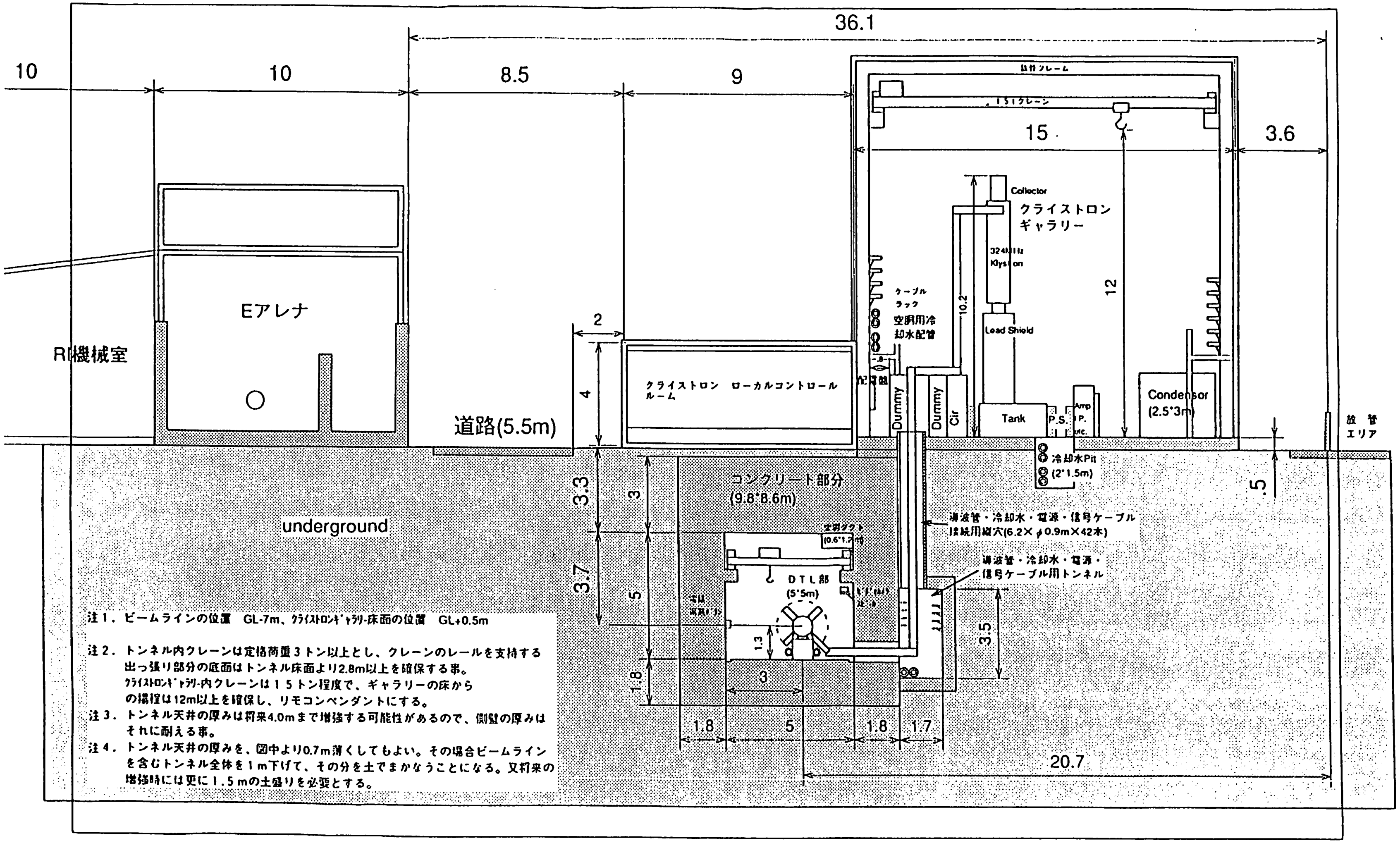
# The JHP 200-MeV Proton Linear Accelerator



注１．ビームラインの位置　GL-7m、ｸﾗｲｽﾄﾛﾝｷﾞｬﾗﾘ-床面の位置　GL+0.5m

注２．トンネル内クレーンは定格荷重３トン以上とし、クレーンのレールを支持する出っ張り部分の底面はトンネル床面より2.8m以上を確保する事。
ｸﾗｲｽﾄﾛﾝｷﾞｬﾗﾘ-内クレーンは１５トン程度で、ギャラリーの床からの揚程は12m以上を確保し、リモコンペンダントにする。

注３．トンネル天井の厚みは将来4.0mまで増強する可能性があるので、側壁の厚みはそれに耐える事。

注４．トンネル天井の厚みを、図中より0.7m薄くしてもよい。その場合ビームラインを含むトンネル全体を１m下げて、その分を土でまかなうことになる。又将来の増強時には更に１.５mの土盛りを必要とする。

※　トンネル断面は、400 MeV 換算で、350MeV以上の空胴部分を表示。

200MeV LINAC:空胴側トンネル+klystron Gallery 断面図案６
平成９年　２月１３日：吉野

# Requirements

Table 1 Required main parameters of the linac.

