MC RF WG Sammary

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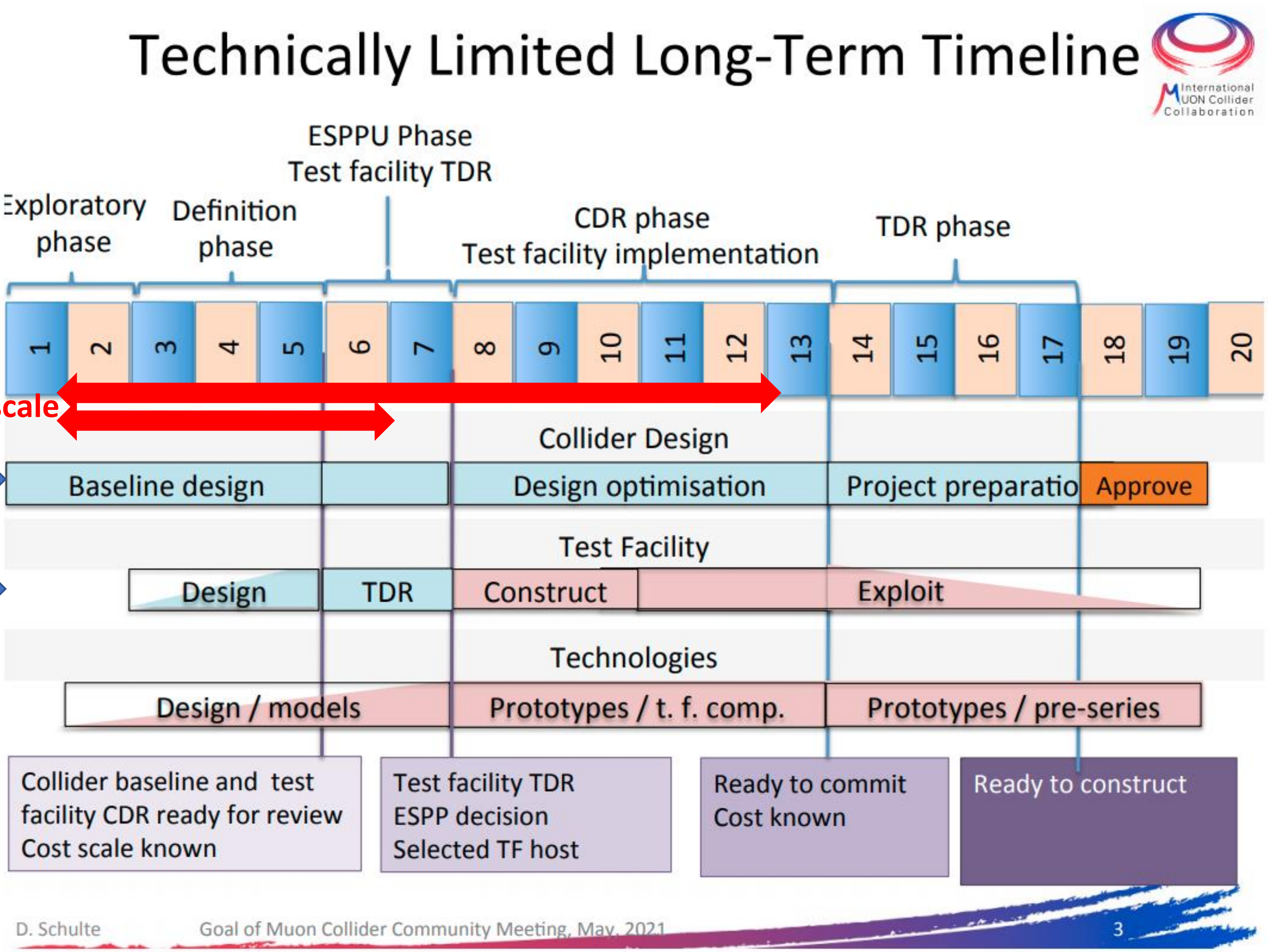
21/05/2021

