Conceptual pre-injector design for the KEK-ERL test accelerator

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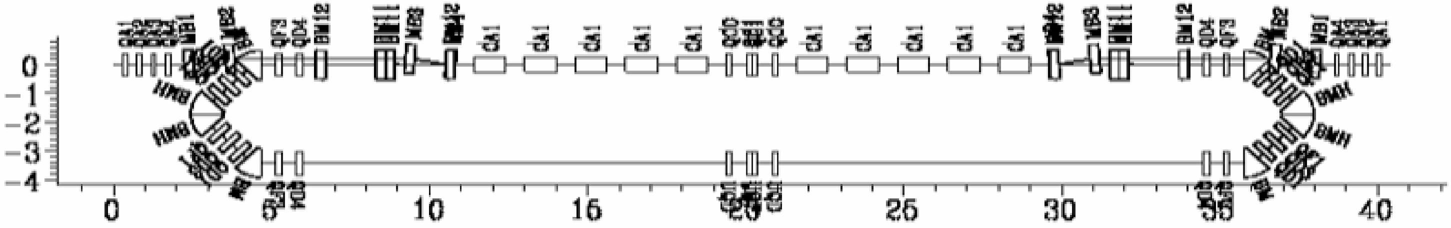
Introduction -brief history & present status-

- **PF division in Institute of Materials Structure Science (IMSS) started design study since 1997 for future PF and PF-AR (reuse of TRISTAN Accumulation ring).**
- **3rd-generation 4-GeV storage ring plan in 1998 was discussed.**
- **Discussions of ERL-based light source combined with a storage ring scheme started in 2002.**
- **Late 2002, plan with ERL alone, which needs to have many beam lines enough to satisfy requirement of both present users and sophisticated users.**
- **Conceptual design report of the 5-GeV KEK-ERL has been published in 2003 [**T. Suwada and A. Iida (eds.), ***Study Report on the Future Light Source at the Photon Factory -Energy Recovery Linac and Science Case-***, March, 2003; Report no. 200502003-KEK**].**
- **Since 2004, design work for the 200-MeV ERL test accelerator has been started towards its proof-of-principle.**

