Community Report on Accelerators Roadmap
LNF – July 13, 2023

RF implications for the muon collider program

Nadia Pastrone

Thanks to many colleagues for the material, discussions and the future!
Errors are only mine…

Input to EU Strategy of Particle Physics

European Strategy Update

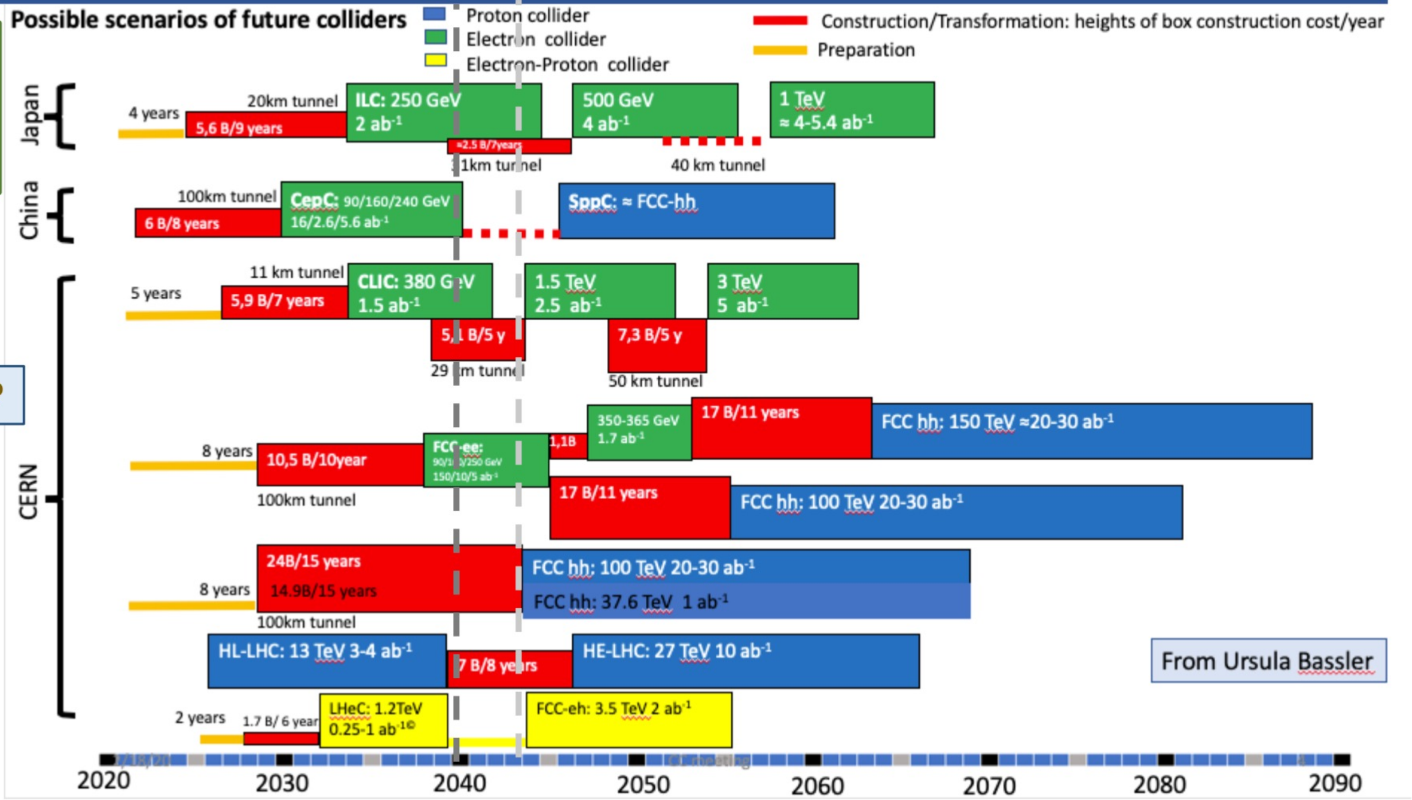
2020 Strategy Update

Halina Abramowicz

High-priority future initiatives

Map of possible future facilities submitted as input to the Strategy Update

Where is the muon collider?



From Ursula Bassler

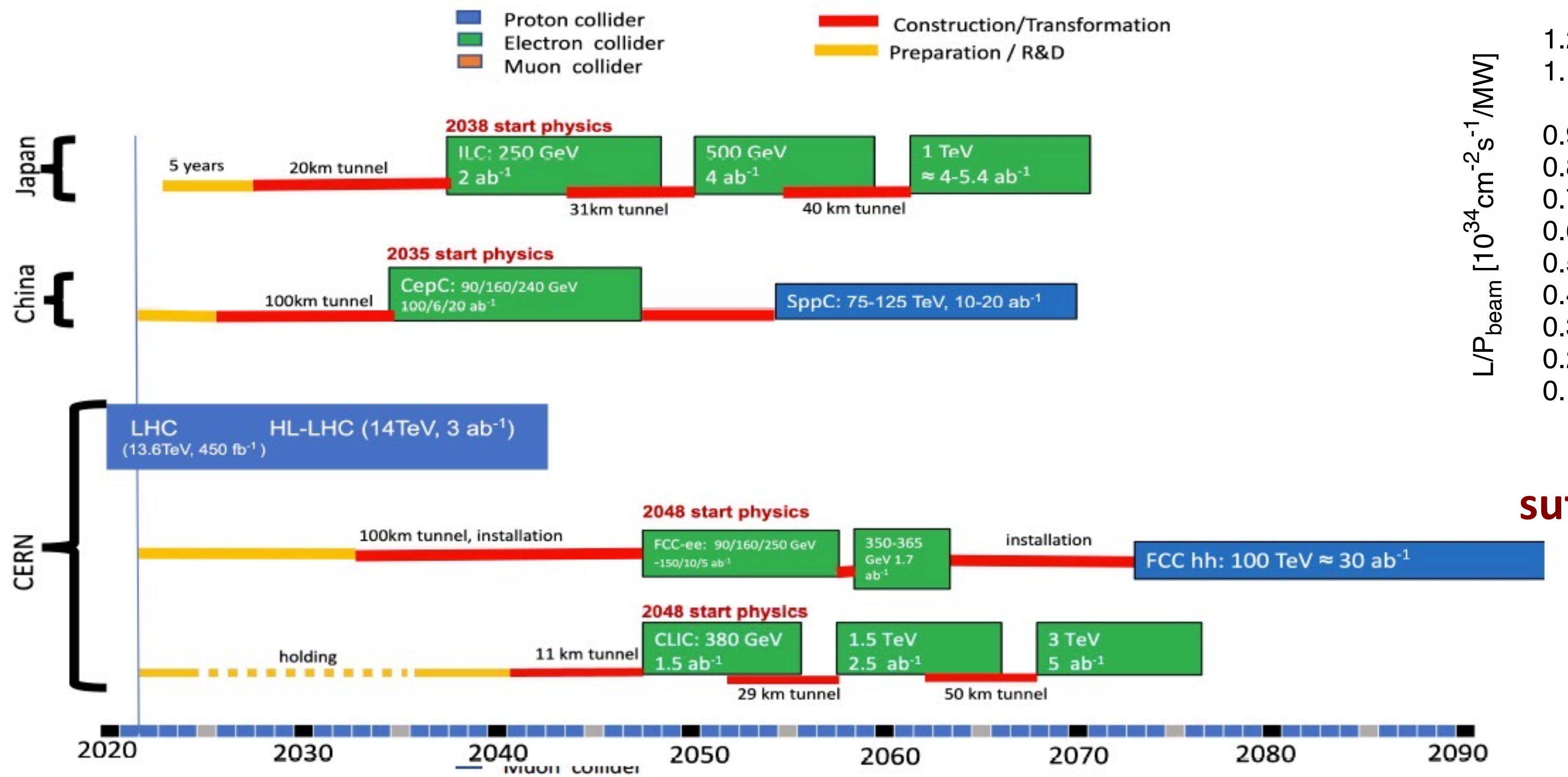
Input Document to EU Strategy Update - Dec 2018:

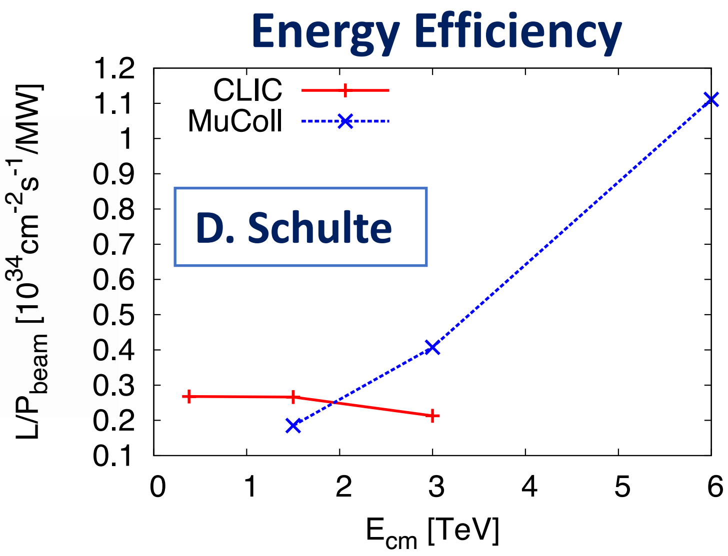
"Muon Colliders," arXiv:1901.06150

by *CERN-WG on Muon Colliders*

J.P. Delahaye et al.

