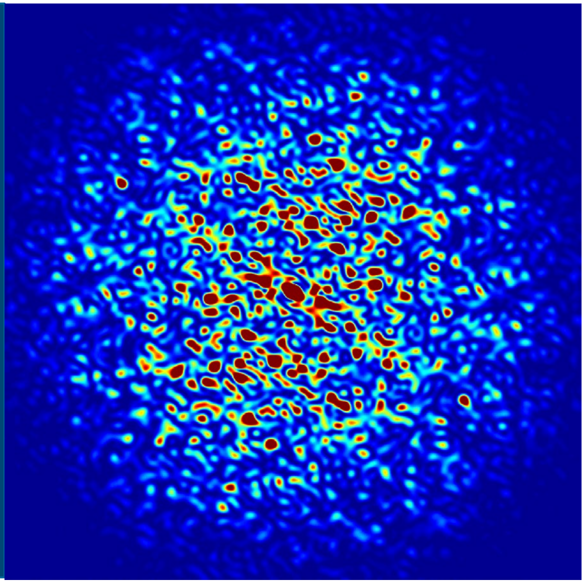
Road to High Charge in the Advanced Photon Source Upgrade (APS-U) Injector



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On behalf of APS-U Injector Team

Accelerator Physics and Engineering Seminar, MSU/FRIB
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Outline

- Motivation
- Challenges for electron beam injector
- Physics predictions and measurements
- 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 3rd generation synchrotron light source.

X-ray brightness increases dramatically.

MAX IV[1] led the development (2015).

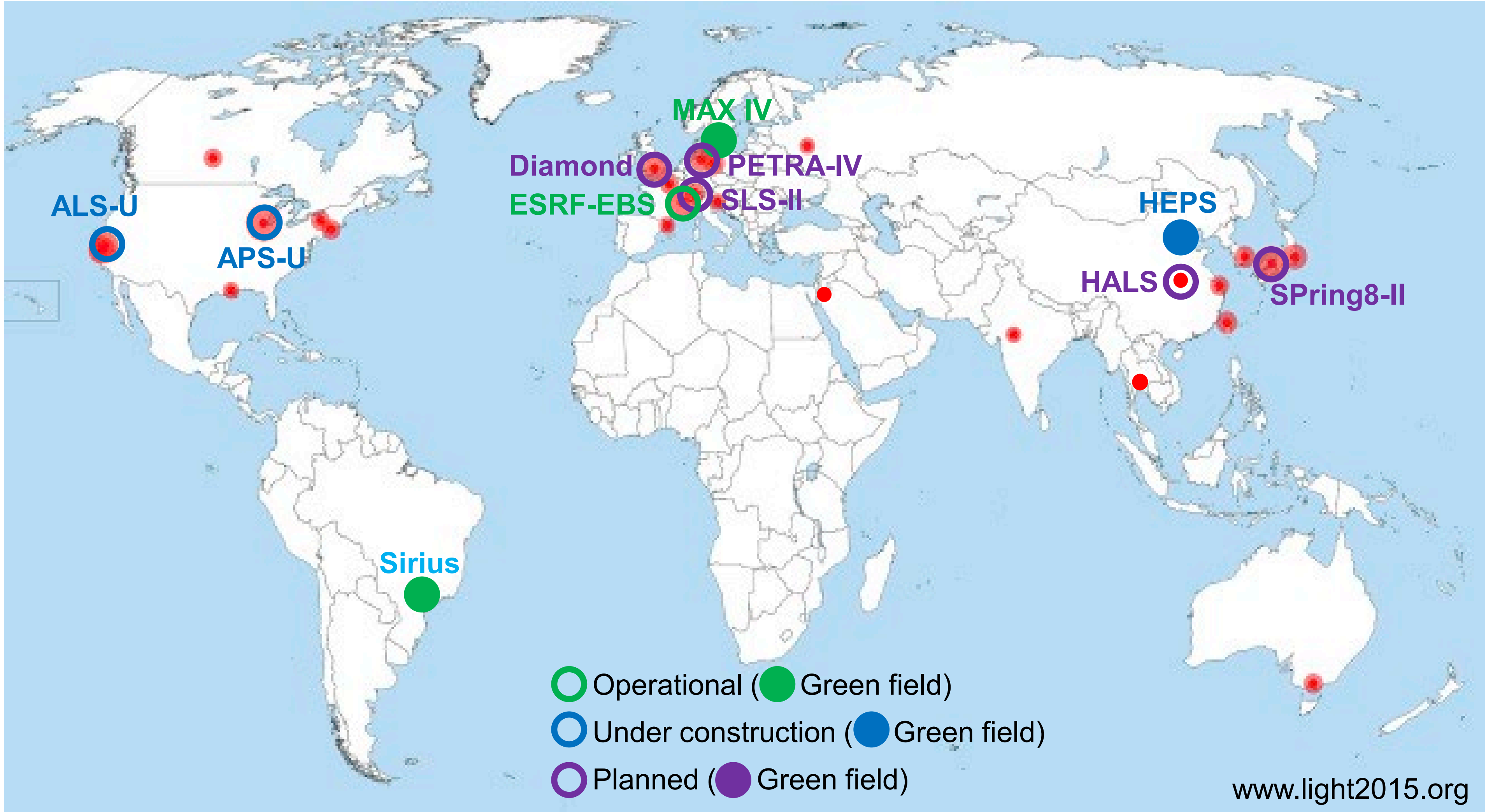
Sirius[2] (2020) and ESRF-EBS[3] (2022) are commissioned.

[1]TUYPLM3, [2]TUPGW003, [3]TUPGW005 IPAC'19

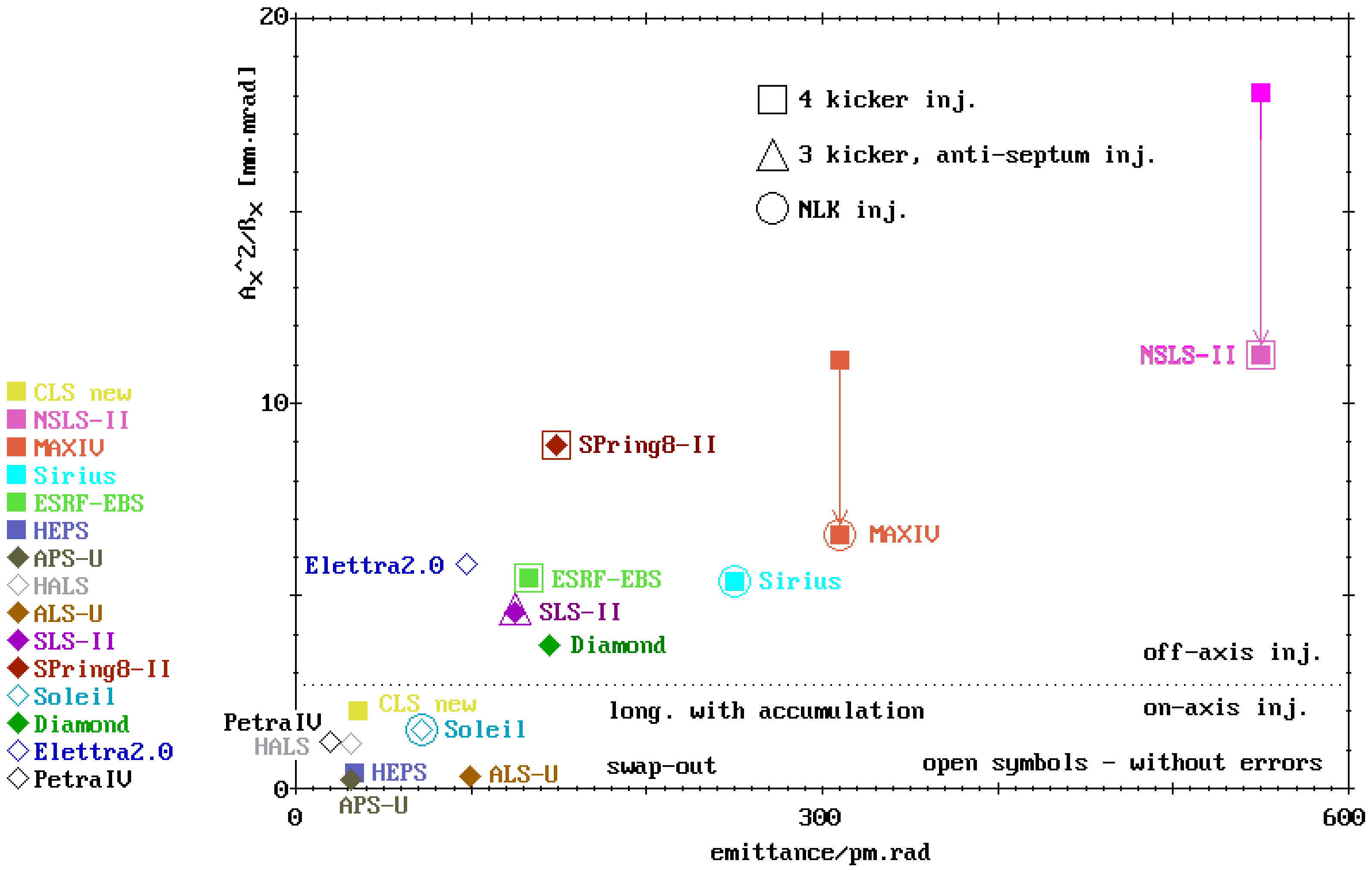
Many light sources pursuing 4th gen storage ring designs

MBAs and variations are known as **4th generation synchrotron light sources**.

Many innovative physics and engineering designs as multiple light sources pursue 4th generation sources, including **solutions for injection**.



