High Current Effects at NSLS-II

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for
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Outline and Scope

- Scope of this talk
- Motivation
- Touschek lifetime – new regime
- IBS – results and questions
- Impedance budget (ID chambers)
- The rest & status review
- Summary and conclusions

Parameter Goals for NSLS-II

I = 500 mA (0.5 mA/bunch)

$\varepsilon_x = 0.5\text{-}1$ nm

$\varepsilon_y = 1$ Angstrom/4π

$\delta E/E = 0.1$ %

Lifetime & Collective Effects

Become harder with higher brightness

- ▪small bunch in all 6D
- ▪high current
- ▪many small gap IDs

⇨

Lower lifetime & instability thresholds

Baseline for NSLS-II:
1.5 GHz SC harmonic cav.

Known solutions — NSLS-II

- Topoff injection (lifetime => radiation) √
- Harmonic RF √
- Z(ω) minimization (HOM-damped RF, BB minimization,…) √
- Multi-bunch feedback systems √

Challenges

- need $|Z/n| < 0.5\ \Omega$ for MW threshold in multi-bunch
- TMCI due to resistive wall from small gap IDs

Single bunch instabilities become most challenging esp. at medium energy

Lifetime Limiting Mechanisms

- Quantum – not a problem
- Gas – Elastic

  Vertical acceptance due to MGUs (gap = 2b = 5mm, L = 5m) is A ~ 1 μm-rad

$$\frac{1}{\tau_{scat}} = \frac{4r_e^2 Z^2 \pi n c}{2\gamma^2}\left[\frac{\langle\beta_x\rangle\beta_{x,max}}{a^2} + \frac{\langle\beta_y\rangle\beta_{y,max}}{b^2}\right] \Rightarrow \tau_{scat} \approx 24 \text{ hours}$$

1/A

@1 nTorr N_2

- Gas – Bremsstrahlung

$$\frac{1}{\tau_{brem}} = \frac{16 r_e^2 Z^2 n c}{411} \ln\left[\frac{183}{Z^{1/3}}\right]\left[-\ln\varepsilon_{acc} - \frac{5}{8}\right] \Rightarrow \tau_{brem} \approx 72 \text{ hours } @ 3\%\ \varepsilon_{acc}$$

Gas contributions to lifetime are small
It's now all about Touschek

Touschek Lifetime Basics

- For flat and transversely non-relativistic beams (works well for NSLS-II)

$$\frac{1}{\tau_{tous\_1/2}} = \frac{\sqrt{\pi}\, r_e^2 c\, N_b}{\gamma^3} \frac{C(\zeta)}{\sigma'_x V \varepsilon_{acc}^2}$$

Needs averaging over the ring

$$\zeta = [\varepsilon_{acc} / \gamma \sigma'_x]^2$$

Acceptance ε_{acc} is likely lattice limited

$$V = 8\pi^{3/2} \sigma_x \sigma_y \sigma_z$$

- Decay is non-exponential, but is assumed linear for frequent topoff

$$N_b(t) = \frac{N_b(0)}{1 + t/\tau_{tous\_1/2}} \Longrightarrow \tau_{total} = 1/(\tau_{gas}^{-1} + \tau_{brem}^{-1} + \tau_{tous\_1/2}^{-1})$$

- Energy spread dependence (through dispersion) is typically weak
- Touschek is peak current effect, i.e. $\tau_{tous\_1/2} \sim \sigma_z/N_b$

Touschek Scaling with Emittance –New Regime

$$\frac{1}{\tau_{tous\_1/2}} = \frac{\sqrt{\pi}\, r_e^2 c N_b C(\zeta)}{\gamma^3 \sigma_x' V \varepsilon_{acc}^2} = \frac{\sqrt{\pi}\, r_e^2 c N_b}{\gamma \varepsilon_{acc}^4} \frac{\sigma_x'}{V} D(\zeta)$$

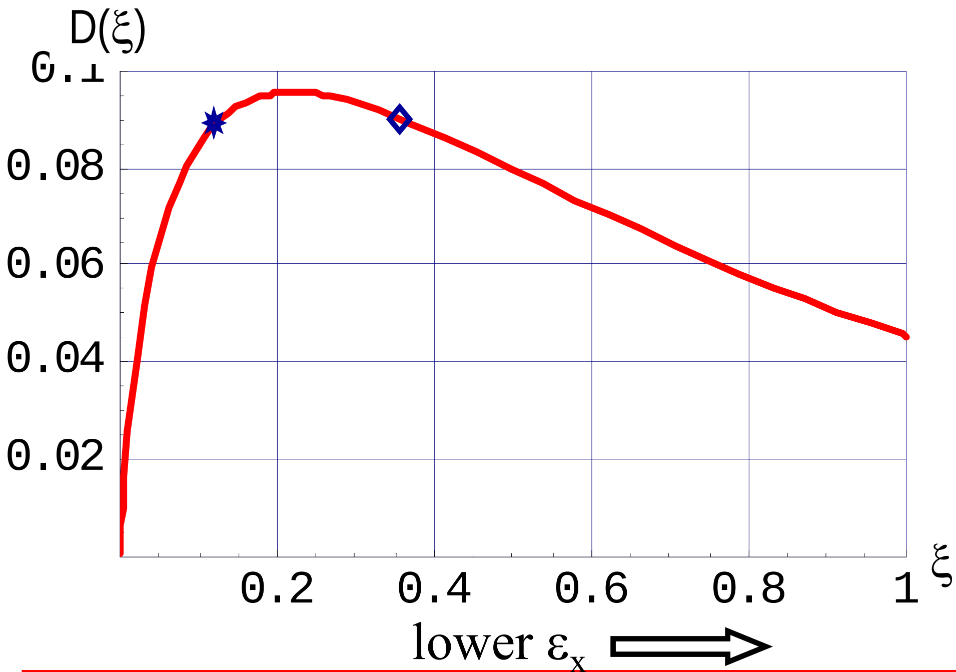
Roughly ε_x independent, for fixed ε_y

$$D(\zeta) = \zeta C(\zeta)$$

Similar to Le Duff

$$\zeta = [\varepsilon_{acc} / \gamma \sigma_x']^2 \approx \frac{\varepsilon_{acc}^2}{\gamma^2} \frac{\beta_x}{\varepsilon_x}$$