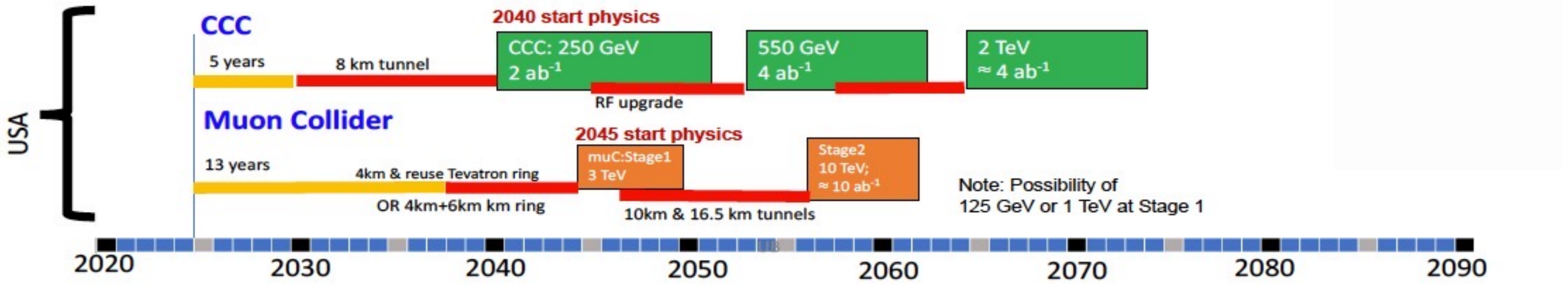
Colliders timescale after Snowmass 2021





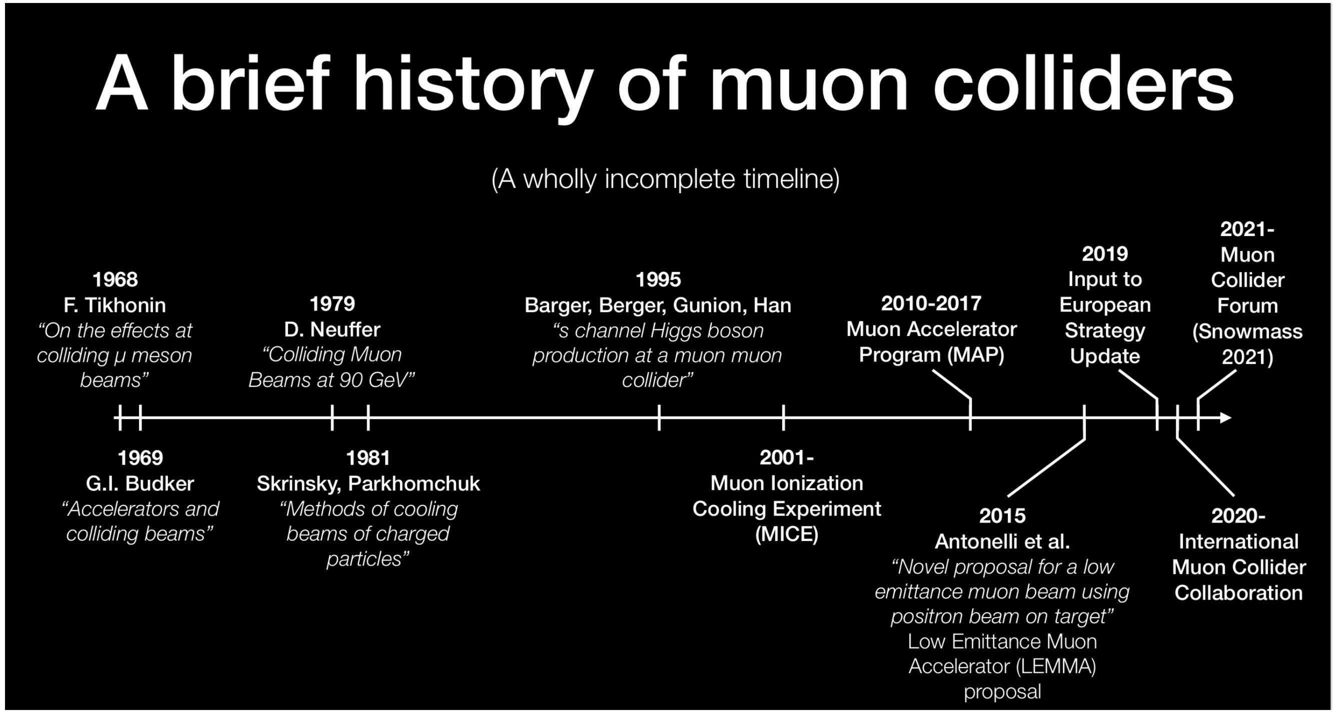
sufficient luminosity required

Proposals emerging from Snowmass 2021 for a US based collider



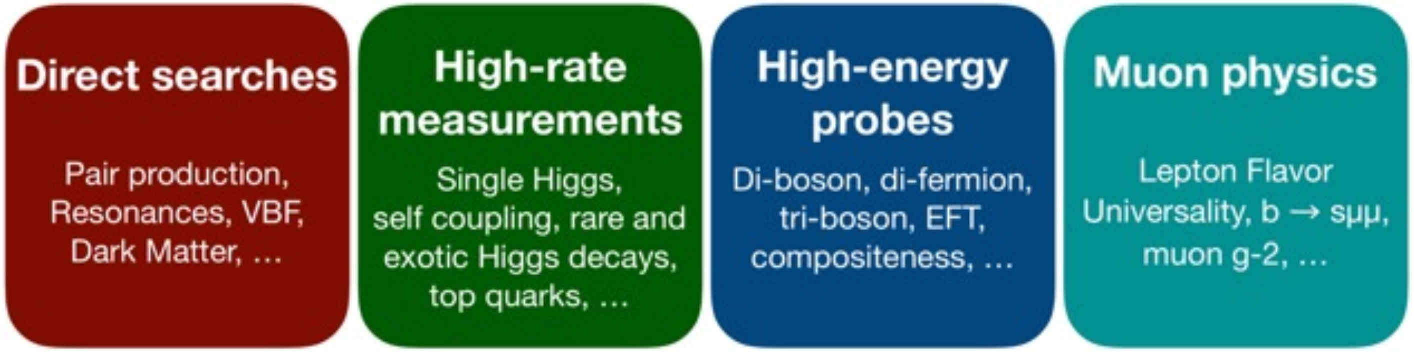
Snowmass 2021

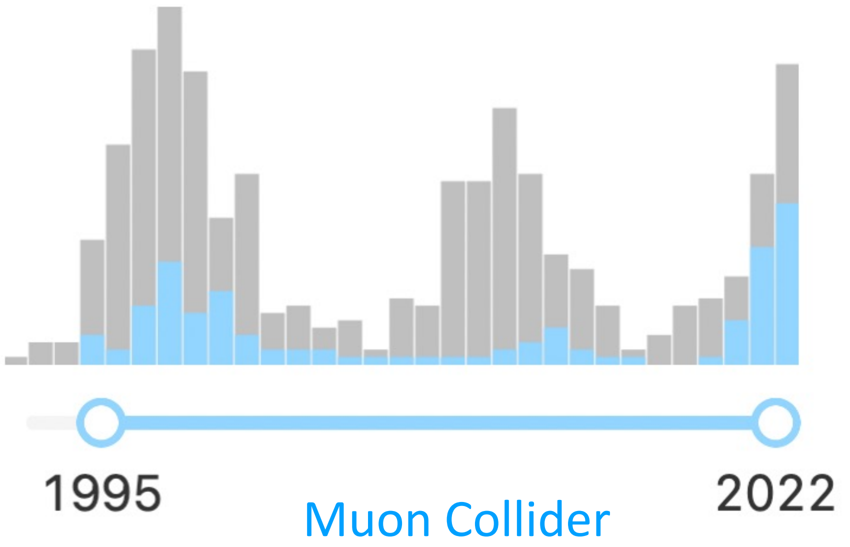
It's not a new idea! *New technologies are available……*



Advances in detector and accelerator pair with the opportunities of the physics case

A unique facility to probe unprecedented energy scales and many different directions at once!





Muon Collider Pheno Papers

EU Strategy ➔ Accelerator R&D Roadmap

3 High-priority future initiatives

***European* Strategy Update – June 19, 2020**: **High-priority future initiatives** [..]

In addition to the high field magnets the **accelerator R&D roadmap** could contain:

[..] an **international design study** for a **muon collider**, as it represents a **unique opportunity** to achieve a ***multi-TeV energy domain*** *beyond the reach of e^+e^- colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider.

The **biggest challenge** remains to produce an intense beam of cooled muons, but *novel ideas are being explored.*

CERN Laboratory Directors Group (LDG) established an Accelerator R&D roadmap

to carry out R&D and construction and operation of demonstrators

The compelling physics reach justifies establishment of an international collaboration to develop fully the muon collider design study and to pursue R&D priorities, according to an agreed upon work plan.

To facilitate implemention of the European Strategy LDG decided (July 2 2020) to:

Agree to start building the collaboration for international muon collider design study

➔International Muon Collider Collaboration kick-off virtual meeting

(>260 participants) https://indico.cern.ch/event/930508/ ***July 3rd, 2020***

International MUON Collider Collaboration

International Design Study facility

- **Focus on two energy ranges:**

3 TeV technology ready for construction in 10-20 years

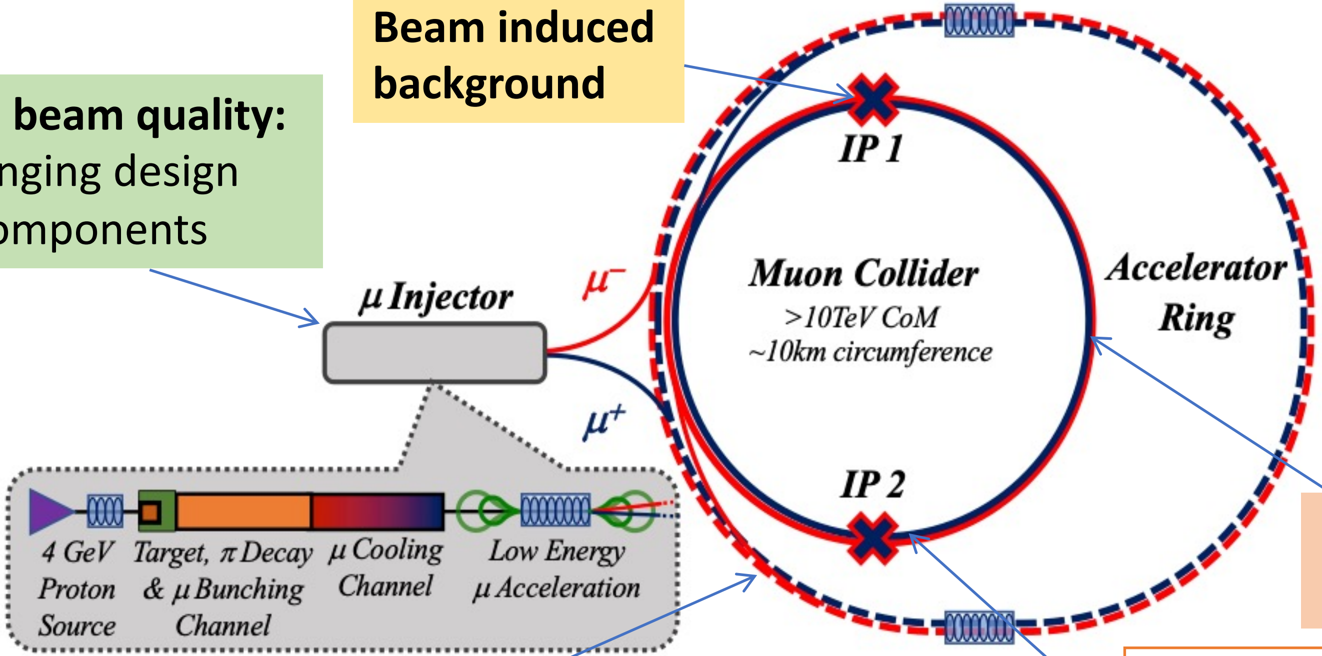
10+ TeV with more advanced technology

Proton driver production as baseline

10+ TeV completely new regime to explore!

