Status of the SPL cryo-module development
(report from WG3)

V.Parma, TE-MSC

(with contributions from WG3 members)

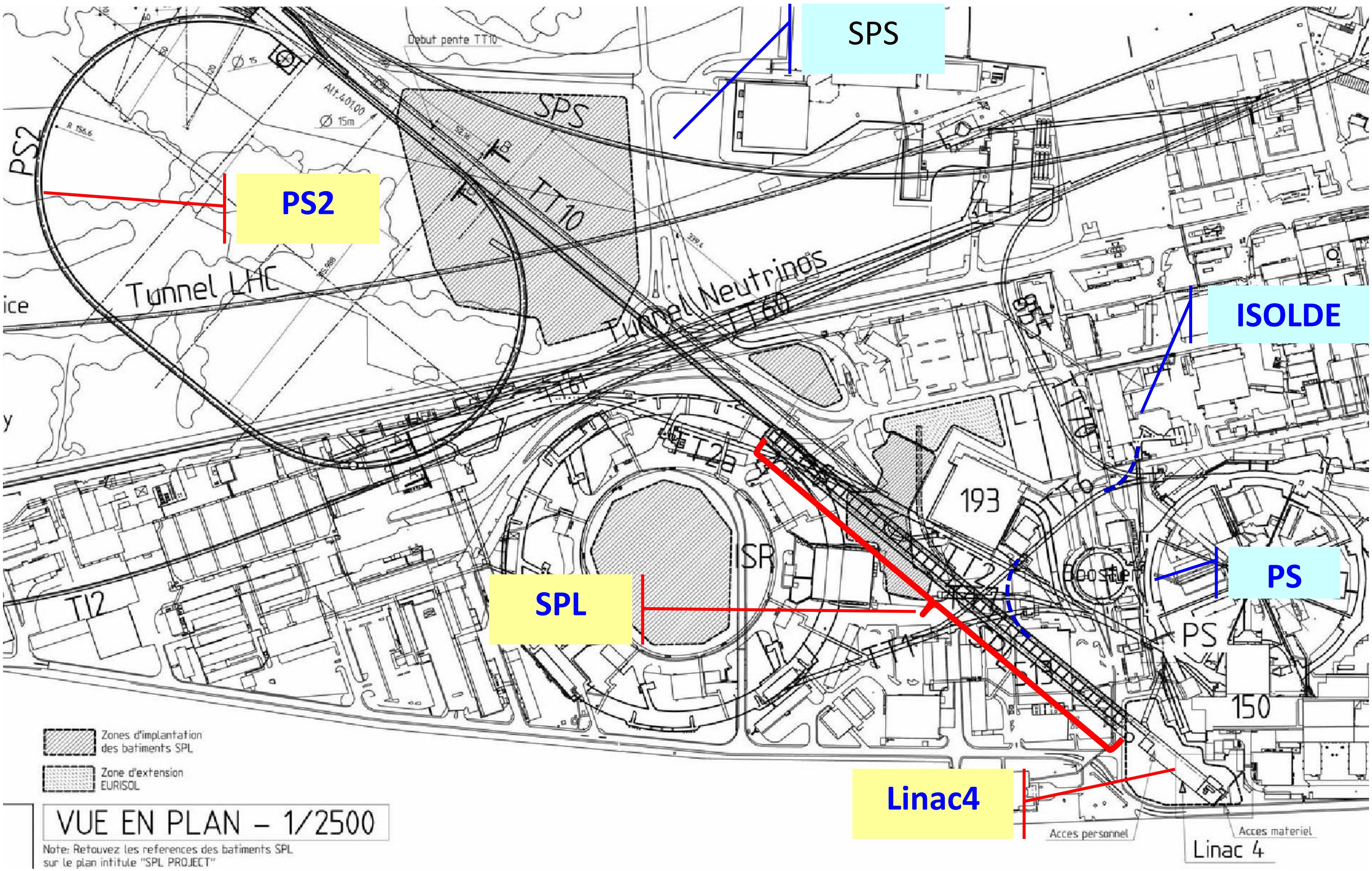
Outline

- Introduction
- New orientation and work organisation
- Layout studies and machine sectorisation (vacuum+cryogenics)
- Recent advances:
  - Supporting schemes
  - Cryogenics
- Summary

Working group (WG3)

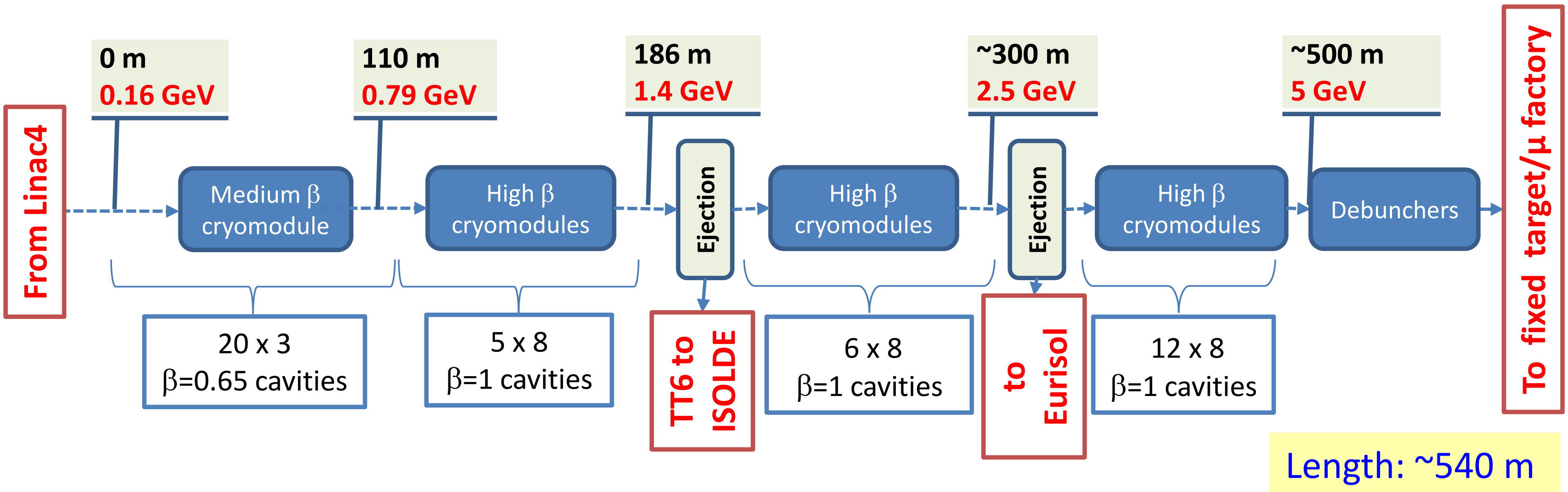
System/Activity	Responsible/member	Lab
Machine architecture	F.Gerigk	CERN
WG3 coordination	V.Parma	CERN
Cryo-module design & Integration CERN	V.Parma. Team: N.Bourcey, P.Coelho, O.Capatina, D.Caparros, Th.Renaglia, A.Vande Craen	CERN
Cryo-module design & Integration CNRS	P.Duthil (P.Duchesne) + CNRS Team	CNRS/IN2P3-Orsay
Cryostat assembly tooling	P.Duthil (P.Duchesne)	CNRS/IN2P3-Orsay
WG 2 activity (RF cavities/He vessel/tuner, RF coupler)	W.Weingarten/S.Chel/O.Capatina/ E.Montesinos	CERN, CEA-Saclay
Vacuum systems	S.Calatroni	CERN
Cryogenics	U.Wagner	CERN
Survey and alignment	D.Missiaen	CERN

Layout injector complex



The SPL study at CERN

- R&D study for a 5 GeV and multi MW high power beam, the HP-SPL
- Major interest for non-LHC physics: ISOLDEII/EURISOL/Fixed Target/Neutrino Factory



HP-SPL beam characteristics

The SPL study: new orientation

New objective of the SPL study:

Up to 2013:

- Focus on R&D for key technologies for the high intensity proton source (HP SPL)

In particular:

- Development, manufacture and test of high-gradient β=1, 5 cellules ,704 MHz cavities
- Development, manufacture and test of RF couplers
- Testing of a string of 4 β=1 cavities in machine-type configuration:
  - Housed in helium vessels
  - Equipped with tuners
  - Powered by machine-type RF coupler

→ Need for a **short cryomodule** for testing purposes

Short cryo-module: Goal & Motivation

Goal:

- Design and construct a ½-lenght cryo-module for 4 β=1 cavities

Motivation:

- Test-bench for RF testing on a multi-cavity assembly driven by a single or multiple RF source(s)
- Enable RF testing of cavities in horizontal position, housed in their helium tanks, tuned, and powered by machine-type RF couplers
- Validate by testing critical components like RF couplers, tuners, HOM couplers in their real operating environment

Cryomodule-related goals:

- Learning of the critical assembly phases:
  - preparation of a long string of cavities in clean room
  - alignment/assembly in the cryostat;
- Proof-of-concept of the innovative supporting of cavities via the RF couplers
- Explore cryogenic operation issues

Planned supplies for β=1 short cryo-module

Institute	Responsible person	Description of contribution
CEA – Saclay (F)	S. Chel (G.Devanz)	1. Design & construction of **1 β=1 cavities** (EuCARD task 10.2.2) 2. Design & construction of **5 helium vessels for β=1 cavities** (French in-kind contribution) 3. Supply of **8 tuners** (French in-kind contribution)
CNRS - IPN – Orsay (F)	P. Duthil (P.Duchesne)	1. Design and construction of **prototype cryomodule cryostat** (French in-kind contribution) 2. Design & construction of **cryostat assembly tools** (French in-kind contribution)
Stony Brook/BNL/AES team	I.Ben-zvi	*(Under DOE grant)* 1. Designing, building and testing of **1 β=1 SPL cavity**.
CERN	O.Capatina	**1. 8 β=1 cavities** **2. 4 He tanks in titanium** **3. 1 He tank in st.steel**
CERN	E.Montesinos	**1. 8 +1 RF couplers** (testing in CEA, French in-kind contribution)

In **blue**, recent changes

Relevant events since last collaboration meeting

- Workshop on cryogenic and vacuum sectorization of the SPL
  - CERN, 9-10 Nov.2009, http://indico.cern.ch/conferenceDisplay.py?confId=68499
  - 22 participants from CEA, IPN Orsay, FNAL, ORNL, JLAB, SLAC, DESY, ESS, and CERN

- Review of SPL RF power couplers
  - CERN, 16-17 March 2010, http://indico.cern.ch/conferenceTimeTable.py?confId=86123#20100316
  - 24 participants from CEA, IPN Orsay, BNL, FNAL, ANL, JLAB, DESY, Lancaster Univ., Uppsala Univ., and CERN

- Intermediate meetings of the WG3:
  - minutes on CERN EDMS
  - Cryomodule documentation on https://twiki.cern.ch/twiki/bin/view/SPL/CryoModules

SPL parameters

(https://twiki.cern.ch/twiki/bin/view/SPL/SPLparameterList, by F.Gerigk)

Parameter	Unit	HP-SPL low-current	HP-SPL high-current	LP-SPL
Energy	[GeV]	5	5	4
Beam power	[MW]	4	4	0.192
Repetition rate	[Hz]	50	50	2
Average pulse current	[mA]	20	40	0-20
Peak pulse current	[mA]	32	64	32
Source current	[mA]	40	80	40
Chopping ratio	[%]	62	62	62
Beam pulse length	[ms]	0.8	0.4	0.9
filling time constant tau_l (b=0.65/1.0)	[ms]	0.54/0.55	0.27/0.27	0.54/0.55
actual cavity filling time: ln(4) x tau_l	[ms]	0.75/0.76	0.37/0.38	0.75/0.76
RF pulse length (filling time + flat top)	[ms]	1.55/1.56	0.78/0.78	1.65/1.66
Protons per pulse for PS2	[10^{14}]	1.0	1.0	1.13
Beam duty cycle	[%]	4	2	0.18
RF duty cycle	[%]	7.8	3.9	0.33
Cryogenics duty cycle	[%]	8.2	4.1	0.35

Cryogenic-specific parameters

(https://twiki.cern.ch/twiki/bin/view/SPL/SPLparameterList, by F.Gerigk)

Parameter	Units	Beta = 0.65 nominal/ultimate	Beta = 1 nominal/ultimate
Cavity bath temperature	[K]	2.0	2.0
Beam loss	[W/m]	1.0	1.0
Static loss along cryo-modules at 2 K	[W/m]	TBD	TBD
Static loss at 5-280 K	[W/m]	TBD	TBD
Accelerating gradient	[MV/m]	**19.3**	**25**
Quality factor (x10^9)		**6/3**	**10/5**
R/Q value		**290**	**570**
Cryogenic duty cycle	[%]	**4.09/8.17**	**4.11/8.22**
Coupler loss at 2.0 K	[W]	<0.2/0.2	<0.2/0.2
HOM loss at 2.0 K in cavity	[W]	<1/<3	<1/<3
HOM coupler loss at 2.0 K (per coupler)		<0.2 /0.2	<0.2/0.2
HOM & Coupler loss 5-280 K	[g/s]	0.05	0.05
Tunnel slope	[%]	1.7%	1.7%
Magnet operating temperature	[K]	ambient	ambient
No of cavities		60	200
No of cryostats		20	25
Cavities per cryostat		3	8
Dynamic heat load p. cavity	[W]	**4.2/13.4**	**5.1/16.2**

