

Superconducting poloidal field magnet engineering for the ARIES-ST

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Abstract

The critical issues of the poloidal systems for the ARIES-ST design have been presented in this paper. Because of the large plasma current and the need of highly shaped plasmas, the poloidal field (PF) coils should be located inside the toroidal field in order to reduce their current. Even then, the divertor coils carry large currents. The ARIES-ST PF coils are superconducting using the internally cooled cable-in-conduit conductor. The peak self field in the divertor coils is about 15 T and the highest field in the non-divertor coils is about 6 T. The PF magnets have built-in margins that are sufficient to survive disruptions without quenching. The costing study indicates that the specific cost of the PF system is \$80/kg. Detailed design and trade-off studies of ARIES-ST are presented and remaining R&D issues are identified.

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1. Introduction

The ARIES-ST reactor is a conceptual commercial reactor based on very low aspect ratio, with small extrapolation from the present engineering databases [1].

The poloidal field (PF) magnets for ARIES-ST have several similarities to the designs for the other ARIES studies [2–5]. However, the design is more demanding due to the much higher coil currents. The PF currents are much larger due to the stability and equilibrium requirements of the highly shaped, high current plasma. The pulsing

requirements of ARIES-ST are similar to those of ARIES-RS [5] and the other previous steady-state studies [2,3], and differ substantially from those of PULSAR, where in addition to a large solenoid for inductive current drive, there were substantial fatigue and cryogenic cooling issues [4].

Low aspect ratio operation has substantial consequences for the PF system of the ARIES-ST reactor design. As mentioned above, the plasma current is substantially larger than in tokamak reactor designs with higher aspect ratio. This requires a larger PF system. The PF system, unlike the toroidal field system in the present ARIES-ST design, has to be made superconducting. This is feasible because there are no maintenance requirements that require that the PF coils

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be demountable, as well as the due to the fact that since there is no need for a central solenoid, the PF coils can be adequately shielded from the plasma radiation. In addition to high plasma current, the PF is driven by requirements on highly shaped plasmas. This is in order to decrease the dissipation in the toroidal field coil, which requires high plasma β and therefore highly shaped plasmas [6].

Low aspect ratio operation has important implications on the critical issues of the PF systems. The objectives of the PF magnet work in ARIES-ST are to review conventional magnet design with conventional materials, in an application where the divertor coils are located inside the toroidal field coils. In addition to the design of the divertor and ring coils, this paper presents options for the design of the current leads to the divertor coils. The current leading to these coils needs to travel through the toroidal field, and therefore experiences large Lorenz forces. Methods of minimizing the cryogenic loads to the divertor coils by the use of high temperature superconducting leads are also described.

This paper also provides details on the formalism utilized by the systems code to evaluate the options and to provide detailed engineering calculations of the critical issues. The cost of the PF magnet, an item that has an impact on the cost of a tokamak reactor, is analyzed. Improvements on the magnet design and construction that could result in decreased cost of the PF magnet have also been investigated.

Material issues are described in Section 2. The engineering design criteria used for the PF system design for ARIES-ST are described in Section 3. The PF scenarios are described in Section 4. Section 5 presents the engineering details of the design. The current leads are described in Section 5.2. The cost assumptions for the PF systems are described in Section 6. The detailed bottom-up costing model was developed for a one-of-a-kind system, without the benefits of tenth-of-a-kind that the ARIES-ST is predicated upon. Likely impacts of a learning curve on the costing are made at the end of that section.

The work presented in Sections 4–6 is relevant to plasmas with low ‘squareness.’ The impact of

the high ‘squareness’ on the PF design are presented in Section 7.

Section 8 summarizes the results of the ARIES-ST PF magnet-engineering study, including remaining critical issues.

The parameters of the detailed analysis are slightly different from those chosen for the final design point. However, it is not expected that the minimal variations between the case investigated and the final design point produce significant differences in the conclusions of this study.

2. Materials

The materials assumed for the PF coils in this study are presently commercially available. Improved manufacturing techniques and reproducibility are assumed. Incorporating these materials and improved design concepts into PF magnets suitable for a commercial tokamak reactor is still a difficult challenge. The reference ARIES-ST design uses a multifilamentary ternary Nb₃Sn for the high field divertor coils inside of the toroidal field coil, combined with NbTi ring coils in the outer regions of the reactor. The value of the peak field in the PF system is 15.5 T at the divertor coil, somewhat higher to that of ITER [7]. Only isotropic structural materials (such as 316 SS and Incoloy 908) have been considered.

The superconducting materials in the design of the PF system are NbTi and Nb₃Sn filamentary superconductors. High- T_c materials do not meet the stipulated level of development/commercialization assumed in this study. Although rapid progress is being made in developing materials and techniques to turn HTS into practical conductors, the materials that are closest to commercial availability today require refrigeration to 4 K and therefore offer marginal advantages over the more developed NbTi and Nb₃Sn.

NbTi is easy to produce in multifilamentary cables and its ductility simplifies magnet fabrication. It has a critical temperature, T_c , of 10 K, and an upper critical field of 14 T. At 4.2 K, it has an operational limit of about 8 T. Although this is not sufficient for the divertor coils, NbTi can be used in the low-field coils of the PF.

A ternary compound Nb_3Sn (Ti) [8] was utilized in the design for fields higher than 8 T. Numerous techniques exist for producing binary and ternary Nb_3Sn , and each technique attempts to provide good mixing between the Nb and the Sn and high-temperature ($\sim 700^\circ\text{C}$) heat treatment for growth of the superconducting phase. Critical properties H_{c2} , T_c , and $J_c(B)$ (critical current density) vary with ternary additions and processing.

Any high-field magnet system experiences very large forces resulting from the Lorentz interaction between the current and the magnetic field. The choice of options for structural materials considered in this work is limited to the stainless steels (in particular, 316LN [9]) and Incoloy 908 [10]. These materials have been extensively studied for cryogenic magnet applications.

