JHF 200-MeV Proton Linear Accelerator

- **Distinctive features of the JHF proton linac**
  - **Requirements**
  - **Configuration**
  - **Focusing scheme**
  - **simulation results**

T. Kato

Requirements

Table 1 Required main parameters of the linac.

The construction plan of the linac consists of two stages.

	Initial requirement	Final goal	
Particles	H^-	H^-	
Output energy	200	400	MeV
Peak current	30	60	mA
Beam width	400	400	μsec
Repetition rate	25	50	Hz
Average current	200	800	μA
Length	<150	~220	m
Momentum spread	± 0.1	± 0.1	%

Features of the requirements

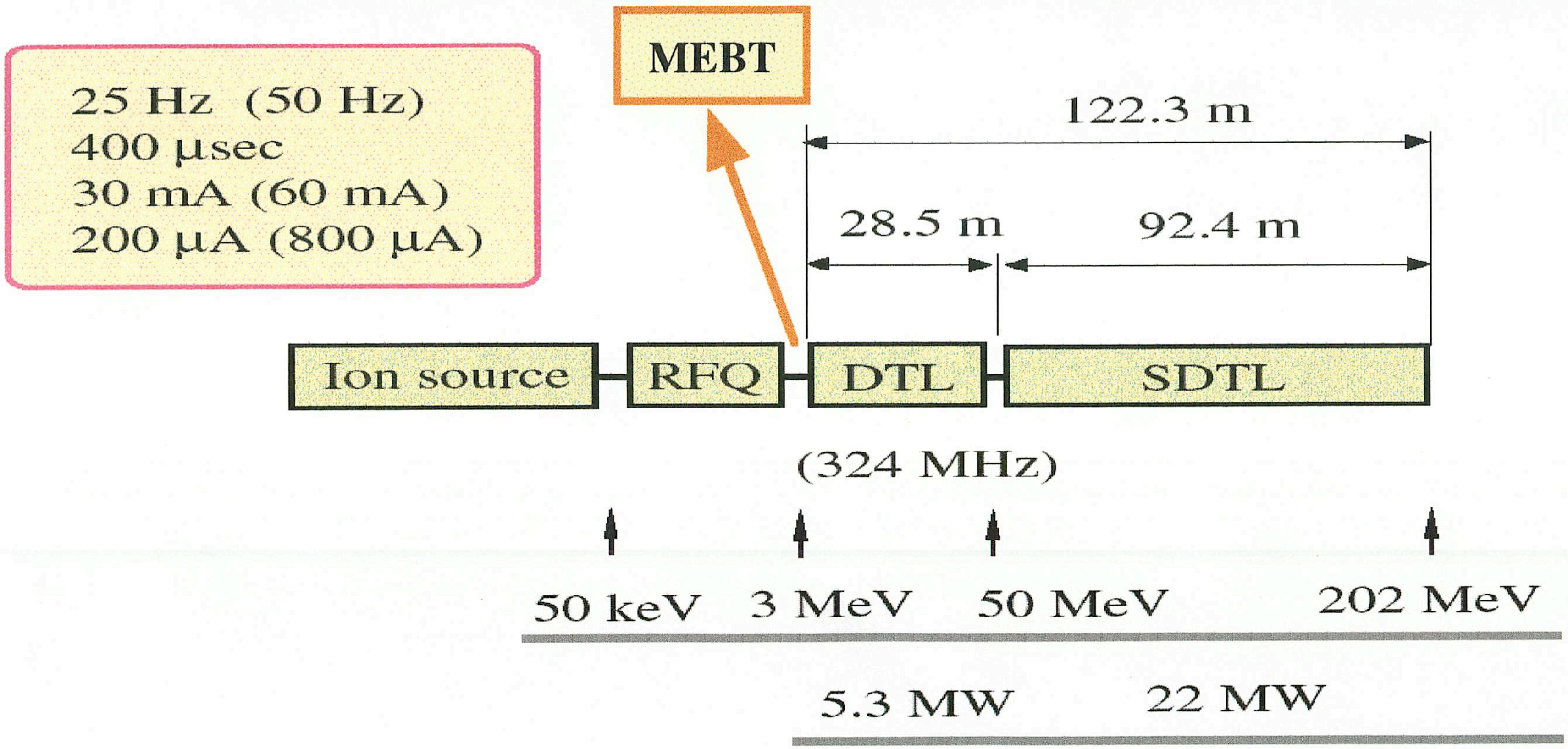
- High intensity - average 200 μA
  - causing beam-loss problem
- Medium peak current - 30 mA
- Medium energy - 200 MeV
- Future upgrade of the energy

The main issue is

How to obtain beams of good quality
without beam losses
not to aim at large peak current

The JHF 200-MeV Proton Linear Accelerator

JHF 200 MeV PROTON LINAC



25 Hz (50 Hz)
400 μsec
30 mA (60 mA)
200 μA (800 μA)

MEBT

122.3 m

28.5 m

92.4 m

Ion source — RFQ — DTL — SDTL

(324 MHz)

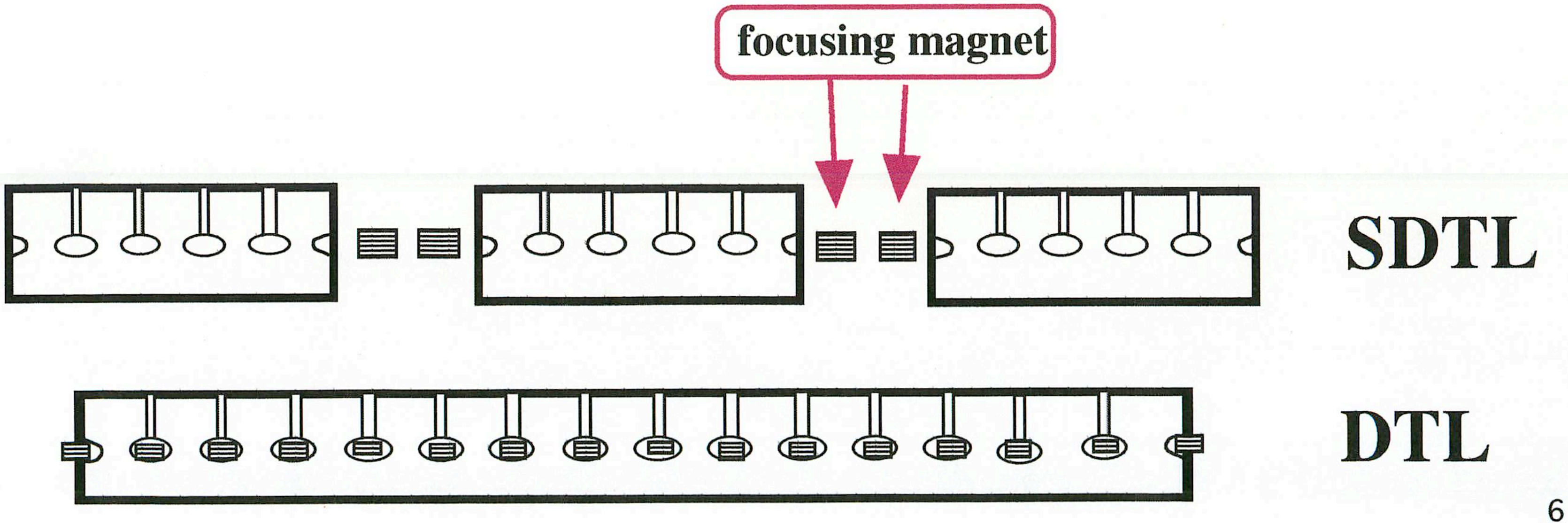
50 keV 3 MeV 50 MeV 202 MeV

5.3 MW 22 MW

SDTL (Separated-type DTL)

- **SDTL structure for a medium energy range - a new structure concept proposed in 1992**
  - **many advantages of beam dynamics and construction**

Focusing magnets are placed between two SDTL tanks (like a CCL focusing scheme)



Merits of SDTL

- Reduce SCE compared with CCL
- Avoid non-linear effects in CCL
- Higher ZTT than DTL and CCL
- Without stabilizing devices
- Mechanical and construction merits
  - Reduce tolerance in alighnment of DT and Tank
  - Reduce number of Q-magnet
  - Simple structure mechanically
  - Reduce heat loss in drift tube

Main parameters

	DTL	SDTL	
Frequency	324	324	MHz
Injection energy	3.0	50.06	MeV
Output energy	50.06	202.5	MeV
Length (structure only)	27.04	65.9	
Length (including drift space)	28.51	92.4	m
Number of tank	3	31	
Number of klystron	3	14	
Rf driving power	3.92	17.4	MW
Total rf power (30 mA)	5.33	22.0	MW
Total length		122.3	m
Total power (30 mA)		27.3	MW
Peak current		30	mA
Beam width		400	μsec
Repetition rate		25	Hz
Average current		200	μA

What is the best linac?

- (1) Good beam quality without beam losses
- (2) High accelerating efficiency
- (3) Stable operation without breakdown
- (4) Cost performance

The above items have been achieved in the design

Reasons for degradation of the beam quality

- Emittance growth and beam halos - space-charge effects
- Accelerating parameters (focusing)
- Transitions in transverse or longitudinal motion
- Errors
  - mismatching, misalignment
  - field errors - in both construction and tuning

To suppress or conquer the above is important.

(1) Strategies for achieving good beam

- **Select higher operating frequency**
- **Avoid longitudinal transition up to 200 MeV**
- **Good focusing design**
- **Avoid difficulties in tuning before DTL injection**
    - **Adopting single tank RFQ**
    - **Tunable transport line from RFQ to DTL**

Why higher frequency is desirable?

201 MHz ⟶ 324 MHz

- **Reduce space-charge effects**
- **Higher shunt impedance**
- **Easy to use klystrons**
- **Reduce rf-structure size**

Difficulties are

1. **RFQ construction**
2. **DTL focusing magnet**

Space-charge effects vs. frequency

Table 3 Accelerator parameters for various operating frequencies.

Frequency	201	300	324	350	432	MHz
Emittance(90%)	0.15	0.15	0.15	0.15	0.15	πcm·mrad (normalized)
Eacc	2	2	2	2	2	MV/m
Beam radius	2.45	1.85	1.77	1.69	1.47	mm
$\Delta\phi$	6.4	8.5	9.0	9.6	11.6	degree
B'	43.3	96.5	112.6	131.4	200.2	T/m
σ_x^0	60	60	60	60	60	degree
σ_x	42.4	50.0	51.1	52.2	54.4	degree
σ_x/σ_x^0	0.71	0.83	0.85	0.87	0.91	
μ_t	0.50	0.31	0.27	0.24	0.18	
EGF	5.0	2.3	1.9	1.6	1.1	%

$$\boxed{\mu = 1 - \left(\frac{\sigma_0}{\sigma}\right)^2}$$

EGF: emittance growth factor due to the field energy of the bunch of Gaussian distribution.

