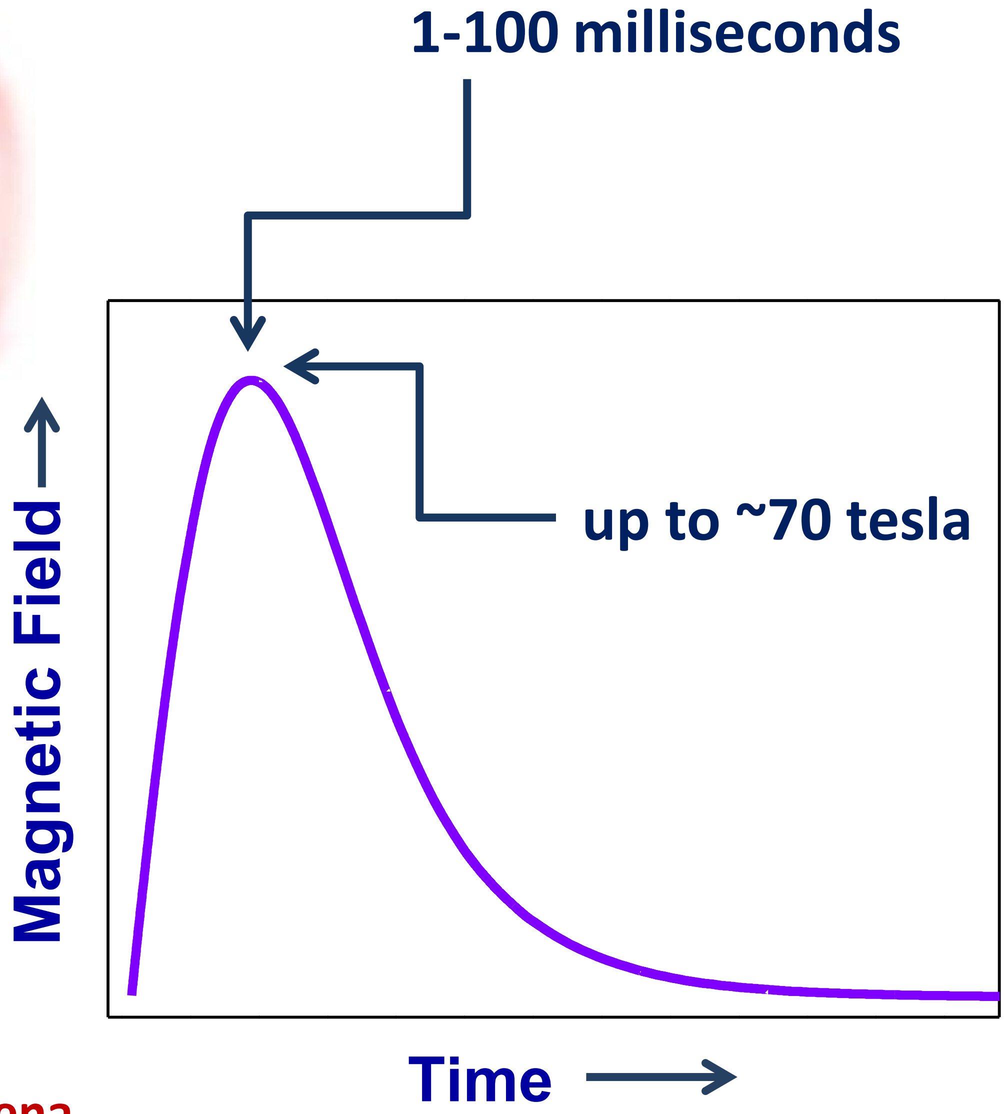


1-100 milliseconds

up to ~70 tesla

-Complete measurement in a few ms
-OK, because relaxation time
< ns for most solid state phenomena

Back-of-the-envelope estimate

Energy conservation

Capacitor Energy => Inductor

$$\frac{1}{2}CV^2 \approx \frac{1}{2}LI^2 \approx \frac{1}{2\mu_0}B^2 \times (\text{coil volume})$$

$$\Rightarrow B \sim \left(\frac{C\mu_0}{\text{volume}}\right)^{\frac{1}{2}} V$$

$$B \sim \text{voltage}$$

$$B \sim (\text{capacitance})^{1/2}$$

$$B \sim \frac{1}{(\text{volume})^{1/2}}$$

$$B \sim (\text{energy})^{1/2}$$

$$\frac{1}{2}CV^2$$

$$\frac{1}{2}Li^2$$

So what does it take to generate 40 T ?

Capacitance ~ 500 mF
Voltage ~ 500 Volts
Energy ~ 75 kJ

Volume ~ (1cm radius)^2 x (10cm length) ~ 10^{-5} m^3

$$B \sim \left(\frac{C\,\mu_0}{\text{Volume}}\right)^{1/2} \text{x voltage x ff,} \qquad \mu_0 \quad \sim \quad 10^{-6}\ \text{N / A}^2$$

$$\sim \left(\frac{0.5\times10^{-6}}{10^{-5}}\right)^{1/2} \times 500 \times \frac{1}{e}$$

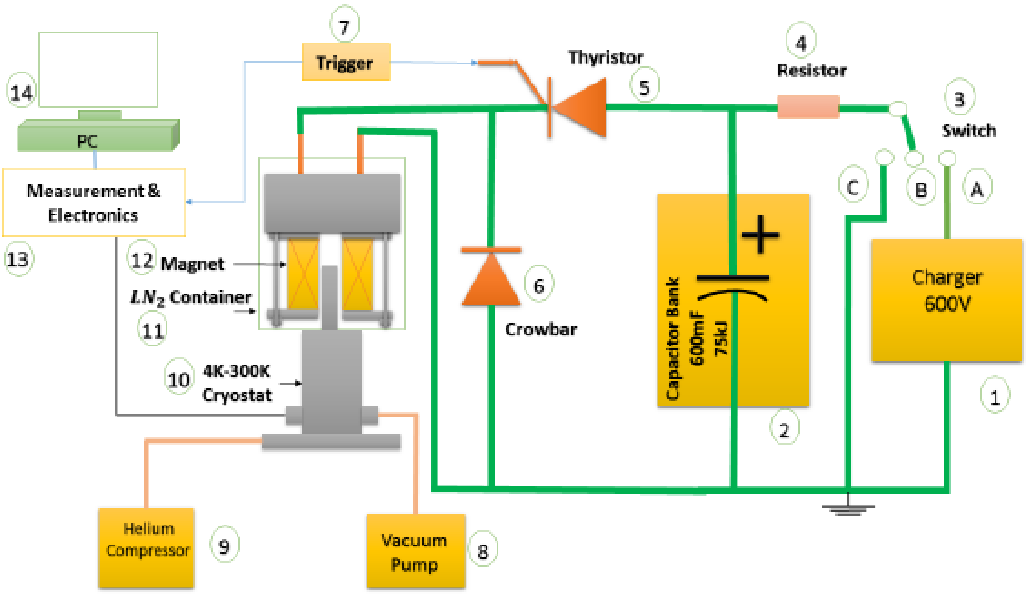
$$\sim 40\ \ \text{tesla}$$

ff = fudge-factor
~ 1/e [losses]

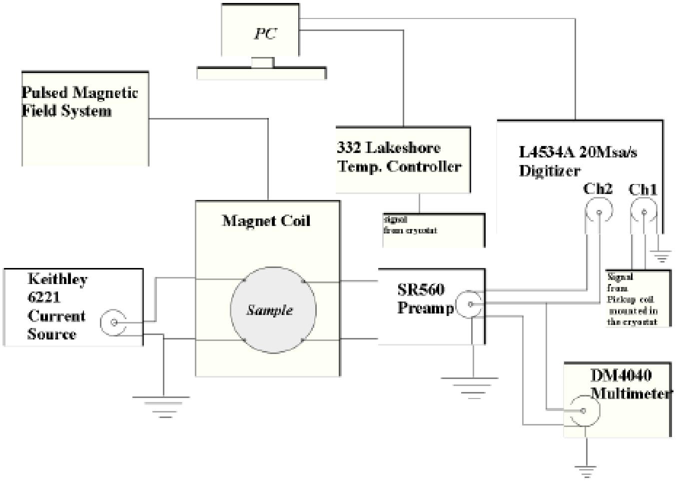
=> It seems possible with these parameters

Let us do-it-ourselves a 35-40 T facility

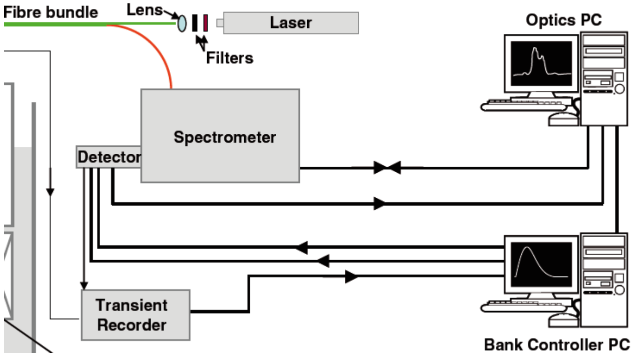
Generator circuit



Transport measurements



Optical spectroscopy



Ingredients

I. Generator circuit
II. Magnet Coil
III. Cryostats
IV. Fast measurement electronics, synchronous data acquisition
V. Safety
VI. Specialized measurement techniques/Noise reduction
  -Transport: e.g., digital lockin
  - Optical spectroscopy
  - Magnetic susceptibility

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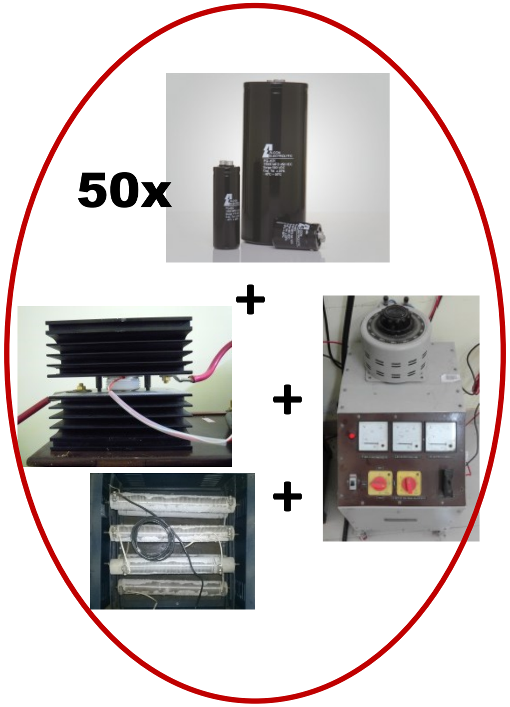
Generator at IISER K

