SPS Crab Cavity Validation Run (2017-2018)

Alick Macpherson
BE-RF-SRF

Acknowledgments
Marton Ady, Vincent Baglin, Philippe Baudrenghien, Krzyzstof Brodzinski, Rama Calaga, Ofelia Capatina, Frederic Galleazzi, Erk Jensen, Antoine Kosmicki, Phoevos Kardasopoulos, Pierre Maesen, Eric Montesinos, Ghislain Roy, Benoit Salvant, Rogelio Tomas, Giovanna Vandoni.

Overview

- **The SPS Installation and Integration Issues**
- **Beam Issues, and Beam time requests**
- **Schedule and planning**

Overview

- The SPS Installation and Integration Issues
- Beam Issues, and Beam time requests
- Schedule and planning

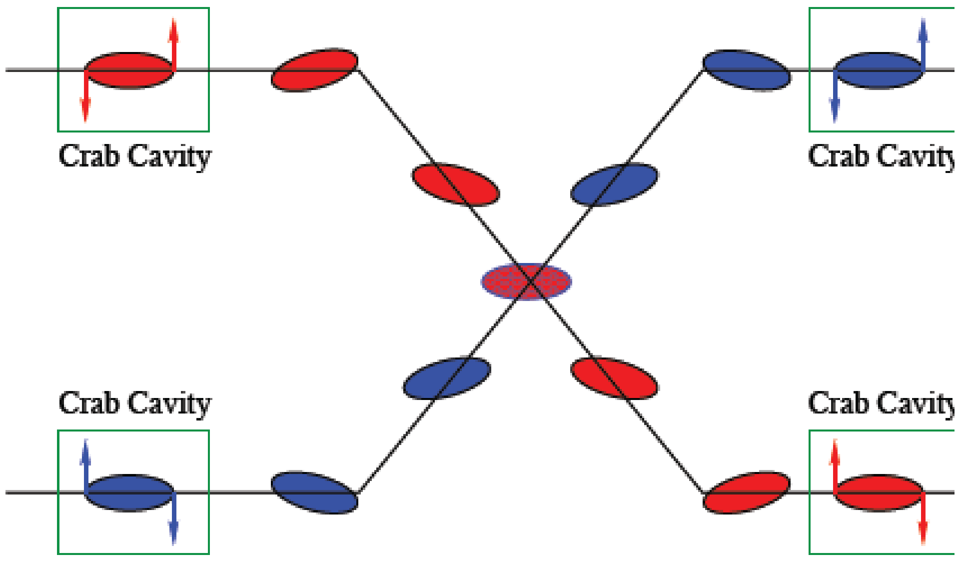
Purpose of the SPS crab cavity validation program

Validate Crab cavity design for proton beams

Validate Crab cavity invisibility to proton beams when not on resonance

Validate operational functionality & Machine protection mechanisms

Overall goal => set inputs for final design

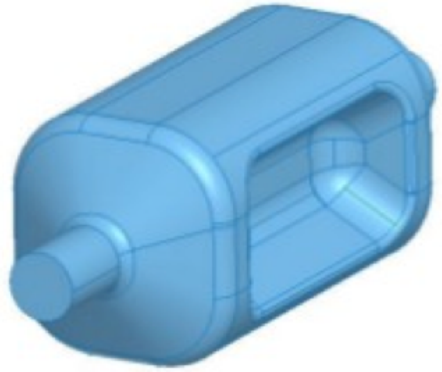


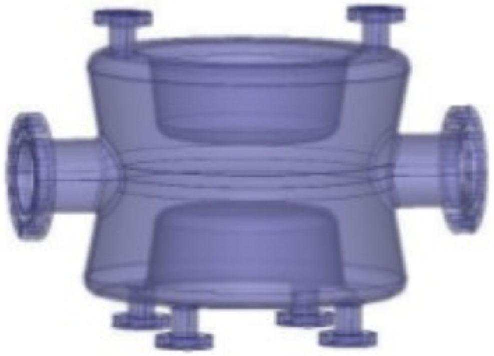
General Overview

- **Baseline parameters**
  - Voltage = 3 MV/cavity
  - Frequency = 400.079 MHz
  - Cavity aperture: 84 mm diameter
  - Operating Temperature= 2K
  - Q_L = 5x10^5 (Assuming R/Q=400)
  - RF power = 40kW tetrode/cavity

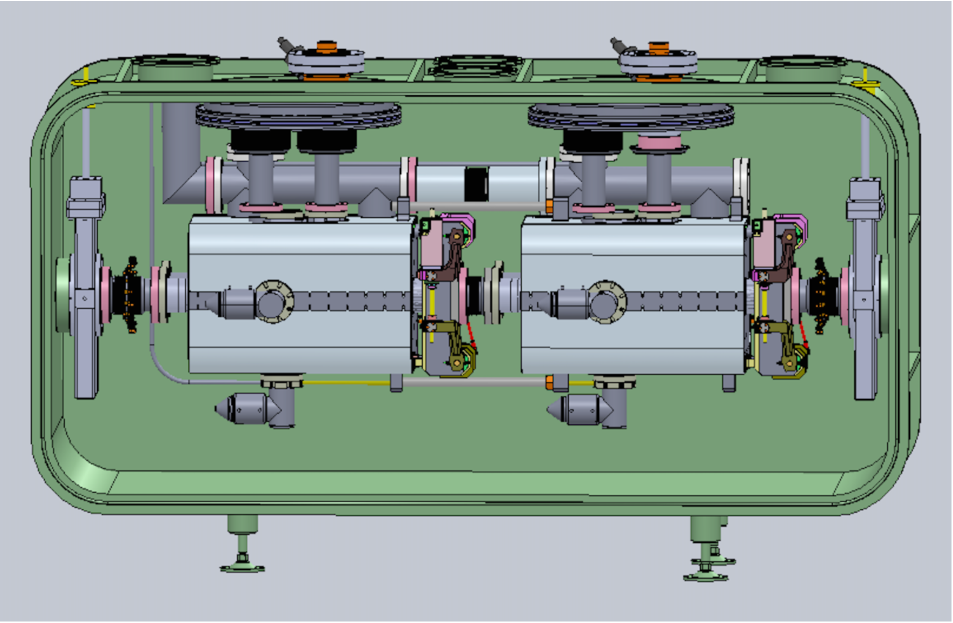
General Overview

- **Baseline parameters**
  - Voltage = 3 MV/cavity
  - Frequency = 400.079 MHz
  - Cavity aperture: 84 mm diameter
  - Operating Temperature= 2K
  - $Q_L = 5x10^5$ (Assuming R/Q=400)
  - RF power = 40kW tetrode/cavity
- **Crab cavity prototypes**
  - 3 designs being taken forward to the SPS test

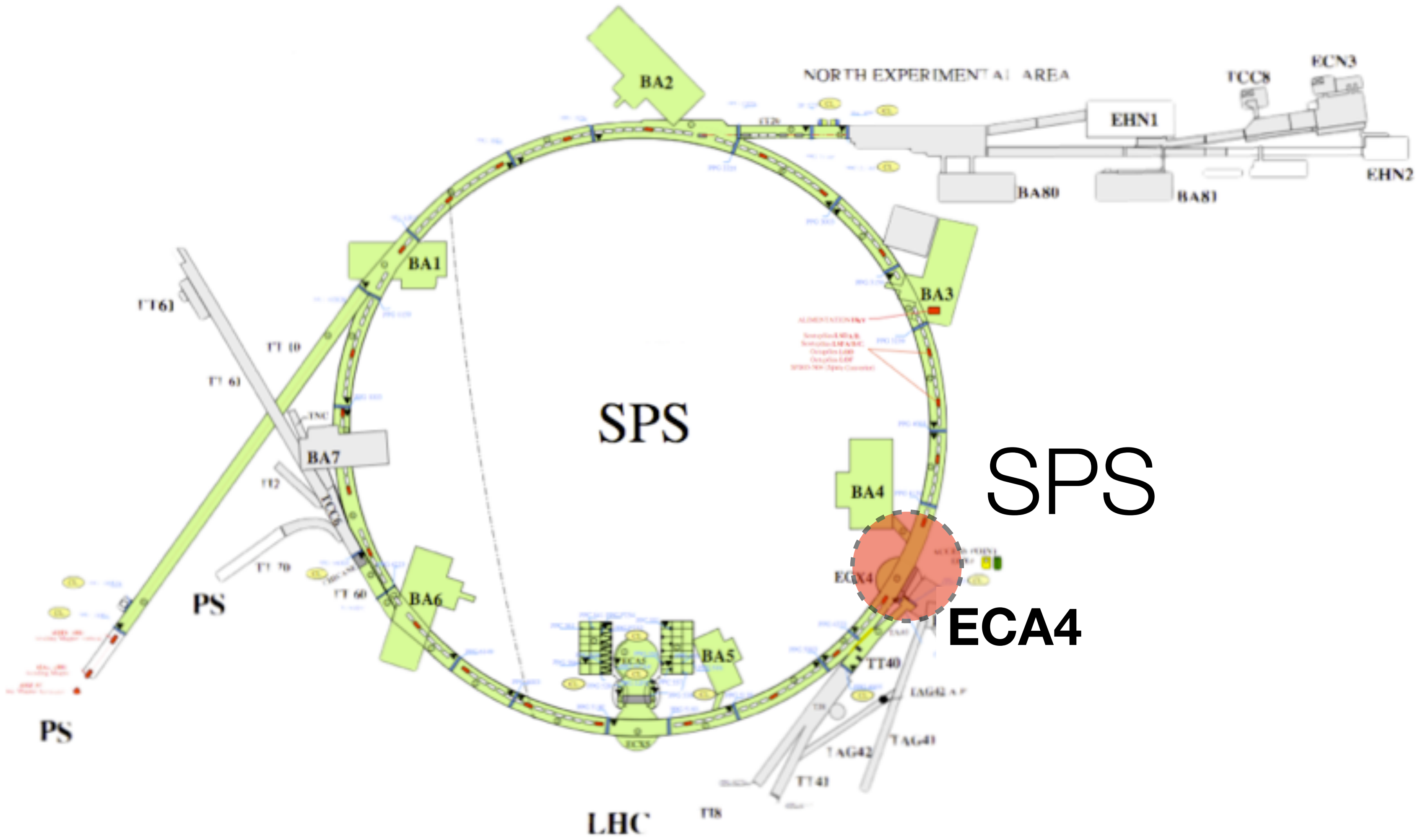




- **SPS Crab Cavity Cryomodule (CCM)**
  - 2 cavities installed in 1 cryomodule
    - cavities of same type
  - 3 different cryomodules
    - should be interchangeable

