Injector requirements for LE storage ring upgrade projects

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ARIES Workshop “Beam Tests and Commissioning of Low Emittance Storage Rings”

18-20 Feburary 2019, KIT, Germany

Typical injectors for 3rd Generation Light Sources

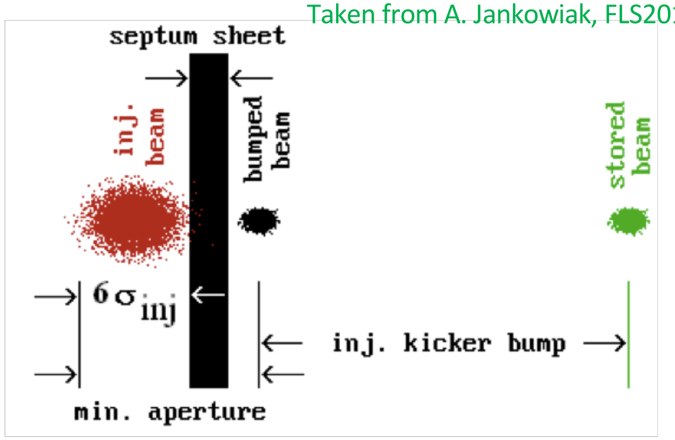
To deliver a full energy beam with a "reasonable" small emittance to SR

- Off-axis (pulsed bump) injection into the storage ring

  $A \geq 6\sigma_{\text{inj}} + 5\sigma_{\text{sto}} + \text{septum and tolerance}(> 3\sim4\text{mm})$

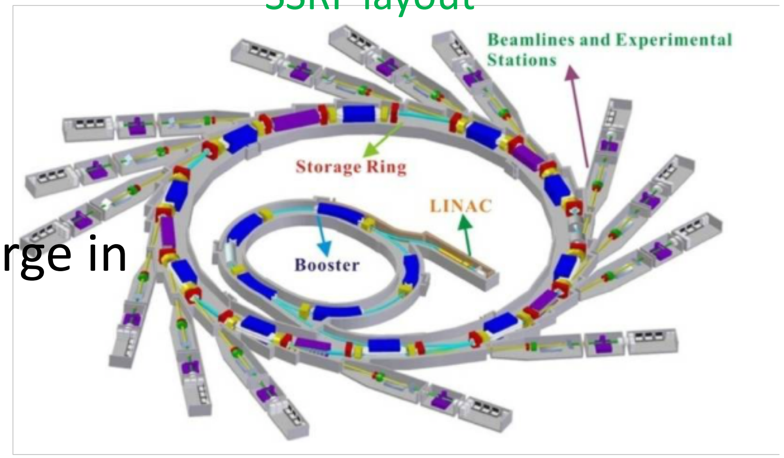
  - SR Acceptance > 10 mm
  - SR emittance: 1 ~ 10 nm
  - Relaxed tolerance for injected beam emittance

Taken from A. Jankowiak, FLS2012



- Linac + booster as a cost effective design
  - Booster E_{ext} / E_{inj} : 10 ~ 30
  - Booster emittance: 10 nm ~ 150 nm level
  - Accumulation in SR requires only moderate charge in the injector

SSRF layout



Trend in horizontal acceptance in LESRs (incomplete list)

