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FREIA

Accelerators and Magnets

Volker Ziemann, FREIA

2011

Today

https://cern.ch/ziemann

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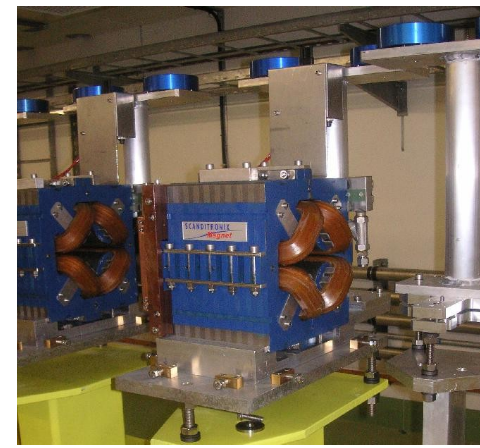
Roadmap

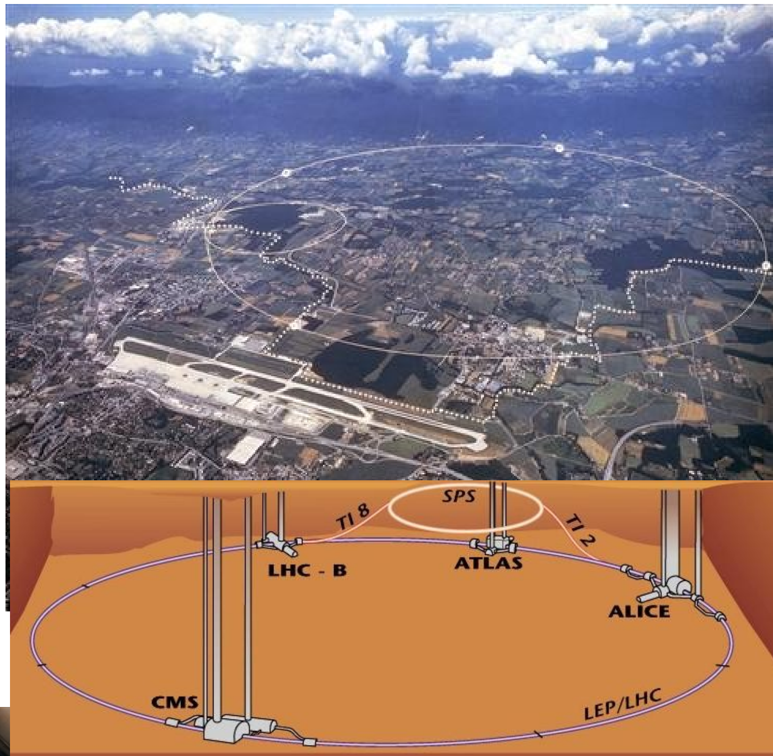
- Accelerators
  - key components

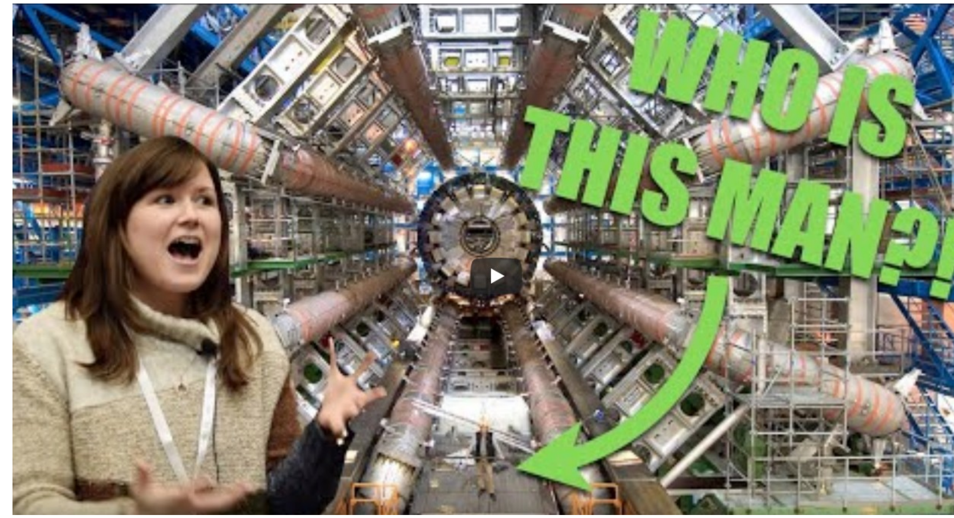


- FREIA
- Iron-dominated magnets
- Current-dominated magnets

- (Permanent magnets)
- (Measurements of magnets)

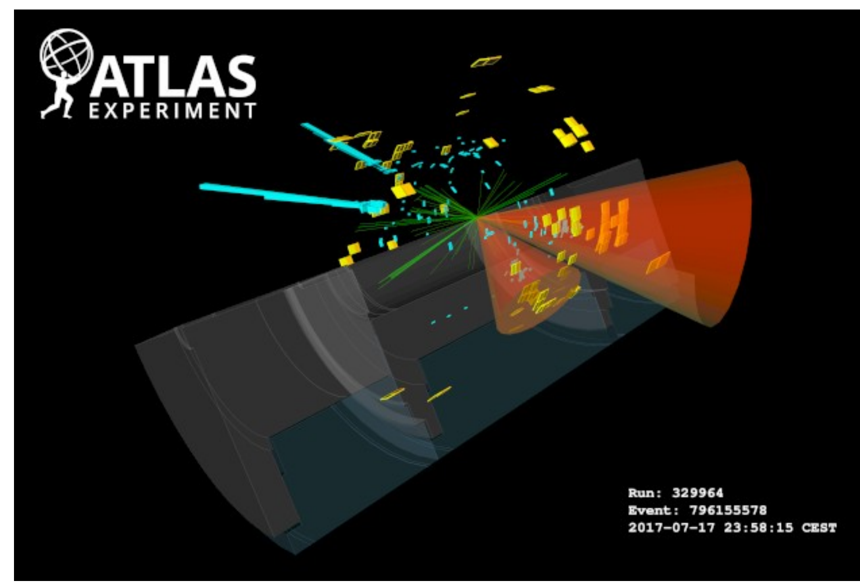
LHC at CERN



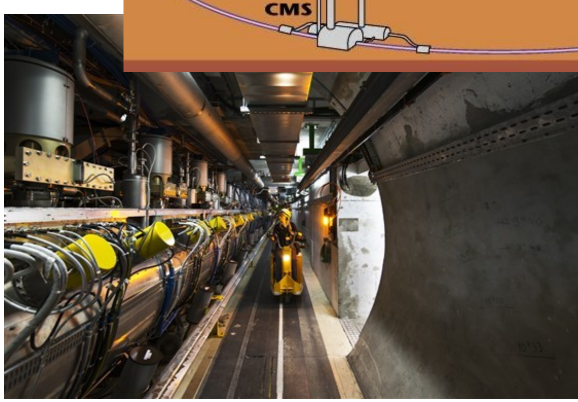


https://www.youtube.com/watch?v=sB0_ohLM3Kg

All images from CERN



Higgs $\rightarrow$ bb (jets) + γγ



Accelerating and bending

LHC does high-energy particle physics

MAX IV and ESS

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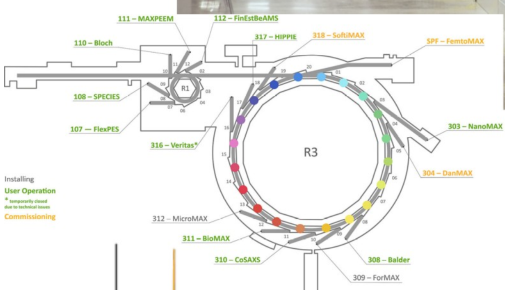
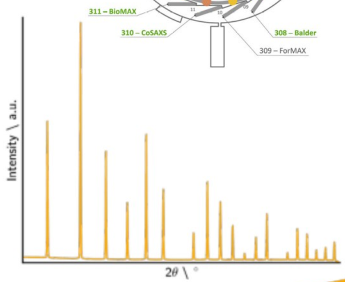
ESS:
proton linear accelerator

