Proton Linac

Linac design

Status of construction (DTL & SDTL)

Issues

2001.2.20

KEK T. Kato

Requirements

Current	
– Average	675 μA
– Peak	50 mA
Pulse	
– Pulse width	500 μsec
– Repetition	50 Hz
– Chopping ratio	54 %
– RF duty	~3% (10 ~ 15% ?)
Beam	
– Energy	400, 600 MeV
– Momentum width	$\Delta p/p = \pm 0.1\%$ (100%)
– Emittance	3 ~ 5 π mm-mrad (99%)

Targets

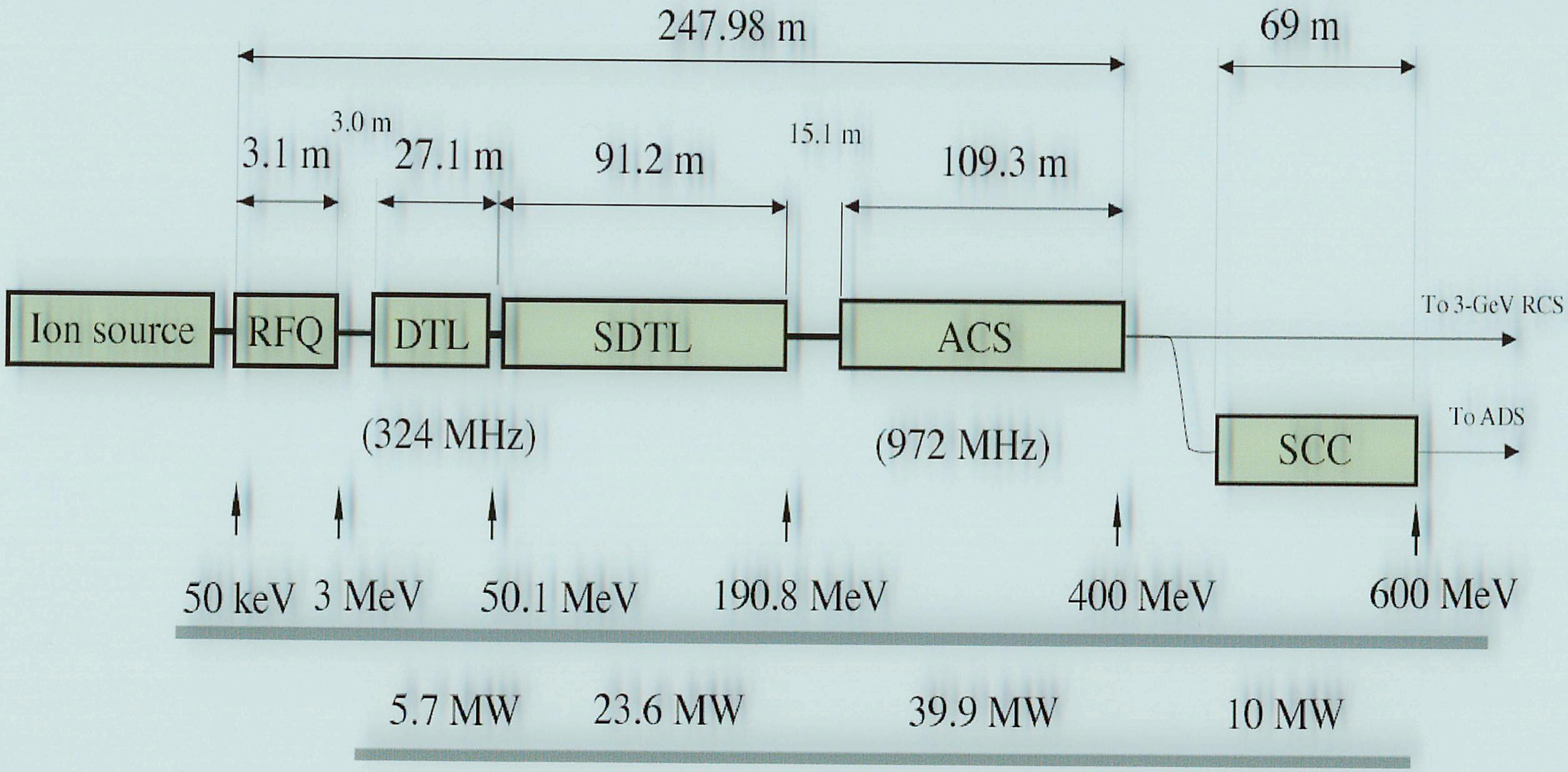
- Satisfy the requirements
  - emittances

$$\frac{\Delta p}{p} = \pm 0.1\%$$

- Stable operation as an injector
  - small fluctuation of the output beam
  - minimize machine troubles during operation

- Low beam losses ~ less than 10^{-3}

600-MeV linac



RFQ, DTL, SDTL,ACS and SCC parameters

	RFQ	DTL	SDTL	ACS	SCC	
Output energy	3	50	191	400	600	MeV
Frequency	324	324	324	972	972	MHz
Total length	3.1	27.1	91.2	109.3	69	m
Structure length	3.1	26.7	65.7	63.2	24.4	m
Number of tank	1	3	32	42	30	
Number of cell		146	160		210	
Accelerating field		2.5~2.9	2.5~3.7	4.4~4.8	12~13.5	MV/m
Stable phase	-30	-30	-27	-30~ -44		deg
Vane voltage	82.9(1.8KL)					kV
Drive power	0.336	3.3	16.6	29.4		MW
Beam power	0.148	2.4	7.0	10.4	10	MW
Total power	0.484	5.7	23.6	39.9		MW

Ipeak=50mA, beam pulse length 500 μsec
Repetition frequency 25/50 Hz
KL=Kilpatrick limit

Design features

- Suppress **space-charge effects** by selecting higher operating frequency, and three times the fundamental one for high-β structure
  - Reduce emittance growth
  - Decrease beam losses
- Balance transverse and longitudinal motion by using **equipartitioning focusing scheme**
- Select relatively higher energies for **structure transitions** from the viewpoint of longitudinal motion; 3 MeV, 50 MeV, 190 MeV

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	$\mu = 1-\left(\frac{\sigma_0}{\sigma}\right)^2$
μ_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 due to the field energy of the bunch of Gaussian distribution.

