RADICAL VISIONS FOR A VLHC

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Abstract

A parametric study is made of the costs of a Hadron Collider main ring (excluding intersection regions). "2-in-1" and "Pipeatron" magnet designs using different superconducting materials and cost assumptions are compared. A cost minimized "Minatron" design is described.

Contents

It is hoped, however that they are realistic enough to give reasonable qualitative dependencies of the amounts of superconductor, copper, iron and stainless steel required.

1 Introduction

This is a parametric study of dipole magnet designs and simple costing. The study dates originally to the SSC, and the unit costs are those derived from SSC costing. The totals quoted here are for a 20 + 20 TeV machine, but the figures should not be interpreted too strictly. A study of this type is not expected to provide actual costs. It is hoped, however, that the dependencies observed will be qualitatively correct, and can thus be used to suggest directions for further study.

The study presented here is an extension of the original SSC work, with emphasis on cost reduction by reducing beam apertures and simplifying the magnet designs. I am particularly indebted to Bill Foster, John Mariner, John Corlett, Brett Parker, Erich Willen and Ramesh Guppta; and I would like to thank Mike Harrison for persuading me to give this presentation.

2 Initial Input

2.1 Assumptions

2.1.1 Introduction

The following formulae are used to specify dipole magnet dimensions and materials used. The formulae are approximate and are not intended to give real designs. It is hoped, however that they are realistic enough to give reasonable qualitative dependencies of the amounts of superconductor, copper, iron and stainless steel required. Costs per mass, cold area, and total linear length were obtained from SSC estimates and used to calculate approximate costs of the differing magnet systems. The cost of quadrupoles, correction magnets, magnet unit costs (ends), tunnel, light and air, access, survey, stands and pickups are crudely estimated by adding a cost proportional to the total ring circumference. Since the formulae are interdependent, they are solved by iteration.

It is understood that the above method is far from accurate. It is an exercise, and should only be treated as such.

2.1.2 General

- Total length of dipoles:

$$Length_{dipoles} \quad = \quad 2\ \pi\ \frac{E}{c\ \ B}$$

- Ring circumference:

$$Length_{ring} = \frac{Length_{dipoles}}{Fac_{filling}}$$

  This filling factor $Fac_{filling}$ is taken to be:

  1. approximately from SSC (75%)
  2. 95% for Pipeatron like magnets.
     the higher filling factor for the pipeatron case is justified by the use of a continuous alternating gradient magnet.

- Linear costs (tunnel, light and air, access, survey, stands, pickups, quads, correctors, and magnet ends) taken from

  1. approximately from SSC
  2. 1/3 of the above, for Pipeatron like magnets.
     the lower linear cost in the pipeatron case is justified by the use of a continuous alternating gradient magnet.

- Beam pipe radius is scaled with bending field for fixed beam impedance:

$$Rad_{beam} \propto B^{-1/3}$$

  normalized to

  1. LHC: $Rad_{beam} = 2.2$ cm at B=8T
  2. Pipeatron: $Rad_{beam} = 0.9$ cm at B=2T
     For the same pipe conductivity, the pipeatron assumption corresponds to a 30 times greater acceptable impedance. With a warm bore, as in the Pipeatron, the ratio is even greater. However John Mariner and, at this meeting, John Corlett have argued that with sufficient feed back beam stability may be possible.

- Superconductor critical current:

$$j_{crit} = j_{crit}(7)\ Fac_{degrade}\ \frac{B_{crit} - B\ \ Fac_{peak}}{B_{crit} - 7}$$

- Stabilizing copper Current density fixed, or lowered to keep the mid plane pressure below a specified value

- Average conductor current density

$$j_{cond} = Fac_{packing}\ \frac{1}{(1/j_{crit} + 1/j_{Cu})}$$

- Cryostat space $\propto \sqrt{\frac{4}{Temp}}$

- Cryostat and cryogenic costs $\propto \frac{\mathrm{Area_{cold}}}{\mathrm{Temp}}$
- Radiation shield, of a specified thickness, required above a fixed specified magnetic field
  In this study, the specified field is taken at 2 T so that The Pipeatron does not require a shield, but all higher field magnets do.

2.1.3 For 2-in-1 dipoles

- Conductor thickness

$$t_{cond} = \frac{2}{\mu_o} \; \frac{(B - B_{Fe})}{Fac_{margin} \;\; j_{cond}}$$

  for the contribution from the iron yoke B_{Fe}, see below

$$IR_{cond} \;=\; Rad_{beam} \;+\; t_{shield} \;+\; t_{insu1}$$

$$OR_{cond} \;=\; IR_{cond} \;+\; t_{cond}$$

$$Rad_{cond} \;=\; IR_{cond} \;+\; \frac{t_{cond}}{2}$$

- Mid plane pressure

$$Press = 0.5 \;\; B \;\; j_{cond} \;\; IR_{cond}$$

  If the pressure exceeds a given maximum, then the conductor current density is reduced.

- Cross section areas of SC and Cu for 2 sides + 2 beams

$$SC\ Area = 4\, \frac{j_{cond}}{j_{crit}}\, (OR_{cond} - IR_{cond})\, (OR_{cond} + IR_{cond})$$

$$Cu\ Area = \;\; 4\, \frac{j_{cond}}{j_{Cu}}\, (OR_{cond} - IR_{cond}) \;\; (OR_{cond} + IR_{cond})$$

- Collar thickness

$$t_{collar} = Fac_{collar} \;\; OR_{cond} + \;\; B \;\; j_{cond} \;\; t_{cond} \;\; \frac{OR_{cond} + IR_{cond}}{4 \;\; T_{collar}}$$

$$OR_{collar} \;=\; IR_{yoke} \;=\; OR_{cond} \;+\; t_{insu2} \;+\; t_{collar}$$

- Cross section area of collars for both beams:

$$Area_{collar} = 2 \;\; t_{collar} \;\; 2 \;\; \pi \;\; \left(OR_{cond} + \frac{t_{collar}}{2} \right)$$

- Field contribution from Yoke

$$B_{Fe} \;\; = \;\; \sqrt{\frac{1}{\left(\frac{2}{B(Rad_{cond}/Rad_{collar})}\right)^2 \;\; + \;\; \left(\frac{1}{B_{sat}}\right)^2}}$$

- Current per side of one coil

$$Current = \;2 \; j_{cond} \;\; t_{cond} \;\; \left(OR_{cond} + \frac{t_{cond}}{2} \right)$$

- The magnetic stored energy in both beams, including field between coil and yoke:

$$Energy \;\; = \;\; \frac{1}{2 \; \mu_o} \;\; 2 \; \left(B^2 \;\; \pi \;\; Rad_{cond}^2 \;\; \left(1 \;\; + \;\; \left(\frac{Rad_{cond}}{IR_{yoke}} \right)^2 \right) \right)$$

- Raduis of yoke to allow flux to flop over to other side without saturation:

$$Flux \;\; = \;\; 2 \;\; B \;\; Rad_{cond}$$

$$OR_{yoke} = \;\; \frac{Flux}{B_{sat}}$$

- Cross section area of yoke:

$$Area_{yoke} \;\; = \;\; (\pi \;\; OR_{yoke}^2 \;\; - \;\; 2 \;\; \pi \;\; IR_{yoke}^2)$$

- Shell thickness

$$t_{shell} = \frac{B \;\; j_{cond} \;\; t_{cond} \;\; Rad_{cond}}{2 \;\; T_{shell}}$$

$$OR_{shell} \;\; = \;\; OR_{yoke} \;\; + \;\; t_{shell}$$

- Shell cross section area:

$$Area_{shell} \;\; = \;\; 2 \; \pi \;\; t_{shell} \;\; OR_{yoke}$$

- Cryostat radius:

$$OR(cryo) \quad = \quad \left(OR_{yoke} \ + \ t_{shell} \ + \ t_{cryo} (4) \ \sqrt{\frac{4}{Temp}} \right)$$

- For cryo cost:

$$Circ_{cold} \quad = \quad 2 \ \pi \ \ OR_{shell}$$

2.1.4 1-in-1

Same as above, except:

- Yoke outsie radius:

$$OR_{yoke} \quad = \quad IR_{yoke} \quad + \quad \frac{Flux}{2 \ \ B_{sat}}$$

- Cross section area of both yokes:

$$Area_{yoke} \quad = \quad 2 \ \ (\pi \ \ OR_{yoke}^2 \quad - \quad \pi \ \ IR_{yoke}^2)$$

- Cross section area of 2 shells:

$$Area_{shell} \quad = \quad 2 \ \ 2 \, \pi \ \ t_{shell} \ \ OR_{yoke}$$

- For cryo cost of both beams:

$$Circ_{cold} \quad = \quad 2 \ \ 2 \, \pi \ \ OR_{shell}$$

2.1.5 Pipeatron

- Gap between poles

$$Gap \quad = \ 2 \ (Rad_{beam} + t_{pipe})$$

- Current per transmission line

$$Current = \frac{4 \ \ B}{Fac_{sat} \ \mu_o}$$

- Average radius of conductor scaled with beam size:

$$Rad_{sc} \quad = \quad Fac_{sc} \ \ Rad_{beam}$$

- Field on conductor

$$B_{sc} \;=\; \mu_o \;\frac{Current}{2\;\pi\;\; Rad_{sc}}$$

- Superconductor current density

$$j_{sc} \;=\; Fac_{degrade}\;\; Fac_{margin}\;\; j_{sc}(7)\;\; \frac{B_{crit}(7)\;-\;B_{sc}}{B_{crit}(7)\;-\;7}$$

