

Crab Cavity Testing in the SPS

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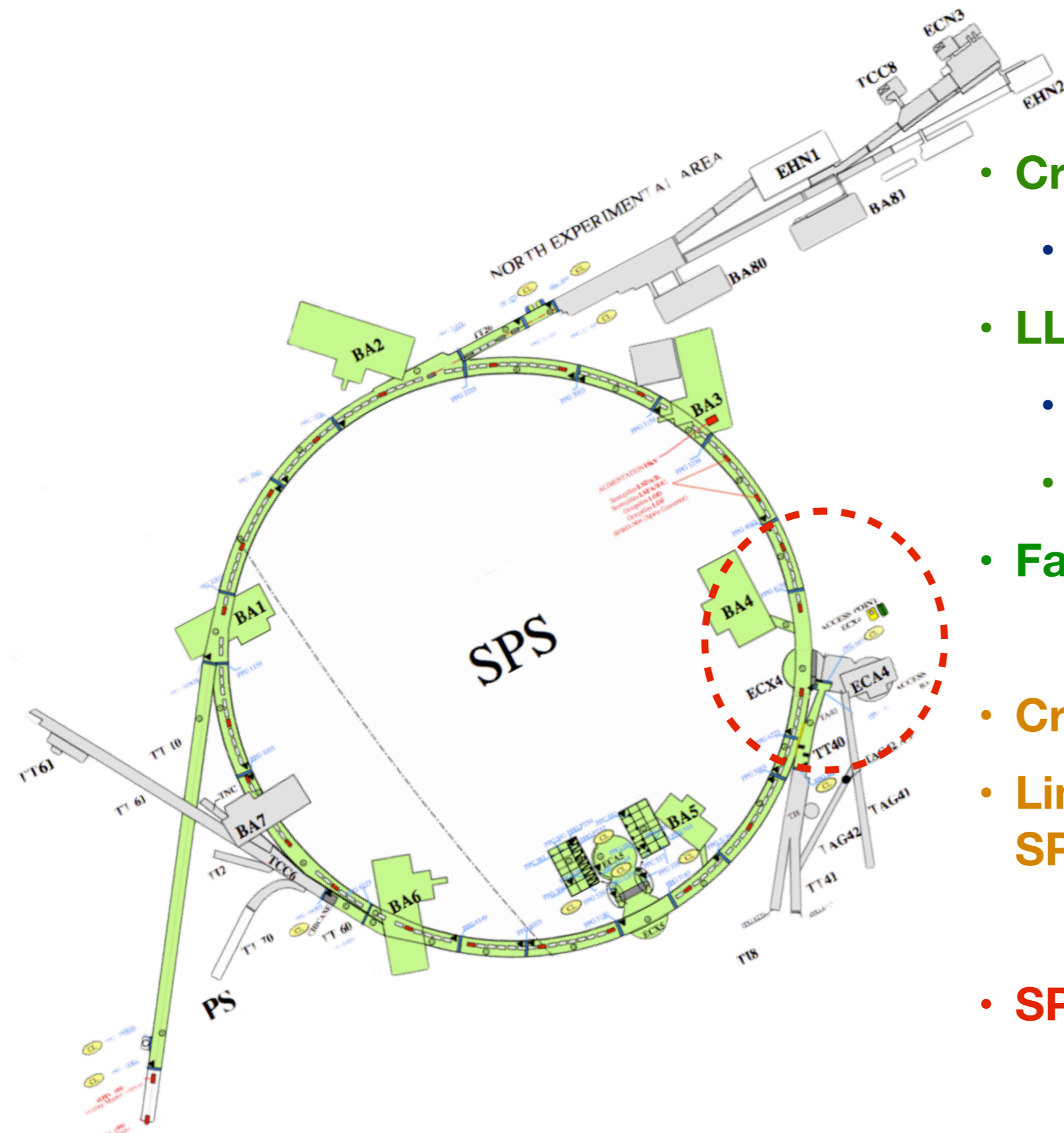
Acknowledgments

Philippe Baudrenghien, Krzysztof Brodzinski, Rama Calaga, Ofelia Capatina, Frederic Galleazzi, Erk Jensen, Antoine Kosmicki, Phoevos Kardasopoulos, Eric Montesinos, Vittorio Parma, Ghislain Roy, Thierry Renaglia, Rogelio Tomas, Giovanna Vandoni

Crab Cavities in the SPS

- **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**
- **Target Deadline**
 - **Completion of the SPS test by the start of LS2**
- **Avoid adding constraints that are particular the SPS environment**
- **Operational Constraint**
 - **Ensure Crab cavity validation run is compatible with SPS operation.**

