DUNE: A New Collaboration for Physics at LBNF

Mark Thomson
on behalf of the DUNE Collaboration

HEPAP Meeting
9th December 2015
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1. The DUNE Collaboration
Introduction: DUNE and P5

Paraphrasing P5

• Called for the formation of **LBNF**:  
  – as an *international* collaboration bringing together the LBL community  
  – ambitious scientific goals with discovery potential for:  
    • Leptonic Charge-Parity (CP) violation  
    • Proton decay  
    • Supernova burst neutrinos

**Resulted in the formation of the DUNE collaboration with strong representation from:**

– LBNE  
– LBNO  
– Other interested institutes
DUNE is up-and-running

It is a rapidly evolving scientific collaboration…

• First formal collaboration meeting April 16th-18th 2015
  – Over 200 people attended in person
• Conceptual Design Report in June (foundations from LBNE/LBNO)
• Passed DOE CD-1 Review in July
• Second collaboration meeting September 2nd-5th 2015
• Successful CD-3a Review in December 2015 (last week)
  – paves the way to approval of excavation in FY17
The DUNE Collaboration

As of today:

803 Collaborators

from

145 Institutes
The DUNE Collaboration

As of today:

803 Collaborators

from

27 Nations

Armenia, Belgium, Brazil, Bulgaria, Canada, Colombia, Czech Republic, France, Germany, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, Spain, Switzerland, Turkey, UK, USA, Ukraine

+ soon to add Finland

DUNE already has attracted broad international support
Organizational Challenges

- **Large and diverse international collaboration**
  - Need to fully engage broad spectrum of collaborators in the DUNE scientific and detector activities

- **The collaboration is likely to grow significantly**
  - Management structures need to be scale effectively to a collaboration of >1000 scientists, c.f. ~3000 in ATLAS or CMS

- **CD-2 in 2019 is a major goal**
  - Need to effectively utilize the collaboration resources, both financial and people
  - Further engage international community
Organizational Challenges

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• **The collaboration is likely to grow significantly**
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  – Need to effectively utilize the collaboration resources, both financial and people
  – Further engage international community

Guided by experience from LHC experiments and elsewhere
Collaboration Management

• **Collaboration rules adopted in April**
  - Defined high-level management structure and executive committee
  - Initial focus was the preparation of the draft CD-1-R documents
    • Set up temporary task forces to draft CDR

• **Since CD-1-Refresh review in July:**
  - Implemented collaboration working group structure and leadership
    • Put in place a very strong far detector leadership team
  - Set up 3 task forces to addresses strategically important questions
  - Defined technical board membership
    • Played an important role in defining/validating the far site requirements for detector grounding and DAQ power
  - Currently developing the work plan for progress towards CD-2 in 2019 and identifying resources required
  - Now in “normal” operational mode with regular WG meetings
DUNE Management

Experienced team in place since April

Co-spokespersons:
A. Rubbia
M. Thomson

Resource coordinator:
C.K. Jung

Technical coordinator:
E. James

International project manager:
S. Kettell

DUNE General Assembly
DUNE Institutional Board

Co-Spokespersons

Executive Committee (Co-Spokesperson)

TC

RC

Project Office (PM)

Technical Board (TC)

Collaboration Resource Board (RC)
By September all coordinators were in place
- Searched widely within the collaboration
- Ended up with a very strong team
- Responsible for coordination of DUNE working groups
DUNE Task Forces

- In addition to WGs, we have set up three “Task Forces” to address strategically important issues:
  - Task force leadership reports the DUNE executive committee
  - Focus on collaboration goals/open questions for CD-2
  - Activities cross boundaries of various working groups
    - For example physics, reconstruction software and far detector WGs
  - Limited duration: deliver report in 18 months

- Assembled strong teams
DUNE Task Forces cont.

• TF1: Near detector optimization
  – End-to-end simulation of Near Detector design and analysis
  – Evaluate impact on far detector systematics
  – Evaluate benefits of alternative designs

• TF2: Far Detector Reconstruction/Physics
  – End-to-end simulation and full reconstruction of far detector
  – Validation (optimization) of design parameters (e.g. wire spacing)
  – Update physics sensitivities with full simulation for CD-2

• TF3: Beam Optimization
  – Further develop physics-driven optimization of the beam line
  – Identify options for improvements and present a first-order cost-benefit analysis
DUNE Task Forces cont.