1st Muon Community Meeting

Input from Daniel



Technically Limited Long-Term Timeline

International MUON Collider Collaboration

Exploratory phase

Definition phase

ESPPU Phase
Test facility TDR

CDR phase
Test facility implementation

TDR phase

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Collider Design

Baseline design | Design optimisation | Project preparatio | Approve

Test Facility

Design | TDR | Construct | Exploit

Technologies

Design / models | Prototypes / t. f. comp. | Prototypes / pre-series

Collider baseline and test facility CDR ready for review
Cost scale known

Test facility TDR
ESPP decision
Selected TF host

Ready to commit
Cost known

Ready to construct

D. Schulte Goal of Muon Collider Community Meeting, May, 2021 3

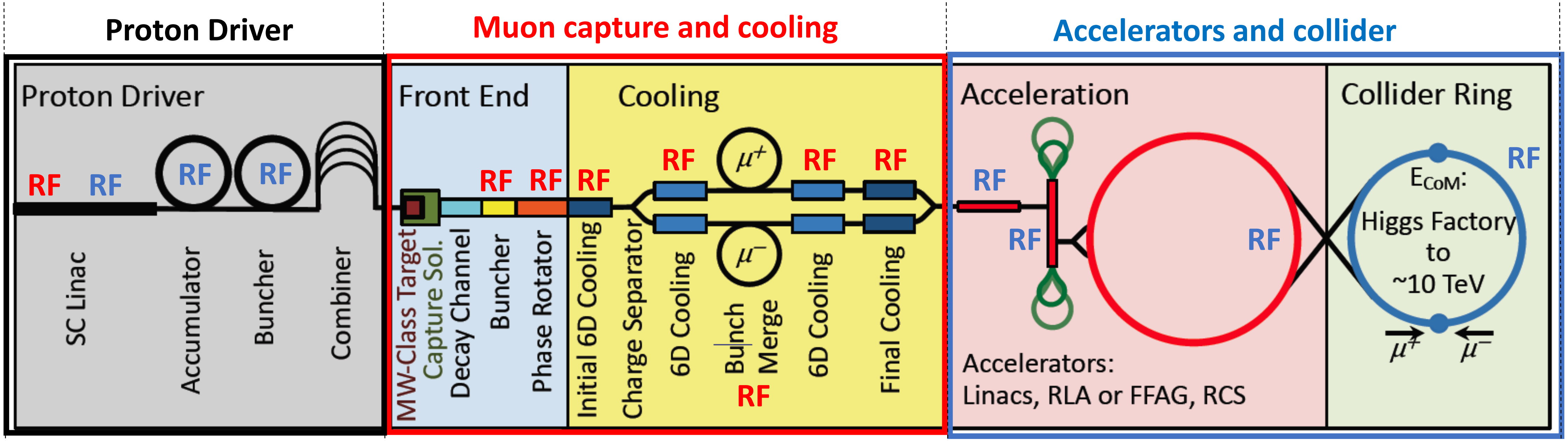
Propose R&D roadmap on this timescale

Collider design timeline

Muon cooling test facility **MCTF** timeline

Muon Colliders and RF systems

Proton driven Muon Collider Concept (MAP collaboration)



	1st muon community meeting		
Specs	Friday 9:00 – 9:30	Thursday 14:25 – 15:50 (MPC+BD)	Thursday 16:10 – 17:30 (HEC + BD)
SOTA	Friday 9:00 – 9:30	Thursday 18:10 – 20:00	Thursday 17:30 – 18:10
R&D	Friday 10:40 – 12:00	Friday 10:40 – 12:00	Friday 10:40 – 12:00

Summary of RF system parameters by 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		
	Energy	GeV/c	0.16	5	5	0.255	0.255	0.255	0.255	1.25	62.5	1500	1500		1500
Beam (system exit)	# 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

Muon capture and cooling

RF system parameters and challenges

- Complex **normal conducting RF (NRF)** system with many independently controlled cavities at many different frequencies in the ranges from 20 to 650 MHz
- Majority of the cavities operate at two main frequencies: 325 and 650 MHz at high gradient in strong magnetic field.
- **Challenges (NRF)**:
  - **Low frequency (large cavity): 325 - 650 MHz,**
  - **High gradient: 25 - 30 MV/m,**
  - **Strong magnetic field: 5 - 10 T**
  - **High peak current before bunch merge:** 3.6E12 μ @325MHz => **187 A**
  - **Large bunch charge after bunch merge:** 7.3E12 μ => **1168nC**
  - **Large beam aperture/window:**
  - **High level of beam losses and decay radiation**
- **Technology is far from being common**, the closest examples:
  - Positron capture RF cavity: high frequency, high gradient in not so strong magnetic field

