GEM-TPC development in Canada

Dean Karlen
Technology recommendation panel meeting
January 16, 2006
KEK
Outline

- Brief summary of GEM-TPC R&D in Canada (1999-2005)
  - X-ray studies with small test cell
  - First GEM-TPC studies of spatial resolution
  - First operation of a GEM-TPC in magnetic fields

- T2K GEM-TPC design
  - Prototype TPC module
    - design and construction
    - HV distribution system
    - initial results

- Summary
  - GEMs and the criteria for the technology recommendation
Space point resolution studies (1999 - 2000)

two stage GEM amplification, 10 x 10 cm GEMs

- x-ray tube
- pin hole
- GEM cell
- 2D micrometer stage
An event
2.5 mm pitch hexagons

Ar CO₂ (90:10)
HQV810 preamps
2 4-channel scopes
Charge sharing result – Ar CO$_2$

resolution ~ 1/50 of pad pitch

$\bar{x} = -0.095$ mm  
$\sigma_x = 0.043$ mm

$(x,y)_{col} = (-0.1, 1.143)$ mm

$\bar{y} = 1.129$ mm  
$\sigma_y = 0.061$ mm

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$y = 1.129$ mm  
$\sigma_y = 0.061$ mm

$x = -0.095$ mm  
$\sigma_x = 0.043$ mm

resolution ~ 1/50 of pad pitch
Small GEM-TPC (2001)

- first GEM-TPC resolution measurements…

15 cm
Cosmic setup (2001)

- Cosmic ray telescope
- Readout pad layout
  - 32 channel FADC

![Cosmic ray telescope with a 32 channel FADC readout pad layout. The layout consists of 32 square pads arranged in a grid with dimensions 5 mm in height and 2.5 mm in width.]
First event (Oct 2001)
New Pad Layout (2002)

- Increased number of pads by multiplexing:
  - 3x multiplexed
  - Ar CO₂ (90:10) and P10
Example Events

- Outer 6 rows are used to define track parameters
  - inner two rows: resolution studies (fit for $x_0$ alone)
  - 2 mm x 6 mm / 3 mm x 5 mm
Transverse resolution

Magnetic field studies (2003-2004)

- New GEM-TPC for operation in magnetic fields
  - for ILC applications use fields up to 5 T
  - fast gases, P5 or P10 used - transverse diffusion reduced
  - 256 channels from STAR TPC
Field termination problem

- Tracking distortions seen with original field terminator

![Graph with data points and wire mesh image]
TPC modification

- New endpiece constructed: wire grid
  - 70 μm wire strung with 2.5 mm spacing
  - matched to GEM active area
Tracking distortions fixed

- With new wire grid, problem is solved
- Wire grid incorporated into T2K GEM-TPC design

![Graph showing mean residual for centre row (mm) vs. x coordinate (mm)]
First GEM-TPC tracking in B fields

- TRIUMF tests (0 – 0.9 T): June 2003
Example events at ~ 25 cm drift

- **Gas:** P10
  - Pads: 2 mm x 7 mm

### Magnetic Field Strengths

- **0 Tesla:**
  - $\sigma = 2.3$ mm

- **0.45 Tesla:**
  - $\sigma = 1.2$ mm

- **0.9 Tesla:**
  - $\sigma = 0.8$ mm
DESY tests (0 – 5.3 T): July/August 2003
Example events at ~ 25 cm drift

- Gas: P5

![Images of event samples at different magnetic fields (B)]
Pulse analysis

- Both induced and real pulses are seen.
- Electronics shaping responsible for the unipolar (real) and bipolar (induced) shapes for these pulses.
Electron transport measurements

- The maximum likelihood track fit includes the standard deviation of the charge clouds as they arrive on the pads, $\sigma$.