Drives **beam quality:** challenging design and components

Beam induced background



Dense neutrino flux mitigation and site

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ \text{ab}^{-1}$

@ 3 TeV ~ 1 ab^{-1} 5 years

@ 10 TeV ~ 10 ab^{-1} 5 years

Roadmap – timescale

The panel has identified a development path that can address the major challenges and deliver a 3 TeV muon collider by the end of HL-LHC (2045)

Scenarios

Aspirational		Minimal	
[FTEy]	[kCHF]	[FTEy]	[kCHF]
445.9	11875	193	2445

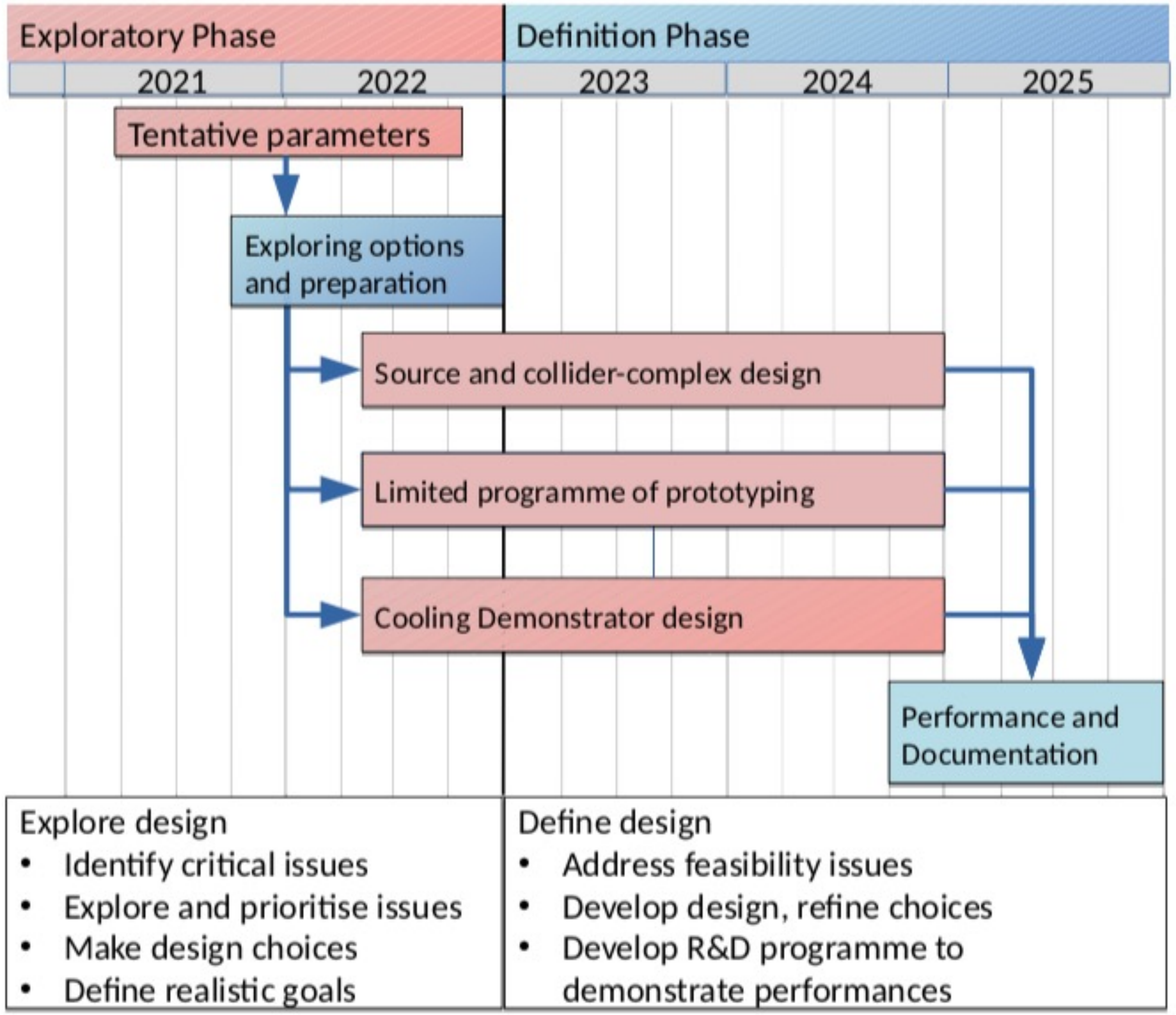
~70 Meu/5 years

[Accelerator R&D Roadmap]
[Detector R&D Roadmap]

RF

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

Plan for next 5 years



- **End-to-end design with all systems**
- **Key performance specifications**
- **Evidence to achieve luminosity goal:**

– beam parameters, collective effects, tolerances …

- **Evidence that the design is realistic:**

– performance specification supported by technology

– key hardware performances

– radiation protection, impact and mitigation of losses

– cost and power scale, site considerations

- **A path forward**

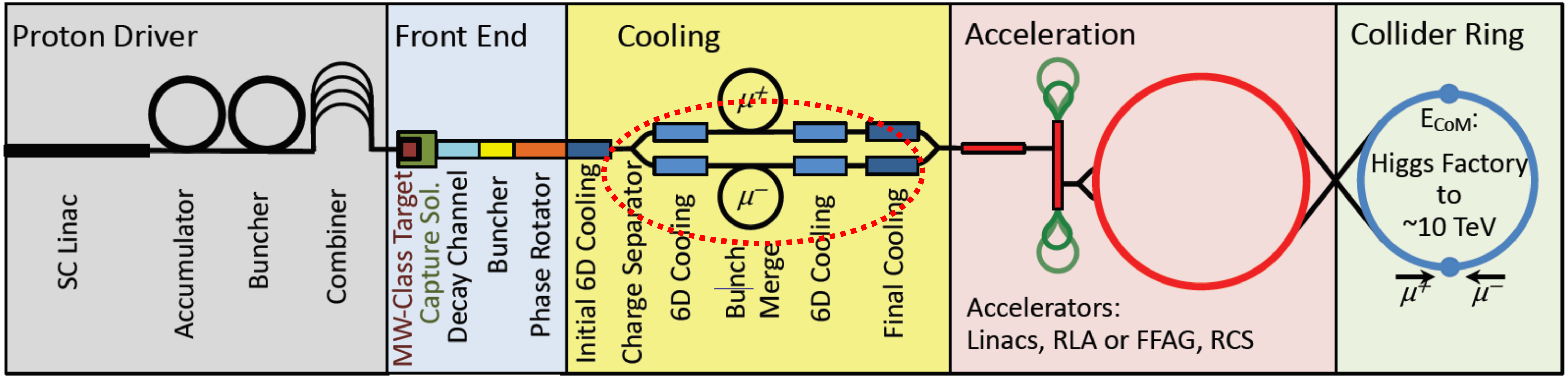
– Test facility

– Component development

– Beam tests

– System optimisation

Proton-driven Muon Collider Concept



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

MICE 4D ionization cooling experiment

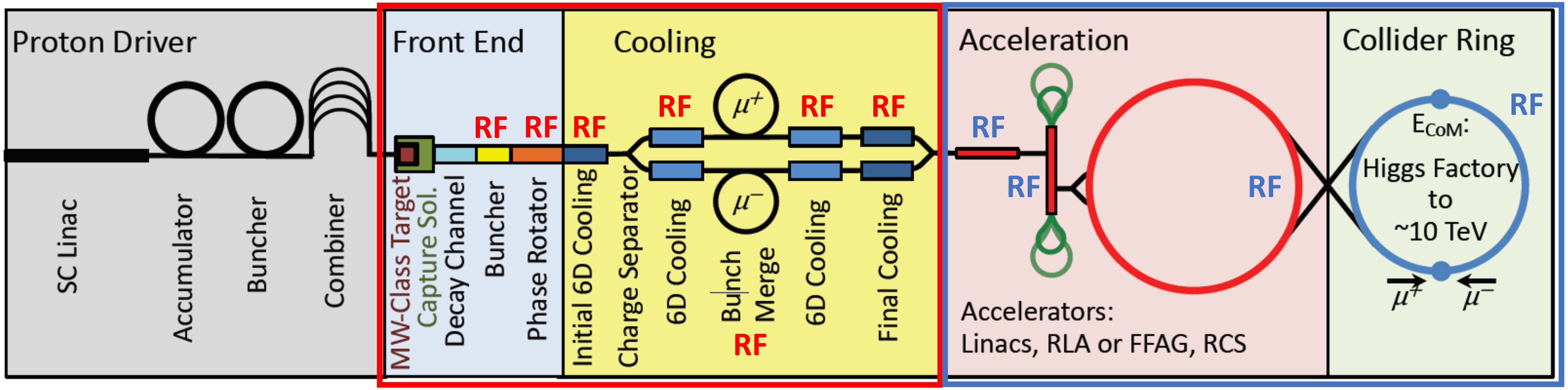
1-4 MW proton beam @ **5-20 GeV**,
compressed to **1-3 ns** bunches at a **5-10 Hz** frequency

U.S. Muon Accelerator Program (MAP)

http://map.fnal.gov/ ***MUON JINST collection***

RF system challenges

Alexej Grudiev (CERN) – Technology for future HEP facilities, July 2021



Normal conducting RF for capture and cooling

- **High-gradient cavities in high magnetic field**
- **High charge, Huge beam size, Important beam losses**
- **Peak RF power**
- **Little synergy with other projects**

6D ionizing cooling

Super conducting RF for acceleration

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- **High efficiency at high gradient**
- **Maintain beam quality**
- **Longitudinal and transverse stability**

