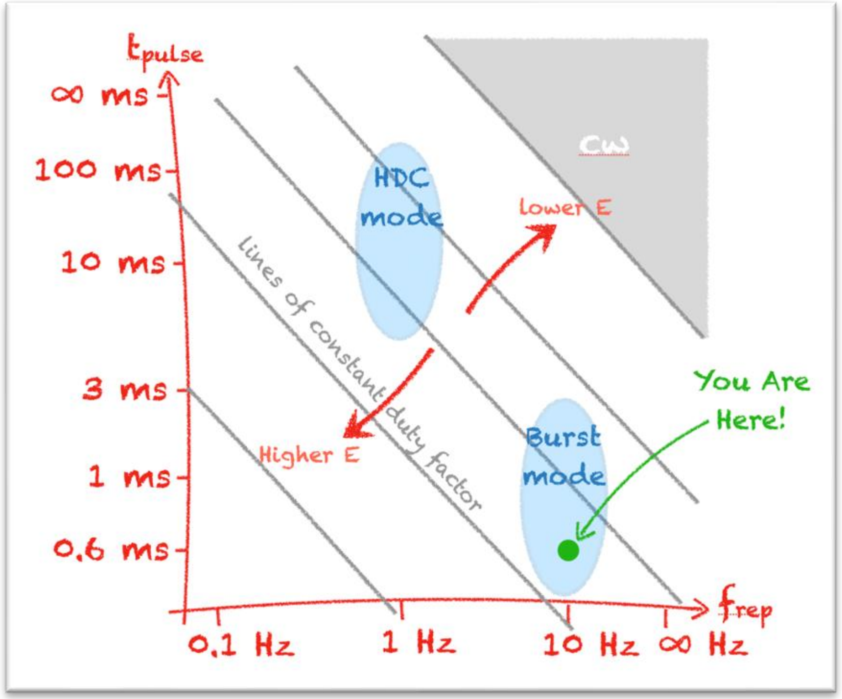
HDC, getting there

selected R&D topics

Julien Branlard

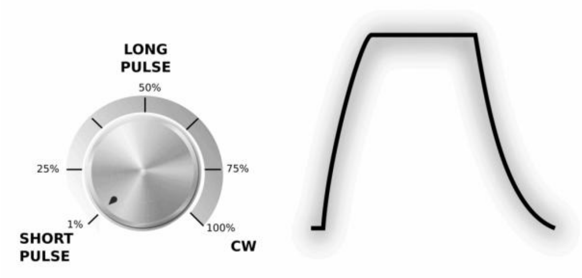
on behalf of the HDC collaboration

HDC Colloquium, June 2nd 2026



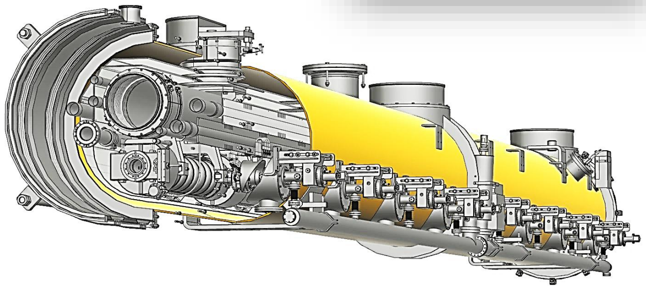
OVERVIEW

- We need to implement "the KNOB"

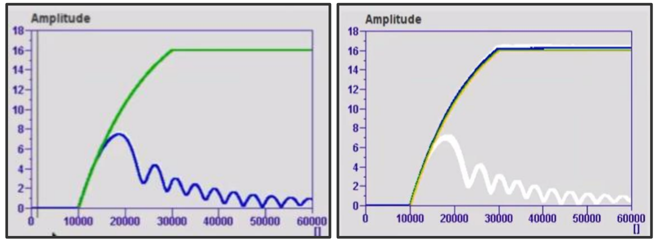


- Selected R&D topics
  - SRF injector

  - Cryo solutions



  - RF solutions



High Duty Cycle Upgrade

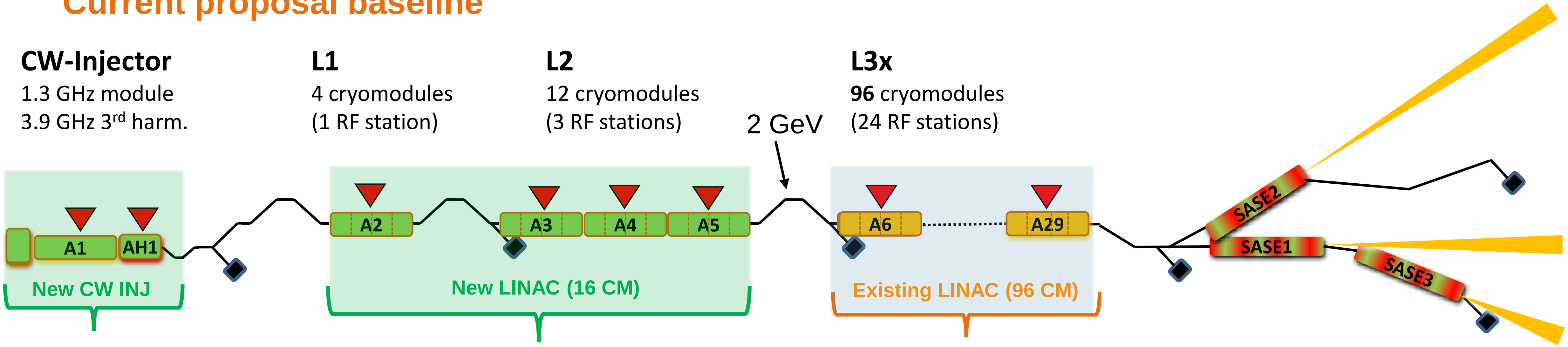
Current proposal baseline

CW-Injector
1.3 GHz module
3.9 GHz 3^{rd} harm.

L1
4 cryomodules
(1 RF station)

L2
12 cryomodules
(3 RF stations)

L3x
96 cryomodules
(24 RF stations)



New SRF injector cavity
Ts4i (test stand)
A1 (1.3 GHz CM)
AH1 (3.9 GHz CM)

16x new CW-cryomodules
Based on new high-Q_0 cavities
How to modify the cryomodules

Maximum heat load supported by 2 phase pipe ?
What are the limits of our existing CMs
Maximum RF power supported by input couplers ?
How to optimize their operation

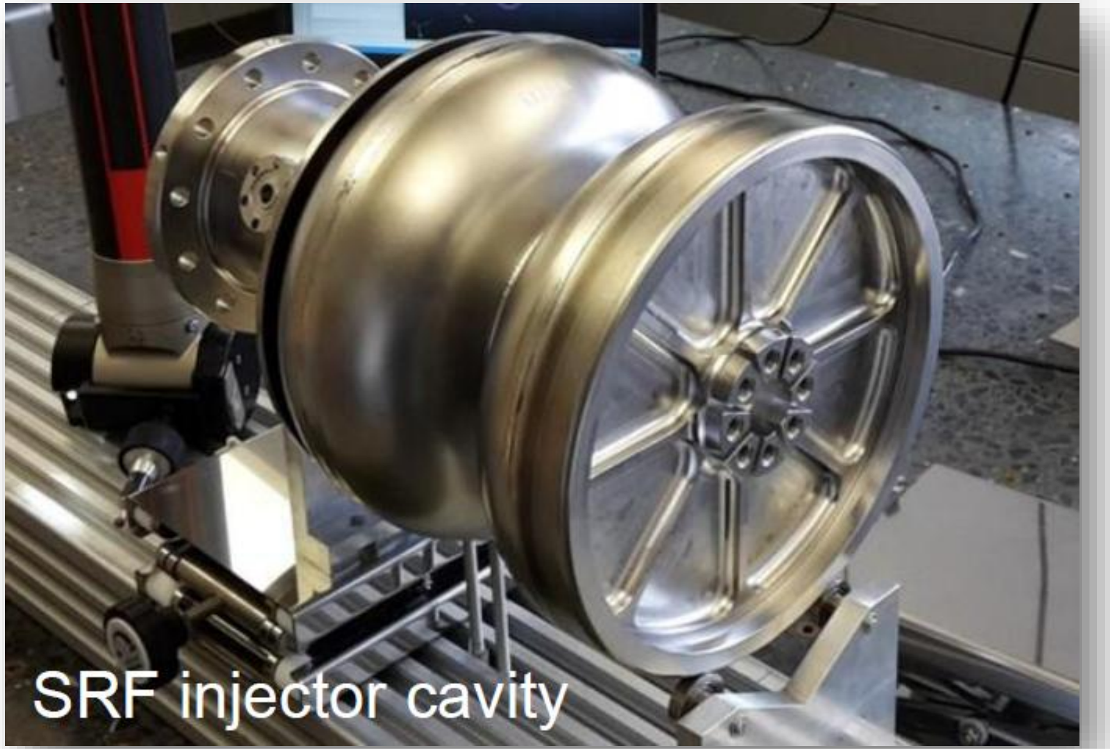
SRF INJECTOR

Developing a CW Injector

- A photoinjector cavity with **high gradient** enables **high beam brightness**

- **SRF** versus **NRF**

Design beam parameters	Unit	NC Cavity	SRF Cavity	
Max. bunch repetition rate	kHz	4500	1000	↘
Bunch charge	pC	20 – 1000	20 – 100	≈↘
Transverse norm. emittance	µm	0.2 – 1.0	0.2 – 0.4	≈
Energy at gun exit	MeV	~6.1	~5	≈
RF parameters				
Duty cycle	%	1	100	↑
Operation frequency	GHz	1.3	1.3	=
Accelerating gradient	MV/m	~31	~28	≈
Electric field at cathode	MV/m	~60	~42	≈
Peak electric field on axis	MV/m	~62	~50	≈



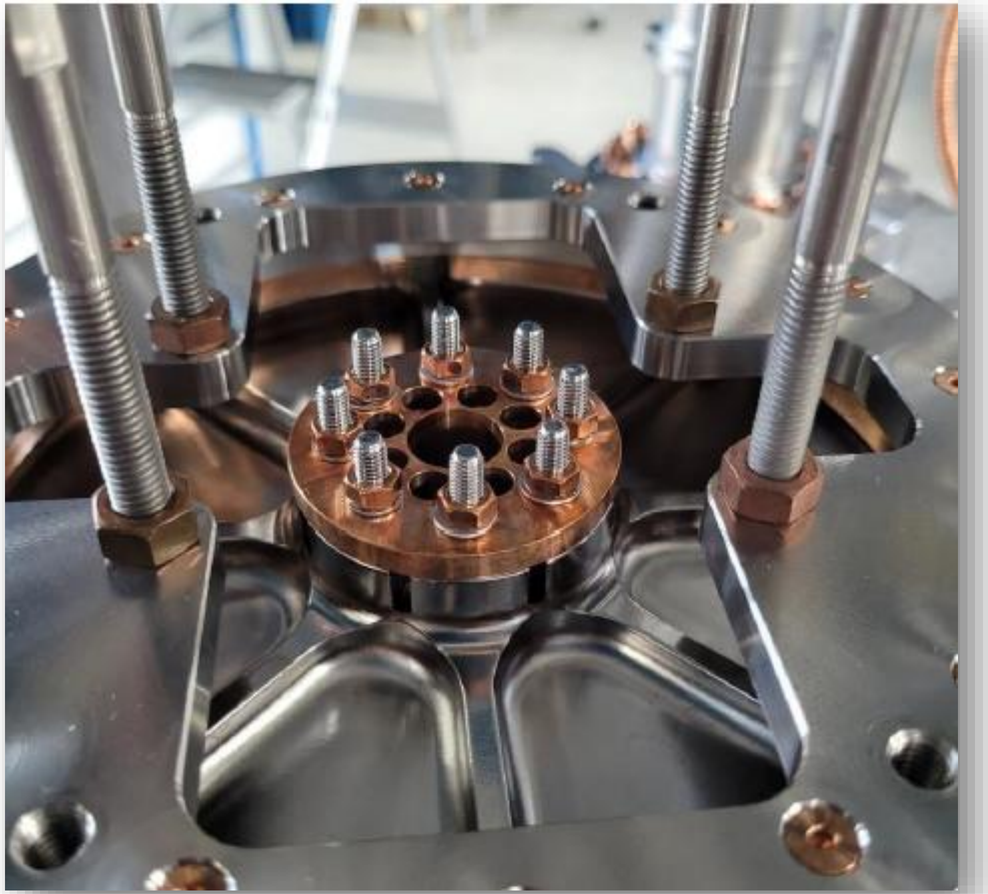
Courtesy S. Jaster-Merz, E. Vogel, D. Bazyl

SRF photoinjector cavity with a Cu cathode

- Until now L-band 1.5 cell injector cavities with **load lock** systems did not demonstrate the required high gradient.

