Vacuum System for SuperKEKB
(mainly for LER arc section)

Y. Suetsugu
on behalf of KEKB Vacuum Group

- Design
  - Upgrade strategy
  - Design of key components
    - Beam pipes
    - Movable masks (collimators)
    - Countermeasures against EC
- Present status and plans
  - Manufacturing of components
  - Plans
- Summary

Upgrade strategy_1

Goal of vacuum-system upgrade is to realize;

- **Ultra-high vacuum**
  - Pressure on the order of 10^{-7} Pa with beam
  - Maintain small emittance, Reduce background noise to detector, Avoid ion instability [HER]
- **Beam pipes (components) with low beam impedance**
  - Maintain small beam emittance and short bunch length, Avoid single and multi-bunch instabilities
- **Stable and robust system**
  - Against high beam current (SR, HOM)
  - Design based on established techniques, but introducing advanced idea at the same time.
- **High cost efficiency**
  - Make use of the change to the nano-beam scheme
  - Continuous use of vacuum systems and reuse components in KEKB as much as possible.

Upgrade strategy_2

In concrete terms;

- **Infrastructures, such as electric lines, cooling water pipes, control systems** are basically reused as it is, after maintenance.
  - Cooling water pipes should be rearranged. Especially for Wiggler section.
  - **Capacity of water cooling system** should be enhanced.
  - **Radiation shielding** scenario should be reconsidered around collimators (Beam loss: ~20 times of KEKB).
- **Pumping and monitoring system**
  - **Pumps:** NEG as main pump, and Ion pump as auxiliary pump: Oil free and capture pumping system
    - Ion pumps are reused, and NEG is replaced with new one.
    - Disconnected to atmosphere during beam operation.
  - **Rough pumping:** Turbo molecular pump and drag pump
    - Oil free, Rough pumping system are reused.
  - **Vacuum gauges** (CCG), L-angle valves, thermo sensors, etc. are reused, with some new backups.

Upgrade strategy_3

- **Beam pipes**
  - **New beam pipe:** Beam pipes with antechambers.
    - Low beam impedance, Higher strength against intense SR
    - Less photoelectron effect to position beam [LER] : Electron-cloud formation is suppressed.
  - Add more powerful **countermeasures against electron cloud (EC) effects** [LER].
    - Solenoid field, Rough surface at side wall, TiN coating
    - **New technique**: Clearing electrode, Grooved surface
- **Main components**
  - **Bellows chambers**, **gate valves**, **movable masks** (collimators), stoppers, etc. are designed to fit the beam pipes.
    - Higher strength against higher beam currents

⇨ **Main upgrade is the replacement of beam pipes and other main vacuum components.**

Design of key components_1

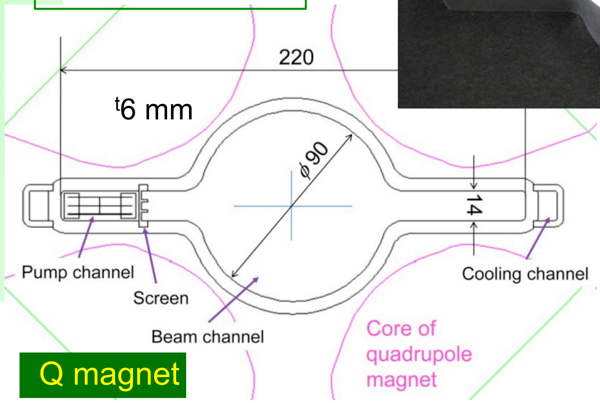
Key components presented here:

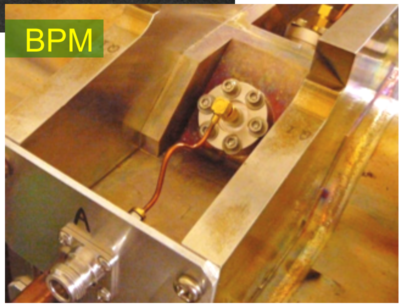
- **Beam pipes**
  - Beam pipes with antechambers
  - Aluminum-alloy beam pipe for LER
  - Countermeasures against electron cloud effects
- **Pumps**
  - NEG strips
- **Connection flange**
  - MO-type flange (Al and Cu)
- **Bellows and Gate valves**
  - Comb-type RF shield
- **Movable mask (collimator)**
  - Conceptual designing has just started.

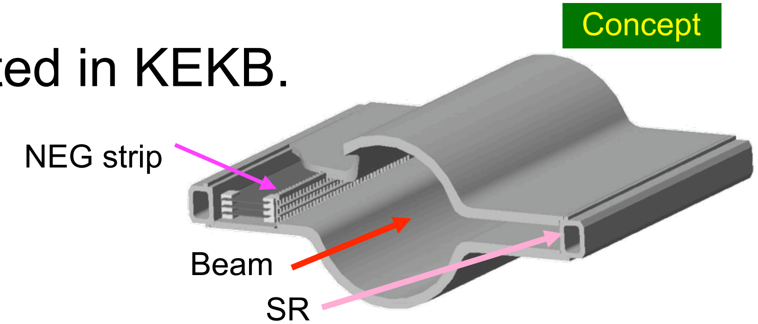
Design of key components_2

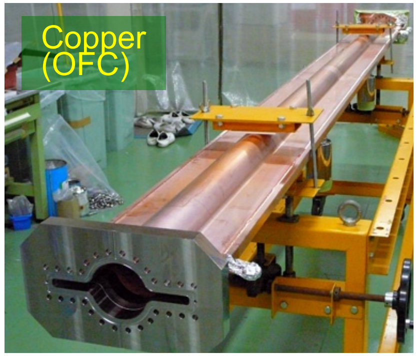
- **Beam pipes:** Beam pipes with antechambers
  - Small effect of photoelectrons, low beam impedance, low SR power density
  - The cross section should fit to the existing magnets.
  - Aluminum alloy is available for LER arc section (see next). Copper is required for wiggler section (and HER).
  - Available by cold-drawing technique (copper) or extrusion technique (aluminum)
  - Copper beam pipes have been tested in KEKB.

Conductance:
~ 88 l/s/m









Design of key components_3

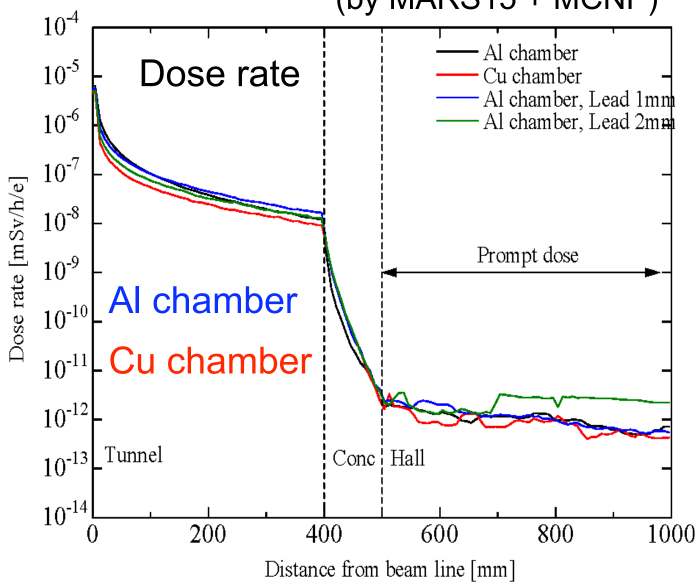
- **Aluminum-alloy beam pipe for LER**
  - In the nano-beam scheme,
    - Max. SR power density ~ 3 W/mm^2 (ref: HER ~15 W/mm^2) owing to long curvature of bend
      → **Aluminum alloy is available.**
  - **Merit (compared to copper):**
    - Cost reduction
    - Easy manufacturing (TIG welding is available.)
    - Easy handling (light)

Aluminum beam pipe with antechambers (extrusion)

Design of key components_4

- **Aluminum-alloy beam pipe for LER**
  - **Problems to be considered (compared to copper case):**
    - Relatively high gas desorption and high secondary electron yield
      → With TiN coating in any way to suppress electron cloud effect
    - High resistive wall impedance
      → Not so serious owing to a large aperture
    - Vibration of beam pipe → Eddy current in Q → Beam oscillation
      → A problem in Spring-8. Rigid fixing of beam pipe was effective.
    - Radiation issues: (T. Sanami, KEK)
      Leakage of SR (ε_r = 1.8 keV):
      − Dose < 1 MGy for 10 years :OK
      − Checked experimentally in KEKB.
      Shielding of loss particle
      – No big difference between Al and Cu in a simulation.

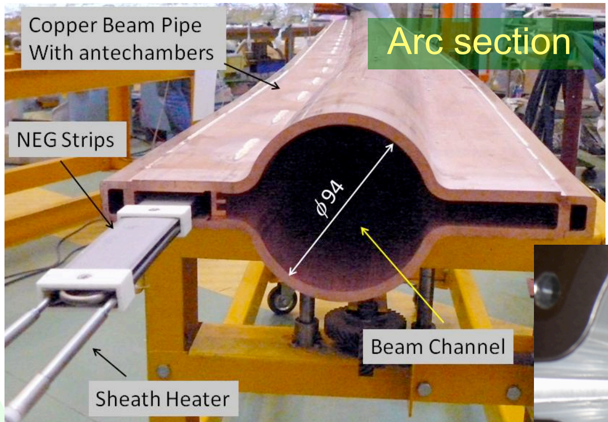
(by MARS15 + MCNP)



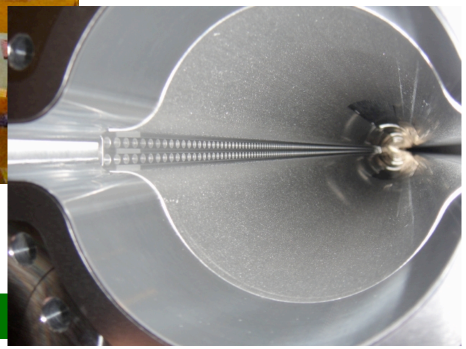
Al-alloy beam pipe is adopted for LER beam pipe