Bank: 75 kJ (500 V, 500 mF)



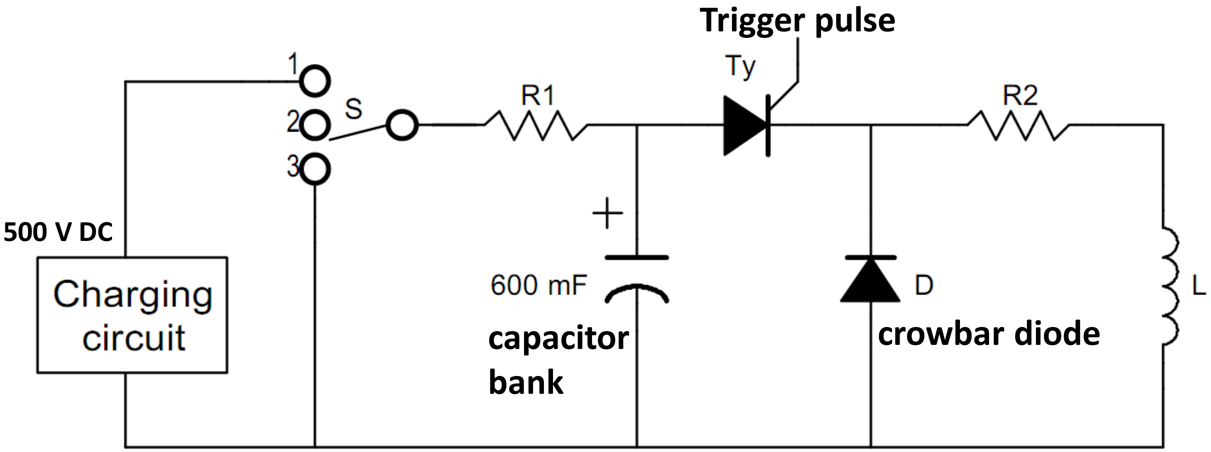
<u>Low voltage (< 500 V)</u>

-Can work with undergraduate students

-Ease of measurements, cheaper

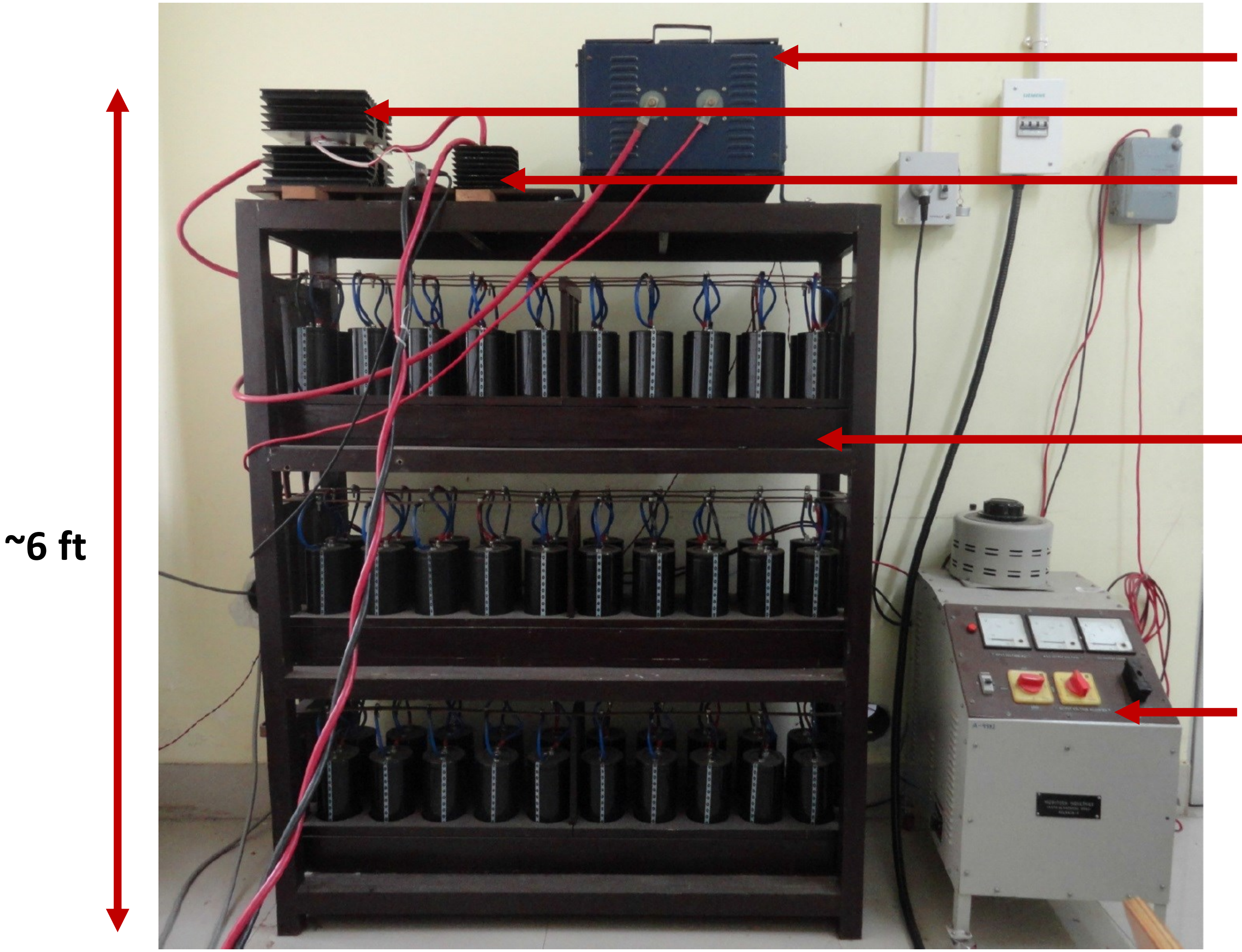
-Much reduced space requirement

-All components locally available, cheaper



Peak current ~ 30,000 A
for 10 milliseconds

Generator at IISER K



~6 ft

Current limit resistor

Thyristor

Diode

Capacitor Bank

Charging power supply

Total Cost ~ 6 lakhs

Assembled by undergraduate students

Ingredients

I. Generator circuit

II. **Magnet Coil**

III. Cryostats

IV. Fast measurement electronics, synchronous data acquisition

V. Safety

VI. Specialized measurement techniques/Noise reduction

  -T

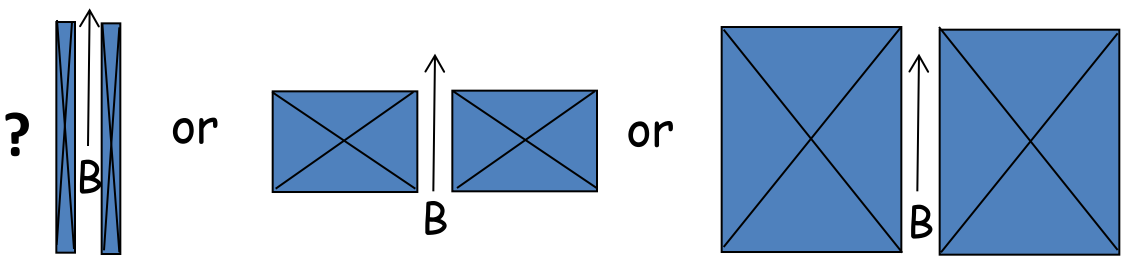
  - C

  - N

This is the most critical aspect

Optimization of field and power

For dc magnets, the power consumption has to be optimized

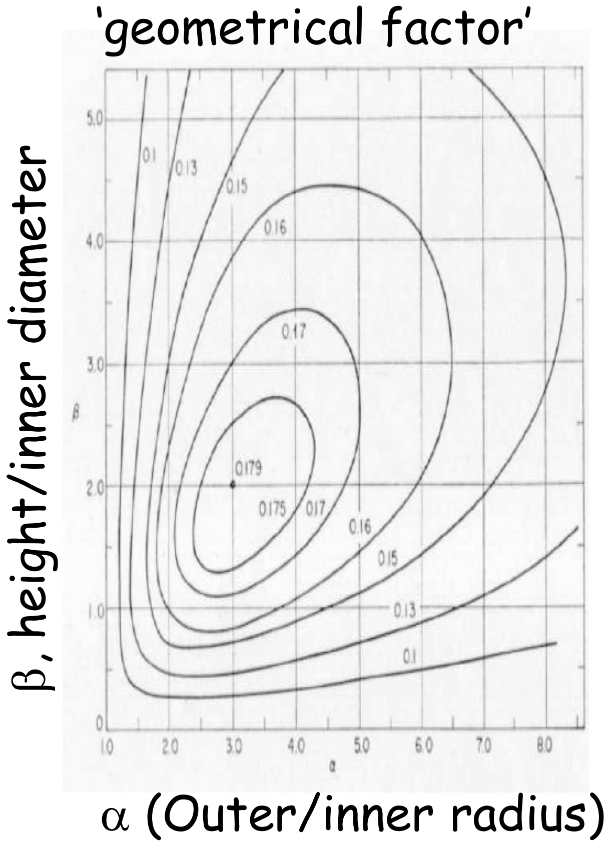


For a thick solenoid:

Peak field = current density x (1/radius) x geometrical factor

Pulsed magnets operate far from this optimization condition

- Energy is fixed, not power
- Heating is adiabatic



The most efficient coil (constant current density) $\alpha \sim 3$, $\beta \sim 2$

Ref: Solenoid Magnet Design by Bruce Montgomery

Optimization of a Pulsed Magnet

- **‘Impedance match’ the coil with the bank**
  for highest field and reasonable pulse length (5-10 ms)

- **Coil should not get too heated**
  (77K-> 300K max.) [if it does, reduce the pulse length
  by increasing the current density].

- **Coil should have enough mass to absorb the heat**
  100kJ requires 1kg copper [77K-> 300K]
  2MJ requires 20kg copper

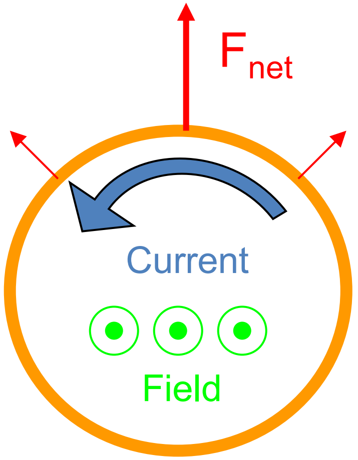
- **<u>Coil should not does not explode!</u>**
  Non-trivial: Components of stress get coupled,
  plastic deformation, material properties not always known

- **Approximate scaling relations can be derived**
- **Peak field is insensitive to number of windings! [zeroth approx.]**

Coping with stress

Stress is the limiting factor for all high field coils

Lorentz force on the conductor!



