New Fast Capacitor Banks for Theta-Pinch-Experiments at the Institut für Plasmaphysik in Garching

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The contents of this report will be presented at the 4th Symposium on Engineering Problems in Thermonuclear Research, Frascati - Rome 23 - 27 May 1966

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Abstract

Three lumped parameter capacitor banks of different stored energies will be described. The approximate data are 10 kJ / 400 kHz, 500 kJ / 100 kHz and 2.6 MJ / 25 kHz, all at 40 kV charging voltage.

The 400 kHz - and 100 kHz - banks are being mounted at present and will be ready for operation this summer and towards the end of this year. Both will be connected to symmetrically double-fed linear coils; this series connection gives rise to a higher discharge frequency. Special features of the first two banks are the collector system, which at the 500 kJ - bank permits alternatively feeding of a toroidal experiment with minimum replacement of components, the use of impulse cable plug contacts and a peculiar coil arrangement for the bias field at the 10 kJ-bank.

The 2.6 MJ-bank "Isar I" has now been in operation at 1,5 MJ (30 kV) more than one year without considerable technical difficulties. About 3000 discharges including those with partial energy have been made. The bank will be prepared for crowbar operation this summer. In addition the collector will be extended in order to improve the flux density distribution in the coil.

The calculated main discharge data of the three reported banks are:

Bank	10 kJ	500 kJ	2,6 MJ
Voltage	2x40 kV	2x40 kV	40 kV
Peak current	580 kA	7,5 MA	22 MA
Frequency	385 kHz	96 kHz	25 kHz
Peak flux density	12,1 kG	95 kG	184 kG
Initial rise of flux density	29,2 kG/us	57 kG/us	28,9 kG/us
Coil length	60 cm	100 cm	150 cm
Coil diameter	15,5 cm	10 cm	10,5 cm

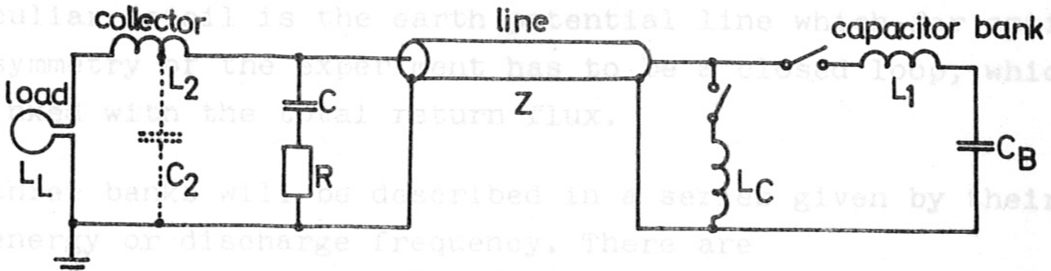
In conclusion some remarks on generalized design relations for capacitor banks are added.

The purpose of this report is to give the data and some design features for three capacitor banks of different sizes which are being mounted or in operation in the Institut for Plasmaphysik in Garching. Preionization systems will be excluded because they vary with the special experiment. It has turned out practical to make an engineering project of the costly main energizing system (main discharge and bias-field e.g.) including the coil assembly for plasma heating and confinement.

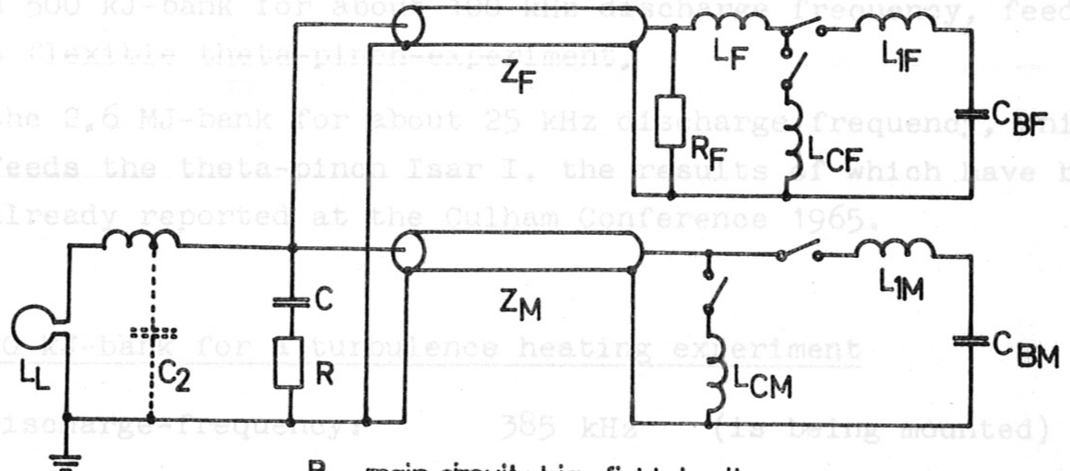
Lumped parameter capacitive energy storage systems become now conventionel equipment in fast plasma experiments. Further technical improvement can here be expected from progress in the technology mainly of insulating materials, from thorough development of components, taking into account general optimization studies.

The present time status of fast plasma experiments and the status of technical development of other than capacitive energy storage systems allow the assumption that even the next generation of fast experiments in the energy range of some tenths of megajoules will require capacitor banks, where technical as well as economical optimization should be an import feature. So it is reasonable to consider present days arrangements to a certain extent as section tests for the next step and to judge them also from this point of view.

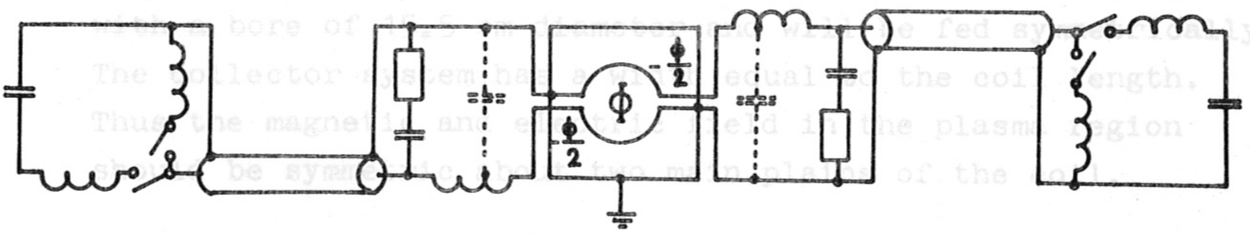
Picture P 051 shows three typical circuit diagrams. The basic circuit A is the standard for production of a pure cosine-voltage loop at an inductive load. Matching units including a decoupling capacitor reduce voltage surges on the load line.



A. main circuit



B. main circuit + bias field circuit



C. main + circuit for double fed coil

P051 capacitor banks - basic circuits

The damped ringing discharge may be clamped e.g. for zero load voltage or current. Due to its type the clamp switch may also be arranged at the collector end of the line.

Circuit B gives the arrangement for main bank plus bias field. For the case of disconnection of the bias field it is practical to have matching resistors at the bank end of the bias field line.

Circuit C represents the main circuit for a double-fed coil. A peculiar detail is the earth potential line which for optimum symmetry of the experiment has to be a closed loop, which is linked with the total return flux.

The three banks will be described in a series given by their stored energy or discharge frequency. There are

1) a 10 kJ-bank for about 400 kHz discharge frequency, feeding a turbulence heating experiment,

2) a 500 kJ-bank for about 100 kHz discharge frequency, feeding a flexible theta-pinch-experiment,

