Comparison of Horizontal- and Vertical-Plane Swap-out Injection Options for APS-U

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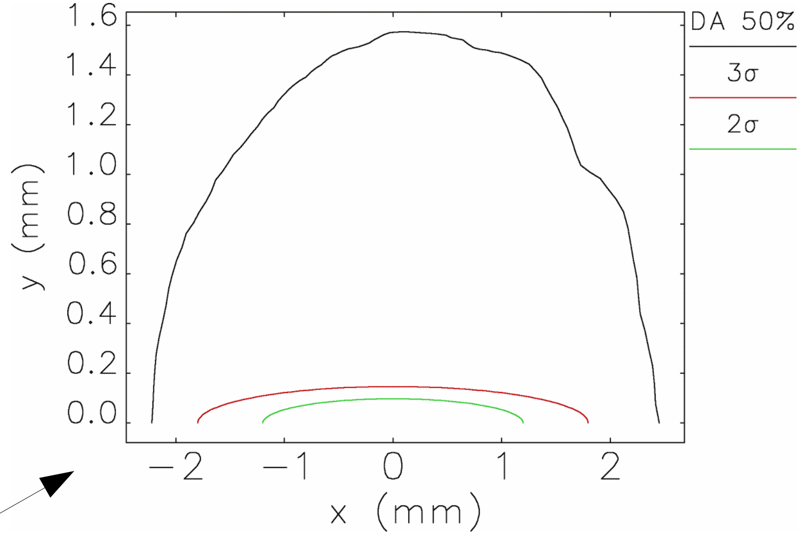
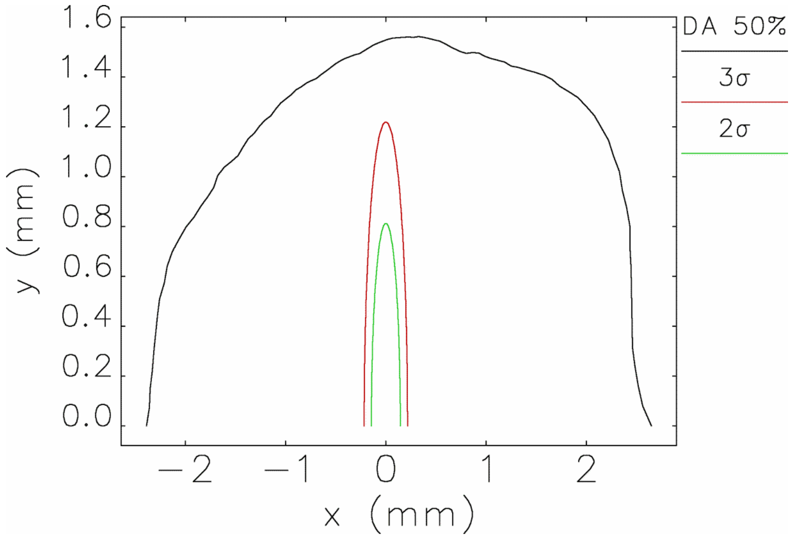
8th Low Emittance Rings Workshop
INFN-LNF, Frascati, Italy
26-30 October 2020

Overview

- APS-U lattice requires on-axis swap-out injection due to aggressive tuning for lowest emittance (42 pm)
- APS booster has relatively high emittance
  - At low charge, measure[1,2] $\varepsilon_x \approx 70$ nm and $\varepsilon_y \approx 1$ nm
  - High charge could inflate this, but not seen in simulations[3]
- Normally, beam sizes at injection point are $\sigma_x \approx 600$ µm and $\sigma_y \approx 50$ µm
  - Natural injection scheme is in vertical plane with Lambertson septum
- Lambertson septum is challenging, so horizontal-plane scheme developed with emittance exchange in BTS





1: K. Wootton, private communication.
2: V. Sajaev, private communication.
3: J. Calvey, NAPAC16, 647.

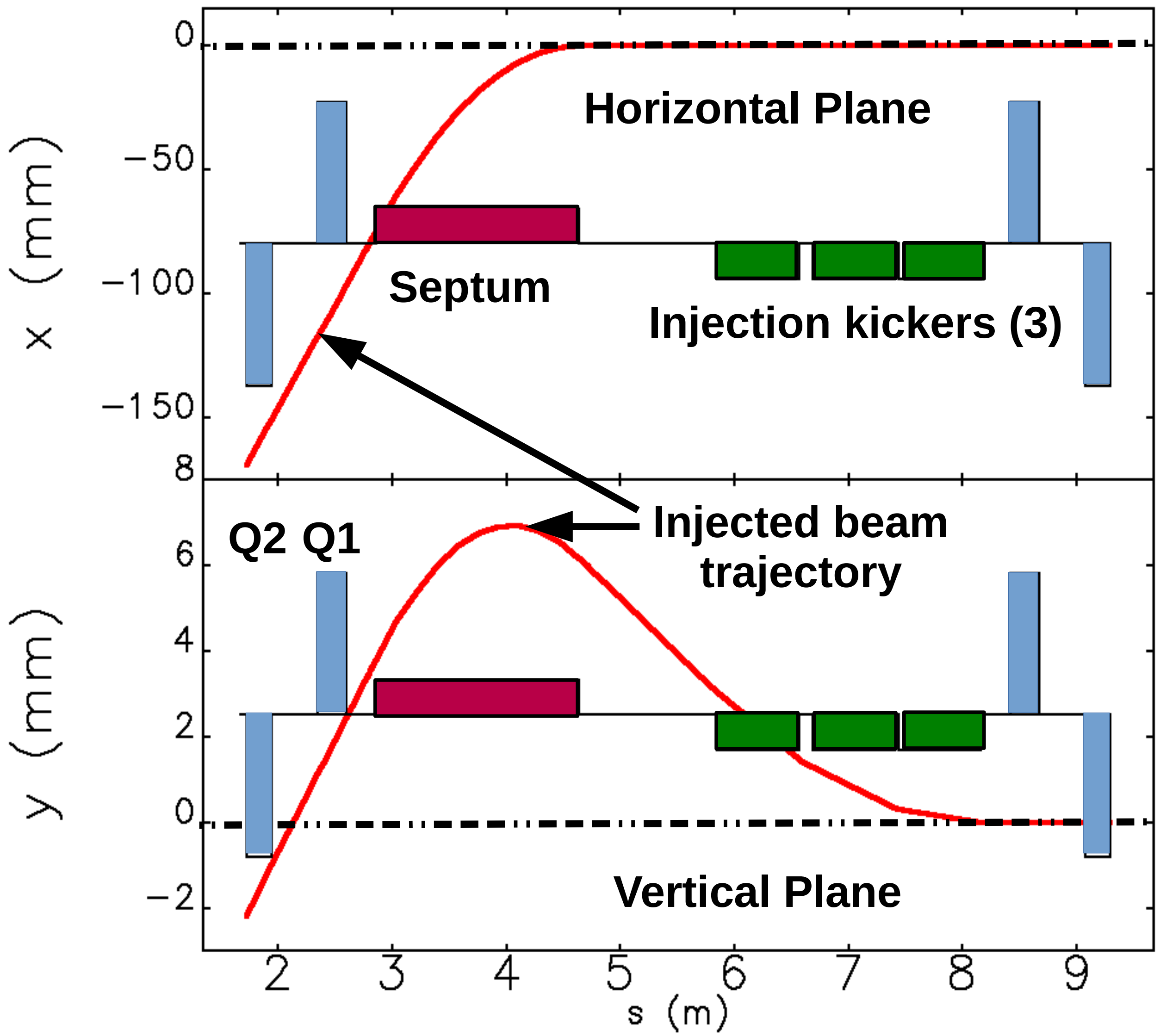
Relevant APS-U performance requirements

- APS-U should need minimal enhancements to existing shielding, requiring[1]
  - Injection efficiency: >95%
  - Beam lifetime: > 3 h @ 200 mA
  - Swapped-out bunches go to a dump inside a longitudinal gradient dipole
- The injection process should not significantly affect beam stability
  - Transient beam motion < 10% of beam size
  - Transient emittance increase < 2%
    - Equivalent to transient brightness drop from replacing one bunch
- Vacuum system requirements
  - > 30 hour gas scattering lifetime
  - Septum (and other special straights) should have ≤10 nT (N_2 equivalent) to limit combined GS lifetime reduction to ~10%
    - Requirement from ion instability is ~3-fold more relaxed[2]

