Commissioning of the Taiwan Photon Source (TPS)

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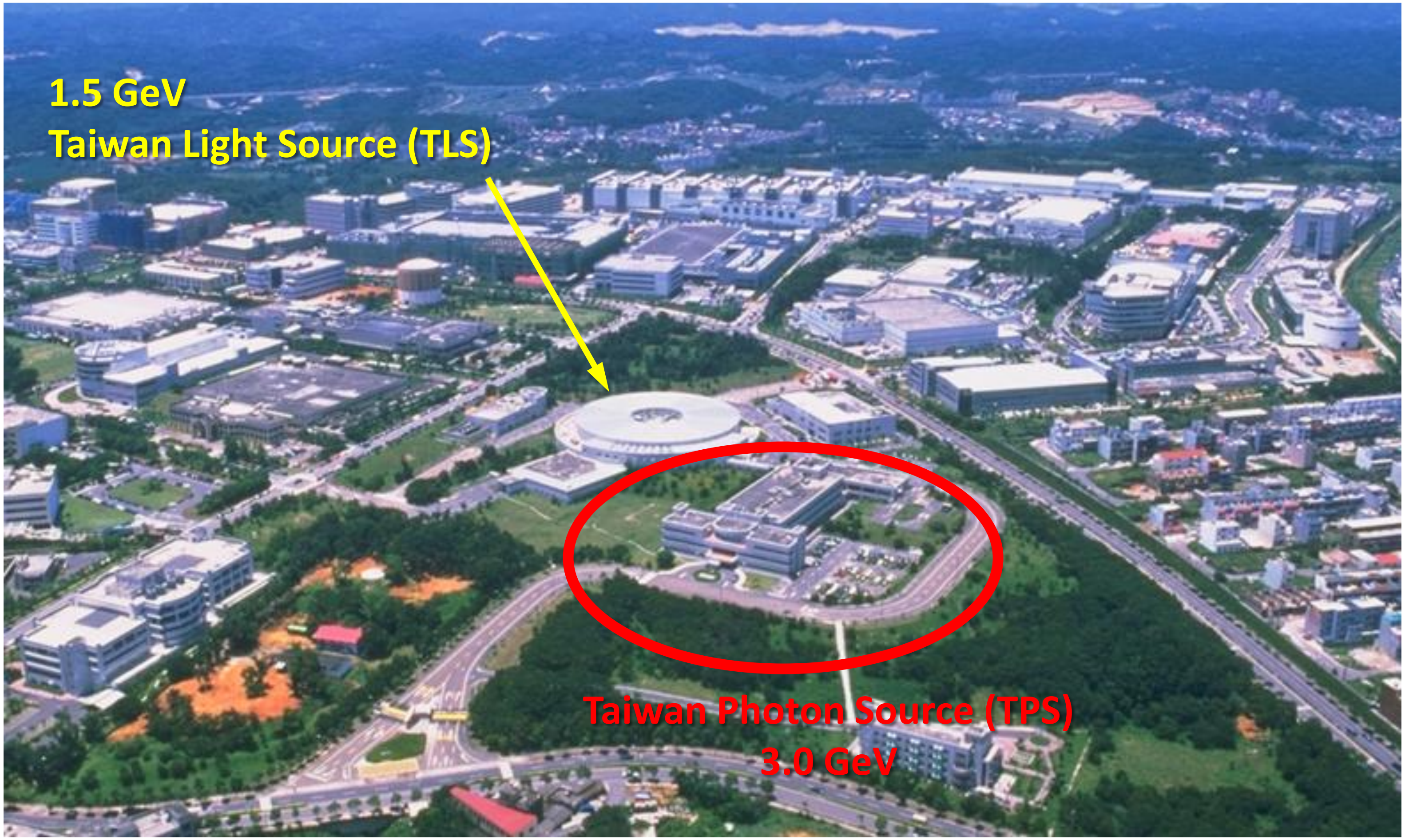
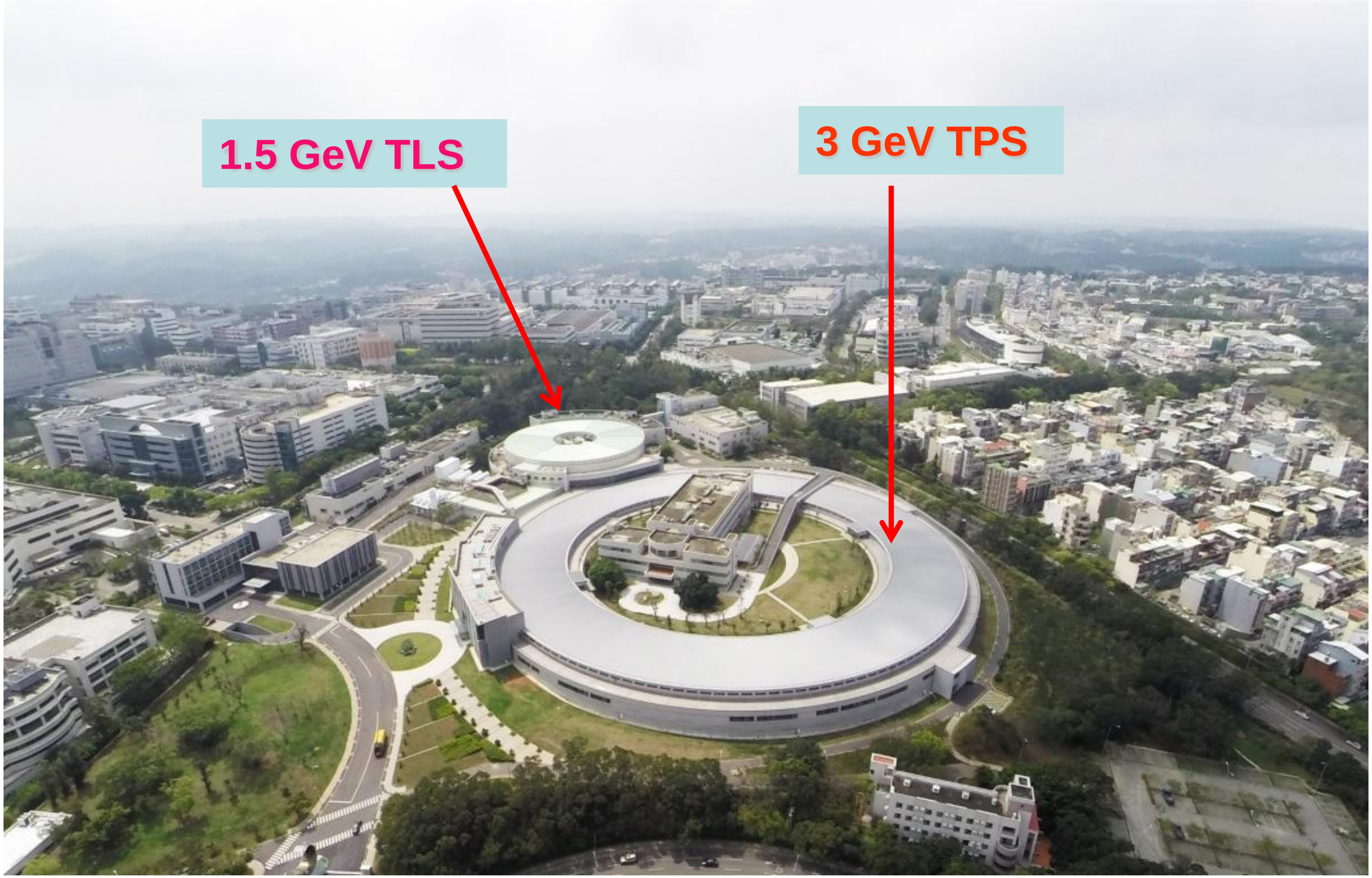
On behalf of the TPS team
IPAC'15 Richmond, May 5, 2015

National Synchrotron Radiation Research Center, Taiwan
Hsinchu Science Park



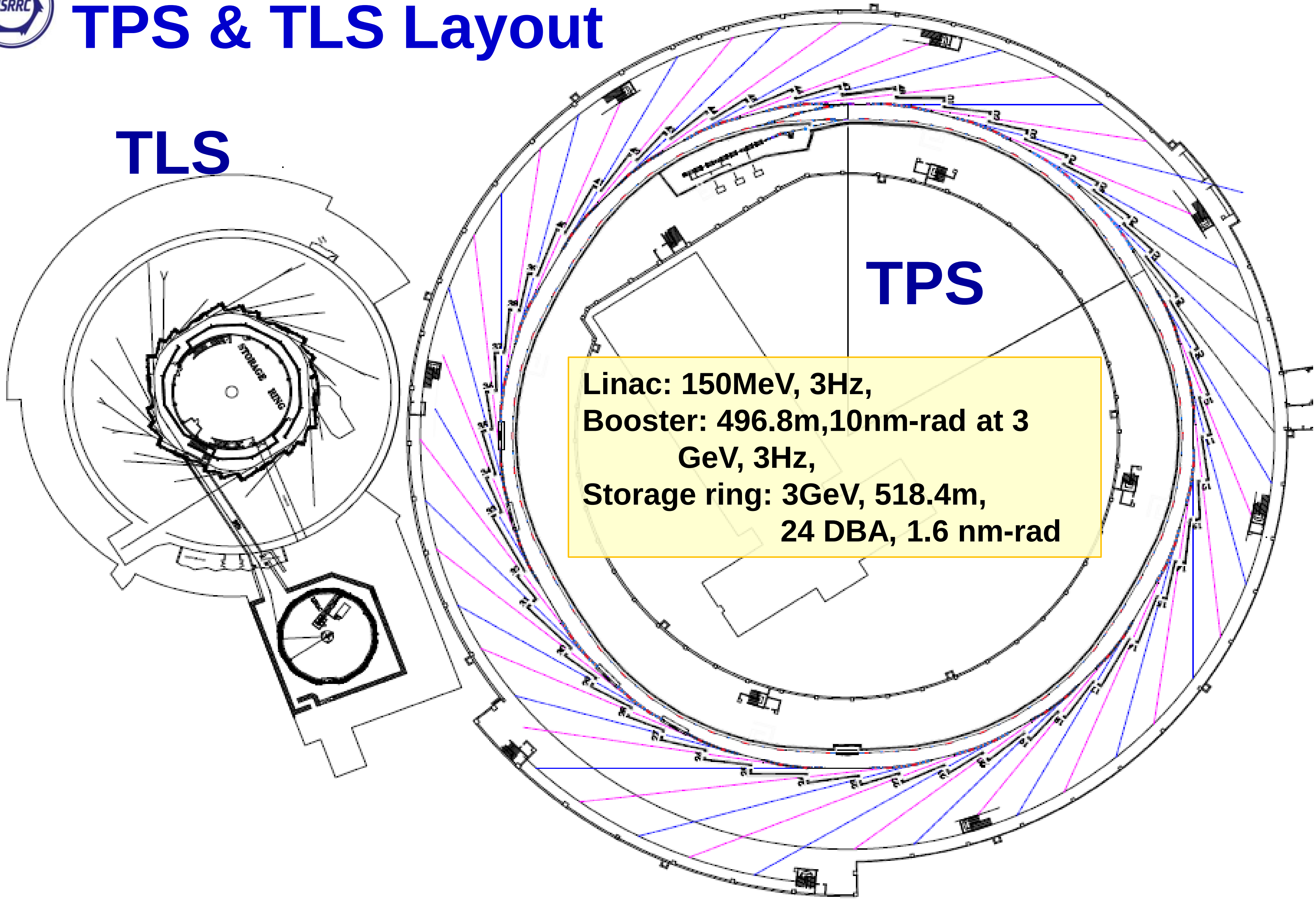
Aerial View of TPS, March 2015



TPS Timeline

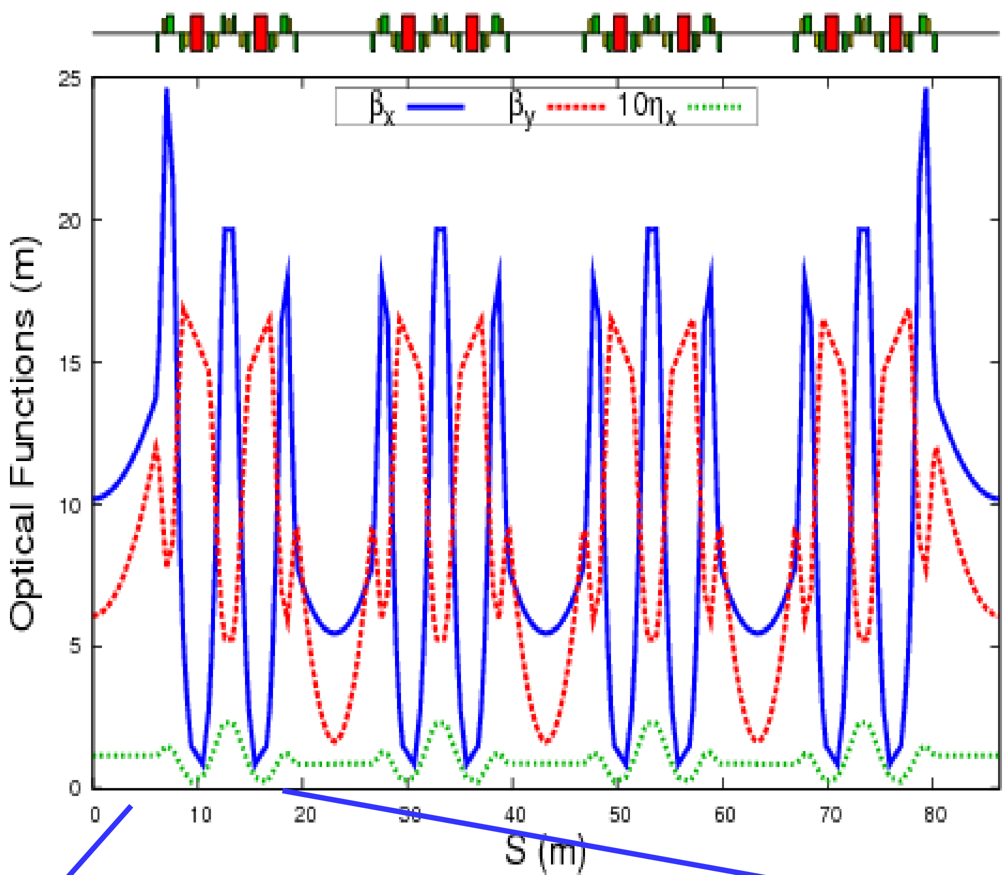
2004 June	TPS feasibility study started
2007 Mar.	Funding approval
2010 Feb.	Ground-breaking
2013 Oct.	Accelerator installation started
2014 Aug.	System test and commissioning started
2015 Mar.	Phase I commissioning completed
2015 Sep.	SRF, ID and Beamline commissioning
2016	Open to public users

