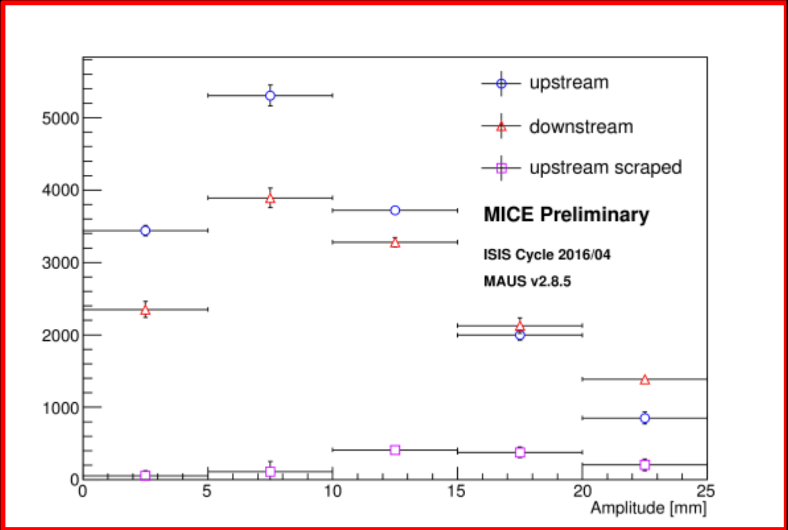
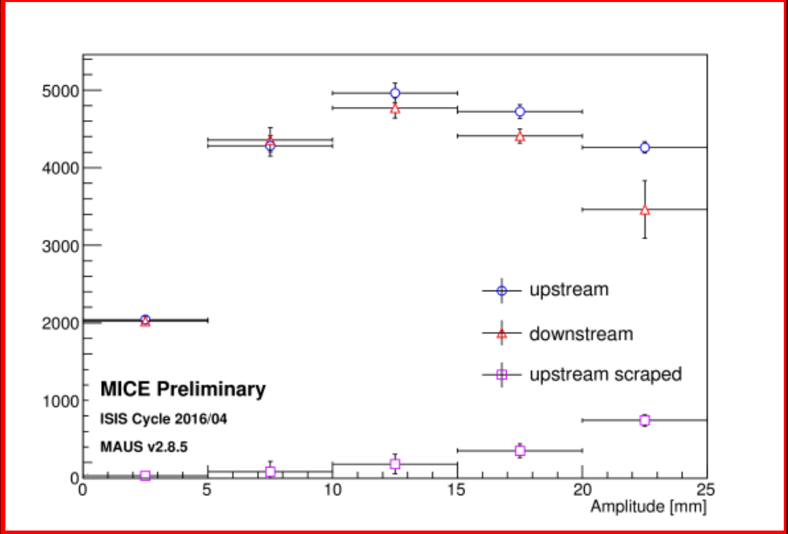
Spokesman’s update

