E1200625-v4
Local Coordinates of Support Tube Ends

This notebook calculates/provides the positions of the centers of the ends of each support tube (for both BSC and HAM chambers) in the building local gravity vector frame. These values can be used to position (or check) that the support tubes are in the proper locations to place the ISI optics tables in their proper locations.

Version History

Ver. 1 D. Coyne 6/16/2012

Ver. 2 D. Coyne 6/21/2012

Ver. 3 D. Coyne 7/31/2012

Ver. 4 D. Coyne 10/3/2012

- Correction to the vertical distance betweent the HAM support tube centers and the global axes (had previously used the distance from the support tube center to the HAM nozzle B center rather than to the global axis).
- Also tables with local coordinates were incorrectly labeled "global".
- Added global and local coordinate tables for all chambers
- Note that there were small discrepancies between the location of the support tube end centers compared to SolidWorks (e.g. LHAM2, D0900365-x094).
a) The vertical distance from support tube center to global axis is 1209.57 mm in SW, whereas in this notebook it was 1209.98 mm. A difference of 0.41 mm. Most of this difference is due to the fact that the SW model has the distance between the support tube center and the nozzle B center as 43.685" whereas this notebook uses the value of 43.70" (a difference of 0.38 mm) from v049-4-128, rev 3, sh1. Since this difference is within the tolerances of the chamber shell, to be consistent with SW, I have changed this dimension to 43.685" (still leaving a difference of 0.02 mm between SW and this notebook).
b) The support tubes in the SW model of LHAM2 (D0900365-x094) are 26.995" and 27.005" laterally separated from the center of the nozzle B center, or 54.000" total. The value for this dimension used in this notebook was 53-15/16" in accordance with PSI v049-4-002, rev 4. Since this difference is within the tolerances of the chamber shell, to be consistent with SW, I have changed this dimension to 54.000".
c) The ends of the support tubes in the SW model of LHAM2 (D0900365-x094) are 47.095" from the center of the HAM chamber. The value for this dimension in this notebook was and remains the same.

0.2. Intialization

```
Off[General::"spell"]
Off[General::"spell1"]

Needs["VectorAnalysis`"]
```

Needs[“Geometry`Rotations`”]
is no longer needed. Use built - in RotationTransform and RotationMatrix
RotationMatrix uses yaw-pitch-roll angles rather than the Euler angles used by RotationMatrix3D

```
RotationMatrix3D[phi_,theta_,psi_]:=RotationMatrix[Pi -
psi, {0, 0, 1}].RotationMatrix[
  theta, {1, 0, 0}].RotationMatrix[Pi - phi, {0, 0, 1}]

RotationMatrix3D[phi, theta, psi]
```

```
{{Cos[phi] Cos[psi] - Cos[theta] Sin[phi] Sin[psi],
  Cos[psi] Sin[phi] + Cos[phi] Cos[theta] Sin[psi],
  Sin[psi] Sin[theta]},
 {-Cos[psi] Cos[theta] Sin[phi] - Cos[phi] Sin[psi],
  Cos[phi] Cos[psi] Cos[theta] - Sin[phi] Sin[psi],
  Cos[psi] Sin[theta]},
 {Sin[phi] Sin[theta], -Cos[phi] Sin[theta], Cos[theta]}}
```

Note: Per J. Wertz, "Spacecraft Attitude Determination and Control", D. Reidel Pub., 1985, pp.763-764, This is a Type 2 Euler Angle representation with a z-x-z rotation sequence.

Needs["Graphics`Shapes`"]
The functionality of `RotateShape`, `TranslateShape`, and `AffineShape` is provided by the newly added kernel functions `Rotate`, `Translate`, `Scale` and `GeometricTransformation`

```
pi = N[π, 10];
```

0.3. Global to Local Coordinate Transformation Matrices

See Tables 10-14 and Tables 25-27 of T980044-v1(aka -10), "Determination of Local and Global Coordinate Axes for the LIGO Sites".

0.3.1. Rhc   -> Hanford Corner station

```
xangle = 619.49 × 10^-6;
yangle = 12.4832 × 10^-6;
```

```
Rhc = RotationMatrix3D[0, yangle, 0].
   RotationMatrix3D[pi / 2, xangle, -pi / 2];
MatrixForm[Rhc]
```

$$\begin{pmatrix} 1. & 0. & -0.00061949 \\ 7.73322 \times 10^{-9} & 1. & 0.0000124832 \\ 0.00061949 & -0.0000124832 & 1. \end{pmatrix}$$

```
MatrixForm[Rhc - IdentityMatrix[3]]
```

$$\begin{pmatrix} -1.91884 \times 10^{-7} & 0. & -0.00061949 \\ 7.73322 \times 10^{-9} & -7.79151 \times 10^{-11} & 0.0000124832 \\ 0.00061949 & -0.0000124832 & -1.91962 \times 10^{-7} \end{pmatrix}$$

```
Rhcinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
   RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhc.Rhcinv]
```

$$\begin{pmatrix} 1. & 1.65436 \times 10^{-24} & 1.0842 \times 10^{-19} \\ 1.65436 \times 10^{-24} & 1. & 0. \\ 1.0842 \times 10^{-19} & 0. & 1. \end{pmatrix}$$

```
MatrixForm[Rhcinv]
```

$$\begin{pmatrix} 1. & 7.73322 \times 10^{-9} & 0.00061949 \\ 0. & 1. & -0.0000124832 \\ -0.00061949 & 0.0000124832 & 1. \end{pmatrix}$$

0.3.2. Rhxm -> Hanford x-mid station

```
xangle = 305.827 × 10^-6;
yangle = 12.0075 × 10^-6;
```

```
Rhxm = RotationMatrix3D[0, yangle, 0].
   RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rhxm]
```

$$\begin{pmatrix} 1. & 0. & -0.000305827 \\ 3.67222 \times 10^{-9} & 1. & 0.0000120075 \\ 0.000305827 & -0.0000120075 & 1. \end{pmatrix}$$

```
MatrixForm[Rhxm - IdentityMatrix[3]]
```

$$\begin{pmatrix} -4.67651 \times 10^{-8} & 0. & -0.000305827 \\ 3.67222 \times 10^{-9} & -7.209 \times 10^{-11} & 0.0000120075 \\ 0.000305827 & -0.0000120075 & -4.68372 \times 10^{-8} \end{pmatrix}$$

```
Rhxminv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
    RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhxm.Rhxminv]
```

$$\begin{pmatrix} 1. & 4.1359 \times 10^{-25} & 0. \\ 4.1359 \times 10^{-25} & 1. & 0. \\ 0. & 0. & 1. \end{pmatrix}$$

