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STUDY OF A BGO CALORIMETER USING ELECTRON AND HADRON BEAMS
FROM 1 TO 50 GeV

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ABSTRACT

A calorimeter of 25 Bismuth Germanate (BGO) crystals equipped with silicon photodiode readout has been tested at the CERN SPS in the energy range 1 to 50 GeV. The response for electrons has been shown to be linear in this energy range and the rms resolution obtained (σ_E/E) is approximately 1%, for $E > 4$ GeV. The electron/pion separation was found to be better than 1:500 in the energy range 1 to 20 GeV. Data on lateral and longitudinal shower development were compared with the results of a Monte-Carlo simulation using the SLAC-EGS program and found to be in good agreement.

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1. INTRODUCTION

The use of single crystals of Bismuth Germanate $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) is now proposed in a number of large fully active electromagnetic (em) calorimeters. The properties of BGO have been well documented [1,2] and hence we only recall its main features here:

- (i) short radiation length, 1.13 cm, compared with 2.54 cm for NaI,
- (ii) Excellent energy resolution for low and intermediate energy ranges up to 10 GeV,
- (iii) good mechanical properties and ease of handling (non-hygrosopic),
- (iv) low afterglow.

In addition, the availability of low noise silicon photodiodes has allowed the possibility of embedding the em calorimeter in high magnetic fields thus permitting the measurement of charged particle momenta as well as precision calorimetry. An example of such a project is the L3 detector [3] designed for use at LEP.

In this paper we report on a small BGO calorimeter tested in the 1 to 50 GeV energy range at the CERN SPS. After the experimental set-up and our calibration techniques are presented, we compare Monte-Carlo em shower production with measured results for lateral and longitudinal shower development. We describe the measurement of energy resolution and linearity as functions of the energy and the number of crystals used in forming the sum. We conclude with a discussion of electron/hadron separation.

2. EXPERIMENT SET-UP

The experiment was performed in the X3 beamline of the CERN-SPS in the autumn of 1983. This was a tertiary beam fed by 210 GeV protons striking a beryllium target. It allowed selection of particles in the 1 to 50 GeV energy range. We measured an rms beam momentum spread of less than 0.5% for $E > 4$ GeV rising to approximately 1.5% for a 1 GeV beam. The X3 beam line incorporated horizontal and vertical collimation, a spectrometer instrumented with multiwire proportional chambers (MWPC), and two threshold Cerenkov radiation detectors as shown in Fig. 1. It was operated in three different modes:

- (a) an unseparated beam of electrons and hadrons;
- (b) an "electron only" beam made possible by the use of a strong vertical sweeping magnet immediately after the target and a lead sheet that converted photons from π^0 decay;
- (c) a "hadron only" mode made possible by the use of a 6 mm lead absorber that removed most of the electrons from the beam.

Two scintillation counters, S1 and S2, in the X3 beamline and a third counter S5 (a circular counter of radius 1 cm), were used to form a trigger for the experiment. There were, in addition, a halo veto counter, A and a muon counter, S6. For beam energies below 15 GeV, the two Cerenkov counters could also be used in the trigger.

The em calorimeter, shown in Fig. 2, consisted of 25 BGO crystals, each $30 \times 30 \times 200$ mm³, constructed in a 5x5 crystal matrix aligned with the beam direction and 3 BGO crystals, each $30 \times 30 \times 120$ mm³, placed vertically behind this matrix to measure the rear energy leakage. The crystals were optically polished on all faces and wrapped in 6 μ m metalized mylar foil. The scintillation light was detected by silicon PIN photodiodes [4] glued [5] to the downstream face of the crystal. The area around the photodiode was painted with standard typing correction fluid to enhance the light collection efficiency. The light output of the crystals was measured with a Cs¹³⁷ source and a photomultiplier. The FWHM resolutions obtained ranged from $\Gamma/E = 16\%$ to 28% , implying a variation of up to a factor of three in light output between different crystals. The non-uniformity of the crystals was typically $\pm 5\%$ over 90% of their length and in most crystals a number of lightly veiled layers could be observed.