1: B. Micklich, private communication.
2: J. Calvey, private communication.

Vertical-plane injection scheme is the default for APS-U[1]

- Vertical-plane injection was first scheme developed, largely to accommodate booster horizontal emittance (nominally $\varepsilon_x \approx \varepsilon_0 \approx 60$ nm)
- Lambertson septum parameters
  - 1.78 m, 0.95 T, and a ~2-mm blade.
  - Rolled slightly so beam path clears poles and coils in Q1 and Q2
- Injection kickers also send depleted bunch to the swap-out dump



1: A. Xiao *et al.*, IPAC18.

Horizontal-plane injection now seems feasible

- Challenging Lambertson septum[1] needed for vertical-plane injection[2]
  - Modeling this magnet pushes the limits of 3D OPERA
    - Unexpectedly high leakage field could have negative consequences
  - Rotation of this magnet makes BTS line alignment a challenge
  - Many manufacturing and design challenges, e.g., vacuum pumping
- Seemed to be no alternative, but horizontal scheme now seems workable
  - Simple x-y emittance exchange gives small horizontal emittance[3]
  - Can obtain much higher pulser voltages than originally thought possible
    - E.g., ±27 kV instead of ±15 kV “limit” established early in APS-U project
  - Conventional pulsed septum magnet can reach well above 1 T[4]
    - APS has several high-quality pulsed septa, but limited to 0.74 T

1: M. Abliz *et al*., NIM A 886, 7-12 (2018).
2: A. Xiao *et al*., IPAC18.
3: P. Kuske *et al.*, IPAC 2016, 2028.
4: M. Paraliev, https:///doi.org/10.23730/CYRSP-2018-005.33

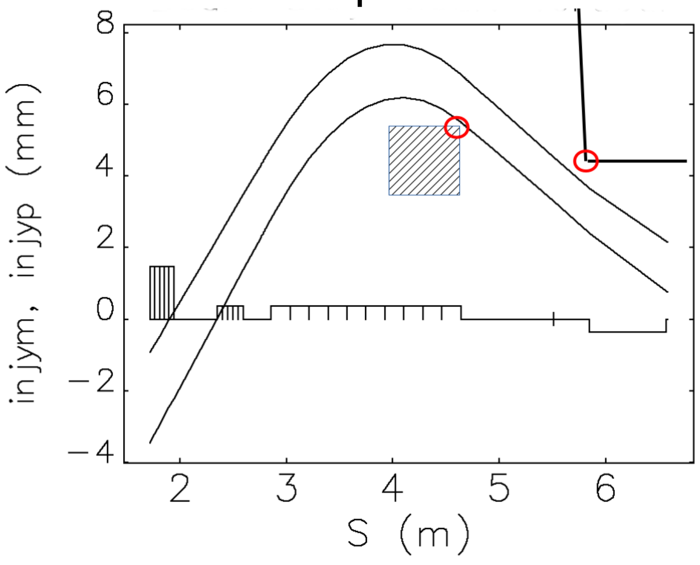
Injection region features similar components

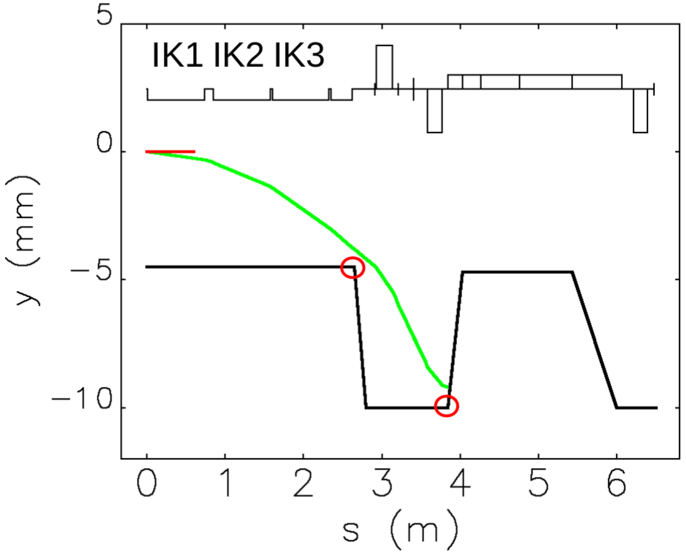
- Stripline kickers identical, but rotated 90 deg as appropriate – more challenging synchrotron radiation shielding for H-Inj
- Septa are different in length, strength, aperture and location
  - H-Inj: off-centered stored beam chamber, septum inner edge x=-3 mm
  - V-Inj: ±4mm(h) by ±3mm(v), centered stored beam chamber (NEG coated)
- Incoming beam is off center in Q1 and Q2
  - H-Inj: larger H offset, giving weaker effects from stray fields
  - V-Inj: smaller H offset + vertical offset → tight aperture limitations

Both schemes optimized using similar approach

- Injected beam is “hemmed in” by the septum on one side and the striplines on the other
  - Stronger kickers may require increasing the minimum stripline aperture
  - Voltage requirement not necessarily a simple linear function assumed kick angle
  - A thicker septum requires higher kicker voltage for fixed stored-beam aperture
- In addition to fitting incoming beam into the DA, provided margin for error and jitter
  - Designed for 0.5-mm margin between 3-σ edge of beam and any physical aperture
- Also constrained by downstream kicker blade and swap-out dump geometry for depleted bunch

