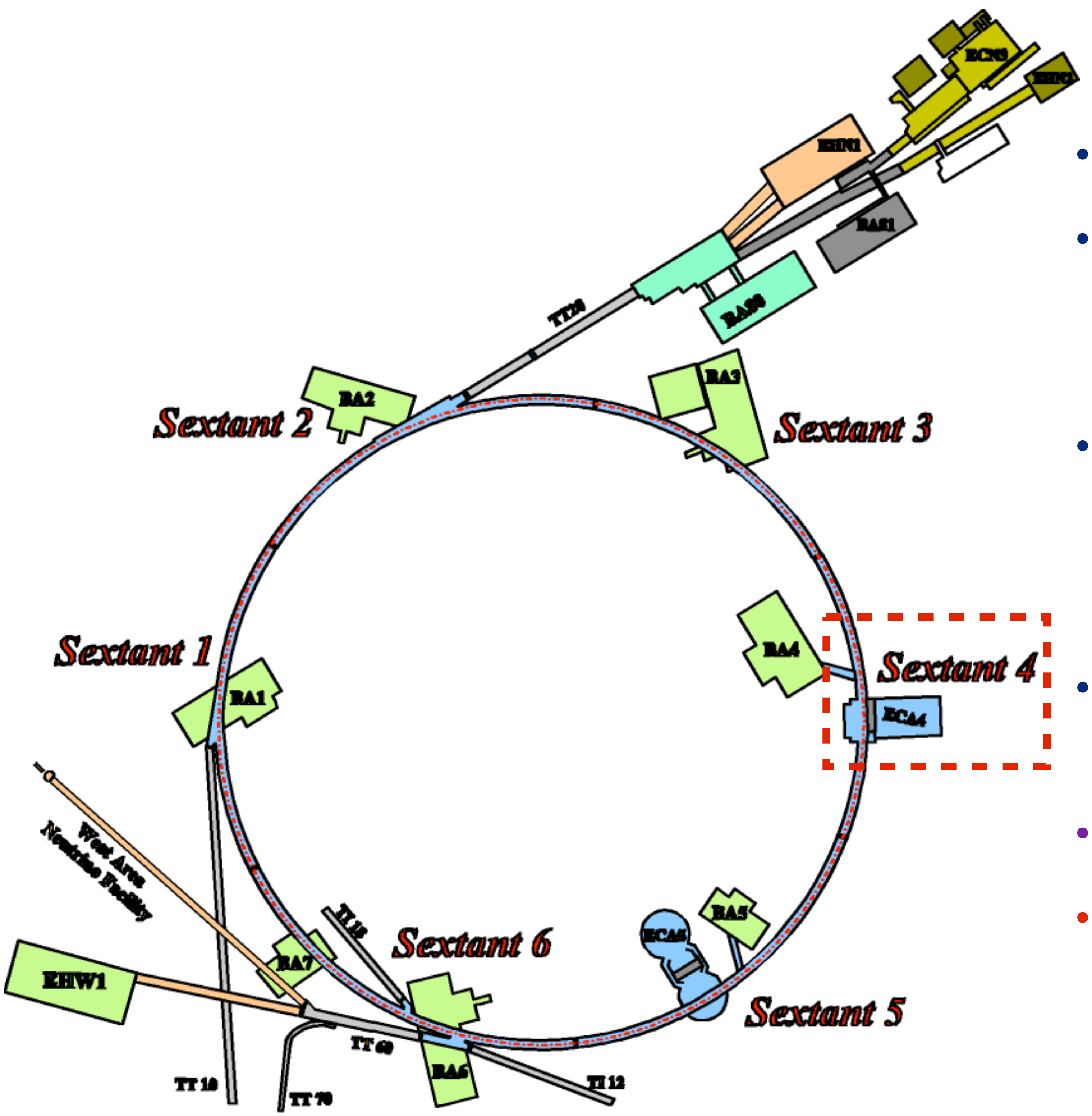
Constraints on the 2016 Crab Cavities SPS Run

Alick Macpherson
LHC Operations Group

Crab Cavities Engineering Meeting
FermiLab
13/12/2012

Presentation based on work from Crab Cavities Technical Coordination Working Group
https://indico.cern.ch/categoryDisplay.py?categId=4482

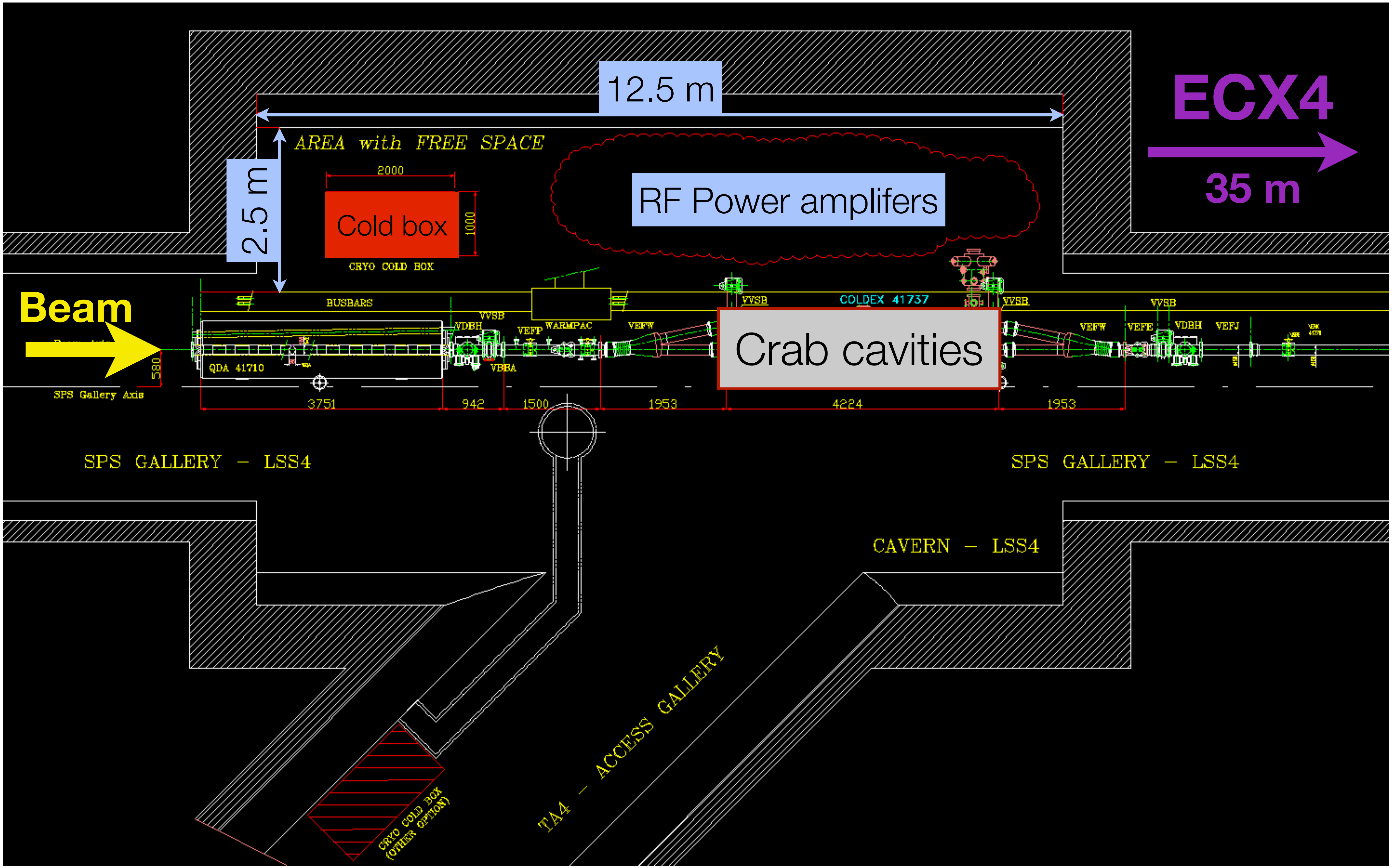
SPS Crab Cavity Tests: Location



Location: SPS Pt 4

- **Cryogenics Infrastructure**
- **Mechanical Beam Bypass** for cavities. Allows Cavities to be taken out of beam line.
- **Experimental cavern (ECX4) close**
  - Viable LLRF location
  - Accessible during operation
- **Beam line space available** for crab Cavities + Instrumentation
- **Crab Cavity space not free till 2015**
- **Limited access to SPS zone** after SPS long shutdown

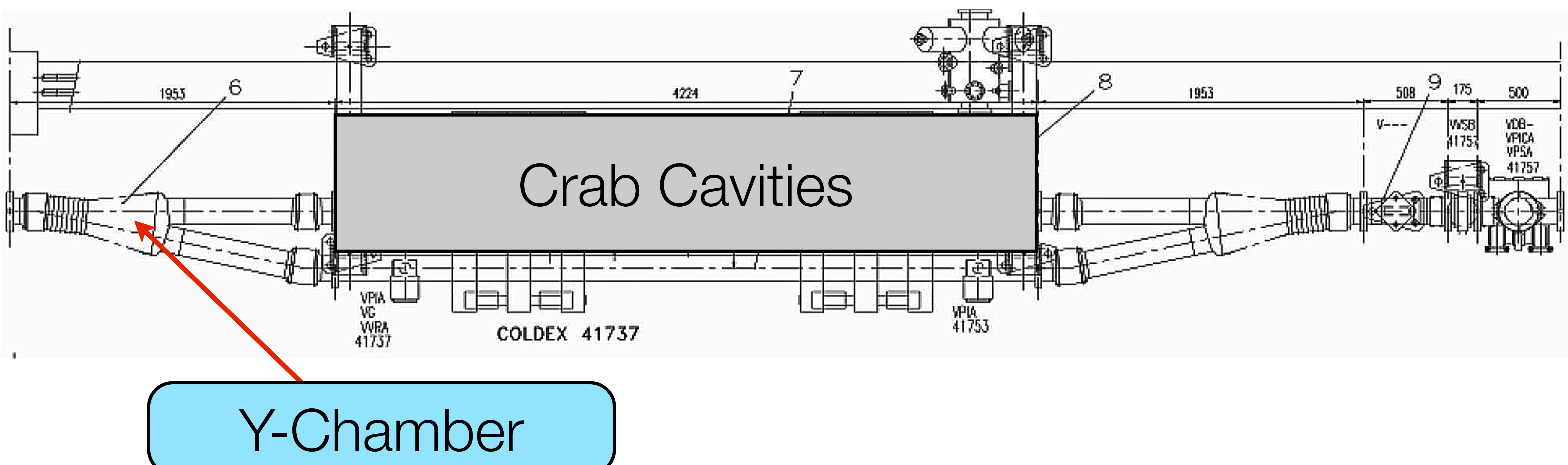
SPS Point 4 - General Location



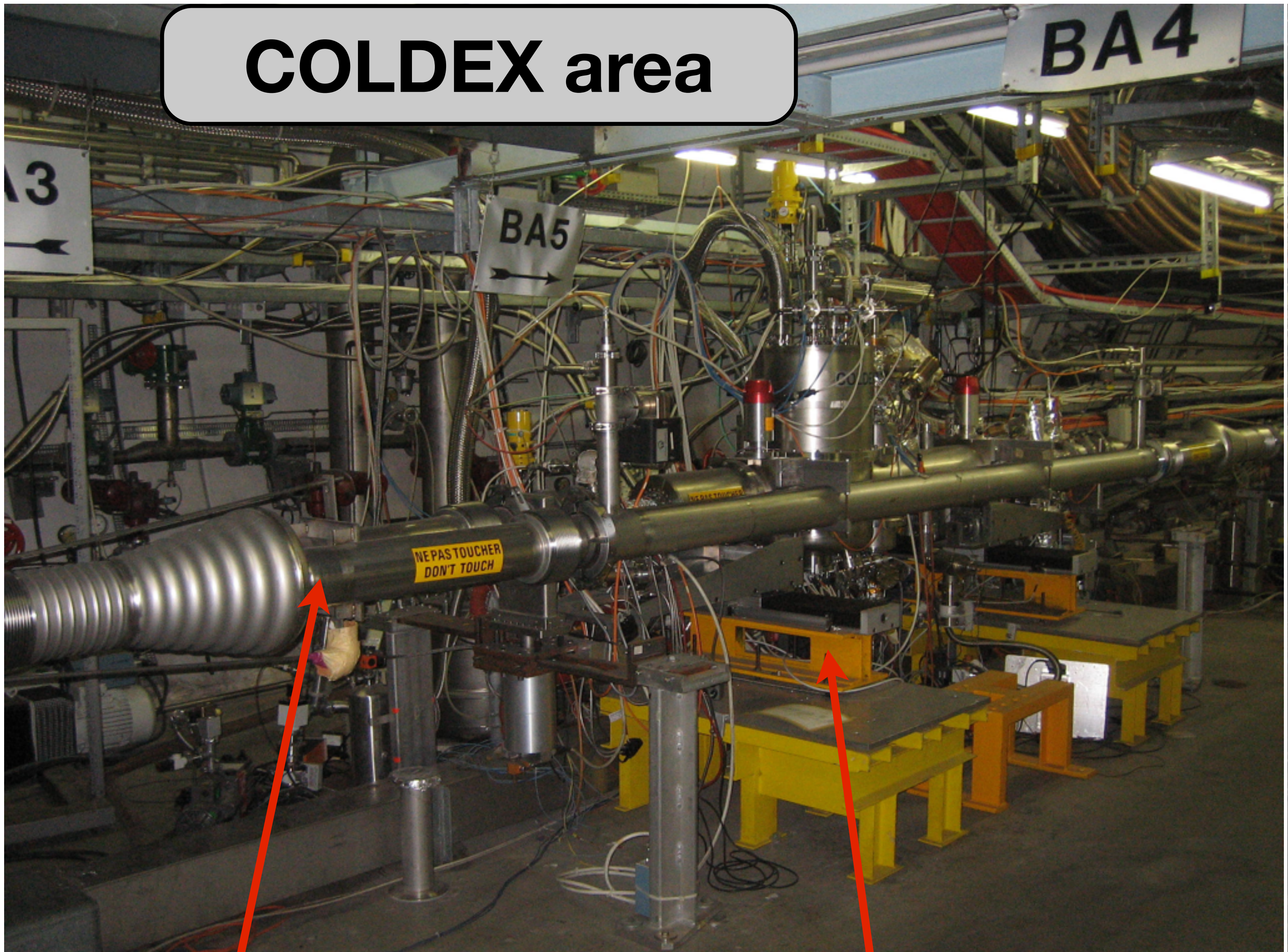
Crab Cavity Location - SPS Pt 4 straight section

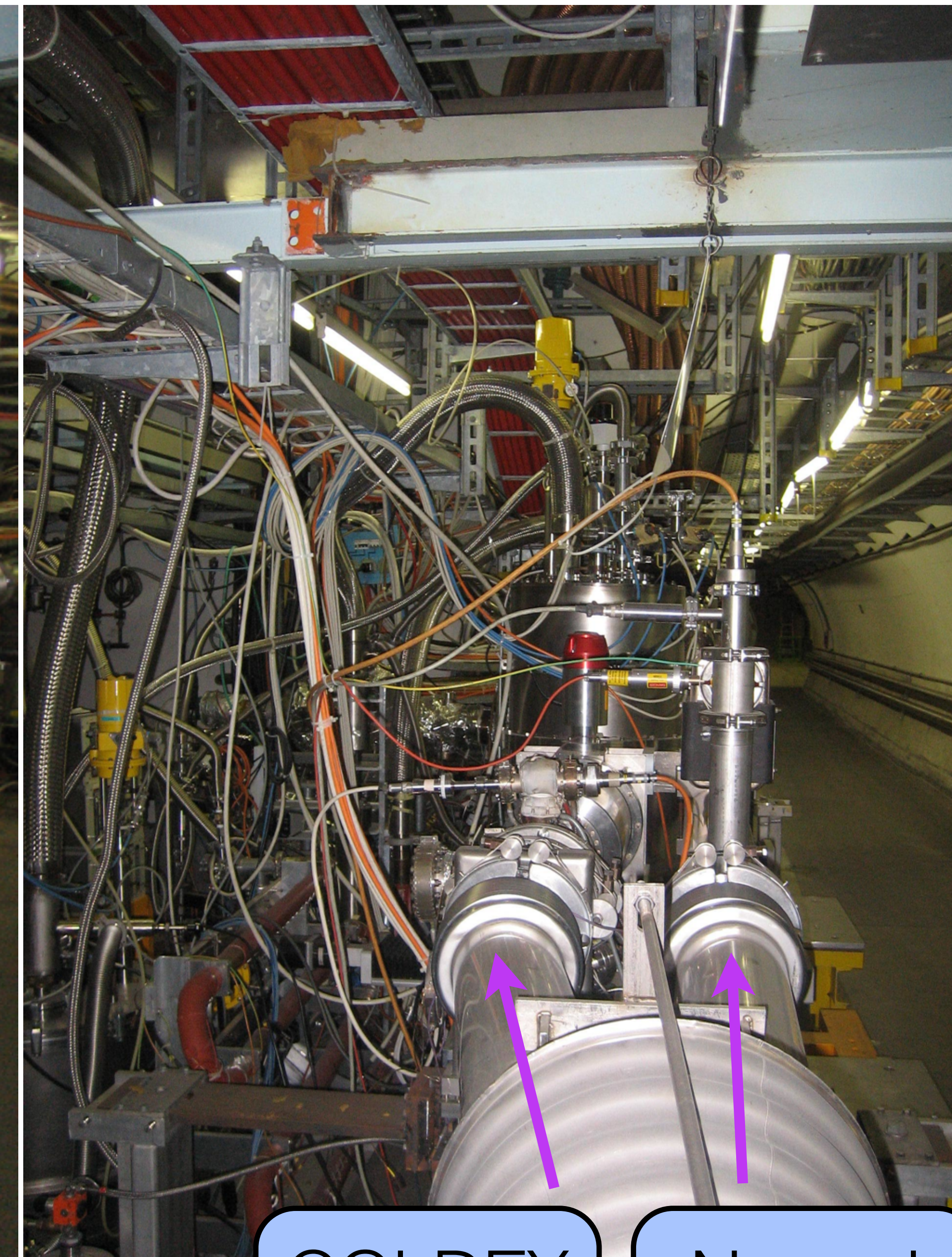
- Crab cavity location -> Use the existing “COLDEX” Location
  - Space for power and cryo infrastructure: as close as possible to cavities
  - **Mechanical Y- chamber**
    - Allows cavities to be pushed into beam line for beam tests
    - => Out of beam line during normal SPS operation