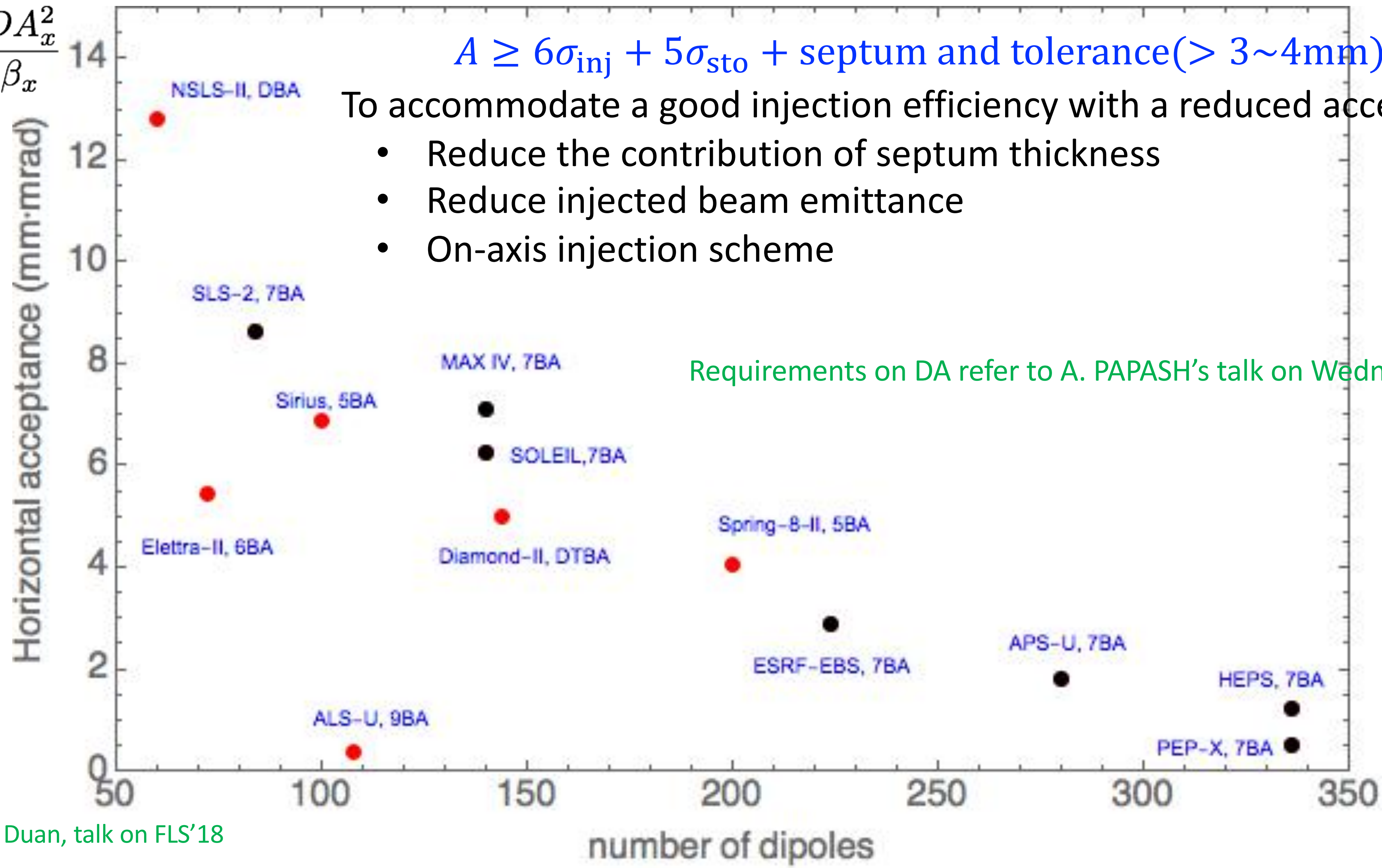
$$A_x = \frac{DA_x^2}{\beta_x}$$

$A \geq 6\sigma_{\text{inj}} + 5\sigma_{\text{sto}} +$ septum and tolerance(> 3~4mm)

To accommodate a good injection efficiency with a reduced acceptance

- Reduce the contribution of septum thickness
- Reduce injected beam emittance
- On-axis injection scheme

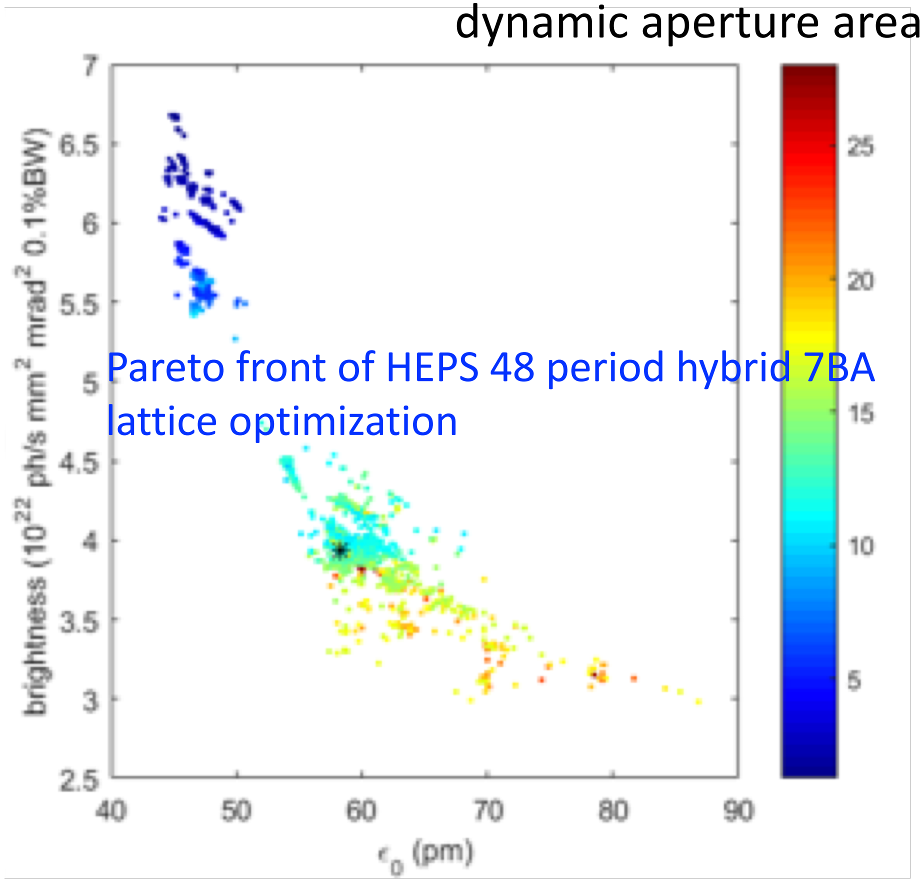
Requirements on DA refer to A. PAPASH's talk on Wednesday



