Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Summary of the Accelerator Frontier Muon Collider Workshop

Katsuya Yonehara

Muon collider forum

March 9, 2022

Scope of AF Muon Collider Workshop

- The online workshop was held on January 26th and 27th 2022
  - https://indico.fnal.gov/event/52701/
- Identify the Accelerator Frontier related subject which will be discussed in the Muon Collider Forum Report
  - The report will describe an interrelation of various beam parameters related to muon colliders discussed among AF, Energy Frontier, and Theory Frontier
    - Example: How to achieve the Center Of Mass energy & Luminosity in a collider ring which are requested from EF and TF?
    - Is it possible to build the collider in the US?
  - It will be submitted to the Snowmass conveners by May 31st
  - It will be made open for everybody interested to sign

Agenda of the Workshop (I)

- Possible elements of the US plan toward a Muon Collider
  - Vladimir Shiltsev
- Physics motivation for a Muon Collider
  - Patrick Meade
- Muon Collider Site Filler
  - Dave Neuffer
- Targetry and cooling for a Muon Collider
  - Katsuya Yonehara
- Muon Acceleration
  - Scott Berg
- Challenges on high field magnets
  - Alexander Zlobin

Agenda (II)

- Normal Conducting and Super Conducting RF technology and Muon Collider needs
  - Tianhuan Luo
- Machine Detector Interface
  - Nadia Pastrone
- Neutrino flux around Muon Colliders and 7 ways to mitigate it
  - Nikolai Mokhov
- Radiation mitigation in the collider ring
  - Christian Carli
- Synergy with European Muon Collider efforts
  - Daniel Schulte
- Muon-ion Collider
  - Wei Li

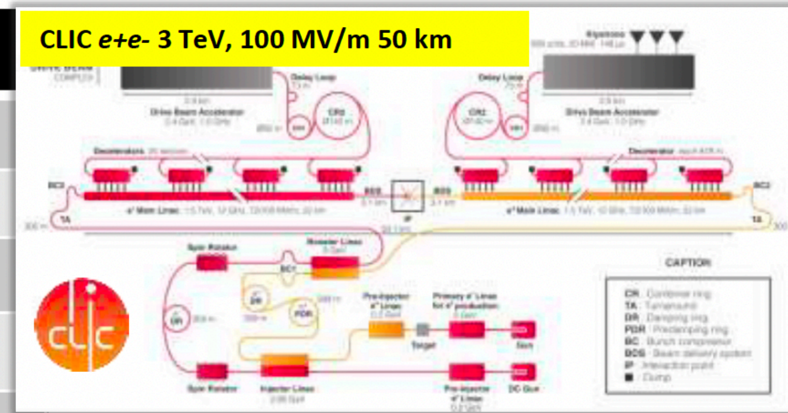
Highlights (landscaping given by Vladimir)

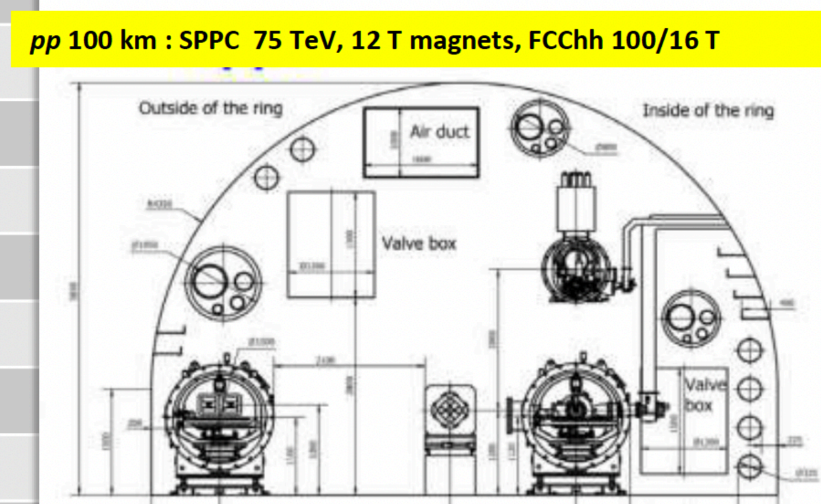
30’000 ft *(~30 years)* View:

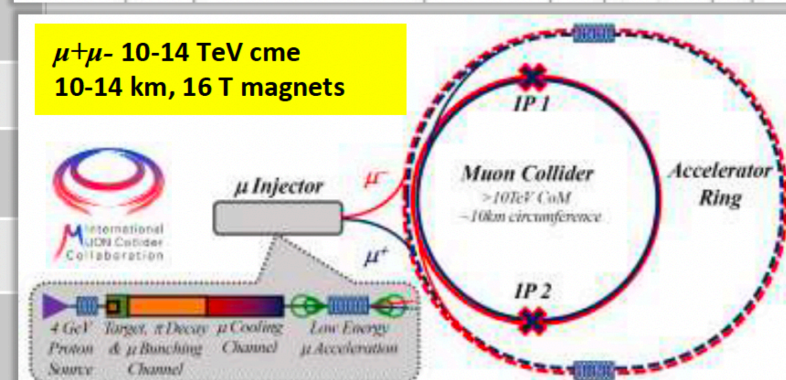
- (we believe that) MC is the most viable option for HEP future:
  - ~ x7 energy reach vs *pp*
  - *μ*’s do not radiate when bent → acceler’n in rings:
    - *Smaller(est) footprint*
    - *Low(est) cost*
    - *(best) power efficiency*
- (we believe that) 3-10 TeV MC can be designed in ~10-15 yrs and built in 20-25 yrs from now
- (the rest of) the HEP community not so sure yet

17 (!) High Energy Collider Concepts/Proposals

Name	Details
Cryo-Cooled Copper linac	e+e-, $\sqrt{s} = 2$ TeV, L= 4.5 $\times 10^{34}$
High Energy CLIC	e+e-, $\sqrt{s} = 1.5 - 3$ TeV, L= 5.9 $\times 10^{34}$
High Energy ILC	e+e-, $\sqrt{s} = 1 - 3$ TeV
FCC-hh	pp, $\sqrt{s} = 100$ TeV, L= 30 $\times 10^{34}$
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 $\times 10^{34}$
Collider-in-Sea	pp, $\sqrt{s} = 500$ TeV, L= 50 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 1 $\times 10^{34}$
FCC-eh	ep, $\sqrt{s} = 3.5$ TeV, L= 1 $\times 10^{34}$
CEPC-SPPpC-eh	ep, $\sqrt{s} = 6$ TeV, L= 4.5 $\times 10^{33}$
VHE-ep	ep, $\sqrt{s} = 9$ TeV
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5$ TeV, L= 1 $\times 10^{34}$
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3$ TeV, L= 2 $\times 10^{34}$
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
LWFA-LC (e+e- and $\gamma\gamma$)	Laser driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
PWFA-LC (e+e- and $\gamma\gamma$)	Beam driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
SWFA-LC	Structure wakefields; e+e-, $\sqrt{s} = 1 - 30$ TeV







10'000 ft *(~10 years)* View:

- Any plans for the energy frontier facility can be/will be affected by the reality of:
  - LHC operation and LBNF/DUNE/PIPII construction
  - Higgs/EW factory developments:
    - Even apparently lower costs Higgs factories will
      - *Suck big part of "free money" out of ~4B$ world's HEP budget*
      - *Demand significant chunk (~1/5) of ~4500 worldwide accelerator sci & eng workforce*
      - *Delay MC timeline for ~10+ years*
- Given higher priority of Higgs factories, MC may end up be "Future Option B"/C for next decade

10’000 ft *(~10 years)* View:

- Regions are not fully coordinated/integrated yet and might have divergent plans:
  - Japan: ILC (or just a neutrino program)
  - Europe: FCCee and FCChh
  - China: CEPC and may be SPPC
  - US: neutrino program now + call for domestic collider but might be OK with int’l one at CERN or ILC
- Formal strategic plan development processes most established in Europe (EPPSU) and the US (Snowmass-P5)
  - Somewhat different and not-synched timelines

Objectives of a (Possible) US MC Plan

1. Muon Collider (pre-) CDR report available at the time of next Snowmass/P5 (2029-30):
   a. Requires machine design work and expt' R&D
   b. Several options: e.g., 3 and 10 TeV cme, domestic and international siting
   c. In collaboration with IMCC, coordinated designs and experimental R&D programs
   d. Includes theory/analysis and MDI/background work
2. Also by 2030 P5: plan for post-(pre)CDR/TDR phase MC design and development in the US
   - Elements and cost of R&D for 2030-37 specified

Possible elements of the US MC Plan

1. Btw now and CSS (Snowmass main mtg) :

   a. Prepare strong recommendation/White Paper – joint EF, TF, AF

      1. Justify physics case for e.g., 3 and 10 TeV cme, and 5-6 TeV cme FNAL site filler (Higgs Fact.?)
      2. Converge on the basic elements of accel R&D plan for 2024-2030; assume collaboration with IMCC – avoid duplication of effort in experimental R&D effort
      3. Identify scope of MDI/background studies in 2024-30

   b. Call for/support creation (as P5'2023 recommenda-tion) of an "*Integrated/Inclusive Future Colliders R&D*" program in the DOE OHEP