0.3.3. Rhxe -> Hanford x-end station

```
xangle = -7.8389 10^-6;
yangle = 11.5318 × 10^-6;

Rhxe = RotationMatrix3D[0, yangle, 0].
    RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rhxe]
```

$$\begin{pmatrix} 1. & 0. & 7.8389 \times 10^{-6} \\ -9.03966 \times 10^{-11} & 1. & 0.0000115318 \\ -7.8389 \times 10^{-6} & -0.0000115318 & 1. \end{pmatrix}$$

```
MatrixForm[Rhxe - IdentityMatrix[3]]
```

$$\begin{pmatrix} -3.07242 \times 10^{-11} & 0. & 7.8389 \times 10^{-6} \\ -9.03966 \times 10^{-11} & -6.64913 \times 10^{-11} & 0.0000115318 \\ -7.8389 \times 10^{-6} & -0.0000115318 & -9.72155 \times 10^{-11} \end{pmatrix}$$

```
Rhxeinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
    RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhxe.Rhxeinv]
```

$$\begin{pmatrix} 1. & 0. & 0. \\ 0. & 1. & 1.69407 \times 10^{-21} \\ 0. & 1.69407 \times 10^{-21} & 1. \end{pmatrix}$$

0.3.4. Rhym -> Hanford y-mid station

```
xangle = 619.97 × 10^-6;
yangle = 325.84 × 10^-6;

Rhym = RotationMatrix3D[0, yangle, 0].
    RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rhym]
```

$$\begin{pmatrix} 1. & 0. & -0.00061997 \\ 2.02011 \times 10^{-7} & 1. & 0.00032584 \\ 0.00061997 & -0.00032584 & 1. \end{pmatrix}$$

```
MatrixForm[Rhym - IdentityMatrix[3]]
```

$$\begin{pmatrix} -1.92181 \times 10^{-7} & 0. & -0.00061997 \\ 2.02011 \times 10^{-7} & -5.30859 \times 10^{-8} & 0.00032584 \\ 0.00061997 & -0.00032584 & -2.45267 \times 10^{-7} \end{pmatrix}$$

```
Rhyminv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
    RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhym.Rhyminv]
```

$$\begin{pmatrix} 1. & 2.64698 \times 10^{-23} & 0. \\ 2.64698 \times 10^{-23} & 1. & 0. \\ 0. & 0. & 1. \end{pmatrix}$$

0.3.5. Rhye   -> Hanford y-end station

```
xangle = 620.45 × 10^-6;
yangle = 639.20 × 10^-6;

Rhye = RotationMatrix3D[0, yangle, 0].
    RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rhxe]
```

$$\begin{pmatrix} 1. & 0. & 7.8389 \times 10^{-6} \\ -9.03966 \times 10^{-11} & 1. & 0.0000115318 \\ -7.8389 \times 10^{-6} & -0.0000115318 & 1. \end{pmatrix}$$

```
MatrixForm[Rhye - IdentityMatrix[3]]
```

$$\begin{pmatrix} -1.92479 \times 10^{-7} & 0. & -0.00062045 \\ 3.96592 \times 10^{-7} & -2.04288 \times 10^{-7} & 0.0006392 \\ 0.00062045 & -0.0006392 & -3.96767 \times 10^{-7} \end{pmatrix}$$

```
Rhyeinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
    RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhye.Rhyeinv]
```

$$\begin{pmatrix} 1. & -5.29396 \times 10^{-23} & 0. \\ -5.29396 \times 10^{-23} & 1. & -1.0842 \times 10^{-19} \\ 0. & -1.0842 \times 10^{-19} & 1. \end{pmatrix}$$

```
(180 / Pi) 619 × 10^-6 // N
```

0.0354661

0.3.6. Rlc -> Livingston Corner station

```
xangle = 312.0 × 10^-6;
yangle = -611.0 10^-6;

Rlc = RotationMatrix3D[0, yangle, 0].
    RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rlc]
```

$$\begin{pmatrix} 1. & 0. & -0.000312 \\ -1.90632 \times 10^{-7} & 1. & -0.000611 \\ 0.000312 & 0.000611 & 1. \end{pmatrix}$$

```
MatrixForm[Rlc - IdentityMatrix[3]]
```

$$\begin{pmatrix} -4.8672 \times 10^{-8} & 0. & -0.000312 \\ -1.90632 \times 10^{-7} & -1.8666 \times 10^{-7} & -0.000611 \\ 0.000312 & 0.000611 & -2.35332 \times 10^{-7} \end{pmatrix}$$

```
Rlcinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
    RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rlc.Rlcinv]
```

$$\begin{pmatrix} 1. & 0. & 0. \\ 0. & 1. & 1.0842 \times 10^{-19} \\ 0. & 1.0842 \times 10^{-19} & 1. \end{pmatrix}$$

0.3.7. Rlxe -> Livingston x-end station

```
xangle = -315.0 10^-6;
yangle = -610.0 10^-6;

Rlxe = RotationMatrix3D[0, yangle, 0].
   RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rlxe]
```

$$\begin{pmatrix} 1. & 0. & 0.000315 \\ 1.9215 \times 10^{-7} & 1. & -0.00061 \\ -0.000315 & 0.00061 & 1. \end{pmatrix}$$

```
MatrixForm[Rlxe - IdentityMatrix[3]]
```

$$\begin{pmatrix} -4.96125 \times 10^{-8} & 0. & 0.000315 \\ 1.9215 \times 10^{-7} & -1.8605 \times 10^{-7} & -0.00061 \\ -0.000315 & 0.00061 & -2.35662 \times 10^{-7} \end{pmatrix}$$

```
Rlxeinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
   RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rlxe.Rlxeinv]
```

$$\begin{pmatrix} 1. & 0. & 0. \\ 0. & 1. & 0. \\ 0. & 0. & 1. \end{pmatrix}$$

```
MatrixForm[Rlxeinv - Transpose[Rlxe]]
```