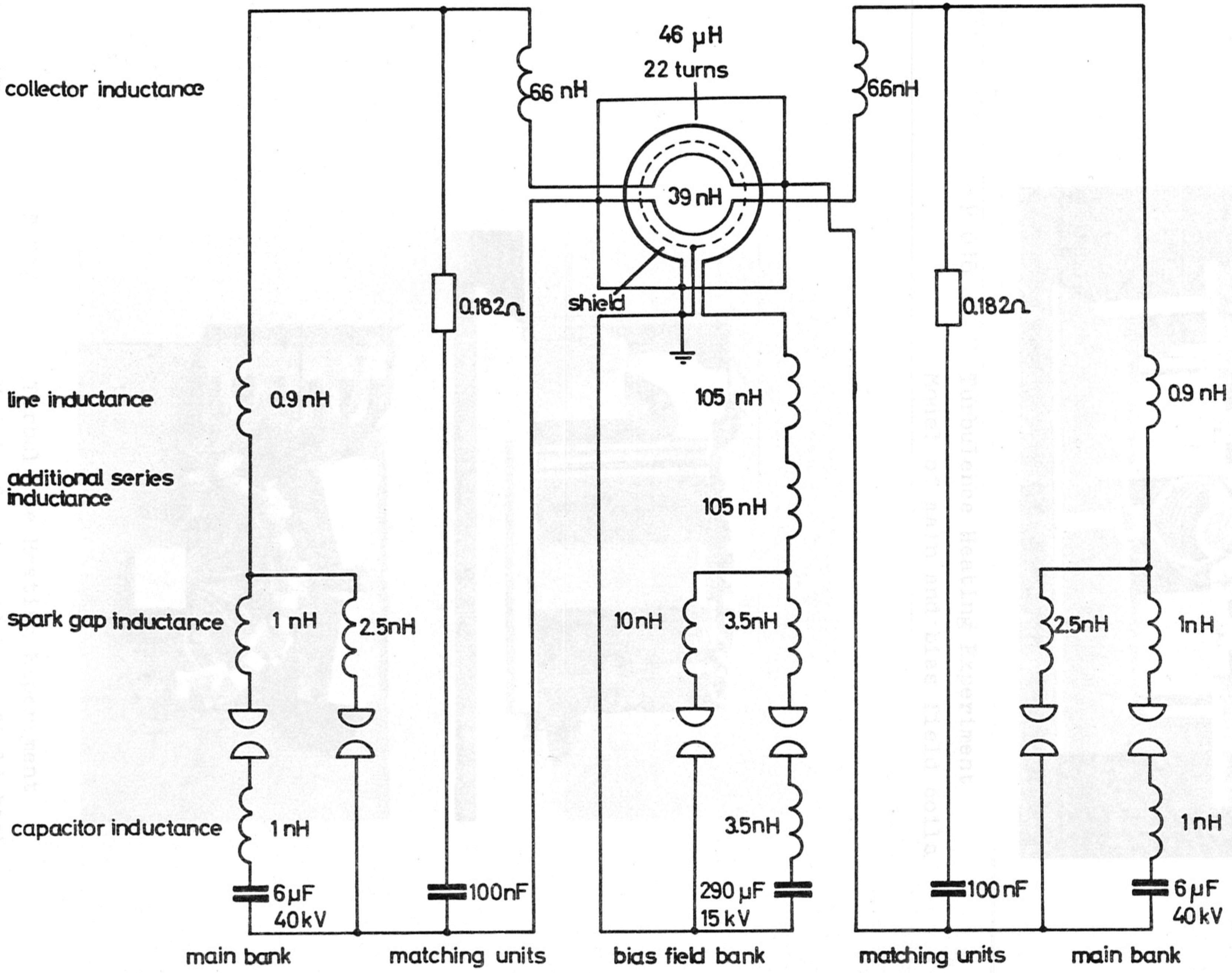
3) the 2,6 MJ-bank for about 25 kHz discharge frequency, which feeds the theta-pinch Isar I, the results of which have been already reported at the Culham Conference 1965.

1) 10 kJ-bank for a turbulence heating experiment

Discharge-frequency: 385 kHz (is being mounted)

Picture P 054 gives the load side circuitry of the bank and the important discharge data. The main coil is 60 cm long with a bore of 15,5 cm diameter and will be fed symmetrically. The collector system has a width equal to the coil length. Thus the magnetic and electric field in the plasma region should be symmetric about two main plains of the coil.

Picture P 017 shows a model of the total bank arrangement without auxiliary equipment. The two parts of the series connected main bank are placed one over the other in order to get an easily accessible coil and a compact storage block. Each half bank is connected by 120 sandwich conductors. Behind the main bank the bias field bank is to be seen, whose energy (41,2 kJ at 12 kV) in this case is more than that of the main bank (9,6 kJ at 40 kV). The bias field bank feeds special multiturn coils surrounding the main coil in order to get a peculiar axial distribution of the biasfield. Main and bias field circuit are dynamically decoupled by a copper shield. For



$J_{max} = 580$ kA

$f = 385$ kc/s

$B_{max} = 12.1$ kG

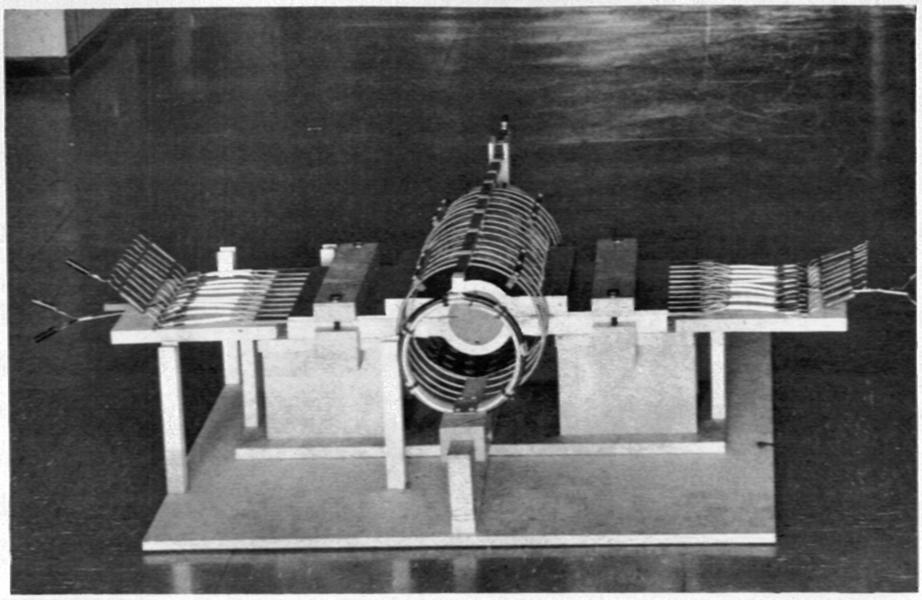
$\left(\frac{dB}{dt}\right)_0 = 29.2 \frac{kG}{\mu s}$

