Preliminary Design of Injector Complex

NSLS-II Accelerator Systems Advisory Committee

October 8th, 2007

T. Shaftan for NSLS-II team

Outline

- Introduction
- NSLS-II injection requirements
- Top-off
- Injection system overview
- Linac
- Booster
- Transport lines
- Cost
- Schedule
- Summary

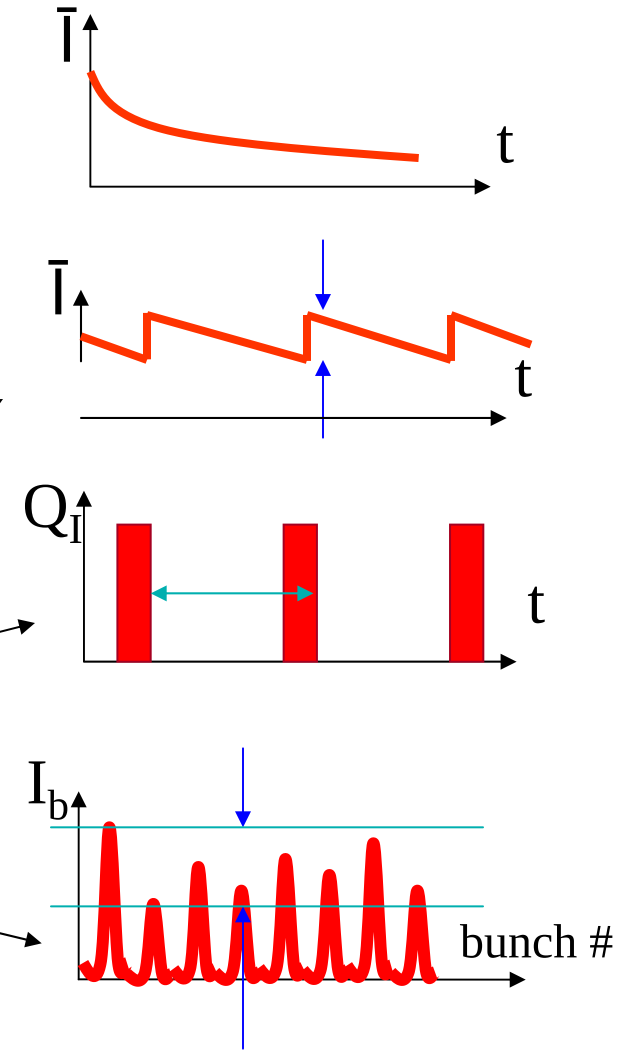
Introduction

- CD-1: in-tunnel booster → most economical solution
- Support from technical reviews
- Concerns expressed by Lehman review regarding booster-ring cross-talk and impact on installation schedule and troubleshooting
- Recommendation from Lehman review to develop injector with a "compact" booster
- Given short schedule: linac and booster are semi-turnkey procurements
- Transport lines and ring injection straight are by BNL
- Maximum energy for the injector is 3.1 GeV

Requirements for NSLS-II Injection

- High reliability
- Reasonable initial fill time
- Low losses

- Lifetime 3 hours (with 3rd HC)
- Top-off
  - Stability of current <1 %
  - Time between top-off injections >1 min
  - Bunch-to-bunch variations of charge <20%

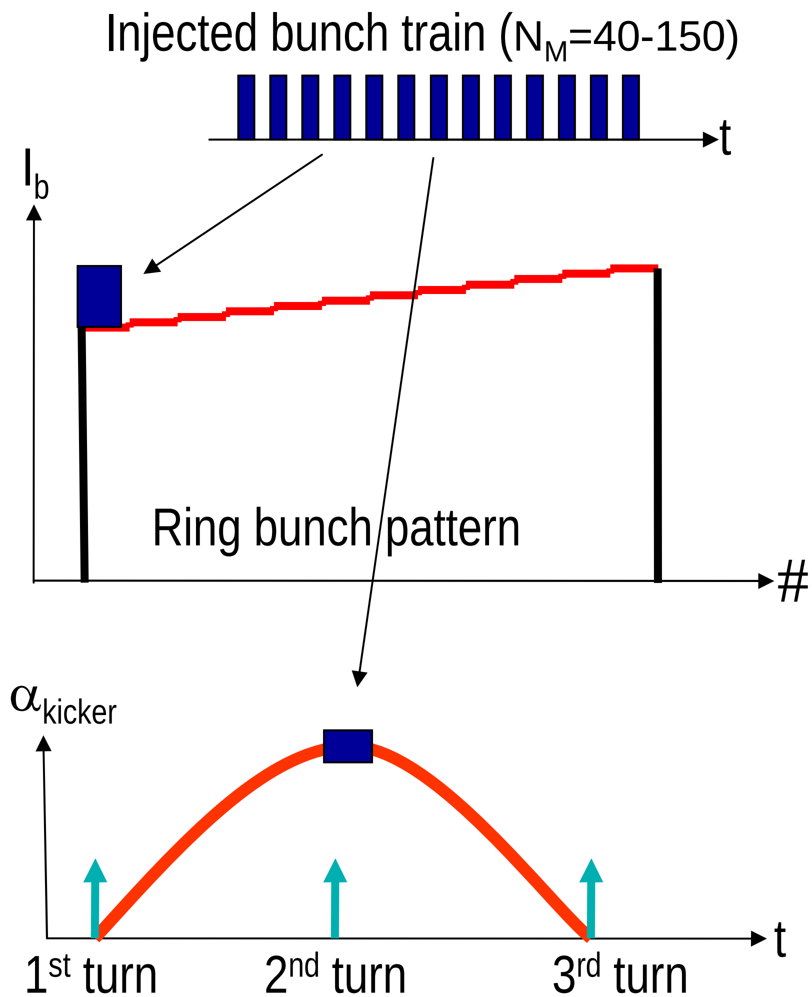


Ring Parameters Related to Injection

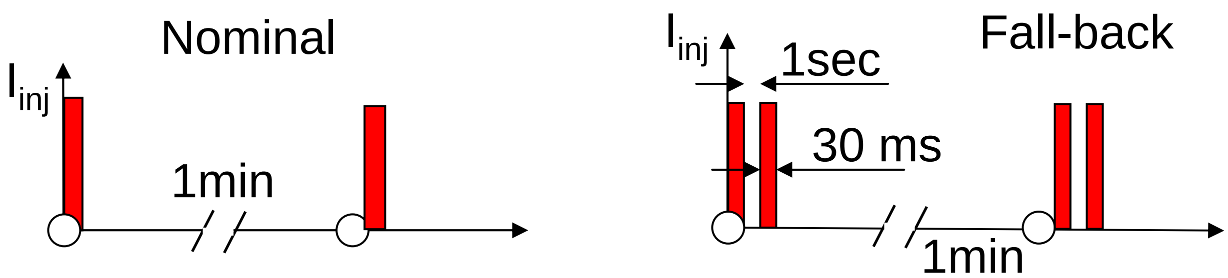
Parameter	Value
Energy, GeV	3
Circulating current, A	0.5
Circumference, m	792
Revolution period, μs	2.6
RF frequency, MHz (wavelength, m)	500(0.6)
Circulating charge, μC	1.3
Total number of buckets	1320
Number of filled buckets	1320·4/5≈1080
Charge per bucket, nC	1.25
Lifetime, hours	3
Interval between top-up cycles, min	1
Current variation between top-up cycles, %	0.55%
Charge variation between top-up cycles, nC	7.3

Injection Scenario

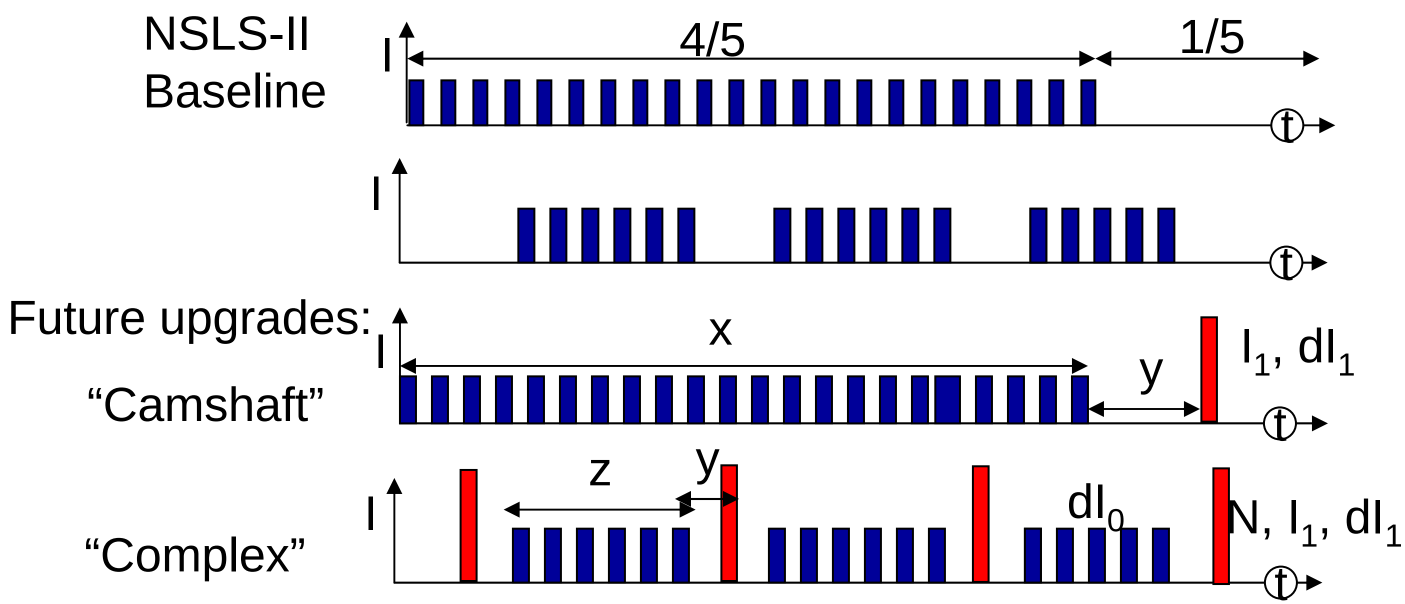
- Many (~1000) bunches in the ring → → multi-bunch injection
    - N_M bunches in the injected train
    - Filling N_M consecutive buckets in the ring
    - Sequentially shift the injection timing
- 1 Hz repetition rate suffices with pulse train injection
- 1 minute between top-off cycles
- Kickers duration are 2 turns long (5.2 μsec) or can be even longer
- Considered in ALS top-off (10 bunches)



