Design Study on the 9 GeV Proton Linac at KEKB Tunnel for the Next Generation Neutrino Experiment

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Outline

- Motivation
- Outline of 9 GeV linac
- Simulation of each straight section
- Summary and prospects

Beam Intensity Upgrade

- Present : 240 kW @ J-PARC MR
  - Linac beam current : 15 mA
  - MR repetition : 2.48 sec

- FY2017 : 750 kW @ J-PARC MR
  - Linac beam current : 15 mA ⇒ 50 mA
  - MR repetition : 2.48 sec ⇒ 1.0 sec

Toward Multi-MW beam power

- Intensity upgrade of J-PARC
  - RCS higher top energy
  - 8 GeV second booster ring
  - etc.

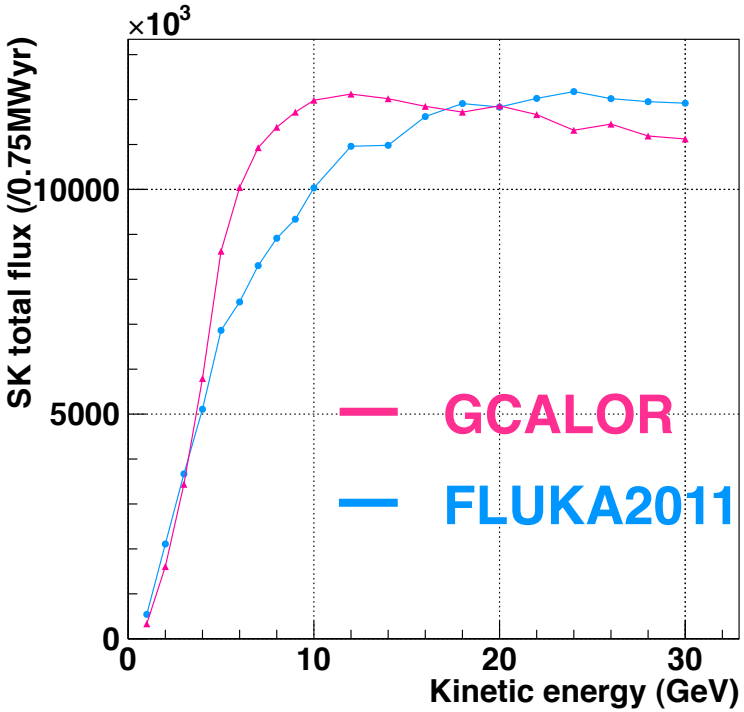
  ⇒ Igarashi-san's talk

- Construction of a new proton driver
  - Linear accelerator for high beam duty

  ⇒ This talk

Beam Energy, Integrated ν Flux

Neutrino flux normalized by beam energy



K. Sakashita

- Neutrino flux at Super Kamiokande as a function of proton energy.
- Hadron generation model.
  - GCALOR
  - FLUKA2011
- Off axis beam 2.5 deg.
- 3 Horn magnet scheme same as T2K.

- At < 9 GeV, Neutrino flux per energy increases as beam energy to be high.
- Then, the flux almost saturates.

Beam power = [Beam energy] x [Peak current] x [Duty]

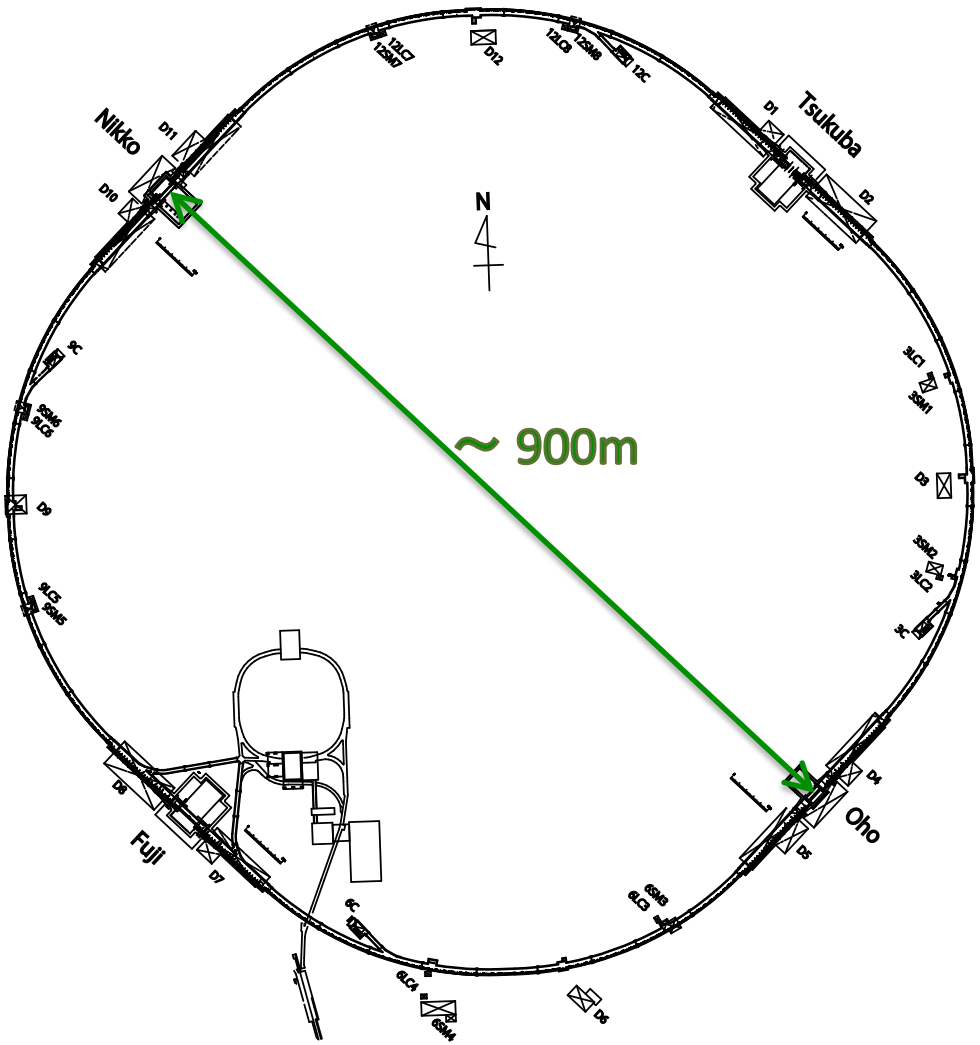
- 9 GeV proton accelerator
- Linac configuration for high duty
- Construction at the KEKB tunnel for cost issue.

Proton Driver in the KEKB Tunnel

KEKB tunnel:

- fourfold symmetric configuration.
- Circumference: ~ 3 km
  - Straight section: beam acceleration
    200 m x 4 = 800 m
  - Arc section: beam transportation to the next straight section.
    550 m x 4 = 2200 m

Top view of the KEKB tunnel



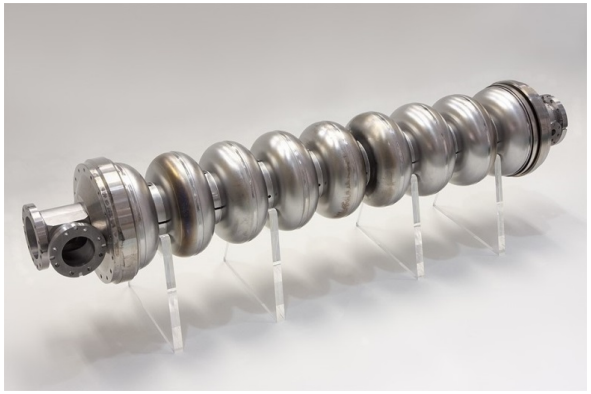
Subjects:

- Feasibility of 9 GeV proton linac in straight sections of 800 m.
  ⇒ High acceleration field is required.
  ⇒ SC accelerator is essential.
- Beam transport at Arc sections.

SC Cavity for 2nd to 4th Straight Sections

For the acceleration in the 2nd to 4th straight section, We choose the ILC cavity.