main coil

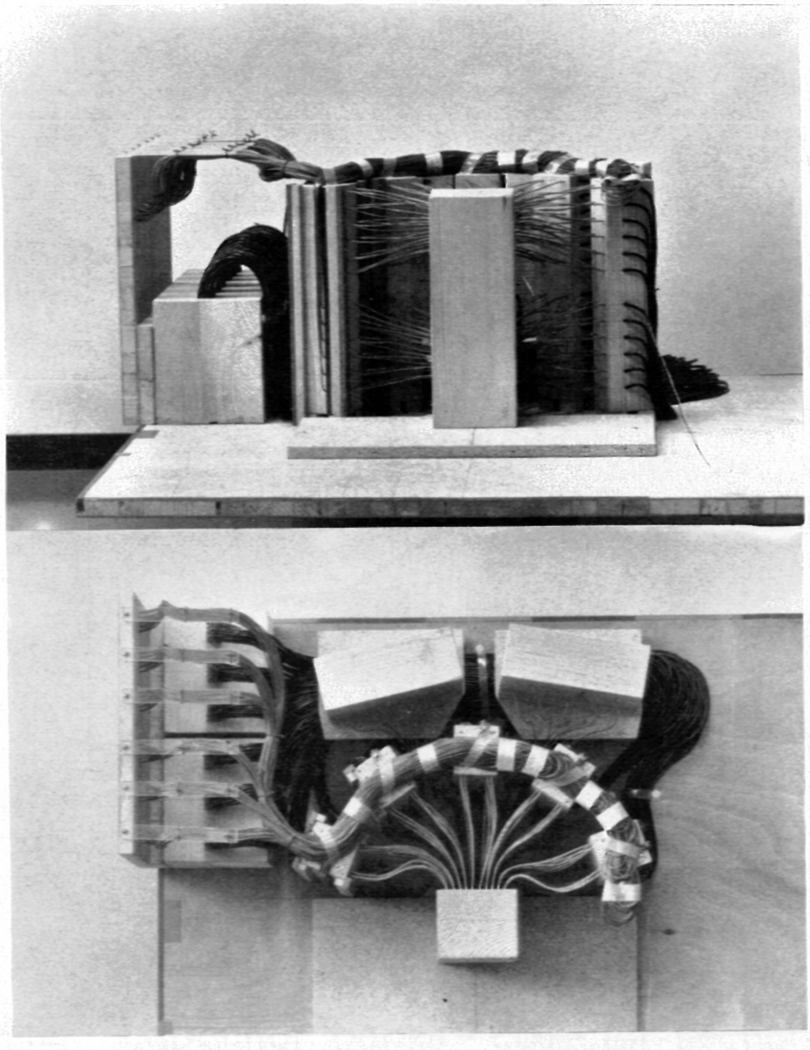
$L = 60$ cm

$D = 155$ cm

P054 Turbulence Heating Experiment circuit diagram



P 016 Turbulence Heating Experiment
Model of main and bias field coils

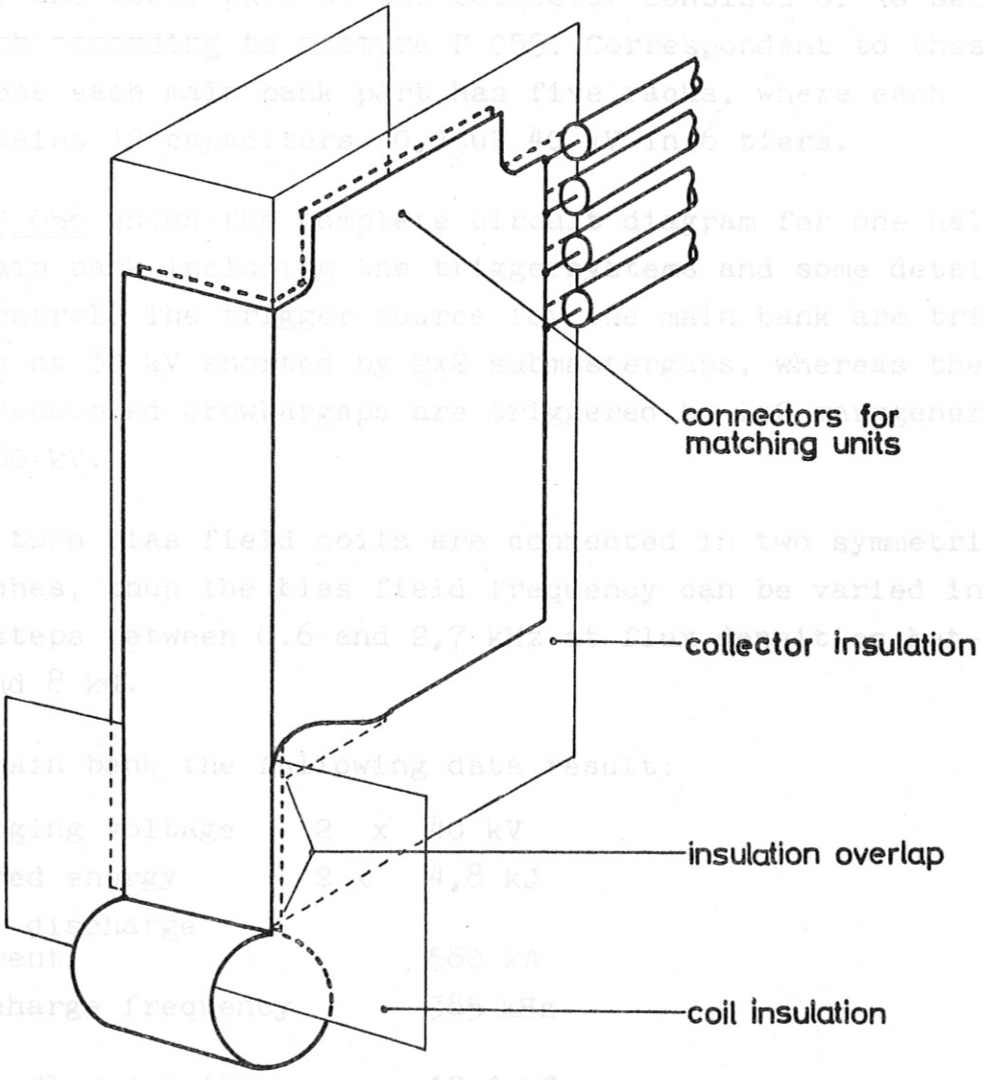


P 017 Turbulence Heating Experiment
Model of main and bias field bank cable loops

sustained field experiments the bias field bank can also be directly connected to the main coil.

Picture P 016 shows a scaled model of the coil arrangement.

Peculiar components of the bank system are the pressurized combined start and crowbarsparkgaps and matching units for the reduction of line reflections - both will be reported separately - as well as the collector system. The principle of this collector is given by picture P 055, which shows one section.



P055 capacitor banks - collector section

One sees, that its inductance depends mainly on the foil insulation overlap region whereas the influence of the number of cables or conductors - that is the energy per unit length of coil - is weak. In addition there is space for the connection of matching units.

Picture P 018 shows a side-on view of the collector with the double-fed main coil and the bias field turns.

Since the flux density is relatively small, there was no heavy problem of governing the mechanical forces. The matching units are connected on the top and below.

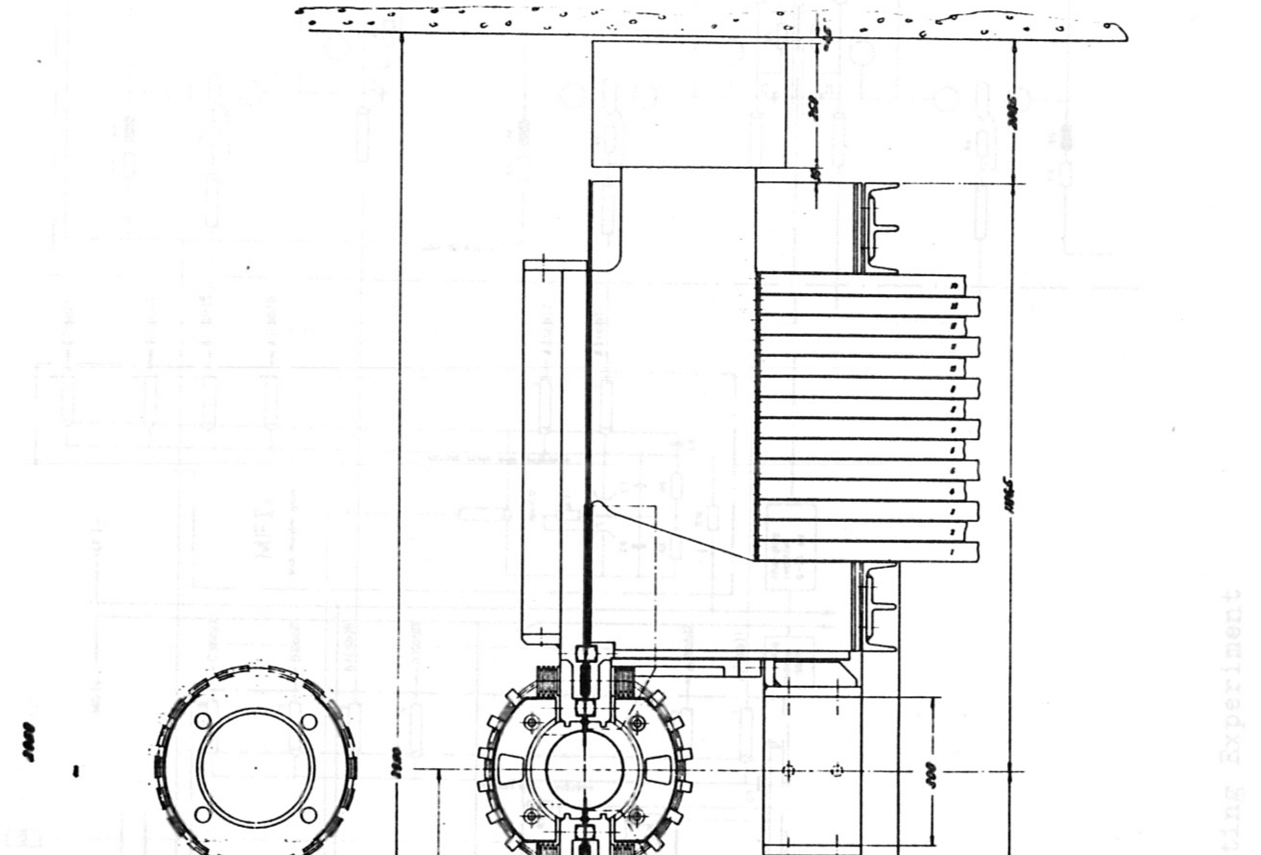
The upper and lower part of the collector consists of 10 sections each according to picture P 055. Correspondant to these 10 sections each main bank part has five racks, where each rack contains 12 capacitors 0,1 µF 40 kV in 6 tiers.

Picture P 056 shows the complete circuit diagram for one half of the main bank including the triggersystems and some details of the control. The trigger source for the main bank are triggercables at 30 kV shorted by 2x2 submastergaps, whereas the ferrite-decoupled crowbargaps are triggered by 2x2 marxgenerators at 60 kV.

