Muon Cooling Demonstrator RF system considerations

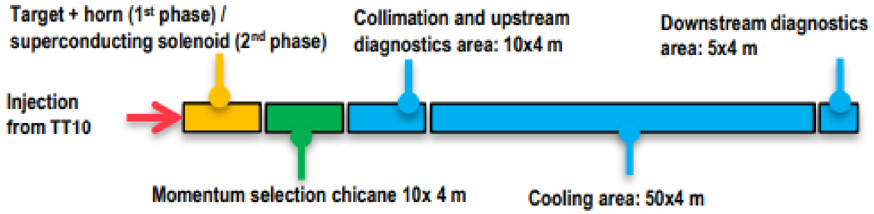
Alexej Grudiev,

With great help of Roberto Losito, Chris Rogers, Igor Syratchev, Davide Aguglia

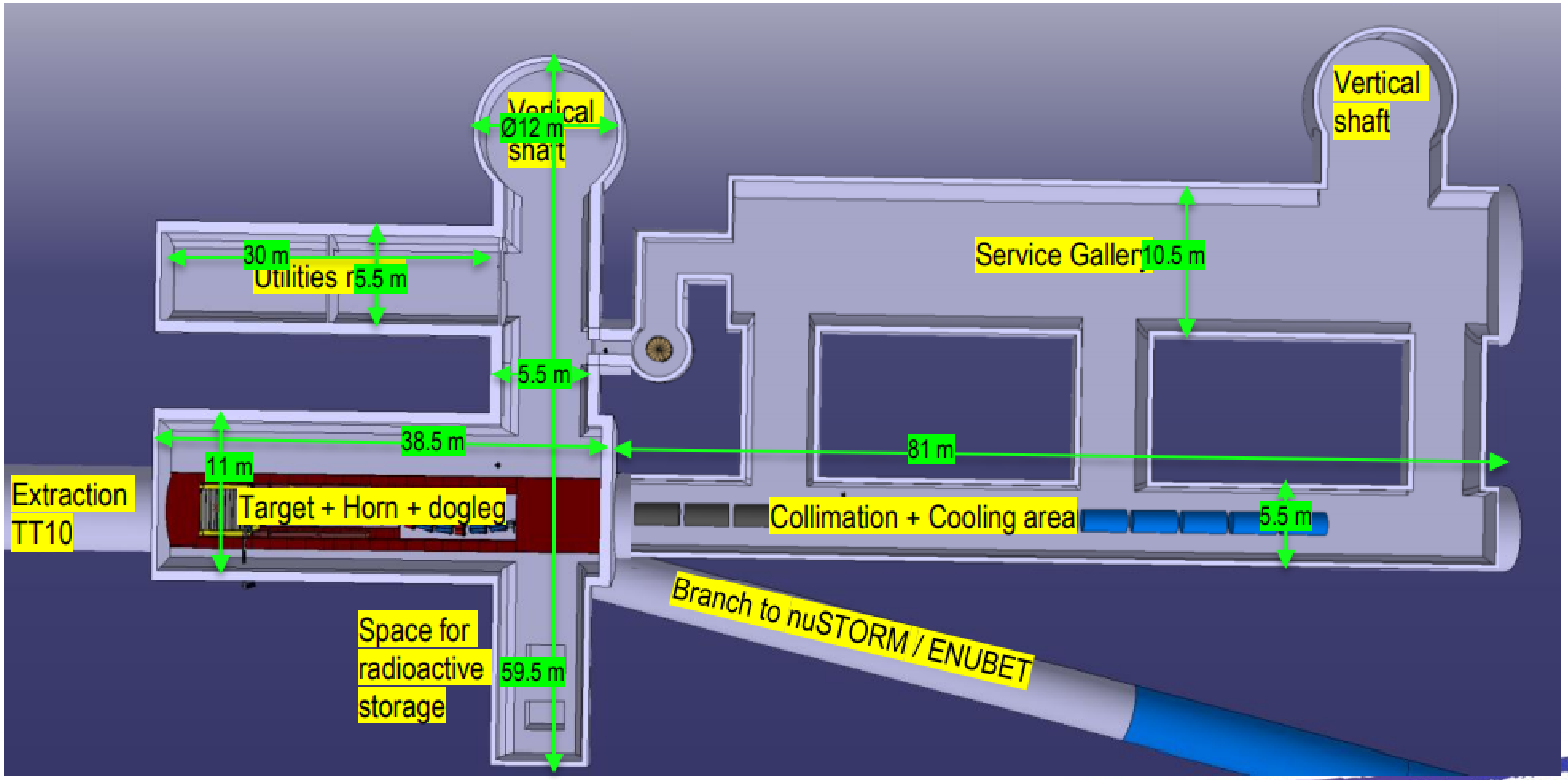
21/06/2023

Conceptual layout

Rui Ximenes
2nd Community meeting



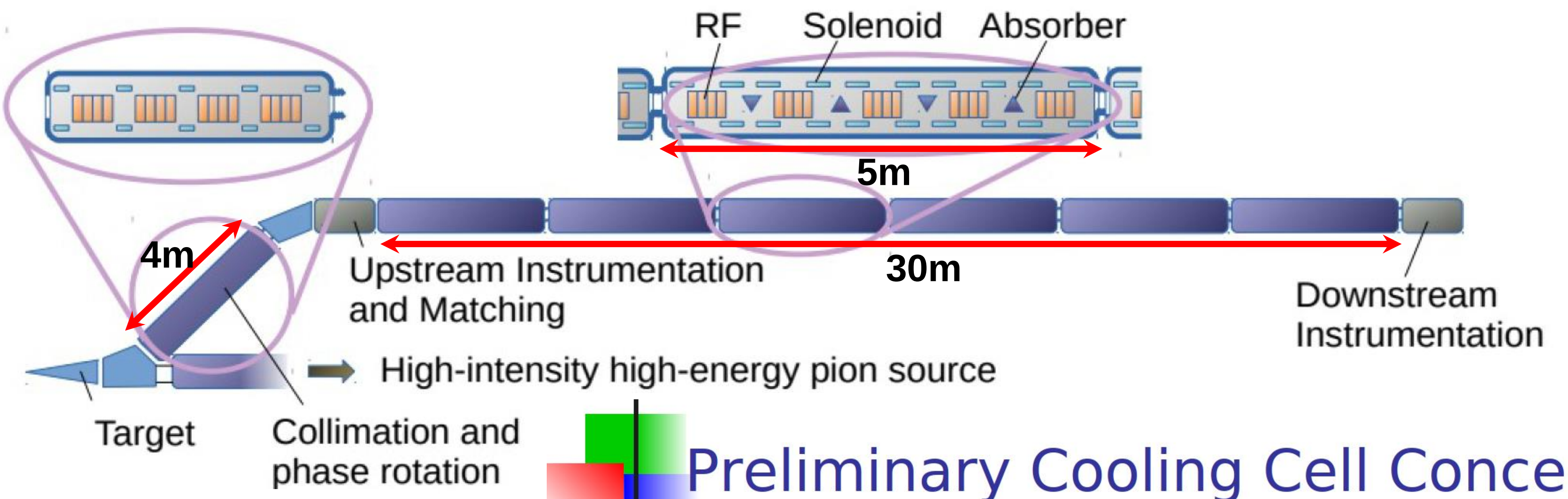
MUC Demonstrator VERY Conceptual layout → To be taken with a "grain of salt"



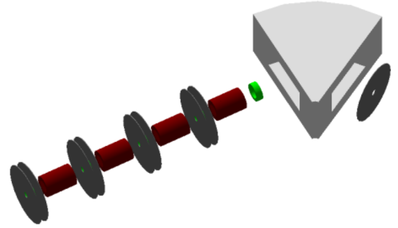
Indicative dimensions. Model is very flexible at this stage

Muon cooling demonstrator layout

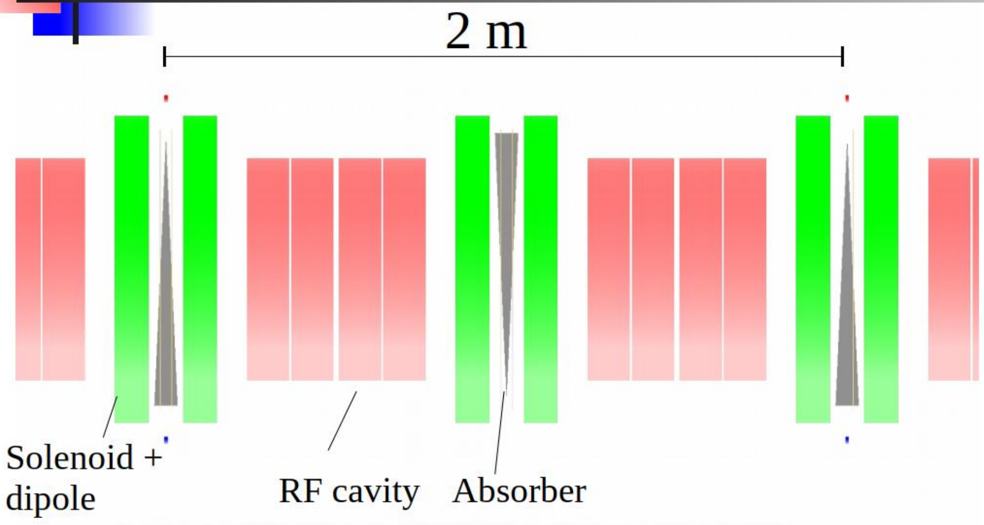
Chris Rogers



Preliminary Cooling Cell Concept



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



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

Parameters of RF system (beam dynamics specifications)

	Collimation system	Cooling cells	comments
	Cavity type 1	Cavity type 1	**One single cavity design can be used**
Number of RF cavities	16	20 x 6 modules = 120	
RF frequency [MHz]	704	704	
Accelerating gradient [MV/m]	15	28.5	No transit time factor is included. It is the amplitude of the accelerating electric field on crest, on axis (For ideal pillbox it is also max surface electric field).
Cavity length [m]	0.125	0.105 or 0.120 (TBC)	
Beam window radius [m]	0.050	0.045 to 0.090 (TBC)	
Beam window thickness (Be) [um]			Assuming 2 windows per cavity

