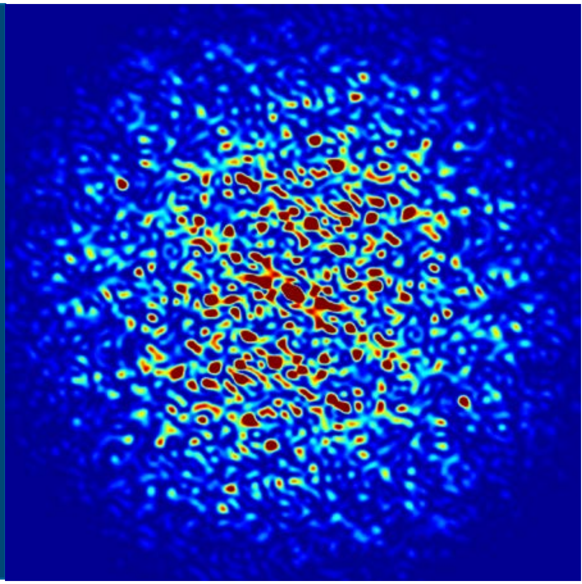
High-charge Injector for On-axis Injection into a High-Performance Storage Ring Light Source



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IPAC 2019, Melbourne
May 20-24, 2019

Outline

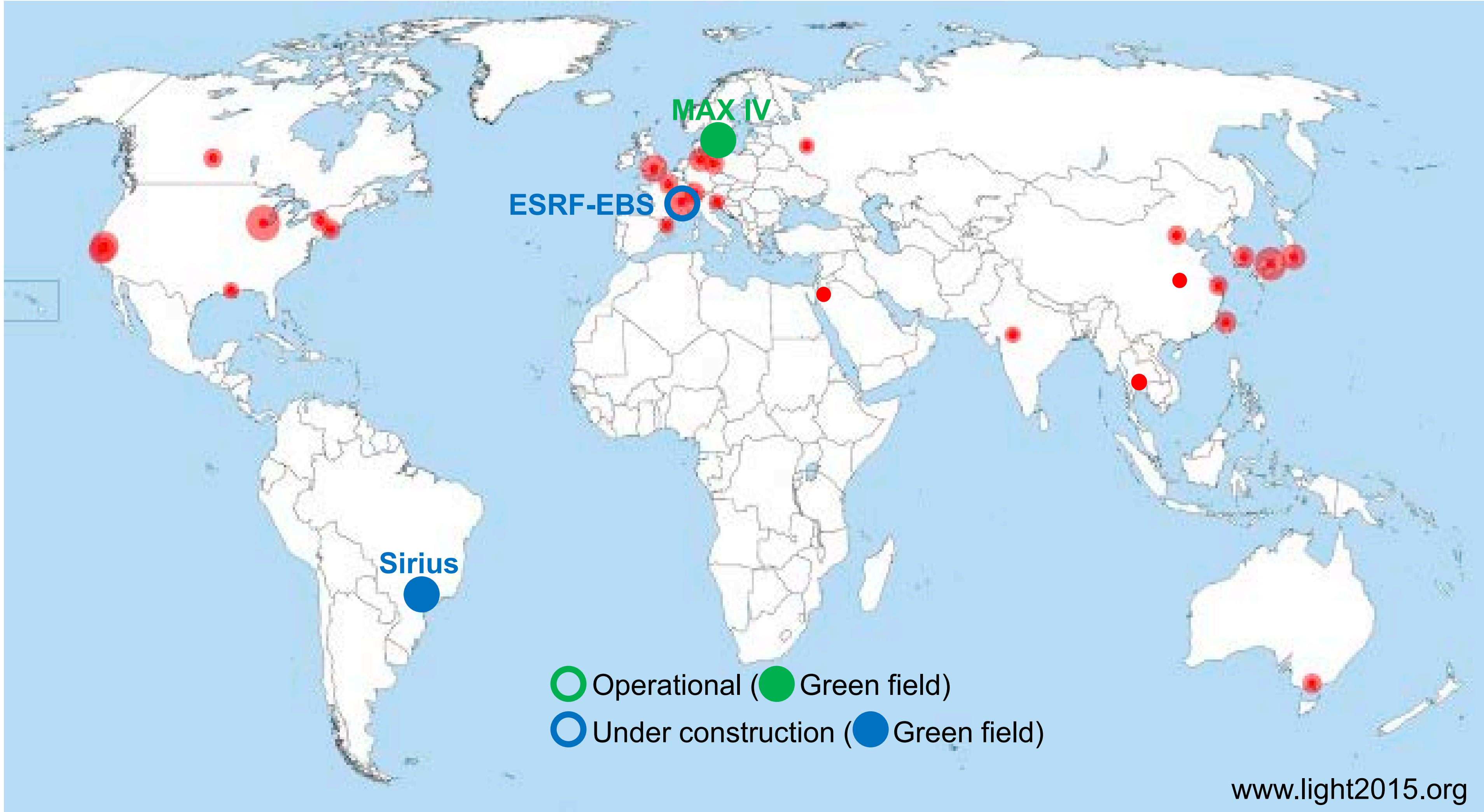
- Introduction
- Challenges for injector
- Design choices: upgrade of existing injector vs green field
  - APS-U, Argonne National Lab
  - ALS-U, Berkeley Lab
  - HEPS, IHEP, Beijing
- Outlook and summary

MBA storage rings launch a new era for light sources

Multibend achromat (MBA) optics can reduce the horizontal emittance by 1-2 orders of magnitude compared to a third-generation storage ring of the same circumference, thereby increasing the x-ray brightness dramatically.