ILC cavity



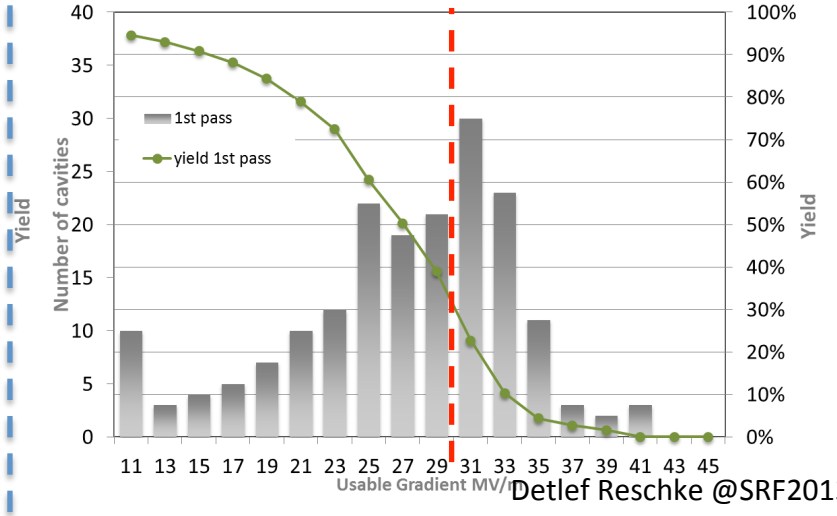
Shape	ellipse
RF frequency	1.3 GHz
# of cells per cavity	9
Quality factor	> 1 x 10^{10} @ 2K

ILC cryomodule

KEK has rich experience and know-how of ILC cavity and cryomodule fabrication.

Average gradiend (E_0) ?

Yield of usable gradient of 185 ILC cavities as received (European XFEL)



Detlef Reschke @SRF2013

Average **usable** gradient:

(26.2 ± 7.5) MV/m

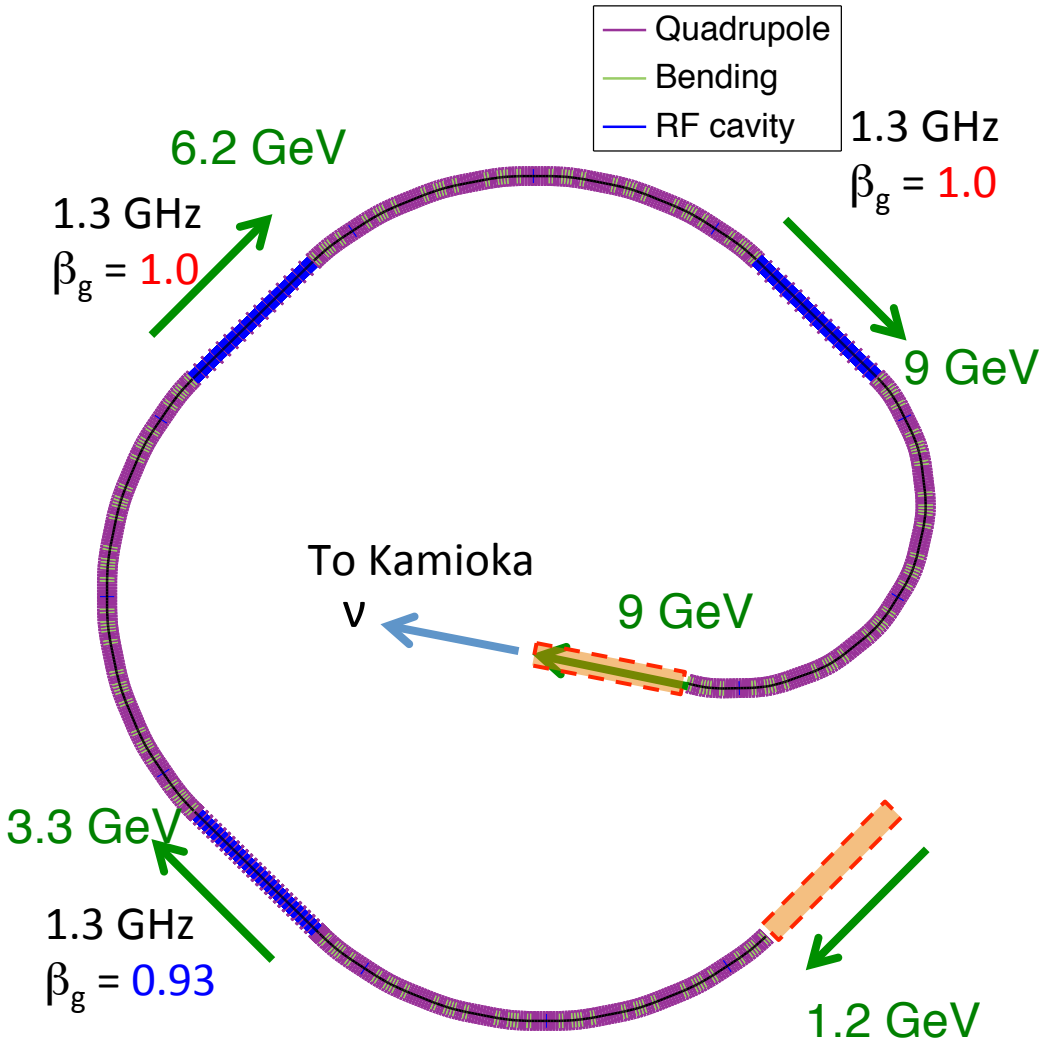
With the expectation of further R&D, we set the E_0 to **30 MV/m**.

Outline of the Proton Driver w/ ILC Cavity

- Outline of acceleration :
  - 1.2 GeV in 1st straight.
  - 3.3 GeV in 2nd straight.
  - +2.9 GeV in 3rd and 4th straight.

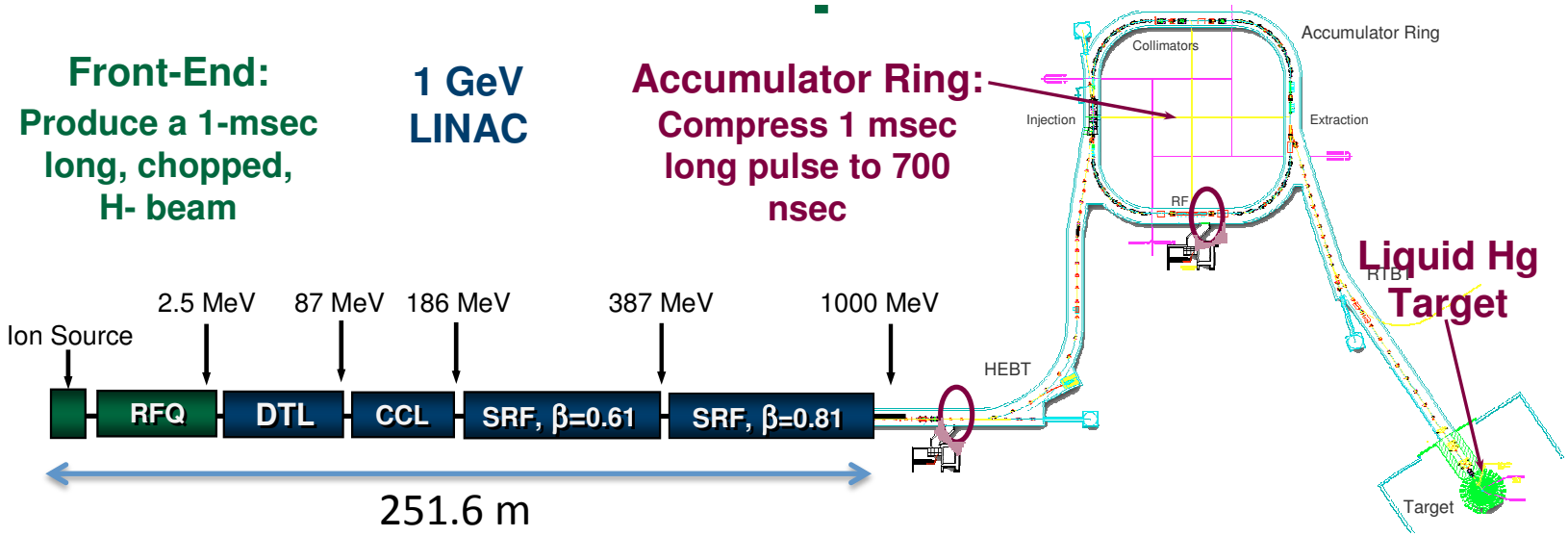
    3.3 + 2.9 x 2 = 9.0 GeV
- Peak current : 100 mA (pulse)
- Beam duty : 1 %
- Beam power :