The Incoloy has the added advantage of requiring a heat treatment that is compatible to the heat treatment of the Nb_3Sn [10]. The material is relatively soft prior to heat treatment, facilitating manufacturing of the conductor, and becomes stronger with the heat treatment process. The disadvantage of the Incoloy 908 is its cost. The possibility of using SS-316 was analyzed due to its larger database and substantially reduced cost [9].

The clearly superior advantage of the Incoloy 908 over 316LN is the increased compatibility with the Nb_3Sn . This is due to comparable thermal contractions from high temperature to 4 K [10]. Evidence indicates increased superconducting properties of the cable by its use. This is the material of choice for the conduit.

3. Poloidal field system design criteria

The PF magnets are responsible for forming and shaping highly elongated plasmas during the startup, burn pulse and shut-down. In ARIES-ST the divertor PF coils need to be inside of the TF system in order to decrease the coil currents to reasonable values. Preliminary calculations with an external PF system required divertor coil currents about 3 times larger than those resulting if the divertor coils are placed inside the TF coils. Since these coils are high field and high current

density, they are designed using internally cooled, cable-in-conduit conductors of ternary Nb_3Sn , as in ITER [11]. Ternary Nb_3Sn is favored over binary because it has higher temperature margins even at the lower fields. NbTi is used in order to decrease the cost of the large ring coils which have relatively low fields.

In ARIES-ST, as opposed to the PULSAR study [4], the PF system is not designed to provide full ohmic initiation and startup, only to provide equilibrium and shaping of the plasma during the transients and the flat-top part of the cycle.

Design allowables for the superconducting PF magnets, similar to those assumed during the ARIES study, are listed in Table 1 along with suggested additional constraints on energy and power balance criteria for recovery from disturbances. The ARIES-ST PF system design follows the ITER recommendations, with the exception that the Tresca membrane allowable stress in the structure is 800 MPa for ARIES-ST. The lower tensile stress limit for ITER is due to fatigue crack-growth limits for pulsed tokamak operation. The ARIES-ST PF coils are more conservative than those of ITER as they are also designed for energy margins $> 0.5 \text{ J/cm}^3$ and fractions of critical current in the well-cooled recovery regime.

In Table 1, f_{critical} is the maximum allowable ratio of conductor current to the critical current, $f_{\text{well-cooled recovery}}$ is the maximum ratio of conductor current to the current at the transition point between well-cooled and ill-cooled behavior during recovery from a disturbance, $T_{\text{max,dump}}$ is the maximum permissible temperature in the winding pack following a coil dump (K), T_{margin}

Table 1
PF-magnet constraints used for ARIES-ST design

V_{terminal} (kV)	20
I_{cond} (kA)	50
B_{max} (T)	15.5
$\sigma_{\text{Tresca membrane}}$ (MPa)	800
f_{critical}	0.7
$T_{\text{max,dump}}$ (K)	150
T_{margin} (K)	1.0
E_{margin}^a (J/cm^3)	0.5–1.0
$f_{\text{well-cooled recovery}}^a$	0.8

^a Suggested values.

is the minimum permissible temperature difference between the local conductor temperature and the current-sharing temperature during a scenario (K), and E_{margin} is the minimum permissible local energy margin, defined as the volumetric energy needed to be deposited anywhere along the conductor that would raise the local helium reservoir temperature to the current-sharing temperature (J/cm^3).

Forced-flow, internally cooled cables have two recovery regimes. In the well-cooled regime, almost the entire local enthalpy of helium in the conduit at constant density, between the bath temperature and the current-sharing temperature, is available for conductor recovery.

The design approach to ARIES-ST is such that it should be able to absorb the losses, forces, and voltage transients from a disruption without resulting in quenching of the PF magnets.

In order to decrease the cost of the PF system, the copper required for quench protection is removed from the superconducting strands. Instead, normal conducting copper strands are co-wound with the superconducting strands. The amount of superconductor and stabilizer in the conductor is small compared with the amount of copper required for quench protection. The cost of the magnet system can be substantially decreased by this approach.

4. Poloidal field scenarios

Fig. 1 shows the plasma shape and the PF coils for the case of ARIES ST. The divertor coils are internal to the TF coils, while the rest of the equilibrium system are outside the TF coil.

For the present design, only one equilibrium in the scenario was developed. Therefore, the startup and shut-down transients in the PF system have not been investigated, but since the machine is steady state, the transients due to normal events should not change the picture much, as long as coil currents during the startup and shut-off transients do not substantially exceed their flat-top values. The effect of disruptions during the flat-top phase have been calculated, both assuming current conserving and flux conserving assumptions. The

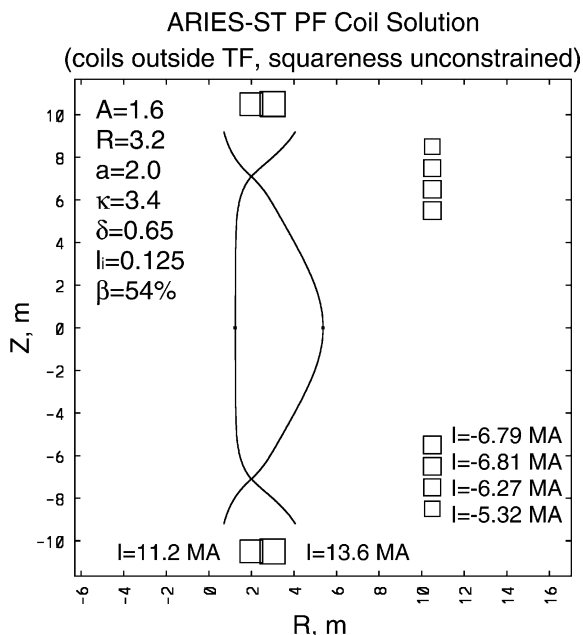


Fig. 1. Equilibrium field parameters for steady-state plasma with low squariness and non-divertor PF coils external to the TF coil.

fractions of critical current are calculated at the flat-top point in the scenario; the effects of strain in the superconductor are taken into account. Critical fractions and margins are also recalculated after disruption simulations.

