John Adams Institute for Accelerator Science

Imperial College London

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITY OF OXFORD

Particle Beam Characterisation

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John Adams Institute for Accelerator Science

At Royal Holloway, University of London

oPAC Advanced School on Accelerator Optimisation

7-11 July 2014, Royal Holloway College, Egham, UK

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Outline

- 6D phase space distribution
  - Motivation
  - Transverse Phase-Space
  - Longitudinal Phase-Space
- Accelerator Operation Principles
  - Accelerator Test Facility (ATF2 at KEK in Japan)
  - Beam production, pre-acceleration, injection, damping, extraction, delivery, characterization and main acceleration, application and termination
- Summary

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High Luminosity

$$L = \frac{P_b}{E_{CM}} \frac{N}{4\pi\sigma_x\sigma_y} H_D$$

Here

P_b is the beam power

E_{CM} is the centre of mass energy

N is the number of particles in the interaction

σ_x and σ_y are the horizontal and vertical dimensions of the collision area

H_D is the luminosity enhancement factor determined by inter-bunch focusing effect, bunch length, etc.

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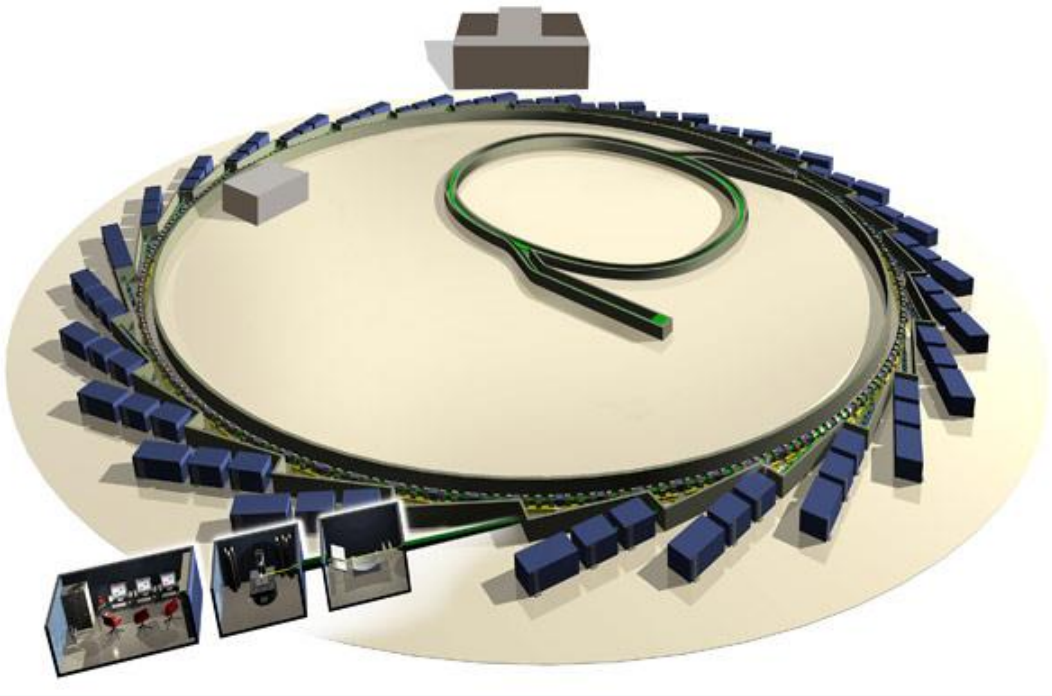
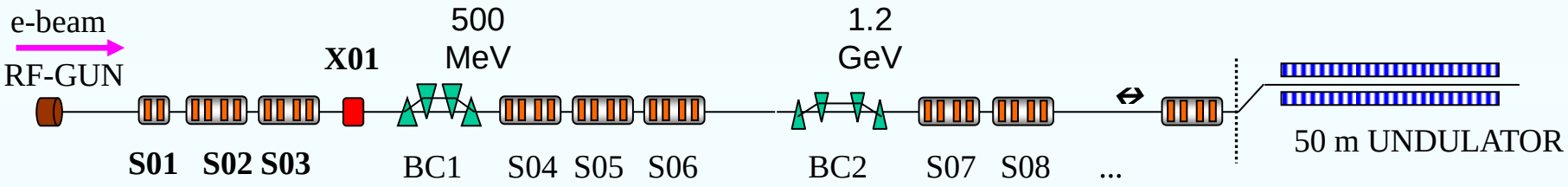
Low divergence X-rays

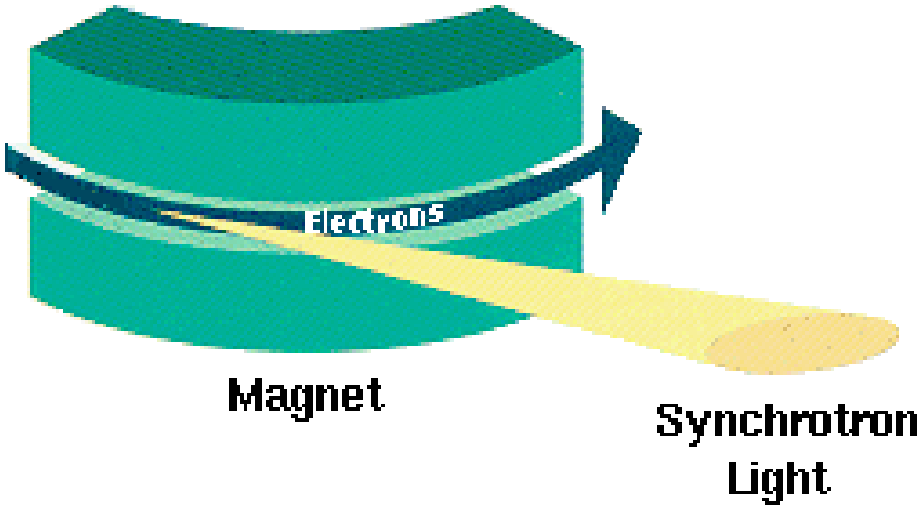


3rd Generation Light Source

4th Generation Light Sources

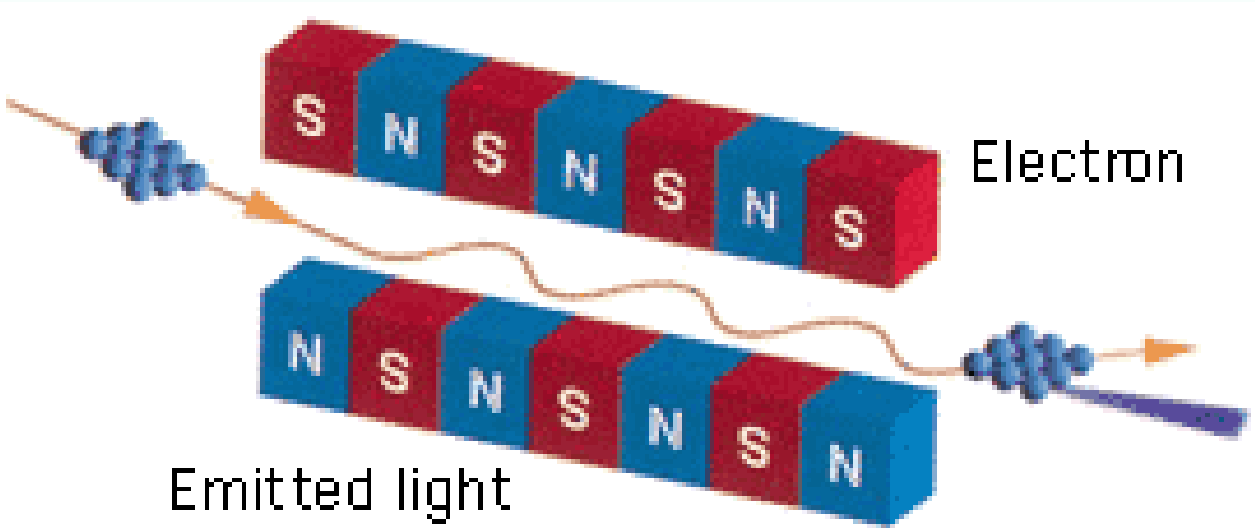


Low divergence X-rays



Single bending magnet

Undulator or wiggler



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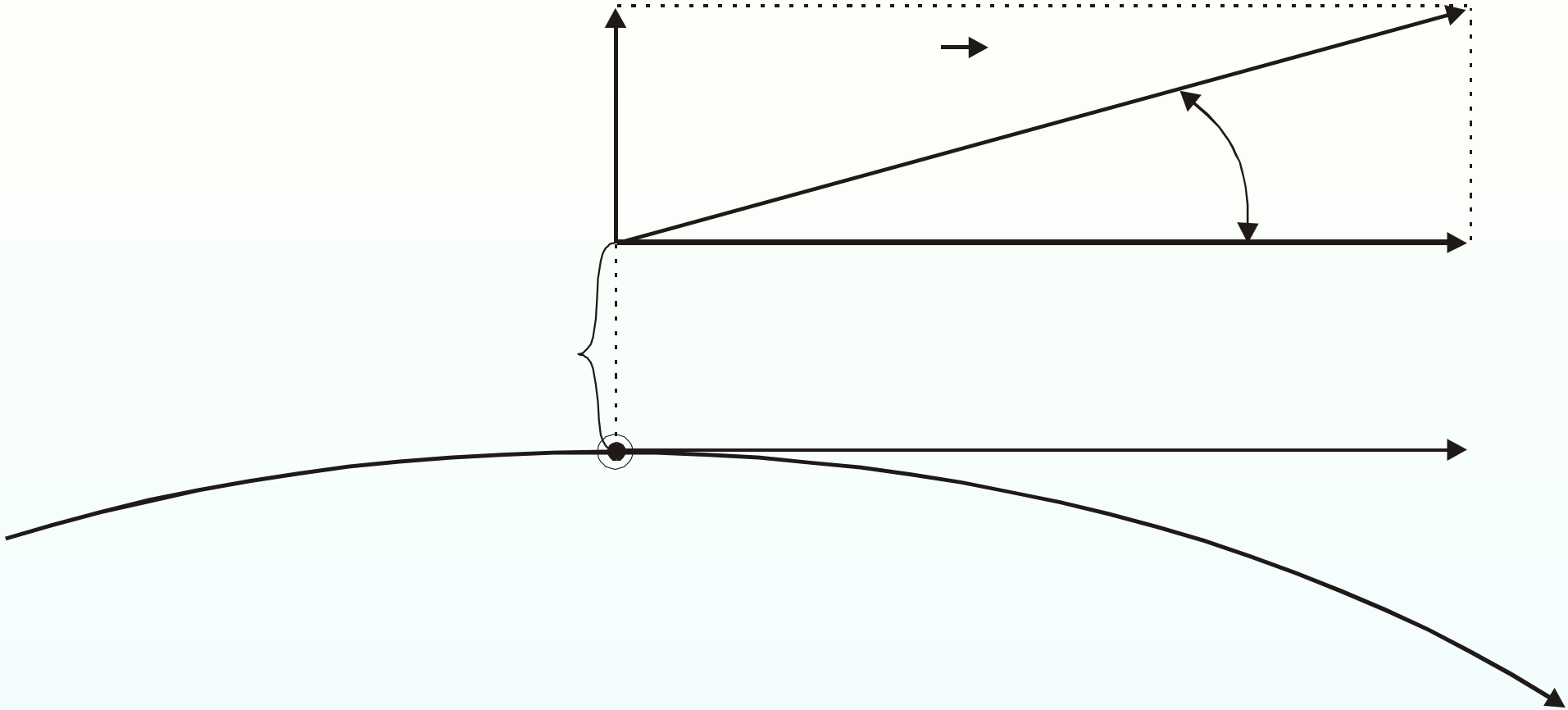
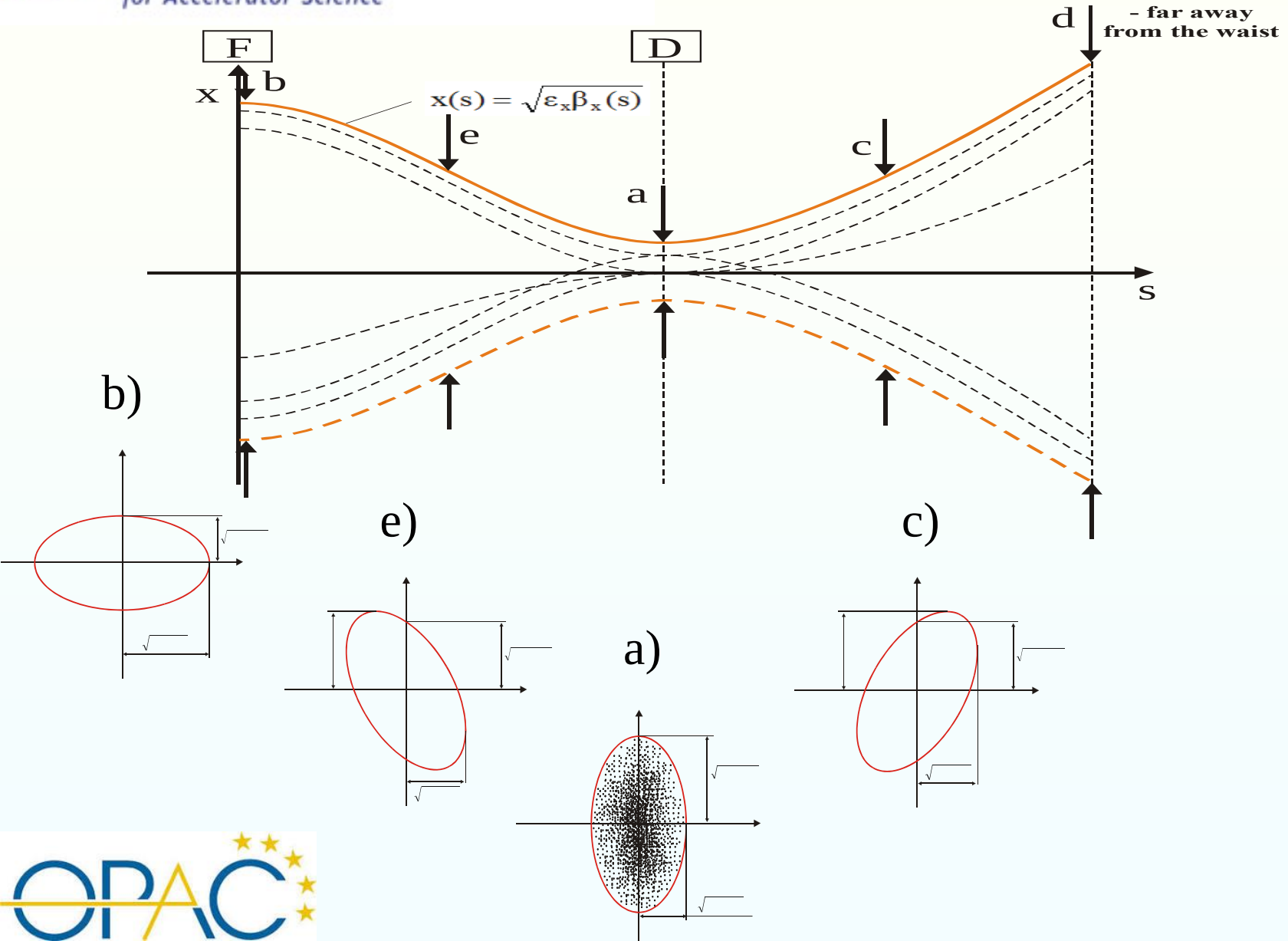
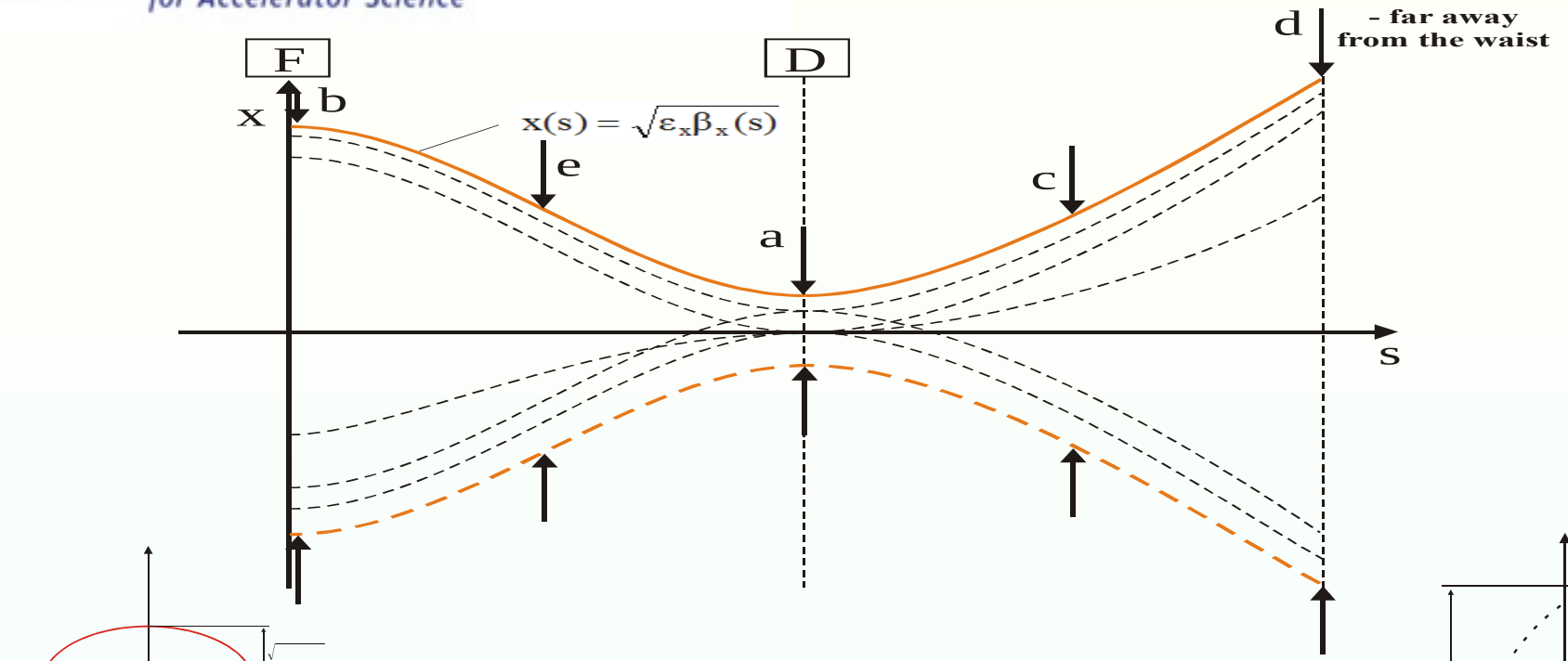
Transverse Phase – Space