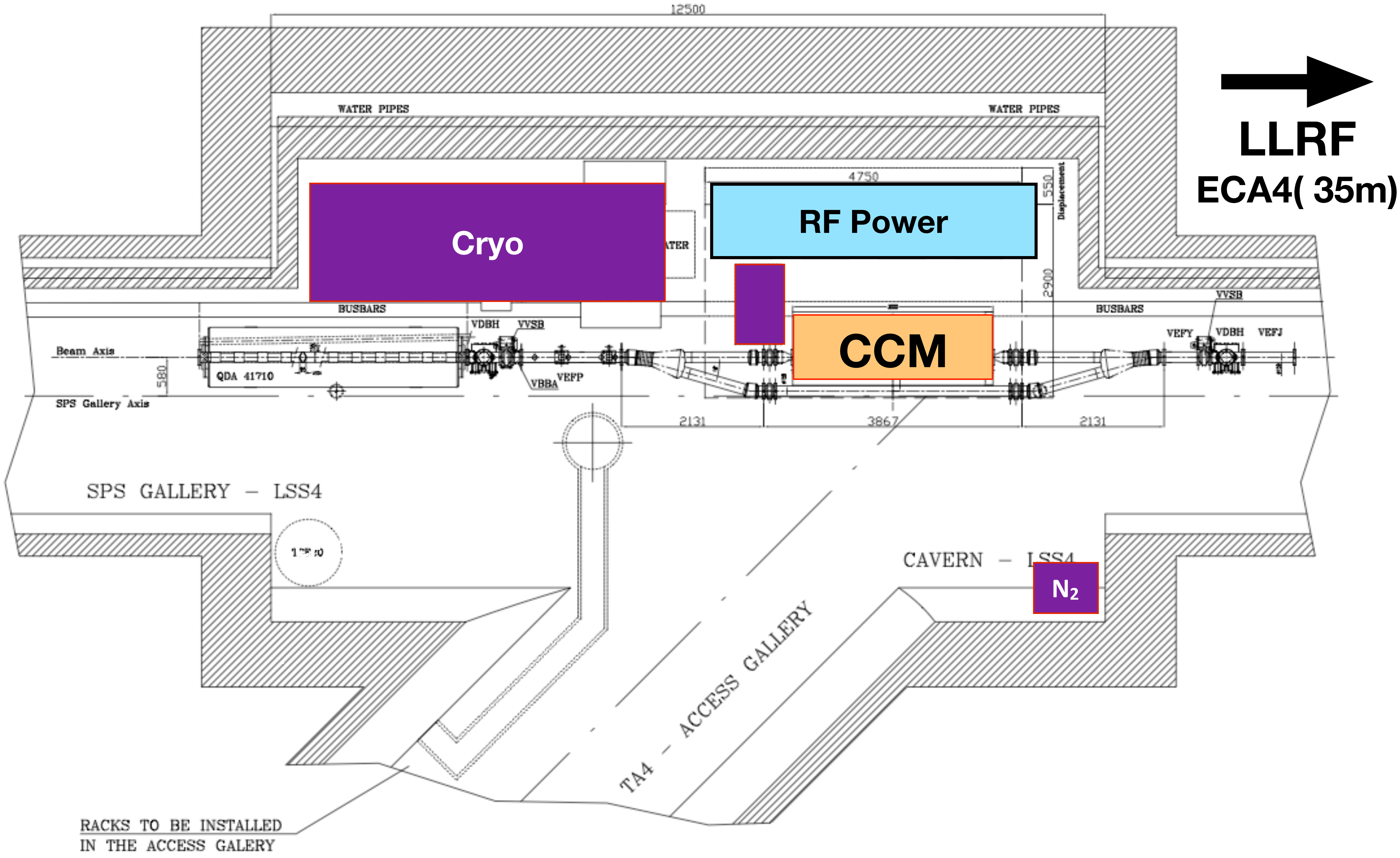


Crab Cavities in the SPS

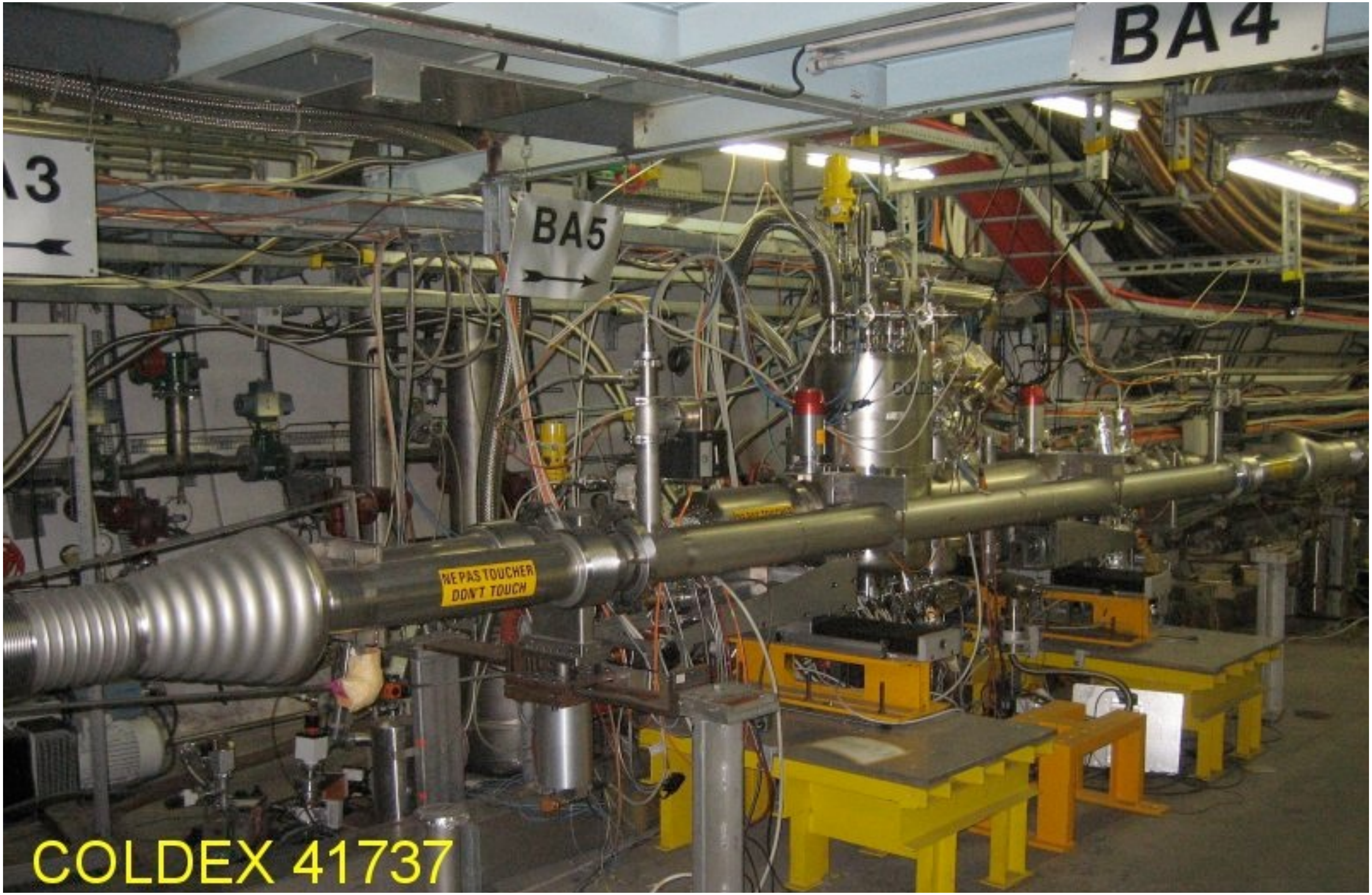


- **Cryogenics Infrastructure: Only SPS Pt 4 is feasible**
- LLRF ~35m away: Experimental cavern (ECA4) accessible with beam
- **Location Availability: Space is not free end of 2015**
- Limited access to SPS zone after SPS long shutdown (2013-2014)
- **Features: Location just upstream of SPS Extraction pt for LHC beam 2**

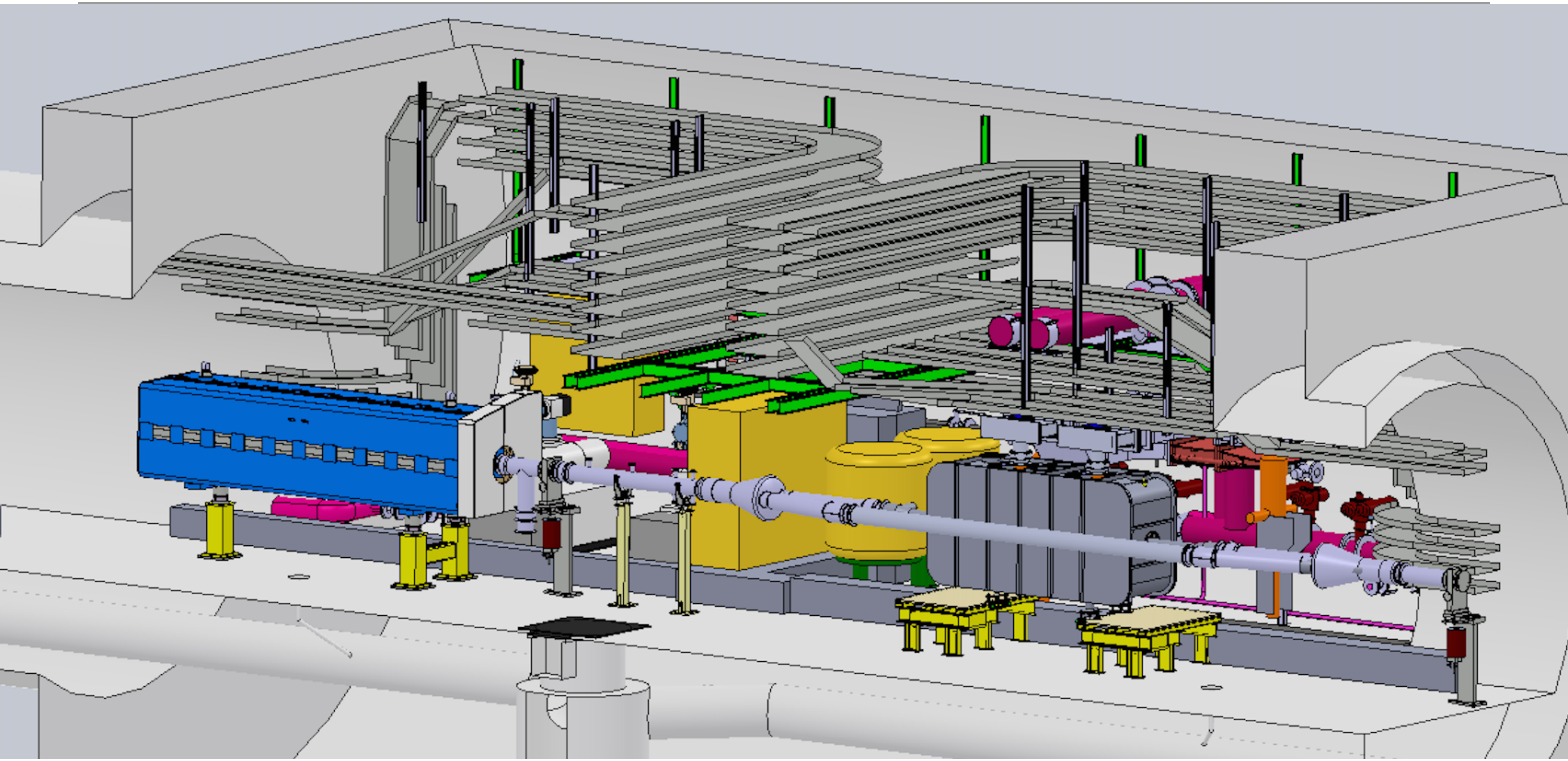
LSS4: Simplified View



SPS LSS4: As it is now



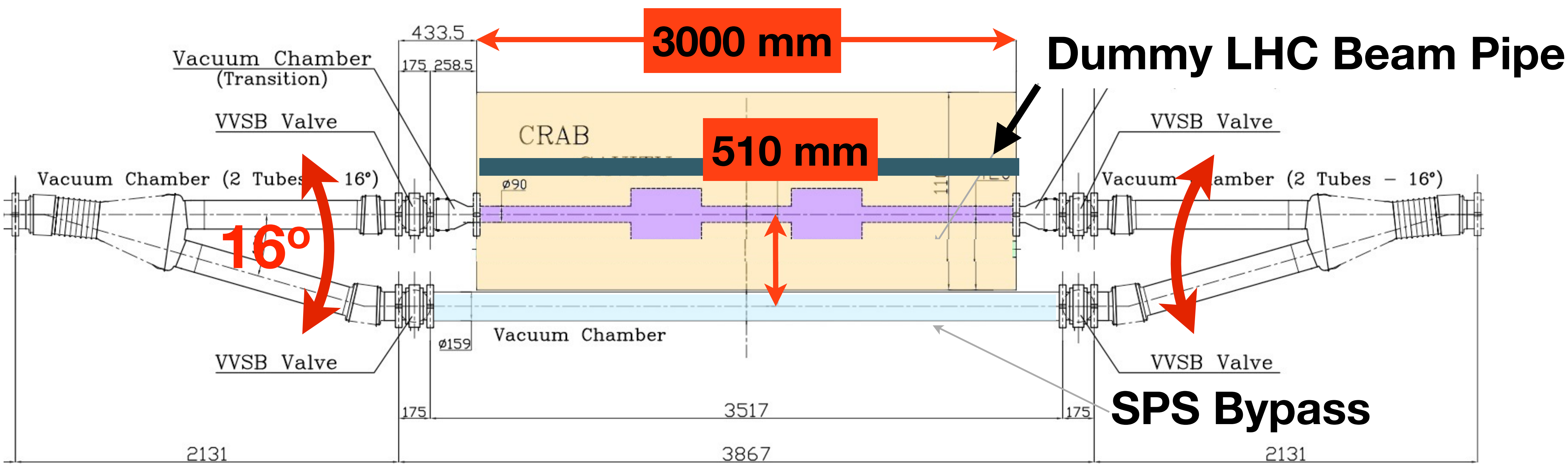
SPS LSS4: Crab Integration



- **Crab Cavities cannot be installed until COLDEX Installation removed**
  - COLDEX must be de-installed by end of 2015
- **LSS4 Alcove: This is now (again) a cryogenic installation.**