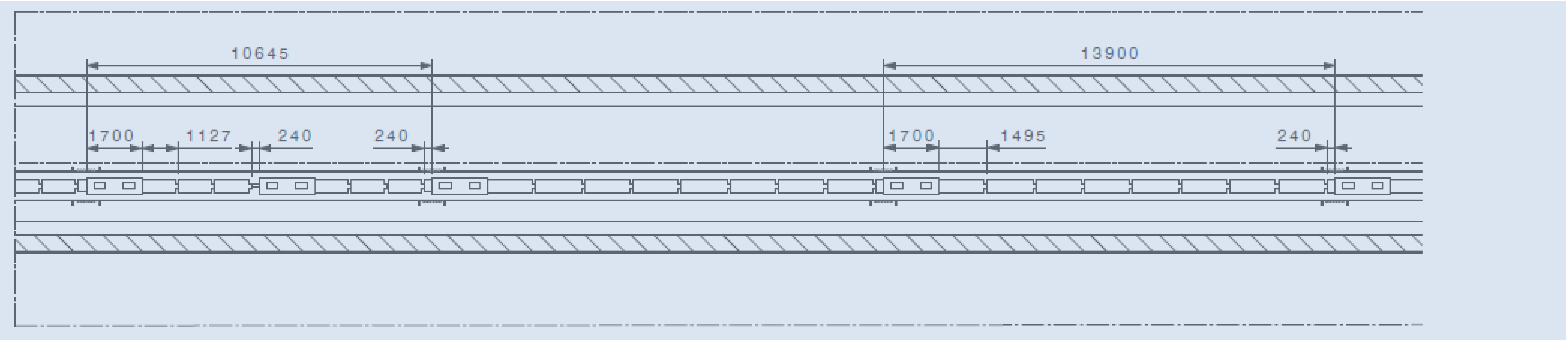
Nominal: 40 mA/0.4 ms beam pulse ; **Ultimate:** 20 mA/0.8 ms beam pulse.

CRYOGENICS AND VACUUM SECTORISATION

Outcome of workshop on cryogenic and vacuum sectorisations of the SPL
(November 9-10, 2009)

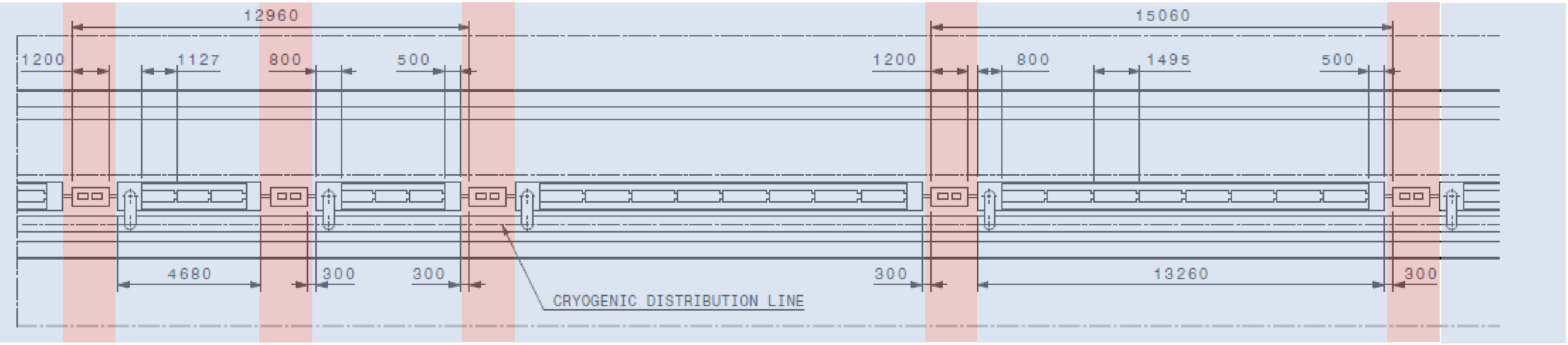
Longitudinal mechanical layouts
«Continuous» vs. «fully segmented» cryostat SPL layouts

Continuous cryostat "Compact" version (gain on interconnections):



➔ **5 Gev version (HP): SPL length = 485 m (550 m max available space)**

"Warm quadrupole" version (with separate cryoline):



➔ **5 Gev version (HP): SPL length = 535 m (550 m max available space)**

Main issues

- Machine availability:
  - "work-horse" in the injection chain

- Reliability of built-in components and operational risks
  - Typical faults expected on: cavities, couplers, tuners...
  - Operation with degraded performance (cavities, optics, leaks...)

- Maintainability:
  - Warm-up/cool-down . Time and reliability. Need for partial or complete warm-up of strings to replace built-in components or even one cryo-module
  - Accessability of components for regular maintenance or repair

- Design complexity of compared solutions

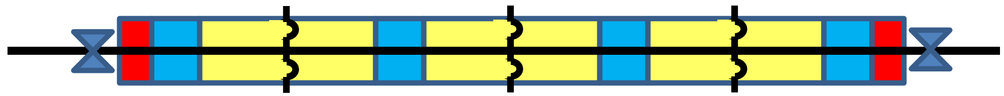
- Operational complexity (e.g.cryogenics with 1.7% slope)

- Installation and commissioning

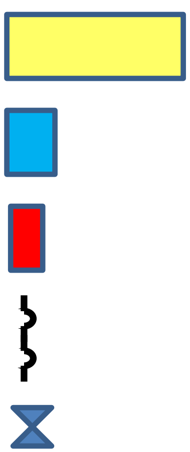
- Safety. Coping with incidents (MCI): Loss of beam and/or insulation vacuum (helium and air leaks):

- Cost differences between options

“continuous” cryostat



- “Long” and “continuous” string of cavities in common cryostat
- Cold beam tube
- “straight” cryogenic lines in main cryostat
- common insulation vacuum (between vacuum barriers, if any present)



String of cryo-modules between TSM

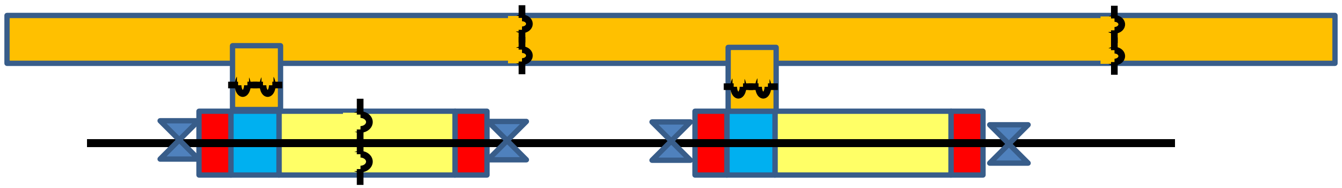
Technical Service Module (TSM)

Cold-Warm Transition (CWT)

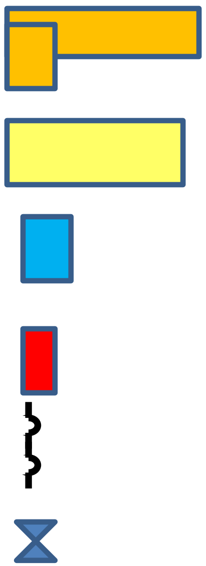
Insulation vacuum barrier

Warm beam vacuum gate valve

“segmented” cryostat



- Cryostat is “segmented”: strings of (or single) cryo-modules, 2 CWT each
- Warm beam zones (where warm quads can be)
- Cryogenic Distributio Line (CDL) needed
- Individual insulation vacuum on every string of cryo-module (Vacuum Barriers, w.r.t. CDL)



Cryogenic Distribution Line (CDL)

String of (or single) cryo-modules

Technical Service Module (TSM)

Cold-Warm Transition (CWT)

Insulation vacuum barrier

Warm beam vacuum gate valve

Conclusions on sectorisation

- **Drivers:**
  - Availability:
    - Reliability/Maintainability. Components with technical risk:
      - RF Coupler, single window. No in-situ repair possible
      - Cavity/tuner, reduced performance. No in-situ repair possible
      - Beam/cavity vacuum leaks. No in-situ repair possible

    → **calls for quick replacement of complete cryo-module (spares needed)**

  - Safety: coping with incidents: accidental loss of beam/cavity vacuum:
    - Cold valves not available (XFEL is considering their development)

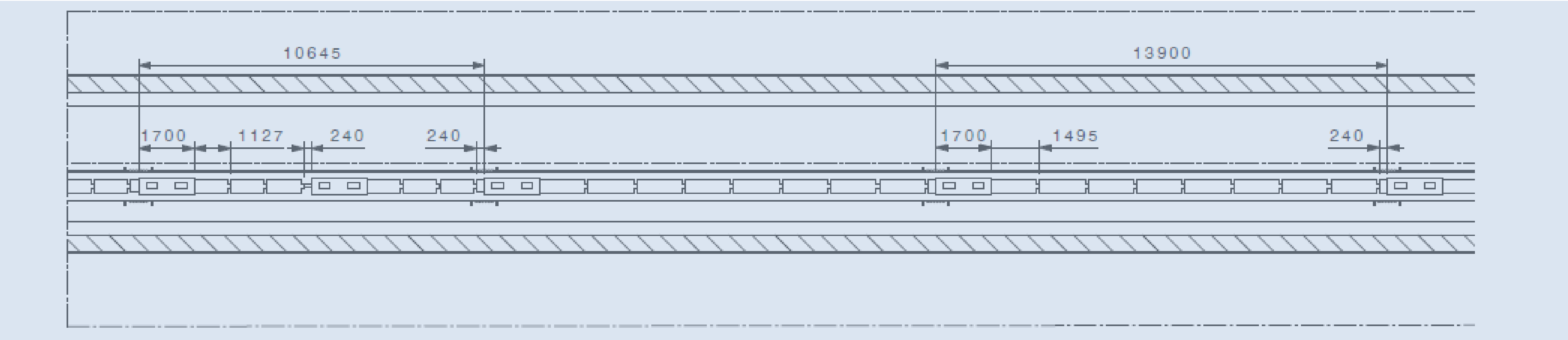
    → **Adopt warm, interlocked valves (not necessarily very fast, XFEL experience)**

➡ **"Segmented" layout with CDL has clear advantages in these respects**

- **Additional advantages:**
  - Magnets can be warm: classical "off-the shelf", easy alignment/maintainability/upgrade
  - and cryo-module internal positioning requirements can ne relaxed (by a factor of 3)
- **Drawbacks:**
  - Less compact layout (~+10% extra lenght)
  - More equipment (CDL, CWT, instrumentation...):
    - Capital cost
    - More complexity = less reliability?
  - Higher static heat loads (but dynamic loads dominate!)

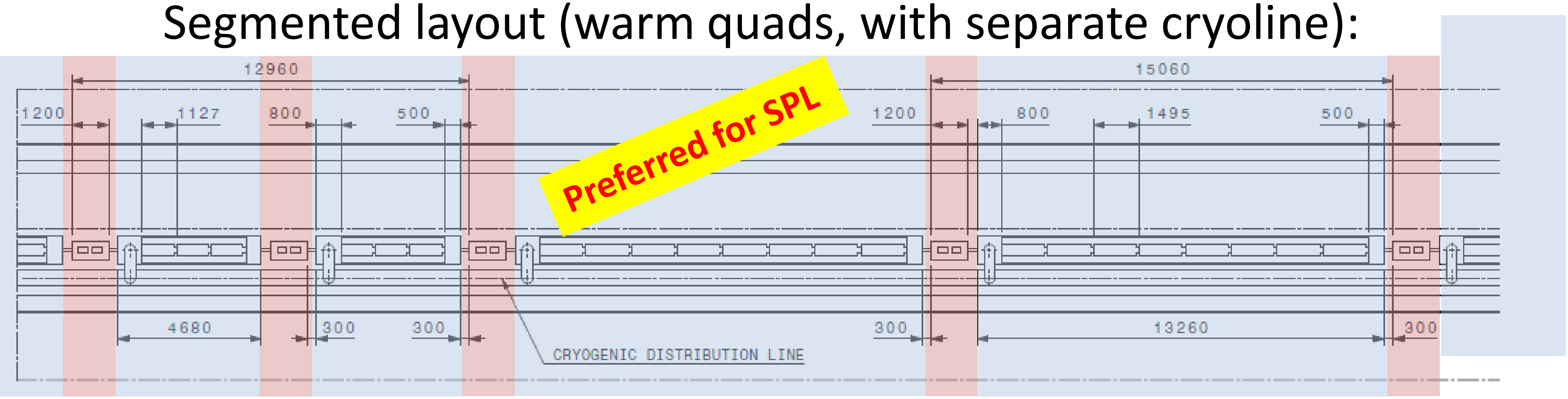
Cryogenic and vacuum sectoriz.of the SPL

Continuous cryostat "Compact" version (gain on interconnections):