MAX IV led the development.[1]

Sirius[2] and ESRF-EBS[3] are under construction.



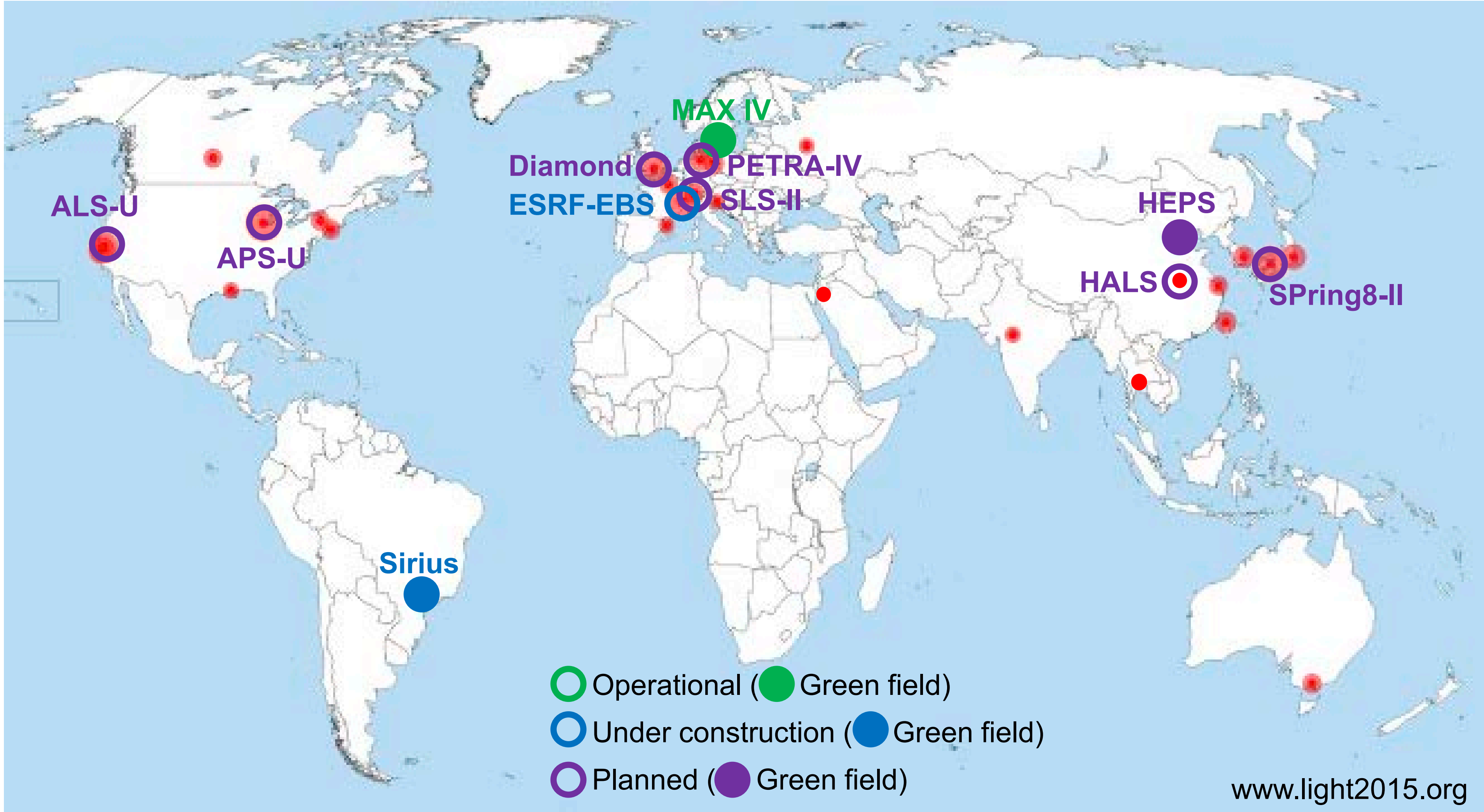
[1]TUYPLM3, [2]TUPGW003, [3]TUPGW005

Many light sources pursuing 4th gen storage ring designs

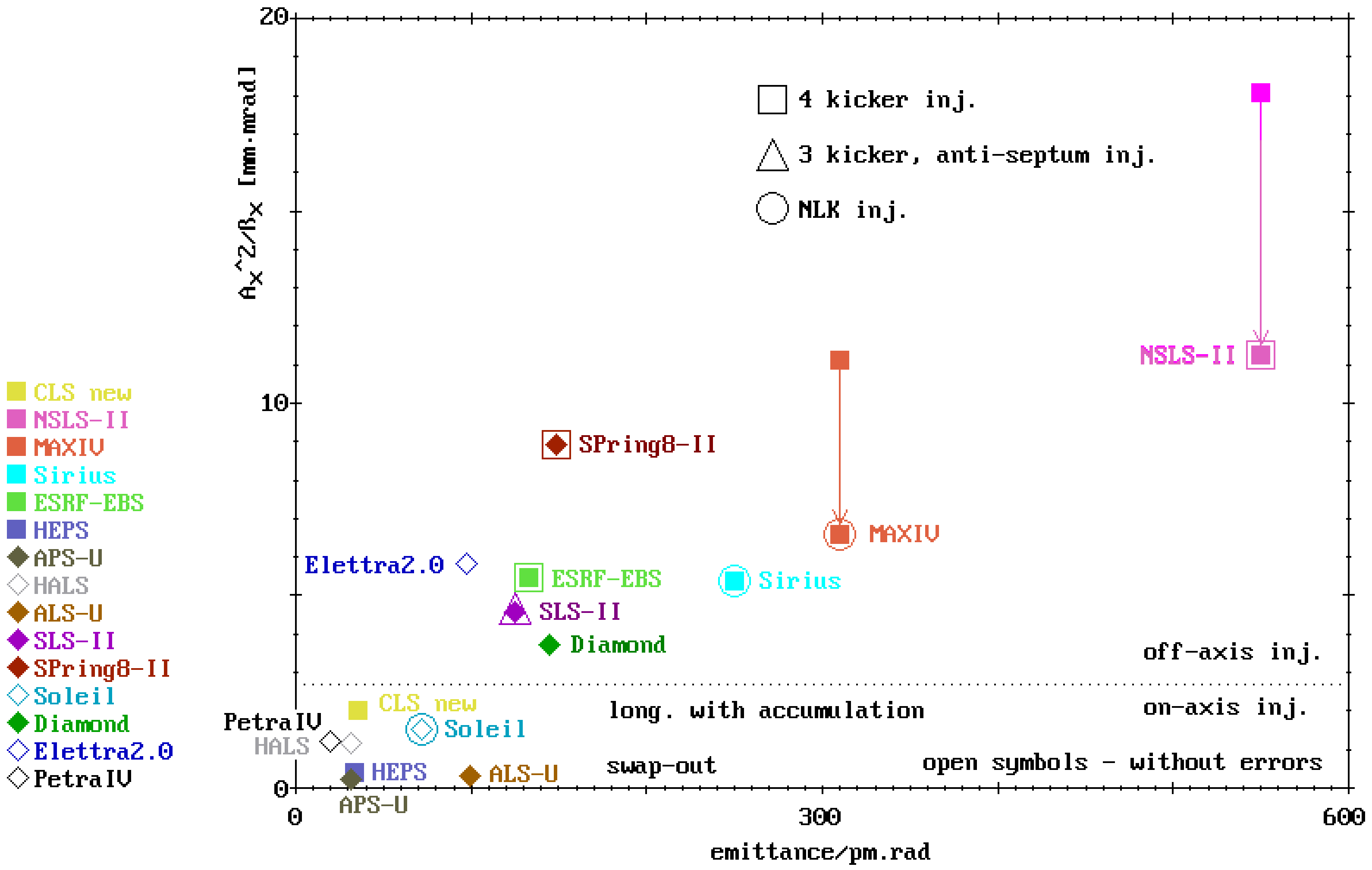
MBAs and variations: 4th generation synchroton light sources.

Many innovative ideas as multiple light sources pursue 4th generation source designs, including solutions for injection.

See references in paper (THYYPLM3); also many new reports here at IPAC'19.



MBA designs presents new challenges for injection



swap-out injection: ALS-U, APS-U, HEPS off-momentum injection: HALS, Soleil

- MBA storage ring (SR) acceptance and emittance are correlated.
- Highest-performance MBA optics requires swap-out injection.
- Focus on challenges for swap-out injector:
  - High single-bunch charge for timing mode.
  - High single- or bunch-train charge for brightness mode.
  - Emittance
  - Instabilities
  - Beam loading

What is swap-out[1] injection and why choose?