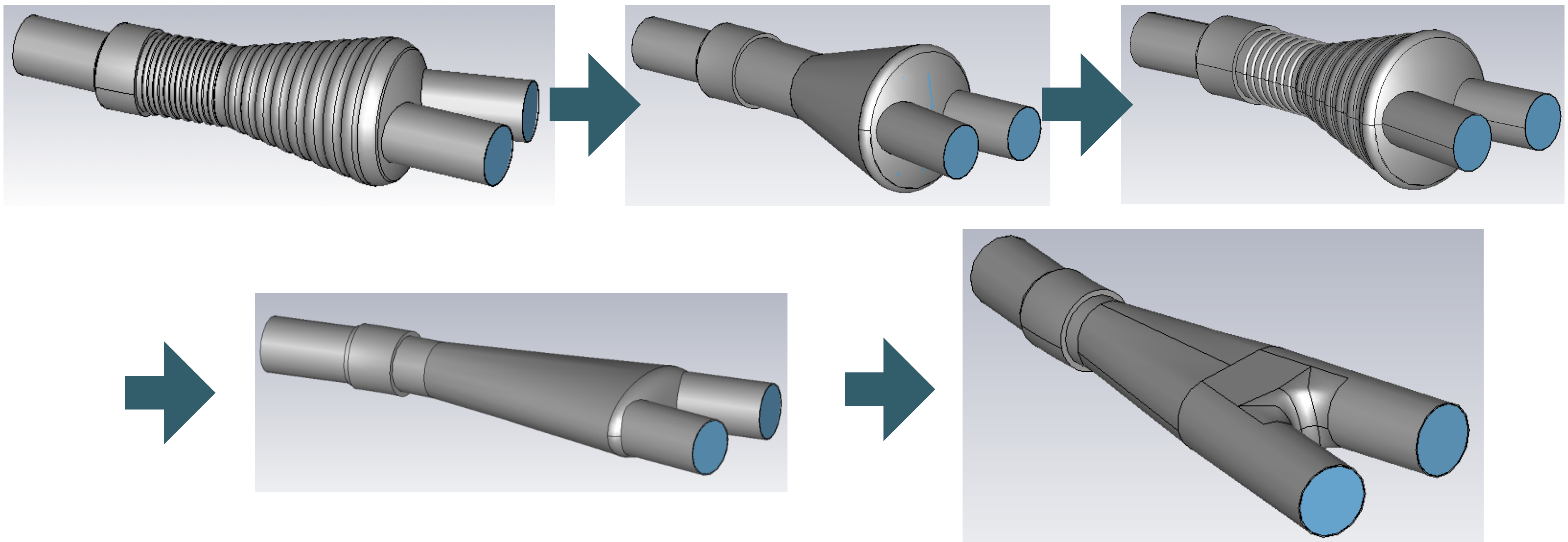
SPS Integration Issues

- **SPS operation must be independent of crab operational availability**
  - Crab Cavity module switchable from in-beam to out-of-beam position
  - Need to increase opening angle of Y-chamber =>New Y-chamber design



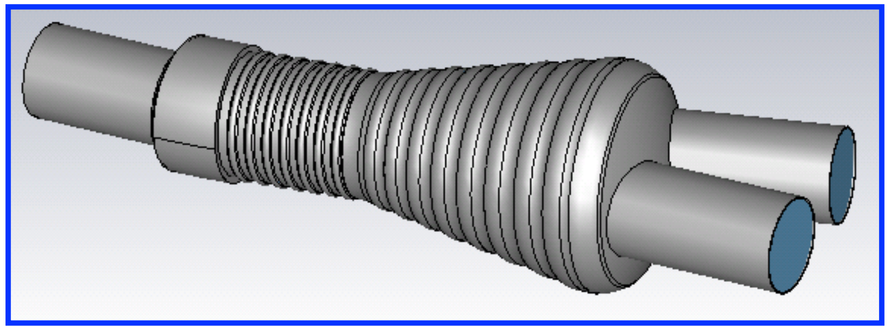
- **CM Movement: In out of beam line**
  - Cryomodule: moved with cavities cold and helium tanks full
  - Duration: less than 20 mins. Acceleration: less than 0.2g
  - Safety requirement: Movement is a remote operation

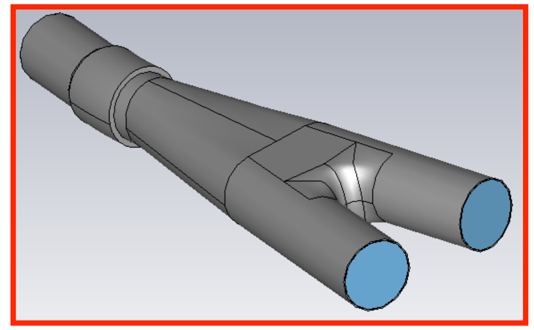
Y-Chamber redesign



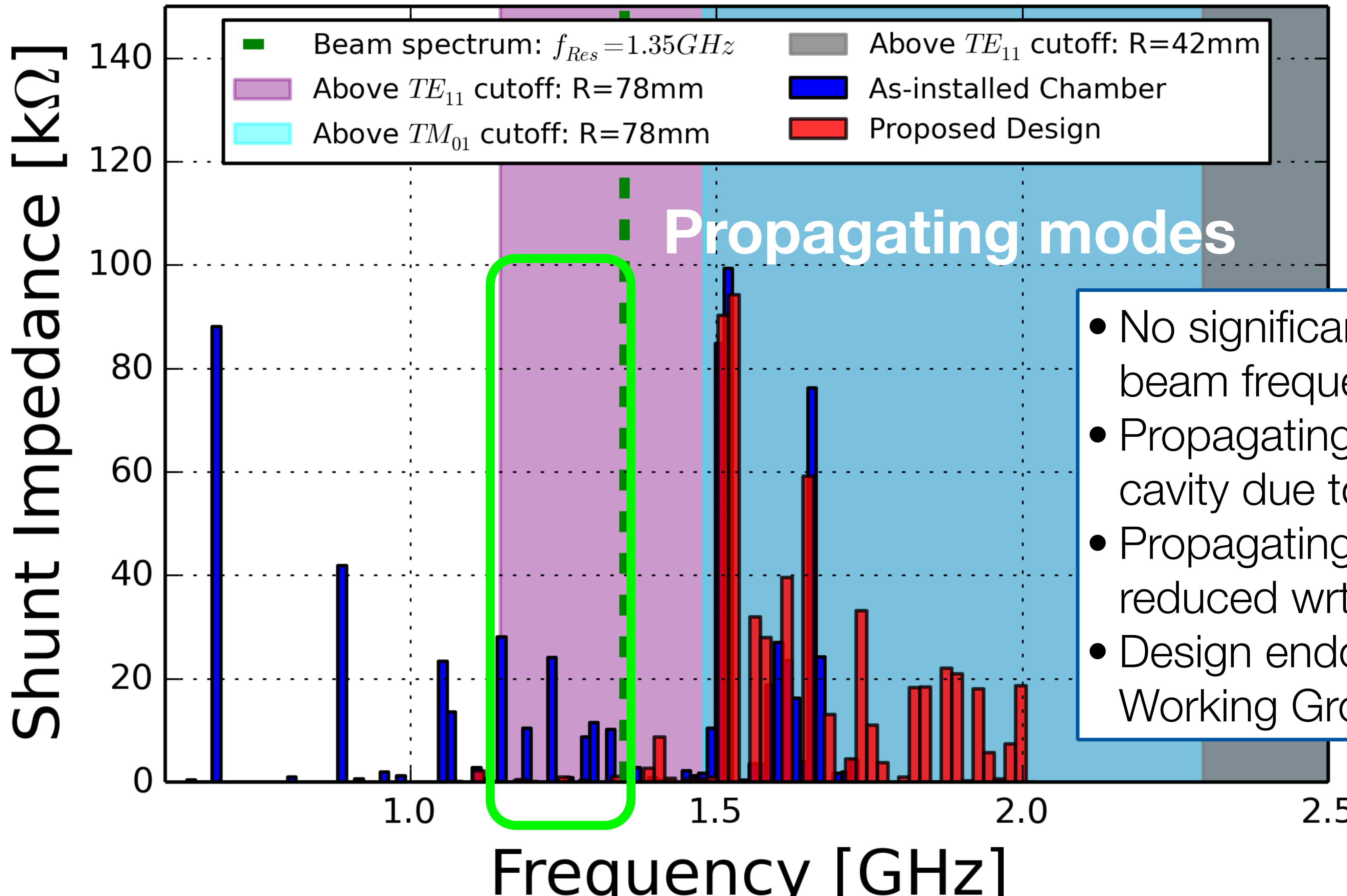
Model	Z	Zx (kOhms/	Zy (kOhms/
Baseline 12 Degree	*2.8*	*0.33*	*0.31*
16 Degree	*3.73*	*0.27*	*1.67*
16 Degree Undulations	*3.69*	*0.41*	*0.53*
Ellipsoid	*1.65*	*0.25*	*0.85*
Proposed	*0.43*	*0.21*	*0.85*

