Muon Cooling via Ionization

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Muons only live a few microseconds before they ultimately decay, as a result of their short lives many of the known cooling techniques (electron, stochastic, and laser cooling) cannot be used to properly cool muons that are being used in proposed accelerators. To solve this problem, researchers are using muon ionization cooling to achieve this goal. However since this cooling technique has never been used many bugs need to be worked out, such as the setup and layout of the cavities, the magnetic fields needed to maintain the beam, and lastly how efficient this technique can be made. A program by the name of ICOOL is being enlisted to help determine the optimal settings needed for muon ionization cooling to work efficiently.

I. INTRODUCTION

Muons need a faster beam cooling technique than those currently in existence; as a result, a new type or rather relived technique is being put to use called ionization cooling. This cooling involves compressing the muon beam and then accelerating it in the beam direction. In order to achieve proper ioinization cooling the cavity layout must be perfected so that the cooling channel efficiently cools the beam while keeping the number of straggling particles at a minimum.

Today many ionization cooling researchers function under the Muon Ionization Cooling Experiment (MICE) whose main goal is to build the proposed cooling channel and prove the feasibility of muon ionization cooling. Researchers for the program have incorporated a number of different particle tracking programs to test a model of the cooling channel and predict the final results and efficiency of their models. One of the programs MICE has put to use is ICOOL, a monte carlo frameworked particle by particle tracking program, which is being used to determine the optimal magnetic field strength to minimize the six dimensional emittance and the number of usable final particles in the muon beam.

II. MUON COOLING

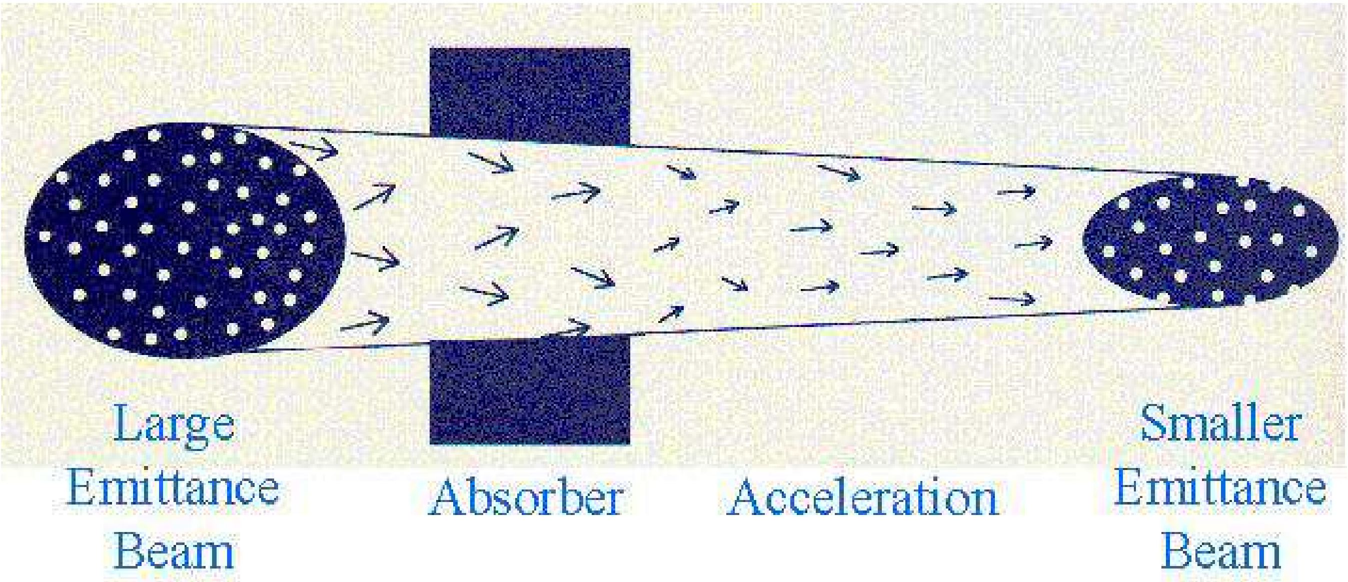


FIG. 1: As can be seen from the above picture, the transverse emittance is reduced after the absorber section of the cooling channel and the longitudinal emittance is increased through the accelerating section.