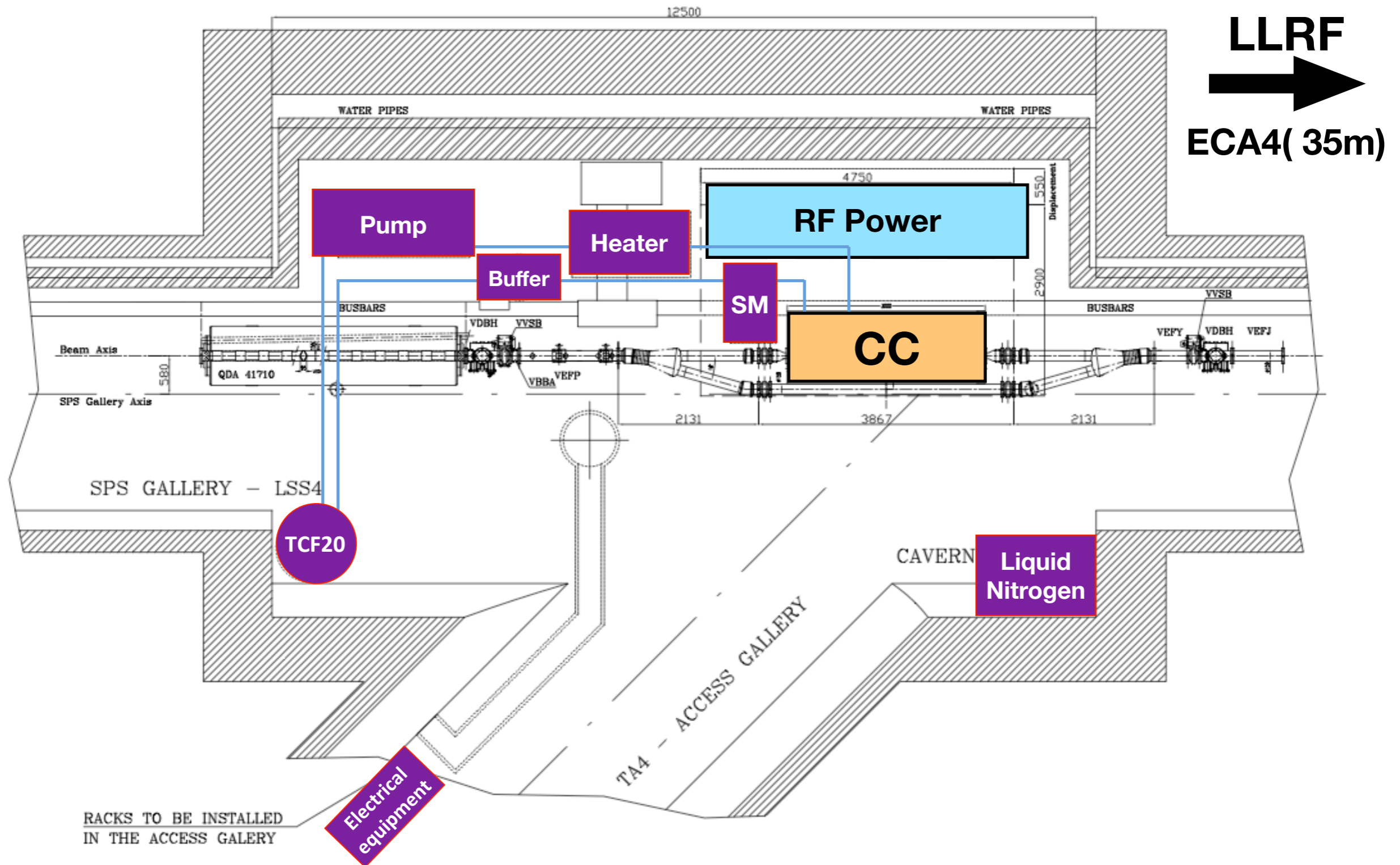
SPS crab cavity location



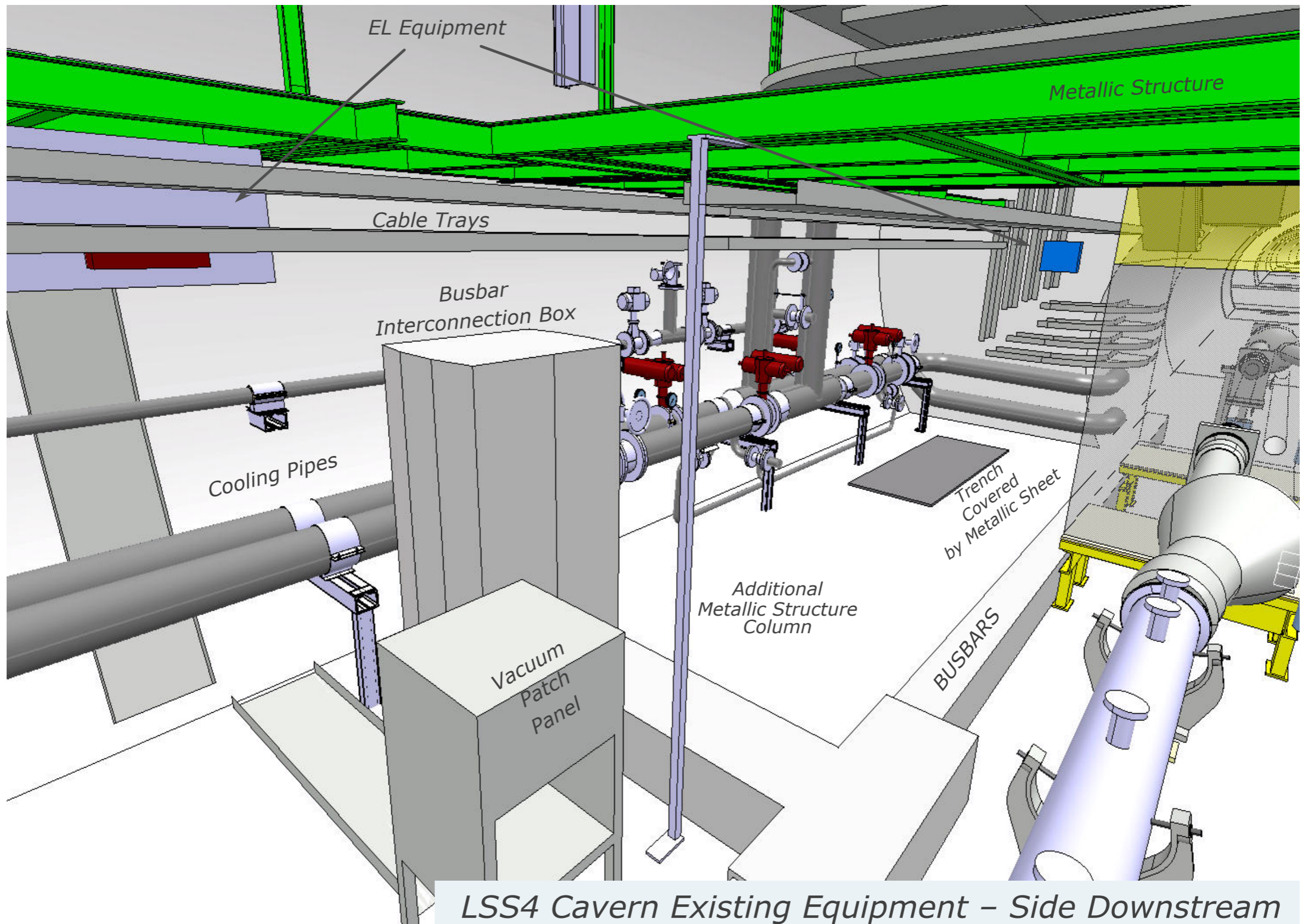
SPS Location: LSS4

- **Cryogenics Infrastructure**
 - Only SPS Pt 4 is feasible
- **LLRF can be close (35m)**
 - Experimental cavern (ECA4)
 - **ECA4 accessible with beam**
- **Facility for switching cavities in/out**
- **Crab Cavity space free end of 2015**
- **Limited access to SPS zone after SPS long shutdown (2013-2014)**
- **SPS Extraction pt for LHC beam 2**

Crab Cavities: Planned SPS Layout

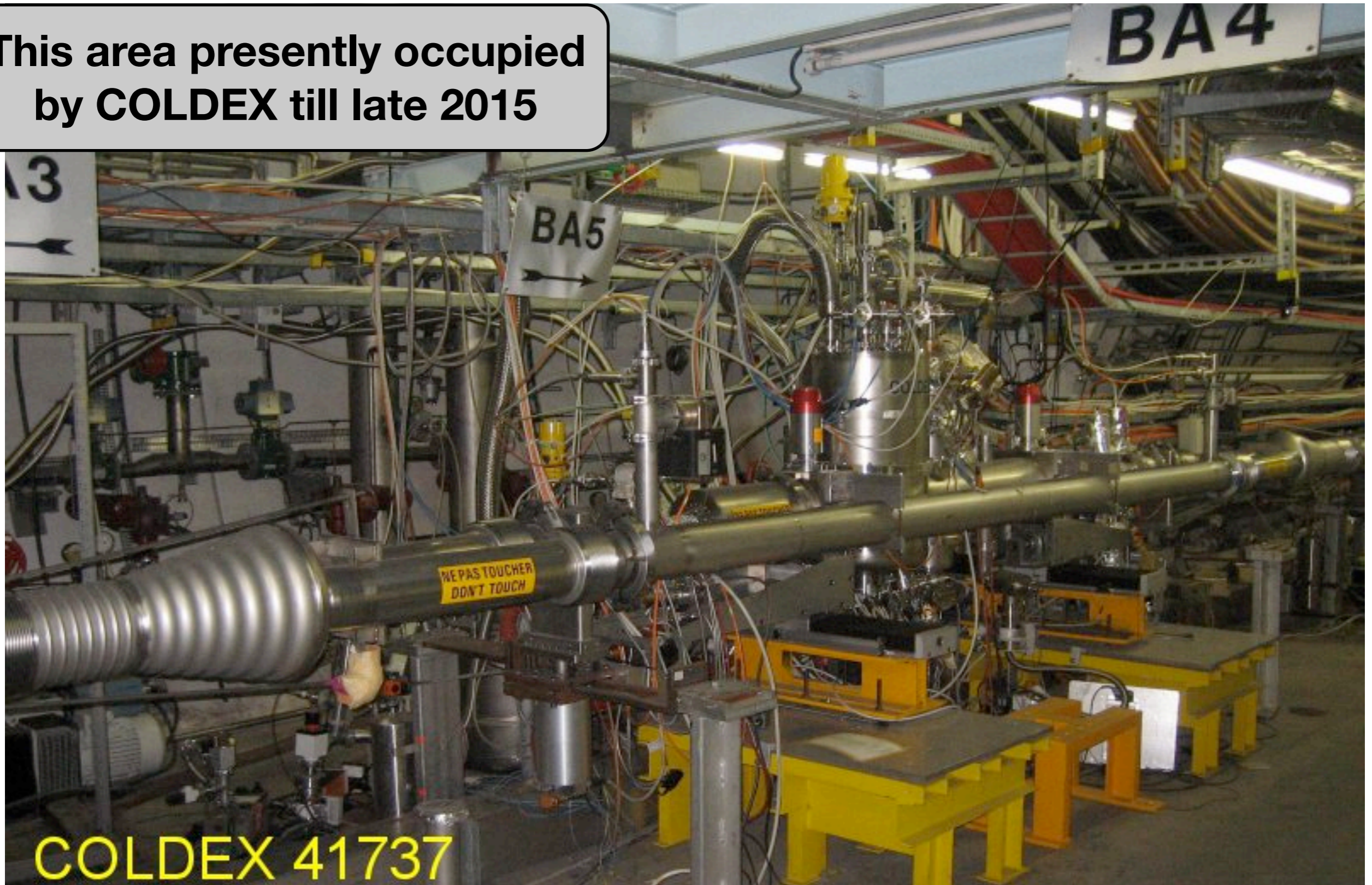


Crab cavities SPS location: space in the alcove



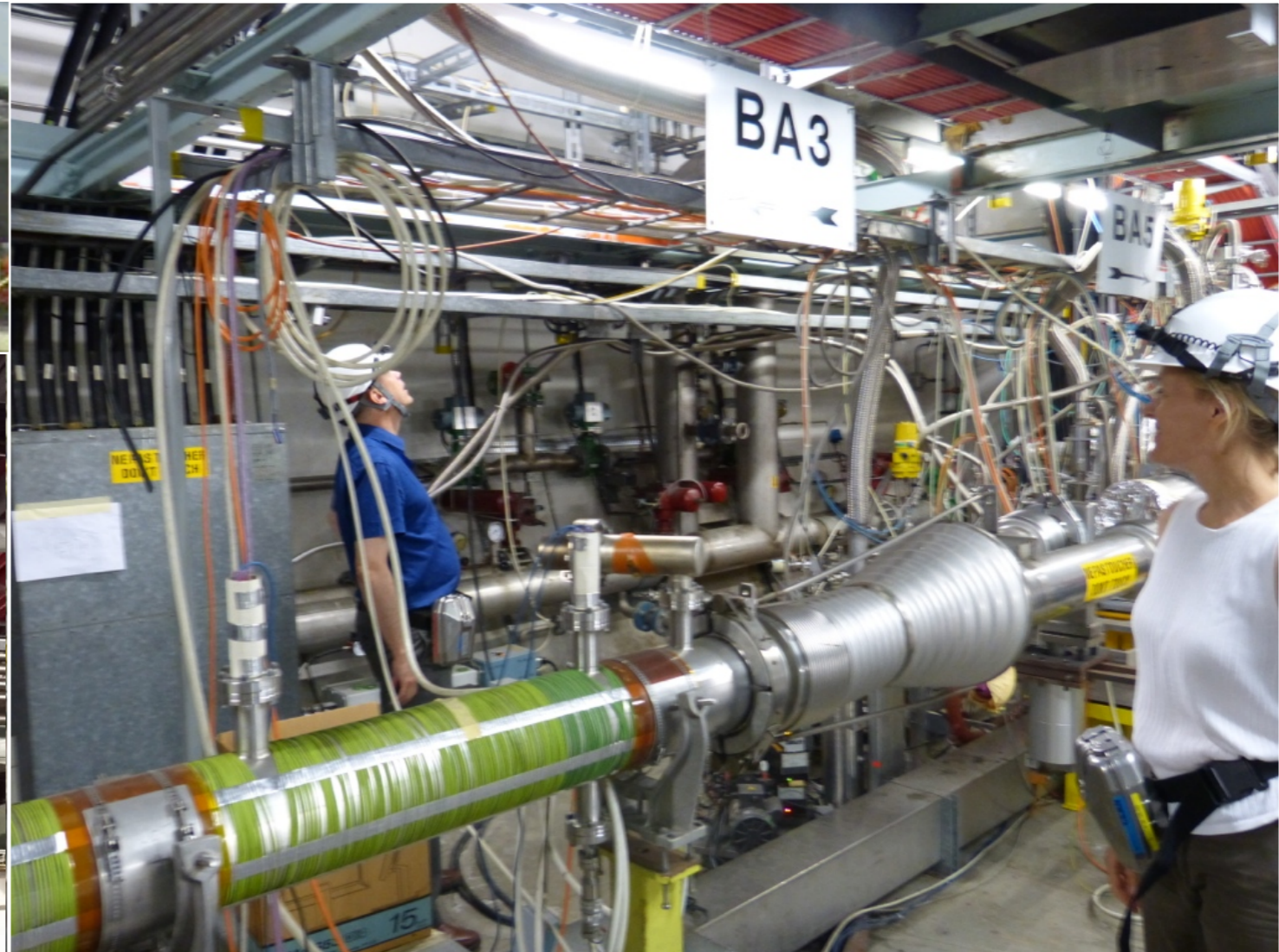
Crab cavities SPS location: the integration reality