Y- Chamber: Changes in shunt impedance





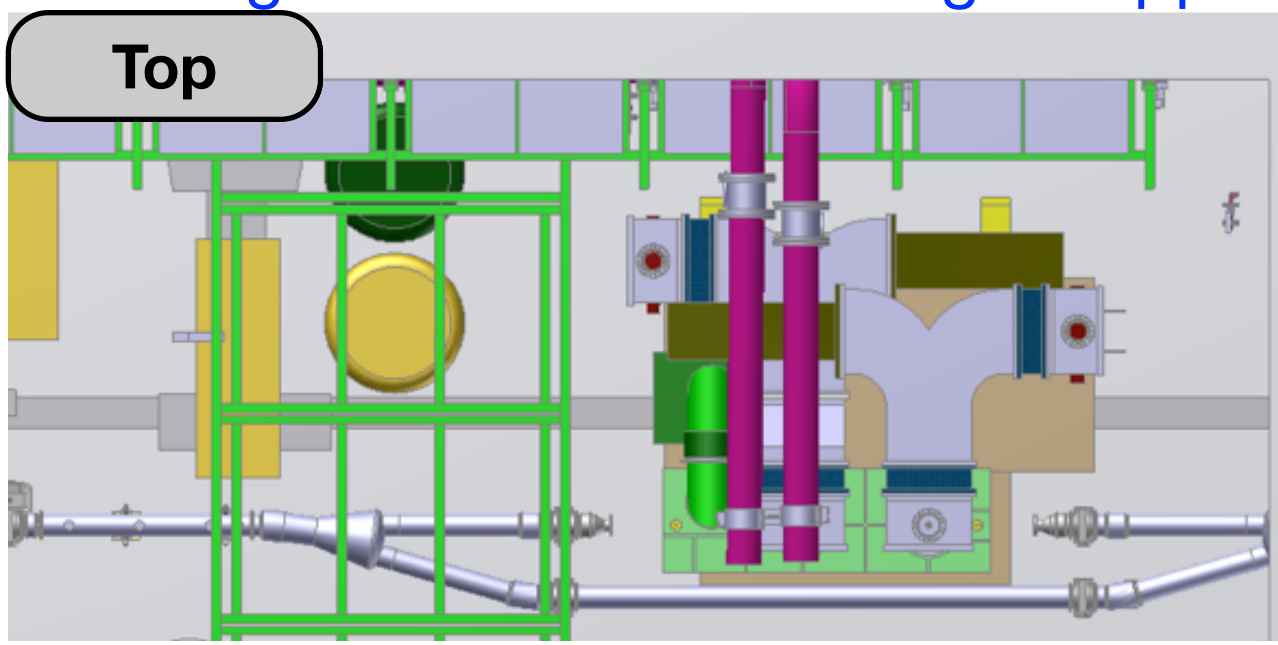
Simulations:
Phoevos Kardasopoulos

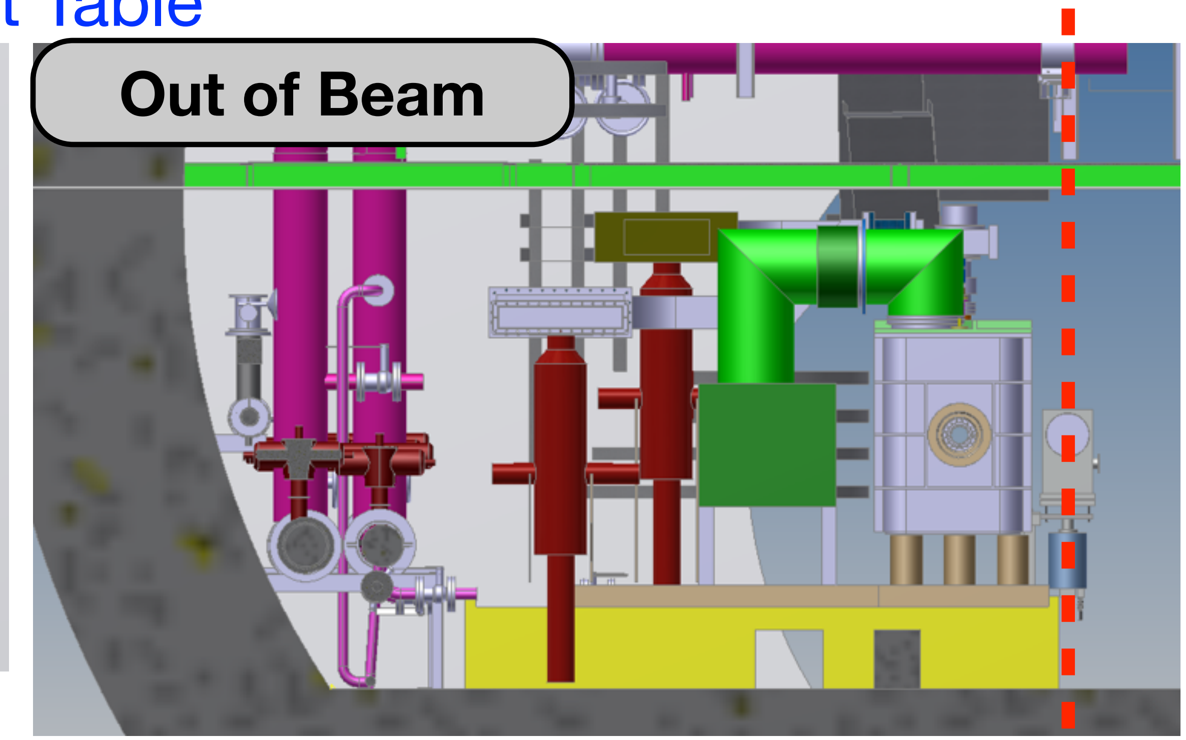


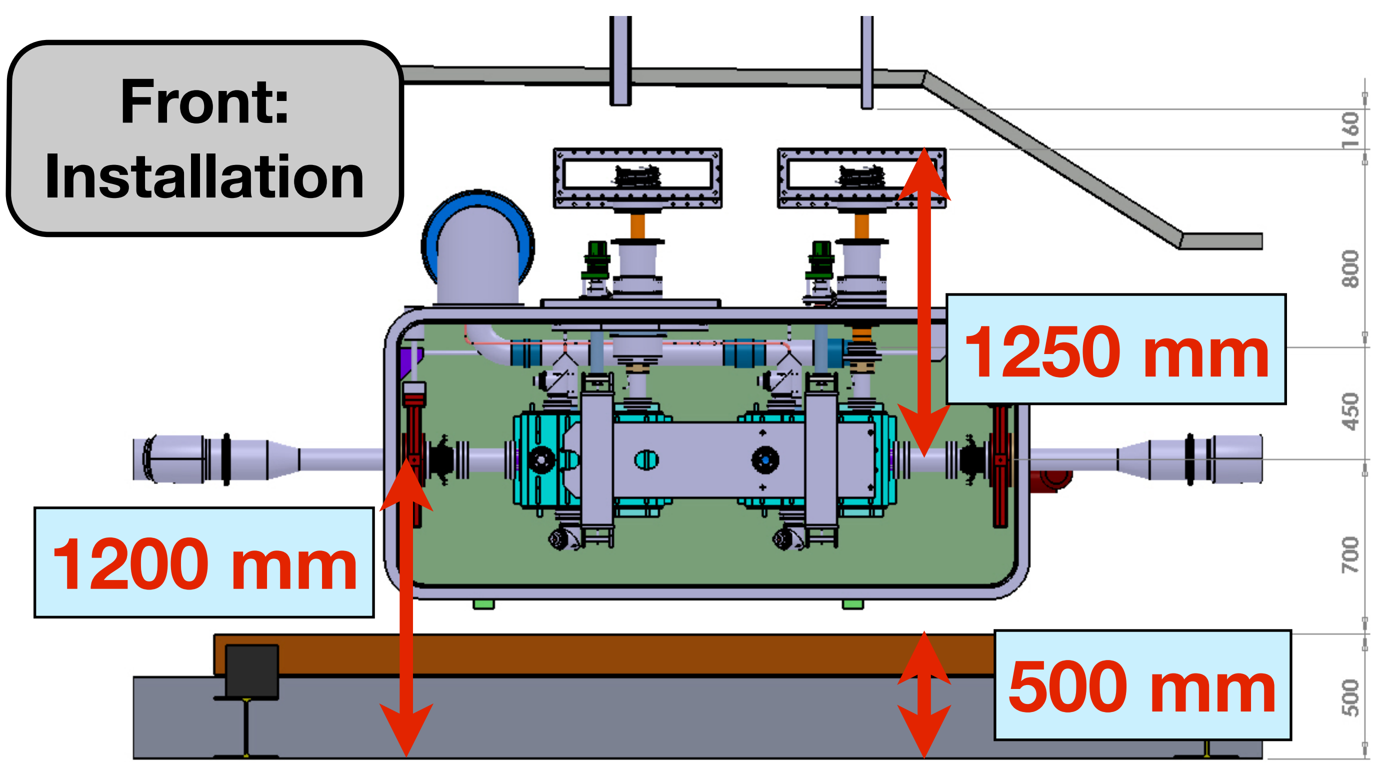
- No significant impedances below beam frequency
- Propagating modes do not reach cavity due to aperture reduction
- Propagating modes into SPS reduced wrt existing design
- Design endorsed by Impedance Working Group

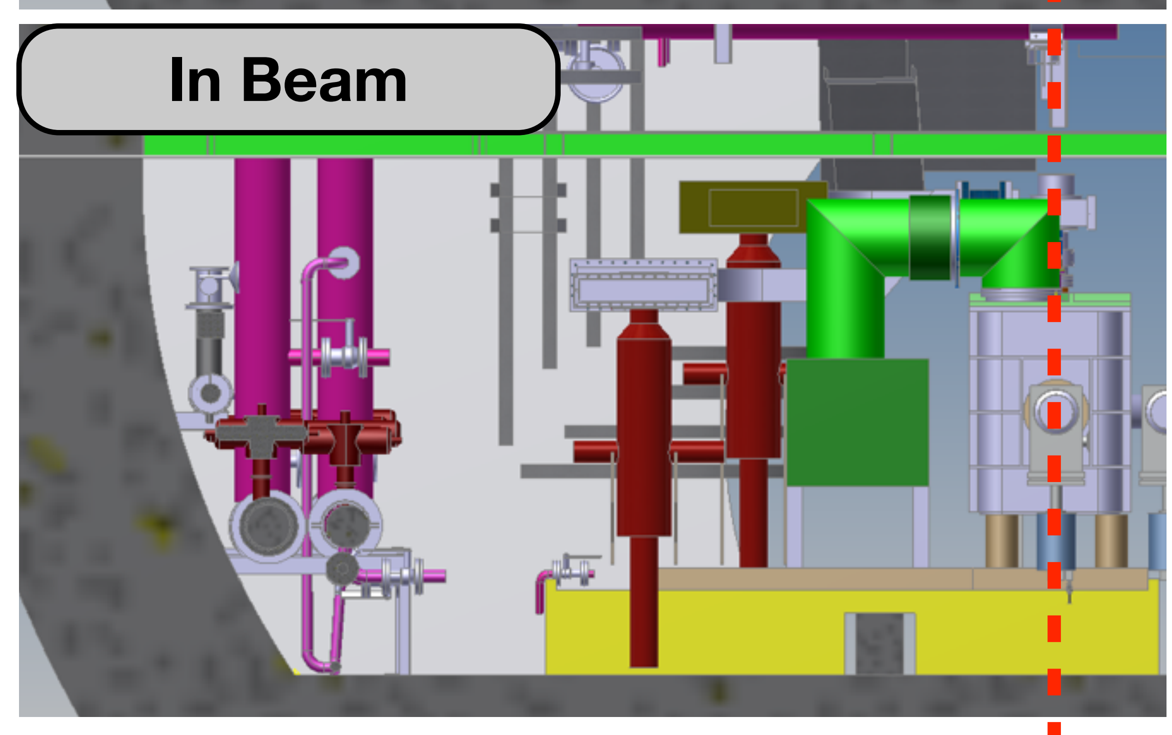
Integration Space

- **Vertical constraints: 700mm (max) between beam axis and top of table**
    - Magnet Busbar + shielding + support Table





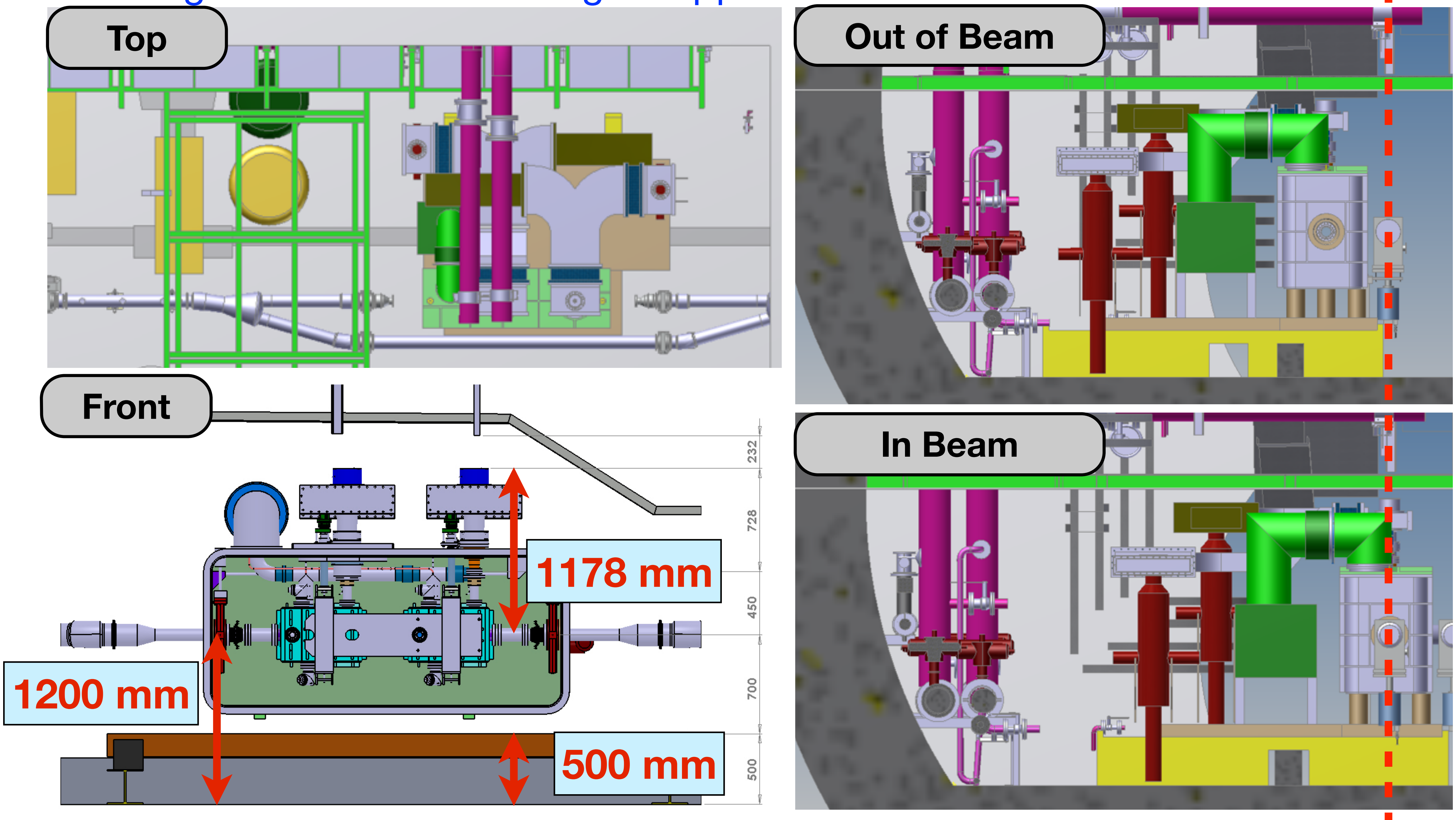




Integration constraints: https://edms.cern.ch/document/1360083

Integration Space

- **Vertical constraints: 700mm (max) between beam axis and top of table**
  - Magnet Busbar + shielding + support Table



Integration constraints: https://edms.cern.ch/document/1360083

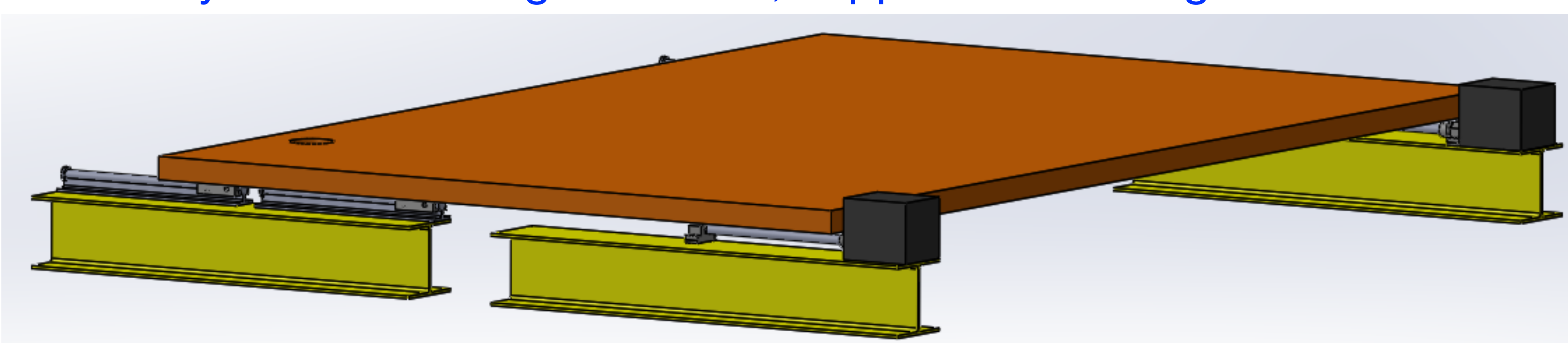
Integration: Cryo Module Interfaces

- **3 different cryomodule: Evolving toward consistent interfaces**
  - Designs not finalised yet, but should be harmonised and made consistent
    - Simplifies support table design, cryomodule exchange, alignment steps