$$\begin{pmatrix} 0. & 0. & 0. \\ 0. & 0. & 0. \\ 0. & 0. & 0. \end{pmatrix}$$

0.3.8. Rlye -> Livingston y-end station

```
xangle = 311.0 × 10^-6;
yangle = 18.8 × 10^-6;

Rlye = RotationMatrix3D[0, yangle, 0].
   RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rlye]
```

$$\begin{pmatrix} 1. & 0. & -0.000311 \\ 5.8468 \times 10^{-9} & 1. & 0.0000188 \\ 0.000311 & -0.0000188 & 1. \end{pmatrix}$$

```
MatrixForm[Rlye - IdentityMatrix[3]]
```

$$\begin{pmatrix} -4.83605 \times 10^{-8} & 0. & -0.000311 \\ 5.8468 \times 10^{-9} & -1.7672 \times 10^{-10} & 0.0000188 \\ 0.000311 & -0.0000188 & -4.85372 \times 10^{-8} \end{pmatrix}$$

```
Rlyeinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
    RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rlye.Rlyeinv]
```

$$\begin{pmatrix} 1. & 0. & 0. \\ 0. & 1. & 0. \\ 0. & 0. & 1. \end{pmatrix}$$

0.4. Chamber Center Global Coordinates

-Global coordinates taken from:

H1: D0901920-v10 (was E1101147-v2, "H1_recycling cavity length .076wedge")

L1: Zemax model "D090xxxx L1 Zemax layout.zar", PDMW vault version x010

H2: D0902345-v8 (was E1101148-v2, "H2_recycling-cavity-length-0.076wedge")

0.4.1. H1 Chambers

```
BSCchambersH1G = {{"WBSC1", 0, 4580, 0},
    {"WBSC2", 0, 0, 0},
    {"WBSC3", 4580, 0, 0},
    {"WBSC9", 4 000 000, 0, 0},
    {"WBSC10", 0, 4 000 000, 0}};
HAMchambersH1G = {{"WHAM1", -22 726.7, 0, 0},
    {"WHAM2", -20 122, 0, 0},
     {"WHAM3", -3831, 0, 0},
     {"WHAM4", 0, -3831, 0},
     {"WHAM5", 0, -20 122, 0},
     {"WHAM6", 0, -22 726.7, 0}};
nBSCchambersH1 = Length[BSCchambersH1G];
nHAMchambersH1 = Length[HAMchambersH1G];

tableHeadG = {"x_global", "y_global", "z_global"};
WBSCTableG = TableForm[BSCchambersH1G[[All, 2 ;; 4]],
    TableHeadings -> {BSCchambersH1G[[All, 1]],
        tableHeadG}];
```

```
WHAMTableG = TableForm[HAMchambersH1G[[All, 2 ;; 4]],
   TableHeadings -> {HAMchambersH1G[[All, 1]],
     tableHeadG}];
```

0.4.2. L1 Chambers

```
BSCchambersL1G = {{"LBSC1", 0.0, 4580.0, 0.0},
{"LBSC2", 0.0 , 0.0, 0.0},
{"LBSC3", 4580.0 , 0.0 , 0.0},
{"LBSC4", 4 000 000.0, 0.0 , 0.0},
{"LBSC5", 0.0 , 4 000 000.0 , 0.0}};
HAMchambersL1G = {{"LHAM1", -22 726.7 , 0.0 , 0.0},
{"LHAM2", -20 122.0 , 0.0 , 0.0},
{"LHAM3", -3831.0 , 0.0 , 0.0},
{"LHAM4", 0.0, -3831.0 , 0.0},
{"LHAM5", 0.0, -20 122.0, 0.0},
{"LHAM6", 0.0, -22 726.7 , 0.0}};
nBSCchambersL1 = Length[BSCchambersL1G];
nHAMchambersL1 = Length[HAMchambersL1G];

tableHead = {"x_global", "y_global", "z_global"};
LBSCTableG = TableForm[BSCchambersL1G[[All, 2 ;; 4]],
   TableHeadings -> {BSCchambersL1G[[All, 1]], tableHead}];

tableHead = {"x_global", "y_global", "z_global"};
LHAMTableG = TableForm[HAMchambersL1G[[All, 2 ;; 4]],
   TableHeadings -> {HAMchambersL1G[[All, 1]], tableHead}];
```

0.5.0. Local Coordinates

0.5.1. H1

H1 Chambers

Convert the global coordinates of the chambers into the local coordinate system

Note that the centers of the central BSC chamber, BSC2, and the end station chambers, are by definition at {0,0,0} local.

```
BSCchambersH1L = BSCchambersH1G;
Do[BSCchambersH1L[[i, 2 ;; 4]] =
    BSCchambersH1G[[i, 2 ;; 4]].Rhc,
   {i, 1, nBSCchambersH1 - 2}];
BSCchambersH1L[[4, 2 ;; 4]] =
   (BSCchambersH1G[[4, 2 ;; 4]] -
      BSCchambersH1G[[4, 2 ;; 4]]).Rhxe;
BSCchambersH1L[[5, 2 ;; 4]] =
   (BSCchambersH1G[[5, 2 ;; 4]] -
      BSCchambersH1G[[5, 2 ;; 4]]).Rhye;

HAMchambersH1L = HAMchambersH1G;
Do[HAMchambersH1L[[i, 2 ;; 4]] =
    HAMchambersH1G[[i, 2 ;; 4]].Rhc,
   {i, 1, nHAMchambersH1}];

tableHeadL = {"x_local", "y_local", "z_local"};
WBSCTableL = TableForm[BSCchambersH1L[[All, 2 ;; 4]],
  TableHeadings -> {BSCchambersH1L[[All, 1]],
    tableHeadL}]
```

	x_local	y_local	z_local
WBSC1	0.0000354181	4580.	0.057173
WBSC2	0.	0.	0.
WBSC3	4580.	0.	-2.83726
WBSC9	0.	0.	0.
WBSC10	0.	0.	0.

```
WHAMTableL = TableForm[HAMchambersH1L[[All, 2 ;; 4]],
  TableHeadings -> {HAMchambersH1L[[All, 1]],
    tableHeadL}]
```

	x_local	y_local	z_local
WHAM1	-22 726.7	0.	14.079
WHAM2	-20 122.	0.	12.4654
WHAM3	-3831.	0.	2.37327
WHAM4	-0.000029626	-3831.	-0.0478231
WHAM5	-0.000155608	-20 122.	-0.251187
WHAM6	-0.000175751	-22 726.7	-0.283702