Cathode specification	NC Cavity	SRF Cavity
Material	Cs_2Te	Copper
Assembly	Load lock system	Thread-mounted to backwall

- Screwing **thread-mounted cathodes** directly to the cavity back-wall requires R&D.
- In particular, preserving the cathode QE (quantum efficiency) during high-pressure rinsing (HPR) treatment of the SRF cavity.

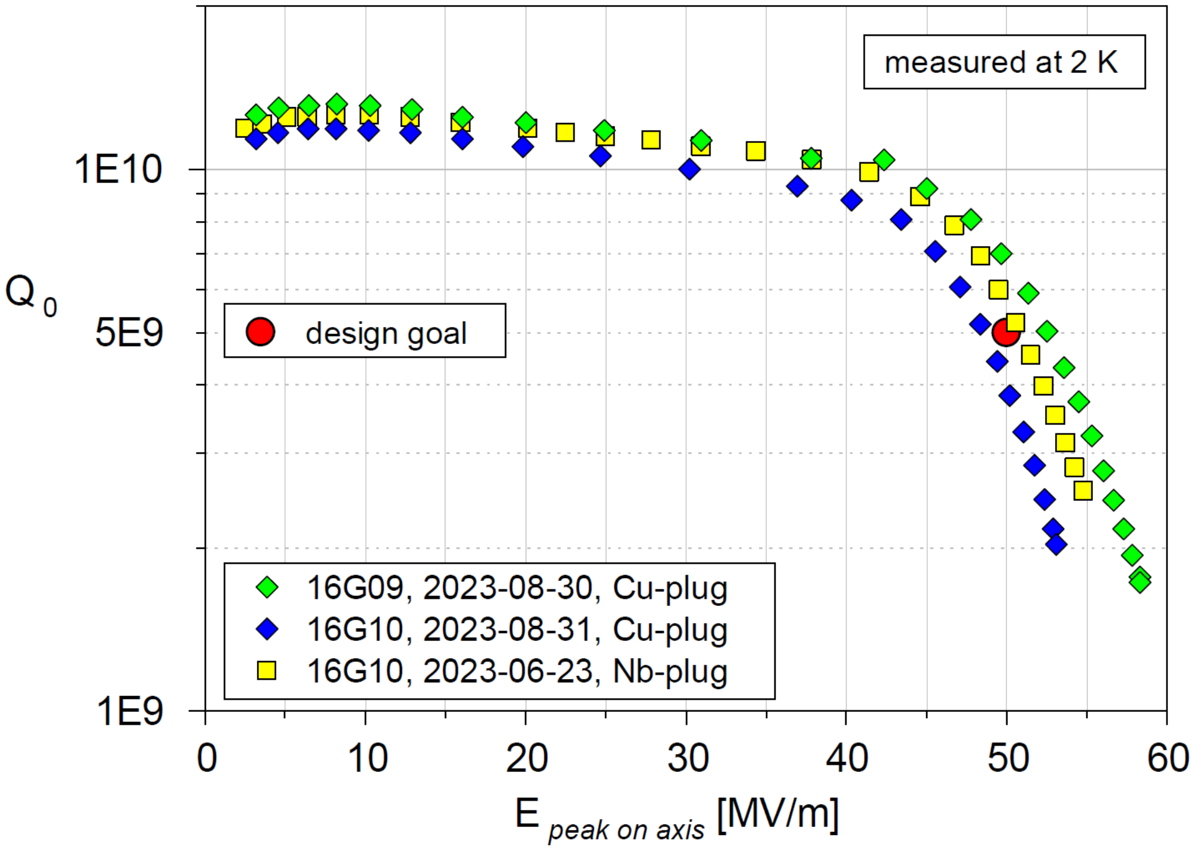


Courtesy S. Jaster-Merz, E. Vogel, D. Bazyl

SRF photoinjector cavity RF performance

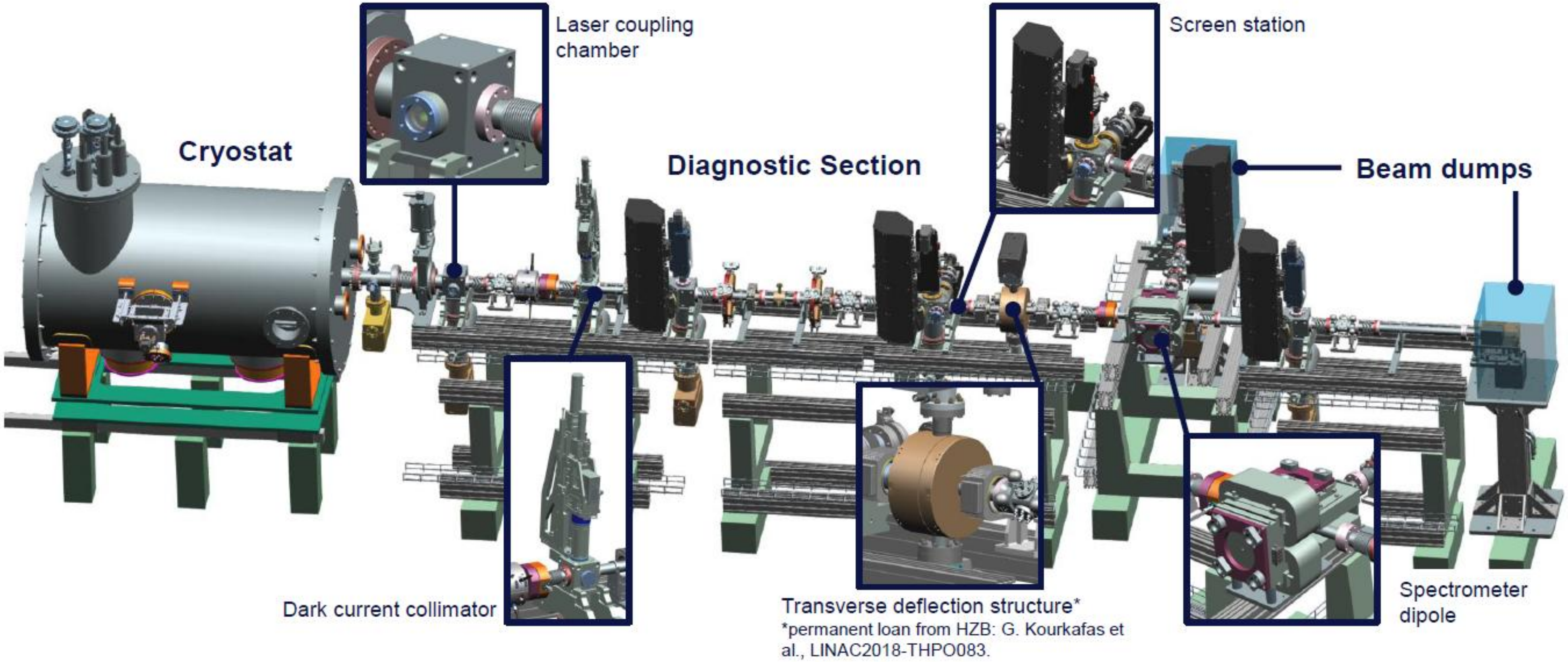
- Using L-band 1.6 cell photoinjector cavities with a cathode directly screwed to the back-wall and performing “standard" SRF cavity preparation after cathode installation, the **required high gradients** in vertical tests **could be demonstrated**!

Courtesy S. Jaster-Merz, E. Vogel, D. Bazyl



Ts4i : a complete SRF photoinjector test stand

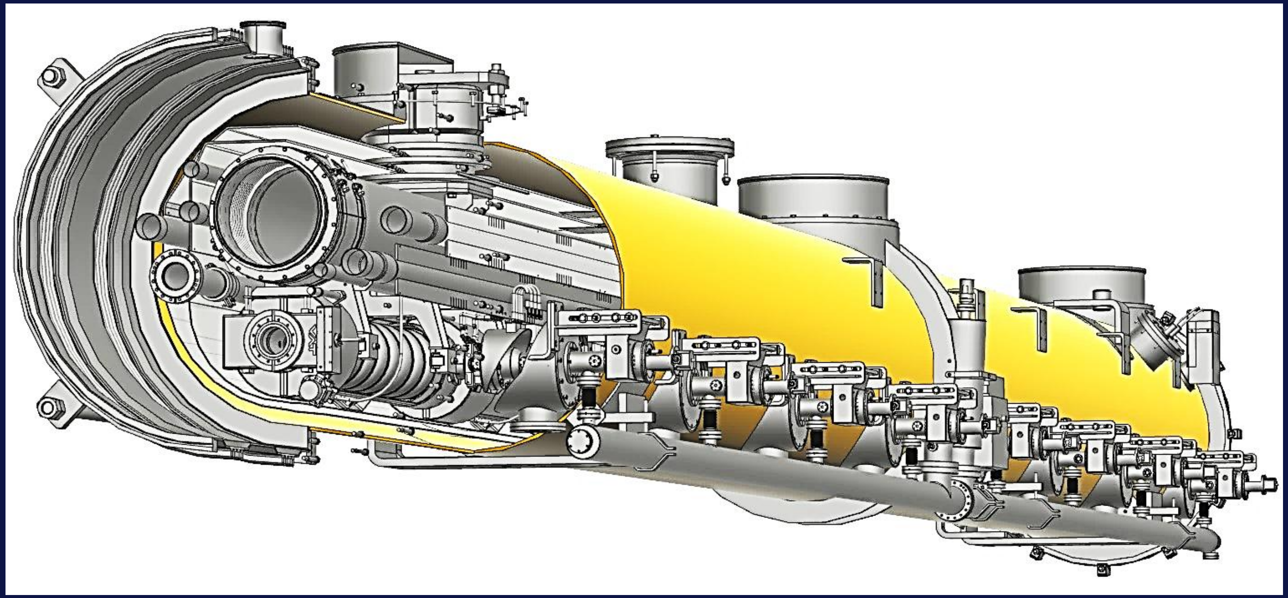
- As next step, we need to **demonstrate beam production**, for that purpose, we are now building the SRF injector test stand **Ts4i** (≈ a small but complete superconducting accelerator).



