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Impact of high design pressures of the cryogenic transfer lines on heat inleaks

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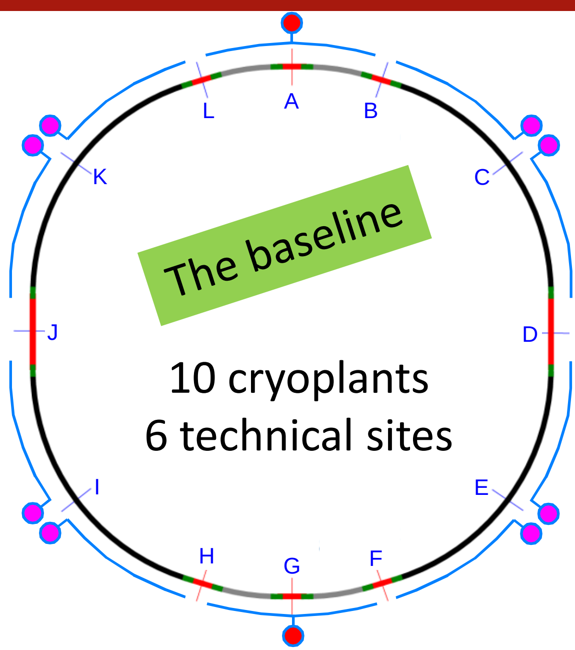
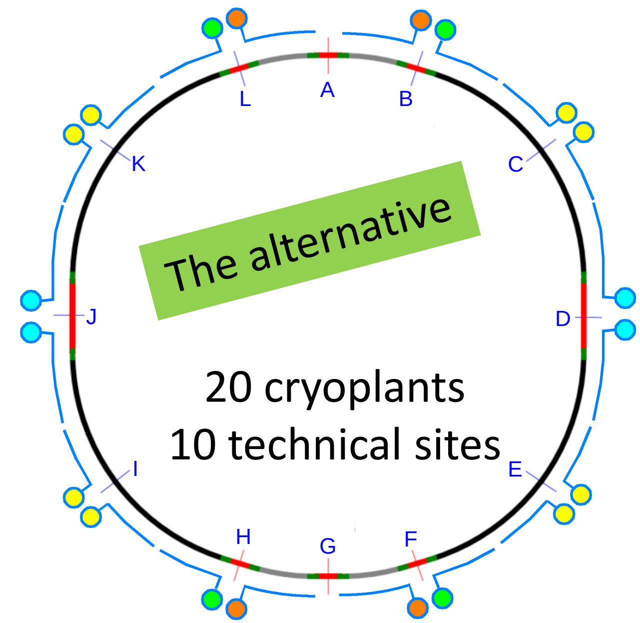
FCC Week, 14 April 2016 Rome