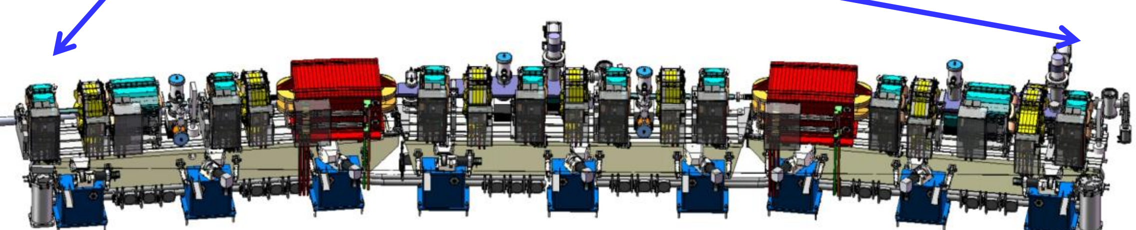
TPS & TLS Layout



Linac: 150MeV, 3Hz,
Booster: 496.8m,10nm-rad at 3 GeV, 3Hz,
Storage ring: 3GeV, 518.4m, 24 DBA, 1.6 nm-rad

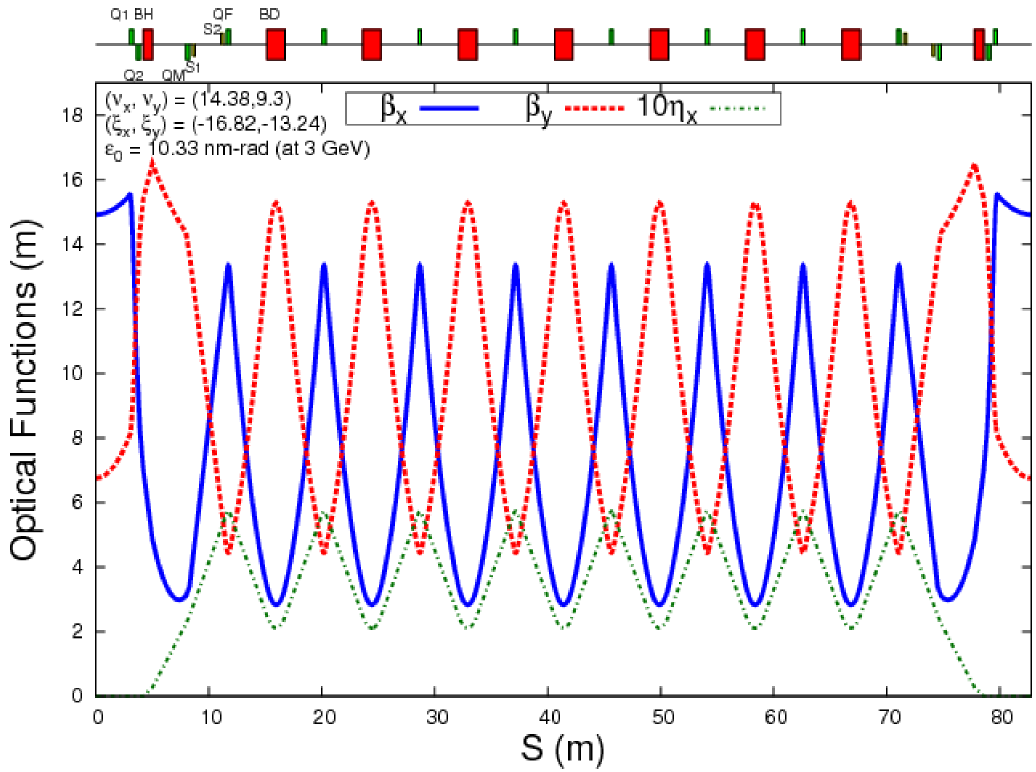
Storage Ring Parameters





Circumference [m]	518.4
Beam energy E [GeV]	3.0
Natural emittance ε_x [nm-rad]	1.6
Betatron tune ν_x/ν_y	26.18/ 13.28
Natural chromaticity ξ_x/ξ_y	-75/ -26
RF frequency [MHz]	499.654
Harmonic number	864
Momentum compaction α_1/α_2	2.4×10^{-4}/ 2.1×10^{-3}
Energy spread σ_E/E	8.86×10^{-4}
Energy loss/turn (dipole) [MeV]	0.8527
Periodicity	6
Straight sections [m]	12(x6)+ 7(x18)

Booster Parameters



Circumference [m]	496.8
Beam energy E [GeV]	0.15→ 3.0
Natural emittance @3GeV ε_x [nm-rad]	10.3
Betatron tune ν_x/ν_y	14.380/ 9.302
Natural chromaticity ξ_x/ξ_y	-16.82/ -13.24
RF frequency [MHz]	499.654
Harmonic number	828
Momentum compaction α_c	2.474×10^{-3}
Energy spread@3GeV σ_E/E	0.095%
Rep. rate	3

Photo in TPS Tunnel

TPS Commissioning Phase

5 stages:Linac, LTB, Booster, BTS, Storage Ring

Two phases in the storage ring commissioning

- ✓ **Phase I: up to 100 mA beam current with room-temperature PETRA cavities → Optimization of basic machine parameters (finished)**
- **Phase II: up to 500 mA beam current with Superconducting RF**

  Insertion Device Commissioning

  Photon Beamline Commissioning

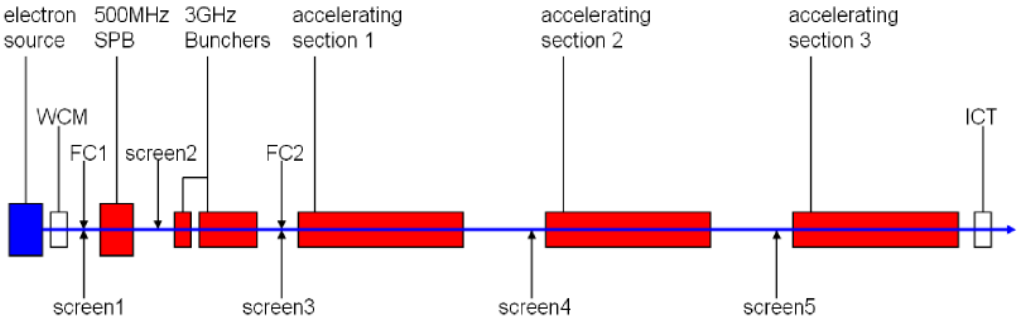
  Open to User Operations → Beam quality control, high beam intensity issues

Linac

TPS 150 MeV Linac

The linac in TPS site

The linac rf stations



Diagnostics tools of linac

TPS Linac Commissioning

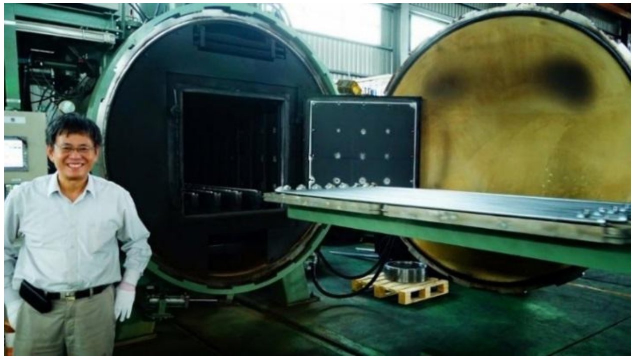
- Linac (from Research Instruments Ltd) pre-test at test-site in 2011
- Moved to TPS site between March and June, 2014
- Permission to test with beam by the AEC on August 1, 2014

Parameter	Specification	Measured
Bunch train length	0.2 to 1 us FWHM $\leq$ 1 ns*	0.2 to 1 us FWHM $<$ 0.8 ns*
Energy (MeV)	$\geq$ 150	$>$ 150
Pulse to pulse energy variation (%)	$\leq$ 0.25 (rms)	$<$ 0.05
Relative energy spread (%)	$\leq$ 0.5 (rms)	0.35 0.11*
Normalized emittance (1σ) (πmm mrad)	$\leq$ 50 (both planes)	(x, y) = (36, 49) (x, y) = (48, 35)*
Single bunch purity (%)	$\leq$ 1	$<$ 1
Pulse to pulse time jitter (ps)	$\leq$ 100	56 49*
*: SBM		

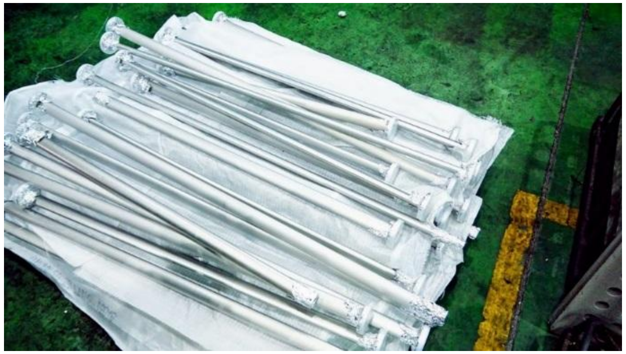
Booster Ring

Reducing Permeability of Stainless-steel 304 Pipes

- We struggled to get a stored beam without success for about 2 months.
- We found on 2014-11-12 that it was caused by high permeability of SS304 vacuum pipes due to cold-draw process during manufacture.
- The permeability was about 1.2 to 2.0 and this induced magnetic field errors larger than the design tolerance specs. by an order of magnitude for the elliptical chamber of 30x20 mm and 0.7 mm thick.
- Reducing permeability of booster beam pipes by heat treatment up to 1050°C
- Relative permeability reduced to less than 1.01 after heat treatment
- Finished in three weeks
- Heat treatment also improved the vacuum conditioning



Chien-Te Chen (TPS project director) standing by the vacuum furnace

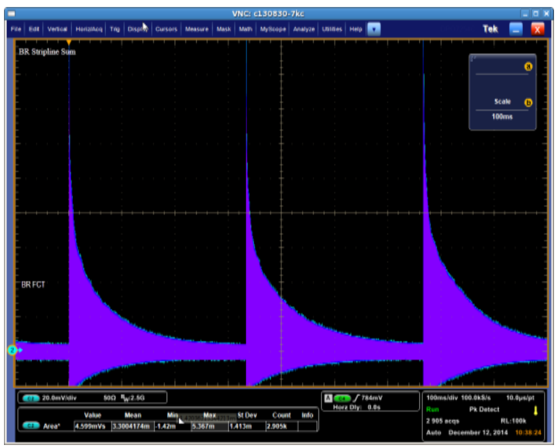


Shiny beam pipes after heat treatment

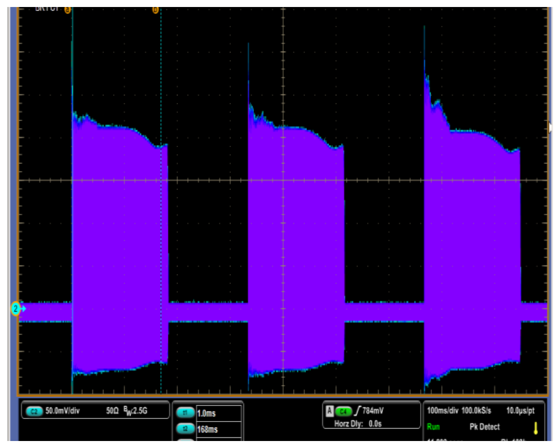
WEPHA049

Booster Beam Stored and Ramped

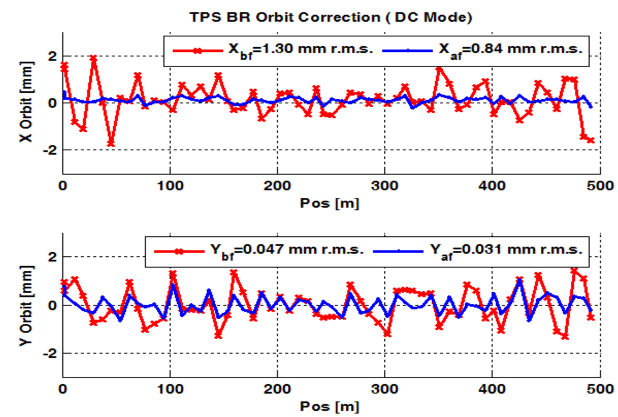
- **Dec. 11, beam survived more than 50 ms**
- **Dec. 12, stored beam**
- **Dec. 16, ramped to 3 GeV**
- **DC mode orbit < +/-1 mm. Corrector < 0.7 A**
- **No ramp in all correctors while ramping to 3 GeV**
- **Orbit kept < +/-1 mm during ramp except in H at low energy**



stored beam at 150 MeV



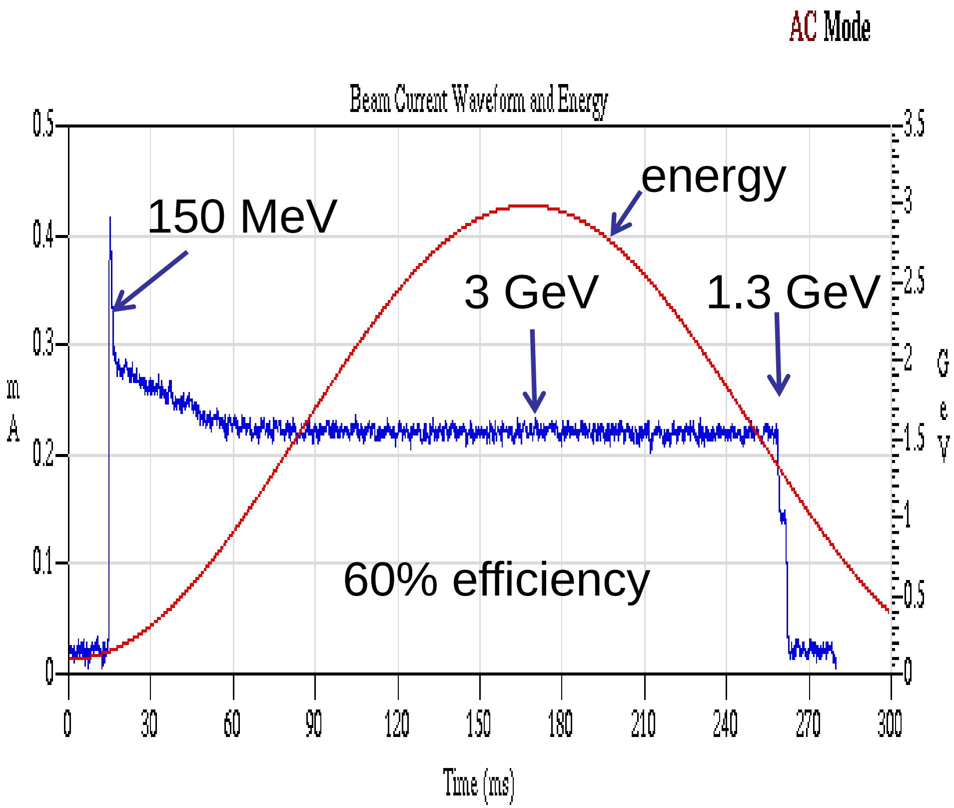
ramped to 3 GeV

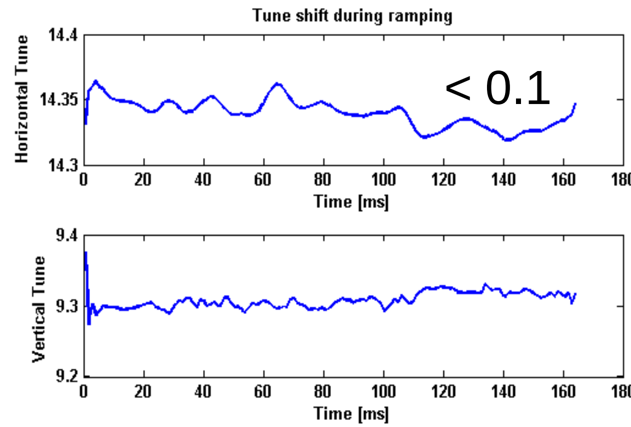


COD before (red) and after (blue)
Correction at 150 MeV,
Max. corrector strength: 1.1 mrad

