Solenoid Magnet Study

Work done by:

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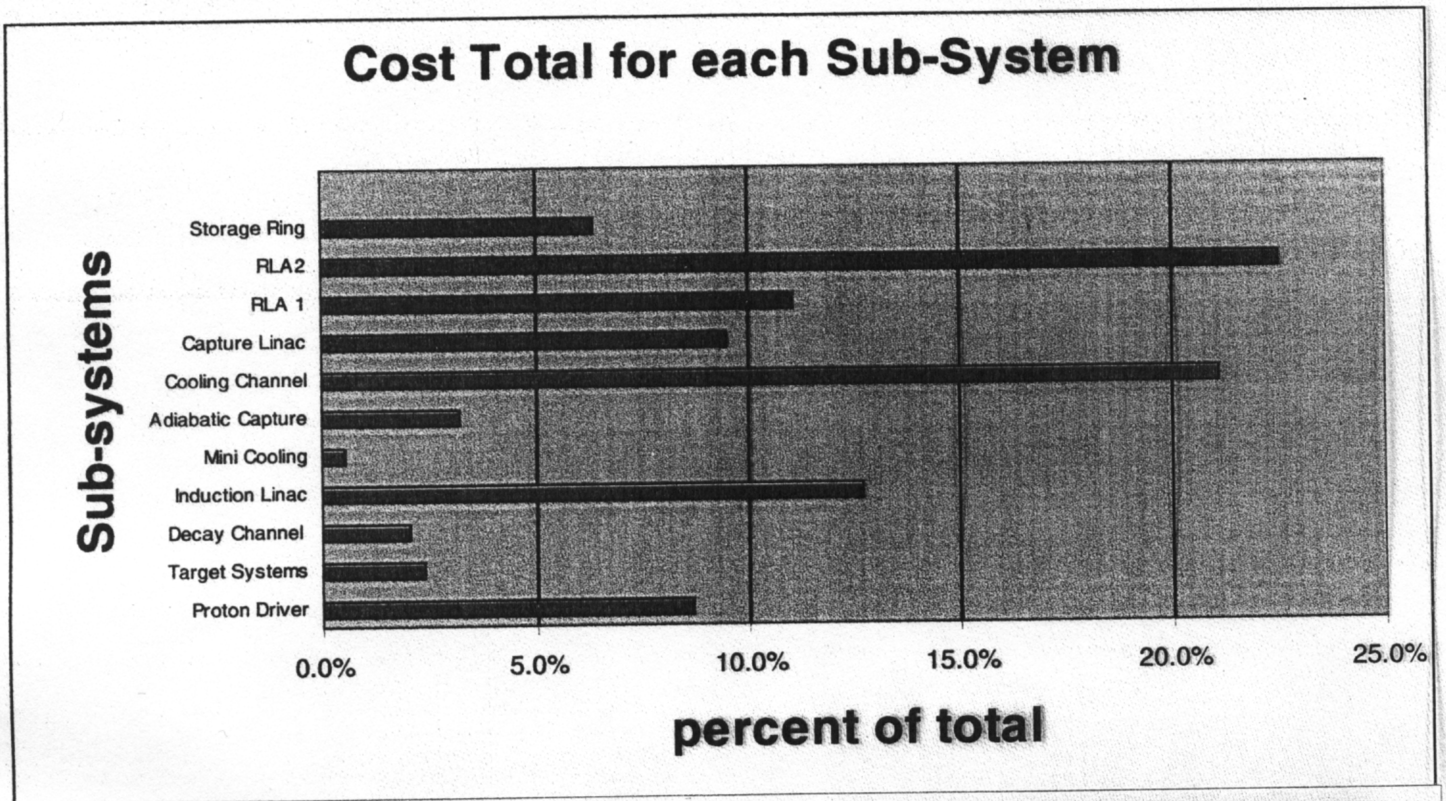