All numbers are provisional

International
MUON Collider
Collaboration

Parameters of the RF system

	Collimation system	Cooling cells	comments
Cavity parameters	Cavity type 1	Cavity type 1	One single cavity design is used
f [MHz]	704	-	
Q-factor	~26000	-	
R/Q [circOhm]	~100	-	
Filling time: ~Q/f [us]	~30	-	
Power source requirements			
Max. Nominal Gradient [MV/m]	20	30	
RF power loss in one cavity [MW]	1	2	
Pulse length: [us]	~30 + 0.1	~30 + 0.1	~ filling time + bunch train
Repetition rate: [Hz]	~5	~5	?
RF power from the klystron(s) [MW]	**1.5**	**3**	**50% margin for all.** ESS:30%
Number of klystrons	**16**	**2x120 = 240**	**1.5 MW per klystron** ESS has ~200 klystrons

RF power source: 704 MHz

Commercially available RF power sources with the parameters closest to the specs are at the frequencies of currently running proton linacs:

For example, ESS:

CPI: VKP-8352A/B: 352MHz, 2.8MW, 100kW

CPI: VKP-8292A: **704**MHz, **1.5**MW, 74kW

CANON: E37504 **704**MHz, **1.5**MW, 74kW, 3.5ms, 14 Hz

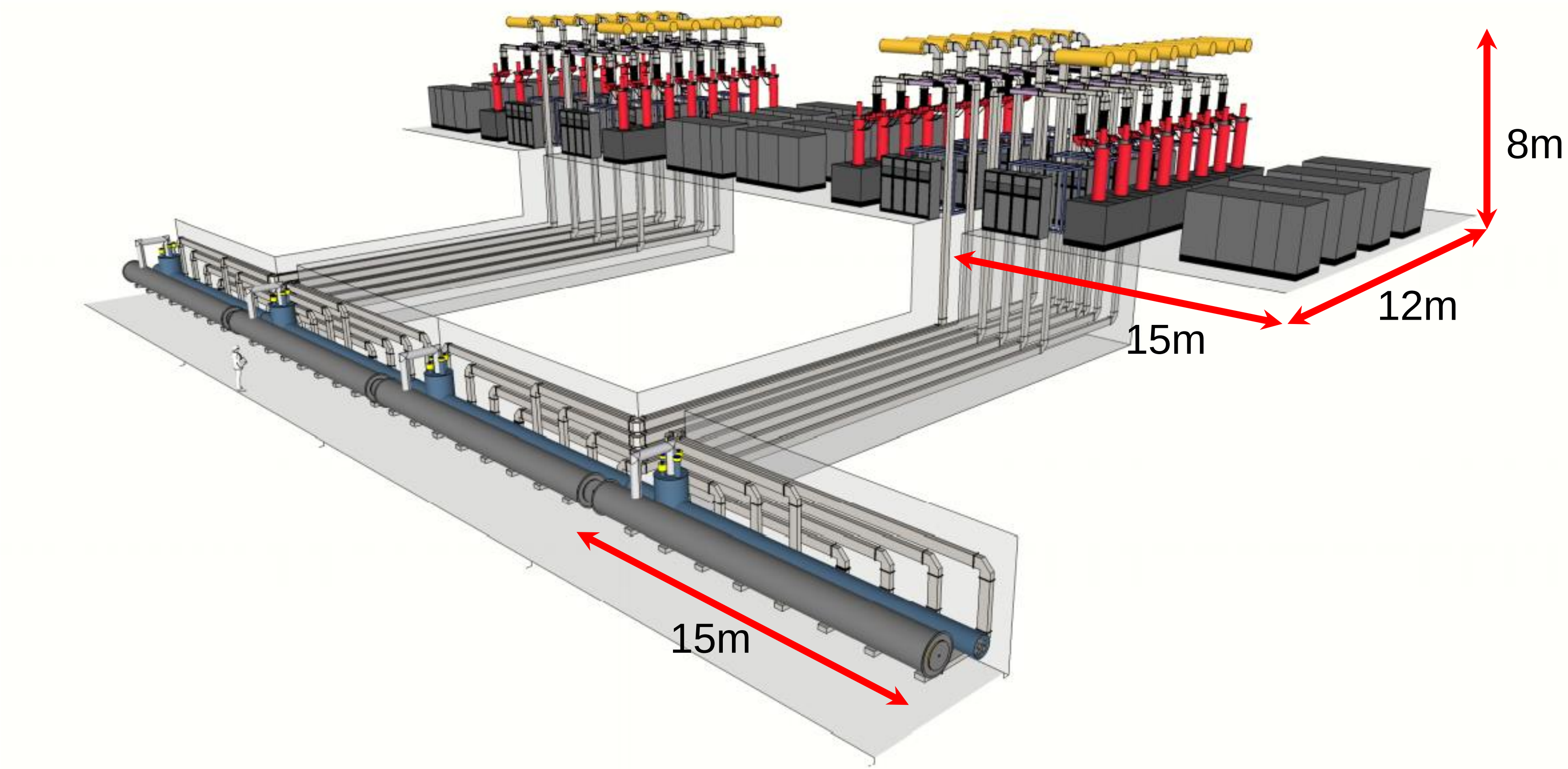
Thales: 2182A **704**MHz, **1.6**MW

International MUON Collider Collaboration

RF station layouts overall

EUROPEAN SPALLATION SOURCE

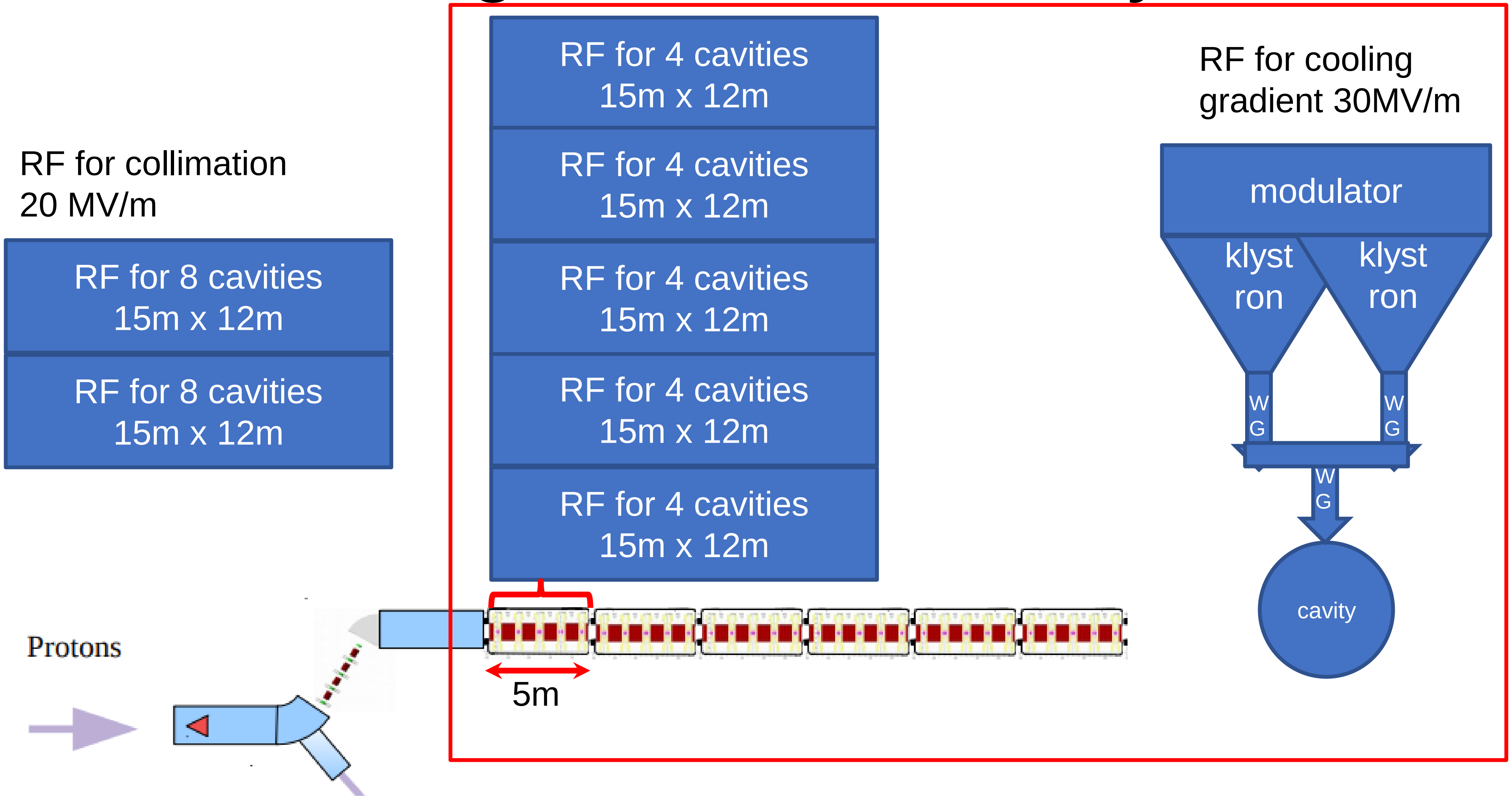
Stub Concept



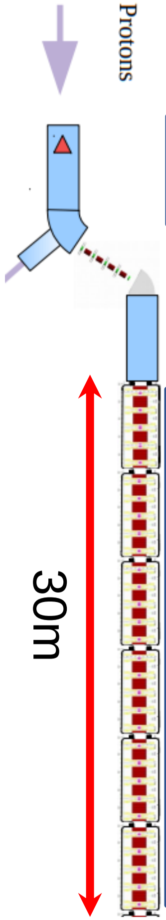
Footprint of 8
RF power sources:
15m x 12m