Tangential stress: $\sigma_{\theta\theta}=jBr$

Zeroth Approximation

Estimate magnetic pressure (Maxwell stress)

$$B = G\sqrt{2\mu_0\sigma}$$

$$G \approx \sqrt{\Delta r / r}$$

G: geometry factor, thick cylinder

Field	UTS	Material
22T	0.2GPa	Soft copper
33T	0.45GPa	Work-hardened copper
35T	0.5GPa	Stainless Steel
50T	1GPa	Beryllium copper
70T	2GPa	Very hard maraging streel

It pays to make a big coil, but only a little

Strength and Conductivity

Lower conductivity

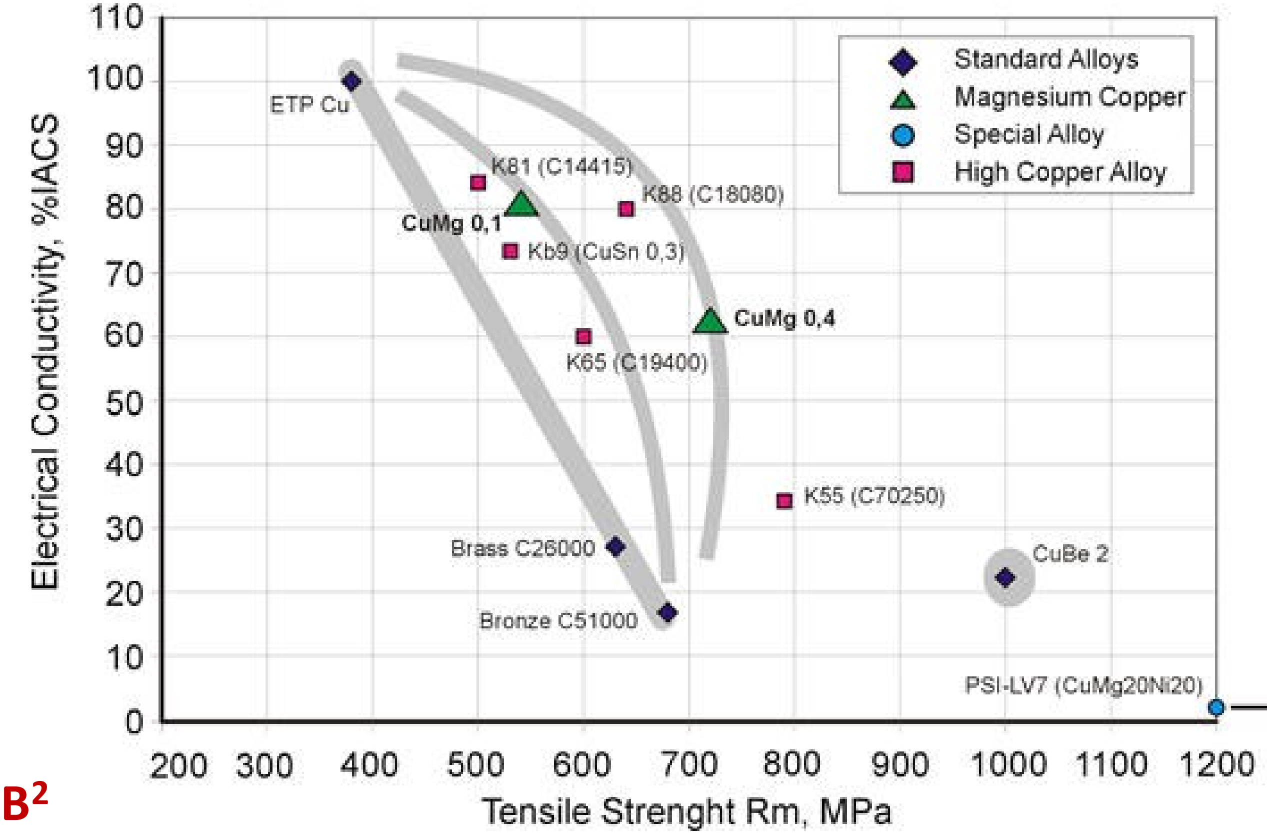
⇒ Much lower field

(LCR circuit)

⇒ Higher dissipation

⇒ Shorter pulse

⇒ Advantage of 77 K is lost with alloys



Both heating and stress ~ B^2

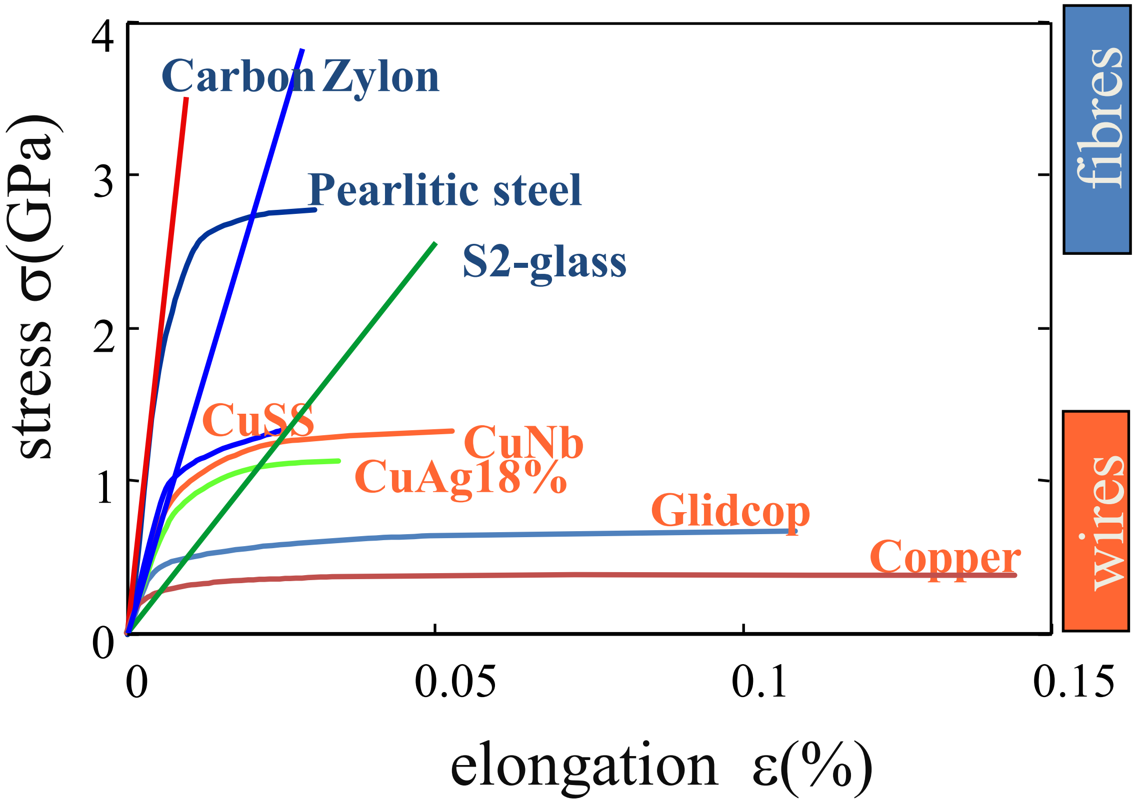
Many different materials have been tried
Esp. composite materials

http://www.conductivity-app.org/alloy-sheet/12

Stress-optimized coils

- Instead of using stronger conductors, stress optimized coils were invented in early 1990’s
- Reinforce the conductor layer with high strength fibre- glass, carbon, zylon (5GPa)
- Thickness of fibre reinforcement is adjusted such that hoop stress is constant across the coil
- Conductor is in the plastic flow regime (behaves like liquid contained by the reinforcement)

Stress-Strain curves: Different materials

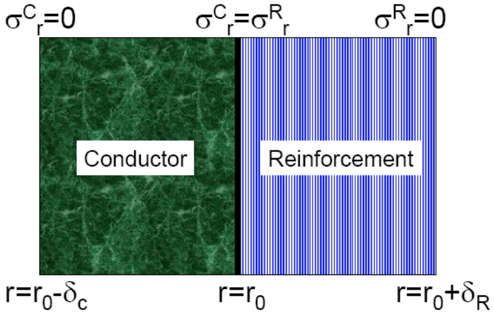


- Use copper as the conductor
- Use fibres for insulation
- Non-uniform current density and reinforcement such that mid-plane stress is constant

Graph from J. Vanacken, Leuven

Stress-optimized coils

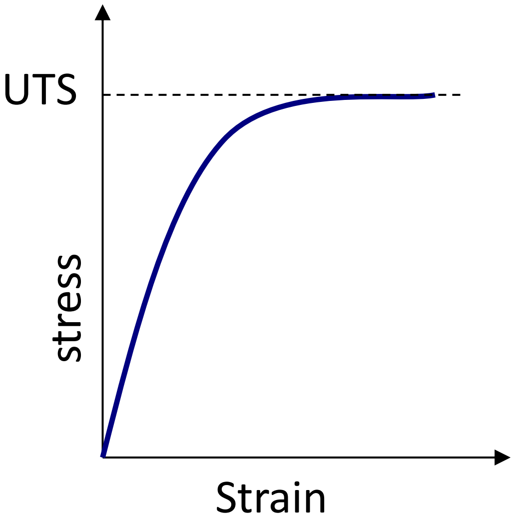
Idea: Reinforce the conductor with high strength fibre (glass, carbon, zylon)



When the wire gets into the plastic flow regime, it behaves like a liquid and is contained by the reinforcement

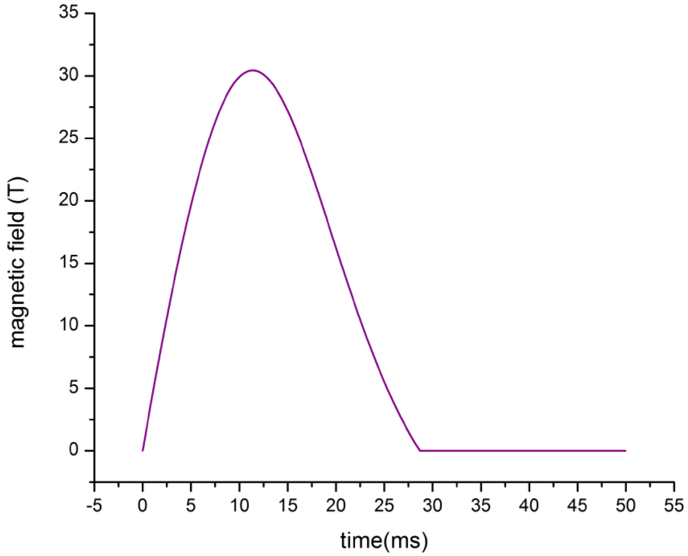
$$\sigma_t^R(r) \approx [jBr - \sigma_t^C]\frac{\delta_C}{\delta_R(r)}$$

