FUTURE CIRCULAR COLLIDER

THE FCCEE SRF SYSTEM: MACHINE LAYOUTS AND CRYOMODULES

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Outline

- The RF System Layout: Baseline

- Alternative Layout architectures:
  - Segmented to continuous cryostats and comparison
  - Cold quads
  - CM repair intervention comparison

- Effect of alternative architectures on tunnel integration

- Summary and next steps

Cavities and Cryomodules

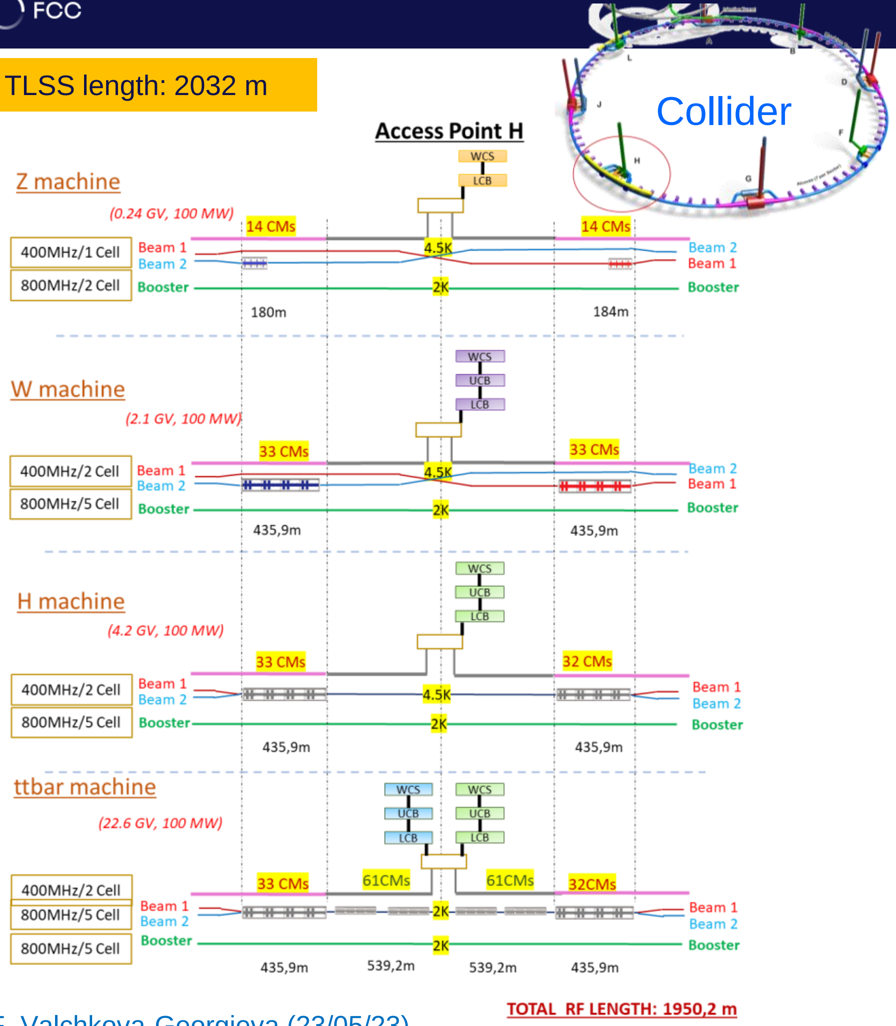
- 366 CM (3 types), 1'464 SRF cavities (4 cavities/CM, present assumption):
  - ➢ 400 MHz single-cell (Nb/Cu), 4.5 K: 28 CM, 112 cavities (removed after Z)

  - ➢ 400 MHz two-cell (Nb/Cu), 4.5 K: 66 CM, 264 cavities

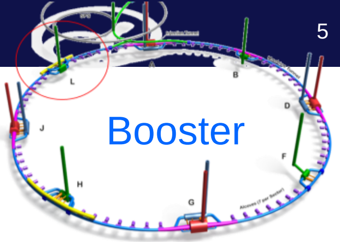
  - ➢ 800 MHz five-cell (bulk Nb), 2 K: 272 CM, 1'088 cavities

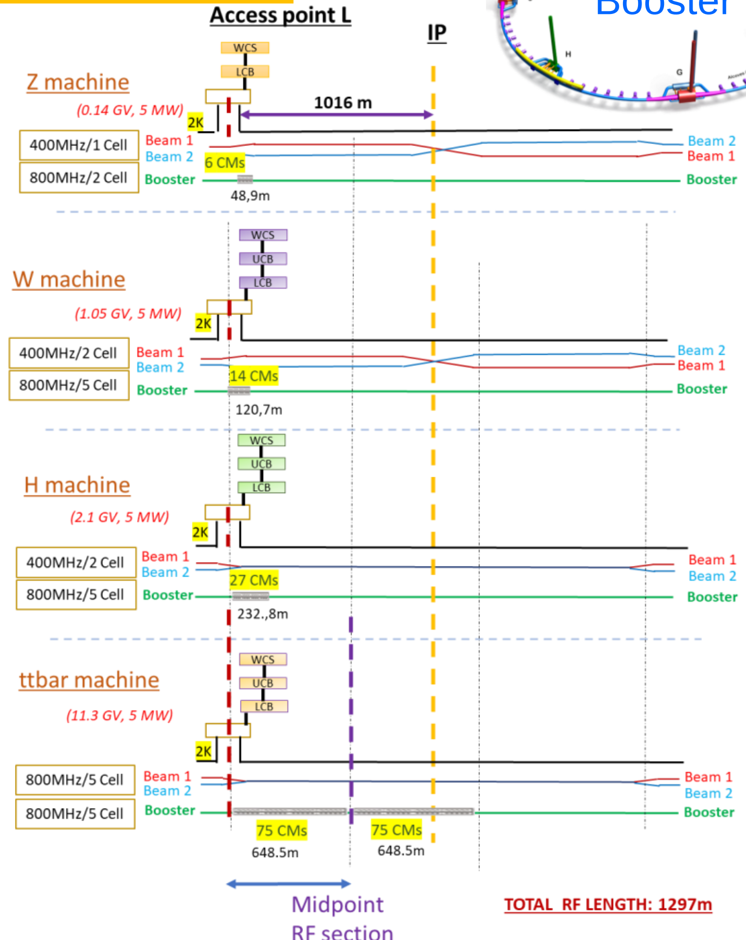
- By machine:
  - ➢ Collider (ttbar): 188 CM (264 cavities 400 MHz, 488 cavities 800 MHz)
  - ➢ Booster (ttbar): 150 CM (600 cavities 800 MHz)

TLSS length: 2032 m



TLSS length: 2032 m

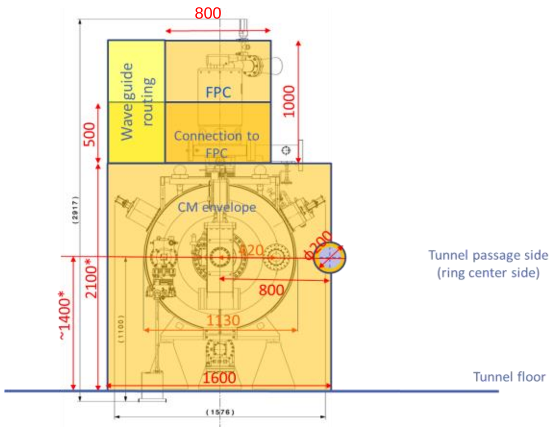


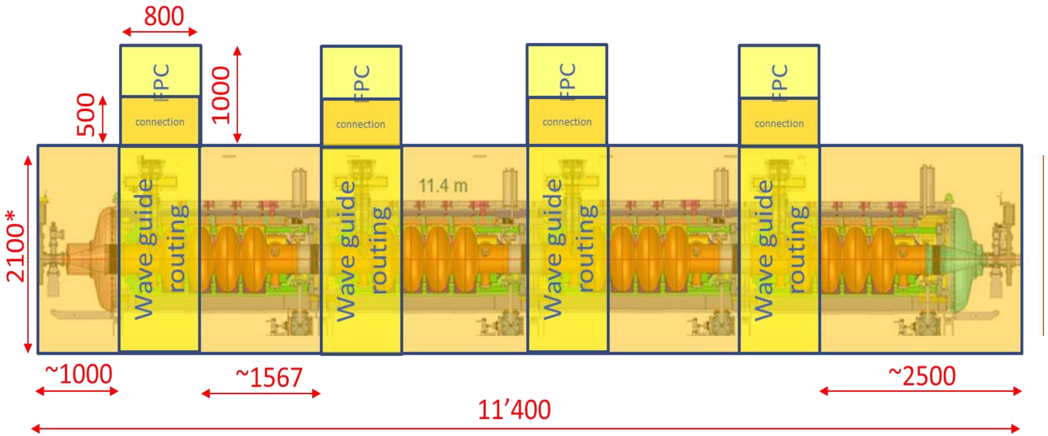


F. Valchkova-Georgieva (23/05/23)

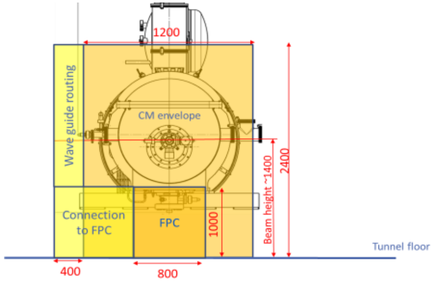
Baseline: CM space occupation for integration

