MuCol WP6:

RF considerations for a high energy muon collider

(CEA, INFN, UROS, Uni. Lancaster,
CERN, Uni. Strathclyde)

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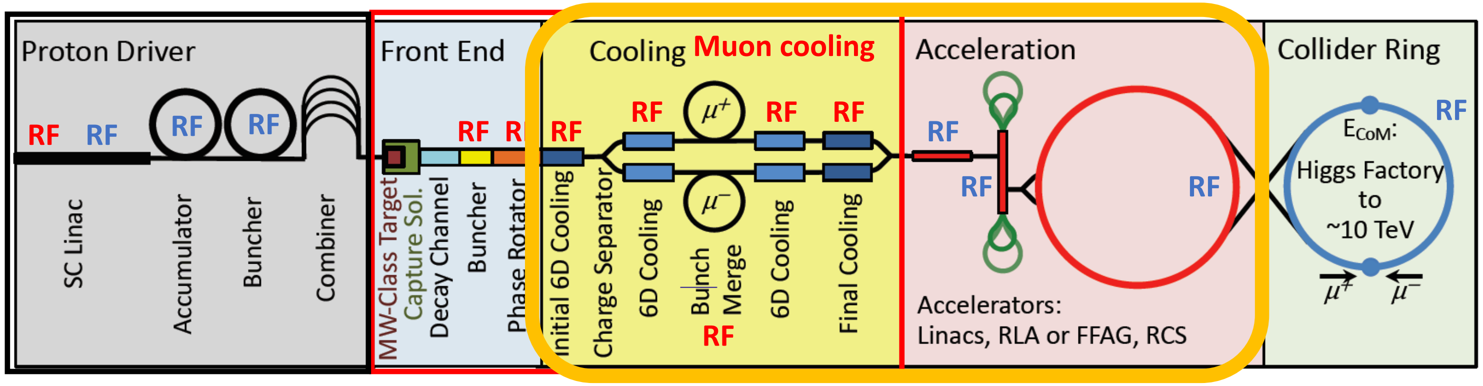

- **WP6 objectives:**

The objective of this work package is to assess crucial feasibility issues and technological challenges of the RF systems. The study will concentrate on the two most challenging sections, the Muon Cooling Complex (MCC), and the muon acceleration stage of the High Energy Complex (HEC), for which a baseline concept of most critical RF components will be outlined based on inputs from WP4, WP5 and WP8 (cavities and RF sources).

- **WP6 tasks and connection to LDG R&D challenges:**

- Task 6.2: Baseline concept of the RF system for acceleration to the High Energy Complex -> LDG 3.5.1 SRF
- Task 6.3: Baseline concept of the RF system for the Muon Cooling Complex -> LDG 3.5.2 NC RF
- Task 6.4: Break down mitigation studies for cavities of the muon cooling cells -> LDG 3.5.2 NC RF
- Task 6.5: Baseline concept of high efficiency and high-power RF sources for the muon collider
  -> LDG 3.5.3, 8.2 Sustainability-Energy efficient technologies-Efficient RF sources

Task 6.2: Concept of RF systems for acceleration to HEC (RCS's)

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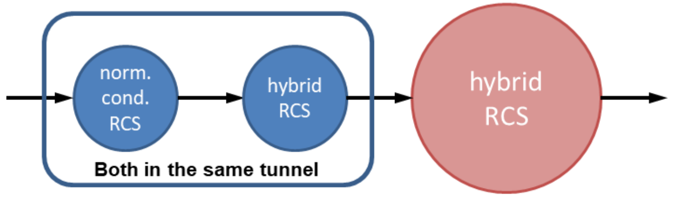
- **Chain of rapid cycling synchrotrons, counter-rotating μ^+/μ^- beams**

  $\rightarrow$ 63 GeV $\rightarrow$ 0.3 TeV $\rightarrow$ 0.75 TeV $\rightarrow$ 1.5 TeV



$\rightarrow$ Fast acceleration to increase muon survival rate

- **Acceleration time only in ms range or less (few 10s of turns)**
- **Repetition rate ~15 Hz, one pulse every ~67 ms**

