Cooling cells + Refrigeration

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IIT

2-day Meeting on:
Feasibility of a Neutrino Source Based on a Muon Storage Ring

Fermilab
Feb 15, 2000

Cooling Channel:

- Series of energy absorbers sandwiched between RF cavities enclosed in superconducting solenoids
- Variety of lattice designs have been considered:

  Alternating solenoid

  FOFO

  SFOFO

  RFOFO

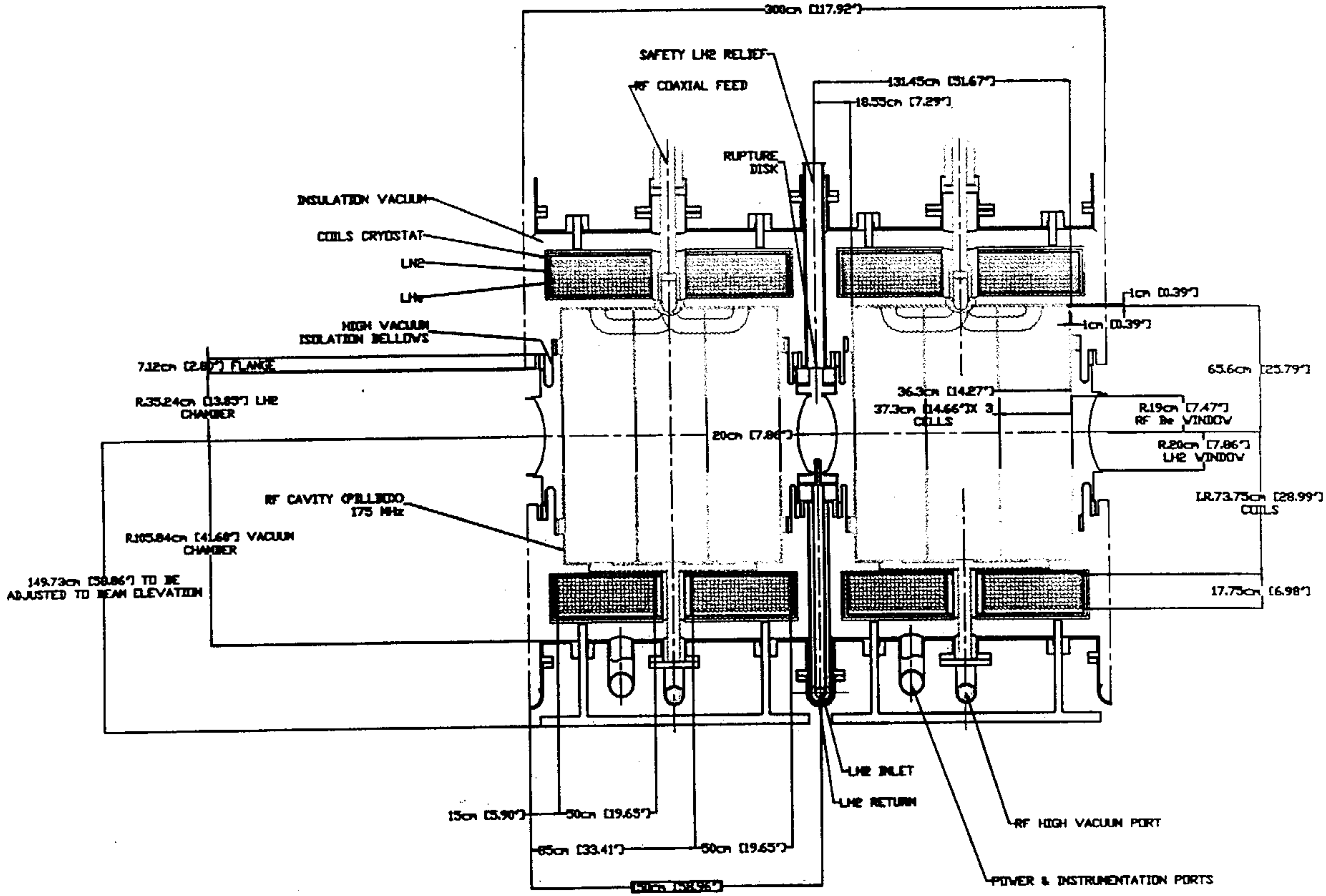
  DFOFO

  ...

- Major components:

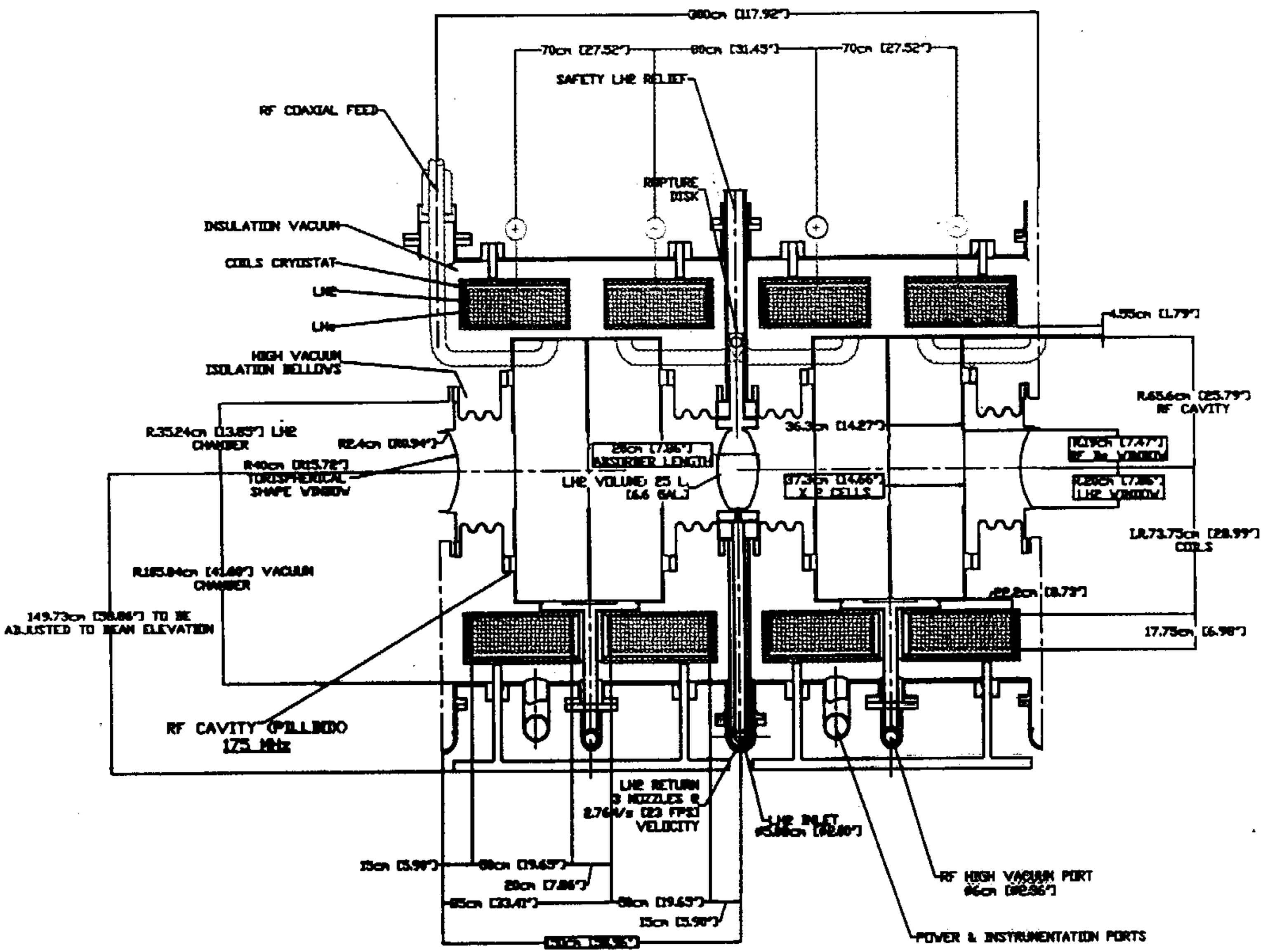
  1. Vacuum vessels
  2. Cryostats
  3. Coils
  4. Absorber assembly
  5. Refrigeration
  6. Controls
  7. Vacuum system
  8. Safety systems

(NOTE: RF cavities, feeds, and power supplies excluded
→covered by other speakers)



First Stage DFOFD Cooling Channel LATTICE

E.L.Black
01/27/2000



1stDFOFO2cell214BK

DFOFO (2 cell RF) Cooling Channel LATTICE

+	−	+	−	DFOFO
+	+	−	−	FOFO

Superconducting Coils

- Most expensive component
- Challenge: must satisfy current-density constraints!
- Example 1: E. Kim's "DFOFO1":

  B_{max} on axis ≈ 3.3 T

  B_{max} at coil ≈ 16.5 T ⇒ $J_{max} \approx 90$ A/mm² (Nb_3Sn) [NHMFL]

  But: $J \approx 158$ A/mm²

- Example 2: C. Kim's "Case 2":