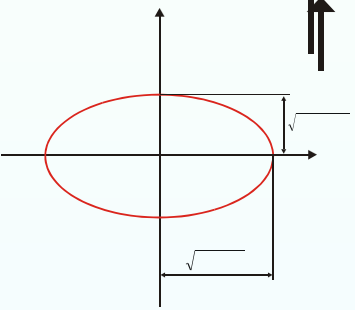


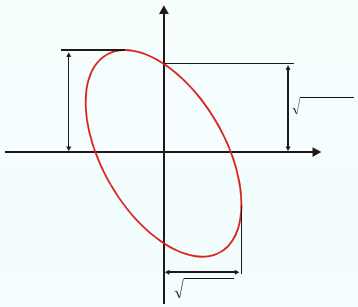
Transverse Phase – Space

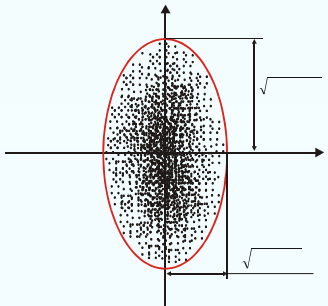


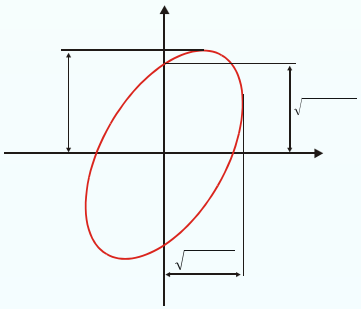
Transverse Phase – Space

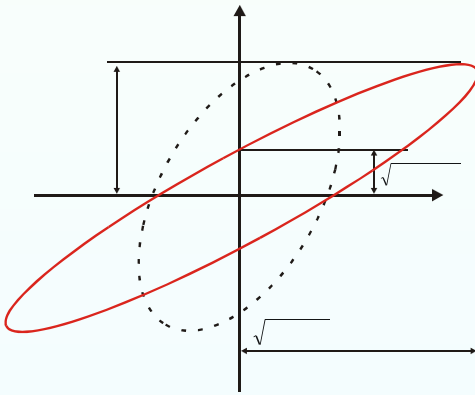












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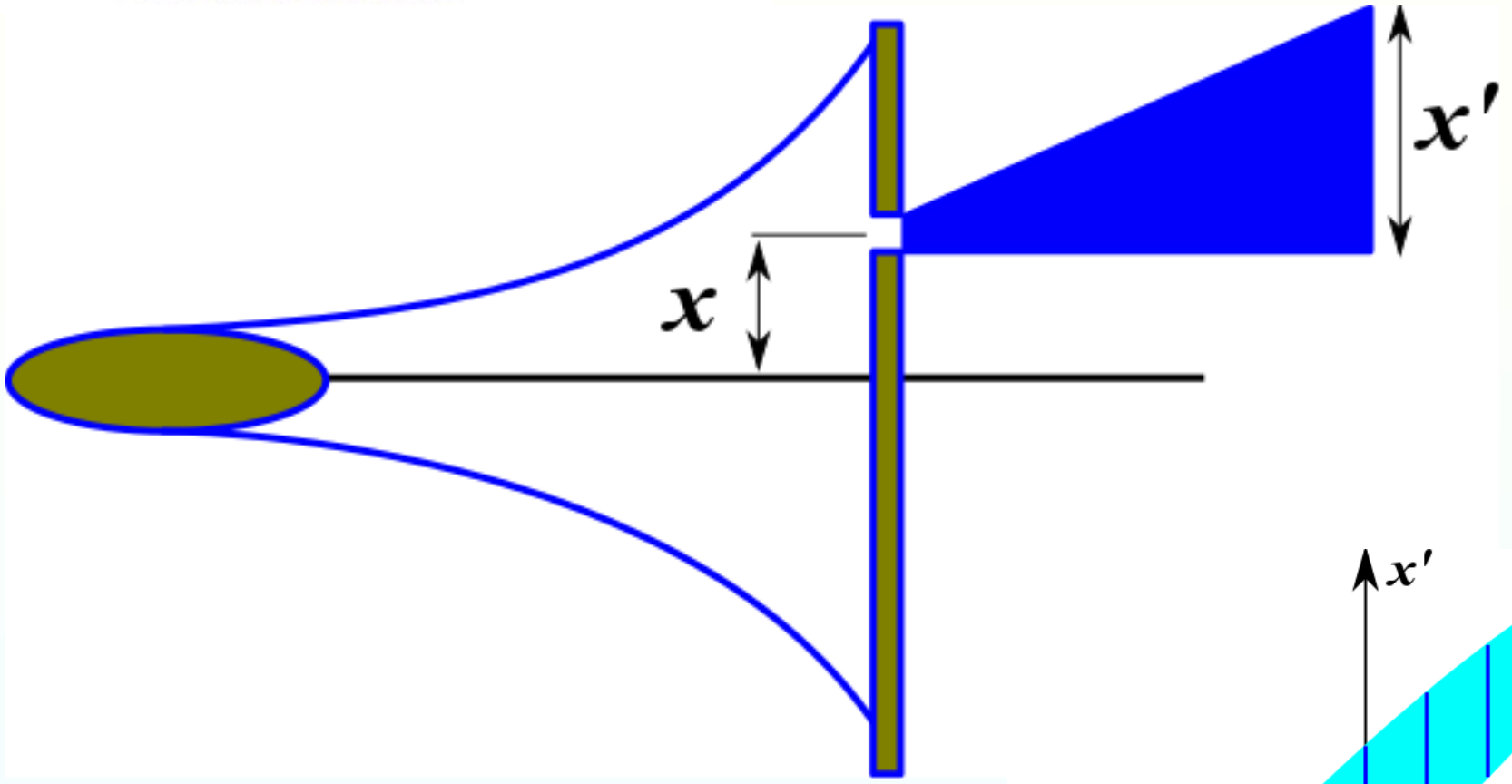
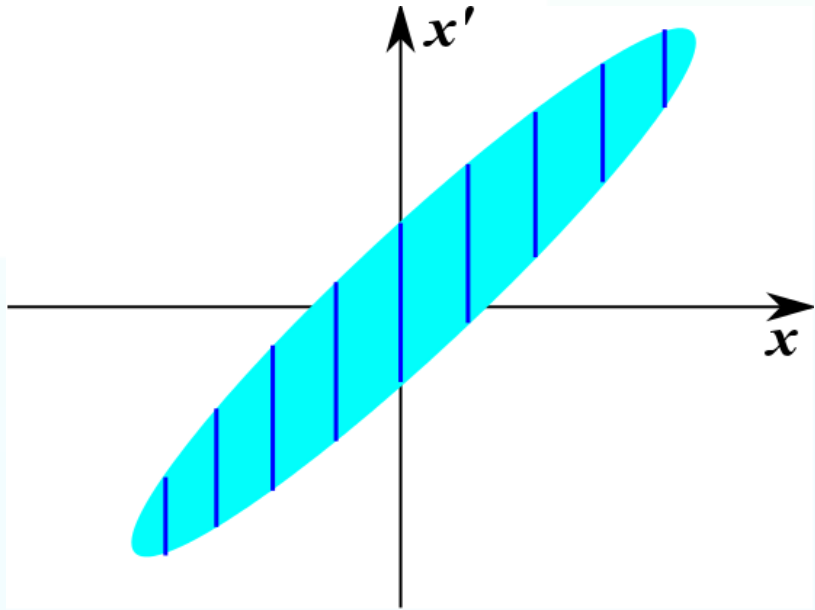
Emittance Characterization
Direct method





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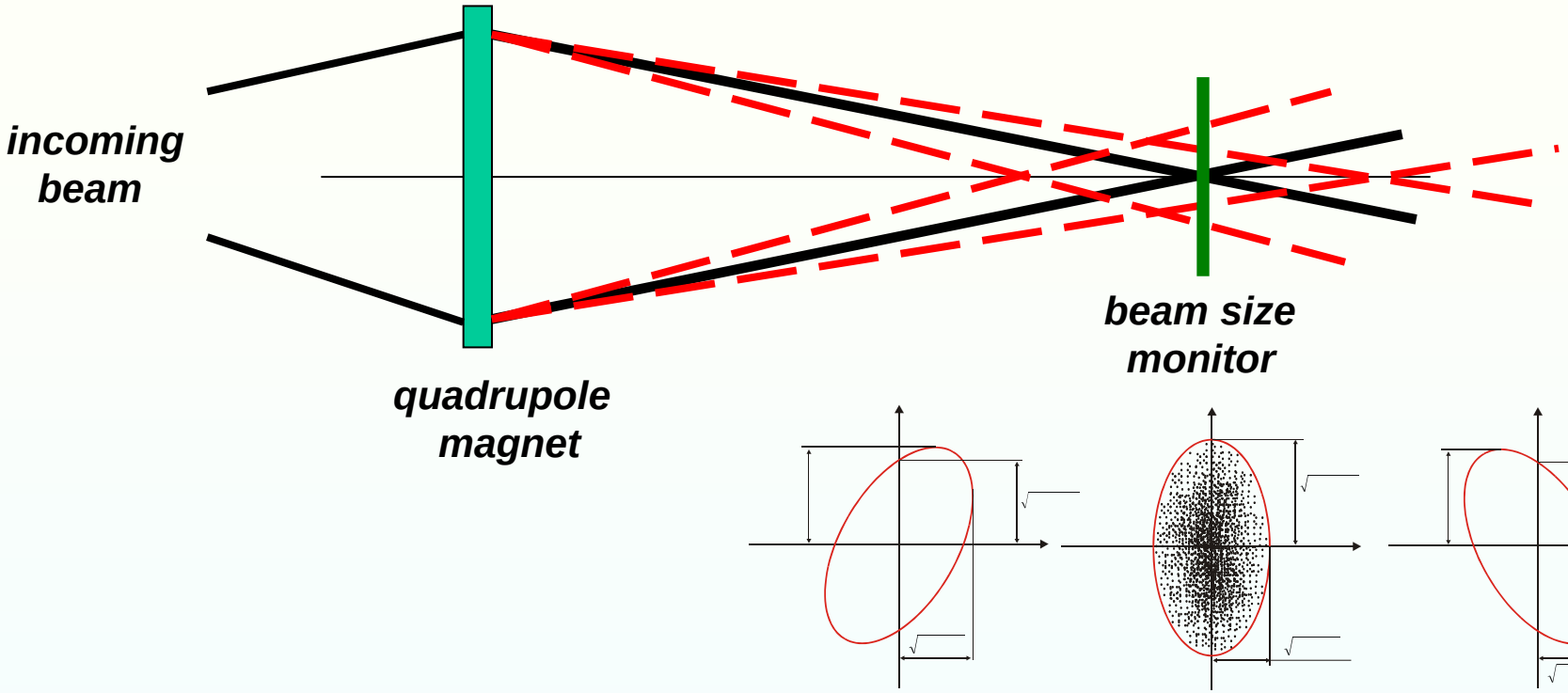
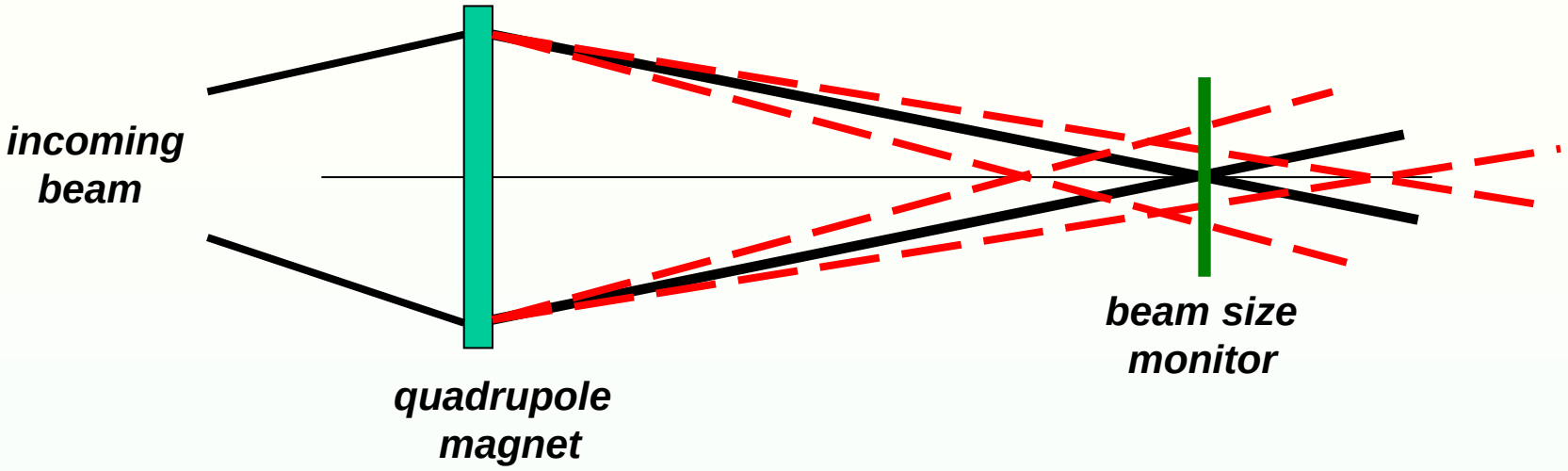
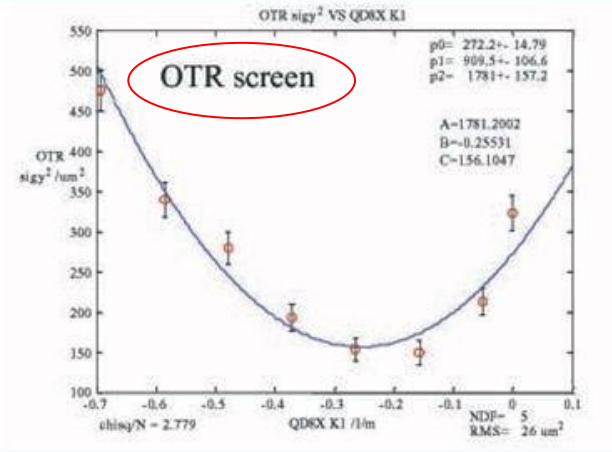
Emittance Characterization
Quadrupole Scan



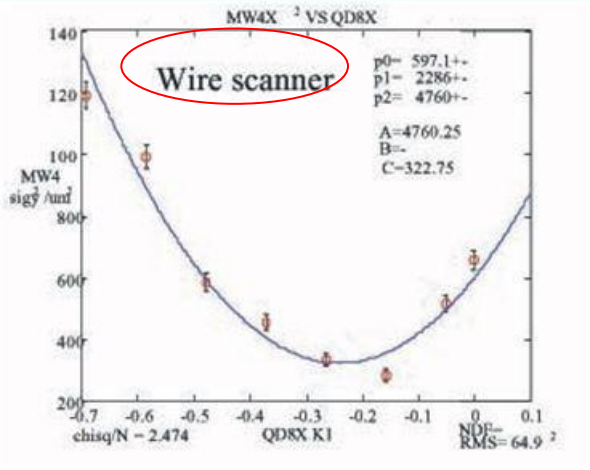
Emittance Characterization
Quadrupole Scan



