PandaX-III: Neutrinoless Double Beta Decay Search at CJPL

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On Behalf of the PandaX-III Collaboration
Outline

• PandaX-III project overview
  • Key concept
  • PandaX family
  • Jin-Ping Lab
• The first 200kg-scale module with Micromegas readout
  • Readout plane
  • Electronics
  • Background discrimination
  • Physics reach
• Prototype TPC
  • Design and construction
  • Initial commissioning data
PandaX-III: high pressure gas TPC for 0νββ of $^{136}$Xe

- TPC: 200 kg scale, symmetric, double-ended charge readout, with 10 bar of $^{136}$Xe
- Main features: good energy resolution and background suppression with tracking

arXiv:1610.08883
PandaX Projects

PandaX-I: 120kg LXe (2009 – 2014)

PandaX-II: 500kg LXe (2014 – 2018)

PandaX-xT LXe (Future)

0νββ searches

PandaX-III: 200kg - 1 ton HPXe (Future)

PRL 117, 121303 (2016)

Dark matter WIMP searches

Ke Han: PandaX-III NLDBD experiement

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PandaX hall at CJPL-II

- PandaX projects
- CDEX WIMP/ $0\nu\beta\beta$ search
- JUNA (accelerator)
- Geo/Solar neutrino detector
- Other $0\nu\beta\beta$ activities
- ......
Recent activities at PandaX hall

- Beneficial occupation started in 2017 for PandaX-II xenon distillation, etc.
- Infrastructure work in progress.
PandaX-III collaboration

Shanghai Jiao Tong University
Univ. of Science and Technology of China
Peking University
China Institute of Atomic Energy
Sun Yat-Sen University
Central China Normal University
Shandong University
University of Maryland
Berkeley Lab
CEA Saclay
University of Zaragoza
Suranaree University of Technology (SUT)

PandaX-III Collaboration Meeting, Shanghai, China, May 2016

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PandaX-III first TPC

- ~4m³ active volume
- Copper pressure vessel
- 10 bar working pressure
- 200 kg of enriched xenon
- Xe+TMA gas mixture
- Charge-only readout with Microbulk Micromegas
- Strip readout with 3 mm pitch size
- ~10000 readout channels
Xe + TMA (trimethylamine) mixture

- Better energy resolution
  - Extrapolated from 511keV and 1.2MeV peaks: 3% FWHM (@Q_{0νββ})
- Better tracks
  - TMA suppress electron diffusion
- Better operation
  - TMA as a quencher gas

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**With TMA**

**W/o TMA**

Microbulk MicroMegas (MM)

- Microbulk MicroMegas films made of Copper and Kapton only
  - Perfect for radio-purity purpose
- ~1000X gain
- 3% energy resolution expected at 2.5 MeV.

- Double side Cu-coated (5 µm) Kapton foil (50 µm)
- Construction of readout strips/pads (photolithography)
- Attachment of a single-side Cu-coated Kapton foil
- Construction of readout lines
- Etching of Kapton
- Vias construction
- 2nd Layer of Cu-coated Kapton
- Photochemical production of mesh holes
- Kapton etching / Cleaning

Andriamonje, S. et al. JINST 02 (2010): P02001
Scalable Radio-pure Readout Module (SR2M)

- SR2M: Mosaic layout to cover readout planes
  - Solderless system
  - Strip and mesh signal readout
  - Dead-zone-free arrangement
  - Designed by Zaragoza and SJTU
From MM films to SR2M
Overview of electronics

- Front-end electronics close to TPC: reads and digitizes strip and mesh signals
- Back-end above water shielding: triggering and data transmission to DAQ
Front end

Based on AGET ASIC chips: generic electronics for TPC from CEA-Saclay

- 64 channel per AGET
- 512 sampling point per channel
- Dynamic range up to 10 pC
- Sampling rate: 1 MHz to 100 MHz
Front end

Based on AGET ASIC chips: generic electronics for TPC from CEA-Saclay

- 64 channel per AGET
- 512 sampling point per channel
- Dynamic range up to 10 pC
- Sampling rate: 1 MHz to 100 MHz

D. Zhu, et al
arXiv:1806.09257

Ke Han: PandaX-III NLDBD experiment
NDM 2018
Back end and DAQ

- The Trigger and Data Concentrator Module – TDCM
  - Designed by Saclay for PandaX-III and T2K-II
  - A custom-made 6U form factor carrier board, a commercial FPGA module, and up to two physical layer mezzanine cards
  - Controls up to 32 FECs
- DAQ software based on MIDAS are under development.