Courtesy S. Jaster-Merz, E. Vogel, D. Bazyl

CRYO-
MODULES
PLANTS

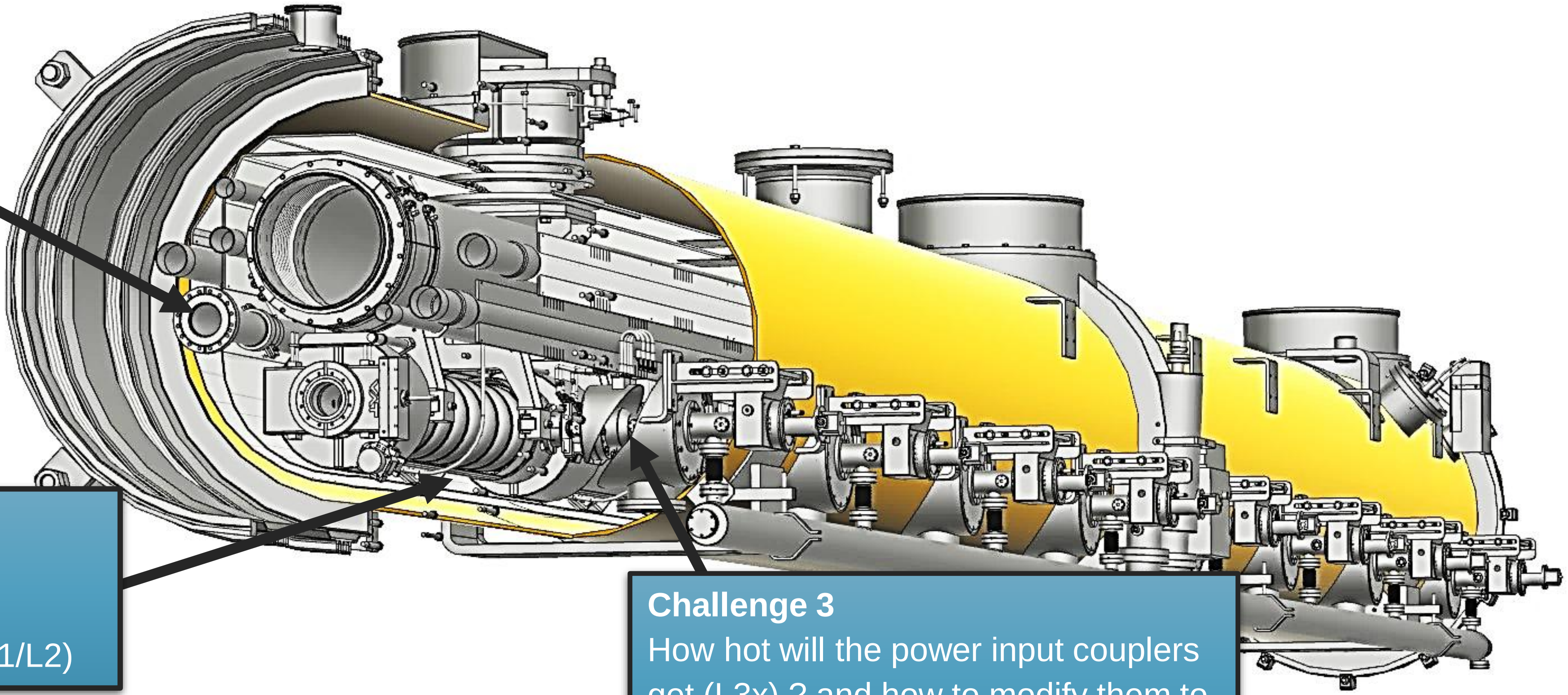
SOLUTIONS



IMPACT OF CHANGING OPERATION MODE ON THE CRYOMODULES

- Two **fundamental questions**
  - What to modify for the new design ? → **L1 / L2**
  - How the existing CMs are going to be affected ? → **L3x**

Challenge 1
How to increase the cooling capacity and get the extra heat out ?

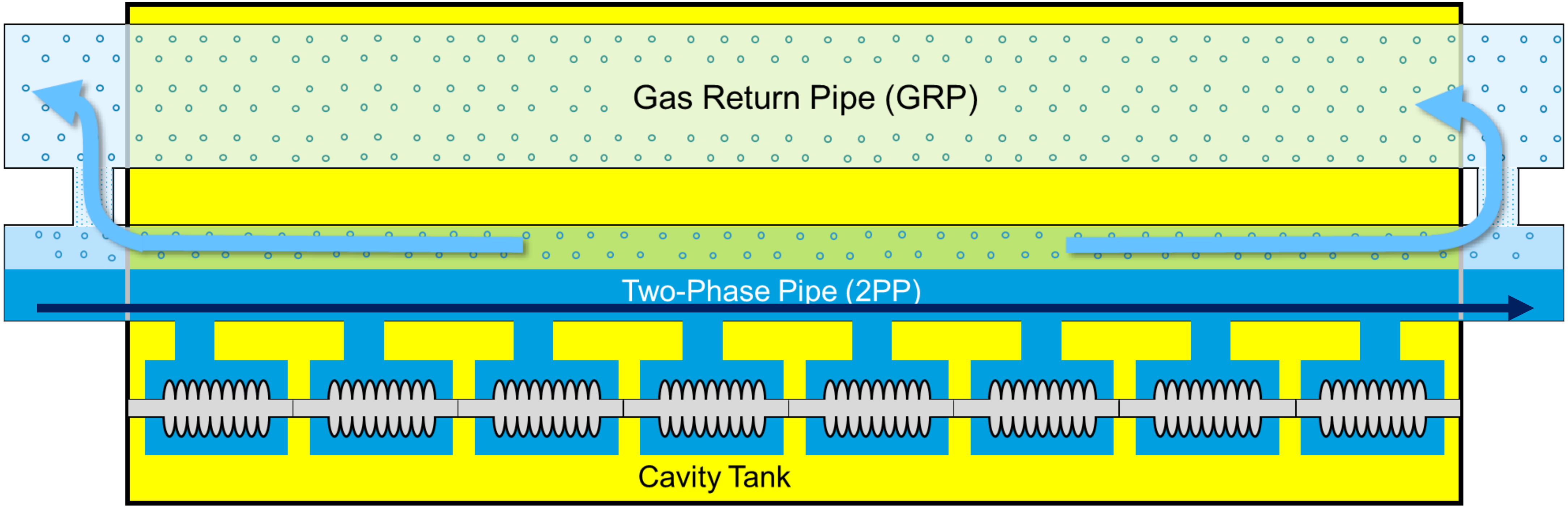


Challenge 2
How much extra dynamic heat load do we expect from our cavities (L3x)
→ produce new cavities with higher Q_0 (L1/L2)

Challenge 3
How hot will the power input couplers get (L3x) ? and how to modify them to improve cooling (L1/L2)

CRYOGENIC SOLUTIONS : more cooling is required !

- An **increased heat load** produced by the cavities will **require an increased helium flow** (liquid + gas)



Courtesy T. Schnautz / A. Dhillon

- This can lead to
  - **pressure instability** in the cavities (i.e. microphonics)

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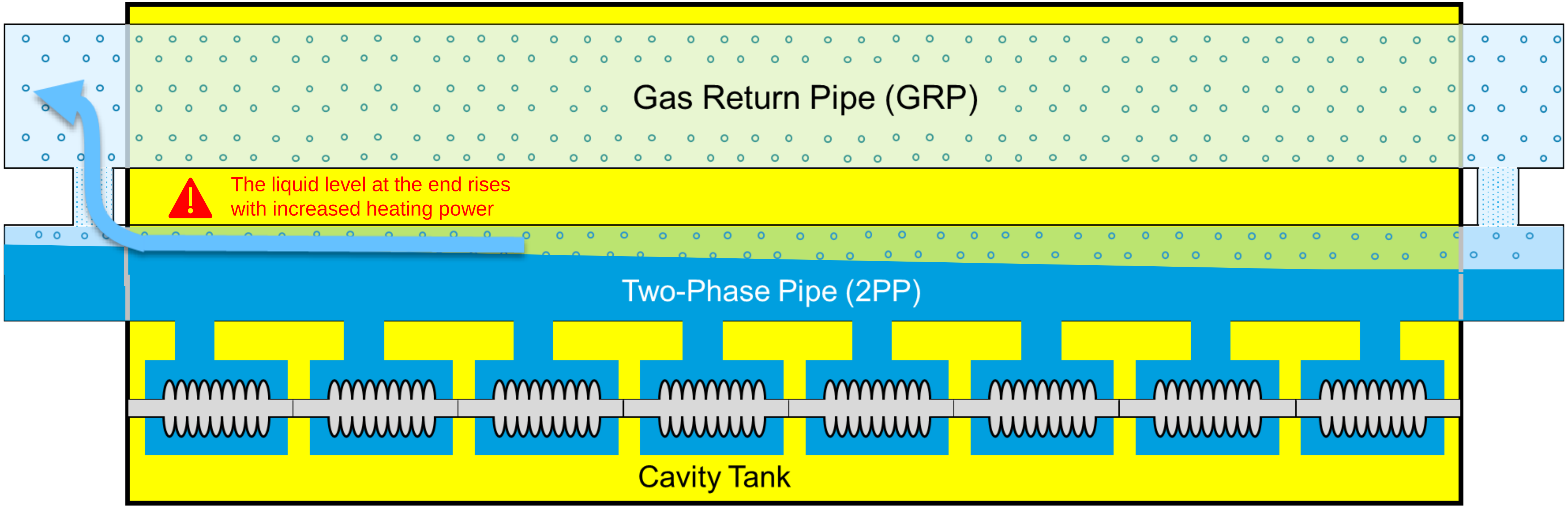
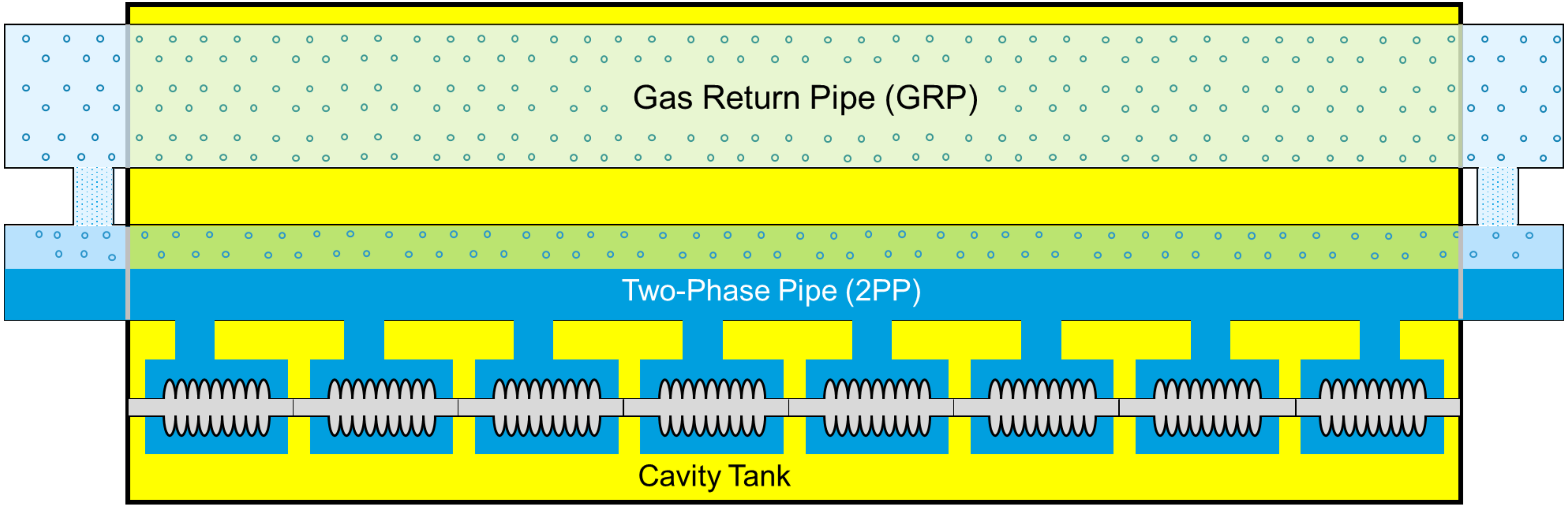


Courtesy T. Schnautz / A. Dhillon

- This can lead to
  - **pressure instability** in the cavities (i.e. microphonics)
  - stronger **level inclination** of the liquid He inside the 2PP, creating a bottleneck (hinders gas flow)

CRYOGENIC SOLUTIONS : more cooling is required !

