Design of Damping Ring

Kikuchi, M., MAC2011, 7 Feb ’11

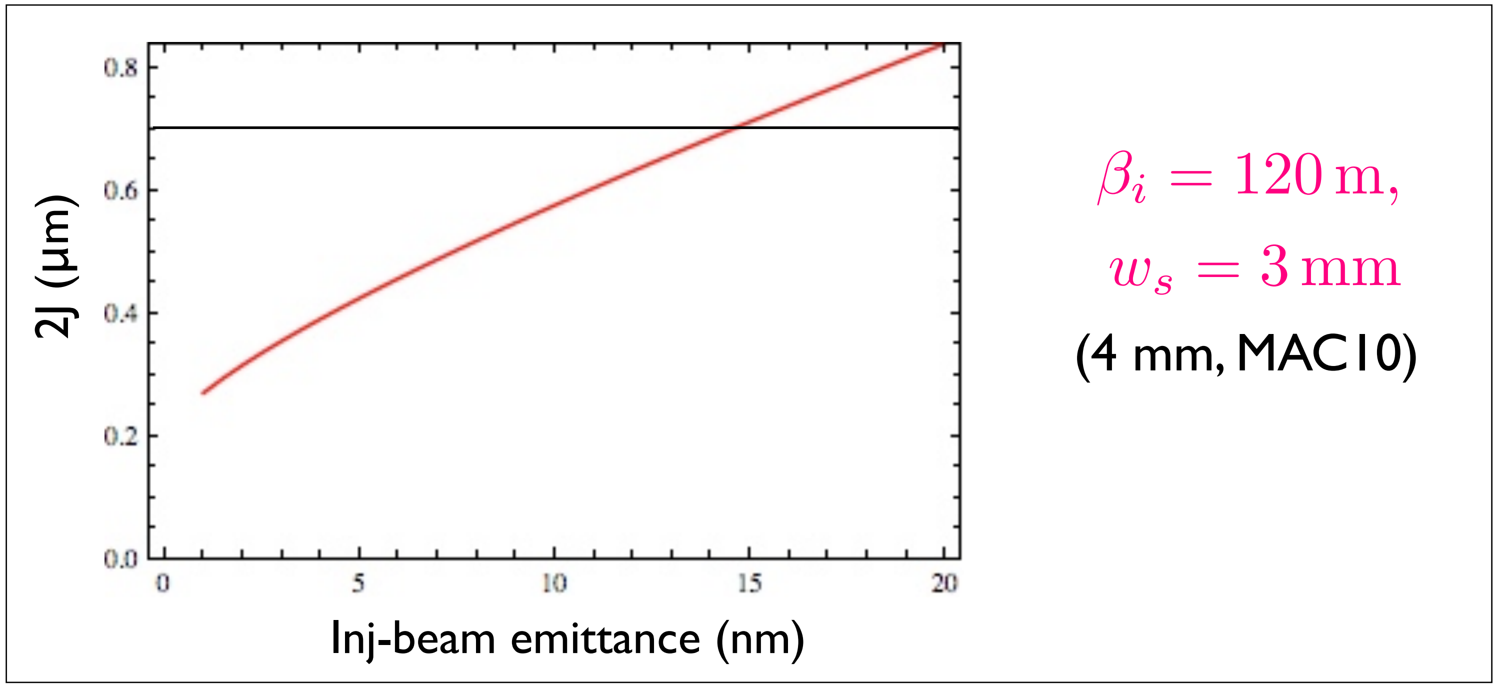
Requirements on emittance and intensity

a. Injection aperture of LER

$2J = 0.7\,\mu\mathrm{m}$ (0.5 μm, MAC10)

- Emittance of Injected beam

$\epsilon_i \leq 14.5\,\mathrm{nm}$ (4 nm, MAC10)



$\beta_i = 120\,\mathrm{m}$,

$w_s = 3\,\mathrm{mm}$

(4 mm, MAC10)

b. Lifetime of LER

$\tau \simeq 600\,\mathrm{sec}$

$\dot{I} = I/\tau = 3.6\ \mathrm{A}/600\ \mathrm{sec} = 6\ \mathrm{mA/sec}$

$\dot{Q} = \dot{I}/f_{rev} = 60\ \mathrm{nC/sec} = 2.4\ \mathrm{nC@25\ Hz}$

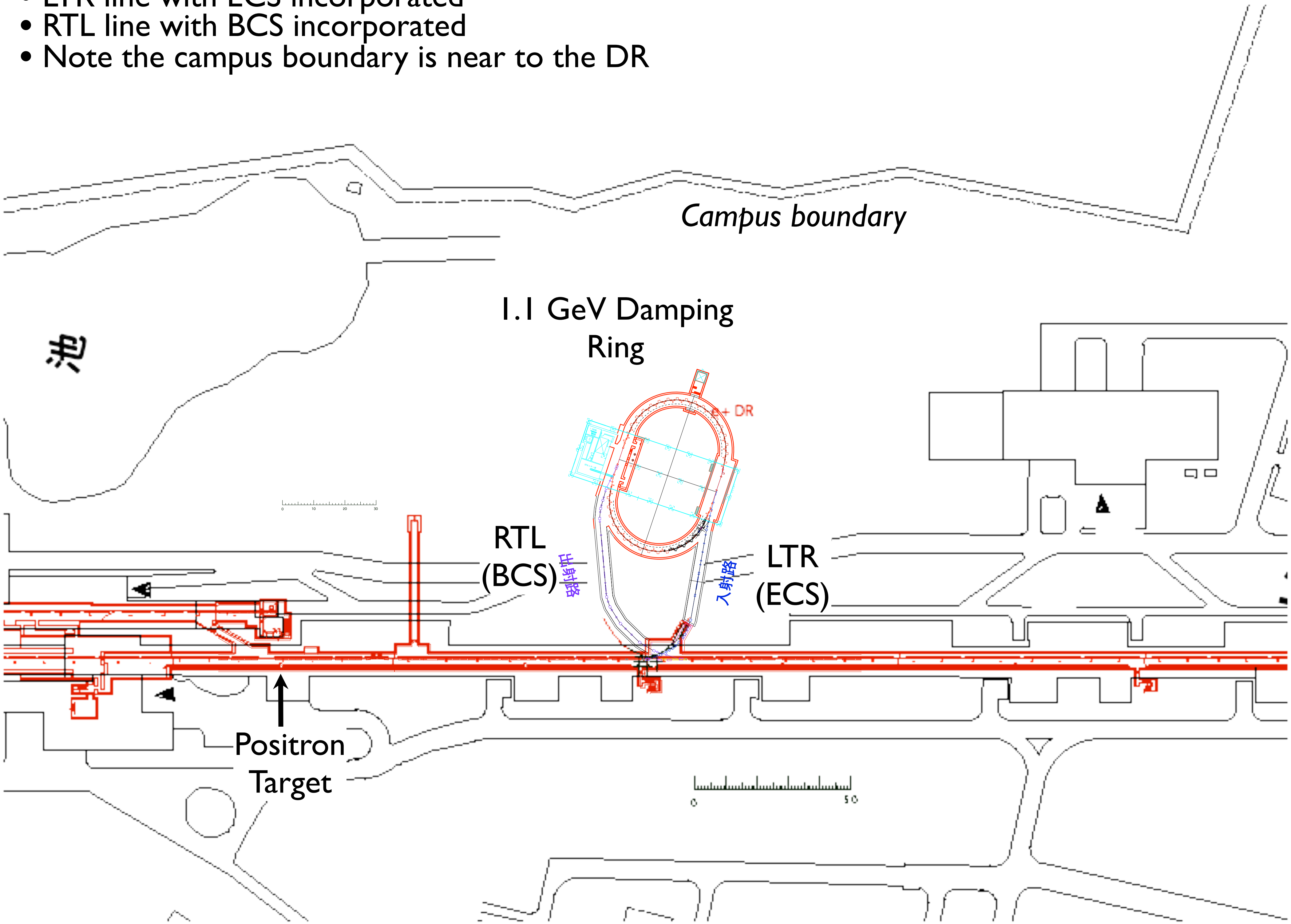
- Intensity of Injected beam

$q \simeq 8\,\mathrm{nC/pulse} = 4\,\mathrm{nC/bunch}$

This corresponds to 30 % injection efficiency

Layout of the System

- Positron target at sector1-4
- Capture + acceleration with L-band+S-band structure
- Extract from Linac at 1.1GeV
- After 2 linac-pulse, re-inject to the Linac
- LTR line with ECS incorporated
- RTL line with BCS incorporated
- Note the campus boundary is near to the DR



Optics

Concept

- Large dynamic aperture
- Shorter damping time with lower bend field

FODO with Reverse Bend

$$\tau = \frac{3T_0}{r_e\gamma^3 J_x I_2} = \frac{3}{2\pi c\, r_e J_x}\frac{\rho}{\gamma^3} C \frac{1-r}{1+|r|}$$
$$= \frac{3}{2\pi c\, r_e J_x}\frac{\rho}{\gamma^3}\left(2\pi\rho + \frac{1-r}{1+|r|}L_1\right)$$

r: Bend ratio $= B1/B2$

(Normal FODO $\longrightarrow$ $r = -1$)

L_1: Total length except bend length

L_1 is effectively reduced by a factor of

$$(1-r)/(1+|r|) = 0.48$$

$$r = 0.35,\ \rho = 2.7\ \mathrm{m},\ L_1 = 100\ \mathrm{m}$$

$$2\pi\rho = 17\ \mathrm{m}$$

- Shorter damping time with lower bend field

$$B = 1.35\ \mathrm{T}$$

Ring Parameters

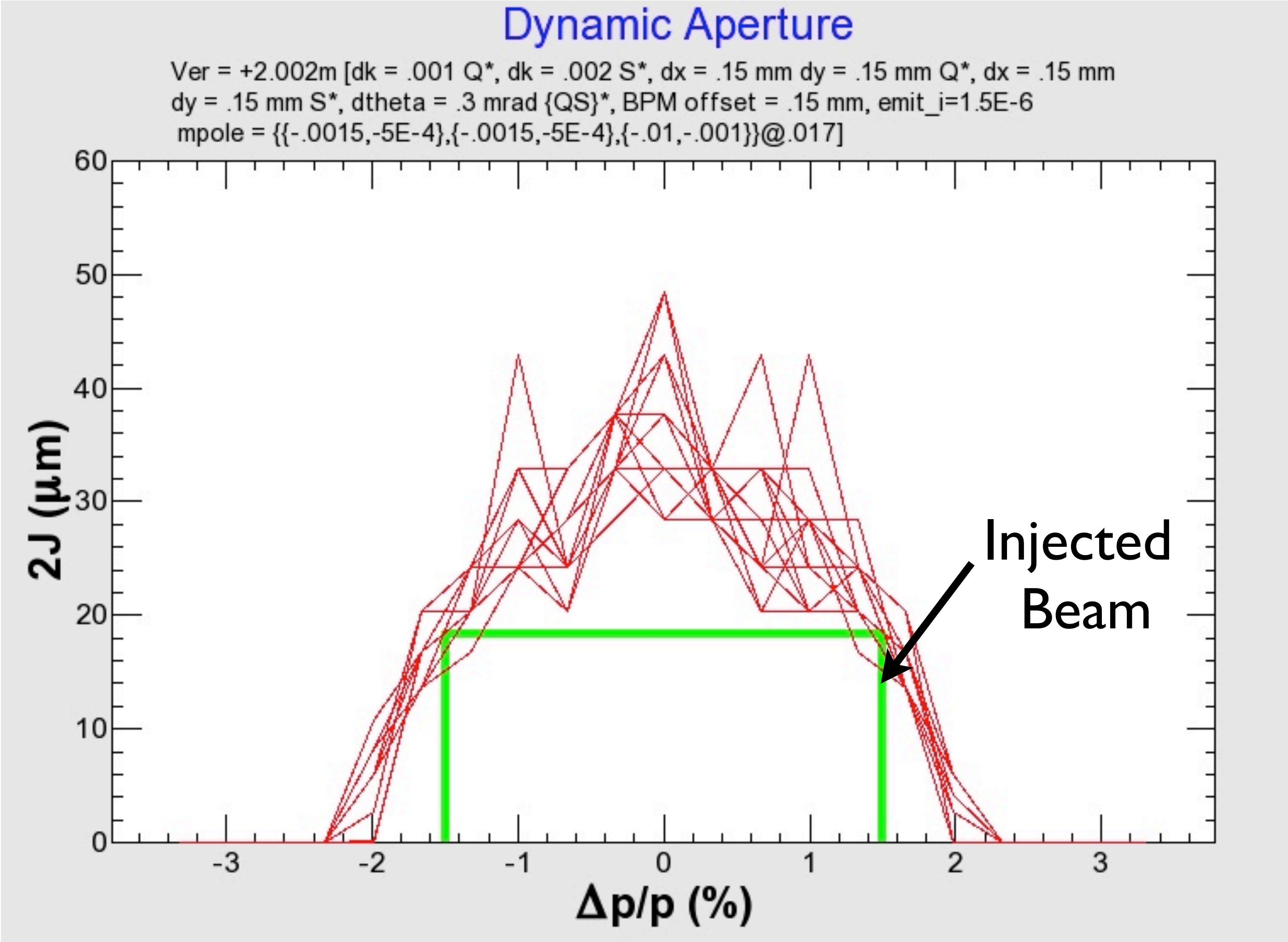
Parameters of the Damping Ring

			MAC10
Energy	1.1	GeV	1.0
No. of bunch trains/ bunches per train	2 / 2		
Circumference	135.5	m	
Maximum stored current*	70.8	mA	
Energy loss per turn	0.091	MV	
Horizontal damping time	10.9	ms	12.7
Injected-beam emittance	1700	nm	2100
Equilibrium emittance(h/v)	41.4 / 2.07	nm	14 / 1.4
Coupling	5	%	10
Emittance at extraction(h/v)	42.5 / 3.15	nm	17.6 / 5.1
Energy band-width of injected beam	± 1.5	%	
Energy spread	0.055	%	
Bunch length	6.5	mm	5.4
Momentum compaction factor	0.0141		0.0019
Number of normal cells	32		
Cavity voltage for 1.5 % bucket-height	1.4	MV	0.26
RF frequency	509	MHz	
Inner diameter of chamber	32	mm	
Bore diameter of magnets	44	mm	

* 8 nC/bunch

- 8 nC/bunch (16 nC/pulse) is the ultimate goal
- The hardware design is based on this value.

