Permanent magnet quadrupoles for the LINAC4 Drift Tube Linac design and procurement
Permanent magnet quadrupoles for LINAC4

- Majority of focusing elements are permanent quadrupoles (136 PMQ and 31 EMQs in the linac).
- 3 families:
  - 45 mm long, 22/60 inner/outer diametre to be housed in drift tubes of tank1 + tank cover: 43 pieces
  - 80 mm long, 22/60 inner/outer diametre to be housed in drift tubes tank2 and 3: 70 pieces
  - 100 mm long, 45/124 inner/outer diametre in CCDTL intertanks (outside beam pipe): 14 pieces
Magnetic Material – Alnico, BaFe, and SmCo

G=6-11 kGs/cm

No pole tips. Harmonic #6 ~6 %, #10 ~2 %, #14 ~0.2 %.

Stepped-pole geometry has been investigated to eliminate Harmonics #6 and #10 with the PANDIRA code by K.H. Halbach and R.F. Holsinger.
Early prototypes

<table>
<thead>
<tr>
<th>February 2006</th>
<th>May 2006</th>
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<tbody>
<tr>
<td>GL= 2.5 Tesla ; L=45 mm ; 30 pieces</td>
<td>GL = 4 Tesla ; L=45 mm ; 16 pieces</td>
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May 2006

.choices

- GL=2.5 Tesla ; L=45 mm ; 16 pieces

All prototypes were within the specs

All prototypes on time and on budget,

Choice was between field quality, strength, cost.
PMQ for the drift tube Linac

• One PMQ installed in each Drift Tube
  – FFDD system
  – Max/Min integrated gradient= 2.4/1.2 T
  – Tolerance : ±0.5% on the field, 1 mrad on the roll, harmonics <0.01 at 75% radius,

• Magnet Material - Samarium Cobalt (Sm$_2$Co$_{17}$)
  – PM material selected to minimize field strength loss due to neutron fluence.

• Housing Material - Stainless Steel (316LN)
  – Use in vacuum
  – Stable against corrosion (galvanic couple with copper)
  – Thermal expansion coefficient similar to copper
  – Low conductivity protects against accidental heating during the welding process

• Installation in Drift tube
  – Each PMQ will be positioned in the centre of the drift tube, oriented with a dowel pin and clamped in position by a spring washer
  – The drift tube will not have a full bore tube and the end-caps, located on the PMQ, will be welded to the body of the drift tube after positioning of the PMQ.
# Critical specifications

| Spec for the PMQ Family 2: PMQ for DTL tank2 and 3 |
|---|---|
| Number of pieces | 70 |
| Integrated gradient (Max) | 2.0 Tesla |
| Integrated gradient (min) | 1.2 Tesla |

## Mechanical tolerances, verified by EN/MME (A. Cherif)

- Mechanical Length: 80 mm
- Inner diameter: 22 mm
- Outer diameter: 60 mm

## Magnetic tolerances, verified by TE/MSC (M. Buzio, G. Golluccio, F. Mateos)

- Gradient integral error (rms): +0.5 %
- Magnetic versus geometric axis: < 0.1 mm
- Harmonic content at 7.5 mm radius: Bn/B2 for n=3,4,...10: < 0.01
- Yaw/pitch: 2 mrad
- Roll: 1 mrad

## Vacuum tolerances verified by TE/VSC G. Vandoni, I. Weavers

- Outgassing rate per magnet below $4 \times 10^{-6}$mbar $1 \text{ s}^{-1}$

## Machining tolerances

Machining tolerances ISO 2768-mK unless indicated in SPLACDTD00009
45 mm

• Procurement of quadrupoles started January 2009 with ASTER (USA).
• 39 quadrupoles for tank1 drift tubes in house, last batch arrived Jan 2011
• Lesson learned
  • Galvanic couple copper-Aluminium: use 316 LN for holder material
  • Specify the vacuum requirement in terms of outgassing
  • Cross calibrate magnetic measurements
- The integrated measured gradient is systematically 0.88 % lower than the specified values.
- The GdL measured by the coil after the latest calibration (reference = PMQ 121) agrees with the simulations within the uncertainties of the 2 systems (0.2 % SSW and 0.3 % Rotating coil @ 1 σ).
- There are no systematic discrepancies between rotating coil and SSW.
Why -1% is ok.

- It is a bias on all quadrupoles, not a scatter.
- It decreases the transverse phase advance everywhere but it stays smooth and the ratio with the longitudinal has the same behaviour.
- Beam can be re-matched from the MEBT.
- Increase of the envelope 20-50microns, rms emitt. increase (+0.5%).
Choice of phase advance

transverse phase advance

- blue dots: k0tx-nomi
- red squares: k0tx-minus1%
80 mm long

• 2 prototyping campaigns
  • Jan 2010: to validate potential new companies (VS, Elytt): Elytt magnetic design validated; tolerances ok, vacuum not ok due to bad shimming material choice.

  • July 2010: to test 316LN and Titanium. Machining of 316LN doesn’t create a problem (screws are silver-plated to avoid galling); Titanium ok but too expensive.
80 mm long PMQs

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To be procured

• 72 “long” quadrupoles: to be produced by Elytt.
  • Sep 2011: 16 quads (tank3)
  • Oct 2011: 15 quads (tank3)
  • Nov 2011: 23 quads (tank2)
  • Jan 2012: 18 quads (tank2)

• 4 “short” quadrupoles: retune existing ones
  • Sometimes in 2012 when the intertanks are assembled

• Spares: 10 “short” + 20 “long”: schedule tbd