Consideration of Impedance Effect on the APS Operation and Mechanical Design

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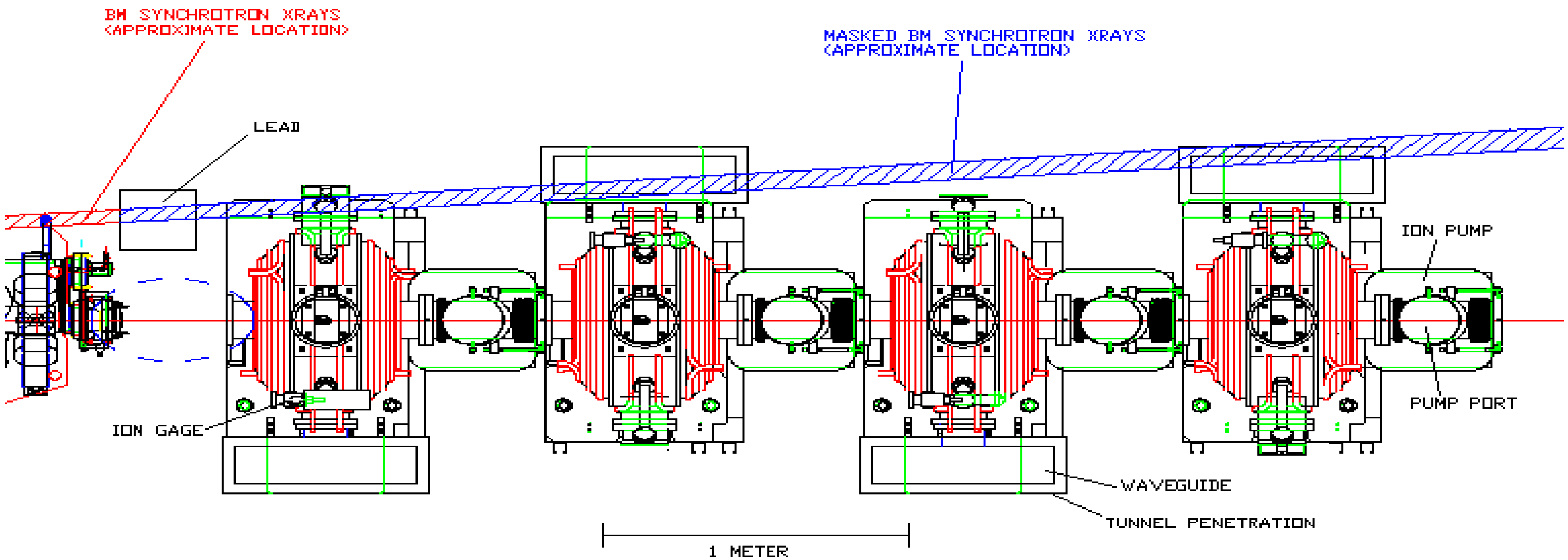
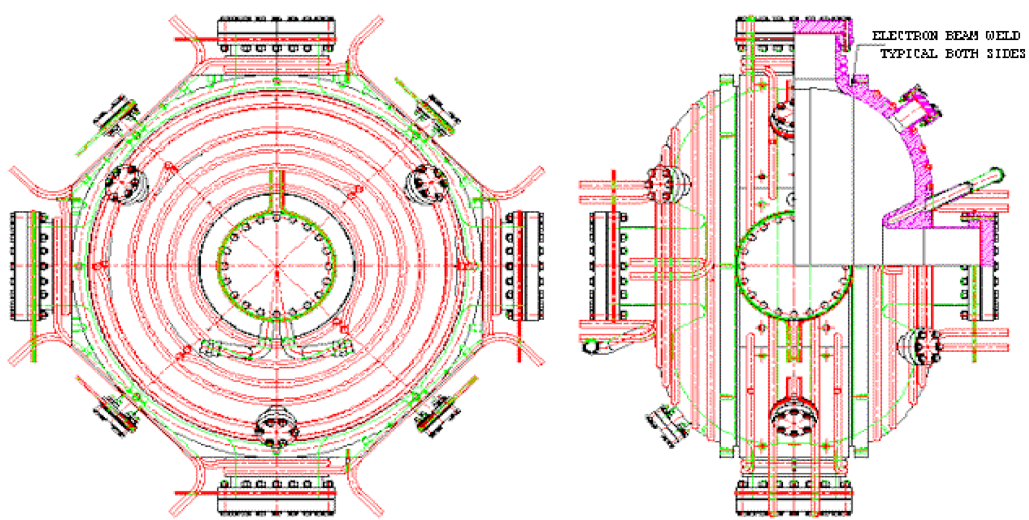
ASD Seminar
June 17, 2013

Overview of Impedance

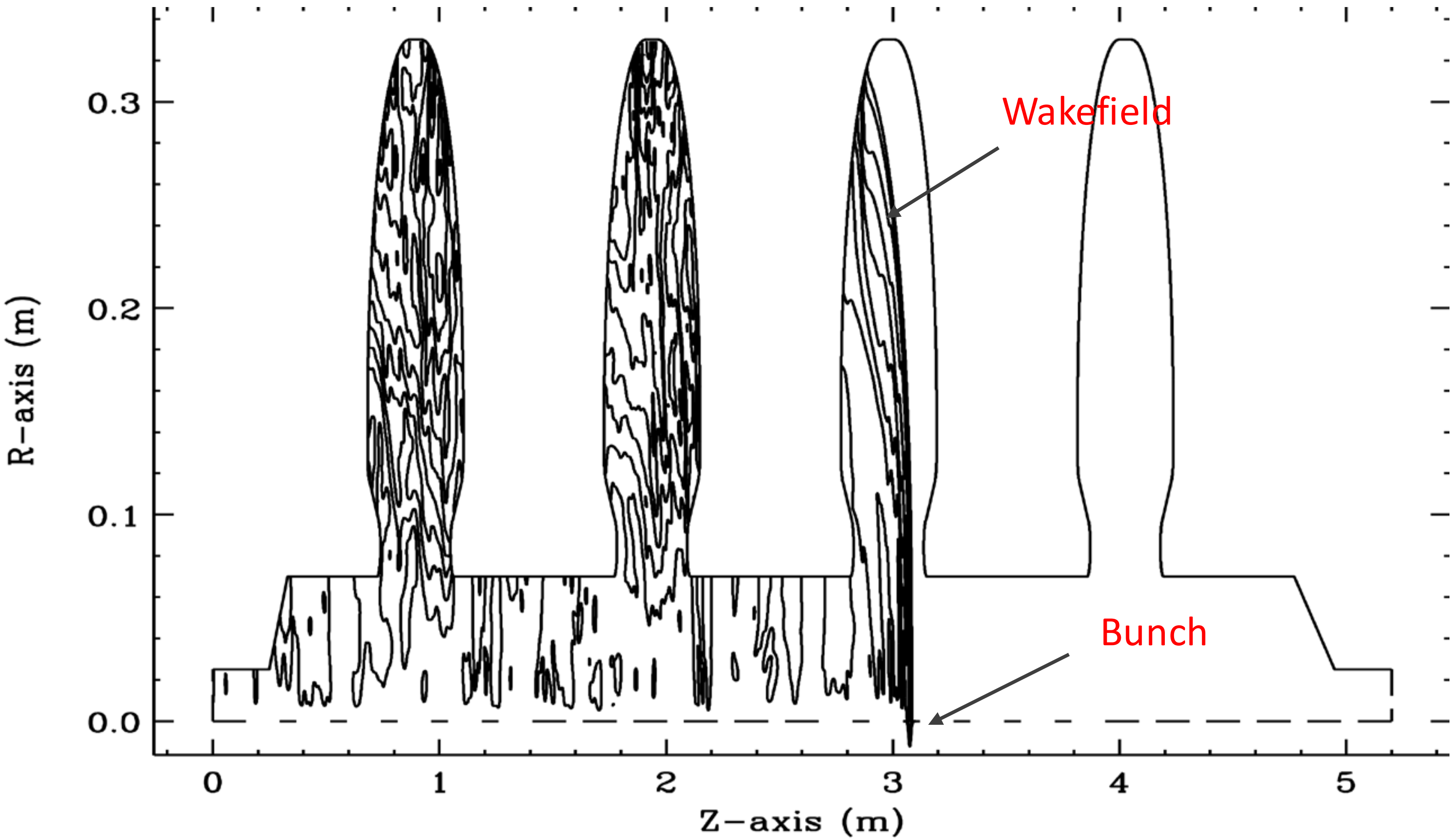
- Definition
  - Wake potential
  - Impedance
- Collective Effect: Beam Dynamics
  - Longitudinal ➔ Bunch Lengthening
  - Horizontal ➔ Saw-Tooth Instability
  - Vertical ➔ Single Bunch Current Limit
- ID Chamber Optimization
- RF Heating
  - S37 Spool Piece Chamber
  - SCU0 Bellow Liner
  - SPX Flange Gap
- Summary

RF Cavity


BM SYNCHROTRON XRAYS
(APPROXIMATE LOCATION)
MASKED BM SYNCHROTRON XRAYS
(APPROXIMATE LOCATION)
LEAD
ION PUMP
ION GAGE
PUMP PORT
WAVEGUIDE
TUNNEL PENETRATION
1 METER

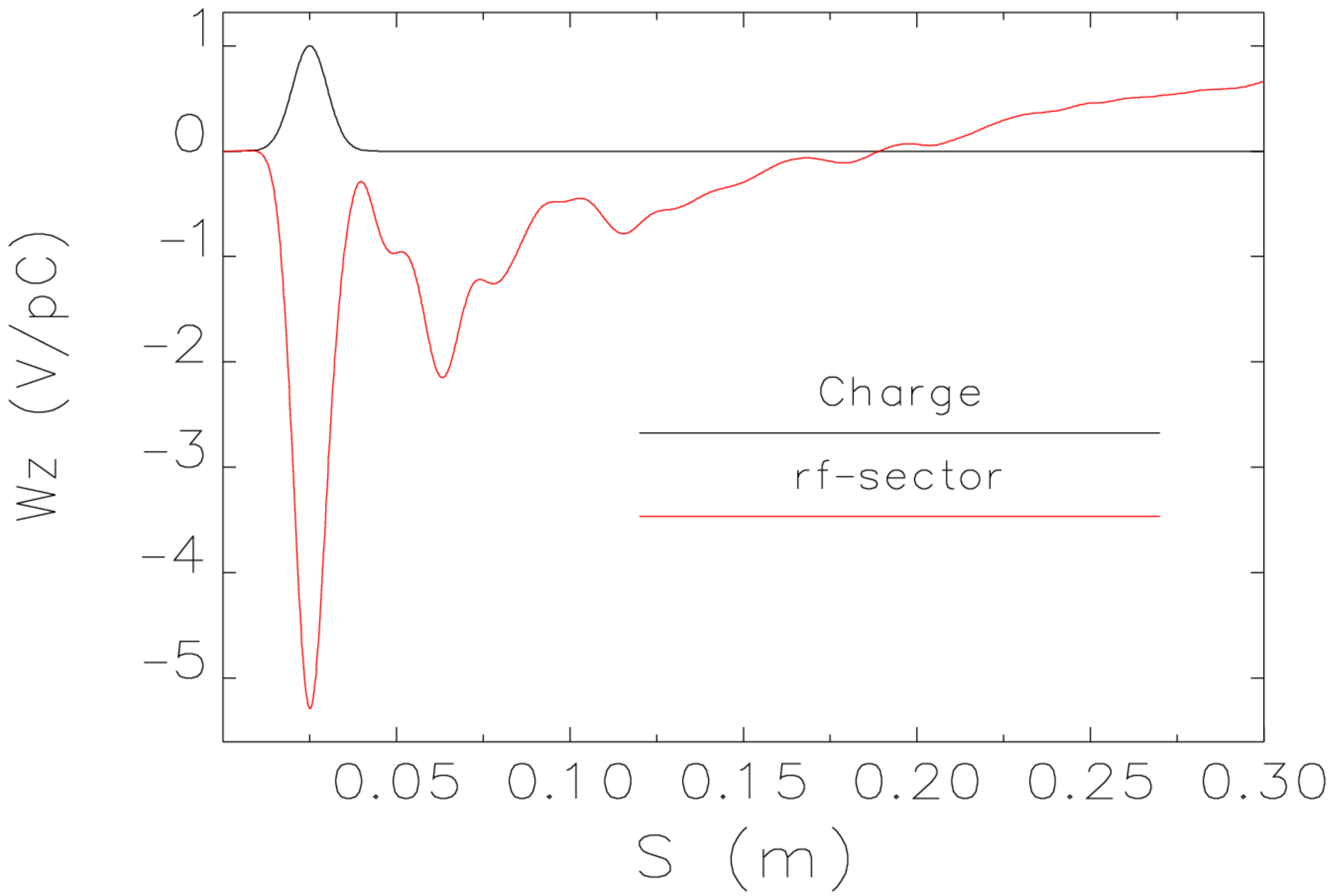

ELECTRON BEAM WELD
TYPICAL BOTH SIDES

RF Cavity: Wakefield (Spatiotemporal Variation)



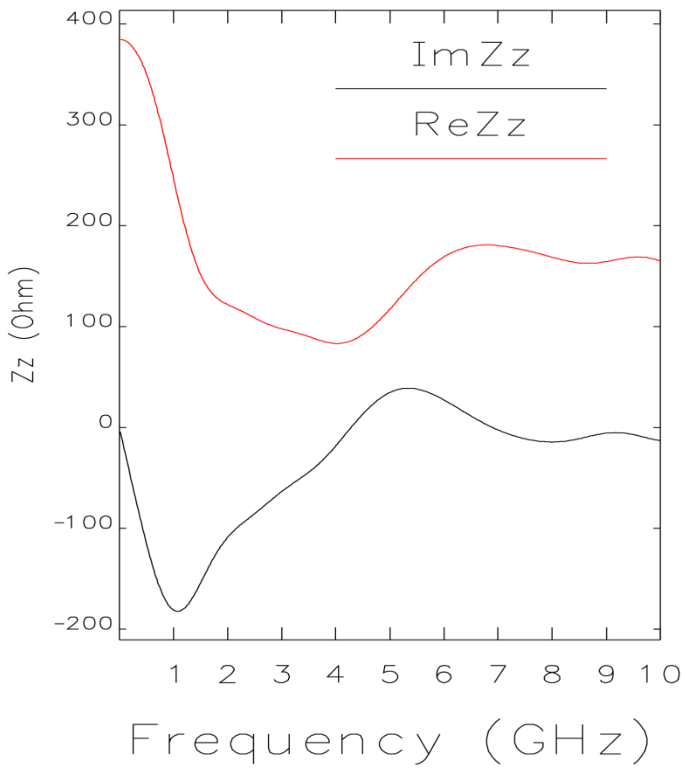
2-D ABCI simulation

RF Cavity: Wakepotential (Time Domain, Volt)

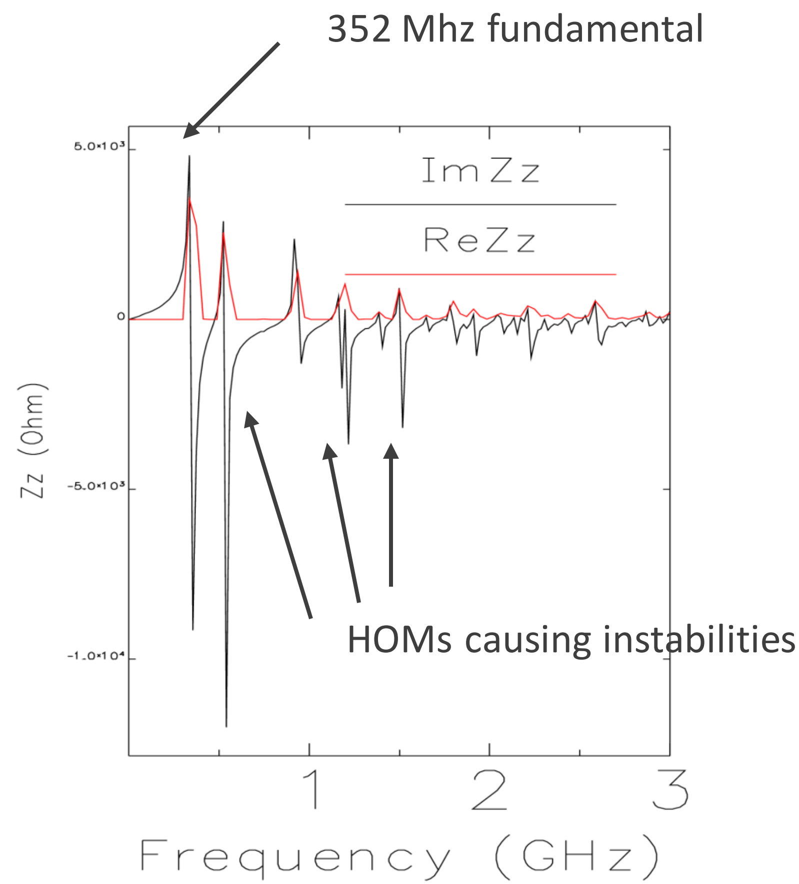


2-D ABCI simulation

RF Cavity: Impedance (Frequency Domain, Ohm)



Broadband: short range including beam loading



Narrowband: long range including beam loading

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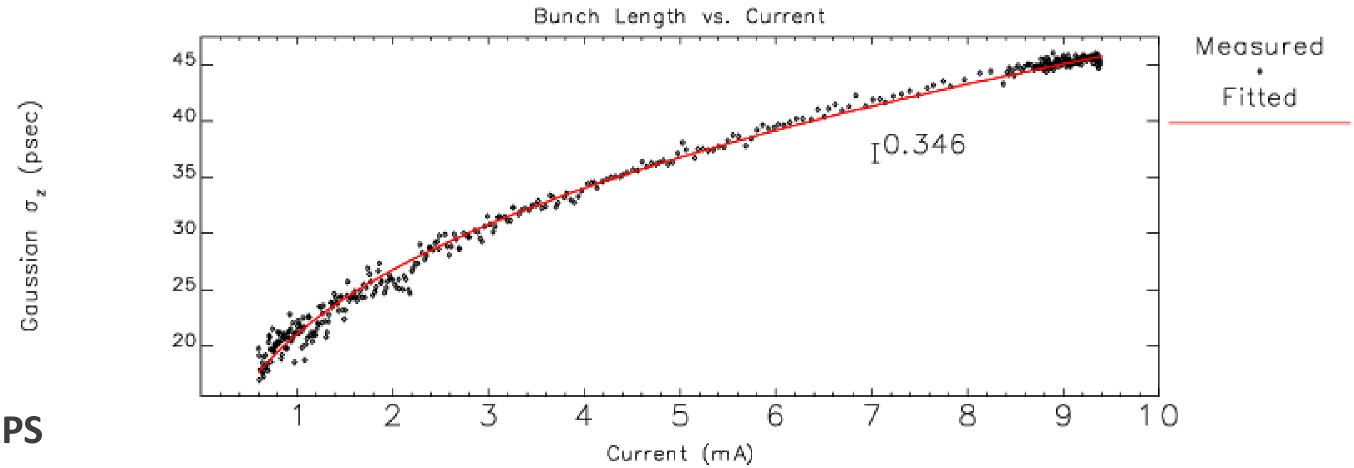
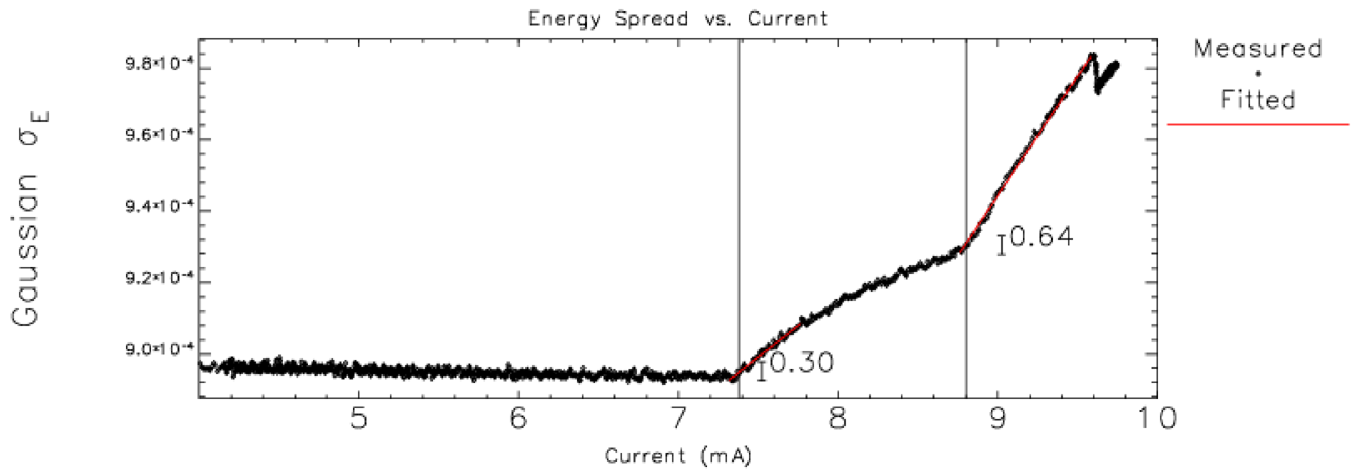
Collective Effect: Longitudinal



