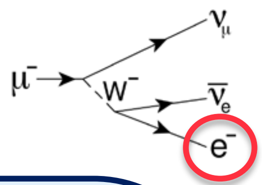
Working Group summary: Radiation challenges due to beam losses

D. Calzolari, A. Lechner
On behalf of many colleagues
Muon Collider Collaboration Meeting
October 14 2022

International MUON Collider Collaboration

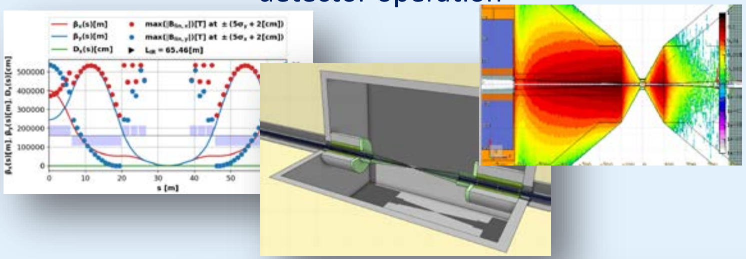
CERN

Introduction



Physics background and radiation damage in detector

Develop a credible **interaction region (IR) design** that yields background levels compatible with detector operation

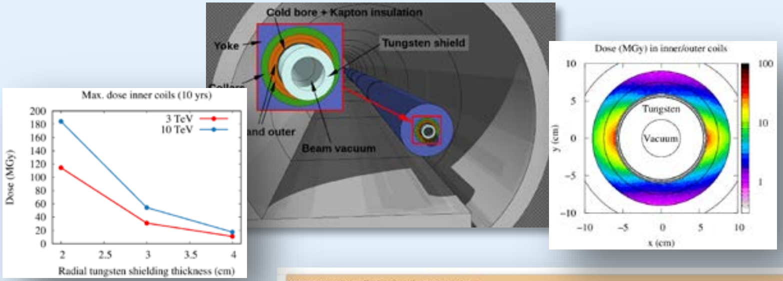


Machine-induced background studies for 1.5 TeV and 3 TeV	*Dr Francesco Collamati*
40/S2-D01 - Salle Dirac, CERN	10:50 - 11:10
…r	*Kyriacos Skoufaris*
	11:10 - 11:30
…e 10 TeV Muon Collider	*Daniele Calzolari*
	11:30 - 11:50
How to use BIB data as input for the detector design	*Nazar Bartosik*
40/S2-D01 - Salle Dirac, CERN	11:50 - 12:10
Magnetic field configurations for the detector	*John Hauptman*
40/S2-D01 - Salle Dirac, CERN	12:10 - 12:30

MDI session, jointly between Physics & Detectors - High-Energy Complex (**Wed, 10h50**)

Heat load and radiation damage in accelerator systems (magnets)

Develop a **shielding design** to sustain the thermal load and to prevent system (magnet) failures due to cumulative radiation damage



R&D towards radiation-hard HTS magnets	*iio masami*
30/7-010, CERN	14:00 - 14:20
Effect of radiation on stabilizer - impact on stability and protection	*Makoto Yoshida*
30/7-010, CERN	14:25 - 14:45
…rgy deposition at the muon collider	*Anton Lechner et al.*
	14:50 - 15:10
…n superconductors summary	*Michael Eisterer*
30/7-010, CERN	15:15 - 15:35
Radiation effects in HTS compact fusion devices	*Zachary Hartwig*
30/7-010, CERN	15:40 - 16:00

Session on radiation damage in magnets (**Wed, 14h00**)

Power load on magnets in different circular machines

(assuming 5 Hz injection frequency)

	HL-LHC		FCC-ee (CDR)	MC ($\sqrt{s}$=3 TeV)	MC ($\sqrt{s}$=10 TeV)
Particles	p		e-/e+	μ-/μ+	μ-/μ+
Particle energy	7 TeV		45.6 … 182.5 GeV	1.5 TeV	5 TeV
Bunches/beam	2760		16640 … 48	1	1
Bunch intensity	2.2×10^{11}		1.8×10^{11} … 2.3×10^{11}	2.2×10^{12}	1.8×10^{12}
Circumference	26.7 km		97.8 km	4.5 km	10 km
Main heat source	pp debris	E-cloud	Synchrotron rad.	Muon decay	Muon decay
Region	Triplet+D1	Arcs	arcs	entire ring	entire ring
Power/meter*	**few 10^{-2} kW/m**	**few 10^{-3} kW/m**	**1.2 kW/m**	**0.4 kW/m****	**0.5 kW/m****
Magnets	**superconducting**		**warm**	**superconducting**	**superconducting**

* Includes contribution from both beams

** Values correspond to **power carried by decay e-/e+** (=1/3 of muon energy)
Here it is **NOT** assumed that the beam is **extracted after a certain number of turns**.

MC = unprecedented power load in a cold machine!

Radiation impact on collider ring magnets

International MUON Collider Collaboration

Muon decay, halo losses

**Point-like quantity*

Decay rate, halo loss rate →

Integral number of decays, integral halo losses (over collider lifetime) →

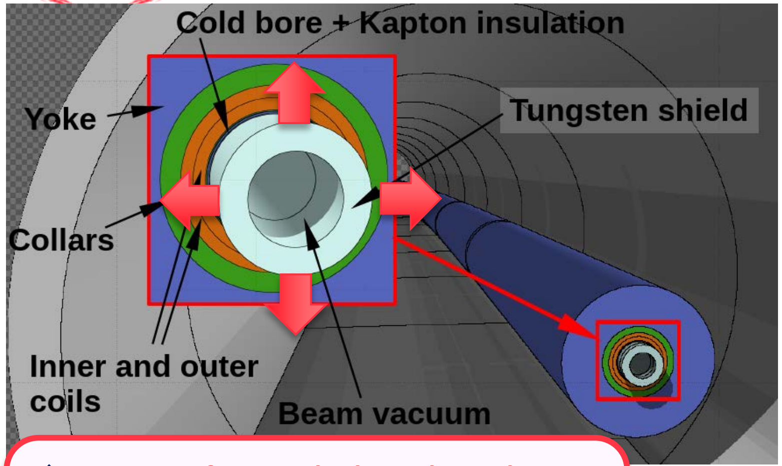
Instantaneous heat deposition

- **Power density in coils*** → must remain safely below quench level of magnets
- **Total power deposition in cold mass** → must be compatible with realistic cooling capacity (costs!), (*most of the heat load must be extracted at higher temperature than the op. temp. of SC magnets*)

