STUDIES ON NORMAL-CONDUCTING COILS FOR WENDELSTEIN VII-X

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IPP 2/310 August 1990

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Abstract

For WENDELSTEIN VII-X, the next step stellarator experiment at IPP Garching, a Helias[1] configuration has been chosen. The goals of WENDELSTEIN VII-X are to continue the development of the modular stellarator and to demonstrate the reactor capability of this stellarator line[2]. The main data of the selected HS5-10 configuration with five field periods are: major radius $R_0 = 5.5$ m, magnetic induction $B_0 = 3$ T and stored magnetic energy $W \approx 0.6$ GJ. For comparison with the superconducting coil system which is foreseen for WENDELSTEIN VII-X, a pulsed water-cooled normal-conducting version has been designed in order to explore the limitations and restrictions of this approach. Limitations are the high ohmic power dissipated in the coils and the electric energy currently available at IPP. Normal-conducting coils would allow to apply the well-known techniques in manufactoring these coils, as successful in use in the WENDELSTEIN VII-AS experiment. But these techniques are applicable also[3] for the conductor proposed for the superconducting coils of WENDELSTEIN VII-X.

In this report the time-dependent current and resistance of the coil system circuit is considered; the electric power needed, the total dissipated energy, and the temperature rise of the coil copper is calculated. Scaling laws are derived and parameter studies are made by varying the geometrical dimensions of the system.

[1] J. Nührenberg, R. Zille: Stable Stellarators With Medium β and Aspect Ratio, *Physical Letters* **114**A, 129 (1986).

[2] Beidler, C., et al., Physics and Engineering Design for WENDELSTEIN VII-X, *Fusion Technology*, Vol.17, No.1, (1990), 148ff.

[3] Sapper, J., et al., The WENDELSTEIN 7-X Stellarator, Technical Design and Engineering, *Proc. of the 16th Symposium on Fusion Technology*, London, UK, 1990.

1. Introduction

The techniques involved in producing normal-conducting coils are well-known, and modular nonplanar coils of this type are successfully in use in WENDELSTEIN VII-AS. It is believed that extending these techniques to larger experiments does not present significant new difficulties. For comparison with the superconducting coils of WENDELSTEIN VII-X, a normal-conducting version has been designed in order to show the limitations and restrictions of this alternative. These limitations are consequences of the high ohmic power dissipated in the coils and the electrical energy currently available. The temperature rise in the coils limits the flat-top time of the magnetic field.

In order to study the electrical power needed, the total dissipated energy, and the temperature rise of the coils, several versions of the coil configuration HS5-10 are considered. The current density in the coils is as low as possible, and the total cross-section of the coils is increased by a factor of 2 or more compared with the related superconducting coils. The space between the plasma and wall is not constricted. In the numerical calculations the increase in the coil resistance during the pulse caused by heating is taken into account. A nonlinear system of differential equations for the coil current $i(t)$ and the heat factor $y(t) = 1 + \alpha\,\Delta\vartheta(t)$ is solved numerically with the initial conditions $i(0) = 0$, $y(0) = 1$. The excitation of the coil system is divided into three phases: the loading phase, the flat-top phase, and the deloading phase. The operating voltage is a free parameter in the calculations and is chosen such that it is about 1.5 times the product of $I_c \cdot R_c$, referred to the flat-top. In this way a comparatively short loading phase is guaranteed, preceding the flat-top time. Transient oscillations of the applied voltage and the related current are not taken into account. The allowable maximum value of the temperature rise in all cases considered is $\Delta\vartheta_{max} = 50$ K. Only one pulse is considered, i.e. it is assumed that the coils are cooled down between the pulses to nearly the initial temperature value of about 20°C.

Cryogenically cooled coils of the configuration HS5-10 have also been studied for comparison. The current pulses are limited by the nearly adiabatic temperature rise too, but one can use a larger intervall due to the lower starting temperature. The investigations are made using liquid nitrogen (LN_2) as cooling medium with an initial temperature of 77 K. In order to provide space for the thermal insulation of the coils the coil winding pack is reduced in cross-section and the current density is increased.

2. The electrical circuit

The calculations are based on N series-connected single-turn coils fed by a controllable voltage source.

The electrical circuit is described by

$$u(t) = L\,\frac{d\,i(t)}{d\,t} + R(t)\,i(t)\,. \tag{1}$$

The adiabatic heat equation is given by

$$\gamma\,c\,\frac{d\,\vartheta(t)}{d\,t} = \rho(\vartheta)\,j^2(t)\,. \tag{2}$$

From equation (2), and with

$$\rho(\vartheta) = \rho_{20}\,(1 + \alpha\,\Delta\vartheta(t))\,,$$
$$\Delta\vartheta(t) = \vartheta(t) - \vartheta_A\,,$$
$$j(t) = \frac{i(t)}{A_c} \tag{3}$$

the equation

$$\int_{t'=0}^{t} i^2(t')\,dt' = \frac{1}{p}\,\ln y(t) \tag{4}$$

results, with the heat-factor being defined as

$$y(t) = 1 + \alpha\,\Delta\vartheta(t)\,, \tag{5}$$

and

$$p = \frac{\rho_{20}\ \alpha}{\gamma\,c\,A_c^2}\,, \tag{6}$$

where

- ρ_{20} = specific resistivity at 20°C = $(1/56 \cdot 10^6)\ \Omega$ m,
- α = temperature coefficient at 20°C = $(1/255)\mathrm{K}^{-1}$,
- c = specific heat capacity at 20°C = 387.5 Ws/kg K,
- γ = mass density of copper = $8.9 \cdot 10^3$ kg/m^3,
- ϑ_A = initial temperature 20°C,
- A_c = coil cross-section,
- V_{Cu} = copper volume of all coils.

The coil resistance is

$$R(t) = R_{20}\ y(t)\,. \tag{7}$$

Hence, equations (1) and (2) can be rewritten using equations (3) to (7)

$$\frac{d\,i(t)}{dt} = \begin{cases} \frac{u(t)}{L} - \frac{R_{20}}{L}\, i(t)\, y(t)\,, & \text{for the loading phase,} \\ 0\,, & \text{for the flat-top phase,} \\ -\frac{R_{20}}{L}\, i(t)\, y(t)\,, & \text{for the discharge phase,} \end{cases}$$

$$\frac{d\,y(t)}{dt} = p\; y(t)\; i^2(t) \qquad \text{for the entire pulse,} \tag{8}$$

with the initial conditions

$$i(0) = 0\,, \quad y(0) = 1\,. \tag{9}$$

The nonlinear system of differential equations (8) of the 1^{st} order with the initial conditions (9) is solved by numerical methods. From the equations (5) and (7) the temperature rise $\Delta\vartheta(t)$ and the increase of the resistance of the coils are derived. Also the maximum power P_{max}, the total dissipated energy W_{tot}, and the current density j_c, are derived from the equations given above. Figure 1 shows the typical distribution of these system parameters as a function of time.

The power and energy increase with the square of the current or the current density. Therefore the current density should be as low as possible. To achieve this a maximization of the coil cross-sections is required. In view of the space available the relation

$$b\,N = f_B\, 2\,\pi\,(\,R_0 - r_c - \frac{h}{2}\,)$$

applies, where

- R_0 = major radius,
- r_c = mean coil radius,
- b = lateral coil width,
- h = radial coil height,
- f_B = covering factor (fraction of the inner bore surface) for the nonplanar coils $\approx$ 0.32, ..., 0.48 .

HELIAS coil systems are characterized by a current concentration at the positions $\varphi = i\,\frac{2\,\pi}{M}$, $i = 0, ..., M-1$, at the coil sides facing the torus centre, M being the number of field periods. The covering factor

$$f_B = b\,N\,/\,2\,\pi\,(\,R_0 - r_c - \frac{h}{2}\,) \tag{10}$$

of the 5-period coil configuration HS5-10 is relatively low compared with the 4-period configuration HS4-8, because in the latter system the coils have less toroidal excursions. This leads to relatively high current densities and short pulse times in HS5-10.