      1. With MC as <u>one of few</u> sub-programs, together with FCC, FNAL site-fillers and linear colliders (eg C^3)

Possible elements of the US MC Plan (2)

For the MC part of the proposed "*Integrated/ Inclusive Future Colliders R&D*" OHEP program :

a. Identify main deliverables by 2030 (pre-CDR, prototypes)
b. Outline synergies with other OHEP R&D programs: GARD magnets, GARD RF, GARD ABP, GARD Targets, detector R&D, etc
c. For the above programs – identify elements to add/focus on in relevance to MC (eg fast cycling booster magnets, etc)
d. Indicate realistic US contributions to the IMCC and expectations to the return (IMCC contributions to US work)
e. Estimate effort and support (FTEs and M$) for all major elements of the US MC R&D program for FY2024-30: account for existing synergetic + new effort/$$ = total

Highlights from Patrick (TF represent)

And we reach the inevitable ask for the AF...

Dark matter

WIMP

Testing QFT and naturalness

Higgs factory

Multi-Higgs

More physics will be addressed

Highlights from Dave, Katsuya, Scott

Site filler Accelerator

- **Largest**

Radius is ~2.65 km

- ~16.5 km Circumference
  - ~2/3 LHC

~RCS accelerator

If B_{ave} = 3 T → E_{μ} = 2.4 TeV

(B_{max} = 8T, B_{pulse} = ±2T)

Doubled ?

B_{ave} = 6.3 T → E_{μ} = 5 TeV

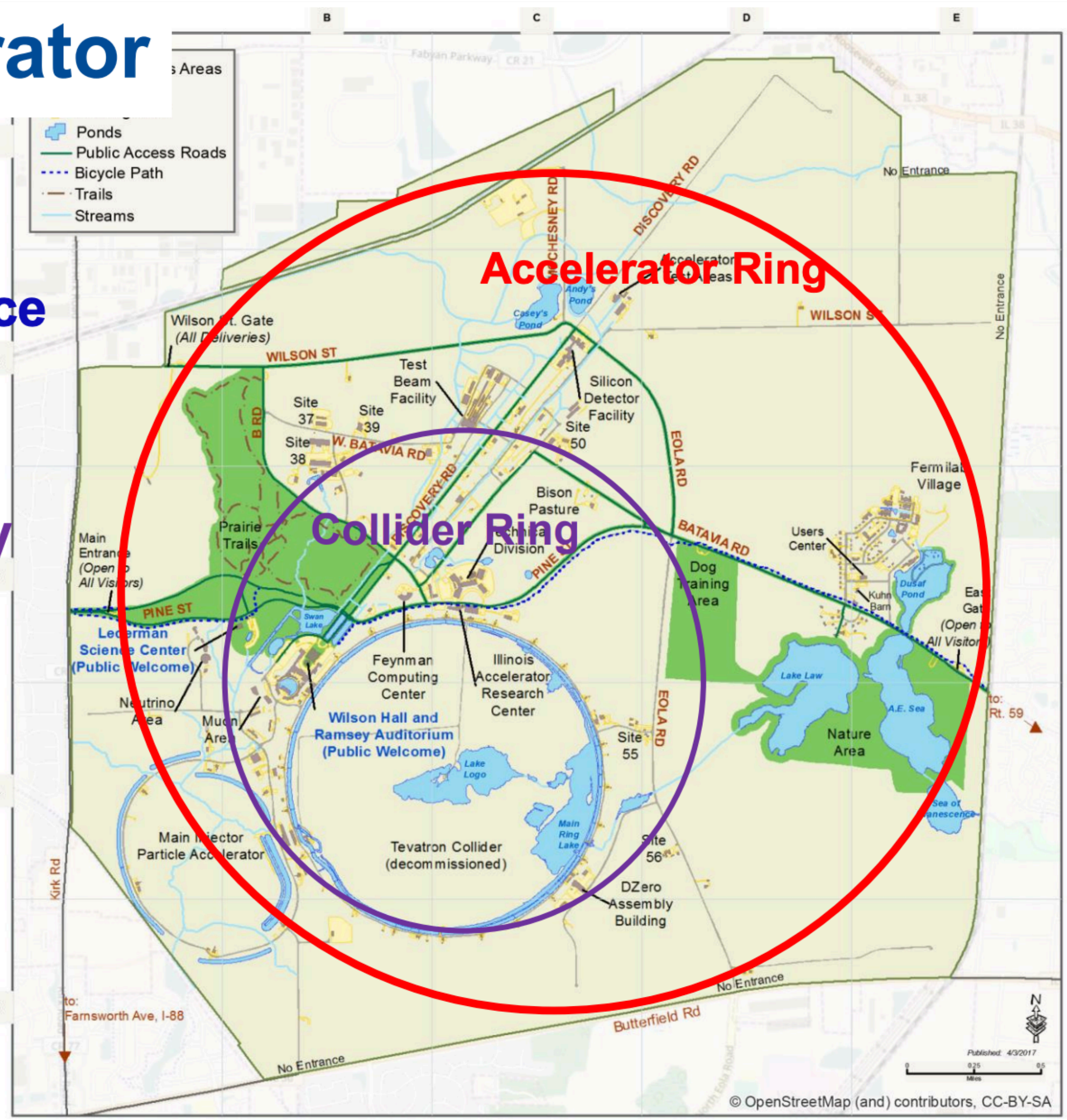
(B_{max} = 16T, B_{pulse} = ±4T)