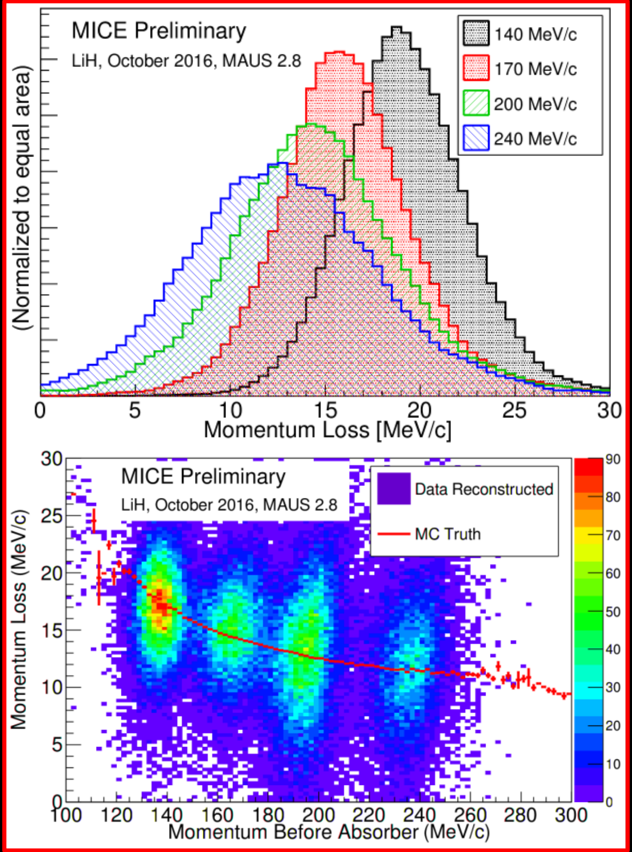
All-hands meeting

K. Long, 25 May, 2017

New for IPAC17



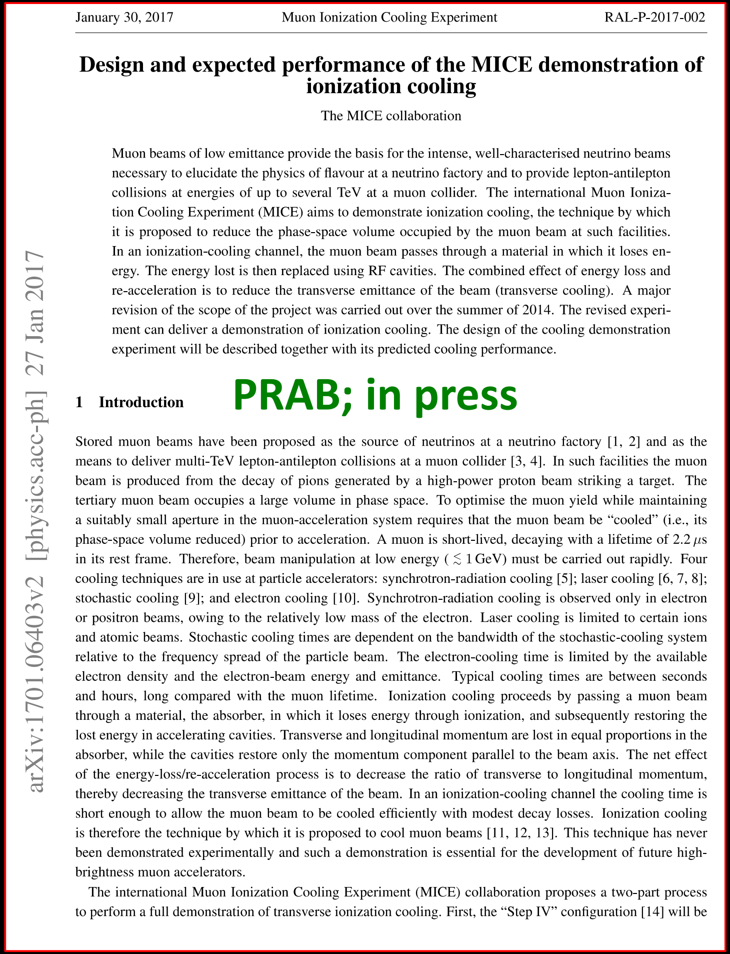




MICE presenters:

- C. Rogers
- P. Franchini
- C. Hunt
- T. Monahai

Demonstration of ionization cooling



January 30, 2017 Muon Ionization Cooling Experiment RAL-P-2017-002

Design and expected performance of the MICE demonstration of ionization cooling

The MICE collaboration

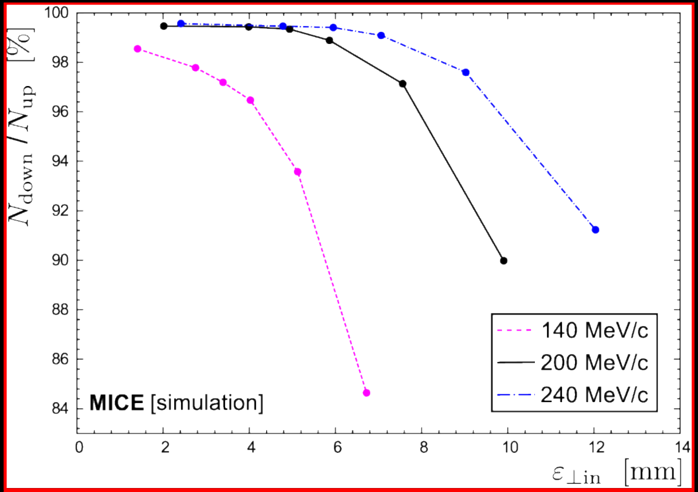
Muon beams of low emittance provide the basis for the intense, well-characterised neutrino beams necessary to elucidate the physics of flavour at a neutrino factory and to provide lepton-antilepton collisions at energies of up to several TeV at a muon collider. The international Muon Ionization Cooling Experiment (MICE) aims to demonstrate ionization cooling, the technique by which it is proposed to reduce the phase-space volume occupied by the muon beam at such facilities. In an ionization-cooling channel, the muon beam passes through a material in which it loses energy. The energy lost is then replaced using RF cavities. The combined effect of energy loss and re-acceleration is to reduce the transverse emittance of the beam (transverse cooling). A major revision of the scope of the project was carried out over the summer of 2014. The revised experiment can deliver a demonstration of ionization cooling. The design of the cooling demonstration experiment will be described together with its predicted cooling performance.

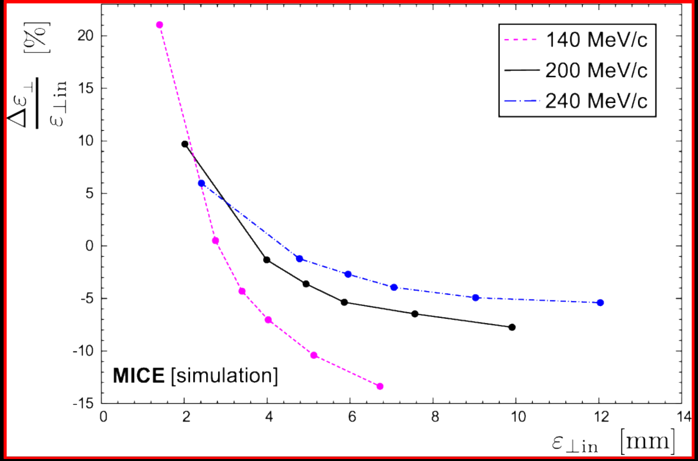
1 Introduction

PRAB; in press

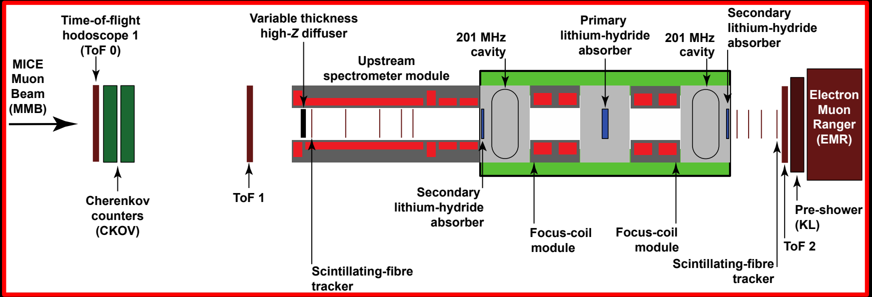
Stored muon beams have been proposed as the source of neutrinos at a neutrino factory [1, 2] and as the means to deliver multi-TeV lepton-antilepton collisions at a muon collider [3, 4]. In such facilities the muon beam is produced from the decay of pions generated by a high-power proton beam striking a target. The tertiary muon beam occupies a large volume in phase space. To optimise the muon yield while maintaining a suitably small aperture in the muon-acceleration system requires that the muon beam be "cooled" (i.e., its phase-space volume reduced) prior to acceleration. A muon is short-lived, decaying with a lifetime of 2.2 μs in its rest frame. Therefore, beam manipulation at low energy ($\lesssim 1$ GeV) must be carried out rapidly. Four cooling techniques are in use at particle accelerators: synchrotron-radiation cooling [5]; laser cooling [6, 7, 8]; stochastic cooling [9]; and electron cooling [10]. Synchrotron-radiation cooling is observed only in electron or positron beams, owing to the relatively low mass of the electron. Laser cooling is limited to certain ions and atomic beams. Stochastic cooling times are dependent on the bandwidth of the stochastic-cooling system relative to the frequency spread of the particle beam. The electron-cooling time is limited by the available electron density and the electron-beam energy and emittance. Typical cooling times are between seconds and hours, long compared with the muon lifetime. Ionization cooling proceeds by passing a muon beam through a material, the absorber, in which it loses energy through ionization, and subsequently restoring the lost energy in accelerating cavities. Transverse and longitudinal momentum are lost in equal proportions in the absorber, while the cavities restore only the momentum component parallel to the beam axis. The net effect of the energy-loss/re-acceleration process is to decrease the ratio of transverse to longitudinal momentum, thereby decreasing the transverse emittance of the beam. In an ionization-cooling channel the cooling time is short enough to allow the muon beam to be cooled efficiently with modest decay losses. Ionization cooling is therefore the technique by which it is proposed to cool muon beams [11, 12, 13]. This technique has never been demonstrated experimentally and such a demonstration is essential for the development of future high-brightness muon accelerators.

