Commissioning Status of the Shanghai Synchrotron Radiation Facility

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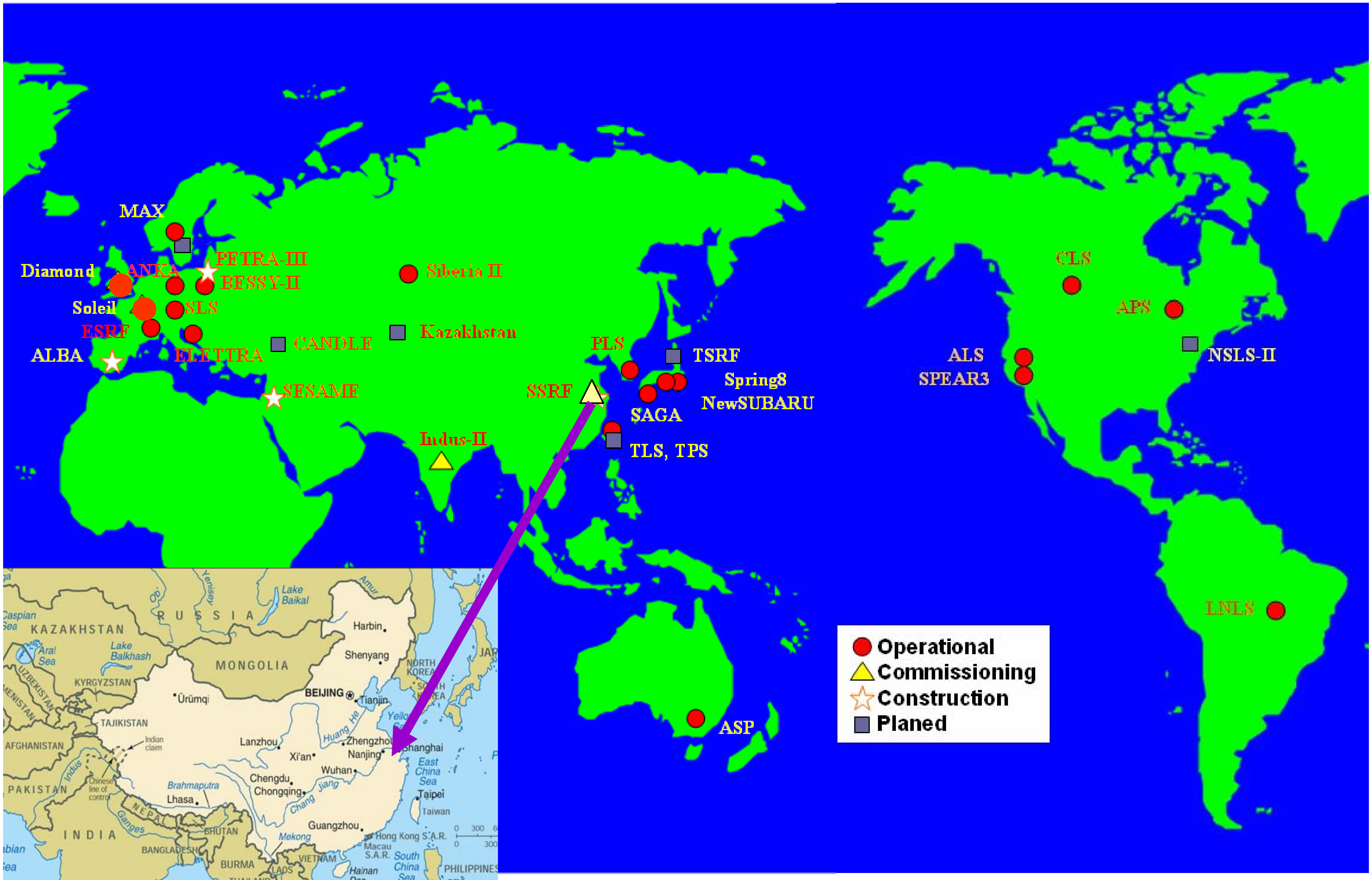
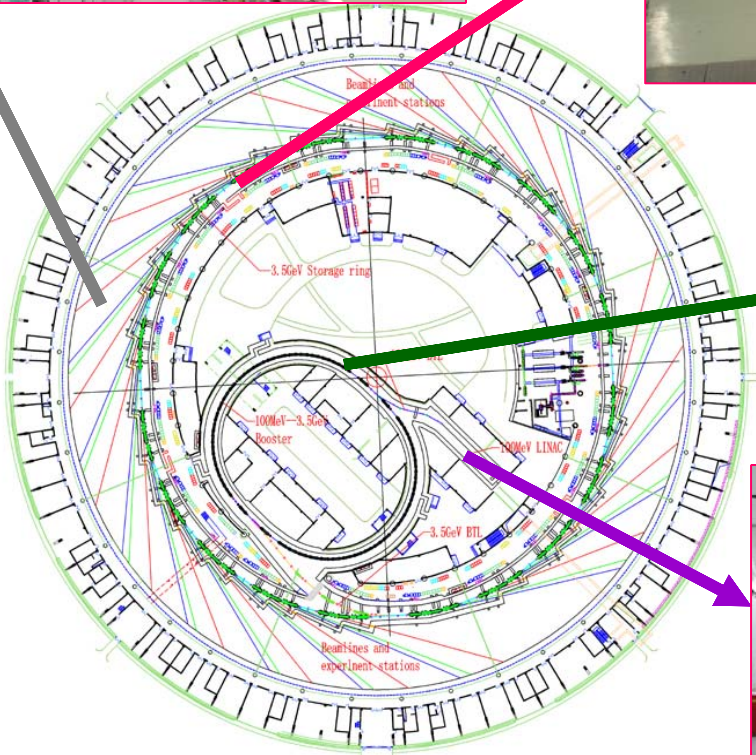
Shanghai Synchrotron Radiation Facility

- SSRF is an intermediate energy 3rd generation light source funded by Chinese Academy of Sciences (CAS), Shanghai local government and central government of China;
- CAS and Shanghai local government made a joint proposal in 1995, and then a R&D program was carried out from Jan. 1999 to Mar. 2001; Later on this project was announced and fully approved in 2004, and its groundbreaking was made on Dec.25, 2004;
- The Linac and booster have been commissioned in 2007, the ring commissioning and the beamline commissioning started on Dec. 21, 2007 and May 9, 2008 respectively. The user operation is scheduled to start in April 2009.

Third Generation Light Sources around the world

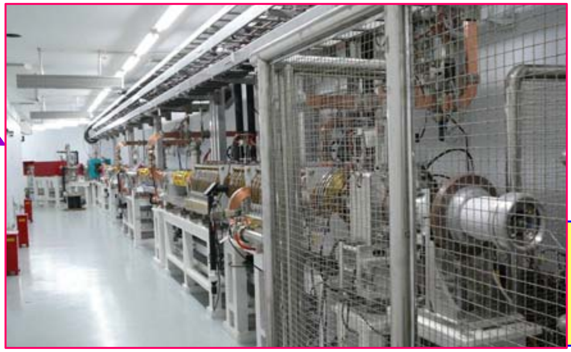


The SSRF Complex



Storage Ring
3.5GeV, C=432m

Booster
3.5GeV, C=180m



Electron Linac
150MeV

The First SSRF Beamlines

- Macromolecular Crystallography (In-Vac Und.)
- High-Resolution X-ray Diffraction (under commissioning)
- X-ray Absorption Fine Structure Spectroscopy (W)
- Hard X-ray Micro-focus and Application (In-Vac Und)
- X-ray Imaging and Biomedical Application (W)
- Small Angel X-ray Scattering (under commissioning)
- Soft X-ray Microscopy (Und.)

The SSRF Construction Schedule

- Dec. 2004 ~ May 2007: Building construction
- Jun. 2005 ~ Jun. 2008: Accelerator equipment and components manufacture and assembly
- Dec. 2005 ~Dec. 2008: Beamline construction and assembly
- May. 2007 ~ Jul. 2007: Linac commissioning
- Oct. 2007 ~ Dec. 2007: Booster commissioning
- Dec. 2007 ~ Dec. 2008: Storage ring commissioning
- May 2008 ~ Mar. 2009: Beamline commissioning
- Apr. 2009: The SSRF operation begins

The SSRF Accelerator Complex

- The SSRF accelerator complex consists of a 150MeV Linac, a full energy booster and 3.5GeV storage ring
  - The energy selected higher than 3GeV for getting higher photon energy;
  - High brightness and high flux optimized for photon energy range of 0.1 - 40keV;
  - High beam position stability requirement @ the long, medium and short terms;
  - Top-up considered as one of the normal operation mode;

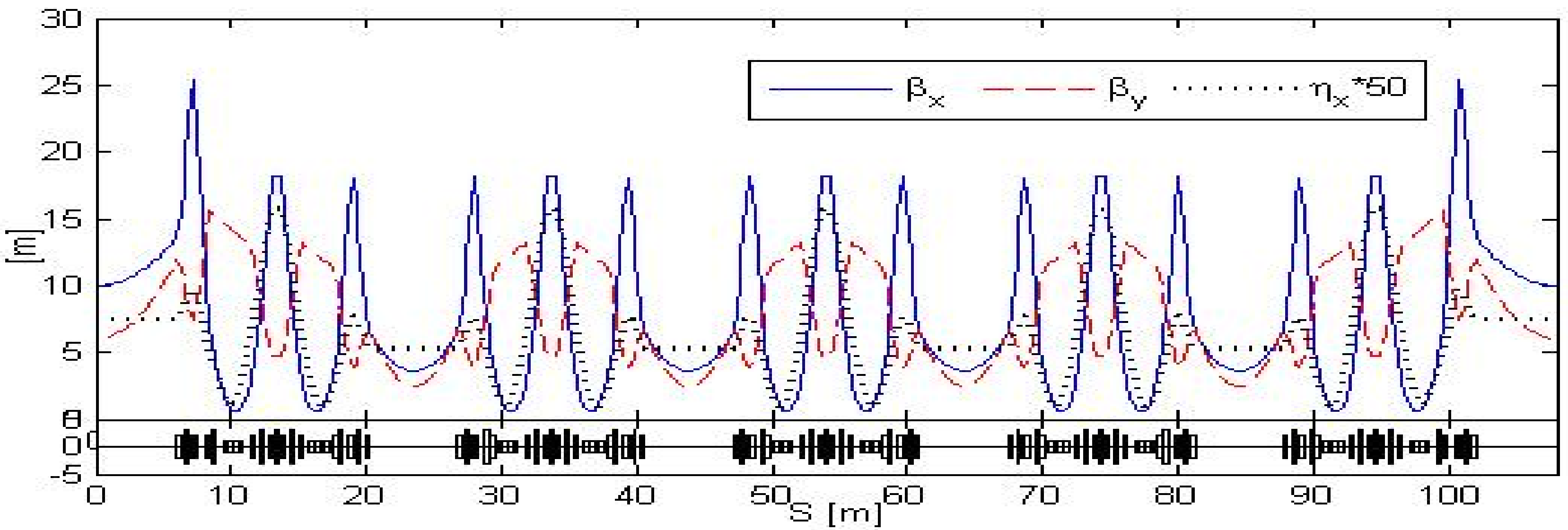
The SSRF Storage Ring

- A 20-cell double bend ring lattice structure with a circumference of 432 m and a natural emittance of 3.9nm-rad;
- 4 fold configuration with two types of straight sections (16x6.5m and 4x12m);
- One 12m straight for accommodating all injection elements, another one for SRF cavities and other 18 for various IDs;
- Reasonable beam sizes, beta functions and dispersion at straight sections;

Main Parameters of the SSRF Storage Ring

	DBA	Low-emittance mode	Normal Mode
Energy	GeV	3.5	3.5
Circomference	m	432	432
Natural Emittance	nm· rad	3.9	11. 2
Current：Multi-bunch（Single）	mA	200~300(5)	200~300(5)
Number of Cells		20/4	20/4
Straights: Length×Number	m	12×4、6.5×16	12×4、6.5×16
$\beta_x/\beta_y/\eta_x$ in middle of 12m straight	m	10.0/6.0/0.15	10.0/6.0/0.0*
$\beta_x/\beta_y/\eta_x$ in middle of 6.5m straight	m	3.6/2.5/0.10	3.6/2.5/0.0*
Betatron Tune Q_x/Q_y		22.22/11.32	22.22/11.32
Chromaticity ξ_x/ξ_y		-56/-19	-56/-19
RF Voltage	MV	4.0~6.0	4.0~6.0
Energy Loss Per Turn (Dipole)	MeV	1.448	1.448
Bunch Length	mm	4.0	4.0