MBA designs presents new challenges for injection



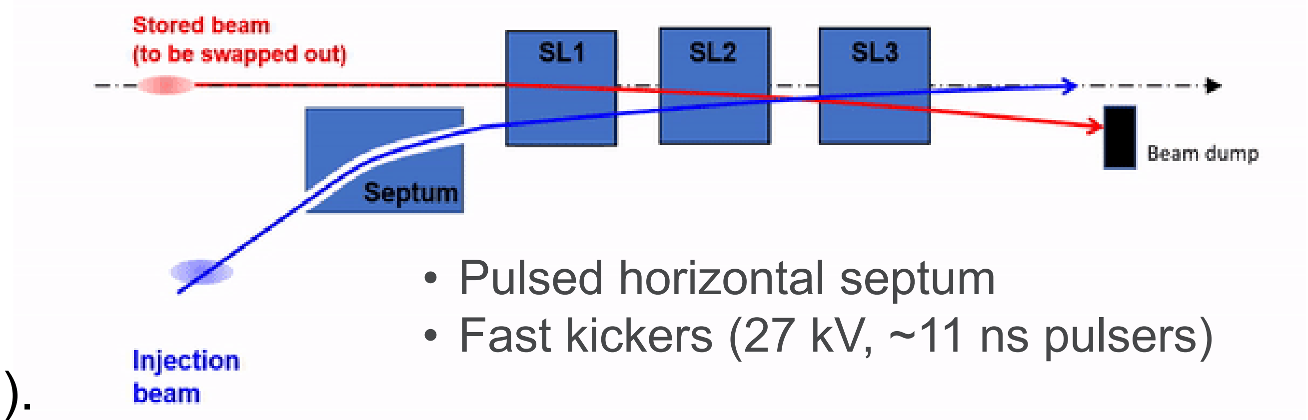
- MBA storage ring (SR) acceptance and emittance are correlated.
- Highest-performance MBA optics requires swap-out injection.
- Challenges for swap-out injector include:
  - Emittance
  - High single-bunch charge for timing mode.
  - High single- or bunch-train charge for brightness mode.
  - Instabilities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

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

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

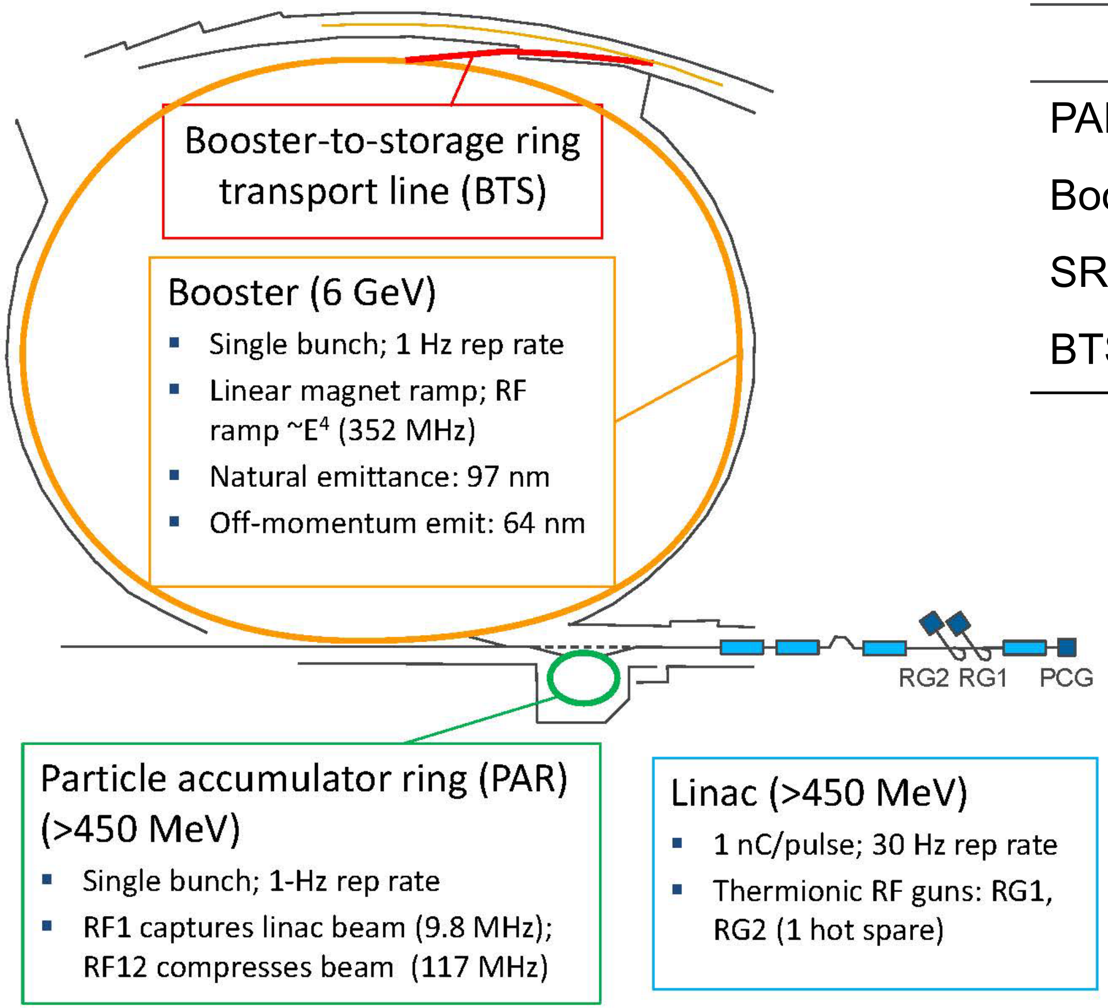
[1] L. Emery, M. Borland, PAC'03.

- Swap-out is on-axis injection without accumulation
- 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.
- Considerations for choosing swap-out include:
  - Enables ultra-low emittance
  - Enables small horizontal-gap or helical undulators.
  - Re-uses existing injector, upgrade in advance (more options with green field).



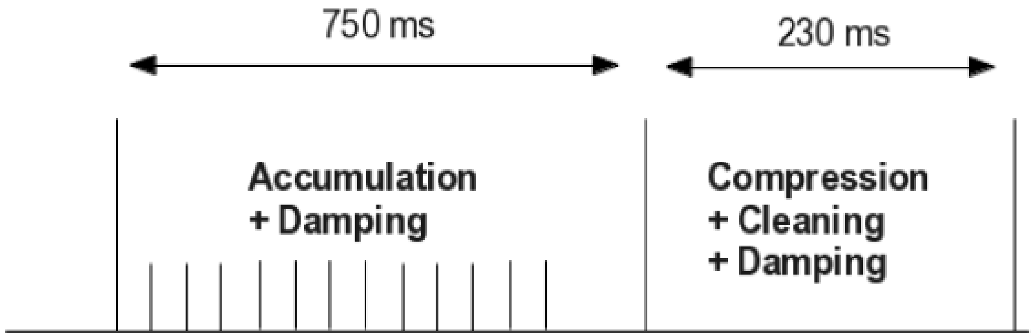
APS Upgrade parameters	Beam energy	Circum-ference	SR natural emittance	Injector emittance	Total current	Bunch charge goal
	6 GeV	1104 m	42 pm	60 nm (booster)	200 mA	2.4-16 nC

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

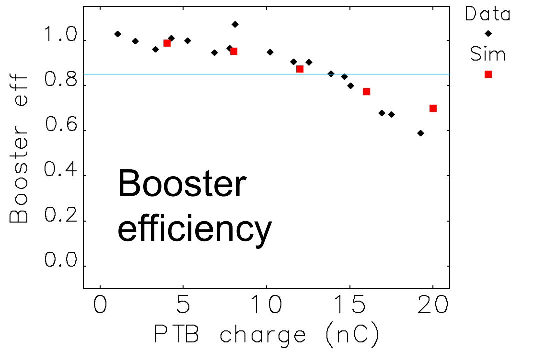
[1] For timing mode. Brightness mode requires 5 nC.

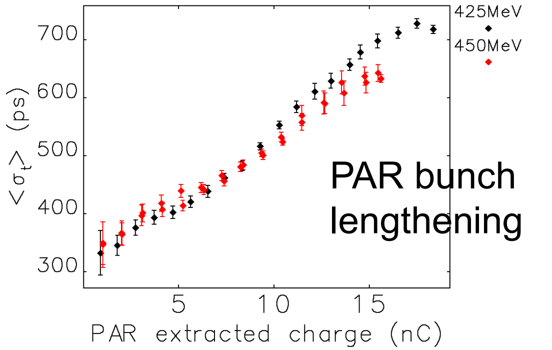


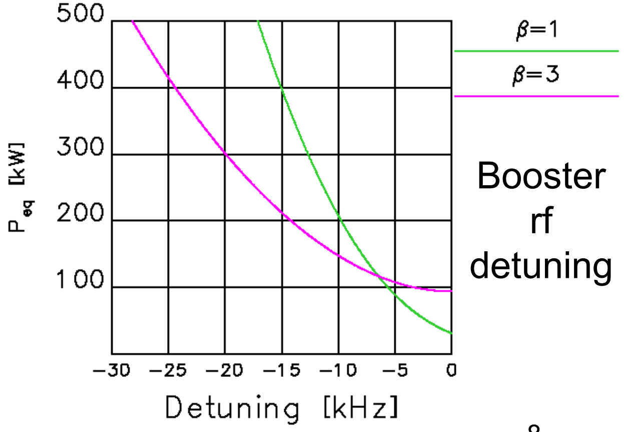
PAR cycle

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

- Injector diagnostics upgrades have been key to understanding and mitigating charge limits.
- Mature booster impedance and machine model closely reproduces observed charge-dependent injection efficiency[1].
- High-charge plan:
  - Increase PAR bunch length compression.
  - Raise linac/PAR energy to >450 MeV to raise PAR instability threshold.
  - Analyze PAR chamber impedance and redesign components where practical.
  - Detune booster rf cavities at injection for beam loading compensation.



