SUPERCONDUCTING TECHNOLOGIES

FOR THE NEXT GENERATION OF ACCELERATORS

WORKSHOP

Eric Montesinos

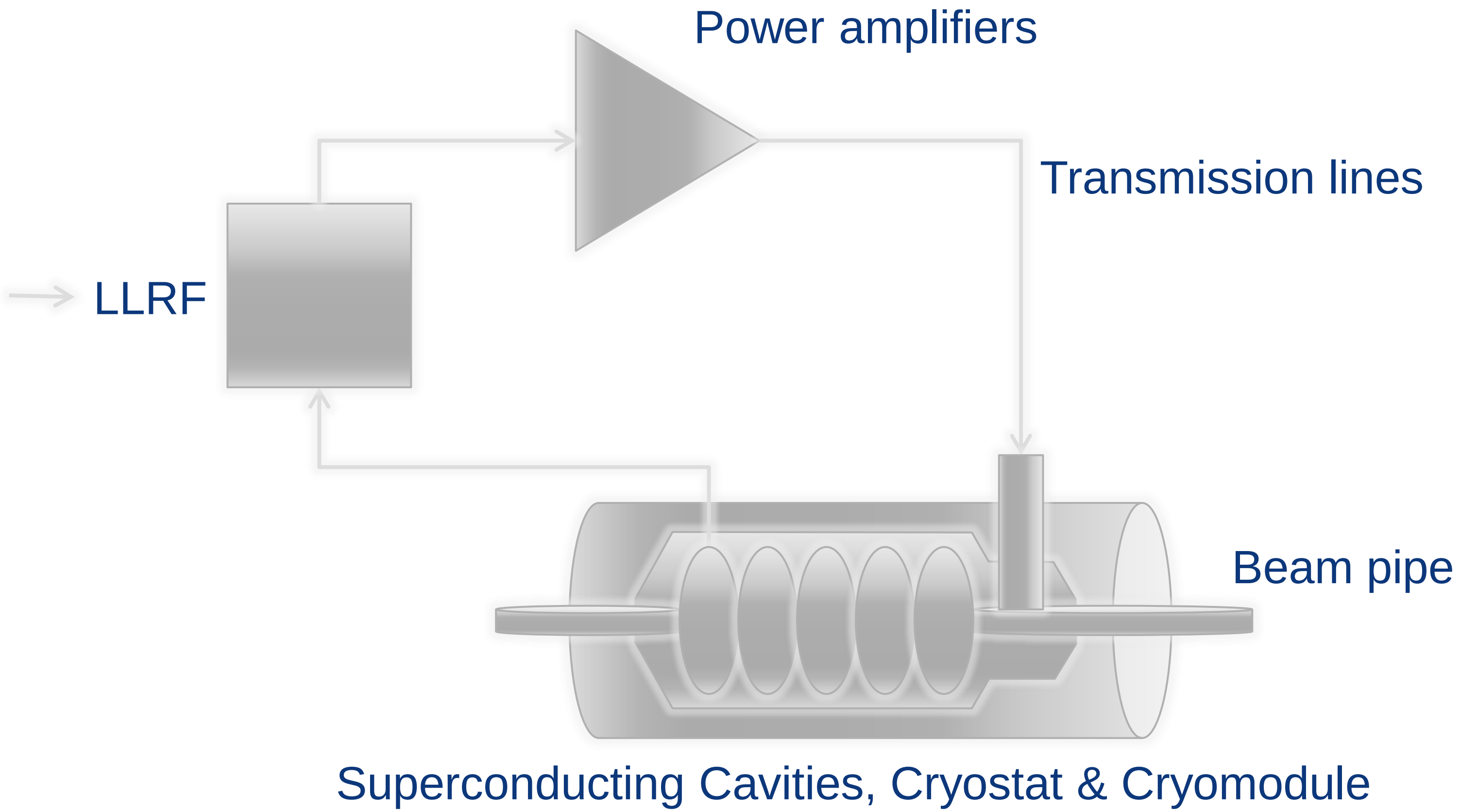
Challenges in RF Fundamental Power Coupler (FPC) Technology

Contents :

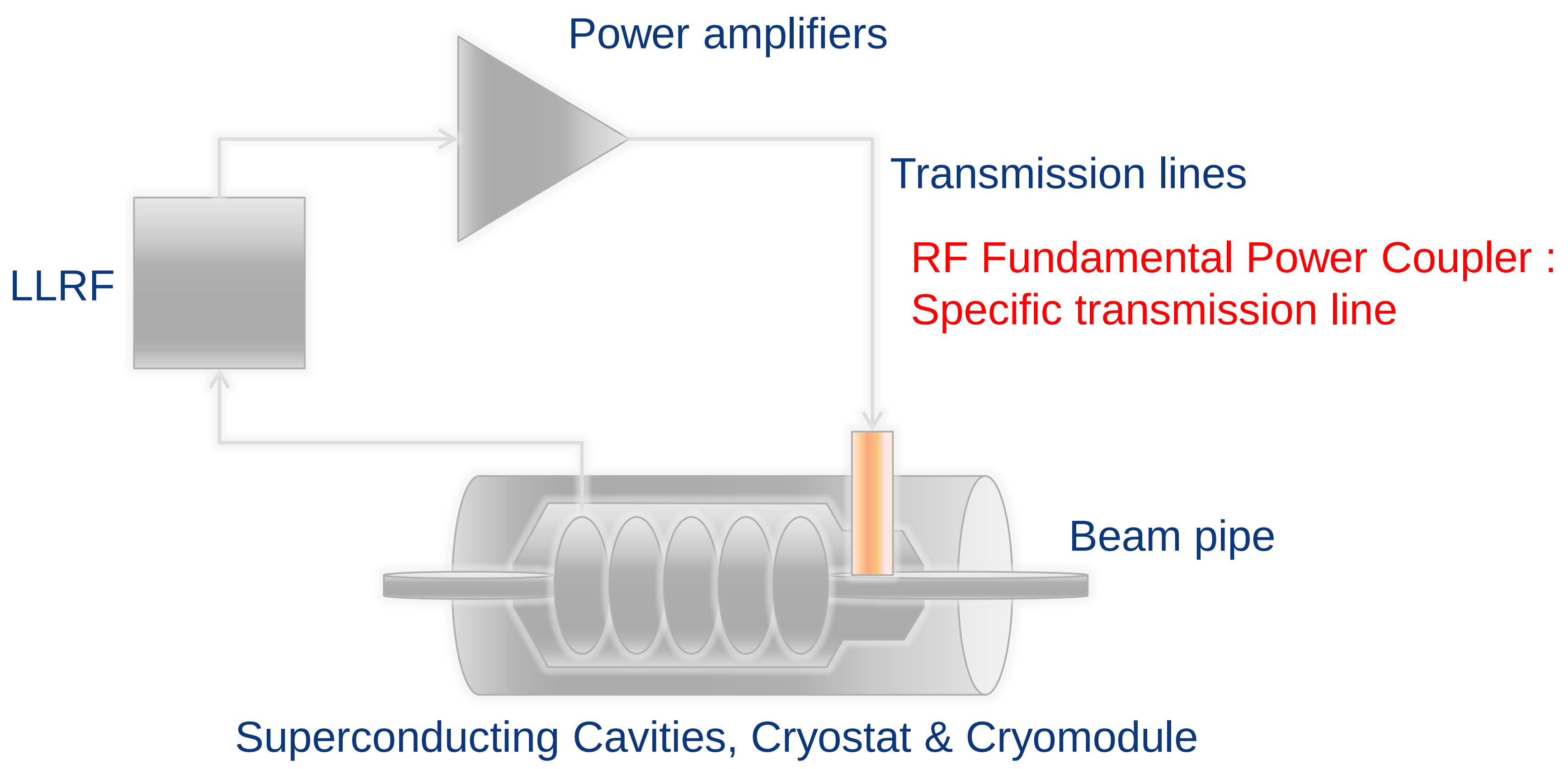
‘talk on couplers, ideally to motivate future R&D by industrials’

- RF Fundamental Power Coupler :
  - Coupling RF power to a cavity
  - Basic function of a coupler
  - Key components
- Design considerations :
  - RF parameters
  - Window
  - Additional SC constraints
  - Operation
  - Fabrication
  - RF conditioning
  - Cost
- Some Technology challenges :
  - Window brazing
  - Window EBW
  - 3D printing
  - Copper coating
  - Ti coating
  - Cleanliness issues
- Future projects in the range of MHz :
  - Some MHz couplers worldwide
  - CERN on going and future projects
  - Prototyping
- Conclusion

