Diamond Light Source – a New Light for Science

Richard P. Walker, Technical Director

1. Introduction
2. The Building
3. The Machine
4. The Beamlines
5. Commissioning
6. Future Plans

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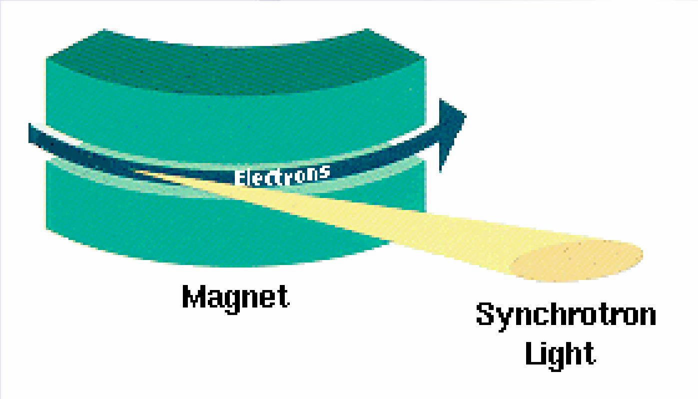
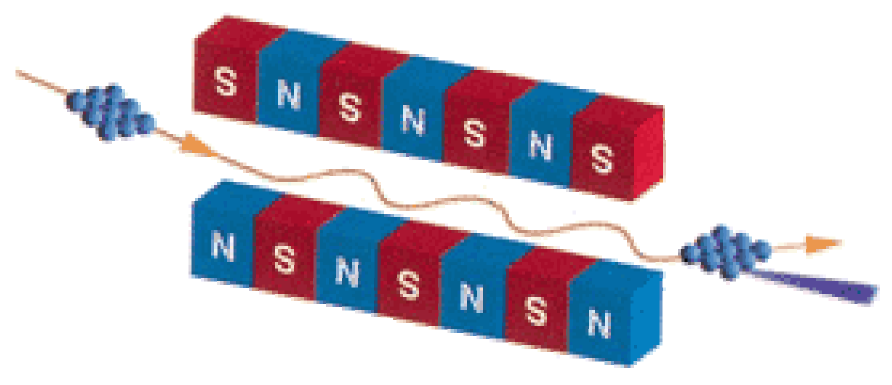
What is Synchrotron Light ?

- **Synchrotron Light is electromagnetic radiation emitted when a high energy beam of charged particles (electrons) is deflected by a magnetic field**

a single bending magnet produces a wide fan of radiation



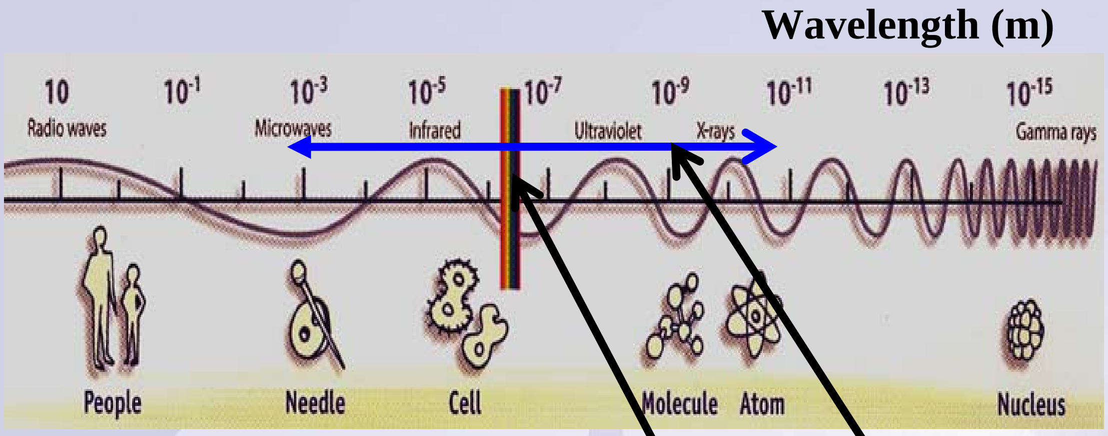
multiple bends in an "undulator" or "wiggler" magnet give higher intensity and brighter radiation



What’s so special about it ?

- **Covers the electromagnetic spectrum from microwaves to hard X-rays:**

  - can select the wavelength required for a given experiment



- **Extremely intense and well collimated:**

  - can be focused to sub-micron spot sizes, allows rapid experiments on small and dilute samples

- **Highly polarised**

  - generally linear, but circular also possible

- **Pulsed time structure**

  - allows dynamic studies of fast chemical or biological processes (10-100 ps scale)

What can it be used for ?

Biomedical -	protein crystallography and cell biology;
Medical research -	microbiology, disease mechanisms, high resolution imaging;
Environmental science -	toxicology, atmospheric research, clean combustion and cleaner industrial production technologies;
Agriculture -	plant genomics, soil studies and plant imaging;
Advanced materials -	nanostructured materials, intelligent polymers, ceramics, light metals and alloys, electronic and magnetic materials;
Engineering -	imaging of industrial processes in real time, high resolution imaging of cracks and defects in structures, operation of catalysts in chemical engineering processes;
Forensic Science -	identification from extremely small and dilute samples.
Archaeometry -	ancient metalworking processes, identification of production sites etc.

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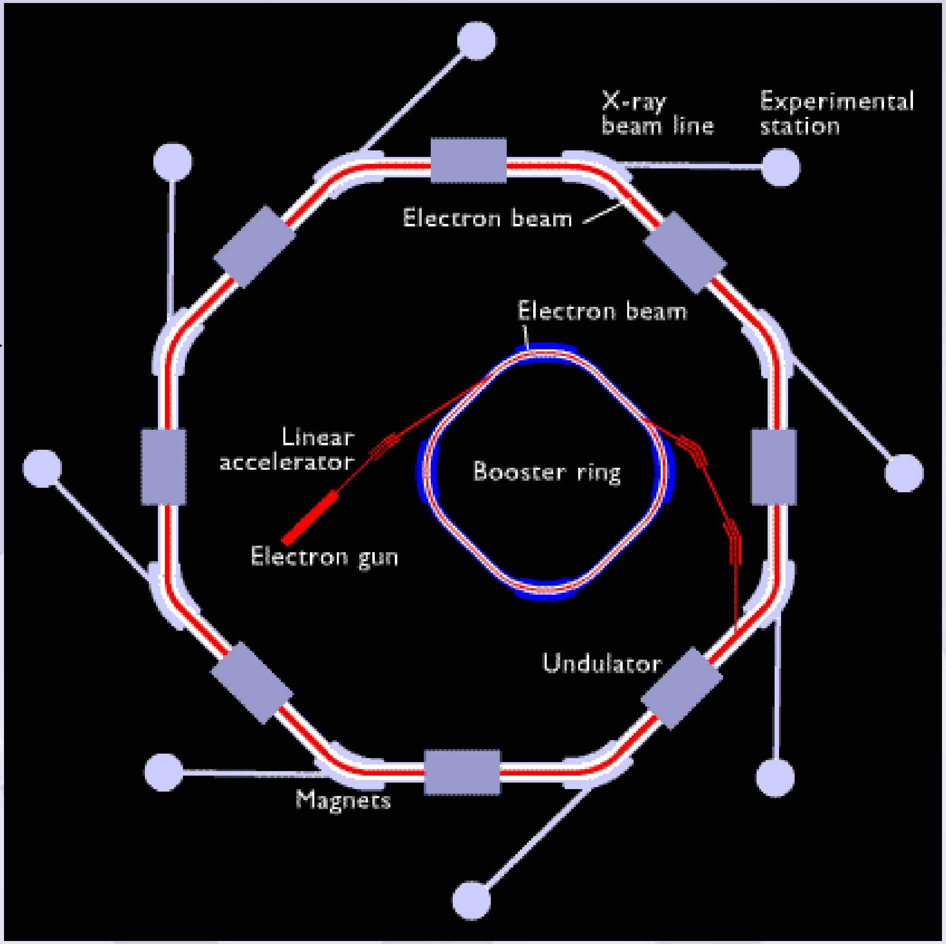
A Brief History of Synchrotron Light Sources :

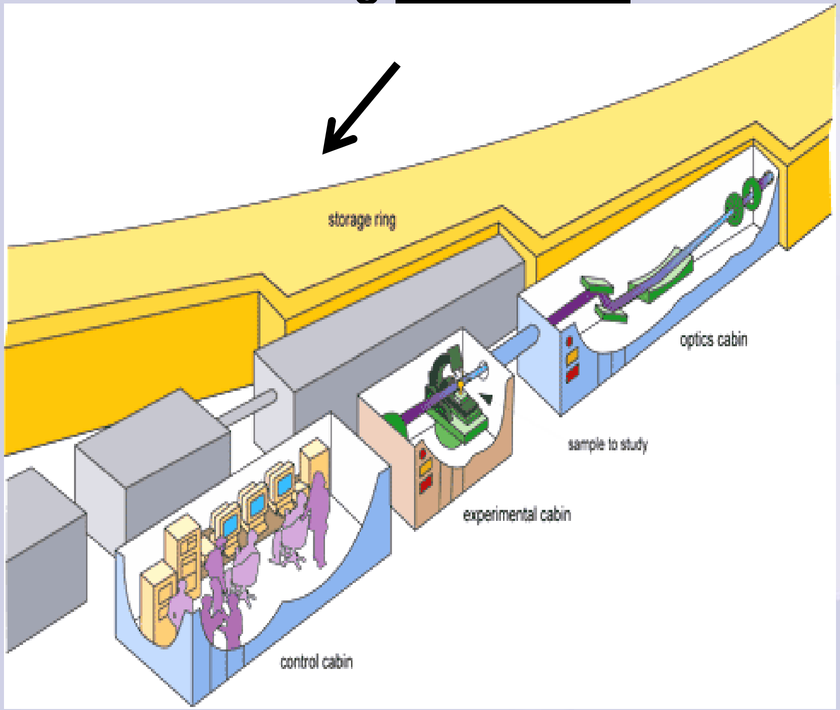
- **Discovery: 1947, General Electric 70 MeV synchrotron**
- **First use for experiments: 1956, Cornell 300 MeV synchrotron**
- **1st generation:**
  machines built for other purposes, mainly High Energy Physics
  e.g. Synchrotron Radiation Facility at the NINA Synchrotron, Daresbury (1971-1977)
- **2nd generation:**
  purpose-built storage rings for synchrotron light
  ***e.g. the SRS at Daresbury, the world's first dedicated synchrotron X-ray source* (1981-2008)**
- **3rd generation:**
  higher brightness synchrotron light sources, using mainly undulators as the X-ray source
  e.g. ESRF, Diamond etc.

How does it work ?

A beam of electrons is accelerated in a linac, further accelerated in a booster, then accumulated in a storage ring.



The circulating electrons emit intense beams of synchrotron light that are sent along beamlines to the



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Diamond Project Evolution

1993	Woolfson Review: SRS to be replaced by a new medium energy machine
1997	Feasibility Study ("Red Book") published 3 GeV, 16 cells, 345 m circumference, 14 nm rads
1998	Wellcome Trust joins as partner
Mar. '00	Decision to build Diamond at Rutherford Appleton Lab.
Oct. '00	3 GeV, 24 cells, 560 m circumference design approved
Apr. '02	Joint Venture Agreement signed (UK Govt./WellcomeTrust) Diamond Light Source Ltd. established Design Specification Report ("Green Book") completed by CCLRC
Jan. '07	Start of Operations

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Diamond Design Criteria

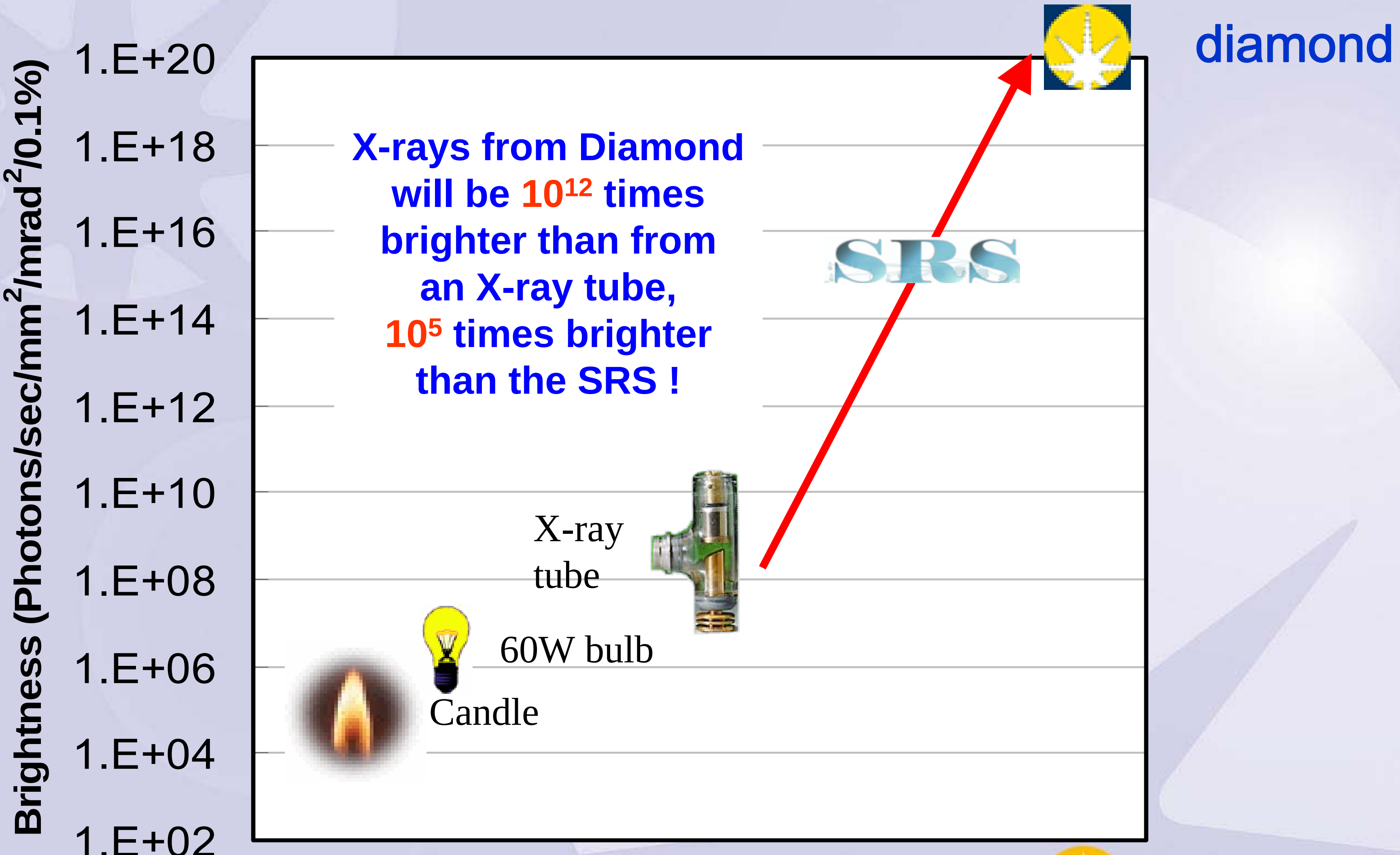
- Large capacity for Insertion Device beamlines
- High brightness synchrotron light from undulators optimised in the range 0.1-10 keV, extending to 15-20 keV
- High flux from wigglers up to 100 keV
- Cost constraint

➔ "medium" energy of 3 GeV

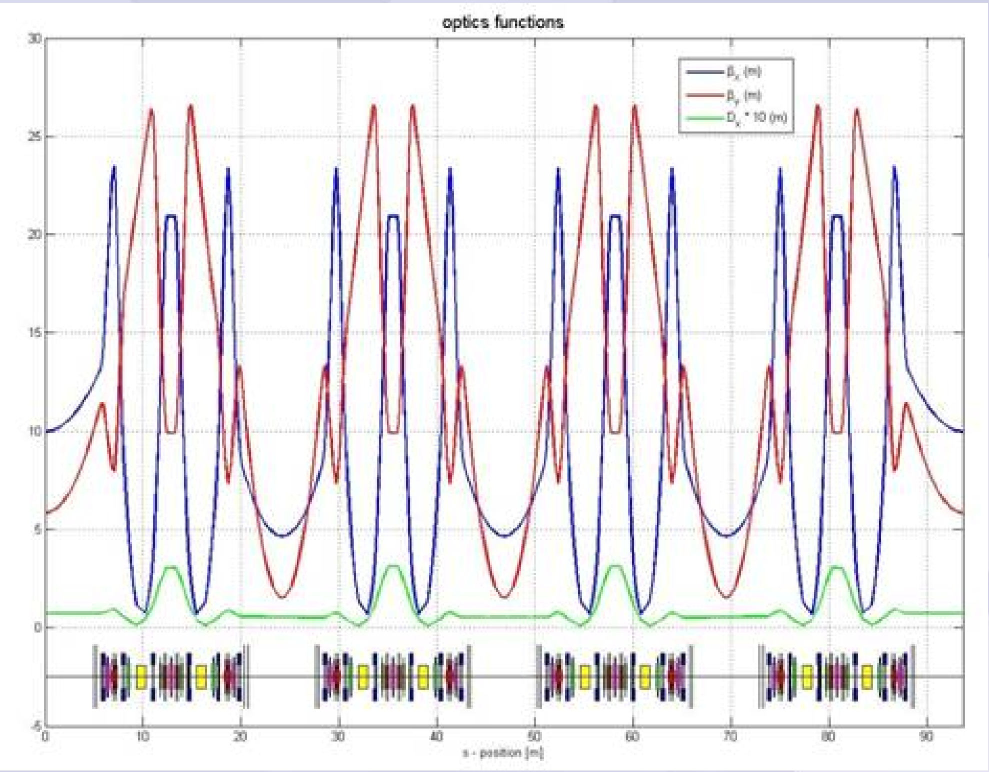
➔ relatively large circumference (562 m) and no. of cells (24) to give large no. of insertion devices and low emittance

➔ extensive use of in-vacuum undulators

it's all about brightness ...



Diamond – Main Parameters



nominal, non-zero dispersion lattice

Energy	**3 GeV**
Circumference	**561.6 m**
No. cells	**24**
Symmetry	**6**
Straight sections	**6 x 8m, 18 x 5m**
Insertion devices	**4 x 8m, 18 x 5m**
Beam current	**300 mA**
Emittance (h, v)	**2.7, 0.03 nm rad**
Lifetime	**> 10 h**
Min. ID gap	**7 mm**
Beam size (h, v)	**123, 6 μm**
Beam divergence (h, v) *(at centre of 5 m ID)*	**24, 4 μrad**

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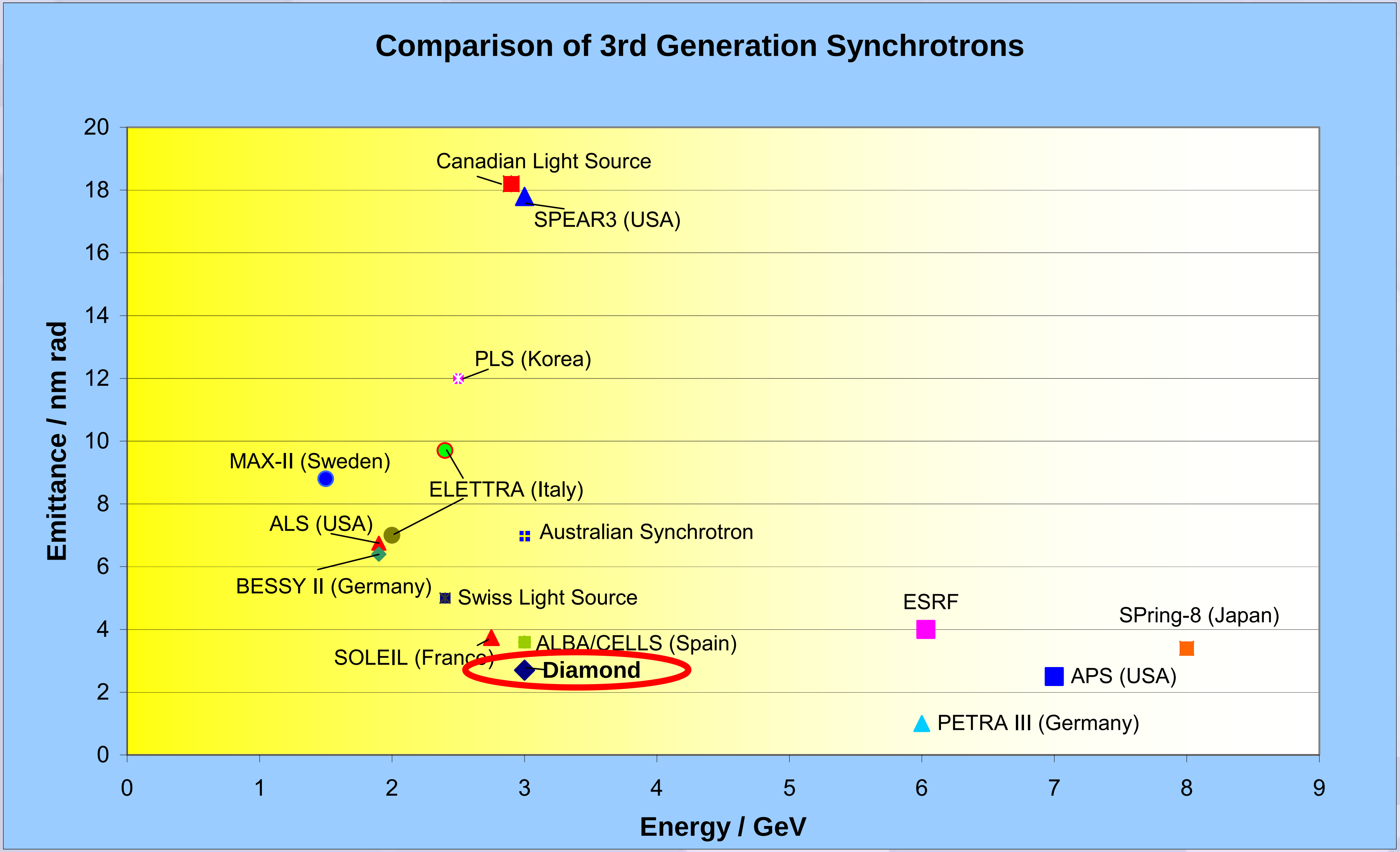
Diamond is a one of a new class of Medium Energy, 3rd Generation Light Sources.



Diamond compared to SRS

	SRS	Diamond
Electron Beam Energy	2 GeV	3 GeV
Storage ring circumference	96.0 m	561.6 m
Available space for Insertion Devices	6x1m	4x8m, 18x5m
Beam current	250 mA	300 mA
Emittance (hor., vert.) (nm rad)	190, 3.8	2.7, 0.03
Minimum ID gap	20 mm	7 mm
Electron beam sizes (hor., vert) (μm)	1000, 160	123, 6
Electron beam divergences (hor., vert)	590, 60	24, 4 μrad
Peak brightness	$3\ 10^{15}$	$2\ 10^{20}$
Peak brightness (1Å)	10^{14}	10^{19}

100,000 times brighter than the SRS !