• TF1: Near detector optimization
  – End-to-end simulation of Near Detector design and analysis
  – Evaluate impact on far detector systematics
  – Evaluate benefits of alternative designs

• TF2: Far Detector Reconstruction Techniques
  – End-to-end simulation and full reconstruction of far detector
  – Validation (optimization) of design parameters (e.g. wire spacing)
  – Update physics sensitivities with full simulation for CD-2

• TF3: Beam Optimization
  – Further develop physics-driven optimization of the beam line
  – Identify options for improvements and present a first-order cost-benefit analysis

Focus on critical questions as we move from CD-1-R to CD-2
Timeline

- Hit many “milestones” in the last nine months
  - 11 March  DUNE Co-spokespersons elected ✓
  - 18 March  DUNE technical coordinator named ✓
  - 24 March  Task Force conveners named – charged to prepare CDR ✓
  - 16-18 April  First DUNE Collaboration Meeting ✓
  - 18 April  Institute Board Rules approved ✓
  - 19 April  First full LBNC Meeting ✓
  - 4 May  First DUNE Executive Committee meeting ✓
  - 2-3 June  CD-1-R Director’s Review ✓
  - 14-16 July  DOE CD-1-R Review ✓
  - 27 July  Scientific/Detector Coordinators appointed ✓
  - 17 August  Technical Board Formed ✓
  - 2-5 Sept  Second DUNE Collaboration Meeting ✓
  - 21 Sept  Move to regular WG meeting schedule ✓
  - 27-29 Oct  DOE CD-3a Director’s Reviews ✓
  - 2-4 Dec  DOE CD-3a Review ✓
2. DUNE Science

A neutrino interaction in the ArgoNEUT detector at Fermilab
DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astroparticle physics:

• **1) Neutrino Oscillation Physics**
  - Discover CP Violation in the leptonic sector
  - Mass Hierarchy
  - Precision Oscillation Physics:
    • e.g. parameter measurement, \( \theta_{23} \) octant, testing the 3-flavor paradigm

• **2) Nucleon Decay**
  - e.g. targeting SUSY-favored modes, \( p \rightarrow K^+\bar{\nu} \)

• **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to \( \nu_e \)
Focus on fundamental open questions in particle physics and astroparticle physics:

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All would be major discoveries - matched to P5 priorities
Neutrino Oscillation Strategy

Measure **neutrino** spectra at 1300 km in a wide-band beam

- **Near Detector at Fermilab:** measurements of $\nu_\mu$ unoscillated beam
- **Far Detector at SURF:** measure oscillated $\nu_\mu$ & $\nu_e$ neutrino spectra
Neutrino Oscillation Strategy

... then repeat for antineutrinos

- Compare oscillations of neutrinos and antineutrinos
- Direct probe of CPV in the neutrino sector

- Near Detector at Fermilab: measurements of $\bar{\nu}_\mu$ unoscillated beam
- Far Detector at SURF: measure oscillated $\bar{\nu}_\mu$ & $\bar{\nu}_e$ neutrino spectra
Neutrino Oscillation Strategy

Long baseline and wide-band beam enables:

- Determine MH and $\theta_{23}$ octant, probe CPV, test 3-flavor paradigm and search for BSM effects (e.g. NSI) in a single experiment
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure $\nu_e$ appearance and $\nu_\mu$ disappearance over range of energies
    - MH & CPV effects are separable

$$E \sim \text{few GeV}$$
DUNE CDR Reference Design =

Far detector: 40-kt fiducial LAr-TPC (four 10-kt modules)

Near detector: Multi-purpose high-resolution detector
Many inputs to calculation (implemented in GLoBeS):

- **Reference Beam Flux**
  - 80 GeV protons
  - 204m He-filled decay pipe
  - 1.07 MW
  - NuMI-style two horn system

- **Optimized Beam Flux**
  - Horn system optimized for lower energies

- **Expected Detector Performance**
  - Based on previous experience (ICARUS, ArgoNEUT, ...)

- **Cross sections**
  - GENIE 2.8.4
  - CC & NC
  - all (anti)neutrino flavors

Exclusive $\nu$-nucleon cross sections
DUNE CDR Sensitivities

Propagate to Oscillation Sensitivities using assumptions for systematics (from the ND)
DUNE CDR Sensitivities

Propagate to Oscillation Sensitivities

using assumptions for systematics (from the ND)

50% CP Violation Sensitivity

\[ \sigma = \sqrt{\chi^2} \]

DUNE Sensitivity
Normal Hierarchy
\[ \sin^2\theta_{13} = 0.085 \]
\[ \sin^2\theta_{23} = 0.45 \]

+ staging from RLS
MH Sensitivity

★ Sensitivities depend on multiple factors:
  ▪ Other parameters, e.g. $\delta$
  ▪ Beam spectrum, …

MH significance
MH Sensitivity

Sensitivities depend on multiple factors:
- Other parameters, e.g. $\delta$
- Beam spectrum, ...