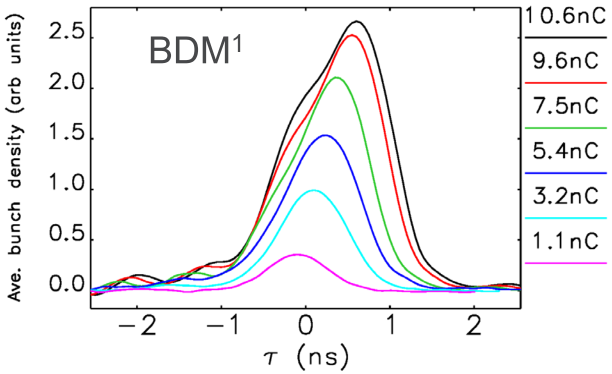


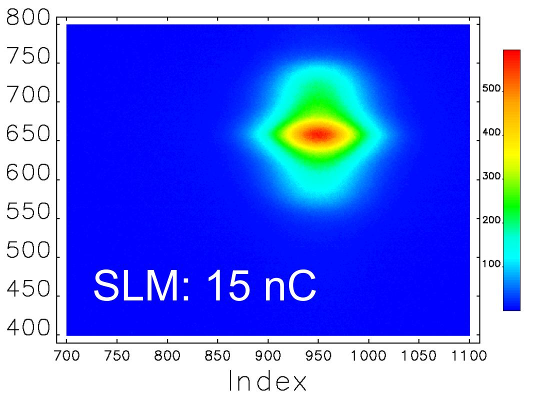


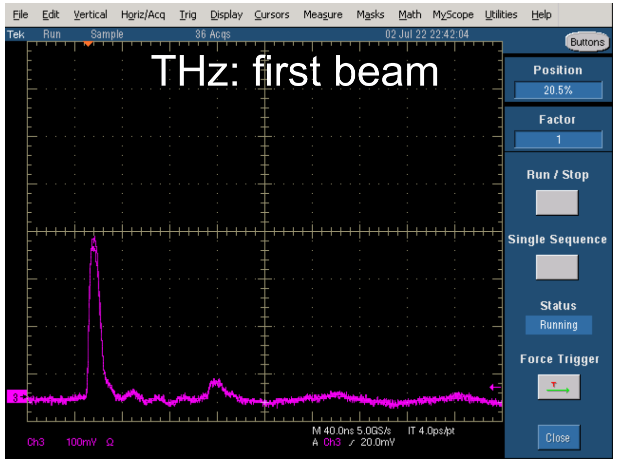
[1]J. Calvey et al., NAPAC'16

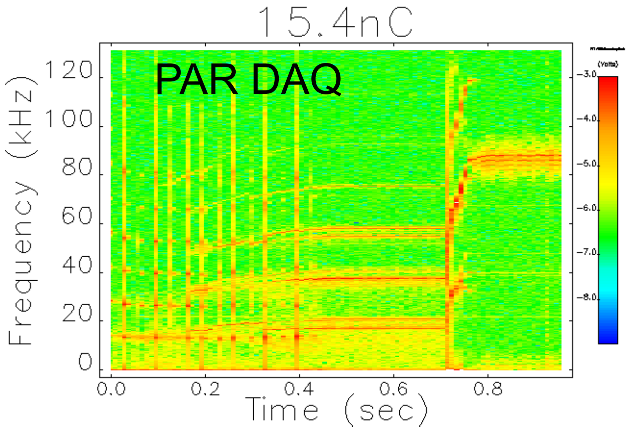
Improved PAR diagnostics and tools key to analyzing beam performance

- Photodetector bunch duration monitor (BDM) and data processing tool.
- East/West synchrotron light monitor (SLM) & digital camera upgrades. Emittance & energy spread analysis.
- THz diagnostic added to SLM East.
- Turn-by-turn BPM prototypes.
- PAR and Booster rf data acquisition (DAQ) systems; guide for rf tuning.







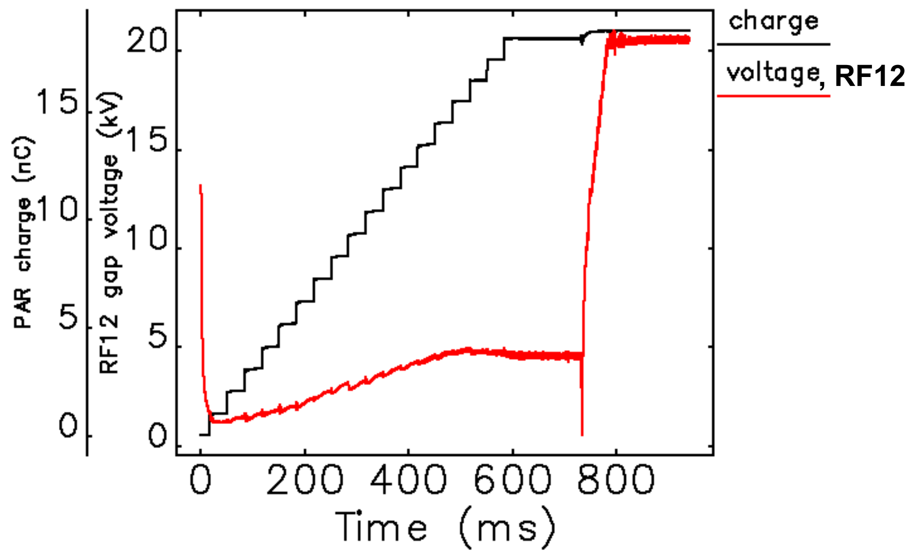


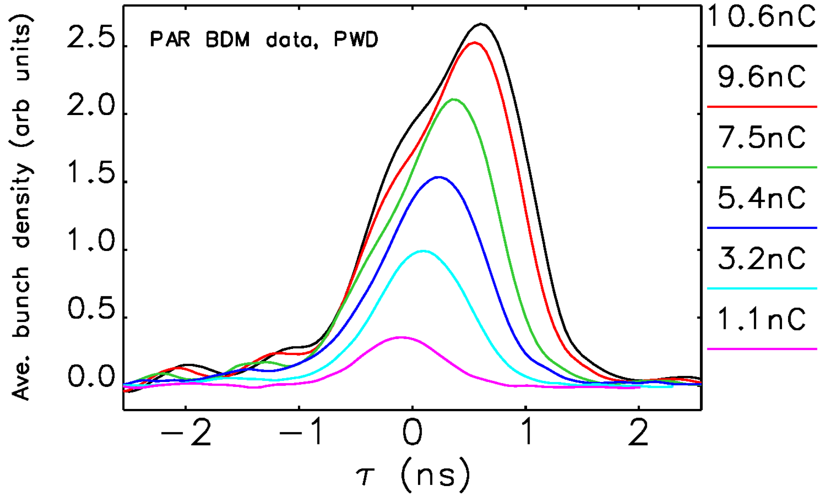
T. Berenc, A. Brill, J. Calvey, J. Dooling, A. Lumpkin, T. Madden, N. Sereno, H. Shang, J. Steinmann (ANL/KIT), K. Wootton, B-X Yang, C-Y Yao

[1] J. Dooling et al., IPAC'18.

PAR performance and analysis at 20 nC

- Achieved high-charge goal of 20 nC in 1-Hz operations.
- Significant bunch length blowup is observed due to longitudinal instability.
  - Significant impact on Booster efficiency.
  - Horizontal beam size growth is consistent with increased energy spread.
- Vertical beam size growth also observed due to ions, but not a major issue for nominal vacuum ~1 nTorr.
- Impedance model [1], analytical calculations [2], and simulations [3] used to model bunch lengthening and energy spread dependence on harmonic gap voltage and beam energy.

