ESS cryo-module strategy

Christine Darve

2-09, SLHiPP-1, CERN, Geneva

Headlines

- ESS short introduction
- Cryo-module activities
- Identify the design requirements
- Alternatives assessments
- Potential strategy and Conclusions

The European Spallation Source

High level objectives (see Dave McGinnis and Suzanne Gysin's talks)

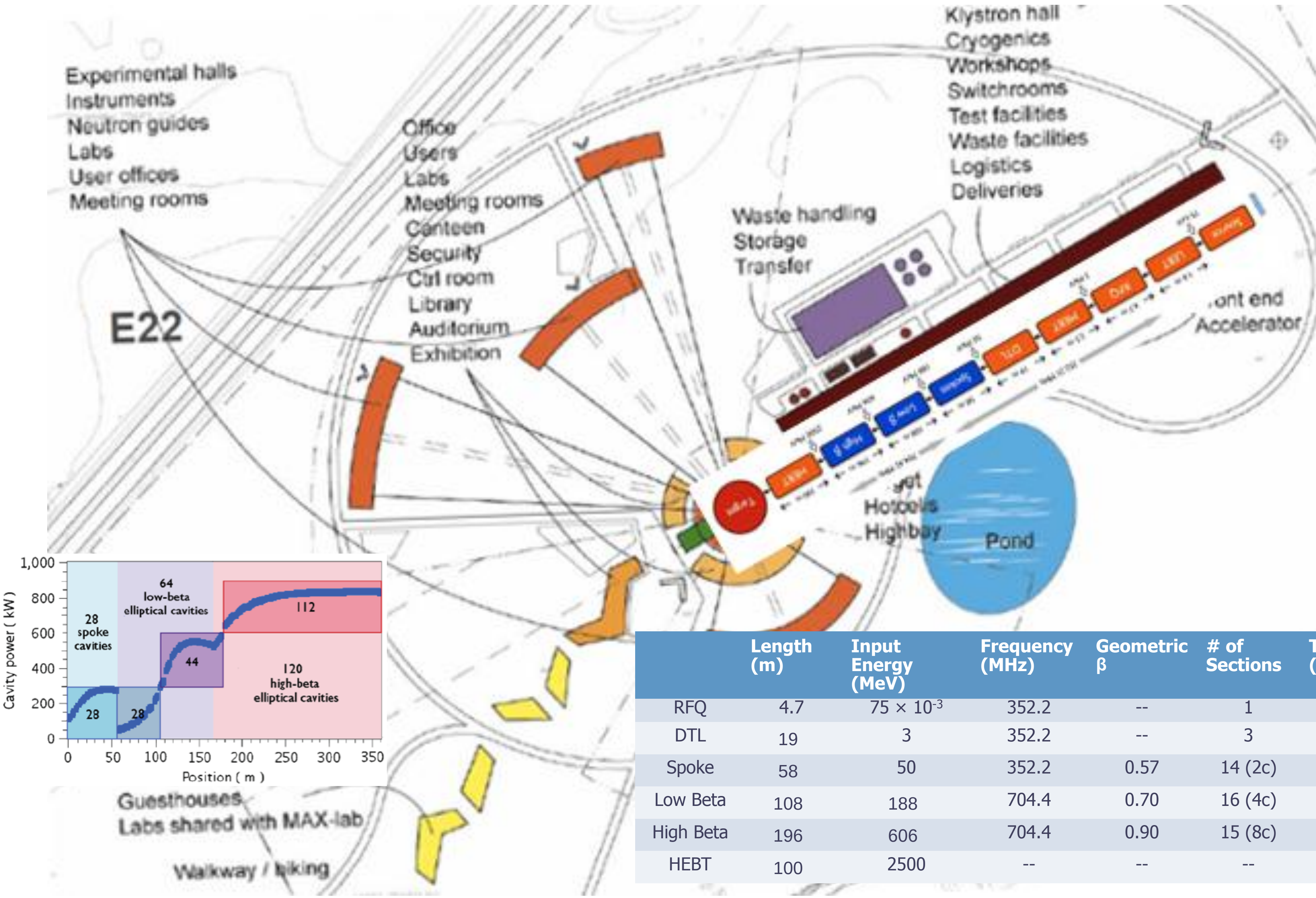
The European Spallation Source is a Partnership of 17 European Nations committed to the goal of collectively building and operating the world's leading facility for research using neutrons by the second quarter of the 21st Century.
A dynamic team: 20 different nationalities so far !

Beam power on target : 5 MW

- Average kinetic energy on target 2.5 GeV
- Protons (H+)
- 2.86 ms pulses @ 14 Hz (no accumulator)
- High reliability >95%
- Maximum average beam loss rate 1 W/m
- 22 instruments
- Cryostats for minimum energy consumption

Neutron Source and Synchrotron Light Source on same site: ESS & MAX-IV

ESS Layout

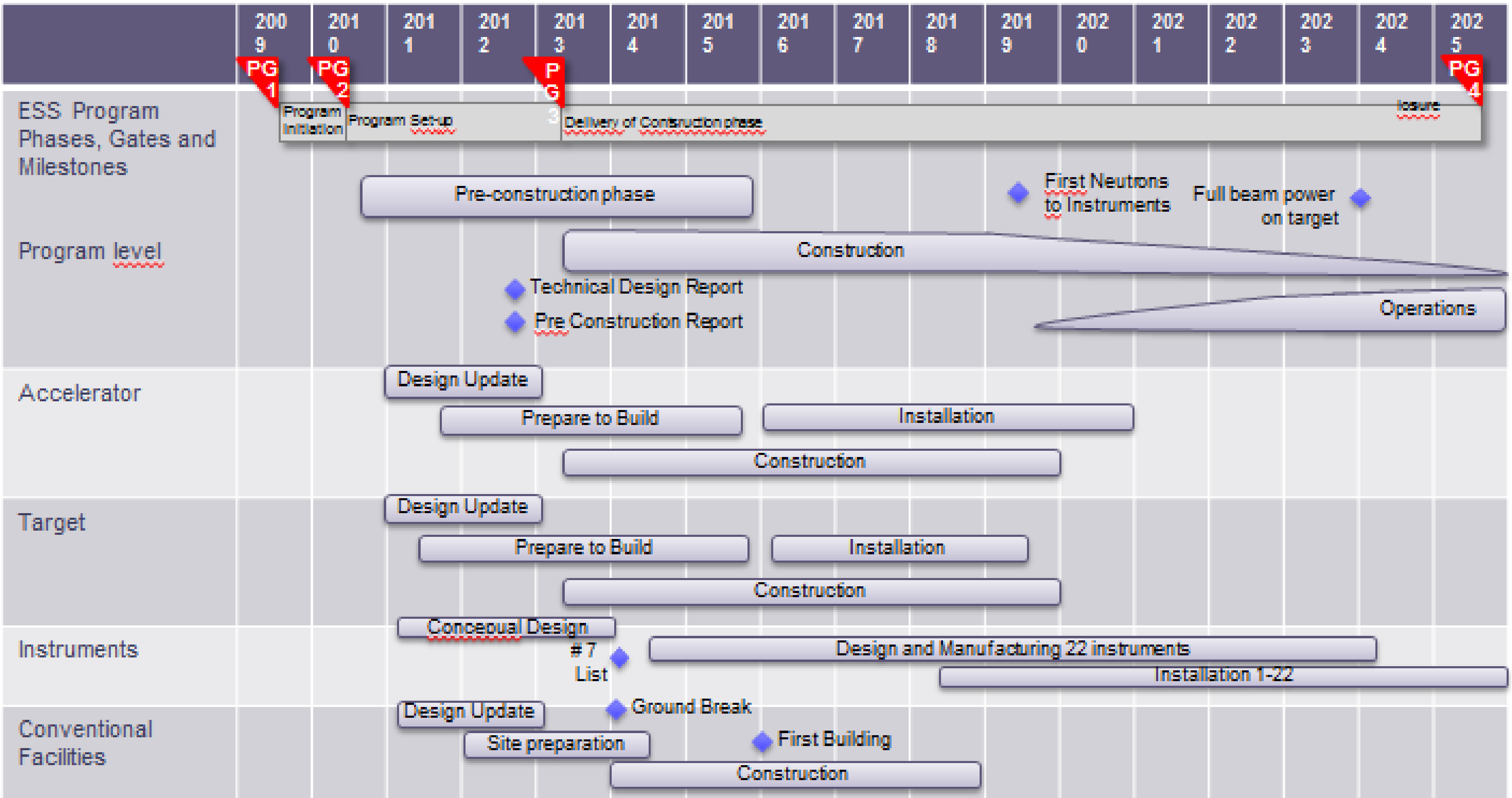


	Length (m)	Input Energy (MeV)	Frequency (MHz)	Geometric β	# of Sections	Temp (K)
RFQ	4.7	75 × 10^{-3}	352.2	--	1	≈ 300
DTL	19	3	352.2	--	3	≈ 300
Spoke	58	50	352.2	0.57	14 (2c)	≈ 2
Low Beta	108	188	704.4	0.70	16 (4c)	≈ 2
High Beta	196	606	704.4	0.90	15 (8c)	≈ 2
HEBT	100	2500	--	--	--	--

ESS Master Program Schedule

EUROPEAN SPALLATION SOURCE

As presented by Mats Lindroos's - AD retreat (December 5th, 2011)



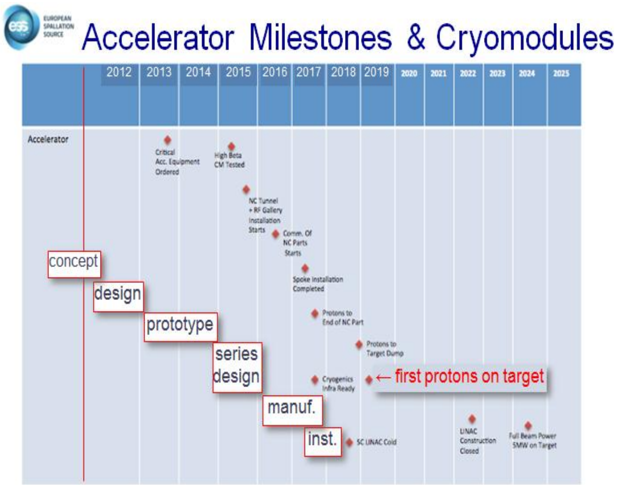
→ Very Aggressive Schedule !

→ How does the cryo-module schedule fit ?

Design, procure, install, commission & operate the cryo-modules by 2019 !

