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STATUS OF ELECTRON COOLING EXPERIMENTS AT LEAR

J. Bosser, M. Chanel, R. Ley, D. Möhl,
F. Ollenhauer, and G. Tranquille

Abstract

Since the initial cooling experiments performed with protons and antiprotons and reported in earlier papers\(^1,2\)), the LEAR electron cooler has undergone a series of improvements and has been used to successfully cool \(O^8+\), \(O^6+\), and \(H^+\) ions. This paper aims to present the major modifications made to the cooler and the LEAR environment since its installation in 1987, and also to review cooling results obtained with the different particles and ions. Future plans for the LEAR cooler will also be discussed.

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STATUS OF ELECTRON COOLING EXPERIMENTS AT LEAR

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ABSTRACT

Since the initial cooling experiments performed with protons and antiprotons and reported in earlier papers\textsuperscript{1,2}, the LEAR electron cooler has undergone a series of improvements and has been used to successfully cool O\textsuperscript{8+}, O\textsuperscript{6+}, and H\textsuperscript{+} ions. This paper aims to present the major modifications made to the cooler and the LEAR environment since its installation in 1987, and also to review cooling results obtained with the different particles and ions. Future plans for the LEAR cooler will also be discussed.

1. INTRODUCTION

The electron cooling device for LEAR was developed by a collaboration between CERN and KfK Karlsruhe and was installed in LEAR in 1987. Initial cooling experiments were performed with protons in November 1987 and March 1988, and with antiprotons in March 1989\textsuperscript{1,2}. In the period between the proton and \(\bar{p}\) tests, cooling of H\textsuperscript{+}, O\textsuperscript{8+}, and O\textsuperscript{6+} ions was performed and in November 1989 O\textsuperscript{8+} ions was successfully accumulated in LEAR using electron cooling.

The LEAR cooler (Fig. 1) is situated at the center of the third straight section (SL3) of the LEAR machine (Fig. 2) and is designed to cool particles with an equivalent momentum up to 308.6 MeV/c. The electron beam is generated in an electron gun and is accelerated to the desired energy via four ring shaped anodes. It is then transported in a solenoidal field and bent into the cooling section by a 36\textdegree toroid magnet. After the cooling section, which is 1.5 m long, the electrons are deflected by another toroid to be recuperated by the collector. A detailed description of the cooler can be found in Ref. 3, and Table 1 gives the typical operational parameters.
Figure 1 - The LEAR electron cooling device.

Figure 2 - Layout of the LEAR machine.
Table 1 - Operational parameters for the LEAR cooler.

<table>
<thead>
<tr>
<th>Beam momentum</th>
<th>308.6</th>
<th>200.0</th>
<th>105.0</th>
<th>147.4</th>
<th>MeV/c/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁻ beam energy</td>
<td>26.93</td>
<td>11.48</td>
<td>3.24</td>
<td>6.23</td>
<td>keV</td>
</tr>
<tr>
<td>e⁻ current</td>
<td>2.5</td>
<td>0.7</td>
<td>0.088</td>
<td>0.24</td>
<td>A</td>
</tr>
<tr>
<td>Solenoid field</td>
<td>445.</td>
<td>300.</td>
<td>145.</td>
<td>268.</td>
<td>G</td>
</tr>
</tbody>
</table>

Apart from the obvious effect of cooling, the cooler also perturbs the circulating beam in a number of ways:

1. The hot cathode and electrons that are lost on the vacuum chamber cause an immediate increase in the mean pressure around the ring. Despite the use of NEG pumps in the collector region the pressure in SL3 has never been better than $6 \times 10^{-12}$ Torr for 30% losses of a 3.2 keV electron beam.

2. The 36° toroids also produce a vertical magnetic field which kicks the beam by 10 mrad in the horizontal plane. Two horizontal deflecting magnets situated on either side of the cooler are used to correct the beam trajectory and to center it in the cooling region.

3. The longitudinal field of the main solenoid also causes the transverse betatron motions of the beam to couple. This could lead to beam loss if the machine is not properly adjusted and the working point is too near to a coupling resonance. Moreover a slight tune shift is observed when the cooler solenoid is switched on and also from the focusing effect of the electron beam. Table 2 shows the combined effect measured for various momenta.