  9000 MeV x 0.1 A x 1 % = **9 MW**
- β_g of SC cavities :
  - 2nd straight : β_g = **0.93**
  - 3rd and 4th straight : β_g = **1.0**
- Normalized RMS emittance
  - Transverse : 0.30 π・mm・mrad
  - Longitudinal : 0.37 π・MeV・deg



Reference of 1st Straight Section (1)

- Spallation Neutron Source (SNS)

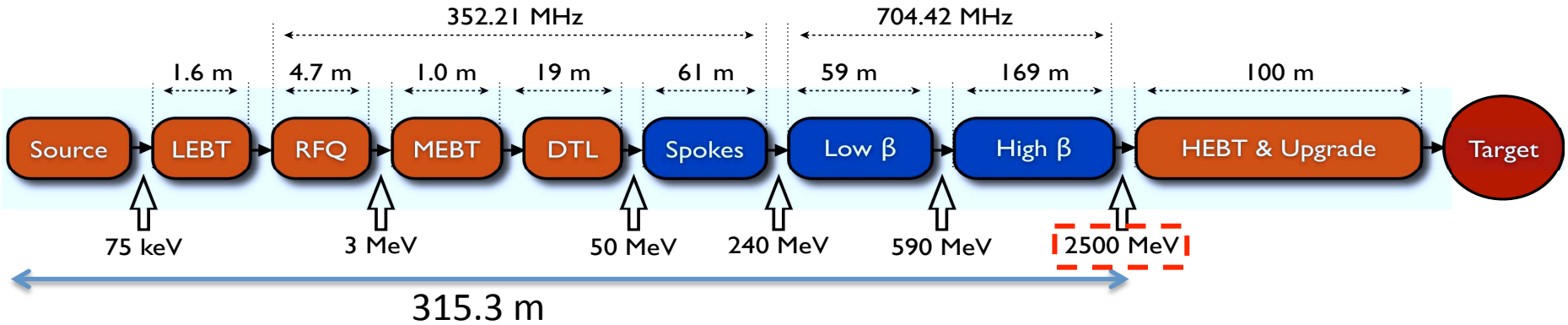


Parameter	Value	Parameter	Value
Ion species	H^-	Repetition (Hz)	60
Output energy (MeV)	1000	Macro-pulse duty factor (%)	6
Peak current (mA)	38	Average beam current on target (mA)	1.4
Chopper beam-on duty factor (%)	68	Beam power on target (MW)	1.4
Pulse width (ms)	1	Length (m)	251.6

Reference of 1st Straight Section (2)

- European Spallation Source (ESS)

M. Eshraqi et. al., TUO1B01, HB2010 (2010)



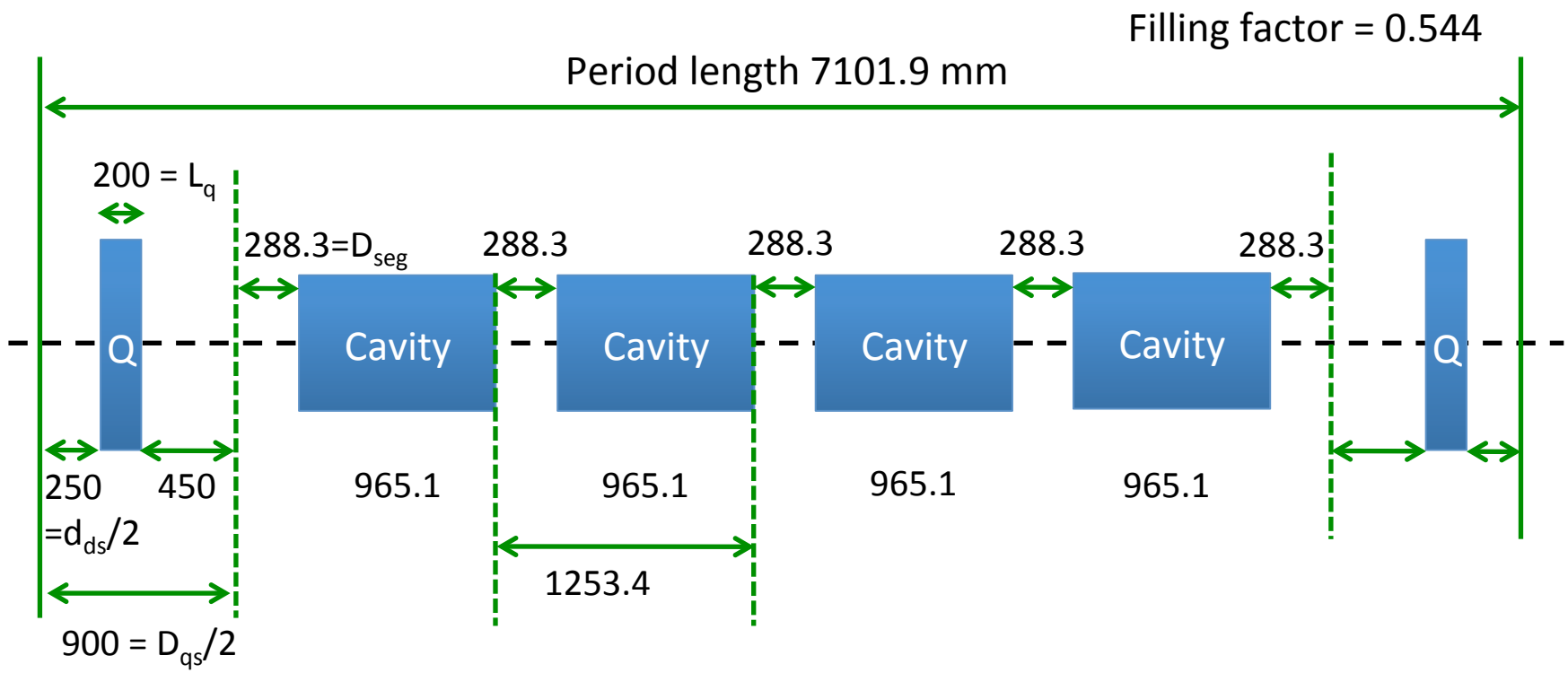
Parameter	Value	Parameter	Value
Ion species	p	Repetition (Hz)	20
Output energy (MeV)	2500	Macro-pulse duty factor (%)	4
Peak current (mA)	50	Average beam current on target (mA)	2
Chopper beam-on duty factor (%)	100	Beam power on target (MW)	5
Pulse width (ms)	2	Length (m)	315.3*

*Energy reaches 1200 MeV at 230 m.

Proton beam can be accelerated to 1.2 GeV in the 1st straight section

Configuration of a Cryomodule at 2nd Straight

- Doublet lattice with SC quadrupole magnets.
- 4 SC cavities (β_g = 0.93) are in each cryomodule.
- 27 cryomodules are placed in the section.
  7.1 x 27 = 192 m



Section 2, $\beta_g = 0.93$

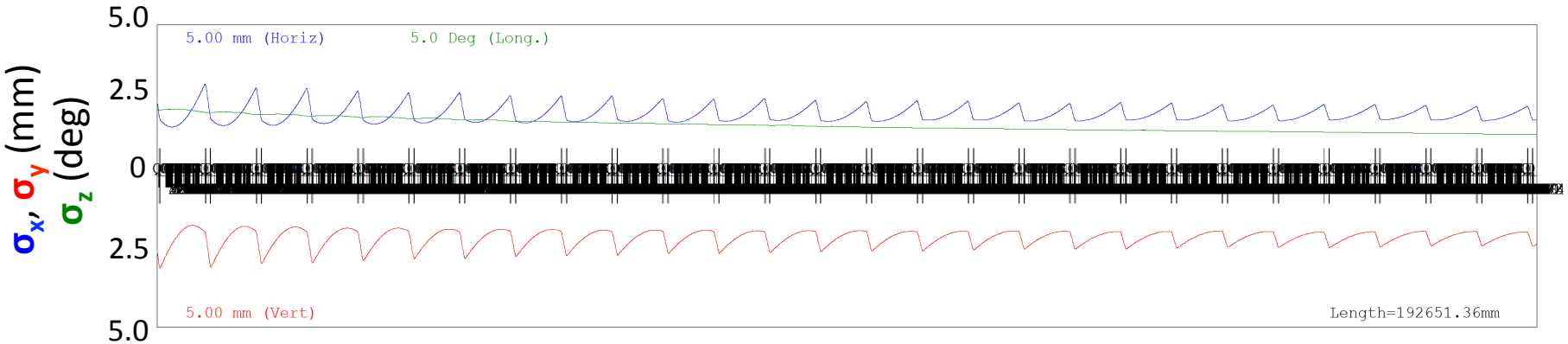
- Frequency : 1.3 GHz
- Geometrical beta : 0.93
- Number of cells per cavity : 9
- Number of cavities per cryomodule : 4
- Number of cavities : 108 (27 modules)
- Beam beta : 0.9 to 0.975
- Beam energy : 1.214 GeV to 3.315 GeV
- Cell geometry : Temporary (Scaled from JAERI 600 MHz design)
- E_0 : **30 MV/m**
- ϕ_s : **-24 deg**
- Phase slip in the first and last cavity : -47 to -1 deg, 9 to -57 deg
- Transit time factor at $\beta = 0.93$: 0.7727
- Cavity filling factor : 0.544
- Length : 193 m
- Real estate accelerating gradient : 10.9 MeV/m

No end-cell effect Included.
The same E_0 is assumed with $\beta_g = 1.0$.