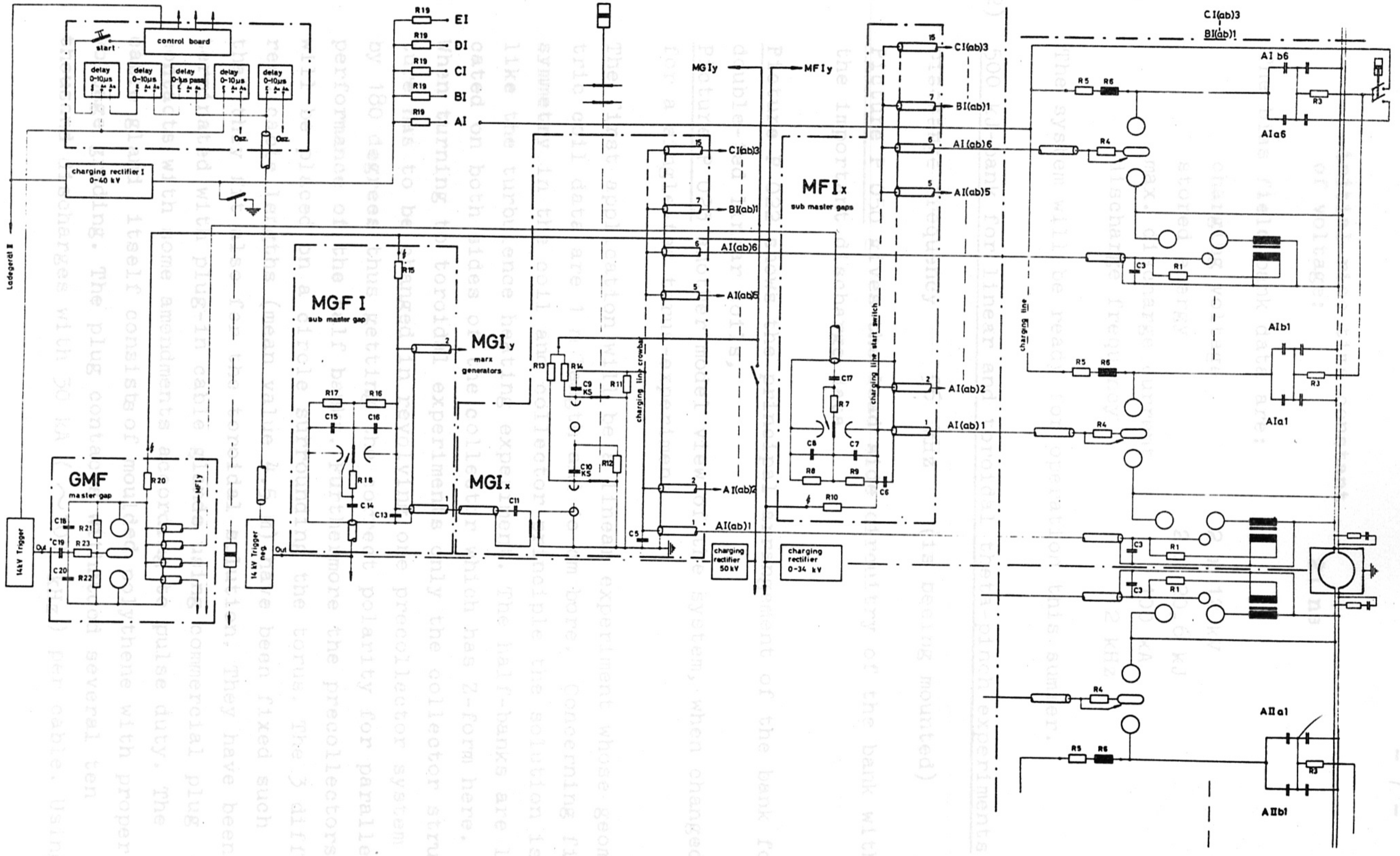
The multiturn bias field coils are connected in two symmetrical branches, thus the bias field frequency can be varied in certain steps between 0.6 and 2,7 kHz at flux densities between 4 and 8 kG.

For the main bank the following data result:

charging voltage	2 x	40 kV
stored energy	2 x	4,8 kJ
max. discharge current		580 kA
discharge frequency		385 kHz
max. flux density		12,1 kG
dutial rise of flux density		29,2 $\frac{kG}{\mu s}$
initial rise of current		1,4 $\frac{MA}{\mu s}$



P 018 Turbulence Heating Experiment
Collector System



P056 Turbulence Heating Experiment

circuit diagram

initial rise time constant of voltage:	21 ns

The bias field bank data are:

charging voltage	2 x 12 kV
stored energy	2 x 20,6 kJ
max. discharge current	100 kA
discharge frequency	2 kHz

The system will be ready for operation this summer.

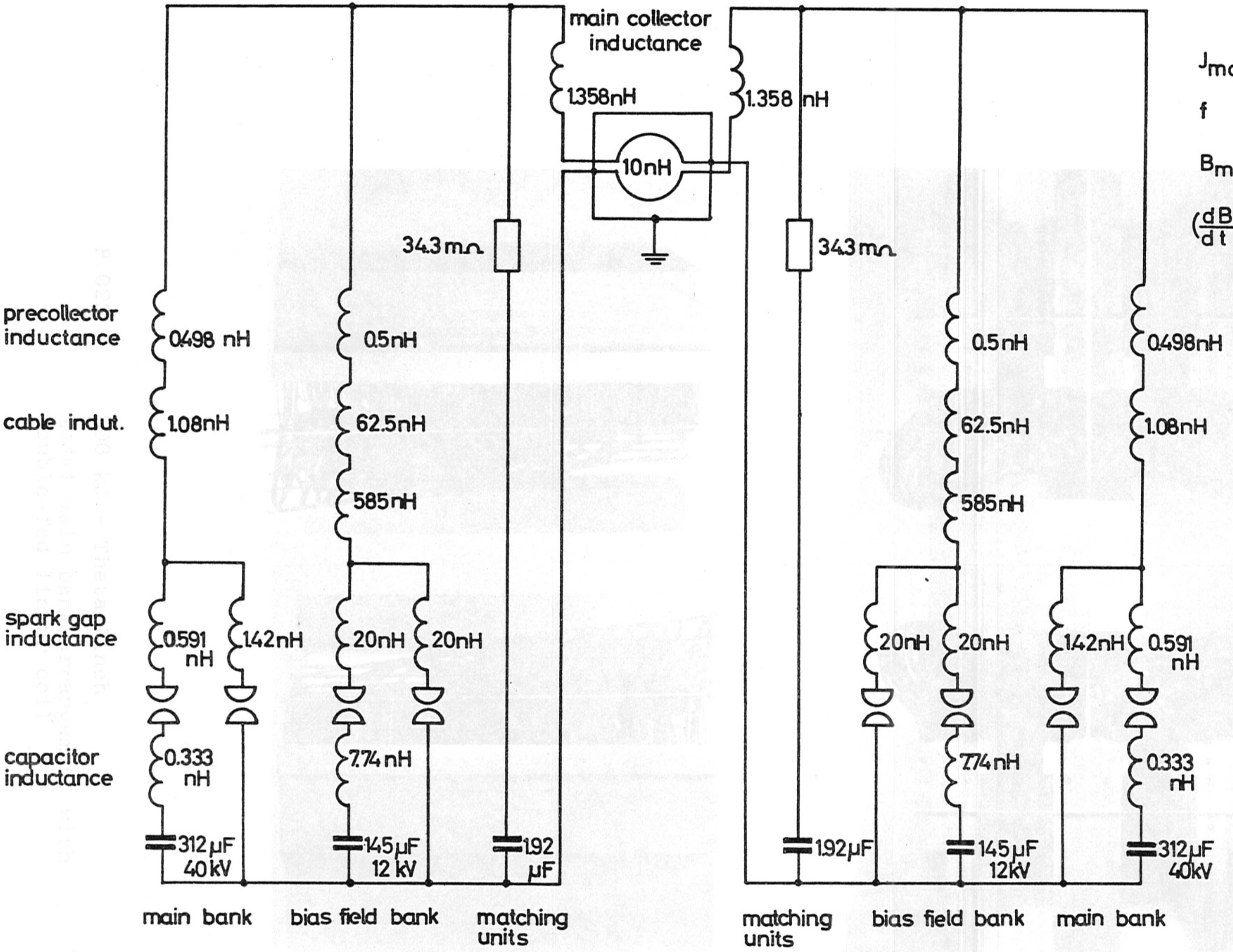
2) 500 kJ-bank for linear and toroidal theta-pinch experiments

Discharge frequency	96 kHz	(is beeing mounted)

Picture P 050 gives the load side circuitry of the bank with the important discharge data.

Picture P 022 shows the principal arrangement of the bank for double-fed linear coils,
Picture P 023 another model view of the system, when changed for a single-fed torus-experiment.