Table 2 - Tune shifts due to electron beam and solenoid

<table>
<thead>
<tr>
<th>Beam momentum</th>
<th>308.6</th>
<th>200.0</th>
<th>105.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta Q_h (10^{-3})$</td>
<td>-11.0</td>
<td>5.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$\Delta Q_v (10^{-3})$</td>
<td>-8.0</td>
<td>0.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

The control room for the cooler is situated some 30 m away from the apparatus itself in a building that houses all the necessary power supplies and the Faraday cage. At present the control system is completely stand alone and consists of an LSI 11/23 computer connected to a two crate CAMAC loop on a fibre optic link. All the power supplies are controlled via DACs of various resolutions and the important parameters are acquired.
via Fischer 12 bit ADCs. At present the LSI is being replaced by a workstation oriented control system similar to that used at LEAR. A detailed description of the control system can be found in Ref. 4. For routine operation at LEAR, planned for this year, it is envisaged to use the cooler in what we call the "pulsed mode" of operation. As the main perturbation induced by the cooler is the deformation of the horizontal orbit, the solenoid is controlled via a GFD (digital function generator) and the dipole bumps needed to correct the orbit are applied before any cooling is performed. In this manner the solenoid can be ramped synchronously with the LEAR machine and at all times the orbit is compensated. The correction coils are adjusted via a program on the ecool control system which sets the correct values for each energy. When the beam has been decelerated onto a standard machine "flat-top" the high voltage supply, which is also controlled by a GFD, is pulsed to the operational value in 120 ms and is kept on for 6 seconds. Figure 3 shows the principle

![Figure 3 - Principle of the pulsed mode of operation](image-url)
of this operation for the low energy (LE) cycle during which electron cooling can be used. In this way we have managed to decelerate proton beams to 105 MeV/c saving some 15 minutes in cooling time as compared to stochastic cooling.

The major hardware modifications made to the cooler since its installation have concerned its reliability and reproducibility in everyday operations. As explained previously GFDs have been introduced as a means of synchronizing the cooler with the LEAR machine for future operation. A great effort was made in increasing the high voltage stability which was the suspected cause of longitudinal instabilities in earlier experiments. A second, more stable, power supply was also added in parallel for electron energies of less than 3 keV and to allow even more flexibility, appropriate electronics were developed to enable a remotely controlled inversion of the uni-polar Delta power supplies used on some steering coils. For the automatic compensation of the cooler toroids and main solenoid, two tilted solenoids have been installed in place of the horizontal correctors DEH31 and DEH32. These solenoids have been calculated to completely eliminate the coupling effect of the main solenoid and are tilted by 15° to kick the beam by 10 mrad in the opposite direction to the cooler toroids. Their effect on the closed orbit can be seen in Fig. 4.

Software development was also very important during this time with a number of additional programs being written for demagnetizing the solenoid, reading and setting the electron cooler security synoptic and also to trigger the high voltage GFD on any of the eight tables available for use. Fibre optic cables were also laid down to transmit to the control room from the Faraday cage the current loss on the different components of the collector. It is envisaged to acquire these currents and status for an alarms/surveillance program currently under development. The hardware necessary for the remote acquisition of the electrostatic pick-ups has also been installed and will be tested during the year.

Apart from the new control system which is at present being implemented\(^4\), two major projects are under development and should be operational before next year. The first is the new collector which is being developed by a CERN/CAPT Lipetsk collaboration \(^5\) (CAPT is a department of INP Novosibirsk). It should greatly improve the recuperation efficiency of electrons and help to improve the reliability of this component. The present collector is too fragile to run with 27 keV electrons. High voltage breakdowns are too frequent to envisage its regular use at 308.6 MeV/c. It is for this reason why we will limit electron cooling operations to 200 MeV/c and under until the present collector can be replaced. The second project concerns the performance of LEAR and consists of the installation of a feedback system known as a damper acting on the circulating beam at
LEAR. In previous experiments it was found that a beam of about $10^9$ (anti)protons became very unstable under the conditions (transverse emittances, momentum spread and particle intensity) reached with electron cooling. It was therefore decided to develop a feedback system to counteract this coherent instability. The characteristics of this device will be explained in more detail in a later section.