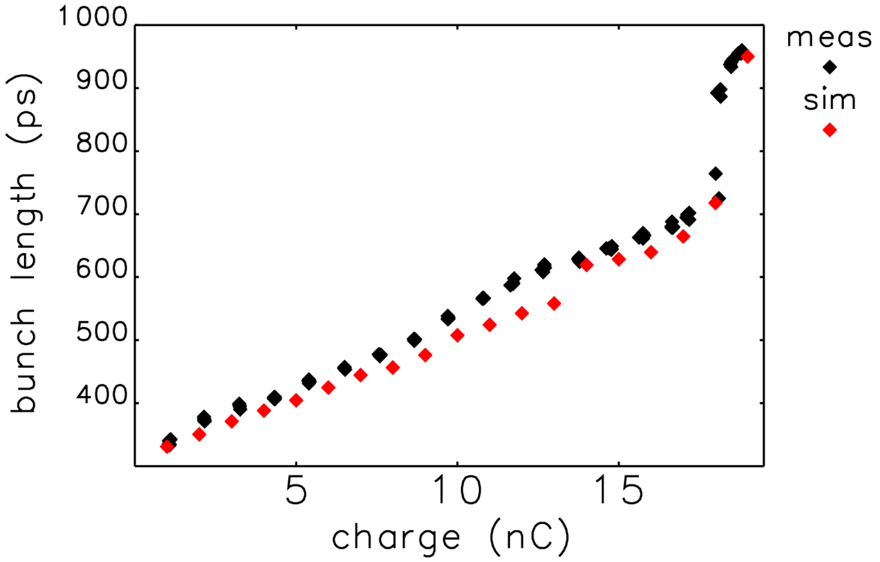


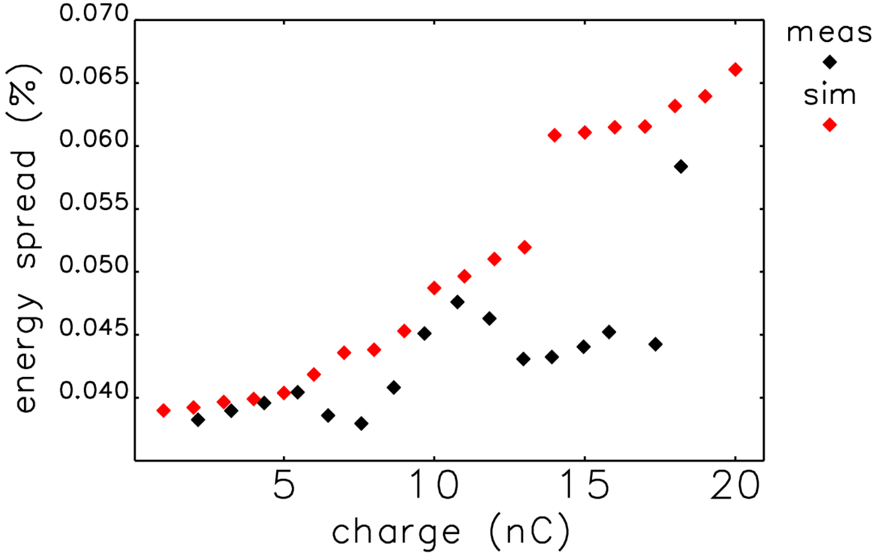


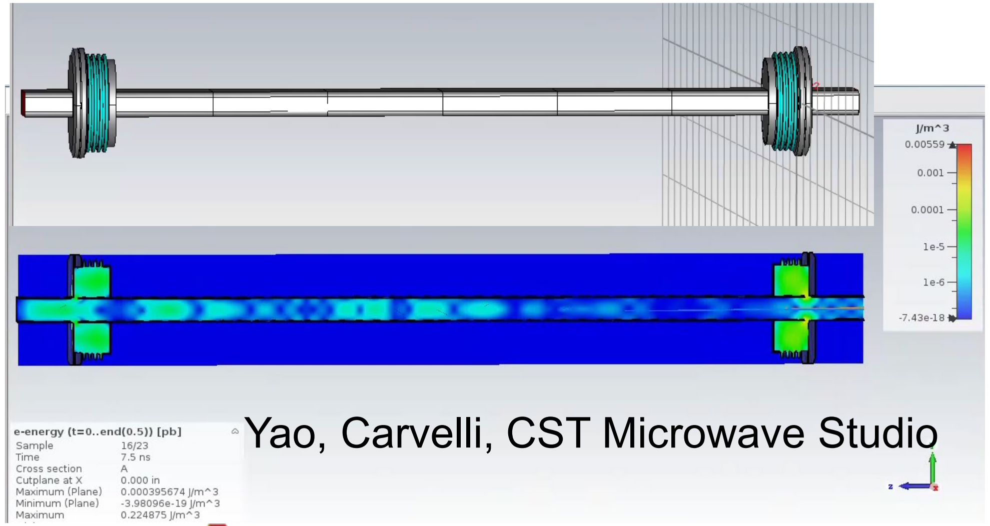
[1] CY Yao et al., Proc. NAPAC'19, MOPLM17.
[2] K. Harkay et al., Proc. NAPAC'19, MOPLM21.
[3] J. Calvey et al., Proc. NAPAC'22, TYPD4.

Simulation results reproduce bunch lengthening[1]

- Simulated bunch length at nominal 22 kV harmonic voltage agrees well with measurements (but a bit lower).
- Energy spread blowup of the same order, but different in detail.
  - Measurement shows dips in energy spread vs charge (also observed elsewhere[2]).
- May be missing high frequency part of impedance[3].





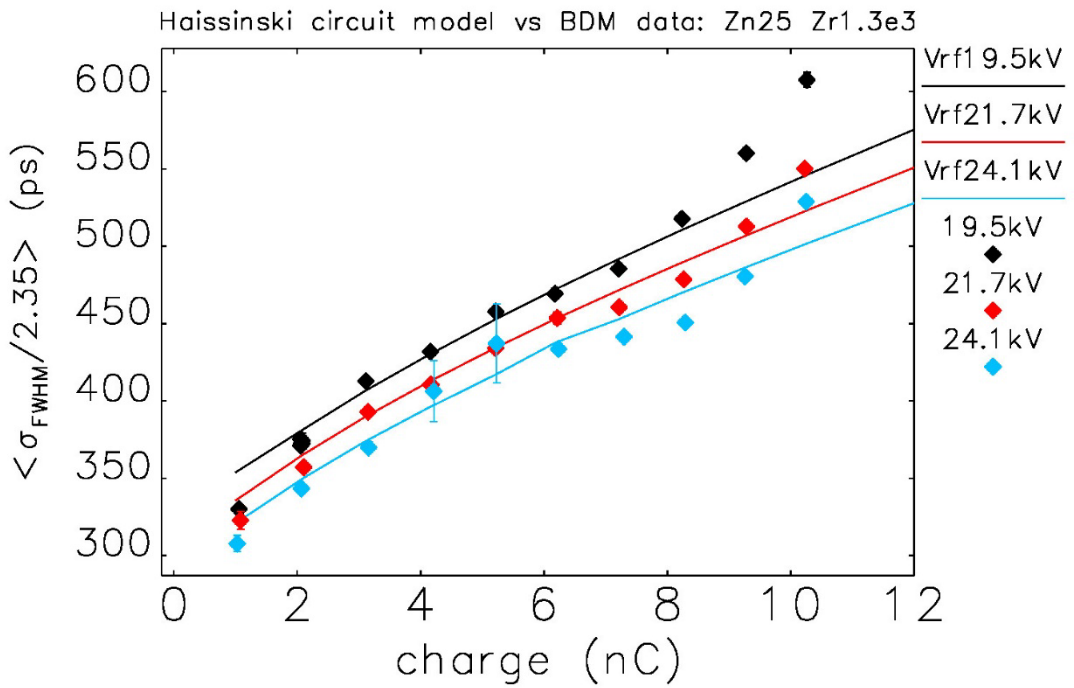


Yao, Carvelli, CST Microwave Studio

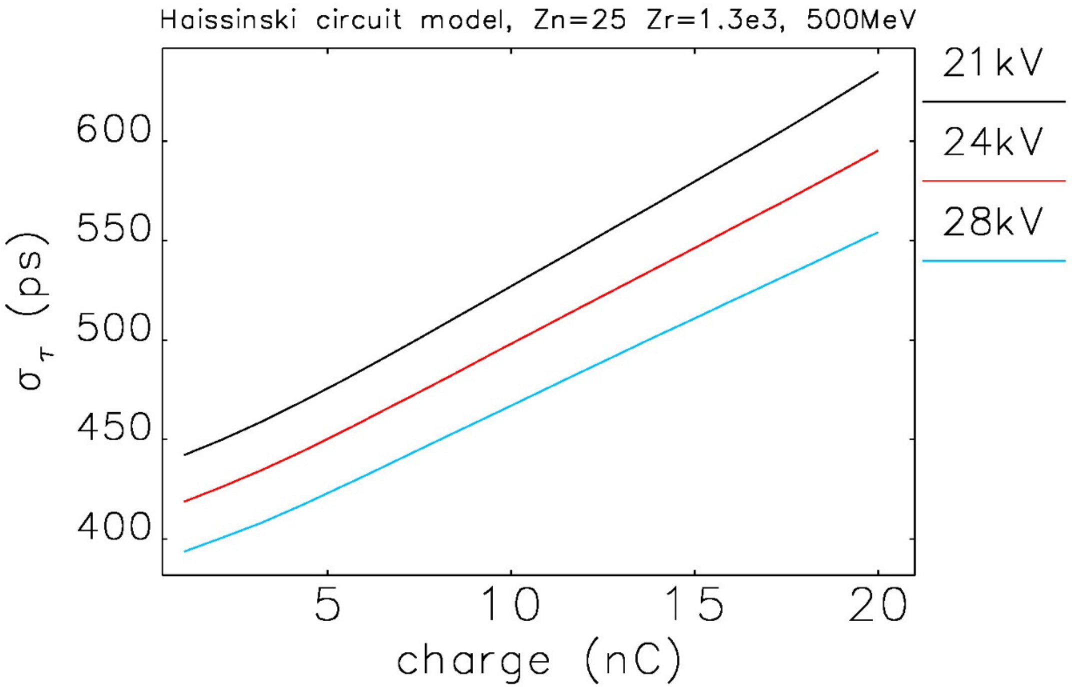
[1] J. Calvey et al., Proc. NAPAC'22, THYD4.
[2] A. Blednykh et al., Scientific Reports vol 8, 11918 (2018).
[3] CY Yao et al., Proc. NAPAC'19, MOPLM17

Shorten bunch with higher gap voltage

- Higher gap voltage shortens the bunch in potential well distortion (PWD) regime.
- BDM data were fit to Haissinski distributions, using circuit impedance model: Zn=25, R=1300[1].
- Calculations for 500 MeV show 30 kV harmonic gap voltage meets 600 ps bunch length goal.
- Voltage droop and 30-kV calculation inform requirement for 10-kW harmonic rf amplifier.