- Conductor current density

$$j_{cond} \;=\; Fac_{packing}\;\left(\frac{1}{(1/j_{sc}\;+\;1/j_{Cu}}\right)$$

- Conductor thickness

$$t_{cond} \;=\; \frac{Current}{2\;\;\pi\;\; Rad_{cond}\;\; j_{cond}}$$

- Conductor cross section areas, including return:

$$Area_{sc} \;=\; 2\;\; 2\pi\;\; Rad_{cond}\;\; t_{cond}\;\;\left(\frac{j_{cond}}{j_{sc}}\right)$$

$$Area_{Cu} \;=\; 2\;\; 2\pi\;\; Rad_{cond}\;\; t_{cond}\;\;\left(\frac{j_{cond}}{j_{Cu}}\right)$$

- Outside radius of conductor

$$OR_{cond} \;=\; Rad_{sc} \;+\; \frac{t_{cond}}{2}$$

- Inside radius of yoke

$$IR_{yoke} \;=\; OR_{cond} \;+\; t_{cryo}(4)\;\;\sqrt{\frac{4}{Temp}}$$

- Outside radius of yoke

$$OR_{yoke} \;=\; IR_{yoke} \;+\; Fac_{width}\;\; 2\;\; Rad_{beam}$$

- Cross section area of yoke

$$Area_{yoke} \;=\; \pi\;\;(OR_{yoke}^2 - IR_{yoke}^2)$$

- Cold circumference for cryogenic cost, including return conductor

$$Circ \;=\; 2\;\; 2\,\pi\;\; OR_{cond}$$

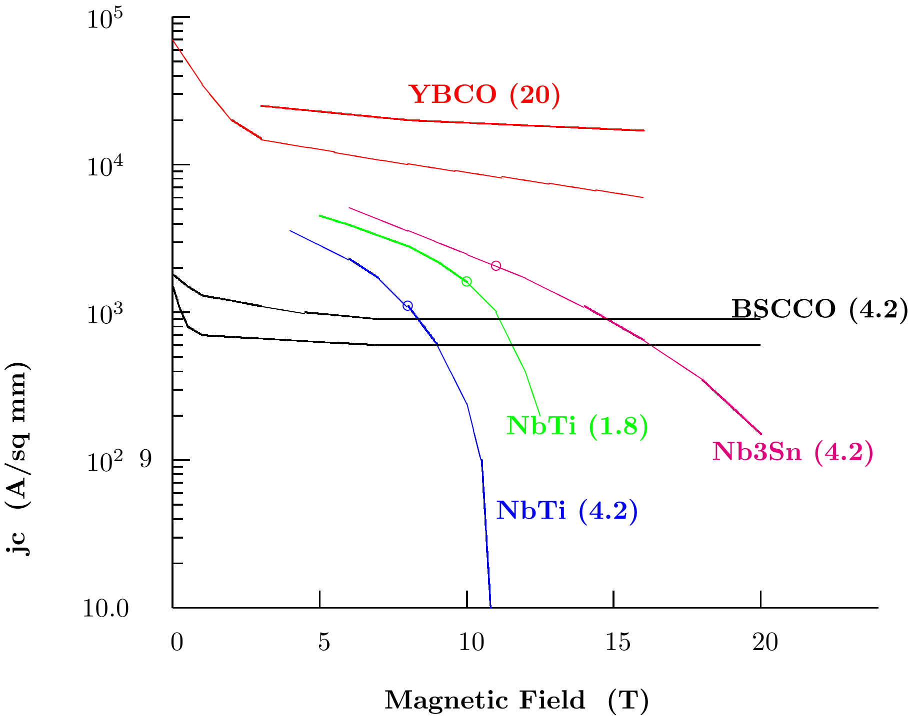
- distance between conductors

$$Spacing \; = \; 2 \;\; OR_{yoke} \;\; Fac_{spacing}$$

- Magnetic energy, including that between the conductor and its return:

$$Energy \; = \; \frac{1}{2 \; \mu_o} \; \left(B^2 \;\; 2 \;\; Gap \;\; (OR_{yoke} - IR_{yoke}) \;\; + 4 \; \pi \;\; B_{sc}^2 \;\; log_e \left(\frac{Spacing}{Rad_{cond}} \right) \right)$$

2.2 Superconductor Performances



We see that

- NbSn is superior to NbTi at all fields. It is, however harder to use and is currently more expensive.
- BSCCO is only superior to NbSn at fields above 15 T.
- YBCO is far superior to all others, in all respects, even at the far higher temperature of 20 degrees. It is however not currently available, and the current density, including support material is not as high as in the material itself.

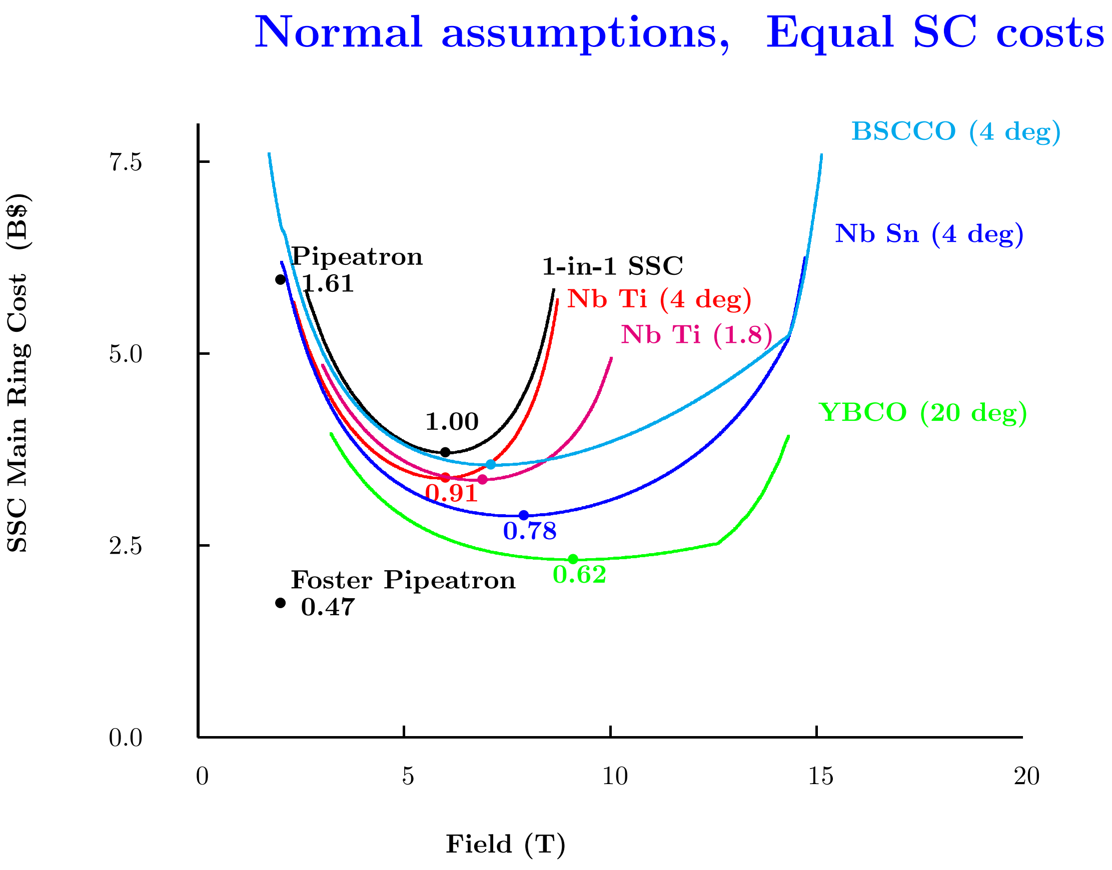
2.3 Data

General			
	linear costs	k\$/m	20
	NbTi cost	\$/kg	625
	stabilizing copper cost	\$/kg	44
	ss collar cost	\$/kgm	10
	cold yoke iron cost	\$/kg	6
	warm yoke iron cost	\$/kg	3
	ss shell cost	\$/kg	10
	cryogenic cost at 4 deg	k\$ /m^2	.5
j_{Cu}	Cu Current density	A/mm^2	1000
$j_{sc}(7)$	NbTi current density at 7T & 4 deg	A/mm^2	1800
$j_{sc}(7)$	NbTi current density at 7T & 1.8 deg	A/mm^2	3200
$j_{sc}(7)$	NbSn current density at 7T & 4 deg	A/mm^2	4000
$j_{sc}(7)$	YBCO current density at 7T & 20 deg	A/mm^2	15000
$j_{sc}(7)$	BSCCO current density at 7T & 4 deg	A/mm^2	1500
B_{crit}	NbTi critical field at 4 deg	T	11
B_{crit}	NbTi critical field at 1.8 deg	T	12.9
B_{crit}	NbSn critical field at 4 deg	T	20.3
B_{crit}	YBCO critical field at 20 deg	T	100
B_{crit}	BSCCO critical field at 4 deg	T	100
E	Beam Energy	TeV	20
Fac_{fill}	Fraction of circ of magnets		.75
$t_{cryo}(4)$	Cryostat space at 4 deg	cm	3
$Fac_{degrade}$	Cabling degredation		.9
Fac_{margin}	Field margin fac		.9
Fac_{pack}	Conductor packing factor		.8
Fac_{peak}	Peak conductor B / central B		1.1
Dipole			
T_{mid}	max pressure in coil	M Pascal	250
Fac_{collar}	min collar thickness/coil rad		.2
T_{collar}	max tension in collar	M Pascal	200
T_{shell}	max tension in shell	M Pascal	400
B_{sat}	Yoke Sat B	T	2
t_{insu1}	inner insulation etc.	cm	.2
t_{insu2}	outer insulation	cm	.1
t_{shield}	radiation shield thickness	cm	.5
B_{shield}	Field when shield required	T	2
Pipeatron			
Fac_{width}	(Pole Width)/beam dia		2.5
Fac_{sc}	sc dia/vac ht		1.5
Fac_{sat}	B(with sat)/ideal		.8
t_{pipe}	(gap-vac ht)/2	cm	.1
$Fac_{spacing}$	spacing/yoke dia		2