Contents

FCC Cryogenic system

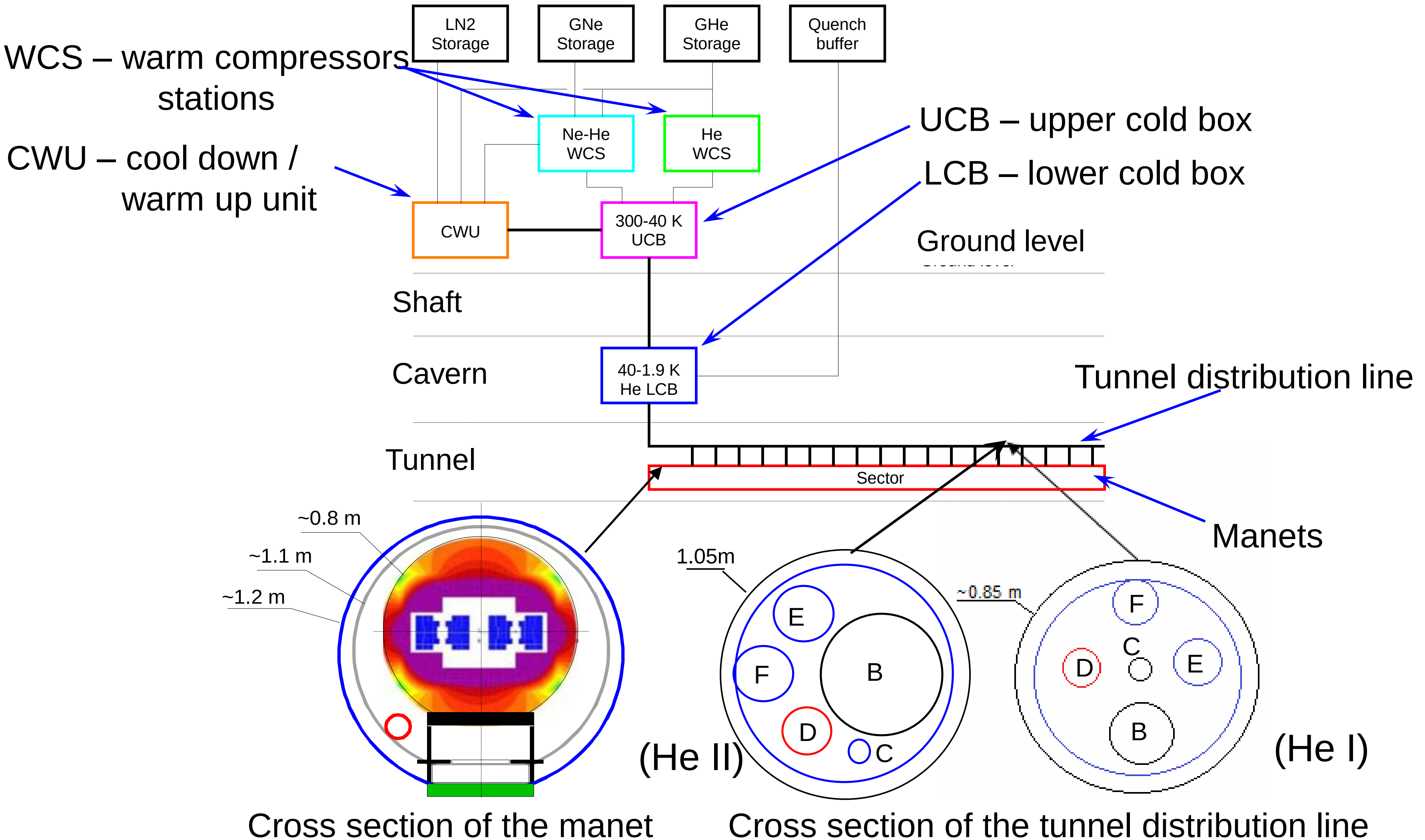




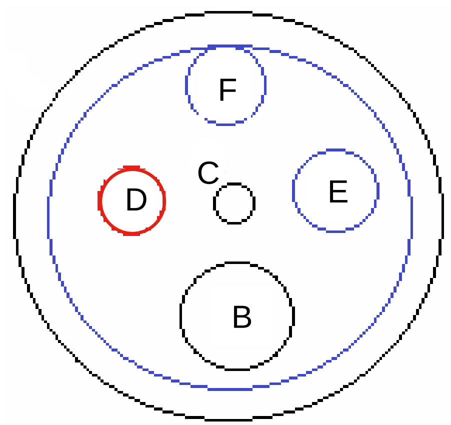
Cryoplant	L Arc+DS km	L distribution km
	2 x 4 = 8	2 x 4.7 = 9.4
	8.4	8.4

Cryoplant	L Arc+DS km	L distribution km
	4	4.7
	4.4	5.1
	4	4
	4.4	6.5

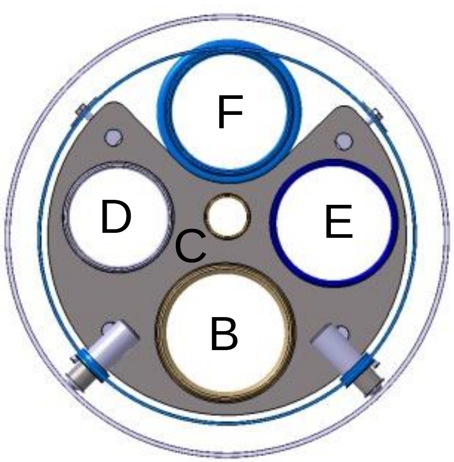
FCC Cryogenic system



Specification of the process pipes of tunnel distribution line of FCC



(He I)



Header	Function	DN mm	Nom. T K	Nom. P_N bar	Design P_D bar	Test P_T bar
Header B	Pumping line	250	4	0.5	4	6
Header C	SHe supply	80	4.6	3	20	29
Header D	Quench line and current lead He supply	200	40	1.3	20	29
Header E	Thermal shield and beam screen He supply	240	40	20 (50)	20 (50)	29 (71.5)
Header F	Thermal shield and beam screen He return	240	60	15 (45)	20 (50)	29 (71.5)
Vacuum jacket	Insulation vaccum enclosure	850	300	0	0 -1.05	1.5

