200-MeV linac

981207 T. Kato

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      - tuning of the trim magnets in high energy region
    - Transmission through the CCL is greater than 98%. Most of this loss is due to the inability to longitudinally capture all of the DTL beam.
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    - Chopper operation has been improved.
        - without Quad between them
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    - 30-mA, 200-MeV beam
    - 180-mA, 400-MeV beam
    - field errors were taken into account; random errors of ±2% in an accelerating field for each cell and each tank and ±3% in an accelerating phase for each tank were assumed in the SDTL simulation. No phase errors for each cell was assumed. In the CCL simulation, random errors of ±2% in an accelerating field both for each cell and each tank, those of ±1% in an accelerating phase for each cell and ±3% for each tank were assumed.
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    - Accuracy of numerical solution of equipartitioning relation has been improved.
    - Error simulation in LINSAC is next step.
45. Construction of the low-energy part
    - IS+RFQ+DTL+SDTL(59 MeV)
    - RF power source
    - Control and monitors
46. Summary
    - The linac design and the report were revised and improved.
        - MEBT and chopper were improved.
        - The linac to ring transfer line was examined.
        - The reasons for selecting JHF linac main parameters were explained.

200-MeV Linac

T. Kato

- **Linac design summary**
- **Answers to the comments and questions**
- **Additional beam-dynamics issues**

Thanks for the Report by the Advisory committee. It was very useful for improving the linac design.
1) Improvements were made for writing the final JHF report (KEK 97-16) during two months after the first Committee.
2) The improvements and modification of the design have been continued after publishing the KEK report.
3) There are some discrepancies among the parameters mentioned here and those in the KEK report. It is due to the difference in the design version.

Main comments by the committee

- specification of the beam
- chopping requirements
- transition and linac configuration
- transverse focusing design
- MEBT & chopping
- Linac to Ring Transfer Line

Specification of the linac beam

Requirements from the ring

Transverse : 90% emittance = 2.8 π mm-mrad
Longitudinal : 100% Δp/p = ± 0.1%

In conclusion, particle simulations showed that both requirements are satisfied in the design.

Table 4.12 Summary of normalized emittances and energy spread in the JHF 200-MeV linac p.4-57.

	Transverse		Longitudinal	
Injection beam	Type-A rms / 90% πmm-mrad	Type-RFQ rms / 90%	Type-A rms / 90% πMeV-deg	Type-RFQ rms / 90%
3-MeV input	0.187 / 0.805	0.248 / 1.06	0.133 / 0.566	0.087 / 0.371
200-MeV output	0.279 / 1.24	0.324 / 1.43	0.274 / 1.18	0.255 / 1.08
99% ΔW (at 200 MeV)			0.917	0.954 (MeV)

After debuncher:

Beam	30 mA, 200 MeV	60 mA, 400 MeV	Table 4.11
Energy spread	0.469 MeV	0.774 MeV	p.4 - 46

Chopping requirements (transient)

1% beam loss in the linac → **1.6 bunches for each chopping pulse**

↓

0.8 bunches for each transient time

↓

Rise/fall time should be less than 3 nsec

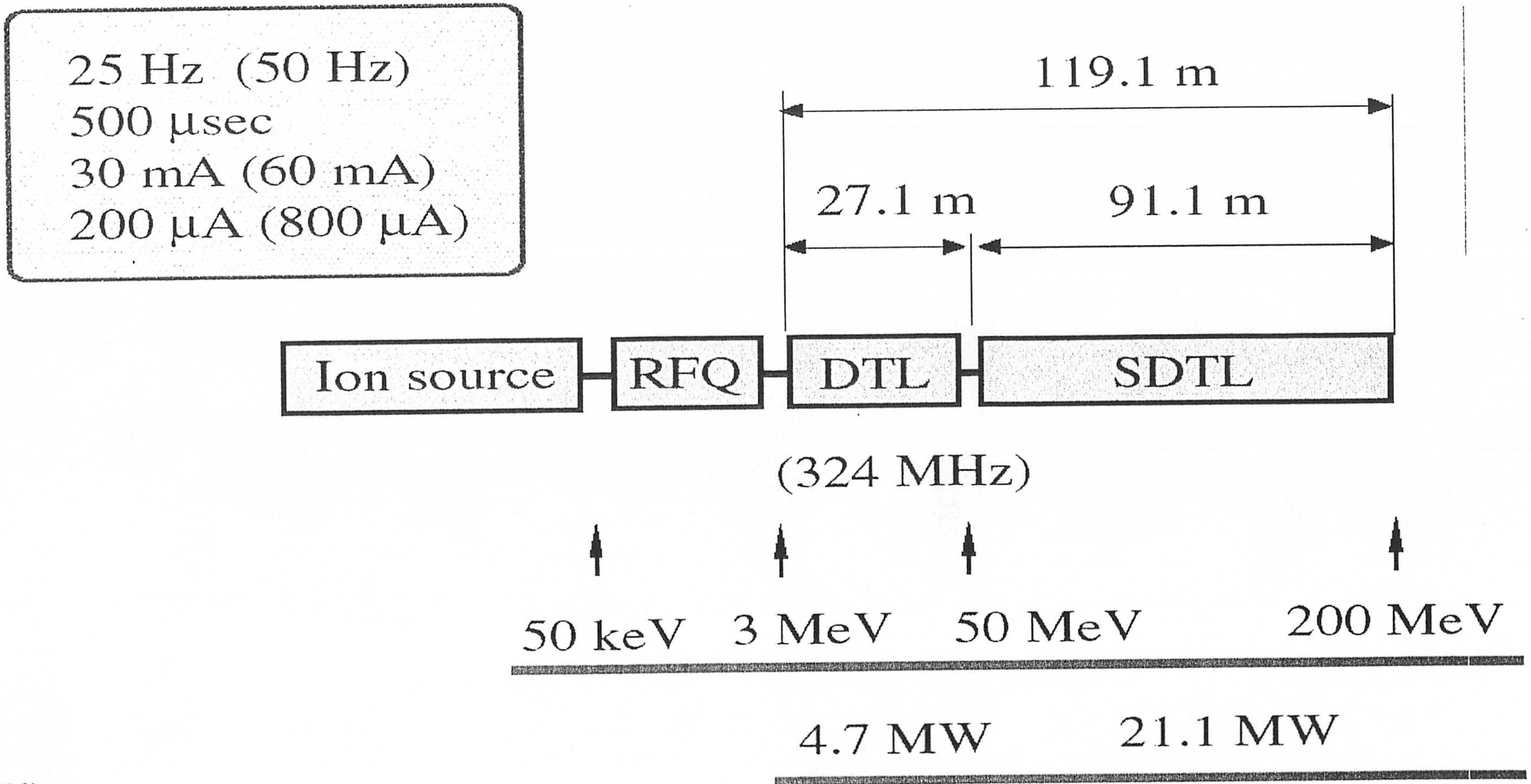
In the design, unstable particle ratio is 0.99%. Moreover, equivalent rise/fall time of 0.2 nsec is achieved by using scrapers (0.08% unstable beam).

Linac design summary

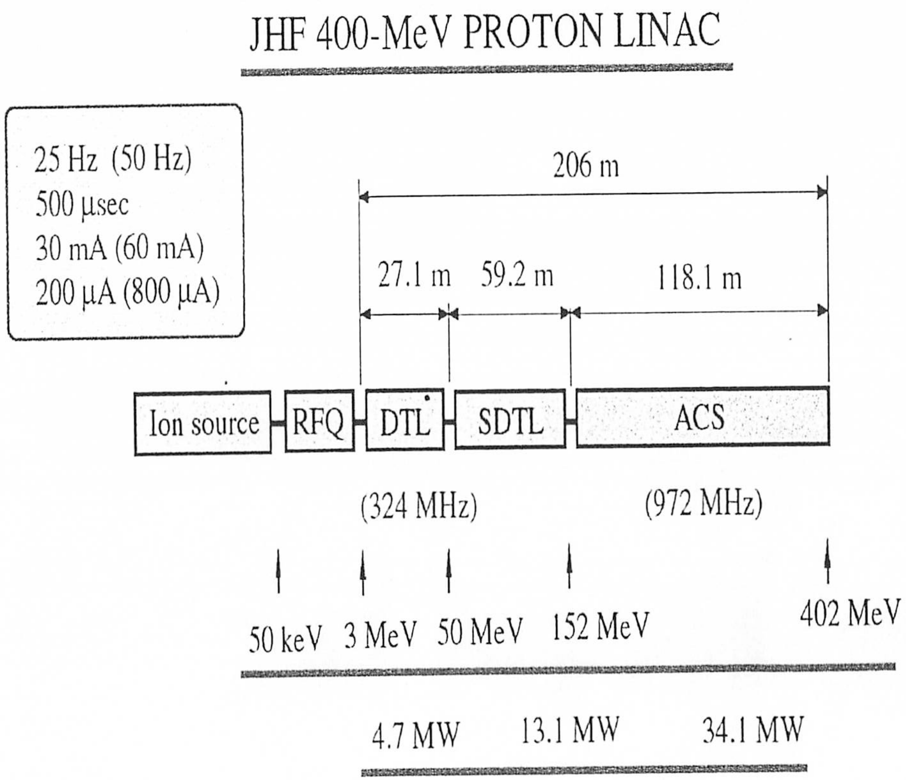
- Linac configuration and main parameters are nearly the same as those in the previous version.
  - some modifications have been made.
- MEBT design has been improved.
- Preliminary design for beam-transport line to the RING was studied.
- Some modifications, after KEK Report 97-16, have been made.