Vertical-plane results





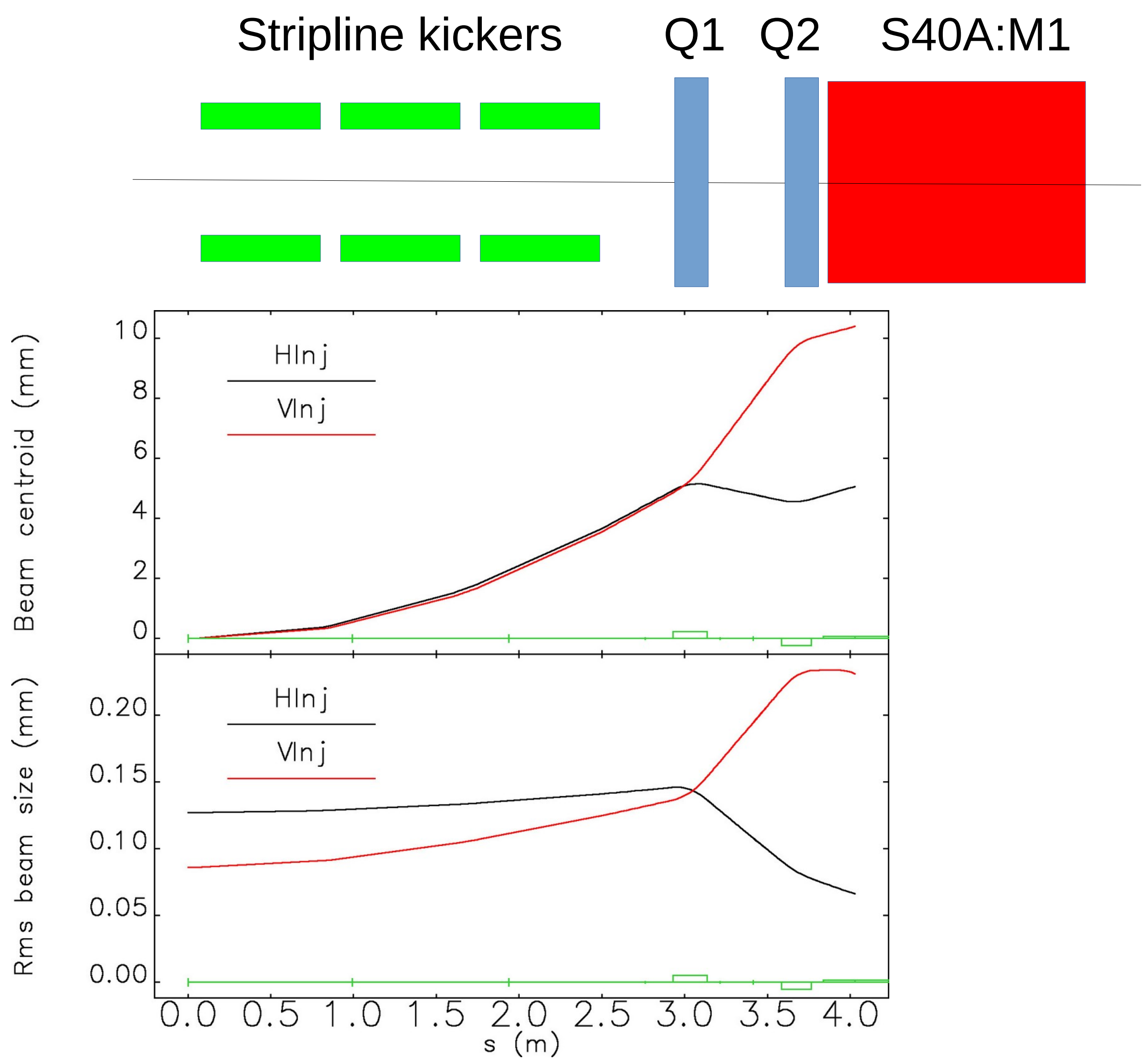
Injection straight optimization

- H-Injection
  - Beam[1] (after emittance exchange)
    $\varepsilon_x/\varepsilon_y$=16/60 nm
    σ_x/σ_y(at ID)=0.288/0.379 mm
  - Stripline kicker (optimized for H-Inj)
    0.752 m long, ±4.95 mm gap
  - Kicker voltages
    ±22.6 kV
  - Septum (pulsed)
    1.5 m, 1.4 T, 3 mm blade
    Inner edge x=-3 mm

- V-Injection
  - Beam[1]
    $\varepsilon_x/\varepsilon_y$=60/16 nm
    σ_x/σ_y(at ID)=0.559/0.196 mm
  - Stripline kicker
    0.752 m long, ±4.95 mm gap
  - Kicker voltages
    ±19.5/25/25 kV
  - Septum (DC)
    1.78 m, 0.95 T, 2.5 mm blade
    Inner edge y=3 mm
    Rotation angle: 104 mrad

1: Design based on assumed partitioning of booster natural emittance between the planes

Swap-out dump inside S40A:M1 magnet

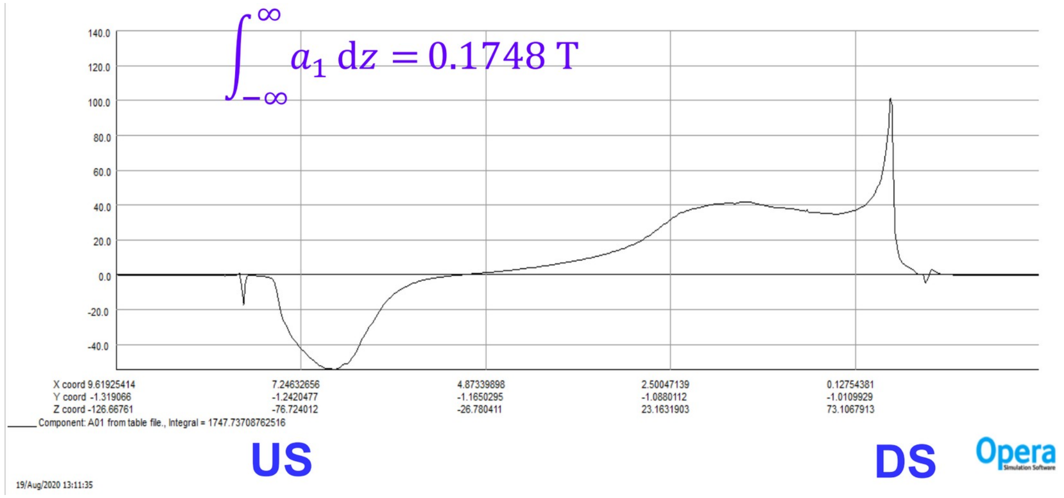


- Similar swap-out dump for both injection schemes:
  ±4.6 mm aperture, rotated 90 deg depending on the injection plane
- V-Inj:
  - To avoid hitting vacuum chamber before the dump, little flexibility for kicker strength adjustment
  - Depleted bunch hits fairly close to the outer edge of the dump
- H-Inj:
  - Beam impacts surface of dump well away from vacuum chamber wall thanks to lower beta function

Leakage field of Lambertson is mostly self-compensating[1,2]

n	b_n (T/mm^{n-1})	a_n (T/mm^{n-1})
0	-0.456	0.482
1	4.6 x 10^{-2}	0.1748
2	1.7 x 10^{-2}	-6.5 x 10^{-3}
3	1.1 x 10^{-3}	1.6 x 10^{-3}
4	5.5 x 10^{-4}	1.5 x 10^{-5}
5	9.3 x 10^{-5}	-5.7 x 10^{-5}