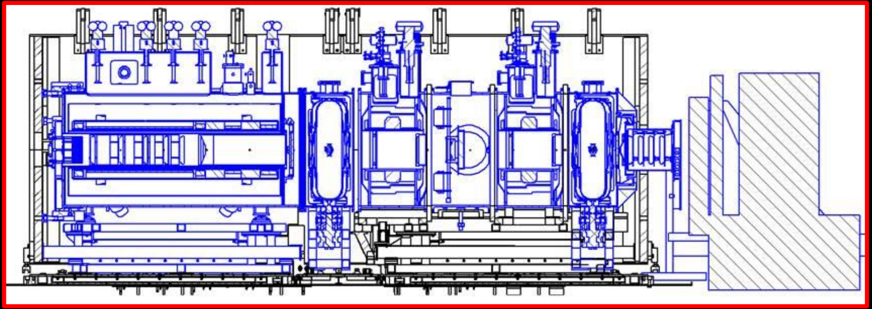
The international Muon Ionization Cooling Experiment (MICE) collaboration proposes a two-part process to perform a full demonstration of transverse ionization cooling. First, the "Step IV" configuration [14] will be

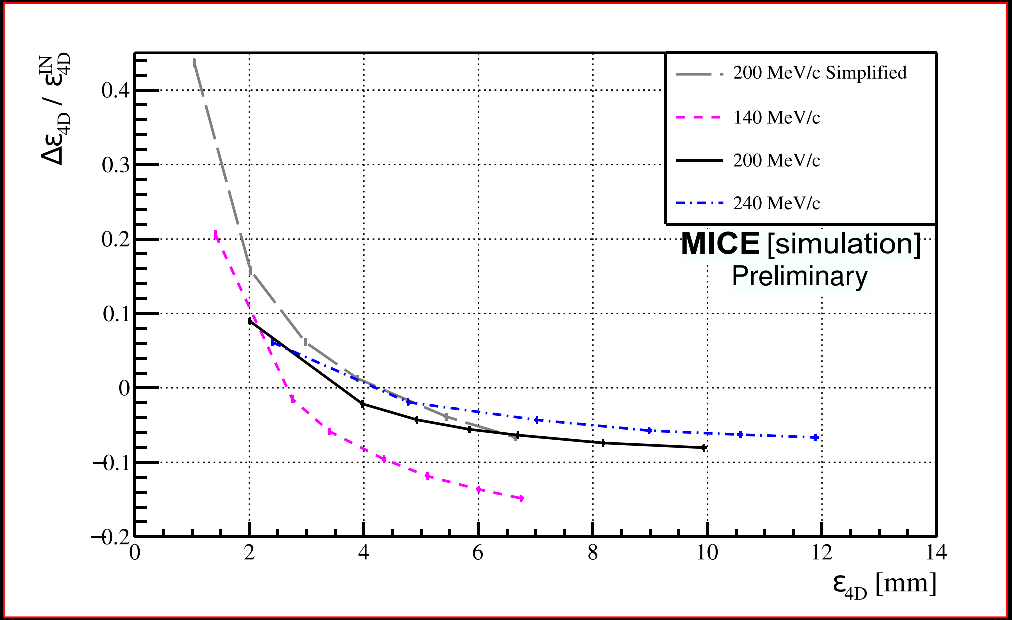




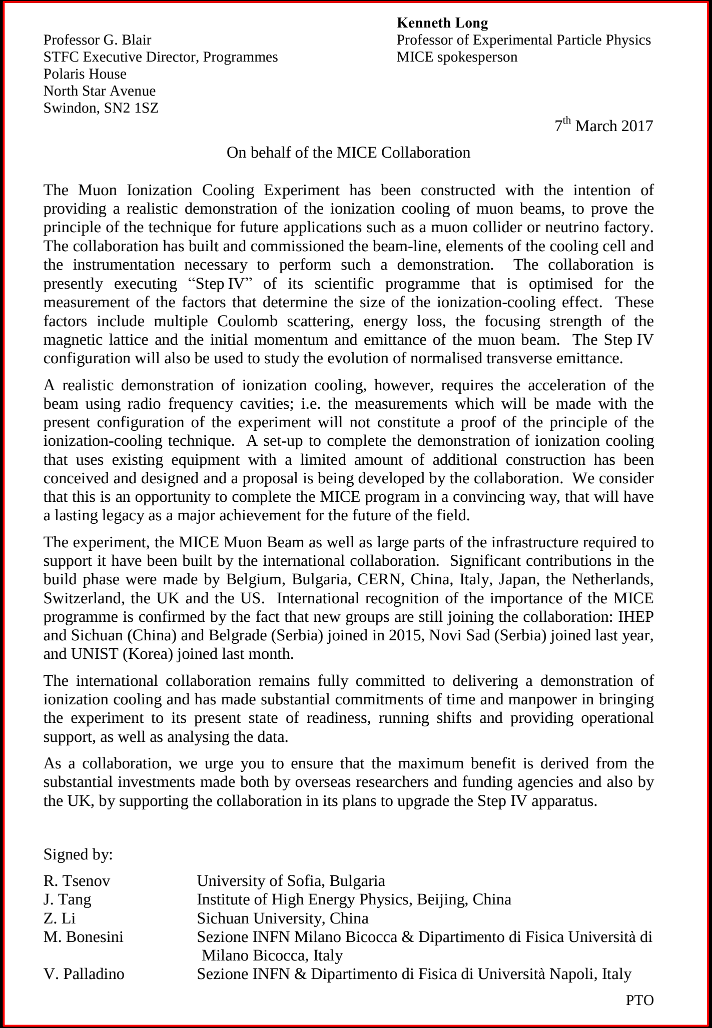
Simplified demonstration







- “Simplified design”:
  - Comparable cooling performance
  - Transmission not as good as in demo configuration



Kenneth Long
Professor of Experimental Particle Physics
MICE spokesperson

Professor G. Blair
STFC Executive Director, Programmes
Polaris House
North Star Avenue
Swindon, SN2 1SZ

7th March 2017

On behalf of the MICE Collaboration

The Muon Ionization Cooling Experiment has been constructed with the intention of providing a realistic demonstration of the ionization cooling of muon beams, to prove the principle of the technique for future applications such as a muon collider or neutrino factory. The collaboration has built and commissioned the beam-line, elements of the cooling cell and the instrumentation necessary to perform such a demonstration. The collaboration is presently executing “Step IV” of its scientific programme that is optimised for the measurement of the factors that determine the size of the ionization-cooling effect. These factors include multiple Coulomb scattering, energy loss, the focusing strength of the magnetic lattice and the initial momentum and emittance of the muon beam. The Step IV configuration will also be used to study the evolution of normalised transverse emittance.