Either one, two or three photodiodes (1 cm²) were glued to each crystal and connected in parallel with each other. The crystal matrix and diodes were encased in a copper foil shield to reduce the effects of pick up. The photodiodes were connected to amplifiers whose outputs were fed to an ADC and recorded on magnetic tape. Two photodiode/amplifier configurations were employed: one used amplifiers connected via 60 cm of shielded twisted pair cable to the photodiodes; the other used hybridized preamplifiers mounted directly on the photodiodes.

A small amount of data was taken with a different system that incorporated both an amplifier and a microprocessor controlled digitizer [6] for each crystal. The essential properties of the light readout and analysis were unchanged.

Some thermal stabilization was achieved using a wooden box around the crystals (the beam window was aluminium foil). Typical temperature fluctuations were $\pm 1^\circ\text{C}$ in a 24 hour period. Each point in an energy scan took an average of 1 hour to complete.

3. CALIBRATION OF THE BGO MATRIX

The intercalibration of the BGO crystals was done by minimum ionizing particles and 10 GeV electrons. Due to the fact that crystals were equipped with 1 to 3 photodiodes and that the light output of the single crystals differed by up to a factor of 3, the calibration constants of different crystals varied by a factor of 3. We have not attempted to continuously monitor the intercalibration but rather to repeat the calibrations for each running period; at most a 10 day time period. In a full em calorimeter it will be necessary to determine all the intercalibration constants with precision of $\sim 1\%$. However, for most of the data presented here we have considered events in which the majority of the energy was deposited in the central crystal (approximately 80% of the total observed energy) and therefore we were able to relax the precision required of the intercalibration.

The electronic noise from the photodiodes, preamplifiers and the beam environment was equivalent to about 2 MeV/crystal. Thus, intercalibration with sources was not practical. We have, therefore, used beam particles to intercalibrate the crystals and readout. By working in the "hadron mode" of X3, we were able to obtain a sample of minimum ionizing particles, mostly pions with a small ($\approx 3\%$) 'contamination' of muons. Using the known energy loss for muons (9.3 MeV/cm) in the BGO and by placing each crystal in turn in the beam, we were able to intercalibrate the matrix. An alternative technique using an electron beam was also used. In this case, we again placed each crystal in the beam and determined the position of the peak in the observed energy spectrum for that crystal. In practice, the intercalibrations from the two methods were in excellent agreement with each other, as shown in Table 1, although the electron method was more

precise. The energy calibration was determined from the linearity studies (light output in function of electron energy), as described in section 5. However, it was not possible to determine an absolute energy calibration with this technique, except by relying on a shower Monte-Carlo.

The hadron peak was broadened by any late interaction in the BGO; we, of course, removed events from the sample where such an interaction gave rise to appreciable energy in any of the other crystals of the matrix. The hadron peak was also broadened by the passage of a charged particle through the photodiode which produced a signal equivalent to about 10 MeV of energy deposited in the BGO. This was not an important effect in electron events because the total energy was in general much higher and because there was a very small probability that charged particles from the shower penetrated more than 18 radiation lengths. Fig. 3 shows a minimum ionizing peak obtained from approximately 15000 muon events identified by S6. Note the apparent double peak in this plot that is probably due to the passage of some of the particles through the photodiode.

Since we performed hadron calibrations at a number of different energies, we attempted to determine the presence of any variation in the most probable energy loss for a single hadron in our energy range. The data was consistent with no energy dependence of dE/dx at the 5% level.

4. SHOWER DEVELOPMENT AND POSITION RESOLUTION

We have compared the results from lateral and longitudinal shower development with the predictions of the Monte-Carlo simulation. The lateral shower development was parameterized by the ratio of the total observed energy in the central crystal to that of the crystals surrounding it. We have calculated the energy in the central crystal, the sum of the central 9 crystals, the sum of 25 crystals and their ratios as shown in Table 2 and in Fig. 4. In addition, we had a crude longitudinal sample of the shower development by considering the ratio of the energy in the three rear shower crystals to that of the matrix. We obtained excellent agreement at better than the 1% level with the Monte-Carlo result.