Manpower:

- ESS staff (1+1+1+..)
- Saclay – Elliptical SRF cavities
- IPNO – Spoke resonators + CM
- CERN – SPL training and expertise, TAC, possible testing of prototype?
- Possible future collaborations: FNAL?, India?
- Lessons learned from PX, X-FEL, SNS, J-PARC, etc..

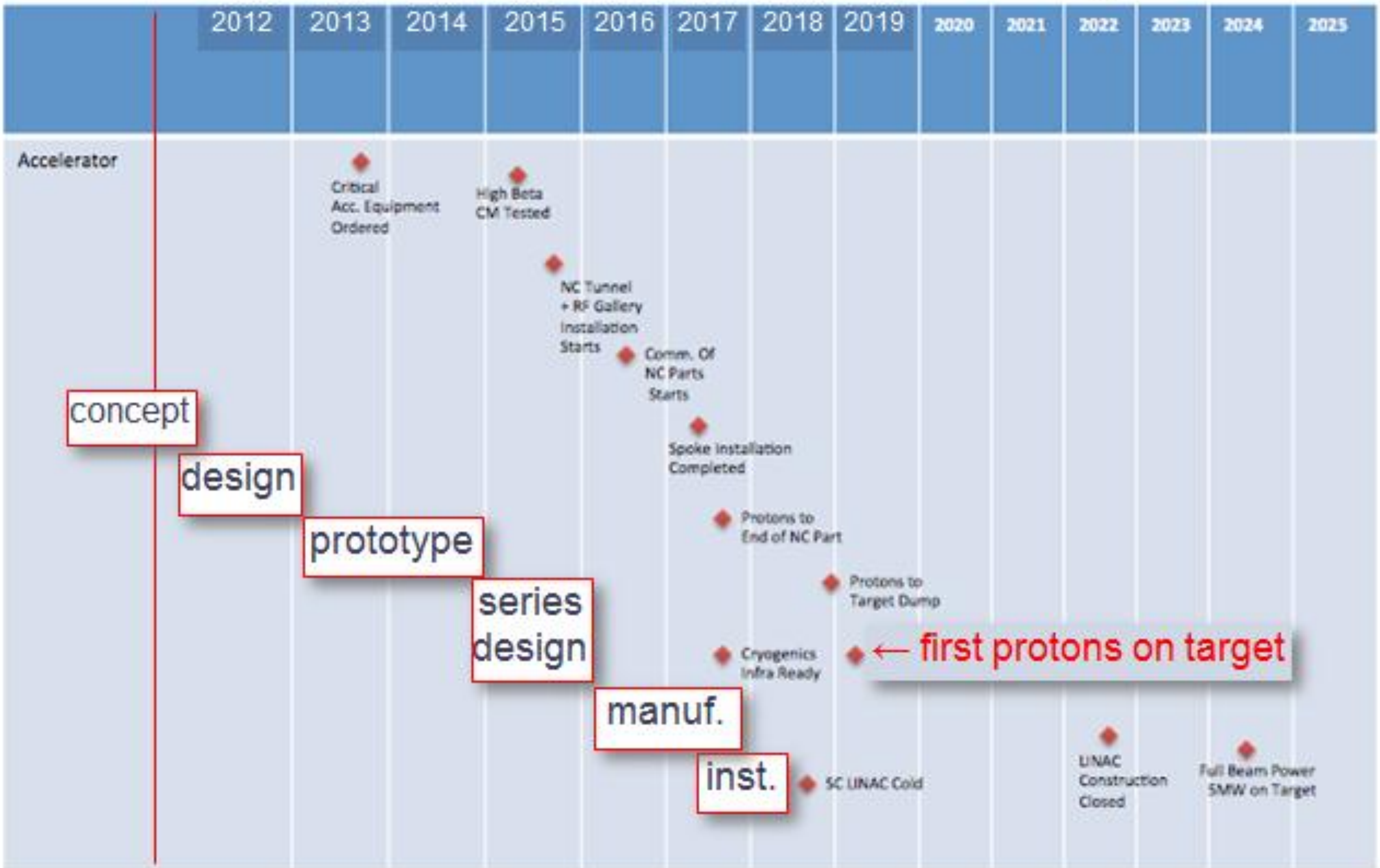


The cost of **cryo-modules** (from design to operation) is distributed in work packages.

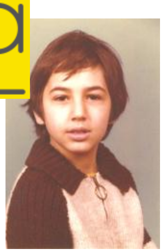
e.g. 1/3 of ILC Project cost for CM, 40 % of it for cavity fabrication, processing, dressing, and qualification (but they use higher gradient, more challenging?).

Danger: failure to achieve an R&D goal has a potential important cost impact by mitigating the design modification.

Accelerator Milestones & Cryomodules



The ESS collaborator : MoU



Romuald Duperrier
(30 years ago)

Steve Peggs

Cristina Oyon

Josu Eguia

Work Package (work areas)

1. Management Coordination – ESS (Mats Lindroos)
2. Accelerator Science – ESS (Steve Peggs)
3. Infrastructure Services – Tekniker, Bilbao (Josu Eguia)
4. SRF Spoke cavities – IPN, Orsay (Sebastien Bousson)
5. SRF Elliptical cavities – CEA, Saclay (Guillaume Devanz)
6. Front End and NC linac – INFN, Catania (Santo Gammino)
7. Beam transport, NC magnets and Power Supplies – Århus University (Søren Pape-Møller)
8. RF Systems – Uppsala university (Roger Ruber)

Mats Lindroos

Guillaume Devanz

Roger Ruber

Søren Pape Møller

Santo Gammino

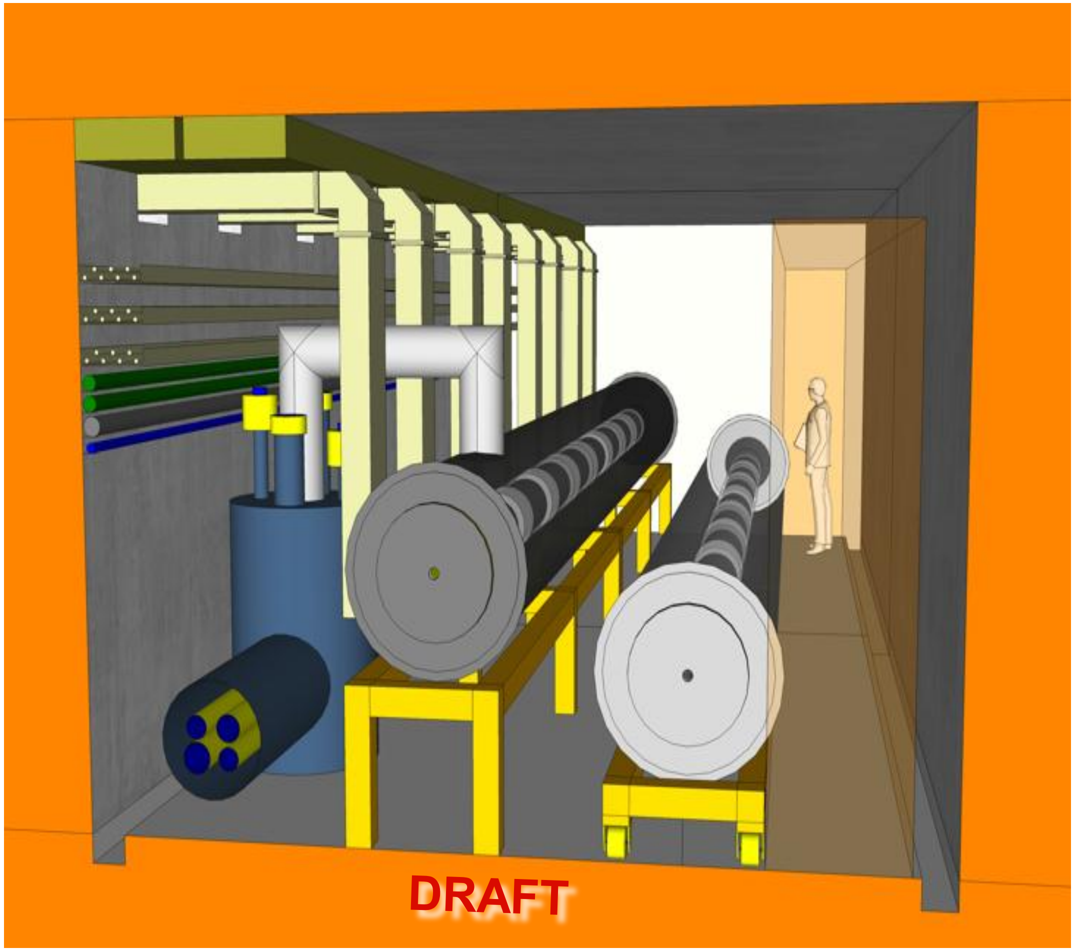
Sebastien Bousson

Physical boundaries, tunnel geometry

(by Wolfgang Hees)

ESS linac tunnel:

- cross section: 5 x 3.5 m^2 TBC
- length: 522 m
  (390 m cold linac)
- slope: none → negligible TBC
- space for external cryo-lines, valve boxes, jumper connections
- space for CM with dia~ 1.2 m
- space for CM transport



Cryo-module Main Functions

- ESS cryo-modules will house:
  - Active components: spoke resonator, low beta elliptical cavities and high beta elliptical cavities,
  - Power coupler, tuner, HOM, BPM, Quad, corrector elements, diagnostic and controlled valves, etc..

→ We need to define and quantify the following requirements !!

- Provide a precise & accurate **positioning** & **alignment** of the active components: account for vibrations, thermo-acoustic oscillations, etc...
- Provide **cryogenic cooling** for the active components: cooling scheme.
- Provide **magnetic shielding** for the active components.
- **Protect** active components from **overpressure** (cold and warm rating).
- **Establish the Maximum Credible Incidents (MCI).**
- Define **appropriate capacity margin**, overcapacity and uncertainty factor.

What do we need (elements) ?

Ultimate goal → Specification of the cryo-plant, distribution lines (P,T, mass-flow), purification system, storage, etc..

- Complete detailed heat load distribution (linac, target)
  - Static (MLI, support, coupler, HOM, tuner) and dynamic heat loads using duty factor.
  - Account for RF cables on each cavity (2x HOM + 1 pickup (No RF losses, static heat load only)).
  - Cold tuning system cables (motor cable+ piezo cable).
  - Account for beam losses; 1 W/m.

- Define **cooling schemes** and **cryogenics – Architecture**

  → Study process to validate feasibility (Udo's preliminary work for SPL).