Dynamic aperture



Injected beam: $\epsilon = 1.5\,\mu\mathrm{m},\ 3.5\,\sigma$

$|\Delta p/p| = 1.5\,\%$

‘Normal’ errors

- Strength: 0.1 % for quads, 0.2 % for sexts
- Rotation: 0.3 mrad for quads and sexts
- Misalignment: 0.15 mm
- BPM offset: 0.15 mm
- Orbit correction

PLUS

Higher order multipoles
(Systematic, ΔB/B at r=17 mm)

- Bend: K2 0.15 %, K4 0.05 %
- Quad: K5 0.15 %, K9 0.05 %
- Sext: K8 1.0 %, K14 0.1 %

(Except quads in straight)

- Bends and quads are in fabrication based on these numbers

Electron Cloud Instability

- Theory

$$\rho_{e,th} = \frac{2\ln 2\pi}{3\sqrt{2}} \frac{\gamma\,\nu_s\,\omega_e\sigma_z/c}{K Q\, r_e \beta L}(1+\frac{\sigma_y}{\sigma_x})$$

$$\omega_e^2 = \lambda_+ r_e c^2/\sigma_y(\sigma_x+\sigma_y)$$

$$Q = \min(5, \omega_e\sigma_z/c) \quad K = 3$$

- Correction factor due to discrepancy between the theory and the simulation: 0.43 (simulation gives smaller threshold)

$$(\rho_e L)_{\mathrm{th}} = 7.0 \times 10^{14}\,\mathrm{m}^{-2}$$

- Simulation results of photo-electron formation

Cloud density: ρ

		Drift	Bend	Q + SX	unit
Length		73.2	36	26.8	m
δ_{MAX}=2	SR=1	1.3	0.6	0.5	10^{12} m^{-3}
δ_{MAX}=1	SR=1	0.4	0.5	0.15	10^{12} m^{-3}
	SR=0.1	0.15	0.11	0.03	10^{12} m^{-3}

- SR is photon-flux ratio to the design flux:
- SR=0.1 mimics the ante-chamber effect
- Electron Cloud is not in proportional to the flux
- δmax=1 expected for TiN coated Al chamber

Electron Cloud Instability 2

- Integrated electron density for δmax=1, SR=1

$$0.51 \times 10^{14}\,\mathrm{m}^{-2} \ll \rho_{e,th} L = 7.0 \times 10^{14}\,\mathrm{m}^{-2}$$

•Electron density is well below the threshold

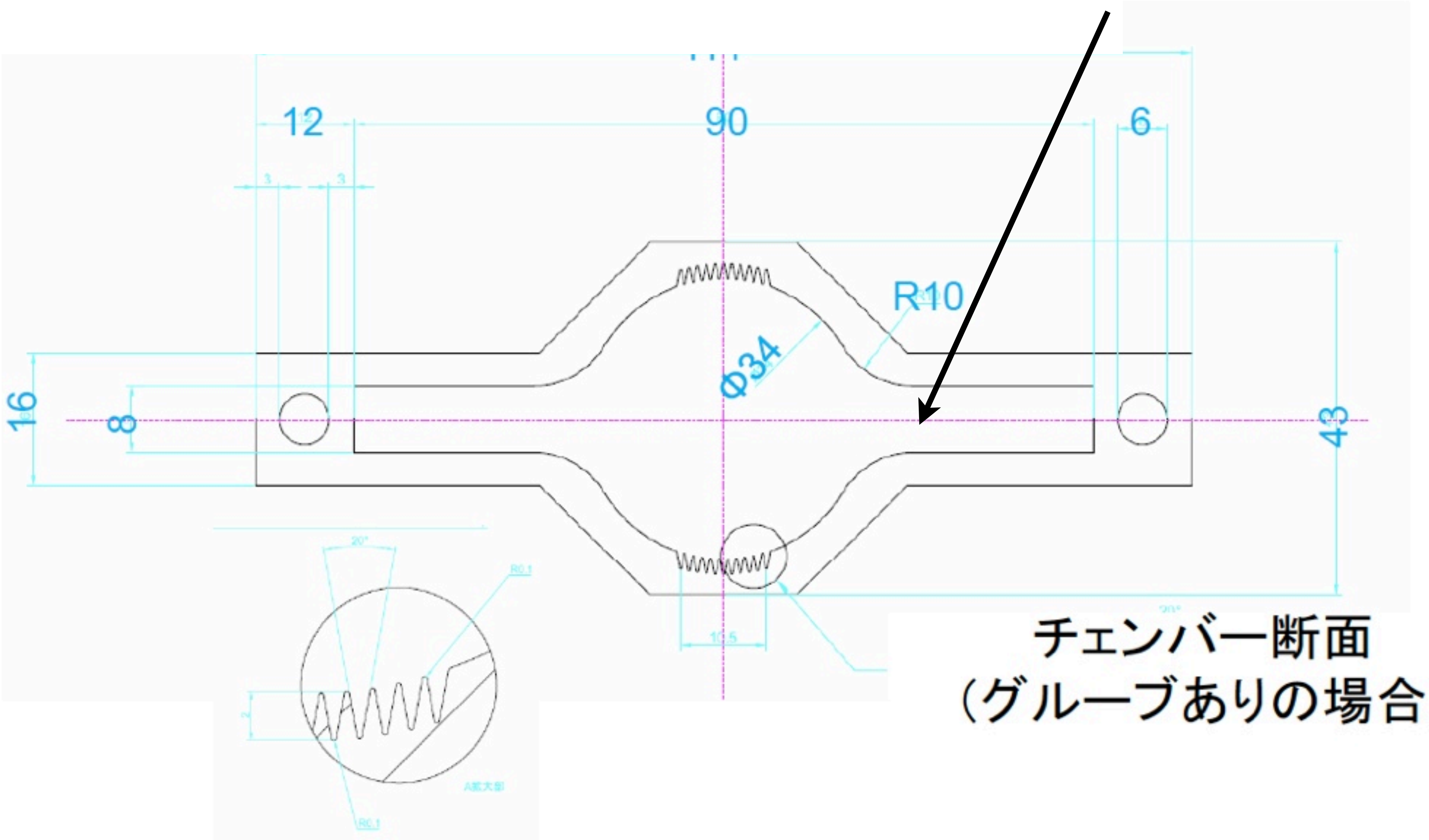
•Electron cloud in reality may be larger than 2D simulation.

•Some mitigation technique will be incorporated in the vacuum design for insurance

•(Antechamber is needed for the impedance-free photon mask)

Chamber (basic plan)

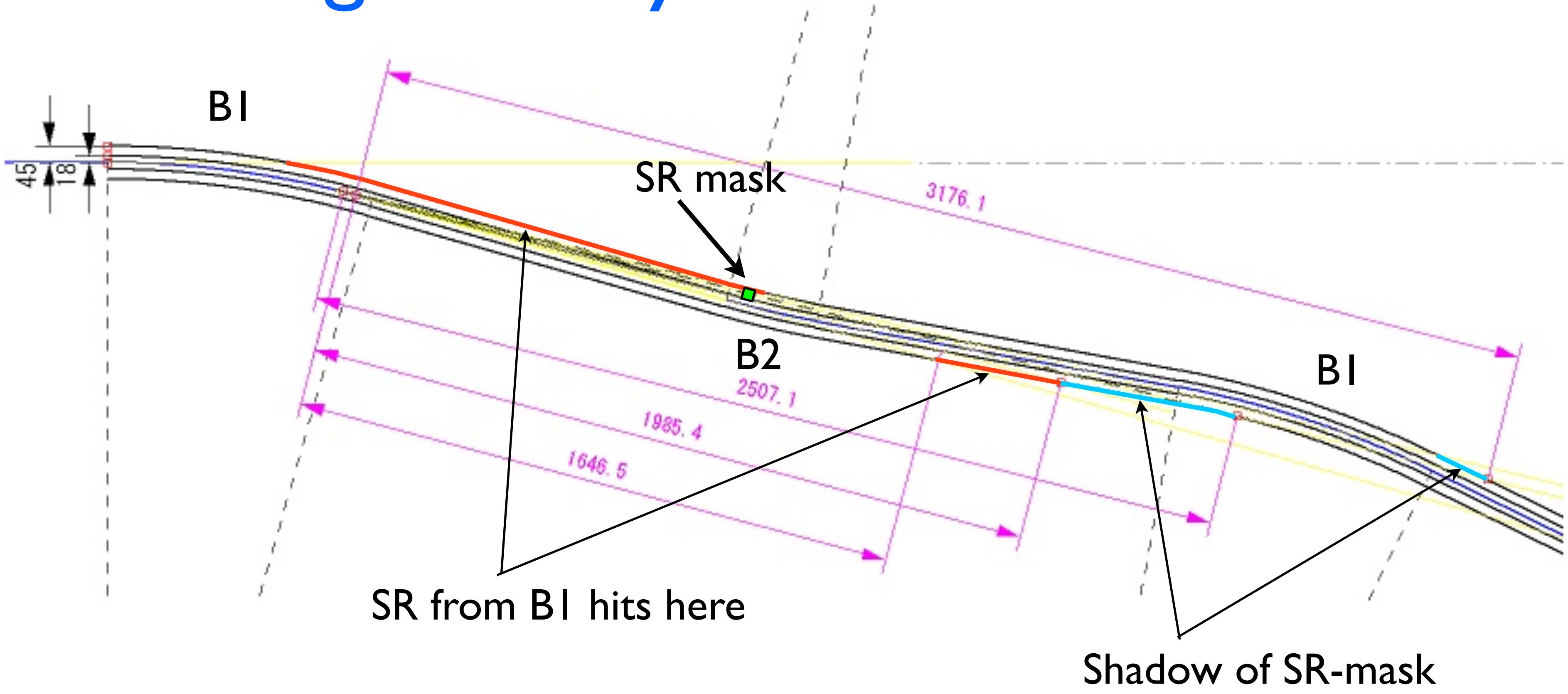
- Al alloy
- Antechamber with cooling-water channels
- Grooved surface on top and bottom of the bend chamber



Photon mask is placed here

チェンバー断面
（グルーブありの場合）

SR fan geometry for B1



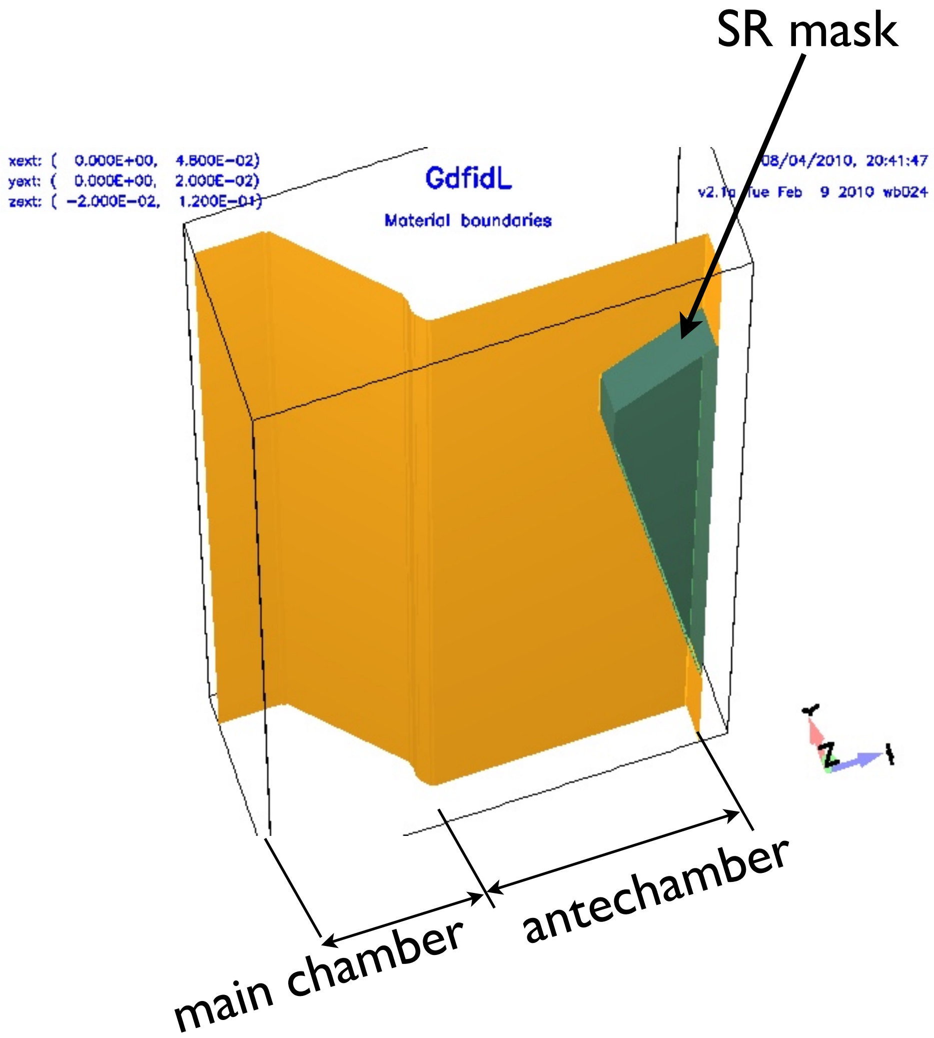
- Antechamber + negative bend provides SR more chance to hit the downstream chamber