Design of key components_5

- **Main Pump (NEG)**
  - **Arc:** Available in one of antechambers (inside of the ring)
    - Make the most of distributed pumping system: effective pumping.
    - Effective pumping speed of ~ 80 l/s/m.
  - **Straight:** Lumped pump ports at both antechambers.
  - Ion pumps: Placed every 10 m
    - Helpful at higher pressure



Diameter ϕ4 mm,
thickness 5 mm
2 row: 333 holes/m
C~2.5x10^{-1} m^3/s/m
S_{eff}~ 1.x10^{-1} m^3/s/m



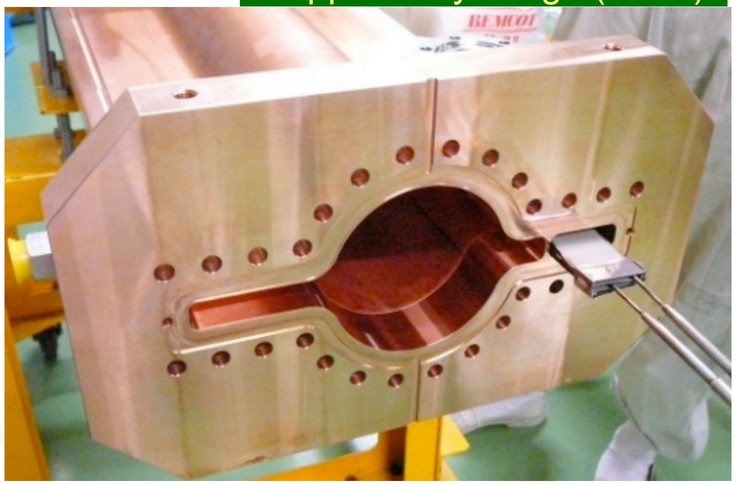
Screen

Straight section
(Wiggler section)

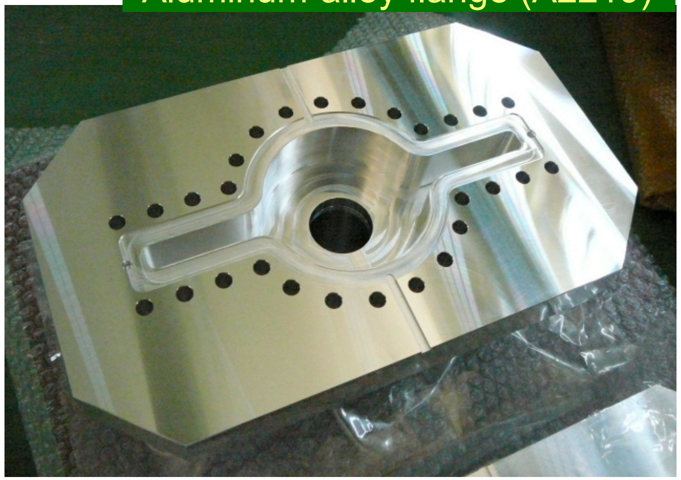
Design of key components_6

- **Flange :** MO-type Flanges
  - Thermally strong, sure RF bridge, applicable to antechamber scheme, low beam impedance
  - In addition to stain-less flanges, **copper alloy** and **aluminum-alloy** flanges had been developed.
    - Easy welding to pipes, reduction in heating by wall loss
  - Several copper flanges have been installed into the ring and tested.

Copper-alloy flange (CrCu)



Aluminum-alloy flange (A2219)

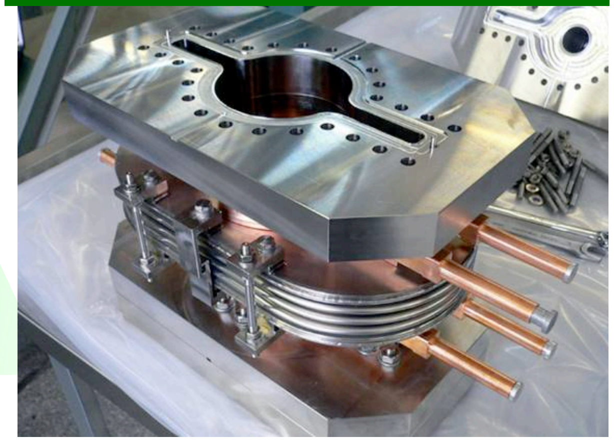


Design of key components_7

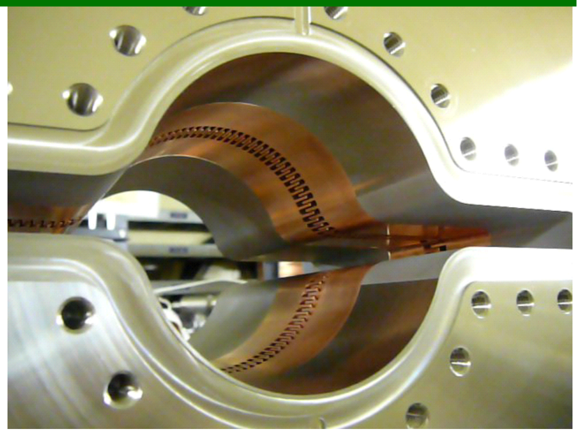
- **Bellows and gate valves** with comb-type RF-shield
  - Sure RF shielding, thermally strong
  - Applicable to antechamber scheme
  - Finger-type for some cases, if flexibility is required.
- Trial models has been installed into the KEKB ring and tested with beam.
  - Fitting to beam pipe with antechambers
  - Reduction in the temperature of bellows has been demonstrated.

Gate valve

Bellows chamber for antechamber



Comb-type RF shield (Gate valve)



Design of key components_8

- **Countermeasures against electron cloud (EC) effect [LER]**
  - Serious issues for recent positron and proton storage rings.

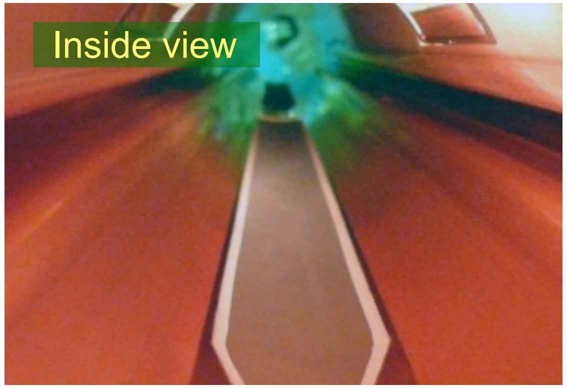
Sections	L [m]	L [%]	Countermeasure	Material
Total	3016	100		
Drift space (arc)	1629 m	54	TiN coating + Solenoid	Al (arc)
Steering mag.	316 m	10	TiN coating + Solenoid	Al
Bending mag.	519 m	17	TiN coating + Grooved surface	Al
Wiggler mag.	154 m	5	Clearing Electrode New	Cu
Q & SX mag.	254 m	9	TiN coating	Al (arc)
RF section	124 m	4	(TiN coating +) Solenoid	Cu
IR section	20 m	0.7	(TiN coating +) Solenoid	Cu or ?

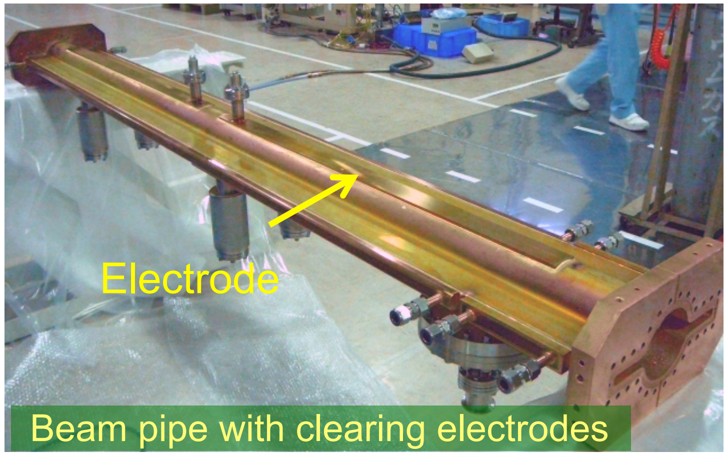
  - By using these countermeasures, the average electron density on the order of 10^{10} e^-/m^3 will be obtained.
    - Threshold of head-tail instability: ~1.6×10^{11} e^-/m^3

Design of key components_9

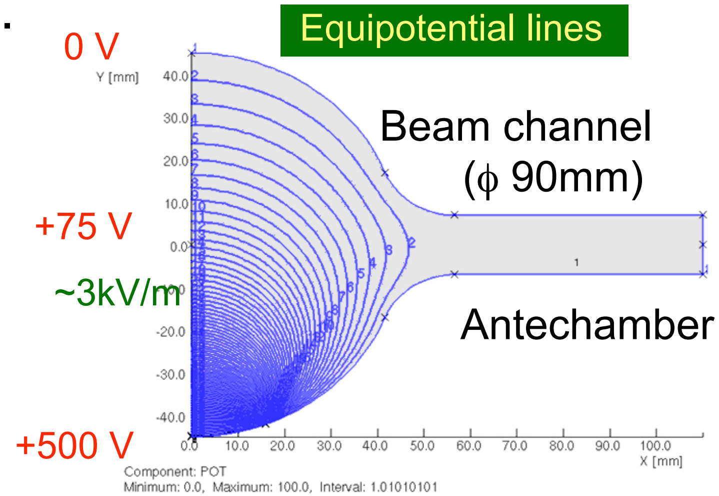
Some new techniques for EC mitigation

- **Clearing electrode** for wiggler section.
  - Attract electrons by electrostatic field
  - Very thin electrode has been developed
    - 0.1 mm tungsten on 0.2 mm Al_2O_3
    - Small impedance and effective heat transfer
  - Have been tested in KEKBdeveloped
    - Expected reduction ratio: 1/100
  - Also demonstrated in CesrTA
  - Manufacturing has already started.


