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RF frontiers for particle physics, the US view

Sergey Belomestnykh

European LDG meeting and Accelerator R&D workshop

BNL, 7 June 2024

Introduction

- In this talk I provide an update on the RF research for future colliders in the U.S., through the prism of Snowmass and P5 report
- During Snowmass, we considered various applications of RF technology to the proposed future colliders and other accelerator- and non-accelerator-based experiments
- P5 narrowed down the choices of future machines. The colliders include circular and linear e^+e^- Higgs factories, and longer-term options such as muon and hadron high energy colliders
- I will start with Snowmass and P5 recommendations
- As it is impossible to cover all possible RF R&D topics, I will discuss only three critical topics relevant to future colliders: efficiency of RF power sources, cold normal conducting RF, and cavities for ionization channel of muon collider
- Progress on SRF accelerating cavities for future colliders will be covered in a separate talk
- The choice of topics reflects my preference and in some cases ignorance, which I think is inevitable when one tries to cover such a broad subject ☺

AF7-RF topical group of Snowmass'21

- The **AF7-RF Topical Group** of Snowmass'21 Accelerator Frontier was co-convened by **Emilio Nanni** (SLAC), **Hans Weise** (DESY) and **Sergey Belomestnykh** (FNAIL).
- The activities and recommendations of the AF7-RF were summarized in the *RF Accelerator Technology R&D* (https://arxiv.org/abs/2208.12368) and the *Accelerator Frontier* (https://arxiv.org/abs/2209.14136) reports to Snowmass.

August 29, 2022

RF Accelerator Technology R&D

Report of AF7-rf Topical Group to Snowmass 2021

AF7-rf Conveners:
Sergey Belomestnykh[1,2], Emilio A. Nanni[3,4], and Hans Weise[5]

Accelerator Frontier

Frontier Conveners: S. Gourlay[1], T. Raubenheimer[2], V. Shiltsev[3]

Topical Group Conveners: G. Arduini[4], R. Assmann[5], C. Barbier[6], M. Bai[2], S. Belomestnykh[3], S. Bermudez[4], A. Faus-Golfe[7], J. Galambos[6], C. Geddes[1], G. Hoffstaetter[8], M. Hogan[2], Z. Huang[2], M. Lamont[4], D. Li[1], S. Lund[9], R. Milner[10], P. Musumeci[11], E. Nanni[2], M. Palmer[12], N. Pastrone[13], F. Pellemoine[3], E. Prebys[14], Q. Qin[15], G. Sabbi[1], Y.-E. Sun[16], J. Tang[17], A. Valishev[3], H. Weise[5], F. Zimmermann[4], A.V. Zlobin[3], R. Zwaska[3]

Contributors: P. Bhat[3], J. Power[16], T. Roser[12], D. Stratakis[3]

Key recommendations for RF technology R&D (1)

SRF

- Studies to push performance of niobium and improve our understanding of SRF losses and ultimate quench fields via experimental and theoretical investigations;
- Developing methods for nano-engineering the niobium surface layer and tailoring SRF cavity performance to a specific application, e.g., a linear collider, a circular collider, or a high-intensity proton linac;
- Investigations of new SRF materials beyond niobium via advanced deposition techniques and bringing these materials to practical applications;
- Developing advanced SRF cavity geometries to push accelerating gradients of bulk niobium cavities to ~ 70 MV/m for either upgrade of the ILC or compact SRF linear collider;
- Pursuing R&D on companion RF technologies to mitigate field emission, provide precise resonance control, enable robust low level RF systems for high gradient and high Q accelerators, etc.;
- Research on application of SRF technology to dark sector searches;

NCRF

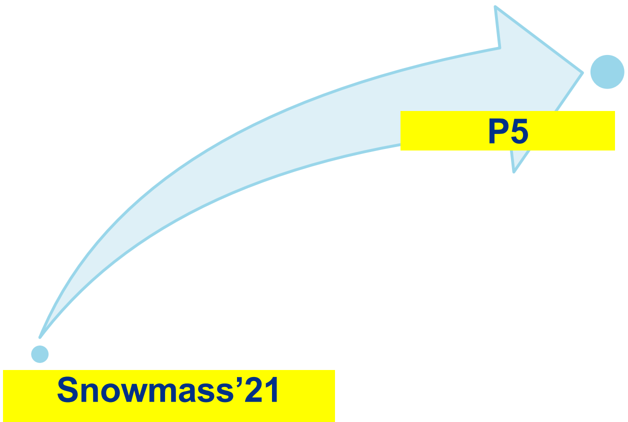
- R&D on high-gradient normal conducting RF structures operating at cryogenic temperatures with a gradient of > 150 MV/m as a promising way toward a compact linear collider;
- R&D on high frequency and multi-frequency structures to transcend limits on shunt impedance and accelerating gradients;
- Development of higher gradient normal conducting cavities in exotic environments (e.g. strong magnetic fields);
- Investigation of novel materials and manufacturing techniques to improve high gradient performance and remove design constraints;

Key recommendations for RF technology R&D (2)

RF Sources	• Developing high efficiency, low-cost RF sources that would benefit many operating and practically every future intensity or energy frontier machine;
Auxiliaries	• Studies dedicated to industrialization and cost reduction of fabricating RF components and systems;
SWFA	• Continue research on advanced SWFA structures to bring them closer to practical applications through higher gradients (>300 MV/m), higher repetition rates and with damping features;
RF breakdown	• Experimental and theoretical research to further our understanding of the RF breakdown physics;
Modeling	• Continued development of computational tools for multi-physics and virtual prototyping; • Developing a community ecosystem for accelerator and beam physics modeling that would incorporate comprehensive set of high-performance simulation tools for RF-based accelerators.