Space-charge effects vs. frequency
Simulation results

- **324 MHz vs. 201 MHz (equipartitioning focusing)**

	324	201
σ_x/σ_{x0}	0.84 - 0.77	0.69 - 0.59
σ_z/σ_{z0}	0.72 - 0.62	0.63 - 0.53
Emit. Growth x	0.66 (relative)	1
Emit. Growth z	0.51	1

Injection beam

$\varepsilon_x/\varepsilon_z$=1/2, 30 mA

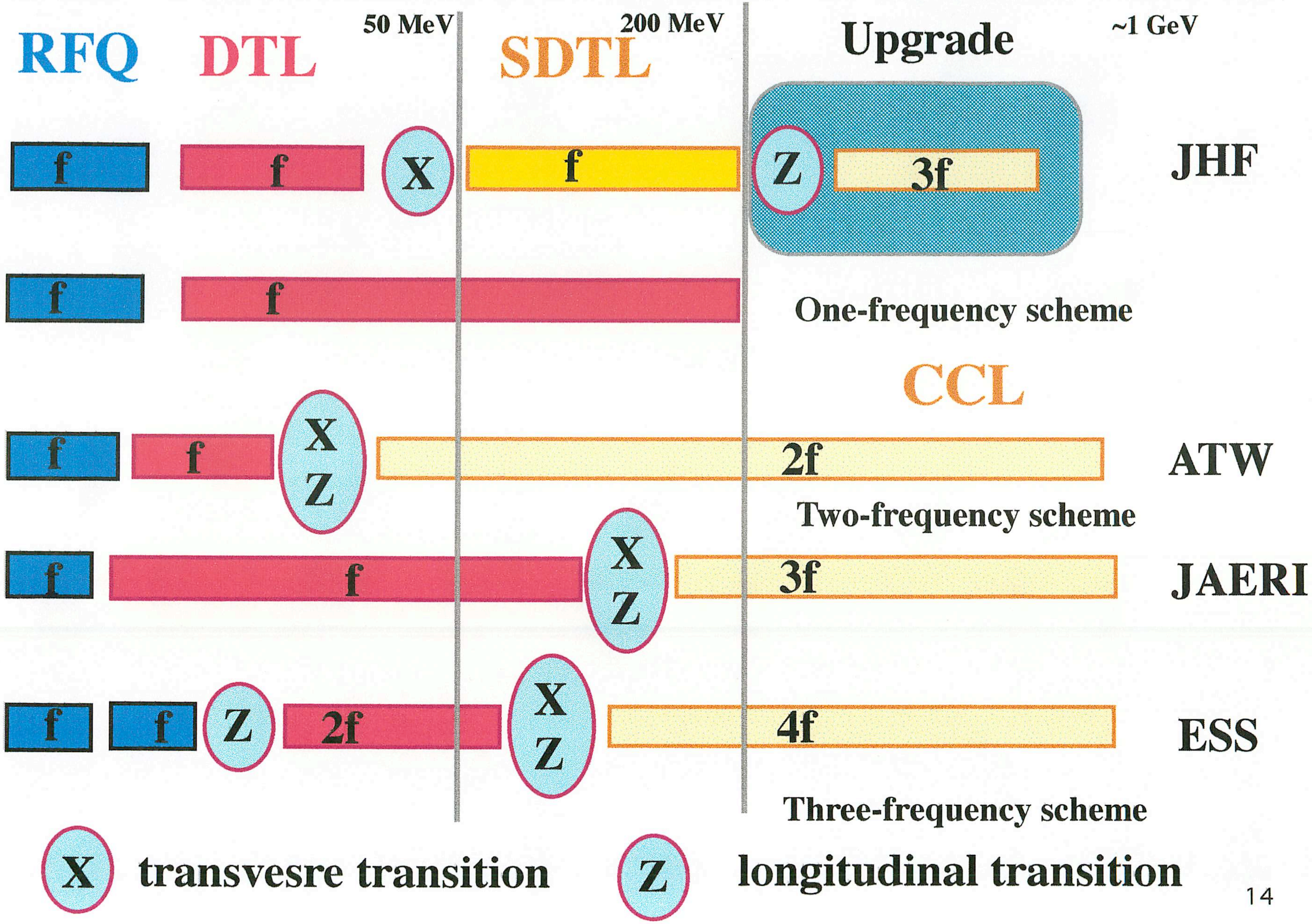
ε_{xrms}=0.187 πmm-mrad

ε_{x90}=0.804 πmm-mrad

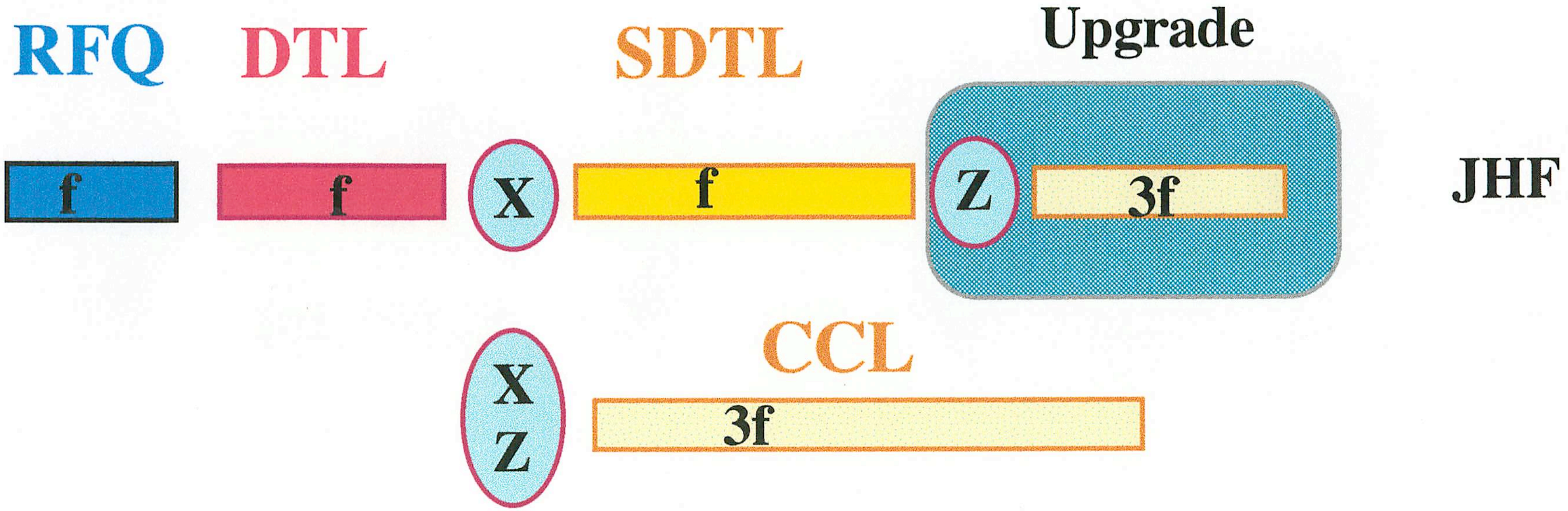
Acceleration from 3 to 148 MeV

E_0=2.1 MV/m for both frequencies

Types of linac configurations (longitudinal and transverse transitions)



By using SDTL, two transitions are separeted



- **Reduce space-charge effects compared with CCL scheme**
  - **due to beam size difference**
- **Avoid rf-nonlinear effects in CCL of higher frequency**

Computer code for simulation

Code LINSAC is mainly used in designing.

- **Features of the code**
  - **accurate distribution of the gap field**
  - **including collsion effects**
  - **vectorized and parallelization**
- **Main results due to collision effects**
  - **about 10% increase in rms properties**
  - **halo-like particles production of order of 10^{-4}**

Details are explained in beam-dynamics section.