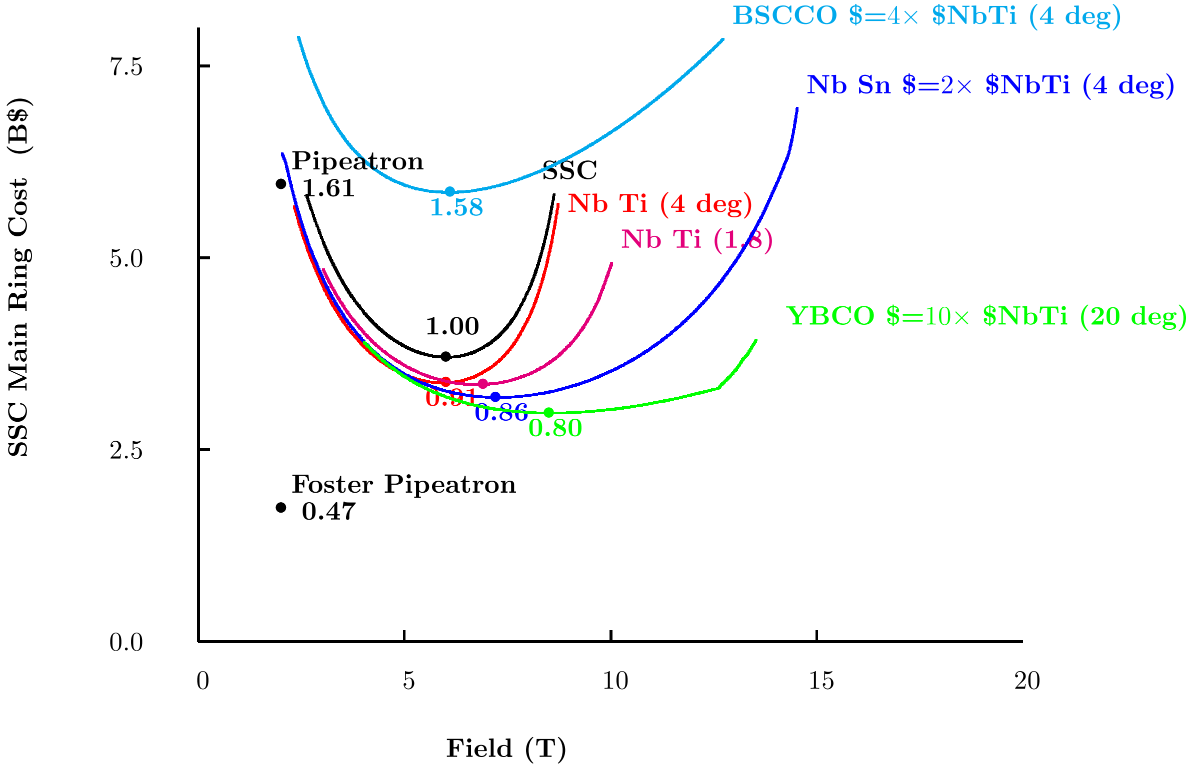
3 "Normal" Assumptions

We first examine designs using the conservative linear costs (from SSC), and beam pipe aperture (from LHC). The only exception is for the "Foster Pipeatron" for which 1/3 of SSC linear costs, and 30 times greater impedance are assumed (note that the term "Foster Pipeatron" refers to a design which is similar, but not identical to the one being designed by Bill Foster et al). All magnet designs are 2-in-1, except the SSC and the Pipeatrons.

Plots of ring costs vs. magnetic field, for a fixed machine energy, are plotted below for two cases: 1) if all superconductors cost the same, and 2) ,more realistically, if the more exotic materials cost more (NbSn, twice as much as NbTi; BSCCO 4 times NbTi; YBCO, 10 times NBTi. Note that these factors are not based on any real data.



Normal assumptions, Differing SC costs



The Fields and costs at minimum cost are:

A) Normal assumptions, Equal SC costs

Example	$B_{minimum}$ T	$\text{Cost}_{minimum}$ B$	Ratio
SSC (Normal Assumptions)	6.0	3.71	1.00
Nb Ti (4 deg)	6.0	3.37	0.91
Nb Ti 1$ (1.8)	6.9	3.35	0.90
$Nb Sn=$NbTi (4 deg)	7.9	2.88	0.78
$BSCCO=$NbTi (4 deg)	7.1	3.55	0.96
$YBCO=$NbTi (20 deg)	9.1	2.31	0.62
Normal Pipeatron	2	5.96	1.61
Foster Pipeatron	2	1.74	0.47

B) Normal assumptions, Differing SC costs

Example	$B_{minimum}$ T	$Cost_{minimum}$ B$	Ratio
SSC (Normal Assumptions)	6.0	3.71	1.00
Nb Ti (4 deg)	6.0	3.37	0.91
Nb Ti 1$ (1.8)	6.9	3.35	0.90
$Nb Sn=2× $NbTi (4 deg)	7.2	3.18	0.86
$BSCCO=4× $NbTi (4 deg)	6.1	5.85	1.58
$YBCO=10× $NbTi (20 deg)	8.5	2.98	0.80
Normal Pipeatron	2	5.96	1.61
Foster Pipeatron	2	1.74	0.47

Tables of these costs and other parameters:

A) Normal assumptions, Equal SC costs

SSC (Normal Assumptions)

B T	j A/mm^2	j_{SC} A/mm^2	lin k$/m	sc k$/m	Cu k$/m	coll k$/m	fe k$/m	shell k$/m	cryo k$/m	mag k$/m	Tot B$	/SSC
5.0	552	2228	20.0	5.03	0.90	1.32	6.67	0.28	5.00	17.9	3.84	1.04
7.5	422	1114	20.0	17.84	1.59	2.79	16.20	1.14	7.69	44.5	4.13	1.11

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	2.6	3.3	4.6	4.6	5.9	15.7	0.2	63	0.96	2.2	745	29.1k
7.5	2.2	2.9	5.7	5.7	7.8	24.0	0.5	90	0.99	1.1	1623	47.8k

Nb Ti (4 deg)

B T	j A/mm^2	j_{SC} A/mm^2	lin k$/m	sc k$/m	Cu k$/m	coll k$/m	fe k$/m	shell k$/m	cryo k$/m	mag k$/m	Tot B$	/SSC
5.0	552	2228	20.0	5.03	0.90	0.66	4.93	0.17	3.11	14.1	3.47	0.94
7.5	422	1114	20.0	17.84	1.59	1.40	14.51	0.76	5.16	39.9	3.79	1.02

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	2.6	3.3	4.6	4.6	5.9	19.6	0.2	63	0.96	2.2	745	29.1k
7.5	2.2	2.9	5.7	5.7	7.8	32.4	0.5	90	0.99	1.1	1623	47.8k

Nb Ti (1.8 deg)

B T	j A/mm^2	j_{SC} A/mm^2	lin k$/m	sc k$/m	Cu k$/m	coll k$/m	fe k$/m	shell k$/m	cryo k$/m	mag k$/m	Tot B$	/SSC
5.0	627	3612	20.0	3.02	0.87	0.62	4.76	0.17	6.76	15.6	3.59	0.97
7.5	555	2270	20.0	7.99	1.45	1.10	12.44	0.64	10.56	33.1	3.40	0.92
10.0	385	927	20.0	33.21	2.46	2.84	33.14	2.35	17.15	88.3	4.94	1.33

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	2.6	3.3	4.4	4.4	5.7	19.2	0.2	69	0.98	3.6	707	28.1k
7.5	2.2	2.9	5.0	5.0	7.0	29.8	0.4	104	1.04	2.3	1376	41.4k
10.0	2.0	2.7	6.9	6.9	10.3	48.2	1.0	133	0.96	0.9	2867	74.5k

Nb Sn (4 deg)

B T	j A/mm^2	j_{SC} A/mm^2	lin k\$/m	sc k\$/m	Cu k\$/m	coll k\$/m	fe k\$/m	shell k\$/m	cryo k\$/m	mag k\$/m	Tot B\$	/SSC
5.0	640	4006	20.0	2.71	0.87	0.61	4.73	0.16	3.03	11.5	3.25	0.88
7.5	612	3262	20.0	5.41	1.41	1.02	11.87	0.61	4.63	23.9	2.88	0.78
10.0	573	2517	20.0	10.38	2.09	1.89	24.54	1.71	6.61	45.3	3.10	0.83
12.5	511	1773	20.0	21.11	2.99	3.71	47.95	4.27	9.24	85.6	3.89	1.05
15.0	332	1029	20.0	61.02	7.23	11.10	128.35	14.11	15.22	225.9	7.36	1.98

