Top-Up Experience at SPEAR3
Contents

• SPEAR 3 and the injector
• Top-up requirements
• Hardware systems and modifications
• Safety systems & injected beam tracking
• Interlocks & Diagnostics
SPEAR3 Accelerator Complex

3GeV Injector (White Circuit)

BTS 5W, 1.6nA

10Hz Single bunch/pulse

3GeV 10nm-rad 500 mA

Environment

XAS

Coherent

13 Surfaces/Coherence/XAS

11-1 Crystallography

11-2 MEIS XAS

11-3 Materials Diffraction

Crystallography

ARPES

5-2 Coherent Scattering

5-4 High-Res ARPES

BM

10-1 NEXAFS/PES

10-2 XAS/X-ray Scattering

7-1 Crystallography

7-2 X-ray Scattering

7-3 Bio-XAS

2-1 Powder/Thin Film Diffraction

2-2 White light

2-3 XAS/Microprobe

SAXS/PX

PX

PD/XAS

NEXAFS

XAFS

10Hz Single bunch/pulse

3GeV Injector
Top 'off' at SPEAR3

- Rebuilt SPEAR into SPEAR3 (1999-2003)
- Operated at 100mA for ~6 years (beam line optics)
- Recently increased to 200mA
- Chamber components get hot at 500mA (450kW SR, impedance)
- 500mA program suspended because of power load transient on beam line optics
- Instead worked to top-off mode (beam decay mode, fill-on-fill)

RF system and vacuum chamber rated for 500mA
Present Status

- 13 exit ports taking SR (9 Insertion Device, 4 Dipole)
- 7 ID ports presently in ‘fill-on-fill’ open shutter mode
- 4 dipole beam lines open shutter injection by end of October 2009
- Last two ID shutters fill-on-fill by June 2010
- Trickle charge 2011
SPEAR 3 100 vs. 500 mA Fill Scenarios

lifetime = 14 h @ 500 mA
            = 60 h @ 100 mA

100mA and 500mA Operation

lifetime = 14 h @ 500 mA
            = 60 h @ 100 mA

\[ \Delta = 180\text{mA} \]

\[ \Delta = 12\text{mA} \]
**500mA Injection Scenarios**

- **delivery time = 8 hr**
  - \( t_{\text{fill}} \approx 6-7 \text{ min} \)

- **delivery time = 2 hr**
  - \( t_{\text{fill}} \approx 1.5-2 \text{ min} \)

- **delivery time = 0.5 hr**
  - \( t_{\text{fill}} \approx 17 \text{ sec} \)

- **delivery time = 1 min**
  - \( t_{\text{fill}} \approx 0.5 \text{ sec} \)
  - (or 10ms single shot)
Hardware Upgrades

- **Gun**
  - higher current
  - stabilize emission rate
  - “laser-assisted” emission

- **Linac**
  - restore 2nd klystron
    (higher energy, feedback)
  - phase-lock linac and booster rf

- **Booster**
  - improve capture with modified lattice
  - improve orbit and tune monitors
  - develop fast turn-on mode

- **BTS**
  - eliminate vacuum windows (done)
  - diagnostics

- **SPEAR**
  - add shielding, interlocks
  - improve kicker response
  - transverse feedback

- **Beamlines**
  - add shielding, interlocks
  - timing
- Vertical Lambertson septum (booster outside ring) - operates DC, skew quadrupole added
- Three magnet bump
- ~15 mm amplitude, ~12mm separation
- Injection across three cells (sextupoles)
- Slotted stripline kickers (DELTA, low impedance)
- Transverse field dependence in K2
Hardware Upgrade: BTS Windows

With windows: ~20% beam loss

No windows: ~no loss

old BTS: rough vacuum + windows
new BTS: high vacuum + no windows

Huang & Safranek
Injected beam profile measurements

Visible diagnostic beam line

Movies…
• Synchrotron oscillations measured with turn-by-turn BPMs:

• Kickers set to dump injected beam each cycle
• Injection energy stable
• Injection time varies over hours
  – RF cable temperature
• Develop method to measure timing with stored beam

Huang, Safranek & Sebek
• Kickers can interrupt data acquisition
  o What is interruption sequence?
    • depends on current ripple, beam lifetime and charge/shot
    • bunch train filling needs new booster RF system
  o Gated data acquisition

Single shot
injection kicker transient = ~10 ms
(~0.1 ms with feedback)

  o Tests with beam lines ➔ no complaints
  o Lots of work to match kicker waveforms

Huang & Safranek
Hardware Upgrade: PEP-II Bunch Current Monitor

**downconverter schematic**

**downconverter chassis**

- visible APD (ASP)
- x-ray APD (CLS)