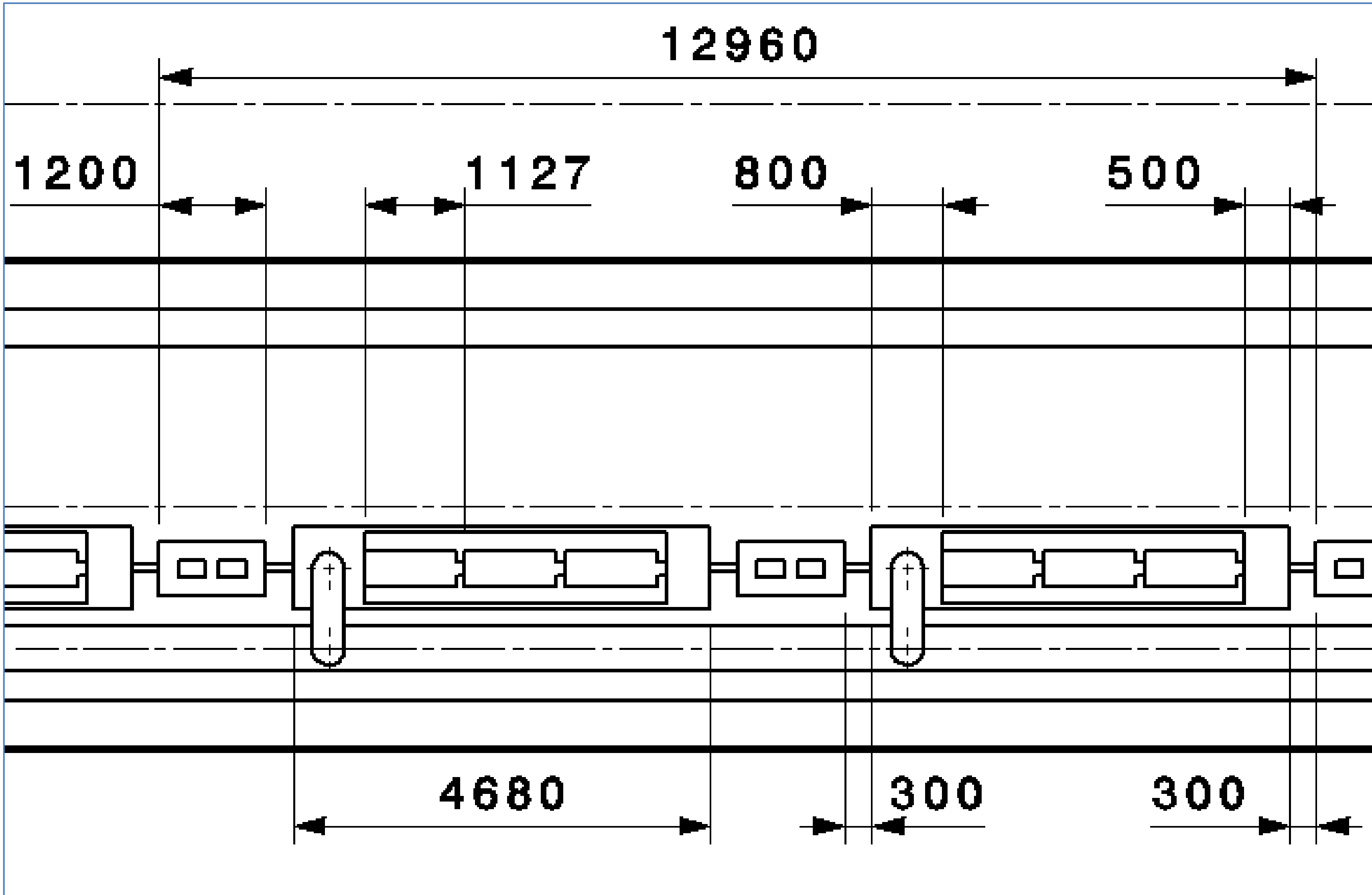
➔ **5 Gev version (HP): SPL length = 485 m**

Segmented layout (warm quads, with separate cryoline):

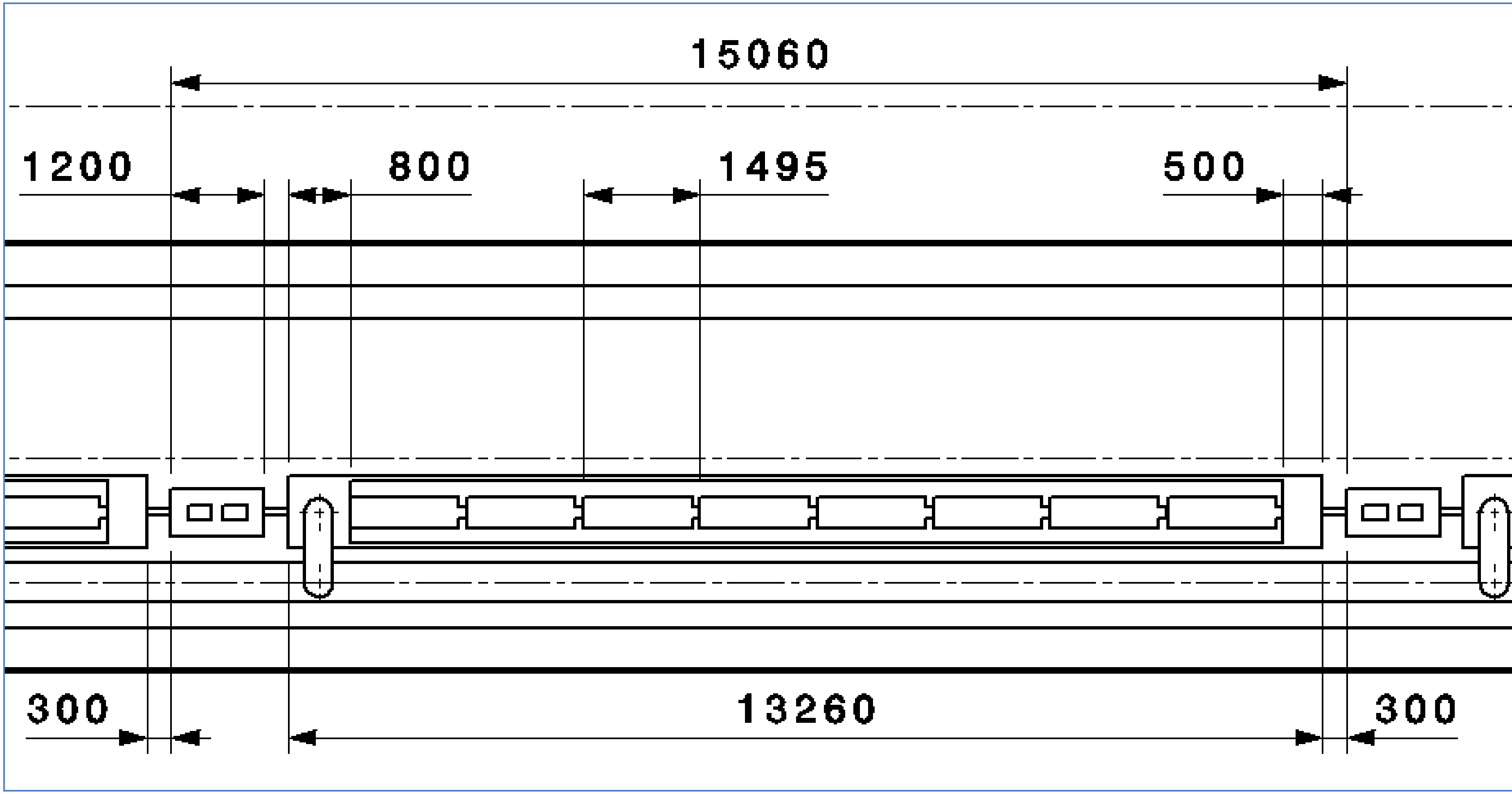


➔ **5 Gev version (HP): SPL length = 535 m**

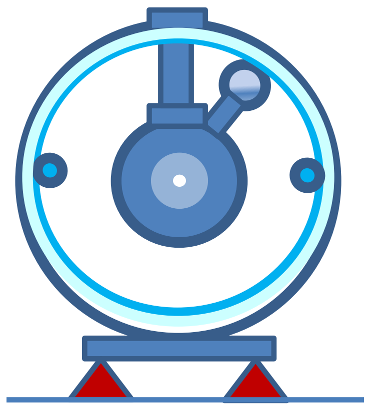
β=0.65 cryo-module

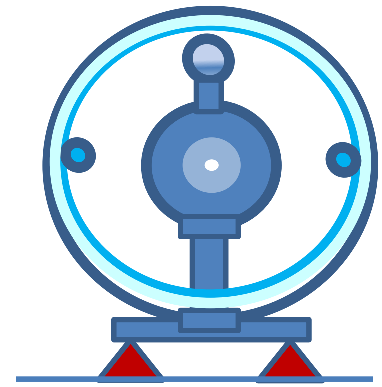


β=1 cryo-module



Coupler position: top or bottom…?





Pros	Contras
Easier mounting of waveguides	Interferes with bi-phase tube → move sideways
Easier access (needed?)	Waveguides/coupler more exposed to personnel/handling (damage, breaking window?)
…	…

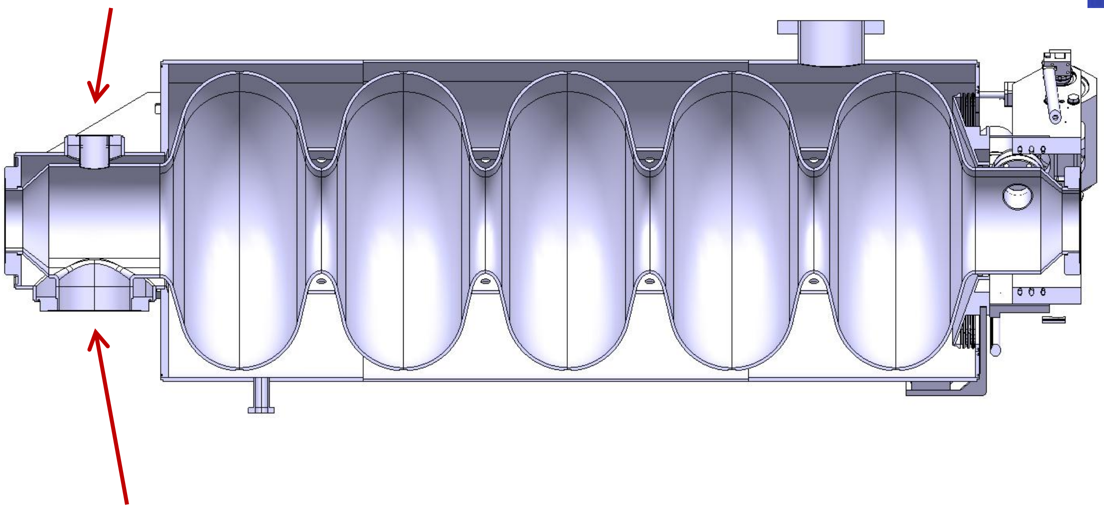
Pros	Contras
Centered bi-phase tube→ symmetry	Space needs for waveguides under cryostat
Waveguides/coupler protected	If coupler not a support (bellows)→ support on top, i.e. centered tube not possible
…	…

No strong decision-making argument…

HOM coupler

- Provisions made to house an HOM coupler (resonator type)
- Port foreseen opposite to RF coupler port
- Superconducting, cooled at 2K
- The HOM coupler needs to be on top
- ...so the RF coupler is at the bottom

HOM port



RF coupler port

Cavity Supporting System

Transversal position specification

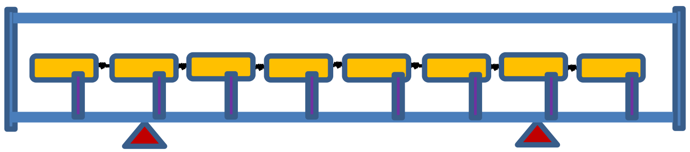
BUDGET OF TOLERANCE			
Step	**Sub-step**	**Tolerances (3σ)**	**Total envelopes**
Cryo-module assembly	Cavity and He vessel assembly	*± 0.1 mm*	Positioning of the cavity w.r.t. beam axis **± 0.5 mm**
	Supporting system assembly	*± 0.2 mm*	
	Vacuum vessel construction	*± 0.2 mm*	
Transport and handling (± 0.5 g any direction)	N.A.	*± 0.1 mm*	Stability of the cavity w.r.t. beam axis **± 0.3 mm**
Testing/operation	Vacuum pumping	*± 0.2 mm*	
	Cool-down		
	RF tests		
	Warm-up		
	Thermal cycles		