Ignores dispersion



β_x=7.2m, ε_{acc} = 3%

✸ ζ=0.13 @ ε_x=1. 4 nm

◇ ζ=0.38 @ ε_x=0.5 nm

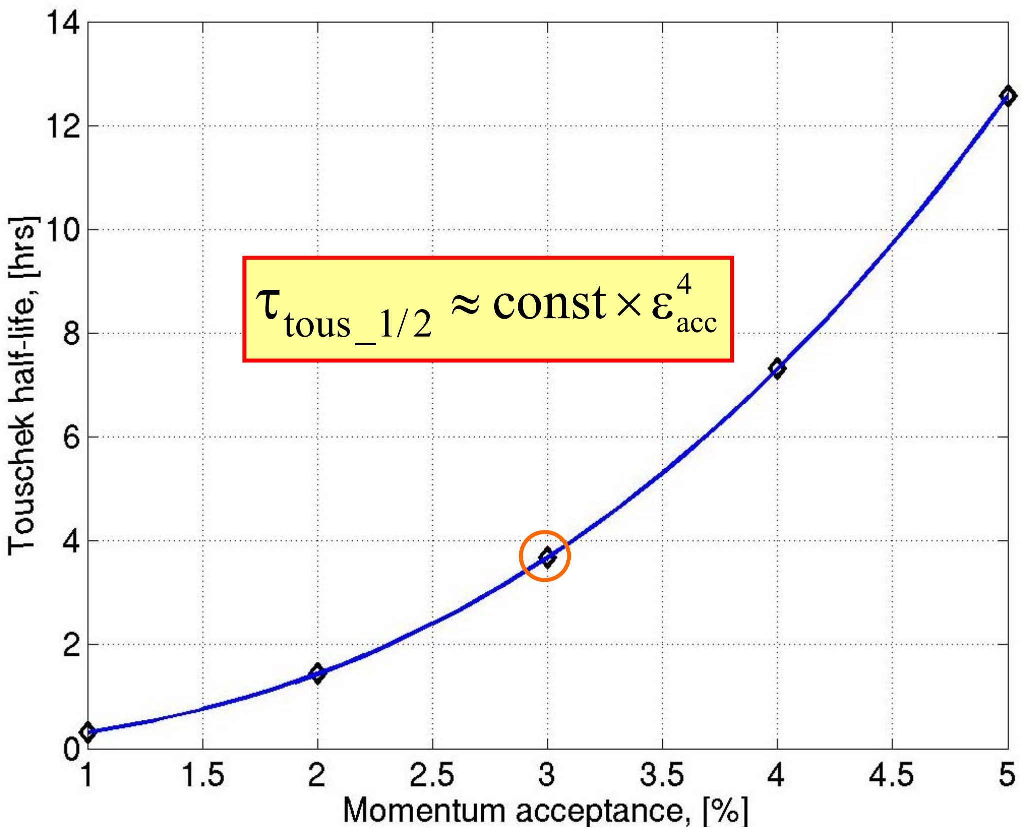
Lattice-averaged rates (σ_z=4 mm ε_{acc} =3%)

τ_{tous}=4 hours @ ε_x=1. 4nm

τ_{tous}=4 hours @ ε_x=0.5nm

For ε_x~1-nm @ 3 GeV Touschek lifetime reaches minimum, and should grow at lower ε_x. Experimental confirmation, anybody?

Touschek Lifetime vs. Acceptance and Total Lifetime



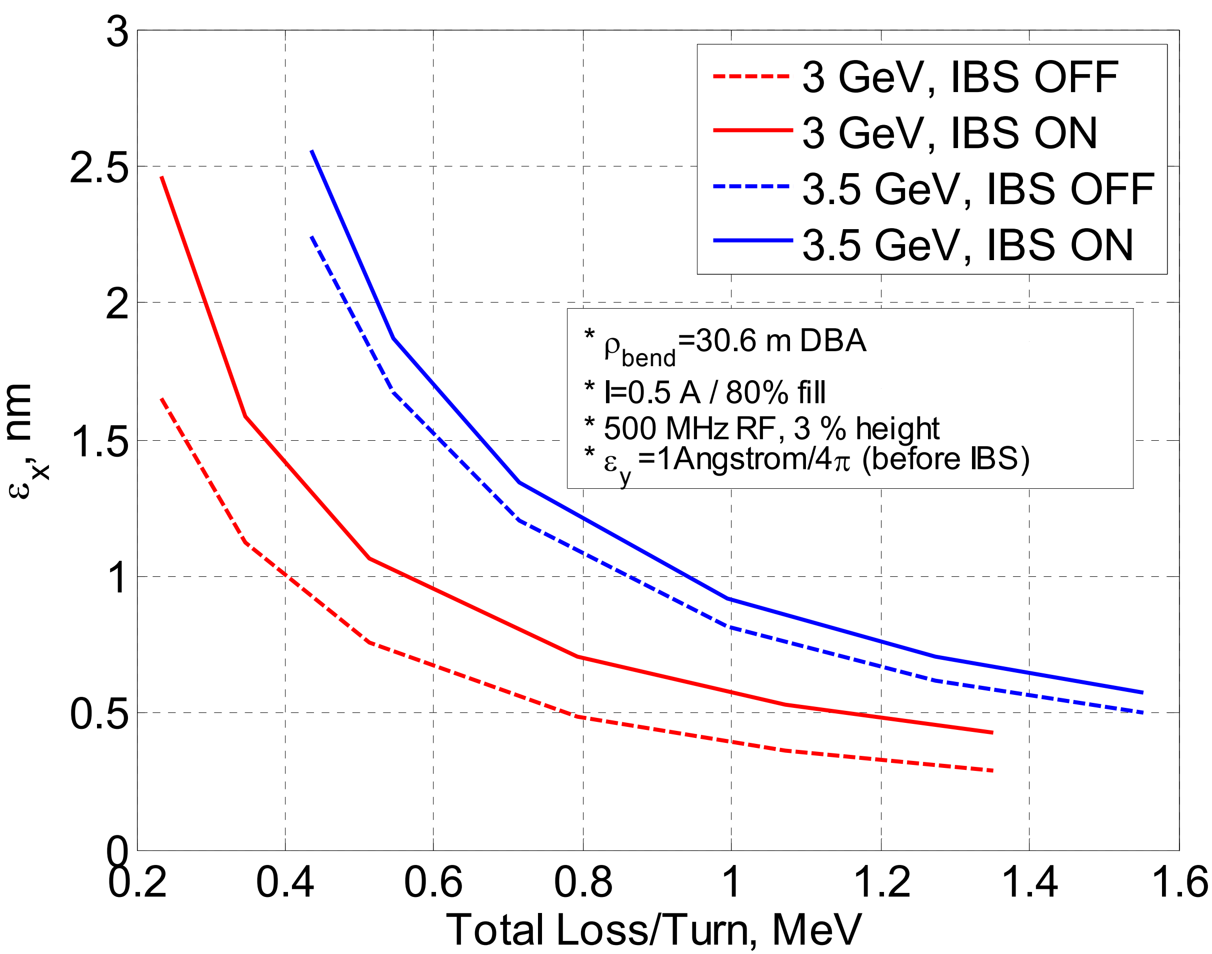
- Most calcs. for bare lattice w/o apertures. Effect of IDs included "by hand" in ZAP
- ZAP, SAD & MAD results agree
- Work in progress to consider other effects, i.e. lattice nonlinearities, α_2, effects of IDs, errors & coupling correction, bunch lengthening, etc.
- Lattice-dependent momentum aperture being done by 6D tracking (Elegant and TRACY2)

$$\tau_{tous\_1/2} \approx 4 \text{ hours @ 3\% RF acc.}$$

$$\tau_{total} = 1/(\tau_{gas}^{-1} + \tau_{brem}^{-1} + \tau_{tous\_1/2}^{-1}) \approx 3\,\text{hours}$$