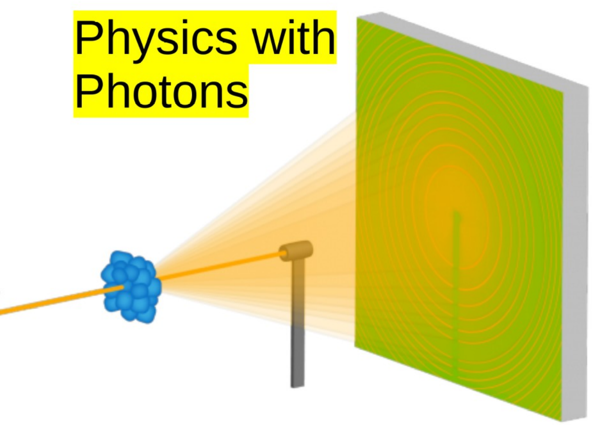
MAX IV:
electron ring

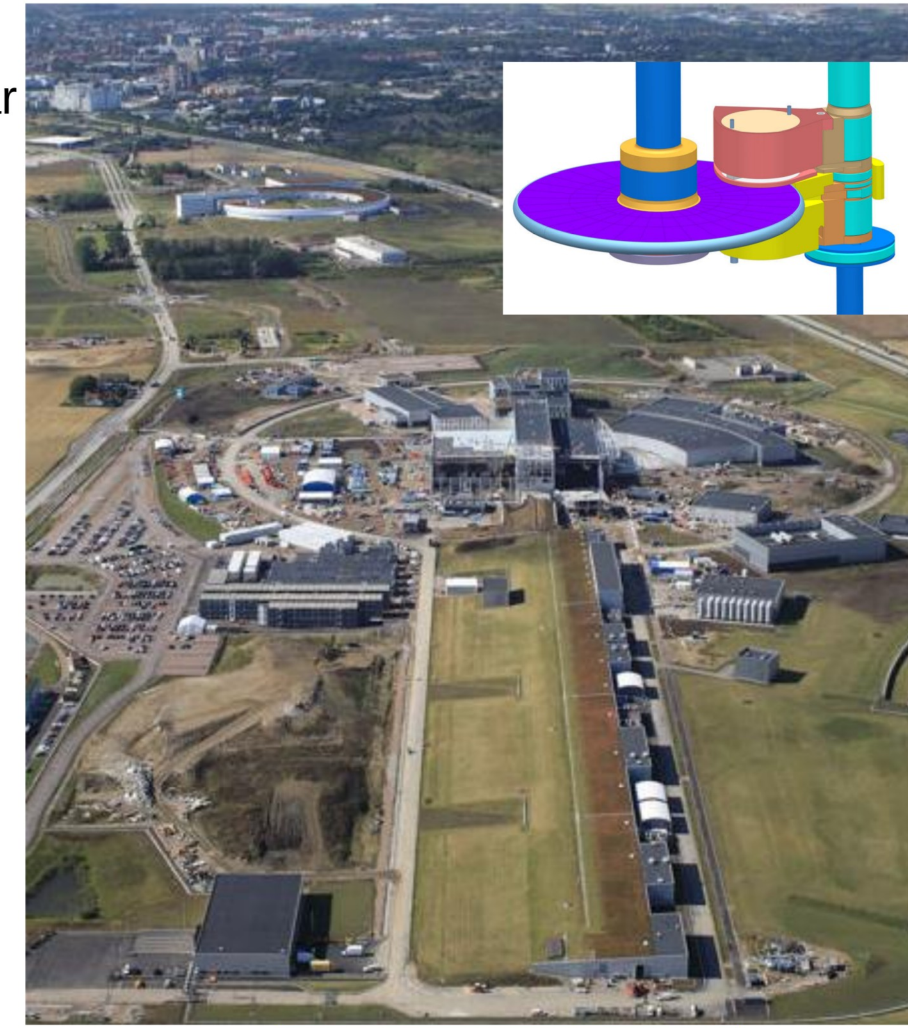


Material and life sciences



Physics with Photons





Physics with neutrons
- neutral particles
- magnetic moment

More magnets

More acceleration structures

Accelerators in Europe

...a small selection...

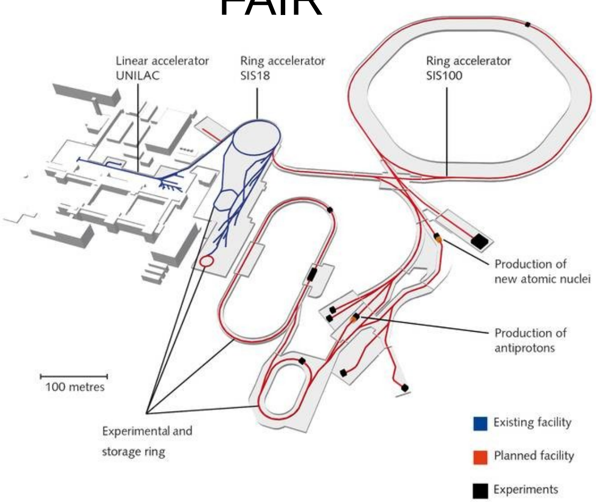
XFEL

Elettra
FERMI

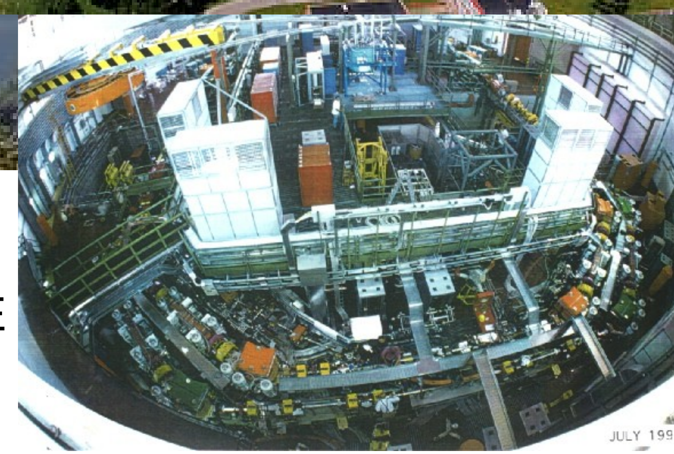
Soleil

ESRF

FAIR



DAFNE



all images stolen from the respective homepages

and the rest of the world

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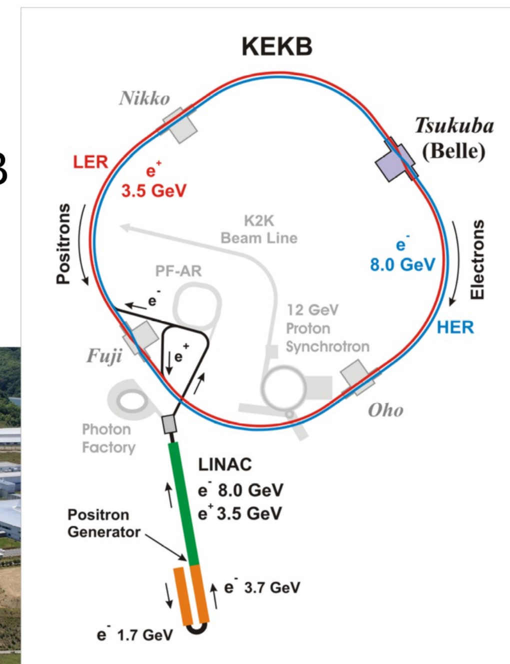
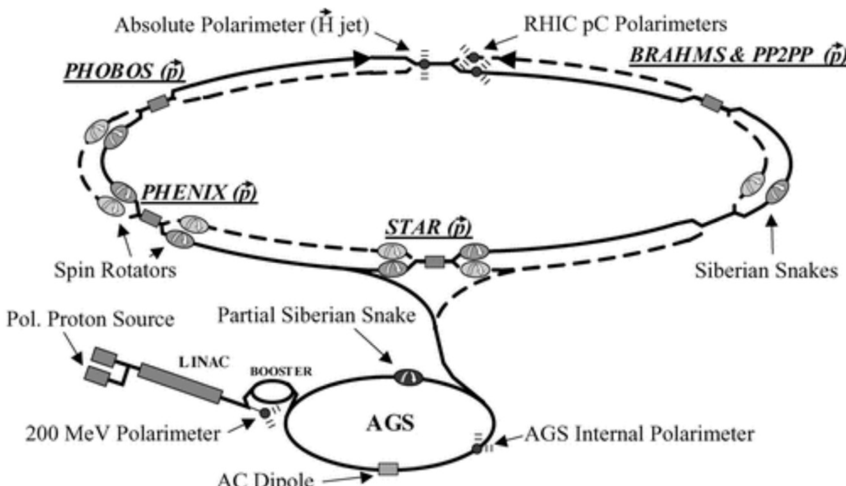
Fermilab

SLAC

KEKB



SACLA



BNL

 ...and many, many more

all images stolen from the respective homepages

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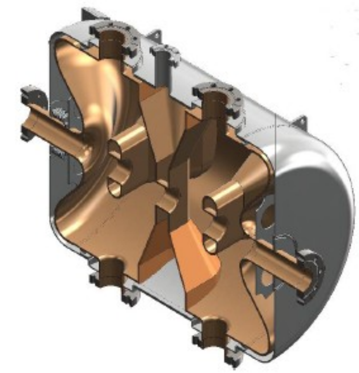
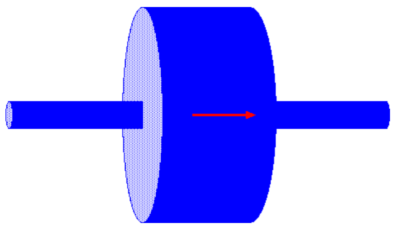
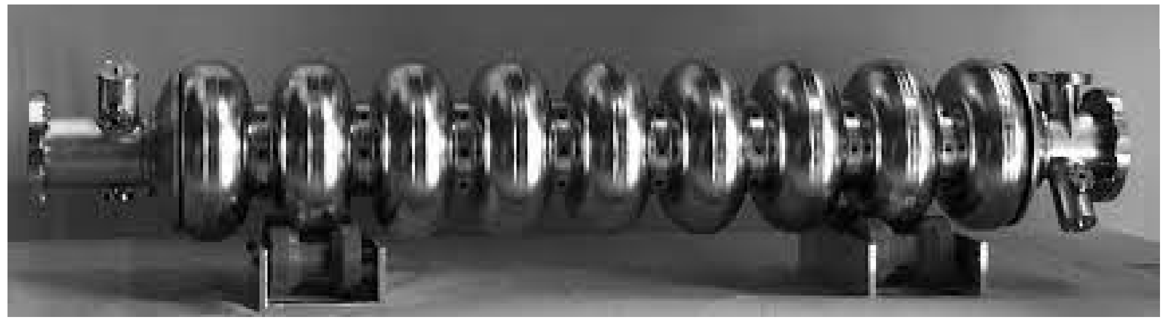
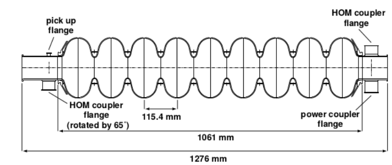
Acceleration

