3.4 Transfer Lines

General transfer line design criteria

1. A transfer line provides matching of transverse beam parameters from one machine to the next. With no vertical bending, i.e. all machines in the same plane like it is planned for the SLS complex, this matching is six-dimensional concerning β_x, β_y, α_x, α_y, η_x and η_x'.
2. Flexibility is needed in order to fulfil the matching for different operation modes of the two machines.
3. With the location of the machines given the transfer line has to fulfil three geometric constraints on translations and total bend angle in order to meet the injection point of the next machine.
4. Magnets cannot be installed everywhere along the beam line because their yokes may transversely interfere with the yokes of the magnets of the rings connected.
5. A transferline has to be reliable and easy to operate. In particular it must not be the bootleneck, beam acceptances should be defined by the machines on both sides of the transferline. This calls for a conservative and generous design. However the requirements on beam losses are relaxed for single pass systems. We consider an acceptance of 2σ as sufficient.

3.4.1 Linac to Booster transfer line

The linac to booster transferline comprises all elements between linac exit and booster injection septum including a side branch to the beam dump inside the bunker. Some of the elements will be located in the linac bunker, others in the booster/storage ring tunnel. All between linac exit and beam dump belong to the linac domain `LI`, the rest to the transferline domain `LB` [1] (see figure f34_a).

Modified and additional requirements

- A long section of beamline without magnets is needed to penetrate the wall of the linac bunker.
- Initial beam parameters according to linac design specifications:
  Energy : >100 MeV including beam loading, we assume a maximum of 150 MeV
  Energy spread: 0.5 % r.m.s., maximum ±1.5%
  Emittance: 0.5 π mm mrad r.m.s, geometric, equal in both planes
- Optical parameters at linac exit are not yet known. Measurements at the SLS test indicate betas of the order of a few meters and zero alphas and dispersions. The transferline optics has to be flexible enough also to match small convergent or large divergent beams, significant dispersion however is unlikely to appear after the linac.
- Final beam parameters are given from the booster design. There is less margin for variations since the booster optics is bound by constraints on periodicity and physical aperture limitations. With a beam according to linac specifications the booster's vacuum chamber of 30 mm full width and 20 mm full height corresponds to about 3σ beam amplitudes (taking 4 mm closed-orbit distortions into account). For the transfer line we demand about similar values.

Optics

For the total geometrical layout and distances see figure f34_a: The linac is followed by an asymmetric triplett `LIMA-QA-1,2,3`. Emittances and beam parameters of the linac will be measured by observing the beam spot on an OTR screen between `QA-2` and `QA-3` and varying `QA-1` and `QA-2.`

The switchyard dipole `LIMA-BY` will guide the beam to the booster at 15° deflection or to the energy spread measurement leg and beam dump at 30° deflection. Synchrotron light will be observed near the entry into the magnet in order to catch the photons for both deflection states of the dipole. A third branch under 45° deflection originally planned for a linac based experimental area (still visible in figure f34_a) was cancelled, possible linac based experiments will be done at the SLS test facility with much better beam quality.

Two triplets, one in the bunker (`LBMA-QB-1,2,3`) , and one in the tunnel (`LBMA-QC-1,2,3`), transport the beam through the shielding wall at low betas and large dispersion. A seventh quadrupole `LBMA-QD` is required for matching the dispersion. A small 10° rectangular dipole `LBMA-BI` bends the beam to leave 7.7° for the injection septum `BOMA-YIN`. Eventually the injection kicker `BOMA-KIN` (13 mrad deflection) puts the beam onto the booster orbit.

Figures f34_b and c show betafunctions and envelopes along the transferline, starting from the linac and ending in the centre of the vertically focussing combined booster bend `BOMA-BD-1G`. The envelope plot f34_c shows a 2σ beam, i.e. assuming double specified linac energy spread and quadruple emittance.