A realistic demonstration of ionization cooling, however, requires the acceleration of the beam using radio frequency cavities; i.e. the measurements which will be made with the present configuration of the experiment will not constitute a proof of the principle of the ionization-cooling technique. A set-up to complete the demonstration of ionization cooling that uses existing equipment with a limited amount of additional construction has been conceived and designed and a proposal is being developed by the collaboration. We consider that this is an opportunity to complete the MICE program in a convincing way, that will have a lasting legacy as a major achievement for the future of the field.

The experiment, the MICE Muon Beam as well as large parts of the infrastructure required to support it have been built by the international collaboration. Significant contributions in the build phase were made by Belgium, Bulgaria, CERN, China, Italy, Japan, the Netherlands, Switzerland, the UK and the US. International recognition of the importance of the MICE programme is confirmed by the fact that new groups are still joining the collaboration: IHEP and Sichuan (China) and Belgrade (Serbia) joined in 2015, Novi Sad (Serbia) joined last year, and UNIST (Korea) joined last month.

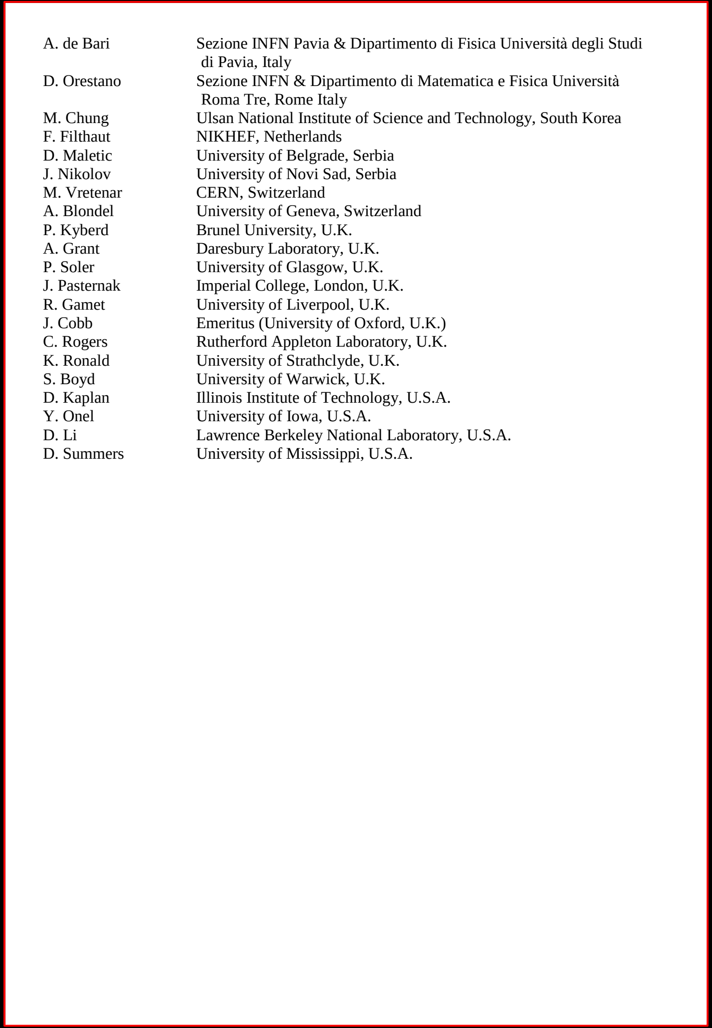
The international collaboration remains fully committed to delivering a demonstration of ionization cooling and has made substantial commitments of time and manpower in bringing the experiment to its present state of readiness, running shifts and providing operational support, as well as analysing the data.

As a collaboration, we urge you to ensure that the maximum benefit is derived from the substantial investments made both by overseas researchers and funding agencies and also by the UK, by supporting the collaboration in its plans to upgrade the Step IV apparatus.