Open points to discuss with MPC WG

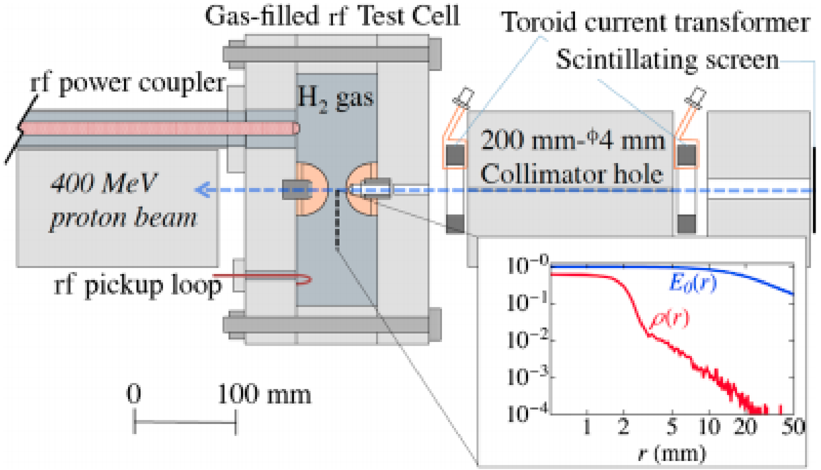
- **Frequency choice:** would we stay at 325, 650 MHz (TESLA) or move to 352, 704 MHz (LEP)? Or something different?
- **Higher gradient:** How do we profit from the higher gradient reached in some test cavities (50 MV/m) compared to current baseline?
- **Gas versus Vacuum:** Are there any non-RF pro and contra arguments? When do we have to finalize the choice?
- Beam **aperture/window** size:
- **Many frequencies** in buncher/rotator.

NRF cavities for muon cooling: State-of-the-art

MICE 200 MHz RF module prototype:
Nominal: 2.5 T, 17 MV/m
Achieved: 0 T, **19 MV/m**;
0.75 T stray field, **14 MV/m**

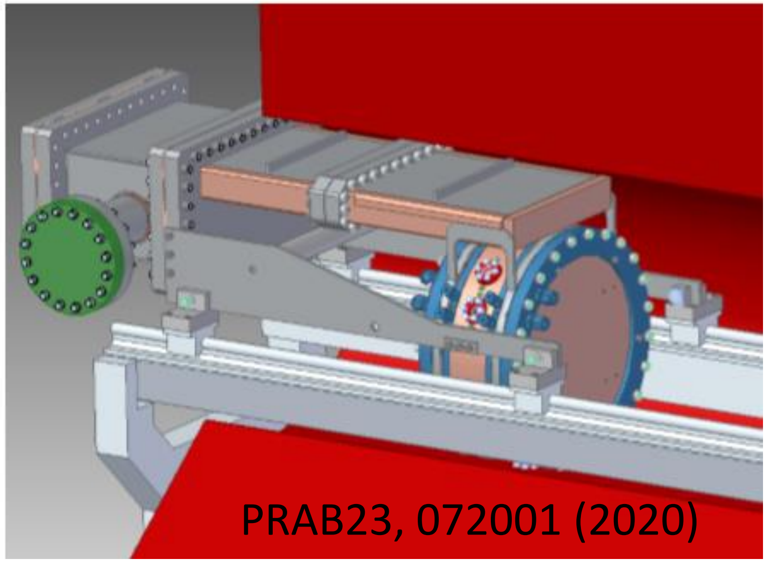
EPAC08, MOPP098 (2008)

800 MHz **Gas** filled RF cavity:
Small gap, 3T, **>50 MV/m**



PRAB19, 062004 (2016)

800 MHz **beryllium** RF cavity:
3T, **>50 MV/m**, 30us@10Hz



PRAB23, 072001 (2020)