Long-term radiation damage

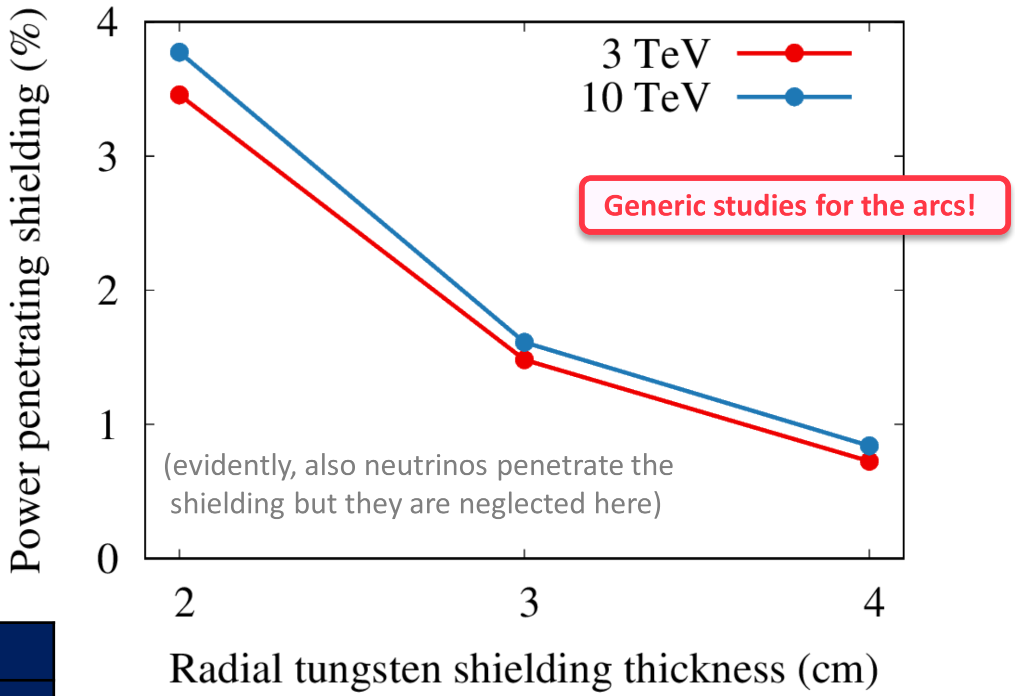
- **Ionizing dose*** (organic materials for *insulation, coil impregnation, etc.*) → must remain below critical level for full collider lifetime
- **Atomic displacements*** (*superconductor, stabilizer*) → must remain below critical level for full collider lifetime

Muon decay: power penetrating shielding



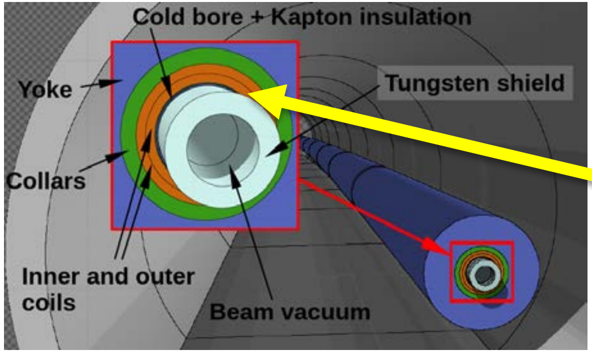
- **Fraction of power leaking through shielding similar for 3 TeV & 10 TeV**
- This power is mostly deposited in cold mass (including cold bore)

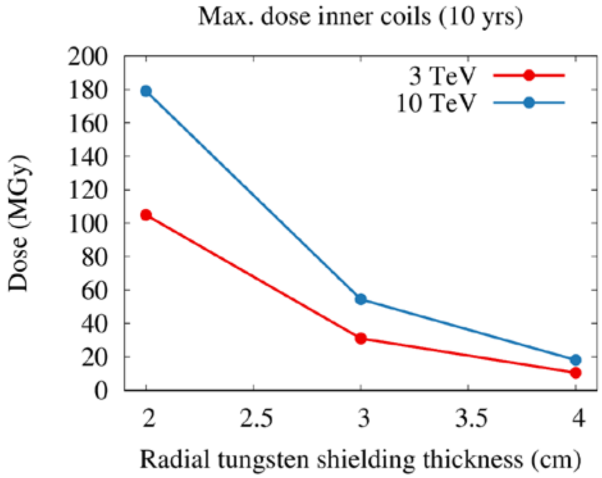
	Power carried by decay e^-/e^+:	Power penetrating shielding		
		2 cm	3 cm	4 cm
3 TeV	410 W/m	14 W/m	6 W/m	3 W/m
10 TeV	500 W/m	18 W/m	8 W/m	4 W/m