Furthermore, a copper filling factor f_F of the coils has to be taken into account. In the WVII-AS experiment, $f_F = 0.66$ could be achieved, i.e. the current density $j_{c_{Cu}}$ in the copper windings is by a factor of 1.5 higher than the overall current density j_c, referred to the outside winding pack cross-section.

Fig. 2 gives an overview of the coil system HS5-10.NLC, Fig. 3 shows a cross-section of this configuration in the plane $z = 0$. In Fig. 4 cross-sections with coils and flux surfaces at different toroidal positions of HS5-10.NLC are shown.

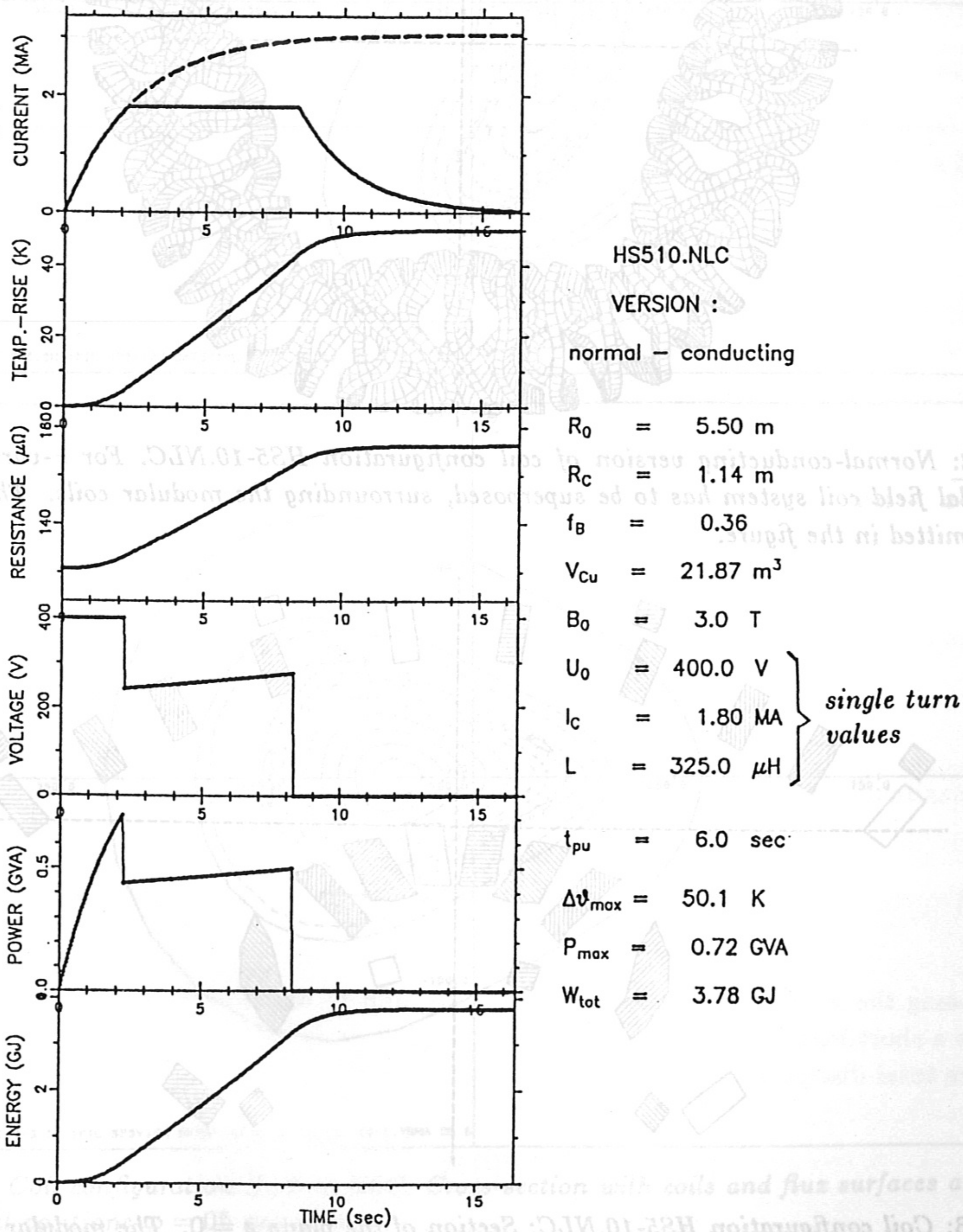


Fig. 1: *Single pulse system parameters of HS5-10.NLC as a function of time.*

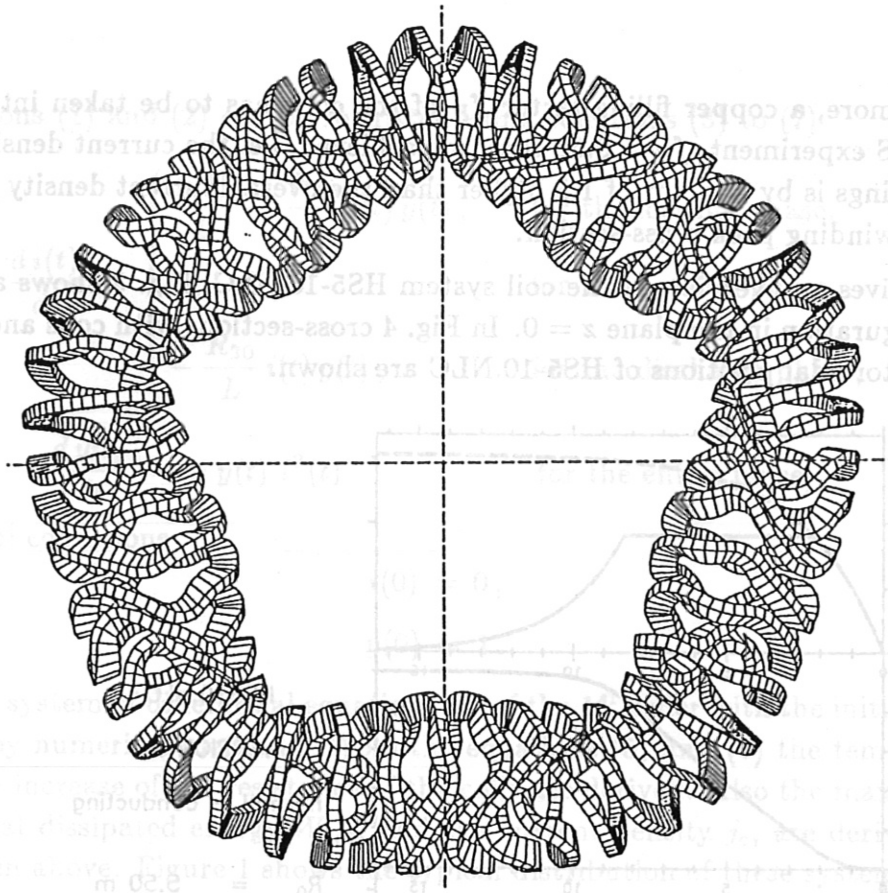


Fig. 2: *Normal-conducting version of coil configuration HS5-10.NLC. For ι-variation, a toroidal field coil system has to be superposed, surrounding the modular coils. These coils are omitted in the figure.*