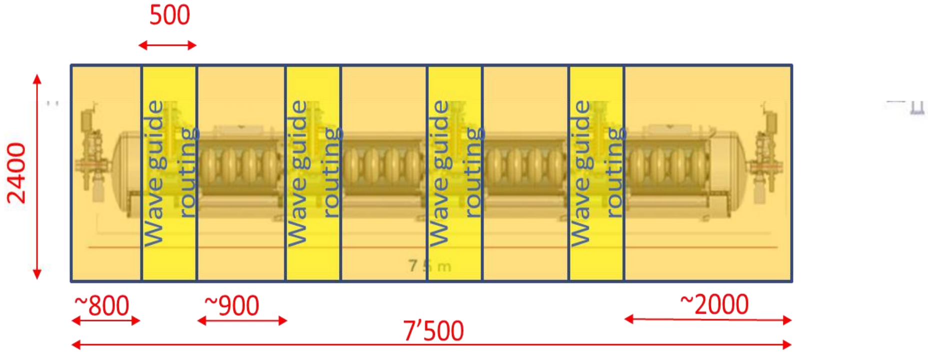
400 MHz Cryomodule (based on LEP, 4-cell cavities)



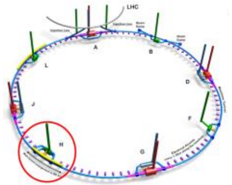


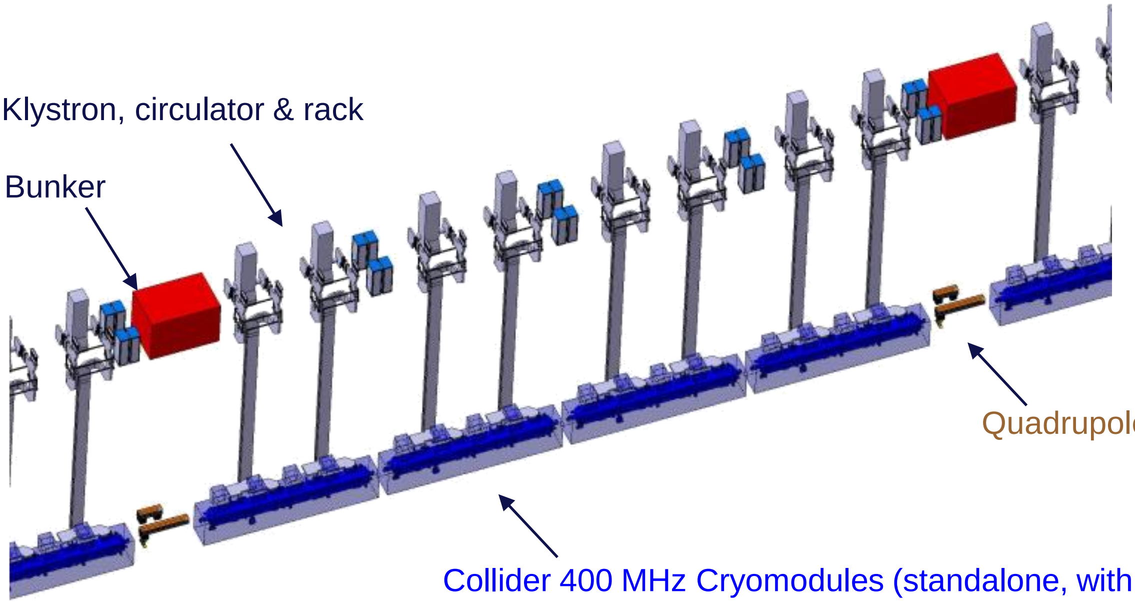
800 MHz Cryomodule (based on SPL, 704 MHz)

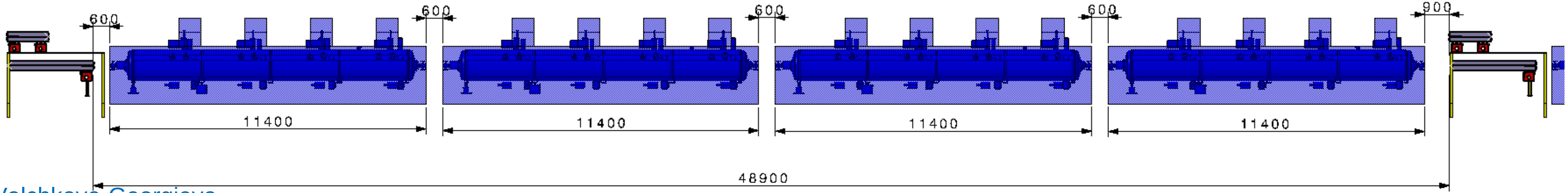




Collider, 400 MHz CMs segment between quads (ttbar machine)







F. Valchkova-Georgieva

Other preferable architectures ?

Baseline: segmented (CM “standalone” connected to cryo line)

Drivers for alternatives:

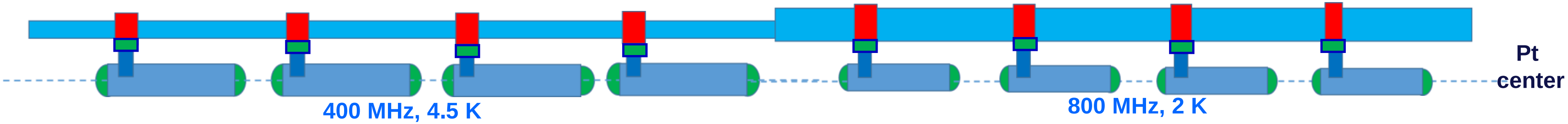
- ✓ Cost containment for large machines (CapEx)
- ✓ Energy efficiency (reduce cryo-power and Opex)
- ✓ Compactness: tunnel integration

Options:

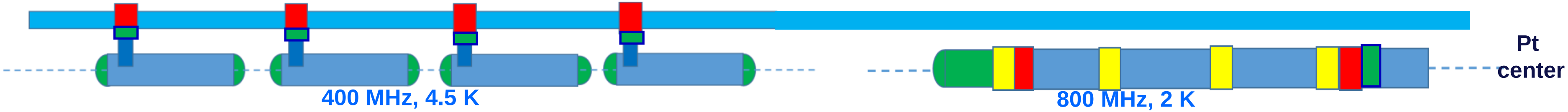
- 2 continuous cryostat variants:
  - ✓ Continuous vacuum (insulation and beam vacuum)
  - ✓ Continuous vacuum + cryomodule integrated cryogenic lines

Collider architecture options (top view, ½ LSS, quads not shown)

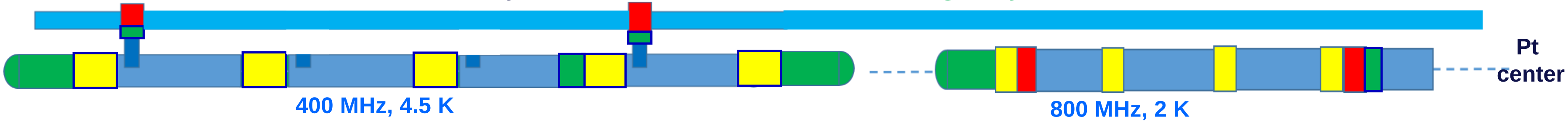
- **A1** (baseline): fully segmented with separate cryo line



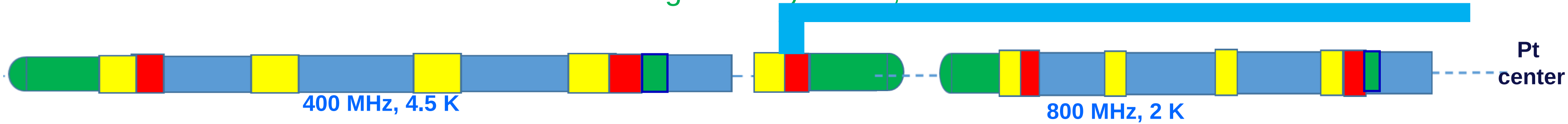
- **AC2**: 800 MHz cont. with integr. cryo lines

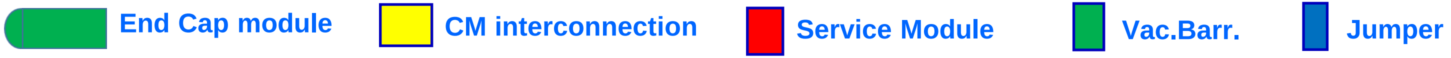


- **AC3**: 400 MHz cont. vac. with cryo line; 800 MHz cont. with integr. cryo lines.