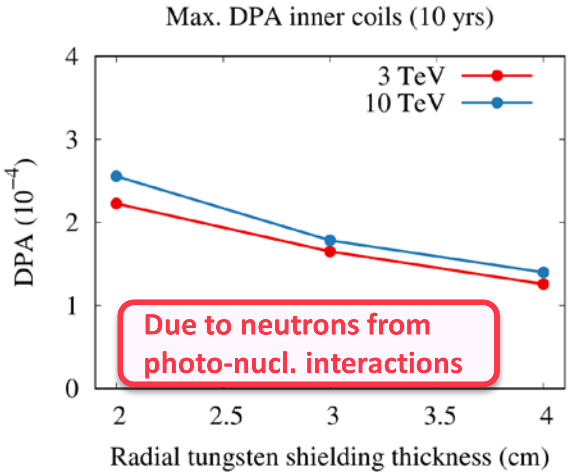


Ideally should stay below 1-2%: **can be achieved with 3-4 cm of W shielding**

Muon decay: cumulative dose and DPA in coils of (generic) arc dipoles







Assumptions:

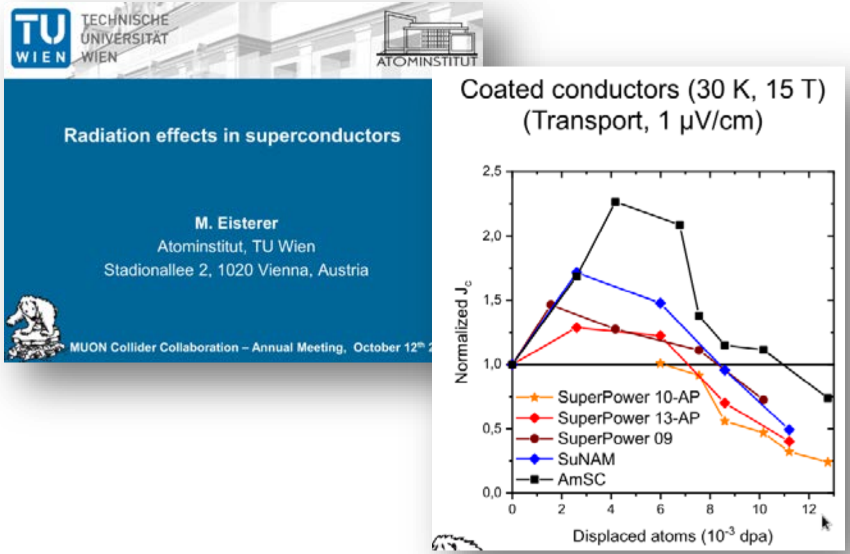
- **200 days operation/year** (conservative 100% machine availability)
- **10 years** of operation

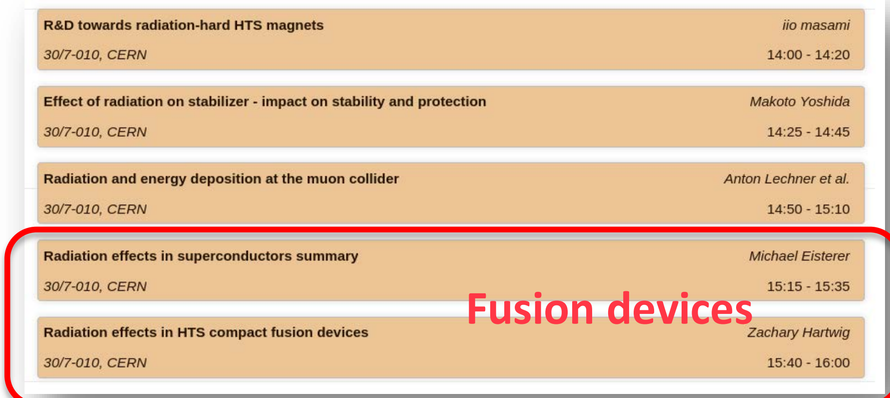
With **4 cm tungsten shielding**, the ionizing dose is **<20 MGy** in coils after 10 years → feasible to use presently existing insulation materials

Neutron fluence/DPA shows (as expected) small dependence on shielding thickness: **2-5x10^{17}n/cm^2** / **1-3x10^{-4} DPA** (10 years)

Degradation of superconductor properties with DPA

- Can profit from the knowledge gained in irradiation experiments carried out for fusion and other applications





R&D towards radiation-hard HTS magnets	*iio masami*
30/7-010, CERN	14:00 - 14:20
Effect of radiation on stabilizer - impact on stability and protection	*Makoto Yoshida*
30/7-010, CERN	14:25 - 14:45
Radiation and energy deposition at the muon collider	*Anton Lechner et al.*
30/7-010, CERN	14:50 - 15:10
Radiation effects in superconductors summary	*Michael Eisterer*
30/7-010, CERN	15:15 - 15:35
Radiation effects in HTS compact fusion devices	*Zachary Hartwig*
30/7-010, CERN	15:40 - 16:00

Fusion devices

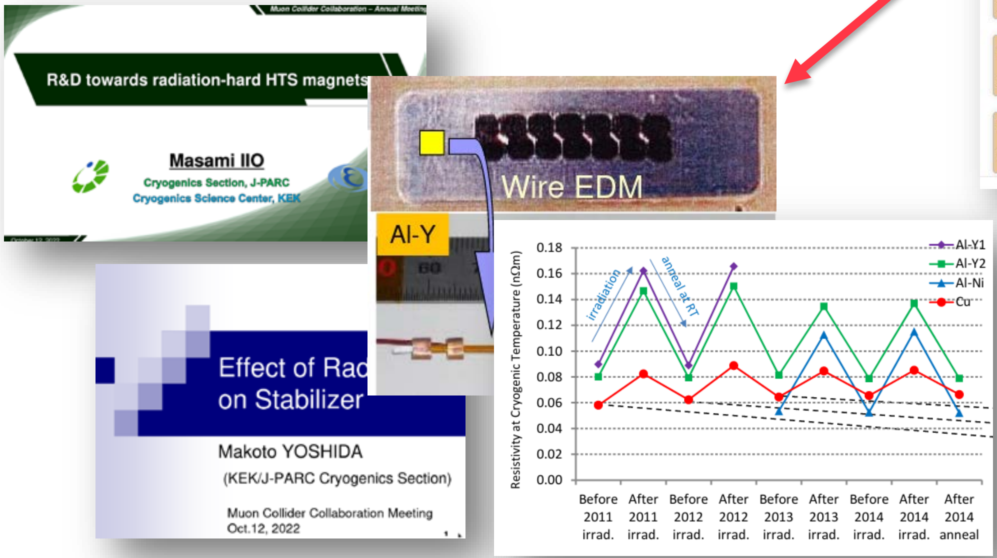
- HTS sample degradation observed **above 10^{-3} DPA, i.e. at larger values expected in muon collider ring**
- An optimized annealing strategy is promising to mitigate degradation