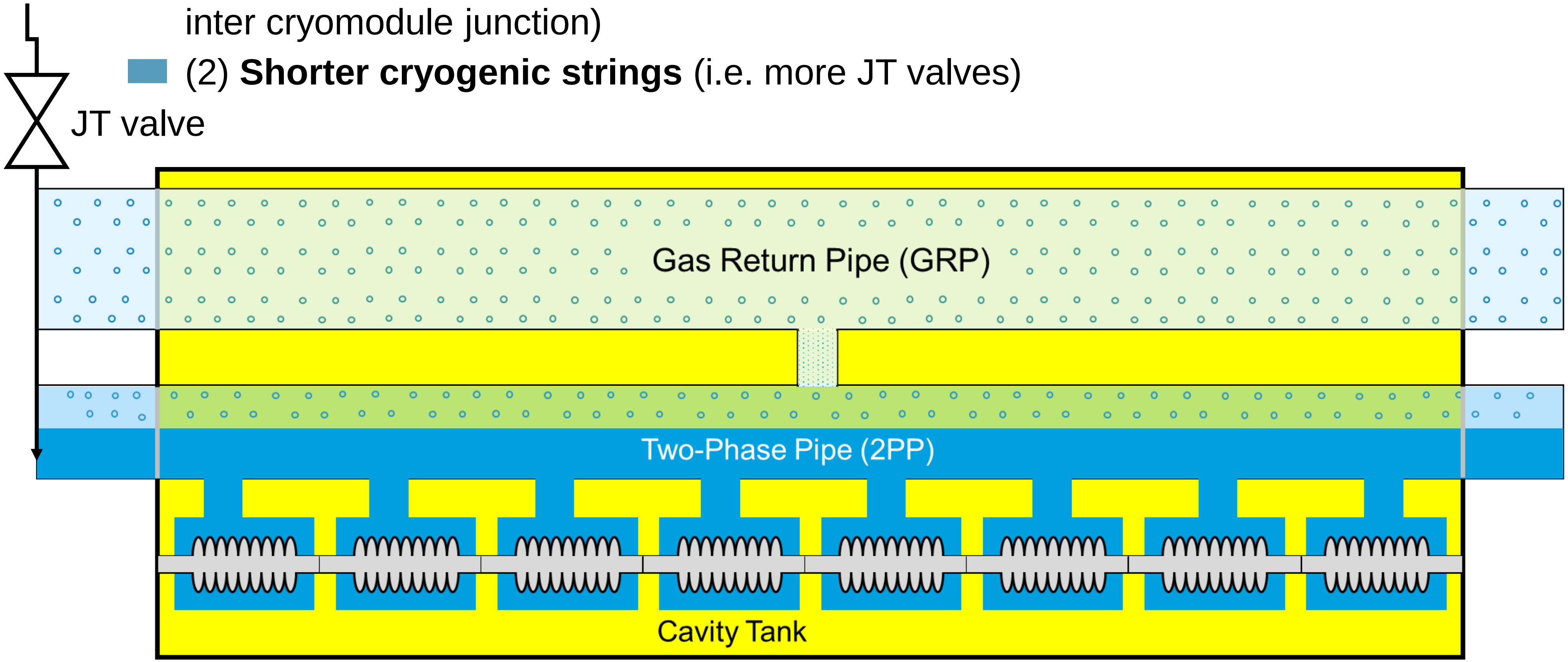
- **Investigated solutions**
  - (1) **One connection** between 2PP and GRP **in the middle** of the cryomodule (instead of 2 at each inter cryomodule junction)



Courtesy T. Schnautz / A. Dhillon

CRYOGENIC SOLUTIONS : more cooling is required !

- **Investigated solutions**
  - (1) **One connection** between 2PP and GRP **in the middle** of the cryomodule (instead of 2 at each inter cryomodule junction)
  - (2) **Shorter cryogenic strings** (i.e. more JT valves)

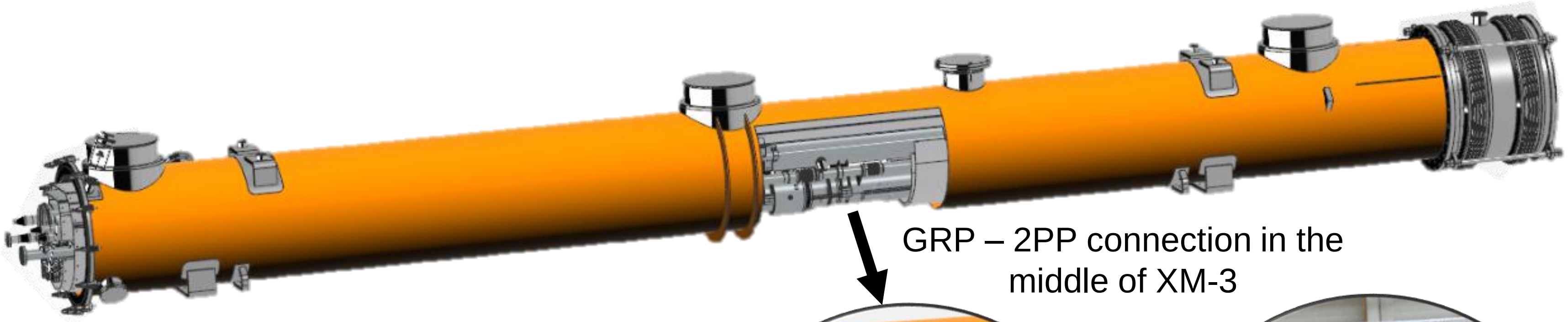


GOAL
sustain higher heat loads:
up to 150 W / cryomodule for L1/L2

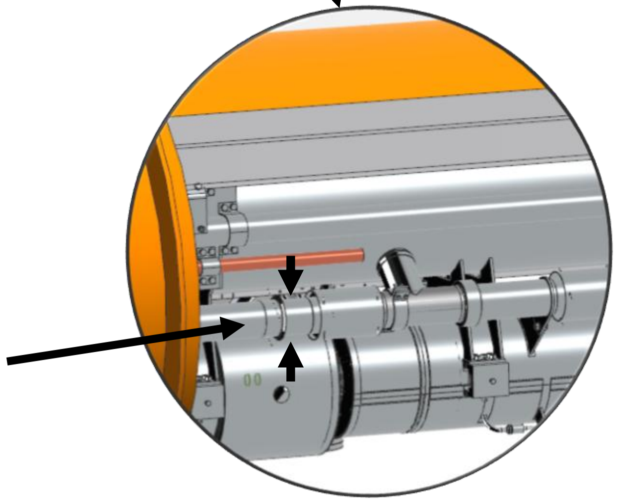
Courtesy T. Schnautz / A. Dhillon

These modifications are currently being tested on XFEL spare cryomodules

- Moving the Two-Phase Pipe (2PP) - Gas Return Pipe (GRP) **connection to the middle** of the cavity string (instead of being at the inter-cryomodule connections)



GRP – 2PP connection in the middle of XM-3

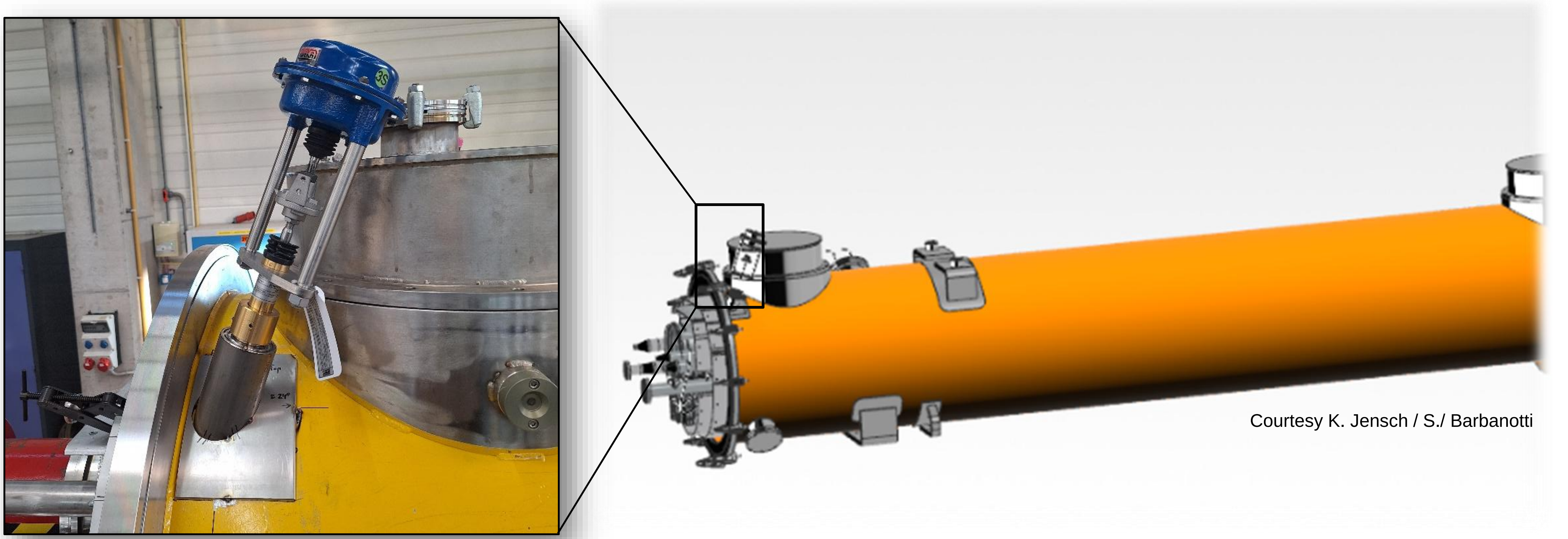


- Increase 2PP diameter (~76 → 89 mm) ?
  - Test in summer 2026 if needed

Courtesy K. Jensch / S. Barbanotti

These modifications are currently being tested on XFEL spare cryomodules

- Placing **one Joule-Thomson valve** per cryomodule (instead of every 12 cryomodules)



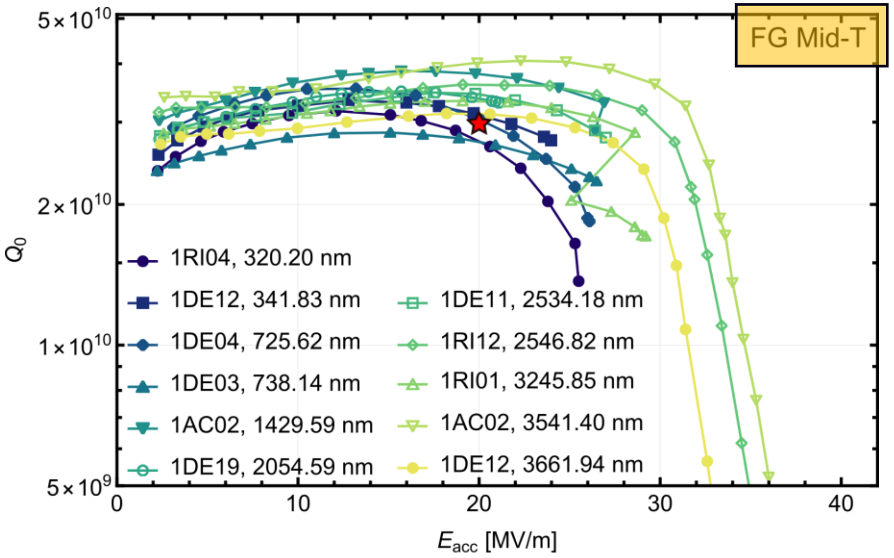
Courtesy K. Jensch / S./ Barbanotti

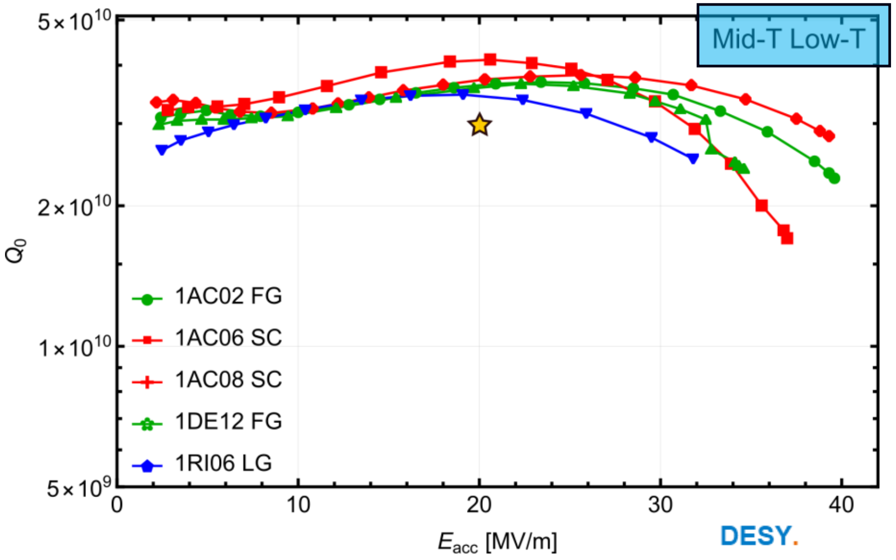
JT valve retrofitted in XM-3

Produce new cavities for low cryogenic losses (high Q_0)