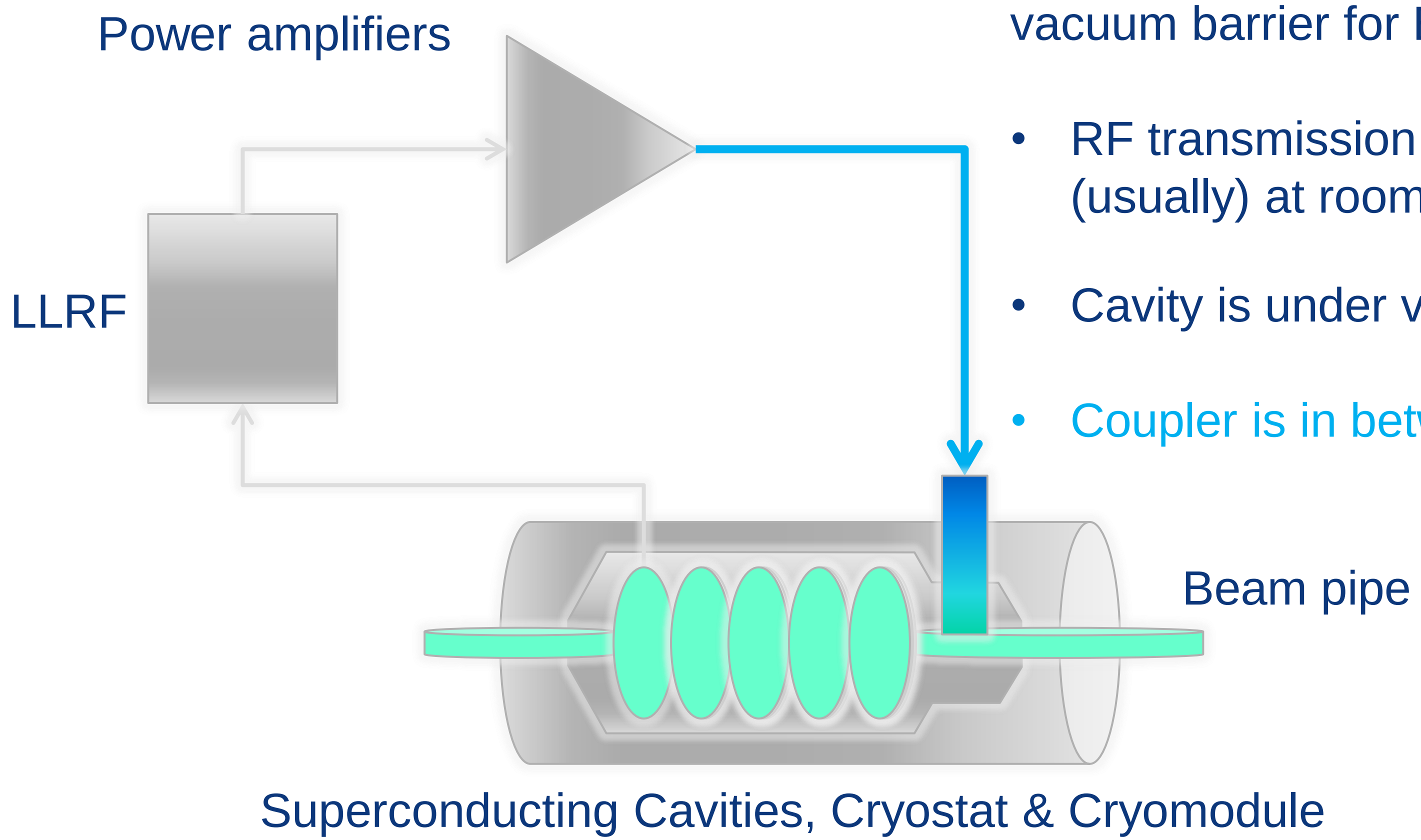
Coupling RF power to a cavity



Coupling RF power to a cavity



Basic function of a RF FPC



To transmit power of amplifiers into the cavity providing a vacuum barrier for Beam pipe :

- RF transmission lines are (usually) at room pressure
- Cavity is under vacuum
- Coupler is in between