The first application will be a linear experiment whose geometric coil data are 1 m length and 1o cm bore. Concerning field symmetry in the coil and collector principle the solution is like the turbulence heating experiment. The half-banks are located on both sides of the collector which has Z-form here. When turning to toroidal experiments only the collector structure has to be changed in revolving one precollector system by 180 degrees thus getting the correct polarity for parallel performance of the half banks. Furthermore the precollectors will be placed on a circle surrounding the torus. The 3 different cable lengths (mean value 4.5 m) have been fixed such that they fit also for the toroidal solution. They have been terminated with plug-in cable glands using commercial plug contacts with some amendments according to pulse duty. The cable gland itself consists of moulded polythene with proper voltage grading. The plug contacts withstood several ten thousand discharges with 30 kA (~100 kHz) per cable. Using



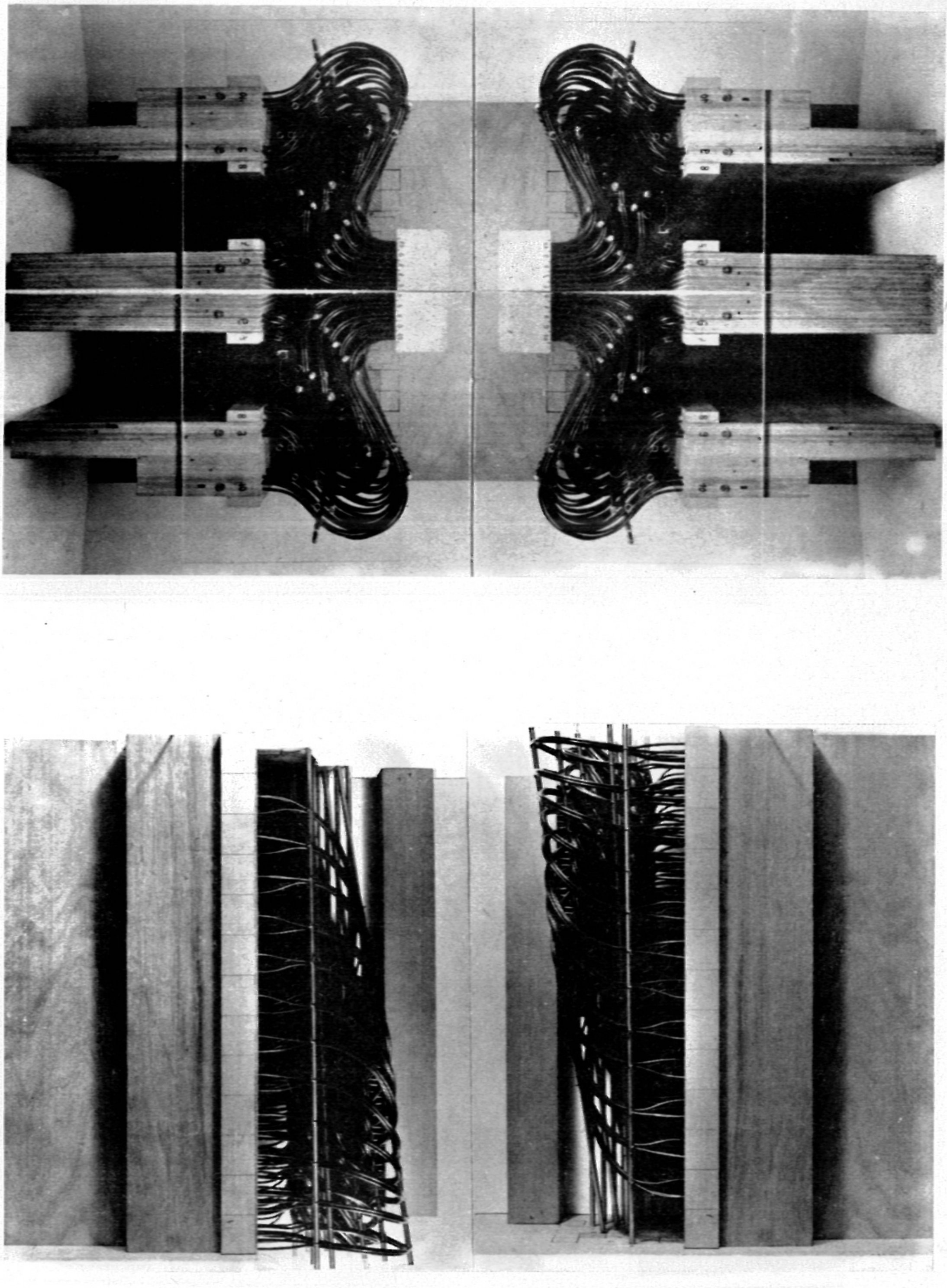
P050 500kJ-Theta-pinch circuit diagram

J_{max} = 7.54 MA

f = 96.1 kc/s

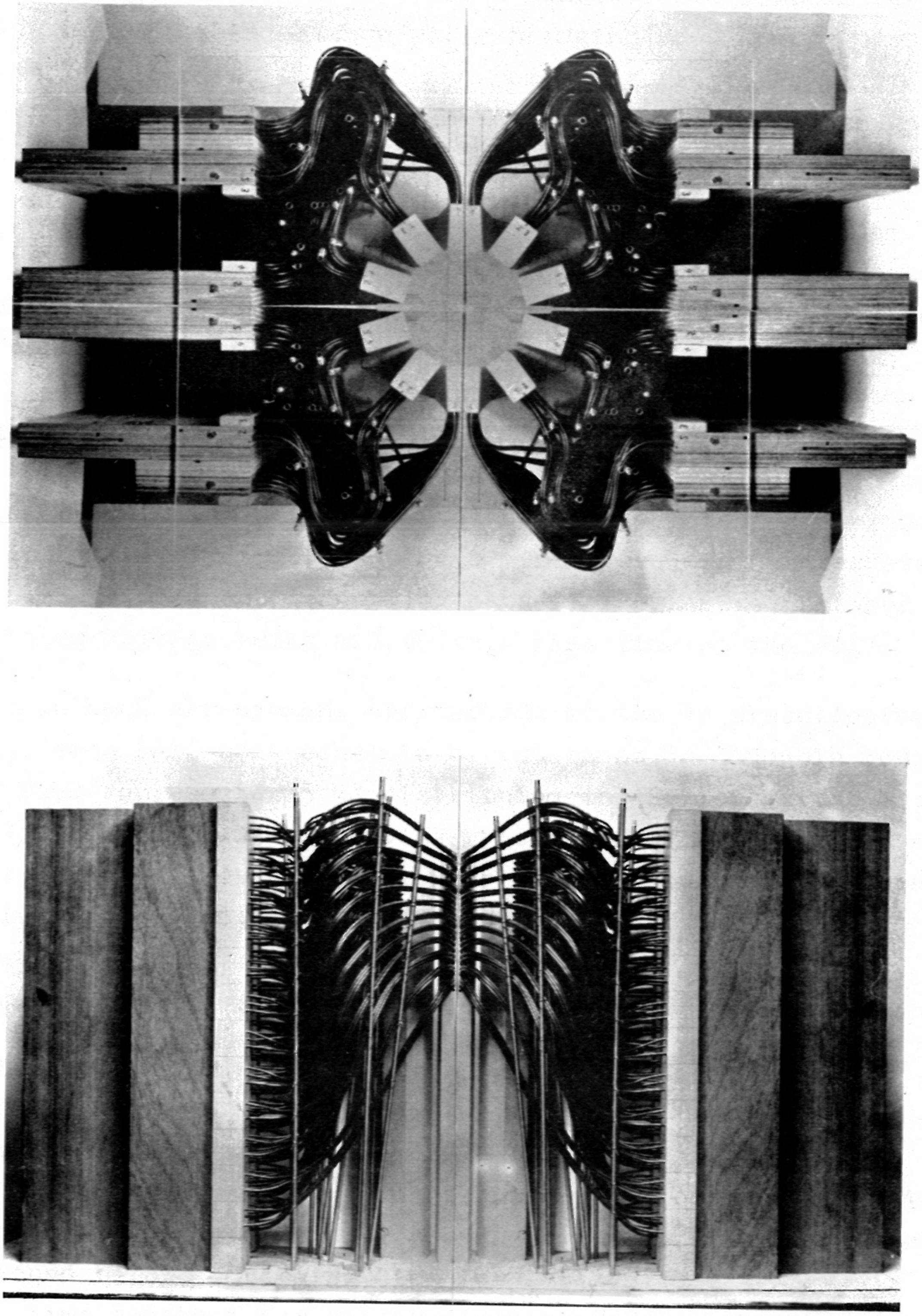
B_{max} = 94.6 kG

$\left(\frac{dB}{dt}\right) = 57 \frac{kG}{\mu s}$



P 022 500 kJ - Theta-Pinch

Model main bank arrangement with double-fed linear coil



P 023 500 kJ - Theta-Pinch

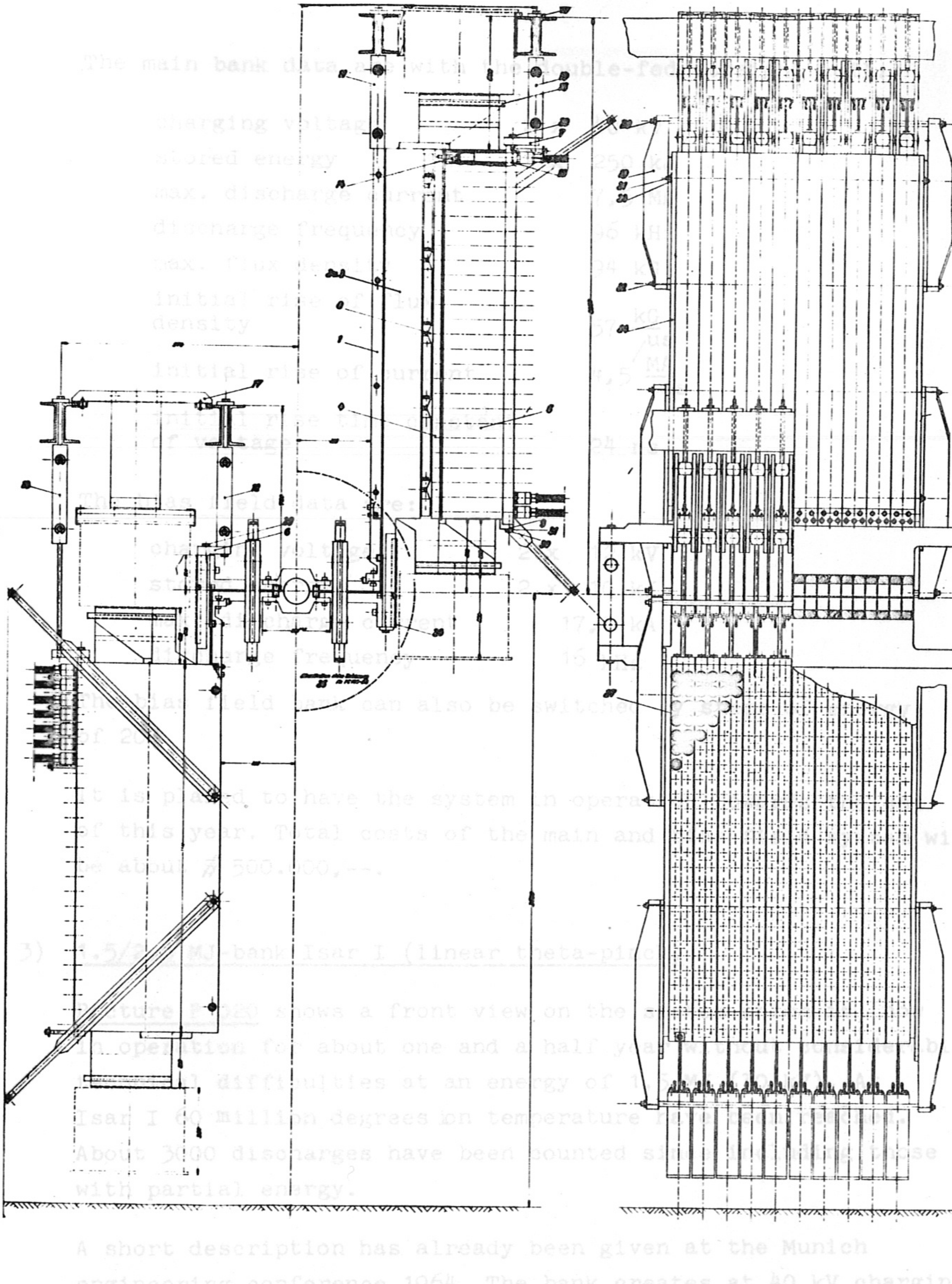
Model of main bank arrangement with toroidal coil plug in cable terminations gives a considerable step in reducing collector inductance while bringing more energy per unit coil length to the load and remaining flexible. Here 480 40 kV-cables of 27 mm diameter are connected within an area of 1.44 sqm. to the collector at one side.

Picture P 021 shows a side-on view of the collector system. The insulation consists of several layers of mylar with a total thickness of 1.2 mm. Mechanically the collector is a prestressed spring-mass-system where the prestress-force is about 5 percent of the peak electromagnetic force. Because of the large number of cables much space is also required for proper matching; thus upper and lower precollector-sides are occupied by matching units. The values of the matching components are approximately: resistance 1.6 times resulting characteristic cable impedance, decoupling capacitor optimized between remaining voltage swing and voltage rise time at the coil.