SPS Operation: Assume bypass line not part of cryo module

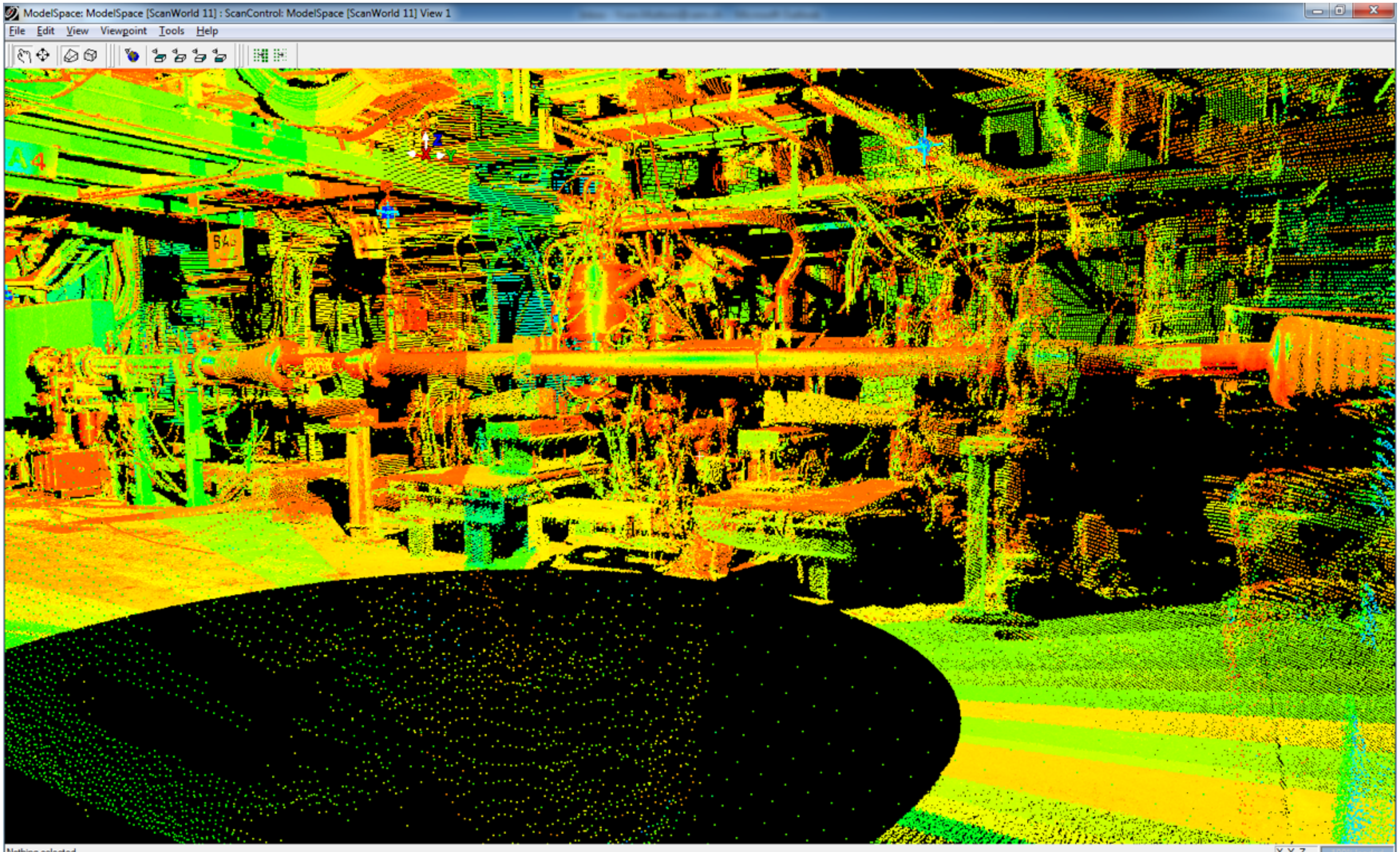


SPS Pt 4 Location: As it is now ...



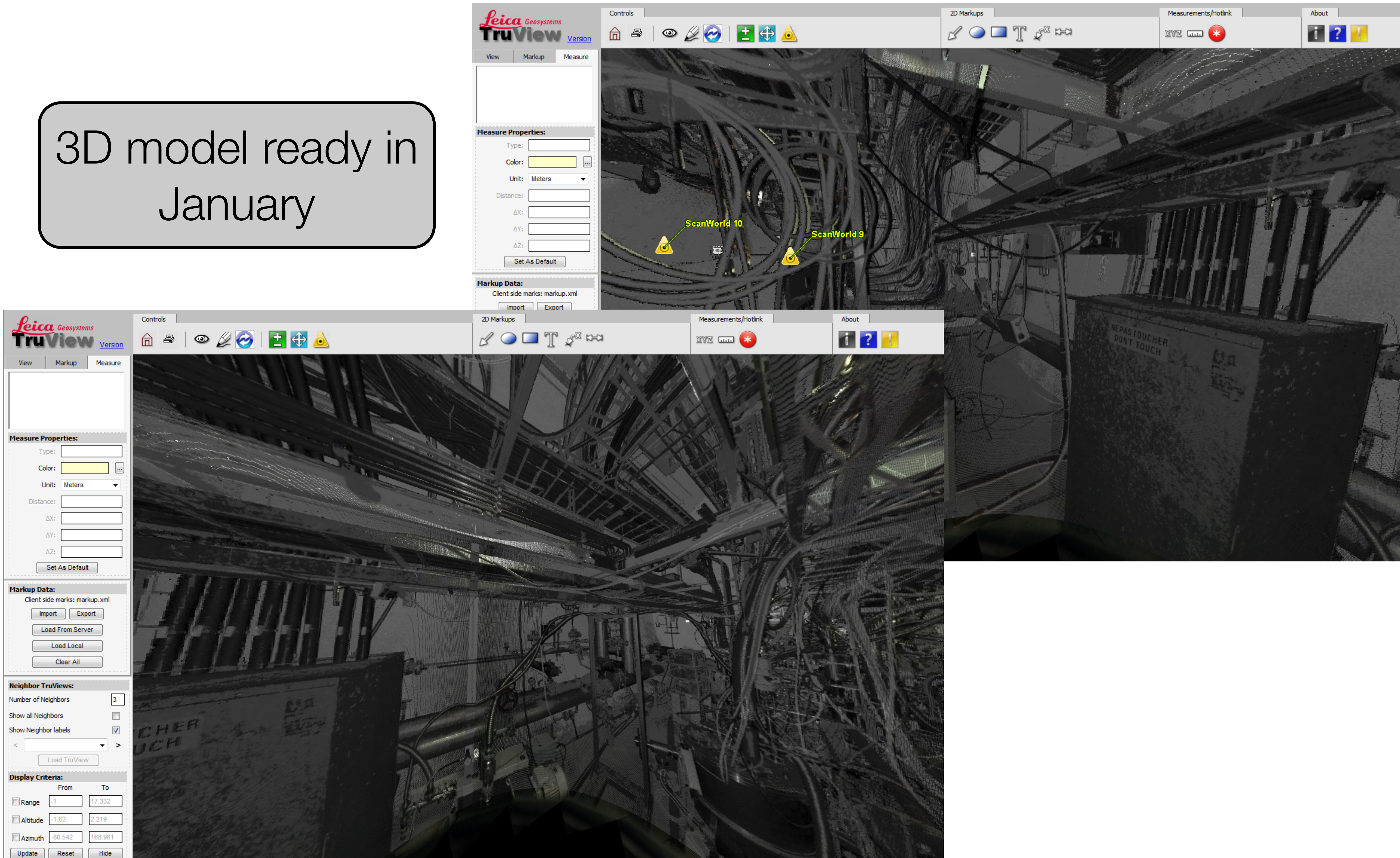


Integration: Full 3D Scan of SPS Area



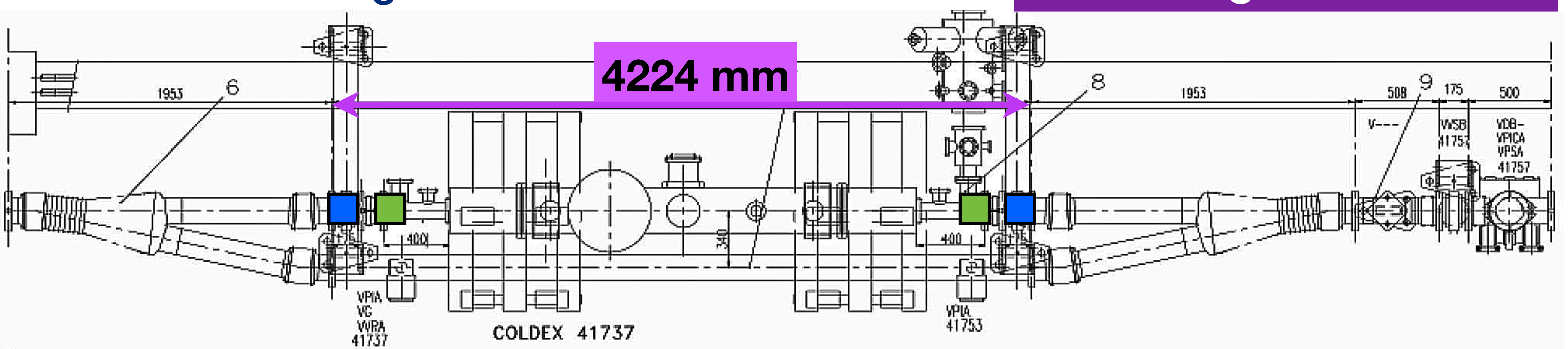
Integration: Full 3D Model of Space & Services

3D model ready in January



Available Space - Longitudinal

- **Assume use existing Y-Chamber**
  - z-length (Coldex - to outside edge of Vacuum valve) = 4224 mm
  - z-length (Coldex - to inside edge of Vacuum valve) = **3874 mm**
- **Assume double vacuum valve installation:** vacuum integrity at installation
  - z-length: 2x (175 +100) = 550 mm
- **Assume BPMs at each end of cryo module:** compact integrated compact
  - z-length: 2x (100) = 200 mm
- **Available z- length** = 3875 -550 -200 = 3125 mm **=> z-length = 3100 mm**

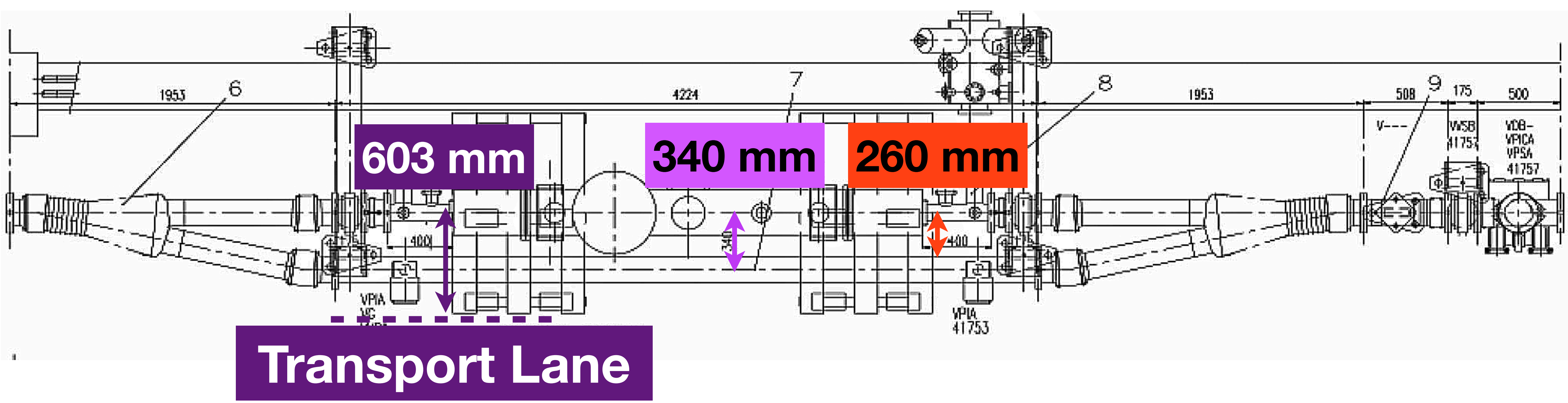


- **Not included:** additional vacuum pump in cavity section.
- **Additional Beam instrumentation:** outside Y-chamber section

Available space - Transverse

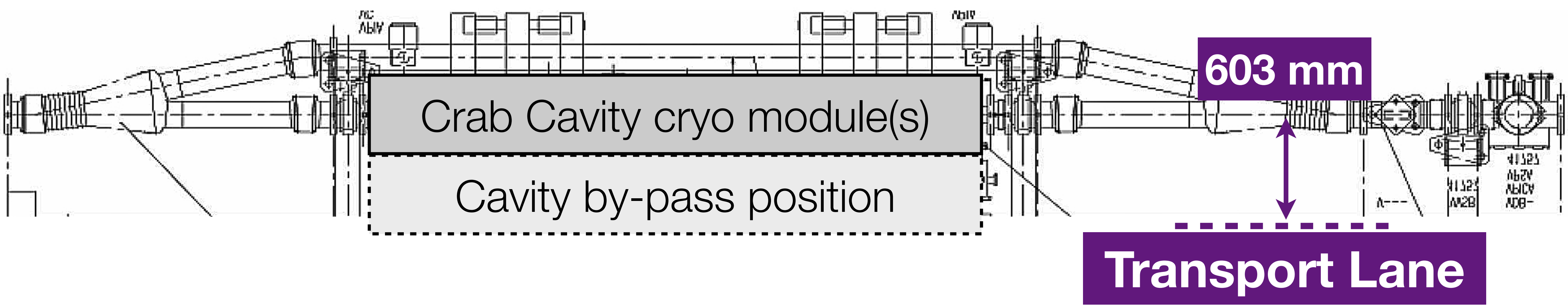
- **Assume use existing Y-Chamber**
  - Horizontal spacing between beam axes (Coldex-bypass) = 340 mm
  - Beam pipe diameter = **159 mm**
- **Distance from beam axis to outer wall of bypass beam pipe: 260 mm**
- **Definition of Envelope:**
  - Stay within equipment zone: ie not infringe on tunnel transport lane
    - **Transport lane: 603 mm**

Alcove side: no real constraint at beam line height (busbar at ground level)



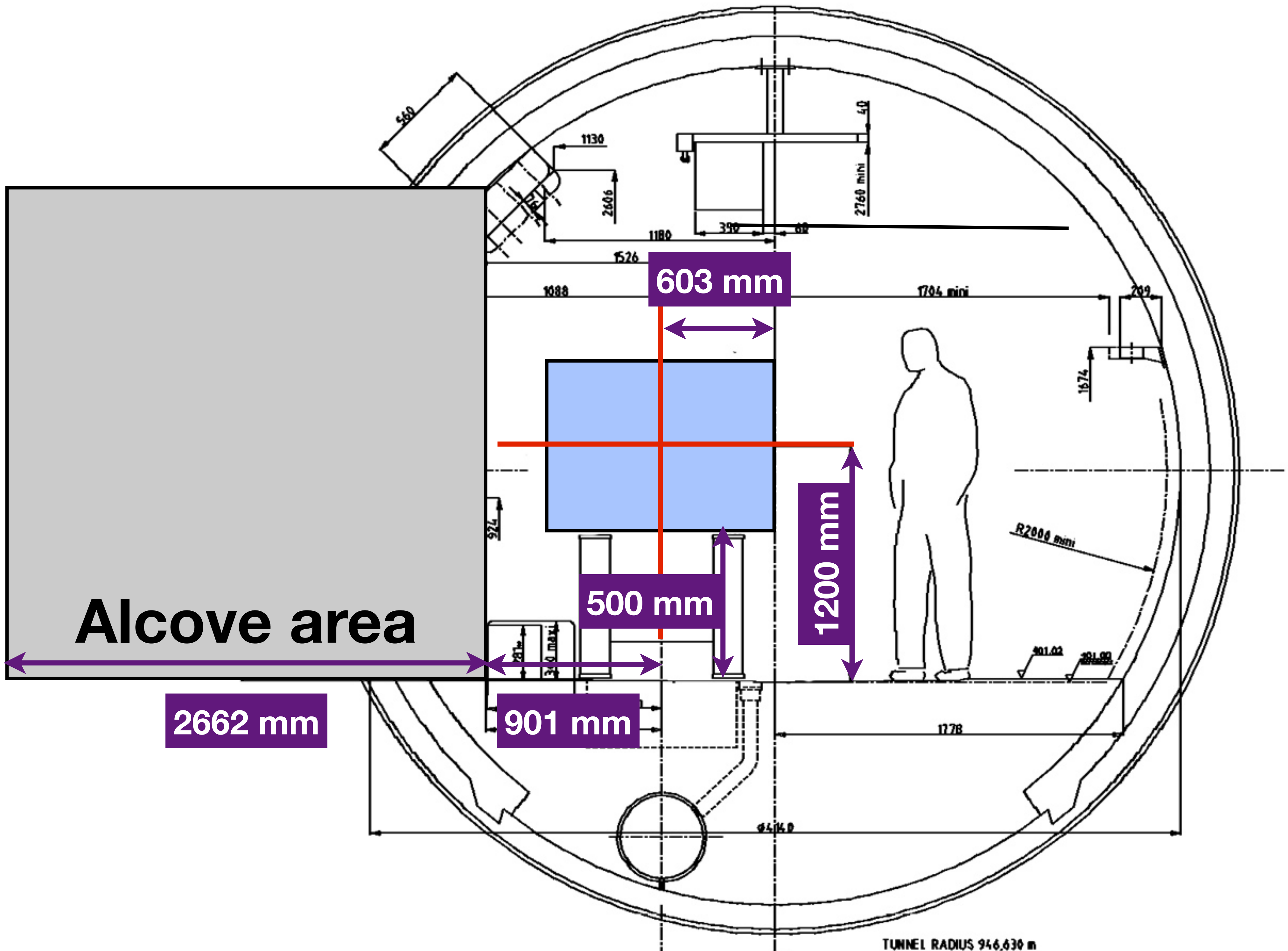
Possibility of swapping cryo modules

- **Crab cavity section on "inside" position**
  - Permits easy access to cavities during SPS run
  - **Possibility of cryo module exchange during 2016 run** **Can it be done?**
    - Exchange of cryo module section in a technical stop period (5 days)
  - Power coupler on vertical orientation
    - compatible with power and cryo feed throughs in vertical orientation
  - **No space for HOM couplers etc on side of cryo module**
    - would violate transport zone when in bypass position

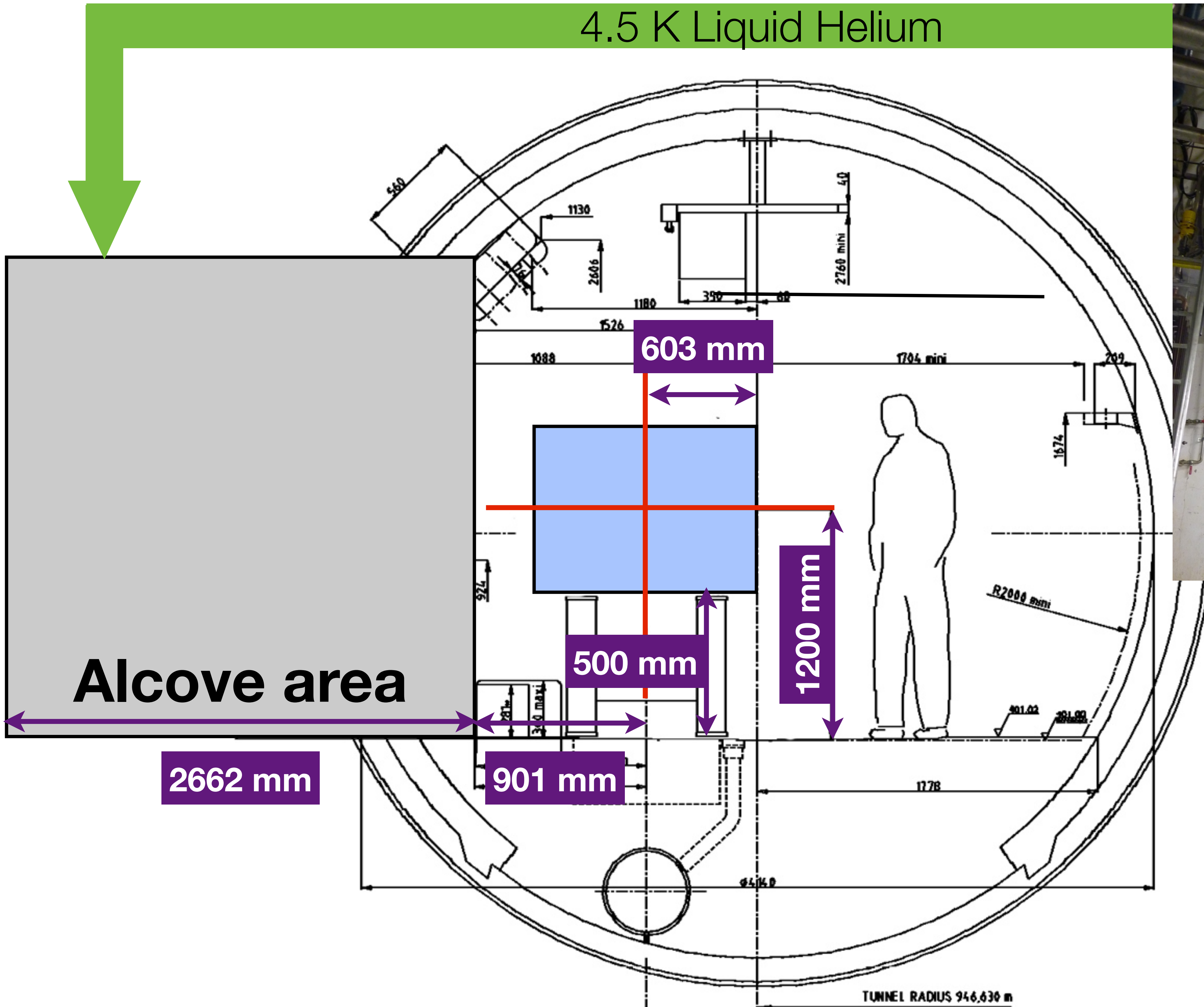


Question: Can all cryo module connections be in the vertical plane?