**bunch-by-bunch processor chassis**

A.S. Fisher
Hardware Upgrade: Thermionic Cathode as a Photo-Emitter

- S-band RF gun with thermionic cathode, alpha magnet, and chopper
- Most charge during the 2 $\mu$s RF pulse stopped at the chopper
- 5-6 S-band buckets pass into the linac, single booster bucket
- SPEAR3 single bunch injection, 10Hz presently ~50pC/shot
Photo-emission cathode (cont’d)

- high singe-bunch charge for top-off
  - reduce beam loading in linac
  - eliminate cathode back bombardment
  - eliminate chopper

Laser-driven configuration

1.5 cell RF gun

cold-cathode

UV or green laser

2.856 GHz (~2μs)

e- beam (~500ps)

Photo-emission cathode (cont’d)

Sara Thorin/MAXLab, EPAC’08

‘Turning the thermionic gun into a photo injector has been very successful’

S.Gierman
The Injected Beam Safety Dilemma

- Radiation Safety: the first hurdle
  - AP studies to demonstrate injected beam can not escape shielding
  - Many clever scenarios (dreams and zebras)
  - BL shielding sufficient? (higher average current, more bremsstrahlung)
  - PPS/BCS interlock modifications
  - Do users wear badges?

- Efficient injection into main ring
  - Injection time, charge/shot, repetition rate

Safety is complicated!
Synchrotron Radiation Exit Ports

SPEAR3 DBA cell

- upstream dipole
- downstream dipole
- e-beam
- Dipole
- ID
- Main Chamber
- Radiation Slot
- Ante-Chamber
- inner wall: 42 mm
- outer wall: 13 mm
Vacuum Chamber Construction

- BPMs
- H1 ABSORBER
- H2 ABSORBER
- H3 ABSORBER
- TSPs
- V1, V2 MASKS
- V3 MASK
- V4 MASK
- 220 L/S ION PUMP
- 150 L/S ION PUMP
- ID BPM
- ADDITIONAL BPM SET
- BELLOWS
- EDDY CURRENT BREAK
- QFC

Dimensions:
- 18.8 mm
- 13 mm
- 24 mm
- 34 mm
- 84 mm

Materials:
- 44.2 mm
- 44 mm
Photon Beam Exit Channel

outside absorber

inside absorber

photon beam

e- beam
A Closer Look...
Top-Up with Safety Shutters Open

NORMAL

SAFE

ACCIDENT
Is this a real possibility?

Simulation is necessary!

• Bad steering, energy

• Bad magnet fields

ACCIDENT

Injected Beam

X-Rays

Stored Beam

Experimental Floor

Shield Wall
SSRL Approach to Calculations

Incoming Beam

SPEAR3 Magnets

Beamline

- No assumptions about initial steering
- All physical positions and angles possible
- Energy errors!

Field simulation region

- Wide fringe fields

Beamline Apertures
Radiation Masks

- No magnetic field
- Straight trajectories

A. Terebilo
Forward Propagation Only

Chamber boundary

Injected Beam

A2 Aperture

Fixed Mask

A1 Aperture

Photon Beam Line

Ratchet Wall
(2-ft Concrete)

Stored Beam
Trajectories in Phase Space

vacuum chamber acceptance
fixed mask

Phase Space at Z = Fixed Mask
Phase Space at Z = Ratchet Wall

Horizontal Position (m)
Horizontal Angle (rad)

Horizontal Position (m)

spread in angles
10° bend
(far fringe field)
Evolution of allowed phase space

Initial: A1 and BPM7
After BPM1

Stored Beam on design orbit

X-Rays to Beamline

Allowed Phase Space in BL coordinates
Z = SD exit
Z = Fixed Mask
Z = Ratchet Wall

-3 -2.5 -2 -1.5 -1 -0.5 0 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2
-0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1 0.12

-0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1
-0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1

-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1
-0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1

-3 -2.5 -2 -1.5 -1 -0.5 0 -0.1 -0.05 0 0.05 0.1 0.15 0.2
-0.24 -0.22 -0.2 -0.18 -0.16 -0.14 -0.12 -0.1 -0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1
-0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1