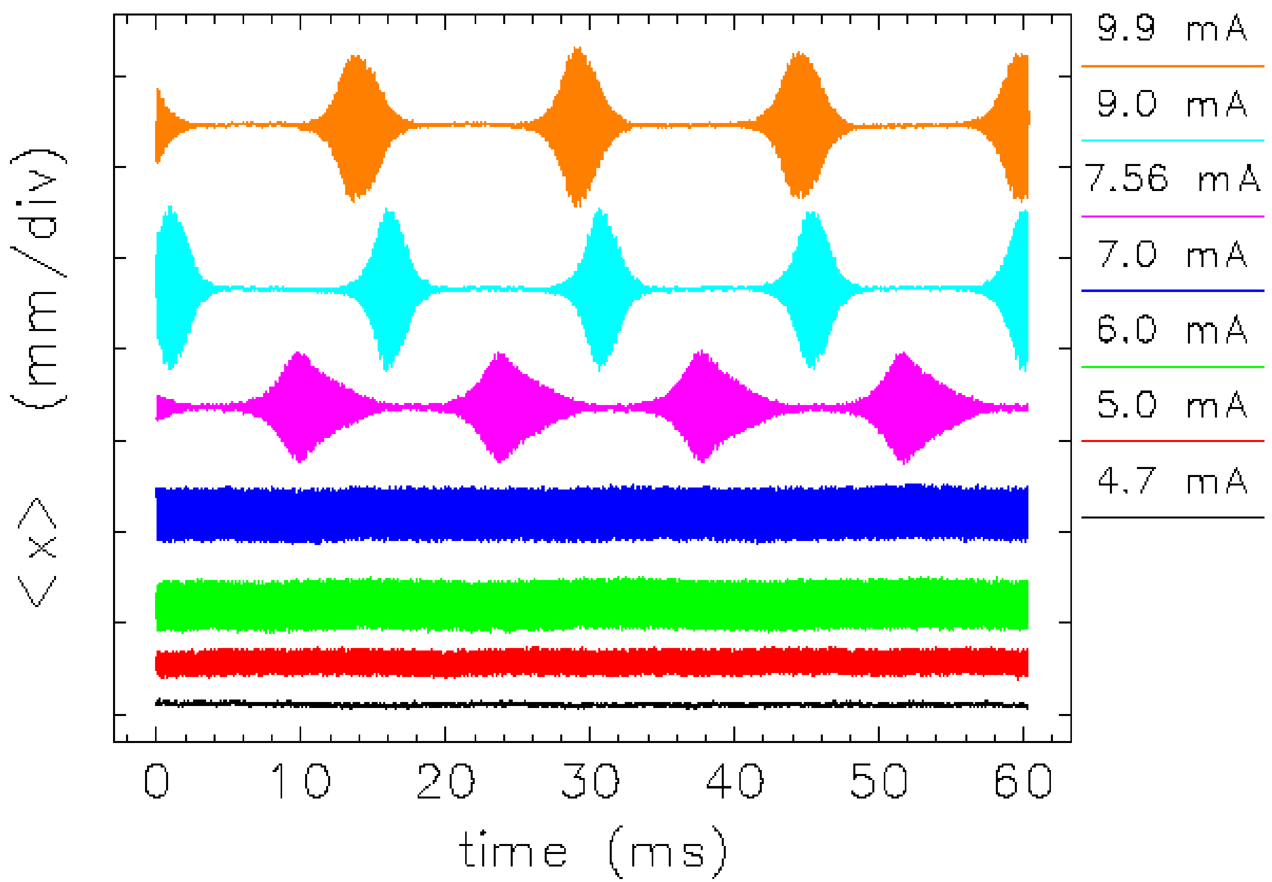
APS
Vrf 9.4 MV



(Y.Chae, L.Emery, A.Lumpkin, J.Song, PAC'01)

Collective Effect: Horizontal

7.5 nm lattice, Vrf=9.4 MV

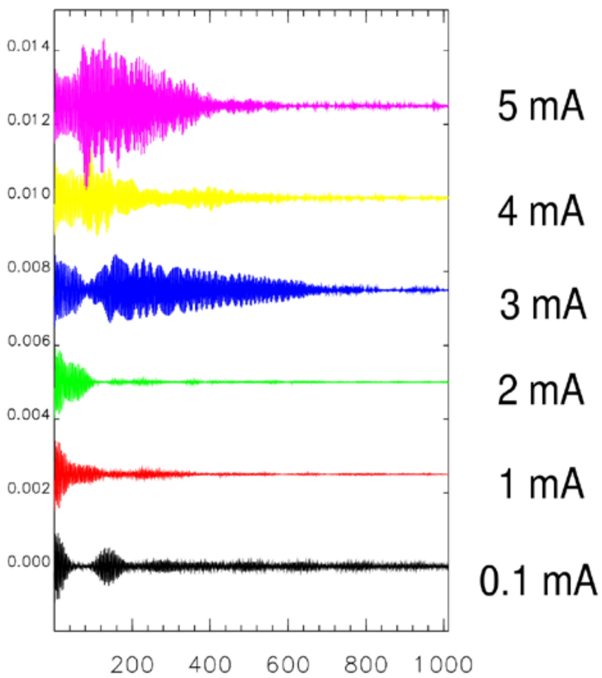


(Courtesy of K. Harkay, PAC'01)

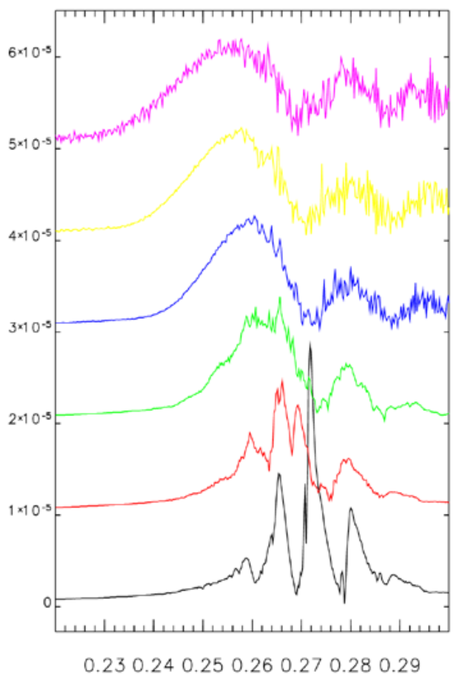
Collective Effect: Vertical

7.5 nm lattice; chromaticity: ξx=4, ξy=4

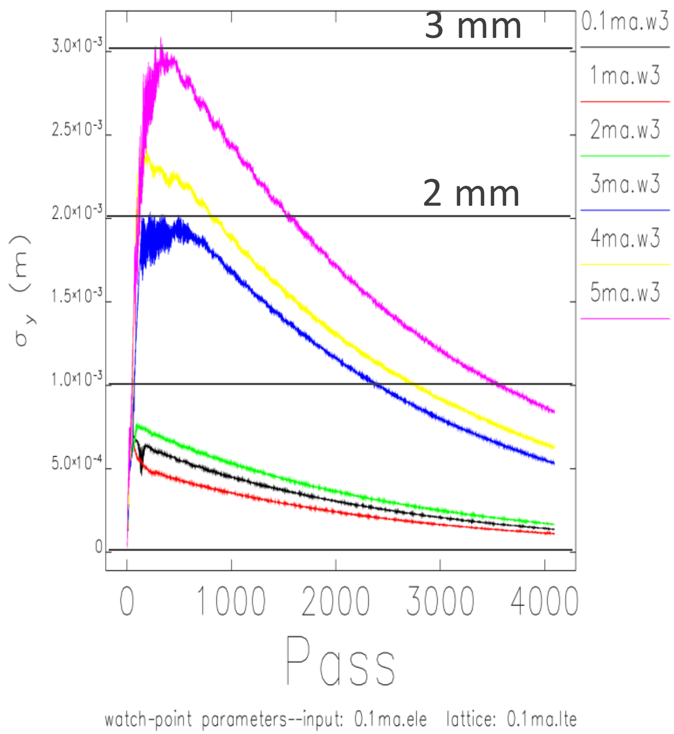
Centroid Kick Δy=1mm



Spectrum



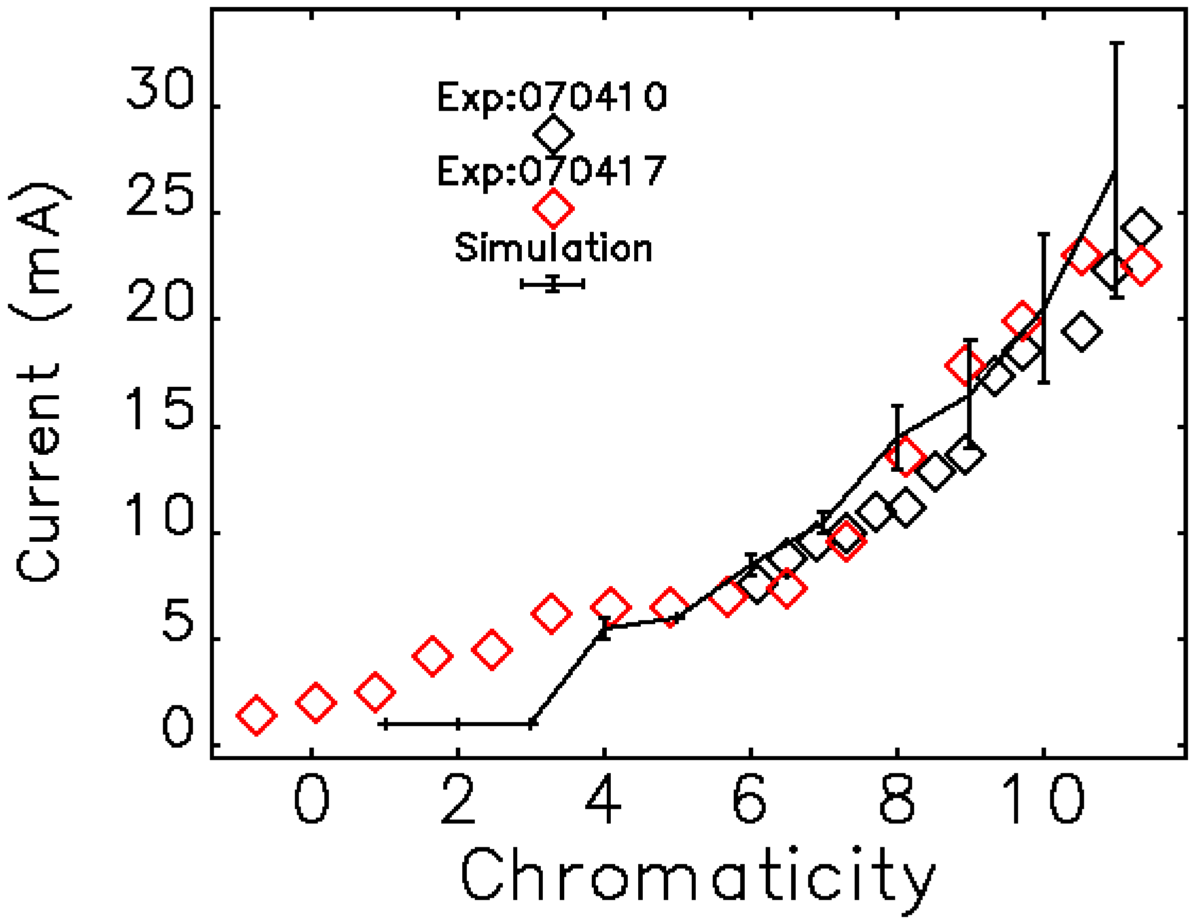
Vertical Beam Size



1. **Well known decoherence behavior at low current**
2. **Mode coupling completes 3 mA**
3. **Beam size blow-up above mode coupling ➔ Beam Loss due to 5-mm Insertion Device Chamber**

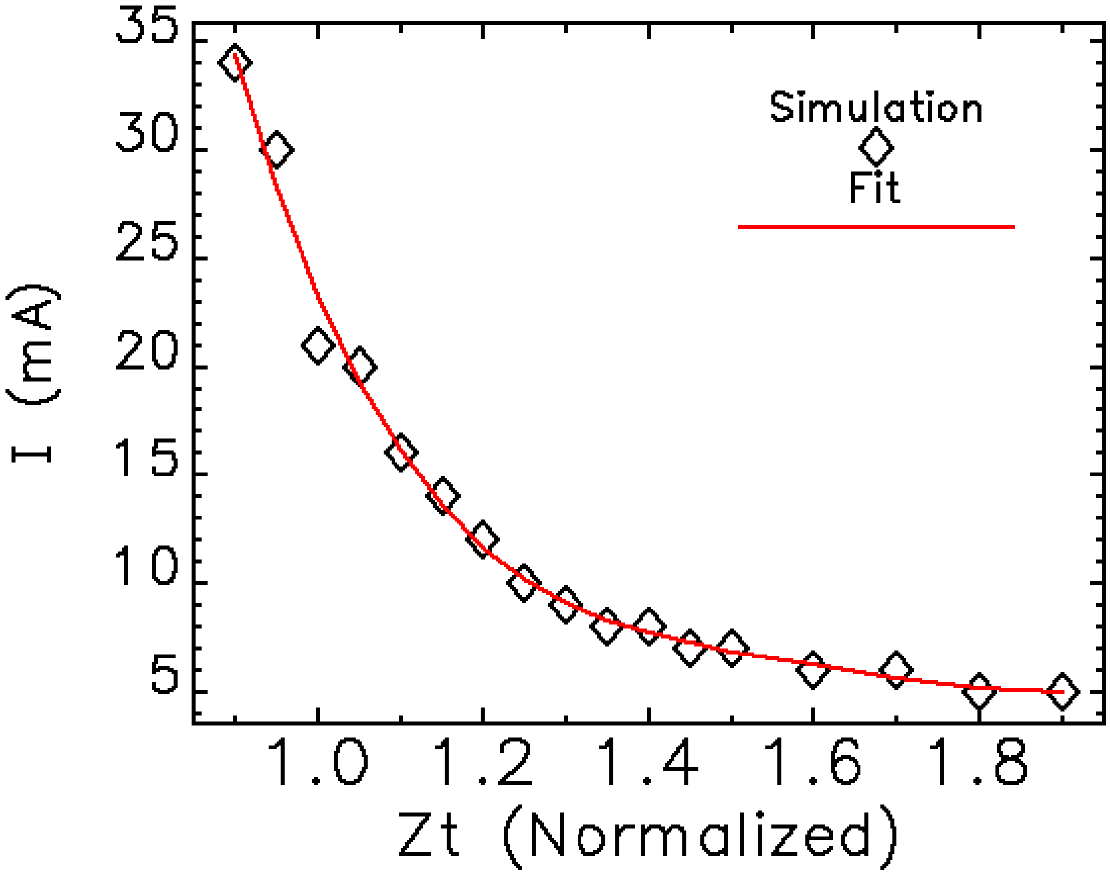
Impact of ID Chamber Impedance at APS-U

- The single bunch current is limited by the vertical impedances in the ring.



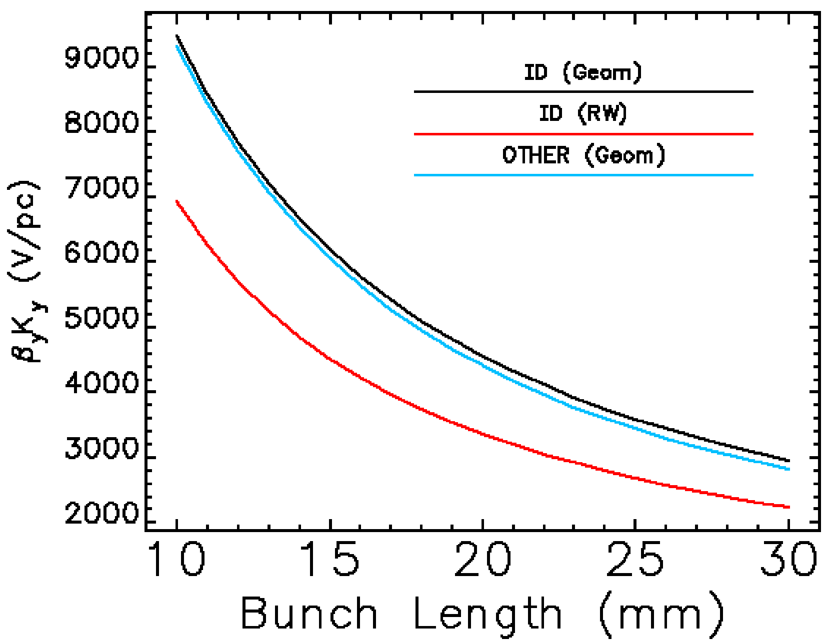
Impedance Effect on the Single Bunch Current

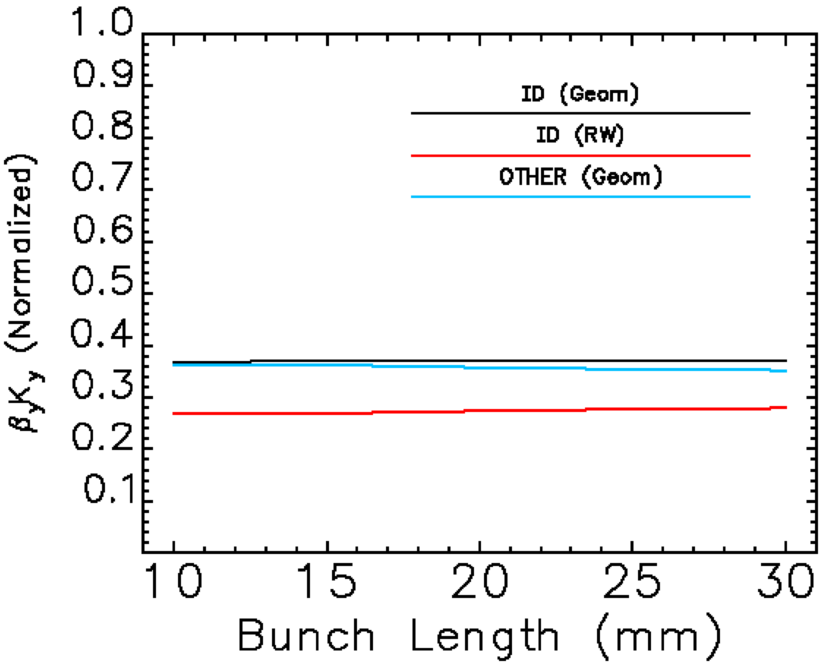
- Shows the single bunch current as function of impedance in the current APS ring. Zt=1 is nominal APS.
- Can predict the current with the hypothetical increase and decrease of impedance in the APS-U



Impedance Component in the Ring

- Use the kick factor to quantify the impedance effect on the beam.
- Found that ID chamber impedance contributes 64% of total ring impedance:
  - ID (Geometric) 37%, ID (Resistive) 27%*.
  - ID impedance is mainly controlled by the gap and transition.
- Major change and addition of ID chamber to the ring in the APS-U will need the critical evaluation.