BSC Support Tubes Ends

Support tube center (nozzle D centerline) height above BSC chamber center = 1130.3 mm (D972001-B, sh 3)

Horizontal distance between the support tube centers and the BSC chamber center = 838.2 mm (PSI v049-4-001, Rev1, sh 2)

Support tube length = 3657.6 mm (D972121-v2, sh 1)

Confirmed with SolidWorks on D0900428 (LBSC2)

```
LGBSCST = 3657.6 / 2;
WGBSCST = 838.2;
ZGBSCST = 1130.3;
```

The orienation of the BSC support tubes are defined in PSI v049-5-003, rev4, sh 1 (corner), v049-5-008, rev3 (x-end), v049-5-009, rev3 (y-end)

The support tube ends will be labelled (numbered) the same way as the nearest HEPI pier, in accordance with G1000125-v8

```mathematica
BSCsupportTubesH1L = Table[0, {4 nBSCchambersH1}, {5}];
Do[j = Floor[i / 4 + 1];
  If[MemberQ[{1, 2, 4}, i + 1],
    BSCsupportTubesH1L[[4 i + 1]] =
     Flatten[{BSCchambersH1L[[i + 1, 1]], "pier 1",
        BSCchambersH1L[[i + 1, 2 ;; 4]] +
         {LGBSCST, WGBSCST, ZGBSCST}}];
    BSCsupportTubesH1L[[4 i + 2]] =
     Flatten[{BSCchambersH1L[[i + 1, 1]], "pier 2",
        BSCchambersH1L[[i + 1, 2 ;; 4]] +
         {-LGBSCST, WGBSCST, ZGBSCST}}];
    BSCsupportTubesH1L[[4 i + 3]] =
     Flatten[{BSCchambersH1L[[i + 1, 1]], "pier 3",
        BSCchambersH1L[[i + 1, 2 ;; 4]] +
         {-LGBSCST, -WGBSCST, ZGBSCST}}];
    BSCsupportTubesH1L[[4 i + 4]] =
     Flatten[{BSCchambersH1L[[i + 1, 1]], "pier 4",
        BSCchambersH1L[[i + 1, 2 ;; 4]] +
         {LGBSCST, -WGBSCST, ZGBSCST}}],
    BSCsupportTubesH1L[[4 i + 1]] =
     Flatten[{BSCchambersH1L[[i + 1, 1]], "pier 1",
        BSCchambersH1L[[i + 1, 2 ;; 4]] +
         {WGBSCST, LGBSCST, ZGBSCST}}];
    BSCsupportTubesH1L[[4 i + 2]] =
     Flatten[{BSCchambersH1L[[i + 1, 1]], "pier 2",
        BSCchambersH1L[[i + 1, 2 ;; 4]] +
         {-WGBSCST, LGBSCST, ZGBSCST}}];
    BSCsupportTubesH1L[[4 i + 3]] =
     Flatten[{BSCchambersH1L[[i + 1, 1]], "pier 3",
        BSCchambersH1L[[i + 1, 2 ;; 4]] +
         {-WGBSCST, -LGBSCST, ZGBSCST}}];
    BSCsupportTubesH1L[[4 i + 4]] =
     Flatten[{BSCchambersH1L[[i + 1, 1]], "pier 4",
        BSCchambersH1L[[i + 1, 2 ;; 4]] +
         {WGBSCST, -LGBSCST, ZGBSCST}}]]
  , {i, 0, nBSCchambersH1 - 1}];
```

Drop the support tubes in WBSC2 by 2.9 mm corresponding to the height difference (in global coordinates) between the ITMs and the BS. This height difference is to be taken up by the HEPI system:

```
Do[BSCsupportTubesH1L[[i, 5]] =
   BSCsupportTubesH1L[[i, 5]] - 2.9, {i, 5, 8}];

pierTableHeadL = {"pier", "x_local", "y_local",
   "z_local"};
tableBSCsupportTubesH1 =
   TableForm[BSCsupportTubesH1L[[All, 2 ;; 5]],
     TableHeadings -> {BSCsupportTubesH1L[[All, 1]],
       pierTableHeadL}];
```

HAM Support Tubes Ends

```
LGHAMST = 94.19 × 25.4 / 2;
WGHAMST = 54 × 25.4;
ZGHAMST = -43.685 25.4 - 100;
```

```
HAMsupportTubesH1L = Table[0, {4 nHAMchambersH1}, {5}];
Do[j = Floor[i / 4 + 1];
  If[MemberQ[{6, 7, 8}, i + 1],
    HAMsupportTubesH1L[[4 i + 1]] =
      Flatten[{HAMchambersH1L[[i + 1, 1]], "pier 1",
        HAMchambersH1L[[i + 1, 2 ;; 4]] +
          {LGHAMST, WGHAMST, ZGHAMST}}];
    HAMsupportTubesH1L[[4 i + 2]] =
      Flatten[{HAMchambersH1L[[i + 1, 1]], "pier 2",
        HAMchambersH1L[[i + 1, 2 ;; 4]] +
          {-LGHAMST, WGHAMST, ZGHAMST}}];
    HAMsupportTubesH1L[[4 i + 3]] =
      Flatten[{HAMchambersH1L[[i + 1, 1]], "pier 3",
        HAMchambersH1L[[i + 1, 2 ;; 4]] +
          {-LGHAMST, -WGHAMST, ZGHAMST}}];
    HAMsupportTubesH1L[[4 i + 4]] =
      Flatten[{HAMchambersH1L[[i + 1, 1]], "pier 4",
        HAMchambersH1L[[i + 1, 2 ;; 4]] +
          {LGHAMST, -WGHAMST, ZGHAMST}}],
    HAMsupportTubesH1L[[4 i + 1]] =
      Flatten[{HAMchambersH1L[[i + 1, 1]], "pier 1",
        HAMchambersH1L[[i + 1, 2 ;; 4]] +
          {WGHAMST, LGHAMST, ZGHAMST}}];
    HAMsupportTubesH1L[[4 i + 2]] =
      Flatten[{HAMchambersH1L[[i + 1, 1]], "pier 2",
        HAMchambersH1L[[i + 1, 2 ;; 4]] +
          {-WGHAMST, LGHAMST, ZGHAMST}}];
    HAMsupportTubesH1L[[4 i + 3]] =
      Flatten[{HAMchambersH1L[[i + 1, 1]], "pier 3",
        HAMchambersH1L[[i + 1, 2 ;; 4]] +
          {-WGHAMST, -LGHAMST, ZGHAMST}}];
    HAMsupportTubesH1L[[4 i + 4]] =
      Flatten[{HAMchambersH1L[[i + 1, 1]], "pier 4",
        HAMchambersH1L[[i + 1, 2 ;; 4]] +
          {WGHAMST, -LGHAMST, ZGHAMST}}]],
    {i, 0, nHAMchambersH1 - 1}];

tableHAMsupportTubesH1 =
  TableForm[HAMsupportTubesH1L[[All, 2 ;; 5]],
    TableHeadings -> {HAMsupportTubesH1L[[All, 1]],
      pierTableHeadL}];
```

