Possible configurations for multicell RF structures for muon cooling

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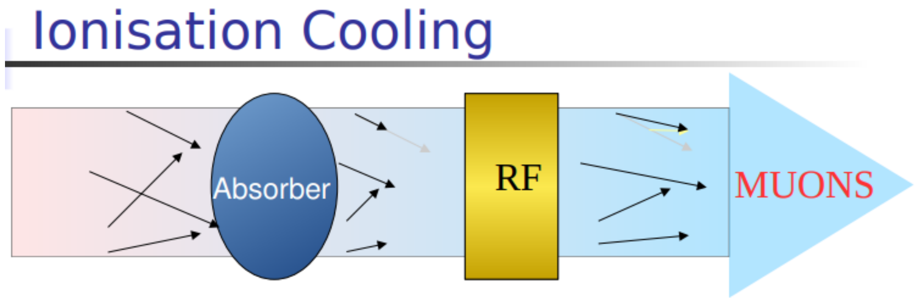
Outline

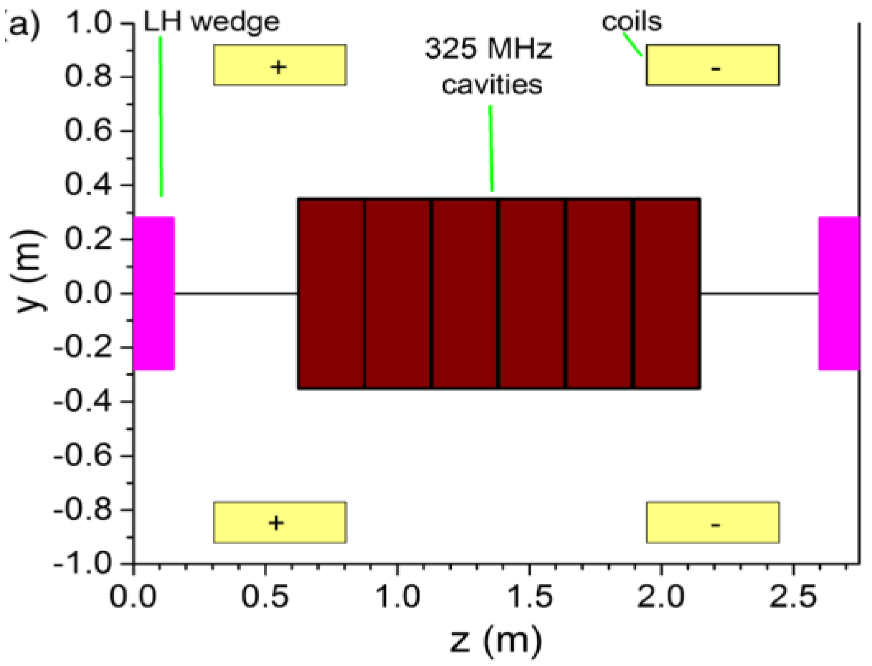
- Introduction
- Different type of RF coupling
  - Distributed RF coupling
  - Magnetic (inductive) cell-to-cell RF coupling
  - Electric (capacitive) cell-to-cell RF coupling
- Standing and Travelling wave RF structures
- Conclusions

RF system for muon cooling (MAP design)

Summarized from:
David Neuffer
Chris Rogers

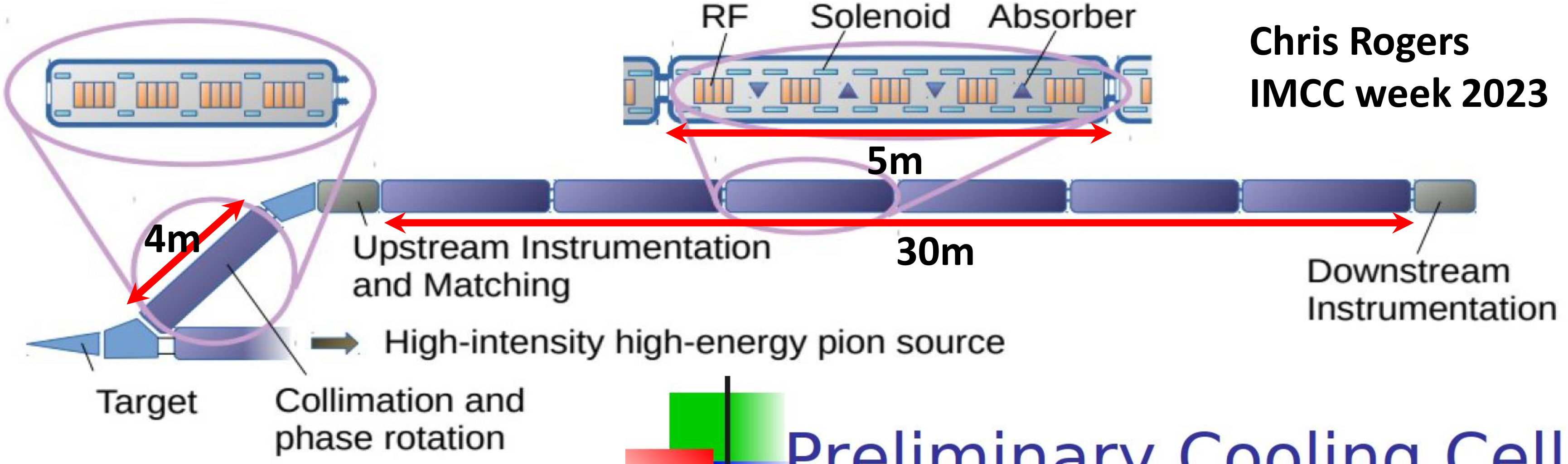
Region	Length [m]	N of cavities	Frequencies [MHz]	Gradient [MV/m]	Magnetic field [T]	Peak RF power [MW/cav.]
Buncher	21	54	490 - 366	0 - 15		1.3
Rotator	24	64	366 – 326	**20**		2.4
Initial Cooler	126	360	325	**25**	**2**	**3.7**
Cooler 1	400	1605 x2	**325, 650**	**22, 30**	**2-3, 4-6**	**4, 2**
Bunch merge	130	26 x2	108 - 1950	**~ 10**		
Cooler 2	420	1746 x2	**325, 650**	**22, 30**	**2-5, 8-13**	**4, 2**
Final Cooling	140	96 x2	325 - 20			
Total	~1300	**7424**				**=> ~20GW**