From Snowmass to P5

"I always tend to assume there's an infinite amount of money out there."
"There might as well be, "Arsibalt said, "but most of it gets spent on […], sugar water and bombs. ***There is only so much that can be scraped together for particle accelerators****."*
– Neal Stephenson

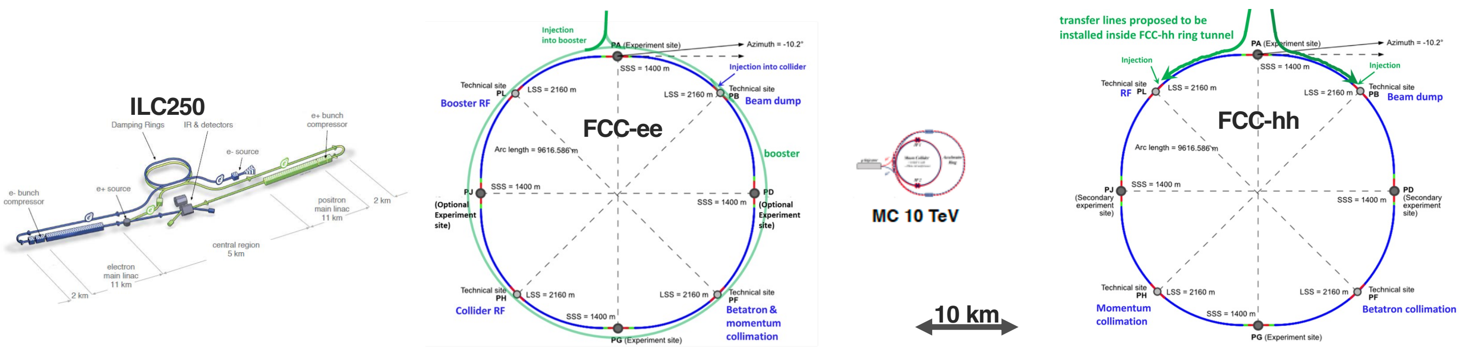


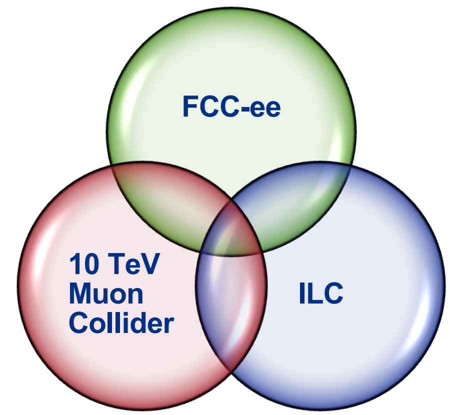
- Many new collider ideas were generated during Snowmass process
- P5 pared them down to a few options to fit within DOE constraints

- **Recommendation 2c:** An **off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of **FCC-ee** and **ILC** meet our scientific requirements. **The US should actively engage in feasibility and design studies**. […]
- **Recommendation 4a:** Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on **proton**, **muon**, or **possible wakefield technologies**, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** […]

- Wakefield concepts for a collider are in the early stages of development. A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout. This will provide an important yardstick against which to measure progress with this emerging technology path.

Scale and timeline for HEP colliders





ILC	FCC-ee, Muon Collider		FCC-hh
2040	2050	2060	2070

Possible years to start collider operation

All "conventional" colliders (ILC, FCC-ee & -hh) and the muon collider would require substantial RF systems (NCRF and SRF) providing very high power to beams

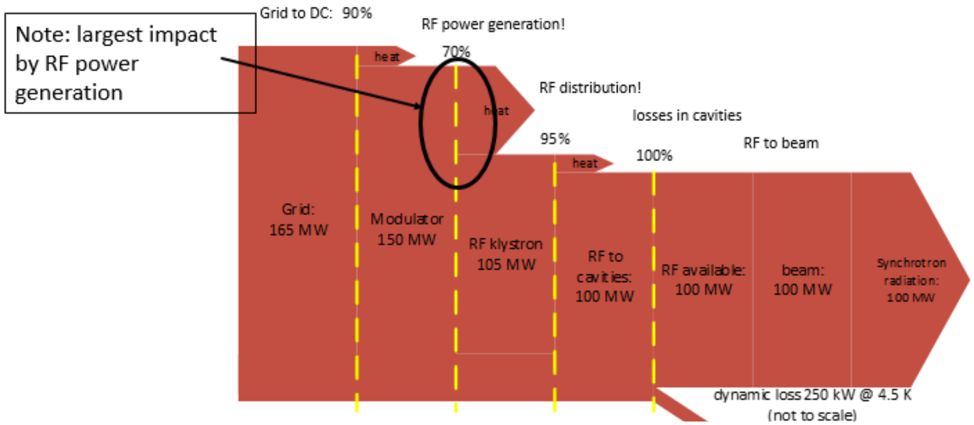
SRF will be covered by Anne-Marie Valente Feliciano