Manageable with nearby correctors



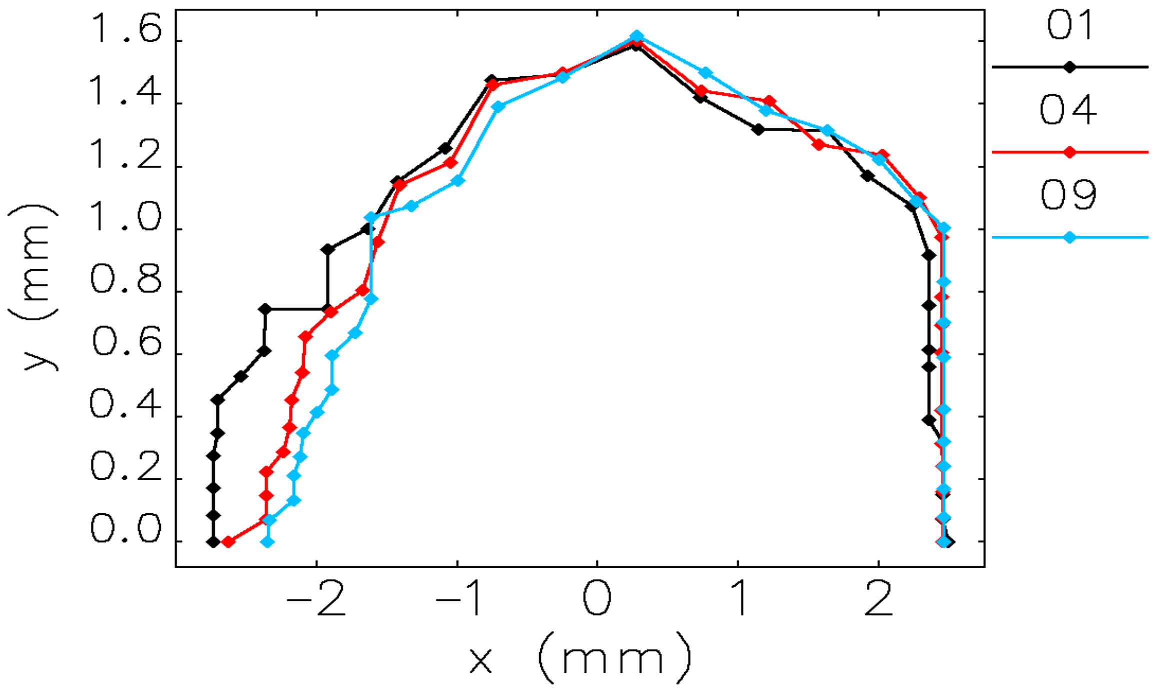
<u>Concern: will the self-compensation work as predicted by OPERA?</u>

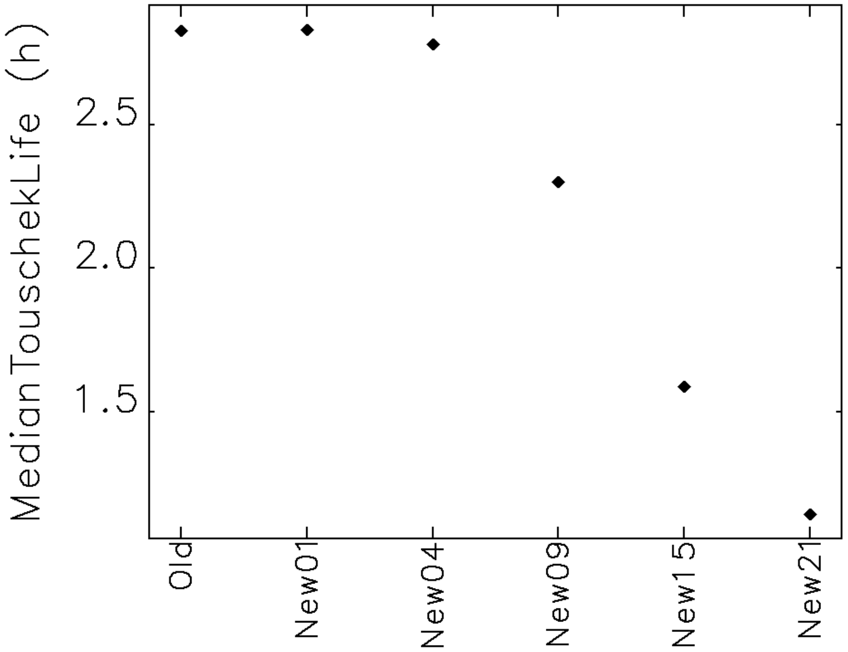
Septum in-vacuum bottom pole with slot for VP-shielded, water-cooled stored-beam chamber. Spacers are to protect against damage during shipping.

1: M. Abliz *et al.*, NIM A 886, 7-12 (2018).
2: M. Abliz, private communication.

Lambertson leakage field has impact on DA/LMA

- Recent simulation results show that larger-than-expected leakage field will have negative impact on dynamic and local momentum acceptance
- The impact is not dramatic for 4-fold increase in leakage field (all terms)
  - 9-fold increase will reduce Touschek lifetime
- Awaiting completion of prototype and measurements to understand if there is an issue

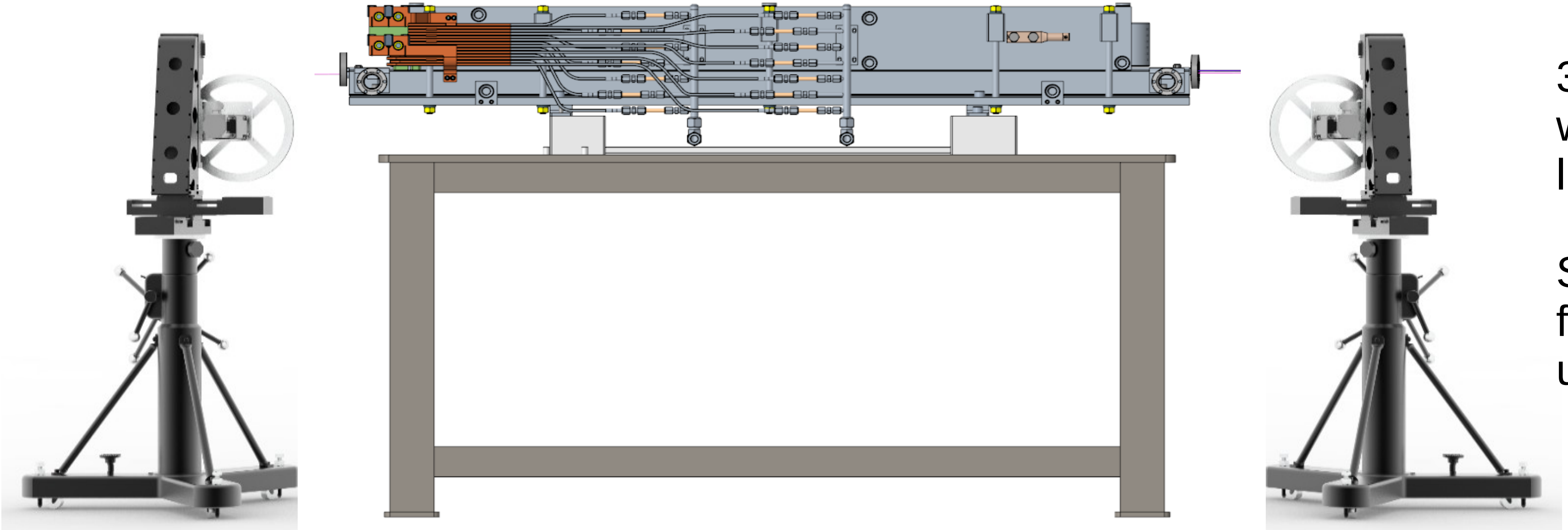




Lambertson is challenging measure

- Measurement of the Lambertson leakage field is challenging due to length and small (±4mm by ±3mm) stored-beam aperture
- Plan is to measure 3D magnetic field map, then use generalized gradient expansion[1,2] for particle tracking

Lambertson stored-beam-chamber field mapping concept (M. Kasa, J. Liu ANL).