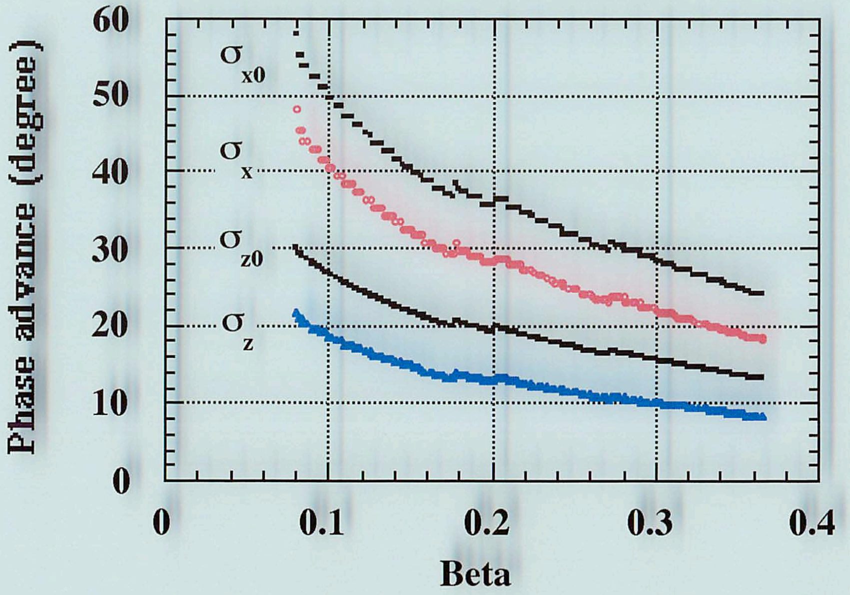
Equipartitioning focusing scheme

Equipartitioning focusing

$$\frac{k_{x0}}{k_{z0}} \propto \text{const}$$

Constant phase advance

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



$$\gamma_0 \frac{\varepsilon_{nx}}{\varepsilon_{nz}} \frac{z_m}{a} = 1$$

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

$$T_\perp = T_\parallel$$

実機にて最適加速を与える横収束法を求める

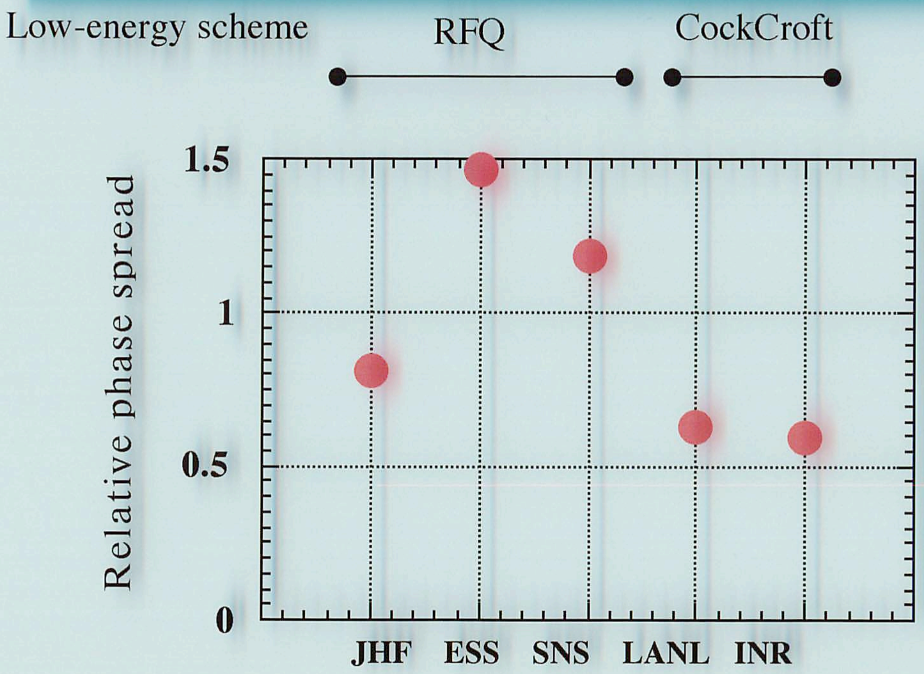
Selection of CCL frequency

	Frequency multiple		injection
LANL	x 4	at 100 MeV	CockCroft
INR	x 5	at 200 MeV	CockCroft
JHF/JAERI	x 3	at 150/200 Mev	RFQ 3MeV
ESS	x 2	at 70 MeV (RFQ---> DTL x 2)	
–			RFQ 5 MeV
SNS	x 2	at 20 MeV	RFQ 2.5 MeV

- **phase damping**

$$\frac{\Delta\phi_2}{\Delta\phi_1} = \left[\frac{\beta_1^3\gamma_1^3 E_1 T_1 \sin\phi_1}{\beta_2^3\gamma_2^3 E_2 T_2 \sin\phi_2}\right]^{1/4}$$

Relative bunch width at CCL injection point



$$\frac{\Delta\phi_2}{\Delta\phi_1} = \left[\frac{\beta_1^3\gamma_1^3 E_1 T_1 \sin\phi_1}{\beta_2^3\gamma_2^3 E_2 T_2 \sin\phi_2}\right]^{1/4}$$

Spread at the RFQ exit is included according to phase damping formula

JHF: 3-MeVRFQ
ESS: 5-MeVRFQ
SNS: 2.5 MeVRFQ

ESS: 175-MHZ RFQ + 350-MHz DTL
SNS: 403-MHz RFQ
JHF: 150-MeV SDTL

DTL - ACS simulation

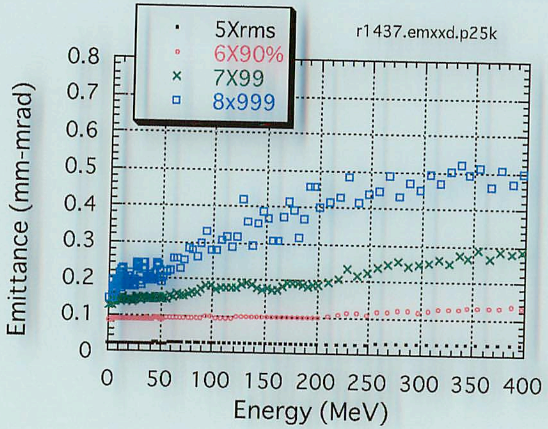
- Two types of beams: Type-C & RFQ-beam
- Beam parameters for the matched beam

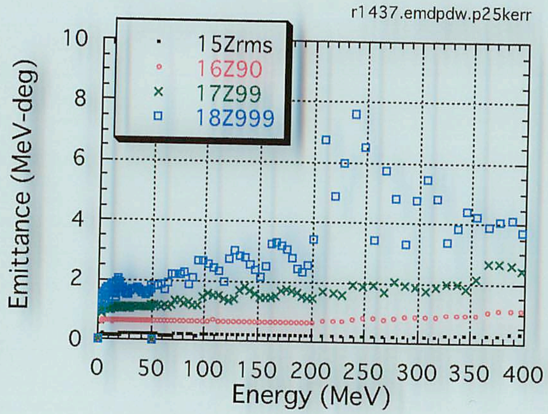
	ε_{xrms} mm-mrad	ε_{zrms} MeV-deg	σ_x/σ_{x0} deg	σ_z/σ_{z0} deg	k_x/k_{x0}	μ_x	k_z/k_{z0}	μ_z
C-30mA	0.2	0.14	42/58	19/31	0.72	0.48	0.61	0.62
C-50mA	0.2	0.15	36/58	15/31	0.62	0.61	0.49	0.76
rfq-30mA	0.16	0.08	38/58	14/31	0.66	0.57	0.44	0.80
rfq-50mA	0.16	0.08	32/58	10/31	0.55	0.70	0.32	0.89

Errors in accelerating parameters

- Error - 1 ---> No beam loss
  - ±1% cell and tank fields
  - ±1% cell phase and ±3% tank phase
  - Q-magnet displacement ±0.05 mm
- Error - 2 ---> ~0.1% beam loss
  - ±2% cell and tank fields
  - ±2% cell and ±6% tank phase
  - Q-magnet displacement ±0.1 mm