KEK-ERL Test Accelerator



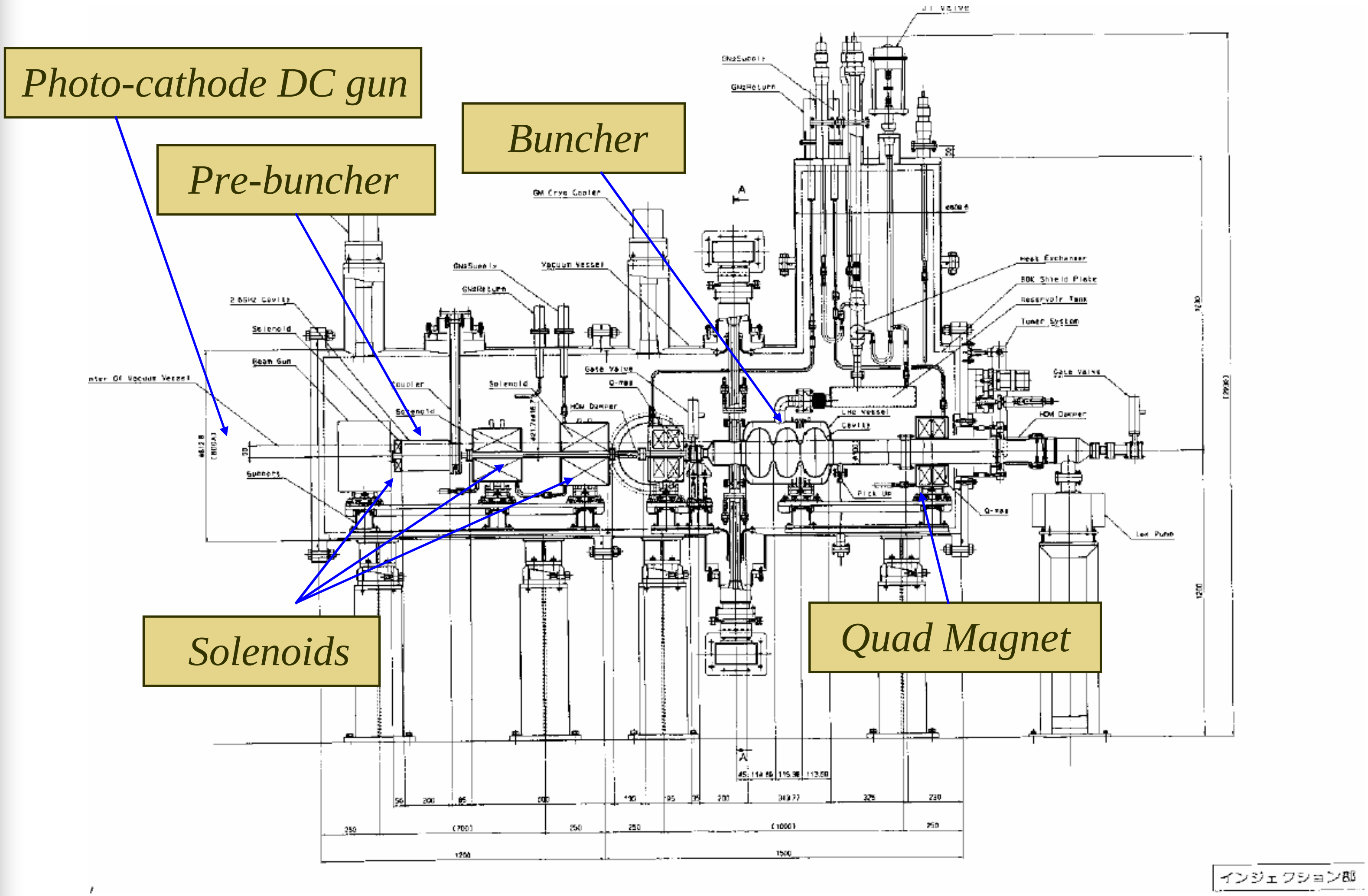
Main parameters

Energy	200MeV
Circumference	112.78m
Bunch length (rms)	1ps
Energy spread	3×10^{-4}
Bunch charge	77pC
Average current	100mA
Injection energy	5MeV
Trans. emit.(norm.)	0.1mm·mrad
Fundamental *rf* freq.	1.3GHz

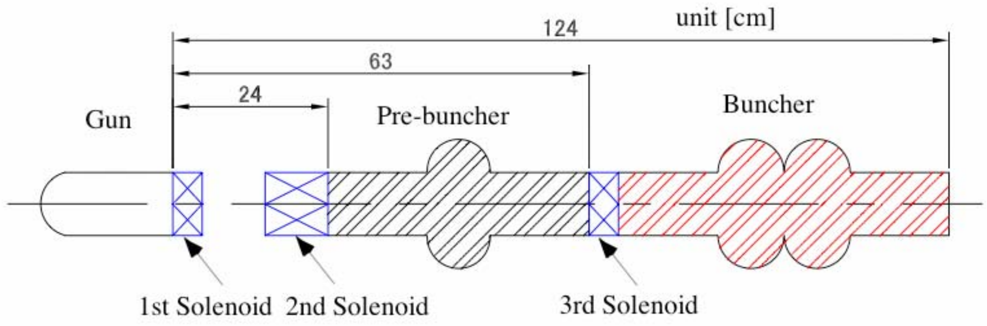
The schedule and funding are not clear yet!

E.-S.Kim and K.Yokoya, presented at *APAC2004*, Hotel Hyundai, Gyeongju, Korea, March 22-26, 2004.

Pre-Injector Design Layout



Pre-Injector Design Parameters for Numerical Simulation



Main parameters for simulation study

Gun high voltage	330 keV
Trans. beam size at gun (uniform)	ϕ1 mm
Bunch length at gun (uniform)	20 ps
Extraction energy	5 MeV
Bunch length after buncher	2 ps
Field gradient of 1-cell pre-buncher	10 MV/m, 1.3 GHz
Field gradient of 2-cell buncher	35MV/m, 1.3 GHz
1st solenoid field/Length	500 Gauss/4.5cm
2nd solenoid field/Length	480 Gauss/9.5cm
3rd solenoid field/Length	220 Gauss/10cm