RF system parameters

J.P. Delahaye

System			Driver			Front-End	Cooling			Acceleration			Collider	TOTAL	CLIC
Sub-system			Driver Linac H- (SPL like)		Accum &Comp	Capture& Bunching	Initial	6D (2 lines)	Final (2 lines)	Injector Linac	RLAs (2stages)	RCS (3stages)	Ring	IMC	Acceleration
Reference expert			F.Gerigk		?	D.Neuffer	C.Rogers	D.Stratakis	C.Rogers	A.Bogacz		S.Berg	E.Gianfelice		
Beam (system exit)	Energy	GeV/c	0.16	5	5	0.255	0.255	0.255	0.255	1.25	62.5	1500	1500		1500
	# bunches (μ+ or μ-)	#	40 mA		1	12	12	1	1	1	1	1	1		312
	Charge/bunch	E12			500	3.57	2.56	7.21	4.39	3.73	3.17	2.22	2.20		3.72E-03
	Rep Freq	Hz	5	5	5	5	5	5	5	5	5	5	5		50
	Norm Transv Emitt	rad-m				1.5E-02	3.0E-03	8.3E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05		660/20E-06
	Beam dimens. (H/V) in RF	mm	?	?	?	?	?	?	?	?	?	?	?		1?
	Norm Long Emitt	rad-m				4.5E-02	2.4E-02	1.8E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03		
	Pulse/Bunch length	m	2.2 ms		0.6 (2ns)	1.1E+01	1.1E+01	9.2E-02	9.2E-02	4.6E-02	2.3E-02	2.3E-02	5.0E-03		4.4E-05
	Power (μ+ and μ-)	W	6.40E+04	2.2E+06	2.0E+06	1.8E+04	1.3E+04	3.0E+03	1.8E+03	7.6E+03	3.2E+05	5.4E+06	5.3E+06		2.8E+07
RF cavities	Technology		NC Linac4	SC	SC	NC	NC	NC Vacuum	NC	SC	SC	SC	SC		NC High Grad
	Number of cavities	#	23	244	2	120	367	7182	32	52	360	2694	?	11076	149000
	RF length	m	46	237	1	30	105	1274	151	82	1364	2802	?	6092	30000
	Frf	MHz	352	704	44	326to493	325	325-650	20-325	325	650-1300	1300	800	4 to 1300	12000
	Grf	MV/m	1-3.7	19 - 25	2	20	20 to 25	19-28.5	7.2-25.5	20	25 to 38	35	?	1 to 38	100
	Aperture	mm	28	80		?	?	?	?	300	150	75	120	28 to 300	2.75
	Magnetic Field	T	0	0		2	3T	1.7-9.6	1.5-4	0	0	0	0	0 to 9.6	0
	Installed RF field	MV	169	5700	4	434	2618	30447	1836	1640	50844	98062	250	1.92E+05	3.00E+06
	Beam Energy gain	MeV	160	4840	0	0	0	0	0	1250	62500	1437000	0	1.51E+06	1.50E+06
	Recirculations	#	1	1		1	1	1	1	1	4.5 to 5	13 to 23	1000	1 to 1000	1
	RF Power/pulse (η=0.6)	MW	25	220	3.E-01	99	429	1172	43	52	360	2024	1.98E-02	4425	1.2E+07
RF power sources	Technology		klystron	klystron						Klytron-IOT					Two Beam
	Cavities/Power Source	#	23	244		4				1 to 2	1 to 2				2
	RF Pulse (fill+beam) estim.	ms	2.20	2.20	3.20	1.00E-01	1.00E-01	1.00E-01	1.00E-01	3.00E-02	5.90E-02	7.25E-01	1.48E+01		1.42E-01
	Prf/Power Source	MW	11.7	1.93						1	1				15
	Total Power Sources	#	17	244		30				52	341			?	1638
	Installed Peak RF Power	MW	34	275		164	515	1407	52	52	341	2429	2.38E-02	5269	2.46E+04
	Average RF power (η=0.6)	MW	0.27	2.13	0.01	0.05	0.21	0.59	0.02	0.01	0.11	14.88	0.00	18.28	143
	Wall plug power (η=0.6)	MW	0.45	3.55	0.01	0.08	0.36	0.98	0.04	0.01	0.18	24.81	0.00	30.46	289

1st Muon Collider Community Meeting May 2021

RF system challenges

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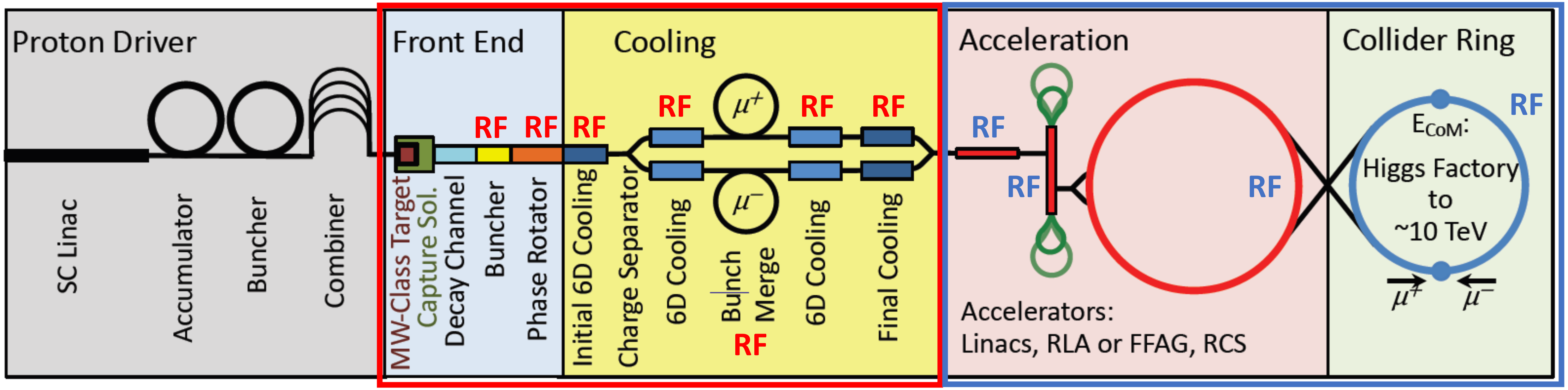

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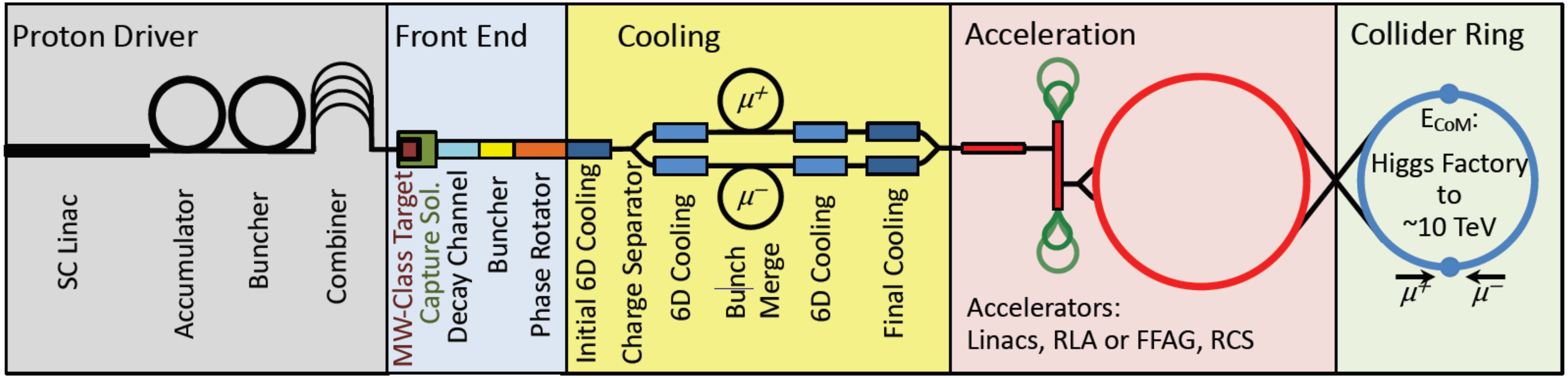
Beam time structure and RF frequency

Dario Giove (INFN-MI-LASA)



Two RF harmonics are used for low and high energy part of the linac

Single p-bunch

Many frequencies are used for bunch manipulations, Majority of cavities at two RF harmonics in 6D cooling

Two single μ+ & μ- bunches

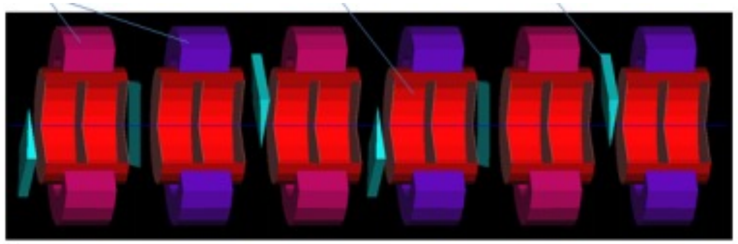
Several RF frequencies are used for low and high energy part of the accelerator complex. Not necessarily harmonics.

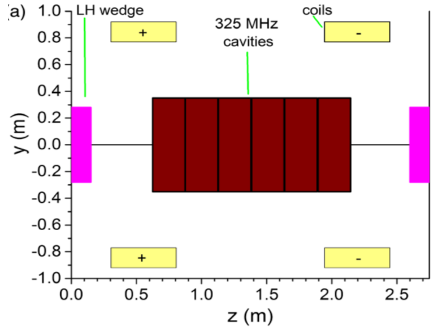
Single bunch operation does NOT require the RF frequency in proton driver linac, muon cooling and accelerator complexes be related

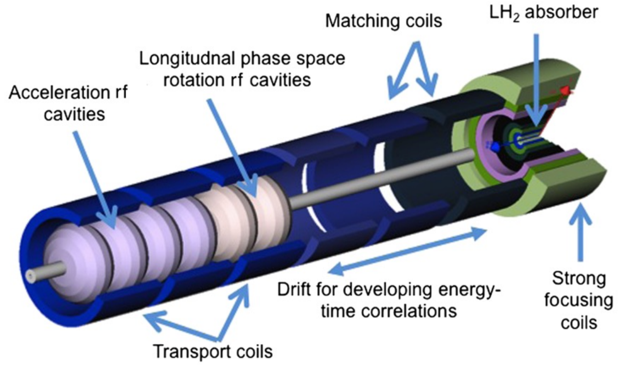
RF system for muon capture and cooling

Region	Length [m]	N of cavities	Frequencies [MHz]	Peak Gradient [MV/m]	Peak RF power [MW/cavity]
Buncher	21	54	490 - 366	0 - 15	1.3
Rotator	24	64	366 - 326	20	2.4
Initial Cooler	126	360	325	25	3.7
Cooler 1	400	1605	325, 650	22, 30	
Bunch merge	130	26	108 - 1950	~ 10	
Cooler 2	420	1746	325, 650	22, 30	
Final Cooling	140	96	325 - 20		
Total	**~1300**	**3951**			~4000 x ~3MW => **~12GW**