Measured and computed: 425MeV

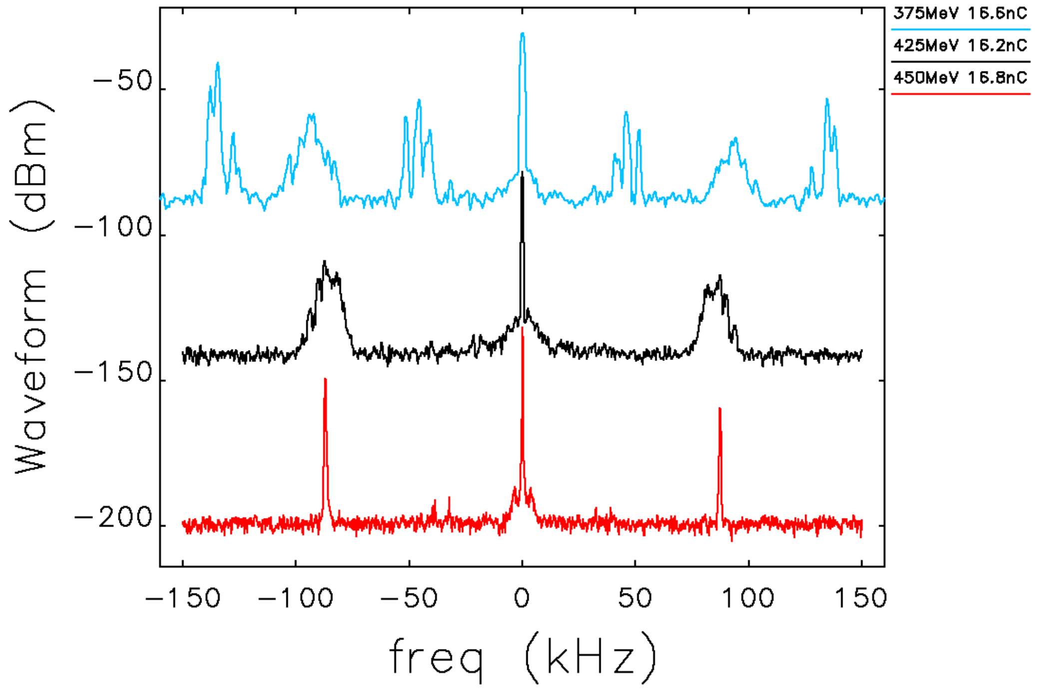


Computed: 500MeV

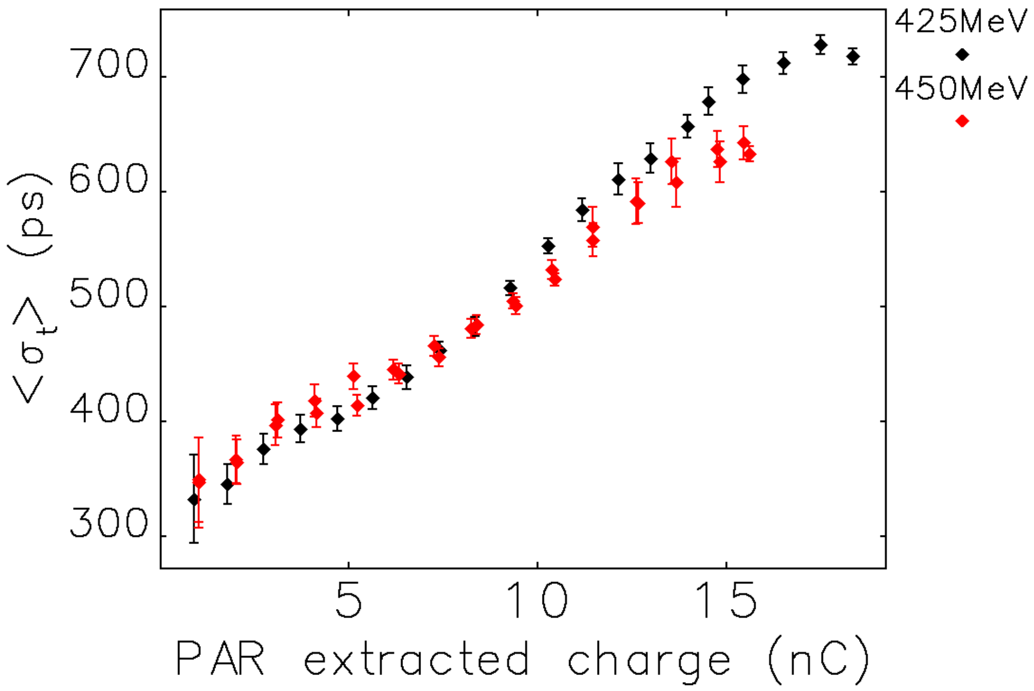
[1] K. Harkay et al, Proc. NAPAC'19, MOPML21

Use higher energy to raise instability threshold

- Lower-charge dynamics is dominated by potential well distortion (PWD), while higher-charge dynamics appears to be dominated by microwave instability.
- Plan is to raise instability threshold by increasing the beam energy.



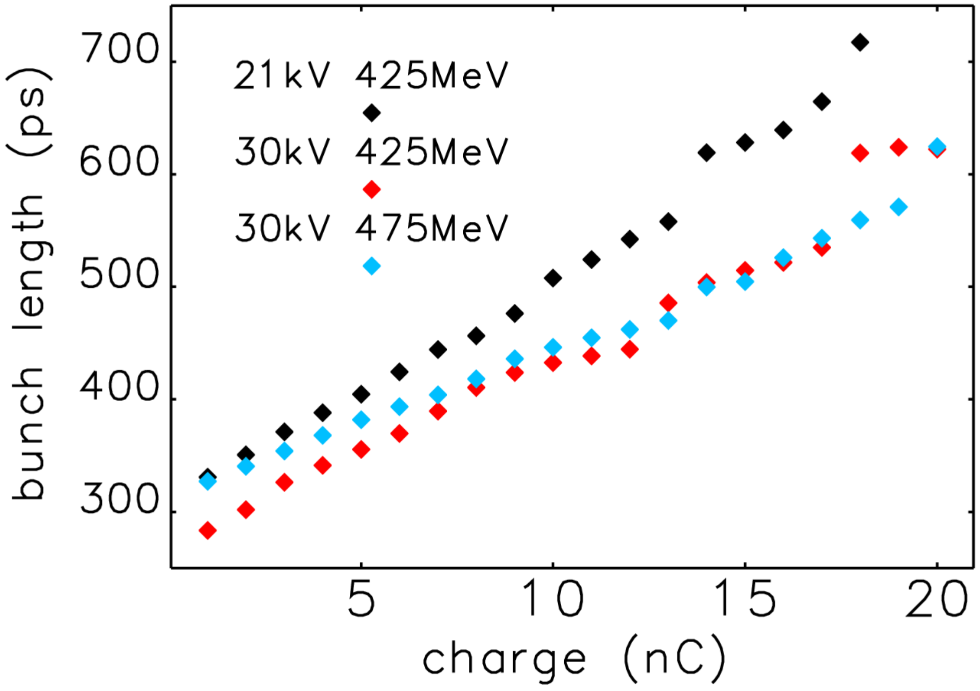
Synchrotron spectra for 450 MeV at high charge appear to be more stable than 375 MeV and 425 MeV.



Preliminary measurements of shorter bunch length at 450 MeV. Instability and harmonic tube amplifier voltage droop prevented further compression.

Reducing bunch length blowup at high charge

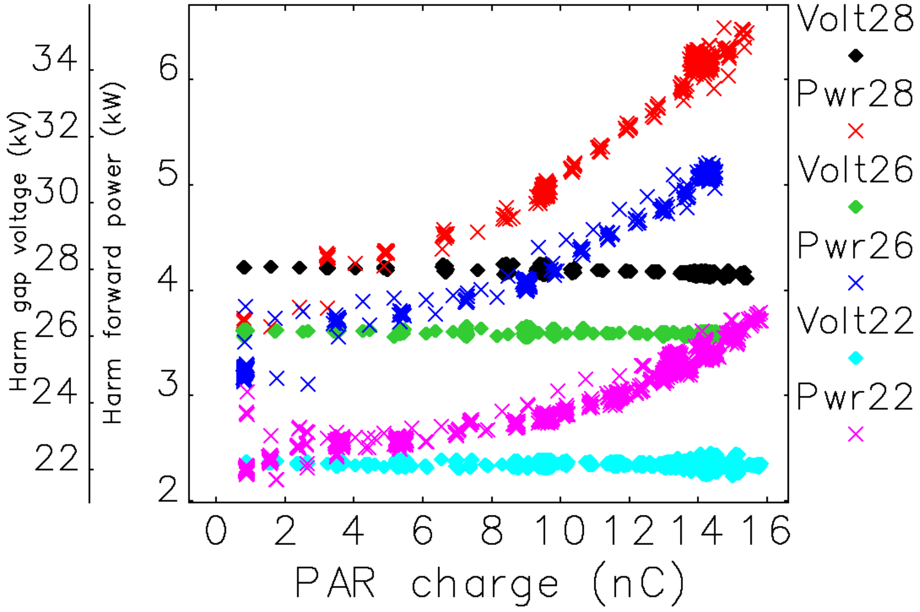
- Simulated both higher 12th harmonic rf voltage and higher PAR beam energy.
- 30 kV greatly reduces bunch length up to a threshold at 17 nC [1].
- 475 MeV pushes the threshold to 19 nC. Consistent with analytical predictions [2].
- Bunch length goal is below 600 ps up to 19 nC.

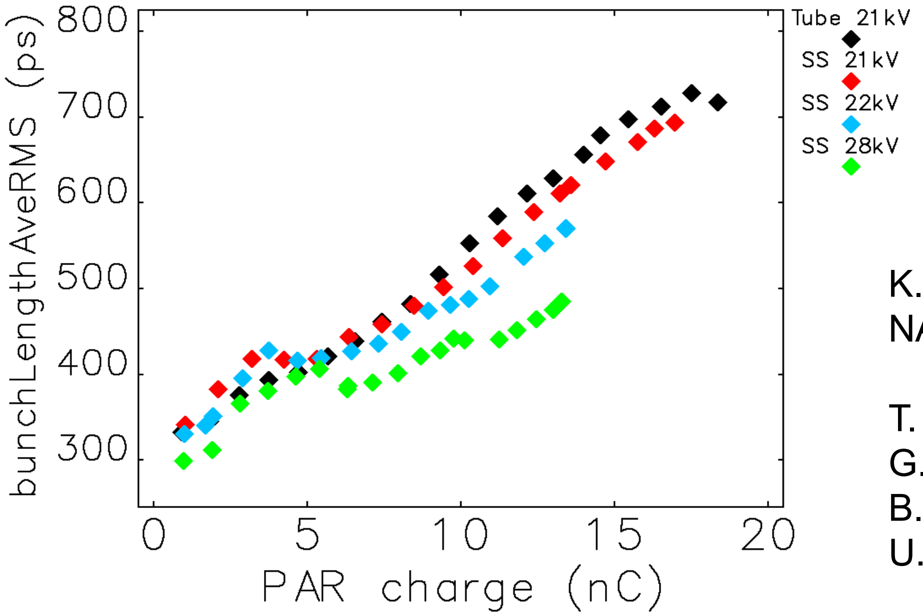


[1] J. Calvey et al., Proc. NAPAC'22, THYD4.
[2] K. Harkay et al, Proc. NAPAC'19, MOPML21.

Shorter bunch demo’d with higher gap voltage

- 10-kW 117 MHz harmonic rf solid-state amplifier (SSA) installed and operating reliably since Nov 2021.
- No drooping of gap voltage at higher charge, as seen with 3-kW tube.
- First beam results: shorter bunch length even above microwave instability at ~10 nC.
- Recent vacuum leak (>10 nTorr) limits charge to ~14 nC; to be fixed.
- Further studies with >425 MeV and booster efficiency also planned.