- Define the **conceptual design of the cryo-modules.**

  → Identify possible show stoppers ? Preferred solution.

– Define cavity supporting scheme: how many, where, thermal intercepts ?
– Number of thermal shields.
– Define accessibility ports for in-cryostat maintenance (tuner motor, 2 HOMs).
– One bellows between each cavity ?
– Materials and feasability of multimaterial connections (case of Ti/SS).
– Define CM assembly/disassembly sequences and its assembly tooling.
– Define type of vacuum pump to use (which capacity is needed?)
– Minimize cavity vibration and coupling of external sources to cavities

What else do we need ?

- Define **standardization** (e.g. pressure code) and **design** standards: e.g. bring together ESS, manufacturers using ASME, ISO.
- Identify **cryogenic instrumentation** and its environment (diagnostic): e.g. RadHard.
- **Complete technical risk analysis** to emphasize requested redundancy.
- Define the **control system**, DAQ
- Define the **safety system**: e.g. Interlock, safety equipment.
- Identify **tools to manage** technical document: eg. Edms, CERN MTF
- Use **risk management** tools whenever possible.

Coordinate and integrate activities with partner institutes as a key ingredient to success !

- Consider the different **operation modes**: and analyze types of intervention:

e.g. cool-down speed to prevent Q-disease, degraded vacuum, response time, availability.

- Define **acceptable operational pressure stability**, w/o over-constraint: e.g. 1 mbar

- **Experimental measurement** for static heat load on **power couplers**

  → In Saclay, Sprint 2012 ?

- Assemble and test **cryo-modules**

  → Possible at CEA or CERN on 2013 ?.

- Stay Optimistic !!! and realistic.

What we already have/know

What do we Have/Know

(see Ofelia Capatina's comparison)

- Official basic parameters as listed in the CDR (Dave McGinnis's talk)
  - Linac Components **(Mammad Eshraqi's talk) :** layout optic optimization

Table 46: Summary cold linac

section	number of modules	module length / mm	section length / m	number cavities per module	number cavities per section
high beta	15	13,641	212.109	8	120
low beta	16	6,799	116.786	4	64
spoke	14	3,670	58.380	2	28
utility (intermodule) slot	*44*	500			
total cold linac	**45**		**386.774**		**212**

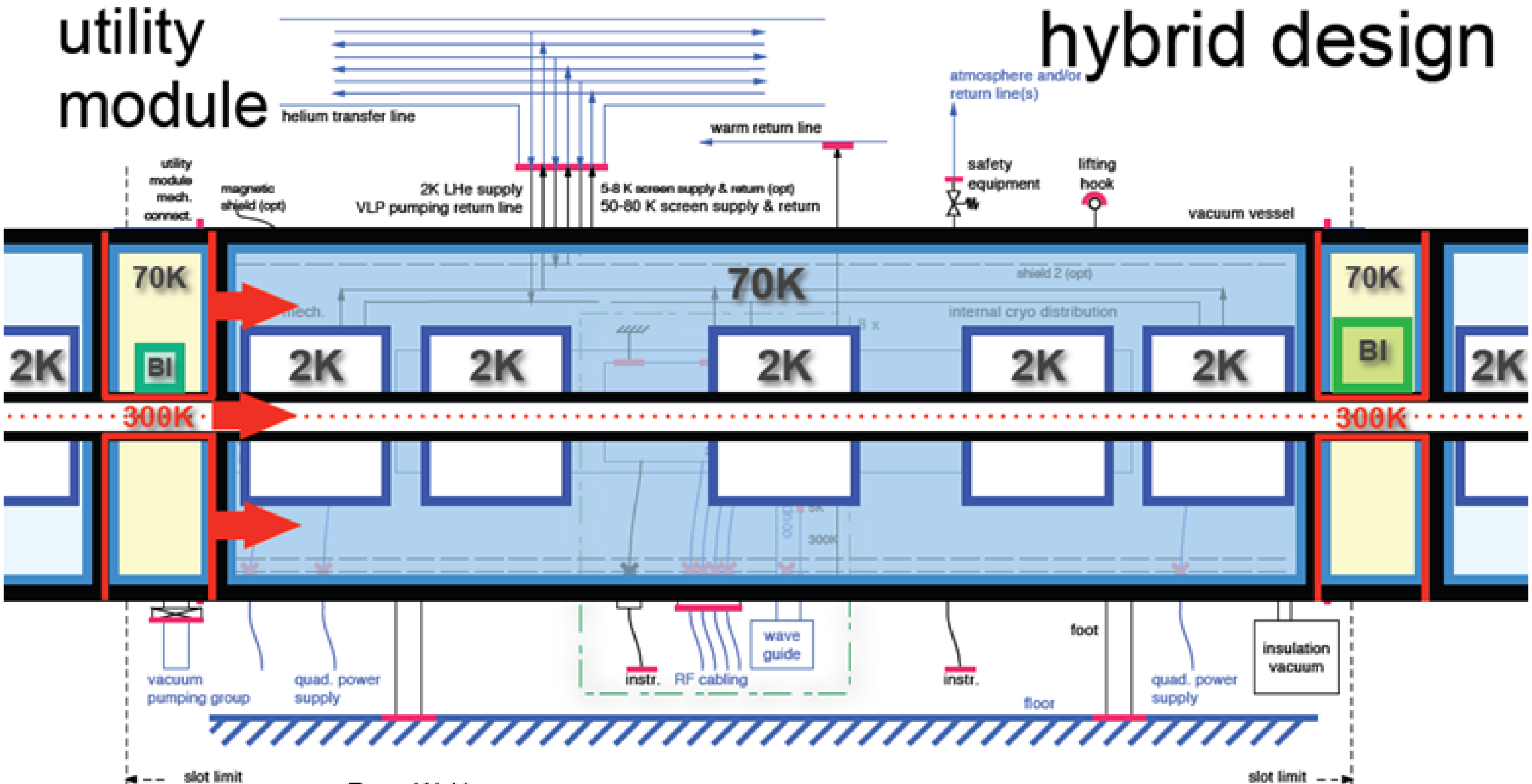
- Preliminary heat load determination based on experimental results.

- Elliptical cavity package (incl. coupler, tuner and helium tank)
  → Saclay / Guillaume Devanz : Conceptual Design Phase
- Spoke resonator cavity package (incl. coupler, tuner and helium tank)
  → Sebastien Bousson / INPO : Conceptual Design Phase
  → Design Spoke CM: to be started in 2012

➔ Still open: Assign elliptical CM package → to be defined in January 2012

Current Conceptual Design Review

Wolfgang Hees - ESS



From W. Hees

Decision about **segmented or continuous** design will be followed by the decision about **cold or warm quadrupoles**.

Spoke resonators – Summary

Sebastien Bousson - IPNO

Cavity RF parameters	
R/Q	426 Ω
G	130 Ω
Q_o at 4K (with R_{res} = 10 nΩ)	$2.6\ 10^9$
Q_o at 2K (with R_{res} = 10 nΩ)	$1.2\ 10^{10}$
E_{pk} / E_{acc}	4.43
B_{pk} / E_{acc}	7.08 mT/(MV/m)

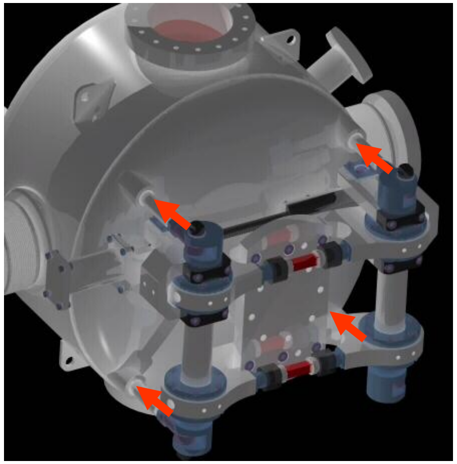
Overall dimension of the cavity	
Cavity β	0.50
Cavity length	780 mm
Cavity diameter	480 mm
frequency	351.8 MHz

Peak fields @ Eacc =8 MV/m

E_{pk} = 35 MV/m

B_{pk} = 57 mT

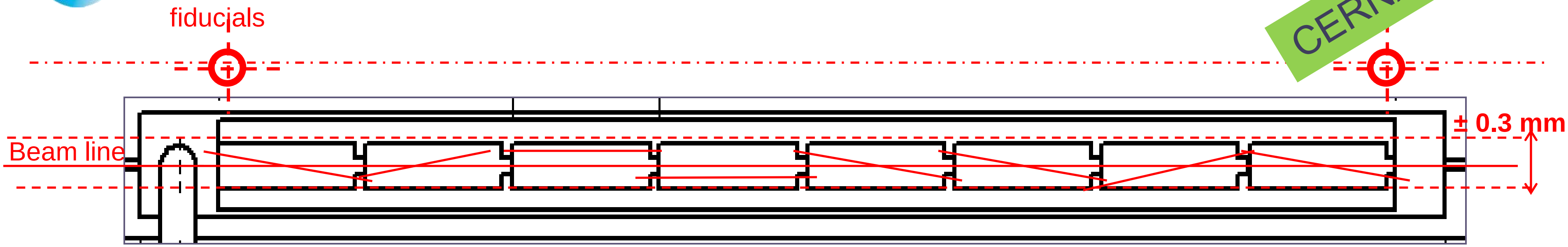
The « One » Risk of the ESS ?



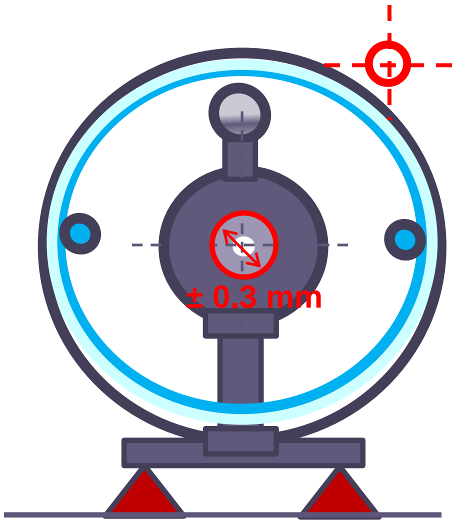
Cover the energy range: ~ 50 MeV to ~ 190 MeV

- Nominal power: 250 kW
- Capacitive coupling
- Maximum reflection coefficient: S_{11} < -30 dB
- Window cooling capabilities
- Relatively simple design for reliability & cost
- Max outer diameter: 100 mm

Cavity alignment requirements



- Position of each cavity shall be precise w.r.t. cryostat mounted external fiducials within ± 0.5 mm
- Position of each cavity axis shall be stable and reproducible within ± 0.3 mm w.r.t. an ideal beam axis
- Cryo-module alignment using cryostat mounted external fiducials (i.e. no need for active alignment of individual cavities)



➔ Do we keep the same alignment criteria for the ESS CM ?