- 90 % of SR power is dropped within 1m from B1

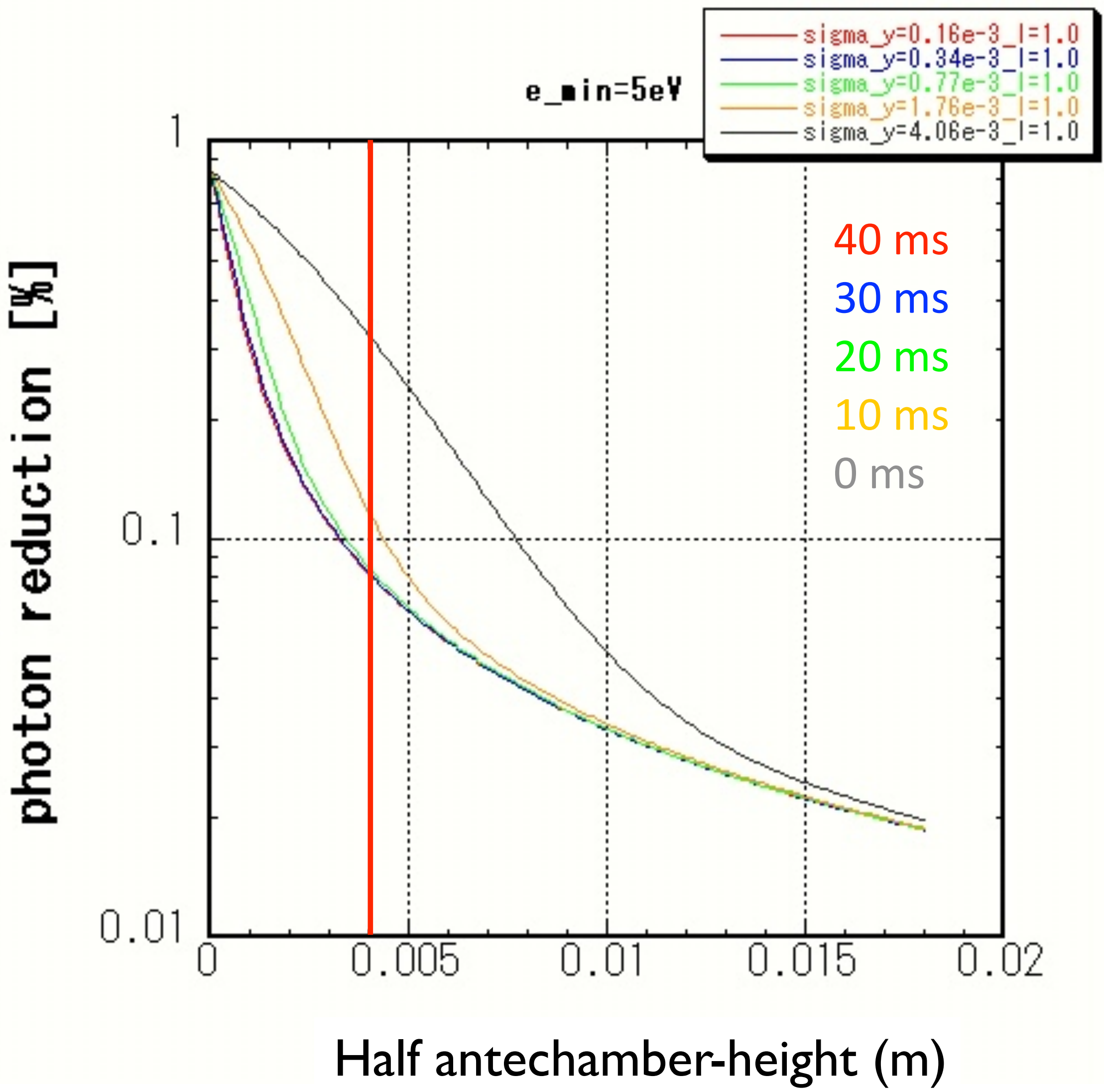
- SR mask housed in the antechamber makes the shadow at more than 2 m from the source point

- The SR mask is useful also to prevent the SR from hitting bellows.

- Th SR mask has negligibly small impedance; 1e-6 compared to the normal mask.



Acceptance of antechamber for the photons



- Vertical axis: Ratio of photons that hit surface of the main chamber
- Neglect photons E < 5 eV
- Distance from source point is 1 m
- Antechamber height of 8 mm is sufficient to accept 90 % of photons in the antechamber if the store time is longer than 10 ms.

Transverse impedance

- Calculation results of the kick factor

2010.04.16

Component	No.		kick_x	N*kick_x	kick_y	N*kick_y
ARES	1		1.74E+13	1.74E+13	-1.70E+13	-1.70E+13
Bellows	88	X	2.93E+11	2.57E+13	-1.56E+08	
		Y	-1.51E+08		2.84E+11	2.50E+13
flange gap	176	X	4.73E+11	8.32E+13	1.06E+07	
		Y	-4.93E+07		5.06E+10	8.91E+12
Pumping port	176	X	1.98E+08	3.48E+10	-1.13E+08	1.99E+10
SR mask	176	XY	2.20E+06	3.87E+08	-2.63E+05	4.63+07
Resistive wall	135.5	XY	-3.6E+12	4.88E+14	-3.6E+12	4.88E+14
BPM	82	X	0.571	46.82	0.483	39.606
Stripline kicker	1	X	33.7	33.7		
			V/Cm	6.14×10^{14}	V/Cm	5.39×10^{14}

- Transverse microwave instability

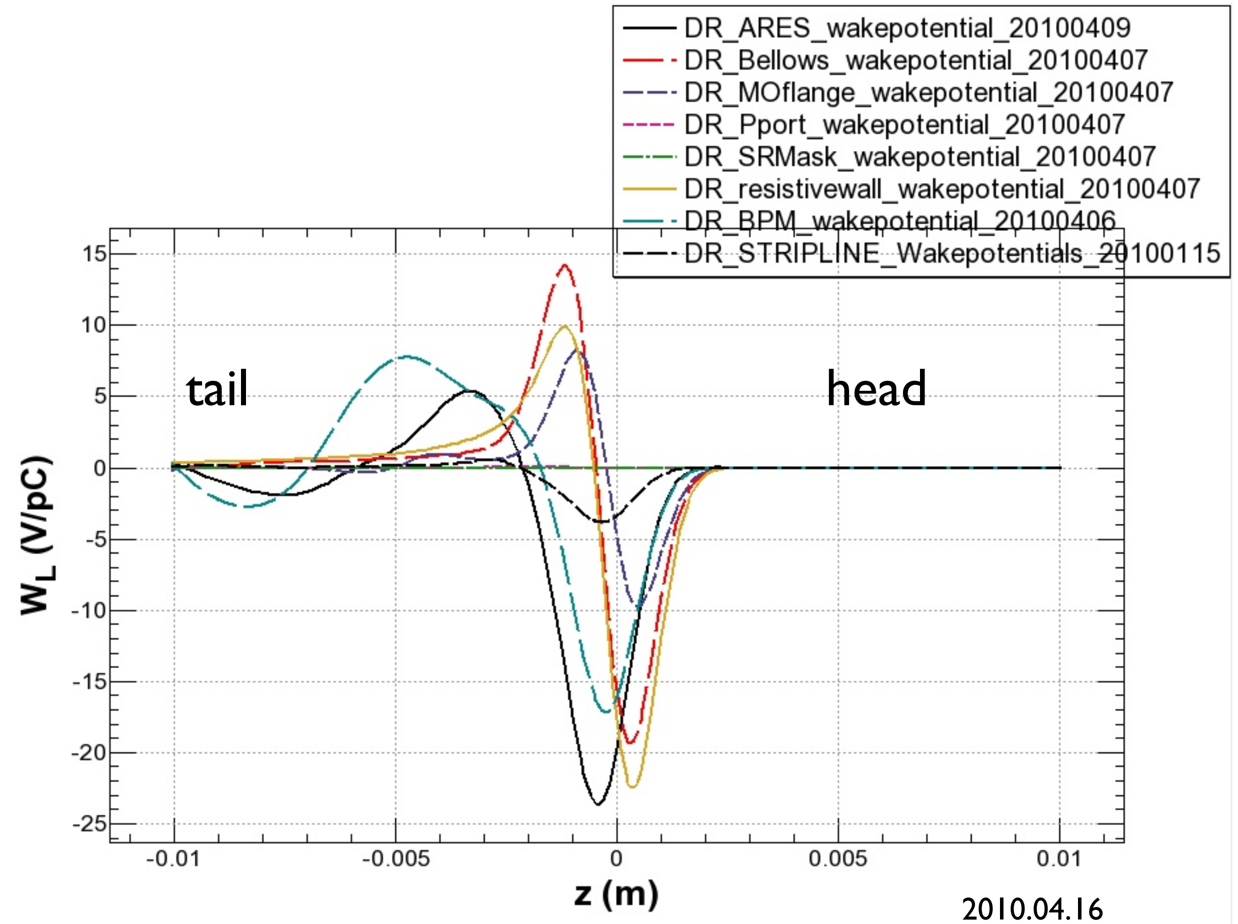
$$I_{th} = \frac{8 f_s E/e}{\sum \beta_i k_i} = 0.41\ \mathrm{A};\ \text{for x} \quad \longrightarrow 183\,\mathrm{nC/bunch}$$

$$0.31\ \mathrm{A};\ \text{for y} \quad \longrightarrow 141\,\mathrm{nC/bunch}$$

Longitudinal impedance

Vacuum chamber component

Shibata, K.



2010.04.16

CSR

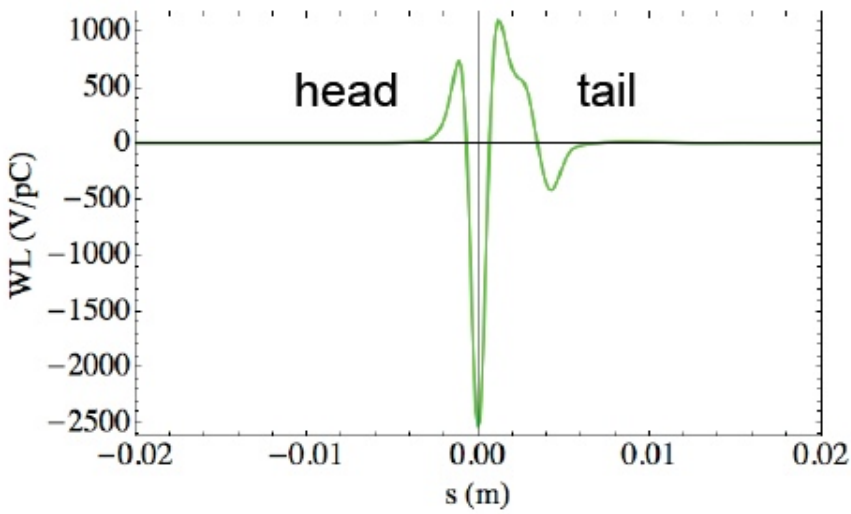
D. Zhou

- Stupakov's code
- Toroidal rectangular chamber (34 x 34)