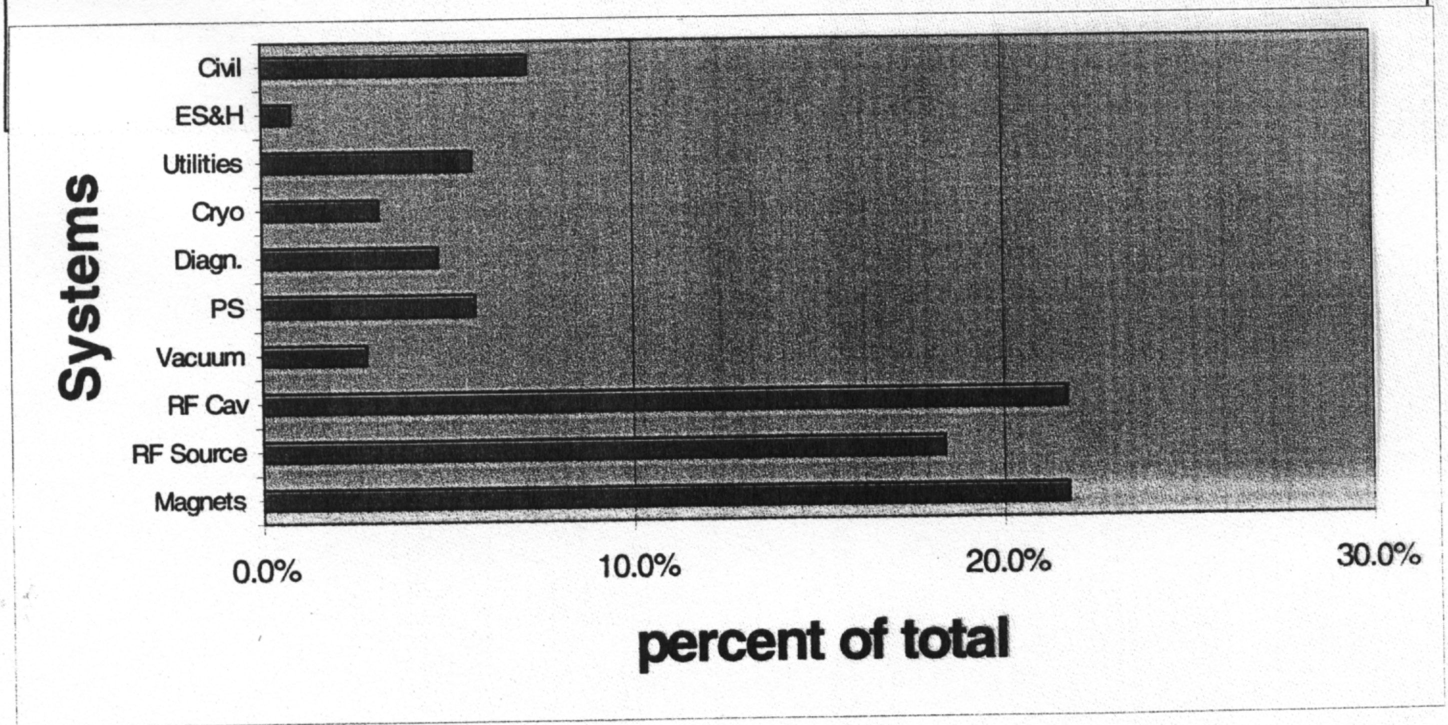
•MC: J. Miller, M. Green for cross check and many helpful discussions