ε_y = 41pm rad



ε_y = 38pm rad



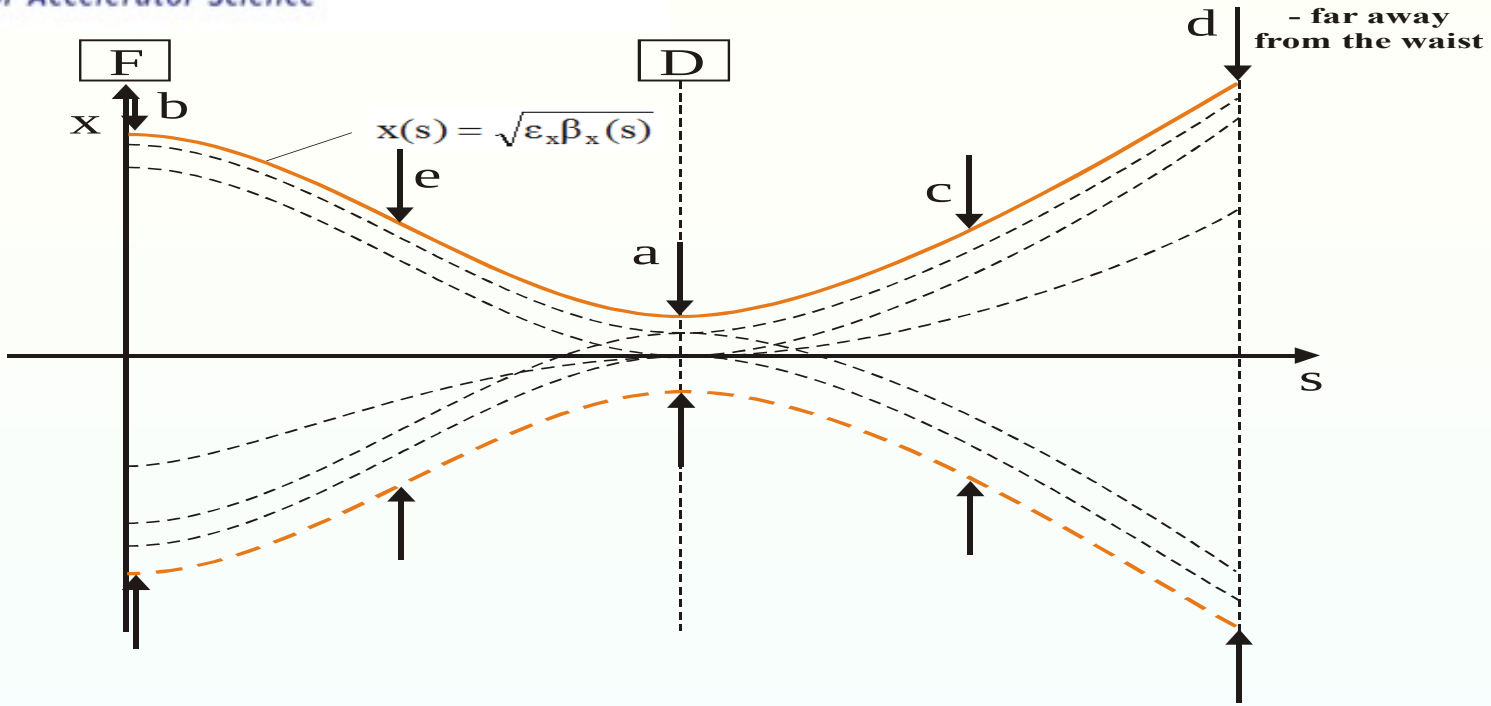
$$\sigma_x^2 = B_x \left(K - A_x\right)^2 + C_x$$

$$\varepsilon_x = \frac{\sqrt{B_x C_x}}{m_{12}^2}$$

$$\beta_{x,0} = \sqrt{\frac{B_x}{C_x}}$$

$$\alpha_{x,0} = \frac{m_{11} - m_{12} A_x}{m_{12}} \beta_0$$

Emittance Characterization
Multi-BSM



3 Beam Profile Monitor ;

60 degrees of phase advance in between the monitors

4 Beam Profile Monitor ;

40-50 degrees of phase advance

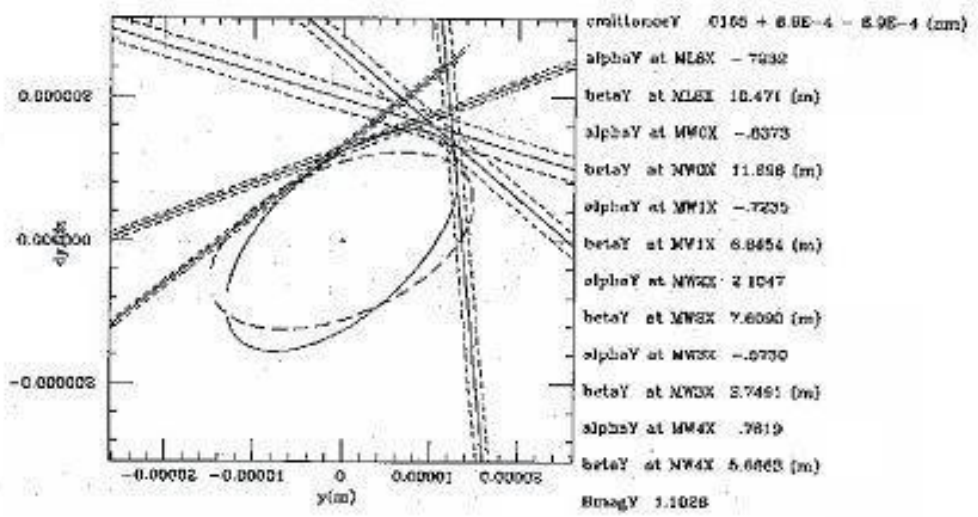
We can evaluate the error of the emittance measurement system.

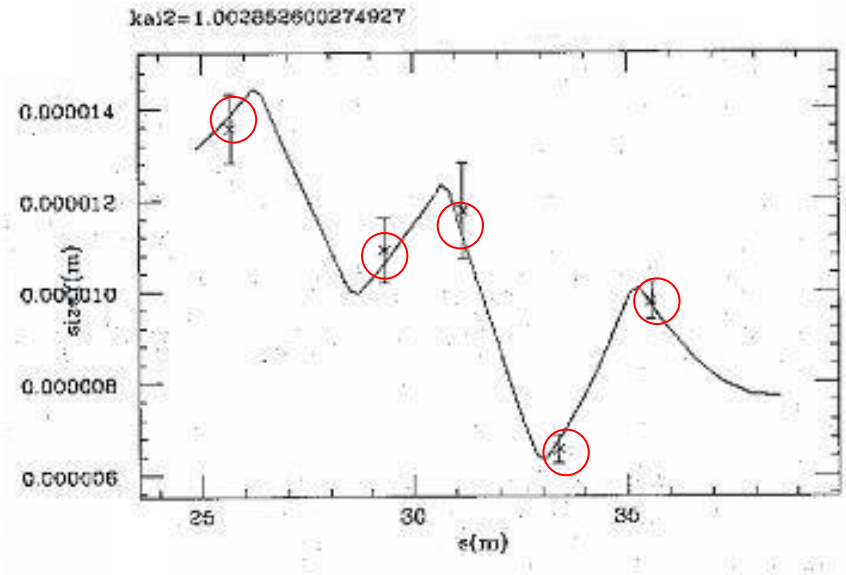
5 beam Profile Monitor ;

30-50 degrees of phase advance are better setting.

We can make a cross check of each measurement .

Emittance Characterization
Multi - BSM





Emittance = 16.5 pm rad

5 wire scanners are used to measure the beam emittance

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Transverse beam size measurement techniques

Invasive:

- Fluorescent Screens
- OTR monitors
- Wire scanners
  - ✓ Direct imaging
  - ✓ PSF technique

Non-Invasive:

- Laser-Wire
  - ✓ e-beams – Compton scattering
  - ✓ H^- beams – Photo-detachment
- ODR monitor
- Synchrotron Radiation
  - ✓ Direct imaging
  - ✓ Interferometers
  - ✓ Pin-hole camera

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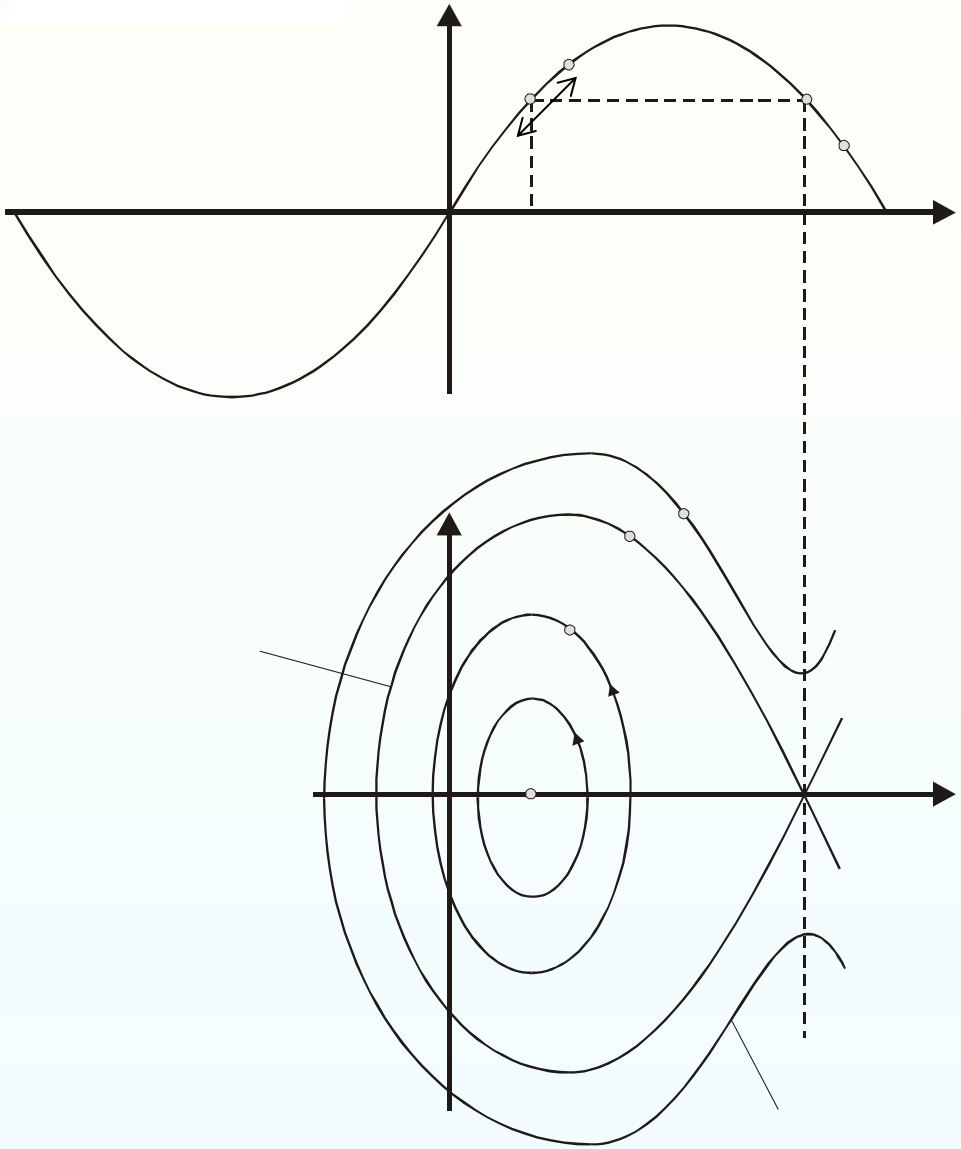
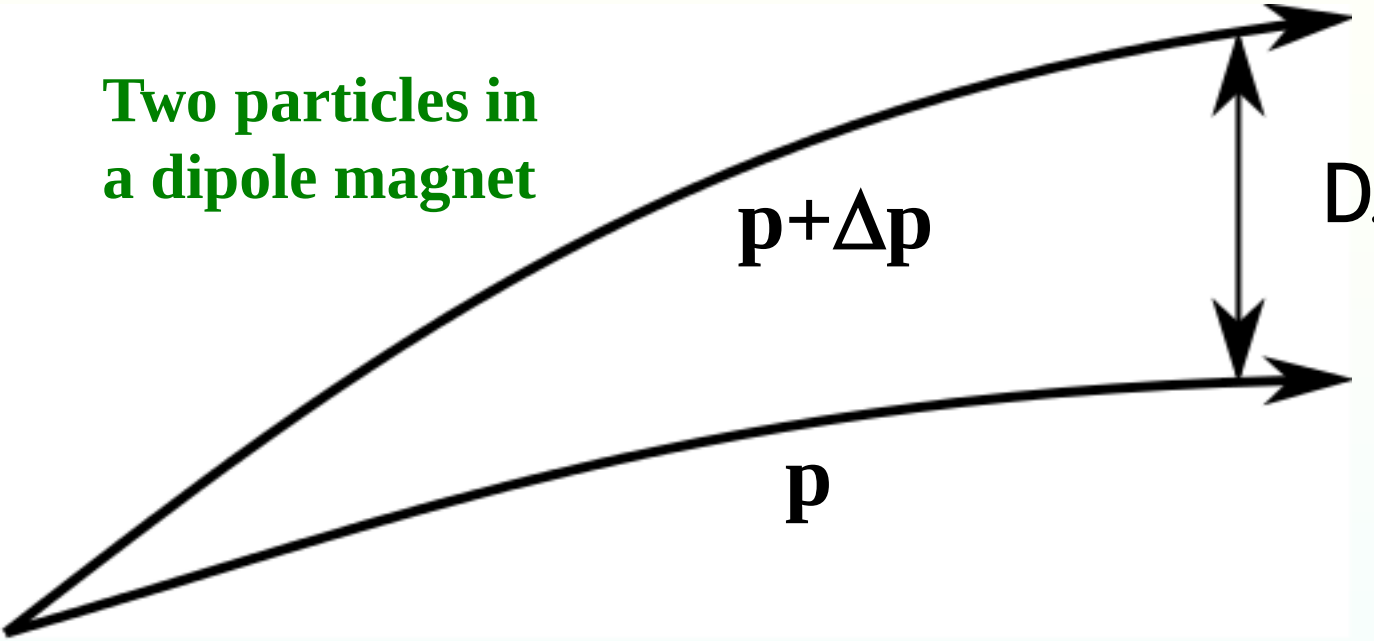
Longitudinal Phase-Space



Dispersion Function and Energy Spread Measurement

Two particles in a dipole magnet



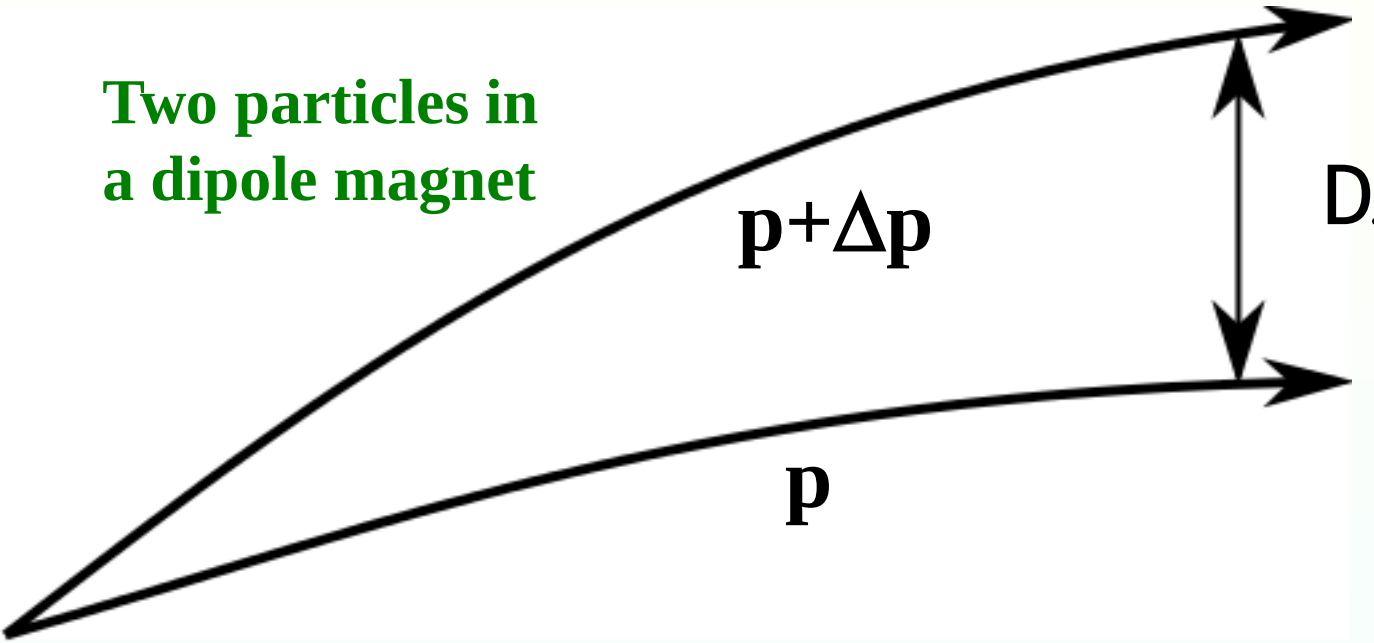
$$\Delta x = D_x \frac{\Delta E}{E}$$

Transverse Beam Size

$$s_x = \sqrt{e_x b_x + D_x^2 \left(\frac{\Delta E}{E} \right)^2}$$

Dispersion Function and Energy Spread Measurement

Two particles in a dipole magnet



$$\Delta x = D_x \frac{\Delta E}{E}$$

Beam Energy Spread measurement

$$\sigma_x \approx D_x \frac{\Delta E}{E} \Rightarrow \boxed{\frac{\Delta E}{E} = \frac{\sigma_x}{D_x}}$$