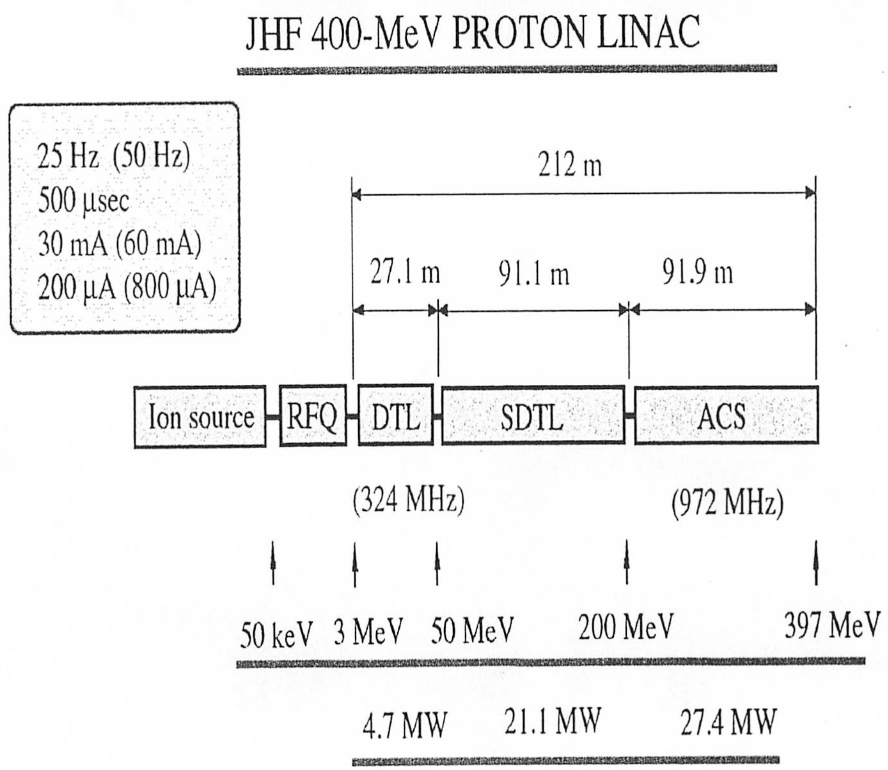
Schematic view of the JHF 200-MeV proton linac

JHF 200-MeV PROTON LINAC



Schematic view of the JHF 400-MeV proton linac





Parameters of the DTL and SDTL

	DTL	SDTL	
Frequency	324	324	MHz
Injection energy	3.0	50.1	MeV
Output energy	50.1	200.2	MeV
Length (structure only)	26.7	65.6	m
Length (including drift space)	27.1	91.1	m
Number of tank	3	31	
Number of klystron	3	15	
Rf driving power	3.3	16.6	MW
Total rf power (30 mA)	4.7	21.1	MW
Total length		119.1	m
Total power (30 mA)		25.8	MW
Peak current	30		mA
Beam width	500		μsec
Repetition rate	25		Hz
Average current	200		μA
chopping ratio	~0.56 (±100 degrees)		

Parameters of the DTL

Tank number	1	2	3	
Output energy	19.7	36.7	50.1	MeV
Length	9.92	9.44	7.32	m
Number of cell	76	43	27	
Rf driving power	1.1	1.2	1.1	MW
Total rf power (30 mA)	1.6	1.7	1.5	MW
Accelerating field	2.5	2.7	2.9	MV/m
Stable phase	-30	-26	-26	degree
Bore diameter	13	22	26	mm

Parameters of the SDTL

Length of unit tank	1.48 - 2.61	m
Number of tank	31	
Number of cell	155	
Rf driving power	0.34 - 0.71	MW
Total rf power (30 mA)	0.48 - 0.86	MW
Accelerating field	3.75	MV/m
Stable phase	-26	degree
Bore diameter	30	mm

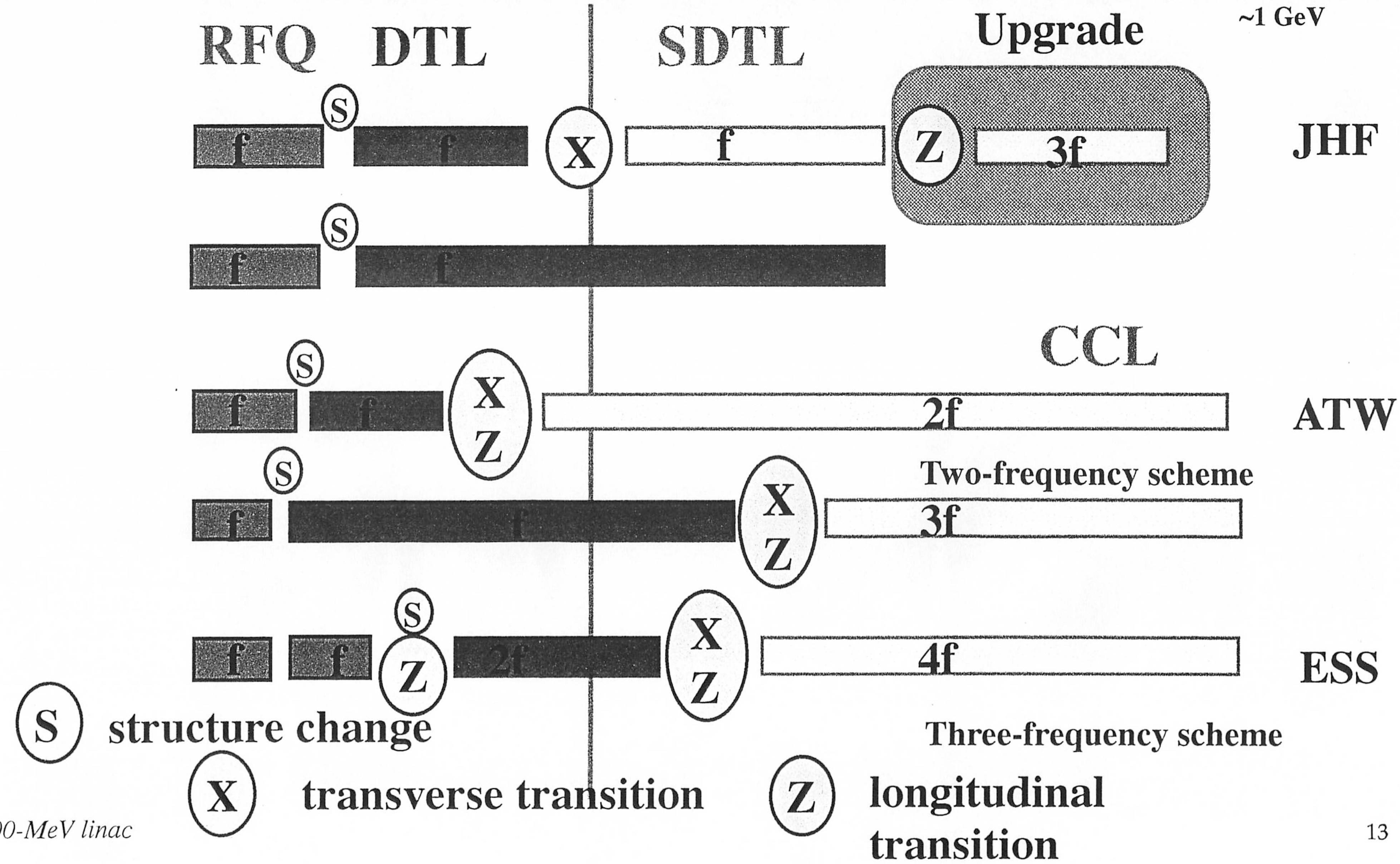
Comments on the transition

In the base line design, around 70 MeV it is proposed to change to a 324 MHz SDTL. This is probably appropriate if the final energy is 200 MeV. For an upgrade scenario with 400 MeV and 160 kW average beam power however, this decision should be reconsidered, especially when the linac length should be limited to about 200m even for the upgrade. For the upgrade, a change from the 330 MHz DTL to a 972 MHz ACS at around 70 MeV is to be studied. In this case, 6D transition matching using only the last elements of the SDTL and the first elements of the ACS (no external matching secton should be studied as a primary option, with a fallback optionbeing an external bunched beam transfer matching line. The advantage of a 70 MeV transition may be that no further change of structure is necessary for accelerating the particles to 400 MeV. Choosing a medium high gradient like the Fermilab 400 MeV "new" linac keeps the total JHF linac length to 200m. Detailed 3D beam dynamic studies have to be performed, as 180 mA effective bunch current has to be transported to the linac end with minimal transverse or longitudinal halo production. Layouts with equipartioning ratios between 0.3 and 3 at the high energy end should not be excluded from being studied, if they keep the longitudinal tune ratio above 0.7.