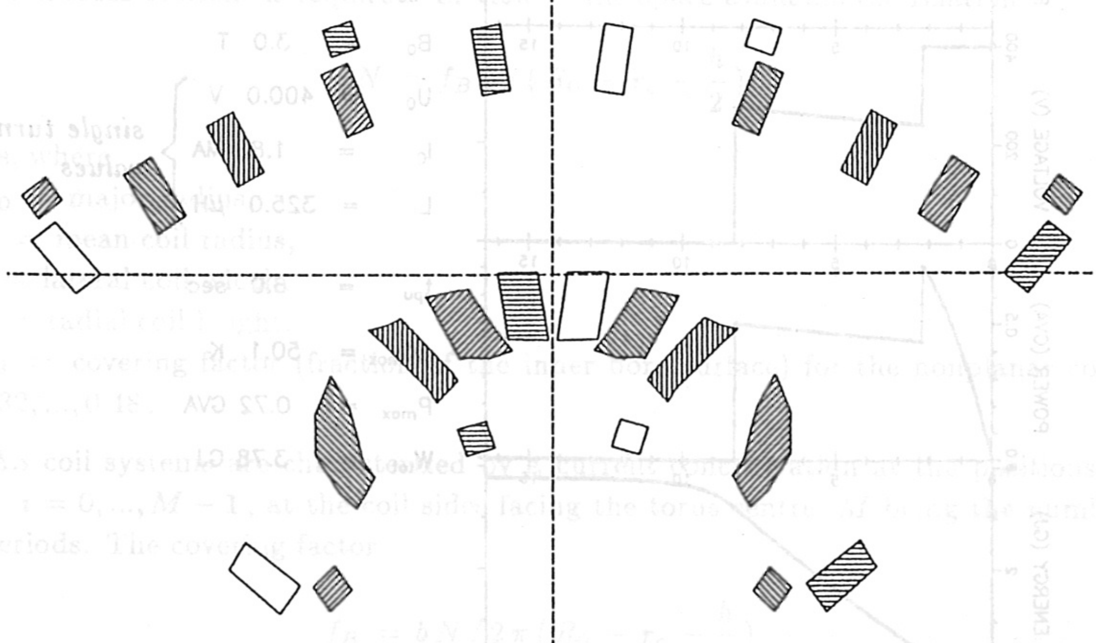
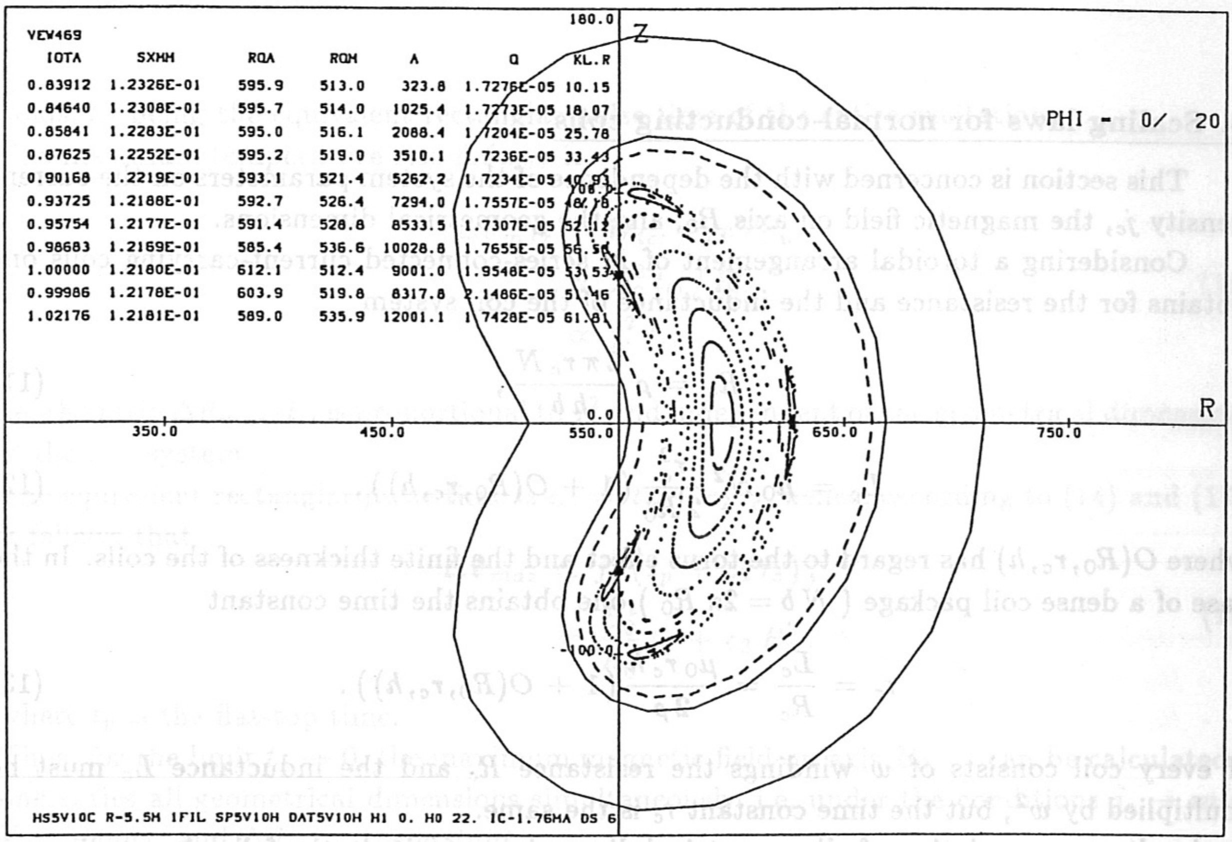


Fig. 3: *Coil configuration HS5-10.NLC: Section of the plane $z = 0$. The modular field coil system and the additional toroidal field coil system for ι-variation are shown.*