\+ infinite straight pipe

- Sum. of single bend wake

$$\sigma_z = 0.5mm$$



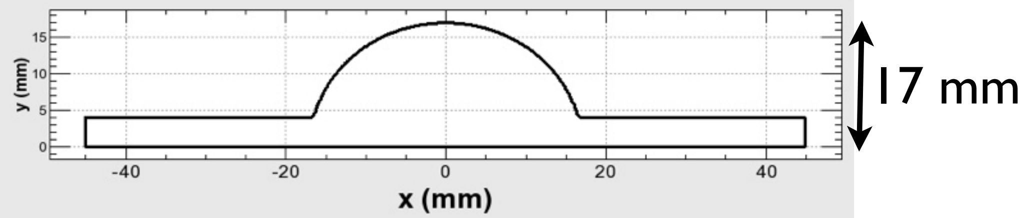
2010.04.23

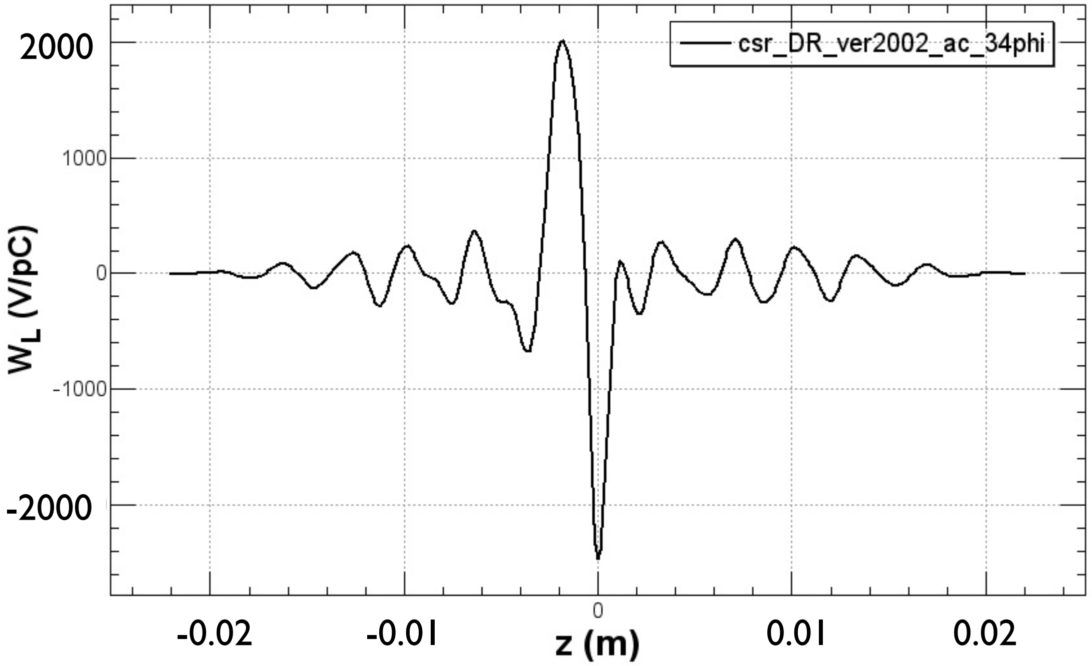
- CSR wake is 100 times larger than the ordinal vacuum-components wake!

CSR

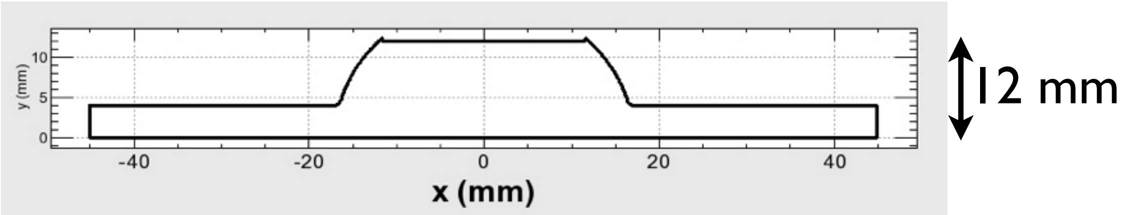
- CSR wake of proposed chambers
  - Numerical Calculation - Oide's code
  - Model : ante-chamber (single bend :ver2002)+ infinite straight pipe
    - summation over 32 × B1 + 38 × B2 + 6 × B3 + 2 × B4
    - σ *z = 0.5mm*

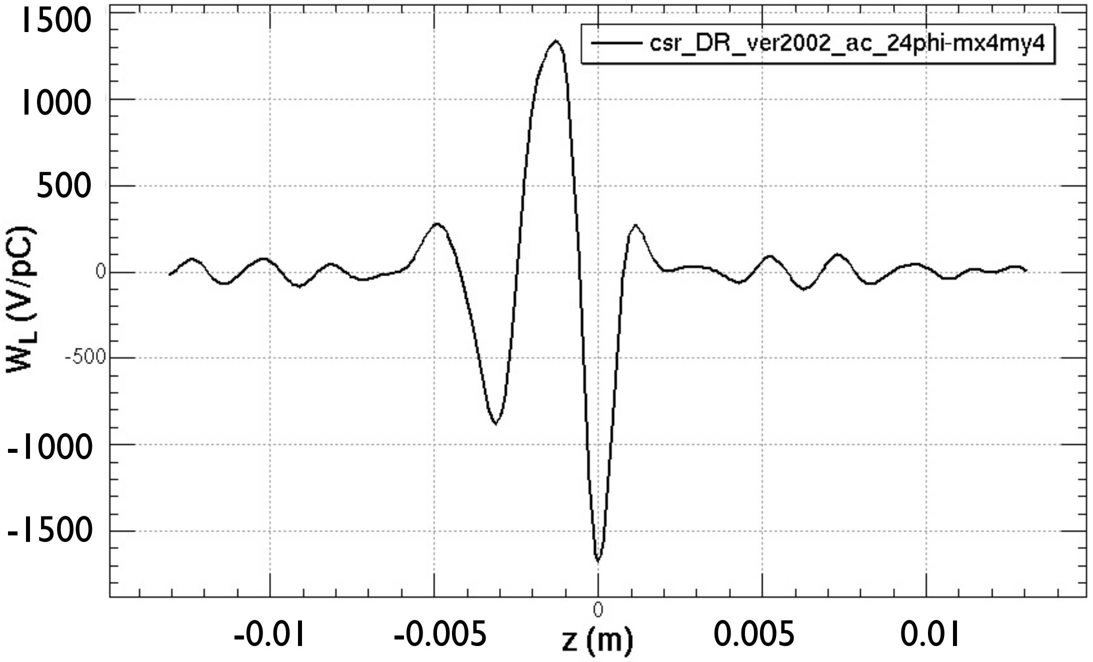
"34Φ"





"24h"

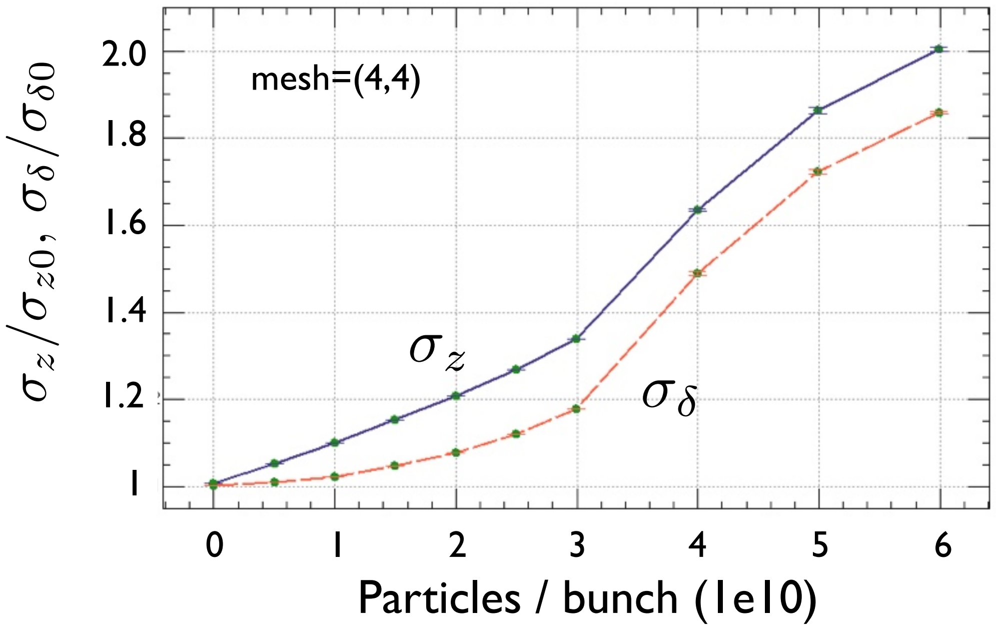




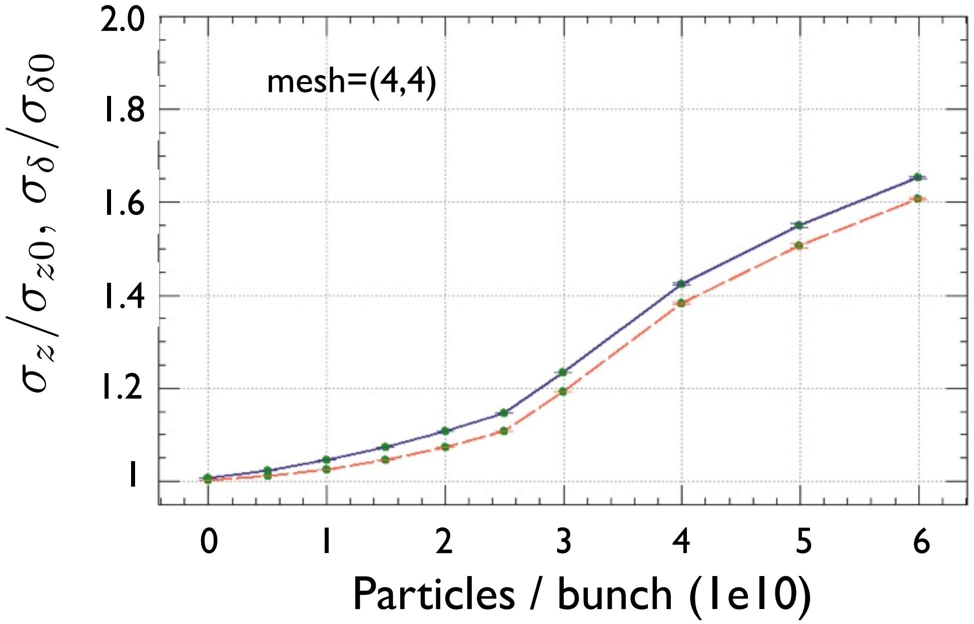
CSR 2

- Multi-particle longitudinal tracking using the CSR wake

"34Φ"



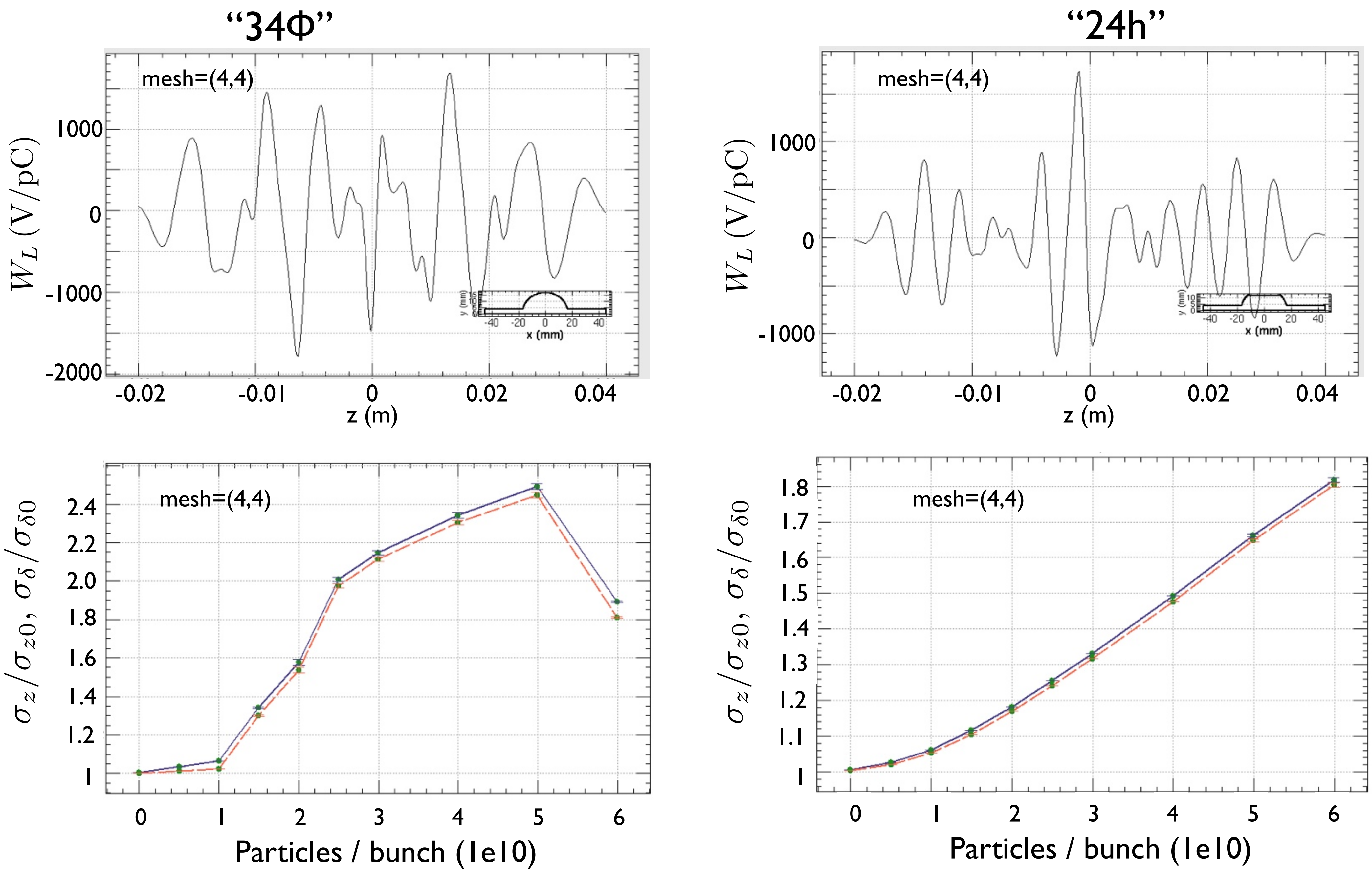
"24h"



- Seems OK for the intensity (2.5e10) but not for 'ultimate goal(5e10)'
- The "24h" type is preferable. Physical aperture is OK for "24h".
- But the simple summation of single-bend wake is questionable because the bend length is short.