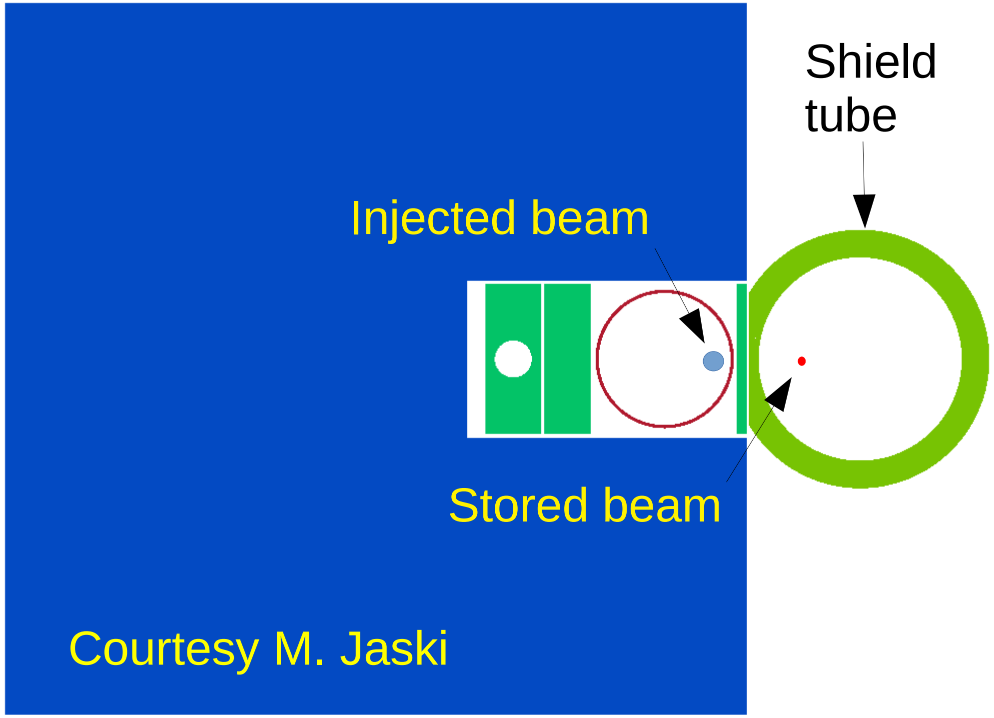
3-axis Hall probe will ride on flexible linear encoder scale.

Similar concept used for superconducting undulator measurements

1. M. Venturini et al., NIM A 437, 387 (1999).
2: C. Mitchell et al., Rev. Mod. Phys. 13 (6) (2010).

Pulsed H-Inj septum requirements achievable

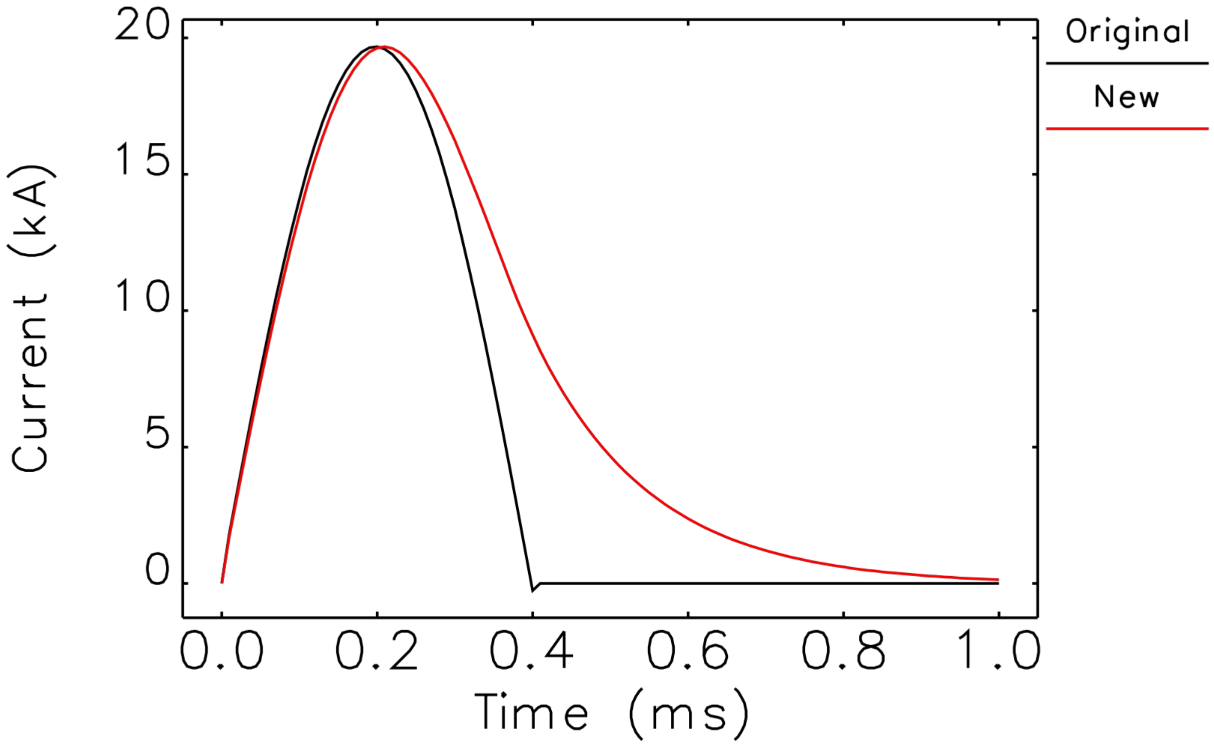
- APS has a high-quality pulsed direct-drive septum[1], but field is only 0.74 T
- APS-U needs much stronger field to ensure
  - Tolerable effect from “stray” fields of S39B:Q1, S39B:Q2
  - BTS magnets clear the ring
- M. Jaski developed 1.4-T design with 3-mm blade
  - Direct-drive with iron shield tube to reduce leakage fields
  - Allows clearing other ring components, even when stray fields are included
  - Large shield tube diameter reduces concerns about vacuum quality
  - Well received at recent detailed review