**This area presently occupied
by COLDEX till late 2015**



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**3D model as-installed geometry
now available.
Equipment owners mostly identified
=> integration work starting**

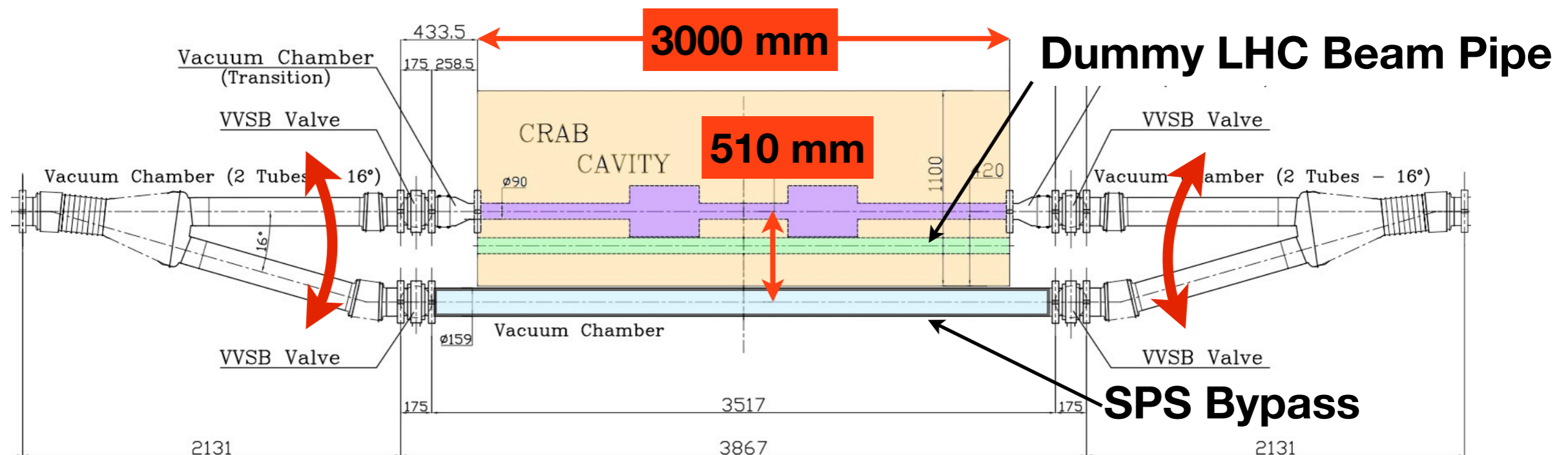
COLDEX 41737

Integration - operational aspects

SPS operation must be independent of crab cavity operational availability

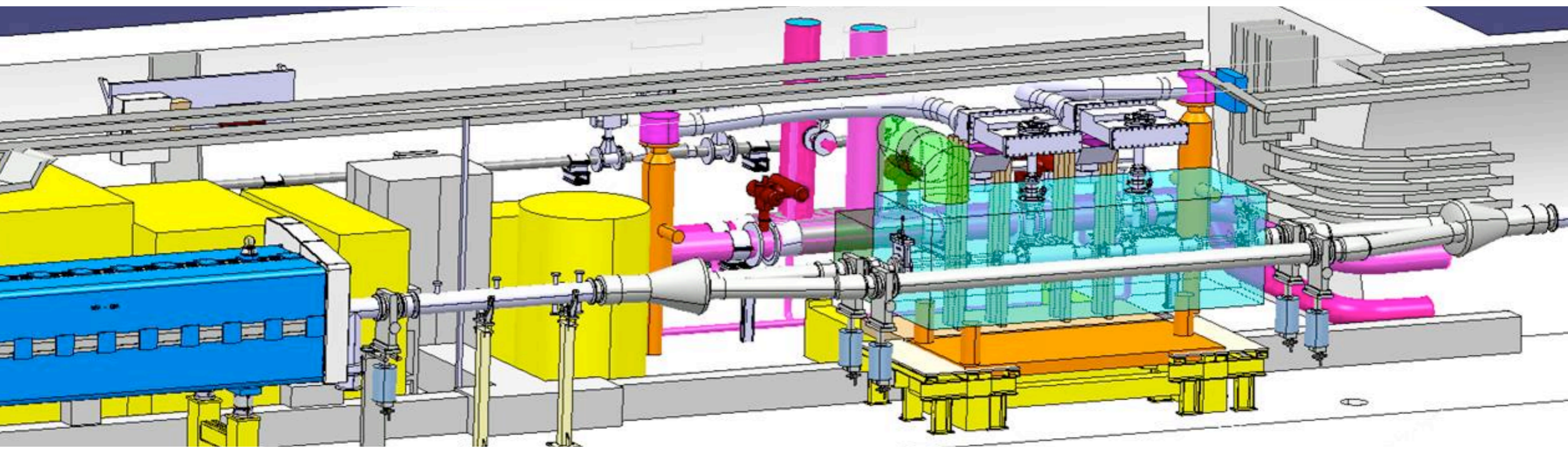
- Crab Cavity module switchable from in-beam to out-of-beam position

=> Mechanical Y-Chamber mounted on support table

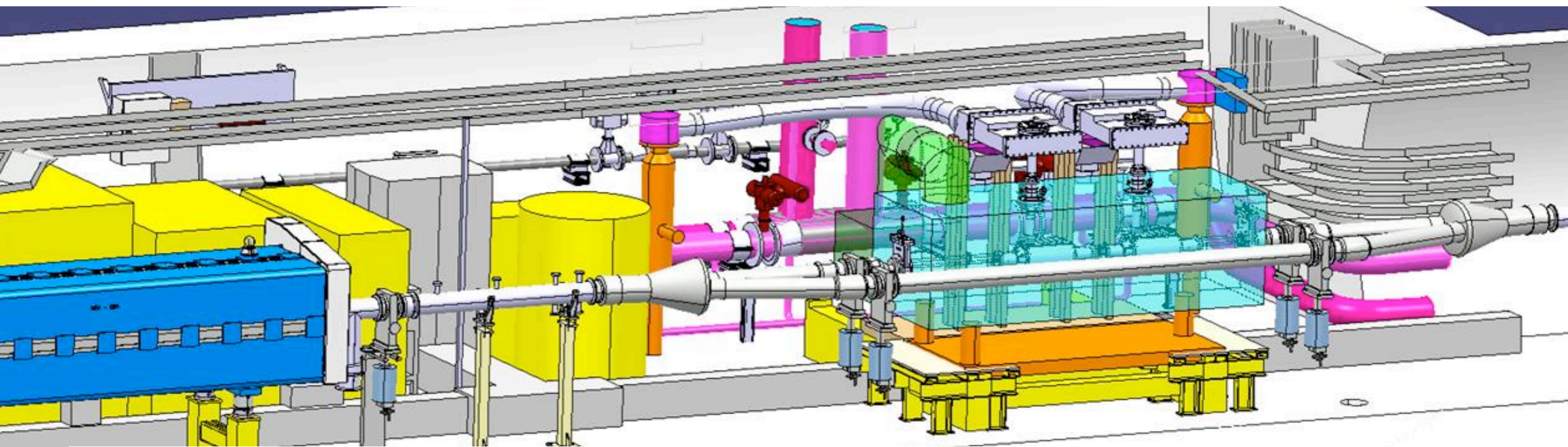


- **Horizontal Movement:** Must be remote controlled
 - Mechanical movement of cold cryomodules, cryo-lines etc
- **Dummy LHC beam pipe integrated into Helium vessel**
 - required to mimic He vessel mechanical rigidity/microphonics expected in LHC

