



Foreseen interlocks for the operation of crab cavities in SPS

G. Vandoni

SPS and LHC Machine Protection Panel – 9th December 2016

Mastering the language...



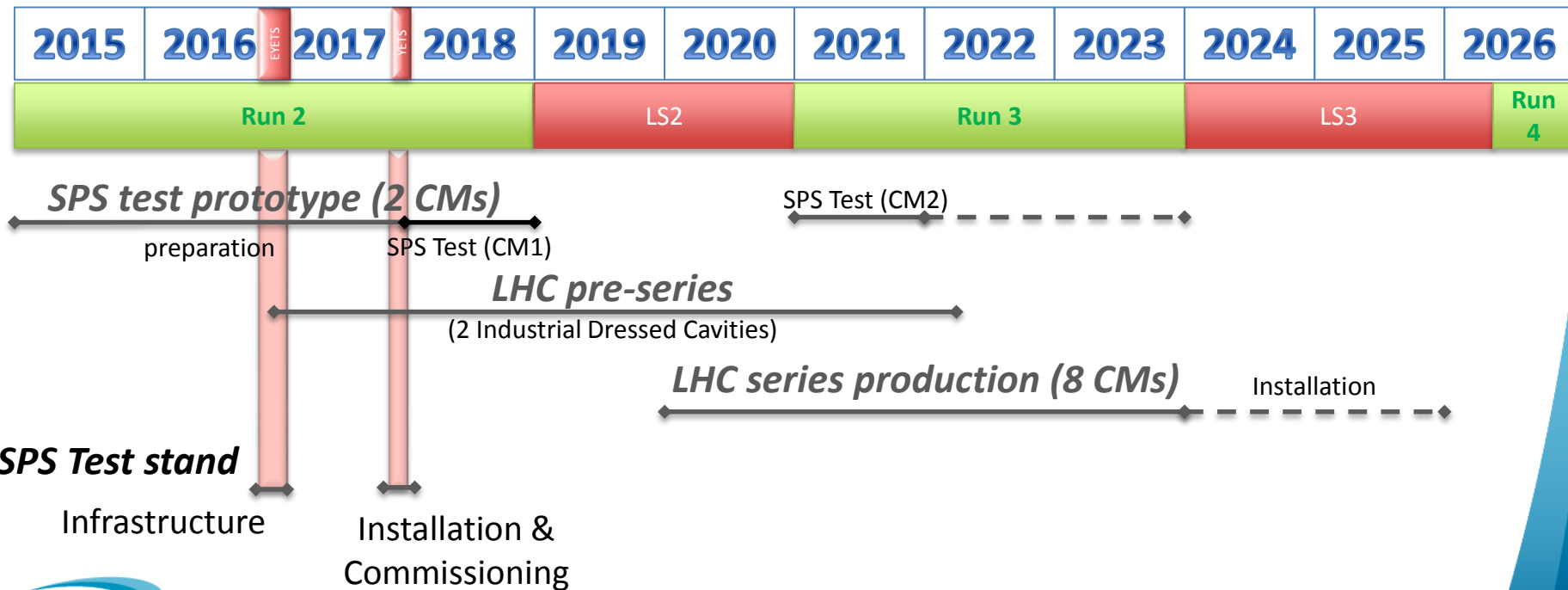
HL-LHC Crab cavities in the SPS

Crab-cavities never tested in hadron beam

Prerequisite for *series production* and *installation in LHC* is the validation of feasibility of safe operation with proton beams

SPS Test-scope

Test 2 prototype cryomodules, DQW (run 2018) and RFD (run 2021)



MD Parameters

Crab cavity tests with proton beams in the SPS

	Units	Value
Energy	GeV	26 – 450
Coast Energy	GeV	55, 120, 270
Intensity	p/bunch	$0.05 - 1.3 \times 10^{11}$
RF Voltage	MV	3.0 – 7.0
4 th Harmonic Voltage	MV	0.0
Bunch Length	ns	< 2.0
Longitudinal Emittance	eVs	0.35 – 0.5
Betatron Tunes		26.12, 26.18
$\beta_{x,y}$	m	40, 80
Dispersion	m	-0.5

G. Arduini, R. Calaga, R. Jones, @ [SPS Test Day #1](#)

Cavity Parameters

	Units	Value
Frequency	MHz	400.79
Number of Cavities		2
Kick Voltage/cavity	MV	3.4
R/Q (linac convention)	Ω	~ 400
Max RF Power	kW	40 (80)
Cavity detuning	kHz	± 100 (-60)
Cavity bandwidth	Hz	800

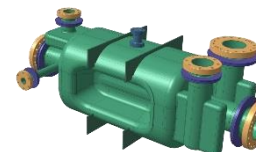
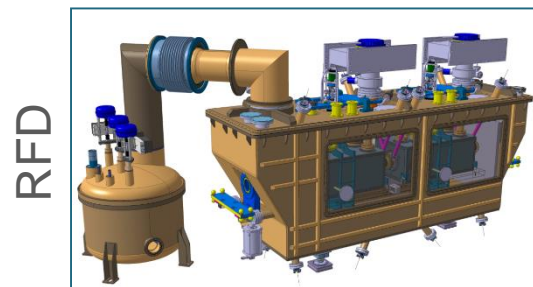
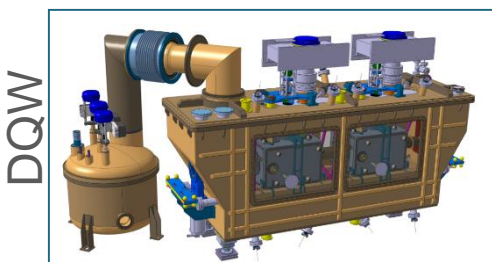