Lattice Functions for One Super-Period

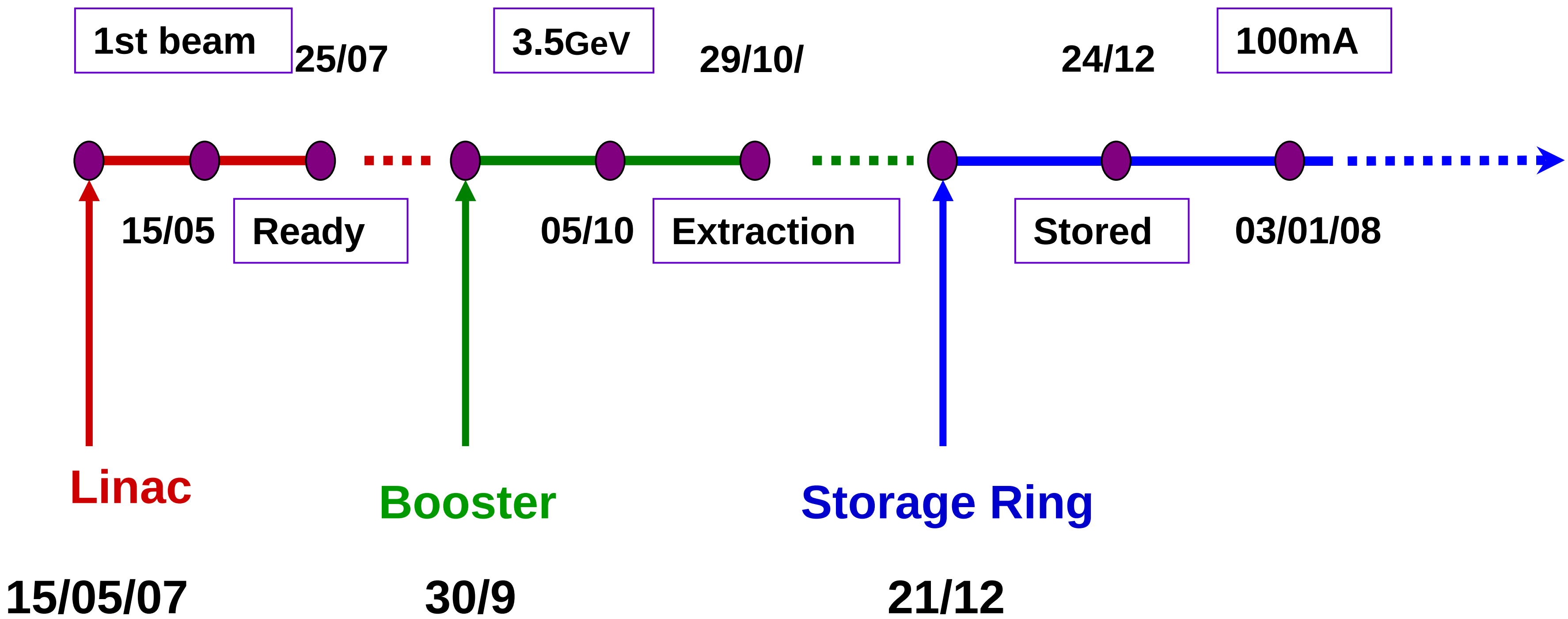


SSRF Beam Sizes at Source Points

Source Point	σ_x (μm)	σ_x' (μrad)	σ_y (μm)	σ_y' (μrad)
Standard Straight (6.5m)	158	33	9.9	3.95
Long Straight (12.0m)	247	20	15	2.55
1°@upstream of SS	70	114	22	1.97
3.1°@upstream of SS	53	94	22	1.97
1°@upstream of LS	77	116	23	1.79
3.1°@upstream of LS	56	96	23	1.79

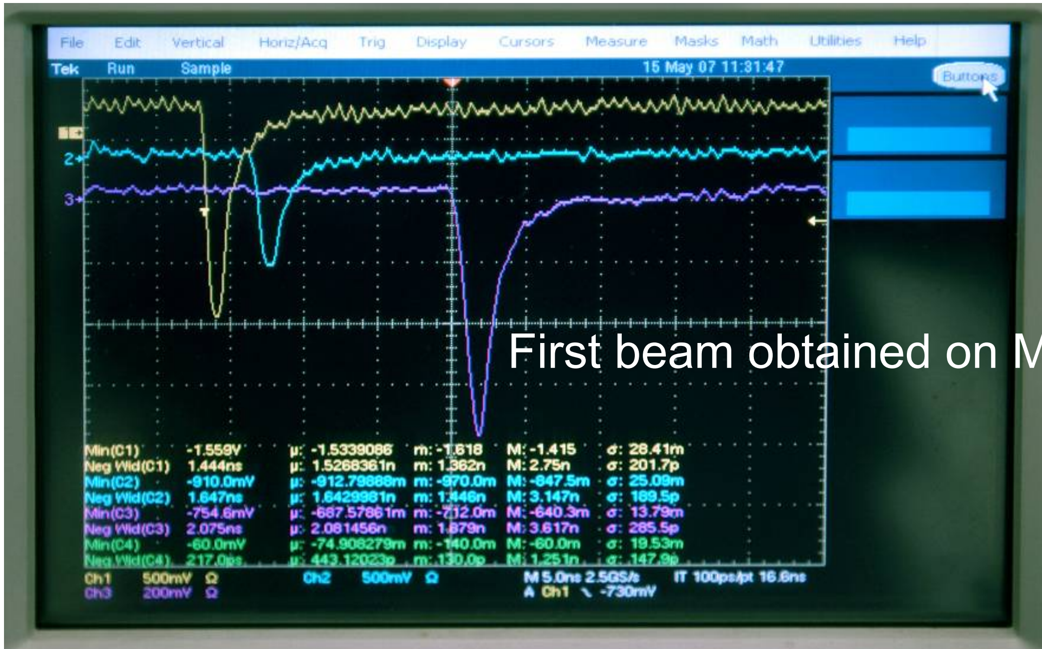

C05

Key Dates of the SSRF Commissioning



The SSRF Linac and its Commissioning

- A dedicated 150MeV Linac for top-up operation and the working frequency of 2998MHz chosen to have harmonic relation with the storage ring RF frequency;
- Main components include two 45MW klystrons, four 2998MHz/3m long accelerating sections, a 500MHz sub-harmonic buncher and a fundamental buncher;
- 100kV thermionic gun with single bunch (1nC/1ns) and multi bunch (3nC/200ns) operation modes;
- The linac commissioning started on May 15, 2007 and beam with energy more than 100MeV was obtained on the first day. The design specifications were achieved in July 2007.



First beam obtained on May 15, 2007

SINAP Shanghai Institute of Applied Physics, Chinese Academy of Sciences

The Main Parameters of the SSRF Linac(1)

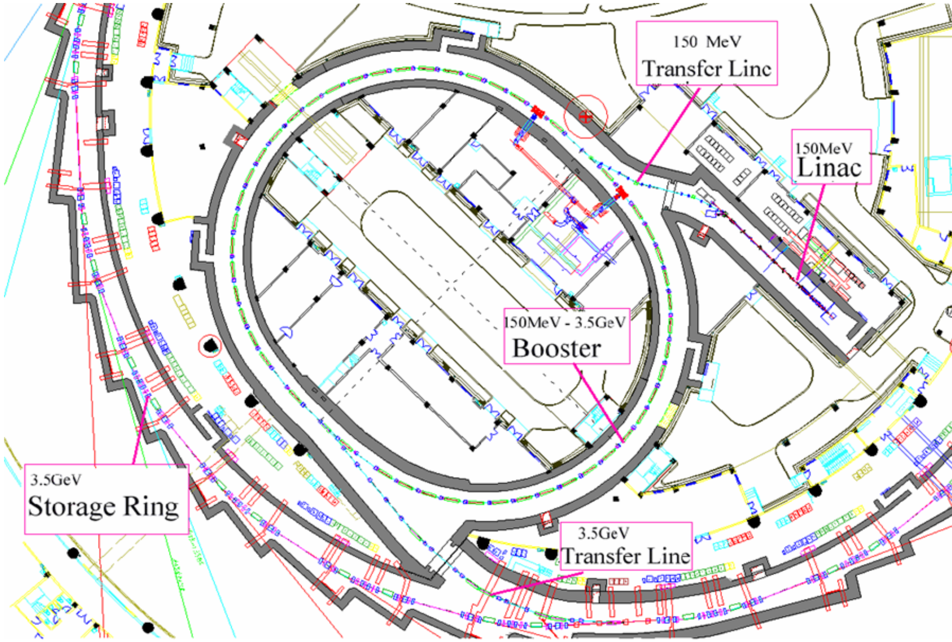
	Designed	Measured
Energy (MeV)	150	152. 162
Current (Single bunch)		
normal	1ns，1nC	0.3nS，1.06nC
low current	1ns， 0.2nC	0.3nS, 0.2nC
Energy stability	0.5% (rms)	0.2%
Relative energy spread	0.5% (rms)	0.2%
Normalized emittance (x)	50 mm-mrad	37 mm-mrad
Normalized emittance (y)	50 mm-mrad	32mm-mrad
Linac Frequncy (MHz)	2997.924	2997.924
Rep. Rate (Hz)	2	2

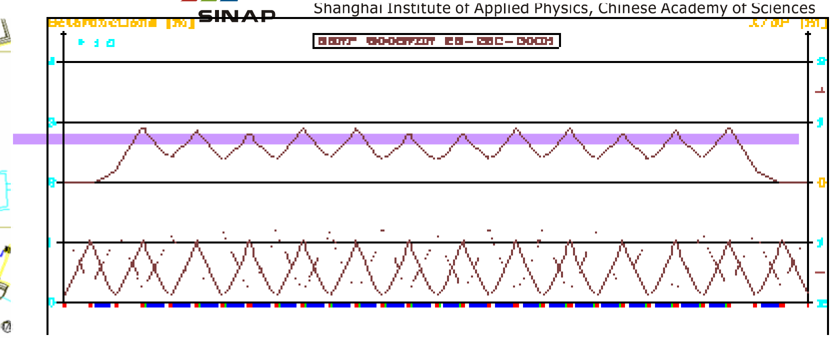
The Main Parameters of the SSRF Linac (2)

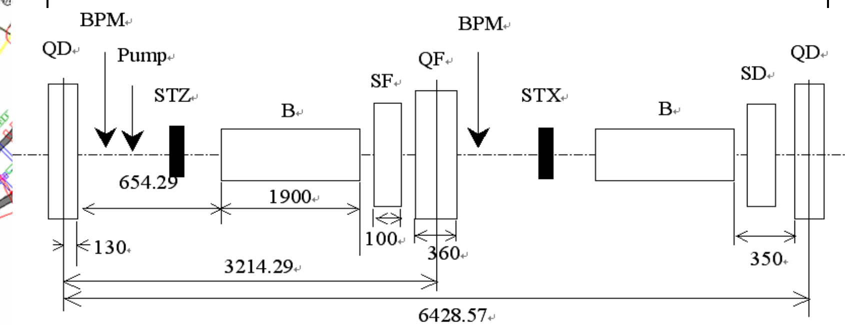
	Designed	Measured
Energy (MeV)	150	151. 162
Beam Current		
Multi-bunch	200ns，3nC	200nS/ 300nS, 3nC /10nC
Energy stability	0.5% (rms)	0.42%
Relative energy spread	0.5% (rms)	0.4%
Normalized emittance (x)	50 mm·mrad	47 mm·mrad
Normalized emittance (y)	50 mm·mrad	43 mm·mrad
Linac Frequncy (MHz)	2997.924	2997.924
Rep. Rate (Hz)	2	2

The SSRF Booster and its commissioning

- A full energy booster optimized for top-up injection;
- Two fold Lattice configuration to accommodating 28 FODO cells with 8 missing dipole magnets;
- Extraction beam emittance designed at ~100 nm-rad for getting a clean top-up operation;
- A circumference of 180m and a injection energy of 150MeV;
- Repeat rates up to 2Hz;


150 MeV
Transfer Line
150MeV
Linac
150MeV - 3.5GeV
Booster
3.5GeV
Storage Ring
3.5GeV
Transfer Line




BPM
QD
Pump
STZ
B
SF
QF
BPM
STX
B
SD
QD
654.29
1900
100
360
130
350
3214.29
6428.57

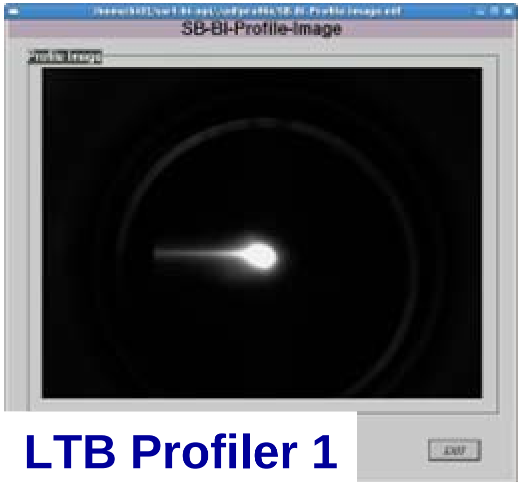
Main Parameters of the SSRF Booster

Injection energy	GeV	0.15	
Extraction energy	GeV	3.5	
Beam Current Single/Multi bunch	mA	1.6/15	
Circumference	m	180	
Cell number/Super periods		28/2	
Energy loss per turn at 3.5 GeV	MeV	0.915	
Natural emittance at 3.5 GeV		104	94.6
Betatron tune, ν_H / ν_V		8.181/5.229	8.416/5.389
Nature Momentum spread		7.799×10^{-4}	7.802×10^{-4}
Momentum compaction, α_P		0.01849	0.0176
Damping time, $\tau_{H,V,L}$	mS	4.8/4.6/2.3	4.8/4.6/2.3
RF Frequency	MHz	499.65	
Required RF voltage V_{RF}	MV	1.8	

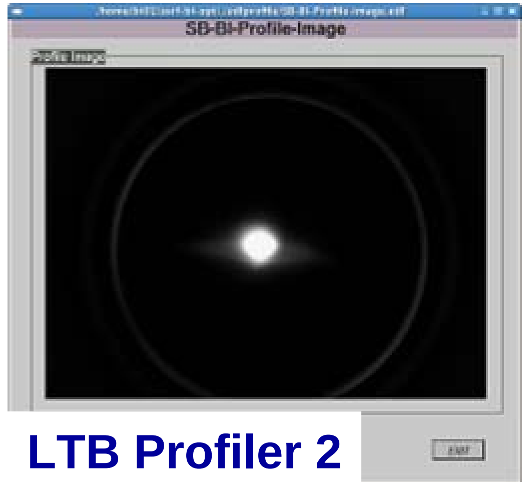
Booster Commissioning Milestones

- Sept. 30: Commissioning started at 20:30, and beam arrived at the booster entrance at 21:58;
- Oct. 01: First turns of the circulating beam in booster achieved at 17:00;
- Oct. 02: First stored beam in the booster obtained at 4:30;
- Oct. 05: Within 60 effective commissioning hours, first ramped beam (3.5GeV) obtained at 4:25;
- Oct. 29: First extract beam from the booster achieved;

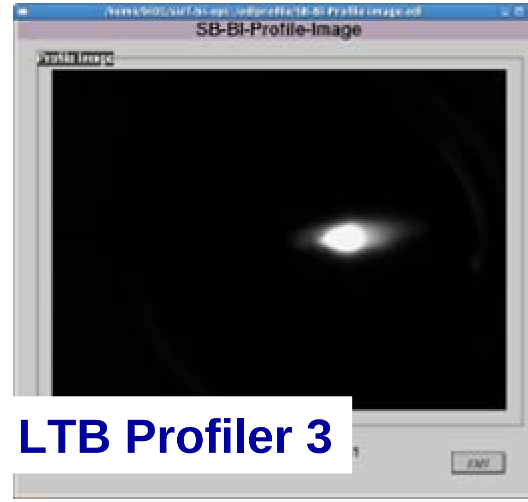
Beam passed LTB transportation line on Sept.30, 23:00