TBD TBD TBD



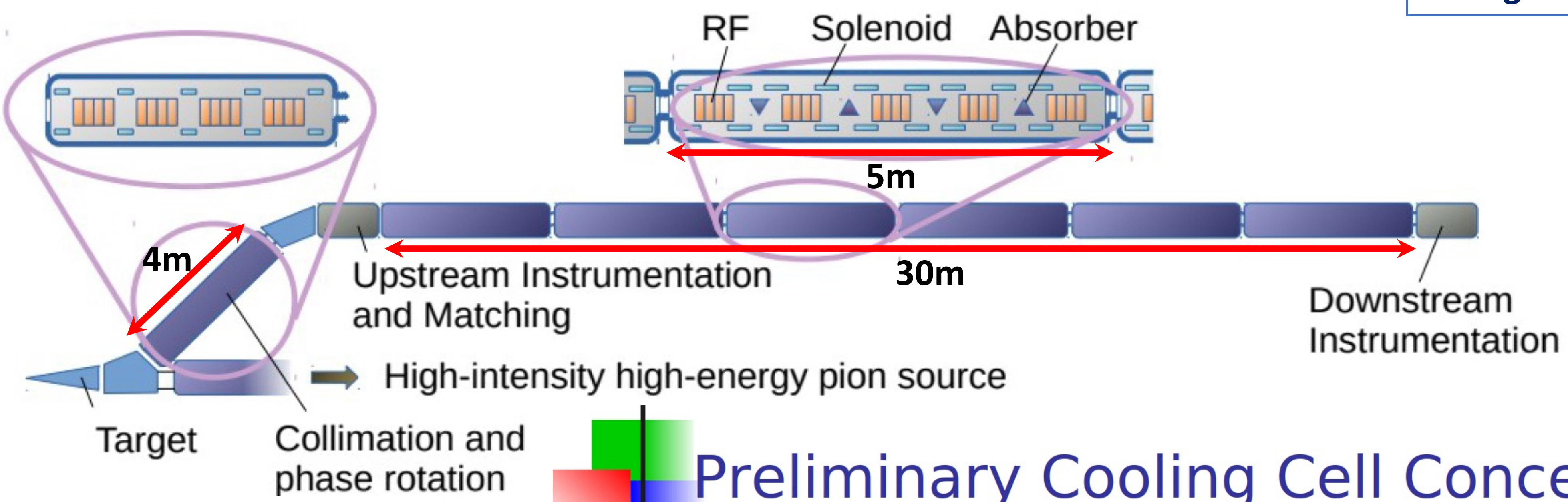


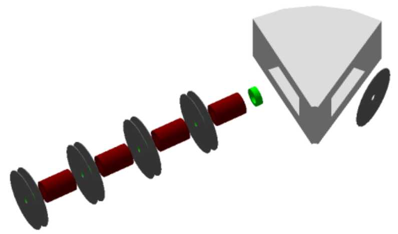


It is a very large and complex RF system with high peak power

Muon cooling demonstrator layout

C. Rogers

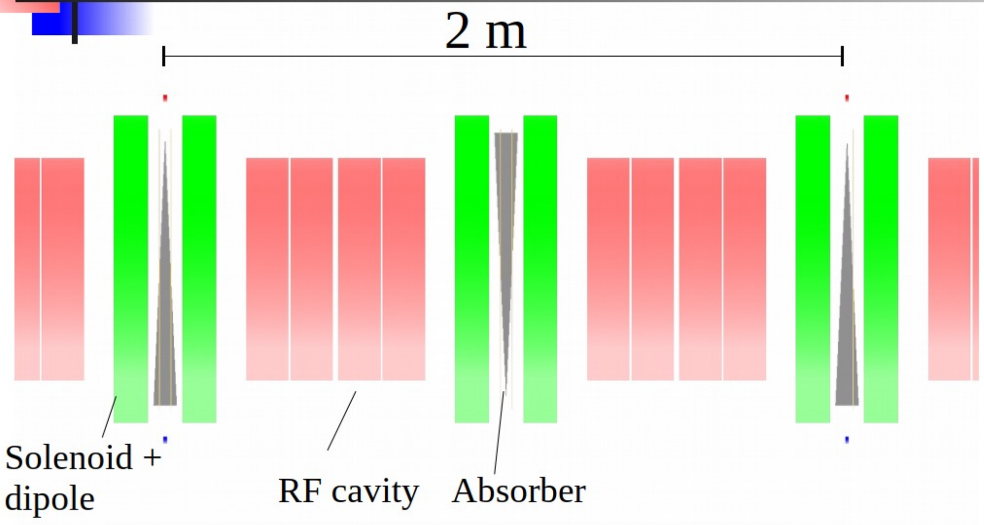




Beam Preparation System	
Parameter	**Value**
Cell length	1 m
Peak solenoid field on-axis	0.5 T
Collimator radius	0.05 m
Dipole field	0.67 T
Dipole length	1.04 m
RF real estate gradient	7.5 MV/m
RF nominal phase	0° (Bunching)
RF frequency	704 MHz

Preliminary Cooling Cell Concept

International MUON Collider Collaboration



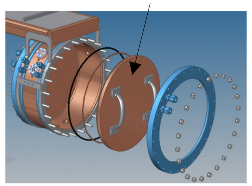
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH

RF cavities for muon cooling

Bowring et al, PRAB 23 072001, 2020

Material	*B*-field (T)	*E*-field (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	$> 49.8 \pm 2.5$

Changeable Cu/Be walls

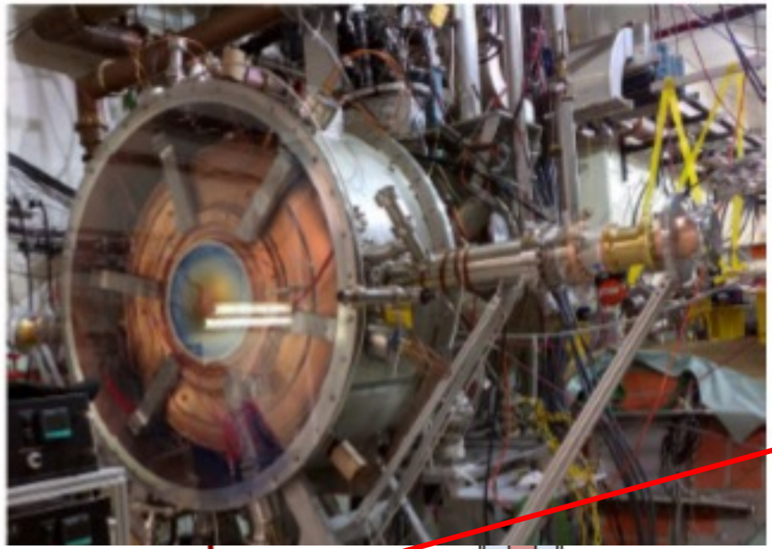


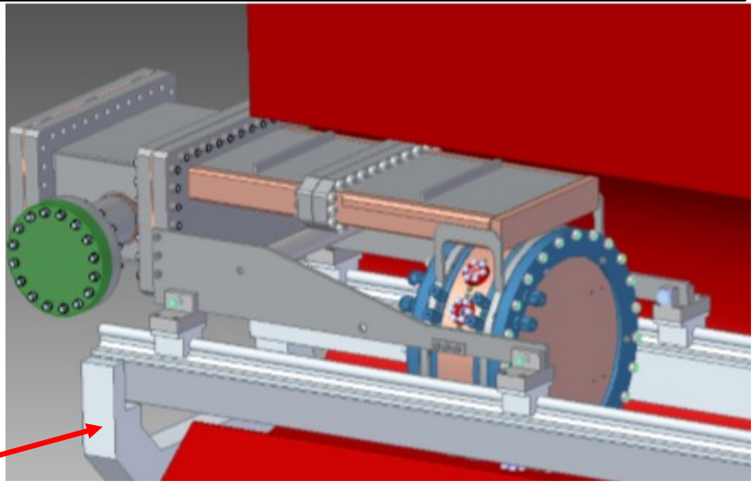
Challenges:

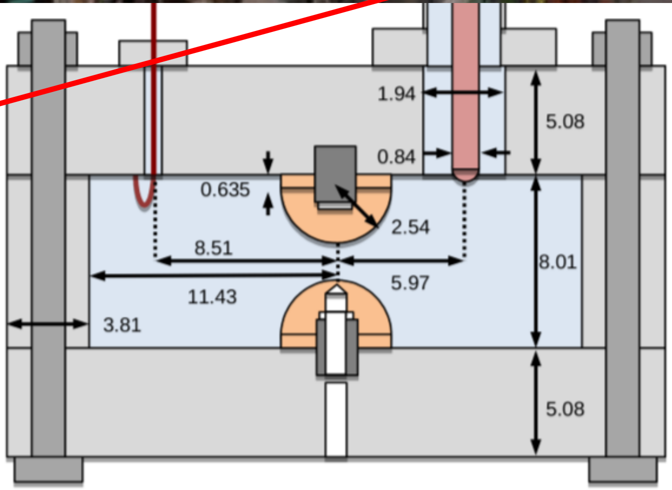
- High Gradient
- High magnetic field
- High radiation
- Technology far from been common

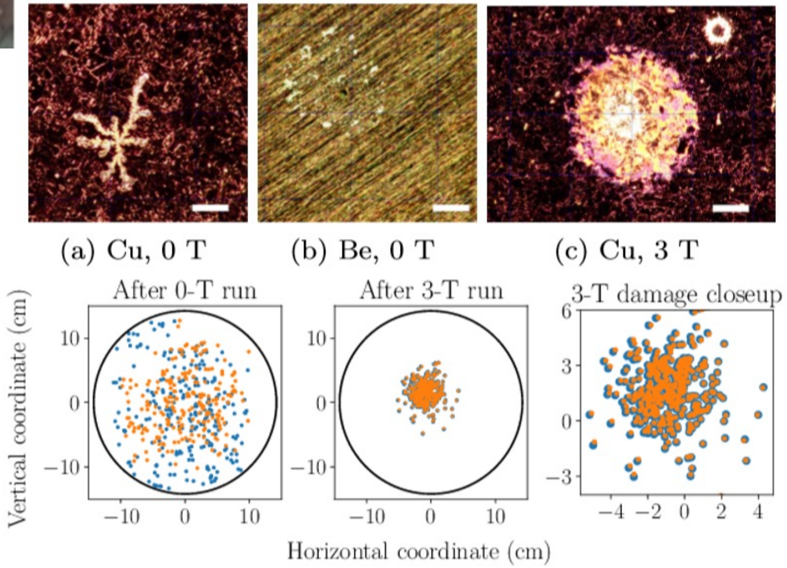
State of the art (not complete):