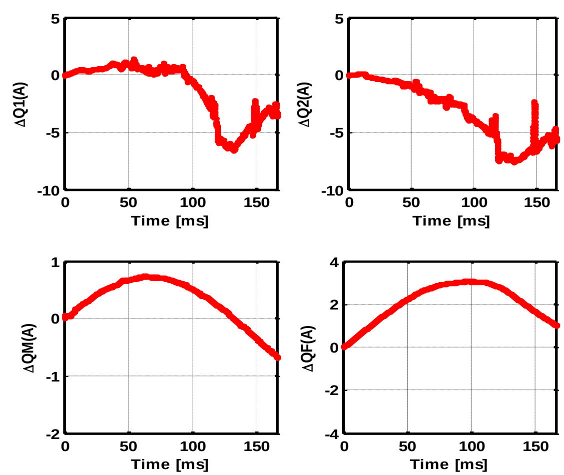
TUPJE053

Energy Ramping and Tune Tracking





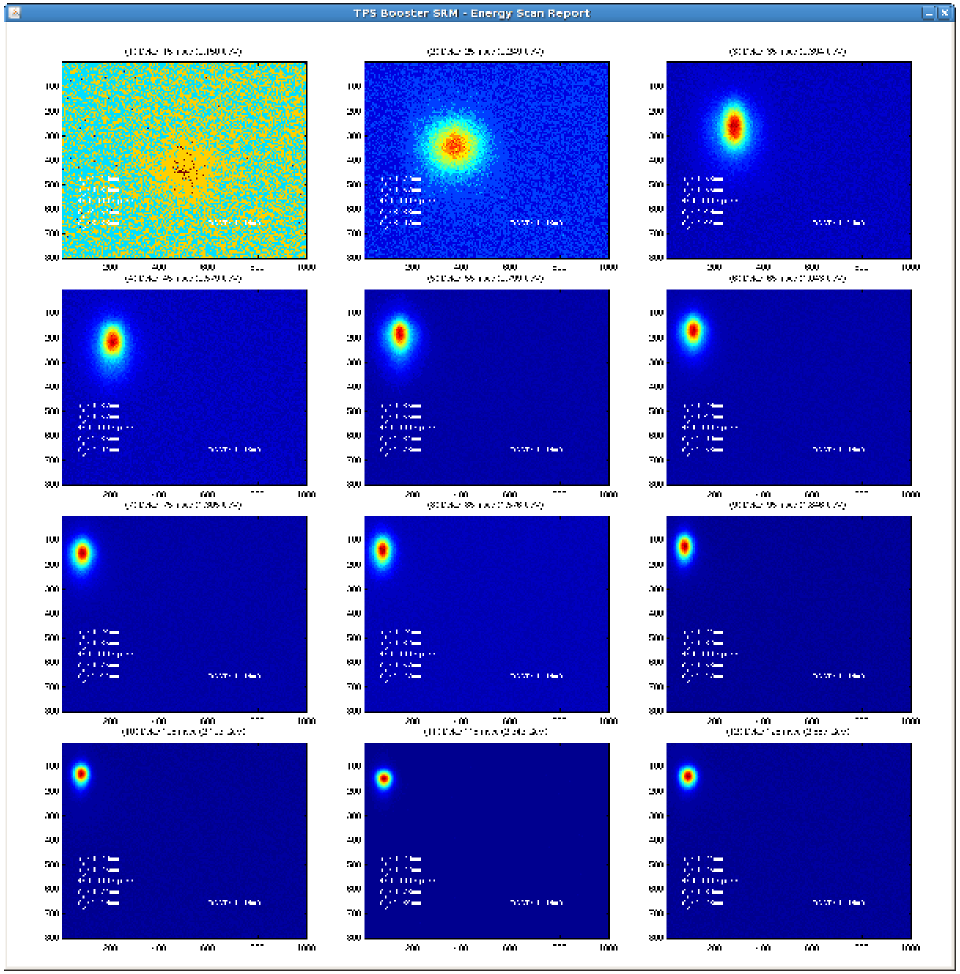
Tune change during ramp



Quadrupole tracking modification

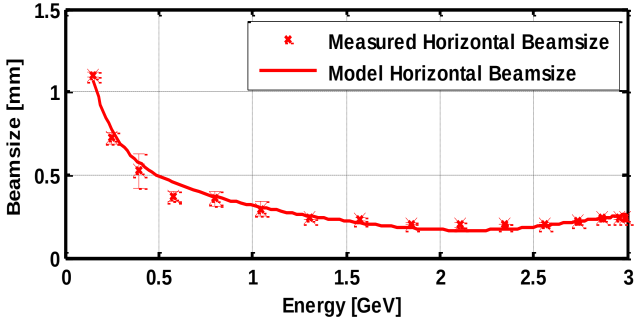
Beam Profile during Energy Ramping

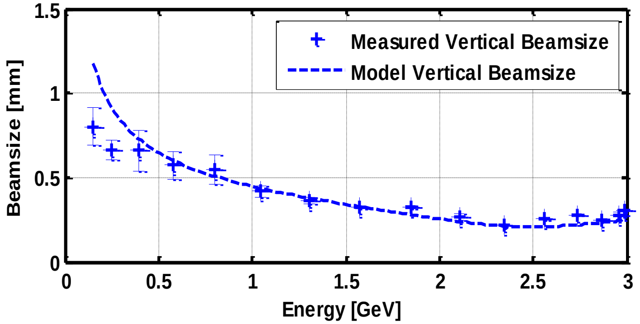
Beam profile during ramp



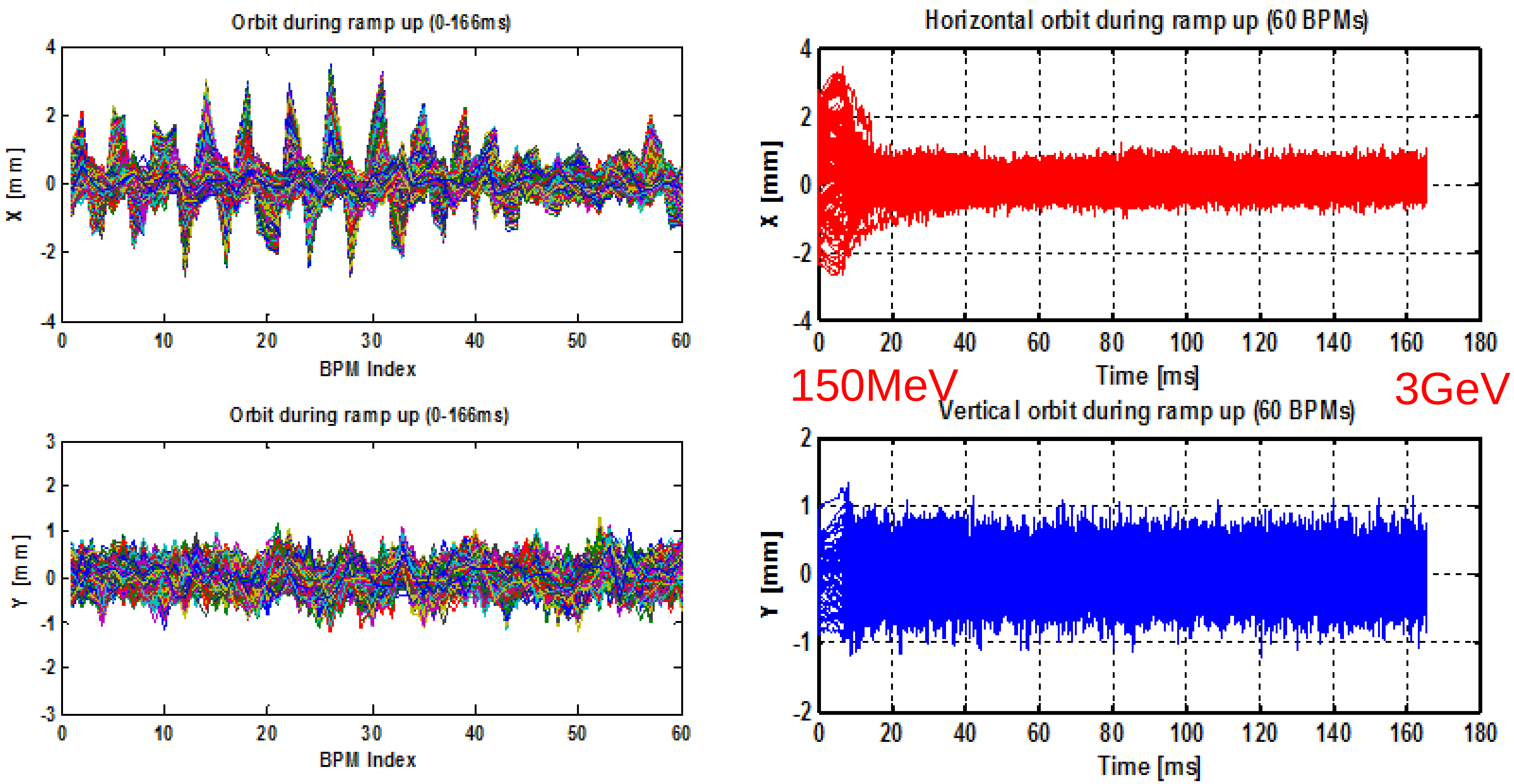
Linac normalized emittance:
36/30 π mm mrad in x/y
Energy spread: 0.35%

Full coupling assumed at 3 GeV



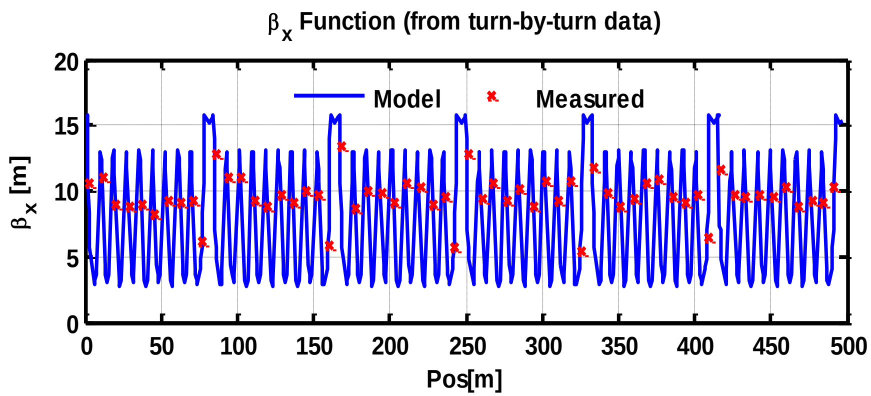


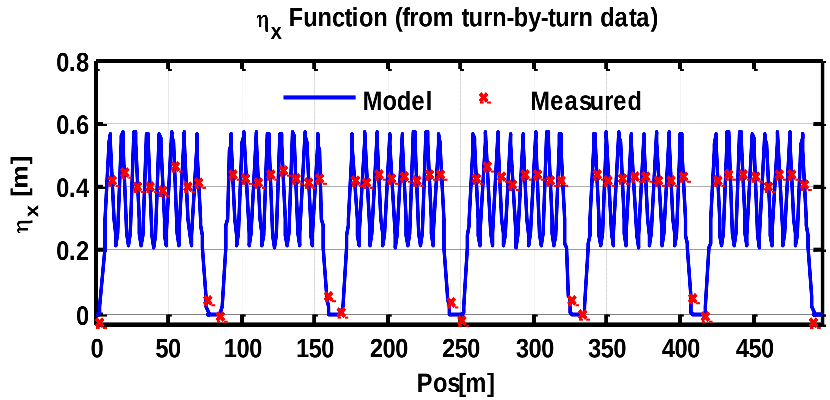
Orbit During Energy Ramp-Up

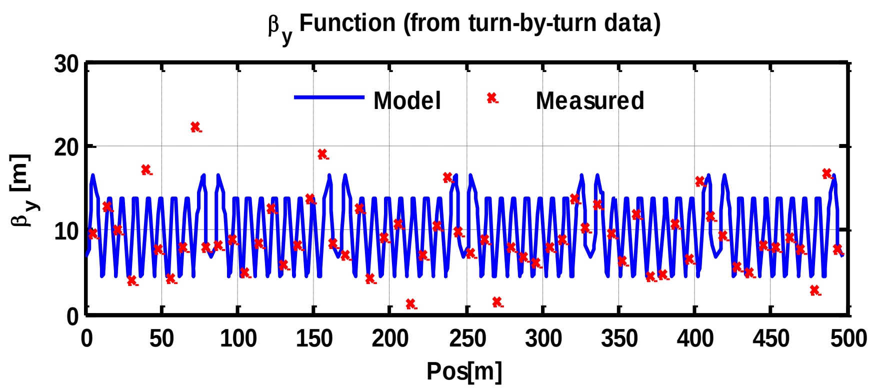


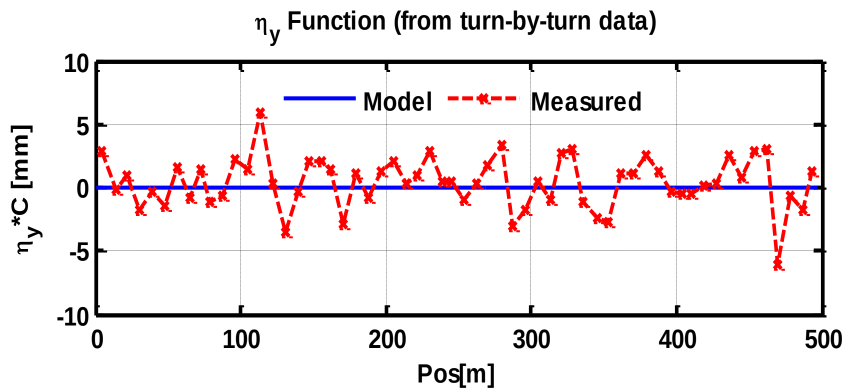
CODs are within 1 mm during energy ramping up except in x at low energy.
No corrector ramp