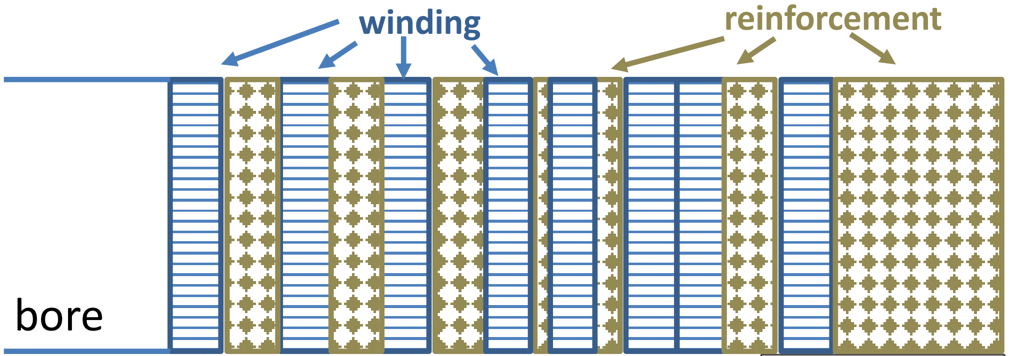
Vary reinforcement in each layer
=>Stress-optimized coil

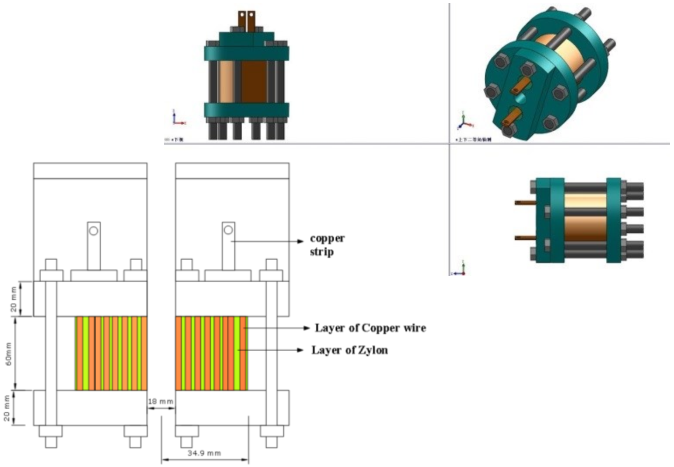


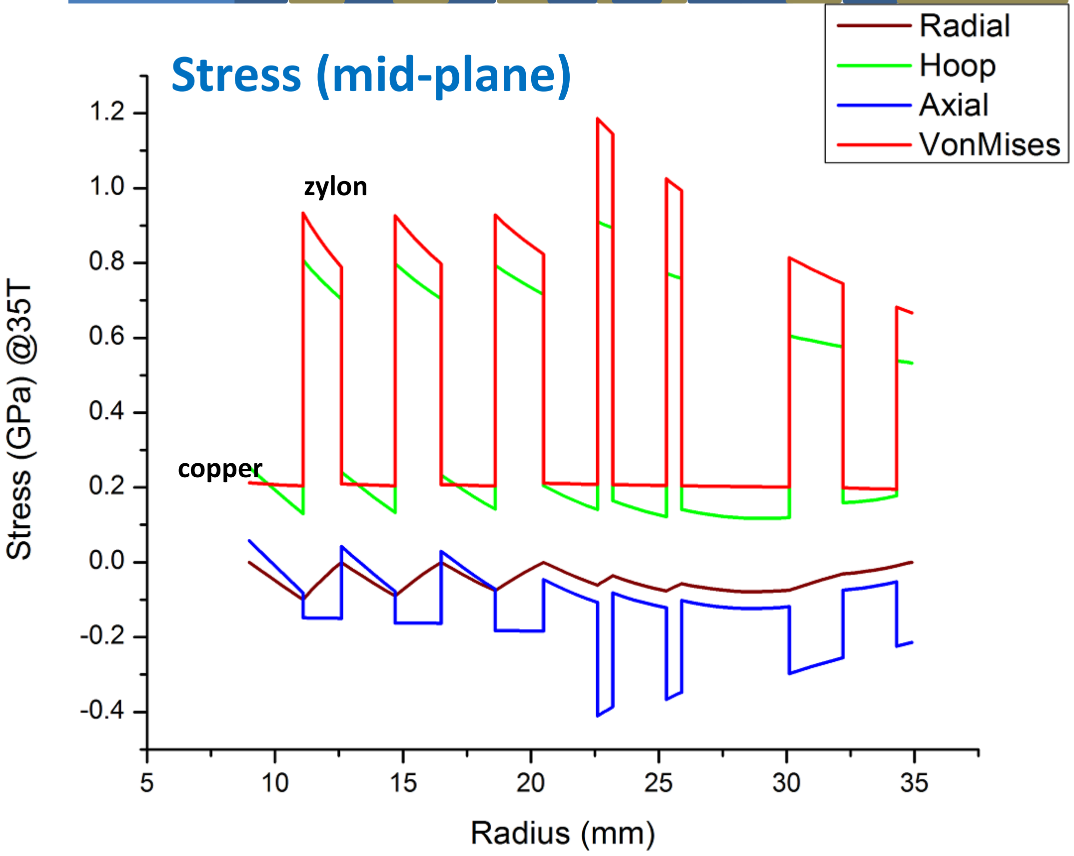
Currently reliable coils can be made up to ~70T (but they need to be very big)

Coil for our bank: simulation



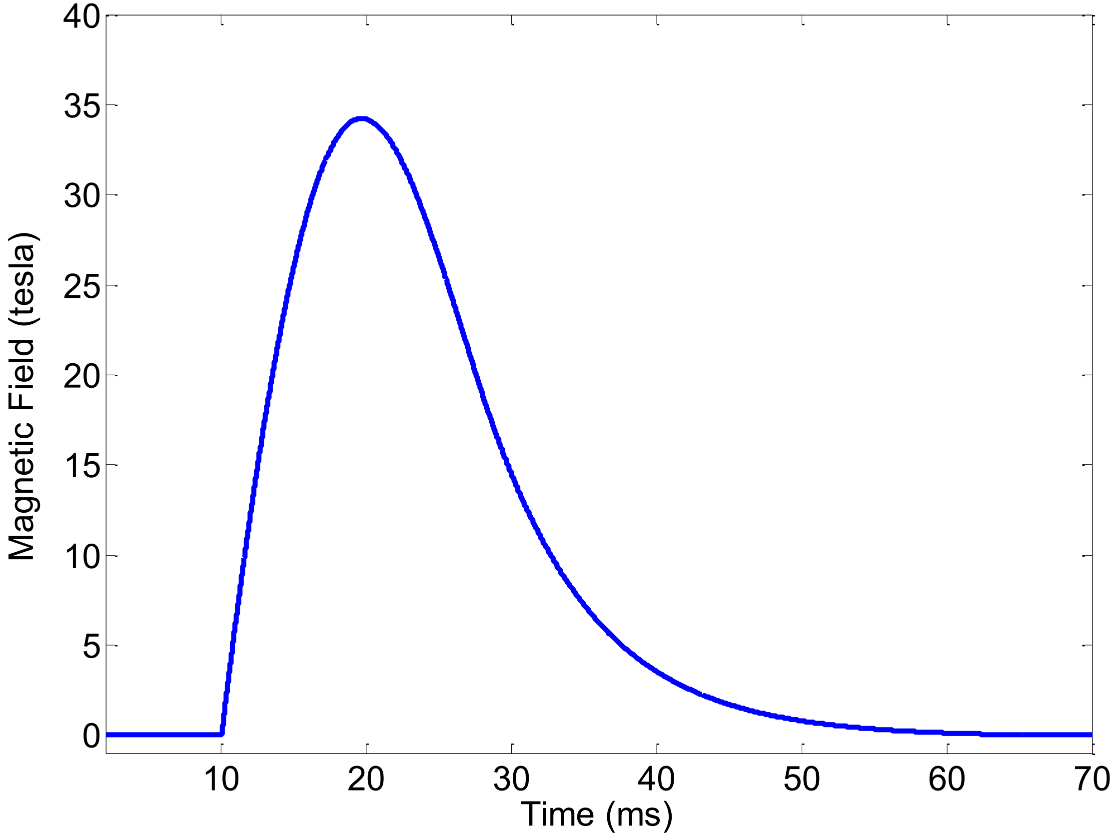


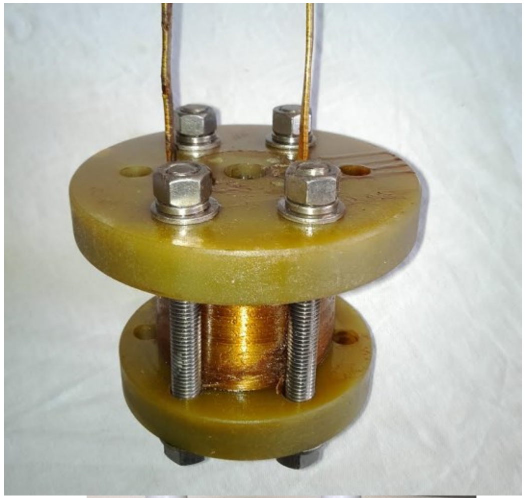


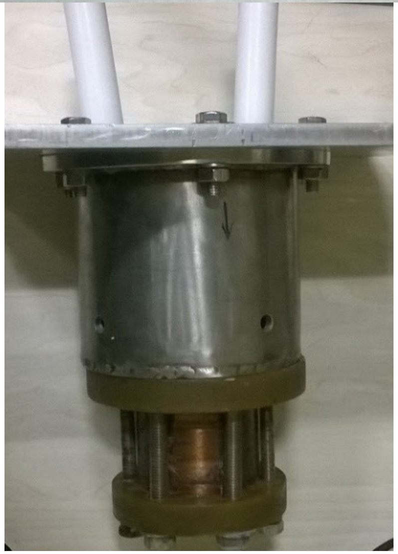


Calculation: Pulsed magnet design software (PMDS)
F. Herlach, J. Vanacken, L. Li, T. Peng