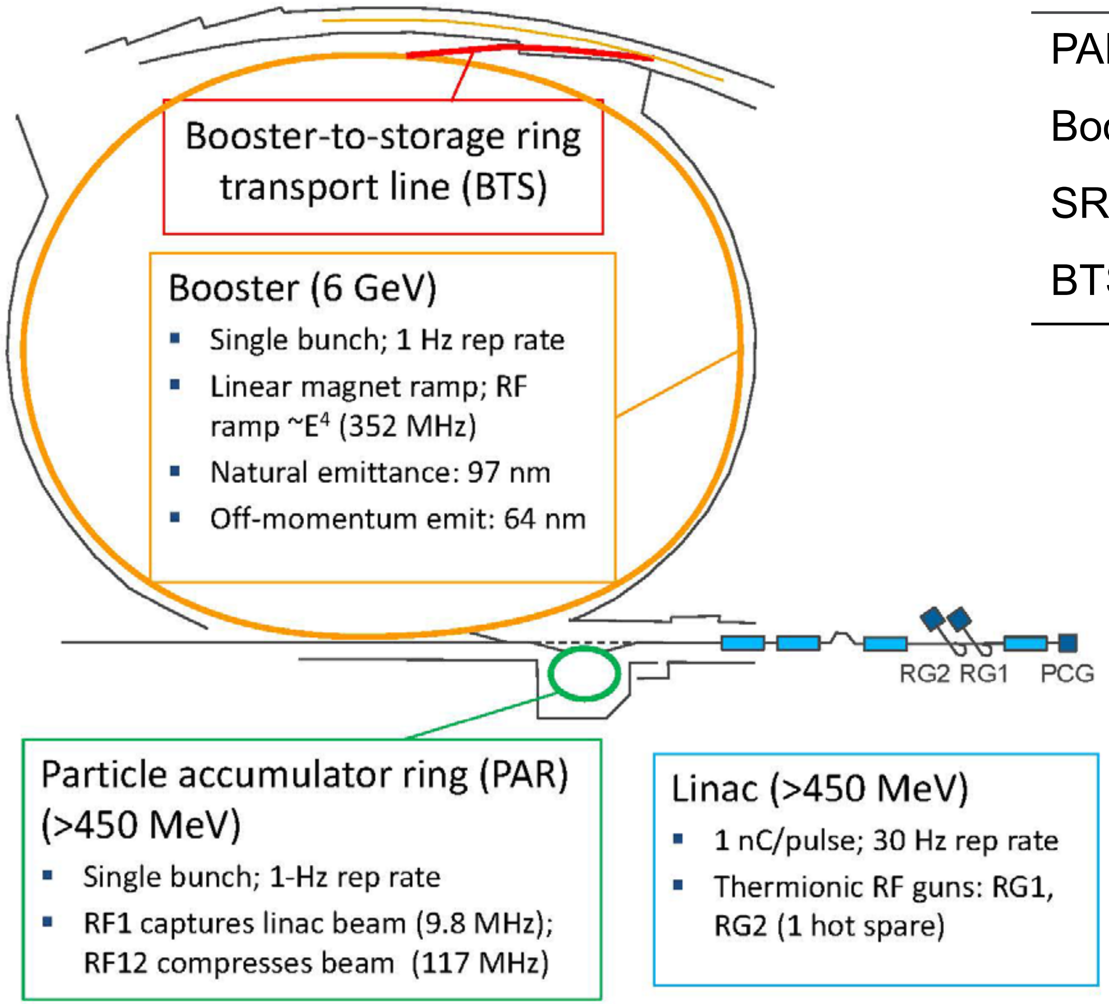
[1] L. Emery, M. Borland, PAC'03.

- Swap-out is used to maintain the beam current – analogous to top-up – except that the injectors produce enough single-bunch charge to perform complete bunch replacement, using on-axis injection without accumulation.
- Besides MBA SR dynamic acceptance, other considerations for choosing swap-out include:
  - Enabling small horizontal-gap or helical undulators.
  - Decision to re-use existing injector; upgrade in advance (more options with green field).

		Beam energy	Circum-ference	SR natural emittance	Injector emittance	Total current	Bunch charge goal
Upgrade existing	APS-U[2]	6 GeV	1104 m	42 pm	60 nm (booster)	200 mA	5-16 nC
Upgrade existing	ALS-U[3,5]	2 GeV	196.5 m	~90 pm	1.9 nm (accum ring)	500 mA	1.2 nC
Green field	HEPS[4,5]	6 GeV	1360 m	34 pm	32 nm (booster)	200 mA	1.3-14.4 nC

[2] APS-U Prelim Design Report (2017). [3]C. Steier, LBL [4]MOPRB027, TUZPLS2 [5] Optimization ongoing.