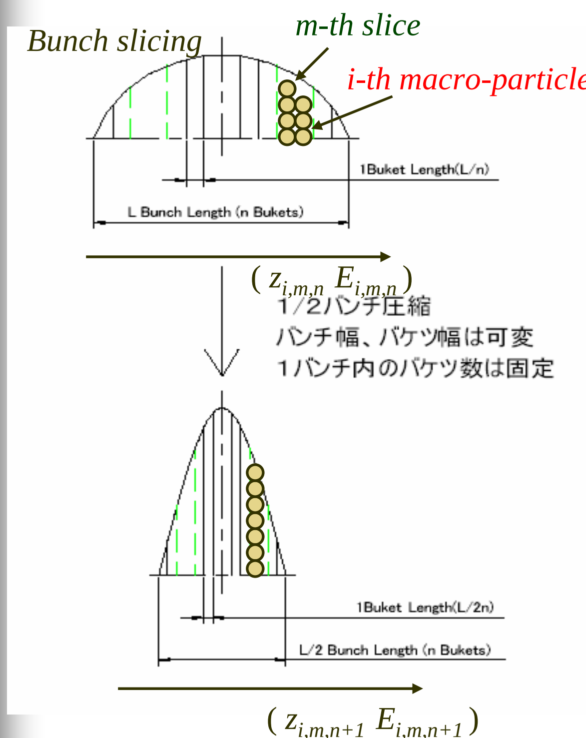
Motivation and New Simulation Code

- ***Motivation***
  - **Several particle tracking simulation codes such as "*Parmela*", "*ASTRA*" and "*GPT*" are generally used for a design of a pre-injector in rf linear accelerators.**
  - **They requires a lot of CPU time for performing fully rigorous simulations based on a 3D particle tracking simulations including space charge effect.**
  - **However, in the initial conceptual design stage, it is difficult to quickly survey physical parameters in terms of accelerator devices (*rf* phase, *rf* amplitude, magnetic focusing, Gun HV…) and beam characteristics itself, which must be optimized in a multi-dimensional parameter space.**

- ***New Simulation Code***
  - **A new simulation code is under way in order to quickly and simply simulate the beam dynamics of an electron bunch at the pre-injector in its initial design stage.**
  - **The bunch motion is simply described using semi-analytical longitudinal and transverse beam dynamics based on well-known envelope equations including space charge effect.**

Simulation study of the pre-injector: Longitudinal beam dynamics

The bunch is longitudinally divided into thin sliced bunches in which macro-particles are distributed by following the longitudinal particle distribution of the bunch.



The longitudinal motion of each macro-particle is developed in time evolution of a small time step (Δt) using the energy and z-position relations of the i-th macro-particle within the m-th sliced bunch after the n-th small time step,

$$E_{i,m,n+1} = E_{i,m,n} + (E_{sc}(z_m) + E_{rf}(z_m))\beta_{i,m,n} c\Delta t$$

$$\Delta z = c\Delta t\left[\frac{1}{\sqrt{1-1/\gamma^2_{i,m,n+1}}} - \frac{1}{\sqrt{1-1/\gamma^2_{i,m,n}}}\right],$$

where the space charge field (E_{sc}) is derived by the space charge potential (ϕ_{sc}) assuming the bunch geometry of an uniform density concentric ellipsoid,

$$\phi_{sc}(z) = \frac{2\rho(z)ab}{\varepsilon_0}\sum_{k=1}\frac{J_0\left(\frac{a}{b}\alpha_k\right)J_1\left(\frac{a}{b}\alpha_k\right)}{\alpha_k^3 J_1(\alpha_k)^2}\left(1-\exp\left(-\frac{\alpha_k z_l}{b}\right)\right)\cosh\left(\frac{\alpha_k z}{b}\right)$$

$$E_{sc}(z_m) = \frac{\phi_s(z_m - 2\Delta z_{sl}) - 8\phi_s(z_m - \Delta z_{sl}) + 8\phi_s(z_m + \Delta z_{sl}) - \phi_s(z_m + 2\Delta z_{sl})}{12\Delta z_{sl}\gamma^2}$$