Gas filled cavity cool thin Be window
Also neutralize space charge

Critical issues and R&D on NRF

- **Gap** between **performance** of the prototype and the test cavities
- **High gradient** in strong magnetic field. Alternative materials, temperatures, pulse shapes
- **Gas** filled cavities suffer from loading by ionization from the beam
- Cavity walls and beam window from **Beryllium ?** (Safety)
- **RF power source**: Existing commercial RF power sources are by design operate at lower peak power but higher average power then we need for muon collider. This is driven by current applications
- **Engineering design:** RF, SC magnet, cryogenics, etc
- **Collective effects**: beam loading, single and multi bunch
- High gradient operation in high **radiation** environment

R&D roadmap proposal NRF:

Scenario 1, minimum program

- **Assumption**: High gradient testing is possible only after MCTF is approved. No resource for a dedicated RF test stand in addition to the MCTF
- **Over the next 5 year**: Design study only. Conceptual and technical design of cavity prototype(s) and RF system for the MCTF
  - Based on the input from MC WG for the MCTF : frequency, gradient, B-field, aperture;
  - Based on the existing test results;
  - Make design choice for the MCTF cavity
  - Integration of cavity prototype in the muon cooling unit
- **Over the next 10 year**: Fabrication and testing.
  - Fabrication of MCTF cavity prototypes
  - Using the first cooling unit for prototype testing before the MCTF facility is fully build.
  - Depending on the prototype performance make one design iteration for the collider CDR
- …

- **Pro**:
  - Minimum R&D resources. (This is short term advantage)
- **Contra**:
  - No dedicated R&D is possible (or it is extremely limited)
  - Testing parameters are limited to the nominal one for the MCTF
  - Risk of not demonstrating nominal performance required for the MCTF
  - Strong impact on potential performance increase
  - Strong impact on potential cost and power reduction

R&D roadmap proposal NRF:
Scenario 2, full program

- **Assumption**: A dedicated RF test stand in addition to the MCTF becomes available in the next 5 years
- **Over the next 5 year**: In addition to the Scenario 1
  - Design, build and test test-cavities: materials (NRF, HTS), temperature, frequency, higher gradient, stronger B-field, pulse shape
  - Understand frequency (and other parameter) scaling; Important if testing parameters are different from the nominal.
  - Take the obtained test results into account in the design of the prototypes for the MCTF
  - Test the prototype for the MCTF earlier, if possible
- **Over the next 10 year**: Performance, cost and power optimization.
  - R&D program beyond the MCTF towards the CDR of the collider
  - Optimize performance of the RF cavities
  - Minimize cost and power in RF systems
- …

- **Pro**:
  - Dedicated R&D is possible
  - Flexibility in terms of testing parameters
  - Potential performance increase
  - Potential cost and power reduction
- **Contra**:
  - More R&D resources

Accelerators and collider

RF system parameters and challenges

- 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
- **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**
- …

FCCee-tt:

2.2E11 e

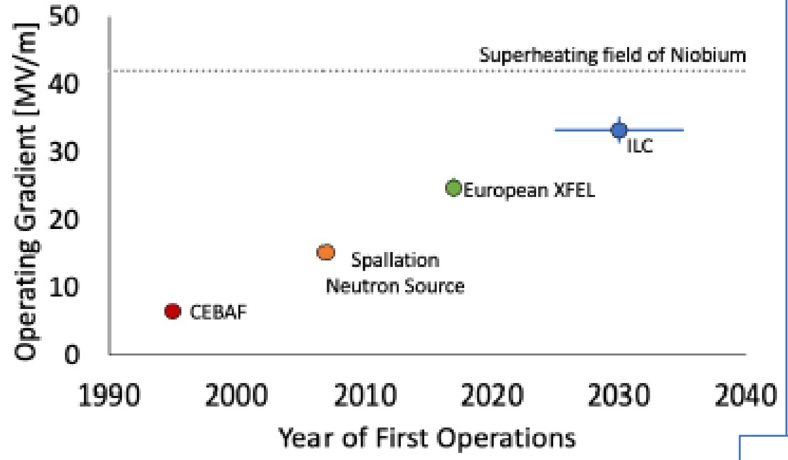
35 nC

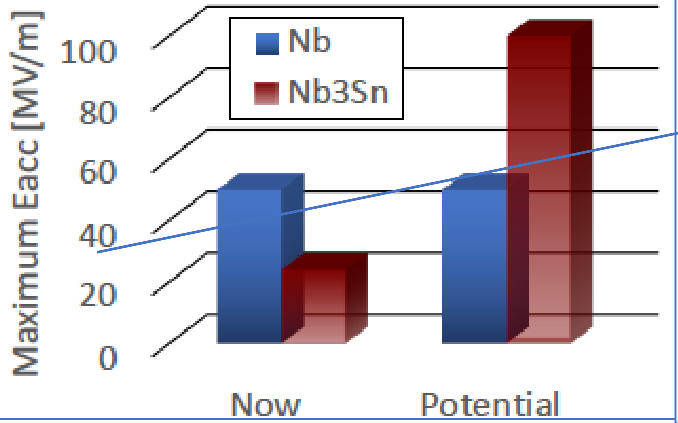
Open points to discuss with HEC WG

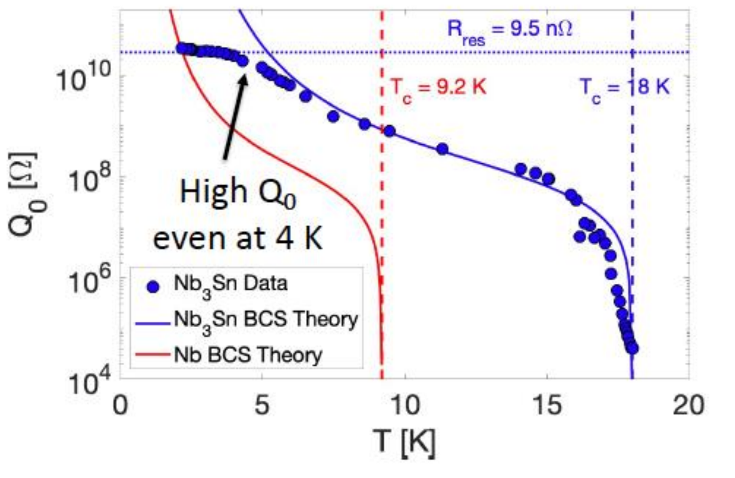
- **RF voltage:** What is the RF voltage (energy gain + over-voltage) in the linacs and rings
- **High gradient:** nominal gradient in the linacs and rings**.**
- **Energy spread:** Energy spread acceptance of the rings?
- Stray **magnetic field** in the cavities (i.e. 0.1T ?)
- Beam loss and radiation power in the SRF cavities
- Collective effects: single bunch, HOMs

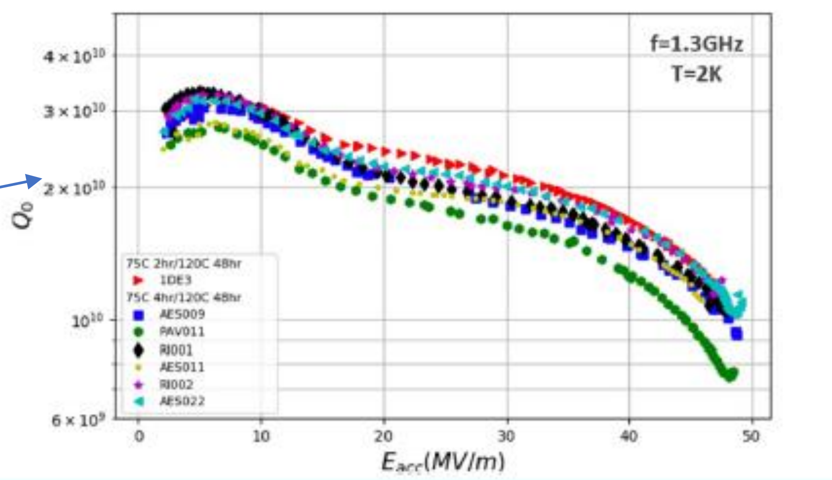
SRF system for Accelerators: State-of-the-art