Booster Optics from Turn-by-Turn Data
150 MeV







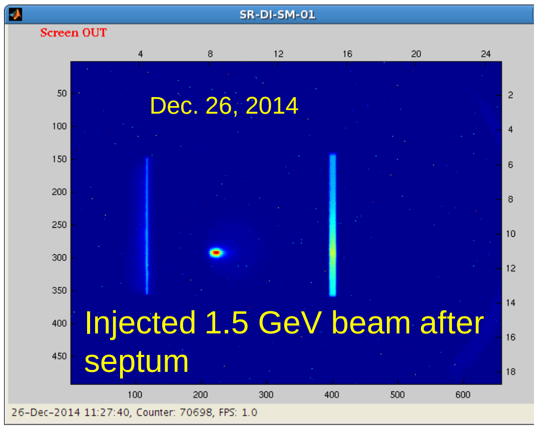


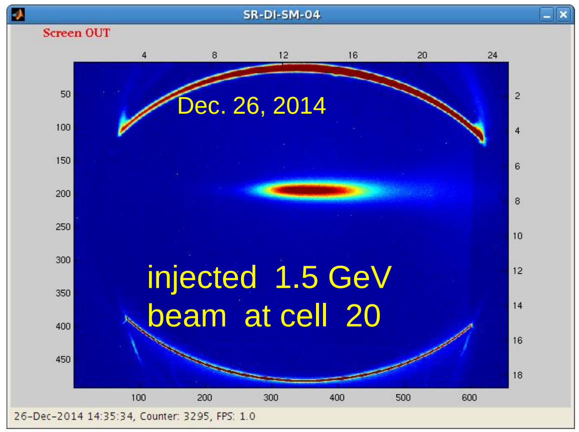
Measured tune: ν_x=14.381, ν_y=9.268
Model tune: ν_x=14.380, ν_y= 9.302

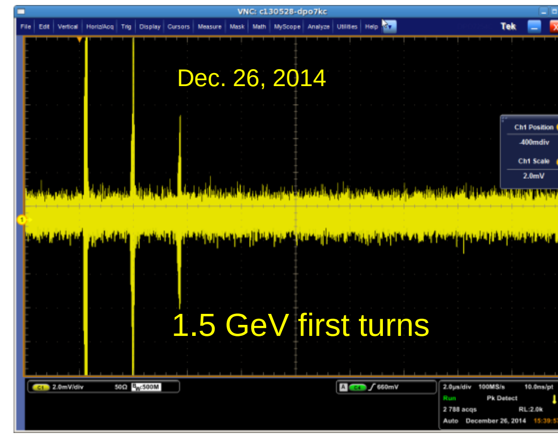
Storage Ring

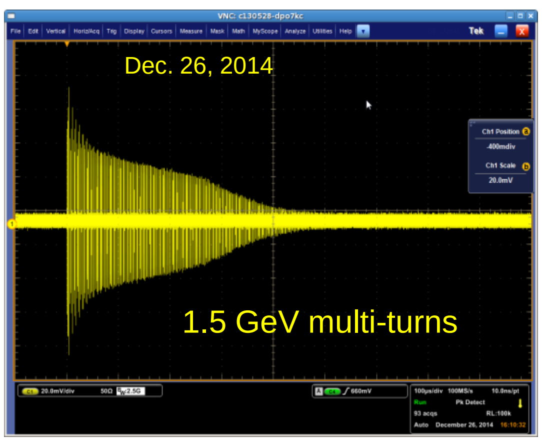
Storage Ring Commissioning at 1.5 GeV

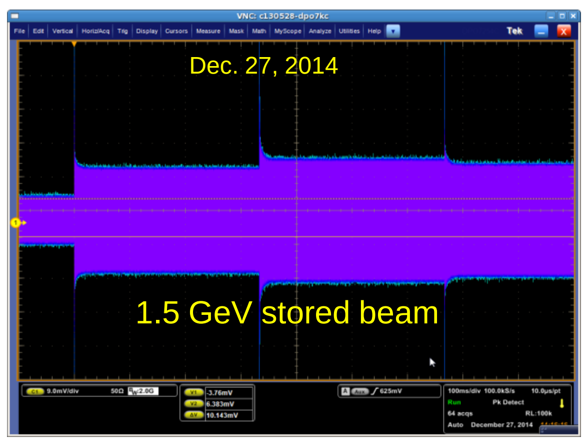
- **Dec. 24, extracted 3 GeV beam but DC septum leakage field affected booster**
- **Dec. 26, 1.5 GeV beam injected, multi-turn with one H corrector**
- **Dec. 27, stored beam with sextupoles and RF on. RF, sextupole, and quad scan**
- **Dec. 29, accumulated beam with kicker scan**

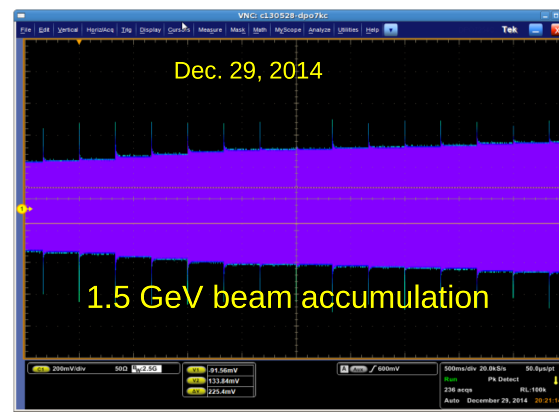






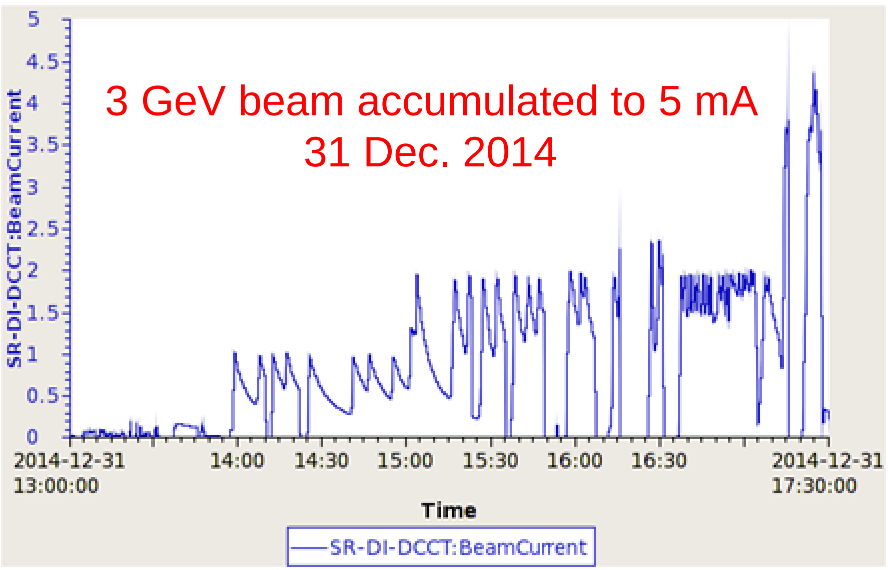


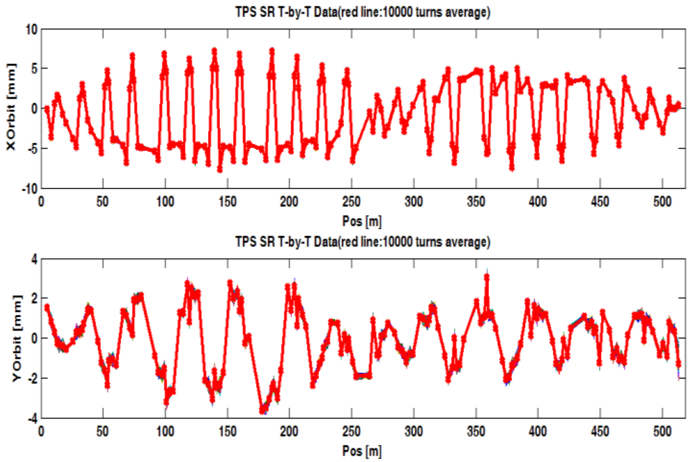




Storage Ring Commissioning at 3 GeV

- **12:20, Dec. 31, 2014, 3 GeV beam circulated in storage ring over 80 turns without activating RF, no sextupole magnets, and no correctors**
- **12:39, Dec. 31, 2014, 3 GeV electron beam was stored in storage ring without activating correctors**
- **13:58, Dec. 31, 2014, 3 GeV beam current was accumulated to 1 mA, the first synchrotron light was observed**
- **3 GeV electron beam was accumulated up to 5 mA in storage ring before shutdown**





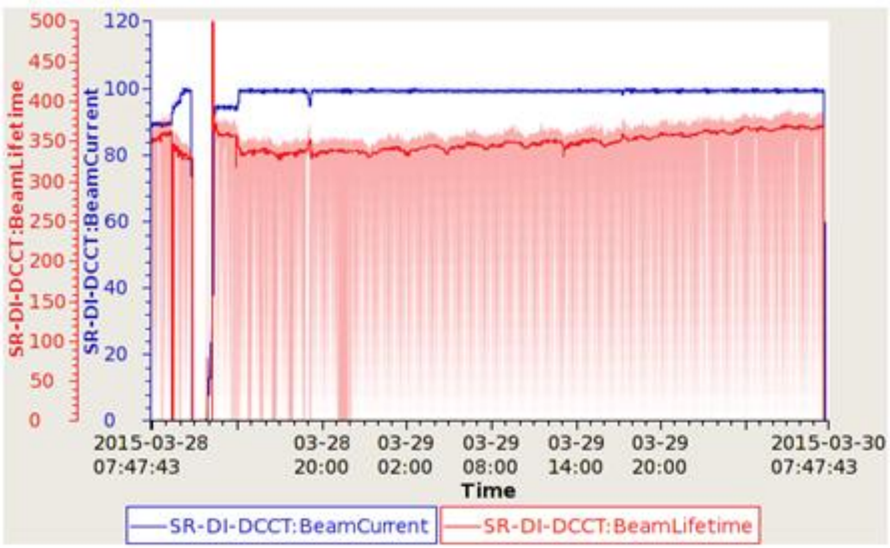
Stored beam orbit→ X: +/- 8 mm, Y: +/- 4 mm, without using any corrector

3 GeV electron beam was stored in the storage ring by the end of 2014

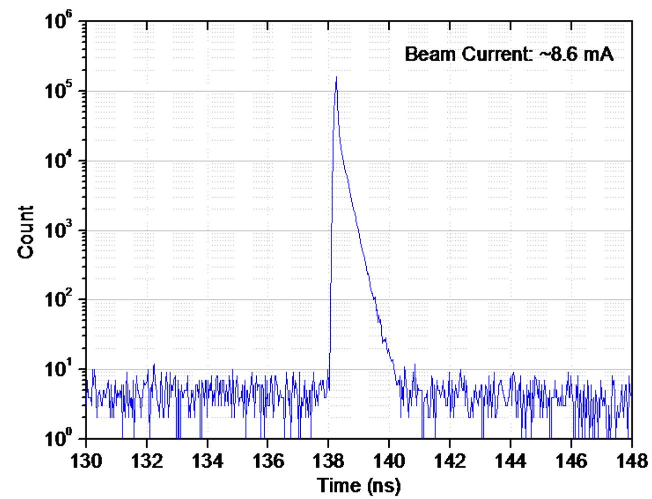
The project is on schedule, within budget

Beam Current

- **Beam current reached 100 mA in multi-bunch mode**
- **Single-bunch recorded 12 mA**
- **~ 0.4 mA/s accumulation rate in multi-bunch mode**



Beam current and lifetime

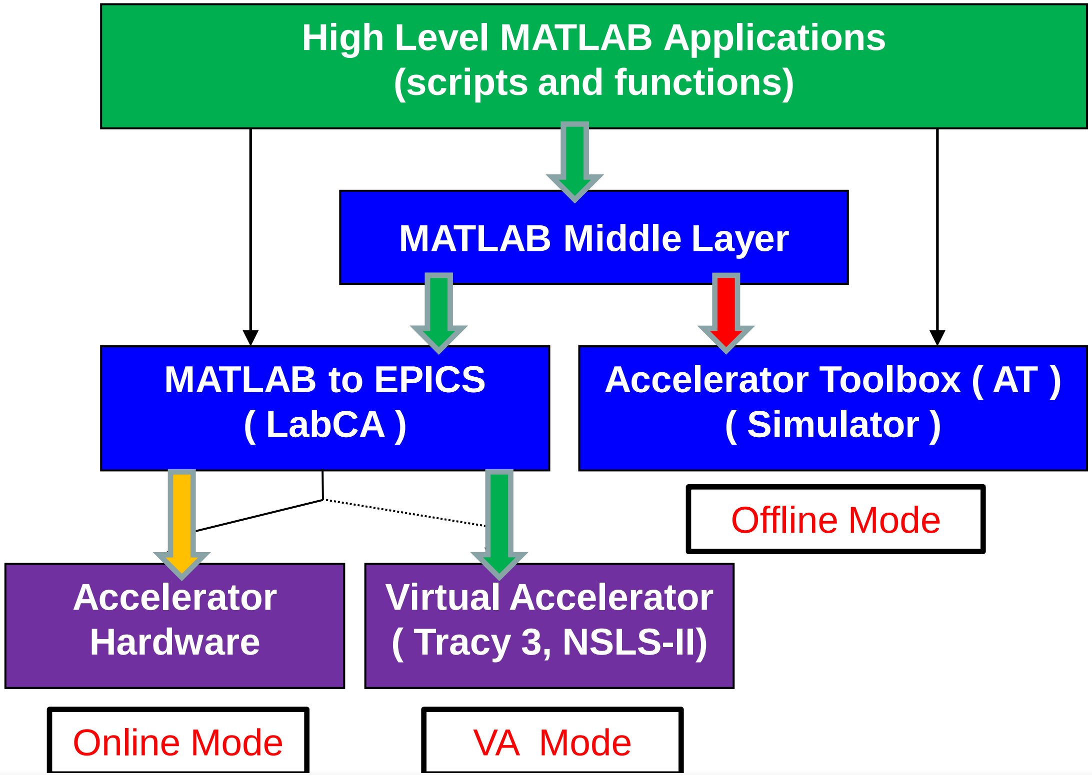


Single bunch impurity (TCSPC) near 10^{-5} with rf knock-out in storage ring

MOPTY074

High Level Applications

High level MATLAB applications and MATLAB Middle Layer (ALS-SSRL) for beam commissioning. (G. Portman, J. Safranek, et al.)