| | 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 | % |

# 特　徴

＊パルス運転

＊高い平均電流

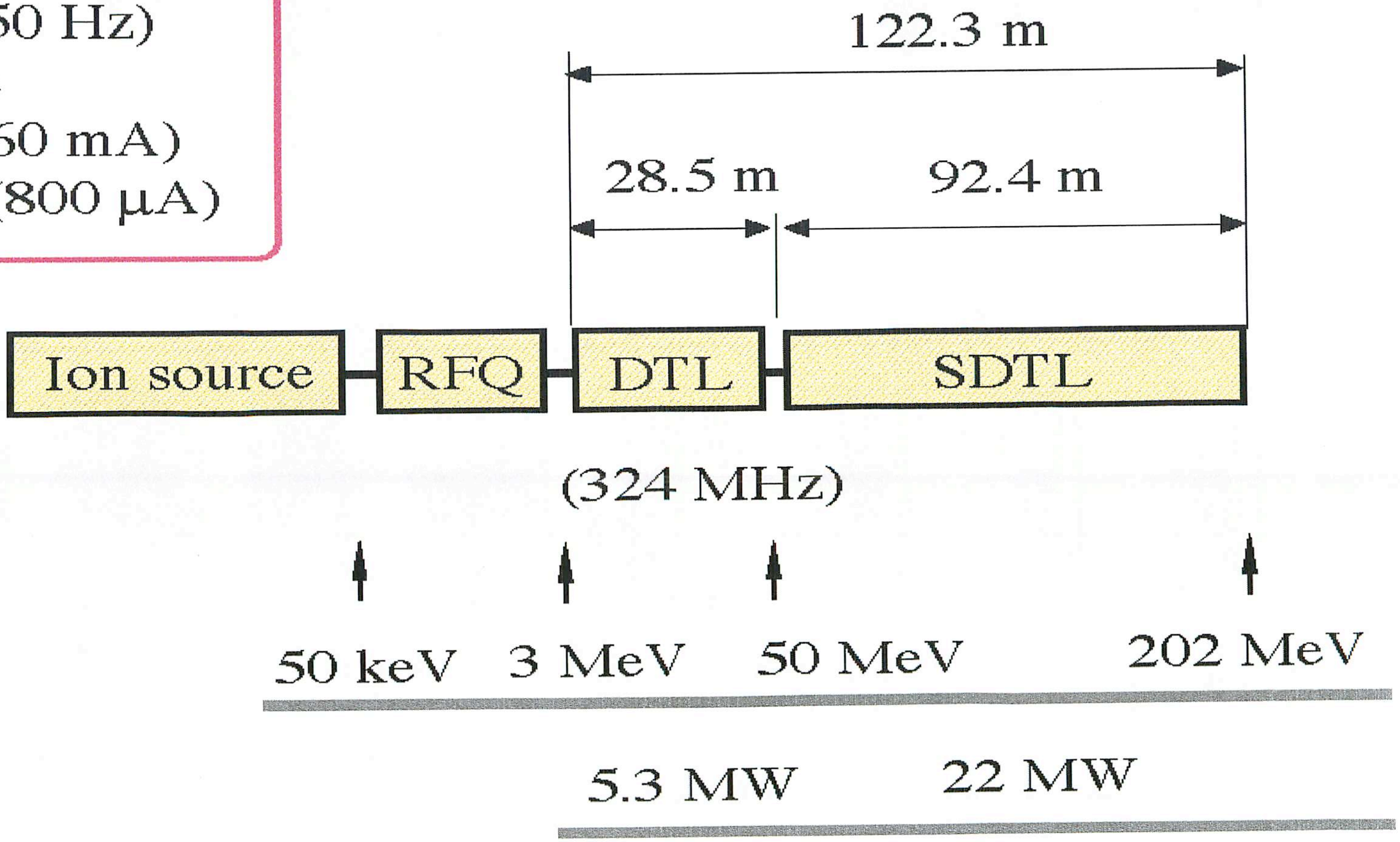
＊高い加速電場　２MeV/m

＊２段階方式の出力エネルギー

# Initial version

## JHP 200 MeV PROTON LINAC

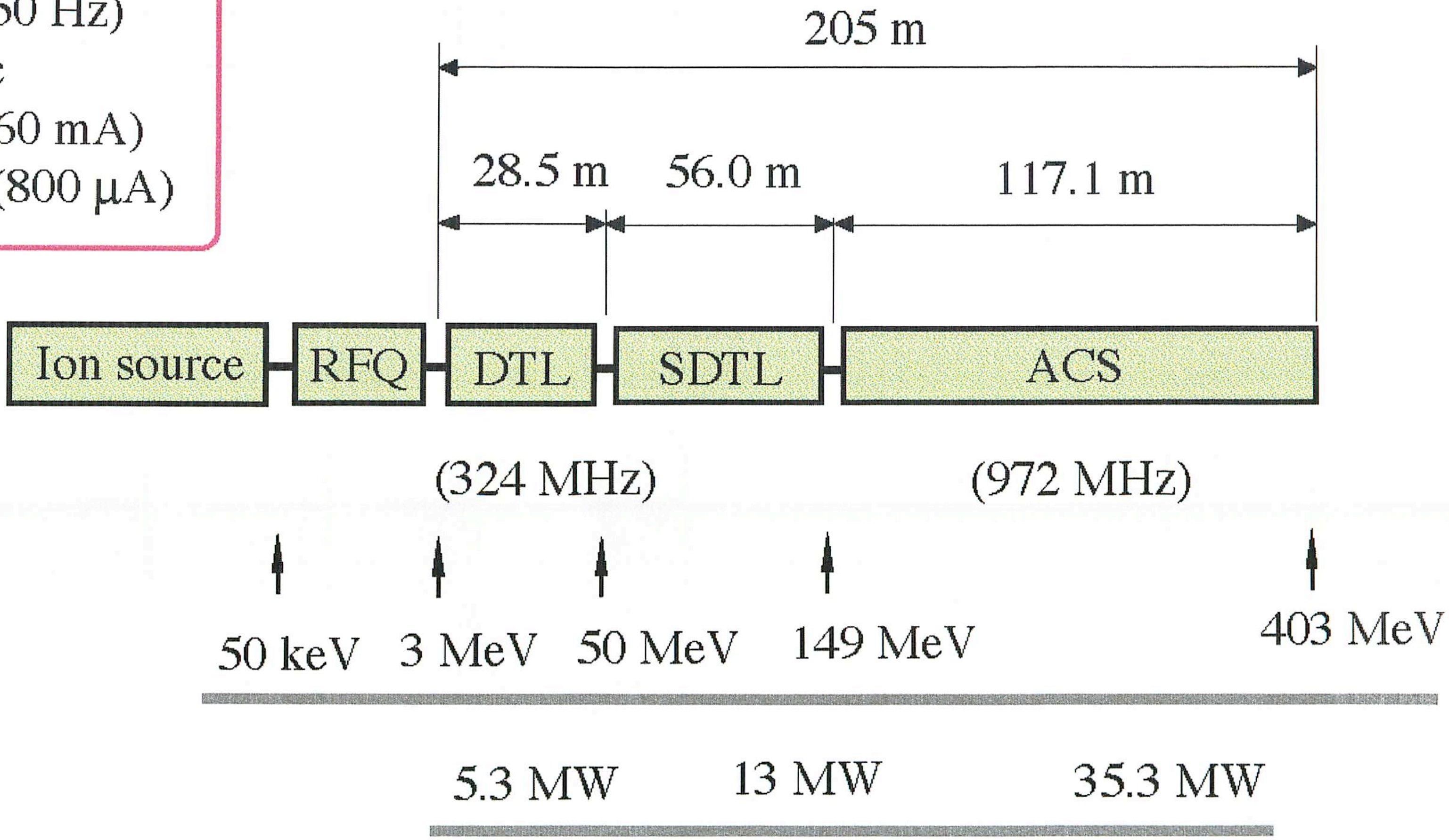
25 Hz (50 Hz)
400 μsec
30 mA (60 mA)
200 μA (800 μA)