For the beam parameters at linac exit we assume $\beta_x = \beta_y = 5$ m, $\alpha_x = \alpha_y = 0$ and call this the nominal betas. The corresponding optics is shown in Figure f34_b. The flexibility of the transferline also allows matching to the booster from rather different initial conditions, like a wide, divergent beam of $\beta_x = \beta_y = 30$ m and $\alpha_x = \alpha_y = -5$ (large betas) or a narrow focussed beam of $\beta_x = \beta_y = 0.3$ m and $\alpha_x = \alpha_y = 0$ (small betas).

The final beam parameters are given by the periodic solution of the booster optics. There can be some variation depending on the tuning of the booster (»waltzing« or periodic cells solution, etc.), but the range is not large.

Figures f34_d and _e show the optics in the analysis branch leading to the beam dump: An OTR screen is located where the dispersion from the swichtyard dipole equals 1 m (with the quadrupole `LIMA-QE` switched off), in order to get a scope of ±1% relative energyspread on a screen of 20 mm diameter. Basically `QE` is not required, but it may help to obtain a sharper image on the screen. The optics as shown in figure f34_d with $\beta_x = 0.2$ m and $\eta = 1$ m at the screen would provide a relative energy resolution of 0.05%. The envelope plot figure f34_e shows, that the beam dump should accept at least within a diameter of 40 mm.

Vacuum system

From the envelope plots we see that a beampipe of at least 30 mm inner diameter is required to accomodate the 2σ beam. With connections made by CF40 flanges, 40 mm would be the adequate pipe diameter[1], also providing sufficient pumping cross sections. Material will be stainless steel. The vacuum chambers inside the switchyard dipole `BY` is wide and flat and probably will be made from solid steel. Mechanical stability requires bottom and top to be made 3–4 mm thick, like in the SLS test facility bending magnet vacuum chambers. In order

[1] If by chance used quadrupoles with larger apertures would become available we might also consider the next size of 63 mm diameter.

to reduce the magnet gap we propose a vertical aperture of approx. ±10 mm inside the dipoles, which seems sufficient when looking at the envelope plots f34_c and _e.

The vacuum quality requirement inside a transferline is relaxed, because the beam passes through only once, and there is no material sensitive to residual gases (like cathodes for example). However the vacuum standard of the adjacent machines should be kept by the transferline too, and this calls for $p < 10^{-8}$ mbar. Probably four 60 l/s getter pumps near linac exit, near septum, at beam dump and somewhere in the middle would be adequate.

A valve at linac exit probably will be provided by the linac supplier. Another valve will separate the transfer line from the booster in front of the septum magnet. More valves are not essential, but could decrease pumping time after reconstructions. Sensible locations would be at the two exits of `BY` and close to the bunker wall in order to separate bunker and tunnel vacuum systems.

Preliminary magnet specifications

Dipoles	`LIMA-BY`	`LBMA-BI`
Type	**30° sector**	**rectangular**
Full gap height	**30 mm**	
Magnetic length	**≈ 40 cm**	**20 cm**
Bending angle	**15° or 30°**	**9.72°**
Entrance edge	**0°**	**4.5°**
Exit edge	**-15° / 0°**	**5.22°**
Max. field at 150 MeV	**0.67 T**	**0.424 T**
Ampere turns NI	**8000 A**	**5900 A**

Comment on `BY`: The good field region of the pole has to be approx. 10 cm wide (paths ±20 mm radius) in order to accomodate well the beam in both operation modes. The synchrotron radiation is observed near the entrance. Thus the yoke has to be arranged properly in order not to shade the synchrotron light.

Comment on `BI`: A simple, rectangular window frame or H magnet. The odd angles result from the given septum and kicker angles and the geometrical arrangements. The entrance edge angle was set to a less odd value in oder to facilitate adjustment.

Quadrupoles `LIMA-QA-1,2,3, LIMA-QE, LBMA-QB-1,2,3, LBMA-QD`	
Number of pieces	**12 (1 as reserve)**
Magnetic length	**15 cm**
Aperture radius	**25 mm**
Required maximum k value from optics calculations	**15 m^{-2}**
Poletip field at 150 MeV	**0.22 T**
Ampere turns NI	**2200 A**

Corrector magnets LIMA-CX-1,2 and LBMA-CX-3,4,5 (X = H,V)	
Pieces	**5**
Deflection angle	**2 mrad**
Field integral at 150 MeV	**10^{-3} Tm**

Correctors will be located after the linac, in front of BY, at both ends of the long straight and in front of BI. Superknobs will be constructed, using the pair CX3/CX4 or CX4/CX5 in order to vary independently position and angle of the injected beam at the septum. The betatron phase distances between the corrector locations are in all cases close enough to 0.25 to allow construction of such types of superknobs.