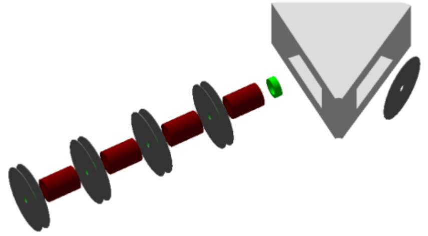
It is a very large and complex RF system

Muon cooling demonstrator layout (2023)



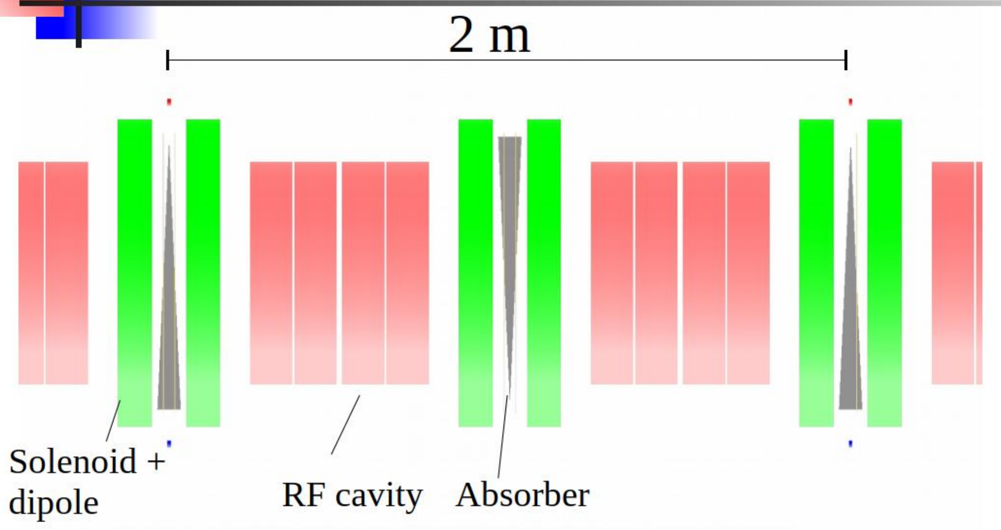
Chris Rogers
IMCC week 2023

Even this, small part of the cooling complex, is a large test facility



Beam Preparation System	
Parameter	**Value**
Cell length	1 m
Peak solenoid field on-axis	0.5 T
Collimator radius	0.05 m
Dipole field	0.67 T
Dipole length	1.04 m
RF real estate gradient	7.5 MV/m
RF nominal phase	0° (Bunching)
RF frequency	704 MHz

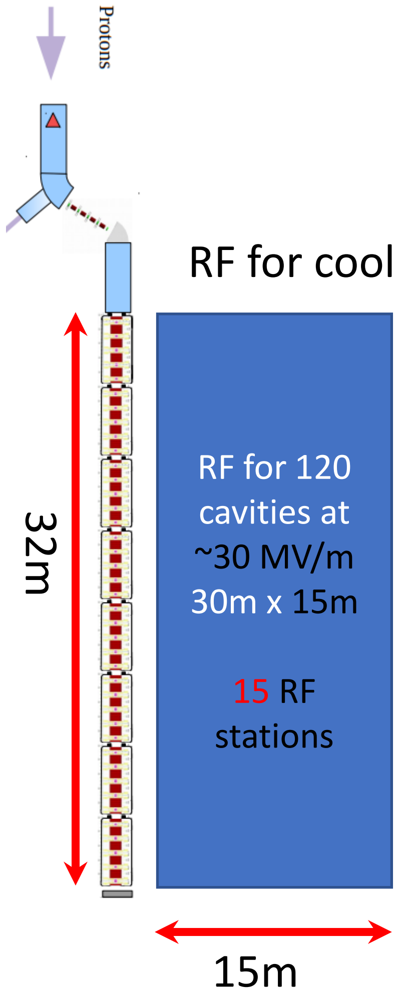
Preliminary Cooling Cell Concept



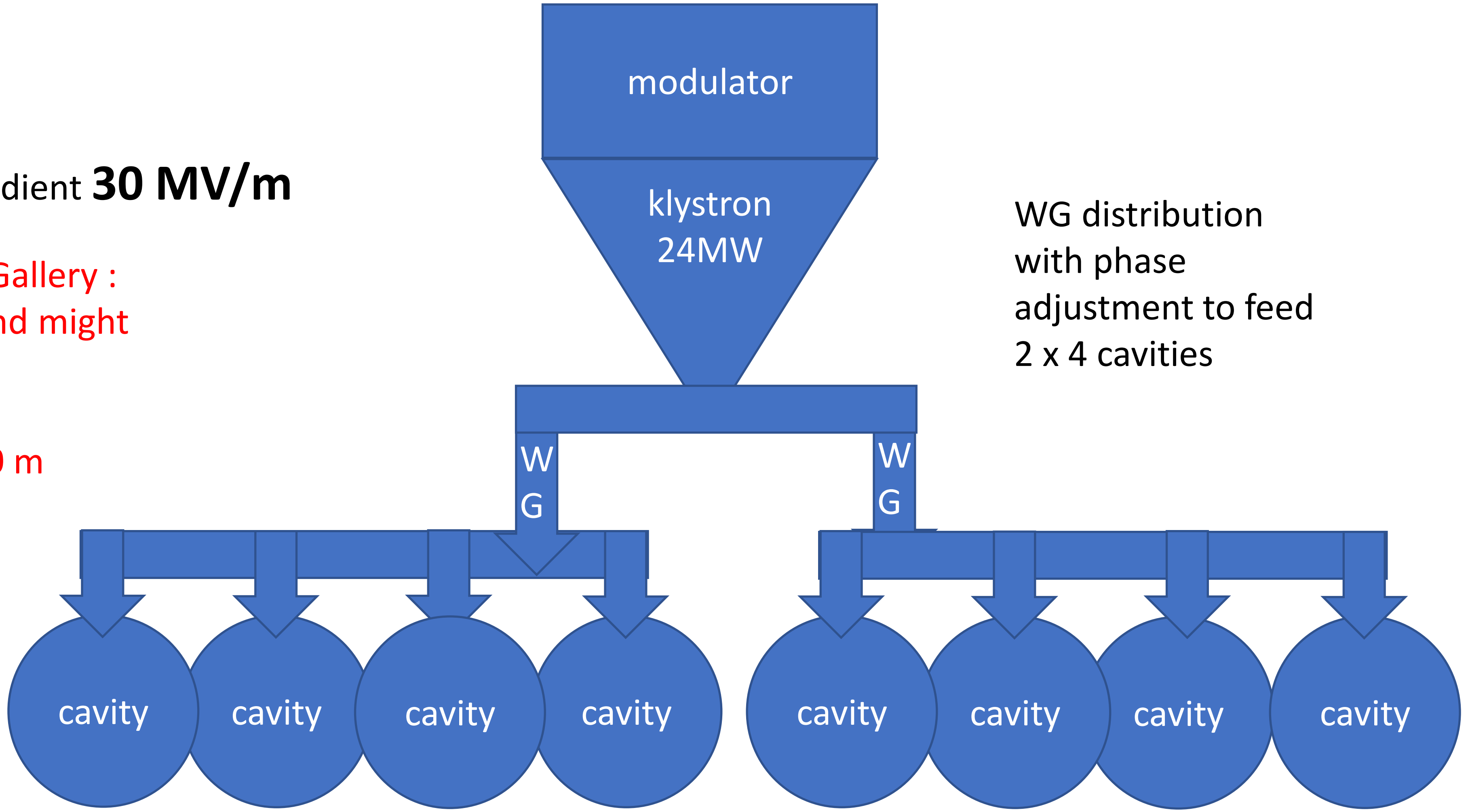
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH

Muon cooling demonstrator layout (2021)
High peak power klystron: 24 MW

RF for cooling: Max. gradient **30 MV/m**

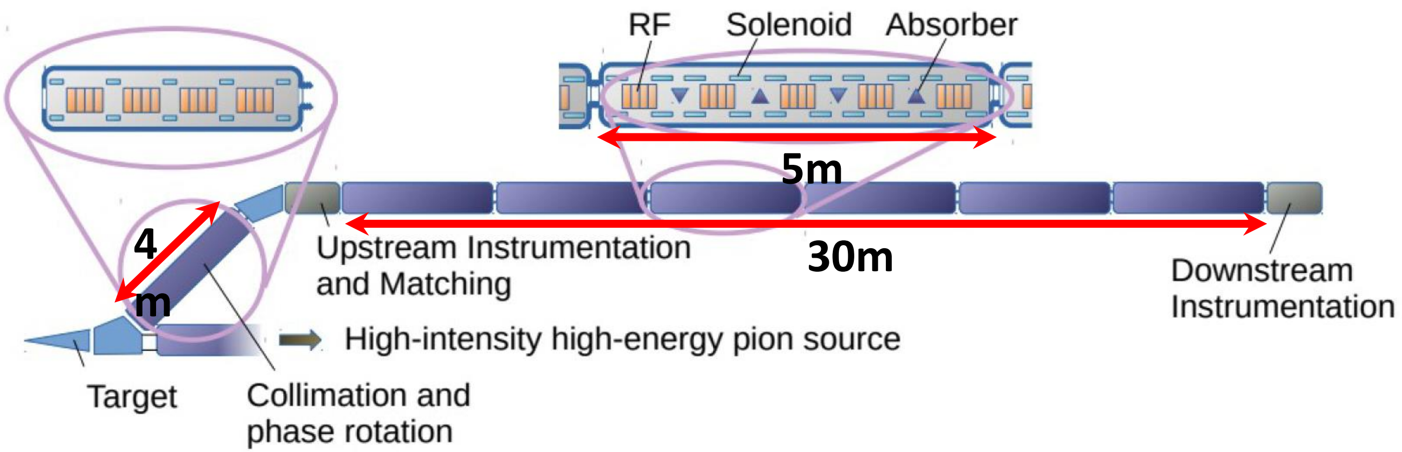


Building -> Gallery :
(underground might
be possible)
30m x **12m**
Height: 8-10 m