Available space - end on view

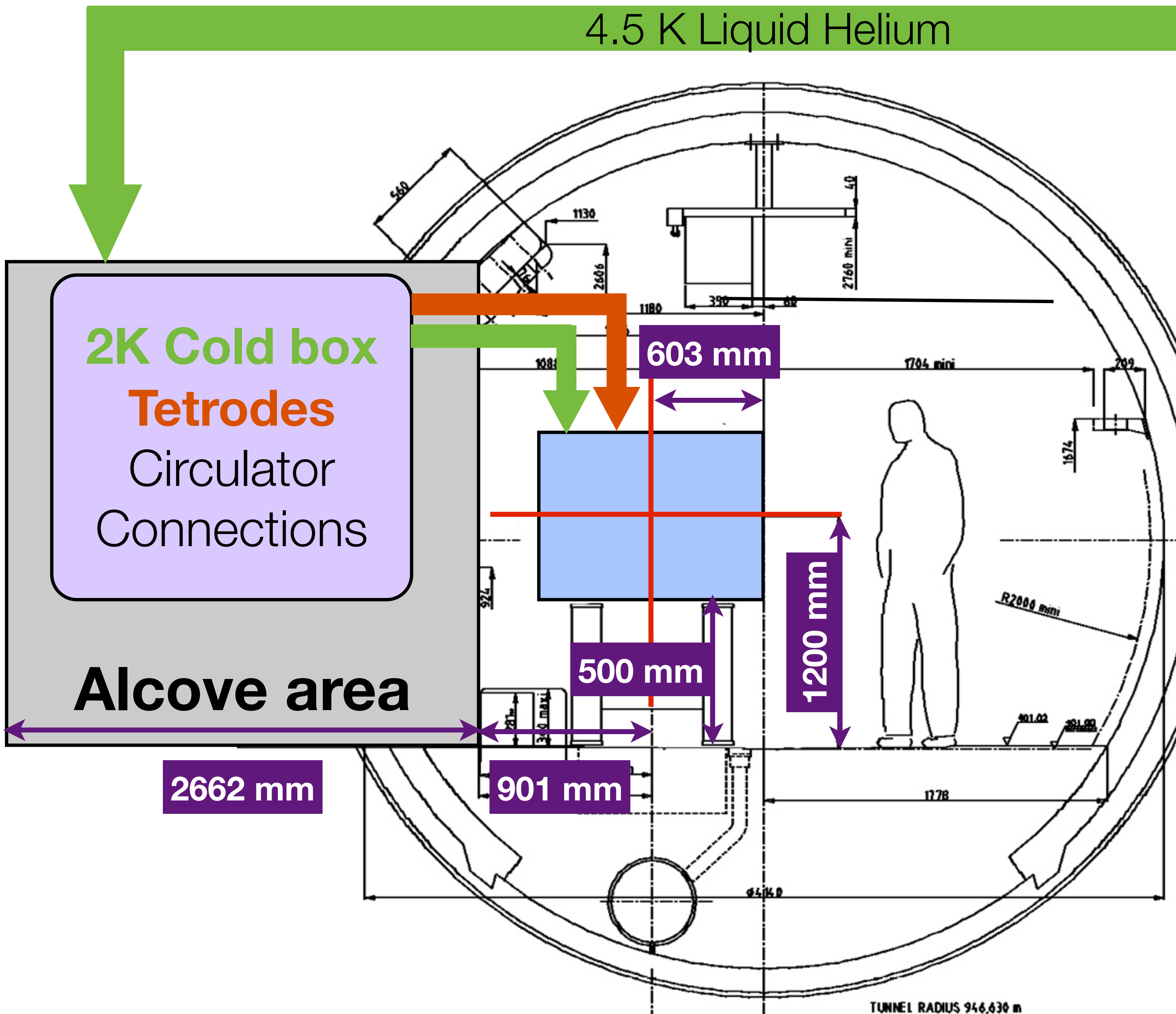


Available space - end on view



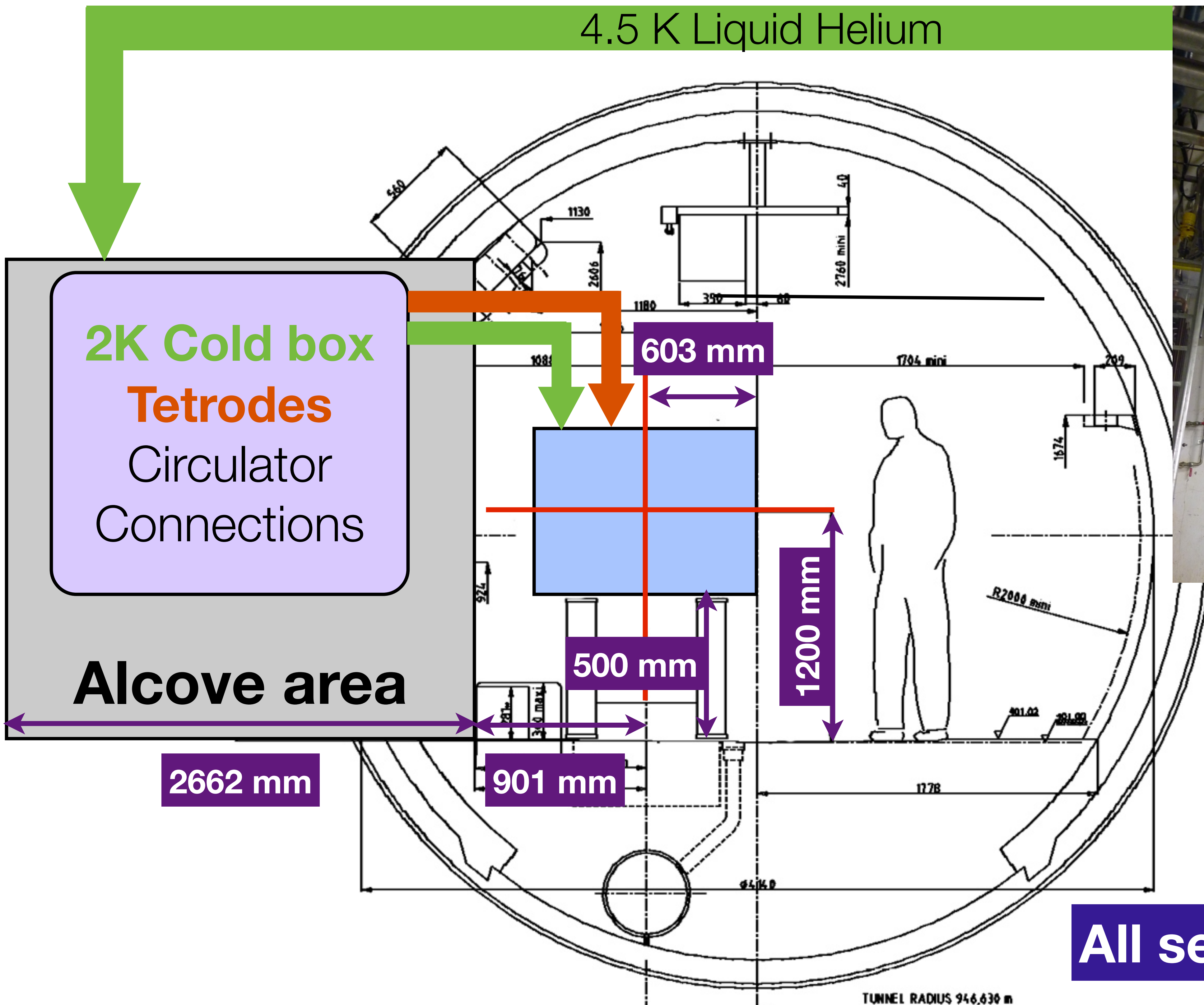
4.5 K Helium Dewar

Available space - end on view



4.5 K Helium
Dewar

Available space - end on view



All services from top?

Space constraints - Summary so far ...

- **Cryo module envelope (W x H x L) = 520 x 1200 x 3100 mm**
  - Space available above cryo module for coupler + cryo connections
- **Envelope implies at most 2 Cavities installed at any one time.**
  - **Minimum of 2 cavities to be installed for LLRF + Machine protection tests**
- **Spacing between cavity and by-pass axes: 340 mm. Use existing Y-Chamber**
- **Cryo module installed on "inside" position**
  - Cryo module exchangeable within an SPS Technical Stop (5 days)?
  - Down selection of cavities not necessary prior to SPS tests
- **Other Options**
  - **Different Inter beam pipe spacing => need to build new Y-Chamber**
    - LHC pt 4 spacing = 420 mm **Maybe more space. Integration Issues**
    - LHC pt 1&5 spacing = 194 mm **Integration Issues.** z-length ~4500 mm

Cryo Module Issues ...

- **2016 SPS Run:** **2 cavities to be installed in SPS at any one time**
- **Is cryo module swappable during an SPS Technical Stop (5 days)?**

  If NO => Only 1 module in 2016 SPS Run => cavity down select by Q1 2015

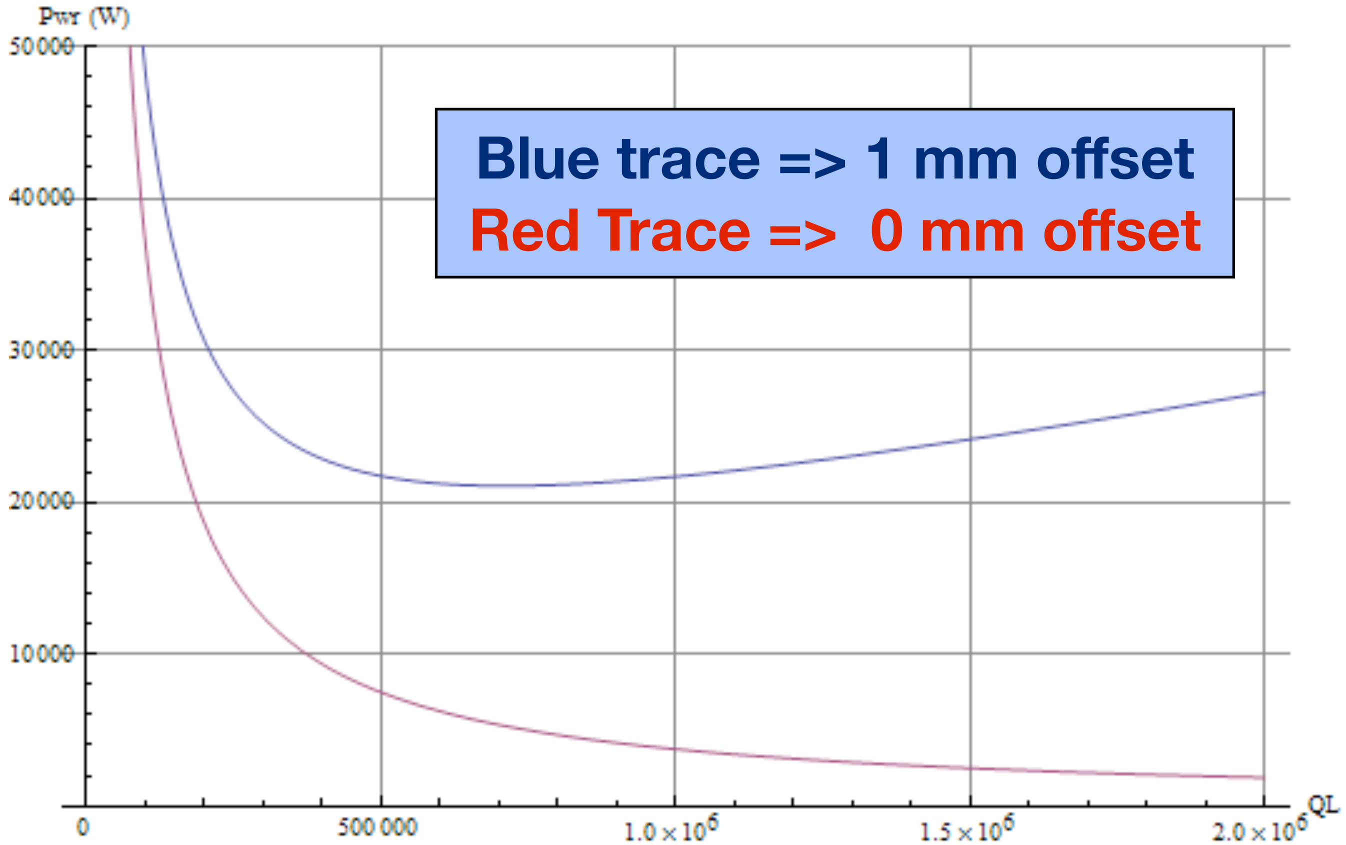
- **How many cavities per module?** **Prefer 2 cavities per module**
  - Machine protection worst case scenarios (quenches) and mitigations
  - 2 cav/mod => reduced heat load => Cryo capacity @ 2K
- **Quench Detection:** **Active system required**
  - Can't rely solely on cryo pressure/temperature monitoring at @ 2K due to superfluid -> liquid He transition.
- **Quench Production:** Needed for Machine protection tests
  - Need to understand mechanism and timescales plus its integration
- **Cavity environment must model LHC scenario**
  - Dummy beam pipe at 194 mm spacing for microphonics. **Beam screens?**

Cavity Alignment constraints ...

- Based on modeling Crab Cavities with multipoles up to octupole order
- **Transverse misalignment tolerances [TMT]**
  - TMT defined as a 1 sigma reduction of dynamic aperture.
  - **TMT = 0.7mm for each cavity**
    - Applies to both planes: different crossing schemes for IR1 & IR5
- **Cavity tilt tolerance.**
  - Based on luminosity loss, closed orbit deformation and tune modulation
  - **Tilt Tolerance: ~ 1mrad.**
- **Questions**:
  - For these LHC based tolerances do we need active alignment?
  - SPS test: how to ensure alignment with mechanical bypass table?
    - **Need to define strategy, and decide what is to be implemented**

Alignment constraint implications ...

- **Power requirement vs. Q_{EXT}**
  - Assume: 3 MV, R/Q=300 ohm, 1.2 ns long bunches, 1.1A DC current,
  - Power is "flat" at ~Q_{EXT} in 25 kW range for Q_{EXT} in [4×10^6, 1.5×10^6]

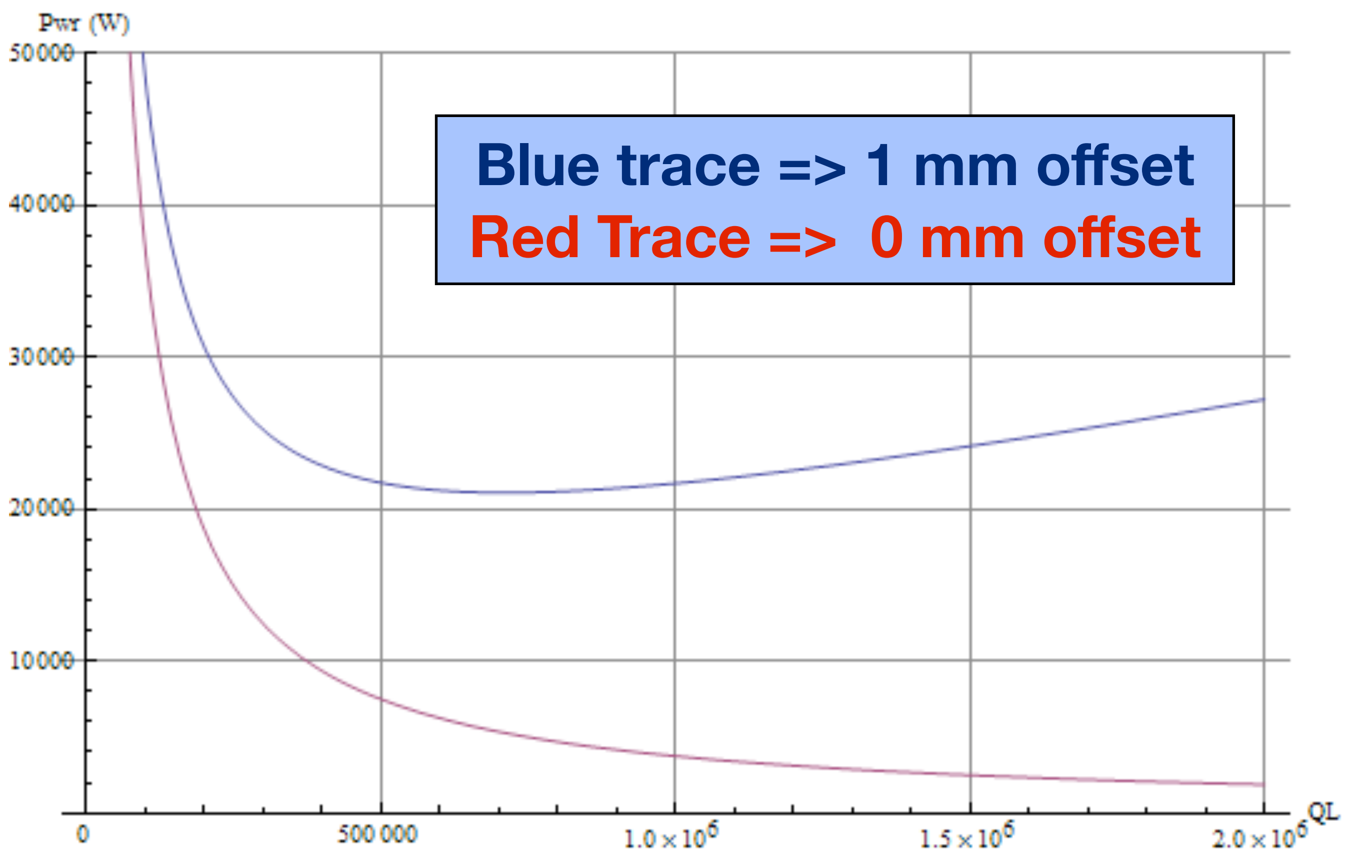


Alignment constraint

1 mm alignment tolerance appears OK for Q_{EXT} power converter, and MPS considerations

Alignment constraint implications ...