D. Calvet, arXiv:1806.07618
Radio-purity control

• ICP-MS at PKU (Beijing)
  • Agilent 7900 ICP-MS
  • Class 10 clean room; class 1 for the ICP-MS hood
  • Reaches sub-ppt level for U and Th in materials

• HPGe detectors at CJPL and SJTU
  • Radio-assay of detector materials and electronics components under way

• Low radioactivity environment
  • Rn-free air (by an Ateko system) in the detector assembly region of the lab
  • Rn-control in water shield
  • Rn-emanation measurements
Background budget

Two independent Geant-4 based MC packages: RESTG4 and BambooMC

- Treat PandaX-III as a simple calorimeter
- Then add detector response
- Calculate signal efficiency and background rejection
- \( \times 35 \) background reduction from topological analysis
  - Track reconstruction and blob identification at both ends
  - Convoluted neural network

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\( ^{232}\text{Th} \) Raw spectrum
Generating MC signals

- Event tracks from Geant4 (Monte Carlo truth)
- Add electron drift and diffusion with gas parameter inputs from Garfield++
- With definition of a PandaX-III specific charge readout scheme, event tracks are converted to MC signal.
- MC signal pulses are identical to physical pulses from DAQ.
Reconstructing a track

- Converts back from pulses to hits on XZ, YZ, and XY (optional) planes
- Reduces the number of hits inside a track by merging closer hits
- Finds the minimum path between hits inside each track
- Improves physical track description after track minimization
- Projects the hits along the reconstructed track to get dE/dx profile.

J. Galan, Neutrino 2018
Traditional “cut” based analysis

Define key parameters (such as energy deposition in a certain blob) and refine cuts

J. Galan, Neutrino 2018
Convolutional Neural network (CNN) for track classification

- XZ, YZ 2D snapshots of an event as input of R and G channels of an image and then rely on CNN to spill out an index of signal/background.
- Prepare image collections for CNN training, validation, and classification.
- No track reconstruction needed.

Impact on Signal/Background Spectra

- Signal/background selection based on the CNN index
- Improved figure of merit compared to the traditional method.

Examples of mis-identified events

Signal mis-identified as background

Background mis-identified as signal

Sensitivity projection

- First 200-kg module:
  - Microbulk Micromegas for charge readout
  - 3% FWHM, $1 \times 10^{-4}$ c/keV/kg/y in the ROI

- Ton-scale:
  - Four more modules with upgraded charge readout and better low-background material screening.
  - 1% FWHM, $1 \times 10^{-5}$ c/keV/kg/y in the ROI

arXiv:1610.08883
Future energy resolution improvement

• TopMetal Direct Charge Sensor
  – Direct pixel readout without gas amplification

• Alternative Micromegas technologies
  – Microbulk technology with segmented mesh for true X and Y strips
  – Bulk technology with better uniformity and less dead area
PandaX-III Prototype TPC

• To see MeV electron tracks
• To demonstrate required energy resolution with a large-scale high pressure TPC
• To optimize the design of Micromegas readout plane
• To develop algorithm of 2D/3D track reconstruction
Prototype TPC at Shanghai

- About 600 L inner volume
- Field cage: 66 cm diameter, 78 cm drift length, single-ended
- 16 kg of xenon at 10 bar
- SS pressure vessel

![Prototype TPC diagram with labeled parts: Electric field shaping cage, Charge readout plane, Micromegas module, To electronics, Top flat flange, Electron drift direction, Cathode, SS pressure vessel, Ports for high voltage, pumping, gas filling, etc. Ke Han: PandaX-III NLDBD experiment. NDM 2018.](image)
Charge readout plane

7 Microbulk Micromegas modules installed and commissioned

- Micromegas module
- Top flat flange
- Through hole for hanging rods
- Copper ring
- Micromegas holding plate
- PMT slot