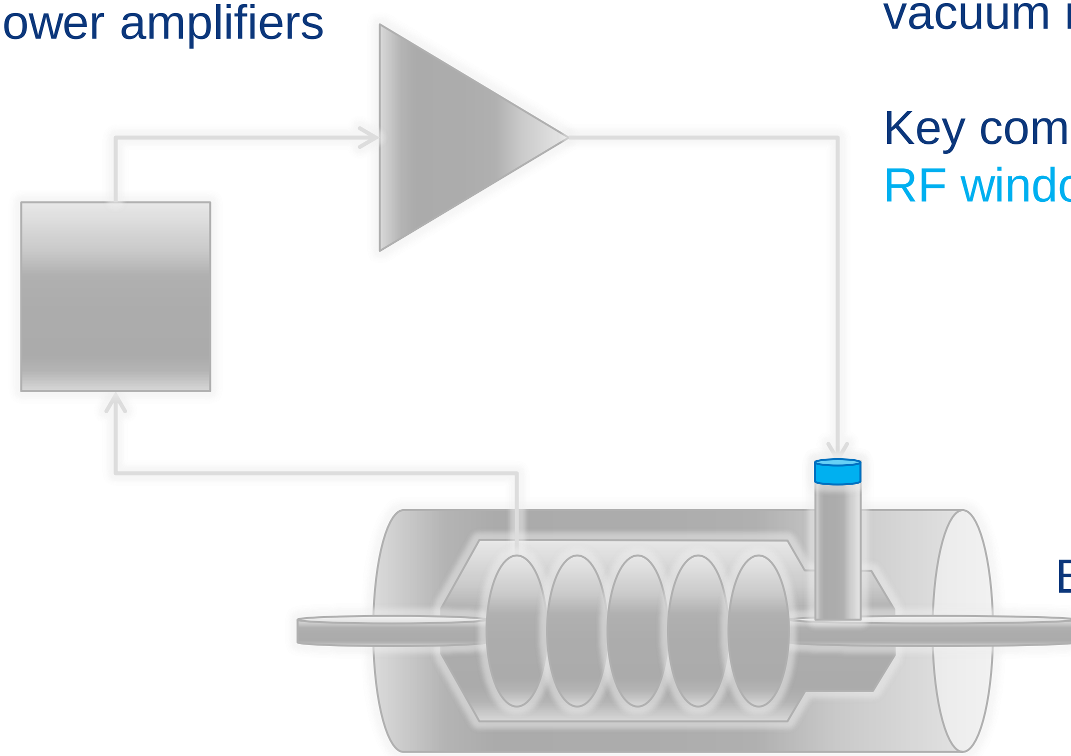
Key components

To perform these two tasks :
RF power transmission &
vacuum integrity

Key component is the
RF window

Power amplifiers

LLRF



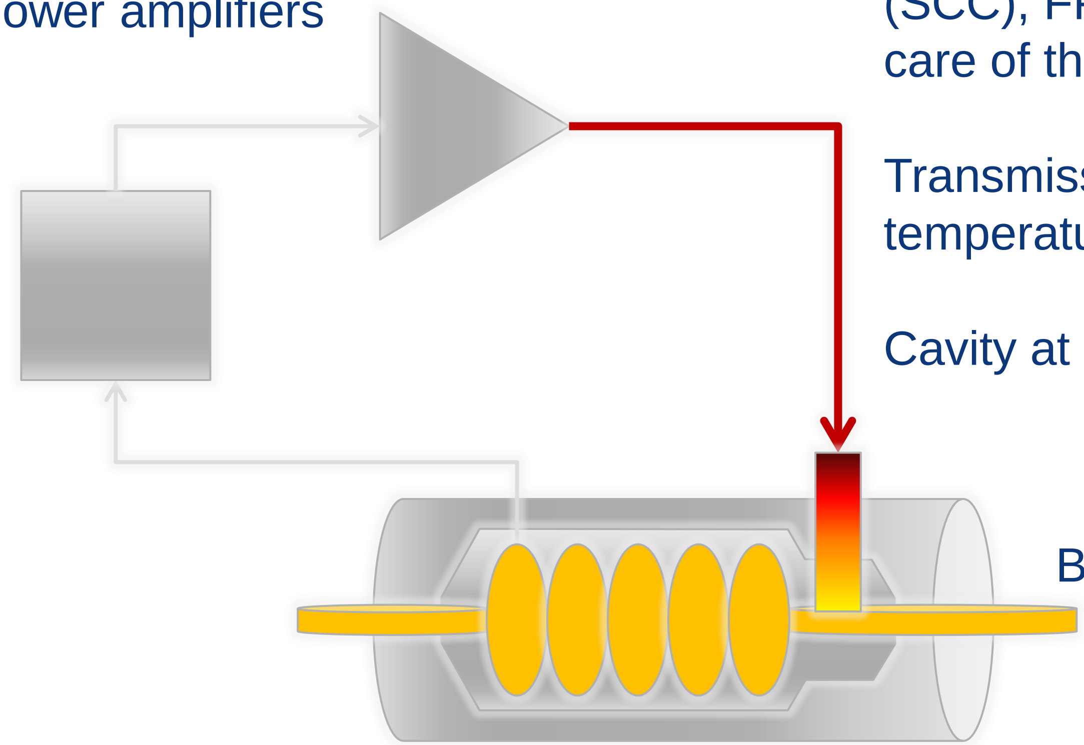
Beam pipe

Superconducting Cavities, Cryostat & Cryomodule

Basic function of a RF FPC

Power amplifiers

LLRF



Beam pipe

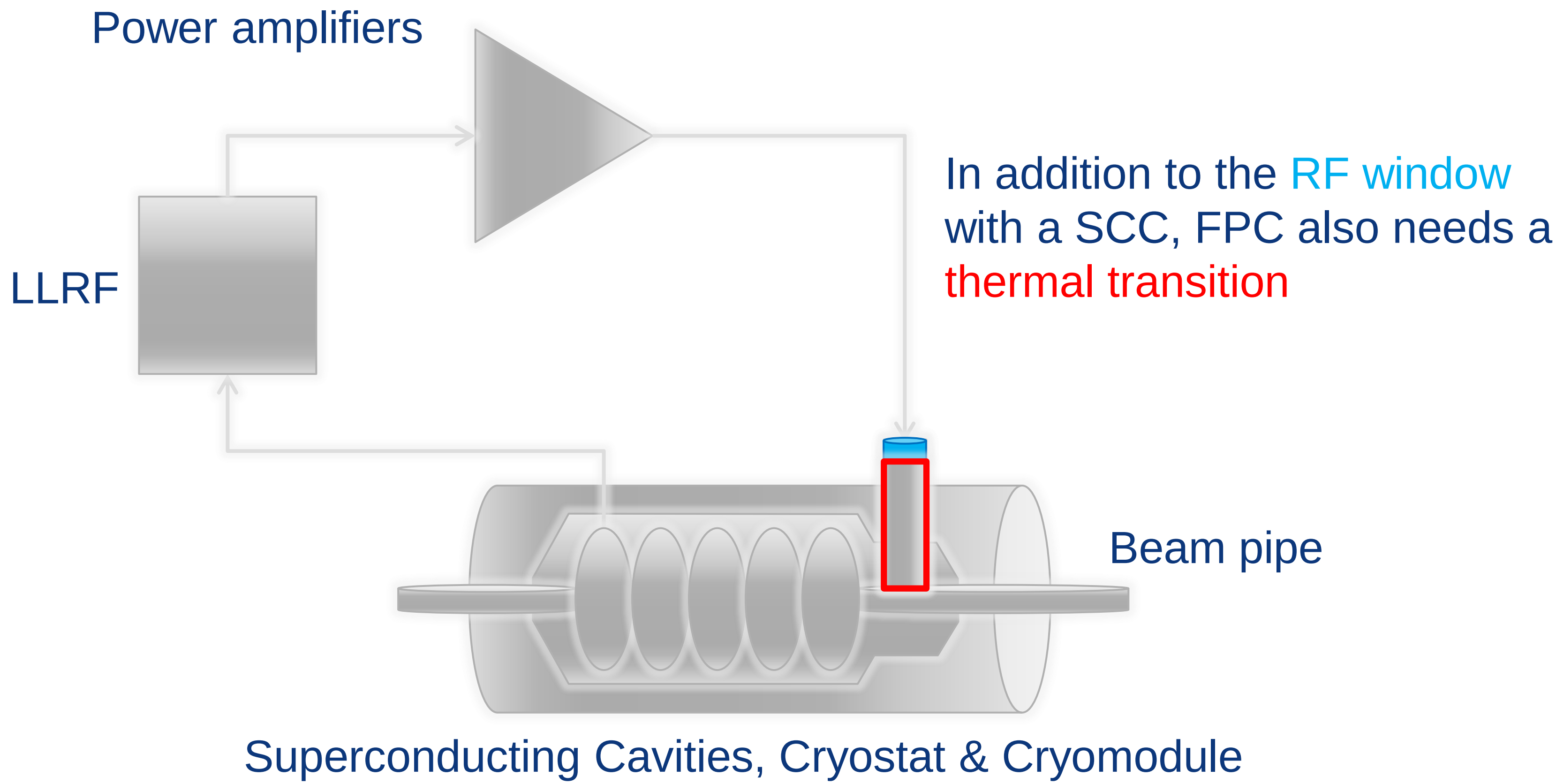
Superconducting Cavities, Cryostat & Cryomodule

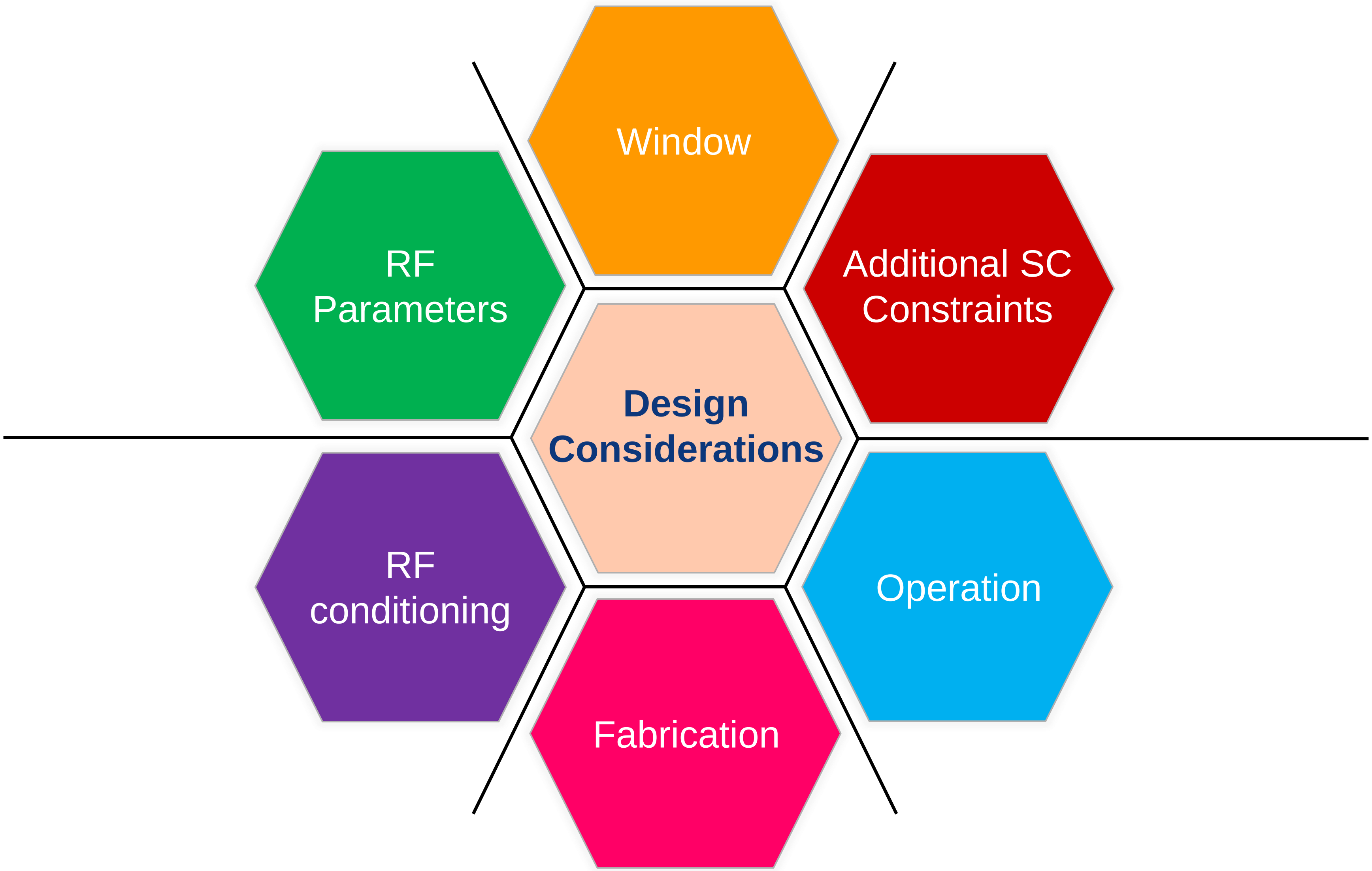
In addition with Superconducting Cavities (SCC), FPC also has to take care of thermal differences:

Transmission Lines at Room temperature

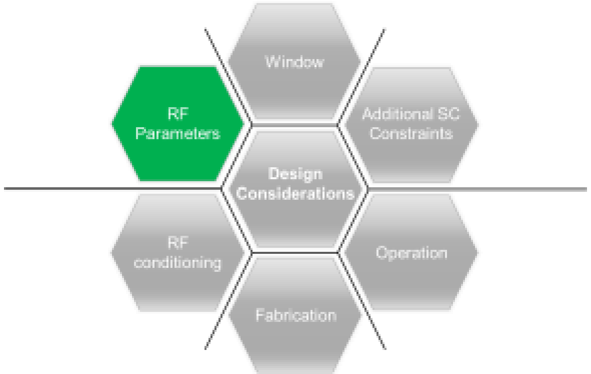
Cavity at Few Kelvin

Key components



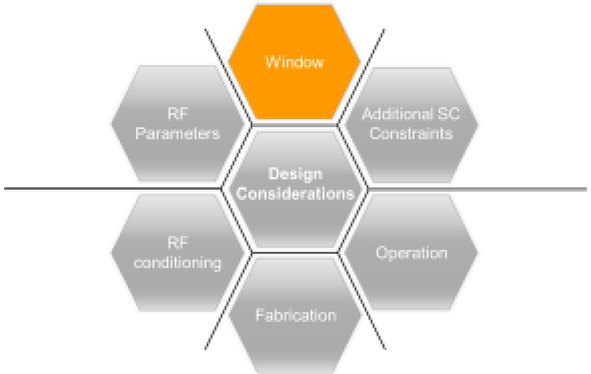

Window
RF Parameters
Additional SC Constraints
Design Considerations
RF conditioning
Operation
Fabrication

RF parameters



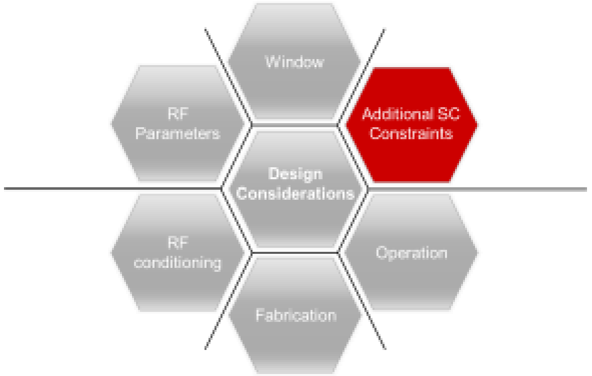
- Center Frequency
- Bandwidth
- Tuning
- **Maximum peak power**
- **Maximum average power**
- Coupler has to match the impedance of the amplifiers to the beam loaded cavity
- There could be a strong mismatch in absence of beam resulting in full reflection
- There Could be a need to change the coupling for different beam loadings -> adjustable or fixed Q_{ext}
- RF simulations
- Multipacting simulations in order to define the best geometry to reduce multipactor

Window



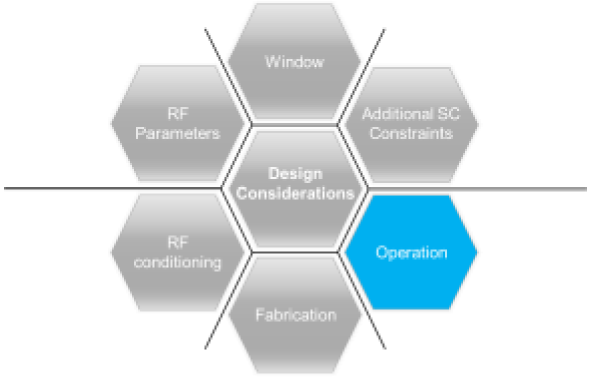
- The critical item of a power coupler is the window
- Usually it is made of AL_2O_3 **ceramic**
- Reason is that ceramic is NOT an electrical conductor
- Its losses factor is acceptable to be inserted along a transmission line
- Ceramic is strong enough to sustain differential pressure
- Ceramic are metallized for collars brazing
- **If possible massive copper brazed for higher power levels**
- If possible ceramic window should be located in E-field minimum to avoid additional losses
- **To avoid multipacting ceramic windows are Ti or TiN coated**
- **Coupler robustness mainly depends on the ceramic window design**
- **The whole accelerator reliability will depend on the ceramic design**
- Cutting (destructive) process for prototype validation
- Failure consequences (sectorization of the machine)
- A single or a double window coupler

Additional SC constraints



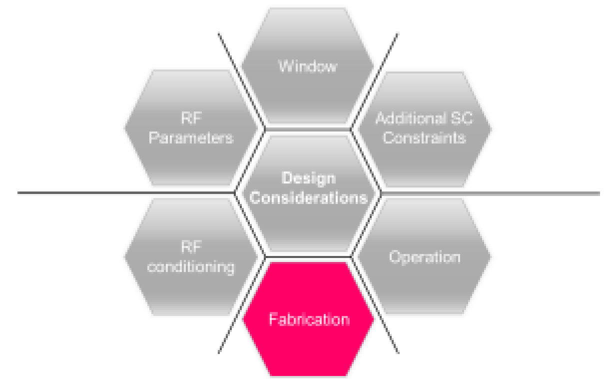
- Coupler must not contaminate accelerator vacuum
- Assembly in clean room for no contamination of beam vacuum parts to guarantee high field gradients
- High pressure rinsing
- Design the thermal transition as being intercept points or Double walled Tubed
- **Copper plating of stainless steel**
- RF losses must be minimized
- Mechanical and Thermal simulation
- Coupler will have to sustain mechanical constraints induced by cryogenic thermal cycles
- **Integration requirements with respect to the cryomodule**

Operation



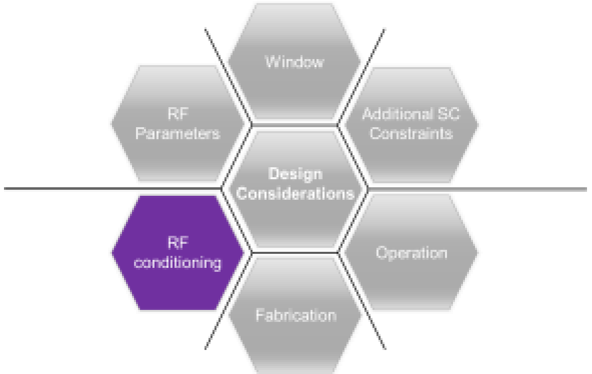
- Easy installation
- Maintenance (air blowers, water pumps)
- Repair
- Spares
- **CERN’s rule : Air cooling is preferred (mandatory when possible) to water cooling in order to ease vacuum leak detection in case of failure**
- Position of the coupler with respect to the cavity (vertically, with an angle)
- DC biasing (if yes with HV polarization or Magnetic polarization)

Fabrication



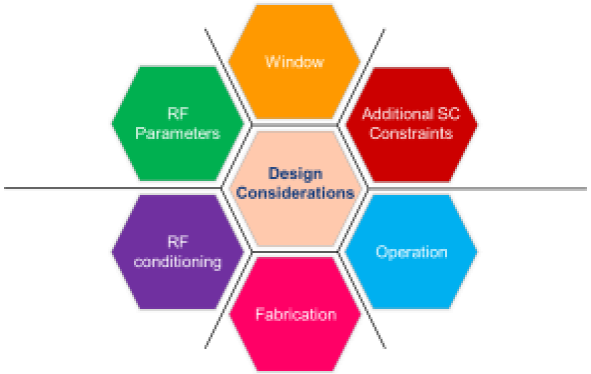
- **As much as possible, use standard :**
  - Material qualities : 316 LN, CU-OFE, Al2O3
  - Sizes : tubes, bellows, flanges,…
  - Fabrication techniques
- Nevertheless 3D forged copper is mandatory for high leak tightness
- Calculate tolerances to be tight when justified, and relax all other ones
- No bellows, easier for higher power levels
- **Some specific processes are needed :**
  - **Brazing under vacuum**
  - **EB welding**
  - **Copper coating**
  - **Ti sputtering, …**
- **Clean handling during all processes is mandatory**