*The kick factors were evaluated at chromaticity 10.

Impact of ID Chamber Impedance at APS-U

- **The single bunch current is limited by the vertical impedances in the ring.**
- **The vertical impedance is dominated by the ID chambers**
  - 68% of total ring impedance
  - 34% by Geometric impedance ➔ shape optimization
  - 34% by Resistive wall impedance ➔ material selection
- **We like to keep 16 mA in the single bunch for hybrid mode**
  - High chromaticity in x and y plane is required to store 16 mA in the single bunch.
  - If the impedance increases, we need to increase the chromaticity to keep 16 mA. However, the sextupole strengths are limited.
- We need to keep the impedance increase as small as possible
  - Smaller gap chambers (7mm-7.5mm) Proposed
  - ID Chamber Optimization

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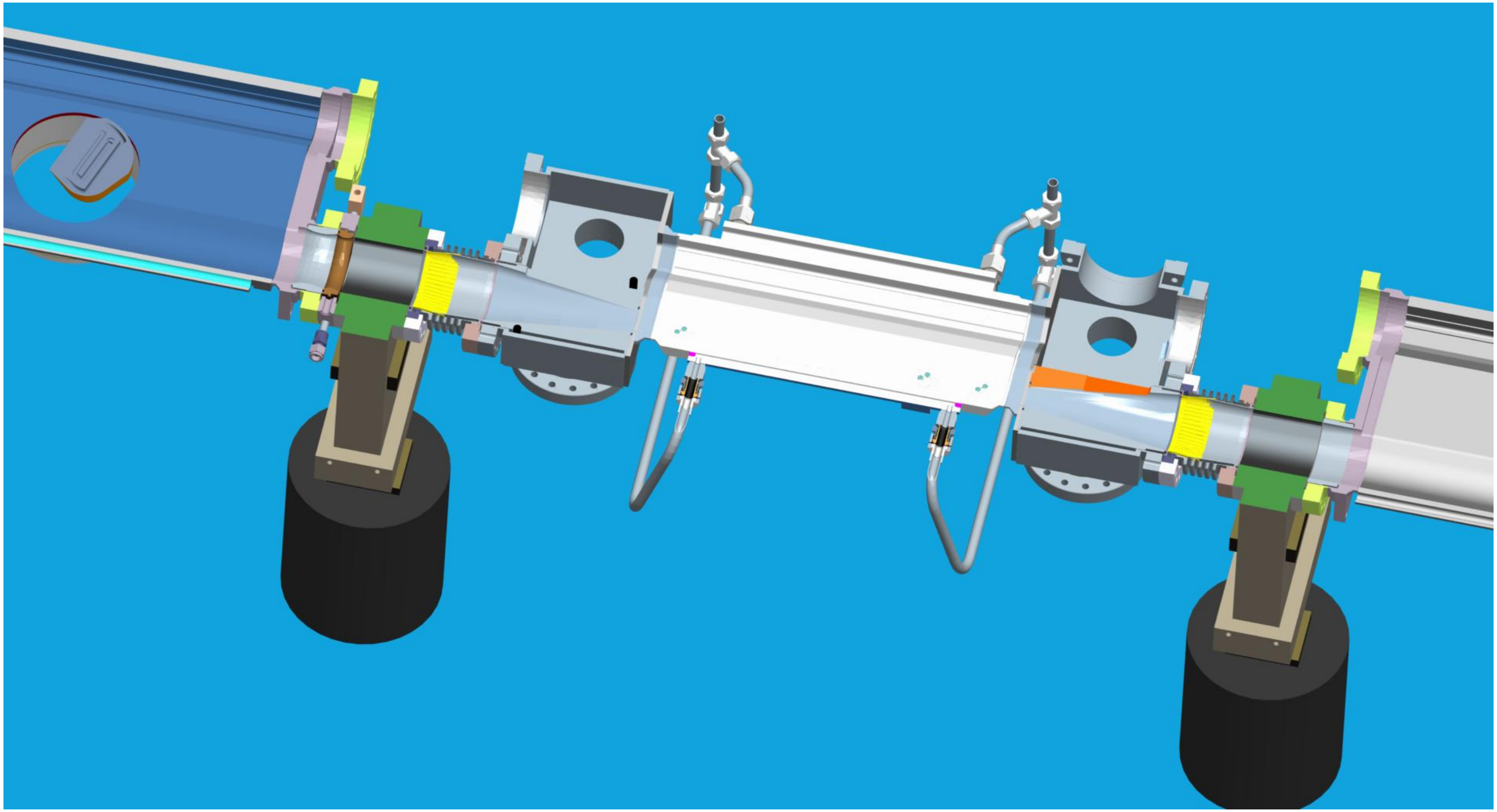
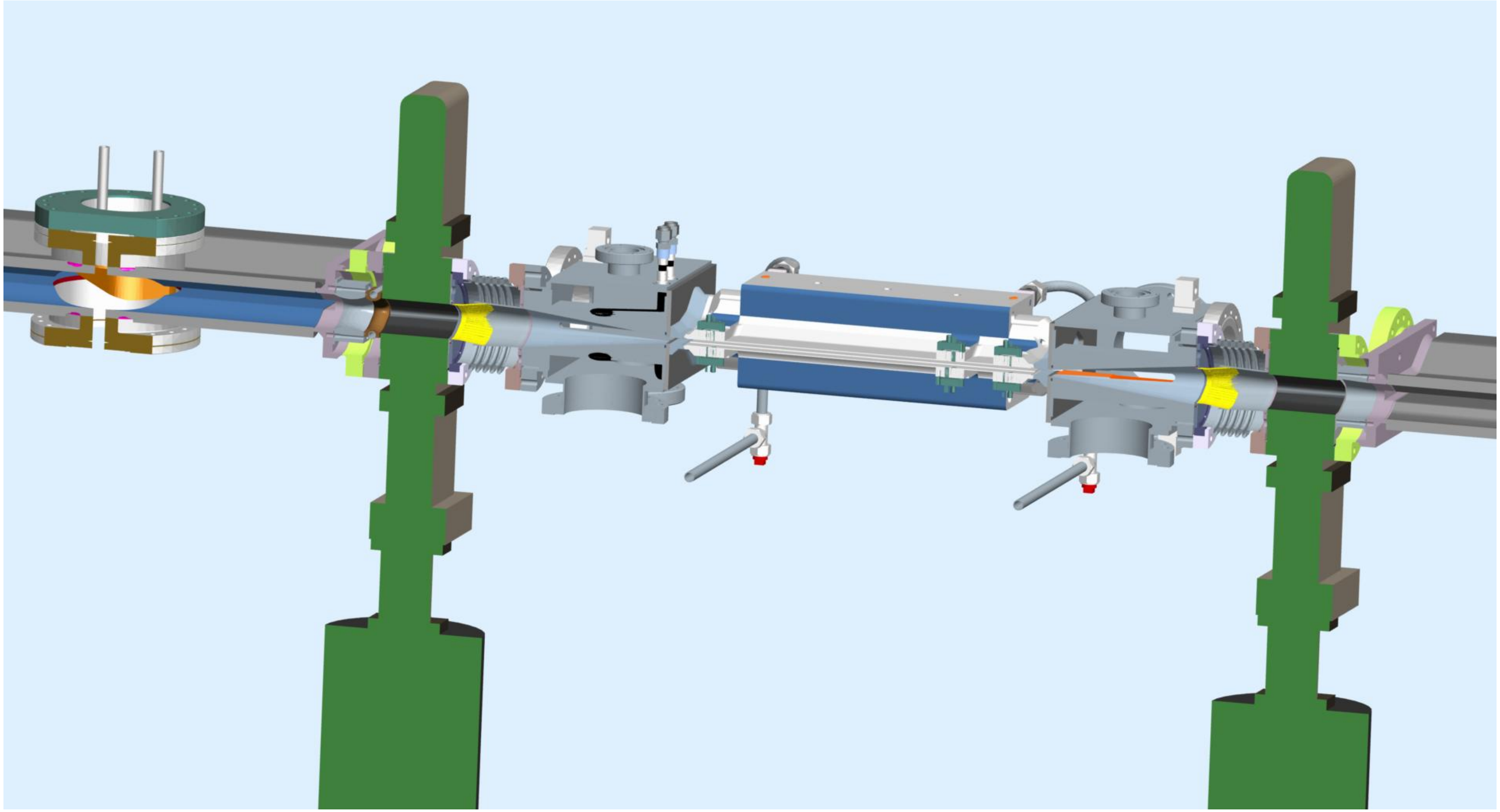
7.5mm Racetrack ID Chamber (H-Plane)



Courtesy by L. Morrison (AES-MED)

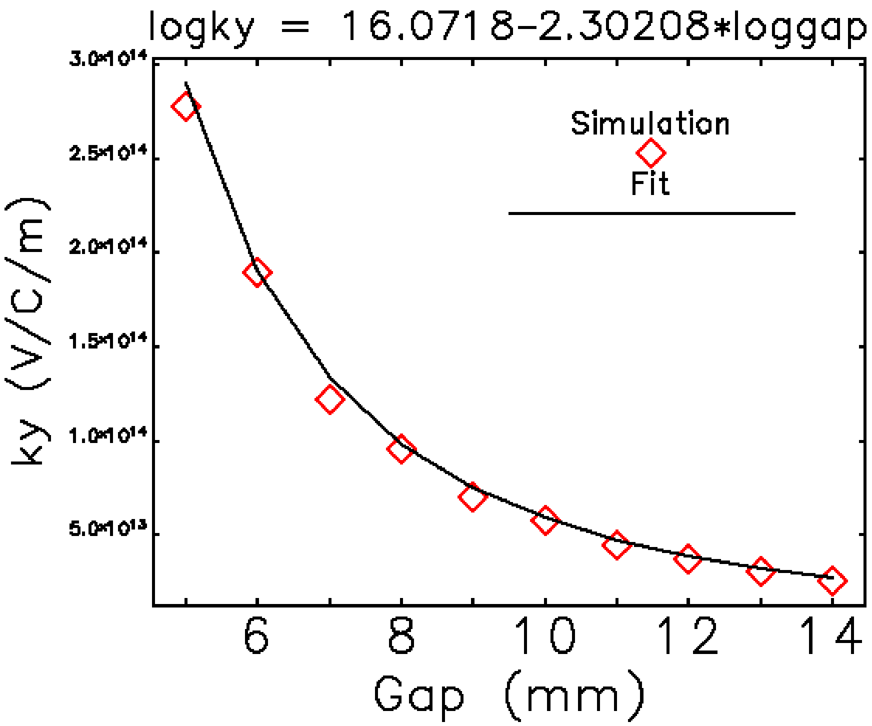
7.5mm Racetrack ID Chamber (V-Plane)

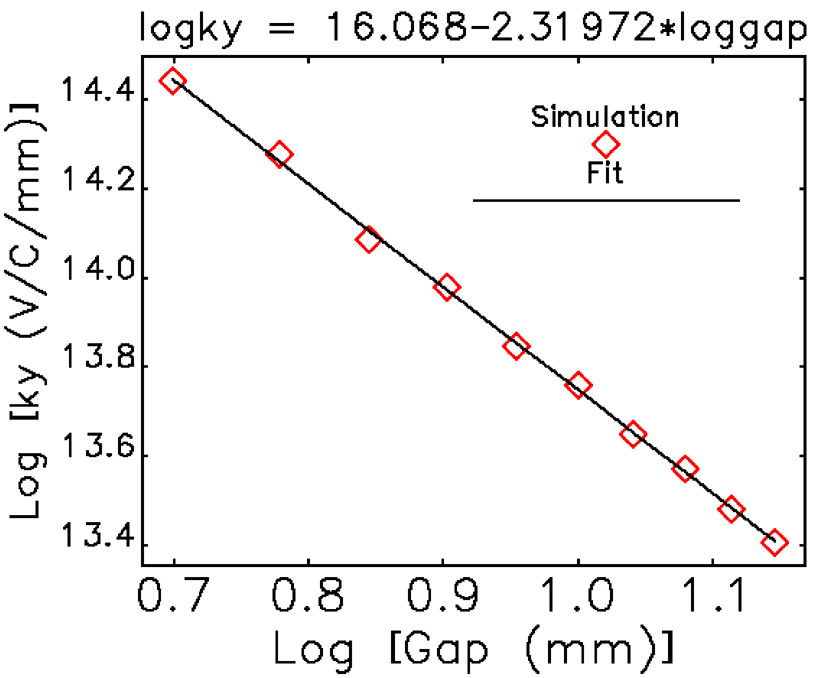


Courtesy by L. Morrison (AES-MED)

ID Chamber Gap

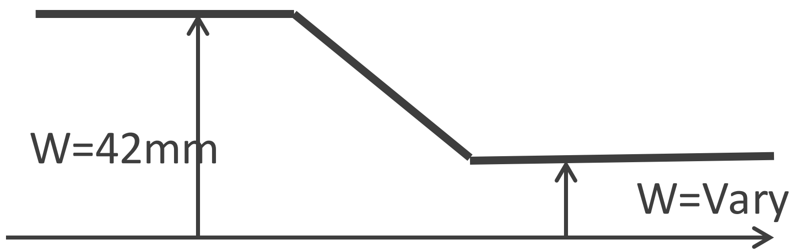
- $ky \propto {}^{1}/_{Gap^{\alpha}}$
- α = 2.1 ~ 2.4 for Gap = [4mm, 14mm]
  - Depends on ID width, transition length, beam offset

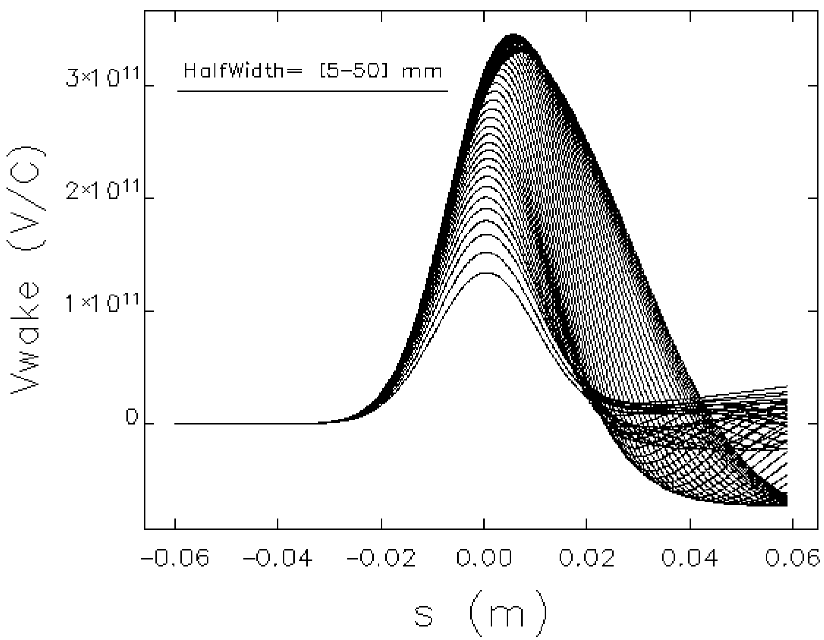


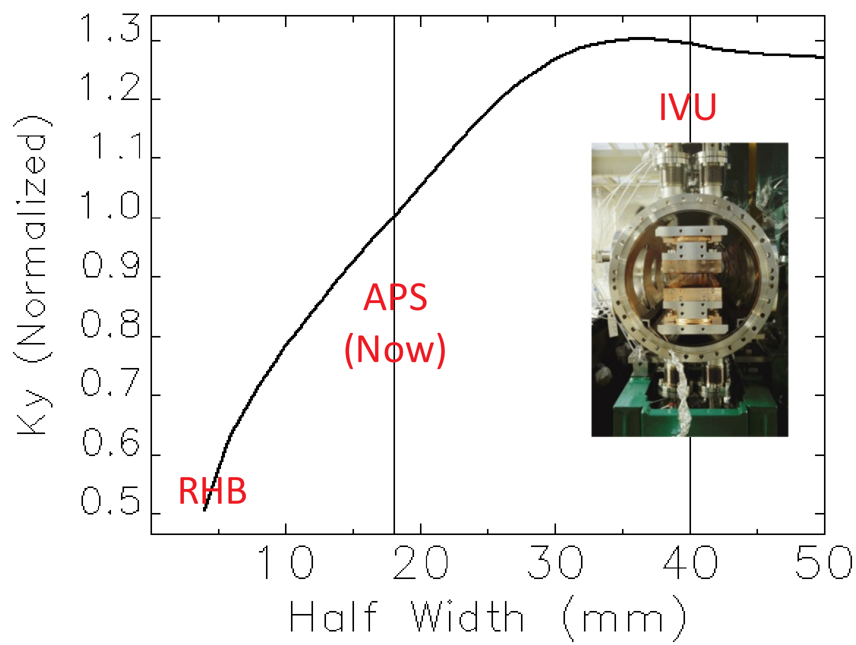


ID Chamber Width

- APS regular chamber has half width w=42 mm → **Fixed**
- APS undulator chamber has half width w=18mm → **Vary**







- **Smaller chamber width requires small beta-x for a good injection efficiency**

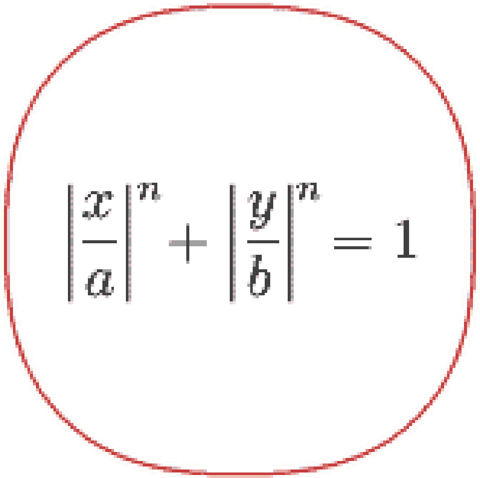
ID Chamber Width (2)

	Energy (GeV)	Size (m)	Total Current (mA)	Bunch Current (mA)	Bunch Charge (nC)
ESRF[a]	6	844.4	200	4	11
APS[b]	7	1104	102	16	59
Spring8[c]	8	1436	100	5~	24~