Table
courtesy R.Calaga

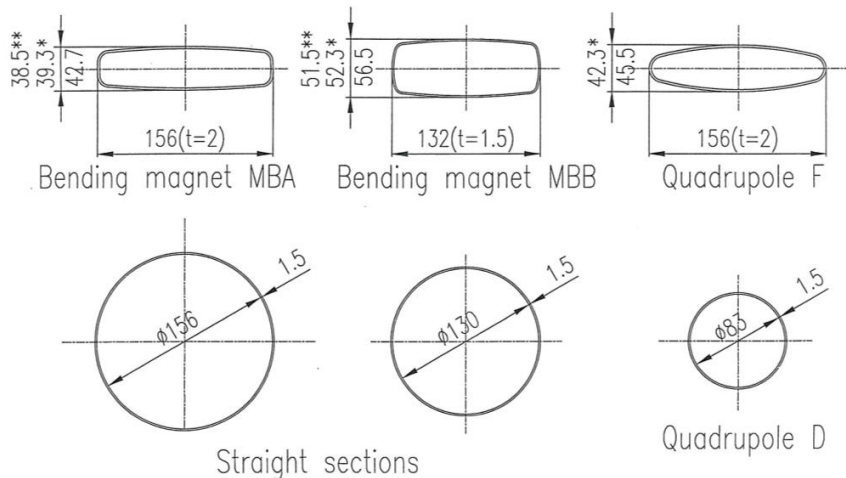


Aperture considerations

	Units	Value
Total Bypass length	m	9.5
Bypass Aperture	mm	156
Cavity Aperture	mm	84
Transverse Cavity Alignment	mm	≤ 0.5
Transverse Tilt	degrees	< 0.3

SPS MAIN VACUUM CHAMBERS

- * Under vacuum
- ** When compressed in magnet




H.Bartosik @

SPS Test Day, I

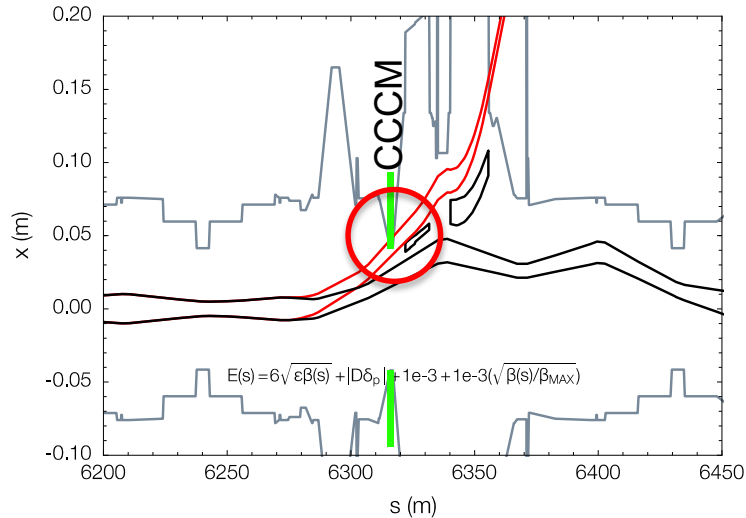
<https://indico.cern.ch/event/463435/>

Crab cavity aperture
(equivalent to "QD")