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Key Dates

Start enabling works	Mar. '03
Start main building works	Oct. '03
Linac commissioning	Aug. - Nov. '05
Booster commissioning	Jan. - Jun. '06
Storage ring commissioning	May – Dec. '06
Start of Operations	**Jan. '07**

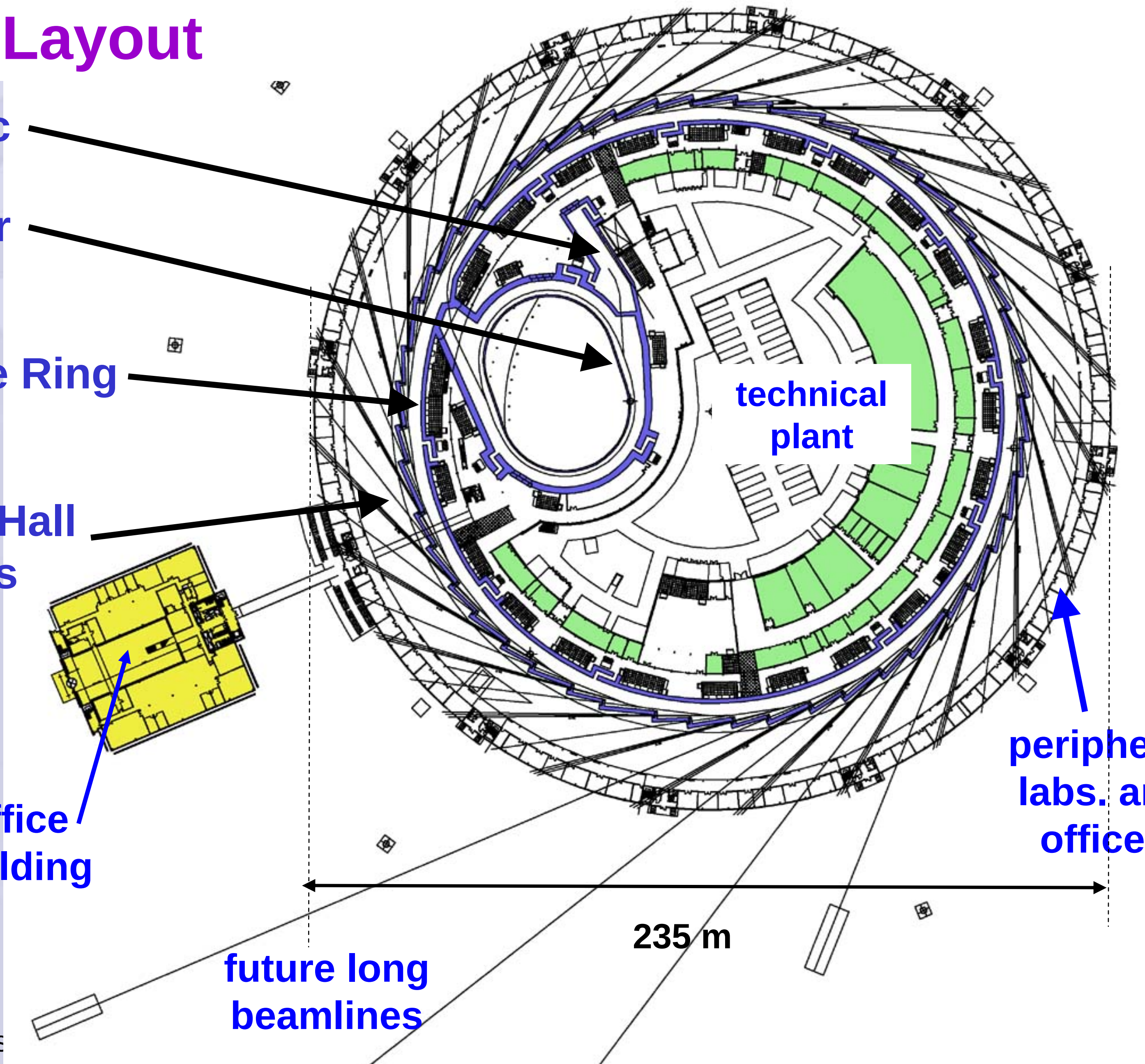
Diamond Layout

100 MeV Linac

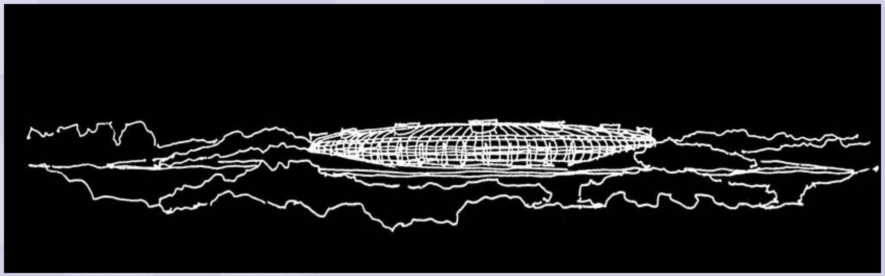
3 GeV Booster
C = 158.4 m

3 GeV Storage Ring
C = 562.6 m

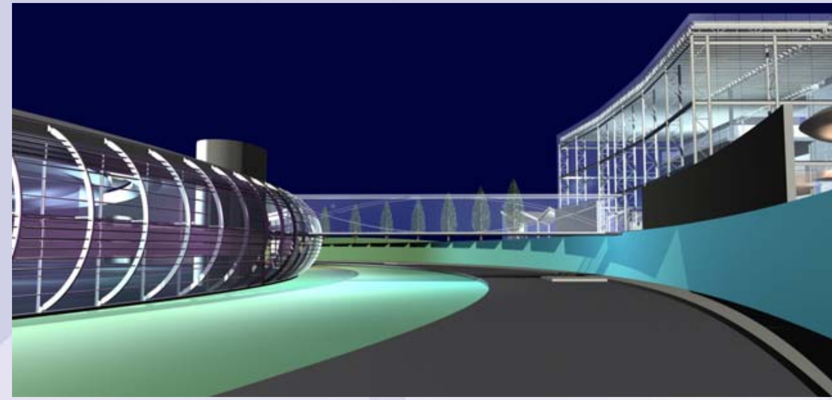
Experimental Hall and Beamlines



Diamond Buildings: architect's concept to reality



"a spaceship landing in the natural landscape.."



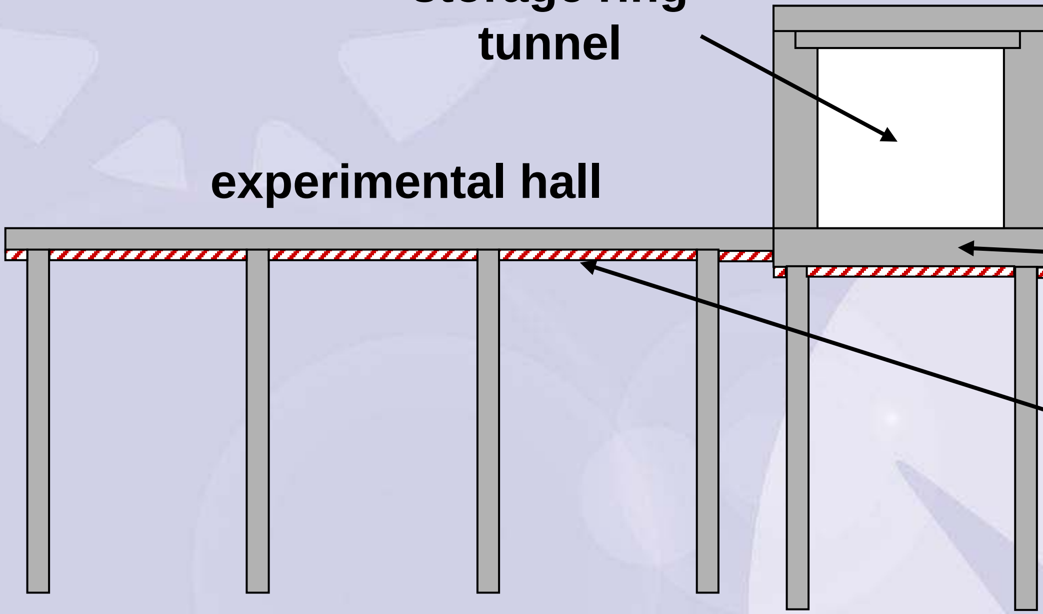
"the curved outer form reflects the form of the synchrotron within .."

Foundations designed to reduce ground movements and vibrations to the minimum practically achievable:

piling rig:

storage ring tunnel

experimental hall



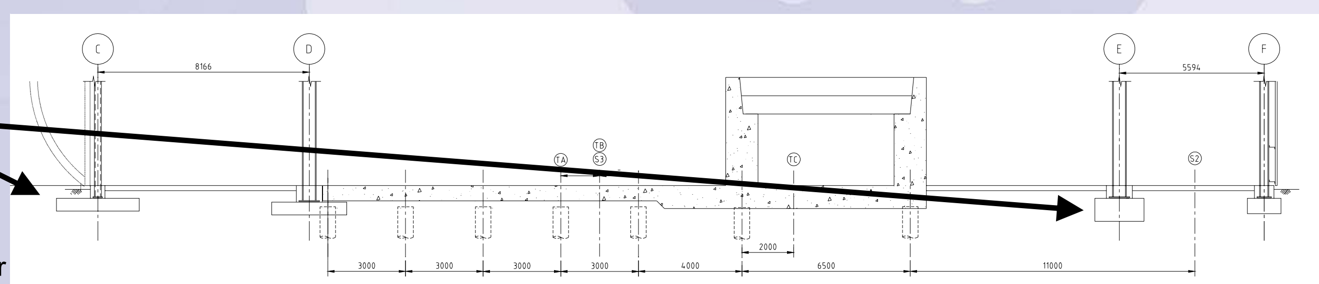
0.6-0.85 m thick concrete slab

void to isolate slab from the ground

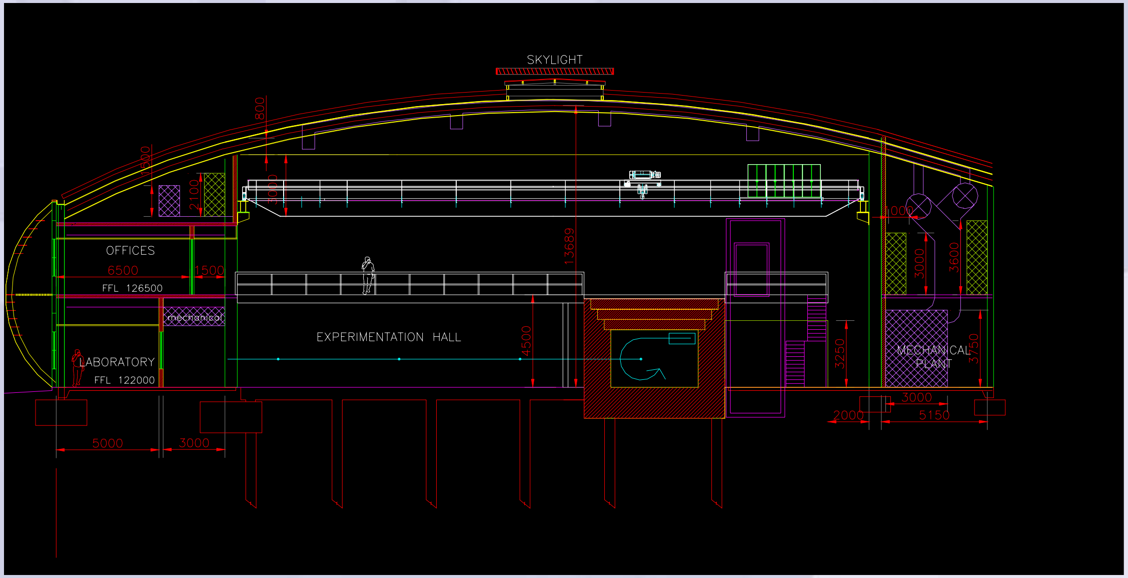
1523 piles, 12-15 m deep

600 mm diam., 3 m apart

separate non-piled foundation for the building structure and plant rooms

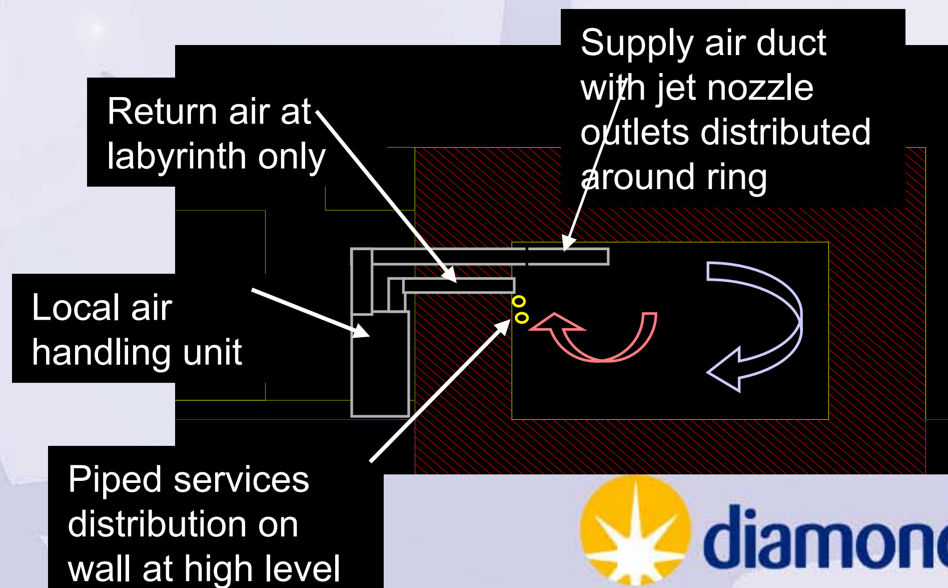


Buildings and services also designed for thermal stability:



experimental hall +/- 1 ^{o}C

storage ring tunnel +/- 0.5 ^{o}C



Courtesy of JacobsGibb Ltd.

June 2003

June 2004

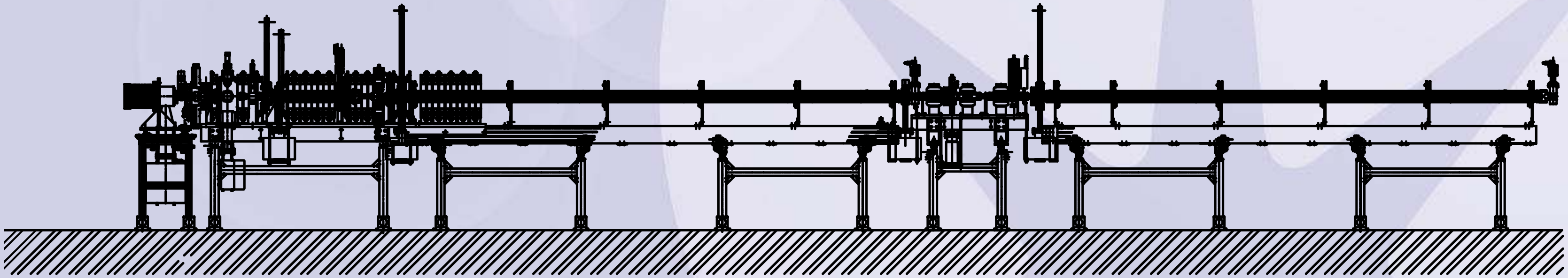
October 2005

The Machine: Linac

- 100 MeV Linac of the DESY S-band Linear Collider Type II design, supplied "turn-key" by Accel Instruments.

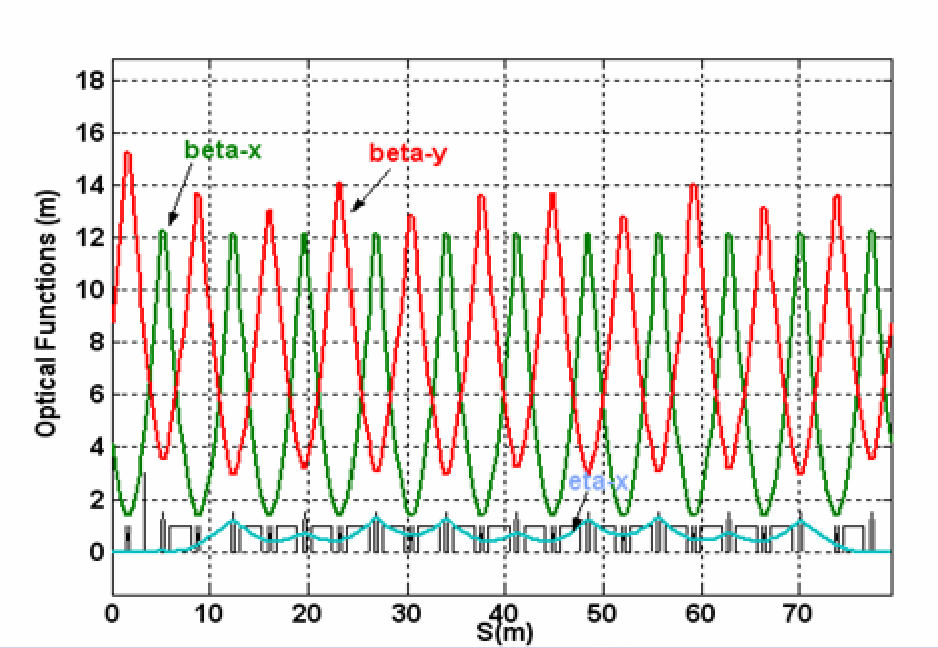
  (DLS supplied diagnostics, vacuum and control system components, and beam analysis software)

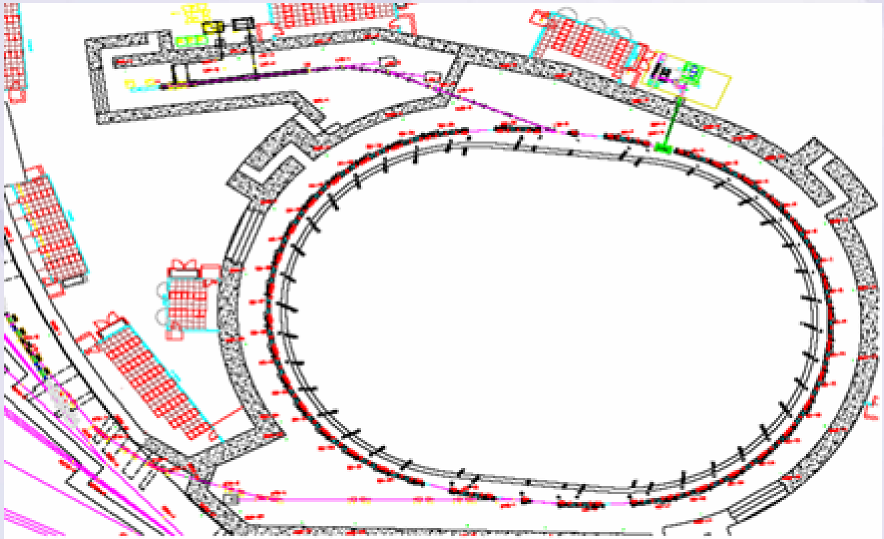
- thermionic gun; short (< 1 ns) and long pulse (0.1-1 μs) modes
- 500 MHz sub-harmonic pre-buncher, 3 GHz primary buncher, 3 GHz final buncher
- two 5.2 m constant gradient accelerating sections fed by independent klystrons



Booster

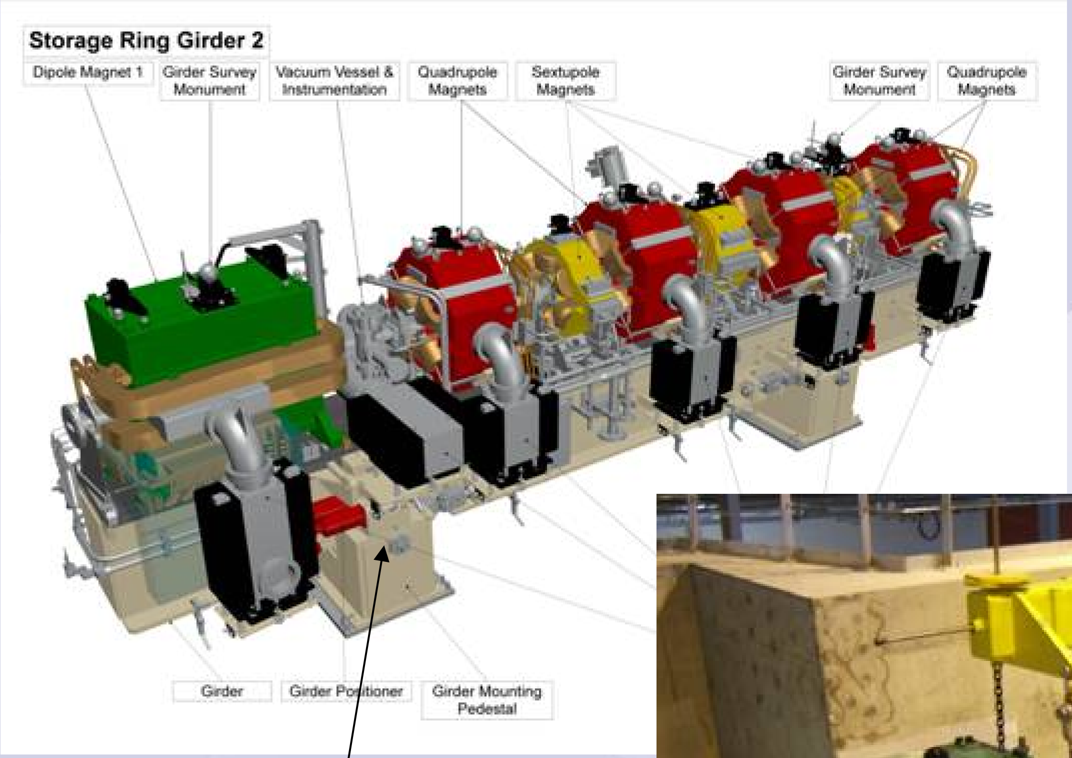
Energy	**3 GeV**
Circumference	**158.4 m**
Emittance	**141 nm rad**
Repetition rate	**5 Hz**
Lattice	**FODO, missing dipole**





Storage Ring

Magnets and vacuum chambers



.. mounted and pre-aligned on 72 precisely machined girders.

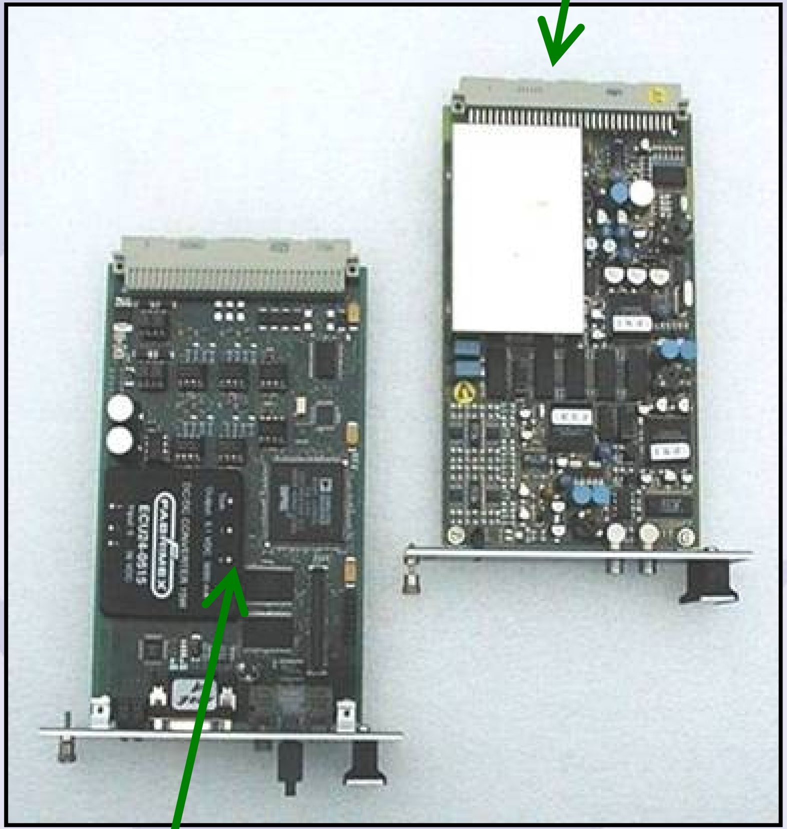
Up to 6 m long and 17 T in weight.

mover system for remote alignment

Power Supplies

Standardisation
- minimum no. of different types
- all 1038 power supplies use the same (PSI type) digital controller and ADC cards.