Top-off formats and bunch patterns

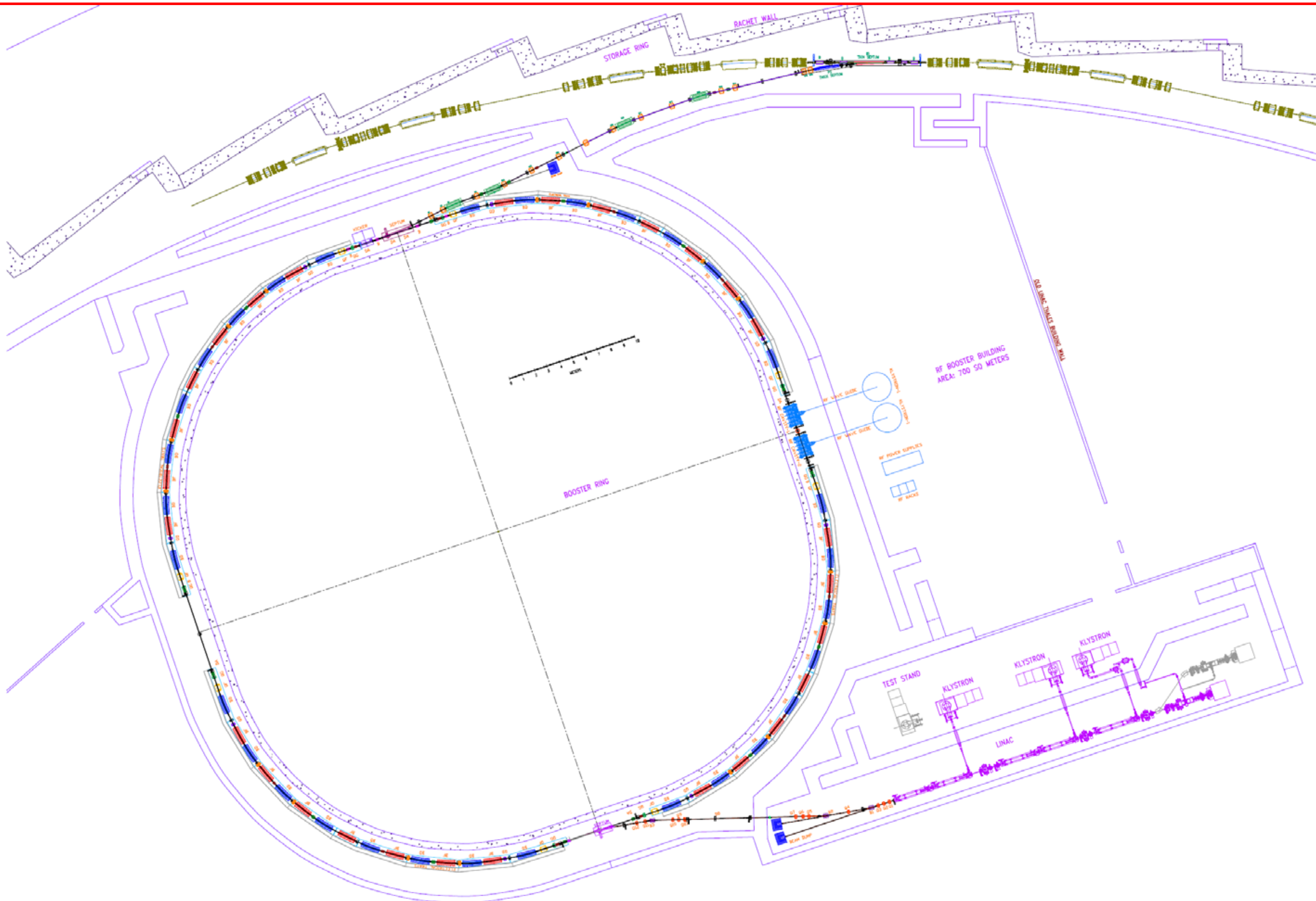


Top-off formats



Bunch patterns

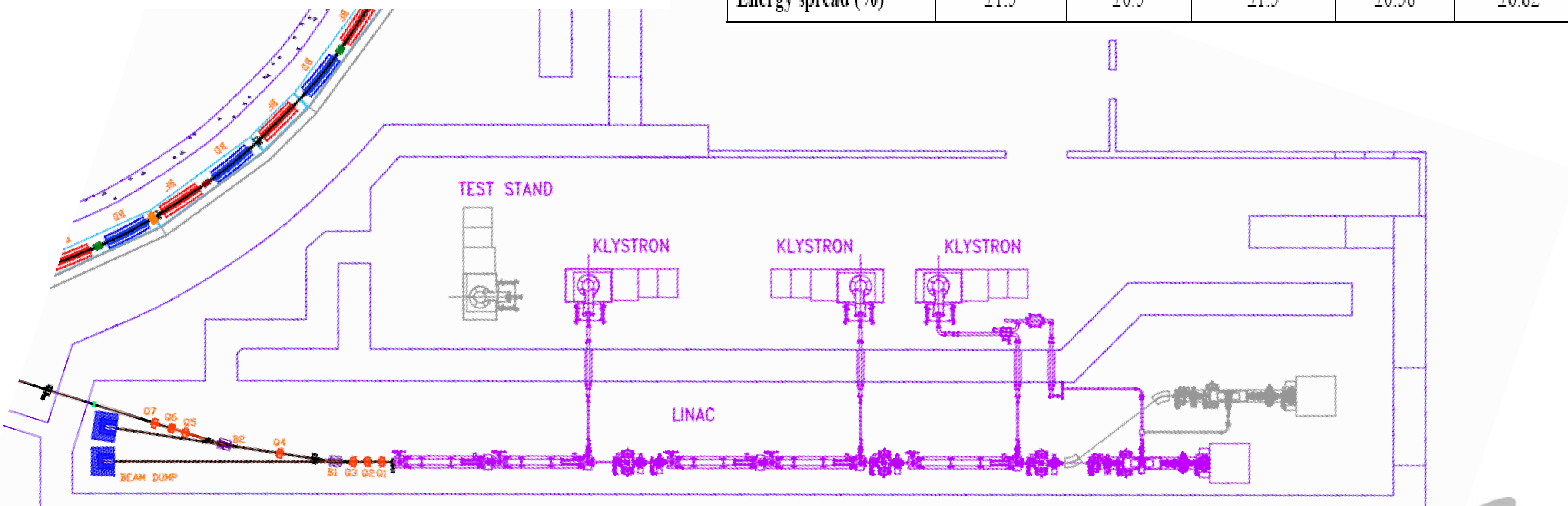
NSLS-II Injector Complex



Linac

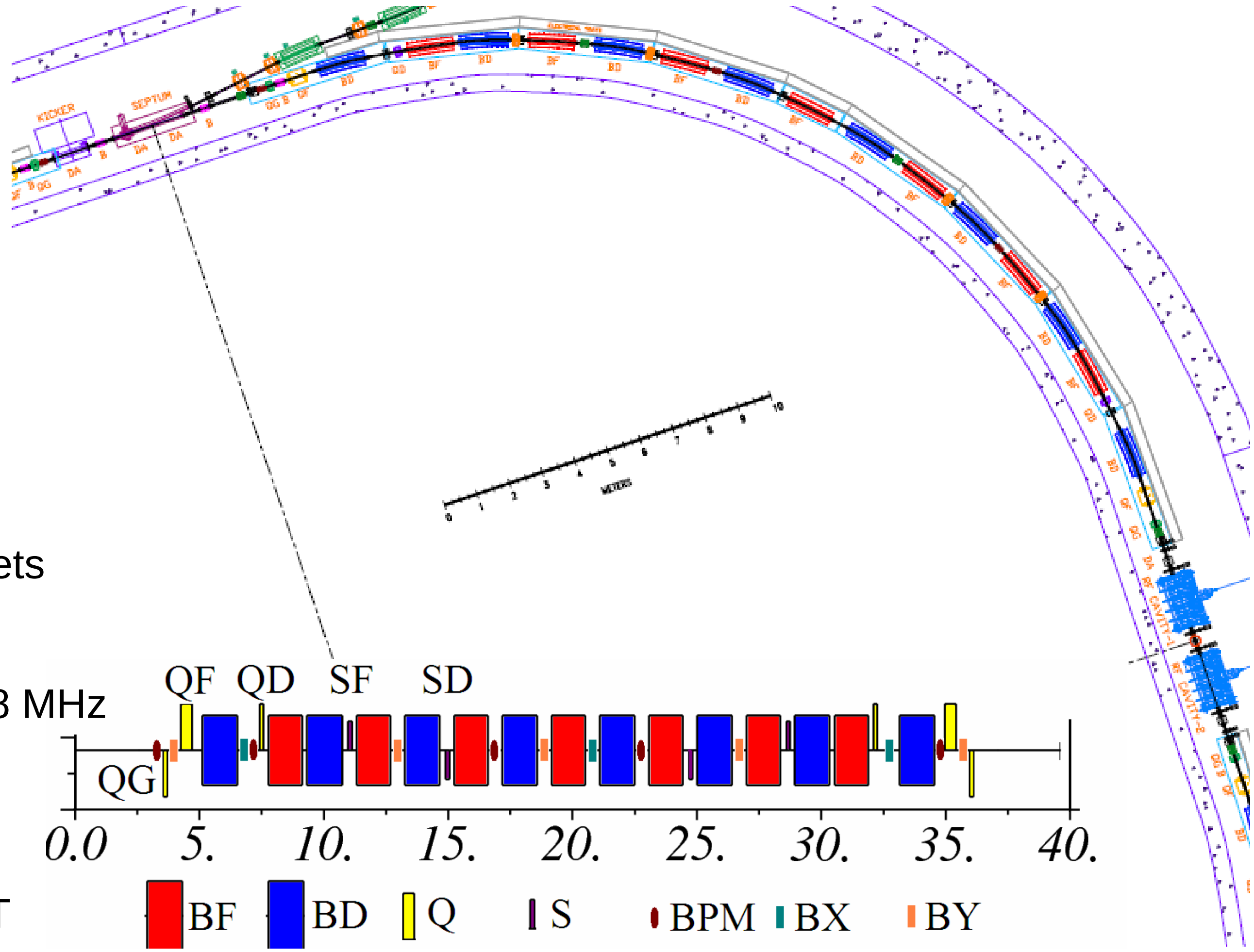
- NSLS-II: 200 MeV, 15 nC/train, ~0.5% energy spread
- 100 MeV linac from THALES is in operations for SOLEIL
- Achieved parameters:
  - 10 nC/pulse in LPM
  - 0.5nC/pulse in SPM
- Close to NSLS-II requirements

	LPM		SPM		
	Specified	Measured	Specified	Measured	
Pulses				1	4
Pulse length (ns)	300	286	<2	1.3	1.3
Energy (MeV)	>=100	108	>=100	110	110
Charge/Pulse (nC)	8	9.3	0.5 and 2	0.52	2.15
Emittance (mm.mrad)					
Horizontal (4βγσσ')	200	47	200	64	67
Vertical (4βγσσ')	200	52	200	67	78
Energy spread (%)	±1.5	±0.5	±1.5	±0.58	±0.82