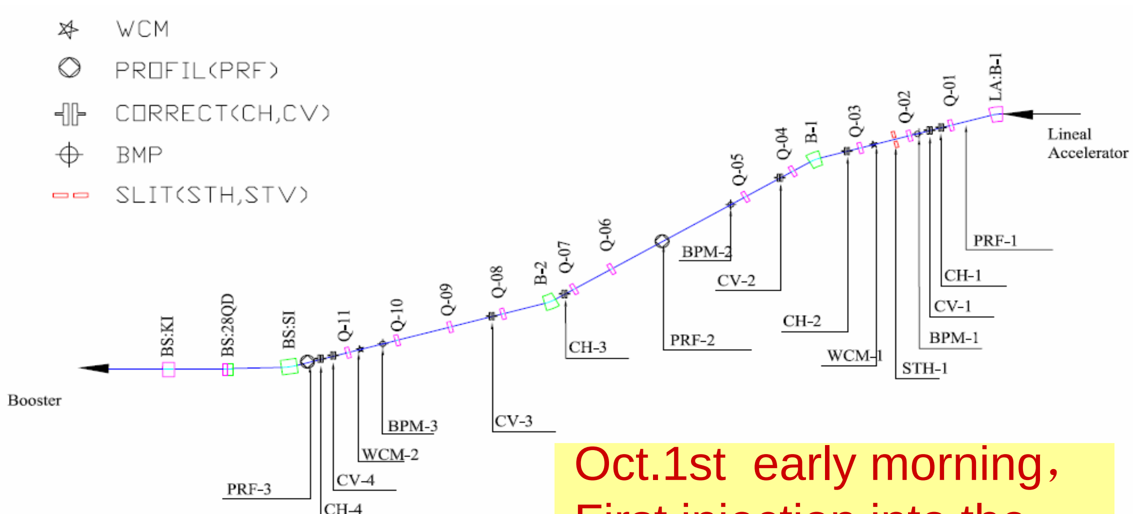
LTB Profiler 1

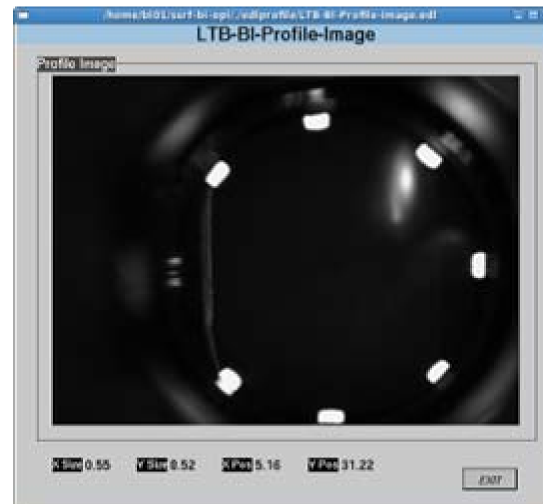


LTB Profiler 2

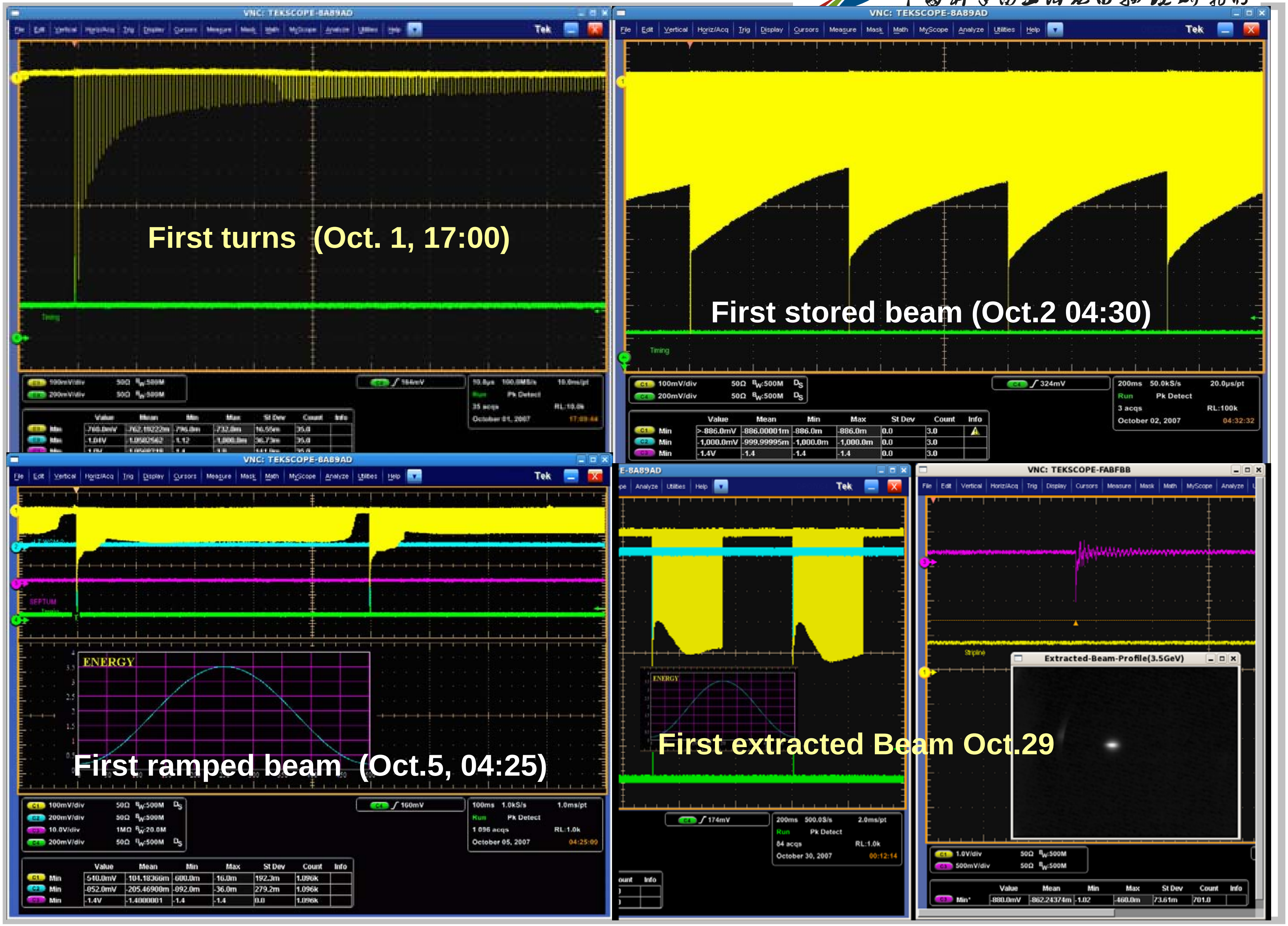


LTB Profiler 3





Oct.1st early morning, First injection into the Booster at 03:45


First turns (Oct. 1, 17:00)
First stored beam (Oct.2 04:30)
First ramped beam (Oct.5, 04:25)
First extracted Beam Oct.29

The SSRF Storage Ring Commissioning

- The SSRF storage ring commissioning started on Dec. 21, 2007, four months ahead of the original schedule, and is being carried out in three phases, according to the practical schedules of liquid helium cryogenics/SRF RF and IDs:

- Phase I (Dec. 2007 to June 2008): Commissioning with normal conducting cavity at 3GeV@100mA and 2 bend; beamlines It is a backup scheme, but this is good for SRF cavity and for simplifying machine commissioning;

- Phase II (from Jul. to Sept. 2008): Commissioning with superconducting cavity at 3.5GeV@200-300mA;

- Phase III (Oct. 2008 to Apr. 2009): Commissioning with 5 IDs (1EPU, 2 In-vac undulators, 2 wigglers) and their corresponding beamlines;

The First Phase Storage Ring Commissioning

- Commissioning with 3 PF retired cavities lent from KEK
  - Liquid helium cryogenics system was not ready in time;
  - 3 PF cavities with RF voltage: <550kV/Cavity
  - Cavity wall dissipated power: <30kW/cavity;
  - Beam loading power: ~80kW;
  - →Maximum Energy of 3GeV and beam current of 100mA;
- Main objectives
  - Beam injection, storage and accumulation;
  - Basic machine calibrations and charaterisations;
  - Measurements and machine studies;
  - Bend beamline commissioning

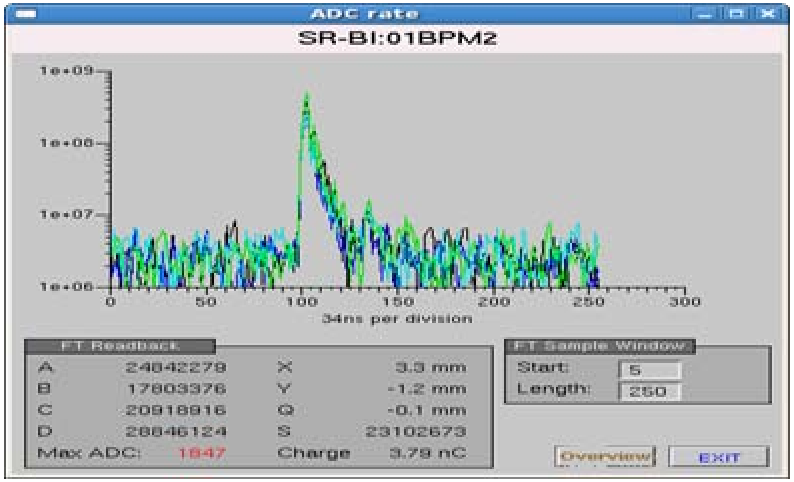
Storage Ring Commissioning Milestones

- Dec. 21, 2007: commissioning started at 18:20, one turn beam achieved at 21:08 and multi-turn beam at 21:18;
- Dec. 23, 2007: 2000~3000 turns achieved at 20:00;
- Dec.24, 2007: first stored beam obtained at 06:54 (in~60hrs)
- Jan.03, 2008: 100mA stored beam achieved at 20:20;
- Mar. 16, 2008: Both horizontal and vertical closed orbit corrected to <50um rms with 80 correctors (137BPMs);
- June 2008: a few of microns beam orbit stability achieved;
- June 15, 2008: Integrated beam current >150 Ahrs obtained;
- June 17 -18, 2008: 200mA at 2GeV and 300mA at 1.5GeV achieved.

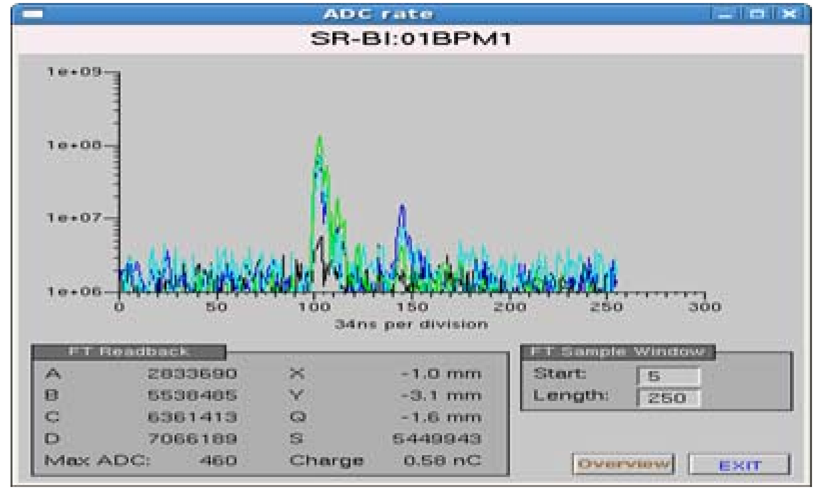
The First turns and Stored Beam

- Achieving first turn and multi-turn beam in storage ring;
  - On axes and off axes injections
  - Only bending dipoles powered on
  - Quadrupoles powered on
  - sextupoles powered on with 20% of the designed values
- Obtaining stored beam
  - Find the most effective corrector
  - RF turned on and RF cavity phasing
  - Bending magnetic field adjustment
  - Frequency adjusting (up to +14kHz)