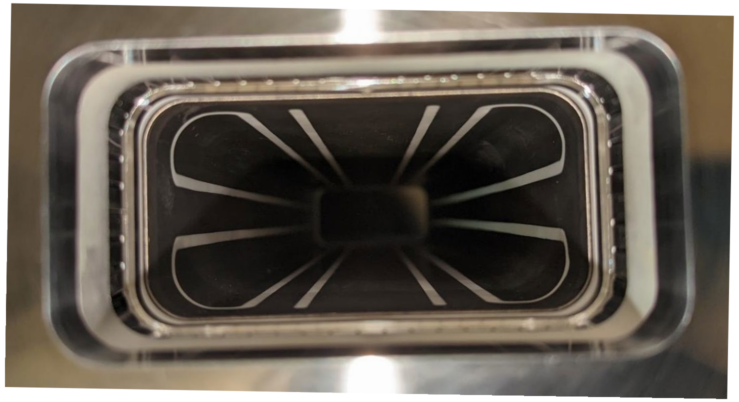
K. Harkay et al., Proc. NAPAC’22, TUPA23.

T. Smith, T. Berenc, G. Fystro, M. Henry, B. Heyeck, A. Nassiri, U. Wienands

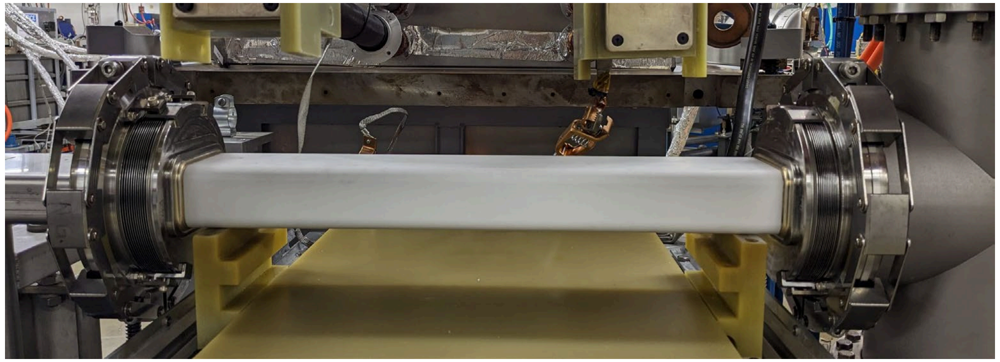
New PAR kicker chamber: innovative patterned coating

- New kicker chambers developed by operations to address the lack of working spares.
- Opportunity to develop a novel patterned coating designed to reduce the impedance while suppressing eddy currents (CY Yao), thereby improving high-charge performance.

	Surface resistivity (Ω/sq)	Loss factor (V/pC)
Old	40-50	0.7
New	2-3	0.13

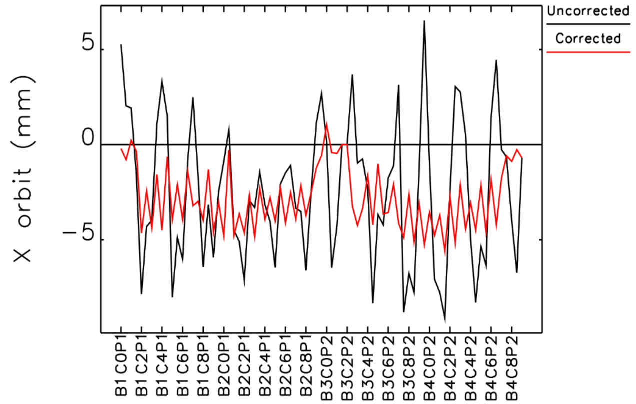


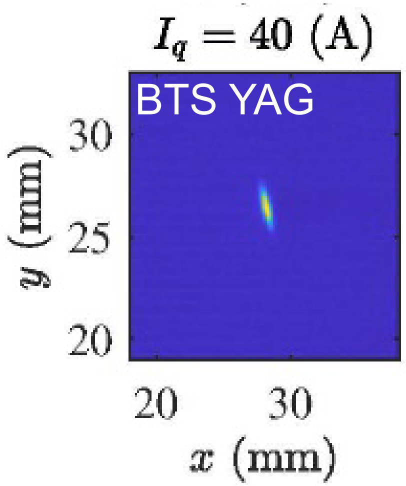
- Simulations show that even one new chamber will lower the PAR bunch length at high charge (J. Calvey). This is expected to improve Booster high-charge injection efficiency.
- One new chamber was installed in Jan 2023.
- If successful, two more new chambers will be installed during the APS-U dark time.

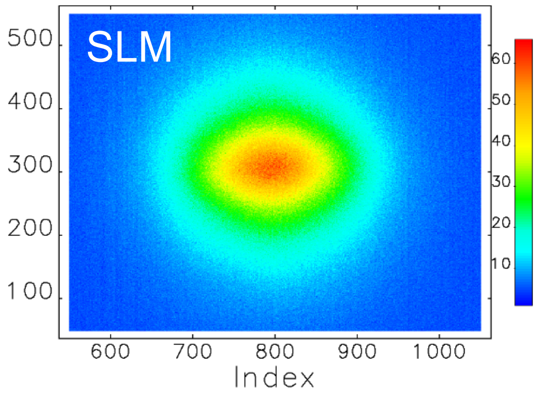


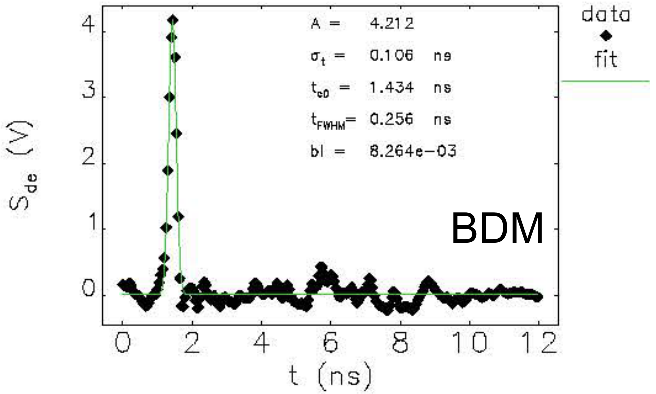
Improved booster diagnostics and tools key to analyzing performance

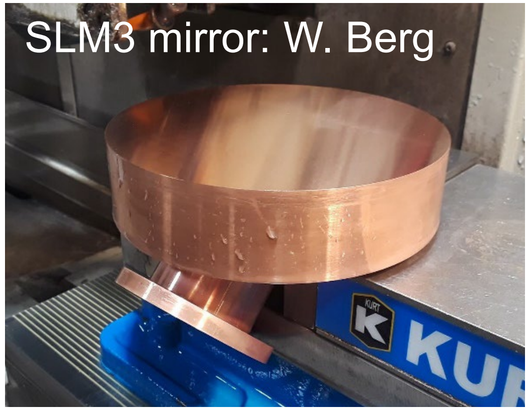
- BPM data acquisition and orbit correction over the ramp.
- Synchrotron light monitor (SLM) digital camera upgrades.
- SLM3 mirror upgrade to address thermal stability issues. Preliminary data shows stable image.
- Booster to storage ring transport line (BTS) emittance diagnostic YAG upgrade.
- Bunch length BDM.
- Beam arrival monitor (BAM) in BTS.
- Chromaticity correction tool.











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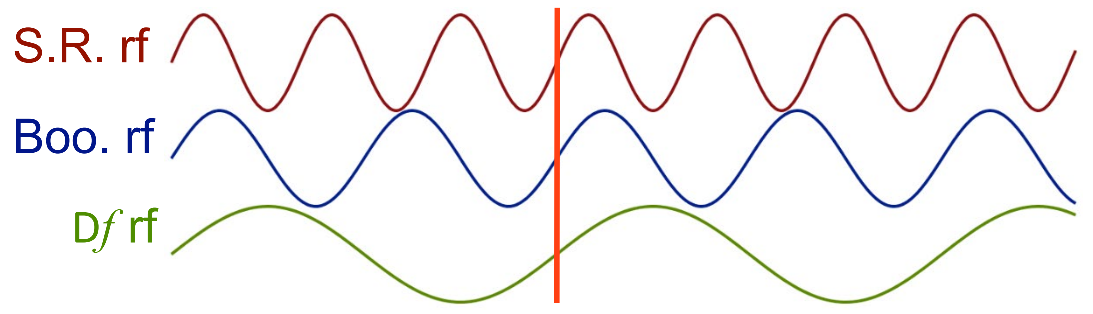
New injection timing system to avoid realigning booster

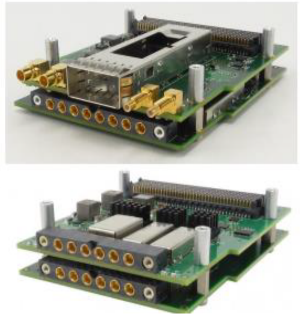
- APS-U SR has smaller circumference, so the rf frequency increases: Df 120 kHz (352 MHz rf)
- Developed a new injection timing system that enables bunch-to-bucket transfer from booster at different rf frequency.
- Requires fully digital low-level rf (DLLRF).
- Provides an additional booster emittance and injection tuning knob:
  - 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.