Plot of corner station pier end positions

```
BSCchamberLabels = Text[#[[1]], 1. #[[{2, 3}]]] & /@
   BSCchambersH1L[[1 ;; 3]];
BSCpierLabels = Text[#[[2]], 1.1 #[[{3, 4}]]] & /@
   BSCsupportTubesH1L[[1 ;; 12]];
BSCpierPlot =
  ListPlot[BSCsupportTubesH1L[[1 ;; 12, 3 ;; 4]],
   PlotStyle → PointSize → Large];
HAMchamberLabels = Text[#[[1]], 1. #[[{2, 3}]]] & /@
   HAMchambersH1L;
HAMpierLabels = Text[#[[2]], 1. #[[{3, 4}]]] & /@
   HAMsupportTubesH1L;
HAMpierPlot = ListPlot[HAMsupportTubesH1L[[All, 3 ;; 4]],
   PlotStyle → PointSize → Large];
plotSupportTubesH1 =
  Show[HAMpierPlot, BSCpierPlot,
   Graphics[{Blue, BSCchamberLabels}],
   Graphics[{Red, BSCpierLabels}],
   Graphics[{Magenta, HAMchamberLabels}],
   Graphics[{Green, HAMpierLabels}], PlotRange → All,
   AspectRatio → 1];
```

H1 Summary

WBSCTableG

	x_global	y_global	z_global
WBSC1	0	4580	0
WBSC2	0	0	0
WBSC3	4580	0	0
WBSC9	4 000 000	0	0
WBSC10	0	4 000 000	0

WHAMTableG

	x_global	y_global	z_global
WHAM1	− 22 726.7	0	0
WHAM2	− 20 122	0	0
WHAM3	− 3831	0	0
WHAM4	0	− 3831	0
WHAM5	0	− 20 122	0
WHAM6	0	− 22 726.7	0

WBSCTableL

	x_local	y_local	z_local
WBSC1	0.0000354181	4580.	0.057173
WBSC2	0.	0.	0.
WBSC3	4580.	0.	−2.83726
WBSC9	0.	0.	0.
WBSC10	0.	0.	0.

WHAMTableL

	x_local	y_local	z_local
WHAM1	−22 726.7	0.	14.079
WHAM2	−20 122.	0.	12.4654
WHAM3	−3831.	0.	2.37327
WHAM4	−0.000029626	−3831.	−0.0478231
WHAM5	−0.000155608	−20 122.	−0.251187
WHAM6	−0.000175751	−22 726.7	−0.283702

tableBSCsupportTubesH1

	pier	x_local	y_local	z_local
WBSC1	pier 1	1828.8	5418.2	1130.36
WBSC1	pier 2	−1828.8	5418.2	1130.36
WBSC1	pier 3	−1828.8	3741.8	1130.36
WBSC1	pier 4	1828.8	3741.8	1130.36
WBSC2	pier 1	1828.8	838.2	1127.4
WBSC2	pier 2	−1828.8	838.2	1127.4
WBSC2	pier 3	−1828.8	−838.2	1127.4
WBSC2	pier 4	1828.8	−838.2	1127.4
WBSC3	pier 1	5418.2	1828.8	1127.46
WBSC3	pier 2	3741.8	1828.8	1127.46
WBSC3	pier 3	3741.8	−1828.8	1127.46
WBSC3	pier 4	5418.2	−1828.8	1127.46
WBSC9	pier 1	1828.8	838.2	1130.3
WBSC9	pier 2	−1828.8	838.2	1130.3
WBSC9	pier 3	−1828.8	−838.2	1130.3
WBSC9	pier 4	1828.8	−838.2	1130.3
WBSC10	pier 1	838.2	1828.8	1130.3
WBSC10	pier 2	−838.2	1828.8	1130.3
WBSC10	pier 3	−838.2	−1828.8	1130.3
WBSC10	pier 4	838.2	−1828.8	1130.3

tableHAMsupportTubesH1

	pier	x_local	y_local	z_local
WHAM1	pier 1	−21 355.1	1196.21	−1195.52
WHAM1	pier 2	−24 098.3	1196.21	−1195.52
WHAM1	pier 3	−24 098.3	−1196.21	−1195.52
WHAM1	pier 4	−21 355.1	−1196.21	−1195.52
WHAM2	pier 1	−18 750.4	1196.21	−1197.13
WHAM2	pier 2	−21 493.6	1196.21	−1197.13
WHAM2	pier 3	−21 493.6	−1196.21	−1197.13
WHAM2	pier 4	−18 750.4	−1196.21	−1197.13
WHAM3	pier 1	−2459.4	1196.21	−1207.23
WHAM3	pier 2	−5202.6	1196.21	−1207.23
WHAM3	pier 3	−5202.6	−1196.21	−1207.23
WHAM3	pier 4	−2459.4	−1196.21	−1207.23
WHAM4	pier 1	1371.6	−2634.79	−1209.65
WHAM4	pier 2	−1371.6	−2634.79	−1209.65
WHAM4	pier 3	−1371.6	−5027.21	−1209.65
WHAM4	pier 4	1371.6	−5027.21	−1209.65
WHAM5	pier 1	1371.6	−18 925.8	−1209.85
WHAM5	pier 2	−1371.6	−18 925.8	−1209.85
WHAM5	pier 3	−1371.6	−21 318.2	−1209.85
WHAM5	pier 4	1371.6	−21 318.2	−1209.85
WHAM6	pier 1	1196.21	−21 355.1	−1209.88
WHAM6	pier 2	−1196.21	−21 355.1	−1209.88
WHAM6	pier 3	−1196.21	−24 098.3	−1209.88
WHAM6	pier 4	1196.21	−24 098.3	−1209.88