Ke Han: PandaX-III NLDBD experiment

NDM 2018
Some example tracks
Data: 1 MM with 1bar Ar:(5%)Isobutane

- $^{241}$Am Gamma source
- Voltage configuration:
  - Mesh: -370V
  - Drift: -2.8 kV ~ -11.8 kV
- Electronics range: 1pC

Detector gain ~8000

Energy spectrum detected of $^{241}$Am at 1 bar Ar:iso

- 9.3% FWHM at 26.3keV
- 11.2% at 20.6keV
- 11.9% at 17.8keV
- 17.1% at 16.8keV (multiple lines)
- 12.5% at 13.9keV
Data: 5 bar Xe:(1%)TMA

- Reached stable gain after more than 1 week of circulation and purification
- FWHM: 14.1% at 59.5 keV
- Drift voltage of -26 kV; mesh voltage of -440 V.

Shielded $^{241}\text{Am}$

$^{241}\text{Am}$ at 5 bar Xe:TMA

arXiv:1804.02863
Conclusions

• PandaX-III aims to build multiple 200-kg scale high pressure xenon TPC for NLDBD search at CJPL.
• The first module is under technical design phase.

• A 20-kg scale prototype TPC is under commissioning.
• With 7 modules of 20×20 cm, it’s the largest application of Microbulk Micromegas.
Table 5  The raw background contribution from different parts in the laboratory and the detector by taking the 3% FWHM detector resolution into account. BI stands for background index.