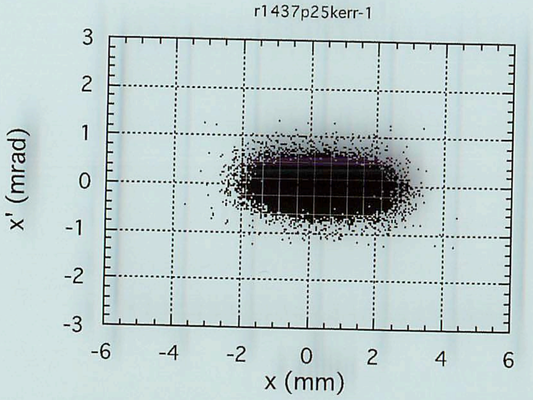
Simulation results: Type C, 50 mA

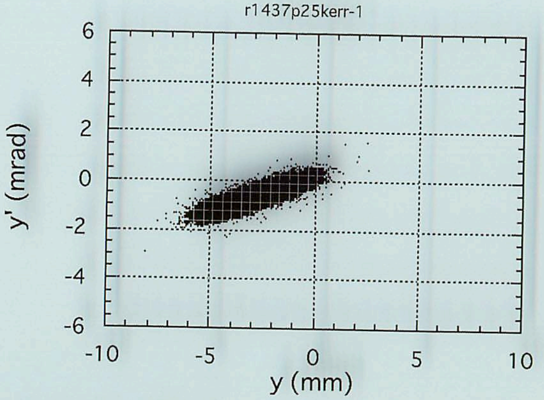


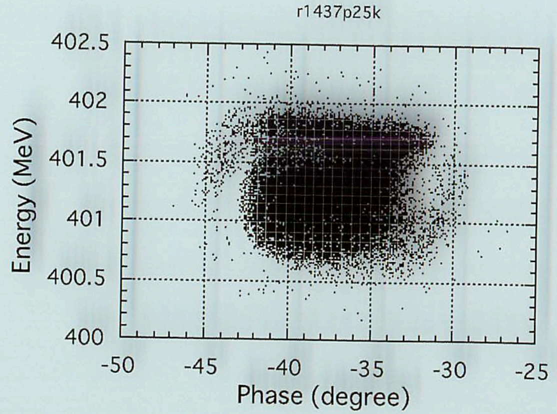


	C-noerr	C-err-1	C-err-2
rms	0.0259	0.0299	0.0628
90%	0.112	0.132	0.283
99%	0.281	0.281	0.826
99.9%	0.574	0.497	2.06

cm-mrad



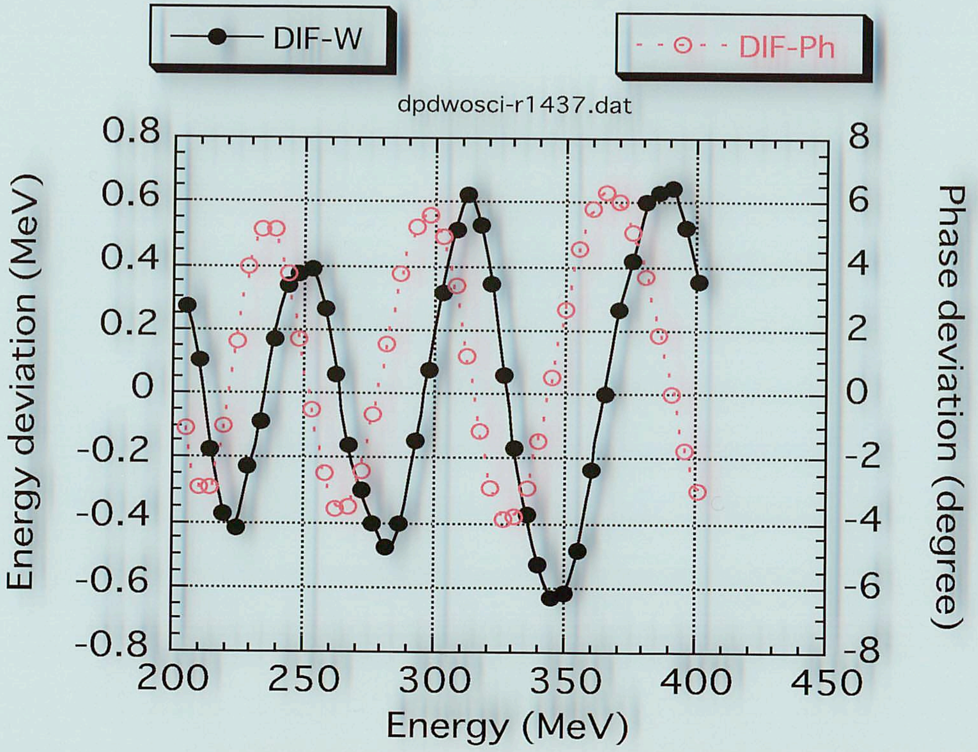




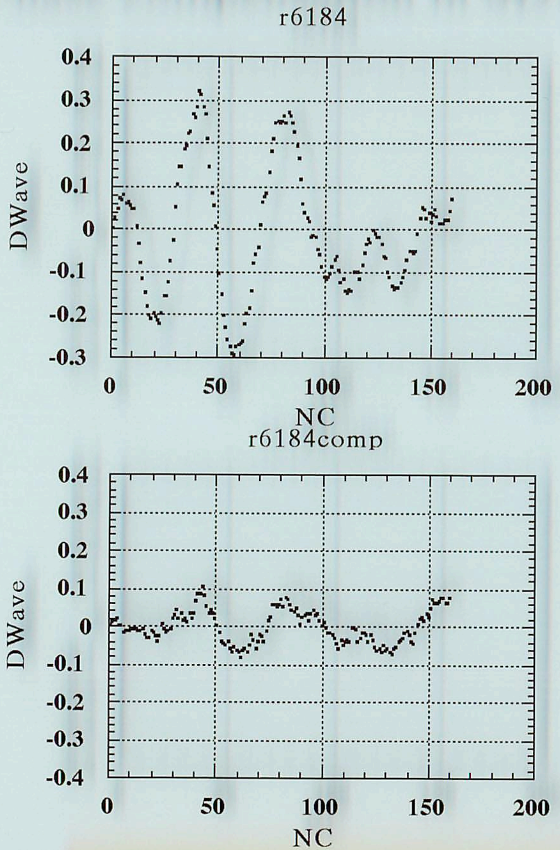
<u>Error - 1 is applied</u>.