plotSupportTubesH1
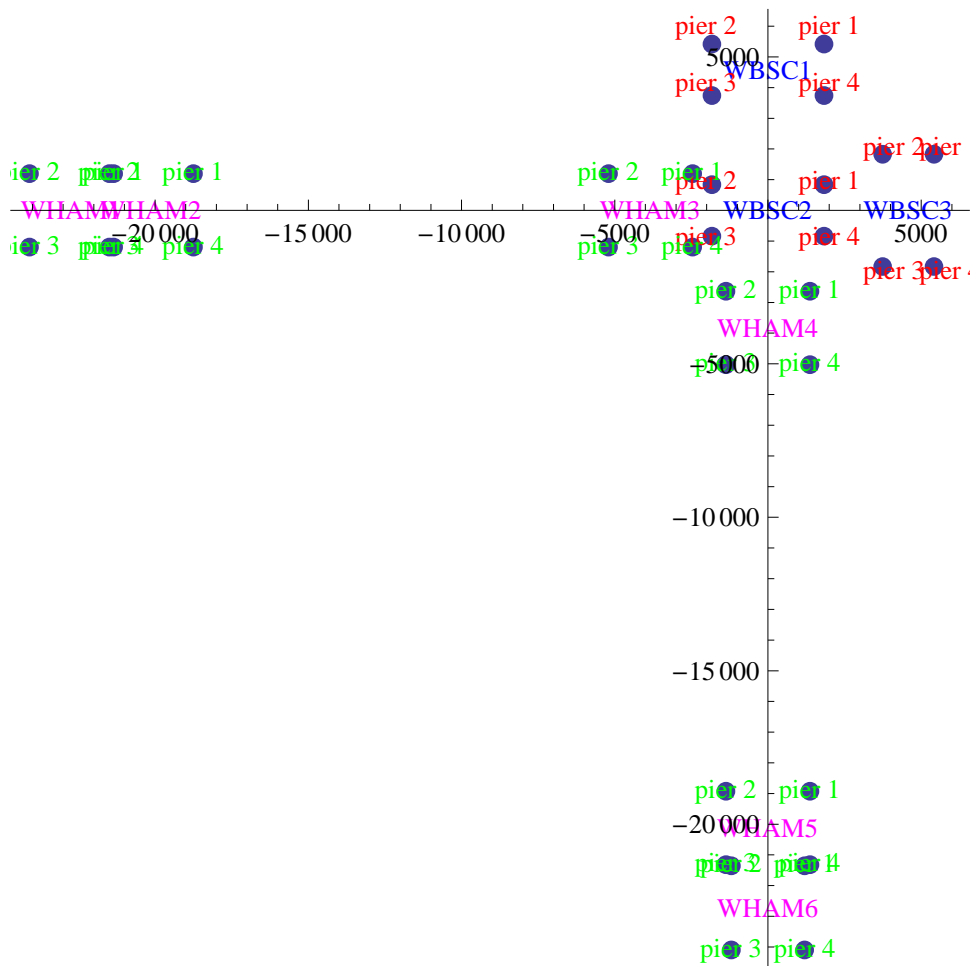
0.5.2. L1

L1 Chambers

Convert the global coordinates of the chambers into the local coordinate system

Note that the centers of the central BSC chamber, BSC2, and the end station chambers, are be definition at {0,0,0} local.

```
BSCchambersL1L = BSCchambersL1G;
Do[BSCchambersL1L[[i, 2 ;; 4]] =
    BSCchambersL1G[[i, 2 ;; 4]].Rlc,
   {i, 1, nBSCchambersL1 - 2}];
BSCchambersL1L[[4, 2 ;; 4]] =
   (BSCchambersL1G[[4, 2 ;; 4]] -
      BSCchambersL1G[[4, 2 ;; 4]]).Rlxe;
BSCchambersL1L[[5, 2 ;; 4]] =
   (BSCchambersL1G[[5, 2 ;; 4]] -
      BSCchambersL1G[[5, 2 ;; 4]]).Rlye;
```

```
HAMchambersL1L = HAMchambersL1G;
Do[HAMchambersL1L[[i, 2 ;; 4]] =
    HAMchambersL1G[[i, 2 ;; 4]].Rlc,
  {i, 1, nHAMchambersL1}];

LBSCTableL = TableForm[BSCchambersL1L[[All, 2 ;; 4]],
   TableHeadings -> {BSCchambersL1L[[All, 1]],
     tableHeadL}]
```

	x_local	y_local	z_local
LBSC1	−0.000873094	4580.	−2.79838
LBSC2	0.	0.	0.
LBSC3	4580.	0.	−1.42896
LBSC4	0.	0.	0.
LBSC5	0.	0.	0.

```
LHAMTableL = TableForm[HAMchambersL1L[[All, 2 ;; 4]],
   TableHeadings -> {HAMchambersL1L[[All, 1]],
     tableHeadL}]
```

	x_local	y_local	z_local
LHAM1	−22726.7	0.	7.09073
LHAM2	−20122.	0.	6.27806
LHAM3	−3831.	0.	1.19527
LHAM4	0.000730311	−3831.	2.34074
LHAM5	0.0038359	−20122.	12.2945
LHAM6	0.00433244	−22726.7	13.886

BSC Support Tubes Ends

Support tube center (nozzle D centerline) height above BSC chamber center = 1130.3 mm (D972001-B, sh 3)

Horizontal distance between the support tube centers and the BSC chamber center = 838.2 mm (PSI v049-4-001, Rev1, sh 2)

Support tube length = 3657.6 mm (D972121-v2, sh 1)