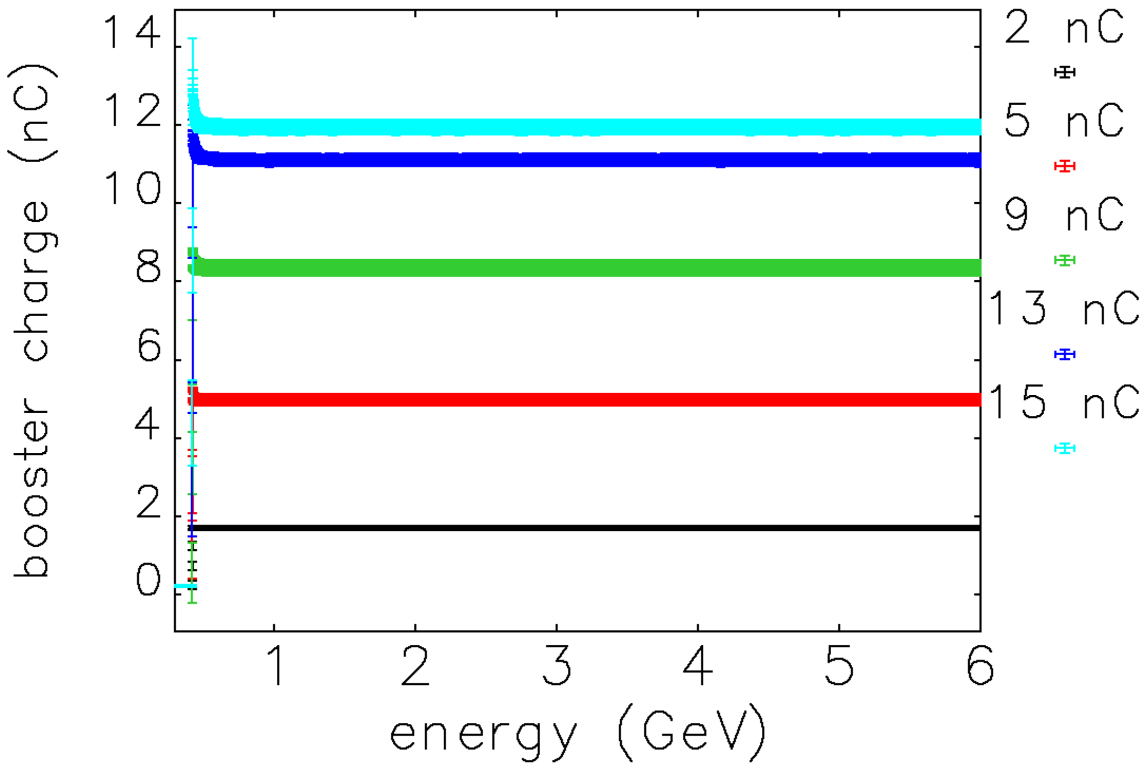
- Booster and PAR LLRF systems will be upgraded to digital
- μTCA for flexibility & scalability
  - A-D and D-A boards by VadaTech in testing
- Strong collaboration with SNS (Eric Breeding)
- Rf design & EPICS interface in house.
- DLLRF fully demonstrated in PAR with beam.



T. Berenc

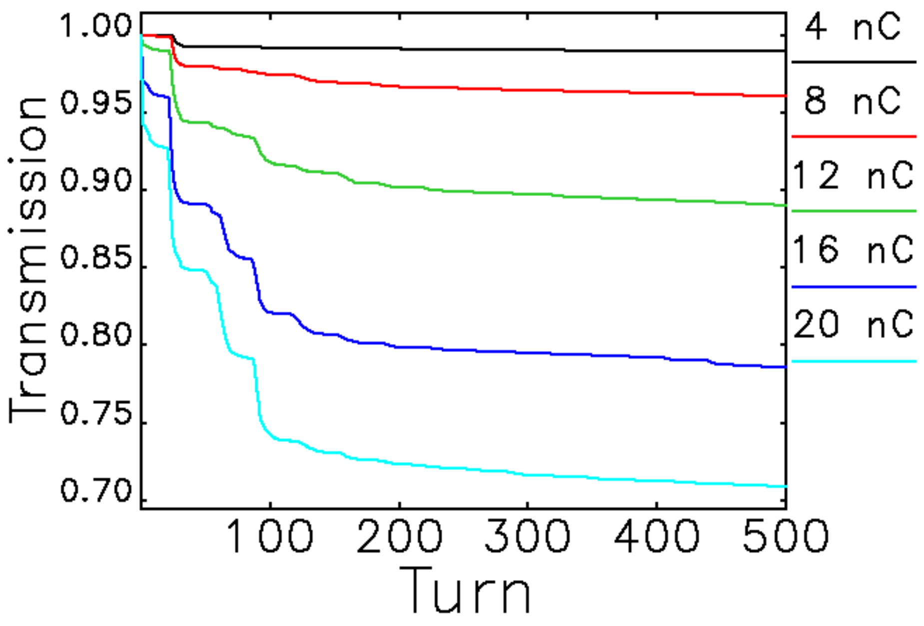
Booster performance and readiness

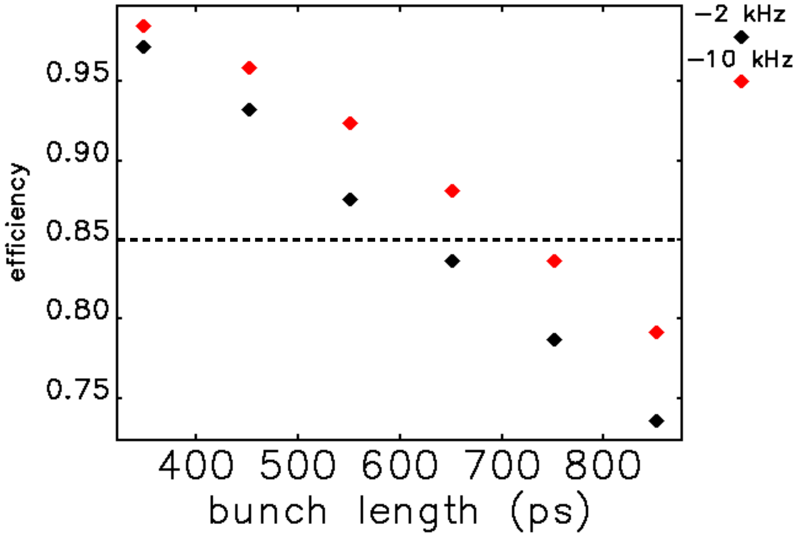
- Highest priority are studies of beam dynamics with APS-U injection/extraction timing system (IETS).
- Reliable booster charge 10 nC is sufficient for APS-U commissioning.
- Made a plan for booster re-commissioning during dark time:
  - Booster beam incompatible with MBA storage ring installation.
  - Booster shut down until 6 weeks before storage ring commissioning.
    - Re-commission rf and ramping supplies.
    - Re-commission beam.

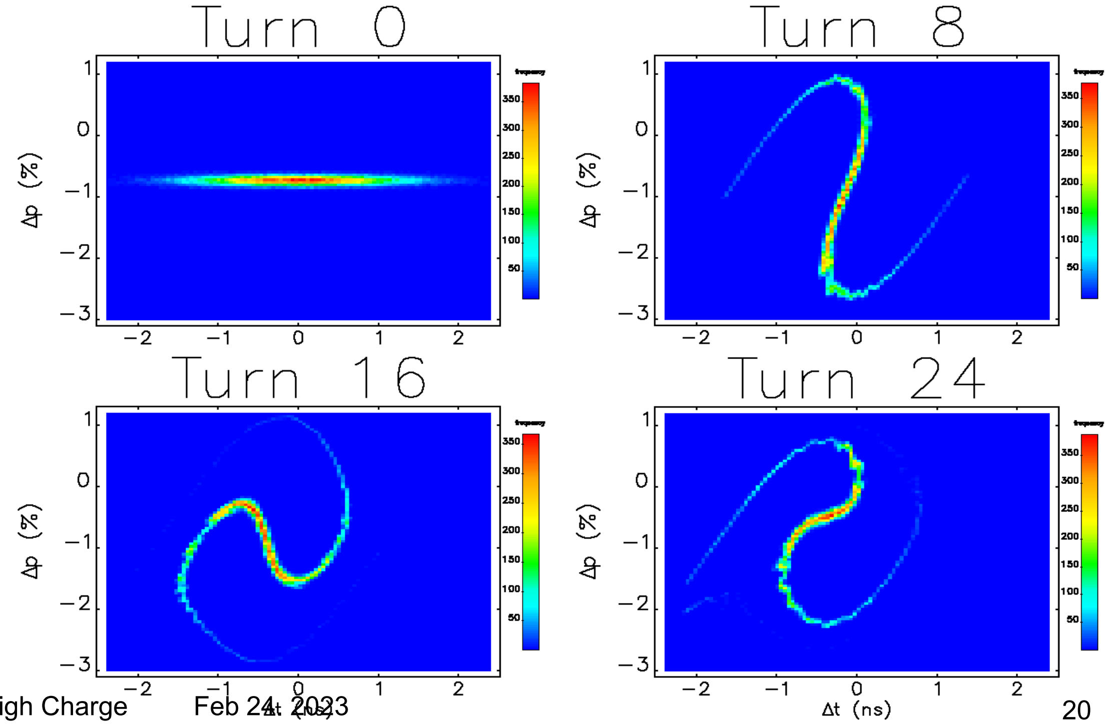


Comprehensive injection model

- Using elegant [1], tracked 3000 booster turns (3.5 ms), where most losses occur.
- Model includes momentum offset (-0.6%), transverse and longitudinal impedance [2], beam loading in rf cavities, and incoming beam parameters (e.g., beam size and bunch length vs charge) derived from measurements.
- Main source of losses: PAR bunch length, beam loading.
- Efficiency can be improved with shorter bunch length (PAR improvements) and detuning cavities.