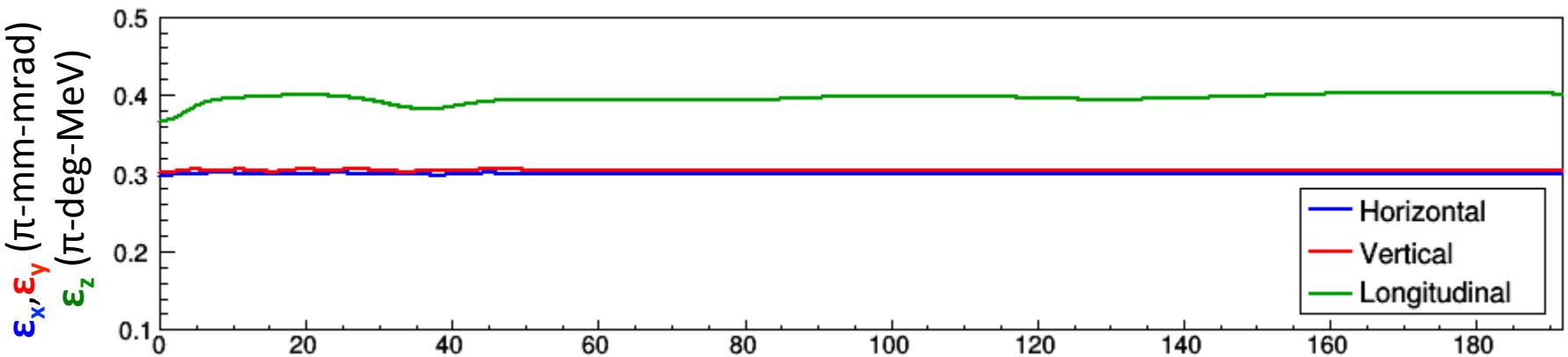
Simulation of 2nd Straight

RMS beam envelope (TRACE-3D simulation)

Peak current : **100 mA**



Normalized Emittance (IMPACT simulation)