Integration: How the area should look



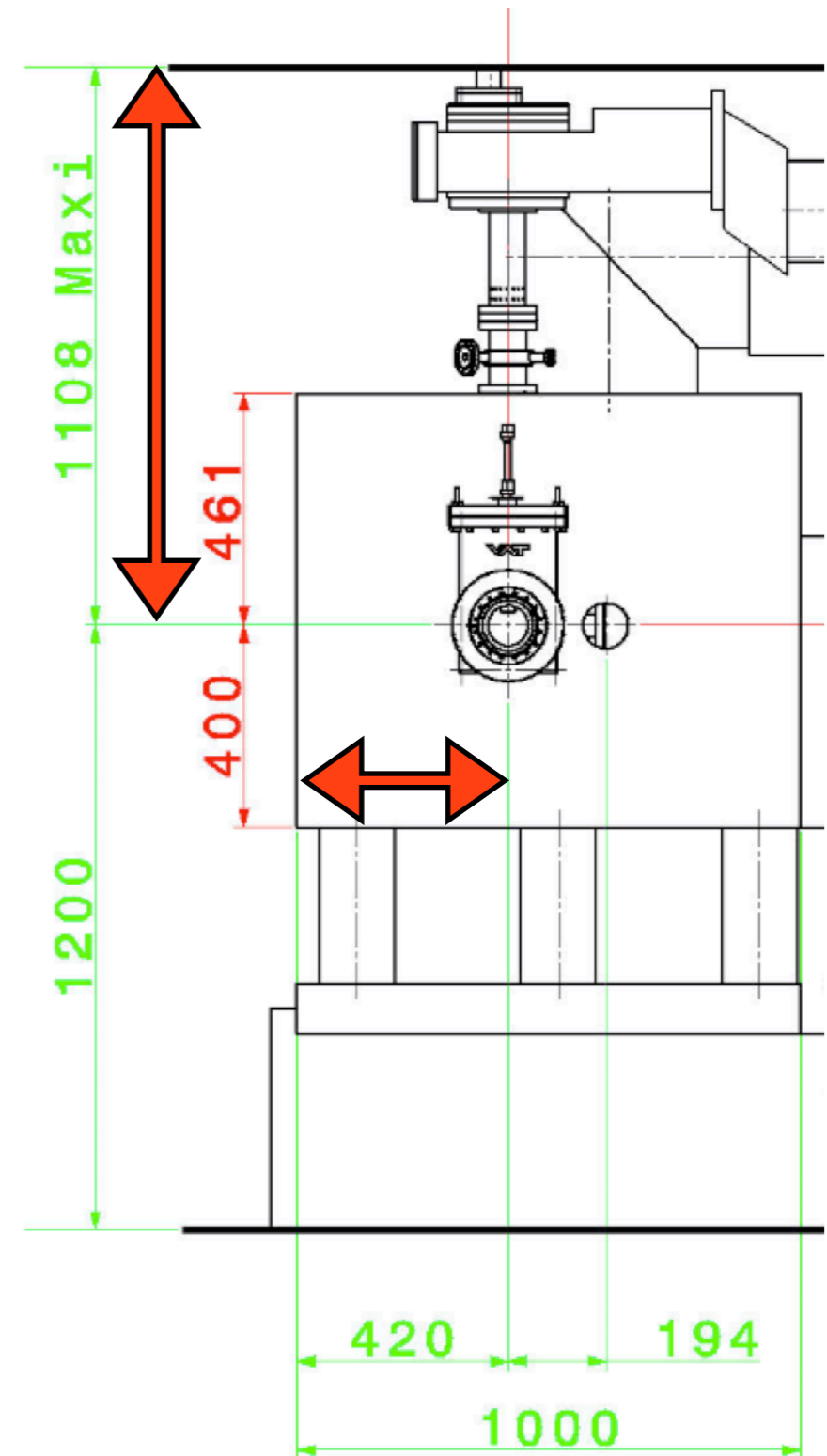
Integration: How the area should look



- **Integration zone: Limited space available**
 - Cryogenics and RF power (2x 400MHz tetrodes) to be **installed in alcove**
- **Support table:**
 - **Load = ~2500kg:** cryo module + 2 circulators + cryo 2K service module
 - **Transverse movement = 51cm. Movement Duration= [20 -30] minutes**
 - Time constraint => **Cryomodule must be moved cold and full of LHe**
 - Horizontal movement and tilt done remotely. Vertical position set manually
 - In beam position: feedback loop to adjust for long term closed orbit drift

Integration issues

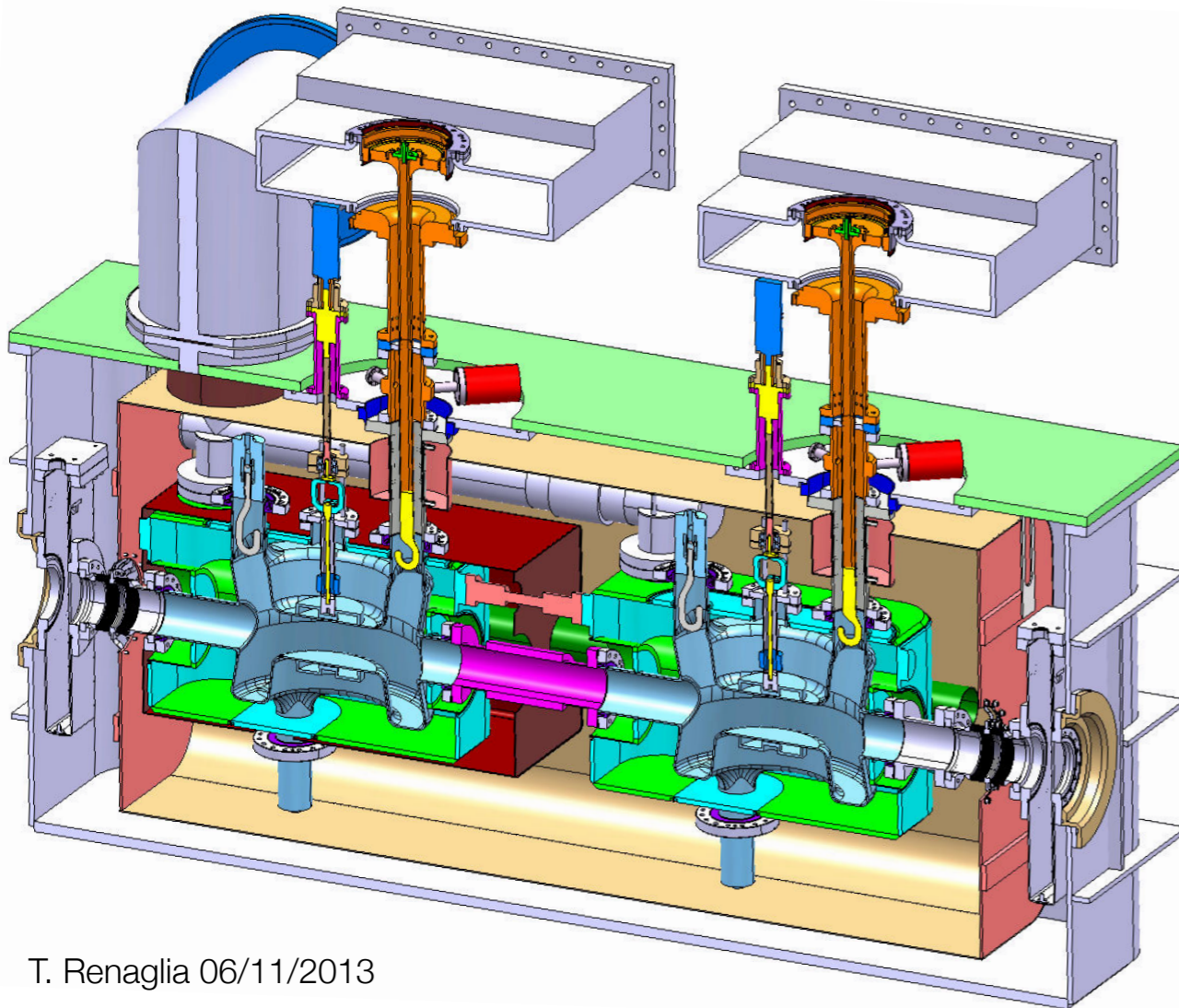
- Distance to SPS bypass => **420mm is maximum space between cavity axis and outer surface of cryo module**
- **Unmovable overpopulated cable trays and mechanical infrastructure => max height (top of cryo module envelope) is 1.108m**
- **Existing Y-chamber for SPS bypass is not sufficient. Needs a new design**
 - Y-Chamber opening angle increased from 12 to 16 degrees
 - Bellows design and impedance studies starting ...
- Longitudinal space not a limiting factor
 - Some upstream beamline space available but access to alcove a concern



SPS Cryomodule Design

SPS tests: 2 identical cavities in 1 cryomodule

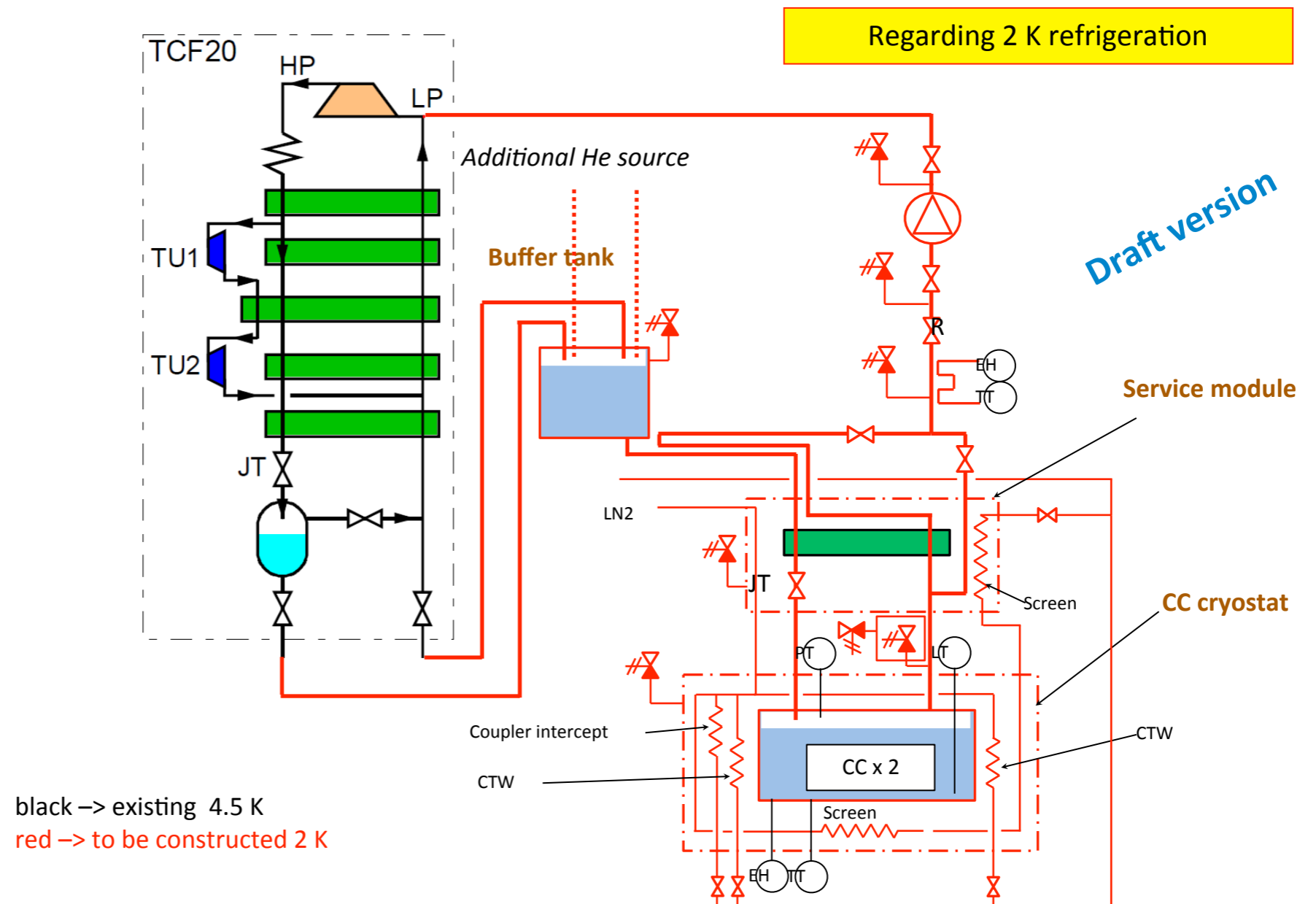
- Cryo modules for SPS not final LHC design
- Cryogenic and power coupler ports to be top mounted