The theory of ionization cooling was developed between 1965 and 1983 by Yury Kolomensky, Alexander Skrinsky, Vasily Parkhomchuk, Valeri Balbekov, and David Neuffer. They came up with a basic principle called ionization cooling that incorporated particles losing energy in the transverse and longitudinal direction followed by the same particles being accelerated in only the longitudinal direction. The first collider concept putting this ionization cooling to work was proposed in 1969 by Gersh Budker and Alexander Skrinsky, however construction for the collider never began.

In 1994 early simulations of muon ionization cooling were carried out using the programs PARMELA and Simucool. However these programs were not considered very flexible, so in 1996 ICOOL and DPGeant were incorporated as an alternative. A research and development proposal was finally made on April 15, 1998 by the Neutrino Factory and the Muon Collider Collaboration that called for the study and testing of muon ionization cooling in a proposed collider.

Muon cooling is achieved by reducing the six dimensional phase space of a beam by passing it through a series of absorbers and accelerating cavities surrounded by a focusing magnetic solenoid lattice. When muons pass through the absorber material they ionize thus losing momentum and energy in all directions, however there are fluctuations in the energy loss from the muons due to straggling. To compensate for this radio frequency (RF) cavities with alternating fields are used to slow down the faster particles and speed up the slower in the z direction. The alternating absorber and acceleration cavities must be used, because due to added energy the beam tends to have a higher divergence after the RF cavities. The end result of muon cooling is a lower transverse emittance and a longer longitudinal emittance. (fig. 1)

III. MICE

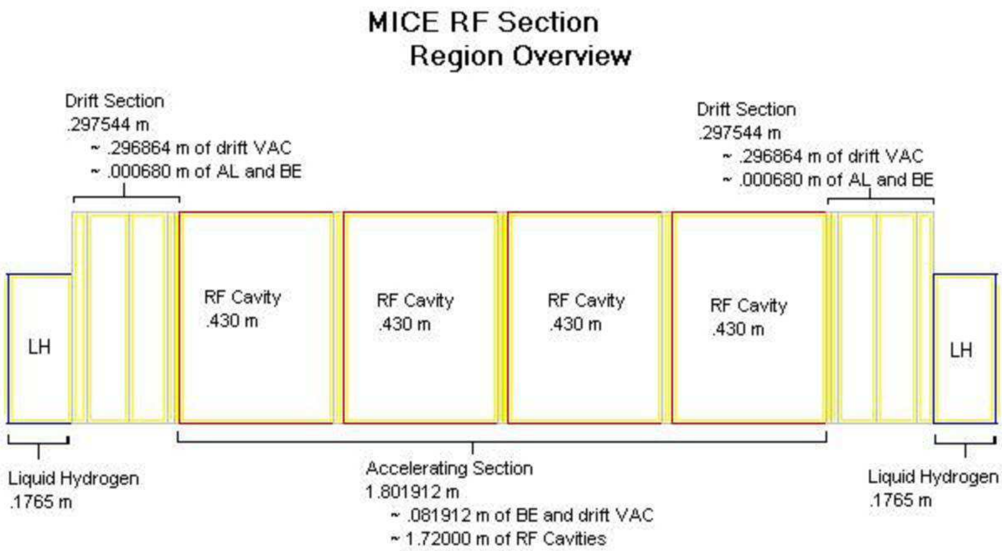


FIG. 2: In the above layout the liquid hydrogen absorber is followed by an accelerating section and then again by a second liquid hydrogen absorber.