The main bank arrangement corresponds to the 10 precollector units: each half bank consists of ten racks in 3 double rows. Each rack represents 25 kJ distributed in 12 tiers with a 40 kV 2.6 μF condensor each. Every condensor has its own combined wide range start and crowbar switch which will be seperately reported at this conference. The start switch has an operating range of 10 ./. 40 kV with a jitter of less than 20 ns.

The bank energy of each half bank can be varied in steps of 20% in such a way, that for all energy steps the feeding remains symmetrical about the middle of the straight coil and equally distributed along the circumference for the torus. The two stage triggersystem corresponds to that of the 10 kJ-bank mentioned before. Charging time for full voltage (40 kV) is 30 s, time constant for safety discharge across the charging resistors 3,25 s. In case of emergency the bank can be shorted at once by the single shorting breakers.

An electronic sensing system surveys the capacitor voltage in groups of six during charging and in the charged state. A second system will trigger the whole bank in case of prefire of one circuit.



P 021 500 kJ - Theta-Pinch
Collector system

The main bank data are with the double-fed straight coil:

charging voltage	2 x	40 kV
stored energy	2 x	250 kJ
max. discharge current		7,5 MA
discharge frequency		96 kHz
max. flux density		94 kG
initial rise of flux density		57 $\frac{kG}{\mu s}$
initial rise of current		4,5 $\frac{MA}{\mu s}$
initial rise time constant of voltage		24 ns

The bias field data are:

charging voltage	2 x	12 kV
stored energy	2 x	10 kJ
max. discharge current		17,0 kA
discharge frequency		16 kHz

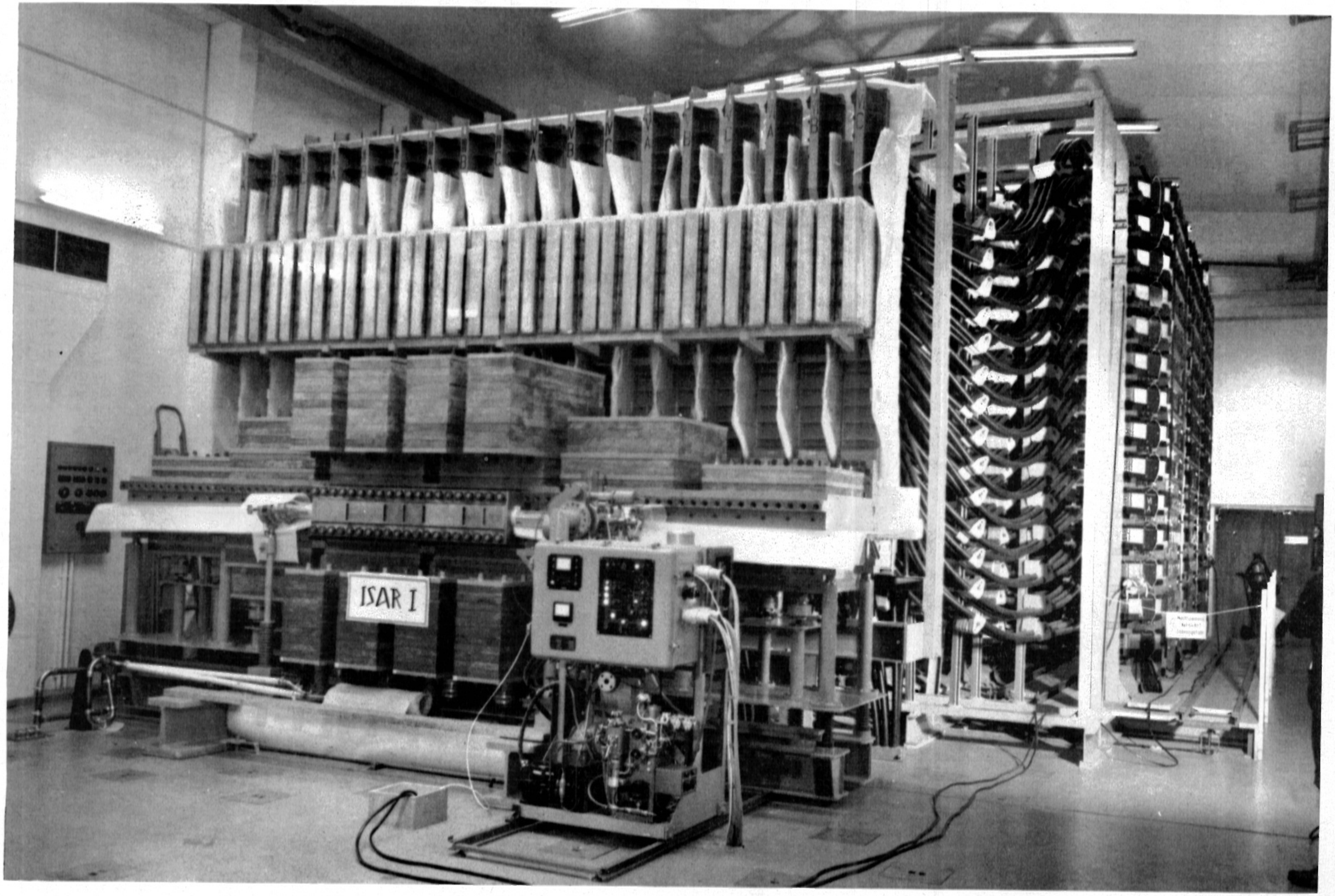
The bias field bank can also be switched by steps of energy of 20%.