- **Alignment: Adhere to LHC constraints**
 - Transverse inter-cavity alignment
 - **0.7mm = 1σ in dynamic aperture**
- **Active alignment internal to cryomodule not foreseen in SPS test**
- Requirements on cryomodule alignment transferred to constraints on support table positioning accuracy
 - Positioning accuracy $\pm 500 \mu\text{m}$
 - Precision $\pm 100 \mu\text{m}$

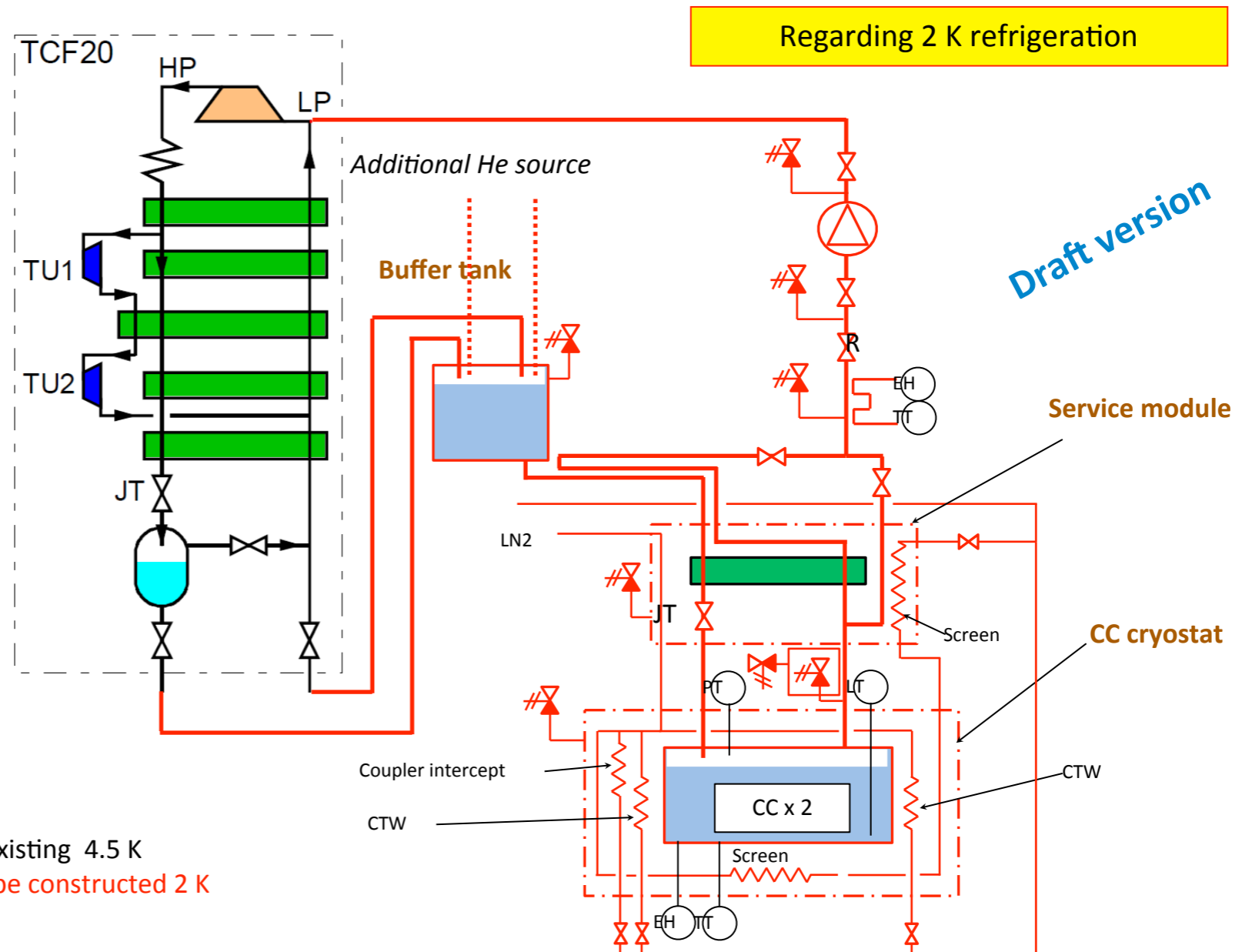
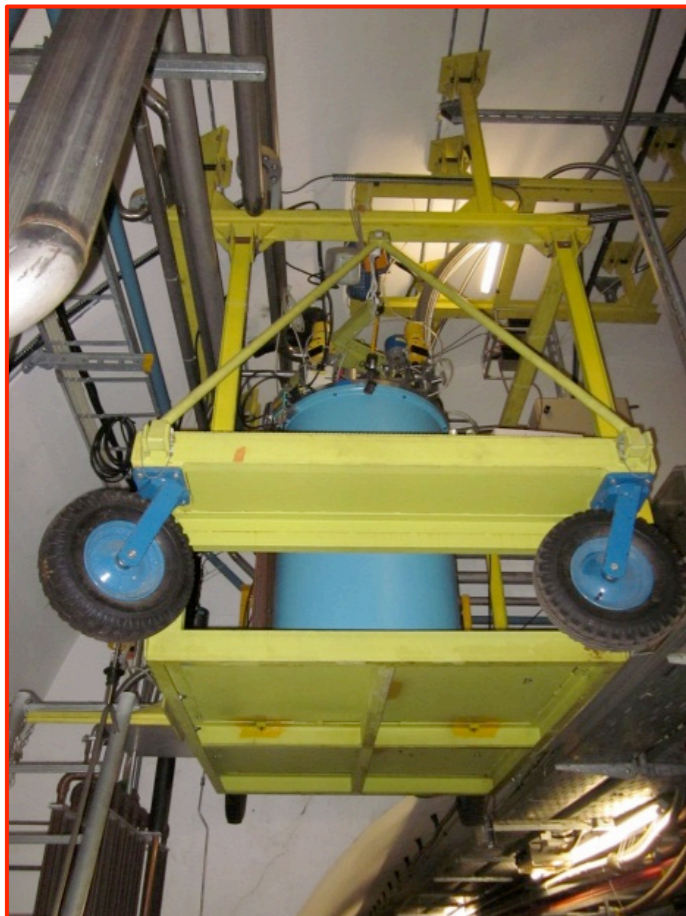
Cryogenics for Crabs in the SPS

- **Crabs to operate at 2K: Cryogenics a key component of the test program**
 - Validation of capacity and reliability ongoing. Infrastructure installed in LS1.
- **Cryogenics at SPS Pt 4 limited in capacity for 2K operation**



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SPS Cryogenics Capacity

Liquefaction capacity [g/s]

0.7 0.85 1.2



CERN isentropic equiv. (20 l/h)

CERN isentropic equiv. with guaranteed refrigeration capacity (85 W)

CERN isentropic equiv. with measured refrigeration capacity (120 W)

New revised static heat load -> ~1.6 g/s

- **Cryogenics installation Objective:**

- **Guarantee > 8hrs of operation (ColdBox + Buffer) ***

- Static heat load: Covered by TCF20 cold box
- Dynamic heat load: Covered by the Buffer tank.

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- Static heat load: Covered by TCF20 cold box
 - Dynamic heat load: Covered by the Buffer tank.

- **Plan A:** Existing ColdBox without LN2 boost + 200L buffer tank. **Not sufficient**