Degradation of stabilizer properties with DPA

- Can profit from the knowledge gained in irradiation experiments carried out for fusion and other applications

J-PARC pion capture solenoid

R&D towards radiation-hard HTS magnets	*iio masami*
30/7-010, CERN	14:00 - 14:20
Effect of radiation on stabilizer - impact on stability and protection	*Makoto Yoshida*
30/7-010, CERN	14:25 - 14:45
Radiation and energy deposition at the muon collider	*Anton Lechner et al.*
30/7-010, CERN	14:50 - 15:10
Radiation effects in superconductors summary	*Michael Eisterer*
30/7-010, CERN	15:15 - 15:35
Radiation effects in HTS compact fusion devices	*Zachary Hartwig*
30/7-010, CERN	15:40 - 16:00



- Coil stabilizers (Al, Cu) showed increased electric resistivity below 10^{17} n/cm^2
- Can be recovered with regular annealing cycles (warm-up)

Radiation load to collider magnets - summary & outlook

- All magnets in the collider ring will be exposed to a high radiation load due to μ-decay
- Generic shower simulation studies show that the **magnet shielding requirements** are **similar** for the **3 TeV** and **10 TeV colliders**
- With a **~4 cm thick tungsten shielding (on each side)**, we expect that the power load and cumulative radiation damage in magnets can be reduced to **acceptable values**:
  - <5W/m to cold mass,
  - <20 MGy/10 yrs,
  - 2×10^{-4} DPA/10 yrs (3×10^{17} n/cm^2/10yrs)
- Next steps: converge on the required beam aperture and repeat shower simulation studies for a realistic lattice, extend simulations to IR magnets
- Possible benefits of other configurations (MAP-like open midplane dipoles) to be studied
- Synergies with other projects (radiation damage experiments) to be fostered

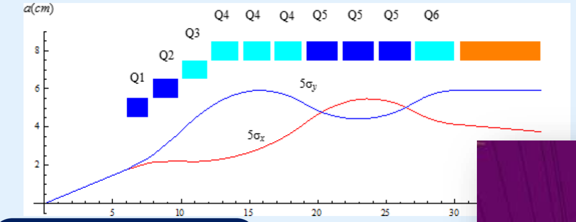
Machine-Detector Interface (MDI)

- Study the beam-induced physics background and identify mitigation strategies
- Develop a credible (**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 the two distinct energy regimes under consideration:
  - $\sqrt{s}$ = **3 TeV**
  - $\sqrt{s}$ = **10 TeV** (IR design to be scaled up further to $\sqrt{s}$ = **14 TeV** if needed)

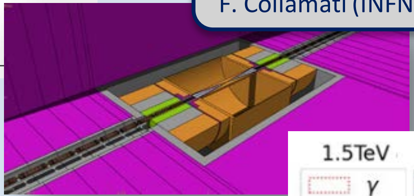
In close collaboration with **Physics and Detector WG** and others!

IR design and BIB studies for $\sqrt{s}$ = 3 TeV collider

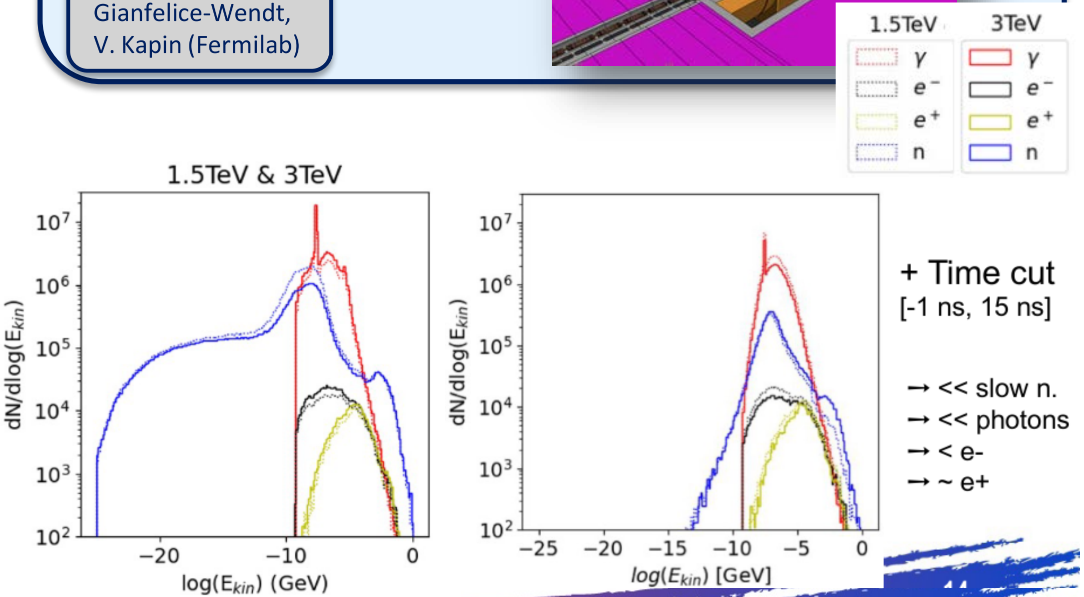
- $\sqrt{s}$ = 3 TeV BIB studies with FLUKA:
  - The procedure used to verify the beam-induced background at $\sqrt{s}$ = 1.5 TeV (F. Collamati et al 2021 JINST 16 P11009) is being used to study background at $\sqrt{s}$ = 3 TeV
  - Nozzle inspired by 1.5 TeV MAP design (N. Mokhov)
- Lattice and optics from Y. Alexahin et al 2018 JINST 13 P11002
  - L* = **6 m**
  - **Quadruplet** final focus with combined function magnets (ß* = 5 mm)
  - Maximum field at inner bore is **12 T**