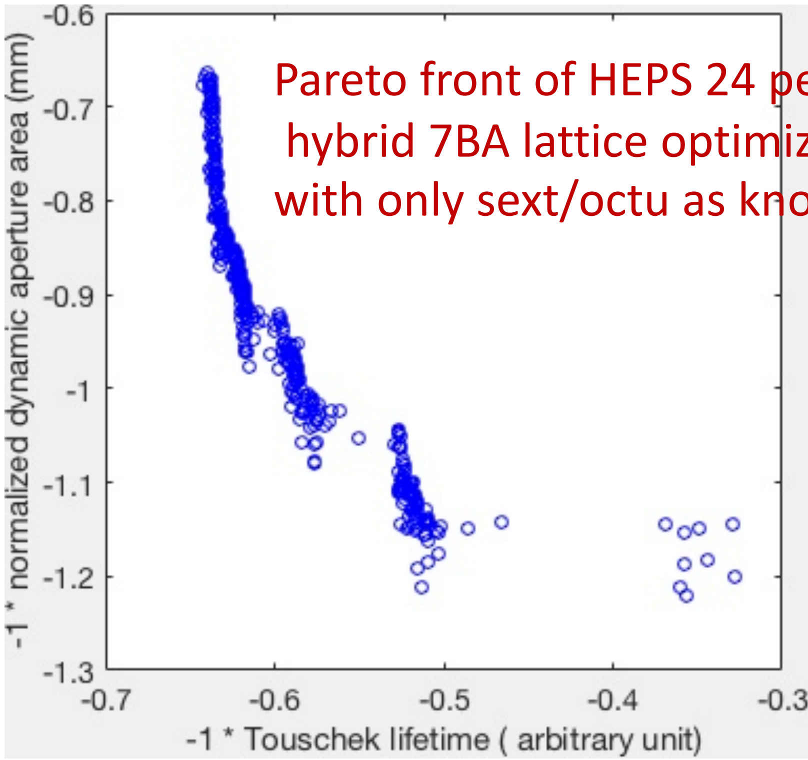
Z. Duan, talk on FLS'18

The DA of NSLS-II & MAX IV are measurement results, others are tracking results with errors.

Compromises in lattice optimization



Courtesy of Yi Jiao, IHEP

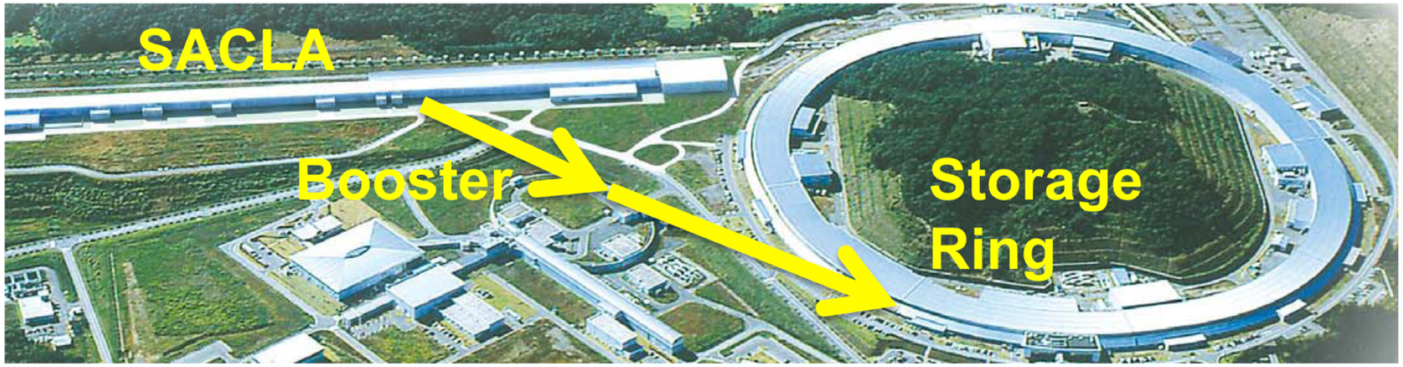


Generally, there is a compromise between brightness (emittance, matching of electron/photon phase space), dynamic aperture and Touschek lifetime in the lattice optimization.

The emittances of existing 3GLS boosters could be awkward, a reduction in injected beam emittance is in favor of a relaxed requirement of DA, beneficial for overall machine performance.

Reduction of injected beam emittance

- Use a full energy linac as the injector
  - Very small emittance (< 1 nm rms), short bunch, ideal for accumulation schemes
  - Costly, shared with on-site FEL/short pulse facility
  - MAX IV, Spring-8-II, HALS



Beam Parameters (8GeV)

Emittance: ~ 60 pmrad (projected)
Energy Spread: 0.05 % (rms)
Bunch Length: < 100 fs (rms)
Electron Charge: ~ 300 pC
Repetition Rate: 1 Hz (~ 60 Hz)

K. Sotoume, talk on USR 2012.

Reduction of injected beam emittance

- Modification of existing injector
  - Lower emittance design: stronger focusing, dispersion at straights
  - Off-energy operation:
    - Separate-function FODO -> Combined-function FODO
  - Emittance exchange in the booster / transport line *P. Kuske, talk on IPAC'16*