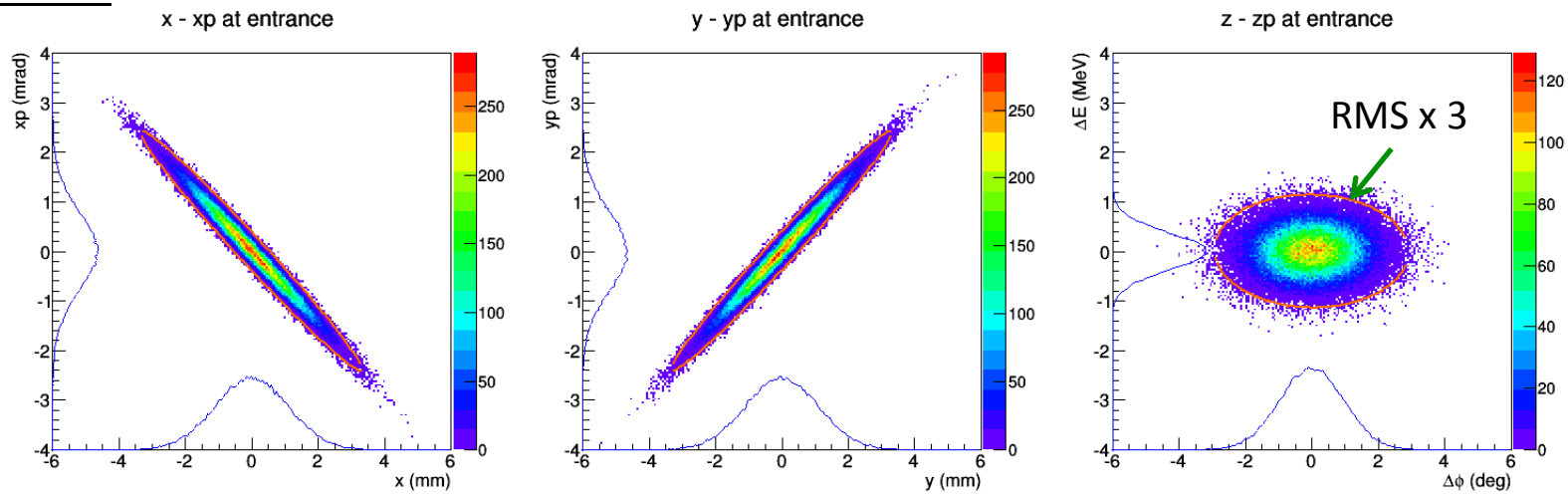


Small emittance growth is observed in longitudinal plane

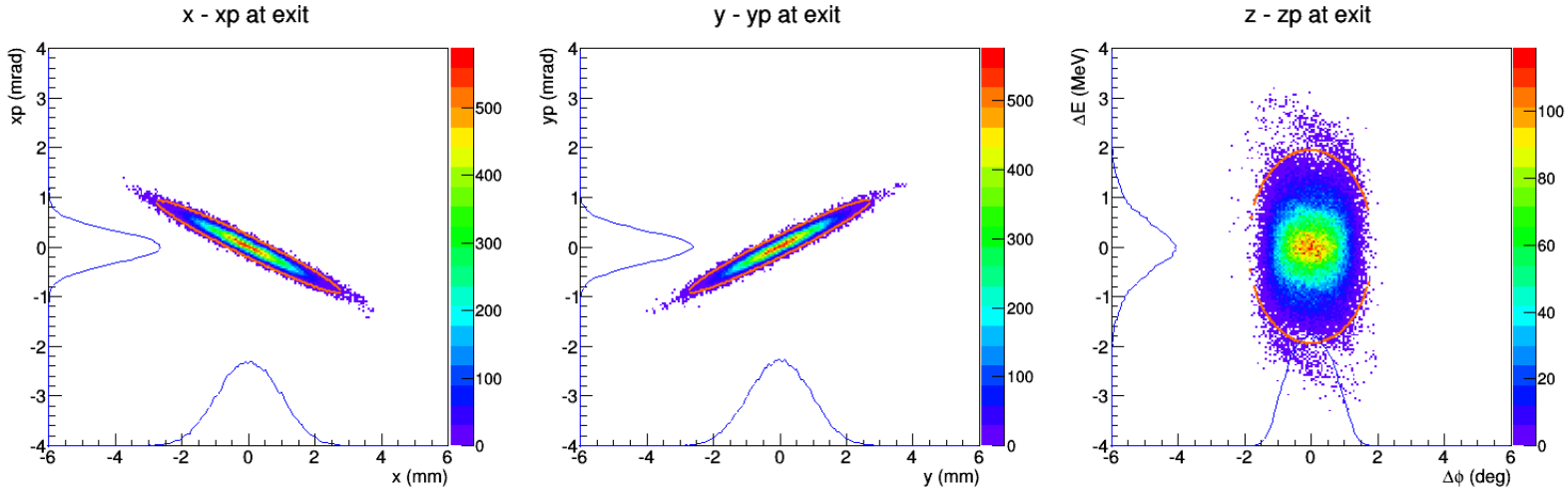
Beam Profile at 2nd Straight

Gaussian distribution, 100 k particles

Entrance

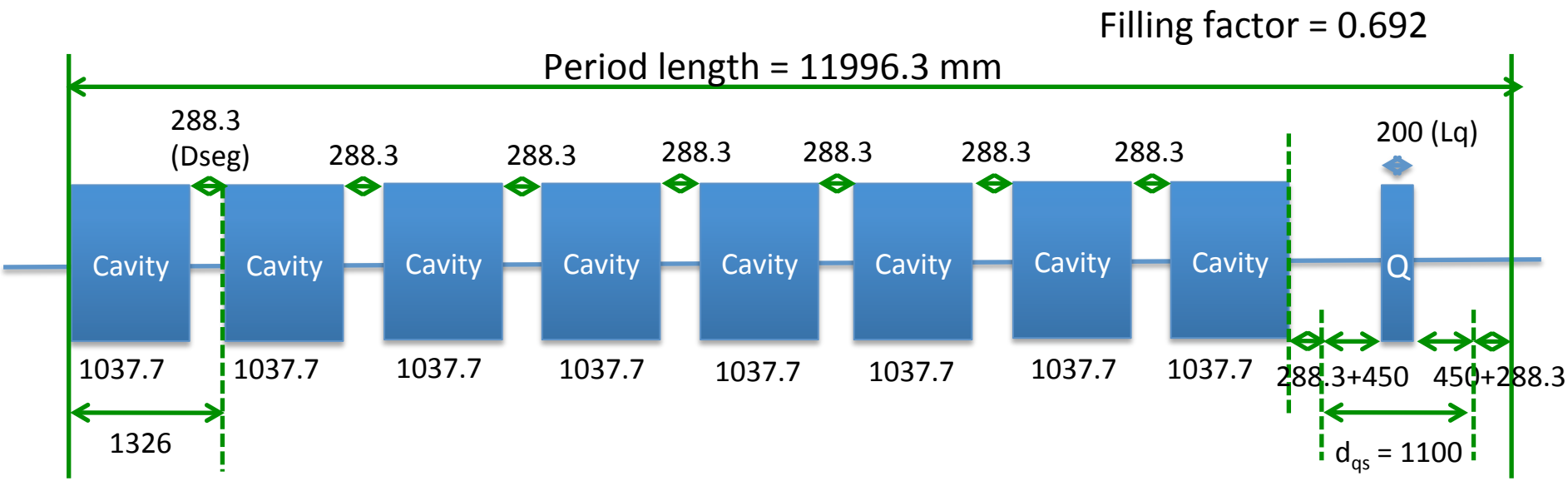


Exit



Configuration of a Cryomodule in 3rd – 4th Strght

- Singlet lattice with a SC quadrupole magnet.
- 8 SC cavities (βg = 1.0) are in each cryomodule.
- 16 cryomodules are placed in each straight section.
  12.0 m x 16 = 192 m



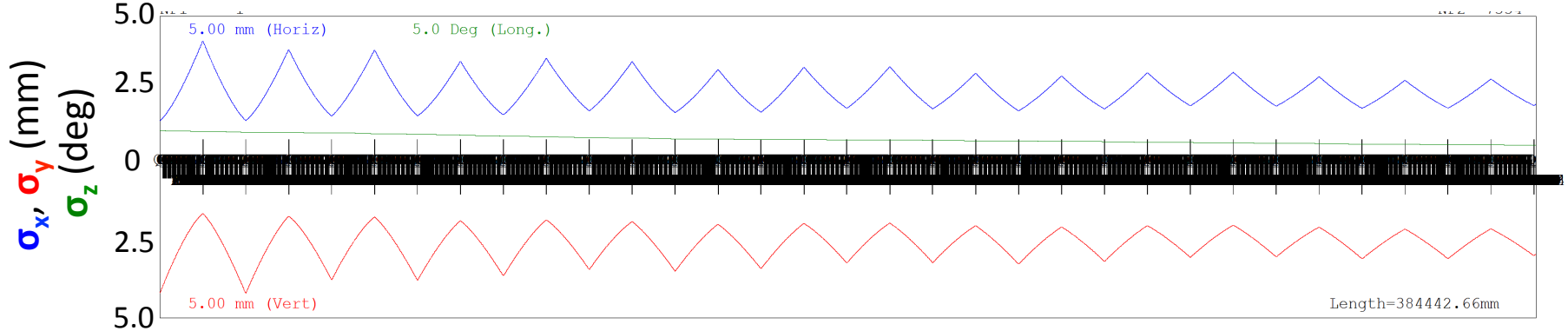
Section 3 and 4, βg = 1.0

- Frequency : 1.3 GHz
- Geometrical beta : 1.0
- Number of cells per cavity : 9
- Number of cavities per cryomodule : 8
- Number of cavities : 256 (32 modules)
- Beam beta : 0.975 to 0.996
- Beam energy : 3.315 to 9.051 GeV
- Cell geometry : Temporary (Scaled from JAERI 600 MHz design
- E_0 : **30 MV/m**
- ϕ_s : **-20 deg**
- Phase slip in the first and last cavity : -38 to -2 deg, -23 to -17 deg
- Transit time factor at β = 1.0 : 0.7739
- Cavity filling factor : 0.692
- Length : 386 m (193 m x 2)
- Real estate accelerating gradient : 14.9 MV/m

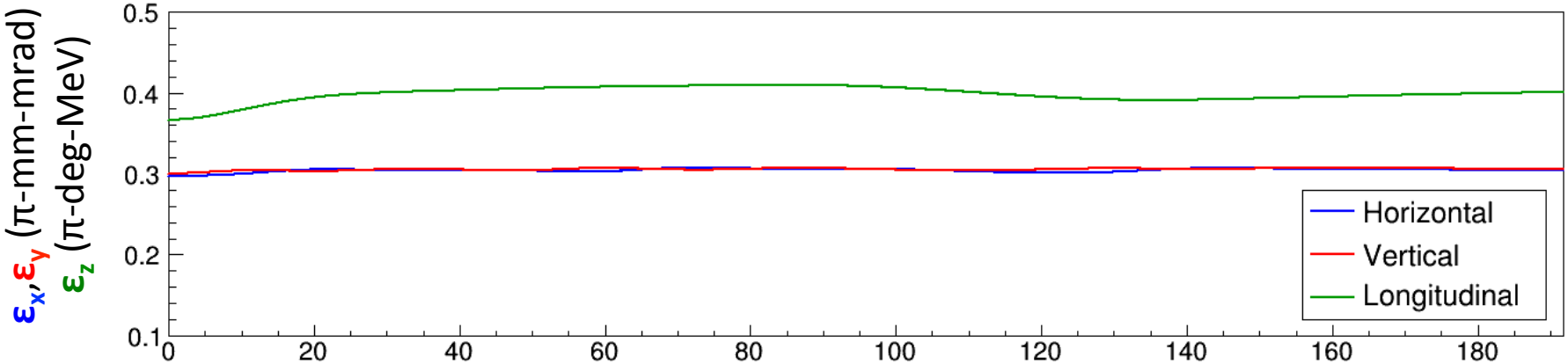
Simulation of 3rd – 4th Straight

RMS beam envelope (TRACE-3D simulation)

Peak current : **100 mA**



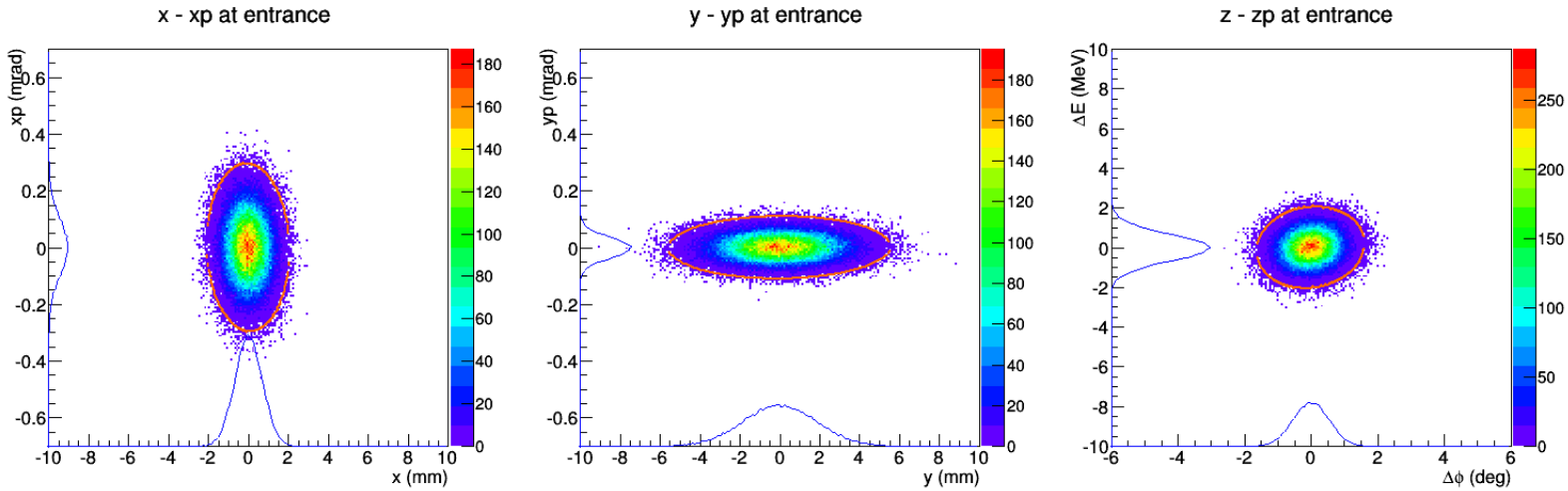
Normalized Emittance (IMPACT simulation)