Multiple Intra-Beam Scattering (IBS)

ZAP Calculations for I=500 mA



- ε_x, $\delta E/E$, τ_{rad}, scaled "by hand" for radiation loss
- Bare lattice case agrees with SAD and Bane's apprx.
- Emittance blow-up: < 50% @ 3 GeV, < 15% @ 3.5 GeV
- Smaller ε_x offset by shorter τ_{rad}
- Will re-run with 3D code SAD with IDs and vertical η

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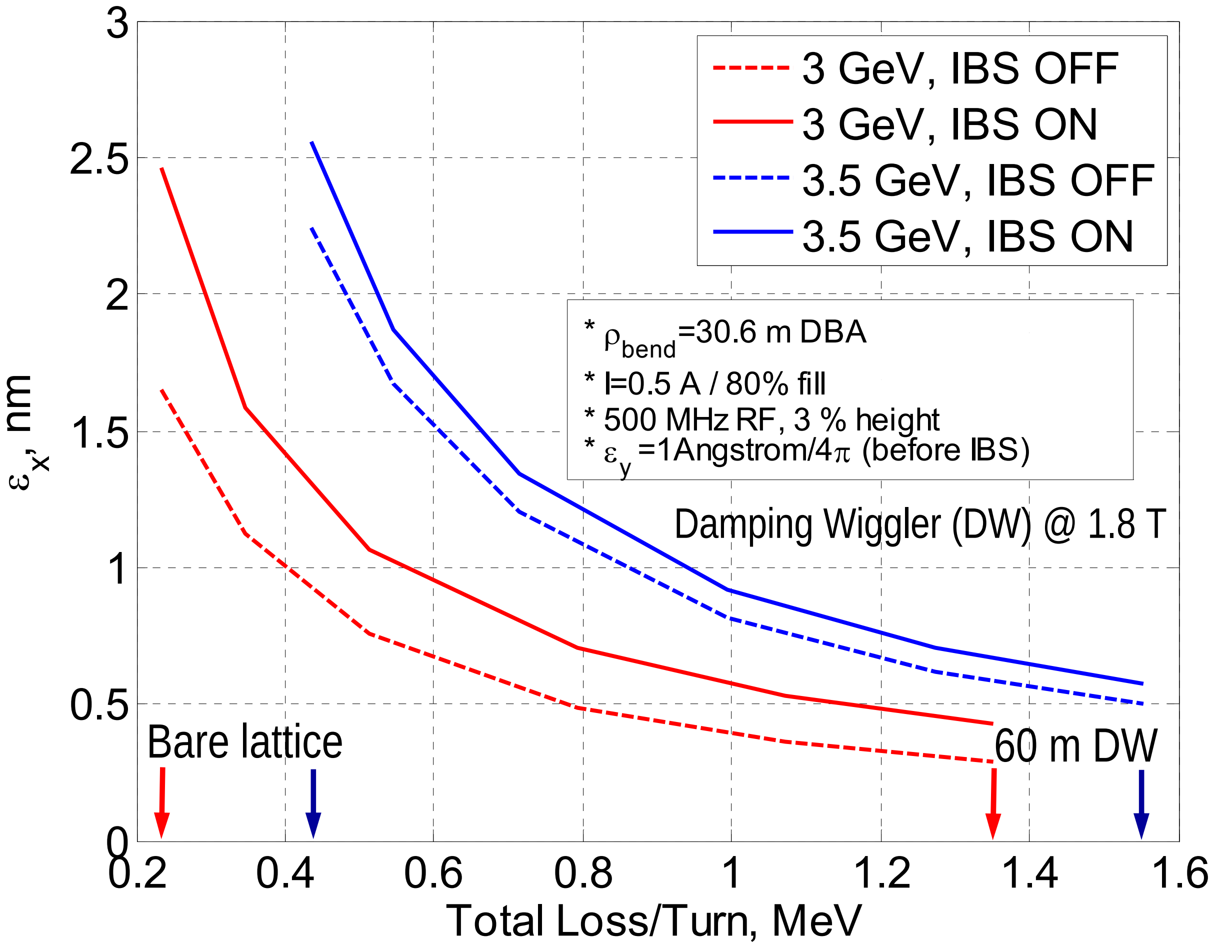

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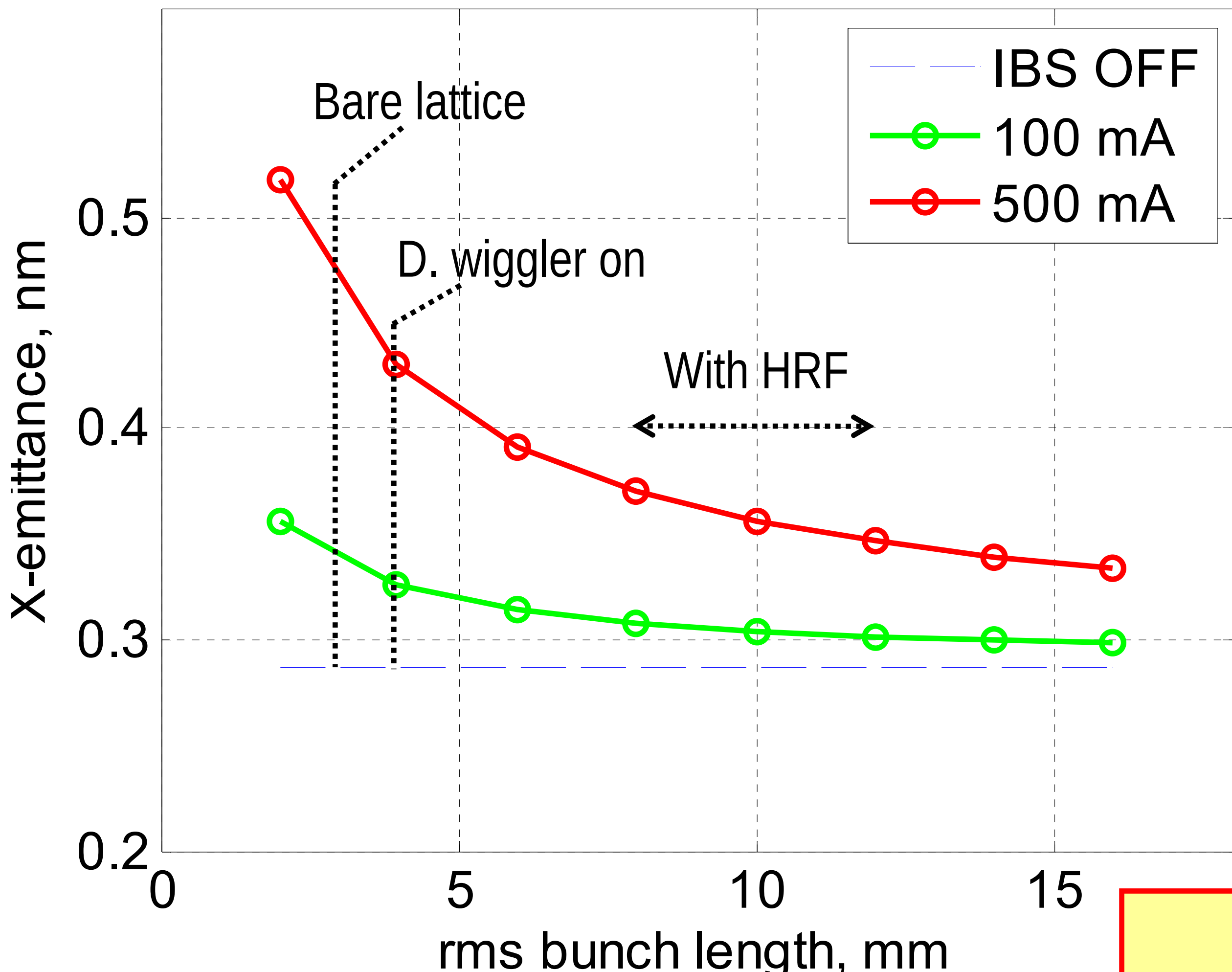
IBS with Bunch Lengthening