Inside view



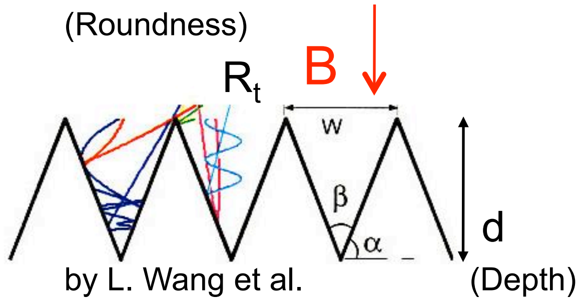
Beam pipe with clearing electrodes



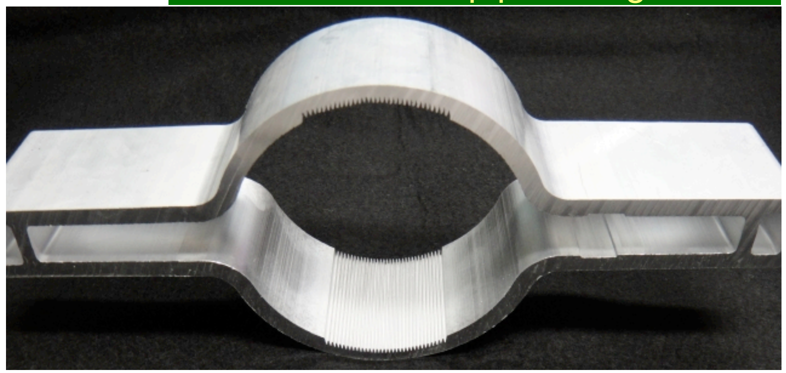
Equipotential lines

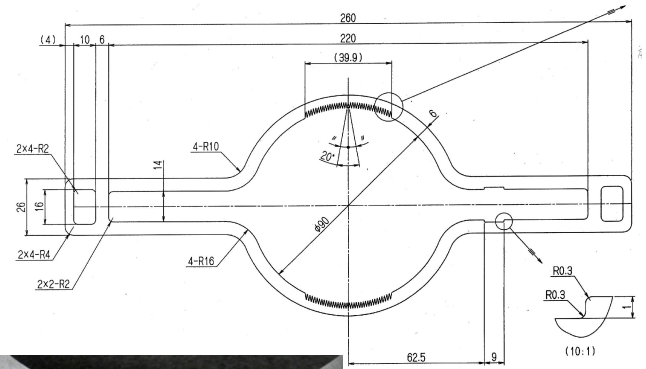
Design of key components_10

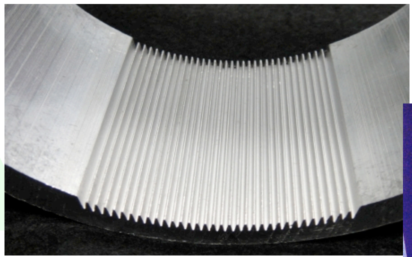
- **Grooved surface** for bending magnets section
  - Reduce effective SEY structurally
  - Have been tested in KEKB, and also in CesrTA
  - Extrusion test of aluminum beam pipe was successful.
  - With TiN coating



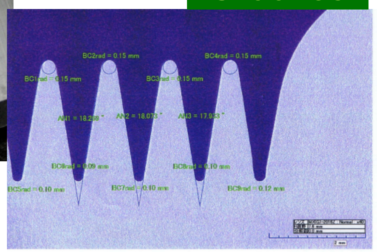
Aluminum beam pipe with grooves







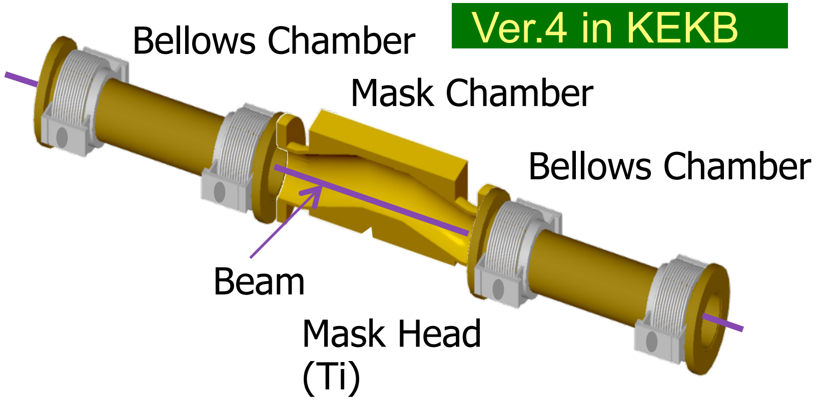
Grooves



Valley : R0.1~0.12
Top : R0.15
Angle : 18~18.3°

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)

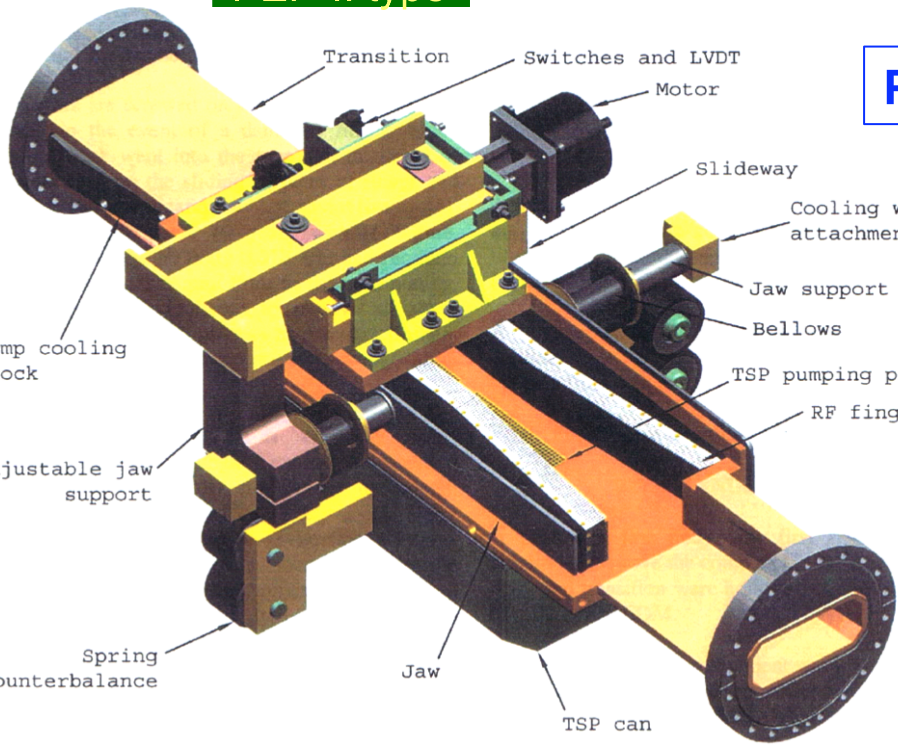
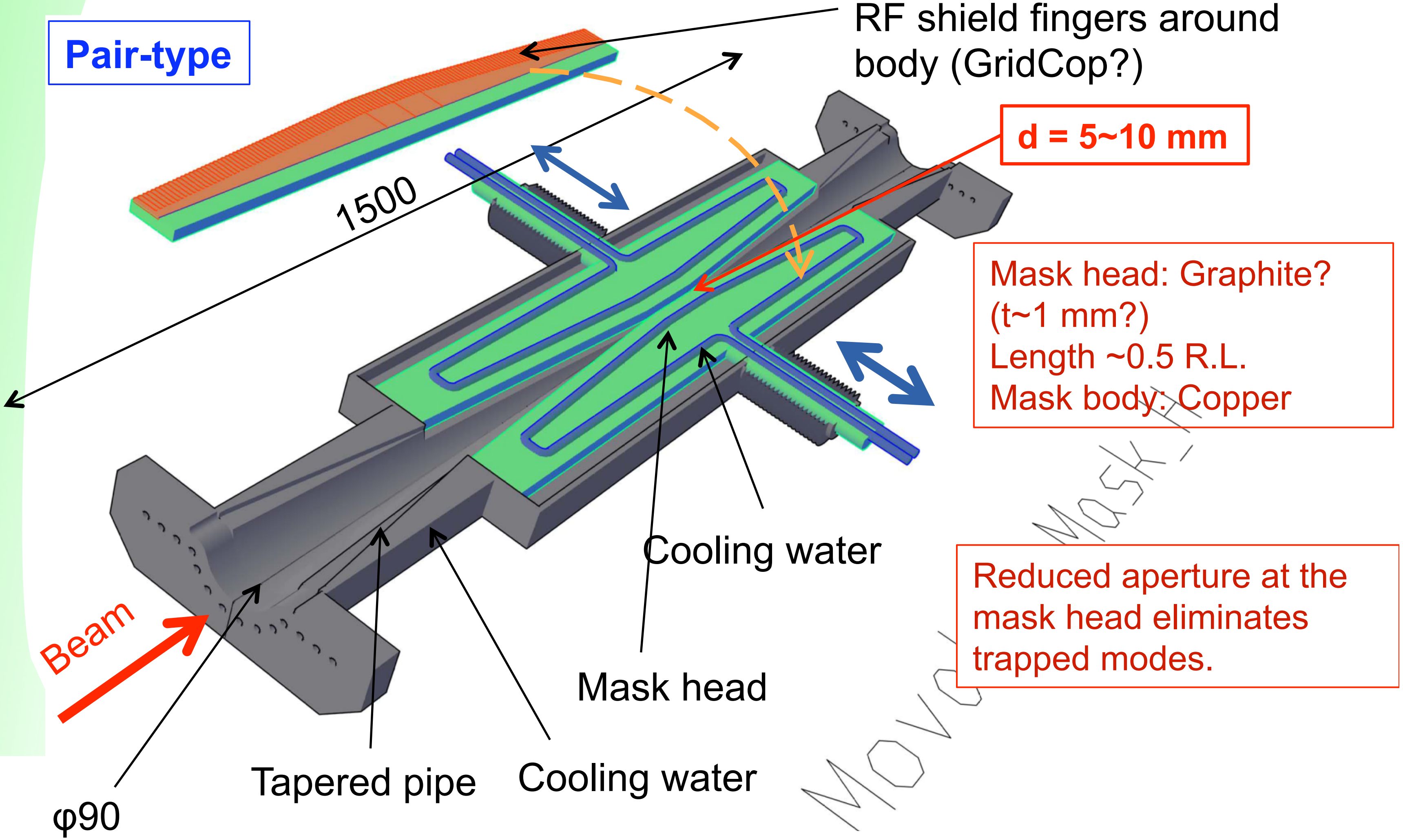