- **AC4**: 400 MHz and 800 MHz cont. with integrated cryo lines;



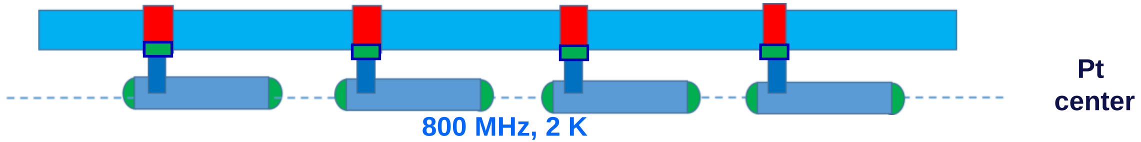


(quads not shown)

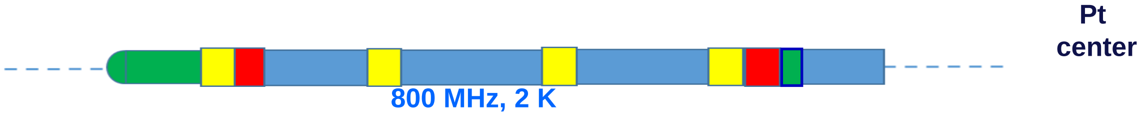
Collider Architecture	Advantages	Drawbacks
A1 (baseline: fully segmented)	- **Easy staged Installation (CM sorting if needed)** - **Maintainability (single CM intervention)** - **reduced # cavities at risk of contamination from accidental venting (warm gate valves)**	- **Higher CapEx** (more HW, cryoline, valves, CWT) - **Highest static HL** (highest OpEx) - **Lowest reliability** (higher complexity from more equip.) - Higher risk of cavity contamination through CWT and adjacent warm equipment
AC2 (400 MHz segmented, 800MHz continuous)	- **No cryo line for 800 MHz** - **Lowest 2 K static HL (lower OpEx)** - **Cryogenic separation of 400 MHz and 800 MHz linacs → maintainability** - **Compactness on 800 MHz tunnel sec.** - **Advantages of A,1 limited to 400 MHz**	- **Drawbacks as A1 but limited to 400 MHz part**
AC3 (400 MHz vac. continuous with cryo line, 800MHz continuous)	- **Lower CapEx: no CWT, longer cryo cell possible i.e. reduced cryo equip)** - **Lower HL (4.5 K)**	- **400 MHz still needs cryo line** - (marginally) longer - CM replace requires WU of the ins vac. Sector (100m long?)
AC4 (400 and 800 MHz continuous)	- **Lowest CapEx (least HW)** - **Lowest static HL (lower OpEx)** - **Compactness on 400 MHz tunnel sec. ?**	- **Large 400 MHz CM** (integrated cryo lines) - Linac (marginally) longer - CM replacement requires WU of the whole 400 MHz linac (~436 m)

Booster architecture options (top view, ½ LSS, quads not shown)

- **A1** (baseline): fully segmented collider with separate cryo line



- AB1: 800 MHz cont. with integr. cryo lines

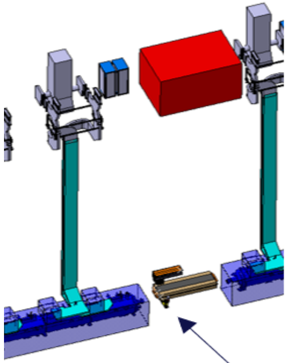


End module | CM interconnection | Service Module | Vac.Barr. Module | Jumper (no quads shown)

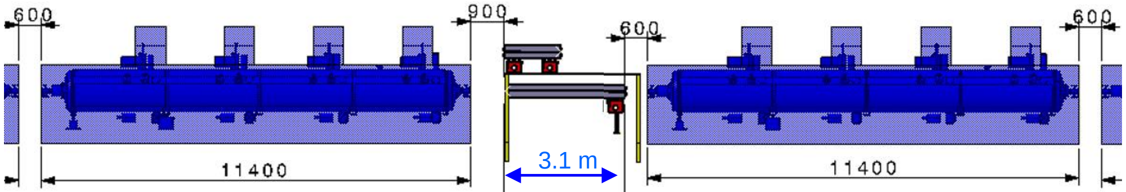
Booster Architecture	Advantages	Drawbacks
A1 (baseline: fully segmented)	- Easy staged Installation (CM sorting if needed) - Maintainability (single CM replacement) - reduced # cavities at risk of contamination from accidental venting (warm gate valves)	- Higher CapEx (more HW, cryoline, valves, CWT) - Highest static HL (higher OpEx) - Lowest reliability (higher complexity from more equip.) - Higher risk of cavity contamination through CWT and adjacent warm equipment
AB1 (400 and 800 MHz continuous)	- Lowest CapEx (least HW) - Lowest static HL (lower OpEx) - Transversal compactness (Cryo line limited to 800 MHz length)	- Larger 800 MHz CM (integrated cryo lines) - (marginally) longer - CM replacement requires WU of the whole 800 MHz linac (~1100 m)

Continuous cryostat needs cold quads

- Warm quads (today's baseline in segmented architecture)



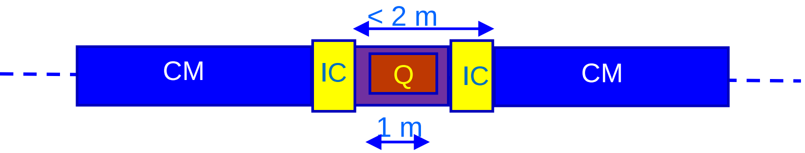
Quadrupole magnets



G-= 10 T/m; L_m = 3.1 m,

- SC quads (in dedicated compact cryostats)

➢ G = 30 T/m; L_m = 1 m : SC conv. Tech. possible (A.Foussat, TE/MSC)

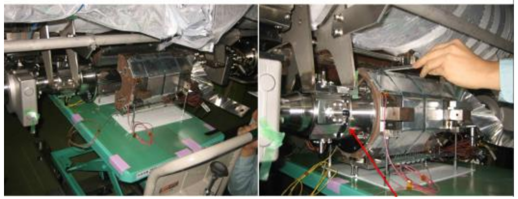


→ SC quads is a possible option

Cold Quads in cryomodules of other machines

Parameter	ILC	XFEL	ASTA	LCLS-II
Integrated gradient, T	36	5.2	3.0	2.0
Aperture, mm	78	78	78	78
Magnet effective length, mm	660	195	2x190	230
Peak gradient, T/m	54	26.7	19.2	8.7
Peak current, A	100	50	50	50
Superconductor diameter quad/dipole, mm	0.5	0.55/0.7	0.5	0.5
Superconductor filament size quad/dipole, um	3.7	6.0/3.5	3.7	3.7
Dipole corrector integrated strength, T-m	0.075	0.009	2x0.005	0.005
Max magnetic center offset in cryomodule, mm	0.3	0.5	0.5	0.5
Total length, mm	800	300	650	350
Quantity required	560	103	-	36

Quadrupole Assembly around Beam Pipe



Example: Split quad, cond.cooled (A.Yamamoto et al.)

In-tunnel repair on CMs (400 MHz)

- Intervention needing WU and ins.vac.vent. (e.g. tuner, HOM, coax cables connectors), assuming 1 day repair

#	In-tunnel CM repair (Collider, 400 MHz)	Baseline	comments	AC3: continuous with cryo line	comments	AC4: continuous with integrated cryo line	comments
#	**Operation**	**No.work days**		**No.work days**		**No.work days**	
1	Warm up of CM	3	Estimate. 1 CM, cryoline cold	7	Estimate. 10 CM (¬150 m ins. Vac.), cryoline cold	14	Entire linac (33 CM)
2	Vent CM Ins.vac.	0.5		2	venting only ins.vac. Sect.	5	Entire linac (33 CM)
3	Repair	1	assumption	1	assumption	1	assumption
5	Pump down ins.vac.	2	1 CM	5	10 CM	7	Entire linac (33 CM)
6	Cool down CM	2	Estimate. 1 CM	5	Estimate. 10 CM	10	Entire linac (33 CM)
7	Cavities RF conditioning	21	LHC CM experience	21	with parallel automated RF conditioning	21	with parallel automated RF conditioning
	Total	**29.5**		**41**		**58**	
	Total # weeks	**4.2**		**5.9**		**8.3**	

✓ Intervention time up to ~6/8 weeks (AC3/AC4) (including RF conditioning)

✓ All architectures compatible with 17 weeks yearly shut-downs

Replacement of CM (400 MHz)