Simulation study of the pre-injector: Transverse beam dynamics

Transverse envelope equation for the m-th sliced bunch

$$\frac{d^2 a_m}{dz^2} + \frac{\gamma'}{\beta^2\gamma}\frac{da_m}{dz} + k a_m - \frac{1}{a_m}\frac{2I_m}{I_0(\beta\gamma)^3} = 0,$$

where k indicates an external force, for rf focusing force,

$$k = \frac{\pi e E_0 \sin\psi(t)}{\lambda m_e c^2 \beta^2 \gamma},$$

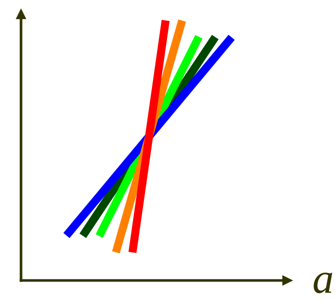
and for solenoidal magnetic focusing force,

$$k = \left(\frac{eB}{2m_e c\beta\gamma}\right)^2,$$

Using a Tayler-series expansion on the envelope, the differential equation is linearized by

$$\frac{d^2 a_m}{dz^2} + \frac{\gamma'}{\beta^2\gamma}\frac{da_m}{dz} + \left(k - \frac{1}{a_{0,m}^2}\frac{2I_m}{I_0(\beta\gamma)^3}\right)a_m = 0,$$

Transverse Phase Space of Envelopes



Transformation of the envelope is analytically described using a transfer matrix for $\omega^2{}_0 \geq 0$,

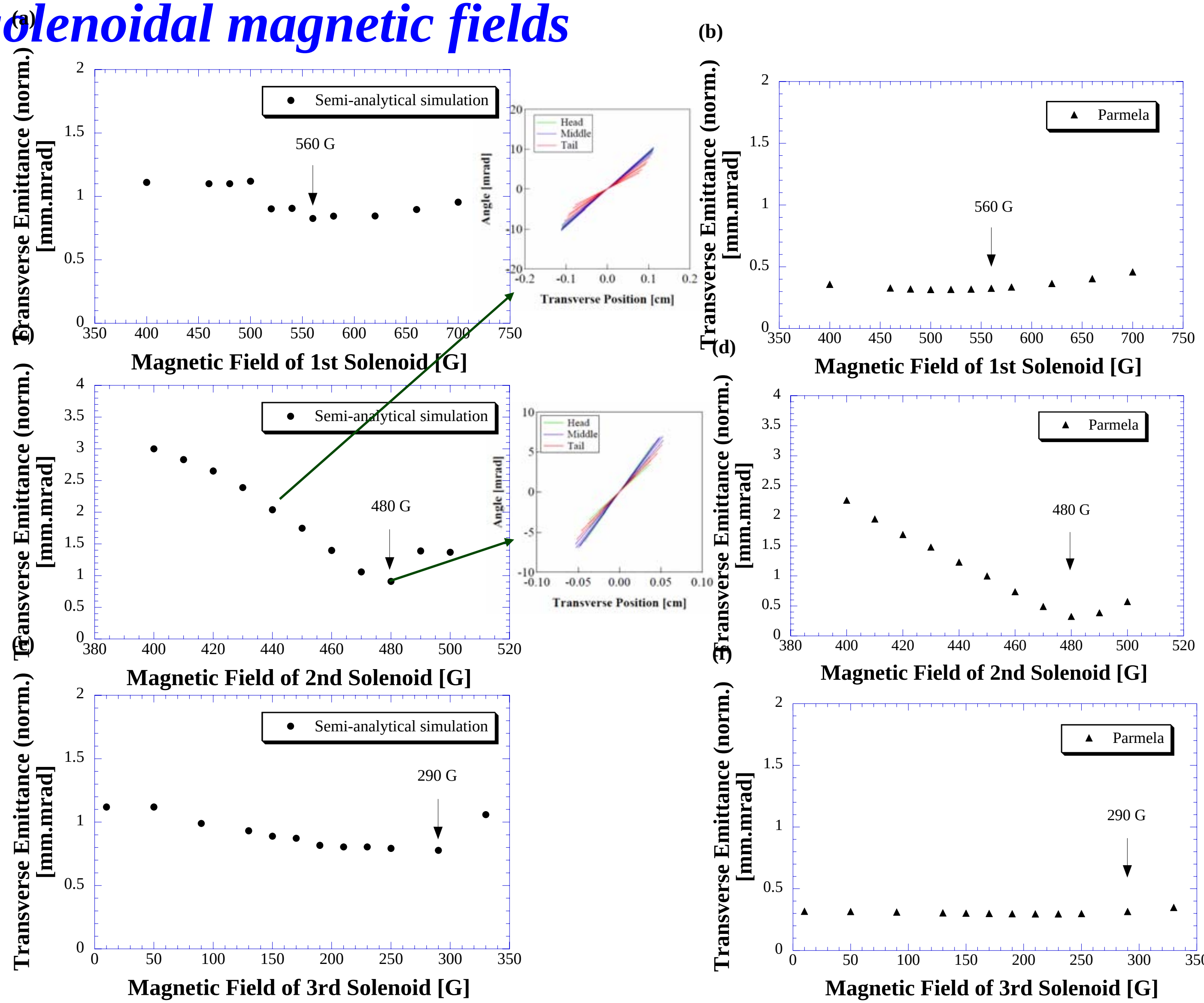
$$\begin{pmatrix} a_{m,n+1} \\ a'_{m,n+1} \end{pmatrix} = \begin{pmatrix} e^{-\Gamma\Delta t/2}\cos(\omega_0\Delta t) & e^{-\Gamma\Delta t/2}\sin(\omega_0\Delta t)/\omega_0 \\ -\omega_0 e^{-\Gamma\Delta t/2}\sin(\omega_0\Delta t) & e^{-\Gamma\Delta t/2}\cos(\omega_0\Delta t) \end{pmatrix}\begin{pmatrix} am,_n \\ a'_{m,n} \end{pmatrix},$$