Maintainability and Reliability
- plug-in modules
- reduced component count
- redundancy of 24 V control power and power modules



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RF System

**Supercon-
ducting
cavities (2)**

IOT-based 300 kW amplifiers

Liquid He plant

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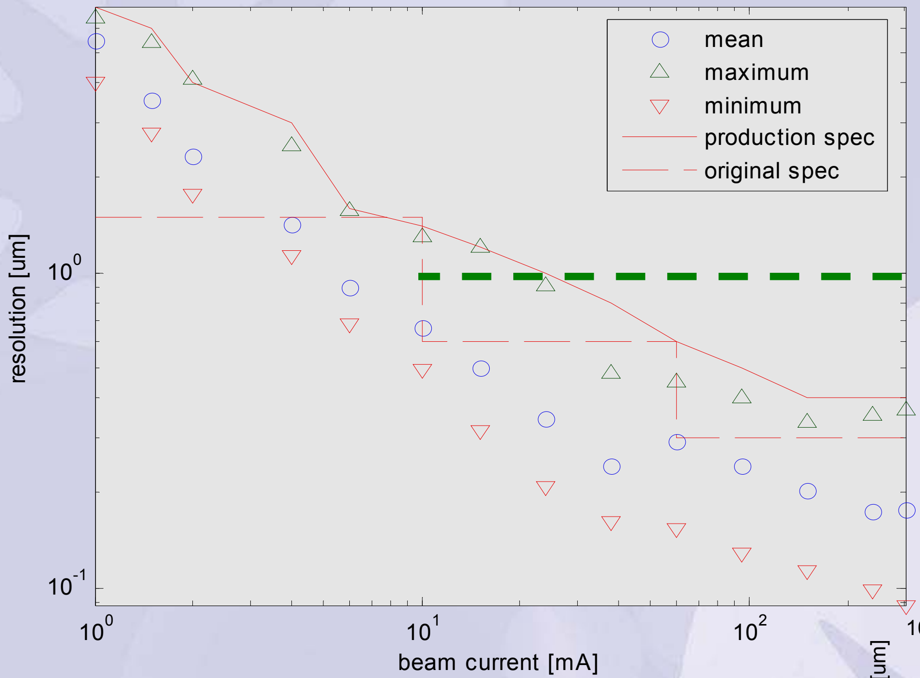
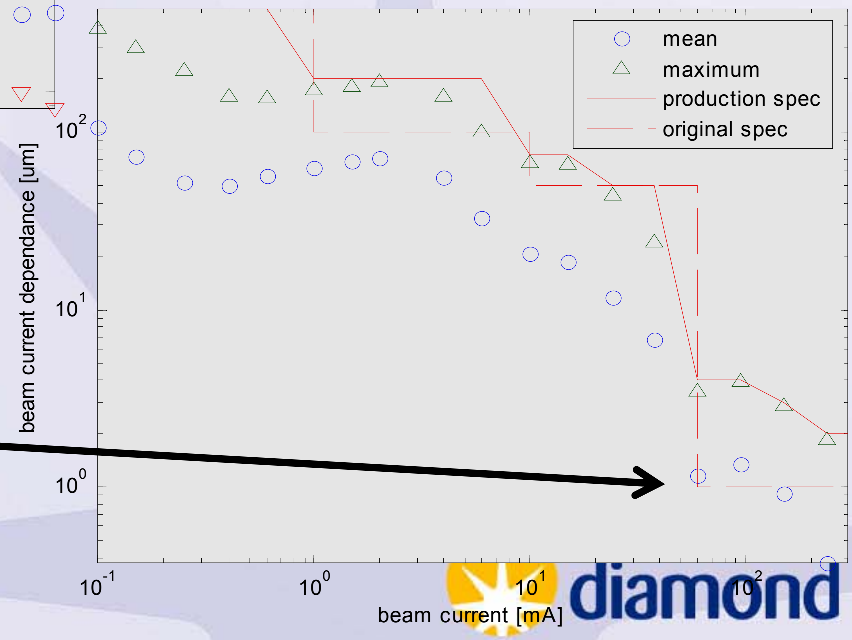
Digital Beam Position Monitor Electronics

(Libera, integrated in EPICS)



Resolution in 2 kHz Bandwidth:
<1 μm at >10 mA

Turn-by-turn (1 MHz b.w.):
~ 100 μm at 1 mA



Beam Current Dependence
< 1 μm at 60-300 mA

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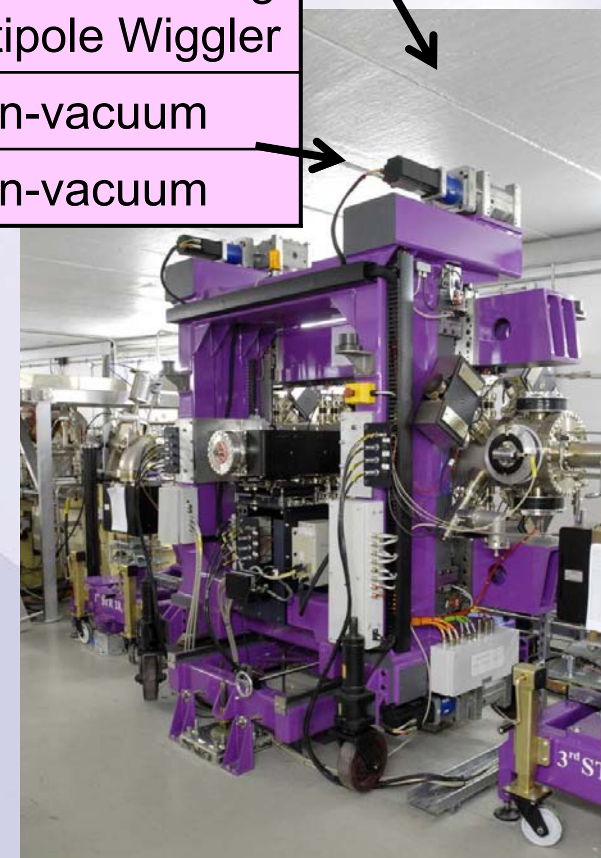
Phase I Insertion Devices

Beamline	ID	Type
I02	U23	In-vacuum
I03	U21	In-vacuum
I04	U23	In-vacuum
I06	HU64	APPLE-II
I15	SCW	Superconducting Multipole Wiggler
I16	U27	In-vacuum
I18	U27	In-vacuum



Beamlines

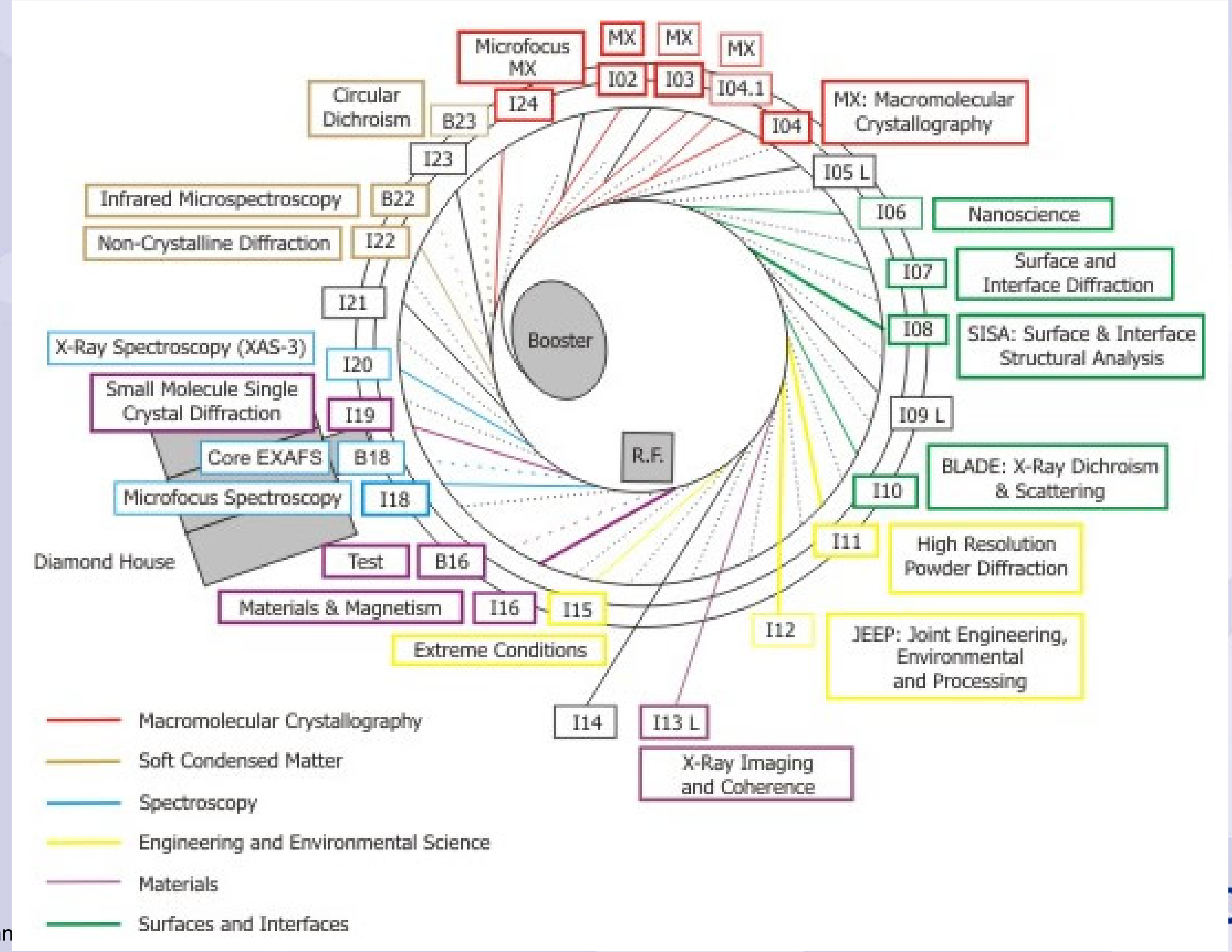
- **Phase I: 7 beamlines** – ready for operations in January 2007
- **Phase II (funded): 15 additional beamlines** at 4 per year from 2008 to 2011/12
- **Phase III (proposal)**: 10 additional beamlines, 2011-2015

Scope of Research

- **Expected Usage**
  - ✓Engineering and Physical Sciences 48%
  - ✓Life Sciences 40%
  - ✓Environmental Sciences 12%

- **Reaching new communities from both academia & industry**
  - ✓Advanced techniques
  - ✓High throughput

Beamline Plan – Science "Villages"



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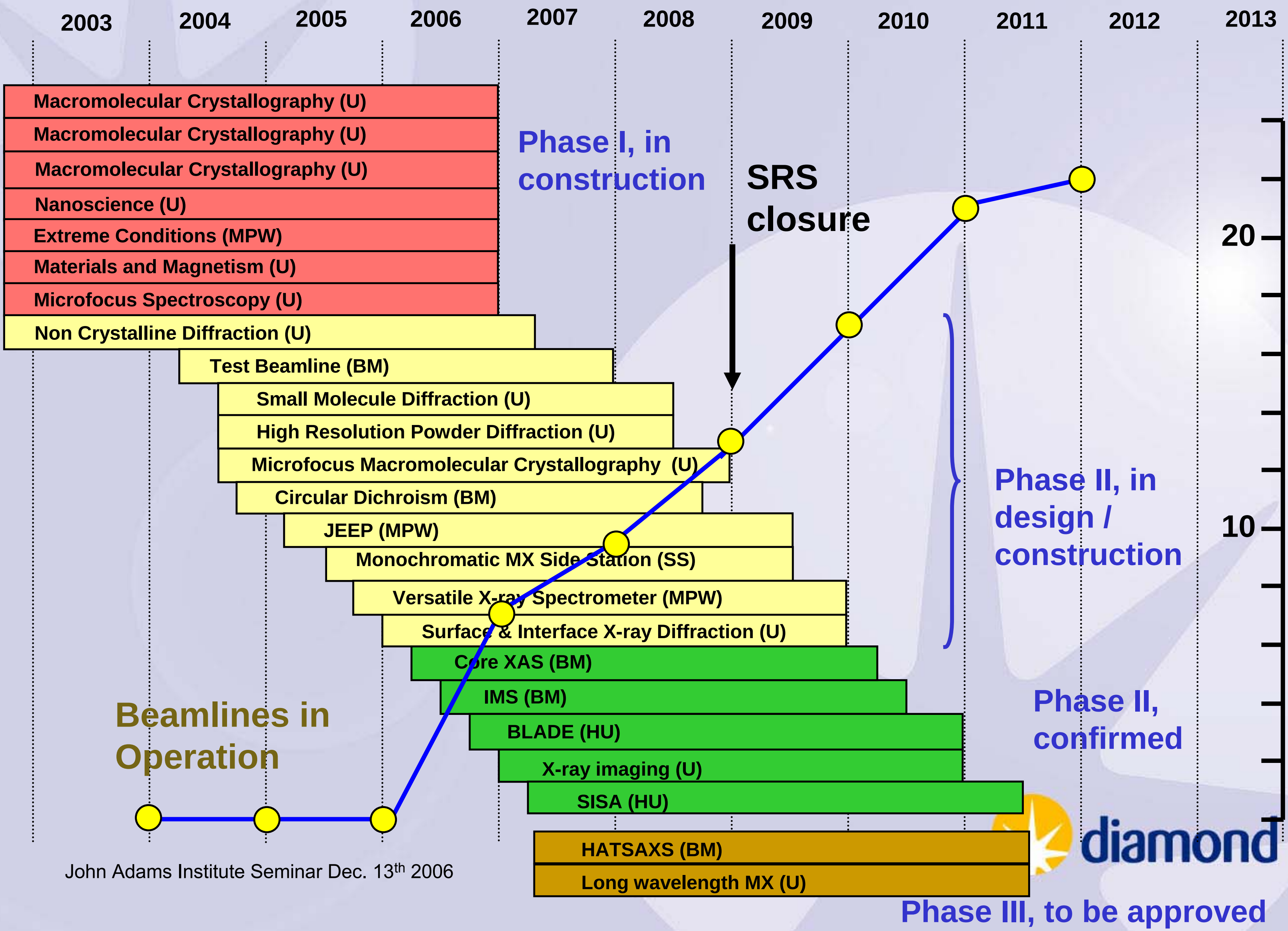
Beamline Programme



Phase I Beamlines

- **I02,3,4 3-25 keV Macromolecular crystallography**
  For the determination of the structure of macromolecules with rapid sample through-put.
- **I06 80- 1500 eV Nanoscience**
  To study the morphology, chemical and magnetic state of nanostructures with <10 nm resolution.
- **I15 5-200 keV Extreme conditions**
  Study of materials at very high temperatures and pressures, typical of planetary interiors and industrial processes.
- **I16 3-25 keV Materials and magnetism**
  Study of materials including magnetic systems, high temperature superconductors.
- **I18 2-13 keV X-ray microfocus spectroscopy**
  Chemical imaging and structural studies of complex multicomponent systems with sub-micron resolution.

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User Access

- **User Office is operational**
- **Call for first users: October 2006**
- **First “experienced” users and optimisation of Phase I beam lines: January - September 2007**
- **Call for 2nd user proposals: May 2007**

Machine Commissioning: Linac

Installation complete:	Aug. 3rd 2005
1st beam from gun:	Aug. 31st 2005
1st 100 MeV beam:	Sep. 7th 2005
Acceptance test complete:	mid-Oct. 2005

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Linac Performance

Parameter	Specification	Single bunch	Multi bunch
Energy [MeV]	> 100	103	103
x norm. emittance [π.mm.mrad]	< 50	18	16
y norm. emittance [π.mm.mrad]	< 50	27	11
Charge [nC]	> 1.5 / 3.0	2.1	4.8
Pulse width [ns]	< 1	~ 0.2 fwhm	~ 0.2 fwhm
Jitter [ps]	< 100	11	11
Energy variation [%]	< 0.25	0.05 rms, 0.21 full	0.05 rms, 0.16 full
Energy spread [%]	< 0.5	< 0.2	0.2

(Same at 1 Hz or 5 Hz)

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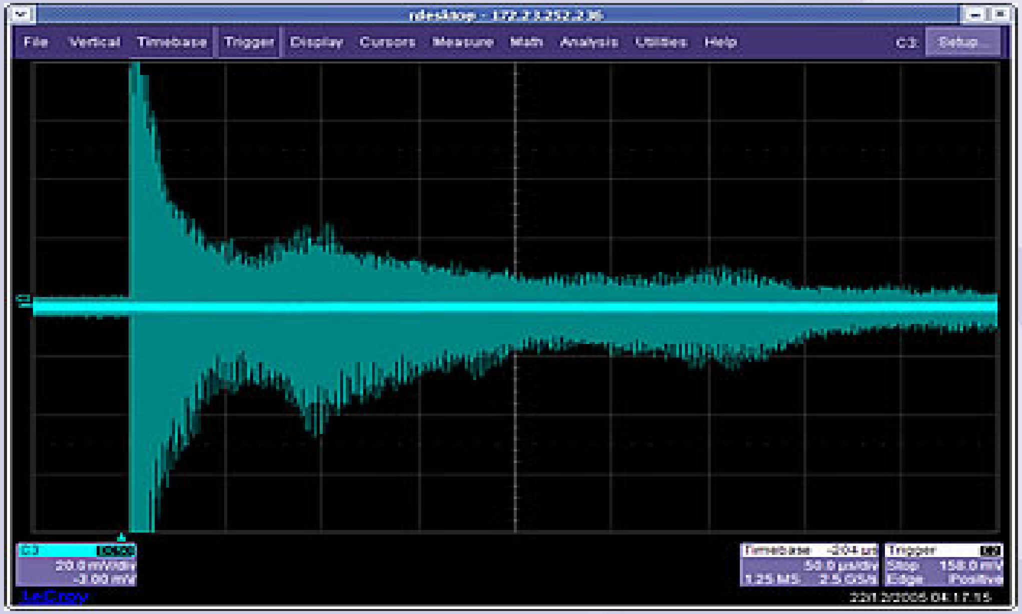
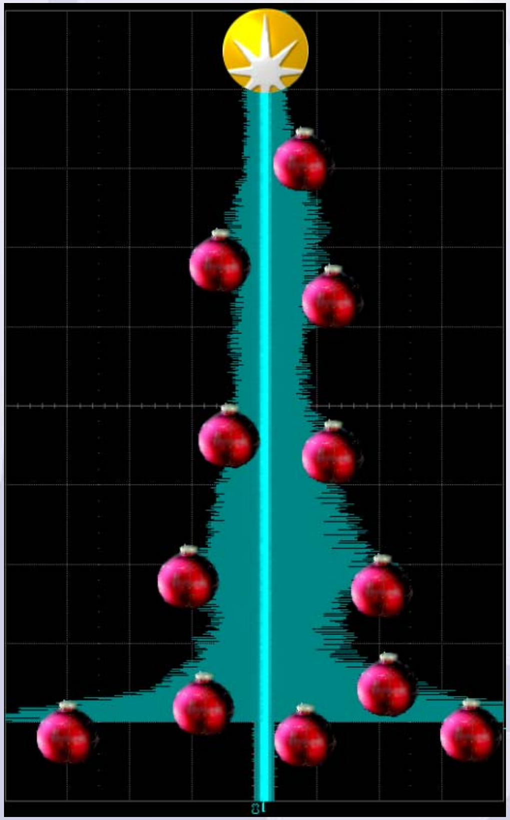
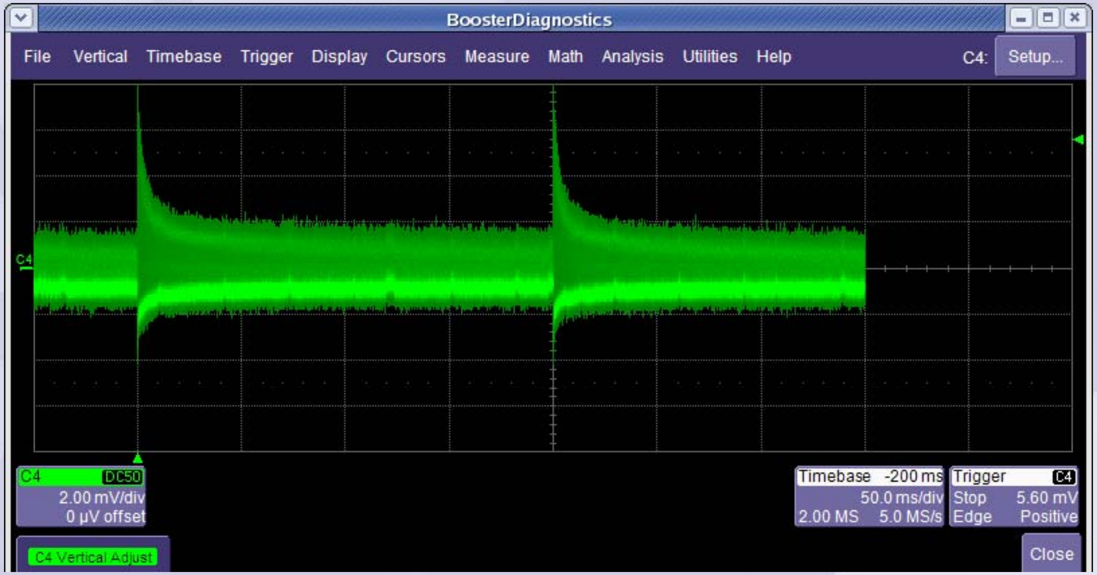
Booster Commissioning

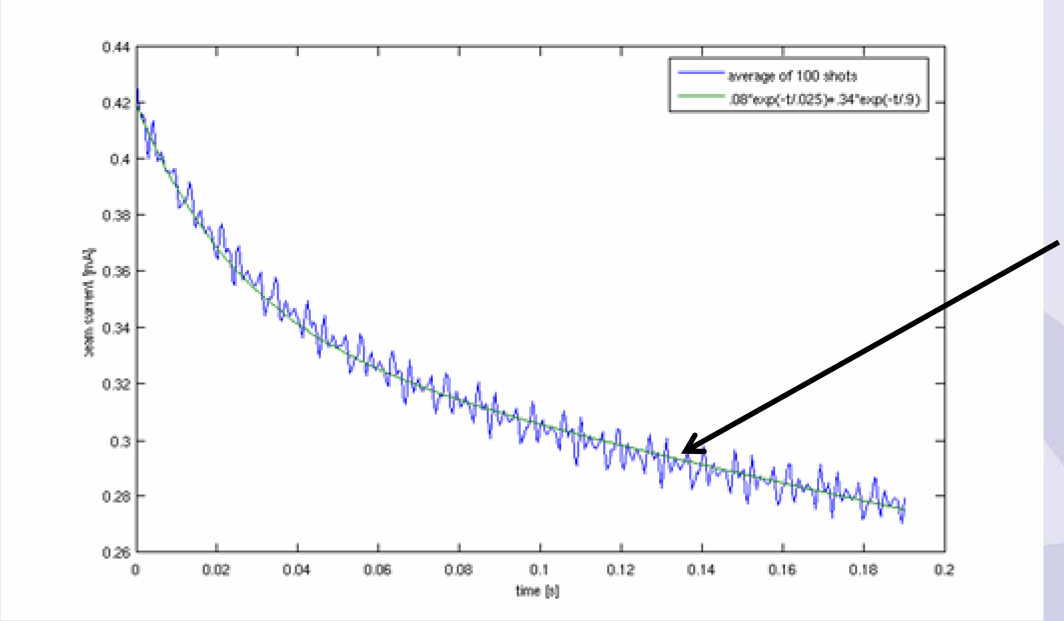
- First beam in the Booster Dec. 21st 2005







