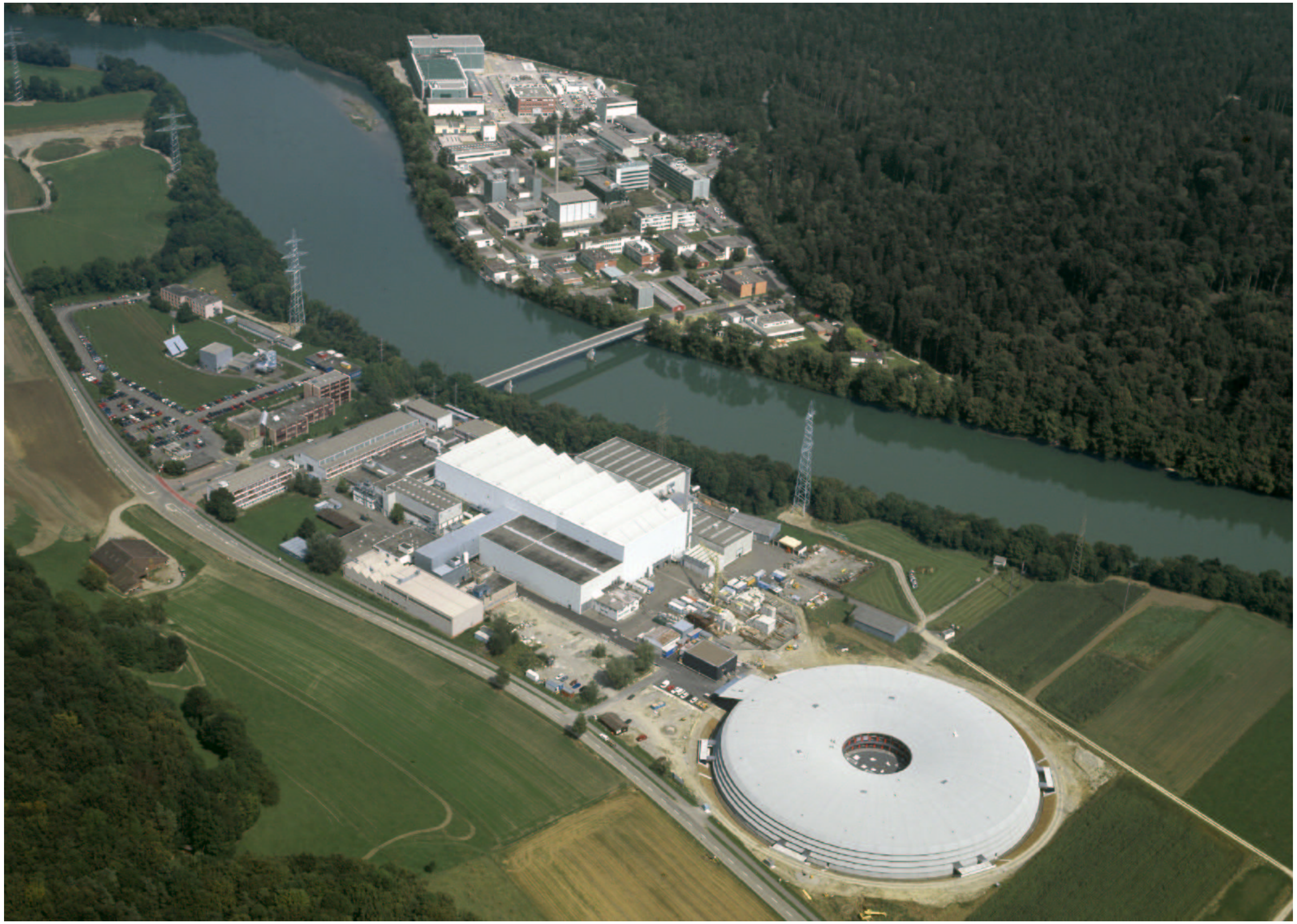
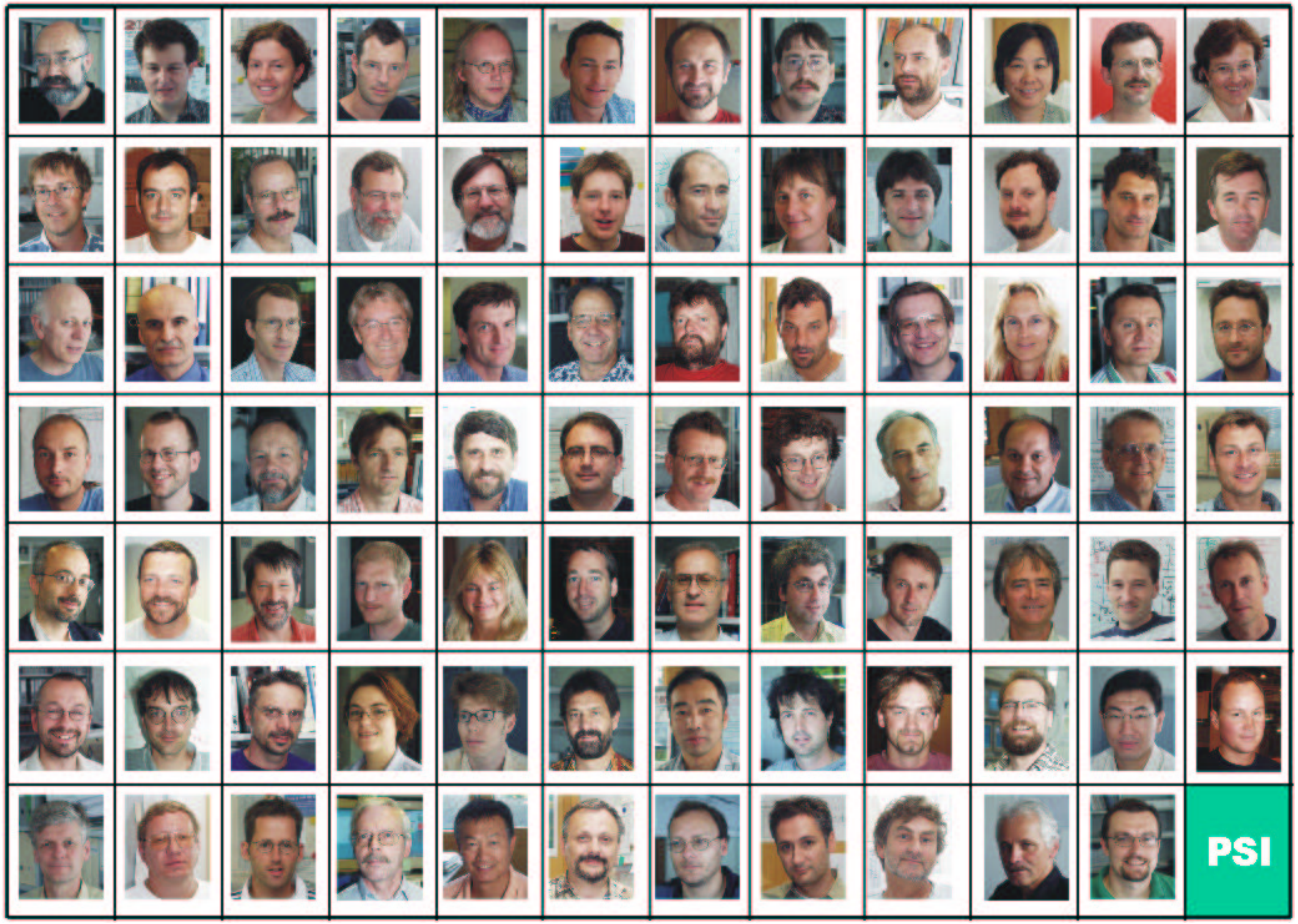
SLS at the Paul Scherrer Institute (PSI), Villigen, Switzerland



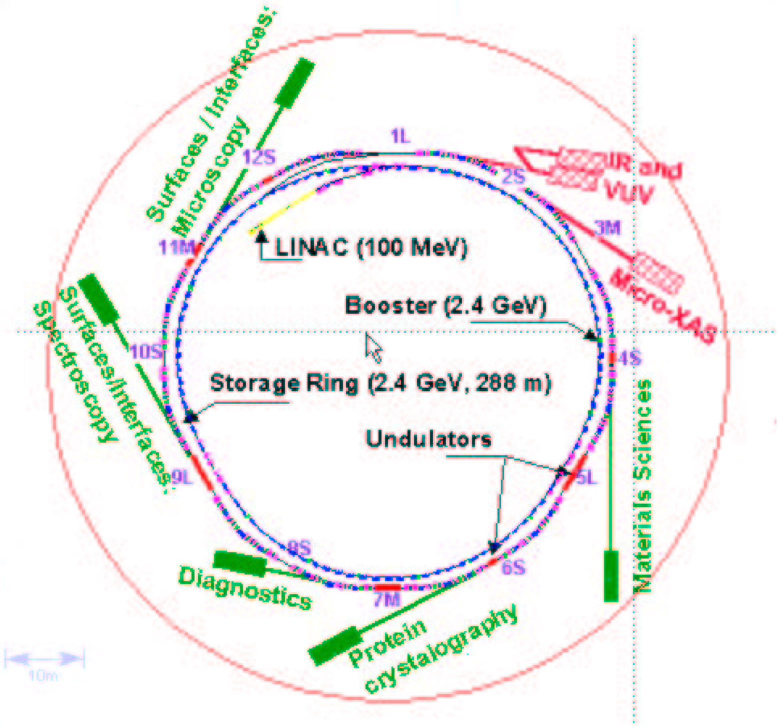
SLS Team at PSI



Contents

SLS Layout

- Pre-Injector Linac
  - 100 MeV
- Booster Synchrotron
  - 100 MeV to 2.7 GeV @ 3 Hz
  - ϵ_x = 9 nm rad
- Storage Ring
  - 2.4 (2.7) GeV, 400 mA
  - ϵ_x = 5 nm rad
- Initial Four Beamlines:
  MS – 4S, PX – 6S,
  SIS – 9L, SIM – 11M



SLS Time Schedule

Sep	1993	Conceptual Design Report
Jun	1997	Final Approval by Swiss Government
Jun	1999	Building Erected
Apr	2000	Linac Commissiong Finished
Sep	2000	Booster Commissiong Finished
Dec	2000	First Stored Beam in Storage Ring
Jun	2001	Design Current of 400 mA reached First Top-up Operation
Jul	2001	First PX Experiment
Aug	2001	70 % User Operation
May	2002	500 Ah Integrated Beam Current

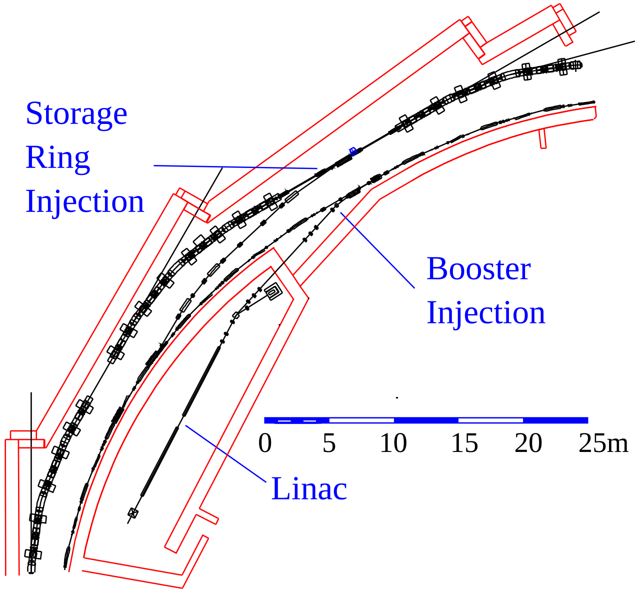
SLS Budget

in MCHF (1 CHF = 0.69 EUR)