through standing E&M waves, called RF
electrical field accelerates

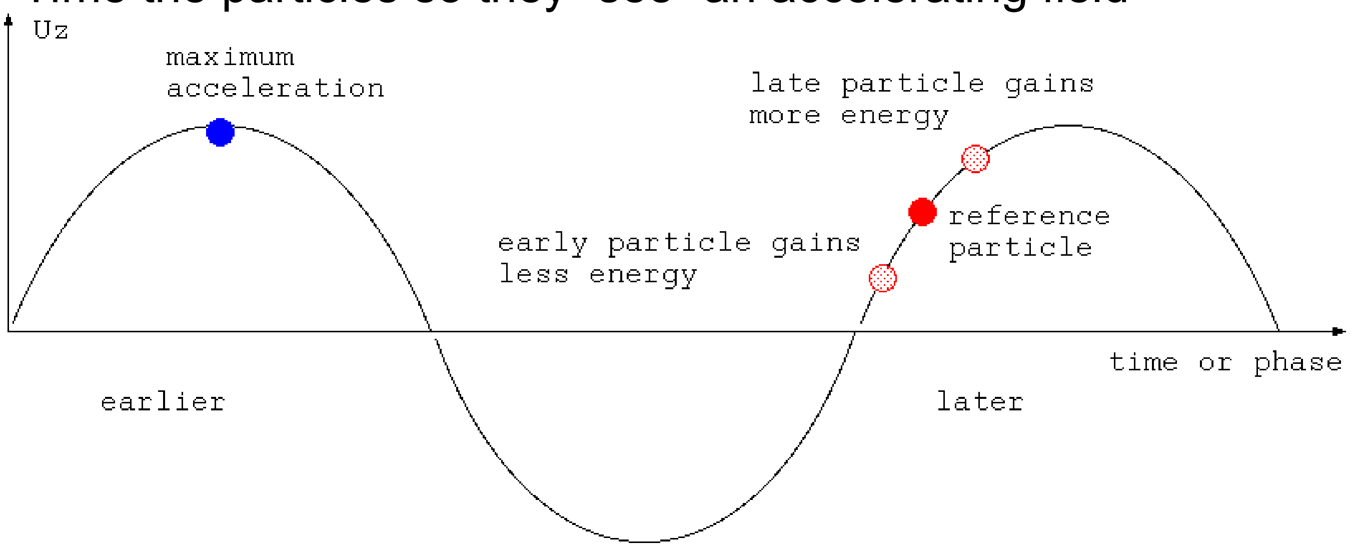




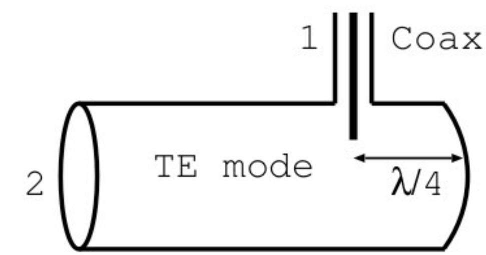


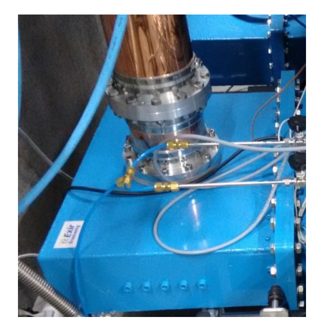


Time the particles so they “see” an accelerating field



Antenna = Coupler

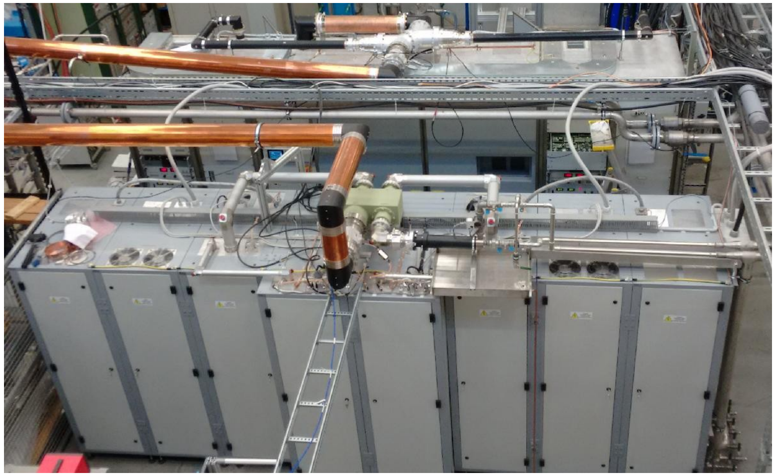




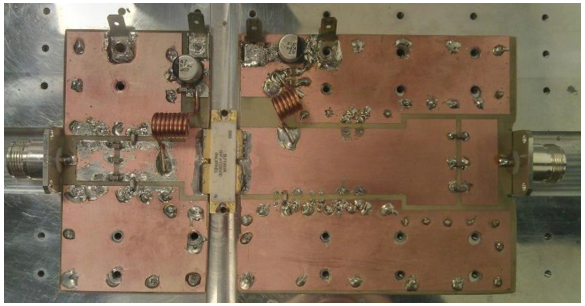
There are normal and superconducting cavities

Power generation

- Transform "wall-plug power" to radio-frequency power



- Power supplies
  - DC or pulsed ("modulators")
- Amplifiers
  - Preamplifiers are often based on transistors



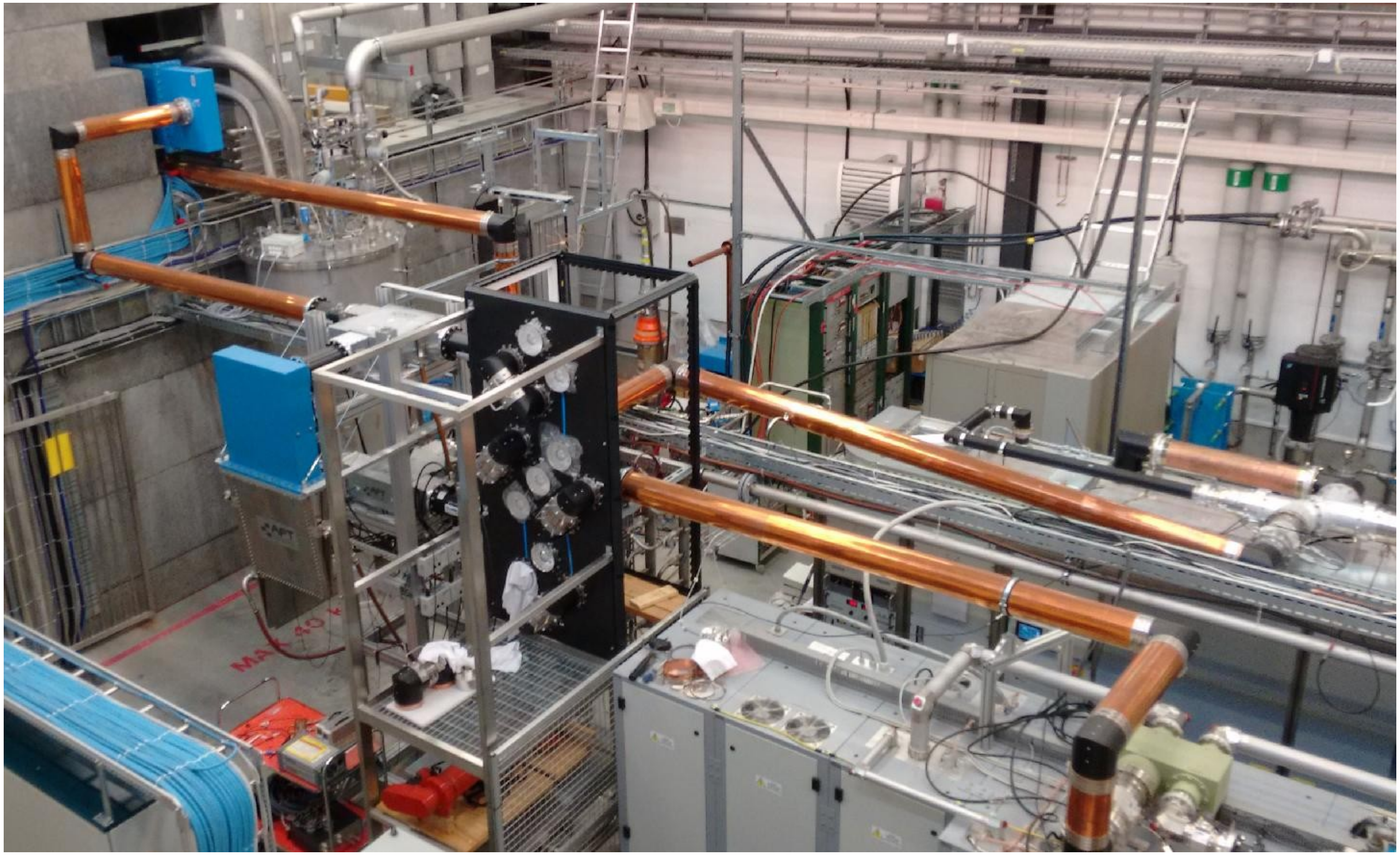
images: FREIA

  - Tetrodes (old TV and radio vacuum tubes)
  - Klystrons (other types of tubes)

FREIA RF-distribution

Third power station with tetrode in the background (now dismanteled)

Rectangular and coaxial waveguides



Circulator och dummy load (resistor)

RF-power switchyard

Two RF power stationer with two tetrodes each 400 kW in 3 ms at 17 Hz

Power combiner

What do we do in FREIA?

Test of Spoke-cavities for ESS

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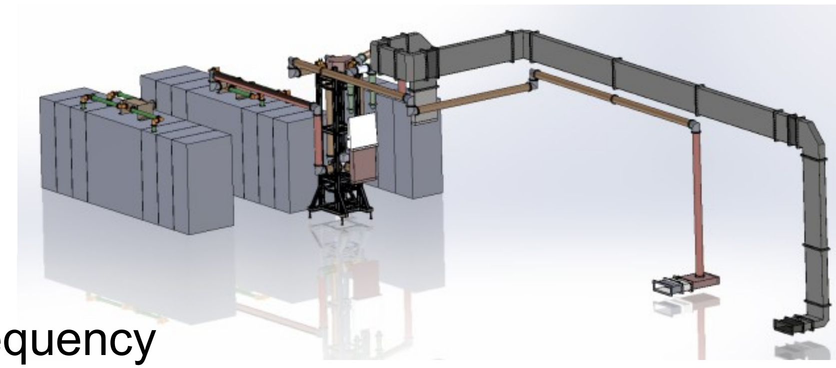
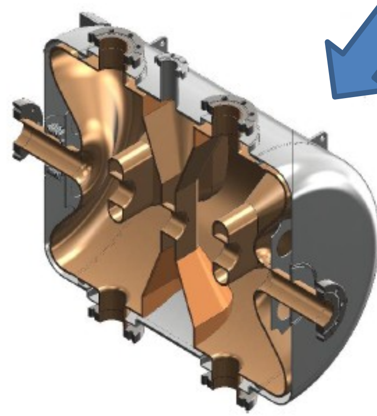


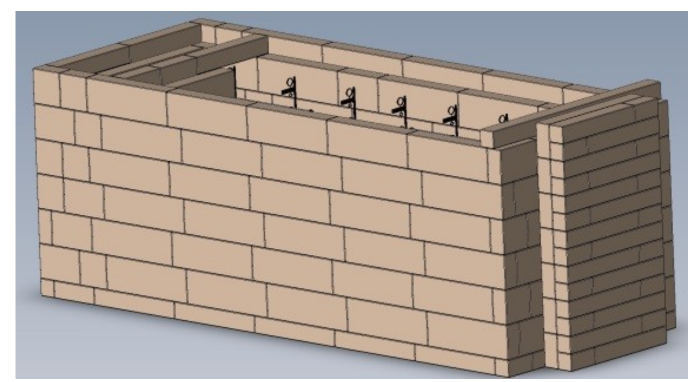
Radio-frequency power amplifier

Cryogenics for LHe

Cryostat



Spoke-cavity superconducting



Bunker for radiation protection

+Diagnostics+Control+...