- Synergy with generic R&D for high gradient SRF for other accelerators (colliders)
- 650 MHz could be a commonly beneficial choice with various projects in the Roadmap Plans and others
- No fundamental reason to get lower surface fields at lower frequency, “only” technological
- Nb3Sn potentially could double the surface fields (gradient0









Critical issues and R&D on SRF

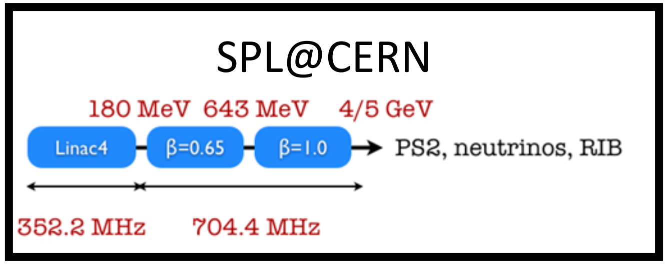
- **High gradient at low frequency multi cell cavities**: 325, 650 MHz
- **Technology** choice: Bulk vs Coating; Different materials: Nb, Nb3Sn, HTS, …
- Cavity **type(shape)** for high gradient and low loss factor
- **Pulsed operation**. **Lorenz force** detuning in pulsed mode.
- **RF power sources**: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

R&D roadmap proposal: SRF

- **Assumption**: No direct connection to the MCTF. R&D follows the collider design timeline
- **Over the next 5 year**: Baseline design
  - Identify potential showstopper and find solutions
    - Energy spread control (large aperture)
    - Bunch length control (high voltage)
    - Required acceleration rate/gradient (high gradient)
  - Provide consistent set of **baseline parameters** for all accelerators and collider
  - Conceptual design of critical items: cavities, ?…
  - Push high gradient SRF R&D at lower frequency (325 MHz) multi-cell cavities defined in the baseline parameters. Exploit synergy with other projects
    - New materials
    - Coatings
    - Power sources
- **Over the next 10 year**: Conceptual design.
  - Conceptual design of RF systems for all accelerators and collider
  - Design, fabrication and testing of high gradient cavity prototype(s)
  - Cost and power reduction
- …

Proton driver: State-of-the-art

NO showstopper found



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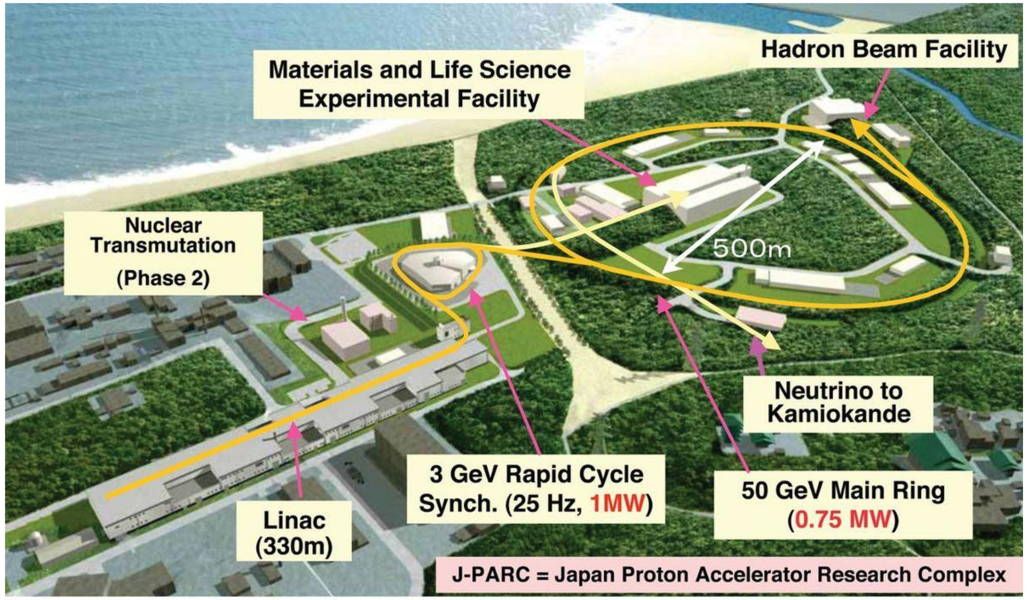

Joint Project between KEK and JAEA

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