Synergies with some U.S. projects and accelerators:

- ***EIC*** *(a NP machine in the DOE lingo): SRF, potentially cold NCRF*
- ***PIP-II****: SRF*
- ***LCLS-II****: SRF*

Importance of RF power efficiency

- We need RF power to accelerate beams and produce high luminosity
- RF systems are significant contributors to overall power budget of Higgs factories
- An improvement of the RF system efficiency would be beneficial
- What is we can improve RF source efficiency by 10%?



(from Erk Jensen, *Higher Efficiency High Power RF Generation*, AF7 - Subgroup RF - miniWorkshop on RF Systems and Sources, Dec 17, 2020)

$$L[\mathrm{cm}^{-2}s^{-1}] = 2.45 \cdot 10^{33} \cdot P_{SR}[\mathrm{MW}] \cdot \frac{\rho[\mathrm{m}] \cdot \xi_y}{E_{beam}^3[\mathrm{GeV}] \cdot \beta_y^*[\mathrm{m}]} \cdot R_{HG}.$$

FCC-ee

- Overall AC power is estimated at 290 MW (CM energy of 240 GeV)
- **RF system contributes 165 MW, or 69%**
- Klystron efficiency 70%, RF system efficiency 60%
- New klystron efficiency 80%: **will save 20 MW** of grid power!

$$L = \frac{P_{beam}}{E_{c.m.}} \cdot \frac{N_e}{4\pi\sigma_x^*\sigma_y^*} \cdot H_D$$

ILC

- Overall AC power is estimated at 111 MW for the baseline luminosity (138 MW for 2× luminosity upgrade)
- **Main linac RF system contributes 24 MW, or 22%** (35 MW, or 25%)
- Klystron efficiency 65%, RF system efficiency ~50%
- New klystron efficiency 75%: **will save 4 - 5 MW** of grid power

High efficiency RF sources

JINST

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SNOWMASS'2021 ACCELERATOR FRONTIER

High efficiency, low cost, RF sources for accelerators and colliders

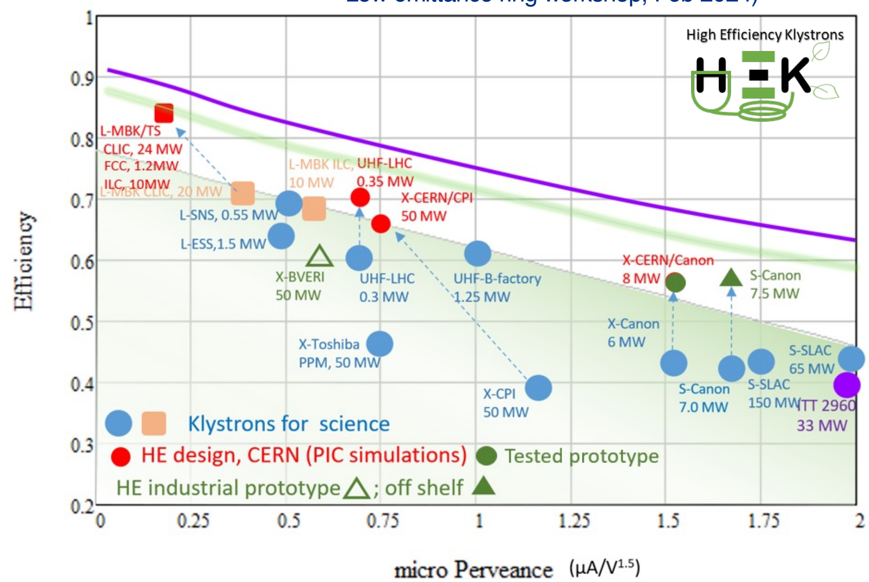
R.L. Ives,[a] M. Read,[a] T. Bui,[a] D. Marsden,[a] G. Collins,[a] H. Freund,[a] R. Ho,[b] L. Higgins,[b] C. Walker,[c] J. Conant,[c] B. Chase,[d] J. Reid,[d] T. Kroc,[d,*] V. Yakovlev,[d] J.C.T. Thangaraj,[d] R.C. Dhuley,[d] J. Potter,[e] A. Jensen,[f] B. Weatherford,[g] E.A. Nanni[g] and S. Tantawi[g]

[a] *Calabazas Creek Research, Inc., 690 Port Drive, San Mateo, CA 94404 U.S.A.*
[b] *Communications & Power Industries, LLC, 811 Hansen Way, Palo Alto, CA 94304 U.S.A.*
[c] *Communications & Power Industries, LLC, Beverley Microwave Division, Beverley, MA U.S.A.*
[d] *Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL, 60510 U.S.A.*
[e] *JP Accelerator Works, Inc., 2245 47th Street, Los Alamos, NM 87544 U.S.A.*
[f] *Leidos, Inc., 11951 Freedom Drive, Reston, VA 20190 U.S.A.*
[g] *SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA U.S.A.*

Table 6. Comparison of projected cost, performance, and status of future RF sources.