Bild from R. Ruber and R. Santigo-Kern

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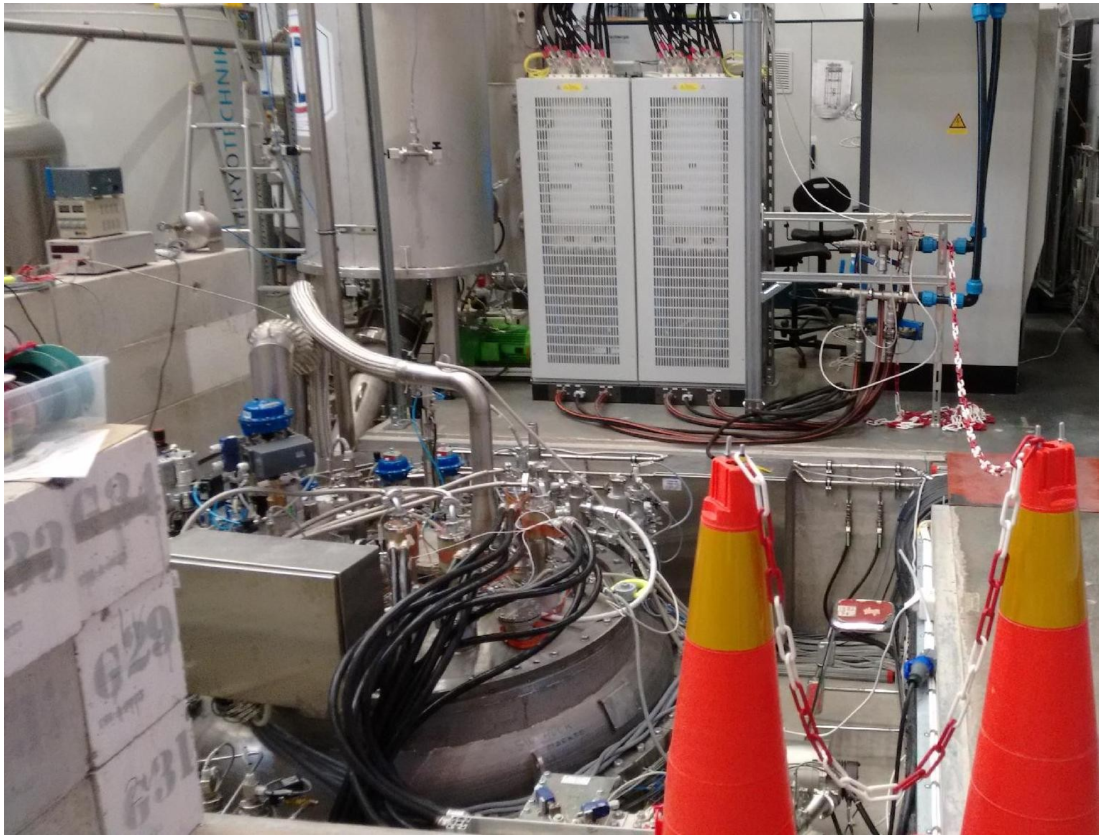
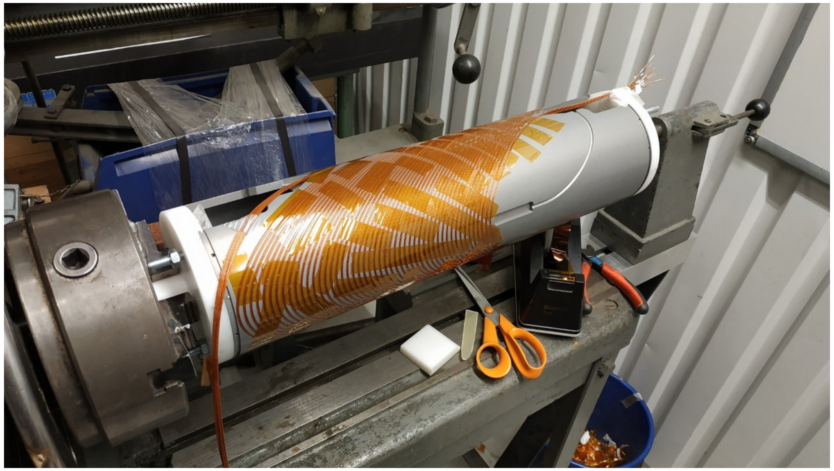
FREIA and Magnets

Test of magnets in FREIA’s vertical cryostat GERSEMI
   * HL-LHC dipoles
   * CCT magnets





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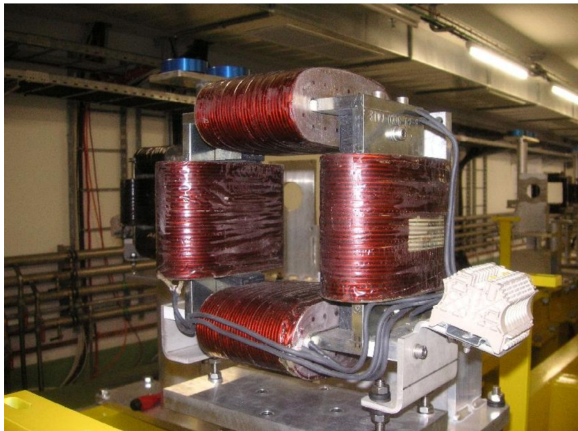
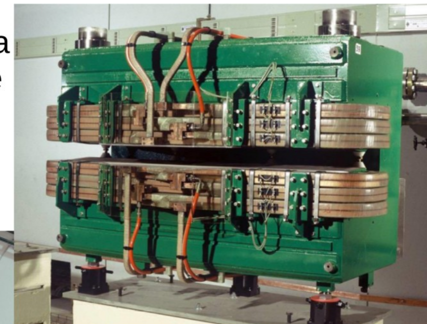
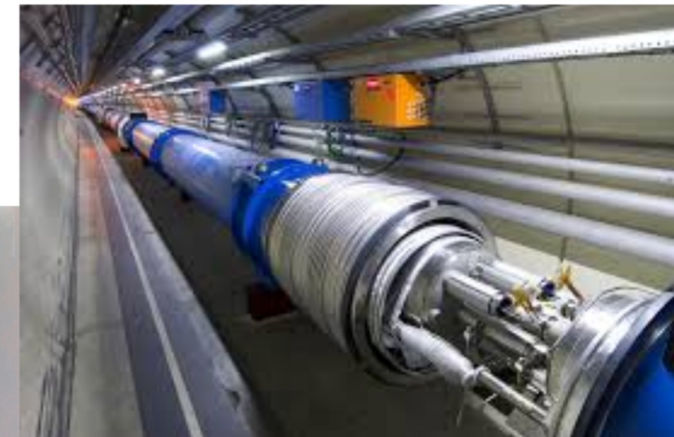
Magneter



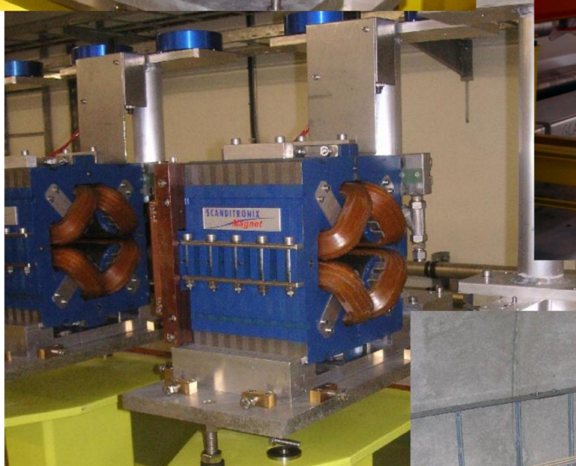


Elettra dipole



from CERN web site

from CERN web site



Photos: R. Ruber

from XFEL web site

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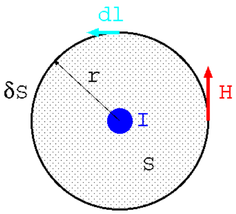
A little theory in 2D



Maxwell's equations lead to Ampere's law

$$\vec\nabla\cdot\vec D=\rho \quad , \qquad \vec\nabla\times\vec E=-\frac{\partial\vec B}{\partial t} \ ,$$

$$\vec\nabla\cdot\vec B=0 \quad , \qquad \vec\nabla\times\vec H=\vec J+\frac{\partial\vec D}{\partial t}$$

$\longrightarrow$ $\int_S \vec J\cdot d\vec S=\int_S\left(\vec\nabla\times\vec H\right)\cdot d\vec S=\int_{\partial S}\vec H\cdot d\vec l$