Total Project Budget	159	159	without salaries
Building	63	63	“turn key” with infrastructure
Accelerators	planned	spent	
General	12	11	
Linac	6	6	
Booster	12	11	
Storage Ring	42	40	
Total	96	92	4 for Beamlines
Beamlines	24	28	

Booster Synchrotron - Design

– 3 FODO arcs with 48 BD (+SD) 6.4410 °and 45 BF (+SF) 1.1296 °
– 3 × 6 Quadrupoles for Tuning, 54 BPMs, 2·54 Correctors
– ± 15 mm × ± 10 mm Vacuum Chamber
– Energy: 100 MeV → 2.7 GeV, Repetition Rate: 3 Hz, Circumference: 270 m
– Magnet Power: 205 kW, ϵ_x @ 2.4 GeV: 9 nm rad



Maximum Energy	GeV	2.7
Circumference	m	270
Lattice		FODO with 3 straights of 8.68 m
Harmonic number		(15x30=) 450
RF frequency	MHz	500
Peak R F voltage	MV	0.5
Maximum current	mA	12
Maximum rep. Rate	Hz	3
Tunes		12.39 / 8.35
Chromaticities		−1 / −1
Momentum compaction		0.005
Equilibrium values at 2.4 GeV		
Emittance	nm rad	9
Radiation loss	keV/ turn	233
Energy spread, rms		0.075 %
Partition numbers (x,y, ε)		(1.7, 1, 1.3)
Damping times (x,y,ε)	ms	(11, 19, 14)

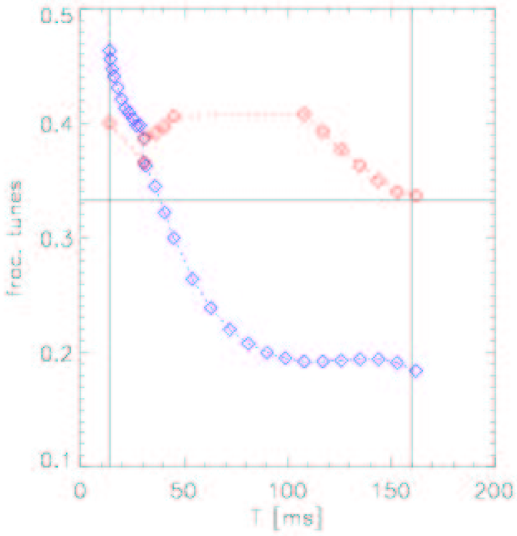
Booster Synchrotron - Commissioning I

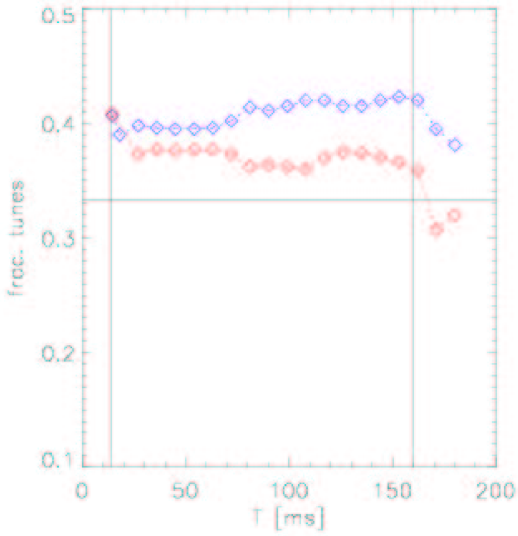
	Jul	3	Start Booster Commissioning
	Jul	11	First Turn WITHOUT Correctors
2000	Jul	13	RF on, 100000 turns @ 100 MeV
	Aug	8	Acceleration to 2.4 GeV
	Sep	20	Charge 1 nC (=1.1 mA) @ 2.4 GeV

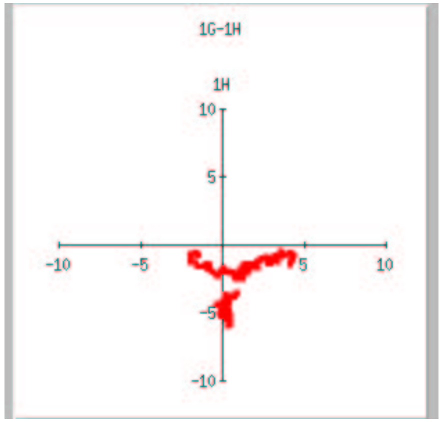
- “Null Orbit” of 2.5 mm rms $\rightarrow$ 0.2 mm rms Magnet Misalignment
- Charge 1 nC $\rightarrow$ Storage Ring Filling Time to 400 mA of $\approx$ 3 min
- Linac – Booster Efficiency after Energy Filtering ($\pm$ 0.5 %) 100 %
- Losses @ 100 MeV: Start Magnet Ramp @ 60 MeV, Inject @ 100 MeV
- ϵ_x = 9 nm rad $\rightarrow$ Booster – Ring Efficiency 100 %

Booster Synchrotron - Commissioning II

- Losses on Ramp: None after Sextupole Correction (Eddy Currents) and Tune Correction on Ramp avoiding 3rd Integer: (→**TUPRI098**)







- Why Success ? Digital Power Supply Control:
  - Allows Precise Control of Optics Parameters on the 160 ms ramp
- Why Success ? “All in One” Digital BPM System

Pre-Injector Linac - Design - Commissioning

ACCEL 100 MeV, 3 GHz S-Band "turn key" System:

- 90 kV grid gun: 1 ns pulse or 500 MHz train
- Sub-Harmonic Pre-Buncher (500 MHz)
- 4-cell Travelling Wave (TW) Buncher (β = 0.6)
- 16-cell TW Buncher (β = 0.95 $\longrightarrow$ 4 MeV)
- 2 $\times$ 50 MeV TW Accelerating Structures (5.2 m, β = 1)

Commissioning (Jan – Apr 2000):

Exceeds	Specifications in	1 ns pulse and	500 MHz train	Mode
Charge	1.5	2	2.3	nC
Energy Jitter	< 0.25	< 0.1	< 0.1	%
Energy Spread	< 0.5	0.2	0.3	%
Emittance	< 0.25	0.25	0.2	mm mrad

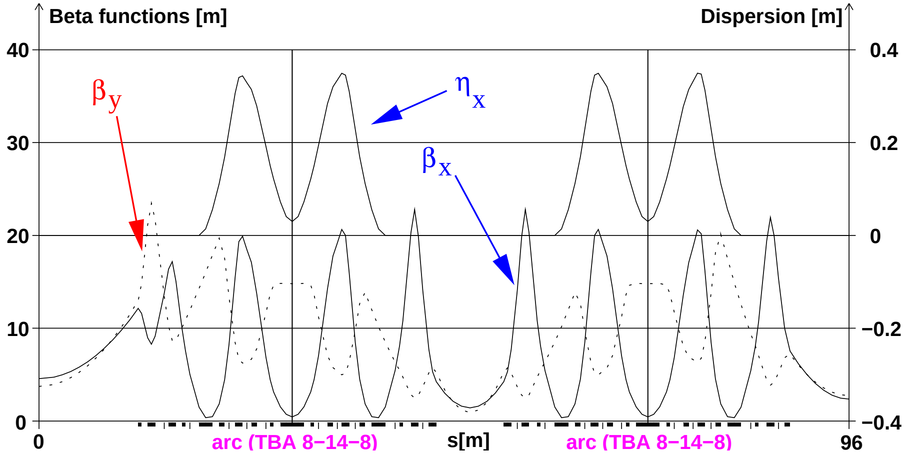
Injectors - Operation

- Pre-Injector Linac:
  - Commissiong Jan – Apr 2000
  - By Apr 2002 **6000 h** of Operation with Excellent Reliability (< 1 Trip/Day) and Reproducibility
- Booster Synchrotron:
  - Commissiong Jul – Sep 2000
  - By Apr 2002 **5500 h** of Operation with Excellent Reliability and Reproducibility

Injectors Reliable and Reproducible !-)
Vital for Top-Up Operation 8-)

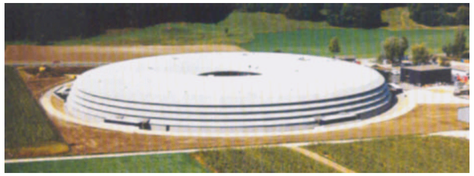
Storage Ring (SR) - Design

- 12 TBA: 8° / 14° /8 °
- 12 Straight Sections:
  - 3 × 11 m (n**L**)
    - ∗ **Injection**, **U212**
  - 3 × 7 m (n**M**)
    - ∗ **UE56**
  - 6 × 4 m (n**S**)
    - ∗ 2× **RF**, **W61**, **U24**
- Energy: 2.4 GeV (2.7 GeV)
- ϵ_x: 5 nm rad
- Current: 400 mA
- Circumference: 288 m
- Tune: 20.38 / 8.16
- Chromaticity: -66 / -21

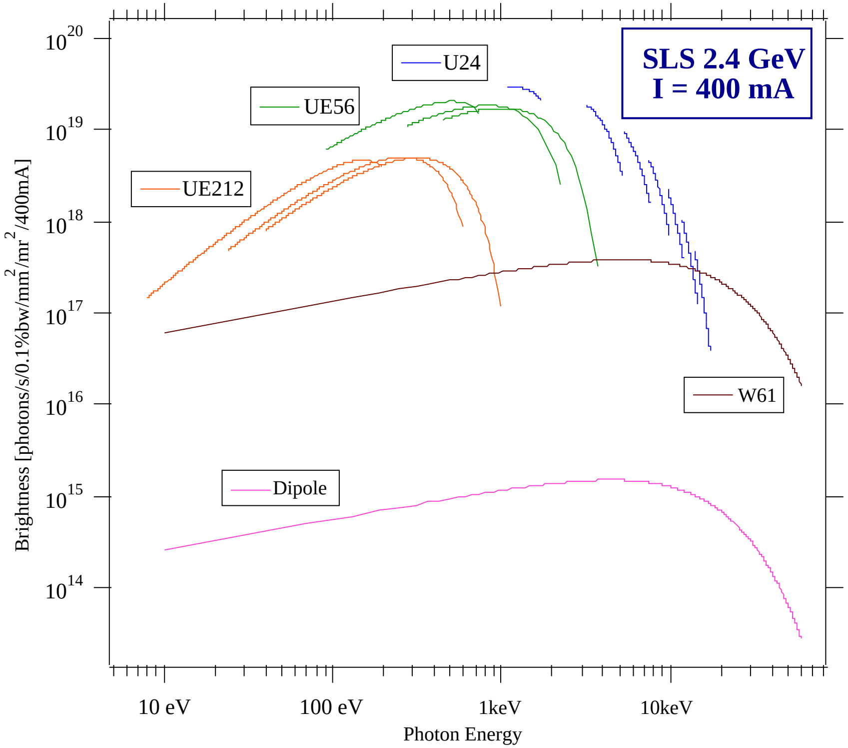


Energy	[GeV]	2.4 (2.7)
Circumference	[m]	288
RF frequency	[MHz]	500
Harmonic number		(2^5x3x5 =) 480
Peak RF voltage	[MV]	2.6
Current	[mA]	400
Single bunch current	[mA]	≤ 10
Tunes		20.38 / 8.16
Natural chromaticity		−66 / −21
Momentum compaction		0.00065
Critical photon energy	[keV]	5.4
Natural emittance	[nm rad]	5.0
Radiation loss per turn	[keV]	512
Energy spread	[10^{-3}]	0.9
Damping times (h/v/l)	[ms]	9 / 9 / 4.5
Bunch length	[mm]	3.5