and the transformation of the envelope is for $\omega^2{}_0 < 0$,,

$$\begin{pmatrix} a_{m,n+1} \\ a'_{m,n+1} \end{pmatrix} = \begin{pmatrix} e^{-\Gamma\Delta t/2}\cosh(\omega_0\Delta t) & e^{-\Gamma\Delta t/2}\sinh(\omega_0\Delta t)/\omega_0 \\ \omega_0 e^{-\Gamma\Delta t/2}\sinh(\omega_0\Delta t) & e^{-\Gamma\Delta t/2}\cosh(\omega_0\Delta t) \end{pmatrix}\begin{pmatrix} a_{m,n} \\ a'_{m,n} \end{pmatrix},$$

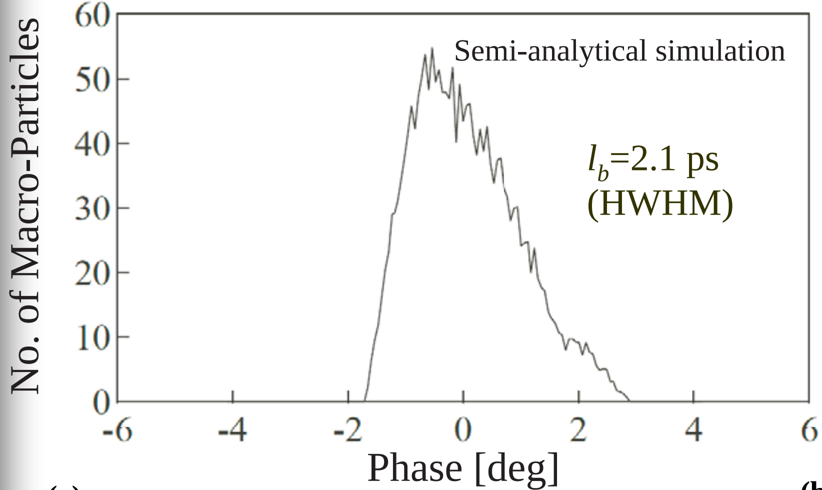
where $\Gamma = \frac{\gamma'}{\beta^2\gamma}$, *and* $\omega_0^2 = \beta c\left(k - \frac{1}{a_{0,m}^2}\frac{2I_m}{I_0(\beta\gamma)^3} - \frac{1}{4}\Gamma^2\right)$

Numerical Simulation Results: Variations of the transverse emittance depending on the solenoidal magnetic fields