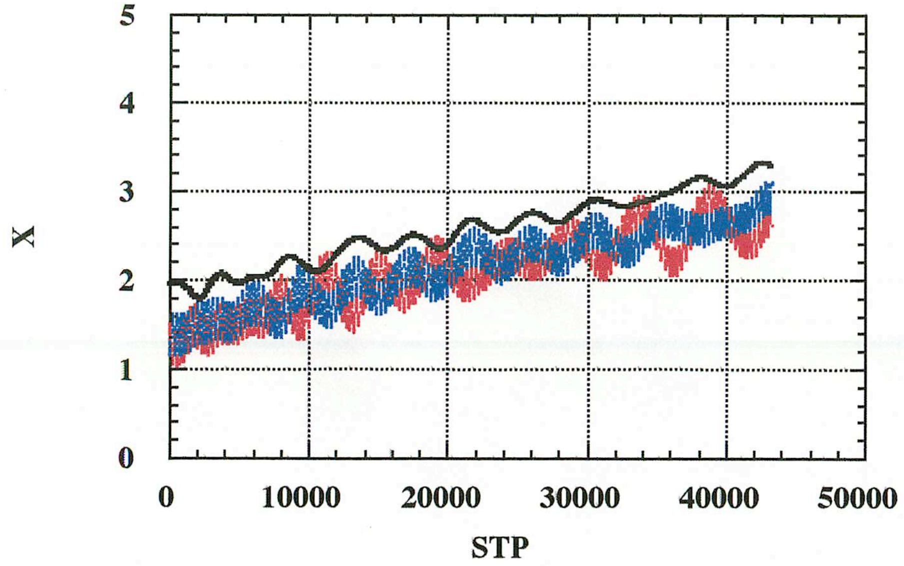
Two types of transverse focusing method

Equipartitioning focusing

$$\frac{k_{xo}}{k_{zo}} \propto \mathrm{const}$$

spherical bunch

ps108equi

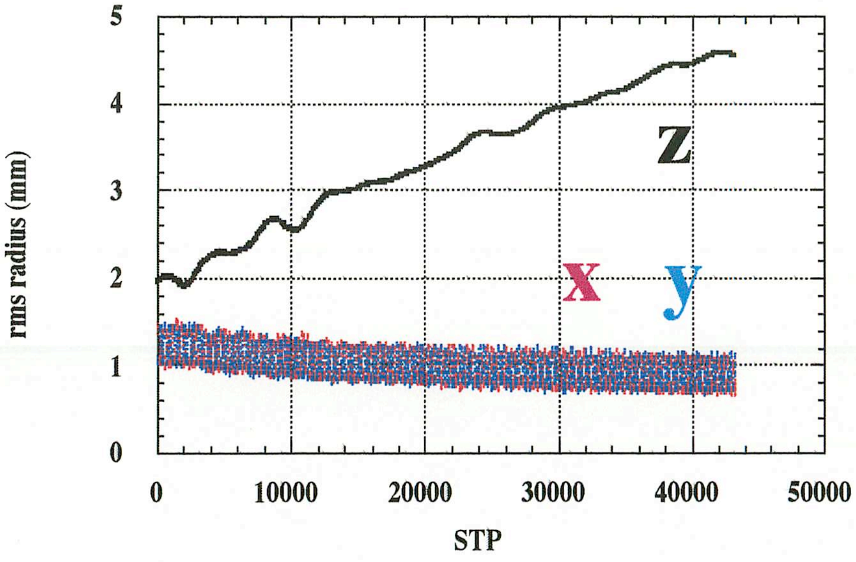


Constant phase advance

$$\frac{k_{x0}}{k_{z0}} \propto \beta_0^{1/2}\gamma_0^{3/2}$$

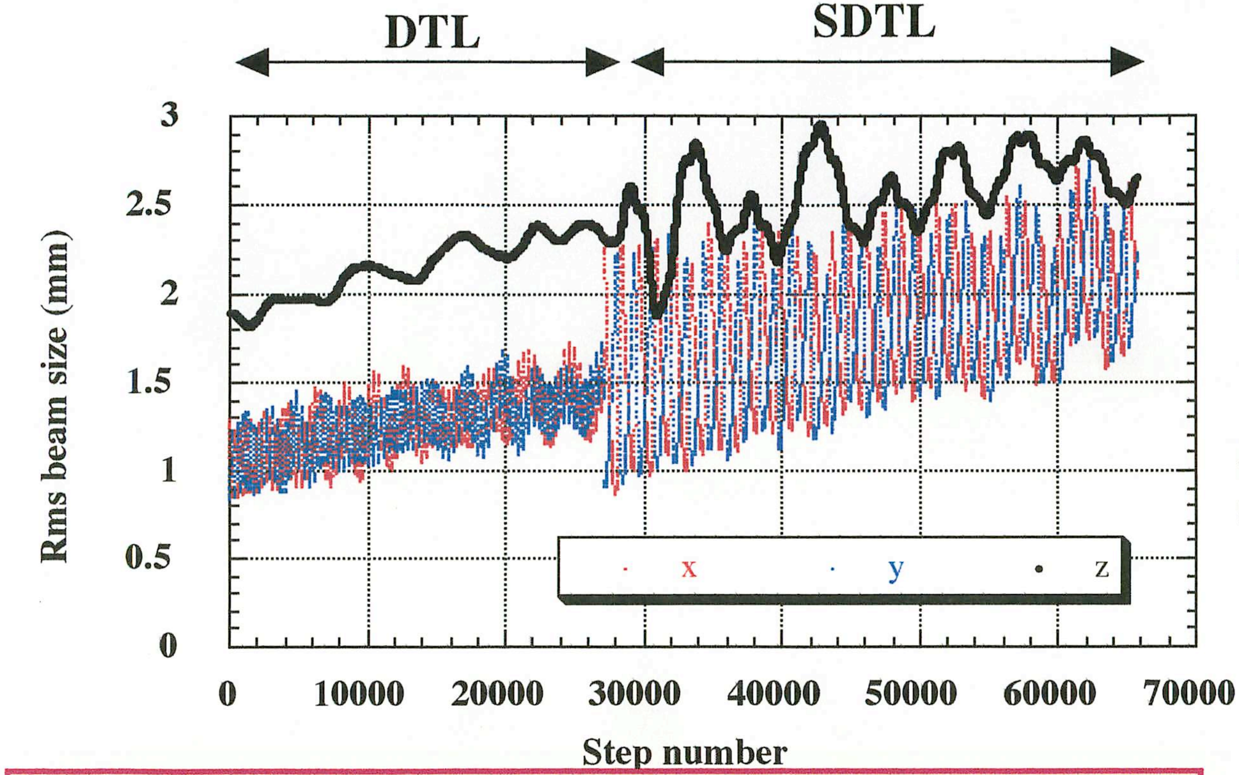
asymmetric bunch

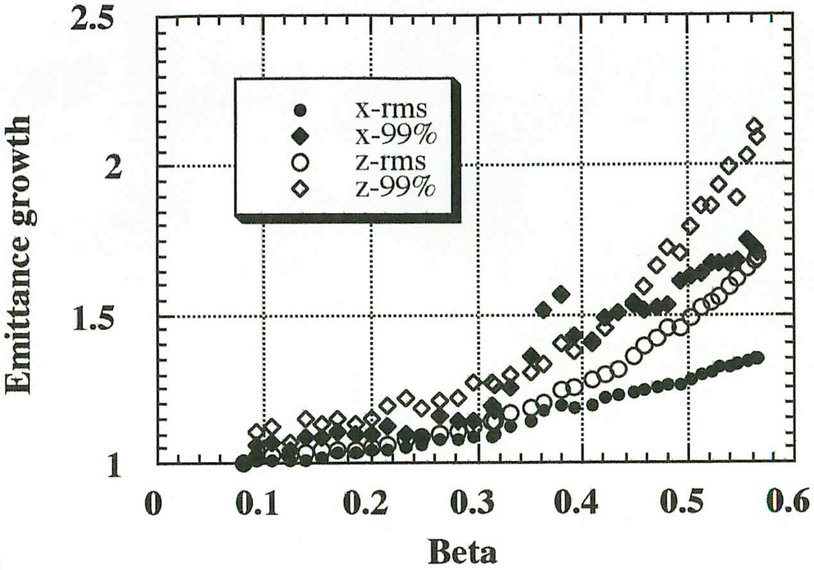
ps111mucon



rms beam size vs. step number (energy)

Beams in the equipartitioning focusing method





An rms beam size in the equipartitioning focusing method is connected smoothly from DTL to SDTL, althoogh there is a transvesre transition of length of focusing periods.

Fig. 4.25 Emittance growth (rms and 99%) along the linac. A 30-mA type-B injection beam is used.

Features of the focusing design

Using LINSAC simulation and Equipartitioning focusing method:

$$\gamma_0 \frac{\varepsilon_{nx}}{\varepsilon_{nz}} \frac{k_x}{k_z} = 1$$

- both emittance growth and halo-formation are considered
- nealy equipartitioned beam is assumed
- keep the ratio of transverse focusing strength to longitudinal one constant during acceleration
  - Equal emittance growth
  - less beam halos in both transverse and longitudinal motion totally
- smooth continuation of rms beam size from DTL to SDTL

Summary of emittance growth

DTL+SDTL vs. all-DTL scheme

(equipartitioning is used)

Transverse 1.1 : 1
Longitudinal 1.06 : 1

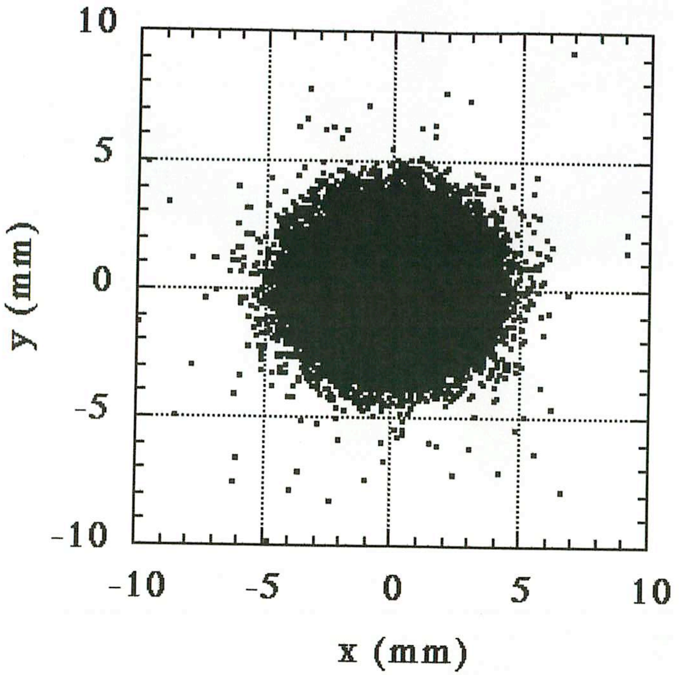
Equipartitioning vs. Constant phase scheme

(all-DTL scheme is used)

Transverse 1.22 : 1
Longitudinal 0.62 : 1

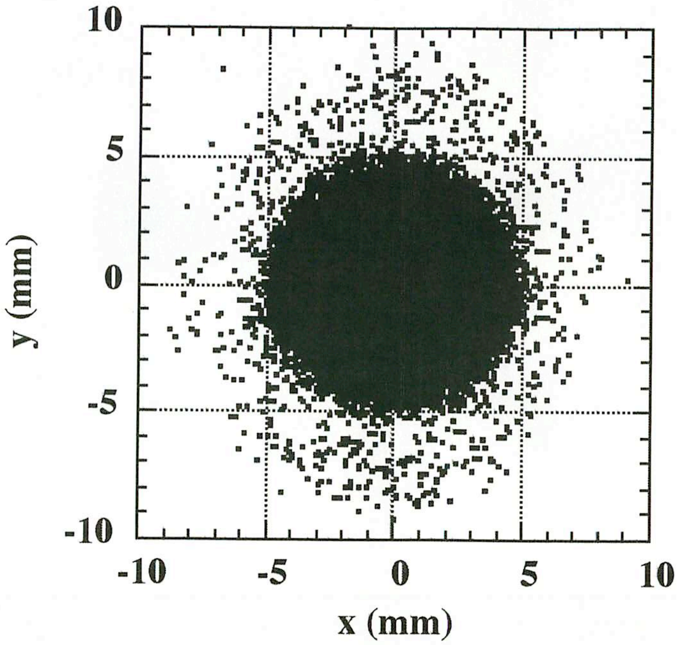
Transverse beam halos in LINSAC

matched injection



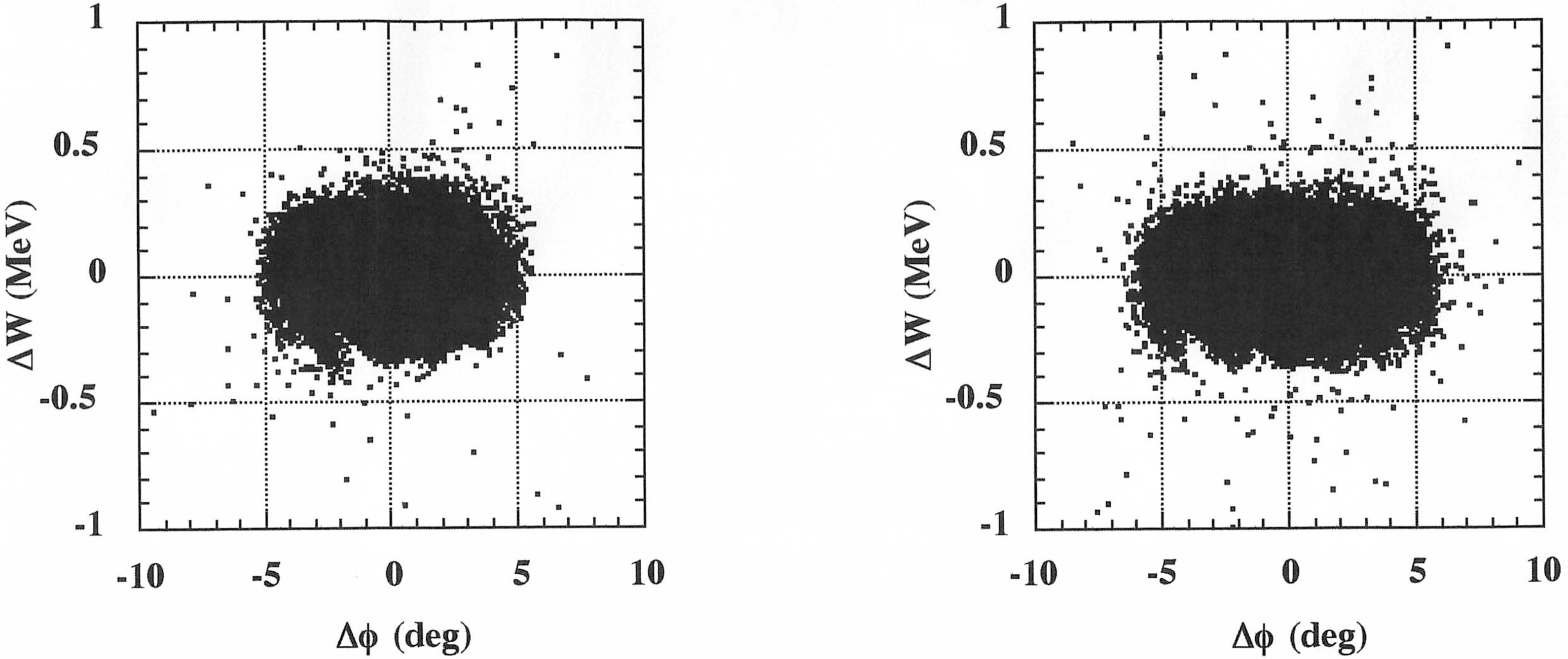
The output profile of the matched injection simulation. The number of particle is 48000. α=0.

mismatched injection



The output profile of the mismatched injection simulation. The number of particle is 48000. α=0.

Longitudinal beam halos in LINSAC


Equipartitioning focusing

Constant phase advance focusing

Longitudinal emittances after acceleration from 3 to 148 MeV. The left is results with the equipartitioning focusing method. The right is results with the constant phase advance method. The number of particles is 48000. The beam current is 30 mA.