#	Exchange of 1 CM (Collider 400 MHz) — Operation	Baseline — No.work days	comments	AC3: continuous with cryo line — No.work days	comments	AC4: continuous with integrated cryo line — No.work days	comments
1	close 4 warm gate valves of CM	0.5					
2	Close cryo valves to isolate CM	0.5					
3	Warm up of entire linac (33 CM)	14	Estimate. No cutting with cold cryo line.	14	Estimate. No cutting with cold cryo line.	14	Entire linac (33 CM)
4	CM Ins.vac.venting	0.5		2	venting ins.vac. Sect.	2	venting ins.vac. Sect.
5	Dismount warm beam lines	0.5					
6	Open jumper IC and cut cryo lines	3		3			
7	Open 2 IC, beam vac.line only		CM replac: 8.5 d	1.5	CM replac: 9.5d		CM replac: 11 d
8	Open 2 IC, beam vac.line + cryo lines					5	
9	Exchange of CM	1		1		1	
10	Close jumper (weld cryo lines +th.shields,etc.)	2		2			
11	Close 2 IC, beam vac.line + cryo lines					5	
12	Close 2 IC, beam vac.lines only			2			
13	Mount warm beam lines, vac.cond. and pumping	2					
14	Pump down ins.vac. and purge cryo lines	7	Entire linac (33 CM)	7	Entire linac (33 CM)	7	Entire linac (33 CM)
15	Cool down CM	10	Entire linac (33 CM)	10	Entire linac (33 CM)	10	Entire linac (33 CM)
16	Cavities RF conditioning	21	LHC CM experience	21	with parallel automated RF conditioning	21	with parallel automated RF conditioning
	Total Work days	**62**		**63.5**		**65**	
	Total # weeks	**8.9**		**9.1**		**9.3**	

- ✓ Intervention time up to ~9/10 weeks (AC3/AC4) (including RF conditioning), no advantage in segmented baseline (cutting cryo lines with cold adjacent equip. not allowed)
- ✓ All architectures compatible with 17 weeks yearly shut-downs

Notes:

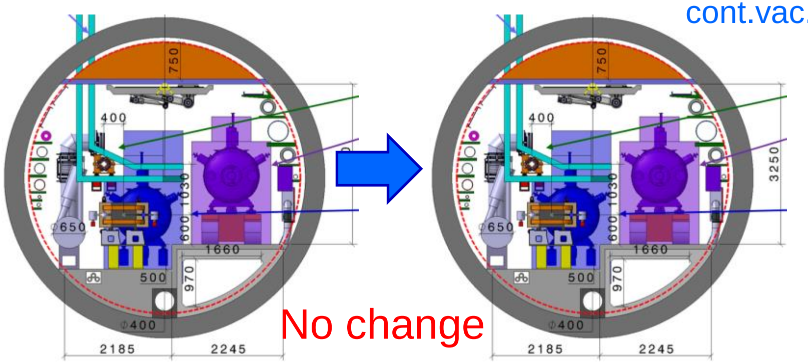
- XFEL (estimate): WU/vent/pump./CD/RF.cond: ~ 7-9 weeks (WU of linac: 3-4 w; ins.vac.vent.:1-2 d; ins.vac.pump.: ~5 d; CD of linac: 3-4 w; RF cond.: 1-2 d)
- LHC dipole replacement: WU/vent/pump./CD: ~ 10 weeks (WU sect.:3.5 w; ins. ins.vac.vent.:~3 d; ins.pump.: 5 d; CD: 6.5 weeks); dipole replacement: ~ 5 weeks

Benefits on Cross Sections (AC3, AB1)

Collider

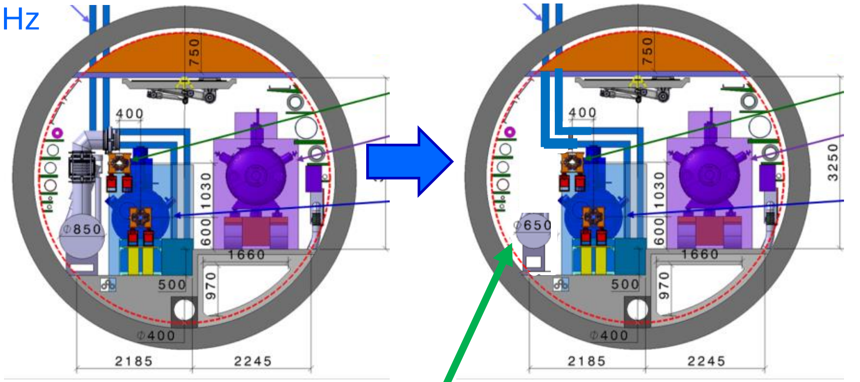
(AC3, 400 MHz cont.vac.+cryoline, 800 MHz cont.)

Baseline — 400 MHz — AC3



No change

Baseline — 800 MHz — AC3

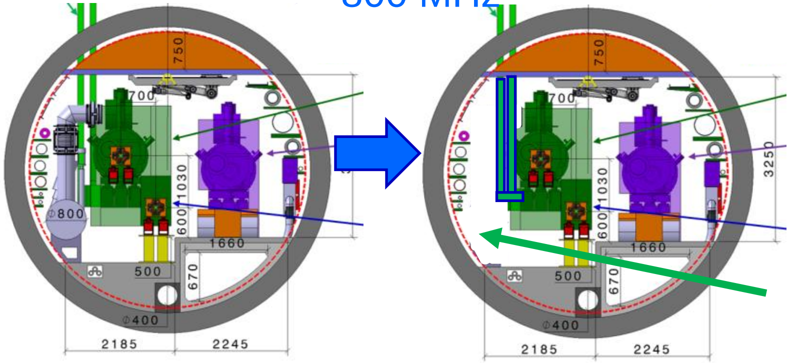


- No large cryo line, no jumper
- Small transfer line (400 MHz feed)
- CM envelope TBC (integr. cryo lines)

Booster (AB1, 800 MHz cont)

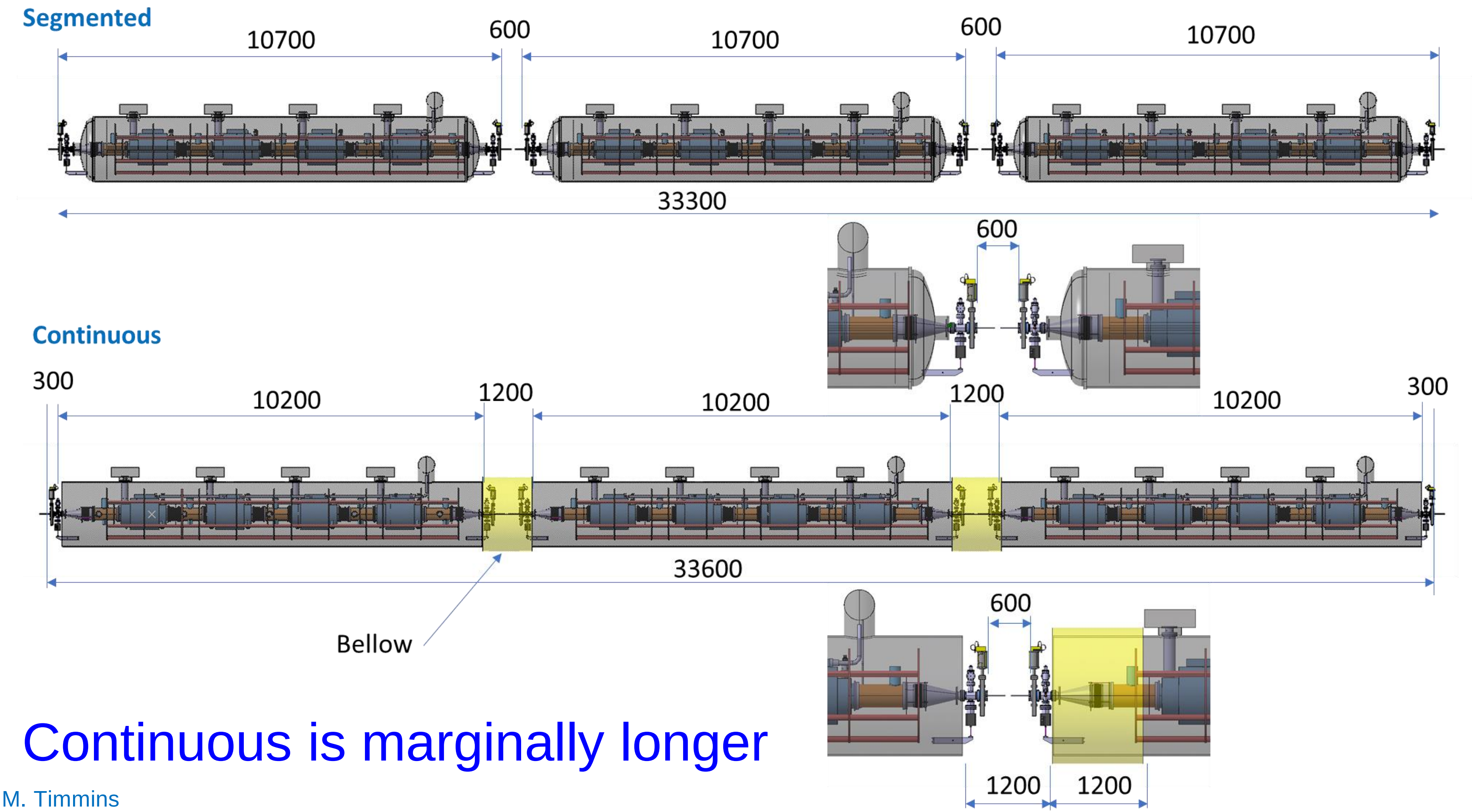
Substantial integration simplifications

Baseline — 800 MHz — AB1



- No cryo line, no jumper
- CM envelope TBC (integr. cryo lines)