- **Power requirement vs. Q_{EXT}**
  - Assume: 3 MV, R/Q=300 ohm, 1.2 ns long bunches, 1.1A DC current,
  - Power is "flat" at ~Q_{EXT} in 25 kW range for Q_{EXT} in [$4x10^6$, 1.5 $x10^6$]



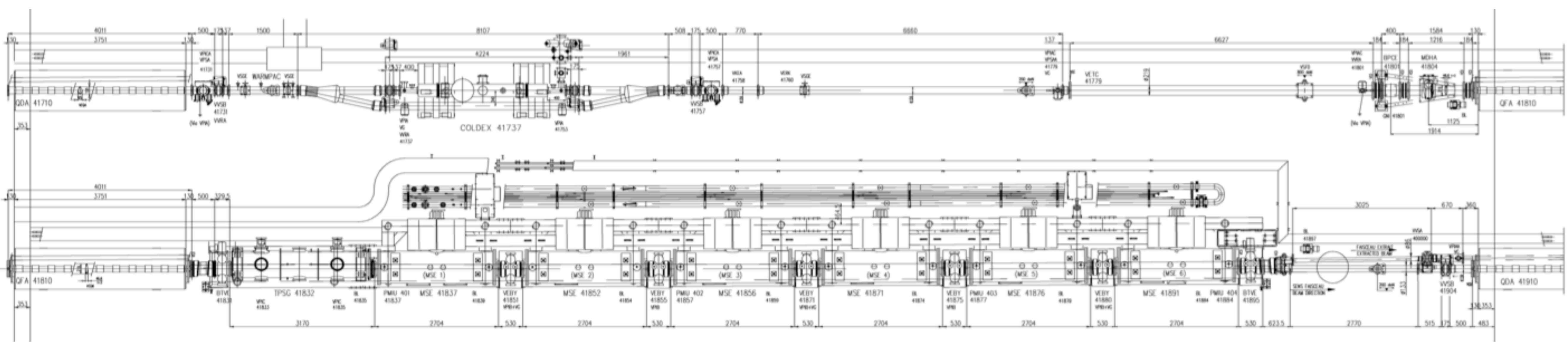
Alignment constraint

1 mm alignment tolerance appears OK for Q_{EXT} power converter, and MPS considerations

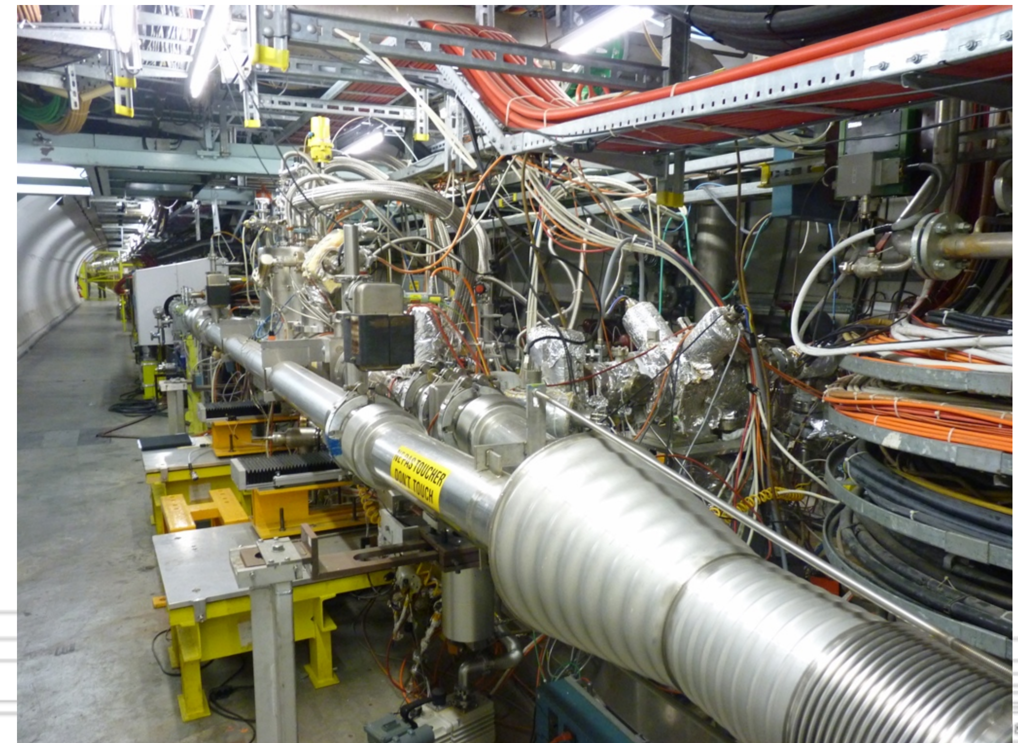
- For $Q_{EXT} = 10^6$ => τ_{power} ~400μs **=> $\tau_{Voltage}$ ~800μs & $\tau_{Beam\ dump}$ ~300μs**

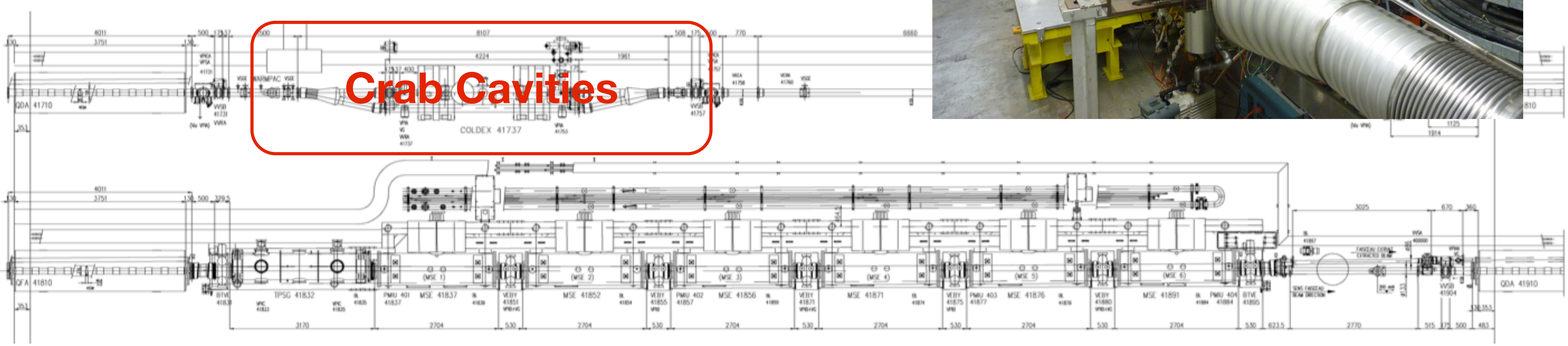
Care needed with Q_{EXT} due to LHC MPS time scale

SPS tests: Infrastructure sketch



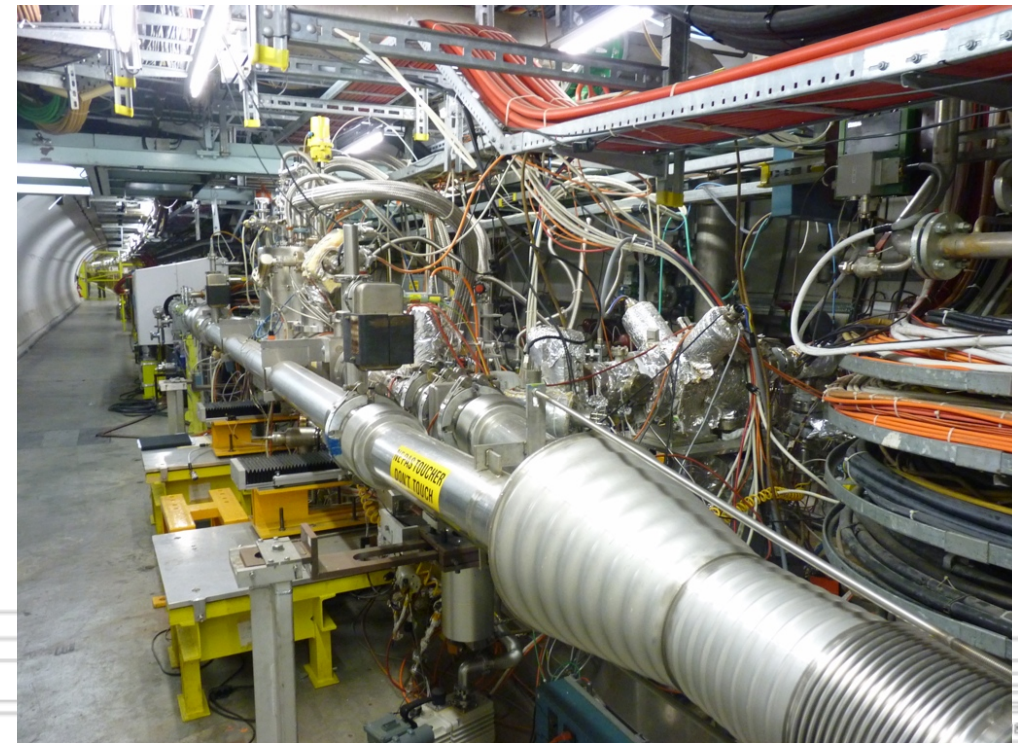
SPS tests: Infrastructure sketch

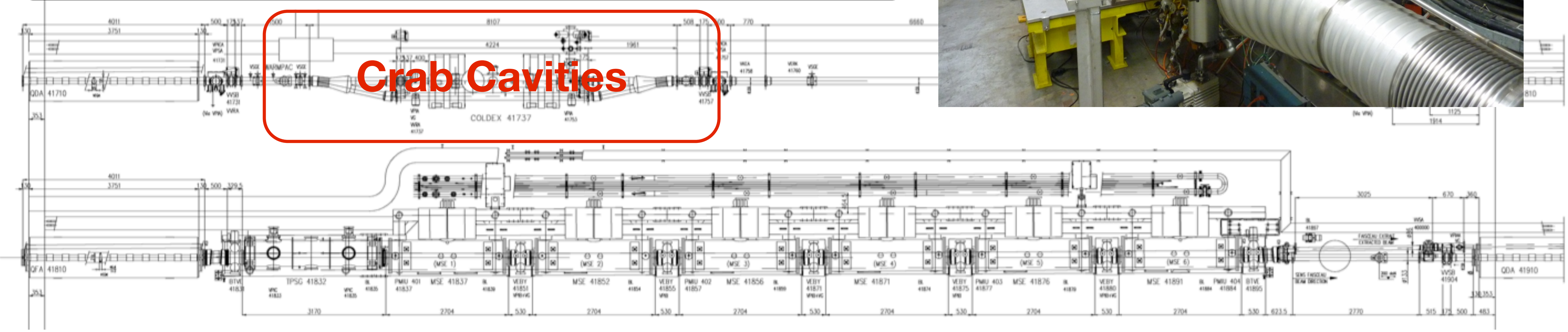




SPS tests: Infrastructure sketch

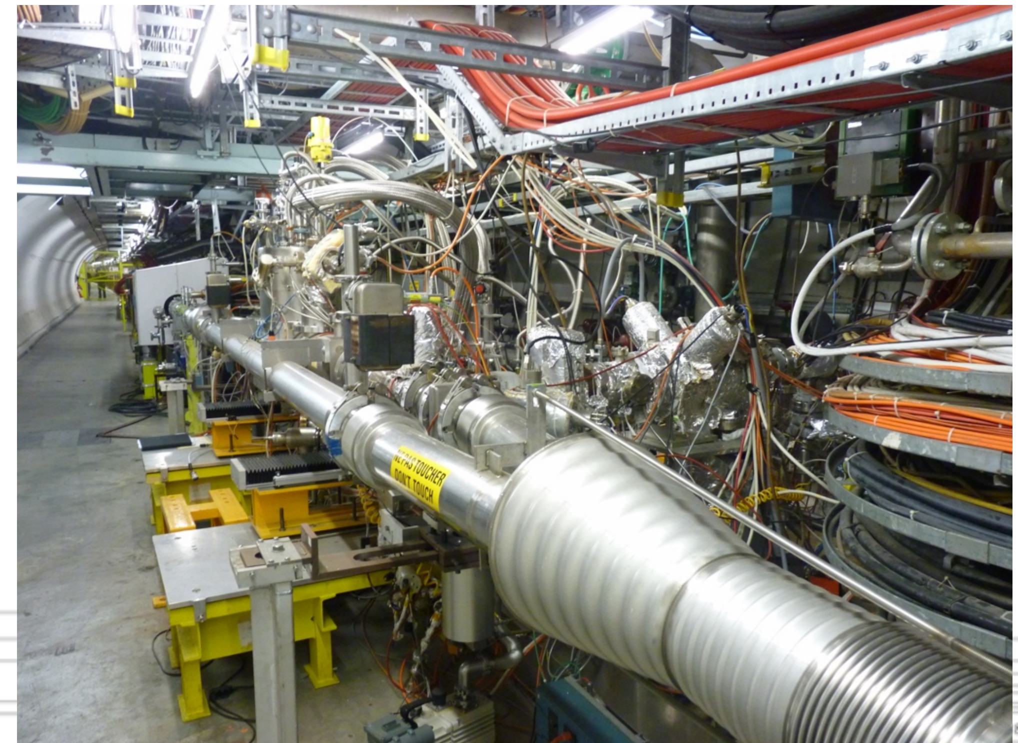
- Tetrodes amplifiers next to cavities
- LLRF: to be installed in ECX4
- **ECX4 ~35m away from CC Location**
  => loop delay: transit time **~250 ns**
- Driver amplifiers close to LLRF (ECX4)
- HV PS (+ controls): ECX4 or BA4 (Surface)

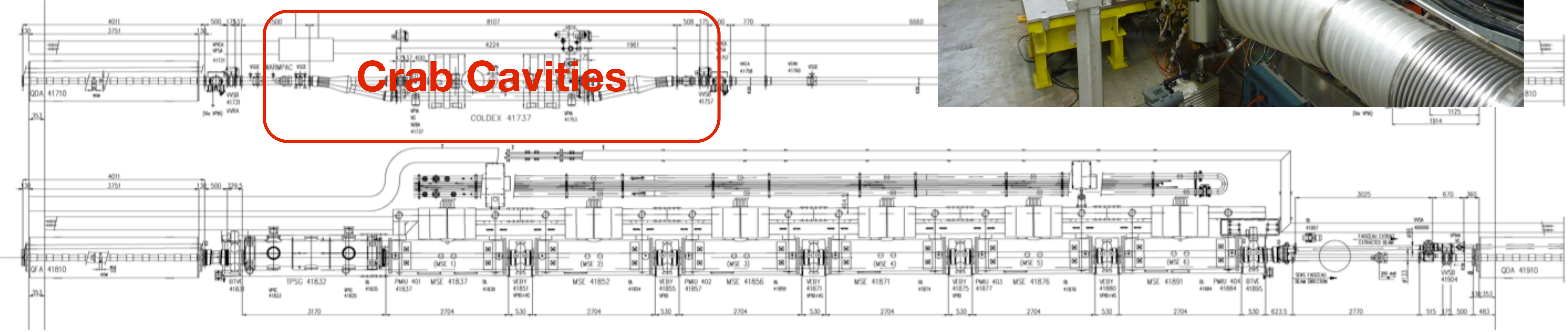




SPS tests: Infrastructure sketch

- Tetrodes amplifiers next to cavities
- LLRF: to be installed in ECX4
- **ECX4 ~35m away from CC Location**
  => loop delay: transit time **~250 ns**
- Driver amplifiers close to LLRF (ECX4)
- HV PS (+ controls): ECX4 or BA4 (Surface)