In Table 2, the PF currents for the flat-top are shown. Since the plasma and the PF system are up-down symmetrical, only the current for the coils located above the midplane (upper coils) are shown.

The PF coil geometry for the design point is described in Table 3. R and Z are the major radius

Table 2
Currents in PF coils from ARIES-ST flat-top used for calculations (in MA)

PF1U	−14.6
PF2U	−15.5
PF3U	8.39
PF4U	8.28
PF5U	6.78
PF6U	3.51
Plasma current	−32
Flux linkage (V s)	61.9

Table 3
ARES-ST PF-system winding-pack and plasma dimensions (m)

Coil	R	Z	R_1	R_2	Z_1	Z_2
PF1U	2.0	10.5	1.72	2.27	10.22	10.77
PF1L	2.0	−10.5	1.72	2.27	−10.77	−10.22
PF2U	3.0	10.5	2.73	3.27	10.23	10.76
PF2L	3.0	−10.5	2.73	3.27	−10.76	−10.23
PF3U	10.5	8.5	10.23	10.76	8.23	8.76
PF3L	10.5	−8.5	10.23	10.76	−8.76	−8.23
PF4U	10.5	7.5	10.23	10.76	7.23	7.76
PF4L	10.5	−7.5	10.23	10.76	−7.76	−7.23
PF5U	10.5	6.5	10.26	10.73	6.26	6.73
PF5L	10.5	−6.5	10.26	10.73	−6.73	−6.26
PF6U	10.5	5.5	10.32	10.67	5.32	5.67
PF6L	10.5	−5.5	10.32	10.67	−5.67	−5.32

Table 4
ARIES-ST conductor characteristics

Coil	Superconductor	n_{pancakes}	n_{layers}	n_{turns}	n_{strands}	D_{strand} (mm)	P_w (m)
PF1U, L	Ternary tin	18	18	324	675	1.12	1.99
PF2U, L	Ternary tin	19	19	361	675	1.02	1.80
PF3U, L	NbTi	13	13	169	1125	1.16	3.41
PF4U, L	NbTi	13	13	169	1125	1.11	3.29
PF5U, L	NbTi	12	12	144	1125	1.15	3.40
PF6U, L	NbTi	8	8	64	1125	1.15	3.41

and height of the coil centroid, R_1 and R_2 are the minimum and maximum major radii, Z_1 and Z_2 are the minimum and maximum heights, respectively. The plasma is up–down symmetric.

5. Poloidal field system design

The winding pack dimensions are given in Table 3, and are schematically shown in Fig. 1. The winding characteristics of the PF system are described in Table 4.

The conductor type of the different coils has been optimally determined for each coil. The higher field coils are made of ternary tin. The large ring coils are made of NbTi. The number of pancakes per coil, n_{pancakes} , and the number of layers in the pancakes, n_{layers} , are chosen in order to set the pack current in each of the coils to about

Table 5
ARIES-ST conductor composition and helium fraction

Coil	f_{He}	$f_{\text{Cu,pure}}$
PF1U, L	0.2	0.38
PF2U, L	0.32	0.63
PF3U, L	0.56	0.65
PF4U, L	0.56	0.66
PF5U, L	0.56	0.65
PF6U, L	0.47	0.70

50 kA. n_{turns} is the number of turns in the coil. D_{strand} is the strand diameter. P_w is the wetted perimeter of the strands. It has been assumed that the resistivity resistance ratio is 100 for the copper stabilizer for all the PF coils. The filament diameter is 10 μm for the ternary tin superconductor, and 5 μm for the NbTi. The effective

Table 6
ARIES-ST winding geometry

Coil	W_{conduit} (mm)	h_{conduit} (mm)	$A_{\text{cu,cond}}$ (mm ²)	A_{noncu} (mm ²)	$A_{\text{ss,cond}}$ (mm ²)	$A_{\text{He,cond}}$ (mm ²)	A_{condenu} (mm ²)
PF1U, L	30.6	30.6	377	169.6	322	128	998
PF2U, L	27.8	27.8	305	69.3	277	176	829
PF3U, L	40.1	40.1	431	91.6	501	666	1691
PF4U, L	38.7	38.7	403	82.5	472	618	1576
PF5U, L	40.0	40.0	429	91.2	499	663	1684
PF6U, L	40.0	40.0	533	94.2	500	556	1685

cross-conductance length is 20 mm for all the conductors.

The helium fraction f_{He} and the fraction of the strands that are pure copper $f_{\text{cu,pure}}$ are shown in Table 5. The value of $f_{\text{cu,pure}}$ was determined separately for each coil. For final design, the helium fraction needs to be provided by varying strand diameter (making some of the pure copper strands of different size to adjust the conductor fraction). This could also allow the flexibility of arbitrarily selecting the pure copper strand to superconducting strand fractions. The cabling process needs to be altered to satisfy this requirement. The wetted perimeter would increase in the case of decreasing the diameter of the pure copper strands, increasing the conductor stability.

The coils PF3–PF6 have large He fraction. It is possible to decrease the size of the coils, which will decrease the He fraction. However, since neither these coils are critical to engineering nor does the large He fraction have an impact on the cost, these coils were not fully optimized.

The corresponding conductor geometry is shown in Table 6. W_{conduit} and h_{conduit} are the width and height of the conduit for each of the PF coils. $A_{\text{cu,cond}}$, A_{noncu} , and $A_{\text{ss,cond}}$ correspond to the copper, non-copper (i.e. superconductor), and steel cross-sectional areas of the conductors of each PF coil. $A_{\text{He,cond}}$ is the corresponding He cross-sectional area, and A_{condenu} is the overall area of the conductor. The number of pure copper strands in the conductor as well as the helium fraction are determined for each coil separately.

The current maxima for each of the PF coils is shown in Table 7. Only one point was used in the design, and therefore one of the extrema is 0 for all

Table 7
Peak currents in PF coils

Coil	$I_{\text{cond,max}}$ (kA)	$I_{\text{cond,min}}$ (kA)
PF1U	0.0	−47.4
PF2U	0.0	−45.1
PF3U	50.9	0.0
PF4U	47.3	0.0
PF5U	50.6	0.0
PF6U	50.5	0.0

cases. Using 50 kA current in the coils decreases the amount of stabilizer required for quench protection and minimizes the cost of the winding process. Larger currents would require more expensive bus and power supplies. The size of each conductor is adjusted in order to limit maximum current in each coil to about 50 kA.