- Introduction
- Description of the Magnet Channels
- Cooling Channel Magnets
  - long (full) period =2.2 m and 3.6 T
  - long period 2.2 m and 5.5 T
  - short period 1.5 m and 3.6 T
- Cryogenics
- Power Supplies
- Cost
- R&D

Cost

- Hot Topic: Proposal for Presentation.





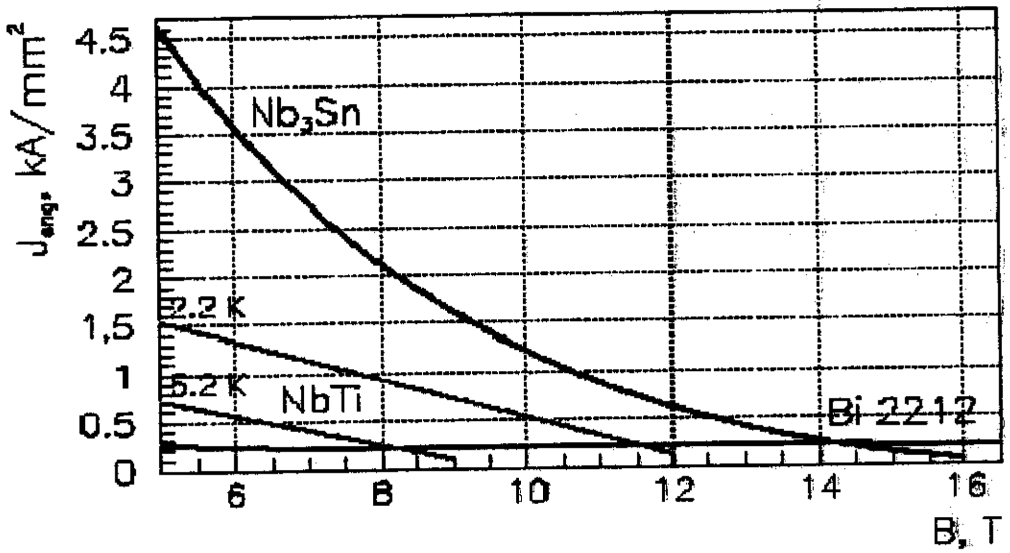
4 Channels

- Channel 1: 50 m decay channel
  - warm/cold bore, no field flip, B=1.25 T, r=30 cm
- Channel 2: 40 m RF phase rotation
  - warm bore, no field flip, B=1.25 T, r=100 cm
- Channel 3: 100 m induction linac
  - warm bore, no field flip, B=1.25 T, r=30 cm
- Channel 4: 100 m cooling channel
  - warm bore, field flip, B=3.6-5.5 T, r=70 cm

- Options:
  - optimize $B^2 \cdot r^2$ with $B \cdot r^2$=const
  - specification of warm/cold bore depend on application
- Result:
  - Cooling channel magnets (Nr 4) are a major uncertainty and a major cost driver (worst combination one can have)

General Engineering

$$J_c(B,T) = J_0\left(1 - \frac{B-5}{5.5} - \frac{T-4.2}{3.2}\right).$$



Engineering current density versus magnetic field for different superconducting materials.

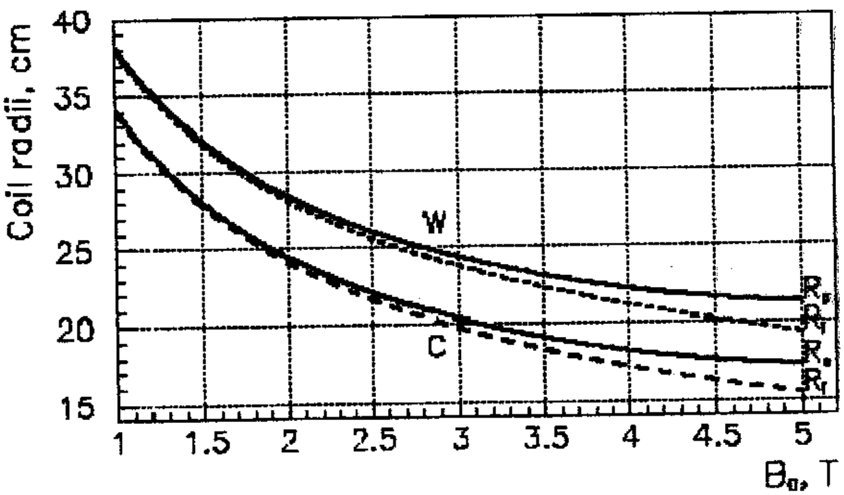


Fig.1. Dependences of inner R_i (dotted lines) and outer R_o (solid lines) radii of coil versus magnetic field for cold (C) and warm (W) bores.

Forces and Cost

- Axial force increases with B^2 .

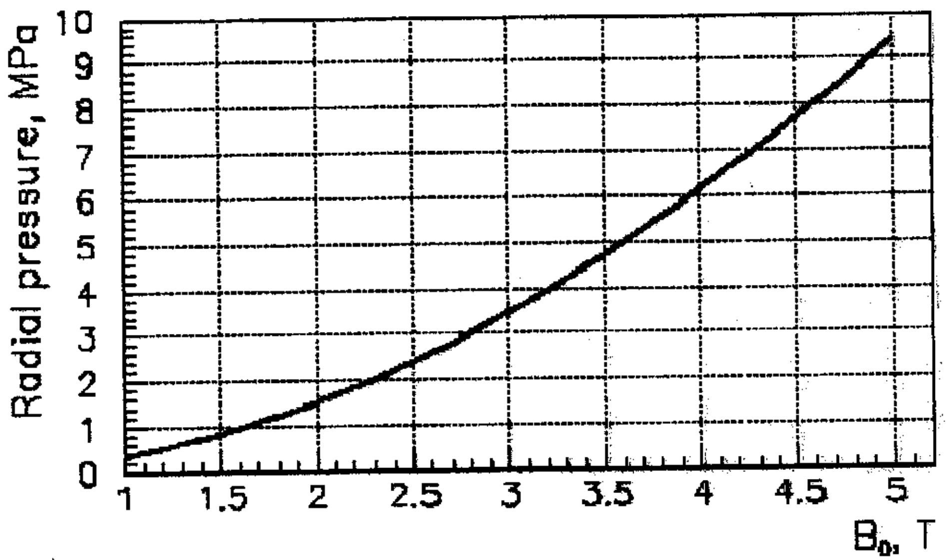


Fig.4. Radial pressure in solenoid against central magnetic field.