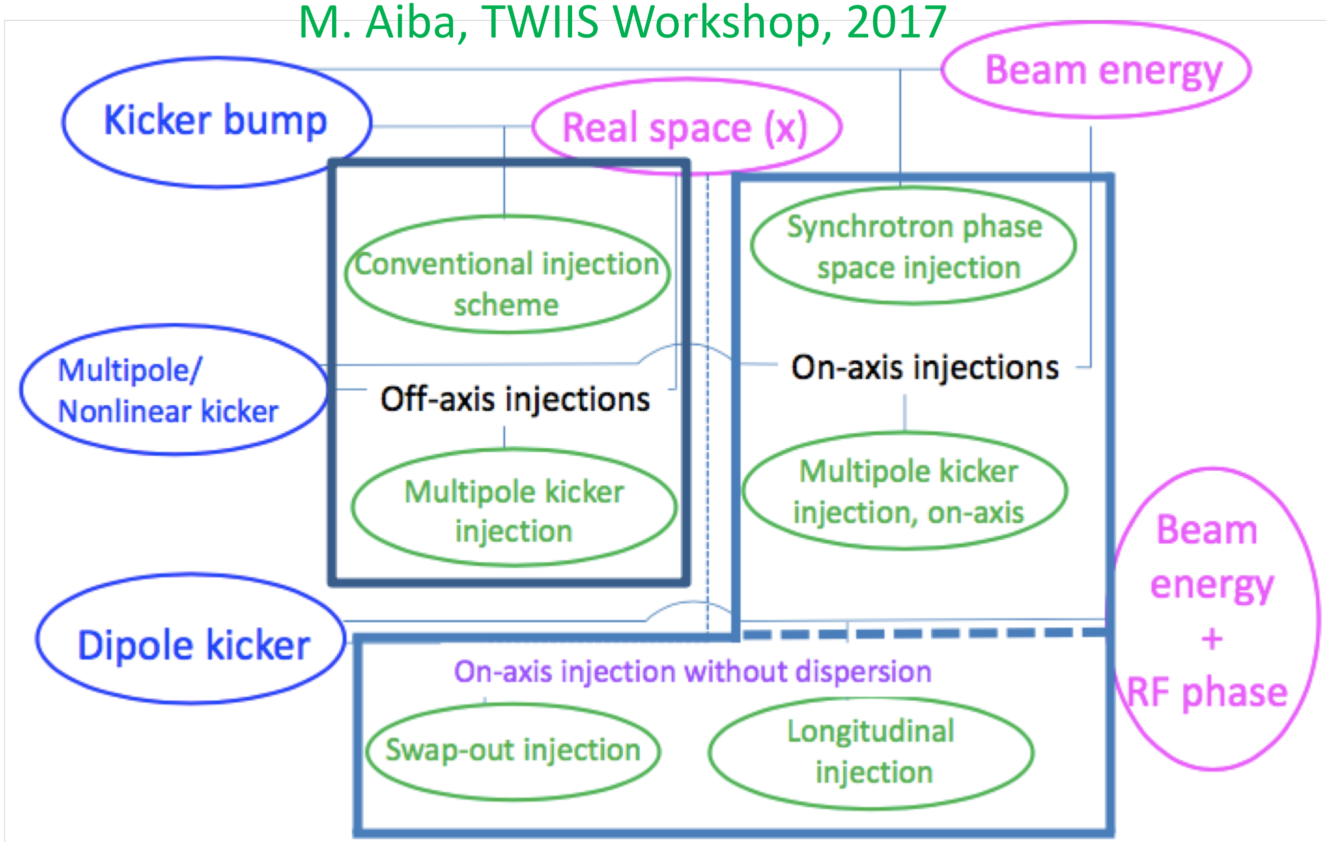
  Will be covered in detail in Nicola/Simon's talk

- Booster redesign / new dedicated accumulator ring
  - Same tunnel w/ SR vs. Separate tunnels w/ SR
  - Lattice structure:
    - Separate-function FODO vs. combined-function FODO
    - DBA, TBA cells as in 3GLSs ? ALS-U accumulator resembles ALS design

- Injected beam emittance could be pushed down to nm-level, further reduction doesn't help relax DA requirement or in other aspects, as far as cost/benefit ratio is concerned.

Collection of injection schemes

M. Aiba, TWIIS Workshop, 2017

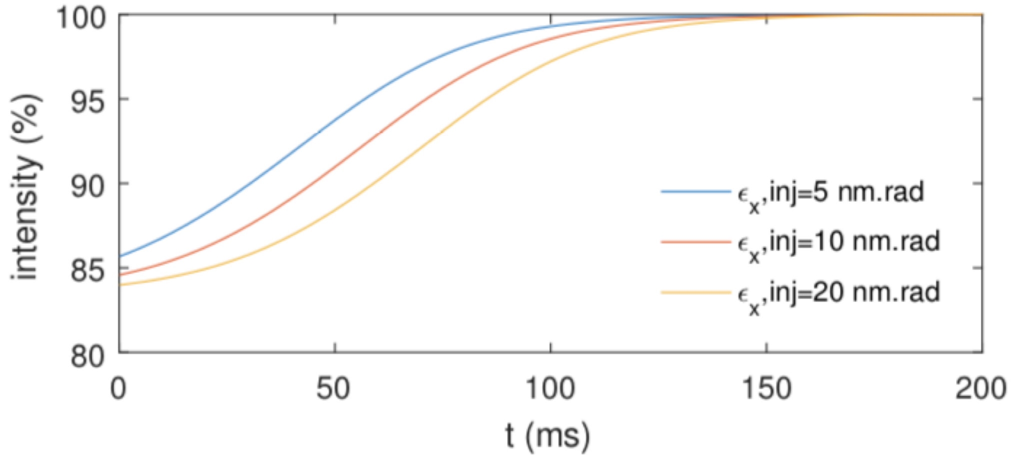


Injection scheme	SR 6D acceptance needs to cover	Required injected bunch charge
Accumulation	σ_{inj}, σ_{sto} and spatial/temporal separation + margin	A fraction of stored bunch
Swap-out	Max(σ_{inj}, σ_{sto}) + margin	Full charge

