Beam-gas background

Coulomb>> bremsstrahlung

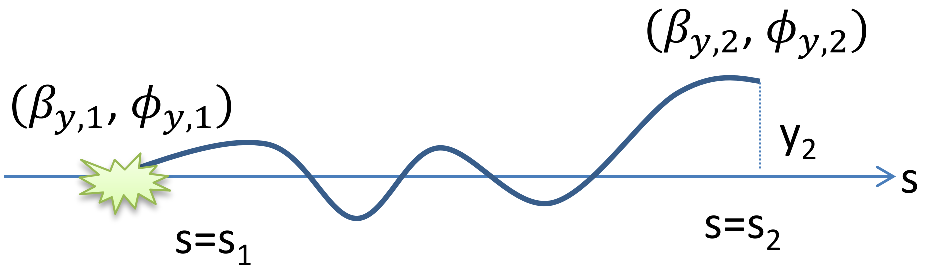
Coulomb BG is naively proportional to P x I.
Also depends on beta function over the ring
and IR physical aperture.

$P = 10^{-7}$Pa is assumed

P = 10^{-7}Pa is assumed

H. Nakano
K. Kanazawa

Beam-gas Coulomb lifetime



θ: Scattering angle

$$y_2 = \theta\sqrt{\beta_{y,1}\cdot\beta_{y,2}}\,\sin(\phi_{y,2}-\phi_{y,1})$$

The minimum scattering angle θ_c to hit QC1 beam pipe

$$\theta_c = r_{QC1}/\sqrt{\langle\beta_y\rangle\cdot\beta_{y,QC1}}$$

Beam lifetime τ_R is proportional to θ_c^2

$$\frac{1}{\tau_R} = cn_G\langle\sigma_R\rangle = cn_G\frac{4\pi\sum Z^2 r_e^2}{\gamma^2}\boxed{\left\langle\frac{1}{\theta_c^2}\right\rangle}$$

	KEKB LER	SuperKEKB LER
QC1 beam pipe radius: r_{QC1}	35mm	13.5mm
Max. vertical beta (in QC1): $\beta_{y,QC1}$	600m	2900m
Averaged vertical beta: $\langle\beta_y\rangle$	23m	50m
Min. scattering angle: θ_c	0.3mrad	0.036mrad
Beam-gas Coulomb lifetime	>10 hours	2200sec

Rate $\propto$P x I x $\langle\beta\rangle$
x β_{QC1} / r_{QC1}^2

Beam-gas lifetime is only x1/100 of KEKB, due to larger vertical beta in QC1 and narrower QC1 physical aperture

Beam Lifetime from Coulomb scattering against residual gas

- Parameters (LER)
  - Gas: CO
  - Pressure: 1 x 10^{-7} Pa
  - Acceptance
    - Vertical: QC1: 13.5mm (β_{ym} ~ 2888m)
    - Horizontal: 20 σ_x
- Lifetime

Z(Z+1) if you include Møller scattering

$$\frac{1}{\tau_C} = c n_G \frac{4\pi r_e^2 \sum_{gas} Z^2}{\gamma^2} \left\langle \frac{1}{\vartheta_c(s)^2} \right\rangle$$

$\langle b_y \rangle$ @50.6m

$$\left\langle \frac{1}{J_c(s)^2} \right\rangle = \frac{\langle b_x \rangle b_{xm}}{2a_{xm}^2} + \frac{\langle b_y \rangle b_{ym}}{2a_{ym}^2}$$

  - Lifetime calculated(@QC1_{ap}=13.5mm)
    - 2100 sec (Coulomb)
    - 1850 sec (Coulomb+ Møller) 14% worse

$P = 10^{-7}$Pa is assumed

LER: β_y (QC1) = 2900m, <β_y>=50m, γ=7830, r_{QC1}=13.5mm → 2100sec

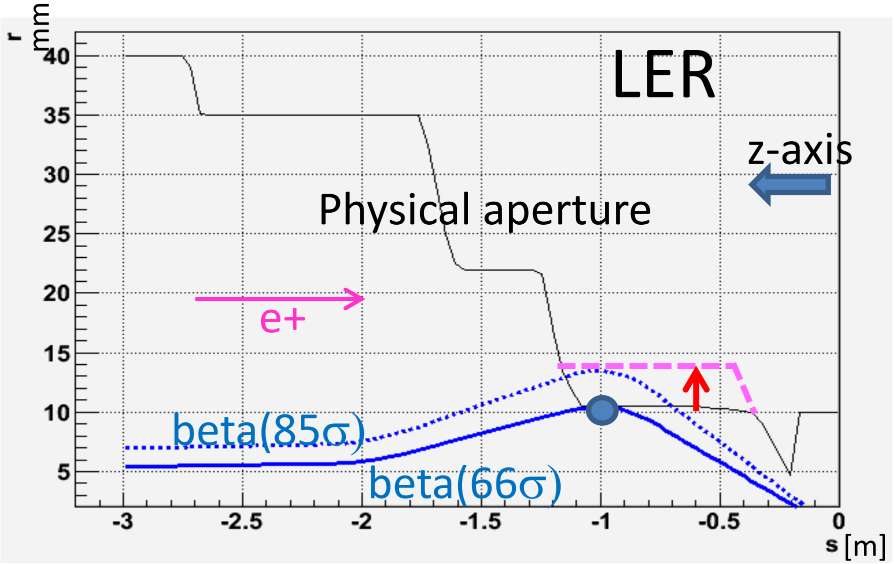
cn_G = $(3x10^8)$ x $(2.43*10^{20})x10^{-7}$ = 7.29e21;
$4\pi r_e^2\Sigma(Z^2) /\gamma 2/2 = 4\pi (2.82x10^{-15})^2 \text{ x } \Sigma(6^2+8^2)/(7828)^2/2$ = 7.991e-35;
(include Moller: 100=36+64→114=42+72, 14% worse)
theta_c = 0.036e-3 (by_max = 2900, <by>= 50, QC1=13.5)

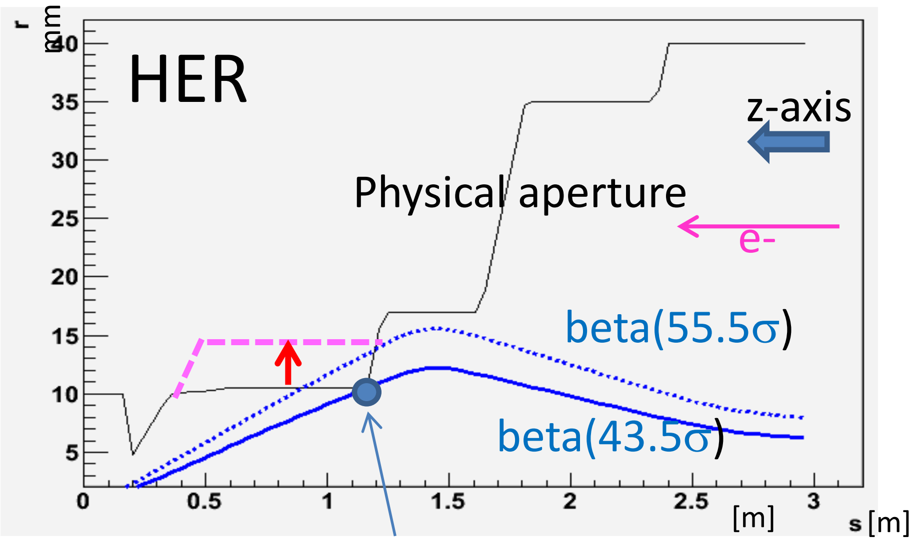
HER: β_y(QC1) = 4390m, <β_y>=54m, γ=13700, r_{QC1}=13.5mm → 4000sec

Strategy to reduce Coulomb BG

$\tau \propto r^2$

- Larger QC1 physical aperture (r=10.5mm→13.5mm)

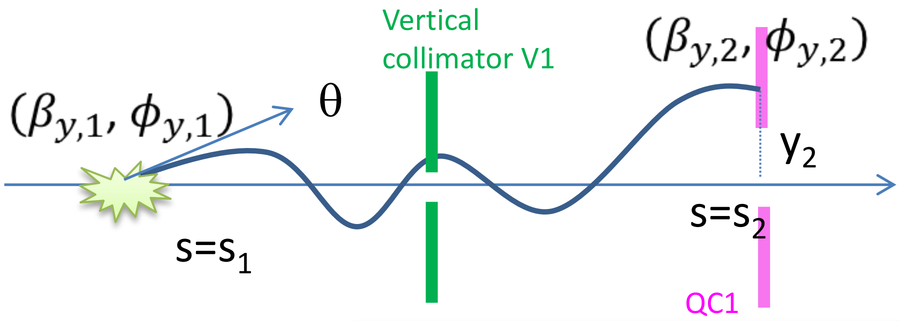




We widened QC1 aperture without major change in QCS design.
Coulomb lifetime improved (LER: 1360→2240sec, HER: 2100→3260sec)

- Vertical collimators!
  - QC1 aperture should not be narrowest over the ring
  - Collimator aperture should be narrower than QC1 aperture
  - Beam instability? (collimators should be very close(few mm) to the beam)

Element-by-element simulation



θ: Scattering angle

$$y_2 = \theta\sqrt{\beta_{y,1}\cdot\beta_{y,2}}\,\sin(\phi_{y,2}-\phi_{y,1})$$

θ_c: critical angle

$$\theta_c(s_1 \to QC1) = r_{QC1} / \sqrt{\beta_{y,s_1}\cdot\beta_{y,QC1}} / \sin(\Delta\phi_{s_1\to QC1})$$

$$\theta_c(s_1 \to V_1) = r_{V_1} / \sqrt{\beta_{y,s_1}\cdot\beta_{y,V_1}} / \sin(\Delta\phi_{s_1\to V_1})$$

Taking into causality, hit rate on QC1 from element s_1 can be calculated by

$$\frac{I_{beam}L_{s_1}n_G}{e}\langle\sigma_R\rangle = \frac{I_{beam}L_{s_1}n_G}{e}\cdot\frac{4\pi\sum Z^2 r_e^2}{\gamma^2}\Delta\left(1/\theta_c^2\right)$$

$$\Delta(1/\theta_c^2) = 1/\theta_c(s_1 \to QC1)^2 - 1/\theta_c(s_1 \to V_1)^2$$

Sum up for all element s_1 over the ring to obtain total hit rate on QC1.