Source	Power	Efficiency	Projected Unit Cost	Cost per delivered Power in quantity	Status
Active Prototype Development Efforts					
Magnetron	100 kW +	> 85%	\$84k	< \$1/W	Phase and amplitude control successfully demonstrated. Available for scaling to other frequencies and power levels. Electronics for feedback control requires additional design and testing.
Multiple Beam Triode	200 kW	90%	\$150k	< \$0.75/W	Additional funding required for rebuild and test of prototype
High Efficiency Klystron	100 kW	80%	\$400k	\$4/W	In preparation for high power tests in March 2023
Multiple Beam IOT	170 kW	85%	\$350k	\$1.75/W	Improved input coupler being fabricated for low power testing. Moly grids being fabricated. Will require additional funding to build and test a prototype MBIOT to confirm performance

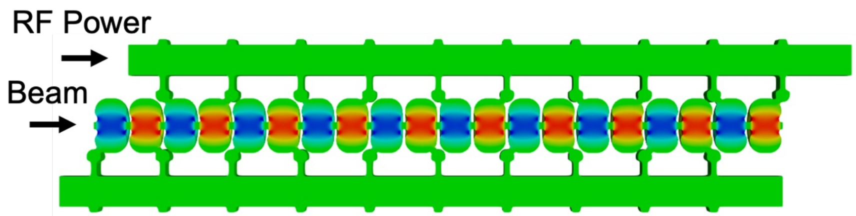
(from I. Syrachev, *Highly efficient RF Power sources*, Low emittance ring workshop, Feb 2024)



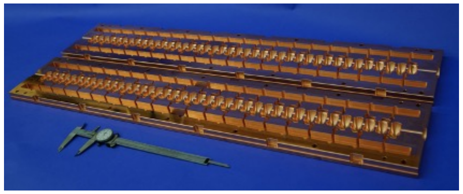
- Development of new RF sources is in progress at CERN (High Efficiency Klystron project) in collaboration with industry
- In the U.S., there are efforts at national labs and industry to develop nigh efficiency, low-cost RF sources

Cold copper RF technology

- The most notable recent development in NCRF field is **parallel-coupled C-band structures operating at liquid nitrogen temperature** for the proposed C^3 collider. SLAC is leading this effort in collaboration with UCLA, LANL, RadiaBeam, and other institutions. While C^3 was not endorsed by P5, the report mentioned this technology as part of the DOE-HEP General Accelerator R&D (GARD) program: "*The normal conducting RF program should incorporate innovative concepts such as cryogenic cool copper and distributed coupling*." The technology will find applications beyond colliders.
- The highly optimized cell shape of the standing wave structure and increased electrical conductivity of copper at 80 K result in **significantly improved shunt impedance and hence reduced RF power**.

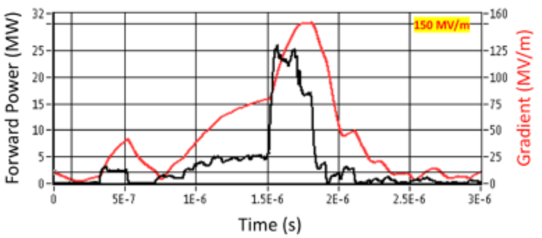


C^3 Prototype One Meter Structure

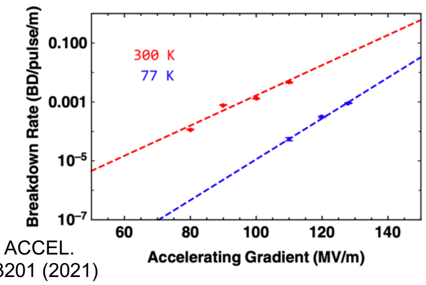


- The lower thermal stresses in the material and improved material strength **reduce probability of breakdown**, allowing to design the collider with an accelerating gradient of **120 MV/m**.
- Prototype one-meter structures have been fabricated and tested at high gradient and at cryogenic temperatures.