10 TeV collider

Collider Ring ~10 km

B_{ave} = 10 T

τ_{μ} = 0.104 s

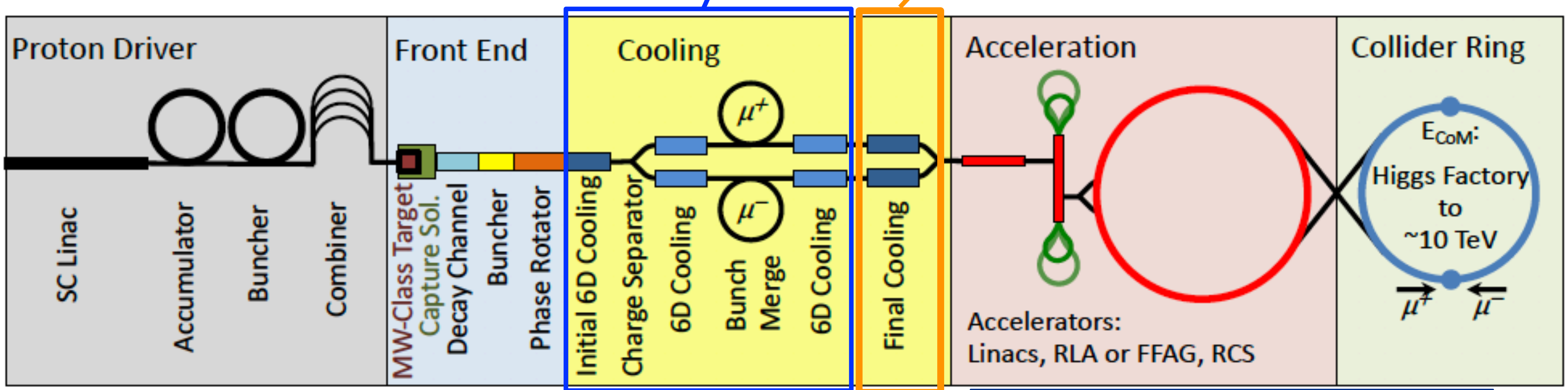


$$R = \frac{B\rho}{B} = \frac{P(GeV/c)}{0.3B(T)}\,m = \frac{P(TeV/c)}{0.3B(T)}\,km$$

MAP baseline

Decay process is involved in an efficiency calculation

Cooling
- Transmission efficiency of 6D cooling is **20 %**
- Transmission efficiency of Final cooling is **50 %**



Proton driver
4 Mega-Watt 8 GeV protons
N_p = **3.13E15** protons on target

Front End
Proton to muon conversion efficiency is **10-15 %** for each sign

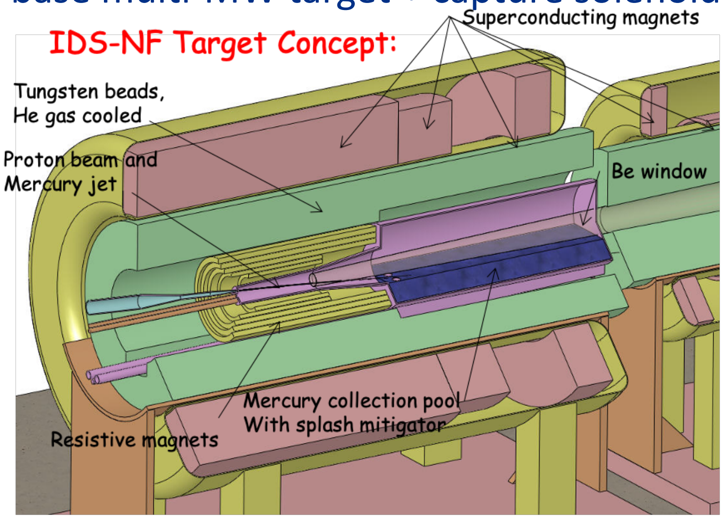
Acceleration & Collider Ring
Total transmission efficiency is **70-80 %**