- Cost
  - cold bore and min. field
    - cost $\propto$ Const. $\cdot$ $R^{1.29}$ $\cdot$ $B^{1.4}$ (M. Green)
    - $B \cdot r^2 = \text{const}$
    - $\Rightarrow$ cost $\propto$ $B^{0.8}$ for 1<B<5 T, no flip
- Stay as low as possible in field

Results for Channel 1-3

- Channel 1+2+3 is not big deal
  - confirmed by J. Miller and M. Green
  - Green & Miller cost consistently higher by factor of < 2
  - Quench protection + PS checked by engineers (D. Wolff & Co . @ FNAL = ok within a factor of 2)
  - larger M$ number has been used for these 3 channels

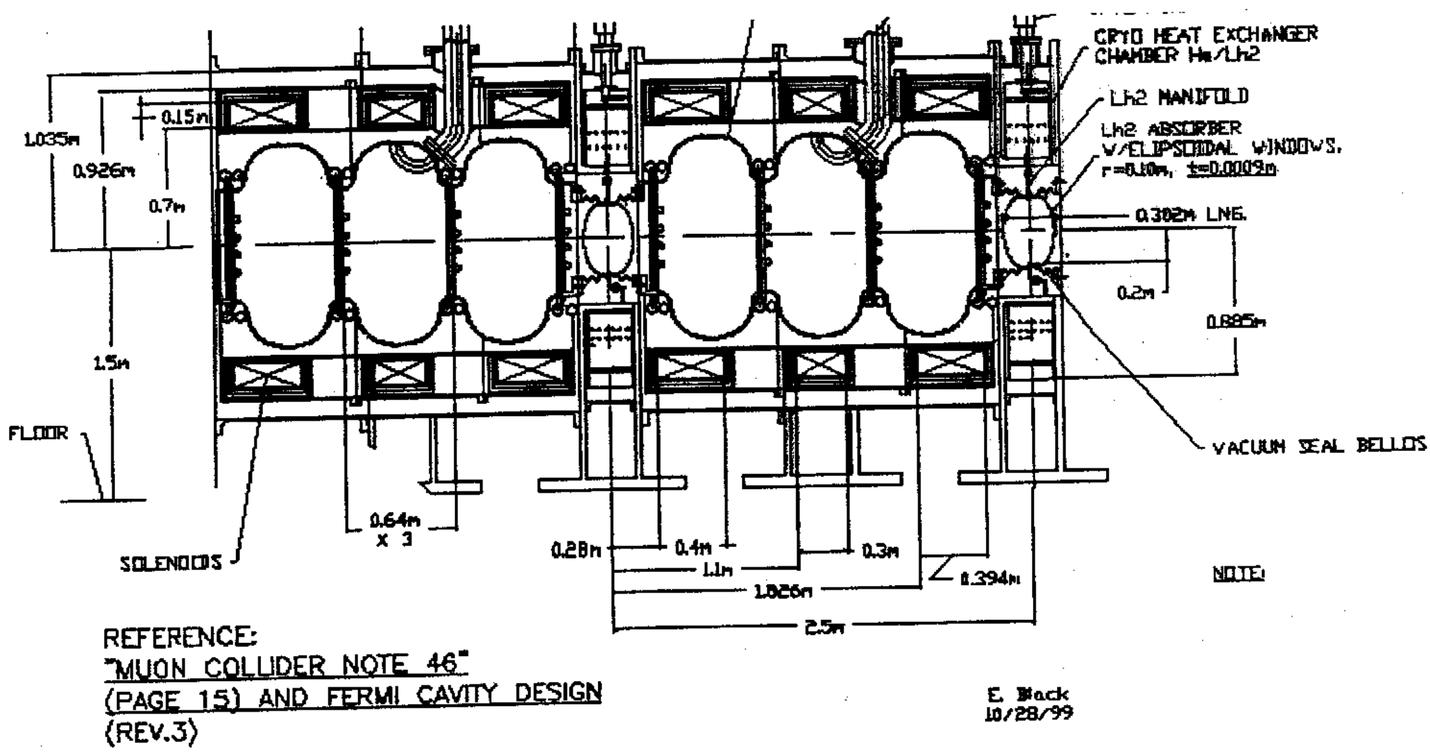
  - <u>all have one PS and one Quench protection system</u>

Channel	Magnets length	total length	stored energy	total stored energy
	m	m	MJ/m	MJ
1	4.7	50	0.21	10
2	1.7	40	1.2	48
3	0.9	100	0.2	20