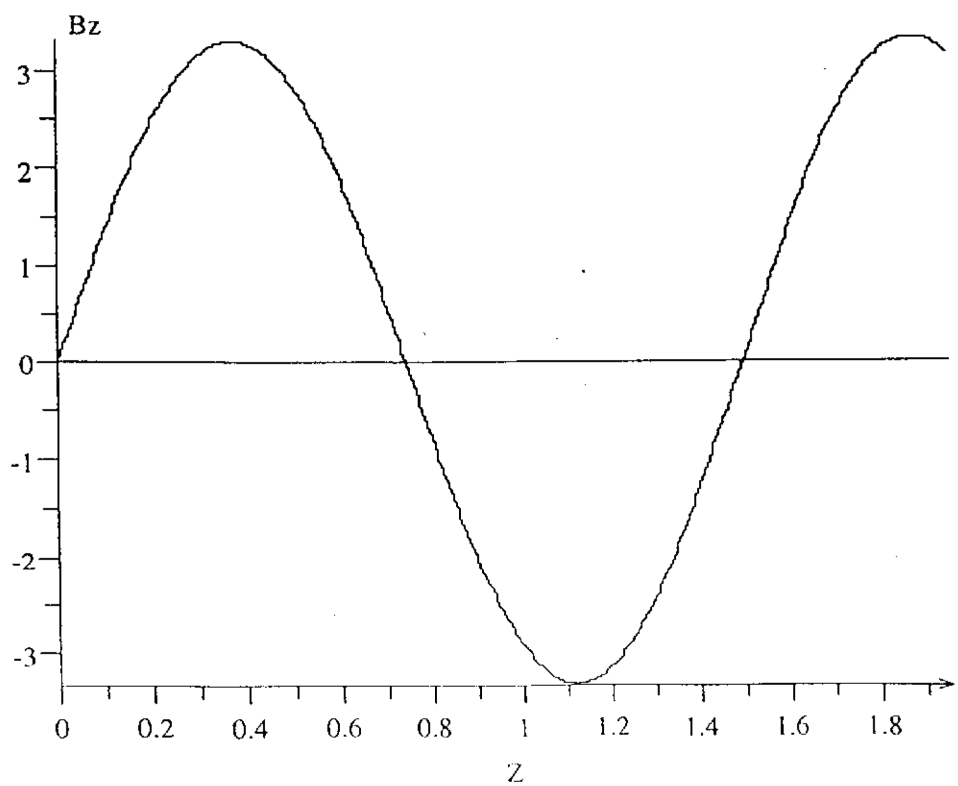
  B_{max} on axis ≈ 6.8 T

  $J \approx 132$ A/mm²

  B_{max} at coil ≈ 2 T ⇒ NbTi OK

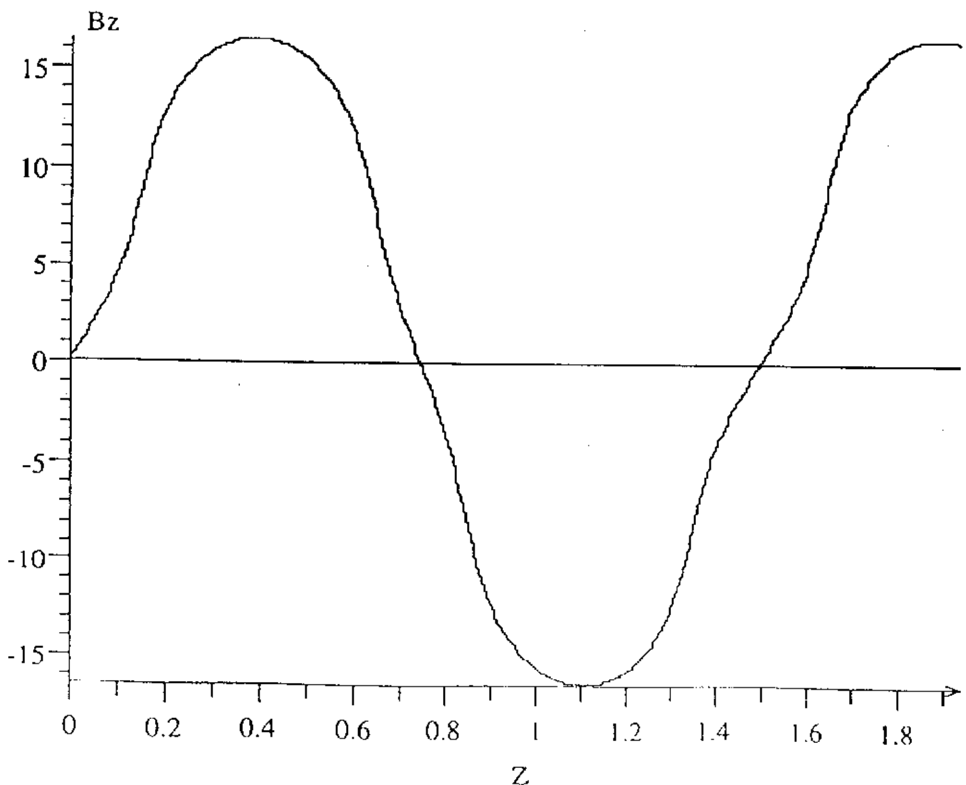
D F0F01

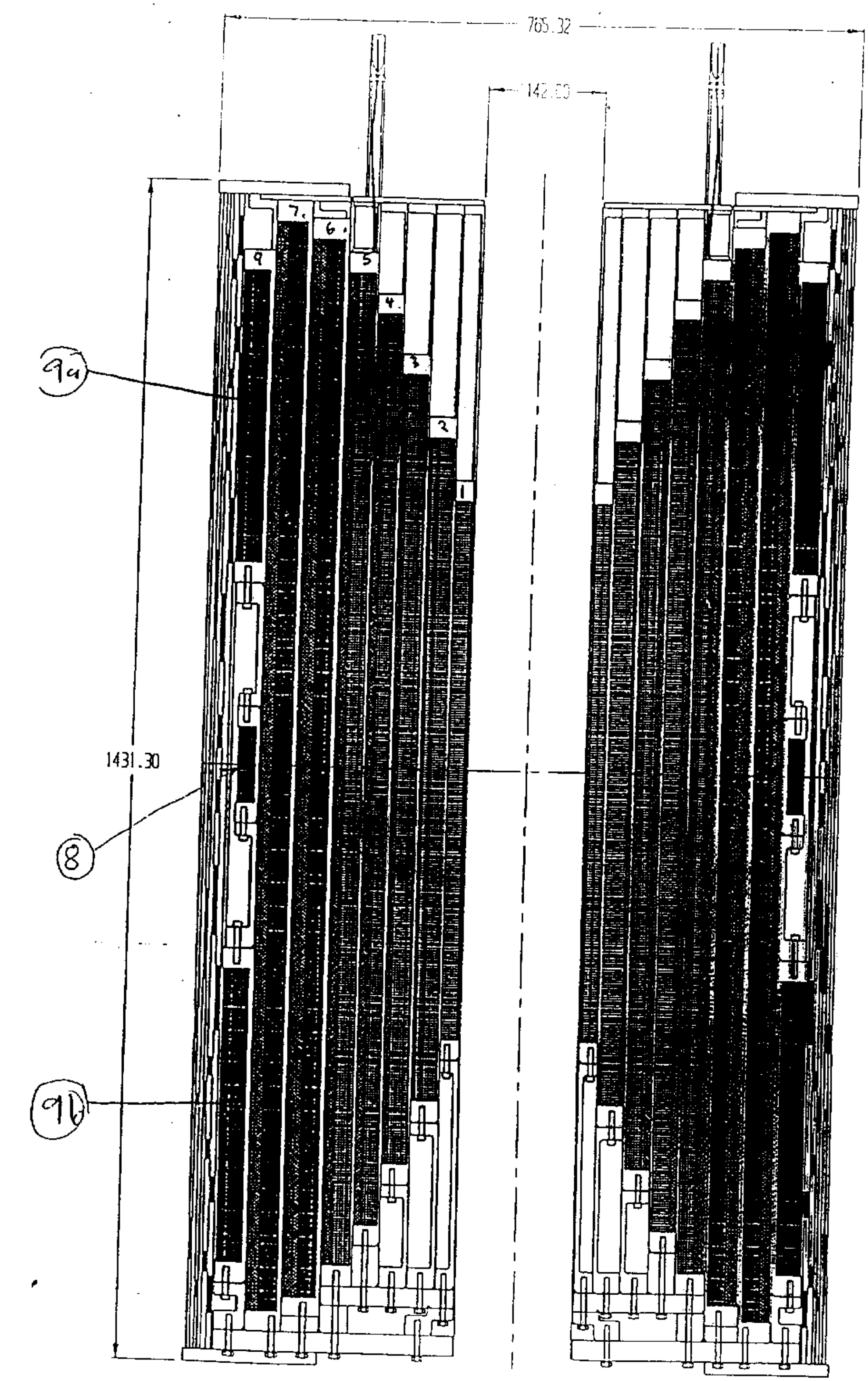
Bz at Radius 0.00000



DFOF01

Bz at Radius 0.73000





NHMFL

900 MHz NMR Magnet
Benchmark Design
V4013108.A3L

DATE
2/7/94

Cooled w/ Superfluid LHe @ 1.8K → < 2.16K
All coils epoxy-impregnated

Dimensions						
a_1	a_2	zmin	zmax	zmax	J_{av}	Field
m	m	m	m	m	A/mm^2	T
0.0750	0.0973	-0.3401	0.3401	0.34	38.57	21.10
0.1032	0.1265	-0.4101	0.4101	0.41	48.52	19.99
0.1325	0.1590	-0.5015	0.5015	0.50	67.76	18.51
0.1726	0.2015	-0.5917	0.5917	0.59	92.35	16.25
0.2265	0.2517	-0.6714	0.6714	0.67	120.44	13.53
0.2856	0.3089	-0.7509	0.7509	0.75	113.62	10.45
0.3392	0.3634	-0.7506	0.7506	0.75	131.12	7.82
0.4149	0.4336	-0.1089	0.1089	0.11	142.40	2.50