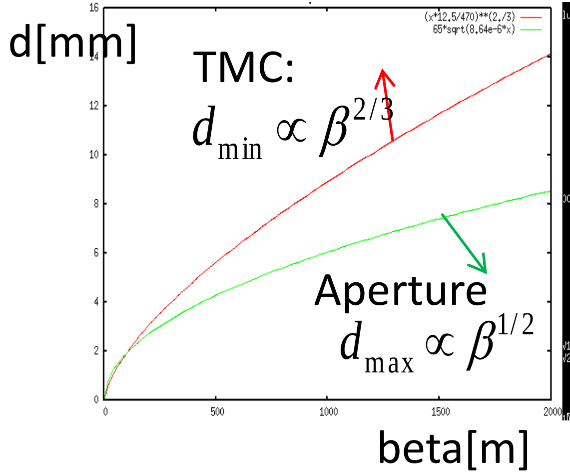
Multi-turn loss is also simulated in similar way ($\Delta\phi$+= $N_{turn}*\Delta\phi_{turn}$), also taking in account the causality

Where we should put vertical collimator?

Collimator aperture should be narrower than QC1 aperture.

$$d/\sqrt{\varepsilon\beta} < r_{QC1}/\sqrt{\varepsilon\beta_{QC1}} \Rightarrow \boxed{d_{\max} \propto \beta^{1/2}}$$

Collimator position



TMC instability should be avoided.

Assuming following two formulae:

$$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i k_{\perp i}(\sigma_z)} > 1.44 \text{ mA/bunch (LER)}$$

taken from "Handbook of accelerator physics and engineering, p.121"

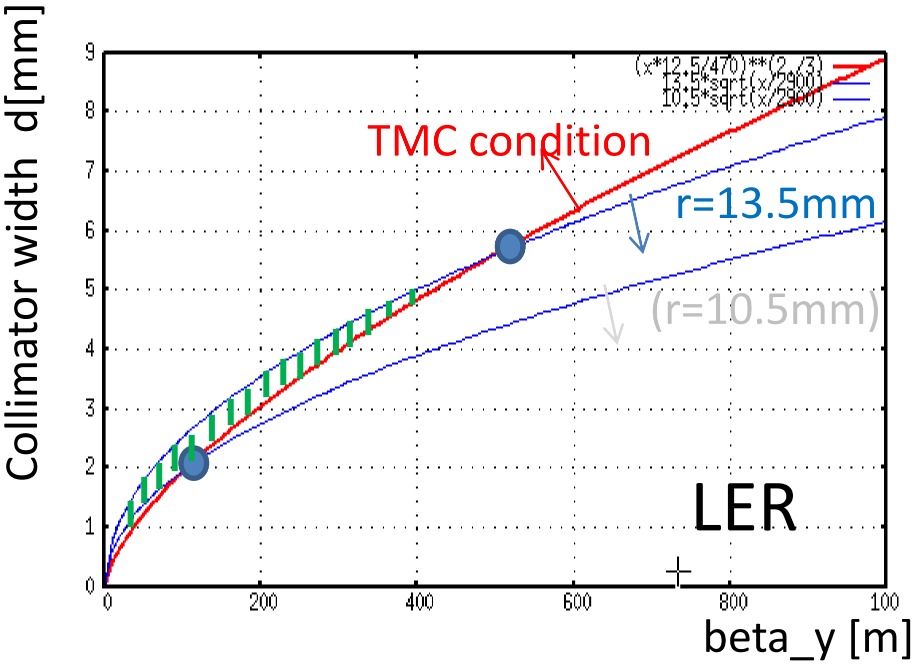
Kick factor $k_\perp = 0.215 A Z_0 c \sqrt{\dfrac{\theta}{\sigma_z d^3}}$

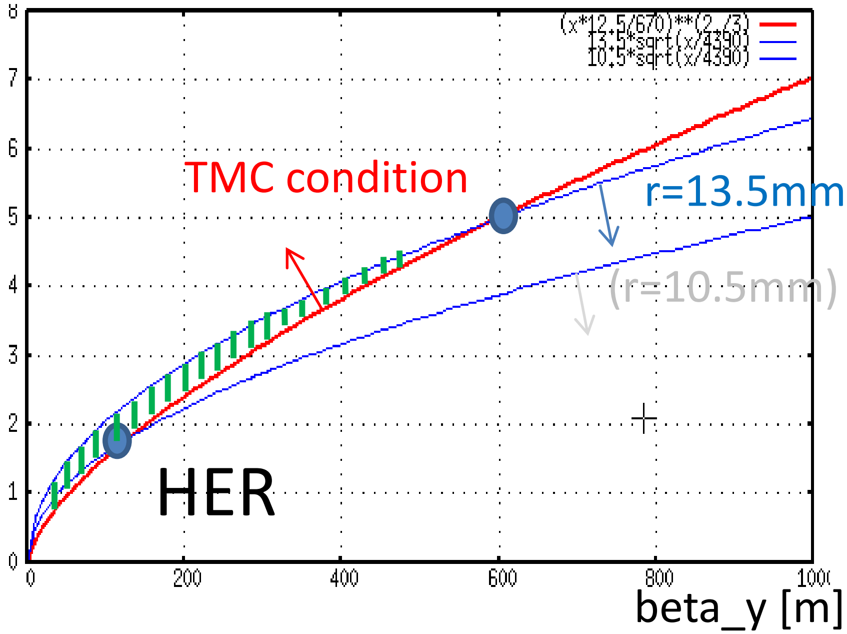
(in case of rectangular collimator window)

$$\Rightarrow \boxed{d_{\min} \propto \beta^{2/3}}$$

We should put collimator where beta_y is SMALL!

Candidate collimator locations





lerfqlc_1604

V1 collimator @ LLB3R (downstream)
(s=-90→-82m, βy=30→146m)
βy=125m, 2.23mm<d<2.81mm

Ny(V1)= 42.82, Ny(QC1)= 44.32

herfqlc5605

V1 collimator @ LTLB2 (downstream)
(s=-63→-61m, βy=81→187m)
βy=123m, 1.74mm<d<2.26mm

Ny(V1)= 1.25, Ny(QC1)= 0.25

Collimator position should satisfy beta_y condition above,
need space(at least 1.5m), and the phase should be close to IP

Vertical collimator width vs. Coulomb loss rate, Coulomb life time

ler1604, V1=LLB3R downstream

V1 width[mm]	IR loss [GHz]	Total loss[GHz]	Coulomb life[sec]
2.40	0.04	153.9	1469.8
2.50	0.05	141.8	1594.8
2.60	0.09	131.0	1724.9
2.70	0.24	121.4	1860.2
2.80	1.65	111.4	2000.5
2.90	11.48	100.8	2014.3
3.00	21.98	90.3	2014.3

her5365,V1=LTLB2 downstream

V1 width[mm]	IR loss [GHz]	Total loss[GHz]	Coulomb life[sec]
2.10	0.0007	49.6	3294.0
2.20	0.001	45.2	3615.2
2.30	0.357	41.0	3951.3
2.40	7.99	33.0	3985.9
2.50	13.1	27.9	3985.9

Based on element-by-element simulation considering causality the phase difference (by Nakayama)

Up to 100turns

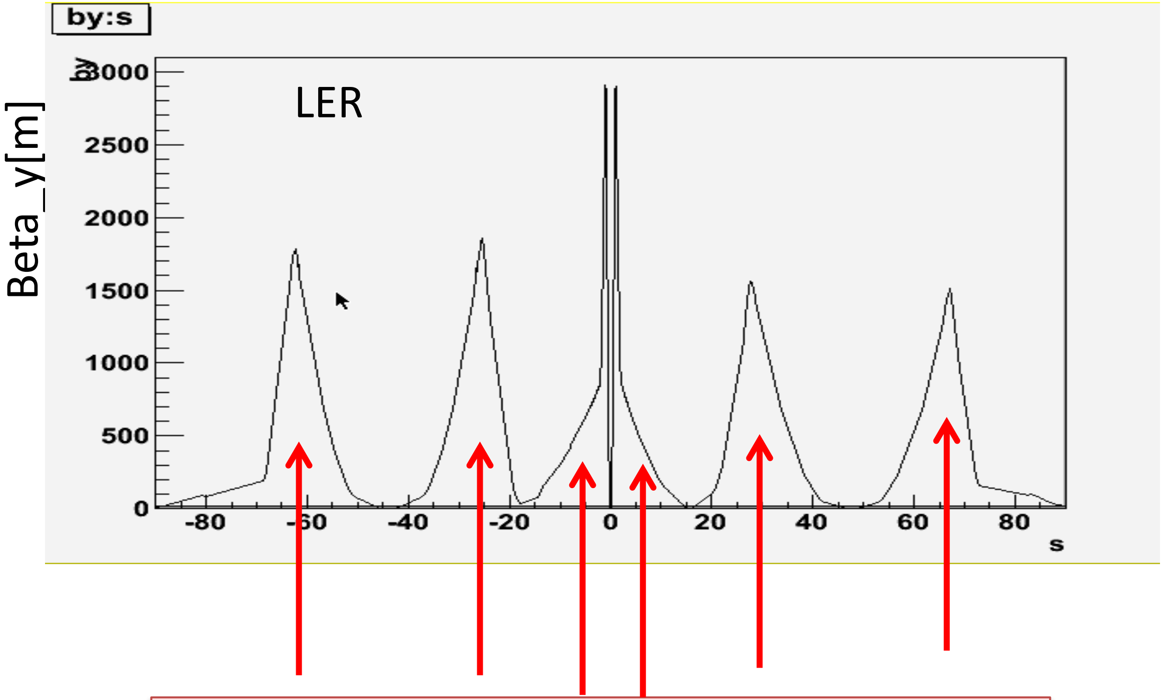
IR loss rate is VERY sensitive to the vertical collimator width.
(Once V1 aperture>QC1 aperture, all beam loss goes from V1 to IR

Typical orbit deviation at V1 : +-0.12mm (by iBump V-angle: +-0.5mrad@IP)

Beta_y and vacuum level

$$\tau_R \propto \left\langle \frac{\beta_y}{P} \right\rangle \cdot \beta_{y,\mathrm{QC1}} / r_{\mathrm{QC1}}{}^2$$

- Vacuum level at large beta_y determines Coulomb lifetime



Very important to achieve good vacuum level in these regions

s	βy	ν_y	
-82m	-	-1.75	V1
-62m	1783m	-1.25	
-25m	1854m	-0.75	
-1m	2905m	-0.25	QC1
+1m	2902m	0.25	
+28m	1564m	0.75	
+67m	1513m	1.25	