The Cooling Cell used for the Engineering Approach

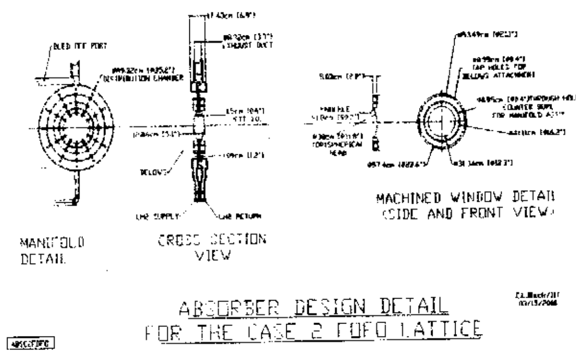
- Had to pick an example for the engineers
- 1.1 m cell length with 2.2 meter periodicity

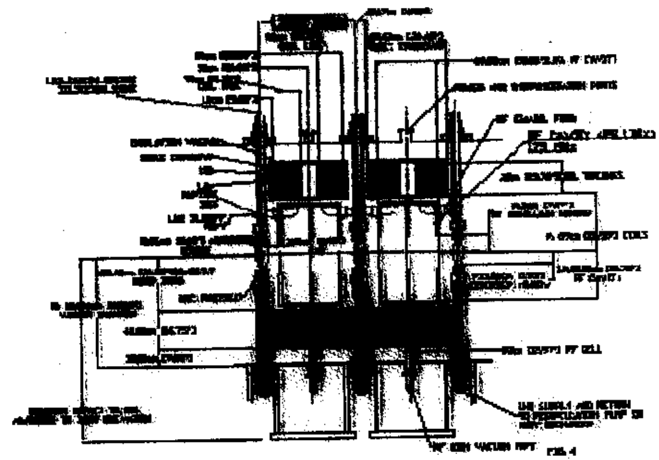
B_z ~ 3.6-5.5 T max (flip), 7 T max (straight)
E_{acc} ~ 15 MV/m @ 200 MHz