CSR 3

- CSR wake of proposed chambers
  - calculation over entire ring 32 × B1 + 38 × B2 + 6 × B3 + 2 × B4

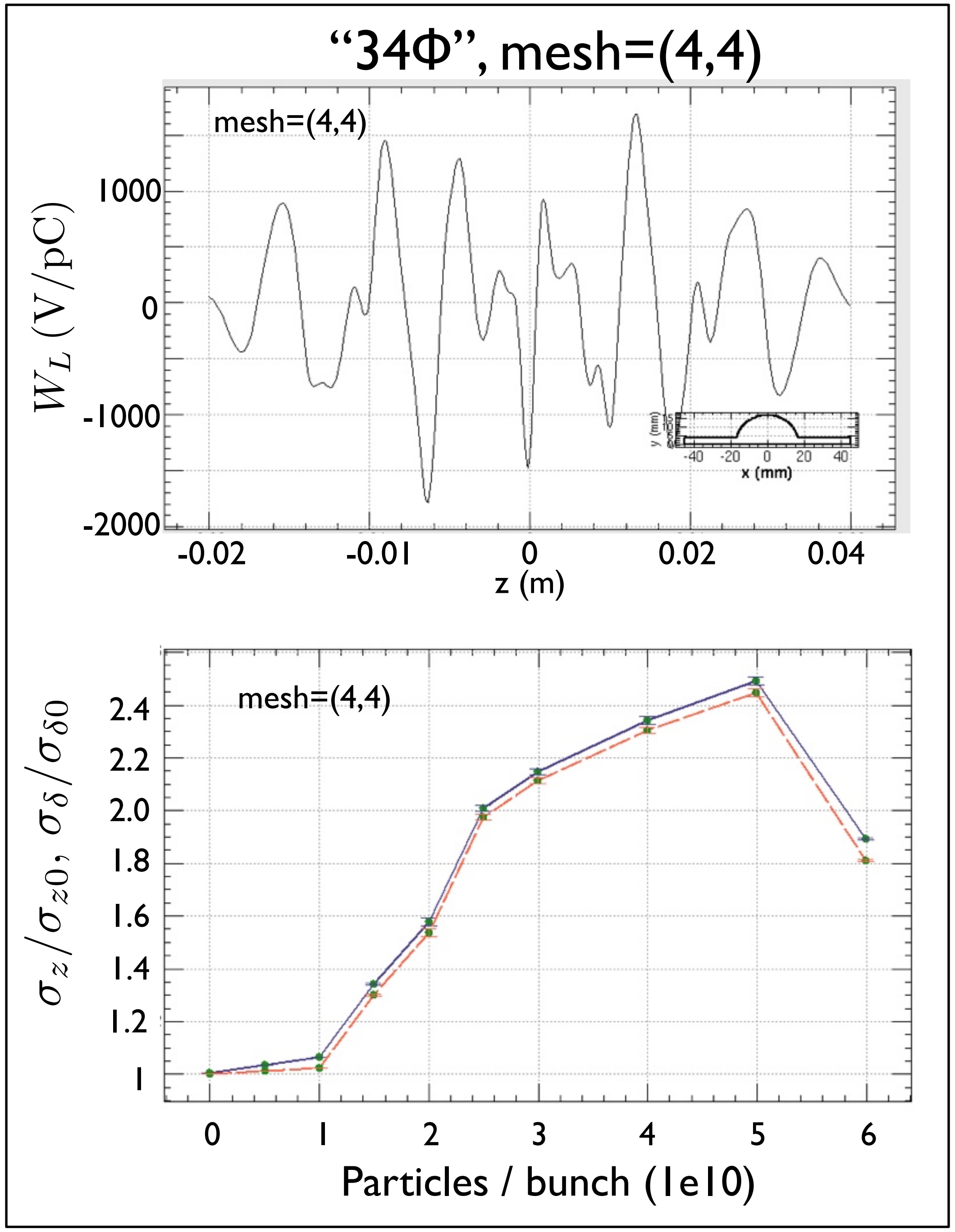

“34Φ”

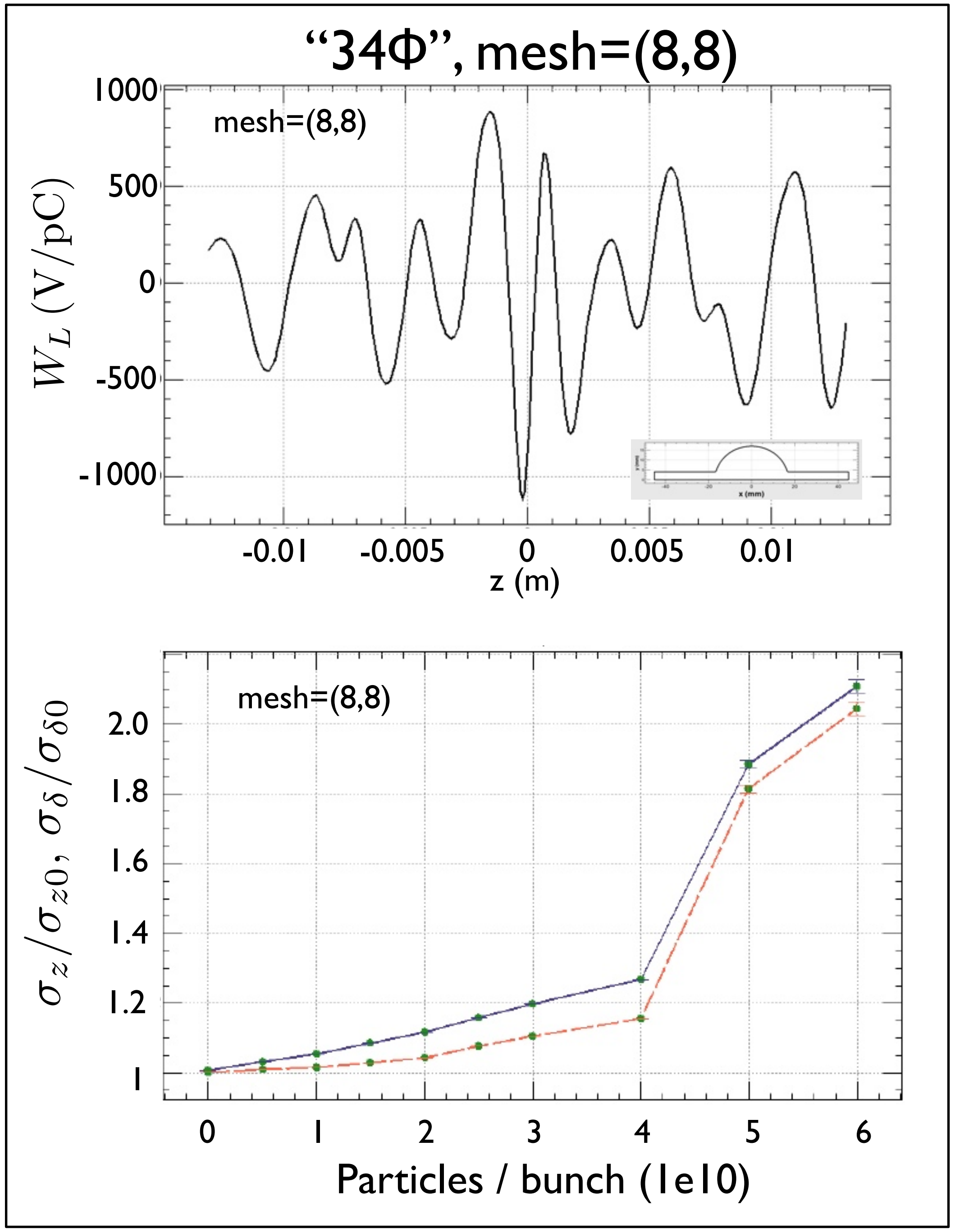
“24h”

- Many spikes due to interference of EM waves of consecutive bends

CSR 4

- Check the convergence of wake calculation as a function of mesh size


“34Φ”, mesh=(4,4)

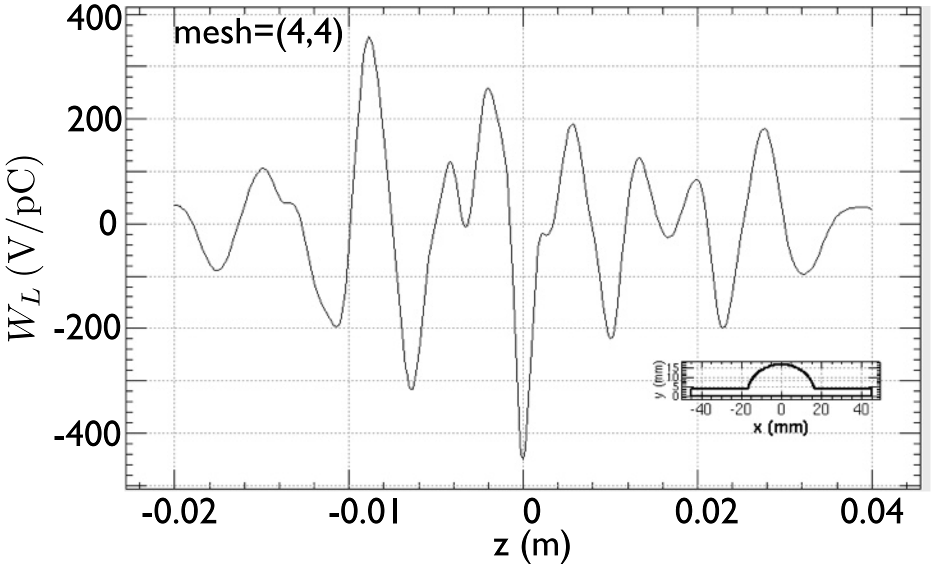

“34Φ”, mesh=(8,8)

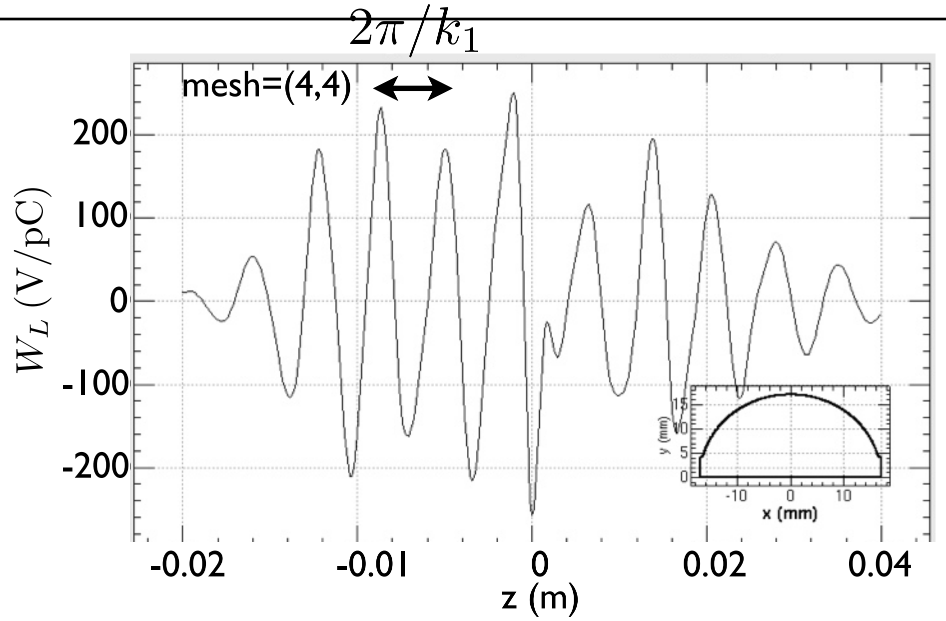
- Still not converged in mesh size (8,8)
- Finer mesh is difficult due to computing power limitation

CSR 5

- Comparison with a normal round chamber

Consecutive
14 bends





- Lowest synchronous mode of a toroidal waveguide with a round cross section (ref. 1)

$$k_1 = 2.12\ \rho^{1/2} a^{-3/2} = 1.57\times 10^3\,\mathrm{m}^{-1} \quad \longrightarrow 2\pi/k_1 = 4.0\,\mathrm{mm}$$

- For the round pipe, the wake function looks like a single resonator wake, whose wave number corresponds to a single toroidal mode. It is a surprise because the geometry is far from a toroid.

- For the antechamber, some other frequencies are mixed.