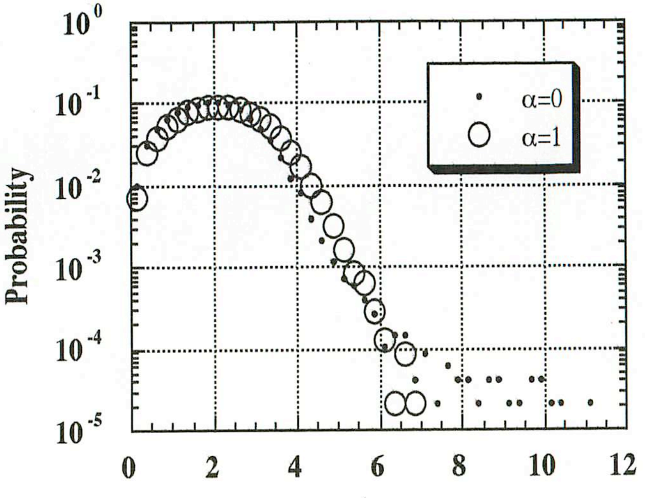
Definition of halos

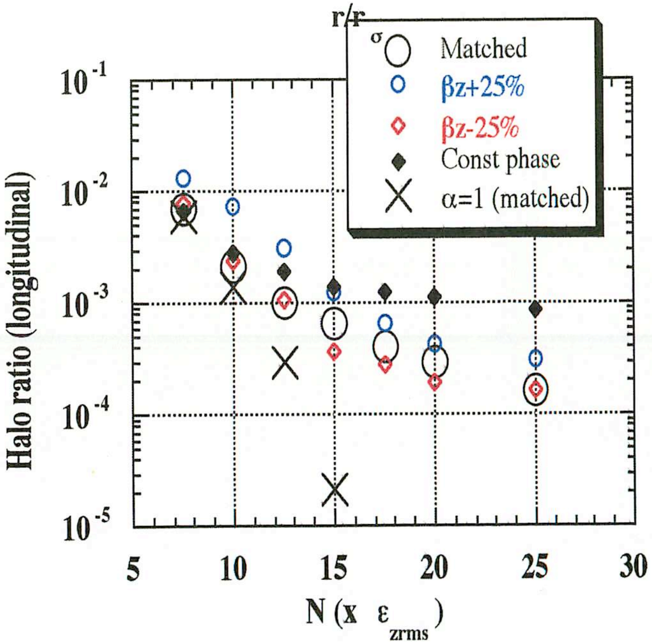
Transverse

Halo-like particles are defined by those in the outside of 6.5 times the standard deviation of the radial distribution of the output beam.

Longitudinal

Halo-like particles are difined by those in the outside of 12.5 times the longitudinal output rms emittance.





Summary of halo-formation

Transverse				
Equipartitioning	DTL	macro	0.1	%
	DTL	real	0.05	
	DTL+SDTL	macro	0.1	
Constant phase	DTL	macro	0.08	
Longitudinal				
Equipartitioning	DTL	macro	0.098	
Constant phase	DTL	macro	0.19	

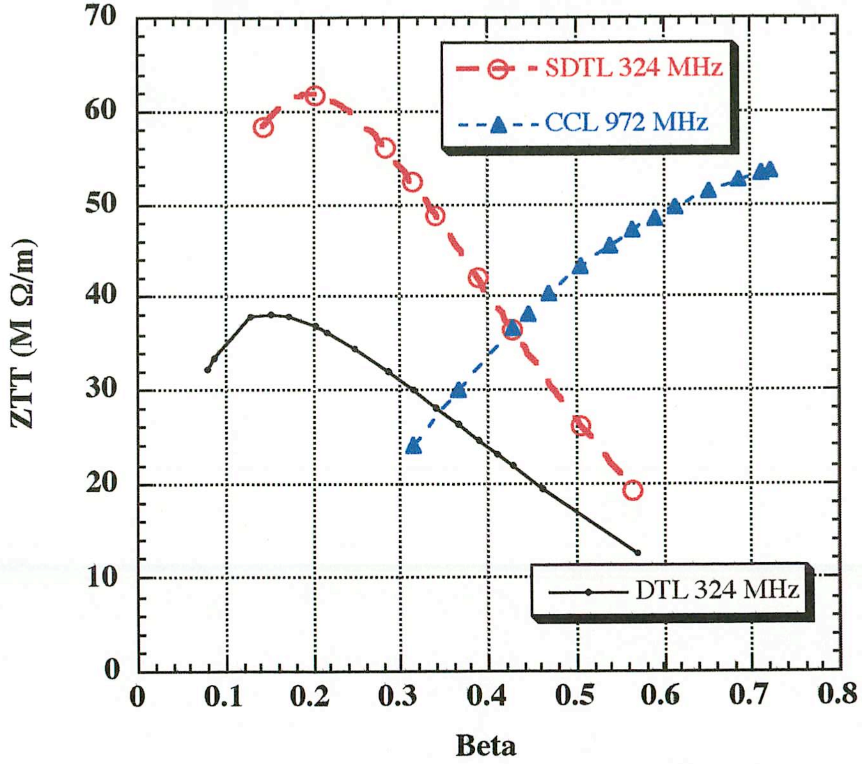
- **Transverse ~0.1% due to collision effects**
- **Longitudinal equipartitioning ~0.1%**
- **Longitidinal constant phase ~0.2%**
- **Mismatched injection causes additional halos**

(2) Strategies for higher accelerating efficiency

- Higher frequency is selected

$Z \sim \omega^{1/2}$

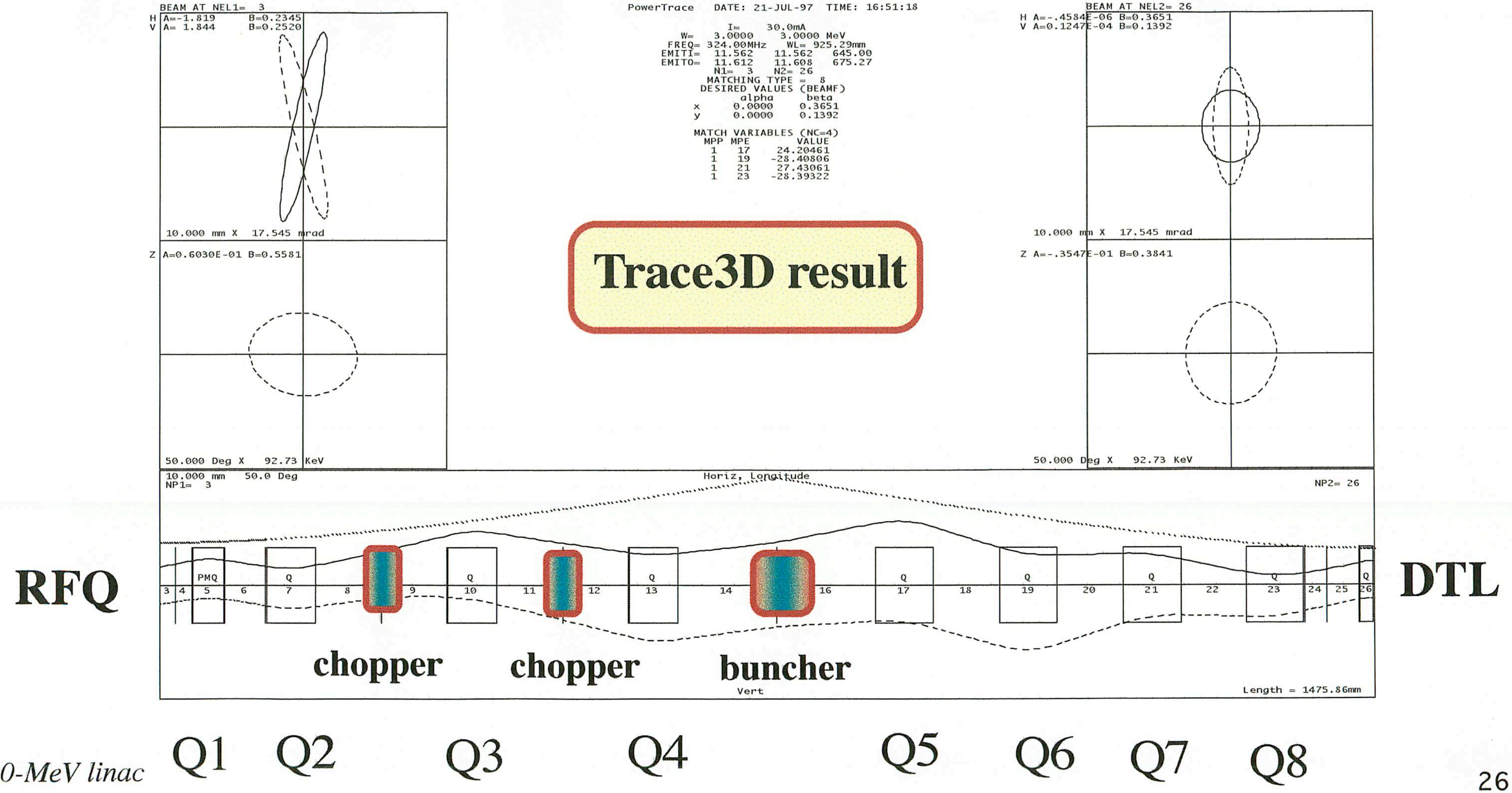
- SDTL structure in higher energy region



ZTT of SDTL is higher than that of DTL by 30~60%.

Beam transport line from RFQ to DTL (MEBT)

Matching and chopping the beam



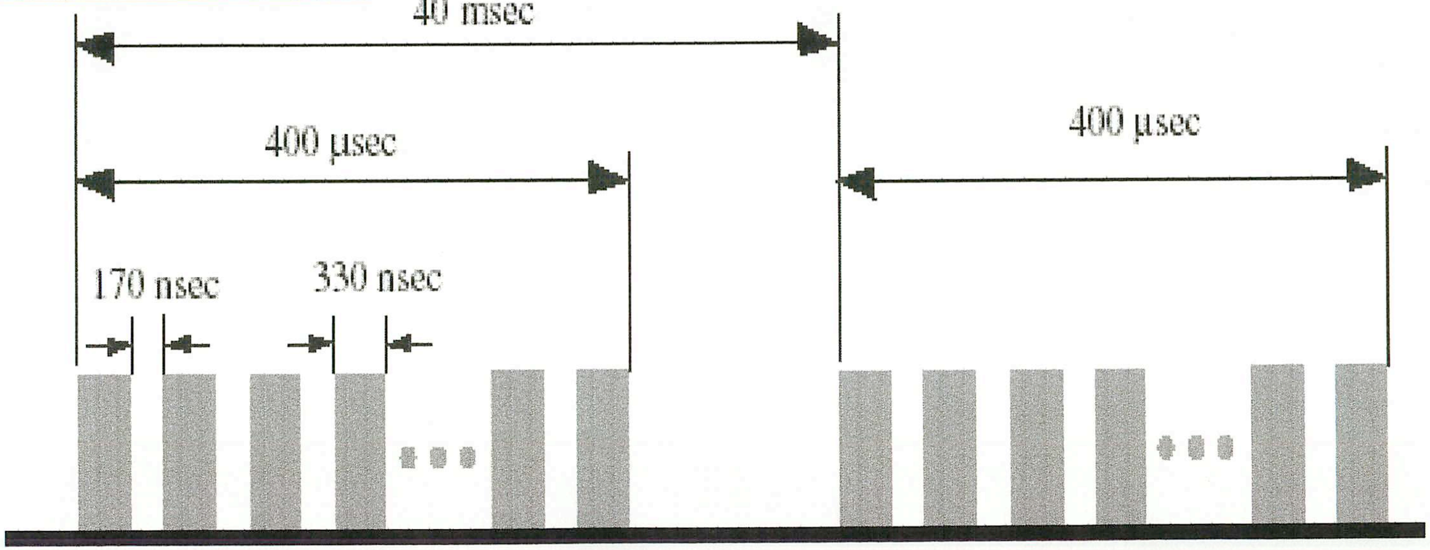
```
PowerTrace   DATE: 21-JUL-97  TIME: 16:51:18

             I=     30.0mA
     W=    3.0000     3.0000 MeV
   FREQ= 324.00MHz    WL= 925.29mm
  EMITI=   11.562   11.562   645.00
  EMITO=   11.612   11.608   675.27
           N1=  3   N2= 26
          MATCHING TYPE =  8
         DESIRED VALUES (BEAMF)
              alpha      beta
      x      0.0000     0.3651
      y      0.0000     0.1392

        MATCH VARIABLES (NC=4)
         MPP MPE         VALUE
          1   17      24.20461
          1   19     -28.40806
          1   21      27.43061
          1   23     -28.39322
```

Trace3D result

MEBT (2)

Two rf choppers ~ 50 kW
One buncher ~200 kV
Eight focusing magnets

Required time structure of the bunch. A pulse length is 400 μsec. A repetition rate is 25 Hz.