ν_y(1 turn)=44.57

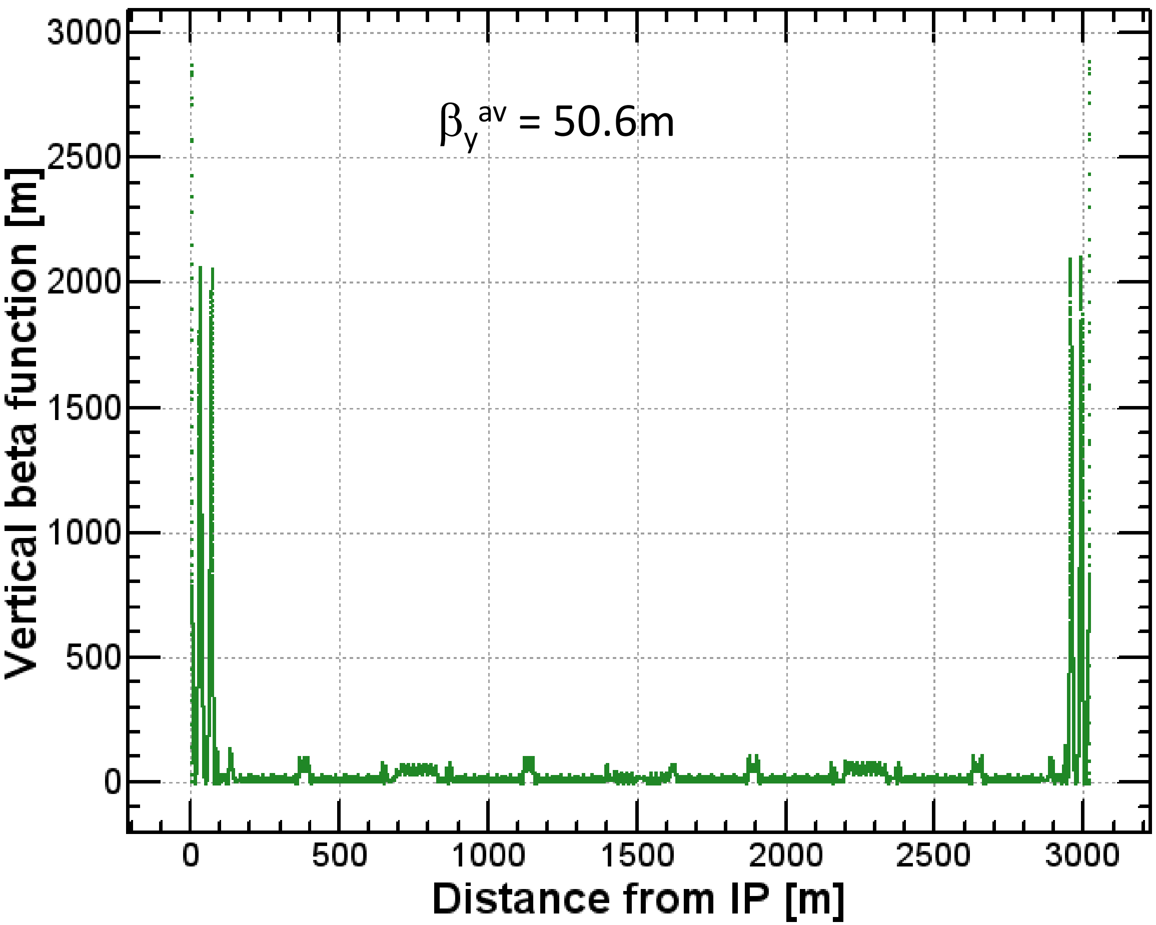
Turn-by-turn loss

ler1604, V1=LLB3R downstream, d_V1=2.6mm

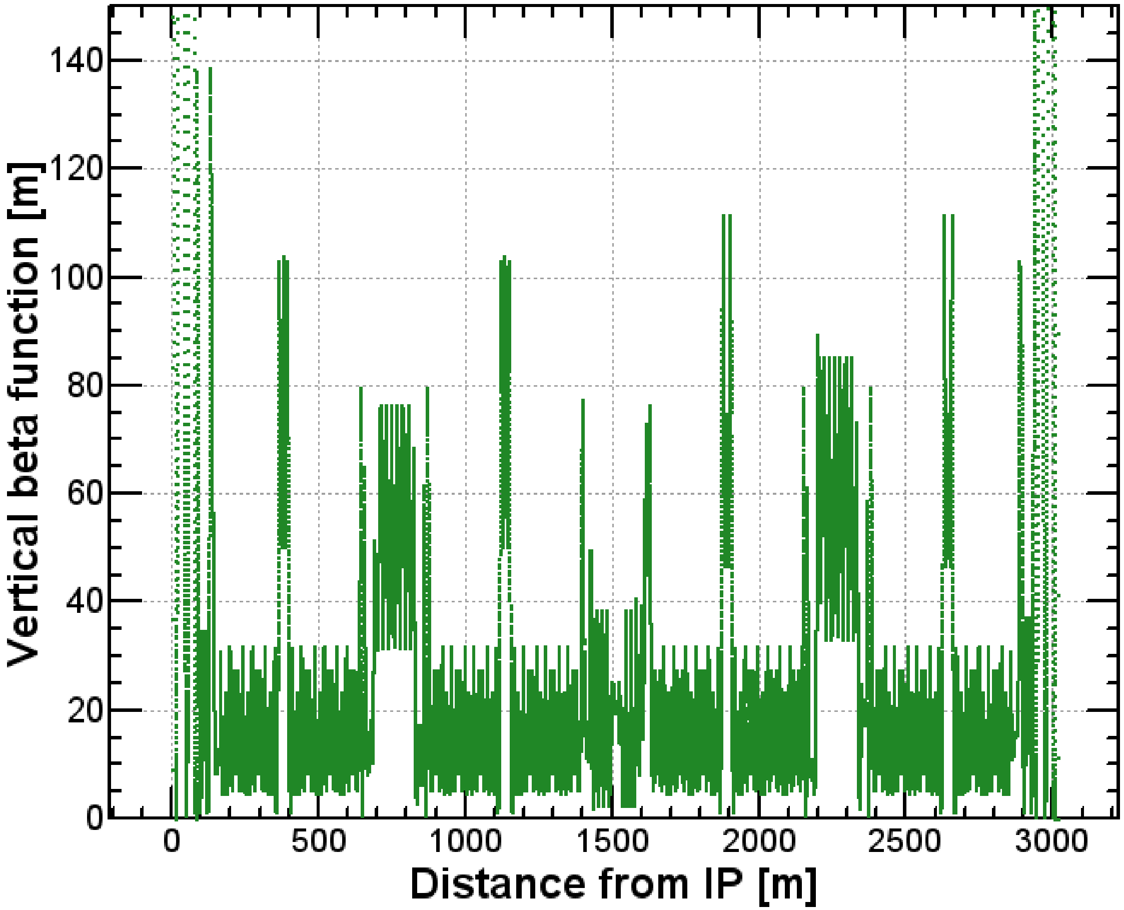
#turn	Loss @ V1	Loss @ QC1
1	32.760	0.090
2	34.220	0.000
3	36.100	0.000
4	17.450	0.000
5	3.720	0.000
6	2.300	0.000
7	0.660	0.000
8	0.040	0.000
9	0.030	0.000
10	0.050	0.000
11	0.320	0.000
12	0.330	0.000
13	0.060	0.000
14	0.060	0.000
15	0.030	0.000
16	0.020	0.000
17	0.030	0.000
18	0.750	0.000
19	0.700	0.000
20	0.030	0.000

#turn	Loss @ V1	Loss @ QC1
21	0.040	0.000
22	0.020	0.000
23	0.010	0.000
24	0.020	0.000
25	0.470	0.000
26	0.410	0.000
27	0.010	0.000
28	0.020	0.000
29	0.010	0.000
30	0.010	0.000
31	0.010	0.000
32	0.140	0.000
33	0.120	0.000
34	0.010	0.000
35	0.010	0.000
36	0.010	0.000
37	0.000	0.000
38	0.010	0.000
39	0.010	0.000
40	0.010	0.000

No loss at nturn>40



$\beta_y^{av} = 50.6\text{m}$



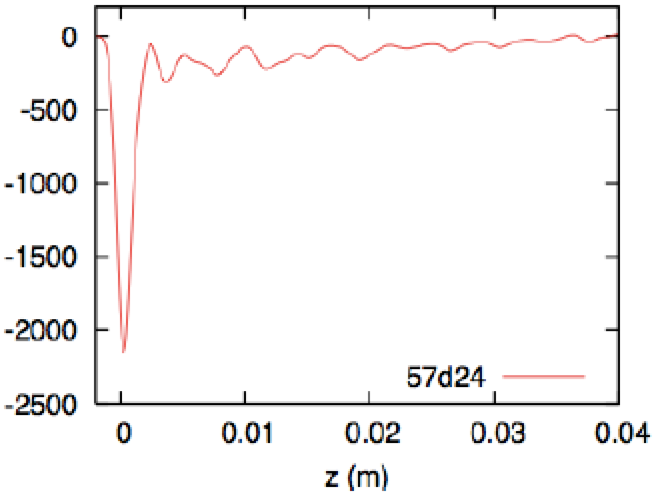
Vertical beta function [m]
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
Distance from IP [m]

Confirmation of TMC conditions with realistic model

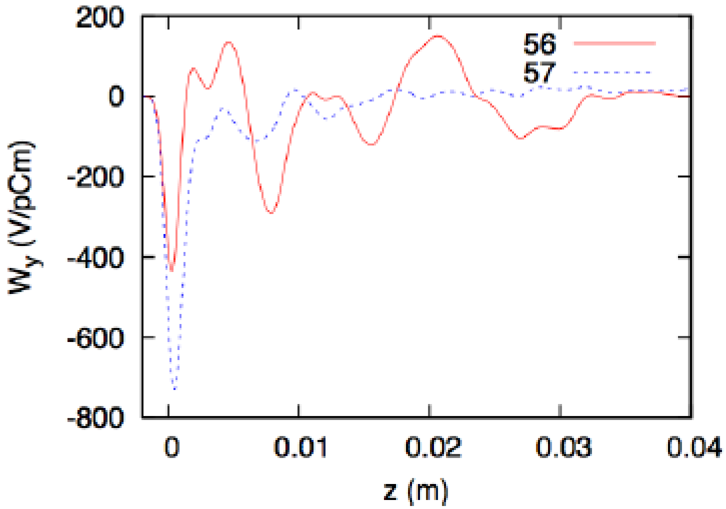
K. Ohmi (KEKB)