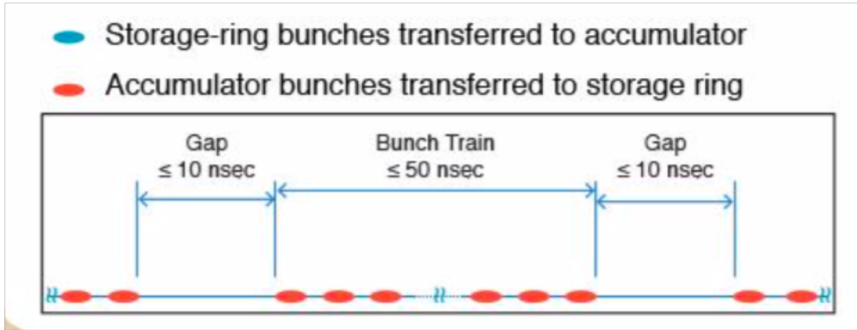
Full charge injector for medium energy LESRs

- Bunch train swap-out to cope with a short lifetime, and consistent with relatively fixed filling pattern
- Addition of a dedicated full-energy accumulator ring in ALS-U, Diamond-II(optional)
- Full energy accumulator vs booster
  - Much reduced emittance (a factor of 10 ~ 100 smaller)
  - Optimized to accumulate more bunch charge
  - Could be costly for 6 GeV LESRs

Intensity loss during swap-out assuming 1/6 of the beam is replaced



I.P.S Martin, and R. Bartolini, IPAC'18, THPMF008



C. Steier, et al., IPAC'17, 2821-2823

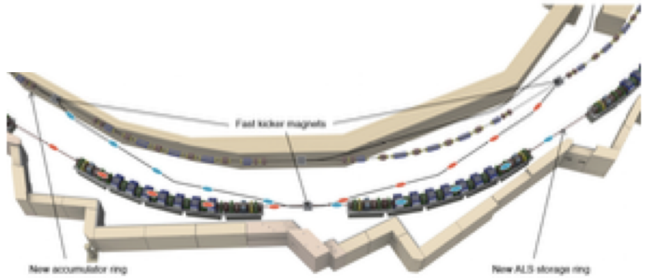


Figure 2: Illustration of the planned swap-out process between the full energy accumulator and the storage ring of ALS-U.

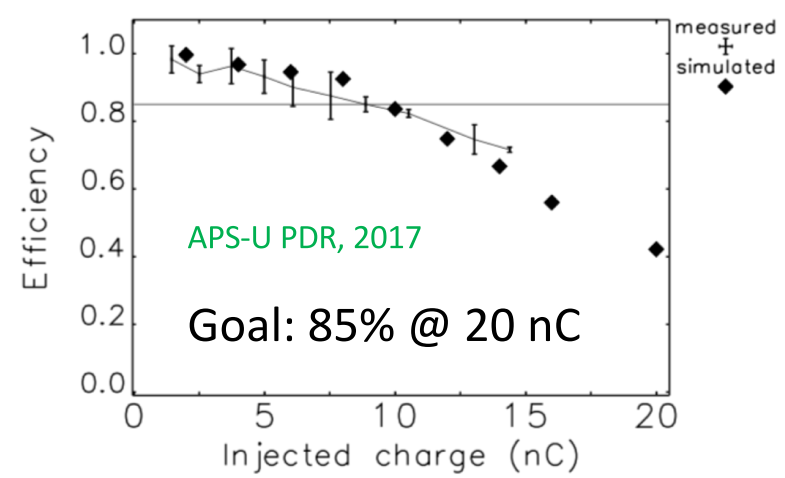
Full charge injector for high energy LESRs

- Bunch-by-bunch swap-out to reduce injection transient and permit flexible filling patterns

Machine	High brightness mode	Timing (high bunch charge) mode
APS-U	324 bunches, 2.3 nC/bunch	48 bunches, 15.3 nC/bunch
HEPS	680 bunches, 1.3 nC/bunch	63 bunches, 14.4 nC/bunch