Stoke's theorem

$\longrightarrow$ $$B(r)=\frac{\mu_0 I}{2\pi r}$$

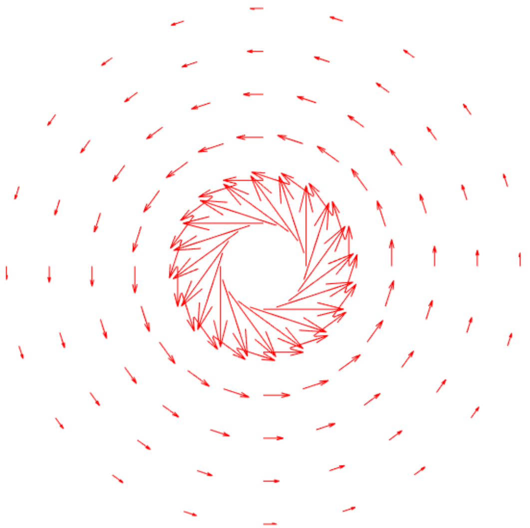
"current I makes field B"

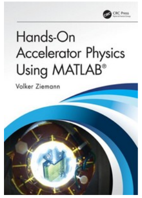
In 2D derive this from complex potential **F(z)**

$$F(z)=(-\mu_0 I/2\pi)\log(z) \longrightarrow B_x(x,y)-iB_y(x,y)=i\frac{dF(z)}{dz}$$

$\longrightarrow$ $$B_x-iB_y=\frac{\mu_0 I}{2\pi i z}$$

```
% field_of_current_filament.m
clear all; close all
r=0.2:0.2:1.2; phi=pi/10:pi/10:2*pi;
[R,PHI]=meshgrid(r,phi);
XX=R.*cos(PHI); YY=R.*sin(PHI)
B=1./(XX+i*YY);
By=real(B); Bx=imag(B);
quiver(XX,YY,Bx,By,'Color','r');
axis square; axis off;
xlim([-1.2,1.2]); ylim([-1.2,1.2])
```





Comment: In 2D are Maxwell's equations equivalent to Cauchy-Riemann equations

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Multipoles

$z = x + iy$

- Expand any *F(z)* in a power series

$$F(z) = -B_0 R_0 \sum_{m=1}^{\infty} \frac{b_m + i a_m}{m} \left(\frac{z}{R_0} \right)^m$$

  – with multipole coefficients a_m and b_m

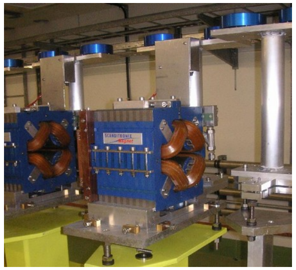
- Magnetic fields

$$i w(z) = B_y + i B_x = -\frac{dF}{dz} = B_0 \sum_{m=1}^{\infty} (b_m + i a_m) \left(\frac{z}{R_0} \right)^{m-1}$$

  – b_m describe upright magnets

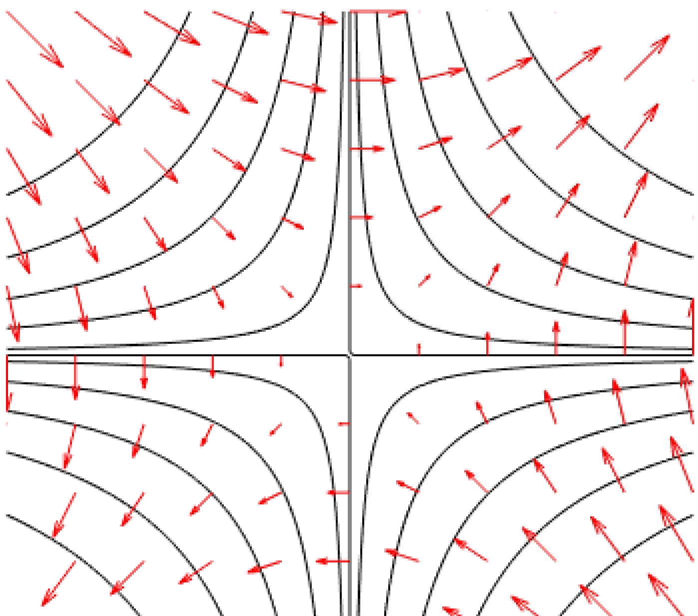
  – a_m describe skew-magnets

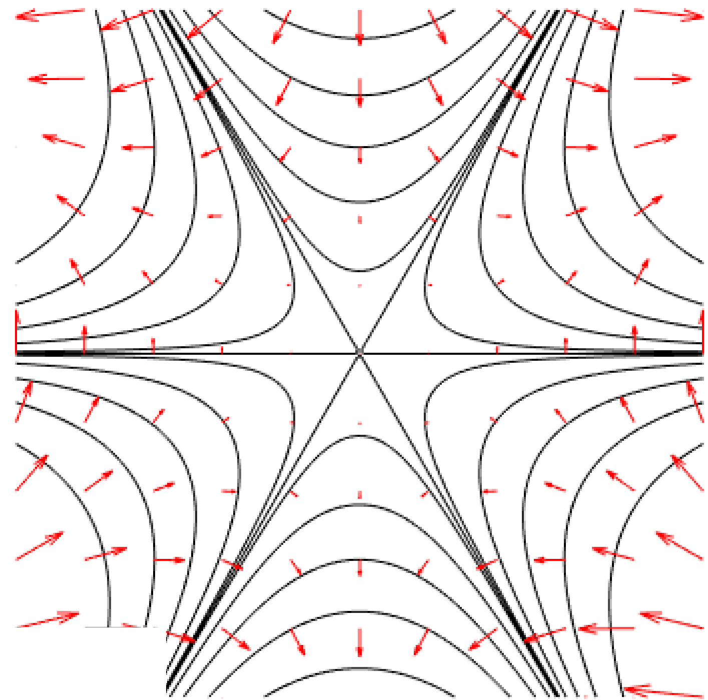
Accelerator people use this a lot!



Equipotential and field lines

- Quadrupole (m=2)
- Sextupole (m=3)

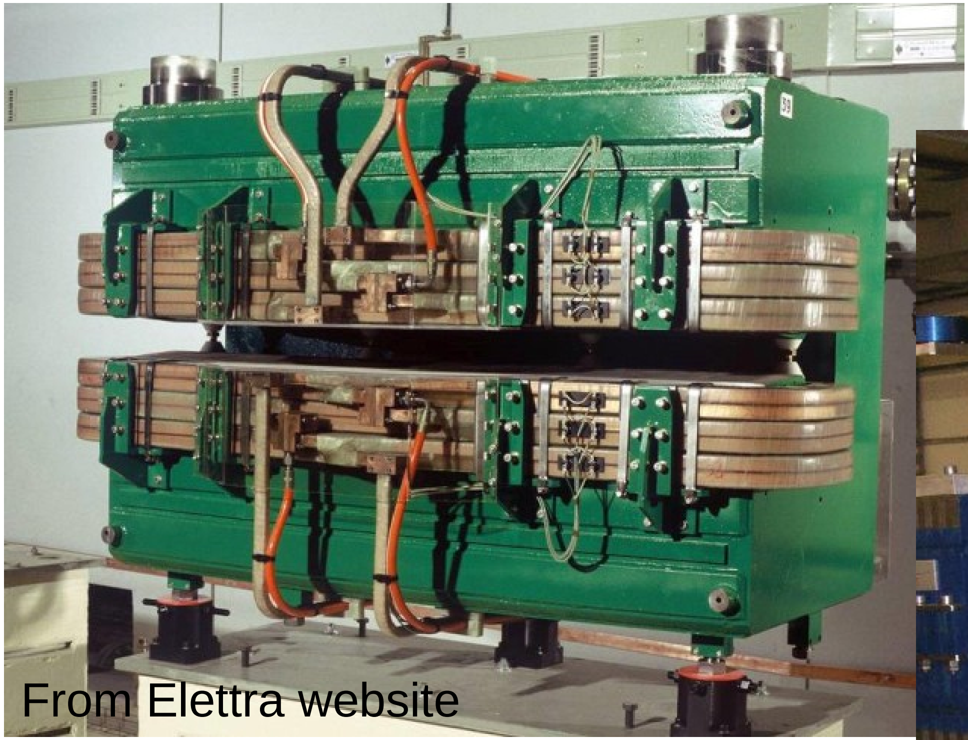


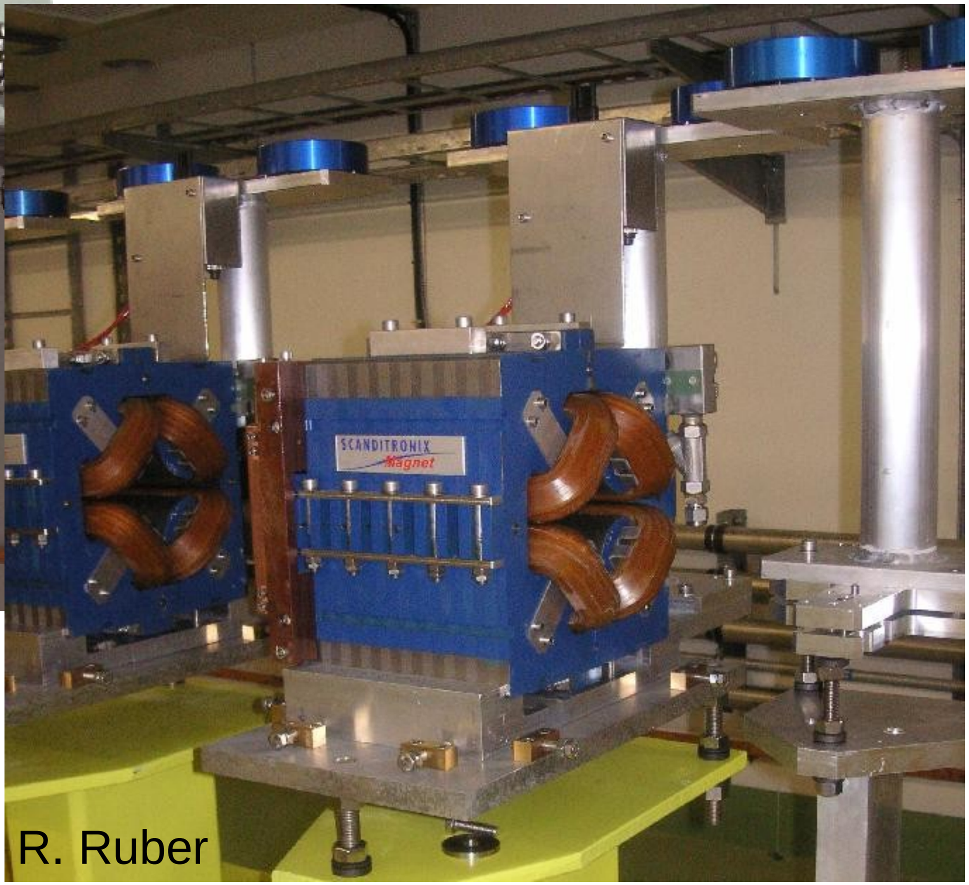


```
% equipot_quad.m
clear all; close all
Vpot=@(x,y)-0.5*x.*y;
r=-5:0.05:5; [X,Y]=meshgrid(r,r); V=Vpot(X,Y); % Pot on fine grid
contour(X,Y,V,'LevelList',[0,quantile(V(:),10)],'Color','k');
r=-5:1:5; [XX,YY]=meshgrid(r,r); % Fields on coarse grid
V=Vpot(XX,YY); [Bx,By]=gradient(-V);
hold on; quiver(XX,YY,Bx,By,'Color','r');
axis square; axis off;
axis([-5,5,-5,5])
```