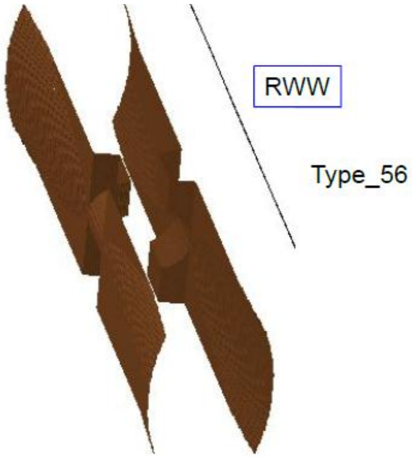
Impedance of realistic collimator

d=2.4mm mask for LER



d=5mm mask for HER





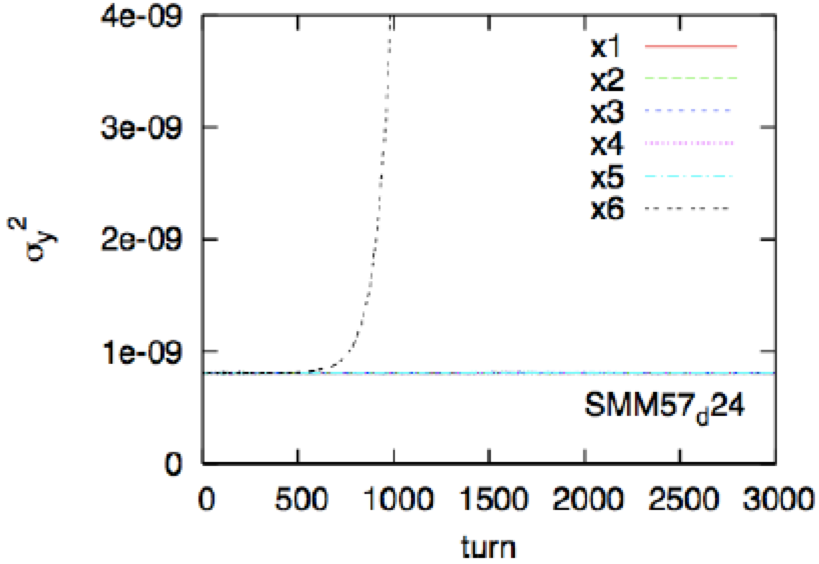
Dedicated collimator design for small impedance

- Round-shape of collimator head
- d=5mm(H), d=2mm(V)

Y. Suetsugu
(KEKB)

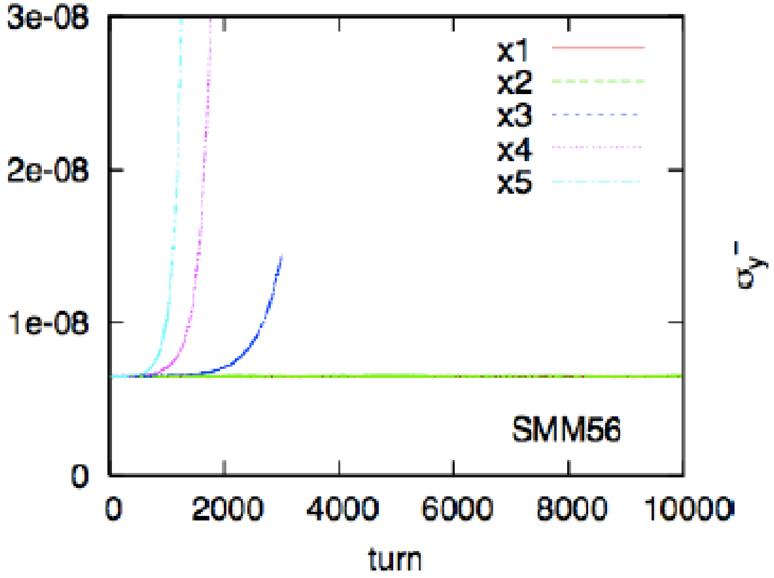
I_{th} calculated by tracking simulation

LER σ_z = 6mm



I_{th}=1.44mAx5~6=7.2~8.6mA

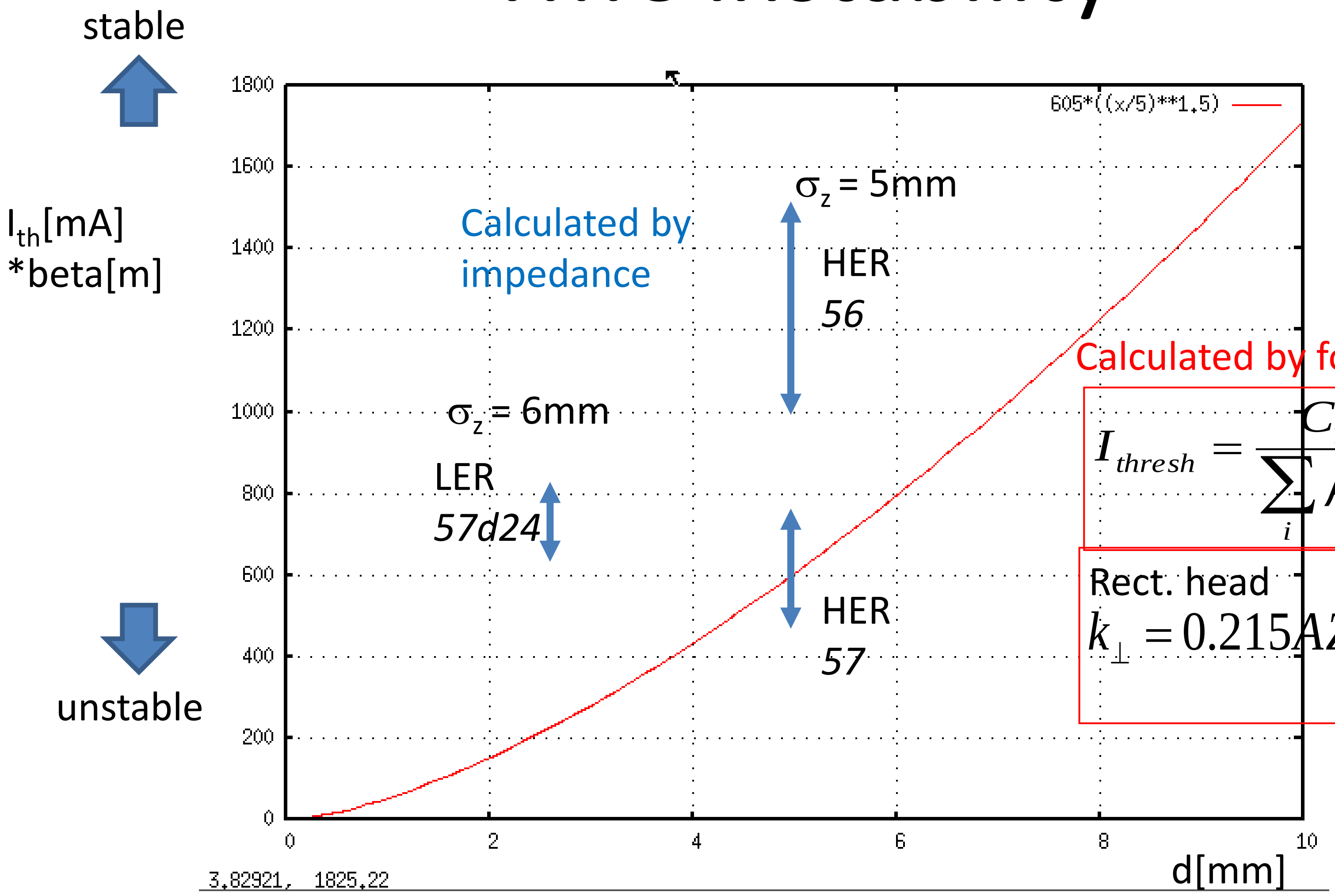
HER σ_z = 5mm



I_{th}=1.04mAx2~3=2~3mA

TMC instability caused by the LER/HER vertical collimators are tolerable.

TMC instability



σ_z = 6mm

Calculated by formulae

$$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i k_{\perp i}(\sigma_z)}$$

Rect. head

$$k_\perp = 0.215 A Z_0 c \sqrt{\frac{\theta}{\sigma_z d^3}}$$

Beam-gas summary

- Coulomb >> bremsstrahlung
- Larger $<\beta_y>$ and narrower IR aperture make Coulomb BG much severer at SuperKEKB than at KEKB
- Vertical collimators , placed at small beta_y, can reduce beam-gas BG down to ~0.1GHz for LER/HER.
- Beam instability for such collimators is confirmed to be tolerable, performing tracking simulation with realistic collimator shape
- Vacuum level at large beta_y affects beam-gas lifetime.
- Simulation using “SAD” is in preparation
- R&D ongoing for collimator which can resist ~100GHz loss

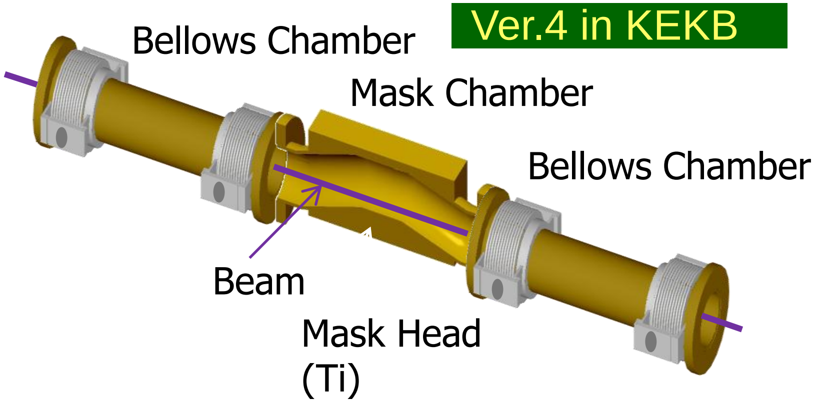
backup

Suetsugu-san’s slides

Design of key components_11

- **Movable mask (collimator)**
  - Indispensable in order to reduce background noise of BELL-II
  - Long R&D history in KEKB
    - Stealth type was proposed, but not yet realized.
  - **For SKEKB,**
    - High thermal strength against wall heating (~ 1 mm from beam for vertical type)
    - Low beam impedance (ex. Against TMC instability)
    - Fitting to antechamber scheme
    - Robust against impact of beam in case
    - Placed at both sides of the ring
    - HOM absorbers (near to masks)
  - Concept of Ver.4 in KEKB will be available, at least in the beginning stage: how to fit to antechamber scheme?