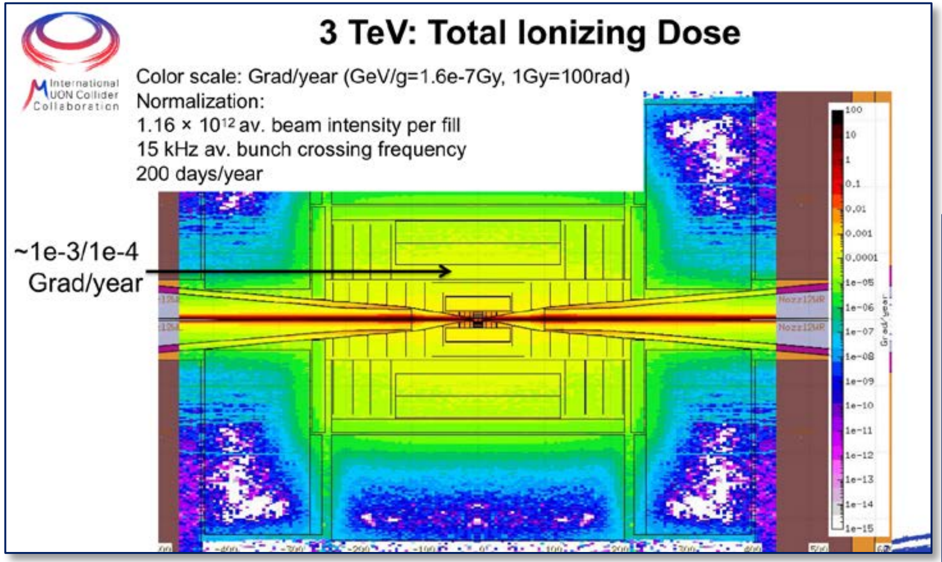
Y. Alexahin, E. Gianfelice-Wendt, V. Kapin (Fermilab)



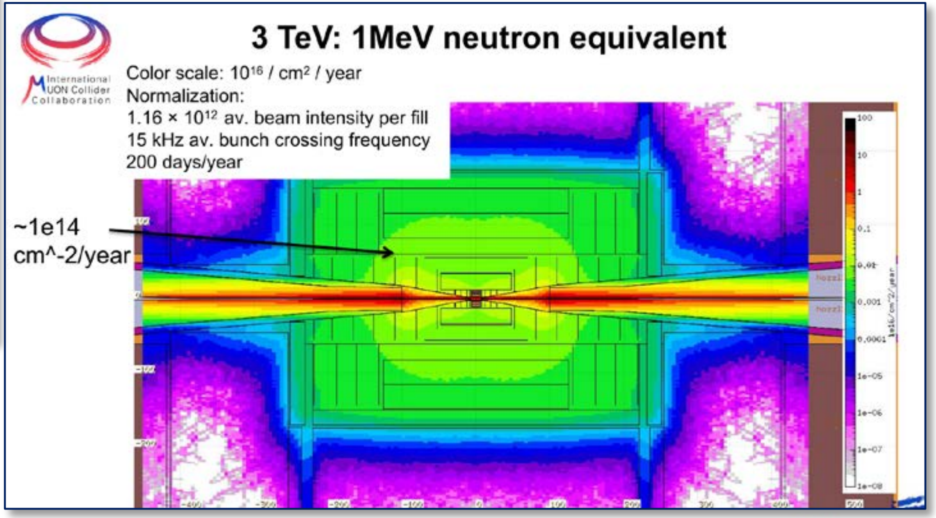
A. Mereghetti (CNAO), C. Curatolo (INFN), F. Collamati (INFN) et al.



Long-term radiation effects in the $\sqrt{s}$ = 3 TeV detector

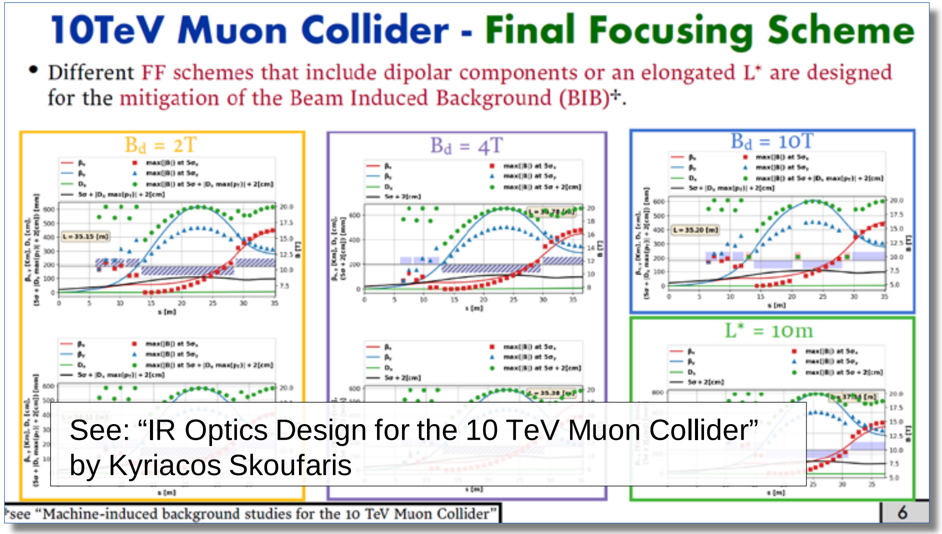


See: "Machine-induced background studies for 1.5 TeV and 3 TeV" by F. Collamati on behalf of the MDI group