# Upgrade version (1)

## JHP 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)

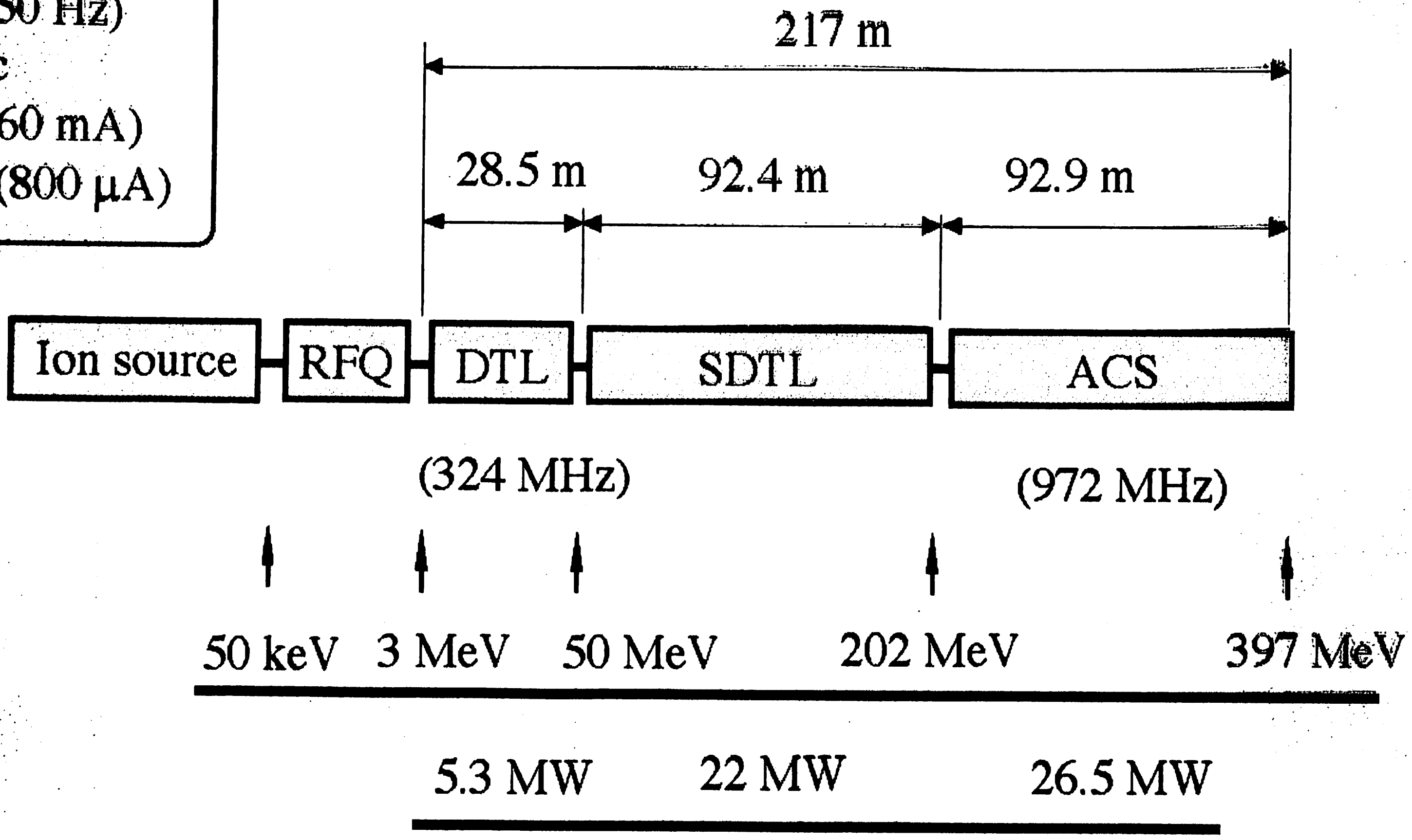
50 keV
3 MeV
50 MeV
149 MeV
403 MeV

5.3 MW
13 MW
35.3 MW

# Upgrade version (2)

## JHP 200/400 MeV PROTON LINAC (2)

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

# Frequency (1)

＊全体仕様

**High-β structure**　周波数比

**Low-β structure**　空間電荷効果

**Beam dynamics**

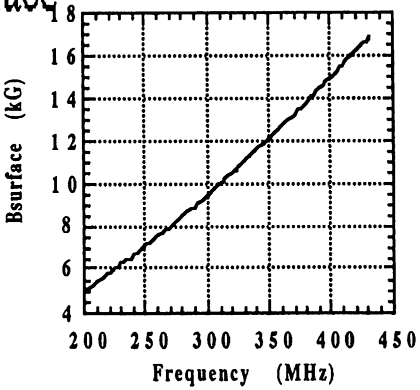
**Tuning and operation**

# Frequency (2) low-β

$$B' \propto \frac{f^2}{\beta}$$

表6-1 周波数に依存する入射点（3 MeV）の基本パラメーターの例。

| 周波数<br>MHz | セル長さ<br>mm | $\beta_{max}$<br>m | ビーム孔半径<br>mm | 磁石半径<br>mm | B'<br>T/m | Bsurface<br>kG |
|---|---|---|---|---|---|---|
| 201 | 119.0 | 0.395 | 9.37 | 11.37 | 43.4 | 4.94 |
| 300 | 79.7 | 0.264 | 7.67 | 9.67 | 96.7 | 9.35 |
| 324 | 73.8 | 0.245 | 7.38 | 9.38 | 112.7 | 10.6 |
| 350 | 68.3 | 0.227 | 7.10 | 9.10 | 131.6 | 12.0 |
| 432 | 55.4 | 0.184 | 6.39 | 8.39 | 200.4 | 16.8 |