Compatibility of crab-cavity CM with SPS Operation


 CCCM aperture

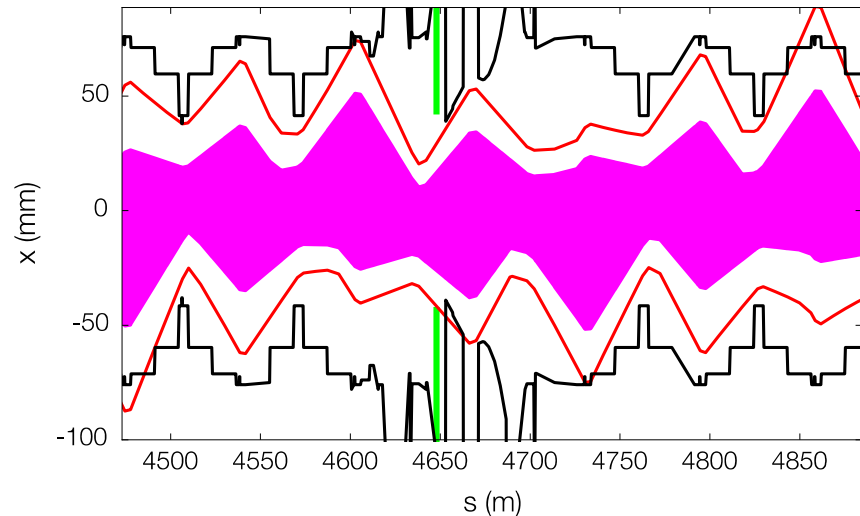
LHC beam extraction in LSS6



Fast extraction to LHC

Crab-cavity in beam does not yield enough aperture for extracted beam

NA slow extraction in LSS6



Slow extraction of fixed target beam

at 400GeV, incl. extraction bump

purple : raw beam envelope

red: beam envelope + tolerance

Crab cavity in beam is compatible with slow extraction to North Area

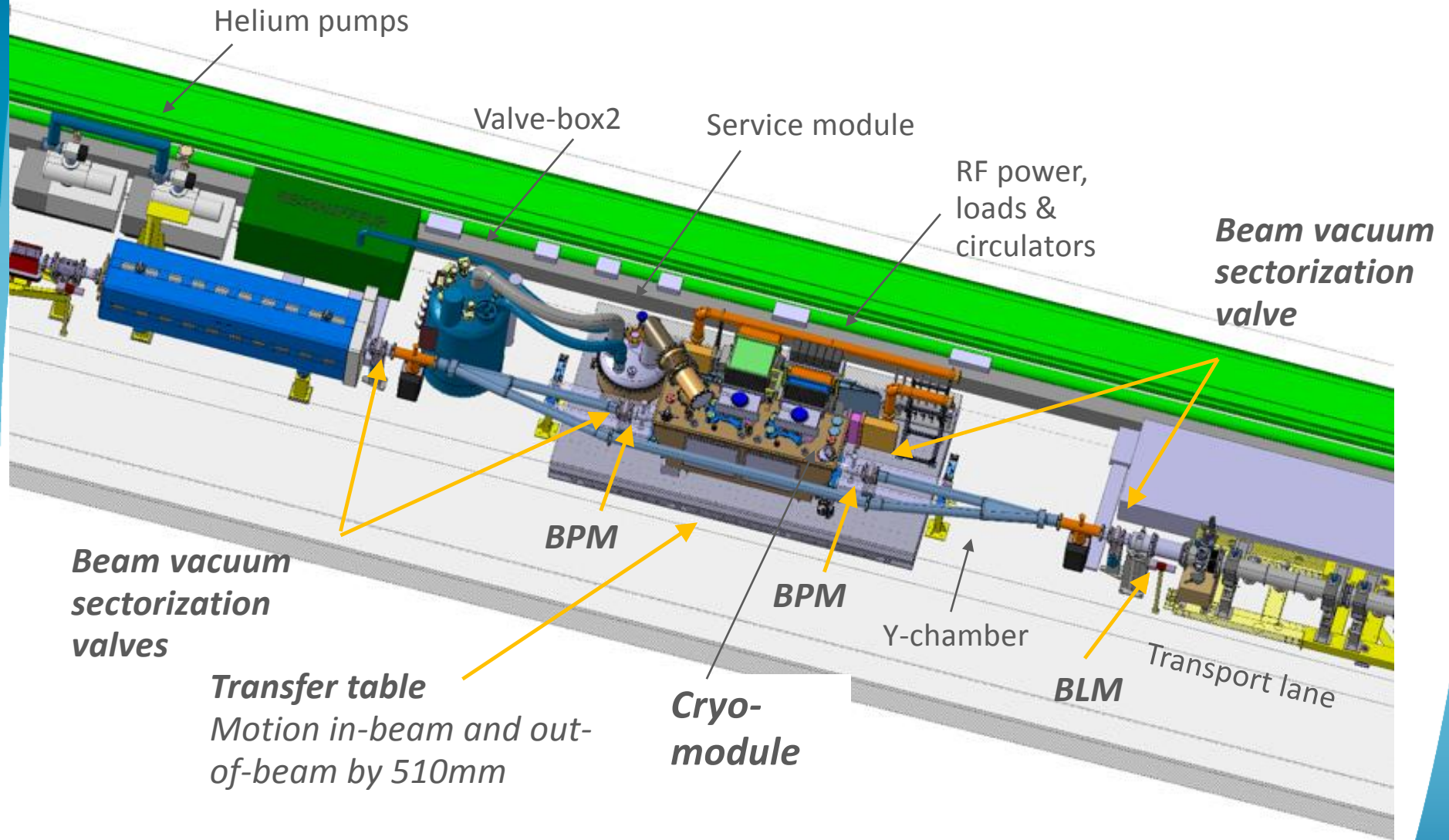
No need for bumper dipole interlocking
(opp. to Coldex)