**Figure 4** - Compensation of the cooler toroid deflection with two tilted solenoids. The first trace shows the normal machine closed orbit. The second trace shows three orbits with the ecool solenoid at 100 A and the compensation solenoids at 300 A, 280 A and 225 A respectively.

For operations in the future it would also seem desirable to replace the present electron gun with a variable perveance gun. This would allow us to increase the cooling efficiency at low energies.
2. INSTRUMENTATION

Electrostatic pick-up stations distributed around LEAR offer the possibility to measure the circulating beam position when bunched. In addition to these, the cooler has four such pick-up stations (Fig. 1) used for position monitoring of the electron beam. The two pick-ups in the drift section can also be used for machine closed orbit measurement when precise matching of the two orbits is required. At positions indicated in Fig. 2, Schottky pick-up electrodes are installed. The Schottky signal is the signal induced by the particles of a coasting beam and represents the density fluctuation. This signal can be observed on a spectrum analyzer where information on the momentum spread and emittance of the beam can be deduced. Great care is necessary in the interpretation of these signals when the beam is strongly cooled such that the random nature of the particle motion is lost. Another means of measuring the beam size is by the use of moveable scrapers installed a few meters upstream from the cooler which are used to sense the beams edges. This method is destructive as it interacts directly with the circulating beam and one should also be very careful in interpreting the results when the beam might be performing coherent oscillations. For protons with a momentum greater than 300 MeV/c the neutral hydrogen channel is a very highly effective way of measuring the cooled beam size and the alignment of the electron and coasting beams. The neutral hydrogen beam, which is created in the cooling section when an electron is captured by a proton, is observed in a detection system mounted at the extension of the vacuum tube of SL3. It consists of a multiwire proportional chamber (MWPC) with two planes and a stack of three scintillators. The MWPC covers an area of 10 cm × 10 cm and their thicknesses in the beam direction are 5 mm, 1 cm, and 1 cm, respectively.

3. EXPERIMENTAL RESULTS

Table 3 - Summary of results of electron cooling of protons and antiprotons

<table>
<thead>
<tr>
<th>Beam momentum</th>
<th>308.6</th>
<th>200.0</th>
<th>105.0</th>
<th>MeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δp/p</td>
<td>0.7</td>
<td>0.4</td>
<td>0.4</td>
<td>0/00</td>
</tr>
<tr>
<td>e/h</td>
<td>1.3</td>
<td>3.0</td>
<td>5.0</td>
<td>π mm.mrad</td>
</tr>
<tr>
<td>e/σ</td>
<td>1.8</td>
<td>5.0</td>
<td>9.0</td>
<td>π mm.mrad</td>
</tr>
<tr>
<td>Cooling time (Δp/p)</td>
<td>0.6</td>
<td>0.3</td>
<td>0.3</td>
<td>seconds</td>
</tr>
</tbody>
</table>
further on. The types of measurements made have usually concentrated on the longitudinal plane and consist of measurements of the longitudinal frictional force and cooling times. Transverse emittances were measured using the scrapers or, when possible, using the neutral hydrogen channel.

3.1 Longitudinal cooling times

For this measurement two similar methods have been tested. The first method (method 1) consists in stepping away the electron beam energy via the high voltage power supply and then resetting it to the operational value. By observing the longitudinal spectral density in a narrow bandwidth around a harmonic of the revolution frequency on a spectrum analyzer which is triggered at the same time as the high voltage step, the cooling time can be determined. The second method (method 2) uses the spectrum analyzer in the same way, but instead of stepping away from the operational voltage, radio-frequency (RF) noise at a different harmonic of the revolution frequency is put on a longitudinal gap with bandwidth and power adjusted to blow the beam up to a momentum spread of about 10⁻³. When this noise is switched off the spectrum analyzer is triggered and the spectral density evolution is observed. Examples of the signals observed are shown in Figs. 5 and 6.