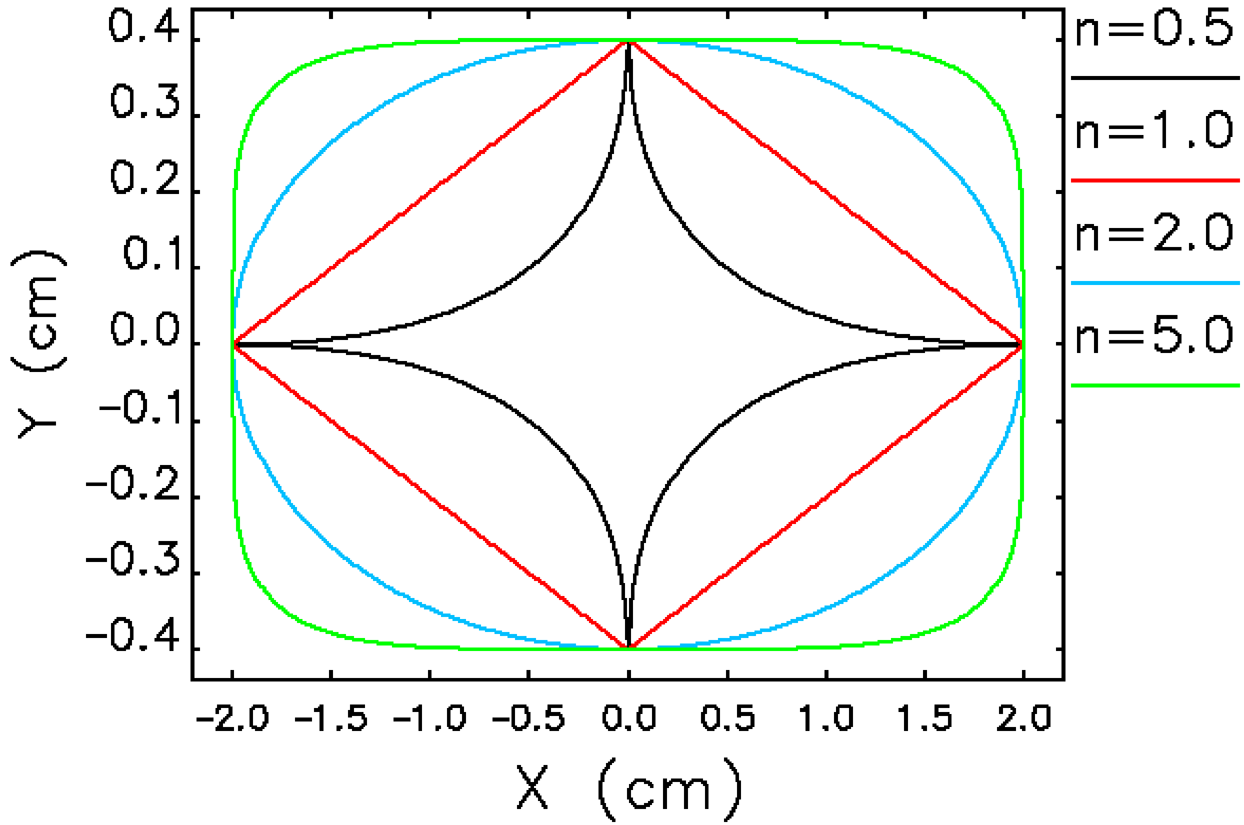
[a] http://www.esrf.eu/Accelerators/Operation/Modes
[b] http://www.aps.anl.gov/Accelerator_Systems_Division/Accelerator_Operations_Physics/SRparameters/node5.html
[c] http://www.spring8.or.jp/en/users/operation_status/schedule/bunch_mode

ID Chamber Profile: Superellipse

- Also called Lamé curve
- n < 2: hypoellipse
- n = 2: ellipse
- n > 2: hyperellipse

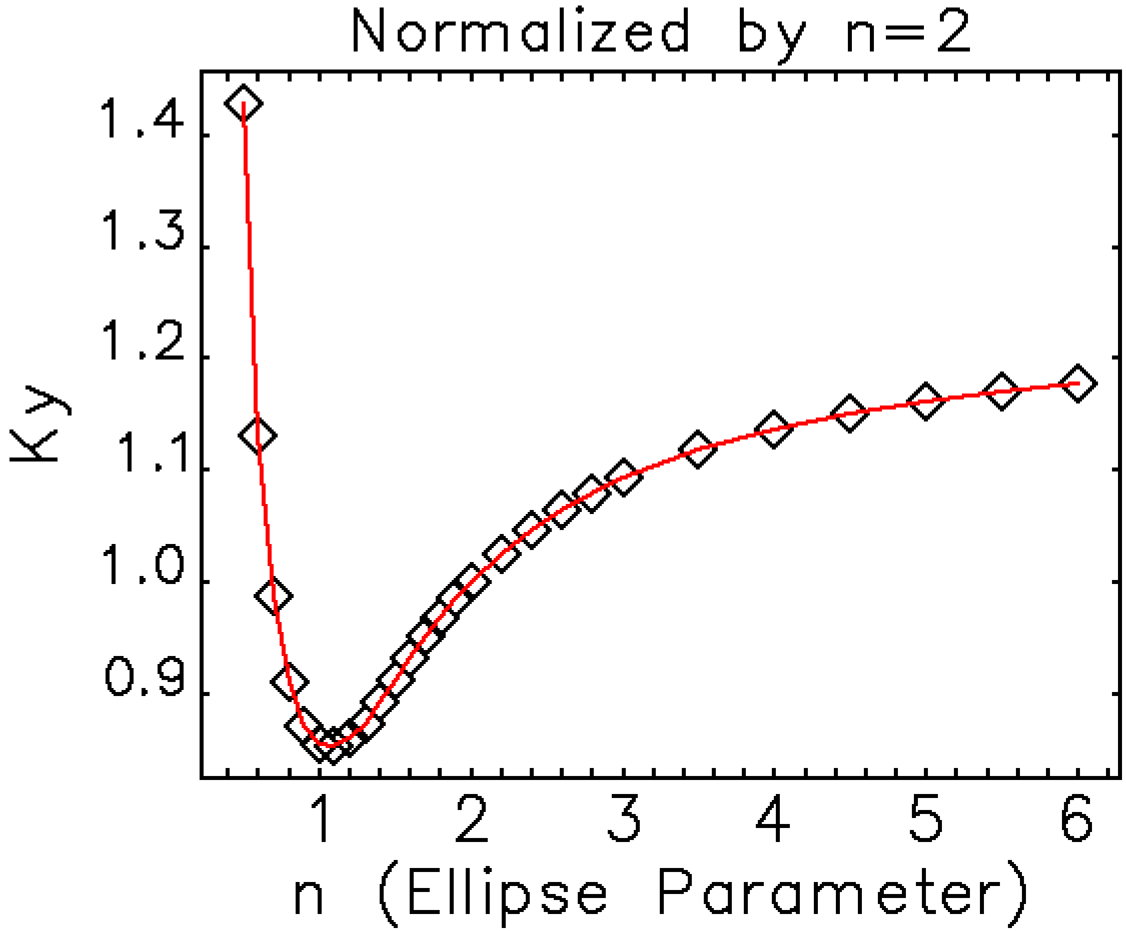


$$\left|\frac{x}{a}\right|^n + \left|\frac{y}{b}\right|^n = 1$$

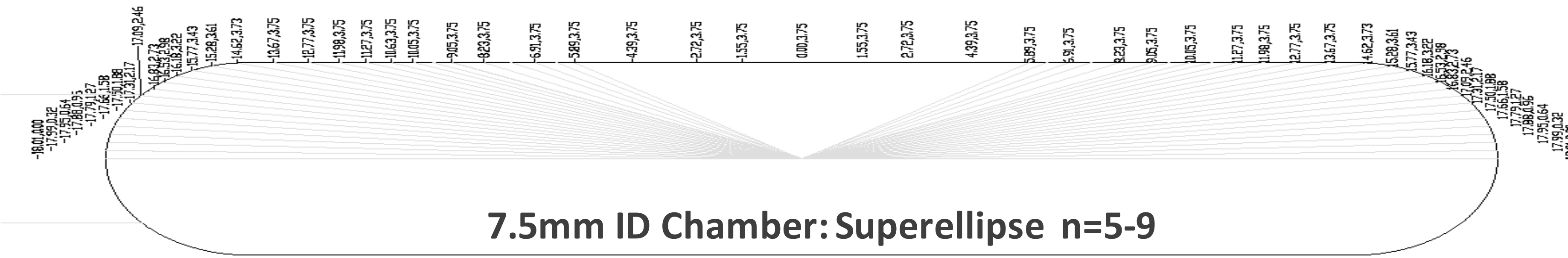


ID Chamber Profile: Superellipse (2)

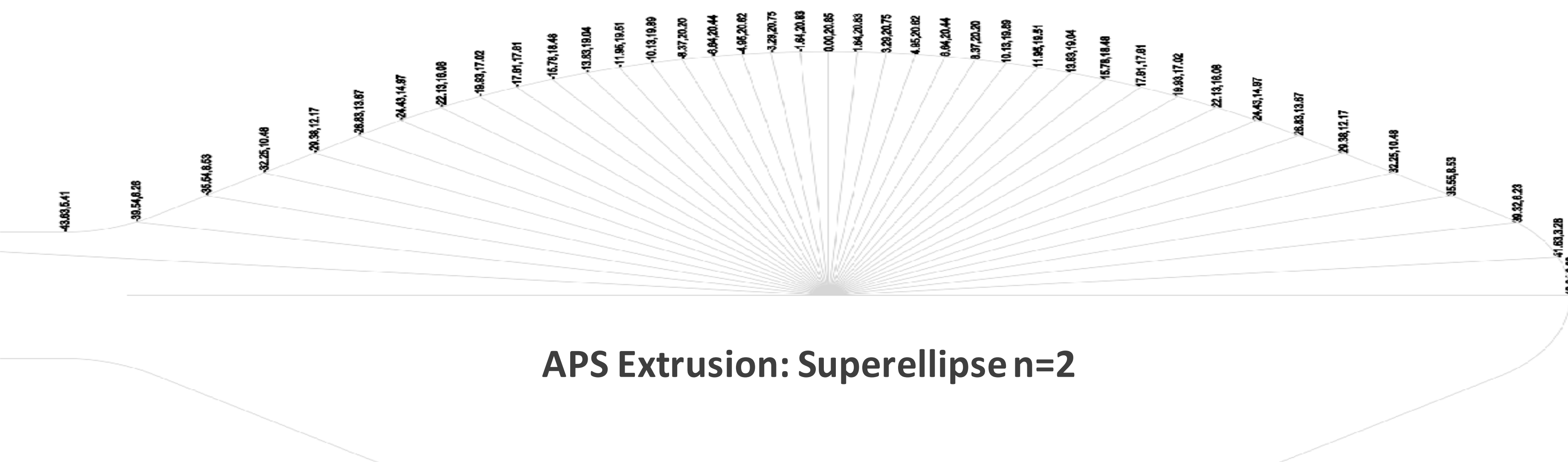
- Studied various ways of reducing the taper impedance



ID Chamber Profile: Superellipse (3)



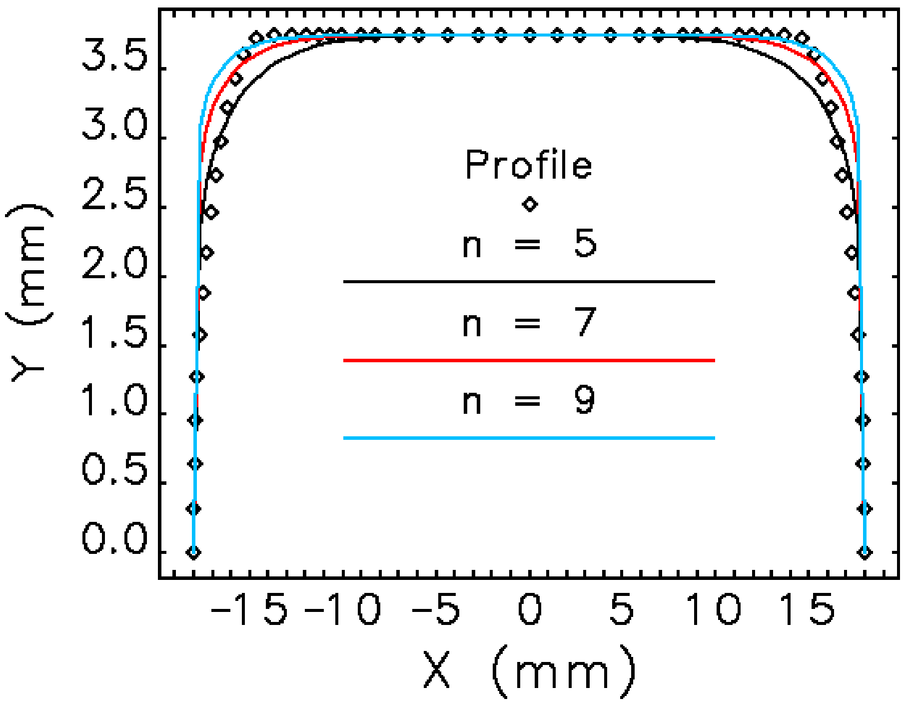
7.5mm ID Chamber: Superellipse n=5-9

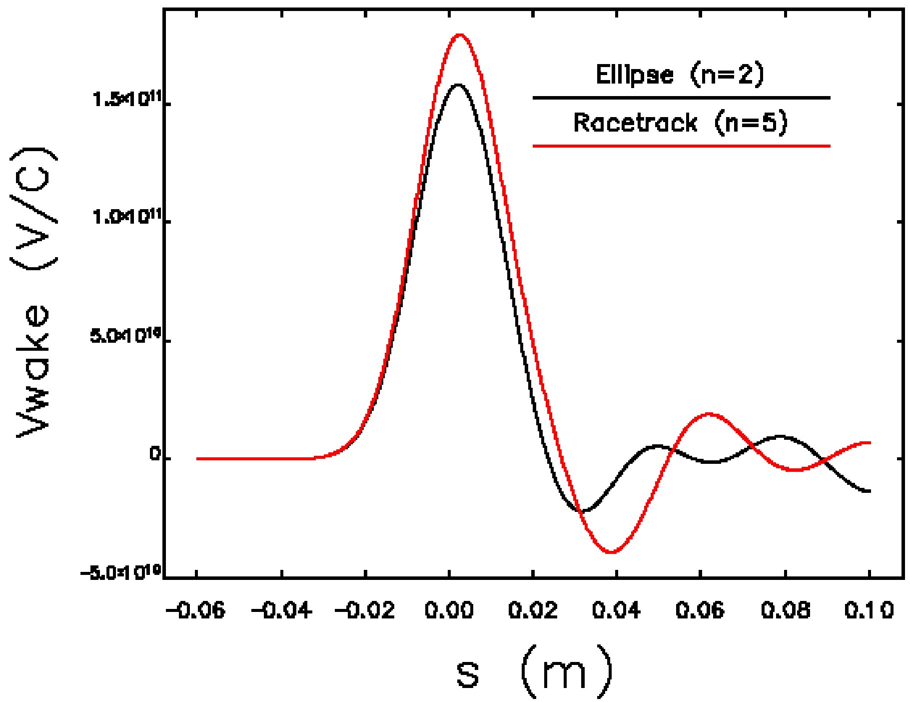


APS Extrusion: Superellipse n=2

- Profile data provided by B. Stillwell (AES-MED)

ID Chamber Profile: Superellipse (4)

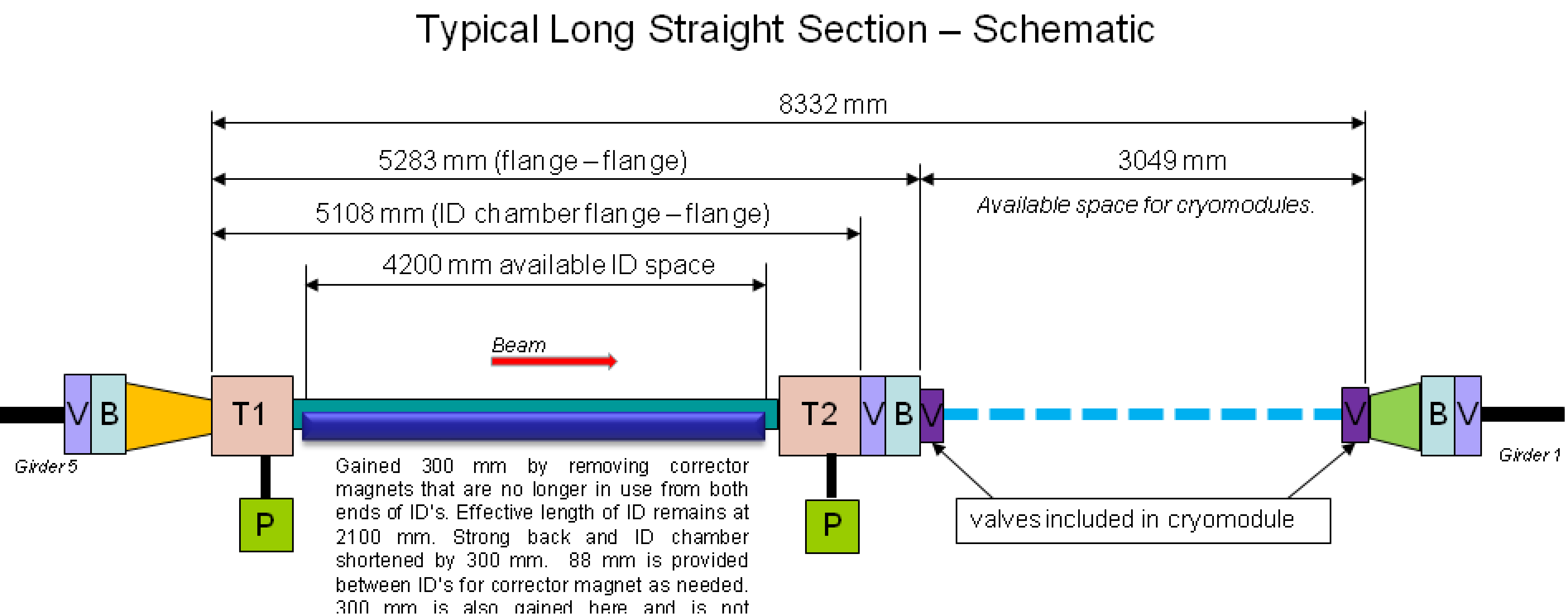




7.5mm ID Chamber: Superellipse n=5-9

- Profile data provided by B. Stillwell (AES-MED)

Transition

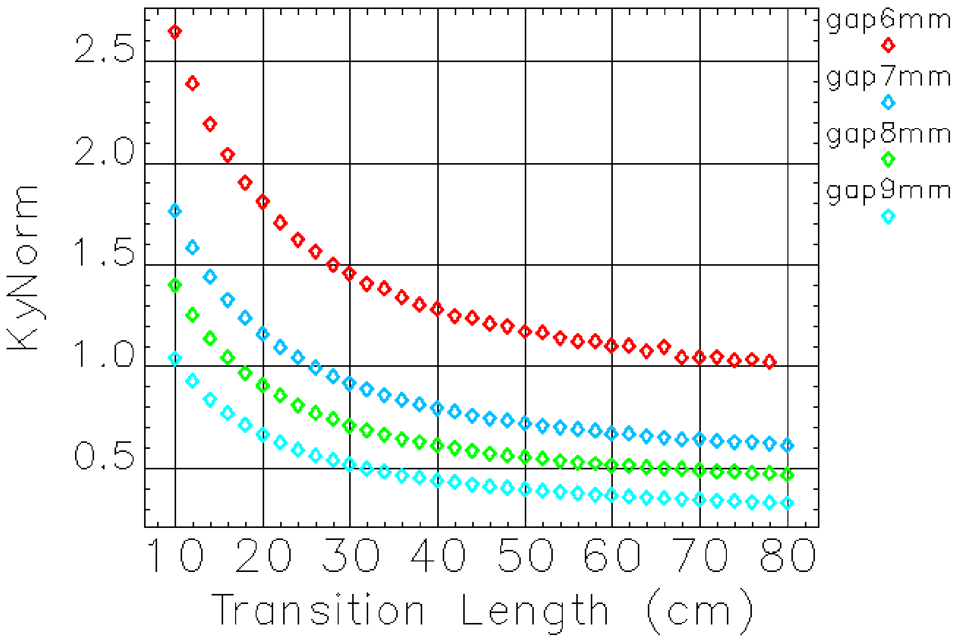


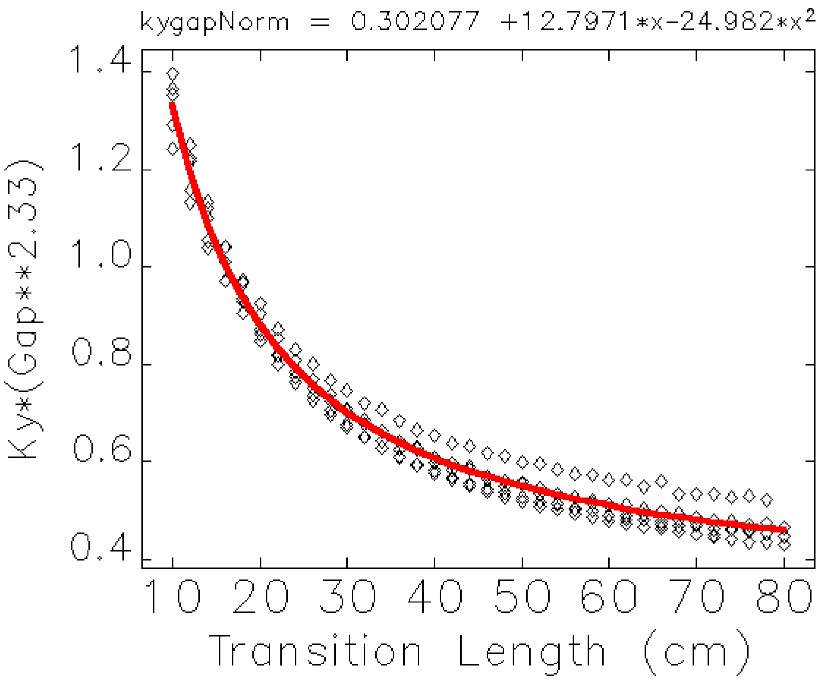
- Symmetric Transition
- Asymmetric Transition