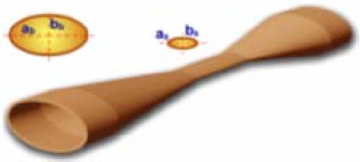
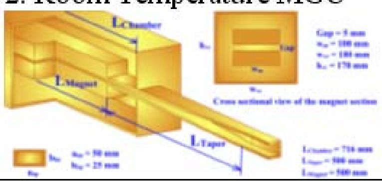
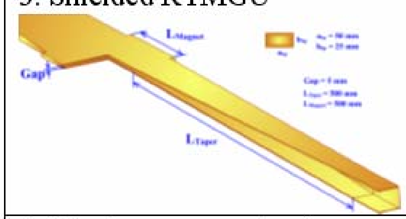
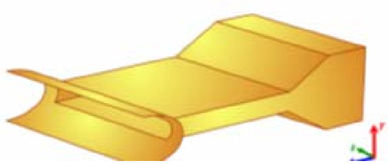


- ZAP calcs shown @ 1.4 MV loss/Trn
- Harmonic RF (HRF) x2-3 in σ_z
- Ignore PWD
- IBS is small
- Will re-run with 3D code SAD with IDs and vertical η

With realistic bunch lengthening IBS effect is small for NSLS-II

NSLS-II Impedance Budget

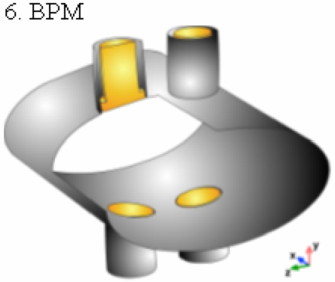
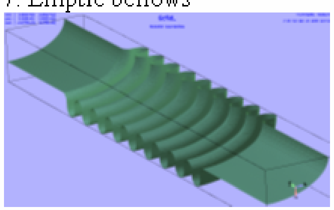
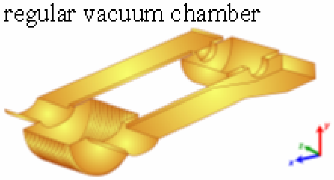
Table 1: Budget impedance of the NSLS-II ring components

Components	$ImZ_y(\omega\to 0)$, Ω/m	$ImZ_x(\omega\to 0)$, Ω/m	$\frac{ImZ_\parallel(\omega)}{\omega}\omega_0 Q_{BB}$, Ω	k_y, V/pC/m	k_x, V/pC/m	k_{loss}, V/pC	Estimated number of components
1. Tapered elliptic vacuum chamber 	**$3\cdot 10^3$ (75 μm)**	**965 (100 μm)**	$30\cdot 10^{-6}$ (100 μm)	**86 (75 μm)**	**30**	**$0.311\cdot 10^{-3}$**	**10**
2. Room Temperature MGU 	**$58\cdot 10^3$ (500μm)**	**$3.9\cdot 10^3$**	$130\cdot 10^{-6}$ (500 μm)	**505**	**112**		**10**
3. Shielded RTMGU 	$22\cdot 10^3$ (500μm) $14\cdot 10^3$ (120μm)	$3\cdot 10^3$ (500μm) $1.5\cdot 10^3$ (120μm)	$127\cdot 10^{-6}$ (500μm) $49\cdot 10^{-6}$ (120μm)	245	73		
4. Dipole vacuum chamber 	**1.1**	**17.6**	$0.073\cdot 10^{-6}$	**$4.6\cdot 10^{-2}$**	**0.68**	**$0.240\cdot 10^{-3}$**	**72**

GDFIDL Results

Alexei Blednykh

NSLS-II Impedance Budget (Cont.)