⇨ **One candidate: PEP-II type**



Design of key components_12

- **Movable masks for KEKB (Ver.4) and PEP-II**

PEP-II type

Pair-type

(Two mask heads)

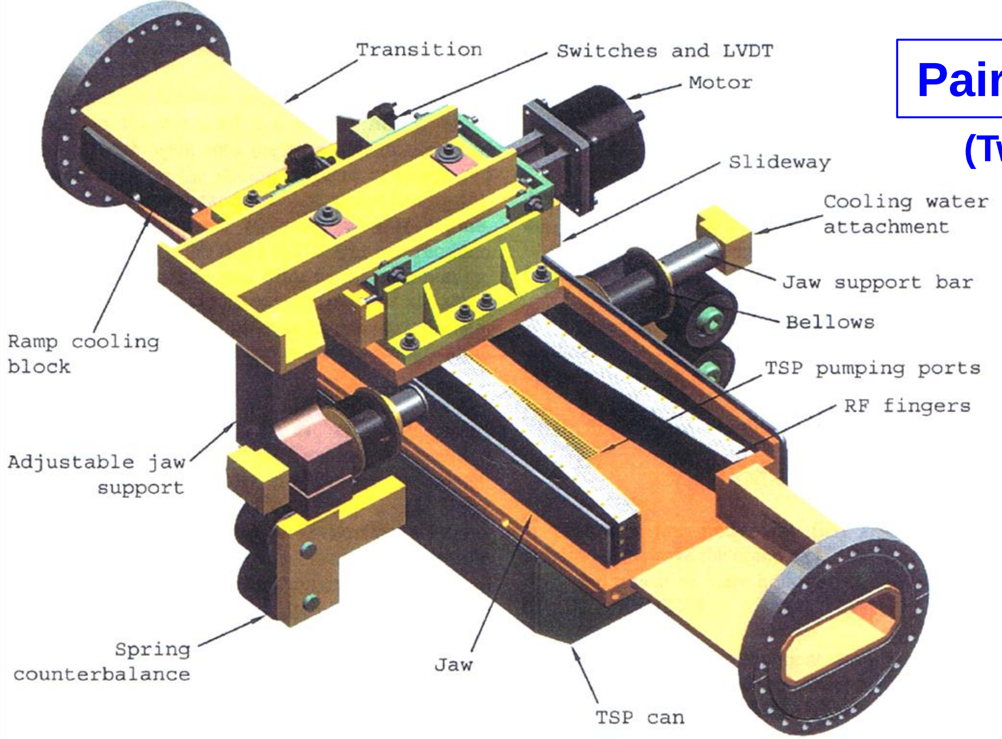
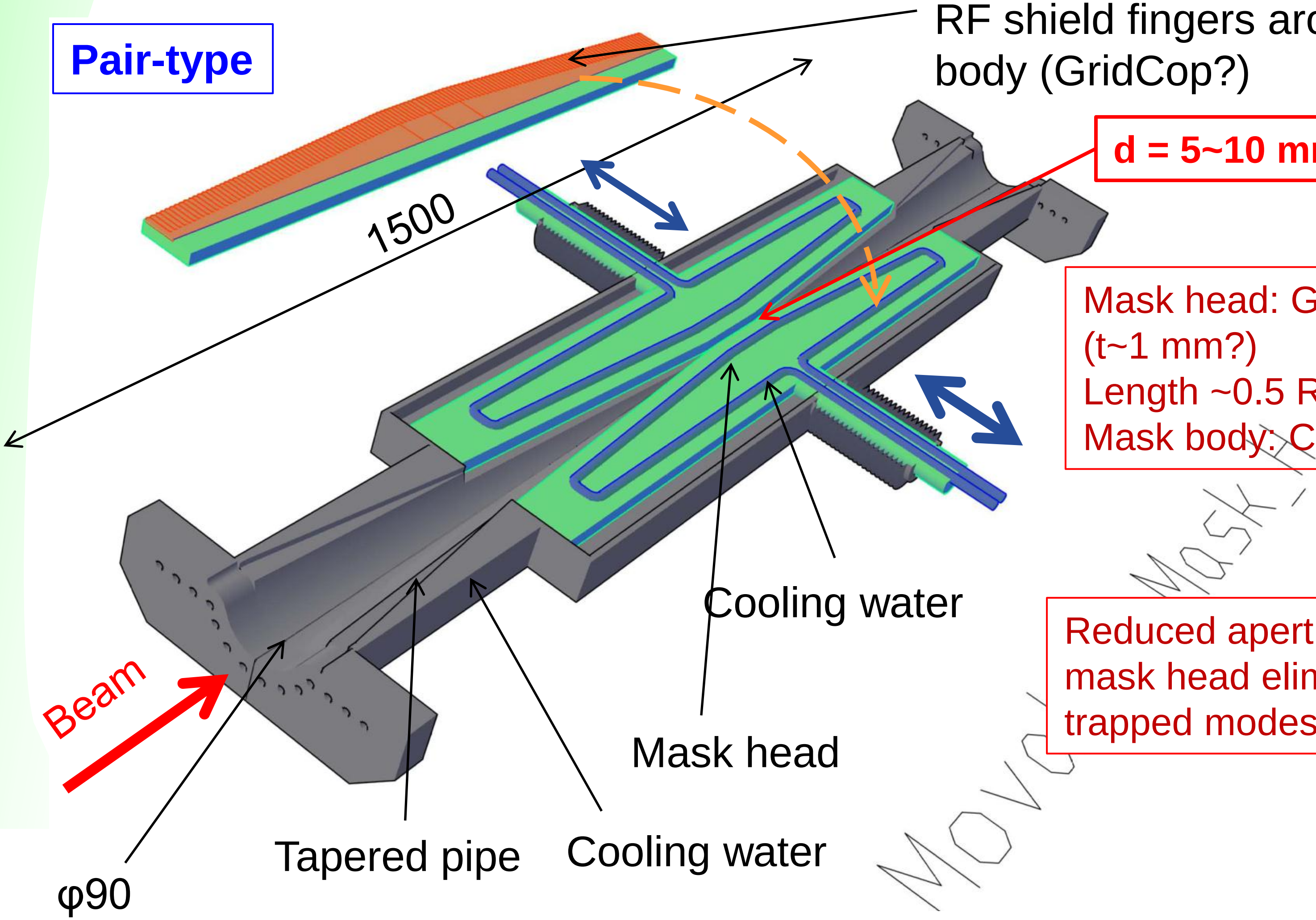


Figure 1: Cutaway view of the HER collimator

“NO structural problem in this design. Intense excited HOM have heated up bellows chambers and NEG elements near the masks.”
(from M. Sullivan [SLAC])

Design of key components_13

- Concept of **horizontal** movable mask



Pair-type

RF shield fingers around body (GridCop?)

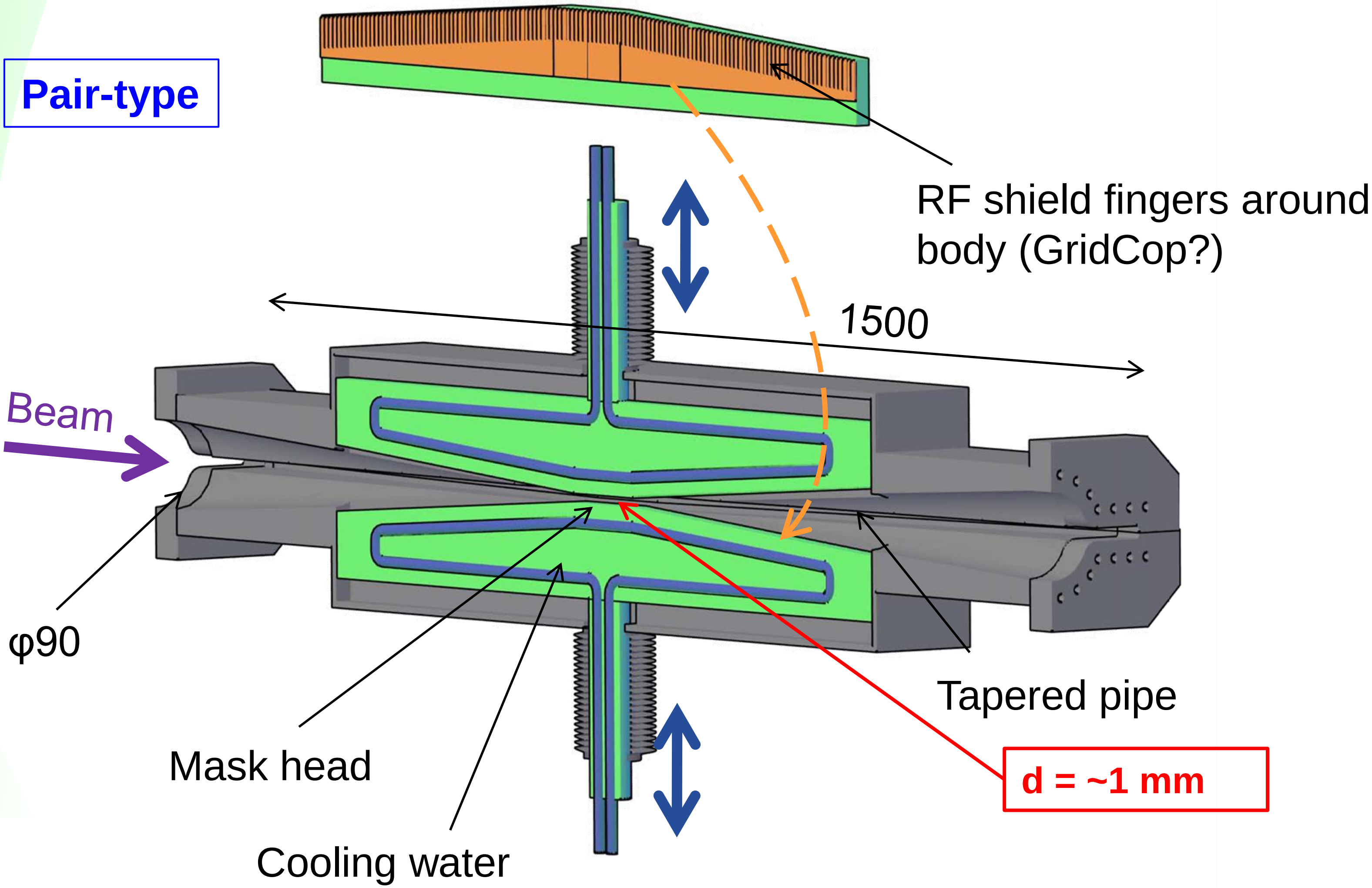
d = 5~10 mm

Mask head: Graphite?
(t~1 mm?)
Length ~0.5 R.L.
Mask body: Copper

Reduced aperture at the mask head eliminates trapped modes.