![Graph showing $\sigma^2$ vs. drift time with P5 data and B = 0.9 T, with notes on defocusing and diffusion.]
Diffusion constants: P5 and TDR gases

- In reasonable agreement with Magboltz
- TDR = Ar CH₄ CO₂ (95:3:2)
Additional magnetic field studies (2004)

- Modify TPC for laser calibration studies
  - sends 1-2 beams through TPC

TPC holder

laser power supply

laser + optics

quartz window
Cosmic ray simulation

- To better understand the results from the cosmic ray samples, a full GEANT3 simulation of cosmic events was developed:

![Diagram showing DESY magnet and Active TPC volume]
Spectrum/asymmetry of muons

Inverse radius of curvature (1/m)

Number of events

-1.0 -0.5 0.0 0.5 1.0

mu +
mu -
Data
dE/dx study

- Use all 11 rows – form truncated average number of electrons collected on the rows per mm of path length
- Overall resolution 17% (86 mm sample)
  - expected 16%
Transverse resolution measurements

- Resolution measurements:

![Graph showing transverse resolution measurements with data points for 4T, 1T, and 0T conditions, along with Monte Carlo simulations (MC)].

Track angle effect

P5 at 4T

azimuthal angle (rad)

resolution (mm)

-0.10 -0.05 0.00 0.05 0.10

0.14

0.12

0.10

0.08

0.06

0.04

-0.10 -0.05 0.00 0.05 0.10

wide

wide MC

narrow

narrow MC
Two track resolution studies

- Bring two laser beams close together at same $z$
  - example (runs 67-69): 3.8 mm separation, $\sigma = 0.5$ mm

![Diagram showing three panels: Beam 1 only, Beam 2 only, and Beam 1 and 2.](image_url)
Two track resolution

- Wide, z = 140 mm
- Narrow, z = 54 mm
- Narrow, z = 263 mm
- Laser simulation
- Muon pair simulation

Track separation (mm)

Two track resolution / single track resolution
Summary of Canadian GEM-TPC R&D

- Experience with GEM-TPCs from several years of R&D:
  - GEMs found to be reliable, if treated carefully
    - only one GEM damaged during this time – during a test of double GEM system in Ar CO₂ (70:30) and GEM operating voltages brought well above nominal value (>460 V cf. 340 V)
  - GEMs make good gas amplification modules for TPCs with or without magnetic fields
    - capable of excellent resolution (\(\sigma \approx 0.1\) mm for a row of 2 mm pads sampling 7 mm)
    - systematic biases can be controlled at a level much smaller than T2K TPC resolution goals
T2K GEM-TPC design

- Strategy of the Canadian group:
  - Design the GEM-TPCs for T2K according to techniques proven in the GEM-TPC R&D program, from experience in building other gas trackers, and following successful practices used by other groups.
  - Take a conservative approach wherever possible.
    - The 3 modules are large scale systems and will be required to operate for many years with limited access.
T2K GEM-TPC design – Gas choice

- Use a low diffusion gas, since the magnetic field is relatively weak (0.2 T)
  - Baseline choice: Ar CO₂ (90:10), with a drift field of about 200 V/cm
    - good experience in our GEM-TPC R&D program, well tested in large TPCs and other gas detectors - low risk
    - COMPASS GEM system uses Ar CO₂ (70:30) since 2002
    - inexpensive, mix non-flammable components in gas system
      - proportion can be adjusted, if needed
      - minor effects for small leak from outer gas volume (CO₂)
  - Higher concentrations of CO₂ reduce the diffusion, but require higher drift fields and lower O₂ concentration
    - concept designed to work at 400 V/cm – provides an additional safety margin against field cage breakdown
T2K GEM-TPC design – readout

- Inner box gas seal done by the readout pad boards themselves
  - many GEM modules attached to a large pad board
  - reduces the number of o-rings, compared to having separate GEM modules
    - all o-rings are compressed by screws
  - design may have 1 or 2 pad boards per endplate
    - have found several suppliers than can provide a PCB large enough for the entire endplate at a reasonable cost
  - all via holes through PCB are covered over with solder-mask during production
T2K GEM-TPC design - endplate
GEM-TPC design – GEM modules

- Follow the example of COMPASS:
  - use a simplified GEM foil design with same active area (309 x 309 mm$^2$)
    - the area is divided into 12 sectors to reduce stored energy – each smaller than the 10 x 10 cm$^2$ GEMs used in the GEM R&D program
  - use 3-stage GEM amplification
    - gives good gas gain with Ar CO$_2$ (90:10)
      - Note: COMPASS uses Ar CO$_2$ (70:30)
    - ~10-20% lower operating voltages needed for 90:10
      - → expect very safe operation for 90:10
    - increase gap between foils – eliminate insulating spacers in contact with active regions of GEM foils
    - reduce the electric field between foils, and between foils and pads
GEM-TPC design – GEM modules