RF Conditioning



- Bake out process
- High vacuum pumping speed helps for shorter processes
- Vacuum gauge near the ceramic (for conditioning)
- Monitoring of : vacuum gauges, temperature sensors, e- probes, light detectors, arc detectors, flow meters
- **Test area available 24/7 devoted to coupler tests, for TW and SW mode, with :**
  - **power source**
  - **Circulator**
  - **power load**
  - **variable short circuit**
- High power tests benches must be available from the very beginning
- **Almost an equivalent work as to design a second coupler !**

Design considerations



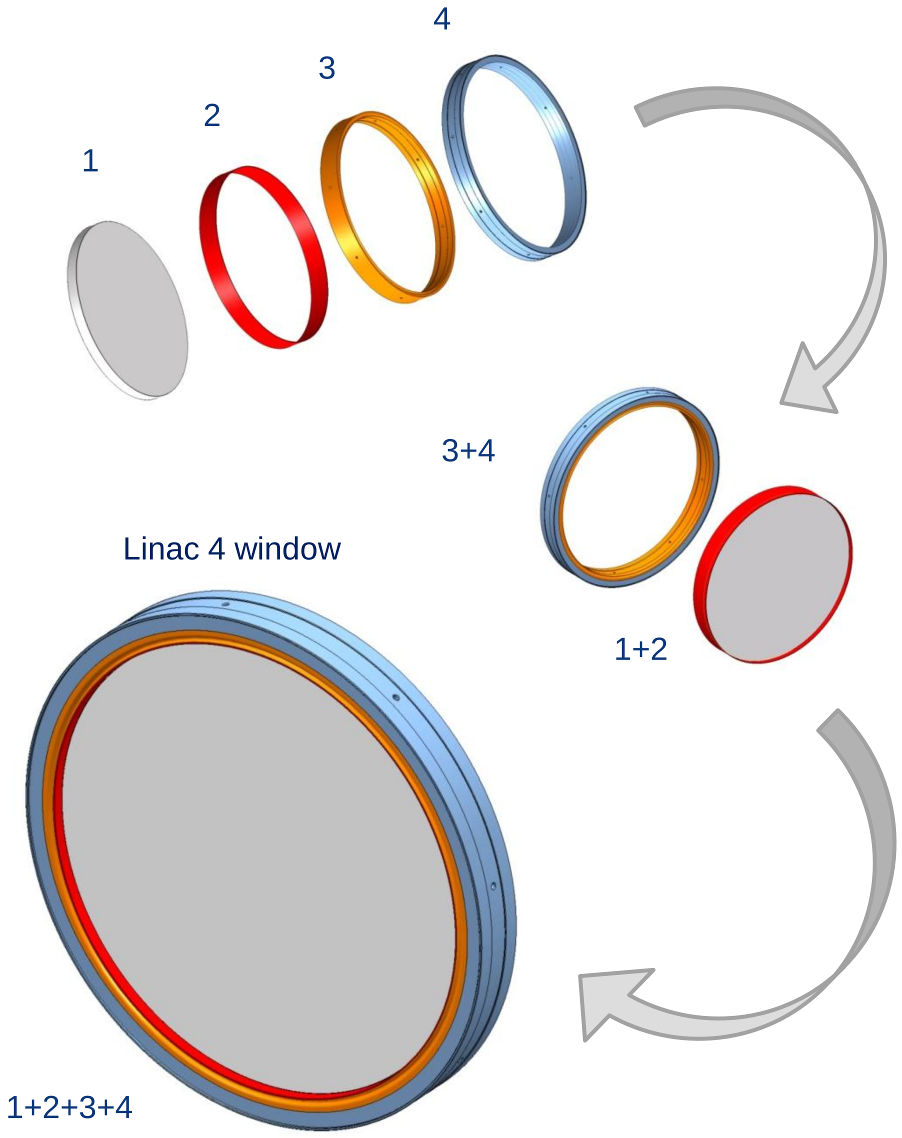
Cost €€€ $$$ CHF

For small series, it will always be very expensive as you have to pay for, simulations, prototyping, test bench, etc… only for few couplers !

Some technology challenges

Window brazing

- (Very simplified) Brazing under vacuum process :
  - 1 Metalized ceramic
  - 1+2 Braze metallic ring on it
  - All EB welding
- Linac 4 new window :
  - Ceramic 12 kg; Ø 400 mm; thickness 25 mm
  - Copper ring; Ø 400/402 mm; Length 45 mm
  - At brazing temperature of 800 ºC :
  - Ceramic (9.2 µm / ºC) Ø +2.86 mm
  - Copper (19.6 µm / ºC) Ø +6.09 mm

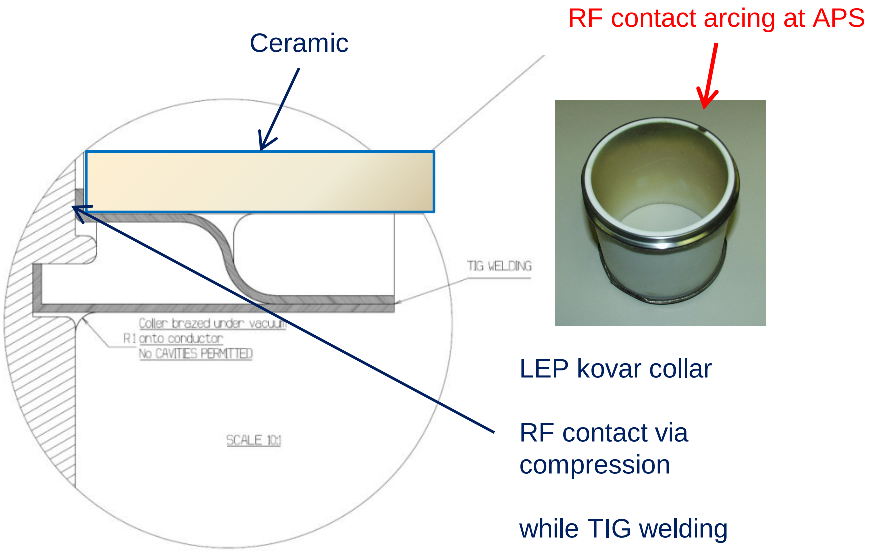


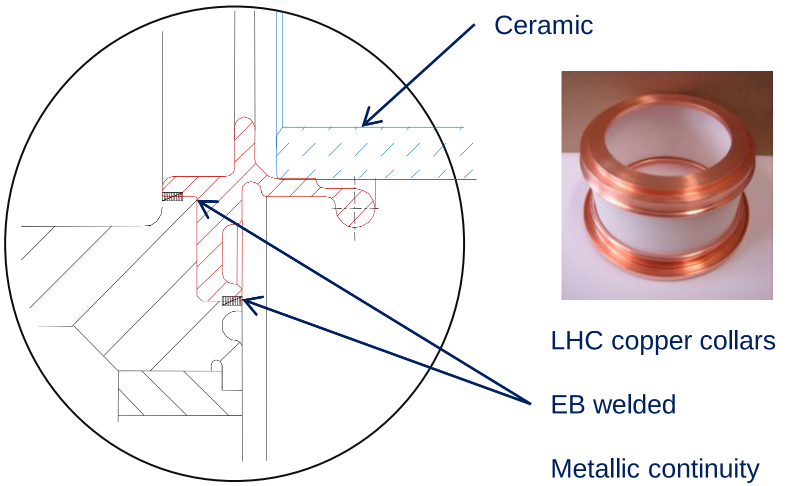
Window brazing

- Improvement of LEP Kovar® window to LHC copper window

- LEP Kovar® window :
  - 550 kW forward + 180 kW reverse
  - Kovar ® rings on both ends
  - Body and Antenna with Stainless Steel rings brazed onto copper
  - TIG welding under mechanical pressure ensuring RF contact
  - Easy Kovar ® brazing process
  - Weakness of the design : RF contact

- LHC copper window :
  - 575 kW forward + 575 kW reverse
  - Massive copper ring for higher power
  - No RF contact, fully continuous RF path
  - Advantage of the design: extremely average powerful