The correctors are made from iron frames with four coils, to do vertical and horizontal correction with the same corrector. For the fifth corrector in front of BI basically a vertical sterrer would be sufficient (CV type), but for the sake of standardization and in order to avoid remanence effects, it will also be a CX-type. Low remanence of the yoke material is important. Sextupole content limits remain to be checked: In the long straight the beam is widended due to large dispersion and will be sensitive to errors.

Diagnostics

Current:

- 2 fast current transformers after the linac and in front of the septum in order to measure the transmission along the transfer line.
- Faraday cup and beam dump.
- Moveable horizontal collimators with current readout after the wall. At this location the betas are low and the dispersion is large, making it a good place for energy filtering of the beam in order to decrease losses in the septum and in the booster synchrotron.

Position and beamsize control:

- Since screens are relatively cheap and turned out to be very helpful at the SLS test facility, the transfer line will be generously equipped for the sake of easy comissioning and operation: A total of 4 OTR screens will be installed into the transfer line, with one after LIMA-QA-2 for emittance measurement, two near LBMA-QB-3 and QC-1 for controlling the beam along the straight, and the fourth after the collimator for observation of energy jittering, etc. Another OTR for energy spread analysis sits in the analysis branch. Every screen is equipped with a CCD camera, multiplexed to the framegrabber.
- Two OTRs inside the booster synchrotron following the injection, the first after BOMA-QF-1, the second one after BOMA-BF-1G, will be used to control injection angle and position in the early commissioning stage, when the BPM system of the booster is not yet working. The betatron tune difference between their locations is 0.3 horizontally and 0.17 vertically, allowing decoupled measurement of angle and position. These two OTRs need to be carefully designed in order not to spoil the booster vacuum chamber impedance.
- Nondestructive position measurement: In routine operation one would like to continously observe and control the beam position without disturbing the beam. For this purpose two BPMs will be installed at both ends of the long straight section.
- Synchrotron light will be observed after dipole BY.

Energy and energy spread:

The beam energy is derived from the `BY` current and position readouts. Energy spread is observered on `LIDI-OTR-E` in the analysis branch or after the collimator.

Safety issues

Linac bunker:

Wall thickness:	1 m concrete
Labyrinth:	0.5 m concrete
Beam dump forward (±7.5°):	1.8 m concrete plus 20 cm lead
Beam dump side:	1.2 m concrete plus 15 cm lead

The bunker wall is already included in the required shielding of the beam dump. So an additional 20 cm conrete fulfills the requirement, as shown in figure f34_a. The forward shielding is given by placing the dump where the wall between tunnel and technical gallery connects to the bunker wall. The forward cone is indicated by dotted rays in figure f34_a. The backward radiation from the beam dump has a small opening angle, corresponding to the beam pipe diameter and sees an effective concrete thickness of more than 2m from the curved bunker wall.

Passive safety:

Bunker and tunnel are separatedly controlled areas. The linac may run inside the bunker while people work inside the tunnel. A double passive system is required to prevent the electron beam from erroneously going into the transfer line. The first component will be a permanent magnet clamped to be beam pipe and deflecting the beam down towards the floor. This magnet would be removed far enough to avoid its stray field affecting the beam when the tunnel is closed. The second system is a shutter in front of the wall.

Active safety:

Dosimeters at the tunnel side of the bunker wall and in particular near the beam pipe exit.

Linac bunker layout

The bunker as partially shown in figure f34_a had to be shaped under following constraints:

- Accomodate the linac and allow to walk around, even with lab carts. Expected maximum linac sizes include following components: DC gun with high voltage cage of max. $(2m)^3$, 500 MHz prebuncher or chopper, free space of 1.5 m for later installation of an alpha magnet for incoupling of RF lasergun, 3 GHz buncher and two linac sections of each 6 m maximum length with 1 m distance between for diagnostics.
- Fulfil the shielding requirements including proper placement of beam dump.
- Follow the circular tunnel wall, with the side walls perpendicular for reason of roof coverage.