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	2.6	3.3	4.4	4.4	5.7	19.1	0.2	70	0.98	4.0	701	28.0k
7.5	2.2	2.9	4.8	4.8	6.7	29.1	0.4	110	1.06	3.3	1305	39.6k
10.0	2.0	2.7	5.5	5.5	8.3	41.3	0.8	158	1.04	2.5	2182	55.7k
12.5	1.9	2.6	6.6	6.6	10.9	57.4	1.5	210	0.97	1.8	3497	81.5k
15.0	1.8	2.5	10.0	10.0	18.0	93.9	2.9	250	0.82	1.5	6924	173.4k

BSCCO (4 deg)

B T	j A/mm^2	j_{SC} A/mm^2	lin k\$/m	sc k\$/m	Cu k\$/m	coll k\$/m	fe k\$/m	shell k\$/m	cryo k\$/m	mag k\$/m	Tot B\$	/SSC
5.0	463	1372	20.0	8.50	0.93	0.73	5.21	0.19	3.21	18.0	3.81	1.03
7.5	457	1332	20.0	14.50	1.55	1.30	13.82	0.72	5.02	35.6	3.55	0.96
10.0	451	1292	20.0	22.22	2.30	2.39	29.13	2.05	7.22	62.9	3.85	1.04
12.5	445	1252	20.0	31.95	3.20	4.35	54.36	4.87	9.85	104.2	4.53	1.22
15.0	331	1212	20.0	51.87	8.01	11.14	128.79	14.16	15.24	218.1	7.15	1.93

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	2.6	3.3	4.8	4.8	6.3	20.3	0.2	56	0.93	1.4	807	30.6k
7.5	2.2	2.9	5.5	5.5	7.6	31.5	0.5	94	1.00	1.3	1543	45.7k
10.0	2.0	2.7	6.3	6.3	9.4	45.1	0.9	141	0.99	1.3	2560	65.7k
12.5	1.9	2.6	7.2	7.2	11.9	61.2	1.6	200	0.94	1.3	3878	92.2k
15.0	1.8	2.5	10.1	10.1	18.1	94.1	2.9	250	0.82	1.9	6941	174.0k

YBCO \$=NbTi (20 deg)

B T	j A/mm^2	j_{SC} A/mm^2	lin k\$/m	sc k\$/m	Cu k\$/m	coll k\$/m	fe k\$/m	shell k\$/m	cryo k\$/m	mag k\$/m	Tot B\$	/SSC
5.0	746	13718	20.0	0.77	0.85	0.57	4.56	0.16	0.59	6.9	2.86	0.77
7.5	744	13319	20.0	1.26	1.34	0.90	10.92	0.55	0.89	15.0	2.38	0.64
10.0	743	12919	20.0	1.85	1.92	1.51	20.98	1.44	1.22	27.4	2.33	0.63
12.5	741	12520	20.0	2.57	2.57	2.56	36.02	3.17	1.60	45.9	2.52	0.68
15.0	331	12121	20.0	5.19	11.75	11.14	128.83	14.16	3.05	163.0	5.61	1.51

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	2.6	3.3	4.2	4.2	5.5	18.7	0.2	79	1.00	13.7	663	27.1k
7.5	2.2	2.9	4.5	4.5	6.2	27.8	0.4	125	1.10	13.3	1183	36.7k
10.0	2.0	2.7	4.9	4.9	7.4	38.0	0.7	181	1.10	12.9	1865	48.0k
12.5	1.9	2.6	5.3	5.3	9.0	49.6	1.3	247	1.04	12.5	2716	61.7k
15.0	1.8	2.5	10.1	10.1	18.1	94.1	2.9	250	0.82	28.3	6943	174.1k

Normal Pipeatron

B T	j A/mm^2	j_{SC} A/mm^2	lin k\$/m	sc k\$/m	Cu k\$/m	coll k\$/m	fe k\$/m	shell k\$/m	cryo k\$/m	mag k\$/m	Tot B\$	/SSC
2.0	627	3612	20.0	0.54	0.16	0.00	4.94	0.00	1.74	7.4	5.95	1.60

B T	r_{vac} cm	gap cm	OR_{He} cm	r_{sc} cm	IR_{yoke} cm	OR_{yoke} cm	spacing cm	MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
2.0	3.5	3.6	5.4	5.5	8.5	26.5	105.9	0	2.00	3.6	294	22.5k

Foster Pipeatron

B T	j A/mm^2	j_{SC} A/mm^2	lin k\$/m	sc k\$/m	Cu k\$/m	coll k\$/m	fe k\$/m	shell k\$/m	cryo k\$/m	mag k\$/m	Tot B\$	/SSC
2.0	625	3584	6.7	0.16	0.05	0.00	0.56	0.00	0.52	1.3	1.74	0.47

B T	r_{vac} cm	gap cm	OR_{He} cm	r_{sc} cm	IR_{yoke} cm	OR_{yoke} cm	spacing cm	MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
2.0	0.9	1.0	1.5	1.7	4.7	9.6	38.6	0	2.00	3.6	87	2.8k

B) Normal assumptions, Differing SC costs

Nb Sn \$=2× NbTi (4 deg)

B	j	j_{SC}	lin	sc	Cu	coll	fe	shell	cryo	mag	Tot	/SSC
T	A/mm^2	A/mm^2	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	B\$	
5.0	640	4006	20.0	5.43	0.87	0.61	4.73	0.16	3.03	14.2	3.48	0.94
7.5	612	3262	20.0	10.82	1.41	1.02	11.87	0.61	4.63	29.3	3.19	0.86
10.0	573	2517	20.0	20.76	2.09	1.89	24.54	1.71	6.61	55.7	3.53	0.95
12.5	511	1773	20.0	42.23	2.99	3.71	47.95	4.27	9.24	106.7	4.59	1.24
15.0	332	1029	20.0	122.05	7.23	11.10	128.35	14.11	15.22	286.9	9.07	2.44

B	r_{vac}	ir_{coil}	r_{sc}	r_{Cu+SC}	r_{collar}	r_{yoke}	t_{shell}	press	B Fe	Cu/sc	I/mag	U_{mag}
T	cm	cm	cm	cm	cm	cm	cm	MPa	T		kA turns	T^2m^2
5.0	2.6	3.3	4.4	4.4	5.7	19.1	0.2	70	0.98	4.0	701	28.0k
7.5	2.2	2.9	4.8	4.8	6.7	29.1	0.4	110	1.06	3.3	1305	39.6k
10.0	2.0	2.7	5.5	5.5	8.3	41.3	0.8	158	1.04	2.5	2182	55.7k
12.5	1.9	2.6	6.6	6.6	10.9	57.4	1.5	210	0.97	1.8	3497	81.5k
15.0	1.8	2.5	10.0	10.0	18.0	93.9	2.9	250	0.82	1.5	6924	173.4k

BSCCO \$=4× NbTi (4 deg)

B	j	j_{SC}	lin	sc	Cu	coll	fe	shell	cryo	mag	Tot	/SSC
T	A/mm^2	A/mm^2	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	B\$	
5.0	463	1372	20.0	34.01	0.93	0.73	5.21	0.19	3.21	43.6	5.94	1.60
7.5	457	1332	20.0	58.01	1.55	1.30	13.82	0.72	5.02	79.1	5.98	1.61
10.0	451	1292	20.0	88.89	2.30	2.39	29.13	2.05	7.22	129.6	6.65	1.79
12.5	445	1252	20.0	127.81	3.20	4.35	54.36	4.87	9.85	200.1	7.74	2.09
15.0	331	1212	20.0	207.50	8.01	11.14	128.79	14.16	15.24	373.7	11.49	3.10

B	r_{vac}	ir_{coil}	r_{sc}	r_{Cu+SC}	r_{collar}	r_{yoke}	t_{shell}	press	B Fe	Cu/sc	I/mag	U_{mag}
T	cm	cm	cm	cm	cm	cm	cm	MPa	T		kA turns	T^2m^2
5.0	2.6	3.3	4.8	4.8	6.3	20.3	0.2	56	0.93	1.4	807	30.6k
7.5	2.2	2.9	5.5	5.5	7.6	31.5	0.5	94	1.00	1.3	1543	45.7k
10.0	2.0	2.7	6.3	6.3	9.4	45.1	0.9	141	0.99	1.3	2560	65.7k
12.5	1.9	2.6	7.2	7.2	11.9	61.2	1.6	200	0.94	1.3	3878	92.2k
15.0	1.8	2.5	10.1	10.1	18.1	94.1	2.9	250	0.82	1.9	6941	174.0k

YBCO \$=10× NbTi (20 deg)

B	j	j_{SC}	lin	sc	Cu	coll	fe	shell	cryo	mag	Tot	/SSC
T	A/mm^2	A/mm^2	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	k\$/m	B\$	
5.0	746	13718	20.0	7.72	0.85	0.57	4.56	0.16	0.59	13.9	3.44	0.93
7.5	744	13319	20.0	12.60	1.34	0.90	10.92	0.55	0.89	26.3	3.01	0.81
10.0	743	12919	20.0	18.53	1.92	1.51	20.98	1.44	1.22	44.1	3.03	0.82
12.5	741	12520	20.0	25.67	2.57	2.56	36.02	3.17	1.60	69.0	3.29	0.89
15.0	331	12121	20.0	51.88	11.75	11.14	128.83	14.16	3.05	209.7	6.91	1.86