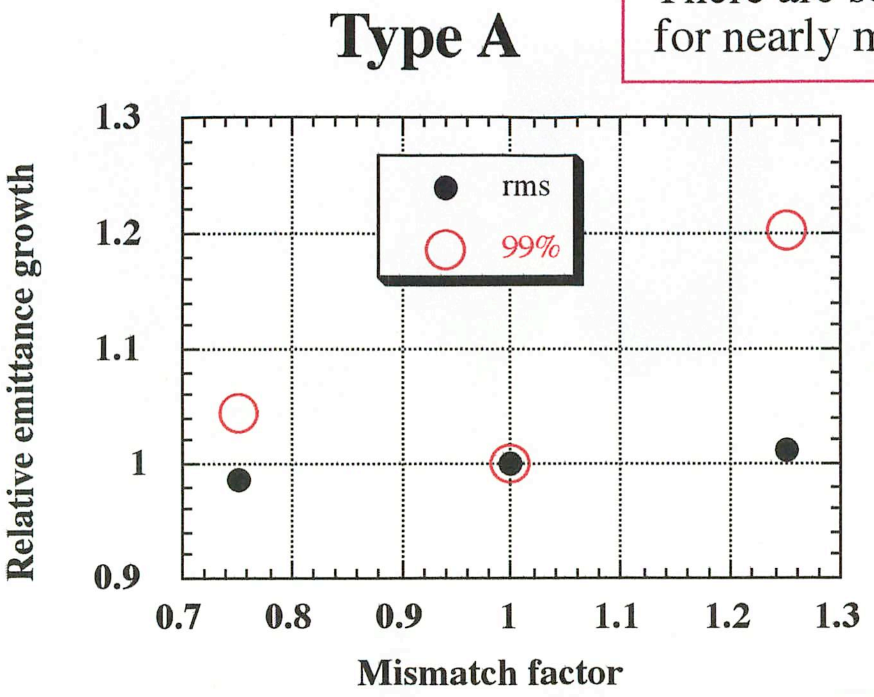


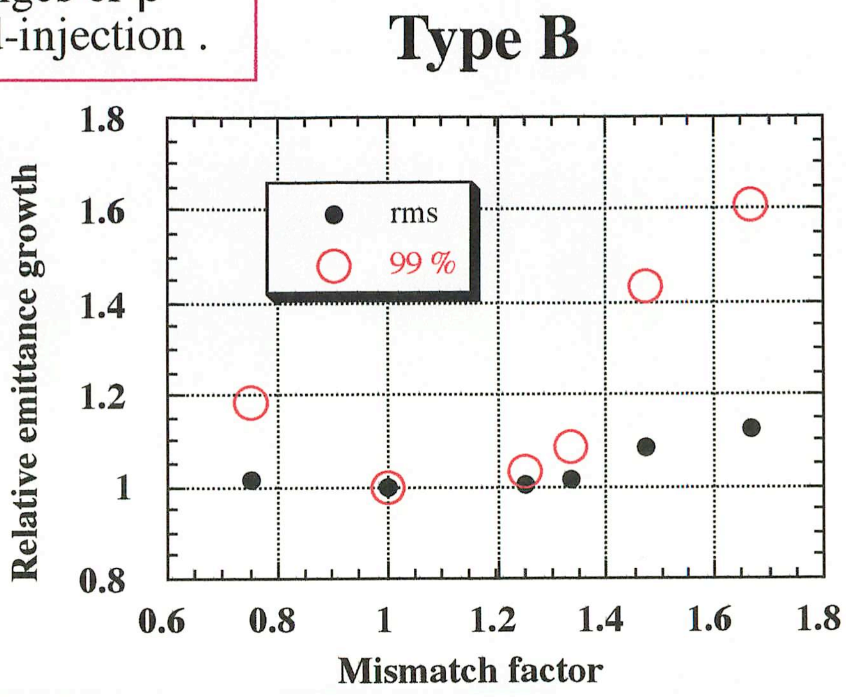
Emittance growth along MEBT
Transverse (rms/99%) 1.1 / 4.4%
Longitudinal (rms/99%) 4.8 / 15%

A fast chopper is required for reducing beam losses after injection into the ring.

Longitudinal matching in MEBT

There are some ranges of β for nearly matched-injection .





A mismatch factor of 0.88 corresponds to the injection beam from the MEBT.

A mismatch factor of 0.96 corresponds to the injection beam from the MEBT.

Longitudinal emittance growth (rms and 99%) as a function of the mismatching factor at the entrance of the DTL. The growth is normalized by that for the matched injection.

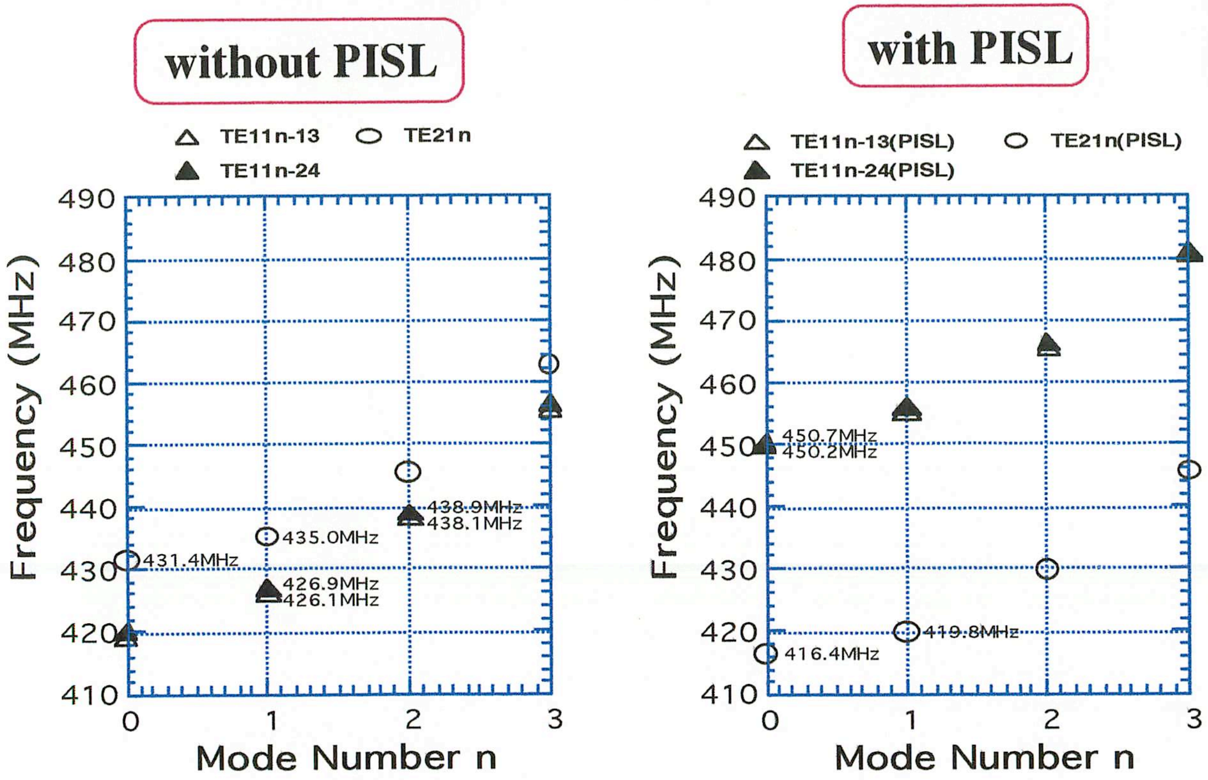
mismatch factor=$\beta_{mismatch}/\beta_{match}$

(3) Stability and reliability

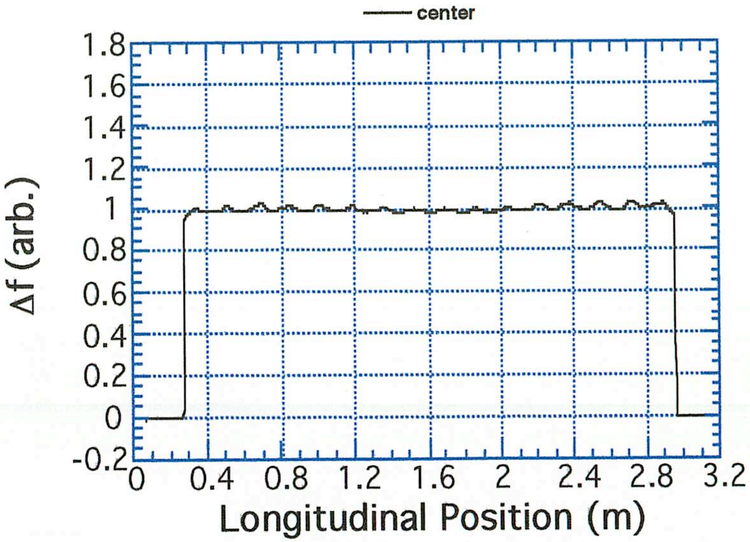
- **RFQ stabilized with PISL** → following section
- **DTL stabilized with post coupler** → following section
- **SDTL of five-cell short tank**
- **Klystron**
- **Margine for beam losses**
  - **avoid longitudinal transition**
  - **equal emittance growth due to equipartitioning**
  - **less emittance growth due to higher frequency**
  - **less halo formation due to equipartitioning**
  - **large bore radius**

3-MeV RFQ is one of key structures

- **experience in construction of 432-MHz RFQ**
- **Stabilized with π-mode stabilizing loop**

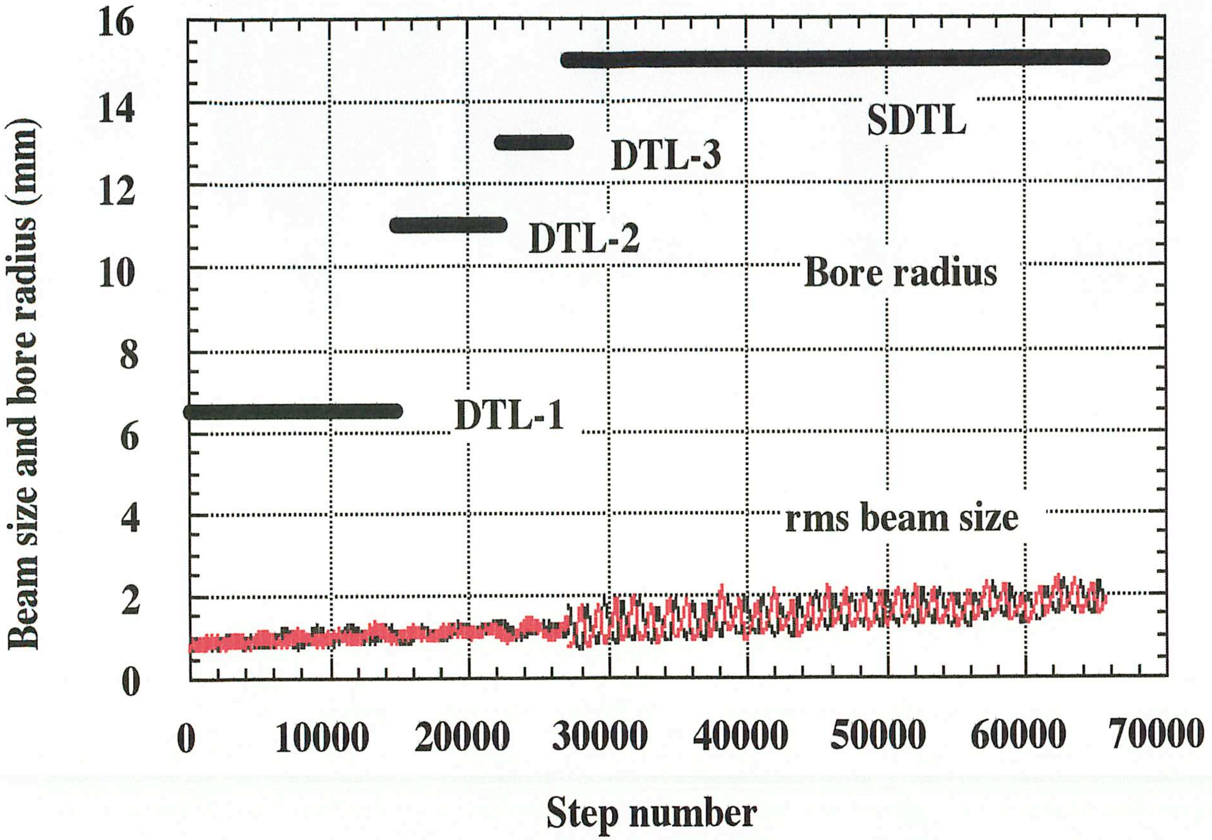


Selective mode shift with PISL



Measured field distribution

Beam size and bore radius



Radius at DTL injection is limited by electro Q-magnet fabrication.