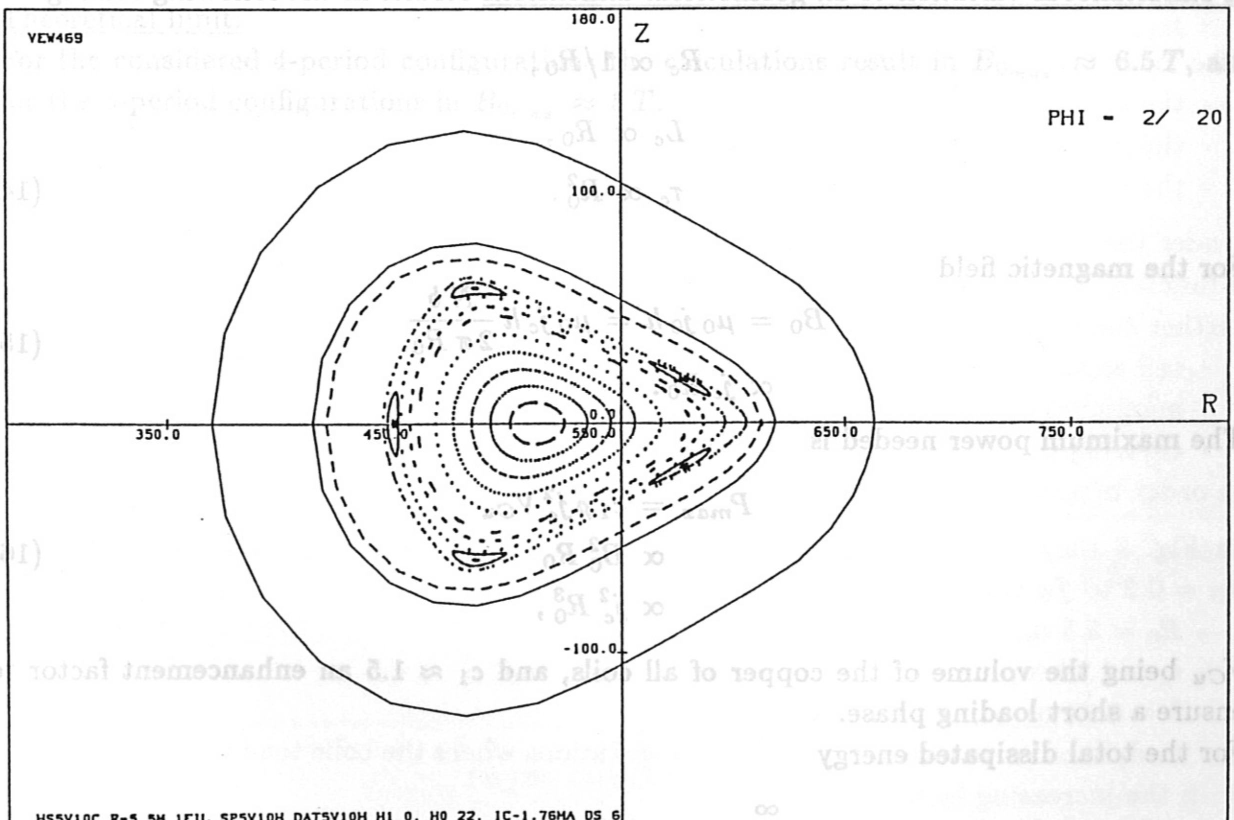


Fig. 4: *Coil configuration HS5-10.NLC: Cross-section with coils and flux surfaces at the toroidal positions* $\varphi = 0^o$ *and* $\varphi = 36^o$*.*

3. Scaling laws for normal-conducting coils

This section is concerned with the dependence of the system parameters on the current density j_c, the magnetic field on axis B_0, and the geometrical dimensions.

Considering a toroidal arrangement of N series-connected current-carrying coils one obtains for the resistance and the inductance of the coil system

$$R_c = \rho \frac{2\pi r_c N}{h b}, \tag{11}$$

$$L_c = \mu_0 N^2 \frac{r_c^2}{2 R_0} (1 + O(R_0, r_c, h)), \tag{12}$$

where $O(R_0, r_c, h)$ has regard to the torus effect and the finite thickness of the coils. In the case of a dense coil package ($N b = 2\pi R_0$) one obtains the time constant

$$\tau_c = \frac{L_c}{R_c} = \frac{\mu_0 r_c h}{2\rho} (1 + O(R_0, r_c, h)). \tag{13}$$

If every coil consists of w windings the resistance R_c and the inductance L_c must be multiplied by w^2, but the time constant τ_c is the same.

A simultaneous variation of all geometrical dimensions results in the following scalings:

$$\begin{aligned} R_c &\propto 1/R_0, \\ L_c &\propto R_0, \\ \tau_c &\propto R_0^2. \end{aligned} \tag{14}$$

For the magnetic field

$$\begin{aligned} B_0 &= \mu_0 j_0 h = \mu_0 j_c h \frac{N b}{2\pi R_0} \\ &\propto j_c R_0. \end{aligned} \tag{15}$$

The maximum power needed is

$$\begin{aligned} P_{max} &= c_1 \rho j_c^2 V_{Cu} \\ &\propto B_0^2 R_0 \\ &\propto j_c^2 R_0^3, \end{aligned} \tag{16}$$

V_{Cu} being the volume of the copper of all coils, and $c_1 \approx 1.5$ an enhancement factor to ensure a short loading phase.

For the total dissipated energy

$$\begin{aligned} W_{tot} &= \int_0^\infty i^2(t) R(t)\, dt = \gamma c V_{Cu} \Delta\vartheta_{max} \\ &\propto B_0^2 R_0 t_\cap \\ &\propto j_c^2 R_0^3 t_\cap, \end{aligned} \tag{17}$$

holds, $t_\cap$ being the equivalent rectanglar pulse time of the entire excitation.
The maximum temperature rise $\Delta\vartheta_{max}$ is

$$\begin{aligned} \Delta\vartheta_{max} &= W_{tot} \,/\, \gamma\, c\, V_{Cu} \\ &\propto B_0^2\, t_\cap \,/\, R_0^2 \\ &\propto j_c^2\, t_\cap\,, \end{aligned} \tag{18}$$

i.e. the ratio $\Delta\vartheta_{max}/t_\cap$ is proportional to j_c^2 and independent of the geometrical dimensions of the coil system.
The equivalent rectanglar pulse time is $t_\cap = t_p + c_2\,\tau_c$, hence, according to (14) and (17), it follows that

$$\begin{aligned} \Delta\vartheta_{max} &\propto j_c^2\,(t_p + c_2\,\tau_c)\,, \\ &\propto \frac{B_0^2}{R_0^2}\, t_p + c_3\, B_0^2\,. \end{aligned} \tag{19}$$

where t_p is the flat-top time.
Thus, for the limit $t_p \to 0$, the maximum magnetic field on axis $B_{0_{max}}$ can be calculated if one varies all geometrical dimensions simultaneously, i.e. under the conditions $j_c \to min$, $V_{cu} \to max$, and $\Delta\vartheta_{max} = constant$.
Theoretical limit:
For the considered 4-period configurations the calculations result in $B_{0_{max}} \approx 6.5\,T$, and for the 5-period configurations in $B_{0_{max}} \approx 5\,T$.

4. Numerical calculations

The calculations are based on the numerical solutions of the nonlinear system of differential equations (8) with the initial conditions (9). The system parameters of the maximum power P_{max}, the maximum dissipated energy W_{tot}, the current density j_c, and the maximum temperature rise $\Delta\vartheta_{max}$ can be derived therefrom.

The maximum voltage u_0 is a free parameter and is chosen such that it is about 1.5 times the product of $I_c \cdot R_c$ at flat-top in order to ensure a comparatively short loading phase. The value of the maximum temperature rise in all cases considered is $\Delta\vartheta_{max} = 50$ K. The pulse time of the flat-top phase follows.

4.1. Constant magnetic field on axis $B_0 = 3.0$ T

The starting-point of the calculations is the standard case of the HS5-10 coil system, characterized by

- $B_0 = 3$ T,
- $R_0 = 5.5$ m,
- $r_c = 1.14$ m,
- $A_c = 0.19 \times 0.44$ m^2,
- $j_c = 21.8$ MA/m^2,
- $j_{c_{Cu}} = 33.0$ MA/m^2.

The following constants for the nonplanar coils of the helical system are used, describing

- the composite construction of the winding pack: filling factor $f_F = 0.66$,
- the nonplanar coil shape: prolongation factor $f_S = 1.12$,
- the helical arrangement of the coils: helicity factor $f_H = 1.09$.

Under these conditions the system parameters are calculated. In Fig. 5 they are given as a function of the major radius R_0, which is varied from $R_0 = 5$ m to $R_0 = 7$ m, using the further constraints

- coil aspect ratio $A_m = R_0/r_c = 4.83$,
- maximum operation voltage $u_0 = const.$,
- covering factor $f_B = 0.359$, as defined in (10),

in order to analyse coils of the type used for HS5-10.

In Fig. 6 they are given as a function of the covering factor f_B, which is varied from $f_B = 0.2$ to $f_B = 0.6$. Here the constraints

- $R_0 = 5.5$ m,
- $r_c = 1.14$ m,
- $h = 0.44$ m.

are used, in order to analyse different configurations where the coils tend to be more planar with the increasing factor f_B.

In the figures the present limits of power and energy are surpassed. These limits are the available values of power $P_{lim} \approx 320$ MVA and energy $W_{lim} \approx 1.8$ GJ at IPP. In these values is taken into account that another substantial part of the installed power and energy is reserved for plasma heating of the experiment.