Example: Cryomodule designs as of week 18 2014

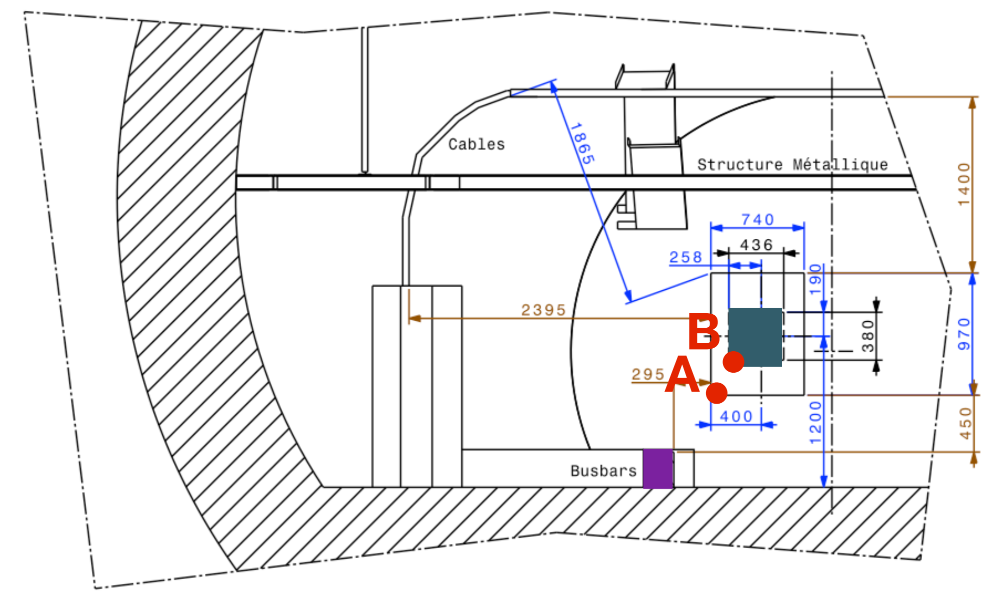
Relative Position of power coupler wrt crab cavity reference position			
Cryomodule	Longitudinal Distance Between Couplers	Transverse offset wrt beam axis	Height (beam axis to centre of waveguide)
BNL	900 mm	0 mm	960.45 mm
ODU	1050 mm	-113 mm	944.94 mm
UK	890.4 mm	25 mm	939.85 mm

- **Support Table functionality becoming more complex**
  - Once cryo module design is frozen, support table design can be finalised



SPS Ambient Magnetic Field

- **Initial 2D simulation results**
  - consider only main magnet busbars
  - use worst case scenario:
- **Identify most critical position.**
  - Pt A: Outer surface of cryomodule
  - Pt B: Outer surface of He Vessel
- **Cavity specifications require a ambient magnetic field < 1 uT**
  - With busbar shield, cryomodule shield factor = 200 (achievable)
  - 10mm busbar shielding to be installed (2015)



To be confirmed by measurement in August 2014

	In-Beam Stray field [mT]		Out-of-Beam Stray field [mT]	
Busbar shielding	**Pt A**	**Pt B**	**Pt A**	**Pt B**
Stainless steel (or no cover)	0.4	0.2	0.6	0.3
Constructional steel, 2 mm thick	0.3	0.2	0.4	0.2
Constructional steel, 10 mm thick	**0.1**	**0.1**	**0.2**	**0.1**

Details: https://edms.cern.ch/document/1377806

Beam Line Around the Cryomodule

- **Vacuum Conditions: Required case operational conditions = 10^{-10} mBar**
  - Present SPS vacuum conditions: ~ 10^{-9} - 10^{-8} mBar
  - Crab Cavity cryo module should not cryo pump the SPS beam line
- **Vacuum infrastructure + Standard RF warm-cold transition at CM**
  - Require: NEG Coating **or** cold trap **or** baked aCarbon on each side of CM
  - Differential pumping: Implemented at beam pipe transition diameter
- **With some beam line modification P_{Cavity} <10^{-10} mBar is achievable**

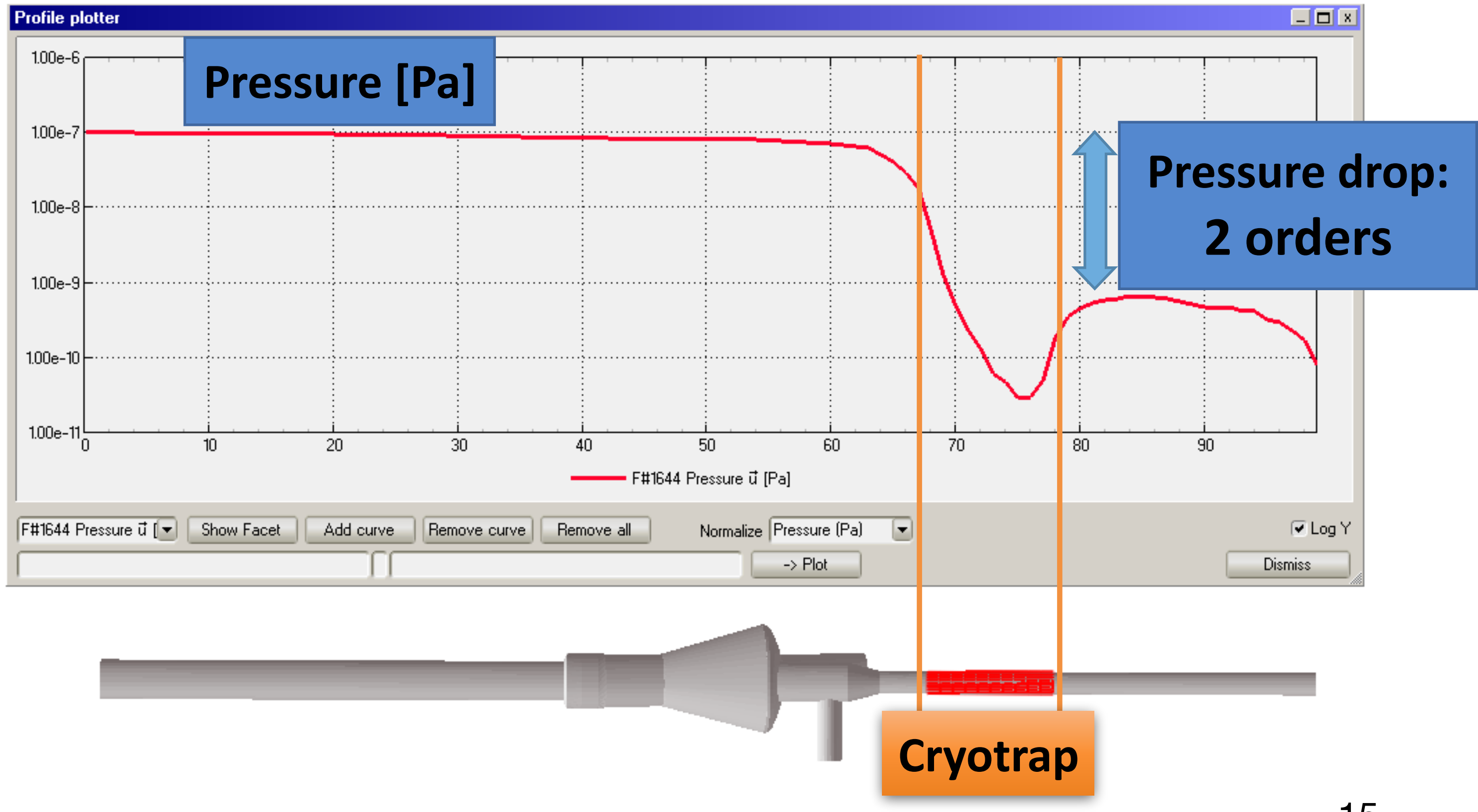
Beam Line Around the Cryomodule

- **Vacuum Conditions: Required case operational conditions = 10^{-10} mBar**
  - Present SPS vacuum conditions: ~ 10^{-9} - 10^{-8} mBar
  - Crab Cavity cryo module should not cryo pump the SPS beam line
- **Vacuum infrastructure + Standard RF warm-cold transition at CM**
  - Require: NEG Coating **or** cold trap **or** baked aCarbon on each side of CM
  - Differential pumping: Implemented at beam pipe transition diameter
- **With some beam line modification P_{Cavity} <10^{-10} mBar is achievable**

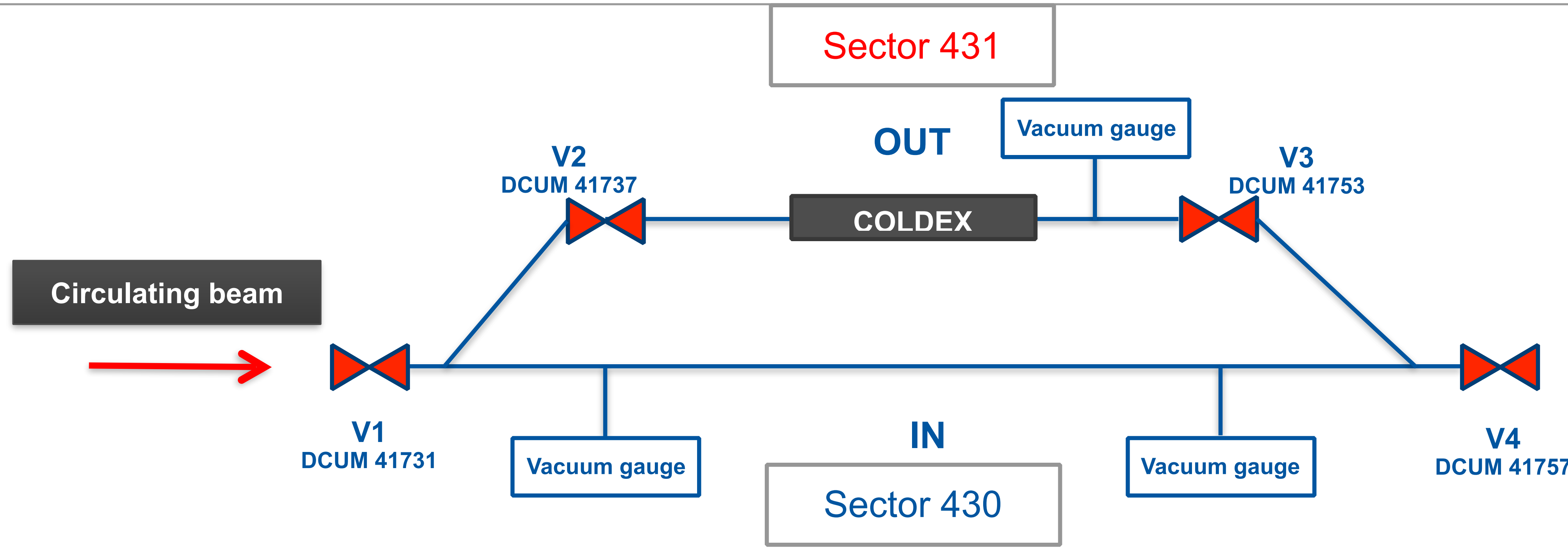
Example: Cryo Trap

Cryo trap: Transmission ratio

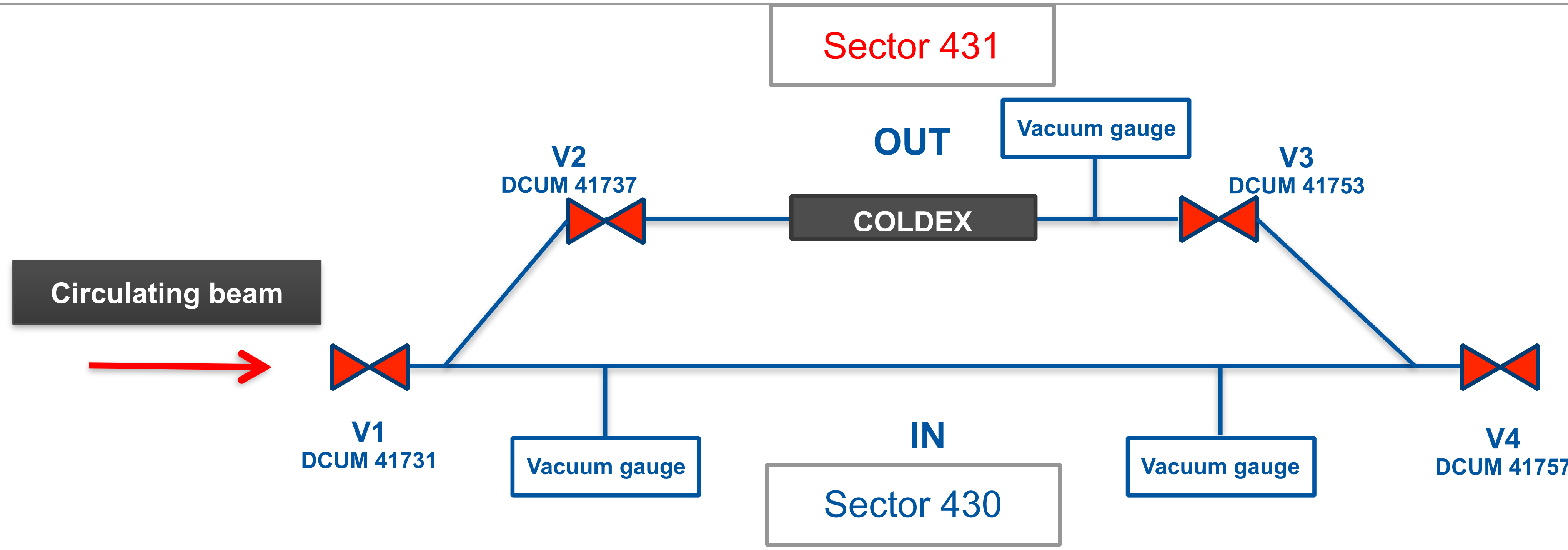
	No cryotrap	0.5m cryotrap	1.0m cryotrap
No pump	100%	1%	0.55%
With pump	10%	0.55%	**0.2%**