Figure 1: Cutaway view of the HER collimator

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

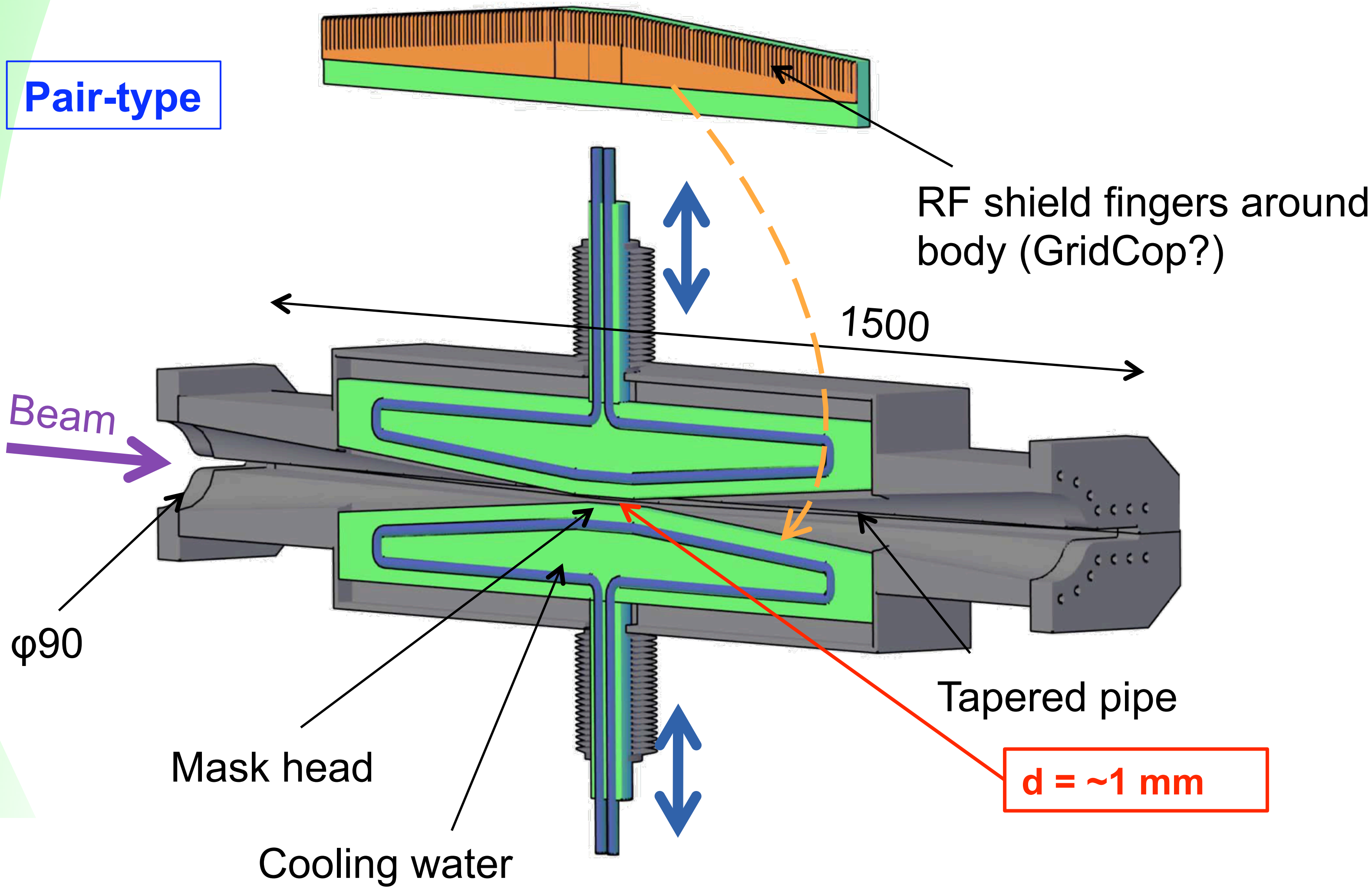
Design of key components_13

- Concept of **horizontal** movable mask



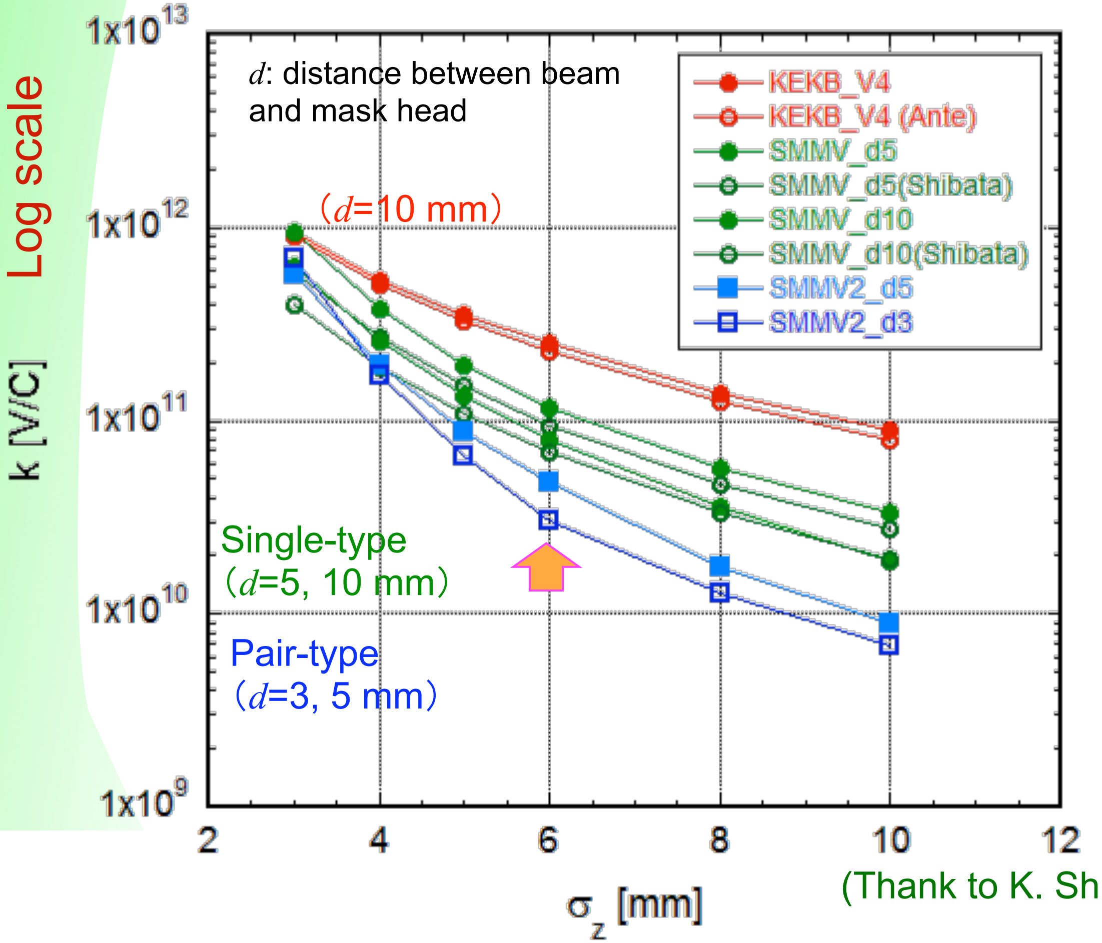
Design of key components_14

- **Concept of vertical movable mask**



Design of key components_15

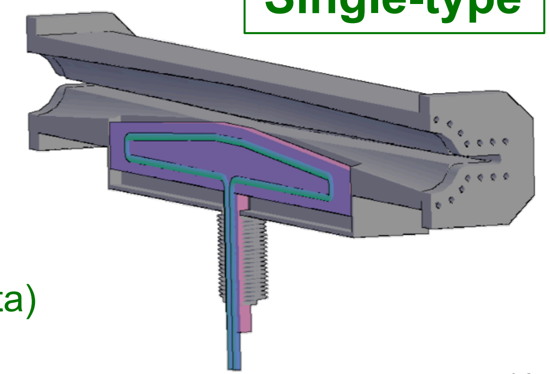
- **Loss factors (*k*)**
  - Calculated by GdfidL, 3D model
  - Dependence on bunch lengths (σ_z)



(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?