One simple algorithm to determine the position of an incoming particle is to use the center of gravity method:

$$x_{\text{BGO}} = \frac{\sum_{i=1}^3 x_i \sum_{j=1}^3 E_{ij}}{\sum_{i,j=1}^3 E_{ij}}$$

where x_i is the x coordinate of the center of each crystal and E_{ij} is the energy deposited in the crystal with coordinates x_i and y_j . In Fig. 5 we compare the center of gravity of the energy in the central 9 BGO crystals with the intercept of the electron track at the BGO measured by the MWPC. Also shown is a functional fit to the Monte-Carlo predictions. Fig. 6 shows the position resolution $\langle \sigma_{x,y} \rangle$ averaged over one crystal, where $\langle \sigma_{x,y} \rangle$ is the rms deviation of the measured center of gravity, from the EGS prediction. For $E > 10$ GeV a position resolution of 1 mm has been reached. The data and the Monte-Carlo simulation are in good agreement.

5. ENERGY RESOLUTION AND LINEARITY

We have measured the energy dependence and resolution of the light produced in BGO by electrons of energy between 1 and 50 GeV. Four different configurations were considered:

- (i) The sum of the central 9 crystals: (Σ_9)
- (ii) Σ_9 plus the rear energy sum: (Σ_{12})
- (iii) The sum of all 25 crystals in the matrix: (Σ_{25})
- (iv) Σ_{25} plus the rear energy sum: (Σ_{28}).

We obtained a standard deviation, σ_E/E , from a gaussian fit to the data. It should be noted that the results from these fits were sensitive to the energy range included in the fit.

Fig. 7 shows the pulse height distribution for electrons at 20 GeV for the Σ_{28} . The distribution of the data is not exactly gaussian (asymmetric with tails at low energy). Two different fits with a single gaussian distribution were applied:

- (a) Wide range fit

$$\langle E \rangle - 3.5\sigma_E < E < \langle E \rangle + 3.5\sigma_E$$

- (b) Narrow range fit

$$\langle E \rangle - 1.5\sigma_E < E < \langle E \rangle + 1.5\sigma_E.$$

The mean values, $\langle E \rangle$, were nearly independent of the fit range, while the standard deviations, σ_E , differed by a factor up to 1.2. In this analysis the results of the two fits were averaged and from the differences we estimated the systematic uncertainties, which are included in the errors on σ_E .

Table 3 and Fig. 8 show the measured resolutions, σ_E/E , at energies from 1 to 50 GeV for different configurations. Main contributions to the energy resolution are the fluctuation of energy leaking out of a finite crystal volume, the momentum spread of the test beam and the electronics noise. The contribution of photon statistics, with a $0.2\%/ \sqrt{E}$ dependence, can be neglected at these energies.

For comparison, the measured momentum resolution, $\delta P/P$, the measured noise contributions and the unfolded energy resolution:

$$\sigma'_E/E = \sqrt{(\sigma_E/E)^2 - (\delta P/P)^2 - (\sigma_{\text{noise}}/E)^2}$$

are given in Table 3. The unfolded energy resolution can be compared to the leakage fluctuations, which are calculated with the EGS program, and are also displayed in Table 3. One sees that the data - except at low energies - are well explained by these contributions.

It is clear from this data that a significant improvement in resolution was obtained by adding the rear crystals (simulating 23 cm of BGO) and that little improvement was obtained by including the outer layer of 16 crystals with the central 9. In fact, the resolution deteriorated at low energies because the amount of electronics noise increased when adding more crystals.

Table 3 also shows the ADC peak channel number for each of the configurations and for each energy. This is shown in Fig. 9 for the sum of all crystals. A small amount of non-linearity was observed at low energies. We believe it results from an ADC non-linearity for small signals.

We have measured the energy dependence and resolution of the light produced by electrons of energy between 1 and 50 GeV for three crystals, two 20 cm long, one 25 cm long. Each of these crystals was used as the center of a matrix of nine. The energy dependences are shown in Figs. 10a) and b) for intercalibrations of the nine crystals with minimum ionising

particles and with 10 GeV electrons, respectively. Deviations from linearity of less than 1% and residual dispersions between crystals of same length of $\pm 1.9\%$ and $\pm 0.4\%$ respectively are observed. Note that no temperature correction was applied and that typical resulting pulse height variations of $\pm 1\%$ can be expected over several hours.