Phase oscillation (longitudinal) & compensation

ΔW and Δϕ along ACS



Phase compensation in SDTL

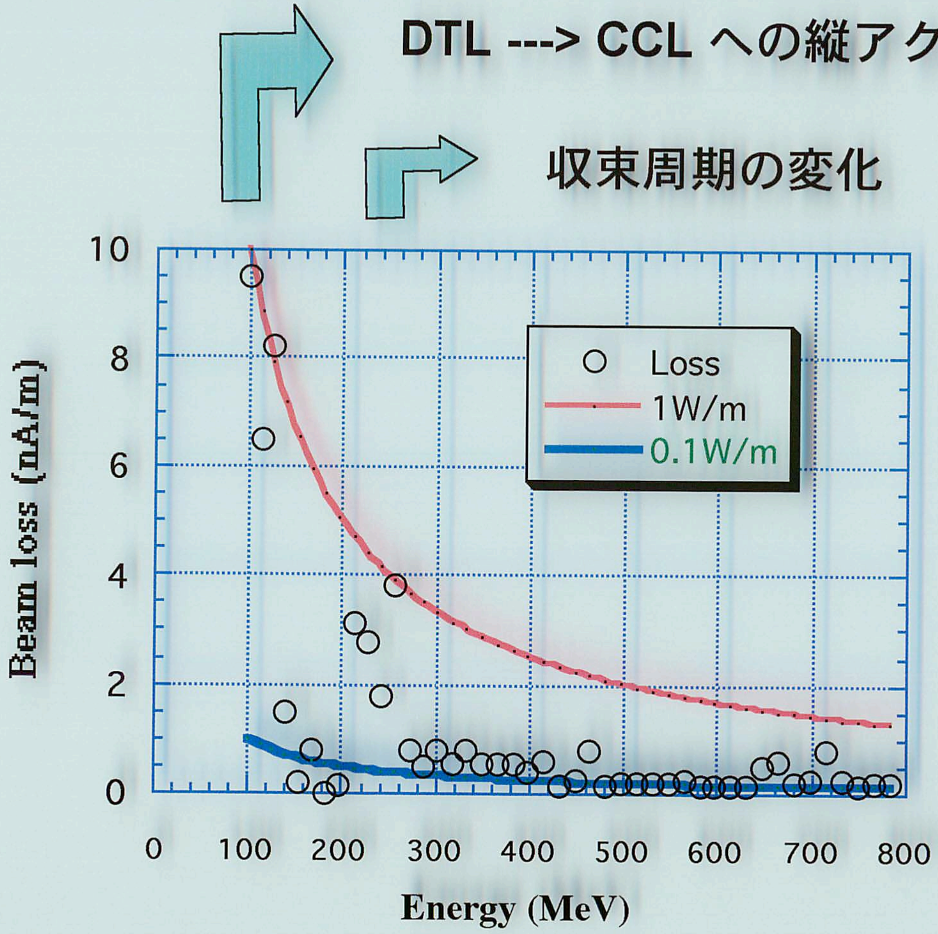


±1% cell and tank fields
±1% cell phase and ±3% tank phase

\+

Phase compensation

LANL beam loss

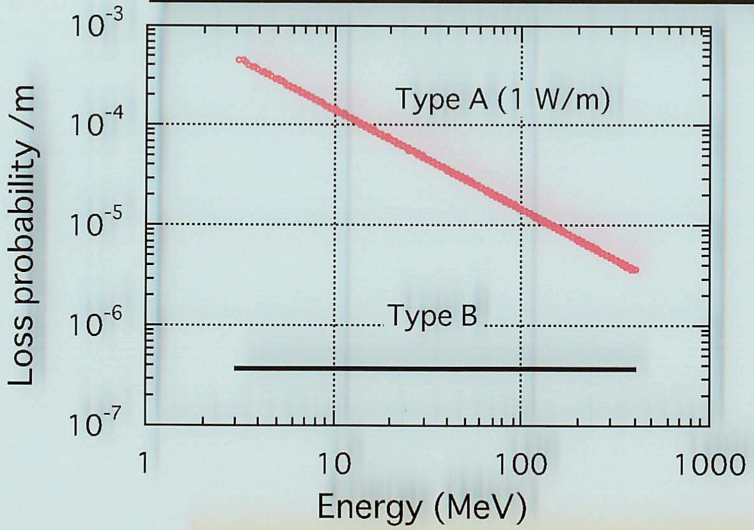


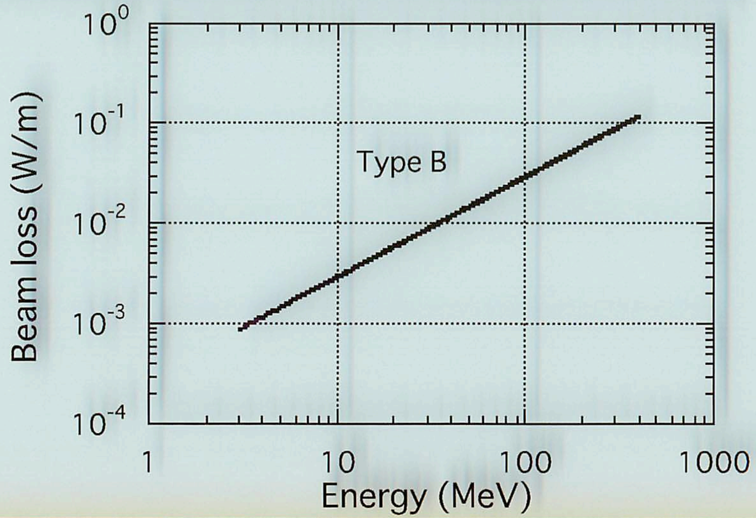
DTL ---> CCL への縦アクセプタンスの不足

収束周期の変化

Beam losses

	Type A	Type B
Definition	loss = 1 W/m	Probability = 4E-7/m
Total loss ratio in the rf structures	3.5E-3	6.4E-5
Total beam-loss power (W)	161	8.2





Type B results in total beam loss ratio of 1E-4 for the 248m linac.
LANL 100 - 800 MeV: beam loss < 10-7 /m , except for transition

Low beam loss

1E-7 / m 程度のビーム損失の実現性

- RFQ is used, instead of Cockcroft
- Three times the frequency for CCL
- Higher transition energy
- Equipartitioning focusing
- No large change in focusing period
- Comparable in Beam handling technique

Decrease beam losses due to transition

Structures' features

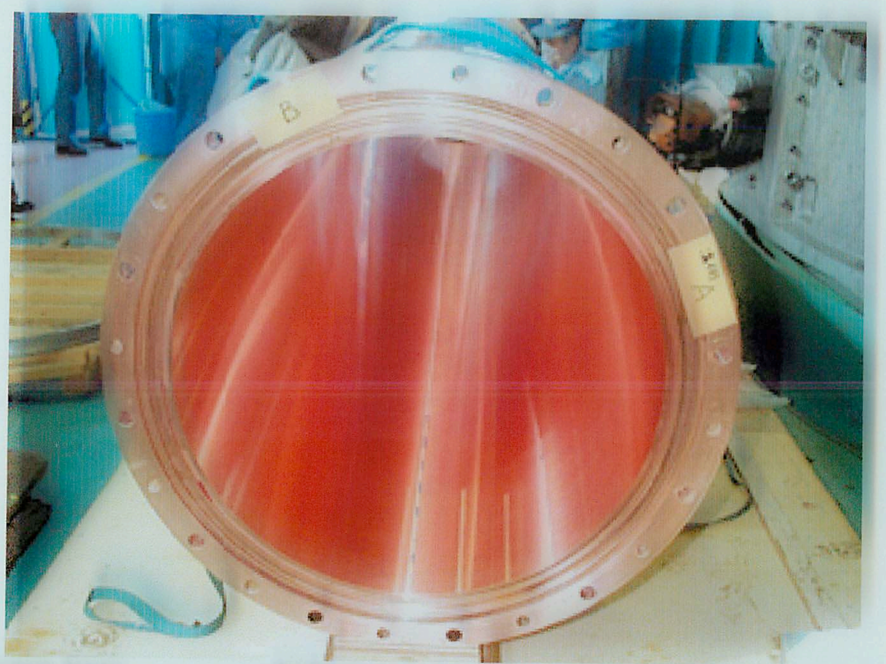
- use stabilized rf structures
  - RFQ, DTL and ACS
- new proposed structure
  - SDTL (Separated-type DTL)
- new developed technique for fabrication
  - PR electroplating method for DTL and SDTL
    - 94% of calculated Q, high breakdown voltage
  - Q-magnets by electroplating method
- use klystrons as rf sources