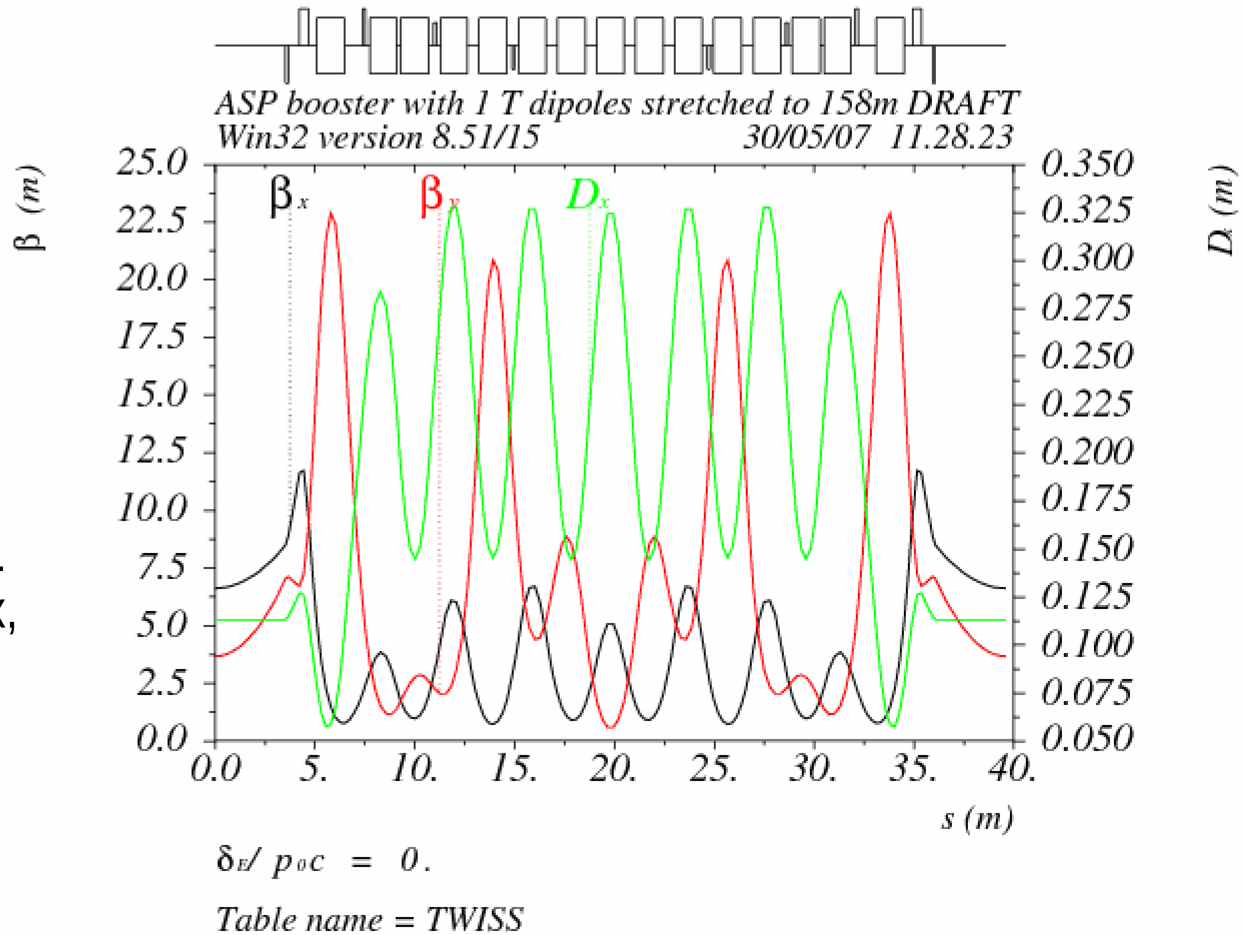
Booster Layout

- C=158.4 m (1/5 of SR)
- E =0.2→3 GeV
- Q =10 nC
- ε_x = 125 →30 nm rad
- σ_γ/γ=0.5→0.1%
- N_b =40-150 bunches
- F_{rep} =1 Hz
- 4-quadrant lattice
- 60 combined-function magnets
- 1 straight → injection
- 1 straight → RF (Two 499.68 MHz PETRA-type cavities)
- 1 straight → extraction
- Low magnet peak field of 1 T
- 200 MeV injection energy



Booster Lattice

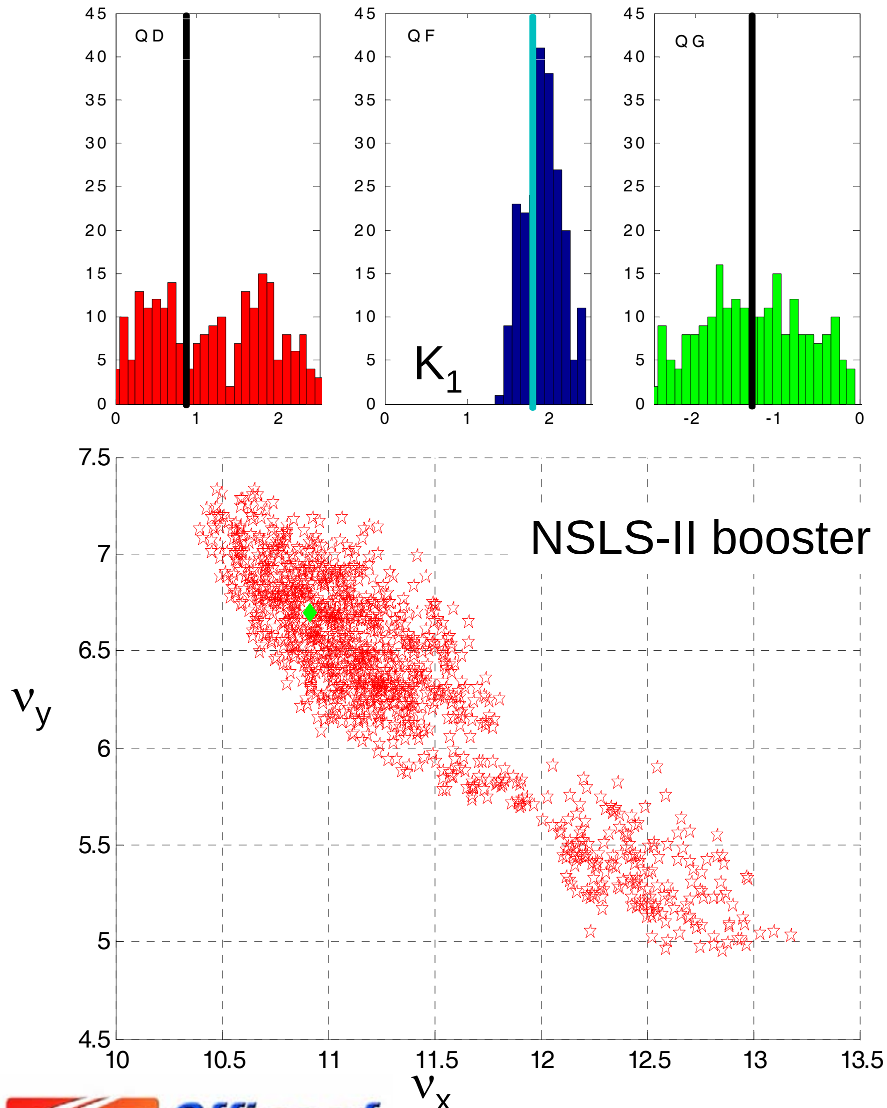
- ASPb-like solution
- Cost-effective design
- Periodicity of 4
- Combined function FODO lattice
- B, K_1, K_2 in dipoles
- Matching triplets (additional quad family for flexibility)
- Low dispersion in long straights
- Discrete sextupoles for eddy-current compensation (+0.5 x, -1.4 y max at 1Hz)
- Preliminary design

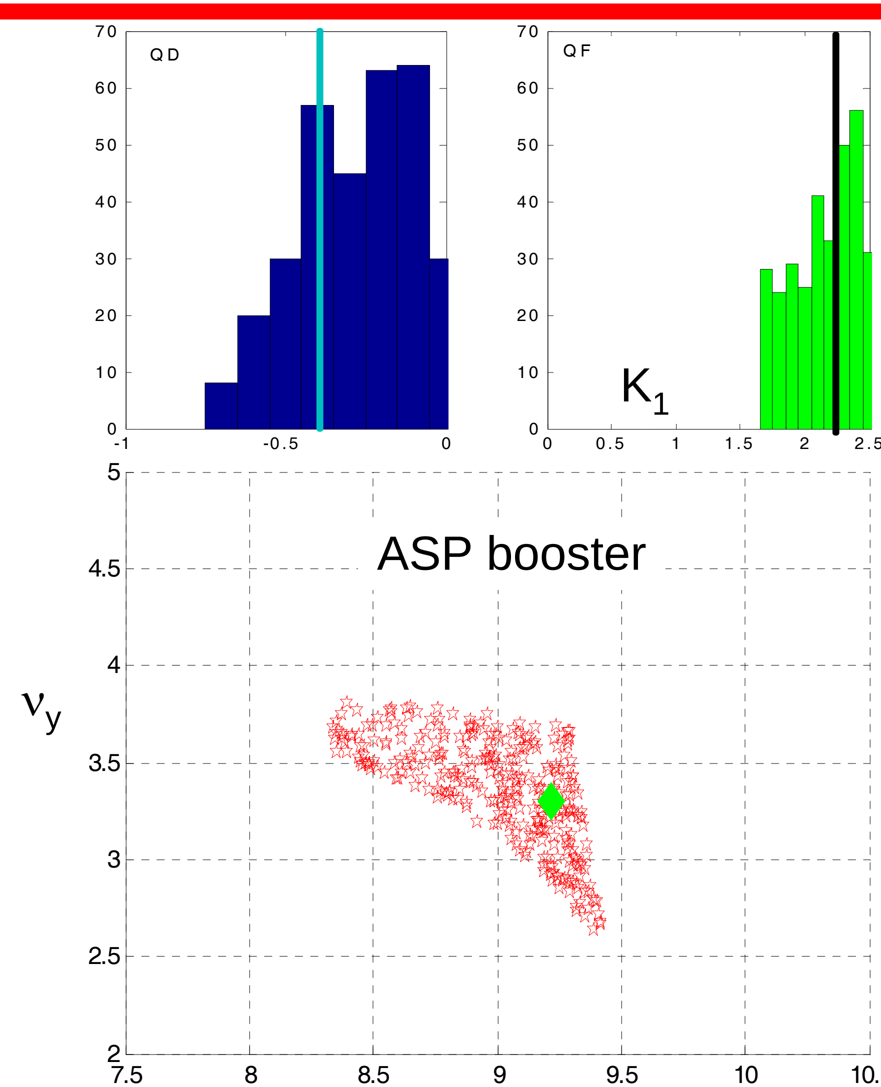


Booster parameters

Parameter	ASP booster	NSLS-II booster
Emittance, nm	34.4	26.6
Circumference, m	130.2	158.4
Revolution time, ns	434	528
RF frequency, MHz	499.654	499.68
RF voltage, MV	1.2	1.2
Harmonic number	217	264
X/Y tune	9.2/ 3.25	10.91/6.69
X/Y Chromaticity	-8.83/-11.5	-13.8/- 18.9
X/Y coupling	5%	
Corrected chromaticities	+0.83/+0.87	+1.7/+1.7
Momentum Compaction	0.0098	0.0072
Energy loss per turn, keV	743	625
X/Y/Z damping time, ms	2.7/3.5/2.0	5.4/5.1/2.5
Damped energy spread, %	0.094	0.078
Damped bunch length, mm	19	13.9

Flexibility of NSLS-II booster

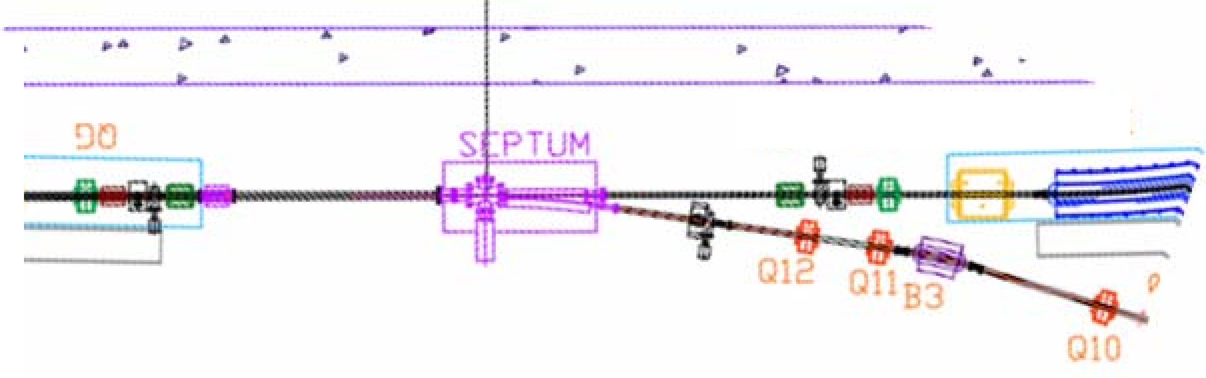




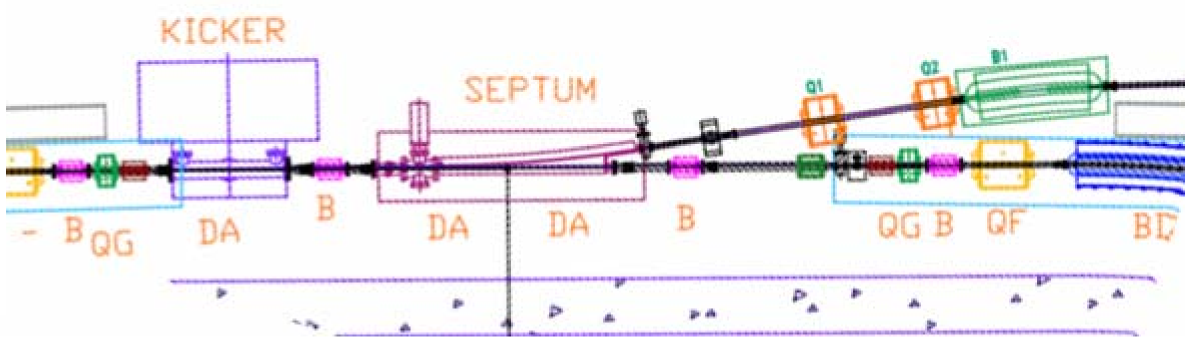
Booster injection and extraction

- Considering booster injection system be able to allow stacking of the low-energy beam at the maximum linac repetition rate of 10 Hz.
- Calculations are in progress of attempting to stack two consecutive (separated by 0.1 seconds) bunch trains transversely in the booster by injecting them with ½ of the nominal kicker strength.
- Combination of DC strong septum and pulsed weak kicker is preferable and will be explored for both injection and extraction