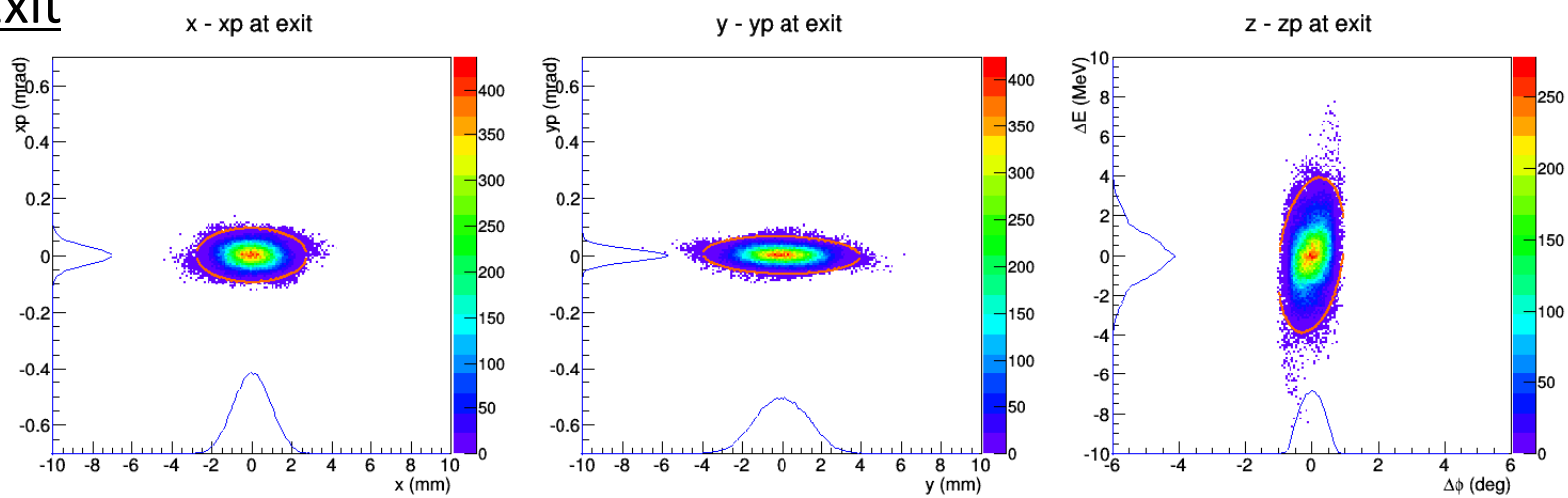
Beam Profile at 3rd to 4th Straight

Gaussian distribution, 100k particles

3rd Entrance

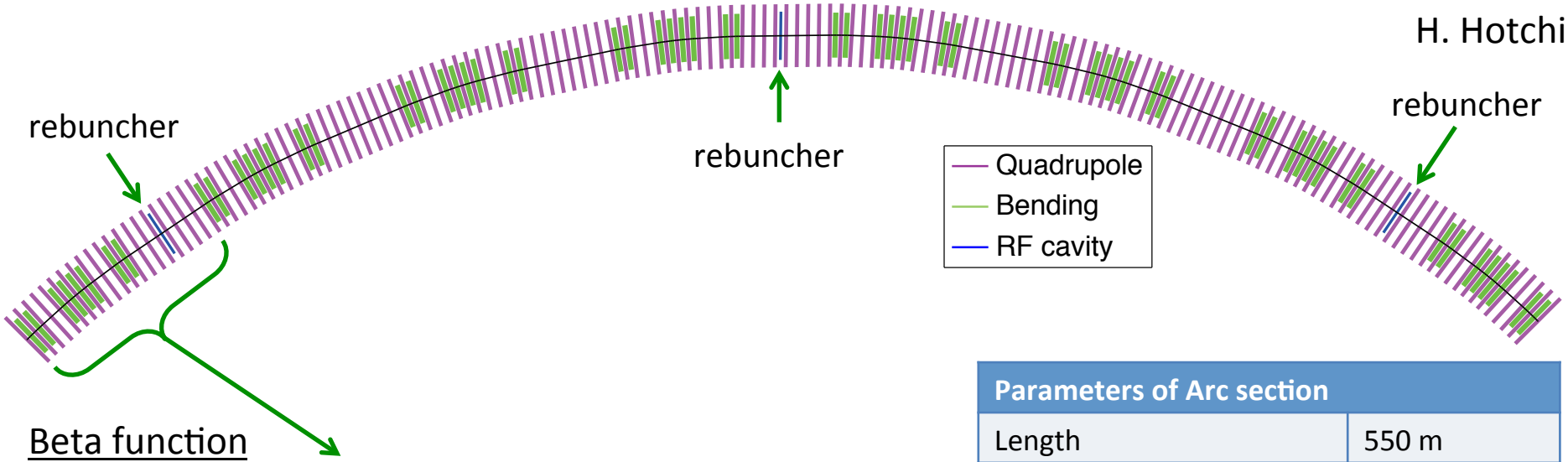


4th Exit

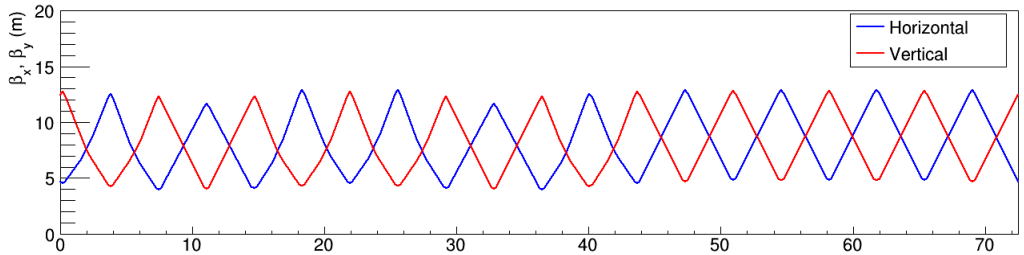


Lattice of Arc section

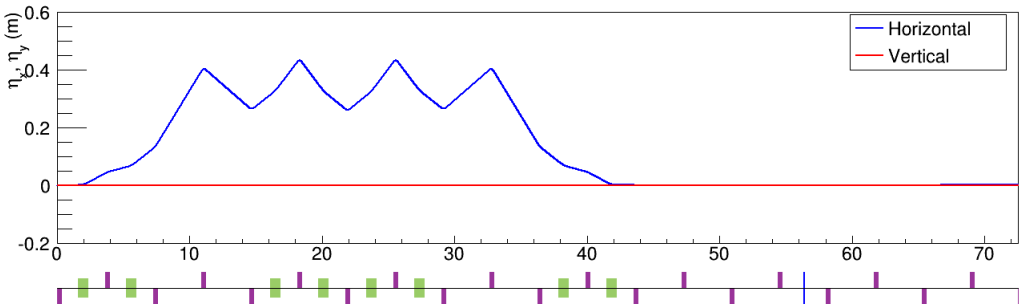
H. Hotchi



Beta function



Dispersion



Parameters of Arc section	
Length	550 m
Aperture	70 mm
Momentum acceptance	±0.8 %
Bending magnet	
# of magnets	64
core length	0.8 m
Quadrupole magnet	
# of magnets	152
core length	0.375 m
drift length between Qs	3.25 m
Rebuncher	
# of cavities	3
RF frequency	0.65 / 1.3 GHz

Summary of SC cavity and magnets

- 2nd – 4th straight section
  - Super conducting cavity : 364
    - $\beta g = 0.93$: 108
    - $\beta g = 1.0$: 256
  - SC quadrupole magnet : 164

- Arc section
  - Rebuncher cavity : 9
  - NC quadrupole magnet : 608
  - NC bending magnet : 256

  } SuperKEKB's magnets could reuse.