![Figure 5 - Longitudinal cooling time measurement using method 1. The curve gives the noise density (which is proportional to the square root of the particle density) at the nominal momentum. Horizontal scale is 1 sec/div.](image-url)
3.2 Longitudinal Frictional Force

In order to determine the frictional force at low relative velocities a method analyzing the distribution in equilibrium between a constant stochastic heating power and electron cooling was developed. The measurement was performed in the following way (Fig. 7). RF noise with a bandwidth of 10 kHz and a power of 5 µW/Hz was injected onto a cooled beam at 13.126 MHz on a RF gap. This produces a broader distribution of the momentum spread which can be increased or reduced by varying the attenuation on the noise.
In order to obtain the velocity dependence of the frictional force $F(v)$ from the equilibrium distribution $\rho(v)$, one has to solve the one-dimensional Fokker-Planck equation for a frequency independent diffusion constant $D$:

$$\frac{\partial \rho}{\partial t} = \frac{\partial}{\partial v} \left( -F(v)\rho(v) + D \frac{\partial \rho}{\partial v} \right)$$

In the equilibrium case $\partial \rho / \partial t = 0$ the shape of the frictional force is determined by the normalized slope of the distribution function:

$$F(v) = D \frac{\partial \rho / \partial v}{\rho(v)}$$

The diffusion constant $D$ is derived experimentally from an independent measurement (Ref. 2, p. 331). Figure 8 shows the result of two measurements made with 50 MeV $\bar{p}$s, one with aligned beams and the other with misaligned beams (angle of about 1 mrad).

![Figure 8](image-url)

**Figure 8** - The longitudinal frictional force $F(v)$ as a function of $v$ for 50 MeV $\bar{p}$s. The filled triangles correspond to the measurement made with aligned beams which the unfilled triangles to the measurement with misaligned beams.
3.3 Results with H\(^{-}\), O\(^{6+}\), and O\(^{8+}\) Ions

Very little time was given to electron cooling for tests with H\(^{-}\), O\(^{6+}\), and O\(^{8+}\) ions as the LEAR machine had other priorities. However, we managed to show that electron cooling could be used effectively to cool these ions with the exception of H\(^{-}\) where the cooled beam intensity decayed rapidly; probably due to mutual ("intra-beam") stripping of the H\(^{-}\) ions on the dense beam.

3.3.1 H\(^{-}\) ions

![Image a) Longitudinal Schottky scan of H\(^{-}\) ions just after injection and (b) with electron cooling switched on. Horizontal scale: \(\Delta p/p = 2 \times 10^{-4}/\text{div.}\)
H⁺ ions (as for protons and other ions at CERN) are produced in the LINAC 1 where they are accelerated to 50 MeV kinetic energy. They are then transported via the 180° loop and the E2 transfer line normally used for proton transfers to LEAR where they can be injected in a number of different modes⁶. The injected intensity was of the order of 10⁸ ions per shot. For electron cooling tests the ions were injected via the normal channel with the LEAR machine in antiproton polarity. Electron cooling was kept on at 2 kV less than the operational and stepped up once a beam had been injected. Figure 9 shows the longitudinal distribution after injection and just after electron cooling has been stepped up to the operational value. If we look at the time evolution (Fig. 10) at the central frequency, we see a very sharp peak just after electron cooling is switched on which would seem to indicate an extremely fast cooling time. However, if one looks at the beam intensity evolution with and without electron cooling (Fig. 11) one sees that the lifetime of the H⁺ ions is greatly reduced when the cooler is on. This phenomenon is probably due to intra-beam stripping where the loosely bound electron is stripped off in a new collision with another H⁺ of the same beam forming a neutral hydrogen atom which is lost.

Figure 10 - Longitudinal cooling time for H⁺ ions.

3.3.2 O⁶⁺ and O⁸⁺ ions

The aim of the tests with O⁶⁺ and O⁸⁺ ions was to obtain some idea of the lifetime of heavy ions in a good vacuum cooler ring and to test the stacking of ions⁷). As will be seen later, electron cooling proved to be an invaluable tool in the stacking process and also to counteract the beam decay due to multiple scattering on the residual gas. O⁶⁺ ions
were delivered at 115.6 MeV/c/n while O\textsuperscript{8+} ions had a momentum of 147.4 MeV/c/n. The measured momentum spread was \( \Delta p/p = \pm 3\% \) and the number of particles was estimated to be about \( 4 \times 10^6 \) per shot.