Signed by:

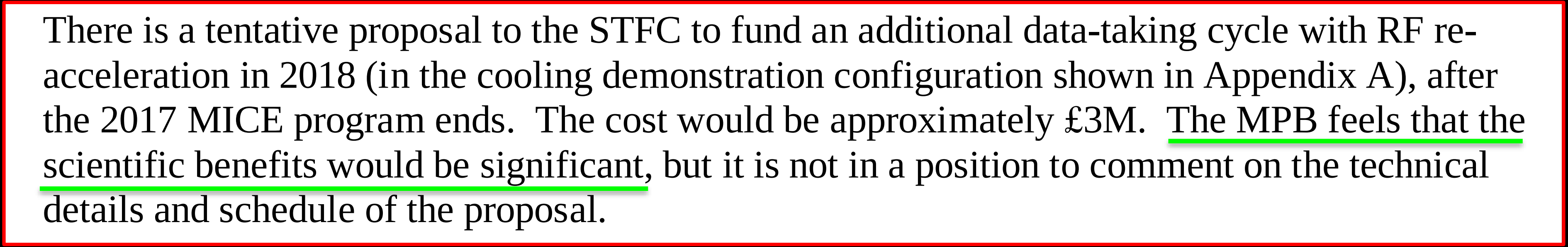
R. Tsenov	University of Sofia, Bulgaria
J. Tang	Institute of High Energy Physics, Beijing, China
Z. Li	Sichuan University, China
M. Bonesini	Sezione INFN Milano Bicocca & Dipartimento di Fisica Università di Milano Bicocca, Italy
V. Palladino	Sezione INFN & Dipartimento di Fisica di Università Napoli, Italy

PTO



A. de Bari	Sezione INFN Pavia & Dipartimento di Fisica Università degli Studi di Pavia, Italy
D. Orestano	Sezione INFN & Dipartimento di Matematica e Fisica Università Roma Tre, Rome Italy
M. Chung	Ulsan National Institute of Science and Technology, South Korea
F. Filthaut	NIKHEF, Netherlands
D. Maletic	University of Belgrade, Serbia
J. Nikolov	University of Novi Sad, Serbia
M. Vretenar	CERN, Switzerland
A. Blondel	University of Geneva, Switzerland
P. Kyberd	Brunel University, U.K.
A. Grant	Daresbury Laboratory, U.K.
P. Soler	University of Glasgow, U.K.
J. Pasternak	Imperial College, London, U.K.
R. Gamet	University of Liverpool, U.K.
J. Cobb	Emeritus (University of Oxford, U.K.)
C. Rogers	Rutherford Appleton Laboratory, U.K.
K. Ronald	University of Strathclyde, U.K.
S. Boyd	University of Warwick, U.K.
D. Kaplan	Illinois Institute of Technology, U.S.A.
Y. Onel	University of Iowa, U.S.A.
D. Li	Lawrence Berkeley National Laboratory, U.S.A.
D. Summers	University of Mississippi, U.S.A.

MPB



There is a tentative proposal to the STFC to fund an additional data-taking cycle with RF re-acceleration in 2018 (in the cooling demonstration configuration shown in Appendix A), after the 2017 MICE program ends. The cost would be approximately £3M. The MPB feels that the scientific benefits would be significant, but it is not in a position to comment on the technical details and schedule of the proposal.

Roadmap for the international, accelerator-based neutrino programme

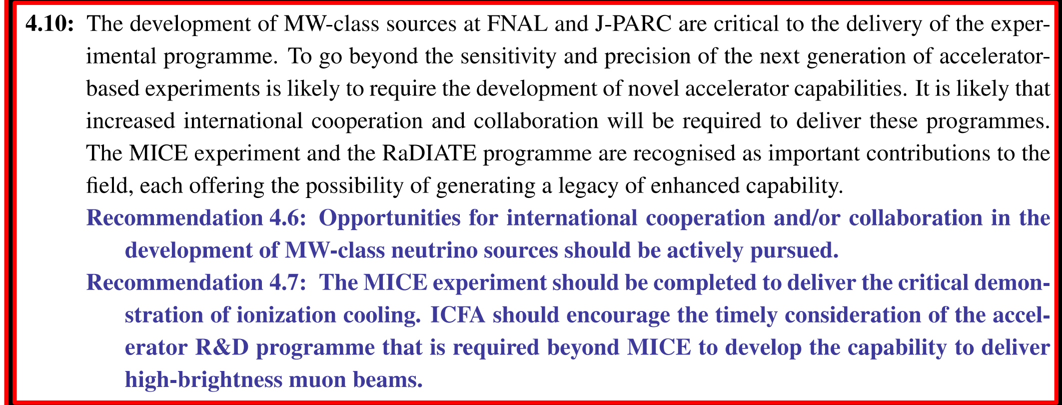
The ICFA Neutrino Panel

Overview

The neutrino, with its tiny mass and large mixings, offers a window on physics beyond the Standard Model. Precise measurements made using terrestrial and astrophysical sources are required to understand the nature of the neutrino, to elucidate the phenomena that give rise to its unique properties and to determine its impact on the evolution of the Universe. Accelerator-driven sources of neutrinos will play a critical role in determining its unique properties since such sources provide the only means by which neutrino and anti-neutrino transitions between all three neutrino flavours can be studied precisely.

In line with its terms of reference [1] the ICFA Neutrino Panel [2] has developed a roadmap for the international, accelerator-based neutrino programme. A "roadmap discussion document" [3] was presented in May 2016 taking into account the peer-group-consultation described in the Panel's initial report [4]. The "roadmap discussion document" was used to solicit feedback from the neutrino community—and more broadly, the particle- and astroparticle-physics communities—and the various stakeholders in the programme. The roadmap, the conclusions and recommendations presented in this document are consistent with the conclusions drawn in [4] and take into account the comments received following the publication of the roadmap discussion document.