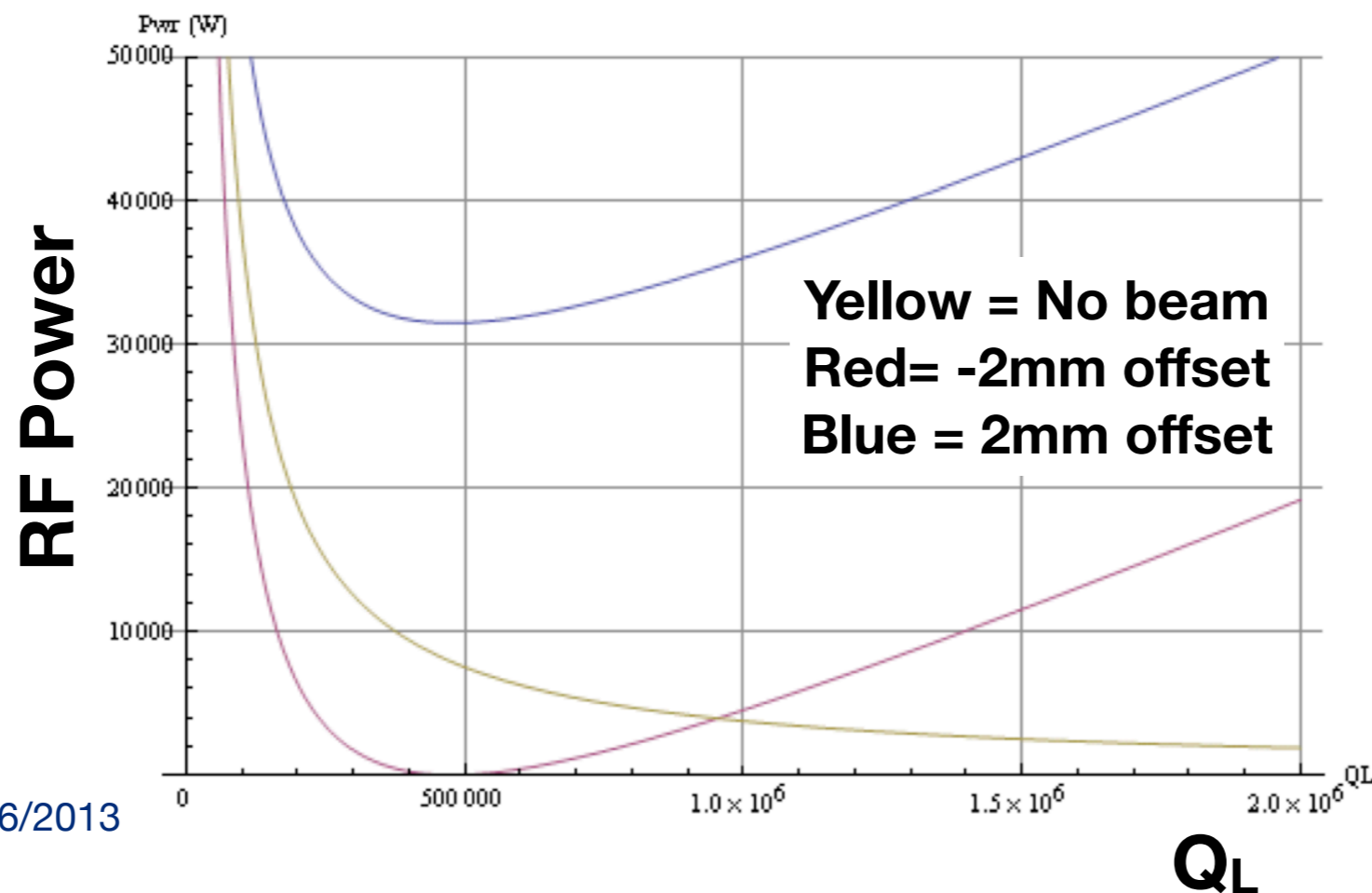
- **Plan B:** Existing ColdBox with LN2 boost + buffer tank. **Measurements ongoing**

- **Plan C:** Install new Cold Box liquefier + with LN2 boost

- **Plan D:** Install 10000L dewar on surface and link it with 200L buffer

Simple observations - power requirements

- **RF Power:** 1 400MHz **50kW** tetrode per cavity: **same for both SPS and LHC**
- Power requirements due to bunched beam loading
 - Cavity at 3 MV with 4*72 bunches of beam at 450GeV. Bunch length=1.6ns
 - **RF Power limitation: Beam offset wrt cavity center < 2mm**
 - 2mm offset \Leftrightarrow 32 kW and $Q_L = 5E5$
 - Add safety margin (30%): Required RF Power = 52 kW. $Q_L = [0.2-1.3] \times 10^6$



**Re-validation test of
at 400MHz ongoing
SPS tetrodes**

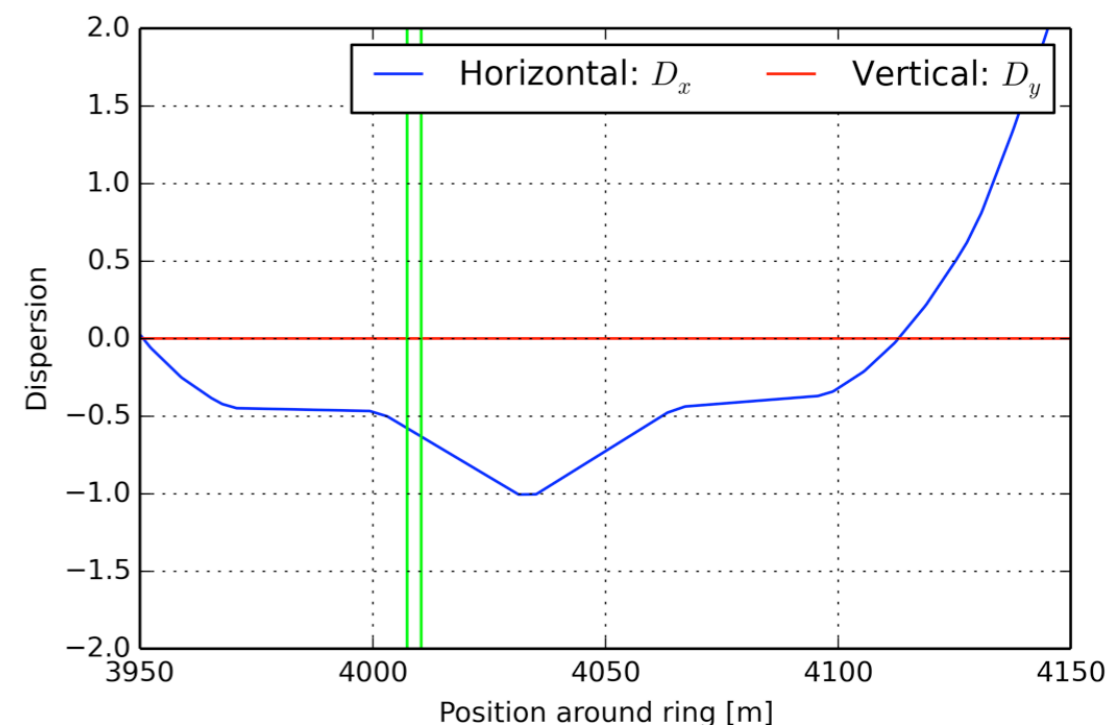
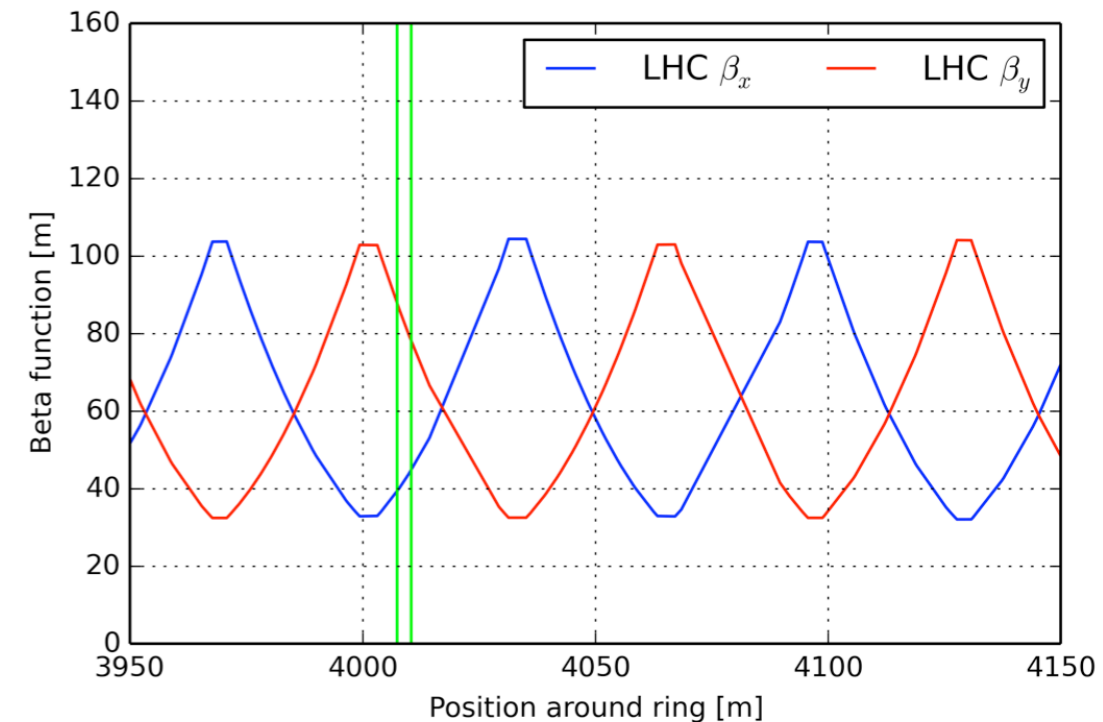
SPS crab cavity location

- **Horizontal and vertical crabbing possibility**

Beta β_x	43.5 m
Beta β_y	83.2 m
Dispersion D_x	-0.609 m
Dispersion D_y	0 m
S location	4009.16 m
phase adv. to HT monitor	60 deg