![Image](image.png)

**Figure 11** - Beam intensity evolution of H\textsuperscript{+} ions with (a) and without (b) electron cooling.

The multi-injection process of ions is performed in four consecutive phases. Figure 12 illustrates the principle of this injection mode where the two LEAR radio-frequency cavities (CRF41 and CRF42) are working respectively on the first and second harmonic of the revolution frequency. This effectively means that the circumference of the machine can be divided into two halves corresponding to what will be called the "injection bucket" and the "stack". The four phases are outlined as follows:
1. CRF41 is ramped to its operational voltage on harmonic 1 followed by CRF42 working on harmonic 2 100 ms later. The voltage on CRF41 is reduced adiabatically to zero and the injection kicker, which is synchronized on the first cavity and delayed in such a manner that the injected beam will fall into the injection bucket, is triggered.

![Diagram](image)

Figure 12 - Principle of the multi-injection process.

2. A few milliseconds after injection CRF42 is also reduced to zero and the beam is debunched, filling the whole circumference of the machine. Electron cooling, which is on during the whole process, reduces the momentum spread and transverse emittances of the coasting beam for a further 1.8 s.
3. CRF41 is then set on and bunches the beam on harmonic 1.

4. CRF42 is brought to its nominal value with the right phase so that the
bunched beam is trapped within the "stack" and the empty "injection bucket"
is filled as described under point 1 above.

The repetition rate for the above process is the LINAC 1 repetition rate of 2.4 s.
This is ample time for electron cooling to reduce the beam characteristics to a \( \Delta \rho/\rho \) of
\( 4 \times 10^{-4} \) and transverse emittances of the order of 3\( \pi \) mm.mrad. Longitudinal cooling
time measurements in fact showed a reduction in momentum spread of a factor of 5 under
300 ms with emittances as low as 1\( \pi \) mm.mrad. Such small spreads in beam energy and
size (Fig. 13) were only possible with the use of the damper which will be described in
the next section.

4. THE TRANSVERSE FEEDBACK SYSTEM - THE DAMPER

4.1 Observations of instabilities

Transverse instabilities can be observed (Fig. 14) on both the Schottky and posi-
tion pick-ups. If the spectrum analyzer is used to observe the variation in amplitude of an
(n-q) sideband as a function of time, the instability manifests itself by an abrupt rise in the
amplitude. This is followed by a cooling period of about 1 to 10 seconds before threshold
is reached again. In the simple case of a dipole type instability where the beam oscillates
like a string, the beam center is represented by a travelling wave type of oscillation with
an amplitude \( x_0(t) \) which grows exponentially in time (chromaticity is neglected):

\[
x(s,t) = x_0 e^{i[(n\pm q)\omega_{rev}t\pm(n/\gamma)]}
\]

Here \( n \) is the mode of the oscillation and \( q \) the non-integer part of the betatron tune \( Q \). We
can observe the signal on the spectrum analyzer at the lower frequencies where we find
the most unstable modes. The mode frequency is given by \( \omega_n = (n \pm q)\omega_{rev} \) and at LEAR
it was found that the low order slow (minus) waves for \( n \leq 3 \) were the most unstable
ones. Usually, when instabilities occur, beam is lost until the number of particles is about
\( 10^9 \). At this intensity the blow-up occurs without noticeable particle loss. It should be
noted that the same process occurs with stochastic cooling but for higher particle
intensities.
Figure 13 - Schottky scans of a cooled O\textsuperscript{8+} beam.
Figure 14 - Transverse instabilities observed on (a) the Schottky pick-up and (b) on the position pick-up. In Fig. a) the height of the transverse Schottky signal near 40 MHz is displayed. The horizontal scale is 1 s/div. The instability occurring at this frequency causes a large coherent oscillation which smears out and leads to an emittance growth during 0.2 s. This blow-up is then compensated during 0.8 s by the cooling before the next burst of instabilities occurs. In (b) the spectral density at low frequency near one of the bands where the instability occurs is displayed. The spike representing the beam oscillation jumps up with each burst of the instability.