Courtesy L. Steder / D. Reschke

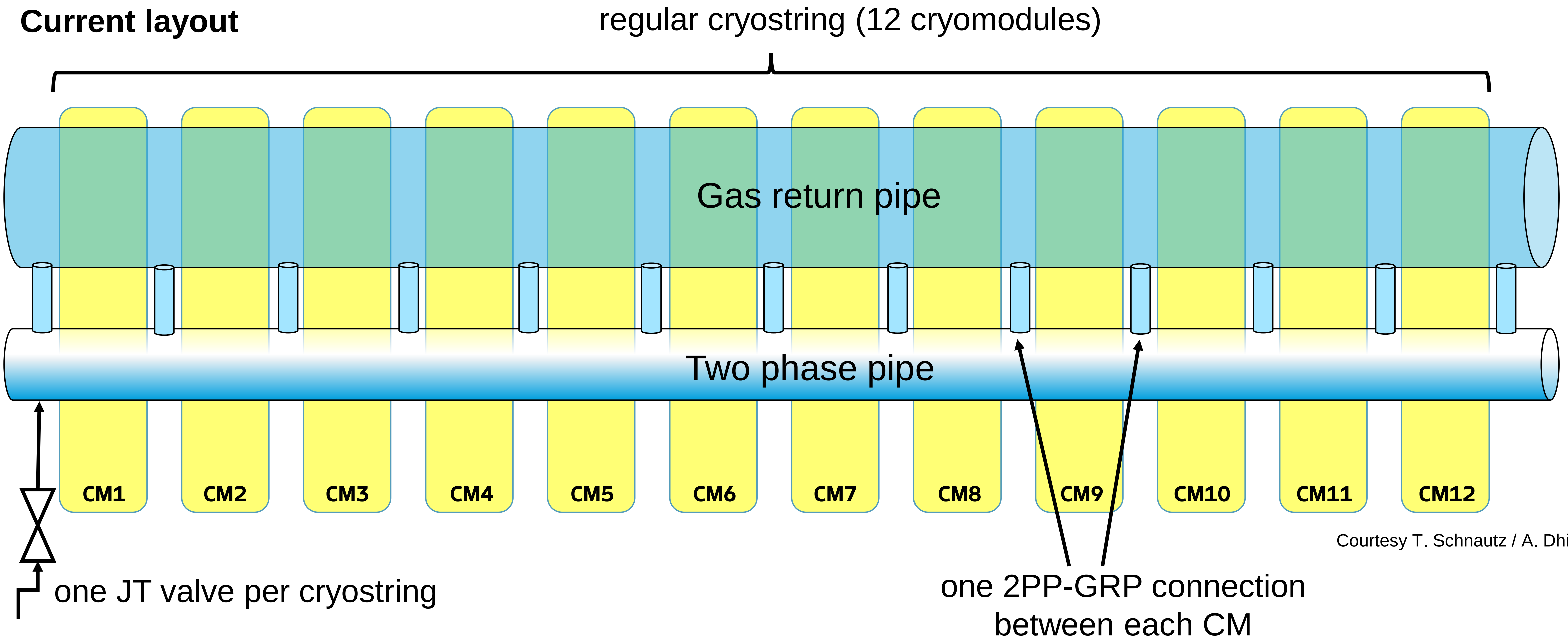
- The “standard” recipe used for EuXFEL not suited for HDC
  - 2007 goal: $Q_0 = 1x10^{10}$ at 23.6 MV/m
  - New goal: $Q_0 = 3x10^{10}$ at 20.0 MV/m
- New recipe required for HDC optimized cavities
  - Cavity surface engineering to improve RF performance
  - **Mid-T bake** well established for single cell cavities meets goal
  - Additional **low-T** treatments for specific cavities result in high Q_0 and high accelerating gradients E_{acc}
- **Goals**
  - Transfer recipe to 9-cell cavity (on-going)
  - Produce 10 new XFEL cavities with mid-T/low-T heat treatments (applied at DESY)
  - **HDC new cryomodule ready for test in 2029**
  - Train next generation experts





WHAT ABOUT L3x CRYOMODULES ?

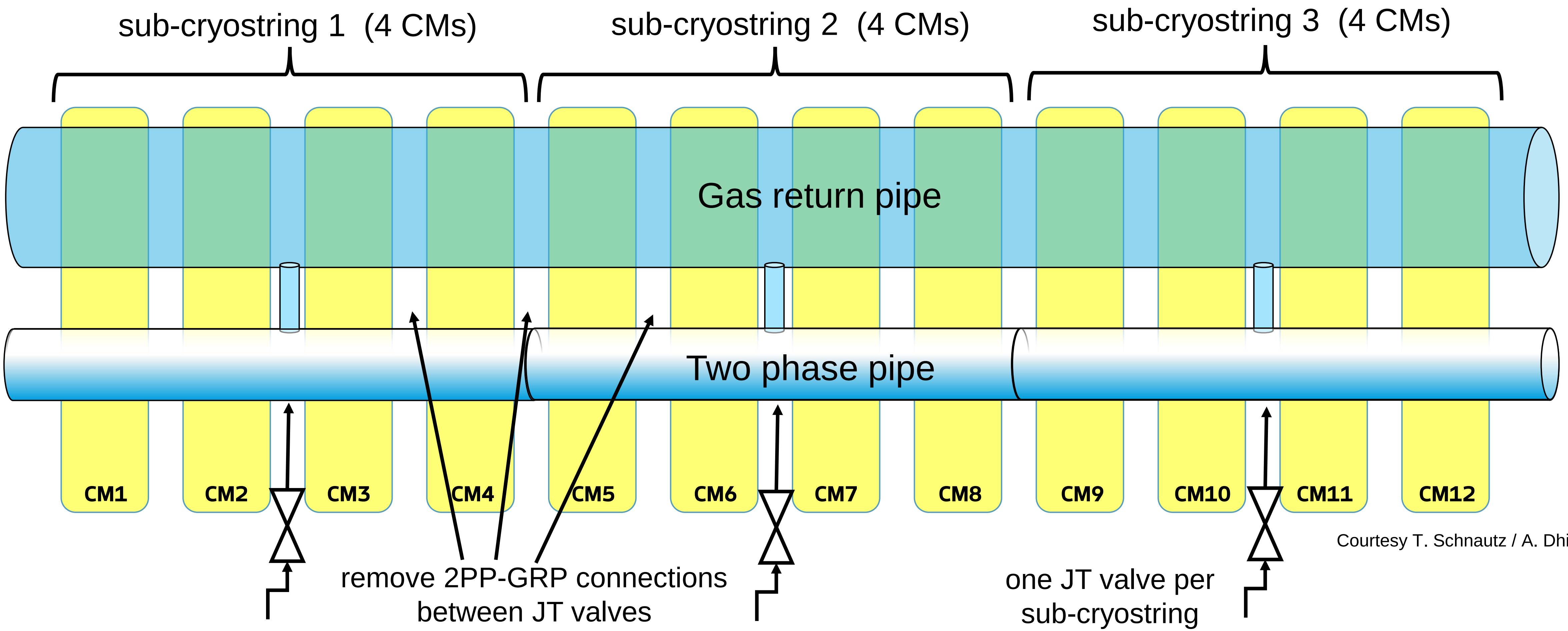
Current layout



Courtesy T. Schnautz / A. Dhillon

- We can’t change the cavities, but…

WHAT ABOUT L3x CRYOMODULES ?



Courtesy T. Schnautz / A. Dhillon

- We can't change the cavities, but **we can modify the string connections for higher heat loads**

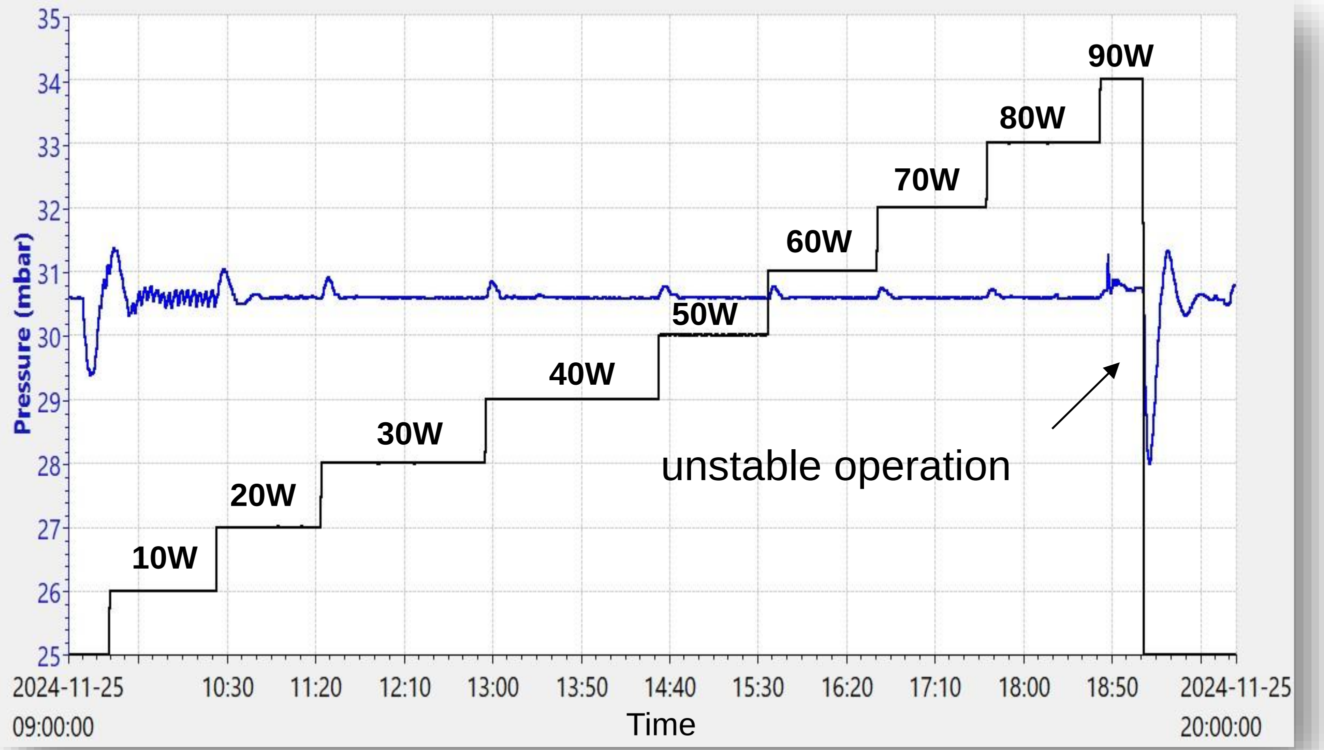
GOAL sustain higher heat loads up to 32 W / cryomodule for L3x

WHAT ABOUT L3x CRYOMODULES ?