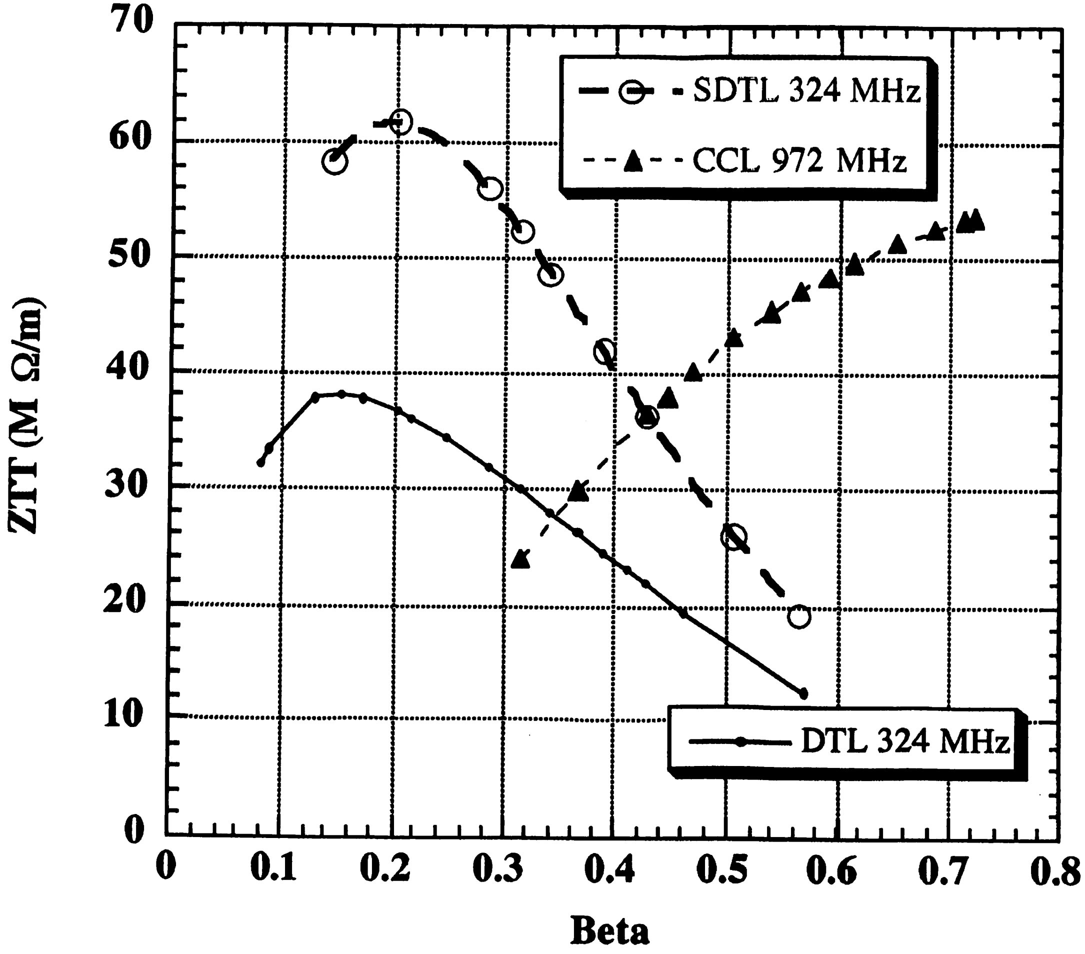
# Frequency (3) beam parameters

表 6 - 2 周波数による加速パラメーターの相違。

| Frequency | 201 | 300 | 324 | 350 | 432 | MHz |
|---|---|---|---|---|---|---|
| Emittance(90%) | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | πcm·mrad |
| 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 |
| $\sigma_x^0$ | 60 | 60 | 60 | 60 | 60 | degree |
| $\sigma_x$ | 42.4 | 50.0 | 51.1 | 52.2 | 54.4 | degree |
| $\sigma_x/\sigma_x^0$ | 0.71 | 0.83 | 0.85 | 0.87 | 0.91 | |
| $\mu_t$ | 0.50 | 0.31 | 0.27 | 0.24 | 0.18 | |
| EGF | 5.0 | 2.3 | 1.9 | 1.6 | 1.1 | % |

EGF: emittance growth factor

# ZTT optimization



# Main parameters

| | | |
|---|---|---|
| Injection energy | 3.0 | MeV |
| Output energy | 202.5 | MeV |
| Frequency | 324 | MHz |
| Particles | $H^-$ | |
| Peak current | 30 | mA |
| Beam width | 400 | µsec |
| Repetition rate | 25 | Hz |
| Average current | 200 | µA |
| Total length (structure only) | 92.9 | m |
| Total length (including drift space) | 122.3 | m |
| Total rf driving power | 21.3 | MW |
| Total rf power (30 mA) | 27.3 | MW |
| Total rf power (60 mA) | 33.3 | MW |
| Number of klystrons(*) | 19 | |

(*)includes for RFQ and debuncher

# DTL parameters(1)

| | | |
|---|---|---|
| Frequency | 324 | MHz |
| Injection energy | 3 | MeV |
| Output energy | 50.06 | MeV |
| Number of tank | 3 | |
| number of cells | 150 | |
| Total length | 28.51 | m |
| Rf driving power (*) | 3.92 | MW |
| Beam power (30mA) | 1.41 | MW |
| Beam power (60mA) | 2.82 | MW |
| Total power (30mA) | 5.33 | MW |
| Total power (60mA) | 6.74 | MW |
| Number of klystron | 3 | |
| Acceptance | | |
| $A_x$ (normalized 90%) | 43 | $\pi$ mm-mrad |
| $A_y$ (normalized 90%) | 41 | $\pi$ mm-mrad |
| $A_z$ (normalized 90%) | 9.3 | $\pi$ MeV-deg |
| Focusing method | Equipartitioned focusing | |
| Stabilization | Post-stabilized | |

# DTL parameters(2)

| 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 | $\beta\lambda$ |
| | 0.737 | 0.742 | | m |