Construction

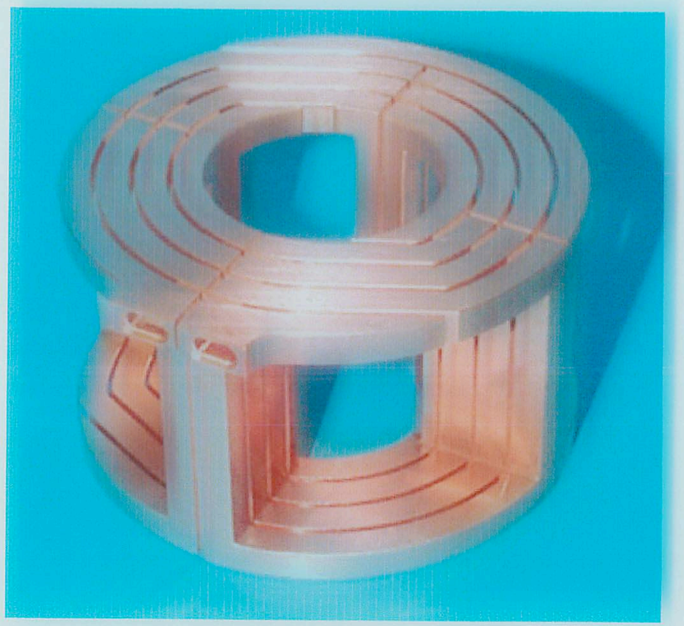
- 60-MeV linac in construction at KEK
  - IS + RFQ + MEBT + DTL + 2 SDTL tanks
    - beam test of the injection part this year
      - » structure, rf system, design, beam monitors, control
- ACS
  - fundamentals were established in 1296-MHz study
  - detailed design of 972-MHz structure is under way

DTL under construction

- **50-MeV, 324-MHz DTL with pulsed Q-magnets**
- **New developed techniques**
  - **Electro-plating tank (Periodic Reverse) : $Q_{measure} \sim 0.94\, Q_{ideal}$**
  - **Pulse Q-magnets with electro-plating**



EP test tank



Q-magnet coil

PR(periodic reverse)電鋳

三菱重工名古屋

- PR低濃度硫酸銅鍍金
  - 塩素イオン　15ppm程度
  - 不純物を含まない　35ppm 以下
    - 有機性添加剤を含まない
  - 電圧の反転（20秒＋４秒）
  - 撹拌
  - 特徴
    - 電気伝導度が良い
    - 放電特性が優れている
    - 溶接が可能
    - 力学特性をイオン濃度により調整可能