A larger bore is possible in SDTL.

Fig. 4.24 Variation of rms transverse beam size and bore radii along the linac. One cell corresponds to 181 steps.

Debuncher

changing the output-energy spread

30 ~ 40m downstream of the linac, two-cell DTL type of 1.5 MV, ~0.5 MW
achieving the required momentum spread

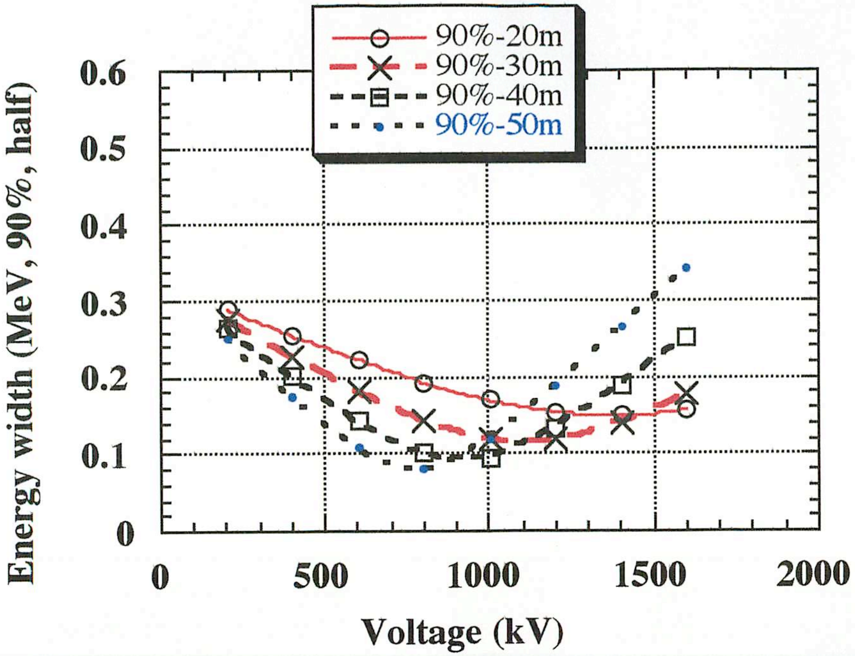


Fig. 4.28 Energy width of the output beam as a function of the debuncher voltage and the drift spaces between the exit of the linac and the debuncher. An ideal acceleration in the SDTL is assumed.

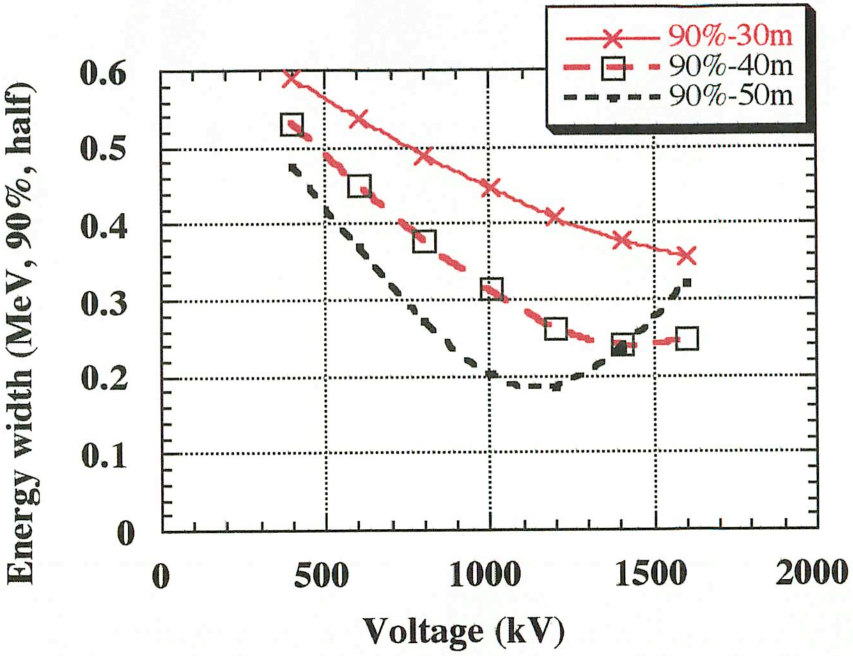
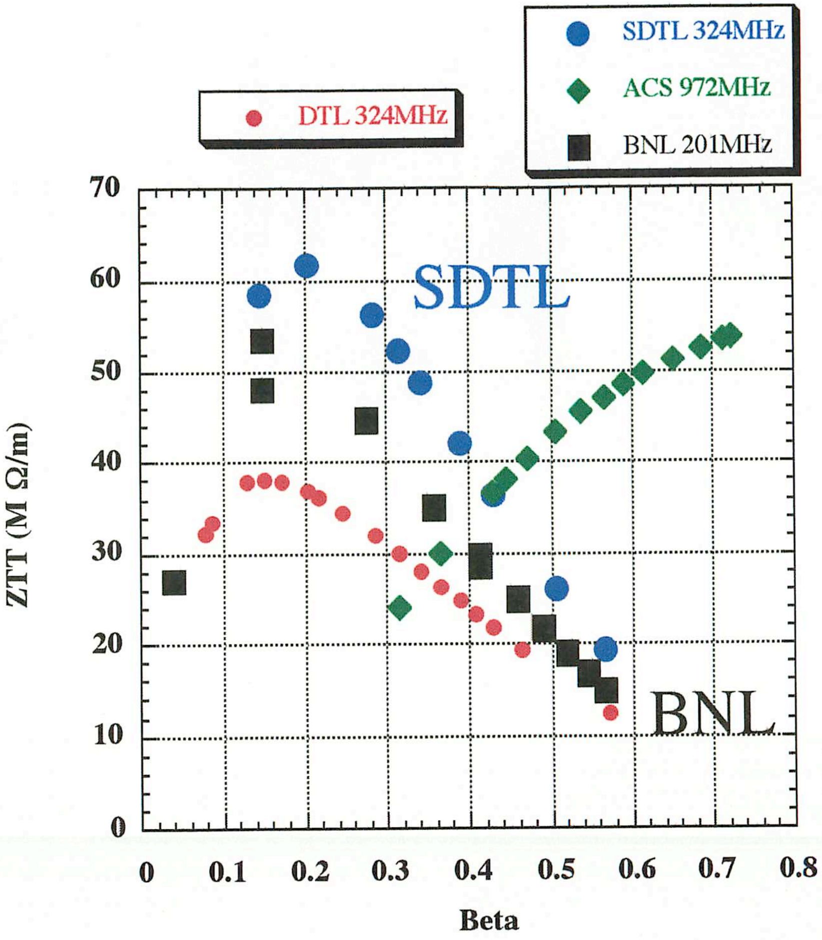


Fig. 4.29 Energy width of the output beam as a function of the debuncher voltage and the drift spaces between the exit of the linac and the debuncher. An injection phase deviation of 10 degrees into the SDTL is assumed.

JHF vs. BNL linac

	JHF	BNL	
Structure	DTL+SDTL	DTL	
Frequency	324	201	MHz
Length	93	138	m
Pc 17.5	15.1	MW	
Eacc	2.5 - 2.9	1.6 - 2.56	MV/m
No. tanks	3 + 31	9	
No. cells	150+155	286	

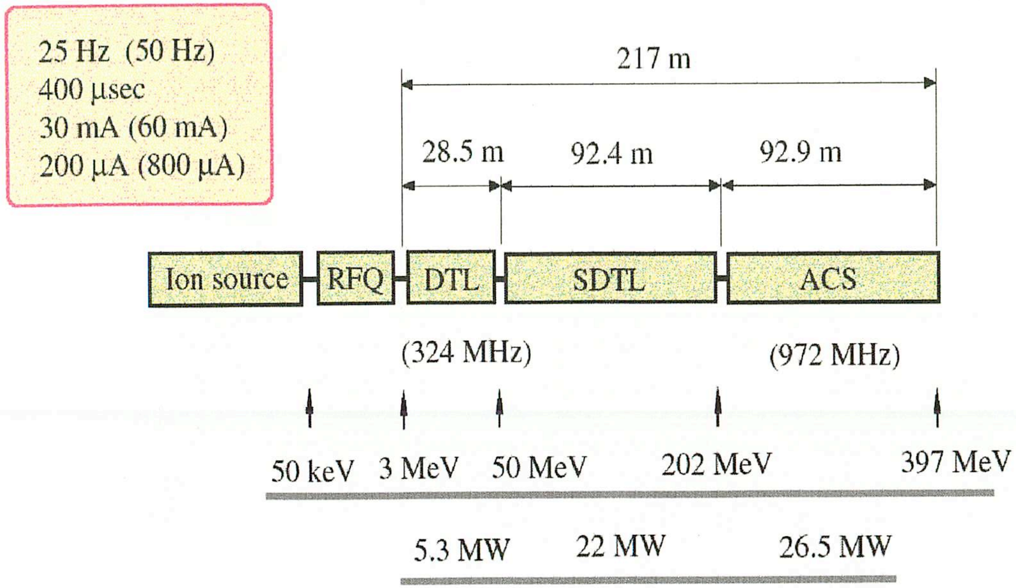


JHF length is 67% of BNL.
RF power is 1.16 times BNL.

Upgrade plan of the linac

- **Beam current 30 ---> 60 mA**
- **Energy 200 -------> 400 MeV**
- **CCL structure ----> ACS of 972 MHz**

JHF 400-MeV PROTON LINAC



25 Hz (50 Hz)
400 μsec
30 mA (60 mA)
200 μA (800 μA)

217 m

28.5 m 92.4 m 92.9 m

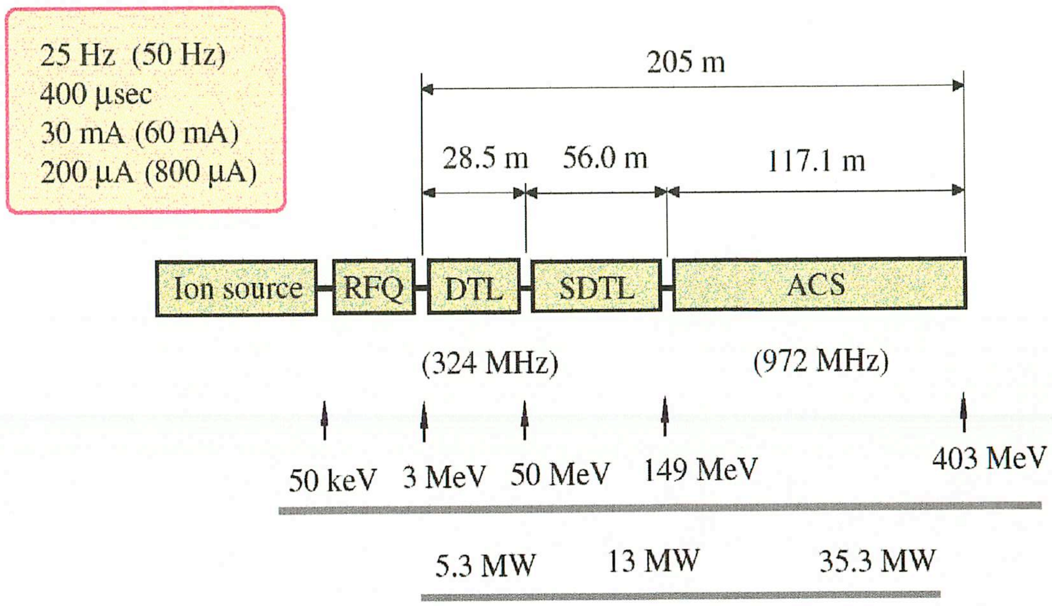
Ion source – RFQ – DTL – SDTL – ACS

(324 MHz) (972 MHz)