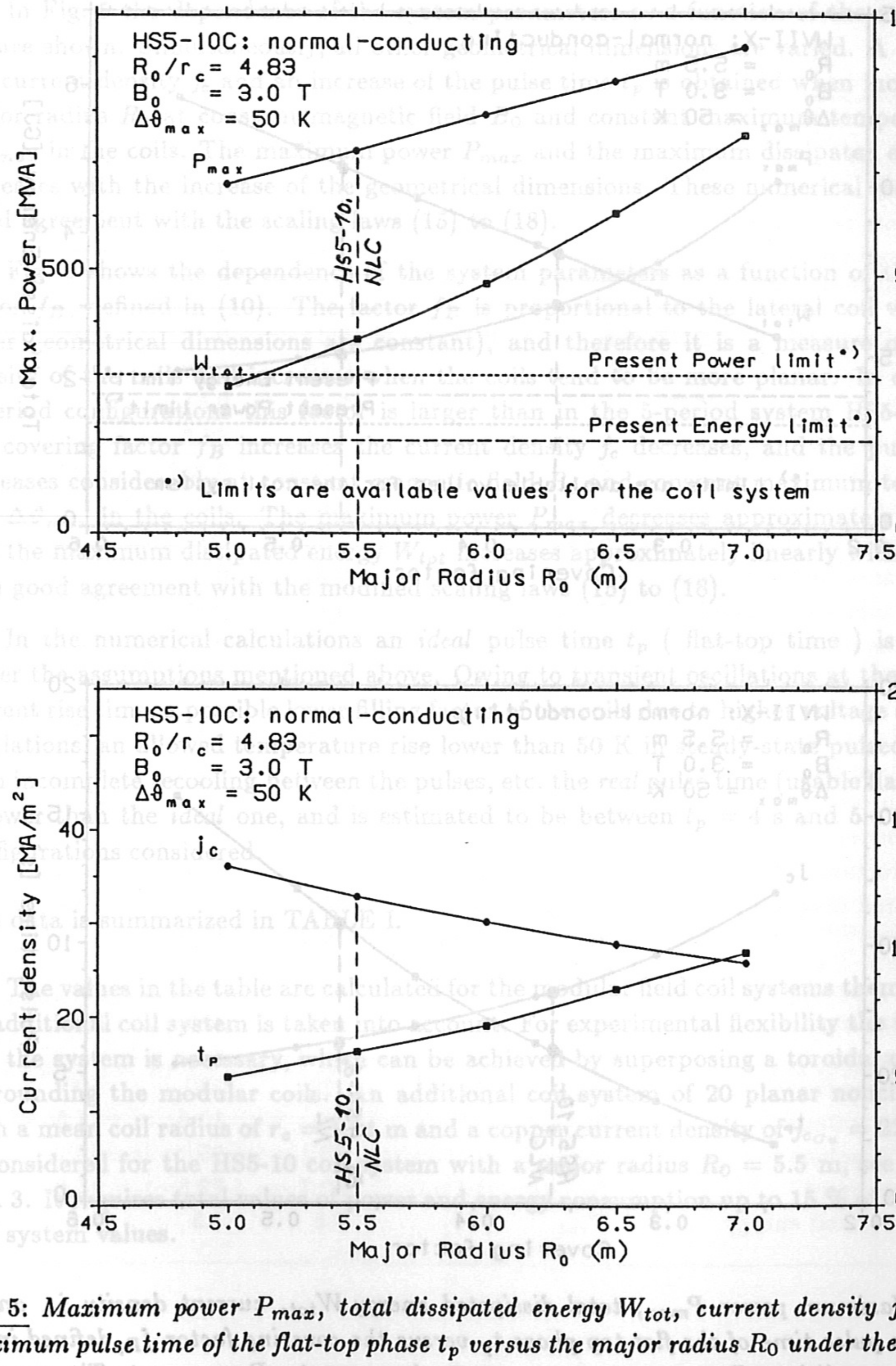
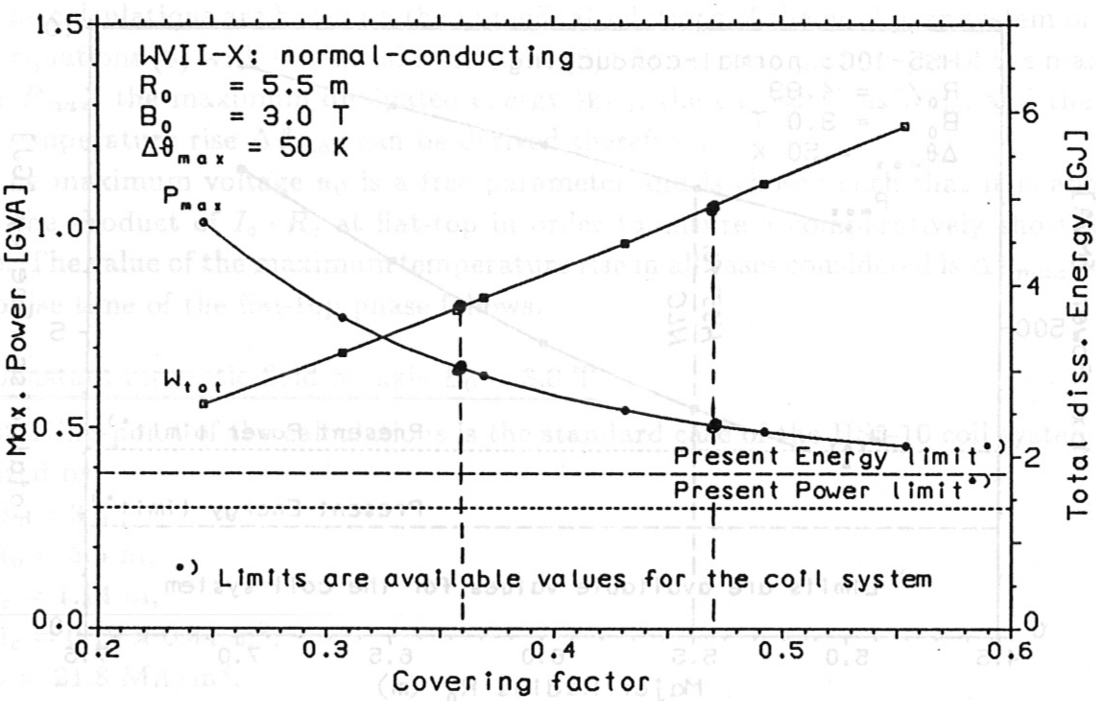


Fig. 5: *Maximum power P_{max}, total dissipated energy W_{tot}, current density j_c, and the maximum pulse time of the flat-top phase t_p versus the major radius R_0 under the conditions $A_m = R_0/r_c =$ const., $B_0 =$ const., $u_0 =$ const., and minimization of the current density. The maximum temperature rise is $\Delta\vartheta_{max} = 50$ K.*