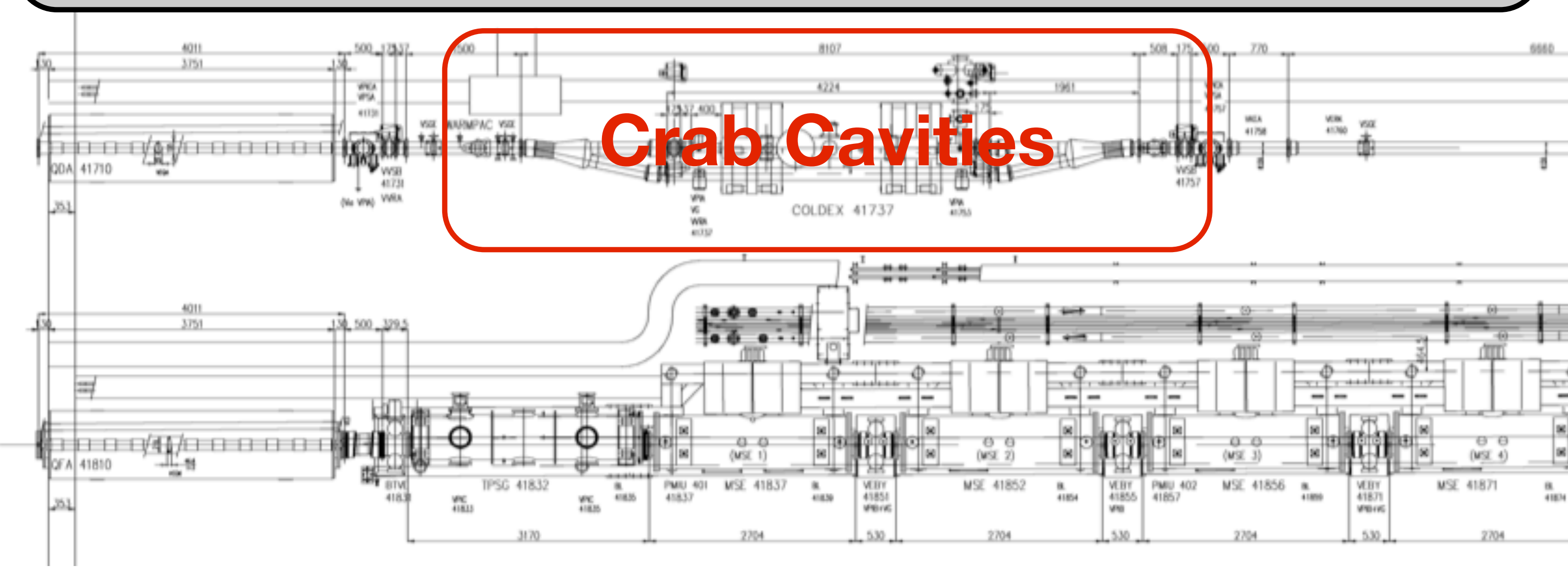


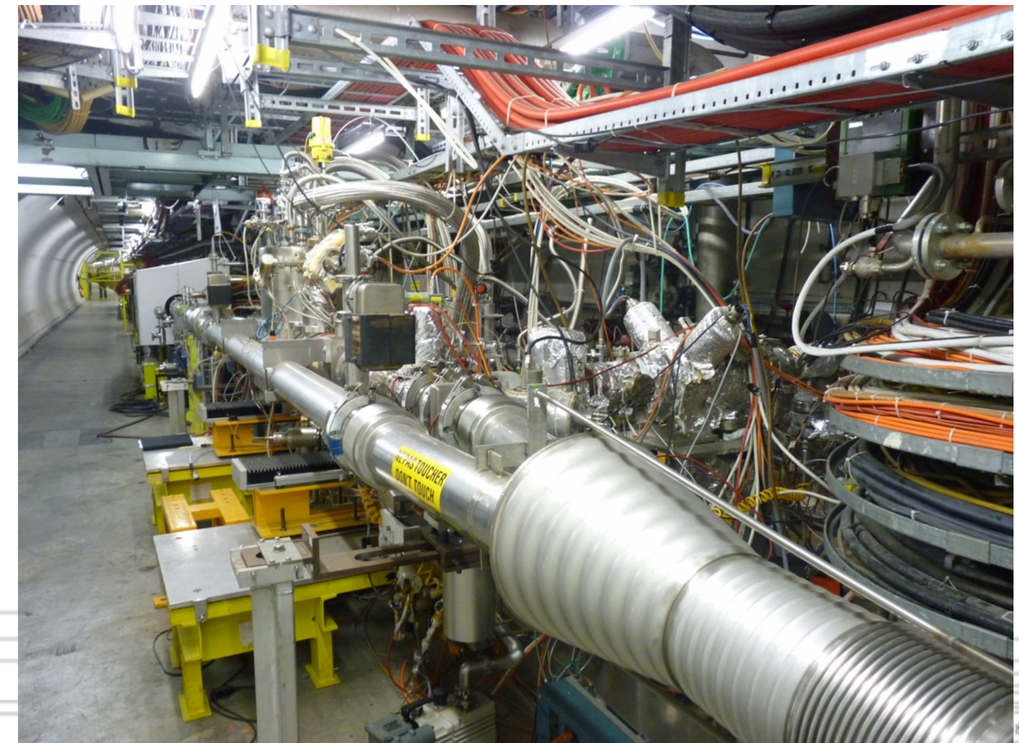
ECX4

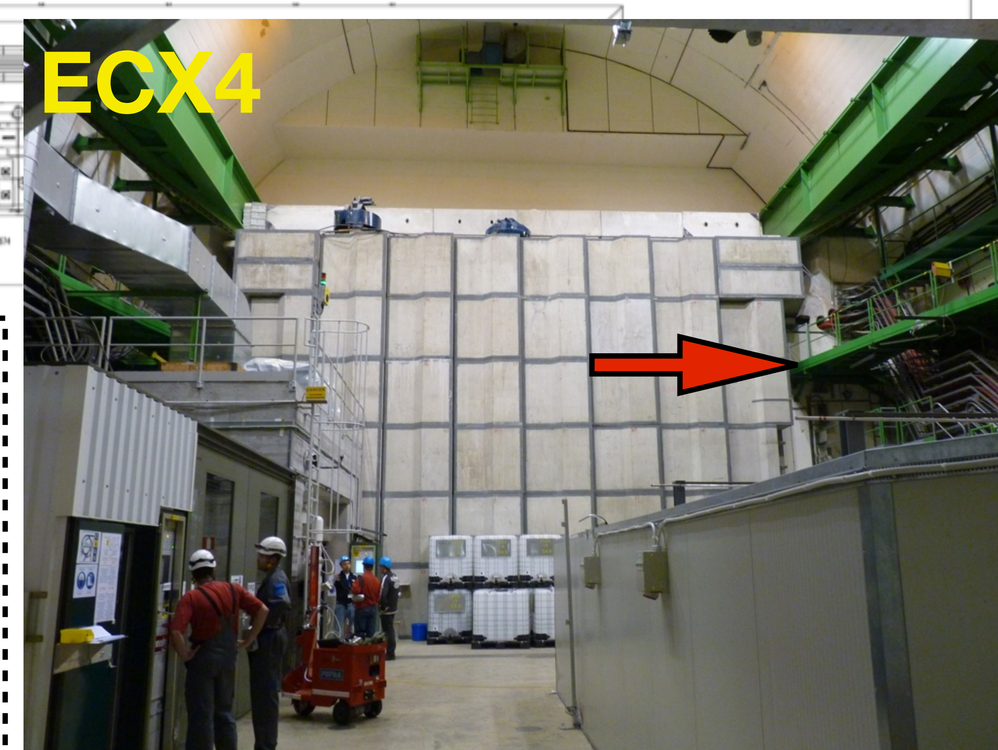
Low Level RF

SPS tests: Infrastructure sketch

- Tetrodes amplifiers next to cavities
- LLRF: to be installed in ECX4
- **ECX4 ~35m away from CC Location**
  => loop delay: transit time **~250 ns**
- Driver amplifiers close to LLRF (ECX4)
- HV PS (+ controls): ECX4 or BA4 (Surface)





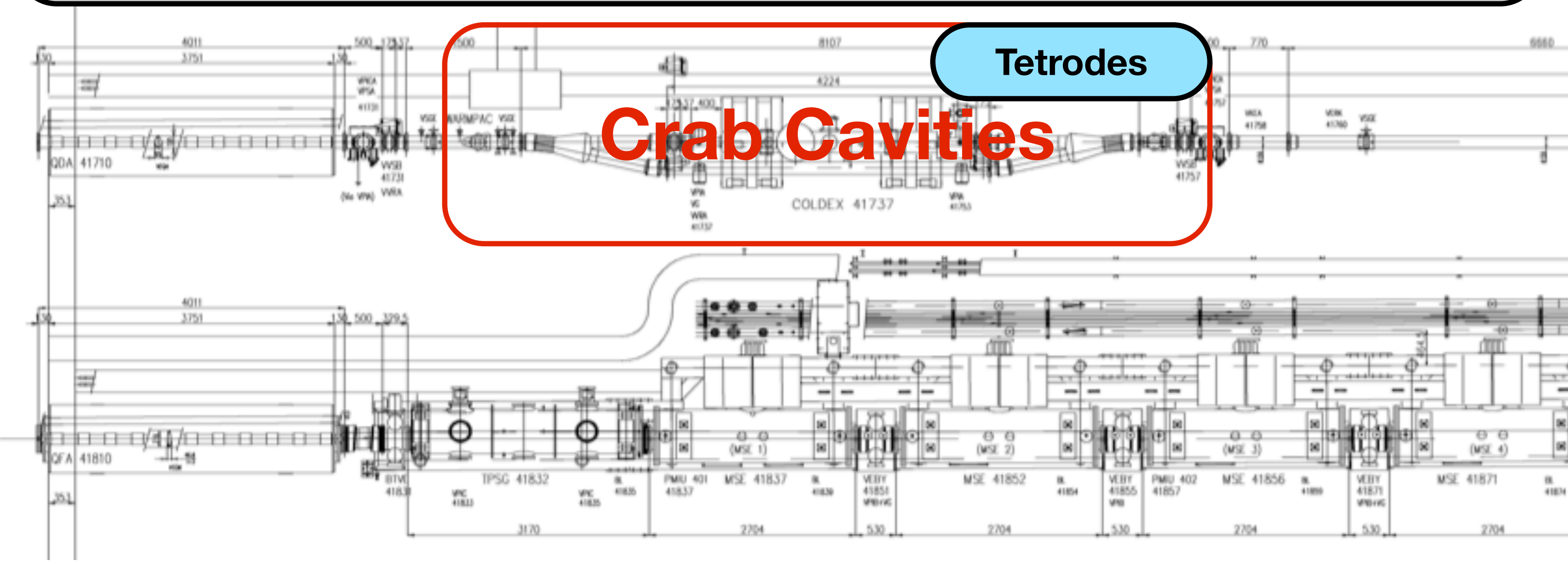


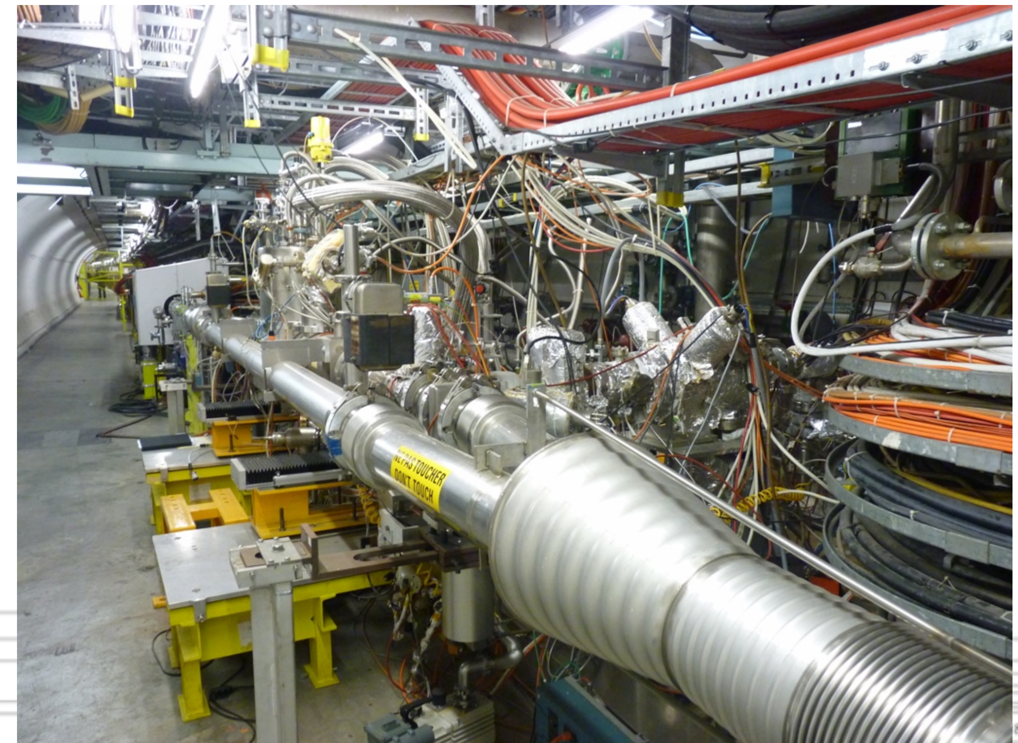
ECX4

Low Level RF

SPS tests: Infrastructure sketch

- Tetrodes amplifiers next to cavities
- LLRF: to be installed in ECX4
- **ECX4 ~35m away from CC Location**
  => loop delay: transit time **~250 ns**
- Driver amplifiers close to LLRF (ECX4)
- HV PS (+ controls): ECX4 or BA4 (Surface)

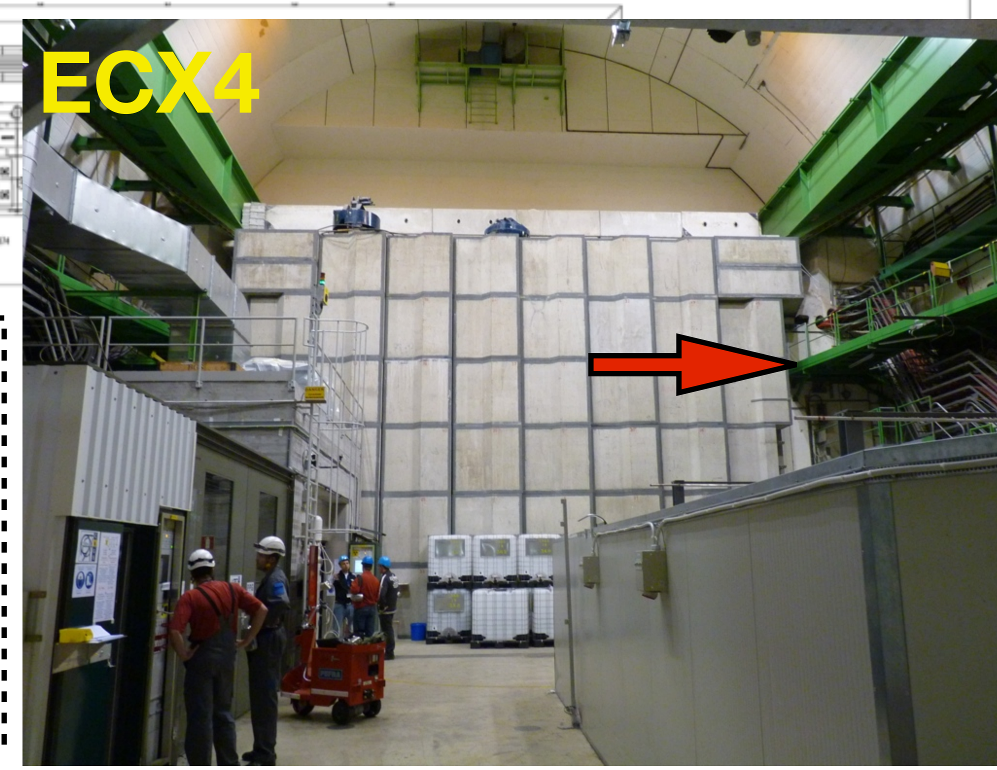




ECX4

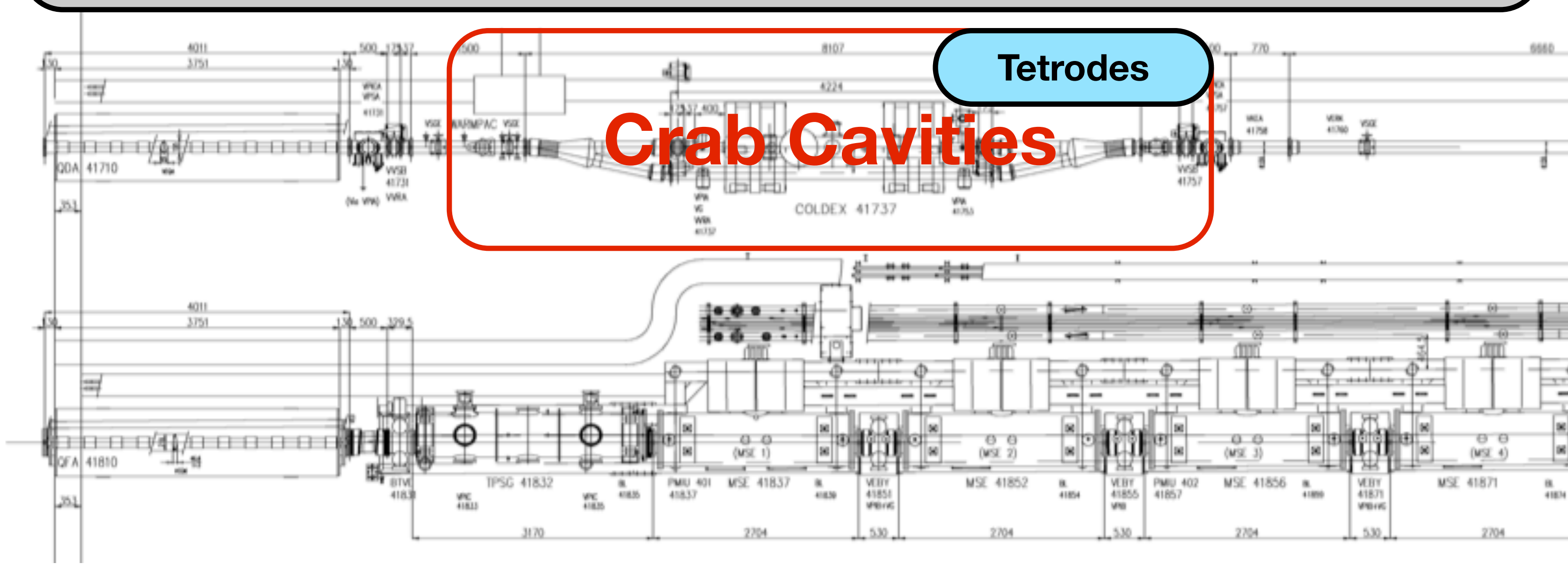
Driver Amp

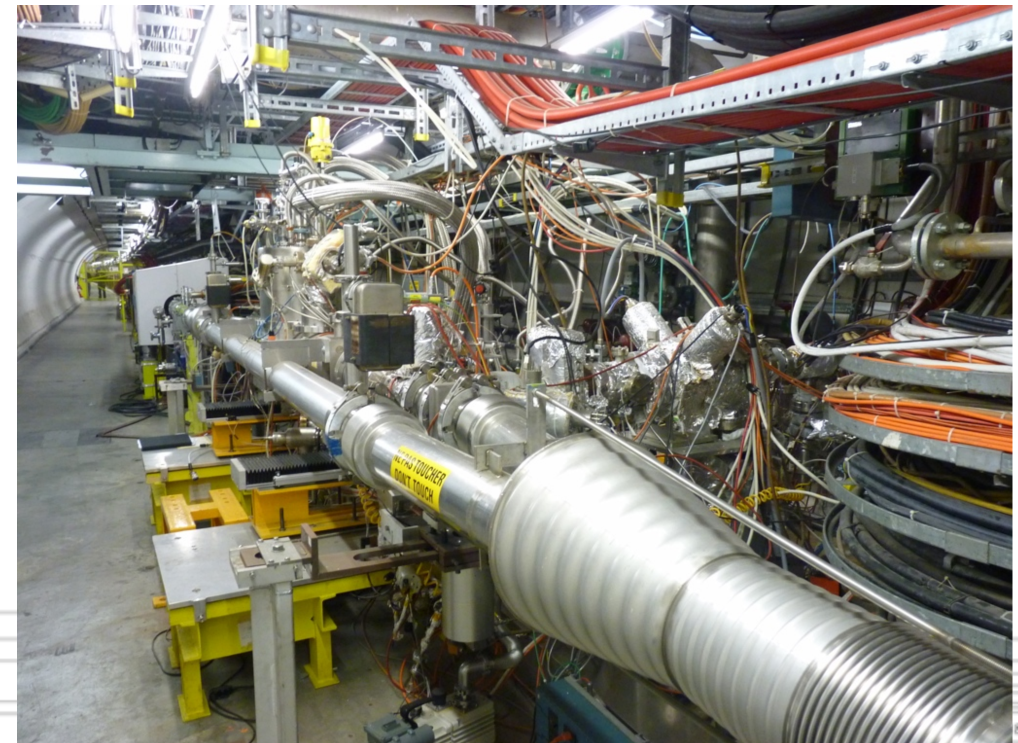
Low Level RF

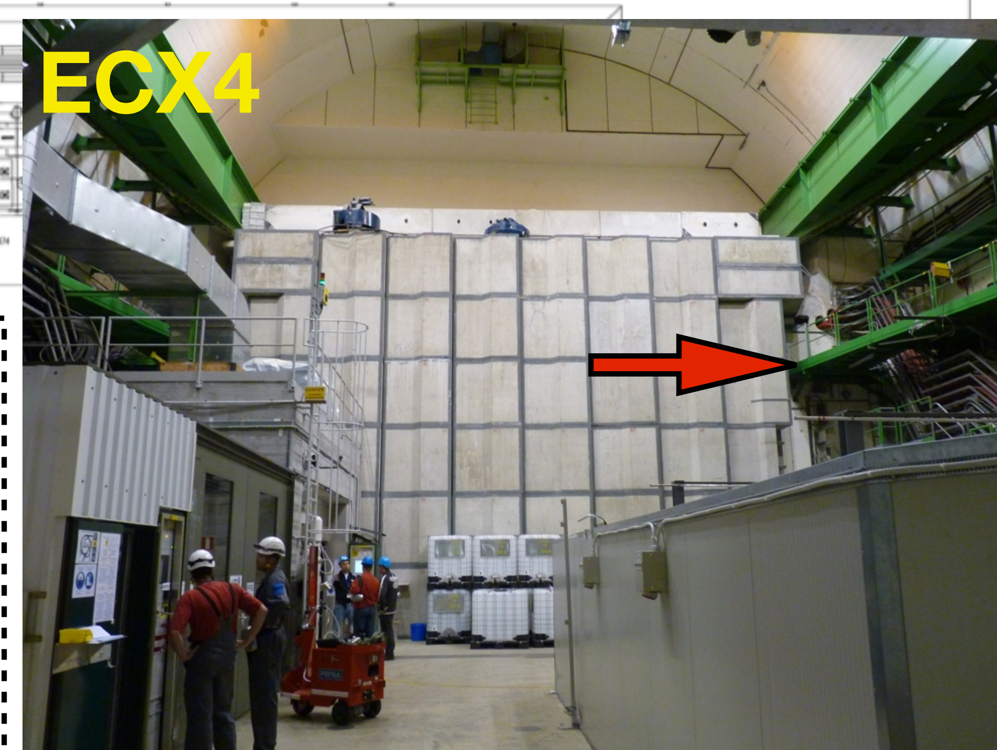


SPS tests: Infrastructure sketch

- Tetrodes amplifiers next to cavities
- LLRF: to be installed in ECX4
- **ECX4 ~35m away from CC Location**
  => loop delay: transit time **~250 ns**
- Driver amplifiers close to LLRF (ECX4)
- HV PS (+ controls): ECX4 or BA4 (Surface)