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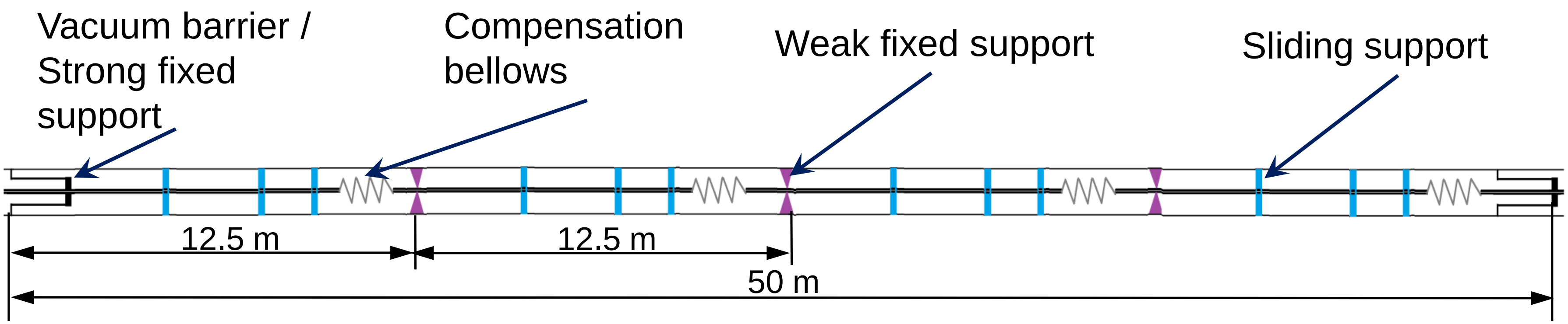
Scheme of the transfer line with stainless steel process pipes



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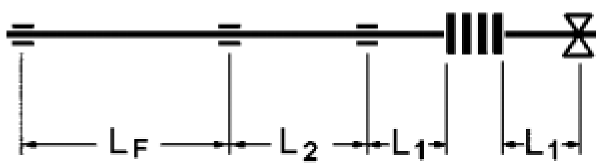
Transfer line compensation and internal support system

Determination of the distance between supports



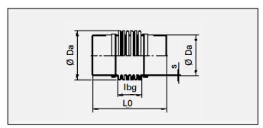
$L_1 = 3 \cdot DN$ – for axial expansion joints
$L_2 = 0.5 \cdot L_F$
L_F - depends on the accepted deflection and the risk of pipe buckling

The forces from pressure and thermal shrinkage

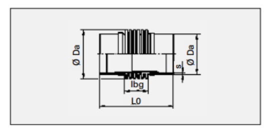
$F_{NP} = F_P - F_{TS}$ – for nominal parameters

$F_{TS} = \Delta L \cdot c_\delta$ – depends on nominal temperature

$F_P = A \cdot P$ - the highest value for the pressure test



Type ARN without inner sleeve



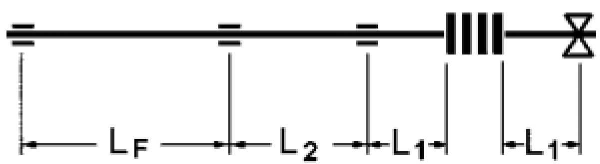
Type ARN with inner sleeve

Nominal dia-meter	Nominal axial movement absorption	Type	Order No. standard version		Overall length	Weight approx.		Weld ends		Bellows			Nominal movement absorption[1)] for 1000 loading cycles		Adjusting force rate		
		ARN 25 ...	without inner sleeve	with inner sleeve		without inner sleeve	with inner sleeve	outside diameter	wall thickness	outside diameter	corrugated length	effective cross-section	angular[1)]	lateral[1)]	axial	angular	lateral
DN	$2\delta_N$	–	–	–	Lo	G	G	D	s	Da	lbg	A	$2\alpha_N$	$2\lambda_N$	c_δ	c_α	c_λ
–	mm	–	–	–	mm	kg	kg	mm	mm	mm	mm	cm^2	degrees	mm	N/mm	Nm/degrees	N/mm
50	17	**.0050.017.0**	417621	417650	210	1.2	1.4	60.3	4	90	50	46.6	22	3.5	321	4.2	1113
50	32	**.0050.032.0**	417622	417651	270	1.8	2	60.3	4	91	110	47.2	33	15	199	2.6	144
65	21	**.0065.021.0**	417623	417652	215	1.8	2	76.1	4	109	55	70.1	23	4.1	272	5.3	1182
65	40	**.0065.040.0**	417624	417653	292	3.2	3.6	76.1	4	111	132	71.6	33	18	218	4.3	166
80	23	**.0080.023.0**	417625	417654	220	2.3	2.6	88.9	4	123	60	90.8	21	4.1	329	8.3	1555
80	42	**.0080.042.0**	417626	417655	290	3.6	4	88.9	4	125	130	92.5	32	17	222	5.7	227
100	23	**.0100.023.0**	417627	417656	212	2.8	3.1	114.3	4	151	52	140	18	3	340	13	3302
100	48	**.0100.048.0**	417629	417657	286	4.6	5.2	114.3	4	152	126	141	30	15	218	8.5	361
125	26	**.0125.026.0**	417630	417658	240	3.9	4.4	139.7	4	174	64	187	18	3.6	450	23	3864
125	52	**.0125.052.0**	417631	417659	304	5.3	6.1	139.7	4	174	128	187	29	14	225	12	483
150	29	**.0150.029.0**	417632	417660	240	4.9	5.5	168.3	4.5	205	64	267	17	3.4	440	33	5410
150	58	**.0150.058.0**	417633	417661	304	6.8	7.7	168.3	4.5	205	128	267	27	13	220	16	676
200	26	**.0200.026.0**	417635	417662	252	8.5	9.4	219.1	6.3	261	72	443	12	2.6	855	105	13759
200	52	**.0200.052.0**	417636	417663	324	11.3	12.6	219.1	6.3	261	144	443	20	11	428	53	1722
200	71	**.0200.071.0**	417637	417664	378	15.2	17.1	219.1	6.3	262	198	445	23	19	376	46	802
250	24	**.0250.024.0**	417638	417665	240	11.5	12.5	273	7.1	320	60	679	8.7	1.6	1298	245	46135
250	48	**.0250.048.0**	417639	417666	300	15.1	16.5	273	7.1	320	120	679	16	6.4	649	122	5762
250	79	**.0250.079.0**	417640	417667	380	19.8	22	273	7.1	320	200	679	21	18	390	74	1245