IR design and BIB studies for $\sqrt{s}$ = 10 TeV collider

- First IR design with and without dipolar magnetic fields in final focus to understand BIB:
  - L* = **6 m, triplet layout** (ß* = **1.5 mm**)
  - Max field at inner bore is **20 T**
- Chromatic correction scheme:
  - Combined function quadrupoles and sextupoles to mitigate neutrino radiation hot spots
- Status of 10 TeV BIB studies with FLUKA:
  - Nozzle: 1.5 TeV MAP design (N. Mokhov) as starting point
  - First results showed that # of BIB particles is similar to lower energies

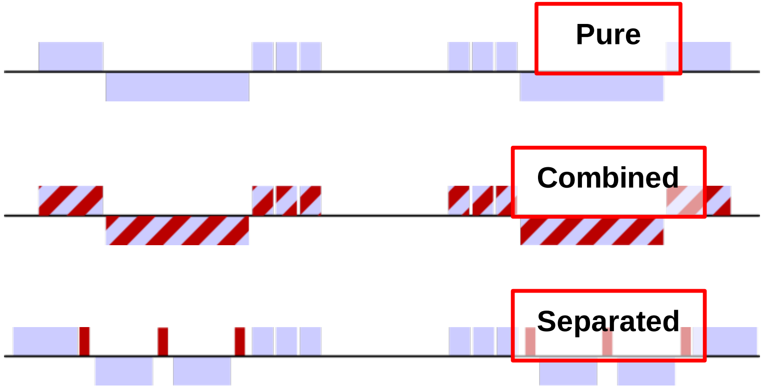


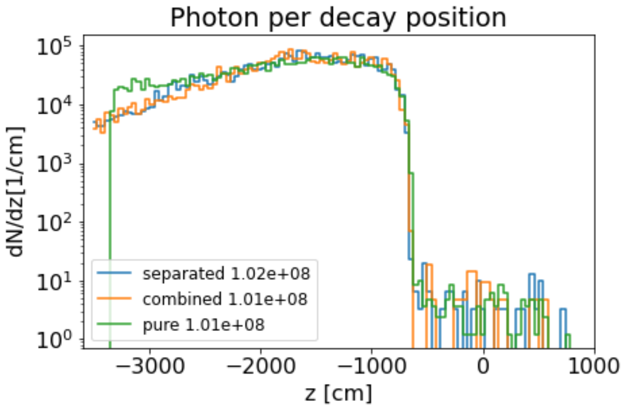
Nozzle not yet optimized for these energies

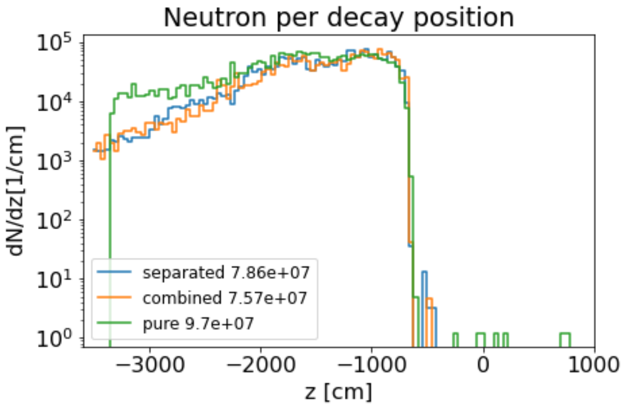
Monte Carlo simulator	MARS15	MARS15	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	62.5	750	750	1500	5000
μ decay length [m]	$3.9 \cdot 10^5$	$46.7 \cdot 10^5$	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$51.3 \cdot 10^5$	$4.3 \cdot 10^5$	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$170 \cdot 10^6$	$86 \cdot 10^6$	$51 \cdot 10^6$	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$65 \cdot 10^6$	$76 \cdot 10^6$	$110 \cdot 10^6$	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$1.3 \cdot 10^6$	$0.75 \cdot 10^6$	$0.86 \cdot 10^6$	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadrons ($E_{h^\pm} > 0.1$ MeV)	$0.011 \cdot 10^6$	$0.032 \cdot 10^6$	$0.017 \cdot 10^6$	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0012 \cdot 10^6$	$0.0015 \cdot 10^6$	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

$\sqrt{s}$ = 10 TeV: effect of final focus layout on BIB

- Different lattice possibilities have been investigated for the final focusing region: using only quadrupoles (**pure**), **combined** function magnets or adding dipole magnets between quadrupoles (**separated**).
- Despite the dipolar component is reducing the BIB, the overall **mitigation** is **limited**.