WG distribution
with phase
adjustment to feed
2 x 4 cavities

Muon cooling demonstrator layout (2023)
High peak power klystron: 24 MW

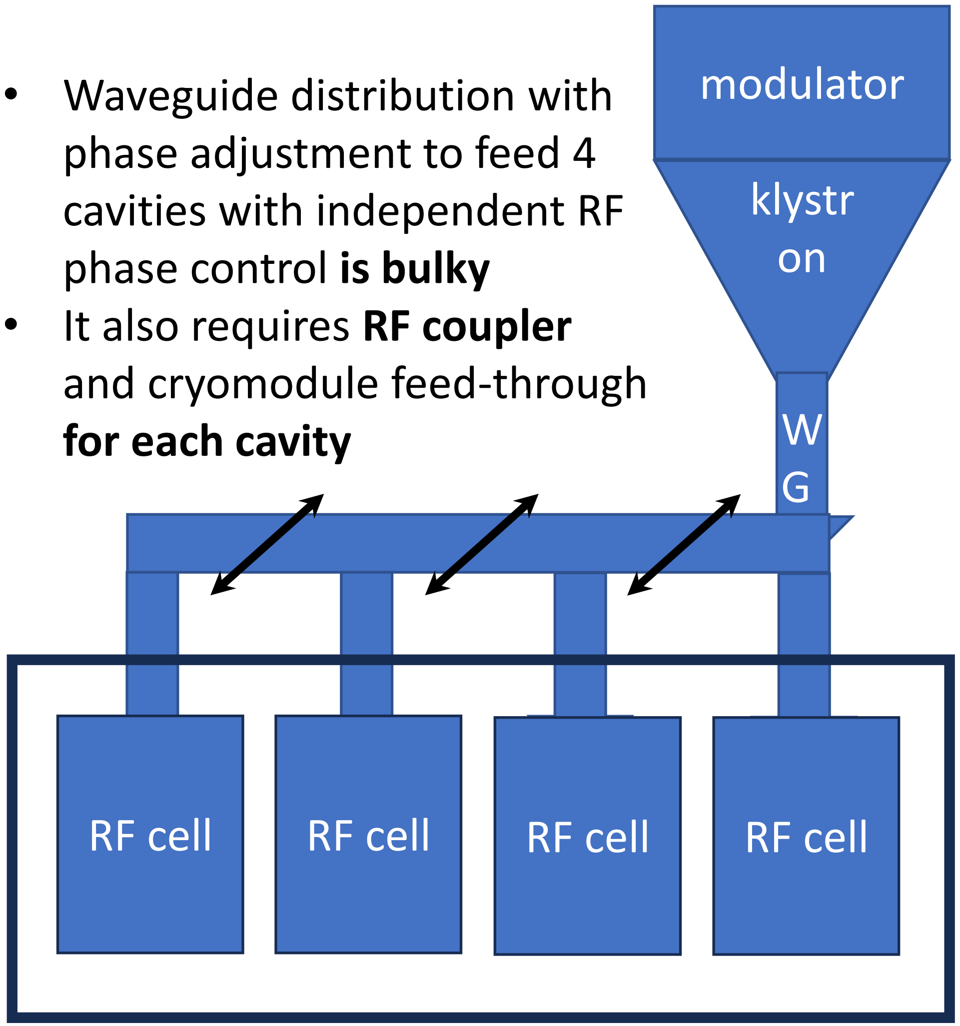


Building -> Gallery : (underground might be possible)
30m x **30m**
Height: 8-10 m

RF for 120 cavities at
44 MV/m
30m x 30m
30 RF stations
1.4 times higher gradient
=> 2 times more RF power

~30m

- Waveguide distribution with phase adjustment to feed 4 cavities with independent RF phase control **is bulky**
- It also requires **RF coupler** and cryomodule feed-through **for each cavity**



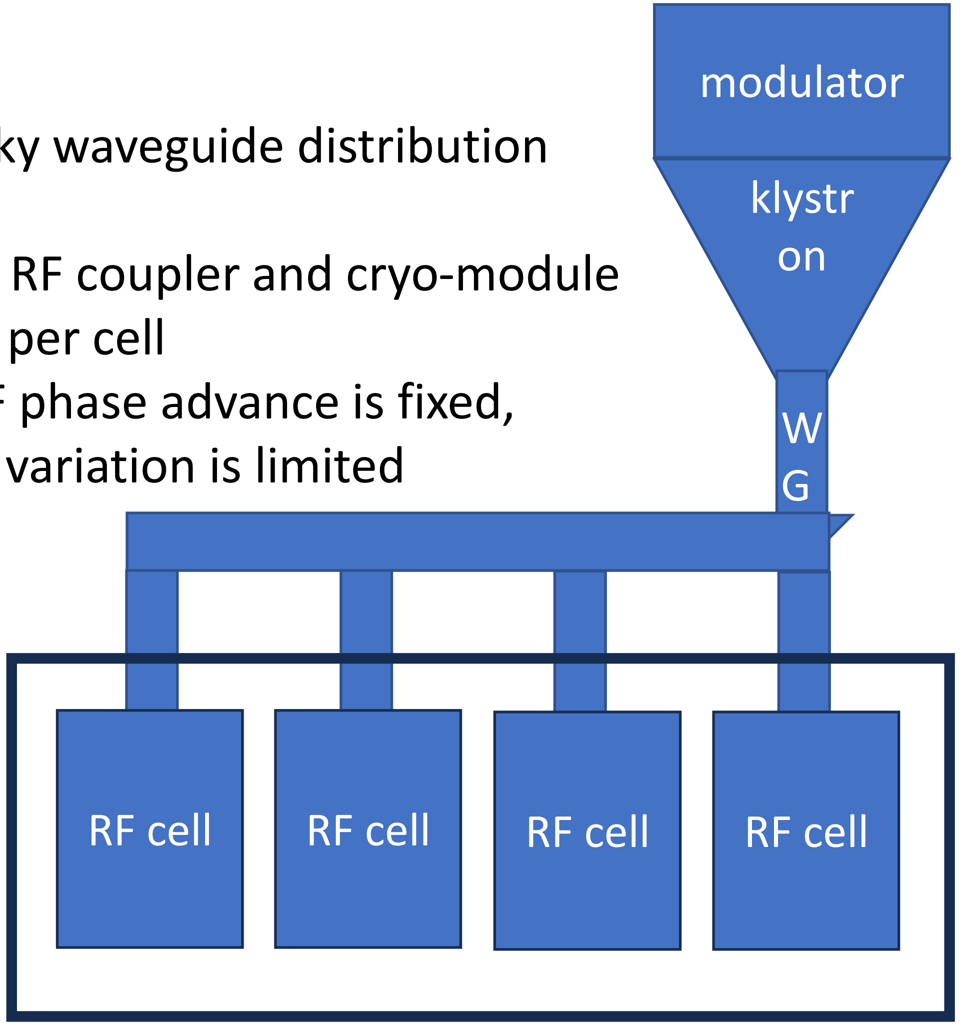
Distributed RF coupling

<u>Advantages:</u>

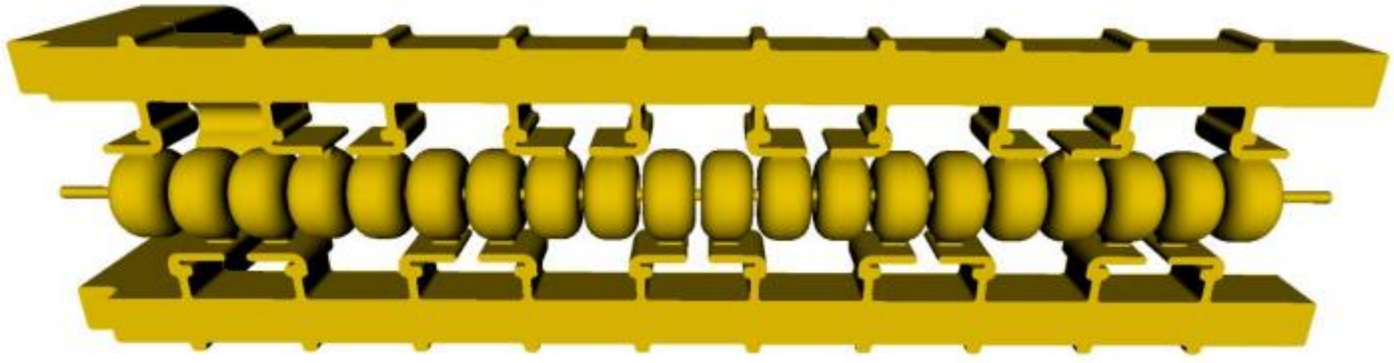
- **Minimum RF power per cell, highest gradient**
- **Arbitrary cell-to-cell RF phase advance, high transit time factor**
- No RF phase shifters, less active components
- Compatible with beam window, high R/Q