- Stretched GEM foils are glued to frames
- 3 framed GEM foils attached together to make a GEM module
- HV to GEM modules are provided through spring contact pins and vias through the PCB
  - no additional gas seals for HV connections
  - no soldered connections – simpler to place and replace GEM modules
- Wire grid placed over GEM module to precisely terminate the long drift field
Prototype GEM-TPC (module -1)

- To check the T2K GEM-TPC concept, a prototype was designed and constructed in 2005.
Prototype construction at TRIUMF

- Composite walls (outer walls) – gluing technique
Prototype construction

- Outer box glued in a heated tent in clean room
Prototype construction

- Hard work!
Prototype construction

- Outer wall of inner box with field strips and matched surface mount resistors
- Jumpers through the wall
Prototype construction

- Rounded corners for inner box being installed
Prototype construction

- Central cathode connection
Prototype construction

- Completed TPC field cage/gas containment
Prototype construction

• A look inside
TPC shipped to Victoria

- brought over by ferry on December 20
Prototype construction

- GEM module preparation at Victoria
  - use 6 CERN GEMs – modified COMPASS design
  - 309 mm x 309 mm active area
Prototype construction

- Alignment and gluing
Prototype construction

- GEM stack

Prototype: pad board accepts one GEM module - tests concept of endplate with two pad boards
Prototype construction

- attaching the wire grid
Prototype construction

- inserting in test box – check with Fe$^{55}$
Prototype construction

- GEM modules inserted into TPC
Prototype construction

- connections/telescope
Prototype construction

- ALICE FECs
- signal inverters
DAQ for prototype

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Prototype HV system

- Isolated DC converters safely power the GEMs while giving complete flexibility
Prototype HV system

- inexpensive DCC controls gain of each GEM separately (DCC outside TPC)
- identical potential for upper surfaces of GEMs – better field uniformity
- no resistor dividers – nominally no currents, voltages can be specified
Control software for prototype HV system
Prototype gas system

- Gas mix maintained by mass flow controllers
- O$_2$ filter for inner volume gas - monitored at inlet and outlet
Prototype operation

- GEMs installed and gas service connections for TPC completed on December 30, 2005
  - Ar CO₂ gas flowing through inner volume and CO₂ through outer volume over New Year’s weekend

- Remaining work completed on Jan 3
  - brought up fields and GEMs for the first time on Jan 3
  - drift field: 180 V/cm, transfer fields: 800 V/cm, GEMs: 330 V
  - tracks seen – it works!

- Remainder of inverter cards arrived Jan 4

- Started collecting large cosmic samples Jan 5
  - TPC left on voltage since then – no incidents
Example event from prototype

coloured according to amplitude

coloured according to arrival time

run 475, event 21
Track Fit

- Likelihood analysis
  - estimate includes sigma: the width of the signal distribution on the pads
Drift velocity

- **Initial data (thought to be: Ar CO₂ 90:10)**

- Cosmic telescope moved by 463 mm
- Shift in mean arrival time is 17.5 us
- \( v_d \approx 26.4 \text{ mm/us} \)
- Too fast for 90:10
- At \( E_{\text{drift}} = 180 \text{ V/cm} \)
- Expect: 12.4 mm/us
Diffusion

Diffusion constant:

283 \text{um}/\sqrt{\text{cm}}

Too large for 90:10 at Edrift = 180 V/cm

Expect: 223 \text{um}/\sqrt{\text{cm}}
Check...

- An overnight run...

Diffusion constant:

\[ v_d \approx 26.7 \text{ mm/us} \]

\[ 277 \text{ um/} \sqrt{\text{cm}} \]
Stability...