RF: 8x1.5MW
15m x 12m

Muon cooling demonstrator layout



Muon cooling demonstrator layout nominal gradient



RF for collimation: Max 20MV/m

RF for 16 cavities
15m x 12m x 2

RF for cooling: Max. gradient 30 MV/m

180m

RF for 120 cavities at ~30 MV/m
15m x 12m x 5 x 6 = 30m x 180m

Big building:
(surface)
30m x 200m
Height: 8-10 m

Large number of very long waveguides
100m surface
+50m shaft
~15% losses

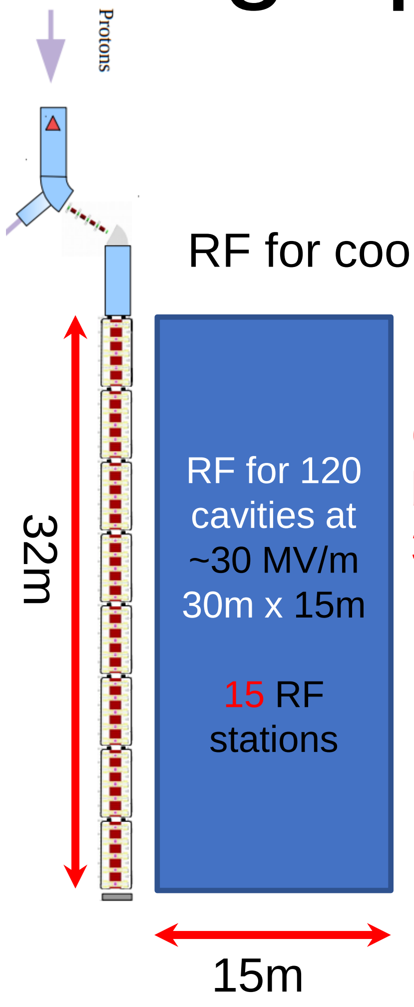
Some reduction of the size of the modulators due to shorter pulse and lower rep. rate is possible.

Some R&D ideas for MC RF system optimization

- Pulse compressors
- **Higher peak power RF sources**
- **Feeding several cavities from one source**

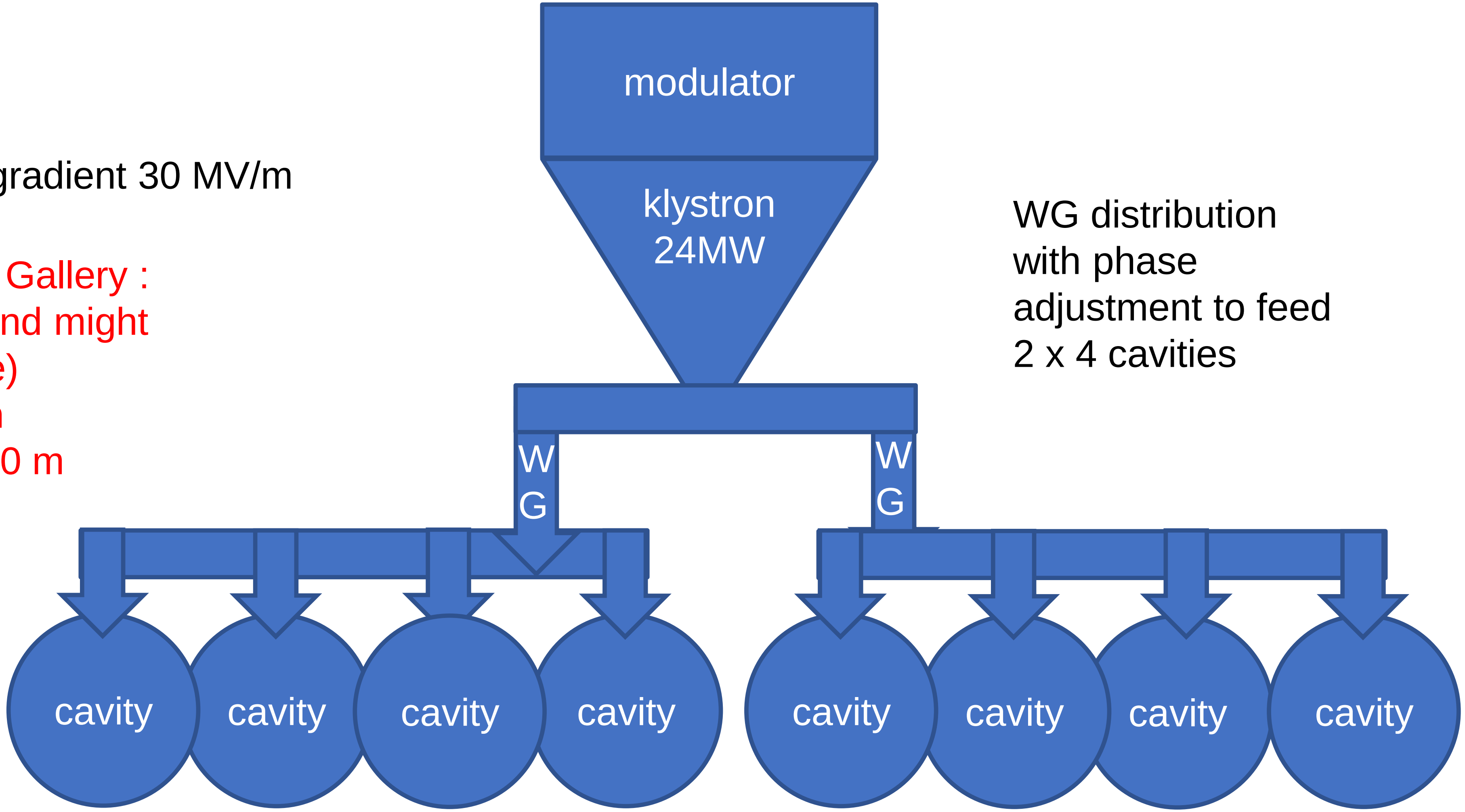
Muon cooling demonstrator layout
High peak power klystron: 24 MW

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

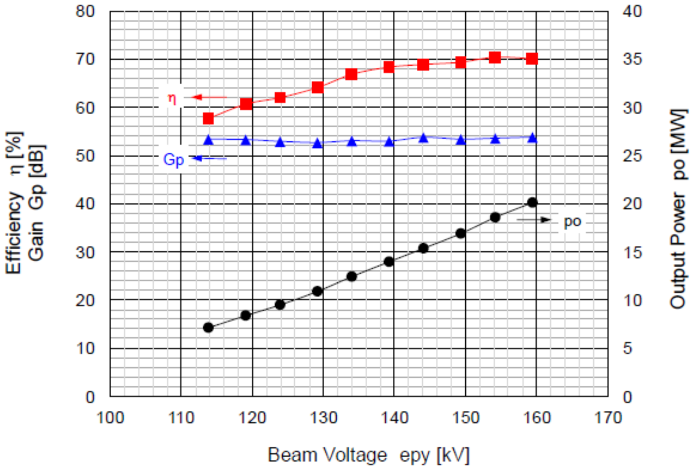


High power L-band Multi Beam Klystrons (MBK). Commercial tubes.

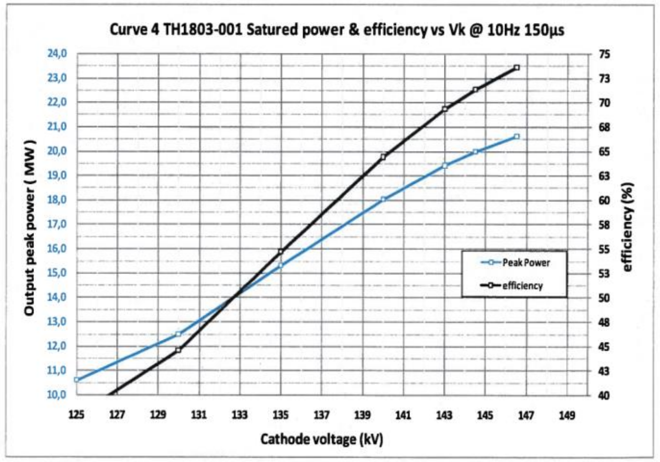
Frequency: **1.0 GHz**
Peak RF power: 20 MW
Efficiency: 70%

Frequency: **1.3 GHz**
Peak RF power: 10 MW
Efficiency: 65%

Two **20MW** MBK CLIC L-band klystron prototypes tested in industry.



F= **999,5 MHz**
P max= **20.2 MW**
T = **150 µsec**
V= **159.4 kV**
I total = **180 A**
Eff.= **70.5 %**
uP= **0.47 µAxV$^{-3/2}$/beam**
Gain = **53.9 dB**



F= **999,5 MHz**
P max = **20.8 MW**
PL = **150 µsec**
V= **146.5 kV**
I= **191 A**
Eff. = **73.5 %**
uP= **0.341 µAxV$^{-3/2}$/beam**
Gain = **51.5 dB**

- *Strong beam interception in the output cavity.*
- *Voltage-Efficiency curve does not show saturation*
- *Unbalanced power split between the two ports.*

Scaling the Canon tube to 0.7GHz, 24MW and 30 μsec.


IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 66, NO. 2, FEBRUARY 2019 1075

Scaling Procedures and Post-Optimization for the Design of High-Efficiency Klystrons

Jinchi Cai, Igor Syratchev, and Zening Liu

Canon E37503
6 beams MBK

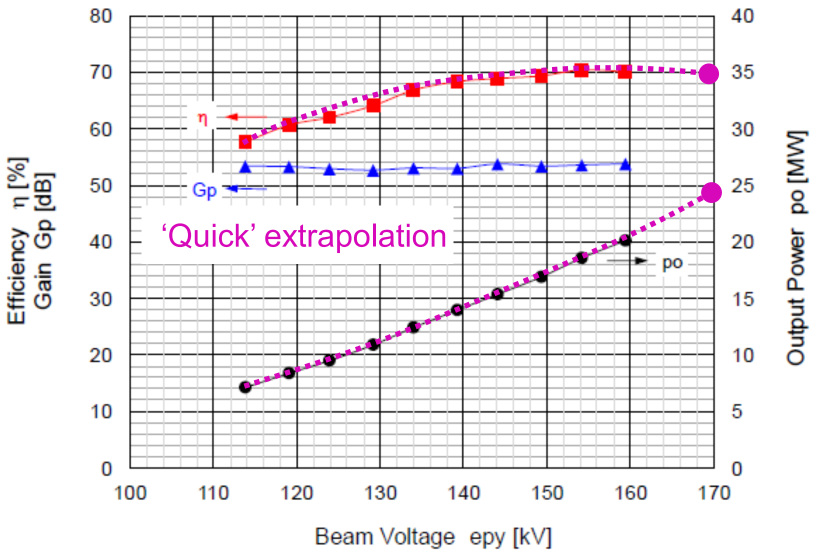
F=	999,5 MHz
P max=	20.2 MW
T =	150 μsec
V=	159.4 kV
I total =	180 A
Eff.=	70.5 %
uP=	0.47 $\mu A x V^{-3/2}$/beam
Gain =	53.9 dB
$P_{average}$ (50Hz)=	150kW

Mu-tube, 0.7 GHz
6 beams MBK

F=	700 MHz
P max=	24 MW
T =	30 μsec
V=	171 kV
I total =	200 A
Eff.=	70.0 %
uP=	0.47 $\mu A x V^{-3/2}$/beam
Gain =	53.9 dB
$P_{average}$ (5Hz) =	3.6kW

To our experience such a scaling is a 'low' risk development:

- For the fixed micro perveance, the tube length is proportional to the frequency
- Lower cathode current density (55%) and increased life time.
- Much lower average power (simpler collector)
- Marginal (~10%) increase of the modulator voltage and current.

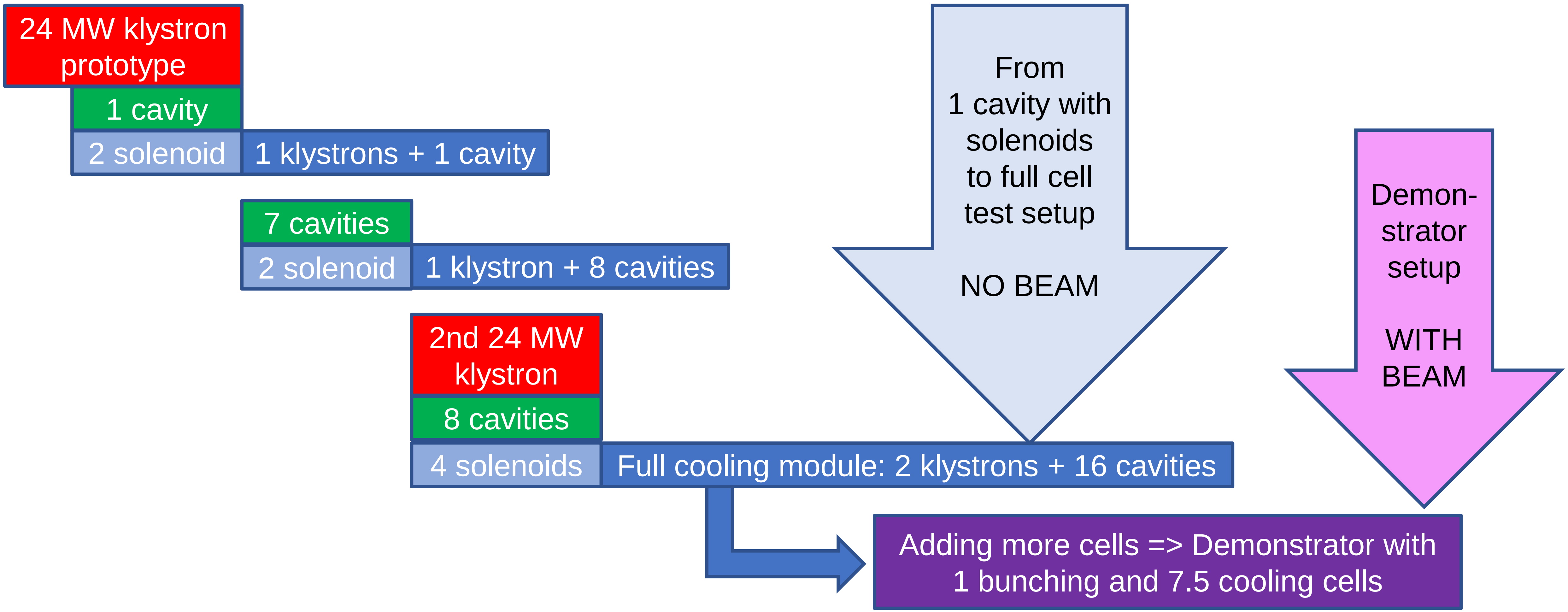


Igor Syratchev

Cost and schedule:

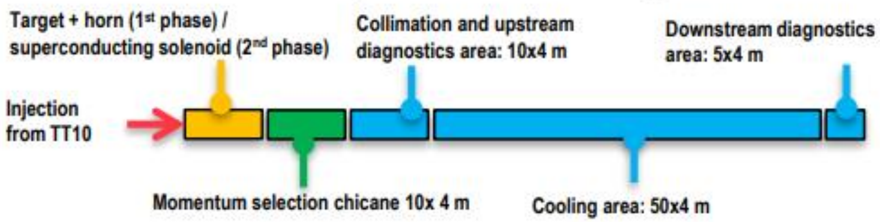
- The CLIC tube prototypes were designed/built about 10 years ago; Canon: **iiiii** and Thales : **iiiiii**. Mu-tube cost will be within this range, as the companies shall do it not from scratch, but could scale it from exiting ones. *Though, today there is no market for such devices, thus the cost of 'unique' prototype could be even higher.*
- Similar to the CLIC tubes, it will take about **24 month** to design, built and test the first Mu-tube prototype. Additional budget will be needed for the testing infrastructure (like RF loads etc.).

Possible staging scenarios



Back up

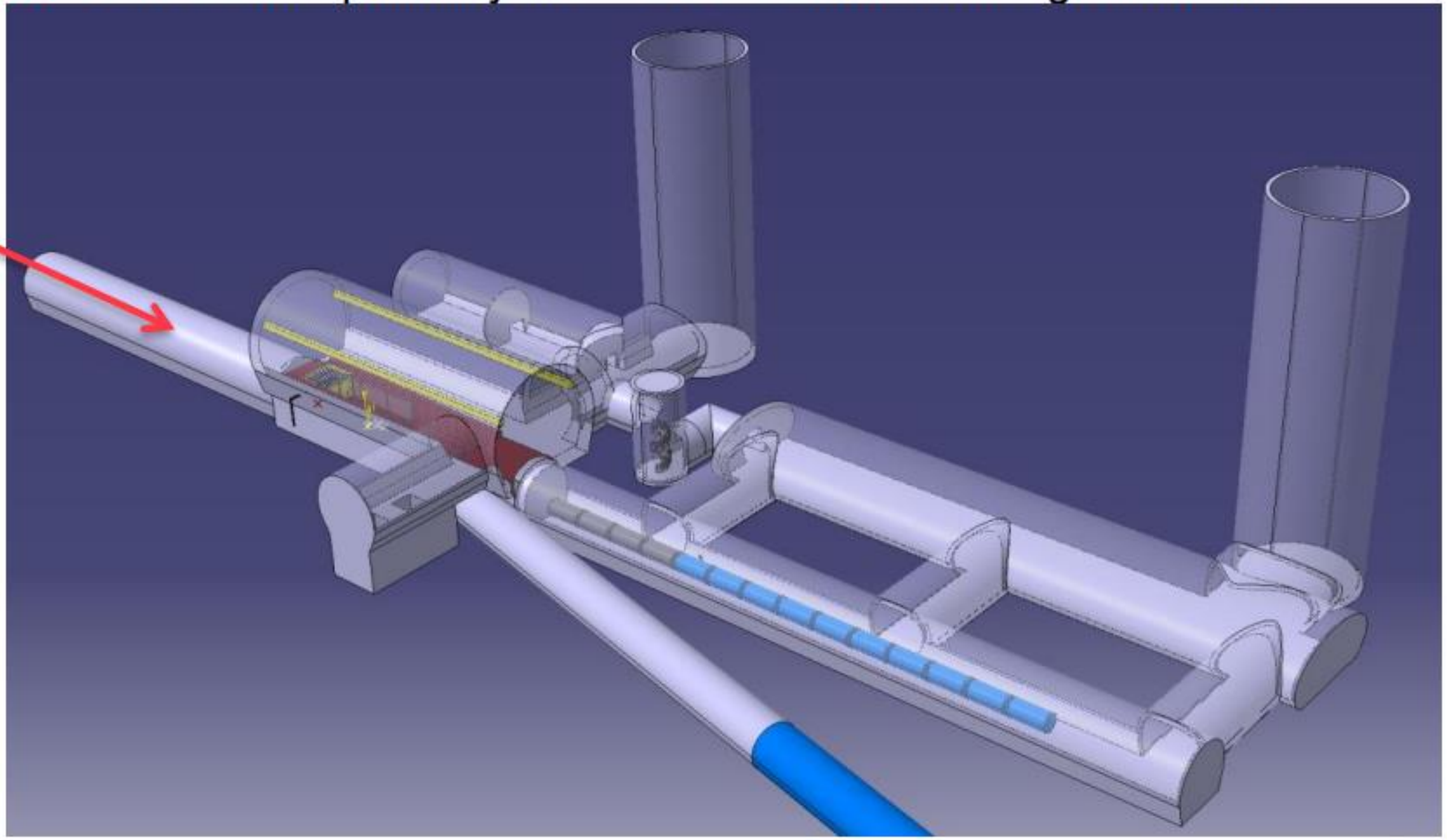
Conceptual layout



Rui Ximenes
2nd Community meeting

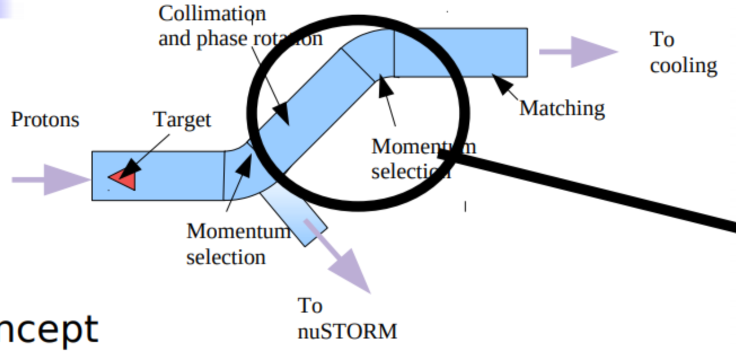
MUC Demonstrator VERY Conceptual layout → To be taken with a "grain of salt"