4.2 The Causes of Instabilities

During the cooling process the beam density $N/\epsilon b e_\gamma e \ell$ increases and the beam can become unstable when this density is greater than a given threshold. An overview of
instabilities in cooled beams can be found in Ref. 8. Under normal circumstances, a beam will resist coherent instabilities by virtue of Landau damping. A small difference in the oscillation frequency prevents the ensemble to respond coherently to the driving force exerted on it by beam induced fields. Cooled beams are susceptible to respond coherently for at least two reasons:

1) the tune spread due to non-linearities and the momentum spread decreases,
2) the induced fields such as direct space transverse charge fields increases as the beam cools down.

One can define a mode frequency shift: $\Delta \omega_n = \pm q \omega_{ev}$ and a mode frequency spread: $\delta \omega_n = (n - q) \delta \omega_{ev} - \omega_{ev} \delta \Omega$. If the mode frequency shift has an imaginary part, we see that the oscillation can self amplify. As a rule of thumb we can say that the stabilization of transverse instabilities by Landau damping requires that:

$$|\Delta \omega_n| \leq \frac{1}{\pi} |(n - q) \delta \omega_{ev} - \omega_{ev} \delta \Omega|$$

An approximation of the threshold for both transverse and longitudinal instabilities is given in Table 4. We see that the loss of Landau damping for a beam of $10^9$ particles occurs when the momentum spread $\Delta p/p$ is about $10^{-4}$. This is also linked to the double peak structure observed on longitudinal Schottky scans of strongly cooled beams\(^9\). Many other phenomena may induce instabilities such as the direct space-charge field or the interaction of the beam with the surrounding structures or ions or electrons from the residual gas trapped in the proton beam.

Table 4 - Transverse (row 1) and longitudinal (row 2) instability thresholds

<table>
<thead>
<tr>
<th>Beam momentum (MeV/c)</th>
<th>308.6</th>
<th>200.0</th>
<th>105.0</th>
<th>60.0</th>
<th>10^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Δp/p) min</td>
<td>0.095</td>
<td>0.235</td>
<td>0.97</td>
<td>2.57</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>(Δp/p)</td>
<td>0.8</td>
<td>1.26</td>
<td>2.56</td>
<td>4.17</td>
<td>10^{-4}</td>
</tr>
</tbody>
</table>
4.3 Damper Characteristics

The damper consists of a horizontal and vertical electrostatic pick-up and a horizontal and vertical kicker placed at an odd number of quarter wavelengths of the betatron oscillation away from the pick-up. The transverse position signal from the pick-ups is linearly amplified, delayed, and then applied to the kicker plates. The bandwidth is directly related to the number of modes to be corrected and the gain is determined by the growth rate of the instability and by the initial perturbation of the beam. The results obtained with our first assembly are very promising and show a drastic increase in the number of particles that can be cooled under stable conditions. A definite version will be installed this year and it will be designed to maintain the damping during ramping in energy. A closed orbit suppressor will be needed to reduce the strong signals which occur when the bunched beam is not perfectly centered at the position pick-up.

5. FUTURE PLANS

As mentioned earlier in the text, until the installation of the new collector we will bring the cooler into routine operation for momenta below 200 MeV/c. Once installed, it is hoped that the new collector will enable us to also work in the momentum range from 200 MeV/c to 380 MeV/c. A test bench for the reception tests of the new collector is at present being set up and will be used later on for testing new collector designs and the "variable permeance gun" that we are at present studying. The transverse feedback system also needs to be modified in order to be operational at all the energies at which electron cooling can be used. We also have plans to replace the electrostatic pick-up on the collector side with a pick-up that could be used for trapping ions that are extracted from the collector.

6. ACKNOWLEDGEMENTS

We would like to thank all the members of the LEAR and LINAC teams who participated actively in the ion runs. Many thanks also to D.J. Williams and J.C. Perrier for their help in the damper development, and to J.L. Vallet and M. Le Gras for their help in preparing the hardware used in the machine development sessions.

7. REFERENCES


4) Tranquille, G. et al., "The New Control System for the LEAR Electron Cooler". This Workshop.

5) Bikovsky, V.et al., "The New Electron Beam Collector for LEAR". This Workshop.