- Over 15 hours, drift velocity and diffusion are stable at the 1% level
Gain stability
Spatial Resolution (drift direction)

- Use a linear fit of y vs. peak time bin #, to define track in y-z plane
  - standard deviation of residuals  resolution per row

![Graph showing spatial resolution vs. drift distance](image)
Spatial Resolution (transverse)

- transverse resolution for 8 mm pads:
Increased CO$_2$ concentration

- The CO$_2$ mass flow controller appears to flow about half the set value – according to a simple flow meter
  - this would explain the drift velocity and diffusion #'s
- The CO$_2$ flow rate was then doubled – with the intention of having CO$_2$ concentration near 10%

GEMs raised to 340 V
vd $\sim$ 12.6 mm/us
(as expected for 90:10)
Diffusion (doubled CO$_2$)

Diffusion constant:

186 um/$\sqrt{\text{cm}}$

Smaller than expected for Ar CO$_2$ 90:10 at Edrift = 180 V/cm

Expect: 223 um/$\sqrt{\text{cm}}$
Resolution (transverse)

- for 8 mm pads:

![Graph showing resolution vs. drift distance](image-url)
Resolution vs azimuthal angle

- track angle effect from non-uniform ionization
- compensated by longer path length through TPC
Attachment

• some indication of electron attachment...
Summary of T2K TPC prototype work

- A great success – a lot of hard work by the UBC/TRIUMF/UVic groups

- Successful demonstration that the concept for a 1.25 m long drift TPC operates well with Ar CO$_2$ 90:10

- Preliminary analyses estimate single row transverse resolutions of 0.6 – 0.8 mm

- TPC on continuously since initial turn on (two weeks now)
Full scale module designs

- The prototype (module -1) has demonstrated that the TPC design concept is basically sound
- Some modifications to the outer box are now under consideration:
  - use of Al structural pieces for robustness
  - elements for integration into the UA1 magnet
  - location for service connections
Chris Hearty is developing a detailed schedule for the design and construction of module 0 and the production modules.
## Canadian Team

<table>
<thead>
<tr>
<th>TPC activity</th>
<th>Canadian personnel</th>
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<tr>
<td>Project leader</td>
<td>D.K.</td>
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<td>Construction mngmnt</td>
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<tr>
<td>• at TRIUMF:</td>
<td>• Chris Hearty</td>
</tr>
<tr>
<td>• at Victoria:</td>
<td>• Paul Poffenberger</td>
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<tr>
<td>Mechanical design and construction</td>
<td>• Robert Henderson</td>
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<td></td>
<td>• Wayne Faszer</td>
</tr>
<tr>
<td></td>
<td>• TBA designer at TRIUMF</td>
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<td></td>
<td>• Alisa Dowling</td>
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<td></td>
<td>• Paul Birney</td>
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<td>• Roy Langstaff</td>
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<td>• Mark Lenckowski</td>
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<td>• Doug Maas</td>
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<td>● Issei Kato</td>
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<td>● Christian Hansen</td>
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<td>● Kyle Fransham</td>
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<td>● TBA technician</td>
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<td>● Reece Hasanen</td>
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<td>High voltage systems</td>
<td>● Kyle Fransham</td>
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<td>Field cage simulation</td>
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<td>● Kyle Fransham</td>
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<td>Laser calibration</td>
<td>● Michael Roney</td>
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<td>● Christian Hansen</td>
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<td>DAQ software</td>
<td>● Konstantin Olchanski</td>
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<tr>
<td>Cosmic and beam tests and analysis</td>
<td>● Kyle Fransham</td>
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<td>● Christian Hansen</td>
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<td>● Juergen Wendland</td>
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Canadian Funding

- The Canadian science funding council (NSERC) has funded the GEM-TPC R&D program since 1999.
- For FY2005, they funded the T2K TPC prototype construction.
- For FY2006-2008 we have submitted a request for the construction of module 0 and the three production GEM-TPC modules.
  - NSERC review of the project last week at TRIUMF:
    - committee reported to us that they strongly support funding the T2K TPC project (and the other Canadian T2K projects)
    - we will notify the grant selection committee about the technology recommendation on Feb 3.
Technology recommendation

Comments regarding GEMs for stated criteria:

- experience of the T2K TPC groups
- cost and supply of the devices
- simplicity in readout module design,
- demonstrated performance
- robustness
- flexibility regarding gas choices
- impact on readout electronics
Supply of GEMs

- CERN GEMs used for prototype – a year ago it was not clear whether they could produce enough GEMs for the T2K TPC modules
  - Two US companies, TechEtch and 3M, have made GEMs for us similar to the CERN GEMs
**Cost of GEMs**

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### Quotation

Valid Until 2/19/06.