<u>Disadvantages:</u>

- It is still a bulky waveguide distribution system
- It still require RF coupler and cryo-module feed-through per cell
- Cell-to-cell RF phase advance is fixed, beam energy variation is limited



<u>Example: S. Tantawi, SLAC, LCWS2019</u>



Magnetic (inductive) cell-to-cell RF coupling

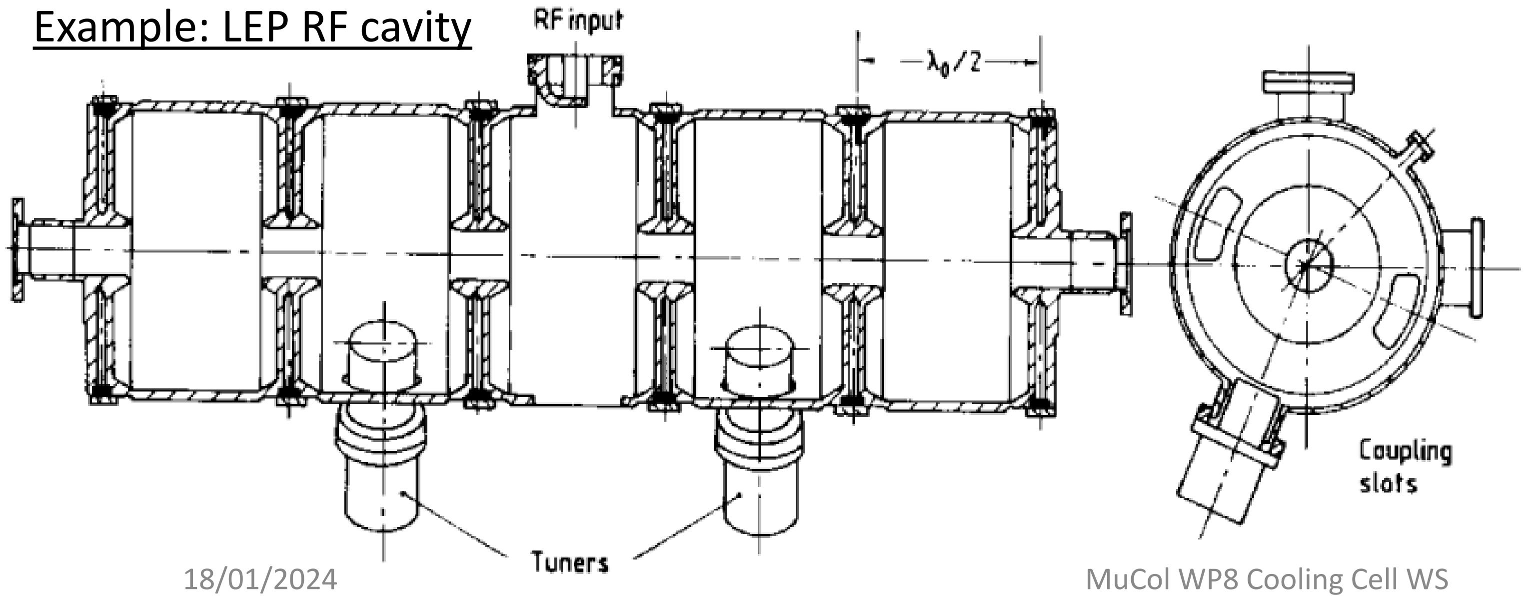
Advantages:

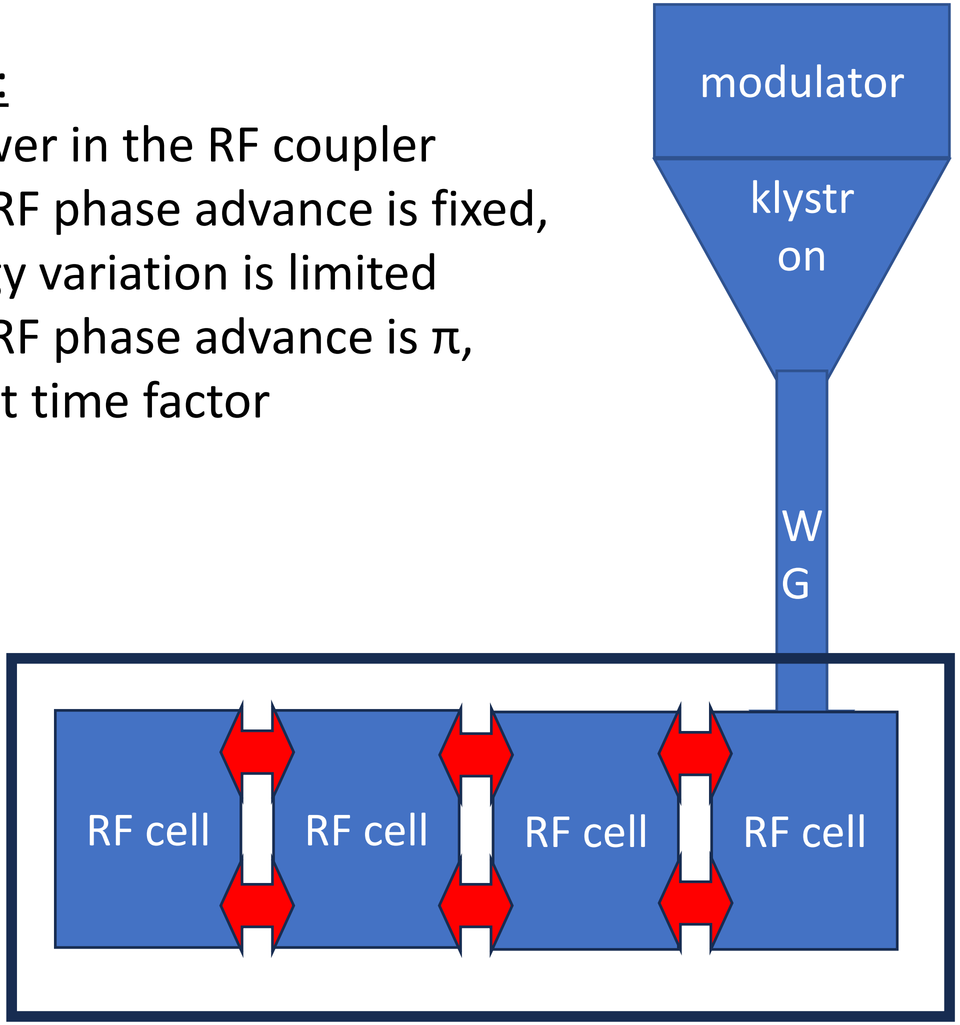
- **Single RF coupler and cryo-module feed-through**
- **Compact RF waveguide network**
- **Single RF cavity unit: RF structure**
- Compatible with beam window, high R/Q