50 keV 3 MeV 50 MeV 202 MeV 397 MeV

5.3 MW 22 MW 26.5 MW

JHF 400-MeV PROTON LINAC



25 Hz (50 Hz)
400 μsec
30 mA (60 mA)
200 μA (800 μA)

205 m

28.5 m 56.0 m 117.1 m

Ion source – RFQ – DTL – SDTL – ACS

(324 MHz) (972 MHz)

50 keV 3 MeV 50 MeV 149 MeV 403 MeV

5.3 MW 13 MW 35.3 MW

Final decision of main parameters is put off in the future.
(frequency, transition energy, type of rf structure)

Summary (1)

- RFQ + DTL + SDTL scheme
  - High and single frequency
    - no longitudinal transition
  - SDTL structure
    - beam dynamics
    - high ZTT
    - mechanical
- Equipartitioning focusing method
- Klystron

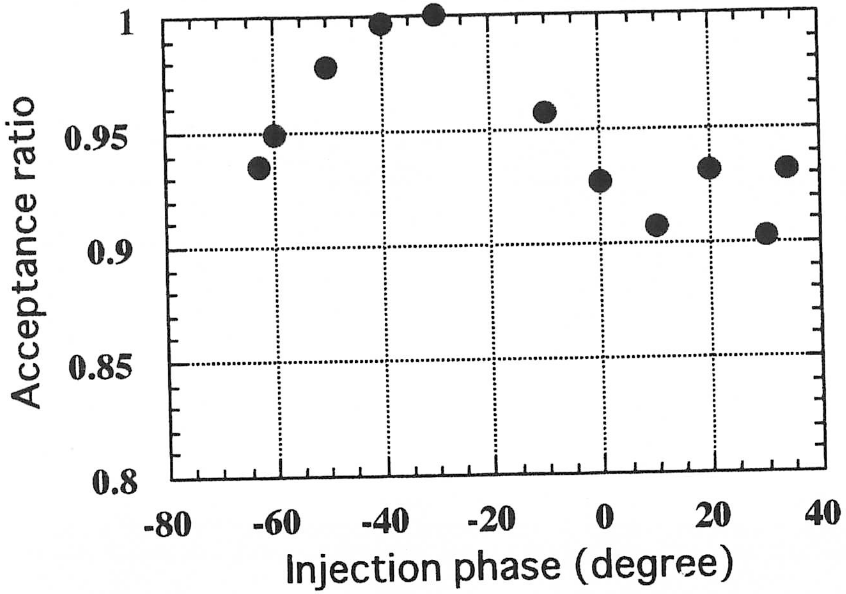
Summary (2)

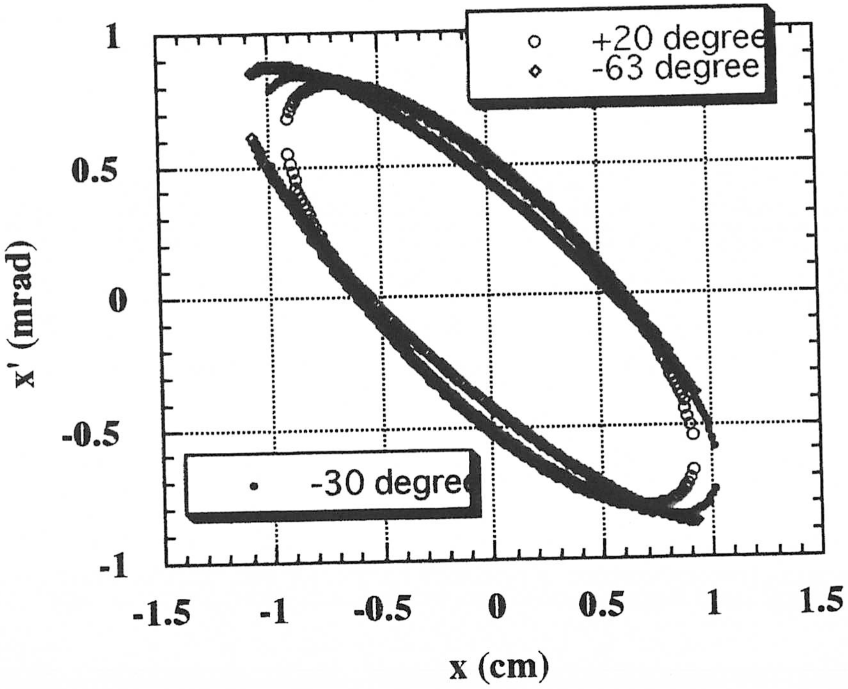
- Good beam quality
  - less emittance growth
  - equal emittance growth in both direction
  - less beam halos totally
- High accelerating efficiency
- Stable operation

Parameters of DTL

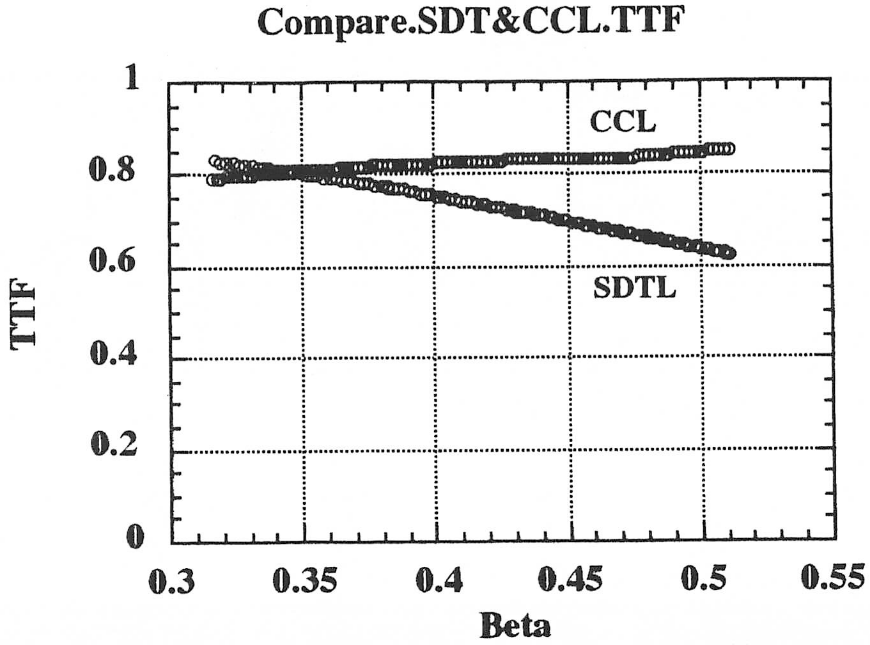
DTL Tank number	1	2	3	
Injection energy	3.0	19.196	35.407	MeV
Output energy	19.196	35.407	50.058	MeV
Tank length	10.36	8.87	7.81	m
Number of cells	80	41	29	
Rf driving power (*)	1.16	1.36	1.40	MW
Beam power (30mA)	0.49	0.49	0.44	MW
Beam power (60mA)	0.98	0.98	0.88	MW
Total power (30mA)	1.64	1.84	1.84	MW
Total power (60mA)	2.08	2.33	2.28	MW
Accelarating field	2.5	2.7	2.9	MV/m
Stable phase	-30	-26	-26	
Drift space	4	3	0	bl
	0.737	0.742		m

Acceptance vs CCL injection phase





TTF of SDTL and CCL



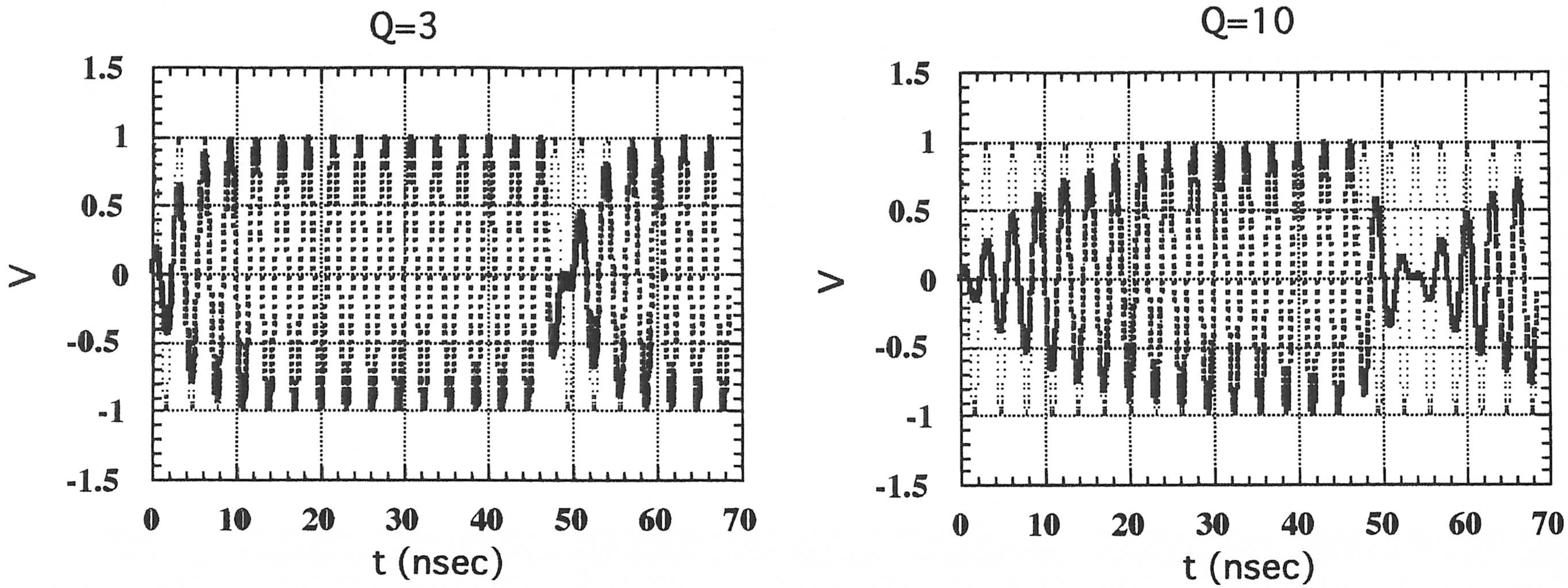
Phase damping is stronger in CCL, provided the other parameters are the same.

New option of JHF+JAERI accelerator

- JHF : 200/400-MeV linac + RCSynchrotron
- NSP : 1000-MeV SC-linac + SR

The joint study has just started, which is beyond today's my talk.

Chopper field examples



Phase change of 180 degrees is added at t~46.

Correction

Design Report
200-MeV Linac p. 4- 63 Table 4.17

DTL acceptance

	old		new	
Ax	43	---------->	12	πmm-mrad
Ay	41	---------->	12	

Bridge coupler for SDTL (1)

Bridge coupler is useful when the several tanks operating π/2 mode are connected.

In contrast, application for only two SDTL tanks with zero-mode operation has no merit.

Bridge coupler for SDTL (2)

1. Noticeable improvement in the accelerating-field errors due to beam loading can not be expected, since the expected field errors due to the beam loading is relatively small in the operation.
2. There are some coupling effects between two adjacent SDTL tanks via bridge couplers.
3. Many advantages associated with π/2-mode operation can not be found in each SDTL tank.
4. There is an additional power loss of an order of a several percents in the bridge couplers.
5. It loses a fine tuning method by using adjustable rf couplers for each tank.
6. It would be more complicated and expensive systems, including vacuum and cooling systems.

ACS parameters

Table 4.15 Parameters of the high-enegy part from 200 to 397 MeV with ACS structure.