Vacuum Considerations

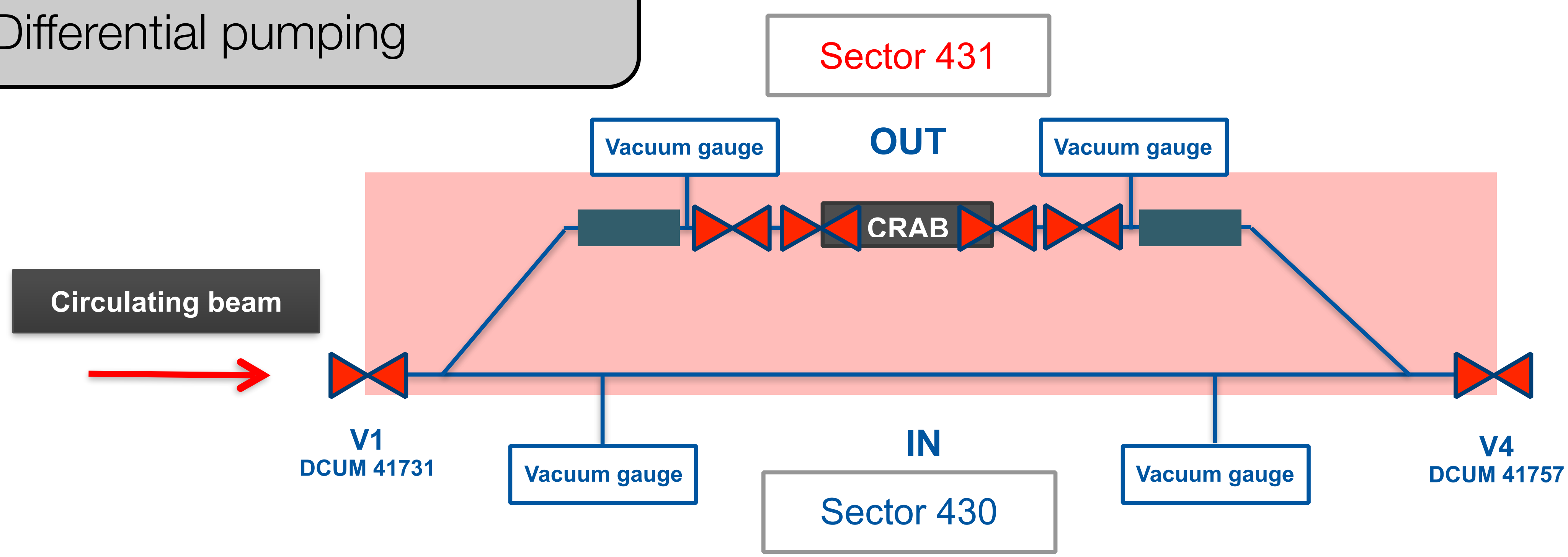


Vacuum Considerations



Isolated beam pipe zone
NEG or cold trap or aCarbon

Differential pumping



Rf Power and Orbit Drifts

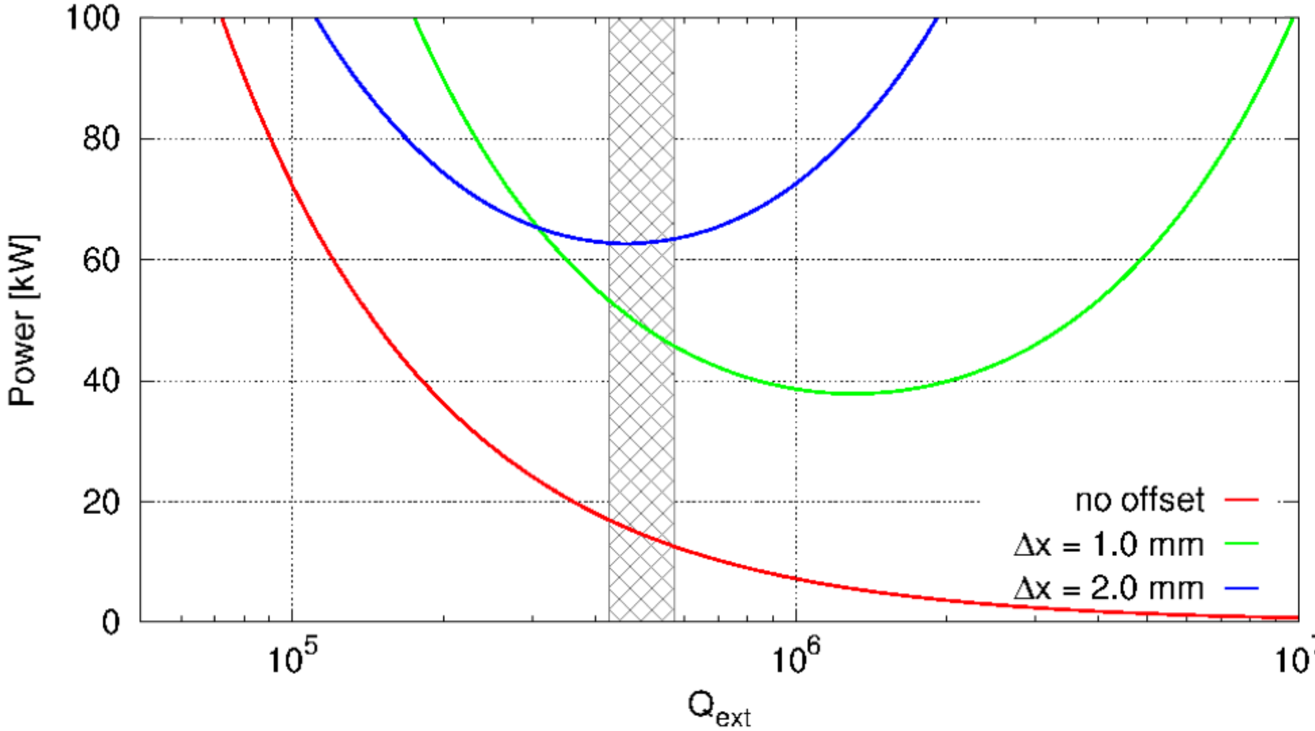
- **Beam position in Cavity:**

Orbit Offset: $V_b \simeq Q_L I_b \frac{R}{Q}(\Delta x)$

Q_L=3-5x10^5, I_b=1.1A, R/Q=400Ω

1mm offset ~0.2 MV/mm beam induced voltage

Tetrode Power vs Beam offset



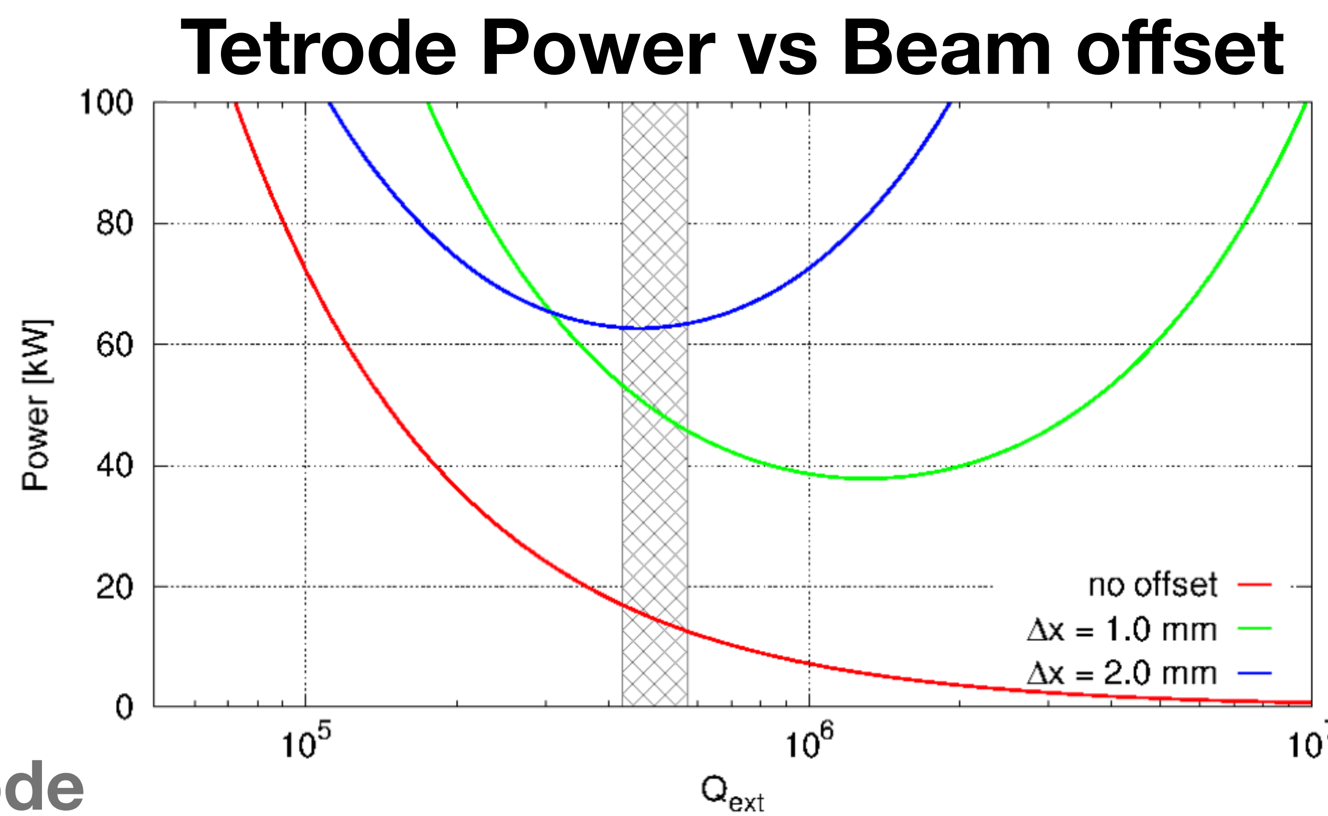
Rf Power and Orbit Drifts

- **Beam position in Cavity:**

Orbit Offset: $$V_b \simeq Q_L I_b \frac{R}{Q}(\Delta x)$$

Q_L=3-5x10^5, I_b=1.1A, R/Q=400Ω

1mm offset ~0.2 MV/mm beam induced voltage



- **Crab Tetrode**
  - Should provide 40 to 50 kW (to be tested)
- **Power constraints => beam must stay centred**
  - SPS closed orbit drift in ramp up to 6mm
  - Correctors at SPS Pt 4 in interlock chain
    - complicates orbit centering
  - Slow orbit drift to be countered by support table adjustment, driven by LLRF
    - **Support Table no longer simple**

SPS Validation Program: 5 Steps

1. **Cavity setup, conditioning, beam injection and initial cavity operation**
2. **Long Term Effects: Coasting Beam [120 -270 GeV]. Low Intensity**
    1. Single + multi-bunch + trains: Emittance growth, Dispersion etc
3. **Short Term Effects: Cycling Beam: [26-450 GeV]. Low intensity**
    1. Direct crabbing measurements: Head tail monitor
    2. Global and Local Crabbing schemes
4. **Machine Protection Issues and Quench studies**
5. **High Intensity Studies**
    - Impedance Studies and Invisibility of detuned cavities

- **Cavity operation with beam: Cryo limit of 8-12 hrs operation**

SPS Validation Program: 5 Steps

1. **Cavity setup, conditioning, beam injection and initial cavity operation**
2. **Long Term Effects: Coasting Beam [120 -270 GeV]. Low Intensity**
    1. Single + multi-bunch + trains: Emittance growth, Dispersion etc
3. **Short Term Effects: Cycling Beam: [26-450 GeV]. Low intensity**
    1. Direct crabbing measurements: Head tail monitor
    2. Global and Local Crabbing schemes
4. **Machine Protection Issues and Quench studies**
5. **High Intensity Studies**
    - Impedance Studies and Invisibility of detuned cavities