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	2.6	3.3	4.2	4.2	5.5	18.7	0.2	79	1.00	13.7	663	27.1k
7.5	2.2	2.9	4.5	4.5	6.2	27.8	0.4	125	1.10	13.3	1183	36.7k
10.0	2.0	2.7	4.9	4.9	7.4	38.0	0.7	181	1.10	12.9	1865	48.0k
12.5	1.9	2.6	5.3	5.3	9.0	49.6	1.3	247	1.04	12.5	2716	61.7k
15.0	1.8	2.5	10.1	10.1	18.1	94.1	2.9	250	0.82	28.3	6943	174.1k

Normal Pipeatron

B T	j A/mm^2	j_{SC} A/mm^2	lin k\$/m	sc k\$/m	Cu k\$/m	coll k\$/m	fe k\$/m	shell k\$/m	cryo k\$/m	mag k\$/m	Tot B\$	/SSC
2.0	627	3612	20.0	0.54	0.16	0.00	4.94	0.00	1.74	7.4	5.95	1.60

B T	r_{vac} cm	gap cm	OR_{He} cm	r_{sc} cm	IR_{yoke} cm	OR_{yoke} cm	spacing cm	MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
2.0	3.5	3.6	5.4	5.5	8.5	26.5	105.9	0	2.00	3.6	294	22.5k

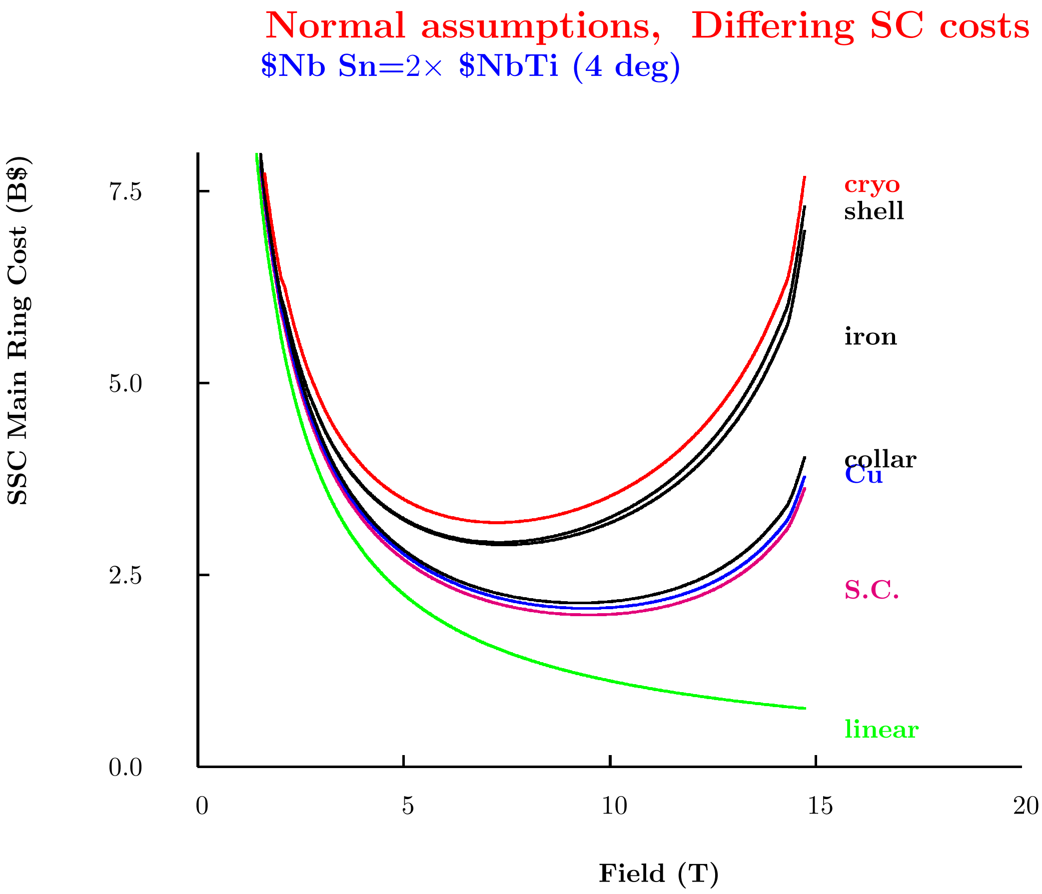
3.0.1 Discussion

We see that:

- The 2-in-1 magnets are 9% cheeper than the SSC separate cryostats.
- With the "Normal" linear cost and impedance assumptions, the pipeatron is 1.6 × the cost of SSC technology.
- The Pipeatron, with a beam pipe with 30 × the impedance and 1/3 the linear costs, is 47% of SSC and 51% of a 2-in-1 using NbTi.
- The fields at cost minima are relatively low
  - The minimum cost for the NbTi magnets at 4 degrees is at 6 T. Not far from the 6.6 T SSC design field.
  - The minimum cost for the NbTi magnets at 1.8 degrees is at 6.9 T. Not far from that of the LHC.
  - With NbSn at 4 degrees and costs equal to NbTi, the minimum has only risen to 7.9 T and is only at 7.2 T if the cost is doubled. A ring with NbSn (2×NbTi cost) at 12.5 T would be 44% more expensive than one made with the same material at 7.5 T.
  - Even with YBCO and costs equal to NbTi (a crazy assunption) it is only at 9.1 T. It falls to 8.5 T at 10 times the cost.
- There is no advantage in using BSCCO unless the field has to be greater than 8T.

- Even with fixed uperconductor costs, the minimum costs of the ring fall by only modest amounts with the better conductors:
  - 14% for NbSn
  - 32 % for YBCO
- With the assumed differing uperconductor costs, the minimum costs of the ring fall by even less with the better conductors:
  - 5% for NbSn
  - 12 % for YBCO

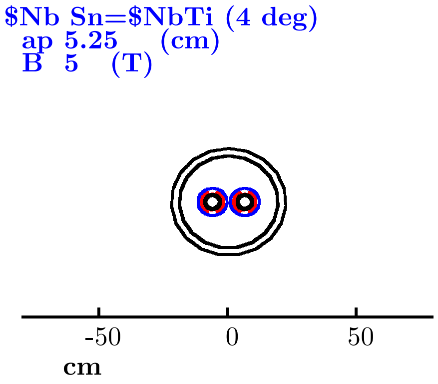
The reasons for the low field for minimum cost is illustrated by plotting the cummulative costs for the different components. For example, for the NbSn case with SC cost twice NbTi:

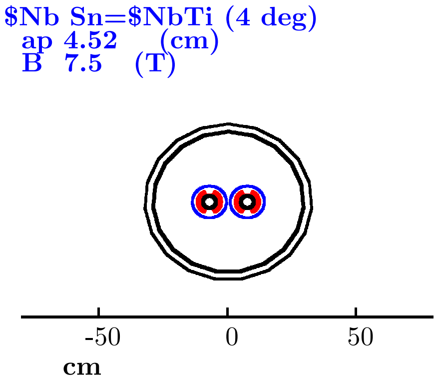


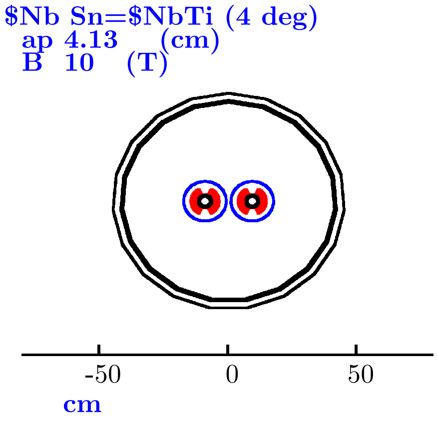
If only superconductor costs are considered, then the cost minimum is at 10 T, but the costs of stabilizing copper, collars and iron are also rising as the magnet field increases, so that the minimum with these included has moved down to 7.2 T.

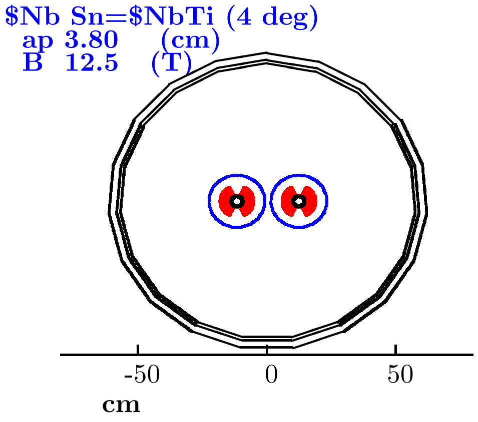
In the following figure, the cross sections of NbSn 2-in-1 magnets are shown at a four different magnetic fields, and then compared with a Pipeatron magnet designed with these same initial impedance assumptions. Finally, a Pipeatron magnet is shown with the beam pipe aperture discussed by Bill Foster et al (with 30 × the impedance.