APS-U injector layout and requirements



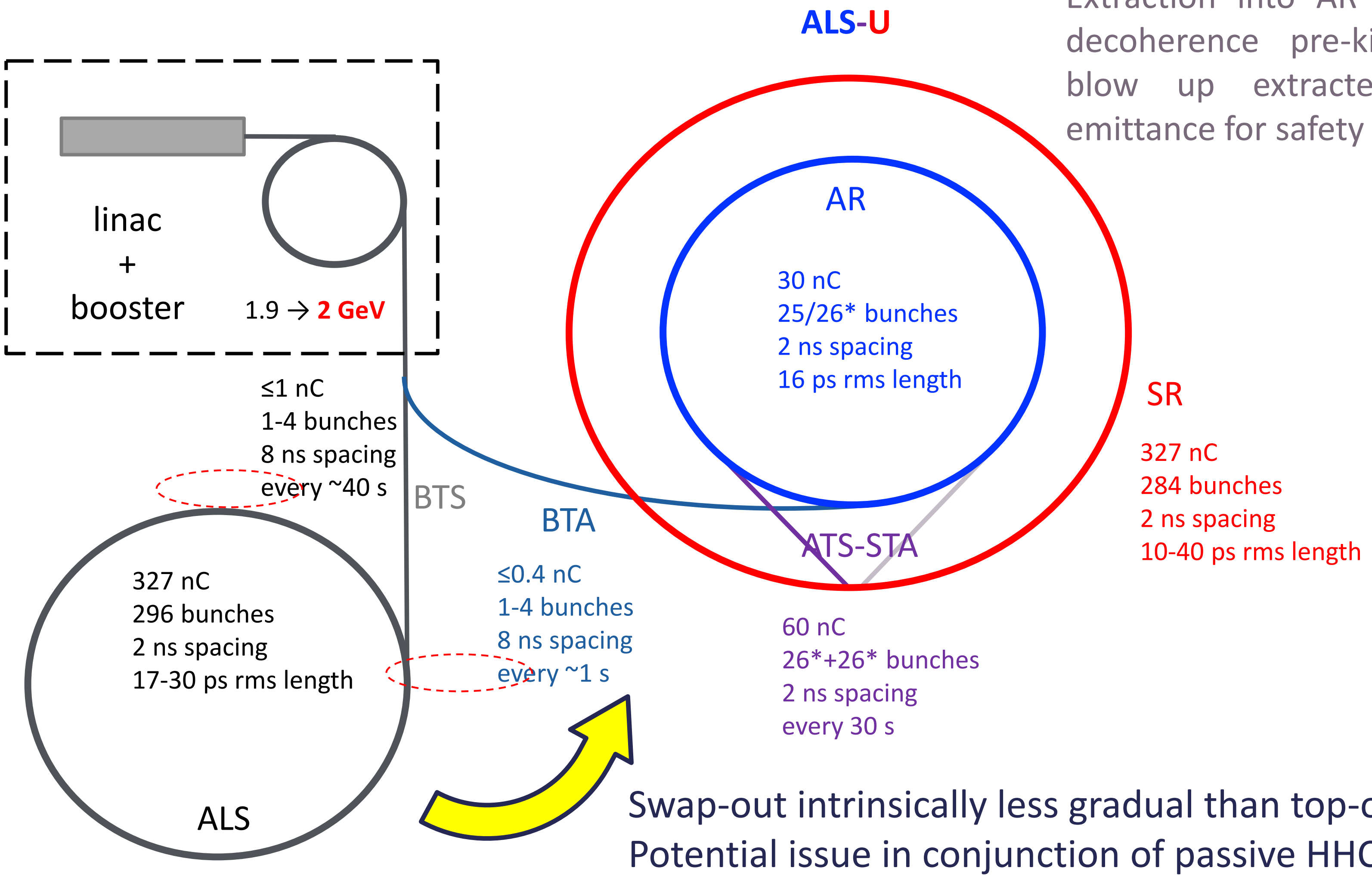
	APS	Achieved	Goal[1]
PAR charge	2-4 nC[1]	20 nC	20 nC
Booster charge	2-4 nC[1]	12 nC	17 nC
SR charge (injected)	Accumulated		16 nC
BTS ε_x at 6 GeV	< 64 nm	–	< 60 nm

[1] For timing mode. Brightness mode requires 5 nC.

- APS has a low-energy accumulator ring originally designed for damping positrons, up to 6 nC.
- Single-bunch injector enables “guard” bunches in brightness mode.
- With small modifications, achieved 20 nC in PAR.
- Instabilities and beam loading are issues; plan to address before MBA upgrade.

ALS-U From Top-off To Swap-out

- ALS-U optimized for brightness mode, 70x70 pm (no timing mode).
- Planning to build a full-energy accumulator ring (AR) in SR tunnel: off-axis accumulation of booster bunch trains, on-axis injection into SR.
- AR to be installed before MBA upgrade.



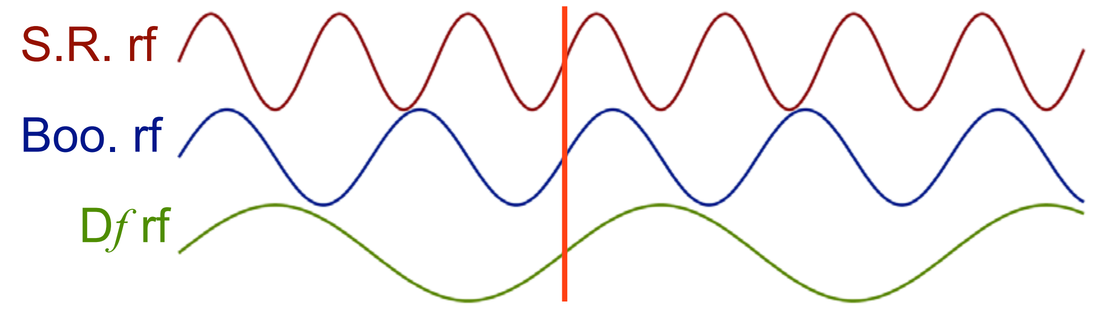
Extraction into AR requires decoherence pre-kicker to blow up extracted train emittance for safety reasons.