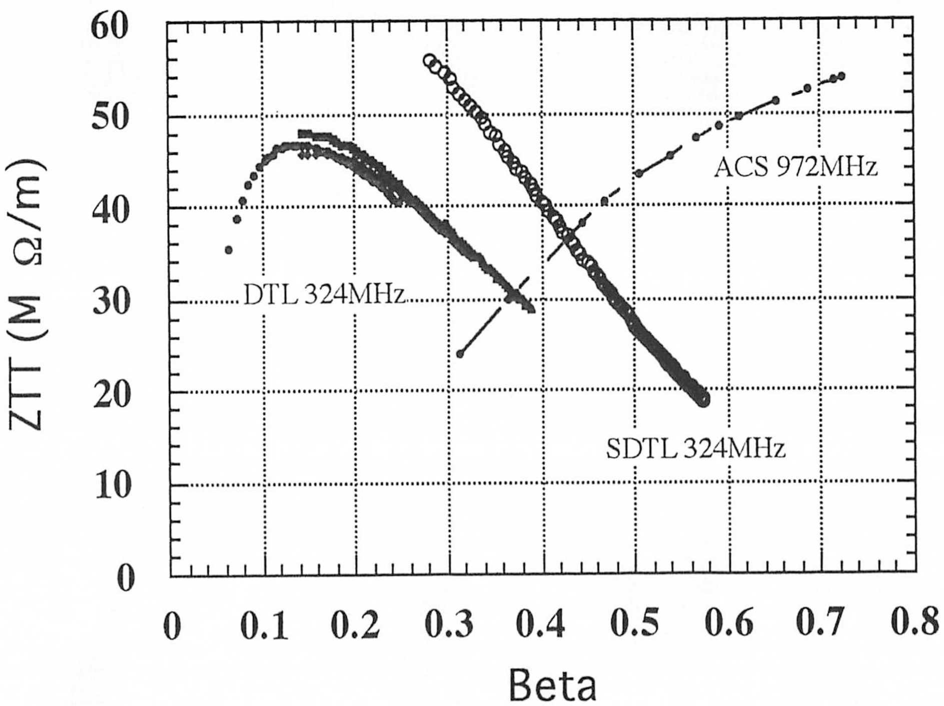
Purposes of transition

- saving cost - construction and operation
  - structure, ZTT
- with minimum degradation of beam qualities
  - emittance growth, beam losses

Types of linac configurations (longitudinal and transverse transitions)



Effective shunt impedance - ZTT



Judging from this plot,

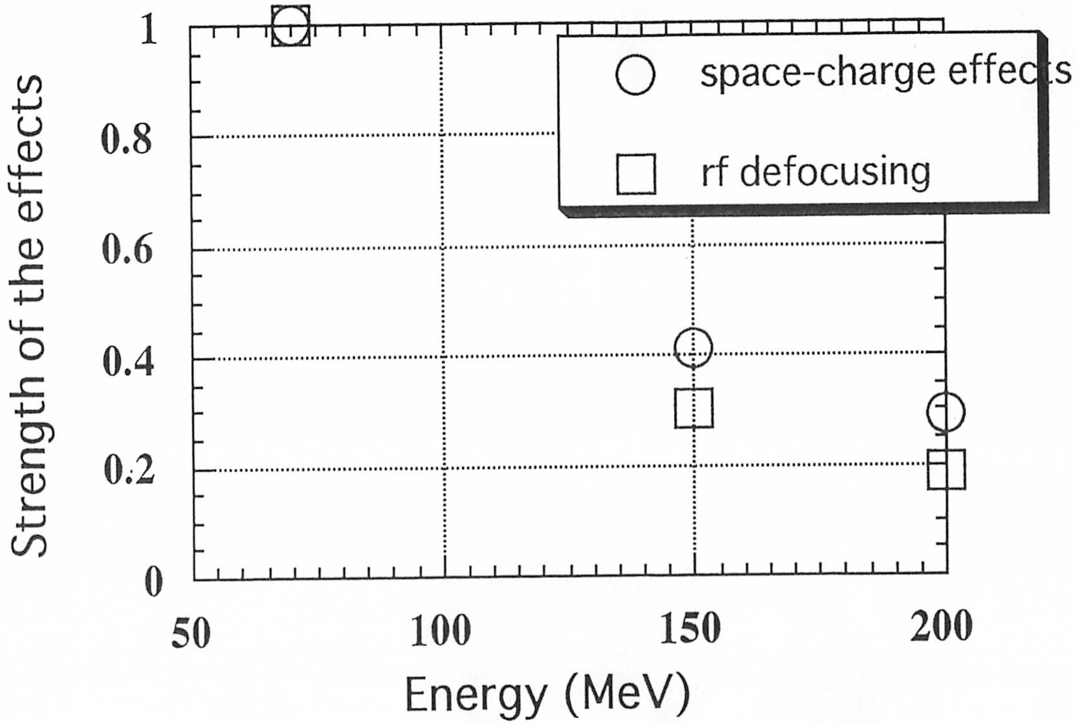
optimum transition energy from DTL to ACS is around 70 MeV,
optimum transition energy from SDTL to ACS is around 100 MeV.

(Phase slip and large stable phase in CCL)

Other factors

- Space-charge forces
- Rf defocusing forces
- Phase width and phase damping
- Phase slip in the constant-beta structure
- Spaces for transverse focusing in CCL structure
- Spaces for transition section

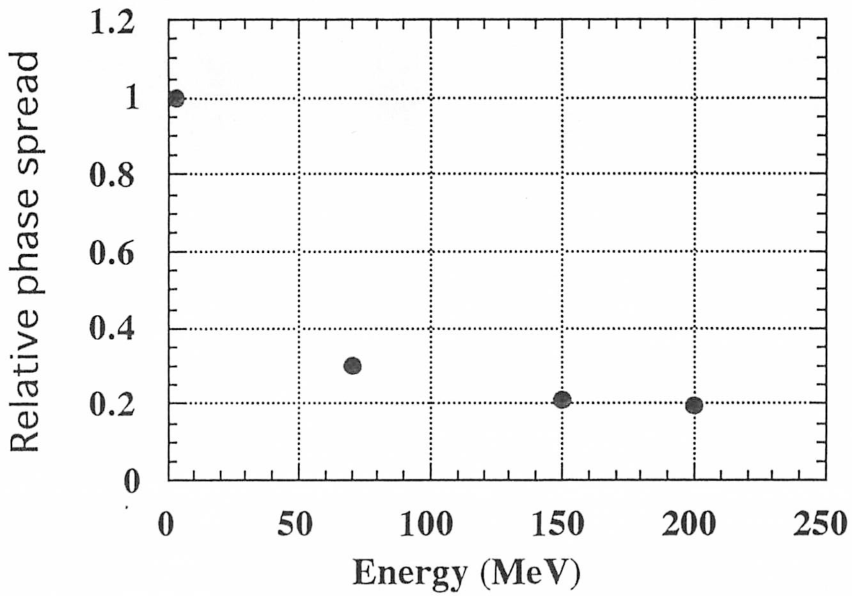
Space charge and rf defocus



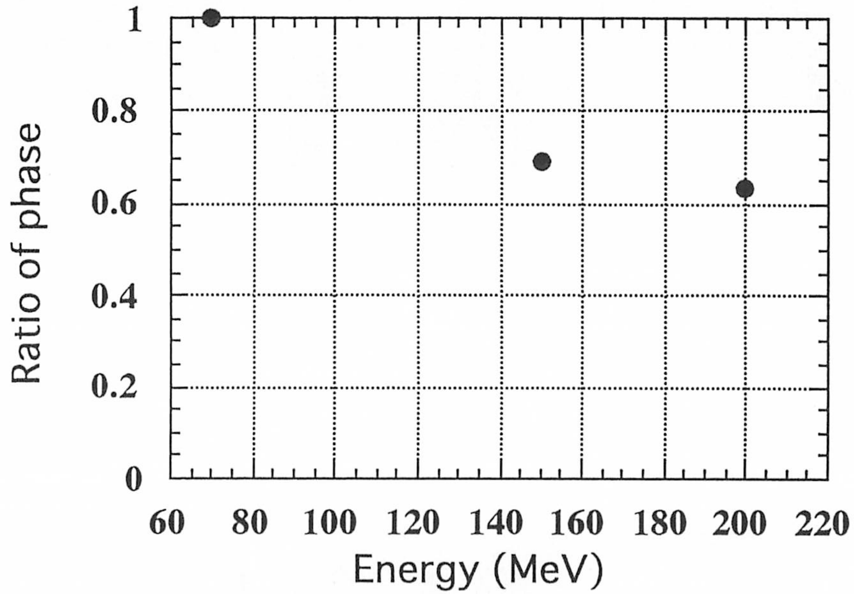
Comparison of space-charge force and rf-defocusing force for three kinds of energies (70, 150 and 200 MeV).

Non-linearity in space-charge force and rf defocusing force have an effect on the beam quality.

Phase width



(Δϕ at 3 MeV=1)



(Δϕ at 70 MeV=1)

Phase width is important from the viewpoint of linearity of an rf force.

Rf defocusing force in a CCL tank

The effect is expressed in transfer matrix form as:

$$\begin{pmatrix} 1 & L_c \\ D & 1 \end{pmatrix}^N \qquad D = \frac{-qE_0 T \sin\phi}{2mc^2\beta^2\gamma^3}$$