- Establishing the **maximum dynamic heat load** in L3x cryomodules

Assessing limit with heaters, with CW RF, at the cavity level, at the cryomodule level

Courtesy E. Abassi / R. Ramalingam

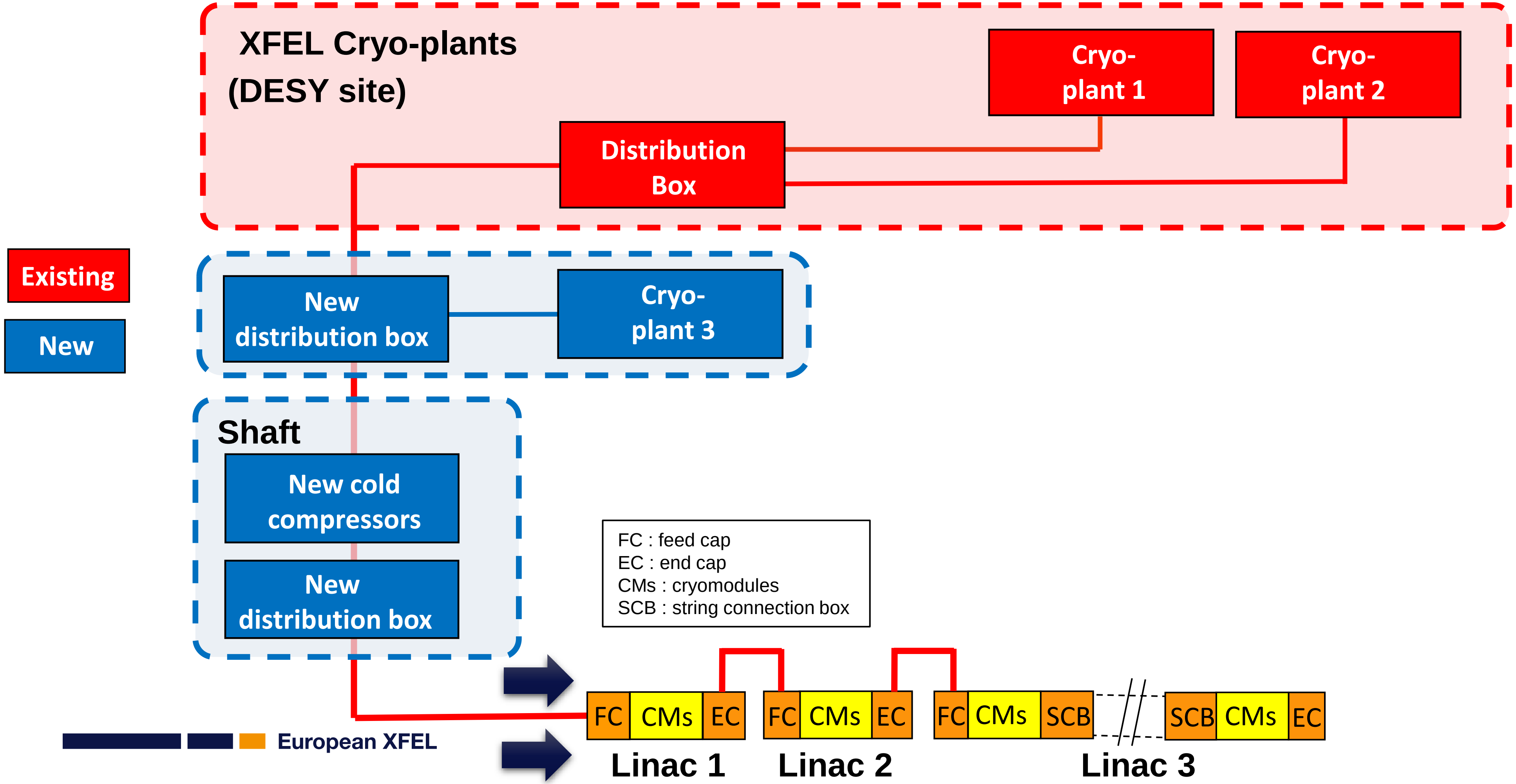


Major impact on the **maximum beam energy**

Two options for cryogenic supply of the future XFEL linac

OPTION 1: Feeding **L1/L2** and **L3x** from **DESY-site**

Courtesy T. Schnautz / A. Dhillon



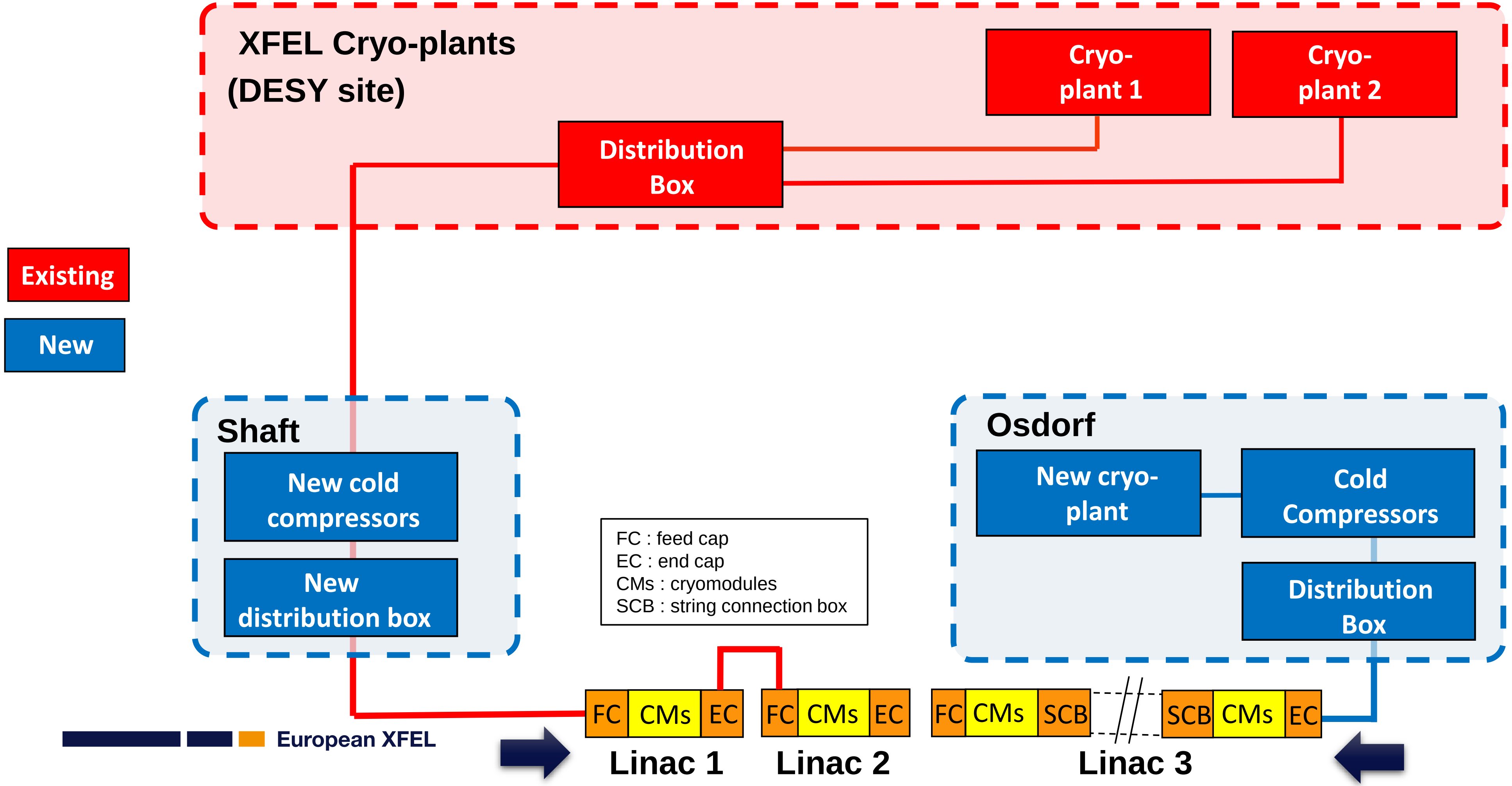
Pros
Cost saving option (partial reuse of infrastructure + unique control room)

Cons
Riskier option (limitation of 2K capacity)
Technical feasibility unclear

Two options for cryogenic supply of the future XFEL linac

OPTION 2: Feeding **L1/L2** from **DESY** and **L3x** from **Osdorf-site**

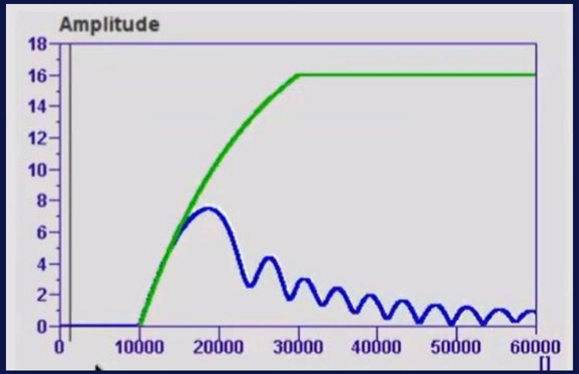
Courtesy T. Schnautz / A. Dhillon

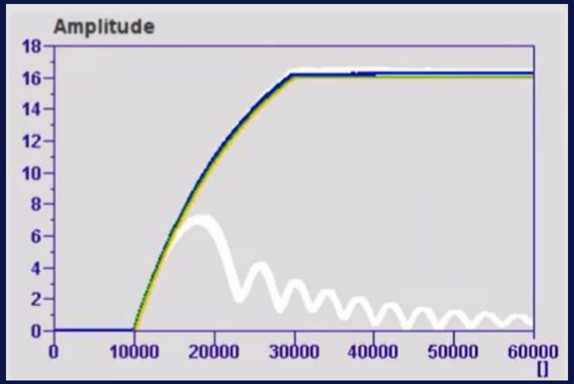


Pros
All heat-load compensation requirements achievable (4.2 kW for L1/L2 and 4.2 kW for L3x)

Cons
Cost intensive (large cryo and civil infrastructure-related work)