Normal assumptions

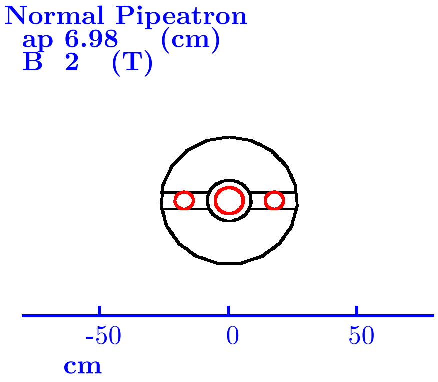


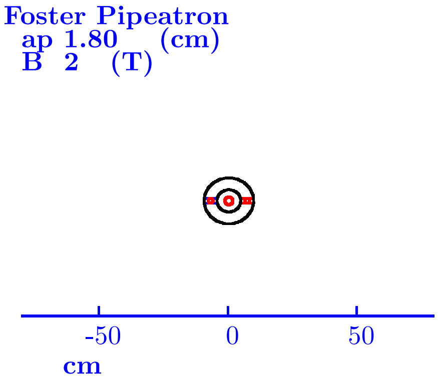






Low Linear $ and Small Bore





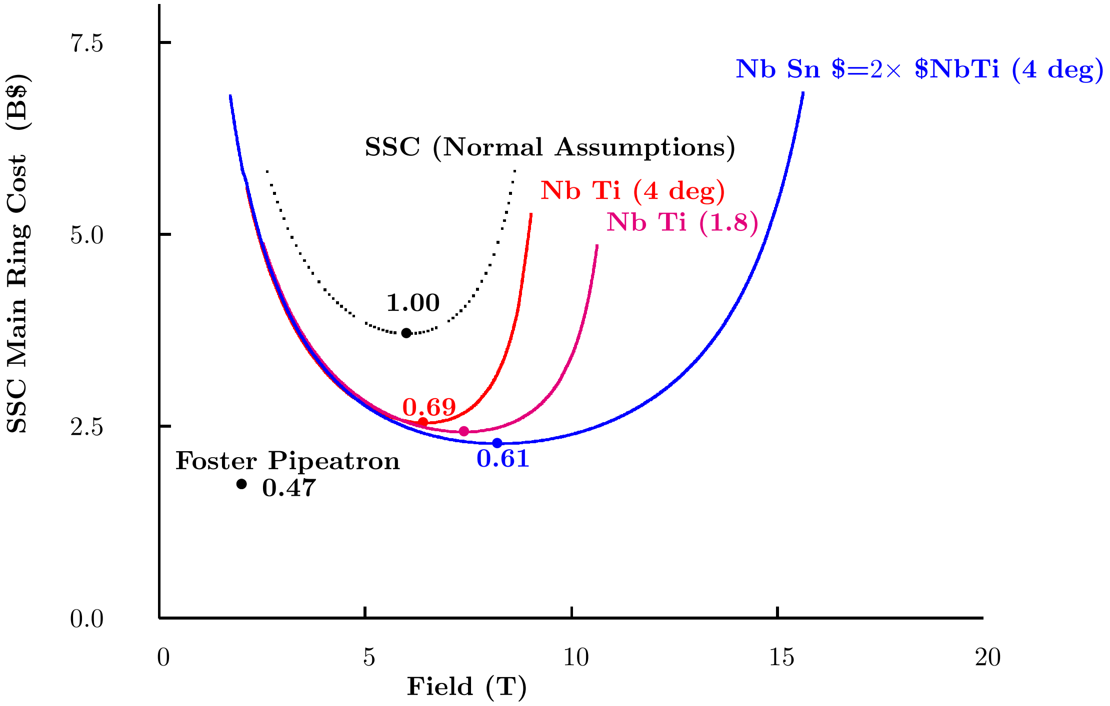
The "Radical" question of the title of this talk (but surely not so radical) is: how will the costs of 2-in-1 magnets change if we apply Pipeatron like assumptions to them. First we make the same impedance assumption, then ask if linear costs could also be similarly reduced.

4 If 30 × Higher Impedance Allowed

The assumption that a 30 × higher impedance can be allowed is based on work by John Mariner and, at this conference, by John Cornlett. With adequate feedback, they have shown that the impedance from a 1.8 cm aperture at 2 T, and a warm pipe, could be acceptable. If the pipe is cold, then the resistance, and thus resitive wall impedance, will be less, and the use of similarly scaled small pipes should be even more acceptable.

First, we consider this impedance assumption, but keep the linear costs the same (i.e. at SSC values). The costs vs. field are now:

Normal linear, 30 × impedance



The Fields and costs at minimum cost are:

Example	$B_{minimum}$ T	$Cost_{minimum}$ B$	Ratio
SSC (Normal Assumptions)	6.0	3.71	1.00
Nb Ti (4 deg)	6.4	2.54	0.69
Nb Ti 1$ (1.8)	7.4	2.43	0.65
$Nb Sn=2× $NbTi (4 deg)	8.2	2.27	0.61
Foster Pipeatron	2	1.74	0.47

and these, plus other parameters are tabulated:

Nb Ti (4 deg)

B	j	j_{SC}	lin	sc	Cu	coll	fe	shell	cryo	mag	Tot	/SSC
T	A/mm^2	A/mm^2	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	B$	
5.0	552	2228	20.0	2.75	0.49	0.23	1.24	0.05	1.62	6.1	2.77	0.75
7.5	422	1114	20.0	11.44	1.02	0.68	5.39	0.30	3.21	21.4	2.72	0.73

B	r_{vac}	ir_{coil}	r_{sc}	r_{Cu+SC}	r_{collar}	r_{yoke}	t_{shell}	press	B Fe	Cu/sc	I/mag	U_{mag}
T	cm	cm	cm	cm	cm	cm	cm	MPa	T		kA turns	T^2m^2
5.0	0.7	1.4	2.7	2.7	3.6	10.2	0.1	38	0.76	2.2	509	7.3k
7.5	0.6	1.3	4.1	4.1	5.6	20.1	0.3	65	0.79	1.1	1305	17.5k

Nb Ti (1.8 deg)

B	j	j_{SC}	lin	sc	Cu	coll	fe	shell	cryo	mag	Tot	/SSC
T	A/mm^2	A/mm^2	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	B$	
5.0	627	3612	20.0	1.61	0.47	0.20	1.15	0.05	3.45	6.7	2.81	0.76
7.5	555	2270	20.0	4.85	0.88	0.48	4.14	0.23	6.21	16.3	2.43	0.65
10.0	385	927	20.0	23.43	1.74	1.64	15.50	1.15	11.89	53.7	3.44	0.93

B	r_{vac}	ir_{coil}	r_{sc}	r_{Cu+SC}	r_{collar}	r_{yoke}	t_{shell}	press	B Fe	Cu/sc	I/mag	U_{mag}
T	cm	cm	cm	cm	cm	cm	cm	MPa	T		kA turns	T^2m^2
5.0	0.7	1.4	2.6	2.6	3.3	9.8	0.1	40	0.79	3.6	469	6.8k
7.5	0.6	1.3	3.4	3.4	4.7	17.5	0.3	71	0.84	2.3	1049	13.5k
10.0	0.5	1.2	5.5	5.5	8.0	33.4	0.7	105	0.80	0.9	2461	34.5k

Nb Sn $=2× NbTi (4 deg)

B	j	j_{SC}	lin	sc	Cu	coll	fe	shell	cryo	mag	Tot	/SSC
T	A/mm^2	A/mm^2	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	B$	
5.0	640	4006	20.0	2.89	0.46	0.20	1.14	0.04	1.54	6.1	2.76	0.74
7.5	612	3262	20.0	6.44	0.84	0.43	3.81	0.21	2.67	14.0	2.29	0.62
10.0	573	2517	20.0	13.53	1.36	0.94	9.78	0.71	4.23	29.6	2.40	0.65
12.5	511	1773	20.0	29.87	2.12	2.12	23.00	2.11	6.46	63.6	3.09	0.83
15.0	406	1029	20.0	83.56	3.44	5.60	59.00	6.58	10.37	162.9	5.45	1.47

B	r_{vac}	ir_{coil}	r_{sc}	r_{Cu+SC}	r_{collar}	r_{yoke}	t_{shell}	press	B Fe	Cu/sc	I/mag	U_{mag}
T	cm	cm	cm	cm	cm	cm	cm	MPa	T		kA turns	T^2m^2
5.0	0.7	1.4	2.5	2.5	3.3	9.7	0.1	40	0.79	4.0	462	6.7k
7.5	0.6	1.3	3.2	3.2	4.4	16.8	0.2	73	0.86	3.3	975	12.4k
10.0	0.5	1.2	4.0	4.0	6.0	26.4	0.5	116	0.86	2.5	1763	21.8k
12.5	0.5	1.2	5.2	5.2	8.4	40.1	1.0	167	0.82	1.8	2990	38.7k
15.0	0.5	1.2	7.4	7.4	13.0	64.0	2.0	224	0.75	1.0	5277	79.6k