L_c =cell length

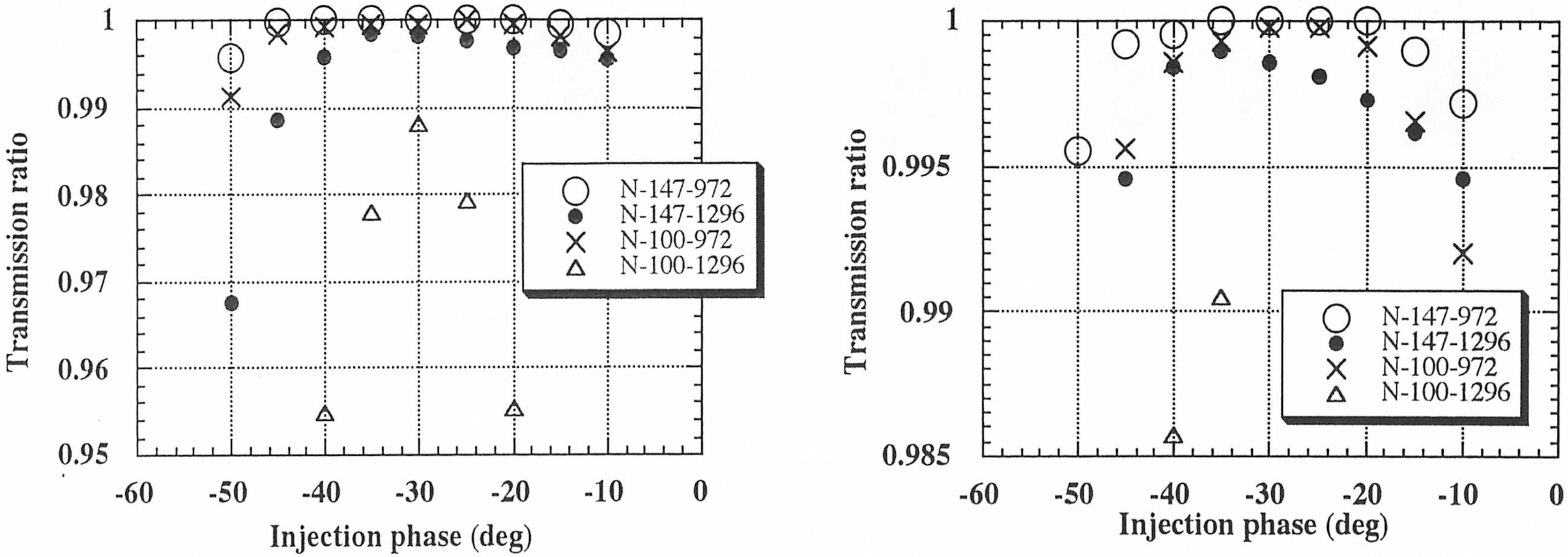
$N = 2L/\lambda$ =number of cells in a tank

L =tank length

λ =wave length

N is usually large ~ 10 - 20.
E_0 is large.
Relative bunch length (phase spread) is large.

Results of beam simulation - beam losses in CCL



'N-147-972' means that transition energy of 147 MeV, CCL frequency of 972(three times).

Fig. 31 Transmission ratio through the CCL as a function of the injection phase for four configurations of the linac. Rf amplitude errors of 1% for each cell and 3% for each tank are assumed. Rf phase errors of zero for each cell and 4% for each tank are assumed. The number of particles is 10000. The ordinates for both figures are different.

Operation of the Fermilab 400-MeV Linac

96 Linac conf. p.329

- The 750 keV line tuning has a large effect on the high energy linac loss.
- As the source current increased, new quadrupole settings were necessary in the high energy linac.
  - new transition quadrupole setting
  - tuning of the trim magnets in high energy region
- Transmission through the CCL is greater than 98%. Most of this loss is due to the inability to longitudinally capture all of the DTL beam.
- beam current 45 - 48 mA, beam loss < 1 mA.

Conclusion for linac configuration

- transverse transition in a lower energy range,
- longitudinal transition in a higher energy range are selected.

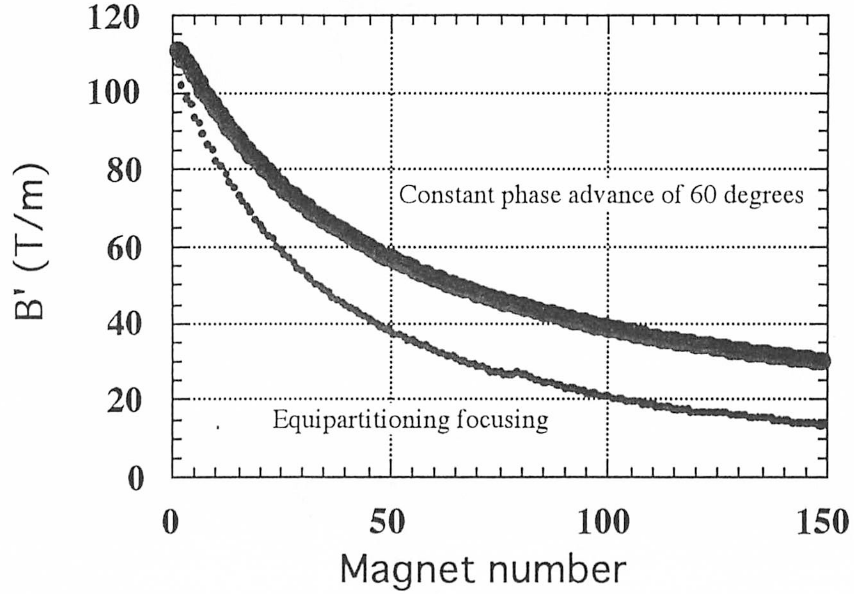
Beam-dynamics calculation regarding the first-stage linac structure of an output energy of 200 MeV and upgrade of an output energy from 200 to 400 MeV by using CCL-type structure is reported in ref. [1]. There, a number of simulations with different types of accelerator complex were performed. Then, it was concluded that an accelerator complex of DTL, SDL and the annular coupled structure (ACS) is a good choice from the viewpoints of both the output beam quality and the accelerating efficiency. There, a frequency of 972 MHz, three times the fundamental frequency, and a transition energies of above 150 or 200 MeV is selected. (Design Report p.4-43)

Ref. 1: KEK Report 96-17

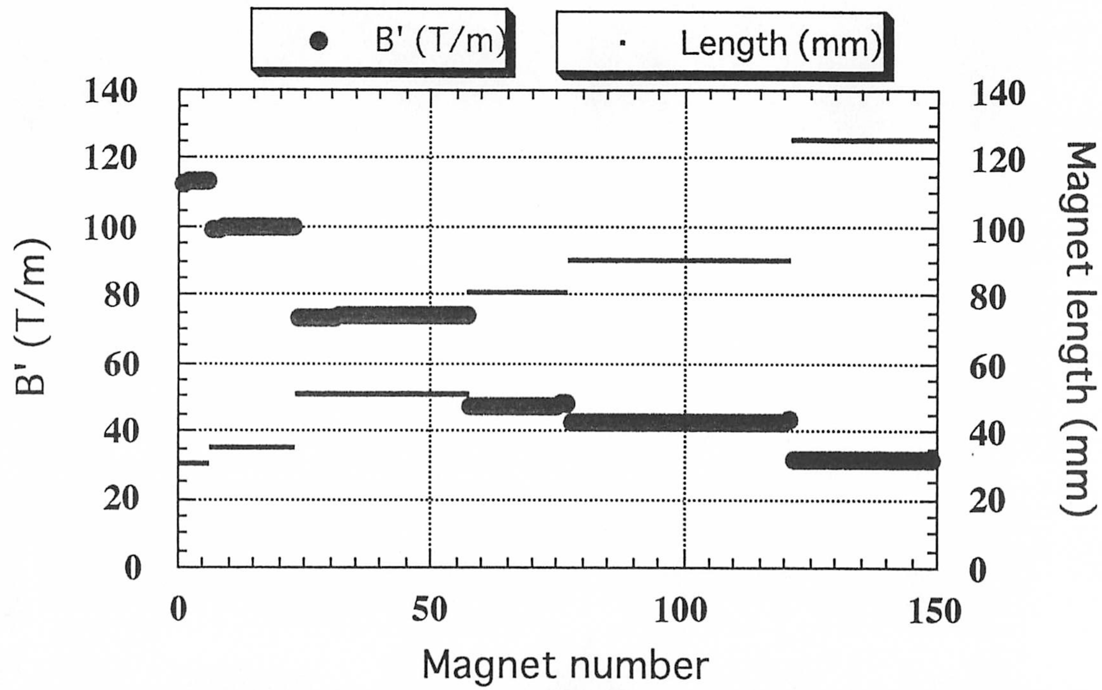
Comments on the focusing design

c) the construction approach will be to use electromagnetic quadrupoles with the stronger focusing required by the "conventional" constant focusing rule. Then the weaker transverse focusing required by the equipartitioned design can also be investigated on the actual machine.

DTL focusing design



Required magnetic field gradient for both focusing scheme.



Magnet length and the required field gradient for constant focusing.

The magnet design meets both requirements.

Comments on MEBT & chopping

The presented layout may not be adequate to incorporate choppers with less than 3 nsec (rise-, fall) time. Designs with longer drift spaces should be evaluated, allowing longer choppers, which relaxes the voltage constraints. In addition, handling varying beam currents is easier, because the whole deflection is done at one place. In the JHF layout, there is a quad between the two chopper elements. The quad strength has to be adjusted independent of the beam current to give optimal deflection for the beam center. A detailed mechanical design was also not presented - the space will be very tight.

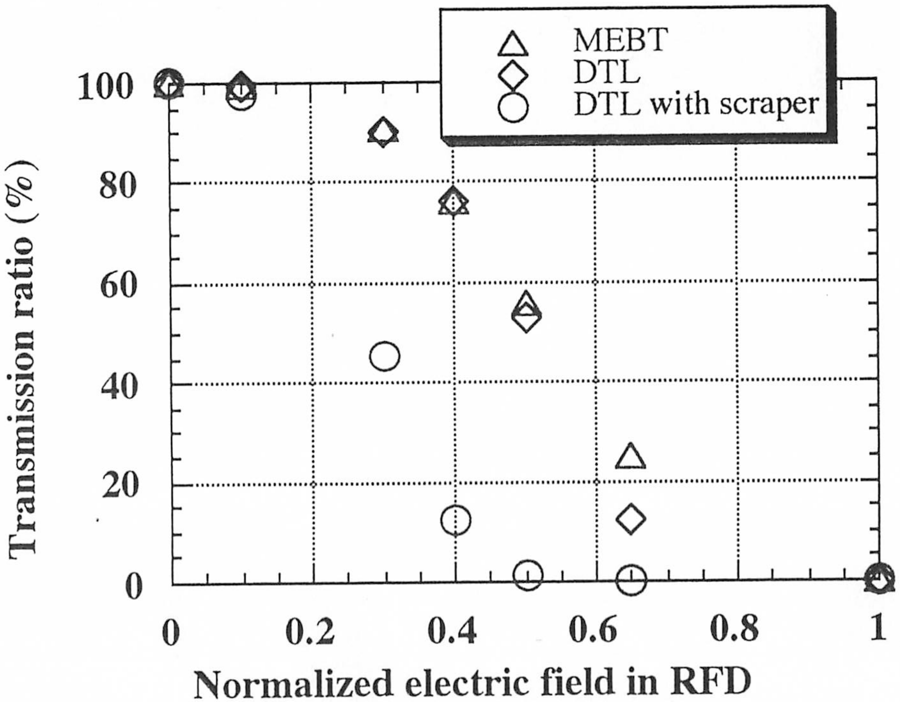
The possibility that longitudinal edge effects may affect chopper performance should be checked.