**To:** University of Victoria & TRIUMF  
Address: Department of Physics and Astronomy  
Vancouver, BC  
Canada  

Attention: Professor Dean Karlen  
Phone: 250.721.6585  
Fax: 250.721.7752  
e-mail: karlen@uvic.ca

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The Electronic Solutions Division of 3M offers the following quotation as submitted:

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<th>Customer Drawing/Part Number: N/A</th>
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#### 3M Part Description
- GEMS Foils  
- 2 Metal Layer  
- 0.7μm Electroless Ni/0.06μm Immersion Au  
- Part Width: 305mm  
- Part Length: 305mm  
- Format: Singulated

#### Prototype Quantity

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#### Prototype Tooling

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**Comments:**

1. 3M will use efforts consistent with good business practices to complete this order. If for some reason 3M cannot build this product, only the tooling will be invoiced.
2. This quotation is governed solely by the standard 3M Terms and Conditions of sale attached.
3. The quoted prices are in US dollars.
4. Delivery time is dependent upon shipment method and customs clearance.

**Ship Schedule:** Parts will be shipped 8 weeks after the latter of receipt of order and design approval.
# QUANTITY DESCRIPTION UNIT PRICE UNITS LEAD TIME
1 250 P/N: T2K GEM FOIL REVISION - 500

GENERAL NOTES:
1. LEAD TIME CORRELATES TO AN INITIAL DELIVERY OF UP TO 25 PIECES WITH SUBSEQUENT DELIVERY SCHEDULE TO BE AGREED ON BY UNIVERSITY OF VICTORIA AND TECH-ETCH.
Supply of GEMs

- Recent discussions between the Geneva University group and the CERN GEM fabrication group sound very promising
  - cost is very competitive
  - well tested production methods (COMPASS)
  - Canada / Geneva cost sharing arrangement possible

- This would be considered as the best option, with private industry as a fall-back solution
Simplicity in GEM readout module design

- modular construction of amplification module
  - single GEM foil on frame can be removed from module – dry assembly

- amplification modules decoupled from pad boards
  - pad boards form gas seal, with only 1 or 2 o-rings per endplate
  - pad alignment issues simplified:
    - relative pad locations fixed and known to high precision across endplate of TPC
    - pad locations relative to external TPC reference positions fixed to high precision
Demonstrated GEM performance

- High precision demonstrations of the GEM-TPC concept have been completed over the past few years for its application as an ILC tracker
  - position systematics at less than 0.1 mm level

- A complete GEM-TPC prototype following the T2K TPC design has been constructed and successfully commissioned
Robustness of GEMs

- COMPASS is an excellent demonstration of the robustness of GEM amplification modules
  - operation of 20 triple GEM modules in a hadron beam since 2002 without incident
  - we propose to use almost identical foils for T2K
- since the T2K TPCs have even more amplification modules (72) and may have an expected lifetime of ~10 years, we reduce the probability of an incident further by operating at reduced voltages, with larger GEM separation, and with lower fields between GEMs
GEM flexibility regarding gas choices

- Ar CO₂ (90:10) is a safe baseline choice – good gain is easily reached
  - could adjust proportions if necessary (to change drift velocity or diffusion properties)
- no hydrocarbon quenchers are needed, but we have operated GEM-TPCs with Ar CH₄ to achieve low transverse diffusion in strong magnetic fields
GEM impact on readout electronics

- The large separation between the last amplification layer and pads (~5 mm) and the low electric field between them (< 800 V/cm) means that the possibility of sparking across the gap is negligible under normal operating conditions.
  - not necessary to include protection diodes on the electronics – simplification, noise reduction
  - we operated the Victoria ILC GEM-TPC prototype without protection diodes (STAR FEC)
  - we operate the T2K GEM-TPC prototype without protection diodes (ALICE FEC)
Conclusion

I would like to thank the members of the Technology Recommendation Panel for helping us make this important decision – so that we can proceed to a final TPC design and construction, and be ready for the physics in 2009!