- **Cavity operation with beam: Cryo limit of 8-12 hrs operation**

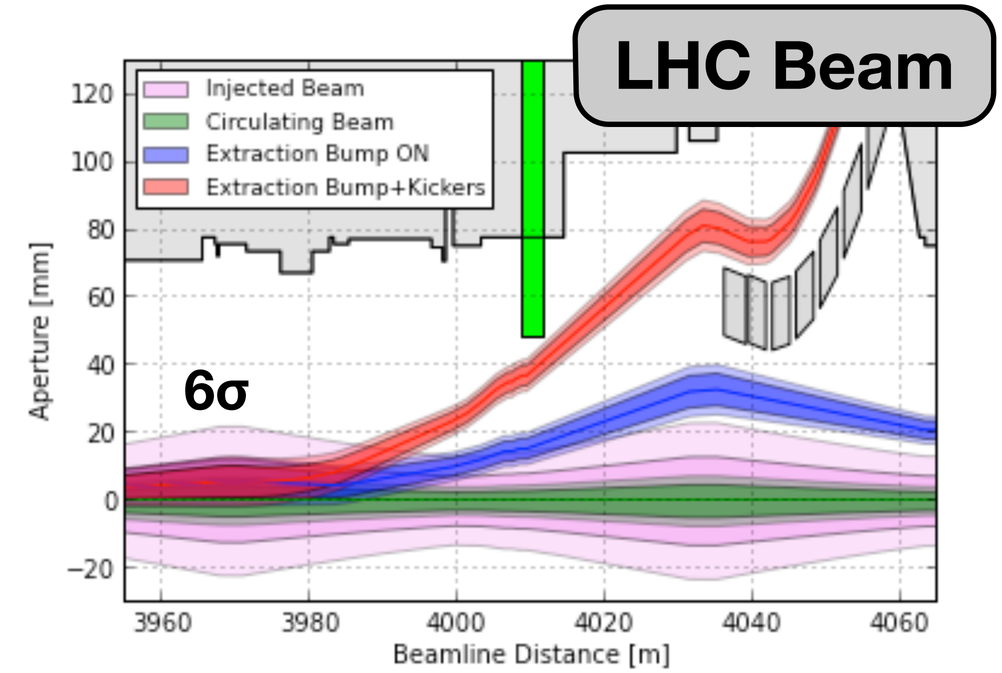
Each MD step: 3 slots of 8hrs of beam => 24 hours of beam per cavity

Test of 2 cavities: 10 days of dedicated MD time spread over 2 years

This is ~1/3 of allocated SPS MD beam time

SPS Beam

- **Crab cavities is need dedicated MD time**
  - LHC beams:
    - cannot be in when LHC beam extracted
  - SPS Fixed Target:
    - large beams at injection & slow extraction

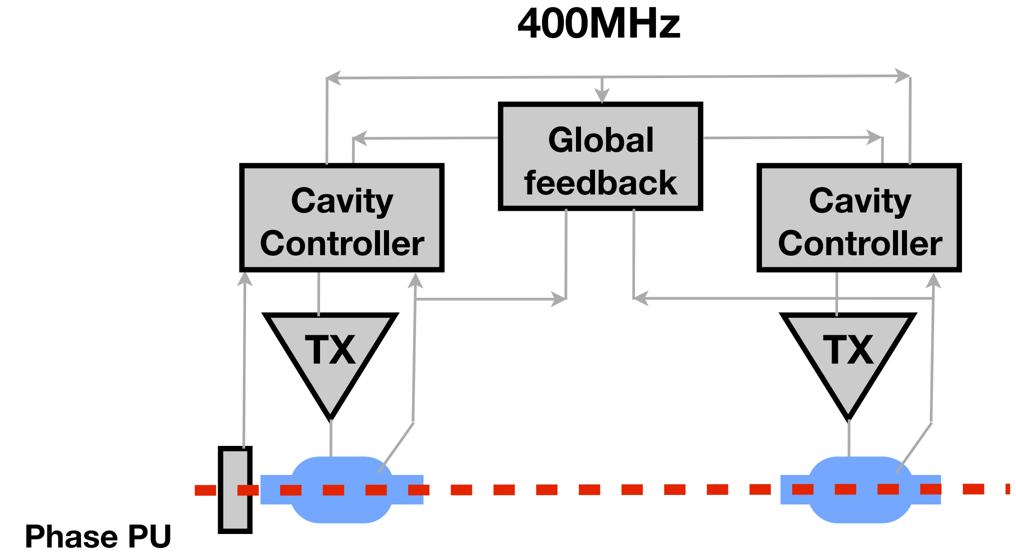


- **Coasting Beam: Crab dispersion and long term emittance growth**
    - Beam Energy > 120GeV to distinguish from natural emittance growth

SPS Natural Emittance Growth Measurements					
Energy [GeV]	Intensity [x 10	Tunes Qx/Qy	RF Voltage [MV]	dεx/dt [%/hr]	dεy/dt [%/hr]
55	1	0.13/0.18	3	140-370%	57%
120	0.5 (12b)	0.13/0.18	2.0-4.0	100-300%	40-90%
120	0.1	0.13-0.33	2.0-4.0	18%	17%
270	0.4	0.13/0.18	3	20-23%	14-24%

What's changed after LS1? => participate in MDs in 2015

LLRF Operation



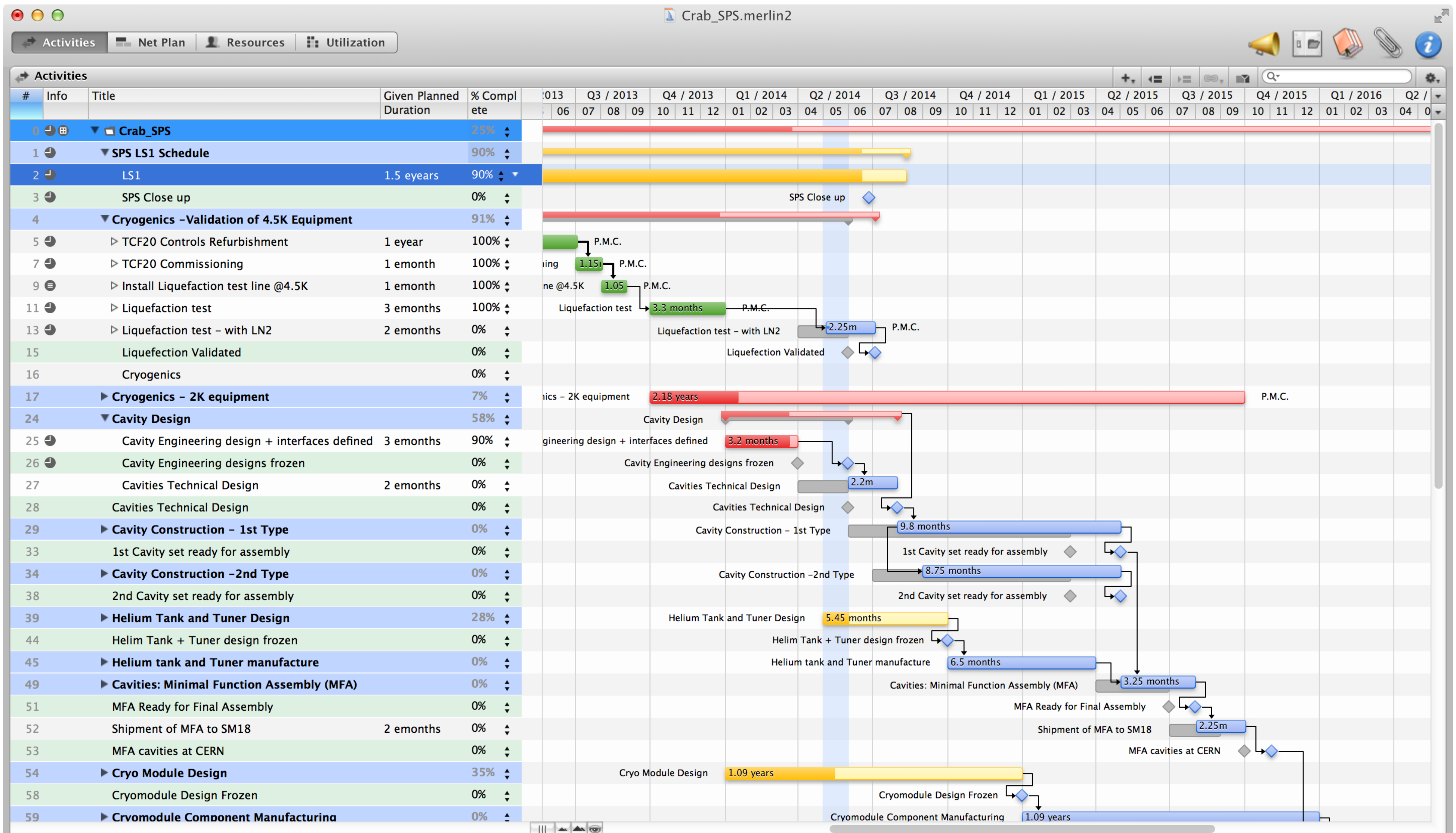
- **Operation:**
  - RF is ON
  - Strong RF feedback + tune controls
  - Cavities are on-tune at all time.
- **Filling, ramping or operation with transparent crab cavities**
  - Cavities kept on-tune with small voltage (0.5MV?) + active tuning system
    - Effect on beam nullified by counter-phasing the cavities
    - RF feedback is used with on-tune cavity to provide stability and keep the beam induced voltage zero if the beam is off-centered.
- **When crabbing is required (at flat top)**
  - Drive counter-phasing to zero.
  - Degree of local crabbing controlled by synchronously changing voltage or phase in both cavities.

Machine Protection

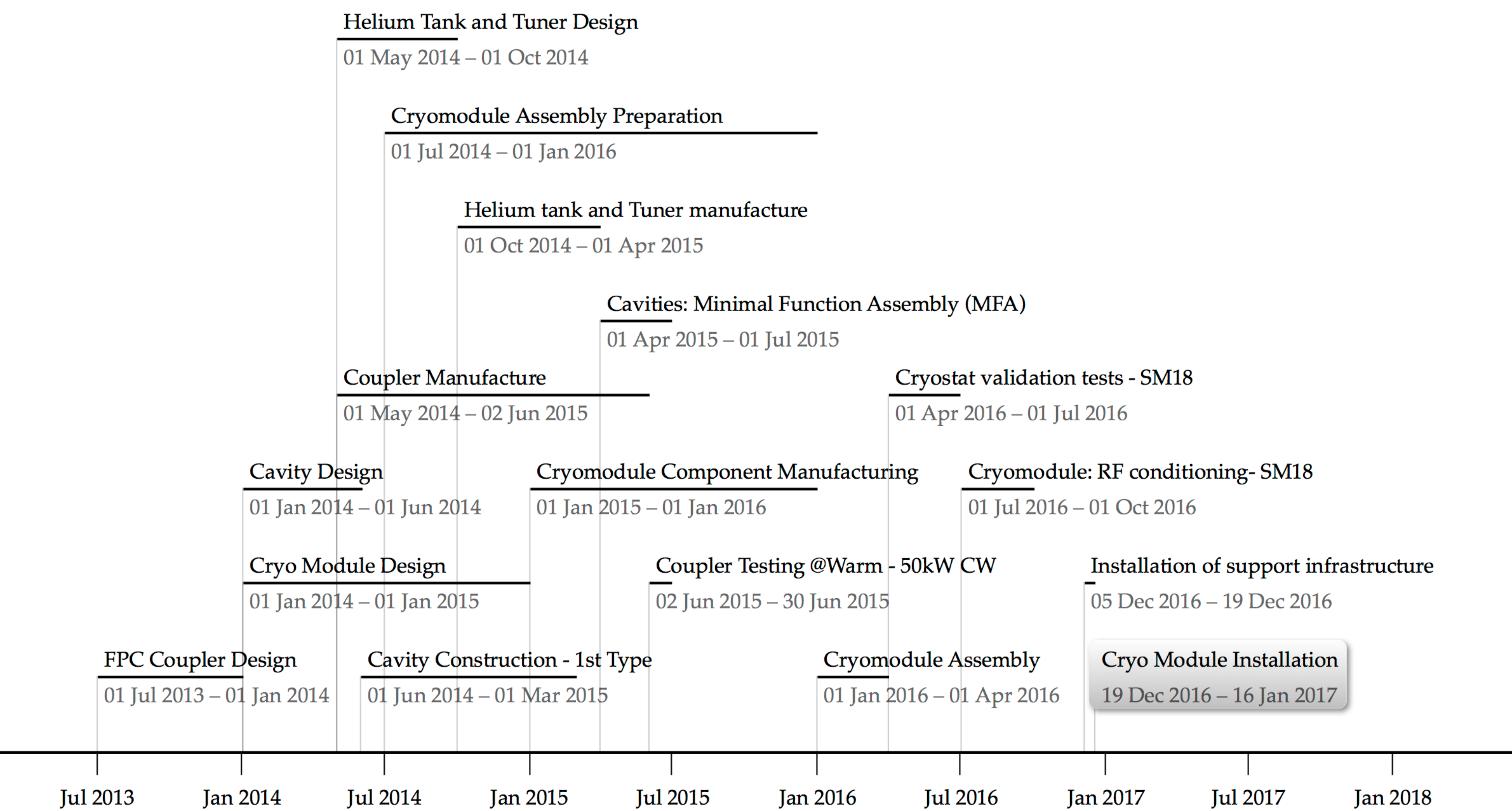
- **Closed Orbit with global deflection**
  - LHC beam: 450 GeV, Cavity Voltage: 3 MV
    - Worst Case: Global scheme in deflecting mode
    - Closed orbit at 90^{o} phase advance: ~1mm offset, no amplitude growth.
- **Interlock Strategy:**
  - Hardwired Interlocks: Inputs into BIS
    - Interlock on vacuum Valves
  - Software interlocks: Inputs into SIS
    - Table Position (In/Out of beam positions)
    - Power load on tetrodes
- **LLRF Mitigations and Interlocks**
  - LLRF FB loop: Timescale of O(10us) => Time for quench mitigation actions
  - SPS test to validate cavity mitigation schemes for failures/quenches
  - TX fault: machine operation can continue if cavity detuned above RF freq.