With its roadmap the Panel documents the approved objectives and milestones of the experiments that are presently in operation or under construction. Approval, construction and exploitation milestones are presented for experiments that are being considered for approval. The timetable proposed by the proponents is presented for experiments that are not yet being considered formally for approval. Based on this information, the evolution of the precision with which the critical parameters governing the neutrino are known has been evaluated. Branch or decision points have been identified based on the anticipated evolution in precision. The branch or decision points have in turn been used to identify desirable timelines for the neutrino-nucleus cross section and hadro-production measurements that are required to maximise the integrated scientific output of the programme. The branch points have also been used to identify the timeline for the R&D required to take the programme beyond the horizon of the next generation of experiments. The theory and phenomenology programme, including nuclear theory, required to ensure that maximum benefit is derived from the experimental programme is also discussed.



4.10: The development of MW-class sources at FNAL and J-PARC are critical to the delivery of the experimental programme. To go beyond the sensitivity and precision of the next generation of accelerator-based experiments is likely to require the development of novel accelerator capabilities. It is likely that increased international cooperation and collaboration will be required to deliver these programmes. The MICE experiment and the RaDIATE programme are recognised as important contributions to the field, each offering the possibility of generating a legacy of enhanced capability.

Recommendation 4.6: Opportunities for international cooperation and/or collaboration in the development of MW-class neutrino sources should be actively pursued.

Recommendation 4.7: The MICE experiment should be completed to deliver the critical demonstration of ionization cooling. ICFA should encourage the timely consideration of the accelerator R&D programme that is required beyond MICE to develop the capability to deliver high-brightness muon beams.

Name	Institution
J. Cao	IHEP/Beijing
A. de Gouvêa	Northwestern University
D. Duchesneau	CNRS/IN2P3
S. Geer	Fermi National Laboratory
R. Gomes	Federal University of Goias
S.B. Kim	Seoul National University
T. Kobayashi	KEK
K. Long (chair)	Imperial College London and STFC
M. Maltoni	Universidad Automata Madrid
M. Mezzetto	University of Padova
N. Mondal	Tata Institute for Fundamental Resarch
M. Shiozawa	Tokyo University
J. Sobczyk	Wroclaw University
H. A. Tanaka	University of Toronto, IPP, TRIUMF
M. Wascko	Imperial College London
G. Zeller	Fermi National Accelerator Laboratory

MICE-UK SOI for upgrade

Muon Ionization Cooling with Re-acceleration - an upgrade for MICE

The MICE-UK Collaboration[1]

1 Introduction

The Muon Ionization Cooling Experiment (MICE) at the Rutherford Appleton Laboratory will complete data-taking in October 2017. The experiment will measure reduction of normalised emittance of a muon beam. Ionization cooling is the key technology required to construct a neutrino factory, in which neutrino beams are created from muon decay, and a high intensity muon collider, in which high-energy muon beams collide to probe physics beyond the Standard Model.

In a neutrino factory, secondary pions from protons impinging on a target decay to produce a muon beam of large emittance. The phase-space volume occupied by the beam is reduced (cooled) using an ionization-cooling channel. The muon-cooling channel consists of a series of low-Z absorbers (either liquid hydrogen or lithium hydride – LiH) inside focussing magnets, with RF cavities to restore the longitudinal momentum of the muons. The transverse four-dimensional (4D) emittance of the muons is reduced due to the effect of energy loss and restoration of momentum by the RF cavities. The cool beam of muons is then accelerated and injected into a storage ring, where the muons decay to produce intense beams of neutrinos with a well-known flavour content. Neutrino beams may then be used to carry out long-baseline neutrino oscillation experiments and perform high-precision CP violation measurements, to resolve the puzzle of the matter-antimatter asymmetry of the universe. Muon colliders offer a very attractive and compact way to achieve a multi-TeV lepton-antilepton collider, to probe new physics at the highest energy scales. Muon collider designs, achieving luminosities of order 10^{34} cm^{-2}s^{-1} require the development of six-dimensional (6D) ionization cooling of muons (including additional longitudinal cooling). *The physics of ionization cooling is being studied for the first time using the world-class MICE facility, after significant investment from STFC and the international collaboration.*

MICE is completing its approved scientific mission of demonstrating reduction of normalised transverse emittance using LiH and liquid hydrogen absorbers, but without re-acceleration. This programme will measure multiple scattering and energy loss for $\sim$200 MeV/c muons in LiH and liquid hydrogen absorbers, and will measure reduction of normalised emittance in the muon beam for the first time. However, it will not demonstrate sustainable cooling with re-acceleration. In this Statement of Interest to STFC, we propose an upgrade to MICE to allow ionization cooling to be demonstrated. The upgrade consists of inserting two 201 MHz RF cavities, two additional secondary absorbers and a second focus coil in the MICE beam. This programme could be completed in 18 months and would cost £3.0M.

2 Ionization-cooling with re-acceleration experiment

The MICE Collaboration has been working on a simplified design, to reduce cost and risk of the cooling demonstration with re-acceleration. In this design (Figure 1) the initial emittance is measured with the upstream spectrometer solenoid and the downstream emittance is measured with a short tracker and a totally active calorimeter that measures the total energy of the muon. The cooling channel consists of a principal LiH absorber, two secondary absorbers, two focus coils and two RF cavities. This design fits inside the existing Partial Return Yoke (PRY). The hardware is in hand so no new hardware would have to be built and no major modifications to the MICE Hall would be required.

The cooling performance has been evaluated. Figure 2 (left) shows the estimated emittance reduction for a nominal $\sim$6 mm emittance muon beam of 200 MeV/c momentum. An emittance reduction of 6.3% is predicted for an input emittance of 5.5 mm, if two secondary LiH absorbers are in place. The fractional emittance reduction can be measured with an estimated systematic uncertainty of 0.1-0.2%. The reduced acceptance of the downstream instrumentation in this configuration causes a reduction in the transmission of the channel (the fraction of particles accepted by the downstream instrumentation) to about 96%, which is an acceptable transmission loss and a significant improvement compared with the current configuration. Figure 2 (right) shows the ionization cooling performance as a function of input emittance for a number of different design scenarios. The baseline includes LiH secondary absorbers (in black) with three downstream tracker planes. Other scenarios include polyethylene absorbers and varying the number of tracker planes and their position in the design. The equilibrium emittance is around 3 mm, so any beam with a larger emittance is likely to cool. These data can then be used to predict the cooling performance of a cooling channel deployed at future muon beam facilities.