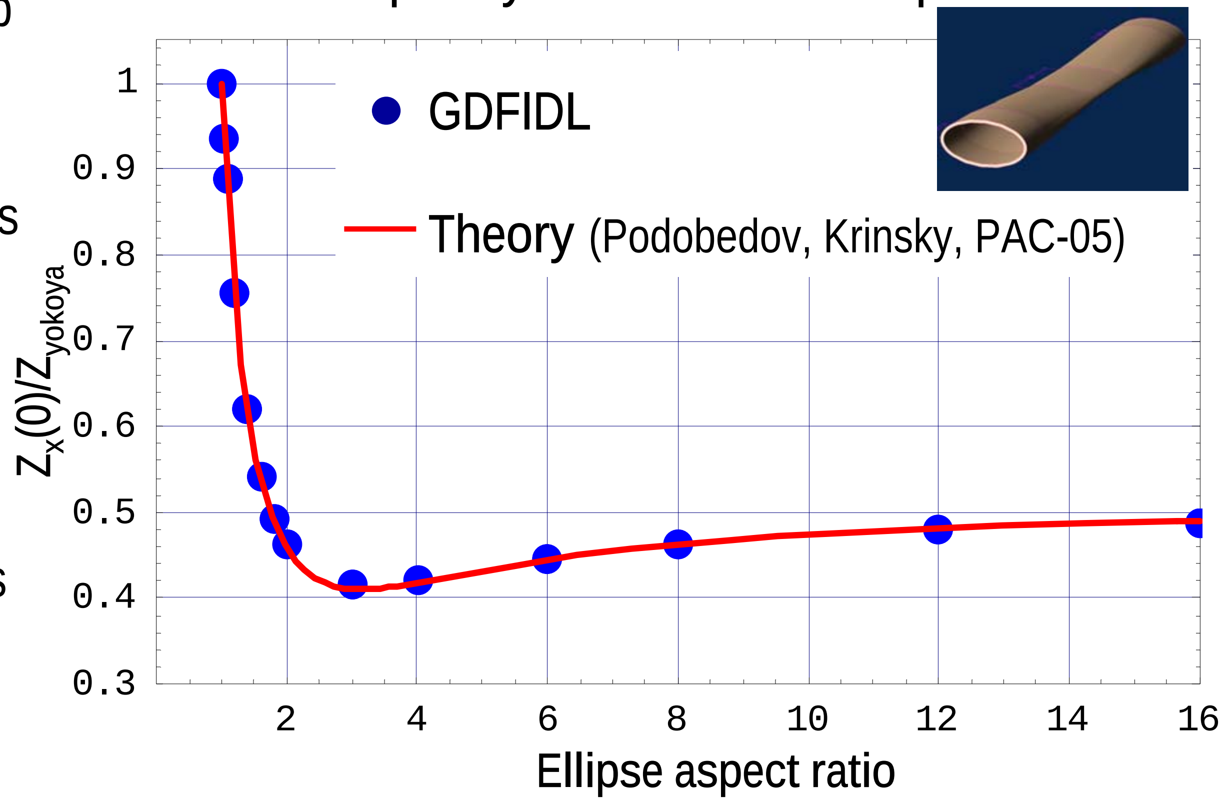
Components	$ImZ_y(\omega\to0)$, Ω/m	$ImZ_x(\omega\to0)$, Ω/m	$\frac{ImZ_\parallel(\omega)}{\omega}\omega_0 Q_{BB}$ Ω	k_y, V/pC/m	k_x, V/pC/m	k_{loss}, V/pC	Estimated number of components
5. Photons absorber 	1.1	17.2	$0.037\cdot10^{-6}$	$2.9\cdot10^{-2}$	0.43	$0.139\cdot10^{-3}$	120
6. BPM 	54	42.1		1.1	0.87	$19.971\cdot10^{-3}$	300
7. Elliptic bellows 	$8.9\cdot10^{3}$	$4.6\cdot10^{3}$		126.2	74.64		
8. Transition from absorber to regular vacuum chamber 	$9.8\cdot10^{3}$	??	$1140\cdot10^{-6}$ (bellows)	55	10.4		48

Alexei Blednykh

Geometric Impedance of Small Gap ID Chambers

- NSLS-II will have ~20 small gap ID chambers of 5mm full gap
- Many LS reported lower TMCI threshold with increased # of IDs
- Existing analytical solution (round x-section or very flat) don't directly apply to NSLS-II
- Obtained analytical solution for $Z_{\perp}(0)$ for gradual confocal tapers
- Confirmed by GDFIDL

Low Frequency Horizontal m=1 Impedance



Impedance of NSLS-**II** ID tapers is <10 kΩ/m, and is less than Res. Wall. Need to understand higher measured numbers from some other LS.

TMCI due to MGU Resistive Wall

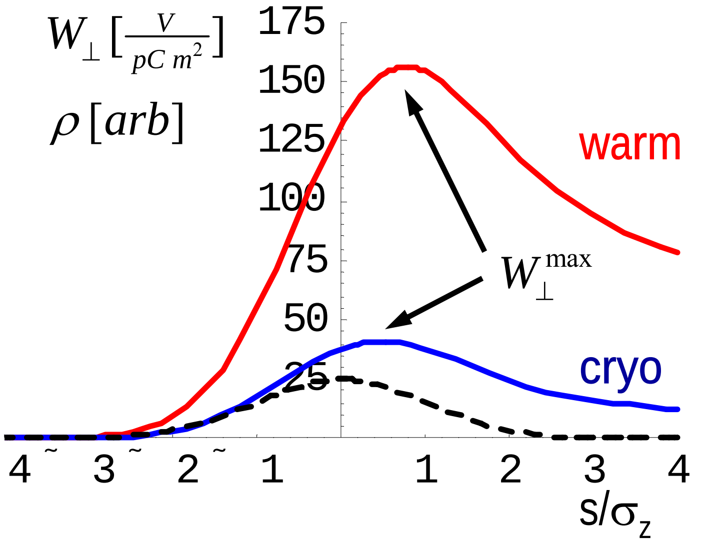
- TMCI driven by small undulator gaps is a concern: $Z_\perp(\omega)/L \sim a^{-3}$
- Threshold: $\Delta\nu_y = \frac{I_{th} W_\perp^{max} \beta_y^* L}{2\omega_{rev} E/e} = \nu_s$
- NSLS-II undulators:

  assume 100 m of *Cu* pipe 5 mm Ø

  $I_{th} \approx 1\, mA/bunch \quad warm$

  $I_{th} \approx 4\, mA/bunch \quad cryo$

  β_y*=5 m, σ_z=3.3 mm, ν_s=0.005



- Also confirmed by simulations (MOSES, tracking)
- This does not change significantly with harmonic RF

At operating value of 0.5 mA/bunch, we are below TMCI threshold

Other Issues Studied

- RF cavity and resistive wall driven coupled bunch instabilities
- Damping of transverse couple bunch inst. with positive chromaticity
- Beam dynamics with harmonic RF
- TMCI particle tracking with harmonic RF included
- Micro-Wave instability (Tracking, Oide-Yokoya method, Fokker-Plank solver)
- Coherent synchrotron radiation instability
- Resistive heat of (SC) undulator chambers

None of these presently appear showstoppers for NSLS-II design

Summary and Conclusions

- NSLS-II is optimized for nominal multi-bunch operation, and uses many known solutions to ease high current effects
- NSLS-II single bunch and high current goals appear to be achievable
- Touschek lifetime of a few hours is in the new regime, experimental confirmation would be welcome. Tracking (Elegant, TRACY2) in progress for momentum acceptance, loss distribution, etc.
- (Multiple) IBS appears insignificant
- Transverse couple bunch instability may require feedback
- Impedance budget work is ongoing. Results will feed into Elegant and other codes, as well as will be re-evaluated analytically
- Would like collaboration with other facilities on understanding measurement results due to small gap ID chambers

EXTRA

Concluding Remarks

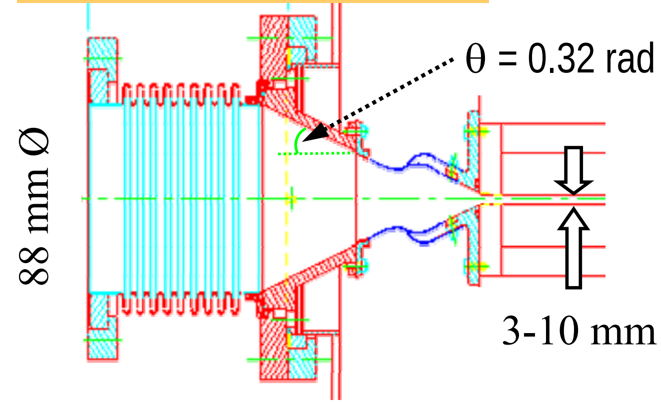
- Single bunch and average current goals appear to be achievable
- Transverse coupled bunch instability may require feedback
- We are facing a theoretical puzzle in regard to microwave instability threshold, which we are working to resolve. However, the threshold is above the 0.4ma required.
- At the moment we are estimating instability thresholds based on the impedances observed at ESRF and APS.
- We are calculating the NSLS-II impedance budget. Once this is done, we will estimate the instability thresholds using the calculated impedance.
- Realistic calculation of the Touschek lifetime is of critical importance. Work on this problem is underway using both TRACY2 and ELEGANT.