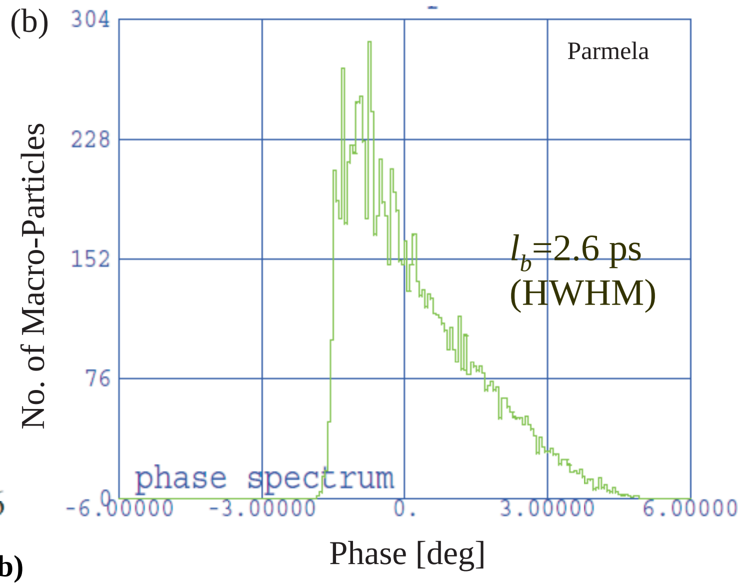


Numerical Simulation Results: Longitudinal macro-particle distributions at the exit of the pre-injector

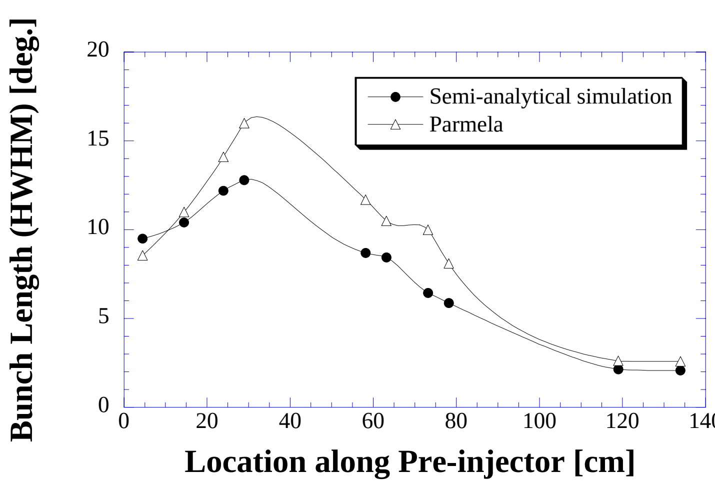
(a)



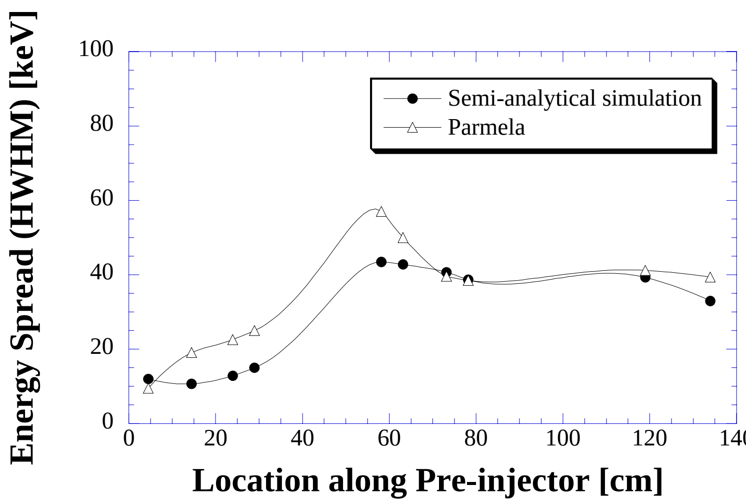
(b)



(a)