Construction precision

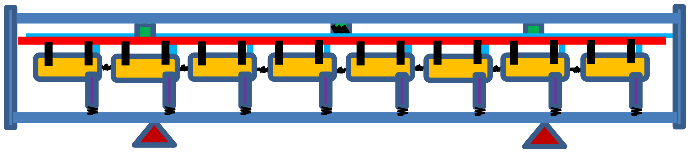
Long-term stability

Comparing supporting solutions

A) Coupler supporting scheme



B) “standard” supporting scheme

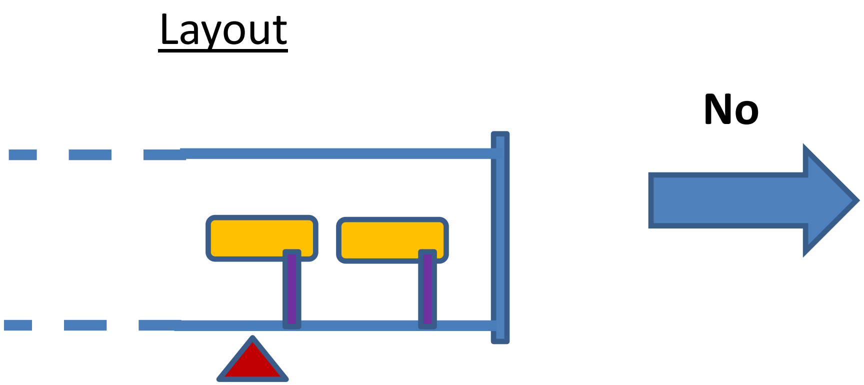


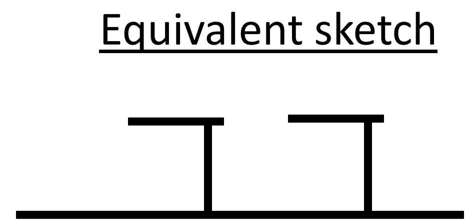
Pros	Contras
Design simplicity: cost effectiveness	Vacuum vessel: - Stiffness (thickness, stiffeners) - Dim. stability - Precision machining - Cost
Single cavity adjustment at assy	Positioning stability (thermal, weld relieving...)
	Inter-cavity guiding

Pros	Contras
Better mechanical isolation of cavities from external perturbations: dim. changes (thermal, weld relieving), vibrations...	Design complexity and cost
Vacuum vessel simplicity: -Reduced machining precision - reduced thickness	Central support needed (?)
	Complex cavity adjustment at assy

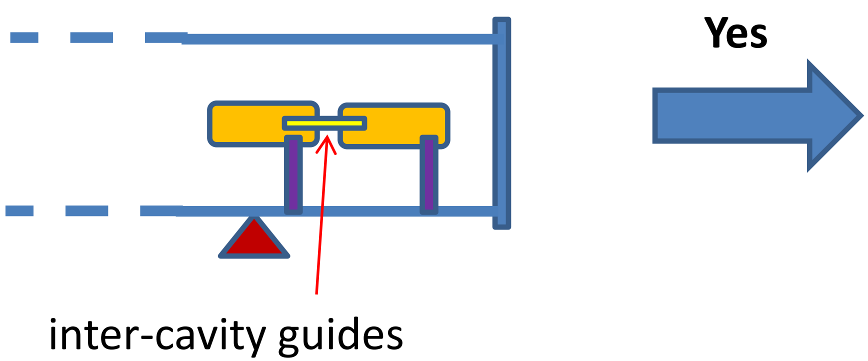
A) Chosen as baseline (“simple is nice”)

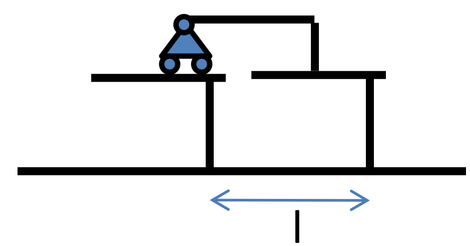
Need inter-cavity support structure?



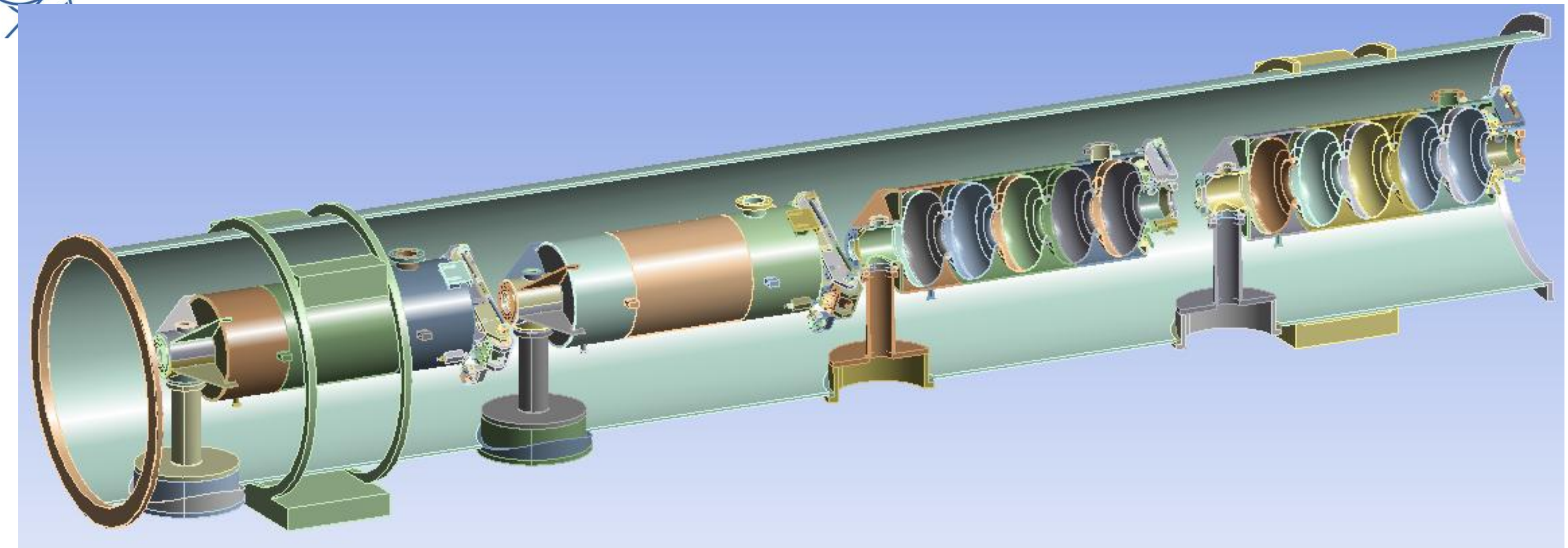


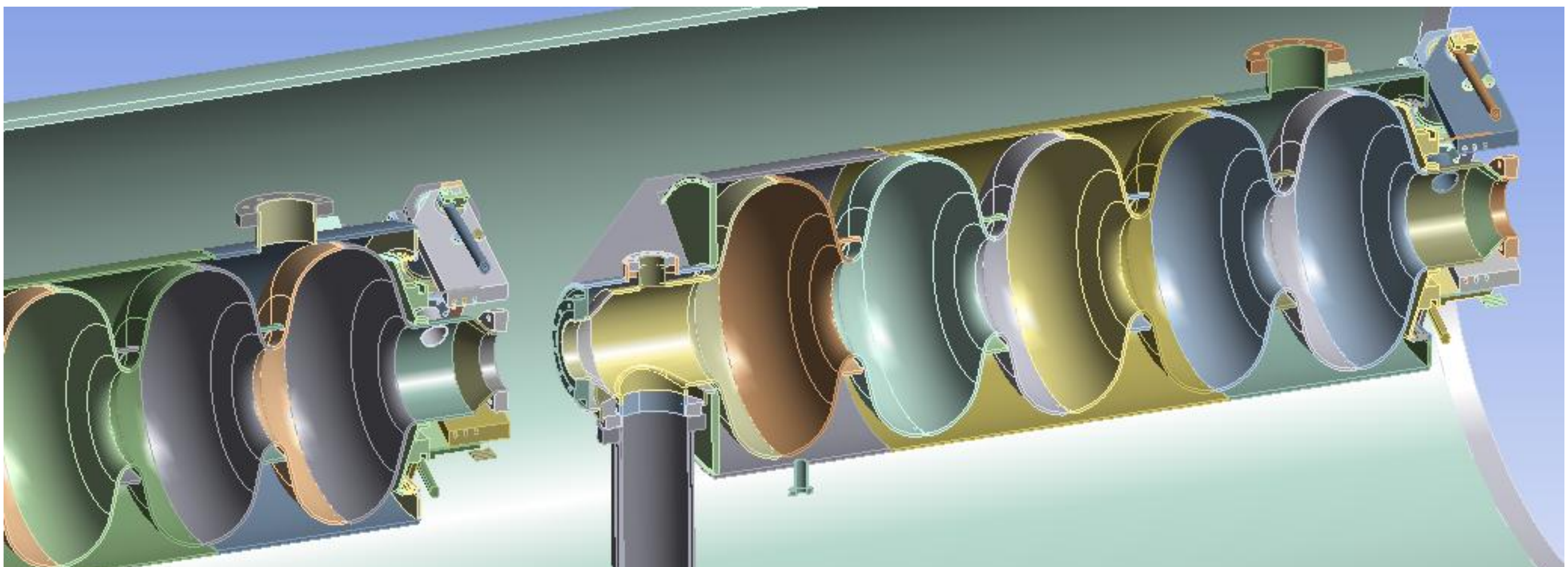
- If sag small enough
- If strenght OK
- isostatic





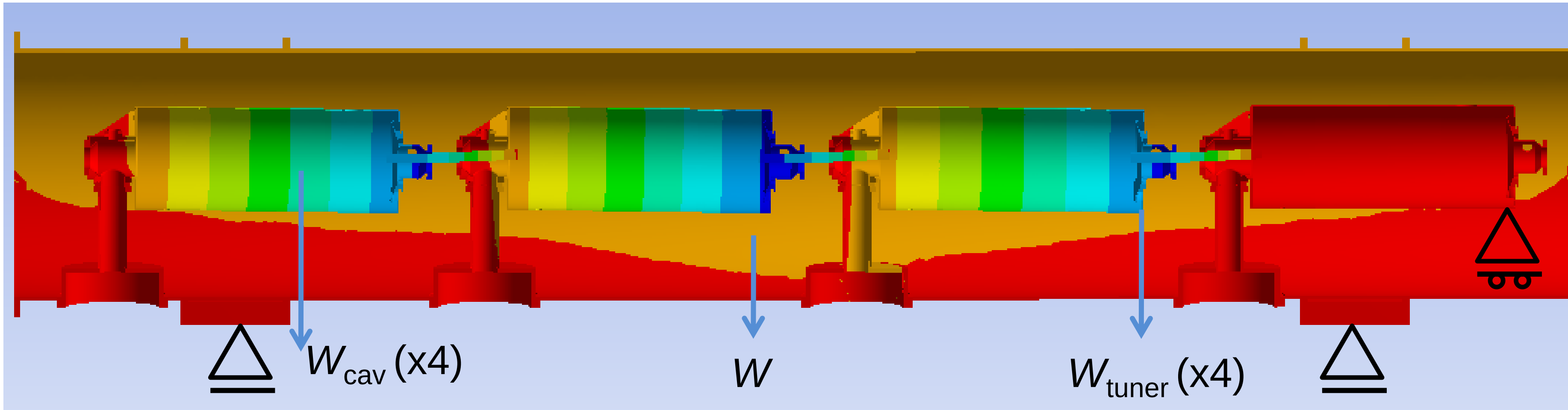
- couple cavities
- hyperstatic

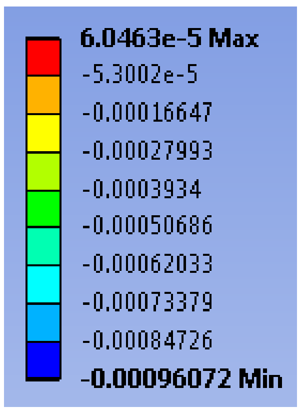




P.Coelho Moreira de Azevedo

Vertical displacement in *m* (body deformation amplified 20 times):



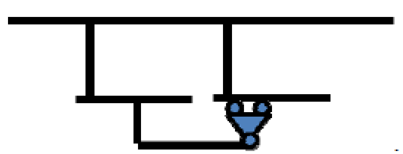


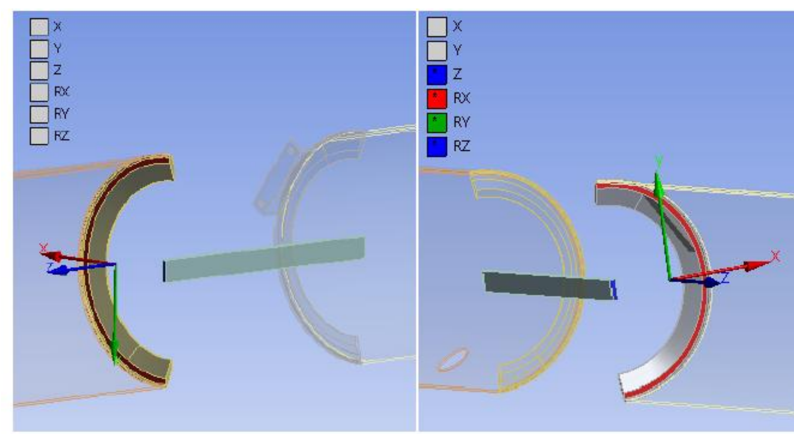
The cavities are not part of the model. The loads are the distributed weight of the represented components, tuners and cavities.

Deflections still excessively high! → goal is 0.1mm (cavity self-weight straigtness),

....still work to do!