Feb. 13th:
Beam surviving for 200 ms between injections at 100 MeV (RF on)



1/e lifetime = 1 s

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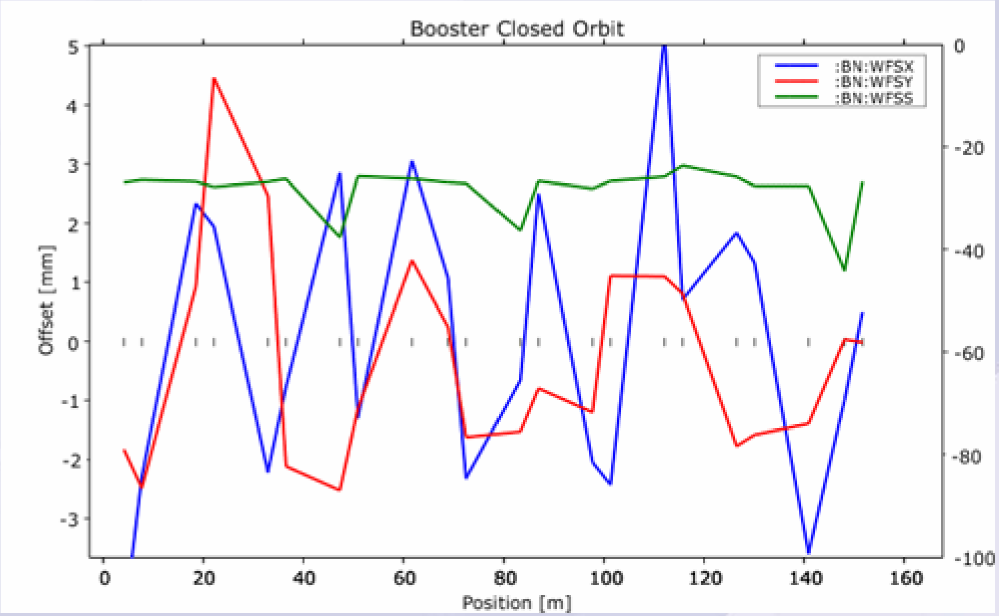
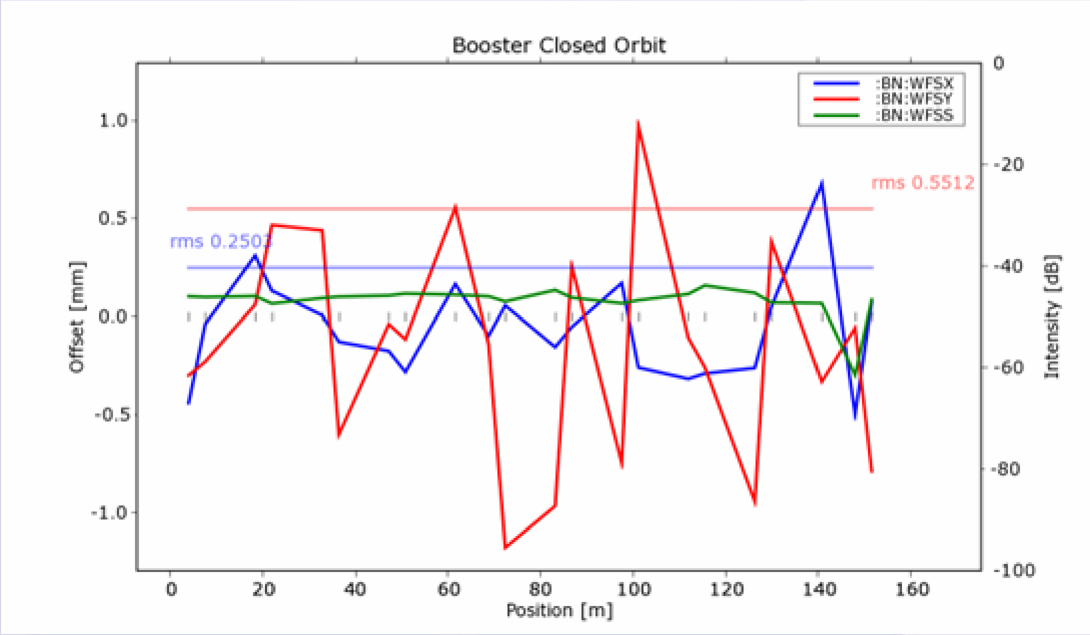


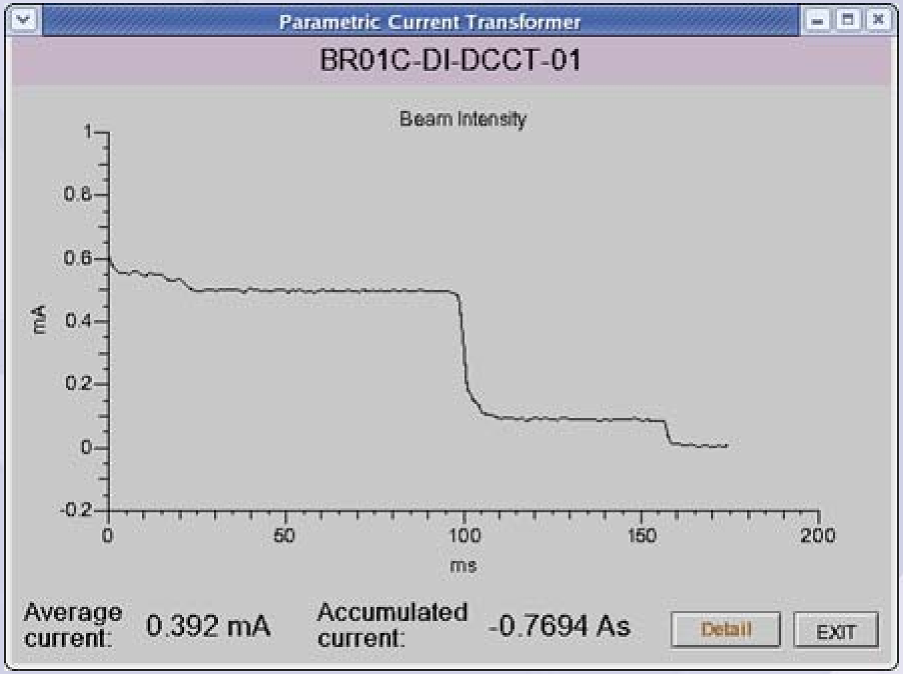
Closed orbit

within +/- 5 mm, with no correctors powered

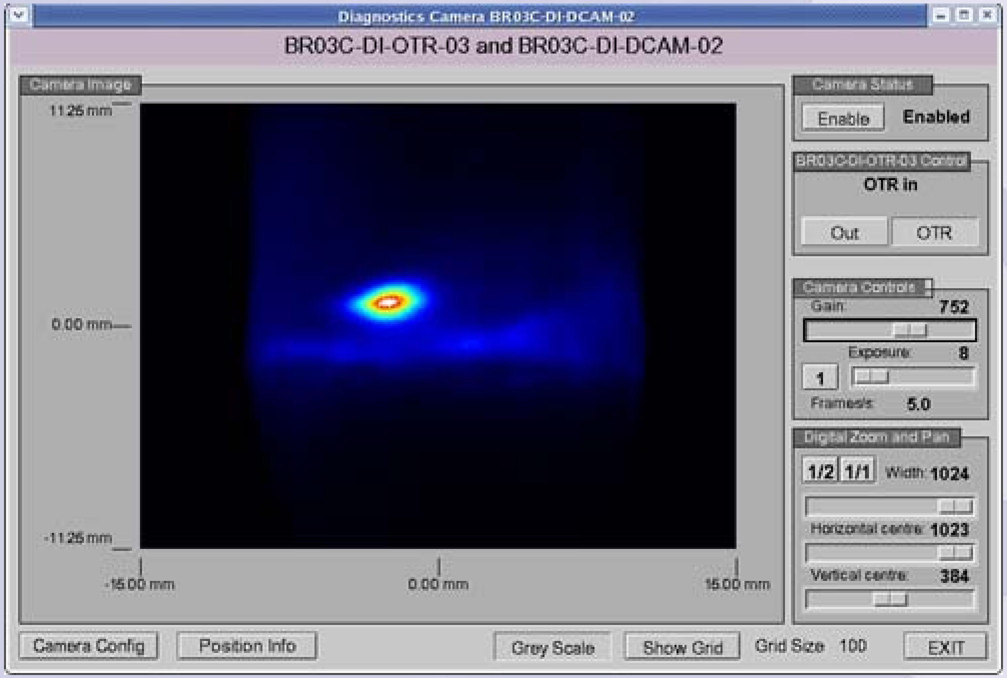


First orbit correction Feb. 17th

within +/- 1 mm



First acceleration to 700 MeV, March 10th



First extraction at 700 MeV, April 4th

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Commissioning to 3 GeV (June 2006)

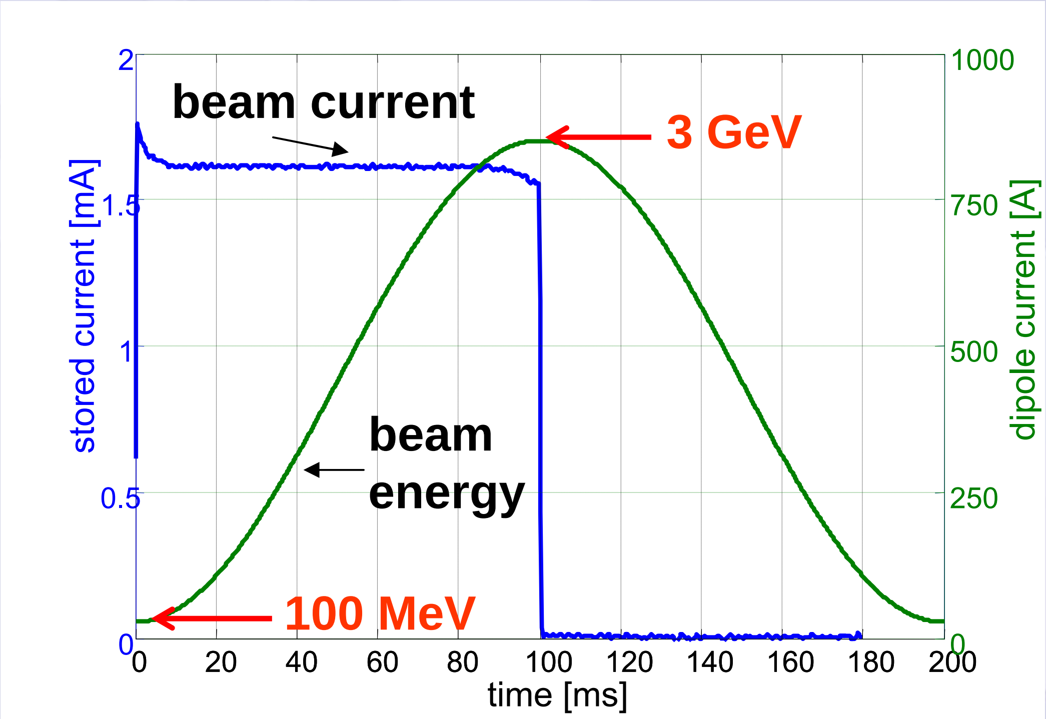
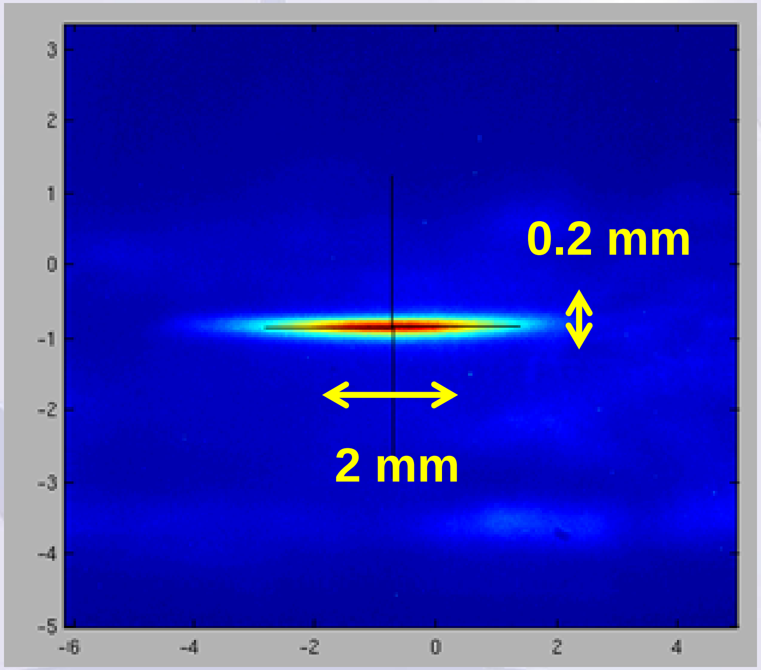
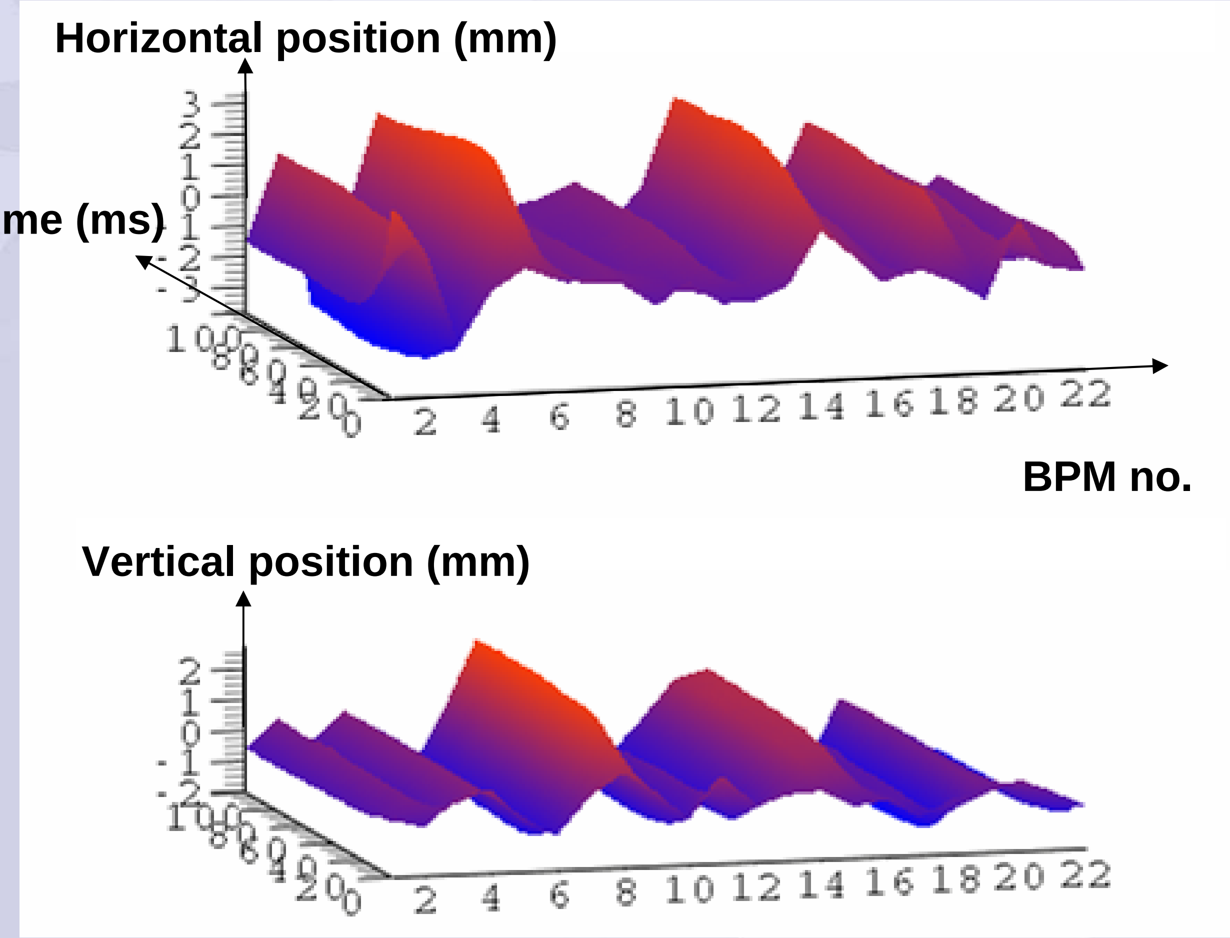


image of the beam extracted from the booster:



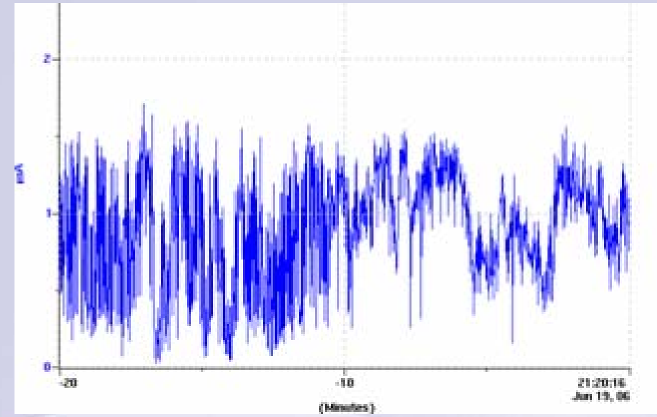
Closed orbit



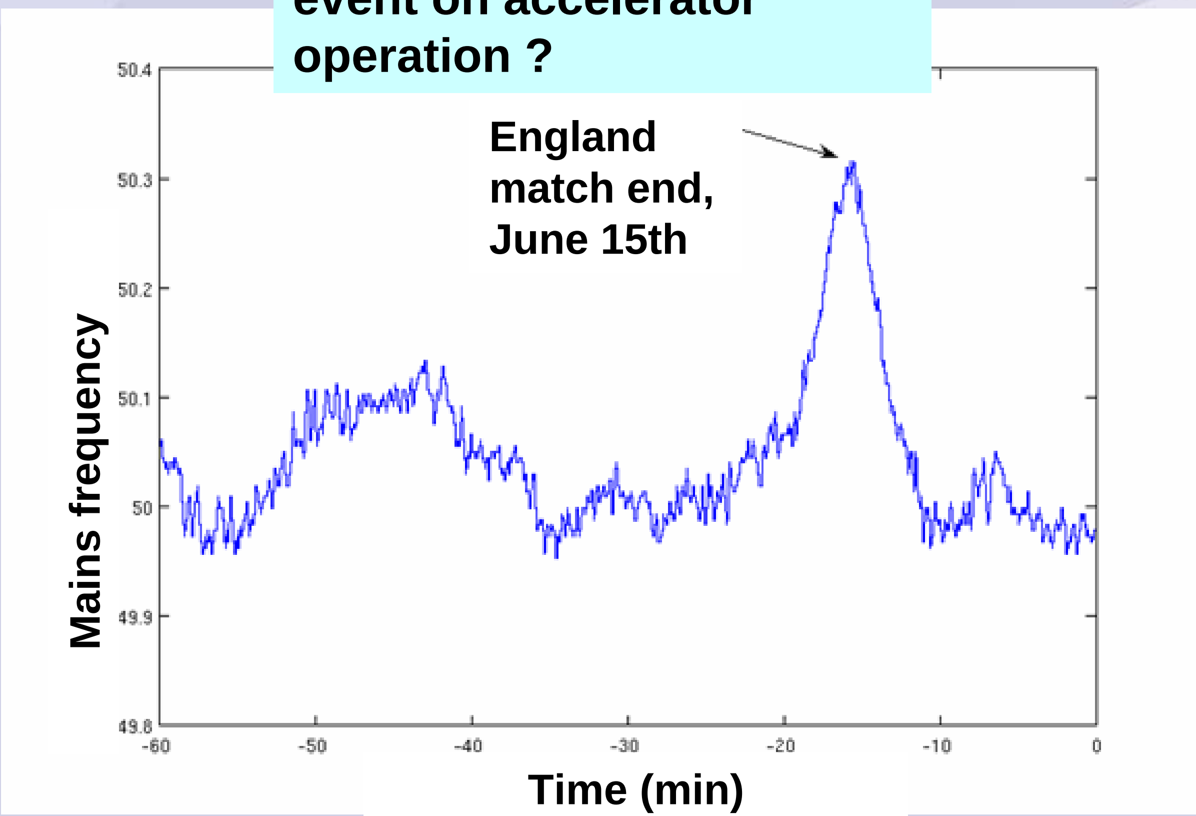
Closed orbit can be corrected during the ramp, but is not needed.

After 400 MeV stays constant, within ± 3 mm.

Initially had some stability problems, linked to mains frequency variations ….particularly during the World Cup !.

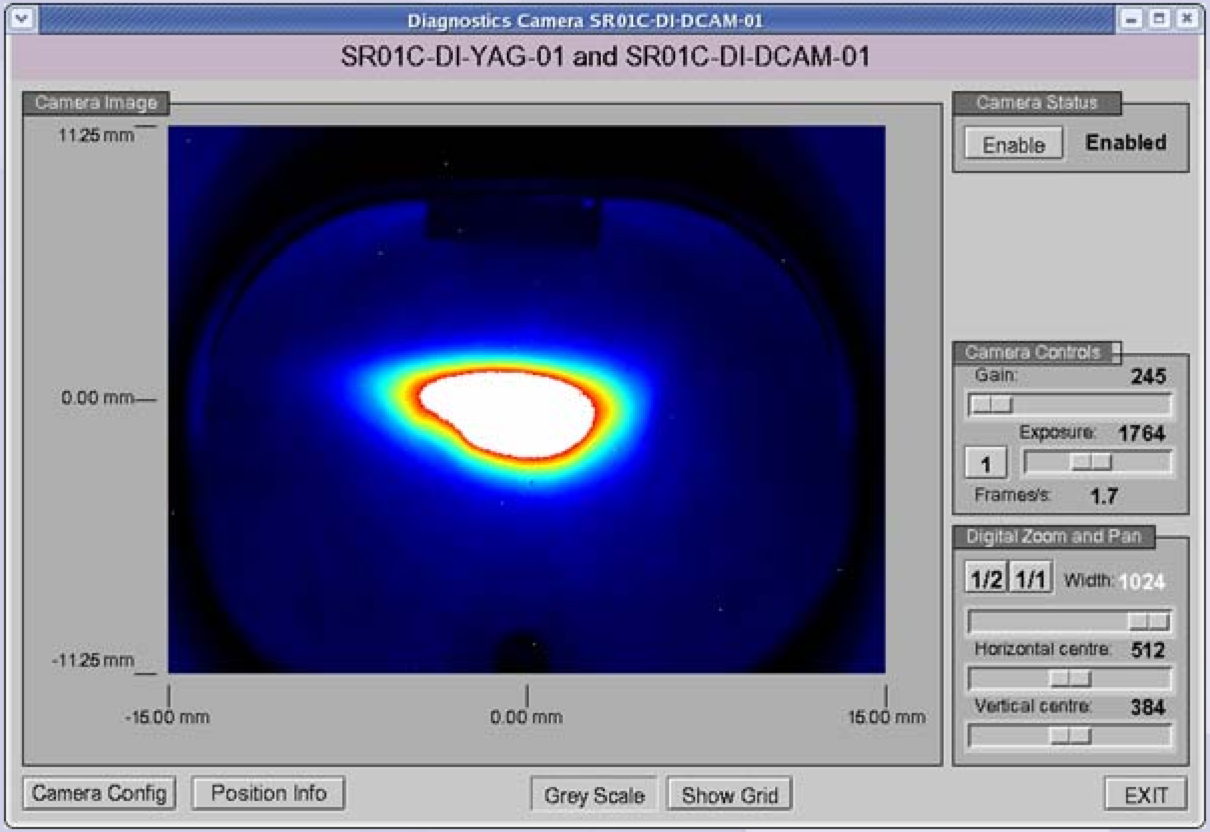


First observation of the effect of a major sporting event on accelerator operation ?