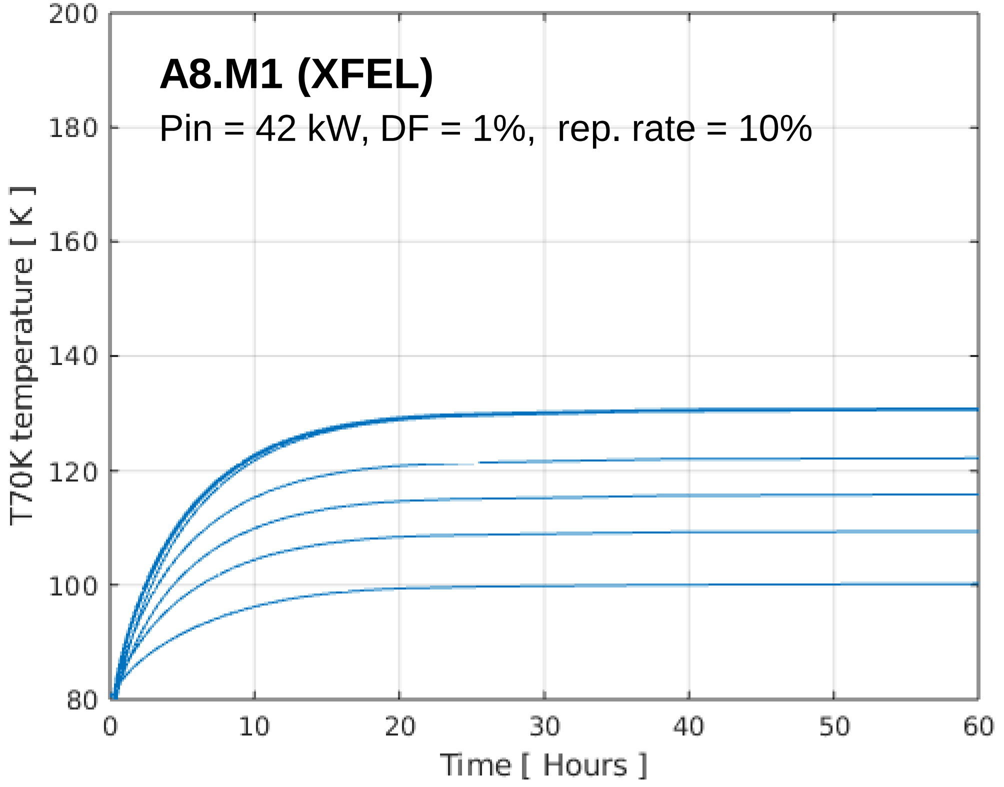
RF SOLUTIONS

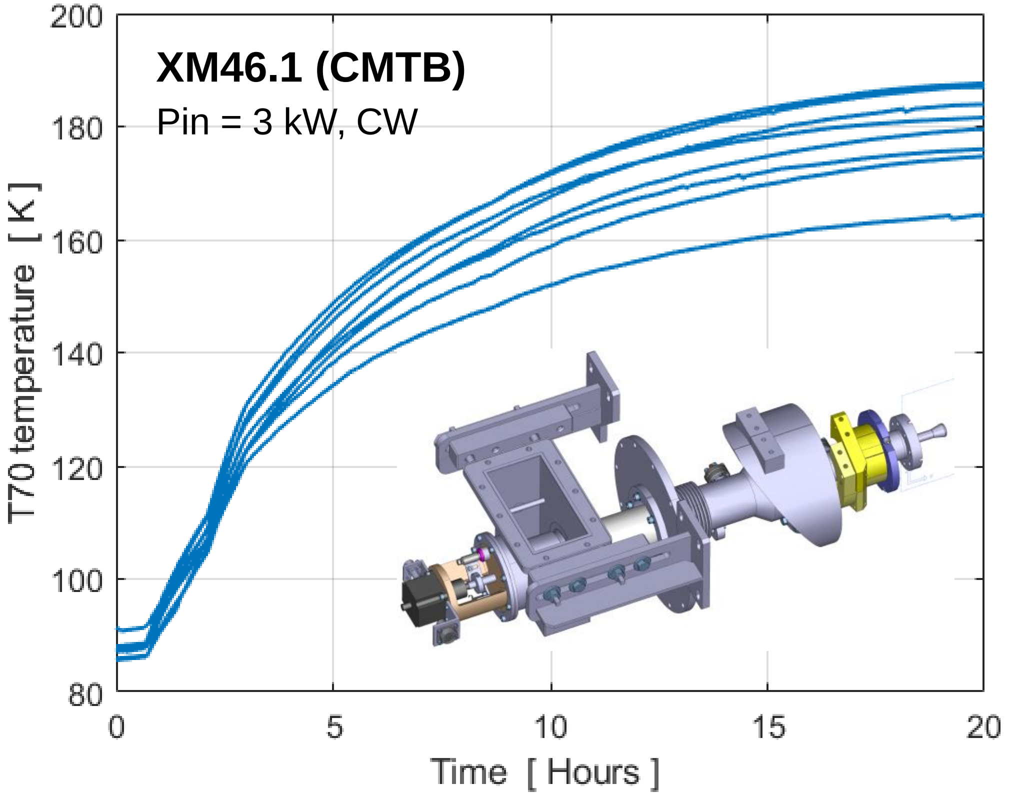




Understanding how much the couplers heat-up in CW / LP

Impact on the maximum input power for the couplers





Major impact on the **maximum beam energy**

The HDC upgrade will require CW capable RF sources

LCLS-II, SLAC
has a service gallery

The HDC upgrade will require CW capable RF sources

SHINE has a larger tunnel

- We need a solution that fits in our tunnel
- Work with manufacturers with foot print optimization in mind

Courtesy D. Wang

The HDC upgrade will require CW capable RF sources

- A **multi-dimension optimization challenge**
  - Max power, efficiency, foot print, cooling, AC supply, etc.

4 kW SSA in AMTF

40 kW IOT in CMTB

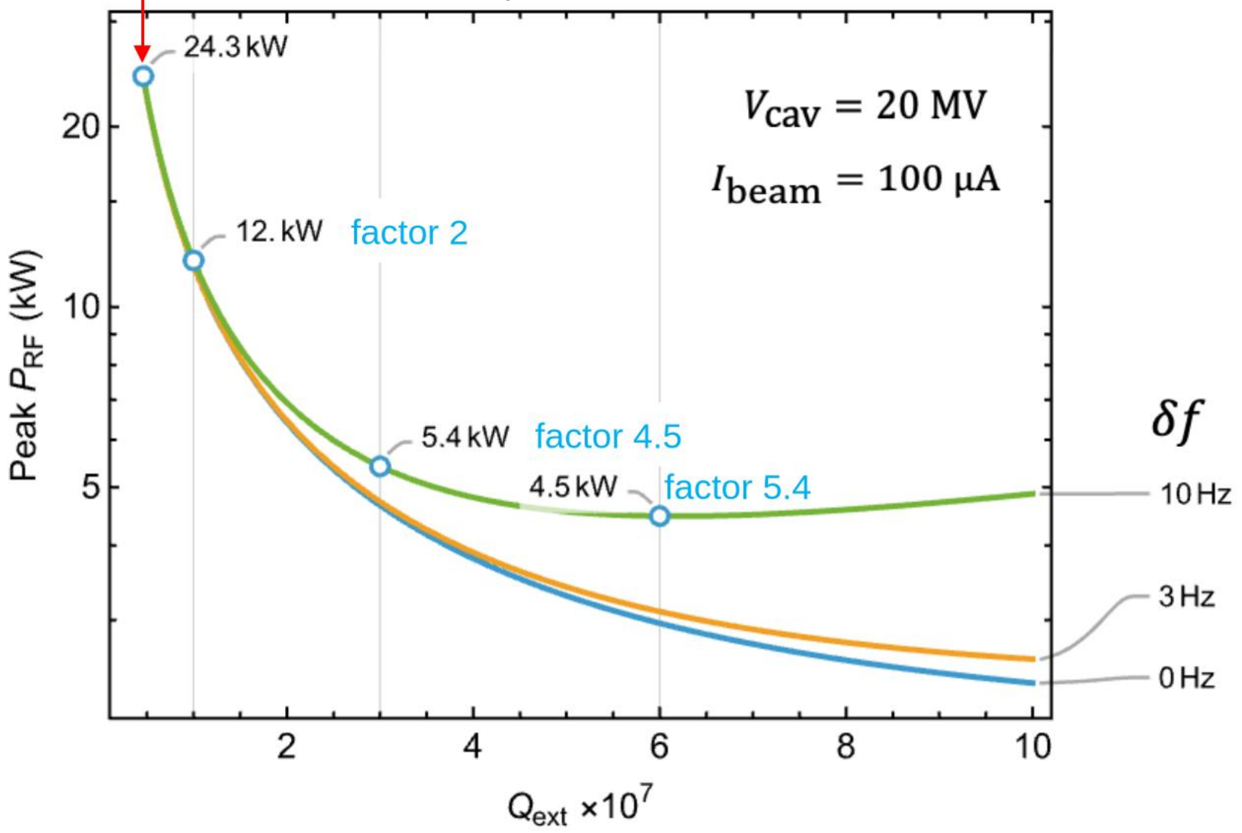
Courtesy M. Bousonville

A few words (again) about Q_{ext} (i.e. cavity bandwidth)

- Operating at higher Q_{ext} is a game changer compared to our operation today
  - It is necessary to lower RF power needs
  - It will make cavity control more challenging
- For L1/L2
  - New couplers designed to Q_{ext} = 6x10^7 target
  - SCAV operation (single cavity control, more on this later)
- For L3x
  - Baseline Q_{ext} = 1x10^7
  - R&D to see if/how go beyond baseline
  - R&D to push limits due to MCAV

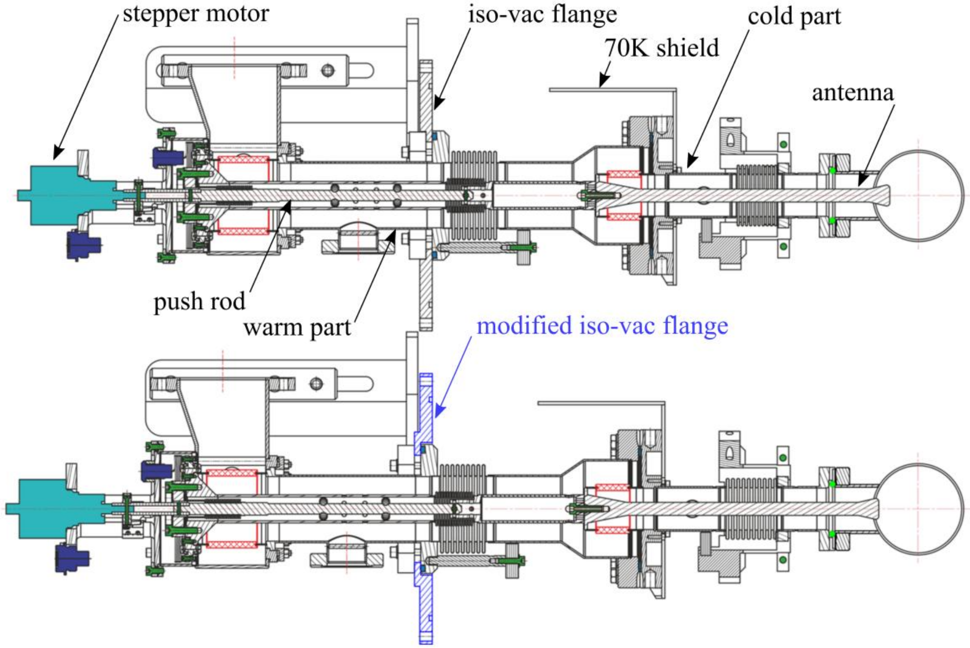
nom. XFEL
Q_{ext} = 4.6×10^6

See previous talk, from Nick Walker



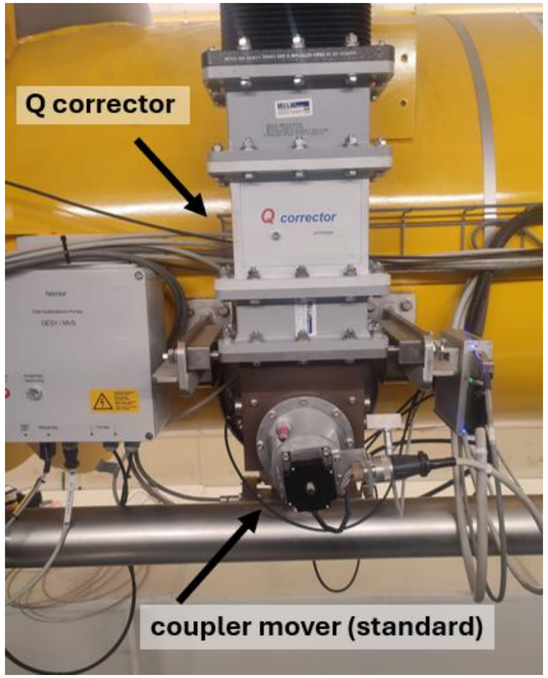
Shifting to higher Q_{ext} by modifying the warm coupler part

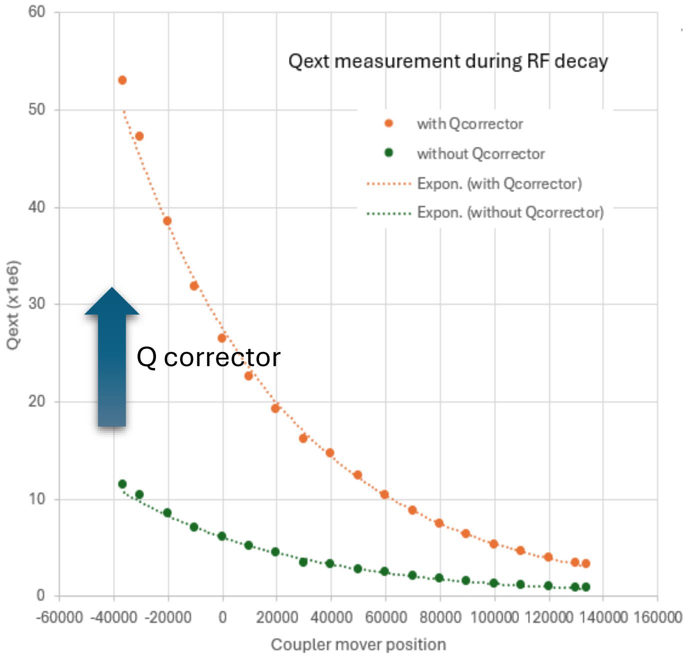
Modified iso-vac-flange



- Tested on 4 CM: XM3, XM50 and XM46 and XM8 (now)
- Can increase Q_{ext} max from 1e7 to >3e7
- Is this approach realistic for ~800 couplers… ?