The peak values of the magnetic field in each coil are shown in Table 8. The peak fields on the PF1 and PF2 are above 10 T. PF1 and PF2 are manufactured with ternary superconductor. PF3 through PF6 have substantially lower fields, and they use NbTi in order to minimize the cost of the system.

As mentioned above, PF1 and PF2, U and L (upper and lower), are inside of the toroidal field

Table 8
Peak field flux (T) on PF coils

PF1U, L	15.5
PF2U, L	10.7
PF3U, L	7.8
F4U, L	7.2
PF5U, L	6.6
PF6U, L	5.6

magnet. As a consequence, the effective magnetic field on the coils consists of the vector addition of the toroidal and the PF fields. The maximum PF for PF1 and PF2 are 15 and 10.3 T, respectively. To this, it is necessary to add the toroidal field. For the design case, the toroidal field is 3.7 and 2.1 T at the location of the highest PF fields in PF1 and PF2, respectively. The maximum field in PF1 and PF2 shown in Table 8 refers to the maximum total field.

The performance of the PF system is shown in Table 9. f_c represents the ratio between the superconductor current to its critical current. The value listed in Table 9 is the maximum value for a given coil, after the worse location on each coil has been identified. This ratio should be less than about 0.7. $Q''_{\max}$ is the critical heat flux from the conductor to the helium bath. f_{tr} is the ratio between the conductor current and the transition current beyond which the critical energy (energy required to drive the superconductor to the current sharing condition) decreases dramatically. ΔT_{head} is the maximum temperature excursion between the operating temperature and the current sharing temperature where the conductor current exceeds the critical current. Similarly, $E_{\text{mar,min}}$ is the energy needed to raise the temperature of the helium bath to the current sharing temperature. $f_{J\text{prot}}$ is the ratio between the actual conductor current and that resulting in a final conductor temperature of 150 K (after a 20 kV dump).

Each of the parameters in Table 9 is calculated along the conductor for each coil, and the entry in the Table is the value of the extrema (maximum or minimum) that is most limiting.

5.1. Poloidal field structural analysis

The average hoop, axial, and Tresca membrane stresses in the conductor conduit were calculated at each point along the conductor in each coil, for the flat-top conditions.

The goal of the design is for all PF magnets to be self-supporting against tensile loads. Obviously, the vertical loads need to be transferred to an external structure. In the case of PF1 and PF2, the external structure is the TF coil. It is necessary to allow the PF coils to move radially with respect to the TF coil, and this is achieved by placing the PF coils in a structural box, and using low coefficient of friction materials at the interface, which is at room temperature. The radial sliding results in minimal heat generation at the low temperature, and care must be taken to intercept the heat before it reaches the PF coil conductor. In order to do this, electrically insulating high thermal conductivity radial shims are used. These shims are made of thin wires in the radial direction, embedded in an insulating matrix. The small size of the conductor minimizes AC losses. Preliminary calculations indicate that it is possible to remove from a 1 mm thick shim (50% high thermal conductivity in a insulating matrix) as much as 10 kW/m³ (10 mW/cm³), or about 5 W/m² (0.5 W/cm²) for a temperature increase of about 0.25 K). The heat transfer rate is dominated by the conduction through the high thermal conductivity material, rather than across the thin insulating layer. For the above assumed conditions, the heat transported along the radial thermal shorts is 25–50 times larger than the thermal transport across the shims.

Table 9
ARIES-ST PF superconductor performance

Coil	f_c	$Q''_{\max}$	f_{tr} (W/cm ²)	ΔT_{head} (K)	$E_{\text{mar,min}}$ (J/cm ³)	$f_{J\text{prot}}$	E_{coil} (MJ)
PF1U	0.68	0.18	0.78	3.13	1.09	0.43	0.30
PF2U	0.67	0.14	0.54	6.02	4.21	0.73	0.27
PF3U	0.73	0.03	0.76	1.16	0.40	1.00	0.19
PF4U	0.59	0.03	0.65	1.46	0.58	1.08	0.17
PF5U	0.47	0.03	0.58	1.73	0.91	0.92	0.14
PF6U	0.35	0.02	0.45	2.14	0.98	0.48	0.06

Table 10
ARIES-ST PF superconductor loads and required structure

Group	F_r/m (MN/m)	F_z/m (MN/m)	F_z (MN)	A_{struts} (m ²)	δ_{strut} (m)	σ_h (MPa)
PF1U, L	88.4	1.5	18.8	0.047	0.0037	571
PF2U, L	−15.3	2.6	48.4	0.121	0.0064	−158
PF3U, L	9.1	−21.6	−1427.5	−3.569	−0.0541	343
PF4U, L	9.5	−1.2	−80.0	−0.200	−0.0030	364
PF5U, L	7.6	10.8	714.8	1.787	0.0271	354
PF6U, L	3.6	8.7	574.6	1.436	0.0218	321

The loads on all the PF coils are shown in Table 10. Only one equilibrium, the long burn was analyzed. The forces resulting from a current conserving disruptions (the plasma current is zero, but the currents of the PF coils do not vary) are shown in Table 11. The current conserving case occurs when the power supplies control fails and the coil currents are kept constant while the plasma current vanishes. This case is an extreme assumption, but the results are usually conservative.

Shown in the tables are the vertical and radial forces per meter and the net vertical force. It is interesting to note that the loads during current conserving disruption do not vary substantially from those during normal operation. It is possible that the loads in PF1 and PF2 increase during a disruption, since PF1 and PF2 are relatively well-coupled to the plasma, and their currents are in the same direction. The structural implications of this case was not analyzed.

The radial loads, assuming that the coils are self-supporting, are shown in Tables 10 and 11. The hoop stresses in the coils, assuming that the coils are self-supporting against the radial loads, are

also shown in both tables. All the external coils can self-support the radial load, even assuming that the superconductor does not share the tensile load.