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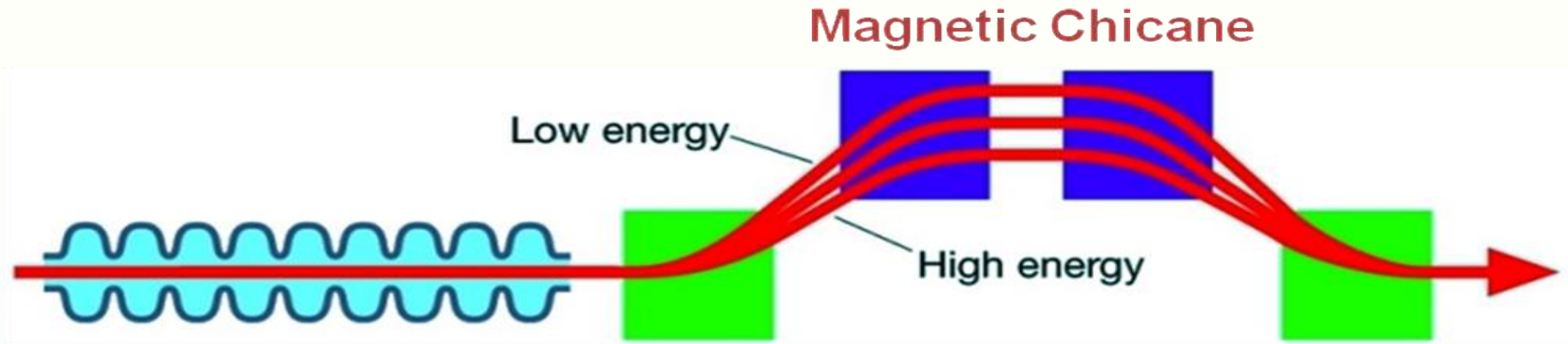
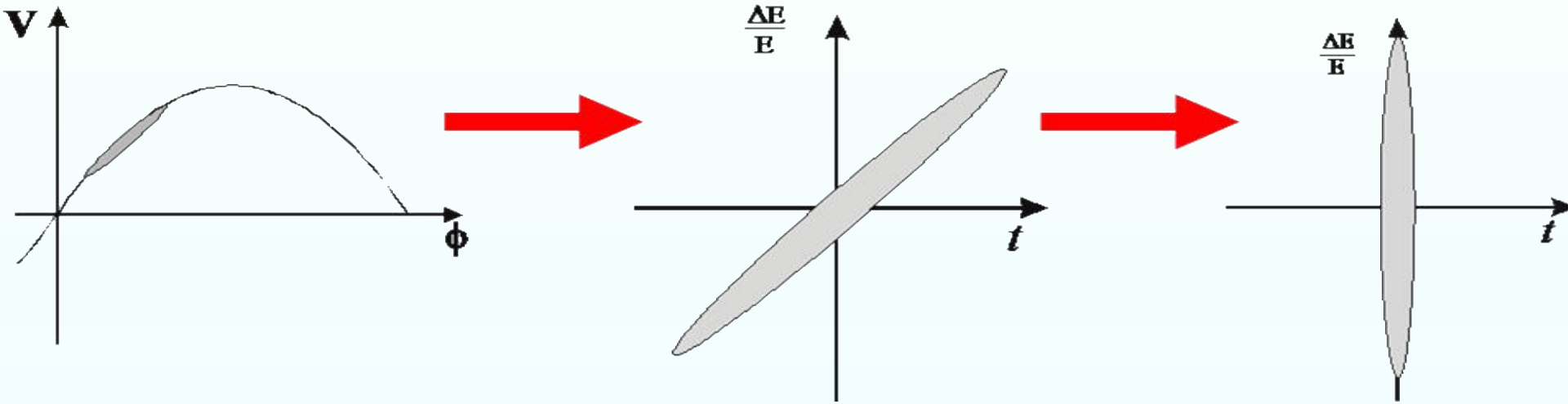
Dispersion Compression





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Bunch Length Characterization

Laser based techniques:

- Laser-Wire scanner
  - Beam-laser time jitter
- Non-linear mixing
  - Destructive
- E-O techniques

RF techniques:

- Streak Camera
  - External source
- RF deflecting cavity
  - Destructive
- RF Accelerating cavity

Coherent radiation spectrum:

- Synchrotron radiation
- Transition radiation
- Diffraction radiation
- Smith-Purcell radiation
- Cherenkov Diffraction rad.

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Operation Principles

- Beam production
- Pre-acceleration
- Injection
- Damping, storage or accumulation
- Extraction
- Delivery
- Characterization and main acceleration
- Application and
- Termination

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KEK-ATF2 facility in Japan

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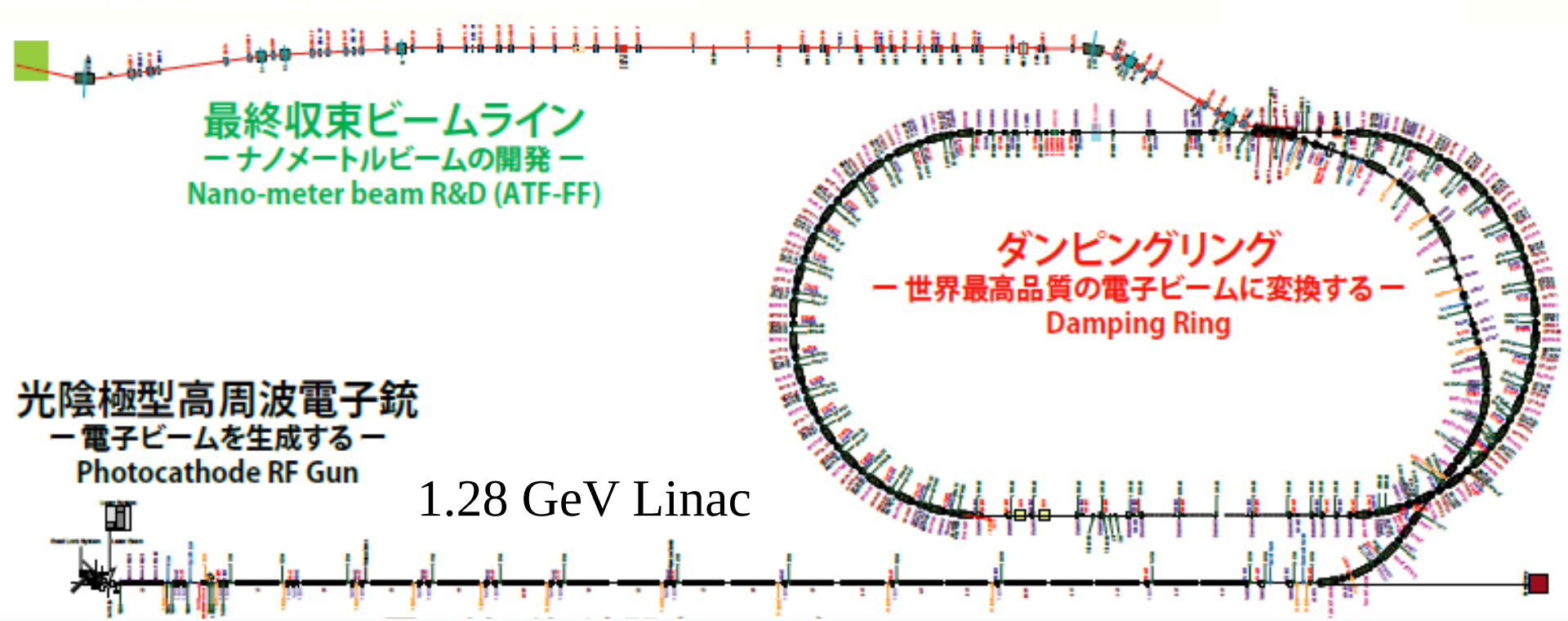
ATF2 Extraction Line



Beam Energy [GeV]	**1.3**
Energy Spread (e^+/e^-) [%]	0.06~0.08
Vertical beta function at IP (β^*_y) [mm]	0.1
Vertical emittance [pm]	**12**
Vertical beam size at IP (s^*_y) [nm]	**37**

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Beam current monitors

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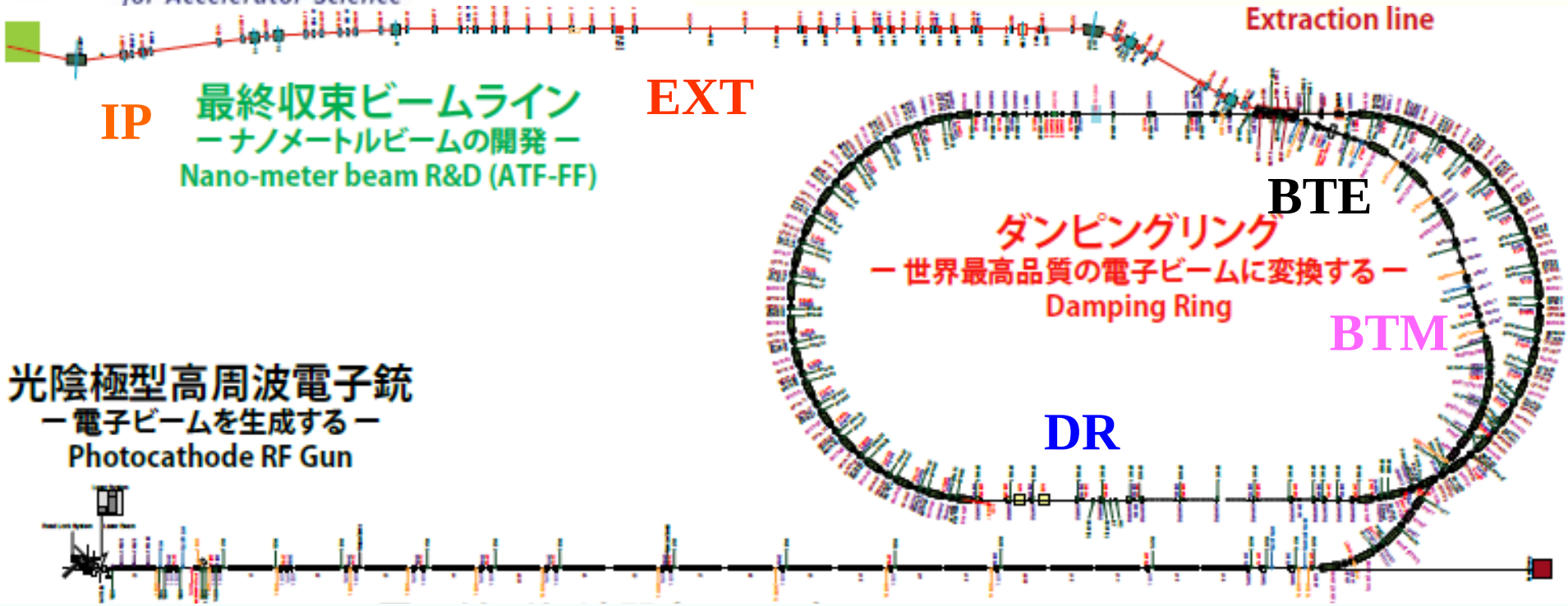

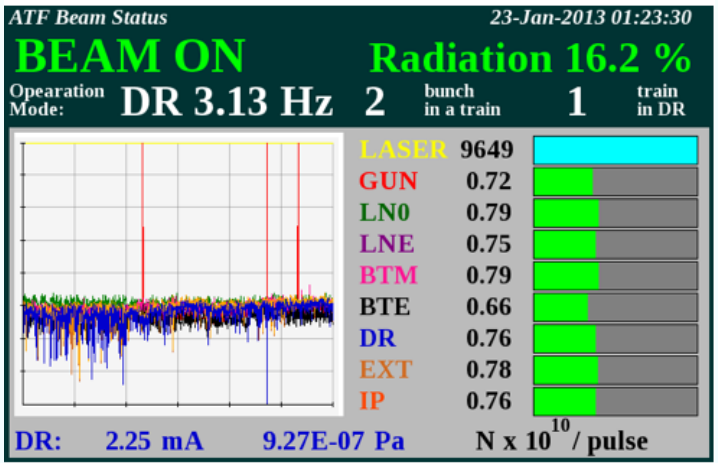

RF GUN and 80MeV pre-accelerator

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RF GUN

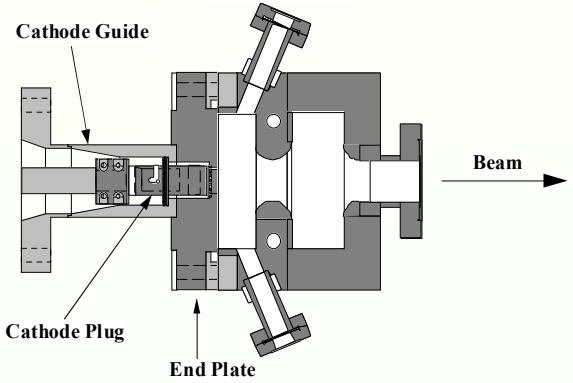
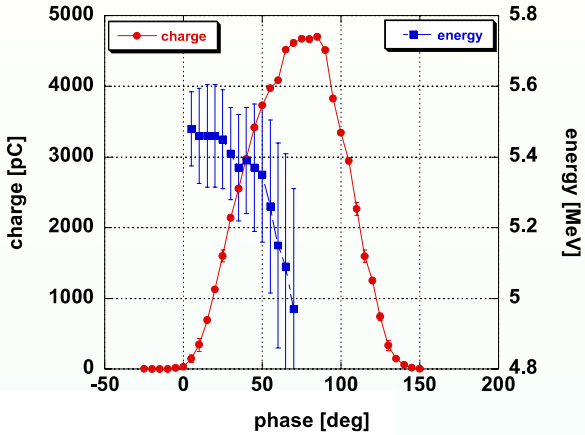


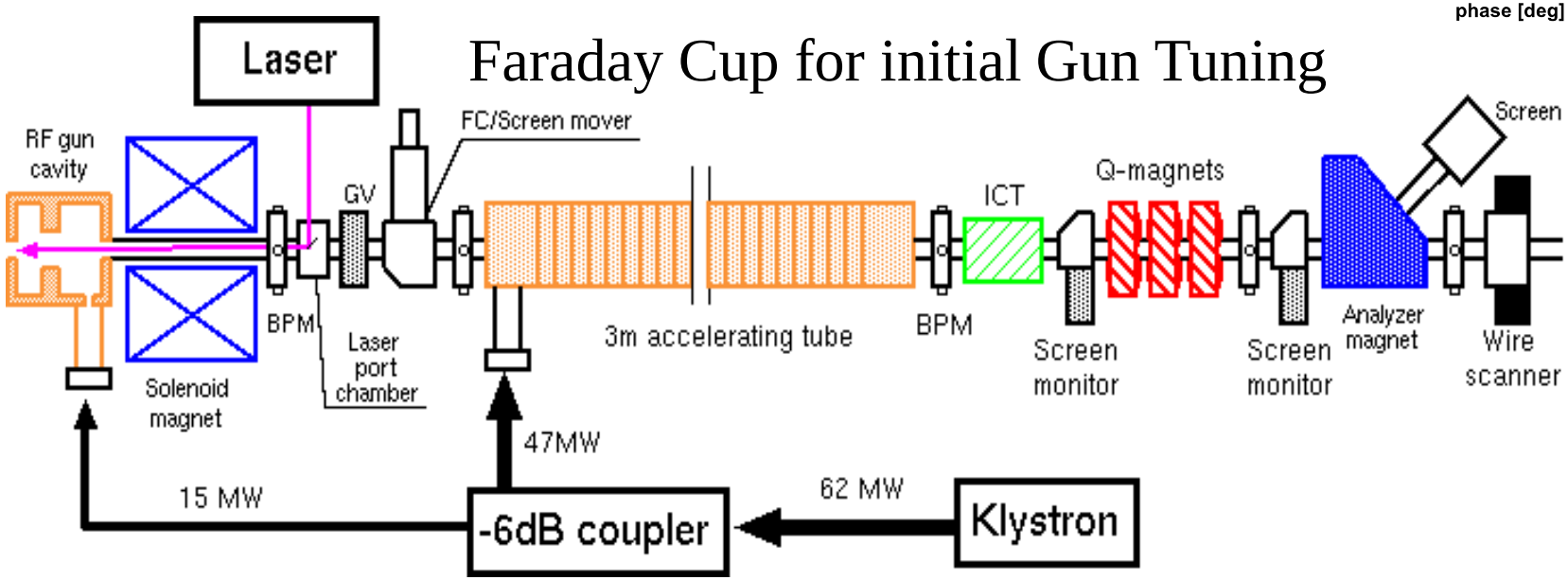
Figure 1: Cross section of the ATF RF gun. Cs-Te cathode plug is loaded from left side.