3.4.2 Booster to storage ring transfer line

Modified and additional requirements

- Maximum beam energy is 2.7 GeV
- A service corridor has to be provided: A person should be able to cross the transfer line by bending down once under a section of free beampipe in order to walk around the tunnel. Access to all elements of the transfer line and the ring should be possible without too large contortions.
- Extraction from the booster is done in the arc, where basically the cell of extraction can be chosen, since the booster has a periodic structure. The transferline should be as short as possible, and the attempt was to be made to extract the beam from cell `6E` instead of `6D` as before.
- Initial beam parameters are given from the booster periodic solution, there is not much range of variation, we basically distinguish between the »regular« and the »waltzing« optics.
- Final beam parameters at the storage ring may vary according on the mode of operation. Here we distinguish between the D0-mode with zero dispersion straight and the D1-mode with dispersive straights for reduced emittance (see section 2.2).
- As an option for future experiments it should be possible to guide the booster beam to the outside of the tunnel by vertically bending it over or under the storage ring injection. Thus the transfer line has to offer spaces for installation of vertically deflecting dipoles.

Geometric matching

The transferline has to connect precisely the points were the beam leaves the booster extraction septum `BOMA-YEX` and where it enters the ring injection septum `RIMA-YIN`. We give coordinates as used in the CATIA model, i.e. with the direction y pointing towards the Aare river and rotated 10° clockwise (mathematically negative) relative to East. In this coordinate system the storage ring appears to be rotated by another 12° clockwise relative to the y direction.

- The extraction process starts with a double kicker module deflecting the beam by 5 mrad. Exploiting the horizontal defocusing of one of the booster magnet a divergence angle of 7.3 mrad and a displacement of 16 mm is reached at the entrance of the extraction septum. After the septum of arc length 1.04 m and deflection 6.47° the extracted beam leaves the booster at an inclination angle of 6.8882°. The coordinates of the exit from the septum make the beamline's initial point and are given by $X_i = -11.2034$ m, $Y_i = +41.5063$ m, $\varphi_i = 17.6000°$
- The injection into the ring is done by a closed bump of 26 mm amplitude. The septum of arc length 0.8 m bends the beam by 5.0° and is shifted with its centre by 0.43 m in +x direction relative to the centre of the injection straight. The entrance into the septum makes the beamlines end point, its coordinates are given by $X_f = 9.1755$ m, $Y_f = 43.0208$ m, $\varphi_f = -7.0000°$

The total bend angle of the transferline is 24.6°. Dividing it onto identical bending magnets of convenient length we arrive at $3 \times 8.2°$. There are four distances between the septa at the ends and the tree bends. We may choose the length of two distances, then the other two are fixed from the geometric matching conditions.

The placing of the third bend `BRMA-B-3` was dictated by the need to stay most far away from the stored beam but avoid conflicts with `RIMA-QLH-12` and `RIMA-KI-1`. Furthermore in view of later extraction the booster beam out of the tunnel the beam should not hit `KI-2` when the bend is switched off. So placing the third bend fixed the fourth distance.

The first distance was set to stay away with `BRMA-B-1` from `BOMA-BD-6F`. Then the two other distances followed. The third one got a length of 7 m and provides a good location for people to slip through under the transfer line.

Optics

Six quadrupoles at adequate locations are necessary and were found sufficient in principle to do the 6-dimensional matching from booster to storage ring. However a seventh quadrupole was added to allow more variation of the optical solutions.
Figure f34_f and g show the optics for matching from the booster in its standard »waltzing« optics to both operation modes of the storage ring. Envelopes are not shown, they are rather small (< 2 mm) due to the low emittance and enery spread of the booster.