- Goal of the European strategy plan is optimizing each element
  - Ex) Improve performance for each
  - Ex) Check feasibility and practicality
- We approach the same goal with a unique way

Targetry and Cooling

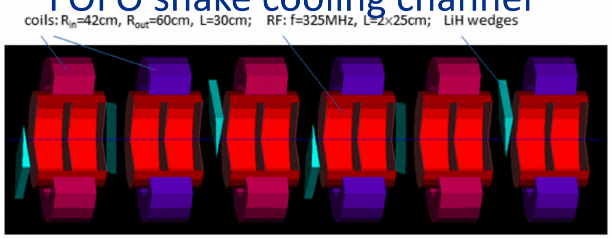
- Multi-Mega Watt Target
- Pion capture structure
- Muon ionization cooling
  - Rectilinear channel
  - FOFO snake channel
  - Final cooling channel
- <u>Better cooling allows us to design more practical accelerator element</u>

Solenoid base multi-MW target + capture solenoid

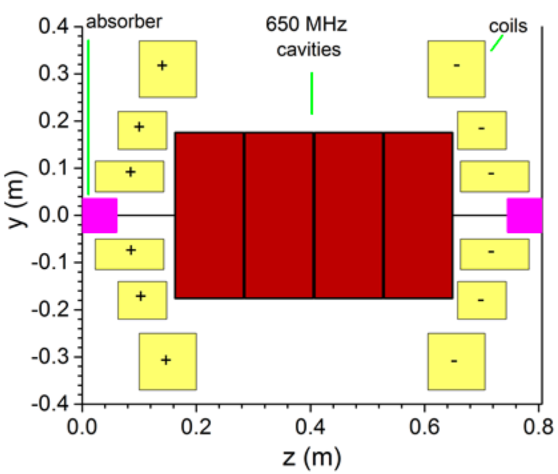


Shielding of the superconducting magnets from radiation is a major issue.
Magnetic stored energy ~ 3 GJ!