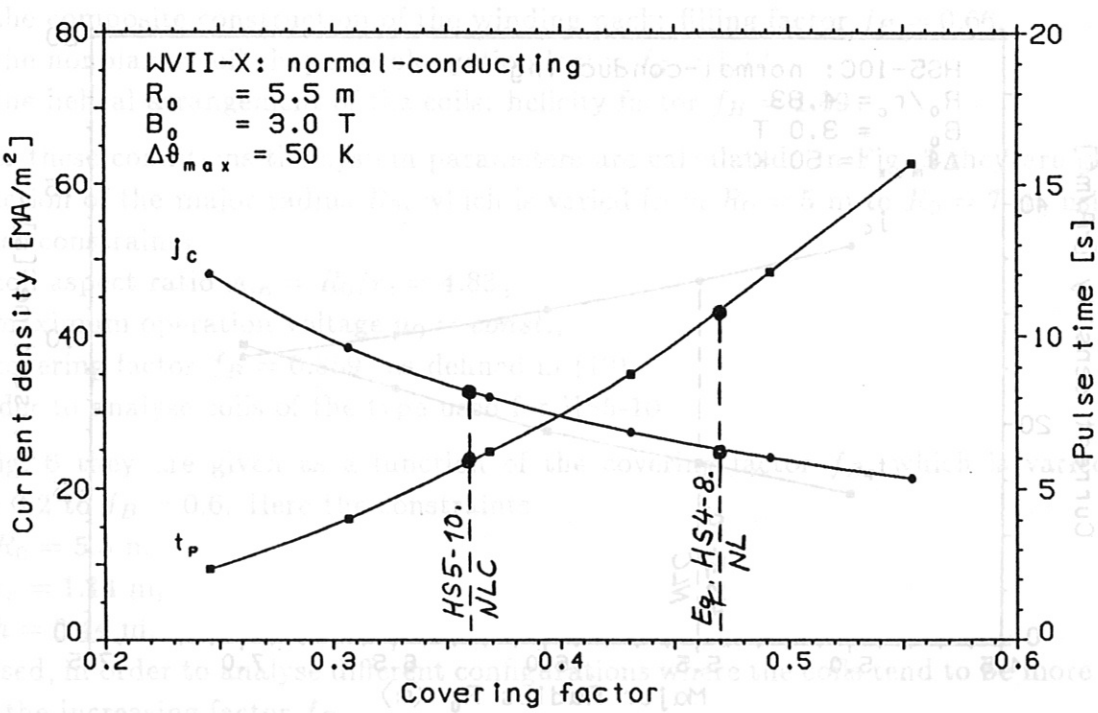


Fig. 6: *Maximum power P_{max}, total dissipated energy W_{tot}, current density j_c, and the maximum pulse time of the flat-top phase t_p versus the covering factor f_B, defined in (10), under the conditions $R_0 = const.$, $r_c = const.$, $h = const.$, $B_0 = const.$ The maximum temperature rise is $\Delta\vartheta_{max} = 50$ K.*

Discussion of the results presented in Figs. 5 and 6:

In Fig. 5 the dependence of the system parameters as a function of the major radius R_0 are shown. Simultaneously, all other geometrical dimensions are varied. A decrease of the current density j_c and an increase of the pulse time t_p is obtained when increasing the major radius R_0 at constant magnetic field B_0 and constant maximum temperature rise $\Delta\vartheta_{max}$ in the coils. The maximum power P_{max} and the maximum dissipated energy W_{tot} increases with the increase of the geometrical dimensions. These numerical results are in good agreement with the scaling laws (15) to (18).

Fig. 6 shows the dependence of the system parameters as a function of the covering factor f_B, defined in (10). The factor f_B is proportional to the lateral coil width b (all other geometrical dimensions are constant), and therefore it is a measure of the local density of the coils and increases when the coils tend to be more planar. In comparable 4-period configurations this factor is larger than in the 5-period system HS5-10. When the covering factor f_B increases the current density j_c decreases, and the pulse time t_p increases considerably at constant magnetic field B_0 and constant maximum temperature rise $\Delta\vartheta_{max}$ in the coils. The maximum power P_{max} decreases approximately with $1/f_B$ and the maximum dissipated energy W_{tot} increases approximately linearly with f_B, which is in good agreement with the modified scaling laws (15) to (18).

In the numerical calculations an *ideal* pulse time t_p (flat-top time) is calculated under the assumptions mentioned above. Owing to transient oscillations at the end of the current rise time, a possible lower filling factor of the coils due to higher voltage and thicker insulations, an allowed temperature rise lower than 50 K in steady-state pulsed operation with incomplete recooling between the pulses, etc. the *real* pulse time (usable flat-top time) is lower than the *ideal* one, and is estimated to be between $t_p = 4$ s and 5 s for the coil configurations considered.

The data is summarized in TABLE I.

The values in the table are calculated for the modular field coil systems themselves, and no additional coil system is taken into account. For experimental flexibility the variation of ι in the system is necessary, which can be achieved by superposing a toroidal coil system, surrounding the modular coils. An additional coil system of 20 planar noncircular coils with a mean coil radius of $r_c = 1.54$ m and a copper current density of $j_{c_{Cu}} = 22.2$ MA/m^2 is considered for the HS5-10 coil system with a major radius $R_0 = 5.5$ m, see Fig. 2 and Fig. 3. It requires total values of power and energy consumption up to 15 % of the modular coil system values.

TABLE I: Characteristic data of normal-conducting versions of HS5-10, and HS4-8:

			HS5-10 .NLC	HS5-10 .NLA	HS4-8 .NL
Rotational transform on axis	ι_o		0.84	0.84	
Rotat. transform on boundary	ι_a		0.99	0.99	
Average major radius	R_0	[m]	5.5	5.5	5.0
Average coil radius	r_c	[m]	1.14	1.14	0.90
Average plasma radius	r_p	[m]	0.53	0.53	
Radial coil height	h	[m]	0.44	0.42	0.46
Lateral coil width	b	[m]	0.19	0.18	0.24
Average coil volume	V_c	[m^3]	0.66	0.61	0.71
Total coil volume	$n \cdot V_c$	[m^3]	33.1	30.3	34.2
Covering factor	f_B		0.359	0.342	0.47
Filling factor	f_F		0.66	→	→
Total copper volume	$n \cdot V_{c_{Cu}}$	[m^3]	21.9	20.	22.6
Min. distance between coils	Δ_c	[m]	0.01	0.006	
Min. distance plasma-coil	Δ_{pc}	[m]	0.18	0.18	
Min. radius of curvature	ρ_c	[m]	0.14	0.15	
Coil number total / per FP	n/np		50/10	50/10	48/12
Total coil current	I_c	[MA]	1.82	1.82	2.18
Induction on axis	B_o	[T]	3.0	3.0	4.0
Overall current density	j_c	[MA/m^2]	21.8	24.	20.
Copper current density	$j_{c_{Cu}}$	[MA/m^2]	33.	36.	30.
Total inductance (one-turn)	L	[μH]	325.	325.	250.
Total stored magnetic energy	W_{mag}	[MJ]	540.	540.	590.
Virial stress	σ_V	[MPa]	16.3	17.6	17.3
Max. temperature rise	$\Delta\vartheta_{max}$	[K]	50.	50.	50.
"Ideal" flat-top time	t_p	[s]	6.0	4.9	6.2
"Real" flat-top time	t_p	[s]	5.	4.	
Maximum power	P_{max}	[MVA]	720.	770.	500.
Operating voltage	$U_{o_{max}}$	[kV]	12.	10.6	11.5
Winding number	w		30	25	50
Winding current	I_w	[kA]	60.7	72.8	43.6
Total dissipated energy	W_{tot}	[GJ]	3.8	3.5	3.9

4.2. Constraint: Available values of power and energy at IPP

In this section the calculations are made under the assumption that the present available values at IPP for feeding the WENDELSTEIN VII-X coil system should not be exceeded. These values are $P_{lim} \approx 320$ MVA and energy of $W_{lim} \approx 1.8$ GJ. The question is: What axis magnetic field B_0 is possible and what pulse time can be reached in this case?

The starting-point of the calculations is again the HS5-10 coil system, but with reduced geometrical dimensions. A further constraint is the current density of $j_c \approx 27$ MA/m^2, which is the design value of WENDELSTEIN VII-AS.
As mentioned in section 4.1. the following constants for the nonplanar coils of the helical system are used, describing

- the composite construction of the winding pack: filling factor $f_F = 0.66$,
- the nonplanar coil shape: prolongation factor $f_S = 1.12$,
- the helical arrangement of the coils: helicity factor $f_H = 1.09$.

Under these conditions the system parameters are calculated. They are given as a function of the major radius R_0, which is varied from $R_0 = 4$ m to $R_0 = 5$ m, using the further constraints

- coil aspect ratio $A_m = R_0/r_c = 4.83$,
- maximum operation voltage $u_0 = const.$,
- covering factor $f_B \approx 0.39$, as defined in (10).

Two cases are considered and summarized in the following tables. In the first case the minimum distance between plasma and wall Δ_{pw} is chosen as large as possible. In the second case the minimum distance between plasma and wall is kept with $\Delta_{pw} = 0.12$ m. Consequently, the radial coil height is lower and the current density is increased or the magnetic field is decreased.