Summary and Prospects

- For the next generation neutrino experiment, we check the feasibility of 9 GeV proton linac in the KEKB tunnel.
  ⇒ It is possible.
  - ILC-type RF cavities for the acceleration from 1.2 to 9 GeV
  - 4 ILC cavities + quadruple doublet in the 2nd straight.
  - 8 ILC cavities + quadrupole singlet in the 3rd and 4th straight.
  - Eightfold symmetric transverse lattice + 3 rebuncher cavities.
- We could extend beam energy to > 9 GeV by placing another straight section after the final arc section.
- Lots of things are needed to study.
  - Design of Injection part (～1.2 GeV).
  - Beam transport to a target.
  - etc.

Back up

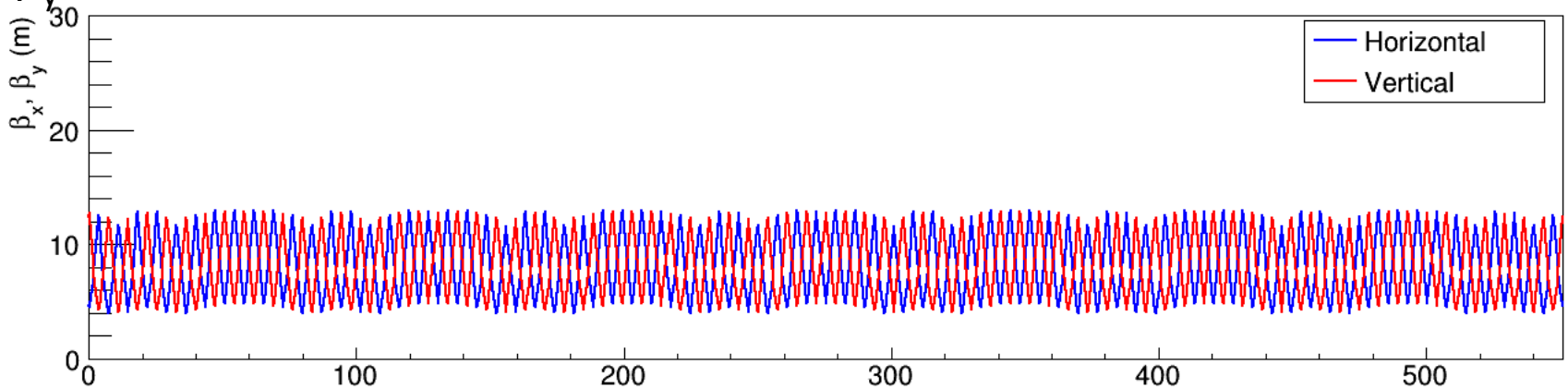
Issues

- Refrigerator
  - Power loss of a SC cavity
    - 1.5 W at E_0 = 30 MV/m and RF duty = 1.5 %.
    - 0.55 kW for all cavities.
  - Required AC power for 2 K refrigerator
    - 1 W at 2 K ⇒ 4.5 W at 4.2 K ⇒ 1.5 kW for AC power
    - 0.55 kW at 2K ⇒ 0.83 MW for AC power
- Input coupler
  - Available coupler : 2 MW at peak
  - Our target : 30 MV/m x 100 mA = 3 MW at peak
    ⇒ 50 % higher peak power than presently available one.
    ⇒ Need R&D.

Lattice of Arc Section

- Bending magnet x 64, core length = 0.800 m
- Quadrupole magnet x 152, core length = 0.375 m, drift length between Qs = 3.25 m
- Rebuncher cavity x 3, RF frequency = 0.65 GHz

β_x, β_y



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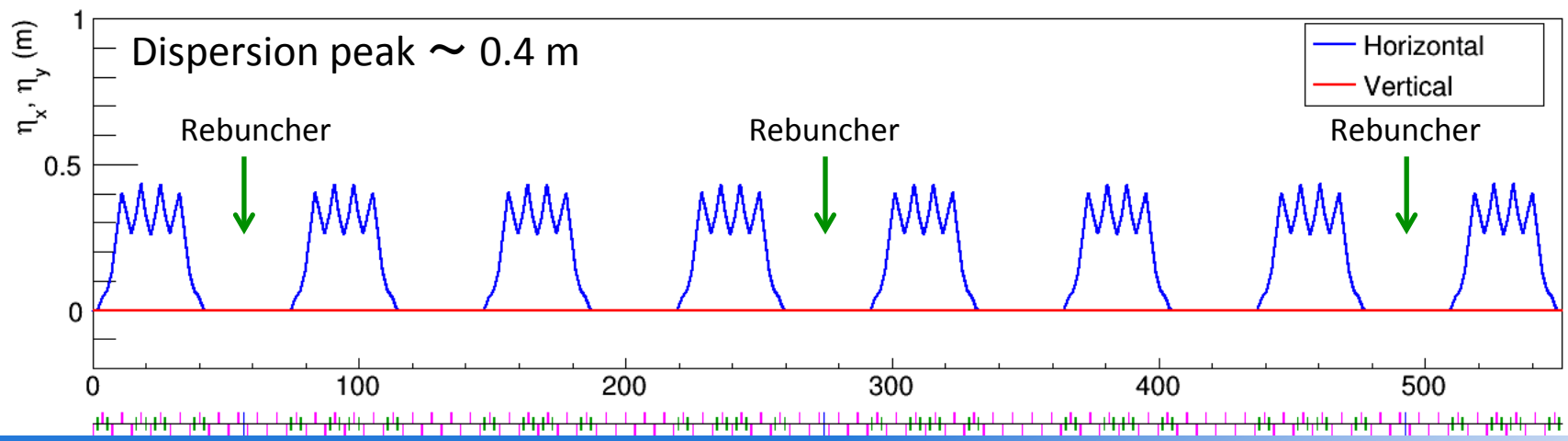
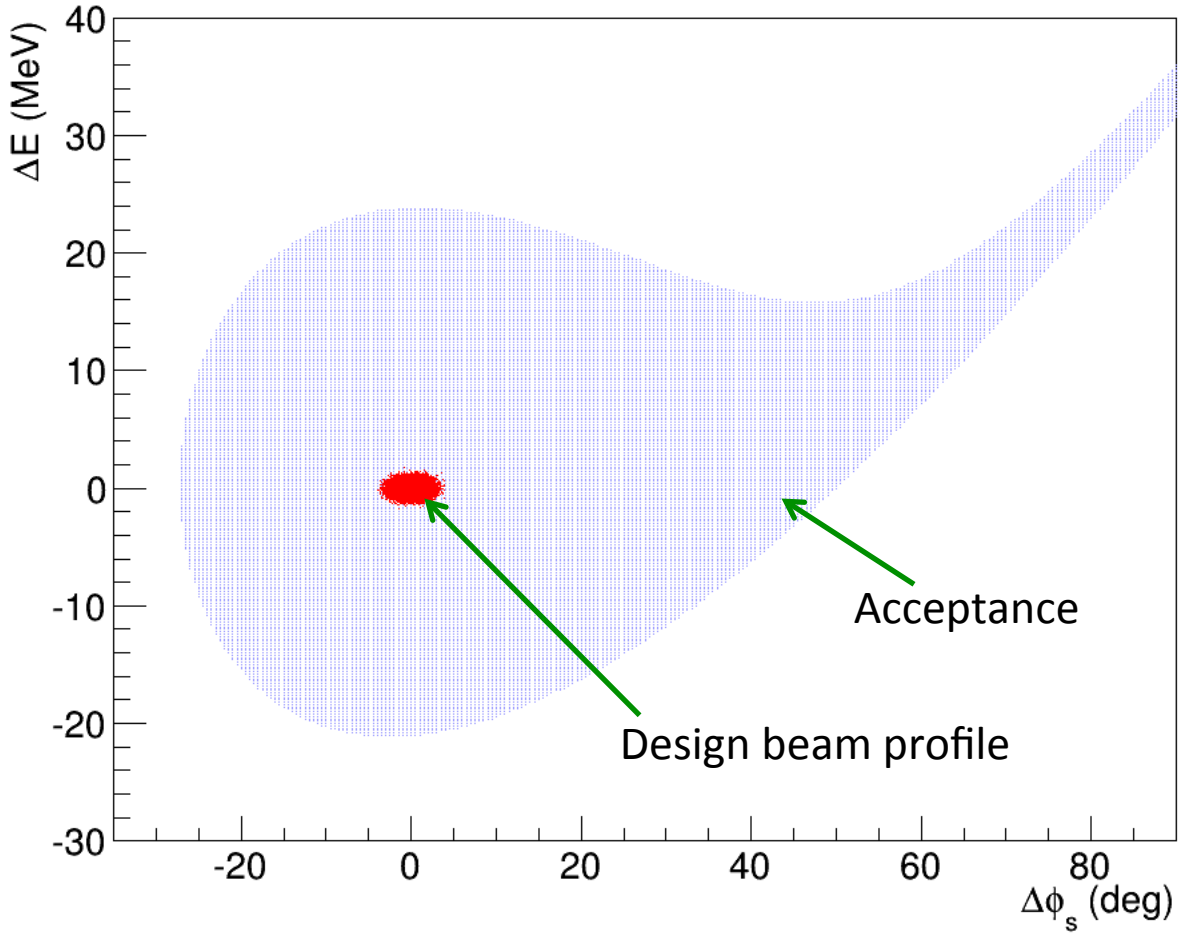