The link between the cavities is established as shown:

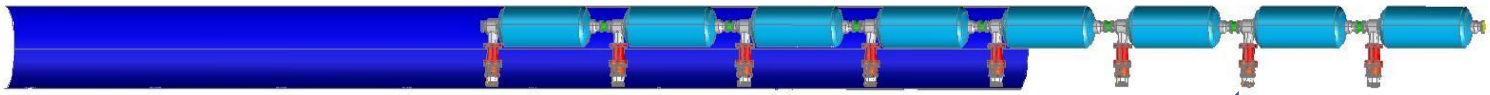


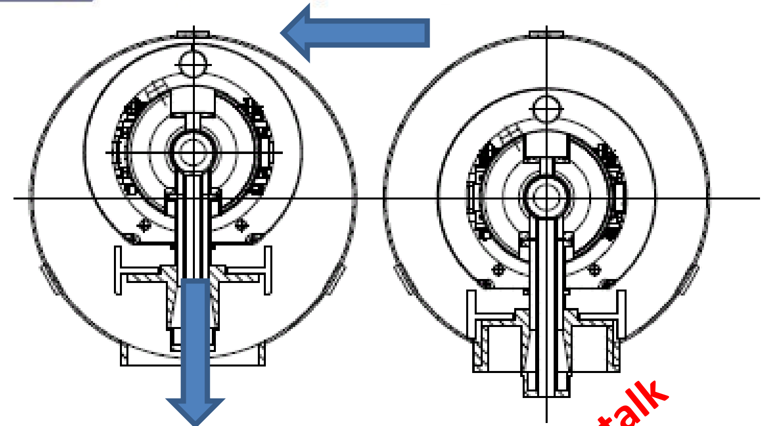


P.Coelho Moreira de Azevedo

Assembly possibilities…

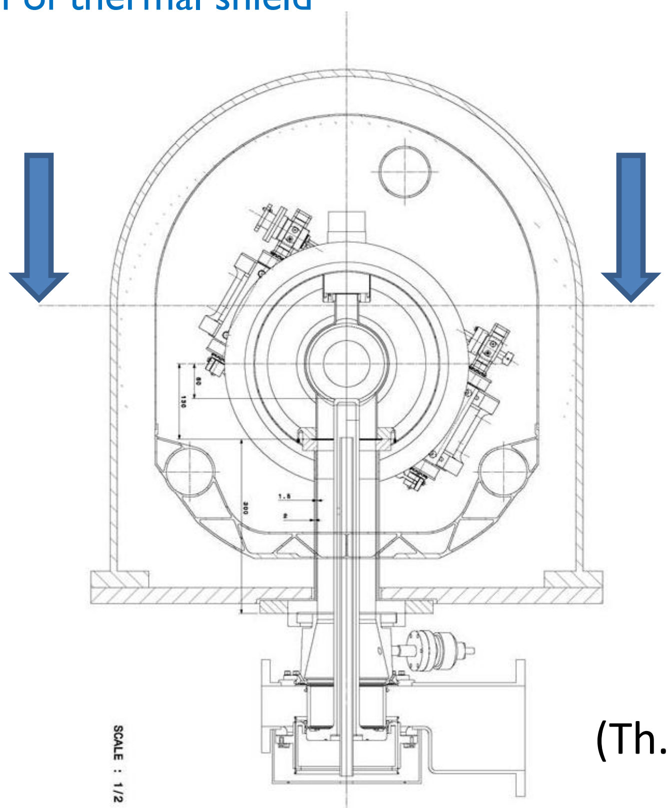
Either…





- Single-window RF coupler → needs assembly to cavities in clean room
- Defines minimum diameter of "pipeline" type vessel:
  - Lenght of double-walled tube
  - Integration of thermal shield

Or…



More in CNRS's talk

- Simple in the cross section…

But…

- Non trivial design of end-caps
- Leak-tightness: seal? welded?

(Th.Renaglia)

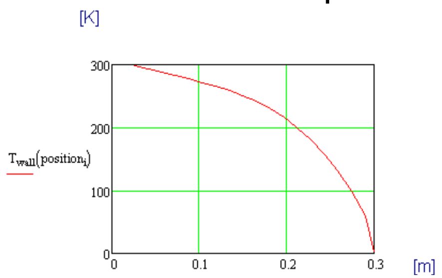
Actively cooled RF coupler tube

More in Ofelia's talk

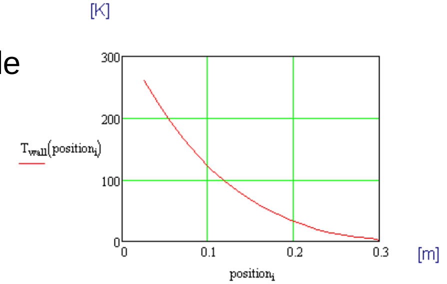
SPL coupler double walled tube, active cooling to limit static heat loads

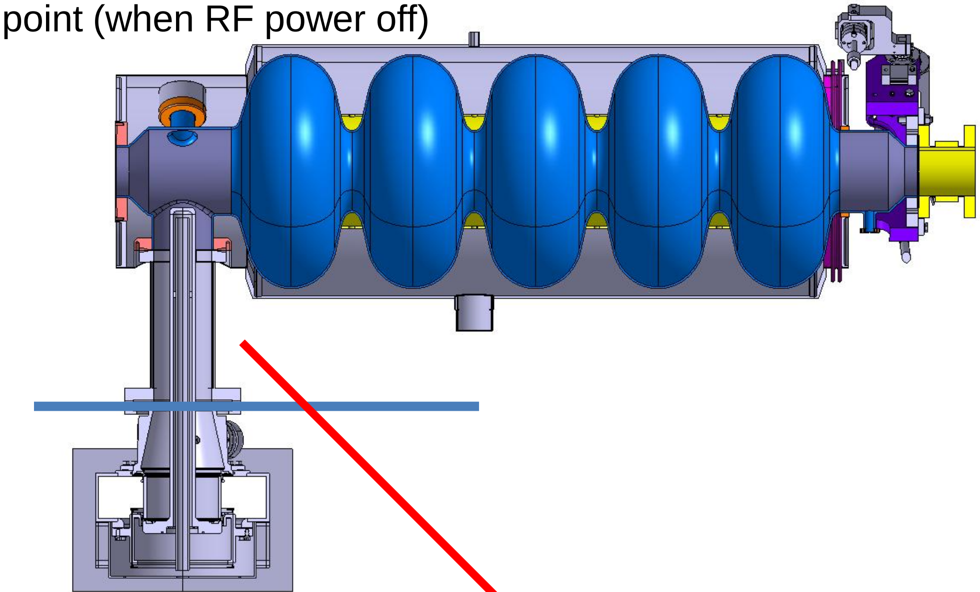
- Connected at one end to cavity at 2K, other end at RT (vessel)
- Requires elec. Heater to keep T > dew point (when RF power off)

No cooling T profile
→ 21W to 2K

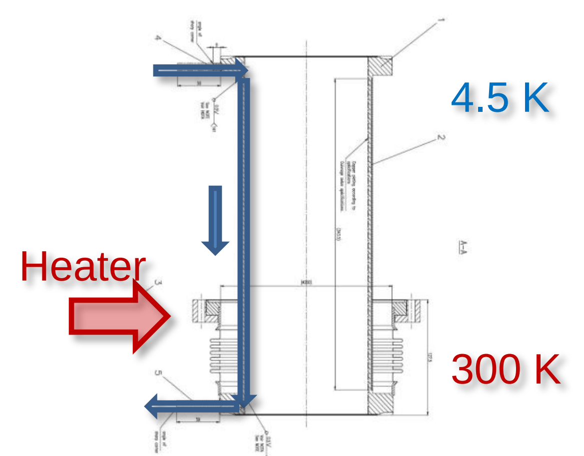


Cooling (42 mg/sec) T profile
→ 0.1 W to 2K





Massflow mgram/sec	21		23		28		35		42	
Power	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
Temp. gas out	286 K	277 K	283 K	273 K	271 K	242 K	255 K	205 K	232 K	180 K
Q thermal load to 2K	2.4 W	0.1 W	1.7 W	0.1 W	0.4 W	0.1 W	0.1 W	0.1 W	0.1 W	0.1 W
Q heater	19 W	32 W	21 W	34 W	29 W	38 W	39 W	41 W	46 W	44 W
ΔL	0.1 mm (0.63-0.53)mm				0.05 mm (0.66-0.61)		~ 0 mm (0.67-0.67)			

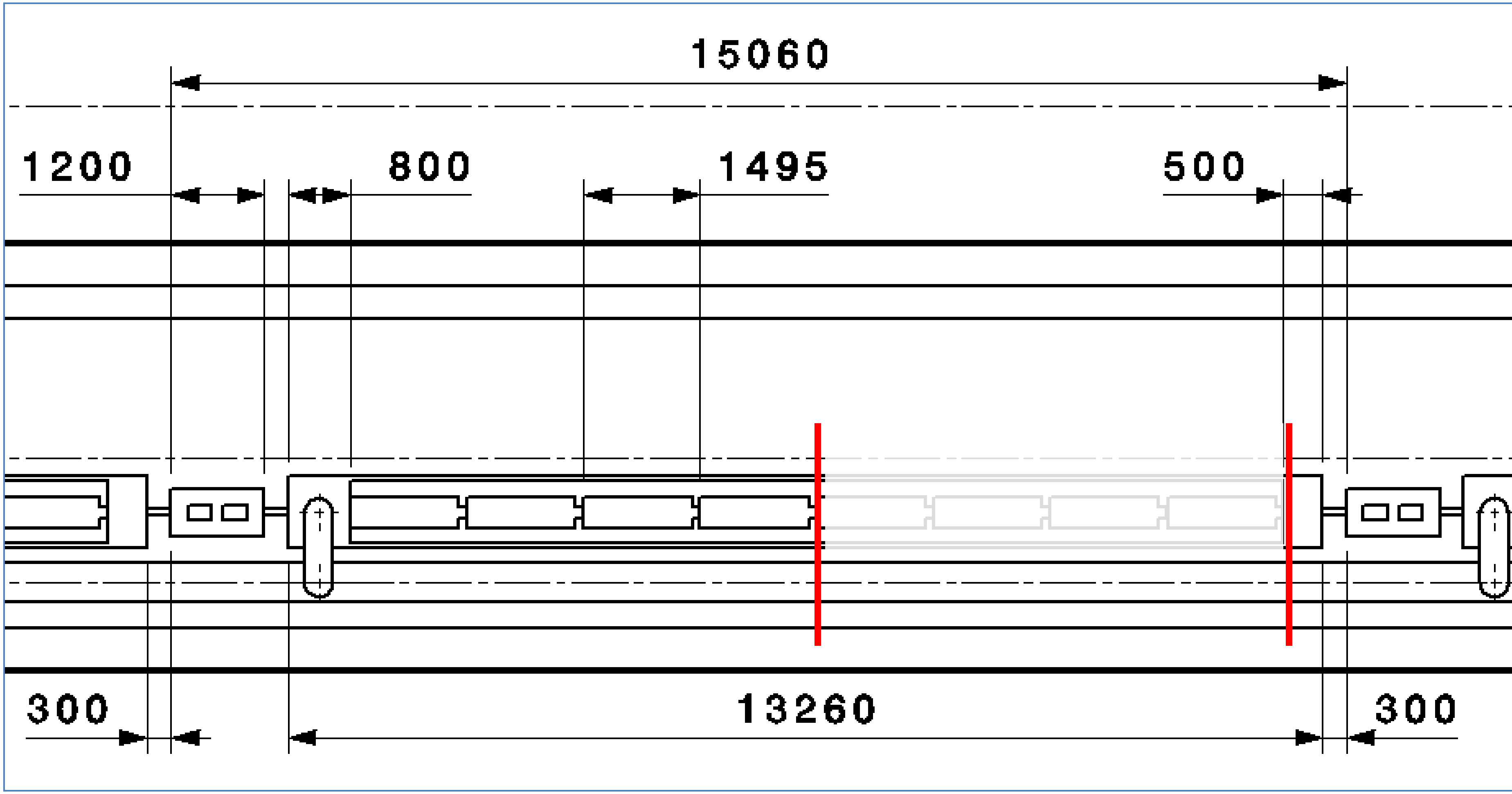


→ Yields a certain degree of position uncertainty (<0.1 mm?)

(O.Capatina, Th.Renaglia)

Helium gas cooling the double wall

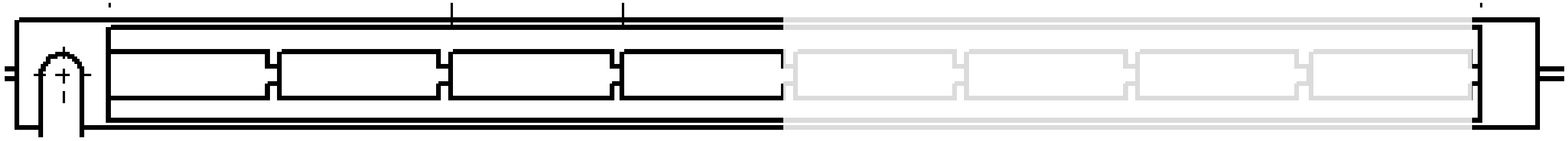
From 8 to 4 cavities…How??



…just remove 4 cavities!