0.3899	0.4389	0.2967	0.6162	0.62	142.21	6.18
0.3899	0.4389	-0.2967	-0.6162	-0.62	142.21	6.18

Nb_3Sn (first five rows)

NbTi (last five rows)

LH_2 Absorbers

Specifications:

Param. \ Config:	**"FNAL"**	**"LBL1"**	**"LBL2"**	**unit**
L	56	14	20	cm
ρ	0.0742	0.0742	0.0742	g/cm^3
areal mass density	4.2	1.0	1.5	g/cm^2
r	20	20	20	cm
V	70	18	25	*l*
T	17	17	17	K
P	1	1	1	atm
b.p.	20.2	20.2	20.2	K
f.p.	13.8	13.8	13.8	K

⇒ "LBL2" is typical of latest configurations

Absorber Heat Load

- What muon rate in?

Assume:

1. $P_{p\text{-source}} = 1.5$ MW
2. 0.1 μ/p into cooling channel
3. 15 Hz

$\Rightarrow 4 \times 10^{12}$ μ/pulse

- Energy absorption vs. muon momentum:

p_μ	‹dE/dx›	‹ΔE›	‹P› (4.10[12]@15Hz)	
(MeV/c)	[MeV/cm]	(MeV)	(W)	
106	0.46	26	247	56 cm
211	0.31	17	168	
317	0.30	17	164	
106	0.46	6.4	62	14 cm
211	0.31	4.4	42	
317	0.30	4.3	41	
106	0.46	9.2	88	20 cm
211	0.31	6.2	60	
317	0.30	6.1	58	