<table>
<thead>
<tr>
<th></th>
<th>Isotope</th>
<th>Activity</th>
<th>Background (CPY)</th>
<th>BI (10^{-5} c/(keV·kg·y))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>BambooMC</td>
<td>RestG4</td>
</tr>
<tr>
<td>Laboratory walls</td>
<td>238U</td>
<td>9.9 Bq/kg</td>
<td>&lt; 0.40 ± 0.03</td>
<td>&lt; 0.09 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>232Th</td>
<td>4.4 Bq/kg</td>
<td>&lt; 0.22 ± 0.02</td>
<td>&lt; 0.15 ± 0.01</td>
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<tr>
<td>Water</td>
<td>238U</td>
<td>0.12 μBq/kg</td>
<td>0.20 ± 0.1</td>
<td>0.22 ± 0.03</td>
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<tr>
<td></td>
<td>232Th</td>
<td>0.04 μBq/kg</td>
<td>0.24 ± 0.06</td>
<td>0.55 ± 0.03</td>
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<tr>
<td>Barrel</td>
<td>238U</td>
<td>0.75 μBq/kg</td>
<td>1.73 ± 0.12</td>
<td>1.77 ± 0.1</td>
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<tr>
<td></td>
<td>232Th</td>
<td>0.2 μBq/kg</td>
<td>4.63 ± 0.18</td>
<td>4.55 ± 0.05</td>
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<tr>
<td></td>
<td>60Co</td>
<td>10 μBq/kg</td>
<td>9.8 ± 1.0</td>
<td>9.9 ± 0.9</td>
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<tr>
<td>End-caps</td>
<td>238U</td>
<td>0.75 μBq/kg</td>
<td>0.83 ± 0.11</td>
<td>0.90 ± 0.11</td>
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<tr>
<td></td>
<td>232Th</td>
<td>0.2 μBq/kg</td>
<td>2.4 ± 0.1</td>
<td>2.2 ± 0.1</td>
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<tr>
<td></td>
<td>60Co</td>
<td>10 μBq/kg</td>
<td>4.4 ± 1.0</td>
<td>4.2 ± 0.9</td>
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<tr>
<td>Bolts</td>
<td>238U</td>
<td>0.5 mBq/kg</td>
<td>7.5 ± 1.5</td>
<td>7.3 ± 0.9</td>
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<tr>
<td></td>
<td>232Th</td>
<td>0.32 mBq/kg</td>
<td>39.8 ± 2.7</td>
<td>46.7 ± 1.9</td>
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<tr>
<td>Field insulator and rings</td>
<td>238U</td>
<td>4.94 μBq/kg</td>
<td>15.0 ± 0.5</td>
<td>15.7 ± 0.3</td>
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<td></td>
<td>232Th</td>
<td>0.1 μBq/kg</td>
<td>2.69 ± 0.03</td>
<td>2.61 ± 0.1</td>
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<tr>
<td></td>
<td>238U</td>
<td>0.75 μBq/kg</td>
<td>0.67 ± 0.01</td>
<td>0.72 ± 0.05</td>
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<td>0.2 μBq/kg</td>
<td>0.95 ± 0.01</td>
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<td>Electronics</td>
<td>238U</td>
<td>0.26 Bq</td>
<td>1.0 ± 0.3</td>
<td>2.4 ± 0.5</td>
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<tr>
<td></td>
<td>232Th</td>
<td>0.07 Bq</td>
<td>2.8 ± 0.2</td>
<td>4.1 ± 0.5</td>
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<tr>
<td>Micromegas</td>
<td>238U</td>
<td>45 nBq/cm²</td>
<td>60.5 ± 1.7</td>
<td>63.7 ± 1.8</td>
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<tr>
<td></td>
<td>232Th</td>
<td>14 nBq/cm²</td>
<td>23.5 ± 0.6</td>
<td>25.3 ± 0.6</td>
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<tr>
<td>Cathode</td>
<td>214Bi</td>
<td>2 nBq/cm²</td>
<td>4.1 ± 0.2</td>
<td>3.3 ± 0.1</td>
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<tr>
<td>Component</td>
<td>Isotope</td>
<td>Background ($10^{-5}$ c/(keV·kg·y))</td>
<td></td>
<td></td>
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<tr>
<td>---------------</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>BambooMC</td>
<td>RestG4</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>$^{238}$U</td>
<td>–</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{232}$Th</td>
<td>0.56</td>
<td>0.63</td>
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<tr>
<td>Barrel</td>
<td>$^{238}$U</td>
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<td>2.41</td>
<td></td>
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<td></td>
<td>$^{232}$Th</td>
<td>7.54</td>
<td>7.86</td>
<td></td>
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<tr>
<td></td>
<td>$^{60}$Co</td>
<td>3.02</td>
<td>2.11</td>
<td></td>
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<tr>
<td>End-caps</td>
<td>$^{238}$U</td>
<td>0.30</td>
<td>1.26</td>
<td></td>
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<tr>
<td></td>
<td>$^{232}$Th</td>
<td>3.89</td>
<td>4.16</td>
<td></td>
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<tr>
<td></td>
<td>$^{60}$Co</td>
<td>2.98</td>
<td>0.76</td>
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<tr>
<td>Bolts</td>
<td>$^{238}$U</td>
<td>3.50</td>
<td>11.9</td>
<td></td>
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<tr>
<td></td>
<td>$^{232}$Th</td>
<td>73.8</td>
<td>78.5</td>
<td></td>
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<tr>
<td>Field insulator and rings</td>
<td>$^{238}$U</td>
<td>19.5</td>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{232}$Th</td>
<td>3.80</td>
<td>3.86</td>
<td></td>
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<tr>
<td></td>
<td>$^{238}$U</td>
<td>1.52</td>
<td>0.45</td>
<td></td>
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<tr>
<td></td>
<td>$^{232}$Th</td>
<td>1.41</td>
<td>1.17</td>
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<tr>
<td>Electronics</td>
<td>$^{238}$U</td>
<td>–</td>
<td>1.42</td>
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<td></td>
<td>$^{232}$Th</td>
<td>5.02</td>
<td>8.69</td>
<td></td>
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<tr>
<td>Micromegas</td>
<td>$^{238}$U</td>
<td>144</td>
<td>158</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{232}$Th</td>
<td>36.9</td>
<td>44.5</td>
<td></td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>308.8</strong></td>
<td><strong>344.4</strong></td>
<td></td>
</tr>
</tbody>
</table>
TPC Field Cage – option 1 (mature)

• Copper shaping rings + resistors + external Acrylic (or other insulating materials) barrel
  • Similar design used and tested extensively in PandaX-I and PandaX-II