The Muon Ionization Cooling Experiment (MICE) consists of a collaboration of scientists at Rutherford Appleton Lab in Oxfordshire, London that are working together on this

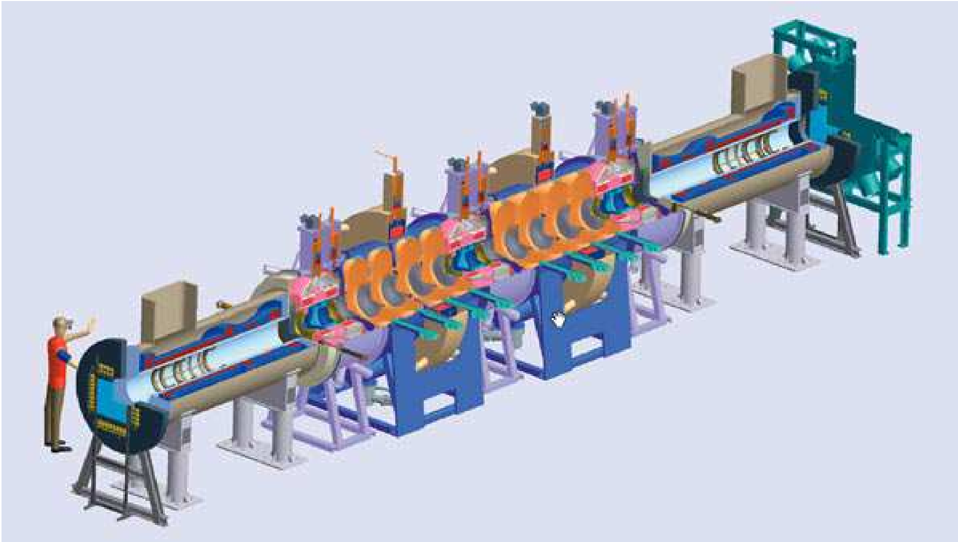


FIG. 3: MICE has proposed the above cooling channel setup which is complete with two accelerating RF cavity sections.

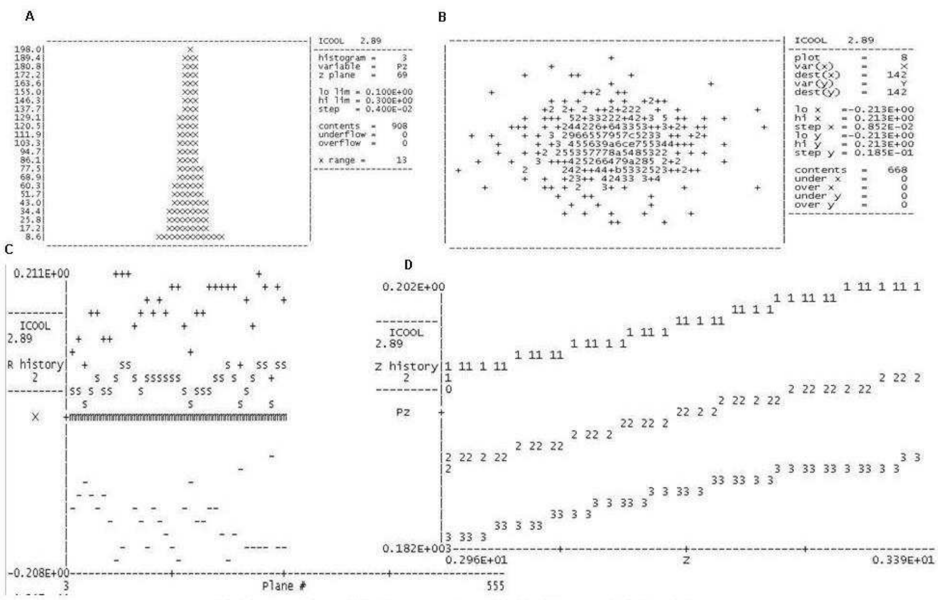
experiment. The experiment is headed by Dan Kaplan in the United States and is made up of many physicists and researchers from many different universities and laboratories all over the world. One of the goals of this experiment is to build a section of a cooling channel that will reduce the transverse emittance of a muon beam by ten percent. Another goal MICE is working towards is to use particle detectors within the cooling channel that would be able to effectively measure the cooling effect on the beam within a .1 percent accuracy. This is experiment is unique in the fact that it would be not only the first time a linear cooling system is used in a collider, but also it would be the first time ionization cooling was incorporated into a collider design.