Discussion of the results of the two cases:

If the frame of the installed power supply system at IPP Garching is assumed, Helias systems of the type HS 5-10 with a magnetic field on axis of around $B_0 = 2$ T are obtained. This value does not vary very much for systems with a major radius between $R_0 = 4$ m and $R_0 = 5$ m. The pulse length of the flat-top phase is rather short; it amounts between $t_p = 4$ s and 5 s. In TABLE II and TABLE III the data of the two cases is summarized.

The values in the tables are calculated again for the modular field coils themselves, and no additional coil system for ι-variation is considered. If external coils are taken into account, the flat-top time would be further reduced.

TABLE II: **Characteristic data of normal-conducting versions of HS5-10C: The minimum distance between plasma and wall Δ_{pw} is as large as possible, and varies between 0.09 m and 0.13 m.**

			HS5-10 .NLC1	HS5-10 .NLC2	HS5-10 .NLC3
Rotational transform on axis	ι_o		0.84	→	
Rotat. transform on boundary	ι_a		0.99	→	
Average major radius	R_0	[m]	4.0	4.5	5.0
Average coil radius	r_c	[m]	0.84	0.94	1.04
Average plasma radius	r_p	[m]	0.39	0.44	0.49
Radial coil height	h	[m]	0.22	0.25	0.27
Lateral coil width	b	[m]	0.15	0.17	0.19
Average coil volume	V_c	[m^3]	0.20	0.28	0.38
Total coil volume	$n \cdot V_c$	[m^3]	10.	14.	19.1
Covering factor	f_B		0.39	0.39	0.39
Filling factor	f_F		0.66	→	→
Total copper volume	$n \cdot V_{c_{Cu}}$	[m^3]	6.6	9.2	12.6
Min. distance between coils	Δ_c	[m]	0.01	0.02	0.02
Min. distance plasma-wall	Δ_{pw}	[m]	0.09	0.105	0.13
Min. radius of curvature	ρ_c	[m]	0.14	0.15	0.17
Coil number total / per FP	n/np		50/10	→	→
Total coil current	I_c	[MA]	0.9	0.97	1.02
Induction on axis	B_o	[T]	2.1	2.0	1.9
Overall current density	j_c	[MA/m^2]	<u>27.3</u>	22.8	19.9
Copper current density	$j_{c_{Cu}}$	[MA/m^2]	41.3	34.6	30.1
Total inductance (one-turn)	L	[μH]	250.	275.	300.
Total stored magnetic energy	W_{mag}	[MJ]	102.	130.	156.
Virial stress	σ_V	[MPa]	10.2	9.3	8.2
Max. temperature rise	$\Delta\vartheta_{max}$	[K]	50.	50.	42.
"Ideal" flat-top time	t_p	[s]	4.4	6.	7.
"Real" flat-top time	t_p	[s]	3.	4.5	5.5
Maximum power	P_{max}	[MVA]	290.	<u>300.</u>	<u>310.</u>
Operating voltage	$U_{o_{max}}$	[kV]	4.5	4.35	4.2
Winding number	w		14	14	14
Winding current	I_w	[kA]	64.3	69.3	72.9
Total dissipated energy	W_{tot}	[GJ]	1.2	1.6	<u>1.8</u>

Limiting values are underlined.

TABLE III: Characteristic data of normal-conducting versions of HS5-10C: The minimum distance between plasma and wall is kept with $\Delta_{pw} = 0.12$ m.

			HS5-10 .NLC1*	HS5-10 .NLC2*	HS5-10 .NLC3*
Rotational transform on axis	ι_o		0.84	→	→
Rotat. transform on boundary	ι_a		0.99	→	→
Average major radius	R_0	[m]	4.0	4.5	5.0
Average coil radius	r_c	[m]	0.84	0.94	1.04
Average plasma radius	r_p	[m]	0.39	0.44	0.49
Radial coil height	h	[m]	0.16	0.22	0.28
Lateral coil width	b	[m]	0.16	0.17	0.19
Average coil volume	V_c	[m³]	0.15	0.25	0.38
Total coil volume	$n \cdot V_c$	[m³]	7.6	12.4	19.4
Covering factor	f_B		0.41	0.39	0.39
Filling factor	f_F		0.66	→	→
Total copper volume	$n \cdot V_{c_{Cu}}$	[m³]	5.0	8.2	12.8
Min. distance between coils	Δ_c	[m]	0.02	0.02	0.02
Min. distance plasma-wall	Δ_{pw}	[m]	$\underline{0.12}$	$\underline{0.12}$	$\underline{0.12}$
Min. radius of curvature	ρ_c	[m]			0.17
Coil number total / per FP	n/np		50/10	→	→
Induction on axis	B_o	[T]	1.62	1.9	2.0
Total coil current	I_c	[MA]	0.7	0.92	1.08
Overall current density	j_c	[MA/m²]	$\underline{27.2}$	24.6	20.2
Copper current density	$j_{c_{Cu}}$	[MA/m²]	41.2	37.2	30.6
Total inductance (one-turn)	L	[μH]	250.	275.	300.
Total stored magnetic energy	W_{mag}	[MJ]	62.	117.	175.
Virial stress	σ_V	[MPa]	8.2	9.4	9.
Max. temperature rise	$\Delta\vartheta_{max}$	[K]	50.	50.	41.
"Ideal" flat-top time	t_p	[s]	4.4	5.2	6.1
"Real" flat-top time	t_p	[s]	3.	4.	5.
Maximum power	P_{max}	[MVA]	245.	$\underline{306.}$	$\underline{314.}$
Operating voltage	$U_{o_{max}}$	[kV]	4.	4.	4.1
Winding number	w		12	12	14
Winding current	I_w	[kA]	58.3	76.7	77.1
Total dissipated energy	W_{tot}	[GJ]	0.85	1.4	$\underline{1.8}$

Limiting values are underlined.

5. Cooling of the coils

During and after the current pulse the coils must be cooled down by water cooling. Assuming the same composition as the WENDELSTEIN VII-AS coil cross-section it is expected that the temperature profiles of the WENDELSTEIN VII-X coils are similarly shaped. The deposited heat energy is transferred from the windings through the high-voltage insulation to the cooling channels through which the water flows. The amount of water for cooling of the coil system with a total heat energy of $W_{tot} \approx 4$ GJ is estimated to be about 90 m^3, and the cooling time is $t_{cool} \lesssim 15$ min.

6. Cryogenically cooled coils

The ohmic losses of a coil system can be considerably reduced in cryogenically cooled coils. This is due to a decrease of the specific resistivity at low temperatures. This specific resistivity is composed in general of three parts: the residual resistivity, the resistivity depending on phonon-electron scattering, and resistivity due to the magnetoresistance[1]. The specific heat capacity c is a function of temperature, hence, the adiabatic heat equation (2) is now given by

$$\frac{d\vartheta(t)}{dt} = \frac{\rho(\vartheta)}{\gamma\, c(\vartheta)}\, j^2(t)\,. \tag{20}$$

When using liquid nitrogen (LN_2) as cooling medium with an initial temperature of 77 K the specific "material function" $f_m = \frac{\rho}{\gamma c}$ can be approximated by a linear analytic function of the temperature excluding magnetoresistance[2]

$$f_m = \frac{\rho(\vartheta)}{\gamma\, c(\vartheta)} = 1.66 \cdot 10^{-17}\, \vartheta \qquad [\frac{\mathrm{K\,m^4}}{\mathrm{A^2\,s}}]\,. \tag{21}$$

Including magnetoresistance of a maximum magnetic field of about 7 T at the coils yields

$$f_m = \frac{\rho(\vartheta)}{\gamma\, c(\vartheta)} = 10^{-17}\,(\,30 + 1.6\,\vartheta(t)\,) \qquad [\frac{\mathrm{K\,m^4}}{\mathrm{A^2\,s}}]\,. \tag{22}$$

The main results of the numerical calculations are:

Because of the decreased coil resistance the time constant τ_c of the coil system is increased. With chosen values of the electric power of $P_{max} \lesssim 300$ MVA and the total energy of $W_{tot} \lesssim 1.8$ GJ, one obtains a pulse time for the flat-top phase of about $t_p = 10.2$ s for the configuration HS5-10, assuming an adiabatic heat pulse. The maximum temperature rise is $\Delta\vartheta_{max} \approx 55$ K; the allowable value would be much higher due to the "Martens-point" of the resin, but in the case considered the total energy is the limiting value. The thermal insulation of the coils requires a reduction of the coil cross-section and the overall current density is increased to $j_c = 28.2$ MA/m^2, corresponding to a copper current density of $j_{c_{Cu}} = 42.7$ MA/m^2. The cooling of the coil system between the pulses using LN_2 as cooling medium may lead to a relatively long cooling time. Figure 7 shows the distribution of the system parameters for a cryogenically cooled version of HS5-10 as a function of time.