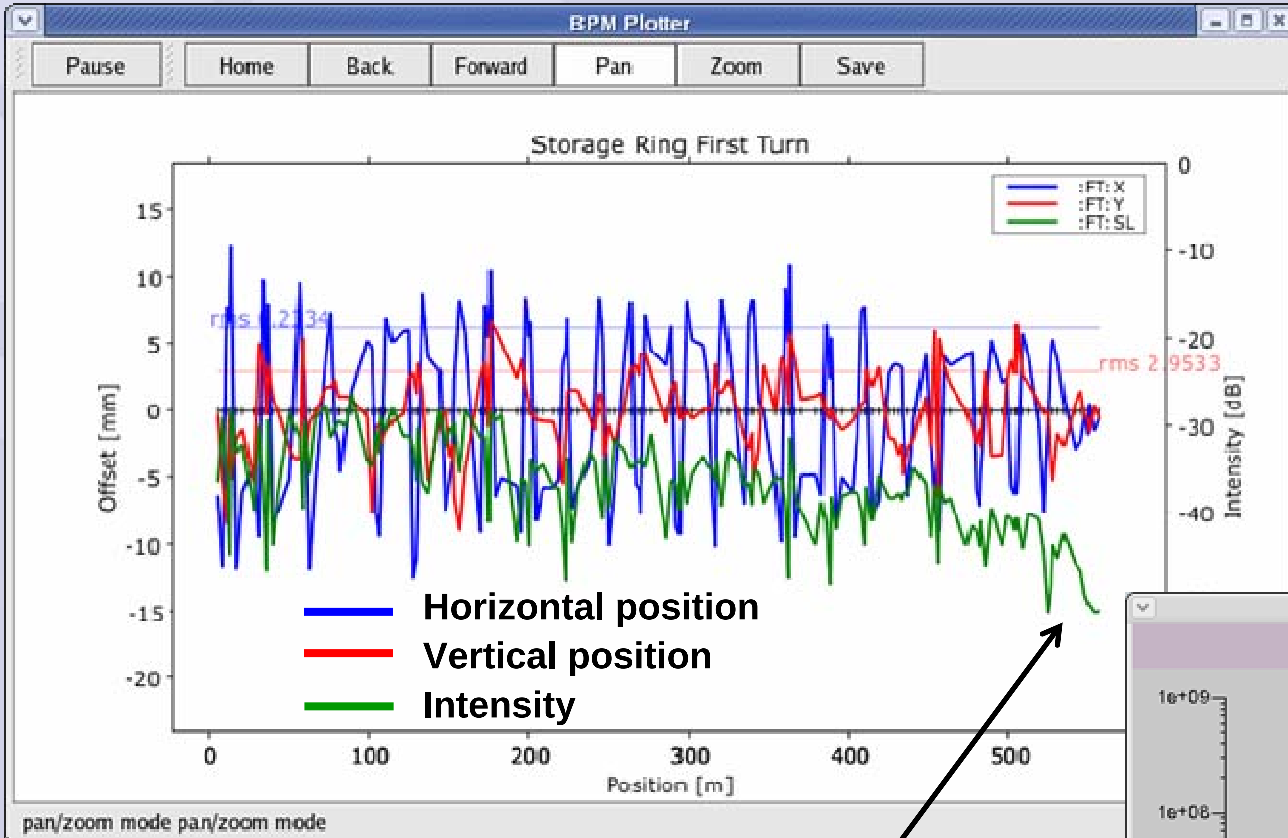
Problem has now been solved by deriving 50 Hz from the timing system, independent of mains frequency.

Storage Ring Commissioning: Phase I - 700 MeV



May 3rd/4th:

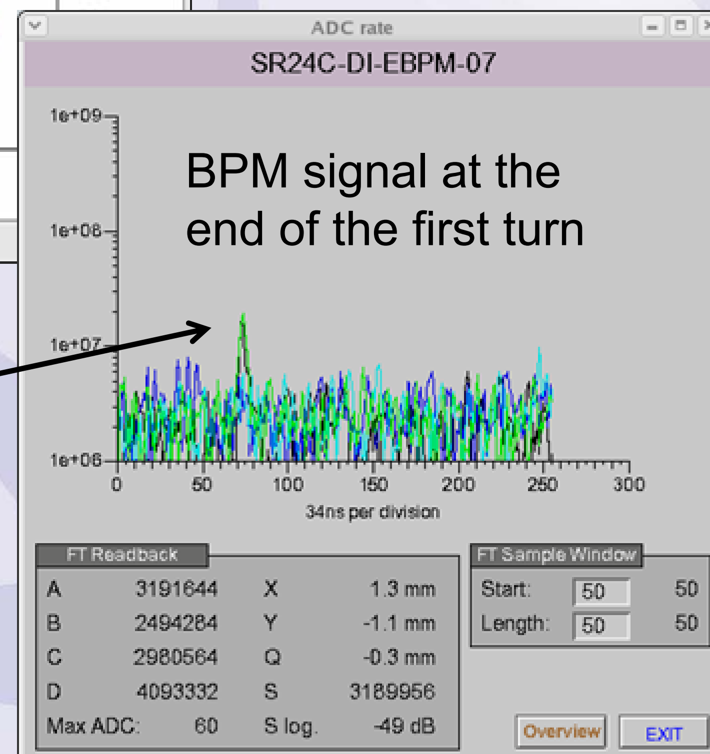
First beam in the storage ring – immediately after the septum



May $4^{th}/5^{th}$:

First turn !

<u>Correctors off</u>

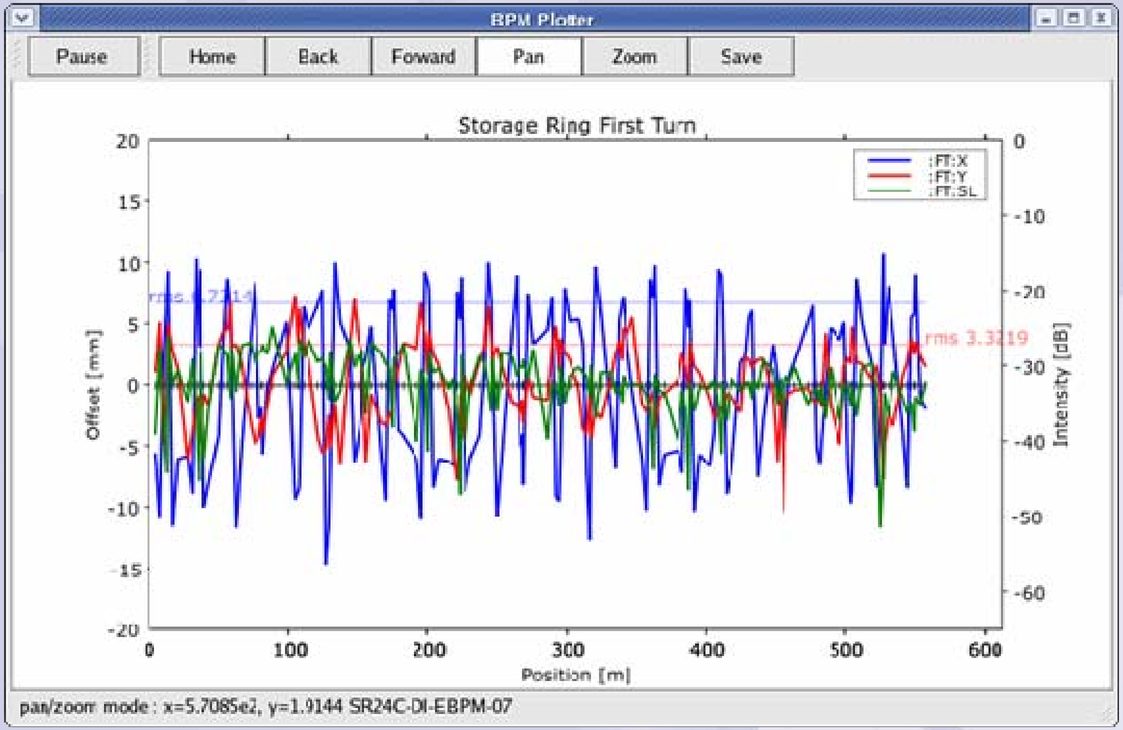


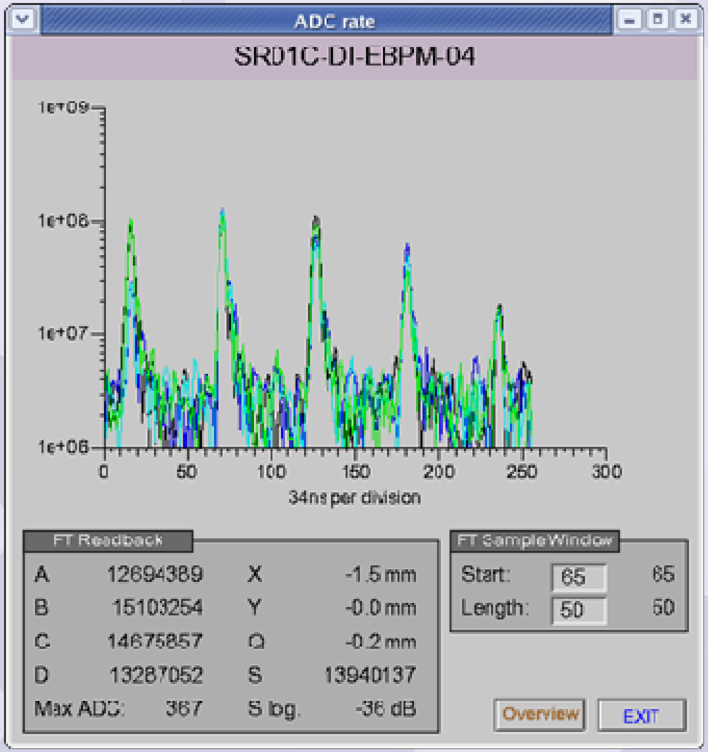
BPM signal at the end of the first turn

low intensity due to two quadrupoles with inverted polarity … but nevertheless..

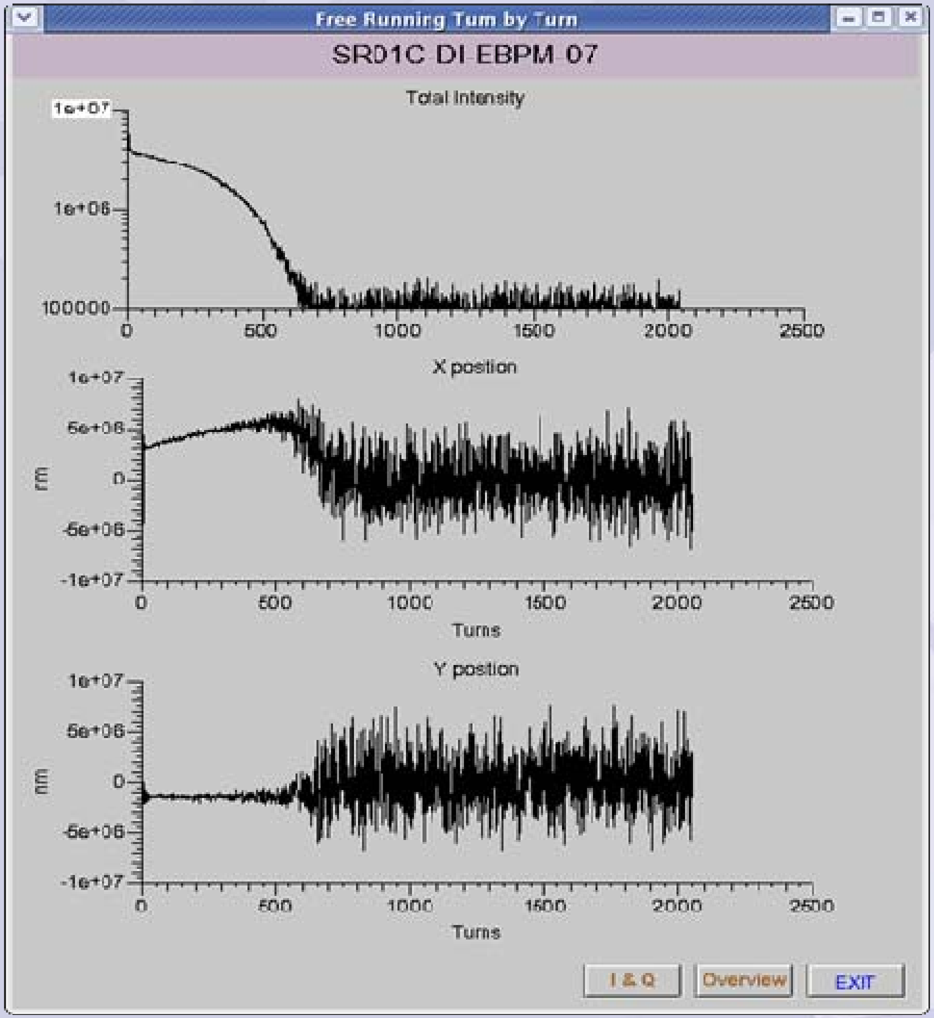
Celebrating the First Turn! – 03:00 May 5th 2006

May 5th/6th: 4 turns

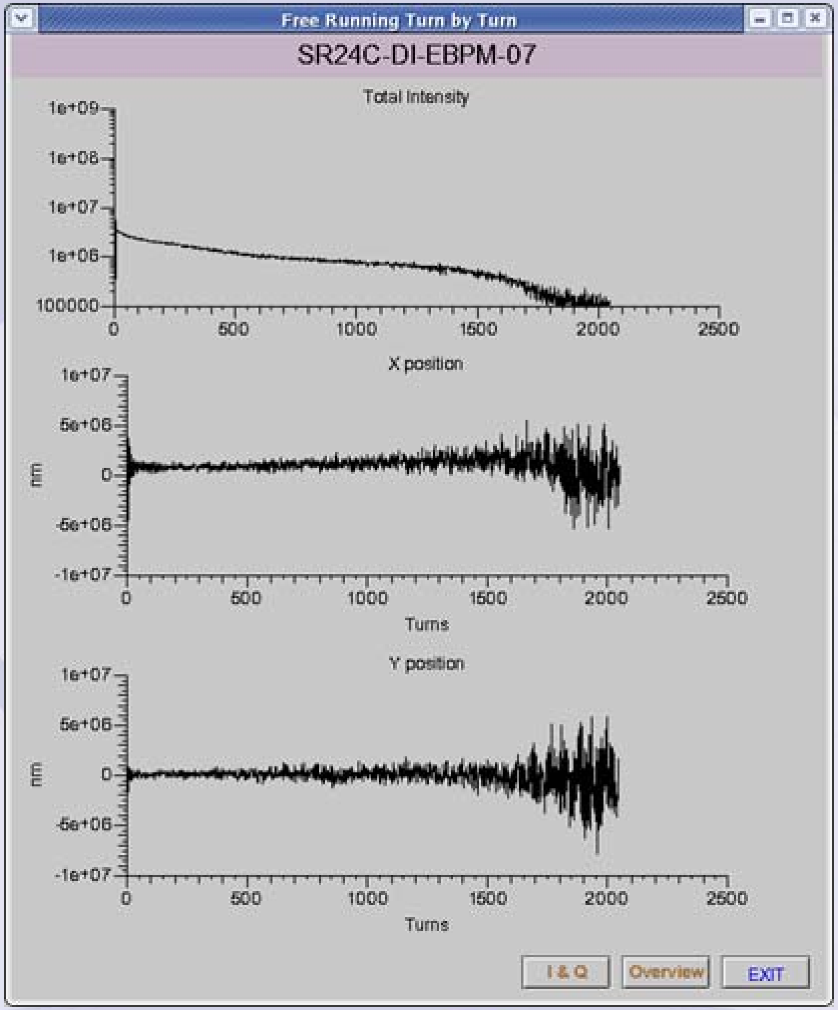




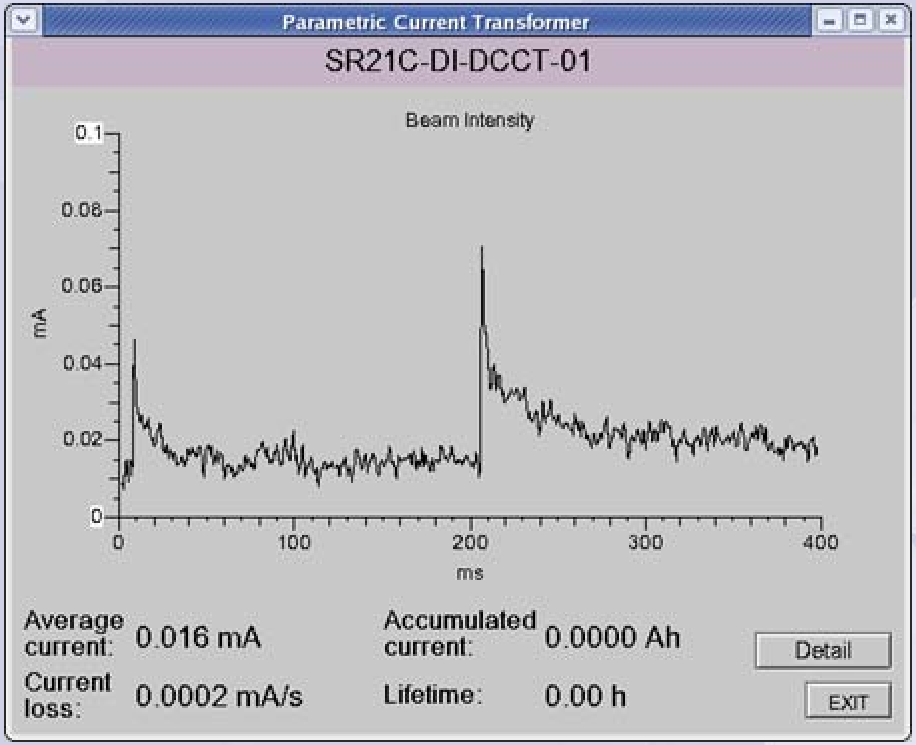
May 6th/7th: 600 turns (sextupoles off, RF off)



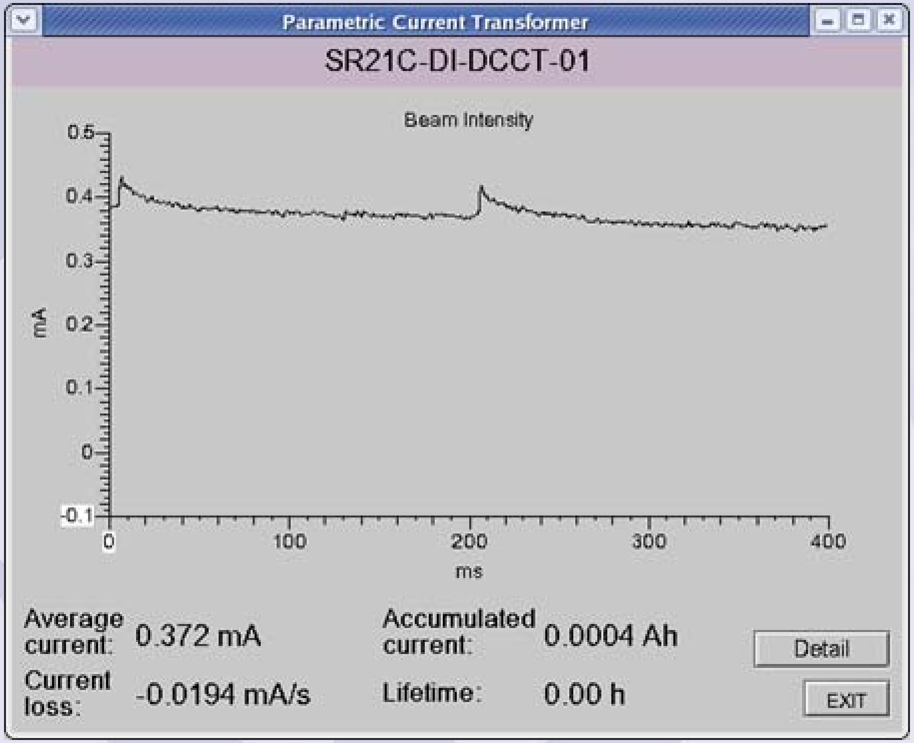
May 19th/20th: 2000 turns (sextupoles on, RF off)



May 20th/21st:
106,764 turns !