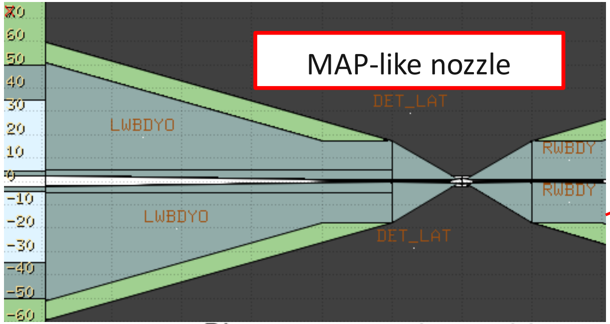


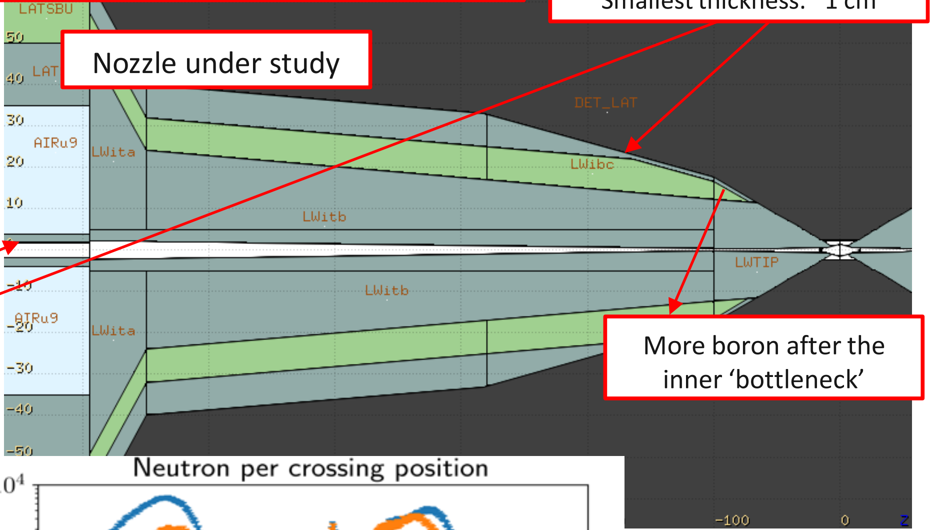


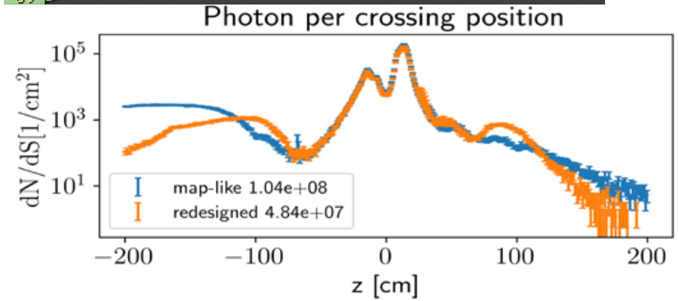
$\sqrt{s}$ = 10 TeV: nozzle optimization for BIB reduction

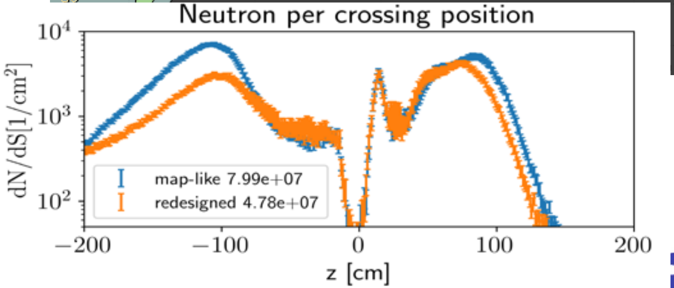
- Considering the particles going in the detector area, a tentative **nozzle** geometry reshaping has been conducted based on the **1.5 TeV MAP nozzle**.
- From preliminary results, the possibility of reducing the BIB is **sizable**.

- Shower development is forward peaked, we can optimize the tungsten nozzle shape.
- To further reduce the neutron component, the borate PE layer is extended towards the IP.



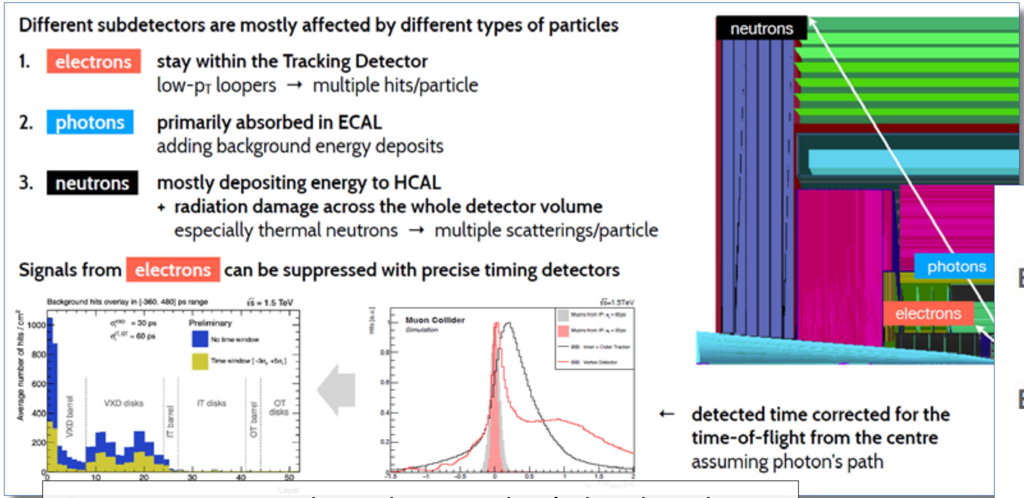






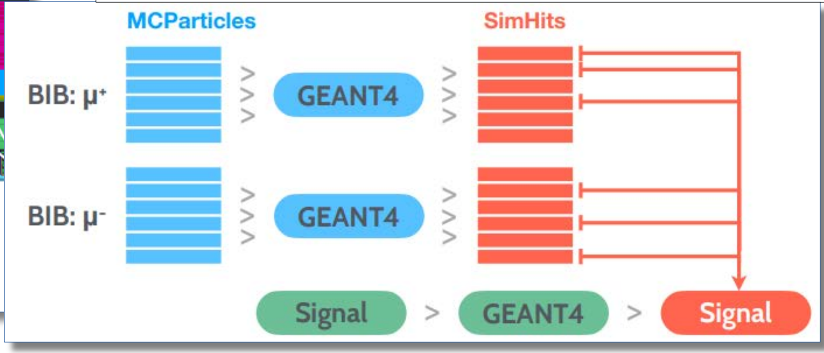
BIB in detectors

- CLIC-like detectors geometry are considered for the muon collider
- Detectors response is currently under study. A common framework to share BIB data among the community is under development (= lot of work to do!)