ECX4

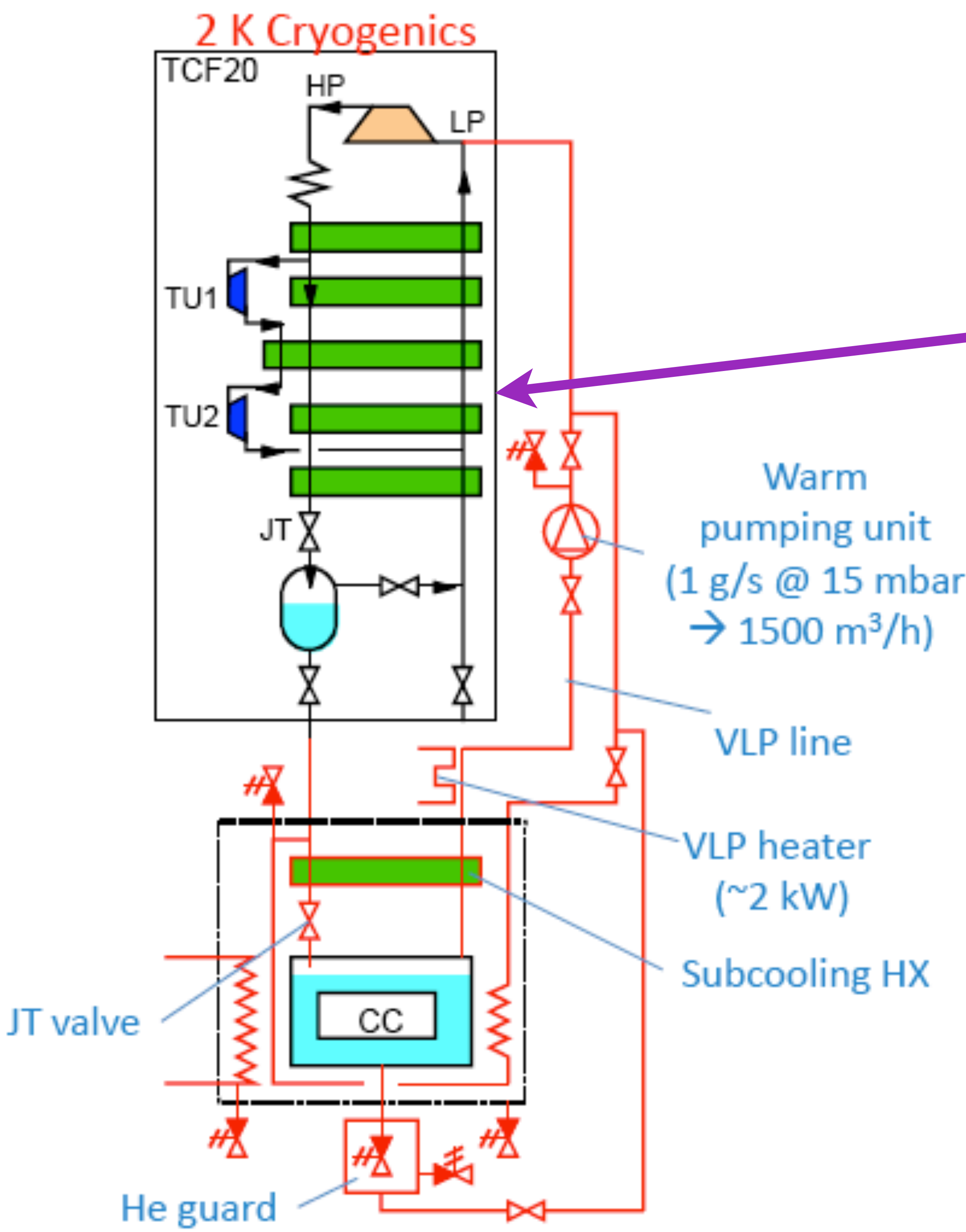
Driver Amp

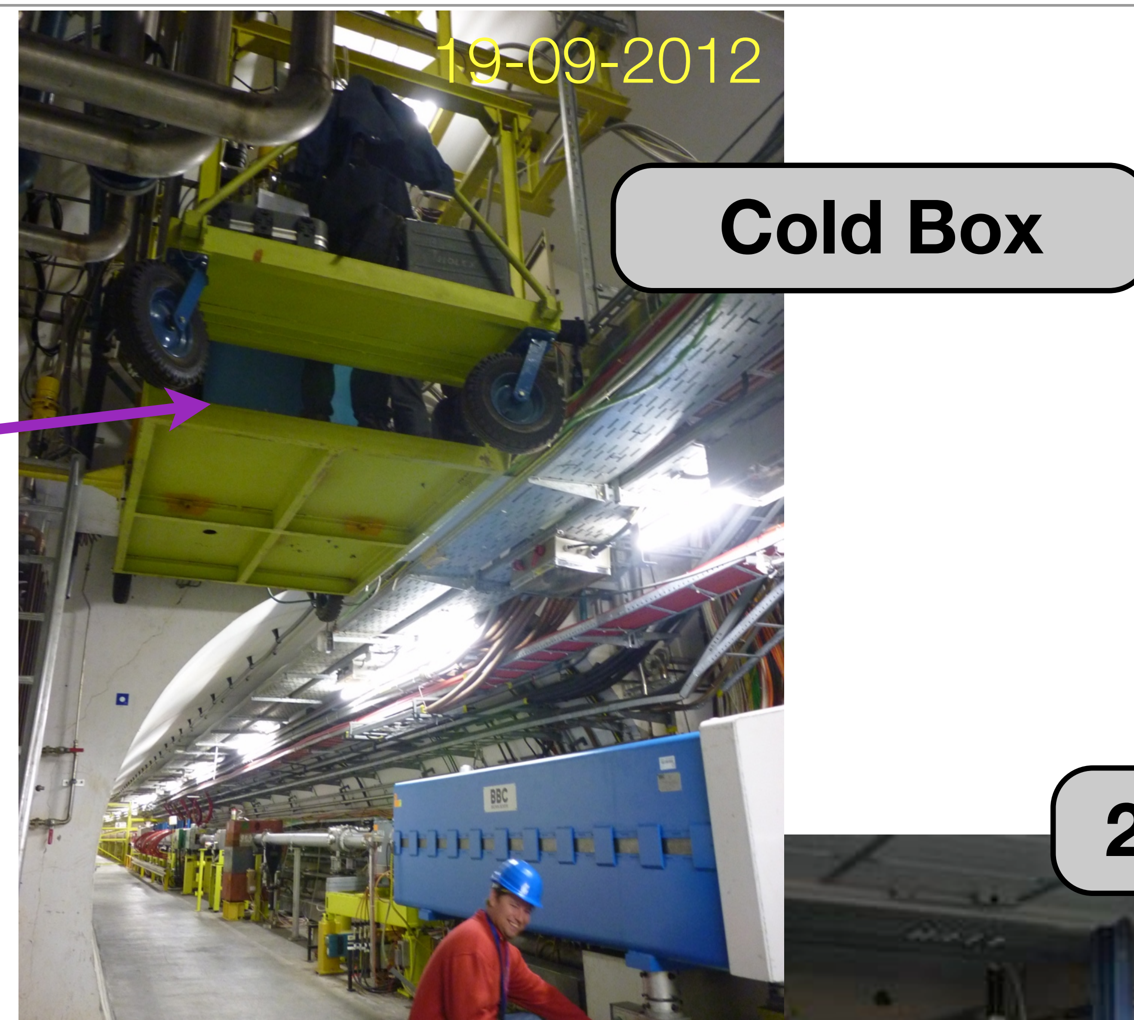
Low Level RF

BA4(Surface)