Magnet specifications

Dipoles `BRMA-B-1,2,3`	
Deflection angle	**8.2° H-type, rectangular, straight**
Magnetic length (arc)	1.1 **m**
Sagitta	**19.6 mm**
Field at 2.7 GeV	**1.17 T**
Full gap	**24 mm**
Ampere turns N×I	**28 × 410A**
Coil type	**15 mm × 8 mm, ∅ 4.5 mm bore**

The quadrupoles are identical to the booster quadrupoles, there are two types of different length but with identical yoke profile. All magnets are laminated, for the booster this is required anyway for ramping, for the transferline it improves the reproducability.

Quadrupoles (Transferline, Booster)	`BRMA-QA, QB-2,QC-1..4 BOMA-QF(6)`	`BRMA-QB-1 BOMA-QD,QE (2x6)`
Pieces (Transferline/Booster/Reserve)	**13 (6/6/1)**	**14 (1/12/1)**
Length	**20 cm**	**36 cm**
Aperture radius	**18 mm**	
Maximum gradient at 2.7 GeV	**11.7 T/m**	
Maximum poletip field at 2.7 GeV	**0.21 T**	
Ampere turns N×I	**15 × 100A**	
Coil type	**5 mm × 5 mm, ∅ 3 mm bore**	

Corrector magnets `BRMA-CX-1..4 (X = H,V)`	
Pieces	**4**

Deflection angle	**1 mrad**
Field integral at 2.7 GeV	**0.01 Tm**

Vacuum systems

Aperture considerations are less important than for the linac to booster transferline since the beam will always be very narrow. The elliptic beam pipe from the booster will probably be used too for the transferline, its inner full width and height are 30 and 20 mm.

References

[1] SLS Functional Device Naming convention, SLS-TME-TA-1998-0001
[2] SLS Teststand phase 2 measurements, August 1997, unpublished

Figures

Layout of the beam transfer region
F34_a: scale 1:100

Linac to booster transfer line
F34_b,c: Betafunctions and envelopes of transfer line
F34_d,e: Betafunctions and envelopes of analysis side branch

Booster to ring transfer line
F34_f,g: Betafunctions and envelopes of transfer line

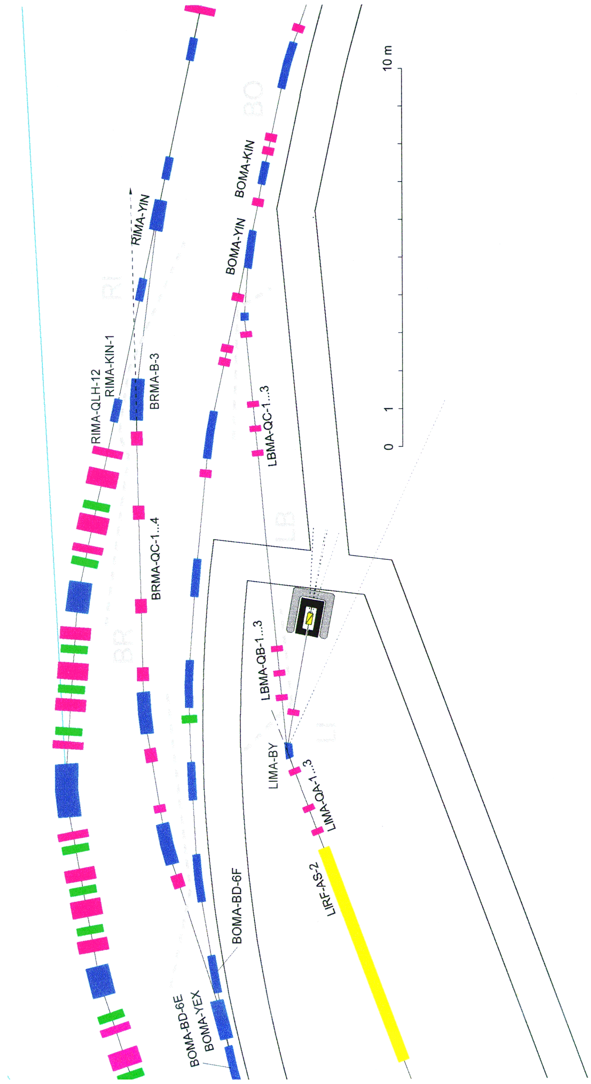

Figure f34 a: Layout of the beam transfer region (scale 1:100)