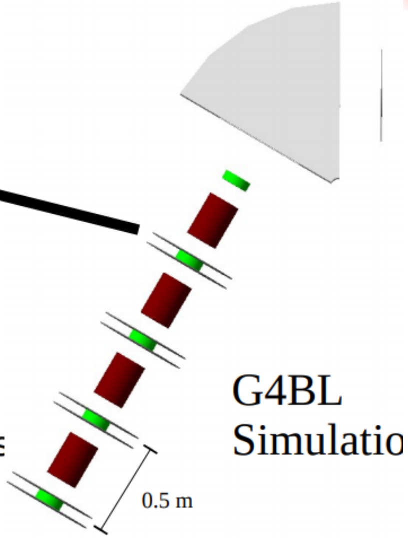
CERN TT10 branch



Collimation Chris Rogers

Collimation System

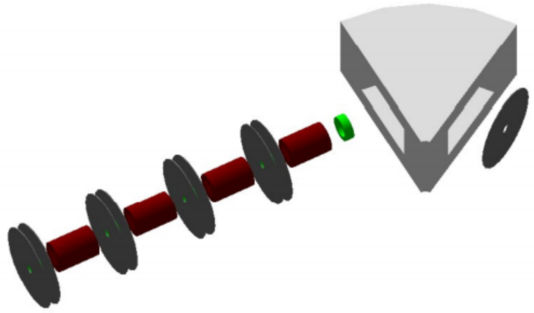




- Concept
  - Dipole to do a first momentum selection
  - Collimation and RF to do phase rotation
  - Second dipole to do a second momentum s
- How clean do we need the beam to be?

Lattice

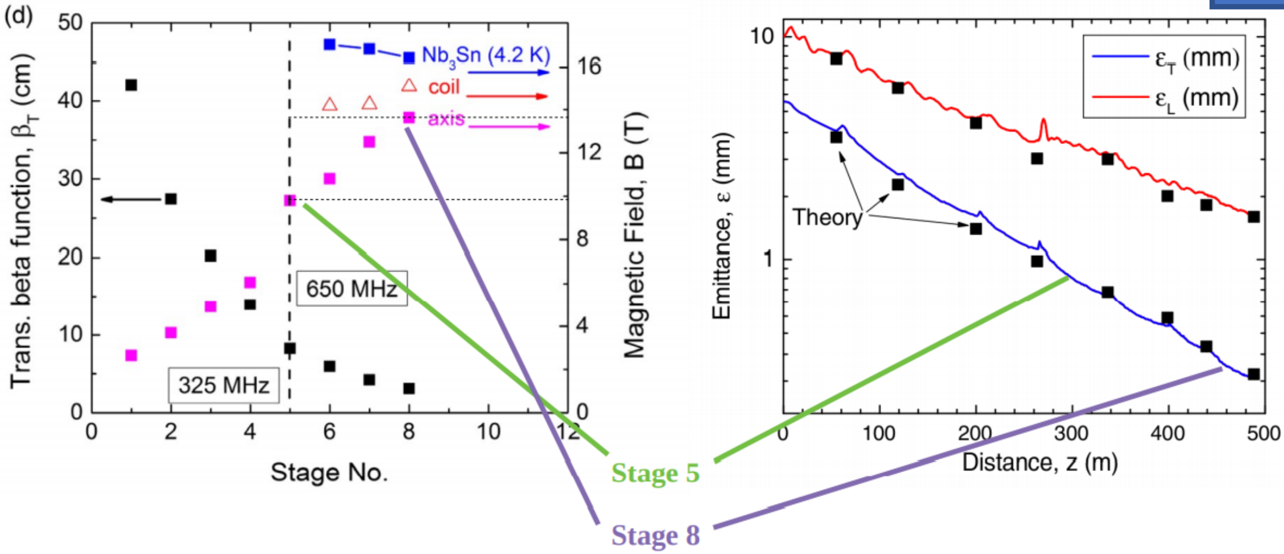
- 1 m cell length
  - 0.5 T solenoids, 50 mm radius pipe
  - 0.125 m, 650 MHz RF cavities
  - 4 cavities per cell (and 4 cells)
  - 15 MV/m peak gradient
  - Running in "bunching" mode
- 0.7 T dipole
  - 45 degree bend
- All apertures are perfect collimators
- No electrons
- No pions



Muon Cooling channel

Chris Rogers

Input beam for cooling channel (Lowest emittance option)

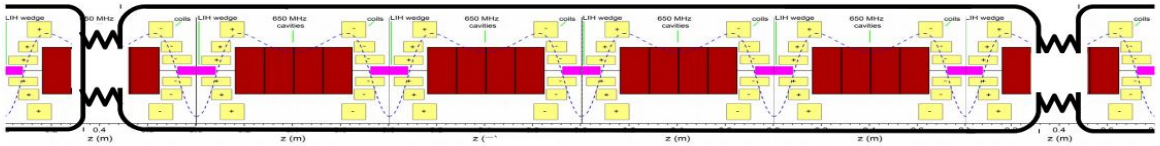


Stage B8

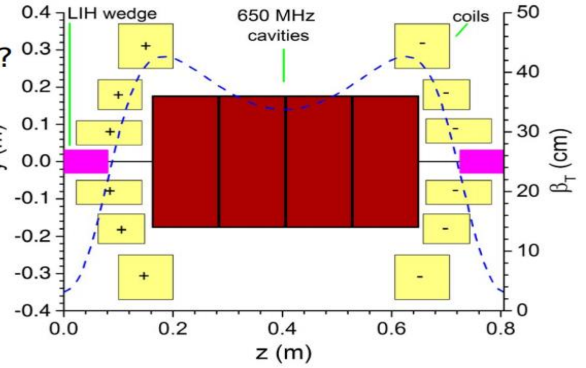
- Collimation system requirement
  - Emittance ~ 0.5 – 1 mm transverse
  - Emittance ~ 2 – 4 mm longitudinal (650 MHz RF)
- Matching (not studied yet)

One of the 4 types: B5 – B8, still to be defined

Cooling channel concept



- Ongoing discussion:
  - What should be the peak field?
  - Lowest emittance @ 13 T
  - ~9 T may be cheaper
    - It is an MRI field
  - Needs consideration
- Plan for ~ 10 cryostats
  - Each containing ~ 5 cells
- Lattice well-established
  - Needs optimisation
  - Needs modification/engineering

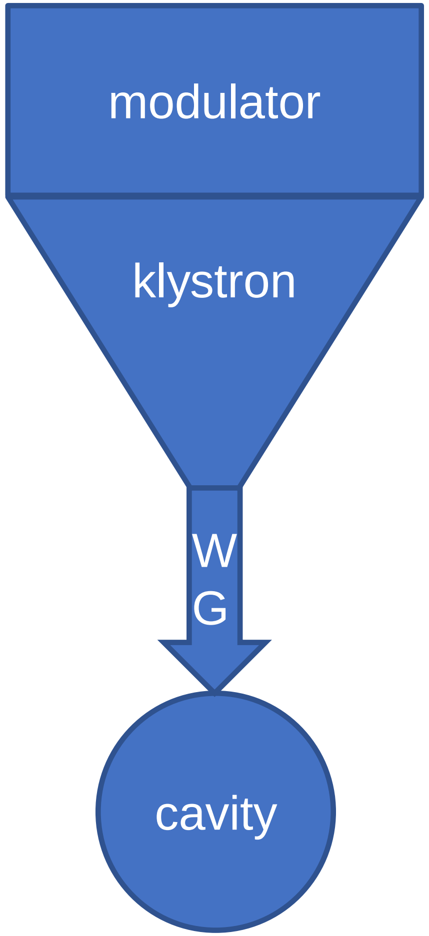


DIKTYS STRATAKIS AND ROBERT B. PALMER Phys. Rev. ST Accel. Beams **18,** 031003 (2015)

TABLE I. Main parameters of a 12-stage rectilinear 6D cooling lattice before and after recombination. Stages A1–A4 and B1–B4 use LH absorber while stages B5–B8 use LiH absorber. Dispersion is calculated at the absorber center at the reference momentum of 200 MeV/c.