H.Bartosik @

SPS Test Day, I

<https://indico.cern.ch/event/463435/>

HL-LHC CrabCavity SPS test stand layout



System architecture in SPS point 6

~40m

PA6 - shaft

RF power coaxials

Warm Cryo pipework

BA6 – surface area

RF power amplifiers IOT

Cryogenic compressor

LLRF Faraday cage
Racks, utilities

Crab-cavity
test stand

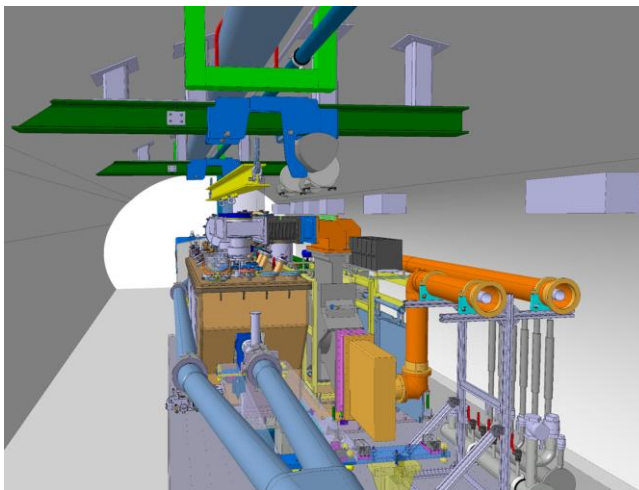
Cryo distribution line

~110m

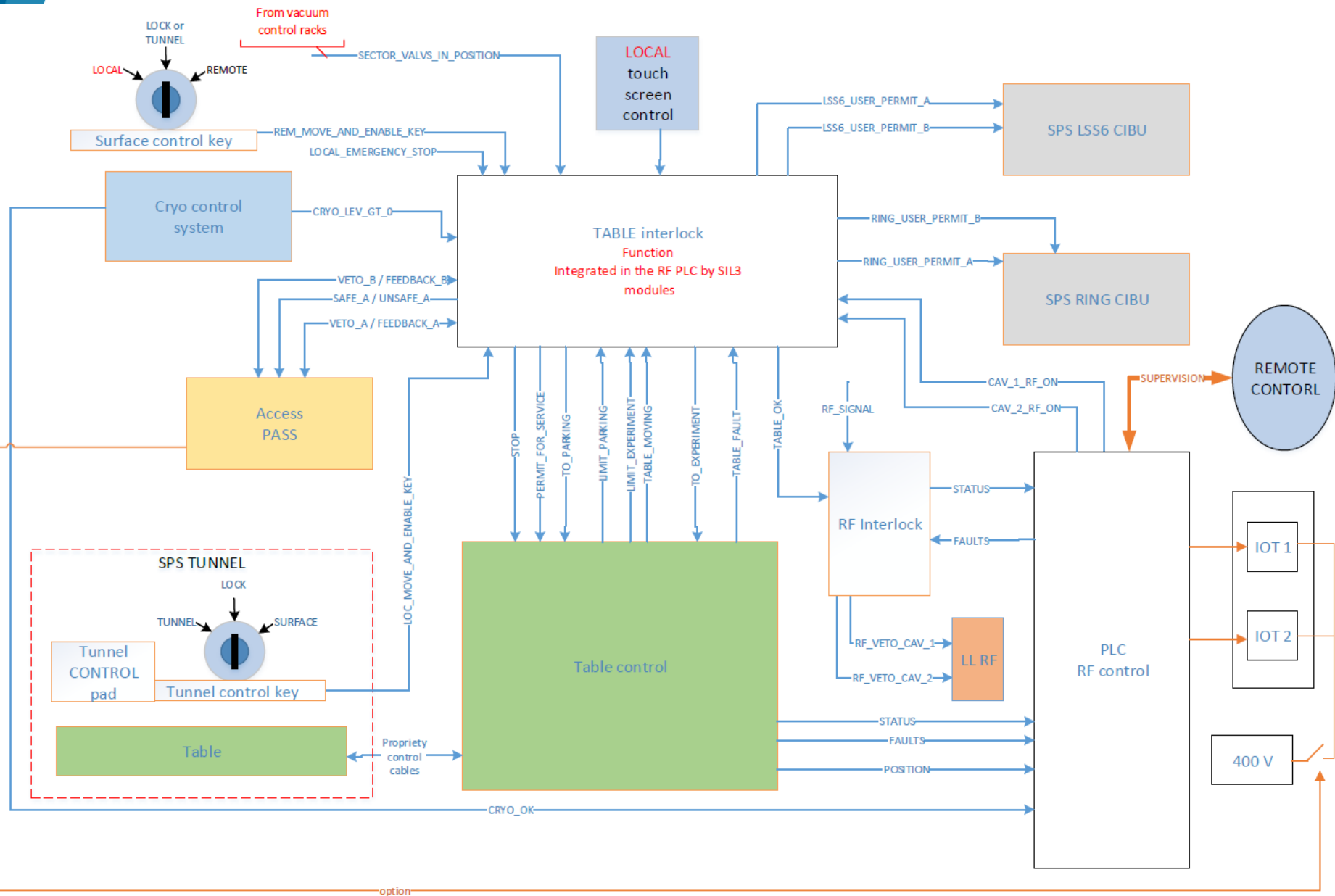
TA6 - alcove

Cold-box
Valve-box

New handling equipment

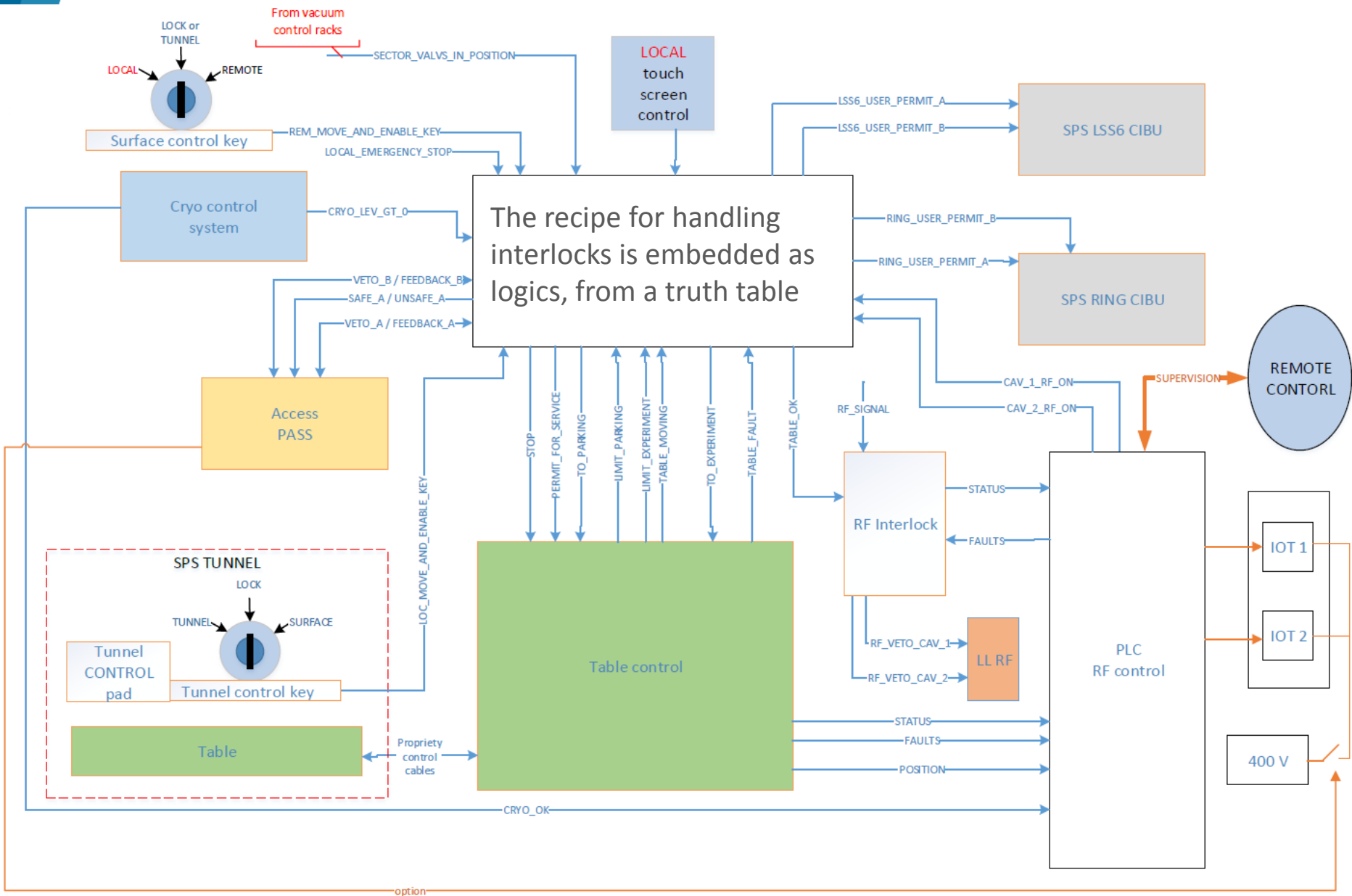


RF and Table controls



option

RF and Table controls



Truth Table

		INPUT																						
		enabled/disabled	Access and		RF			BI	RP	Transfer Table					Cryogenics		Vacuum, beam and insulation							
(U) nmaskable/(M) askable		Access safe SPS chain 1	Access safe BA6	RF power ON	RF reflected power	Cavity field	Set of RF conditions	BLIM signal	Rpsignal < level 1	OUT_switch contact	IN_switch contact	Table error	Table moving	Table move enable (remote key)	Table move enable (local key)	Cryo 1 OK	LHe level > 0 in the cryomodule	Vacuum_beam 1 level 1 OK	Vacuum_Beam 2 OK	Isolation vacuum 1 OK	VVS1 & VVS3 open	VVS2 & VVS4 open		
OUTPUT																								
Safety	RF Power	enabled	TRUE							TRUE		FALSE	FALSE	FALSE										
	RF Power	enabled	TRUE								TRUE	FALSE	FALSE	FALSE										
	Table move enable	enabled	TRUE		FALSE										TRUE							FALSE	FALSE	
	Table move enable	enabled	FALSE													TRUE		FALSE				FALSE	FALSE	
		V1 & V3 open	enabled								FALSE	TRUE	FALSE	FALSE	FALSE				TRUE	TRUE				
Machine protection	U Beam OK (table out of beam)	enabled	TRUE							TRUE	FALSE	FALSE	FALSE	FALSE									TRUE	
	U Beam OK (table in beam)	enabled	TRUE							FALSE	TRUE	FALSE	FALSE	FALSE								TRUE	TRUE	
	U Beam extraction LSS6 OK (table out of beam)	enabled								TRUE	FALSE	FALSE	FALSE	FALSE										
	M Beam OK (table in beam)	disabled								FALSE	TRUE	FALSE	FALSE	FALSE										
	M Beam OK (SPS protection)	disabled				TRUE	TRUE		TRUE															
Cav	M Beam OK (cavity protection)	disabled					TRUE	TRUE																
Equipment	RF Power	enabled														TRUE		TRUE		TRUE				
																TRUE		TRUE		TRUE				

Truth Table

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Safety	(U) nmaskable/(M) askable	enabled/disabled																					