1-20 bunch with 2.8n spacing
Charge : 1-3nC/bunch
N. emittance : 5um.rad
Energy: 80±0.8~2.4 MeV

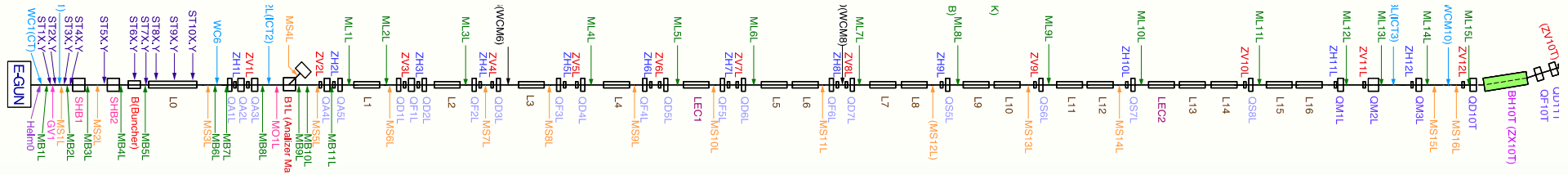
- Laser Phase
- RF Gun Phase
- LN0 Phase (2.8 GHz)



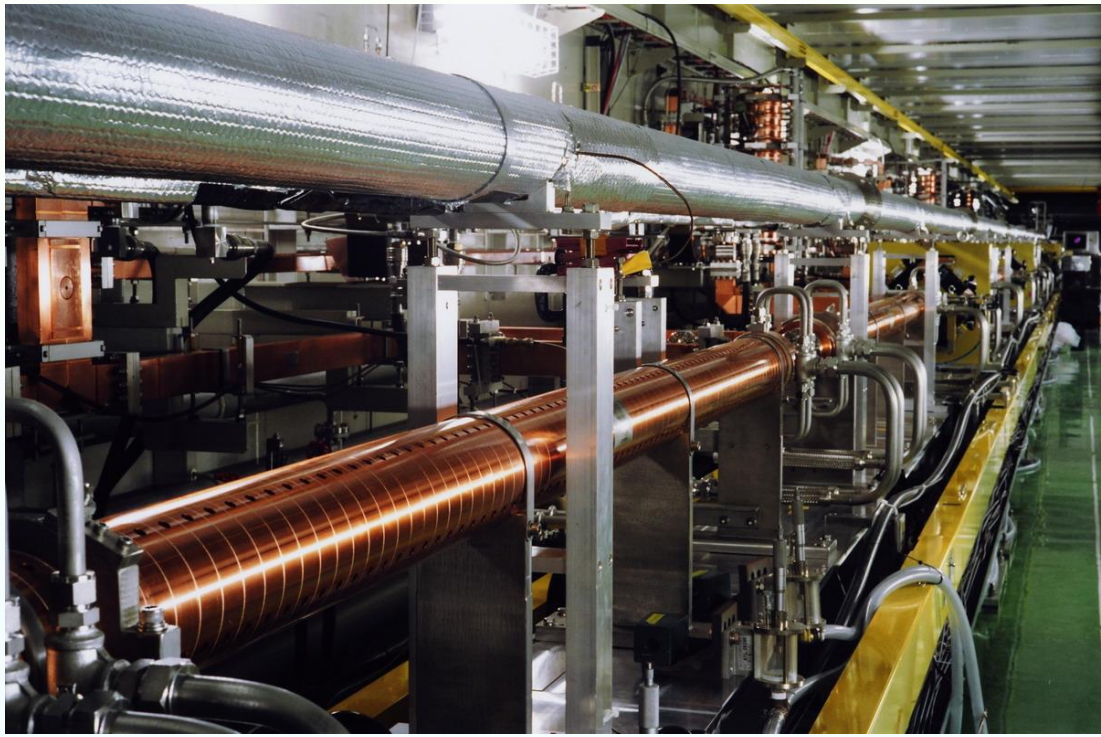
Faraday Cup for initial Gun Tuning



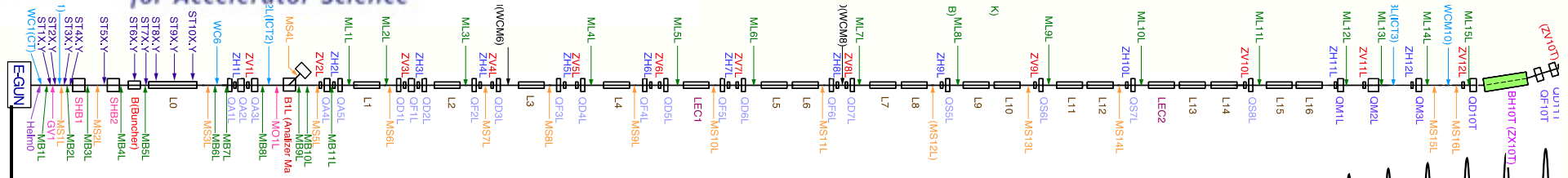
1.3 GeV Linac



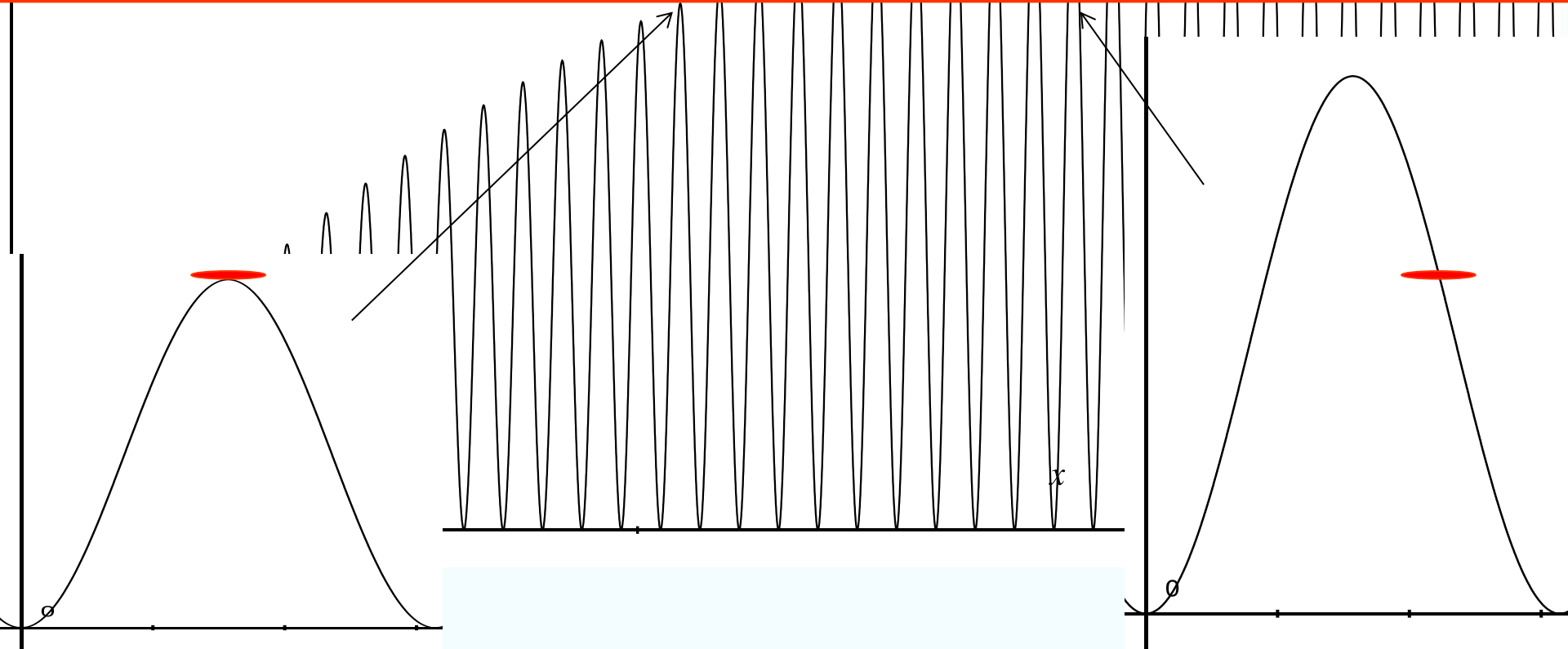
- Beam Energy
- RF is set wrt LN0
- Klystrons #1 - #8
- Beam trajectory
- Instrumentation:
  BPMs, ICT, Wire Scanners, Screen monitor



1.3 GeV Linac Klystron #8



Right power level



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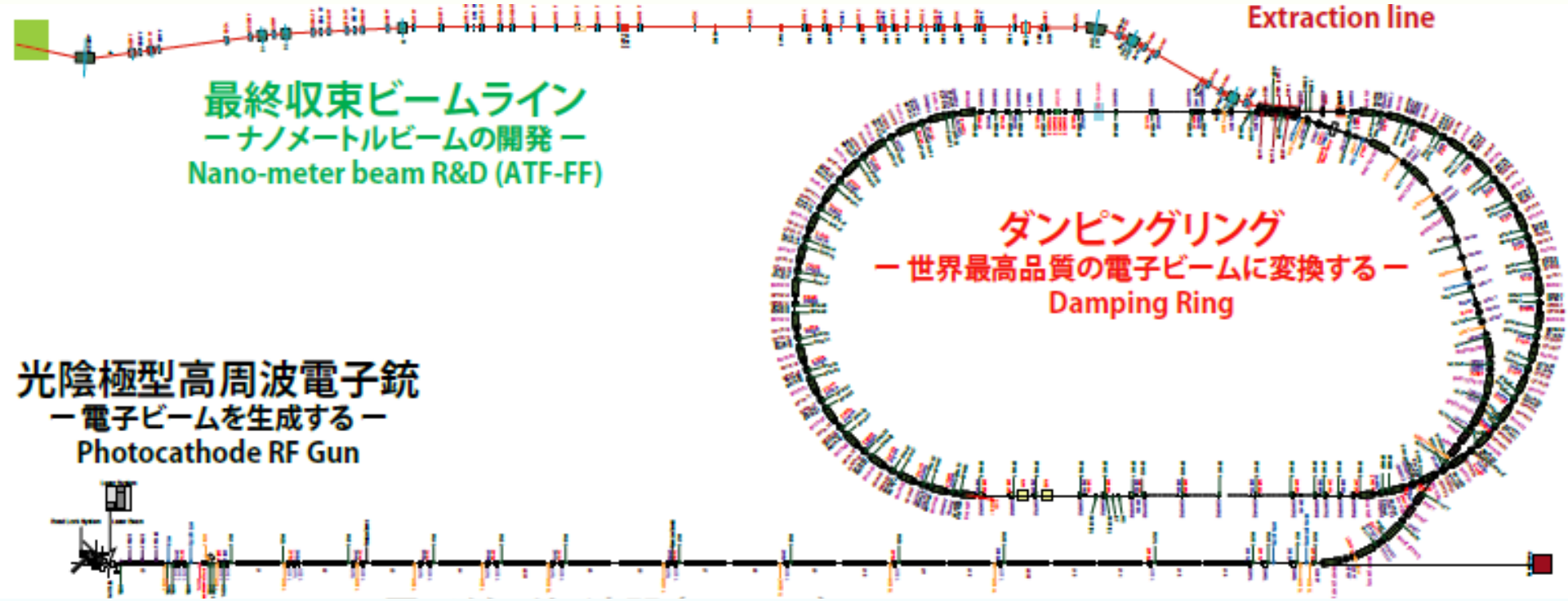
Trajectory in the Linac and in the Beam transport line



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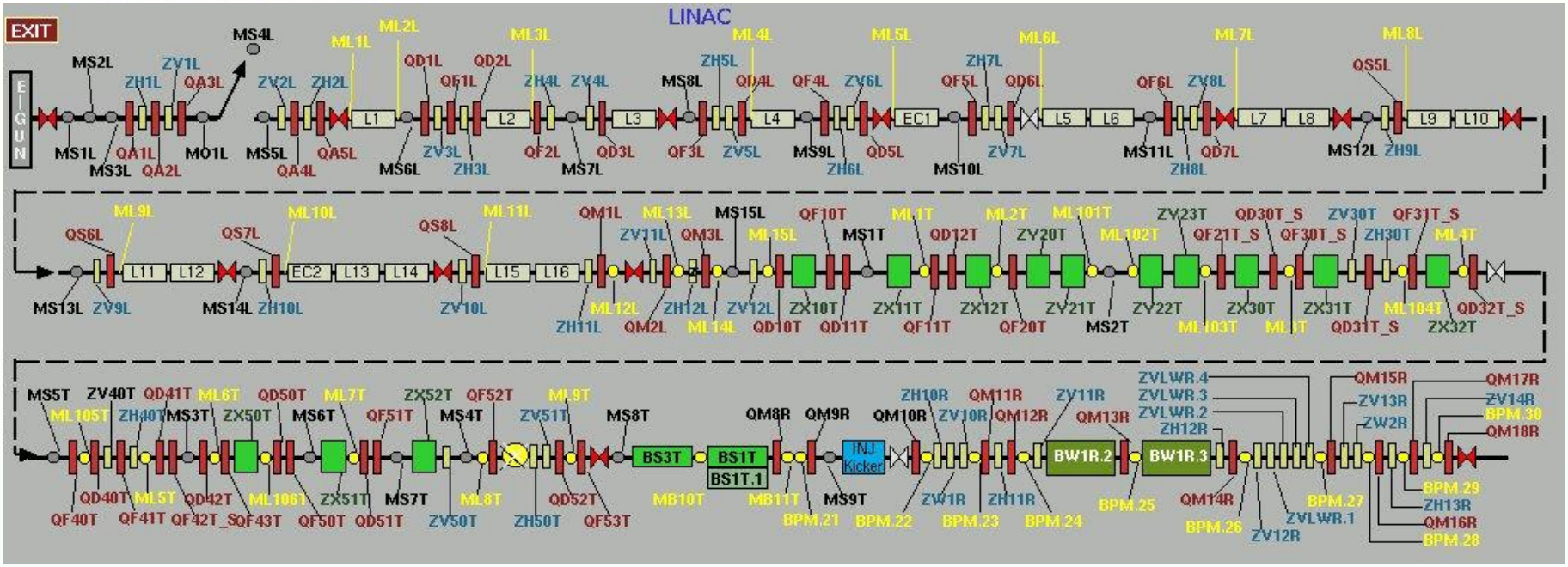
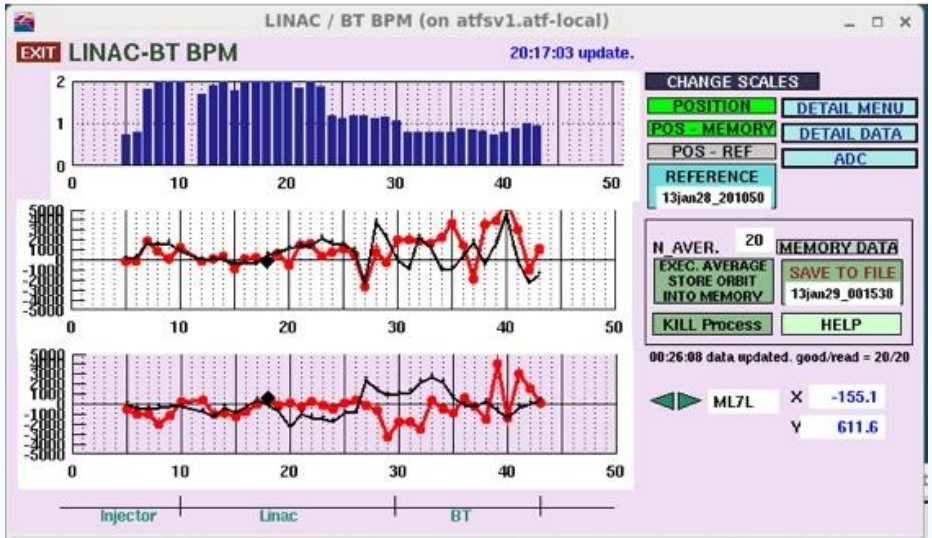
Trajectory in the Linac and in the Beam transport line