Transfer line compensation and internal support system

Increases the number of sliding supports

Determination of the distance between supports



$L_1 = 3 \cdot DN$ – for axial expansion joints
$L_2 = 0.5 \cdot L_F$

L_F - depends on the accepted deflection and the risk of pipe buckling

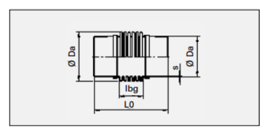
The forces from pressure and thermal shrinkage

$F_{NP} = F_P - F_{TS}$ – for nominal parameters

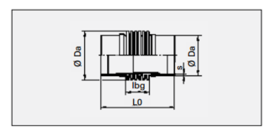
$F_{TS} = \Delta L \cdot c_\delta$ – depends on nominal temperature

$F_P = A \cdot P$ - the highest value for the pressure test

The most critical - determines the dimensions of the strong fixed support



Type ARN without inner sleeve



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DN	$2\delta_N$	–	–	–	Lo	G	G	D	s	Da	lbg	A	$2\alpha_N$	$2\lambda_N$	c_δ	c_α	c_λ
–	mm	–	–	–	mm	kg	kg	mm	mm	mm	mm	cm^2	degrees	mm	N/mm	Nm/degrees	N/mm
50	17	**.0050.017.0**	417621	417650	210	1.2	1.4	60.3	4	90	50	46.6	22	3.5	321	4.2	1113
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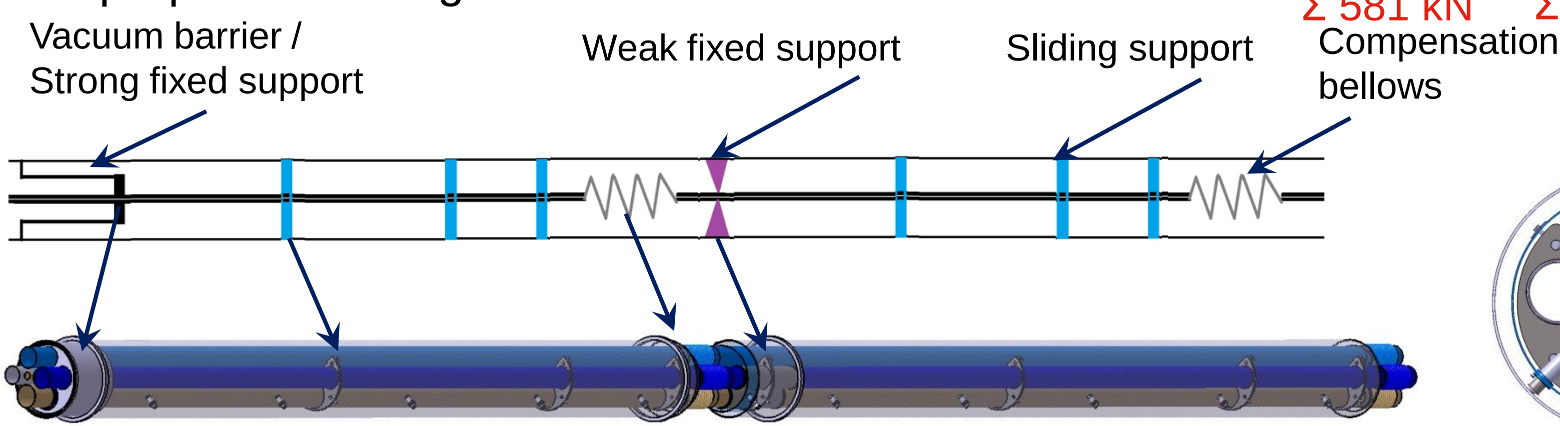
250	48	**.0250.048.0**	417639	417666	300	15.1	16.5	273	7.1	320	120	679	16	6.4	649	122	5762
250	79	**.0250.079.0**	417640	417667	380	19.8	22	273	7.1	320	200	679	21	18	390	74	1245