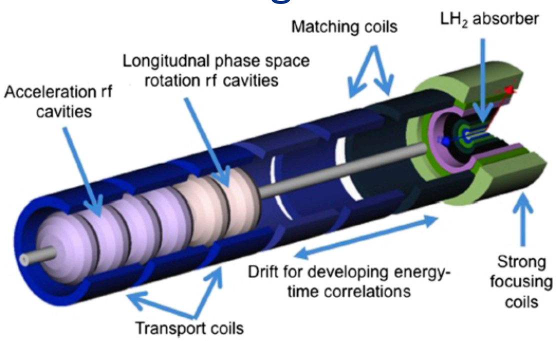
FOFO snake cooling channel



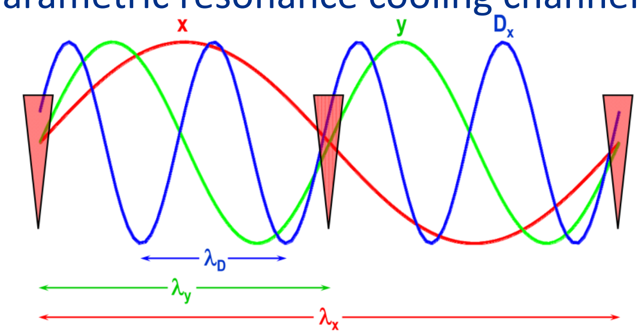
Rectilinear channel



Final cooling channel



Parametric resonance cooling channel



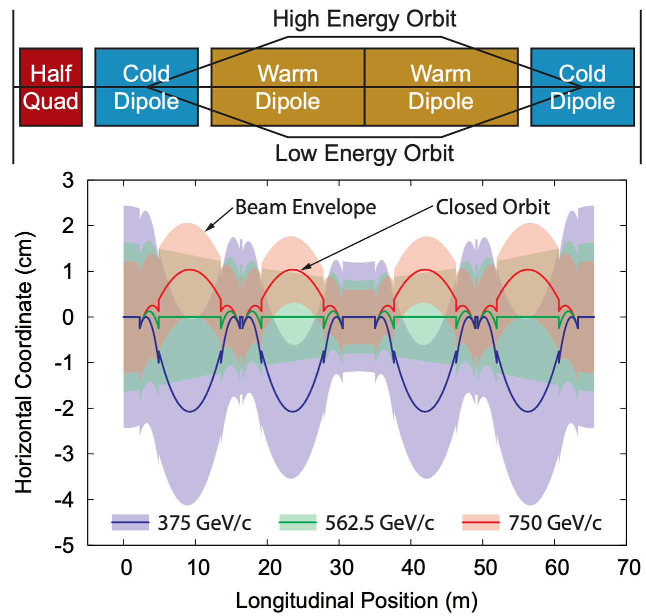
Accelerator options

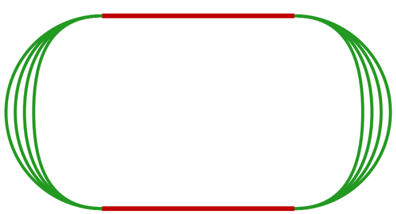
- Rapid Cycling Synchrotron (RCS) or Pulsed Synchrotron
- Fixed Field alt. grad. Accelerator (FFA)
- Vertical FFA
- Recirculating Linear Accelerator (RLA)
- Each option has pros/cons

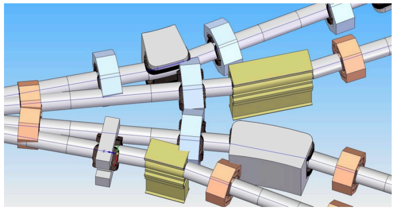
Summary:

- RCS can be most efficient though
  - High average bend field
  - Larger number of turns
  - Pow. Supp. would be a cost driver
- FFAs are a good alternative
- Collective effects may be significant

Pulsed synchrotron



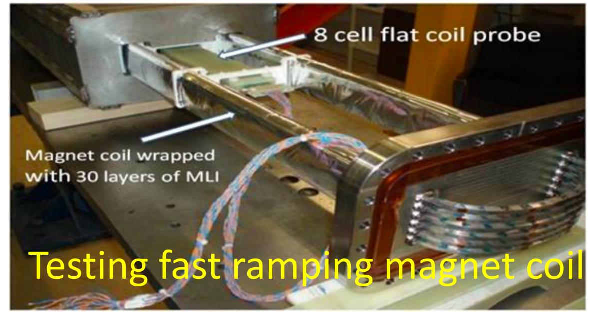


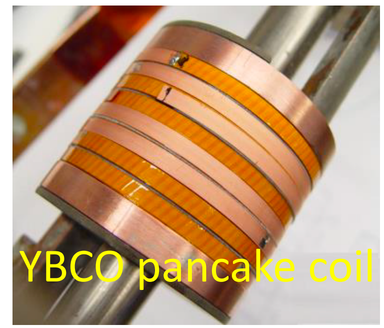


Highlights from Sasha and Tianhuan

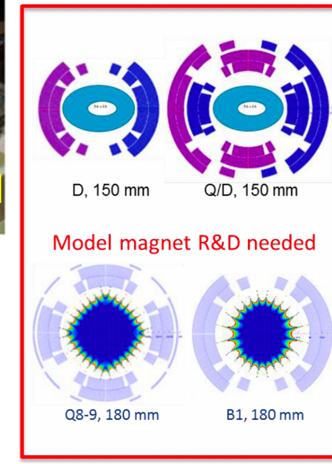
Magnet

- 20-Tesla production target solenoid
  - Extend advanced Detector & Fusion technologies
- 50-Tesla cooling solenoid
  - Extend advanced LTS-HTA Hybrid solenoid technology
- Fast ramping magnet: Increase B and f
- Large bore final focusing magnet