(2 cell) string 400 MHz: segmented vs continuos

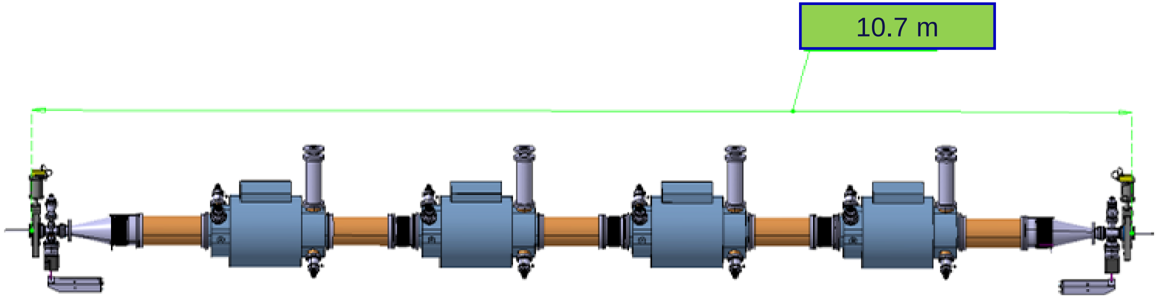


Continuous is marginally longer

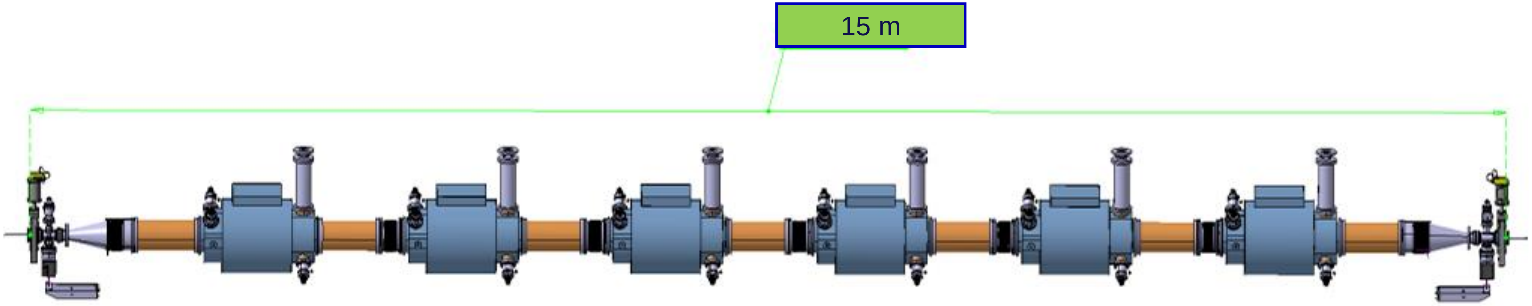
Increasing the no. of 400 MHz cavities per CM ?

400 MHz (2 cell cavities): 4 to 6 cavities ?

- 6 cavities is at the limit for road transport (15m LHC dipoles) and handling (overhead cranes >15t, tunnel shafts ~ 16m)



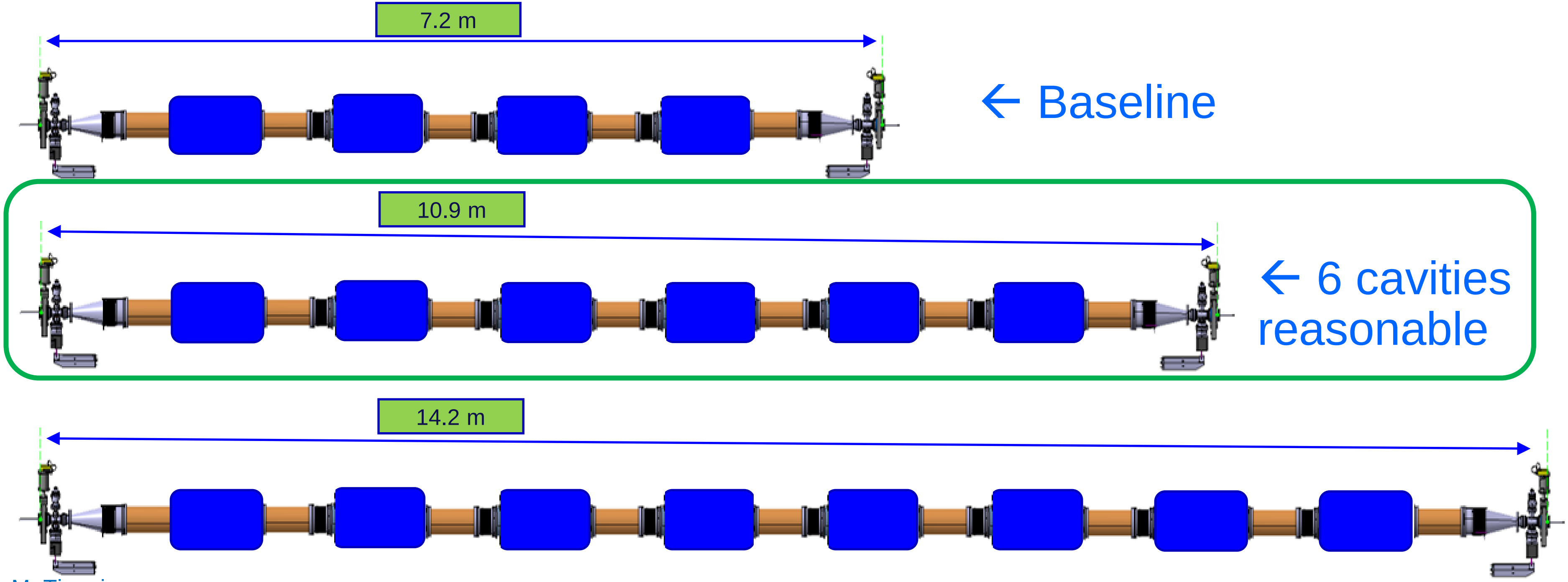
← keep 4 cavities (for now)



Increasing the no. of 800 MHz cavities per CM ?

800 MHz (5 cell cavities): 4 or 6 or 8 cavities ?

✓ Provisional, only RF design (no mechanics yet) :



M. Timmins

½ LSS Collider length (ttbar), by architecture

Length [m], 1/2 LSS Collider, ttbar	A1 (baseline)		A1 (revised CM lenght)		AC2		AC3/AC4		AC3/AC4 (6 cav. 800 MHz)	
	800 MHz (seg)	400 MHz (seg)	800 MHz (segm)	400 MHz (segm)	800 MHz (cont)	400 MHz (segm)	800 MHz (cont)	400 MHz (cont) with/no cryo line	800 MHz (cont)	400 MHz (cont) with/no cryo line
N (#cavityies/CM)	4	4	4	4	4	4	4	4	6	4
Standalone CM lenght (flange to flange) for N cavity	7.5	11.4	7.18	10.70		10.70				
Cont.CM lenght (flange to flange) for N cavity					7.53		7.53	10.70	10.87	10.70
No. cavities	244	132	244	132	244.00	132	244.00	132.00	244.00	132.00
No.CM	61	33	61	33	61.00	33	61.00	33.00	41	33.00
Total lenght of CMs	457.5	376.2	437.98	353.1	459.33	353.1	459.33	353.10	442.05	353.10
Total length of IC	33.43	21.12	33.43	21.12	33.43	21.12	33.43	21.12	22.10	21.12
No.quads	9	7	9	7	9	7	9	7	9	7
Quads spacing	52	52	52	52	52	52	52	52	52	52
Quads length	3.1	3.1	3.1	3.1		3.1				
Cold quad length (+ 1 IC)					1.85		1.85	1.85	1.85	1.85
No.of CM between quads	6.93	4.56	7.24	4.86	6.91	4.86	6.91	4.86	4.78	4.86
Total lenght of quads space	27.9	21.7	27.9	21.7	16.65	21.7	16.65	12.95	16.65	12.95
Cryo valve/Jumper box length					0.75		0.75	0.75	0.75	0.75
No. valve boxes					9		9	7	9	7
Cryo cell length (assumption)					51.04		51.04	50.44	49.12	50.44
No.CM per cryo cell					6.78		6.78	4.71	4.52	4.71
Total length of Jumper/valve boxes					6.75		6.75	5.25	6.75	5.25
Vac.Barrier box length (+ 1 IC)					2.35		2.35	2.35	2.35	2.35
Vac.sectorisation length (assumption)					100		100	100	100	100
No.of Vac.sectorisations					6		6	4	5	4
No.of Vac. Barrier boxes					4		4	2	3	2
Total length of Vac.Barrier boxes					9.4		9.4	4.7	7.05	4.7
Total lenght of 2 end of cryostat boxes					4		4	4	4	4
Contributions 800 MHz & 400 MHz [m]	**519**	**419**	**499**	**396**	**530**	**396**	**530**	**401**	**499**	**401**
Total length 1/2 LSS [m]	**938**		**895**		**925**		**931**		**900**	