The possible exception are PF1 and PF2. The tensile hoop stresses are high for PF1, and the radial loads in PF2 are negative, resulting in compression of the coil, instead of tension. Compressive forces are difficult to support, as they could result in buckling. The best manner to support the loads in PF2 is to transfer them to PF1, simultaneously reducing the tension in PF1. The force can be transferred using radial struts, which are loaded in compression. The stresses in PF1 are decreased to about 400 MPa, which is a value that can brings the PF1 loads to a value that is comparable to those of the external coils.

The vertical forces of the internal coils, PF1 and PF2, need to be supported by the toroidal field coil, since there is no other structure around. The magnetic loads dominate over the gravitational loads. PF1 and PF2 weigh ~ 260 and 360 kN, respectively. Shown in the tables are the required areas of struts, A_{strut} needed to transfer the loads to the TF coil, when loaded to 400 MPa. Also

Table 11
ARIES-ST PF vertical and radial loads during current conserving disruption

Group	F_r/m (MN/m)	F_z/m (MN/m)	F_z (MN)	A_{struts} (m ²)	δ_{strut} (m)	σ_h (MPa)
PF1U, L	86.4	2.0	25.6	0.064	0.0051	558
PF2U, L	−17.1	3.3	62.9	0.157	0.0083	−177
PF3U, L	9.2	−22.1	−1459.2	−3.648	−0.1553	346
PF4U, L	9.6	−1.7	−115.1	−0.288	−1.0044	365
PF5U, L	7.6	10.4	683.0	1.707	0.0259	353
PF6U, L	3.5	8.4	557.2	1.393	0.0211	315

shown are the required strut thickness, δ_{struct} , assuming that the strut is a uniform shell located at the major radius of the coil, and operating at a stress of 400 MPa. The thickness of the uniform shell strut is about 1 cm, if a single one is used to transfer the loads from both PF1 and PF2. The support is not a critical issue for the design. Neither is maintenance, since it is assumed that the PF coils are life-time components and therefore PF1 and PF2 can be directly attached to the aluminum shell TF coil.

The vertical loads of the external PF coils are large. They can be supported by a shell-type structure. As is the case for the internal coils, the thickness required for the shell has been determined assuming that the stresses in the shell are 400 MPa. The resulting thickness is also shown in [Tables 10 and 11](#). The negative values are used to indicate that the respective loads result in compression of the support shell. The compressive loads of PF3 and PF4 add up and are about the same value as addition of the tensile loads of PF5 and PF6. Because of this there is little forces that need to be carried out from the upper to the lower sets of coils, minimizing the structure required between PF6U and PF6L and simplifying the assembly of the system. These loads and resulting thicknesses have been calculated assuming normal operation. Off-normal load conditions may actually drive the structural requirements. Structural responses due to off-normal events have not been calculated.

It should be noted that the vertical loads in PF3U–PF6U approximately cancel each other. Therefore, the thickness of the shell at the midplane can be made small, in so far as the normal and disruption cases analyzed indicate. It is possible, if desired, to physically separate the upper coils' structure from the lower coils' structure, and connect them through locks, as in the ALCATOR C-MOD structure. This would minimize the height of the component, since a single unit would be more than 23 m tall.

5.2. Current leads

In ARIES-ST, the PF is substantially larger than the toroidal field at the location of the coils.

An issue that needs to be addressed is the current leads for the PF1 and PF2 coils, which are internal to the toroidal field coil. These leads are the subject of large loads due to the interaction of the current with the toroidal magnetic field and with the self-fields.

The optimal location of the leads is limited to regions where the loads are easily manageable. For PF1, the leads are connected to the coil at the outer coil midplane. At this location, the PF is only about 2 T, mainly in the vertical direction. The toroidal field is around 3 T at this location.

For PF2, the location on the coil with minimum PF is located at the inner radii where it is around 8 T. The corresponding toroidal field is ~ 2 T. The field is not much larger elsewhere (10 T at the top, bottom and outer walls). Joints between pancakes should be performed at the inner radii.

Coaxial, normal conducting feed lines are used to bring the current to the PFs coils. Using coaxial lines eliminates the net force interacting on the leads. However, high voltages are present, especially during coil dumps.

The solution proposed for ARIES-ST is similar to the current feedthrough for the central solenoid in ALCATOR C-MOD [\[15\]](#). In this machine, the solenoid is located within the toroidal field, at fields approaching 17 T. The ALCATOR C-MOD has been designed for a peak central solenoid conductor current of about 50 kA similar to the maximum value of the current for PF1 and PF2. And the peak voltage, required for fast initiation, is on the order of 20 kV, similar to the maximum voltage in the PF system during the dump following a quench.

By using normal conducting leads and placing the normal-to-superconducting joint close to the PF coils, it is possible to place an additional normal joint near the coil, facilitating machine assembly.

High temperature superconducting leads are used to transition the current between the normal conductor and the superconductor. The background field (3.5 T for PF1, 8 T for PF2) is shielded from the high- T_c current leads to increase the superconducting current density and therefore minimize the required cross-sectional area and the associated thermal load of the superconductor. It

is possible to shield the HTS current lead by surrounding the HTS current leads with a high temperature superconductor monolith [12].

The HTS monolith can be made of BSCCO 2212 material, which when operating at a temperature of 20 K has a critical current of about 10 kA/cm², relatively independent of field [13]. Therefore, a 0.5-cm thick shell of BSCCO can shield about 1 T. For PF1, the thickness of the monolith needs to be about 2 cm, while for PF2 the thickness increases to 4 cm. The HTS monolith can be segmented in several shells, facilitating manufacturing, assembly, and support.

Optimized HTS current leads decrease the heat leak to about 0.1 W/kA per transition. Since the current in the coils is about 50 kA, the heat loads per coil associated with the current leads is 10 W, a small value [14].