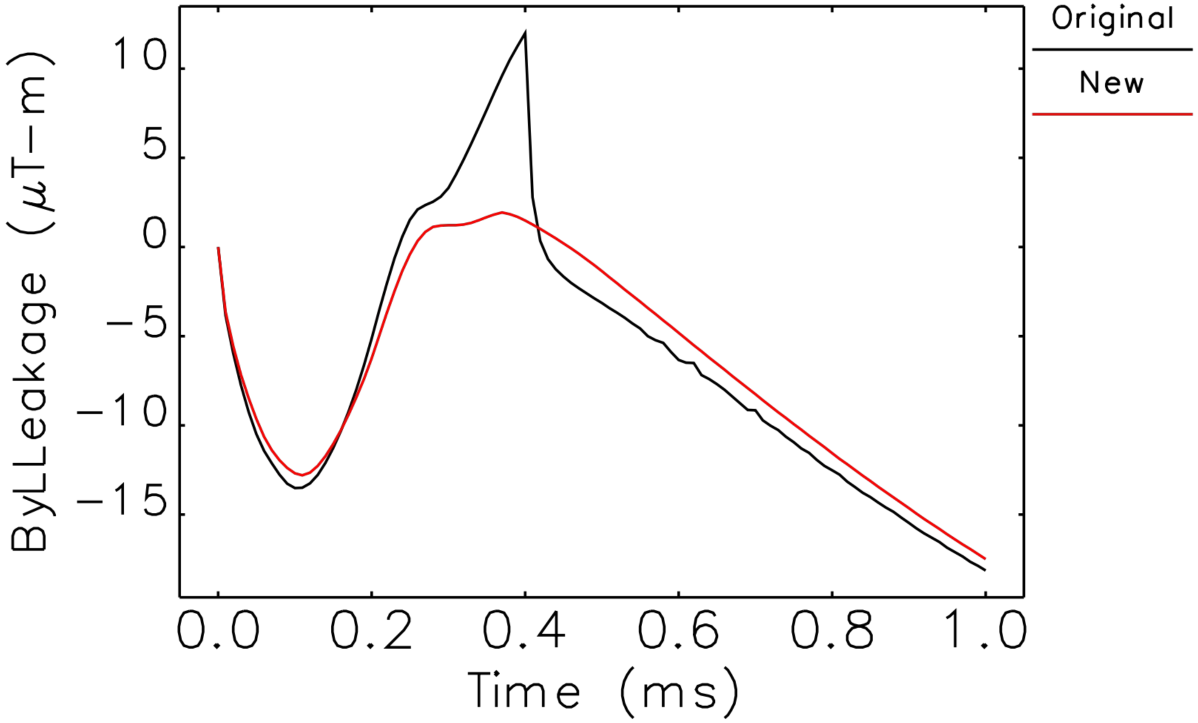


1: M. Jaski et al., PAC01, 3230.

Pulsed septum leakage field initially looked unacceptable

- Initially, a simple half-sinusoidal drive waveform was used
- Resulted in a spike in the leakage field, which was very hard to compensate
- Adding a taper on the end of the drive pulse eliminated this issue

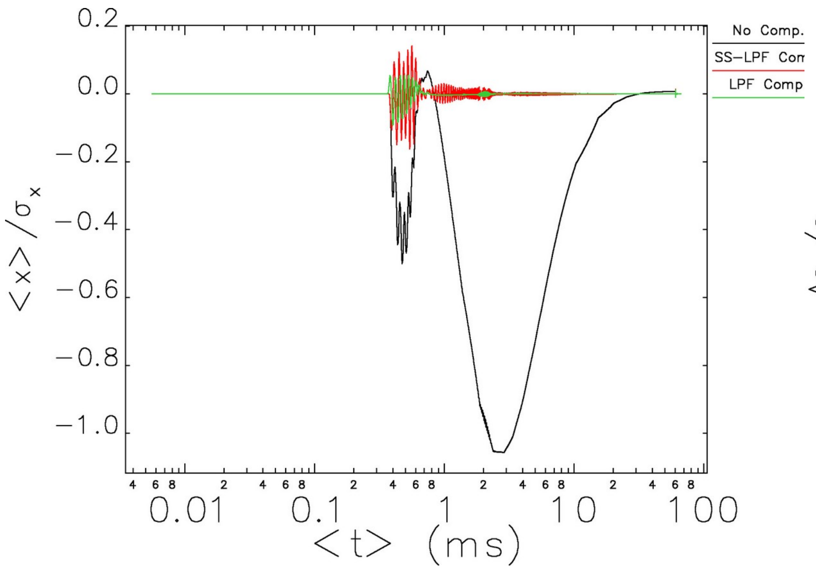


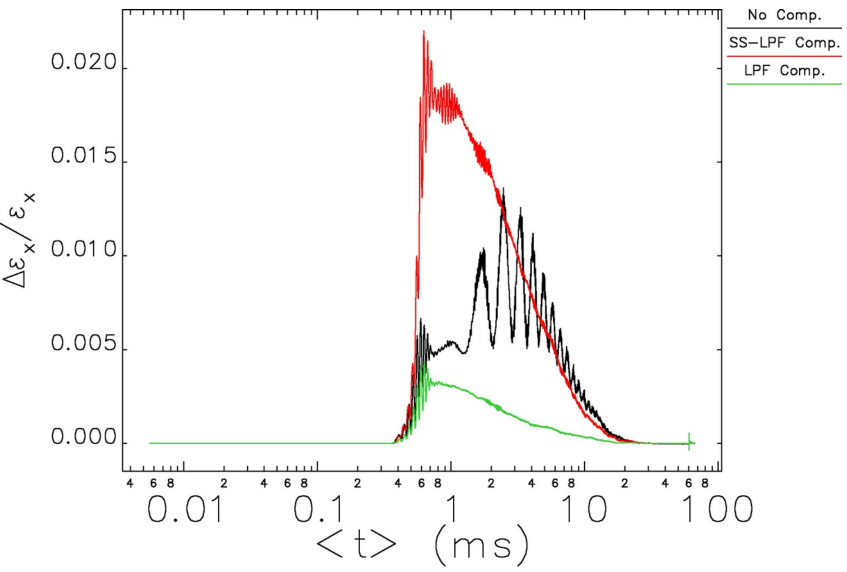


M. Borland et al., Comparison of Horizontal- And Vertical-Plane Swap-out Injection Options for APS-U, LER2020, Frascati, Italy

Pulsed septum leakage field appears manageable

- Leakage field can have transient impact on beam emittance, position
  - Want brightness reduction of ~2% or less due to septum leakage
    - Same as swapping in high-emittance booster bunch (48 bunch mode)
  - Want beam motion of less than 10% of beam size
- Using data from time-dependent magnet model (M. Jaski), simulations show we can compensate for leakage field, but need AFG-driven power supplies
  - Since this was done, modified design to give even smaller leakage[1]





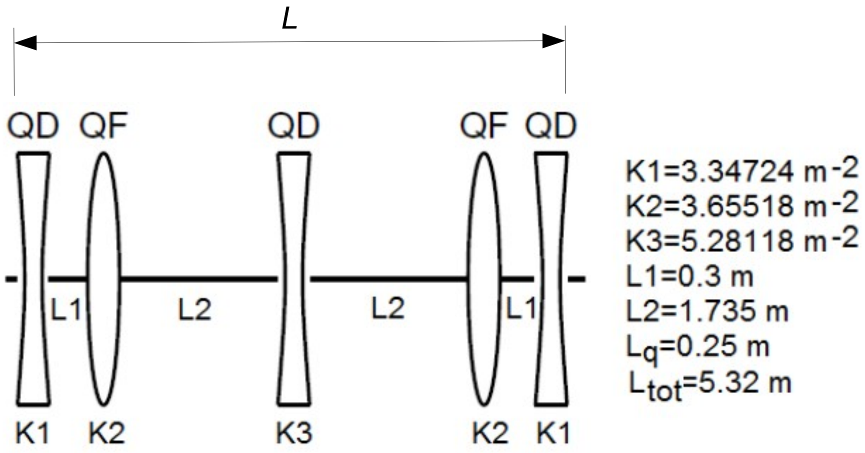
SS-LPF: 22-kHz stair-step waveform from orbit feedback system in feedforward mode, with 10-kHz low-pass filter from corrector and chamber

LPF: inverted replica of leakage waveform, with 10-kHz low-pass filter

1: M. Jaski, private communication.