relative conductivity

OFC	102
PR硫酸銅	102
no-PR硫酸銅	77
ピロリン酸	80

円柱テスト空洞　98％ Q_0

RFテスト空洞　94%　Q_0

電鋳面の比較

直流通電

ＰＲ通電

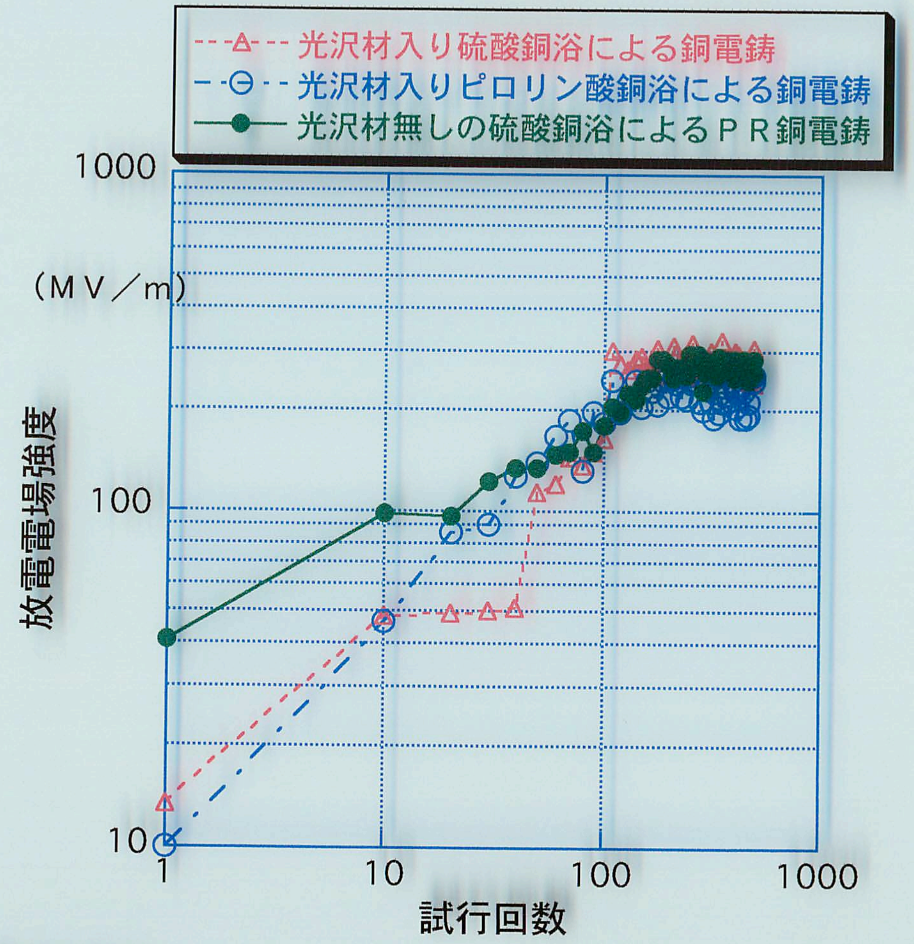
塩素イオン～３５ppm

ＰＲ通電

塩素イオン～１５ppm

放電特性

埼玉大学 小林、KEK 斉藤



放電開始電圧

	MV/m
PR	41
no-PR	13
ピロリン酸	10
OFC (lathe)	20
OFC (Epolish)	16
OFC (diamond)	70

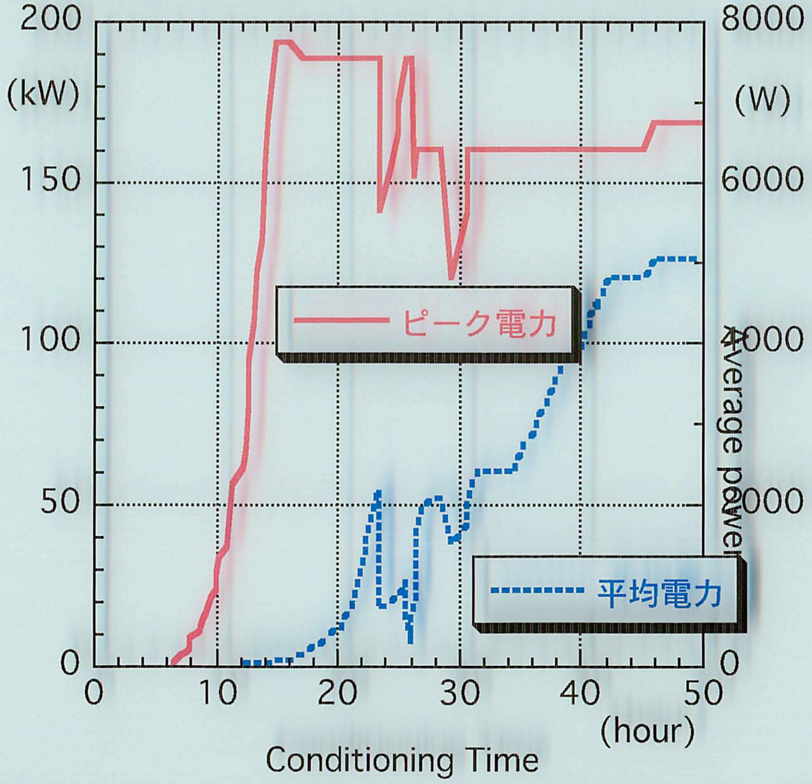
Problems in construction so far

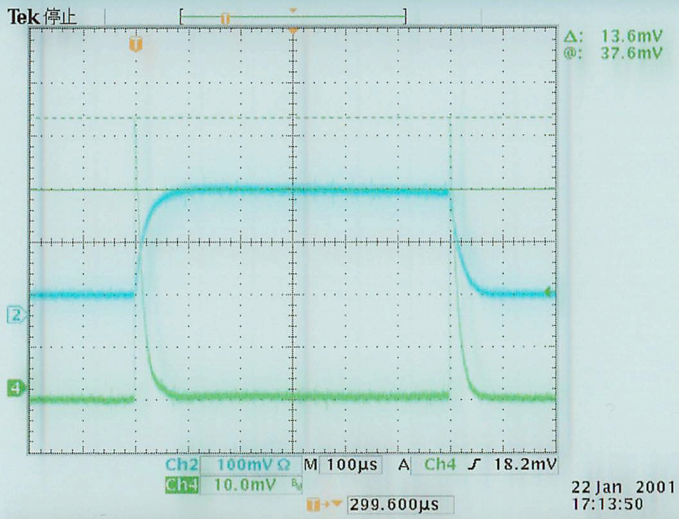
- Crack in RF-coupler window
- Deviation of DT-Q-magnet center from mechanical center during fabrication processes ~ 50 μm
- Establish reliable mass production technique of Q-magnet (150 pieces)

RF high-power test

Naito et al.

Conditioning history of the DTL hot model





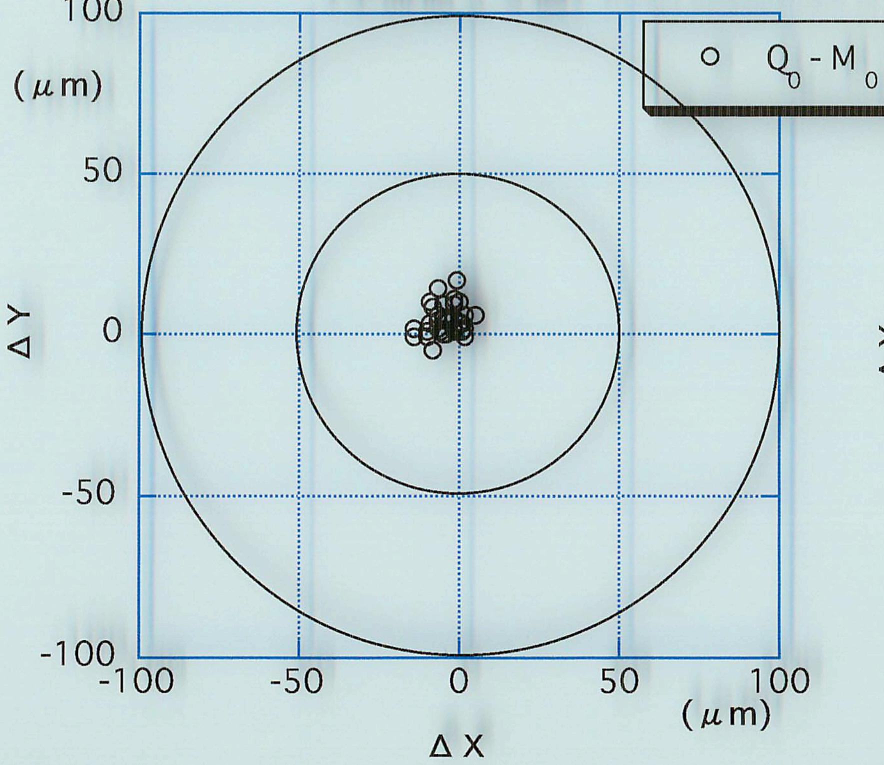
Proton linac

定格電場 2.5 MV/m　　4.3 MV/m 達成

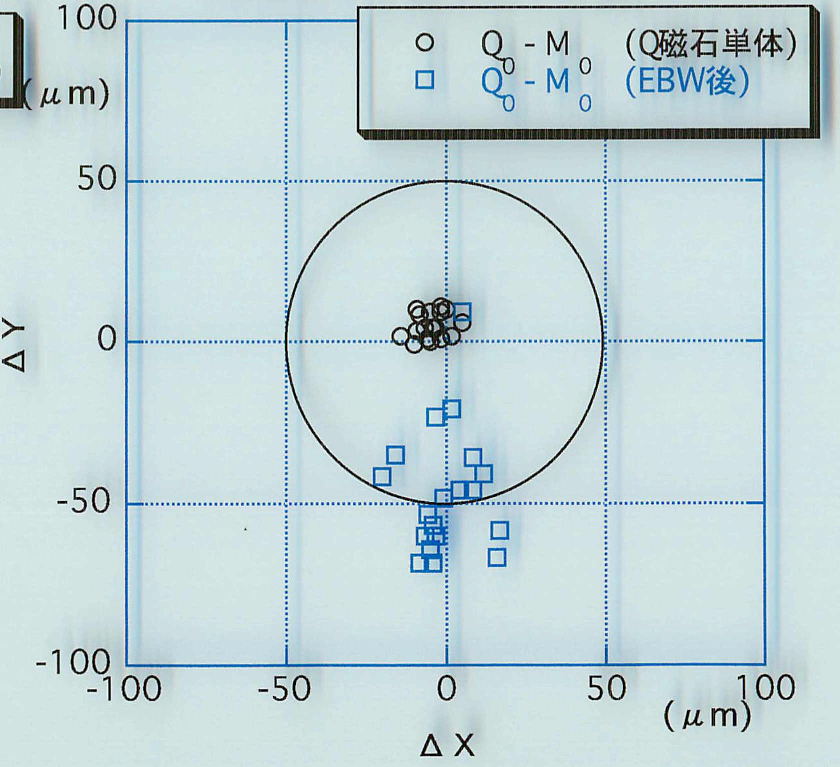
DT Quadrupole magnets

Naito et al.

Q磁石単体測定結果
（上流側３３個）(Direct measurement of Q



Q磁石単体及びＤＴ封入ＥＢＷ後の測定結果
（上流側３３個中の１８個）



Beam monitors for tuning and operation

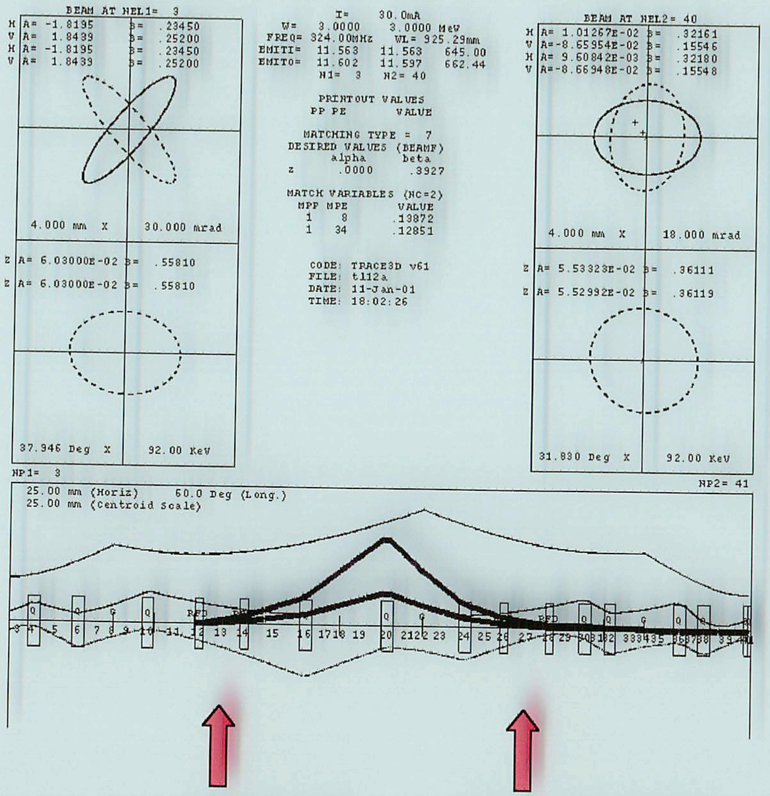
- Monitors during tuning
  - emittance monitor, profile monitor
  - energy width, bunch length monitor
  - and, non-destructive type
- Monitors during operation
  - non-destructive type
  - watching deviation
    - Longitudinal
      - phase monitor
    - Transverse
      - BPM (beam position monitor)
      - beam width by BPM
- Beam loss monitor (fast type)