Disadvantages:

- Highest power in the RF coupler
- Cell-to-cell RF phase advance is fixed, beam energy variation is limited
- Cell-to-cell RF phase advance is π, lower transit time factor

Example: LEP RF cavity



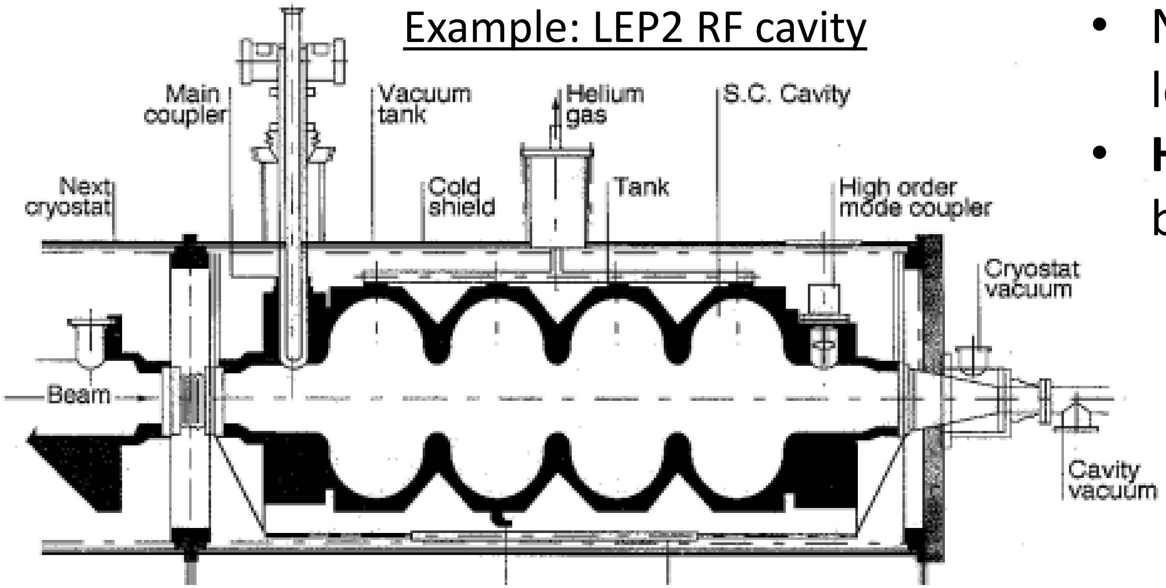


Electrical (Capacitive) cell-to-cell RF coupling

<u>Advantages:</u>

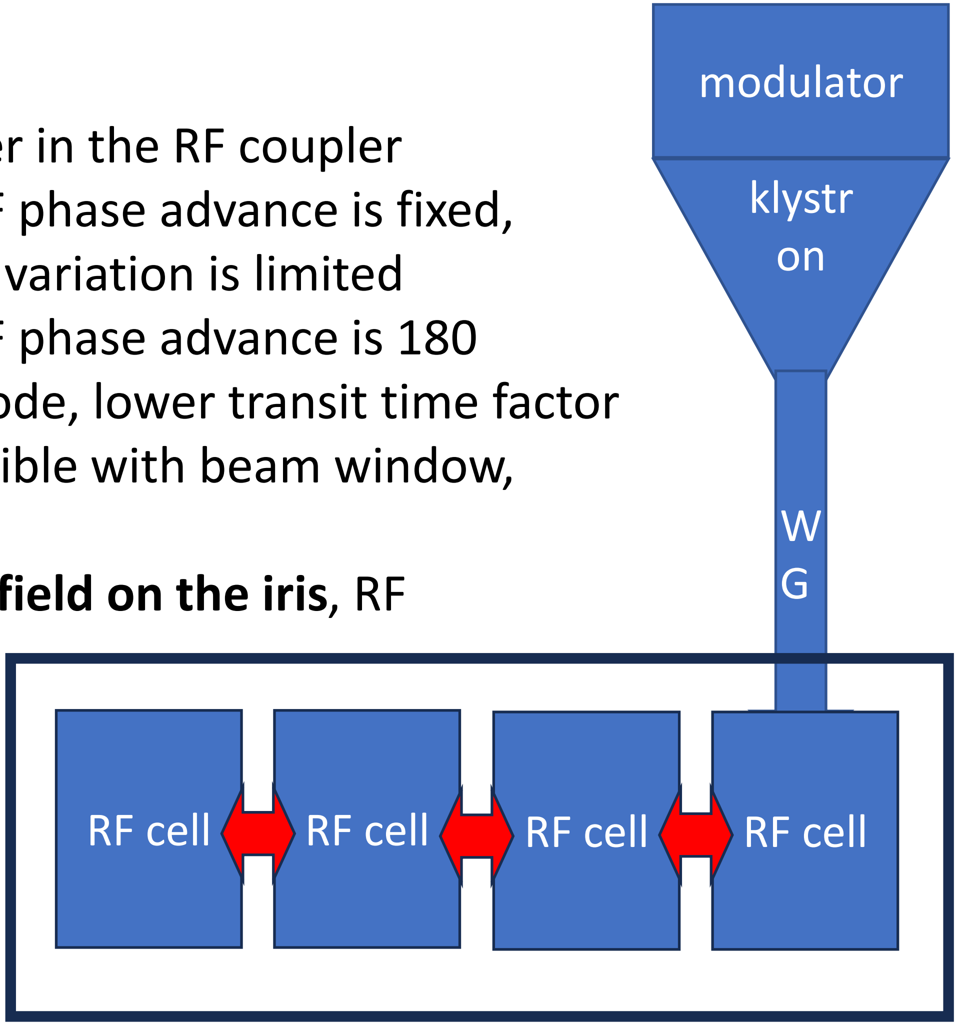
- Single RF coupler and cryo-module feed-through
- Compact RF waveguide network
- Single RF cavity unit: RF structure