Emittance exchange is surprisingly easy

- Exchanging x-y emittances possible with 5 skew quads



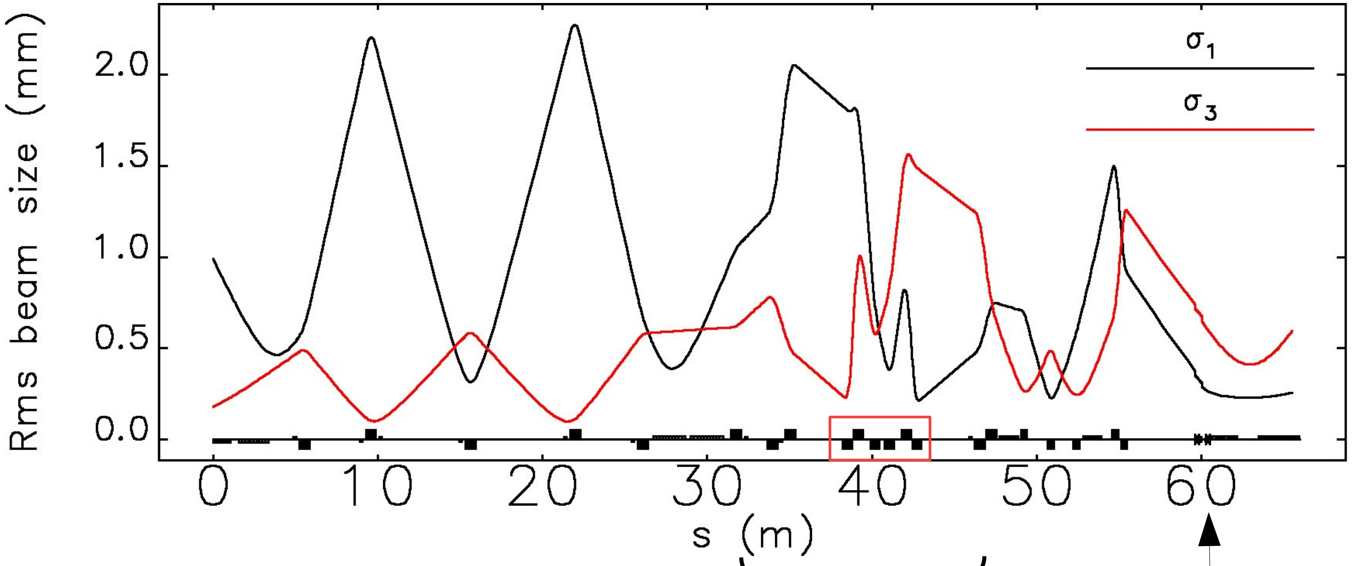
From P. Kuske and F. Kramer, IPAC 2016, 2028.
See also M. Aiba, IPAC15, 1716.

- Transport matrix has a convenient form, with *L* the system length

$$M = \begin{pmatrix} 0 & D \\ D & 0 \end{pmatrix} \qquad D = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

- A ~5-m space is sufficient even at 6 GeV
- Conveniently, BTS has a ~15-m zero-dispersion region available

BTS design with EXS is very reasonable-looking



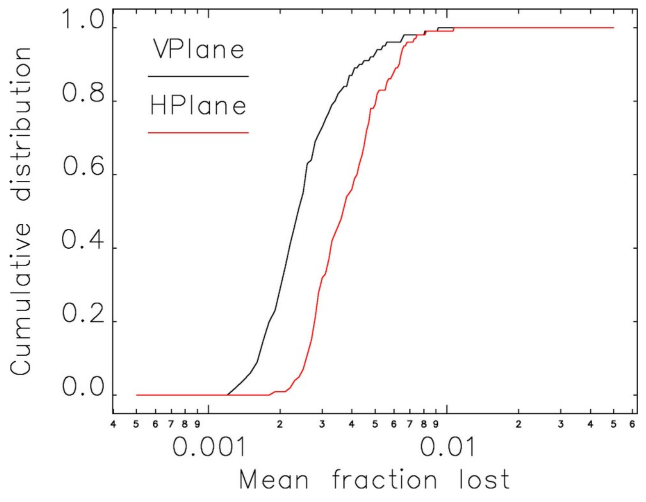
Dispersion-free section with emittance exchange system

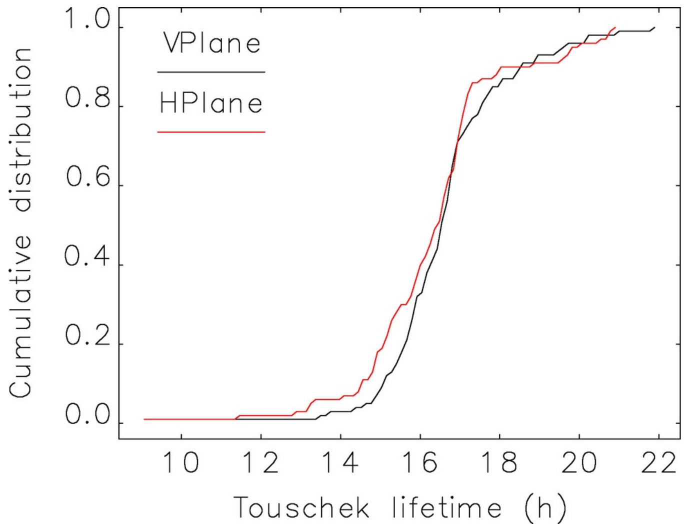
Name	Type	Length m	K1 $1/m^2$	B1 T/m
BTS:AQ1	ExistingQuad	0.600	-0.597462	11.958
BTS:AQ2	ExistingQuad	0.600	0.592357	-11.855
BTS:AQ3	ExistingQuad	0.600	-0.568960	11.387
BTS:AQ4	ExistingQuad	0.600	0.568699	-11.382
BTS:AQ5	ExistingQuad	0.600	-0.335412	6.713
BTS:BQ1	ExistingQuad	0.600	0.207413	-4.151
BTS:BQ2	ExistingQuad	0.600	-0.825225	16.516
BTS:BQ3	ExistingQuad	0.600	0.700285	-14.015
BTS:BQ4	ExistingQuad	0.600	-0.932897	18.671
BTS:BQ5	ExistingQuad	0.600	0.936638	-18.746
BTS:CQ1	NewQuad	0.350	1.359336	-27.206
BTS:CQ2	NewQuad	0.350	-2.844626	56.932
BTS:CQ3	NewQuad	0.350	-0.250803	5.020
BTS:DQ1	NewQuad	0.350	3.047466	-60.992
BTS:DQ2	NewQuad	0.350	-2.809669	56.232
EXQ1	SkewQuad	0.544	-1.779322	35.611
EXQ2	SkewQuad	0.544	2.500000	-50.035
EXQ3	SkewQuad	0.544	-2.267343	45.378