Coping with the "ghost" cavities…

- Assume they still exist
- Design the systems as if they where there:
  - Cryogenics (p,T, mass flows)
  - Distribution lines (ID, pres.drops)

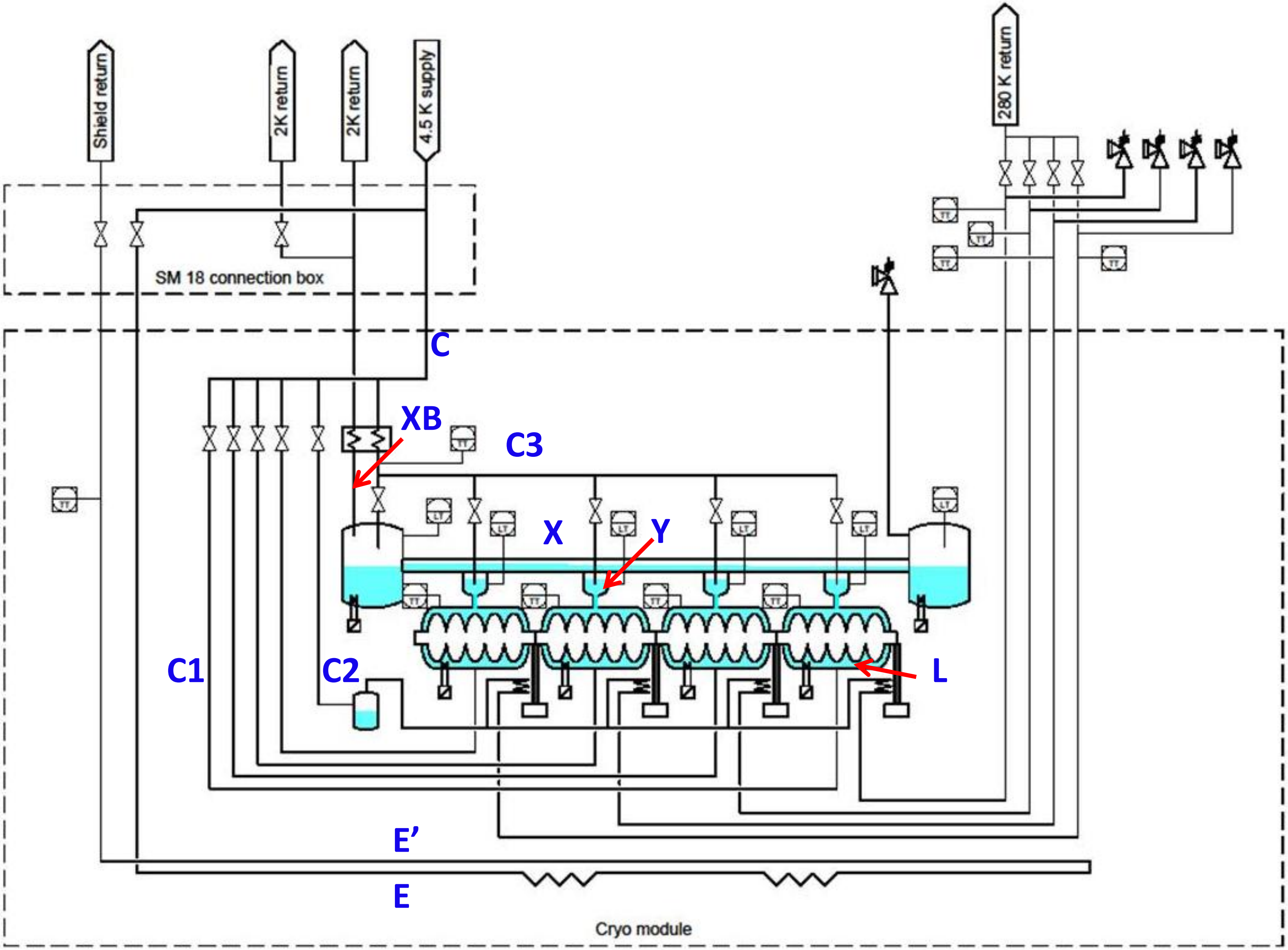


Heat Loads

Heat loads @ 2K (He bath)	b=0.65	b=1
	nominal/ultimate	
beam loss	**1 W**	**1 W**
static losses	**<1 W (tbc)**	**<1 W (tbc)**
accelerating field	19.3 MV/m	25 MV/m
quality factor	$6/3 \times 10^9$	$10/5 \times 10^9$
cryo duty cycle	4.09%/8.17%	4.11%/8.22%
power coupler loss at 2 K	**<0.2/<0.2 W**	**<0.2/<0.2 W**
HOM loss in cavity at 2 K	**<1/<3 W**	**<1/<3 W**
HOM coupler loss at 2 K (per coupl.)	**<0.2/<0.2 W**	**<0.2/<0.2 W**
dynamic heat load per cavity	**4.2/13.4 W**	**5.1/16.2 W**
Total @ 2 K	**7.6/18.8 W**	**8.5/21.6 W**
+15% margin (for testing)	**8.7/21.6 W**	**9.8/25 W**

For 8 beta=1 cavity cryomodule: 8x25=200W, equivalent to 10 g/s helium flow

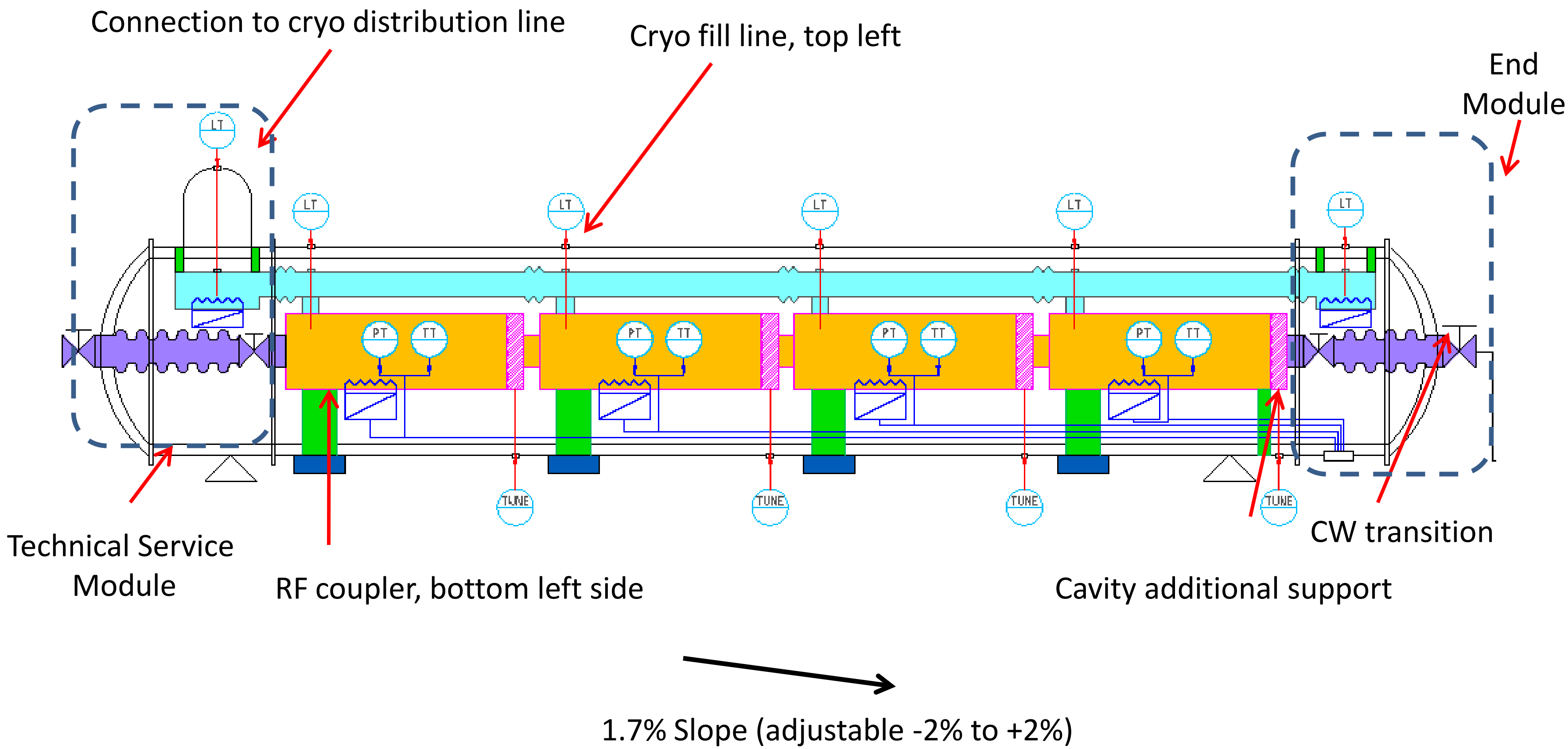
Cryogenic scheme (preliminary)



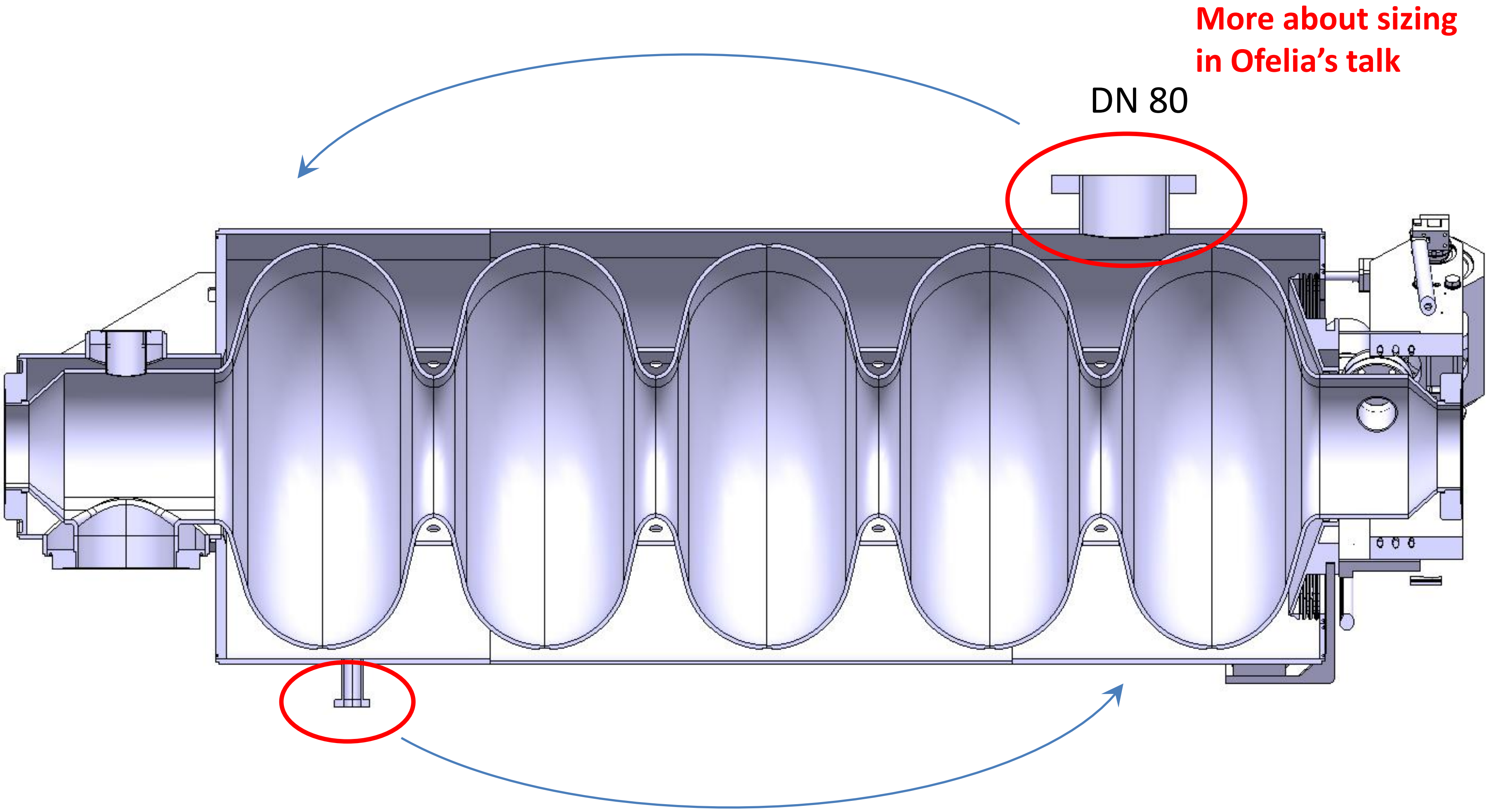
Pipe sizes and operating conditions *(preliminary)*

Line	Description	Pipe Size (ID,mm)	Normal operating pressure [MPa]	Normal operating temperature [T]	Cool-down/warm-up pressure [MPa]	Cool-down/warm-up temperature [K]	T range [K]	Maximum operating pressure [MPa]	Design pressure [MPa]	Test pressure [MPa]	Comment
L	Cavity helium enclosure	400	0.0031	2	0.13 @ 293K 0.2 @ 2K	293-2	2-293	0.13 @ 293K 0.2 @ 2K			
X	Bi-phase pipe	100	0.0031	2	0.13 @ 293K 0.2 @ 2K	293-2	2-293	0.13 @ 293K 0.2 @ 2K			
Y	Cavity top connection	80	0.0031	2	0.13 @ 293K 0.2 @ 2K	293-2	2-293	0.13 @ 293K 0.2 @ 2K			
XB	Pumping line	100	0.0031	2	0.13 @ 293K 0.2 @ 2K	293-2	2-293	0.13 @ 293K 0.2 @ 2K			
E	Thermal shield supply	40 (TBD)	2.0	50-75	2.0	293-50	50-293	2.0	2.0		Heat intercept
E'	Thermal shield return	15 (TBD)	2.0	50-75	2.0	293-50	50-293				Return only
W	Cryostat vacuum vessel	1000 (TBD)	vacuum	293	vacuum	293	237-293	O.P. 0.1	I.P. 0.15	N.A.	
C1	Cavity bottom filling	15	0.1	4.5	0.1	293-4.5	4.5-293				Liquid supply
C2	Coupler cooling	15	0.1	4.5-293	0.1	293-4.5	4.5-293				Gaseous supply
C3	Cavity top supply	15	0.1	2	0.1	293-4.5	2-293				Liquid supply