Confirmed with SolidWorks on D0900428 (LBSC2)

```
LGBSCST = 3657.6 / 2;
WGBSCST = 838.2;
ZGBSCST = 1130.3;
```

The orienation of the BSC support tubes are defined in PSI v049-5-003, rev4, sh 1 (corner), v049-5-008, rev3 (x-end), v049-5-009, rev3 (y-end)

The support tube ends will be labelled (numbered) the same way as the nearest HEPI pier, in accordance with G1000125-v8

```
BSCsupportTubesL1L = Table[0, {4 nBSCchambersL1}, {5}];
Do[j = Floor[i / 4 + 1];
  If[MemberQ[{1, 2, 4}, i + 1],
    BSCsupportTubesL1L[[4 i + 1]] =
      Flatten[{BSCchambersL1L[[i + 1, 1]], "pier 1",
        BSCchambersL1L[[i + 1, 2 ;; 4]] +
          {LGBSCST, WGBSCST, ZGBSCST}}];
    BSCsupportTubesL1L[[4 i + 2]] =
      Flatten[{BSCchambersL1L[[i + 1, 1]], "pier 2",
        BSCchambersL1L[[i + 1, 2 ;; 4]] +
          {-LGBSCST, WGBSCST, ZGBSCST}}];
    BSCsupportTubesL1L[[4 i + 3]] =
      Flatten[{BSCchambersL1L[[i + 1, 1]], "pier 3",
        BSCchambersL1L[[i + 1, 2 ;; 4]] +
          {-LGBSCST, -WGBSCST, ZGBSCST}}];
    BSCsupportTubesL1L[[4 i + 4]] =
      Flatten[{BSCchambersL1L[[i + 1, 1]], "pier 4",
        BSCchambersL1L[[i + 1, 2 ;; 4]] +
          {LGBSCST, -WGBSCST, ZGBSCST}}],
    BSCsupportTubesL1L[[4 i + 1]] =
      Flatten[{BSCchambersL1L[[i + 1, 1]], "pier 1",
        BSCchambersL1L[[i + 1, 2 ;; 4]] +
          {WGBSCST, LGBSCST, ZGBSCST}}];
    BSCsupportTubesL1L[[4 i + 2]] =
      Flatten[{BSCchambersL1L[[i + 1, 1]], "pier 2",
        BSCchambersL1L[[i + 1, 2 ;; 4]] +
          {-WGBSCST, LGBSCST, ZGBSCST}}];
    BSCsupportTubesL1L[[4 i + 3]] =
      Flatten[{BSCchambersL1L[[i + 1, 1]], "pier 3",
        BSCchambersL1L[[i + 1, 2 ;; 4]] +
          {-WGBSCST, -LGBSCST, ZGBSCST}}];
    BSCsupportTubesL1L[[4 i + 4]] =
      Flatten[{BSCchambersL1L[[i + 1, 1]], "pier 4",
        BSCchambersL1L[[i + 1, 2 ;; 4]] +
          {WGBSCST, -LGBSCST, ZGBSCST}}]]
  , {i, 0, nBSCchambersL1 - 1}];
```

Drop the support tubes in WBSC2 by 2.9 mm corresponding to the height difference (in global coordinates) between the ITMs and the BS. This height difference is to be taken up by the HEPI system:

```
Do[BSCsupportTubesL1L[[i, 5]] =
    BSCsupportTubesL1L[[i, 5]] - 2.9, {i, 5, 8}];

tableBSCsupportTubesL1 =
  TableForm[BSCsupportTubesL1L[[All, 2 ;; 5]],
    TableHeadings -> {BSCsupportTubesL1L[[All, 1]],
      pierTableHeadL}];
```

HAM Support Tubes Ends

Confirmed with SolidWorks on D0900365.

```
LGHAMST = 94.19 × 25.4 / 2;
WGHAMST = 54 × 25.4;
ZGHAMST = -43.685 25.4 - 100;
```

```
HAMsupportTubesL1L = Table[0, {4 nHAMchambersL1}, {5}];
Do[j = Floor[i / 4 + 1];
  If[MemberQ[{6, 7, 8}, i + 1],
    HAMsupportTubesL1L[[4 i + 1]] =
     Flatten[{HAMchambersL1L[[i + 1, 1]], "pier 1",
        HAMchambersL1L[[i + 1, 2 ;; 4]] +
         {LGHAMST, WGHAMST, ZGHAMST}}];
    HAMsupportTubesL1L[[4 i + 2]] =
     Flatten[{HAMchambersL1L[[i + 1, 1]], "pier 2",
        HAMchambersL1L[[i + 1, 2 ;; 4]] +
         {-LGHAMST, WGHAMST, ZGHAMST}}];
    HAMsupportTubesL1L[[4 i + 3]] =
     Flatten[{HAMchambersL1L[[i + 1, 1]], "pier 3",
        HAMchambersL1L[[i + 1, 2 ;; 4]] +
         {-LGHAMST, -WGHAMST, ZGHAMST}}];
    HAMsupportTubesL1L[[4 i + 4]] =
     Flatten[{HAMchambersL1L[[i + 1, 1]], "pier 4",
        HAMchambersL1L[[i + 1, 2 ;; 4]] +
         {LGHAMST, -WGHAMST, ZGHAMST}}],
    HAMsupportTubesL1L[[4 i + 1]] =
     Flatten[{HAMchambersL1L[[i + 1, 1]], "pier 1",
        HAMchambersL1L[[i + 1, 2 ;; 4]] +
         {WGHAMST, LGHAMST, ZGHAMST}}];
    HAMsupportTubesL1L[[4 i + 2]] =
     Flatten[{HAMchambersL1L[[i + 1, 1]], "pier 2",
        HAMchambersL1L[[i + 1, 2 ;; 4]] +
         {-WGHAMST, LGHAMST, ZGHAMST}}];
    HAMsupportTubesL1L[[4 i + 3]] =
     Flatten[{HAMchambersL1L[[i + 1, 1]], "pier 3",
        HAMchambersL1L[[i + 1, 2 ;; 4]] +
         {-WGHAMST, -LGHAMST, ZGHAMST}}];
    HAMsupportTubesL1L[[4 i + 4]] =
     Flatten[{HAMchambersL1L[[i + 1, 1]], "pier 4",
        HAMchambersL1L[[i + 1, 2 ;; 4]] +
         {WGHAMST, -LGHAMST, ZGHAMST}}]],
   {i, 0, nHAMchambersL1 - 1}];

tableHAMsupportTubesL1 =
  TableForm[HAMsupportTubesL1L[[All, 2 ;; 5]],
   TableHeadings -> {HAMsupportTubesL1L[[All, 1]],
      pierTableHeadL}];
```