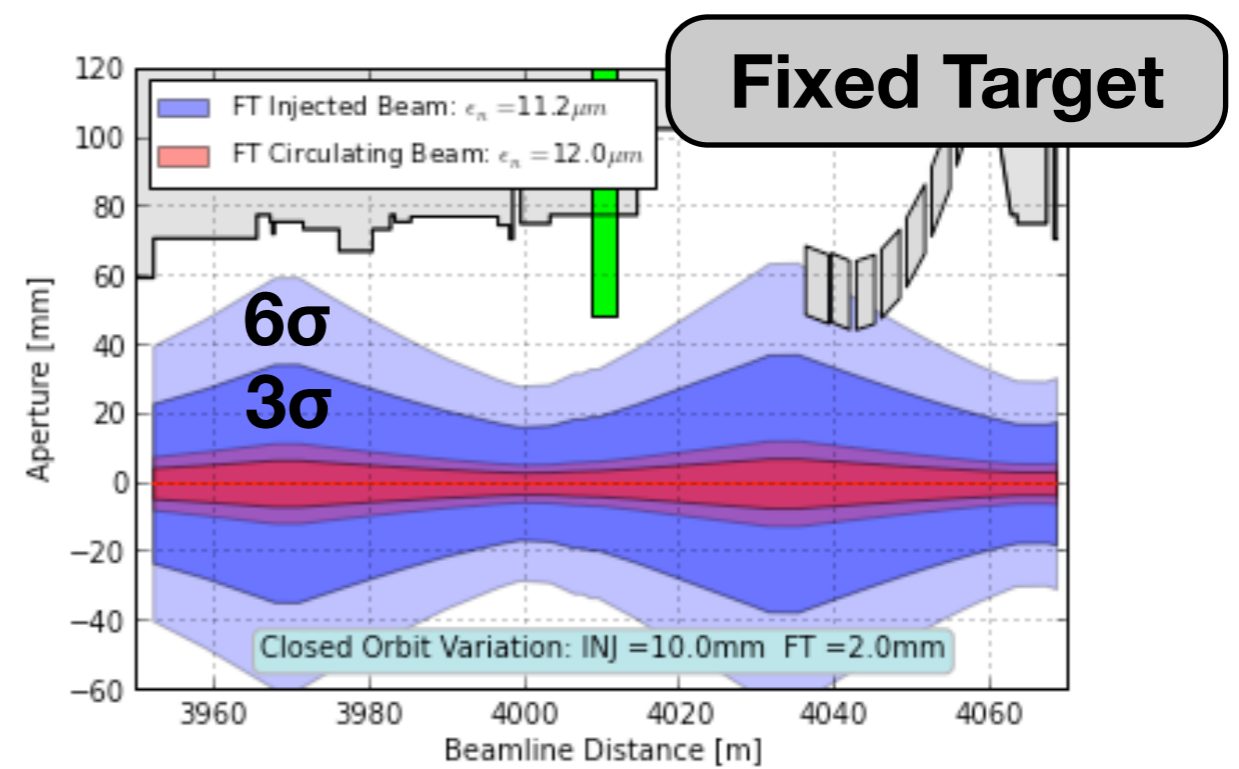
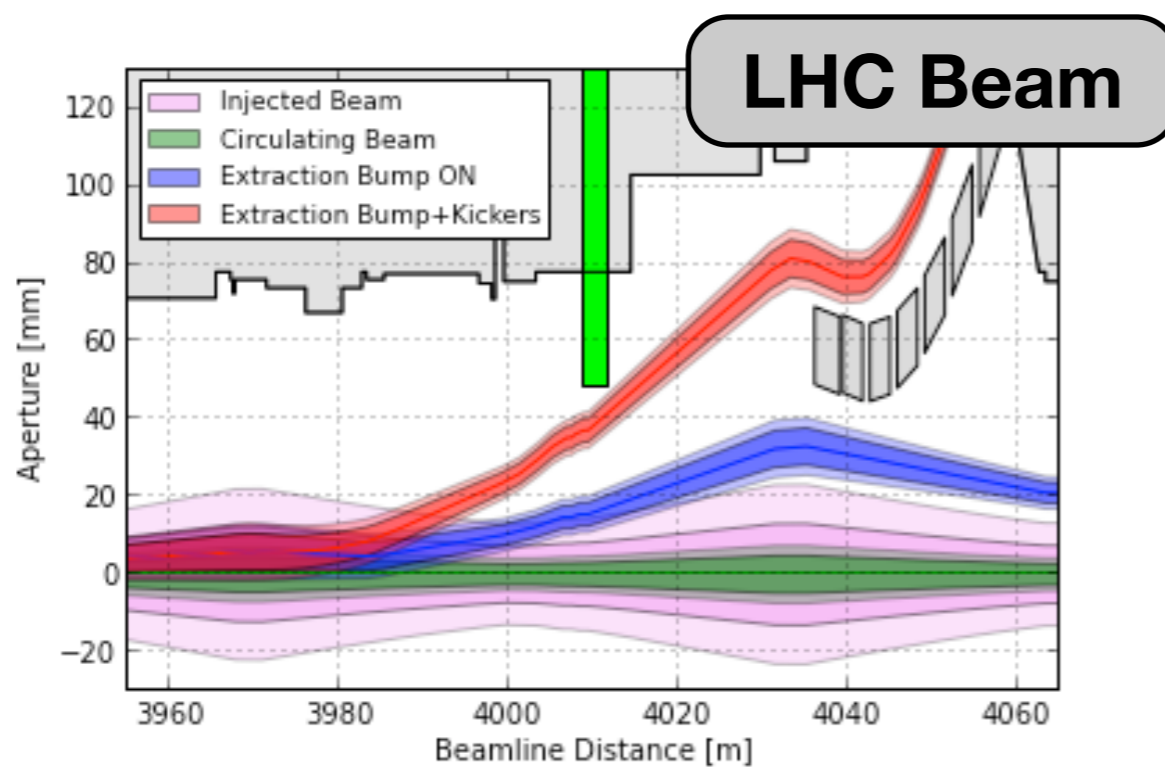
- **Positioning cryo module wrt beam**

- Monitoring transmitted Power
- Support table positioning/alignment
 - Slow feedback loop to adjust for drifts
- Beam adjustment: upstream correctors



SPS: Aperture issues

- **Horizontal aperture:** Crab Cavity = 42mm (radius) Extraction septa = 44.7 mm
 - But 35% gain in margin due to $\beta_{CC} \Rightarrow$ **CC in ~shadow of MSE**
 - **To consider: Feasibility an upstream absorber.** (~1.5m space @ BA4)
- **Crab cavities with SPS beams**
 - **LHC beams: CC** cannot be in when LHC beam extracted
 - **Fixed Target:** beams larger at injection and debunching at slow extraction
 - **To consider: Can CC stay in during SPS Fixed target cycle**
 - Implications to the crab cavity MD request



Operating crab cavities in the SPS

- **Crab operation with beam**

- Cryo capacity limits operation to 8-12 hrs: Buffer tank refill ~16hrs
- CC cannot be in beamline when LHC filling => **Machine Interlocks required**
- 2 Crab Cavities => **Global and Local crabbing schemes possible**
 - **Local scheme** => closed crabbing “bump” => minimal disturbance around ring => suitable for long term + reliability studies
 - **Global scheme** => crabbing and deflecting(90° phase shift) used for direct measurements of functionality

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- **Initial MD time:**

- Dedicated MD: establish operational parameters and procedures
- Invisibility criteria: Establish compatibility with SPS operation

- **Subsequent testing time:** measurement and performance program

- Dedicated MD time with coasting beam for long term effects

- **Possibility of CC cycle in SPS supercycle:**

- CC performance tests + Machine protections tests

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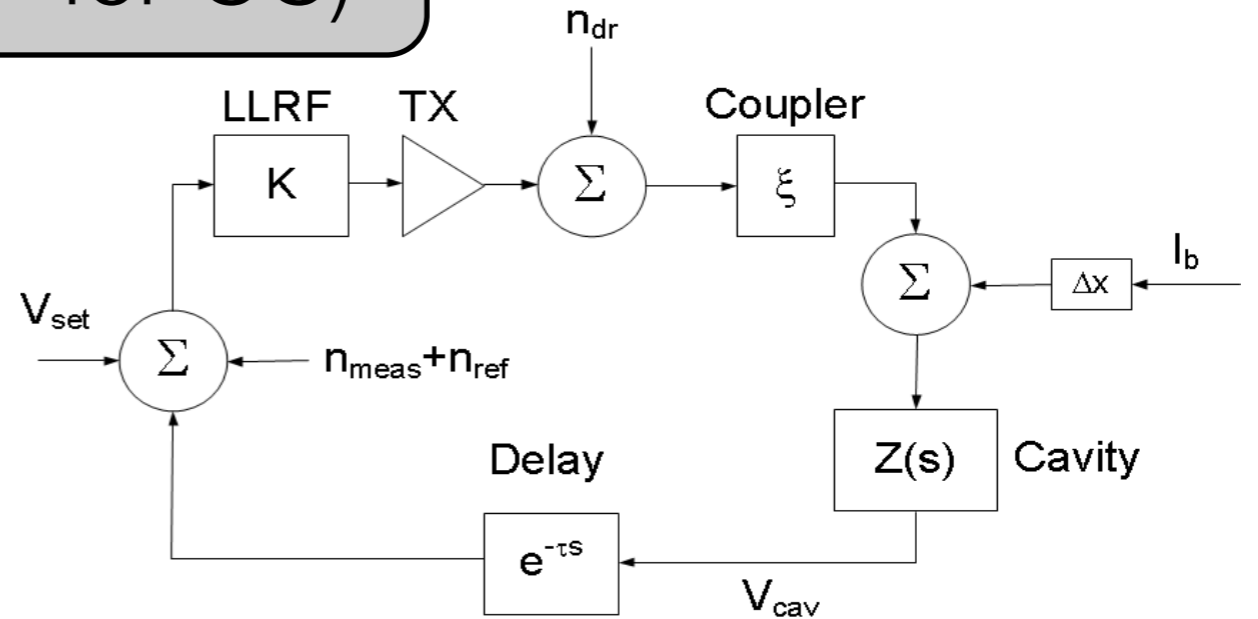
**Outline structure of CC
beam time request at
IEFC in early 2014**

- **Subsequent testing time:** measurement and performance program

- Dedicated MD time with coasting beam for long term effects
- **Possibility of CC cycle in SPS supercycle:**
 - CC performance tests + Machine protections tests

Cavity RF Noise

- RF feedback noise sources:
 - ▣ The RF **reference noise** n_{ref}
 - ▣ The demodulator noise (**measurement noise**) n_{meas}
 - ▣ The **TX (driver) noise** n_{dr} (process noise). It includes also the LLRF noise not related to the demodulator
 - ▣ The Beam Loading $I_b \Delta x$
- We get



$$Z(s) = \frac{\omega}{c} \frac{\left(\frac{R}{Q}\right)_{\perp} Q_L}{1 + 2 Q_L \frac{s}{\omega_0}}$$

with $s = j \Delta\omega$

Main coupler

$$V_{cav} = \frac{K G e^{-\tau s} Z(s)}{1 + K G e^{-\tau s} Z(s)} [V_{set} + n_{ref} + n_{meas}] + \frac{Z(s)}{1 + K G e^{-\tau s} Z(s)} \left[\Delta x \quad I_b + \sqrt{\frac{Z_0}{\frac{R}{Q} Q_L}} n_{dr} \right]$$