Tuning procedure
Operation procedure

Improve chopper operation

Wang and Fu

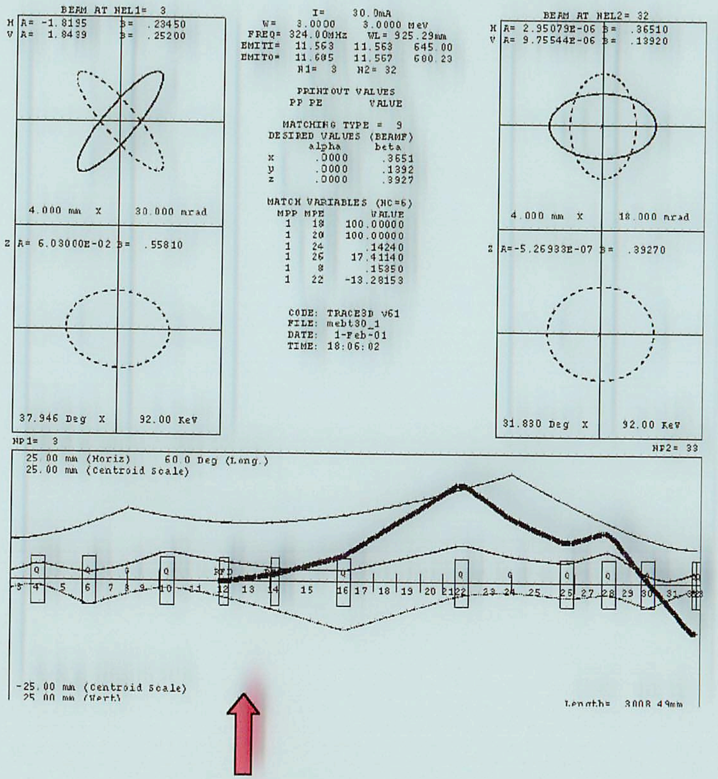
0.08% unstable particles



```
BEAM AT NEL1=  3
H A= -1.8195     B=  .23450
V A=  1.8439     B=  .25200
H A= -1.8195     B=  .23450
V A=  1.8439     B=  .25200
4.000 mm  X      30.000 mrad
Z A= 6.03000E-02 B=  .55810
Z A= 6.03000E-02 B=  .55810
37.946 Deg  X    92.00 KeV
```

```
         I=     30.0mA
    W=   3.0000     3.0000 MeV
 FREQ= 324.00MHz   WL= 925.29mm
EMITI=  11.563   11.563   645.00
EMITO=  11.602   11.597   662.44
         N1=  3   N2= 40

     PRINTOUT VALUES
    PP PE      VALUE

    MATCHING TYPE =  7
  DESIRED VALUES (BEAMF)
        alpha     beta
  z      .0000     .3927

  MATCH VARIABLES (NC=2)
   MPP MPE      VALUE
    1    8      .13872
    1   34      .12851

   CODE: TRACE3D v61
   FILE: tl12a
   DATE: 11-Jan-01
   TIME: 18:02:26
```

```
BEAM AT NEL2= 40
H A= 1.01267E-02 B=  .32161
V A=-8.65954E-02 B=  .15546
H A= 9.60842E-03 B=  .32180
V A=-8.66948E-02 B=  .15548
4.000 mm  X      18.000 mrad
Z A= 5.53323E-02 B=  .36111
Z A= 5.52992E-02 B=  .36119
31.830 Deg  X    92.00 KeV
```



```
BEAM AT NEL1=  3
H A= -1.8195     B=  .23450
V A=  1.8439     B=  .25200
4.000 mm  X      30.000 mrad
Z A= 6.03000E-02 B=  .55810
37.946 Deg  X    92.00 KeV
```

```
         I=     30.0mA
    W=   3.0000     3.0000 MeV
 FREQ= 324.00MHz   WL= 925.29mm
EMITI=  11.563   11.563   645.00
EMITO=  11.605   11.567   680.23
         N1=  3   N2= 32

     PRINTOUT VALUES
    PP PE      VALUE

    MATCHING TYPE =  9
  DESIRED VALUES (BEAMF)
        alpha     beta
  x      .0000     .3651
  y      .0000     .1392
  z      .0000     .3927

  MATCH VARIABLES (NC=6)
   MPP MPE      VALUE
    1   18   100.00000
    1   20   100.00000
    1   24      .14240
    1   26    17.41140
    1    8      .15350
    1   22   -13.28153

   CODE: TRACE3D v61
   FILE: mebt30_1
   DATE:  1-Feb-01
   TIME: 18:06:02
```

```
BEAM AT NEL2= 32
H A= 2.95079E-06 B=  .36510
V A= 9.75544E-06 B=  .13920
4.000 mm  X      18.000 mrad
Z A=-5.26933E-07 B=  .39270
31.830 Deg  X    92.00 KeV
```