This gives us a first idea about the shape of the pole faces

Iron-dominated magnets


From Elettra website



R. Ruber

Iron shapes the field

“Coils pump flux lines into the iron”

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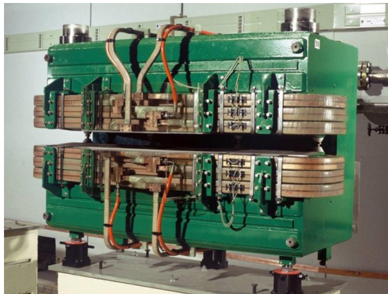
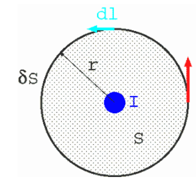
Calculate with Ampere's law

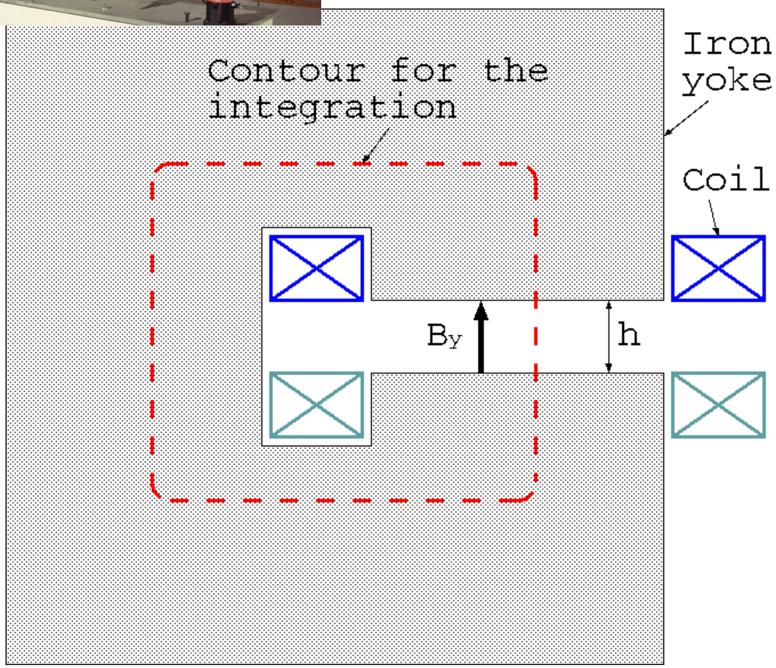


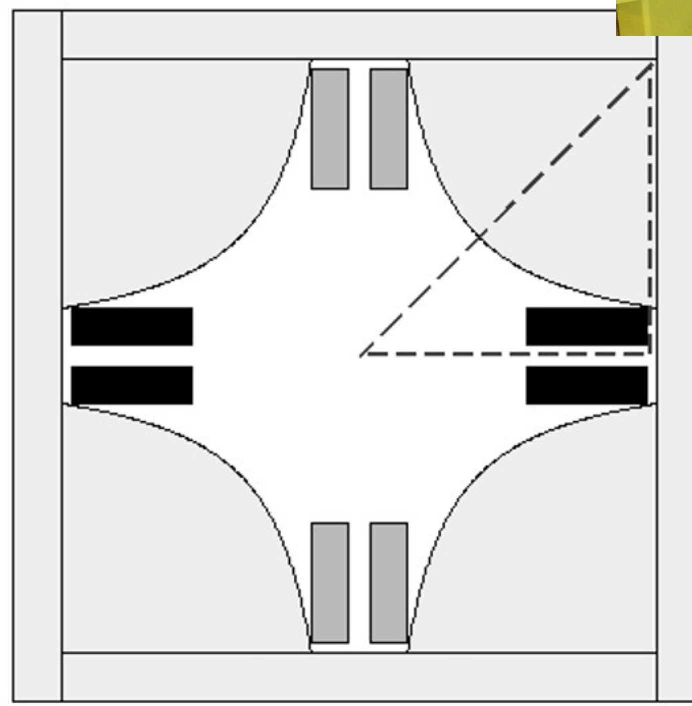
Enclosed current gives *Hdl*

$$\int_S \vec{J}\cdot d\vec{S} = \int_S \left(\vec{\nabla}\times\vec{H}\right)\cdot d\vec{S} = \int_{\partial S} \vec{H}\cdot d\vec{l}$$



Deflects the beam and treats all particles equally





Magnetic lens focuses the particles

$$2NI = \int_{\text{gap}} H_y dy + \int_{\text{iron}} H_{\text{iron}} dl = \int_{\text{gap}} \frac{B_y}{\mu_0} dy + \int_{\text{iron}} \frac{B_{\text{iron}}}{\mu_0\mu_r} dl \approx \frac{B_y h}{\mu_0}$$

$$NI = \int_{\text{horiz}} \frac{Bdl}{\mu_0} + \int_{\text{iron}} \frac{Bdl}{\mu_0\mu_r} + \int_0^a \frac{grdr}{\mu_0} \approx \frac{ga^2}{2\mu_0}$$

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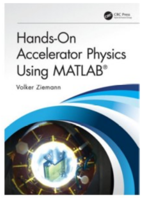
Next step: numerical



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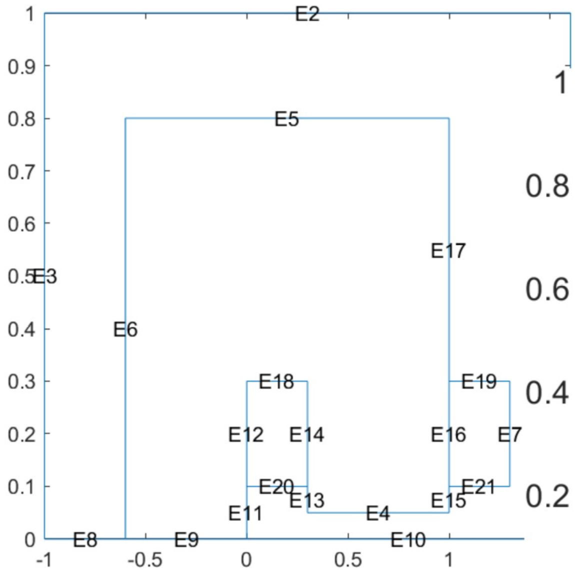
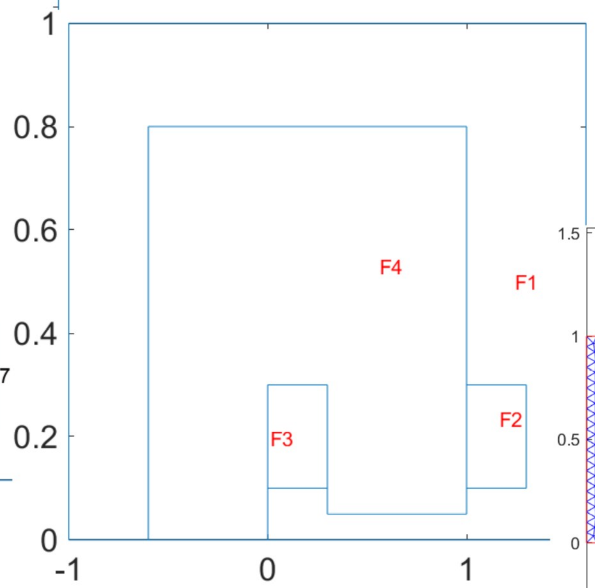
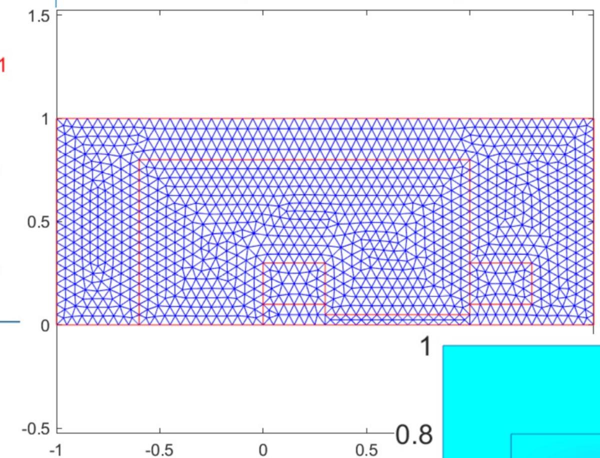
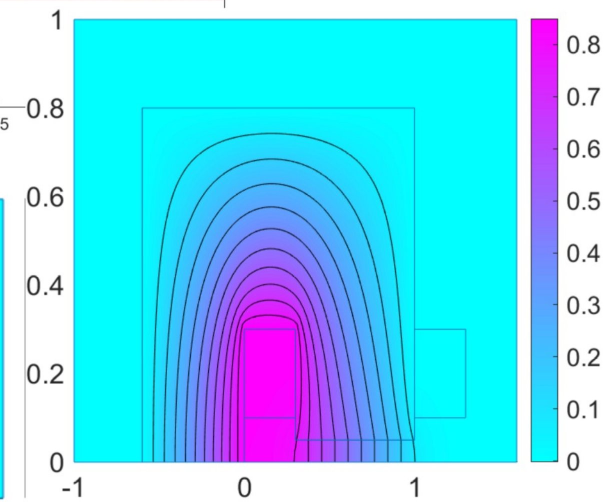
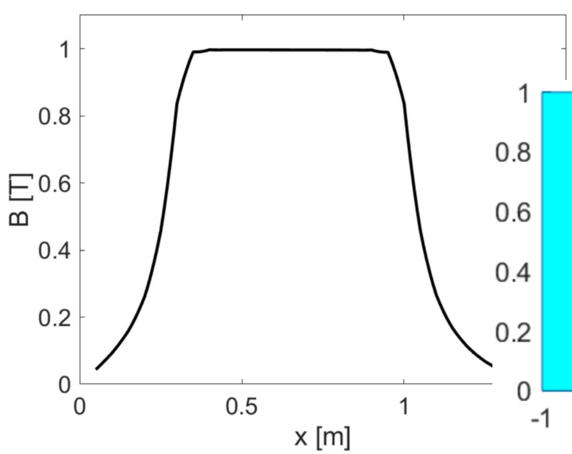
* Define geometry
* What carries current, what is iron?
* Boundary conditions
* Generate mesh
* Solve the system
* Post-processing