Actual Magnetic Field

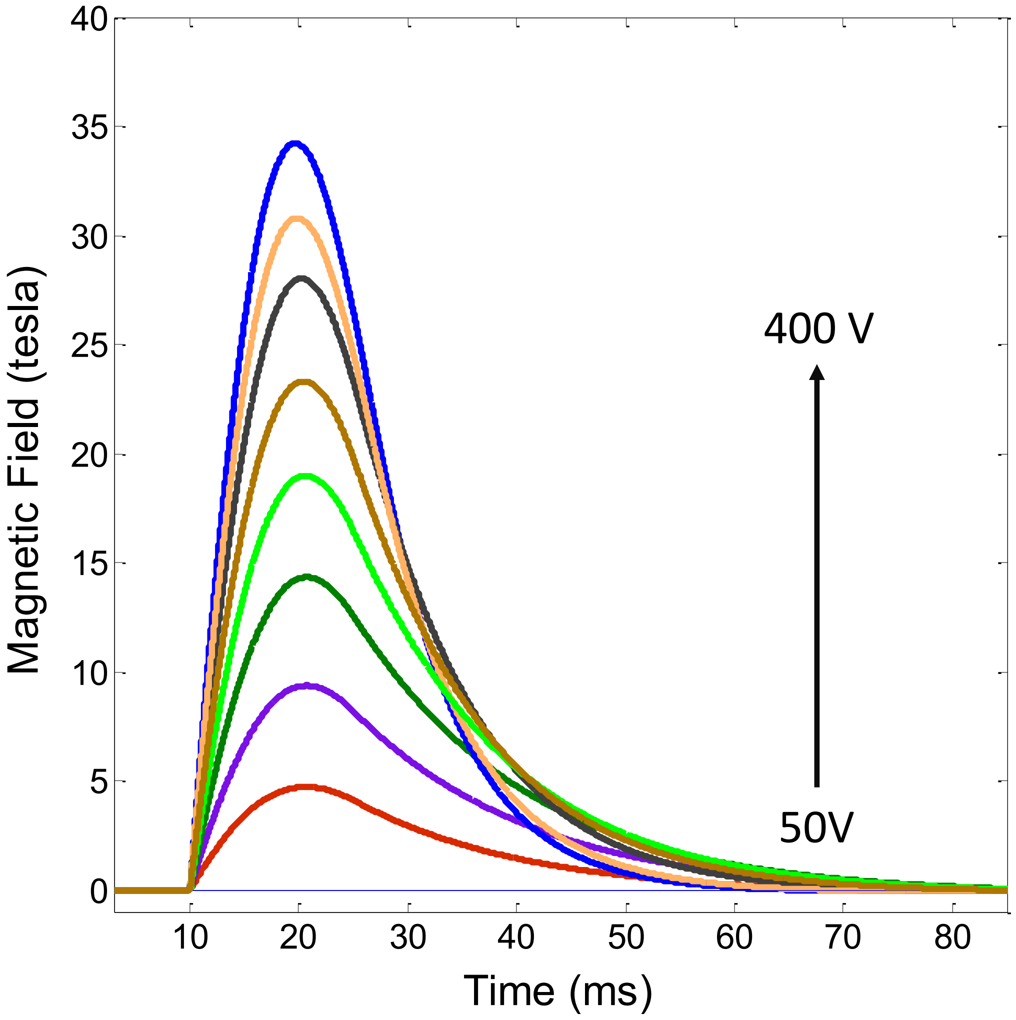


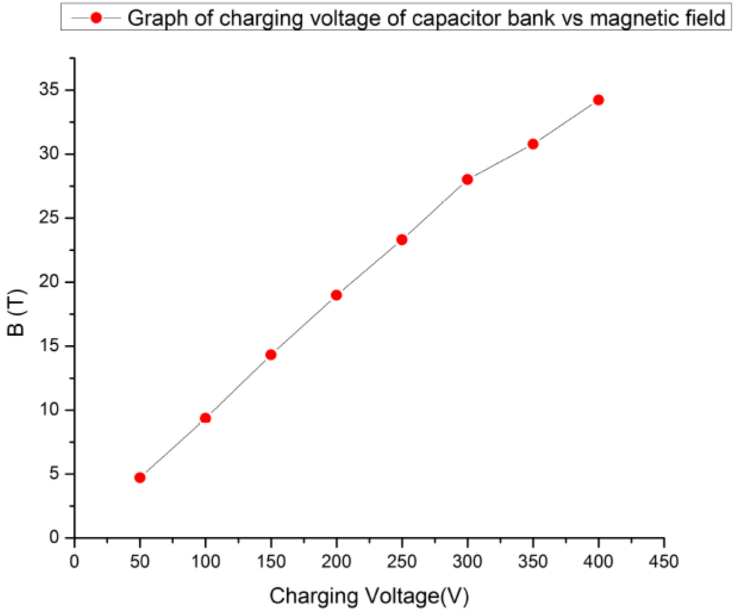




Coil wound at Wuhan University of Science and Technology (China), Dr Tao Peng [gratis]

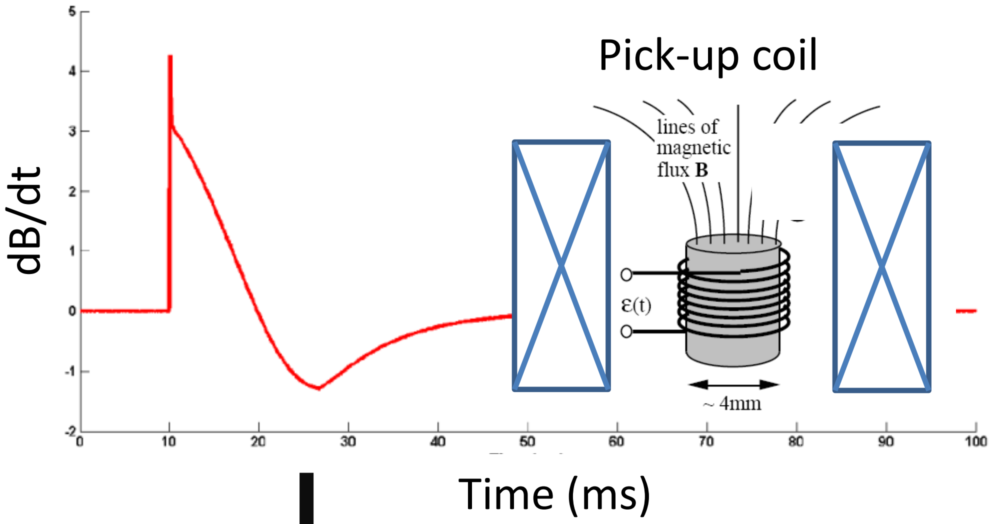
Peak Field vs Charging Voltage





Potential reach 40T, but the coil is designed by 35 T

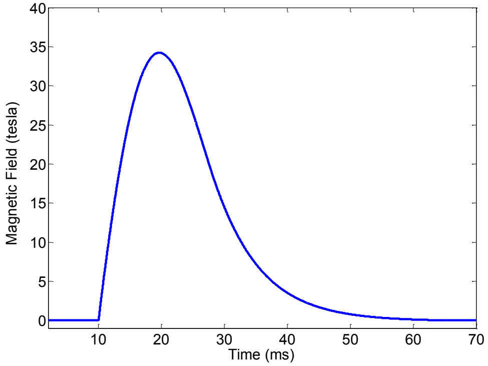
Measurement of magnetic field



Pick-up coil of known area

$$V_{ind}(t) = -\frac{d\Phi_B(t)}{dt} = -Area\,\frac{dB(t)}{dt}$$

$$=> \mathrm{B(t)} = -\frac{1}{Area}\int_0^t V_{ind}(t')dt'$$



Calibration Methods

-pick up coil calibrated at large facility (Wuhan)

-comparison with low field data in commercial magnets

-Commercial high-field Hall bars

-Phase transition

-Zeeman splitting of impurity levels in diamond

If we know the Area, then we can determine the magnetic field

Ingredients

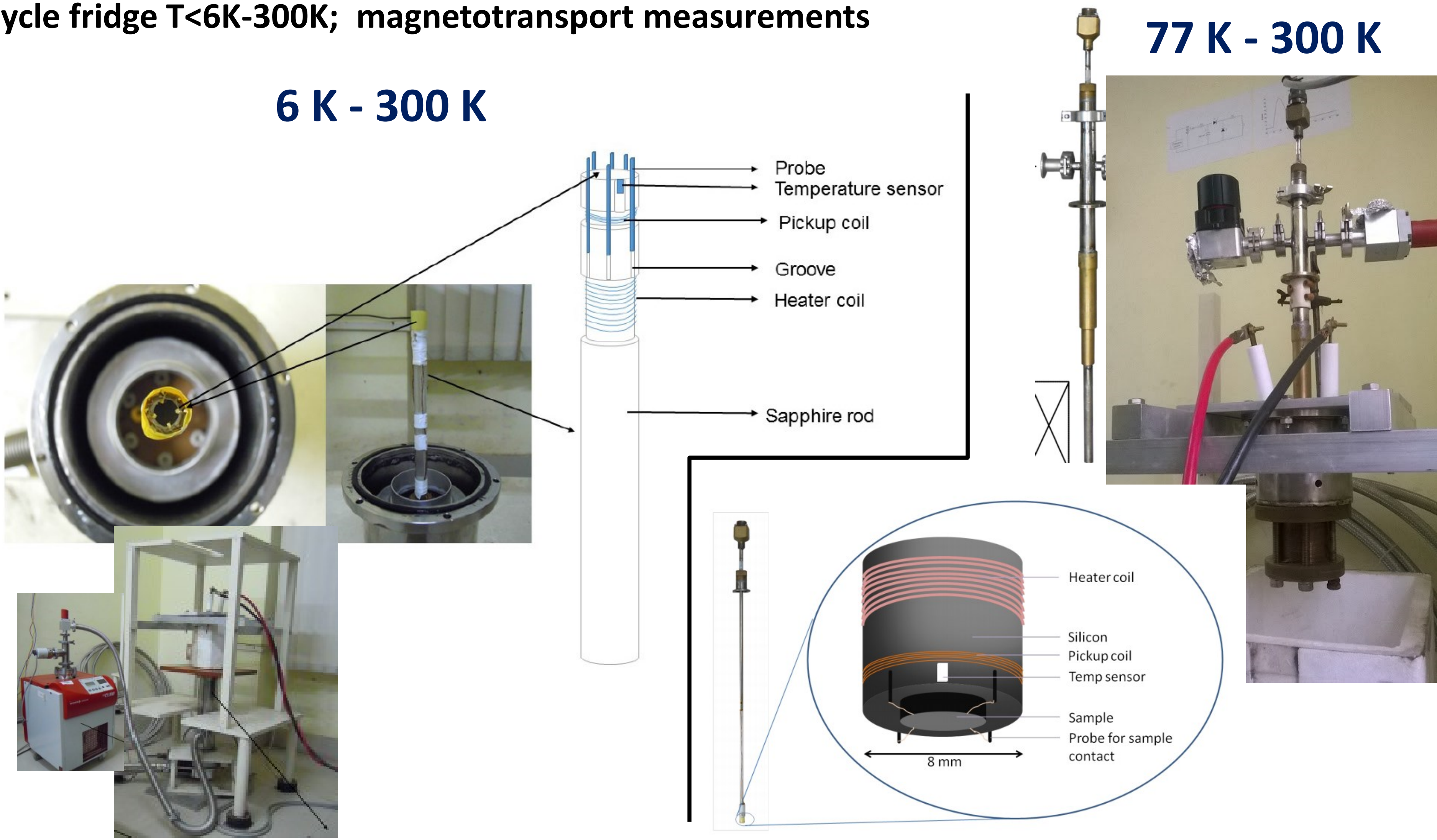
I. Generator circuit
II. Magnet Coil
III. **Cryostats**
IV. Fast measurement electronics, synchronous data acquisition
V. Safety
VI. Specialized measurement techniques/Noise reduction
  -Transport: e.g., digital lockin
  - Optical spectroscopy
  - Magnetic susceptibility