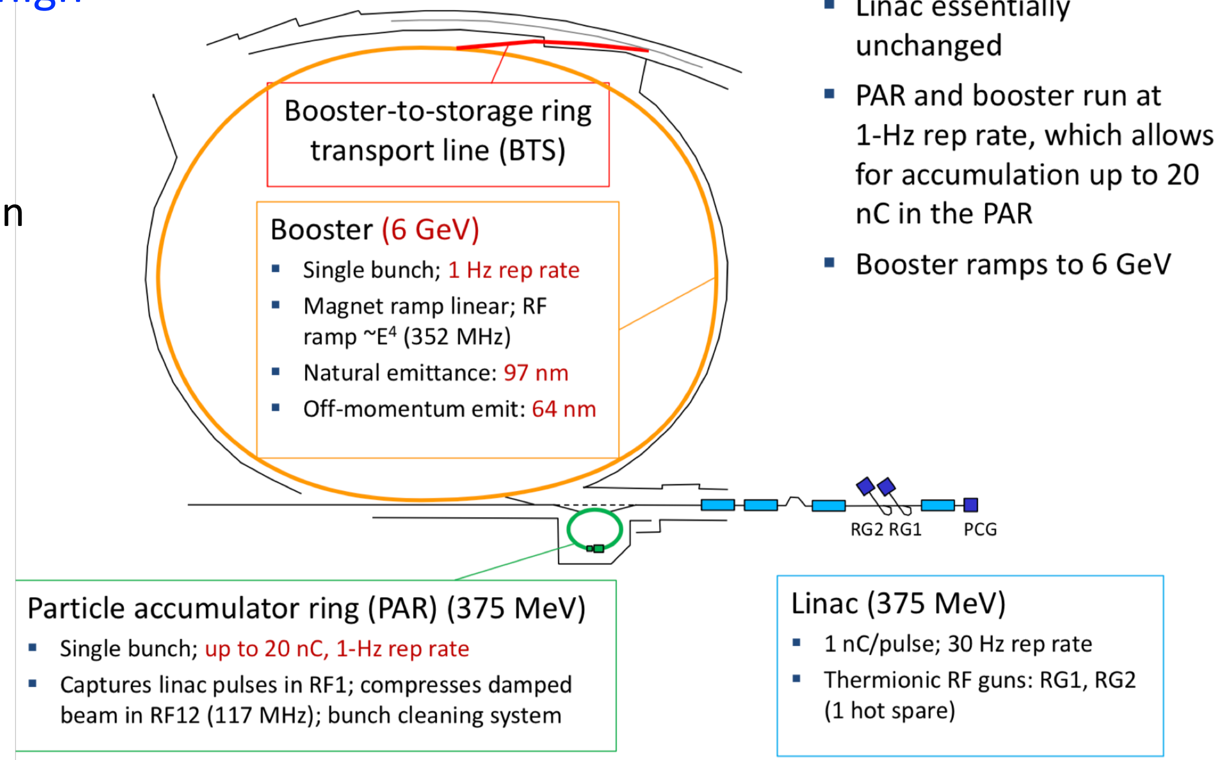
APS-U: improvements of existing low-energy accumulator ring + booster to deliver high bunch charge, key issues include

- Ion effects in PAR
- Long bunch extracted from PAR
- Heavy beam-loading at booster injection



APS-U injectors for high charge operation

J. Calvey, talk on TWIIS Workshop 2017



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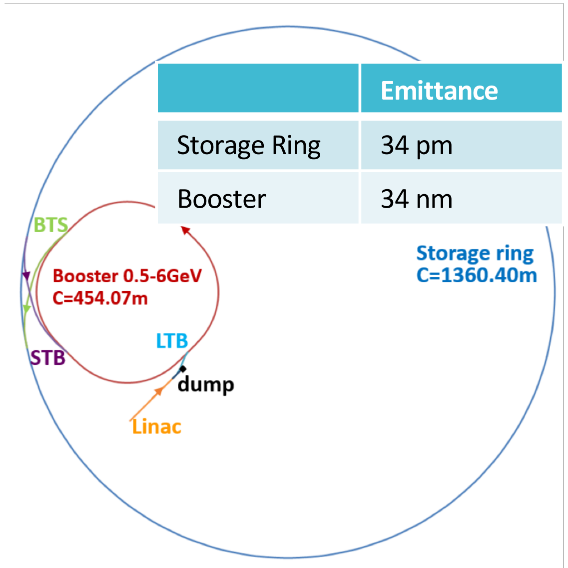
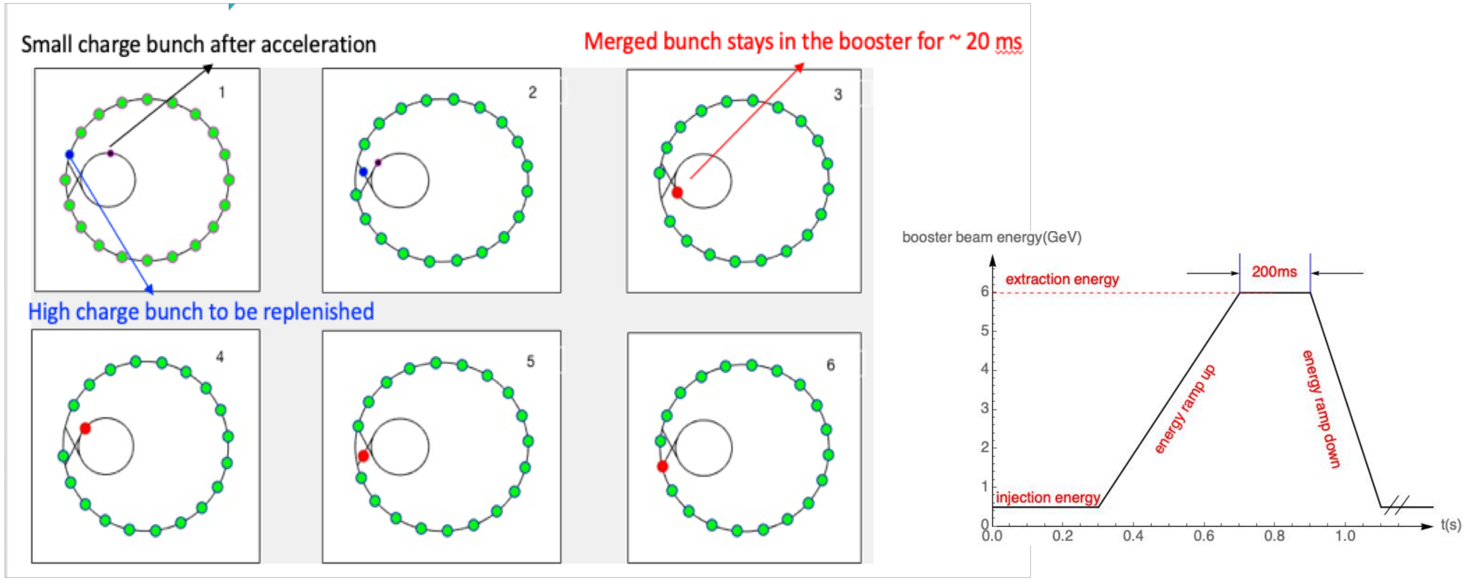
HEPS: “Charge recovery” in the booster at 6 GeV   Z. Duan et al., IPAC’18, THPMF052