Booster injection



Booster extraction

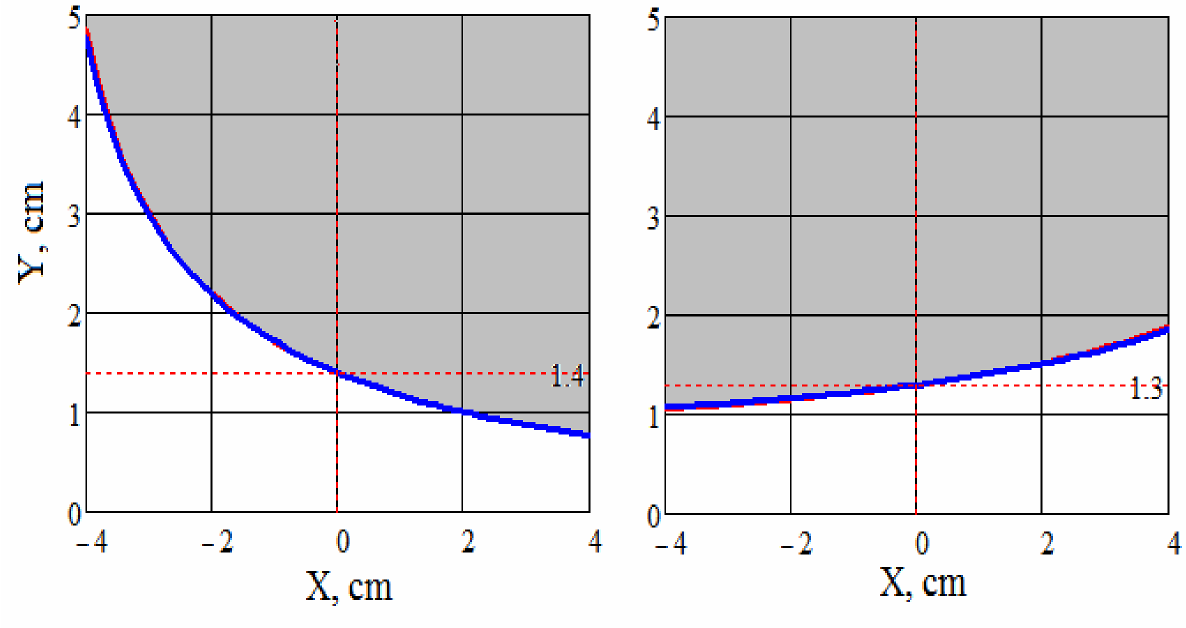


Part Count / Magnetic element properties

Parameter	ASP	NSLS-II
Number, BF/BD	28/32	28/32
Length, BF/BD	1.35/1.15 m	1.35/1.4 m
Angle, BF/BD	3.43/8.25°	3.43/8.25°
Injection energy	100 MeV	200 MeV
Field, BF/BD (inj)	0.015/0.042 T	0.030/0.069 T
Field, BF/BD (ext)	0.443/1.25 T	0.443/1.00 T
Quadrupole K1, BF/BD (ext)	0.82595/-0.66977 m^{-2}	0. 0.82800/-0.63831 m^{-2}
Sextupole K2, BF/BD (ext)	3.54/-4.925 m^{-3}	4.10/-5.65 m^{-3}

Parameter	ASP	NSLS-II
Number, QF/QD/QG	8/8	8/8/8
Length, QF/QD/QG	0.25/ 0.15 m	0.45/0.15/ 0.15 m
K1, QF/QD/QG (inj)	-0.0784/ 0.0133 m^{-2}	0.123/0.058 /-0.0869 m^{-2}
K1, QF/QD/QG (ext)	-2.351/ 0.400 m^{-2}	1.84/0.871 /-1.30 m^{-2}

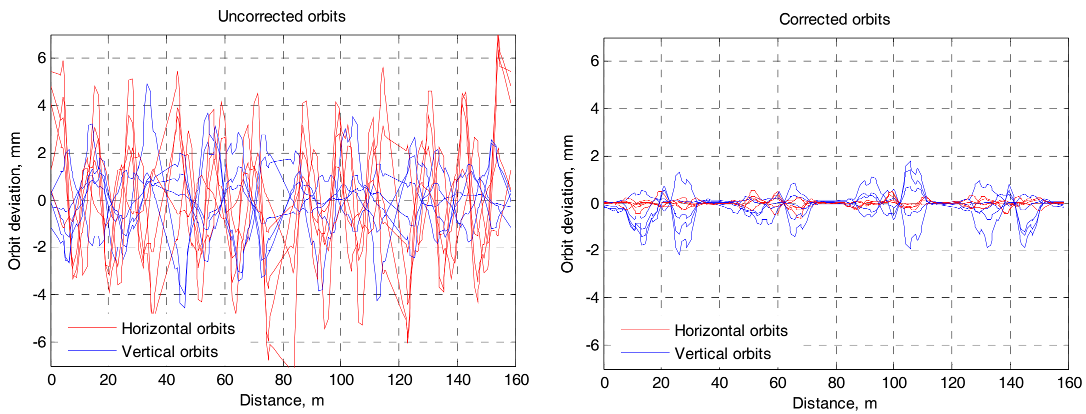
Focusing and defocusing dipole pole tips



Parameter	ASP	NSLS-II
Number, SF/SD	8/8	8/8
Length, SF/SD	0.2/0.2 m	0.15/0.15 m
K2, SF/SD (ext)	50/-30 m^{-3}	40/-40 m^{-3}

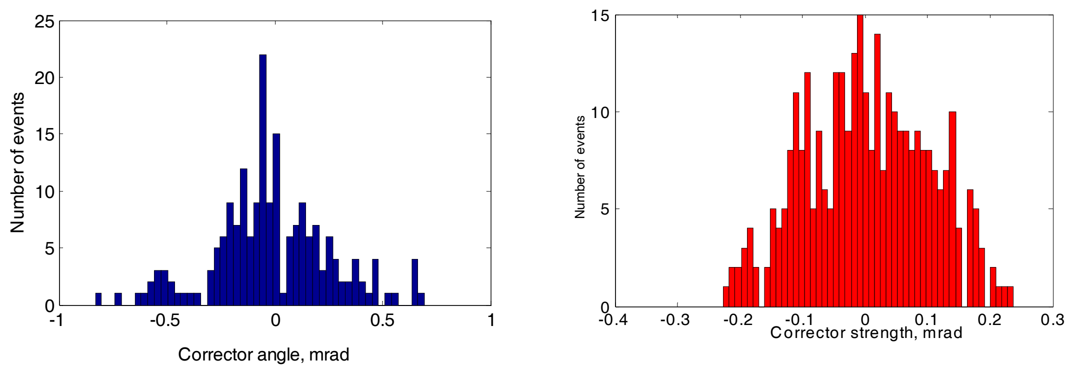
Thanks to S. Mikhailov (Duke Univ.)

Orbit correction and tolerances



Uncorrected and corrected orbits

(red - X, blue - Y)



Corrector maximum angles <1mrad

- Tolerances
  - Dipole length 0.1%
  - Dipole field 0.1%
  - Dipole ‖ displ. 1mm
  - Dipole ⊥ displ. 0.1mm
  - Dipole roll 0.5mrad
  - Quad ⊥ displ. 0.2mm
  - Quad gradient 0.02%

Diagnostics and Instrumentation for Booster

- Measured parameters

Parameter	Value	Accuracy
Current	30 mA	0.1%
Fill pattern	40-150 bun.	1%
Closed orbit		0.01 mm
Beta-functions	<30 m	
Dispersion	<35 cm	
X/Y Tunes	10.9/6.7	0.01
X geom. emittance	~30 nm·rad	10%
X/Y chromaticities	-13.8/-18.9	0.3
Coupling	<10%	1%
Bunch length	16 ps RMS	2 ps
Synchrotron Frequency	~20 kHz	1 kHz

- Continuously monitored beam parameters:
  - Current
  - X/Y Tunes
  - Orbit
  - Beam shape

- Diagnostics:
  - 20 X-Y BPMs
  - 1 DCCT
  - 2 striplines
  - 6 Fluorescent Screens
  - Fast Current Transformer
  - Synchrotron Light Monitor
  - Tune Measurement System
  - Bunch cleaner

- Comments:
- Booster is a turnkey procurement; diagnostics to be supplied by vendor according to our requirement
- Libera BPM receivers are functional at two revolution frequencies therefore the same modules suitable for both ring and booster

Layout of LB TL

- Diagnostics:
- Gun: 3 Wall Current Monitors
- Linac

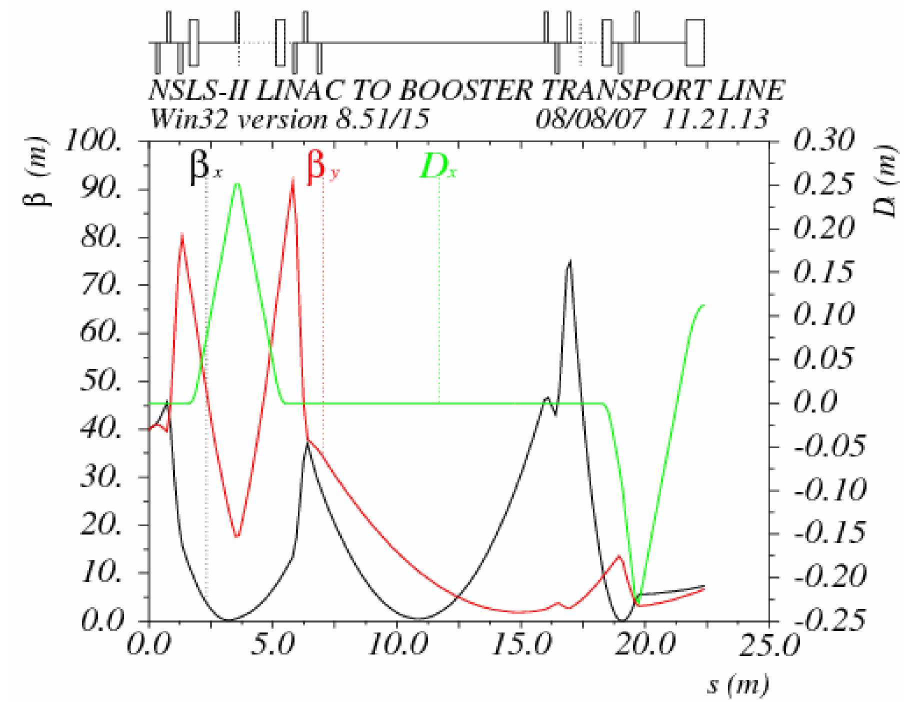
  4 Fluorescent Screens
  2 Current Transformers
- Linac to Booster Transfer Line