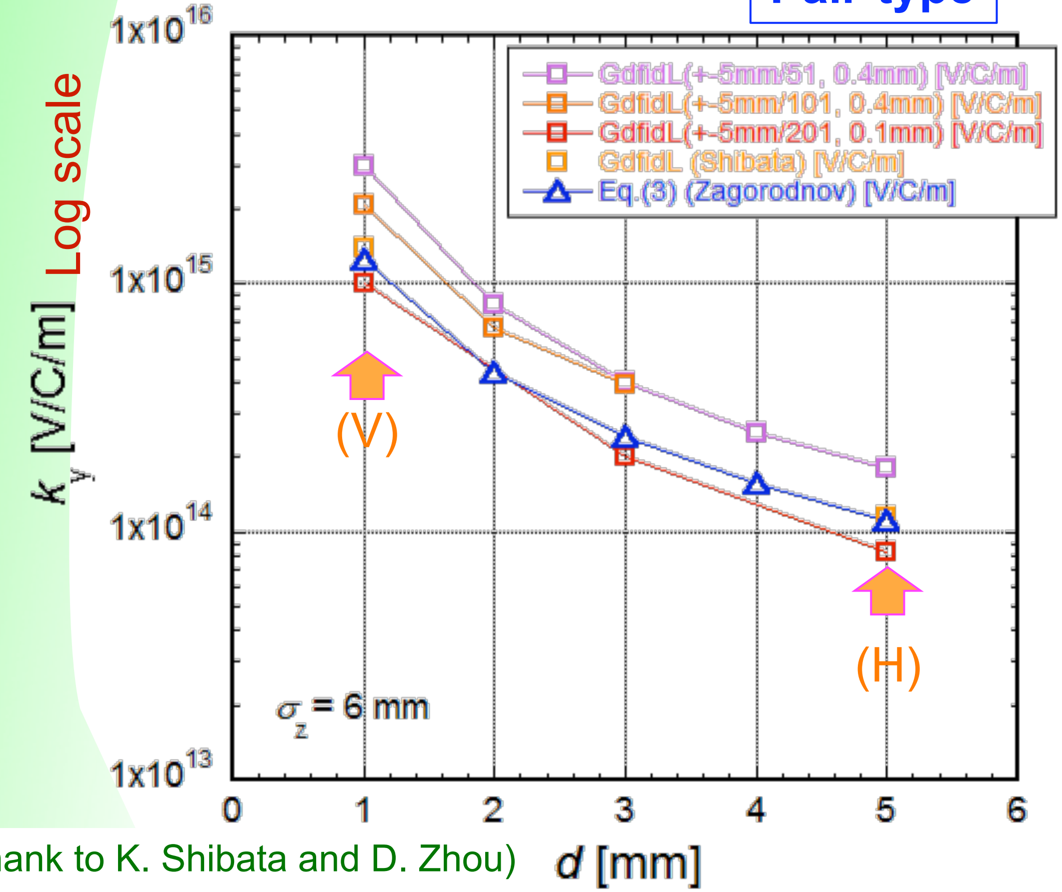
Single-type



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 = 8×10^{13} V/C/m → I_{th} = 43 mA/bunch
d = 1 mm [V, Arc]: k_y = 1 ×10^{15} V/C/m → I_{th} = 3.4 mA/bunch
d = 1 mm [V, LC]: k_y = 1 ×10^{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 $\boldsymbol{d}$ **= 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, $\boldsymbol{P}$ **= 50 W/mm^2 (32 × π/2).**
    → Very hard to deal
  - If **tungsten** (σ_c=2×10^7 1/Ωm) instead, $\boldsymbol{P}$ **= 5 W/mm^2**
    → Well manageable with water cooling.
    How about damage? Easy replaceable?

Design of key components_19

For movable mask;

- **The design has just started.**
  - Start with a conventional idea
- **To be investigated are;**
  - Bench marking of simulation code.
    - Results of GdfidL seem to Strongly depends on mesh sizes.
  - Evaluation of influence on beam dynamics
    - TMC, Banana effect, etc.
  - Choice of head material
    - Good electrical conductivity, High thermal strength, Easy bonding
    - Candidates: Mo, Ta, W, Re, Rh, Ru,,,
    - Simulation of heating by EGS4 has also started. (by T. Sanami)
  - Possibility of increasing beam size
    - Non linear optics (under investigation by Y.Ohnishi)
- **If novel ideas are required;**
  - Spoiler using channeling in a crystal (Si)
  - Collimator using Laser, Electron beam,,,,

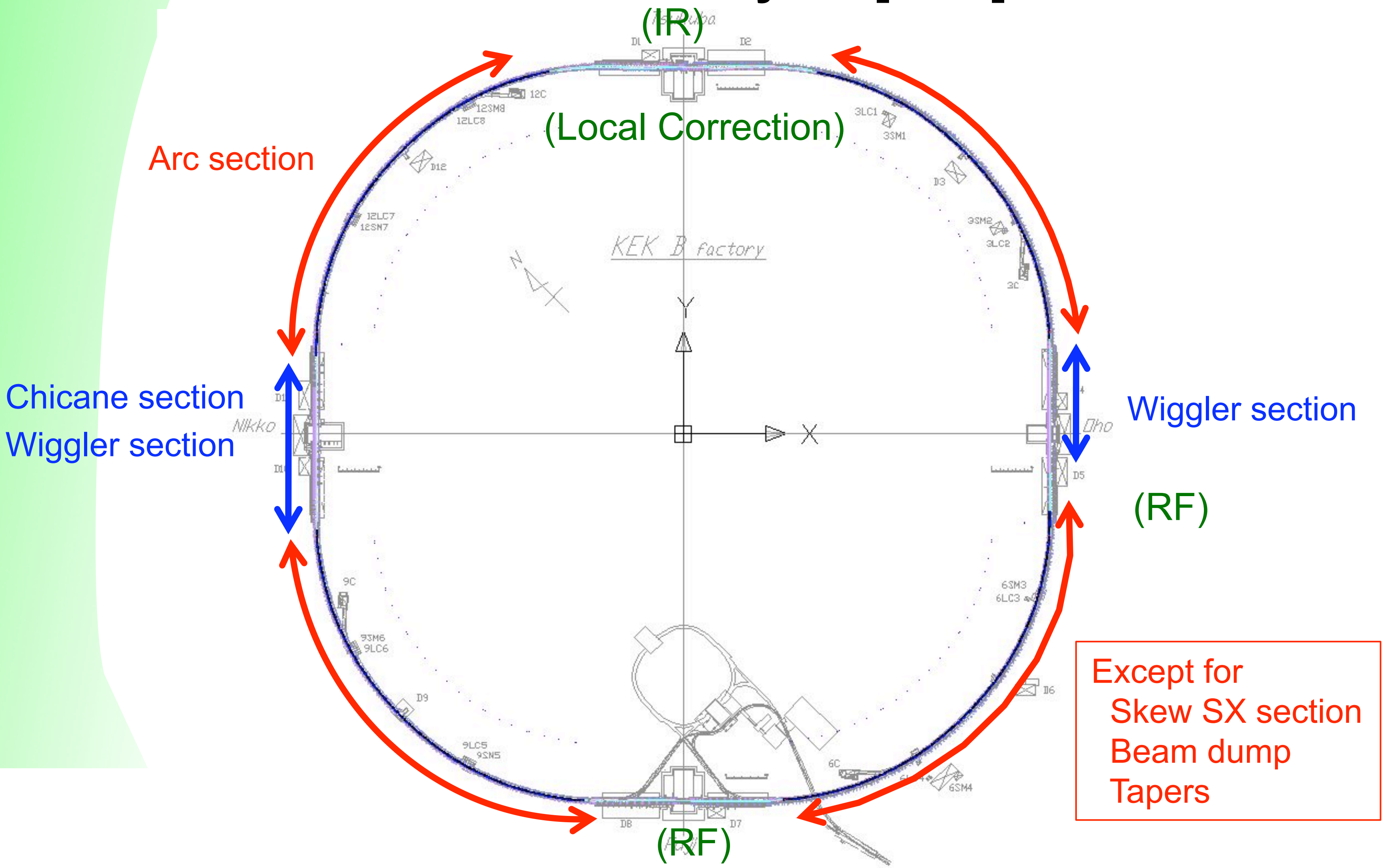
Long term has restarted again……

Present status and plans_1

- **R&Ds of components have almost finished.**
  - Conceptual design of movable masks has just begun.
- **Manufacturing of some beam pipes had started.**
  - Beam pipes with clearing electrode and Q beam pipe for LER wiggler section is under manufacturing (~220 m).
    - Copper beam pipes
    - will be delivered this fiscal year.
    - Together with some bellows chambers (16 pieces)
  - Beam pipes and bellows chambers for **LER arc sections and straight sections** will be ordered soon.
    - **LER arc** : Beam pipes for drift **[S]**, beam pipes for bend **[B]**, beam pipes for quad (with BPM) **[Q]**: ~1860 m (Al alloy)
    - **LER straight**: Chicane section and downstream of wiggler section and wiggler beam pipes: ~135 m (Cu)
    - Bellows chambers: 450 pieces (Al)

Present status and plans_2

- **Delivered and ordered this year [LER]**



Present status and plans_3

- **Varieties of beam pipes for arc section**

B beam pipe

名前	長さ [mm]	本数[本]	図番号
DBA1635aP	1635	2	1
DBA2147aP	2147	2	2
DBA2650aP	2650	1	3
DBA3650aP	3650	1	4
DBA4711aP	4711	100	5
5	484964	106	

Q beam pipe

名前	長さ [mm]	本数[本]	図番号
DQA1424dP	1424	22	1
DQA1488dP	1488	1	2
DQA1676dP	1676	1	3
DQA1691dP	1691	2	4
DQA1691uP	1691	2	5
DQA1818dP	1818	3	6
DQA1826dP	1826	28	7
DQA1826uP	1826	27	8
DQA1870dP	1870	2	9
DQA1870uP	1870	2	10
DQA1951dP	1951	2	11
DQA1951uP	1951	2	12
DQA1961dP	1961	1	13
DQA1992dP	1992	54	14
DQA1992uP	1992	74	15
DQA2320dP	2320	41	16
DQA2320uP	2320	42	17
DQA2430dP	2430	2	18
DQA2430uP	2430	2	19
19	621641	310	