Mechanical loads on the vacuum barriers

	Parameters of bellows					Parameters of process pipes					Determination of forces				
	2δ	A	c_δ	c_α	c_λ	Nom. P	Design P	Test P	ΔL	Prestr.	F_P	$F_{\Delta L}$	F_{NP}	F_{P20bar}	F_{P50bar}
	mm	cm2	N/mm	N/deg	N/mm	bar	bar	bar	mm	mm	kN	kN	kN	kN	kN
DN80	42	92.5	222	5.7	227	3	20	28.6	37.5	20	-2.8	3.9	1.1	-26	-26
DN200	52	443	428	53	1722	1.3	20	28.6	37.5	20	-5.8	7.5	1.7	-127	-127
DN240F	79	679	390	74	1245	20 (50)	20 (50)	28.6 (71.5)	37.5	20	-135.8	6.8	-129.0	-194	-485,5
DN240R	79	679	390	74	1245	15 (45)	20 (50)	28.6 (71.5)	37.5	20	-101.9	6.8	-95.0	-194	-485,5
DN250	79	695	370	78	1350	0.5	4	5.72	37.5	20	-3.5	6.5	3.0	-40	-40

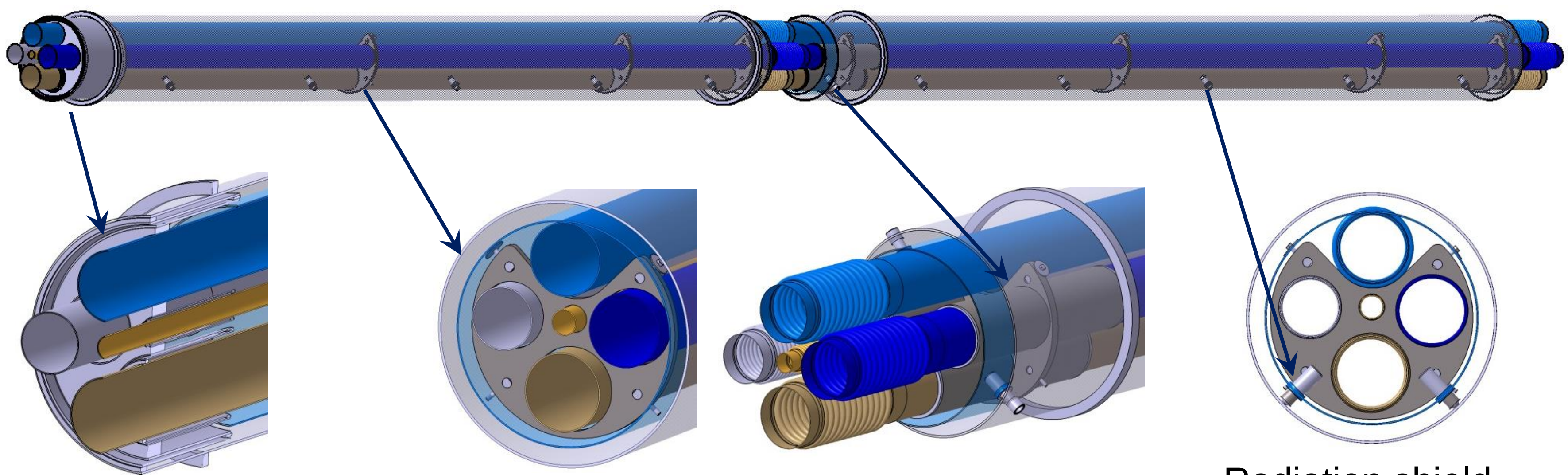
Σ 581 kN   Σ 1163 kN !