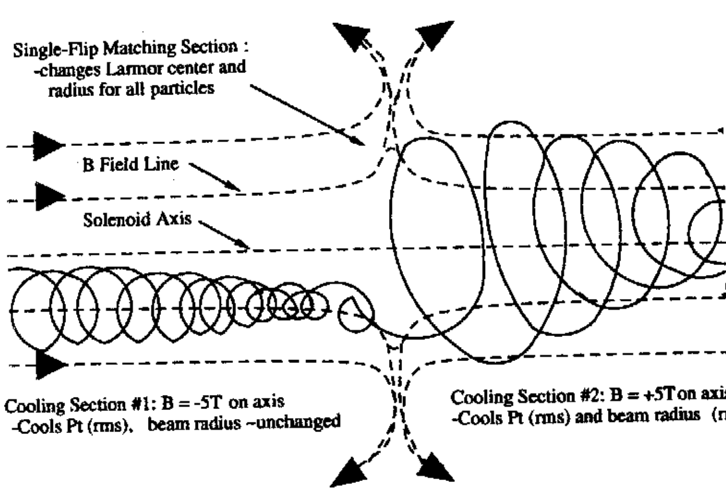
Other Cooling Channels

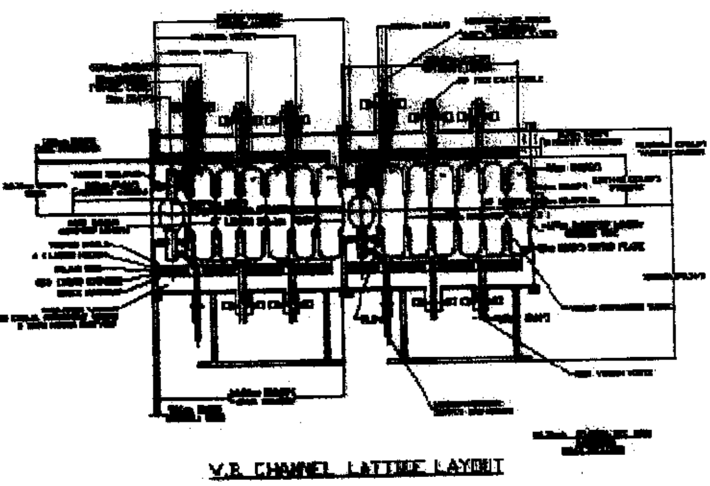
- Baseline: FOFO





- Single Flip

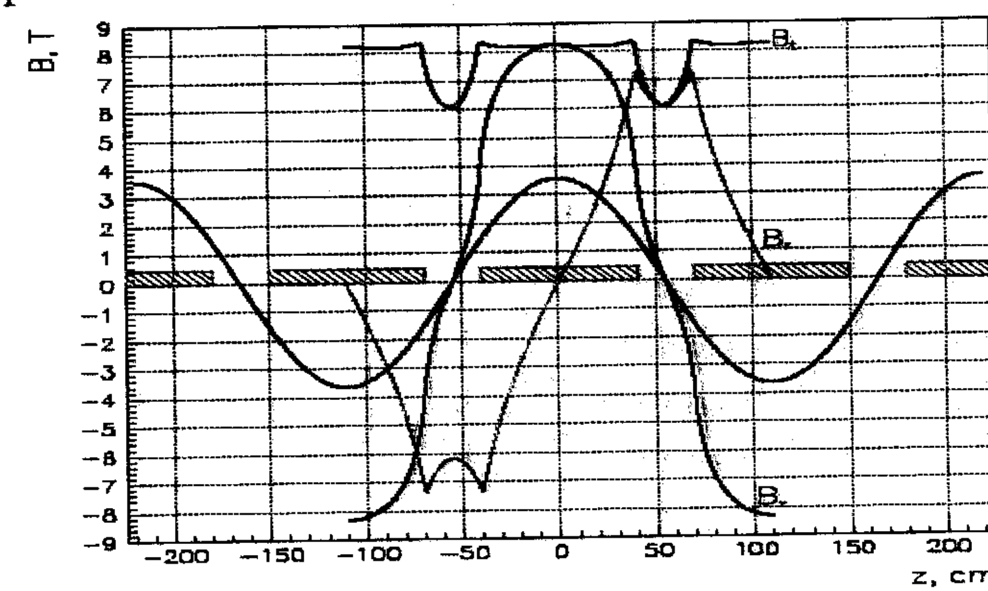




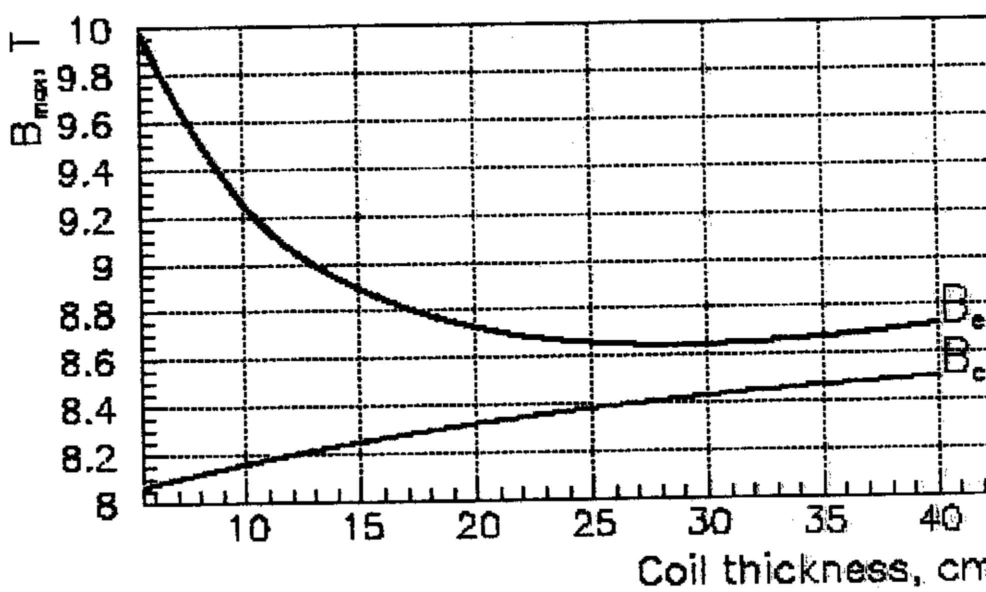
Channel 4

- B_z = 3.6-5.5 T, full period 2.2 m
- later: B_z = 3.6, full period 1.5 m

Optimum for coil versus gap length: 80 cm-17.5



Optimum for coil thickness for given geometry



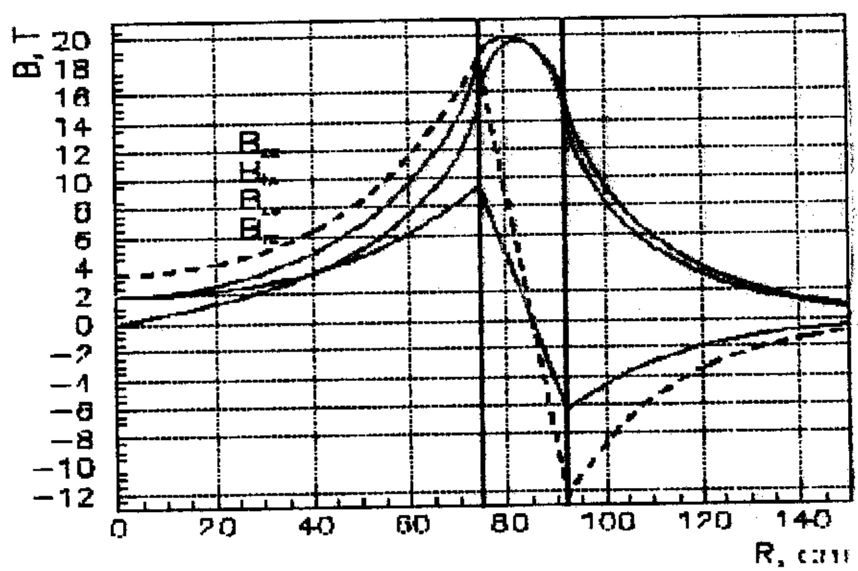
Axial pressure = -90 Mpa

Estored = 48 MJ