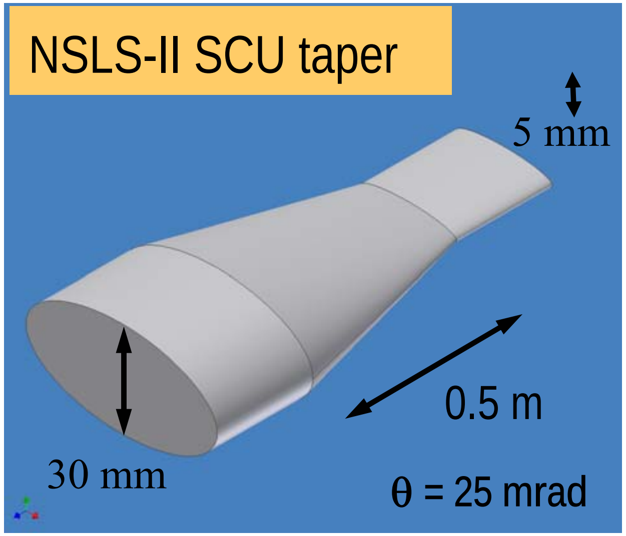
MGU-driven Transverse Single Bunch Instabilities

- TMCI and/or TMW instabilities are observed at many synchrotrons and may limit single bunch current
- Generally both the geometric (transitions) and resistive wall wakes contribute
- For typical short, warm, MGUs the geometric wake exceeds the resistive wall

Geometric wake will be made small with shallow taper and optimal transition design to minimize the geometric contribution to the impedance and avoid the TMCI instability

NSLS-1 MGU taper





Resistive Wall for Normal and Anomalous Skin Effect Regimes

- (Warm) Permanent Magnet MGUs (Cu @ 300 K)

(l - conducting e^- mean free path
δ_{sk} - classical skin depth)

Normal Skin Effect: $l/\delta_{sk} << 1 \quad \Longrightarrow \quad Z_{s\_normal}(\omega) = \sqrt{\frac{\omega\mu}{2\sigma_{cond}}}(1-i)$

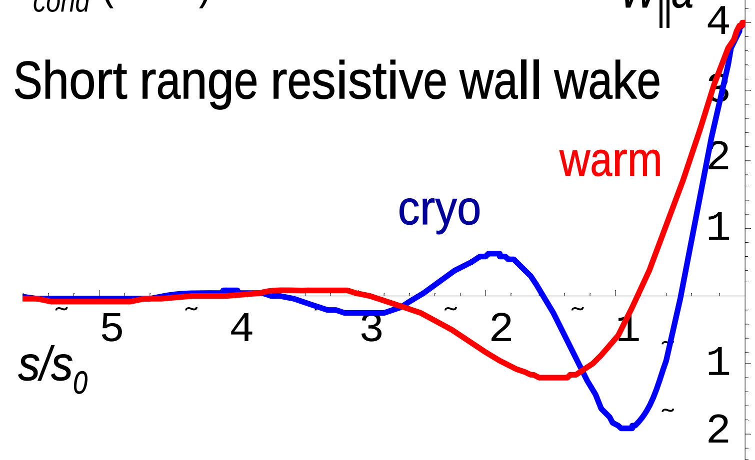
- (Cold) Superconducting SCUs (Cu @ 4.2 K)

Extreme Anomalous Skin Effect:

$$l/\delta_{sk} >> 1 \quad \Longrightarrow \quad Z_{s\_extreme}(\omega) = A\omega^{2/3}(1-i\sqrt{3})$$

with A=0.033 ps$^{5/3}$ V/pC for Cu, independent of σ_{cond} (RRR)

We derived most resistive wall related quantities (short/long range wakes, loss/kick factors, instability thresholds, etc.)



Resistive Wall Heating

- (Warm) Permanent Magnet MGUs (Cu @ 300 K)

$$P/L = 5.6 \times 10^{-5} \frac{I_{av}^2 \lambda_{RF}}{a\ \sigma_z^{3/2}}$$

> P/L ~ 28 W/m (warm Cu), or 140 W for 5 m undulator, easily handled

average current I_{av}	500 mA
rms length σ_z	3.3 mm
RF wavelength λ_{RF}	60 cm
half ID gap a	2.5 mm
off-center error Δ	0.5 mm

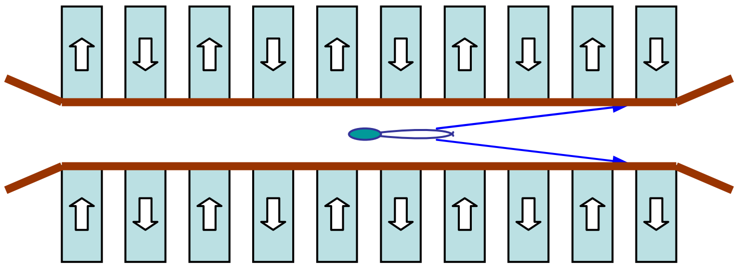
- (Cold) Superconducting SCUs (Cu @ 4.2 K)