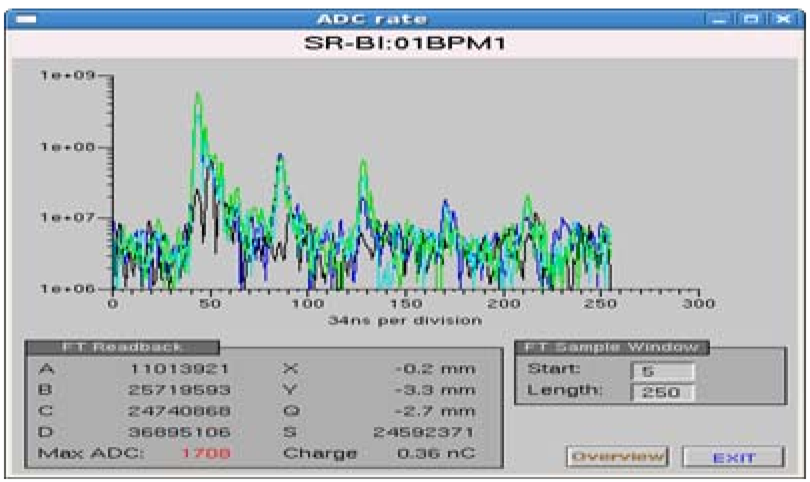
The Storage Ring BPM Signal



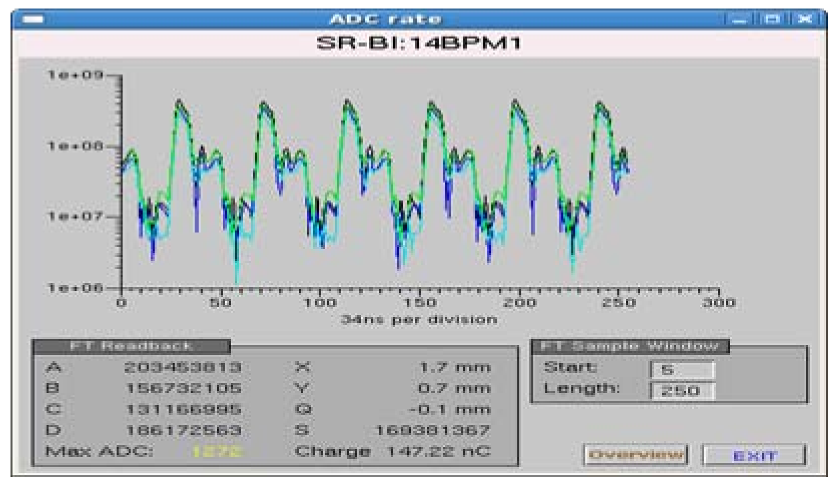
Injected beam



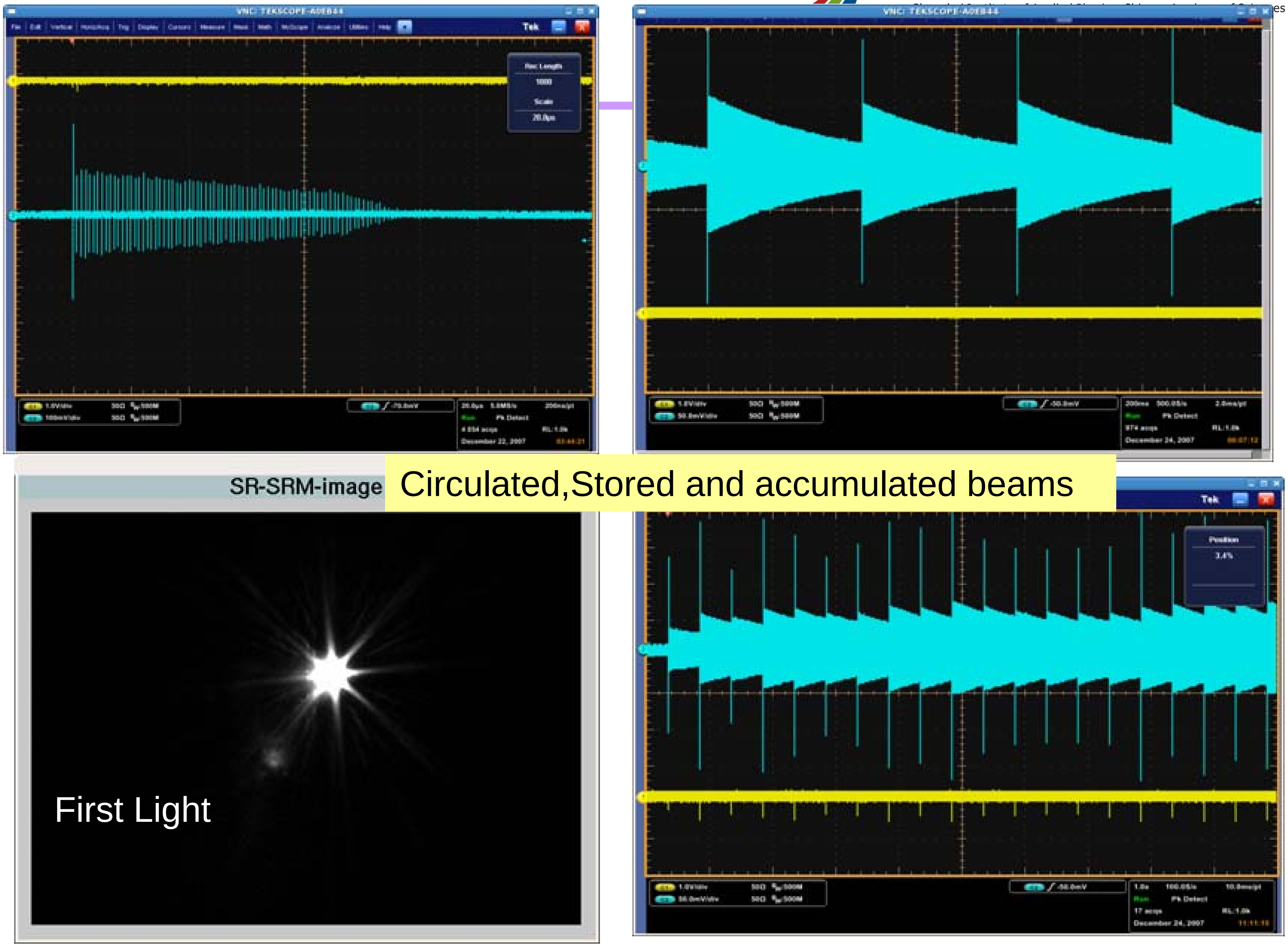
First turn



Multi turns



Stored beam

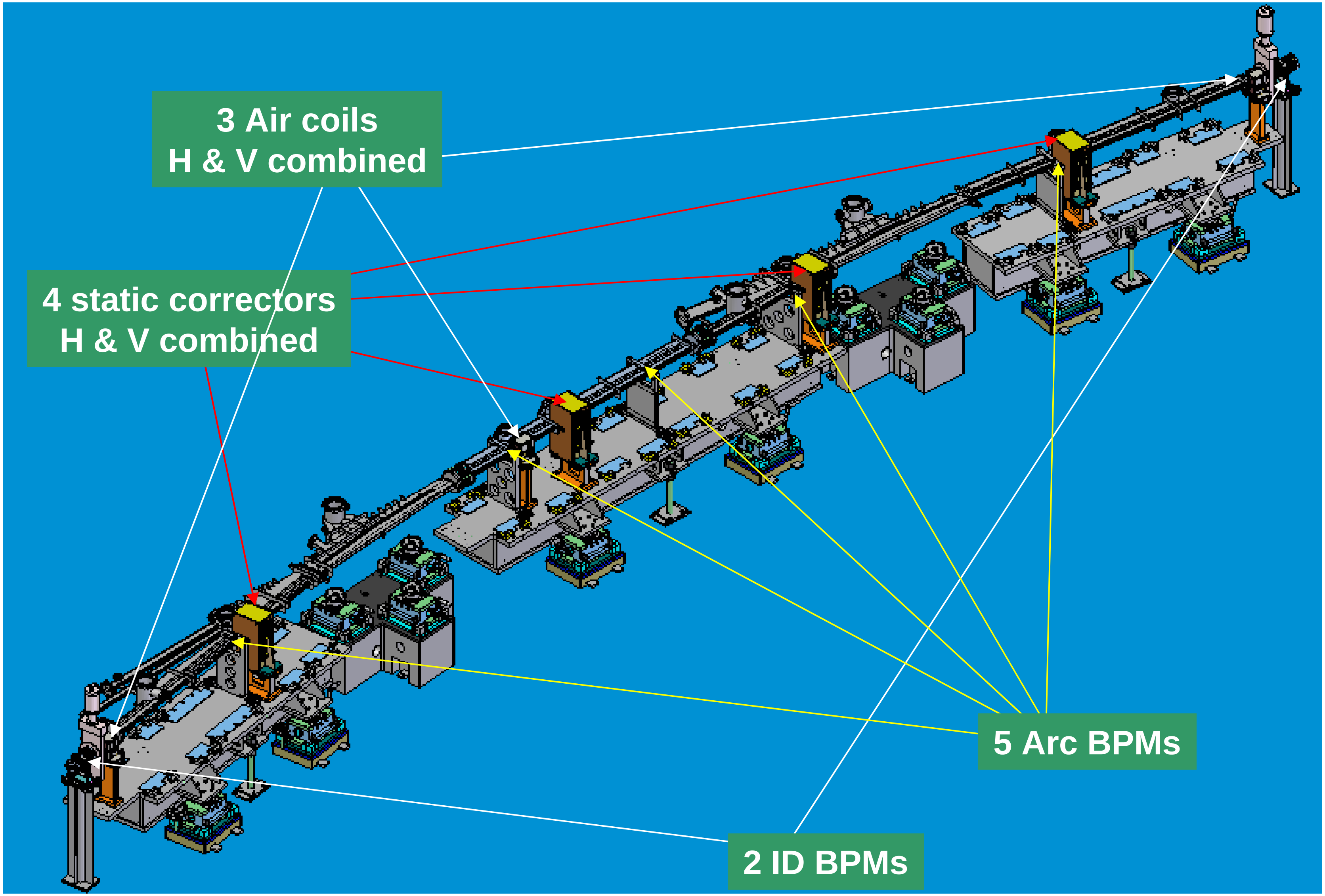

SR-SRM-image
Circulated,Stored and accumulated beams
First Light

Celebrating the Stored Beam 06:55, Dec.24, 2007

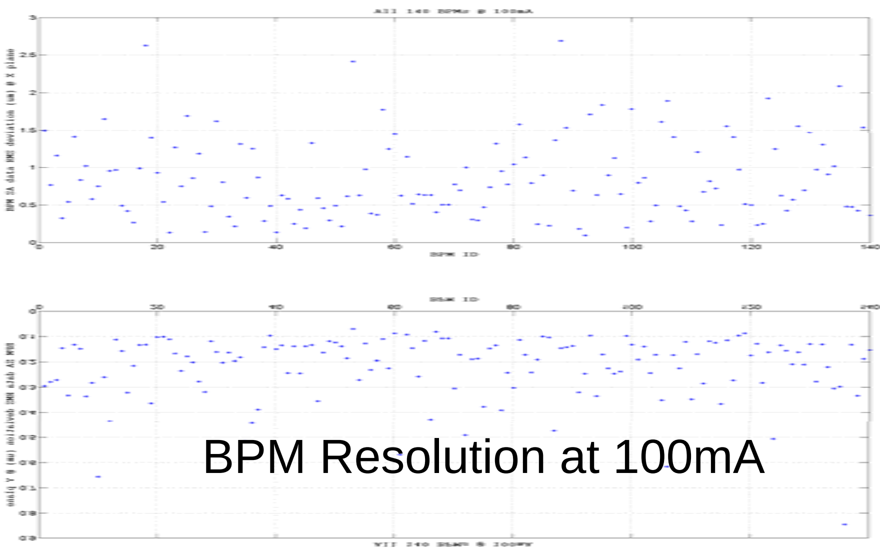
Beam Orbit Corrections

- Initial beam orbit correction
  - Correct orbit with the most effective corrector (MICADO);
  - Enable Response Matrix (RM) measurement and beam based alignment (BBA) work, SVD based orbit correction;
  - Get the orbit interlock work (±5mm, ±2mm) switched on at current above10mA;
- Further orbit corrections for smaller residual closed orbit
  - Measure the RM and perform BBA;
  - Correcting orbit based on RM measurement and BBA;
  - First round at 10mA and obtained the residual orbit <100um;
  - Second round at 100mA, obtained the residual orbit <50um;

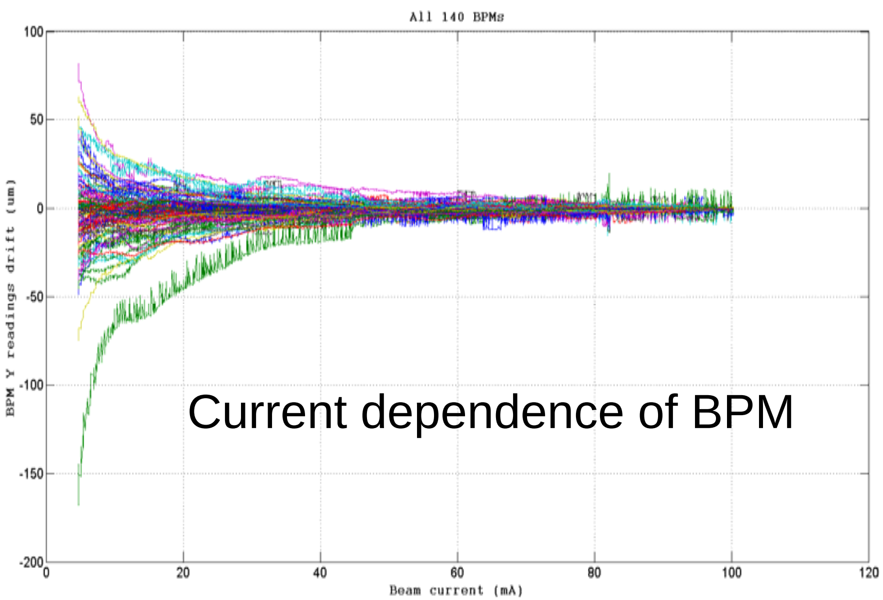
Storage ring BPM pickups (buttons) and correctors