Cryostats

Sapphire or silicon cold-finger integrated with an old helium closed cycle fridge T<6K-300K; magnetotransport measurements

6 K - 300 K

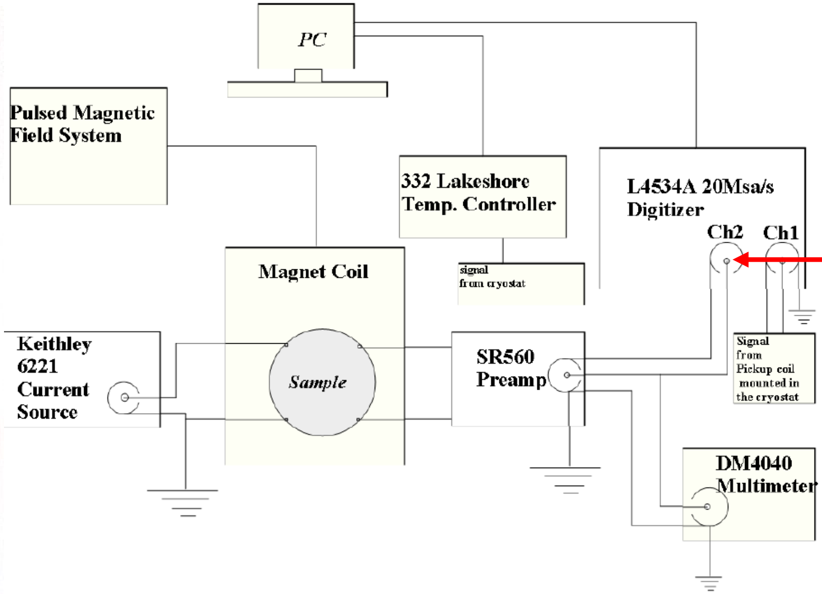
77 K - 300 K

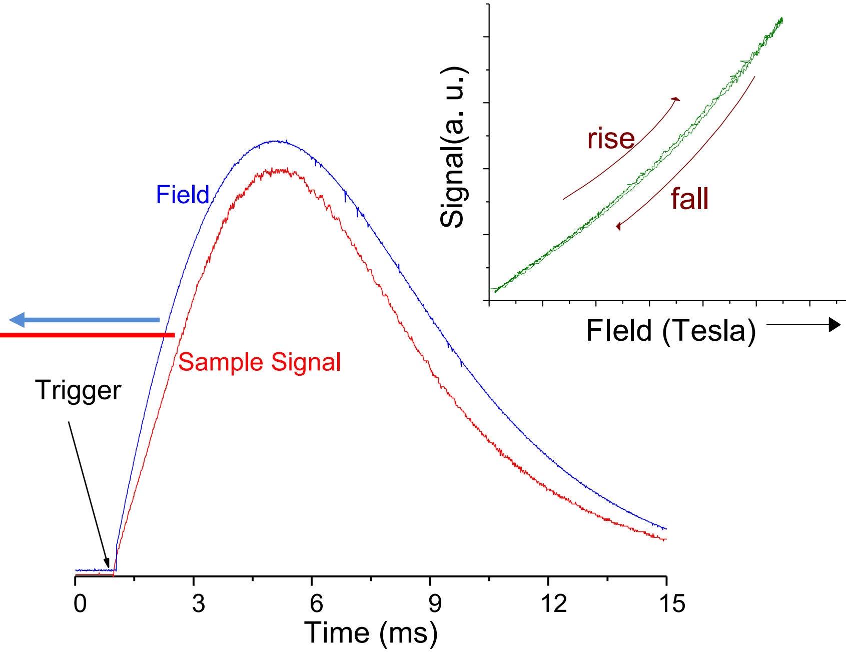


Ingredients

Fast measurement electronics, synchronous data acquisition (20 MHz, 4 ch, 16 bit)

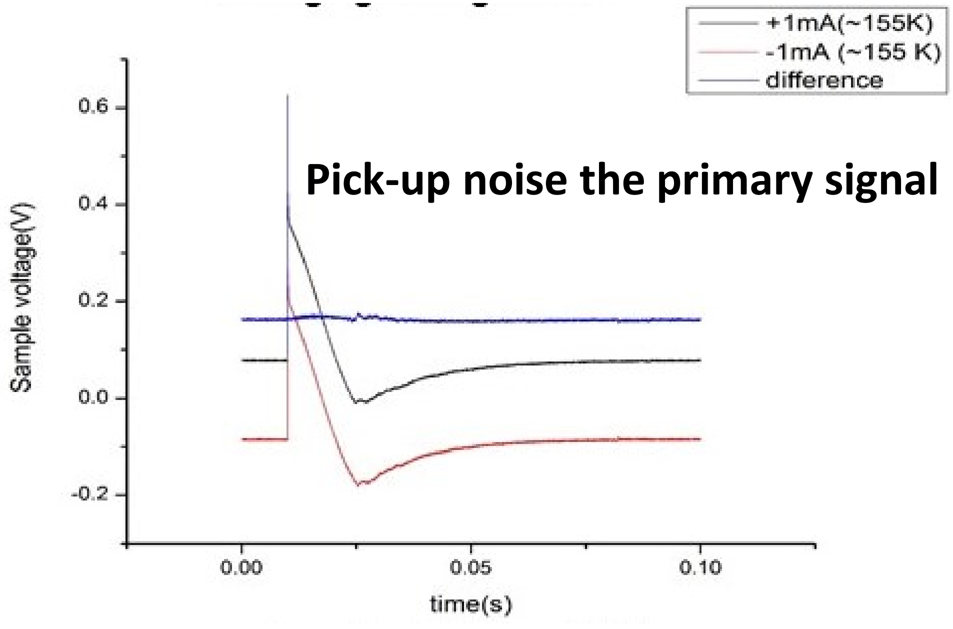
- Measurement electronics and the capacitor bank are simultaneously triggered
- Thousands of data points are recorded during the pulse, both on the rising and falling edge
- Experiment is over in a few milliseconds!
- Field is recorded simultaneously





Problems with Pulsed Fields

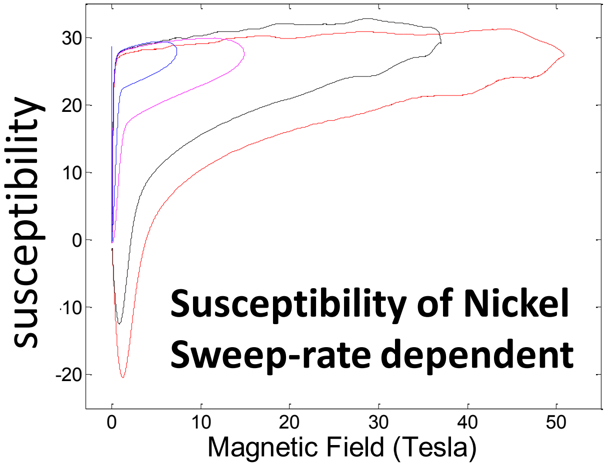
- Eddy currents (Conducting samples). Measurements below 4K are usually not useful
- Noise (Vibration): lot of trouble initially
- Large Background signal due to pickup
- Time-dependent field



Pick-up noise the primary signal

Advantages with Pulsed Fields

- **Eddy currents**
  [contactless conductivity measurements?]



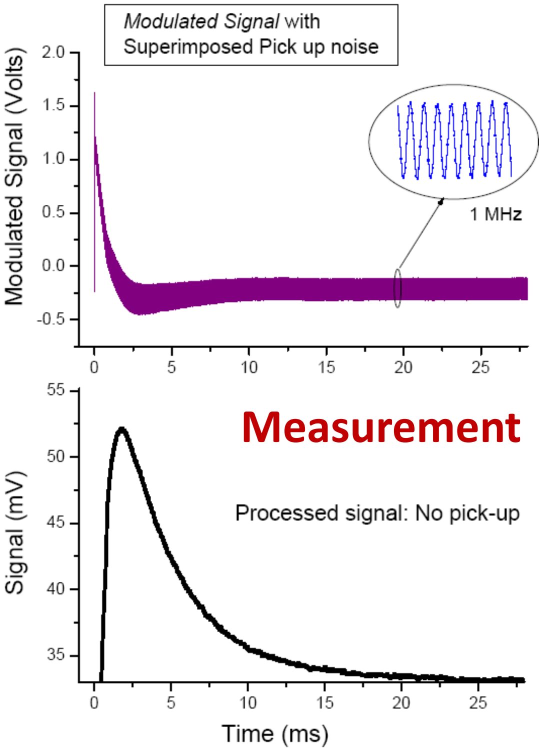
Susceptibility of Nickel
Sweep-rate dependent

- Time-dependent field **[dB/dt > 10,000 tesla/sec!]**
  Can we study rate dependence of slow phenomena?
  Landau-Zener tunneling between two degenerate states
  Non-equilibrium phase transitions
  Dynamical hysteresis, critical slowing down, Kibble-Zurek
  Metastable states in first-order phase transitions