6. Poloidal field costing

The PF costs were determined according to the cost algorithm developed by J. Schultz for superconducting magnet costing [16]. These algorithms are sufficiently detailed and realistic to correctly take into account the amount of superconductor, stabilizer, structure, insulation, and the complexity of winding and assembly. These algorithms need to be modified to take into account tenth-of-a-kind costing, as opposed to first-of-a-kind such as ITER. This is done at the end of this section.

The cost is determined from a bottom-up estimate, with models for the cost of the superconductor, conductor manufacturing, assembly, and manufacturing of the PF coils. As many characteristics of the PF system are analyzed as practical, including superconductor type, number of independent pure copper strands (for quench protection), material of the conduit, and structural material.

The costing code was used to determine the cost of the PF system in ARIES as well as the dependence of the cost on the main design parameters of ARIES-ST. Table 12 shows the cost of the conductor for all the PF coils. There are two coils in each set of coils. The number shown in this table and in the following ones is the cost per coil.

As will be shown in the next few tables, the cost of the strands is a small fraction (about 12%) of the cost of the PF coils winding pack. Although the coils PF1 and PF2 are made of more expensive Nb₃Sn conductor, the cost is dominated by the much larger coils PF3–PF6. The cost of the conductor for the PF coils about doubles when NbTi is replaced by Nb₃Sn in these coils. The ring coils also have larger fraction of superconductor material (lower fraction of pure copper strands). The cost of the additional superconductor is more than made up by the use of a cheaper superconductor.

PF1 and PF2, made of Nb₃Sn conductor, are costed assuming that the coils are using ‘react and wind’ method.

The cost of the winding pack (i.e. the actual PF assemblies) is shown in Table 13. The manufacturing cost of the coils is comparable to the cost of the conductor. Only the fraction of the cost that is value-added experiences a learning curve. Learning curves have been applied to value-added items, both in Tables 12 and 13. Table 14 shows the final cost of the coils, including supports, engineering, and other indirect costs. The minimized direct cost of the PF system is, then, about \$190 M, with a total cost (direct plus indirect) of \$290 M. Since the mass is about 800 tonnes, then the total cost of first-of-a-kind PF coil system is about \$380/kg. This cost is substantially higher than in the case of PULSAR [4] or ARIES-RS [5]. The cost of the PF coils with Nb₃Sn are comparable per unit weight to those in PULSAR, at around \$800/kg. However, the cost of the NbTi coils in ARIES-ST is substantially higher than in PULSAR. This is because of the higher fields in ARIES-ST require a higher superconductor ratio in the winding, by about one-third, resulting in a higher unit cost for the coils (since it is using a higher fraction of more expensive materials).

In the total for each entry, an additional small value for administration and operating expenses has been added. The values of engineering and contingency are substantially larger in the methodology described in Ref. [16] than what the ARIES-ST systems study assumes. The relevant charge for the system code, direct charges prior to

Table 12
ARIES-ST PF system conductor costs (in M\$)

Coil	Strands	Coat	Cable	Waste	Sheath	Encapsulation	Additional material	Conductor Sub.
PF1U, L	4.9	0.3	0.7	1.5	0.2	0.2	0.0	7.7
PF2U, L	3.6	0.5	1.1	1.3	0.2	0.3	0.1	7.0
PF3U, L	1.3	0.7	1.5	0.9	0.7	0.4	0.1	5.7
PF4U, L	1.3	0.7	1.6	0.9	0.7	0.4	0.1	5.7
PF5U, L	1.1	0.6	1.2	0.7	0.6	0.4	0.1	4.6
PF6U, L	0.5	0.3	0.6	0.4	0.3	0.2	0.1	2.4
Total PF	25.4	6.0	13.6	11.3	5.3	3.7	0.9	66.3

indirect charges, are shown in Table 16 (after the effect of a learning curve has been included).

The bottom-up total cost scaling is shown in Table 15. These are total costs using first-of-a-kind and today's technology. These equations are intended for a device like ITER, a first-of-a-kind experimental reactor.

6.1. Learning curve effects on costs

The ground rule adopted by the ARIES team is that the value-added capital costs will be observing a 75% learning curve on the unit cost. The cost of value added PF tenth-of-a-kind component is reduced by $10^{\ln(0.75)/\ln(2)} \sim 0.385$ [17].

The costs of the strands is a small fraction of the cost of the PF coils. The costs of NbTi is well-established. However, it is assumed that the cost of the Nb₃Sn will decrease from about \$1000/kg to

about \$250/kg, with improved manufacturing and Q&A techniques.

The costing of the PF system is shown in Table 16. The first-of-a-kind costing repeats the results presented above, in 1998 \$M dollars. Two types of scaling are used in the Table. IM means improved method of fabrication. This is the case for the strands. LCE stands for learning curve experience, and as mentioned above, 0.385 multiplier is used.

The cost of engineering for the tenth-of-a-kind has been arbitrarily decreased to zero. Clearly, the engineering will be much smaller than for the first few, but after the problems and the process has been identified, the need for engineering is to maintain the processes, rather than to develop them.

The direct cost of the PF system is decreased from \$190 to \$65M. Adding contingency and PACE, the cost increases to about \$72M, down from \$290M. The specific unit cost is decreased

Table 13
ARIES-ST system winding pack costs (M\$)

Coil	Conductor	Insulator	Tooling	Winding	Dummies	Heat	Leads	Total winding pack
PF1U, L	7.7	0.4	0.5	3.3	0.2	0.2	0.1	12.3
PF2U, L	7.0	0.3	0.5	4.3	0.2	0.2	0.1	12.6
PF3U, L	5.7	0.1	0.3	5.5	0.9	0.0	0.1	12.5
PF4U, L	5.7	0.1	0.3	5.4	0.8	0.0	0.1	12.5
PF5U, L	4.6	0.1	0.3	4.4	0.8	0.0	0.1	10.3
PF6U, L	2.4	0.0	0.2	2.6	0.6	0.0	0.1	6.0
Total PF	66.3	2.2	4.2	50.9	7.1	0.7	1.2	132.6

Table 14
ARIES-ST total PF system costs (\$M)