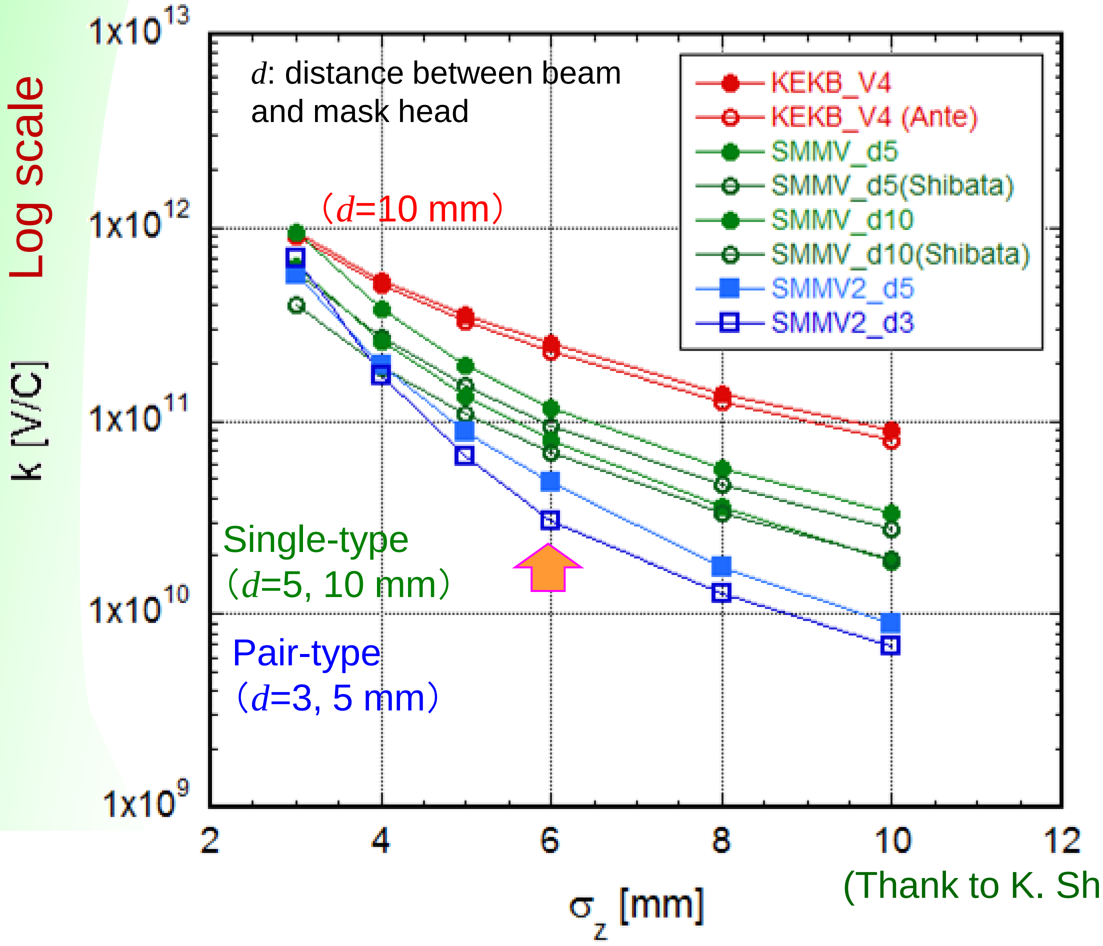
Design of key components_14

- **Concept of vertical movable mask**



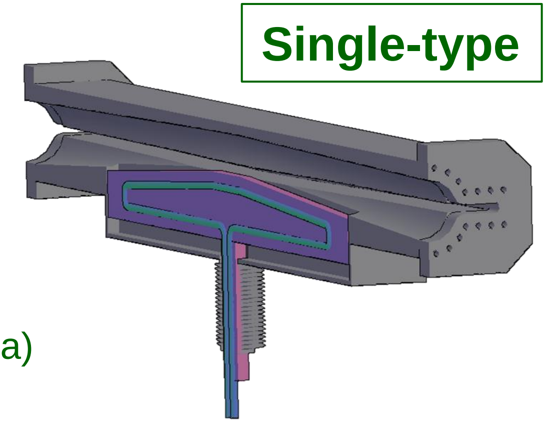
Design of key components_15

- **Loss factors (*k*)**
  - Calculated by GdfidL, 3D model
  - Dependence on bunch lengths (σ_z)



(Thank to K. Shibata)

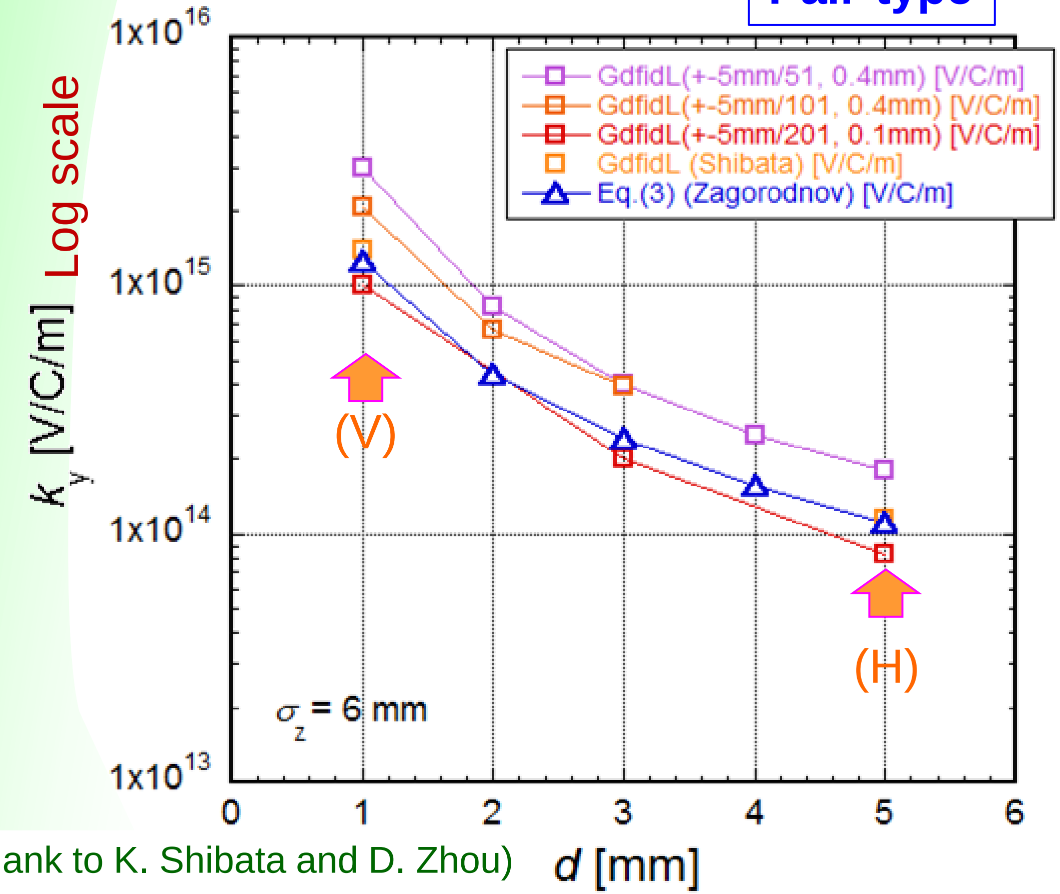
- Smaller than that for present Ver.4 (KEKB): owing to long ramp?
- Small dependence on *d*
- No big difference between single- and pair-type versions: Pair-type is smaller?



Design of key components_16

- **Kick factors (*k_y*)**
  - Calculated by GdfidL, 3D model, σ_z = 6 mm
  - Dependence on *d*

Pair-type



(Thank to K. Shibata and D. Zhou)

- Large dependence on d
- k_y for pair-type is approximately twice of that for single-type.

Horizontal

d = 5 mm

$k_y = 8\times10^{13}$ V/C/m

Vertical

d = 1 mm

$k_y = 1\times10^{15}$ V/C/m

Ref.:I. Zagorodnovet al., EUROTeV-Report-2006-074

Design of key components_17

- **Threshold current for TMC (LER)**
  - Transverse mode coupling instability (TMC)
  - Threshold formula (from B. Zotter, Handbook of Accelerators)

$$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i k_{\perp i}(\sigma_z)} \quad \text{[A/bunch]}$$

where

$C_1 \sim 8$

$f_s = 2.13 \times 10^3$ Hz

$E/e = 4 \times 10^9$ eV

$\beta \sim 20$ m (in Arc), ~1 m (in Local Correction)

$k_\perp(\sigma_z)$ = (kick factor, V/C/m)

Σ = (total number)

- Design bunch current = 1.44 mA/bunch
- For **1** mask (**2** heads)

d = 5 mm [H, Arc]: $k_y = 8\times10^{13}$ V/C/m → I_{th} = 43 mA/bunch

d = 1 mm [V, Arc]: $k_y = 1\times10^{15}$ V/C/m → I_{th} = 3.4 mA/bunch

d = 1 mm [V, LC]: $k_y = 1\times10^{15}$ V/C/m → I_{th} = 68 mA/bunch

(With non-linear collimation scheme)

⇨ 4 horizontal at arc masks will be available.
1 vertical masks at LC will be OK.

Design of key components_18

- **Wall loss**
  - For a beam pipe with a radius of a [m], a bunch with a length of σ_z [m], the wall loss per meter is (from A. Piwinski, Handbook of Accelerators)

$$P' = \frac{\Gamma(3/4) I_b^2 C}{4\pi^2 a \sigma_z^{3/2} \sqrt{2\mu\sigma_c / Z_0}}$$

I_b=Bunch current
C=Circumference(=3000m)
Z_0=Vacuum impedance(= 377Ω)
σ_c=Conductivity (1/Ω)
μ = 1, Γ(3/4) = 1.225

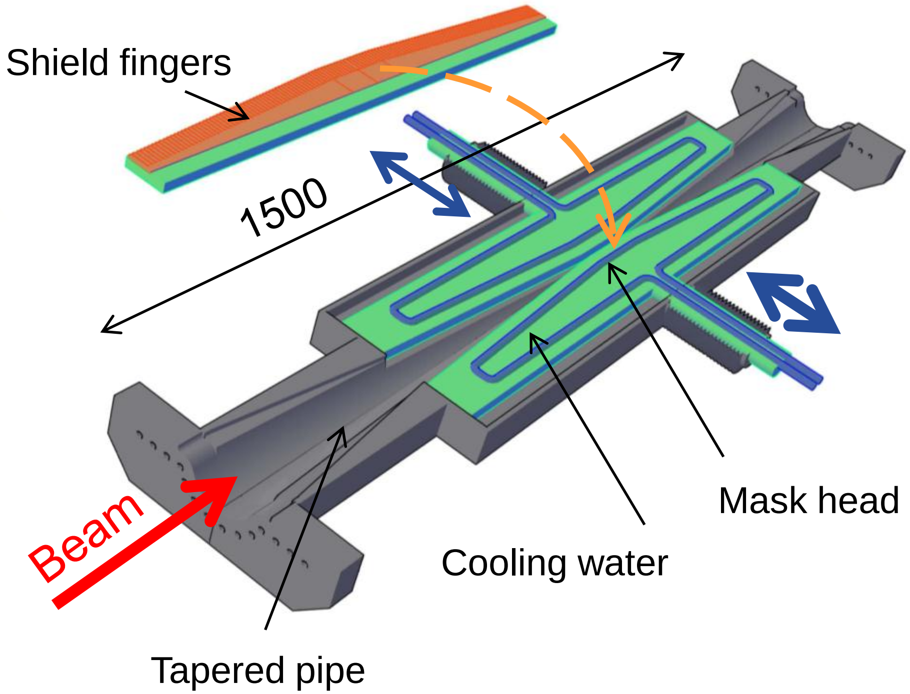
  - For ***d*** **= 1** mm:
  - If **graphite** (σ_c=2×10^5 1/Ωm) is used, P'=2.55 W/m. For 2500 bunches、P'= **32 kW/m**. If ½ of total current concentrated in 1 mm width, ***P*** **= 50 W/mm² (32 × π/2).**

    → Very hard to deal
  - If **tungsten** (σ_c=2×10^7 1/Ωm) instead, ***P*** **= 5 W/mm²**

    → Well manageable with water cooling.
    How about damage? Easy replaceable?