- This suggests that the real wake might be composed of several single mode wakes.

ref 1: G.V. Stupakov and I.A. Kotelnikov, PRST-AB 6(2003) 034401

CSR 6: Theoretical estimation of the threshold (1)

S-H theory on CSR instability

[1] G. Stupakov, S. Heifets, *Beam instability and microbunching due to coherent synchrotron radiation*, PRST-AB, 5(2002), 054402

- 1-D Vlasov equation for coasting beam

$$\frac{\partial \rho}{\partial s} - \eta \delta \frac{\partial \rho}{\partial z} - \frac{r_0}{\gamma} \frac{\partial \rho}{\partial \delta} \int_{-\infty}^{\infty} dz' \, d\delta' \, W(z - z') \rho(\delta', z', s) = 0, \quad (1)$$

- Use CSR wake for free space

$$W(z) = \frac{2}{(3R^2)^{1/3}} \frac{\partial}{\partial z} z^{-1/3} \quad \text{for } z > 0, \qquad (2)$$

- Beam is unstable if (k: perturbation wave number)

$$kR < 2.0 \Lambda^{3/2} \qquad \Lambda = \frac{n_b r_0}{|\alpha| \gamma \sigma_\delta^2} \frac{R}{\langle R \rangle}$$

R: Bending radius
n_b: local density

- For bunched beam

$$N_{th} = \frac{\pi^{1/6}}{\sqrt{2}} \frac{\gamma L}{r_0 R^{1/3}} |\alpha| \sigma_\delta^2 \sigma_z \frac{1}{\lambda^{2/3}}$$

L : Circumference

(Lattice parameters were optimized from those of MAC10 to maximize the threshold).

CSR 7: Theoretical estimation of the threshold (2)

- Validity condition of the theory

1. Bunch is longer than perturbation wave length: $k\,\sigma_z \gg 1$ or $\lambda \leq \sigma_z$
2. Shield effect is small: (h is chamber height) $R/h \leq \Lambda$ (79 < 117)
3. Wake formation time is shorter than instability frequency : $\dfrac{N r_0}{\sqrt{2\pi}\gamma\sigma_\delta\sigma_z} \ll 1$ (0.007)
4. Dilution due to transverse beam size is negligible: $\dfrac{\sigma_x L}{\sigma_z \nu_\beta R} \ll 1$ (0.29)
5. Shield effect by chamber: $\lambda < 2\sqrt{h^3/R}$

All these conditions are satisfied in the next examples, but no4 is marginal.

CSR 8

- Estimated threshold

Parameters			SKB-DR	UVSOR-II	NSLS VUV
Energy	E	GeV	1.1	0.6	0.737
Circumference	L	m	135.5	53.2	51.0
Bend radius	R	m	2.7	2.2	1.91
Momentum compaction	α		0.0141	0.028	0.0235
Bunch length	σz	mm	6.5	75*	50
Energy spread	σ_δ		5.5E-04	3.4E-04	4.6E-04
Chamber height	h	mm	34	38	40
Design intensity	N	10^{10}	5.0		
Threshold (S-H[1])	Nth	10^{10}	2.44	7.63	8.75
Observed threshold	Nth	10^{10}		8.9	10.6
Λ			117	91	78
R/h			79	58	48
$Nr_0/(\sqrt{2\pi}\gamma\sigma_\delta\sigma_z)$			0.0073	0.0033	0.0036
$\sigma_x L/(\sigma_z\nu_\beta R)$			0.29		

*) Measured bunch length just before the onset of bursting phenomenon.

CSR 9: Theoretical estimation of the threshold (2)

Linearized Vlasov(LV) solution on microwave instability with CSR wake

[1] K.L.F. Bane, Y. Cai, G. Stupakov, *Comparison of simulation codes for microwave instability in bunched beams*, IPAC'10 Proceedings, 2096

- Use of Vlasov-Fokker-Planck code and LV code for the bunched beam
- CSR wake for the parallel plates
- Beam dynamics depends on the two parameters

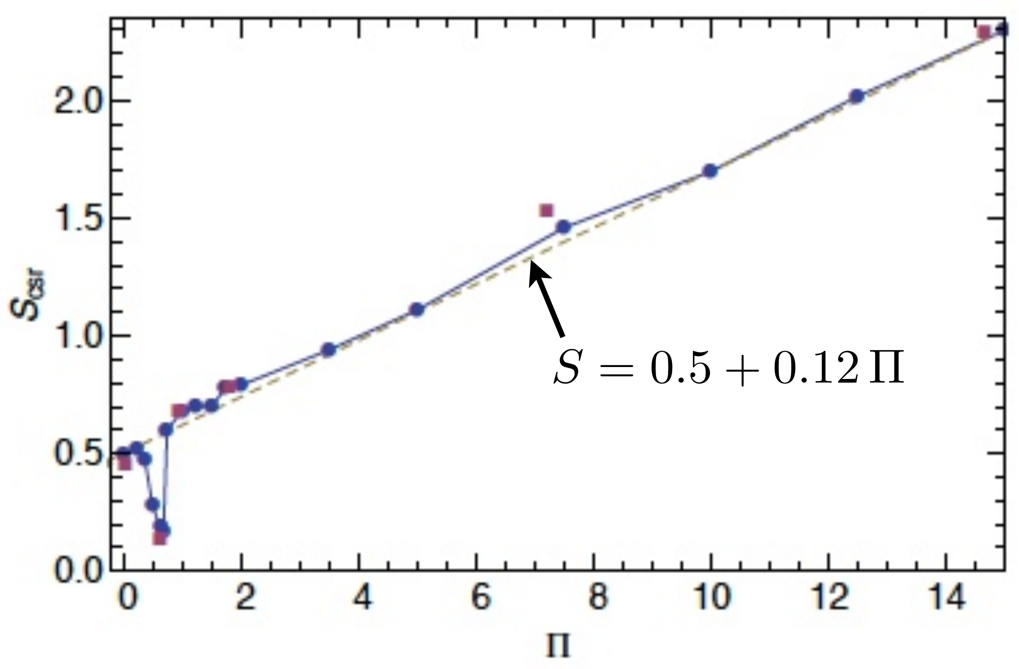


Figure 2: For the CSR wake, threshold value of S_{csr} *vs.* shielding parameter, $\Pi = \rho^{1/2}\sigma_{z0}/h^{3/2}$. Symbols give results of the VFP solver (blue) and the LV code (red).

'Intensity': $S = \dfrac{r_e N_b\,\rho^{1/3}}{2\pi\nu_s\gamma\,\sigma_{\delta 0}\,\sigma_{z0}^{4/3}}$

'Shielding': $\Pi = \sigma_{z0}\,\rho^{1/2}/\,h^{3/2}$

Threshold

$$S_{th} = 0.5 + 0.12\,\Pi$$

For SKB-DR

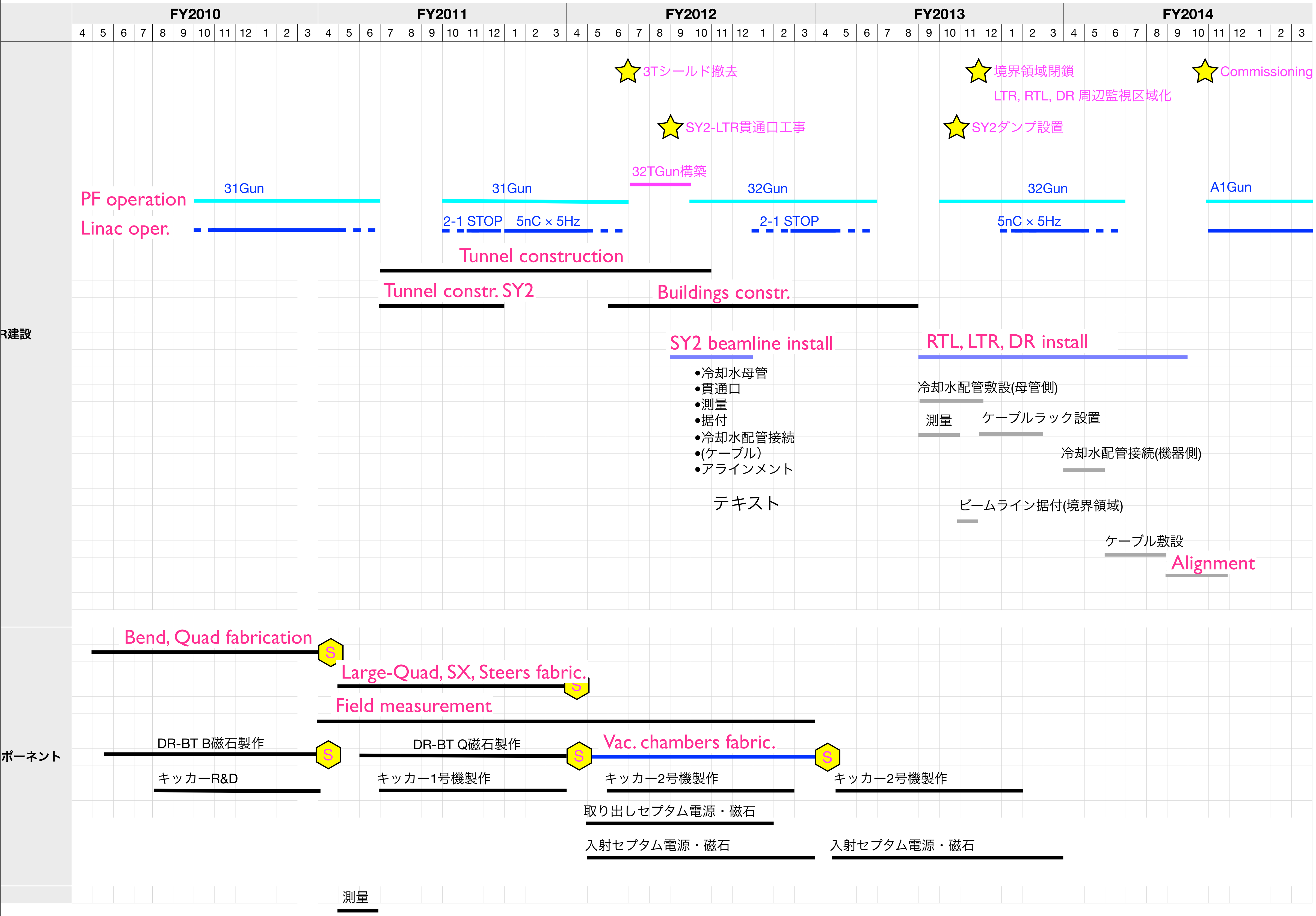
$$\Pi = 4.85$$

$$N_b = 6.4 \times 10^{10}$$

Summary

- Lattice parameters were optimized from the last MAC to suppress the microwave instability due to CSR.
- Electron cloud density is lower than the threshold.
- Chamber design employing antechamber has been proposed.
- Threshold of the transverse microwave instability is much higher than the design current.
- Longitudinal wake is dominated by CSR wake.
- Calculation of CSR wake for entire ring is important.
- Poor convergence in mesh size yet.
- CSR calculation is presently in chaos.
- Prediction by theories scatters from 4 nC/bunch (S-H) to 10 nC/bunch (KB).
- Fabrication of chambers is scheduled in the FY 2012.

Schedules



FY2010 FY2011 FY2012 FY2013 FY2014

4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3

R建設

3Tシールド撤去

境界領域閉鎖
LTR, RTL, DR 周辺監視区域化

Commissioning

SY2-LTR貫通口工事

SY2ダンプ設置

32TGun構築

PF operation

31Gun

31Gun

32Gun

32Gun

A1Gun

Linac oper.

2-1 STOP

5nC × 5Hz

2-1 STOP

5nC × 5Hz

Tunnel construction

Tunnel constr. SY2

Buildings constr.

SY2 beamline install

- 冷却水母管
- 貫通口
- 測量
- 据付
- 冷却水配管接続
- (ケーブル)
- アラインメント

テキスト

RTL, LTR, DR install

冷却水配管敷設(母管側)

測量

ケーブルラック設置

冷却水配管接続(機器側)

ビームライン据付(境界領域)

ケーブル敷設

Alignment

ポーネント

Bend, Quad fabrication

S

Large-Quad, SX, Steers fabric.

S

Field measurement

DR-BT B磁石製作

S

DR-BT Q磁石製作

S

Vac. chambers fabric.