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[1] Author list in the appendix.

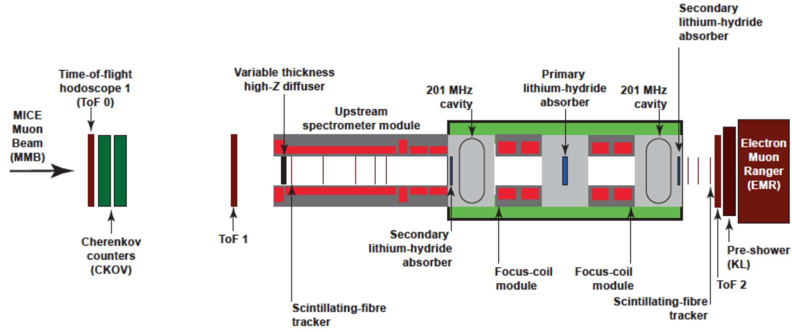
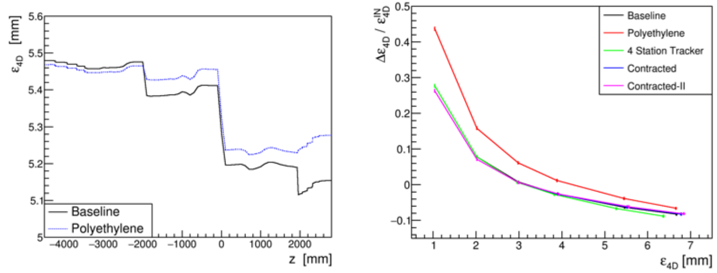


Figure 1: Muon ionization cooling demonstration with re-acceleration.



- Submitted to ASB for its meeting on the 22Mar17:
  - Cost £3.02M
  - Schedule:
    - Given Oct17 start, project complete by Mar19

Formal feedback from STFC

- STFC MICE-UK Oversight Committee; 28Apr17:
  - STFC:
    - At this time STFC does not have the resources necessary to entertain a proposal to upgrade the experiment
  - OsC comment:
    - UK and international collaborations should plan on this basis

- ASB (in letter to P. Soler, 11May17):
  - In response to the SOI from MICE-UK:
    - The "… *ASB noted the statement from STFC that there is no available funding at present within the accelerator programme to fund the presented project, so (barring some change in circumstances) a full proposal will not be invited for evaluation.*"

Collaboration Board at CM48

- Consider means by which to raise resource s.t.
  - Cost to STFC is reduced (substantially) allowing MICE-UK to argue that the situation has changed

- Consider alternative strategies:
  - E.g. implementation of demo at IHEP Protvino

Moving forward:

- **Excellent scientific programme at Step IV:**
  - **Essential to remain focused …**

Scientific programme

Step IV:

Material properties of LH_2 and LiH that determine the ionization-cooling performance

Observation of $\epsilon_\perp^n$ reduction

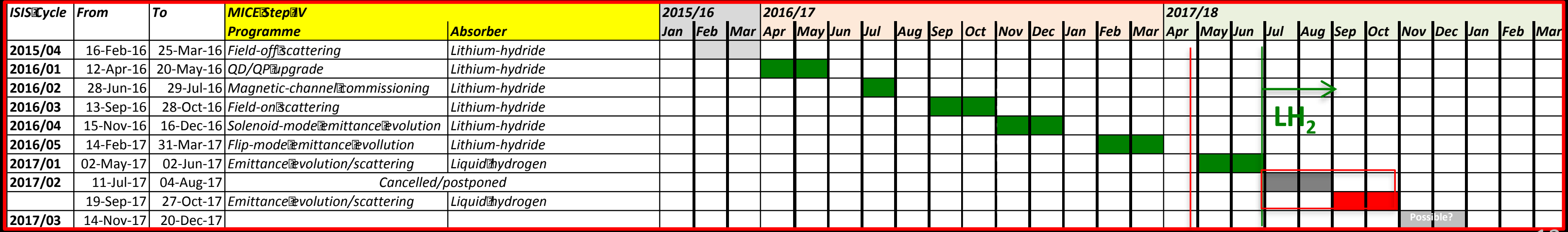
MICE demonstration of ionization cooling:

Observation of $\epsilon_\perp$ reduction with re-acceleration

Observation of $\epsilon_\perp$ reduction and $\epsilon_{||}$ evolution

Observation of $\epsilon_\perp$ reduction and $\epsilon_{||}$ and angular momentum evolution†

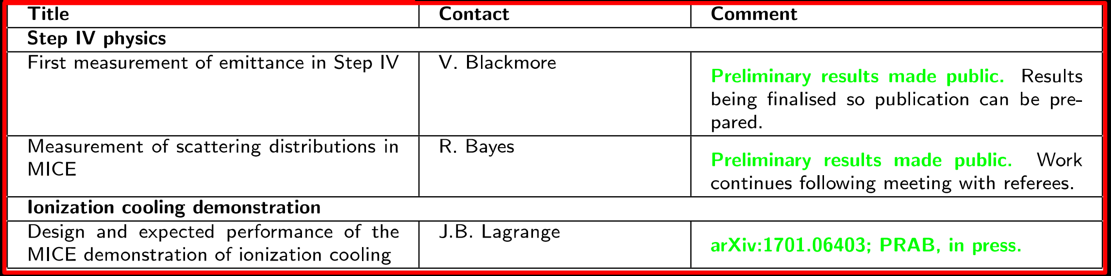
† Requires systematic study of “flip” optics.