	RF Power	enabled	TRUE							TRUE		FALSE	FALSE	FALSE									
	RF Power	enabled	TRUE								TRUE	FALSE	FALSE	FALSE									
	Table move enable	enabled	TRUE		FALSE										TRUE							FALSE	FALSE
	Table move enable	enabled	FALSE													TRUE		FALSE				FALSE	FALSE
	V1 & V3 open	enabled									FALSE	TRUE	FALSE	FALSE	FALSE				TRUE	TRUE			
Machine protection	U Beam OK (table out of beam)	enabled	TRUE							TRUE	FALSE	FALSE	FALSE	FALSE									TRUE
	U Beam OK (table in beam)	enabled	TRUE							FALSE	TRUE	FALSE	FALSE	FALSE								TRUE	TRUE
	U Beam extraction LSS6 OK (table out of beam)	enabled								TRUE	FALSE	FALSE	FALSE	FALSE									
	M Beam OK (table in beam)	disabled								FALSE	TRUE	FALSE	FALSE	FALSE									
M Beam OK (SPS protection)	disabled				TRUE	TRUE		TRUE															
Cav M Beam OK (cavity protection)	disabled					TRUE	TRUE																
Equipment	RF Power	enabled														TRUE		TRUE		TRUE			
																TRUE		TRUE		TRUE			

Truth Table

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OUTPUT																							
Safety	RF Power	enabled	TRUE							TRUE		FALSE	FALSE	FALSE									
	RF Power	enabled	TRUE								TRUE	FALSE	FALSE	FALSE									
	Table move enable	enabled	TRUE		FALSE										TRUE							FALSE	FALSE
Machine & cavity Protection		enabled	FALSE												TRUE		FALSE					FALSE	FALSE
	V1 & V3 open	enabled								FALSE	TRUE	FALSE	FALSE	FALSE				TRUE	TRUE				
Machine protection	U Beam OK (table out of beam)	enabled	TRUE							TRUE	FALSE	FALSE	FALSE	FALSE									TRUE
	U Beam OK (table in beam)	enabled	TRUE							FALSE	TRUE	FALSE	FALSE	FALSE								TRUE	TRUE
	U Beam extraction LSS6 OK (table out of beam)	enabled								TRUE	FALSE	FALSE	FALSE	FALSE									
	M Beam OK (table in beam)	disabled								FALSE	TRUE	FALSE	FALSE	FALSE									
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Equipment	RF Power	enabled														TRUE		TRUE		TRUE			
																TRUE		TRUE		TRUE			

Truth Table

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	Table move enable	enabled	FALSE												TRUE		FALSE					FALSE	FALSE
	V1 & V3 open	enabled									FALSE	TRUE	FALSE	FALSE	FALSE				TRUE	TRUE			
Machine protection	U Beam OK (table out of beam)	enabled	TRUE							TRUE	FALSE	FALSE	FALSE	FALSE									TRUE
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																TRUE		TRUE		TRUE			