S

キッカーR&D

キッカー1号機製作

キッカー2号機製作

キッカー2号機製作

取り出しセプタム電源・磁石

入射セプタム電源・磁石

入射セプタム電源・磁石

測量

Spares

Optics: optimized to CSR

$$F = \frac{L\gamma}{\rho^{1/3}}\alpha\sigma_\delta^2\sigma_z \tag{1}$$

$$\sigma_\delta^2 = C_q\frac{\gamma^2}{J_\epsilon\rho} \tag{2}$$

$$\sigma_z = \frac{c\alpha}{\omega_s}\sigma_\delta \tag{3}$$

$$\omega_s^2 = \frac{\alpha h\omega_0^2 eV\cos\phi_0}{2\pi E} \simeq \frac{\omega_{RF}eV}{m_0c^2}\frac{c\alpha}{\gamma L} \tag{4}$$

$$\sigma_z = \left(\frac{m_0c^2}{eV\omega_{RF}}\right)^{1/2}(c\alpha\gamma L)^{1/2}\sigma_\delta \tag{5}$$

Putting (2)-(5) into (1) one gets the expression of F as

$$F = \left(\frac{C_q}{J_\epsilon}\right)^{3/2}\left(\frac{m_0c^3}{eV\omega_{RF}}\right)^{1/2}\frac{(\alpha L)^{3/2}}{\rho^{11/6}}\gamma^{9/2} \tag{6}$$

Requirements from machine parameters

B field

$$B\rho = p/e \qquad \rho = 1.703 \times 10^{-3}\frac{\gamma}{B} = c1\frac{\gamma}{B} \tag{7}$$

Synchrotron tune

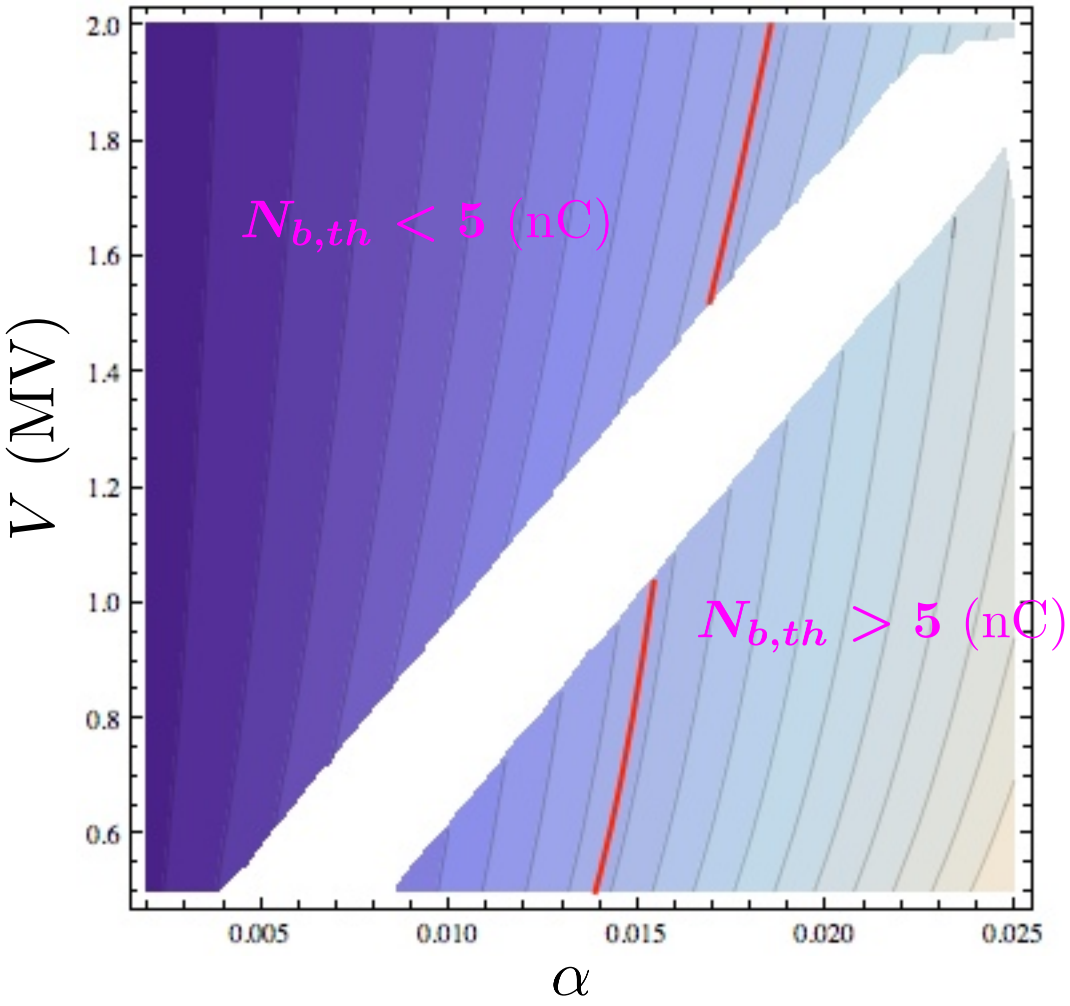
$$\nu_s^2 = \frac{\omega_{RF} eV}{2\pi m_0 c^2}\frac{1}{2\pi c}\frac{\alpha L}{\gamma} \geq \nu_{s0}^2 \qquad \nu_{s0} = 0.008 \tag{8}$$

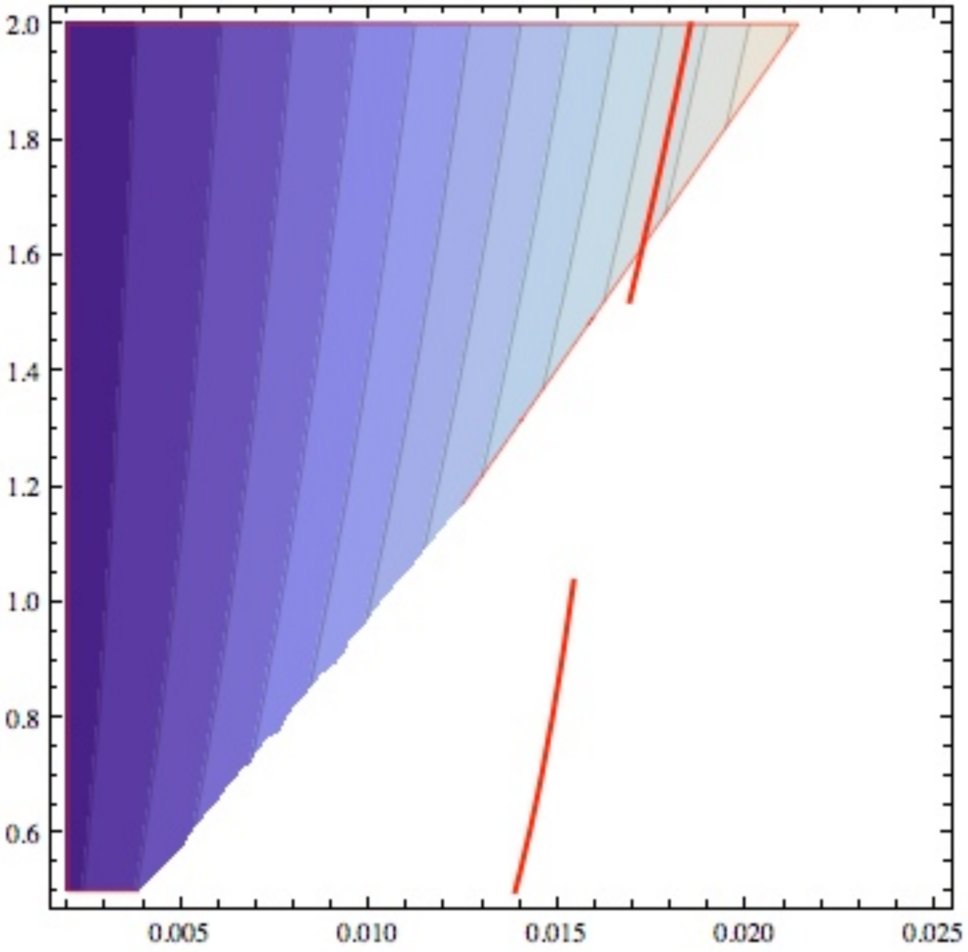
Damping time

$$\frac{1}{\tau} = \frac{r_e\gamma^3}{3T_0}J_x I_2 = \frac{2\pi c r_e J_x}{3}\frac{\gamma^3}{\rho L}\frac{1+r}{1-r} \geq \frac{1}{\tau_0} \qquad \tau_0 = 12 \text{ ms} \tag{9}$$

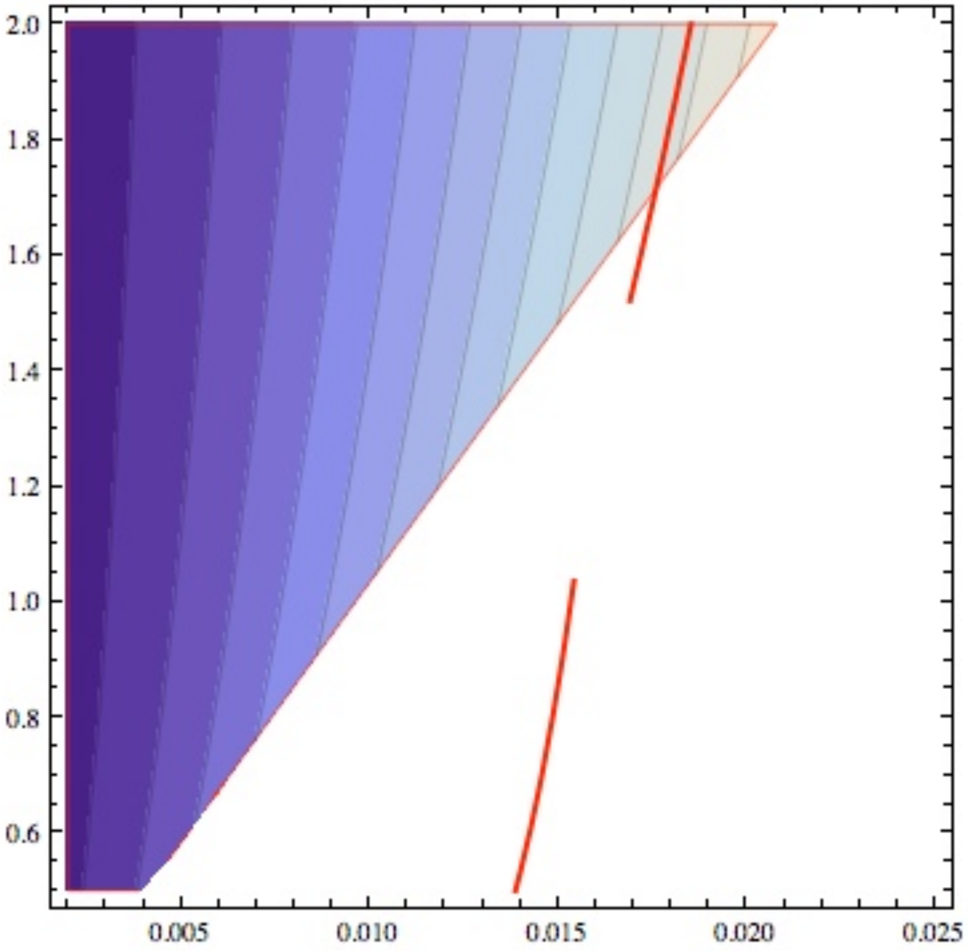
Bucket height

$$\left(\frac{\Delta E}{E}\right)^2 = \frac{U_0}{\pi\alpha h E}F\left(\frac{eV}{U_0}\right) \simeq \frac{2eV}{\pi\alpha h E} = \frac{4ceV}{m_0 c^2\omega_{RF}}\frac{1}{\alpha\gamma L} \geq \left(\frac{\Delta E}{E}\right)_0^2 \qquad \left(\frac{\Delta E}{E}\right)_0 = 0.015 \tag{10}$$