- Nonlinear Transition
- Segmented Transition

Symmetric Transition

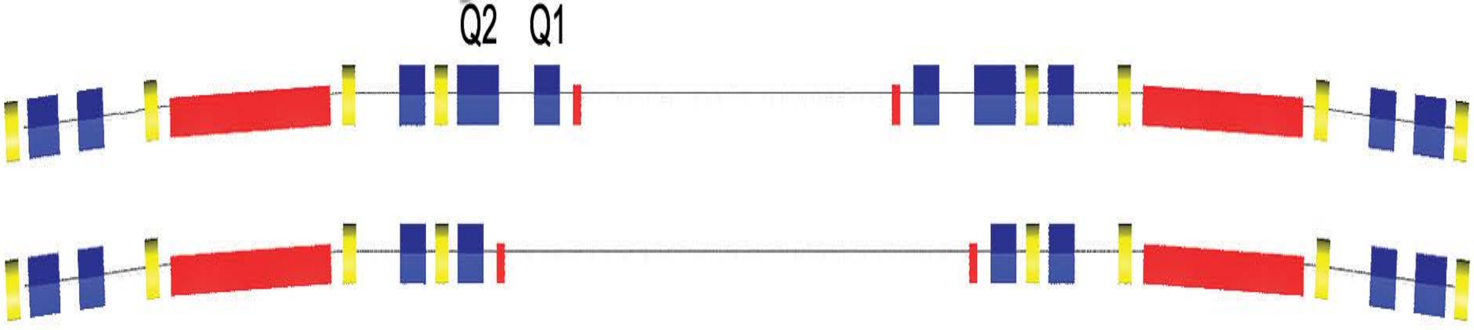
- Constraint: L=L1+L2 is fixed
- **L1=L2, β1=β2**





Symmetric Transition (2)

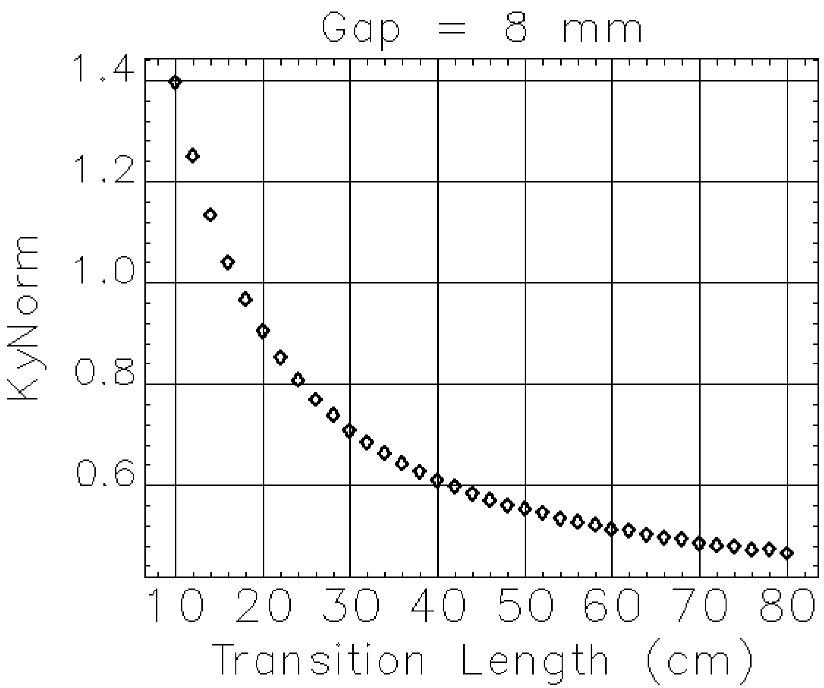
- The length will increase roughly from 5 m to 8 m
  - This will increase the ID's geometric impedance by 8/5 due to the increased β_y at the taper.
  - This will increase the ID's resistive impedance by 8/5+α due to longer length and increased $< \beta_y >$.
- If uncorrected the 4-LSS will decrease the single bunch current by 6 mA.

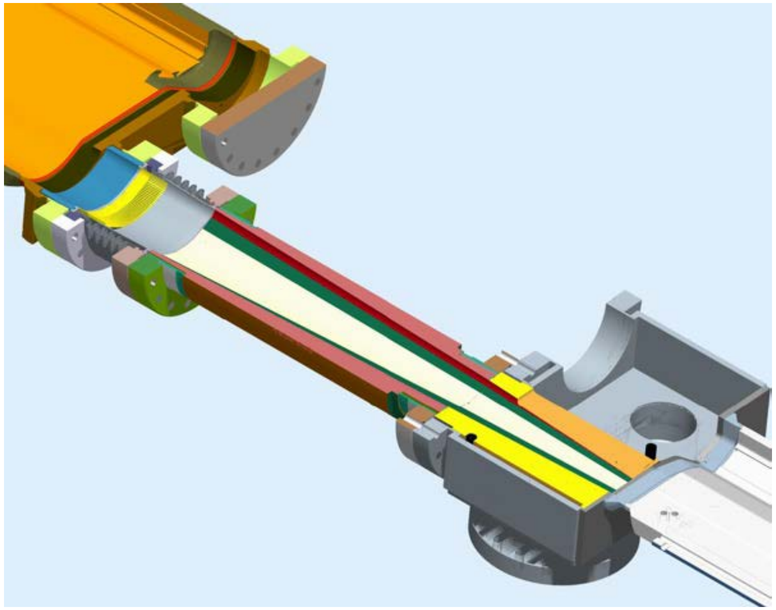


- LSS Taper (Geometric) ➔ **Reduce to 5/8** ➔ Taper Optimization
- LSS Undulator Chamber (Resistive) ➔ **Reduce to 5/8** ➔ Silver/Copper Coating (R&D)

Symmetric Transition (3)

- Studied various ways of reducing the taper impedance
  - Found that the long taper is simple and effective solution for the APS-U.
  - Necessary transition length was 40~50 cm for 8-mm gap chamber.
  - AES-MED group designed the new chamber for the APS-U.

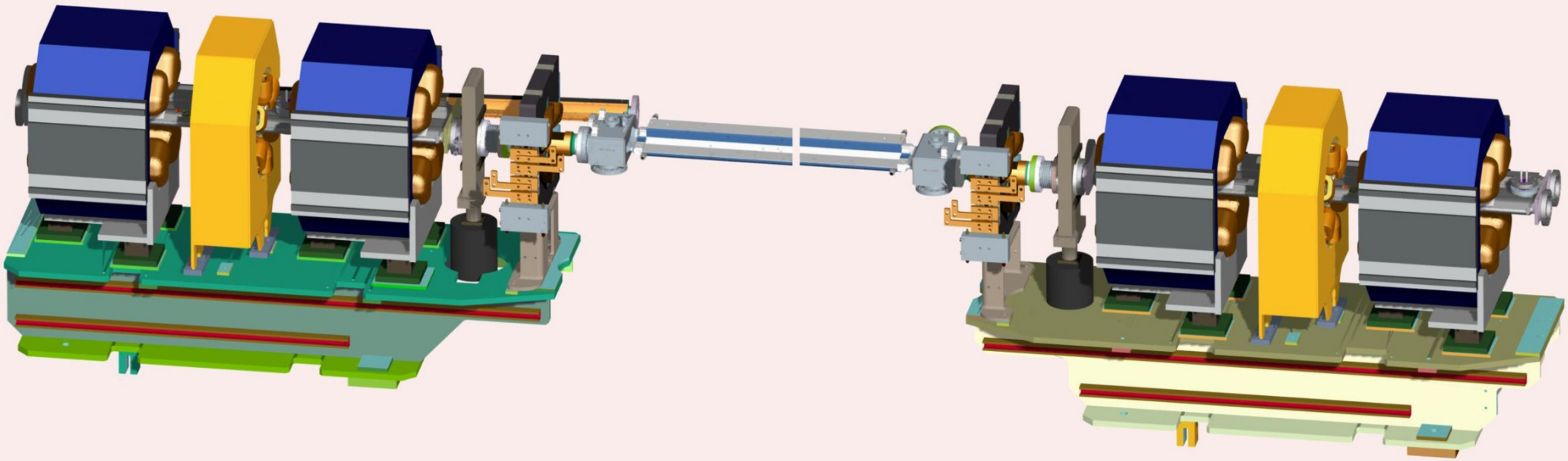




Courtesy of L. Morrison , M. Givens

Symmetric Transition(4)

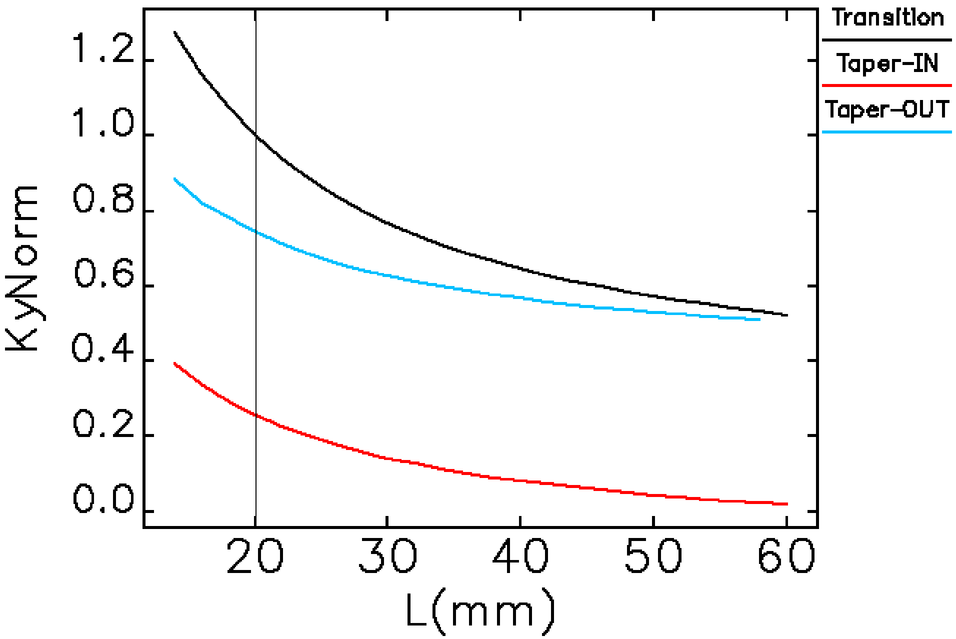
- New long straight sector with magnets are shown
  - Note that the magnets around the new taper.
  - The new taper does not take any extra space compared to the regular transition.

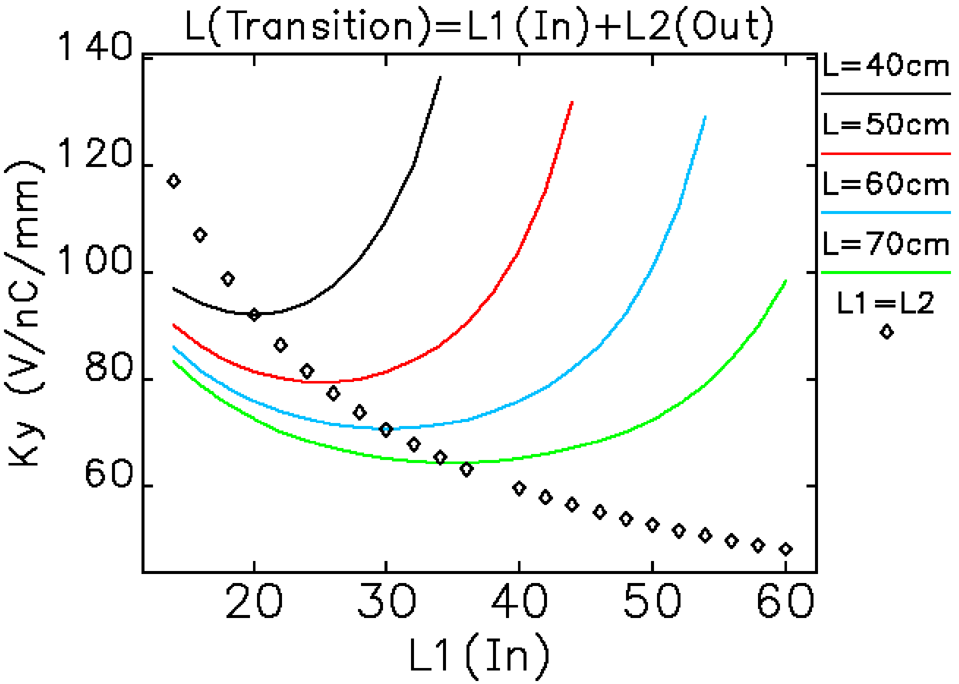


Courtesy of L. Morrison , M. Givens

Asymmetric Transition

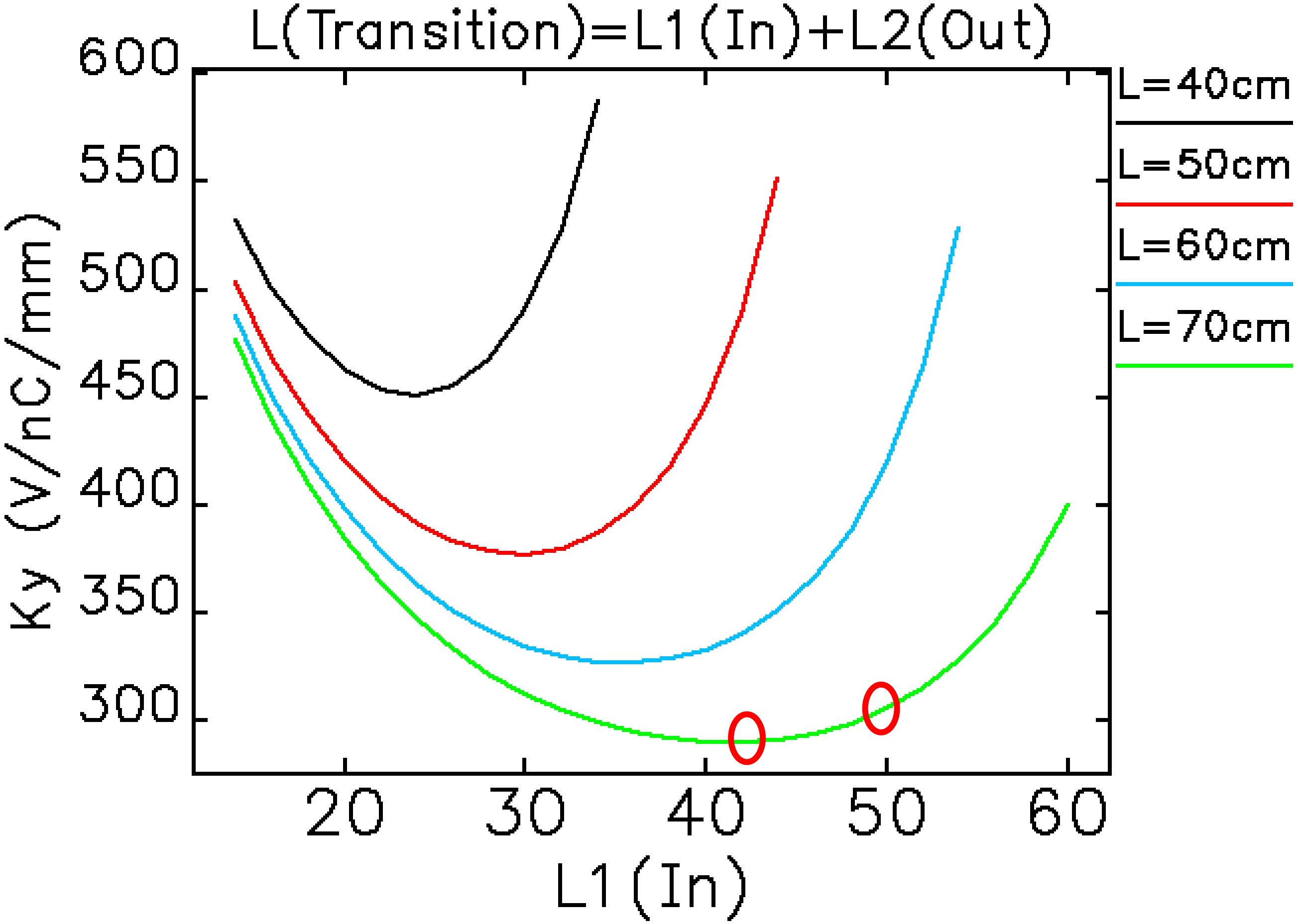
- Constraint: L=L1+L2 is fixed
- **L1≠L2, β1=β2**





Asymmetric Transition (2)

- SPX Chamber: **L1=50cm, L2=20cm**, **β1=8m, β2=4m**
- **Optimize: β1*Ky1 + β2*Ky2**



Nonlinear Transition

Impedance Formula for constant width chamber

$$Z_y^{rect} = j\frac{Z_0 w}{4}\int_{-\infty}^{\infty} dz \frac{h'(z)^2}{h(z)^3}$$

- Optimize w → narrow horizontal aperture
- Optimize linear h’(z) → long taper
- Optimize h(z) → nonlinear taper

Nonlinear Transition (2)