The pulse height resolutions (σ_E/E of a fitted gaussian) for the three crystals are shown in Fig. 11 as a function of energy. Taking into account the error bars, due mainly to the uncertainty in the fitting procedure, one can observe some variation from one crystal to another but an improvement with 25 cm is noticeable, particularly at high energy. Energy resolutions measured with electrons of three energies impinging on a 1 cm^2 area centered between four 20 cm long crystals are also shown. In this case we used the sum of 12 crystals, being a 4×4 matrix with missing corner crystals. No severe loss of energy resolution in the gap region, where the bulk of the energy is shared equally between 4 crystals, was noticeable.

From 4 to 50 GeV the measured resolutions in all our studies were always in the 1% region, a result which confirms the expected good performance of BGO when using a large array of crystals with photodiode readout.

6. ELECTRON / PION SEPARATION

Data were taken with the hadron beam at 2, 4, 10 and 20 GeV to determine the electron/pion discrimination. The pion sample was selected by requiring no signals in the Cerenkov counters or muon counters. Additionally, only events in which the coordinate calculated from the MWPC system was within the central $2 \times 2 \text{ cm}^2$ area of the central BGO crystal, were used. Fig. 12 shows the pulse height distribution of 4 GeV pions in the BGO, demonstrating that only a few events show pulse heights compatible with the nominal energy. The energy scale was derived from the measured mean pulse height of the electrons in the BGO.

In this study we performed electron/pion discrimination by using the momentum/energy correlation. We assumed ideal conditions in which $\delta p/p$

was much less than σ_E/E and compared the deposited energies in a 3 by 3 array from pions and from electrons. Using the measured energy resolution from Table 3 we simply counted the number of hadron events falling in a $\langle E \rangle \pm 3\sigma_E$ interval. Table 4 shows the results from 2 to 20 GeV. It can be seen that the discrimination for pions was about 1/500.

Due to the low statistics we tried to perform a detailed study of the pion discrimination as a function of the electron efficiency by parametrizing the high energy tail of the pion pulse height distribution. This parametrization has the advantage that the results can easily be extended to experiments where the momentum resolution is comparable to or even worse than the energy resolution. A fit to the pion spectra of the form:

$$P(\xi)d\xi = \beta \alpha e^{-\beta(\xi-\gamma)},$$

where $\xi = (\text{Energy deposited in BGO})/(\text{Incident Energy})$ and $\gamma \leq \xi \leq 1$ for $\gamma = 0.3$ gave good results for the 2, 4 and 10 GeV spectra. The energy independent fit parameters are

$$\alpha = 0.26 \qquad \beta = 7.7.$$

Fig. 13 shows the high energy part of the spectrum of Fig. 12 together with the fitted distribution. Using the parametrized pion spectrum it was easy to apply different energy cuts. Particles were identified as electrons with a detection efficiency η_e for electrons and η_π for pions if the pulse heights survived the cuts. Fig. 14 - where η_π is plotted versus η_e - shows the results for 4 and 10 GeV. It can be seen that η_π strongly depends on η_e for $\eta_e > 98\%$ and is nearly independent of η_e for $\eta_e < 96\%$, where we observe $\eta_\pi \sim 0.1\%$.

We have not yet applied any cuts on the transverse energy distribution for electron and hadron events. At the expense of some loss of electron tagging efficiency we can expect significant gains in the pion rejection efficiency by using this technique.

6. CONCLUSION

We have tested a BGO calorimeter with photodiode readout using pions and electron beams of 1 to 50 GeV. We obtain the following results:

- energy resolution of about 1% at high energies, which is consistent with expectations;
- electron/pion separation of about 1/500 in this energy range;
- excellent agreement between the measured shower development and that predicted by EGS.

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*) Property of BMFT Germany.

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TABLE CAPTIONS

- Table 1 A comparison of electron and hadron intercalibration constants for 9 crystals. This data was taken using the microprocessor readout scheme.
- Table 2 Lateral and longitudinal shower development data compared with the results of an EGS Monte Carlo.
- Table 3 Electron energy resolution for beam energies from 1 to 50 GeV and for various crystal configurations.
- Table 4 Hadron rejection efficiencies for 2 to 20 GeV.