BPM resolution and Current dependence

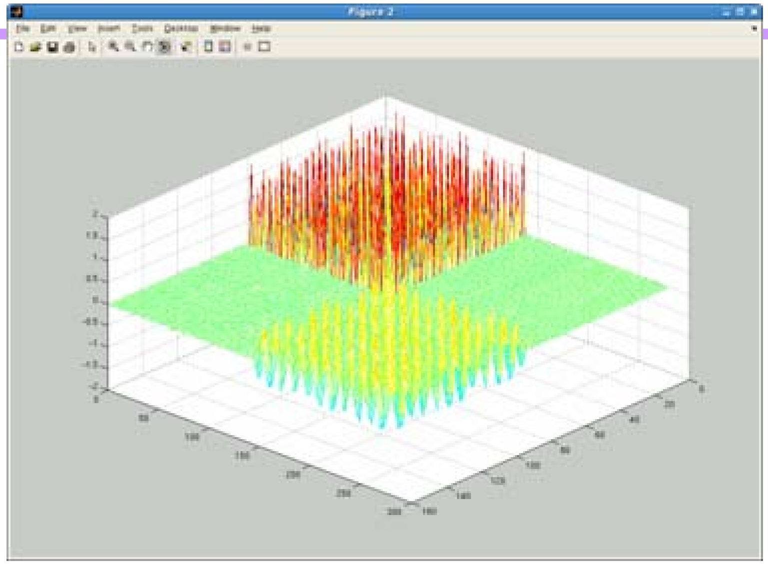


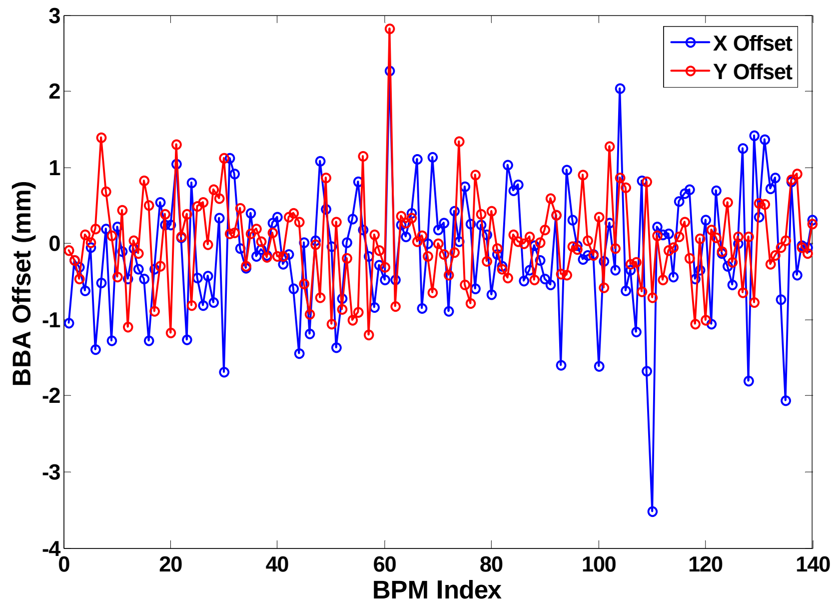
BPM Resolution at 100mA



Current dependence of BPM

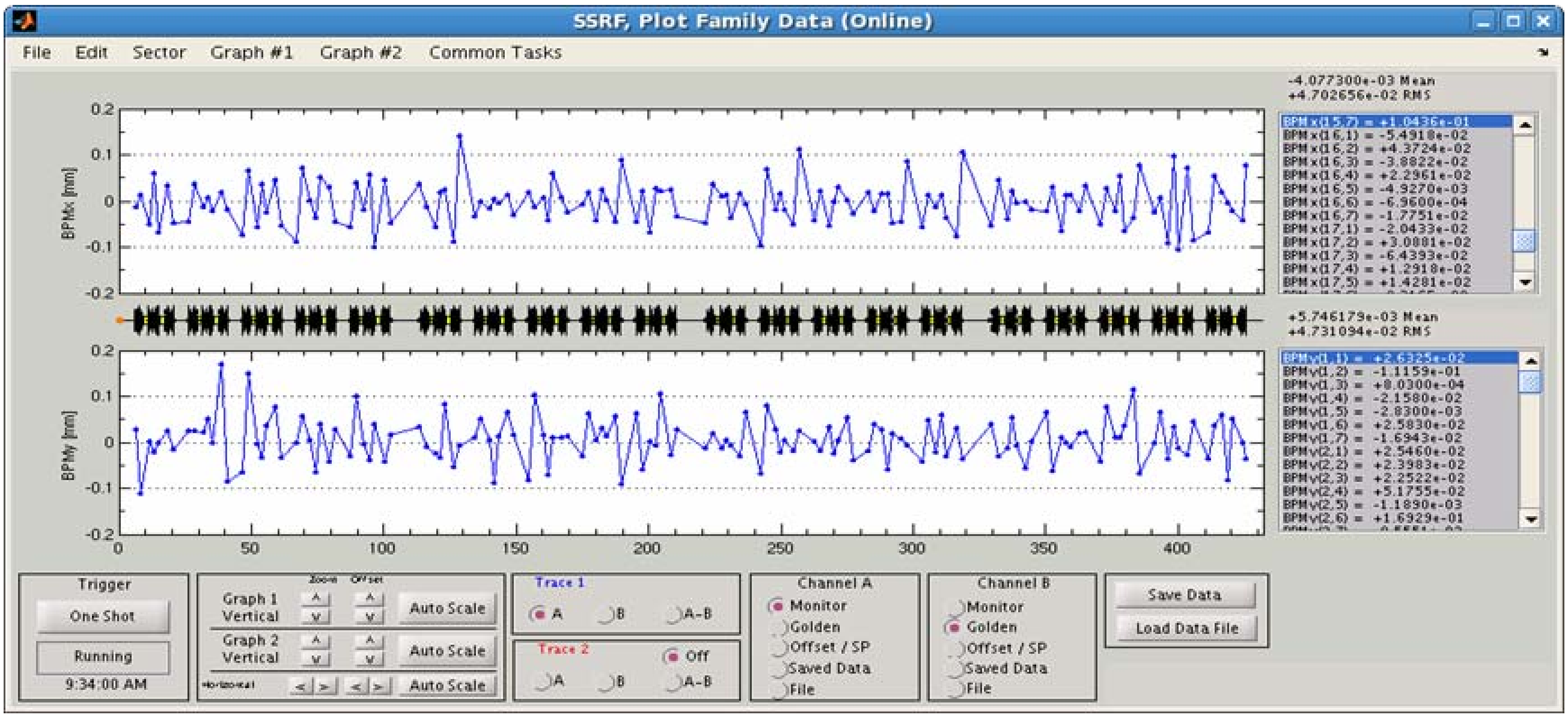
RM and BBA at 100mA



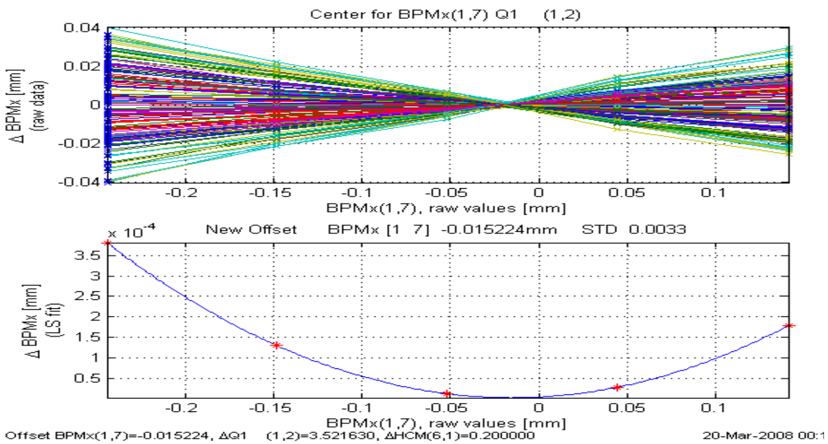


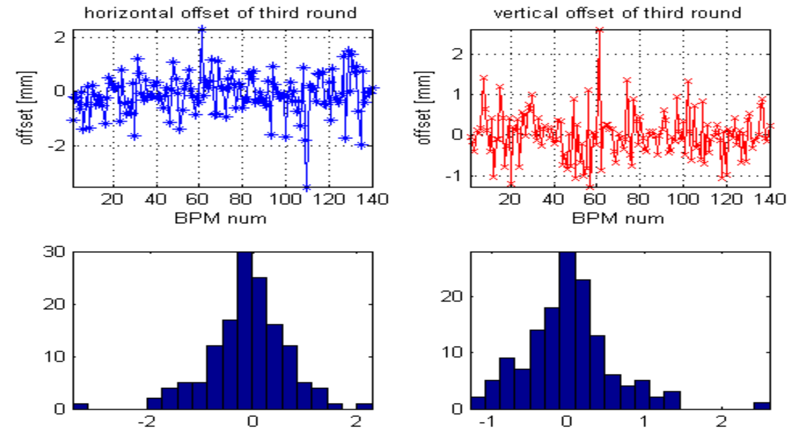
Residual closed orbit at 100mA: <50um rms

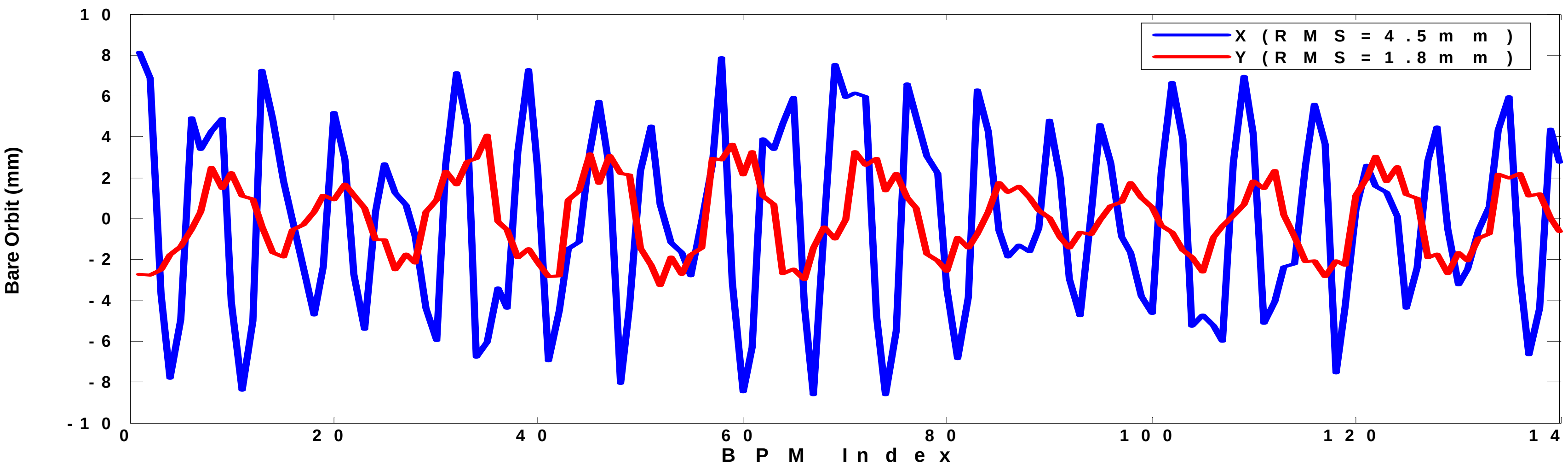
- With 137BPMs and 80 correctors for each of the horizontal and vertical planes
- Closed orbit was corrected to (rms): 47um (horizontal) and 47 um (vertical)
- Maximum corrector strengths are: 0.17mrad (horizontal) and 0.18mrad (vertical)



Bare Orbit in the SSRF Storage Ring (all correctors off)





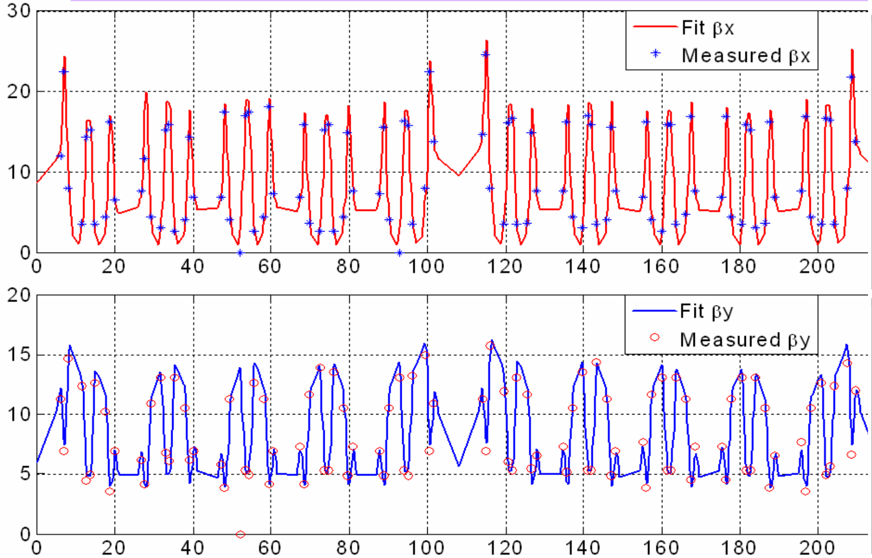


consistent with quads positioning tolerance

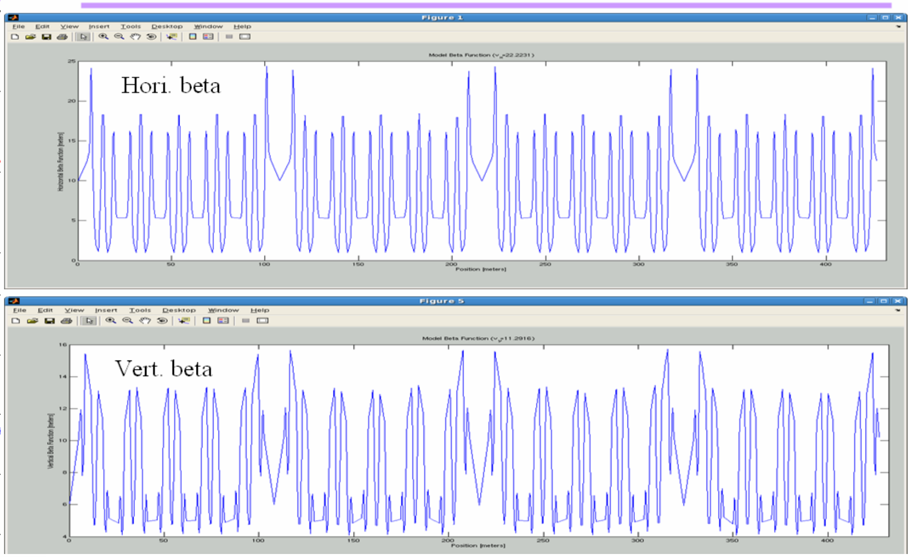
Calibration of Storage Ring Linear Optics

- Beta function restoration with beatings within ±1%
  - Beta function measurement;
  - LOCO simulation based on measured response matrix;
  - Adjust quadrupole field family by family and finally magnet by magnet based LOCO model results;
  - Iteration of RM measurement and LOCO simulation as well as quadrupole field adjustment;
- Dispersion restoration with beating within ±1%
  - Dispersion measurement;
  - Same LOCO simulations described above;
- LOCO and MIA
  - Turn by turn data based MIA agrees well with LOCO;