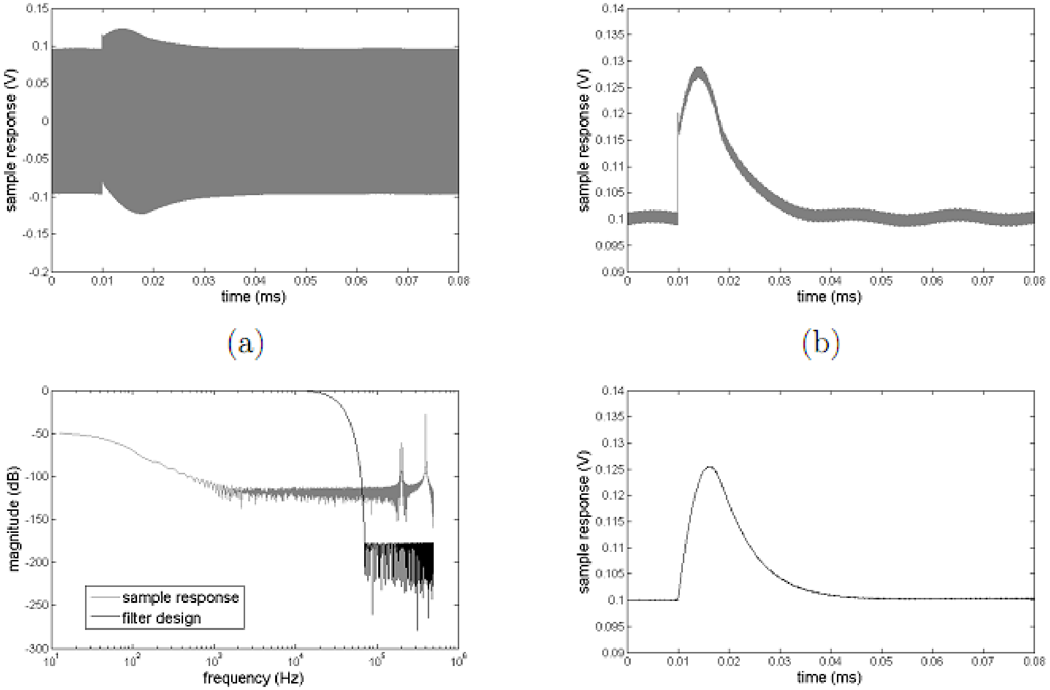
A small homemade set up allows for play. Not possible in large facilities.

Digital Lock-in Amplifier

- **Modulate the signal at ~ 1MHz**
- **Digitize both the reference and the signal (~20 MHz, 16 bit)**
- **Implement the lockin later, digitally**



Simulation



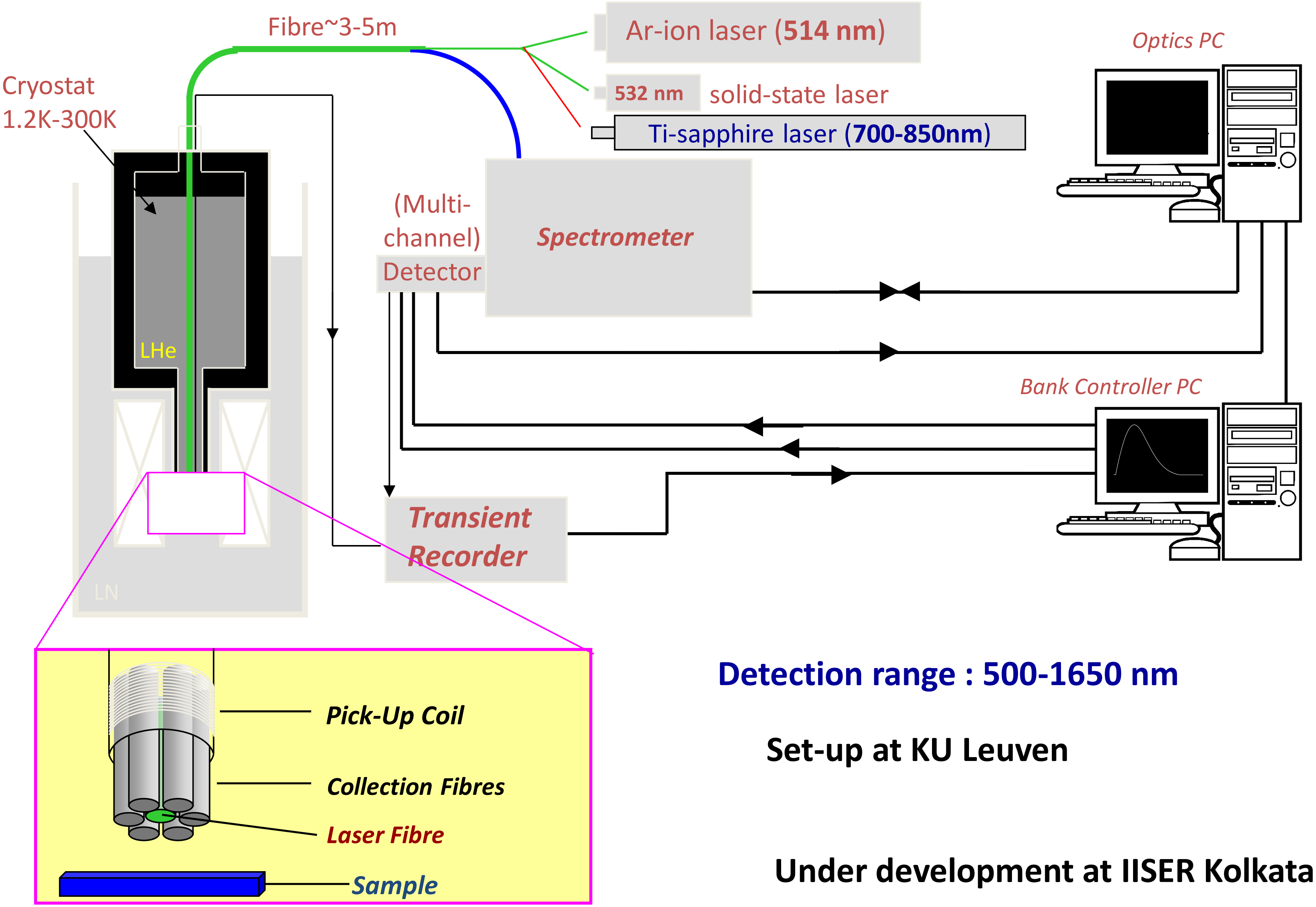
$$V^{ref}(t) = V_0^{ref}\sin\omega t$$

$$V^{sig} = V_0^{sig}(t)\sin(\omega t + \phi(t)) + \mathtt{Noise(t)}$$

$$V^{ref}\times V^{sig}\left[\xrightarrow{\text{lowpass } \omega_{cutoff} \ll \omega}\right] \frac{V_0^{ref}\times V_0^{sig}(t)}{2}\cos\phi$$

Conventional lockin amplifiers won't work [SR 830: 100kHz, 10-30us time constant]

Photoluminescence in pulsed fields

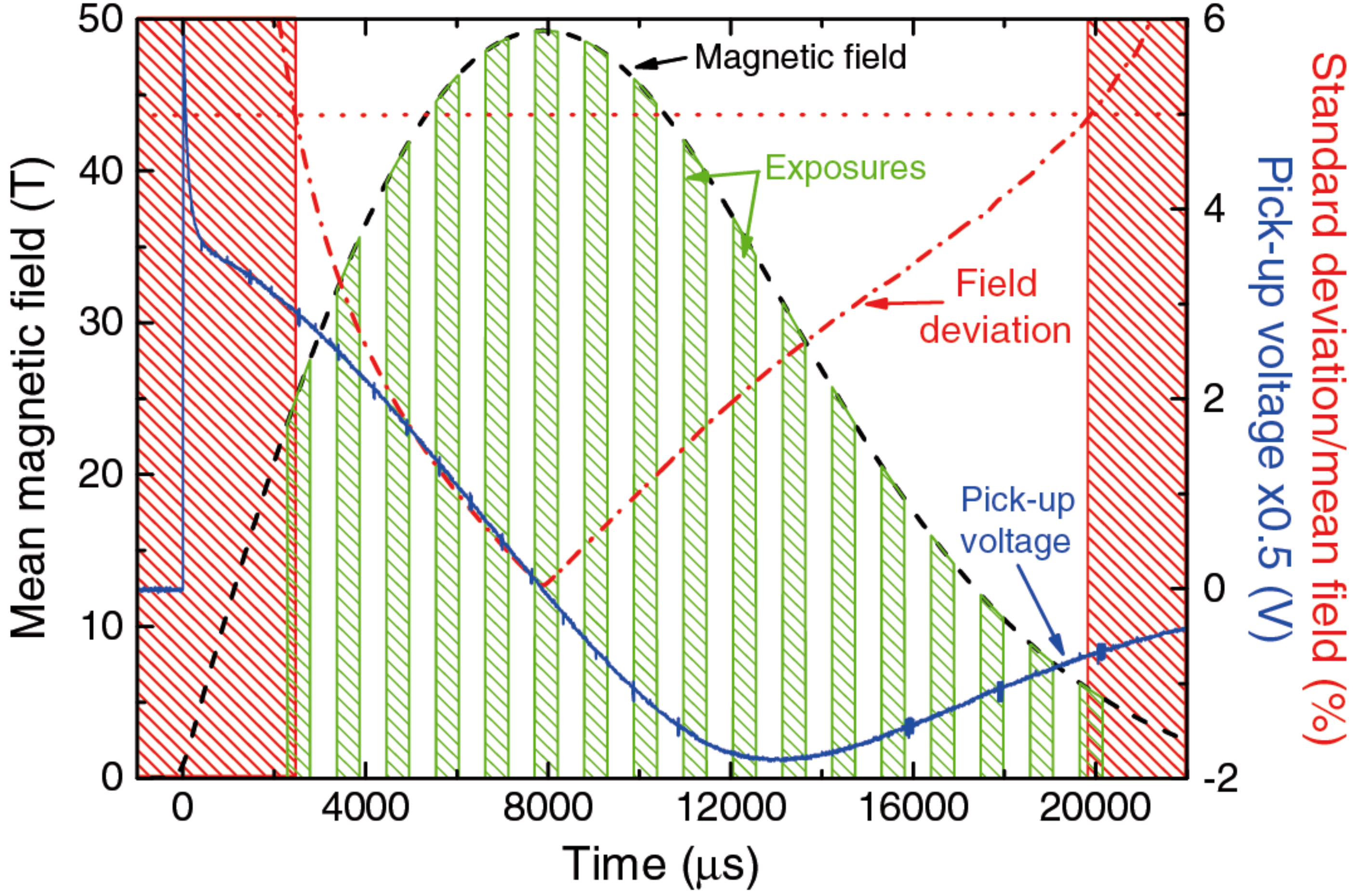


Detection range : 500-1650 nm

Set-up at KU Leuven

Under development at IISER Kolkata

Photoluminescence in pulsed fields



Some big pulsed field facilities around the world

European Magnetic Field Laboratory Consortium
Grenoble High Magnetic Field Laboratory , Grenoble (France). DC -35T, 42.5 T (hybrid)
Laboratoire National des Champs Magnétiques Pulsés , Toulouse (France). Pulsed 81.3 T, long 70T (10.2 ms) pulse.
Hochfeld-Magnetlabor Dresden, in Dresden (Germany). Pulsed (max 94.2 T).
High Field Magnet Laboratory, Nijmegen (Netherlands). DC 38 T resistive magnet and a 45T hybrid (under development)

National High Magnetic Field Laboratory (USA) with facilities at:
The **Magnet Lab at Florida State University** DC Field Facility. The World's strongest magnet, the 45 T hybrid
Los Alamos National Laboratory , Los Alamos (New Mexico). Pulsed 100 T

Wuhan National High Magnetic Field Centre Wuhan (China). Pulsed 83 T.