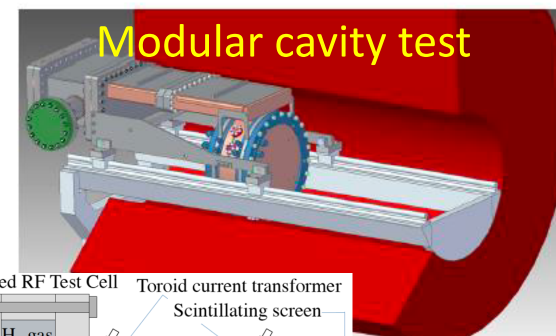


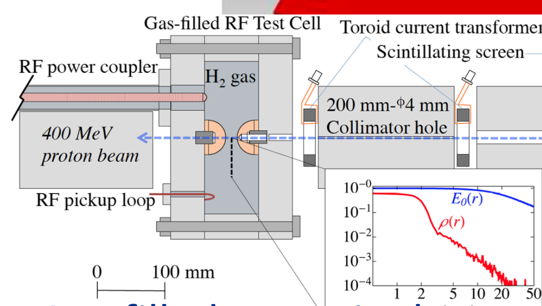
Large bore IR magnet



RF

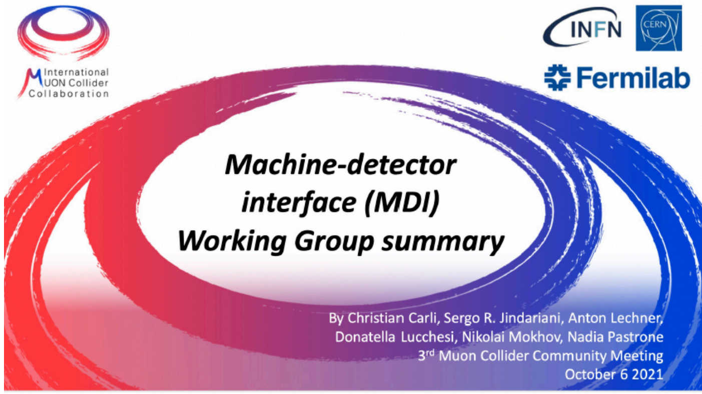
- Continue R&D
  - High gradient NCRF in multi-Tesla fields
  - Beam loading & plasma simulation
  - Damage tolerance of SRF by decayed muon
- Integrate RF system into cooling magnets
- RF power source





Gas-filled RF cavity beam test

Highlights from Nadia, Nikolai and Christian



MDI WG Summary

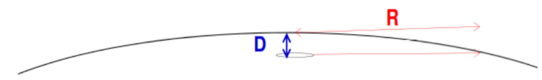
Can base the new studies on the valuable experience gained within MAP (N. Mokhov et al.)

- Study the beam-induced background and identify mitigation strategies
- Develop a **(conceptual) interaction region (IR) design** that yields background levels compatible with detector operation, i.e. show that
  - ➢ the desired physics performance can be reached
  - ➢ the cumulative radiation damage in the detector remains acceptable
- Address **different centre-of-mass energies**, with particular attention to:
  - ➢ **3TeV**
  - ➢ **10TeV** (IR design to be scaled up further to **14TeV** if needed)

✓ By end of 2022, aim to have a **first level IR optimization**
 3 TeV option: start optimizing the IR design starting from MAP layout
 10 TeV option: obtain a first IR design, first quantification of background
✓ By 2025, aim to have a **mature IR design**
 Demonstrate feasibility of reaching detector performance goals for both collider options
✓ Meetings with common discussions inviting contact persons from other WPs
✓ Interface with Snowmass is important

7 ways to mitigate neutrino flux around muon colliders

1. Place collider deep underground
2. Isolate MC site from residential area
3. Minimize Field-Free regions
4. Beam Wobbling or/and 5. Magnet Movers (CERN approach)
6. Reduce Muon Beam Intensity by Better cooling or/and 7. Strong final focusing