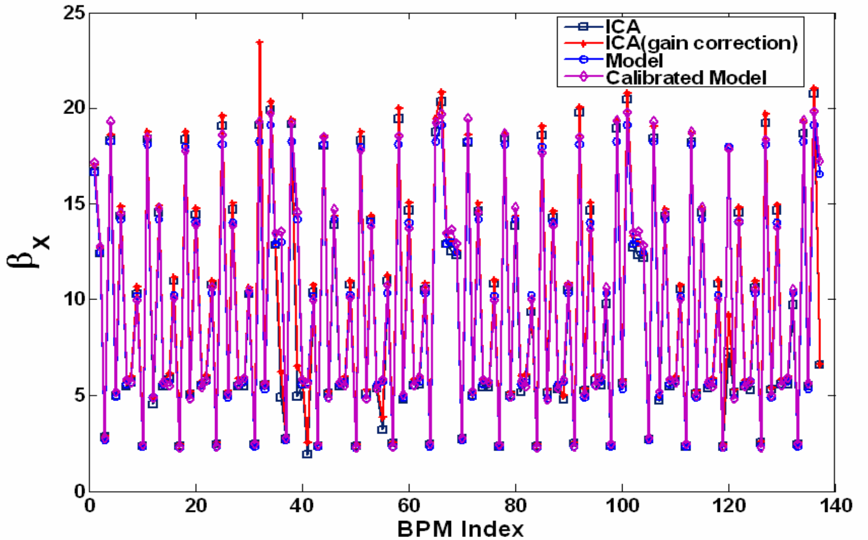
Comparison between LOCO Model and measurements



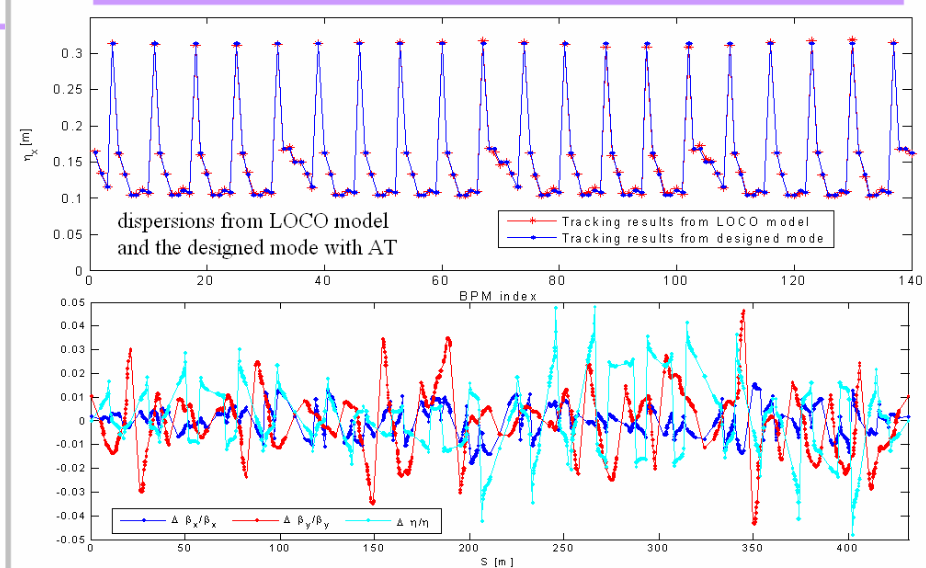
Restored Beta functions from calibrated LOCO Model (91#)



LOCO vs. MIA (H)



Restored dispersion from the calibrated LOCO model (91#)



Calibration results of main optical parameters @3.0GeV

Parameters	Designed Mode	LOCO Model	Measurement
Tune Q_x/Q_y	22.22/11.29	22.2231/11.2916	~22.2213/11.2905
$\beta_x/\beta_y/\eta_x$(m) in the centers of straight sections	10/6.0/0.15 3.6/2.5/0.10	10.02/6.06/0.15	
Natural emittance (nm-rad) @3.0GeV	2.86	2.86	~2.8
Natural chromaticity ξ_x/ξ_y	-55.70/-17.94	-55.68/-17.93	~-50/-17
Momentum compaction factor	4.27×10^{-4}	4.27×10^{-4}	

Calibration of Storage Ring Linear Optics

- Chromaticity correction
  - Measurements of chromaticity and natural chromaticity;
  - Correcting the horizontal and vertical chromaticity to above zero;
- Calibration of different configurations and different energies
  - Dispersion free mode and distributed dispersion mode;
  - Low and high tunes: (19.22, 7.32),(23.32 11.23);
  - Configuration at energies: 2.75GeV, 2.0GeV and 1.5GeV, at 100mA and 200-300mA beam current;

Operational Modes Commissioned at 3GeV

Modes	Dispersion	Dispersion-free	Low tune	High tune
Circumference (m)	432m			
Cell/Super-period	20 DBA/4			
Tune Q_x/Q_y	22.22/11.29		19.22/7.32	23.32/11.23
$\beta_x/\beta_y/\eta_x$(m) in the centers of straights	10/6.0/0.15 3.6/2.5/0.10	10/6.0/0 3.6/2.5/0.006	15/8.0/0.15 13.5/4.6/0.14	12/6.0/0.17 2.5/2.0/0.102
Natural emittance Norminal (nm-rad)	2.86	8.4	3.98	2.47
Natural chromaticity ξ_x/ξ_y	-55.64/-17.94	-55.56/-18.09	-45.77/-21.81	-64.39/-19.93
Momentum compaction factor	4.2118×10^{-4}	5.4249×10^{-4}	5.89×10^{-4}	3.61×10^{-4}

Commissioning at Various Energies

Energy (GeV)	3	2.75	2	1.5
Maximum Current Achieved (mA)	100	120	220	300
Nominal Natural emittance (nm.rad)	2.86	2.40	1.27	0.71
Damping time (ms)	11.19 11.15 5.57	14.53 14.48 7.23	37.76 37.65 18.79	89.52 89.23 44.55
Tunes	22.22/11.29			
$\beta x/\beta y/\eta x$(m) in the centers of straight sections	10/6.0/0.15 3.6/2.5/0.10			
Natural chromaticity $\xi x/\xi y$	-55.64/-17.94			
Momentum compaction factor	4.2118×10^{-4}			

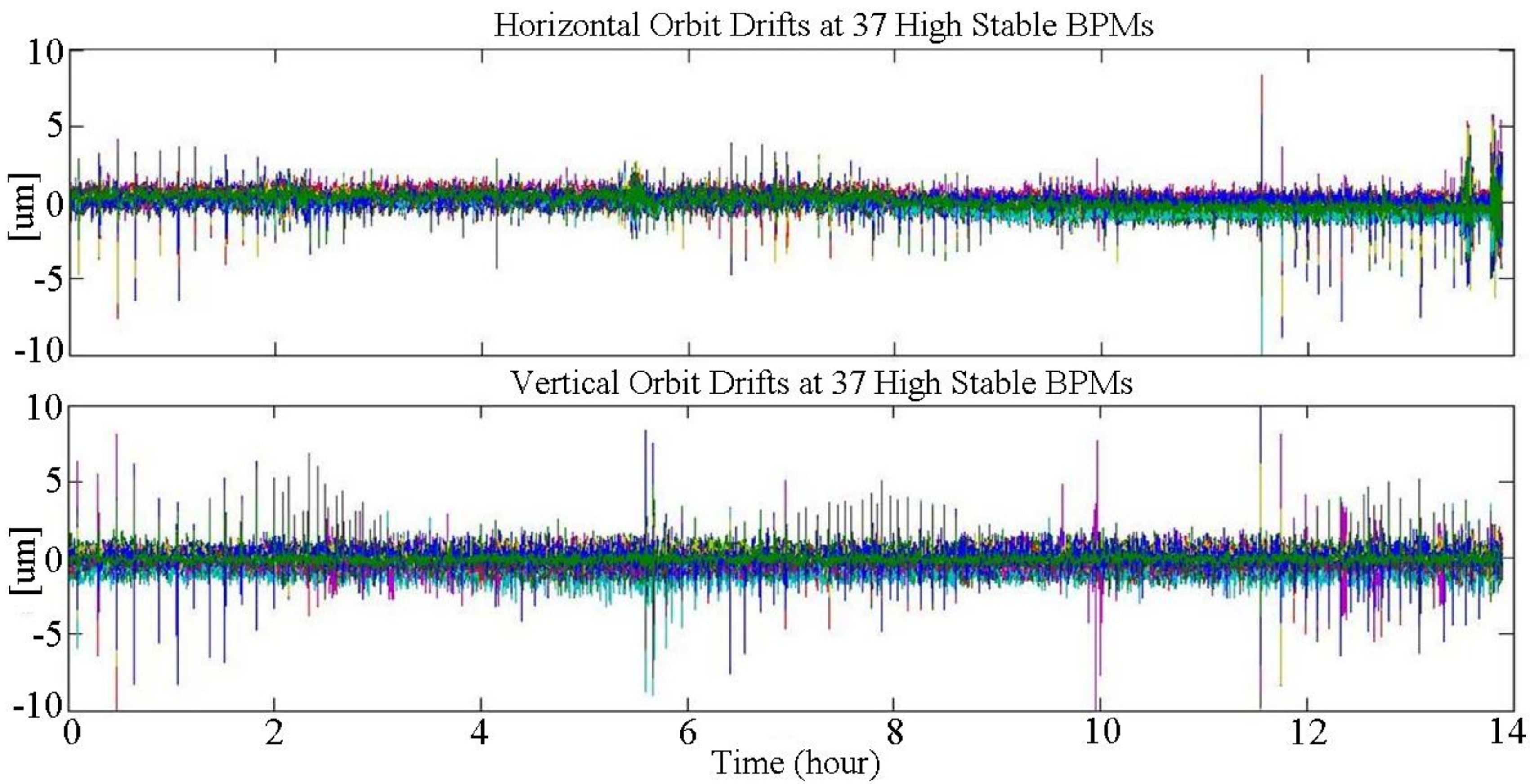
Measurements and Machine Studies

- Machine parameter measurements are made and need to do carefully in the second commissioning phase:
- Beam current and beam lifetime (3GeV, 100mA, ~15hrs)
- Tunes: longitudinal, horizontal and vertical (22.22, 11.29)
- Beta function and Dispersion function
- Chromaticities and corrections, RF frequency optimization
- Coupling (~0.5%), emittance and energy spread
- Momentum compaction factors: α_p, α_2
- Broadband impedance: $Z_{\perp\ eff}$ = 98~136 kΩ/m, $Z_{//eff}$ = 0.22~0.30 Ω
- Resistive wall, ion related, sawtooth instabilities observed
- Beam size blow up threshold appeared
- Tests of TMFB and Zero Mode feedbacks

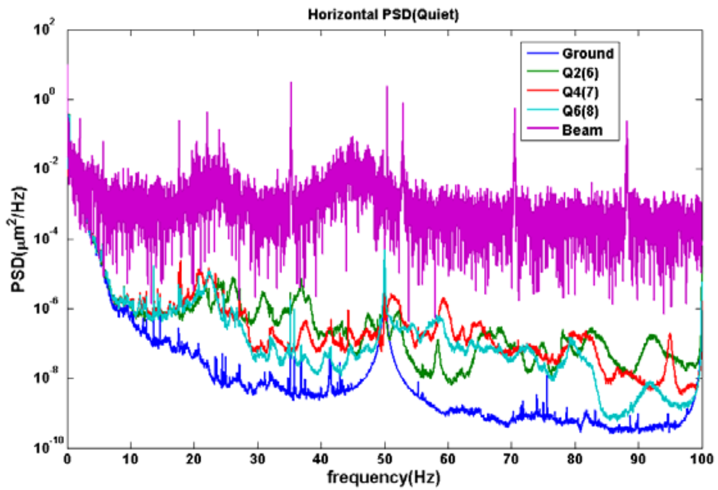
Beam Orbit Stability Investigations

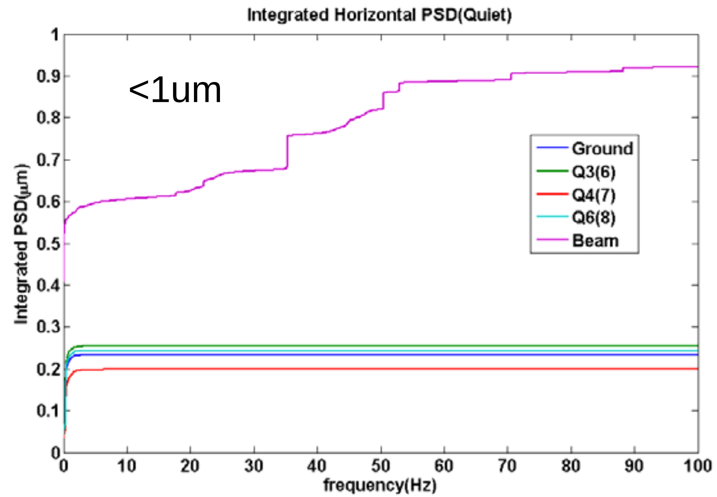
- Reduce disturbances to orbit stability
  - Reduce corrector power supply's ripple;
  - Measure and control the temperature-circumference effect: →frequency feedback;
  - Slow orbit feedback (0.01-0.1Hz): within ±1um ~ few um;
- Vibration effects (quad vibration and beam position spectra)
  - Traffics on the campus and adjacent roads;
  - The position and movement of the experimental hall crane;
  - Knock the cooling water pipe and experimental hall's floor ;
  - Vibration situation at the quiet and noisy periods;
  - The abnormal beam position sideband signal (~40Hz) found;