Swap-out intrinsically less gradual than top-off.
Potential issue in conjunction of passive HHC use:
Filling an empty SR will have to be done gradually, avoiding inducing large transients in the cavities.

Stefano De Santis

New injection timing system if injector re-used

- Multi-bend SR has smaller circumference; therefore, the rf frequency increases:
  - APS-U: 120 kHz (352 MHz rf)
  - ALS-U: 750 kHz (500 MHz rf)
- Both facilities decided to build a new injection timing system that enables bunch-to-bucket transfer at different rf frequencies.
- Requires fully digital low-level rf; APS-U upgrade in progress, ALS upgraded in 2018.
- Provides an additional booster emittance and injection tuning knob, exploited at APS-U:
  - Presently running booster -0.6% off-momentum, which lowers the transverse emittance due to well-known partition function effect.
  - Plan to run -0.8% off-momentum at extraction, and closer to on-momentum at injection. This enables higher charge.

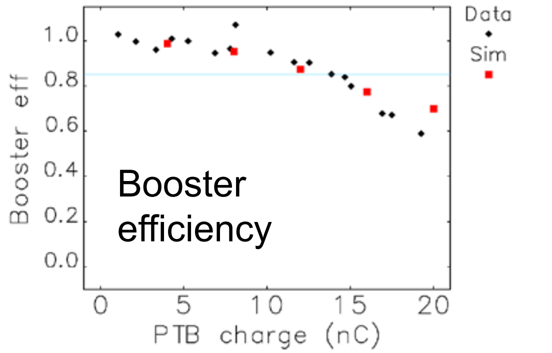


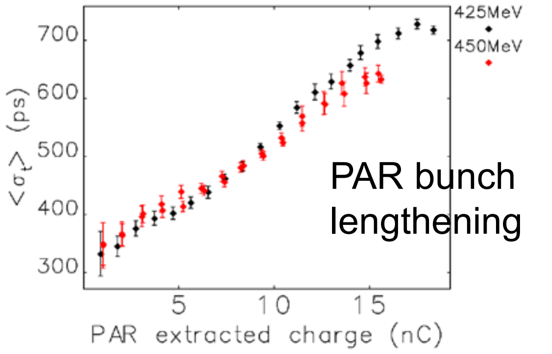
Schematic of rf frequencies (Df exaggerated)

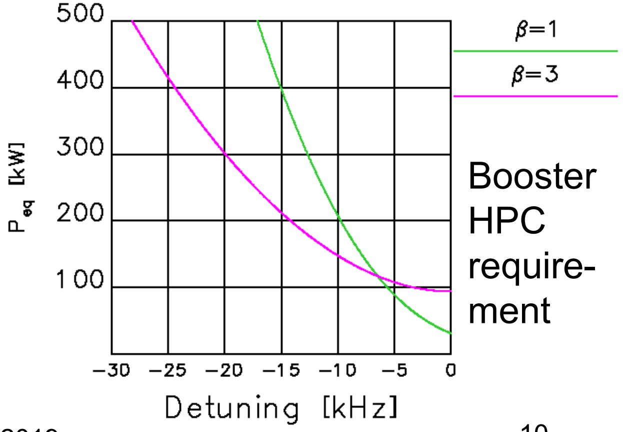
U. Wienands, “Booster-APS-U MBA Synchronization,” white paper (Oct 2017).

High single-bunch injector charge for APS-U timing mode

- Injector diagnostics upgrades have been key: e.g., digital rf data acquisition, bunch duration monitors[1], SLM digital cameras, YAG screen in emittance diagnostic in booster extraction line.
- Mature booster impedance and machine model closely reproduces observed charge-dependent injection efficiency[2].
- High-charge plan:
  - Raise linac/PAR energy to >450 MeV to raise PAR instability threshold. Analyze PAR chamber impedance and redesign components where practical.
  - Increase PAR bunch length compression with higher-voltage harmonic rf.
  - Detune booster rf cavities at injection for beam loading compensation. Install high-power rf couplers (HPC) to handle high effective power at extraction. Higher coupling coefficient extends detuning range.