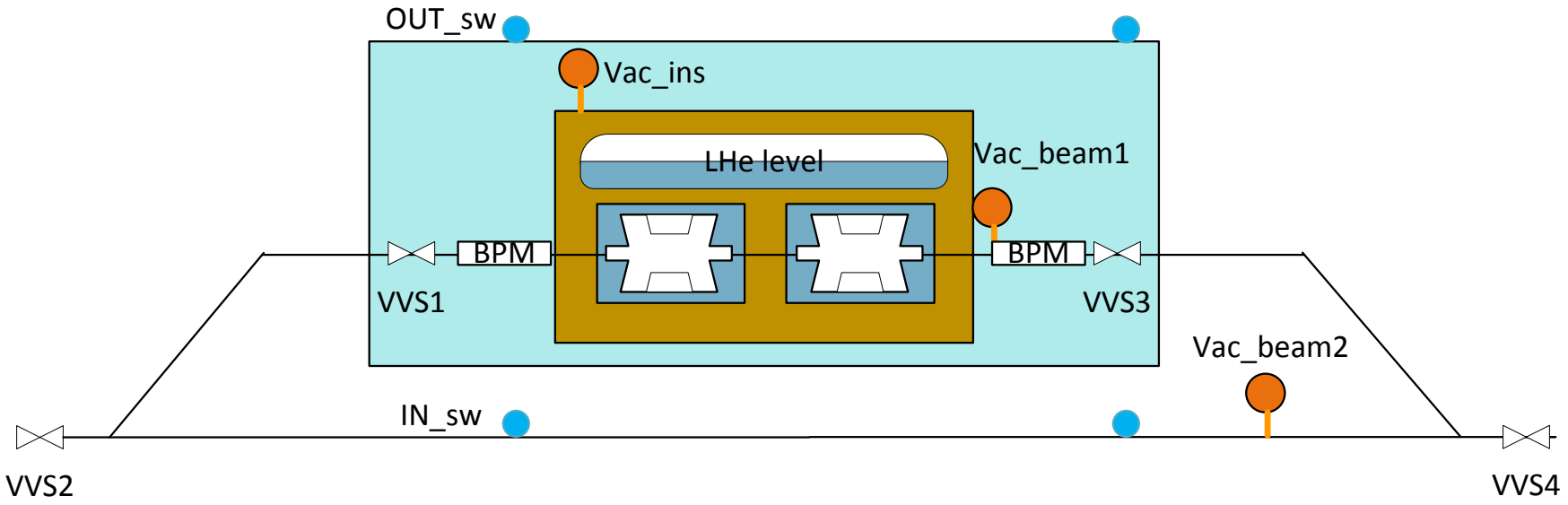
Equipment Protection

The latter much more extended than shown here

Main Safety Hazards

	Hazard	Origin	Location
RF Power	RF power 400MHz equipment and amplifiers, 80kWx2		
	Radiological risk	Stray electrons, X-rays	Tunnel, alcove
	High voltage hazard	RF power equipment	Tunnel, BA6
Cryogenics	Presence of cryogenic fluids, 400l (50kg) LHe in tunnel (+70kg in external gas storage), LN ₂		
	Oxygen Deficiency Hazard	Cryo spillout Risk increased by table movement	Tunnel, TA6
	Pressure hazard	Pressurized Cryo equipment	Tunnel, BA6
	Noise	Cryo compressor	BA6
	Environmental risk	Compressor machine oil	BA6
Mechanical	Pressure, movement		
	Pressure hazard	Cryomodule elements	Tunnel
	Mechanical risk	Transfer Table	Tunnel

Valves layout



Summary of truth table for Safety

	Enable/ disable	SPS Access safe	RF Power ON	Table OUT	Table IN	Table key OK	V1&V3 open	V2&V4 open	He Level >0
1 RF Power ON	Enable	TRUE		TRUE					
2 RF Power ON	Enable	TRUE			TRUE				
3 Table move	Enable	TRUE	FALSE				FALSE	FALSE	
4 Table move (local)	Enable	FALSE	FALSE			TRUE	FALSE	FALSE	FALSE
4 V1&V3 open	Enable				TRUE				

Summary of truth table for Safety

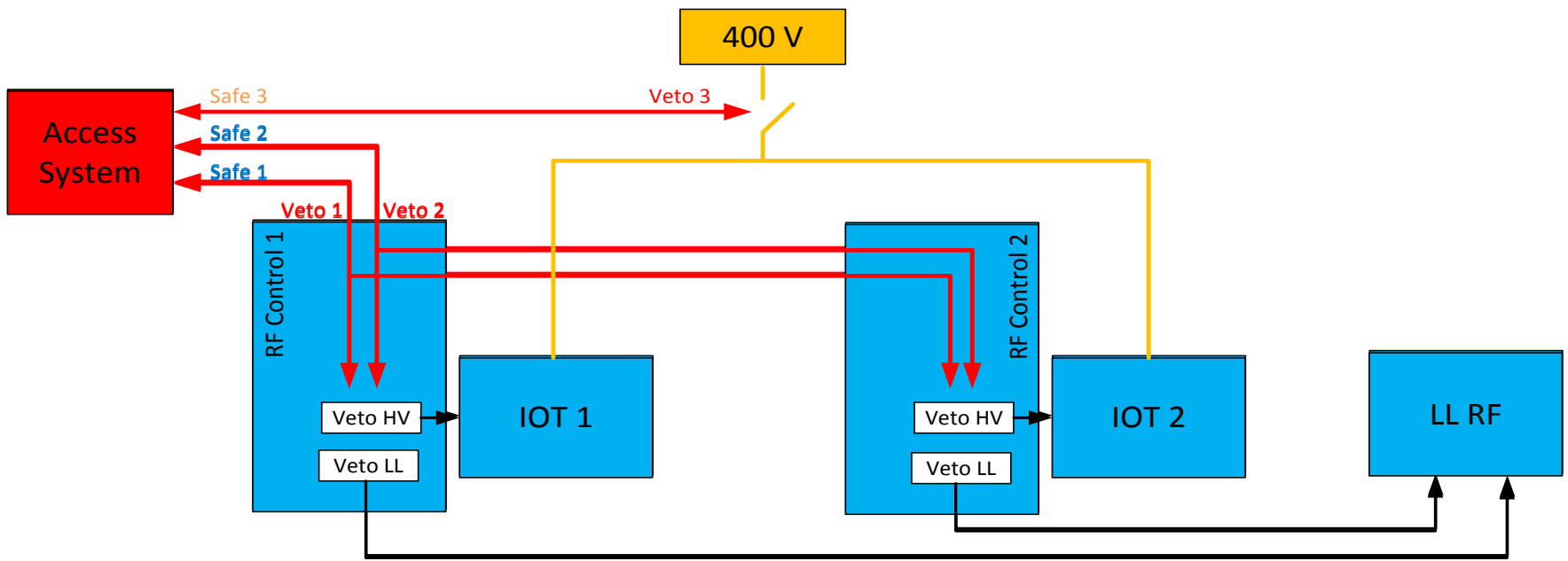
	Enable/disable	SPS Access safe	RF Power ON	Table OUT	Table IN	Table key OK	V1&V3 open	V2&V4 open	He Level >0
1 RF Power ON	Enable	TRUE		TRUE		EIS			
2 RF Power ON	Enable	TRUE			TRUE				
3 Table move	Enable	TRUE	FALSE				FALSE	FALSE	
4 Table move (local)	Enable	FALSE	FALSE			TRUE	FALSE	FALSE	FALSE
4 V1&V3 open	Enable				TRUE				