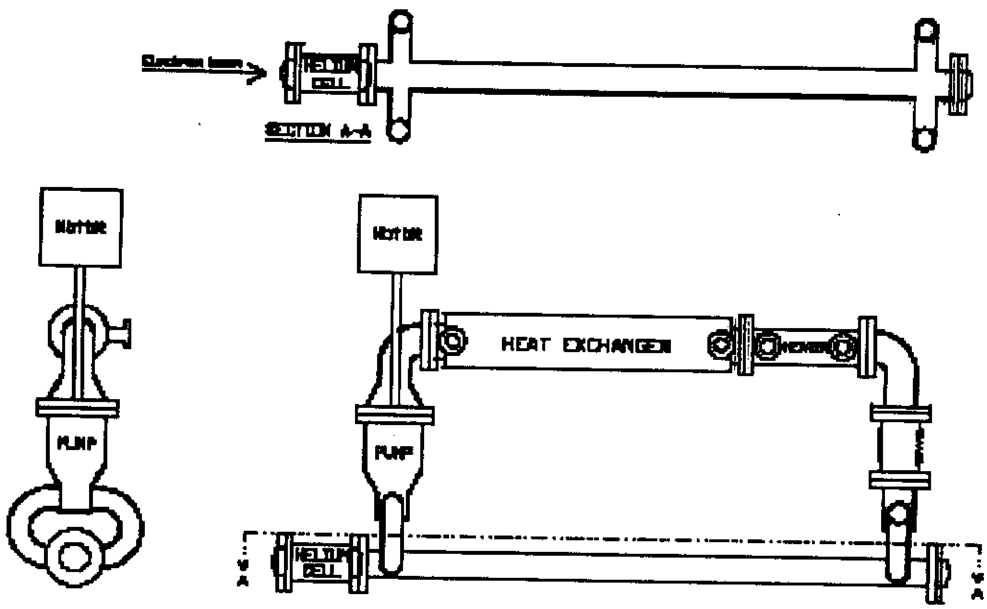
$\Rightarrow$ Take 100W/absorber as $\approx$worst case

Key Problem:

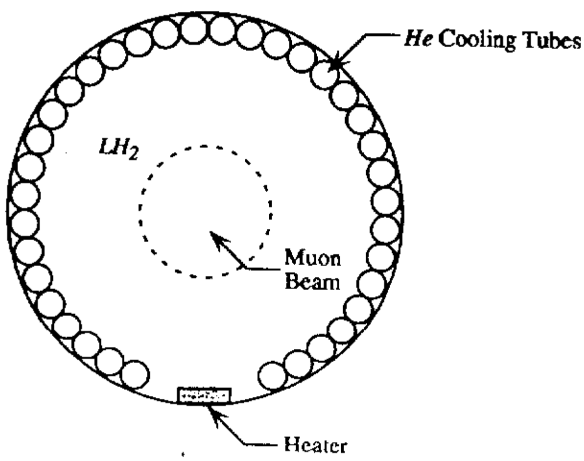
- How to get the heat out?

→ Two design approaches:

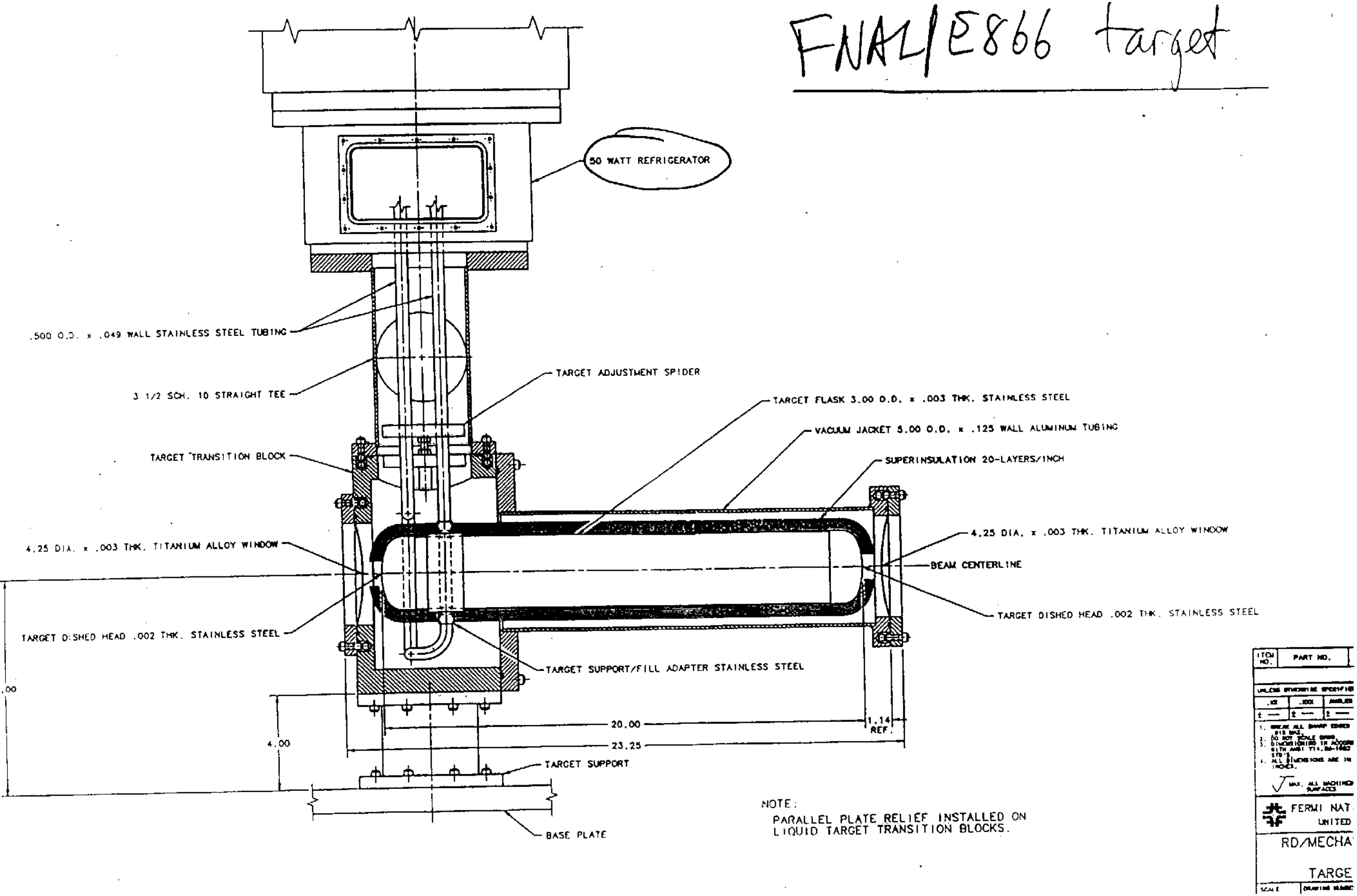
1. External cooling loop



2. Absorber as heat exchanger



FNAL/E866 target



NOTE:
PARALLEL PLATE RELIEF INSTALLED ON LIQUID TARGET TRANSITION BLOCKS.

LH_2 Cooling

1. External-loop design (á là SLAC, Bates...):

$$c_p = 7.9 \times 10^3 \text{ J/kg}\cdot\text{K}$$

$$\Delta T / s = \frac{\langle P \rangle}{c_p V \rho}$$

$$\leq \frac{100\,\text{W}}{7.9 \times 10^3\,\text{J/kg}\cdot\text{K} \times 25\,l \times 0.0742\,\text{kg}/l} \approx 0.007 \text{ K/s}$$

$\rightarrow$ Indep. of L since both $\langle P \rangle$, $V \propto L$

$\Rightarrow$ need < 0.007 volume change/s

= 0.17 l/s (20-cm case)

$\rightarrow$ easy!

LH_2 Cooling (cont'd)

2. Convection approach (K. Cassel, IIT):

Rate of heat transfer from LH_2 to He coolant:

$$\dot{q} = -\frac{A(T_o - T_i)}{\left(\frac{1}{h_{LH_2}} + \frac{\Delta x}{k_w} + \frac{1}{h_{He}}\right)\ln\left(\frac{T_{LH_2} - T_o}{T_{LH_2} - T_i}\right)}$$

where

A	=	surface area of cooling tubes
T_i	=	temp. of helium in
T_o	=	temp. of helium out
T_{LH_2}	=	avg. temp. of LH_2
h_{LH_2}	=	convective heat transfer coeff. for LH_2
h_{He}	=	convective heat transfer coeff. for He
Δx	=	thickness of cooling-tube walls
k_w	=	thermal conductivity of cooling-tube walls

Example (20-cm case):

$$\dot{q} \approx -\frac{0.25\,\text{m}^2(15\text{K} - 14\text{K})}{\left(\frac{1}{300\text{W/m}^2\cdot\text{K}} + \frac{10^{-3}\text{m}}{170\text{W/m}\cdot\text{K}} + \frac{1}{1580\text{W/m}^2\cdot\text{K}}\right)\ln\left(\frac{17-15}{17-14}\right)}$$

≈ 155 W @ $\dot{m} = 12$ g/s $\Rightarrow \dot{m}/\rho = 3.4\ l/\text{s}$ (1 atm)