Example RF parameters of RCS chain

		Unit	RCS-LE	RCS-ME	RCS-HE
Injection energy	E_{inj}	[TeV]	0.063	0.3	0.75
Ejection energy	E_{inj}	[TeV]	0.3	0.75	1.5
Circumference	$2\pi R$	[km]	**6**	**6**	10.7
Stable phase	ϕ_s	[°]	45	45	45
RF voltage per turn	V_{RF}	[GV]	**20.1**	**11.8**	**16.0**
Gradient in straight section	$\Delta E/l$	[MV/m]	11.2	6.6	5.0
Phase slip factor	η		0.0024	0.0024	0.0024
RF frequency	f_{RF}	[GHz]	**1.3**	**1.3**	**1.3**

F. Batsch, MC RF WG meeting #7, Jan 1, 2022

- **Task objectives**:
  - by iterating with BD (WP5), determine a full set of parameters for all cavities addressing longitudinal beam dynamics and stability… (f, R/Q, Vmax, Q_L,…)
  - provide a conceptual design of cavities (eg RCS-HE)
- **Challenges**:
  - Short muon lifetime -> huge RF voltages = need for high gradients (SRF cavities, eg XFEL like)
  - Optimize distribution of RF cavities along the cyclotron circumference
  - High intensity of muon bunches -> strong beam loading & wake field effects

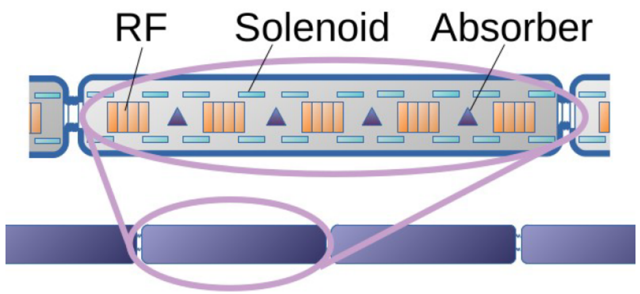
Task 6.3: Concept of RF systems for the muon cooling complex

- Normal conducting cavities
- $f \sim 325\ MHz, 650\ MHz$
- Short RF pulses (~μs)
- High gradients (~30 MV/m)
- High magnetic field (up to13 T)

Region	Length [m]	N of cavities	Frequencies [MHz]	Peak Gradient [MV/m]	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**	**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**			**~12GW**

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

- **Task objectives**:
  - by iterating with BD (WP4), determine a full set of parameters for all cavities
  - provide a conceptual design of cavities
- **Challenges**:
  - High beam loading
  - Breakdown needs to be mitigated (task 6.4)



Task 6.4: Break-down mitigation studies for muon cooling cell cavities

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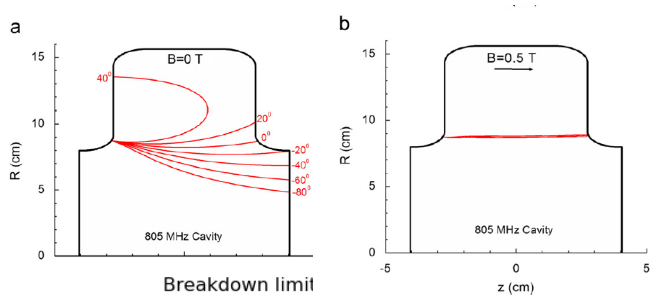
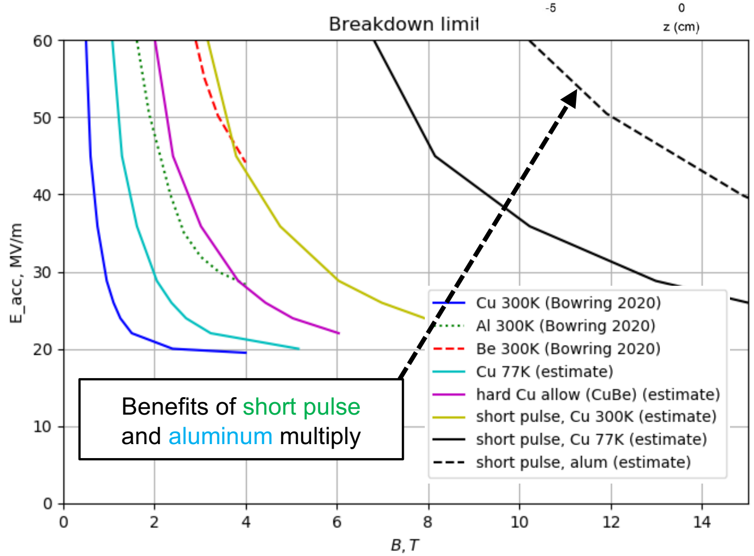