High Gradient Operation at 150 MV/m



Cryogenic Operation at X-band



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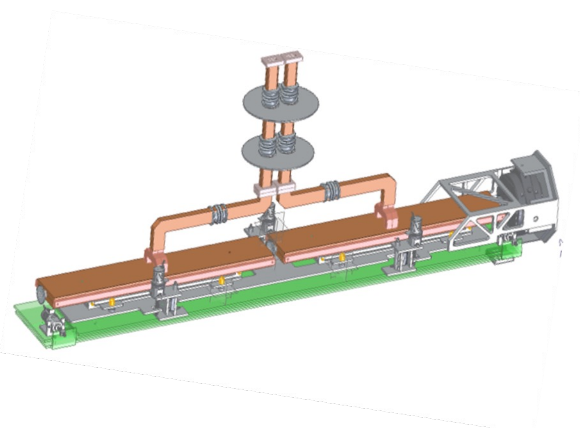
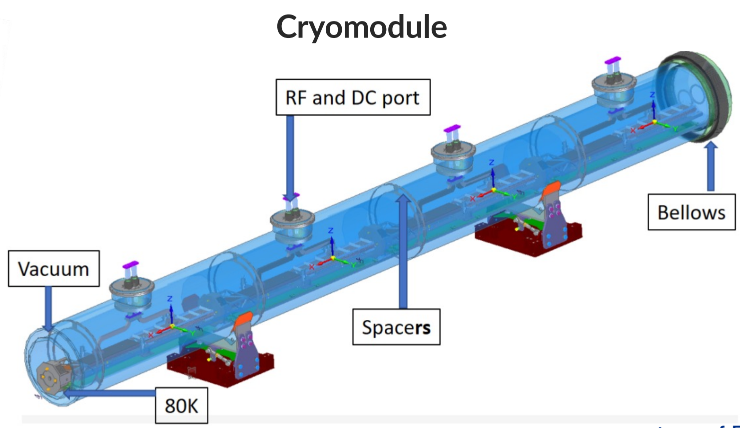
C^3 technology synergies with future colliders

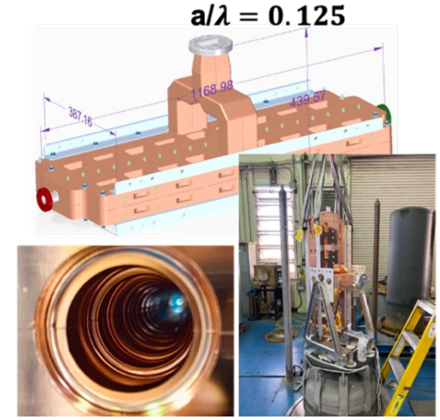
C^3 technology could contribute to future colliders

- ILC - options for electron driven positron source based C^3 technology
- FCC-ee - common e^+e^- injector linac from 6 to 20 GeV based on cold copper, reducing length 3.5 times or reducing RF power 3.5 times
- Muon Collider - high gradient cryogenic copper cavities in cooling channel, alternative linac for acceleration after cooling





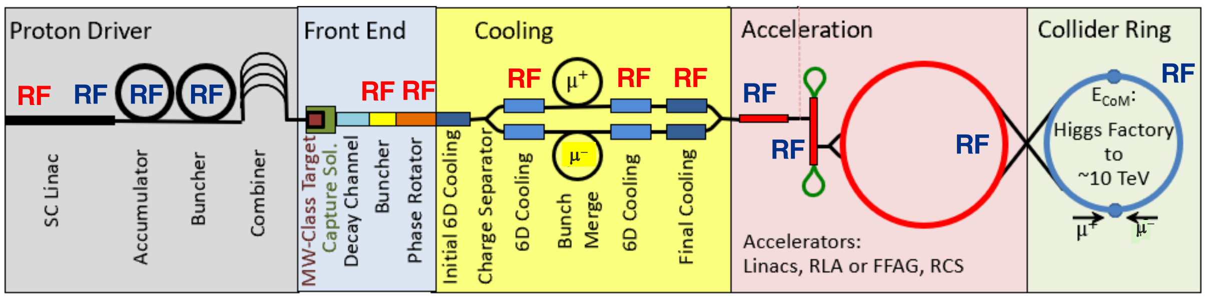
Wide Aperture S-band Injector Linac
$a/\lambda = 0.125$



courtesy of E. Nanni

Muon collider RF systems

The muon collider concept was developed by U.S. Muon Accelerator Program (2011-2016)



MW-scale proton driver

muon production target

Capture 200 MeV bunches

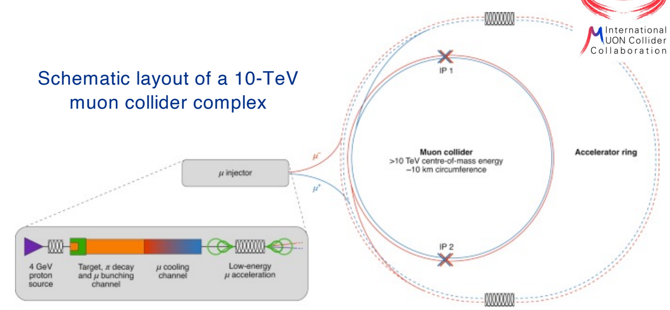
Ionization cooling channel to reduce 6D emittance

Acceleration to TeV scale energy

Collider ring for counter-propagating muons

In 2022 International Muon Collider Collaboration (IMCC) was formed, hosted by CERN