- 30 BPMs
- 9 screens
- 40 dipoles
- 62 quadrupoles



- Energy
- Trajectory
- Beta-function

Septum area: injection and extraction

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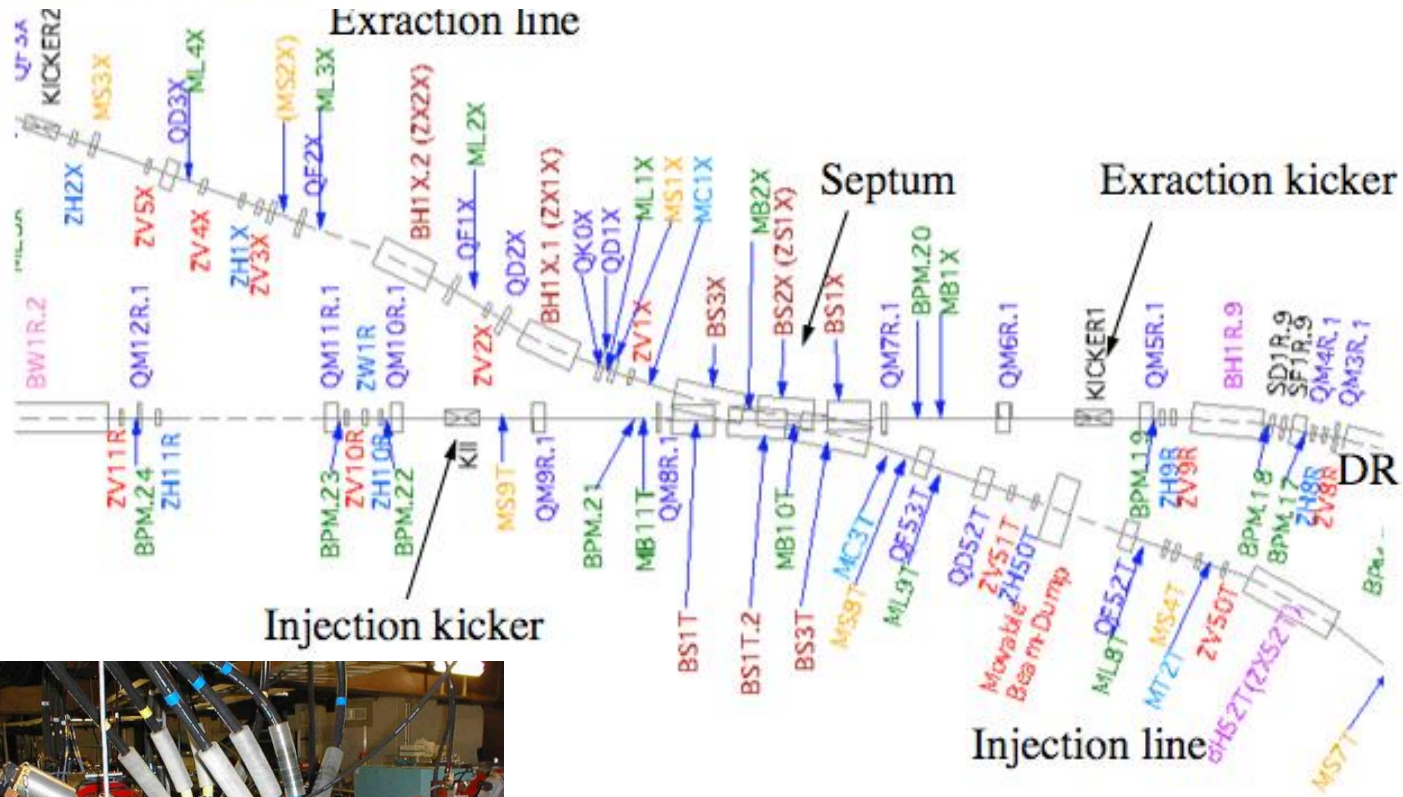
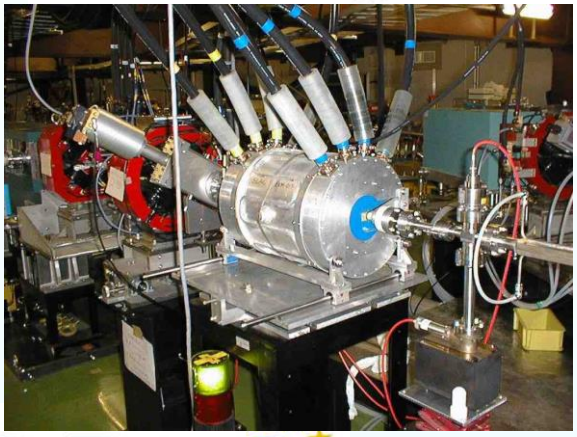
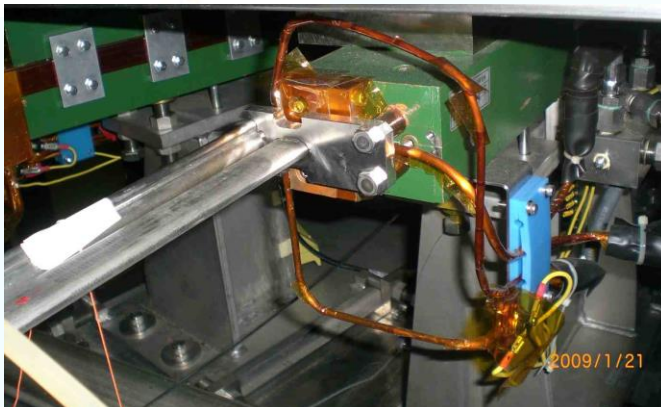




Kicker

Septum



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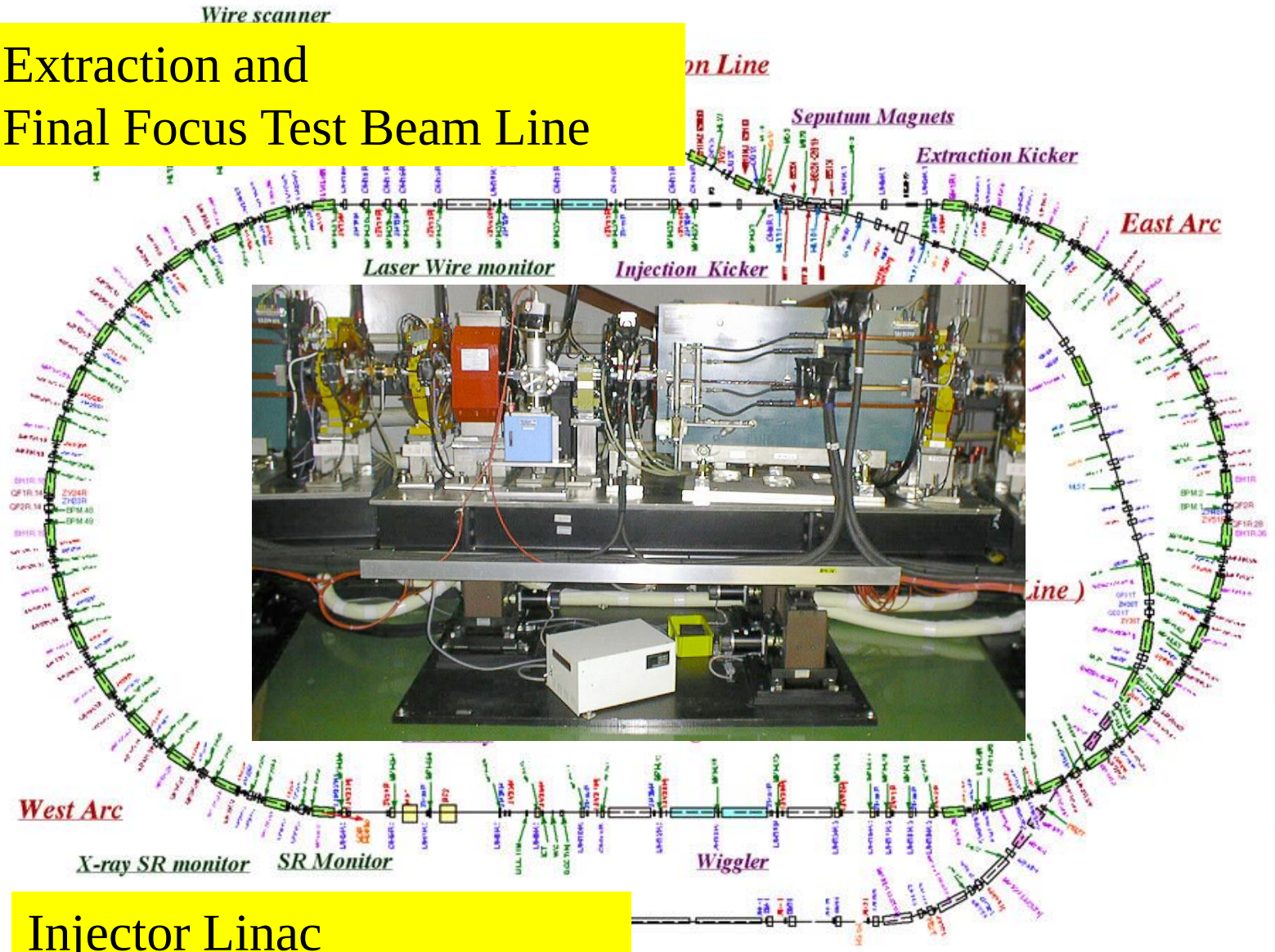
Damping Ring

Extraction and
Final Focus Test Beam Line



Injector Linac

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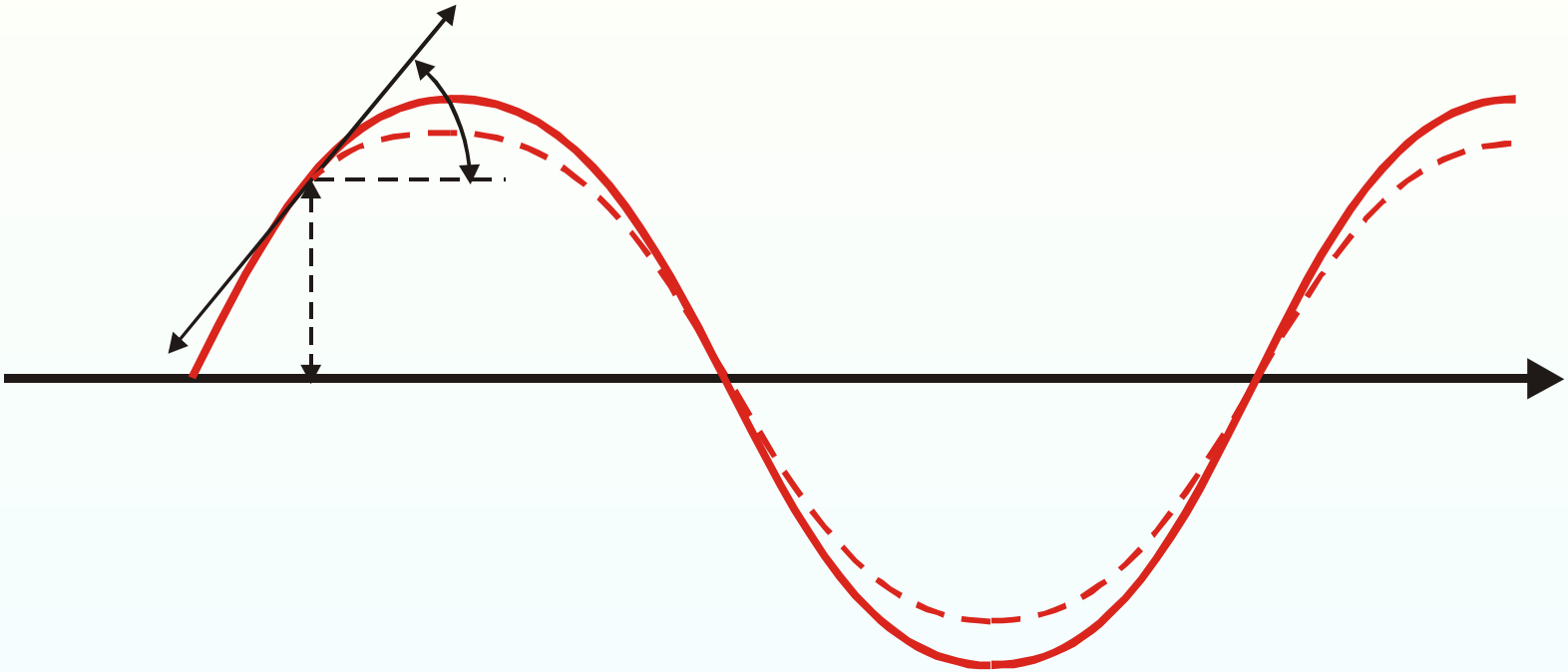
Radiation Damping of Betatron Oscillations



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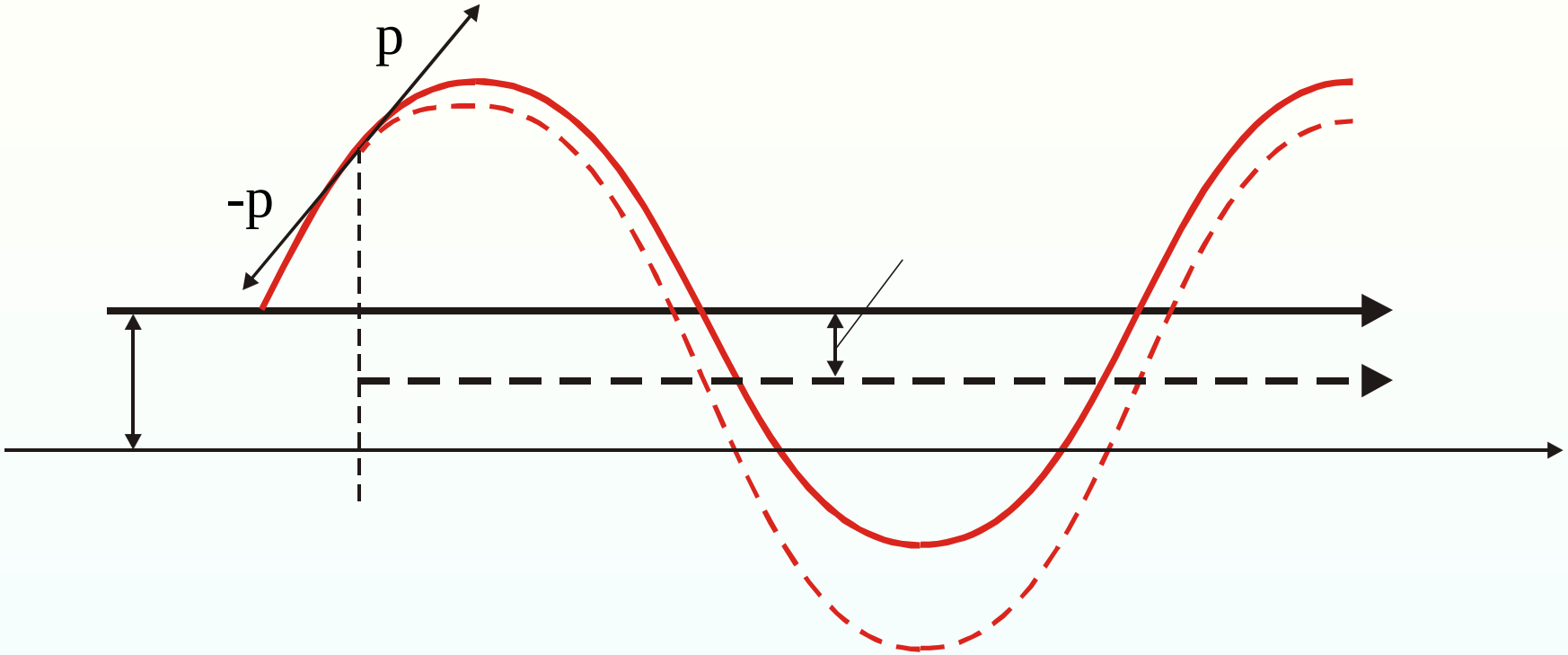
Excitation of Betatron Oscillations