Evaluation of chopping operation

Chopping operation of our RF-chopper can be evaluated by counting the fraction of unstable particles.

Unstable particles are defined as those deflected insufficiently and transmitted through the DTL with distorted transverse emittances, since these particels may be lost in the following accelerators.

Beam transmission during transient times



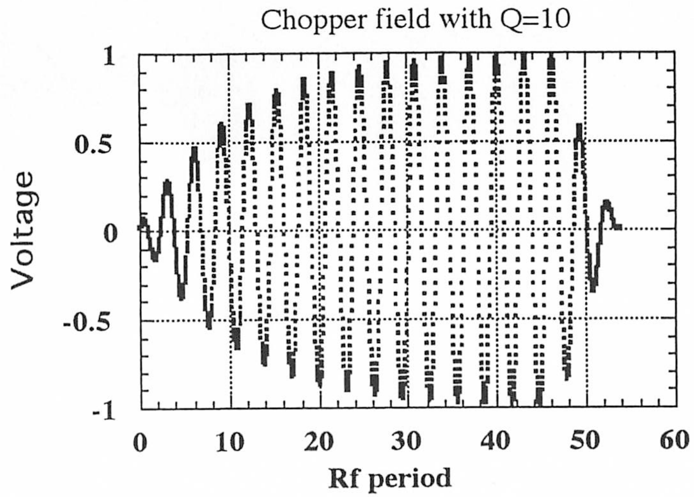


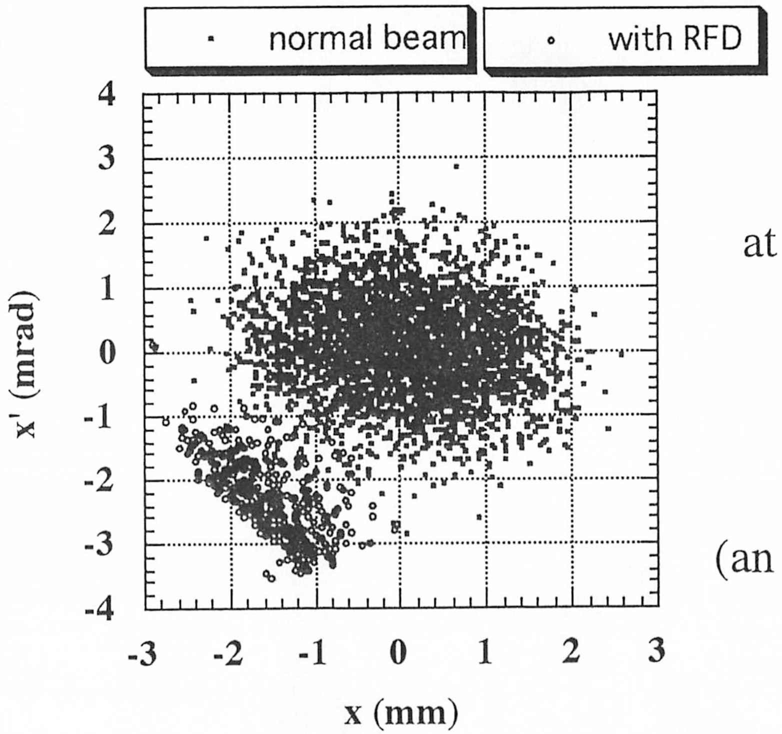
Fig. 4.6(c) Calculated transmission ratios for the micro bunches through the accelerating systems with the MEBT and the 50-MeV DTL, as a function of the electric field in the RFD.

Each symbol in the left figure corresponds to the micro-bunches during transient periods of the chopper field.

Three scrapers just after each DTL tank are used. The scrapers in the DTL capture about 1% of the total beam.

Emittance shape of the insufficiently deflected beam

P. 4 - 18



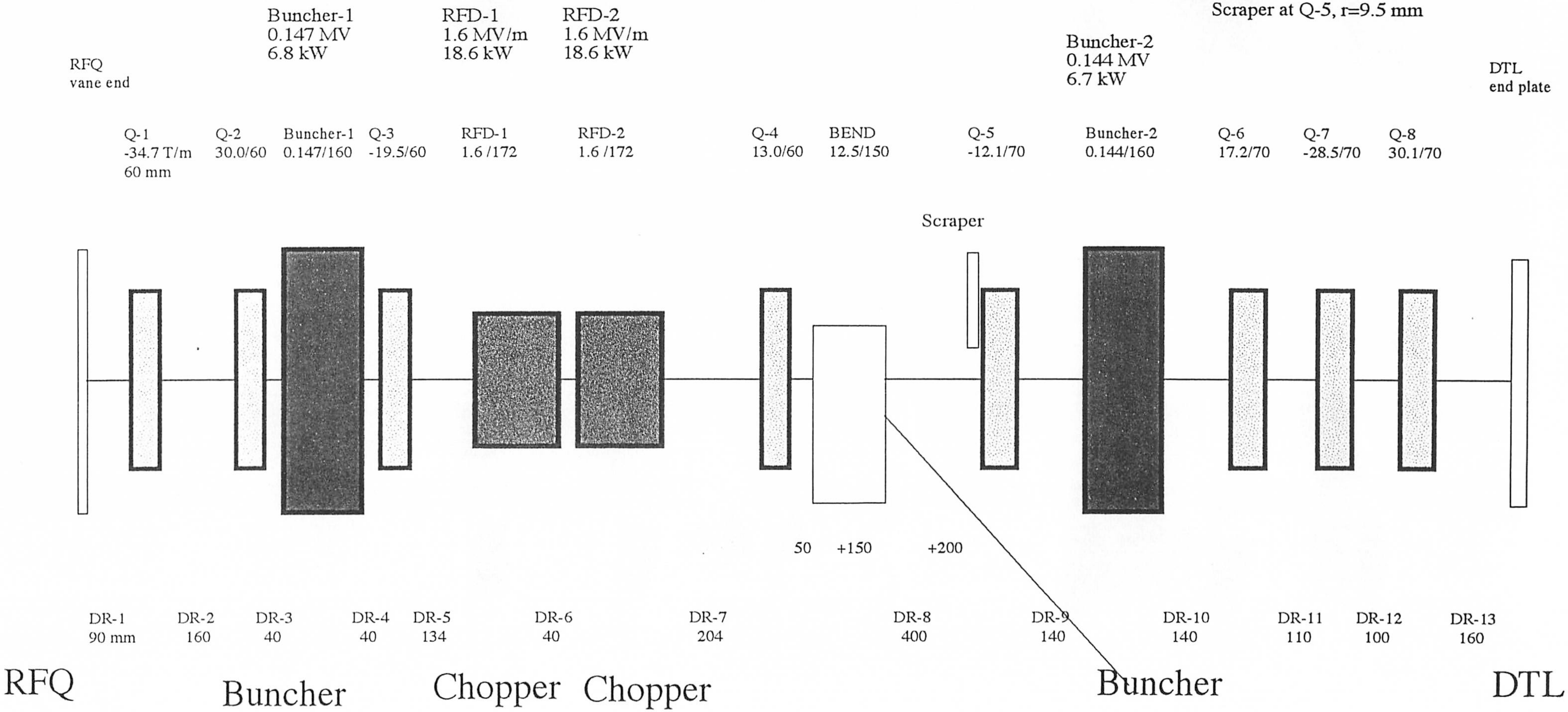
at the DTL exit

(an example of unstable particles)

Fig. 4.6(d) Output emittances for the normal-unchopped bunch and the chopped one with a 40%-RFD field at the DTL exit. Two scrapers after DTL tank-1 and tank-2 are used for eliminating the outer part of the chopped bunch. The ratio of number of particles of the chopped bunch is 12.4% of the normal one in this case.