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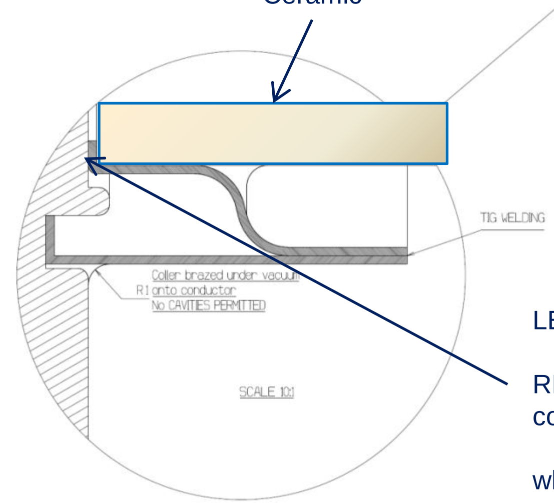
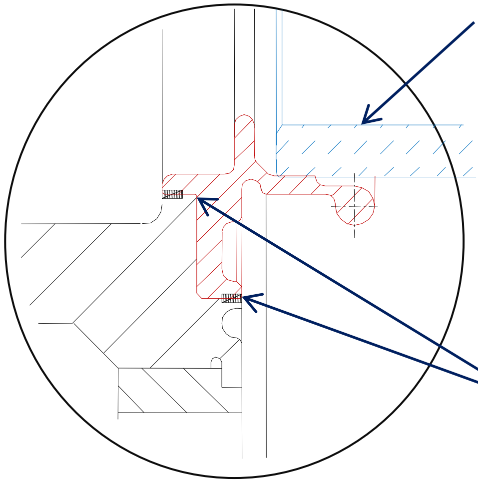


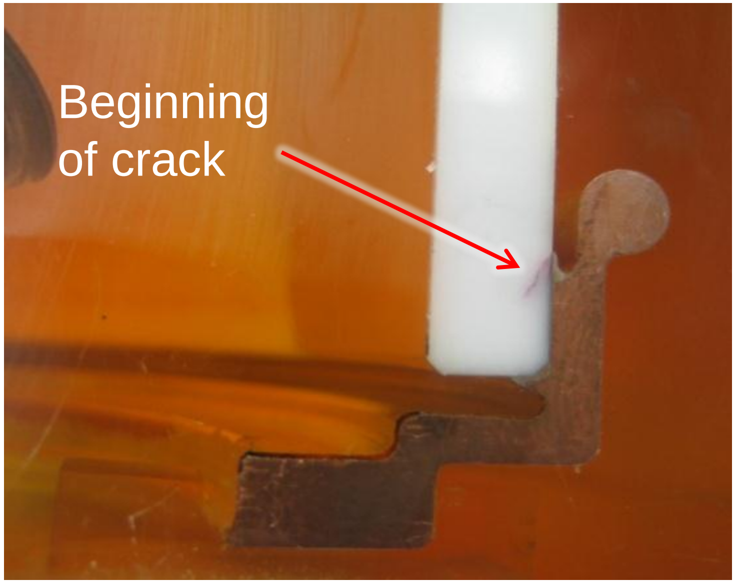


Window brazing

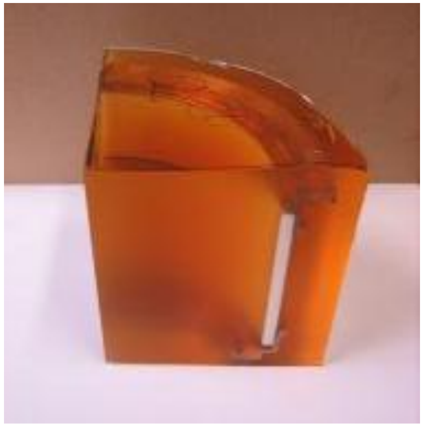
- Studies from 1996 to 2002 were necessary to finalized the design because of beginning of cracks

- Special (destructive) cutting process :
  - Paint the ceramic with ultrafluid
  - Mould it
  - Cut it with a special tool able to cut at the same time :
    - Ceramic
    - Copper
    - Arraldit
  - Only colorized cracks were there before cutting

LHC window



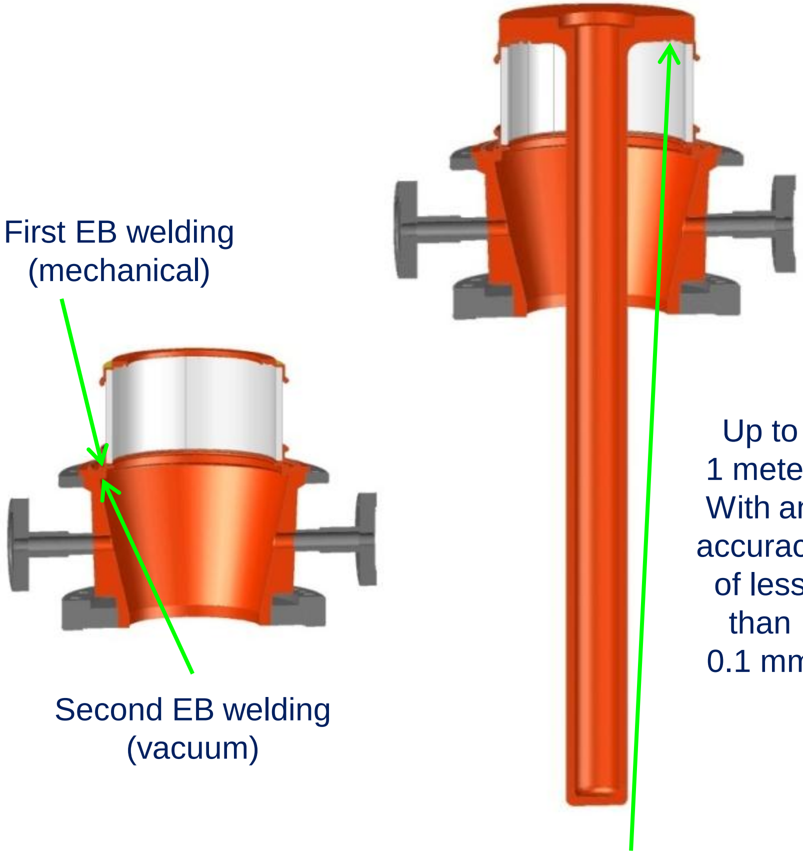
¼ LHC window



LHC window

EB welding

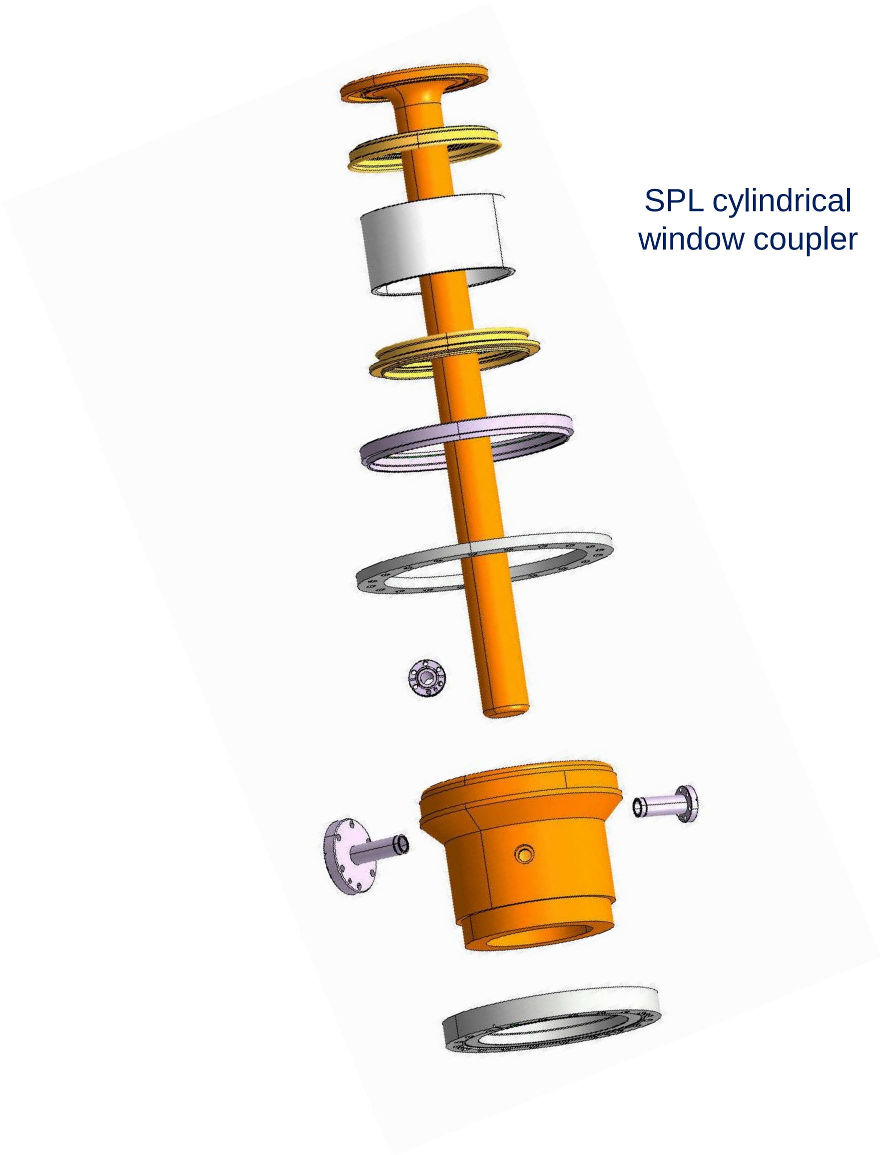
- Once we have the window, we have to assemble it with the other parts of the coupler
- EB welding :
  - Strange angles
  - (very) long distance shoots
  - No mistake possible as welding items which have taken months (years) to be produced
- For larger series production, we will need industrials to be ready to perform such difficult and risky processes