$$X_{\mathrm{D}E} = D_x \frac{\mathrm{D}E}{E}$$

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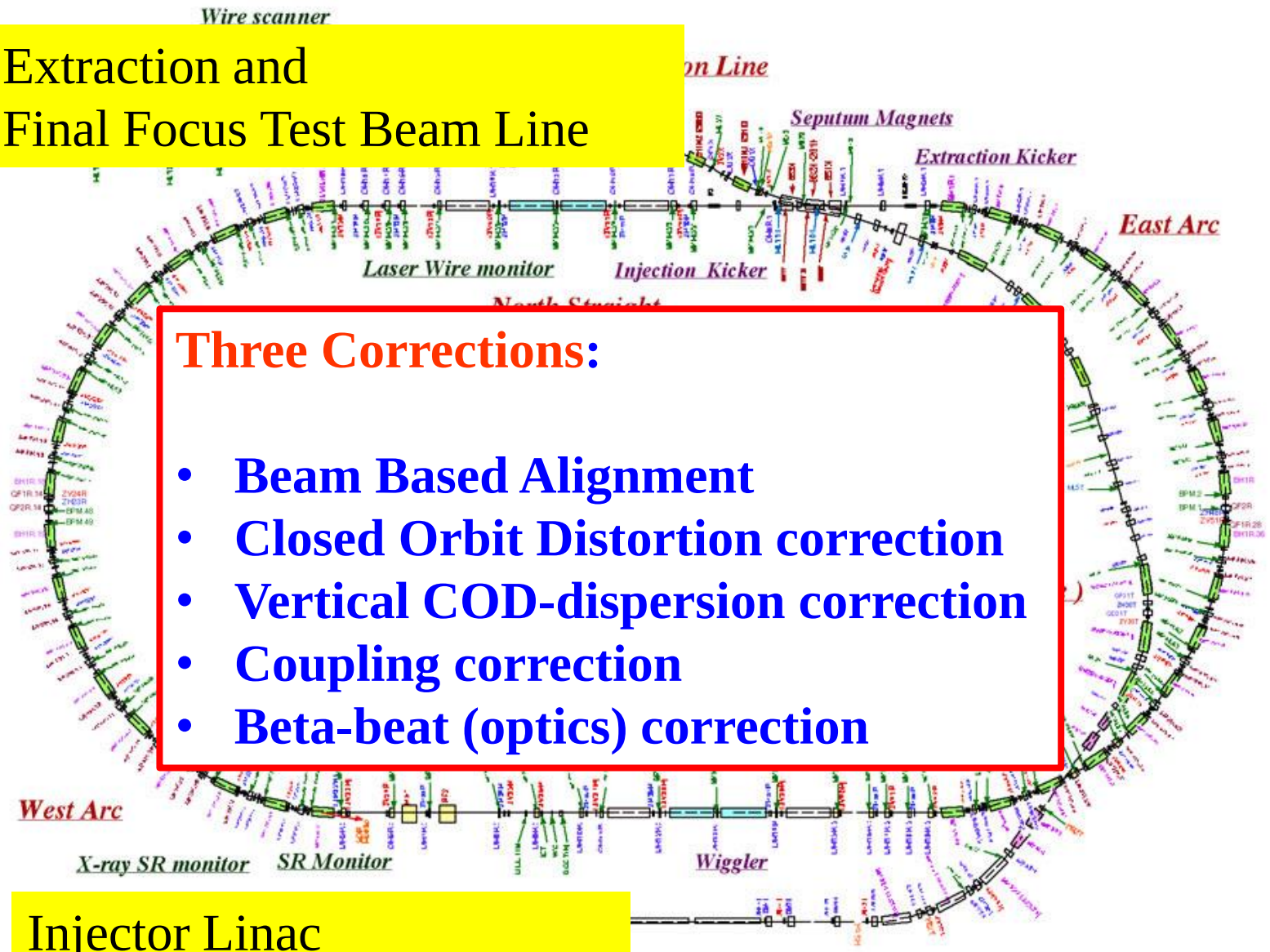
Damping Ring

Extraction and
Final Focus Test Beam Line



Three Corrections:

- **Beam Based Alignment**
- **Closed Orbit Distortion correction**
- **Vertical COD-dispersion correction**
- **Coupling correction**
- **Beta-beat (optics) correction**

Injector Linac

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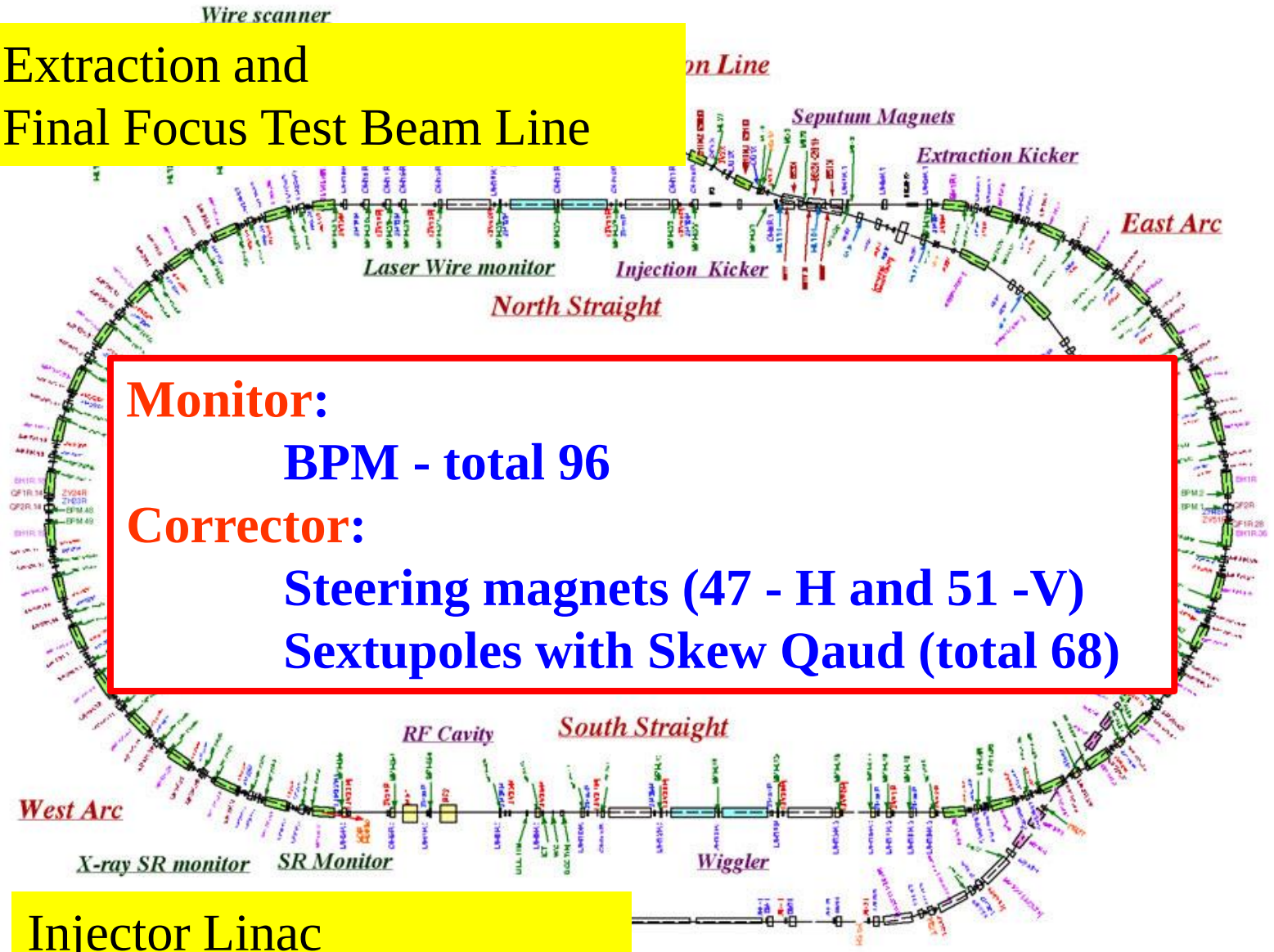
Damping Ring

Extraction and
Final Focus Test Beam Line



Monitor:

BPM - total 96

Corrector:

Steering magnets (47 - H and 51 -V)

Sextupoles with Skew Qaud (total 68)

Injector Linac

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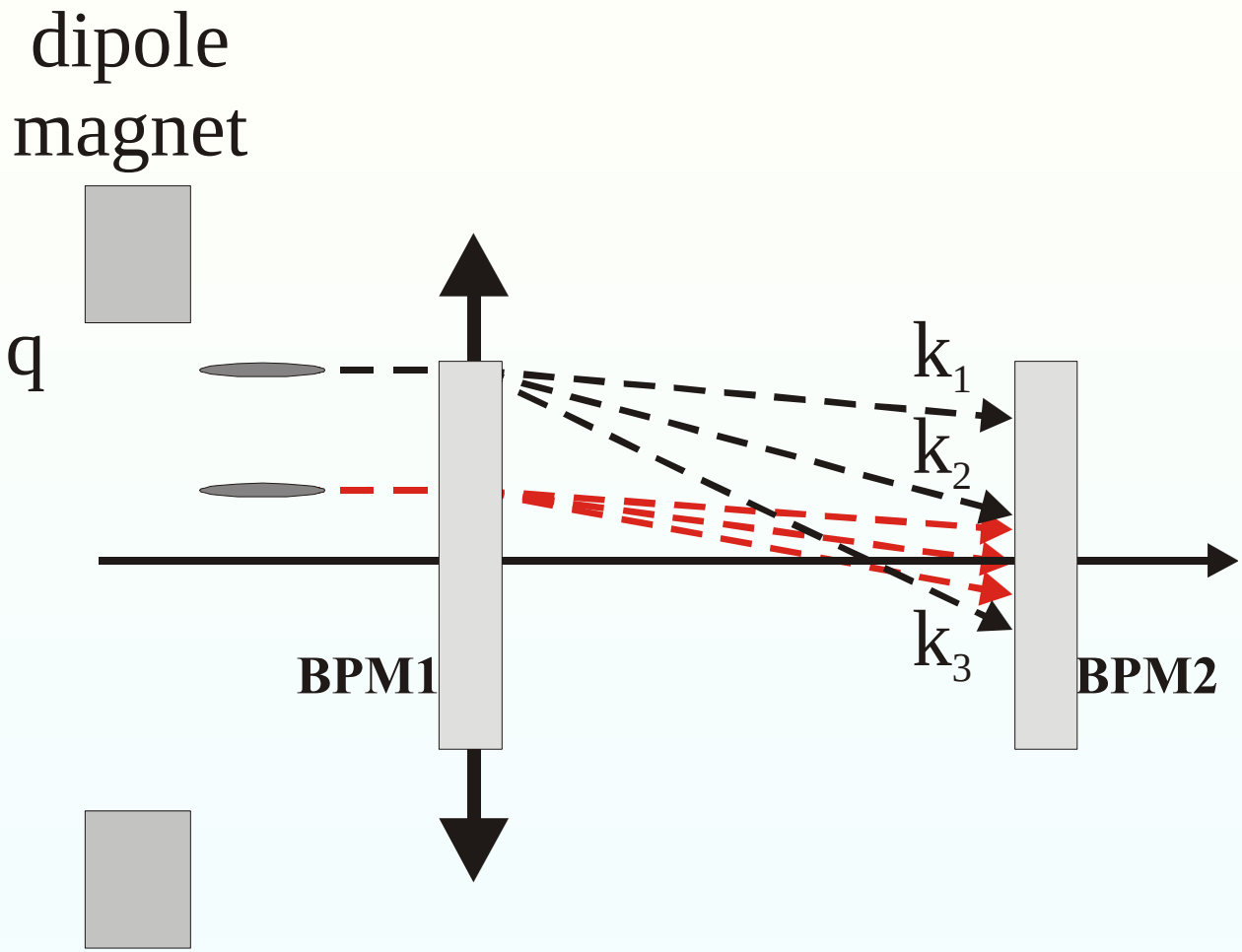
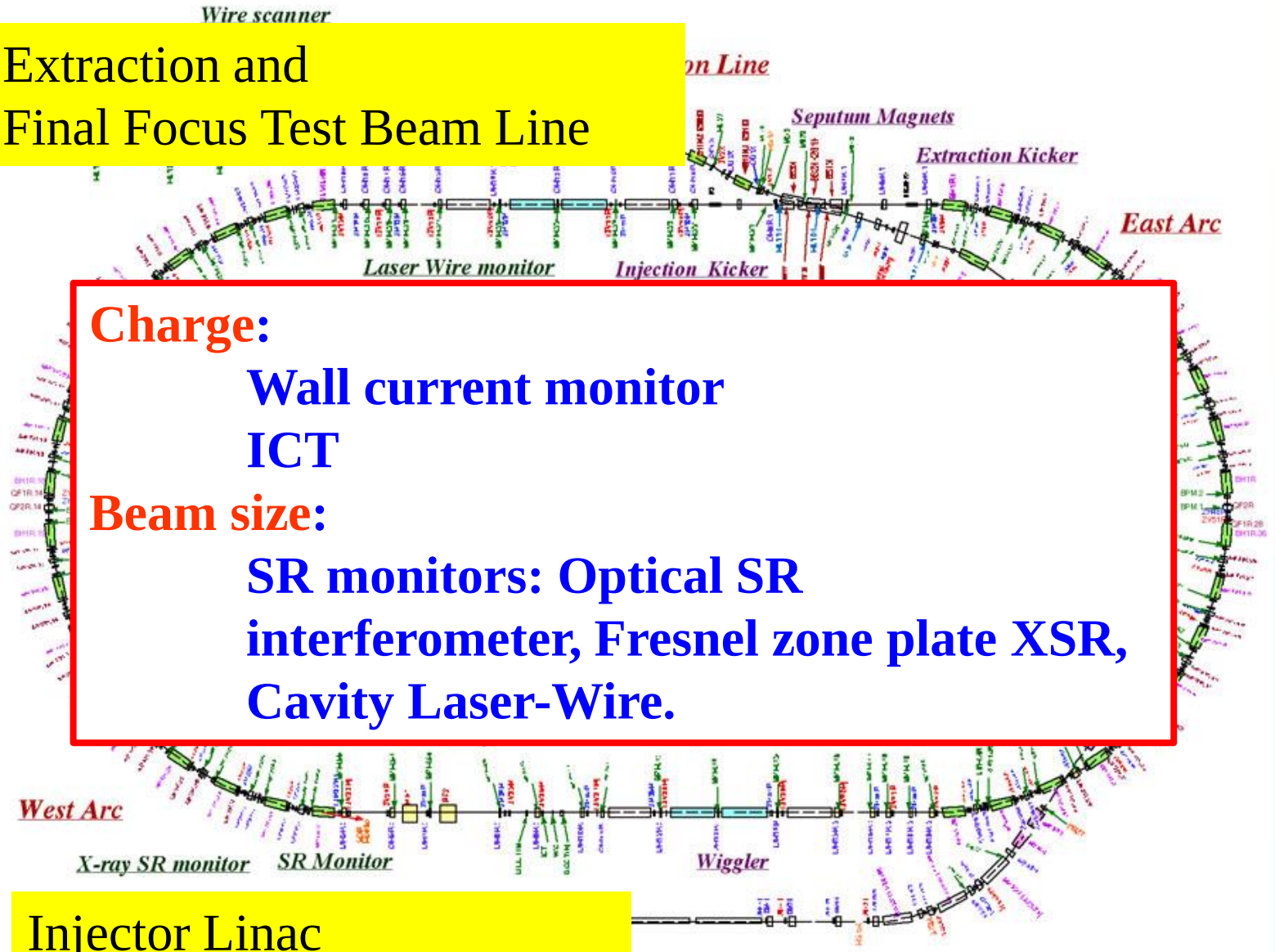
Beam based alignment



Other instrumentation

Extraction and
Final Focus Test Beam Line



Charge:

Wall current monitor

ICT

Beam size:

SR monitors: Optical SR interferometer, Fresnel zone plate XSR, Cavity Laser-Wire.