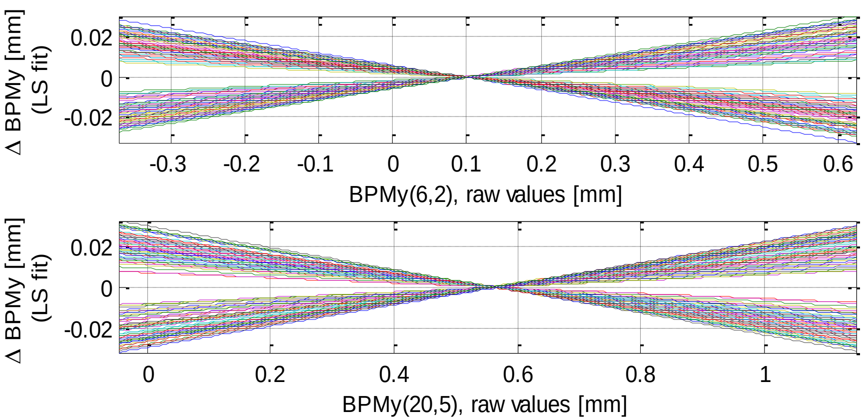
Offline Mode : application programs for some simulations
Online Mode : access the data from the real machine by EPICS channel access
VA Mode : use "Tracy 3" to build the virtual accelerator to test the channel access function between MML and the virtual accelerator

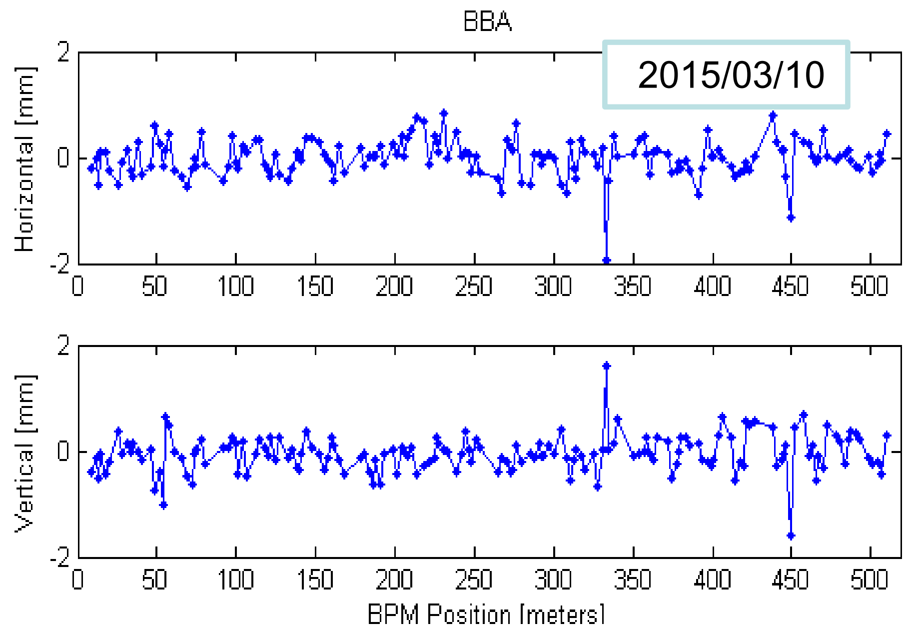
Beam Based Alignment (BBA)

- **Applying BBA to obtain BPM-Quad center offset**

$$f(\theta_{cm}) = \frac{1}{166}\sum_{i=1}^{166}\left(x_i(+\Delta k) - x_i(-\Delta k)\right)^2$$

θ_{cm} : the strength of the corrector magnet
$x_i(\Delta k)$: orbit after changing the quadrupole by Δk
i : BPM index





X: 0.344 mm (rms)
Y: 0.346 mm (rms)

LOCO (Linear Optics from Closed Orbits)

(J. Safranek)

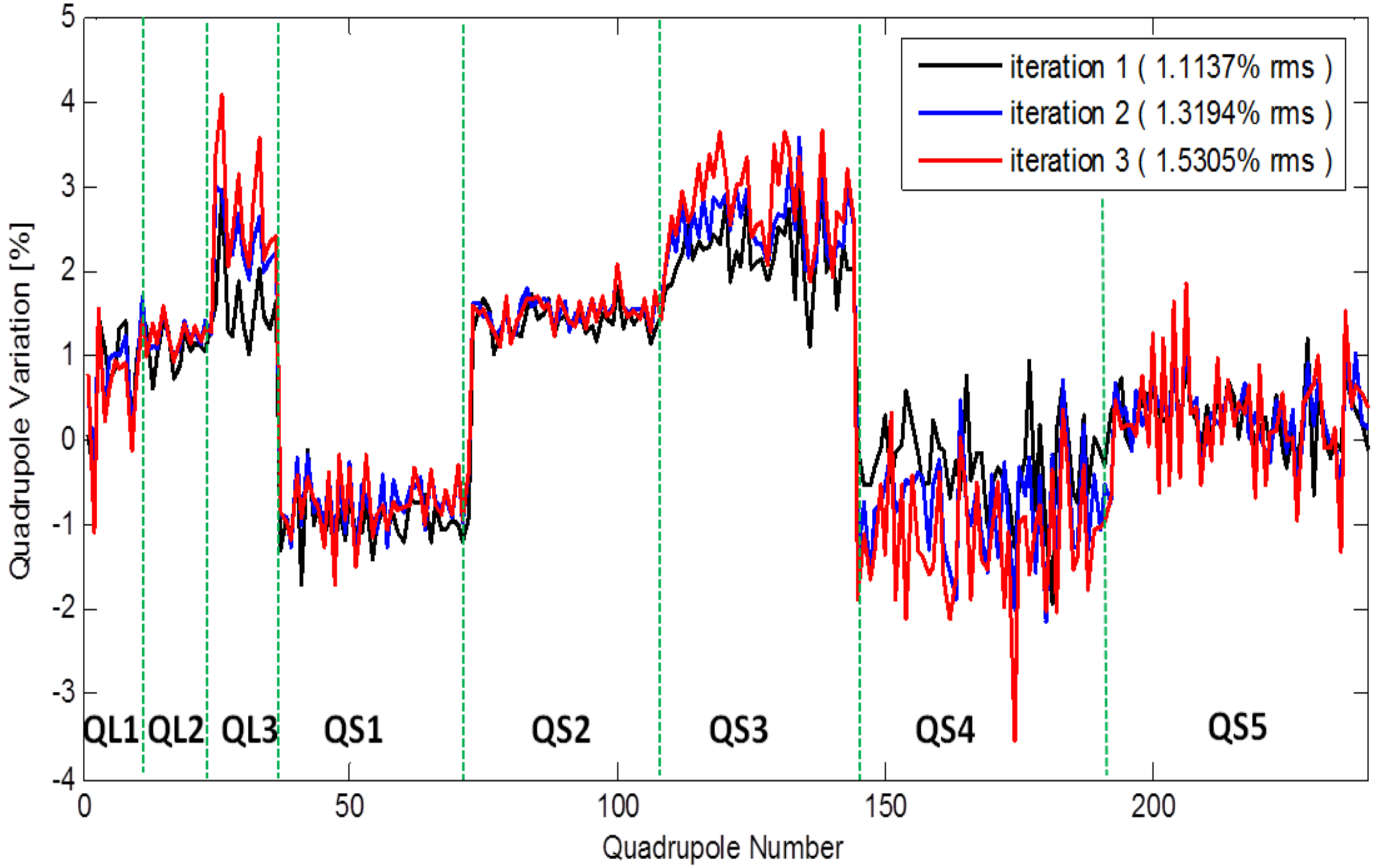
LOCO application adopted for optics calibration and optimization.

Skew gradients, steering gain and tilt, BPM gain and coupling, as well as quad gradients are included.

Total data points:
166(BPM)*168(HC)+166(BPM)*168(VC)=55776

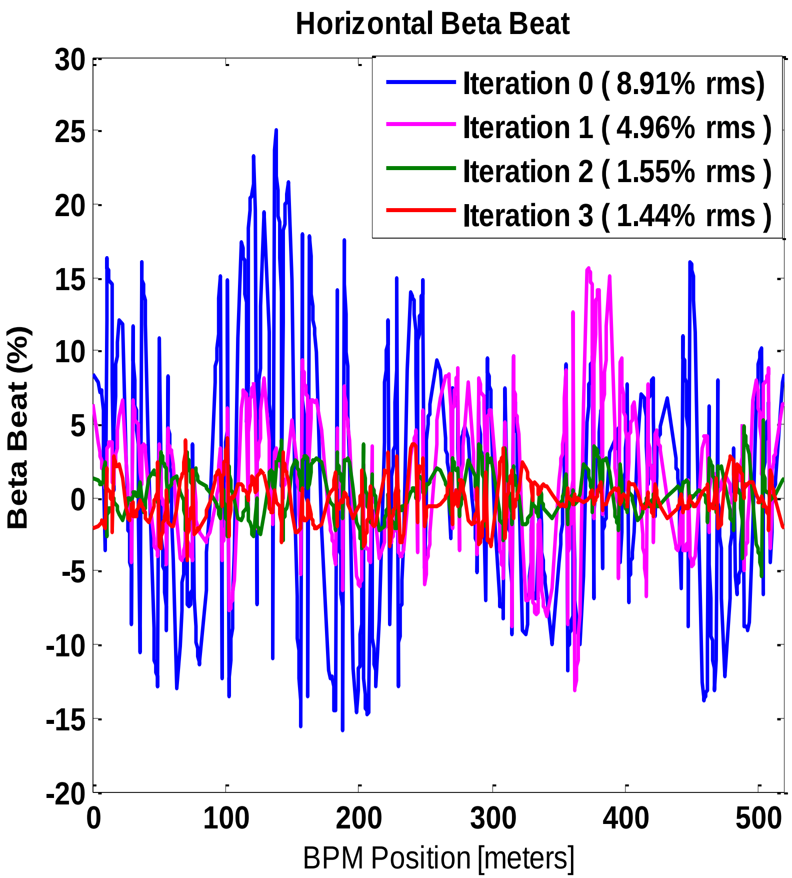
Fitted parameters: 1744

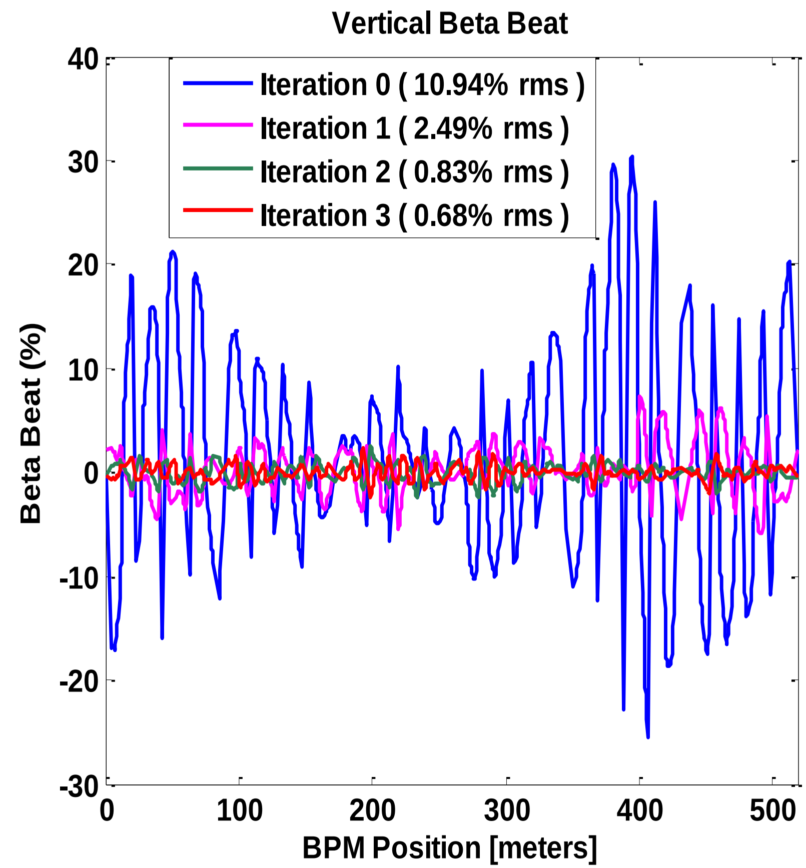
Quadrupole Strength Variation with LOCO



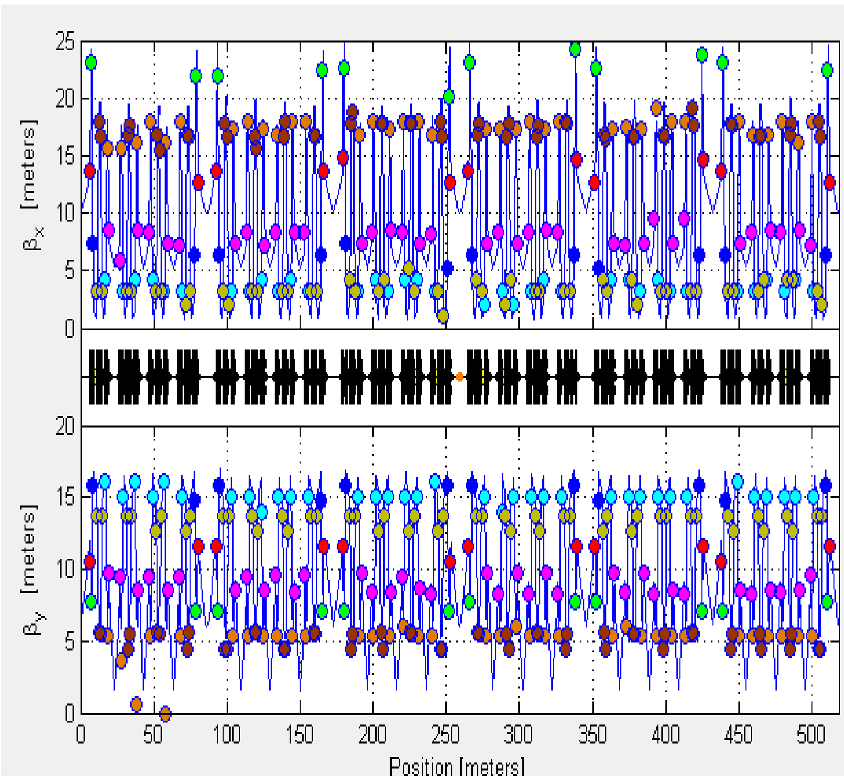
Beta Beating after LOCO Iteration

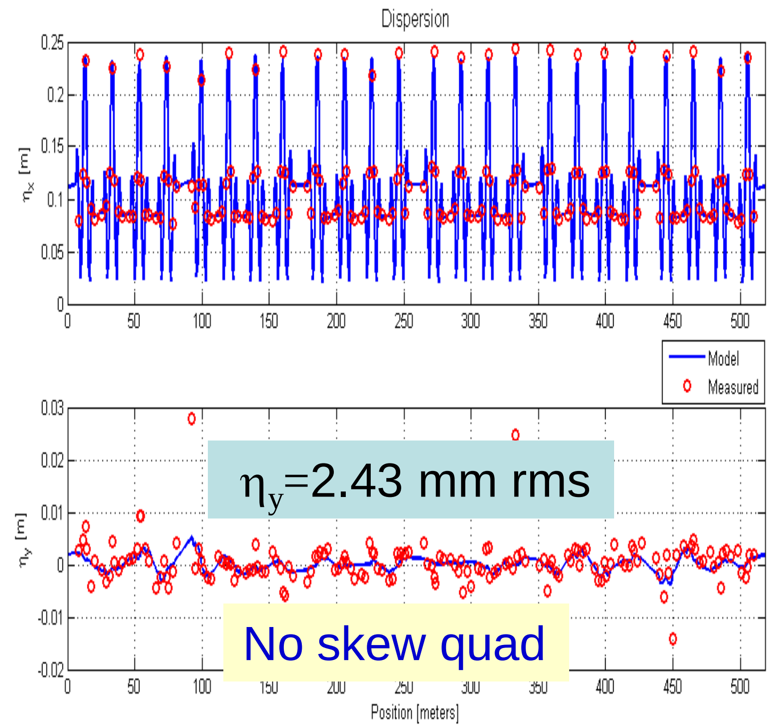
4 iterations H: from 8.91 to 1.44% rms, V: from 10.94 to 0.68% rms