Schematic layout of a 10-TeV muon collider complex



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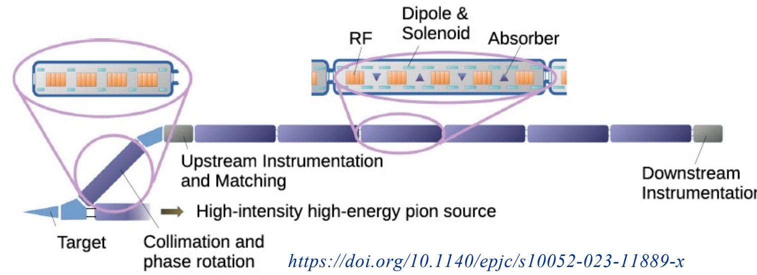
www.nature.com/naturephysics

- RF systems for the muon collider are complex and prevailing throughout from the proton driver to muon collider
- Versatile functions: fast acceleration, ionization cooling, longitudinal beam manipulation, etc.
- Broad range of operation conditions: **NCRF** and **SRF**, frequency from dozens of MHz to a few GHz, gradients up to 30+ MV/m
- Unique challenges: strong magnetic field background, enclosed cavity apertures, gas-filled, radiation from muon decays, very high bunch intensity

NCRF for ionization cooling

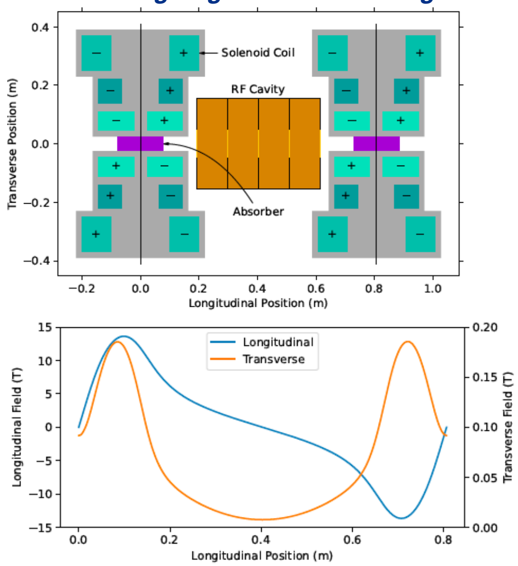
- Ionization cooling channel consists of 1,000+ muon cooling cells
- The cooling of muons requires very compact assembly of normal conducting RF cavities, superconducting solenoids, and either liquid hydrogen or LiH absorbers
- Large bore solenoids: from 2 T (1 m aperture) in early-stage to 14 T in final-stage ionization cooling cells
- RF cavities (300-800 MHz) must operate in multi-tesla fields

Schematics of the muon cooling demonstrator

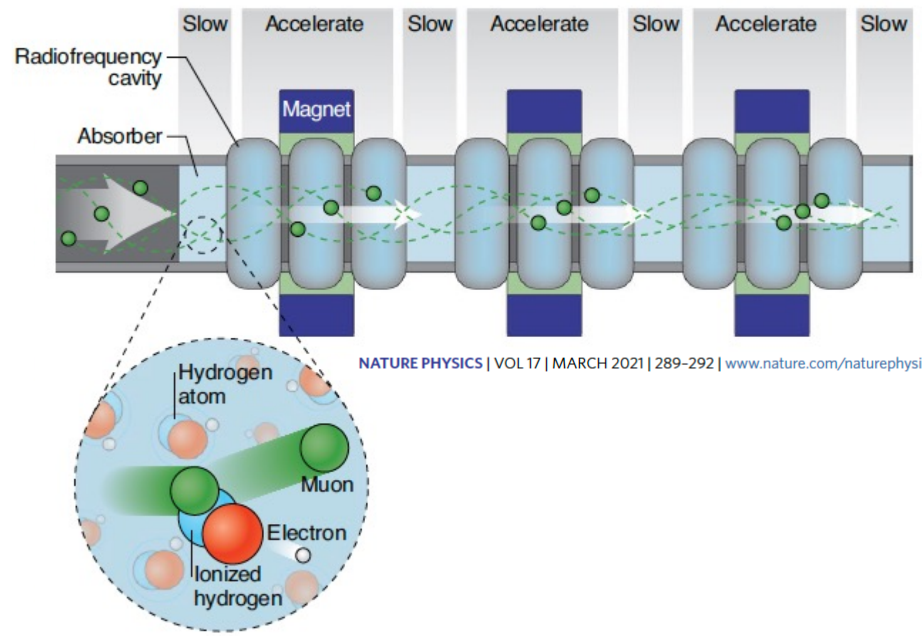


https://doi.org/10.1140/epjc/s10052-023-11889-x

Final cooling stage ionization cooling cell



(from J.S. Berg, et al., IPAC'24)