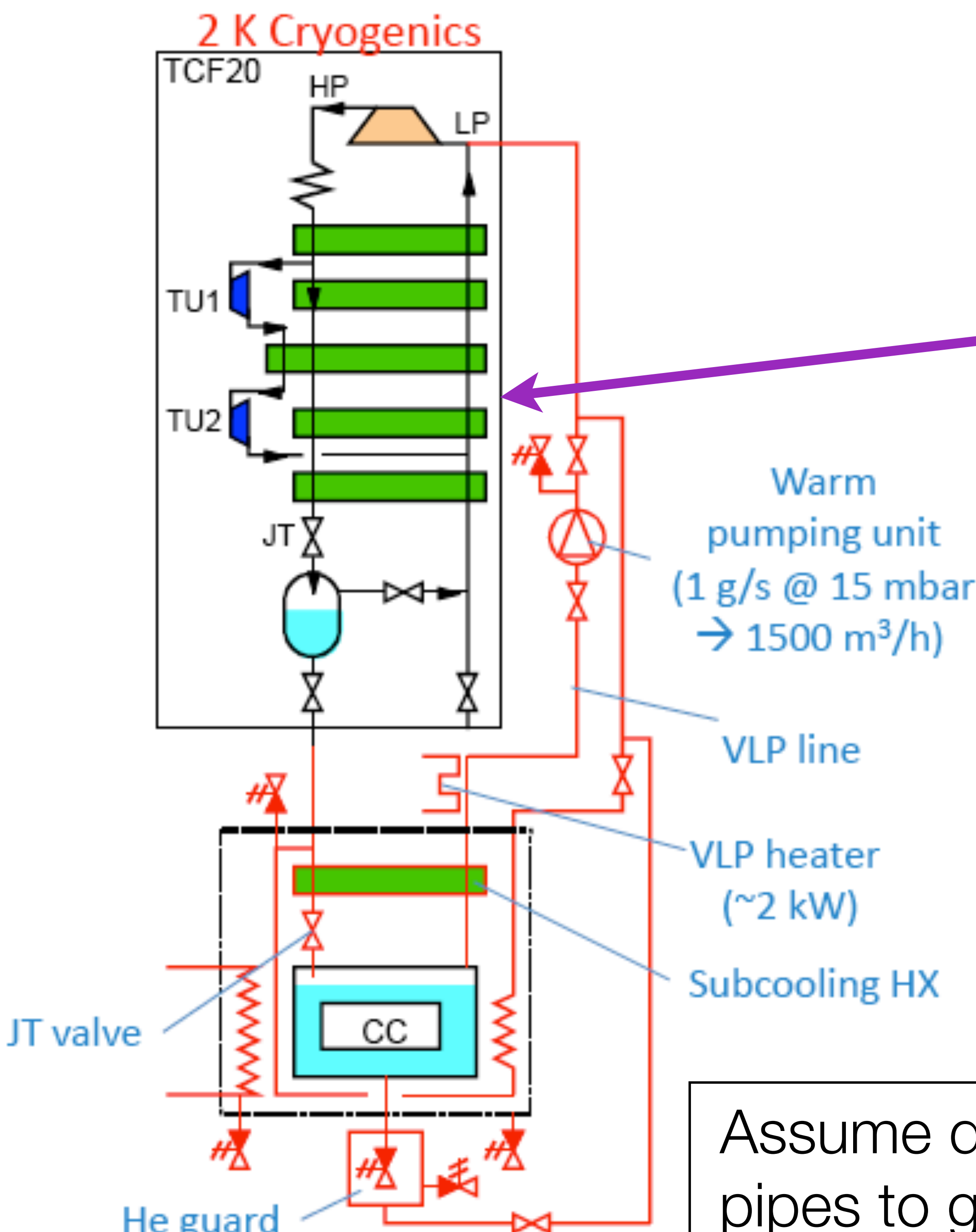
HV PS

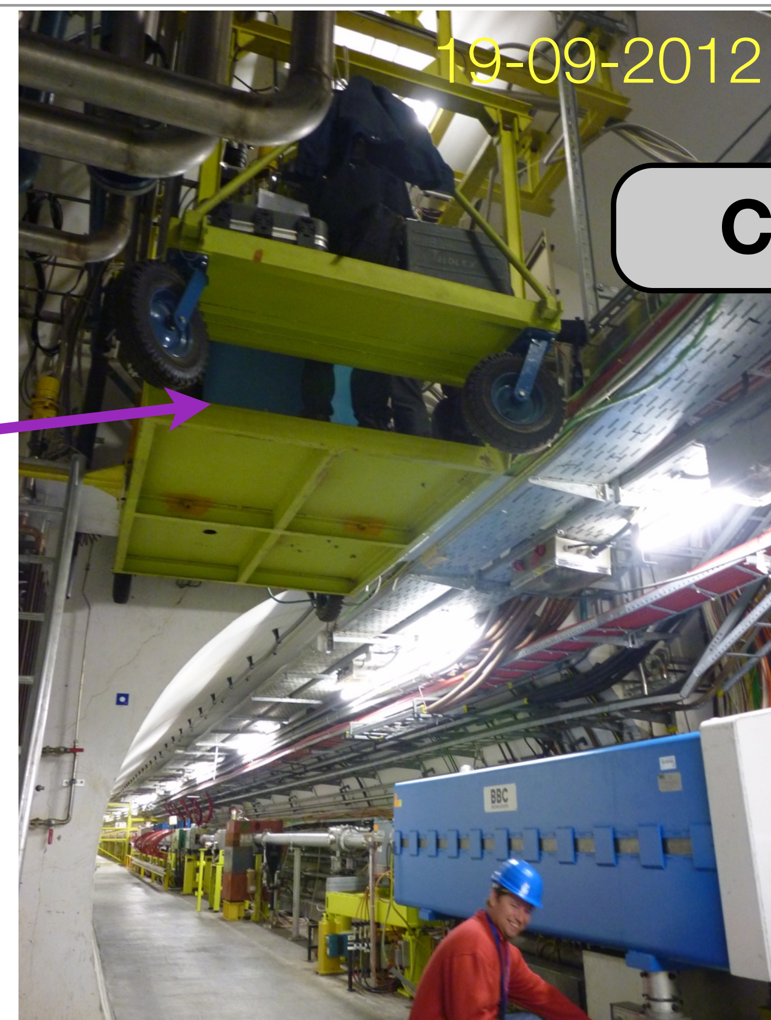
Cryogenics - 4.5K and 2K infrastructure





Cryogenics - 4.5K and 2K infrastructure





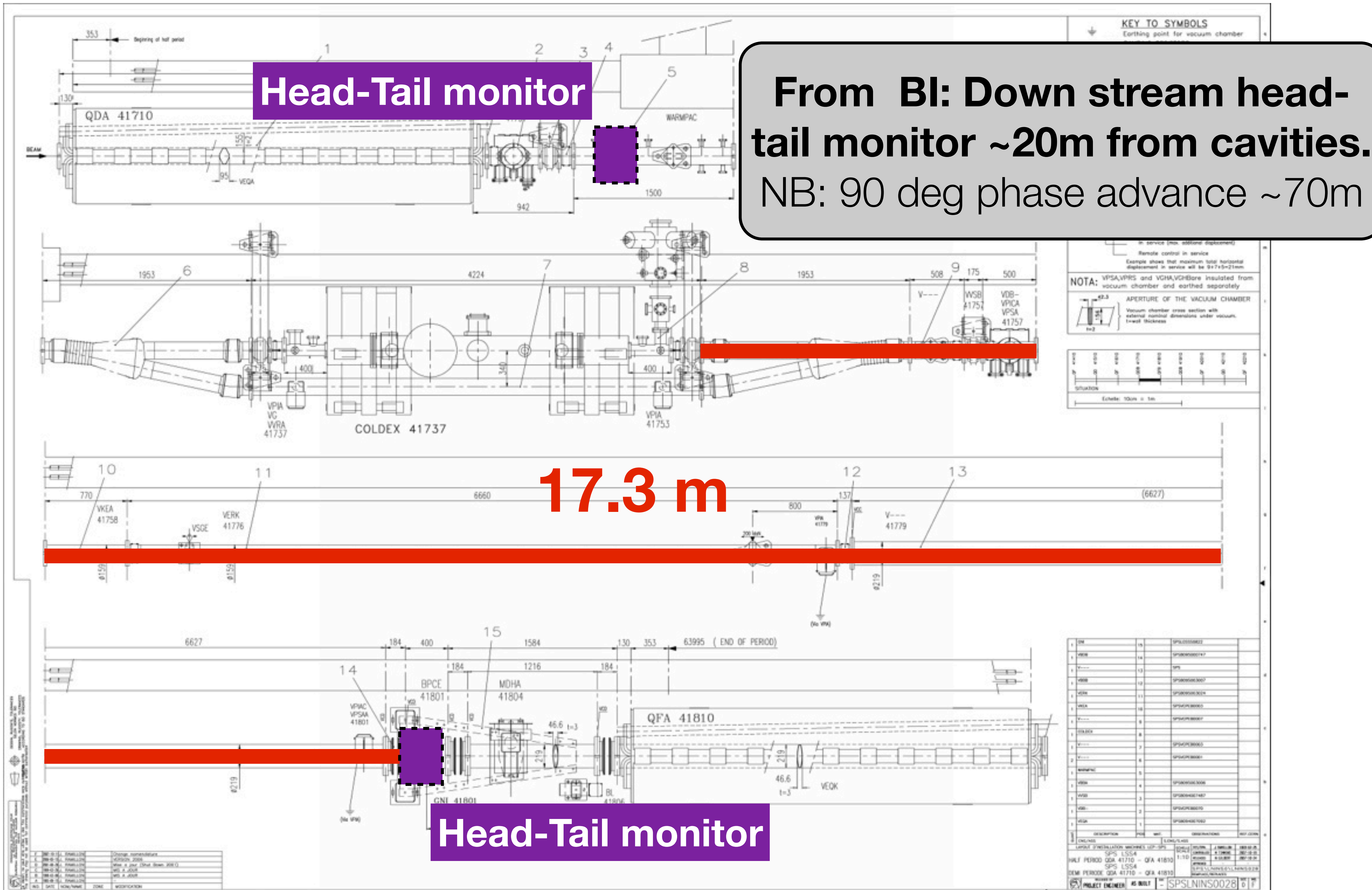
Cold Box

2K Pumping

Assume dismounting of beam pipes to get cold box installed

2K Cooling to be installed in LS1

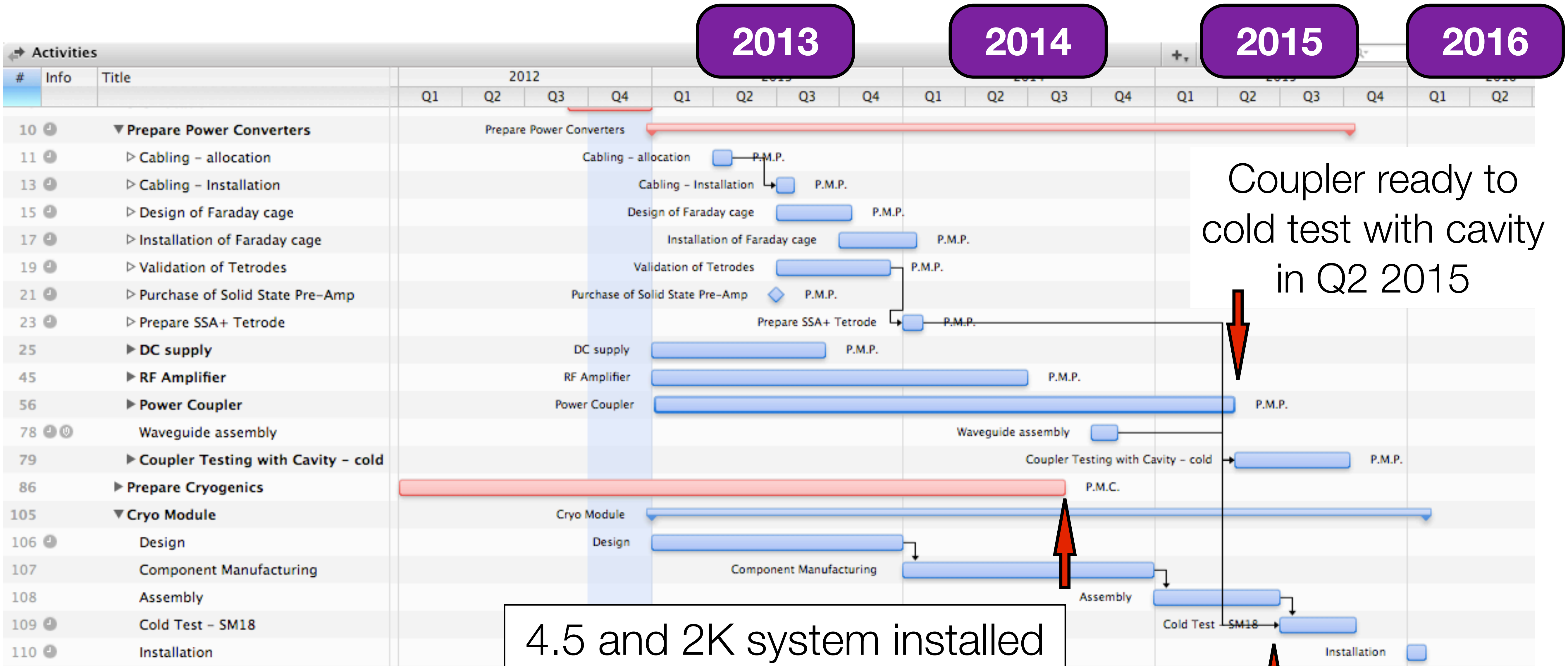
Instrumentation - Head tail monitor



Rough Draft Schedule

- **SM18 Cold testing: Complete chain not ready in SM18 before Q3 2015**
  - use SM18 as much as possible to validate/test components & functionality
- **Installation in SPS: During 2015-2016 winter stop [~ 6-8 weeks duration]**
  - Cannot be done earlier as COLDEX running till 2015
  - Installation cannot start before COLDEX removed.
- **Cabling: Must be installed in SPS before end SPS_LS1 (25 July 2014)**
- **Cryogenics: Both 4.5 K and 2K cryo installed/validated by end SPS_LS1**
- **LLRF Installation:** ECX4 accessible => no strong constraints
- **2016 SPS Run: Only limited number of access periods** (~5 Technical Stops)
  - Technical stops => Mechanical movement of Cavity/bypass
  - Possible exchange of cryo module during a Technical Stop (5 day max)

Rough Draft Schedule ...



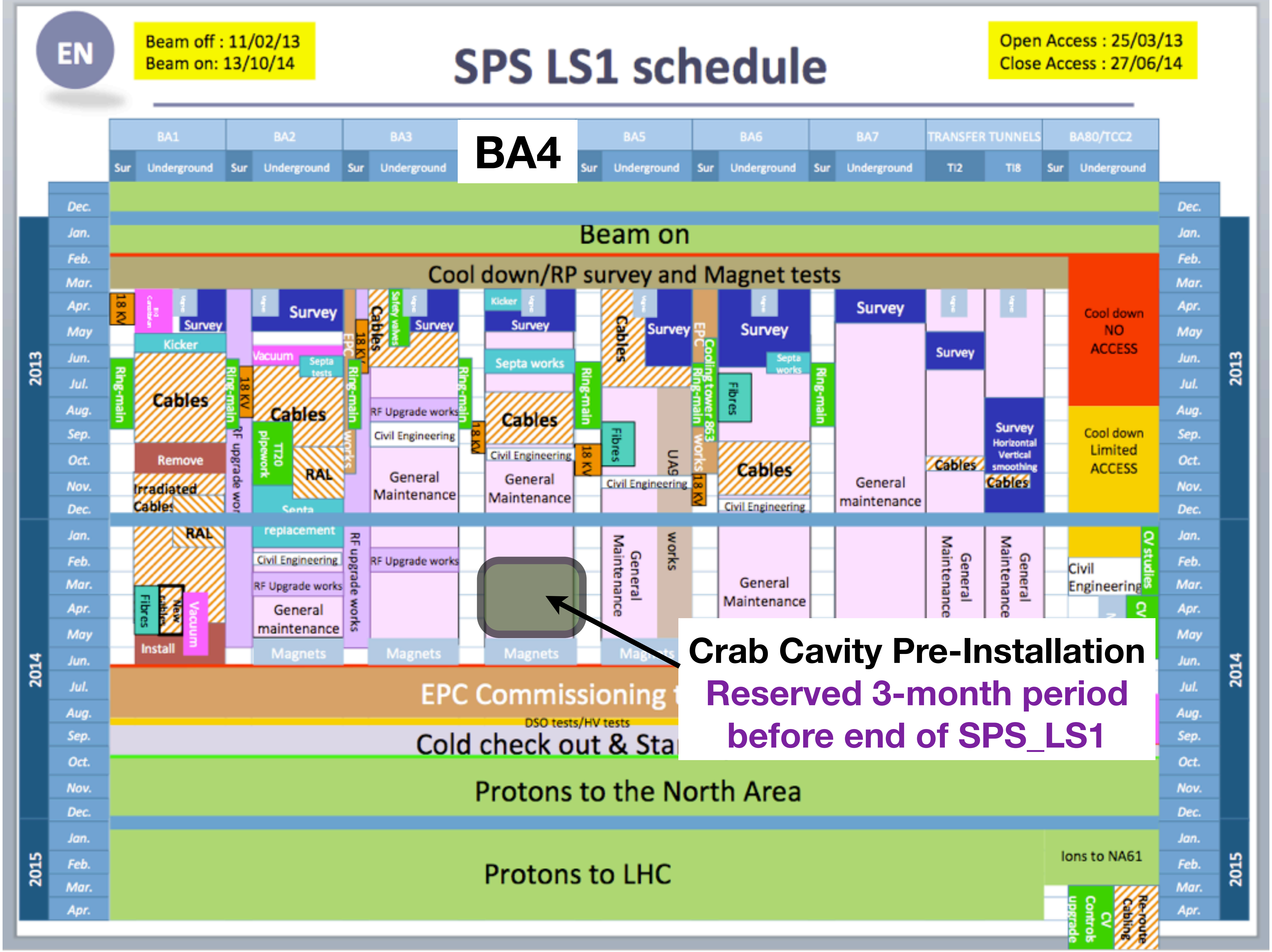
Coupler ready to cold test with cavity in Q2 2015

4.5 and 2K system installed at SPS close up after LS1

Schedule endgame will compact against SPS startup

Have to develop and prepare measurement program in both SM18 and SPS

Cryo module ready to cold test in Q3 2015


EN
Beam off : 11/02/13
Beam on: 13/10/14
SPS LS1 schedule
Open Access : 25/03/13
Close Access : 27/06/14
BA1
BA2
BA3
BA4
BA5
BA6
BA7
TRANSFER TUNNELS
BA80/TCC2
Sur
Underground
TI2
TI8
2013
2014
2015
Dec.
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Beam on
Cool down/RP survey and Magnet tests
18 KV
Survey
Kicker
Ring-main
Cables
Remove
Irradiated Cables
RAL
Fibres
New cables
Vacuum
Install
RF upgrade works
Septa tests
TI20 pipework
Septa replacement
Civil Engineering
RF Upgrade works
General maintenance
Magnets
EPC
Safety valves
General Maintenance
Septa works
Cooling tower 863
UA9 works
Survey Horizontal Vertical smoothing
Cool down NO ACCESS
Cool down Limited ACCESS
CV studies
Crab Cavity Pre-Installation
Reserved 3-month period before end of SPS_LS1
EPC Commissioning
DSO tests/HV tests
Cold check out & Sta
Protons to the North Area
Protons to LHC
Ions to NA61
CV Controls upgrade
Re-route Cabling

SPS Test Program

- **Invisibility of Cavities:**
  - De-tuned cavities must be shown to be transparent to beam operation
    - Use counter-phasing to make cavity field invisible to the beam.
- **Normal Operation at Top Energy**
  - Moving to on-tune settings shown to be transparent to circulating beam
  - Reduce detuning while keeping voltage set point very small, keeping cavity impedance small (beam stability)
  - Measurement with crabbing-uncrabbing; BI need to understand program to prepare instrumentation. Existing BPMs and BLMs should be OK
  - Estimating scaling between transverse emittance growth & RF noise
  - Field control with off-centered beams
- **Machine Protection**
  - Response of single cavity under both worst-case failure & quench conditions
    - Understand time scales: Quench development
  - Validate mitigation techniques with 2 cavities and LLRF

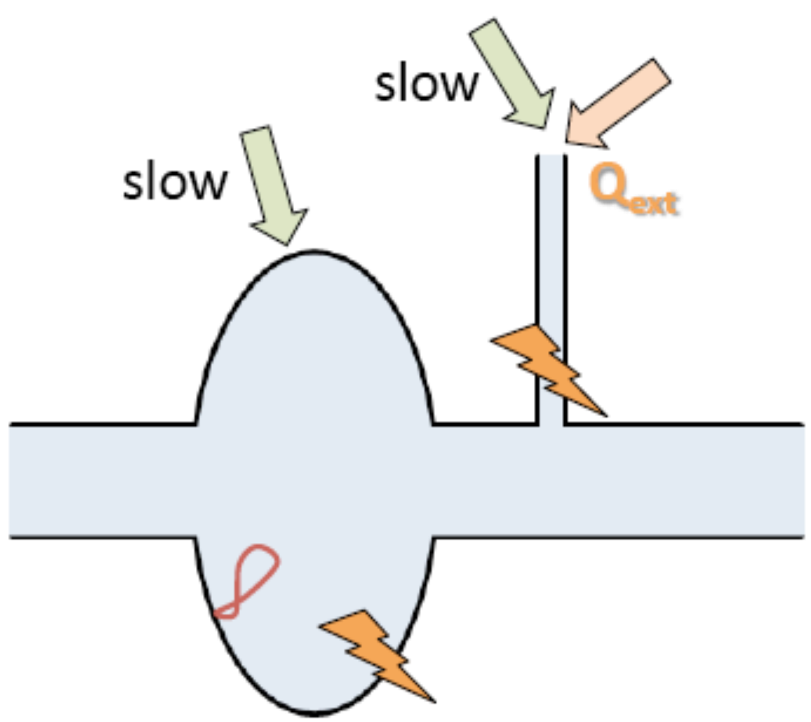
Machine Protection: Failure modes

LHC beam dump time scale: within 3 turns (~270us) after detection

Slow (external) failures
- Power cut
- Cryogenic failures
- Mechanical changes (tuner problem)
- …

Very fast external failures
- Control-logics failure
- Operational failure
- Equipment failure
- …

Timescale determined by Q_{ext} (and available power).



Ultra fast (internal) failures
- Multipacting (≈1μs)
- Cavity quench (>≈100μs)
- Arc in coupler

?

Timescales < 1 turn possible.

J. Tuckmantel, LHC-CC10.

Machine Protection: Failure mode implications

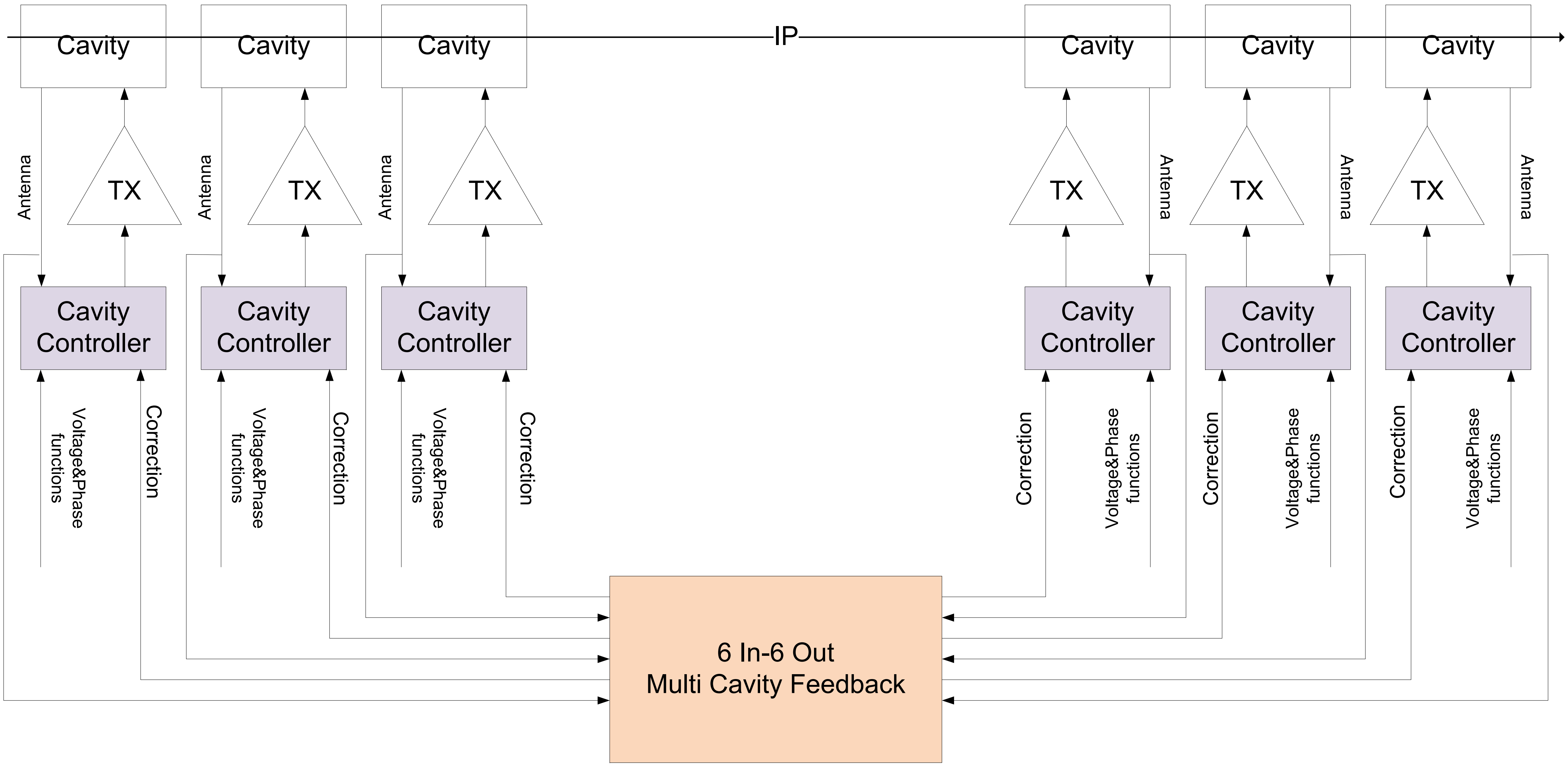
- **Failure modes:** Must be understand response time and test mitigation
  - **RF hardware problems** - power stored in cavity goes back to the load
    - Choice of Q_{EXT} defines timescale power dissipation: can be slow
    - **MPS: track sum of crabbing voltages, apply individual transmitter FB**
  - **Cavity Quench:**
    - Power dissipated in cavity wall (not through coupler)
    - Q_0 decreases with power still on => high power transfer when $Q_0 \sim Q_{EXT}$
      - **thermal runaway until RF switched OFF**
    - **Time scale: Not clear.** (τ ~90us assumed) => **ultra fast MPS failure**
      - Need to know quench characteristics to set **MPS Controllers strategy**
    - **Detection of quench - How?**
      - He pressure monitoring - slow: τ ~O(0.5s)
      - Electrical? LHC_QPS style monitoring of U_{RES}
    - **MPS Test: Need mechanism in cryo module to provoke quenches**

Need quench time scales and detection mechanism

LLRF: Cavity controllers

- **Individual Cavity Controllers** (1 per cavity)
  - For tuning and regulating individual cavity field (low loop delay feedback).
  - Located close to the cavity (ideally with TX).
  - 2 Reference antennas ($Q_{EXT} >> Q_0$) [1 for monitoring, 1 for feedback]
- **Multi-Cavity feedback:** monitors total crabbing vs. un-crabbing voltage
  - In case of single cavity failure, try to ramp-down voltage in cavities on other side of IP => attempt to keep sum crabbing+uncrabbing at zero.

- **LLRF Multi-Cavity loop delay**
  - **LHC: ~several μs [Single cavity loop delay ~650ns]**
    - (150, 50, 30, 400 ns) for (klystron, circulator/driver, LLRF, Cabling
  - **SPS:** ECX4 ~35m away => **250 ns**
- **SPS tests must validate LLRF response, especially for LHC loop delays**



Cavity Controller

Strong RF feedback (< 1 μs loop delay) regulating the individual cavities

6 In-6 Out
Multi Cavity Feedback

Global feedback regulating the relative crabbing-uncrabbing actions. Sligthly larger loop delay (< 5 μs loop delay?)

τ_{MC_Loop} ~5μs $\tau_{Beam\ dump}$ ~300μs => Mitigation scale looks OK

Conclusions ...