設計・製作_19

- **可動マスク(コリメータ)**
  - PEPIIタイプで検討中
  - 水平マスク(垂直マスクはヘッドがビームに近く厳しい)
  - マスクヘッド部の開口を水平・垂直とも狭くすると捕捉モードがない
  - ロスファクター:~1x10^{11} V/C @σ_z=6mm, d = 5 mm:Ver.4 (KEKB)よりも小さい: 長いスロープ(テーパ)のおかげ?



- ヘッド長さ:約2 R.L. は欲しい(中村氏)
- リング外側にも必要
- 位置決め精度:0.05mm
- ビーム位置のフィードバック:両側のBPMを使う?
- ビームの衝突に対する対処

設計・製作_20

- **可動マスク(コリメータ)**
  - TMC(Transverse Mode Coupling Instability)
    - キックファクター：~2x10^{14} V/C @σ_z=6mm, *d* = 5 mm
    - *d*に大きく依存：*d* = 1mmで3x10^{15} V/C
    - もしβ = 10 m: *d* = 5mmでは12台でもOK
    - *d* = 1mmでは1台程度が限界
    - 本当のβで評価する必要あり

$$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i k_{\perp i}(\sigma_z)}$$

[A/bunch]

- **壁損失**
  - *d* =1mmの時、もしグラファイト(σ_c=2×10^5 1/Ωm)を用いると*P* = 50 W/mm^{2}と非常に厳しい。
  - 例えば導電率の良いタングステン(σ_c=2×10^7 1/Ωm)では、*P* = 5 W/mm^{2}と全く問題ない

$$P' = \frac{\Gamma(3/4) I_b^2 C}{4\pi^2 a \sigma_z^{3/2} \sqrt{2\mu\sigma_c / Z_0}}$$

[W/m]　(A. Piwinski)

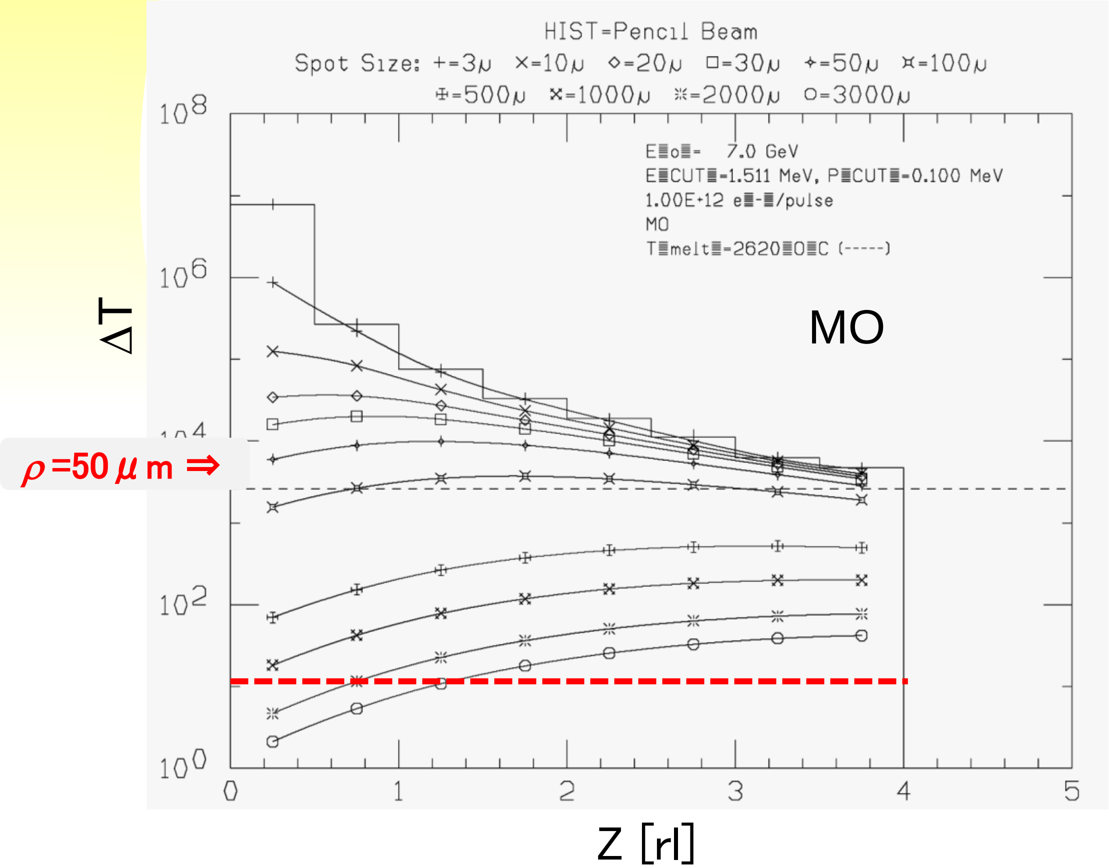
設計・製作_21

- **可動マスク(コリメータ)**
  - **ヘッド材料：候補**
    - 基本的に高融点
（ビームロスによる発熱具合に依る。）
    - 高熱伝導率：冷却
    - 高導電率：インピーダンス、ジュール損
    - 加工性、接合性、入手の容易さ
    - 真空特性：低蒸気圧
  - **ビーム衝突時の温度計算**
    - EGS4による計算(佐波氏)
    - 円柱形状の材料にビームを打ち込んで温度上昇を調べた。
    - モンテカルロ計算は初期値を振ったペンシルビームで行い、その結果を重ね合わせて、各々のビームサイズの場合の温度上昇を求める。
    - ビームサイズρはシ グマで入力し、ラウンドビーム。円柱はr-zのメッシュに切られている。:実効的にρ ~50 μm

	融点
Al（参考）	659
Be	1278
C	3600
Co	1495
Cr	1857
Cu（参考）	1083
Hf	2227
Ir	2443
Mo	3620
Nb	2468
Pd	1552
Pt	1769
Re	3180
Rh	1966
Ru	2250
Ta	3015
Ti	1800
W	3400
Zr	1852

設計・製作_22

- **可動マスク(コリメータ)**
  - **ヘッド材料：候補)**
    - 計算結果：Moの例



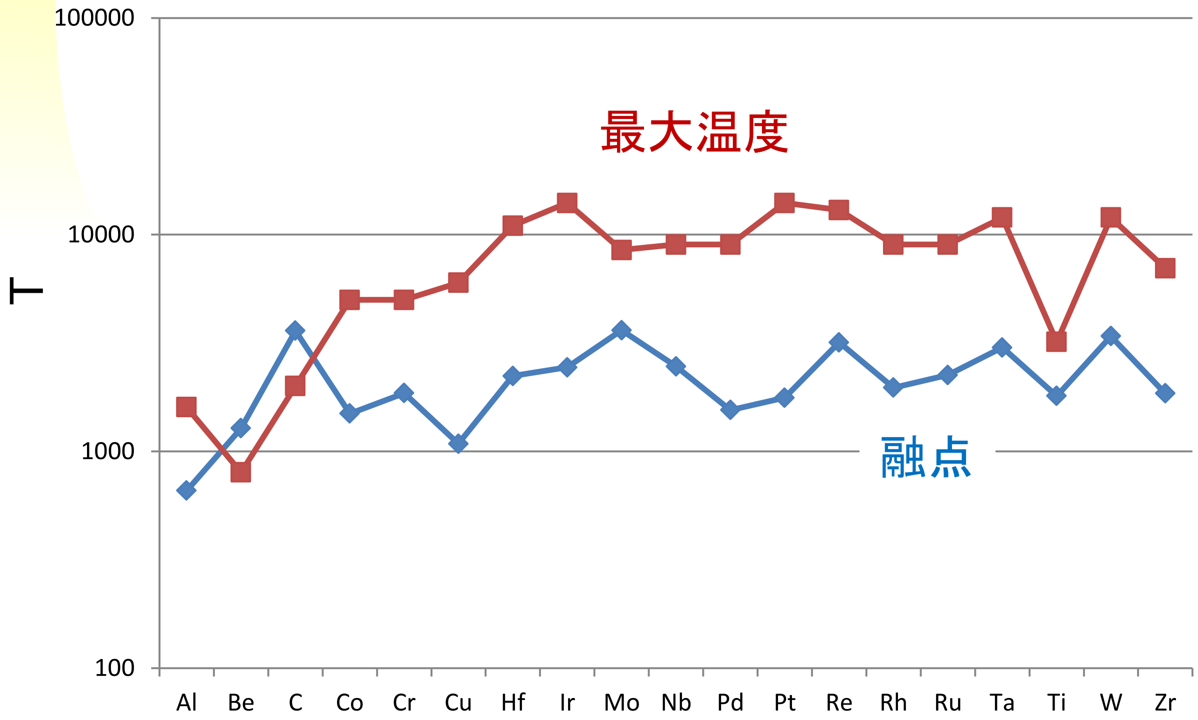
- 計算：1x10^{12} e^{-}/pulse:全バンチの入力だとすると、16 mAに相当。
- ビーム電流3.6 Aでは、2.25x10^{14} e-/pulse。225倍。融点を実効的に下げたものを赤破線で示す。
- ビームサイズρを約50μmとすると、どの厚さでも溶ける。
- RL=0.5の範囲で、ρ = 2mm = 3000μmなら大丈夫か。

設計・製作_23

- **可動マスク(コリメータ)**
  - **ヘッド材料：候補(温度)**
    - 融点との差が小さいもの：Be、C 、Cr、Mo、Ti、W
    - だが、周回しているビームが全て当たるとどの材質でも溶ける！

→容易に(?)ヘッド交換できるようにする。

→できるだけ速いアボートシステムを！！



- $1\text{x}10^{12}$ e^{-}/pulse(計算条件)、$\rho = 50\ \mu\text{m}$ 相当として、各材質で、RL0.5までの最大温度と融点をプロット