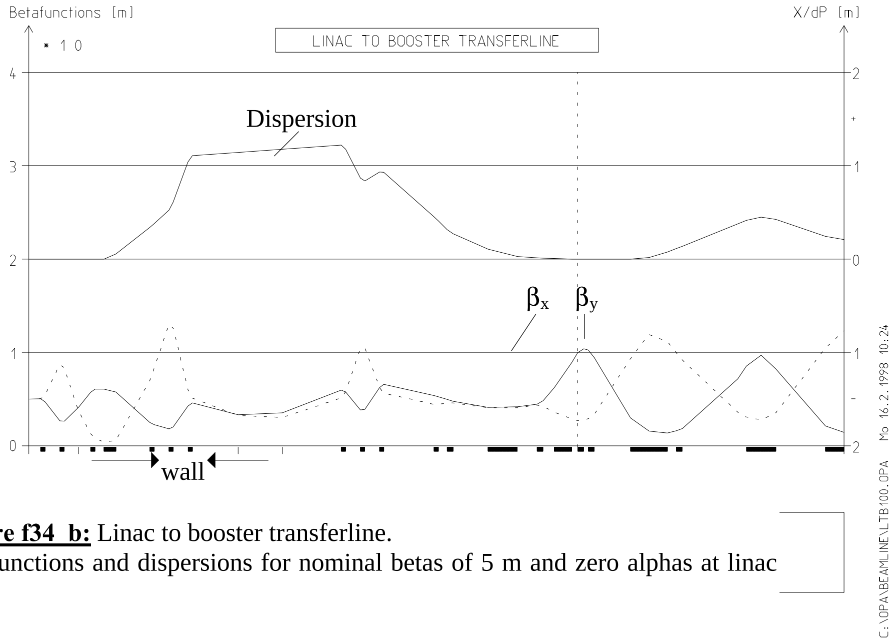

Figure f34_b: Linac to booster transferline.
Betafunctions and dispersions for nominal betas of 5 m and zero alphas at linac exit.

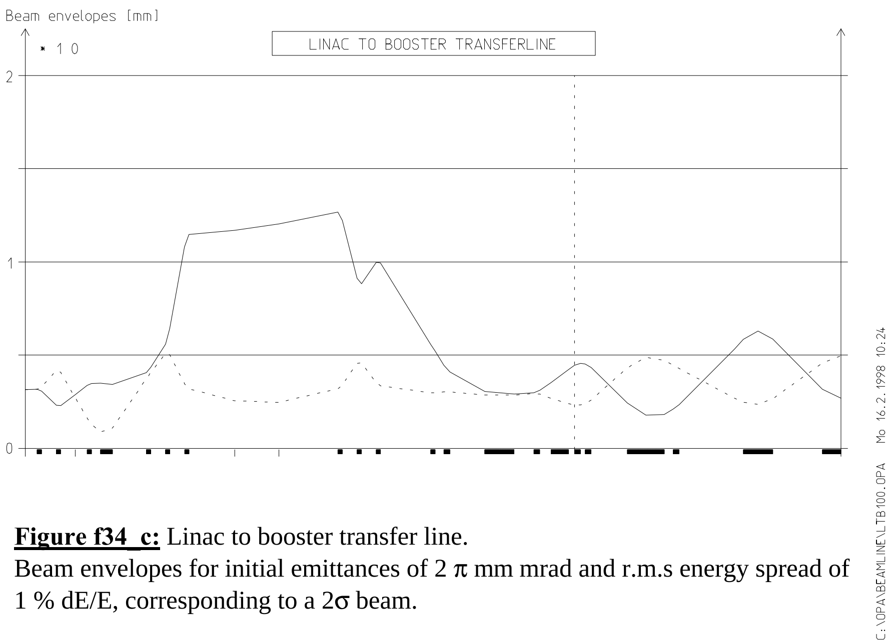

Figure f34_c: Linac to booster transfer line.
Beam envelopes for initial emittances of 2 π mm mrad and r.m.s energy spread of 1 % dE/E, corresponding to a 2σ beam.