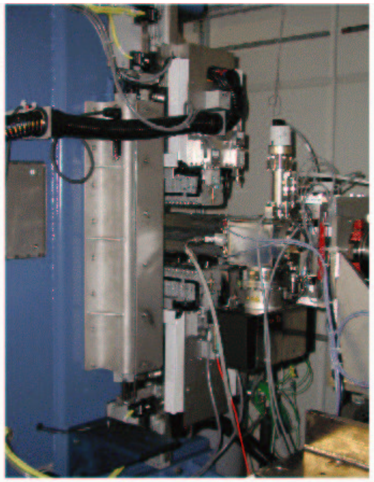
Beamlines and Insertion Devices (IDs)



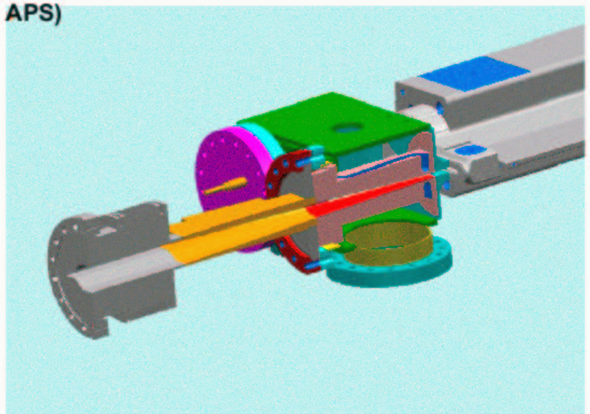
SIS/9L	Surfaces and Interfaces Spectroscopy
ID:	2 × Electromagnetic Twin Undulator
Energy:	**UE212** → 8-800 eV
SIM/11M	Surfaces and Interfaces Microscopy
ID:	2 × APPLE II Type Twin Undulator
Energy:	**UE56** → 90 eV-3 KeV
PX/6S	Protein Crystallography
ID:	In-Vacuum Undulator
Energy:	**U24** → 8-14 KeV (from Spring-8)
MS/4S	Material Science
ID:	High Field Wiggler
Energy:	**W61** → 5-40 KeV

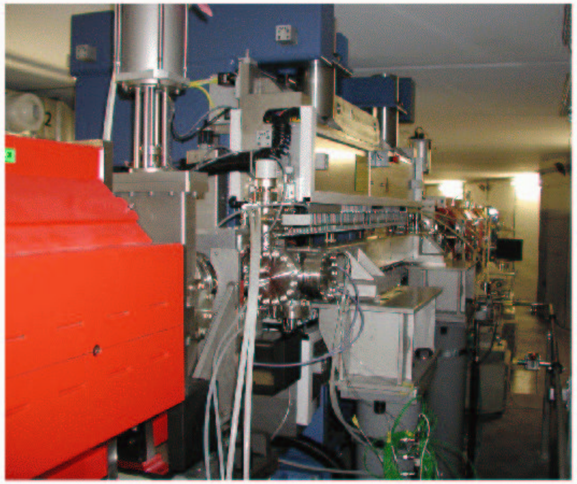


IDs - High Field Wiggler W61 (5-40 KeV)

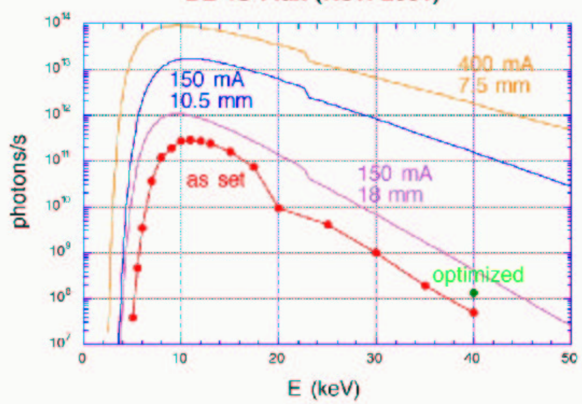


Taper–Section, Small Gap ID–Chamber (PSI / APS)

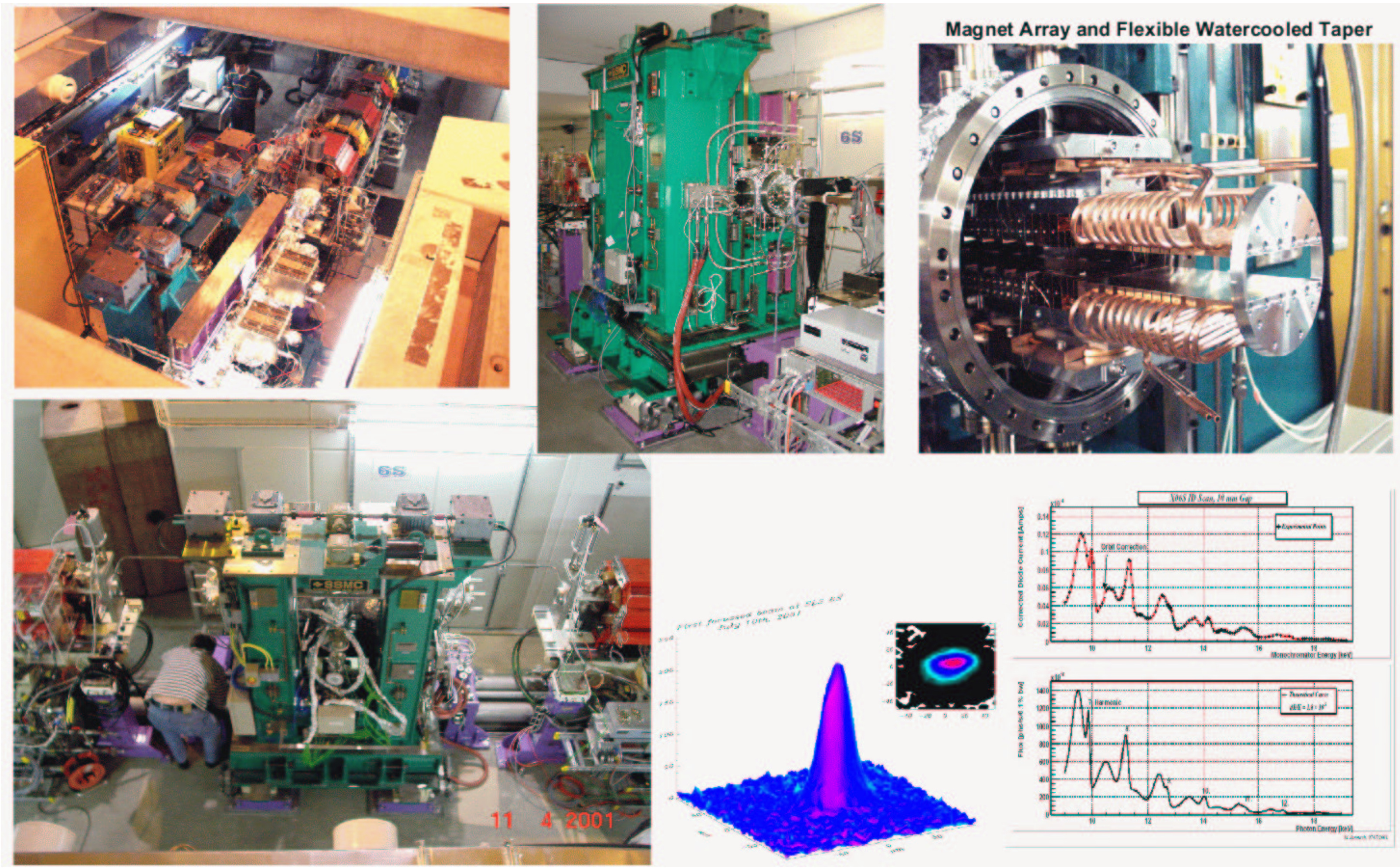




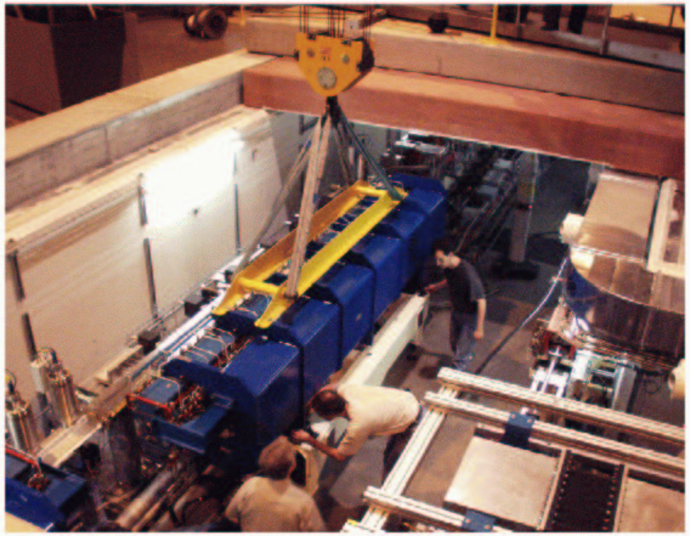
BL-4S Flux (Nov. 2001)



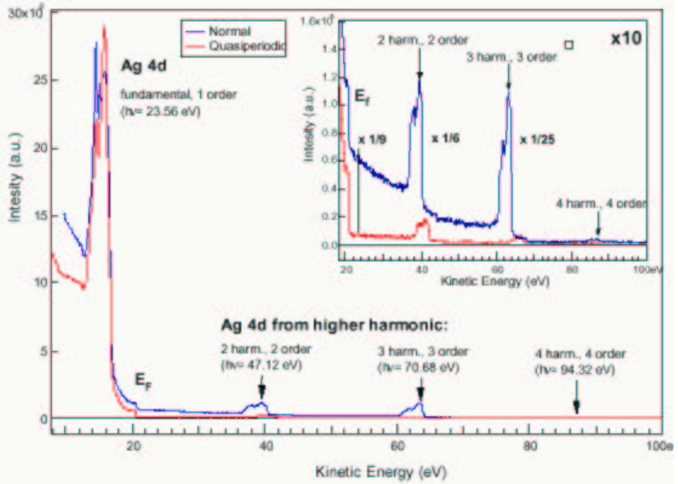
IDs - In-Vacuum Undulator U24 (8-14 KeV)