Definitive (5$\sigma$) determination of the Mass Hierarchy
MH and CPV Sensitivities

- Sensitivities depend on multiple factors:
  - Other parameters, e.g. $\delta$
  - Beam spectrum, ...
MH and CPV Sensitivities

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  - Beam spectrum, ...

Genuine CPV discovery potential + measurement of $\delta$
Beyond discovery: measurement of $\delta$

- CPV “coverage” is just one way of looking at sensitivity…
- Can also express in terms of the uncertainty on $\delta$

Start to ~approach current level of precision on quark-sector CPV phase (although takes time)
Physics Milestones

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for Mass Hierarchy:
  - Reach $5\sigma$ MH sensitivity with 20 – 30 kt.MW.year

  Discovery

  ~2 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$):
  - Reach $3\sigma$ CPV sensitivity with 60 – 70 kt.MW.year

  Strong evidence

  ~3-4 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$):
  - Reach $5\sigma$ MH sensitivity with 210 – 280 kt.MW.year

  Discovery

  ~6-7 years

★ Genuine potential for early physics discovery
DUNE Detector Strategy
Staged Approach to 40 kt (fiducial)

Cavern Layout at the Sanford Underground Research Facility (SURF) discussed in detail jointly by LBNF and DUNE

- Decision based on: strategic + technical input
  - four chambers hosting four independent 10-kt FD modules
    - Allows for staged construction of FD
    - Gives flexibility for evolution of LAr-TPC technology design
      - Assume four identical cryostats: 15.1 (W) x 14.0 (H) x 62 (L) m³
      - Assume the four 10-kt modules will be similar but not identical
LAr-TPC Technologies

LAr-TPC technology has been demonstrated by ICARUS.

DUNE is considering two options for readout of ionization signals:

• **Single-phase wire-plane readout** (reference design)
  – Ionization signals (collection + induction) read out in liquid volume
  – As used in ICARUS, ArgoNEUT/LArIAT, MicroBooNE
  – Long-term operation already demonstrated by ICARUS T600

• **Dual-phase readout** (alternative design)
  – Ionization signals amplified and detected in gaseous argon above the liquid surface
  – Being pioneered by the WA105 collaboration
  – If demonstrated, potential advantages over single-phase approach

Underpinned by strong LAr-TPC development program.
LAr-TPC Technologies

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Underpinned by strong LAr-TPC development program
Far Detector Reference Design

Single-phase APA/CPA LAr-TPC:

- Design is already well advanced for CDR stage
- Supported by strong development program at Fermilab
  - 35-t prototype (operational in 2015) almost ready to fill with LAr
  - MicroBooNE (operational in 2015)
  - SBND (aiming for operation in 2018)
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- “Full-scale prototype” with ProtoDUNE at the CERN Neutrino Platform
  - Engineering prototype
    - 6 full-sized drift cells c.f. 150 in the far detector
  - Approved by CERN SPSC (October 2015)
  - Aiming for operation in 2018
**DUNE FD Staging Strategy**

Far Detector Implementation strategy

- **First 10-kt will be the single-phase APA/CPA design**
  - Represents lowest risk route to installation in 2021
  - Production lines set up for DUNE single-phase prototype at CERN

- **Experience at CERN and Fermilab**
  - Evolution of LArTPC design, either through:
    - Refinements of single-phase design
    - Validation of operation of dual-phase design

- **Technology choice for 2\textsuperscript{nd} & subsequent 10-kt modules:**
  - Based on risk, cost and physics performance
  - Review process will organized by the DUNE technical board
  - Ultimate decision by DUNE executive committee
  - Process repeated for 3\textsuperscript{rd} & 4\textsuperscript{th} 10-kt module
The DUNE Near Detector

CDR reference design is the NOMAD-inspired Fine-Grained Tracker (FGT)

- **Consisting of:**
  - Central straw-tube tracking system
  - Lead-scintillator sampling ECAL
  - Large-bore warm dipole magnet
  - RPC-based muon tracking systems

Will result in unprecedented samples of $\nu$ interactions

- >100 million interactions over a wide range of energies:
  - strong constraints on systematics
  - the ND samples will represent a huge scientific opportunity

- **Also evaluating other ND options (in ND Task Force)**
  - High-pressure gaseous argon TPC as a tracker
  - Augmenting the ND with a LAr-TPC
5. DUNE & P5
DUNE Reference Design & P5

P5 identified the following “minimum requirements to proceed”:

• reach an exposure of 120 kt.MW.years by 2035
• Far detector underground with cavern space for expansion to 40 kt LAr (fiducial)
• 1.2 MW beam upgradable to multi-MW power
• Demonstrated capability for supernova neutrino bursts
• Demonstrated capability for proton decay, providing a significant improvement over current searches

P5 “goal” is for \(3\sigma\) CPV coverage for > 75 % of \(\delta\) values
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P5 “goal” is for $3\sigma$ CPV coverage for $>75\%$ of $\delta$ values

DUNE design meets the P5 goals
5. Relation to SBN & CERN $\nu$ Platform
5. Relation to SBN & CERN ν Platform

- Fermilab SBN and CERN neutrino platform provide a strong LArTPC development and prototyping program
Relation to SBN & CERN ν Platform

DUNE is actively trying to build on potential synergies across FNAL SBN & CERN programmes

• Single-phase vs. Dual-phase @ CERN
  – Pursuing path under DUNE organization with common/shared activities between WA105 & ProtoDUNE

• Already benefiting from MicroBooNE
  – Sharing of software MicroBooNE → 35-t prototype
  – Discussing how to transfer “lessons learned”

• Held workshops to explore potential synergies
  – DUNE – SBND TPC workshop
    • Common development of cold electronics
  – DUNE – SBN – WA105 DAQ workshop
    • Potential to share “online” tools across programme
    • Potential for common backend DAQ (ProtoDUNE-WA105-ICARUS)
  – LArTPC workshop on LArSoft Requirements & Reconstruction
    • Follow up meetings in the new year
Relation to SBN & CERN \( \nu \) Platform

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    - Common development of cold electronics
  - DUNE – WA105 DAQ workshop
    - Potential to share “online” tools across programme
  - LArTPC workshop on LArSoft Requirements & Reconstruction
  - Follow up meetings in the new year

Good working relationship between all parties
6. Summary
Summary

★ DUNE has come together as a large international collaboration to pursue physics with LBNF
  ▪ full collaboration structure in place and operating
  ▪ successfully delivered CD-1-R & detector interfaces in CD-3a scope
★ DUNE will deliver science that meets P5 goals
  ▪ and can do so in a timely manner
★ DUNE has a clear strategy for the far detector
  ▪ backed up by a strong prototyping phase
★ DUNE engaging wider community
  ▪ actively pursuing potential synergies
★ DUNE has made a great deal of progress in the last year
  ▪ many challenges ahead – but believe we are on the right track
Thank you
Backup Slides
Top-level management structure defined in collab. governance document – approved by DUNE institute board in April

- All collaboration members discussion forum
- Representatives from each institute: defines collab. rules
- EFIG: formal interface between DUNE & LBNF
- Executive Committee: Decision making
- Technical & Resource Management

DUNE management: Co-spokespersons
Technical Coord.
Resource Coord.

DUNE project management

Co-spokespersons:

- DUNE General Assembly
- DUNE Institutional Board
- Co-Spokespersons
- Executive Committee (Co-Spokesperson)
- TC
- RC
- Project Office (PM)
- Technical Board (TC)
- Collaboration Resource Board (RC)

DUNE Management
Liquid Argon TPC Basics

A modular implementation of Single-Phase TPC

- Record ionization in LAr volume ➞ 3D image

![Diagram of a Liquid Argon TPC with Anode and Cathode planes, a 3D image, and dimensions: 14.4 m, 12 m, 3.6 m, and 12 m with a 3.6 m grid for wire number and time / ms. ]
Liquid Argon TPC Basics

A modular implementation of Single-Phase TPC

- Record ionization in LAr volume ➔ 3D image
Systematics & Performance
Evaluating DUNE Sensitivities

- **Systematic Uncertainties**
  - Anticipated uncertainties based on MINOS/T2K experience
  - Supported by preliminary fast simulation studies of ND

<table>
<thead>
<tr>
<th>Source</th>
<th>MINOS $\nu_e$</th>
<th>T2K $\nu_e$</th>
<th>DUNE $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux after N/F extrapolation</td>
<td>0.3 %</td>
<td>3.2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Interaction Model</td>
<td>2.7 %</td>
<td>5.3 %</td>
<td>~ 2 %</td>
</tr>
<tr>
<td>Energy Scale ($\nu_\mu$)</td>
<td>3.5 %</td>
<td>Inc. above</td>
<td>(2 %)</td>
</tr>
<tr>
<td>Energy Scale ($\nu_e$)</td>
<td>2.7 %</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>2.4 %</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5.7 %</td>
<td>6.8 %</td>
<td>3.6 %</td>
</tr>
</tbody>
</table>