- Optimum profile found by B. Podobedov and I. Zagorodonov*

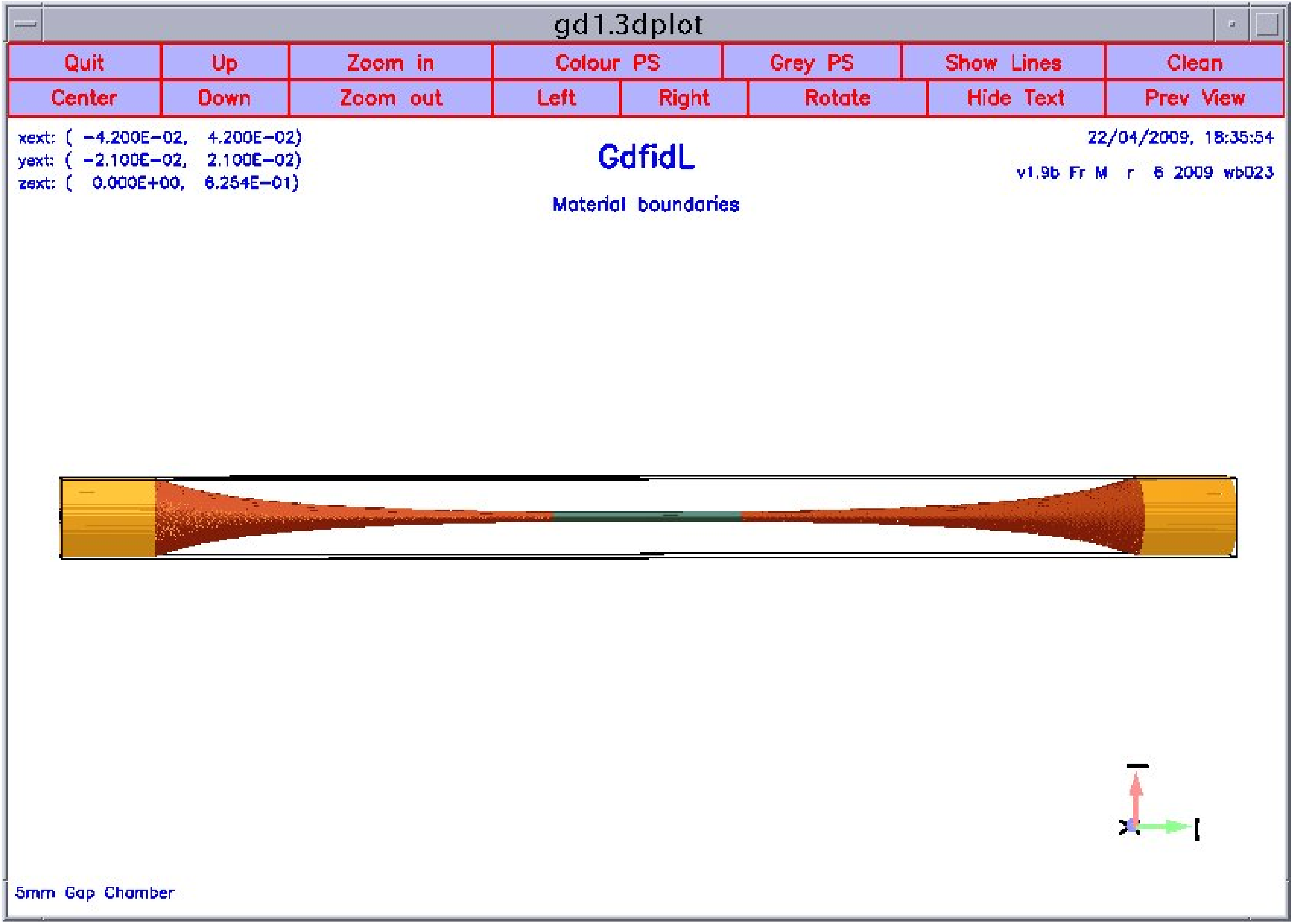
$$h(z) = \frac{h_{\min}}{\left(1+\left(\beta^{-1/2}-1\right)z/L\right)^2}, \quad \beta \equiv \frac{h_{\max}}{h_{\min}}$$

$$\frac{Z_y^{optimum}}{Z_y^{linear}} = \frac{8\beta}{(1+\beta)\left(1+\sqrt{\beta}\right)^2}$$

APS Chamber
hmax=21 mm, hmin=4 mm
Ratio=5/8

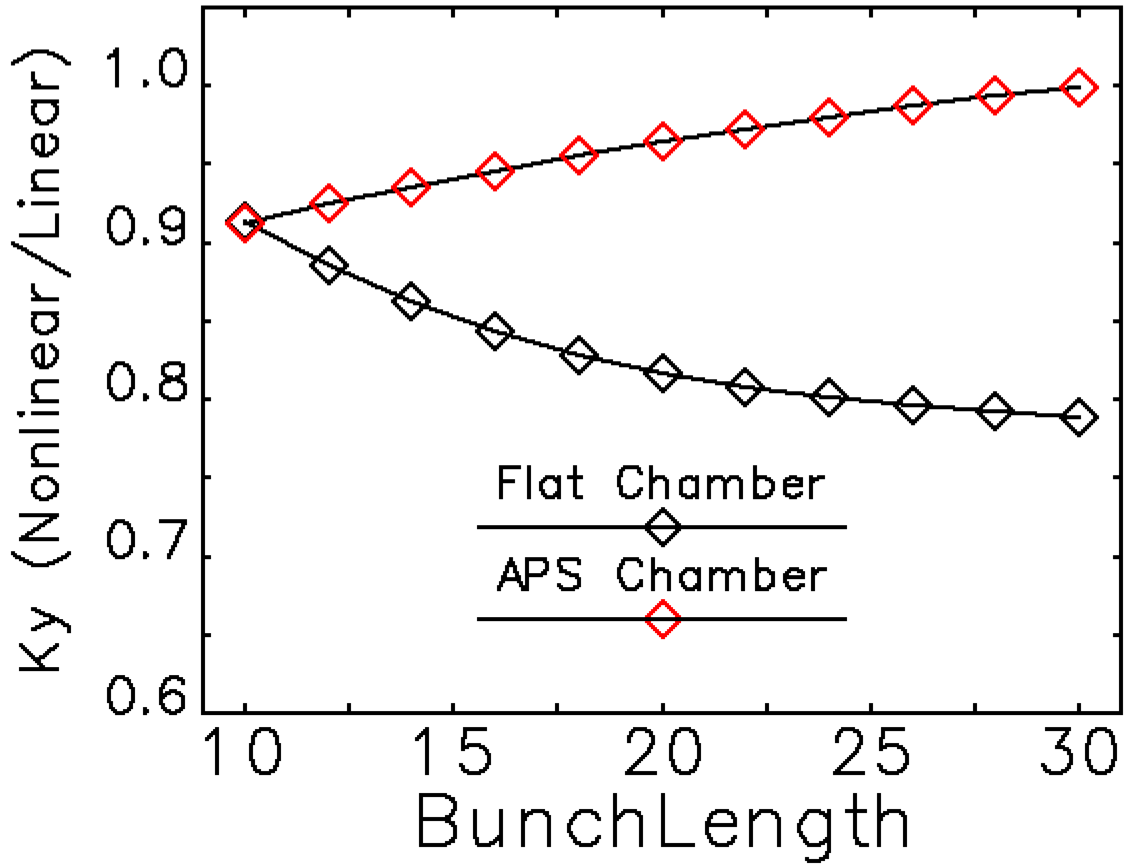
*B. Podobedov, I. Zagorodonov, "Impedance Minimization by Nonlinear Tapering," Proc. of PAC2007, p. 2006.

Nonlinear Transition (3)



Nonlinear Transition(4)

- APS 8-mm gap chamber: h_{max}=21 mm, h_{min}=4 mm



1. ID Chamber

- Gap
- Width
- Profile

L1, β1

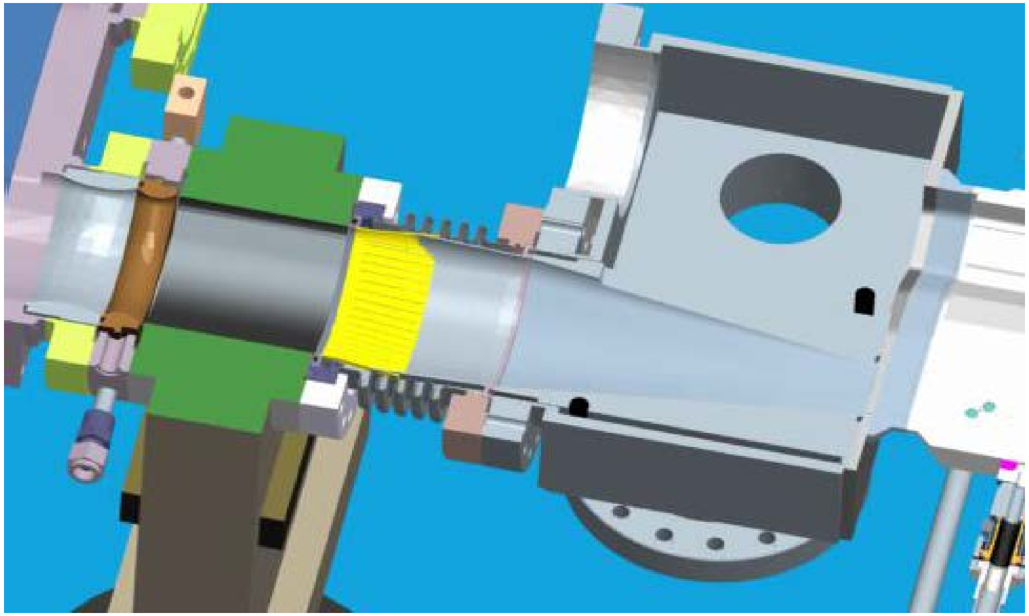
L2, β2

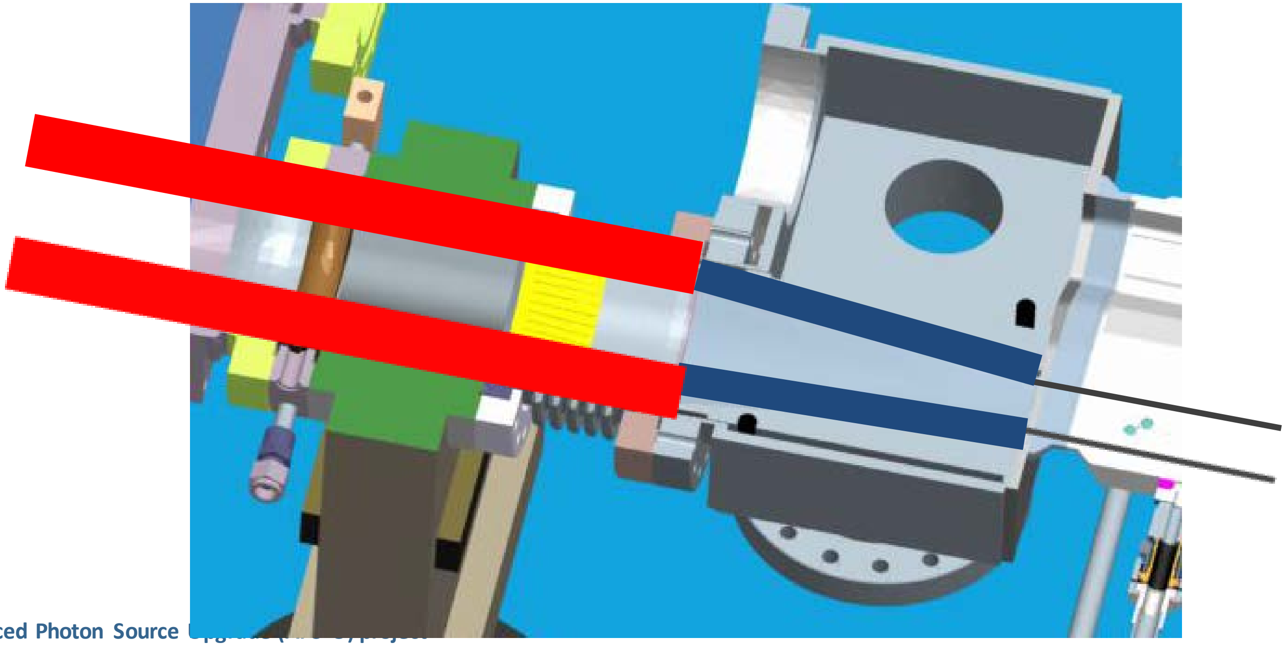
3. APS Chamber

- Width
- New Taper

2. Transition

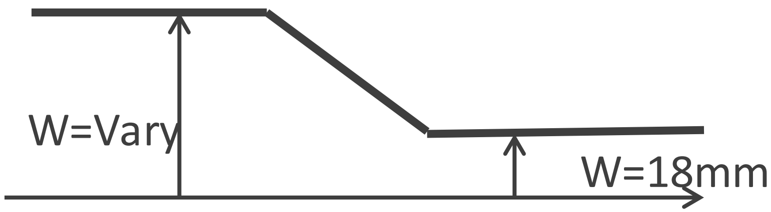
- Length
- Symmetric
- Asymmetric
- Nonlinear Taper



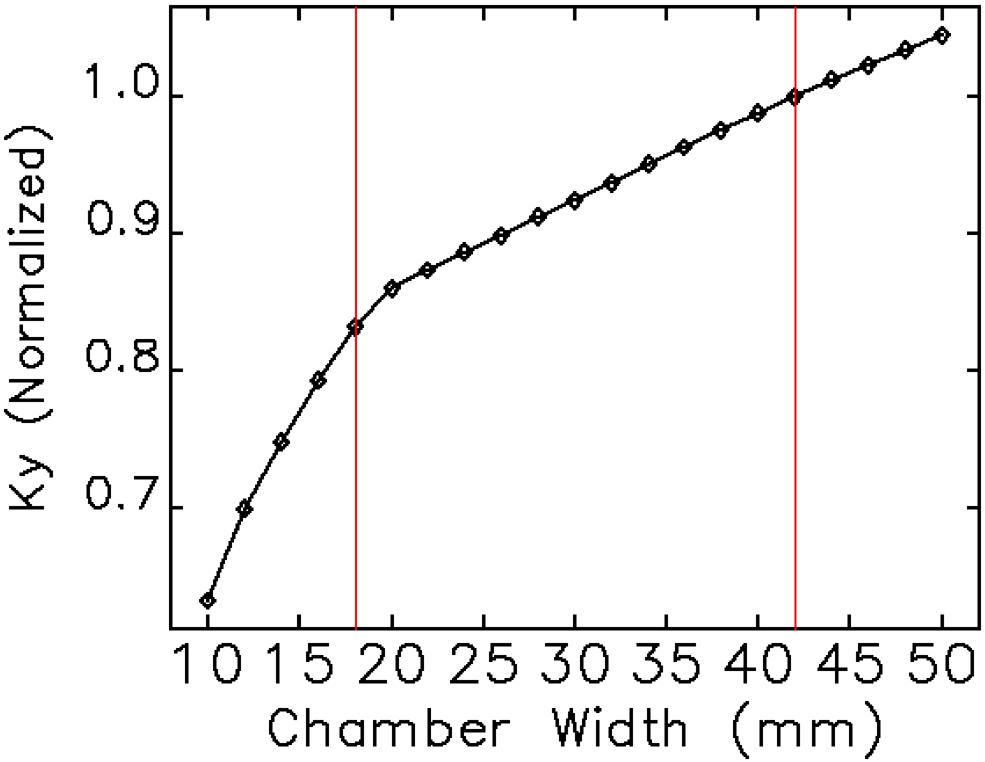


APS Chamber Width

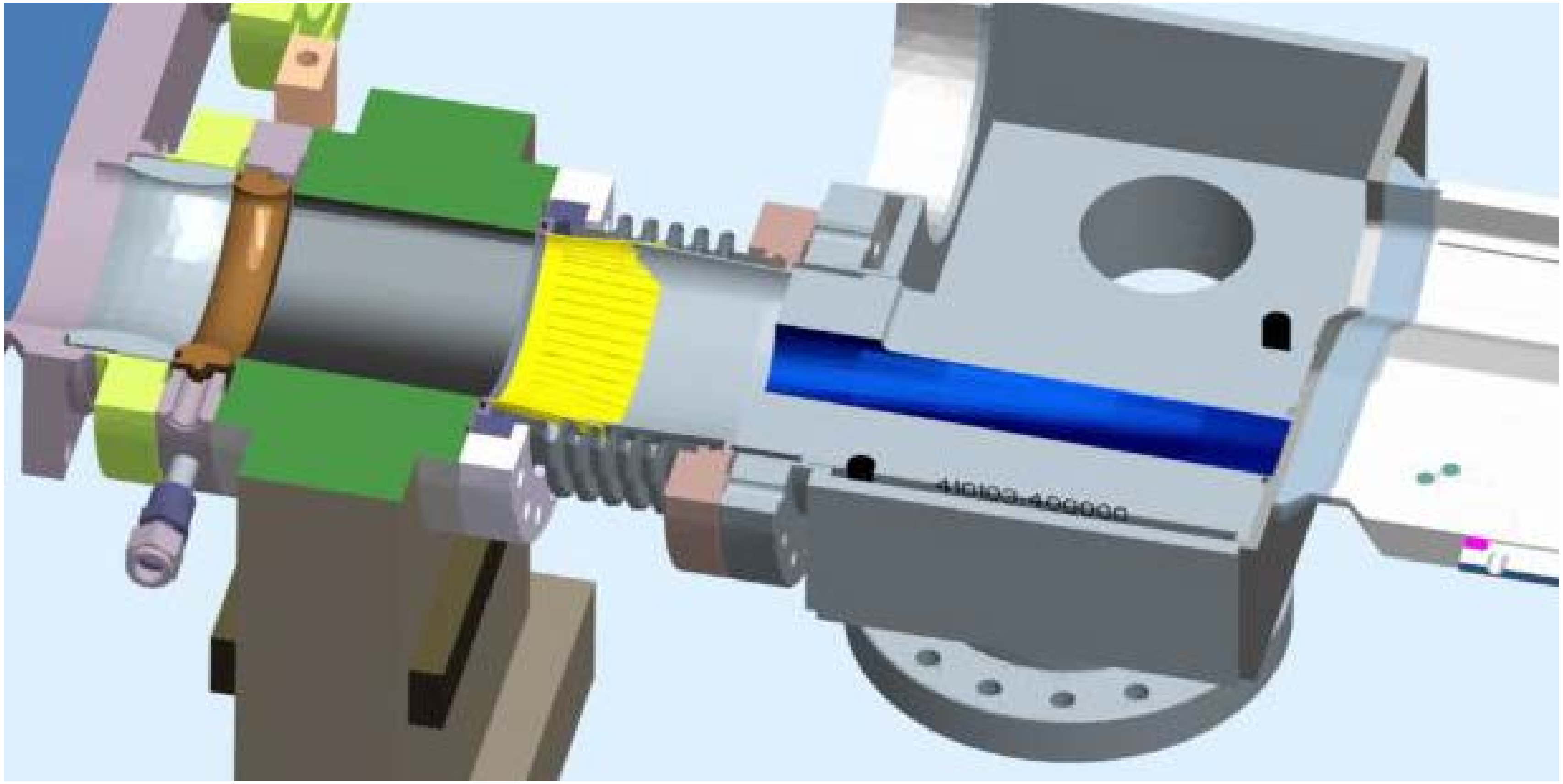
- APS undulator chamber has half width w=18mm ➔ **Fixed**
- APS regular chamber has half width w=42 mm ➔ **Vary**