* including a factor of 1.3

# 200 MeV デザインの特徴

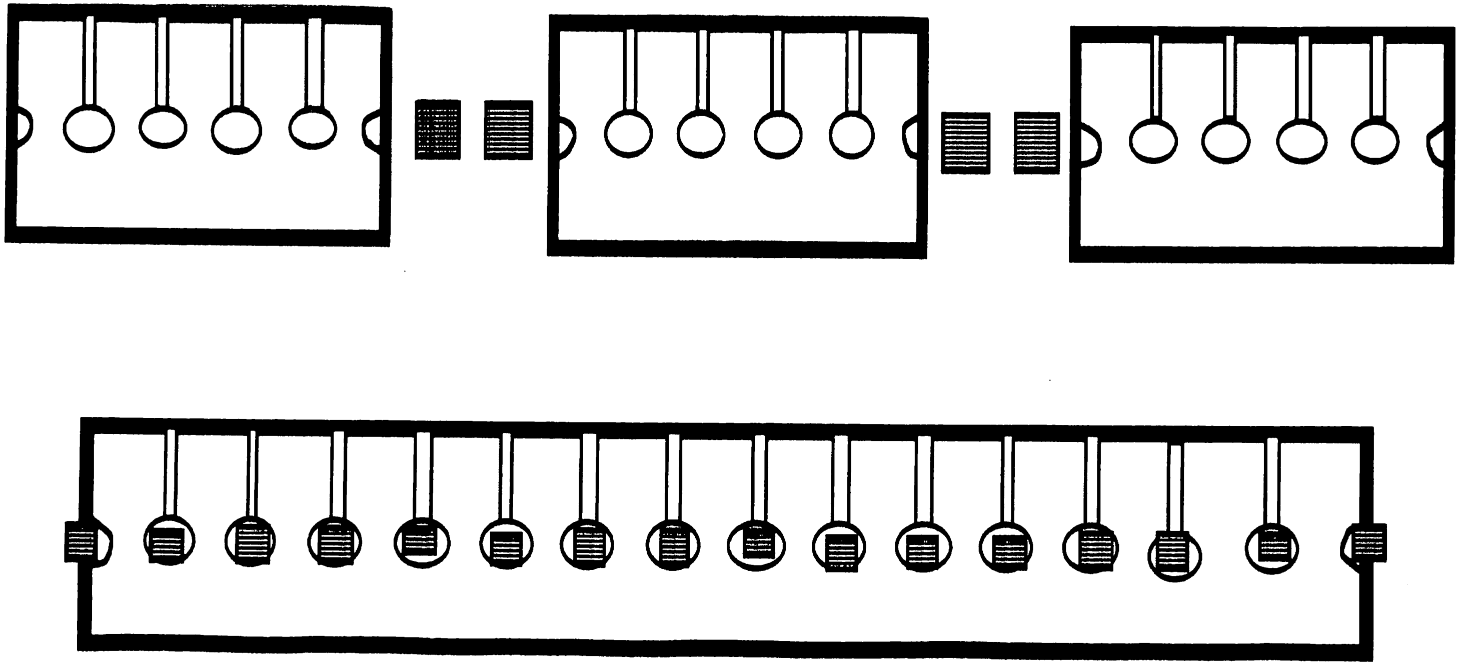
周波数のトランジションがない

separated-type DTL (SDTL)の採用

→ 縦と横のトランジションの分離

クライストロンの使用

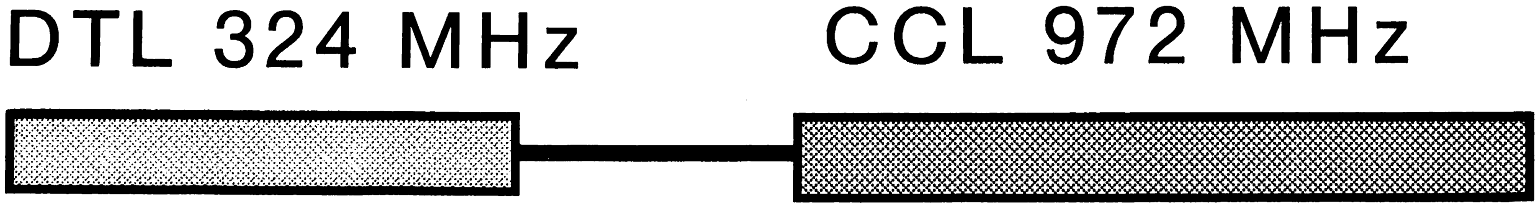
# SDTL structure



# Transition?

＊縦叉は横の収束が大きく変化する所

全体の効率化のため



＊周波数３倍変わる

＊同時に横の収束周期も変わる

# Merits of SDTL

1）横トランジションは、空間電荷効果を緩和
2）縦トランジションは、CCL加速の非線形効果の減少
3）ZTTの最適化が自由に行え、高いZTT
4）DTの発熱除去が容易
5）DTの整列精度及びタンク相互の整列精度が緩和
6）空洞の安定化の必要が軽減
7）四極収束磁石の数の減少
8）機械的な構造が簡単化

# Demerits of SDTL

1）タンクの数が増える。
2）高周波系が複雑になる。
3）余分なドリフトスペースが増える。
4）非常に大きいアクセプタンスは実現しにくい。
5）チューニングのパラメーターが増える。

# SDTL parameters

**SDTL**

| | | |
|---|---|---|
| Frequency | 324 | MHz |
| Injection energy | 50.058 | MeV |
| Output energy | 202.488 | MeV |
| Number of tank | 31 | |
| number of cells | 155 | |
| Structure length | 65.9 | m |
| Total length | 92.4 | m |
| Rf driving power (*) | 17.4 | MW |
| Beam power (30mA) | 4.6 | MW |

| | | |
|---|---|---|
| Beam power (60mA) | 9.2 | MW |
| Total power (30mA) | 22.0 | MW |
| Total power (60mA) | 26.6 | MW |
| Number of klystron | 14 | |
| Accelerating field | 3.86 | MV/m |
| Energy gain | 2.86 - 1.92 | MeV/m |
| Drift space (**) | 0.67-1.03 | m |
| Acceptance | | |
| $A_x$ (normalized 90%) | $21.3\pi$ | mm-mrad |
| $A_y$ (normalized 90%) | $18.6\pi$ | mm-mrad |
| $A_z$ (normalized 90%) | $40.4\pi$ | MeV-deg |

(*) including a factor of 1.2.

(**) shorter length is possible.

# DTL vs. SDTL (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 |

# Transition from DTL to SDTL

- ＊出力ビームの性質
- ＊加速効率
- ＊タンクの長さ
- ＊without buncher

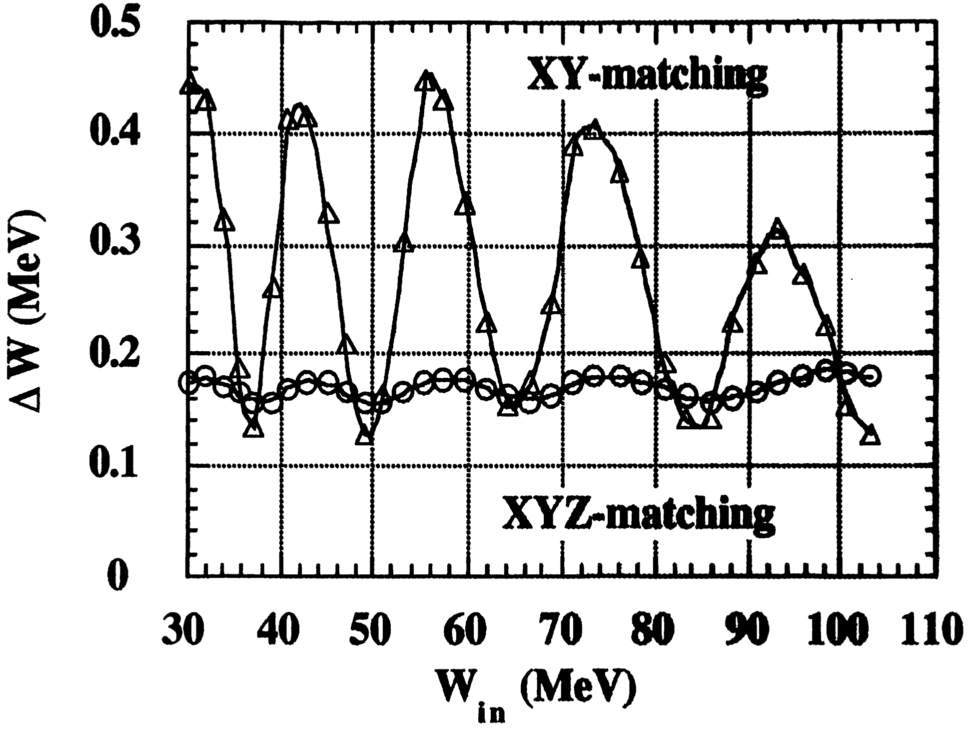
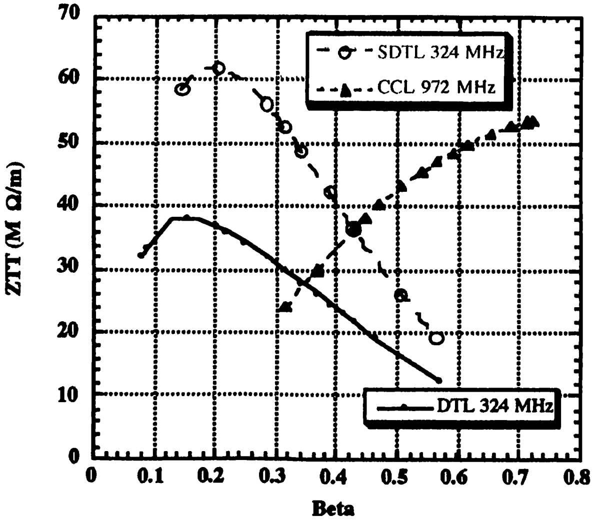


Fig. 4 Energy-width of the SDTL output beam as a function of the injection energy.