- **DUNE goal for $\nu_e$ appearance < 4 %**
  - For sensitivities used: 5 % $\oplus$ 2 %
    - where 5 % is correlated with $\nu_\mu$ & 2 % is uncorrelated $\nu_e$ only
Evaluating DUNE Sensitivities

- Assumed* Particle response/thresholds
  - Parameterized detector response for individual final-state particles

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Threshold (KE)</th>
<th>Energy/momentum Resolution</th>
<th>Angular Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^\pm$</td>
<td>30 MeV</td>
<td>Contained: from track length Exiting: 30 %</td>
<td>$1^\circ$</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>100 MeV</td>
<td>MIP-like: from track length Contained $\pi$-like track: 5% Showering/Exiting: 30 %</td>
<td>$1^\circ$</td>
</tr>
<tr>
<td>$e^\pm/\gamma$</td>
<td>30 MeV</td>
<td>2% $\oplus$ 15 %/$\sqrt{(E/\text{GeV})}$</td>
<td>$1^\circ$</td>
</tr>
<tr>
<td>p</td>
<td>50 MeV</td>
<td>$p &lt; 400$ MeV: 10 % $p &gt; 400$ MeV: 5% $\oplus$ 30%/$\sqrt{(E/\text{GeV})}$</td>
<td>$5^\circ$</td>
</tr>
<tr>
<td>n</td>
<td>50 MeV</td>
<td>$440%/$\sqrt{(E/\text{GeV})}$</td>
<td>$5^\circ$</td>
</tr>
<tr>
<td>other</td>
<td>50 MeV</td>
<td>5% $\oplus$ 30%/$\sqrt{(E/\text{GeV})}$</td>
<td>$5^\circ$</td>
</tr>
</tbody>
</table>

*current assumptions to be addressed by FD Task Force
Proton Decay

Nucleon (proton) decay is expected in most new physics models – not yet observed

- Image particles from a single nucleon decay in detector volume
  - For example, look for kaons (from $dE/dx$) from SUSY-inspired GUT $p$-decay modes such as $p \rightarrow K^+ \bar{\nu}$

$E \sim O(200 \text{ MeV})$
Proton Decay

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  - For example, look for kaons (from dE/dx) from SUSY-inspired GUT p-decay modes such as \( p \rightarrow K^+ \bar{\nu} \)

Remove incoming cosmic ray

\[ E \sim O(200 \text{ MeV}) \]
$p \rightarrow K \nu$

- DUNE for various staging assumptions
SNB

• Energy and timing sensitive to particle & astrophysics

• Event Rates:
Supernova vs

A core collapse supernova produces an incredibly intense burst of neutrinos
• Trigger on and measure energy of neutrinos from galactic supernova bursts
  – In argon (uniquely) the largest sensitivity is to $\nu_e$

$$\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$$

Physics Highlights include:
  ▪ Possibility to “see” neutron star formation stage
  ▪ Even the potential to see black hole formation!
## Physics Milestones

<table>
<thead>
<tr>
<th>Physics milestone</th>
<th>Exposure $\text{kt} \cdot \text{MW} \cdot \text{year}$ (reference beam)</th>
<th>Exposure $\text{kt} \cdot \text{MW} \cdot \text{year}$ (optimized beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^\circ \theta_{23}$ resolution ($\theta_{23} = 42^\circ$)</td>
<td>70</td>
<td>45</td>
</tr>
<tr>
<td>CPV at $3\sigma$ ($\delta_{\text{CP}} = +\pi/2$)</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>CPV at $3\sigma$ ($\delta_{\text{CP}} = -\pi/2$)</td>
<td>160</td>
<td>100</td>
</tr>
<tr>
<td>CPV at $5\sigma$ ($\delta_{\text{CP}} = +\pi/2$)</td>
<td>280</td>
<td>210</td>
</tr>
<tr>
<td>MH at $5\sigma$ (worst point)</td>
<td>400</td>
<td>230</td>
</tr>
<tr>
<td>$10^\circ$ resolution ($\delta_{\text{CP}} = 0$)</td>
<td>450</td>
<td>290</td>
</tr>
<tr>
<td>CPV at $5\sigma$ ($\delta_{\text{CP}} = -\pi/2$)</td>
<td>525</td>
<td>320</td>
</tr>
<tr>
<td>CPV at $5\sigma$ 50% of $\delta_{\text{CP}}$</td>
<td>810</td>
<td>550</td>
</tr>
<tr>
<td>Reactor $\theta_{13}$ resolution</td>
<td>1200</td>
<td>850</td>
</tr>
<tr>
<td>($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPV at $3\sigma$ 75% of $\delta_{\text{CP}}$</td>
<td>1320</td>
<td>850</td>
</tr>
</tbody>
</table>