It is planed to have the system in operation towards the end of this year. Total costs of the main and bias field system will be about $ 500.000,--.

3) 1.5/2.6 MJ-bank Isar I (linear theta-pinch)

Picture P 020 shows a front view on the system which is now in operation for about one and a half year without considerable technical difficulties at an energy of 1,5 MJ (30 kV). At Isar I 60 million degrees ion temperature have been reached. About 3000 discharges have been counted since including those with partial energy.

A short description has already been given at the Munich engineering conference 1964. The bank creates at 40 kV charging voltage a damped ringing 25- kHz discharge whose first current maximum is about 22 MA. In the 1.5 m long single-turn coil with a bore diameter of 1o5 mm a maximum flux density of 184 kG is attained. The maximum voltage at the coil is 25.5 kV.



P 020 1,5/2,6 MJ - Theta-Pinch Isar I

Front view

The bank comprises 2520 individual capacitors, each with 1.33 µF and a supply voltage of 30/40 kV. These capacitors are connected in parallel in groups of 10 via foil-insulated sandwich conductors 120 mm wide. The 252 groups of 10 thus formed are contained as compactly as possible in 18 capacitor racks, each in fourteen tiers. These capacitor racks were arranged in 6 rows of 3 each so that the shape of the bank is optimum with regard to the pulse cable length. From each of the capacitor groups insulated from one another, i.e. from the spark gap right beside the group, 3 pulse cables run vertically along the appropriate row of racks to the load. Additional capacitors in RC series connection of low-inductance suppress transient phenomena.

The 252 capacitor groups are connected in parallel at the collector. For the given data there occur naturally in this section considerable electromagnetic forces which in the present case are intercepted in the vicinity of the cable connections by mechanical prestressing and, in the actual collector system in which the current concentration described is effected, by a total of 38 t of lead. In this system the lead blocks running vertically can jump freely. The lead blocks situated below are supported by soft springs so as to make the system mechanically symmetrical. The practical performance agrees very well with the design data. The behaviour of the pulse contacts was up to now (operating voltage 30 kV) satisfactory.

The charging time for 40 kV is about 80s. Triggersystem, voltage sensing device and prefire watching circuit are corresponding to those of the 500 kJ-bank.

The calculated discharge date with 40 kV will be

stored energy	2.6 MJ
max. discharge current	22 MA
discharge frequency	25 kHz
max. flux density	184 kG
initial rise of flux density	28.9 $\frac{kG}{\mu s}$

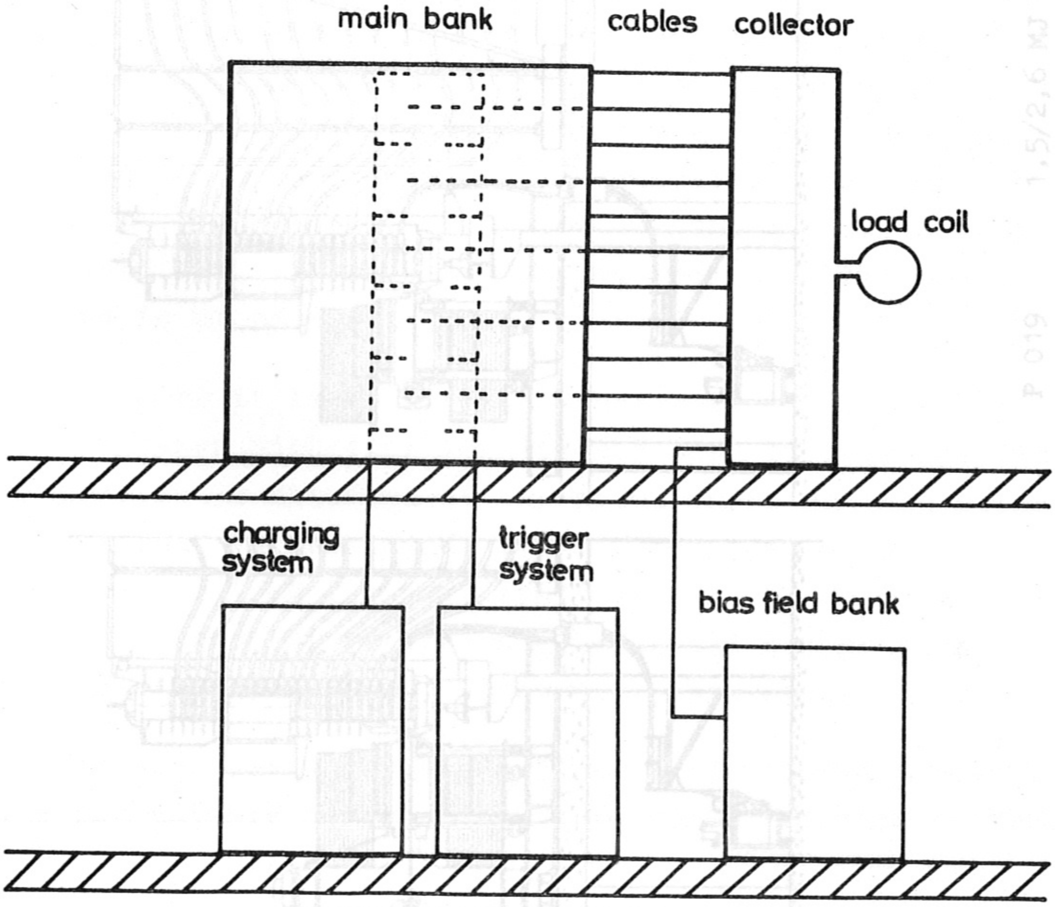
initial rise of current	3.45 $\frac{MA}{/us}$
initial voltage rise time constant	24,1 ns

Total bank system costs were about 1 million dollars.