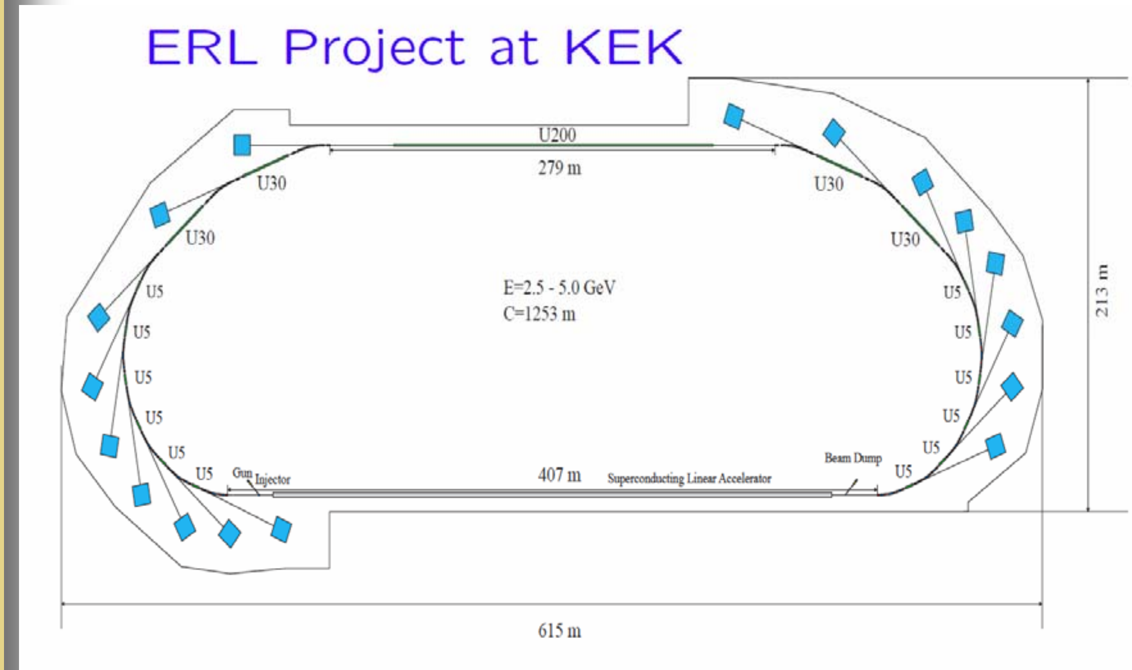
(b)

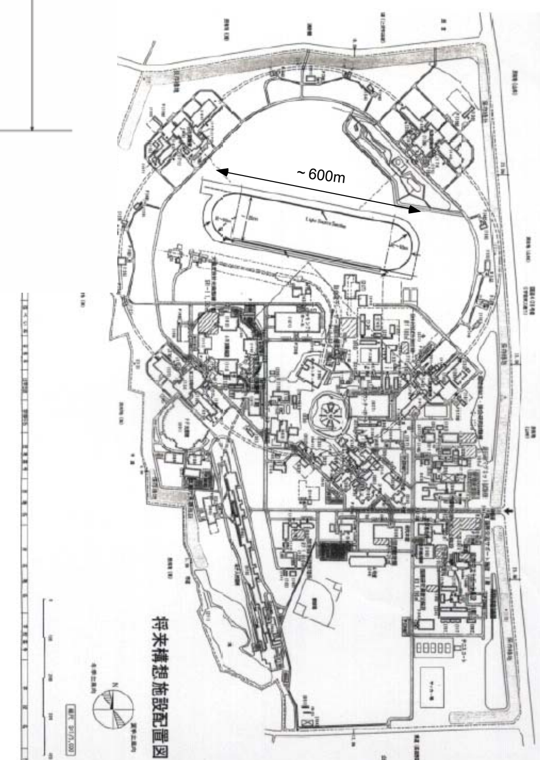


Summary

- A conceptual pre-injector design study for the KEK-ERL test accelerator is under development using the new simulation code in order to optimize the accelerator devices and beam parameters in the initial design stage.
- The new simulation code simply describes semi-analytically the time evolution of a bunch motion in the transverse and longitudinal phase spaces.
- For the longitudinal motion, the difference is about 30% at maximum in comparison with the Parmela code.
- For the transverse motion, although the quantitative consistency is not very good between these two codes, the new code reproduced qualitatively well the Parmela results.
- The new code reduces the CPU time by an order of 0.1 times for the optimization calculation at the expense of the calculation accuracy in comparison with the Parmela code.
- IMSS together with Accelerator Division started the KEK-ERL 200-MeV test accelerator design towards its proof-of-principle of future next-generation light source.
- Several simulation studies are under way (beam dynamics for main linac, pre-injector, BBU, CSR effect, bunch compression, *etc*.).
- And also several R&D tasks (high voltage DC photo-cathode gun, basic study on HOM absorbers for SRFs, *etc*.) has started since the end of last year.

KEK-ERL Conceptual Design Layout





The dimensions of the 5-GeV KEK-ERL
must be inside the KEKB rings
at Tsukuba campus.