Stage	Cell length [m]	Total length [m]	rf frequency [MHz]	rf gradient [MV/m]	rf #	rf length [cm]	Coil tilt [deg]	Pipe radius [cm]	Dispersion [cm]	Wedge angle [deg]
A1	2.000	132.00	325	22.0	6	25.50	3.1	30.0	10.7	39
A2	1.320	171.60	325	22.0	4	25.00	1.8	25.0	6.8	44
A3	1.000	107.00	650	28.0	5	13.49	1.6	19.0	4.2	100
A4	0.800	70.40	650	28.0	4	13.49	0.7	13.2	1.9	110
B1	2.750	55.00	325	19.0	6	25.00	0.9	28.0	5.2	120
B2	2.000	64.00	325	19.5	5	24.00	1.3	24.0	5.0	117
B3	1.500	81.00	325	21.0	4	24.00	1.1	18.0	4.6	113
B4	1.270	63.50	325	22.5	3	24.00	1.1	14.0	4.0	124
B5	0.806	73.35	650	27.0	4	12.00	0.7	9.0	1.4	61
B6	0.806	62.06	650	28.5	4	12.00	0.7	7.2	1.2	90
B7	0.806	40.30	650	26.0	4	12.00	0.8	4.9	1.1	90
B8	0.806	49.16	650	28.0	4	10.50	0.6	4.5	0.6	120

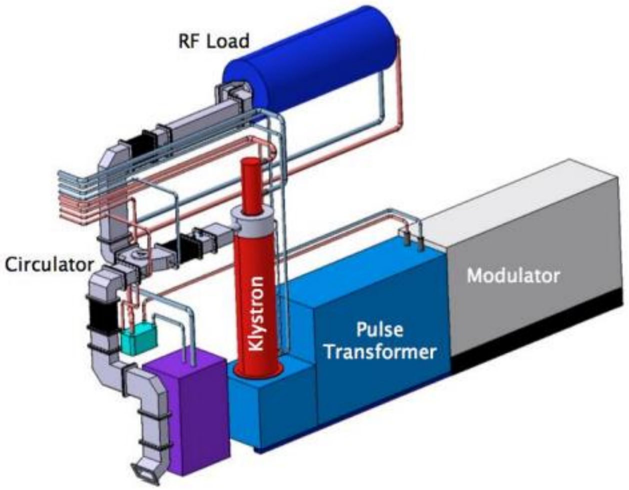
RF station layouts (1) one klystron per modulator

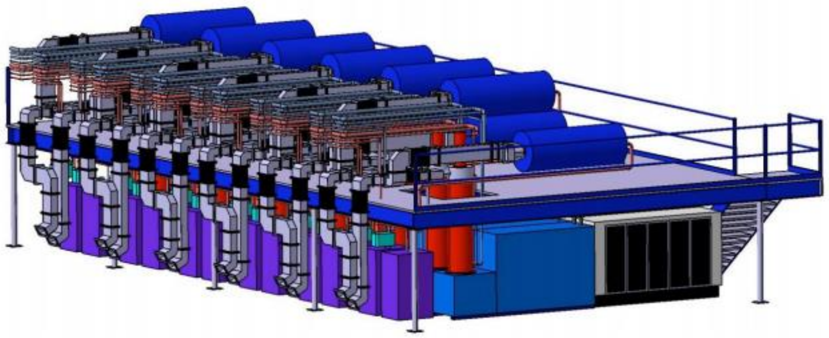


EUROPEAN
SPALLATION
SOURCE

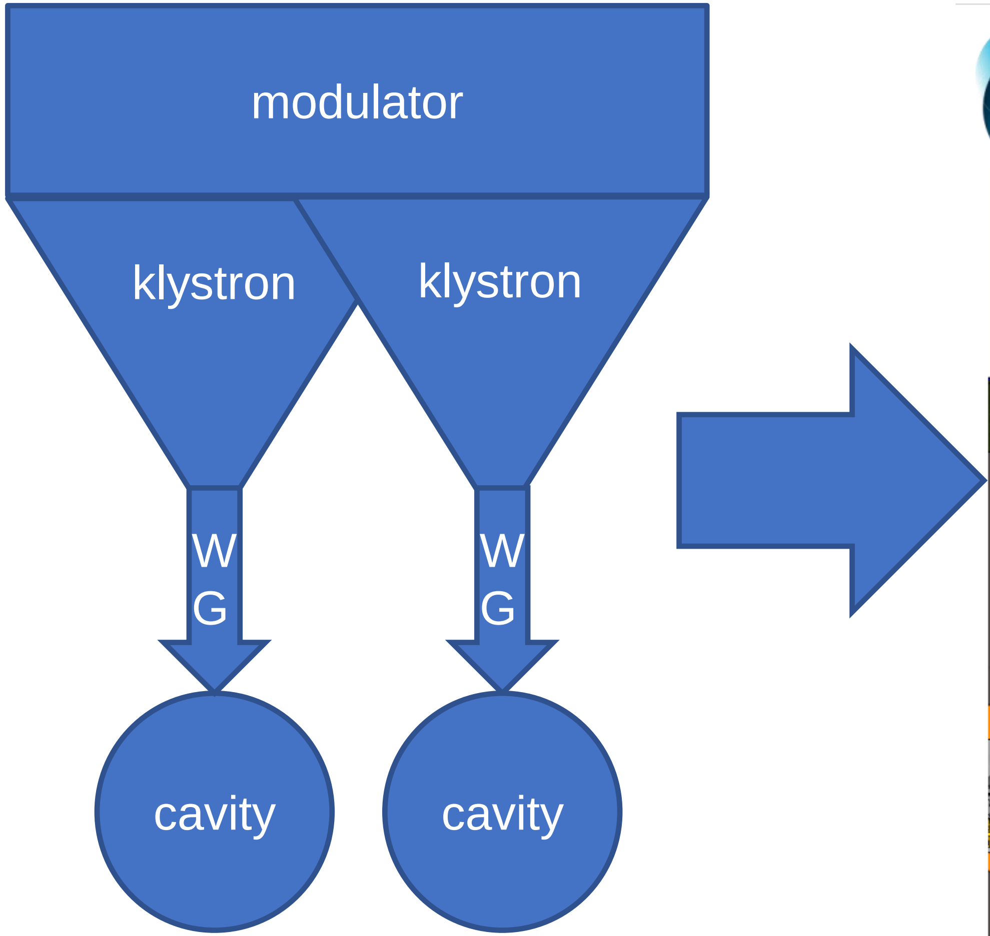
One Modulator Per Klystron

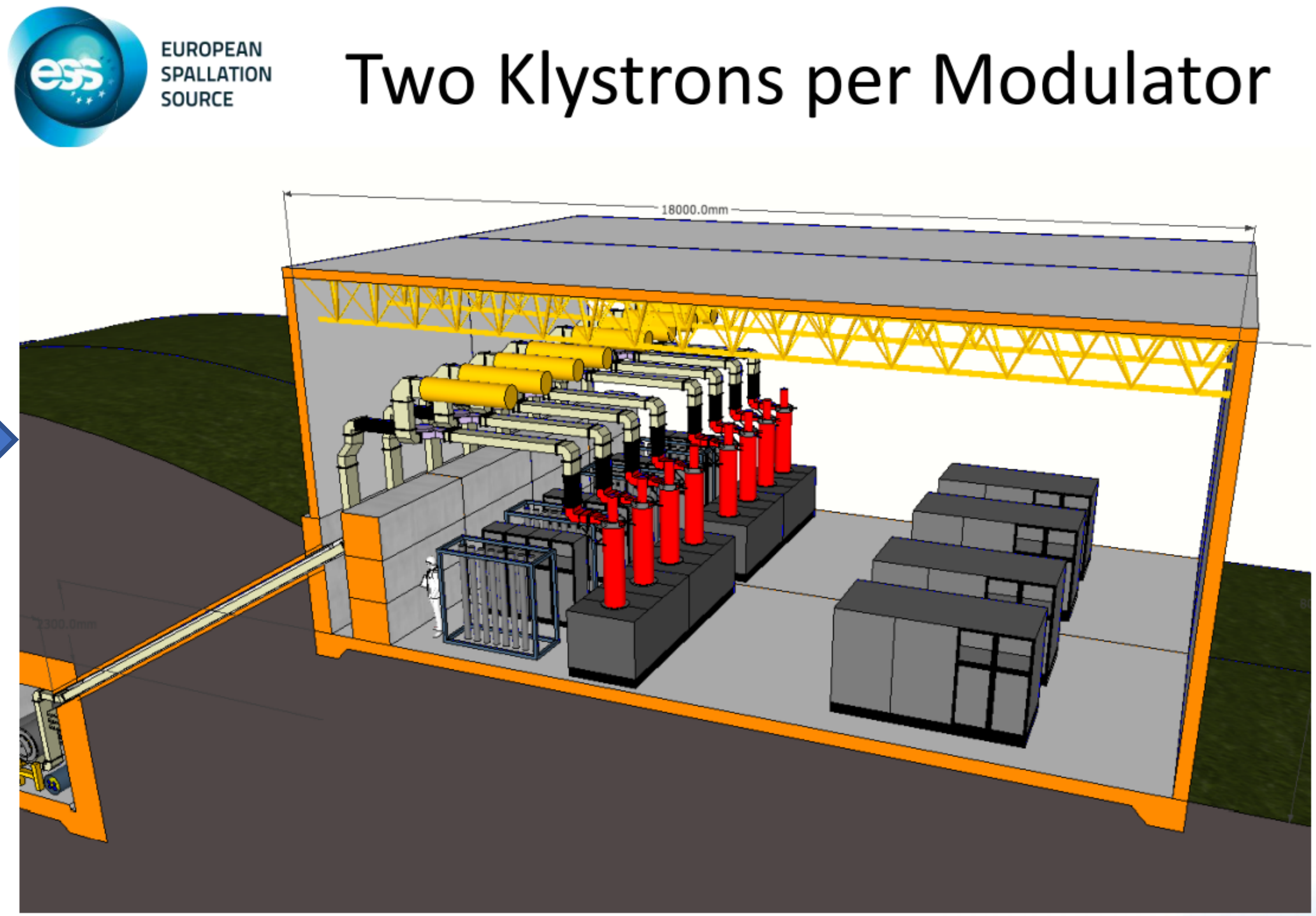
- Limited space for assembly and repair



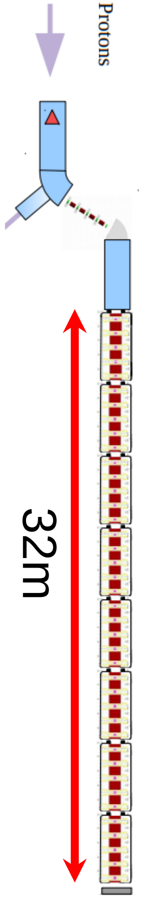


RF station layouts (2)
two klystrons per modulator





Muon cooling demonstrator layout lower gradient: 20 MV/m



RF for collimation: Max 20MV/m

RF for 16 cavities
15m x 12m x 2

RF for cooling: Max. gradient 20 MV/m

RF for 144 cavities at ~20 MV/m
15m x 2 x 12m x 9 = 30m x 108m

32m

108m

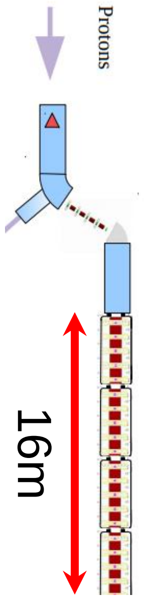
Not an option since gradient is part of the cooling design

Big building:
(surface ?)
30m x **120m**
Height: 8-10 m

Very long waveguides
50m surface
+50m shaft ?