Longitudinal Acceptance of 2nd Straight



同期位相を-30degから-24 degに変えたことで、位相方向のアクセプタンスは～20%減少したが、99.9%ビーム幅（設計値）と比べて10倍広いため、問題無いと思われる。

Proton Sources - 2.45 GHz ECR - Status

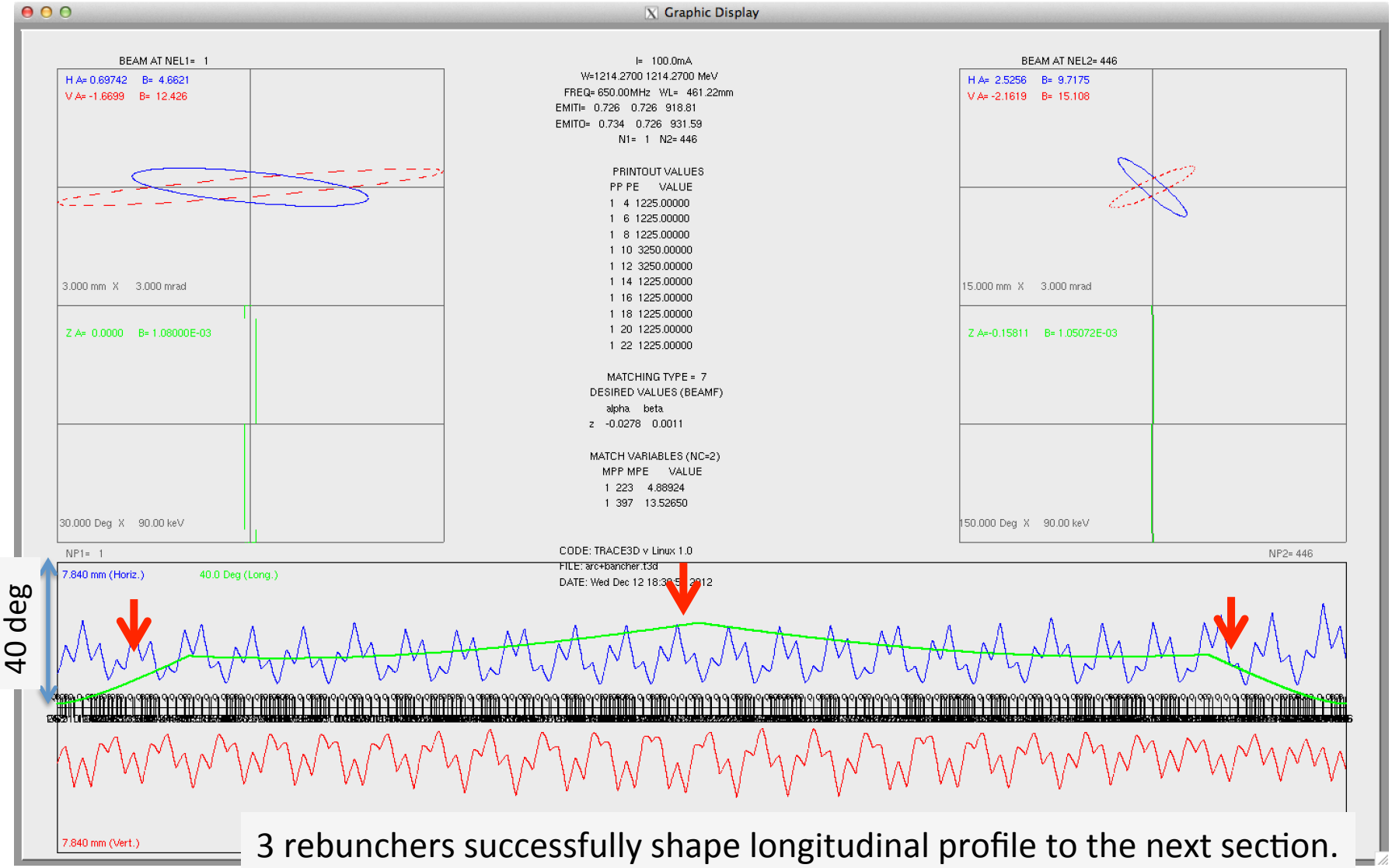
	CEA	TRIPS	LANL - LEDA	CEA
Type	2.45GHz ECR	2.45GHz ECR	2.45GHz ECR	2.45GHz ECR
Particle	p+	p+	p+	D+
Current (mA)	130	60	117	129
Duty Factor	100%	100%	100%	0.002
Dischange Power (W)	800	1000	800	900
Emittance	0.15†	0.18†	0.2	
H+/D+ Fraction	83%	90%	90%	96%
Lifetime (hrs)	336	142	480	

† Emittances are r-r'
Estimated (90% proton fraction)
Lifetime results are for available tests, not including HV sparking.
CEA Deuteron beam tests limited to avoid activation.

1st Arc Section w/ Rebunchers

Three rebunchers are placed.

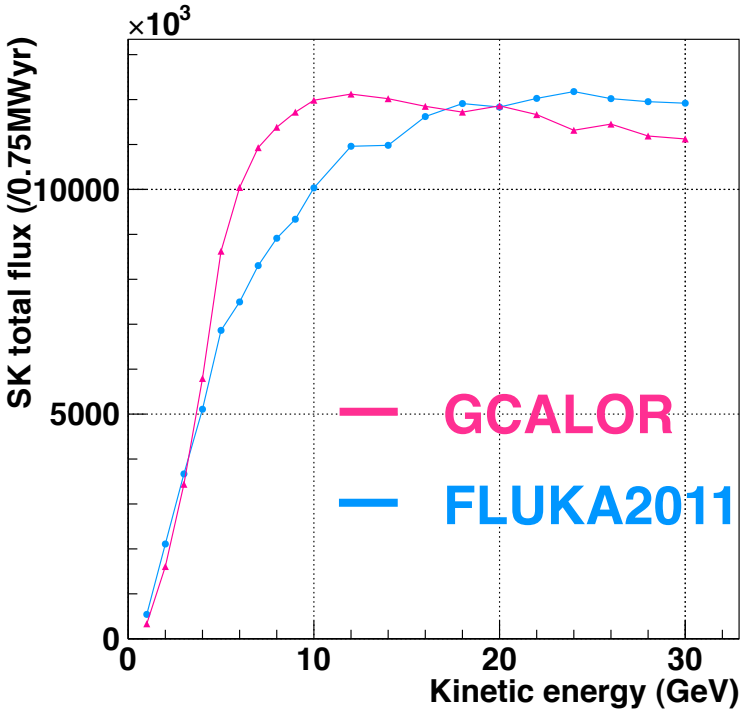
Peak current : **100 mA**



3 rebunchers successfully shape longitudinal profile to the next section.

Integrated ν Flux/energy vs. Beam Energy

Neutrino flux normalized by beam energy



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