• Supporting barrel are critical
  • Dielectric strength
  • Displacer for $^{136}$Xe

• Designing a new version of with Kapton PCB + SMD resistors
TPC Field Cage – option 2

- Resistive coating layer + dielectric barrel
  - Works as continuous field shaping rings.
  - No more resistors
  - No more soldering
  - No copper rings
- Diamond-like carbon sputtering or commercial DLC or Ge film
- SUT (Thailand) is collaborating with SJTU on developing this option
- Acrylic barrel ready for prototype TPC at SJTU
- DLC coating on Kapton will be done in Japan.
  - Kobe developed DLC resistive strips for ATLAS Micromegas.
  - Resistivity and uniformity is key

From Atsuhiko Ochi, Kobe University
Field shaping around SR2M

Internal rim and external rim

- Shape E field
- Guide electrons to active area
PandaX-III MM: a minor update

• Custom-designed connector instead of Samtec

• Face to face connection with expanded PTFE disk for elasticity.

• Dummy connectors is going through repeated thermal cycles to stress test reliability.
Signal feedthrough

- Micromegas signals are read out through Kapton extension cables.
- Extension cables *glued* in matching slots in flanges.
- Leak test shows upper limit for leak rate is *gram level xenon per year* per feedthrough at 10 bar.
High voltage system

- Feedthrough for high voltage and withstand 10 bar gas pressure
  - PTFE wrap with a stainless steel rod
  - Squeezed by a Swagelok for gas tightness
- Tested on the prototype TPC
  - 70 kV in air
  - 95 kV in 10 bar $N_2$
- Extensive tests with 10 bar pressure: no leaks
Gas System

- A custom-designed system to fill, mix, circulate, purify and recuperate gas mixtures of xenon and argon gas.
- Room temperature and hot getters.
Electronics and DAQ

- Commercial front- and back-end electronics based on AGET chips.
- Established the data flow of 7 Micromegas simultaneously
- 896 channels tested with ASAD + CoBo
- Custom front-end electronics card tested on the prototype TPC data
## PandaX vs. NEXT

<table>
<thead>
<tr>
<th>PandaX-III first TPC</th>
<th>NEXT-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 kg Xe(enriched) + 1% TMA</td>
<td>Detector medium</td>
</tr>
<tr>
<td>----------------------</td>
<td>------------</td>
</tr>
<tr>
<td>Light</td>
<td>Primary + electroluminescence light readout by PMTs</td>
</tr>
<tr>
<td>Micromegas</td>
<td>SiPM</td>
</tr>
<tr>
<td>3%</td>
<td>Projected energy resolution</td>
</tr>
<tr>
<td>2-3 mm</td>
<td>Tracking pitch size</td>
</tr>
<tr>
<td>X,Y</td>
<td>Fiducialization</td>
</tr>
<tr>
<td>Since 2015</td>
<td>Since ~2008</td>
</tr>
</tbody>
</table>

Ke Han: PandaX-III NLDBD experiement

NDM 2018
MM Characterization

Gain and gain uniformity measured
- Argon + CO₂ (30%)
- 1 bar flowing gas
- 7.5% RMS uniformity

Future updates:
- Motorized source scanning
- More uniform drift field
- Pressurized xenon gas
- Multiple MM cross comparison
# 200 kg module vs prototype

<table>
<thead>
<tr>
<th></th>
<th>First 200 kg module</th>
<th>Prototype TPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Symmetric</td>
<td>Single-ended</td>
</tr>
<tr>
<td>Active volume</td>
<td>~3.5 m$^3$</td>
<td>0.25 m$^3$</td>
</tr>
<tr>
<td>Number of MM</td>
<td>82</td>
<td>7</td>
</tr>
<tr>
<td>Readout channels</td>
<td>10496</td>
<td>896</td>
</tr>
<tr>
<td>Electronics</td>
<td>AGET + Custom FEC</td>
<td>ASAD/CoBo; then Custom FEC</td>
</tr>
<tr>
<td>HP vessel</td>
<td>OFHC copper</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Field cage</td>
<td>2$\pi$ acrylic wall with resistive film</td>
<td>Copper rings with Teflon bars</td>
</tr>
</tbody>
</table>