# Envelope eq. and equipartitioning

$$k_{x0}^2 a - \frac{3}{2}\frac{Nr_c}{\beta_0^2\gamma_0^3}\frac{1}{az_m}\left(1-\frac{g_0}{2}\frac{a^2}{\gamma_0^2 z_m^2}\right)-\frac{\varepsilon_{nx}^2}{\beta_0^2\gamma_0^2 a^3}=0$$

$$k_{z0}^2 z_m - \frac{3}{2}\frac{Nr_c}{\beta_0^2\gamma_0^5}\frac{g_0}{z_m^2}-\frac{\varepsilon_{nz}^2}{\beta_0^2\gamma_0^6 z_m^3}=0$$

**equipartitioning** $\gamma_0\dfrac{\varepsilon_{nx}}{\varepsilon_{nz}}\dfrac{k_x}{k_z}=1$

# Focusing in acceleration

横の収束 $\sigma_0$=const

$$k_{x0} = \frac{\sigma_{x0}}{2\beta_0\lambda}$$

$$k_{x0} \propto \frac{1}{\beta_0}$$

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

**equipartitioning focusing**

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

$$\sigma_{x0} \propto \frac{1}{\left(\beta_0\gamma_0^3\right)^{1/2}}$$

$$\frac{k_{x0}}{k_{z0}} = \left(\frac{3}{2}\frac{\varepsilon_{nz}}{\varepsilon_{nx}} - \frac{1}{2}\right)^{1/2}$$

# Focusing parameters

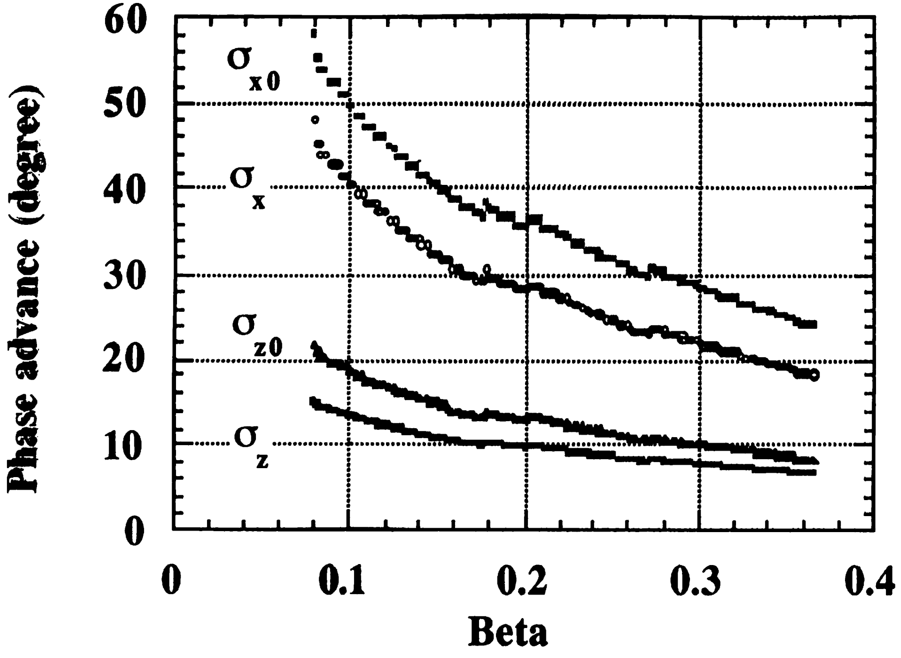


Fig. 5 Phase advances in both the transverse and longitudinal phase spaces along the DTL. A peak current of 30 mA is assumed.

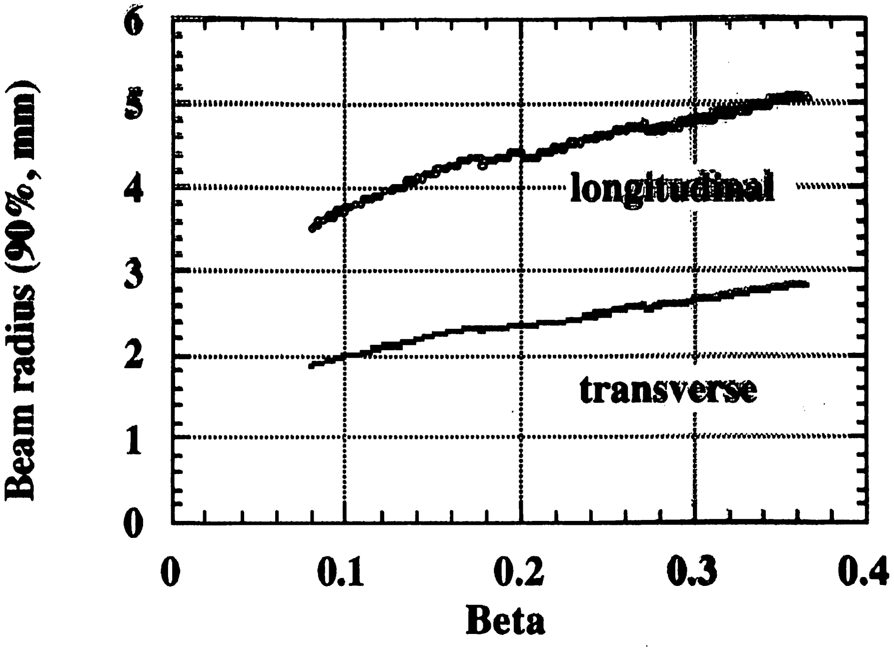
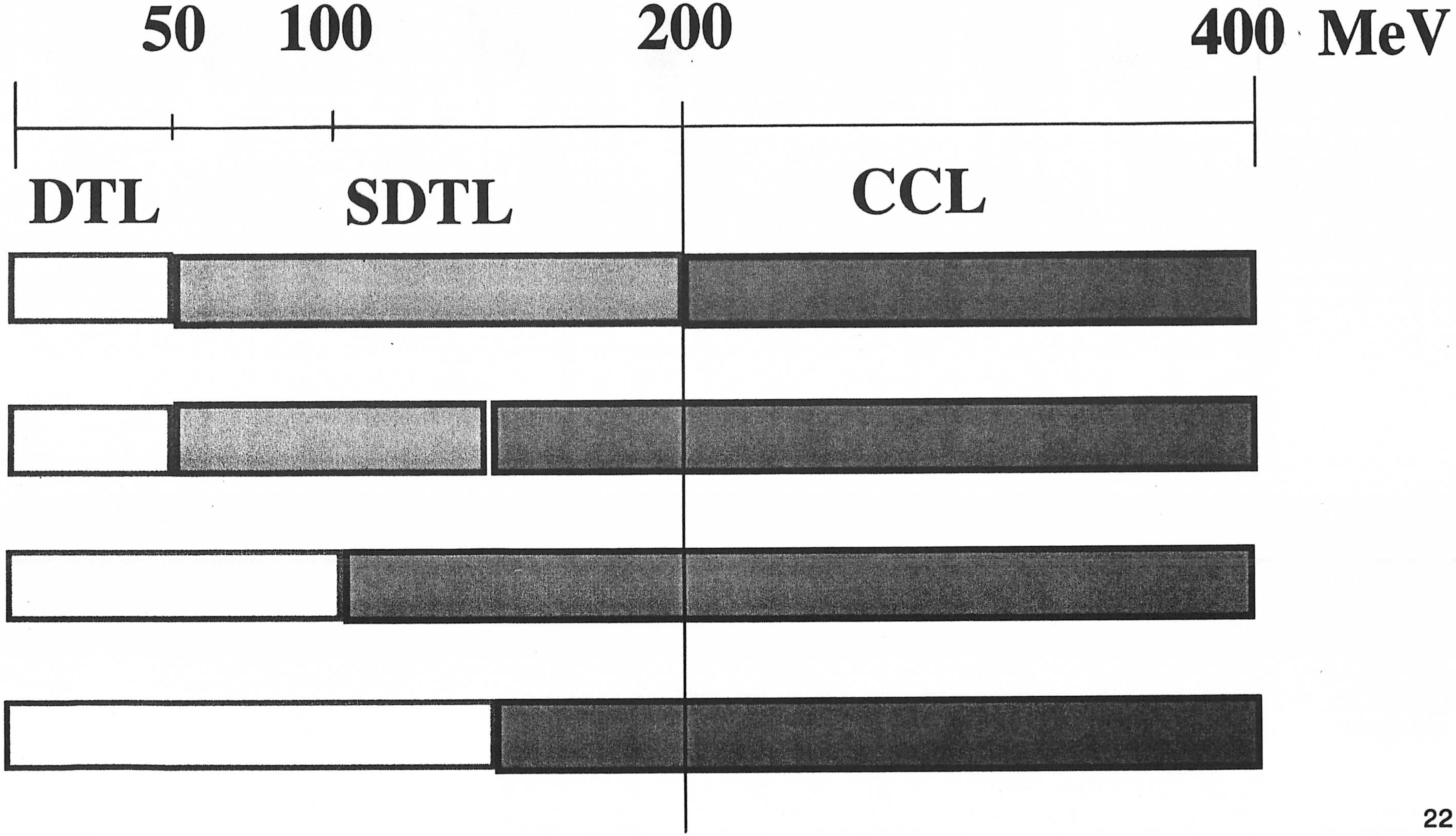