3D printing

- Before we launch complex machining, Brazing, EB welding,… some years ago we tried 3D printing

Zcorporation ZP510 3D printer



SPL cylindrical window coupler

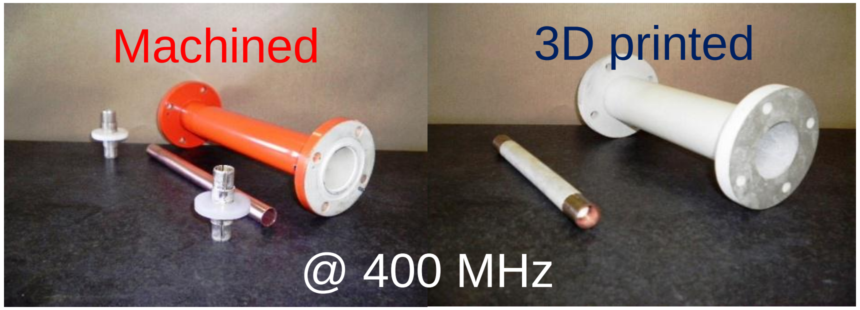
3D printing


SPL 3D printed individual items

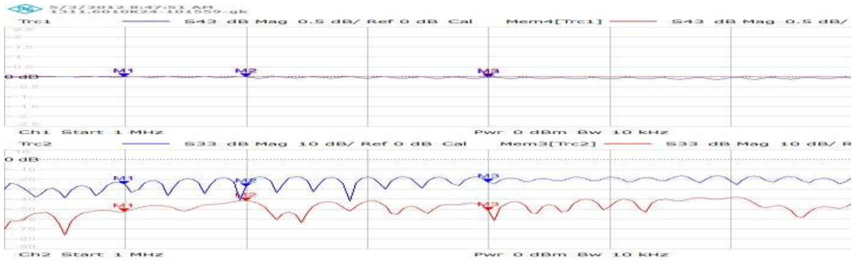

SPL 3D printed items assembled

- We obtained 3D printed items with an accuracy of 0.1 mm
- It helped us to mechanically check several key components and assembly processes

3D printing



S21 = 0.01 dB	S21 = 0.03 dB
S11 = -40 dB	S11 = -25 dB

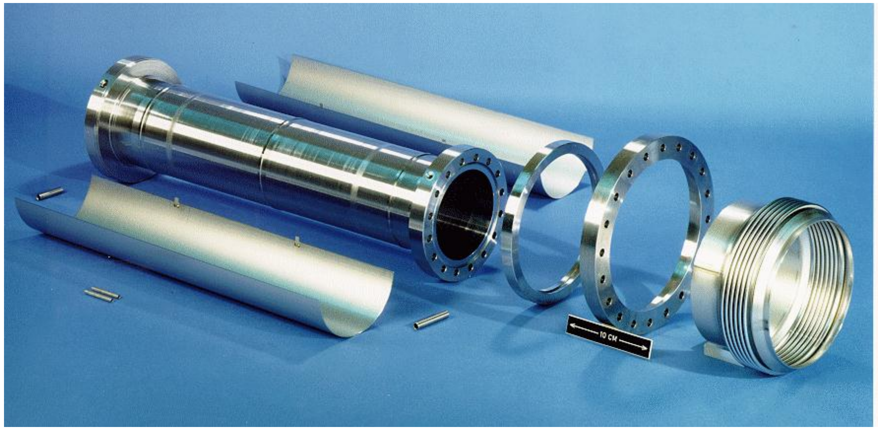


	Delay [days]		Cost [€]	
	Machined	3D	Machined	3D
Simple 	4	2	220	200
Complex 	15	5	7000	3000
	3 Grams		10	
	50 Grams		120	

- We also successfully made it available for RF tests with a special silver paint
- This saves a lot of machining time and helps to avoid conceptual mistakes

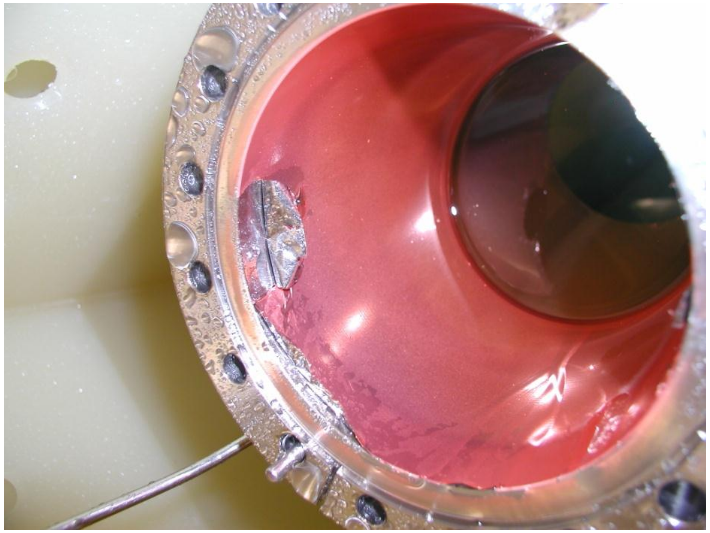
Copper coating

- With SCC & high average power, thermal transition is often a Double Walled Tube
- From Cryomodule point of view, this is a Stainless Steel tube
- From RF point of view this a simple layer of copper with an ideal uniform thickness of few µm only
- Try to avoid complex shapes, bellows, which make the coating difficult
- The well known difficulty is adhesion of copper on stainless steel, this could easily lead in a one year delay of your project



LEP Double Walled Tube

SPL Double Walled Tube, copper coating peeling



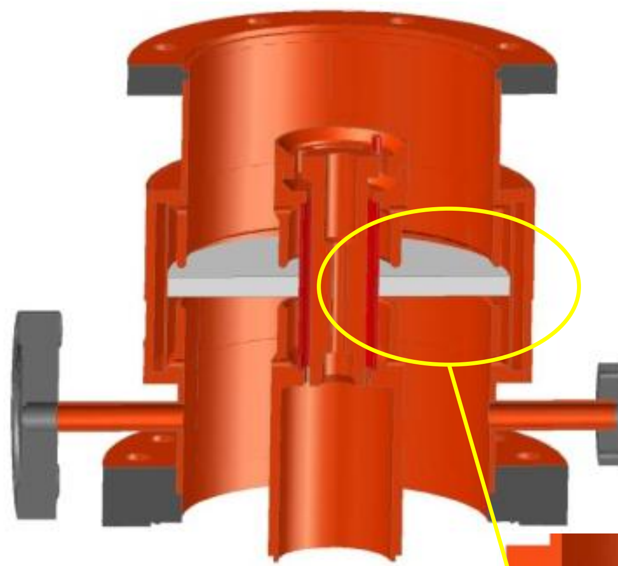
Ti coating

- Secondary Electron Emission Yield (SEY) of ceramic is not very good (SEY ~7), so to avoid multipacting, vacuum side of the window is Ti (or TiN) coated (SEY ~1.5)

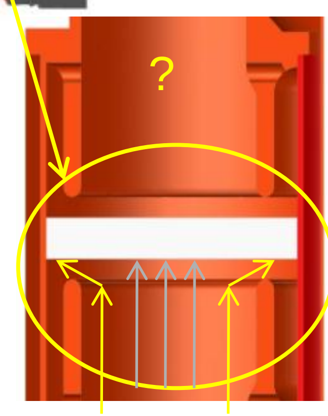
- Ti coating is a well mastered process at CERN, however :
  - How to measure Ti coating ?
  - Too thin, not multipactor suppressor
  - Too thick, adding a layer with RF losses, break the ceramic
  - In case of special shape, how guaranty Ti coating is really everywhere ?
  - Electrostatic discharges

- A new innovative alternative multipacting suppressor would be very welcomed

SNS Window



How to ensure the TI coating behind the chokes ?