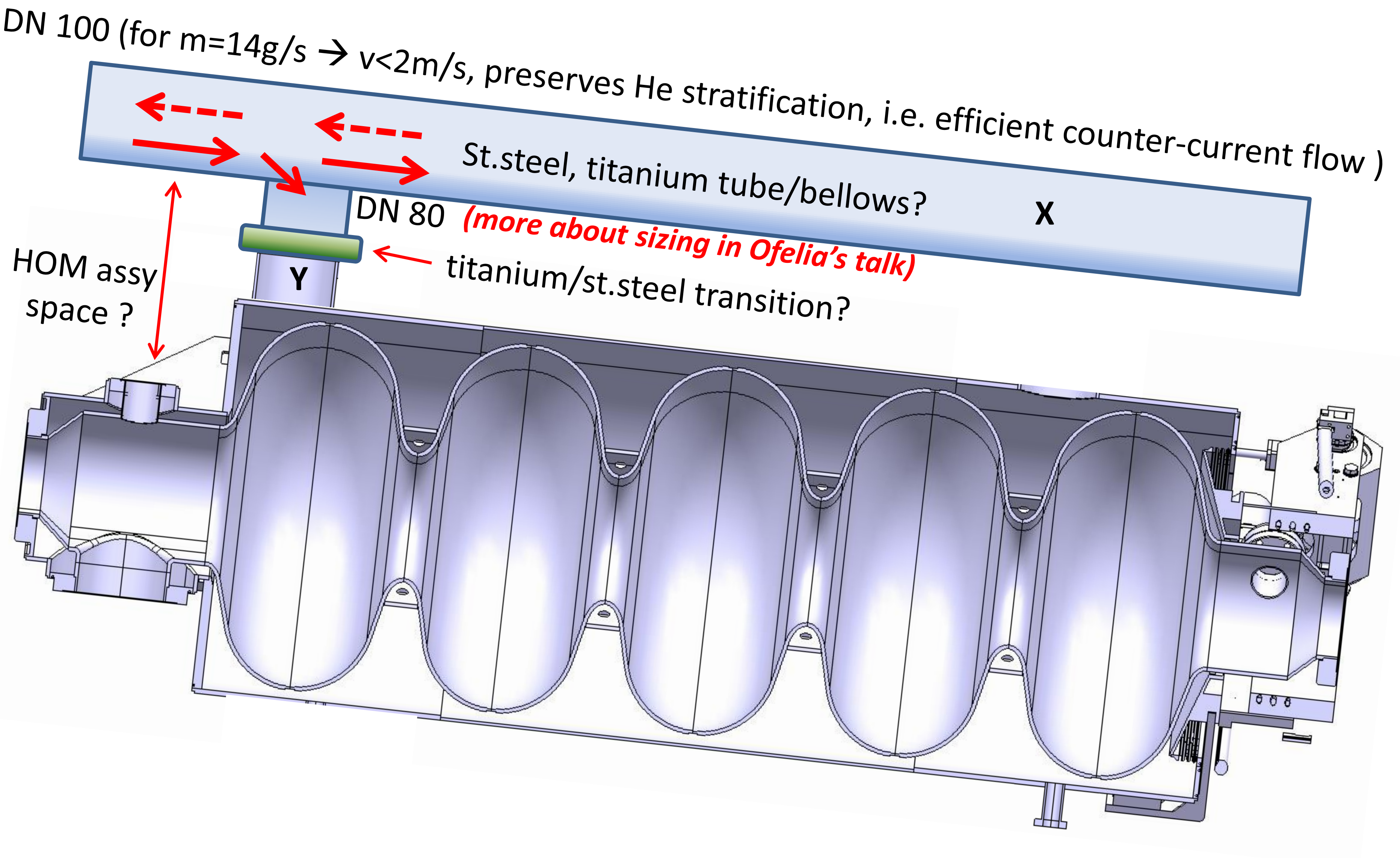
Short cryomodule: layout sketch



Helium tank interfaces: issues for discussion

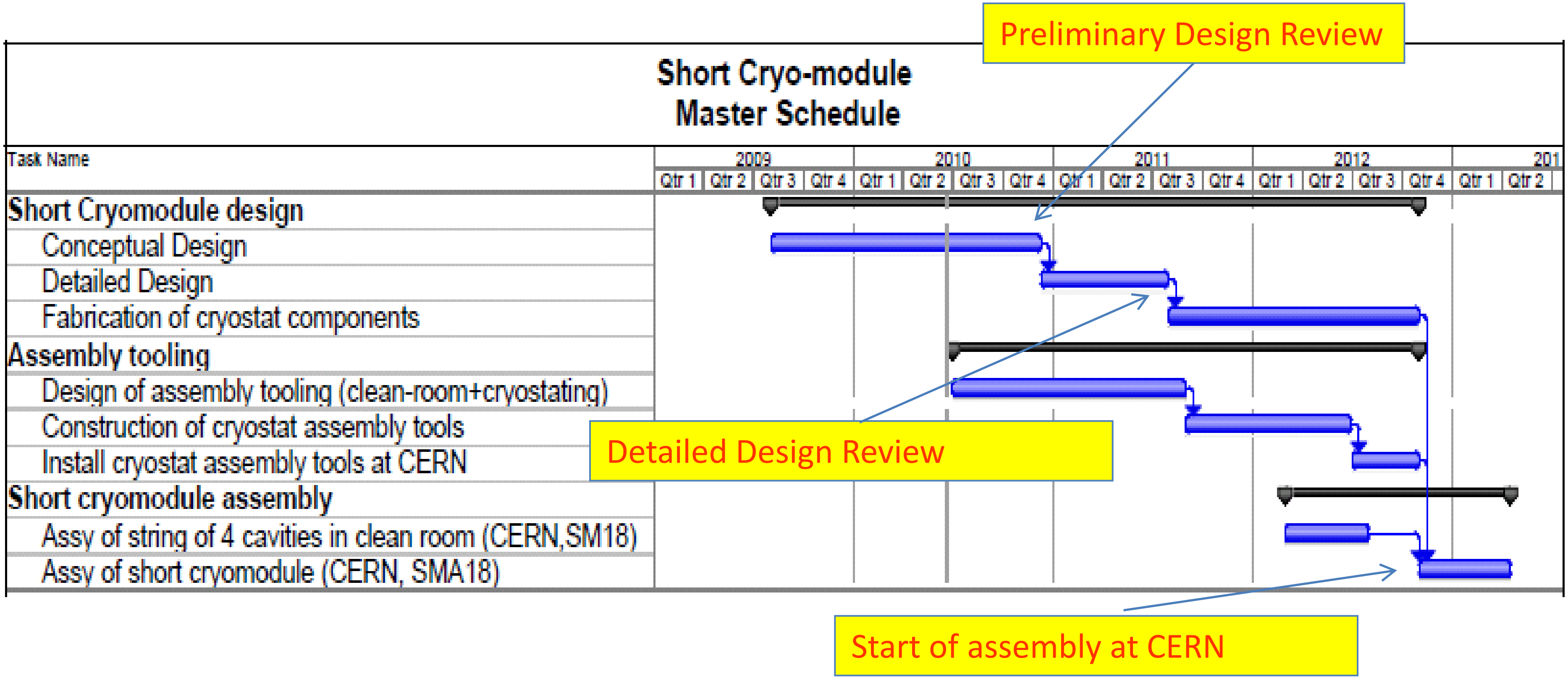


Lines X and Y



DN 100 (for m=14g/s → v<2m/s, preserves He stratification, i.e. efficient counter-current flow)
St.steel, titanium tube/bellows?
X
DN 80
(more about sizing in Ofelia's talk)
Y
titanium/st.steel transition?
HOM assy
space ?

Master Schedule



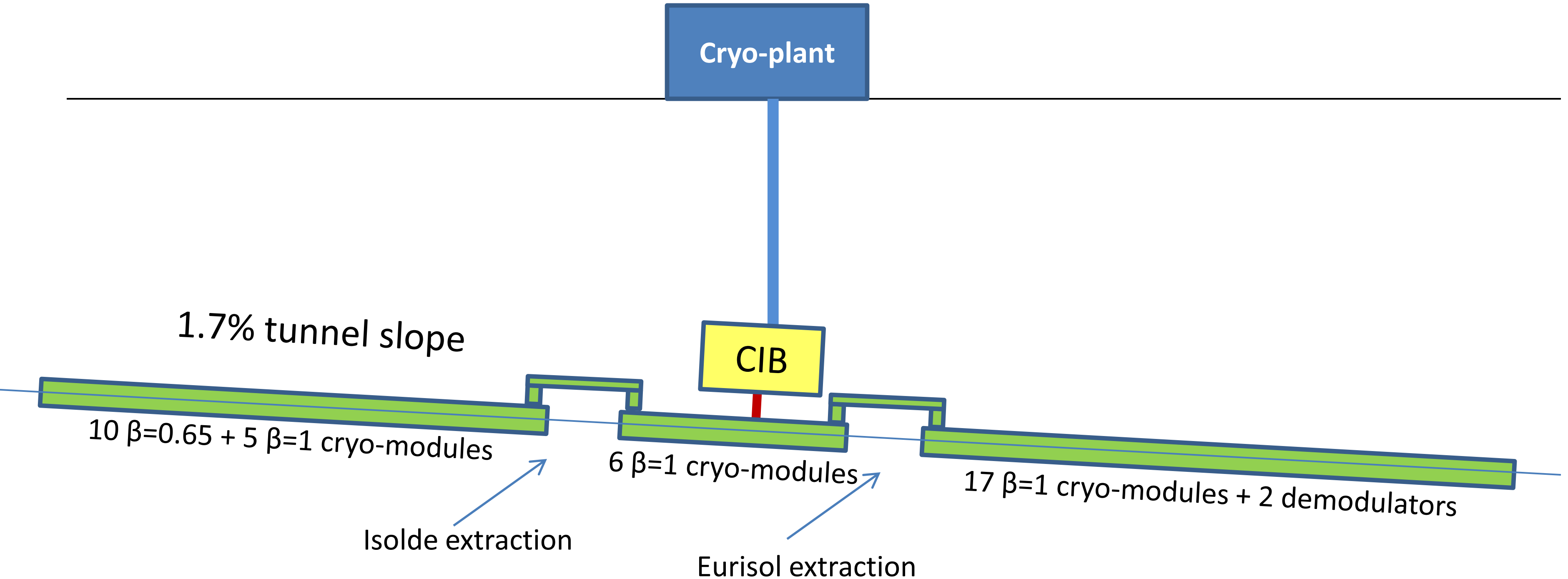
Summary

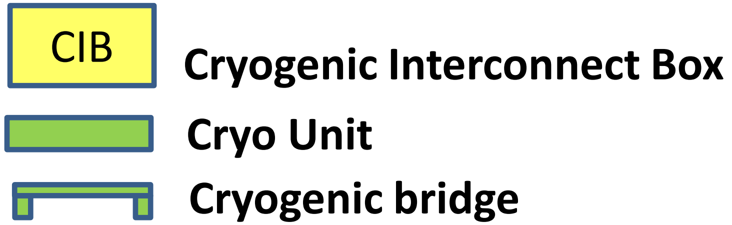
- SPL cryomodule studies are now concentrated on a 4 β=1 cavity short cryomodule aimed at testing the cavities in machine-like configuration
- The short cryomodule is designed as a shortened machine unit
- The short cryomodule will also allow exploring important design issues for machine cryomodules:
  - Innovative supporting system
  - Assembly principles
  - Cryogenic operating schemes
  - …
- Position of the coupler at the bottom is now settled
- The cryogenic scheme is being elaborated
- As a consequence piping sizes and pressures are being defined
- A technical specification for the cryomodule is in preparation and possibly ready by September next
- A preliminary design review will take place by the end of 2010

Thank you
for your attention!