NbTi / Cu 5% / 95% conductor ratio (very optimistic)

Channel 4

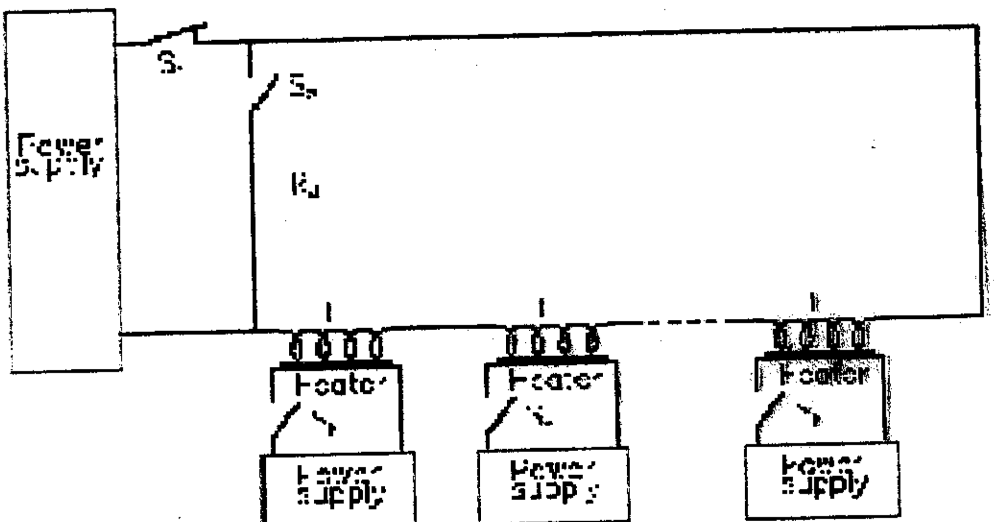
- Disagreement between Protvino Study and today's feasibility:
  - solution: bigger coils!
  - But: more conductor, more stored energy, less pressure (55 MPa), but a lot more money......
- Go to 5.5 Tesla
  - Nb_3Sn -> 50 mm stainless steel bandage
  - not further worked on
- smaller period length (2.2 m ⇒1.5 m) (B_{max}: 9 ⇒ 18T):
  - only HTS is possible



. Radial field distribution in solenoid cell with magnetic field period of 1.5 m.