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[1] B. Oswald: Berechnungsgrundlagen, Optimierung und Kostenfaktoren normalleitender, kryotechnischer und supraleitender Magnete für die experimentelle Plasmaphysik, Report IPP 4/96, November 1971.

[2] M. Söll: Thermal Analysis of the ZEPHYR Tape-wound Toroidal Magnet System, Report IPP 4/195, Dezember 1980.

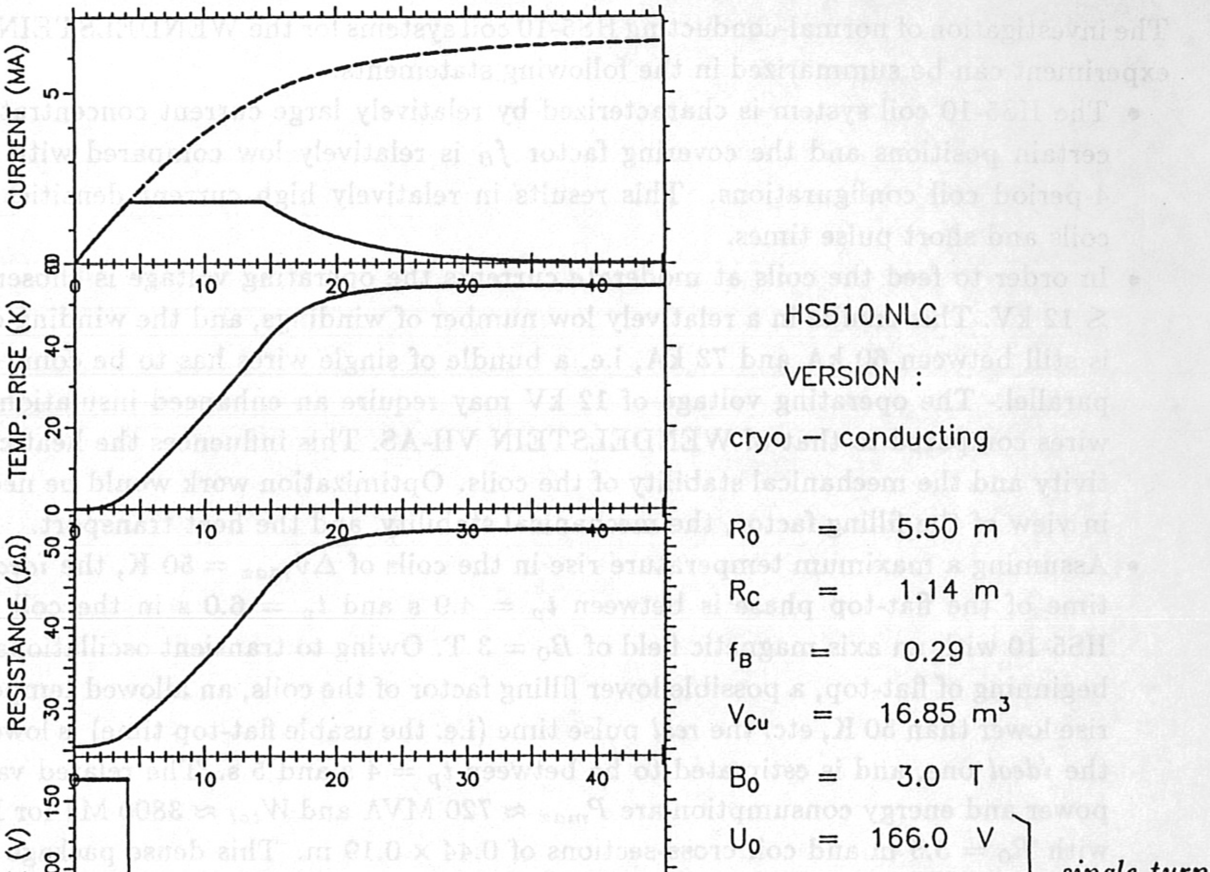

Fig. 7: ***Single pulse system parameters of the cryogenically cooled version of HS5-10 as a function of time, taken into account the material function (22).***

7. Summary and conclusions

The investigation of normal-conducting HS5-10 coil systems for the WENDELSTEIN VII-X experiment can be summarized in the following statements:

- The HS5-10 coil system is characterized by relatively large current concentrations at certain positions and the covering factor f_B is relatively low compared with former 4-period coil configurations. This results in relatively high current densities in the coils and short pulse times.
- In order to feed the coils at moderate currents the operating voltage is chosen to be $\lesssim$ 12 kV. This results in a relatively low number of windings, and the winding current is still between 60 kA and 73 kA, i.e. a bundle of single wires has to be connected in parallel. The operating voltage of 12 kV may require an enhanced insulation of the wires compared to that of WENDELSTEIN VII-AS. This influences the heat conductivity and the mechanical stability of the coils. Optimization work would be necessary in view of the filling factor, the mechanical stability, and the heat transport.
- Assuming a maximum temperature rise in the coils of $\Delta\vartheta_{max} = 50$ K, the *ideal* pulse time of the flat-top phase is between $t_p = 4.9$ s and $t_p = 6.0$ s in the coil system HS5-10 with an axis magnetic field of $B_0 = 3$ T. Owing to transient oscillations at the beginning of flat-top, a possible lower filling factor of the coils, an allowed temperature rise lower than 50 K, etc. the *real* pulse time (i.e. the usable flat-top time) is lower than the *ideal* one, and is estimated to be between $t_p = 4$ s and 5 s. The related values of power and energy consumption are $P_{max} \approx 720$ MVA and $W_{tot} \approx 3800$ MJ for HS5-10 with $R_0 = 5.5$ m and coil cross-sections of 0.44×0.19 m. This dense package results in a total copper volume of $V_{Cu} = 21.9$ m^3.
- If an additional toroidal coil system for ι-variation is taken into account, the values of power and energy consumption increase up to about 15 % of the values of the modular coil system.
- The power supply system at IPP Garching would have to be upgraded if a normal-conducting coil system for the WENDELSTEIN VII-X experiment with a magnetic field on axis of $B_0 = 3$ T had been chosen.
- Assuming the frame of the installed power supply system at IPP Garching, Helias systems of the type HS 5-10 with a magnetic field on axis of $B_o \approx 2$ T would be obtained. The flat-top time would be rather short; it amounts between $t_p = 4$ s and 5 s, and would be reduced if external coils are taken into account.
- Cryogenically cooled coils offer the advantage of extending the flat-top time to approximately the double value of the normal-conducting version at reduced values of power and energy consumption in the coils. This coil system needs a thermal insulation of the coils and a refrigeration system is required. The time for cooling down between the pulses may be a critical issue for such systems, and the achievable flat-top time is not yet covering all experimental demands.