Spoke in ESS : a world premiere !

Sebastien Bousson/IPNO

About 15 spoke resonators prototypes (SSR, DSR, TSR) have been constructed and tested worldwide. None have accelerated beam until now !
ESS linac will be the first accelerator to operate spoke cavities.

T=4 K

Lab	Type	Frequency [MHz]	Optimal beta	E_{accMAX} [MV/m]	V_{MAX} [MV]	E_{pk}/E_{acc}	B_{pk}/E_{acc} [mT/MV/m]
IPN Orsay	Single	352	0.20	4.8	0.8	6.7	14.5
	Single	352	0.36	8.1	2.5	4.7	12.8
ANL	Single	855	0.28	4.4	0.3	5.5	12.7
	Single	345	0.29	8.7	2.2	4.6	12.1
	Single	345	0.40	7.0	2.4	6.3	16.7
	Double	345	0.40	8.6	4.5	4.7	9.2
	Triple	345	0.50	7.6	6.6	3.7	11.5
	Triple	345	0.62	7.9	8.7	3.9	12.0
FZ-Juelich	Triple	760	0.20	8.6	1.4	5.1	13.3
LANL	Single	350	0.21	7.5	1.3	5.1	13.3
	Single	350	0.21	7.2	1.3	5.0	10.1
Fermilab	Single	325	0.21	12.0	2.4	3.6	5.8
	Single	325	0.21	16.7	3.4	3.6	5.8
IPN Orsay	**Triple**	**352**	**0.3**			**4.1**	**9.1**

Elliptical cavities – Summary

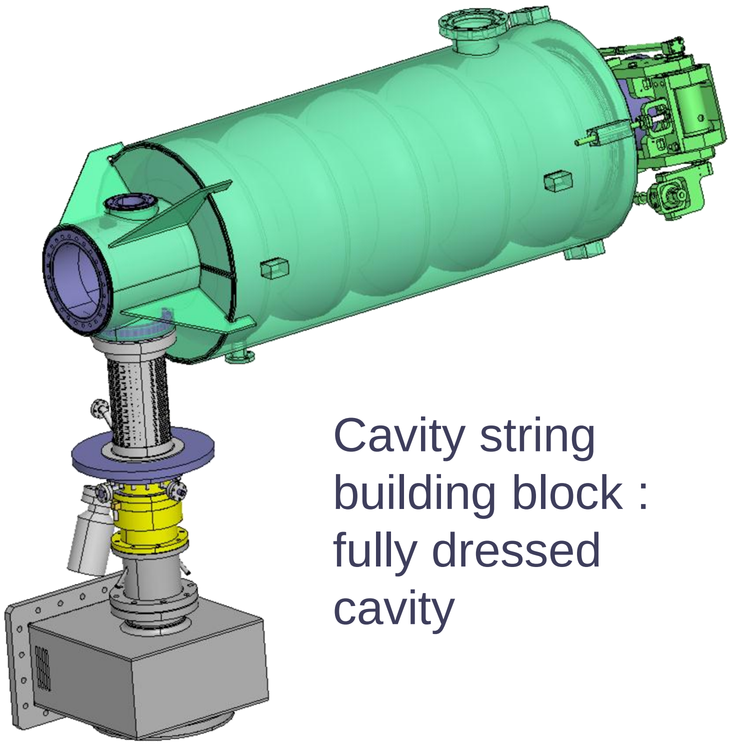
Guillaume Devanz - CEA

- 5-cell cavities, bulk niobium
- frequence = 704.42 MHz
- operating temperature 2K

β g=0.86		unit
Frequency	704.42	MHz
Nr of cells	5 (sym.)	
Cell to cell coupling	1.8	%
π and 4π/5 mode separation	1.2	MHz
Epk/Eacc	2.2	
Bpk/Eacc	4.3	mT/(MV/m)
Max. r/Q	477 @ β=0.92	Ω
G	241	Ω
Low field Qo	3e10	
Qo at nominal Eacc	6e9	

Two beta families

beta	Eacc VT (MV/m)	Eacc Linac (MV/m)
0.65	17	15
0.86	20	18

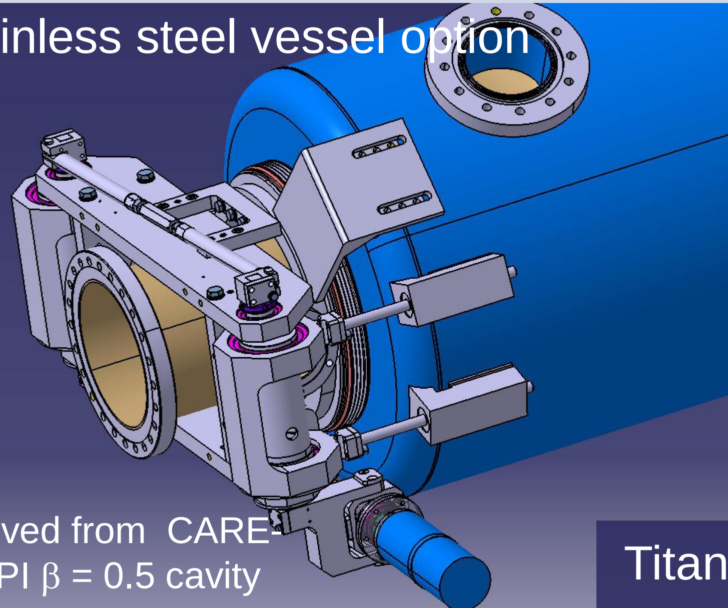


Cavity string building block : fully dressed cavity

He vessel and tuner integration

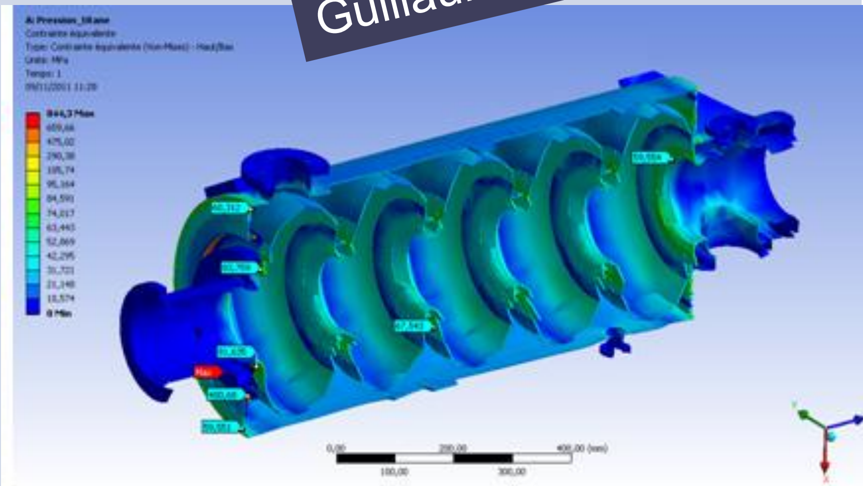
Guillaume Devanz/CEA

Stainless steel vessel option

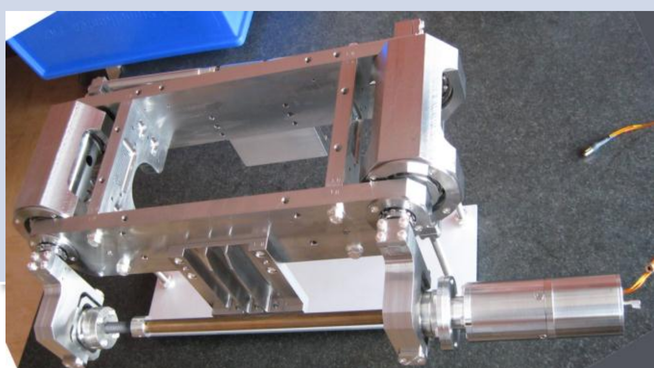


Derived from CARE-HIPPI β = 0.5 cavity

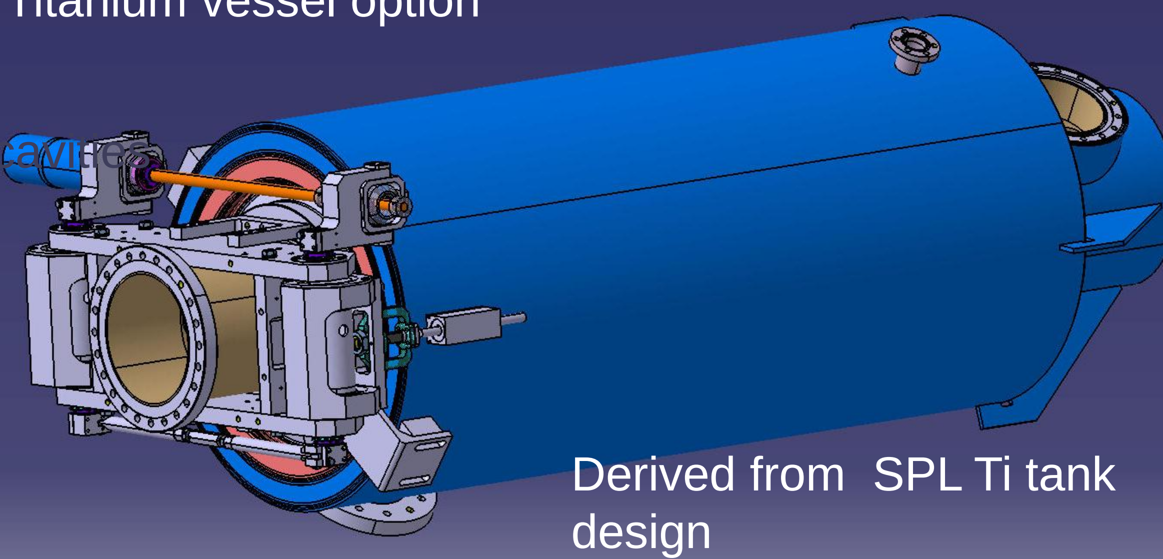
Titanium tank NbTi flanges, Al Hex seals (single bellows)