Schedule Issues

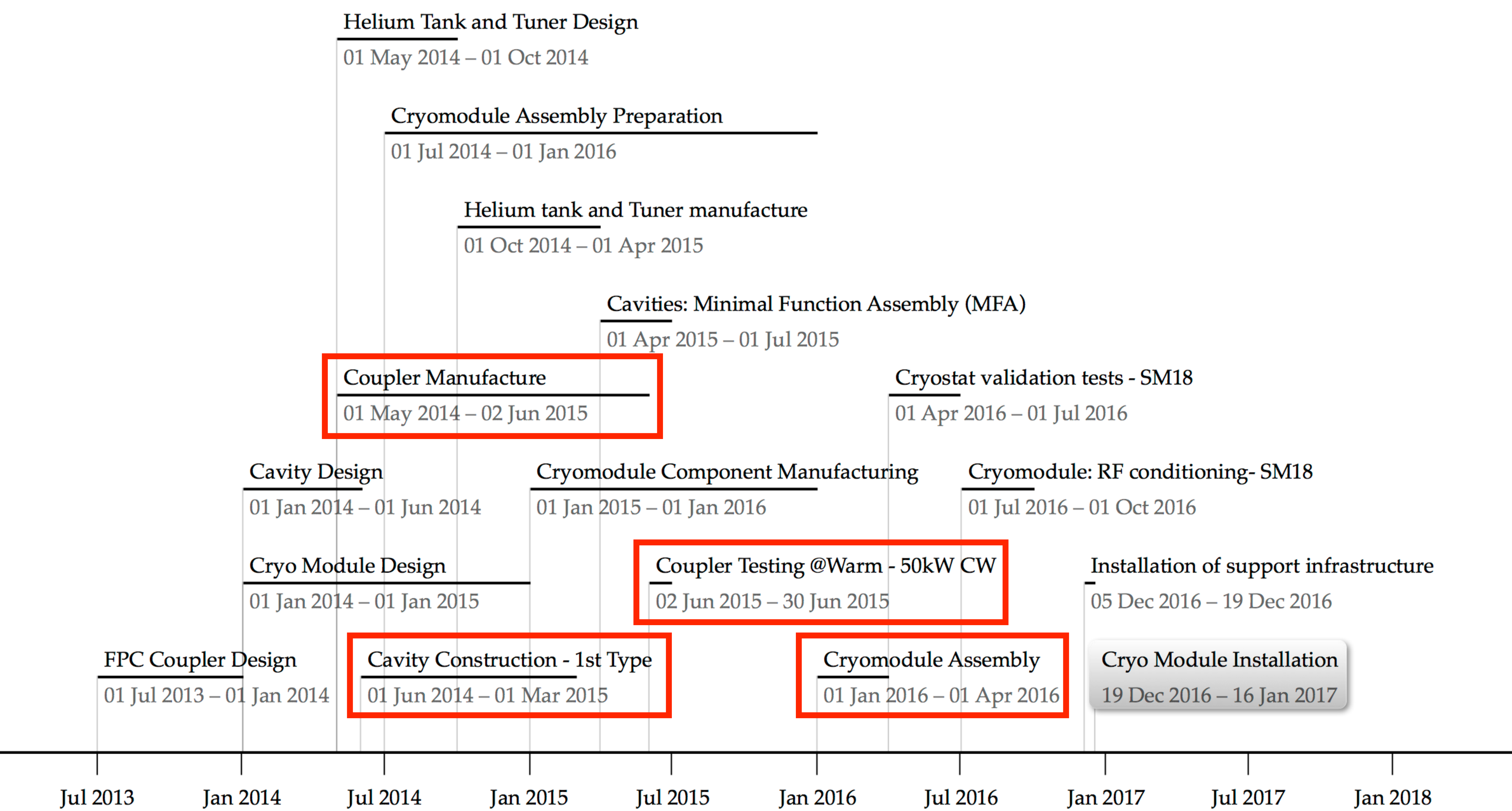
- **SPS Crab Validation Run: 2017 and 2018**
- **SPS Crab schedule: Available Online**
  - Please see http://kiwi.web.cern.ch/kiwi/Crab_SPS/index.html



Schedule: Cavity + CryoModule TimeLine

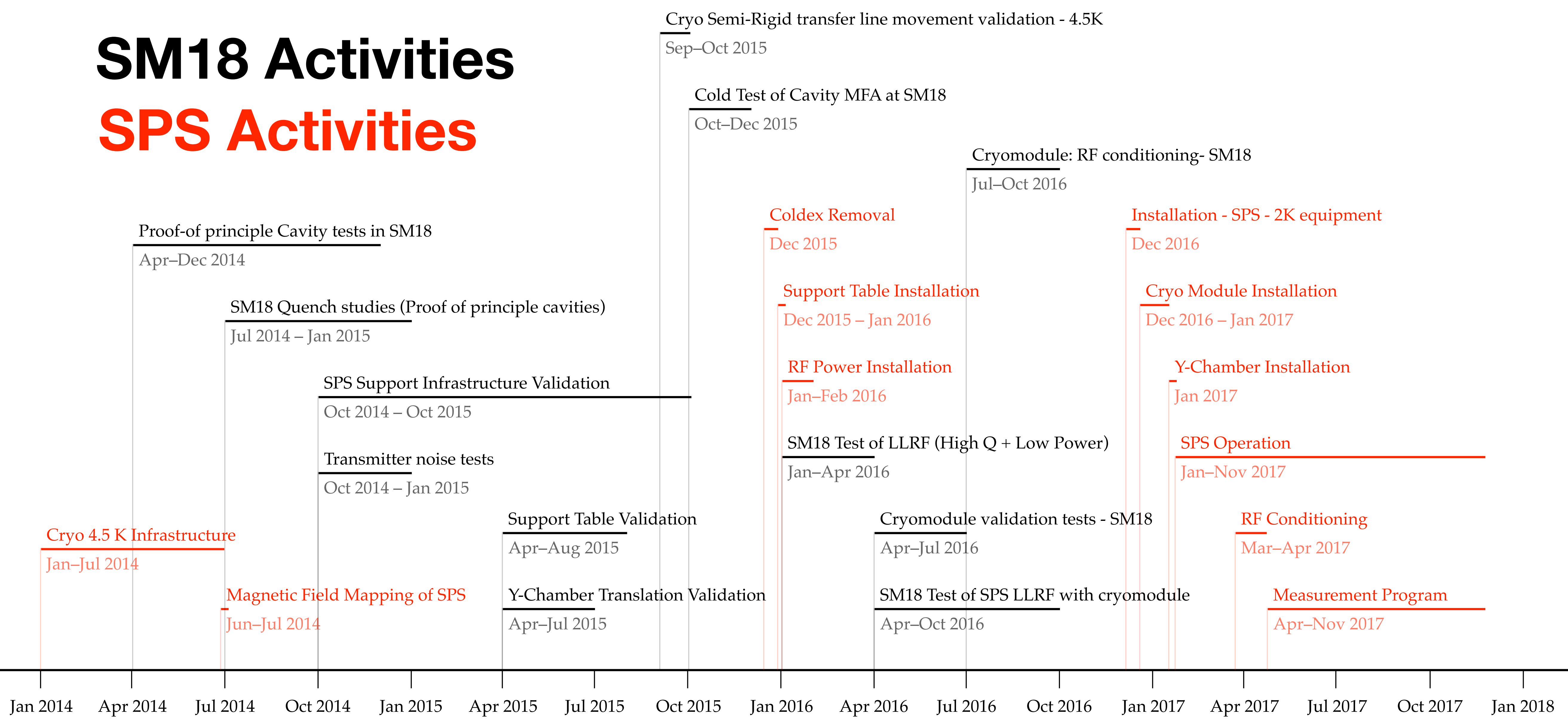


Schedule: Cavity + CryoModule TimeLine



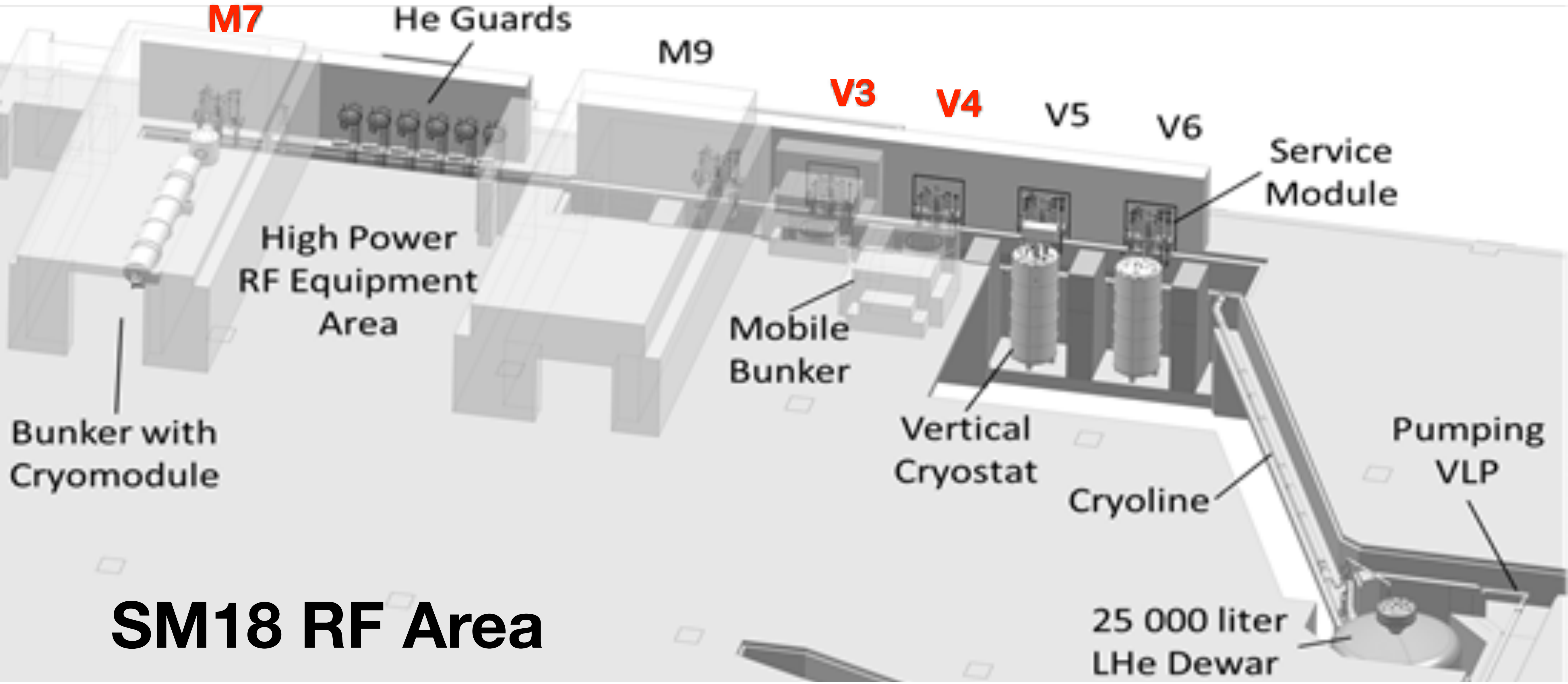
Schedule: SM18 + SPS

- **SM18:**
  - CavityTesting, Cryo Module assembly and testing, Infrastructure validation
- **SPS**
  - Preparation of Infrastructure, Validation of Services, Operations Interface



SM18 RF Test facility

- **M9 Bunker: Horizontal Tests**
  - LHC cryomodule
  - HIE-ISOLDE cryomodule
  - And later: FCC 400 MHz project
- **M7 Bunker: Horizontal Tests**
  - CRAB cryomodule
  - SPL half cryomodule
  - And later: 800 MHz project



Summary Comments

- **Integration**
  - Integration of Crab infrastructure ongoing. Alcove space fully used
  - 2015 Xmas stop must be used to remove COLDEX

- **SPS Beam Time**
  - Crab Cavity Validation needs dedicated SPS MD time
  - Initial estimates of MD time request: 5 x 24hrs per cavity
  - MD program must include:
    - Crab functionality, cavity invisibility, LLRF op, failure mitigation
  - LLRF conceptual design now advancing

- **Planning and schedule**
  - 2015 Xmas stop: installation of crab infrastructure in SPS
  - 1st Crab Cryomodule installed 2016 Xmas stop
  - 2 Cryomodule Installation periods (Xmas stops): can’t hot swap modules
  - Use 2016 for cryomodule “sector test” in SM18