<u>Example: LEP2 RF cavity</u>



<u>Disadvantages:</u>

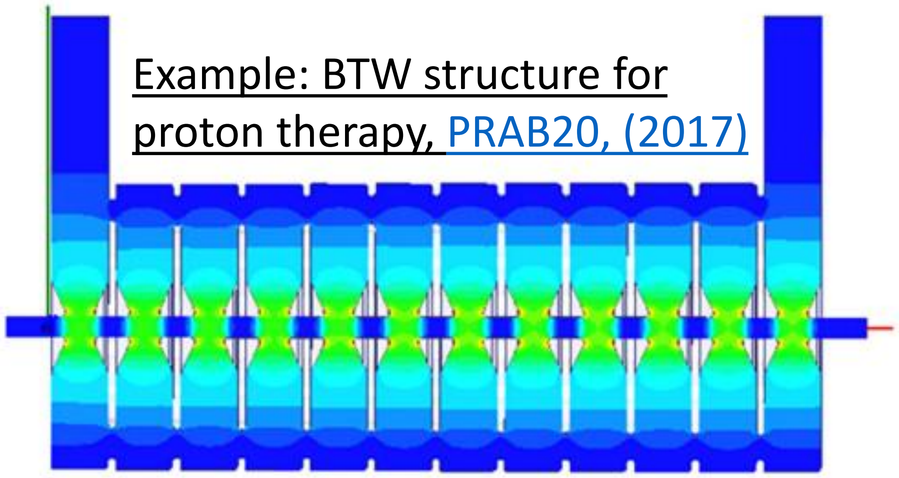
- Highest power in the RF coupler
- Cell-to-cell RF phase advance is fixed, beam energy variation is limited
- Cell-to-cell RF phase advance is 180 degree: Pi-mode, lower transit time factor
- NON-Compatible with beam window, lower R/Q
- **High electric field on the iris**, RF breakdown



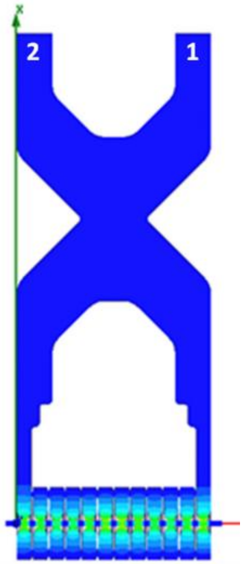
Travelling wave structure with recirculation

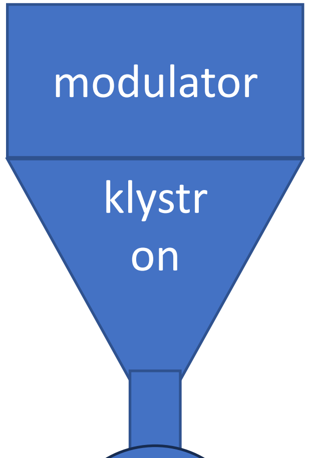
Advantages:
- **Arbitrary cell-to-cell RF phase advance, high transit time factor**
- Single RF cavity unit: RF structure
- Compatible with both Electric and Magnetic cell-to-cell coupling

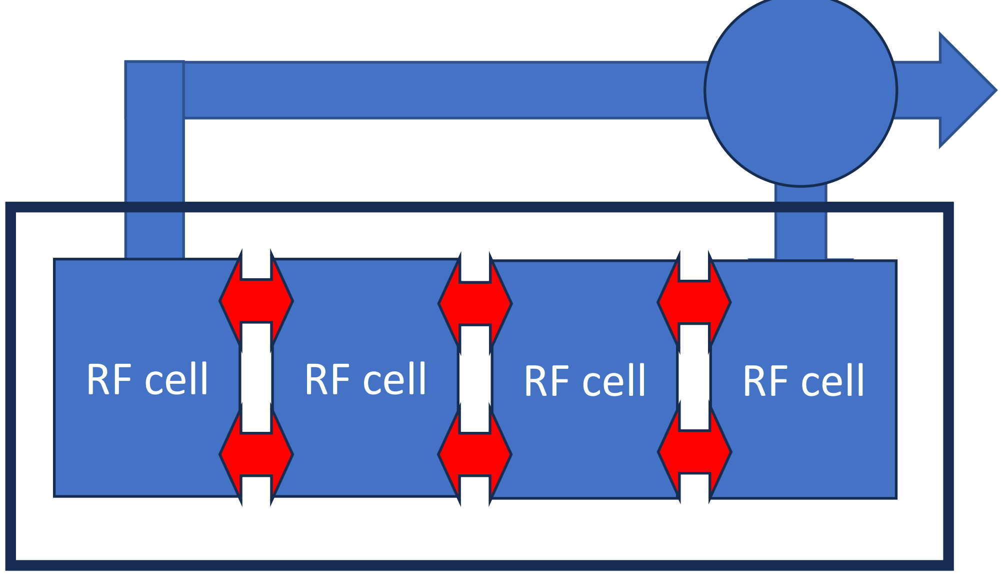
Disadvantages:
- Less compact RF waveguide network
- Two RF couplers and cryo-module feed-throughs
- Highest power in the RF couplers
- Cell-to-cell RF phase advance is fixed, beam energy variation is limited