New Saclay piezo tuner for SPL cavities



Titanium vessel option

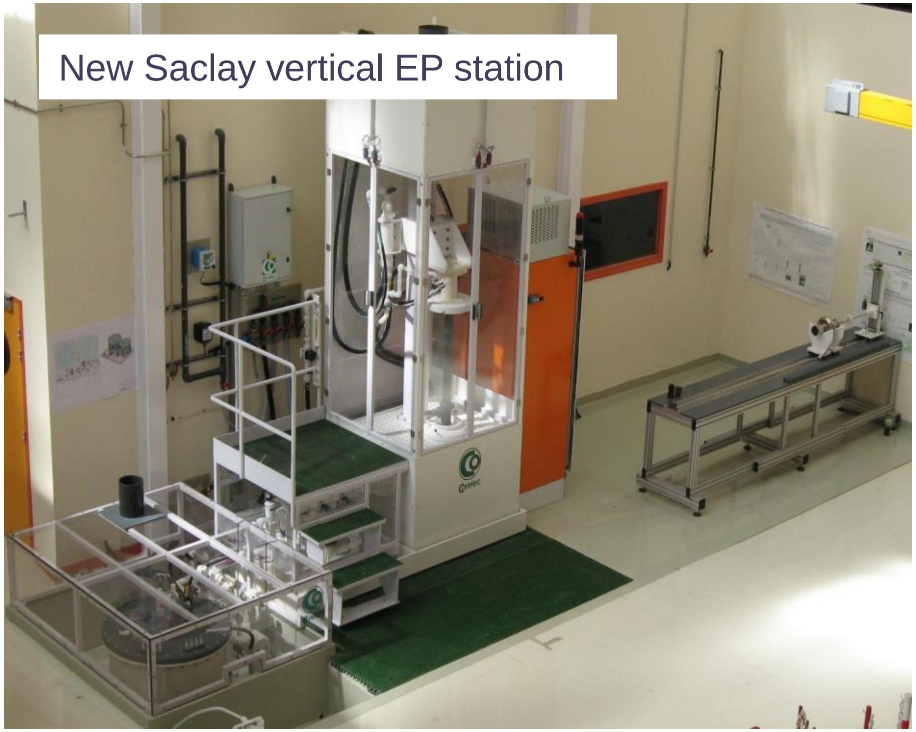


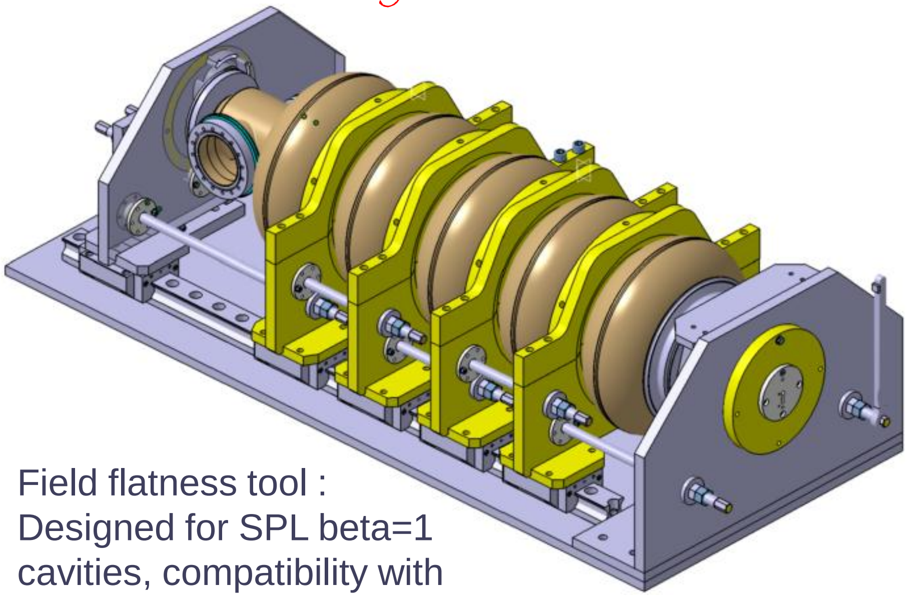
Derived from SPL Ti tank design

EUROPEAN SPALLATION SOURCE

Elliptical – Saclay status

Guillaume Devanz – AD Retreat Tuesday December 6th

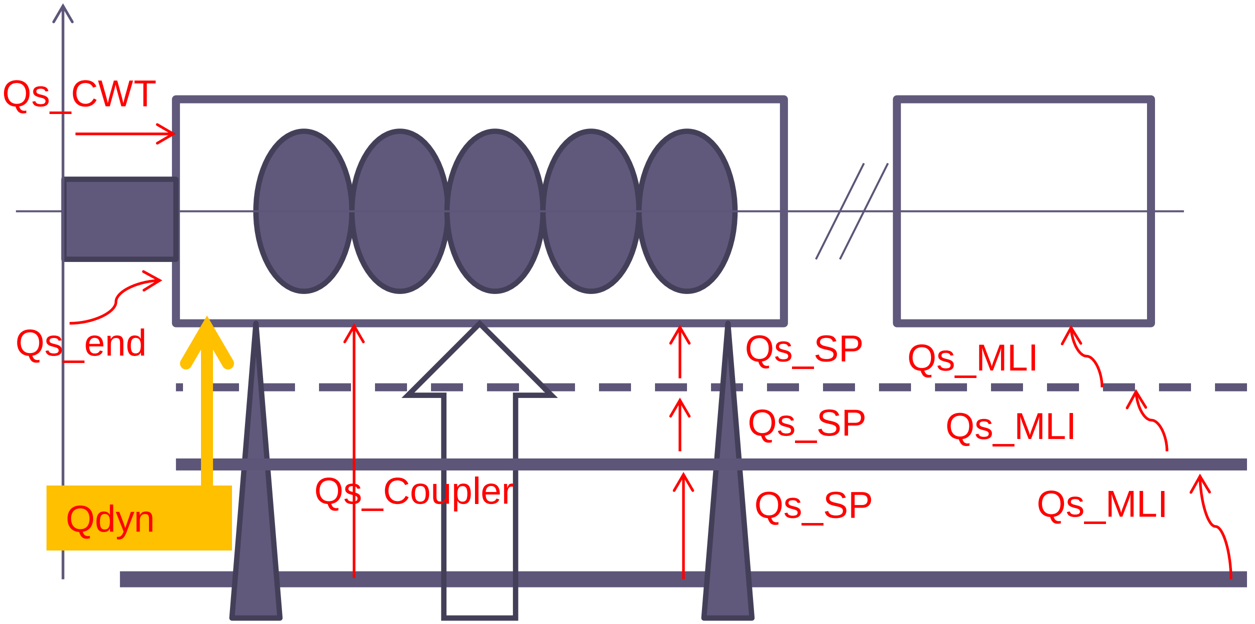

New Saclay vertical EP station



Field flatness tool :
Designed for SPL beta=1 cavities, compatibility with ESS high beta cavity included (larger flanges, stiffening rings, shorter cells)

- RF design of the cavity is done
- Mechanical design of cavity and helium vessel done
- Order of RRR >250 Nb launched in early october
- Technical specification for cavity fabrication done
- Call for proposal for cavity manufacturing : 3 candidates
- Launch of call for tender foreseen this week (December 8, 2011)

Preliminary - heat load estimates



Used experimental results from PX, SNS, X-FEL, LHC

More than 70% of **dynamic heat load** contribution.
Large contribution (+ uncertainty) of the coupler heat load.

→ **Hybrid thermal budget 2% less BUT complicate the design.**

Example for PX →

TABLE 3.7-1
Heat loads for one RF unit of 3 cryomodules with 26 cavities. All values are in watts.

	2 K		5-8 K		40-80 K	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
RF Load		22.4	4.2		97.5	
Supports	1.8	0.0	7.2		18.0	
Input coupler	1.6	0.5	4.4	4.0	46.5	198.2
HOM coupler (cables)	0.0	0.6	0.9	5.5	5.5	27.1
HOM absorber	0.4	0.0	9.4	1.6	9.8	32.6
Beam tube bellows		1.1				
Current leads	0.9	0.9	1.4	1.4	12.4	12.4
HOM to structure		3.6				
Coax cable (4)	0.2					
Instrumentation taps	0.2					
Diagnostic cable			4.2		7.4	
Sum	5.1	29.0	31.7	12.5	177.6	270.3

Goal : Fill in table with estimates

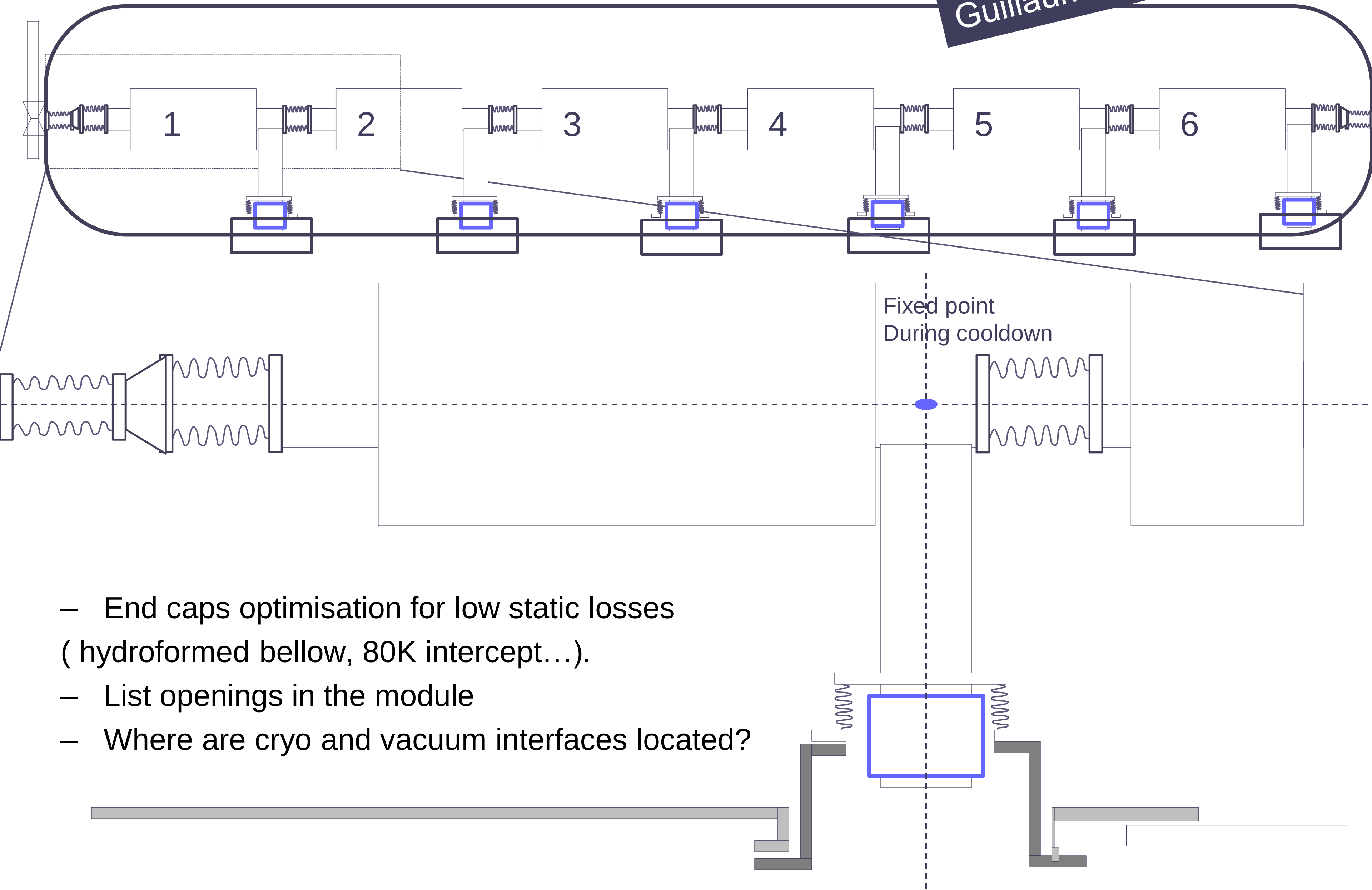
By iterations with close collaboration with the team !