Improved MEBT design (1)

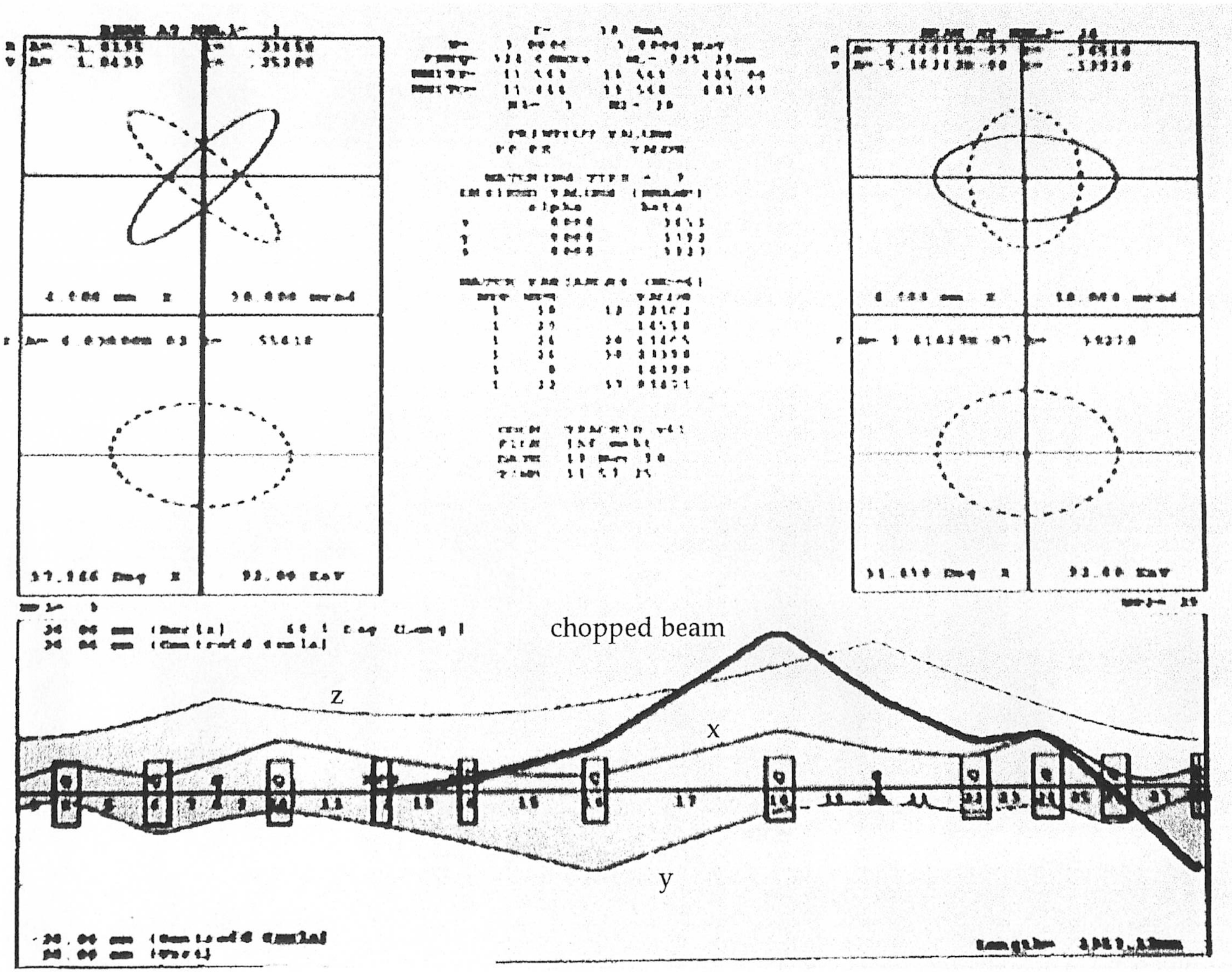
negative charge
Total length 2960 mm
Normal beam size < 7 mm
Deflected < 26 mm
Scraper at Q-5, r=9.5 mm



(DR = drift space)

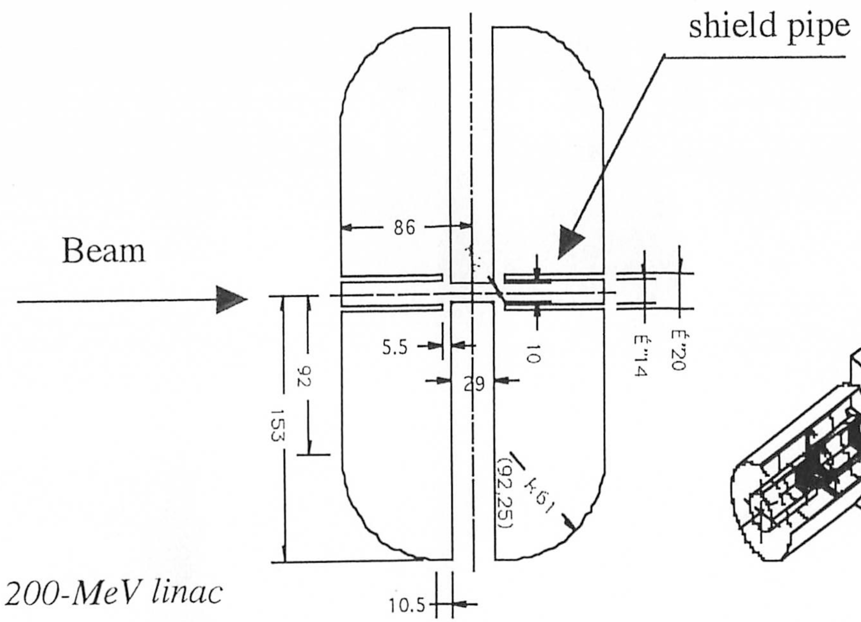
Total length = 2.96 m

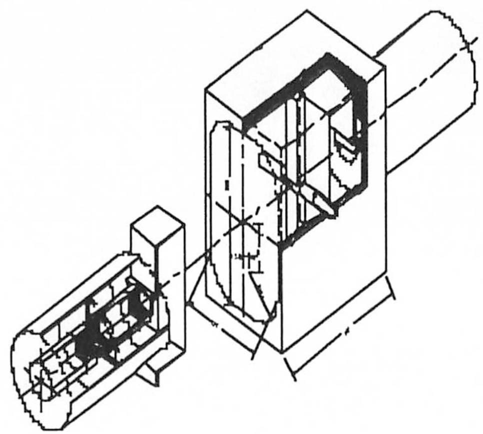
Improved MEBT design (2)



longitudinal edge effects in chopper operation

- **The effects of shield pipes on the operation were studied:**
  - **E and B fields calculated with MAFIA**
  - **Trace-3D simulation with the MAFIA fields**





Without beam pipes, the net deflection becomes below 50%.

Details will be explained by Dr. Fu.

Summary of the MEBT design

- **Two bunchers are used for achieving longitudinal matching.**
- **Chopper operation has been improved.**
  - **without Quad between them**
  - **Large deflection angle gives large separation between the chopped and unchopped beams.**
- **Sufficient spaces for both mechanical construction and beam monitors are considered.**
- **Equivalent rise/fall time of less than 0.2 nsec is obtained (0.08% unstable particles).**

Details of the MEBT design will be reported by Dr. Fu in the afternoon session.

Comments on the beam

e) Only rms performance has been presented so far. The total beam size is the most important aspect, as particles may be scraped off radially, so characterization of the design has to be concerned with the total beam - a difficult problem.

Energy spread vs beam fraction (simulation result)

P.4-45

Table 4.10 Energy spreads of the 30-mA, 200-MeV output beam after passing the debuncher of 1.3 MV for four kinds of fraction of the beam.

Fraction of the beam	90%	99%	99.9%	100%	
Number of particles in the simulation					
3200	113	177	262	273	keV
48000	104	163	224	506	keV

Therefore, simulation with 3200 particles and 100%-energy width is used in the linac-to-ring beam-transport line. More than 99.9% of the particles are included.

 (Emittances both for longitudinal and tarnsverse are shown later (in Linac to Ring Transfer Line part, OHP p.37 - 38).

Comments on Linac to Ring Transfer Line

This transfer line has to be studied in a joint effort between the linac and booster groups. Questions to be answered during the study period include: is momentum ramping necessary for achieving loss free ring injection? is momentum collimation needed for loss free ring injection? what kind of momentum spread reduction is wanted after the bunch rotation cavity?

For the presented conceptual JHF study, it is not clear how to overcome the design difficulties, if the linac energy is raised from 200 MeV to 400 MeV later on. The transfer line design should anticipate the upgrade and up to 180 mA bunch current. In this case, the momentum spread is changing by a factor of two over the first 50m beyond the linac because of space charge forces. Therefore, any momentum collimation system can be placed only after the bunch rotation cavity. Beam loss evaluation is also necessary in this region. If it becomes necessary to include an achromatic bend section, this will become a major issue.

Preliminary beam simulation with debunchers

- **code LEBT (LINSAC-like code without acceleration) is used.**
- **3200-particles simulation and 100%-energy width is considered.**
- **FD-transverse focusing is used.**
- **30-mA, 200-MeV beam**
- **180-mA, 400-MeV beam**
- **field errors were taken into account;** random errors of ±2% in an accelerating field for each cell and each tank and ±3% in an accelerating phase for each tank were assumed in the SDTL simulation. No phase errors for each cell was assumed. In the CCL simulation, random errors of ±2% in an accelerating field both for each cell and each tank, those of ±1% in an accelerating phase for each cell and ±3% for each tank were assumed.