Coil	Winding Pack	Support	Engineering	Hardware and engineering	Contingency	PACE direct	OPEX	G&A	Total
PF1U, L	12.3	0.6	3.7	16.6	4.9	21.4	1.9	0.7	24.1
PF2U, L	12.6	0.9	3.8	17.3	5.1	22.4	2.0	0.8	25.1
PF3U, L	12.5	2.6	4.4	19.4	5.8	25.2	2.3	0.9	28.4
PF4U, L	12.5	2.6	4.4	19.4	5.8	25.2	2.3	0.9	28.3
PF5U, L	10.3	2.1	3.6	16.0	4.8	20.7	1.9	0.7	23.3
PF6U, L	6.0	1.1	2.0	9.1	2.7	11.8	1.1	0.4	13.3
Total PF	132.6	19.4	43.6	195.6	58.0	253.6	22.6	8.7	285.0

from \$380/kg for first-of-a-kind to \$80/kg for tenth-of-a-kind. It should be noted that \$100/kg was used in the previous ARIES studies for performing calculations of the PF system.

7. Poloidal field implications of high squareness plasmas

In order to obtain the large values of plasma β used in the study, a high value of the plasma ‘squareness’ is desired. The base case PF system that has been analyzed in this paper and in the ARIES-ST studies, generated a relatively low value of the squareness of the plasma. In this section, the implications of the increased squareness on the PF system are described.

Table 17 shows the currents on the PF coils for both the high and low values of squareness. The coils are located either at the same height as the innermost coils (with varying radii), or are at the outermost radii (and varying height). The coil loci

is therefore along a rectangular grid. The number and location of the coil has not been optimized. The PF system with low squareness is similar to the one analyzed previously in this paper, with divertor coils on the order to 10–15 MA, and modest external coils. However, the number of coils is much larger than necessary, and has been chosen to directly compare with the case of higher squareness, also shown in Table 17. In the case of high squareness, the current in the PF system increases dramatically, with single coil currents in some cases on the order of 40 MA. In order to provide for the shaping requirements, the divertor coils need to increase substantially. The current in the divertor coils (coils 1 and 2 in Table 17) are bucked by currents in the coils 3 and 4, located closely to the divertor coils but outside the toroidal field coil. The net current of the coils in the upper region of the plasma does not change much between the two cases, but the actual currents are much larger than in the case with lower squareness.

Table 15
Total cost related parameters

Coil	Coil current		Mass of winding pack (tonnes)	Unit cost		
	(MA m)	(MA m T)		(\$/kA m)	(\$/kA m T)	\$/kg
PF1U, L	185.2	2818	27	127.8	8.3	857
PF2U, L	298.2	3208	35	83.0	7.7	697
PF3U, L	553.5	4338	91	51.0	6.5	309
PF4U, L	546.2	3948	90	51.6	7.1	311
PF5U, L	447.3	2956	73	51.8	7.8	313
PF6U, L	231.5	1295	42	57.2	10.2	311
Total PF	4524.1	37 133	782	65.4	7.9	378

Table 16
Impact of experience on PF system costs (1998 \$M)

Operation/material	First-of-a-kind	Scaling	Tenth-of-a-kind
<i>Conductor</i>			
Strands	25.4	IM	12.7
Coat	6.0	LCE	2.3
Cabling	13.6	LCE	5.2
Waste	11.3		0.0
Sheath	5.3	LCE	2.0
Encapsulation	3.7	LCE	1.4
Additional material	0.9		0.0
Conductor subtotal	66.3		23.8
<i>Winding pack</i>			
Insulation	2.2	LCE	0.8
Tooling	4.2		0.0
Winding	50.9	LCE	19.0
Dummies	7.1		0.0
Heat treatment	0.7	LCE	0.3
Leads	1.2	LCE	0.4
Winding pack subtotal	132.6		44.9
Support	19.4	LCE	7.5
Engineering	43.6		0.0
Hardware and engineering	195.6		52.4
Contingency	58.0	20%	10.4
PACE direct	253.6		62.9
PACE G&A	22.6	10%	6.3
OPEX	8.7		0.0
<i>Total</i>	285.0		69.2

In order to obtain the high squareness required, the case of internal PF coils was preliminarily investigated. The divertor coils, coils 1 and 2, have been assumed internal in the base case. The rest of the PF system was also brought inside the toroidal field coil.

Fig. 2 shows results from equilibrium calculation for the case of high squareness plasma, using PF coils internal to the TF coil.

The current distribution, with only nine coils, is given in Table 18. The height of the divertor coils has been decreased, decreasing the distance from the coils to the plasma. This was done to take advantage of the larger engineering current density in the coils (that makes them smaller). In the equilibrium calculations, it had been assumed that

Table 17
PF coil currents for conventional and high squareness parameter (ζ)

Coil no	R^a (m)	Z^a (m)	$\zeta = -0.15$	$\zeta = 0.1$
1	2	10.5	10.01	48.26
2	3	10.5	12.00	15.74
3	4	10.5	9.05	-26.82
4	7	10.5	-0.99	-13.72
5	8	10.5	-2.12	-3.92
6	9	10.5	-2.57	0.89
7	10.5	10.5	-2.59	2.94
8	10.5	9.5	-3.45	5.79
9	10.5	8.5	-4.27	8.26
10	10.5	7.5	-4.84	8.12
11	10.5	6.5	-4.9	2.91
12	10.5	5.5	-4.23	-7.17
13	10.5	4.5	-2.76	-16.14
14	10.5	3.5	-0.65	-13.35
15	10.5	2.5	1.73	7.96

^a Coil location is around the loci of a rectangle, as described in the text.