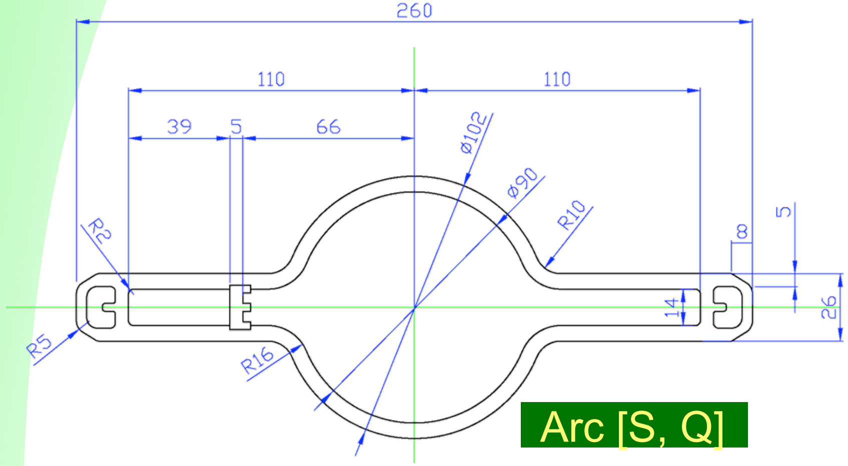
S beam pipe

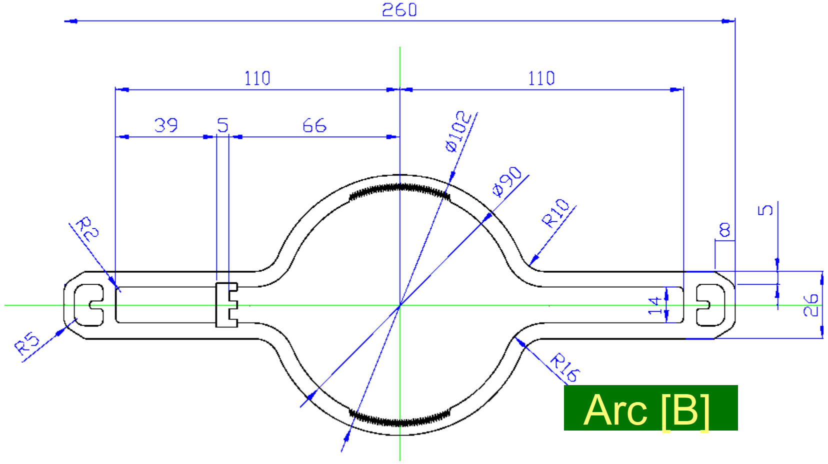
名前	長さ [mm]	本数[本]	図番号
DSA0930aP	930	1	1
DSA1500aP	1500	2	2
DSA2444aP	2444	4	3
DSA2487aP	2487	1	4
DSA2510aP	2510	1	5
DSA2607aP	2607	4	6
DSA2724aP	2724	5	7
DSA2842aP	2842	38	8
DSAi1211aP	1211	3	9
DSAi1651aP	1651	43	10
DSAi2390aP	2390	1	11
DSAi2398aP	2398	1	12
DSAi2588aP	2588	43	13
DSAi2592aP	2592	1	14
DSAi2790aP	2790	4	15
DSAi2887aP	2887	4	16
DSAi2955aP	2955	1	17
DSAi3302aP	3302	1	18
DSAi4501aP	4501	39	19
DSAi4631aP	4631	4	20
DSAi4735aP	4735	4	21
DSAig2148aP	2148	1	22
DSAig4061aP	4061	9	23
DSAir2308aP	2308	39	24
DSAir2390aP	2390	2	25
DSAir2495aP	2495	1	26
DSAir2518aP	2518	1	27
DSAir2558aP	2558	8	28
DSAirg1868aP	1868	5	29
29	754311	271	

Total: 1860 m (except for bellows chambers)
Bellows chambers 450 : 90 m

Present status and plans_4

- **Typical cross sections**



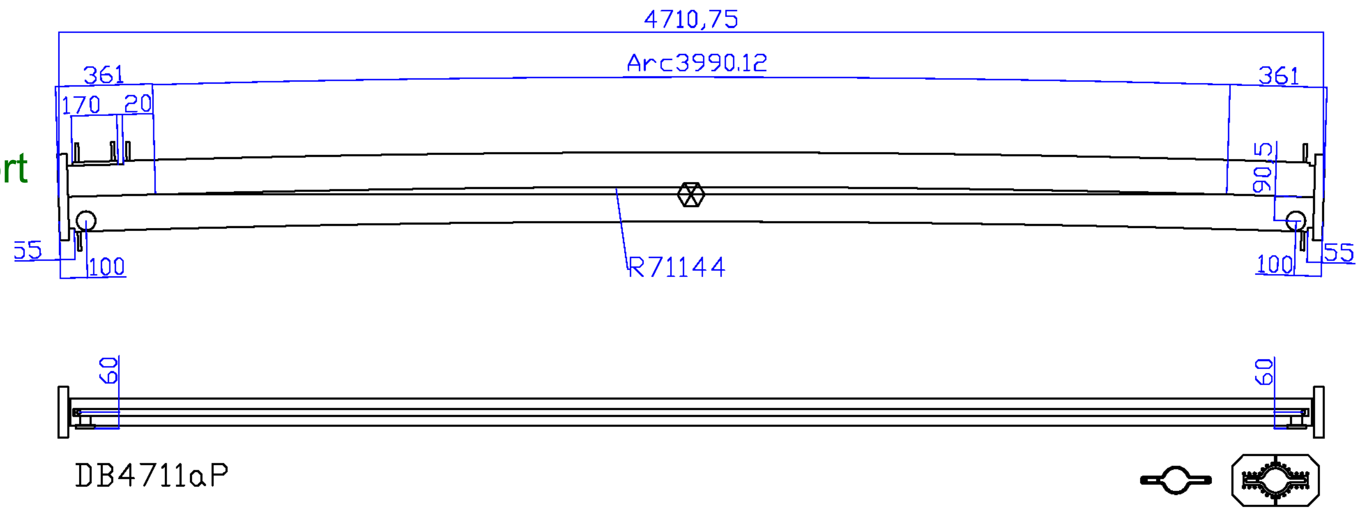


Grooved surface

- **Typical B beam pipe**

NEG pump port

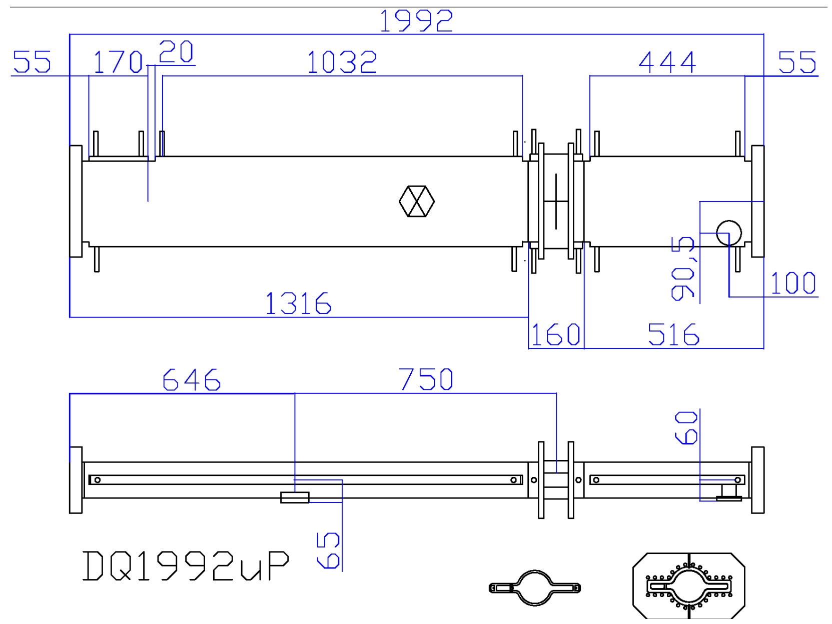
Photon mask



Present status and plans_5

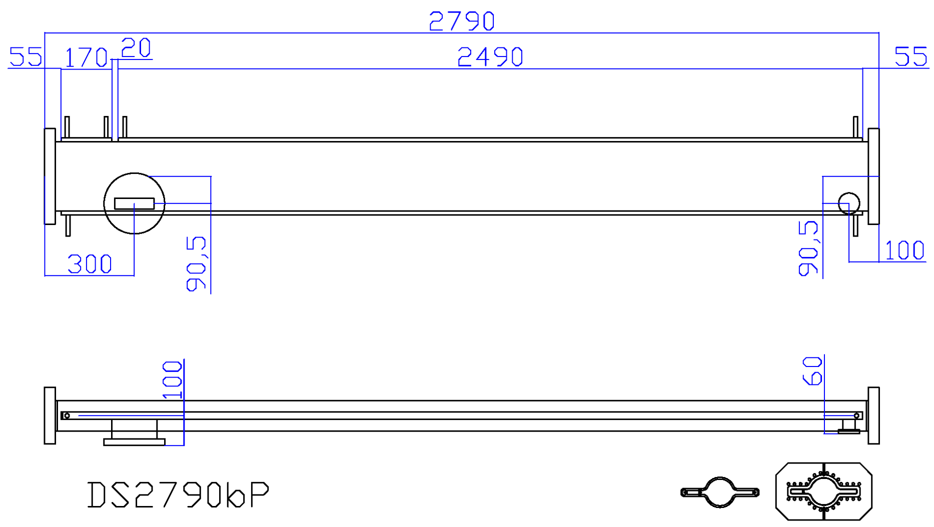
- **Typical Q beam pipe**

  BPM block
  NEG pump port
  Photon mask



- **Typical S beam pipe**

  Ion pump port
  NEG pump port
  Photon mask



Present status and plans_6

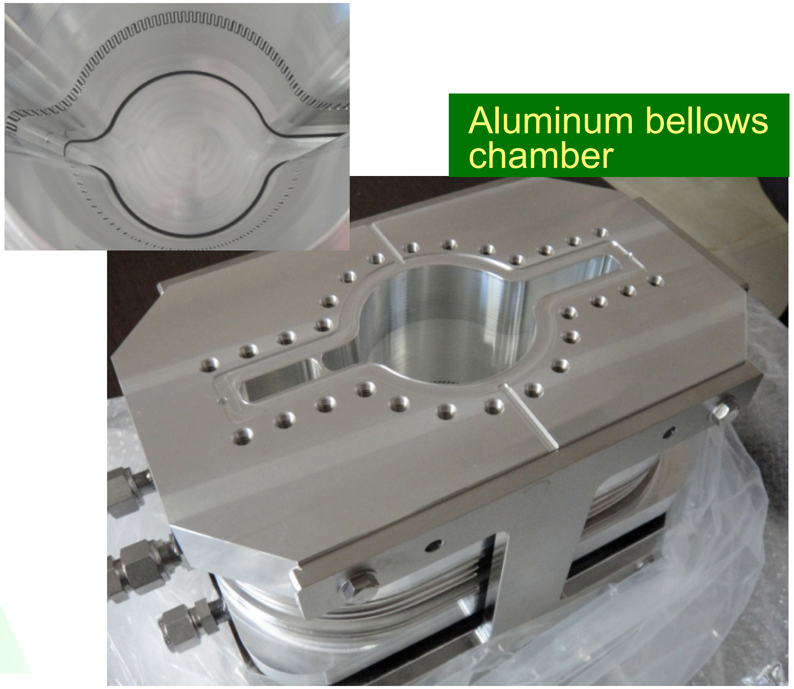
- **Wiggler beam pipes (Cu)**
  - Beam pipes and bellows chambers have been gradually delivered.
  - They will be stored for a while in a new tent.
    - The beam pipes are filled with dry nitrogen
    - The packages of bellows are filled with dry nitrogen