4.0.2 Discussion

We see that

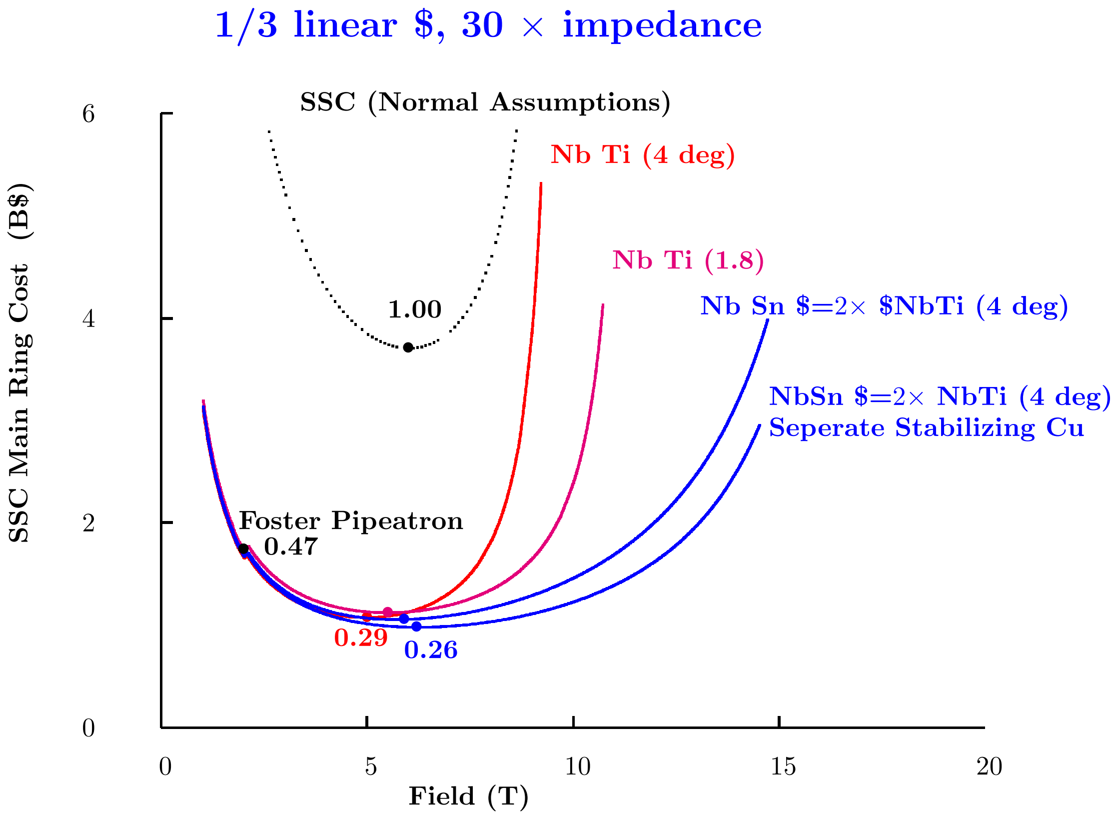
- The minimum cost for NbTi has been reduced by 24%, and for NbSn by 30%.

- The fields for cost minimum have not changed significantly.

But it may be noted that the 2-in-1 magnet at 5 T (near its minimum cost) is not so much more expensive than the Pipeatron. And its strored magnetic energy is only about 3 times that of the Pipeatron. We can ask then if the 2-in-1 magnet could not be made continuous, like tyhe Pipeatron, and thus justify the same low linear costs.

5 If 30 × Z Impedance & Linear Costs = 1/3

We now look at the costs if we assume both higher impedance and linear costs a factor of 3 less. In addition, since we will be considering low magnetic fields, the following calculations will assume, as in RHIC, no collar.



The Fields and costs at minimum cost are:

Example	$B_{minimum}$ T	$Cost_{minimum}$ B$	Ratio
SSC (Normal Assumptions)	6.0	3.71	1.00
Nb Ti (4 deg)	5.0	1.08	0.29
Nb Ti 1$ (1.8)	5.5	1.12	0.30
$Nb Sn=2× $NbTi (4 deg)	5.9	1.06	0.28
$NbSn=2× $NbTi (4 deg) Sep Cu	6.2	0.98	0.26
Foster Pipeatron	2	1.74	0.47

These costs and other dimensions are tabulated:

Nb Ti (4 deg)

B T	j A/mm^2	j_{SC} A/mm^2	lin k$/m	sc k$/m	Cu k$/m	coll k$/m	fe k$/m	shell k$/m	cryo k$/m	mag k$/m	Tot B$	/SSC
5.0	552	2228	6.7	2.45	0.44	0.00	1.32	0.04	1.57	5.8	1.08	0.29
7.5	422	1114	6.7	10.31	0.92	0.00	5.44	0.27	3.10	20.0	1.51	0.41

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	0.7	1.4	2.6	2.6	2.7	9.9	0.1	36	1.12	2.2	443	8.0k
7.5	0.6	1.3	3.9	3.9	4.0	19.4	0.3	62	1.24	1.1	1156	18.8k

Nb Ti (1.8 deg)

B T	j A/mm^2	j_{SC} A/mm^2	lin k$/m	sc k$/m	Cu k$/m	coll k$/m	fe k$/m	shell k$/m	cryo k$/m	mag k$/m	Tot B$	/SSC
5.0	627	3612	6.7	1.44	0.42	0.00	1.22	0.04	3.36	6.5	1.13	0.30
7.5	555	2270	6.7	4.38	0.79	0.00	4.18	0.20	6.01	15.6	1.26	0.34
10.0	385	927	6.7	21.18	1.57	0.00	15.32	1.00	11.43	50.5	2.41	0.65

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	0.7	1.4	2.5	2.5	2.6	9.5	0.1	38	1.15	3.6	408	7.5k
7.5	0.6	1.3	3.3	3.3	3.4	17.0	0.2	68	1.30	2.3	929	14.8k
10.0	0.5	1.2	5.2	5.2	5.3	32.1	0.6	100	1.35	0.9	2196	37.1k

Nb Sn $=2× NbTi (4 deg)

B T	j A/mm^2	j_{SC} A/mm^2	lin k$/m	sc k$/m	Cu k$/m	coll k$/m	fe k$/m	shell k$/m	cryo k$/m	mag k$/m	Tot B$	/SSC
5.0	640	4006	6.7	2.57	0.41	0.00	1.21	0.04	1.50	5.7	1.07	0.29
7.5	612	3262	6.7	5.81	0.76	0.00	3.85	0.18	2.59	13.2	1.13	0.30
10.0	573	2517	6.7	12.26	1.23	0.00	9.71	0.62	4.08	27.9	1.46	0.39
12.5	511	1773	6.7	27.07	1.92	0.00	22.59	1.84	6.21	59.6	2.23	0.60
15.0	406	1029	6.7	75.60	3.11	0.00	57.52	5.70	9.92	151.9	4.44	1.20

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	0.7	1.4	2.4	2.4	2.5	9.5	0.1	39	1.15	4.0	403	7.4k
7.5	0.6	1.3	3.1	3.1	3.2	16.3	0.2	70	1.32	3.3	863	13.7k
10.0	0.5	1.2	3.9	3.9	4.0	25.5	0.5	111	1.43	2.5	1573	24.1k
12.5	0.5	1.2	5.0	5.0	5.1	38.6	0.9	159	1.51	1.8	2676	42.9k
15.0	0.5	1.2	7.0	7.0	7.1	61.3	1.8	214	1.56	1.0	4729	87.8k

NbSn \$=2× NbTi (4 deg) Sep Cu

B T	j A/mm^2	j_{SC} A/mm^2	lin k\$/m	sc k\$/m	Cu k\$/m	coll k\$/m	fe k\$/m	shell k\$/m	cryo k\$/m	mag k\$/m	Tot B\$	/SSC
5.0	1372	4006	6.7	2.30	0.12	0.00	1.15	0.04	1.46	5.1	1.01	0.27
7.5	1250	3262	6.7	4.80	0.21	0.00	3.43	0.17	2.44	11.0	1.01	0.27
10.0	1095	2517	6.7	9.58	0.32	0.00	8.16	0.54	3.74	22.3	1.23	0.33
12.5	891	1773	6.7	20.59	0.49	0.00	18.22	1.51	5.58	46.4	1.79	0.48
15.0	613	1029	6.7	58.62	0.80	0.00	46.17	4.64	8.89	119.1	3.52	0.95

B T	r_{vac} cm	ir_{coil} cm	r_{sc} cm	r_{Cu+SC} cm	r_{collar} cm	r_{yoke} cm	t_{shell} cm	press MPa	B Fe T	Cu/sc	I/mag kA turns	U_{mag} T^2m^2
5.0	0.7	1.4	1.9	2.3	2.4	9.2	0.1	65	0.98	1.3	367	5.0k
7.5	0.6	1.3	2.2	2.8	2.9	15.3	0.2	102	1.11	1.1	738	8.0k
10.0	0.5	1.2	2.6	3.4	3.5	23.3	0.5	145	1.20	0.8	1291	12.8k
12.5	0.5	1.2	3.4	4.4	4.5	34.6	0.9	190	1.28	0.6	2168	22.1k
15.0	0.5	1.2	5.1	6.2	6.3	54.9	1.7	234	1.37	0.3	3920	48.2k

5.0.3 Discussion

For NbTi at 4 degrees (red):

- The field for minimum cost is now only 5 T, and is now only 0.29 of the SSC, 0.32 times a NbTi 2-in-1 with normal assumptions, and less than (60%) the Foster Pipeatron.
- The stored magnetic energy (8000 T^2m^2) is approximately 1/5 of the SSC, 1/10 of a 12.5 T 2-in-1 NbSn design, and only 3 times that of the Pipeatron (2800) T^2m^2.

We note from the other curves and tables:

- the cost minimum is higher for NbTi at 1.8 degrees, so there is nothing to be gained here.
- If NbSn costs twice NbTi (upper blue line), then the minimum cost is approximately the same as with NbTi, but if the NbSn cost were the same, it would be 10% less (0.26 of the SSC). In either case, the magnetic stored energy is less (7400 T^2m^2).

- The lower blue line shows the cost with a further modification (separate stabilizing copper) that will be discussed below. It shows a minimum cost of 0.26 SSC with NbSn costing 2 times NbTi, or 0.23 times SSC with NbSn costing the same as NbTi.