- MICE 200 MHz RF module prototype: 4T, 10 MV/m, 1ms@1Hz
- 800 MHz **beryllium** cavity @ FNAL: 3T, **50 MV/m**, 30us@10Hz
- **Gas** filled RF cavity: Small gap, 800 MHz, >50 MV/m









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

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:

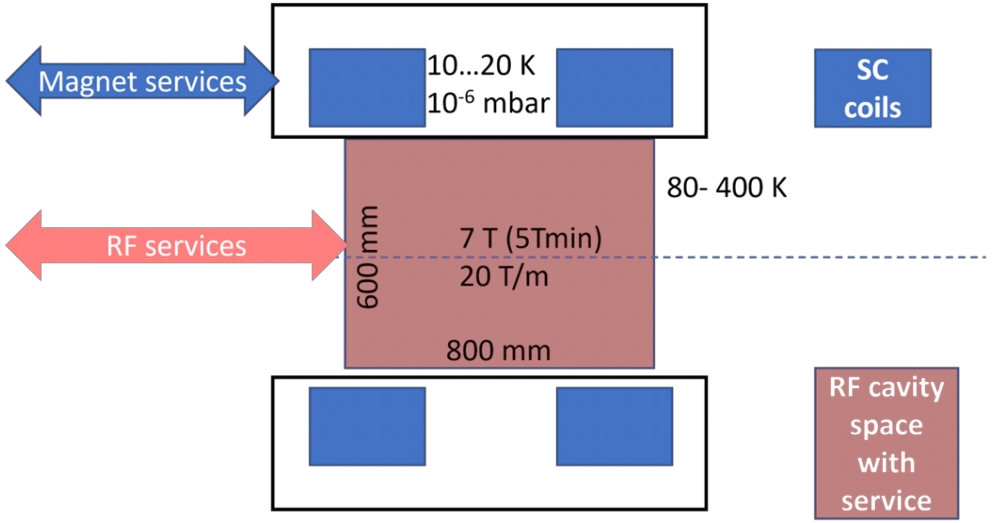
CPI: VKP-8352A/B: 352MHz, 2.8MW, 100kW

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

General layout of the RFMF test station

L. Rossi et al.

Schematic of the RFMF test facility single cryostat



Preliminary design aimed at fitting a cavity of the size up to a 700 MHz system

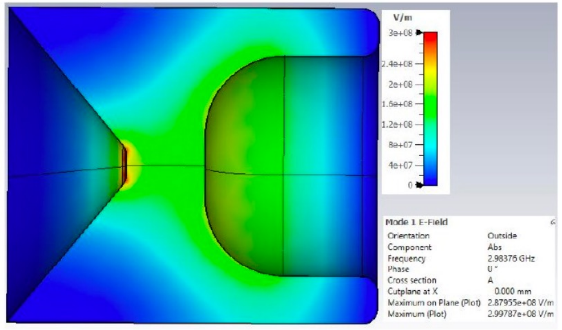
- Minimum bore of the split coil

600 RT free bore for RF

700 mm minimum SC coil diameter

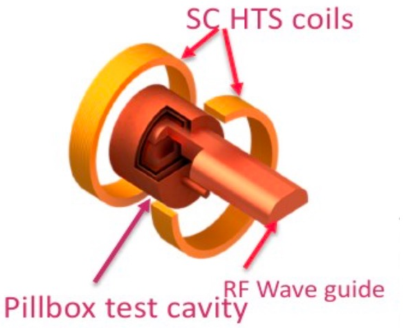
Planning for a test facility before the demonstrator

- Studying options to test RF cavities in B-field
  - Possibility at Daresbury lab, INFN LASA, CEA Saclay, CERN
  - 3 GHz tests likely possible
- No resource to test RF at design frequency
  - Large bore solenoid with appropriate RF equipment does not exist
  - Significant cost to bring RF source

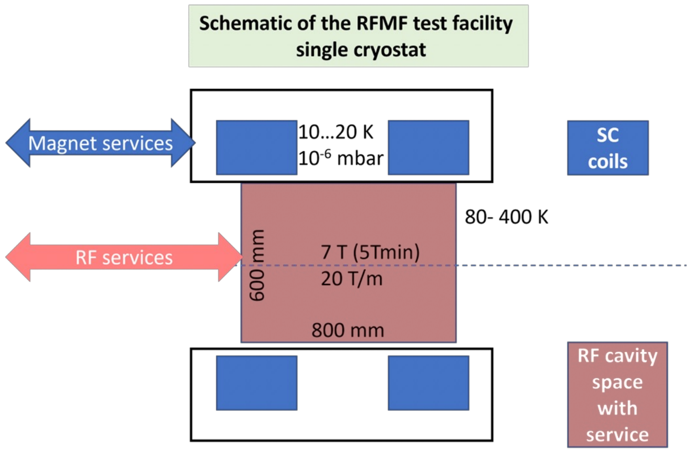


C. Rogers, L.Rossi, D. Giove et al.

Bare coils and RF cavity



General layout of the RFMF test station



LOOKING FOR SYNERGIES ON TECHNOLOGIES AND PHYSICS

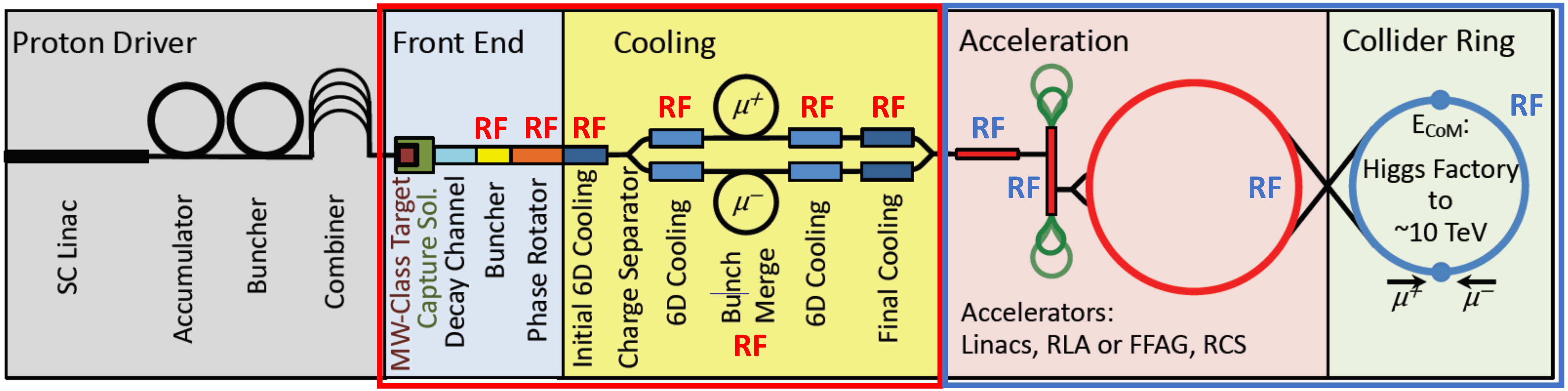
Preliminary design aimed at fitting a cavity of the size up to a 700 MHz system

R&D directions and test facility towards feasibility demonstration of muon cooling

- **Stage 1: High gradient RF test facility**
  - Frequency: 200 - 800 MHz
  - Magnetic field: 0 - 5T, different field configurations
  - Different materials: Cu, Be, Al, …
  - Different temperatures: **Cryogenic NC**, HTS RF, …
  - Different gases and pressure: 0 – few Bars
  - Different designs
- **Stage 2: Prototype(s) for cooling test facility**
  - Design of realistic cavity prototypes: frequency, beam aperture, integration
  - Parameters defined based on the results of Stage 1 and the (re-)design of the muon cooling complex (higher gradient,…)
  - May include irradiation capability to check its impact on the performance
- **Stage 3: Muon cooling demonstrator**

RF system challenges

Alexej Grudiev (CERN) – Technology for future HEP facilities, July 2021



Normal conducting RF for capture and cooling

- **High-gradient cavities in high magnetic field**
- **High charge, Huge beam size, Important beam losses**
- **Peak RF power**
- **Little synergy with other projects**