[1]J. Dooling et al., IPAC'18. [2]J. Calvey et al., NAPAC'16

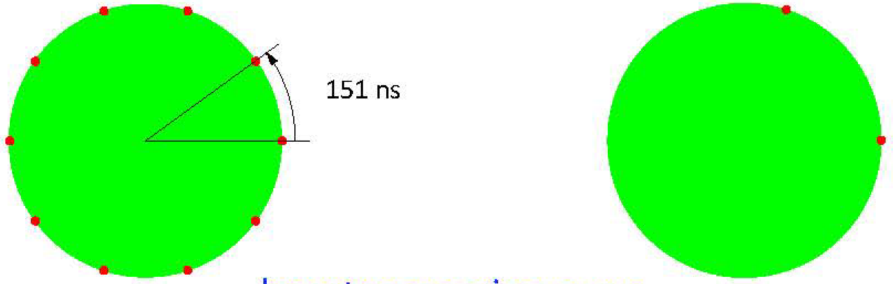
As green-field design, HEPS has more injector options

Multi-bunch injection per booster cycle

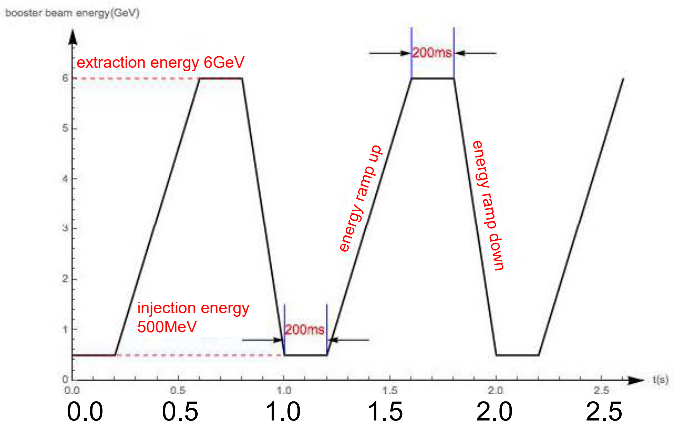
booster filling patterns

1.3 nC for SR high brightness mode

14.4 nC for SR high bunch charge mode

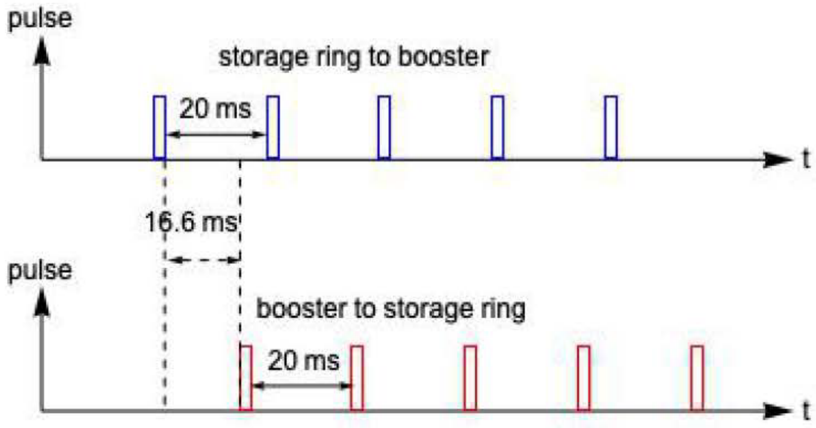


booster ramping curve



parameter	value
linac repetition rate	50 Hz
booster repetition rate	1 Hz
flat-bottom/flat-top	200 ms / 200 ms
kicker/bumper repet. rate	50 Hz
kicker pulse width	< 300 ns (half-sine)

Time structure in the two transport lines



- Booster used as injector and accumulator.
- SR and booster rf frequency ratio 1:3.
- Booster can ramp energy up/down.
- Multibunch injection for faster fill from zero.
- Future options considering full-energy linac.

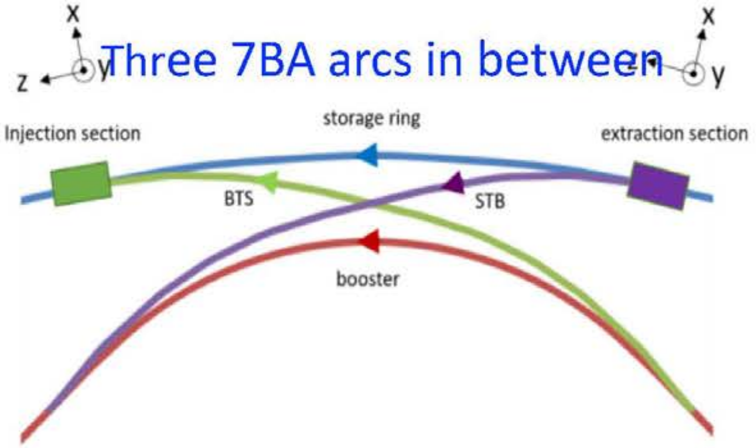
High single-bunch injector charge for HEPS timing mode