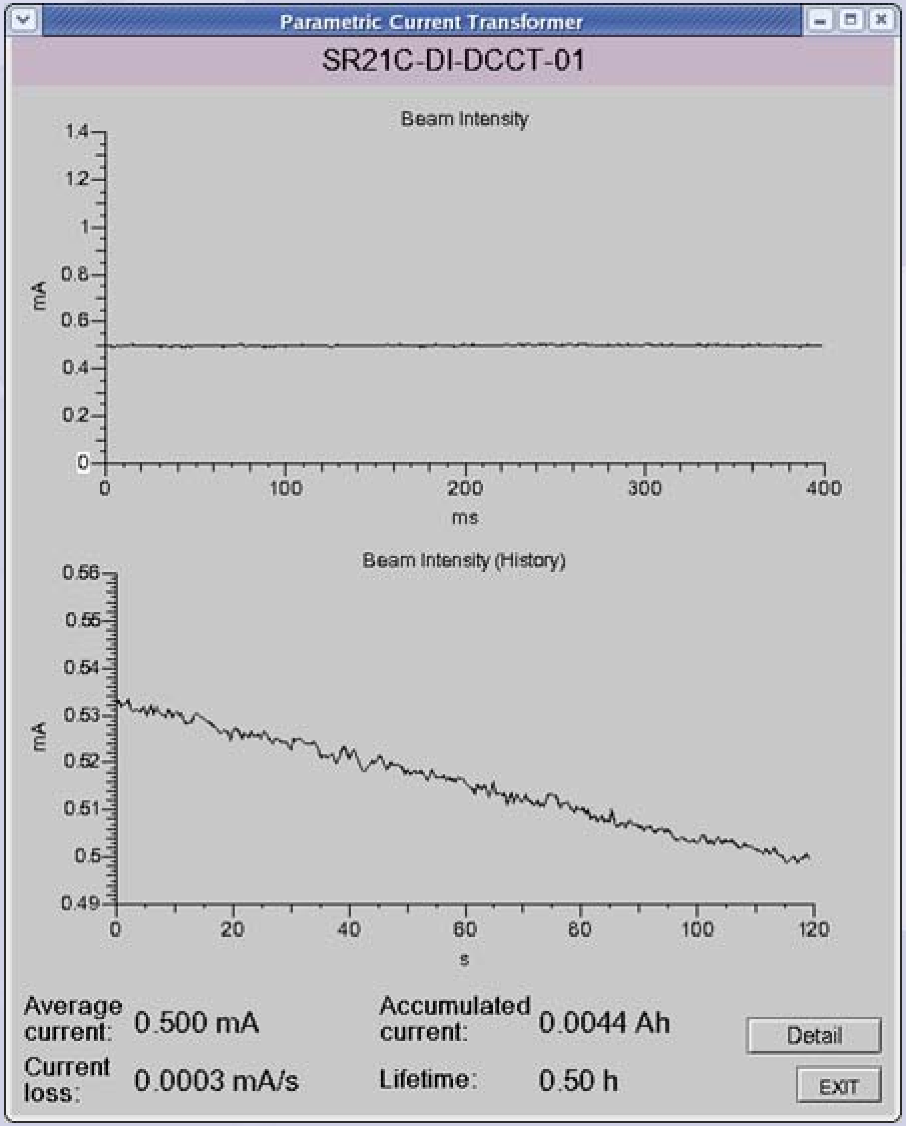


May 21st/22nd:
0.4 mA



diamond

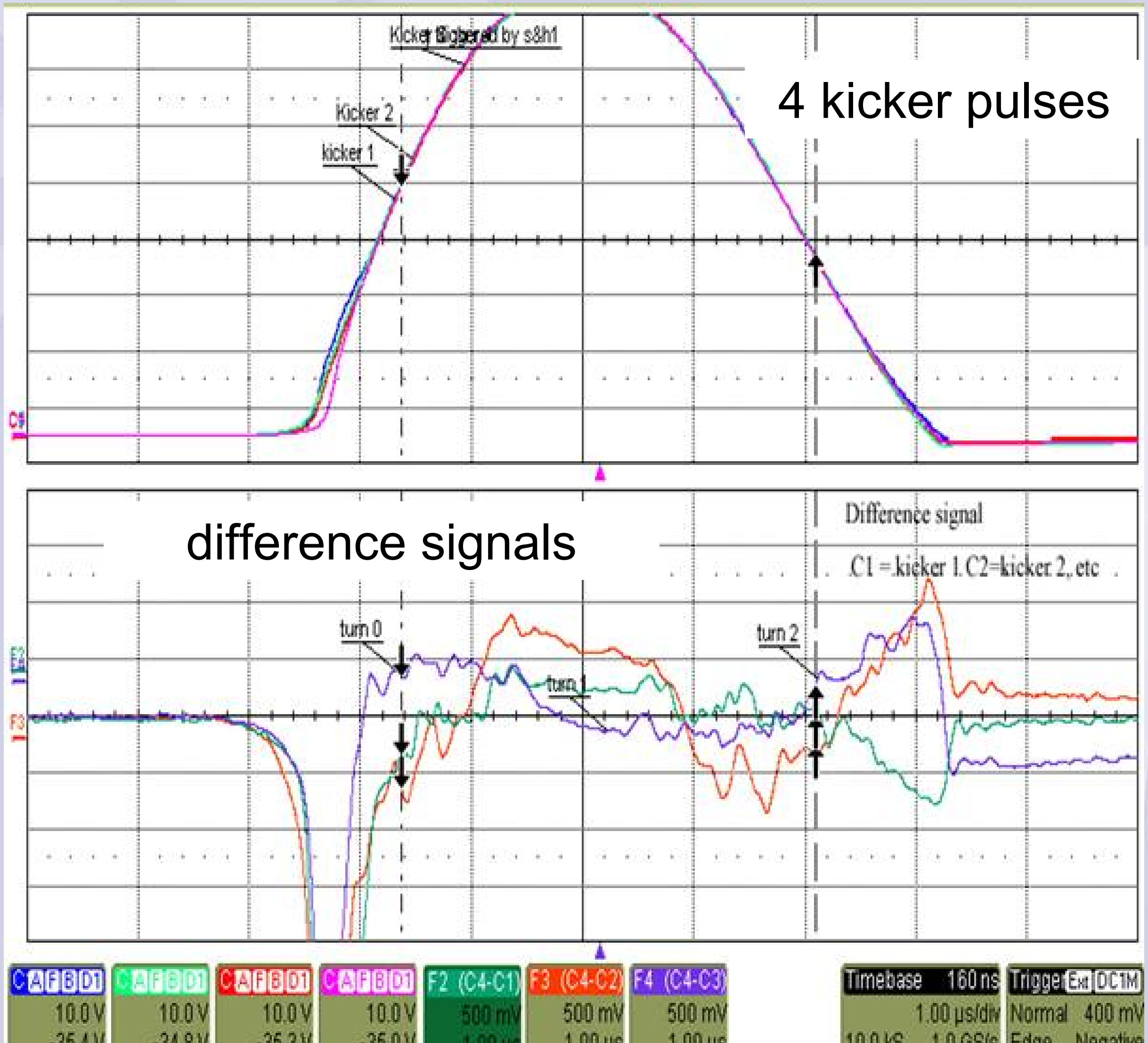
First stored beam ! …



0.5 hour lifetime at 0.5 mA

diamond

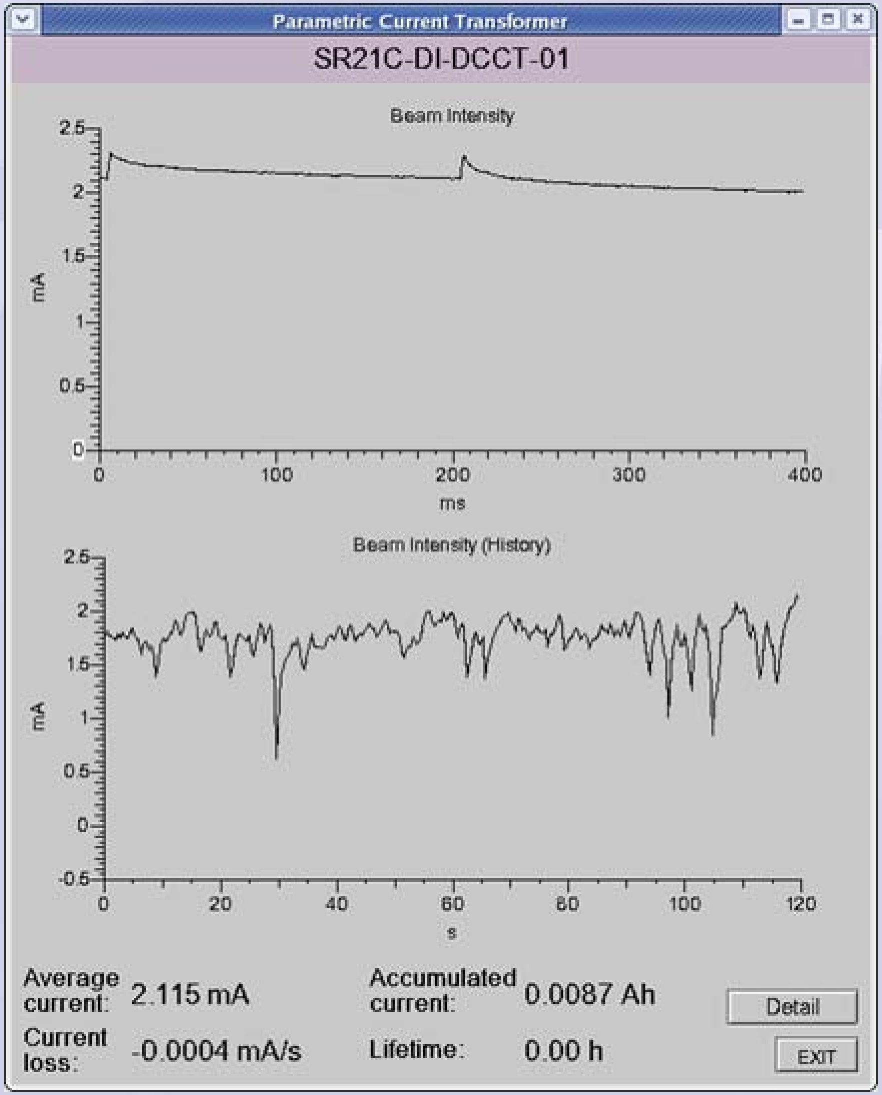
But initially the beam did not accumulate …



- believed to be due to differences between the kicker pulse shapes (which were not tuned for operation at 700 MeV)

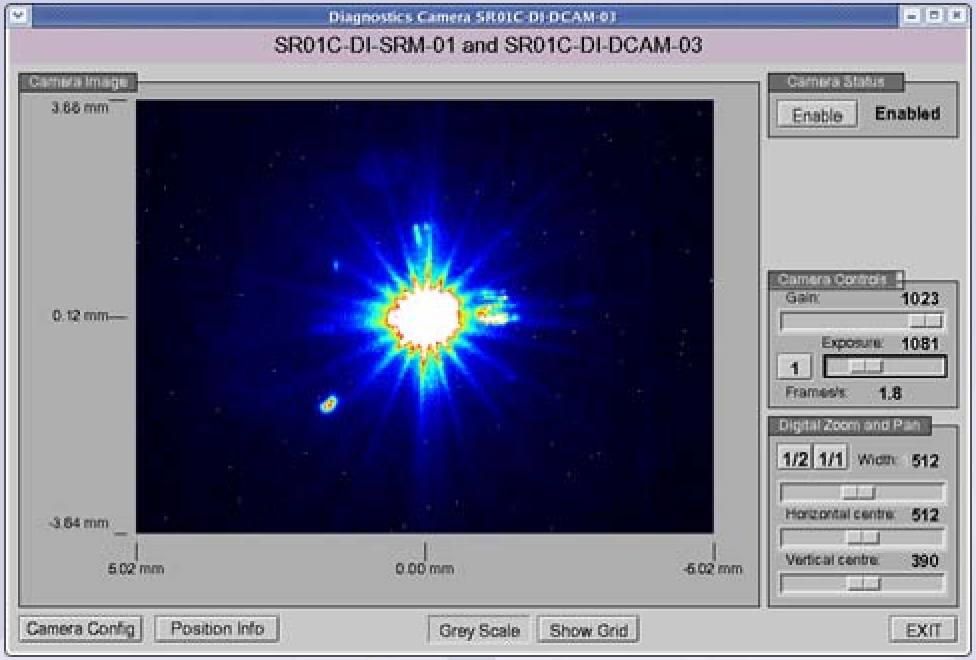
then after an "optimisation procedure" …..

> 2 mA "accumulated" .. but not easily

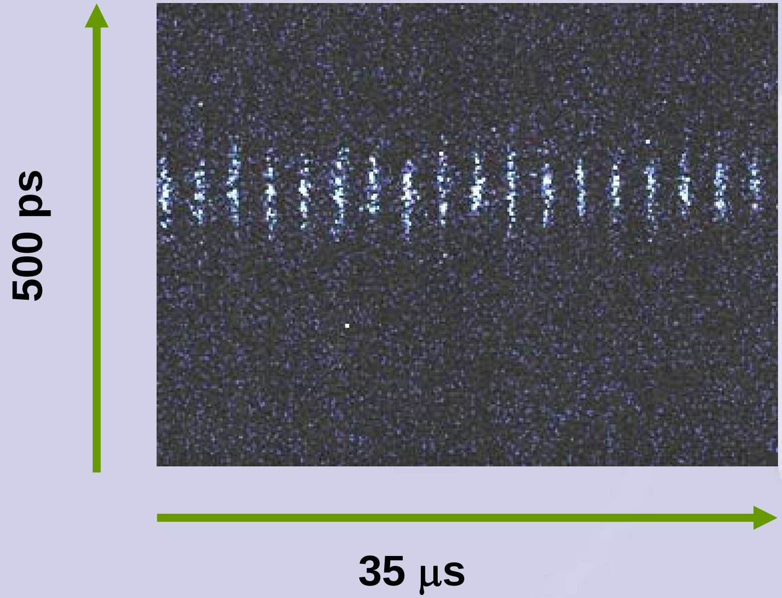


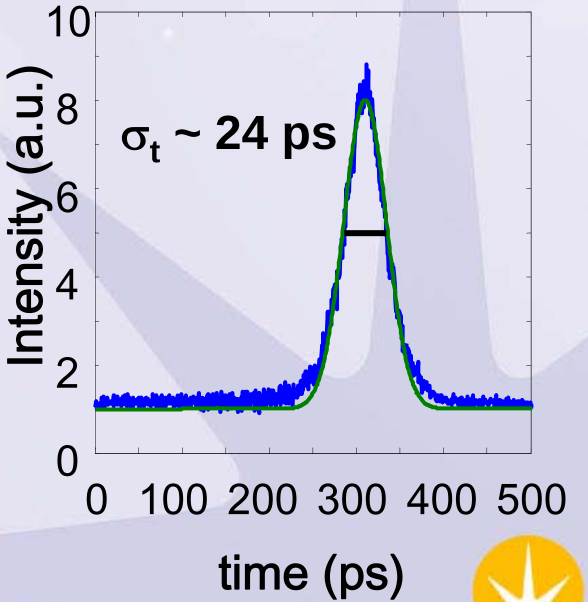
First Synchrotron Light !

- from the visible Synchrotron Light Monitor



First use of the streak camera:





diamond

Storage Ring Commissioning: Phase II - 3 GeV

Sep. 4th/5th – 5 turns, no correctors !

Sep. 5th/6th – 120 turns, no RF on

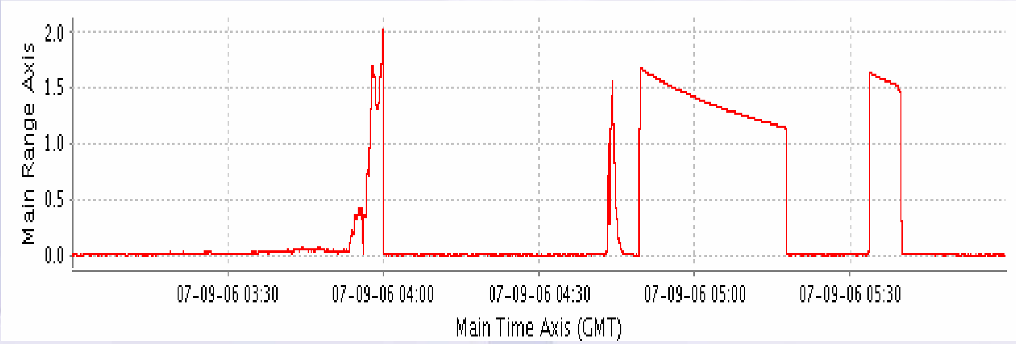
Sep. 6th/7th – RF on .. 2 mA stored;
(limited since absorber water flow interlocks not commissioned ..)

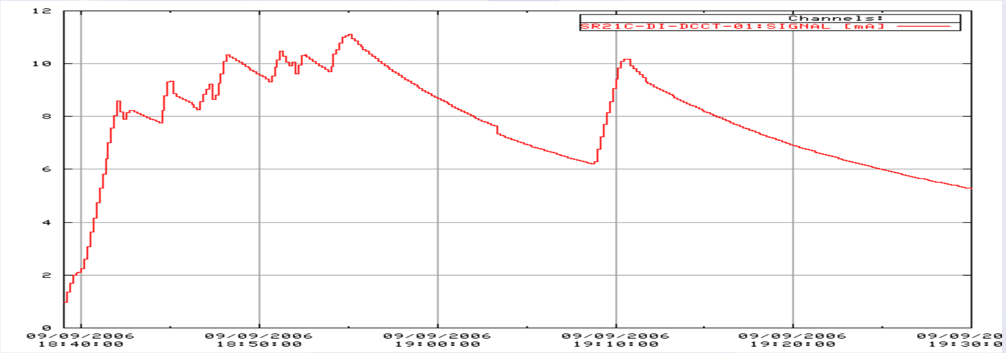
Sep. 9th – 10 mA;
(limited since orbit interlock not commissioned ..)