Some reduction of the size of the modulators due to shorter pulse and lower rep. rate is possible.

Muon cooling demonstrator layout lower shorter cooling channel



RF for collimation: Max 20MV/m

RF for 16 cavities
15m x 12m x 2

RF for cooling: 2x shorter cooling channel

RF for 72 cavities at ~30 MV/m
15m x 2 x 12m x 9 = 30m x 108m

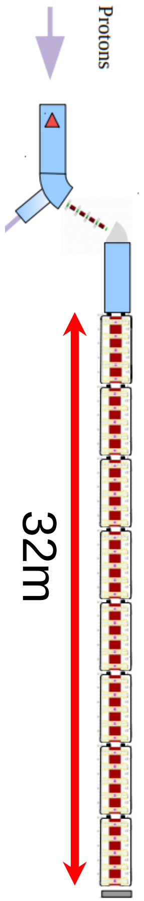
108m

Big building:
(surface ?)
30m x **120m**
Height: 8-10 m

Very long
waveguides
50m surface
+50m shaft ?

Some reduction of the size of the modulators due to shorter pulse and lower rep. rate is possible.

Muon cooling demonstrator layout
RF pulse compression: x2



RF for cooling: Max. gradient 30 MV/m

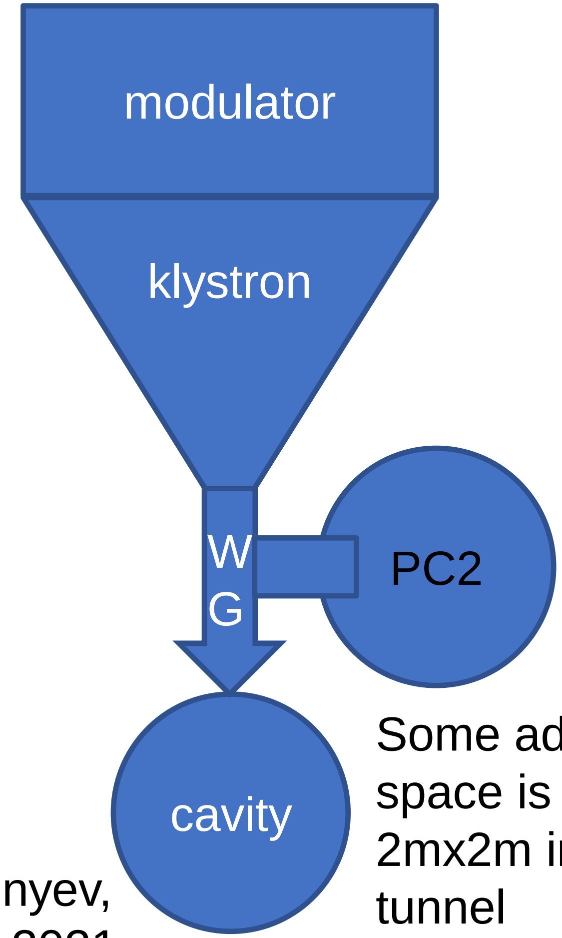
RF for 144 cavities at ~30 MV/m
15m x 2 x 12m x 9 = 30m x 108m

144 RF pulse compressors with power gain factor 2

108m

Big building:
(surface ?)
30m x **120m**
Height: 8-10 m

Very long waveguides
50m surface
+50m shaft ?

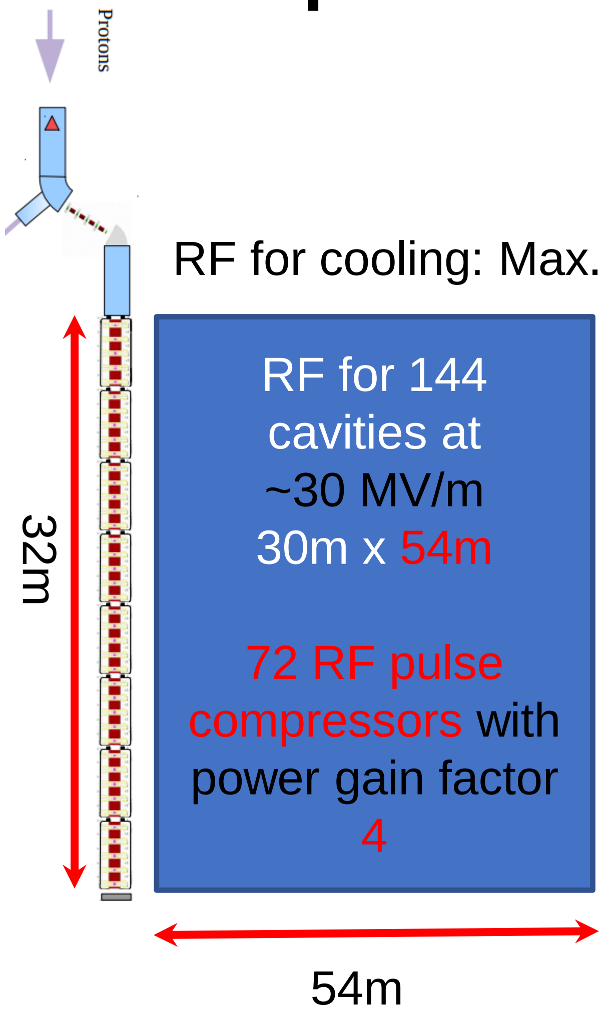


Some additional space is needed 2mx2m in the tunnel

See more details here S. Arsenyev, MC RF WG meeting 31st Aug. 2021: [Diapositive 1 (cern.ch)]

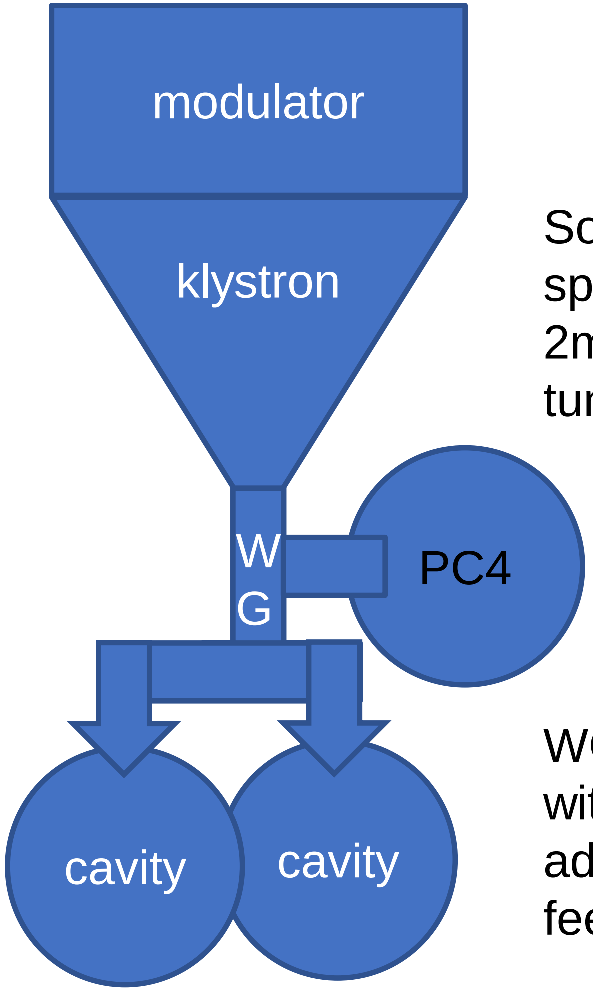
Muon cooling demonstrator layout
RF pulse compression: x4

RF for cooling: Max. gradient 30 MV/m



Big building:
(surface ?)
30m x **60m**
Height: 8-10 m

Very long
waveguides
30m surface
+50m shaft ?