The proposal of design



Cross section

Heat transfer thought the internal supports



Vacuum barrier x 2 Sliding support x 12 Weak fixed support x 3 Radiation shield sliding support x 20

	$Q_{VB\ 20bar}$ W	$Q_{VB\ 50bar}$ W	Q_{SS} W	Q_{WFS} W
DN80	0.2	0.3	0.33	0.07
DN200	1.28	1.45	0.03	0.1
DN240 F	1.41	2.13	0.03	0.1
DN240 R	33.71	39.65	-0.63	7.9
DN250	1.21	1.53	0.24	0.5

	Q_{RSSS} W
DN240 R	3.1

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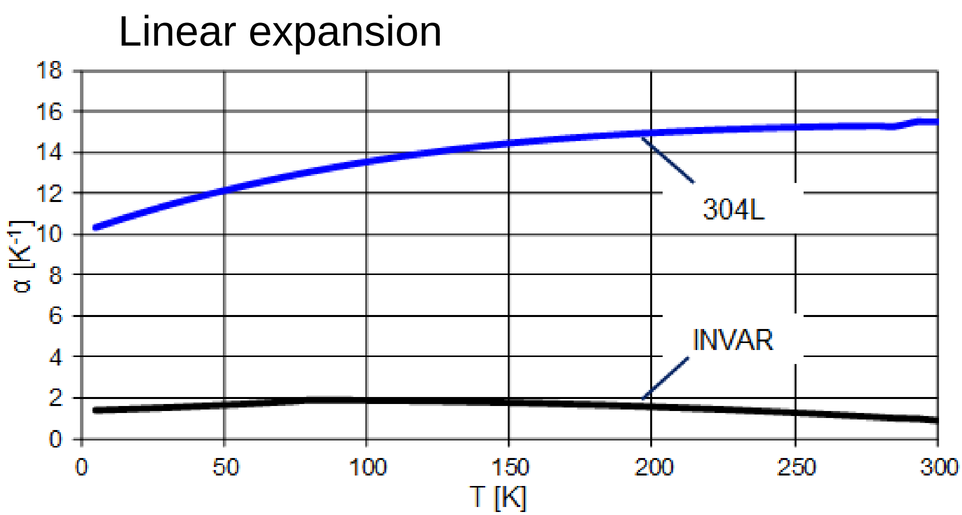
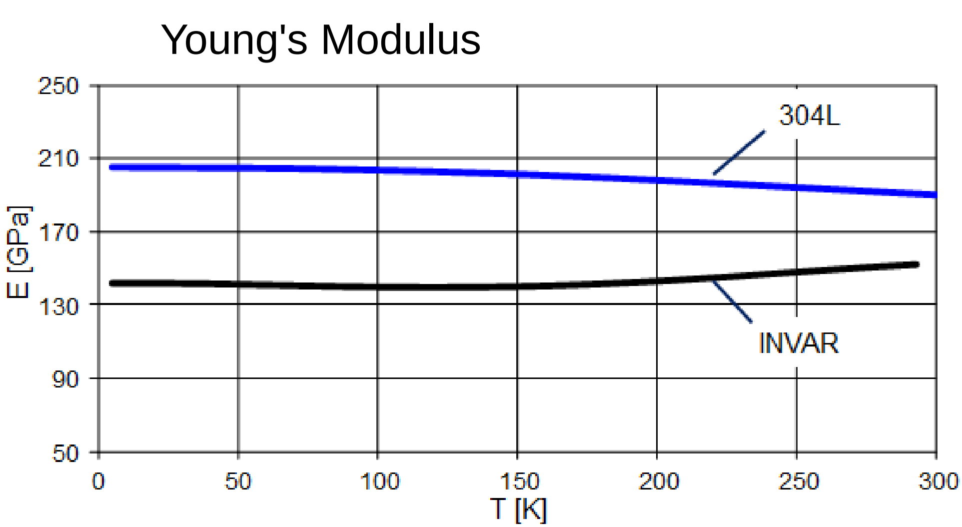
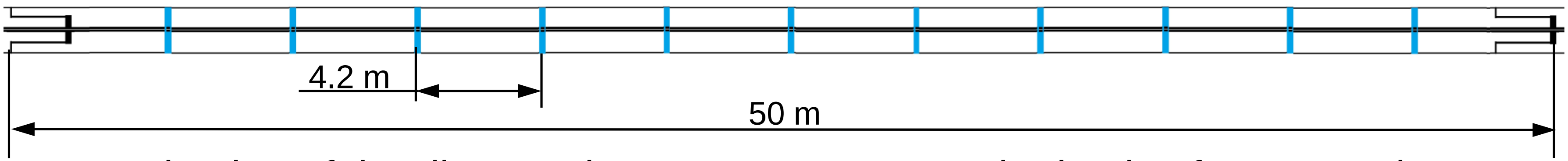
INVAR vs. stainless steel - comparison of material properties





Material	Units	Invar 36	304 Stainless Steel
Density	g/cm^3	8.05	8.00
Young's Modulus	GPa	141	193
Poisson's Ratio	-	0.26	0.27
Yleld Strength	MPa	248	230-260
Thermal Expansion Coefficient	x10^{-6}K^{-1}	1	14.7
Thermal Conductivity	W/m K	10.4	16.2
Specific Heat	J/kg K	515	500
Specific Stiffness	-	17.5	24.1
Thermal Diffusivity	10^{-6} m^2/s	2.6	4.1
Thermal Distortion (Steady State)	μm/W	0.10	0.91
Thermal Distortion (Transient)	s/m^{2}K	0.38	3.68