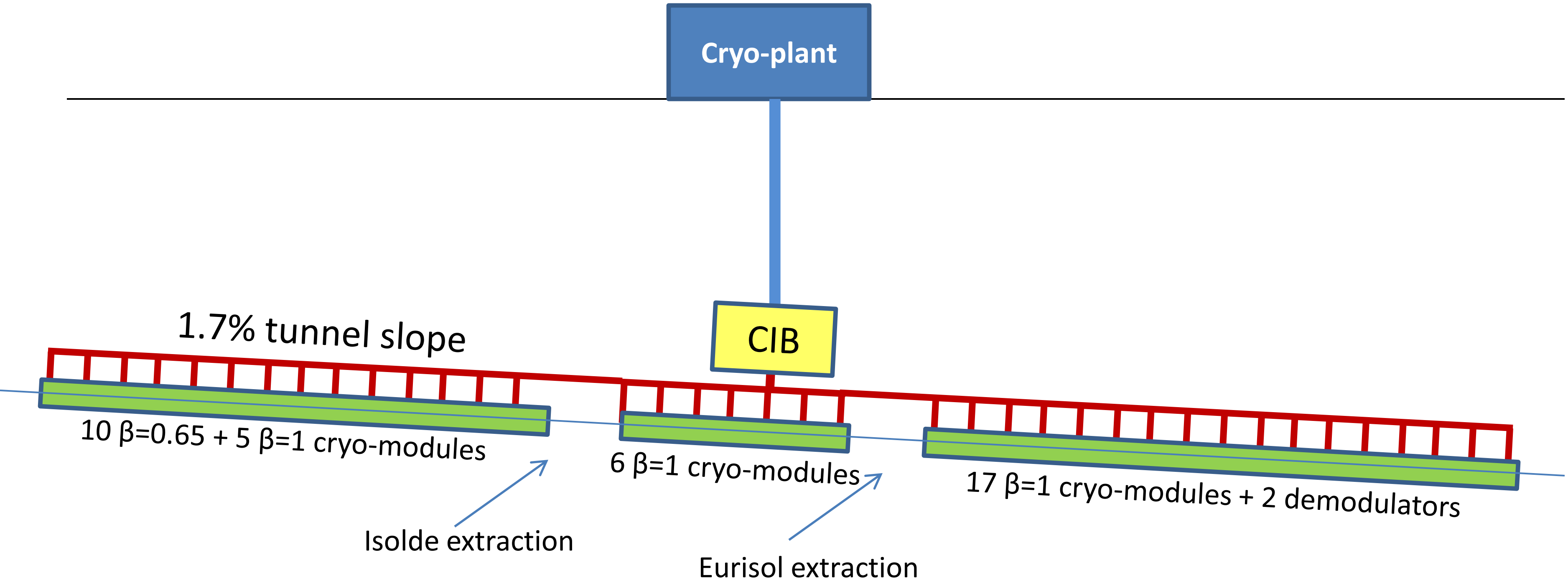
Spare slides

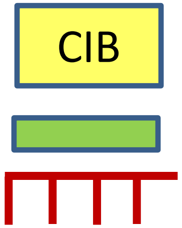
Possible cryogenic feeding: "continuous" cryostat





Possible cryogenic feeding: Cryogenic Distribution Line





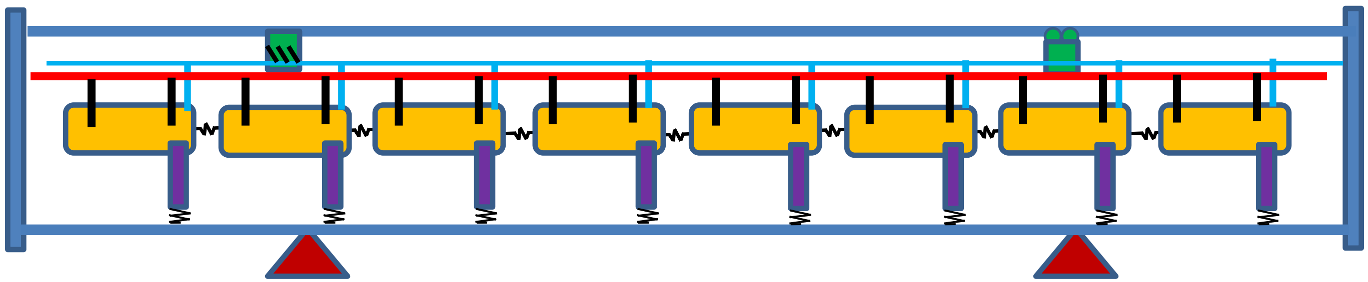
Cryogenic Interconnect Box

Cryo-module Units

Cryogenic Distribution Line

Possible supporting schemes

“standard” supporting scheme



Two-support preferrable → isostatic (=well defined forces on supports)

...but is cavity straightness enough?? If not...

RF coupler (with bellows)

Invar longitudinal positioner

Inertia beam

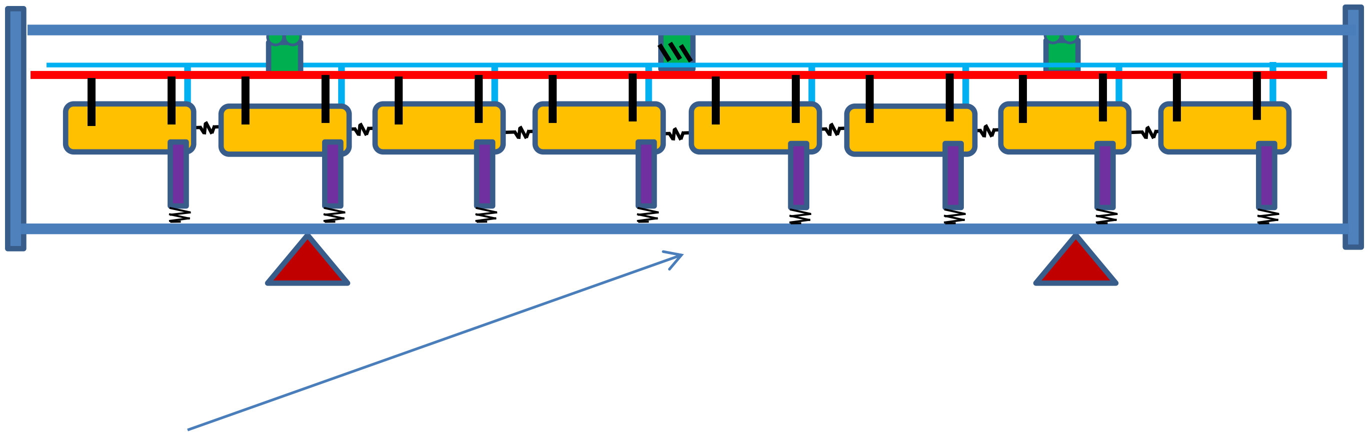
Fixed support

Sliding support

External supports (jacks)

Possible supporting schemes

"standard" supporting scheme



...add 3rd support → becomes hyperstatic (= forces depend on mech. coupling vessel/inertia beam)

RF coupler (with bellows)

Invar longitudinal positioner

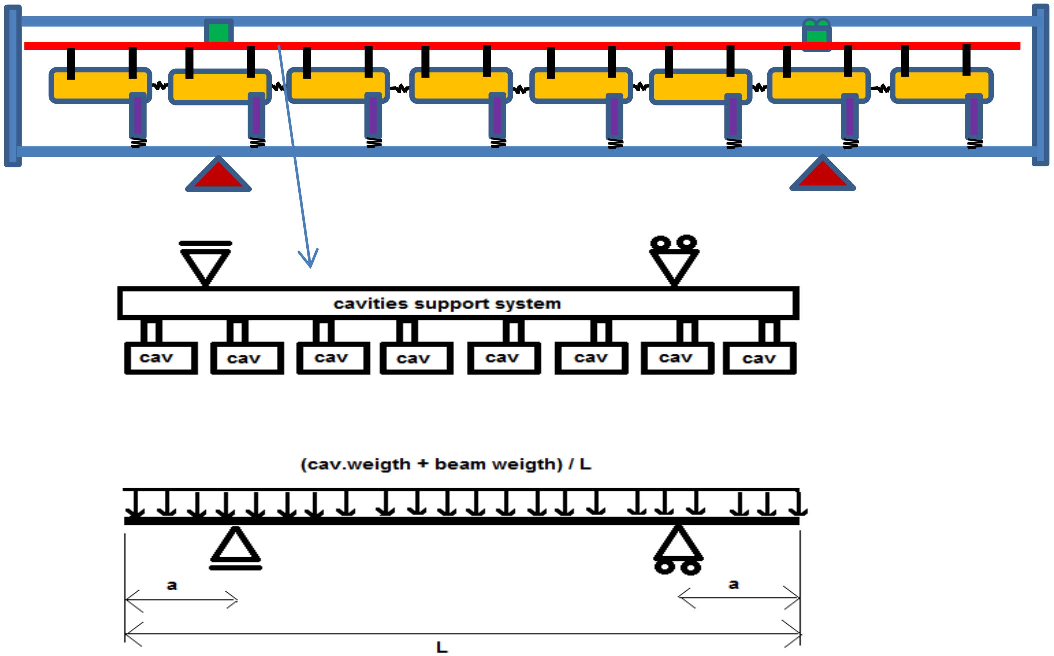
Inertia beam

Fixed support

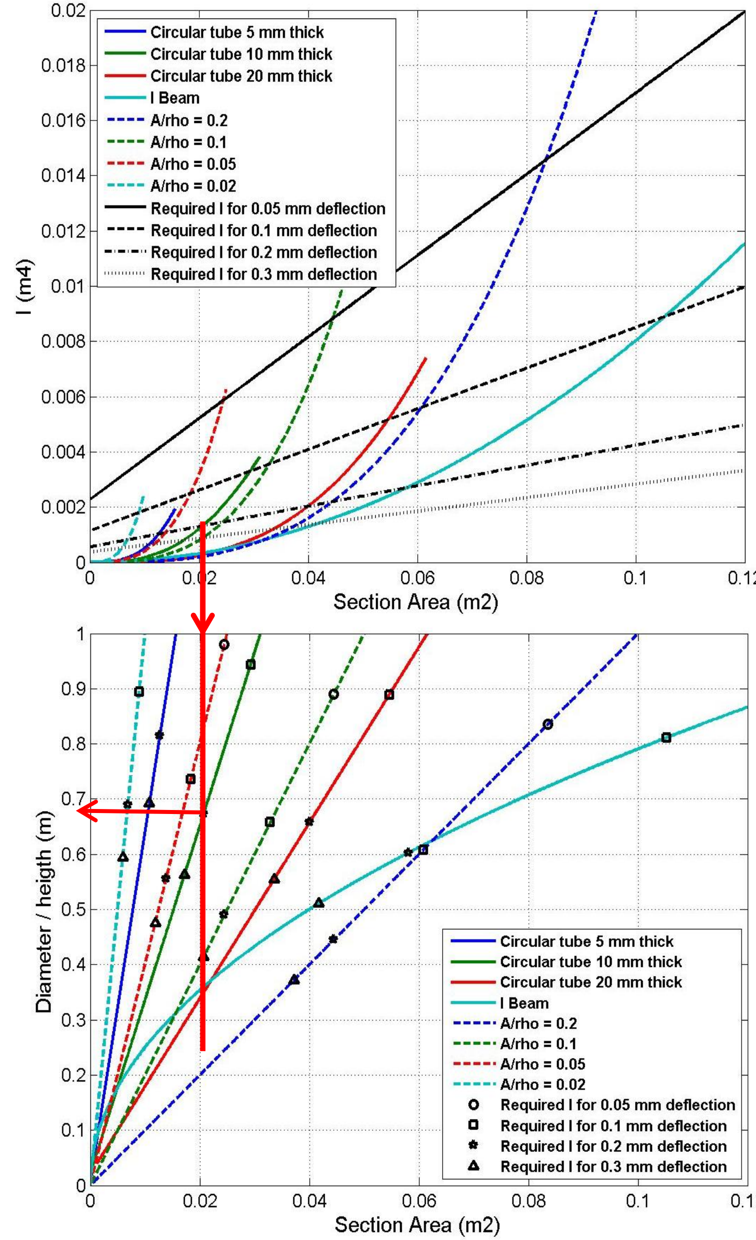
Sliding support

External supports (jacks)

“standard” supporting



Max. sag minimized at *a/L=0.20.*

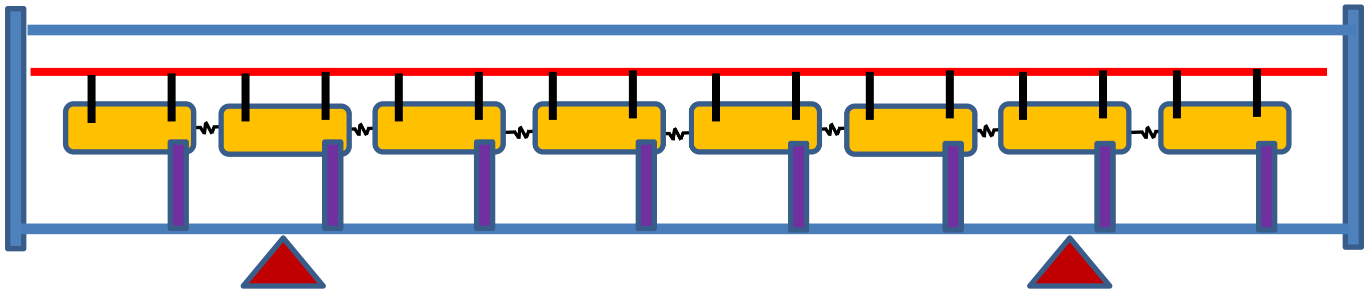


To limit self-weight sag below **0.2 mm**, requires an inertia beam equivalent to a 10**-mm thick ~700-mm diam. tube** (almost vac.vessel size)

→ A 3rd central support is mandatory

Possible supporting schemes

Alternative: coupler supporting scheme



...the coupler is also a supporting/aligning element

RF coupler + longitudinal positioner + vertical support

Intercavity support structure

External supports (jacks)