1 & 2 are part of the **EIS** chain. Rules in [EDMS](#)
 Identified in layout
 Identified on cables
 Cabling scheme according to safety integrity level 3 (SIL3)

RF Power as EIS - Access Interlock Interface

RF Powering of cavities is interlocked with SPS Access Safety System, chain 1
RF Power to cavities only in Beam Mode
Access VETO maintained in Access mode (incl Magnet Patrol)



VETO via the RF Controls PLC **AND** via direct action on the RF amplifiers powering (400V)

Summary of truth table for Safety

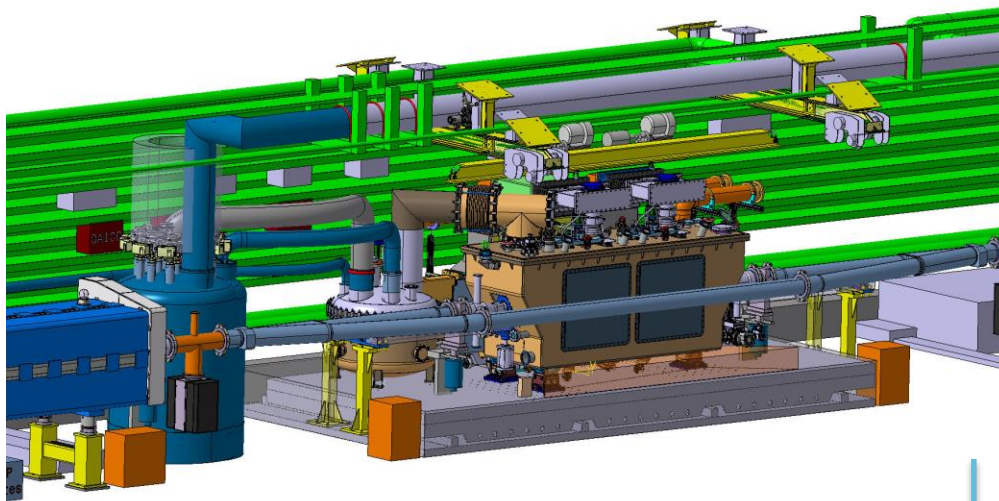
	Enable/ disable	SPS Access safe	RF Power ON	Table OUT	Table IN	Table key OK	V1&V3 open	V2&V4 open	He Level >0
1 RF Power ON	Enable	TRUE		TRUE					
2 RF Power ON	Enable	TRUE			TRUE				
3 Table move	Enable	TRUE	FALSE				FALSE	FALSE	
4 Table move (local)	Enable	FALSE	FALSE			TRUE	FALSE	FALSE	FALSE
4 V1&V3 open	Enable				TRUE				

Safe choice, ensuring no mechanical nor cryogenic enhanced risk

Local key-box permits commissioning, but only w/o LHe

Valves enclosing the CM are **(always)** closed when the cryomodule is out-of-beam

Transfer table



All controller hardware in BA6

Hardware Interlocks on table:

1. Passive switches that detect (closed) experiment and parking position (± 0.5 mm) cabled to BA6
2. **Brakes on motor closed when not powered.**

Two situations with local intervention:

1. Testing, commissioning and maintenance with local control panel (with key)
2. Manual recovery mode

- Total Payload 7500 kg
- Lateral horizontal motion
- Nominal range 510 mm
- Transfer time 10 min.
- ~ 0.85 mm/s
- Maximum acceleration 2 m/s^2
- Displacement sensors:
 - 4 LVDTs
 - resolver
- Table CE marked (market survey + specification)

Cryomodule displacement:

- with cryo fluid (no motion if liquid He present and available access to tunnel)
- without RF power

Summary of truth table for beam interlocks

BIC			Enable/ disable	Table IN	Table OUT	Set of beam param SMP	Set of cond 1, cavity & RF	BLM/ BPM	Set of cond 2, cavity & RF
1	U	Beam OK	Enable						
2	U	Beam OK	Enable						
3	U	LSS6 Extr OK	Enable						
4	M	Beam OK	Disable			?			
5	M	Beam OK	Dump			?			
6	M	Beam OK	Dump			?			

Summary of truth table for beam interlocks

BIC			Enable/ disable	Table IN	Table OUT	Set of beam param SMP	Set of cond 1, cavity & RF	BLM/ BPM	Set of cond 2, cavity & RF
1	U	Beam OK	Enable			Aperture			
2	U	Beam OK	Enable						
3	U	LSS6 Extr OK	Enable						
4	M	Beam OK	Disable			?			
5	M	Beam OK	Dump			?			
6	M	Beam OK	Dump			?			

APERTURE related interlocks: all UNMASKABLE

Summary of truth table for beam interlocks

BIC			Enable/ disable	Table IN	Table OUT	Set of beam param SMP	Set of cond 1, cavity & RF	BLM/ BPM	Set of cond 2, cavity & RF
1	U	Beam OK	Enable						
2	U	Beam OK	Enable						
3	U	LSS6 Extr OK	Enable					Verena's interlock	
4	M	Beam OK	Disable			?			
5	M	Beam OK	Dump			?			
6	M	Beam OK	Dump			?			

MASKABLE Interlock: Beam disabled when the Table is in-beam
Requires manual operator's action to unmask and allow for MD

Summary of truth table for beam interlocks

BIC			Enable/ disable	Table IN	Table OUT	Set of beam param SMP	Set of cond 1, cavity & RF	BLM/ BPM	Set of cond 2, cavity & RF
1	U	Beam OK	Enable						
2	U	Beam OK	Enable						
3	U	LSS6 Extr OK	Enable						
4	M	Beam OK	Disable			?			
5	M	Beam OK	Dump			?			
6	M	Beam OK	Dump			?			

5) Protect the SPS:

MASKABLE with, w/o SMP?