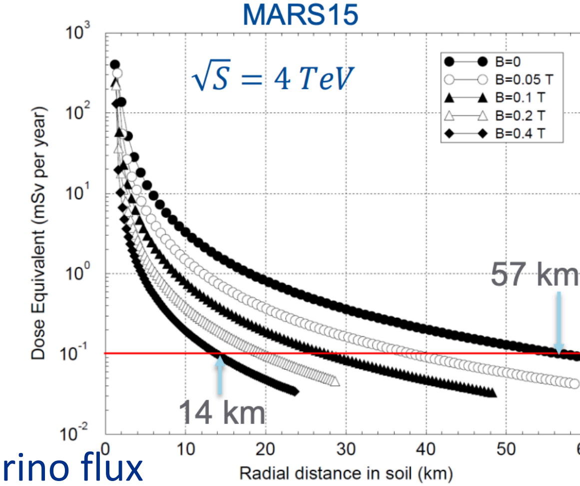


$$R = \sqrt{2R_{earth}D}$$

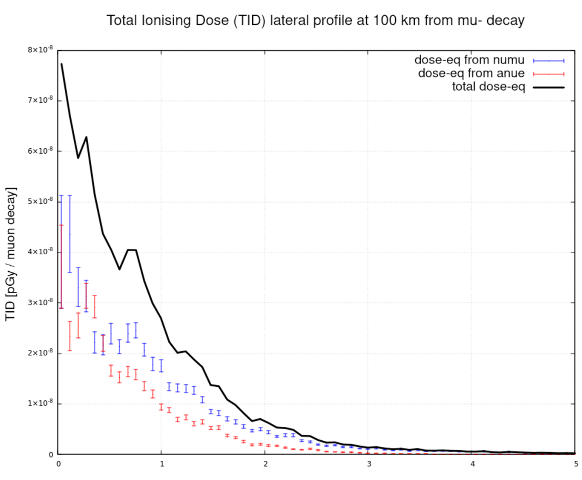
	$\sqrt{s}$ (TeV)	0.5	1	2	3	4
	$N \times 10^{21}$	0.2	0.2	1.2	1.2	1.2
1 mSv	R (km)	0.4	1.1	6.5	12	18
	D (m)	≤ 1	≤ 1	3.3	11	25
0.1 mSv	R (km)	1.2	3.2	21	37	57
	D (m)	≤ 1	≤ 1	34	107	254

0.01 mSv/yr -> D=300 m for 3TeV case

Beam wobbling



CERN has started working neutrino flux study



Apply geoprofile to estimate neutrino flux

Highlights from Wei (Muon-Ion collider)

Design Parameters

	MuIC (BNL, or FNAL?)				LHmuC (CERN)
E_p (GeV)	0.275			0.96 (upgrade)	7
E_μ (GeV)	0.1	0.5	0.96	0.96	1.5 (IMCC)
	(staged muon energy)				
$\sqrt{s_{\mu p}}$ (GeV)	0.33	0.74	**1.0**	1.92	**6.5**
L_{int} ($\times 10^{33}$ $cm^{-2}s^{-1}$)	0.63	3.1	6	6	4.3

MuIC: re-use EIC (polarized) hadron/ion ring at BNL (or FNAL?)

- **~8x EIC energy**: a new frontier of QCD, EWK and nuclear physics
- Another **2x** if upgrading the hadron ring

LHmuC: re-use LHC ring at CERN and run concurrently with 3 TeV $\mu^+\mu^-$ (IMCC)

– exceeding FCC-eh energy (100km tunnel)!

Acosta, Li

Extra slides

- Vladimir itemized “Educated Guess”
- Daniel Schulte commented those items (font colored blue)

“Educated Guess” of Vladimir, with comments

- Theory and MDI work – with EF and TF
  - We need to strengthen this key area
- Machine design: optics and beam physics issues, incl. ~~neutrino hazard and~~ neutrino flux mitigation
  - Neutrino flux impact benchmarking, impact on beam operation and technologies are common
  - All lattice designs can be common for all energies, with exception of last accelerator and collider rings
  - Could find a very efficient setup
- Proton driver accumulator and bunch compressor design – synergy with post-PIPII FNAL complex
  - Would appreciated help in proton complex design for the collider in collaboration with ESS
- Muon cooling IMCC magnet, RF & diagnostics design work
  - We have tasks for each technology and we plan to design a muon cooling module for the test facility
  - also have to work on absorbers (including windows)

“Educated Guess” of Vladimir, with comments

- Muon acceleration RF – simulations and exp test beam loading in ILC-type cavities at FNAL FAST
  - we are looking into beam loading effects, tests are good, should consider other frequencies when possible
- Muon acceleration fast cycling 500-1000 T/s HTS magnet prototypes
  - should also consider field range, normal conducting magnets are also critical (10kT/s)
- 12-16 T dipoles design and tests, incl. mechanical tilt – synergetic with the US MDP
  - Yes. should also consider NbTi for 3 TeV and HTS for 10 TeV. Is 20 T feasible?
  - I guess mechanical tilt is neutrino flux mitigation? Very important.
- 2-4 MW proton target design and development – with GARD targets
  - a number of technologies to be considered: graphite, fluidized tungsten, liquid metal, …
- MC Target magnet design - synergetic with IMCC
  - in particular the shielding and the stress are important
- Final cooling solenoids design and HTS short magnets tests – synergetic with US MDP
  - yes

"Educated Guess" of Vladimir, with comments

- Final focus quadrupoles – design extension beyond US LARP/LHC AUP
  - yes
- (Later) compile (pre-) CDR, come up with semi-engineering "bottom-to-top" cost estimates O(50%) range for a) various options of high energy MC; b) objecvtives, cost and timeline of the post-CDR US MC R&D program 2030-2036
- Do you consider test facility in US? Shall there be one common effort for test facilities or one per site?
- We need a new test stand for the muon cooling RF (magnetic field is unique, CEA might go for one in the long run))
- Targets and absorbers require experimental work
- Need also to include other fields of expertise
  - cryogenics, vacuum, …
- May need to think how we can prepare cost estimate for efficient use in all regions