Define accurately the MODEL, BOUNDARY CONDITIONS the LOAD and the CONSTRAINTS

	2K Static load (W)	2K Dynamic load (W)	80K static load (W)	80 K dynamic load (W)	remarks
Cavity	0	6	0	0	For 1 cavity
Power coupler	?	1	0	0	For 1 power coupler
Cavity supports	**?**	0	?	0	For 1 cavity
80K shield	?	0	?		For 1 module
HOM cables	?	?	?	?	For 1 cavity, 2HOM couplers
Pick-up cables	?	0	?	0	For 1 cavity
Tuner cables	?	?	?	?	For 1 cavity
Temp. Sensors cables	?	0	?	0	For 1 cavity
He level sensor cables	?	0	0	0	???
End cap+ end bellows	?	0	?	?	For 2 endcaps (1 module)
300K radiation	0	0	?	0	For 1 module
80K shield supports	0	0	?	0	For 1 module
TOTAL for a the linac					

Tasks for a SNS-like module, longitudinal

Guillaume Devanz/CEA



- End caps optimisation for low static losses (hydroformed bellow, 80K intercept…).
- List openings in the module
- Where are cryo and vacuum interfaces located?

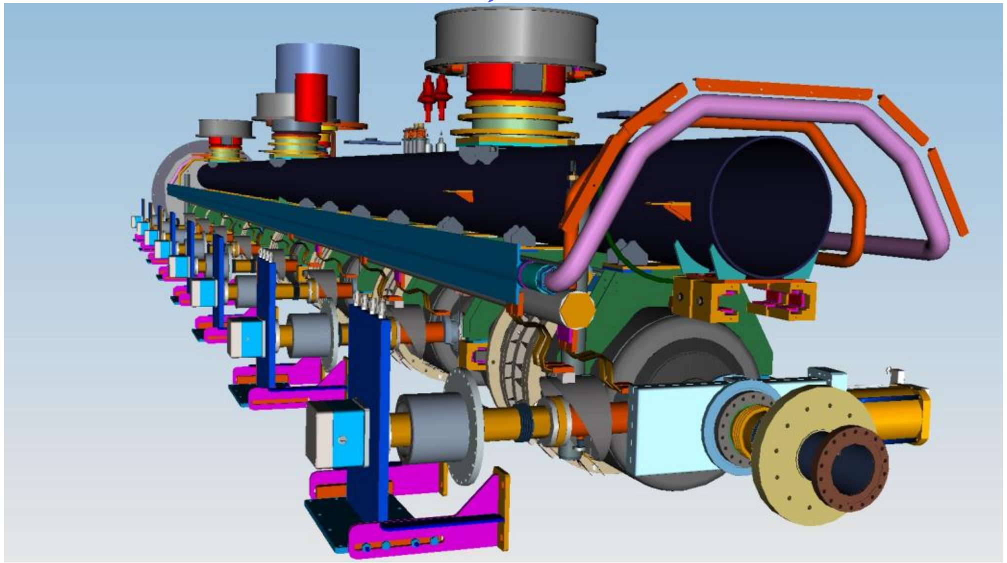
Use existing FNAL Expertise ??

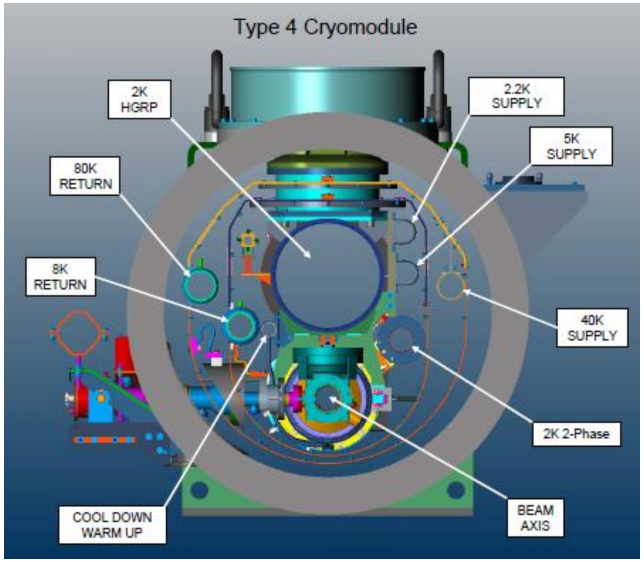
Possible Issues:

- Different frequency.
- Power coupler orientation

➔ Complete redesign (time, cost, manpower)

- Estimate ~ 4 FTE ?
- Over-head

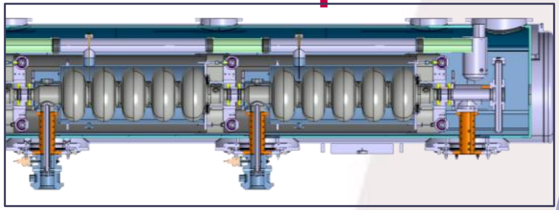




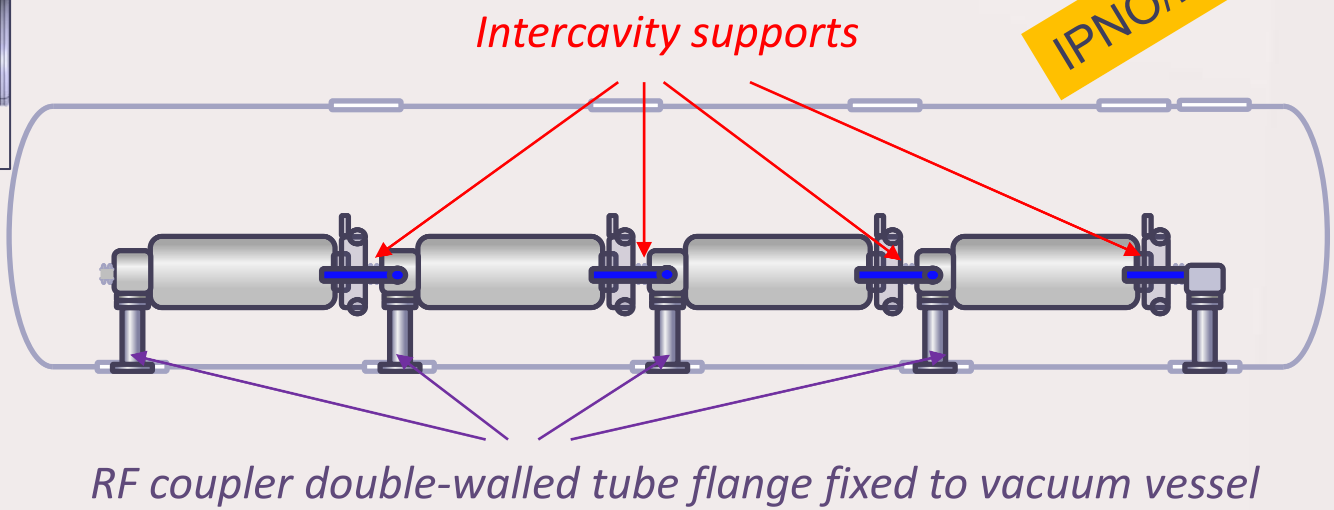
Re-use existing SPL design ?

IPNO/Patxi

The concept



RF coupler as main support of cavity ?



The RF coupler (its double-walled tube) provides:

- fixed point for each cavity (thermal contractions)
- mechanical supporting of each cavity on the vacuum vessel

The intercavity support provides:

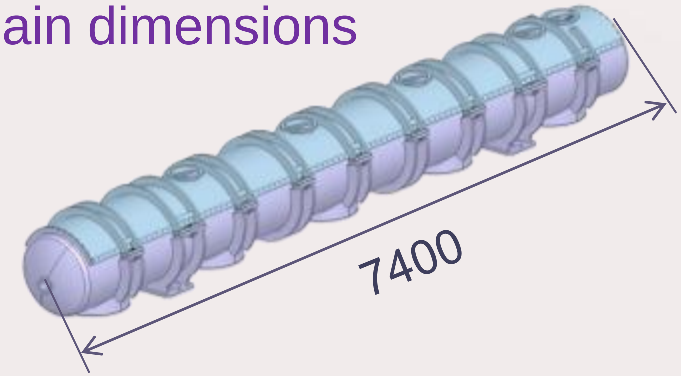
- a 2nd vertical support to each cavity (limits vertical self-weight sag)
- relative sliding between adjacent cavities along the beam axis
- enhancement of the transverse stiffness to the string of cavity (increases the eigenfrequencies of first modes)

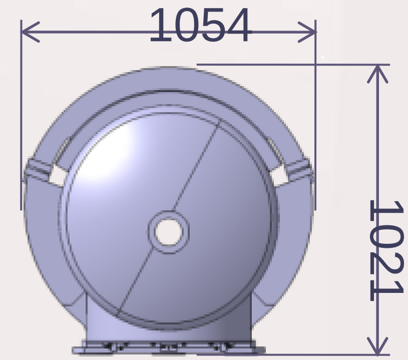
Re-use existing SPL design ?