The design for the cooling channel starts with an absorbing section made up of liquid hydrogen followed by a vacuum section of drift channel with aluminum windows. Liquid hydrogen is highly flammable so windows are needed to contain the liquid in order to ensure proper safety standards. Liquid hydrogen is the best energy absorbing material for the muon beam as in ICOOL simulations it was shown that liquid hydrogen with safety windows was still five percent more effective at cooling the beam than helium or lithium hydride. The safety windows in the vacuum chamber are made from aluminum which can achieve a minimal amount of scattering while at the same time being quite thin and cheaper than most other materials that with the same properties.

The RF section of the layout is made up of four copper RF cavities in a row with beryllium windows in between each of the cavities. The RF cavities have alternating currents that rotate between acceleration and neutral currents in order to try to mineralize the energy spread between muons in the beam. The windows between the RF cavities must be thin enough to prevent scattering while at the same time being able to conduct away the heat generated by the RF currents. Beryllium is a great material for this because it not only has a high strength, but it also has good electrical and thermal conductivity.

After the RF section, the layout is finished off with yet another drift chamber leading into the next liquid hydrogen absorber section. This ensures that the beam is properly compressed and collimated for the next section of the collider. This whole design layout is contained inside a magnetic channel which is intended to contain and direct the beam. (fig. 2) Current MICE cooling layouts have called for a second RF cavity section and a third liquid hydrogen absorber section after the proposed layouts. (fig. 3)

IV. ICOOL



A) Beam line B) Scatterplot C) R history D) Z history

FIG. 4: This is a collage of the different diagnostics output by ICOOL. One can see the r and z histories as well as the beam line and scatterplot of the transverse section of the beam.

In order to optimize the capability of the muon cooling channel, ICOOL, a particle tracking program, will be used along with cavity layout and magnetic field spread to determine the beam phase, six dimensional space, and the number of usable particles that made it through the cavity.

$$\frac{d\epsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(0.014)^2}{2E_\mu m_\mu L_R} \tag{1}$$

Where ϵ_N = normalized transverse emittance, s = path length, E_μ= beam energy, $\beta = \frac{v}{c}$, L_r = radiation length of absorber medium, and $\beta_\perp$ = betatron function of the beam. In the above formula, one can see that by changing the beta (focusing) values in the magnetic field a more focused beam with the maximum number of final usable particles can be achieved with optimal efficiency.

ICOOL models particle by particle transmission through the different materials and solenoid fields present in the cooling channel; the transmission through the materials includes variables for particle scattering, energy loss, and muon decay. Diagnostics produced from ICOOL can be used to predict the transverse and longitudinal emittance of the beam as well as the number of particles and the six dimensional phase space of the final beam. Final readouts give z and r histories as well as scatterplots. (fig. 4)

V. FUTURE OF MUON IONIZATION COOLING

After this experiment has been completed, the feasibility of six-dimensional muon ionization cooling will have been demonstrated and researchers can move onto putting it to use. Most of the work done after MICE has been completed will make way for different cooling channel designs and a new type of collider with extremely high energy.