Tsukuba Magnet Laboratory, Japan. Maximum fields are 32 T Hybrid magnet and 50 T Pulsed Magnet. Record for the highest magnetic field produced using a superconducting magnet 24 T.
- **International Megagauss Science Laboratory**, Tokyo (Japan). Pulsed magnetic field up to 80T by non destructive magnets and from 100 up to 730 T (the world strongest as an indoor record) by destructive (the single turn coil and the electro-magnetic flux compression) methods.

Other magnetic field facilities are:
- **Long Pulse Magnet Facility** in Zaragoza, Spain (31T, 2000 ms).
- **Wills Physics Laboratory**, Bristol (UK). Pulsed fields up to 60 T
- **Pulsed Field Facility** in Leuven (Belgium). Fields up to 70 T

World record: 2800 T
[explosive flux compression]

Source: http://lbtuam.es/?page_id=212 [edited]

More “serious” generators

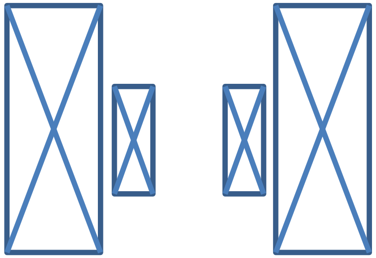
Dresden

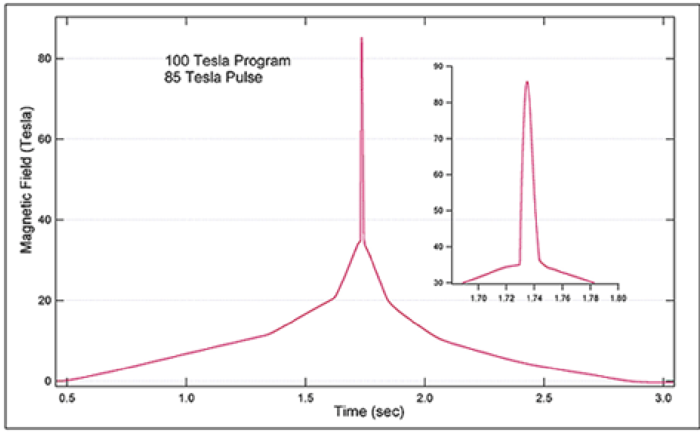
Toulouse
Area: 500 m^2
Weight: 100 tonnes
16 MJ, 24 kV

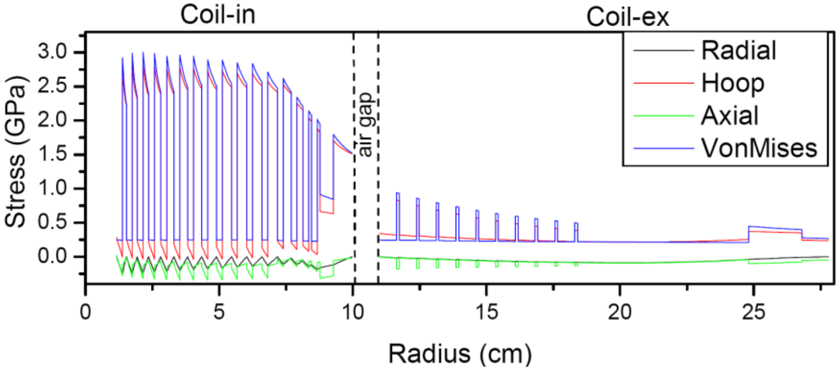
Two-coil idea

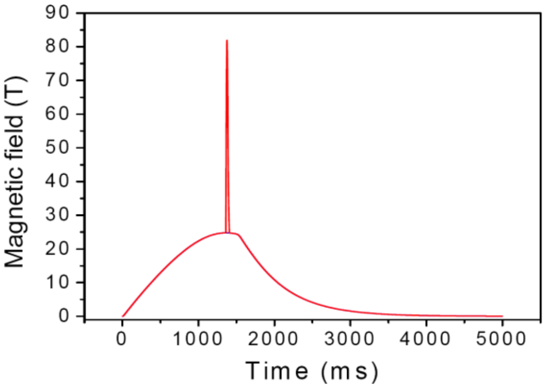
How about adding the fields of two magnets

1. **Hybrid: Superconducting + DC (45 T)**
2. **Pulsed + Pulsed (80-100 T): Los Alamos, Dresden, Toulouse**









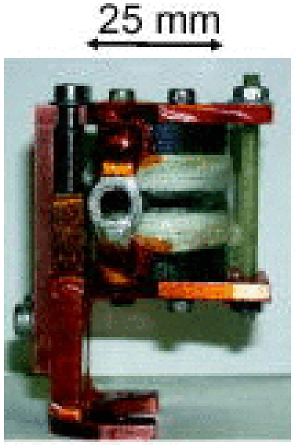
My design for an
80T two coil magnet
using dc generator
(Nijmegen 2008)

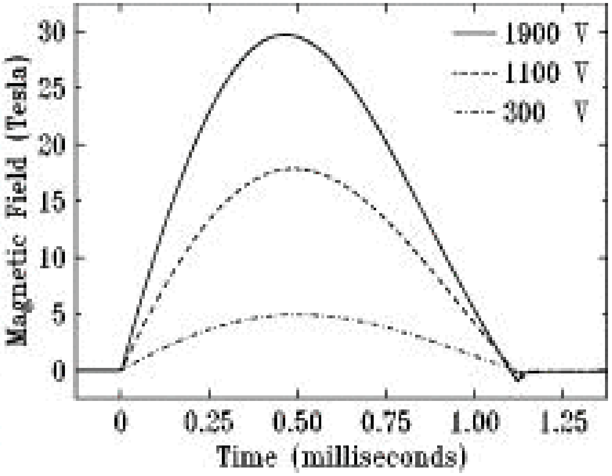
Miniature coils?

Can we implement the same idea even more compactly?

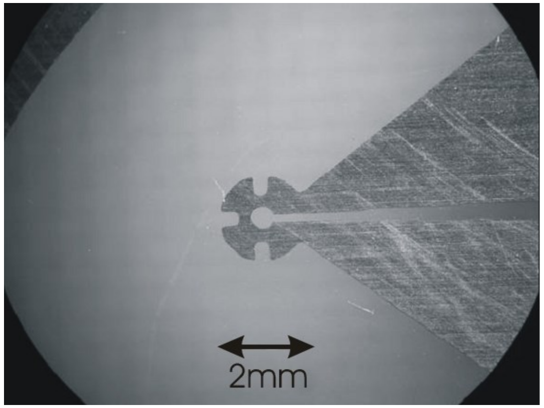
The samples are usually very small anyway

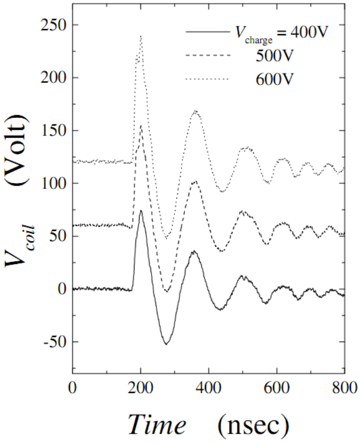
Split micro-coil magnet for XRD



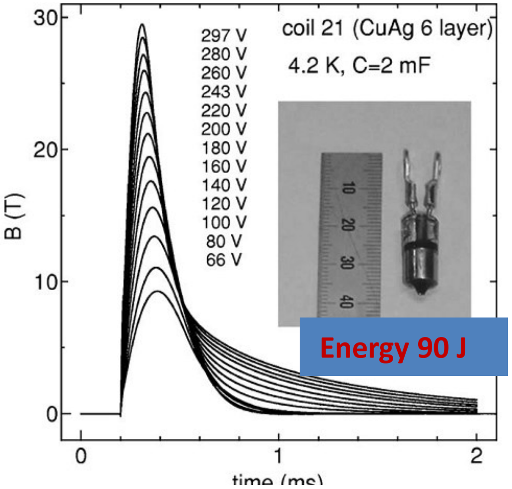


Islam, et al., Rev. Sci. Instrum. **80**, 113902 (2009);





Magnetotransport



Energy 90 J

E. Ohmichi and T. Osada
Rev. Sci. Instrum. **76**, 076103 (2005)

A perspective on pulsed fields

There is a resurgence of interest since the late 1990s

- One focus area of current condensed matter physics
- Better measurement techniques
  - Transport experiments have dramatically improved after the invention of the digital lockin technique
  - Serious spectroscopy possible with new detectors with fast exposure and high sensitivity [esp. EMCCD]
- Integration with other facilities
  - Free electron laser (terahertz)
  - Synchrotron (XRD measurements)
- Small laboratories are on their way out (unfortunately)

Globally the focus is on concentrating effort in a few places

And finally…

I will be very happy to

- share my experience and resources if you want to set up a (bigger, better) facility
- And of course do some physics together with you

Thank you!

Acknowledgments

IISER Kolkata group [past and present]

- **Sujeet Kumar Choudhary** [MS Thesis]
- **Arsalan Ashraf** [MS Thesis]
- **K. S. Sujith** [MS Thesis]
- **Dr. Pradip Khatua**
- **Dr. Uday Kumar**
- **Sumitabha Bhramachari** [summer student]

Coil winding and magnet design software

- **Prof. Tao Peng** [Wuhan, China]
- **Prof. Fritz Herlach** [Leuven, Belgium]

The following people have taught me many things about pulsed fields

- **Prof. Fritz Herlach** [Leuven, Belgium] (who has been working with pulsed fields >50 years!)
- **Prof. Manus Hayne** [Lancaster, UK]
- **Prof. Johan Vanacken** [Leuven, Belgium]
- **Prof. Jean Leotin** [Toulouse, France]
- **Prof. V. Venkataraman** [IISc Bangalore]