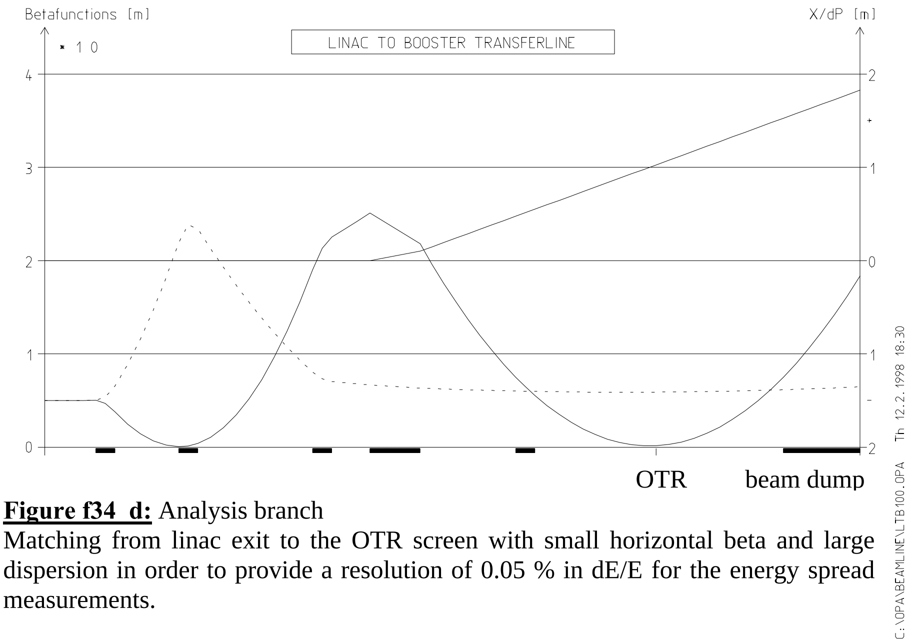

Figure f34_d: Analysis branch
Matching from linac exit to the OTR screen with small horizontal beta and large dispersion in order to provide a resolution of 0.05 % in dE/E for the energy spread measurements.

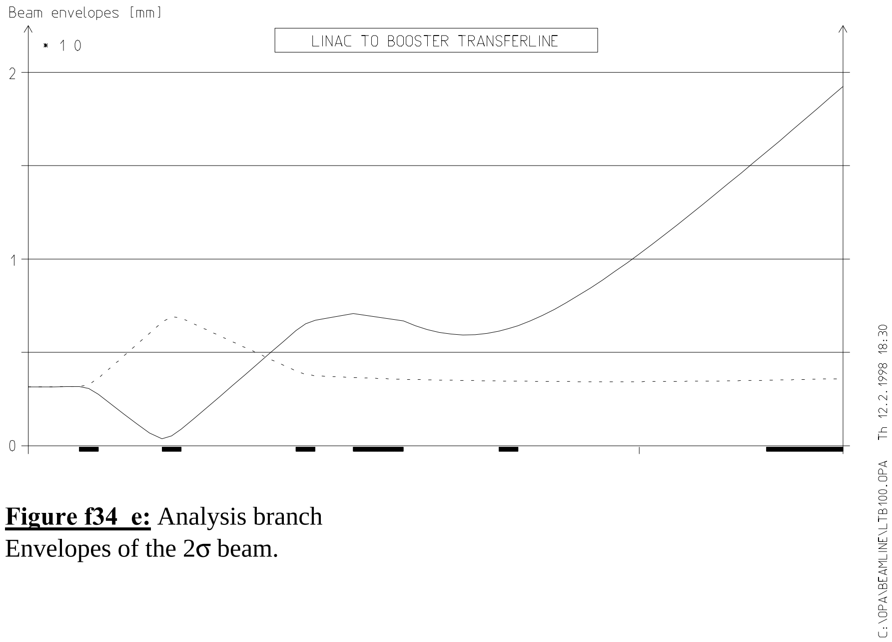

Figure f34_e: Analysis branch
Envelopes of the 2σ beam.