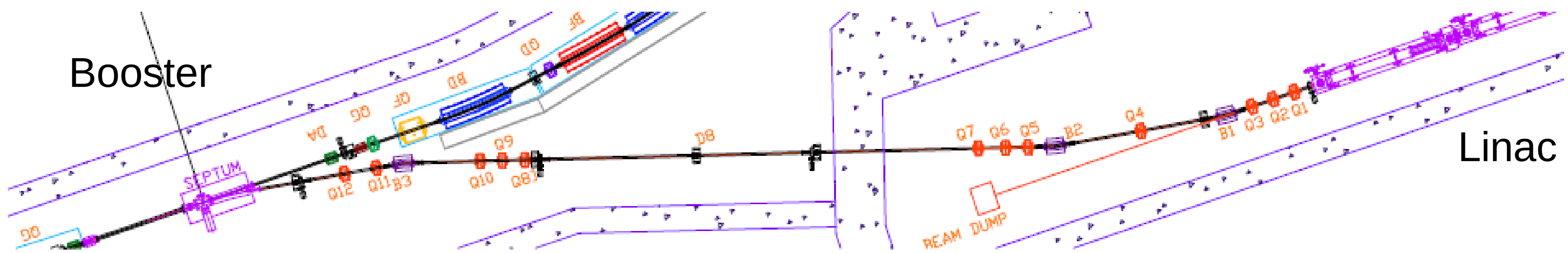
  5 Fluorescent Screens

  Integrating Current Transformer

  3 Four-Button pick-ups

- E =200 MeV
- Q =15 nC
- ε_n = 50 mm mrad
- σ_γ/γ= 0.5%
- N_b =40-150 bunches
- LB TL will allow fast linac commissioning

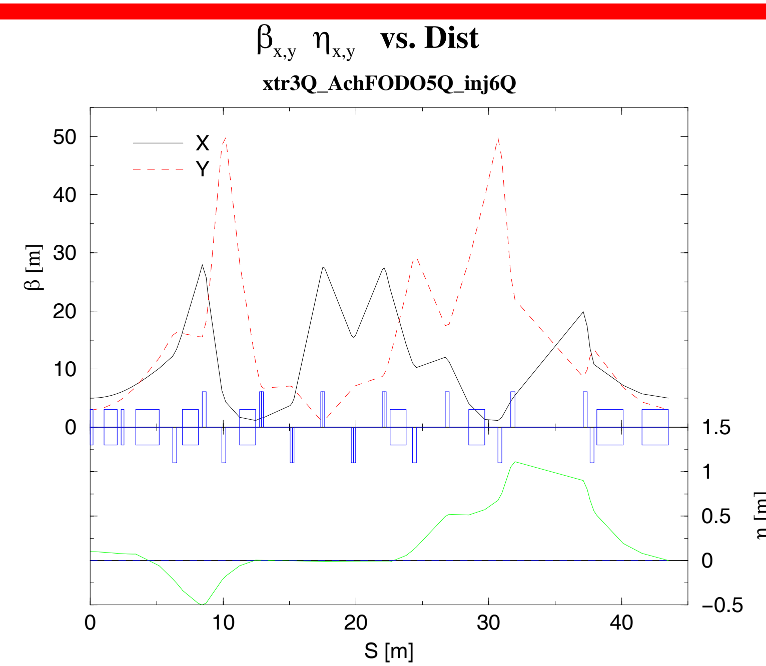


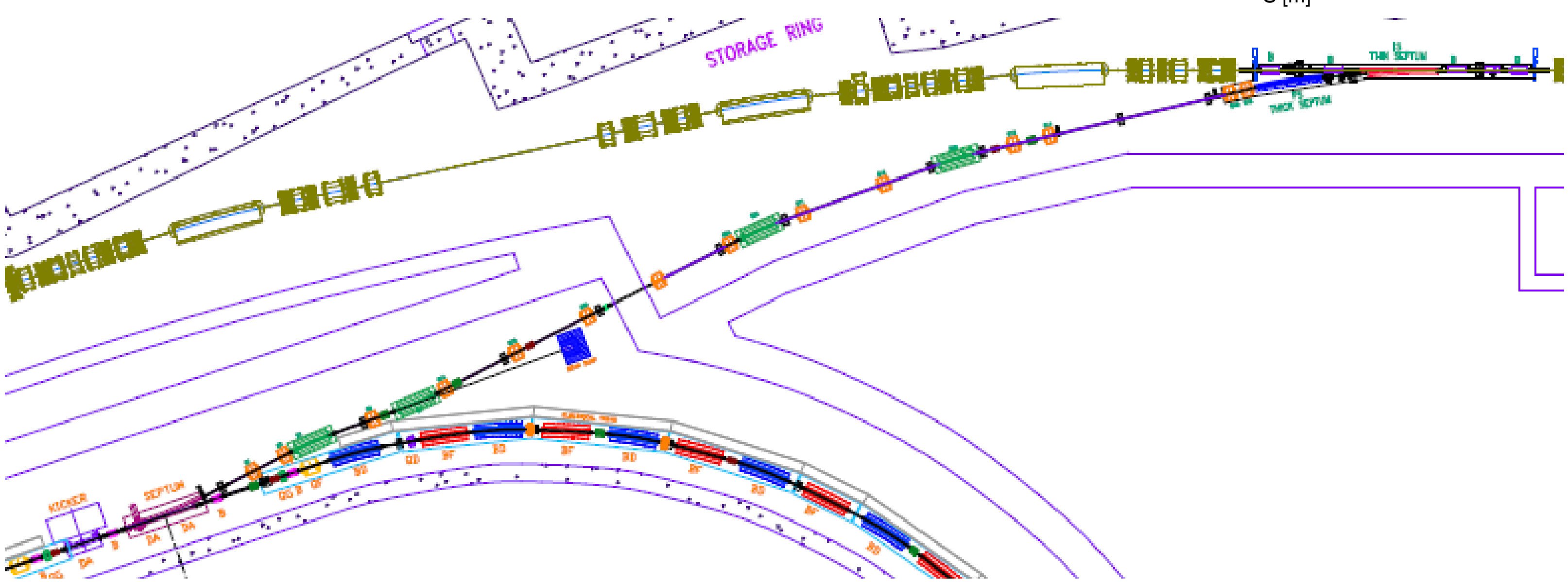


Layout of BSR TL

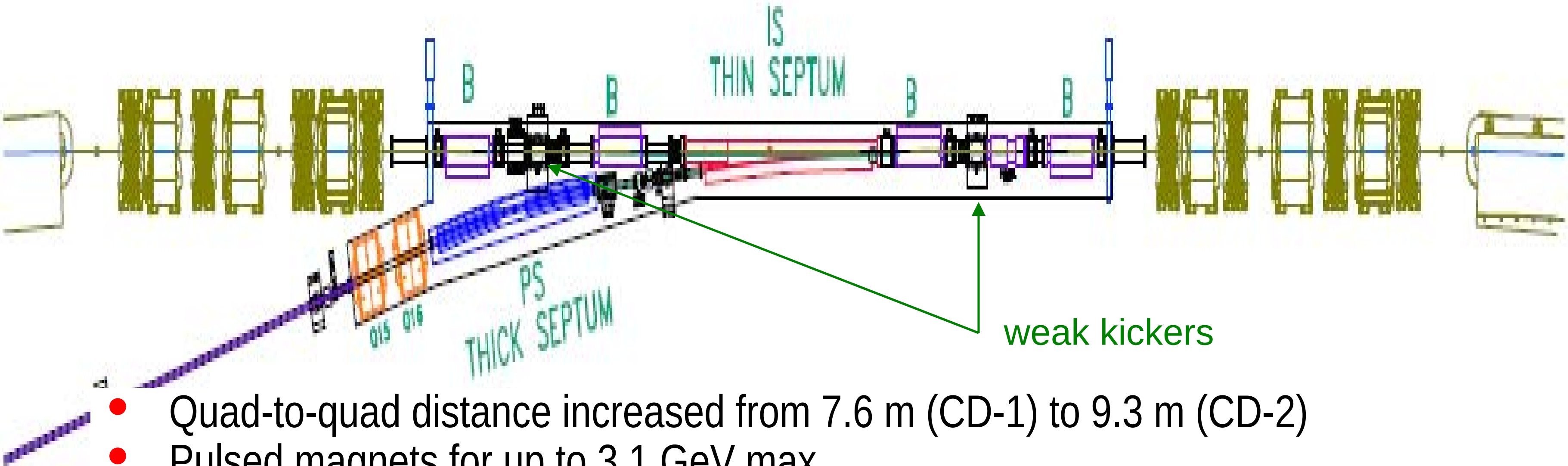
- E =3 GeV
- Q =10 nC
- ε_x = 30 nm rad
- σ_γ/γ=0.1%
- N_b =40-150 bunches

- Diagnostics:
  - 6 Fluorescent Screens
  - Integrating Current Transformer
  - 6 Four-Button Pick-ups with Libera receivers
  - Two Cameras with external trigger





Storage ring injection straight



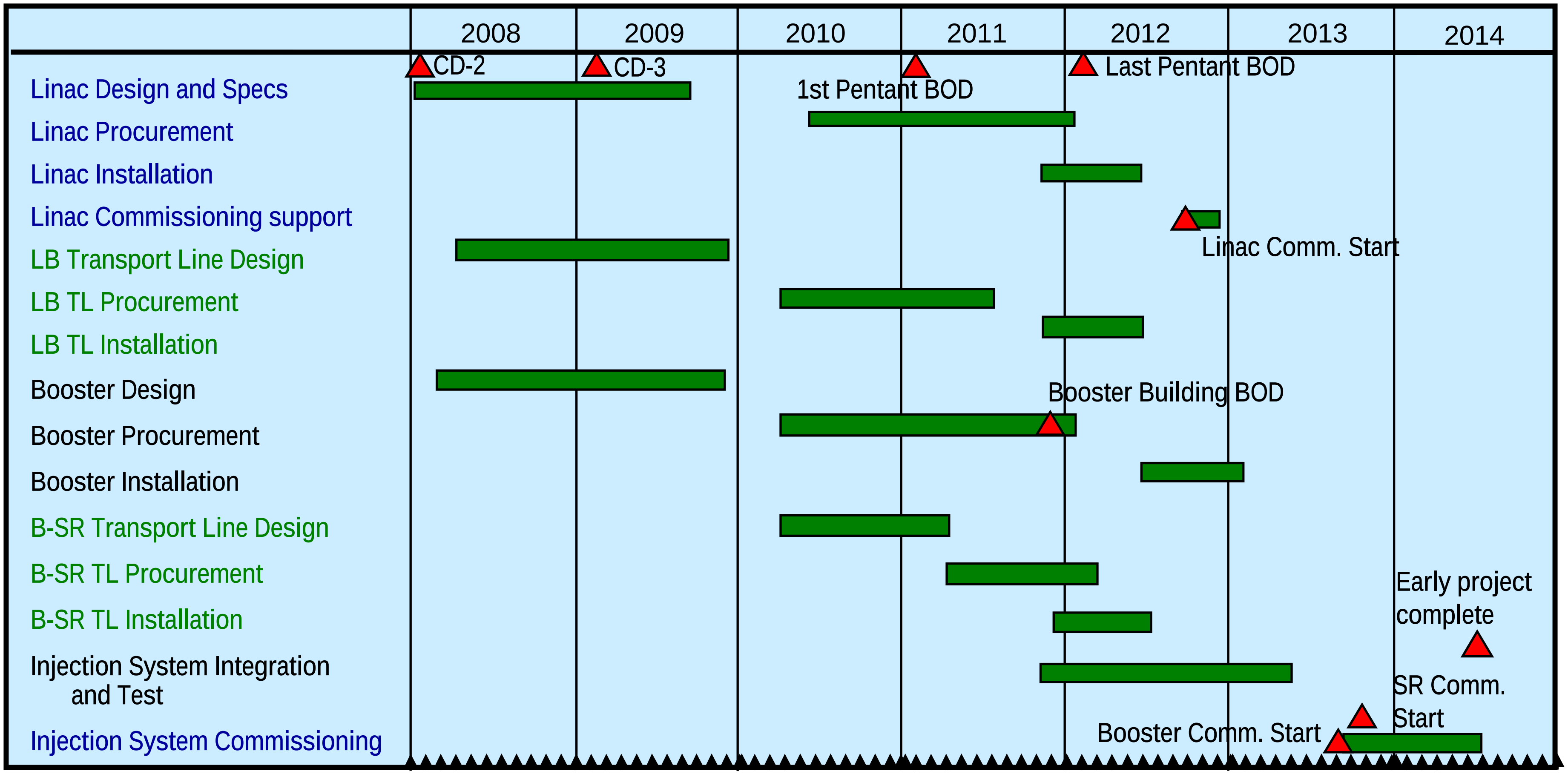
- Quad-to-quad distance increased from 7.6 m (CD-1) to 9.3 m (CD-2)
- Pulsed magnets for up to 3.1 GeV max
- Combination of strong DC pre-septum with pulsed septum
- Closed bump of 15 mm
- Kickers with 5.2 μs long pulse powered separately
- Pulsed magnets are within vendors capabilities
- Proposal on development and optimization of pulsed magnets and PS (total of 13 magnets for NSLS-II) in-house: Pulsed Magnet Lab