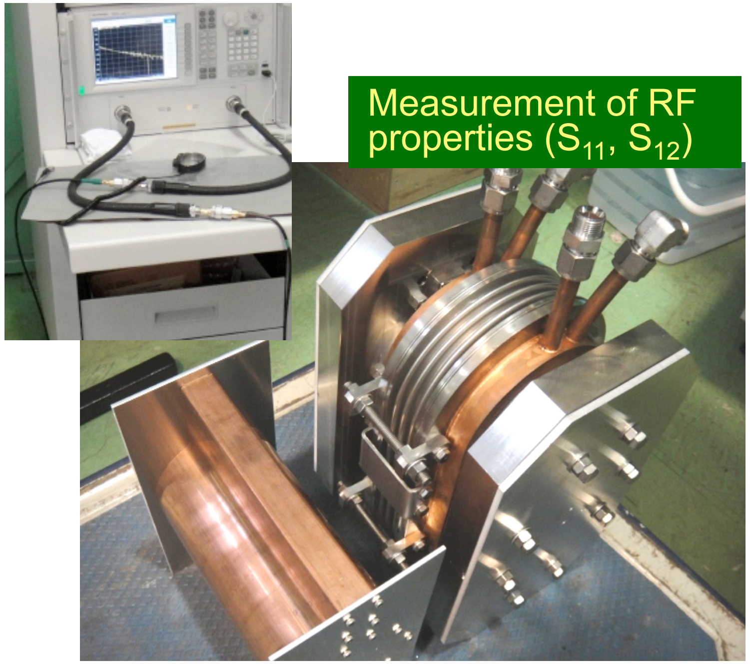
Stock area of beam pipes

(Thank to M. Shirai)

Present status and plans_7

- **Bellows chambers**
  - Some bellows chambers for wigglers have delivered.
  - Bellows chambers with **aluminum body** were manufacturing for test.
  - RF properties were checked by comparing a dummy pipe.





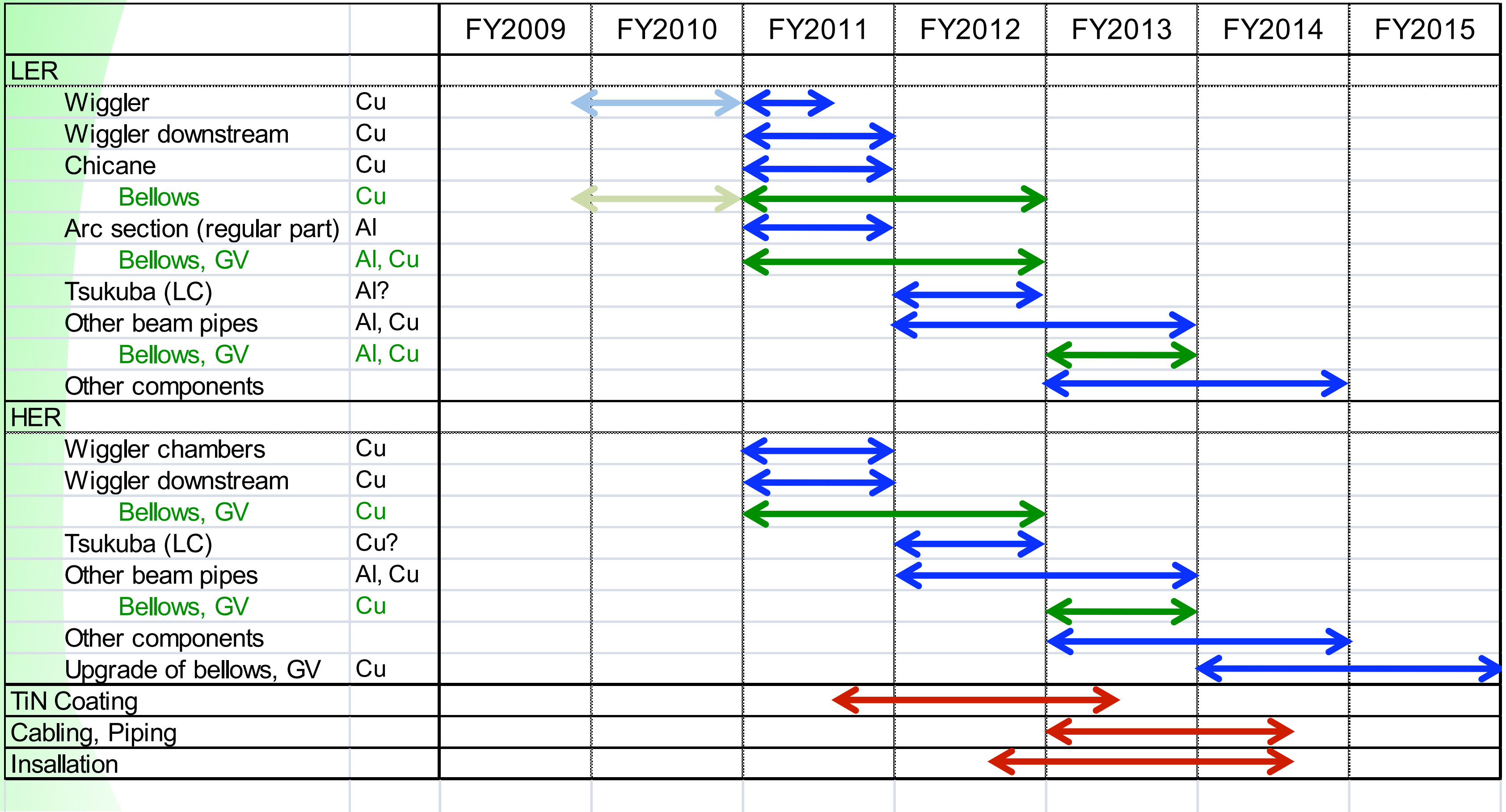
(Thank to T. Abe, KEKB RF group)

Present status and plans_8

- **Remained beam pipes [fixed plan]**
  - **Tsukuba straight sections** incl. **local correction sections**: 165x2 = 330 m (Cu 200 m?) [LER and HER]
  - **Fuji cross sections** [LER]: 7 m [LER]: 11 m [HER]
  - **HER Wiggler sections**: 121 m
  - **Special beam pipes**, ex. Tapered beam pipe, dump chambers, X-ray monitor chambers [LER and HER]
  - **IR beam pipe** [HER and LER]
  - For ARES cavities (Fuji, Nikko, Oho): 182 m
- Manufacturing of these chambers will start soon.
- Design of special chambers, such as injection chambers, dump chambers, X-ray monitor chambers, will also start soon.

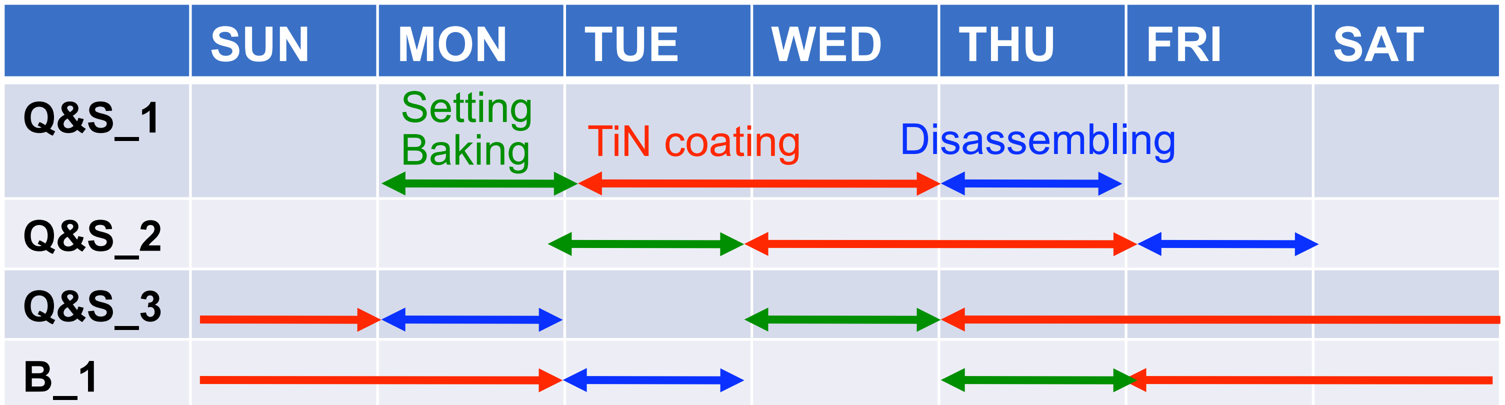
Present status and plans_9

- **Beam pipe manufacturing time schedule (preliminary)**



Present status and plans_10

- **Pre-baking and TiN coating in KEK**
  - Workflow of beam pipe assembly
    - Transfer of beam pipes to OHO experimental hall.
    - **TiN coating**
    - Assembly of NEG pumps
    - Prebaking (150°C 24 hours)
    - N_2 filling
    - Transfer of beam pipes to reservation area, or into tunnel.
  - TiN coating
    - 5 sets for Q and S beam pipe, and 2 sets for B beam pipe.
    - One coating process will take 4~5 days.
    - Coating for 800 beam pipes (arc section) will take ~1.5 years.