30-mA, 200-MeV simulation results

p. 4-47

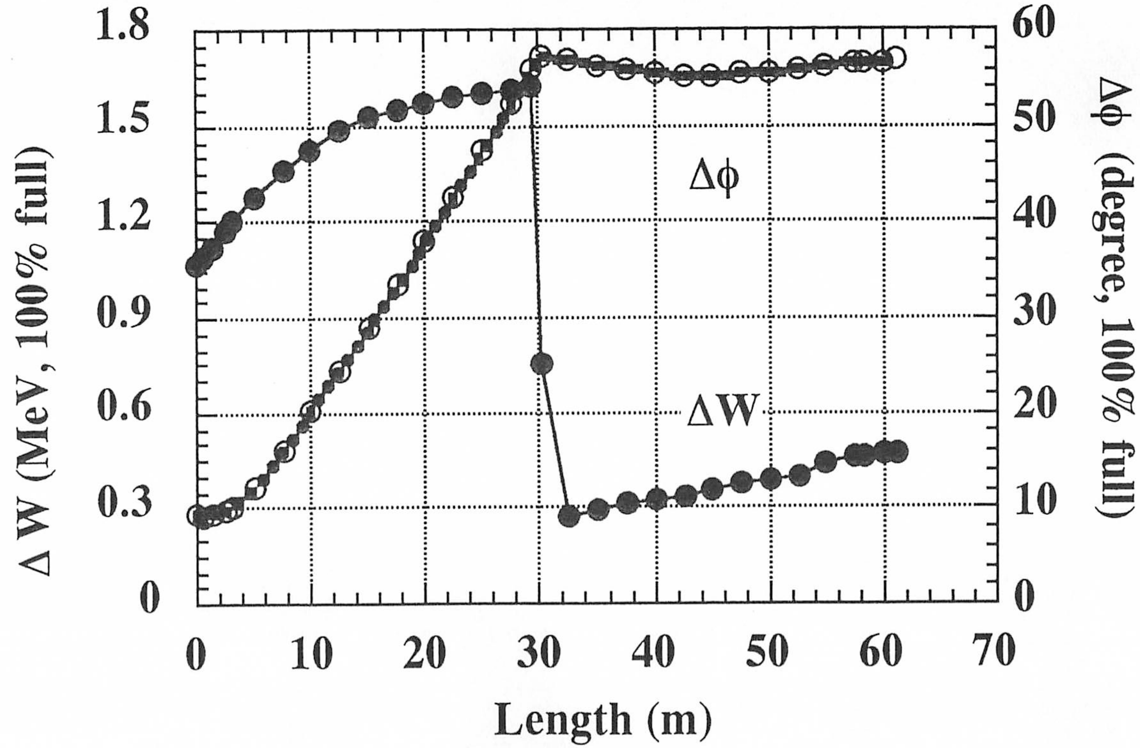


Fig. 4.29 Variation of spreads of phase (in terms of 324 MHz) and energy along the 200-MeV beam-transport line. A debuncher of 1.3 MV is placed at a position of 30 m from the entrance of the beam-transport line. The peak current of 30 mA is assumed. The number of particles is 3200.

Longitudinal emittance of 48000-particles simulation

p.4-49

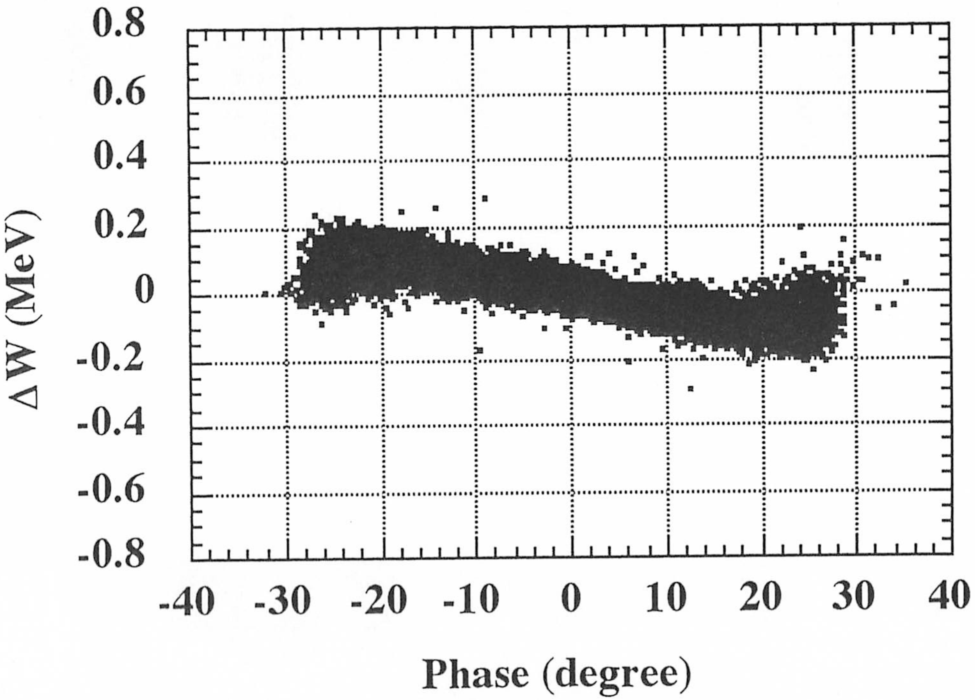
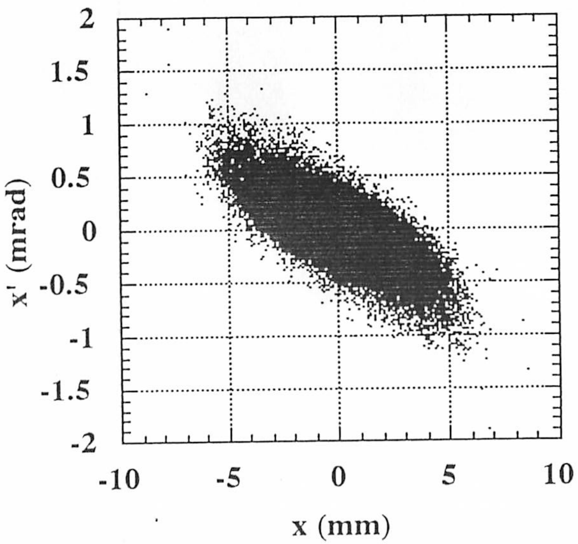


Fig. 4.33 Longitudinal emittance of a 30-mA, 200-MeV beam at a position of 60 m from the entrance of the beam-transport line. The number of particles is 48000. The 48000 particle simulation shows an additional increase of 23% in the full-energy width.

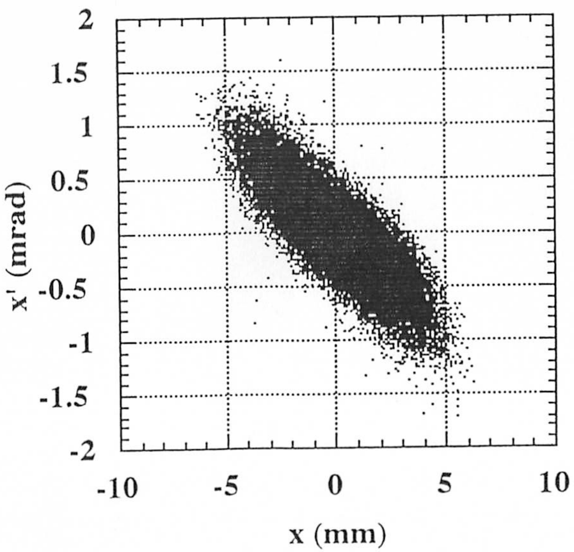
Transverse emittance of 48000-particles simulation



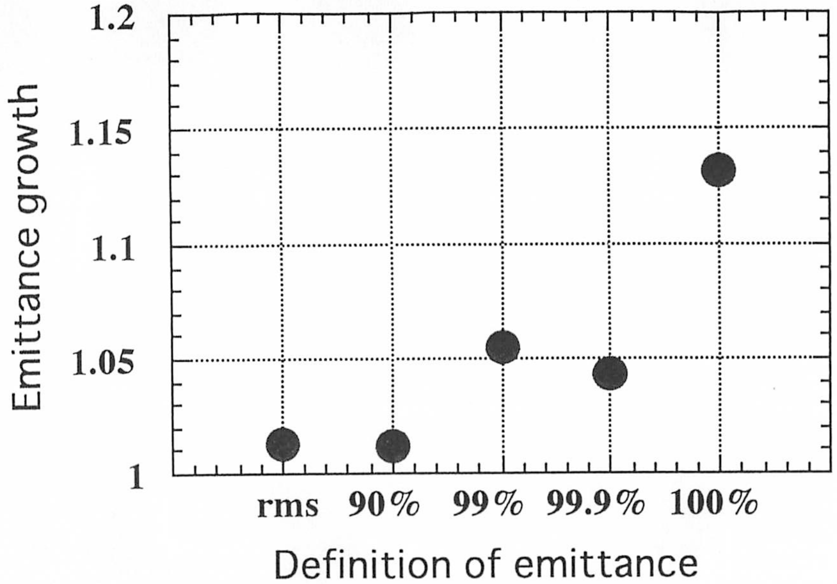
At the entrance of the beam line

ε_{90}=1.27 πmm-mrad

ε_{99}=2.51 πmm-mrad



At the exit of the beam line (60 m away)



Emittance growth (x-x') in the 60-m beam line, calculated with 48000 particles.