Injector cost

Activity	Labor, hr	Bare Cost, M$
Linac	4087	9.963
Booster	16139	17.23
L-B TL	7163	1.345
B-SR TL	9796	1.808
Injector utilities	5015	0.871
Injector installation	16644	1.107
Injector testing	9308	0.731
Injector commissioning	9659	0.743
Total:	44.62 FTE	33.754

- Large procurements: Linac (~9M$) and Booster (~15M$)

Schedule



2008
2009
2010
2011
2012
2013
2014
CD-2
CD-3
1st Pentant BOD
Last Pentant BOD
Linac Design and Specs
Linac Procurement
Linac Installation
Linac Commissioning support
Linac Comm. Start
LB Transport Line Design
LB TL Procurement
LB TL Installation
Booster Design
Booster Building BOD
Booster Procurement
Booster Installation
B-SR Transport Line Design
B-SR TL Procurement
B-SR TL Installation
Early project complete
Injection System Integration and Test
SR Comm. Start
Booster Comm. Start
Injection System Commissioning

Summary

- NSLS-II full energy injector will support top-off operations in presence of short beam lifetime
- Multi-bunch injection with high charge per bunch train
- Linac and booster are semi-turnkey procurements
- NSLS-II booster is based on existing ASP design with some modifications
- We choose low-emittance cost-effective solution for NSLS-II booster
- We developed design of injection straight and transport lines
- Injector cost and schedule are developed
- Preliminary level of design

Acknowledgements

J. Rose, I. Pinayev, R. Heese, S. Ozaki, F. Willeke, W. Guo, B. Nash, J. Bengtsson, E. Johnson,

R. Meier, S. Sharma, D. Hseuh, N. Tsoupas,

G. Ganetis, H. Nishimura, D. Robin, T. Shaftan,

J. Skaritka, R. Grubb, J. O'Connor, C. Lavelle,

T. Mennona

Back-up

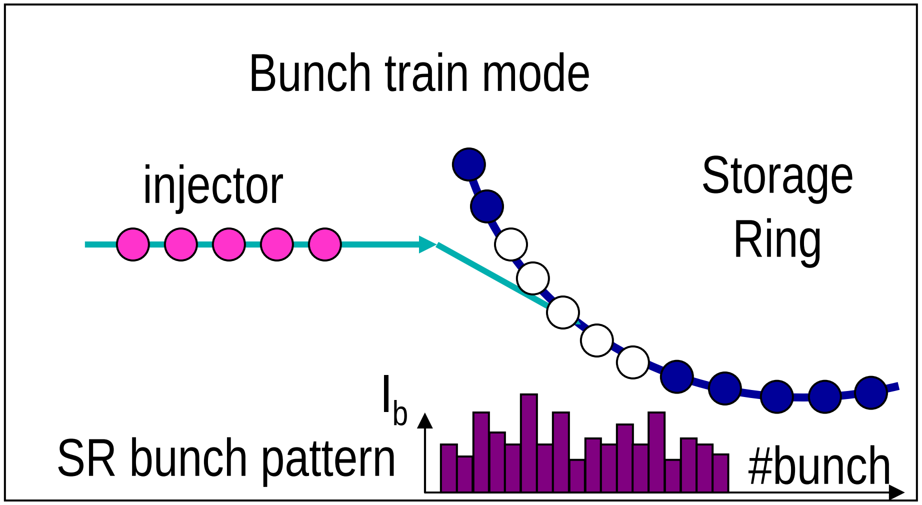
Previous ASAC comments

Injection System with a Booster in Separate Tunnel (T. Shaftan)

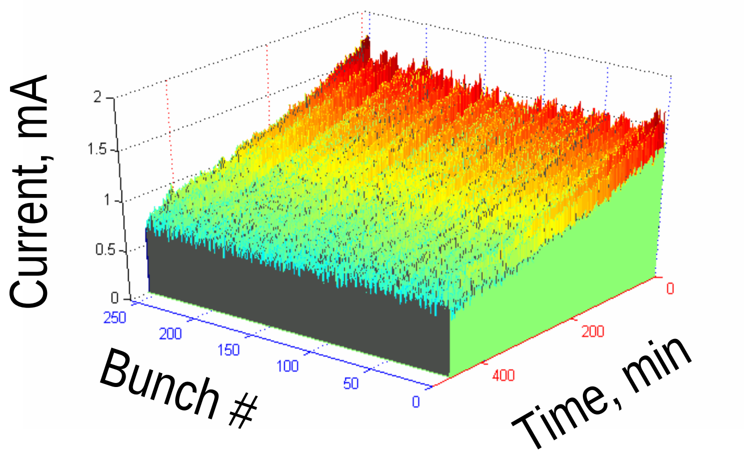
- The committee is pleased with the injection tracking studies and recommends their continuation, including all insertion device effects and lattice errors.
- From experience elsewhere, the committee is not fully convinced that the present high beta straight for injection is long enough to accommodate injection equipment, and in particular is fully compatible with state of the art top-up requirements. In order to assess the adequacy of available space, an engineering layout of the injection straight of the storage ring should be generated. It is the feeling of the committee that a longer straight for injection could easily be accommodated in the lattice (see comments above).
- A possible operation at a 3.6 GeV energy was mentioned several times and the committee recalls that if NSLS-II intends to run at this energy, it should be included in the specifications of all systems such as magnets, absorbers, RF, Booster, and injection/extraction systems.
- The committee recommends a horizontally movable septum magnet at the ring injection point in order to ease commissioning through a near on-axis injection configuration as well as to optimize the kicker currents in relation to the final horizontal aperture.
- The Australian Light Source booster lattice design which is used as a reference design for the proposed booster lattice presents the drawback of limited flexibility in the tunes. The committee recommends the investigation of solutions which increase the accessible tune range.
- The proposed lattice for the booster synchrotron is pretty tight and the committee ask for an engineering layout in order to check that there is enough space for the correctors, diagnostics, vacuum pumps, etc. The committee recommends that the space required and the positioning of injection and extraction magnets inside the booster lattice be investigated (in particular the impact of the high value of the dispersion function in the injection and extraction straights has to be evaluated as well as the low beta values).
- The committee notes that there is no definite requirement yet for hybrid filling modes, but nevertheless recommends including this capability from the outset, since a need is almost certain to arise in the future.
- Regarding the issue of whether or not to use a single power supply for all storage ring injection kicker magnets, the committee believes that there will inevitably be differences from kicker to kicker (due to mechanical tolerances, thickness of ceramic coating, etc.). So the committee recommends that individual power supplies be used in order to optimize the bump closure and hence minimize the disturbance of the stored beam, in view of top-up operation.

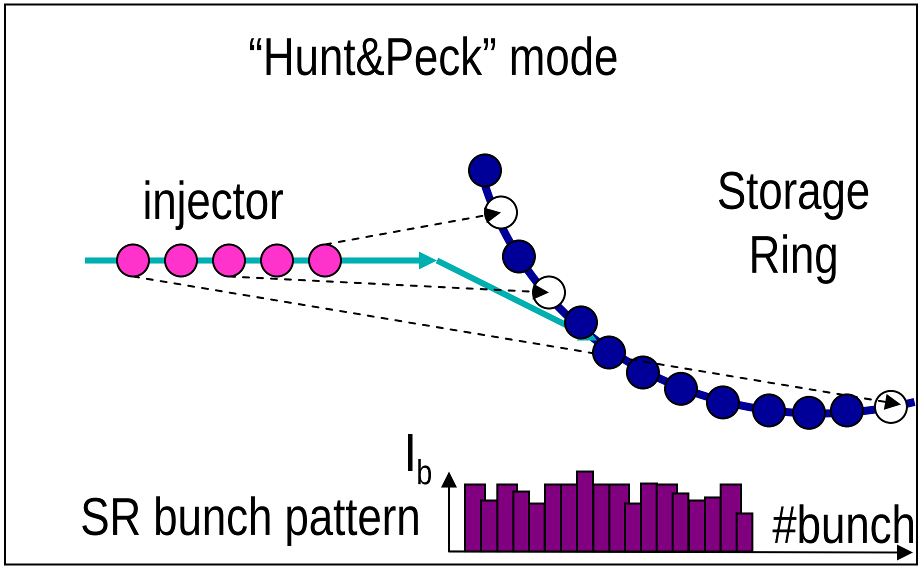
Multi-bunch Injection

- Short lifetime → multi-bunch mode
- SLS experience: feedback for enhancement of the bunch pattern purity
- "Hunt&Peck" mode: is it necessary for NSLS-II ?
- Studies at ALS on pattern evolution