Optics Measurement after LOCO





η_y=2.43 mm rms

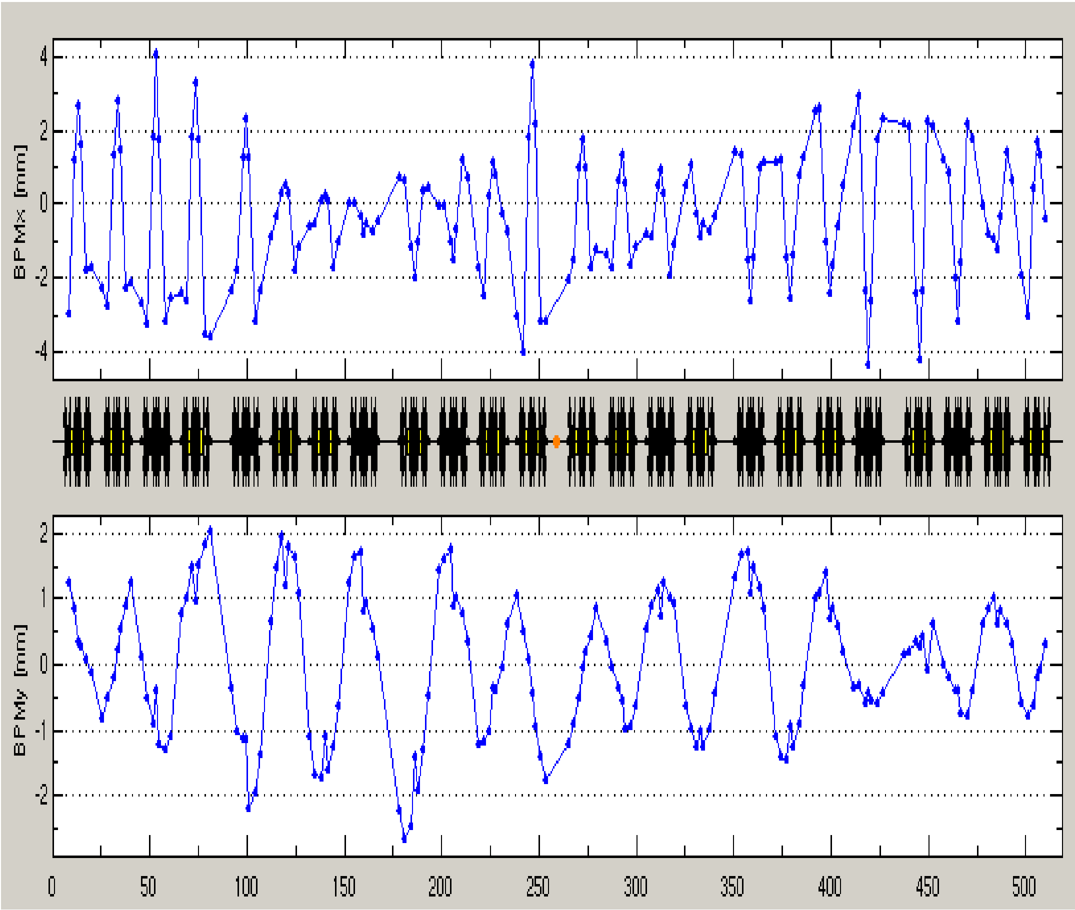
No skew quad

Blue line is LOCO fitting result

η_y=1.77 mm rms with skew quad

Measured COD with all Correctors OFF

(After LOCO and BBA applied)



Horizontal:
1.78 mm rms

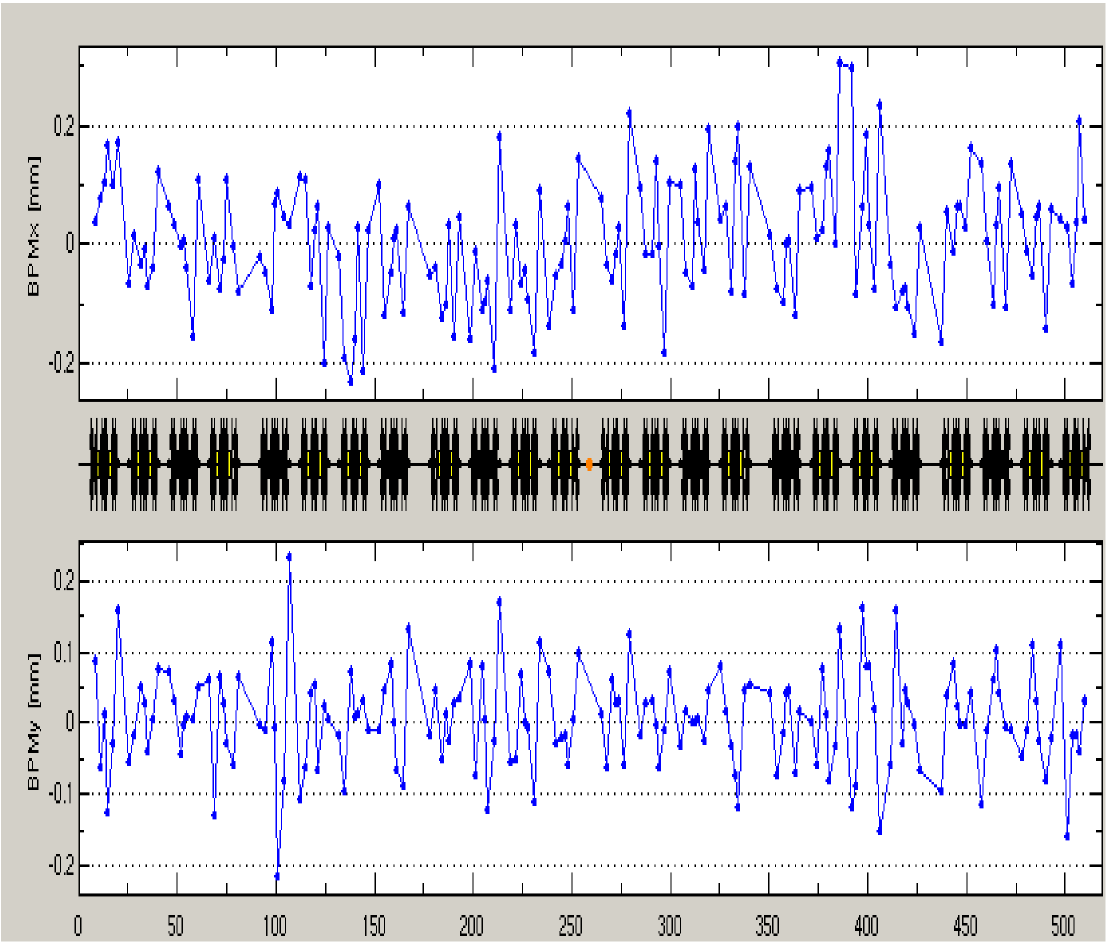
Vertical:
1.04 mm rms

Close to model simulation from alignment and dipole field data
→excellent work on alignment and magnets

Talk: TUAD1 & THYB2

Measured COD after Correction

(After LOCO and BBA applied)



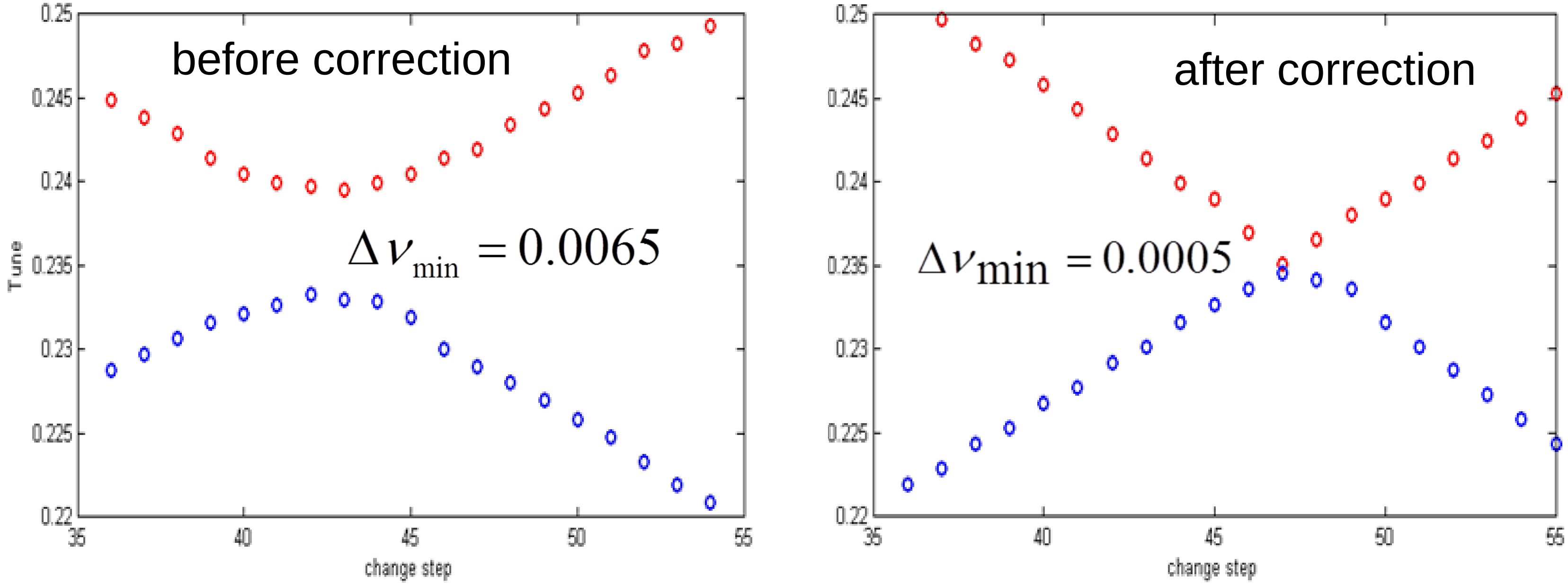
Residual orbit
X: 103 um (rms)
Y: 69 um (rms)

Moderate Corrector strength
X: 0.038 mrad rms
0.25 mrad max
Y: 0.018 mrad rms
0.10 mrad max

Could reduce COD further with stronger corrector strengths

Linear Betatron Coupling

(before and after coupling correction)

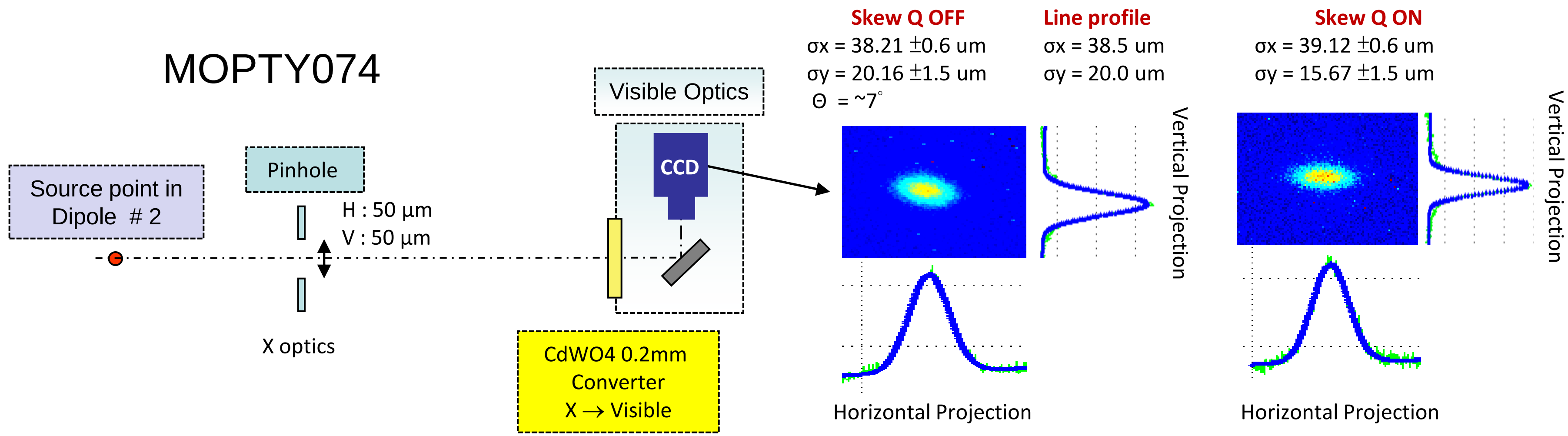


$$\Delta = 26.1831 - 13.2945 - 13 = -0.1114$$

$$\kappa = \frac{\left|\Delta\nu_{min} / \Delta\right|^2}{2 + \left|\Delta\nu_{min} / \Delta\right|^2} = 0.17\% \text{ before correction}$$

$$\kappa = \frac{\left|\Delta\nu_{min} / \Delta\right|^2}{2 + \left|\Delta\nu_{min} / \Delta\right|^2} = 0.001\% \text{ after correction}$$