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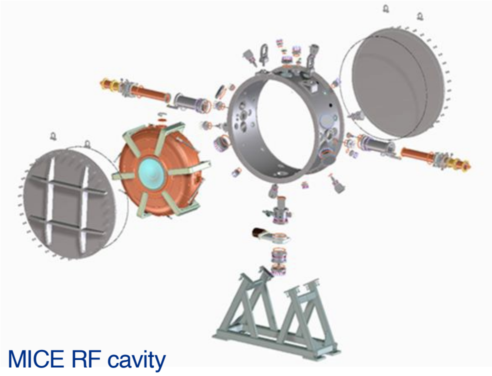
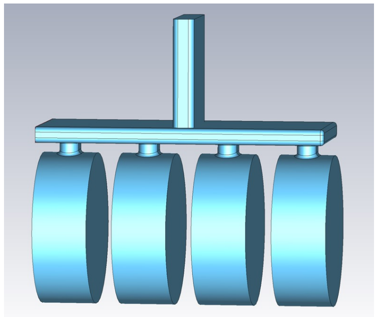
NCRF cavities in high magnetic fields

Challenges for MC NCRF cavities

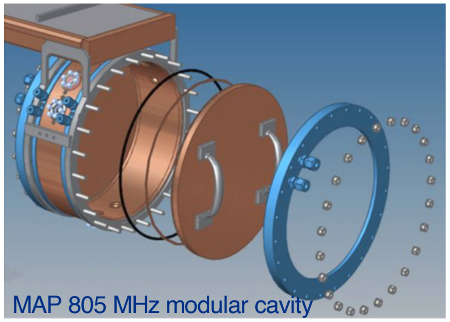
- Variety of parameters along the cooling channel: accelerating gradient, frequency, magnetic field, beam window thickness, etc. Will need high-power, short-pulse RF power sources
- Considerable cavity R&D have been carried out in MAP and pre-MAP era to understand the RF breakdown in strong B field and how to mitigate it. For the field gradient demonstration: an 805 MHz MAP vacuum modular cavity and an 805 MHz high pressure hydrogen-filled cavity have achieved ~50 MV/m in a 3 T B field
- The MICE 201 MHz cavity is a fully operational single cell cavity that has achieved the design gradient (~11 MV/m) in a ~0.2 T B field
- Much more must be learned about RF breakdown. Both simulations and experimental studies in a dedicated test facility are needed to explore different materials (e.g., aluminum, CuAg and other copper alloys, Be-coated copper,…) and magnetic field configurations.
- Cold copper technology might be a good choice, synergy with C^3 R&D



MICE RF cavity



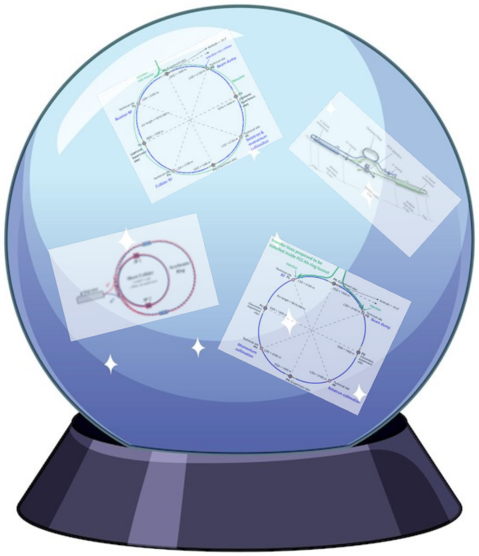
A conceptual vacuum model of the distributed coupling for a 4-cell cavity module
(from T. Luo and D. Merenich, IPAC'24)



MAP 805 MHz modular cavity

Summary

- P5 recommended to actively engage in feasibility and design studies of two off-shore Higgs factories, ILC and FCC-ee
- Also, P5 recommended to support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies
- All “conventional” colliders (ILC, FCC-ee & -hh) and the muon collider need substantial RF systems (NCRF and SRF) providing very high power to beams
- The collider designs are at different stages of maturity, but all require quite extensive NCRF and SRF technology R&D efforts covering a wide range of challenging topics
- In this presentation I covered three critical topics in the NCRF and RF power generation
- Any future collider will require very high AC power to operate, and RF systems is one of the main contributors. Special attention should be given to R&D topics that would improve efficiency of RF power sources.
- R&D on innovative concepts, such as cold copper RF, should be supported as the results could benefit future colliders and wider range of accelerators
- RF systems for the muon collider face unique challenges. Active RF R&D in this area is critical to the success of a muon collider demonstrator and formulation of the MC conceptual design
- There are synergies between future collider developments and accelerator projects in the U.S.