Three main ideas of cooling channel design are in progress right now. The first proposed idea is to transform the linear cooling channel into a ring and wrap a circular magnet around the beam pipe (fig. 5), however there has been problems getting the beam in and out of the beam pipe. The model being used in MICE is the second idea and it is by far the simplest and the most cost effective.(fig. 3) A third idea has been put forth by Muons Inc., in which there would be a spiral shaped dipole magnet present inside of the beam pipe to rotate with the beam. This would achieve dispersion at the same time as acceleration, rather than having to switch fields as in the ring and linear cooling designs. (fig. 6)

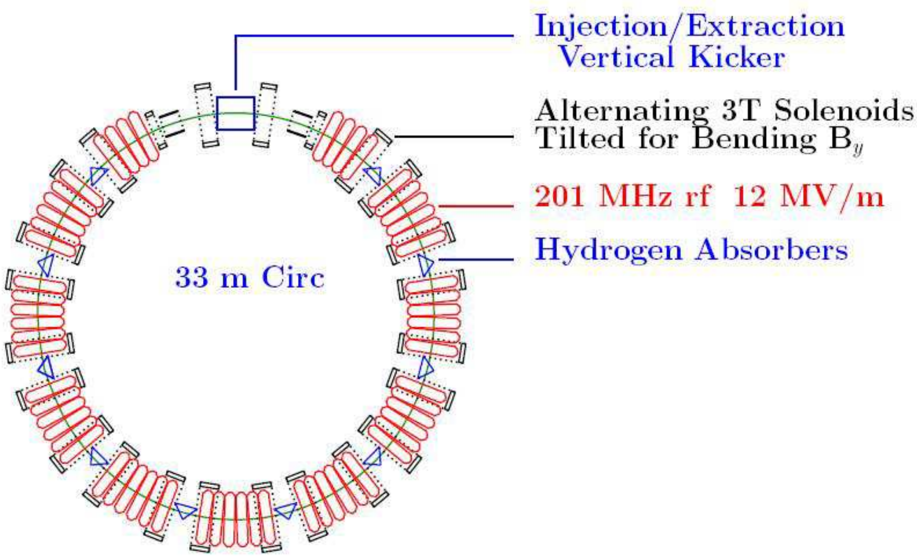


FIG. 5: This is the proposed ring cooling section.

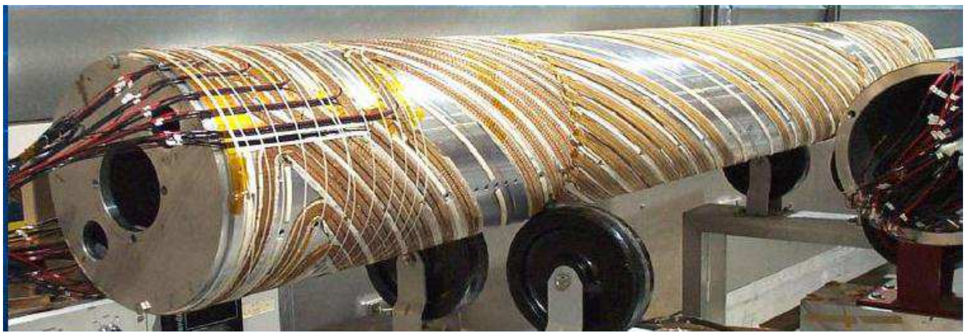


FIG. 6: This is the cooling channel built at Muons Inc.

MICE leads to a very important step in way of colliders as the perfection of using muons can lead to a very high energy neutrino factory. Muons can be stored to produce neutrinos which in turn would have the capability to produce well defined and intense beams of neutrinos at high energies (well above those needed to produce tau particles). Measurements taken from these neutrino factories could enable researchers to understand the matter-antimatter symmetry of the universe. According to an article in the CERN Courier:

Neutrino factories are therefore the ultimate tool for precision studies of neutrino oscillations and of leptonic charge parity (CP) violation, a measurement that might prove decisive in understanding the matter-antimatter asymmetry of the universe.[3]

One of the proposed colliders is being designed to take place at the Rutherford Appleton