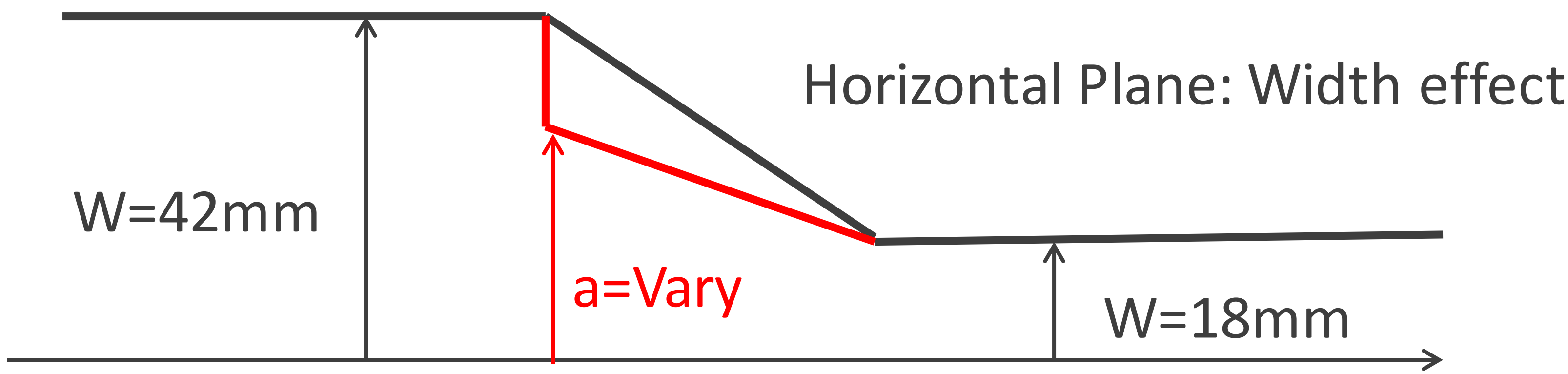
Very interesting,
But not practical

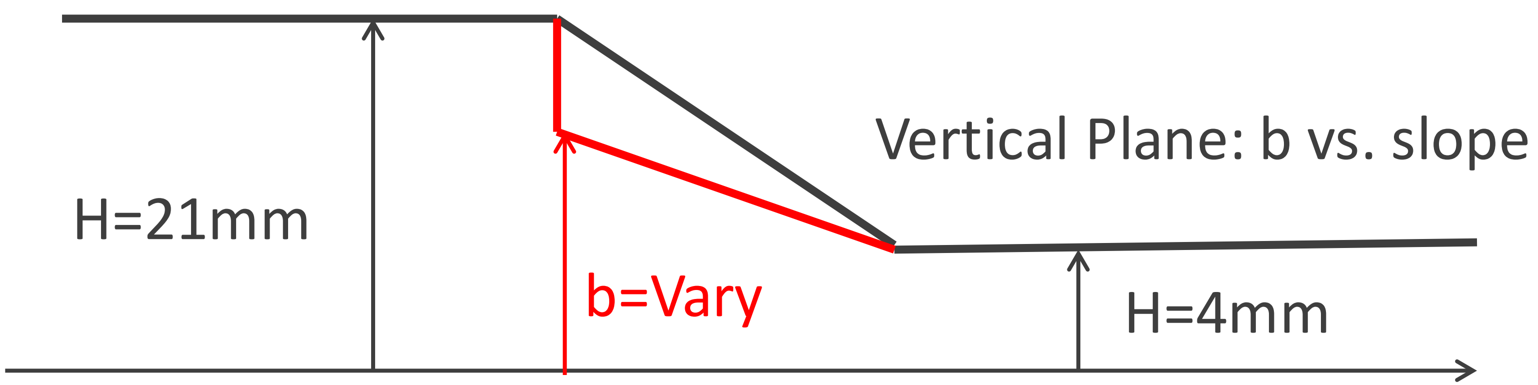


New Taper

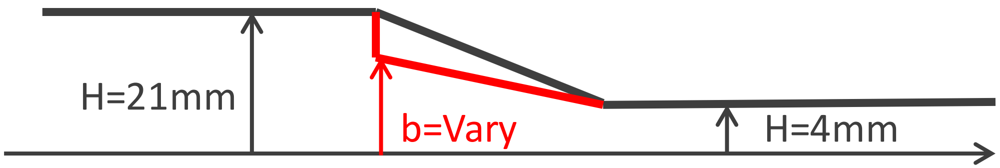


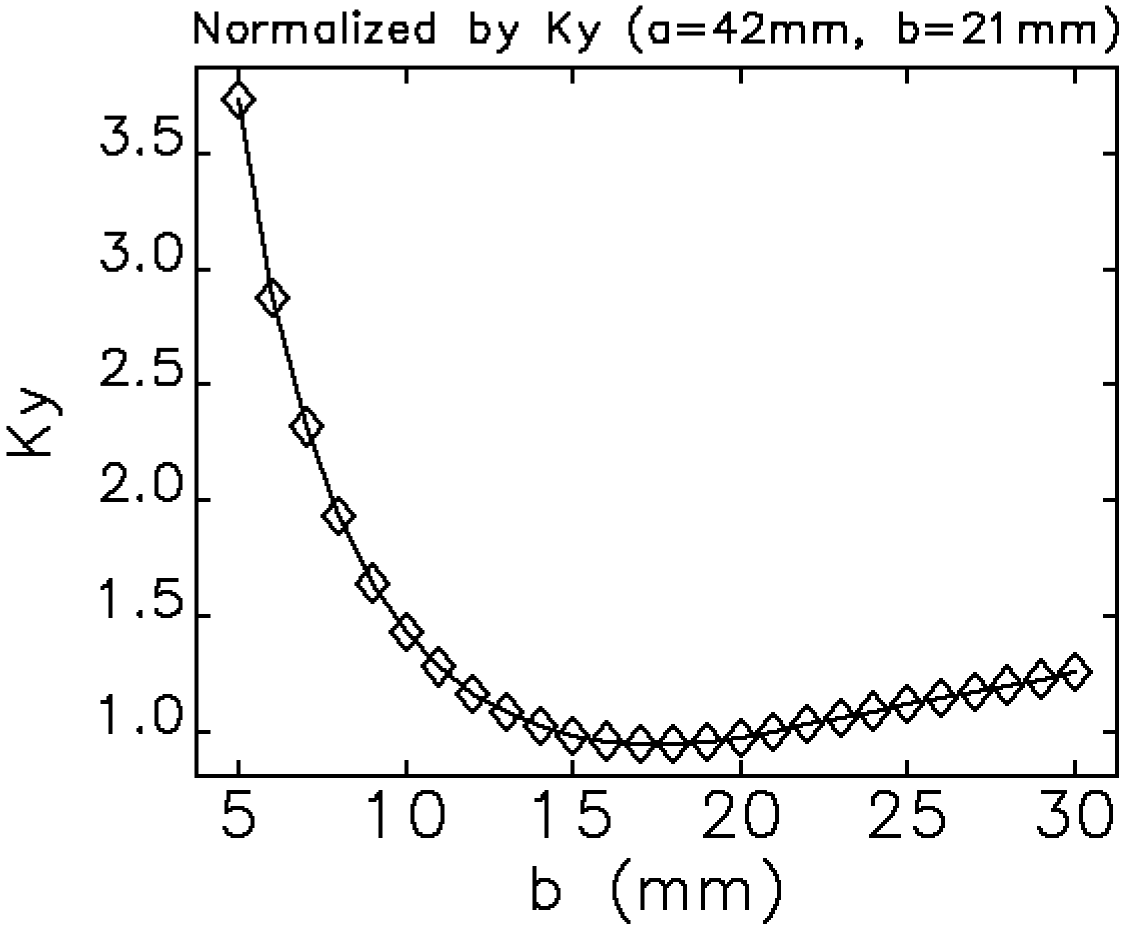
New Taper Optimization



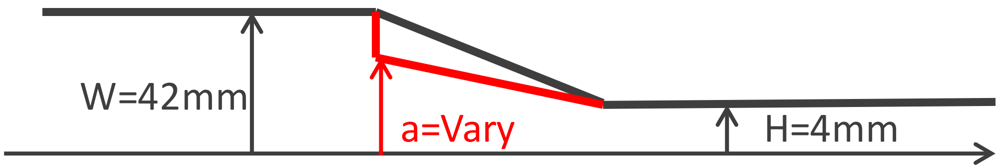


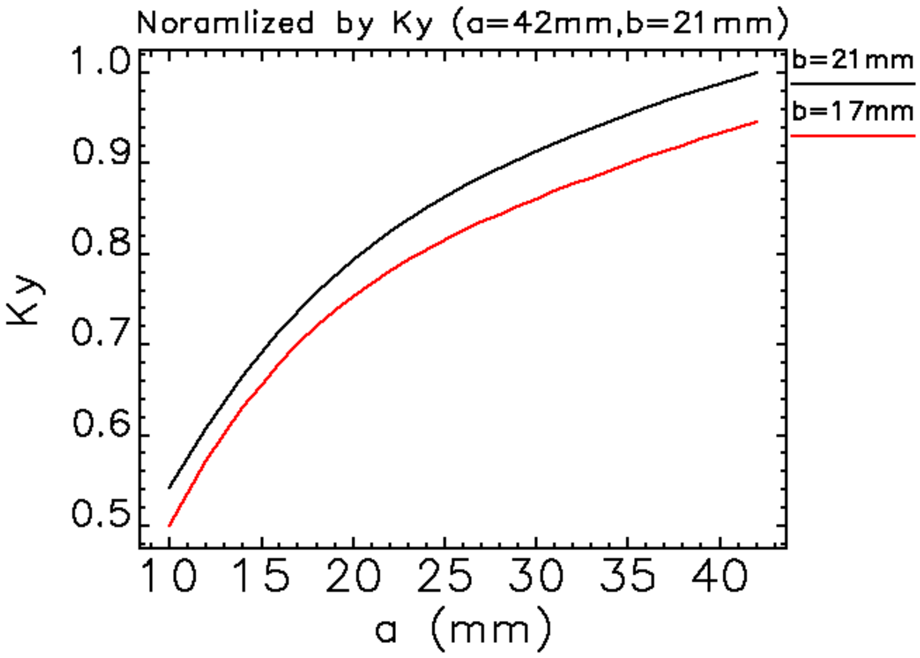
New Taper Optimization: fixed a

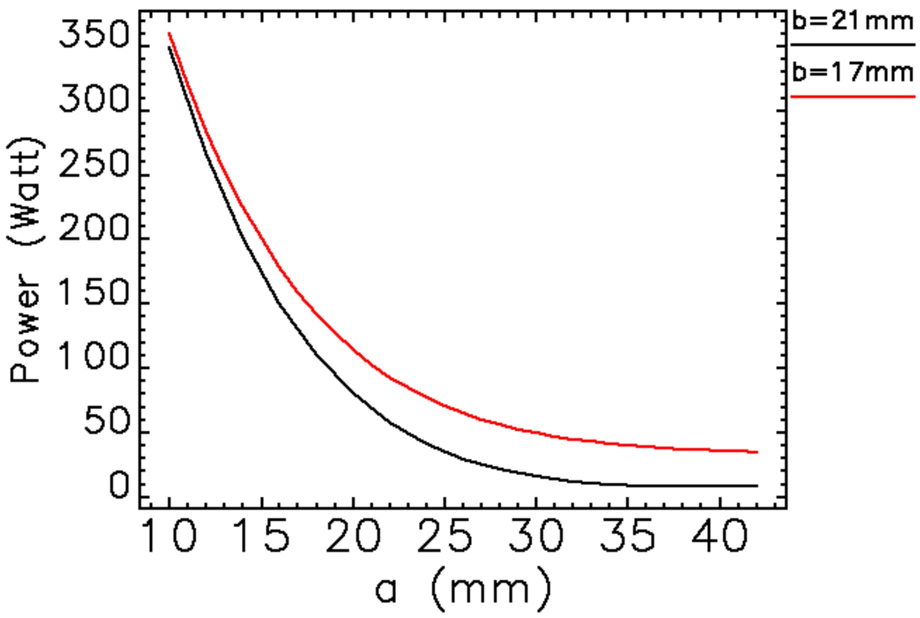




New Taper Optimization: fixed b

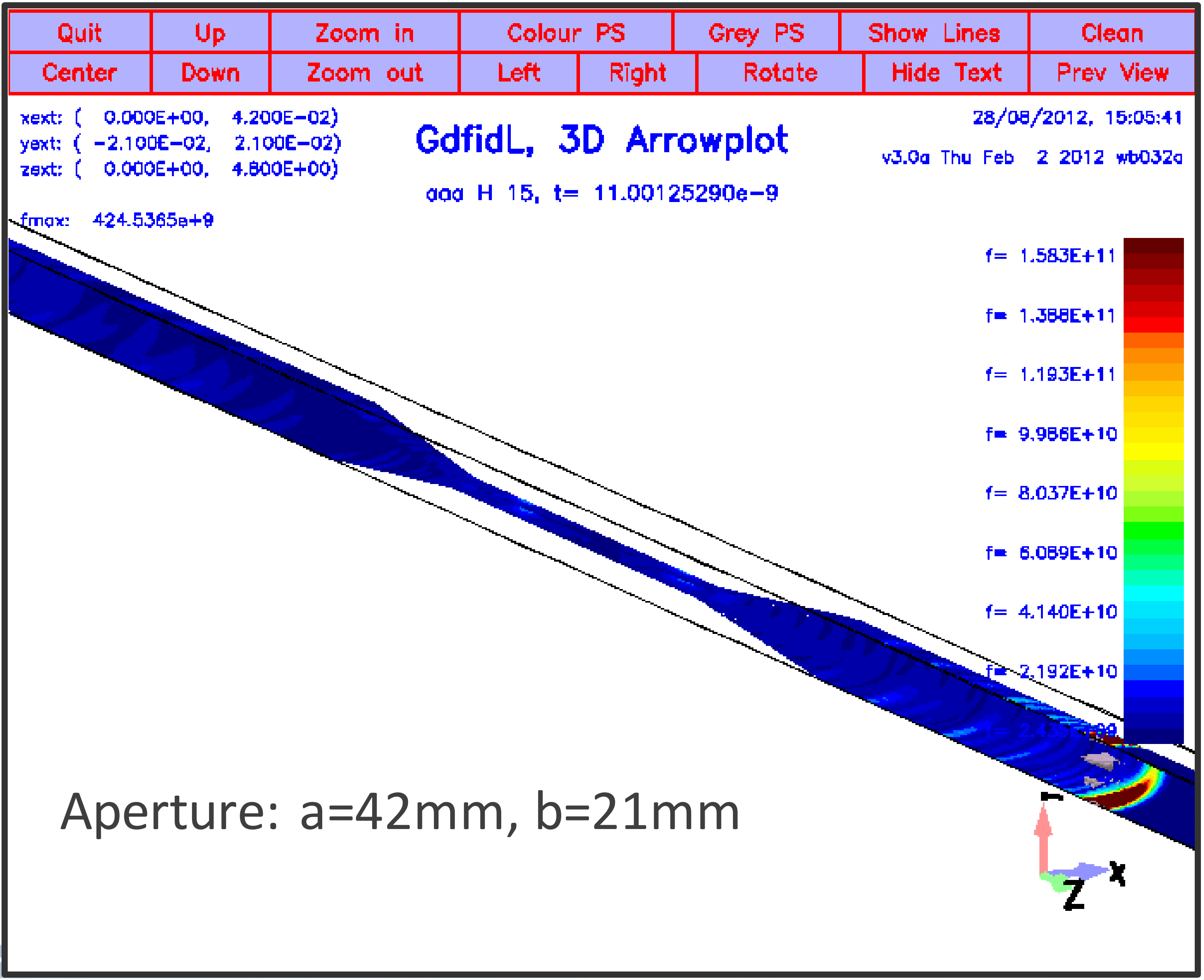






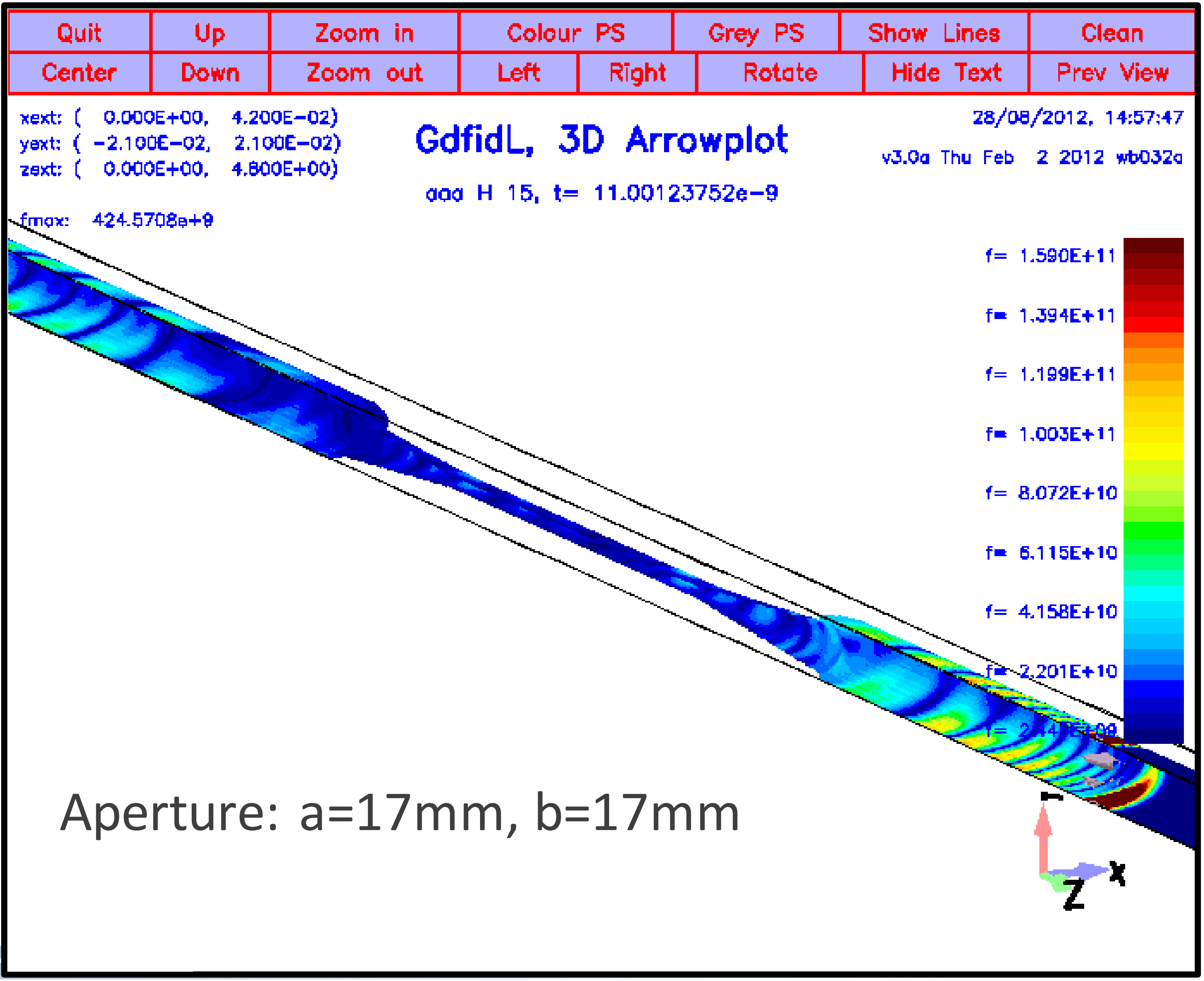
- As "a" decreases, Ky also decreases
- As "a" decrease, rf heat load increases
- **We determined that a=b=17 mm, or a=b=15mm**