Mechanical loads on the vacuum barriers for INVAR process pipes



Determination of the distance between supports on the basis of process pipes permissible deflection f = 3 mm

$$x = \min \left| \sqrt[4]{\frac{87\, f E \left(D_i^4 - d_i^4\right)}{20\, g\, \left(\rho_{INV} \left(D_i^2 - d_i^2\right) + \rho_{He} d_i^2\right)}} \right|_i^1$$

i – number of process pipe

Determination of forces on the vacuum barriers based on Hooke's law

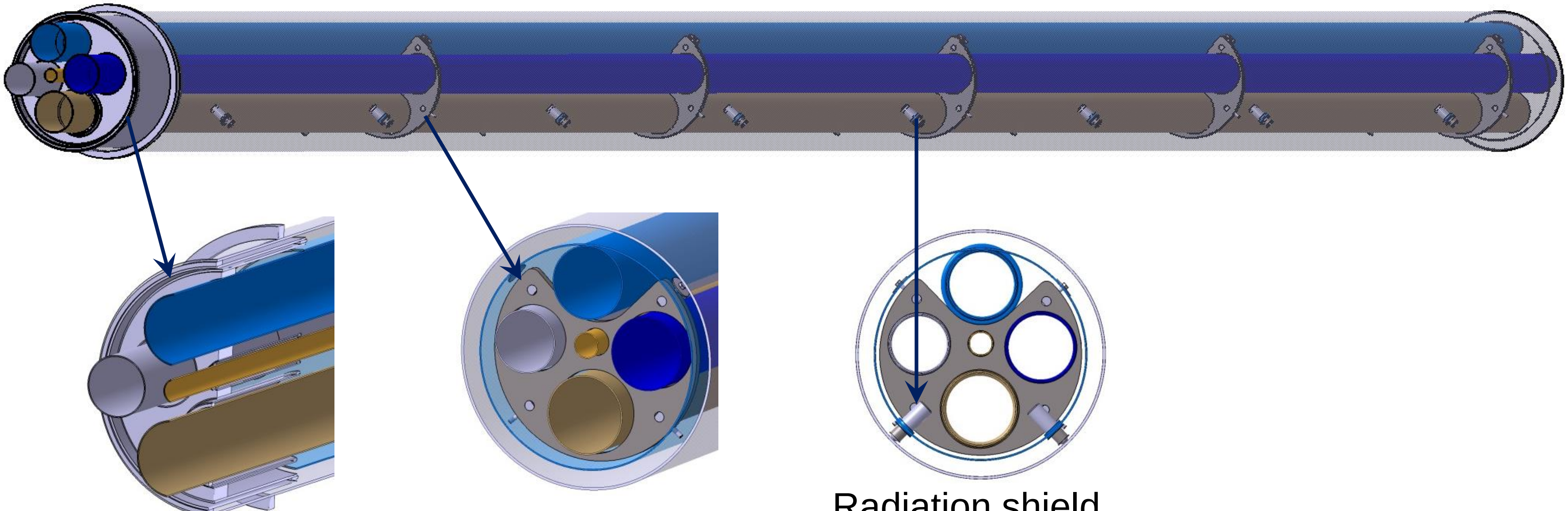
$$F = AE \frac{\delta l}{L}$$

A – cross section of process pipe
E - Young's Modulus
δl – thermal shrinkage
L - distance between the vacuum barriers

	T	δ l	L	A	E	F
	K	mm	m	mm²	GPa	kN
DN80	4.6	20	50	546	141.7	30.94
DN200	40	20	50	1836	141.7	104.0
DN240 F	40	20	50	2384	141.7	135.1
DN240 R	60	20	50	2384	140.8	134.3
DN250	4	20	50	1703	141.7	96.5

The forces acting of the supports slightly dependent on the preassure **Σ 501 kN**

Heat transfer thought the internal supports for INVAR process pipes



Vacuum barrier x 2 Sliding support x 11 Radiation shield sliding support x 20

	Q_{VB} W	Q_{SS} W
DN80	0.19	0.33
DN200	1.21	0.03
DN240 F	1.33	0.03
DN240 R	27.42	-0.63
DN250	1.17	0.24

	Q_{RSSS} W
DN240 R	3.1

- lighter construction of the vacuum barrier
- sliding supports structure is the same as for steinless steel pipes

Contents

Comparison of the supports system and heat fluxes

	Number of VB	Number of WFS	Number of SS	Number of SSRS	Number of welds	Number of bellows
Stainless steel	2	3	12	20	80	20
INVAR	2	0	11	20	25	0