Sep. 25th – 25 mA

Oct. 2nd – 60 mA

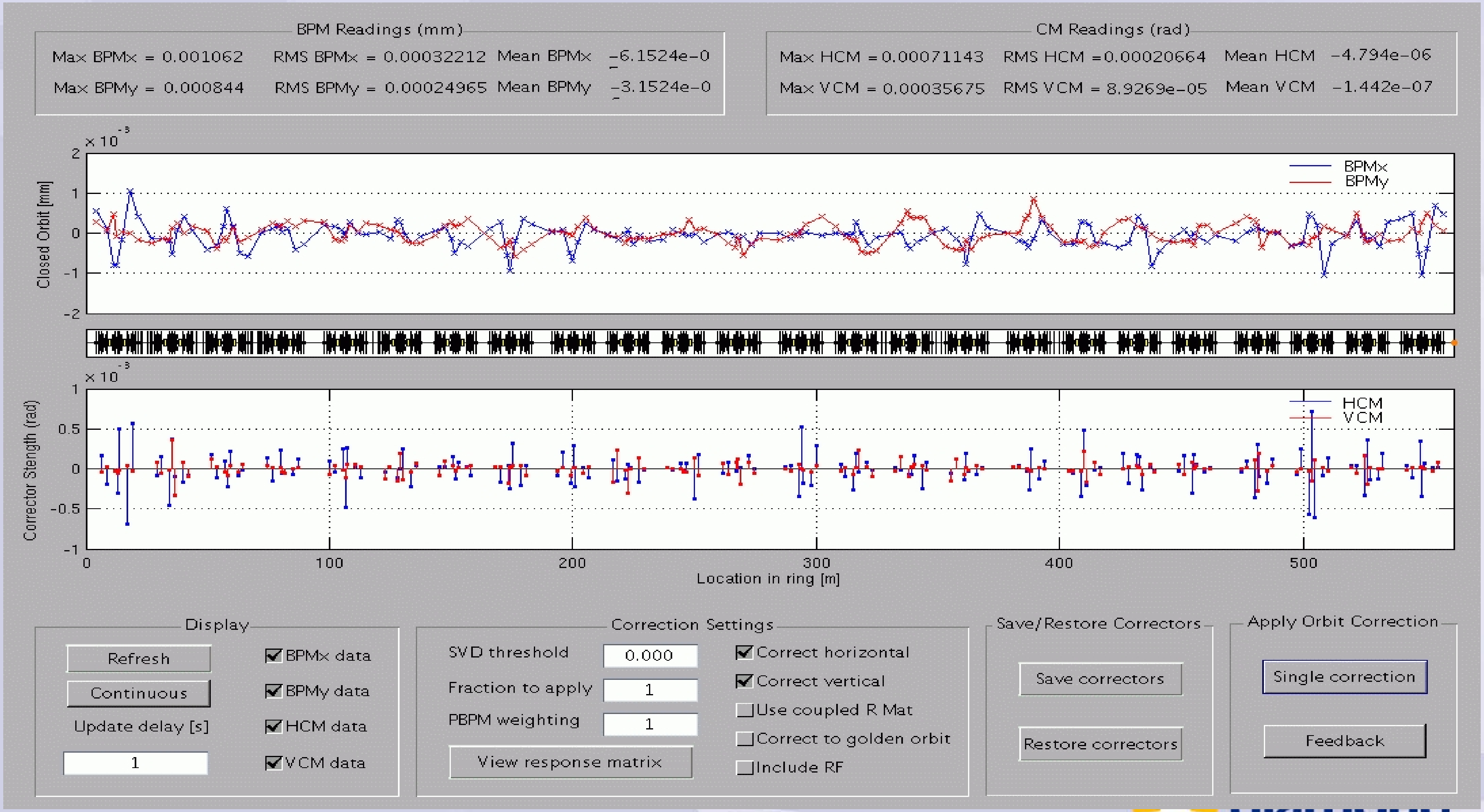
Oct. 10th – 90 mA



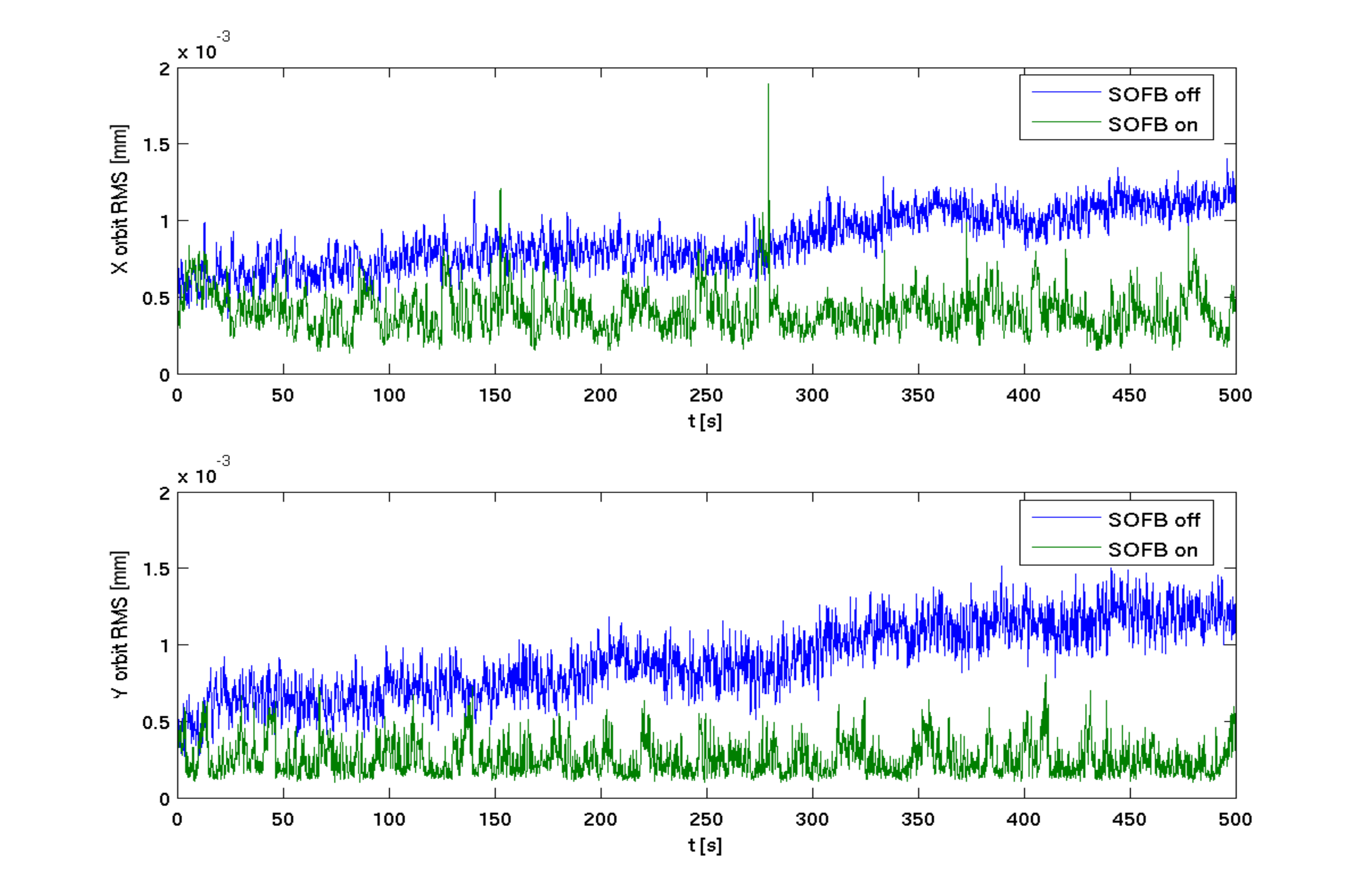


Closed Orbit

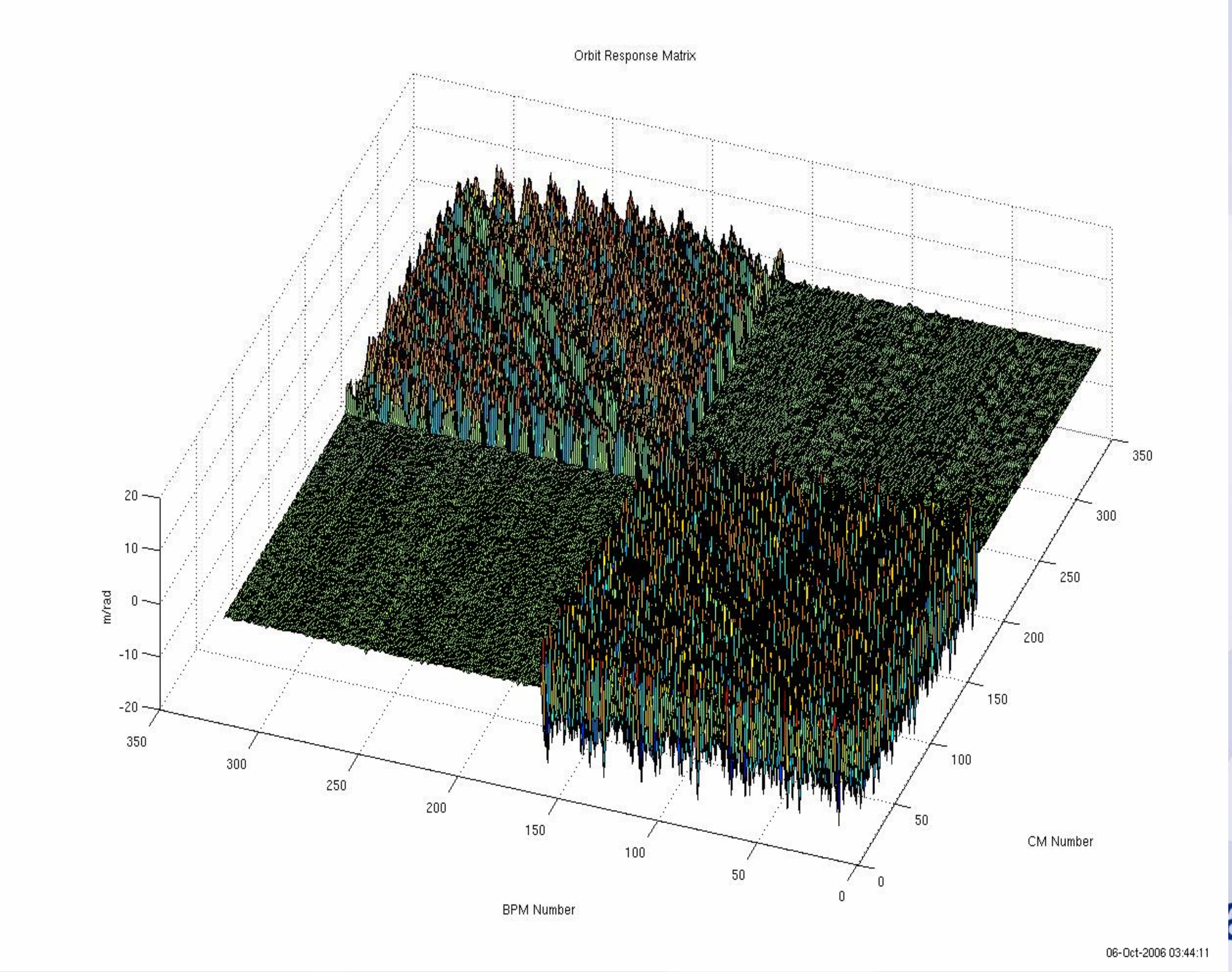
Following Beam Based Alignment, the closed orbit has been corrected to the 1 μm level at the BPMs …



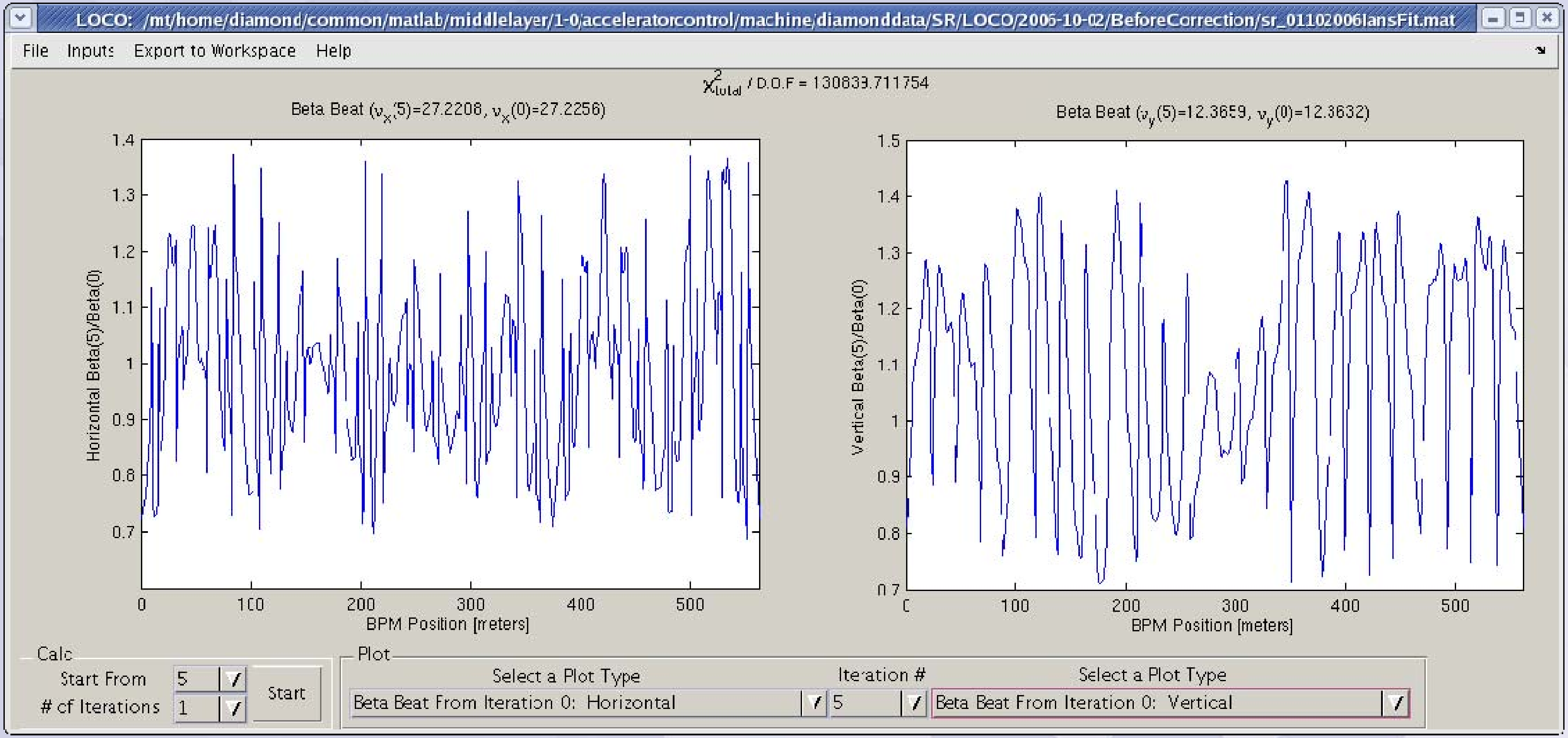
… and is maintained using Slow Orbit FeedBack (SOFB)



Optical functions measured and corrected using the response matrix technique and "LOCO".

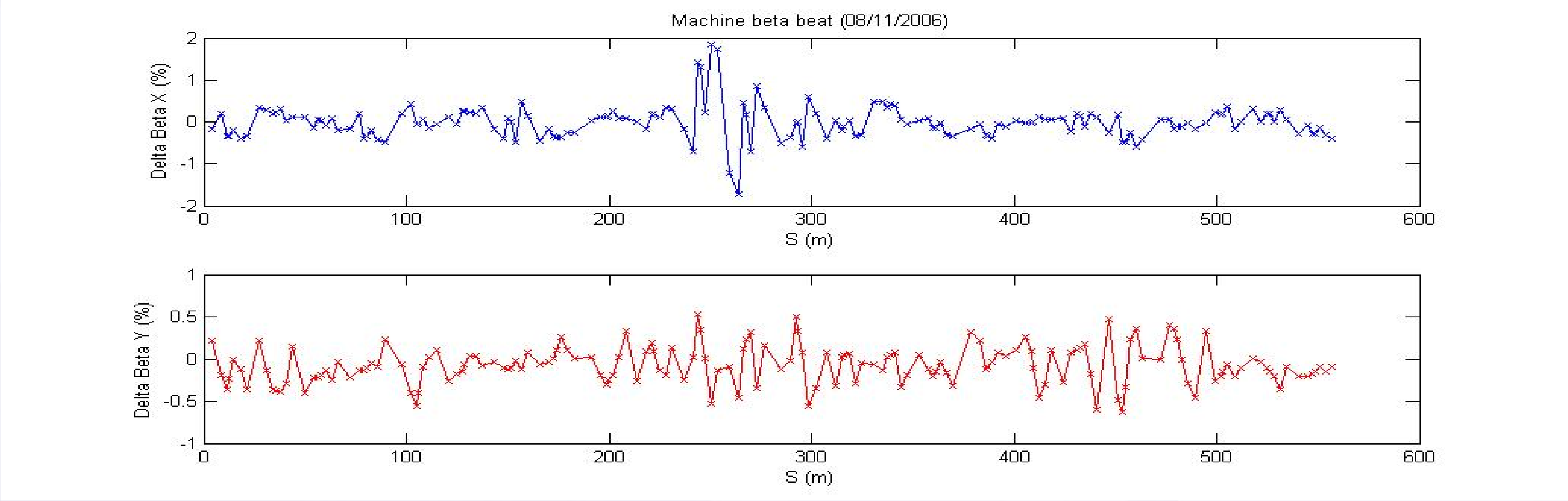


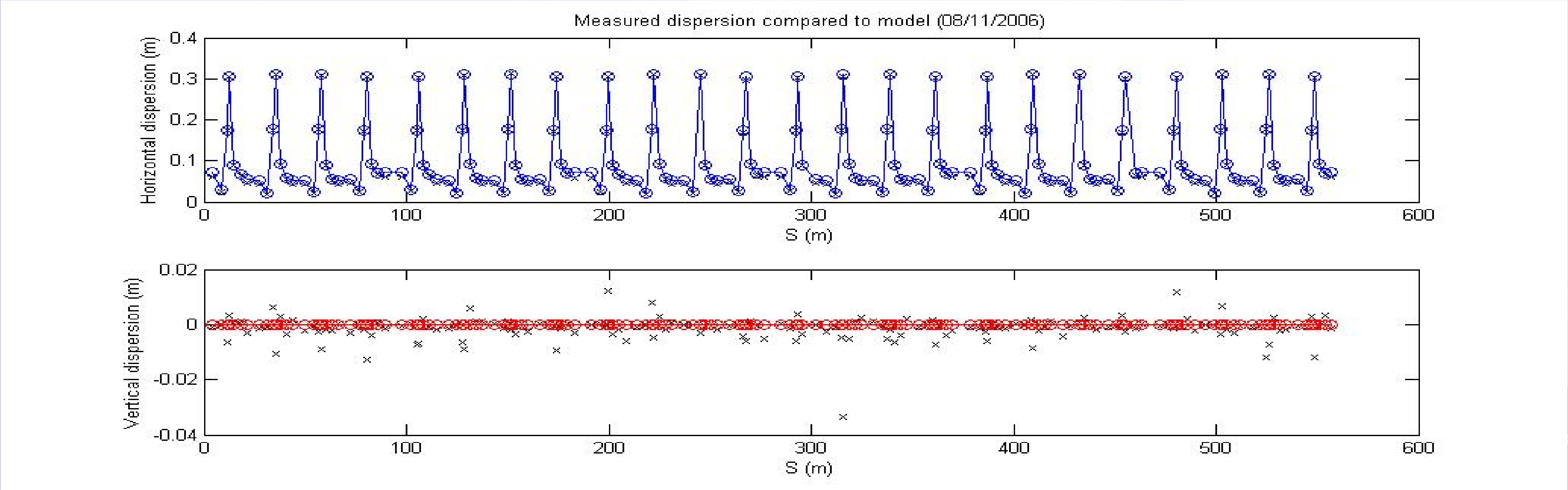
Optical functions before correction:



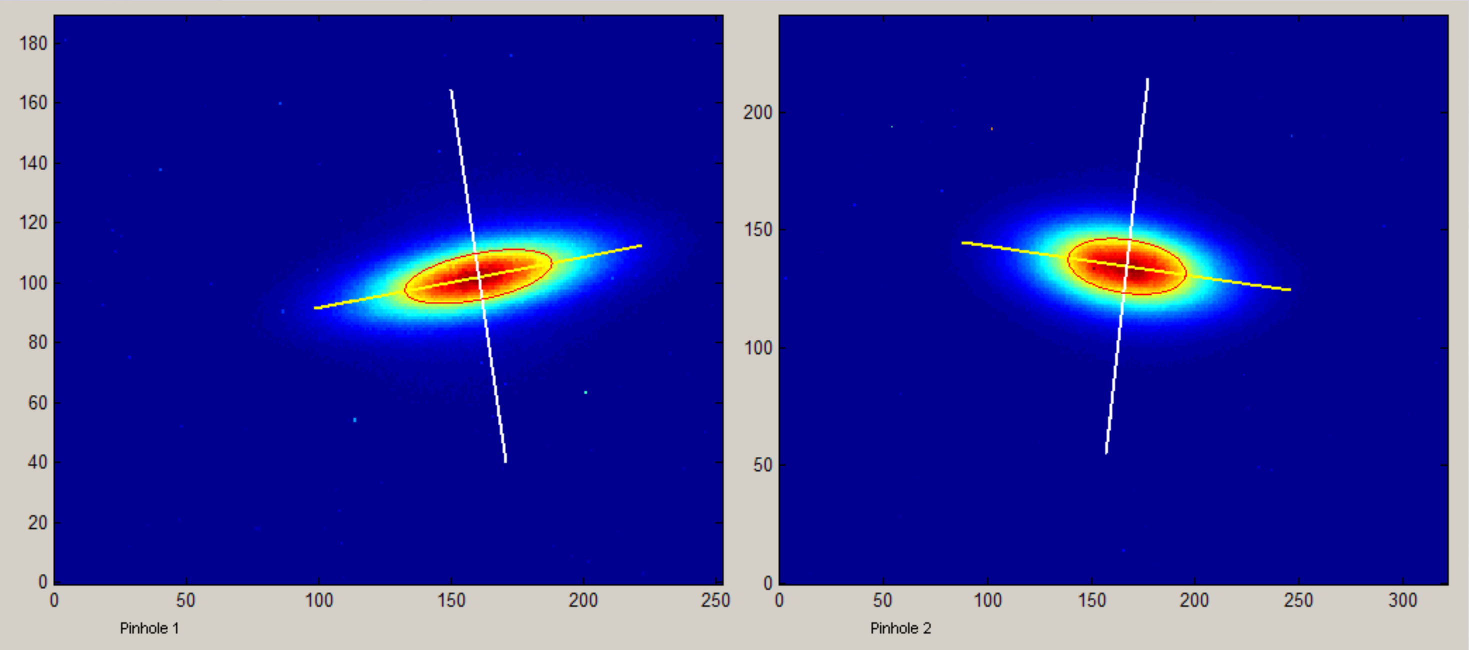
- errors in the beta functions up to 40%

Optical functions after correction:





Measured beam sizes and emittance (from two X-ray pinhole cameras)



Pinhole camera #1	nominal:	Pinhole camera #2	nominal:
sigma-x = 56 μm	52 μm	sigma-x = 47 μm	45 μm
sigma-y = 14.5 μm	25 μm	sigma-y = 19 μm	25 μm

Best fit: emittance 3.2 nm, energy spread 0.012%, coupling 0.4%

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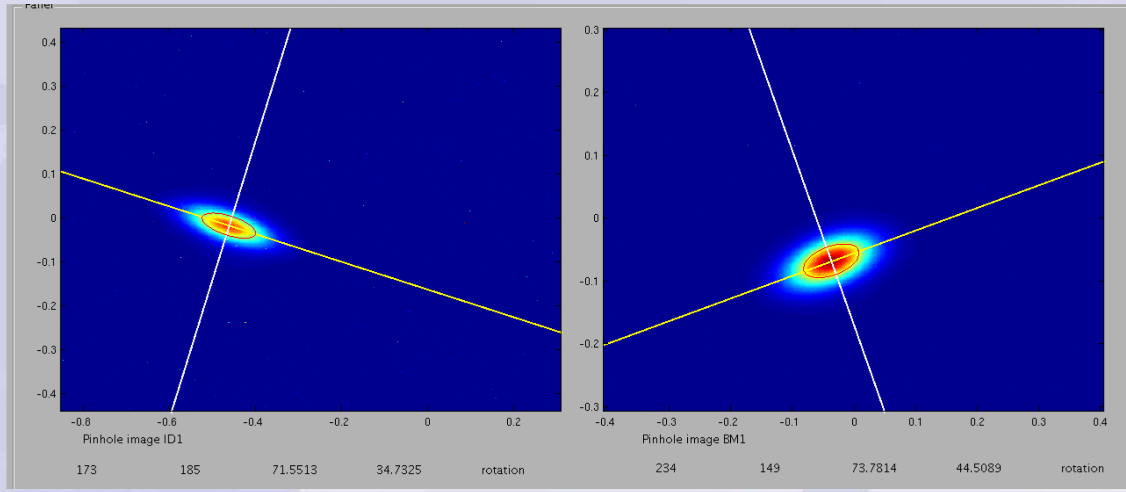
Coupling correction using skew-quadrupoles