Plot of corner station pier end positions

```
BSCchamberLabels = Text[#[[1]], 1. #[[{2, 3}]]] & /@
    BSCchambersL1L[[1 ;; 3]];
BSCpierLabels = Text[#[[2]], 1.1 #[[{3, 4}]]] & /@
    BSCsupportTubesL1L[[1 ;; 12]];
BSCpierPlot =
  ListPlot[BSCsupportTubesL1L[[1 ;; 12, 3 ;; 4]],
    PlotStyle → PointSize → Large];
HAMchamberLabels = Text[#[[1]], 1. #[[{2, 3}]]] & /@
    HAMchambersL1L;
HAMpierLabels = Text[#[[2]], 1. #[[{3, 4}]]] & /@
    HAMsupportTubesL1L;
HAMpierPlot = ListPlot[HAMsupportTubesL1L[[All, 3 ;; 4]],
    PlotStyle → PointSize → Large];
plotSupportTubesL1 =
  Show[HAMpierPlot, BSCpierPlot,
    Graphics[{Blue, BSCchamberLabels}],
    Graphics[{Red, BSCpierLabels}],
    Graphics[{Magenta, HAMchamberLabels}],
    Graphics[{Green, HAMpierLabels}], PlotRange → All,
    AspectRatio → 1];
```

L1 Summary

LBSCTableG

	x_global	y_global	z_global
LBSC1	0.	4580.	0.
LBSC2	0.	0.	0.
LBSC3	4580.	0.	0.
LBSC4	$4. \times 10^6$	0.	0.
LBSC5	0.	$4. \times 10^6$	0.

LHAMTableG

	x_global	y_global	z_global
LHAM1	−22 726.7	0.	0.
LHAM2	−20 122.	0.	0.
LHAM3	−3831.	0.	0.
LHAM4	0.	−3831.	0.
LHAM5	0.	−20 122.	0.
LHAM6	0.	−22 726.7	0.

LBSCTableL

	x_local	y_local	z_local
LBSC1	− 0.000873094	4580.	− 2.79838
LBSC2	0.	0.	0.
LBSC3	4580.	0.	− 1.42896
LBSC4	0.	0.	0.
LBSC5	0.	0.	0.

LHAMTableL

	x_local	y_local	z_local
LHAM1	− 22 726.7	0.	7.09073
LHAM2	− 20 122.	0.	6.27806
LHAM3	− 3831.	0.	1.19527
LHAM4	0.000730311	− 3831.	2.34074
LHAM5	0.0038359	− 20 122.	12.2945
LHAM6	0.00433244	− 22 726.7	13.886

tableBSCsupportTubesL1

	pier	x_local	y_local	z_local
LBSC1	pier 1	1828.8	5418.2	1127.5
LBSC1	pier 2	− 1828.8	5418.2	1127.5
LBSC1	pier 3	− 1828.8	3741.8	1127.5
LBSC1	pier 4	1828.8	3741.8	1127.5
LBSC2	pier 1	1828.8	838.2	1127.4
LBSC2	pier 2	− 1828.8	838.2	1127.4
LBSC2	pier 3	− 1828.8	− 838.2	1127.4
LBSC2	pier 4	1828.8	− 838.2	1127.4
LBSC3	pier 1	5418.2	1828.8	1128.87
LBSC3	pier 2	3741.8	1828.8	1128.87
LBSC3	pier 3	3741.8	− 1828.8	1128.87
LBSC3	pier 4	5418.2	− 1828.8	1128.87
LBSC4	pier 1	1828.8	838.2	1130.3
LBSC4	pier 2	− 1828.8	838.2	1130.3
LBSC4	pier 3	− 1828.8	− 838.2	1130.3
LBSC4	pier 4	1828.8	− 838.2	1130.3
LBSC5	pier 1	838.2	1828.8	1130.3
LBSC5	pier 2	− 838.2	1828.8	1130.3
LBSC5	pier 3	− 838.2	− 1828.8	1130.3
LBSC5	pier 4	838.2	− 1828.8	1130.3

tableHAMsupportTubesL1

	pier	x_local	y_local	z_local
LHAM1	pier 1	−21 355.1	1196.21	−1202.51
LHAM1	pier 2	−24 098.3	1196.21	−1202.51
LHAM1	pier 3	−24 098.3	−1196.21	−1202.51
LHAM1	pier 4	−21 355.1	−1196.21	−1202.51
LHAM2	pier 1	−18 750.4	1196.21	−1203.32
LHAM2	pier 2	−21 493.6	1196.21	−1203.32
LHAM2	pier 3	−21 493.6	−1196.21	−1203.32
LHAM2	pier 4	−18 750.4	−1196.21	−1203.32
LHAM3	pier 1	−2459.4	1196.21	−1208.4
LHAM3	pier 2	−5202.6	1196.21	−1208.4
LHAM3	pier 3	−5202.6	−1196.21	−1208.4
LHAM3	pier 4	−2459.4	−1196.21	−1208.4
LHAM4	pier 1	1371.6	−2634.79	−1207.26
LHAM4	pier 2	−1371.6	−2634.79	−1207.26
LHAM4	pier 3	−1371.6	−5027.21	−1207.26
LHAM4	pier 4	1371.6	−5027.21	−1207.26
LHAM5	pier 1	1371.6	−18 925.8	−1197.3
LHAM5	pier 2	−1371.6	−18 925.8	−1197.3
LHAM5	pier 3	−1371.6	−21 318.2	−1197.3
LHAM5	pier 4	1371.6	−21 318.2	−1197.3
LHAM6	pier 1	1196.22	−21 355.1	−1195.71
LHAM6	pier 2	−1196.21	−21 355.1	−1195.71
LHAM6	pier 3	−1196.21	−24 098.3	−1195.71
LHAM6	pier 4	1196.22	−24 098.3	−1195.71

plotSupportTubesL1