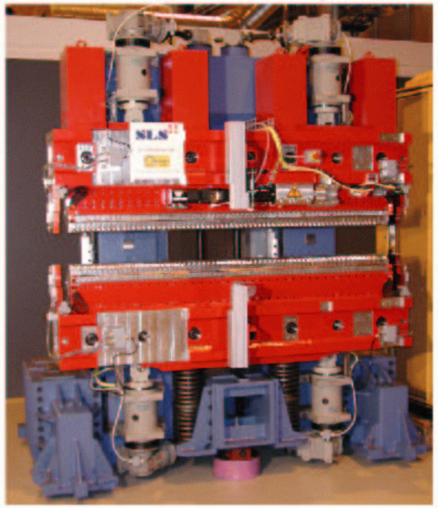
IDs - Electromagnetic Twin Undulator UE212 (8-800 eV)

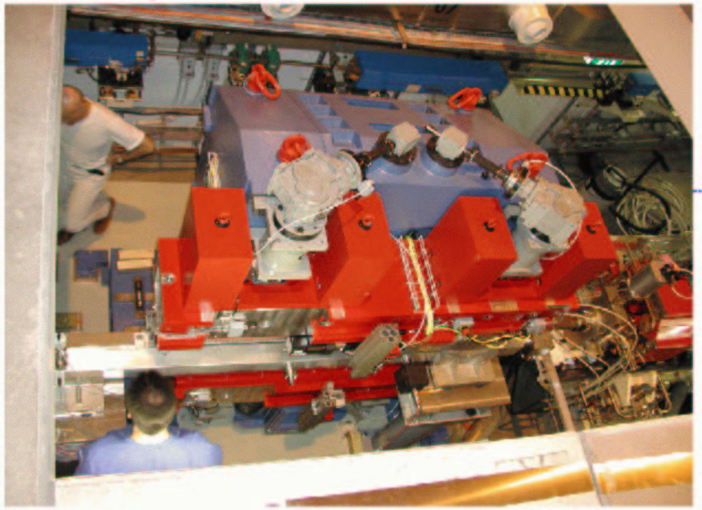


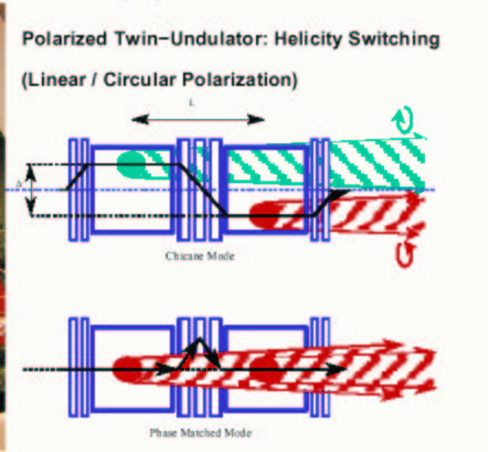
Polarized Twin Undulator, Quasi-Periodic

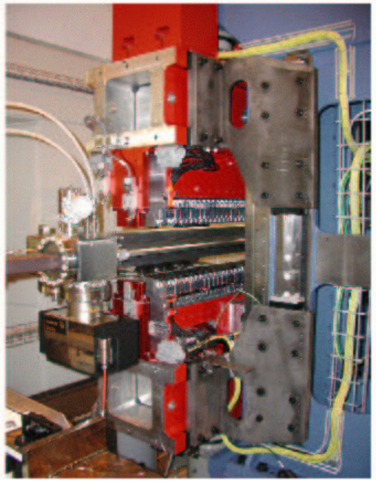


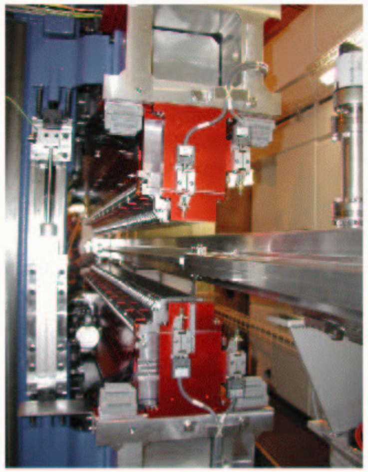
IDs - APPLE II Type Twin Undulator UE56 (90 eV-3 KeV)





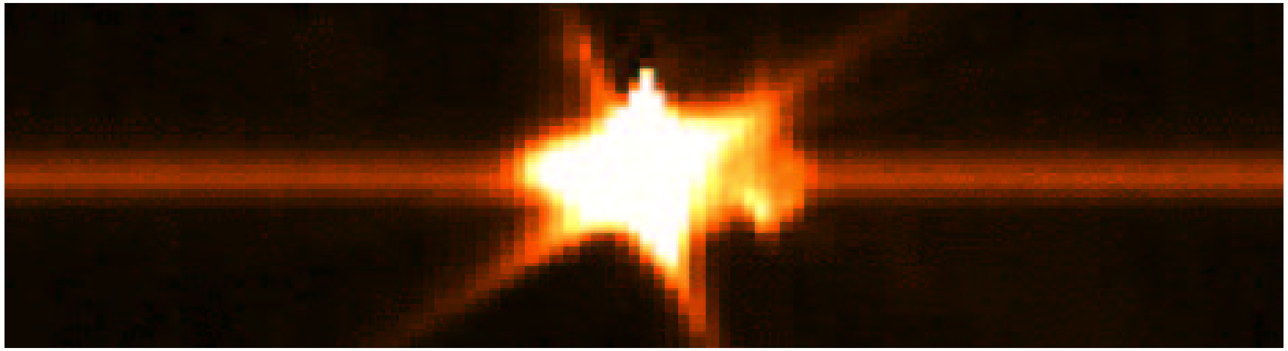






ID Control (PSI)

SR - “Milestones 2000”



Dec 13	First turn
Dec 15	First stored beam of 3 mA at 10 min lifetime
Dec 19	Lifetime of ≈ 8 h at 3 mA

SR - "Milestones 2001"

Jan 19	Current of 18 mA in a relaxed optics mode
Feb 28	Current of 100 mA, operation in the optics modes: low emittance, distributed dispersion
Apr 8	First single bunch operation
Apr 26	Measurement / correction of beta functions
May 4	Closed orbit correction to μm level
Jun 5	Design current of 400 mA
Jun 23	First top-up injection
Jul 10	**PX** beamline operational
Jul 19	Slow global orbit feedback operational
Aug 9	First operation of the multi-bunch feedback
Aug 9	**MS** beamline operational
Aug 10	**SIS** beamline operational
Nov 21	**SIM** beamline operational

SR - Emittances, Energy Spread I

- **Design and Simulation:**

  Natural Emittance: ϵ_{x0} = 5.0 nm rad

  Emittance Ratio: ϵ_y/ϵ_x = 0.1 %

  Energy Spread: $\sigma_e = 0.9 \cdot 10^{-3}$

- **Measurements:**

  Betatron Coupling κ (Closed Tune Approach):

  – κ = 5.0 % $\rightarrow$ κ = 0.7 % (sextupole shortcuts)

  – κ = 0.1 % with skew quadrupoles

  Dispersion (Difference Orbit):

  – $\sqrt{< \eta_y^2 >} \approx 4$ mm

  – $\rightarrow \epsilon_y \approx$ 15 pm rad, $\epsilon_y/\epsilon_x \approx 0.3$ %

  Pinhole Array:

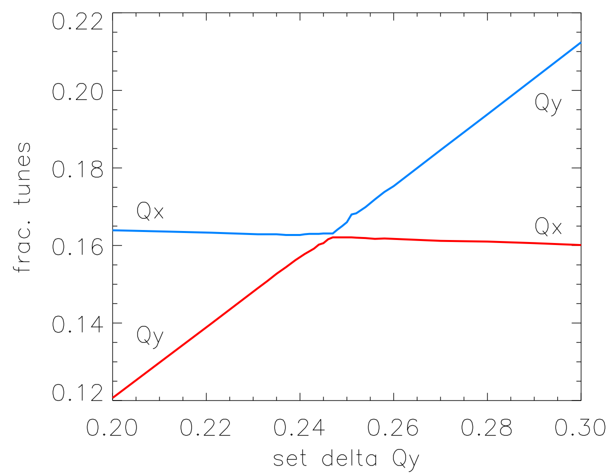
  β_x = 0.8 m, β_y = 14.8 m, η_x = 4.4 cm, $\eta_y \approx$ 1 cm

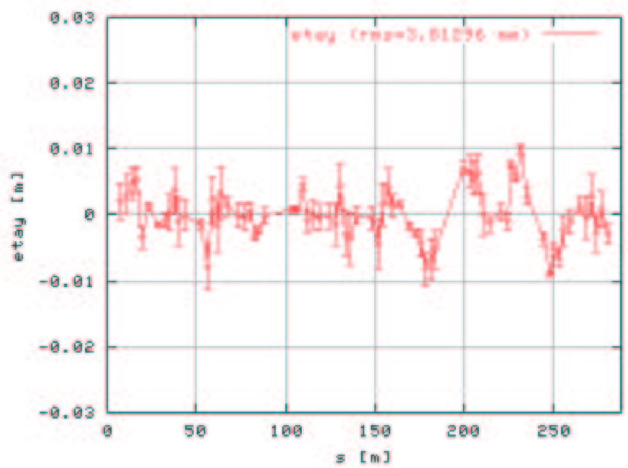
  – On Coupling Resonance:

  – $\sigma_y \rightarrow \epsilon_{x0}$ = 5.28 nm rad, $\sigma_x \rightarrow \sigma_e = 1.47 \cdot 10^{-3}$

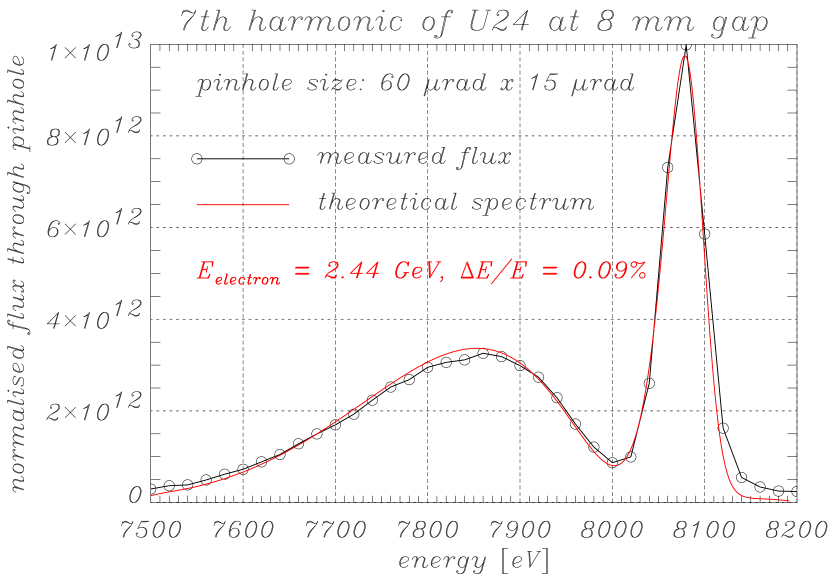
  – At Normal Working Point:

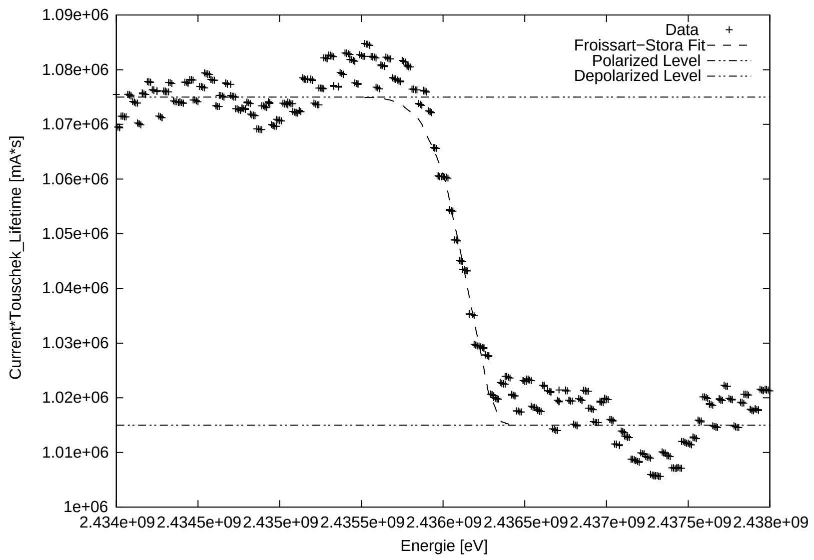
  – $\sigma_x \rightarrow \sigma_e = 1.5 \cdot 10^{-3}$, $\sigma_y \rightarrow \epsilon_y/\epsilon_x$ = 1.5 %





SR - Energy Spread II, Energy





- 7th Harmonic of **U24** at 8 mm gap:
  - $\sigma_e = 0.9 \cdot 10^{-3}$
  - Beam Energy E = 2.44 GeV
- Resonant Spin Depolarization: ν_{spin} = 5.45, $P_{eq} \approx$ 91 % with τ_p = 30 min (→ **TUPRI011**)
  - Beam Energy $E = 2.4361 \pm 5 \cdot 10^{-5}$ GeV

SR - Working Points

Design:

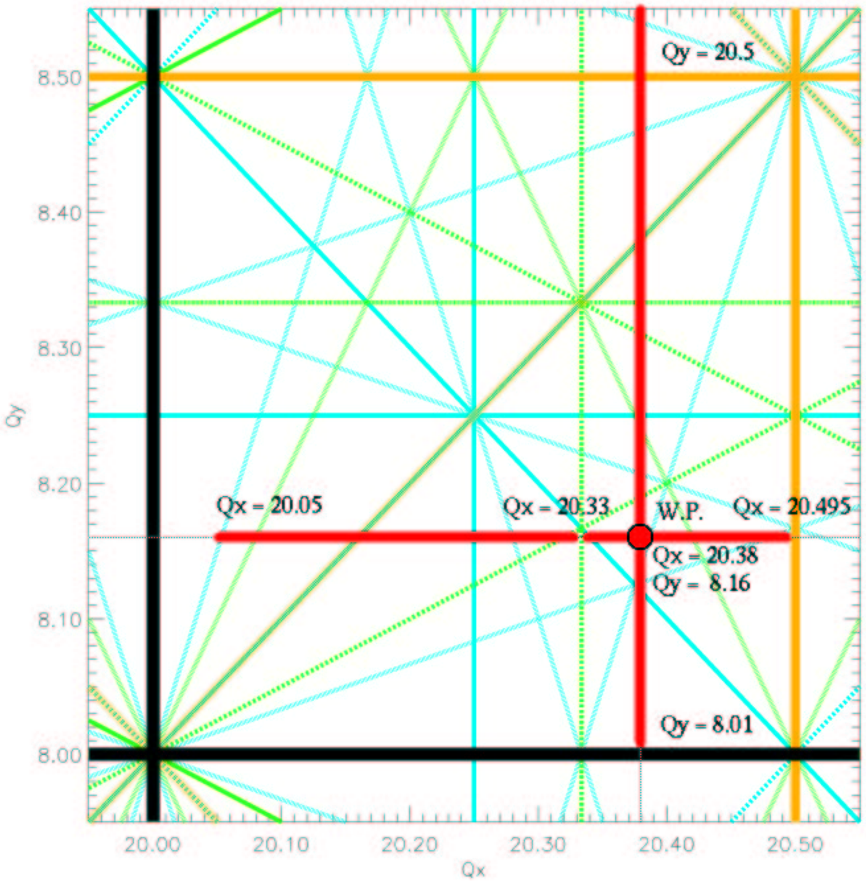
- ν_x = 20.82 / ν_y = 8.28

Operating:

- ν_x = 20.38 / ν_y = 8.16
- ν_x = 20.38 / ν_y = 11.16
- ν_x = 20.42 / ν_y = 8.19

Tuning Range:

- ν_x: 20.05 $\rightarrow$ 20.495 ($\times\ 20\frac{1}{3}$)
- ν_y: 8.01 $\rightarrow$ >20.5 ($\times\ 8\frac{1}{2}$)
  - order 1,2,3,4
  - - - - non systematic
  - $\cdot\cdot\cdot$ skew



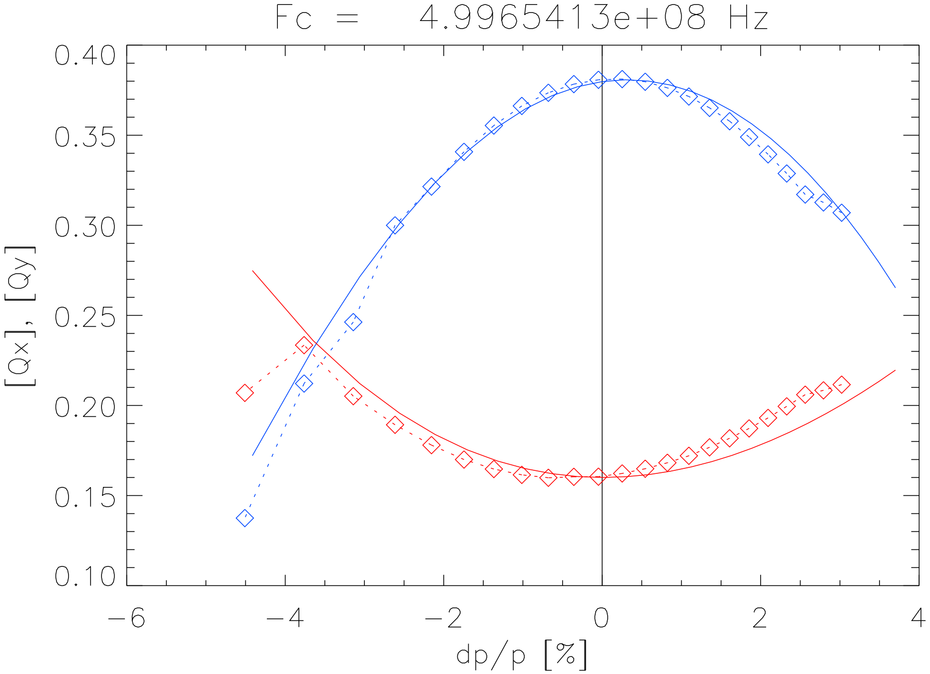
SR - Chromaticities, Energy Acceptance

Chromaticities:

- Sextupoles Off:
  $\xi_x = -66$ / $\xi_y = -21$
- Sextupoles On:
  $\xi_x = +1$ / $\xi_y = +1$
- Measured:
  $\xi_x = +1.6$ / $\xi_y = +0.5$

Tune ν(dp/p): Simulate/Measure $\rightarrow$

- Δf = –12 KHz $\rightarrow$ +10 KHz
- Δp/p = +3.0 % $\rightarrow$ –4.7 %
- $\Delta f/f = \alpha \Delta p/p + \alpha_1 (\Delta p/p)^2$
  - $\alpha = 6.52 \cdot 10^{-4}$
  - $\alpha_1 = 4.56 \cdot 10^{-3}$



SR - Beta Functions

174 Quadrupoles with Individual PS

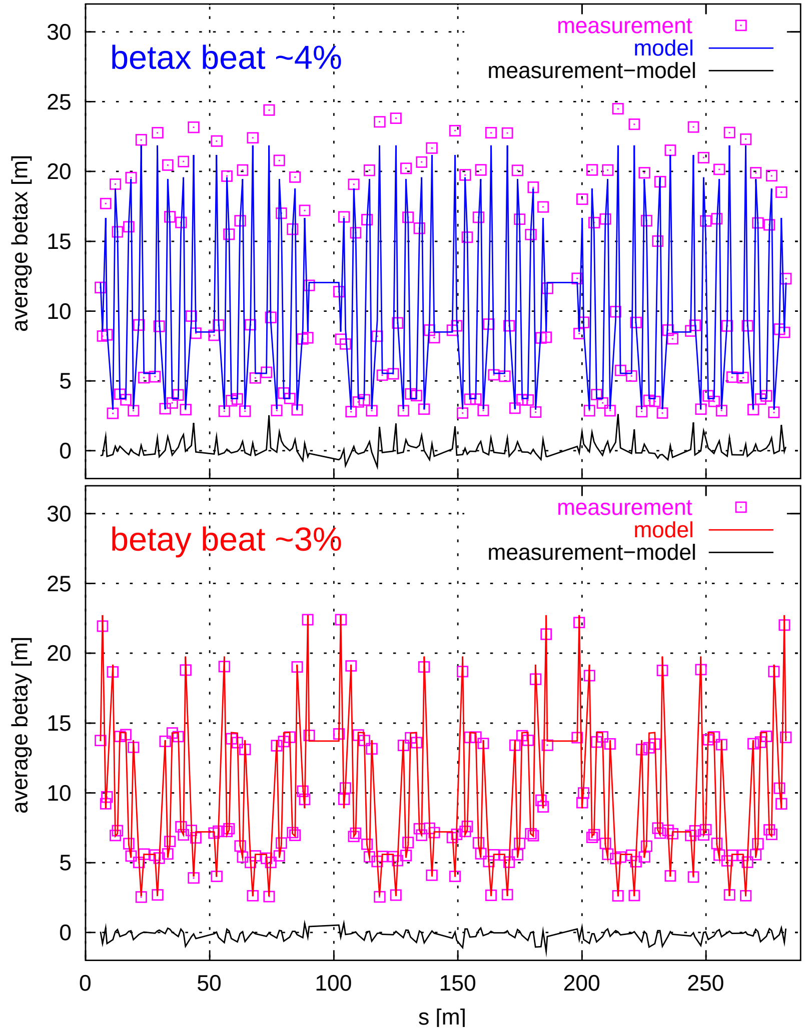
$\longrightarrow$

Gradient Correction:

- Procedure:
  1. Measure $<\beta_i>$ for i=1..174

     $\delta\nu = -\frac{1}{4\pi}\oint \beta(s)\delta k(s)ds$

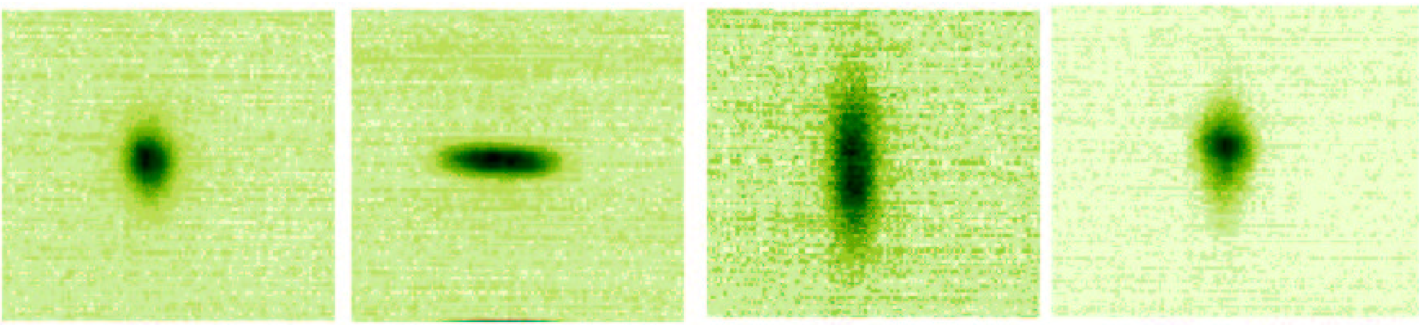
     Precision: ≈ 1.5 / 1.0 %
  2. Fit Errors δk_i to $<\beta_i>$ (SVD)
  3. Correct $<\beta_i>$ with -δk_i
  4. Measure $<\beta_i>$ again
- Results:
  - Horizontal β Beat: ≈ 4 %
  - Vertical β Beat: ≈ 3 %



SR - Beam Current

Design & Achieved: I = 400 mA
Transverse Instability:

- Vertical/Horizontal Multi-Bunch Instability (MBI) for $\xi_y \approx 1$ / $\xi_x < 0$
- No Correlation to Higher Order Modes (HOMs) in Cavities (→ **TUPRI009**)
- Cures:
  - Large $\xi_y \approx +4\text{-}5$, Moderate $\xi_x \approx +2$
  - Gap in Filling Pattern (390 bunches in 480 buckets)
  - Low Residual Gas Pressure
  - Transverse Multi-Bunch Feedback (TMBF)
  - Pinhole Images @ 100 mA, No Gap:

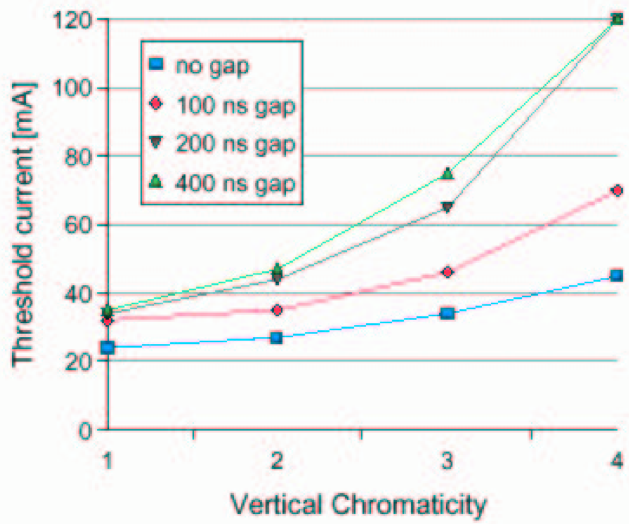


ξ_x/ξ_y +6/+6 −1/+6 +6/+4 +6/+4/ TMBF

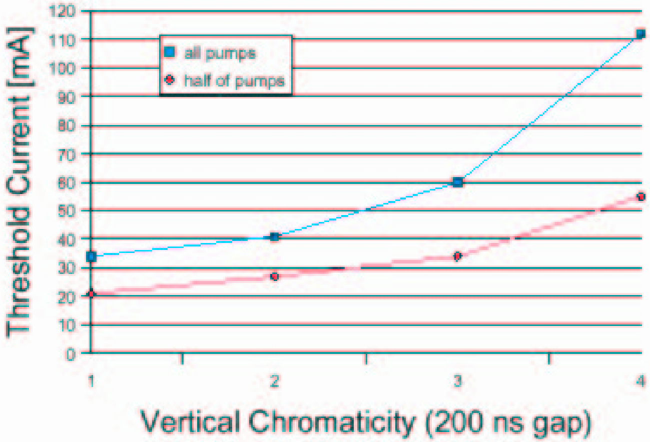
SR - MBI - Ion Trapping

Indications for ion trapping

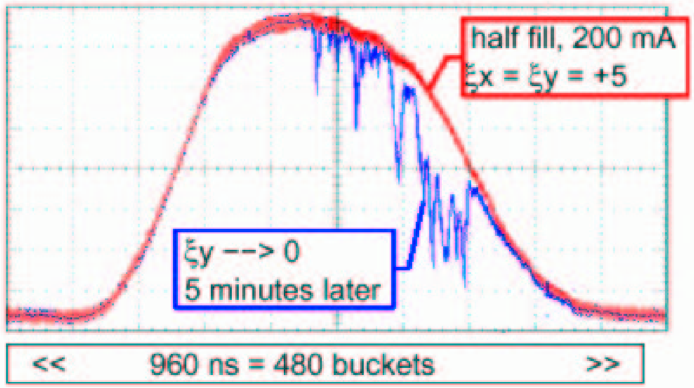
1. Threshold* increases
   with gap in filling pattern →



2. Threshold* decreases
   with pressure ↓



3. Losses mainly from tail →



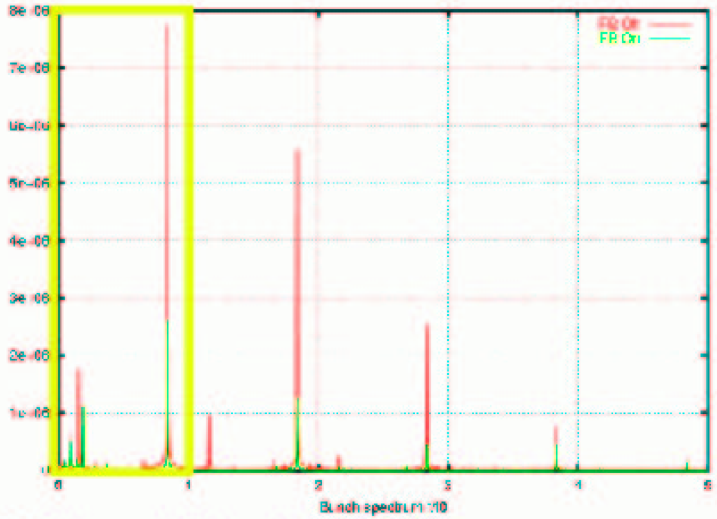
* Threshold := peak is 50 dB of central peak

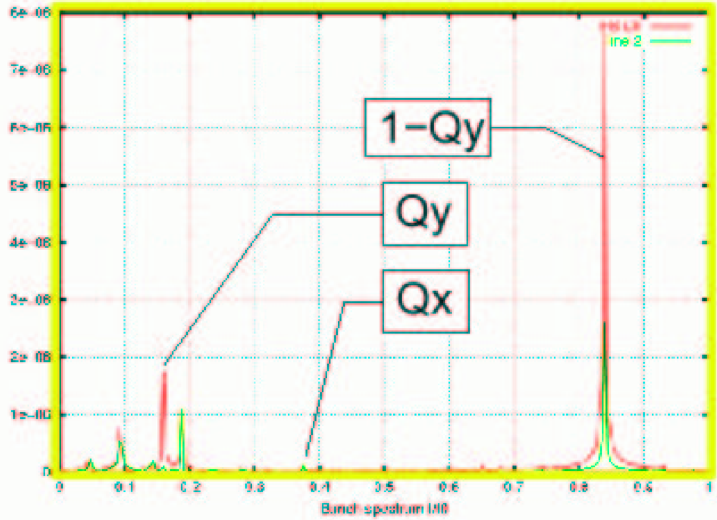
SR - MBI - Resistive Wall

Indications for resistive wall impedance

1. Threshold vs. Q_y: $Q_y = 8 + 0.16 \rightarrow 25$ mA
$Q_y = 8 - 0.16 \rightarrow 5$ mA

2. Signature: $(n - Q_y)$ line stronger than $(n + Q_y)$ (**FB off** / **FB on**)





3. Simulation (MAFIA):

modes with $\tau_{rise} < \tau_{damping}$:

without IDs: 3
with IDs: 20

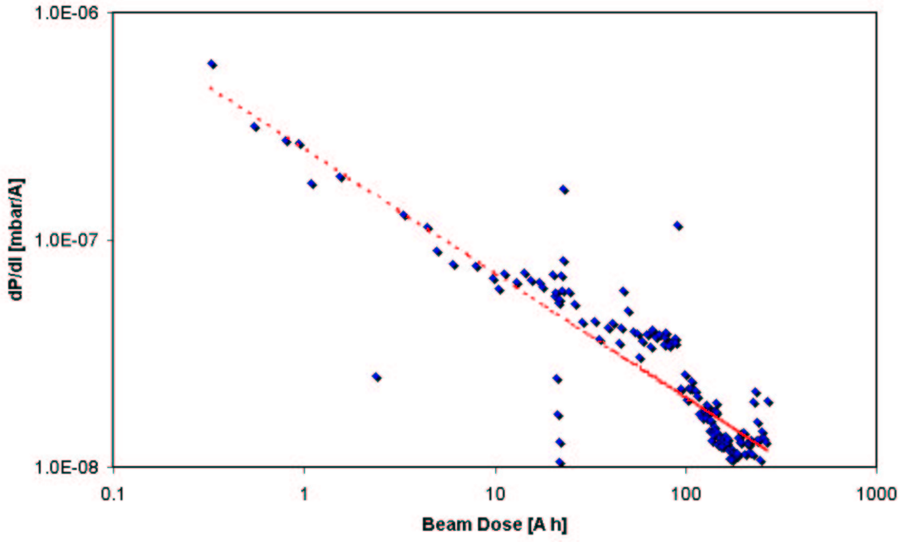
Narrow ID vacuum chambers:

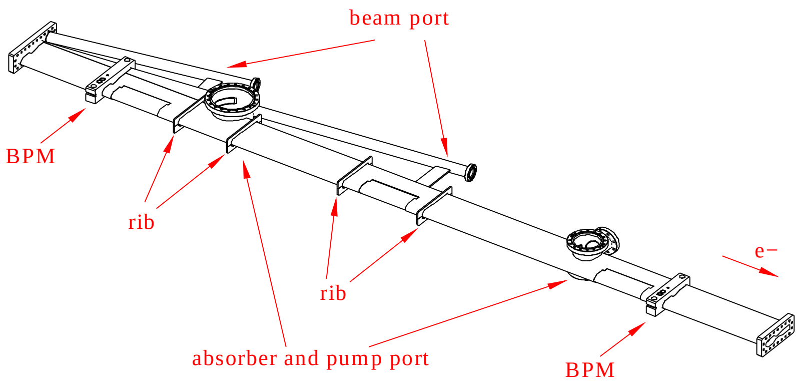
Stainless steel	±8.00 mm ×	10.8 m
Aluminium	±5.50 mm ×	4.5 m
Aluminium	±6.00 mm ×	2.0 m
Cu− coated >	±3.25 mm ×	1.5 m

SR - Vacuum

Design & Achieved: N_2 Equivalent Pressure @ 400 mA → $2 \cdot 10^{-9}$ mbar

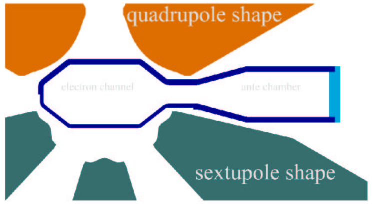
Evolution of the Dynamic Pressure dP/I:





Partial Pressures: Hydrogen (70 %) and Carbon Monoxide (30 %)

→ Success for Stainless Steel Antechamber Design With External Bakeout



SR - Lifetime

Simulation: 3.5 hrs for 400 mA with 4 mm gap IDs (A_y = 1.8 mm mrad)

Measurements: (June 2001) (Oct. 2001)

	June 2001	Oct. 2001
Beam dose	50 A hrs	160 A hrs
Pressure	$1.6 \cdot 10^{-9}$ mbar without beam $1.2 \cdot 10^{-8}$ mbar at 400 mA	$5 \cdot 10^{-10}$ mbar

Lifetime		measured	theory
Multibunch	250 mA	14 hrs	13 hrs
Single bunch	6 mA	2.5 hrs	2.7 hrs

approximate formula for SLS:

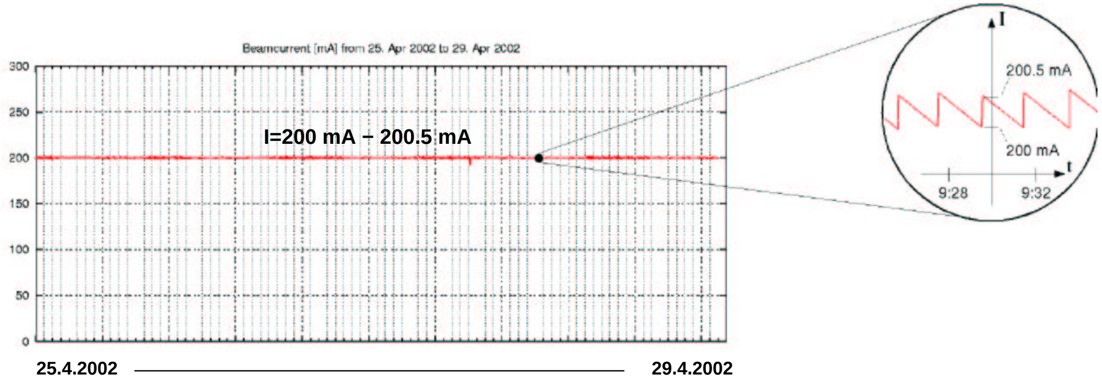
$$\frac{1}{\tau\ [\mathrm{h}]} = \left(1 + \frac{5}{A_y[\mathrm{mm \cdot mrad}]}\right) \frac{p\ [10^{-9}\ \mathrm{mbar}]}{380} + \frac{I_{\mathrm{singlebunch}}}{200\sqrt{\epsilon_y/\epsilon_x}}$$

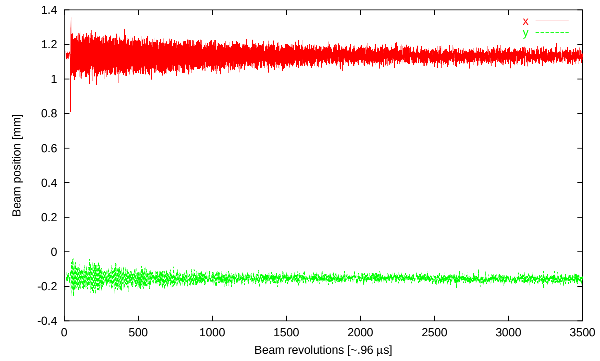
A_y = 5 mm mrad from UE212 chamber

$\kappa \approx 0.01$ (no correction) $\rightarrow$ estimate $\varepsilon_y/\varepsilon_x \approx 0.6$ %

SR - Top-Up

Typical Top-Up Run in April 2002: (→**TUPRI012**)





- Beam Current Constant: $\Delta I/I < 3{\cdot}10^{-3}$
- Kicker Bump Closed: $x_{rms} \approx 100\ \mu$m, $y_{rms} < 50\ \mu$m
- Injection (every ≈ 2 min) with Closed Gaps: Losses @ **ID**s OK
- Injection with Shutters Open: Radiation in Experimental Areas OK
- Injection Efficiency: ≈ 80 % (large $\xi_y \approx +4$)
- Linac and Booster Alwarys Running → Gun and Kicker Triggers On/Off
- Users Like Top-Up (-: Mostly Top-Up Runs Scheduled :-)

SR - Stability

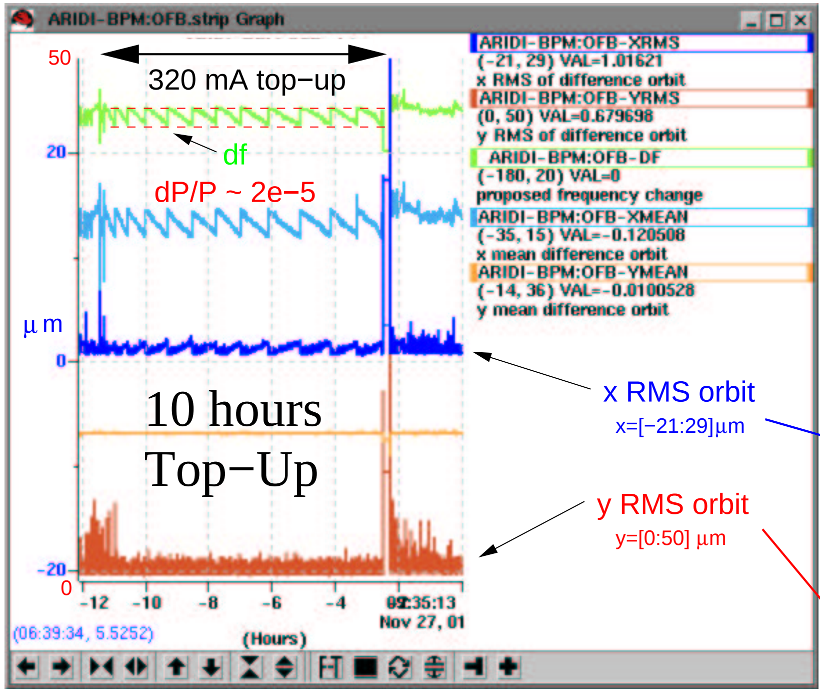
Requirement: Orbit jitter < 1 µm at insertion devices

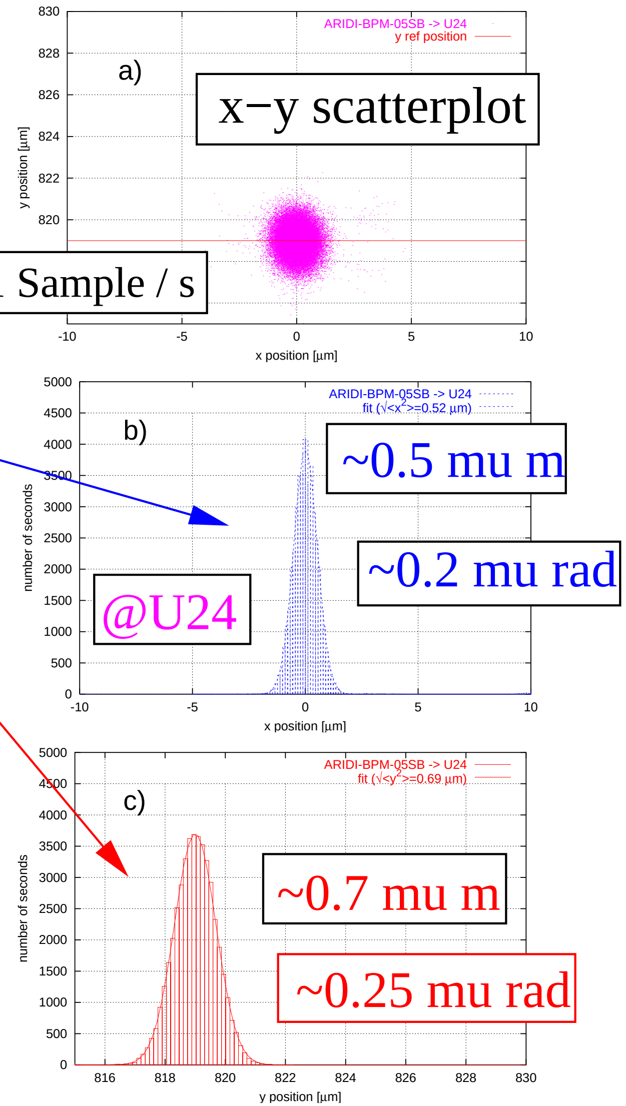
Worst case Noise estimate	30	60	Hz
Seismic measurements	300	30	nm
Damping by hall's concrete slab	neglected		
Girder resonance max amplification	< 10	< 10	
Closed orbit amplification hor./vert.	8/5	25/5	
→ Maximum Orbit jitter hor./vert	24/15	7.5/1.5	µm
Attenuation by orbit feedback	−55	−35	dB
→ **Maximum Orbit jitter hor. /vert.**	**40/30**	**130/30**	**nm**

Noise Measurements	
Cross talk from booster ramping:	< 1 µm
Girder resonances 16 Hz and 24 Hz:	< 3 µm
50 Hz and harmonics on RF:	< 3 µm (10 ppm ΔE/E)

(values at max. betas, no orbit feedback)

SR - Slow Global Orbit Feedback





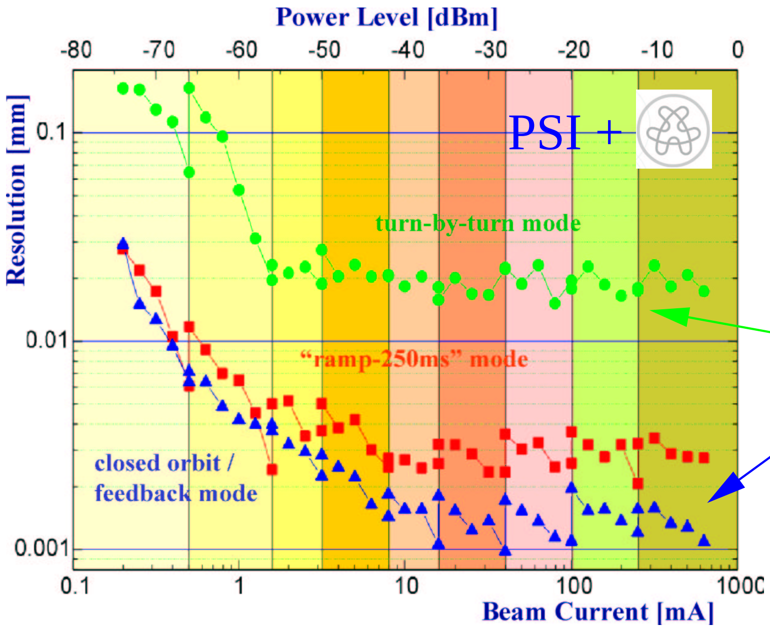
Slow Global Orbit Feedback (SOFB)
(−> THXGB001,THPRI030)

dE/E~1e−5

- 2 Hz Orbit Sampling Rate
- 1/3 Hz Correction Rate (1 x/y Cycle)
- Path Length Correction with RF