- Revised CM lengths provide 4% reduction to baseline length
- Continuous cryostats are (marginally) longer (effect of additional HW)
- Increasing # cavities/CM reduces linac length, compensating continuous cryostat overlength

→ AC3 (or AC4) with 6 cav./CM 800MHz yields a 4% length reduction (900 m) wrt the baseline

Note: for Booster, see spare slides

Summary and next steps

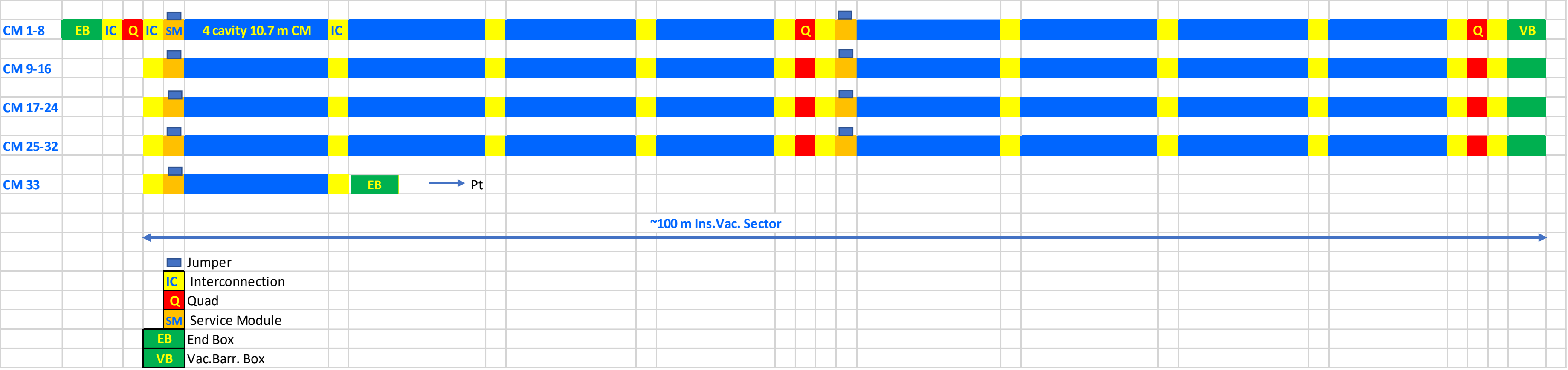
- Baseline is fully segmented linacs, for both Collider and Booster
- Continuous cryostat architectures interesting both for capital and operation cost reductions. Quantitative assessments as next steps.
- Architecture developments to continue to integrate cryogenic and vacuum cells (cryo valves, vac.Barrier, beam pumping etc.). Beam instrumentation also to be defined (BPMs, etc.).
- Tunnel cross sections: 800 MHz continuous with integrated lines more compact (no cryoline and jumpers)
- Linacs lengths. With updated CM lengths, increased # cavities/CM (4→6) of the 800 MHz, linac lengths are shorter even though continuous cryostats are (marginally) longer. At this stage of the design study, some margin should be kept.

Thank you for your attention.

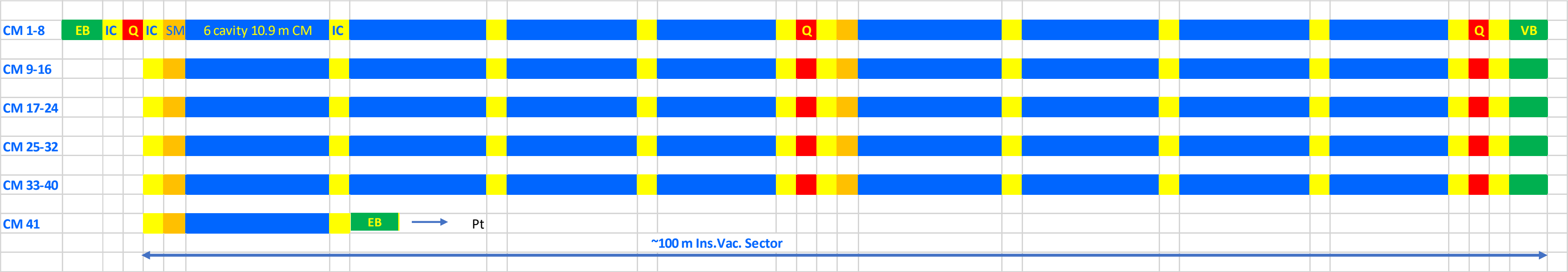
Spare slides

Possible layout for Collider AC3

400 MHz



800 MHz



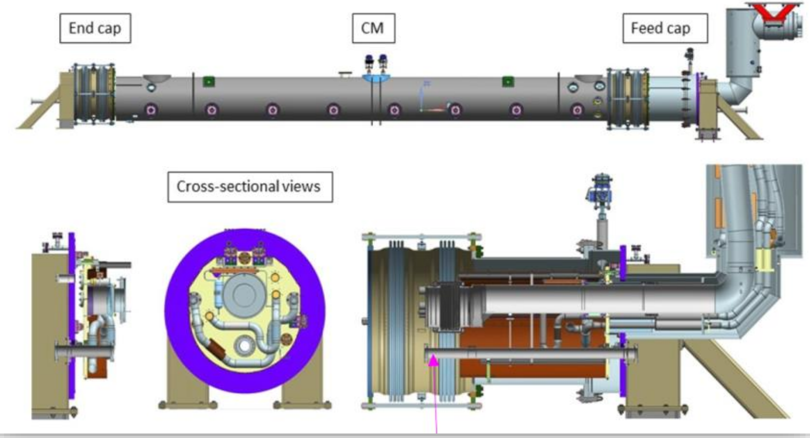
Booster length (ttbar), by architecture

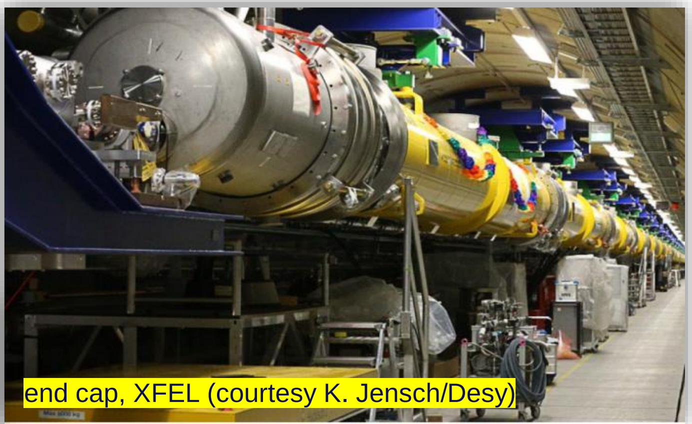
Long. length [m], Booster linac (Point L), ttbar	A1 (baseline)	A1 (revised CM lenght)	AB1 (4 cav. 800 MHz)	AB1 (6 cav. 800 MHz)
	800 MHz (seg)	800 MHz (segm)	800 MHz (cont)	800 MHz (cont)
N (#cavityies/CM)	4	4	4	6
Standalone CM lenght (flange to flange) for N cavity	7.5	7.18		
Cont.CM lenght (flange to flange) for N cavity			7.53	10.87
No. cavities	600	600	600	600
No.CM	150	150	150	100
Total lenght of CMs	**1125**	**1077.00**	**1129.50**	**1087.00**
Total length of IC	**83.01**	**83.01**	**83.01**	**55.16**
No.quads	9	9	9	9
Quads spacing	52	52	52	52
Quads length	3.1	3.1		
Cold quad length (+ 1 IC)			1.85	1.85
No.of CM between quads	6.93	7.24	6.91	4.78
Total lenght of quads space	**27.9**	**27.9**	**16.65**	**16.65**
Cryo valve/Jumper box length			0.75	0.75
No. valve boxes			9	9
Cryo cell length (assumption)			125.50	120.78
No.CM per cryo cell			16.67	11.11
Total length of Jumper/valve boxes			**6.75**	**6.75**
Vac.Barrier box length (+ 1 IC)			2.35	2.35
Vac.sectorisation length (assumption)			100	100
No.of Vac.sectorisations			13	12
No.of Vac. Barrier boxes			11	10
Total length of Vac.Barrier boxes			**25.85**	**23.5**
Total lenght of 2 end of cryostat boxes			**4**	**4**
Total length 1/2 LSS [m]	**1236**	**1188**	**1229**	**1159**