- Crab cavity/cryo module envelope for SPS Run outlined
- Number of cavities installed at any one time is 2
- Measurement program: cavity performance, LLRF control, machine protection

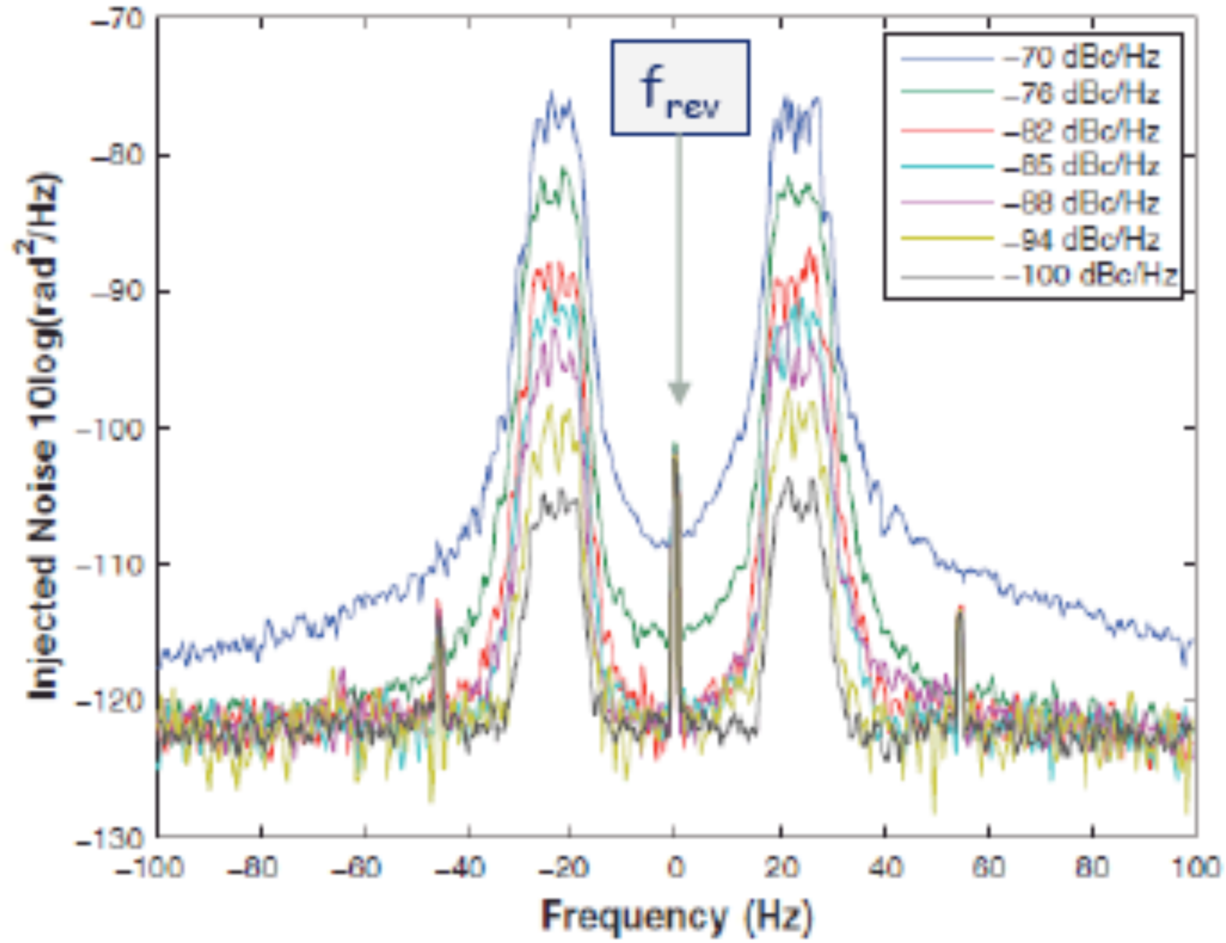
- **Issues where decisions needed**
    - How many cavities per cryo module?
        - MPS view: 2 cavities per 1 cryo module
    - Is cavity/cryo-module to be exchanged during SPS Run (ie in a 5 day TS)

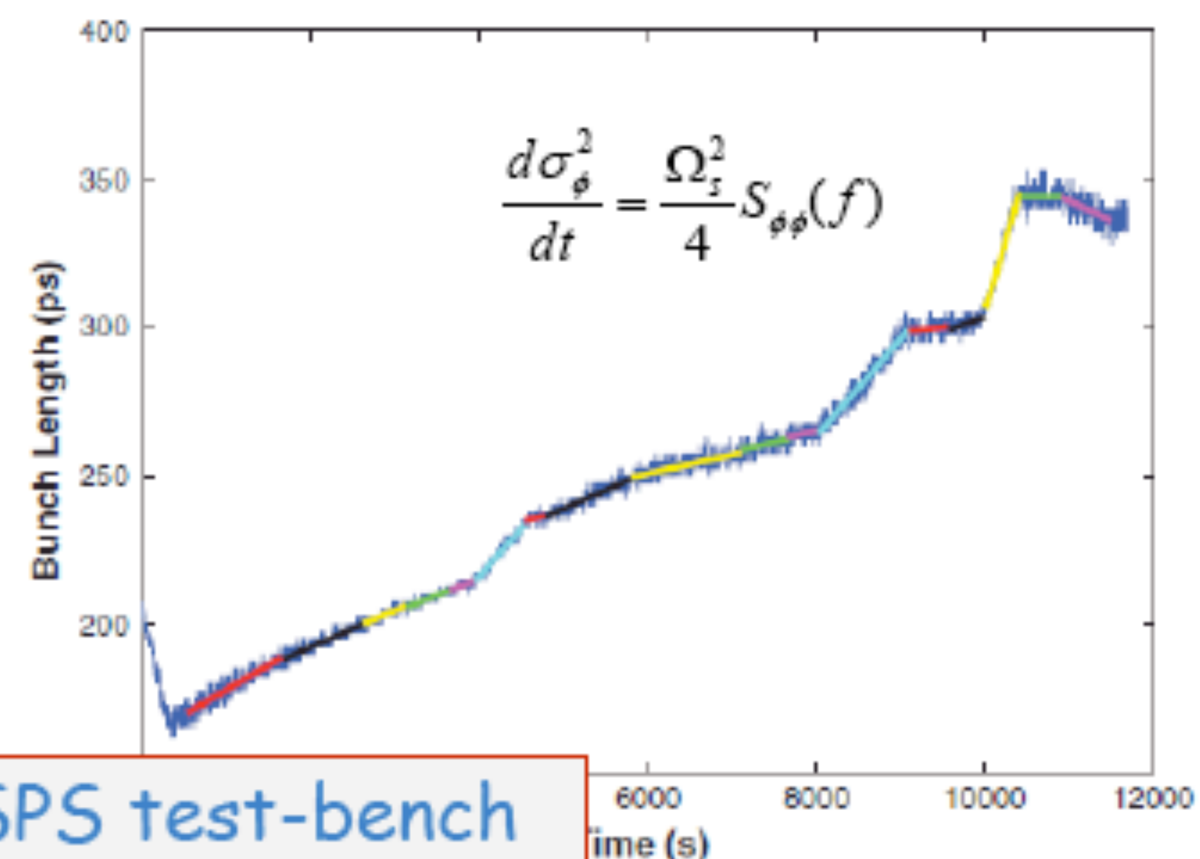
- **Issues for discussion**
    - How to implement alignment constraints: alignment mechanisms
    - Firm up beam instrumentation requests based on measurement program
    - MPS: Quench production and detection an crucial part SPS test

- **Schedule:** Install in SPS in 2015-2016 winter break => tight schedule
    - SM18 test program must be developed in parallel with SPS program
    - Based on 2016 SPS Run followed by LHC Pt4 in 2017? (before LS2)

Back up slides

- Phase noise was injected in one RF cavity, with a bandwidth of 10 Hz, centered on the first revolution band: $f_{rev} \pm f_s$
- The power of the injected noise was varied during the test
- Bunch length was monitored
- With large noise power, the effect became dominant, allowing for a good calibration of emittance growth (slope of bunch lengthening) vs RF noise power

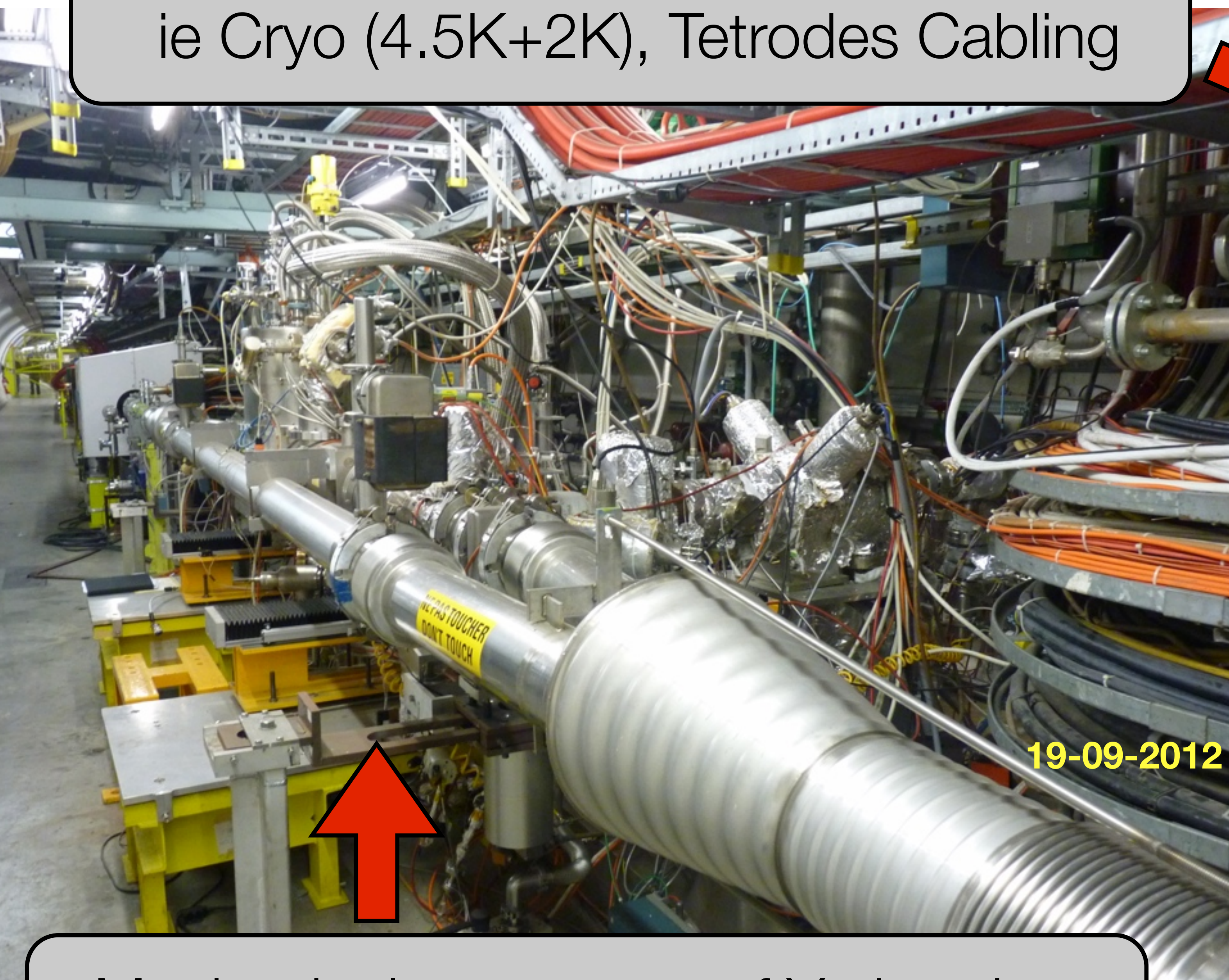


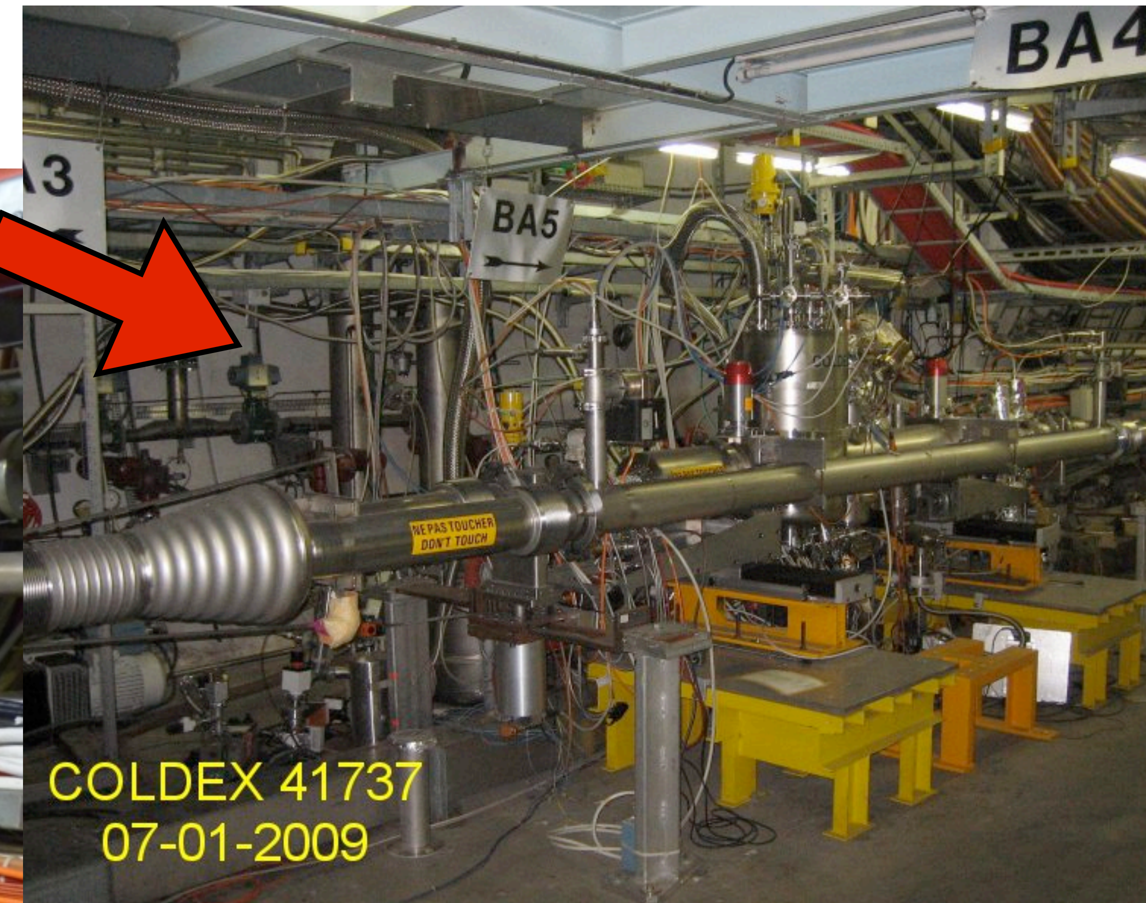


Will be done on the SPS test-bench

SPS Crab Cavities test: Location

Pre-install before end of LS1
ie Cryo (4.5K+2K), Tetrodes Cabling





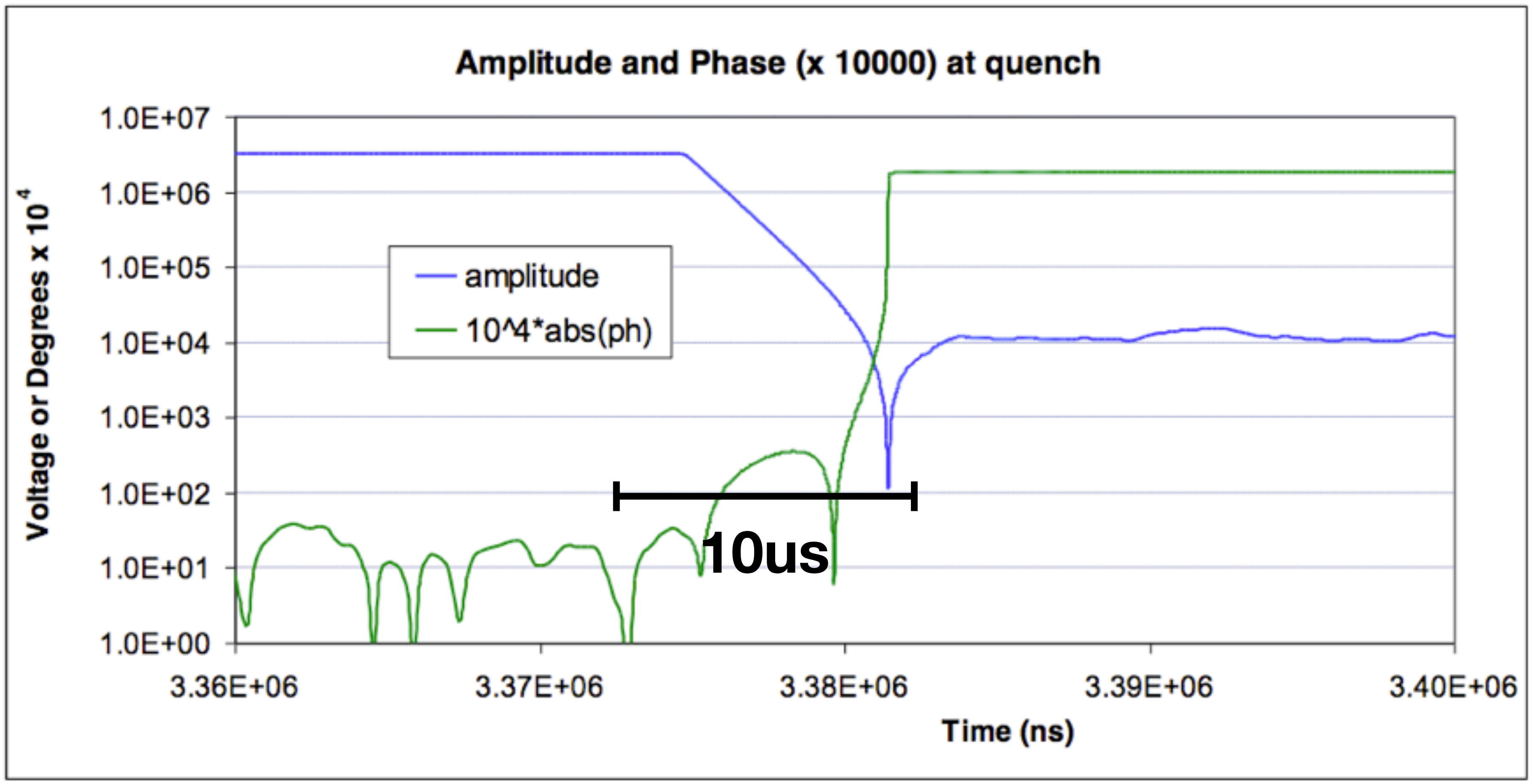
- Coldex to run in 2014-2015
- CC in SPS:
  only feasible location= COLDEX
- Pre-install infrastructure in LS1
  CC installation:
  2015-2016 Xmas break

Mechanical movement of Y-chamber
=> mechanical integration

Quenches

Quench

Quench is simulated by letting intrinsic Q fall to 1500
As expected the amplitude falls to a small level before the phase shift is significant



After quench and even if the beam is steered through cavity then the beam could still deposit 6 kW in cavity which is way too much for the cryo system. There is still a requirement to dump the beam after a crab cavity quench.

Operational Scenario

- Strong RF feedback + tune controls always ON: Stability and short loop delay
- **During filling, ramping or operation with transparent crab cavities**,
  - Detune cavity but keep a small field requested for the active Tuning system.
  - Use counter-phasing to make the small cavity field invisible to the beam.
  - RF feedback on detuned cavity to provide stability and keep the Beam Induced Voltage at zero if the beam is off-centered.
- **At flat top**
  - Reduce the detuning while keeping the voltage set point very small.
    - RF feedback keeps the cavity impedance small (beam stability) and compensates for beam loading as the cavity moves to resonance
  - Cavities on tune: crabbing by synchronous voltage change in all cavities