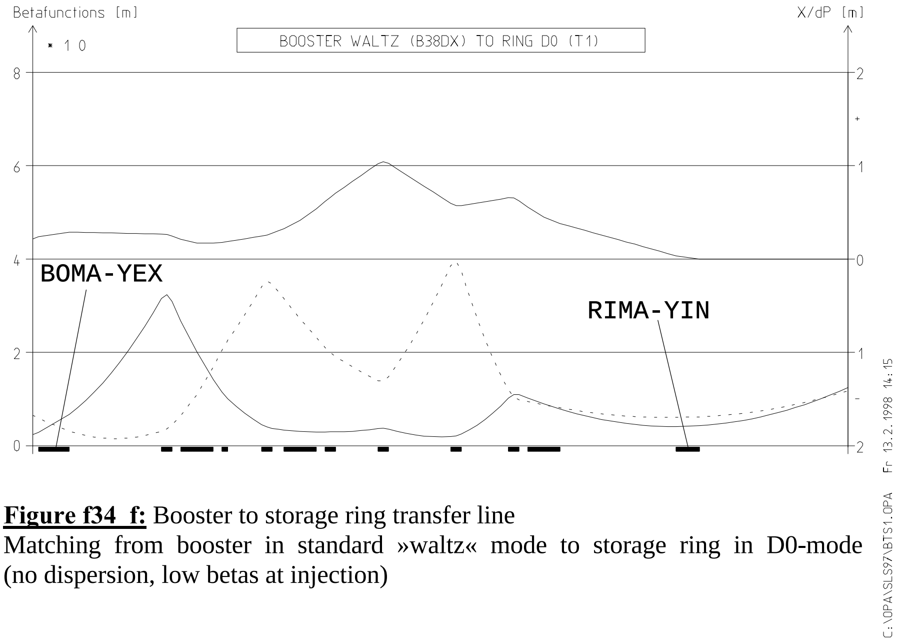

Figure f34_f: Booster to storage ring transfer line
Matching from booster in standard »waltz« mode to storage ring in D0-mode (no dispersion, low betas at injection)

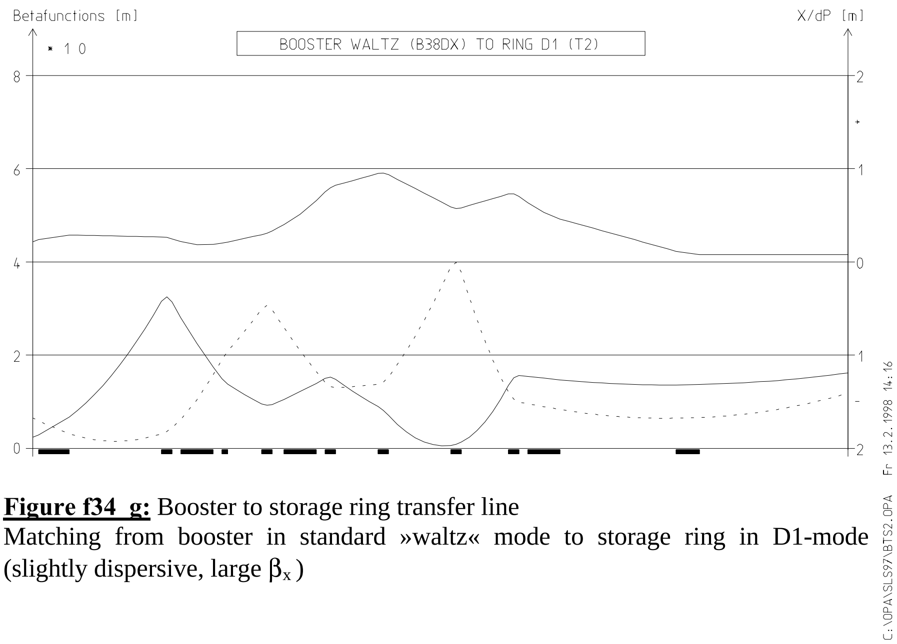

Figure f34_g: Booster to storage ring transfer line
Matching from booster in standard »waltz« mode to storage ring in D1-mode (slightly dispersive, large β_x)