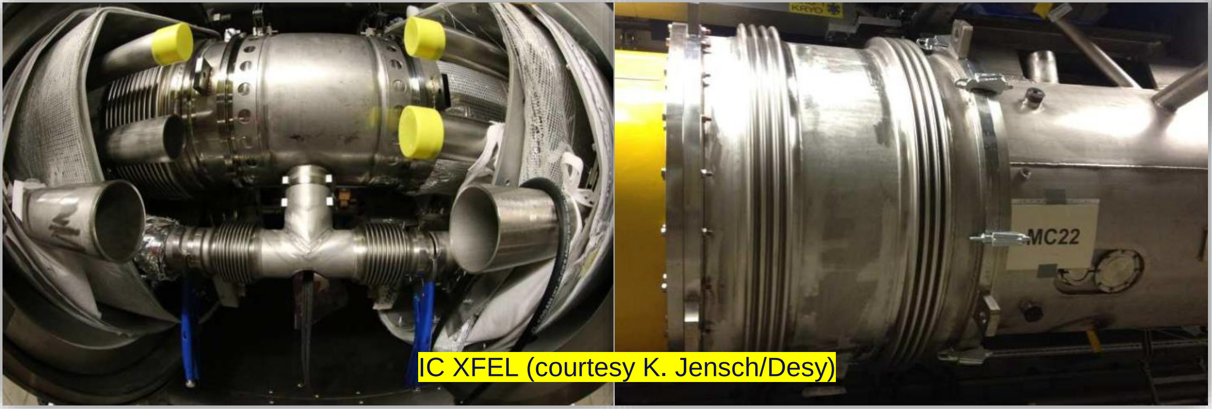
- Revised CM lengths provide 4% reduction to baseline length
- Continuous cryostats are (marginally) longer (effect of additional HW)
- Increasing # cavities/CM reduces linac length, compensating continuous cryostat overlength
- AB1 with 6 cav./CM 800MHz yields a 6% length reduction (1159 m) wrt the baseline

Pictures/drwgs from XFEL and LCLS-II

End/feed caps, LCLS –II (courtesy T. Petersen/SLAC)

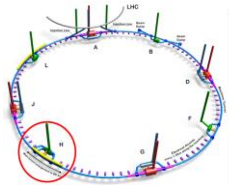


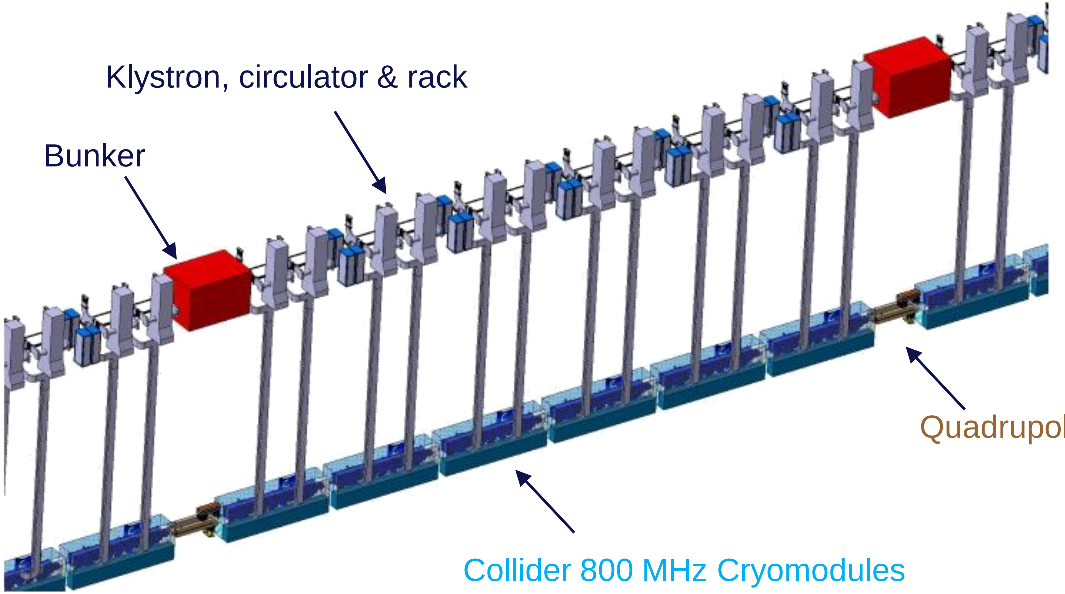

end cap, XFEL (courtesy K. Jensch/Desy)

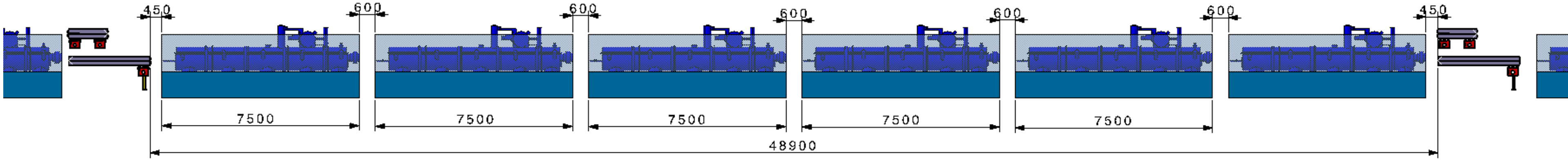


IC XFEL (courtesy K. Jensch/Desy)

Collider, 800 MHz CMs segment between quads (ttbar machine)