Example: BTW structure for proton therapy, PRAB20, (2017)





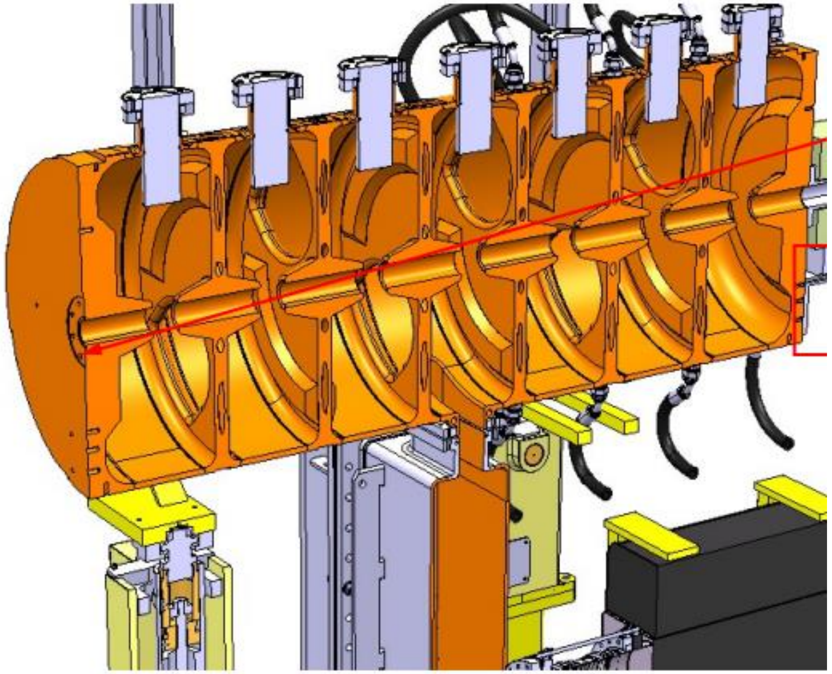


RF recirculation, see I. Syratchev LINAC12

Conclusions I

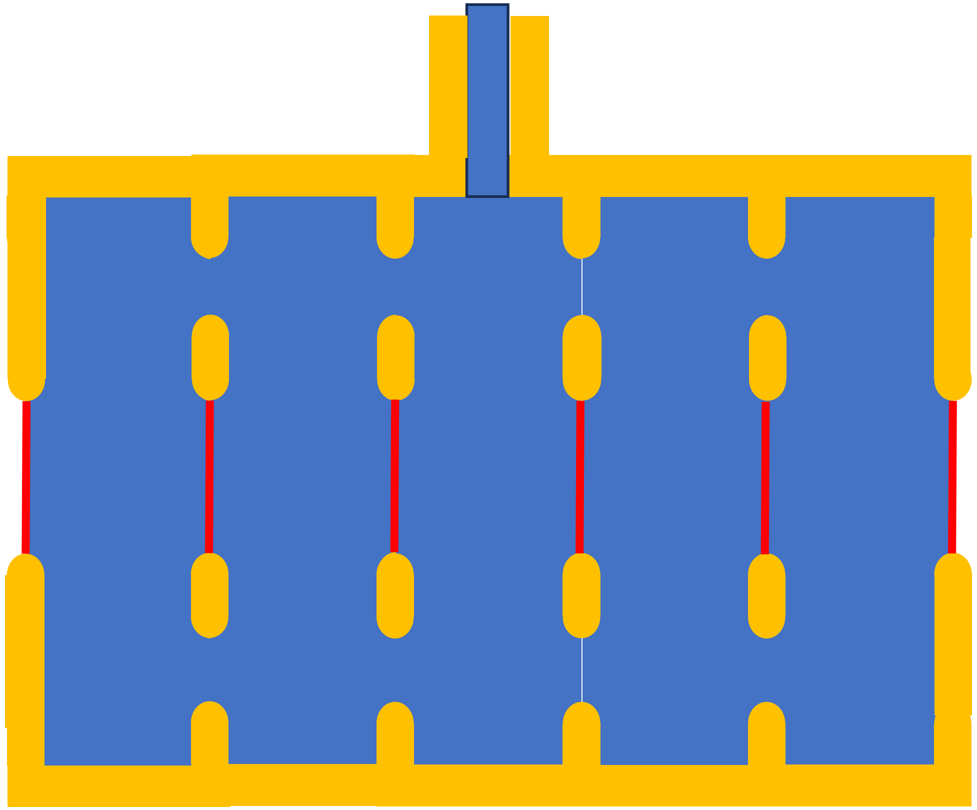
- Combining a set of independent RF cavities into a multicell RF structure requires giving up independent RF phase control of each cavity.
- The **RF phase** difference between cavities become **fixed** to **cell-to-cell RF phase advance**
- This is true for all concepts presented above
- Some flexibility in operation is lost. The RF structure only works effectively in a certain limited range of beam energies, since relativistic beta < 1
- On the positive side, the complexity of the system is greatly reduced
- In fact, this is how all the low energy ion linacs are designed and operated. Each RF structure works in a certain limited energy (beta) range

Example: CERN Linac4
PIMS structure PAC2009
Design beta = 0.43
Energy range: 102-160 MeV/p



Conclusion II (Baseline proposal)

- In case, beam window can be used. **Magnetic coupled standing wave structure** provide solution with the most compact waveguide network
- Only **one RF coupler** and cryo-module feed-through is necessary to feed all the RF cells
- Number of **beam windows** is reduced from 2*Ncells to Ncells+1
- There are two disadvantages:
  - Higher (x Ncells) RF power per coupler
  - Lower transit time factor: from 0.83 (Chris's design) to 0.7 (pi-mode)
- …



Conclusion III (Interesting alternatives)

- **Magnetic coupled traveling wave structure with recirculation** provide solution with higher transit time factor.
- But the price to pay is:
  - Two RF power couplers: input and output
  - Special waveguide component for recirculation: directional coupler
  - More (shorter) cells for the same total RF structure length

- **Electric coupled structure** provide solution in case beam window cannot be used
- There are some disadvantages compared to magnetic coupling:
  - High electric field on the iris, RF breakdown
  - Lower R/Q, in particular for large aperture