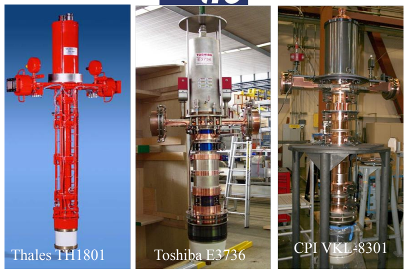
Model developed by US labs, checked against measurements in high B. Papers: Palmer et.al PRAB 2009, Stratakis et.al NIMPR 2010, Bowring et.al PRAB 2020

- **Task objectives**:
  - find best cavities & RF properties to minimize breakdown due to HG in high magnetic field (material type, gas filled, temperature, pulse length, …)
- **Methodology:**
  - 1/scaling using no-diffusion beamlet model (done)
  - 2/develop semi-analytical model based on simulations of the electron beam in the cavity (like done in US beamlet approach)
  - 3/adjust coefficients of semi-analytical model on existing and maybe new experimental data (UK) (MICE 200 MHz Be, MUCOOL 800 MHz Be, …)
  - 4/test new ideas (cavity length, couplers,..)

Task 6.5: Concept of high efficiency and high power RF sources

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%

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

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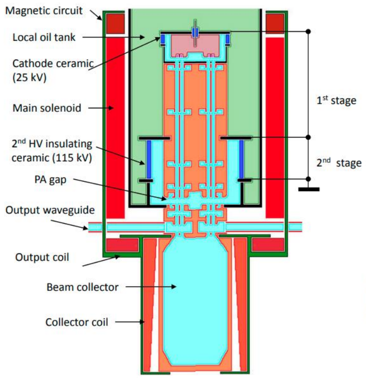
Scaling Procedures and Post-Optimization for the Design of High-Efficiency Klystrons

Jinchi Cai, Igor Syratchev, and Zening Liu

Canon E37503 6 beams MBK ⇨ **Mu-tube, 0.7 GHz 6 beams MBK**

	Canon E37503, 6 beams MBK	Mu-tube, 0.7 GHz, 6 beams MBK
F=	999,5 MHz	700 MHz
P max=	20.2 MW	24 MW
T =	150 µsec	30 µsec
V=	159.4 kV	171 kV
I total =	180 A	200 A
Eff.=	70.5 %	70.0 %
uP=	0.47 µAxV$^{-3/2}$/beam	0.47 µAxV$^{-3/2}$/beam
Gain =	53.9 dB	53.9 dB
$P_{average}$	(50Hz)= 150kW	(5Hz) = 3.6kW



- **Task objectives**:
  - collect requirements for all RF power sources of the muon collider (f, peak power, efficiency) and identify the most challenging ones (wrt to commercially available RF sources)
  - provide a conceptual design for those, in particular for the muon cooling section that may be used for the muon cooling demonstrator, with emphasis on high efficiency to ensure sustainability

Methodology:
- build upon experience acquired in the HEIKA collaboration on CLIC, combining novel designs
- possibly scale over the range of frequencies

Table 3.1b

Work package number	6	**Lead beneficiary**				CEA	
Work package title	RF considerations for a high energy muon collider						
Participant number							
Short name of participant	CEA	Uni. Lancaster	UROS	INFN			
Person months per participant:	24	36	12	36			
Start month	1			**End month**	48		

Table 3.1c : List of Deliverables

Deliverable (number)	Deliverable name	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date (in months)
6.1	Report on RF for MCC and HEC (tasks 6.2,6.3,6.4)	6	CEA, INFN	R	Public	48
6.2	Report on design of high power and high efficiency RF power sources (task 6.5)	6	Uni. Lancaster	R	Public?	42

Table 3.1d: List of Milestones

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification
6.1	Preliminary report on breakdown mitigation for cavities for muon cooling cells	6.4	24	Report approved by StCom
6.2	Preliminary report on RF acceleration for rapid cycling cyclotrons of HEC	6 .2	36	Report approved by StCom
6.3	Preliminary set of parameters for cavities for muon cooling complex	6 .3	36	Report approved by StCom
6.4	Preliminary assessment of specifications for RF power sources for muon collider	6.5	24	Report approved by StCom

Table 3.1e: Critical risks for implementation

Description of risk (indicate level of (i) likelihood, and (ii) severity: Low/Medium/High)	Work package(s) involved	Proposed risk-mitigation measures

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Thank you
for attention