	Emittance
Storage Ring	34 pm
Booster	34 nm





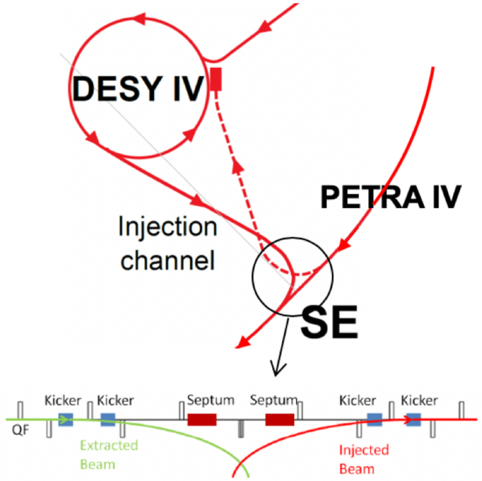
- Only a moderate charge (up to 5 nC) is captured in the booster, relax challenges to capture and accelerate 15~20 nC bunches at the booster injection energy
- Accumulation at the flat-top allows multi-bunch filling in the booster, to cope with a small beam lifetime
- The performance of booster also working as a full energy accumulator ring looks promising.

Full charge injector for high energy LESRs

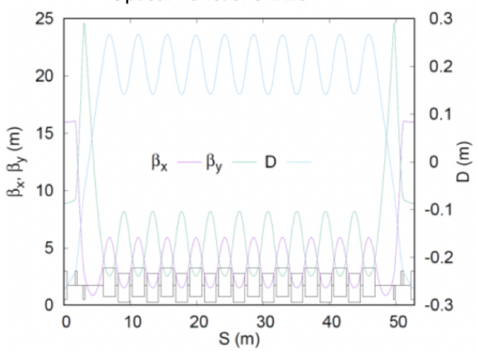
PETRA IV considerations, J. Keil, talk on this workshop

Injection and Booster

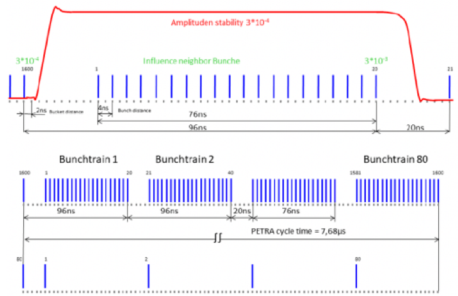
- **Injection scheme**
  - Dynamic aperture with realistic errors too small for off-axis injection
  - Horizontal on-axis swap-out injection in straight SE
  - Injection of 80 bunch trains; 20 or 1 bunches per train
- **Booster synchrotron DESY IV**
  - DESY II nat. emittance (ε_x~335 nm·rad) too large
  - New design of a 6 GeV booster with 19 nm·rad @ 6 GeV in same tunnel using CF magnets (dipole, quadrupole, sextupole)
  - Goal: deliver $5 \cdot 10^{10}$ particle per bunch
  - Accumulation in PIA II at 700 MeV
  - Dump of the extracted PETRA IV bunch train; recycling?



Optical Functions DESY IV



Filling Pattern



Brightness mode
B = 1600

Timing mode
B=80

Robust top-up operation

- Injectors are expected to work at least as stable as in 3GLSs.
- It could be challenging for swap-out injection to reach the same level of beam current stability as in accumulation schemes.
- Short lifetime + full charge injector (swap-out), injector reliability could also be a concern.