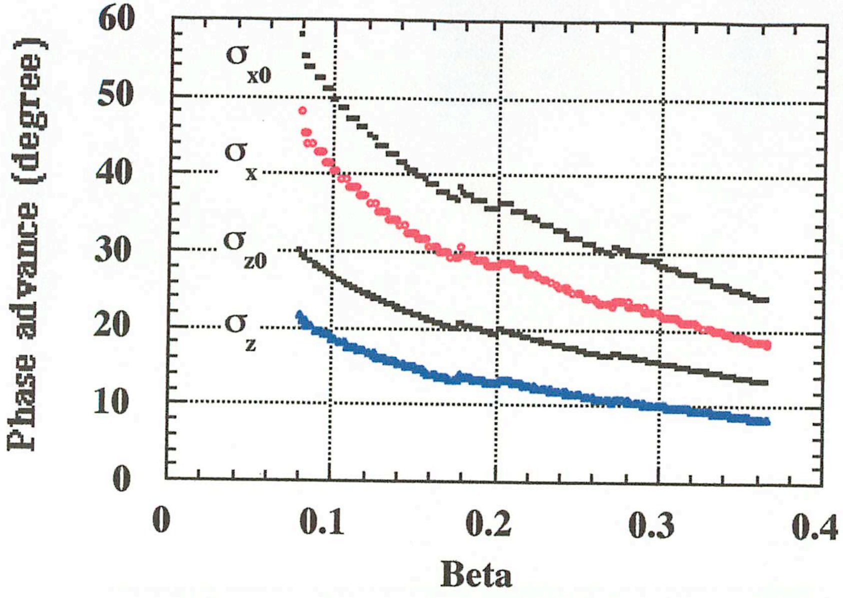
Frequency	972	MHz
Injection energy	200.0	MeV
Output energy	397.3	MeV
Number of tank	36	
number of cells	624	
Structure length	61.8	m
Total length	91.9	m
Rf driving power (*)	21.5	MW
Beam power (30mA)	5.9	MW
Beam power (60mA)	11.8	MW
Total power (30mA)	27.4	MW
Total power (60mA)	33.3	MW
Accelerating field	4.4 - 4.8	MV/m
Energy gain	3.0 - 3.3	MeV/m
Drift space (**)	0.77 - 0.98	m

(*) including a factor of 1.2.

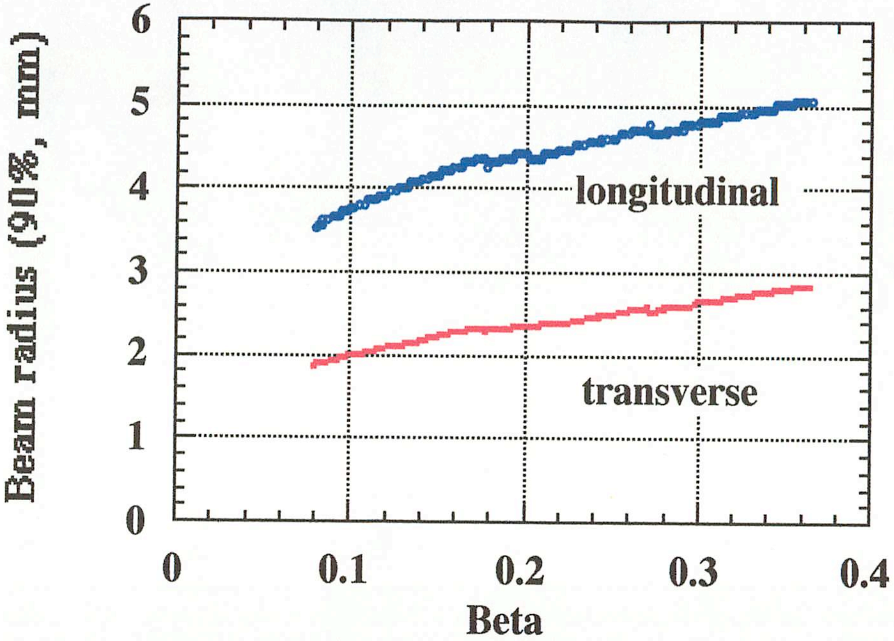
(**) shorter length is possible.

Focusing parameters

Both equipartitioning focusing and constant phase advance methods are assumed.



Phase advances in both the transverse and longitudinal phase spaces along the DTL. A peak current of 30 mA is assumed.



Variation of the beam size along the DTL in the equipartitioning focusing scheme.

SDTL vs. DTL at 50 MeV

	DTL	SDTL	
Tank diameter	56	52	cm
DT diameter	13	9	cm
Bore radius	1.3	1.5	cm
Outer corner radius	2.5	2.2	cm
Inner corner radius	1.0	0.5	cm
Z	78.2	75.9	MΩ/m
T	0.703	0.830	
ZTT	38.6	52.3	MΩ/m
Esurface peak	4.02	5.87	MV/m

Merits of SDTL

- Reduce SCE compared with CCL
- Avoid non-linear effects in CCL
- Higher ZTT than DTL and CCL
- Without stabilizing devices
- Mechanical and construction merits
  - Reduce tolerance in alighnment of DT and Tank
  - Reduce number of Q-magnet
  - Simple structure mechanically
  - Reduce heat loss in drift tube

Demerits of SDTL

- **Increase in the number of unit tanks**
- **Increase in drift spaces between unit tanks**
- **Increase in the number of tuning parameters ?**
- **Some degradation of beam quality compared with DTL acceleration**

Additional transverse emittance growth ~+10%
Additional longitudinal emittance growth ~+6%

Power ratio among SDTL tanks

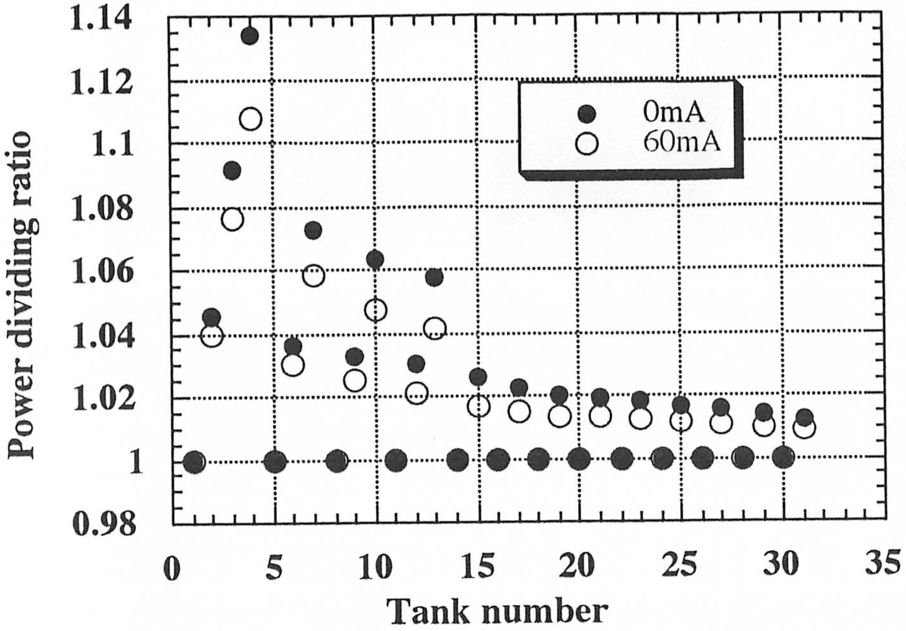


Fig. 4.31 Relative required power ratio among SDTL tanks driven by klystrons of the same amount of an rf output. In the system, there are one four-combined tanks, three three-combined tanks and nine two-combined tanks.

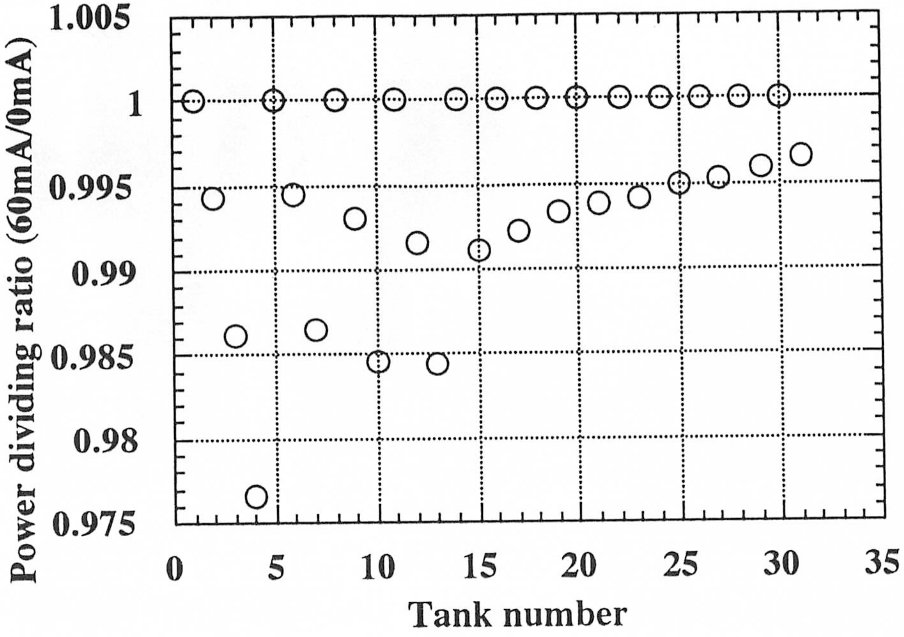
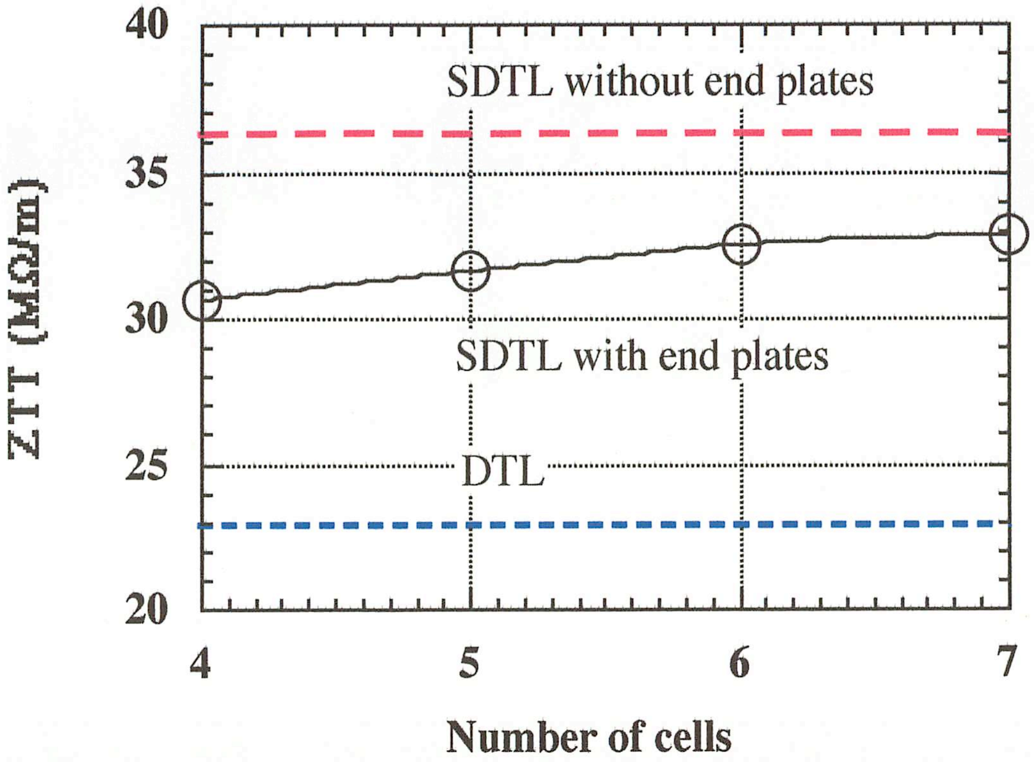


Fig. 4.32 Ratio between the power dividing ratio with zero current and that with 60 mA

End-plates effect of SDTL on ZTT



A decrease in the ZTT of the SDTL due to both end plates as a function of the number of unit cells in a unit tank.