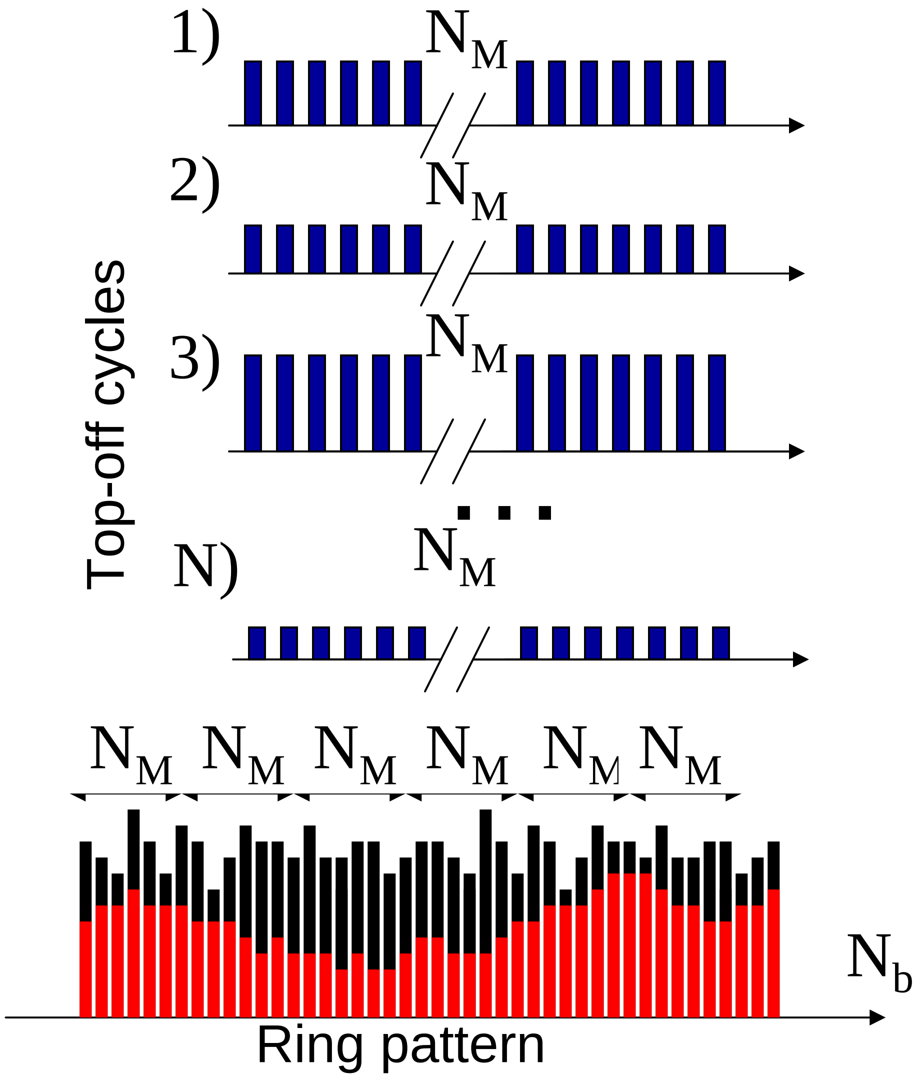
Studies at NSLS and ALS (in progress)





"Hunt & Peck": Adjusting Average Value

- Measure charge in the ring buckets
- Every top-off cycle adjust gun grid voltage → adjust charge per bunch
- Inject macropulse (N bunches) with average charge equal to missing charge in N-bunches in the ring
- Eliminates all bunch-bunch variations on $N_b > N_{MICRO}$ scale
- Can be done is "sequential" or "hunt & peck" modes
- Reducing harmonics of SR bunch pattern: requires R&D



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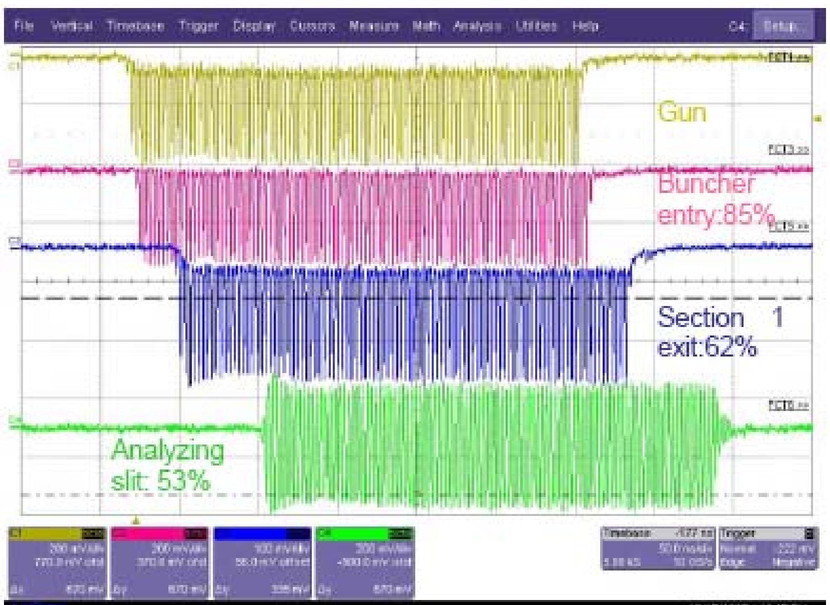
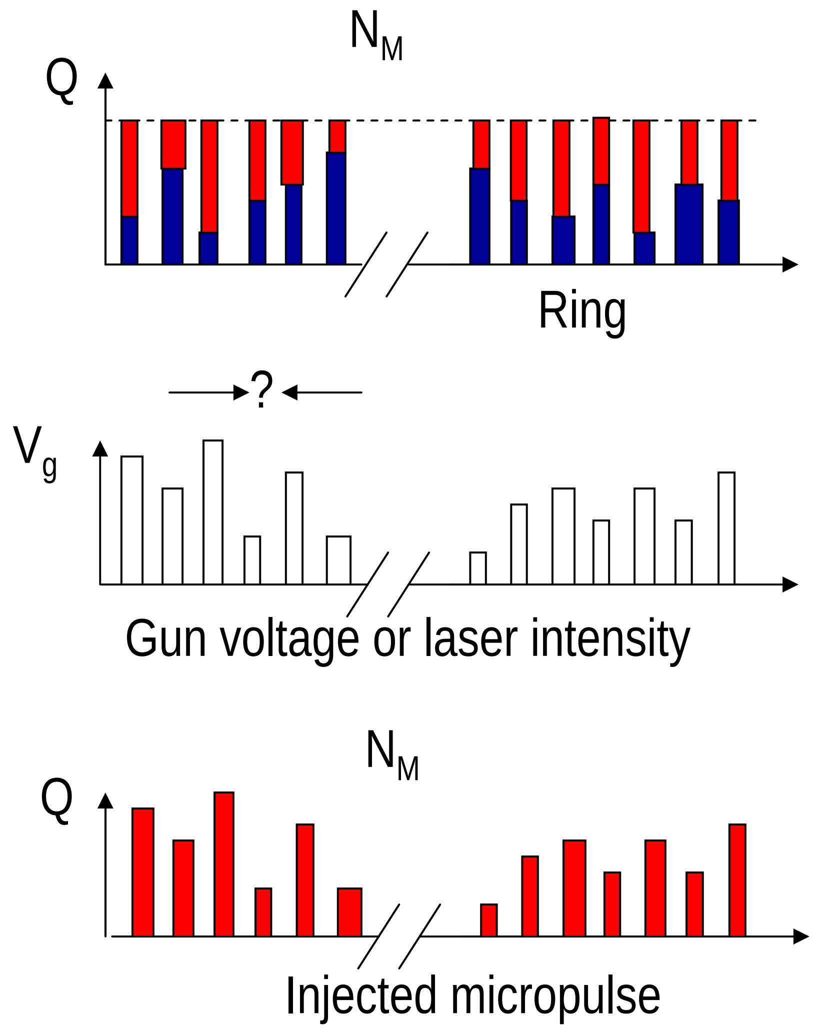
"Hunt & Peck": Fast modulation of macropulse

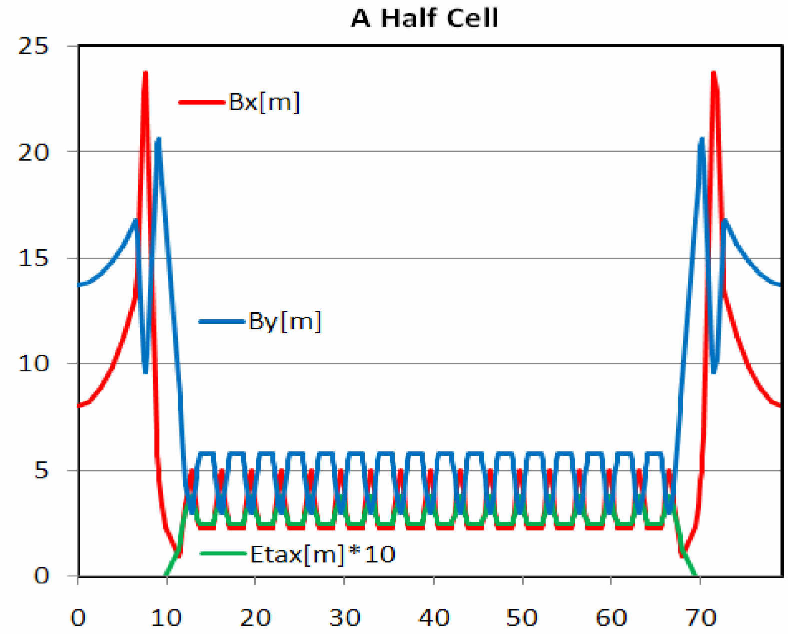
- Measure charge in the ring buckets
- Modulate gun voltage (laser intensity) with inverse of the charge/bunch in the pattern
- or
- Stack bunches in the booster via multiple injections
- Inject "premodulated" macropulse into the ring

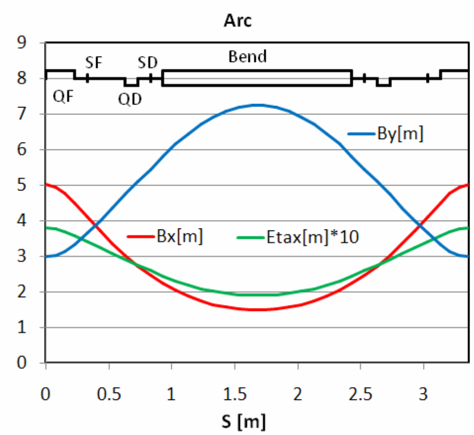


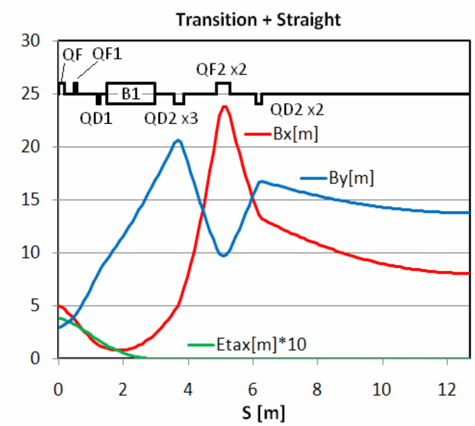


Alternative version by H. Nishimura (ALS)

- Circumference = 158.40000 [m]
- Betatron Tunes X/Y = 9.26706/ 4.19942
- Momentum Compaction = 7.51991E-003
- Chromaticity H = -11.46993
  V = -7.17248
- Radiation Loss = 8.33737E+002 [keV]
- Natural Energy Spread = 1.45518E-003
- Natural Emittance = 1.61981E-008
- Radiation Damping H = 1.67192 [msec]
  V = 3.80238 [msec]
  E = 5.23937 [msec]
- Periodicity of 2 (racetrack)
- Combined function FODO lattice
- B, K_1 in dipoles
- 2 s_x, 2 s_y sextupoles per cell
- Booster Dynamic Aperture gives about ±30 mm in both planes (in middle of straight)
- Needs more realistic chromaticity correction
- Preliminary design