K. Yokoya, presented at *APAC2004*, Hotel Hyundai, Gyeongju, Korea, March 22-26, 2004.

Main Parameters

- **Main parameters**
  - **Circumference length** **1253m**
  - **Beam energy** **2.5(*1st*)→5GeV(*2nd stage*)**
  - **Acceleration rf frequency** **1.3 GHz**
  - **Acceleration gradient** **10(*1st*)→20MV/m(*2nd stage*)**
  - **Injection Energy** **10MeV**
  - **Beam current at max.** **100mA**
  - **Bunch charge** **77pC**
  - **Transverse emittance (norm.)0.1mm·mrad**
  - **Relative energy spread** **5 x 10^{-5}**
  - **Bunch length (rms)** **1~2ps (in main linac)**
  - **Bunch length (rms) <100fs (after bunch compression in arc)**

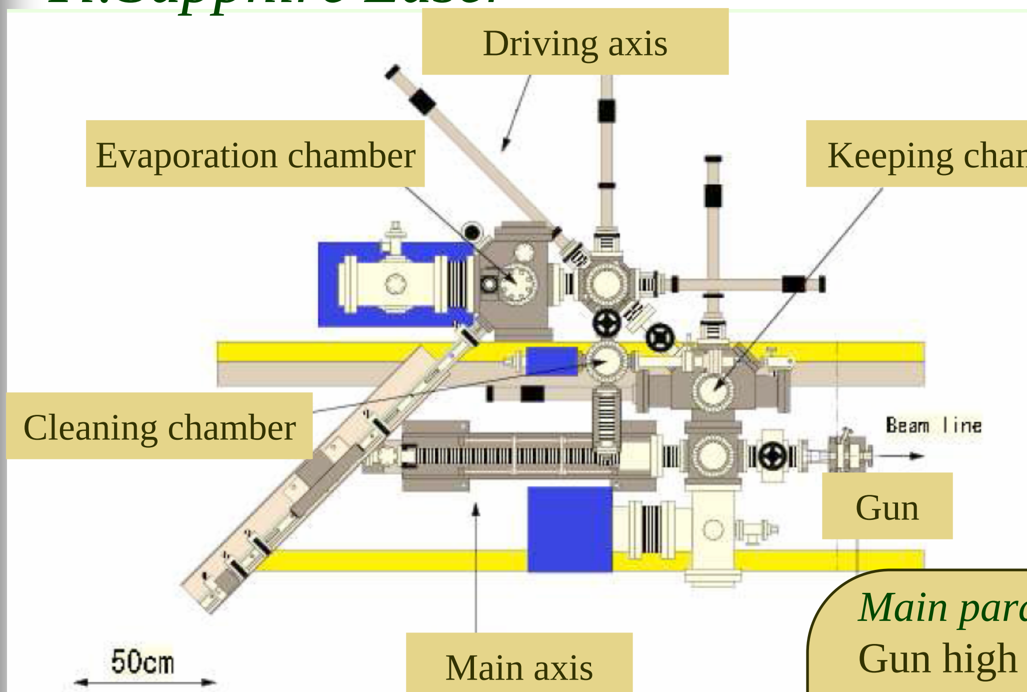
Required Specification

- ***Special photon characteristics required by scientists***
  - **Generation of high-bright hard X-ray (~1Å) by 1st harmonic at diffraction limit**
  - **Generation of very short pulsed photon with a pulse length of femto-second region.**
  - **Dedicated 100-m-long undulator**
- ***Required specification for light source***
  - **Number of insertion device**
    - **5-m-long(~20), 30m-long(2~4), >100m-long(1)**
  - **Average photon brightness@λ=0.1nm(~12keV)**
    - **~10^{22} (ph/s/0.1%/mm^2/$mrad^2$)**
  - **Average photon flux@λ=0.1nm(~12keV)**
    - **~10^{16} (ph/s/0.1%)**

T. Suwada and A. Iida (eds.),
Study Report on the Future Light Source at the Photon Factory -Energy Recovery Linac and Science Case-, March, 2003 [in Japanese]; Report no. 200502003-KEK.

DC Photo-Cathode Gun

with NEA(Negative Electron Affinity) GaAs and Ti:Sapphire Laser



Main parameters (ultimate goal)

Gun high voltage	500 kV
Trans. beam size	ϕ1 mm
Bunch length	~20 ps
Average current	100 mA
Bunch charge	77 pC
Trans. emittance (norm., rms)	0.1 mm·mrad
Longitudinal emittance (rms)	4 keV·deg
Repetition rate	1.3 GHz