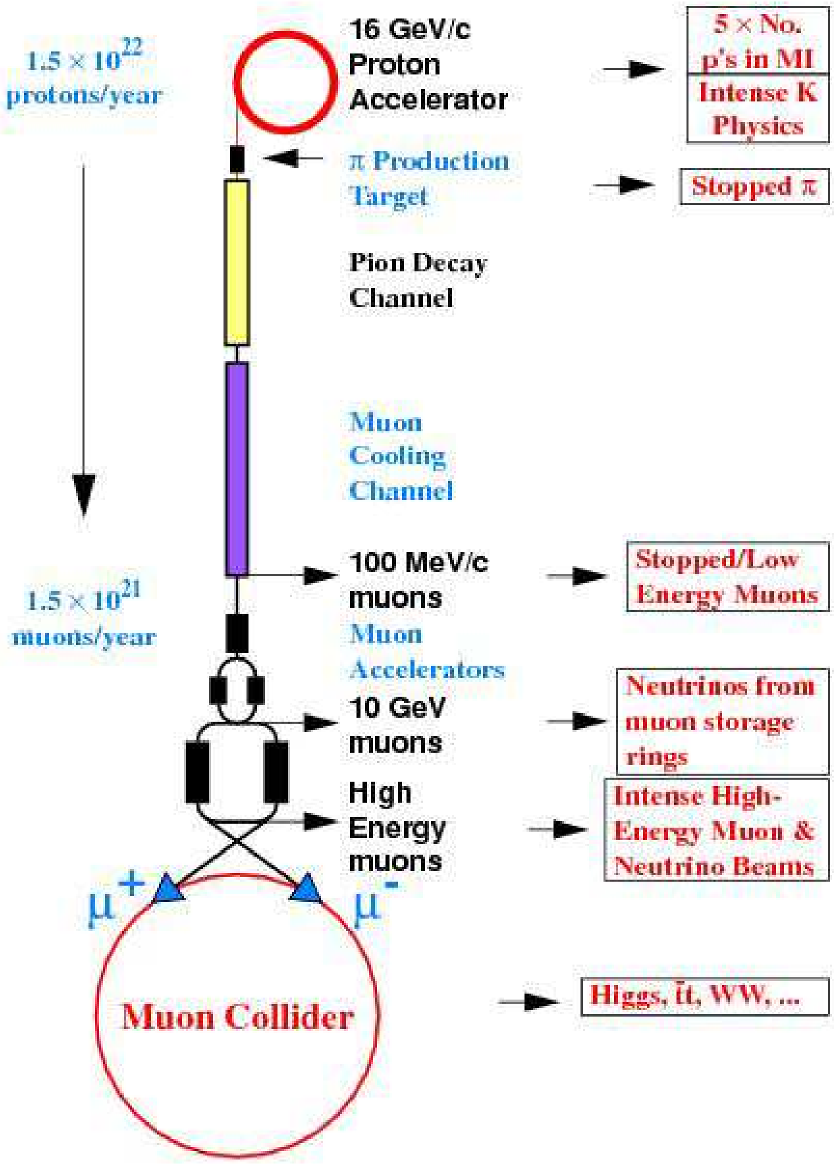


FIG. 7: This is one of many proposed muon collider setups.

Laboratory where MICE is currently underway. This collider calls into use ISIS, the neutron and muon source at the lab, as a muon source for the collider. After the muons are produced they would be cooled and then sent into a collision ring where measurements would be taken. Yet another collider design calls for the use of a proton accelerator which would be directed at a target and allowed to decay into muons. After cooling the muon beam it would then be sent through accelerators and into the muon collider ring. (fig. 7)

VI. RESULTS AND CONCLUSIONS

It can be seen from Table 1 that not all the final emittances are lower than the initial value. According to formula 1 the smaller beta value should lead to a lower six-dimensional beam emittance, however some of the final six-dimensional emittances are actually larger than their initial counterpart. This could be a result of some of the problems we ran into with the data files, a weakness in cavity layout, or possibly even a limit to the amount of improvement that can be reached with the current cavity layout.