Fig. 7 Variation of the beam size along the DTL.

# Beam simulation



# Beam simulation (200 MeV)

Table 5 Final rms emittances forfour configurations at the exit of the linac (200 MeV).

| CCL configuration | x | y | z |
|---|---|---|---|
| | π mm-mrad | | π MeV-deg |
| 147 MeV - 972 MHz | 0.509 | 0.523 | 0.48 |
| 147 MeV - 1296 MHz | 0.570 | 0.535 | 0.51 |
| 100 MeV - 972 MHz | 0.602 | 0.843 | 0.43 |
| 100 MeV - 1296 MHz | 0.708 | 1.06 | 0.48 |
| DTL 51 MeV +SDTL | 0.433 | 0.443 | 0.364 |
| Injection beam at 3 MeV | 0.373 | 0.379 | 0.268 |

* z-z' emitannces are normalized to those at 324 MHz forcomparison.

# Beam simulation (400 MeV)

Table 6 Final rms emittances forfour configurations at the exit of the linac (400 MeV).

| CCL configuration | x | y | z | |
|---|---|---|---|---|
| | mm-mrad | | π MeV-deg | |
| 147 MeV - 972 MHz | 0.539 | 0.534 | 0.468 | no bean loss |
| 147 MeV - 1296 MHz | 0.572 | 0.628 | 0.641 | 0.18% beam loss |
| 100 MeV - 972 MHz | 0.675 | 0.585 | 0.600 | no beam loss |
| 100 MeV - 1296 MHz | 0.733 | 1.05 | 0.545 | 0.12% beam loss |

* z-z'emitannces are normalized to those at 324 MHz forcomparison.

# Transmission

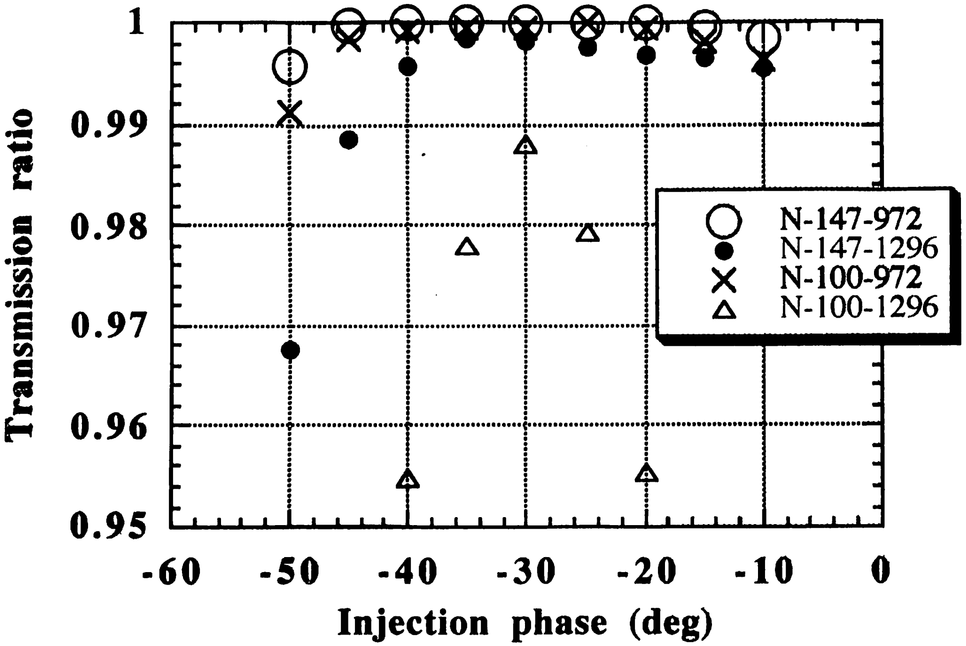


Fig.8 Transmission ratio through the CCL as a function of an injection phas for four configurations of the linac. N field errors are assumed. The number of particles is 10000. The notation ‘N-147-972’ means an injection energy o 147 MeV and a frequency of 972 MHz.

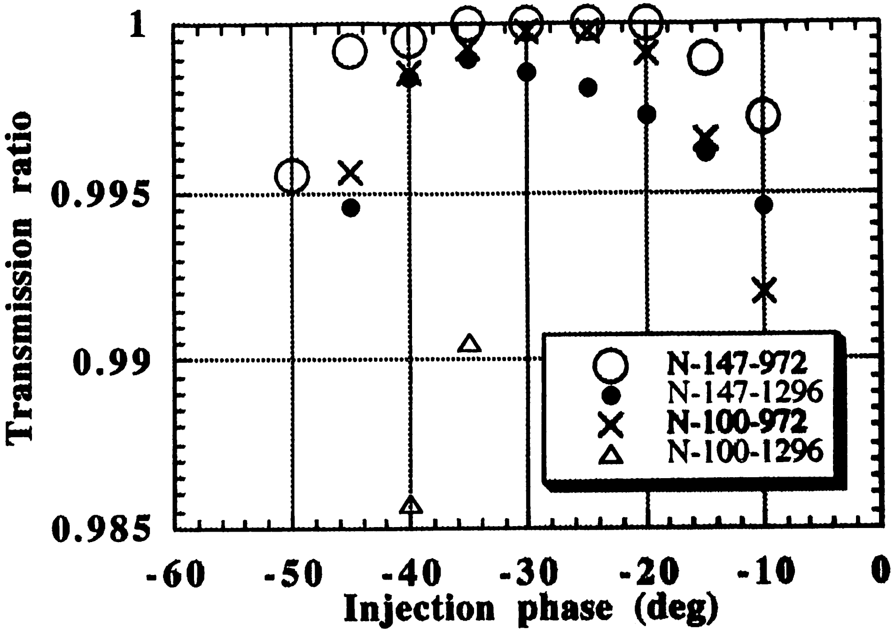


Fig. 9 Transmission ratio through the CCL as a function of the injection phas for four configurations of the linac. R amplitude errors of 1% for each cell and 3% for each tank are assumed. Rf phase errors of zero for each cell and 4% for each tank are assumed. The number of particles is 10000.