Retained concept

Cylindrical vacuum vessel with
long top aperture

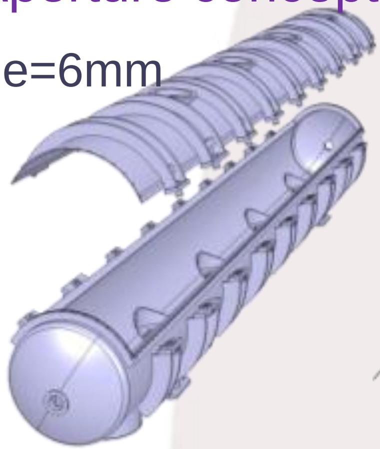
• Main dimensions



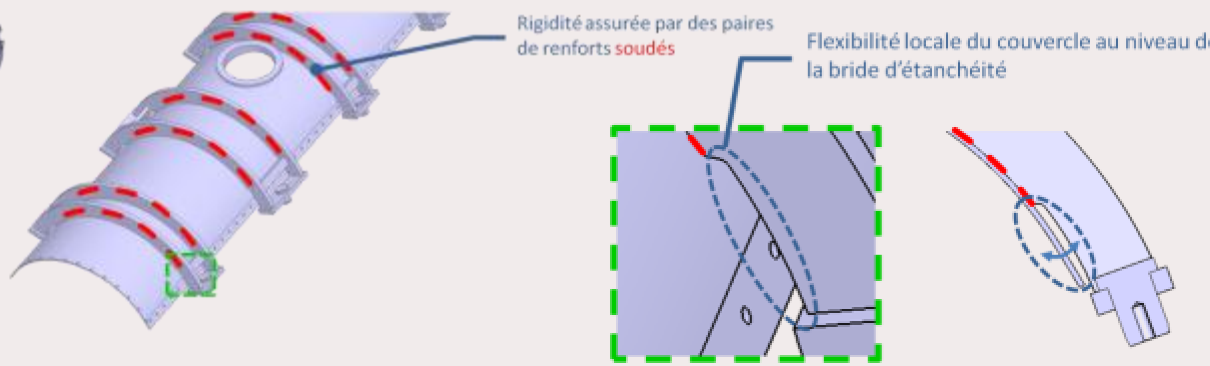


• Aperture concept

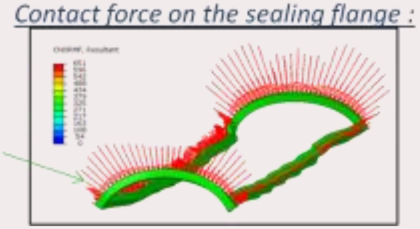
e=6mm



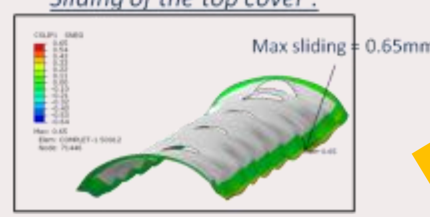
e=10mm



Contact force on the sealing flange :



Sliding of the top cover :



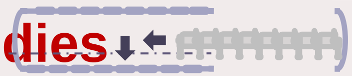
IPNO/Patxi

Aperture sealing

• Prototype (short cryomodule) : polymer seal placed in a groove / welding
• Machine cryomodule (long) : welding

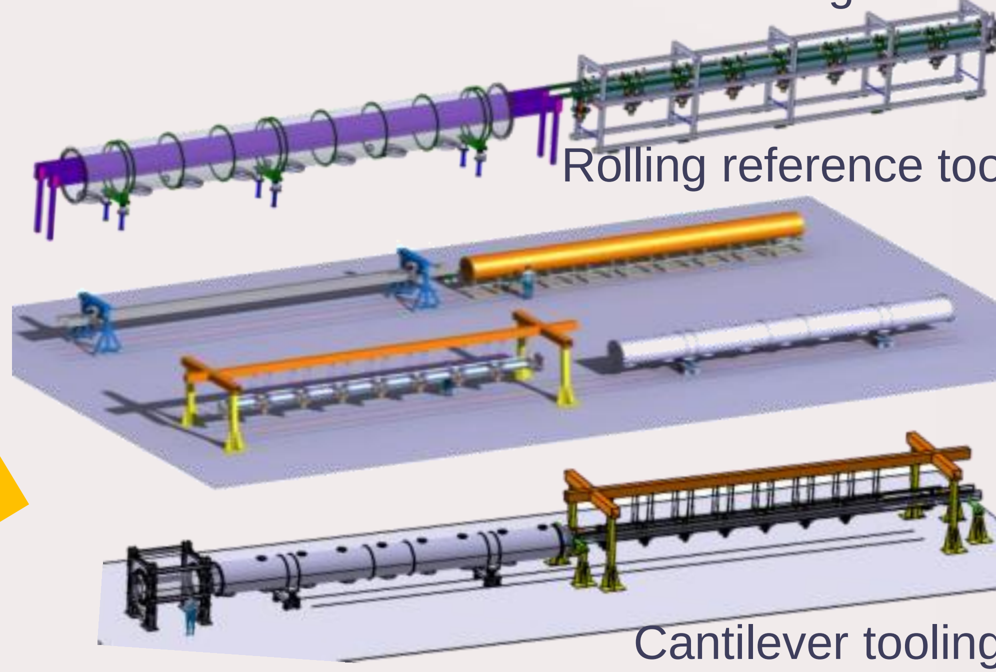
Choice for the tooling ?

➢ Horizontal cryostating Tooling Studies



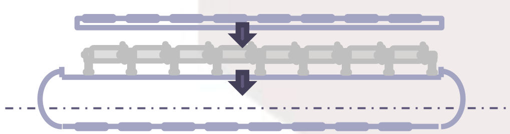
3 concepts were studied (8 cavities)

- Tooling design studies
- Assembly procedure studies
  - dressing of the string of cavities
  - alignment
  - cryostating
- Tooling comparison (for long and short cryostats)

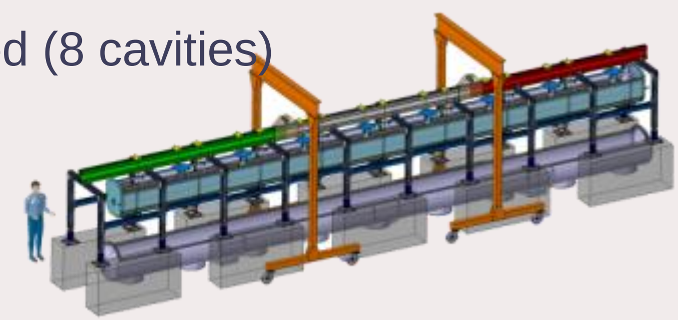


IPNO/Patxi

➢ Vertical Cryostating Tooling Study



1 concept was studied (8 cavities)



• All tools were compared (for long and short cryomodule)

Potential strategy and conclusions

- Define the complete cryo-modules concept !
  → January 2012 (IPNO) for spoke CM; package to be assigned for the elliptical cavities.
  → Choice: Segmented or continuous, warm or cold quadruple.
  → Use existing solutions for cost-effective fabrication and operation.
  → Think of possible trade-offs?
  → Keep it Simple and Goal oriented !
  → From experience, we do need a close follow-up with our partners.

- **Using this collaboration as a working platform**, re-estimate the preliminary heat load
  → Update: [First considerations for the design of the ESS cryo-modules by Aurelien Ponton] + Ofelia estimate + expertise from LHC, ILC, SNS, Tesla..

- Prepare a **comprehensive technical (conceptual) and design review** using external audits.
  → Underlining the SLHiP **branching** ! Its strength and weakness.

- Propose a realistic schedule to plan alternative **cryo-module prototype testing**.

- **Assess the risks** (Severity= Probability x Impact) and include risk abatement strategies.
  → Define a risk management database, and a risk watch list
  → Integrate the risk management and prioritize other activities at ESS.

- **Complete sizing of the ESS cryo-plant**: including Target contribution 8.2 kW at 20K [Target Baseline v2, ref. EDMS 1166507]

A new and (dynamic) team, who is not afraid of the COLD temperature in SWEDEN

LET'S DO IT NOW !

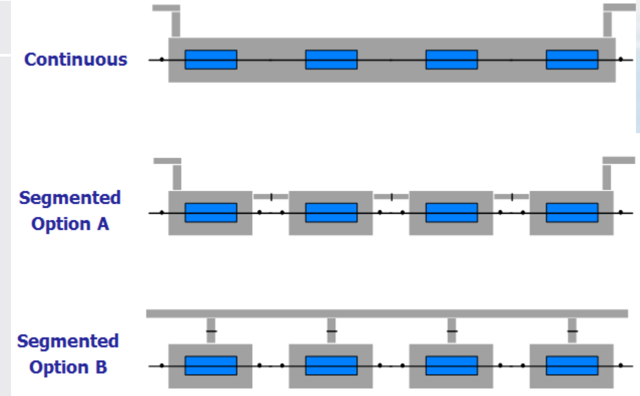
Coordination and knowledge to success !