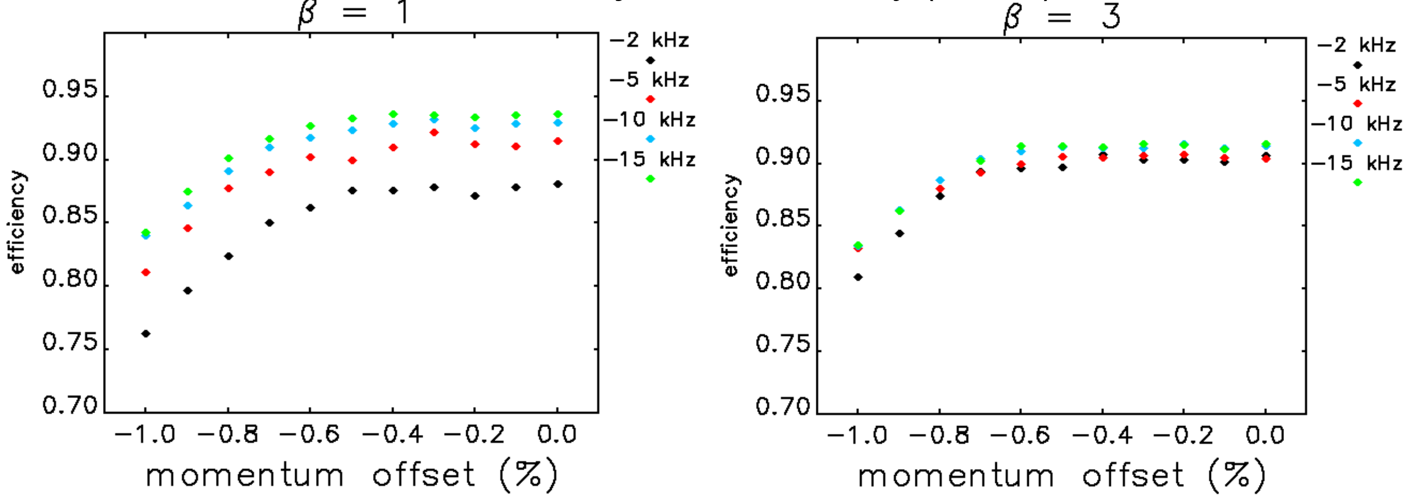
[1] M. Borland. ANL/APS LS-287, (2000). Y. Wang et al. *Proc. PAC'07*, 3444.
[2] R. R. Lindberg et al. *Proc. IPAC'15.*, TUPJE078.

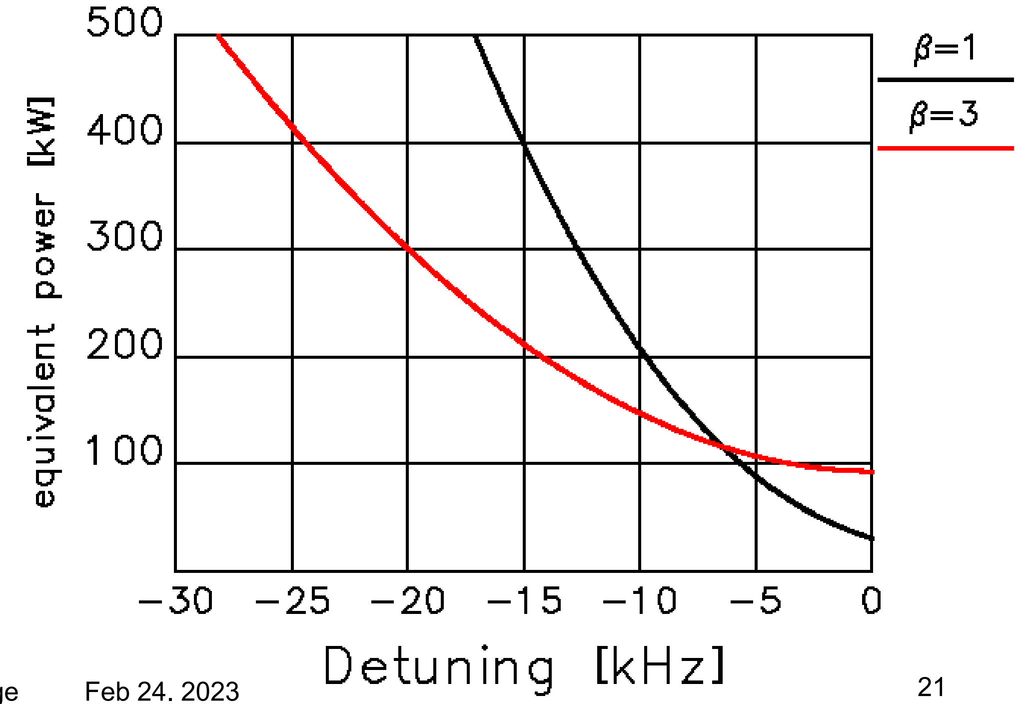
Booster high charge plans [1]

- IETS system allows for frequency ramp in booster.
  - Inject close to on-momentum to maximize injection efficiency.
  - Extract off-momentum to minimize horizontal emittance for SR injection.
- Cavities will be detuned at extraction due to frequency ramp.
  - Need high-power coupler for large ramp.
  - Can be over-coupled (β=3) to mitigate beam loading and reduce equivalent power at extraction.

$$P_{eq} = P_{fwd}\left(1 + \sqrt{\frac{P_{rev}}{P_{fwd}}}\right)^2$$

Simulated injection efficiency (20 nC)

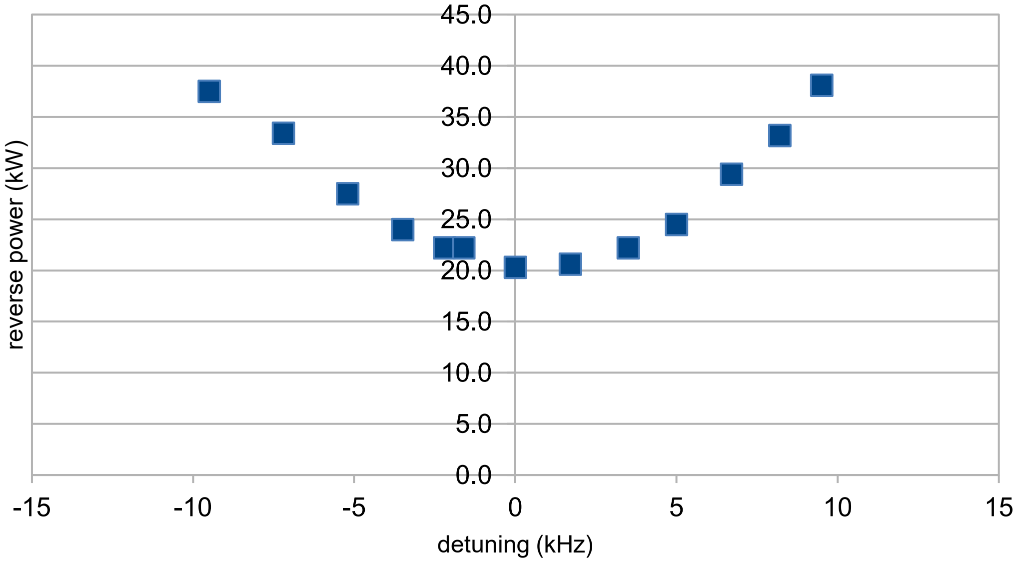


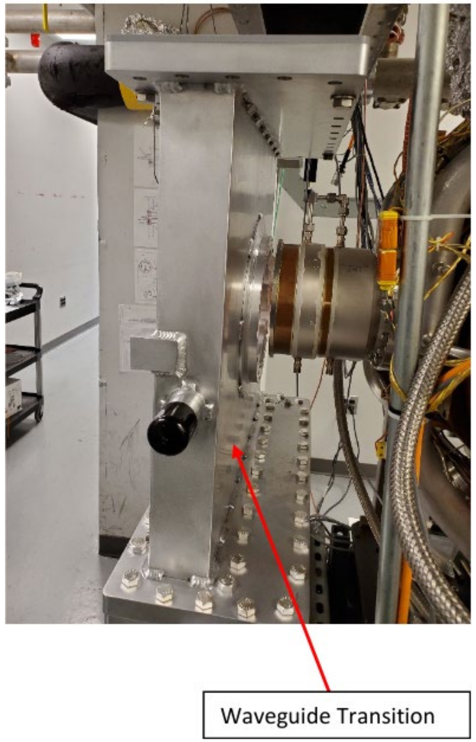


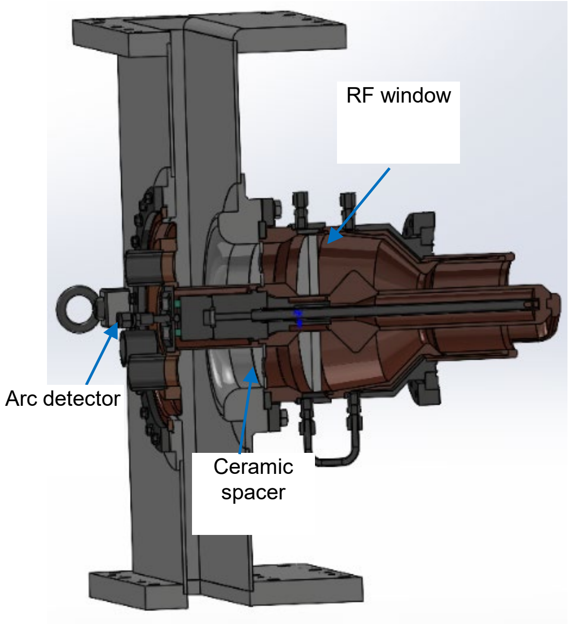
[1] J. Calvey et al., AOP-TN-2018-074

High power coupler prototype performed well

- 500 kW prototype coupler design by Canon.
- Installed in one booster cavity (of four), changed β from 1 to 3; operated Jun-Dec 2021.
- No major operational issues.
- Machine studies: varied detuning, tested high charge. Performed as expected.
- Water-vacuum joint discovered; design had to be modified.
- Descoped for now.







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.
- Installed additional supplemental shielding in PAR in 2021 (over 50 tons of steel; each panel weighs 2,100 lb). Shielding performance matches predictions.
- Installing beam loss monitors[1] as a diagnostic to aid in injection tuning.

[1]J. Dooling et al., IPAC’15.

Outlook and Summary

- Designs for 4th generation light sources based on MBA variations are being pursued world-wide to dramatically increase the x-ray brightness, compared to 3rd generation sources.
- High-performance MBA designs and other considerations drive the decision to implement swap-out injection, which imposes challenges on the injectors.
- APS-U injectors have been upgraded to double the design charge: 12 nC. More work in progress to raise charge to 17 nC to enable timing mode.
- Injectors will be ready for APS-U commissioning Jan-Apr 2024, delivering 10 nC reliably.

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