Cleanliness issues

- Coupler should be built with the same clean process as the one applied to cavities:
  - Individual cleaning of items
  - Assembly in same clean room (or same level)

- Handling & transport :
  - Intermediate storage of parts shall be in cabinets filled with N2 or under vacuum
  - No intermediate packing in polymeric bags as polluting surfaces of the coupler (degradation of performances)
  - Transport containers specially designed (air tight, mechanical supports)


LHC coupler under cleaning

LAL coupler clean room


SPL test cavity in DESY clean room


DESY coupler storage cabinet


SPL transport frames


Cleanliness issues

DESY
Clean room

Final assembly must not pollute cavities
Need special process to assemble coupler onto cavity

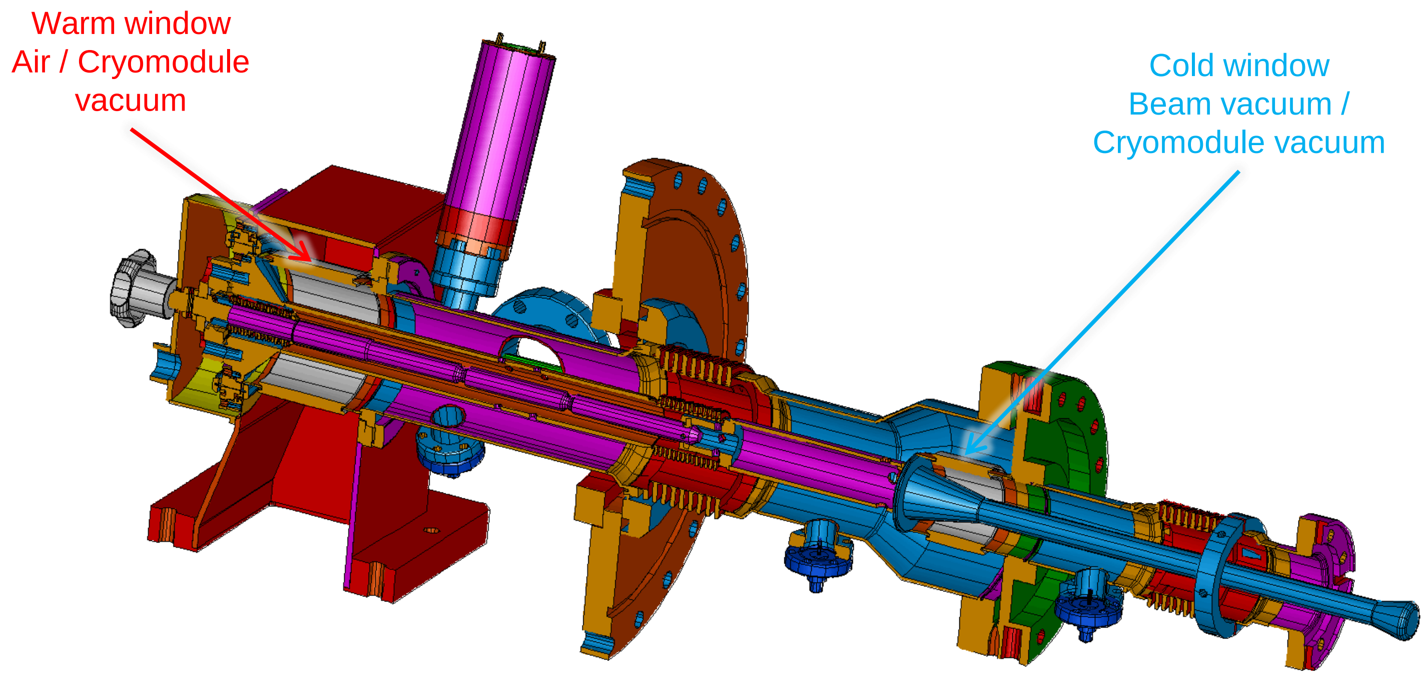
Future projects in the range of MHz

Some MHz couplers world wide

	Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# in operation or constructed
Coaxial disk	SNS	805	78	2000	93
	JPARK	972	30	2200	23
	SPS	200	550	800	16
	KEKB	509	300	1420	8
	IHEP	500	150	270	2
	CEA-HIPPI	704	120	1200	2
WG	SPS	801	120	120	8
	Cornell	500	350	350	4
	LBNL	700	800	800	2
Cylindrical	LEP († 1989-2000)	352	550	565	252
	LHC	400	550	575	16
	SPS († 1976-2000)	200	375	500	16
	New ESRF	352	300	300	1
	New APS	352	100	100	1
Two windows	TTF III	1300	4.5	1100	16
	APT	700	1000	1000	2
	Cornell ERL	1300	75	75	2

Future couplers

Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# Under construction
XFEL	1300	4.5	1100	**>640**
ESS	704	50	1000	**>180**

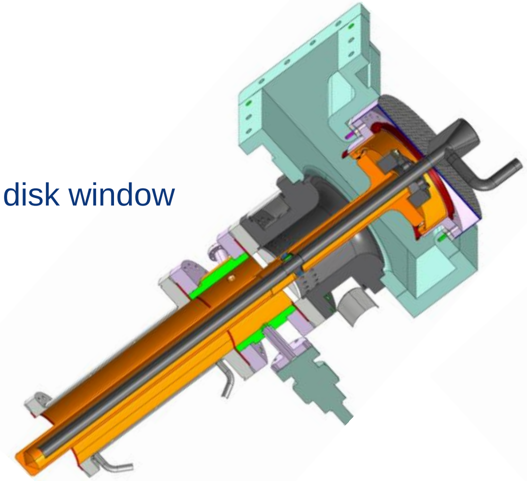


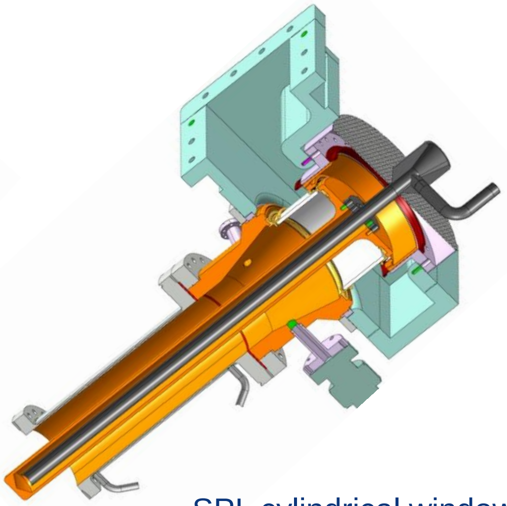
XFEL two cylindrical windows coupler (courtesy W-D Mueller)

CERN ongoing and future projects

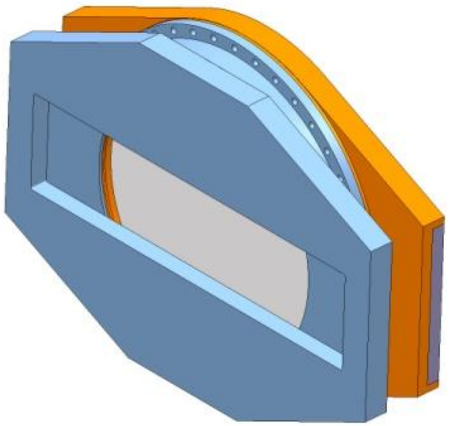
Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# to be constructed
SPL	704	100	1000	4 + 4 **(+ >250 ?)**
Linac 4	352	100	1000	**30**
LIU SPS 200	200	500	1000	**30**
SPS 800	801	150	150	**12**
Crab Cav x 3	400	100	100	**3 x 2 (+ 24)**

SPL disk window





SPL cylindrical window



Linac 4 window

Prototype time scale

From scratch to a prototype : 3 - 4 years	**[month]**
Design & RF simulations	3-6
3D modelling	3
2D construction drawings	3
Material procurement	6-9
Workshop machining, brazing and EB welding	3-6
Surface treatments	3
Tests preparation	3
First validation RF power tests	3-6
Total	**30 - 42**

- Coupler teams are rarely working on couplers only, could even be longer…
- Series production cannot be launched before prototypes have been validated
- Industrials should carefully follow up coupler R&D to be ready when series production will be required within, usually, very tight schedules

Conclusion

- Being involved in coupler R&D would certainly help your company to gain knowledge in all these specific technologies :
  - Brazing of ceramics
  - EB welding
  - Copper coating
  - Ti coating
  - Clean mounting

- This would certainly be an added value for other subjects than couplers

Thank you very much for your attention

SRF 2003 DESY, Brian Rusnak : http://srf2003.desy.de/fap/paper/TuT02.pdf

CAS 2010, Wolf-Dietrich Möller : http://cas.web.cern.ch/cas/Denmark-2010/Lectures/Moeller.pdf

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APS

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RF group :

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