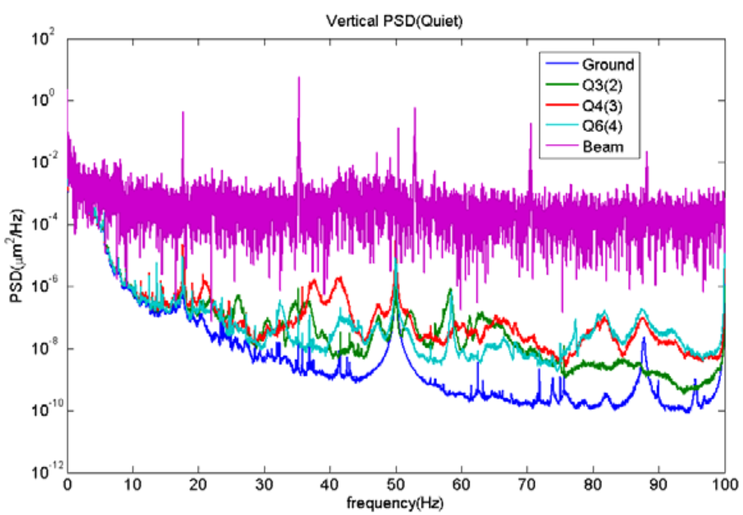
Orbit Stability : Slow Orbit Feedback

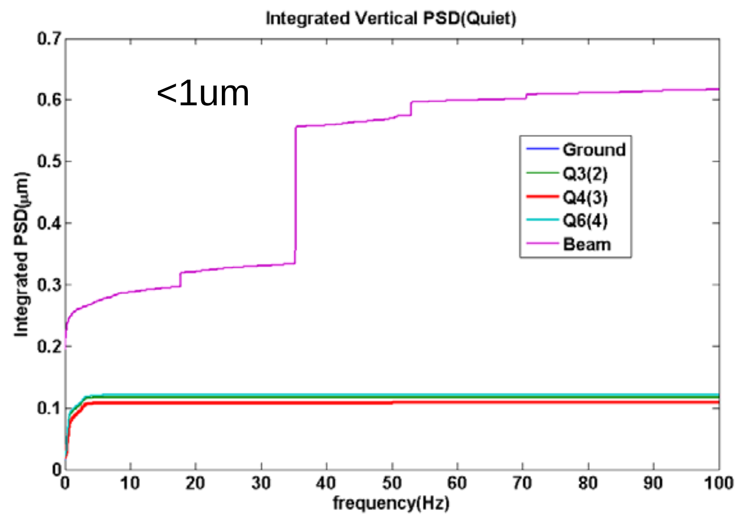


Orbit Stability: Vibrations at quiet period (short term)

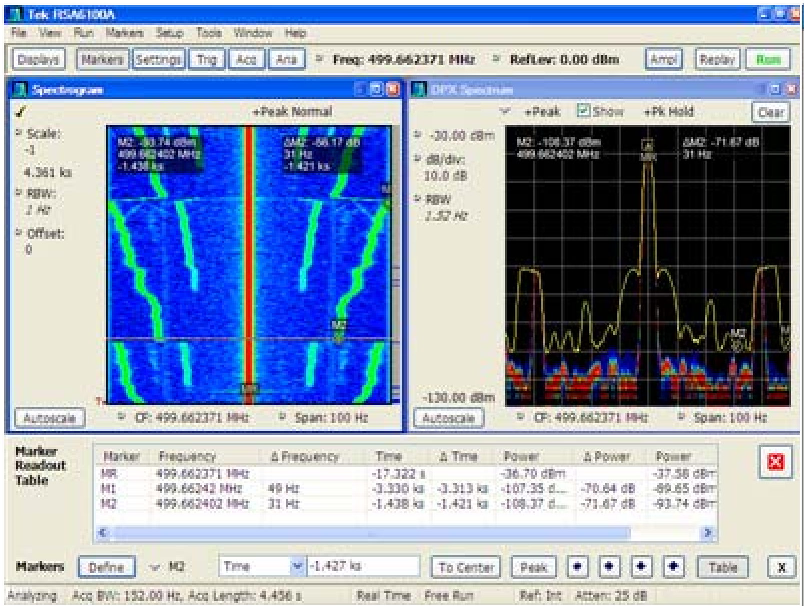


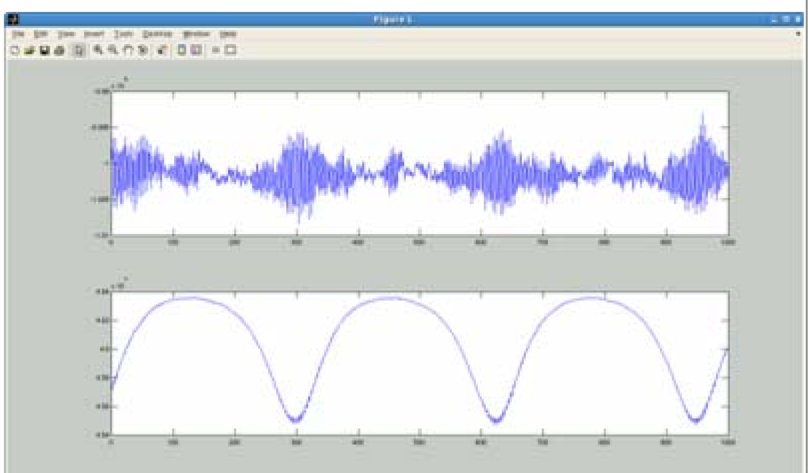


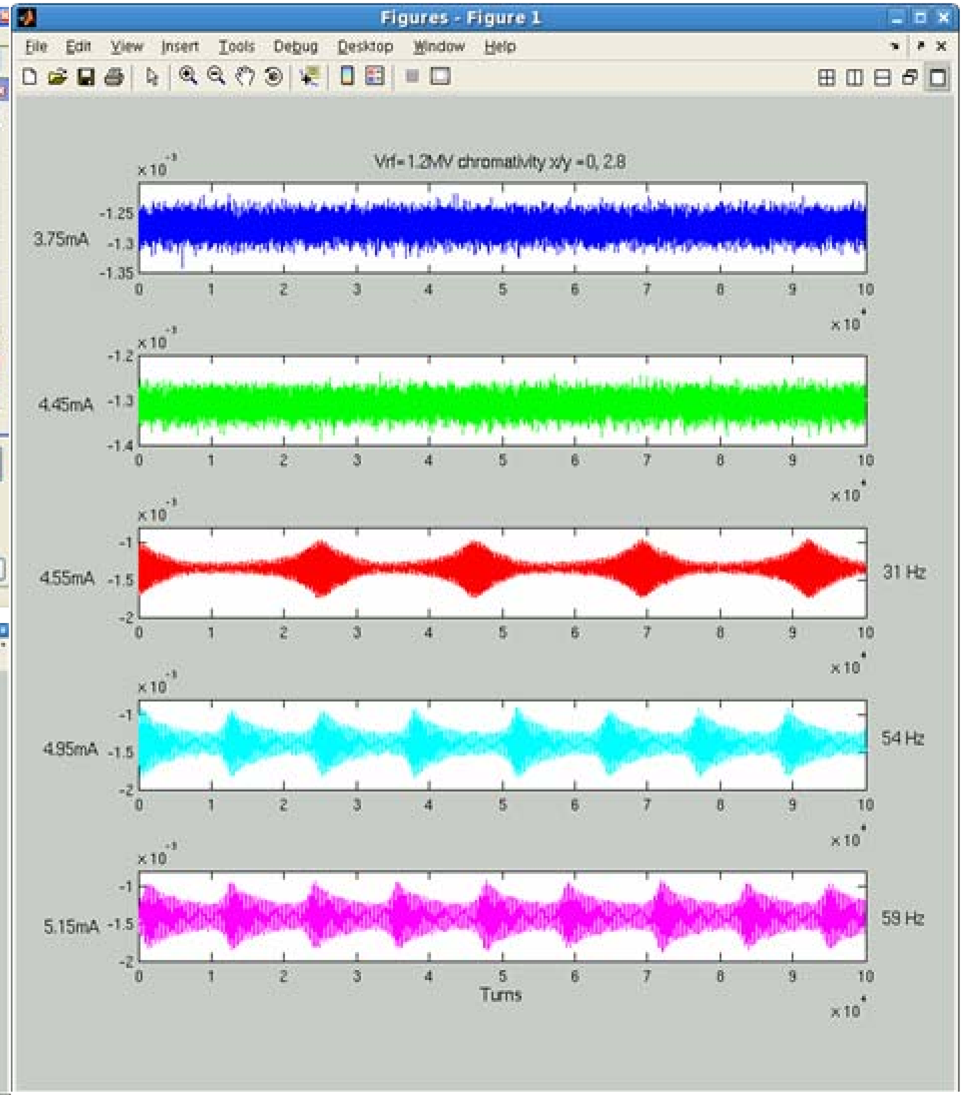




What's the reason/needs to identify

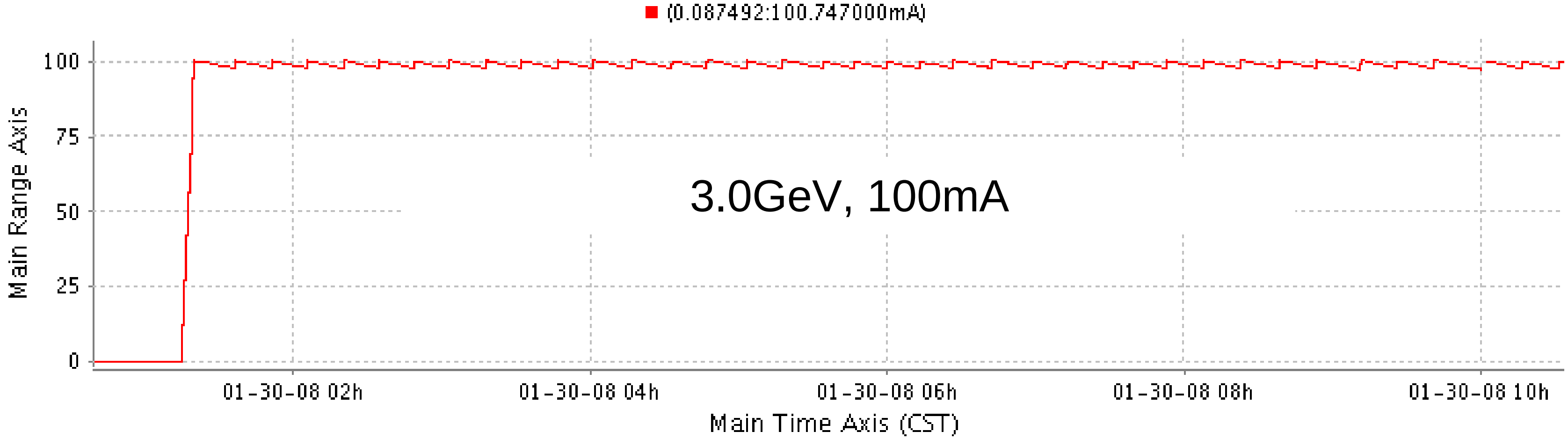


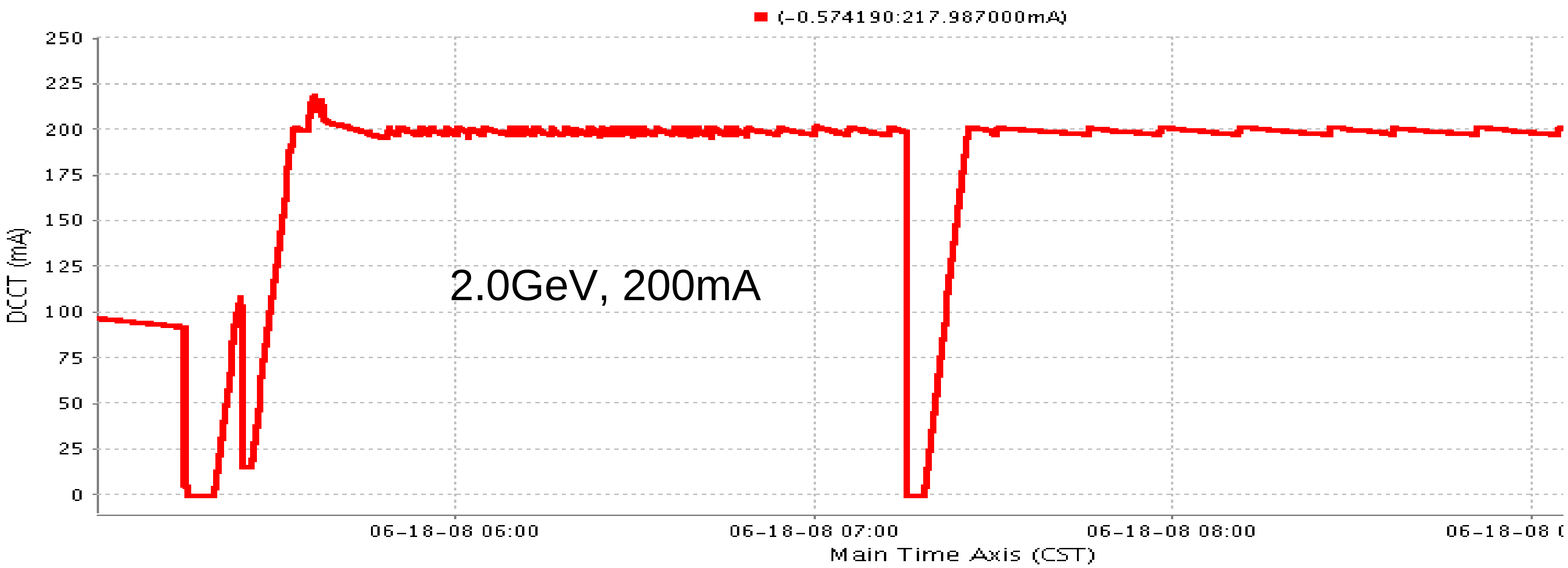


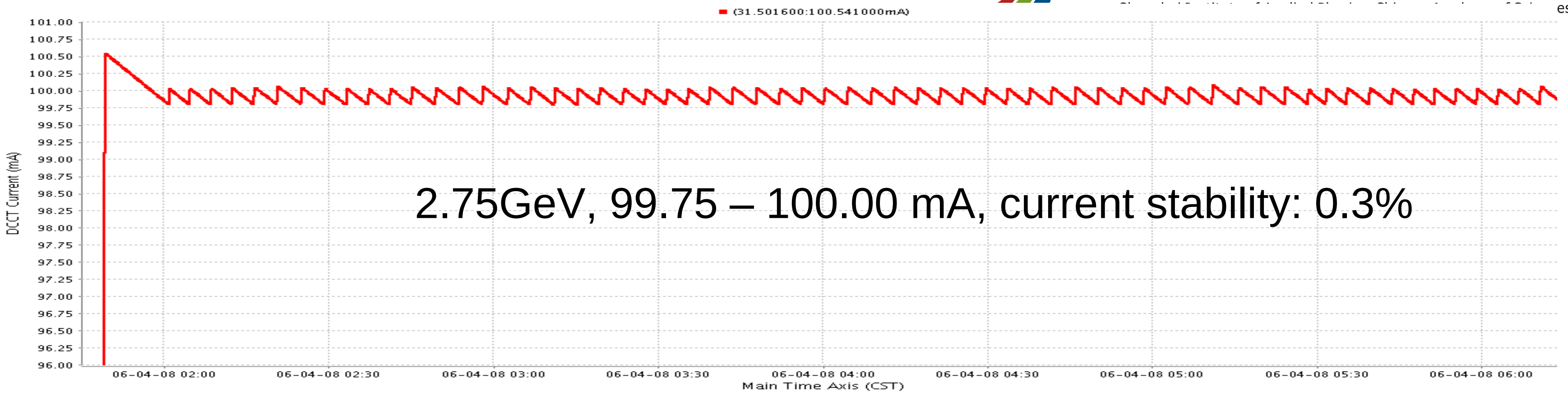


Beam Current and Top-up Injection

- High beam current commissioned at various energies
  - Limitations are from temporary RF system;
  - 100mA at 3GeV, 120mA at 2.75GeV, 200mA at 2.0GeV and 300mA at 1.5GeV were obtained;
  - Long time operation of top-up injection at 100mA@3GeV for vacuum conditioning;
- Top-up injection efforts
  - Top-up injection to keep 100mA stored current stabled within 0.25mA;
  - Low charge injection and bunch charge monitor
  - Optimizations of kickers to reduce the orbit disturbances during injection: <100um (H) and <30um (V) obtained;