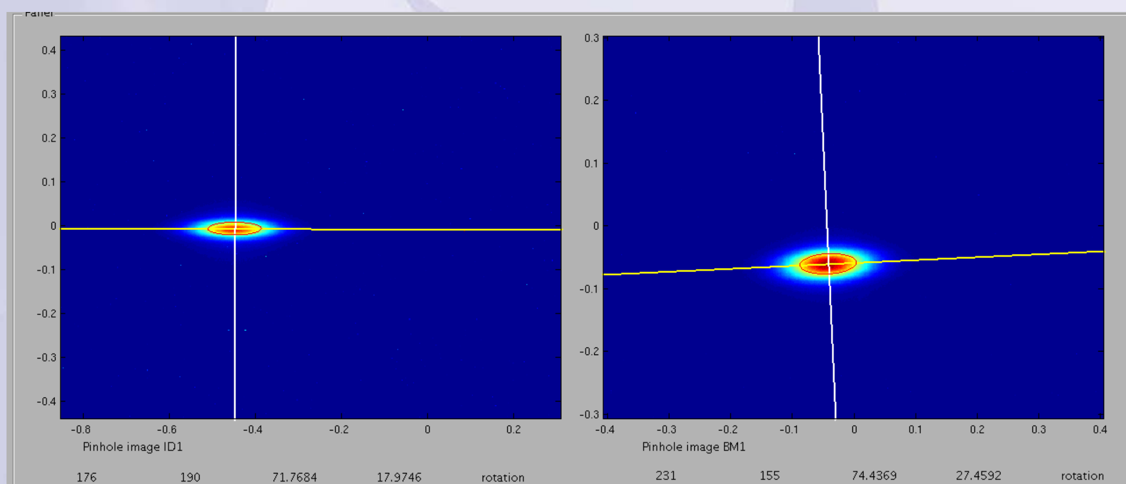
before correction

K = 0.4%

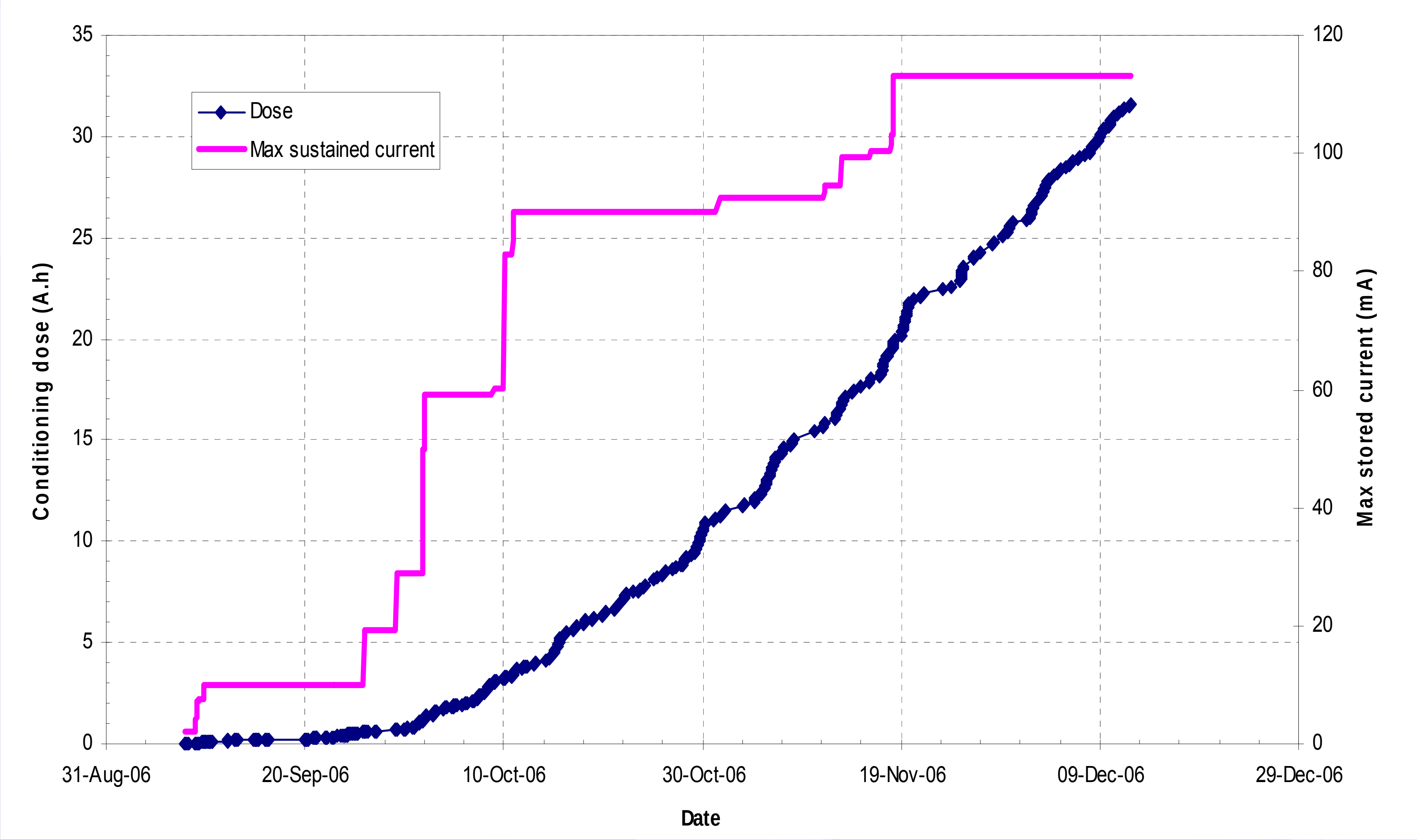


after correction

K = 0.04%



Storage ring vacuum conditioning progress



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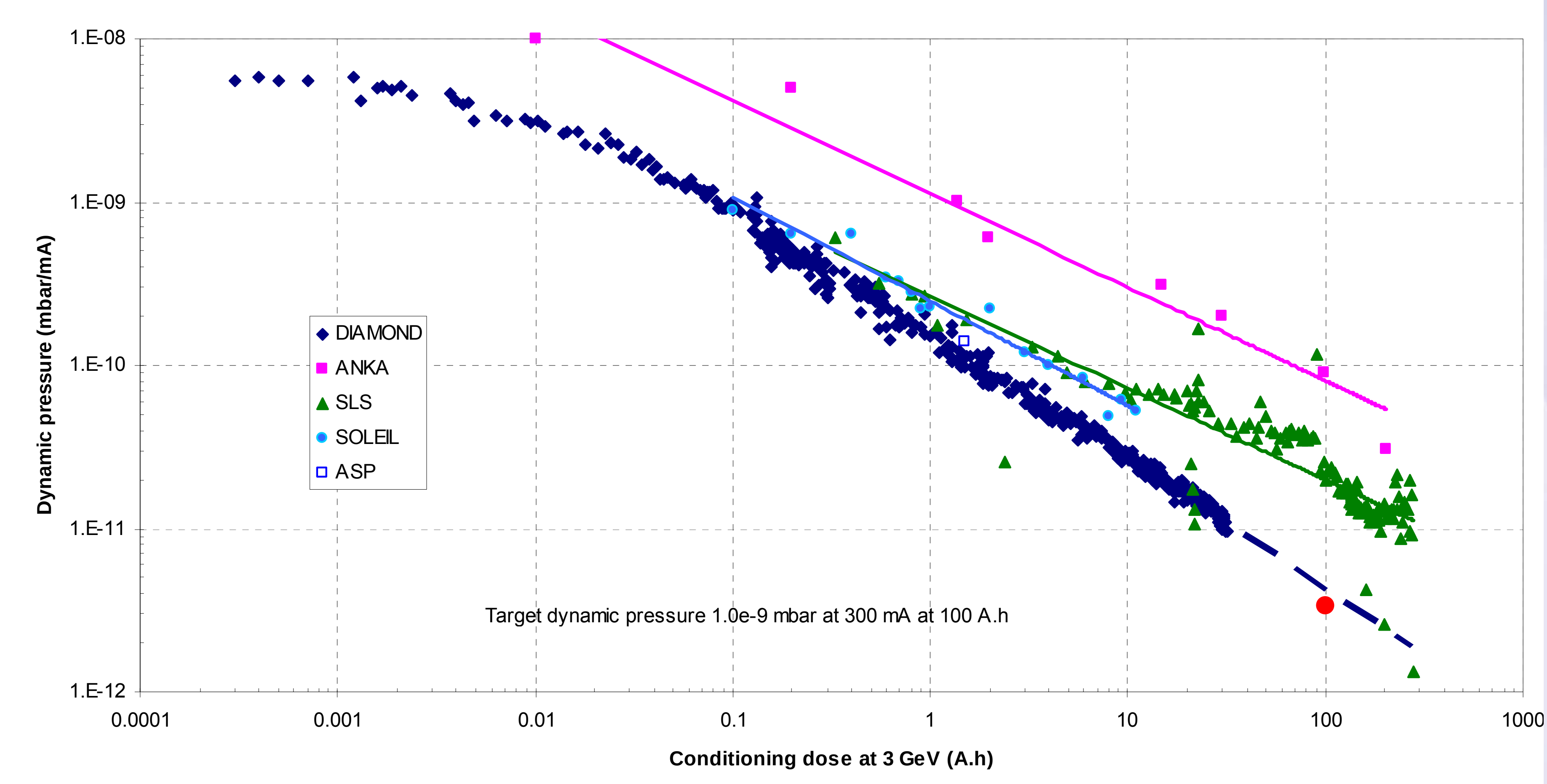
Dynamic pressure vs. “dose”



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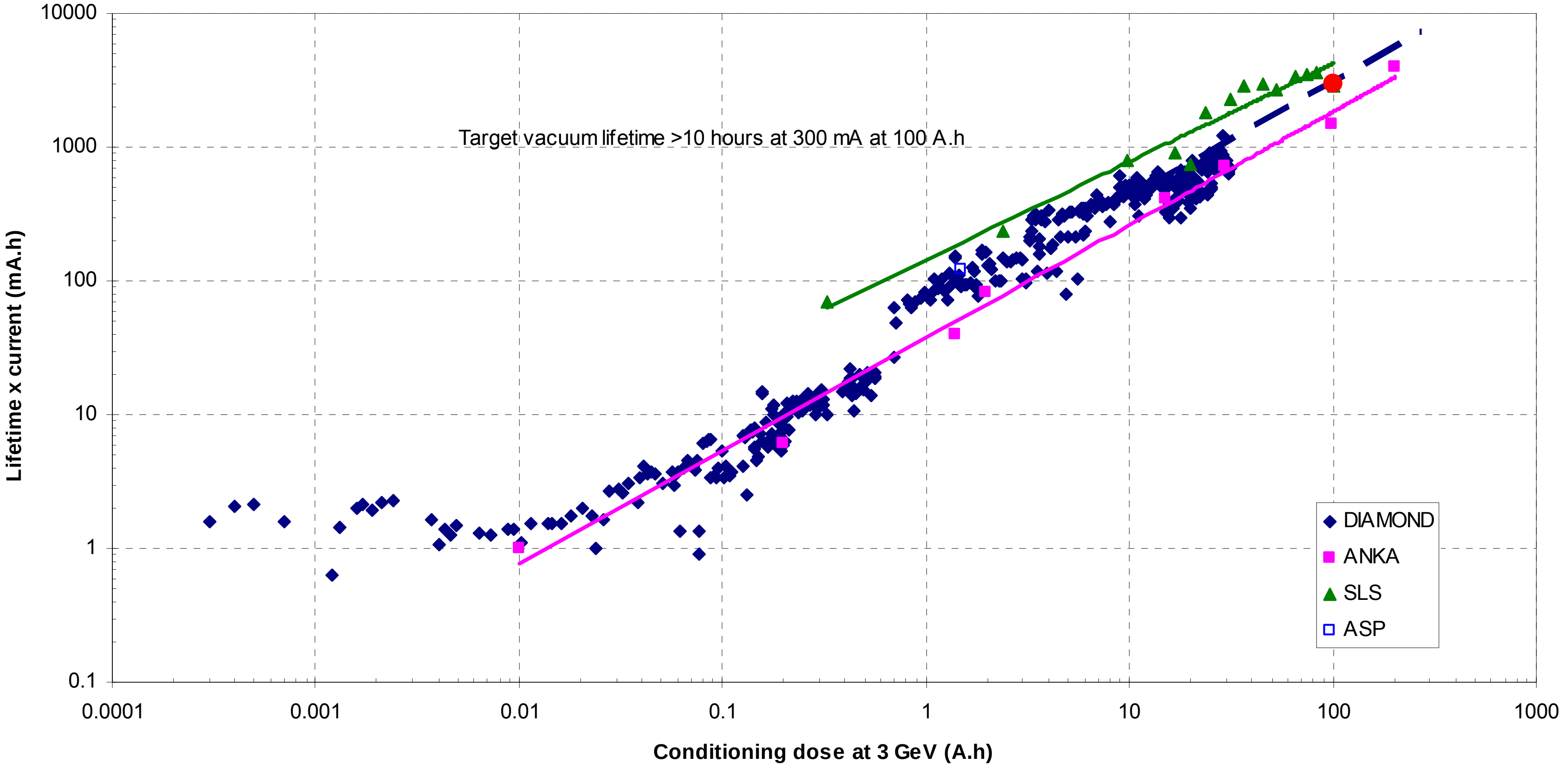
Beam lifetime vs "dose"



Machine Status Summary

- All systems working; reliability so far is good
- 125 mA achieved
  Closed-orbit and optics well corrected
  Good injection efficiency
  Measured emittance close to nominal
- All 7 Insertion Devices commissioned with beam
- Vacuum conditioning progressing in line with expectations
- 24h/day operation, and regular beamline commissioning shifts, have started.

Future Plans, and Possibilities

2007 (*definitely*):

- **3000h of User Mode**
- **Install 3 more Insertion Devices and Front-Ends**
- **300 mA, 10 h lifetime by end of September**
- **implement Fast Orbit Feedback**
- **implement Transverse Multibunch Feedback**
- **prepare for Top-up**

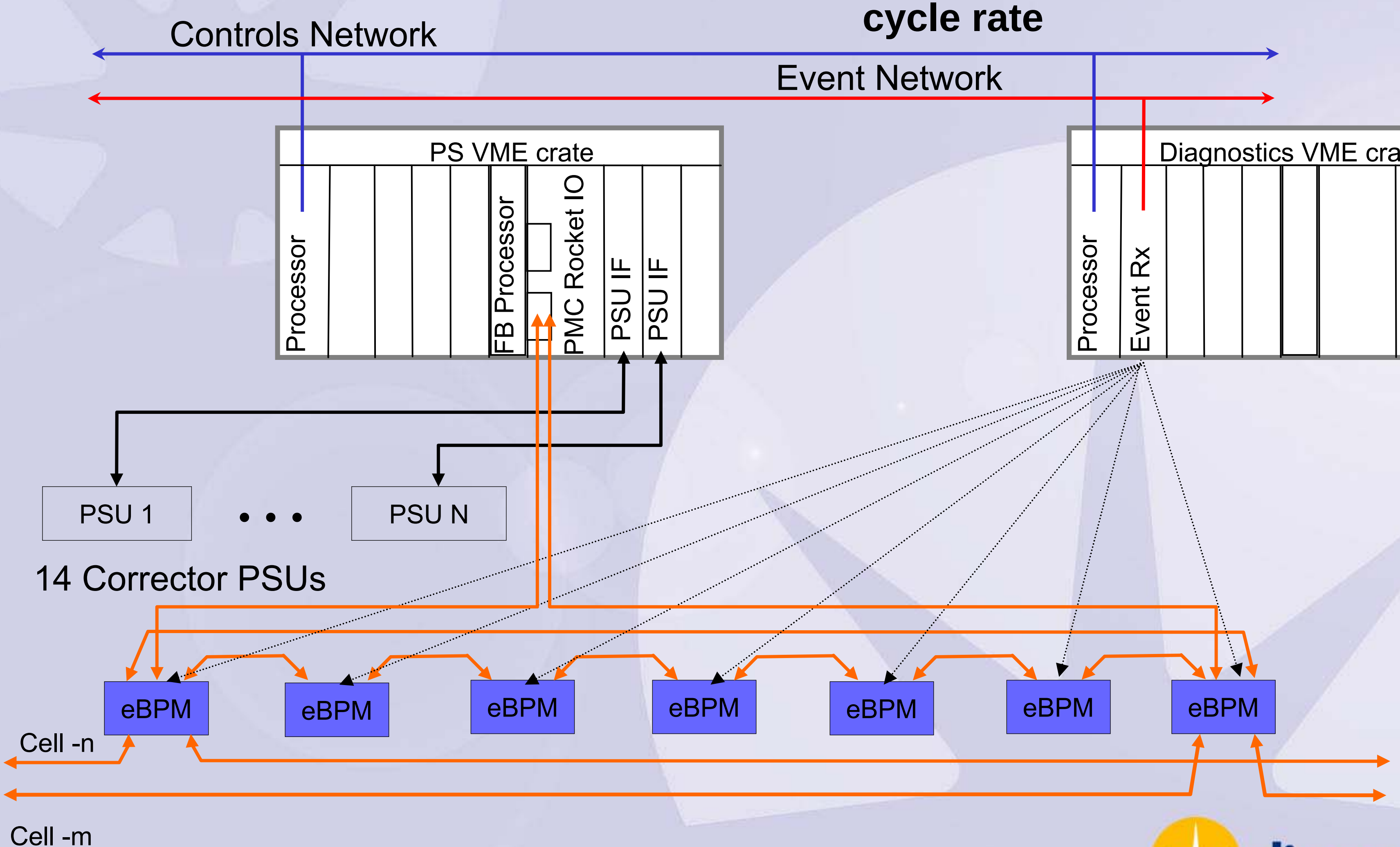
Later (*maybe*):

- **Cryo-cooled permanent magnet & Superconducting undulators**
- **3rd Harmonic cavity (bunch lengthening, and shortening)**
- **Short pulses: various options being considered – "low-alpha" optics, crab cavities, etc.**

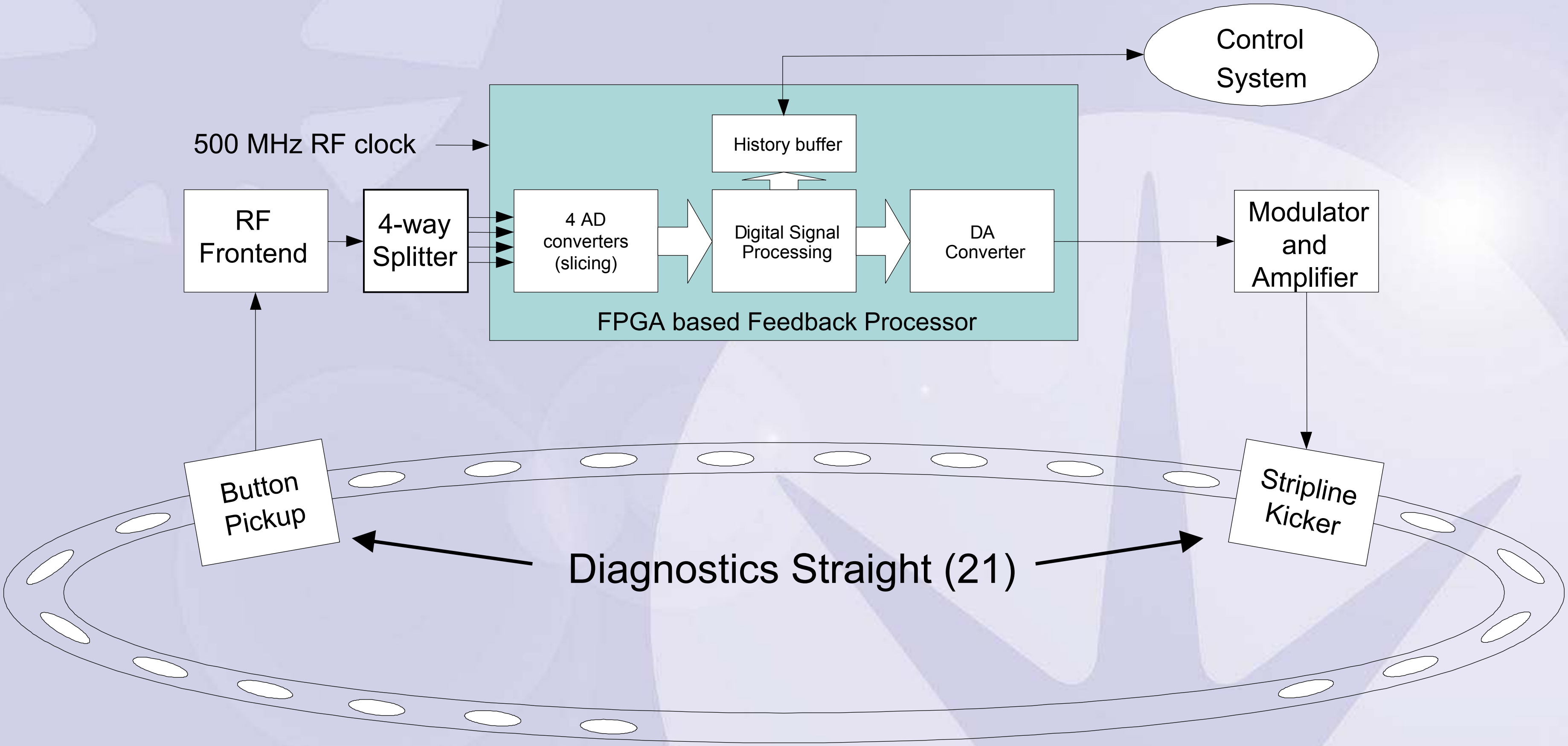
diamond

Fast Orbit Feedback

This implementation will allow full global functionality, with high level of fault tolerance, at 10 kHz cycle rate



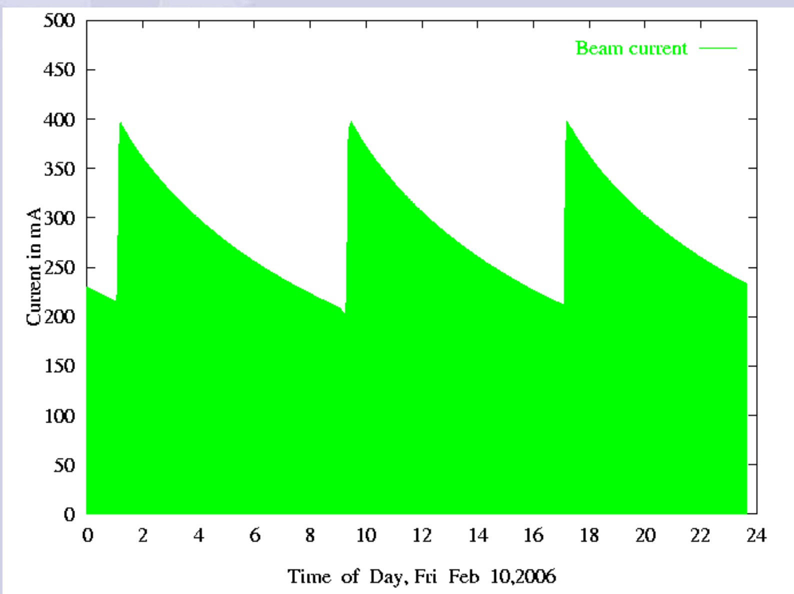
Transverse Multibunch Feedback



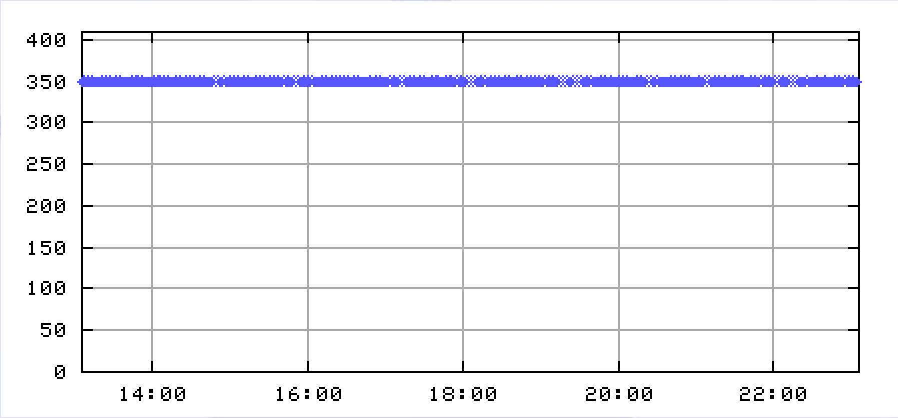
Top-up Operation

<u>Usual operation</u> for the majority of Synchrotron Light Sources: injection at intervals of 8-24 h, with beam decay in between:

Beam current



<u>Top-up mode</u> that will be used for Diamond, keeping the beam current constant (as at APS, SLS, Spring-8), providing increased average intensity, and better beam STABILITY:



Time

Short pulses: "low-alpha" mode

$$\sigma_z = \frac{\alpha c}{2\pi f_s} \sigma_\varepsilon \propto \sqrt{\frac{\alpha \gamma^3}{dV_{RF}/dz}}$$

bunch length

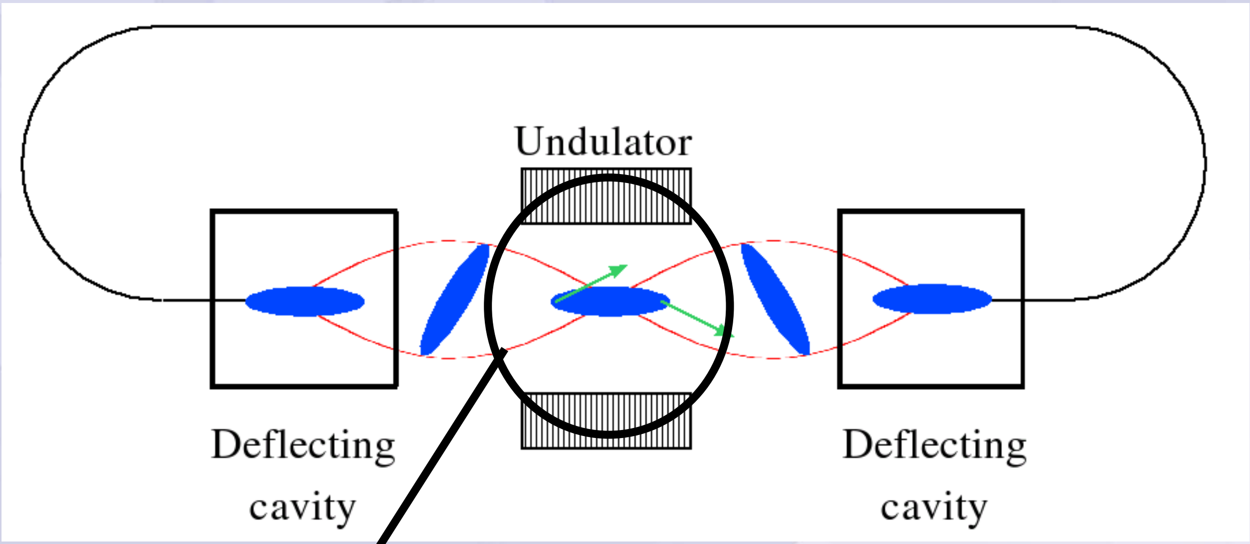
momentum compaction factor

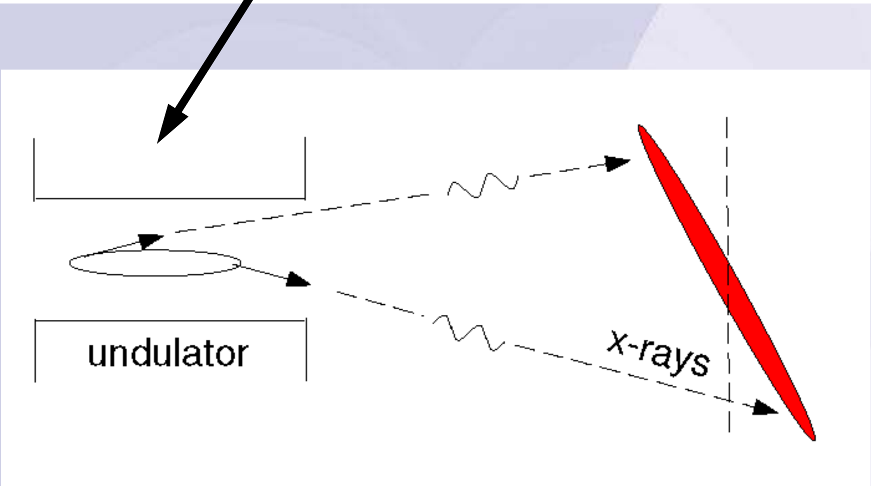
α (normal, $1.7 \cdot 10^{-4}$) → σ_z = 2.8 mm (9.4 ps)

α (low-alpha optics) $\approx 10^{-6}$ → $\sigma_z \approx$ 0.3 mm (1 ps)

I_b (mA)	Normal	Low α
0.01	10 ps	1 ps
1.0	13 ps	12 ps
10.0	25 ps	25 ps

Short pulses: Crab-Cavities †





Preliminary studies* show the feasibility of the crab-cavity scheme to generate 1 ps pulses in Diamond.

*** in collaboration with K. Harkay, M. Borland, APS**

† **A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A425 (1999)**

diamond

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