Extra slides

Accelerator Parameters

Parameter	Unit	Value
Ion source output energy	MeV	0.075
RFQ output energy	MeV	3
DTL output energy	MeV	50
Spoke resonator output energy	MeV	188
Elliptical low beta output energy	MeV	606
Elliptical high beta output energy	MeV	2500
Proton kinetic energy on target	MeV	2500
Ion source length	m	2.5
LEBT length	m	1.6
RFQ length	m	4.0
MEBT length	m	2.5
DTL length	m	19.0
Spoke resonator section length	m	58.0
Elliptical low beta section length	m	108.0
Elliptical high beta section length	m	196.0
HEBT length, to first vertical bend	m	100.0
Length, source-to-first vertical bend	m	491.6
Depth of linac below ground level	m	10
Number of accelerating gaps per spoke cavity		3
Number of cells per low beta elliptical cavity		5
Number of cells per high beta elliptical cavity		5
Spoke resonator cavities per cryomodule		2
Low beta elliptical cavities per cryomodule		4
High beta elliptical cavities per cryomodule		8
Geometric beta, spoke resonators		0.57
Geometric beta, low beta elliptical cavities		0.70
Geometric beta, high beta elliptical cavities		0.90
Operational gradient, spoke resonators	MV/m	8
Operational gradient, low beta elliptical cavities	MV/m	15.44
Operational gradient, high beta elliptical cavities	MV/m	18.17
Elliptical power coupler power, to beam	MW	0.9

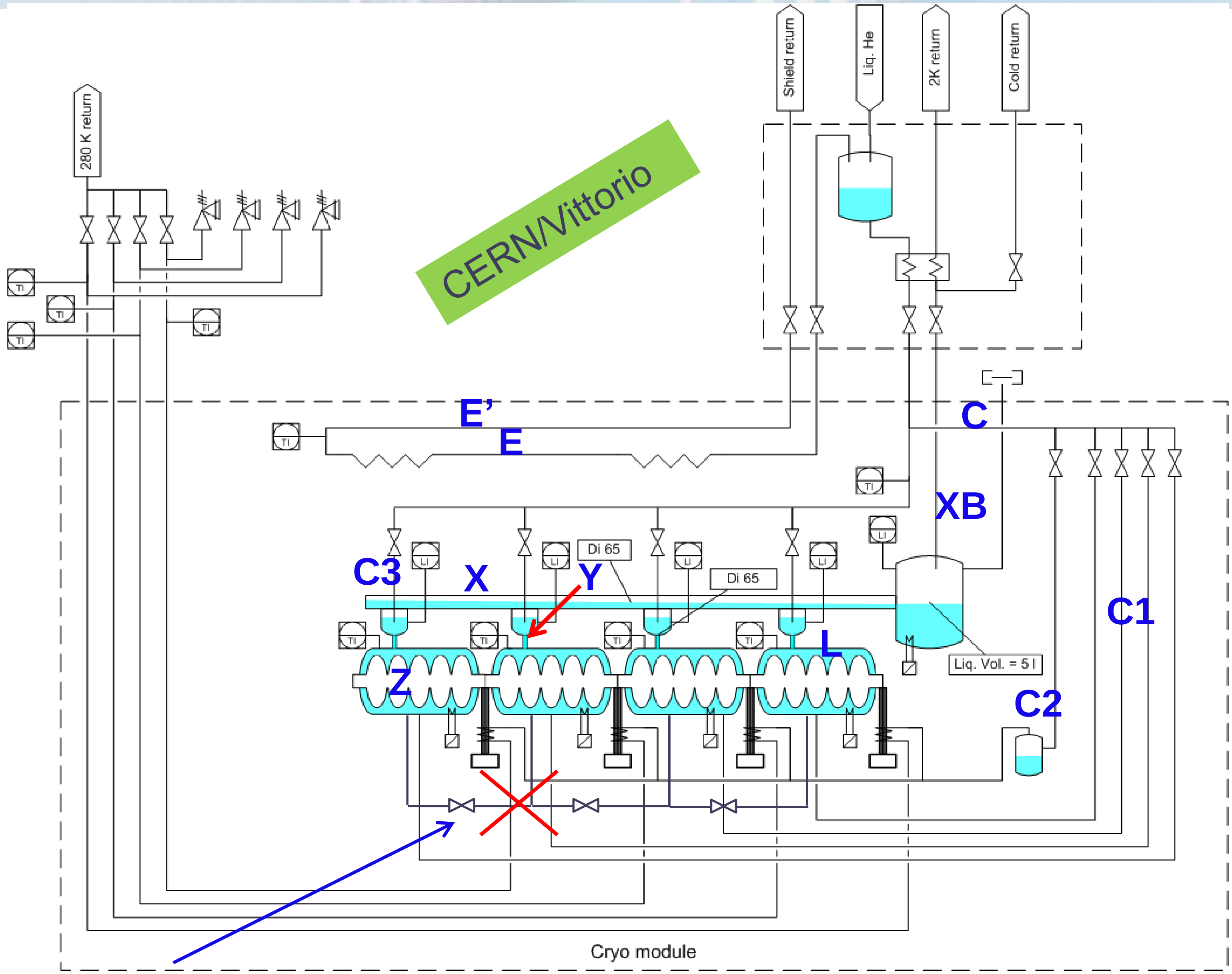
Table 19: *Lattice and Accelerator Science* parameters, H. Danared, June 22, 2011.



	Segmentation-Cold Quad	Segmentation-Warm Quad	
Advantage	*Limit zones of warm-up and opening of vacuum system – cost & downtime. *Increased flexibility. *operational flexibility. *Reduce down-time. *More modular design. *Decoupling of problems. *Staged acceptance tests. *Minimize cold equipment – access, alignment, repairs, upgrades, unnecessary outgassing, leaks, etc. *Modules are complete & tested before installation.	➔ Idem + *Classical "off-the shelf" warm magnets. *Easy alignment. *Maintainability/upgrade. *Cryo-module internal positioning requirements can ne relaxed. * Standard Diagnostics	* Compact longitudinal layout – fewer CWT, fewer RF contacts. * Helium transfer line can be integrated – less vac systems. *Less tasks for systematic repairs on modules – venting, repumping
Dis-advantage	*Diagnostic development in cold environment. *More cold to warm transitions, intermodules, more heat load. *More volumes to commission. *More equipment, more maintenance. *More risk of equipment failure. *More Interlocks.	*More cold to warm transitions, intermodules, more heat load. *More volumes to commission. *More equipment, more maintenance. *More risk of equipment failure. *More Interlocks.	*Cold Diagnostic Instrumentation *Cold BPM *Cavities need to be recommissioned if vented. *Equipment will see more thermal cycles. * Beam vacuum sectors long- cold sector valves don't exist! * Some sensitive equipment is imprisoned in cryostat - needs vacuum compatibility and validation

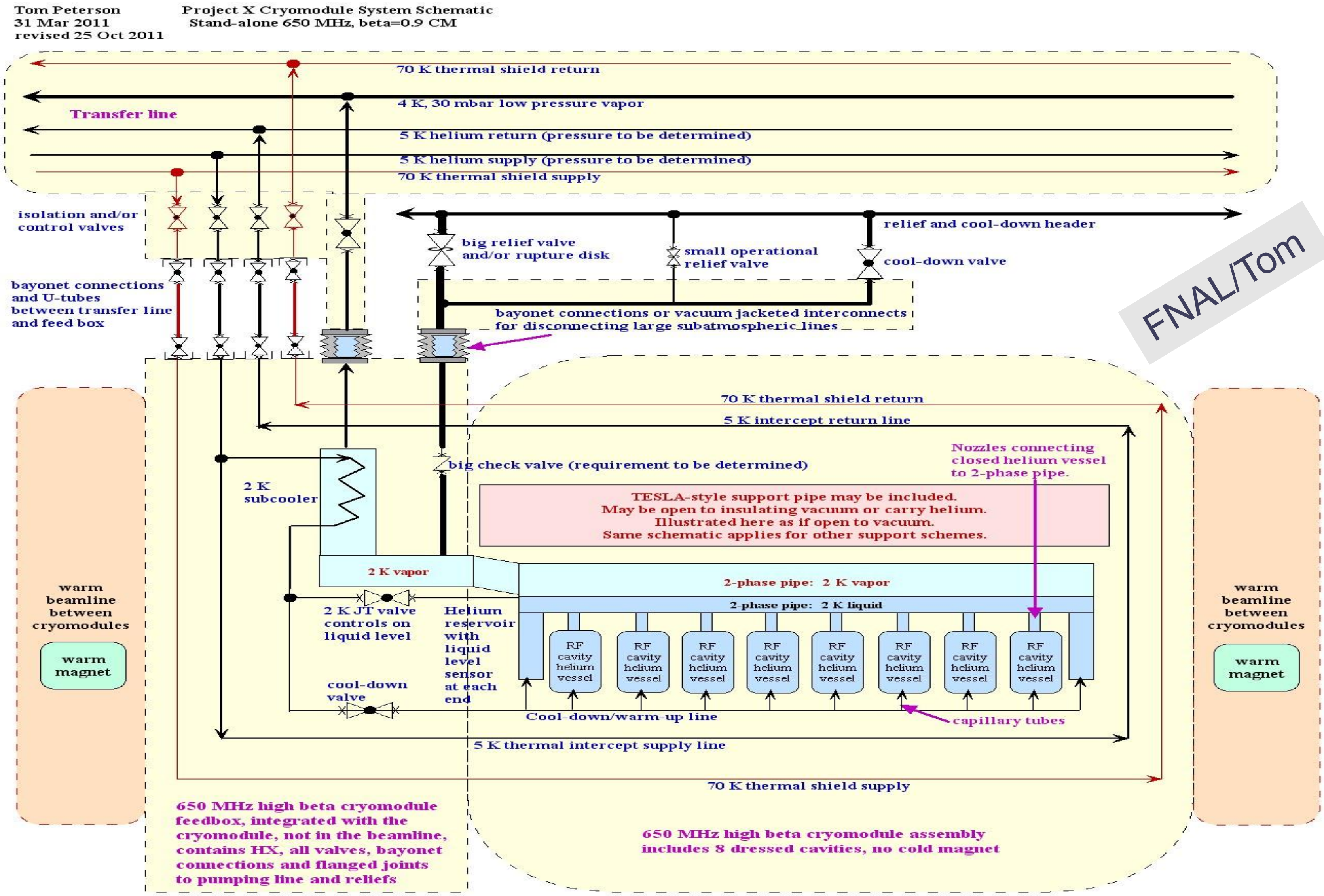
On-going Analysis

Do we re-use SPL cryogenic Scheme ?



Inter-cavity hydraulic connection recently removed, (considered unnecessary)

Do we re-use SPL cryogenic Scheme ?



Ex.: 2 K Heat Loads (per β= 1 cavity)

EUROPEAN SPALLATION SOURCE

Operating condition	Value	
Beam current/pulse lenght	**40 mA/0.4 ms beam pulse**	**20 mA/0.8 ms beam pulse**
cryo duty cycle	4.11%	8.22%
quality factor	10 x 10^9	5 x 10^9
accelerating field	25 MV/m	25 MV/m
Source of Heat Load	**Heat Load @ 2K (per cavity)**	
Beam current/pulse lenght	**40 mA/0.4 ms beam pulse**	**20 mA/0.8 ms beam pulse**
dynamic heat load per cavity	5.1 W	20.4 W
static losses	<1 W (tbc)	~ 1 W (tbc)
power coupler loss at 2 K	<0.2 W	<0.2 W
HOM loss in cavity at 2 K	<1	<3 W
HOM coupler loss at 2 K (per coupl.)	<0.2 W	<0.2 W
beam loss	1 W	1 W
Total @ 2 K	**8.5 W**	**25.8 W**

CERN/Vittorio