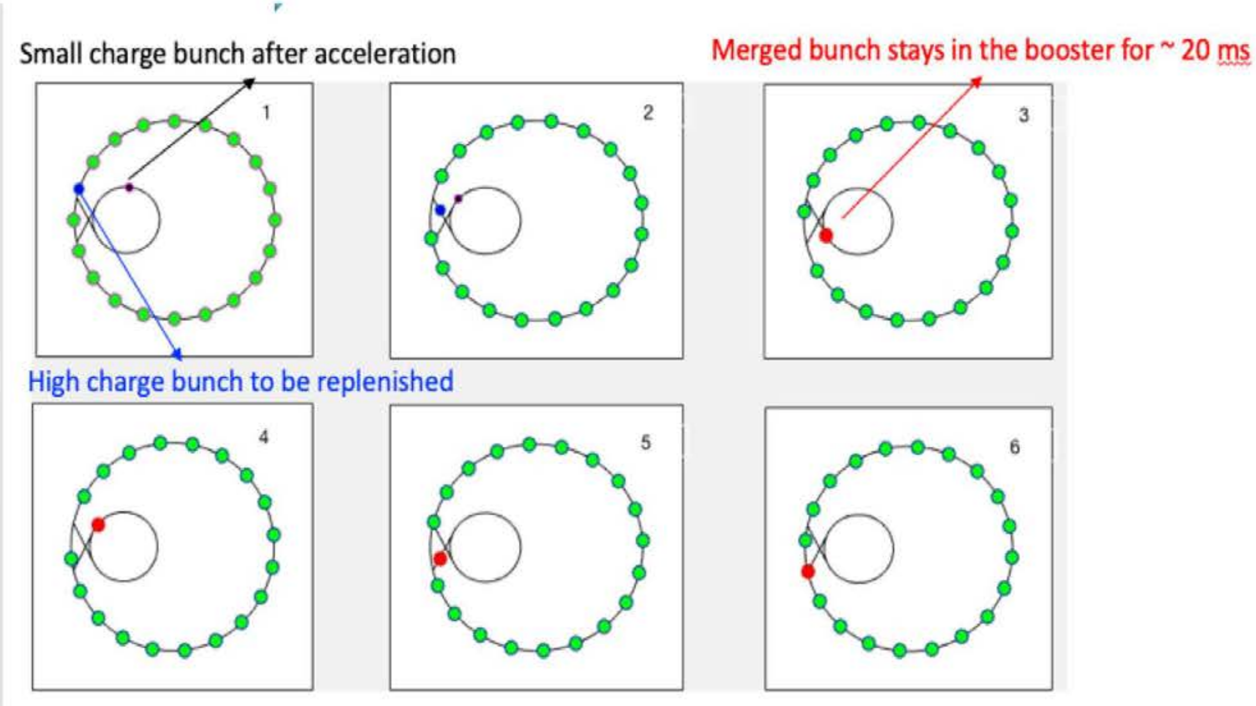
Challenge of "swap-out" injection : a full charge injector

→ "Charge recovery" in the booster at 6 GeV

Two high-energy transport lines

Three 7BA arcs in between





Higher beam losses possible with high-charge swap-out

- Swap-out requires more frequent injection of higher charge per pulse: 10s of seconds compared to minutes for top-up.
- Off-axis accumulation injection efficiency in present rings ~90%.
- On-axis swap-out efficiency inherently less lossy; ≥ 97% achievable.
- Radiation shielding needs to be evaluated, and supplemented as needed.
- APS-U[1] and ALS-U are installing beam loss monitors as a diagnostic to aid in injection tuning.

[1]J. Dooling et al., IPAC'15.

Outlook and Summary

- 4th generation light source designs based on MBA variations are being pursued world-wide to dramatically increase the x-ray brightness, compared to 3rd generation sources.
- High-performance designs and other considerations drive the decision to implement on-axis swap-out injection.
- Injector upgrades or green field designs must meet requirements for timing and/or brightness modes (higher and lower single-bunch charge, respectively).
- Injector upgrade plans (APS-U, ALS-U):
  - New injection timing system needed for asynchronous rf frequencies.
  - Accumulator ring a practical solution for increasing single bunch or bunch train charge.
  - Instability mitigation and/or beam loading compensation are likely needed.
- Green field injector options (HEPS):
  - Choose harmonically-related rf frequencies for injector and SR.
  - Use booster for both injector and accumulator.
- Longer-term approaches may include high-charge full-energy linac or other schemes.

Acknowledgements

Thanks to APS-U Injector Team:

I. Abid, T. Berenc, W. Berg, M. Borland, A. Brill, D. Bromberek, J. Calvey, J. Carvelli, J. Dooling, L. Emery, T. Fors, G. Fystro, A. Goel, D. Hui, R. Keane, R. Laird, F. Lenkszus, R. Lindberg, T. Madden, B. Micklich, L. Morrison, S. Pasky, V. Sajaev, N. Sereno, H. Shang, T. Smith, J. Stevens, Yine Sun, G. Waldschmidt, Ju Wang, U. Wienands, K. Wootton, A. Xiao, B.X. Yang, Yawei Yang, C.Y. Yao (ANL); A. Blednykh (BNL); A. Lumpkin (FNAL)

Also thanks to:

R. Hettel, J. Kerby (ANL/APS-U); J. Byrd (ANL)

Special thanks to:

Peter Kuske (HZB); Qing Qin, Ping He, Jiuqing Wang, Gang Xu (IHEP); Stefano De Santis, Daniela Leitner, Fernando Sannibale, Christoph Steier, Changchun Sun (LBL); Patricia Nallin (Sirius).