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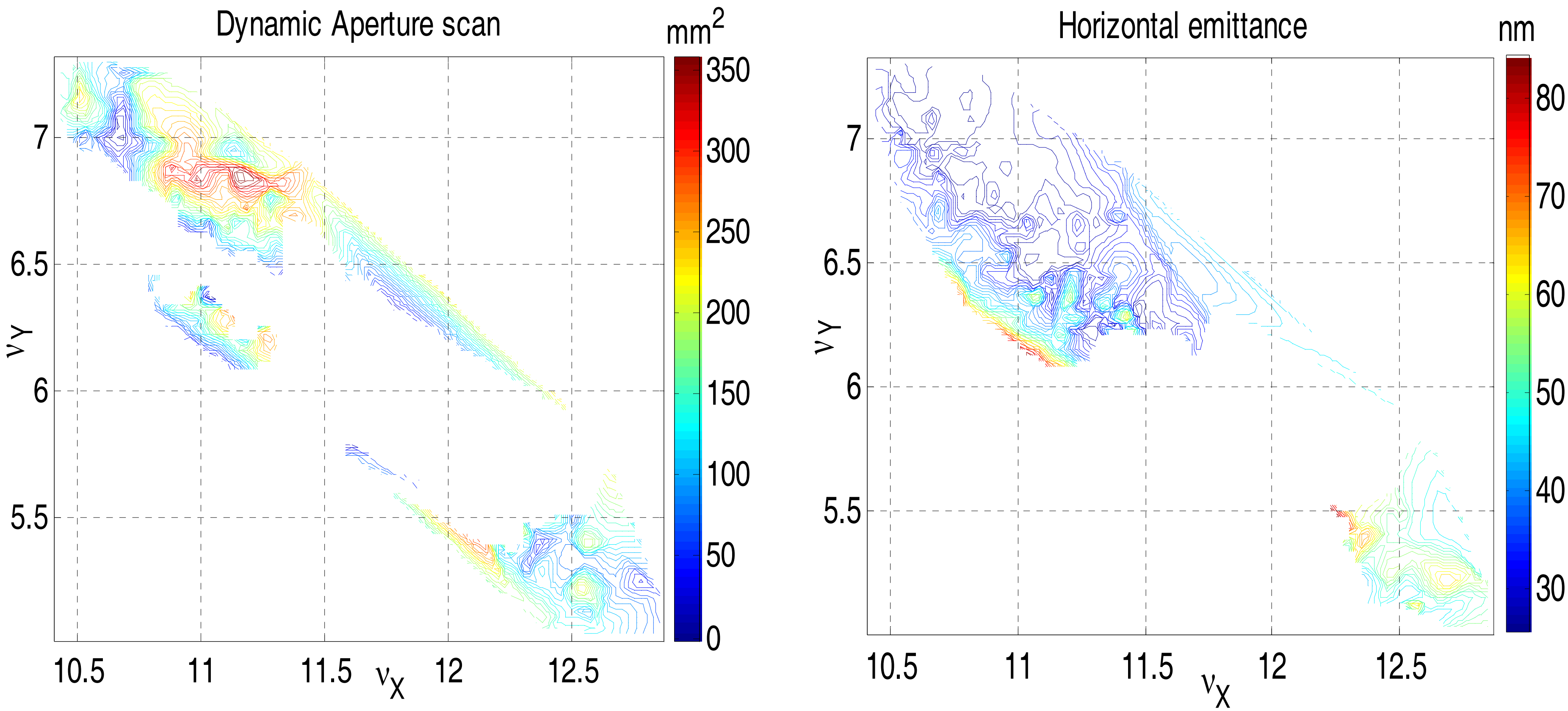
DA and Emittance scan



- Maximum of DA is ±10 mm in both planes
- Emittance of 26 to 100 nm·rad within tune footprint
- Broad range of optics solutions

Diagnostics in Linac & Linac-to-Booster Transport Line

- Measured parameters (at Linac exit):

Measured parameters (at Linac exit)	Value	Accuracy
Charge	15 nC	0.2%
Fill pattern		
Energy	<270 MeV	0.5%
Energy spread	<0.5% RMS	0.05%
Beam positions		0.1 mm
Beam sizes	~2 mm	0.1 mm
Norm. emittances	~50 mm·mrad	5%

- Continuously monitored beam parameters:
  - Charge
  - Energy
  - Beam positions
  - Bunch train pattern
- Diagnostics:
- Gun:
  - 3 Wall Current Monitors or Fast Current Transformers
- Linac
  - 4 Fluorescent Screens
  - 2 Integrating Current Transformers
- Linac to Booster Transfer Line
  - 5 Fluorescent Screens
  - Integrating Current Transformer
  - 3 Four-Button Pick-ups with Libera BPM receivers

- Comments:
- Linac is a turnkey procurement; diagnostics to be supplied by vendor according to our requirement; transport line we are developing ourselves
- Diagnostics suite must enable early commissioning of Linac and demonstration beam parameters required for lossless injection into Booster
- Charge monitoring will be used for interlocks

Diagnostics in Booster-to-Storage Ring Transport Line

- Measured parameters (at Booster exit):

Measured parameters	Value	Accuracy
Charge	10 nC	0.2%
Fill pattern		
Energy	3 GeV	0.5%
Energy spread	<0.1% RMS	0.05%
Beam positions		0.1 mm
Beam sizes	<1 mm	0.1 mm
Geom. emittances	~30 nm·rad	5%

- Continuously monitored beam parameters:
  - Charge
  - Energy
  - Beam profile and position
  - Bunch train pattern

- Diagnostics:
  - 6 Fluorescent Screens
  - Integrating Current Transformer
  - 6 Four-Button Pick-ups with Libera receivers
  - Two cameras with external trigger capability

- Comments:
- Transport Line we are developing ourselves
- Diagnostics suite must enable early commissioning of Booster and demonstration of beam parameters required for lossless injection into Storage Ring
- Charge monitoring will be used for interlocks

Injector Service Area

1. Booster Service Area (20 m x 8 m) 160 m^2

2. L-B TL Service Area (3 m x 10 m) 30 m^2

3. B-SR TL Service Area 57 m^2

4. AC power disconnects/ switch gear 24 m^2

5. 2 entry labyrinths 2· (3 m·3 m) 18 m^2

7. Bathroom 25 m^2

8. Local Injection System Control room 54 m^2

10. Equipment storage area (spare parts and test instruments) (9 m ·9 m) 81 m^2

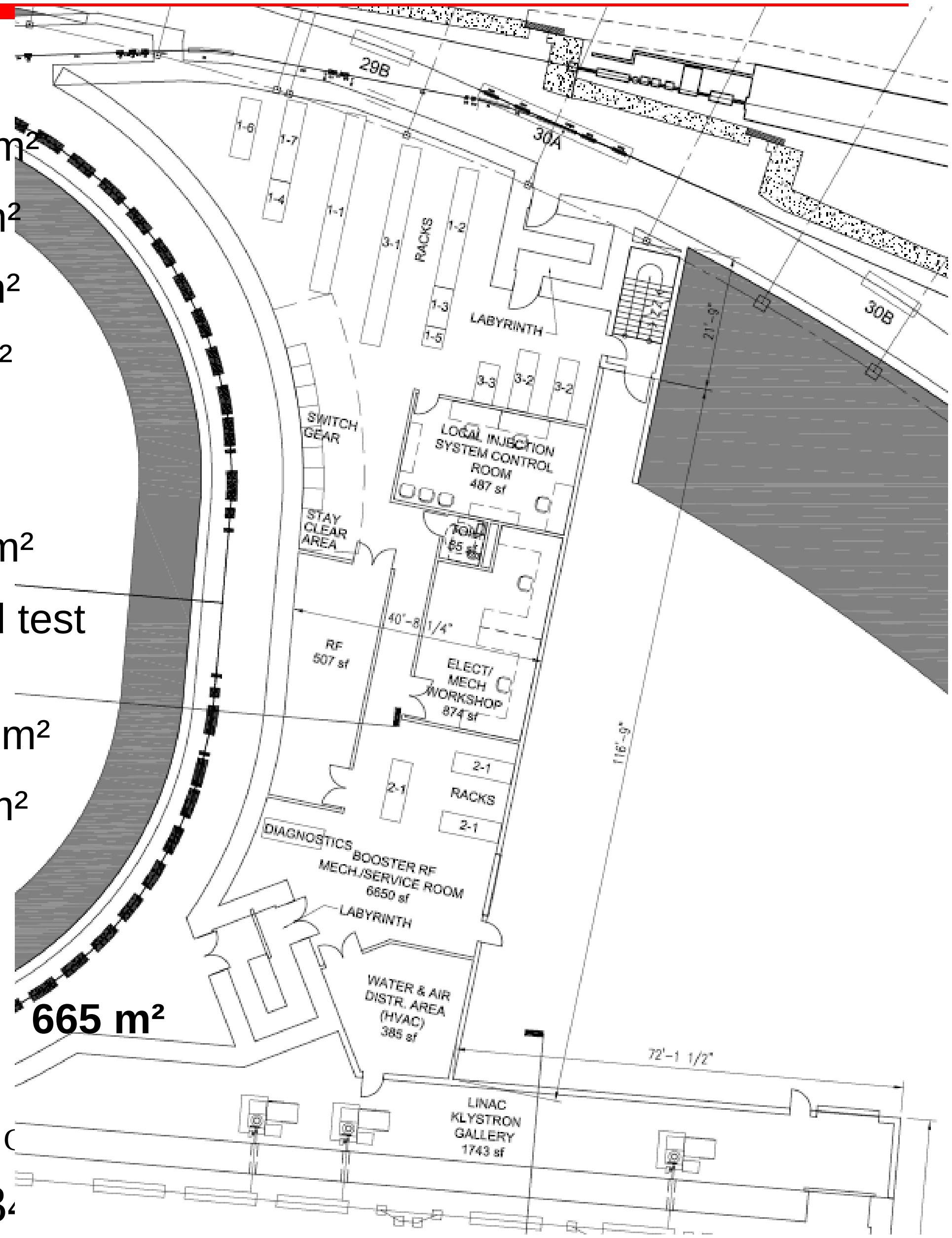
11. Electronic/Mechanical Workshop 100 m^2

12. Water and air distribution area 36 m^2

Total square footage 585 m^2

Walkways and corridors: 80 m^2

Total for building: **665 m^2**



Booster Schedule

Activity Name	Original Duration	Finish
Built-In Days for Funding Profile - Booster	389	21-Apr-09
Booster Ring - Preliminary Design/Specification	83	19-Aug-09
Booster Ring - Prepare Solicitation	42	19-Oct-09
Booster Ring - Vendor Selection	90	03-Mar-10
Booster Ring - Award Contract	0	03-Mar-10
Booster Ring - Detail Design Vendor	292	29-Apr-11
Booster Ring - Detail Design Support	292	29-Apr-11
Booster Ring - Design Finished	0	29-Apr-11
Booster Ring - Vendor Manufacturing Leadtime	146	01-Dec-11
Booster Ring - Manufacturing Support	146	01-Dec-11
Booster Ring - 1st Design/Contract Review	5	24-Mar-10
Booster Ring - 2nd Design/Contract Review	5	29-Jun-10
Booster Ring - 3rd Design/Contract Review	5	03-Nov-10
Booster Ring - 4th Design/Contract Review	5	13-May-11
Booster Ring - Final Design/Contract Review	5	13-Sep-11
Booster Ring - Vendor Delivery	83	17-Jan-12
Booster Vendor Leadtime - Built-In Float	120	06-Jul-12
Booster Ring - is Delivered to BNL	0	06-Jul-12
Booster Installation - Start Milestone	0	
Booster - Installation	111	14-Dec-12
Booster Installation - Built-In Float	21	17-Jan-13
Booster - Integrated Testing	84	17-May-13
Booster - Ready for Commissioning	0	17-May-13
Booster Ring - Commissioning	88	24-Sep-13
Booster Commissioning - Built-In Float	21	24-Oct-13
Storage Ring Beam Commissioning - Start	0	
Storage Ring w/o ID - Commissioning	86	03-Mar-14
IVU - Installation	20	31-Mar-14
IVU - Integrated Test	10	14-Apr-14
Storage Ring w/ ID IVU - Commissioning	50	24-Jun-14
Storage Ring Commissioning - Complete	0	24-Jun-14
Early Project Completion	0	24-Jun-14
NSLS-II Project - Built-In Float	250	25-Jun-15
CD-4b Approve Start of Operations	0	25-Jun-15*