5.1 Lowering 2-in-1 Linear Costs

In order to justify using pipeatron estimates for linear costs, we must avoid magnet ends and separate quadrupoles and feeds. This will require:

- Continuous conductors
- No length contraction when cooled
- Combined Function focussing
- Low stored magnet energy

5.1.1 Continuous Conductors

With the modifications described below, the stored energy is less than twice that of the pipeatron (5000 vs. 2800 $T^2 m^2$). It is thus reasonable to consider, as they do, continuous conductors passing round the entire ring without any "ends" . But unlike the pipeatron, there would be 5 such conductors on each side of each "coil", for a total of 20 such conductors, each powered by a separate power supply. The currents per cable will be 80 kA each.

With such separate cables and power supplies, all systematic, saturation induced, and beam to beam coupling, field errors can be corrected by the power supplies.

5.1.2 Non contracting Design

In order to avoid expansion joints, the magnet should be designed to maintain it length as it cools. This would require:

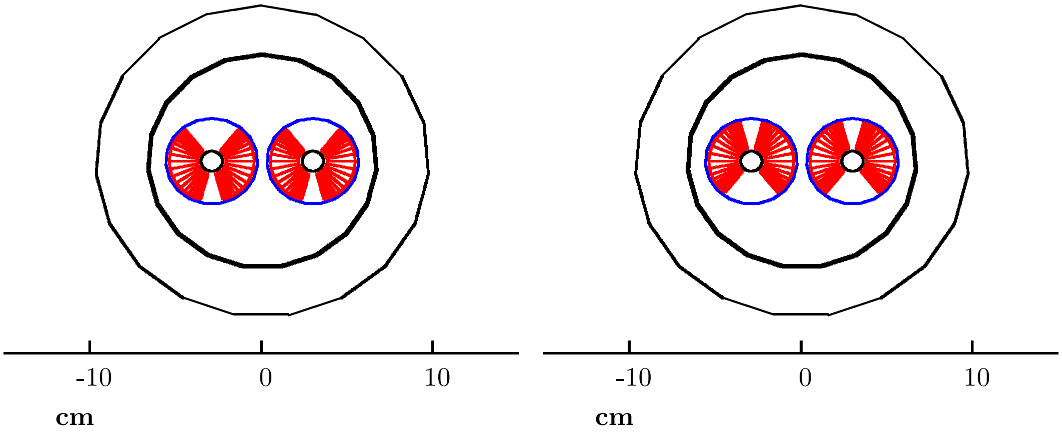
- An Invar yoke shell
- A Titanium (as suggested by Foster), or other low expansion, but non magnetic, inside helium containment pipe.
- A floating uncooled perforated liner. This would also have to be made of a low expansion metal. For impedance considerations it would be desirable to use a low conductivity material, or plating, for, or on, the liner. Tungsten or Be might be considered, because they, unlike titanium, have high conductivity.

5.1.3 Skew Combined Function

In such a continuous magnet, focusing must be supplied by periodically changing the magnet cross sections so as to generate alternating gradients. The changes from one gradient to the other can easily be made slow enough to avoid problems with the NbSn.

Conventional alternating gradients could be achieved by alternating horizontal displacements of the poles, and introducing spacers between the conductors, first on one side and then on the other. This can be done, but a much simpler way has been proposed by Brett Parker:

Instead of combining the bend field with upright quadrupoles (gradient of bending with horizontal position), one can combine the bending field with alternating skew quadrupoles. In this case there is also an ”alternating gradient”, but the gradient is of the bending field with respect to the vertical dimension. This can be generated by alternating the widths of the poles, leaving the entire coil packages the same. No spacers are required. The alternation is generated simply by changing the iron laminations:



5.1.4 Low stored Energy

- **No Collar**

  At low fields, as in RHIC, there is no need for a collar. The conductors can by insulated by a kapton layer and supported directly by the iron yoke laminations. The use of iron in the pole pieces would normally be rejected because of the saturation effects, but with separate powering of the conductors, such effect can easily be corrected.

- **NbSn**

Since the conductors do not have to go round any ends, there should be no problem with the use of react and ”wind” NbSn (or NbAl).The higher current density in this material allows the conductors to be narrower, nearer to the pipe and thus more efficient.

- **Separate stabilizing Copper**

  Again, in order to reduce the radial width of the conductor, and thus bring it closer to the beam and increase its efficiency, we could allow a high copper current density (3000 A/mm^2) in the sc cable, but add a separate outer copper cable, wrapped in the same insulation as the superconductor. In the calculations here, the average current density in both cables is kept to the previous specification of 1000 A/mm^2. However, there is little cost constraint on the radial extent of this outer copper cable, so it may be chosen to make the total cable near, or fully, cryostable.

  With this modification the cost drops by approximately 10 %, and the stored energy is reduced by 33% to 5000 T^2m^2: less than twice the Pipeatron (2800 T^2m^2).

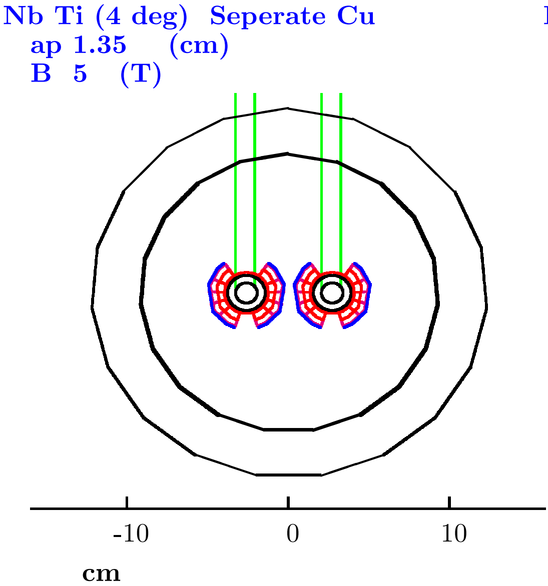
5.2 Optimized Design

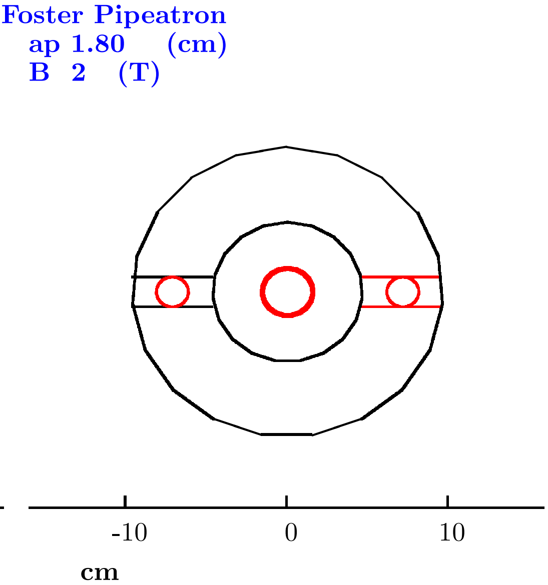
Parameters for this design are:

B	j	j$_{SC}$	lin	sc	Cu	coll	fe	shell	cryo	mag	Tot	/SSC
T	A/mm^2	A/mm^2	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	k$/m	B$	
5.0	1372	4006	6.7	2.30	0.12	0.00	1.15	0.04	1.46	5.1	1.01	0.27

B	r$_{vac}$	ir$_{coil}$	r$_{sc}$	r$_{Cu+SC}$	r$_{collar}$	r$_{yoke}$	t$_{shell}$	press	B Fe	Cu/sc	I/mag	U$_{mag}$
T	cm	cm	cm	cm	cm	cm	cm	MPa	T		kA turns	T^2m^2
5.0	0.7	1.4	1.9	2.3	2.4	9.2	0.1	65	0.98	1.3	367	5.0k

The following figure shows the resulting ”Minatron” design with a skew combined function field and vacuum pumping ports. A pipeatron design is shown for comparison.





6 Conclusion

This study suggests that:

- A 2-in-1 magnet system would cost about 20% less than a 1-in-1 SSC design, and the total ring cost, including linear terms, would cost about 10% less.
- The cost optima for 2-in-1 magnets are at relatively low magnetic fields (5-8 T). For example: a NbSn 2-in-1 design, assuming NbSn costs double NbTi, has a minimum at 7.2 T. A 12.5 T magnet ring would cost 30% more than a ring at 7.5 T.
- With the same cost and impedance assumptions, a Pipeatron ring, with large aperture and SSC linear costs, is more expensive than dipole designs (1.6 times SSC).
- As noted by Bill Foster significant cost savings can come from:
  - Reducing the beam aperture, e.g. eqivalent to a 30 times greater impedance.
  - Making a continuous simple magnet with no separate quads or ends, e.g. resulting in a factor of 3 less "linear" cost.
- A Pipeatron with these assumptions is cheaper (.47 times SSC) than one with Dipole magnets and conventional assumptions.

- But with the same small aperture and low linear cost assumptions, a cost minimized 2-in-1 design would cost about 1/2 of a pipeatron, about 1/3 of a 2-in-1 with conventional assumptions, and about 1/4 of the SSC.

Warning

The formulae used here are approximate and were not intended to give real designs. The costs of materials etc. date back 1983 and have not been checked since. A study of this type is not expected to provide accurate costs. It is hoped that the depedencies observed will be qualitatively correct, but this cannot be guaranteed. These results should thus be regarded as only suggestive. They can best be used to motivate further study.