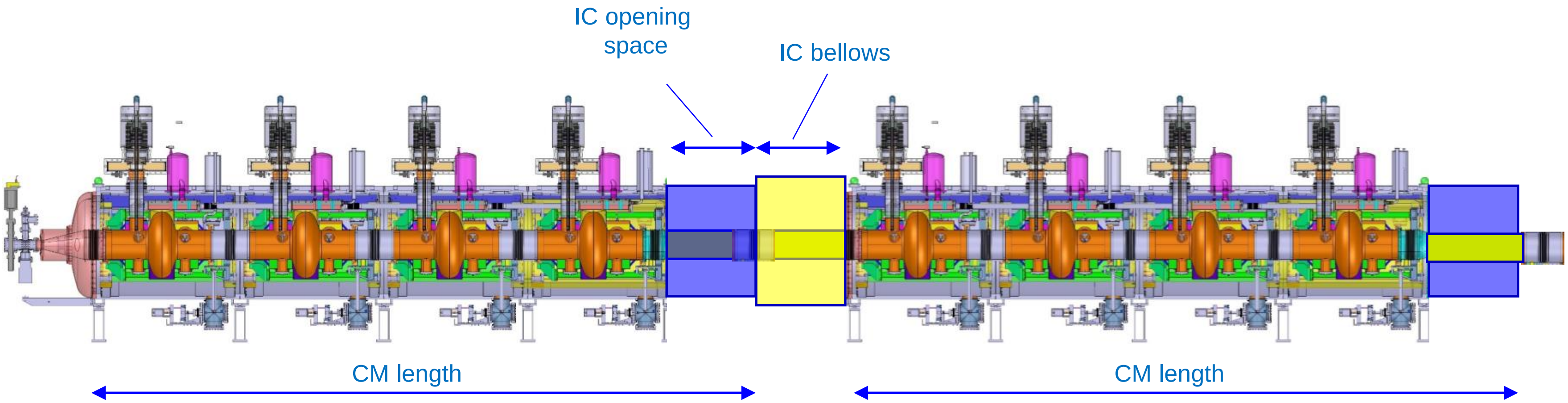






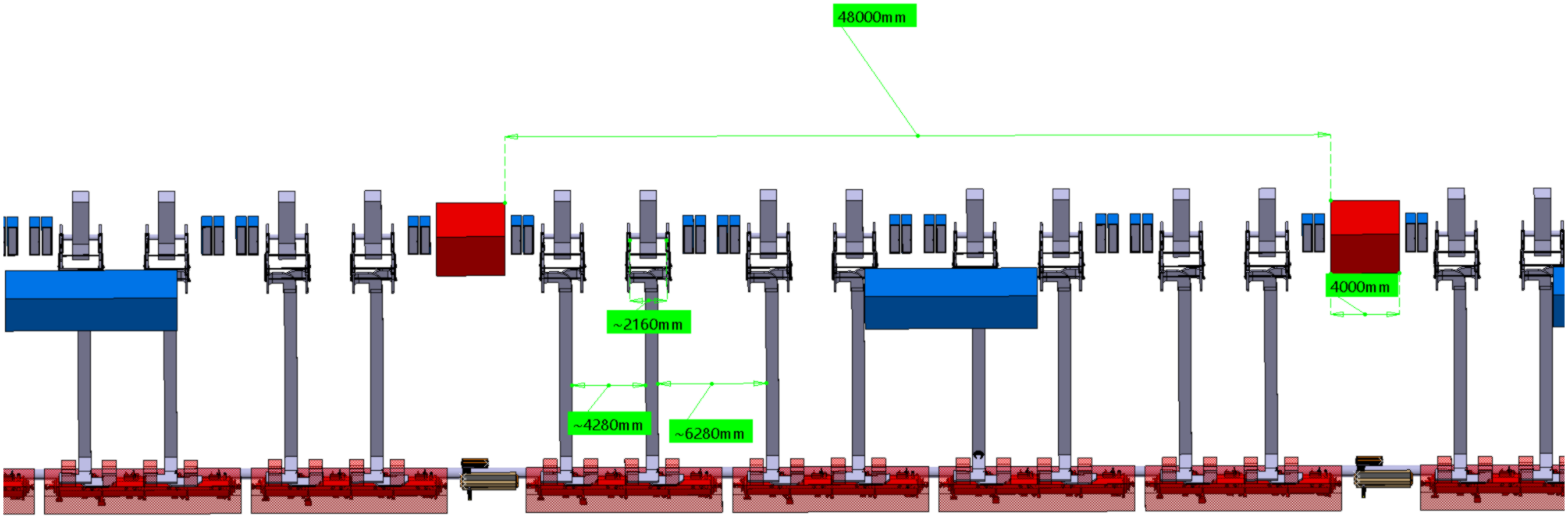
F. Valchkova-Georgieva

Interconnections IC length

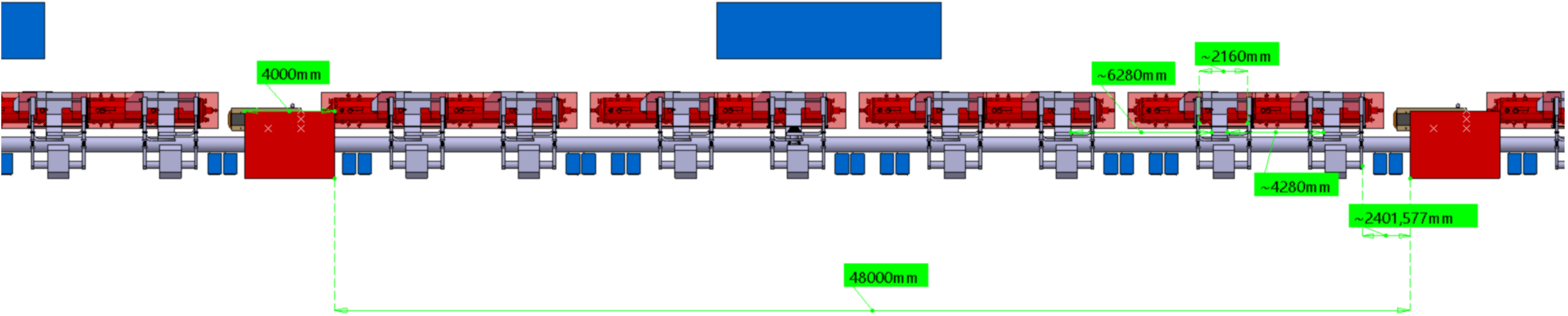


Opening of IC requires **sliding length along cylindrical CM vessel**

Klystron gallery, side view (400 MHz)

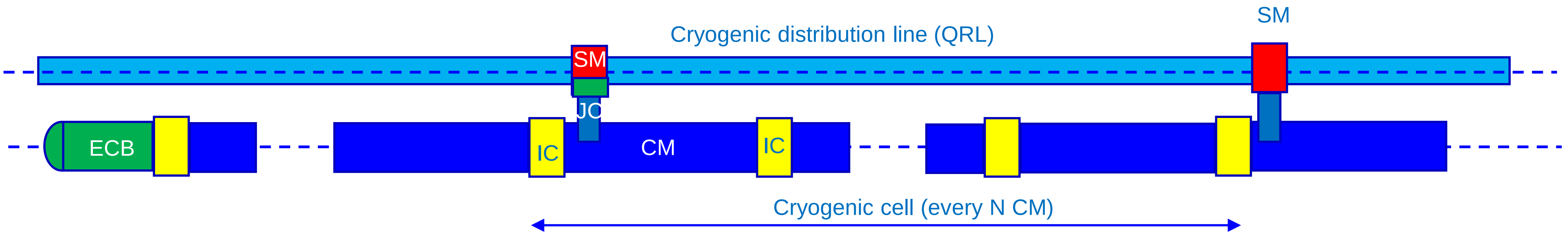


Klystron gallery, top view (400 MHz)

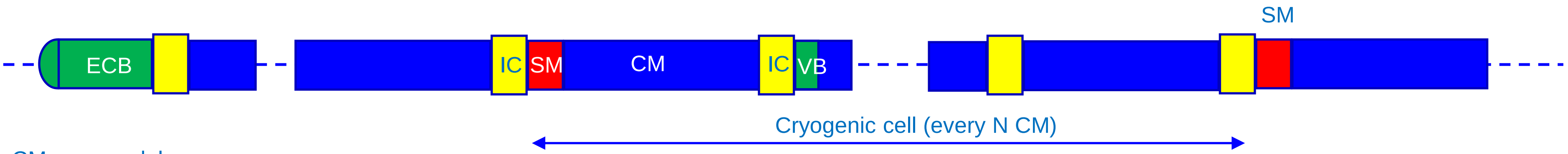


Continuous cryostat options (top views)

- Continuous vacuum and cryogenic distribution line



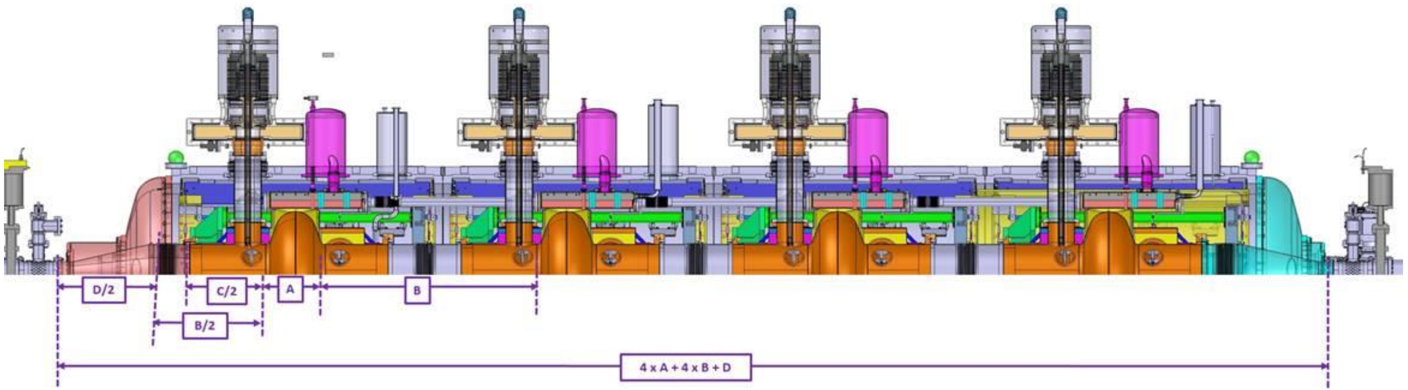
- Continuous vacuum and integrated cryogenic lines



CM: cryomodule
IC: interconnection
SM: Service Module
VB: Vacuum Barriers
JC: jumper connection
ECB: End Cap Box (restrains high ins. vac. forces)

Only possible with IC circular bellows → i.e. cryostat vacuum vessel are cylindrical ! (e.g. LHC, XFEL)

Cavity spacing (SRF lengths only)



22-Feb-23	Length of the main elements in the FCC cryomodules				
	Length A [m]	Length B [m]	Length C [m]	Length D [m]	Total CM length [m]
1-cell 400 MHz	0.32	1.50	0.80	1.00	8.26
2-cell 400 MHz	0.75	1.50	0.80	1.00	9.98
5-cell 800 MHz	0.92	0.75	0.50	0.50	7.17

Note:
- Present assumption is 4 cavities/CM. More cavities/CM is an option

F. Peauger