Introduce stub-like tuners



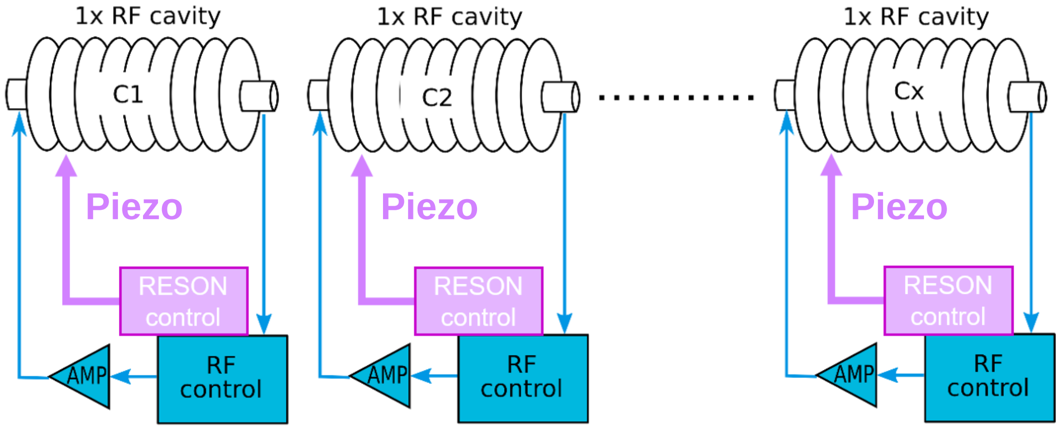


- Currently tested on XM8
- Can increase Q_{ext} range by factor 10 !
- But increases heating of coupler, "safe for couplers ?"

Major impact on the **maximum required AC/RF power**

Cavity field control architecture – SCAV vs. MCAV

SCAV: Single Cavity control

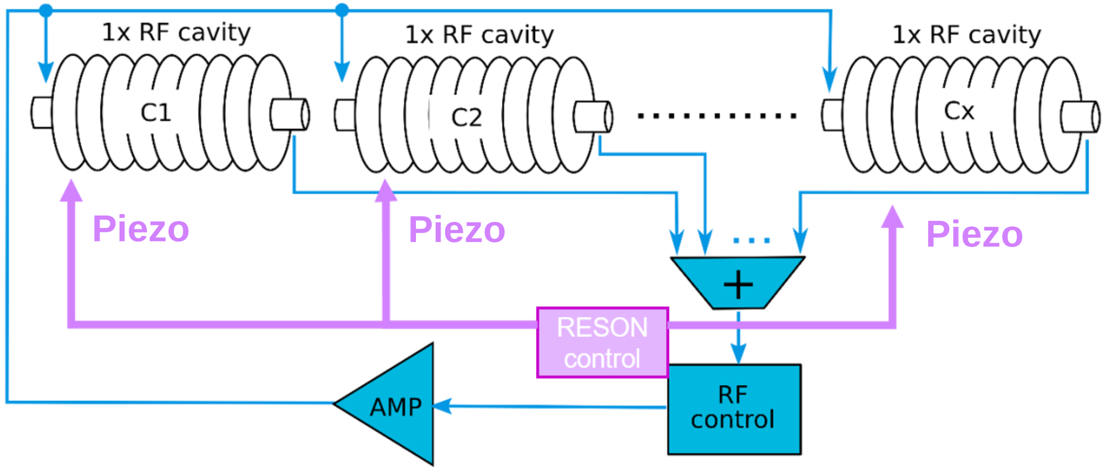


"each cavity has its own control loops"

Both **field** and **resonance** can be controlled independently for every cavity.

Standard approach for CW accelerators

MCAV: Multiple Cavity control



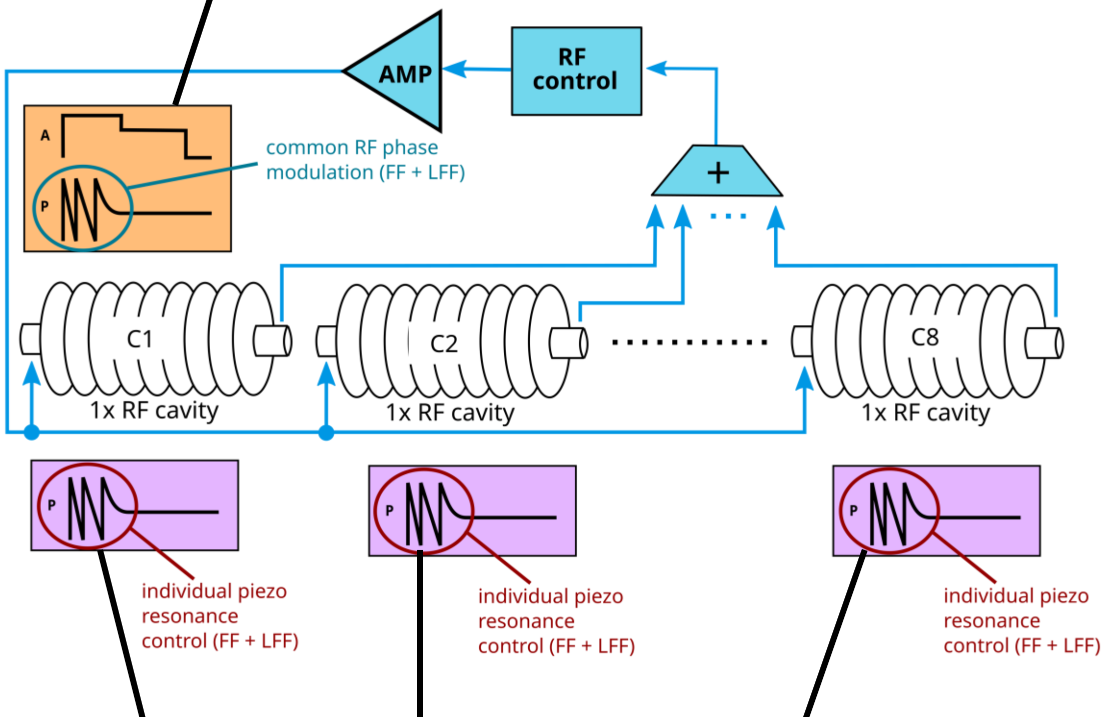
"the field controller controls the sum the cavity fields"

No individual **field** control. Only **resonance** can be controlled through individual piezos.

Current approach at XFEL

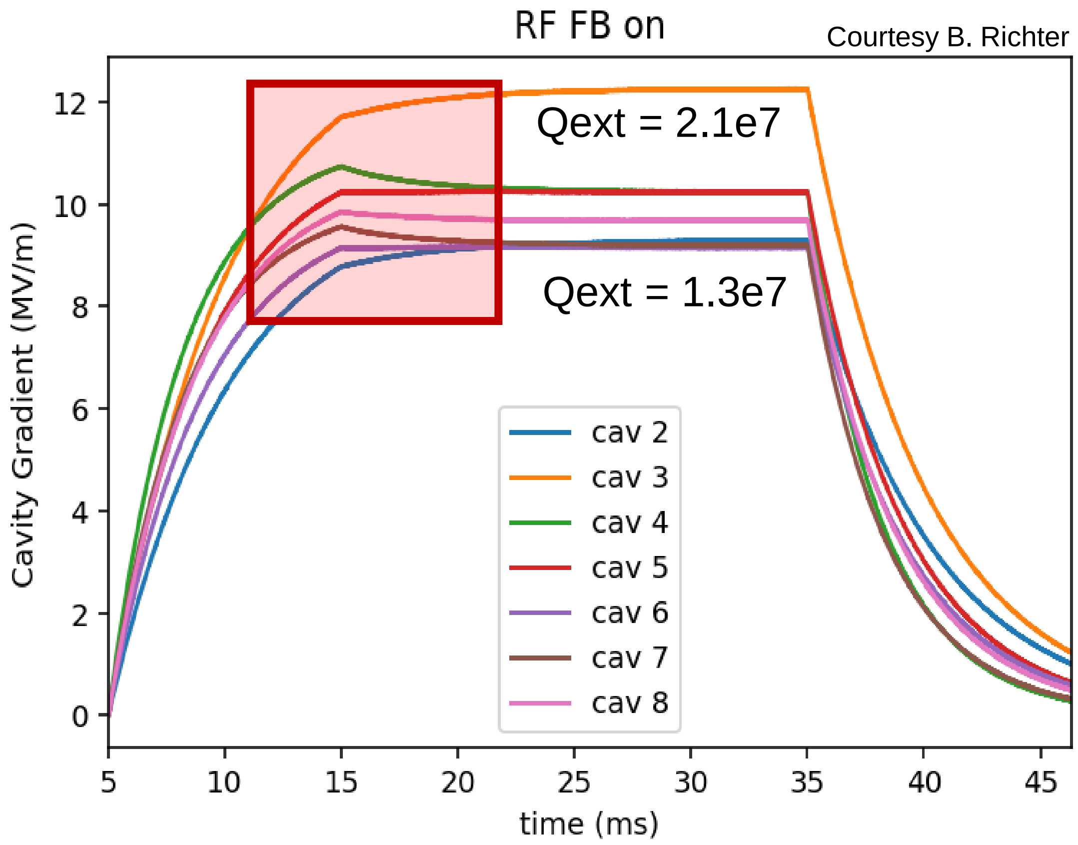
R&D to operate MCAV with high Q_{ext}

Drive all cavities in the VS with a **common RF phase modulation** to match the cavity resonance during fill



Compensate for remaining frequency mismatches with **individual piezo detuning compensation**

Courtesy B. Richter



Demonstration at CMTB, MCAV (7 cavities), in long pulse operation with $Q_{ext} > 1x10^7$

SUMMARY and OUTLOOK

- There is **much more** (for example timing, control system, DAQ, beam diagnostics, etc.) This is only an R&D selection…
- The FOS captured the **required R&D** to answer technical challenges
- **R&D roadmap** defined for next 5 years
- Note that **Ts4i** will also serve as **test bench** for many subsystems (e.g. timing and diagnostics)

			2027	2028	2029	2030	2031	beyond
Cryogenic Solutions								
1	Final cryogenic design for L1/2 cryo-module	Q4/27	◆					
2	Final recommendation for HDC cryo plant	Q4/27	◆					
1.3 GHz Superconducting Cryomodules								
1	CW-optimized prototype cryomodule for L1/2 tested	Q4/29			◆			
2	Final modification recommendation for L3x cryo-module	Q3/27		◆				
RF Solutions								
1	HPRF solution for L1/2 defined	Q4/27	◆					
2	HPRF Solution for L3x defined	Q4/28		◆				
3	Recommendation to reach higher Qext available	Q2/28		◆				
4	Feasibility assessment of RF solutions available	Q3/28		◆				
5	RF source prototypes available	Q4/30				◆		
6	SCAV and MCAV RF solution demonstrated	beyond 2031						◇
Photoinjector								
1	Verification of feasibility of nano-structured cathodes	Q4/28		◆				
2	Ts4i ready for beam	Q4/28		◆				
3	Critical Ts4i beam tests completed	Q2/30				◆		
4	Technical design for complete injector in 2nd tunnel completed	Q1/30					◆	
Control and Timing System								
1	X3TIMER firmware for basic HDC operation available	Q4/30				◆		
2	JDD includes CW mode display capability and archiving system	Q4/30				◆		
3	Demonstrator for archiving system and DAQ CDR available	Q4/30				◆		
4	X3TIMER operation for HDC demonstated	Q4/31					◆	
Diagnostic and Feedback Systems								
1	Simulations of heat dissipation due to HDC simulated	Q1/28		◆				
2	HDC-ready firmware and software verified at Ts4i	Q2/29			◆			
3	HDC--ready feedback systems ready for implementation	Q4/30				◆		


Thank you for your attention!
... and to all the HDC colleagues!