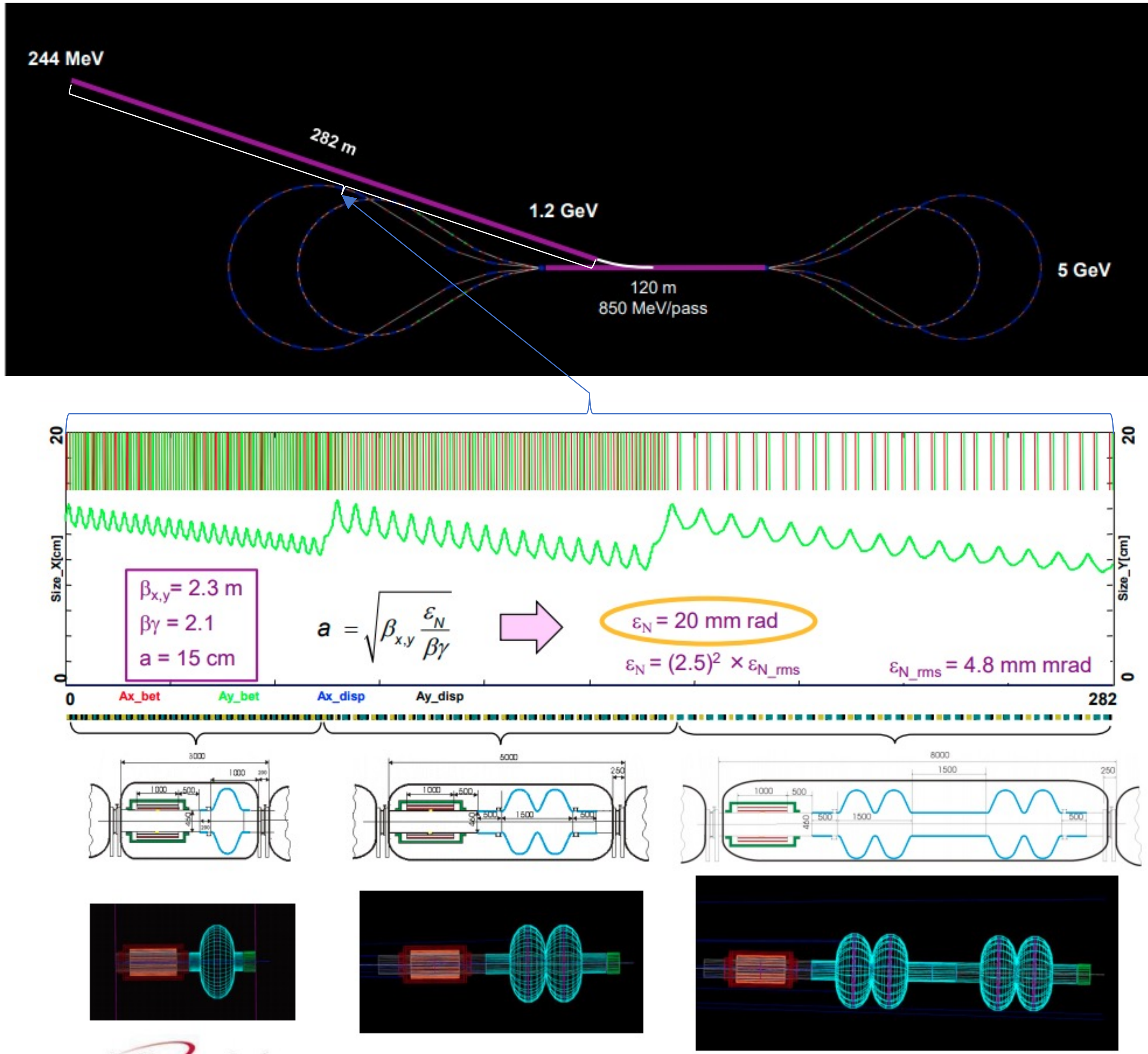
6D ionizing cooling

Super conducting RF for acceleration

- **High charge, short bunch, low current**
- **High efficiency at high gradient**
- **Maintain beam quality**
- **Longitudinal and transverse stability**

Initial acceleration

- Limited muon lifetime requires highest possible accelerating gradient to reach higher energies
- Large emittance require large acceptance
  - Additional voltage
  - Low frequency
  - Large aperture
- Very large bunch charge: ~5x10^{12} causes collective effects which must be addressed
- Transmission and decay beam losses
- Strong focusing magnets with large apertures
  - Stray magnetic fields
  - Low filling factor
  - Cryogenic NC RF might help in the linac



Accelerators and collider

- Super conducting RF (SRF) system for high efficiency and highest possible acceleration rate to minimize the muon decay losses on the way to very high energies: ~10TeV is required
- **Challenges**:
  - **Large bunch charge in the linacs:** 3.6E12 μ => **576nC**
  - **Large bunch charge in the rings:** 2.2E12 μ => **352nC**
  - **Short bunch length in the collider: 1.5 mm**
  - **Highest possible gradient**
  - **Power efficiency**
  - **High energy gain per turn in the rings**
  - **High level of radiation**
  - **Stray magnetic field**
- …

High energy acceleration: Rings

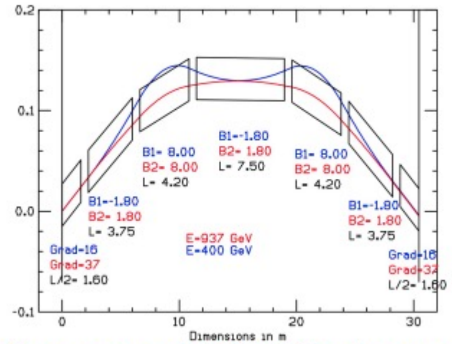
- **Limited muon lifetime requires highest possible acceleration rate**
- Although the rate is defined by the magnet ramping rate, **the SRF must follow**
- Small number of turns (~100) for very high collision energy ~10 TeV requires very high voltage: ~100 GV
- **It operates in quasi pulsed mode:**
  - RF is on only during acceleration (~ 10 ms)
  - Transients
- Longitudinal bunch compression/manipulation require additional voltage
- **High gradient for 'compact' RF system**
- **Very large bunch charge**: ~4x10^{12} cause collective effects which must be mitigated
- Transmission and decay beam losses
- Power efficiency

An example of parameters for CERN site implementation

Muon Acceleration to 4 TeV in the LEP Tunnel

- **LEP Tunnel. Neuffer, Shiltsev, JINST 13 (2018) T10003**
  Interleave 16T (13%) and ramping ∓1.9T (87%) dipoles

Tunnel	Circ. m	B(max) T	Pack Frac	RF GV	orbits	freq. Hz	muon surv	E_{final} TeV
ISR	942	1.8	0.78	1	48	1260	0.81	0.063
SpS	6900	1.8	0.76	15	26	360	0.85	0.45
LEP	26 700	3.7	0.85	50	71	70	0.83	4



Interleaved ramping/fixed superconducting dipole example. arXiv:0707.0302
Lucien Cremaldi is running Bob Palmer's 2007 path length Basic code
Must adjust muon orbital radius to stay in phase with the SRF

Monday, 5 October 2020
Muon Collider Meeting

CERN (page 11)

Don Summers
U. of Mississippi–Oxford

Collider ring

- **Limited muon lifetime requires smallest possible circumference to maximize the number of turns before muons decay**
- Although the circumference is defined mainly by the magnets bending radius, the SRF must follow
- **High gradient for 'compact' RF system**
- Main function of RF is to maintain short bunch length for high luminosity and compensate small SR energy loss
- Very large bunch charge: 2×10^{12} and short bunch length: 1 mm cause strong **collective effects** which must be mitigated
  - Aperture restriction
  - HOM power
- Transmission and decay beam losses

Tentative Target Parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV	FCC-ee
L	10^{34} cm^{-2}s^{-1}	1.8	20	40	
N	10^{12}	2	2	2	0.2
f_r	Hz	6	4	4	
P_{beam}	MW	5.8	12.8	17.9	
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	2.4
β	mm	5	1.5	1.07	
ε	µm	25	25	25	
$\sigma_{x,y}$	µm	3.0	0.9	0.63	

Scaled from MAP parameters

Emittance is constant $\sigma_E \sigma_z = \text{const}$

Collider ring acceptance is constant $\frac{\sigma_E}{E} = \text{const}$

Bunch length decreases $\sigma_z \propto \frac{1}{\gamma}$

Betafunction decreases

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

D. Schulte   Muon Colliders, CERN, July 3, 2020   6

Single bunch beam loading (energy spread):
Energy spread ~ Loss factor x Bunch charge

R&D directions for SRF for muon acceleration

- **Highest possible gradient**
  - Pulsed operation of ~1ms (linac) -> ~10ms (RCS) may help
- Resilience to beam losses and (stray) magnetic field
- Design of the cavity considering
  - High gradient
  - High efficiency
  - Longitudinal and transverse beam dynamic requirements
- …

Critical issues and R&D topics on SRF

- **High gradient at low frequency multi cell cavities**: 325, 650 MHz
- **Technology** choice: Bulk vs Coating; Different materials: Nb, Nb3Sn, HTS, …
- Cavity **type(shape)** for high gradient and low loss factor cavity design studies
- **Pulsed operation**. **Lorenz force** detuning in pulsed (strong transient) mode
- **RF power sources**: pulsed, high peak power, **high efficiency**
- Tolerance to external (stray) **magnetic** field
- Tolerance to the radiation and beam loss
- Power couplers (4 MW per MC, far from state-of-the-art)