Injector Linac

Septum area: injection and extraction

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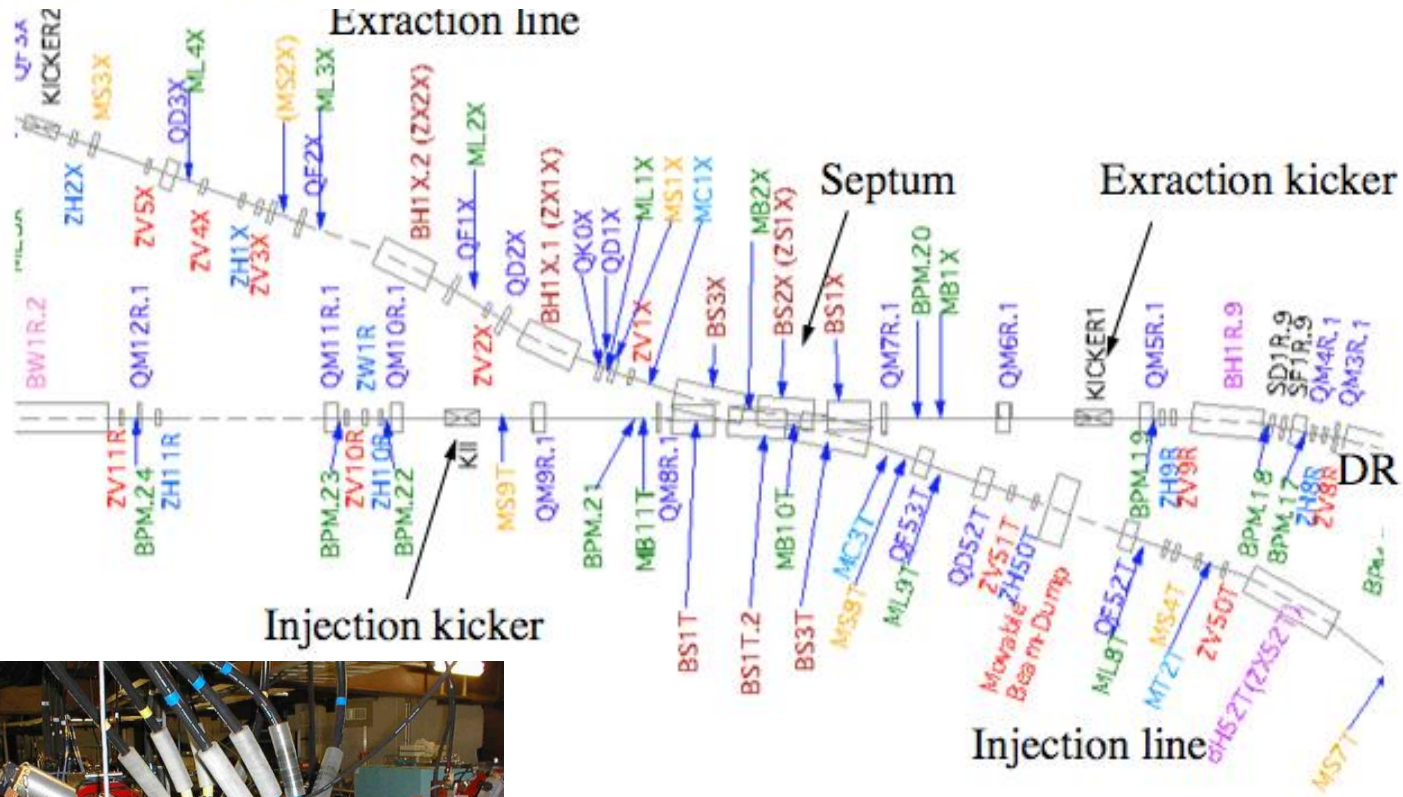
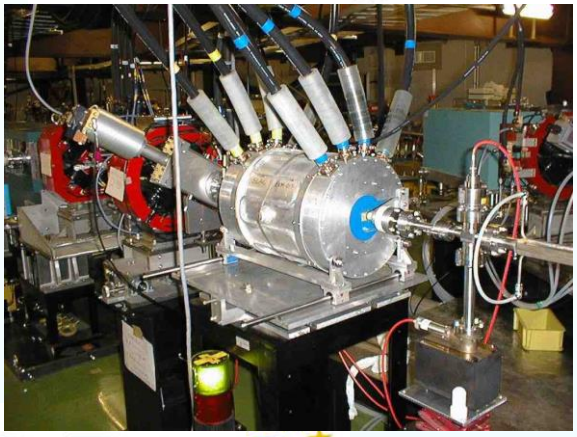
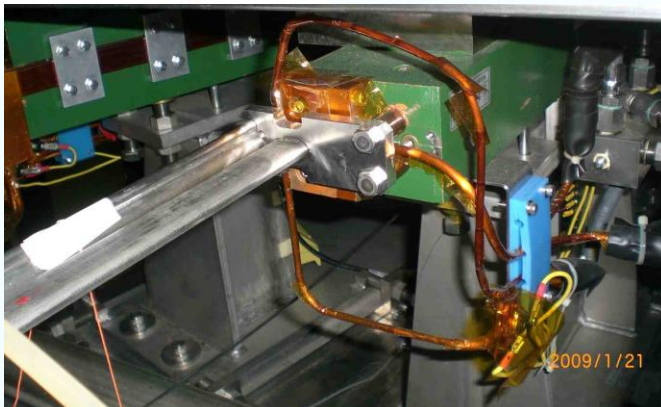




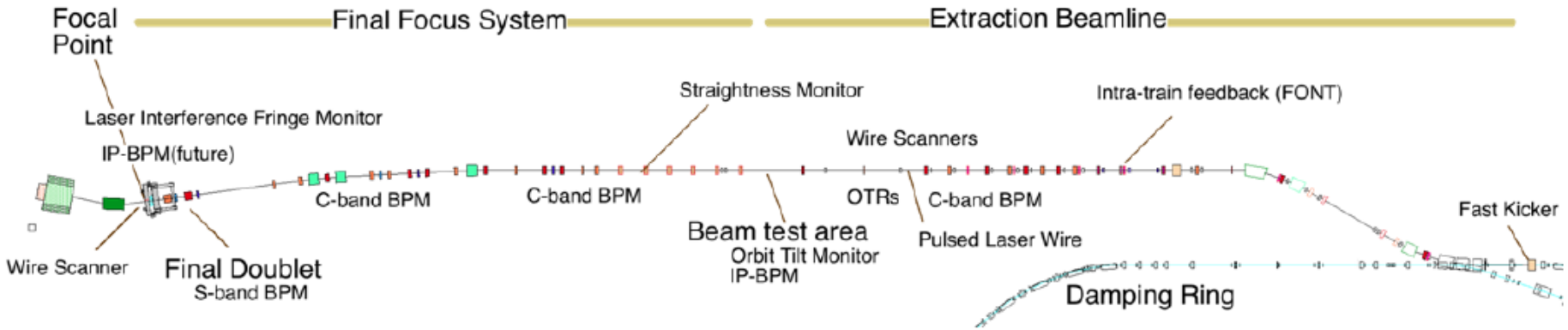
Kicker

Septum



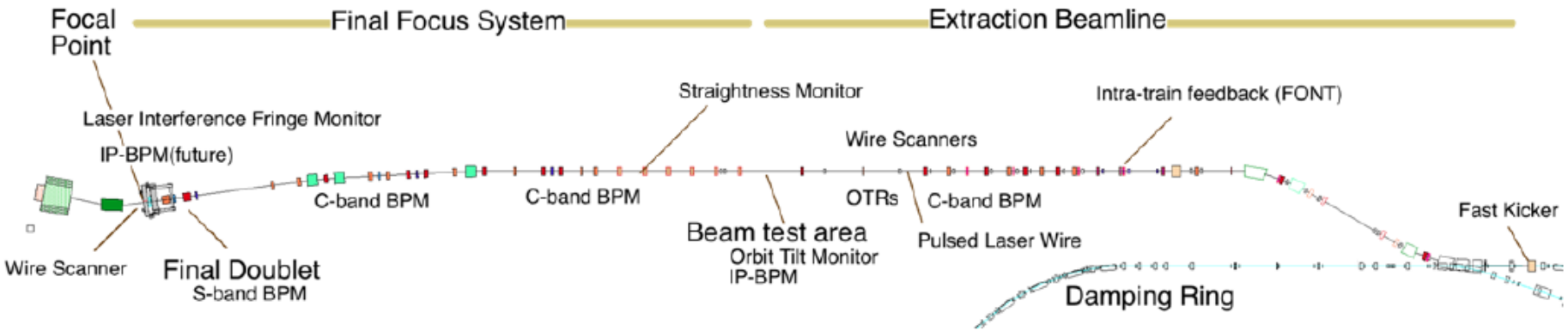
OPAC

Extraction line and Final Focus



- 40 Cavity BPMs
- Orbit tilt monitor
- 5 wire scanners
- 5 OTR monitors
- Sub-um OTR monitor
- Pulsed Laser-wire
- Laser Interferometer
- Intra-train FB
- Beam loss monitor

Extraction line and Final Focus

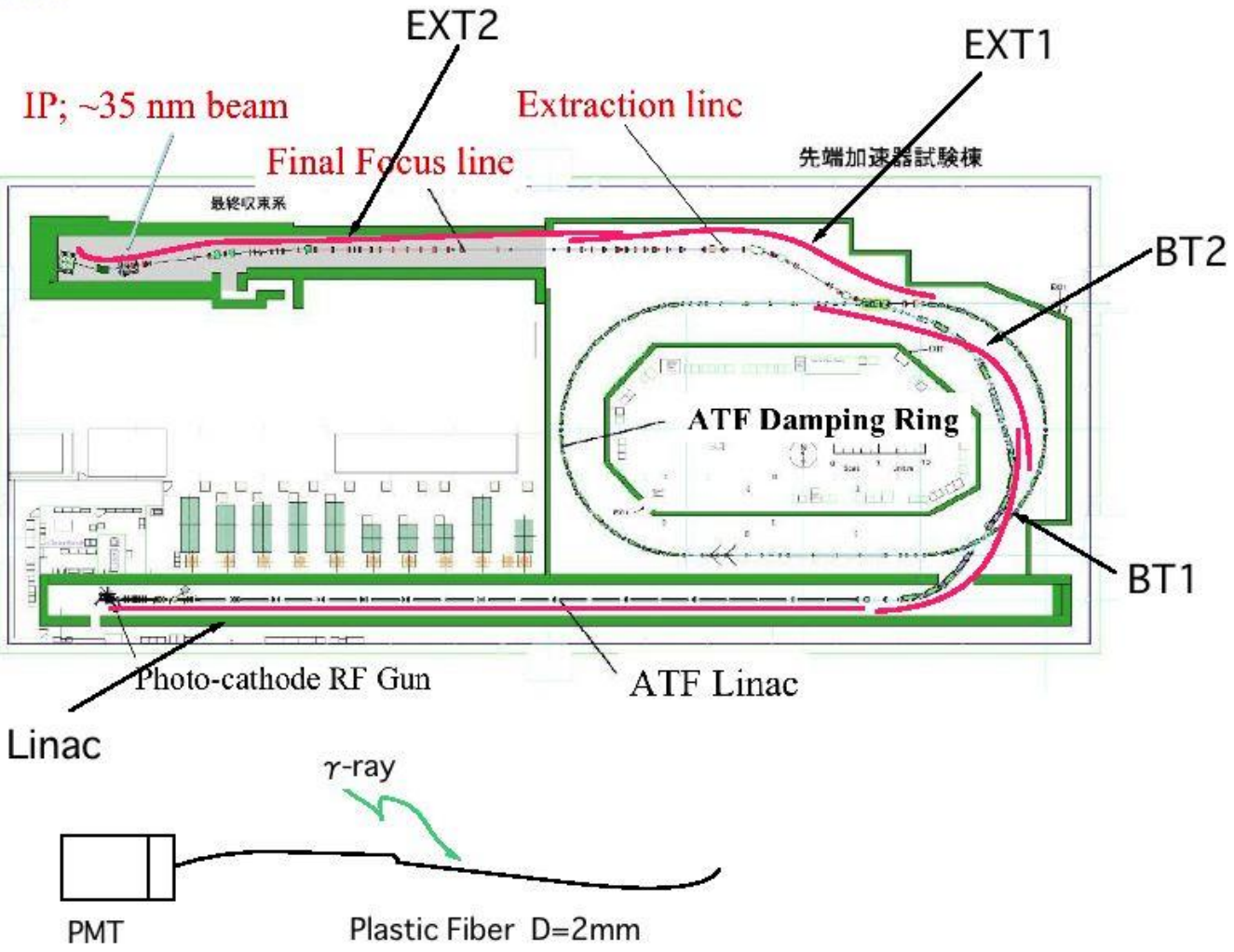


Corrections

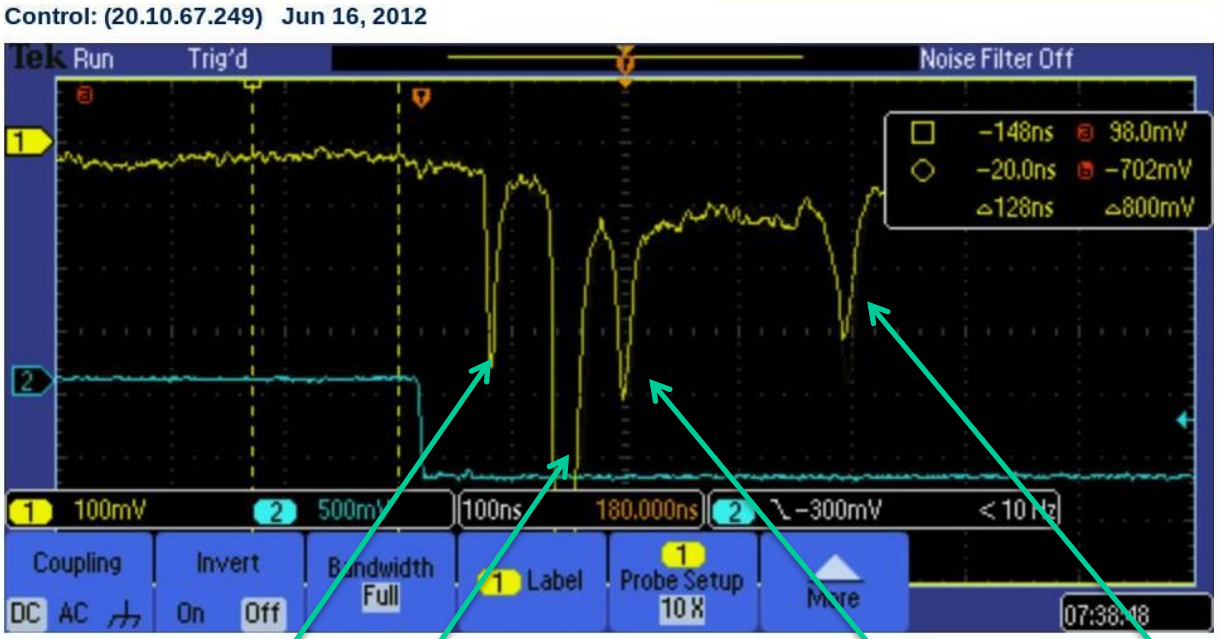
- Orbit correction
- Dispersion correction
- Beta-matching
- Skew correction

67 nm beam was achieved:
G. White, ATF2 Collaboration, PRL 112, 034802 (2014).

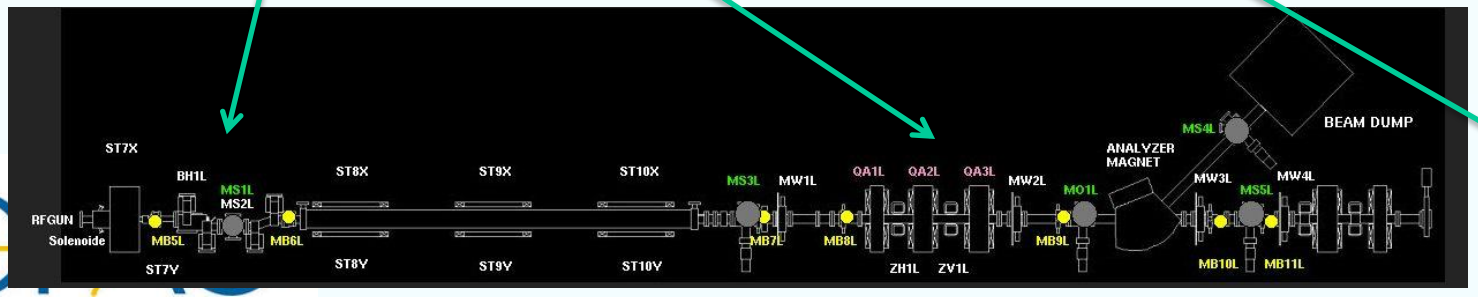
Beam loss monitoring



Beam loss monitoring



1) Chicane or L0 2) Between MS3L to MS5L 3) L1 input 4) L3 input



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Summary

- The characterization begins from the source
- Every Accelerator subsection should be equipped with a comprehensive set of diagnostics equipment
- 6 D phase space and intensity, position, direction, arrival time, beam losses are equally important.

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