See: "Detector Design using BIB simulation data" by Nazar Bartosik

See: "How to use BIB simulation data in analysis" by Nazar Bartosik



MDI studies and IR design - summary & outlook

- First studies based on the MAP nozzle design* showed that the **beam-induced background** (# of BIB particles entering the detector envelope) is **comparable at different center of mass energies** (1.5 – 3 – 10 TeV)
- **Optimizing the nozzle** has a larger potential to decrease the BIB than adding a dipolar component in the final focus region
- The effect of a **larger L*** (10 m instead of the present 6 m) on the BIB is currently **under investigation** for the 10 TeV collider
- Further steps: iterate on the nozzle design – the idea is to use a simple metric for a general optimization, a larger background sample is then generated for “reference” IR+layouts as input for detector simulations

*Optimized for 1.5 TeV

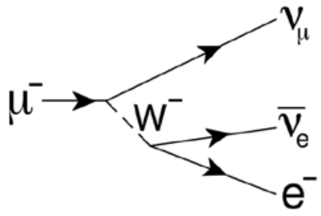
International MUON Collider Collaboration

CERN

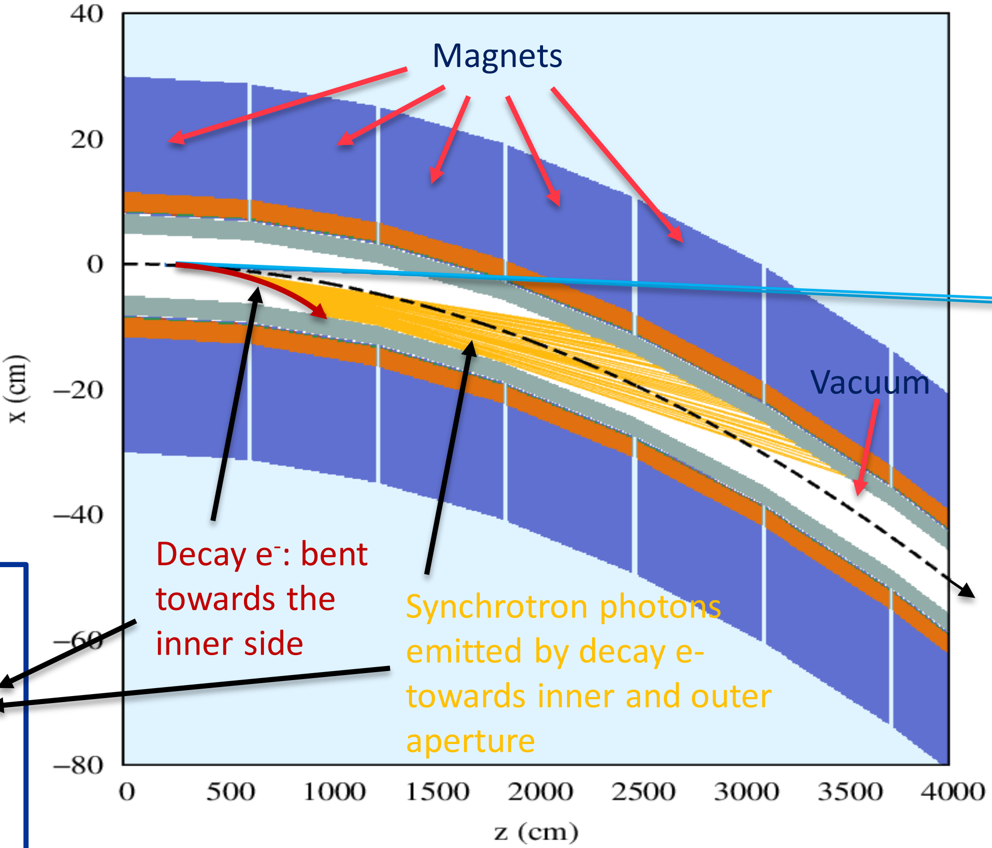
Thank you for your attention!

International MUON Collider Collaboration

Muon decay in the collider – a qualitative view



e^- carries on average 35% of muon energy



Picture shows the horizontal plane of a generic arc section (dipoles only)

Decay neutrinos: irrelevant for radiation load to machine

Black dashed line: μ^- beam trajectory

Inside magnets:
- Secondary EM cascades (e^-, e^+, γ)
- Neutron production (photo-nuclear interactions)

Similar picture applies to $\mu+$

Recap of main radiation sources in the MC (in regular collider operation)

- Certainly a **main source of detector background** for all collider options
- The **main source** of **heat load** and **radiation effects** in collider equipment
- Neutrinos give rise to dose at large distances (Radiation Protection)

- Potential source of detector background
- Was found not to be an issue at energy of $\sqrt{s}$=2 TeV* (with a solenoid field of a few T)
- **Nevertheless to be studied for the $\sqrt{s}$=10+ TeV collider option**

- **Muon decay** around the ring
- **Incoherent e^-/e^+ pair production** during bunch crossing in IP
- **Beam-halo losses** at aperture bottlenecks

- Halo losses near detector can yield non-negligible background contribution
- Possible impact on machine equipment to be assessed
- **Acceptable halo loss levels to be defined (halo cleaning)**

*See also talk of **N. Mokhov**
1st Muon Collider community meeting