ISIS Cycle	From	To	MICE Step IV		2015/16			2016/17												2017/18											
			Programme	*Absorber*	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
2015/04	16-Feb-16	25-Mar-16	*Field-off scattering*	*Lithium-hydride*		▨	▨																								
2016/01	12-Apr-16	20-May-16	*QD/QP upgrade*	*Lithium-hydride*				🟩	🟩																						
2016/02	28-Jun-16	29-Jul-16	*Magnetic-channel commissioning*	*Lithium-hydride*							🟩																				
2016/03	13-Sep-16	28-Oct-16	*Field-on scattering*	*Lithium-hydride*									🟩	🟩																	
2016/04	15-Nov-16	16-Dec-16	*Solenoid-mode emittance evolution*	*Lithium-hydride*											🟩	🟩															
2016/05	14-Feb-17	31-Mar-17	*Flip-mode emittance evollution*	*Lithium-hydride*														🟩	🟩												
2017/01	02-May-17	02-Jun-17	*Emittance evolution/scattering*	*Liquid hydrogen*																	🟩	🟩									
2017/02	11-Jul-17	04-Aug-17	*Cancelled/postponed*																				▨	▨							
	19-Sep-17	27-Oct-17	*Emittance evolution/scattering*	*Liquid hydrogen*																					🟥	🟥					
2017/03	14-Nov-17	20-Dec-17																									▨ Possible?	▨			

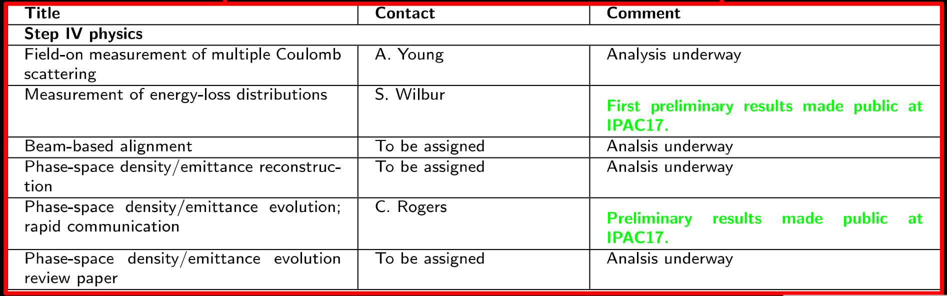
Papers

Papers in progress



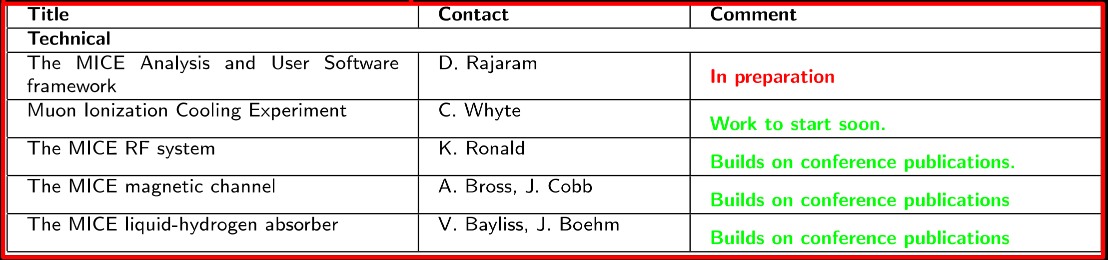
Title	Contact	Comment
Step IV physics		
First measurement of emittance in Step IV	V. Blackmore	**Preliminary results made public.** Results being finalised so publication can be prepared.
Measurement of scattering distributions in MICE	R. Bayes	**Preliminary results made public.** Work continues following meeting with referees.
Ionization cooling demonstration		
Design and expected performance of the MICE demonstration of ionization cooling	J.B. Lagrange	**arXiv:1701.06403; PRAB, in press.**

Step IV field-on papers

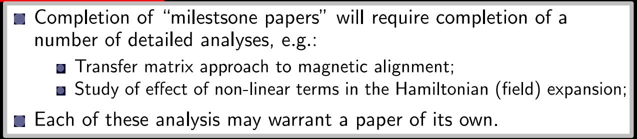


Title	Contact	Comment
Step IV physics		
Field-on measurement of multiple Coulomb scattering	A. Young	Analysis underway
Measurement of energy-loss distributions	S. Wilbur	**First preliminary results made public at IPAC17.**
Beam-based alignment	To be assigned	Analsis underway
Phase-space density/emittance reconstruction	To be assigned	Analsis underway
Phase-space density/emittance evolution; rapid communication	C. Rogers	**Preliminary results made public at IPAC17.**
Phase-space density/emittance evolution review paper	To be assigned	Analsis underway

Papers in progress



Title	Contact	Comment
Technical		
The MICE Analysis and User Software framework	D. Rajaram	**In preparation**
Muon Ionization Cooling Experiment	C. Whyte	**Work to start soon.**
The MICE RF system	K. Ronald	**Builds on conference publications.**
The MICE magnetic channel	A. Bross, J. Cobb	**Builds on conference publications**
The MICE liquid-hydrogen absorber	V. Bayliss, J. Boehm	**Builds on conference publications**



- Completion of "milestsone papers" will require completion of a number of detailed analyses, e.g.:
  - Transfer matrix approach to magnetic alignment;
  - Study of effect of non-linear terms in the Hamiltonian (field) expansion;
- Each of these analysis may warrant a paper of its own.

Preparation of LH2 system

- Excellent progress:
  - System cold, and liquid-neon test underway:
    - Gremlins being ironed out
- Now moving to long-term stability test:
  - Of system with liquid and cold, gaseous neon
- Data taking in parallel:
  - Requires tracker r/o:
    - Recovering from cold-head maintenance and water contamination of VLPC cryostats
  - Anticipate tracker r/o ready by Sunday 28May17

Run plan for remaining portion of 2017/01

- Continuation/completion of liquid-neon stability test

- In parallel:
  - Field-off data taking with “empty” absorber
    - Tracker calibration (timing w.r.t. ISIS RF) and alignment
    - Explore apertures related to LH2 vessel
    - Begin preparation for LH2-scattering measurement

Discussion