Crystal number	Pion Calib. constant	Electron Calib. constant
1	$2.33 \pm .05$	$2.23 \pm .02$
2	$1.52 \pm .05$	$1.46 \pm .02$
3	$2.00 \pm .05$	$2.13 \pm .02$
4	$2.10 \pm .05$	$2.16 \pm .02$
5	1	1
6	$1.68 \pm .05$	$1.71 \pm .02$
7	$2.65 \pm .05$	$2.73 \pm .02$
8	$2.16 \pm .05$	$2.17 \pm .02$
9	$2.12 \pm .05$	$2.17 \pm .02$

Table 1

	4 GeV		8 GeV	
Ratio	Monte-Carlo (EGS)	Data	Monte-Carlo (EGS)	Data
$\frac{\text{center}}{\text{sum of 9}}$	81.4%	82.3%	81.7%	81.4%
$\frac{\text{center}}{\text{sum of 25}}$	79.4%	79.0%	79.8%	79.0%
$\frac{\text{sum of 9}}{\text{sum of 25}}$	97.6%	96.0%	97.7%	96.0%
$\frac{\text{sum of 9}}{\text{sum of 12}}$	99.0%	99.2%	98.7%	99.0%

Table 2

Σ_9 CRYSTALS

E[GeV]	peak * channel number	σ_E/E [%]	$\delta P/P$ [%]	$\sigma_E(\text{noise})/E$ [%]	σ'_E/E [%] data unfolded	σ_E/E [%] leakage (EGS)
1	405	$2.8 \pm .3$	$1.4 \pm .2$	$0.8 \pm .2$	$2.3 \pm .7$	$1.5 \pm .2$
2	762	$2.2 \pm .2$	$0.7 \pm .1$	$0.9 \pm .1$	$1.9 \pm .4$	$1.2 \pm .2$
4	1490	$1.7 \pm .2$	$0.45 \pm .1$	$0.5 \pm .1$	$1.6 \pm .4$	$0.9 \pm .2$
6	2239	$1.3 \pm .1$	$0.35 \pm .1$	$0.3 \pm .1$	$1.2 \pm .3$	$0.9 \pm .2$
8	3025	$1.3 \pm .1$	$0.25 \pm .1$	$0.2 \pm .1$	$1.3 \pm .3$	$0.9 \pm .2$
10	3780	$1.4 \pm .1$	$0.25 \pm .1$	$0.2 \pm .05$	$1.4 \pm .2$	$0.9 \pm .2$
15	5980	$1.3 \pm .1$	$0.25 \pm .1$	$0.1 \pm .05$	$1.3 \pm .2$	$0.9 \pm .2$
20	7961	$1.2 \pm .08$	$0.25 \pm .1$	$0.1 \pm .05$	$1.2 \pm .2$	$0.9 \pm .2$
35	13912	$1.1 \pm .08$	$0.25 \pm .1$	$0.06 \pm .02$	$1.1 \pm .2$	$0.9 \pm .2$
50	20213	$1.2 \pm .08$	$0.25 \pm .1$	$0.04 \pm .02$	$1.2 \pm .2$	$0.9 \pm .2$

* A systematic uncertainty of $\pm 1\%$ should be added to the peak channel result from point to point.

 Σ_{12} CRYSTALS

E[GeV]	peak * channel number	σ_E/E [%]
1	408	$2.9 \pm .4$
2	768	$2.2 \pm .2$
4	1503	$1.5 \pm .2$
6	2263	$1.3 \pm .1$
8	3060	$1.1 \pm .1$
10	3825	$1.3 \pm .1$
15	6040	$1.1 \pm .1$
20	8047	$1.0 \pm .08$
35	14079	$1.0 \pm .08$
50	20529	$0.8 \pm .08$

 Σ_{25} CRYSTALS

E[GeV]	peak * channel number	σ_E/E [%]
1	421	$3.5 \pm .3$
2	790	$2.3 \pm .3$
4	1547	$1.8 \pm .1$
6	2320	$1.4 \pm .1$
8	3061	$1.2 \pm .1$
10	3897	$1.4 \pm .1$
15	6164	$1.1 \pm .1$
20	8188	$1.2 \pm .08$
35	14275	$1.1 \pm .08$
50	20738	$1.2 \pm .08$