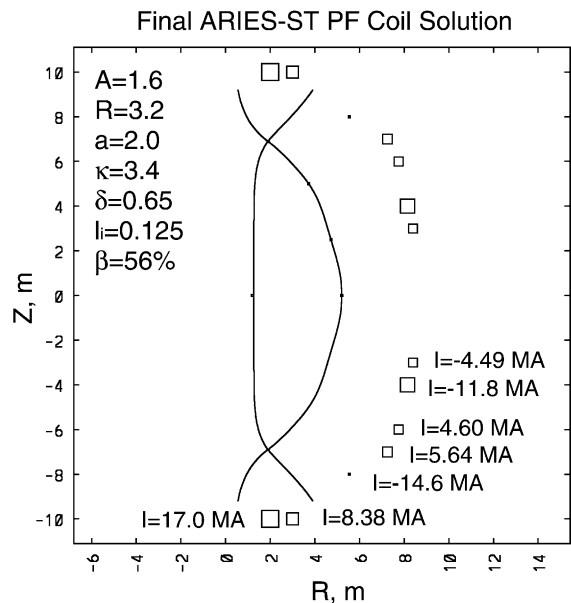


Fig. 2. Equilibrium field parameters for steady-state plasma with high squareness and PF coils internal to the TF coil.

the current density of these coils could be 20 MA/m², but it was found in the detailed engineering analysis above that the current could be increased to as much as 30 MA/m². The net current in the

Table 18

PF coil currents for high squareness, internal coils

Coil no.	R (m)	Z (m)	Coil current (MA)	Optimum coil current (MA)
1	2	10	10.55	12.7
2	3	10	9.35	10.1
3	5.5	8	−6.115	−7.71
4	5.6	7	−4.922	−3.32
5	6.15	6	3.508	3.88
6	6.6	5	0.458	Eliminated
7	8.15	4	−6.089	−9.08
8	8.4	3	−5.467	−3.99
9	8.55	2	0.75	Eliminated

divertor coils is smaller than in the base case with lower squareness with external non-divertor coils.

In this section, engineering analysis of this case will be presented. Only condensed results will be presented.

The coil currents for the case of optimized PF coils are also shown Table 18. The number of coils has not been optimized. These results are therefore serve as a guideline, and the optimal solution may be better.

In the design, the cross-section of the coil was determined assuming that the current density was 30 MA/m² for the divertor coils, and 50 MA/m² for the rest. With this assumption, the fraction of helium and the composition of the coils was determined, similar to Table 5. The performance criteria of the coils with this helium and composition was calculated, and is shown in Table 19. This table should be compared with Table 9 for the base case.

It should be noted that this system has high energy margins and temperature margins. This is a result of the large amount of helium in the system. The size of the coil was held constant, and the coils were filled with helium as the metal fraction (superconductor and normal conductor) of the coil was lowered to meet the design criteria given in Table 1. Clearly, the coil cross-section can be reduced by eliminating some of the helium, but this iterative process was not completed for the case of the internal PF coils.

The effect of the toroidal field on the peak field of the PF coils is small in the case when all the PF coils are inside the toroidal field. For the innermost divertor coils, with a peak PF of 12 T, the toroidal field is about 3 T and the total field is increased to about 12.5 T. For the other coils, the toroidal field is even lower and only has a marginal effect on the critical current of the superconductor.

Table 19

Superconducting performance of internal PF for high squareness plasma

Coil	f_c	$Q''_{\max}$ (W/cm ²)	f_{tr}	ΔT_{head} (K)	$E_{\text{mar,min}}$ (J/cm ³)	$f_{j\text{prot}}$	$B_{\max}$ (T)
PF1	0.618	0.1674	0.762	5.554	2.304	0.645	11.9
PF2	0.625	0.1005	0.526	7.686	3.723	0.795	8.2
PF3	0.603	0.0310	0.697	1.795	5.505	0.557	6.5
PF4	0.629	0.0277	0.671	2.083	8.469	0.615	5.8
PF5	0.617	0.0243	0.618	2.679	3.339	0.334	4.4
PF6	0.629	0.0179	0.500	3.544	5.330	0.208	2.5
PF7	0.632	0.0287	0.641	1.969	6.209	0.786	6.0
PF8	0.623	0.0271	0.623	2.184	7.998	0.839	5.5
PF9	0.644	0.0184	0.513	3.462	4.992	0.386	2.7

The costing of the internal PF system was also investigated. The first-of-a-kind costing was decreased substantially, with a direct cost of the PF system of \$110 M, as opposed to the base case, with a direct cost of \$190 M. The cost of the internal PF system, with a much more aggressive shaping requirements, decreases by about a factor of 2 when the PF system is moved closer to the plasma. Extrapolating these savings to tenth-of-a-kind, the cost of the PF system for the internal PF case is \$40 M.

8. Summary and conclusions

The critical issues of the poloidal systems for the ARIES-ST design have been presented in this paper. The implication to the PF system due to low aspect ratio operation has been investigated by performing a detailed analysis of one case.

A substantial difference in the requirements of ARIES-ST PF system from those of the ARIES study has to do with the large plasma current and the need of highly shaped plasmas. The divertor coils have to be placed inside the toroidal field in order to reduce their current. Even then, the divertor coils carry large currents.

In order to allow for high ‘squareness’ required for high plasma pressure, it is necessary to move even the non-divertor coils inside of the toroidal field coil. The implications of this option, which is the final design point of the ARIES-ST study, have been briefly described.

The PF coils are superconducting using internally cooled cable-in-conduit conductor. For the case of external non-divertor coils, the peak field in the PF system is ~ 15 T in the divertor coils, while it is 8 T in the ring coils, mainly because of the large self-fields in these coils. For the case of internal non-divertor coils, the peak self-field in the divertor coils is reduced to about 12 T, while the highest field in the non-divertor coils is about 6 T.

The PF magnets have built-in margins that are sufficient to survive disruptions without quenching, at least during the flat-top.

The costing study indicates that the specific cost of the PF system is \$80/kg.

There are outstanding issues with respect to the idea of segregating the copper for quench protection and the superconducting strands. These issues include the current sharing between the different superconducting strands and current transfer between the superconducting and normal conducting strands in the conductor plus further understanding of the ramp-rate limitations on the CICC.

Additional work needs to be completed to address unfinished issues. These issues include fault conditions and their effects on the PF coil system. Single PF coil failure, and effects of plasma disruptions on the PF system are areas that need substantial additional work.

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