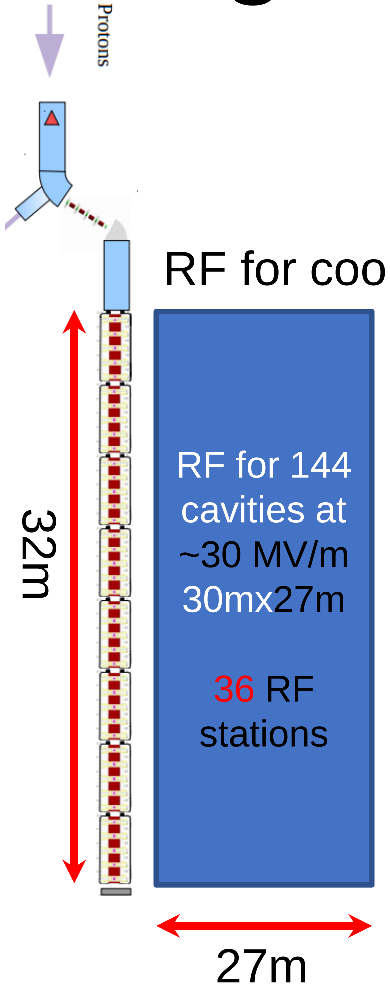


Some additional space is needed 2mx2m in the tunnel

WG distribution with phase adjustment to feed 2 cavities

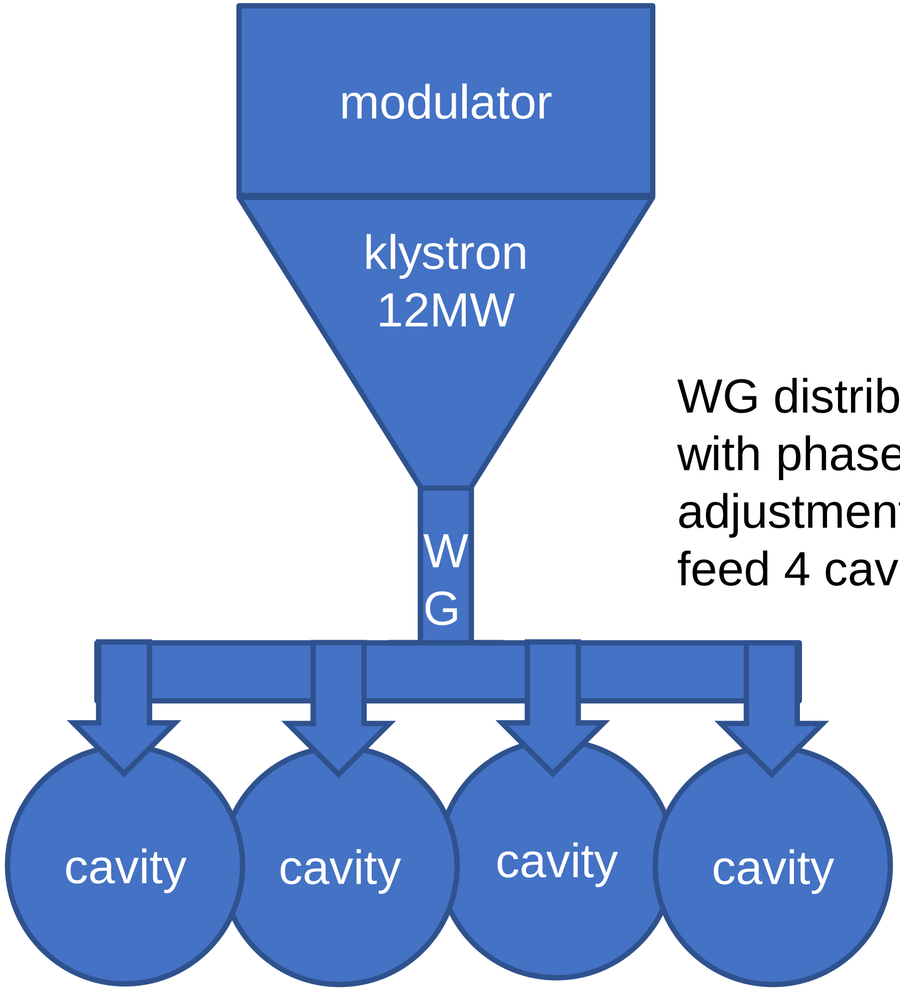
Muon cooling demonstrator layout
High peak power klystron: 12 MW

RF for cooling: Max. gradient 30 MV/m



Building:
(surface ?)
30m x **30m**
Height: 8-10 m

Long waveguides
15m surface
+50m shaft ?



WG distribution with phase adjustment to feed 4 cavities

New ideas for CLIC 1GHz klystron

Novel design
Two-stage (TS)
multi beam klystron (MBK)

CLIC project meeting
15 June 2021
[Igor Syratchev (cern.ch)]

High Efficiency 24 MW, 1 GHz, CLIC TS MBK performance summary (PIC CTS/3D)

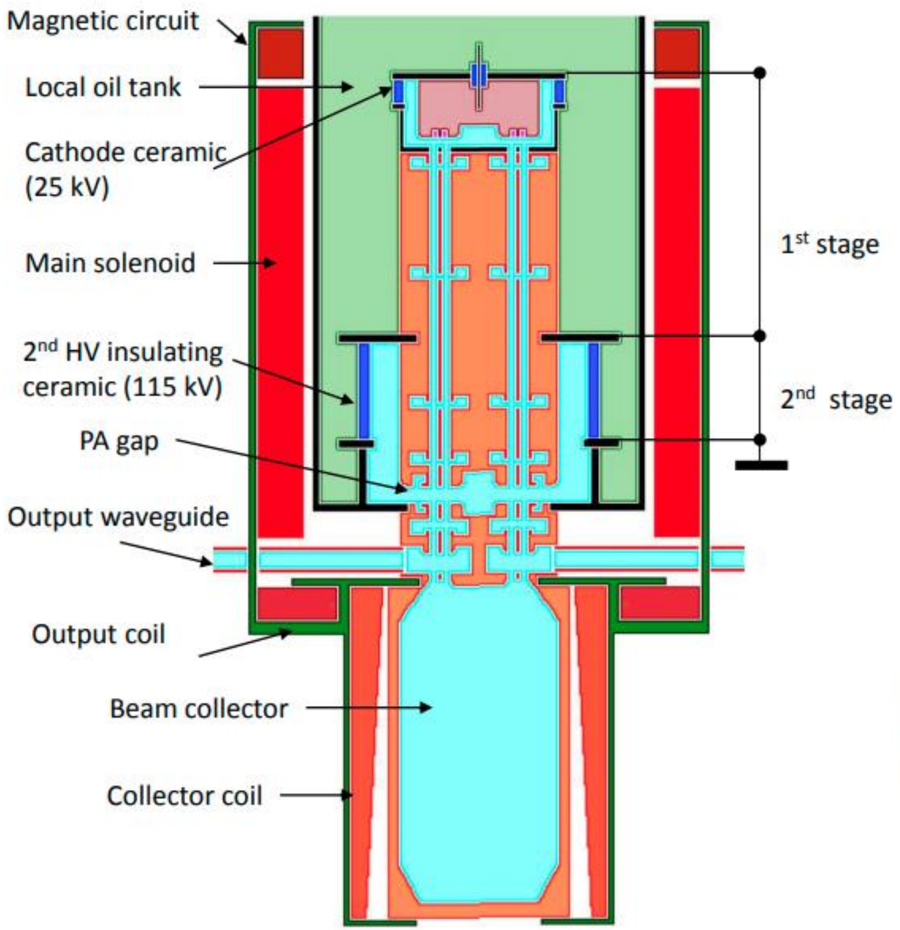
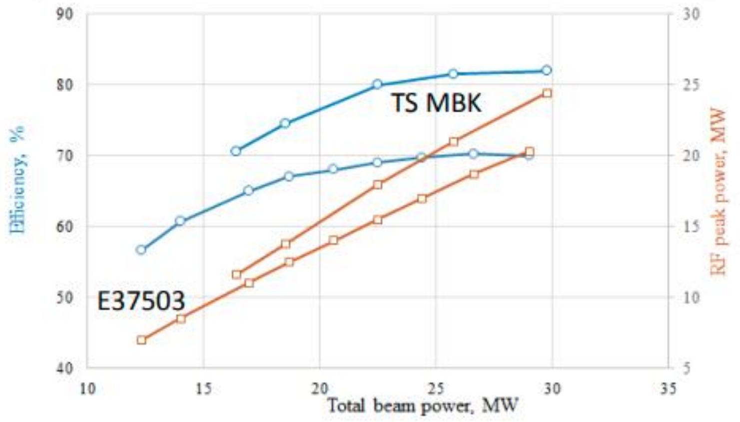


TABLE I. DESIGN AND SIMULATED PARAMETERS (CST/3D) OF THE CLIC TS MBK AND CANON MBK E3750 CATALOGUE DATA

Parameter	TS MBK	E37503	Unit
Operating frequency	1000	1000	MHz
Voltage at the 1st stage	25	160	kV
Voltage at the 2nd stage	140		
Total beam current	212	180	A
Number of beamlets	30	6	
Number of cavities	6	6	
Perveance at the 1st stage	1.77	0.47	$\mu A/V^{3/2}$
Perveance at the 2nd stage	0.133		
Output RF power	24.1	20	MW
Saturated power gain	52	54	dB
Saturated efficiency	82	70	%
Length of RF circuit	900	1500	mm



CLIC L-band klystron modulator - ETH

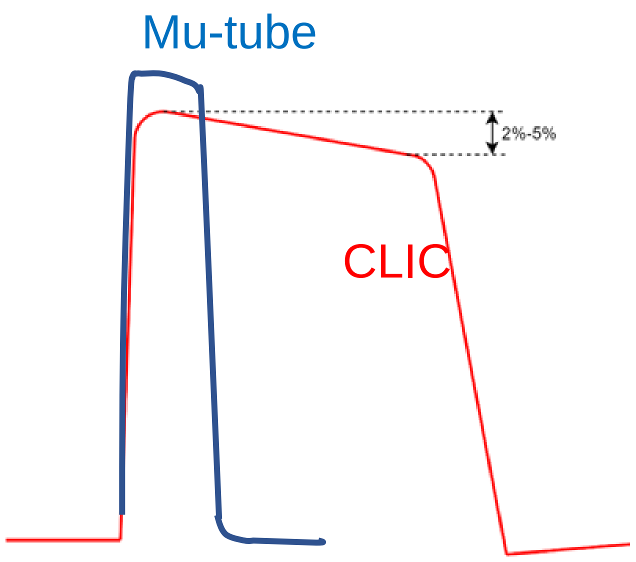
Max voltage	180 kV (160A)
Max current	190 A (@ 150 kV)
Flat-top	140 µs
Rise/fall-time	3 µs
Max rep rate	50 Hz

- Turnkey system (no CERN electronics can manage this)
- Situation: worked on dummy load, since more than 2 years trying to restart-it – electronics issues – difficulties due to turnkey & pandemic influence on components availability
- Requires lot of resources – no spares – re use for muons will be extremely demanding in resources (M&P)
- Second unit was foreseen in CLIC project (simplified version with CERN electronics and degraded flat-top performances) – funds not available anymore…

CLIC L-band klystron modulator – second (CERN based)

- Second unit intended to verify the design of the pulse transformer and to have a s
- Simpler version with only:
  - A charger (120 kW, 20 kV) → Already bought (110 kCHF)!
  - A capacitor bank
  - Power electronics (mainly a switch)
  - A pulse transformer → Studies carried out (CERN internal design), partner company interested

MS sent out in 2018 (industry interested for this simplified version)



Specs for two modulators modulator

	CLIC Mu-tube
Max voltage	170 kV 171kV
Max current	180 A 200 A
Pulse length	150 µs 30 µs
Flat-top	2-5% NA

- Projected cost (CERN based) is iiiii . Construction time is about two years.
- Down-sized for the Mu-tube (less average power, increased flat top stability and rise/fall), will make the project cheaper and less time consuming. All these parameters relaxations can be accepted as the cavities will integrate all the imperfection in RF signal amplitude, provided simple enough RF phase feed-back control.