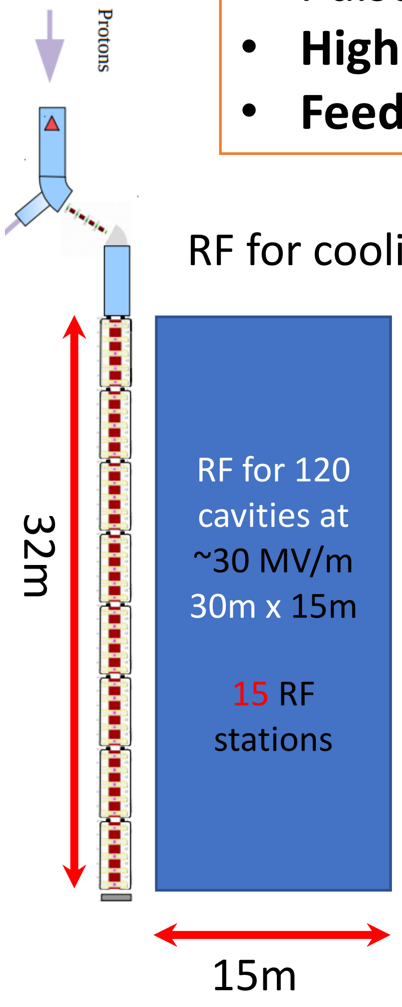
Synergy with other projects

Muon cooling demonstrator power studies

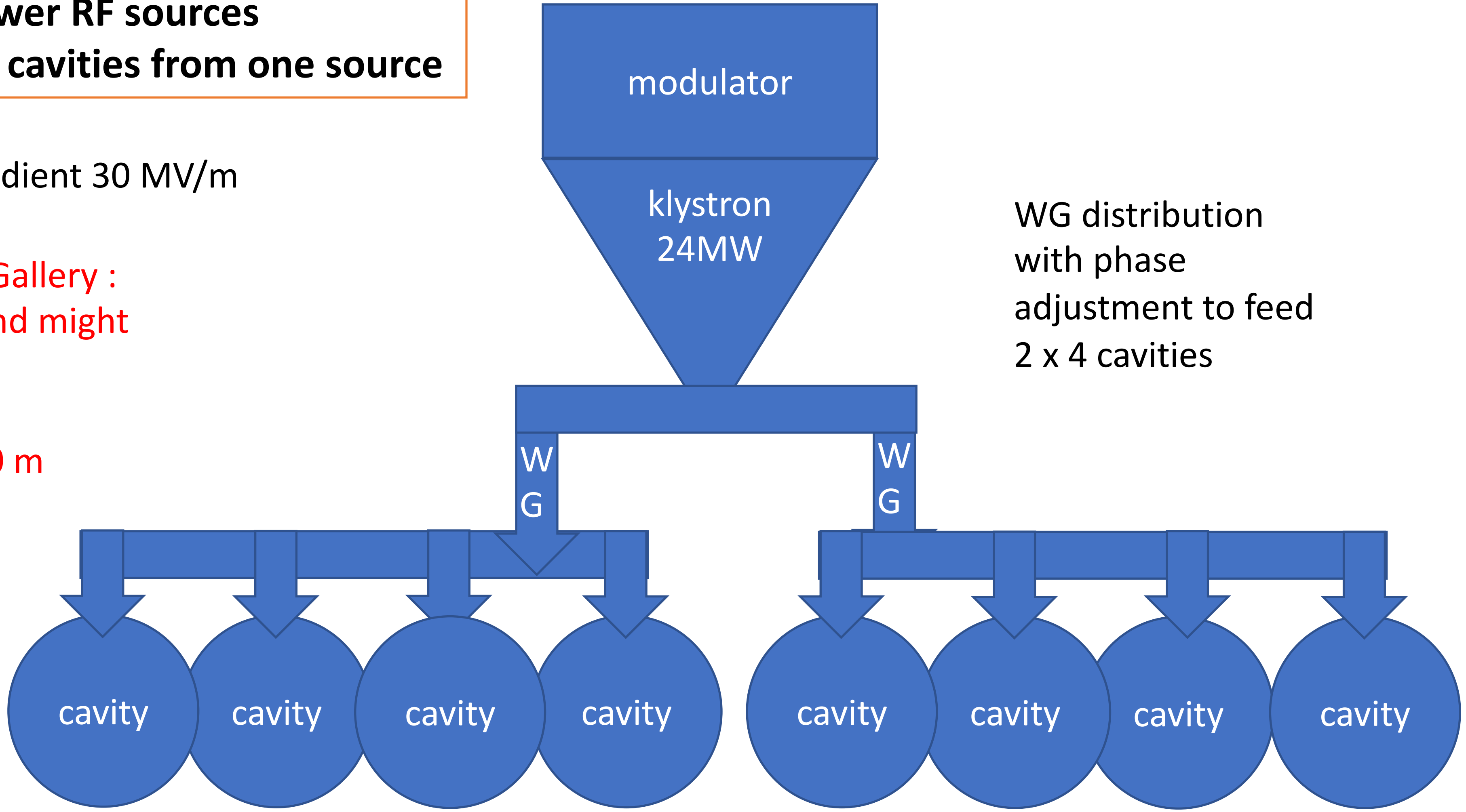
High peak power klystron: 24 MW

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

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%

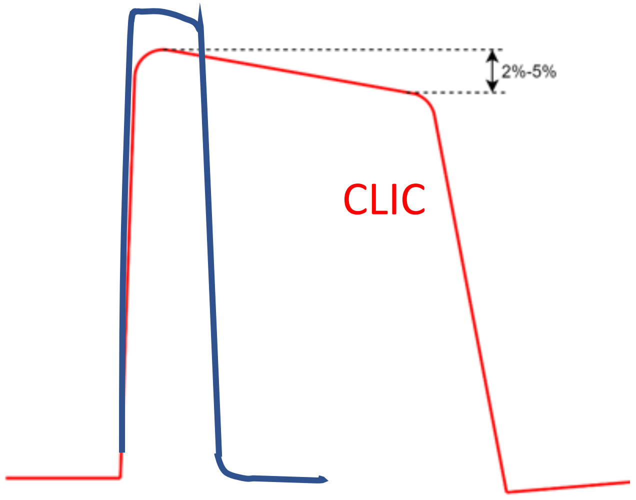
Frequency: **1.3 GHz**
Peak RF power: 10 MW
Efficiency: 65%

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 spare
- 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

  (A capacitor bank and power electronics:) 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 stability	2-5%	NA
Rise/fall-time	3-5 µs	>5 µs
Max rep rate	50 Hz	5 Hz

- 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.

Motivations and step forward – personal view

- A lot of challenges and opportunity:
  - the cooling system: cell, module and demonstrator are the challenges
  - one or more dedicated RF and integration cell test facility are mandatory
  - a full demonstrator design crucial to be ready to start construction at next ESPPU GO!

- Muon beams manipulation set unique working conditions

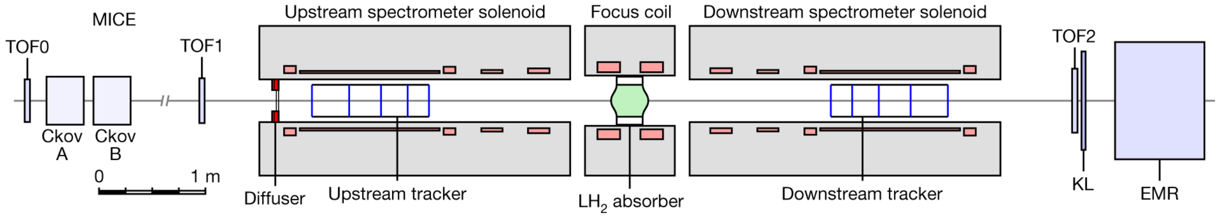
- High efficiency RF amplifiers will profit from synergy developments

- Several challenges to explore new ideas, training youngest and engage with industries

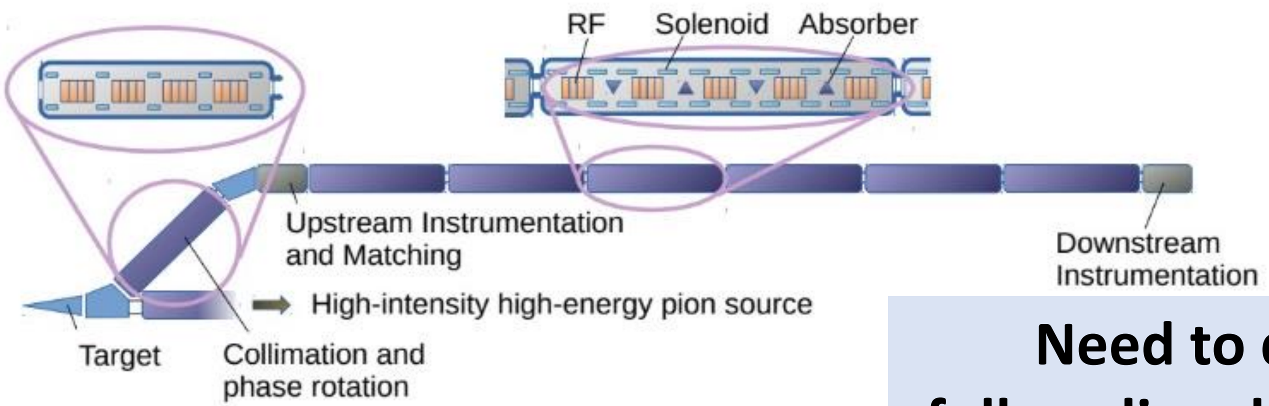
Thanks for the opportunity and the attention!

extras

Proposed cooling demonstrator vs MICE



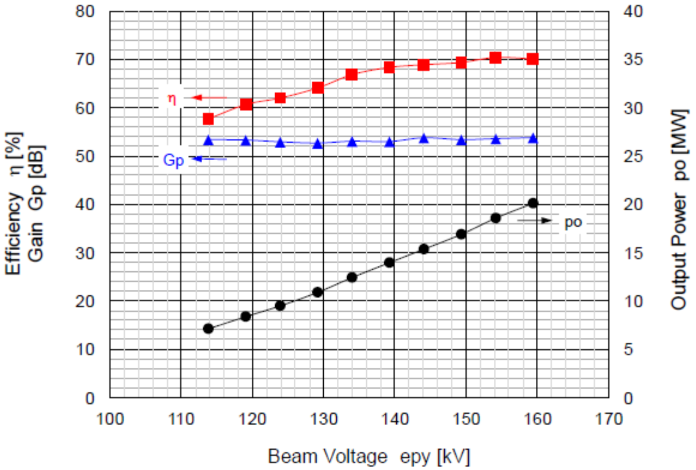
IMPORTANT to deliver a realistic end-to-end 6D design



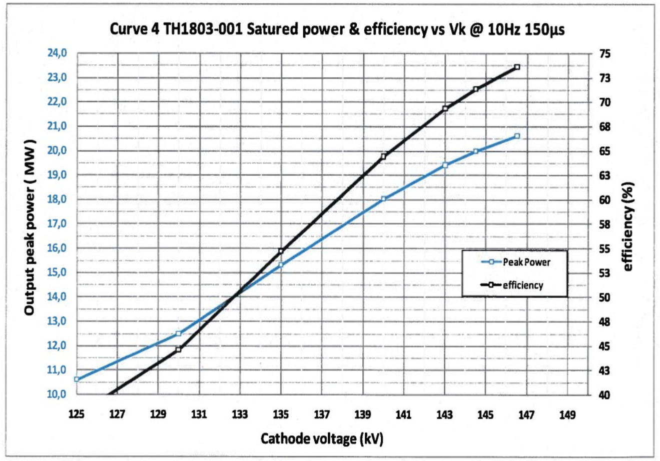
Need to develop full cooling demonstrator

	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style

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 $\mu AxV^{-3/2}$/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 $\mu AxV^{-3/2}$/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.

International MUON Collider Collaboration


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

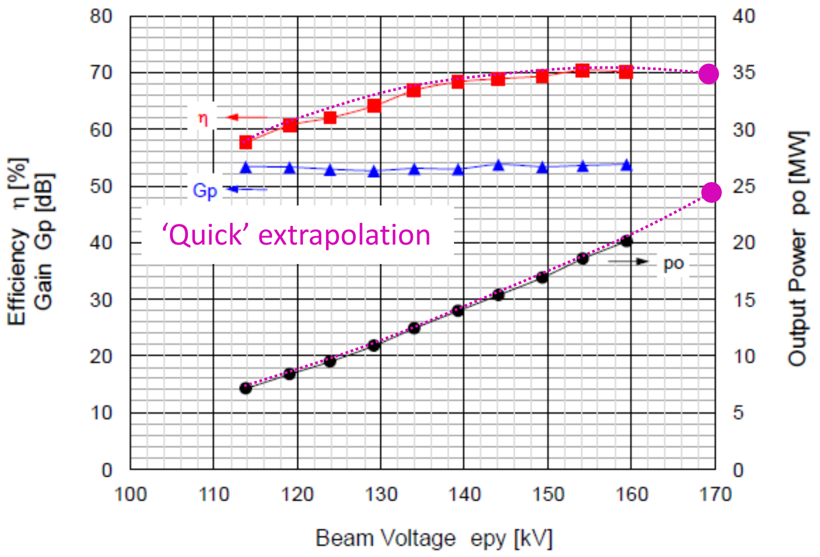
→

Mu-tube, 0.7 GHz
6 beams MBK

Canon E37503		Mu-tube, 0.7 GHz	
F=	999,5 MHz	F=	700 MHz
P max=	20.2 MW	P max=	24 MW
T =	150 µsec	T =	30 µsec
V=	159.4 kV	V=	171 kV
I total =	180 A	I total =	200 A
Eff.=	70.5 %	Eff.=	70.0 %
uP=	0.47 µAxV$^{-3/2}$/beam	uP=	0.47 µAxV$^{-3/2}$/beam
Gain =	53.9 dB	Gain =	53.9 dB
$P_{average}$ (50Hz)=	150kW	$P_{average}$ (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.).