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Acknowledgments

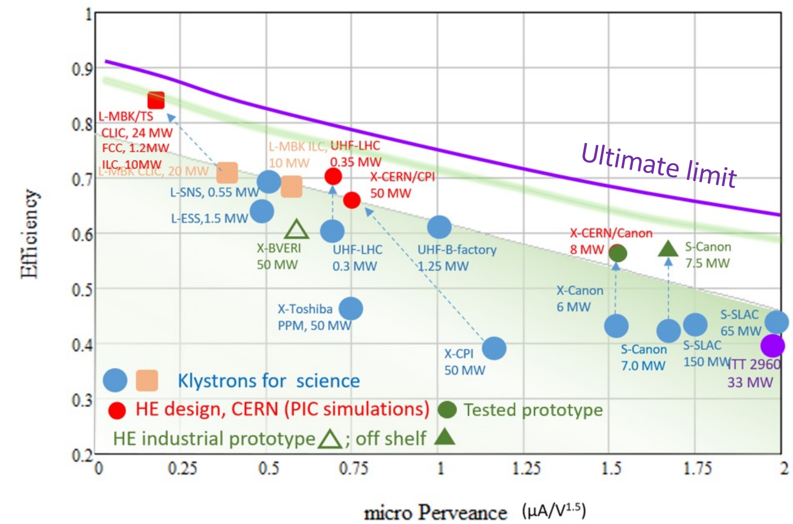
- E. Nanni (SLAC) and H. Weise (DESY), my co-conveners of the Snowmass AF7-RF Topical Group
- T. Luo (LBNL)
- K. McGee (Fermilab)
- V. Shiltsev (NIU)

and many others who directly or indirectly helped me to prepare this presentation

Thank you!

High-efficiency RF sources

- High-efficiency klystrons are needed to reduce overall AC power consumption of the machine
- CERN-led HEIKA collaboration is targeting to improve efficiency and performance of klystrons for various applications
- Example: the klystron efficiency upgrade from existing 65% to 80% would potentially save ~1 TWh in 10 years of FCC-ee operation
- Several options of klystron design improvements are explored, some in collaboration with industry
- An off-the-shelf Canon klystron was retrofitted and tested, showing significant improvement



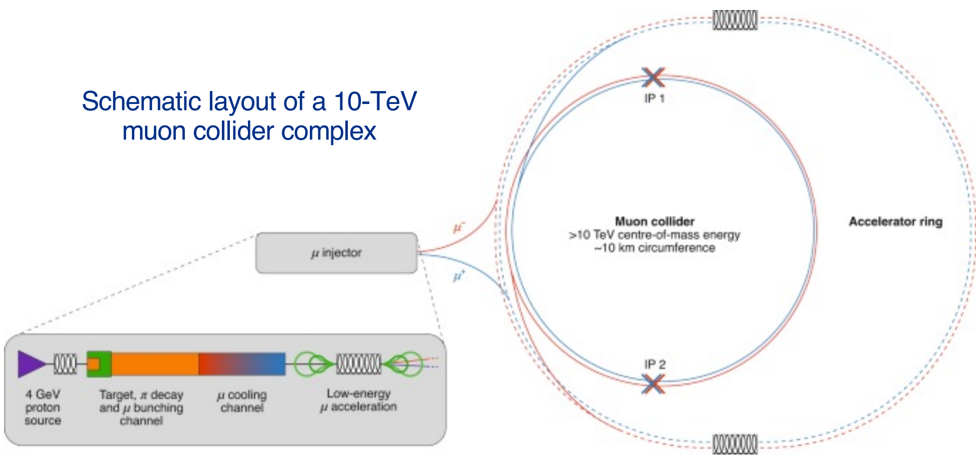
Canon

8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	94	94
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	48
Efficiency, %	42	56.4
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.42
RF circuit length, m	**0.127**	**0.127**

Muon collider

- Muon collider combines precision and energy reach needed to test the deepest questions of particle physics
- Smaller footprint than proton-proton-collider for the same pCM energy
- Muons are 207 times heavier than electrons and are not limited by synchrotron radiation
- BUT muons decay (2.2 μs lifetime at rest), hence must be accelerated rapidly
- 5-7 years of R&D to prepare a concept of demonstration facility

Schematic layout of a 10-TeV muon collider complex



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Tentative parameters based on U.S. Muon Accelerator Program (MAP) studies

Parameter	Unit	Higgs Factory	3 TeV	10 TeV
COM Beam Energy	TeV	0.126	3	10
Collider Ring Circumference	km	0.3	4.5	10
Interaction Regions		1	2	2
Est. Integ. Luminosity	ab^{-} 1/year	0.002	0.4	4
Peak Luminosity	10^{34} cm^{-2} s^{-1}	0.01	1.8	20
Repetition rate	Hz	15	5	5
Time between collisions	μs	1	15	33
Bunch length, rms	mm	63	5	1.5
IP beam size σ^*, rms	μm	75	3	0.9
Emittance (trans), rms	mm-mrad	200	25	25
β function at IP	cm	1.7	0.5	0.15
RF Frequency	MHz	325/1300	325/1300	325/1300
Bunches per beam		1	1	1
Plug power	MW	~ 200	~ 230	~ 300
Muons per bunch	10^{12}	4	2.2	1.8
Average field in ring	T	4.4	7	10.5

$$\mathcal{L} = \frac{N_+ N_- n_{eff} f_{rep}}{4\pi\sigma_x^* \sigma_y^*}$$

$n_{eff} \approx 150\bar{B}$ is an *effective* number of turns

- The muon collider concept was developed by U.S. Muon Accelerator Program (2011-2016)
- In 2022 International Muon Collider Collaboration (IMCC) was formed, hosted by CERN

International MUON Collider Collaboration

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