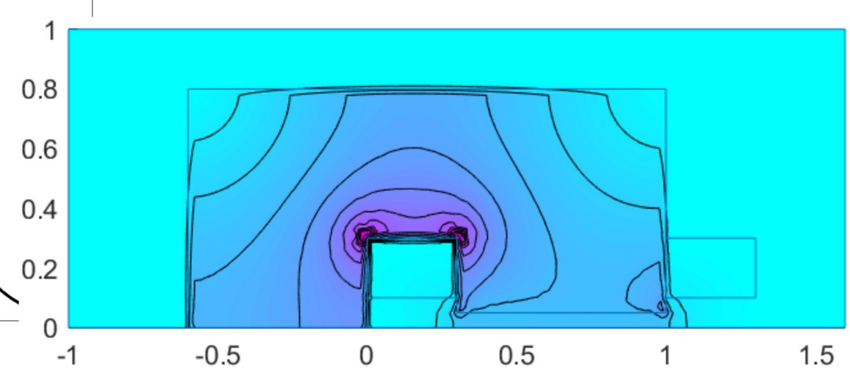








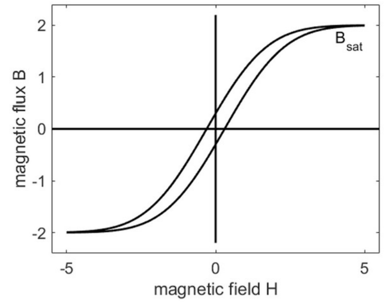




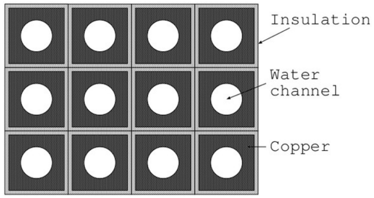
and then come 3D calculations

Technological aspects

- Hysteresis and standardization
- Maximum field up to about 2 T.



- Eddy currents and laminated (transformer) steel
- Water cooling through holes in the conductors (up to ~10 A/mm^2)



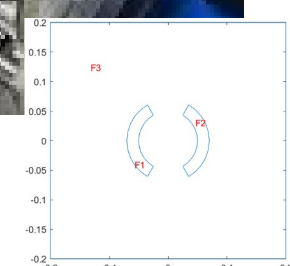
- Air-cooled magnets up to ~1A/mm^2

Current-dominated magnets

super-conducting magnets

Required for fields exceeding 2 T such as the dipoles and quadrupoles for LHC

But also in high-field magnets for magnetic imaging



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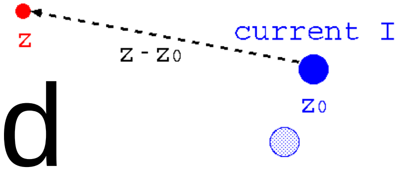
Multipoles from a displaced current filament with $F(z)=\frac{\mu_0 I}{2\pi}\log(z-z_0)$



Field $$\underline{\hat{B}}^* = \hat{B}_x - i\hat{B}_y = \frac{\mu_0 I}{2\pi}\frac{i}{z-z_0} = \frac{-i\mu_0 I}{2\pi z_0}\sum_{n_0}^{\infty}\left(\frac{z}{z_0}\right)^n$$

Introduce cylindrical coordinates $z = re^{i\phi}$ $z_0 = r_0 e^{i\phi_0}$

$$\underline{\hat{B}}^*(\phi_0) = \frac{-i\mu_0 I}{2\pi r_0}\sum_{n_0}^{\infty}\left(\frac{r}{r_0}\right)^n e^{in\phi}e^{-i(n+1)\phi_0}$$

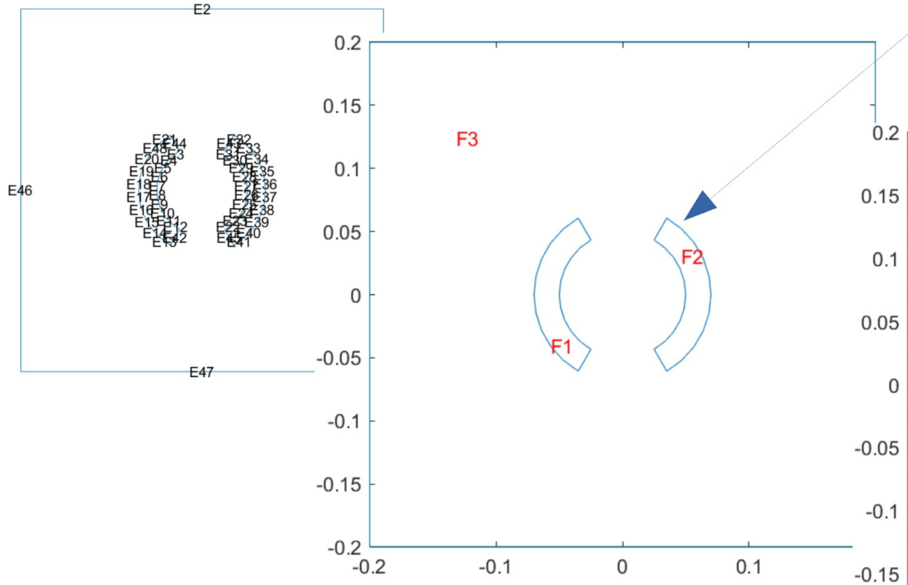
For a cos(mφ) current distribution $dI/d\phi_0 = \hat{I}\cos(m\phi_0+\hat{\phi})$

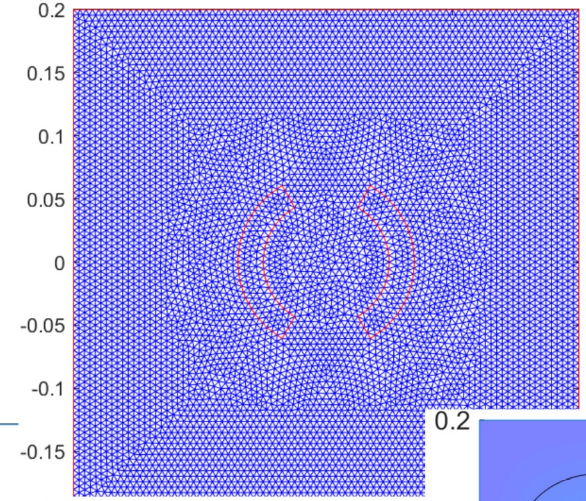
$$\underline{B}^* = \frac{-i\mu_0\hat{I}}{2\pi r_0}\left(\frac{r}{r_0}\right)^n e^{in\phi}\int_0^{2\pi} e^{-i(n+1)\phi_0}\cos(m\phi_0+\hat{\phi})d\phi_0$$

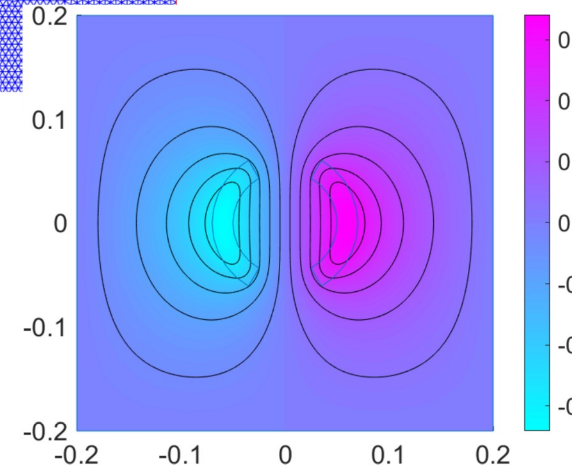
Only non-zero for m=n+1 → cos((n+1)φ) and r^n