設計・製作_24

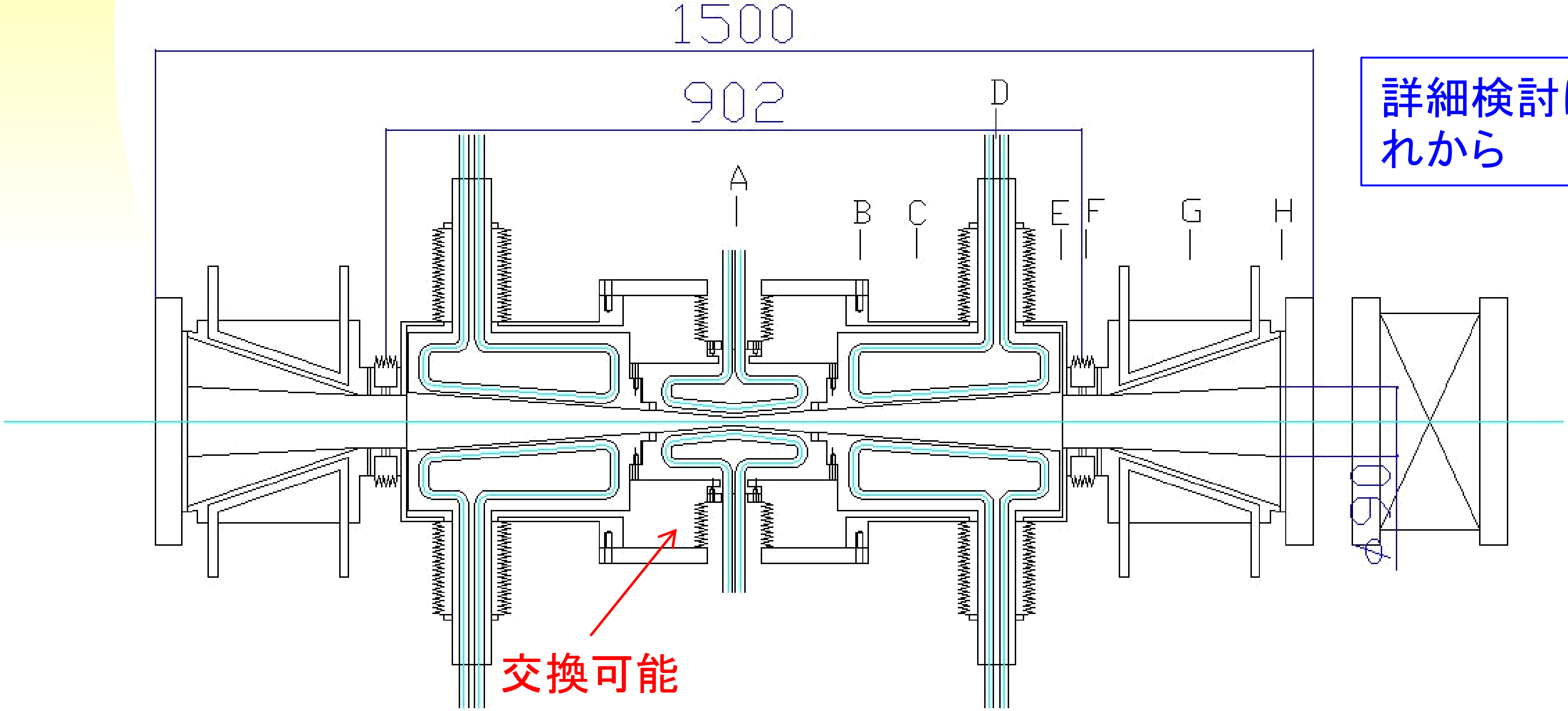
- **可動マスク(コリメータ)**
  - **ヘッド材料：候補(加工性、接合性)**
    - Mo、W、Taは、ブロックであれば入手に問題なし。接合性はWが良い。
    - レアメタル(Ir、Rh)は入手に難(少量なら問題なし?)
    - Beは加工時注意が必要：2RL必要だと700 ㎜必要!
    - W、Mo、Ir、Rhの導電率、熱伝導率が良い

		原子番号	原子量	密度 [g/cm3]	融点 [℃]	比熱 [J/g/K]	比熱 [J/cm3/K]	熱伝導率 [W/m/K]	比抵抗 [nΩm]	放射長 [mm]	線膨張率 [1e-6/C]
銅	Cu	29	63.5	8.93	1083.4	0.386	3.44698	397	16.94	14.73	17
クロム	Cr	24	52	7.19	1857	0.461	3.31459	91.3	132	21.21	6.5
コバルト	Co	27	58.9	8.9	1495	0.427	3.8003	96	63.4	15.63	12.5
ハフニウム	Hf	72	178.49	13.28	2227	0.147	1.95216	22.9	322	5.20	6
イリジウム	Ir	77	192.2	22.4	2443	0.13	2.912	146.9	51	2.93	6.8
モリブデン	Mo	42	95.94	10.2	2620	0.251	2.5602	137	57	9.84	5.1
ニオブ	Nb	41	92.9	8.57	2467	0.268	2.29676	54.1	160	11.86	7.2
パラジウム	Pd	46	106.42	12.16	1552	0.247	3.00352	75.2	108	7.74	11
白金	Pt	78	195.08	21.45	1769	0.134	2.8743	73.4	105.8	3.04	9
レニウム	Re	75	186.2	21.03	3180	0.138	2.90214	47.6	187	3.18	6.6
ロジウム	Rh	45	102.9	12.44	1966	0.243	3.02292	148	47	7.62	8.5
ルテニウム	Ru	44	101	12.2	2250	0.234	2.8548	116.3	77	7.95	9.6
タンタル	Ta	73	180.9	16.6	3015	0.142	2.3572	57.55	135	4.11	6.5
チタン	Ti	24	47.88	4.5	1667	0.528	2.376	21.6	540	31.21	8.9
タングステン	W	64	183.85	19.3	3400	0.138	2.6634	174.3	54	4.58	4.5
ジルコニウム	Zr	40	91.22	6.5	1852	0.289	1.8785	22.6	440	16.07	5.9
ベリリウム	Be	4	9.02	1.84	1287	2.052	3.77568	194	33	353.57	12
グラファイト	C	6	12	2.25	<3370	0.7	1.575	100	500	190.97	

最有力⇒ タングステン

設計・製作_25

- **可動マスク(コリメータ)**
  - 構造案：ヘッド部分を取り換え可能にする？
  - 両側をユニバーサルベローズ構造にしてオフセット可能とする。
  - 場所、数は未確定。Verticalマスクも必要？
  - 本年度は、タングステンと銅ブロックとの接合(HIP)試験。
  - 実機製作は2年後？



交換可能

詳細検討はこれから

可動マスクについて

- **可動マスク(コリメータ)**
  - TMC
    - キックファクター：~1x10^{14} V/C @σ_z=6mm, *d* = 5 mm
    - *d*に大きく依存：*d* = 1mmで1x10^{15} V/C
    - β = 10 m: *d* = 5mmでは12台でも大丈夫。
    - β = 10 m: *d* = 1mmでは2台程度が限界
    - 正規のβで評価する必要あり。

$$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i k_{\perp i}(\sigma_z)}$$

[A/bunch]

$C_1 \sim 8$

$f_s = 2.13 \times 10^3$ Hz

$E/e = 4 \times 10^9$ eV

β [m]

$k_\perp(\sigma_z)$ = (kick factor, V/C/m)

Σ = (total number)

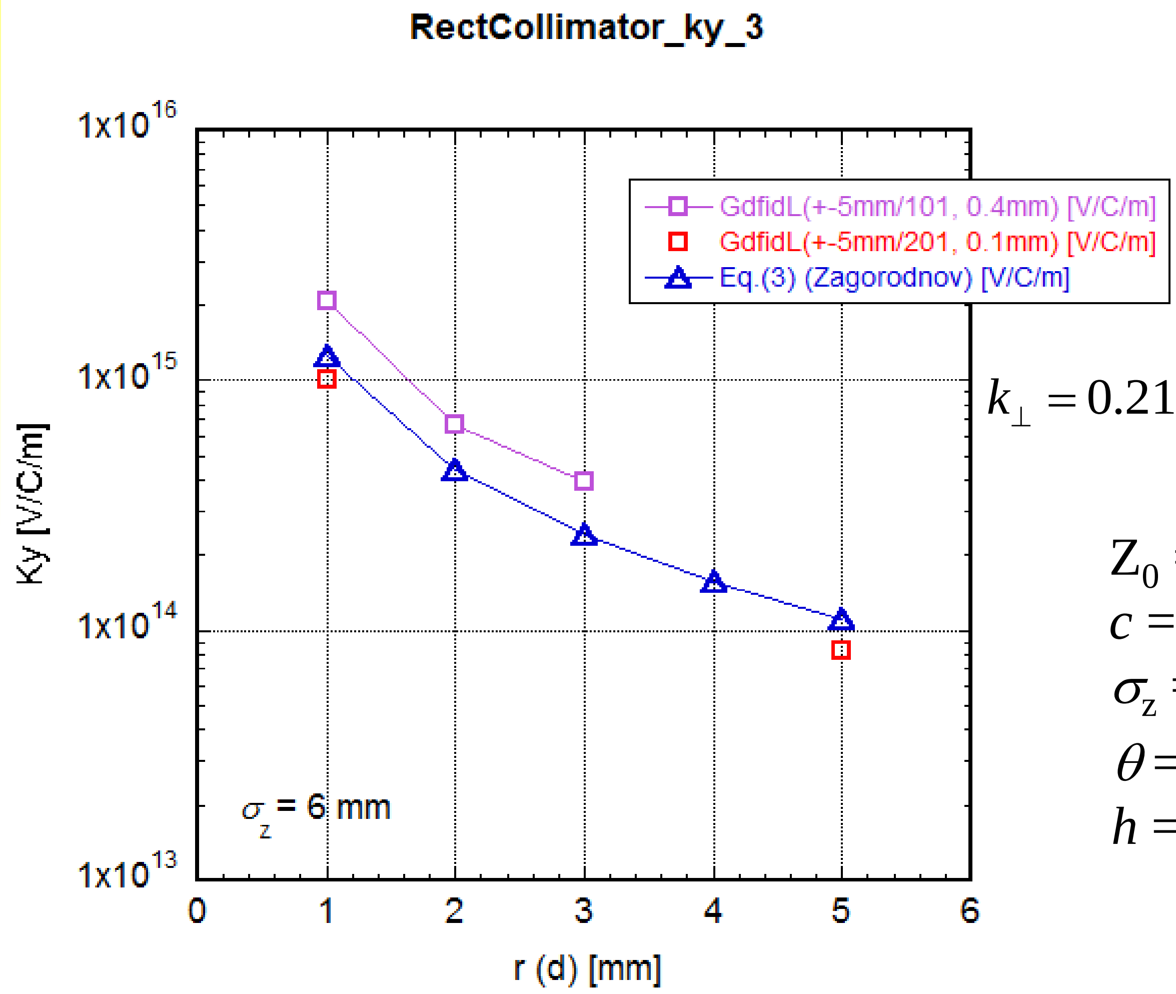
I_{thresh}=3.6/2500 =1.44 mA/bunch

$$\sum_i \beta_i k_{\perp i}(\sigma_z) = \frac{C_1 f_s E/e}{I_{thresh}} = 4.7\times 10^{16}$$

もし：$\beta \sim 680$ m → $k \sim 7\times 10^{13}$ V/C/m → d~7 mm

可動マスクについて

- **可動マスク(コリメータ)**
  - TMC



$$k_\perp = 0.215 A Z_0 c \sqrt{\frac{\theta}{\sigma_z d^3}}, \quad A = \frac{1}{2} (\sim 1)$$

$Z_0 = 377\ \Omega$
$c = 3.0 \times 10^8$ m/s
$\sigma_z = 6$ mm
$\theta =$ slope angle ~0.063
$h = 50$ mm