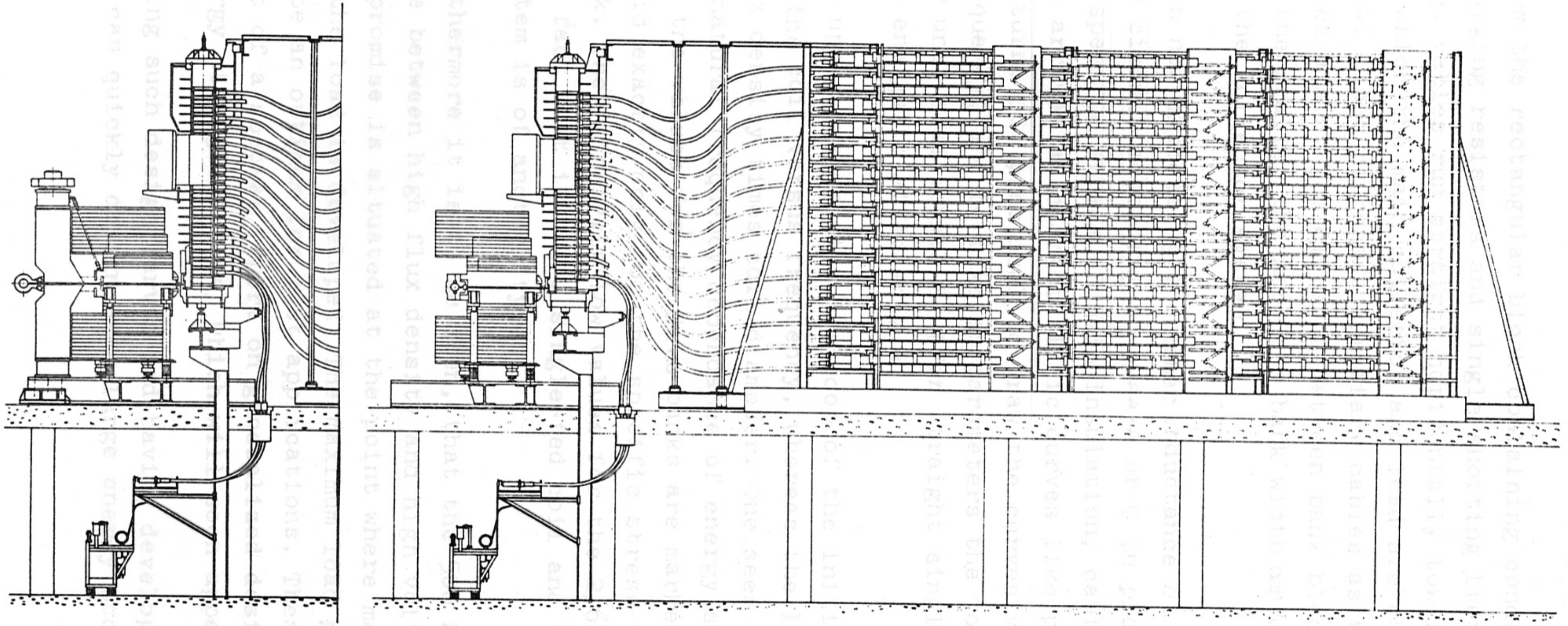
<u>Picture P 019</u> shows the main bank in a side-on view including also an improved collector system with an extension which shall be mounted this summer. The effect should be a considerable improvement in the symmetry of the coil field, which causes an increase of about 1 nH in total circuit inductance. The collector extension is mechanically a prestressed springmass system with resin-clad reinforced concrete blocks as backing up elements in order to get the metallic structure away from the coil. The blocks act at the same time as additional masses which reduce the movement of the collector plates to about 150 /u.

In conclusion a few remarks on generalized design relations for capacitor banks may be added.

When seeking for such relations, one has at first to choose an optimum geometric structure. As it is to be seen from the three banks reported, here the system according to picture P 052 was taken



PO52 capacitor banks - optimum structure



P 019 1,5/2,6 MJ - Theta-Pinch Isar I
Main and bias field bank with two collector versions

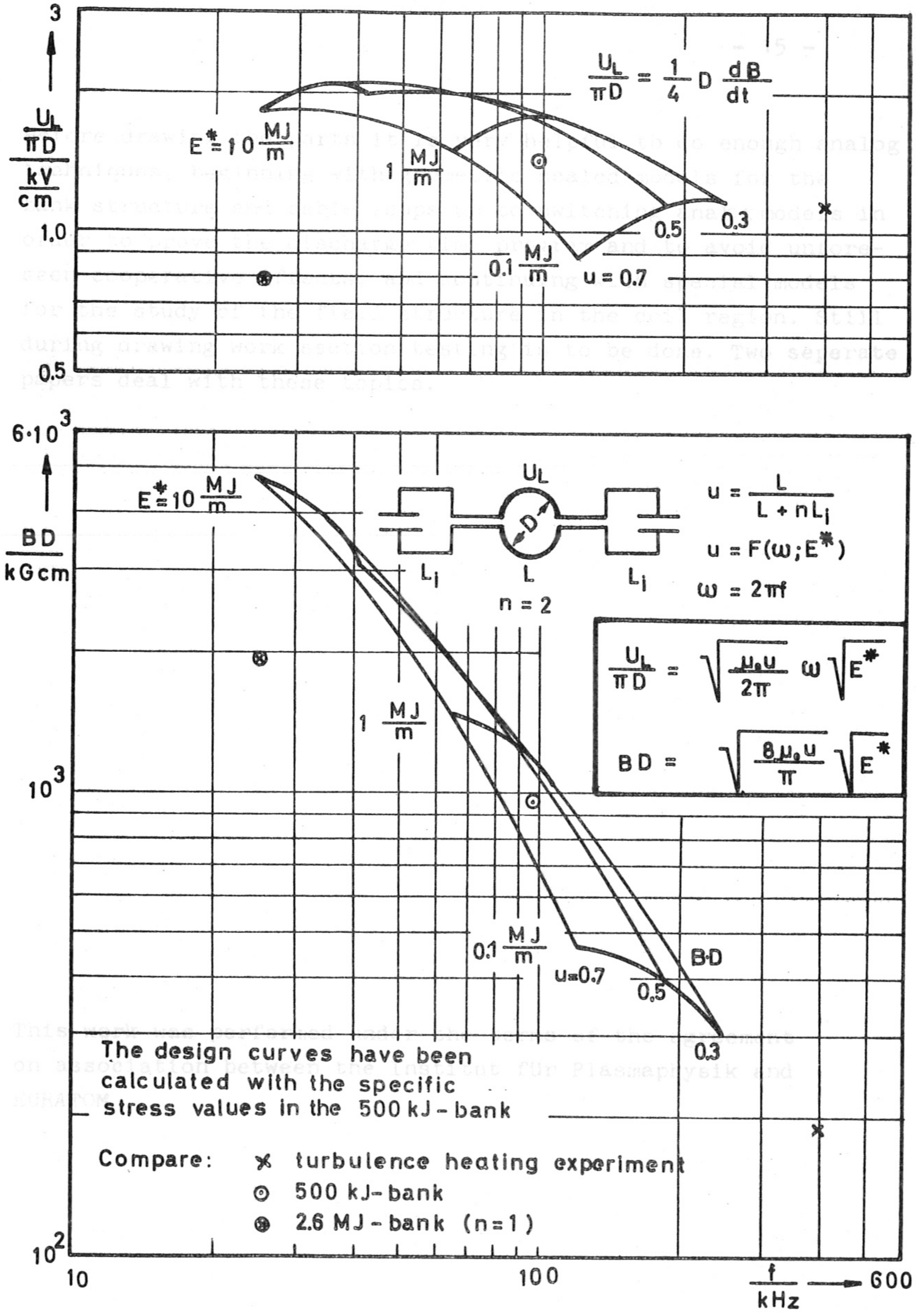
From the rectangular block containing condensors, switches, charging resistors and single shorting breakers the load lines e.g. cables run straight horizontally towards the collector, to which the main collector and load are connected. The vertical lines represent auxiliary cables as trigger and charging lines a.s.o. The distance between bank block and collector can be the smaller the more the bank width corresponds to the width of the collector system.

When now expressing the inner inductance of a bank with a basic circuit according to case A or C in picture P 051 in terms of specific stress of main insulation, cables, capacitors a.s.o. one arrives at characteristic curves like picture P 053.
It turns out practical to draw the curves versus discharge frequency, and to take as parameters the total stored energy per unit load length E^+ (for straight single turn coils) and the energetic efficiency u.

The upper curves give the loop of the initial voltage gradient in the coil versus frequency, whereas the lower curves give the flux density times coil diameter. One sees that there is a sort of natural frequency dependance of energy storage. For comparison the values for the three banks are marked; the curves are valid exactly only for the specific stress values in the 500 kJ-bank. The relatively low values for the 2,6 MJ-bank are due to the fact that it has a single-fed coil and that the collector system is of another type.

Furthermore it is to be seen, that the 500 kJ-bank is a compromise between high flux density and high voltage gradient. The compromise is situated at the point where maximum pulse power in the load is developed. The maximum load power condition seems to be an optimum for most applications. These short remarks are part of a special report on generalized design relations for energy storage systems, which will soon appear.

Having such design curves and having developed proper components one can quickly design even large energy storage systems.



P 053: Capacitor banks
Generalized design curves
Load voltage and flux density versus discharge frequency

Before drawing the parts it is very helpful to do enough analog techniques, beginning with geometric scaled models for the bank structure and cable loops up to switching analog models in order to prove the discharge time program and to avoid unforeseen cooperative effects, and continuing with special models for the study of the field structure in the coil region. Still during drawing work section testing is to be done. Two seperate papers deal with these topics.

This work was performed under the terms of the agreement on association between the Institut für Plasmaphysik and EURATOM

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The co-work of all those is to be mentioned here, whose names do not occur in any components report in this conference.

The following names stand for many others:

E. Breit, G. Kaspar, M. Mahl, K. Maischberger, R. Pöhlchen, H. Stoll

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