Closed Loop response CL(s)

- Equal to ~1 in the CL BW
- Increase of K increases the BW
- Within the BW, reference noise and measurement noise are reproduced in the cavity field

Beam Loading response = effective cavity impedance Zeff(s)

- Equal to ~1/KG in the CL BW
- Increase of K decreases Zeff within the CL BW
- Within the CL BW, TX noise and beam loading are reduced by the Open Loop gain KG

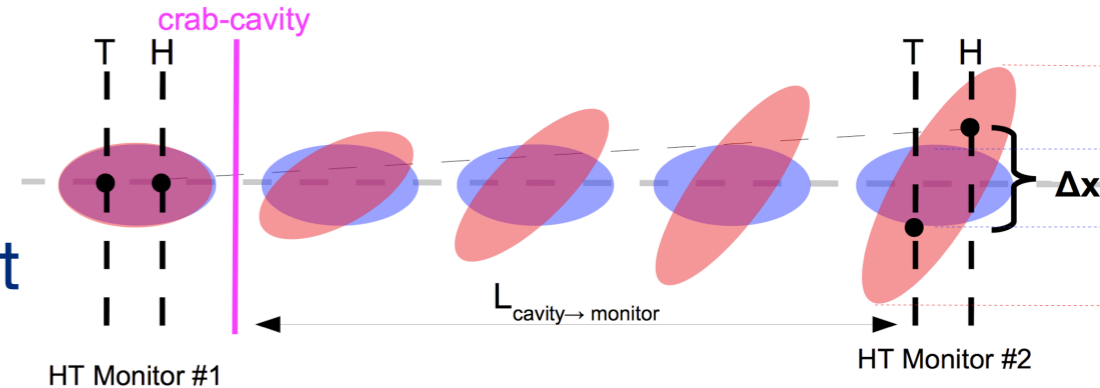
Simple observables

- **Closed Orbit**

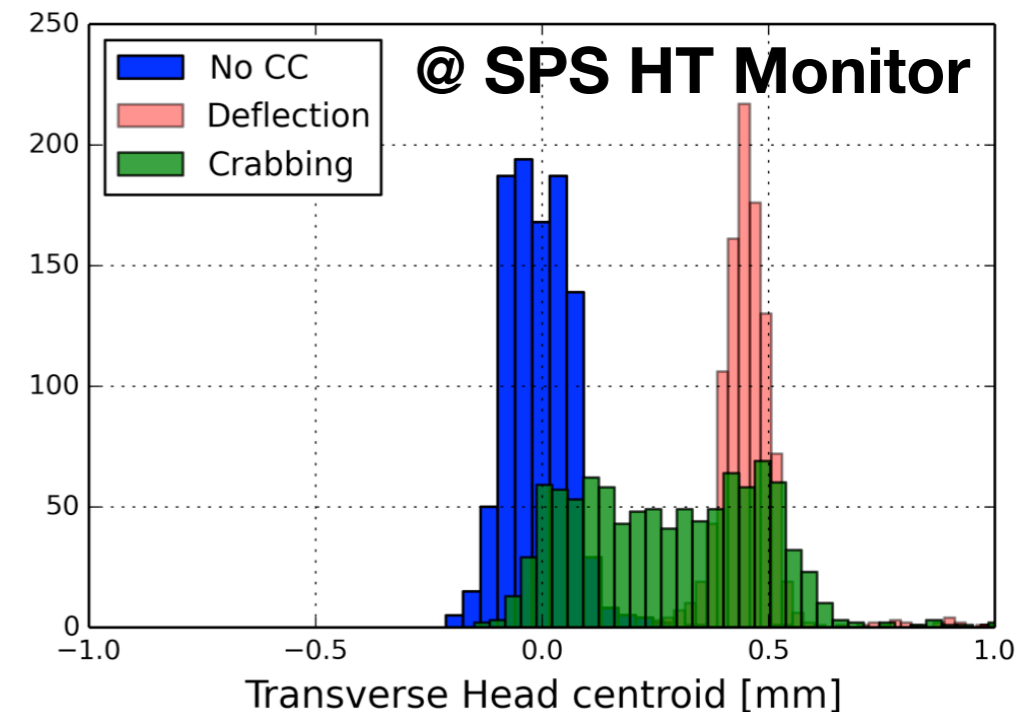
- LHC beam: 450 GeV, Cavity Voltage: 3 MV
- Observe: Closed orbit transverse position at 90° phase advance from CC
- Global scheme in deflecting mode: ~1mm offset, no amplitude growth.

- **Head Tail**

- LHC beam: 450 GeV, Cavity Voltage: 3 MV.
- Observe: transverse beam centroids at SPS HeadTail monitor
- Crabbing Mode: Expect broadening of head-tail centroids
- Deflecting Mode: No significant change in head-tail centroids



Head Tail: see R. Steinhagen 4th LHC CC workshop



MADX thin track simulations

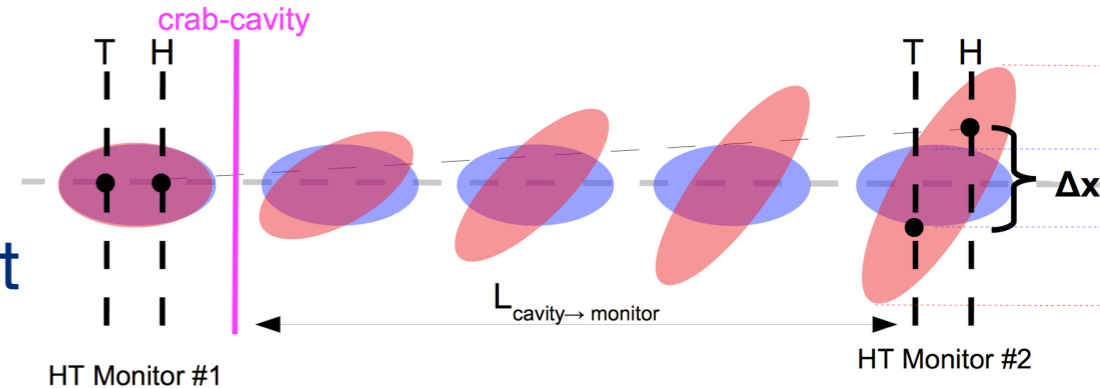
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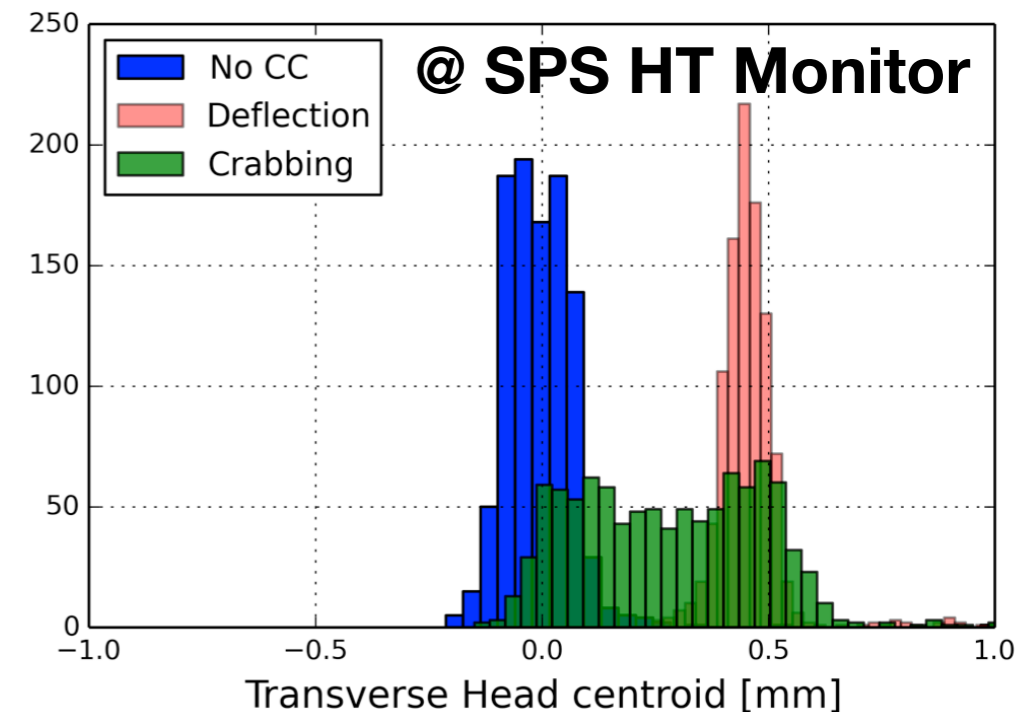
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MADX thin track simulations

Need a catalog of achievable SPS observables that categorize SPS CC functionality and failure modes

Comments and other things to note

- **SPS Test duration: Nominal SPS MD time spread over 2 years prior to LS2**
 - Could foresee test of more than 1 cryomodule in SPS
 - Foresee initial installation in SPS over Xmas shutdown [typical time ~8 wks]
 - Initial CC installation (cryomodule, RF power) cannot start until after Coldex finish tests in 2015 and removed.
- **SPS Integration work ongoing:** Space is tight but no show stoppers
- **Measurement program** structure needs definition in order to clarify beam time and beam instrumentation requests
- **A few dates**
 - Install cryogenics infrastructure (except 2K service unit) by end SPS_LS1
 - Conceptual designs of cryomodule: expected end of 2013
 - Power couplers available for cryostating: Q2 2015
 - SM18 cryomodule test == 1st cold test of dressed cavity: late 2015
- **Active alignment concept** (internal to cryomodule) not in scope of SPS test.
 - To be done in SM18 prior to LHC

Spare slides

LLRF Location: ECA4

- LLRF: Racks can be installed ~40 m away from CC installation next to shielding wall, with controls area in counting house at back of ECA4
- Access to ECA4 counting house: anytime
- Access to rack location next to shielding wall: only when no beam