VII. ACKNOWLEDGEMENTS

I would like to extend a big thanks to my mentor Don Hartill of Cornell University for his generosity and impartation of knowledge upon me as we worked together on this project. I would also like to thank all the other students in the REU program as they made each day of the program fun and filled with laughter. Our principal investigator, Rich Galik, included us in many events not only around campus but also in many other departments of Cornell University. He was a true joy and blessing if any questions or problems did arise at any time during our stay. I would also like to thank the National Science Foundation and their generous grant PHY-0353994 and research cooperative agreement PHY-9809799.

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[3] "MICE project gets the green light". CERN Courier. IOP (1998-2006)

[4] Kaplan, Daniel M. Introduction to Muon Cooling. Illinois Institute of Technology

[5] For more information on MICE go to: http://www.fnal.gov/projects/muon_collider/cool/cool.html

		Comparison	of for020 files			
# RF	Field	extra repeats	Beta value	initial Emittance	final Emittance	final # Particles
5						
	standard					
			10	1.523640E-07	1.123910E-07	647
			17	1.172850E-07	1.475990E-07	911
			25	1.058020E-07	1.519600E-07	991
			40	9.668340E-08	1.356740E-07	991
	90-0-90-0-90					
			10	1.523640E-07	1.123910E-07	647
			17	1.172850E-07	1.475990E-07	911
			25	1.058020E-07	1.519600E-07	991
			40	9.668340E-08	1.356740E-07	991
7						
	standard					
			10	4.195190E-07	1.026120E-07	40
	90-0-90-0-90					
			10	1.854620E-07	4.593760E-08	44
10						
	standard					
		originals				
			10	4.421490E-07	1.228570E-07	253
		modified LH				
			10	1.591940E-07	6.156840E-07	452
			17	1.290550E-07	4.562900E-07	789
			25	1.129440E-07	7.041640E-07	915
			40	1.038750E-07	4.804120E-07	957
	90-0-90-0-90					
			10	1.524240E-07	2.332200E-07	462
			17	1.173010E-07	2.232910E-07	831
			25	1.058080E-07	2.796120E-07	949
			40	9.668280E-08	1.996490E-07	978
15						
	standard					
			10	1.537040E-07	3.883910E-08	140
			17	1.184880E-07	2.779730E-07	243
			25	1.067880E-07	8.976510E-07	315
			40	9.738560E-08	7.633060E-07	354
	90-0-90-0-90					
			10	1.524240E-07	2.856680E-07	364
			17	1.173010E-07	1.905260E-07	793
			25	1.058080E-07	1.184350E-07	935
			40	9.668280E-08	7.663900E-08	970
17						
	standard					
			10	2.469380E-07	2.582980E-07	486
			17	1.173010E-07	1.851090E-07	869
	90-0-90-0-90					
			10	1.173010E-07	2.162990E-07	832
20						
	standard					
			10	1.524140E-07	3.949870E-07	281
			17	1.172990E-07	2.002990E-07	783
			25	5.807000E-08	1.242630E-07	930
			40	9.668190E-08	1.345030E-07	966
25						
	standard					
			10	1.249960E-07	9.479910E-07	624
	90-0-90-0-90					
			10	1.058080E-07	2.801970E-07	949
30						
	standard					
			10	3.463460E-07	-8.460950E+05	3
			17	2.269690E-07	1.477690E-07	665
			25	3.271630E-07	1.916120E-07	871
			40	1.912880E-07	4.077760E-07	937
40						
	standard					
			10	1.050150E-07	1.208420E-06	693
	90-0-90-0-90					
			10	9.864520E-08	2.238780E-07	976

FIG. 8: Comparison of for020 files