BUT - need to understand $h_{LH_2} \Rightarrow$ C.F.D. study

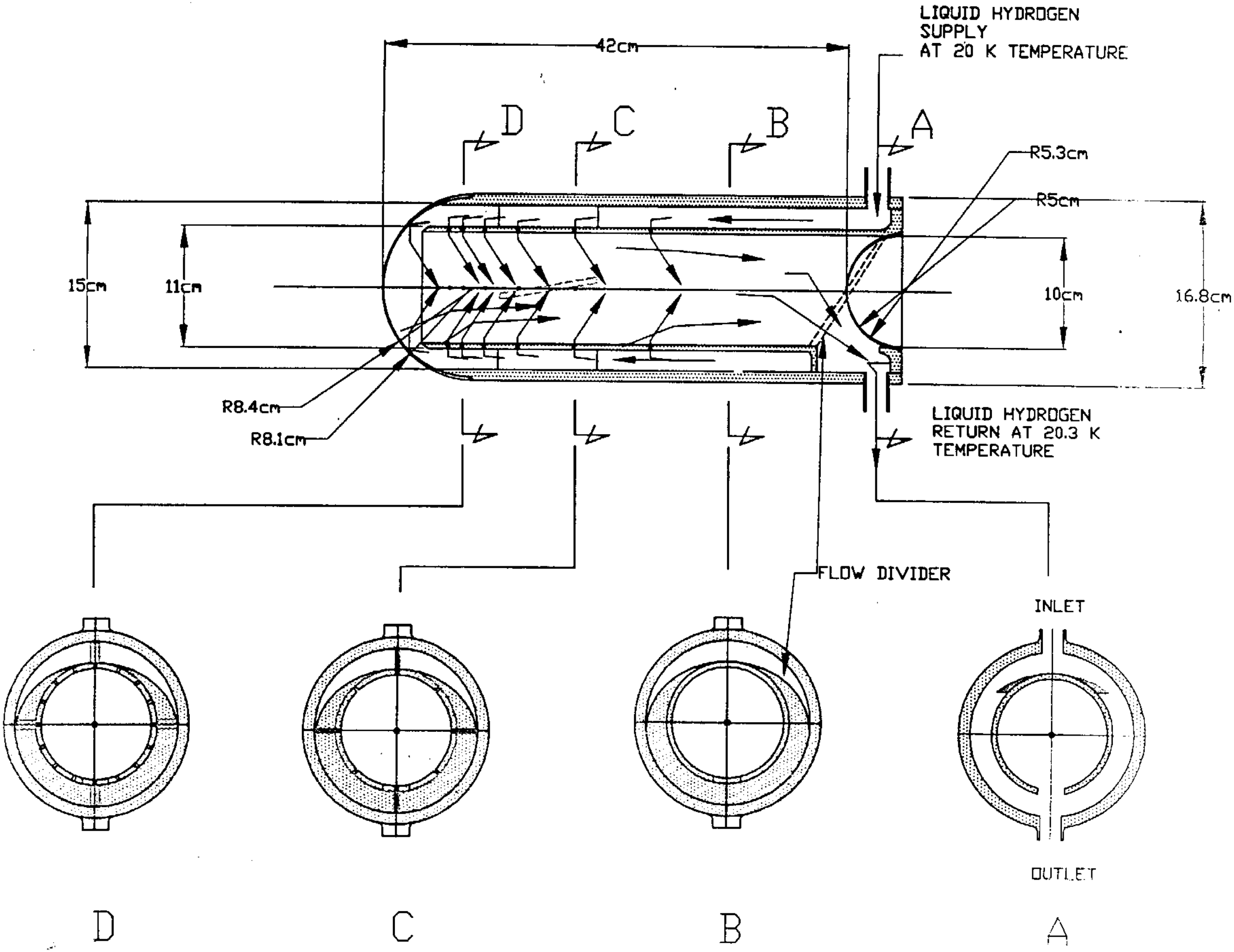
Spatial distribution of heat load:

- Energy deposition highly concentrated in the middle:

→ By end of cooling channel, areal power density along axis is $\approx 10^2 \times$ average over face of absorber

⇒ need to ensure cross-flow near beam rather than longitudinal flow

- occurs naturally in convective design
- also straightforward in external-loop design in FOFO-type channels
  (have unencumbered access to periphery)



LIQUID HYDROGEN
SUPPLY
AT 20 K TEMPERATURE
42cm
D
C
B
A
R5.3cm
R5cm
15cm
11cm
10cm
16.8cm
R8.4cm
R8.1cm
LIQUID HYDROGEN
RETURN AT 20.3 K
TEMPERATURE
FLOW DIVIDER
INLET
OUTLET
D
C
B
A

Window Thickness

Assume 1 atm pressure differential

- ASME UG-32, window thickness for pressure vessels:

hemispherical: $$t = \frac{0.5PL}{SE - 0.1P}, \quad s = L = 0.5D$$

ellipsoidal: $$t = \frac{0.5PD}{SE - 0.1P}, \quad s = 0.25D$$

torospherical: $$t = \frac{0.885PD}{SE - 0.1P}, \quad s = 0.169D$$

where
P = pressure differential
L = radius of curvature
D = length of major axis
S = max allowable stress
E = weld efficiency
s = sagitta

Notes:
1. ellipsoid has (major axis) = 2 × (minor axis)
2. torosphere has $r_2 = 6\% \; r_1$

- Fermilab/ASME safety factors:
  S = smaller of $S_u/4$, $S_y/1.5$

- Take $E \approx 0.9$ (inspected full-penetration welds), Al alloy:

$\Rightarrow t =$

0.14 mm	hemispherical	$D = 40\,\text{cm}$
0.29 mm	ellipsoidal	
0.51 mm	torospherical	

BRUSH WELLMAN
ELECTROFUSION PRODUCTS
44036 South Grimmer Boulevard • Fremont, California 94538
Tel: (510) 623-1500 • Fax: (510) 623-7600 • E-Mail: Electrofusion@BrushWellman.com

FAXED

Date: 10 February 2000

To: Fermi National Laboratory
Attn: **Mr. Edgar Black**
FAX (630) 840-6211

From: José Villanueva, Engineered Products Estimator Telephone (510) 661-9723

Subject: AlBeMet Ellipsoidal Dish Head
Ref.: 1) Your RFQ dated 19 January 2000
2) BW-Electrofusion Budgetary Quote Reference No. 2001090

Thank you for your inquiry. Edgar in our telephone conversation you asked me to also quote this assembly using beryllium or aluminum. To manufacture this assembly out of beryllium will require more time, and my understanding is that you are under a time restraint for your presentation. BW-Electrofusion is pleased to present the following quote:

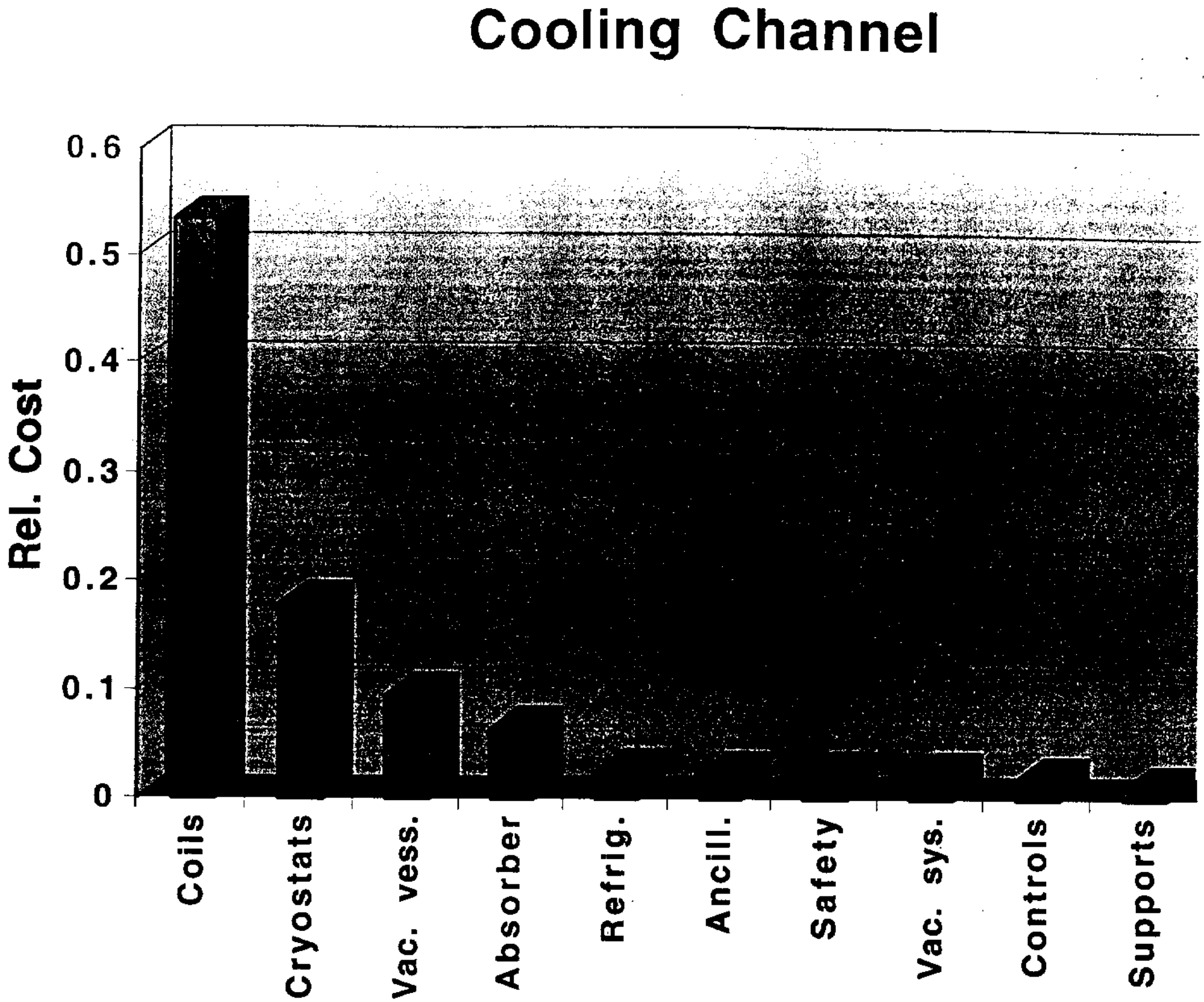
ITEM	DESCRIPTION	QTY	EACH	TOTAL
01	AlBeMet Machined and Electron Beam welded Ellipsoidal Dish Head to customer supplied Absorber W/Integral Heat Exchanger & Heater	3	$ 46,669.00	$140,007.00
		10	38,905.00	389,050.00
		20	36,859.00	737,180.00
		40	36,019.00	1,440,760.00

- Part to be leak tight to 1×10^{-9} std. cc/sec He
- BW-Electrofusion liability limited to our labor and material only when working with customer supplied components.
- Exception to your drawing: 0.002" center dimension to be 0.010"- 0.015"
- These commodities must be exported from the United States in accordance with the Export Administration Regulations. Diversion contrary to U.S. law prohibited.
- Nuclear end use/user or diversion requires approval by BW and US Dept. of Comm.
- Ship Date: TBD
- FOB: Fremont, California, U.S.A., prepaid and billed
- Quote validity: Budgetary Terms: Net 30 days

Please contact us if we may be of further assistance in any way.

Best Regards,

José Villanueva


Cooling Channel
Rel. Cost
0.6
0.5
0.4
0.3
0.2
0.1
0
Coils
Cryostats
Vac. vess.
Absorber
Refrig.
Ancill.
Safety
Vac. sys.
Controls
Supports

To Do:

1. Decide lattice
2. More performance optimization?
3. Consider system integration issues
4. Refine absorber parameters
   a. F.E. structural analysis
   b. C.F.D. calc. of fluid flow
   c. Understand window heating & pulsed effects
5. Get more bids
6. Finish detailed design
7. Safety review
8. Prototype and test windows
9. Prototype and test absorber cells (incl. high-power beam test)
10. Perform MUCOOL experiment to certify cooling performance