ID Chamber - Wakefield



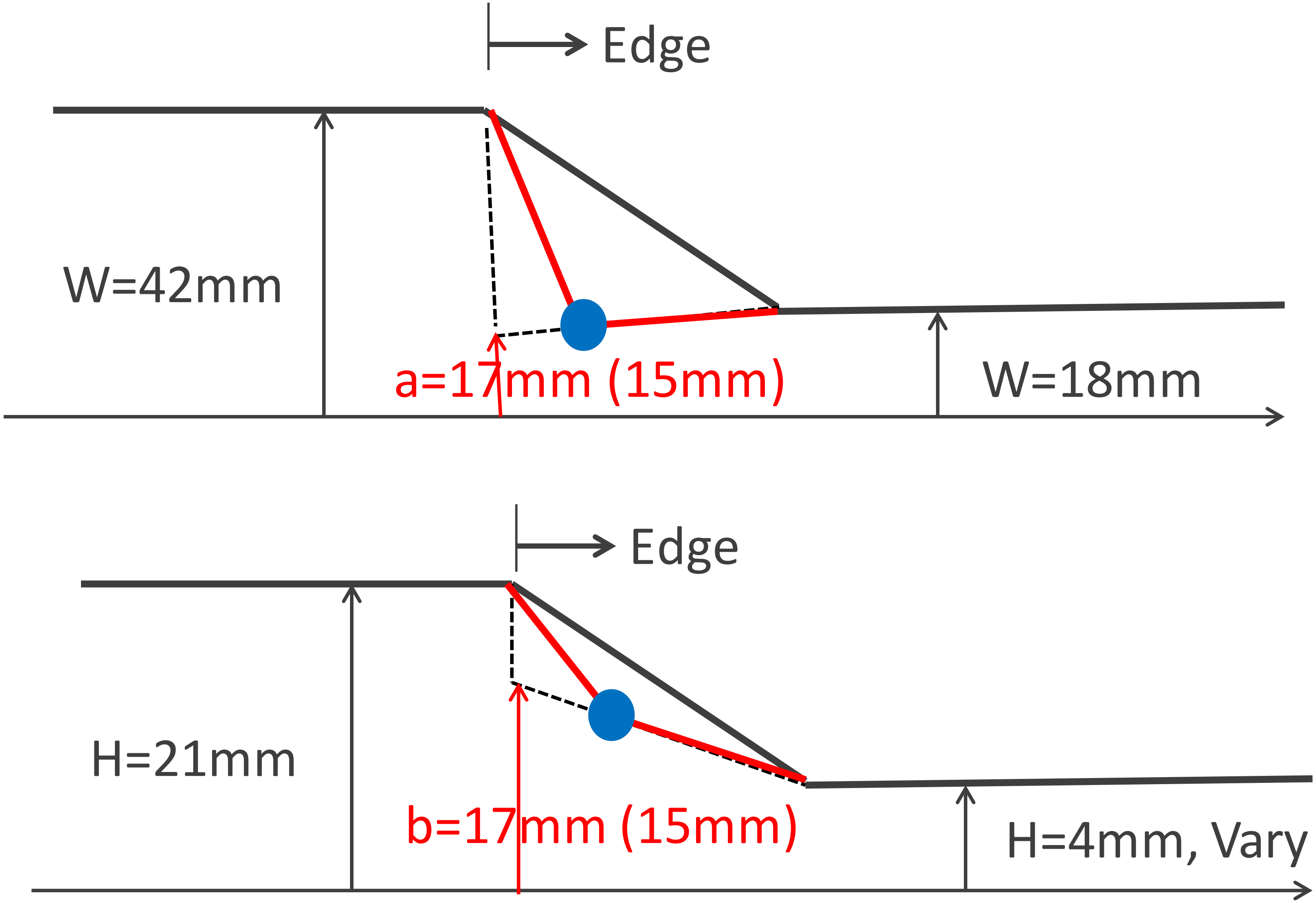
Aperture: a=42mm, b=21mm

ID Chamber with New Transition - Wakefield

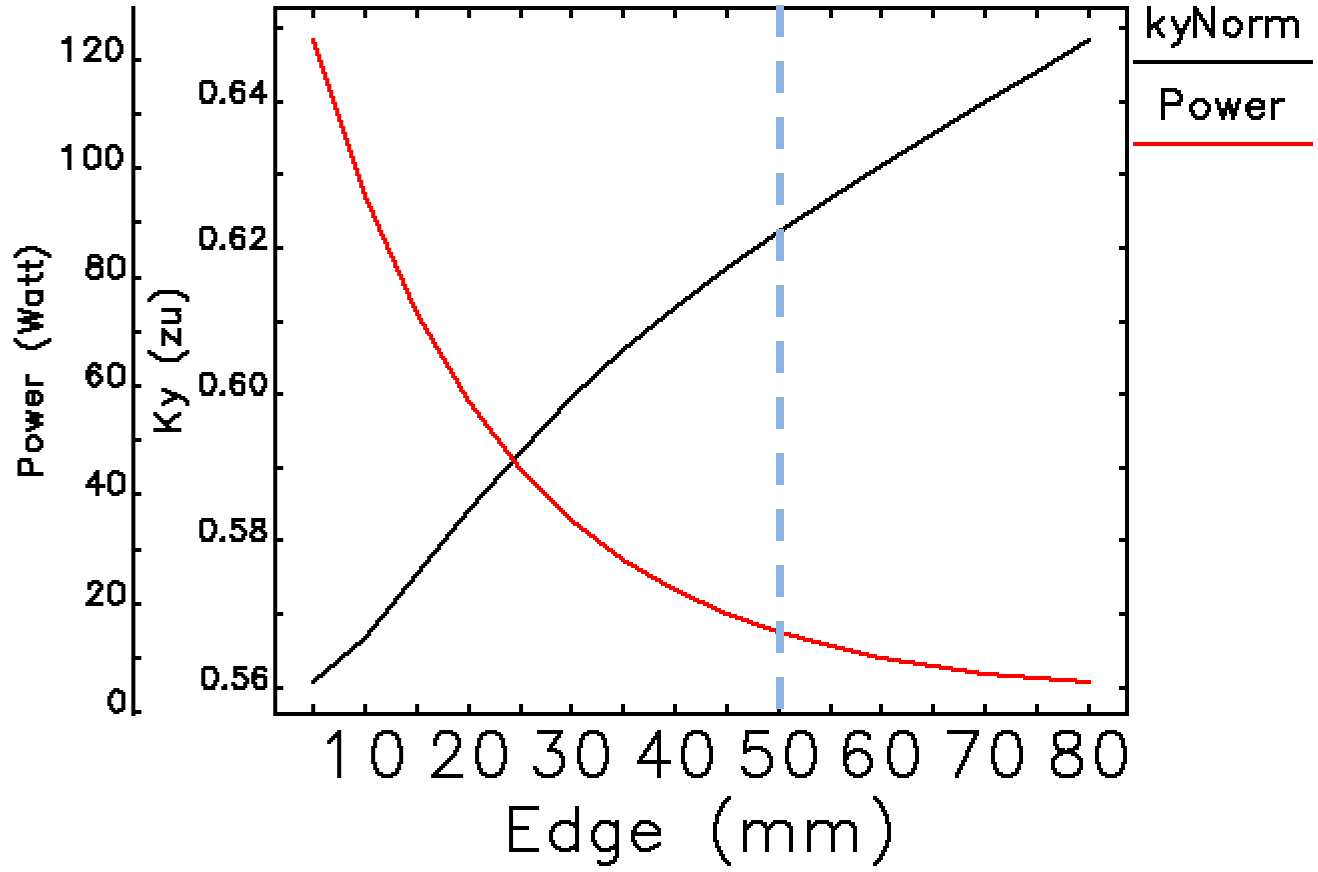


Aperture: a=17mm, b=17mm

Optimize the taper for Power & Ky (a=b=17mm)



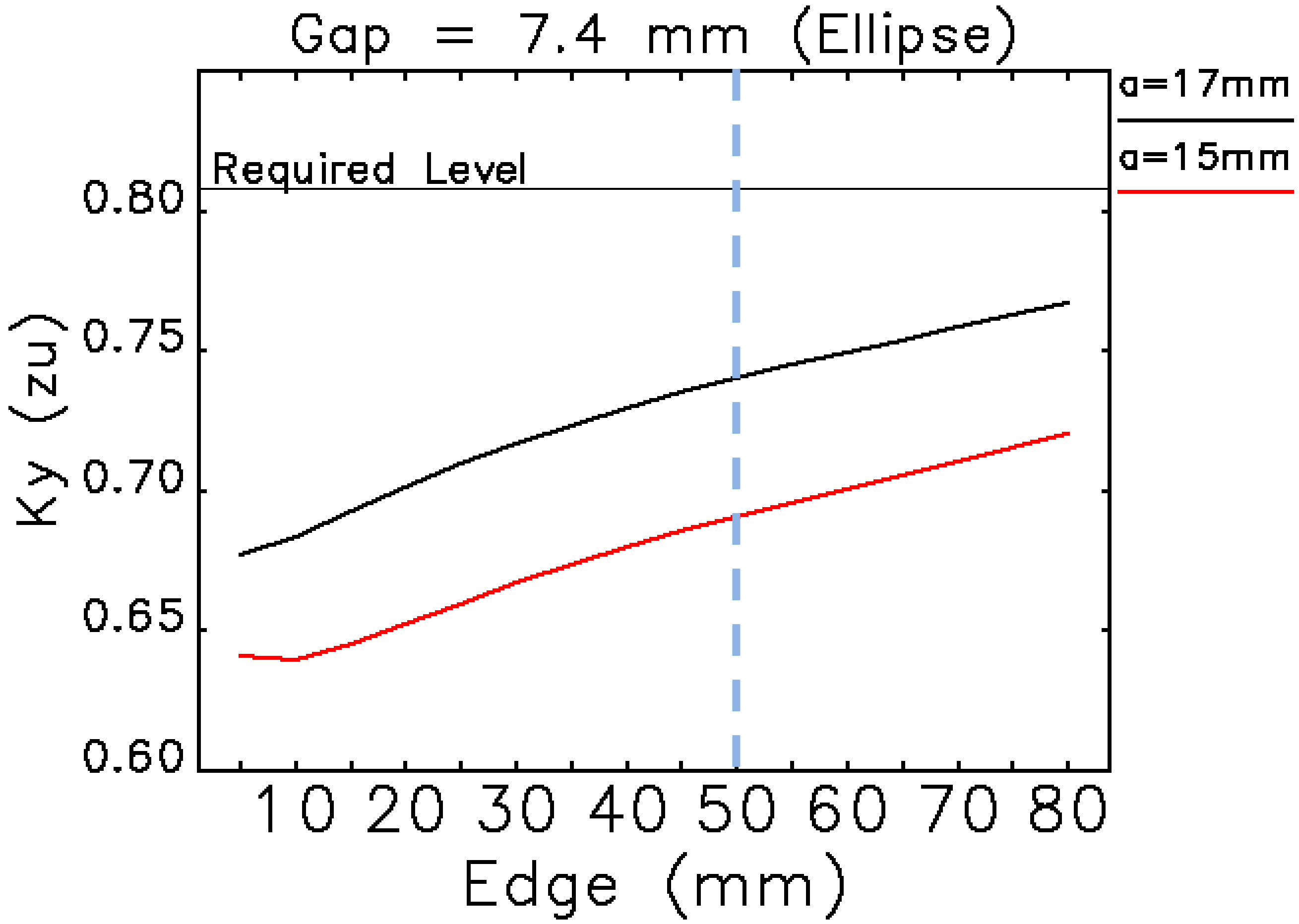
ID Chamber: Full Gap=8mm (Half Width=18mm)



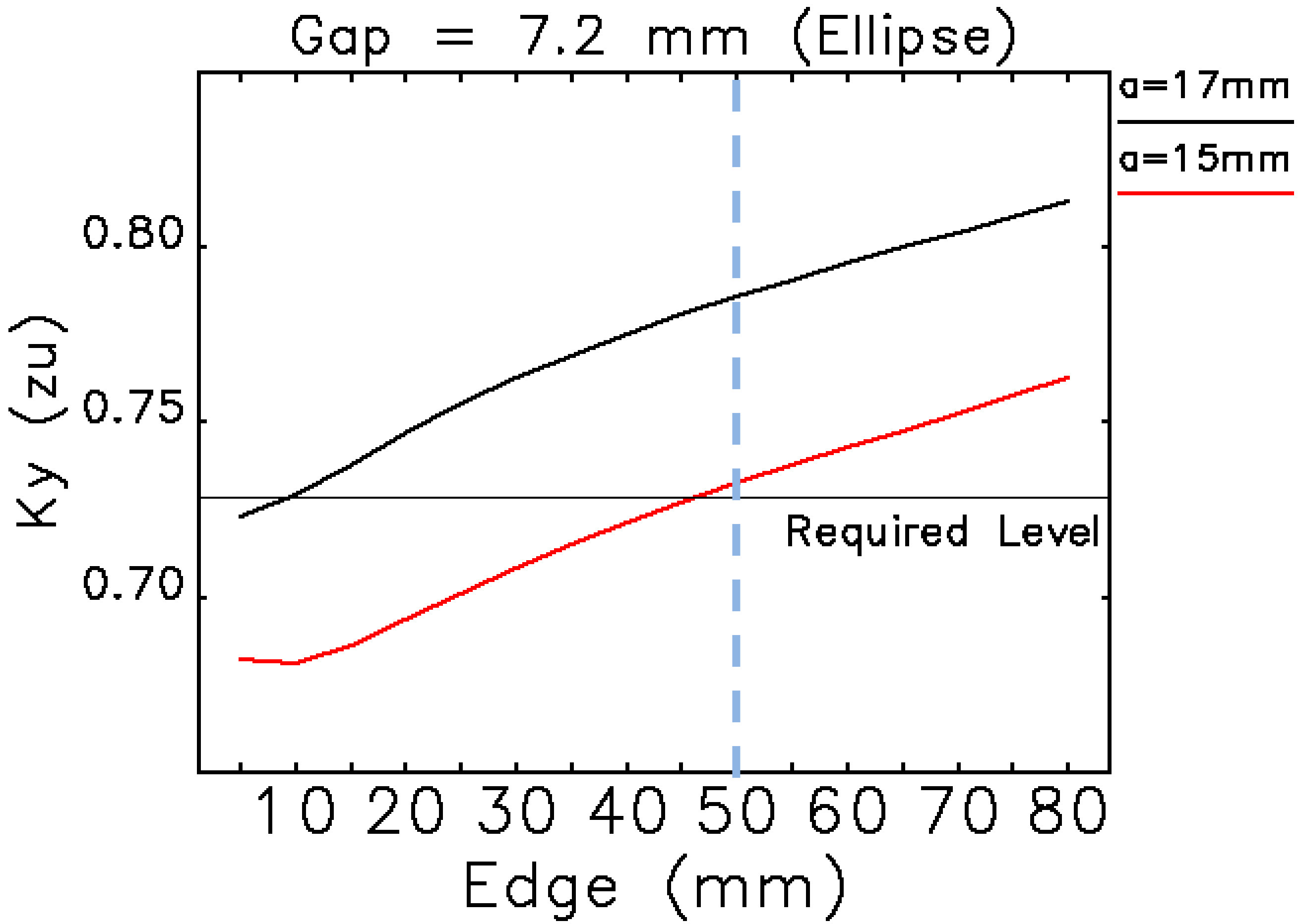
Required Impedance Level (8.0mm Ellipse)

Gap (mm)	Total Impedance (zu)	Resistive Wall Impedance (zu)	Geometric Impedance (zu)
8	1.73	0.730	1.0
7.8	1.73	0.788	0.942
7.6	1.73	0.851	0.879
7.4	1.73	0.922	0.808
7.2	1.73	1.001	0.729
7.0	1.73	1.090	0.640
	Condition	Analytic	Required to achieve

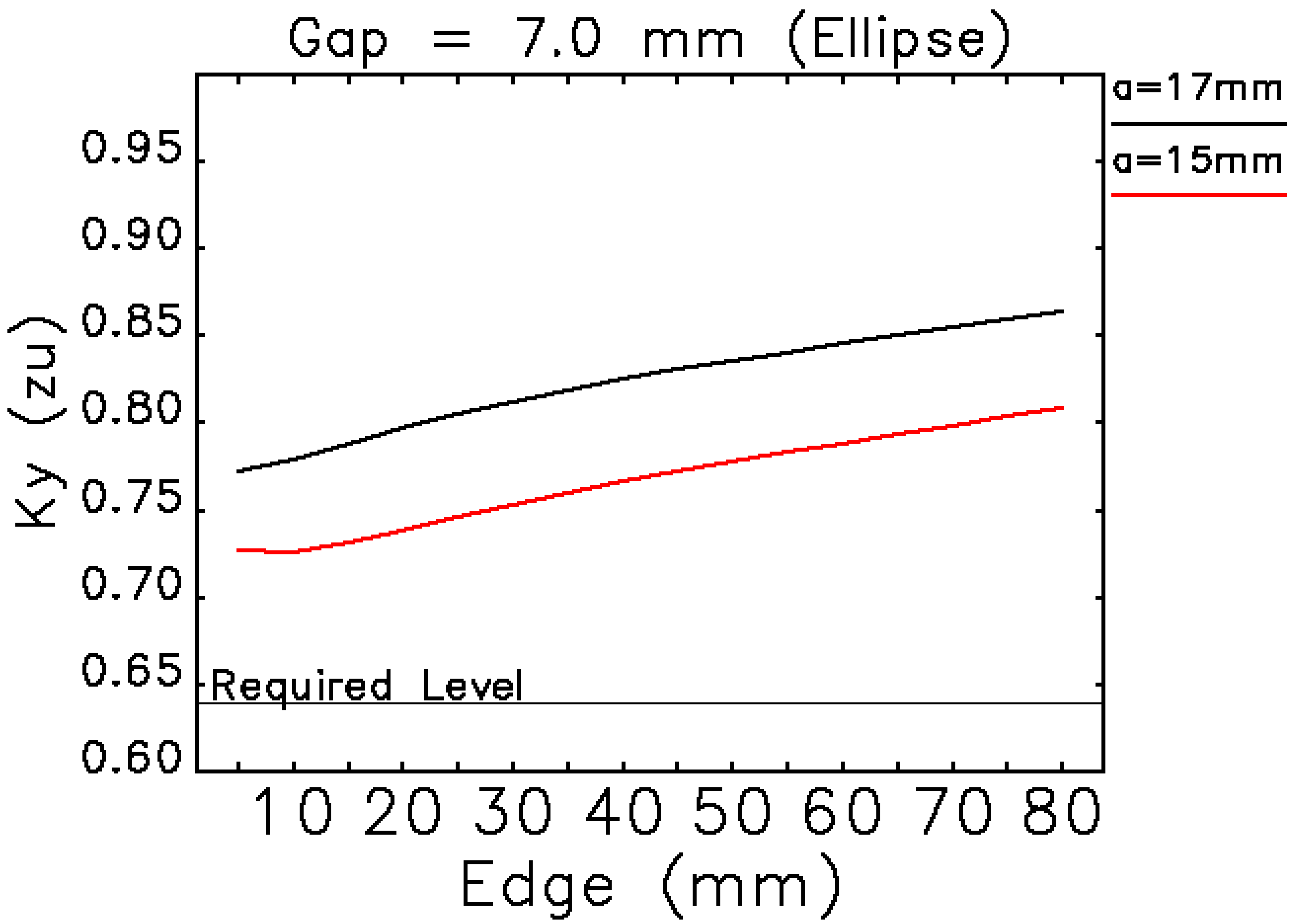
ID Chamber: Full Gap=7.4mm (Half Width=18mm)



ID Chamber: Full Gap=7.2mm (Half Width=18mm)



ID Chamber: Full Gap=7.0mm (Half Width=18mm)



Acceptable Chamber Replacements with New Taper for 16-mA Operation

5.0 (#)	8.0 (#)	7.5R (#)	7.4	7.2	7.0	Total Impe	Imax (mA)	
1	24	9				1	23	2013 Run-2
1	33					0.848	42	NEW a=17mm
1			33			0.949	28	NEW a=17mm
1				33		0.989	24	NEW a=17mm
1					33	1.034	20	NEW a=17mm

Overview of Impedance

- Definition
  - Wake potential
  - Impedance
- Collective Effect: Beam Dynamics
  - Longitudinal ➔ Bunch Lengthening
  - Horizontal ➔ Saw-Tooth Instability
  - Vertical ➔ Single Bunch Current Limit
- ID Chamber Optimization
- RF Heating
  - S37 Spool Piece Chamber
  - SCU0 Bellow Liner
  - SPX Flange Gap
- Summary

Summary

- Impedance is the source of collective effect and rf heating
- Single bunch current limit is determined by vertical impedance
  - Minimize the ID impedance and maximize the sextupole strength ➔ close to the limit
  - Impedance control is only way to keep 16 mA for APS-Upgrade
- ID Chamber Optimization
  - We considered gap, width, length, taper transition for optimization
  - We found that the taper with narrow aperture on the APS chamber side significantly reduce the impedance

Summary (2)

- Result of Using Optimized ID Chamber
  - We can replace each 8-mm gap chamber with NEW 7.3-mm gap chamber
  - We can replace each 7.5-mm (Racetrack Chamber) with NEW 7.0-mm gap chamber
  - We can replace 9x7.5-mm (Racetrack) and 24x8-mm gap chambers with NEW 33x7.2-mm chambers
  - The long taper used for LSSs can be replaced by 20-cm NEW transition (if the 5-mm gap chamber will be replaced by NEW chamber simultaneously)

Recommendation

- ID Chamber
  - Use Elliptic Profile
  - Use Half Width 18 mm (or less)
- Transition
  - Use Edge Length 50 mm
  - Use Edge Aperure 17 mm (or less)