13.9 MA total current per coil and 425MPa

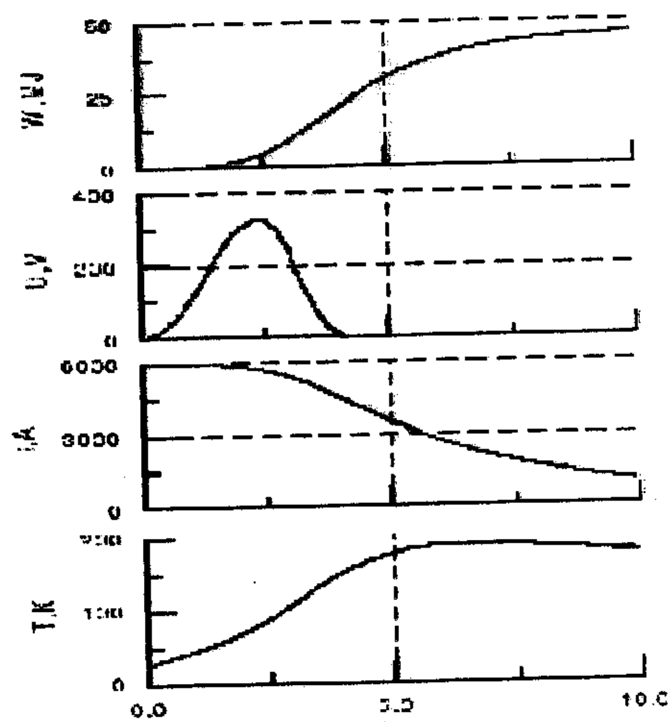
Quench Protection



Quench prot. system

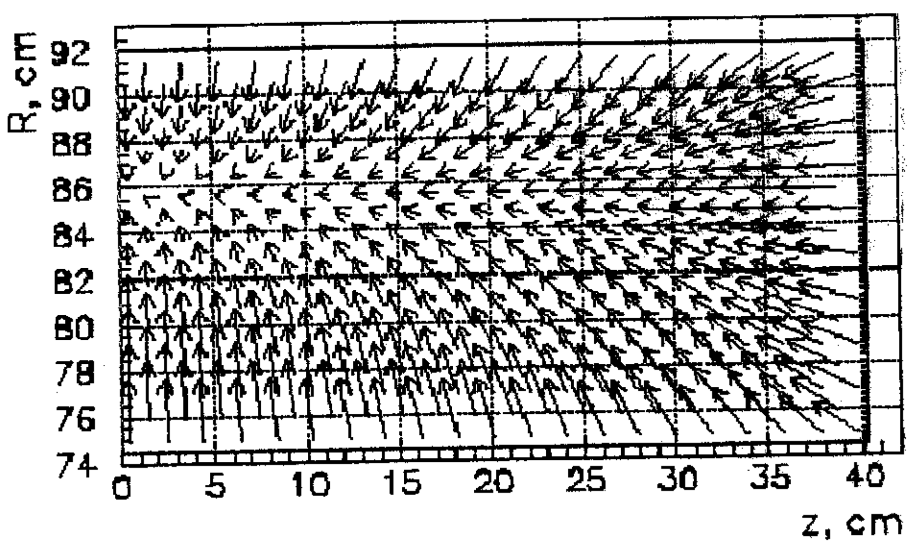
The time dependent behavior of the system

Parameters for the Power Supply	
Voltage	500
Current	6 kA
tot. Induct	230 H
dI/dt	0.9
charge time	3600



How do we get to the R&D ?

- The SC coils are one of the largest uncertainties today in terms of:
  - technical feasibility
  - cost
- Items to be addressed:
  - Ratio NbTi/ Cu = 5% / 95% ? Conductor
  - Pressure will make special copper necessary to improve yield strength ⇒needs test



Distribution of ponderomotive forces in solenoid coil.

Parameters

Parameter	Unit	Value		
Magnet number		1	2	3
Period	m	2.2	2.2	1.5
Magnet coil length	m	0.805	0.805	0.475
Central field	T	3.6	3.6	3.4
Maximal field in coil	T	8.8	8.6	19.5
Total ampere-turns	MA	9.64	11.68	13.9
Bore radius	mm	700	700	700
Coil thickness	mm	175	350	125
Inner radius	mm	745	745	745
Outer radius	mm	920	1095	870
Stored energy	MJ	48	67	130
Volume of superconductor (without copper)	m^3	0.0263	0.0363	0.3012

The table below shows channel arrangement with magnets from the table above

Parameter	Unit	Value	
Magnet number		1,2	3
Length	m	50	50
Number of magnets		45	67
Gap between magnets	m	0.295	0.275

Magnetic forces acting on single magnet and solenoid in string are presented in the table:

Magnet number	1	2	3
Radial pressure, MPa			
Single magnet	30.4	36.3	135.7
Magnet in string	15.2	16.0	60.3
Axial pressure, MPa			
Single magnet	-68.9	-42.9	-425.8
Magnet in string	-89.1	-56.4	-354.0
Axial forces, MN			
Single magnet	-61.8	-86.6	-264.8
Magnet in string	-79.9	-114.6	-220.2
Interacting force	-18.1	-28.0	-44.6

R & D

- Needs further engineering to investigate:
  - temperature rise ⇒ stress during quench
  - detailed force calculation for most recent design
  - Cryo layout
  - quench protection layout
  - completely engineer one test coil
  - run it and see what happens...
- Proposal:
  - use the Russian collaborating institutes, at least for engineering
  - they have conductor (left from UNK) which is probably usable
  - ⇒ get a lot more engineering and R&D per $