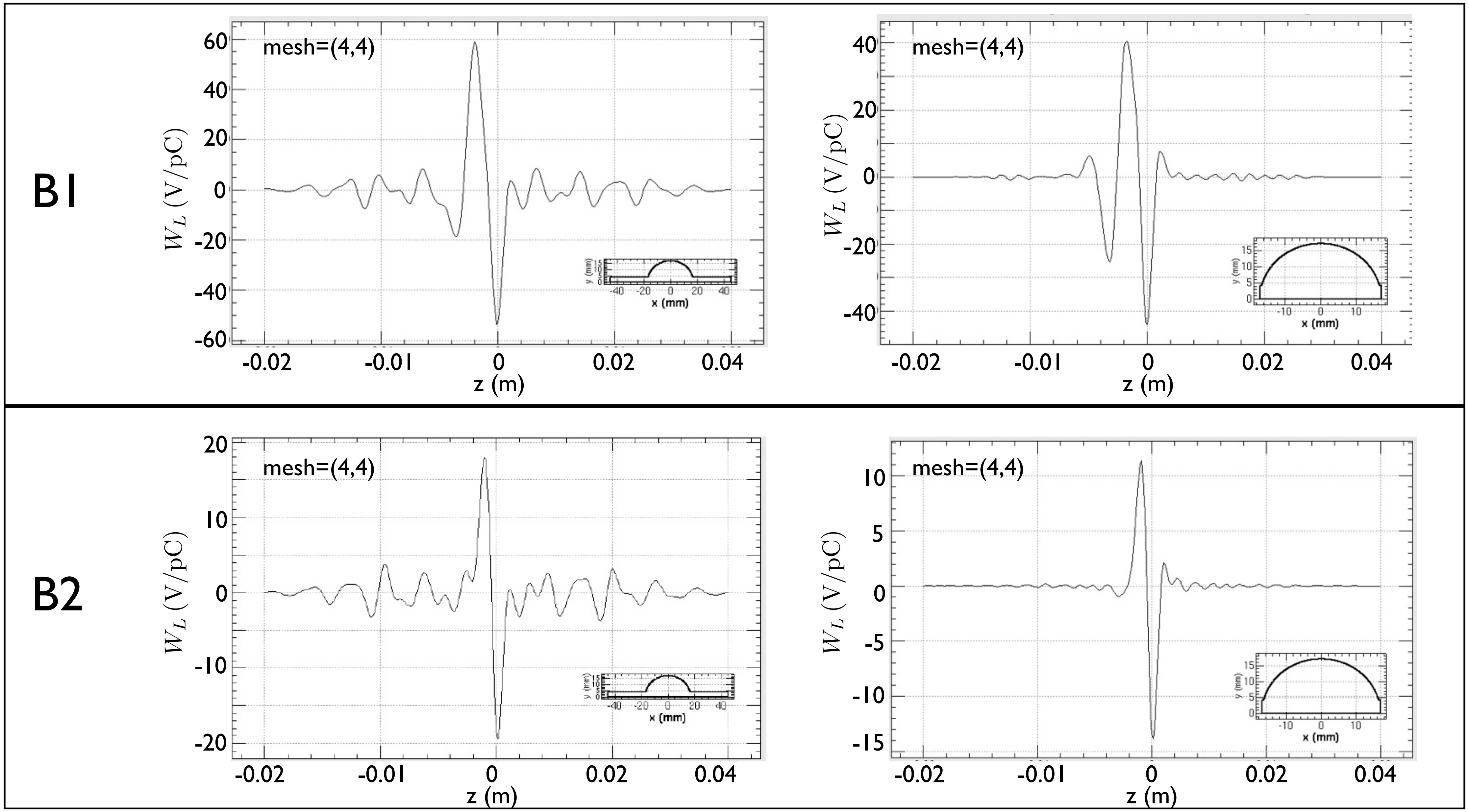
$\sigma_z < 7$ mm



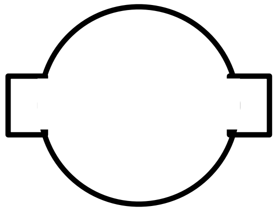
$\Delta E/E > 1.5$ %

CSR 5

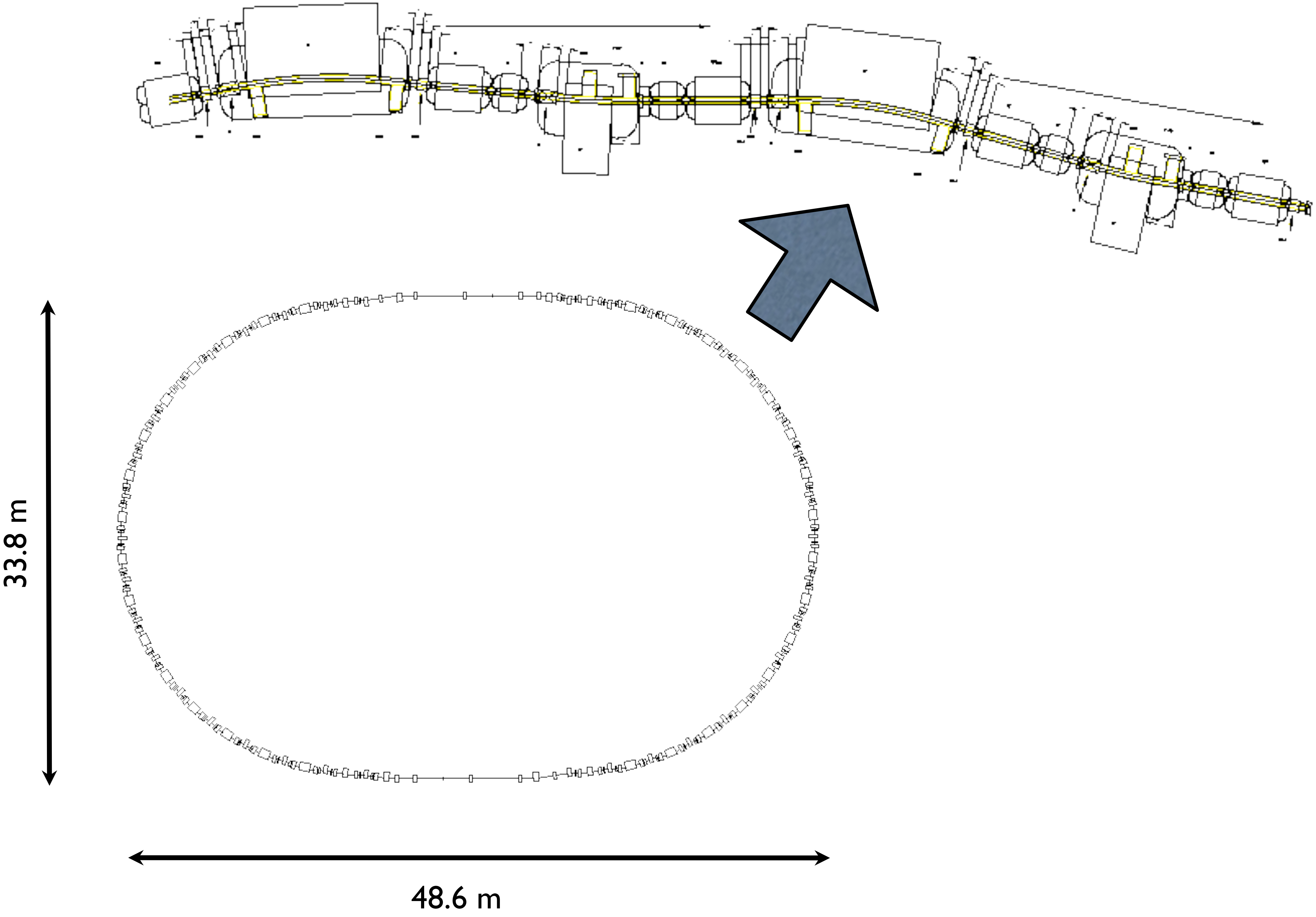
- Comparison with a normal round chamber



- Reflections from side wall of antechamber contributes to spikes
- Shallow antechamber may be a better solution?



Beam line is occupied with magnets

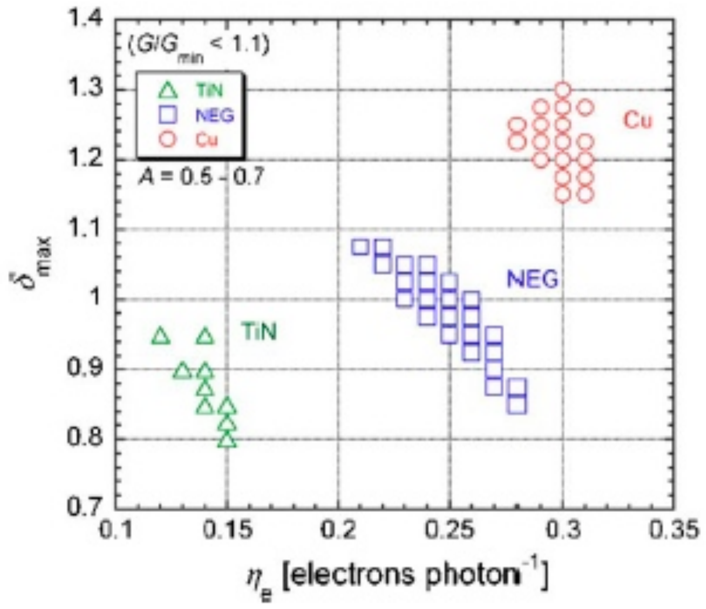


Instability 5

- $\rho_e \leq 3 \times 10^{11}\ \mathrm{m}^{-3}$ or $\rho_e L \leq 0.4 \times 10^{14}\ \mathrm{m}^{-2}$

- Mitigation is necessary to reduce SEY much less than 1.2
- TiN coating
- Groove (Vacuum people favors)

SEY (measured at KEKB)

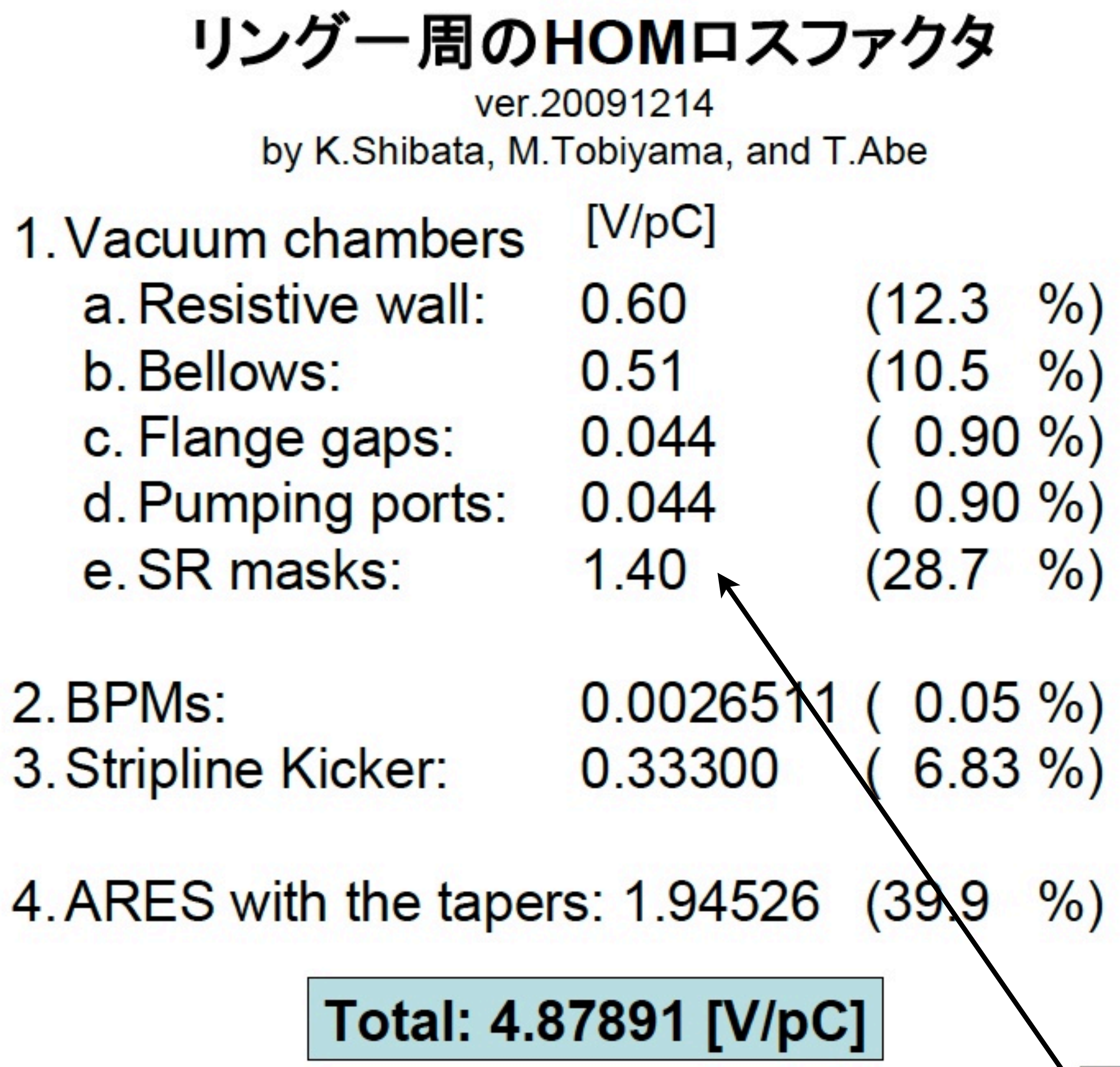


Y. Suetsugu et al. , NIM A 556 (2006)

Impedance Budget

K. Shibata et al.

- Loss factor



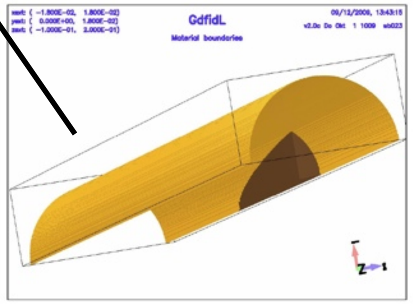
リング一周のHOMロスファクタ

ver.20091214

by K.Shibata, M.Tobiyama, and T.Abe

	[V/pC]	
1. Vacuum chambers		
a. Resistive wall:	0.60	(12.3 %)
b. Bellows:	0.51	(10.5 %)
c. Flange gaps:	0.044	(0.90 %)
d. Pumping ports:	0.044	(0.90 %)
e. SR masks:	1.40	(28.7 %)
2. BPMs:	0.0026511	(0.05 %)
3. Stripline Kicker:	0.33300	(6.83 %)
4. ARES with the tapers:	1.94526	(39.9 %)

Total: 4.87891 [V/pC]



H. Fukuma

- Resistive wall instability

$$\text{growth rate } g = \frac{cI}{4\pi\nu_\beta E}\sum_{p=-\infty}^{\infty}\mathrm{Re}\,Z((pM+\mu)\omega_0+\omega_\beta)$$

$$\mathrm{Re}Z = sign(\omega)\cdot\frac{Z_0\cdot R}{b^3}\cdot\delta$$

$$\delta = \sqrt{\frac{2c}{Z_0\sigma|\omega|}}$$

I = 70.8 mA, E = 1 GeV, M = 4, R = 21.6 m, b = 0.016 m , σ(Al) = 4 10^7 1/ohm/m at 0 C

ν_β=12.24 / 4.265 (H/V)

growth time : 77 / 26 ms (H/V) > transverse damping time 12.7 ms