Coupling Ratio and Emittance



Pinhole camera	without skew quad	with skew quad
H. Emittance (nm.rad)	1.55	1.64
V. Emittance (pm.rad)	**25.6 ±3**	**15.7 ±3**
Emittance ratio (%)	1.65	0.96

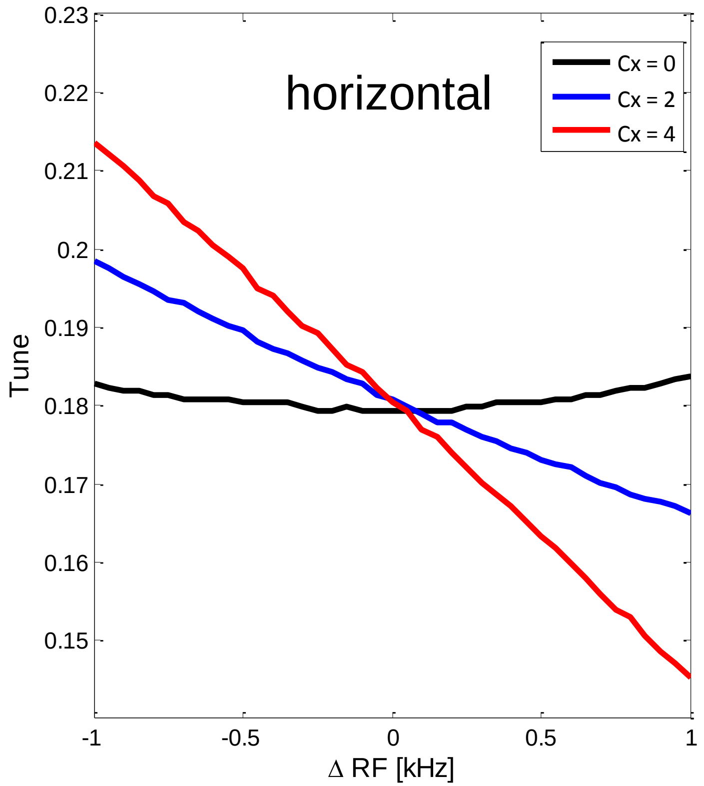
Estimated Emittance ratio (%)	without skew quad	with skew quad
Betatron Coupling	0.170	0.001
Vertical Dispersion	0.156	0.038

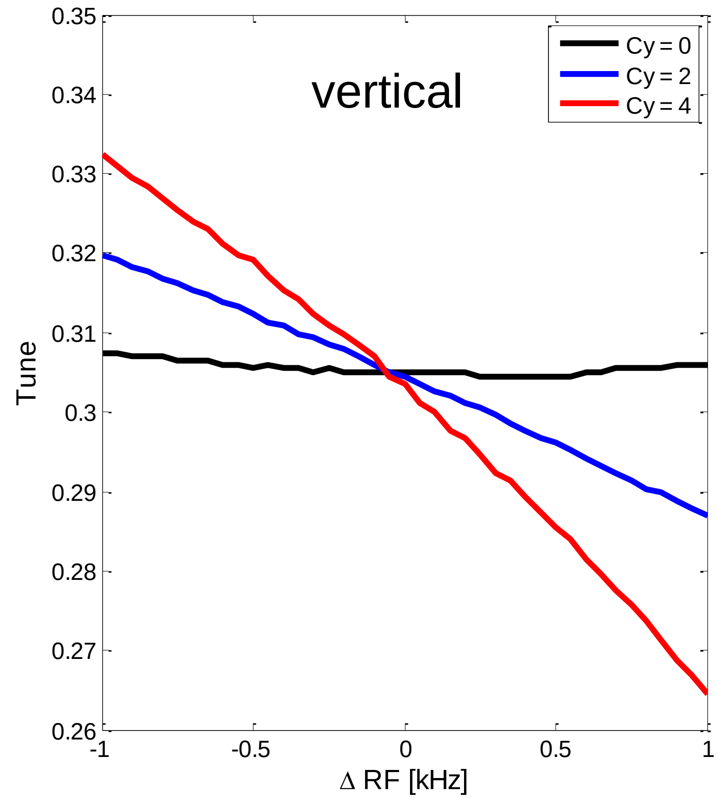
Discrepancy: Orbit noise, instabilities, resolution in instrument

Design Natural Emittance $\boldsymbol{\varepsilon_{x0} = 1.6}$ ***nm.rad***

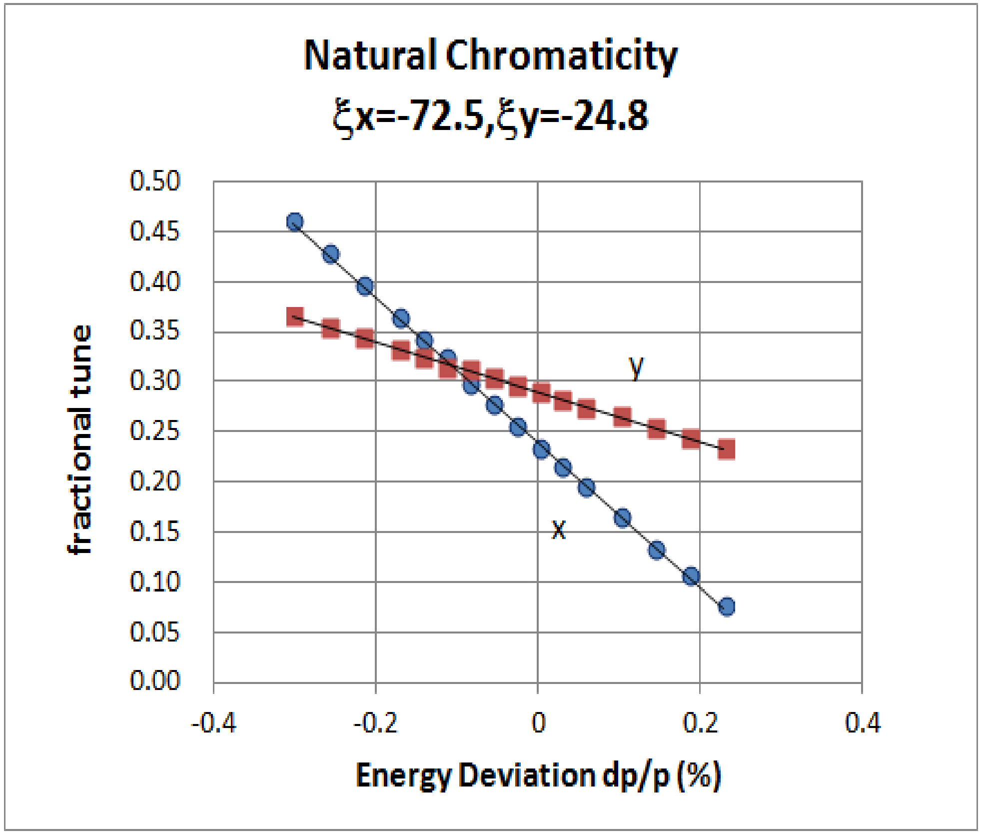
RF Frequency Centering

Center RF frequency: (nominal +1.228kHz)
Circumference shrinkage: (design -1.27 mm)





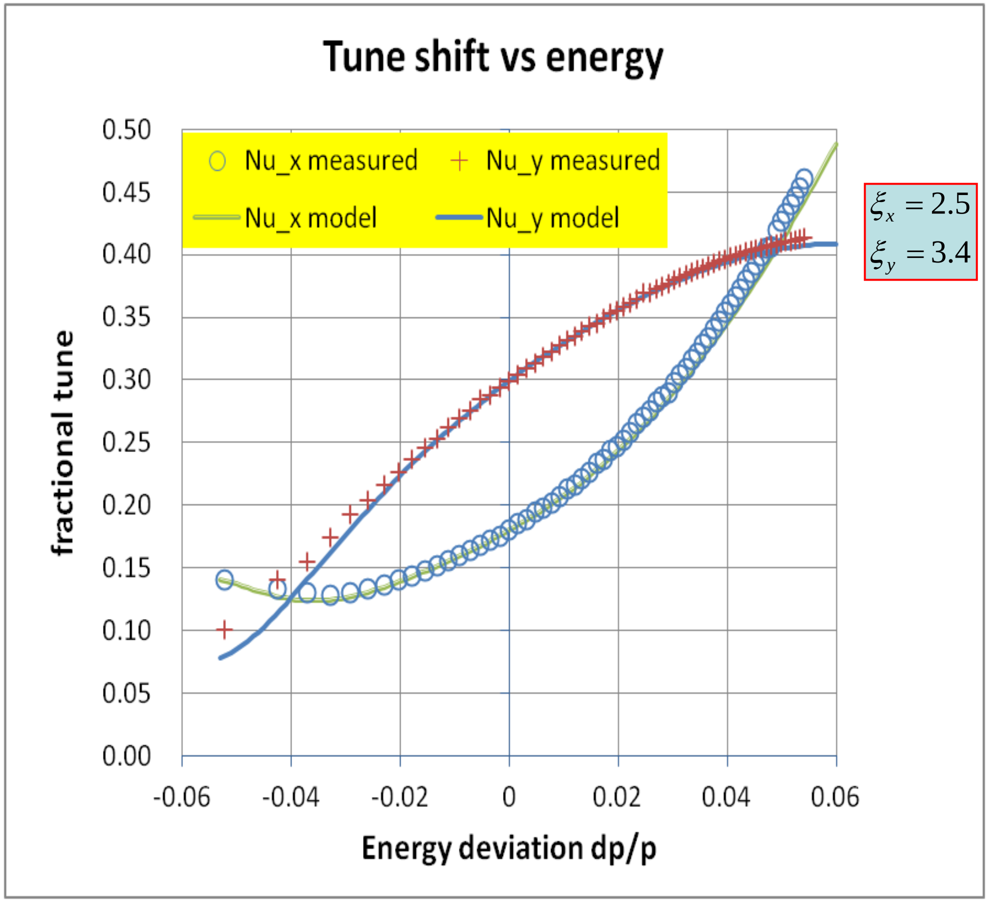
Natural Chromaticity



	Nat. ξ_x	Nat. ξ_y
model	-75	-26
measured	-72.5	-24.8

Change dipole strength and measure tune shift. Dipole field well calibrated

Tune Shift with Energy



Change rf frequency and measure tune shift

Momentum compaction

$\alpha_1 = 2.4\times10^{-4}$

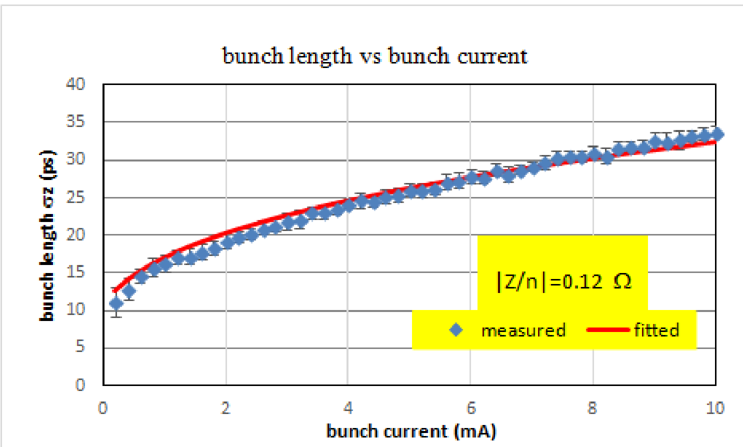
$\alpha_2 = 2.1\times10^{-3}$

$$\frac{\Delta f}{f} + \alpha_1\delta + \alpha_2\delta^2 = 0$$

$$\delta = -\frac{\alpha_1}{2\alpha_2}\left(1 - \sqrt{1 - \frac{4\alpha_2}{\alpha_1^{\,2}}\frac{\Delta f}{f}}\right)$$

Impedance

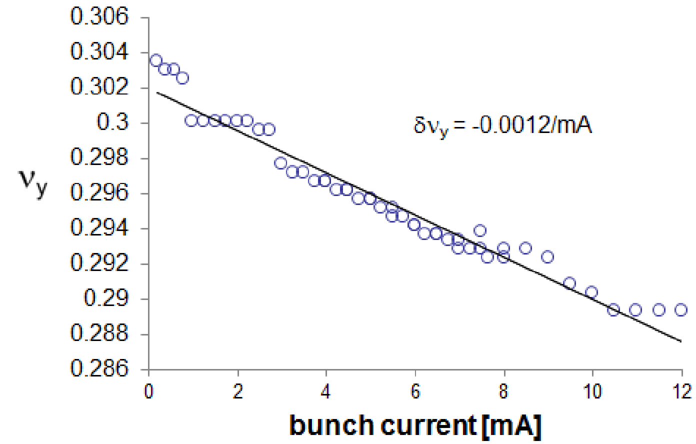
Dual-sweep streak camera (C10910 Hamamatsu Photonics) used to measure bunch length.



$$\left(\frac{\sigma_l}{\sigma_{l0}}\right)^3-\left(\frac{\sigma_l}{\sigma_{l0}}\right)=\frac{1}{\sqrt{2\pi}}\frac{\alpha_c e I_b}{E_0\nu_{s0}^2}\left(\frac{c}{\omega_0\sigma_{l0}}\right)^3 \mathrm{Im}\left[\left(\frac{\mathrm{Z}}{\mathrm{n}}\right)_{eff}\right]$$

From Zotter's potential-well bunch lengthening eqn:

$|Z/n|_{eff}=0.12\ \Omega$ → **Smooth chamber**



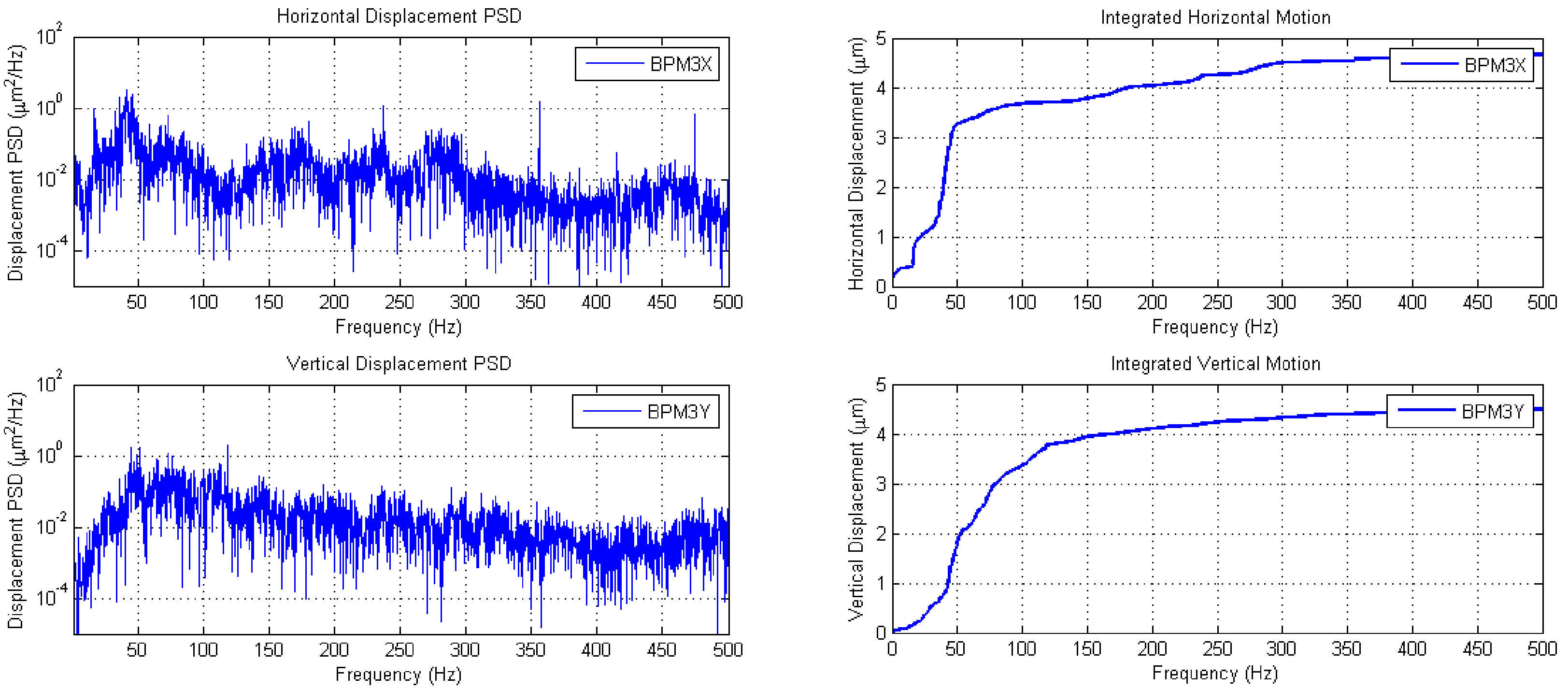
$$\frac{\Delta\nu_y}{\Delta I[mA]}=10^{-3}\frac{c^2}{4\sqrt{\pi}(E/e)\nu_y\omega_0^2\sigma_\ell}\mathrm{Im}(Z_\perp)_{eff}$$

$\mathrm{Im}(Zy)_{eff}$ =-0.175 MΩ/m

$\mathrm{Im}(Zx)_{eff}$ =-0.154 MΩ/m

Beam and BPM noise

- Water turbulence in vacuum chambers and mechanical pumps are major sources of noise
- At high beam current, instabilities contributed a significant amount



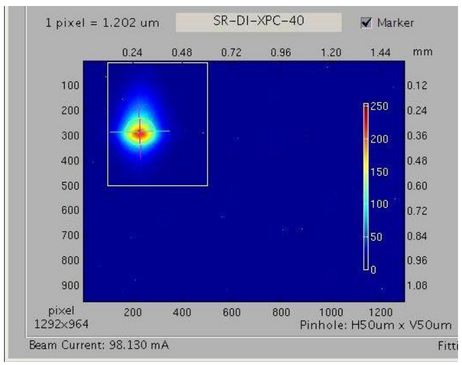
MOPTY075

No orbit feedback

Instability

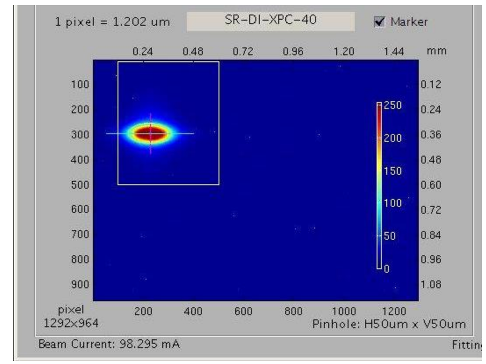
- **Need high chromaticity and vertical feedback system to damp the vertical instability at high current, e.g., 100 mA**
- **Longitudinal instability showed up around 85 mA. (PETRA cavities)**

100 mA, vertical feedback off

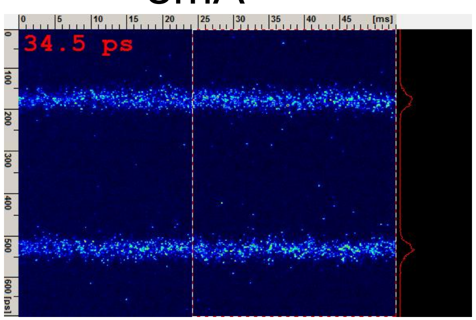


Beam profile image

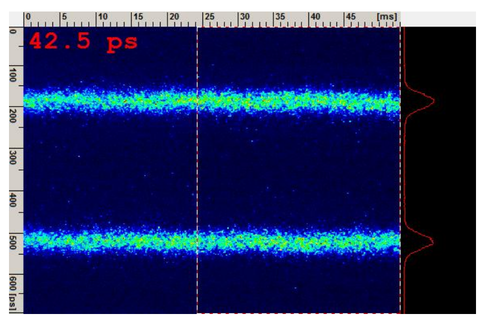
100 mA, vertical feedback on



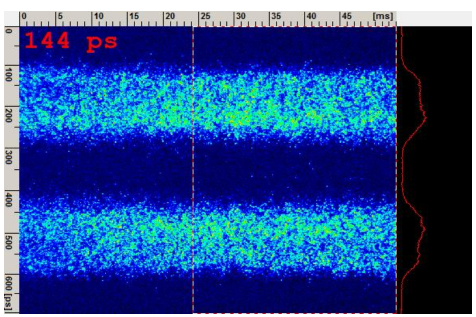
5mA



40mA



85mA

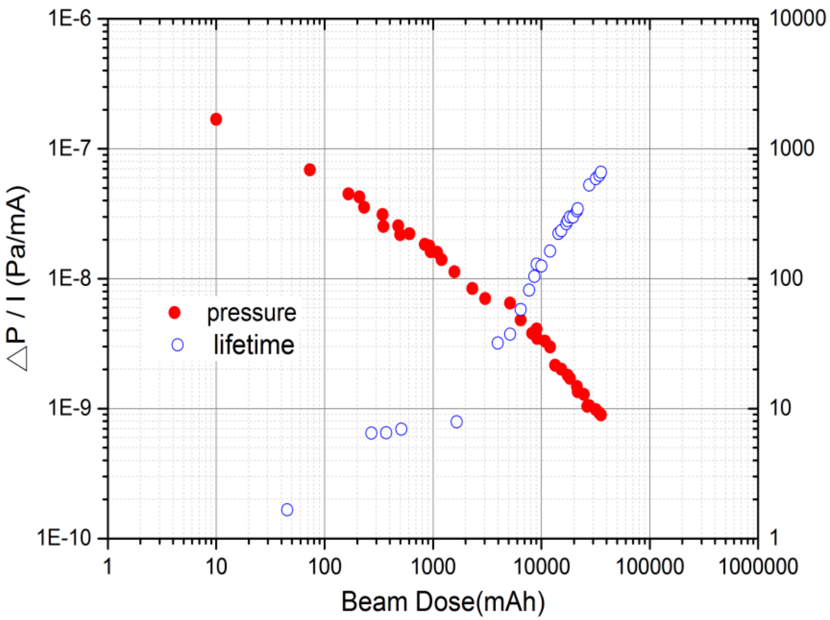


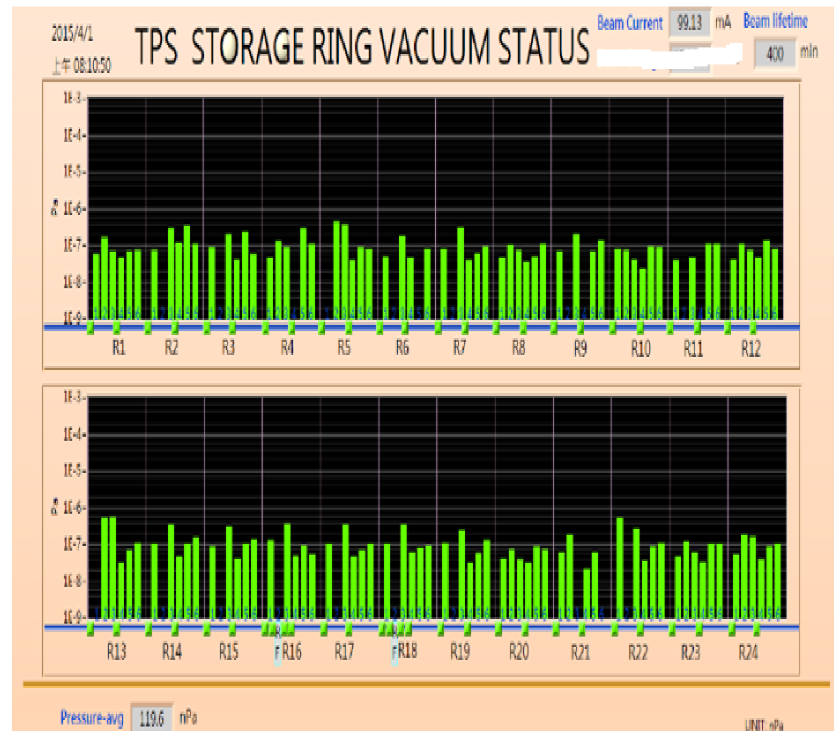
Streak camera image

MOPTY074

Vacuum Conditioning

- **Dynamic pressure reached 1.17 10^{-7} Pa at 100 mA after 35 A.h beam dose**
- **Lifetime at 100 mA reached more than 6 hours**





WEPHA048

Summary

- High permeability vacuum chambers caused a delay in the booster commissioning and was recognized on 2014-11-12.
- Heat treatment solved the problem within a month and booster ramped to 3 GeV on 2014-12-16.
- 3 GeV stored and accumulated beam in storage ring on 2014-12-31.
- 100 mA reached in March 2015 (limited by RF cavities).
- Storage ring lattice optics was well calibrated and measured in agreement with model values.
- Measured horizontal emittance is 1.6 nm-rad consistent with design value.
- Emittance coupling is less than design goal of 1%.
- Measured lattice energy acceptance is large, same as design.
- Storage ring impedances were measured and indicate a smooth chamber.
- Beam and BPM noise were measured and identified.
- Vacuum conditioning was in good progress.

Next Step

- SRF and ID commissioning in September, 2015
- Beamline commissioning after SRF and ID commissioning
- Improvement of beam transmission efficiency
- Reduction of beam and BPM noise by eliminating noise sources and using feedbacks
- Study of instabilities and cures
- Nonlinear beam dynamics study
- And others

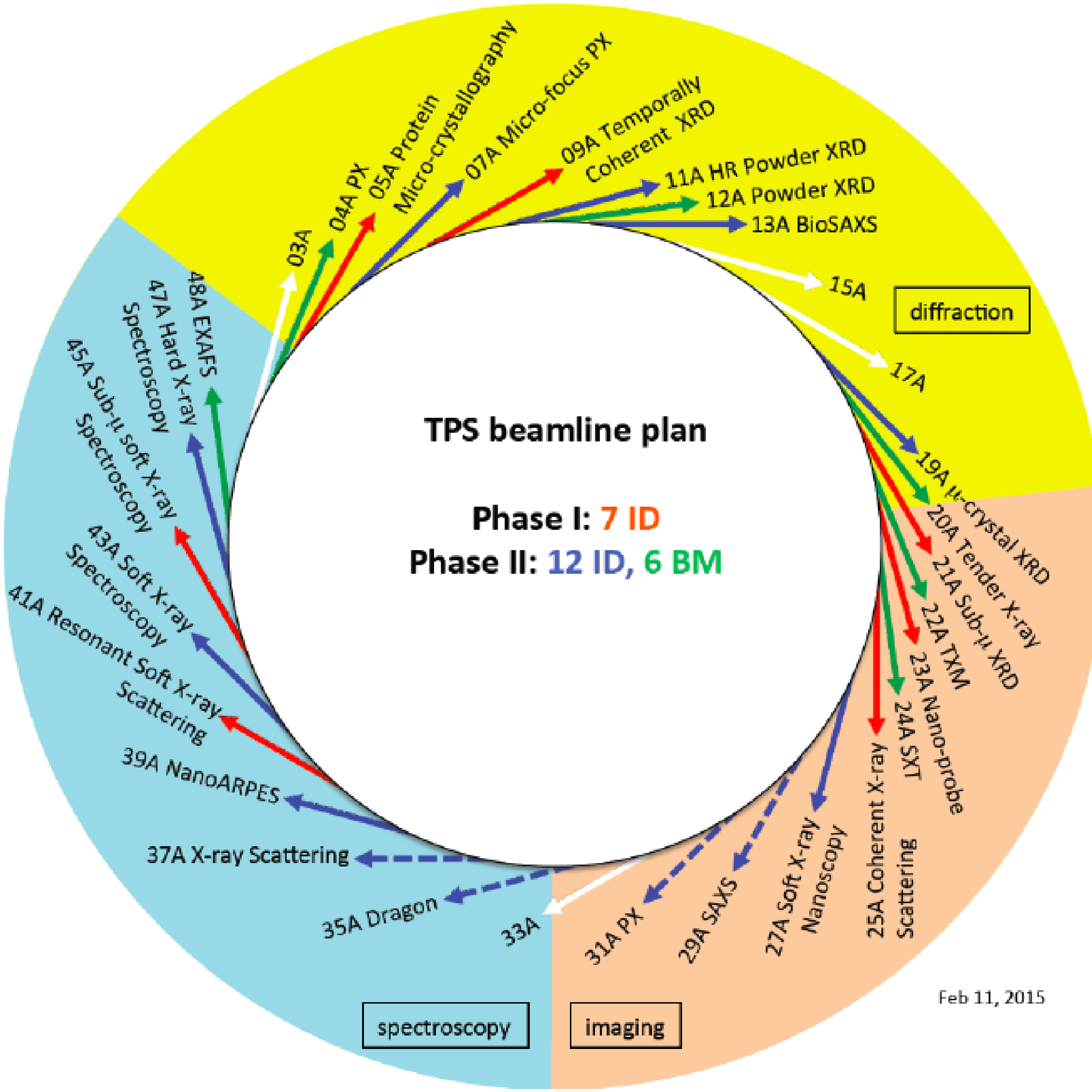
Acknowledgement

- We thank the TPS team for their enthusiasm and devotion to the project, and efforts made to accomplish the system integration and commissioning successfully in such a short period.
- We also thank for all the help from accelerator experts worldwide for this progress.

Thank you for your attention

extra

TPS Beamline Plan



Radiation Safety

< 2 uSv per 4 hours