$$P/L = 4.2 \times 10^{-6} \frac{I_{av}^2 \lambda_{RF}}{a\ \sigma_z^{5/3}}$$

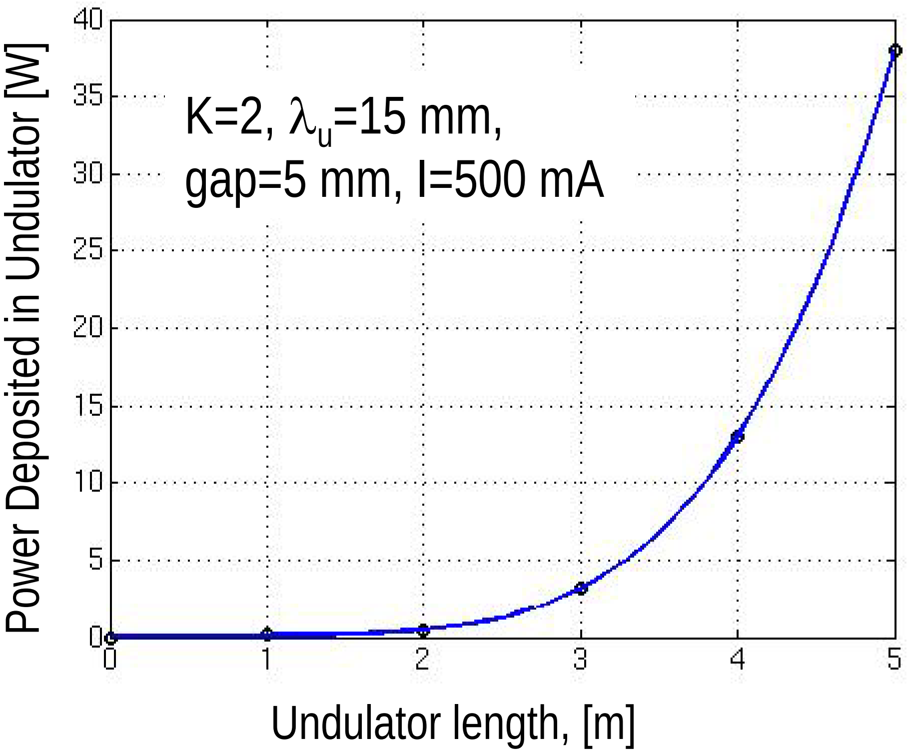
> Conservative Estimate*: P/L ~ 5 W/m (cold Cu), or 25 W for 5 m undulator, exceeds off-the-shelf single cryo-cooler capacities but could be handled by individual refrigerator. Harmonic RF may reduce this a factor of ~ 6.

*Ignore bunch lengthening, ignore chamber ellipticity, allow for Δ by a -> $a - \Delta$, 4/5 RF buckets filled -> +25%

Synchrotron Radiation Heat Load on Undulator



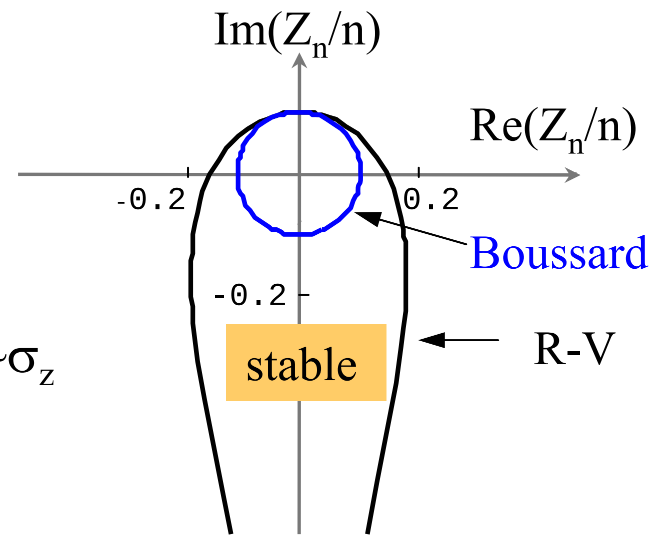
- Undulator radiation has finite opening angle
- Small fraction hits the cold bore
- P ~ 40 W for 5 m undulator



Warm MGU – easily handled
Cold SCU - exceeds off-the-shelf single cryo-cooler capacities but could be handled by individual refrigerator.

Longitudinal Single Bunch Instabilities

- Microwave $\lambda_{inst}/\sigma_z \ll 1$
  - Boussard criterion **$|Z_n/n| <\sim 0.1\ \Omega$** <– low!
  - Lower $|Z_n/n|$ are believed achievable (i.e. ILC DR)
  - However, Boussard criterion is conservative
  - Harmonic RF (and PWD) increases the threshold $\sim\sigma_z$



- Mode-Coupling $\lambda_{inst}/\sigma_z > \sim 1$
  - Scaling NSLS ring $Z(\omega)$ gives $I_{total} > 1$ A
  - Scaling is very simplistic =>$Z(\omega)$ budget is needed
  - Harmonic RF increases the threshold but slower than $\sim\sigma_z$

- Self-stabilize through increase in $\delta E/E$
- Not significantly driven by MGUs

Tight impedance control will be required

Passive Third-harmonic Landau Cavity (1.5 GHz)

Use of a bunch lengthening Landau cavity can increase Touschek lifetime, raise microwave instability threshold and decrease intrabeam scattering.

Initial estimates indicate we can increase bunch length by factor of ~2.5

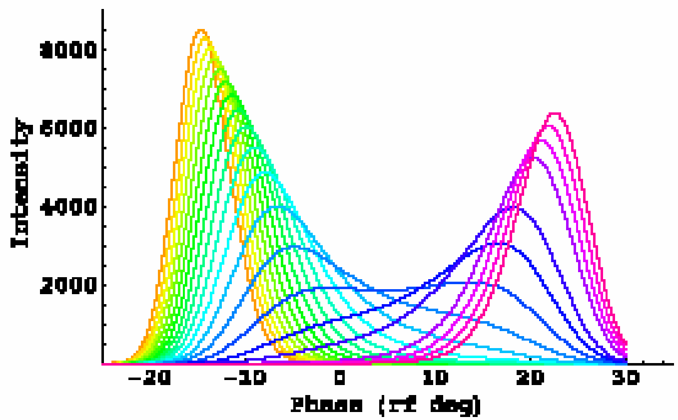


Figure 1: Line densities of bunches uniformly sampled along the length of an 80%-fill bunch train. The leading edge of each bunch is on the right and the progression of leading bunches to trailing bunches is from left to right. Each bunch is normalized to unity with respect to ring azimuthal angle.

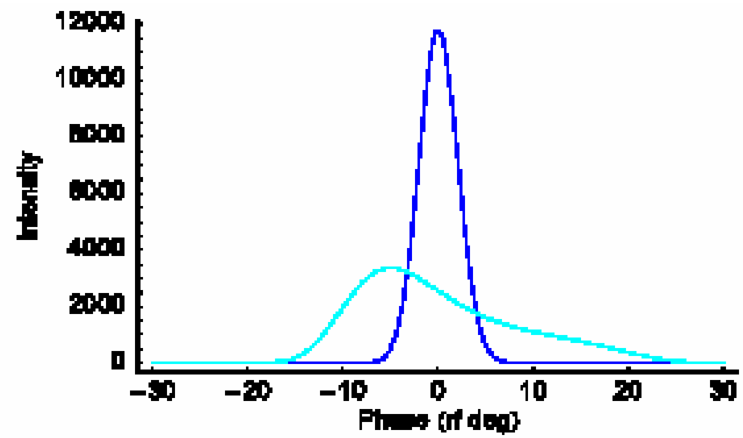


Figure 3: Line densities of unstretched (blue) and stretched (aqua) bunches in a uniform fill.