If a pre-established set of cavity, BLM, BPM parameters is exceeded → beam dumped

6) Protect the cavity:

If a pre-established set of cavity or RF parameters is exceeded → beam dumped

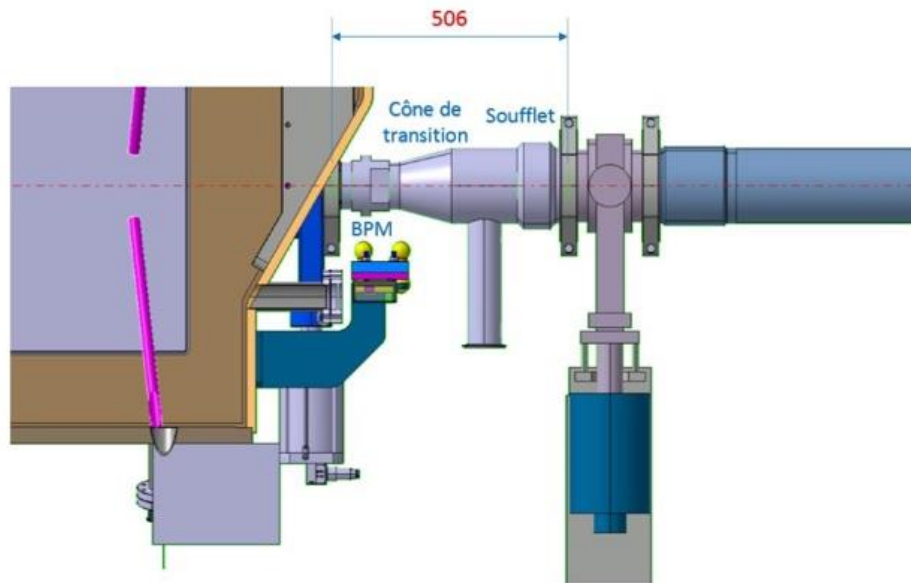
BPM

Button BPM, with Roman pot button (not enlarged LHC type button)

Measured deviation <0.5mm

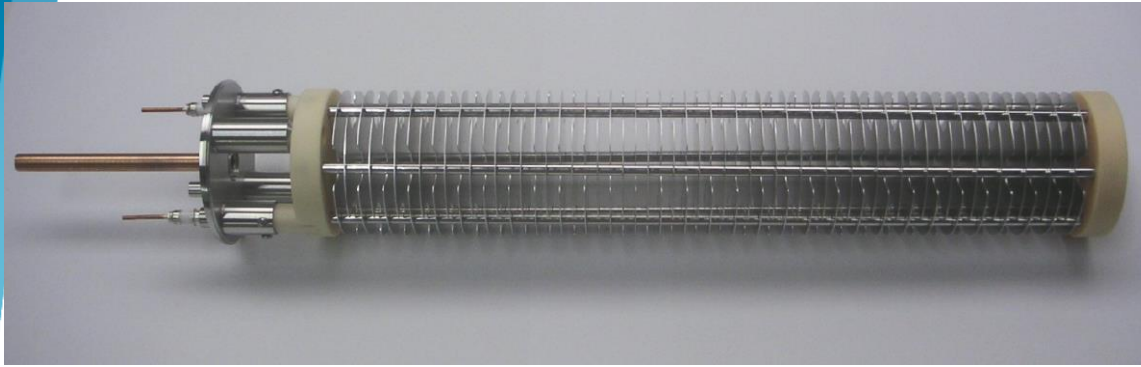
BPM bandwidth ~ 3 GHz

BPM filter bandwidth 70 MHz.



Design not frozen

BLM



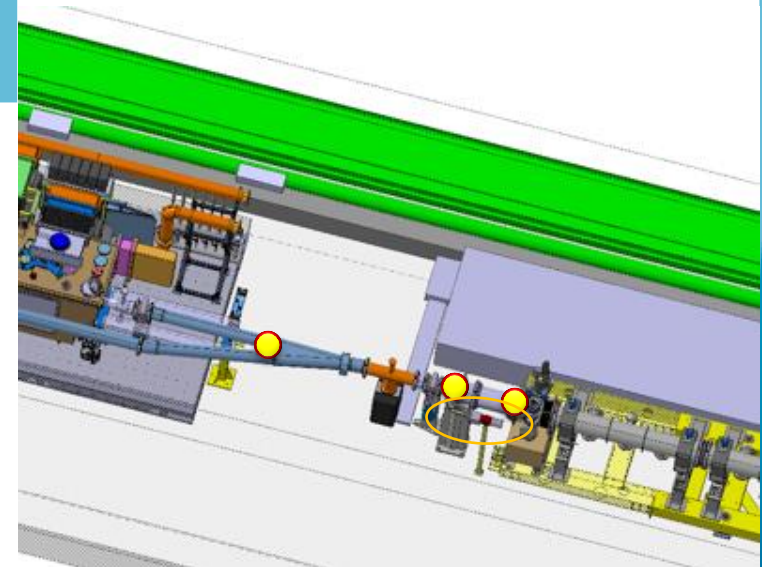
LHC-type ionization chamber

Diameter: 89mm

Length: 600mm

Bias voltage: 1500V

For correct positioning, Fluka calculation would be needed, but missing resources until Fall 2016



MD scenarios in 2018

3 x LHC Technical Stops

3 x 48h SPS stops, then beam to NA

Test program

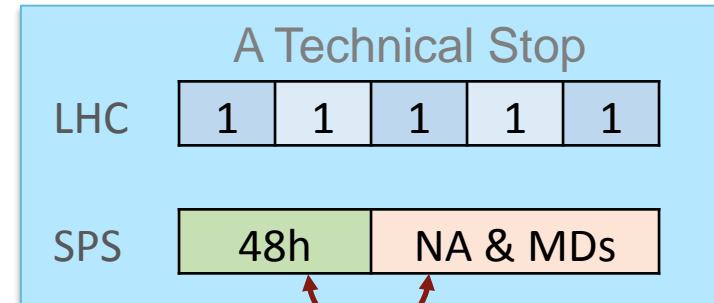
Commissioning with beam

Operation, reliability, transparency

Emittance growth study

High intensity beam

≤ 4 trains, at injection energy 26GeV, check beam induced cavity issues; machine protection; impedance.



Emptying/Refilling LHe:
2h+3h

Wednesday MDs 10h weekly

but compatible with LHC beam request

- Minimal time (≤10min) to displace table
- No access to SPS



Thank you for your attention