−> Closed Orbit: xrms = yrms ~1 mu m

SR - Innovative Subsystems - Digital BPM System



Only One BPM System in Different Operation Mode for All Machines

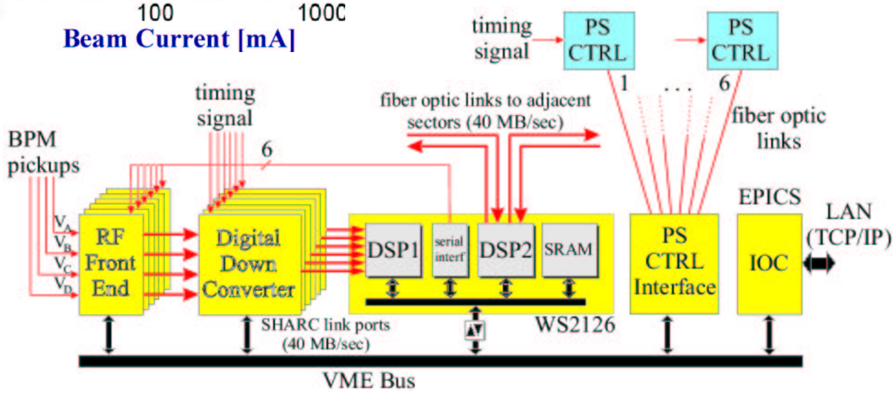
Turn−by−Turn:

1 MSample/s, <20 mu m

Closed Orbit:

4 KSample/s, <1.2 mu m

Turn−by−Turn:
Vital for Commissioning



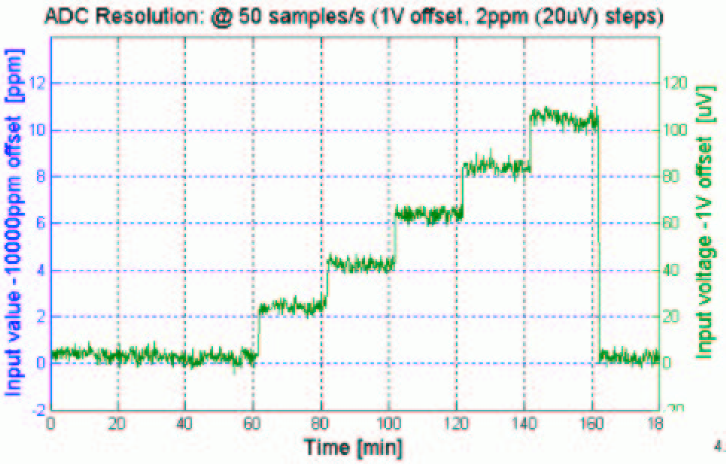
Closed Orbit Mode −> Fast GlobalOrbit Feedback

(−> THXGB001,THPRI030)

SR - Innovative Subsystems - Digital Power Supplies

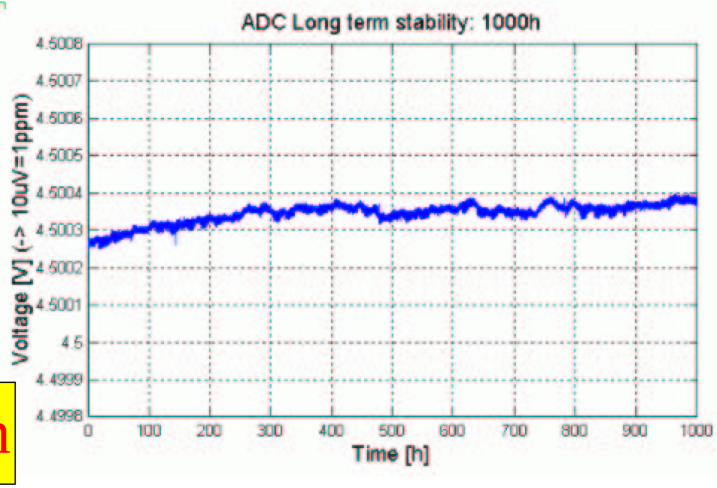
One Digital Control Unit for ~600 power supplies of the SLS

Precision of the AD converter card



- Resolution up to **1ppm**
- Short- term stability (<60s) better than 10ppm

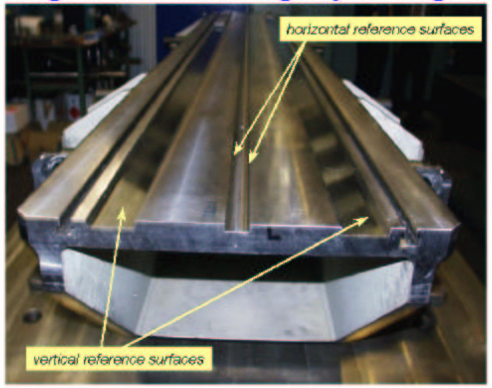
- Long- term stability (1000h) better than 30ppm
- Reproducibility better than 30ppm

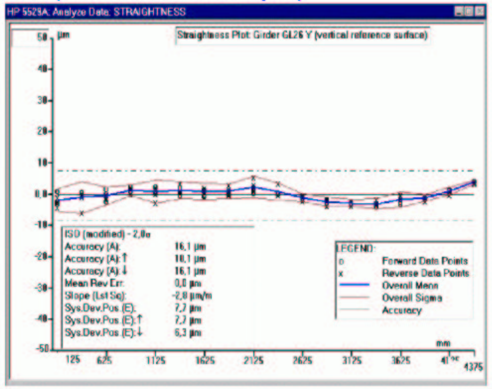


Short/Long Term: 1/30 ppm

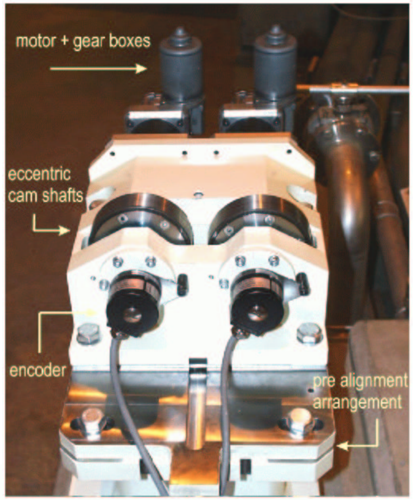
SR - Innovative Subsystems - Magnet Girders

Magnet mounted rigidly onto girders ("MAX-2 concept")





Girder rail precision 15 µm , Magnet axis calibration 30 µm

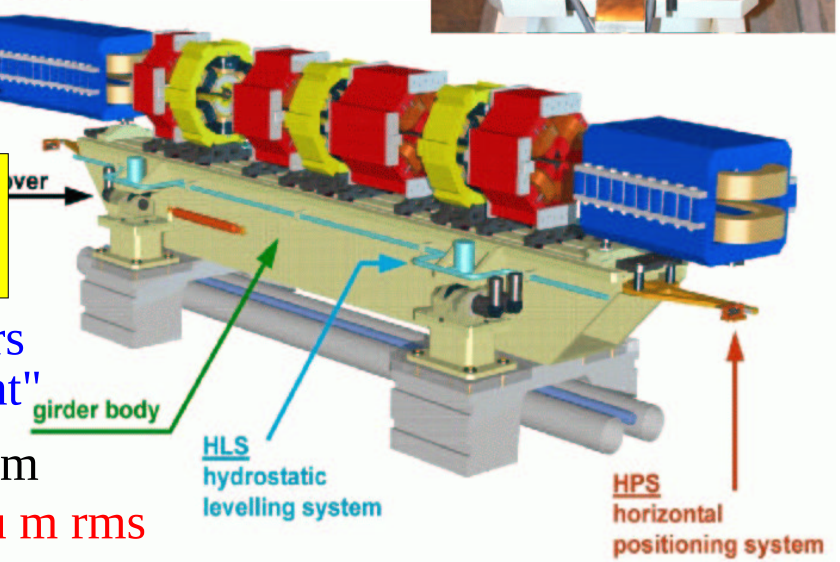


Girders movable in 5 degrees of freedom

Position monitoring systems on girders

Beam based girder alignment

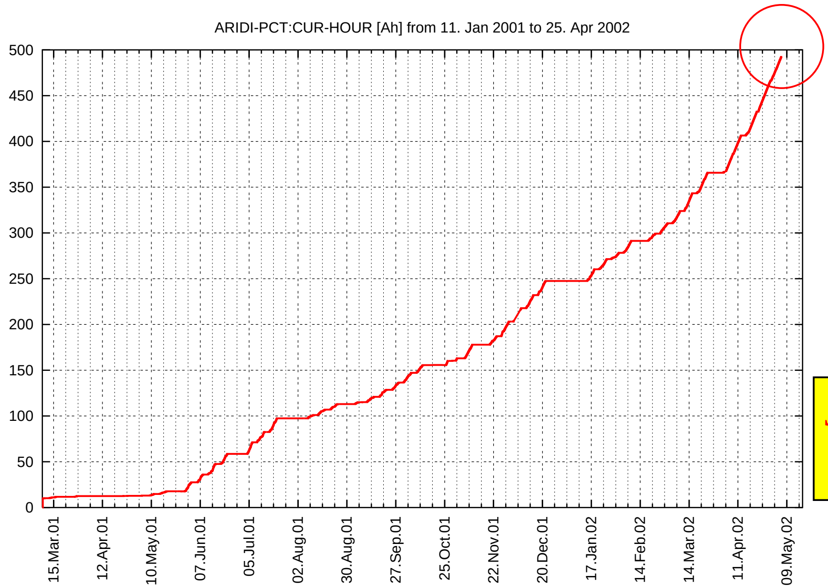
Girder Rail Precision: 15 mu m
Magnet Axis Calibration: 30 mu m



Remotely Controlled Girder Movers
−> "Beam−Based Girder Alignment"

Null Orbit: xrms~2 mm, yrms~1 mm
−> Magnet Misalignments < 50 mu m rms

SLS Operation Experience



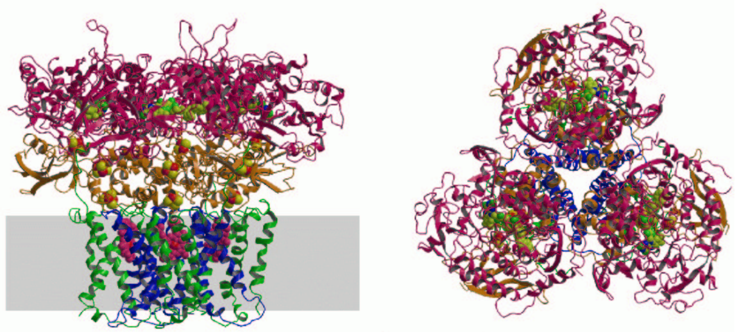
May 2002: 500 Ah accumulated
in 2002: 250 Ah

70% for Users

Jan−Apr 2002: 1300 h Operation for Users
with 90% Availability

First Exciting Results from PX:

Succinate dehydrogenase (complex II) from *E. coli* at 3.1 Å (S. Iwata et al.)



space group R32, cell dimensions of a=b=130 Å and c=550Å
crystals contain one monomer (120kDa) with 3 FeS clusters and one haem in ASU

Industrial Users @ PX Beamline in 2002:

Number of industrial users served (test shifts)	8
Number of industrial contracts signed (CH, F, D)	7
Number of industrial contracts in preparation	1
Number of shifts sold (3-12 2002)	68

68 Shifts Sold

NOVARTIS, Roche, morphochem, BIOTAL, ACTELION, serono, Boehringer Ingelheim, proteros biostructures GmbH

Proprietary Operation

Thursdays reserved for proprietary users
Regular industrial user operation started in March 2002