M. Borland, NAPAC2016, WEPOB02

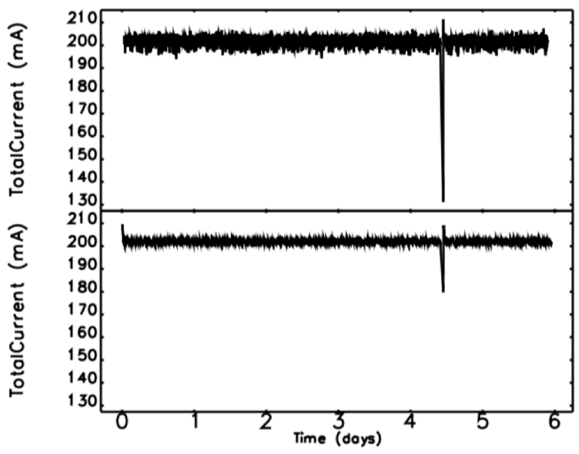


Figure 4: Total current vs time for the first week of s lated operation for 48-bunch (top) and 324-bunch (bott modes with round beams and existing rf systems.

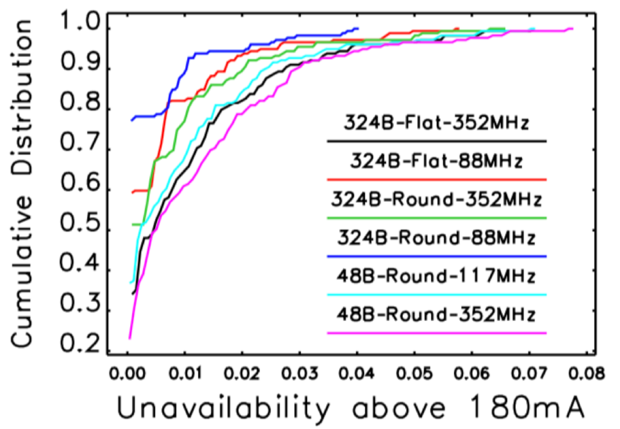
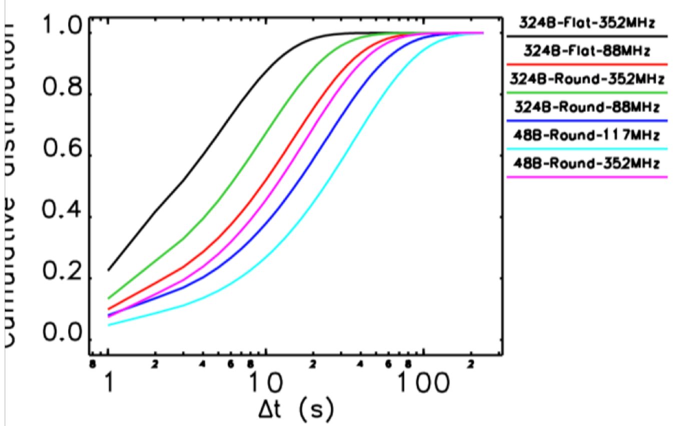


Figure 5: Cumulative distribution of unavailability of 180 mA for different fill modes and rf choices.



igure 6: Cumulative distribution of interval between two vap-out shots for different fill modes and rf choices.

Injector parameters of 3GLSs /LE upgrade and green-field LESRs (incomplete list)

3rd Generation Light Source				Low emittance upgrade project				
Name	Energy (GeV)	Ring Nat. emittance (nm)	Booster emittance (nm)	Name	Energy (GeV)	Ring Nat. Emittance (pm)	Injection scheme	Injector Modification
ALS	2	2	140	ALS-U	2	109	Swap-out	New accumulator ring
SLS	2.4	5.5	9	SLS-II	2.4	102	Off-axis	Emittance exchange?
SOLEIL	2.75	4	150	SOLEIL Upgrade	2.75	72	MKI Long. inj	New booster design?
ELETTRA	2 ~ 2.4	7	226 / 166 @2.5 GeV	ELETTRA 2.0	2 2.4	250 @ 2 GeV	Off-axis	None in preCDR
ESRF	6	3.8	120	ESRF-EBS	6	135	Off-axis	Off-energy operation, round beam
APS	7	2.5	132	APS-U	6	42	Swap-out	Off-energy operation
Spring-8	8	3.4	230	Spring8-II	6	157	Off-axis	Use linac injector
PETRA III	6	1.3	335	PETRA IV	6	17	Swap-out	New booster

Green field projects					
Machine	Energy (GeV)	Ring Nat. mittance (pm)	Injection scheme	Injector type	Injector emittance(nm)
MAX IV	3	0.33	MKI	linac	~0.7
Sirius	3	0.24	MKI	Linac + booster	3.47
HEPS	6	34	Swap-out	Linac+ booster	34

Summary

- A low emittance injector is generally favored for LE upgrade projects
  - Different approaches are available
  - Choice should be made based on cost/benefit evaluation.
  - Successful commissioning and operation of 3GLSs gave us confidence to commission a low emittance booster in a relatively short time.
- Swap-out injection promises higher brightness/less disturbance, but also introduces nontrivial challenges to injector design and operation
  - Full charge injector: dedicated accumulator ring or using booster
  - Challenges remain to deliver ~ 15 nC bunches with a high efficiency
  - Potential concerns: Injector charge variation, hardware reliability

Thank you for your attention!