N. Towne

Geometric Impedance of Axially Symmetric Tapers

- At low frequency shallow taper impedance is imaginary and small

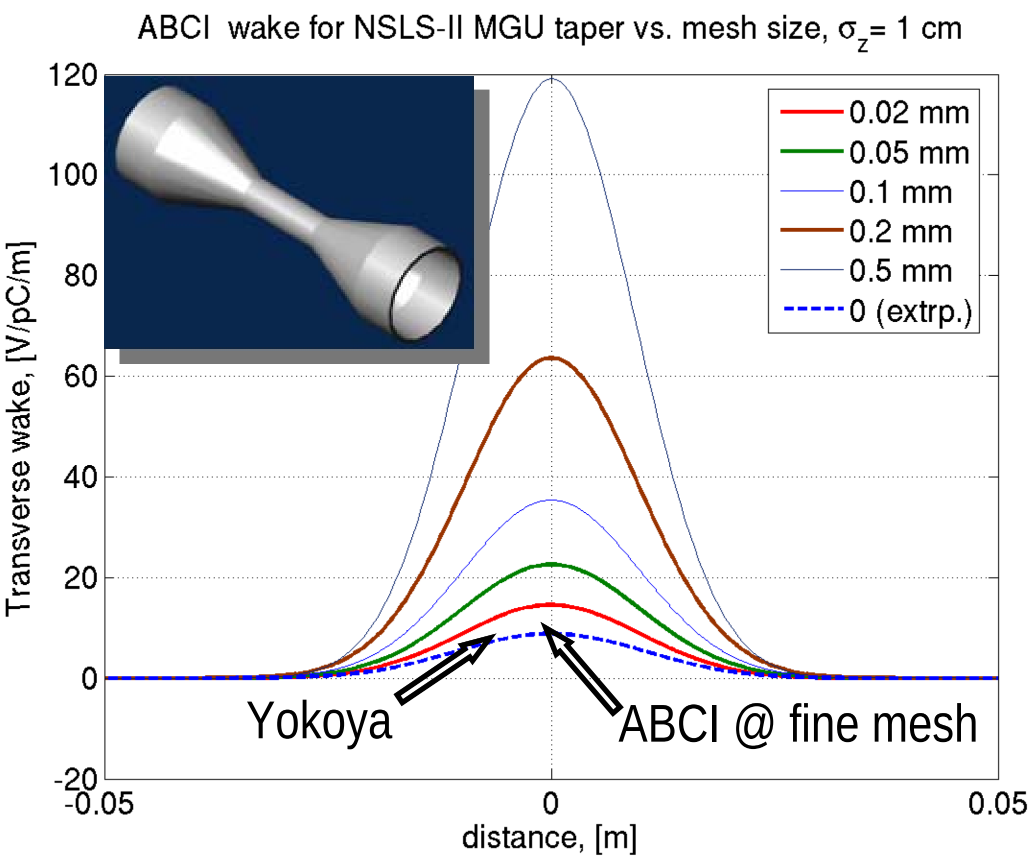
$$\mathbf{Z(\omega) \sim} \boldsymbol{i}\,\theta, \qquad (\sigma_z >> a\,\theta)$$

- Analytical expressions exist for impedance in this (Yokoya) regime

NSLS-II 0.5 m (θ=25 mrad) MGU tapers result in sufficiently low impedance to avoid MW and TMCI instabilities

$|Z_{||}/n|=0.2\ m\Omega \qquad Z_{\perp}=1\ k\Omega/m$

Estimates confirmed by simulation

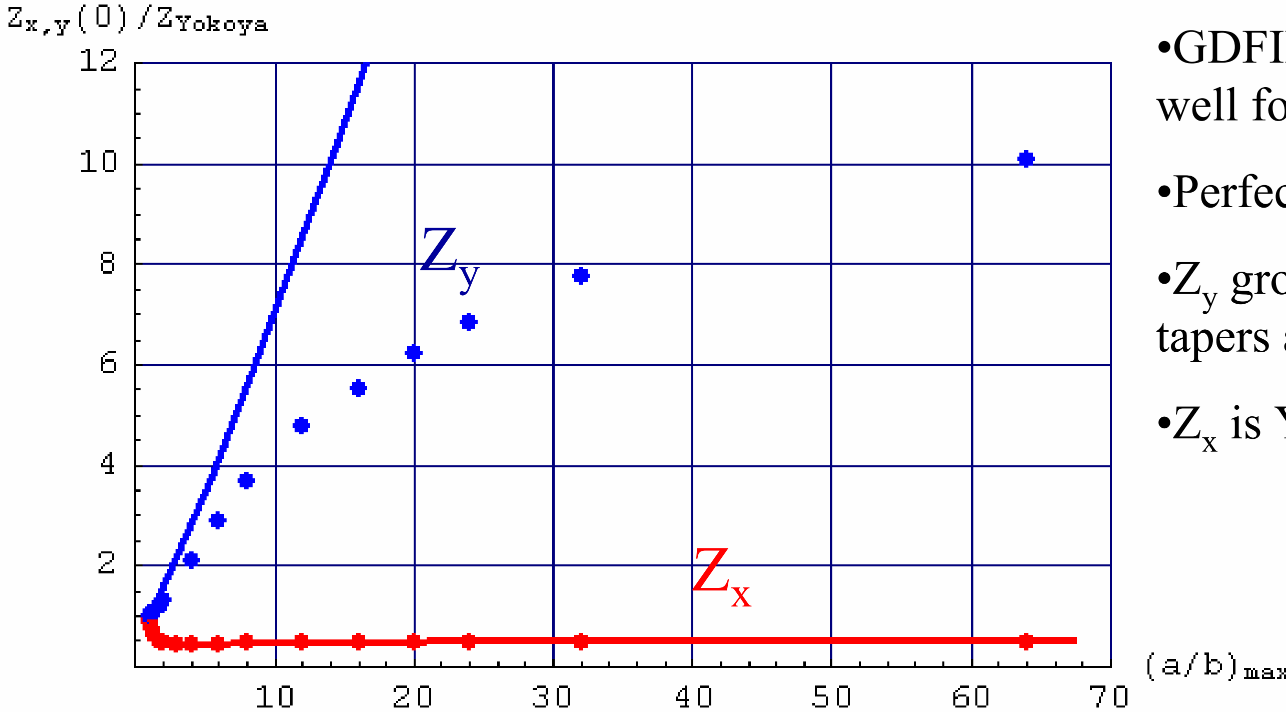


Also considered elliptical chambers

Z_y grows factor of ~6 but still low enough for TMCI

New Results (Convex Structure)

First order PT $Z_{x,y}$ and New GDFIDL Results



- GDFIDL & 1st order PT agree well for weakly elliptical case Z_y
- Perfect agreement for Z_x
- Z_y growth saturates for very flat tapers at ~10*Yokoya
- Z_x is Yokoya/2 for flat tapers

- PAC-05 Conjecture: PT clearly breaks down for flat structures <= Not for Z_x

  Example: Z_x should be 0 (not 0.5) for a flat structure <= wrong

- To confirm needed to extend the PT to higher orders