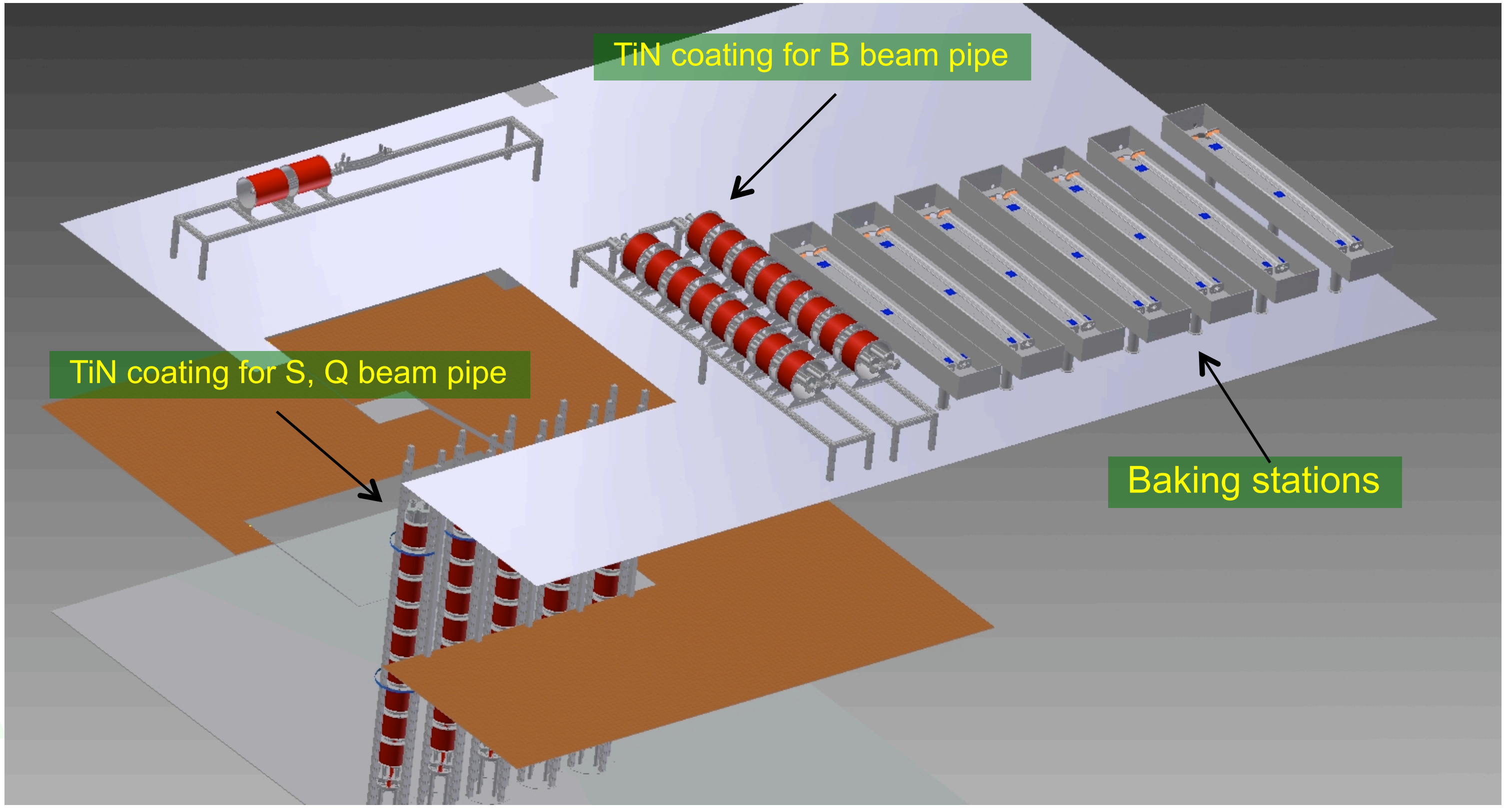


(by K. Shibata, M. Shirai)

Present status and plans_11

- **Pre-baking and TiN coating facility in KEK**
  - The facility will be set up in autumn at OHO experimental hall this year.
  - Three floors

(by H. Hisamatsu)



Summary

- **Upgrade of the vacuum system for Super-KEKB has started.**
  - The design basically continues the policy in KEKB, introducing new ideas.
  - Most of designs and R&Ds for key components have finished.
    - Aluminum-alloy beam pipe is now adopted for LER.
    - More powerful countermeasures against EC effects are embedded especially in dipole magnets.
    - Further studies are required for movable masks.
    - Baking and TiN coating facilities will be ready this year.
  - Manufacturing of beam pipes and bellows chambers for LER wiggler sections had started last year.
  - For LER arc and straight sections, It will start this year.
  - Remained parts of LER and HER will follows.

Thank you for your attention

Movable Mask

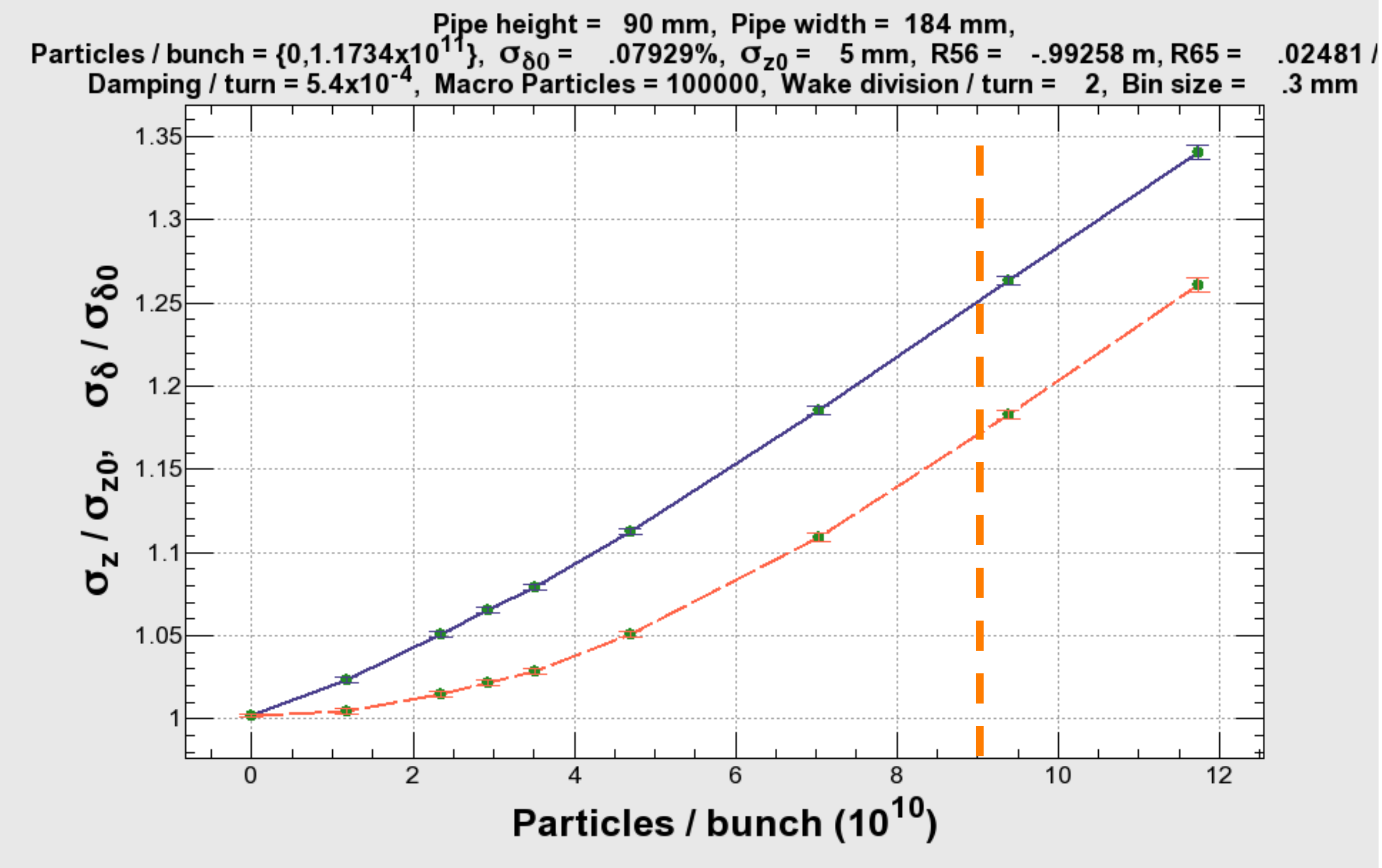
- **Possible mask locations and beam parameters (Y. Ohnishi)**

		LER Arc	LER SL*	HER Arc	HER SL*	
H-mask	σ_x	272	217	475	167	μ
	β_x	23.2	14.8	52.4	6.52	m
	ε_x	3.2	←	4.3	←	nm
	d_x	11.1	0.81	8.04	0.084	mm
V-mask	σ_y	16	2.35	17	2.48	μ
	β_y	30	0.64	27	0.57	m
	ε_y	8.64	←	10.8	←	pm
	$\varepsilon_y/\varepsilon_x$	0.27	←	0.25	←	%
	d_y	1.04	0.81	1.15	2.1	mm

*Non-linear collimation scheme

CSR (LER)

- **Microwave Instability (H. Ikeda, K. Oide)**
  - For σ_z = 5 mm



k_z and k_y

- **Loss factors and kick factors for main components**

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Component		Loss factor [V/C]	Number of items	Loss factor (total) [V/pC]		Kick factor (total) [V/pC/m]
Resistive wall	Al	1.14E+09	3000 [m]	3.42		
	Cu	8.22E+08	3000 [m]			
Pumping port		3.65E+02	3000 [m]	1.10E-06		
Flange connection		1.45E+07	2000	0.03		
Bellows		2.00E+09	900	1.80		35.00
Gate valve		3.00E+09	40	0.12		
SR mask		1.82E-03	1000	1.82E-12		
Movable mask		1.00E+11	8 ?	0.80		~1000
Taper		3.83E+08	100	3.83E-02		
BPM		1.63E+08	450	0.07		
BxB FB BPM		5.90E+08	10	5.90E-03		
FB kicker		5.01E+11	1	0.50		2.50
IP chamber		8.00E+08	1	8.00E-04		?
Groove		1.00E+08	550 [m]	5.50E-02		5.50
Groove (RW x 0.14)*		1.60E+08	550 [m]	8.77E-02		
Clearing Electrode		2.00E+08	160 [m]	3.20E-02		27.00
Cle Ele (RW-W)**		8.70E+08	160 [m]	1.39E-01		
Cavity (ARES)		4.35E+11	18	7.83		1.20
Total	Al			14.9	+ α	

* RW 50%増し x 80/(90* π)

** タングステン 40mm分

Materials of mask head

- **Temperature rise simulation by EGS4**