180-mA, 400-MeV simulation results

p.4-50

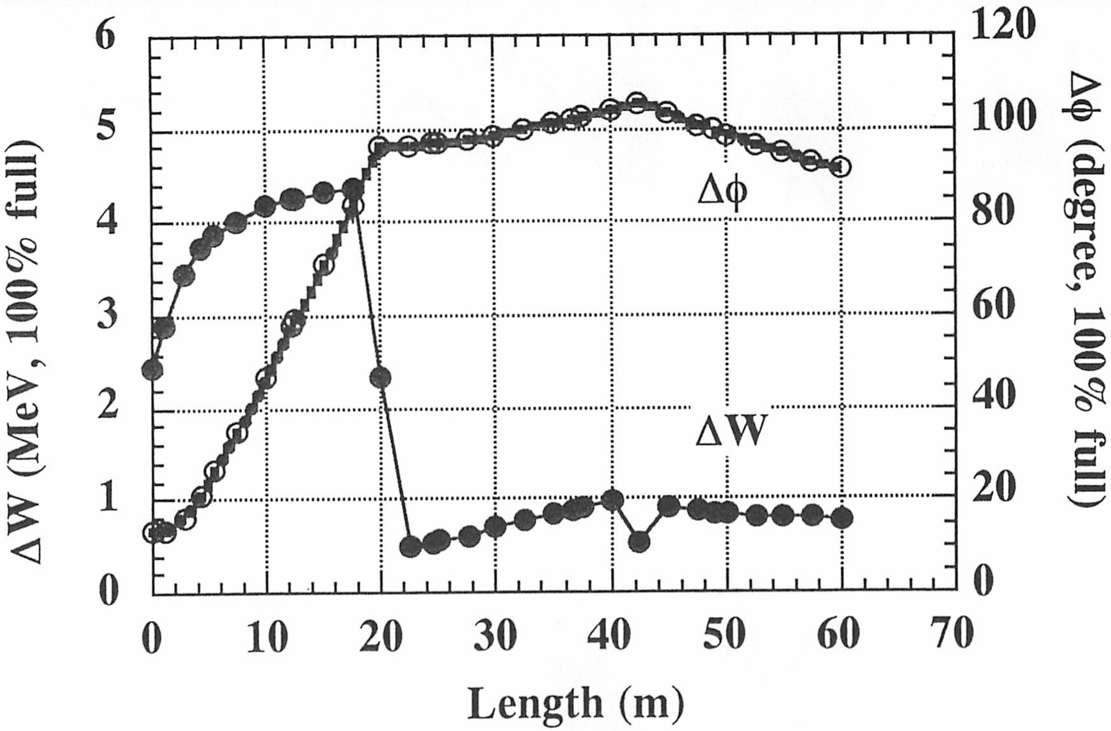


Fig. 4.36 Variation of spreads of phase (in terms of 972 MHz) and energy along the 400-MeV beam-transport line. Two debunchers are used. The voltages are 2.1 and 0.6 MV. They are placed at a position of 20 and 42.5 m from the entrance of the beam-transport line. The peak current of 180 mA is assumed. The number of particles is 3200.

Summary of debuncher operation

Beam	30 mA, 200 MeV	60 mA, 400 MeV
Debuncher-1 position / voltage	30 m / 1.3 MV	20 m / 2.1 MV
Debuncher-2 position / voltage	------------------	42.5 m / 0.6 MV
Energy spread	0.469 MeV	0.774 MeV (180 mA equivalently)
Requirements	0.730 MeV	1.36 MeV

On condition that 100% full width of 3200 particle-simulation >= 99.9% of 48000 particle-simulation.

Comments on a 60 mA current operation

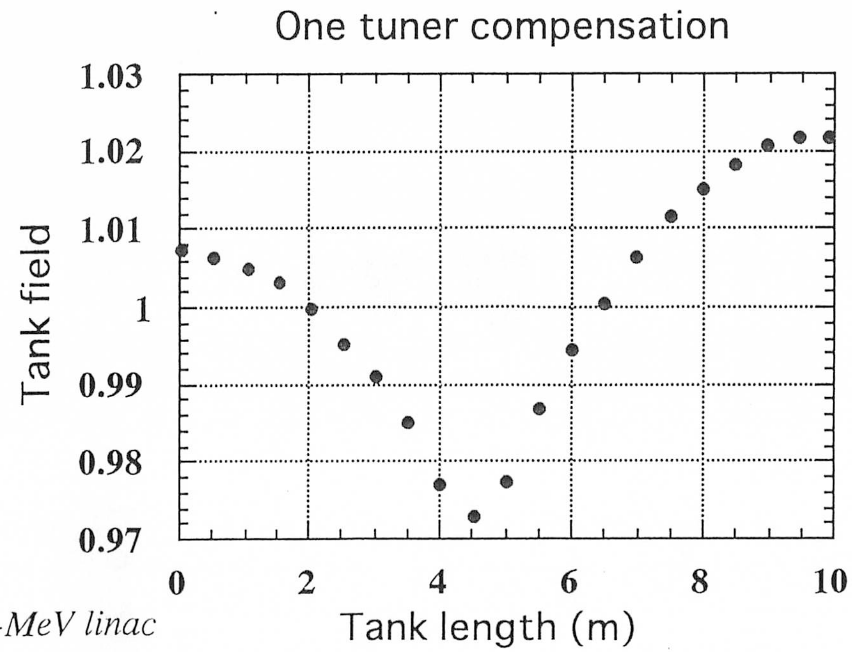
There should be no problem with the DTL at either the 30 mA or for the 60 mA upgrade current. The chosen accelerating gradient of 2 MeV/m is a conservative one (however,the heat dissipation in the first drift-tubes must be carefully checked.).

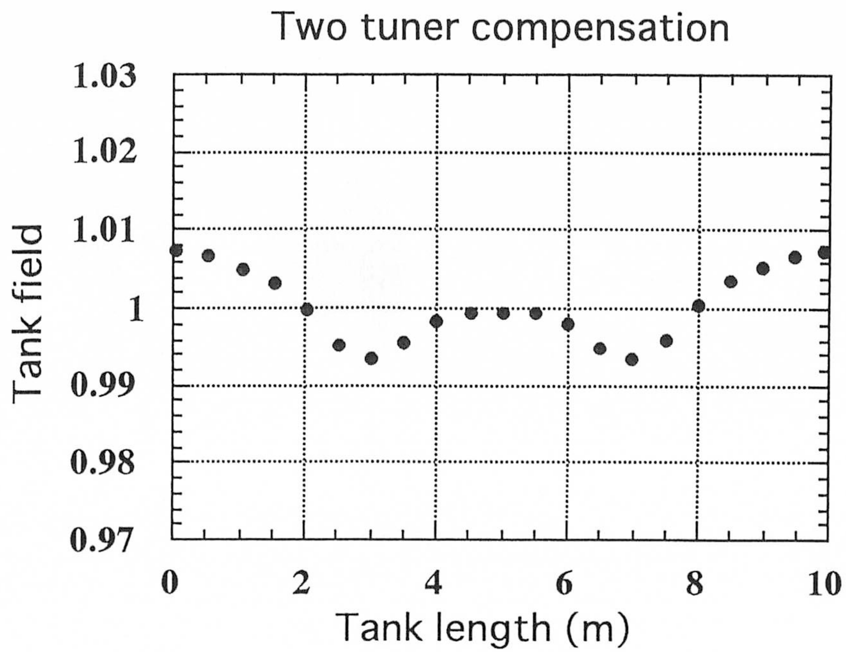
Upgrade operation

- **No serious problem in 60-mA beam dynamics**
- **Cooling of the first tank - 3% duty**

An example of drift-tube cooling and field distribution (First DTL tank length is 9.9 m)

2 degrees drift tube temperatire rise causes a tank frequency shift of 13 kHz, resulting in accelerating field deviation of ± 0.4%. This is not a problem. However, a frequency compensation by tuners causes some field deviation, shown in the figures.





Comments on the next step

f) In the next steps, a more precise design will include:

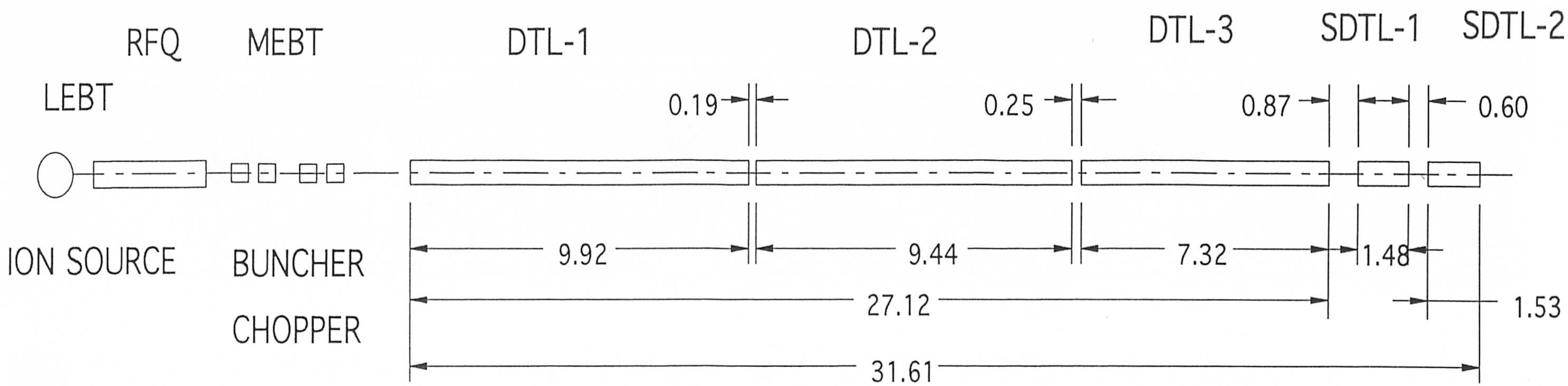
- better matching (e.g., longitudinal)
- exact solution of the equipartitioning relations
- resolution of the collision a setting in the 3D space-charge routine
- misalignment/error simulation. Proper simulation of misalignment requires a completely 3D code

Some improvements

- Accurate longitudinal matching has been introduced in the MEBT.
- Accuracy of numerical solution of equipartitioning relation has been improved.
- Error simulation in LINSAC is next step.

Construction of the low-energy part

- **IS+RFQ+DTL+SDTL(59 MeV)**
- **RF power source**
- **Control and monitors**



Summary

- The linac design and the report were revised and improved.
  - MEBT and chopper were improved.
  - The linac to ring transfer line was examined.
  - The reasons for selecting JHF linac main parameters were explained.