(0.087492:100.747000mA)
3.0GeV, 100mA
Main Range Axis
100
75
50
25
0
01-30-08 02h
01-30-08 04h
01-30-08 06h
01-30-08 08h
01-30-08 10h
Main Time Axis (CST)

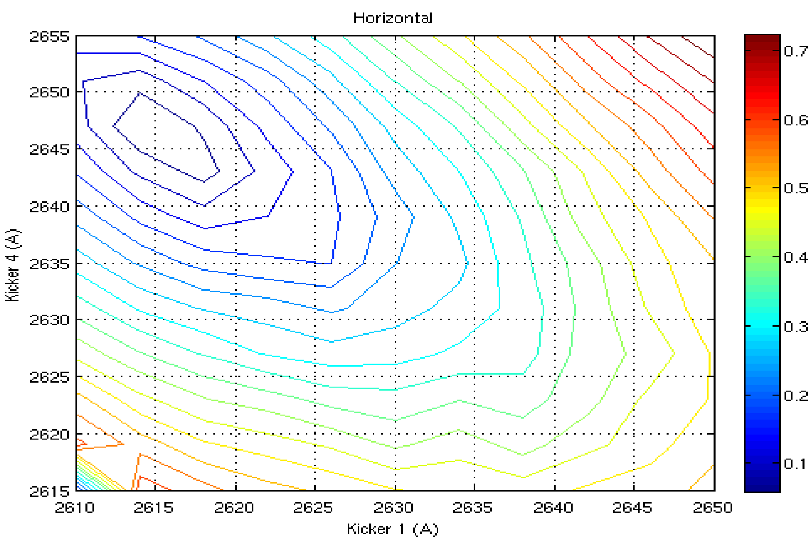

(-0.574190:217.987000mA)
2.0GeV, 200mA
DCCT (mA)
250
225
200
175
150
125
100
75
50
25
0
06-18-08 06:00
06-18-08 07:00
06-18-08 08:00
Main Time Axis (CST)

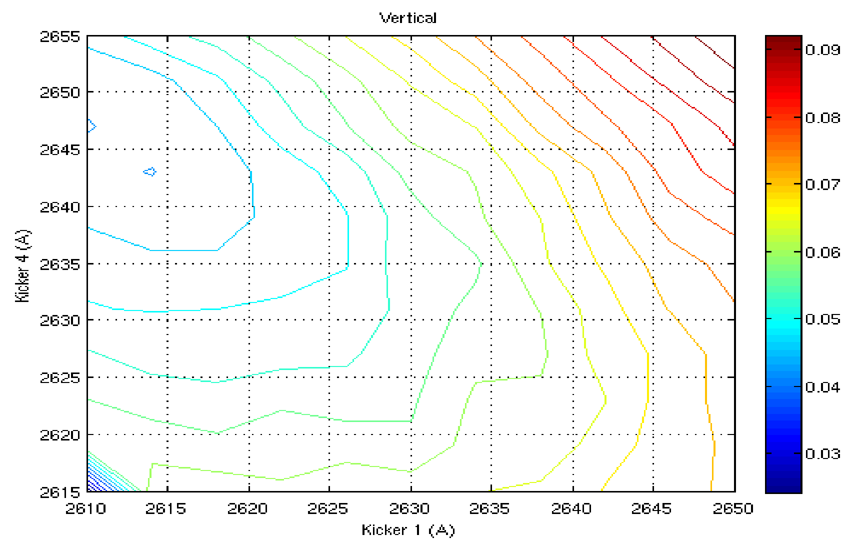


Maximum orbit disturbance (canning the strength of KIK1 and KIK4)

Below left: minimum horizontal disturbance is less than 0.1mm;

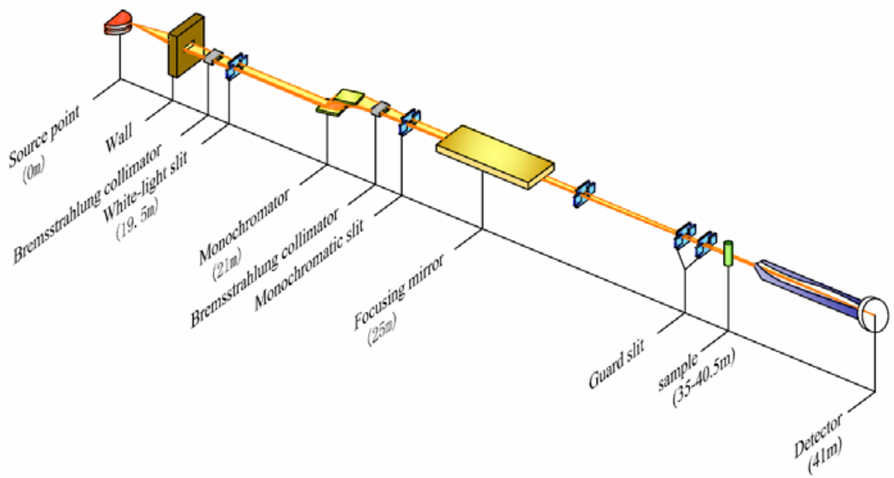
Below right: minimum vertical disturbance is less than 30μm, still possible to reduce to less than 10μm by adjusting the kickers' tilt angle;





Commissioning of Beamline SAXS

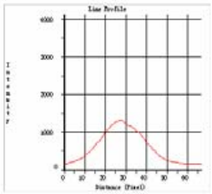
❑ Small-angle x-ray scattering beamline (BL 16B1)



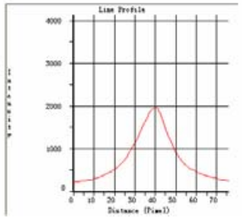
Commissioning of the beamline

Beam dimension at the focus(E=10KeV)

A CCD image at the focus



FWHM 0.5mm at vertical

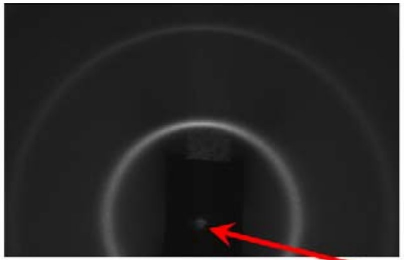


FWHM 0.47mm at horizontal

Sample:

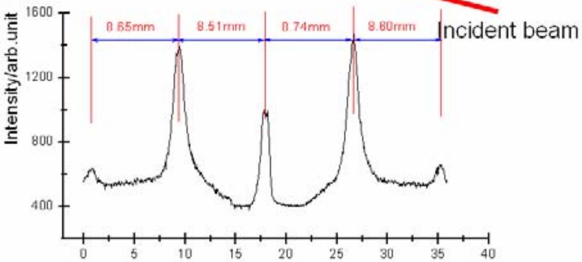
Silver-behenate, d=5.84nm $(CH_3CH_2)_{20}COO\text{-}Ag)$

Small angle diffraction pattern:

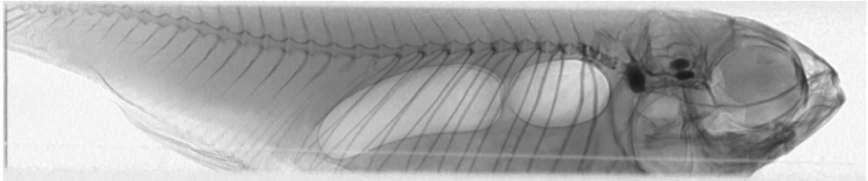


	n=1	n=2
θ (mrad)	10.6	21.2

E=10keV (0.124nm)

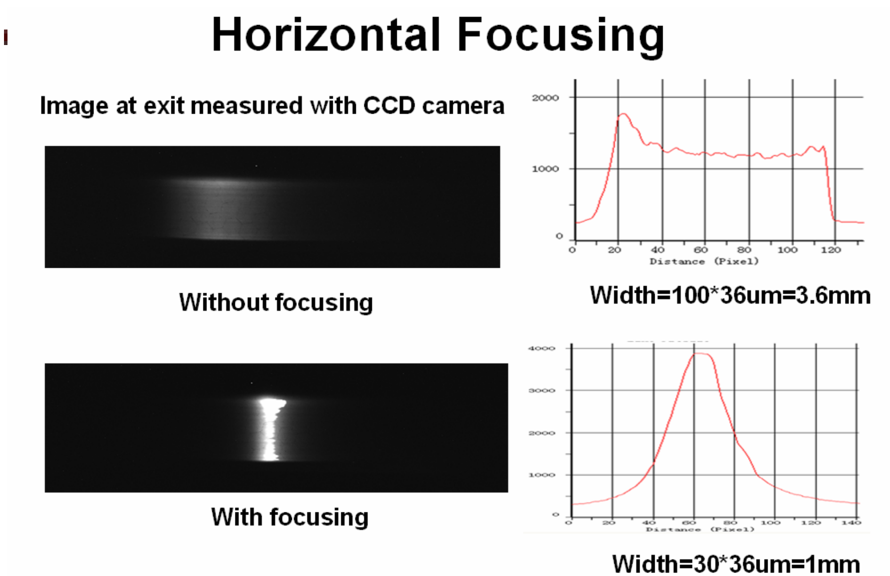


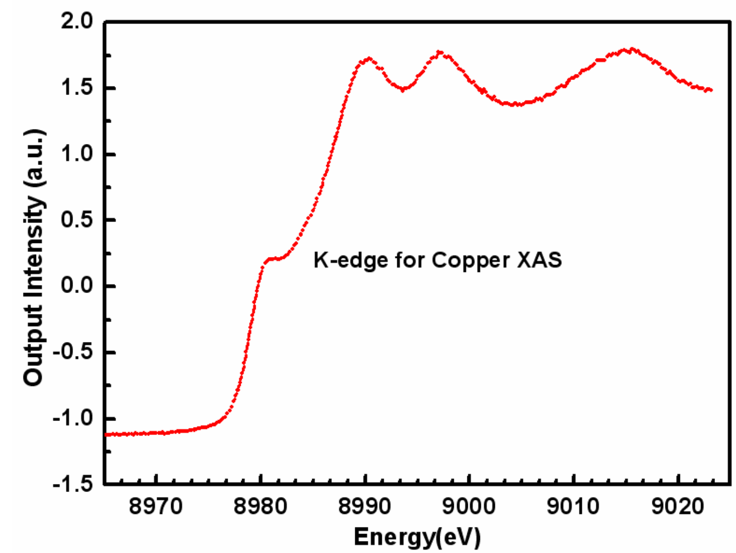
X-ray imaging experiment at SAXS end-station

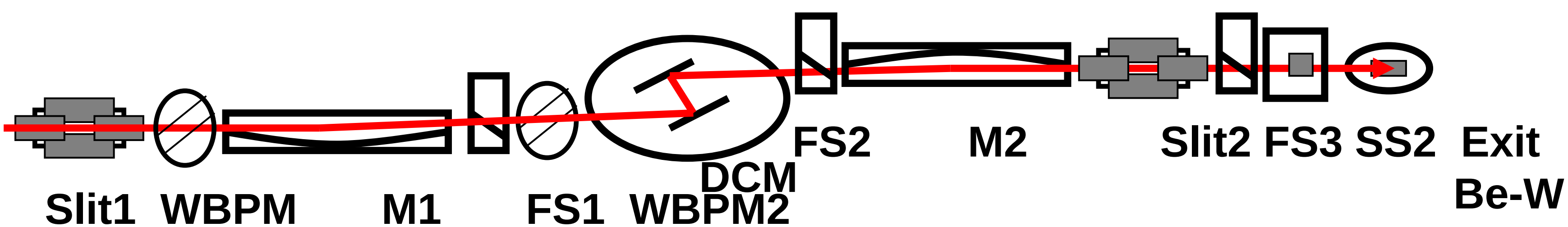


Commissioning of Beamline XRD

❑ X-ray Diffraction Beamline (BL 14B XRD)







Conclusions

- The SSRF accelerator commissioning was carried out rapidly, smoothly and successfully;
  - The SSRF injector (linac and booster) commissioning was completed and it has been operating reliably since Dec.2007;
  - The first phase storage ring commissioning with KEK PF retired copper cavities was completed, main storage ring performances at 3GeV were characterized, calibrated and optimized;
- The second phase storage ring commissioning with SRF cavities will begin on July 25, 2008, to obtain the design performance at 3.5GeV and 200-300mA at end of 2008.

Acknowledgement

Thank all of the members of the SSRF team for their dedications and contributions to the design, construction, installation and commissioning of the SSRF complex.

Thanks to the experts and colleagues of SLAC, LBL, ANL, BNL and CLS in America, KEK, Spring-8, PLA, NSRRC, SSLS, IHEP and NSRL in Asia, ELETTRA, SLS, ESRF, SOLEIL, DIAMOND, ALBA, ANKA, DESY and BESSY in Europe, and many others for their great helps and supports to the SSRF design and construction over passed years.

Thank you for your attention