 Σ_{28}

E[GeV]	peak * channel number	σ_E/E [%]	$\delta P/P$ [%]	$\sigma_E(\text{noise})/E$ [%]	σ'_E/E [%] data unfolded	σ_E/E [%] leakage
1	424	$3.9 \pm .3$	$1.4 \pm .2$	$2.1 \pm .3$	$3.0 \pm .8$	$1.0 \pm .2$
2	799	$2.3 \pm .3$	$0.7 \pm .1$	$1.3 \pm .2$	$1.8 \pm .6$	$0.9 \pm .2$
4	1562	$1.7 \pm .1$	$0.45 \pm .1$	$0.6 \pm .1$	$1.5 \pm .3$	$0.6 \pm .2$
6	2346	$1.3 \pm .1$	$0.35 \pm .1$	$0.4 \pm .1$	$1.2 \pm .3$	$0.5 \pm .2$
8	3170	$1.1 \pm .1$	$0.25 \pm .1$	$0.4 \pm .1$	$1.0 \pm .3$	$0.5 \pm .2$
10	3943	$1.3 \pm .1$	$0.25 \pm .1$	$0.5 \pm .1$	$1.2 \pm .3$	$0.8 \pm .2$
15	6222	$0.9 \pm .1$	$0.25 \pm .1$	$0.3 \pm .1$	$0.8 \pm .3$	$0.8 \pm .2$
20	8271	$1.0 \pm .08$	$0.25 \pm .1$	$0.25 \pm .1$	$0.9 \pm .3$	$0.8 \pm .2$
35	14445	$1.0 \pm .08$	$0.25 \pm .1$	$0.2 \pm .1$	$0.9 \pm .3$	$0.8 \pm .2$
50	21023	$0.9 \pm .08$	$0.25 \pm .1$	$0.1 \pm .05$	$0.9 \pm .2$	$0.7 \pm .3$

Table 3

Beam Energy GeV	# of events collected	# of events under electron peak ($\pm 3\sigma_E$)	90% Confidence Limit pion rejection efficiency
2	972	2	> .994
4	822	3	> .992
10	3223	3	> .998
20	3397	6	> .997

Table 4

FIGURE CAPTIONS

- Fig. 1 Schematic of the X3 beamline.
- Fig. 2 Schematic of the BGO calorimeter (BGO (A) and (B) mark the two positions at which data were taken).
- Fig. 3 Calibration peak for a single crystal using muons identified by the S6 counter.
- Fig. 4 Ratio of energy deposited in a 1x1, 3x3 and 5x5 BGO matrix to that in the 5x5 matrix.
- Fig. 5 Plot of BGO energy center of gravity versus MWPC reconstructed point of incidence. The solid curve is a fit to the Monte-Carlo predictions.
- Fig. 6 Position resolution $\langle\sigma_{x,y}\rangle$ averaged over one crystal, together with the Monte-Carlo prediction.
- Fig. 7 Pulse height distribution of 20 GeV electrons in ξ_{28} crystals. The gaussian curve is a fit to the region $\langle E \rangle \pm 1.5 \sigma_E$.
- Fig. 8 Energy resolution as a function of beam energy for the ξ_9 and ξ_{28} matrices.
- Fig. 9 Peak channel number for the ξ_{28} crystals as a function of beam energy.
- Fig. 10 Energy dependence of crystal matrices with three different central crystals:
a) using pion intercalibration
b) using 10 GeV electron intercalibration.
- Fig. 11 Energy resolution measured for each of the three different 9 crystal matrices as in Fig. 10. Also shown are the energy resolutions obtained with electrons impinging on a 1 cm² area centered between four 20 cm crystals (open squares).
- Fig. 12 Pulse height distribution for 4 GeV pions.
- Fig. 13 High energy tail of the 4 GeV pion spectrum together with our parameterized fit.
- Fig. 14 Electron, η_e , and pion, η_π , detection efficiencies for 4 and 10 GeV.

X3 Beam line with Trigger Counters

Test area

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10 a)

Fig. 10 b)

Fig. 11

Fig. 12

Fig. 13

Fig. 14