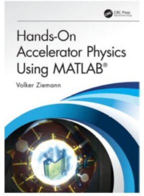
Dipole with PDE toolbox

define a function that writes a
circle segment for the geometry description

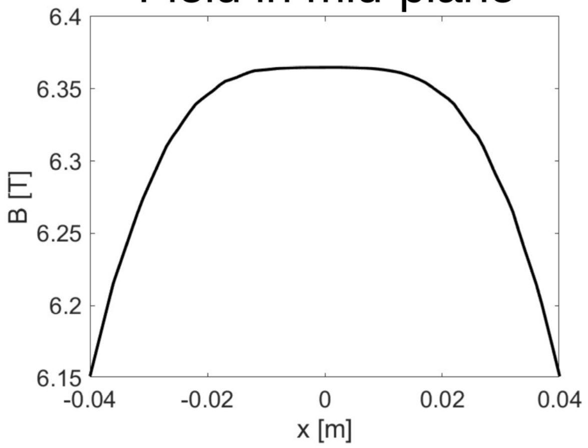


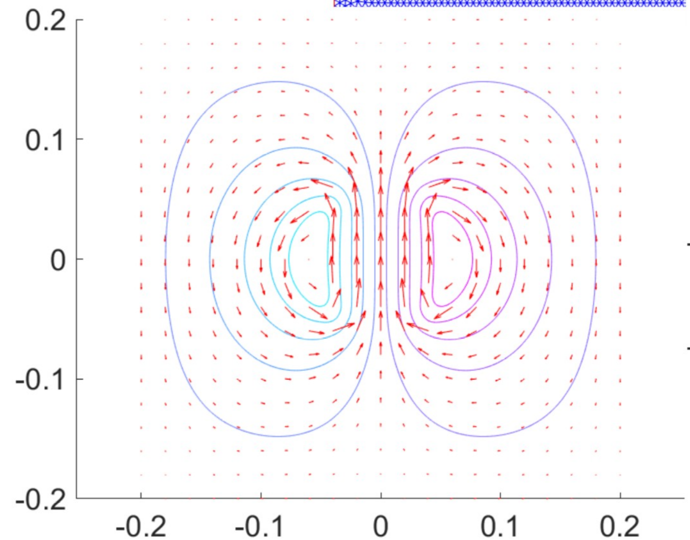






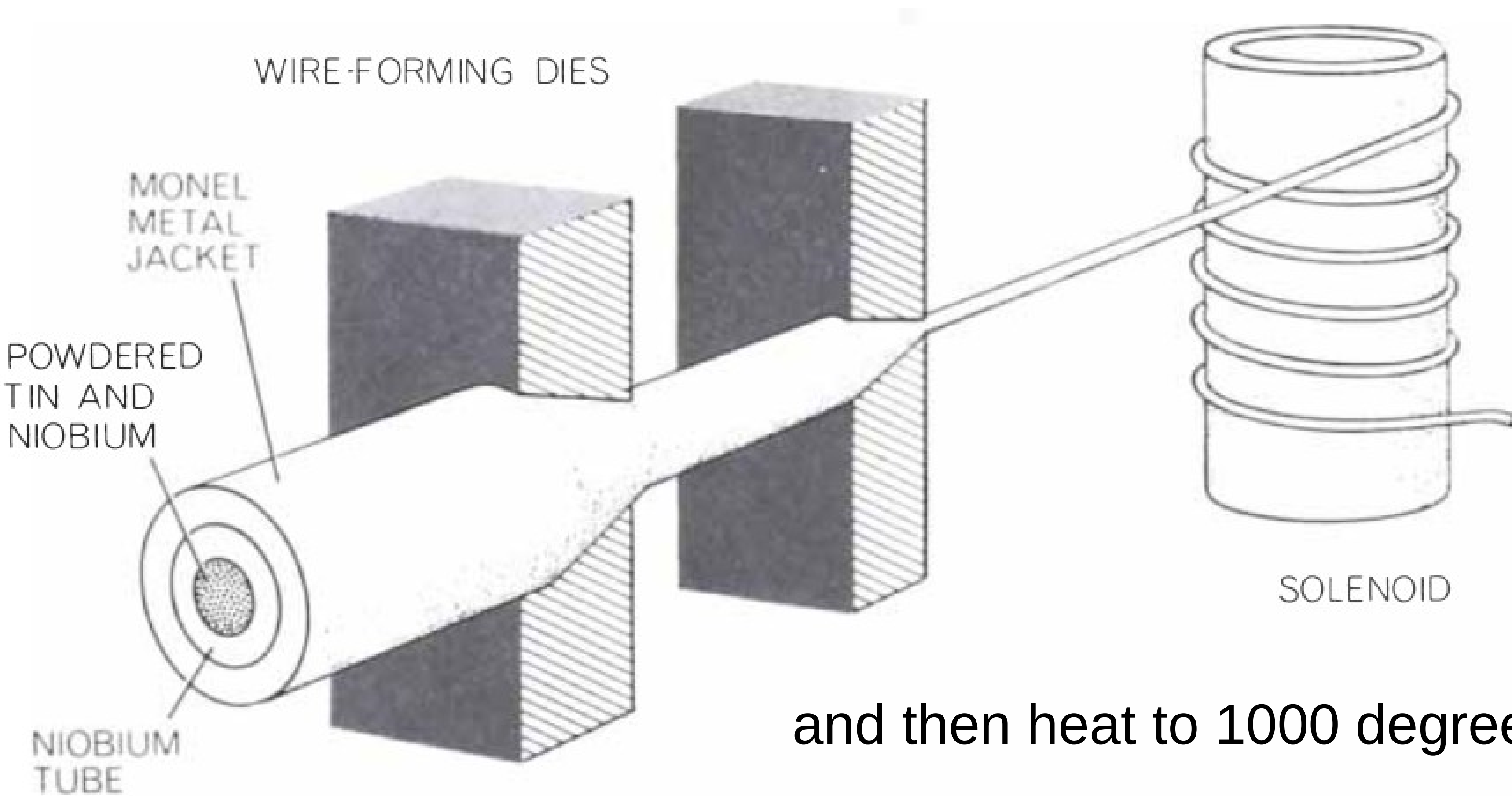
Field in mid-plane





SCdipole2.m

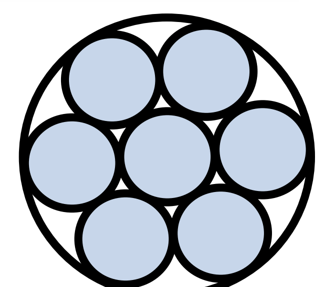
Super-conducting cables



and then heat to 1000 degrees C

from Scientific American, June 1962

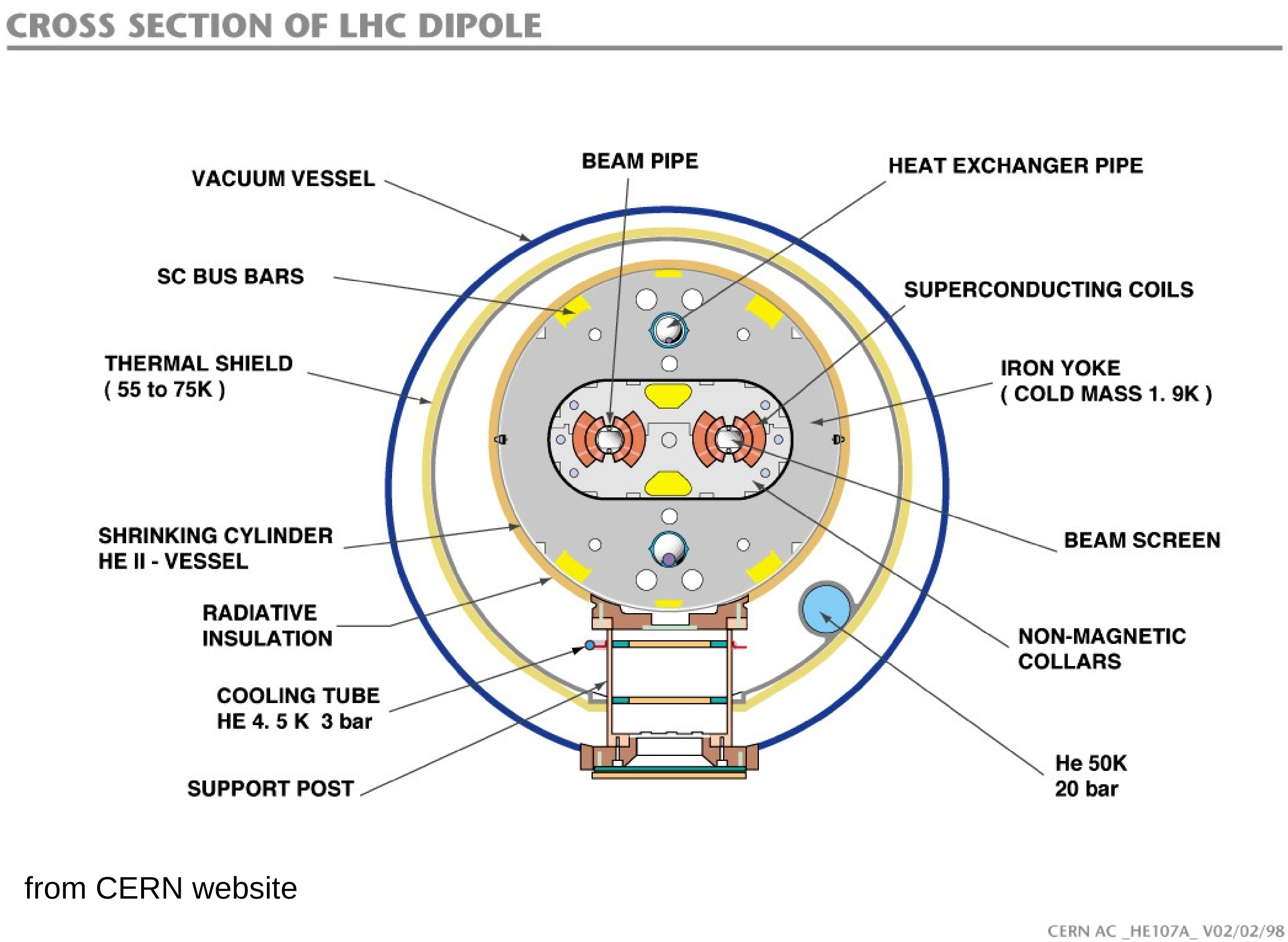
Your CCT cable...

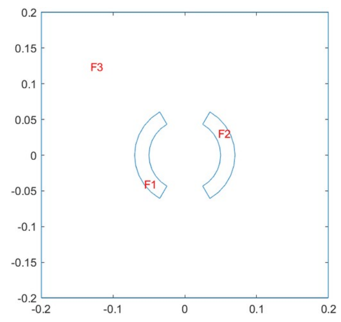


Technical aspects of super-conducting magnets

- Cooled with liquid helium at 4.2 or 1.9 K.
- Zero DC-conductivity.
- Type-II super-conductors
- reach higher fields H_{c2} and partially expel fields between H_{c1} and H_{c2}.
- Nb-Ti can carry $J \sim kA/mm^2$.
- Eddy-currents in strands limit ramp-speed.
- Forces between strands in the super-conducting cables cause friction and subsequent quenches.

LHC dipoles





from CERN website

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Next time

- Short recap of today’s material
- Permanent magnets
- Magnet alignment
- Magnetic measurements