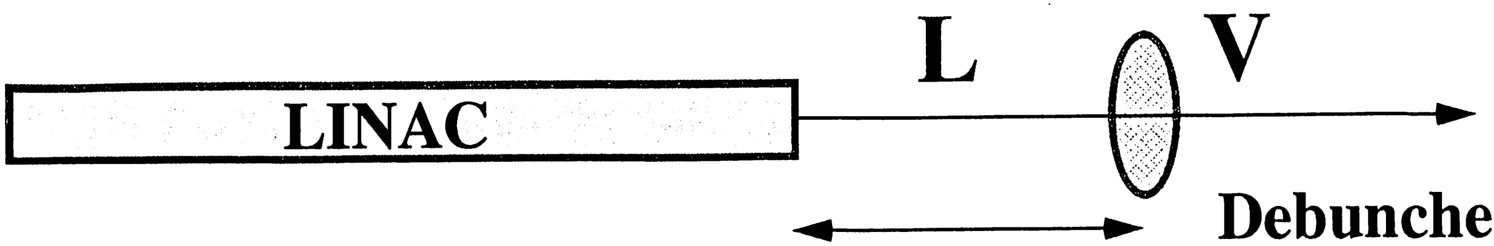
# Injection beam

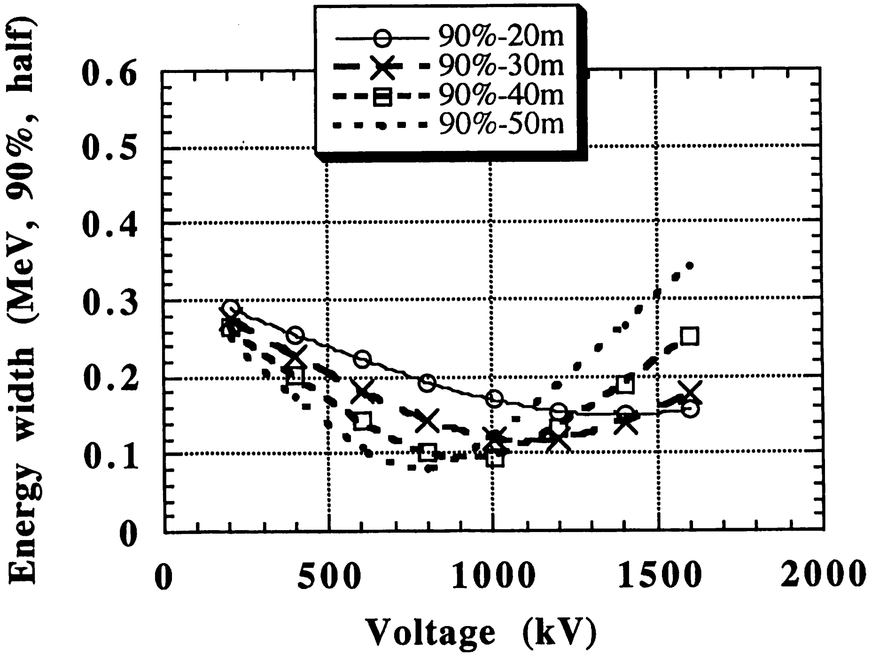
**Table 7 Beam parameters used forthe simulations.**

Results of the preliminary simulation of 3-MeV324 MHz RFQ.

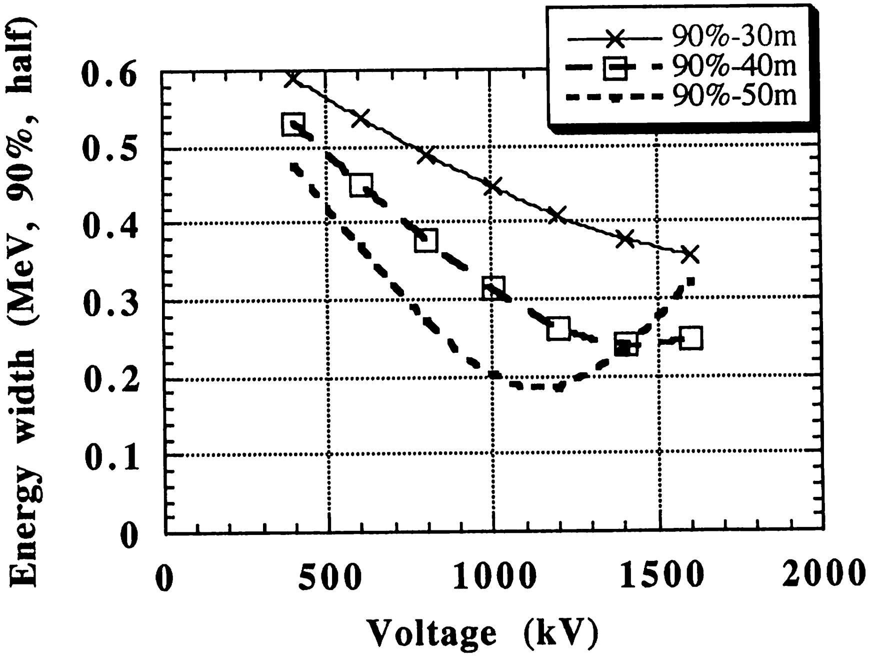
| | x | | | y | | |
|---|---|---|---|---|---|---|
| Normalized emittances | rms | 90% | 100% | rms | 90% | 100% |
| | π mm-mrad | | | π mm-mrad | | |
| Injection into RFQ | 0.193 | 0.822 | 1.49 | 0.196 | 0.831 | 1.47 |
| Output from RFQ | 0.282 | 1.29 | 3.04 | 0.270 | 1.23 | 3.34 |
| Δφ (full width) | 48.4 degrees | | | | | |
| Δw(full width) | 116 keV | | | | | |
| Injection beam into the DTL (10000 particles for LINSAC simulation) | | | | | | |
| DTL injection beam | 0.373 | 1.59 | 2.88 | 0.379 | 1.61 | 2.85 |
| Δφ (full width) | 50.5 degrees | | | | | |
| Δw(full width) | 155 keV | | | | | |

# Debuncher operation





## No injection error



## $\Delta\phi$ shift

# RF klystron

by Anami

| | | |
|---|---|---|
| 構造 | 5空洞、垂直設置、収束コイル内蔵 | |
| Frequency | MHz | 324 |
| ピーク出力 | MW | 2.5 |
| 平均出力 | kW | 81 |
| ぱルス幅 | μsec | 650 |
| 繰り返し | Hz | 50 |
| duty | % | 3.25 |
| カソード電圧 | kV | ‹110 |
| カソード電流 | A | ‹45 |
| Mアノード電圧 | kV | ‹95 |
| 効率 | % | ›50 |
| 利得 | dB | ›43 |
| 数 | 本 | 19 - 20 |