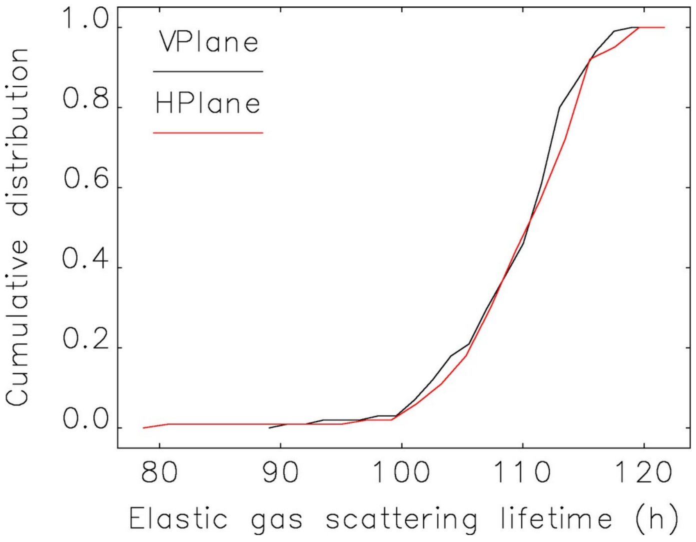
- EXS built from six identical quads for simplicity
- New quads are strong (up to 61 T/m), but BSC is <10mm, so not a problem
- Included significant stray field effects of Q2 and Q1 magnets, based on OPERA-generated field maps

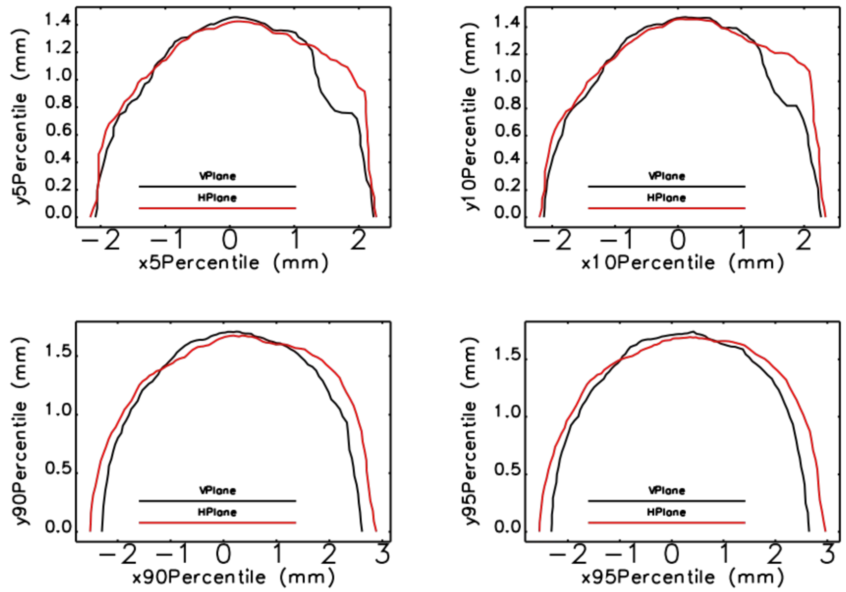
Both schemes have similar overall performance

- H-plane injection efficiency simulation initially disappointing, but improved with revised MOGA
  - Usual 12 sextupole families around the ring
  - 6 sextupole knobs on each side of injection point
- Both schemes now very similar when evaluated with 100 post-commissioning ensembles





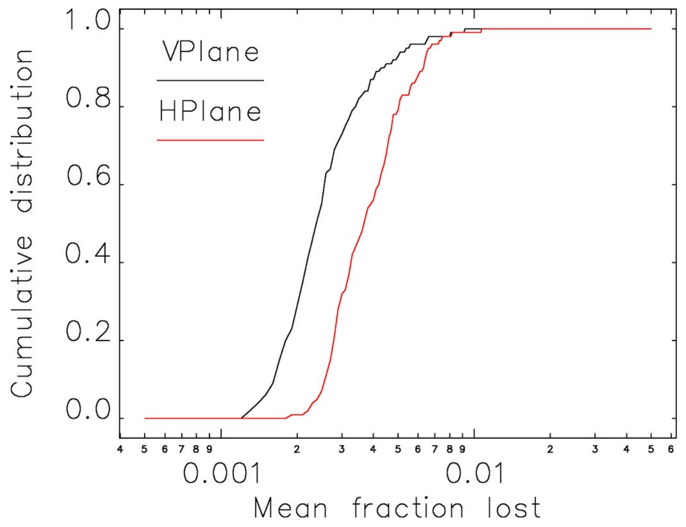


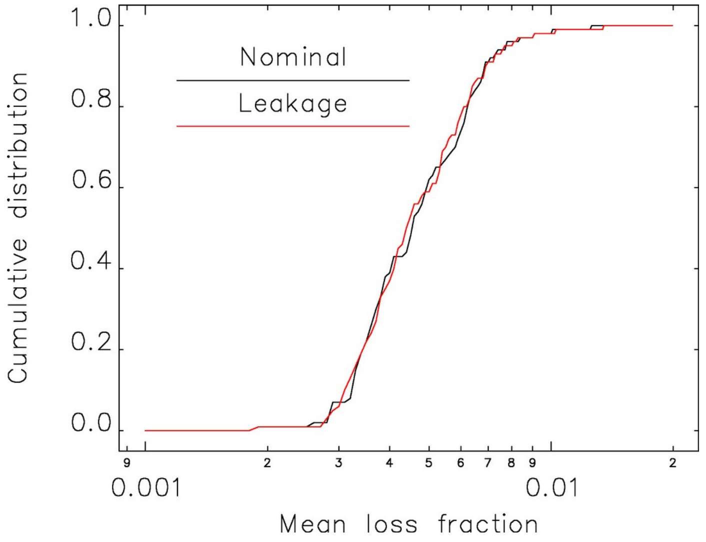


N.B. These results use an earlier Lambertson septum model than those on slide 12.

Injection systems aim to include everything

- Injection simulations are performed with parallel ELEGANT using gaussian-weighted uniform distributions covering ±4σ
- Simulations include errors in booster and BTS, e.g.,
  - Orbit variation
  - Pulsed power supply jitter
  - Magnet strength errors
- Also included are physical apertures of the transport line, septum, injection kickers, etc.
- For H-Inj scheme, did a second round including uncompensated time-dependent leakage multipoles
  - No significant effect was seen





Conclusions

- Developed both horizontal- and vertical-plane injection schemes for APS-U
  - Very similar expected performance
- For vertical-plane injection, challenges include
  - Obtaining and verifying acceptably low leakage field of septum
  - Modeling effects of measured leakage fields
  - Achieving good vacuum pressure in the small stored-beam chamber
  - Alignment of BTS line with numerous rolled elements
  - Tighter aperture constraints
- For horizontal-plane injection, challenges include
  - Controlling the injection transient from strong pulsed septum's leakage field
  - Many new, strong quadrupoles and skew quadrupoles
  - Shielding stripline blades from synchrotron radiation
- Overall, the horizontal-plane scheme seems less difficult, but vertical scheme may win on cost and schedule if no show-stoppers are found

Acknowledgments

- Thanks to M. Abliz, J. Downey, A. Jain, M. Jaski, M. Kasa, J. Liu, J. Wang --- magnet design, PS design, magnetic measurement, mechanical design.
- G. Decker, V. Sajaev, U. Wienands --- H/V risk, simulation, Zone F. etc.
- Simulation codes
  - Serial and parallel versions of ELEGANT[1,2] and related tools[3]
  - OPERA 3D
- Computations used ANL's Blues and Bebop clusters, ASD's Weed cluster

1: M. Borland, LS-287.
2: Y. Wang et al., AIP Conf. Proc 877.
3: M. Borland et al., IPAC2003.