	T	Q_{STELL} 20bar	Q_{STELL} 50bar	Q_{INV}
	K	W	W	W
DN80	4.6	4.6	4.6	4.0
DN200	40	3.2	3.7	2.8
DN240 F	40	3.5	4.9	3.0
DN240 R	60	146	158	110
DN250	4	6.8	7.4	5.0

Comparison of cumulative failure rates

Probabilities of defect occurrence (failure rates) of the most common process pipes defects

Stainless steel		
Defect	Failure rate	Ref
FR_1 Cold weld rupture	$2.53\cdot10^{-7}$ $m^{-1}\cdot year^{-1}$	[1]
FR_2 Cold pipe leakage	$4.61\cdot10^{-6}$ $m^{-1}\cdot year^{-1}$	[2]
FR_3 Cold pipe rupture	$4.54\cdot10^{-7}$ $m^{-1}\cdot year^{-1}$	[2]
FR_4 Cold bellows rupture	$8.76\cdot10^{-5}$ $year^{-1}$	[3]

INVAR	
Defect	Failure rate
FR_1 Cold weld rupture	$5.06\cdot10^{-7}$ $m^{-1}\cdot year^{-1}$
FR_2 Cold pipe leakage	$4.61\cdot10^{-6}$ $m^{-1}\cdot year^{-1}$
FR_3 Cold pipe rupture	$4.54\cdot10^{-7}$ $m^{-1}\cdot year^{-1}$

Calculation of cumulative failure rate CFR

$CFR_1 = FR_1\cdot L_W$ L_W - length of welds

$CFR_2 = FR_2\cdot L_P$ L_W - length of pipe

$CFR_3 = FR_3\cdot L_P$

$CFR_4 = FR_4\cdot n$ n - the number of bellows

1. Cadwallader L.C.. Cryogenic System Operating Review for Fusion Application. Idaho National Engineering Laboratory. USA. 1992
2. Failure Frequency Guidance. Process Equipment Leak Frequency Data for Use in QRA. http://www.dnv.com/services/software/products/phast_safeti/safeti/leak_frequency_guidance.asp
3. Cadwallader L. Vacuum Bellows. Vacuum Piping. Cryogenic Break and Copper Joint Failure Rate Estimates for ITER Design Use. Idaho National Laboratory. USA. 2010

Comparison of cumulative failure rates

Calculation of cumulative failure rate for stainless steel

	Circuit of pipe	Length of pipe	Number of welds	Length of welds	Number of bellows	CFR_1	CFR_2	CFR_3	CFR_4	CFR
	m	m	-	m	-	1/yer	1/yer	1/yer	1/yer	1/yer
DN80	0.279	50	16	14.0	4.0	2.3E-06	2.3E-04	2.3E-05	3.5E-04	6.1E-04
DN200	0.688	50	16	34.4	4.0	5.6E-06	2.3E-04	2.3E-05	3.5E-04	6.1E-04
DN240F	0.804	50	16	40.2	4.0	6.5E-06	2.3E-04	2.3E-05	3.5E-04	6.1E-04
DN240R	0.804	50	16	40.2	4.0	6.5E-06	2.3E-04	2.3E-05	3.5E-04	6.1E-04
DN250	0.858	50	16	42.9	4.0	6.9E-06	2.3E-04	2.3E-05	3.5E-04	6.1E-04

Σ 3.0E-3 1/yer

Calculation of cumulative failure rate for INVAR process pipes

	Circuit of pipe	Length of pipe	Number of welds	Length of welds	CFR_1	CFR_2	CFR_3	CFR
	m	m	-	m	1/yer	1/yer	1/yer	1/yer
DN80	0.279	50	5	1.40	7.1E-07	2.3E-04	2.3E-05	2.5E-04
DN200	0.688	50	5	3.44	1.7E-06	2.3E-04	2.3E-05	2.5E-04
DN240F	0.804	50	5	4.02	2.0E-06	2.3E-04	2.3E-05	2.6E-04
DN240R	0.804	50	5	4.02	2.0E-06	2.3E-04	2.3E-05	2.6E-04
DN250	0.858	50	5	4.29	2.2E-06	2.3E-04	2.3E-05	2.6E-04

Σ 1.3E-3 1/yer

Contents

Summary

INVAR	Stainless steel
• Less types and numbers of supports • Lower heat fluxes • No compensation bellows • Lower numbers of welds • Lower forces on the vacuum barriers • Lower probability of failure	• Conventional design • A well-known method of welding • Pipes are commonly available

Using of invar process pipes seems to be very attractive alternative for FCC

Acknowledgment

The analysis was realized within the CERN-WrUT agreement FCC-GOV-CC-0036