X [m]
X' [rad]
The Metric: Separation in Phase Space to Apertures

Phase Space at Z = Fixed Mask
Phase Space at Z = Ratchet Wall

Fixed Mask Opening
Ratchet Wall Opening
The Extreme Ray

Beamline Axis
Extreme Ray
Stored Beam on design orbit

Beam pipe w/apertures
Separation at Fixed Mask
rise/run ~ -0.1

Extreme Ray
All other Trajectories
Condition for ‘Abnormal’ Scenario

- Large SPEAR3 magnet field error
  - and/or -
- Large injected beam energy error
  - AND -
- “extensive intentional steering”
## Parameter Sensitivity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>To Pass Beyond Mask</th>
<th>Fixed</th>
<th>To Pass Beyond Ratchet Wall</th>
<th>Target Value for Interlock Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E_{\text{INJ}}/E_{\text{SPEAR}}$</td>
<td>+59%</td>
<td>+100%</td>
<td>+10%</td>
<td></td>
</tr>
<tr>
<td>$\Delta B/B$</td>
<td>-48%</td>
<td>-60%</td>
<td>-1% (-10%)</td>
<td></td>
</tr>
<tr>
<td>$\Delta QF$</td>
<td>-100%</td>
<td>Only with polarity reversed</td>
<td>-25%</td>
<td></td>
</tr>
<tr>
<td>$\Delta QD$</td>
<td>+300%</td>
<td></td>
<td>55% (PS Limit)</td>
<td></td>
</tr>
<tr>
<td>$HCOR$</td>
<td>22 mrad</td>
<td>30 mrad</td>
<td>3 mrad (2 x PS Limit)</td>
<td></td>
</tr>
</tbody>
</table>
Alignment of Apertures is Critical

SPEAR Apertures

Beamline-Specific Aperture

Insertion Device

QF

QD

BEND

SD

HCOR

PM

Stored Beam on design orbit

X-Rays to Beamline

Ratchet Wall

A1

A2

A3

+60 / -43 mm

+50 / -43 mm

BL9: +112 / -101 mm
Mechanical Drawings & Tolerances

Experimental Floor

ID source

Ring Aperture

Fixed Mask

Documentation

Periodic checks

More documentation
3-GeV beam hits points A, B or C of fixed mask. The maximum dose rate outside optical hutch is 1, 0.1 or 0.03 rem/h/W. Trajectory study shows uniform loss over fixed mask → 1.7 rem/h at 5 W.
Passive Systems
-Limiting apertures in transport line (BTS)
-Limiting apertures in SPEAR3 and beam lines
-Permanent magnets for dipole beam lines

Active Systems (Redundant Interlocks)
- Injection energy interlock
  - BTS dipole supply
- SPEAR3 magnet supplies
- Stored beam interlock
- Radiation detectors at each beam line
### A Rastafarian Logic Table

#### Top-Off injection fault table for SPEAR3 ID beam lines

<table>
<thead>
<tr>
<th>Injected Beam Condition</th>
<th>Global BCS</th>
<th>Magnet BCS</th>
<th>Non-BCS</th>
<th>Radiation Monitors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TOSCI Intl’k</td>
<td>Inject Energy Intl’k</td>
<td>QF Error Intl’k</td>
<td>Dipole Intl’k</td>
</tr>
<tr>
<td>Accumulation</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Beam lost before FM (safe)</td>
<td>OK*</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Injected beam lost between FM and Ratchet Wall</td>
<td>OK*</td>
<td>BCS failure</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td>OK*</td>
<td>OK</td>
<td>BCS failure</td>
<td>OK</td>
</tr>
<tr>
<td>Injected Beam Lost past Ratchet Wall (Dipole Short)</td>
<td>BCS failure</td>
<td>OK</td>
<td>BCS failure</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td>BCS failure</td>
<td>OK</td>
<td>BCS failure</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td>BCS failure</td>
<td>OK</td>
<td>BCS failure</td>
<td>yes</td>
</tr>
</tbody>
</table>

* stored beam very unlikely

* local ray trace analysis requires $E_{inj} > 45\%$ - not possible

**NOTES:** all BCS systems redundant (2x)

FM = Fixed Mask
SCI = Stored Current Interlock

Corbett & Schmerge
1. Load operational lattice
   - software check of PS readbacks
2. Inject to <20 mA (orbit interlock)
3. Start orbit feedback (few microns)
4. Inject to 50 mA – top-off permit
5. Open beam line injection stoppers
6. Fill 500 mA maximum (FOFB runs continuous)
7. Fill-on-fill or trickle charge
Top up vs. top off

Which definition?

**top up** *vb.* *(tr., adv.*) **Brit.**

1. to raise the level of (a liquid, powder, etc.) in (a container), usually bringing it to the brim of the container:
   *top up the sugar in those bowls.*

**top off** *vb.*

*(tr., adv.)* to finish or complete, esp. with some decisive action:
*he topped off the affair by committing suicide.*