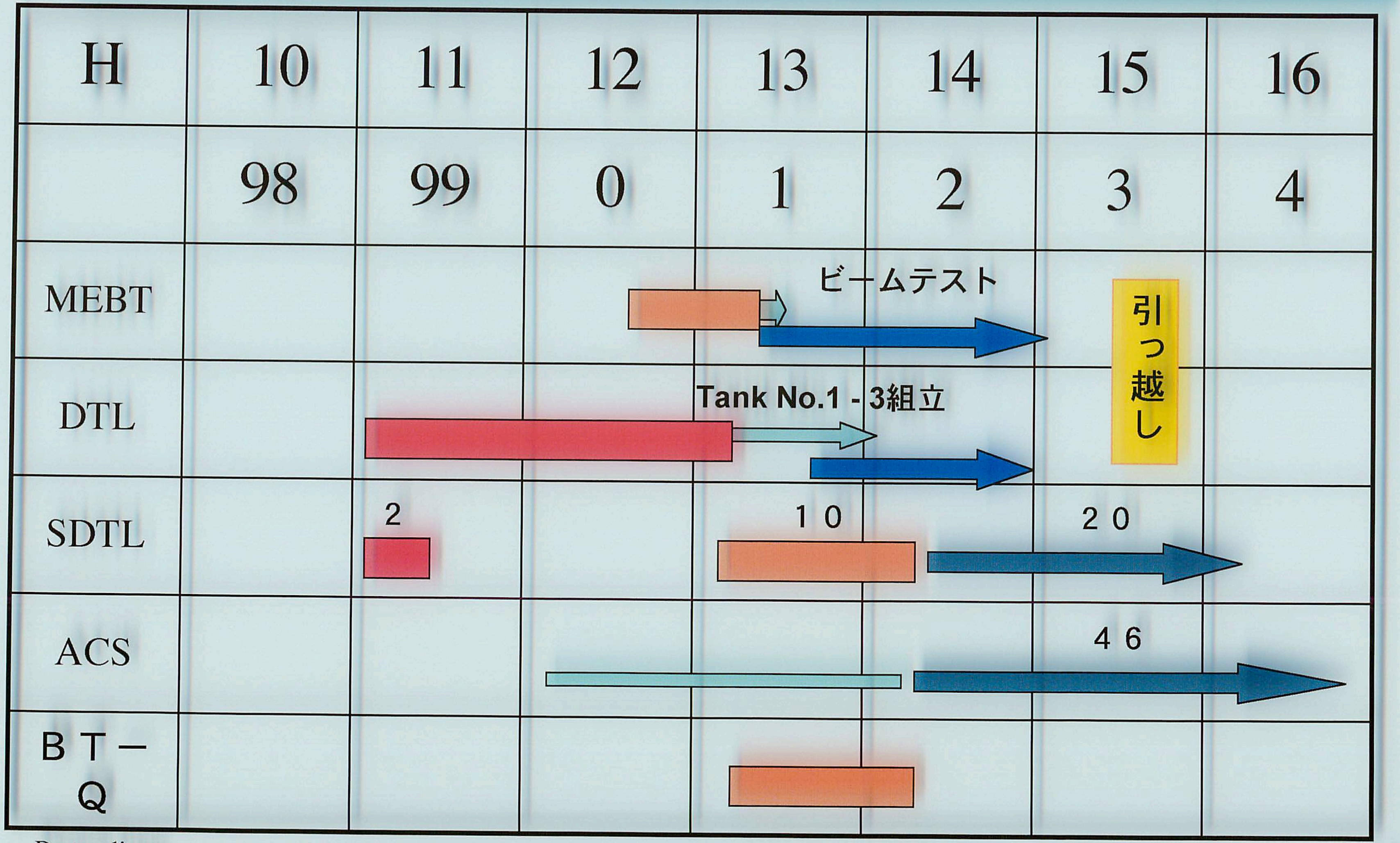
Proton linac

chopper

anti-chopper

chopper

Schedule



H	10	11	12	13	14	15	16
	98	99	0	1	2	3	4
MEBT					ビームテスト	引っ越し	
DTL				Tank No.1 - 3組立			
SDTL		2		１０		２０	
ACS						４６	
ＢＴ－Ｑ							

Summary

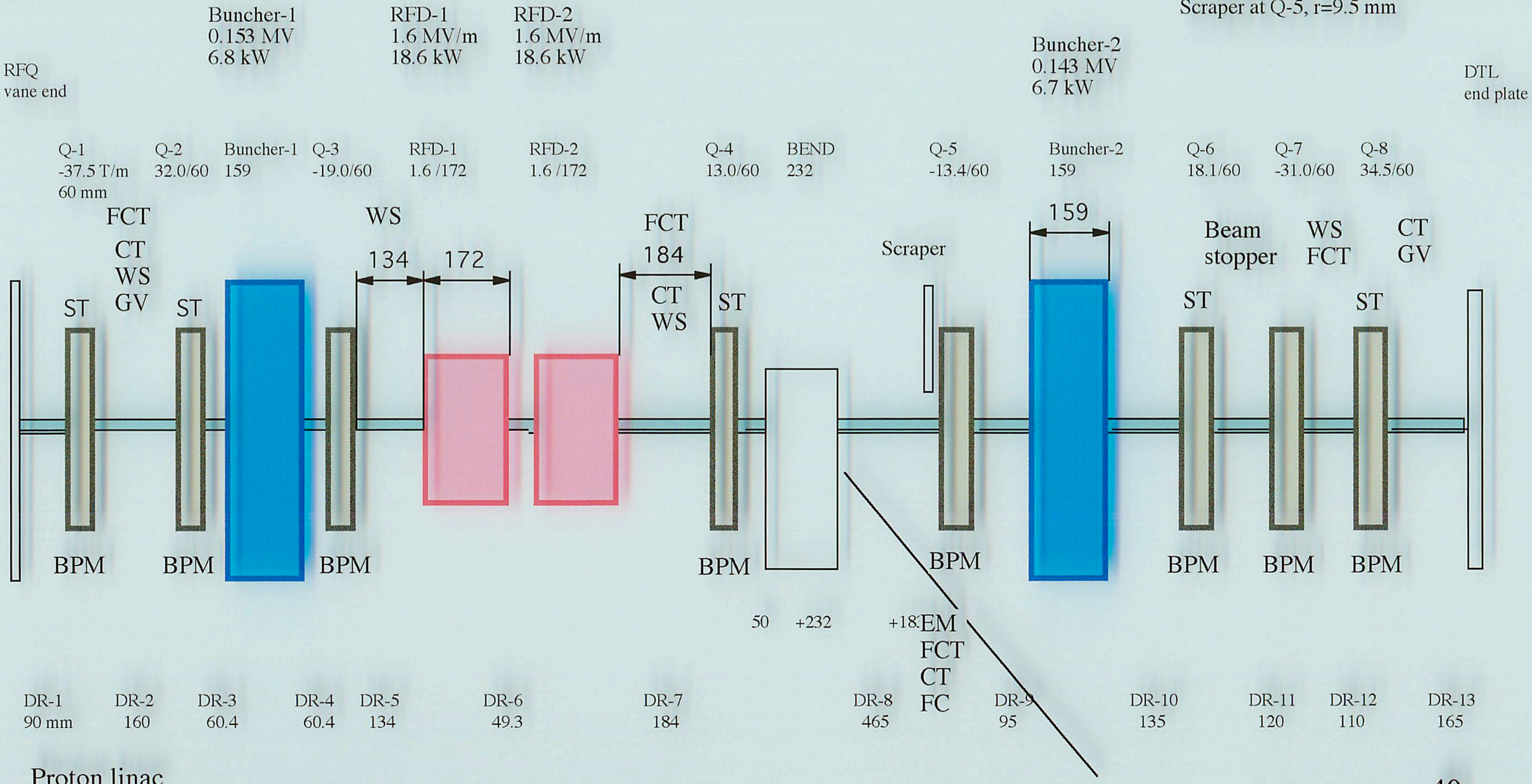
60-Mev リニアックの建設運転

- 低エネルギー領域のビームの性質
  - IS, RFQ, MEBT, DTL, SDTL
- Chopped beam operation
- Monitor, tuning & control system
- RF system
- Laser alignment system

- 今後の課題
  - Ion source & RFQ (50 mA 目指しての開発)
  - Monitor
    - non-destructive profile monitor
    - beam-loss monitor
  - ACS デザイン及び製作
  - Beam transport
  - Initial tuning and operation procedures

MEBT layout

negative charge
Total length 2971.3 mm
Normal beam size < 10 mm
Deflected < 26 mm
Scraper at Q-5, r=9.5 mm



Buncher-1
0.153 MV
6.8 kW

RFD-1
1.6 MV/m
18.6 kW

RFD-2
1.6 MV/m
18.6 kW

Buncher-2
0.143 MV
6.7 kW

RFQ
vane end

DTL
end plate

Q-1
-37.5 T/m
60 mm

Q-2
32.0/60

Buncher-1
159

Q-3
-19.0/60

RFD-1
1.6 /172

RFD-2
1.6 /172

Q-4
13.0/60

BEND
232

Q-5
-13.4/60

Buncher-2
159

Q-6
18.1/60

Q-7
-31.0/60

Q-8
34.5/60

DR-1
90 mm

DR-2
160

DR-3
60.4

DR-4
60.4

DR-5
134

DR-6
49.3

DR-7
184

DR-8
465

DR-9
95

DR-10
135

DR-11
120

DR-12
110

DR-13
165

Proton linac