Liquid Lead Target R/D

T. Omori (KEK)

20-Oct-2010

ILC-CLIC WS at Genéve

for Collaborators:

J. Urakawa, M. Kuriki, N. Okuda, K. Yokoya, N.Terunuma, N. Iida, T. Kamitani, T. Mimashi, H.Nakamura, M. F. Blinov, V. Golikov, P. Logachev, W. Liu, W. Gai

with Many thanks to KEKB team

Target Issues
of
ILC e+ Source

Target Issues

Two Issues

- Heat Load (by beam): Time Scale ~ 1 m sec.
- Thermal shock wave: Time scale ~ sub micro sec.

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- **Undulator Scheme (base line)**
  - In order to create e+s, it uses e- beam in the main linac.
  - It creates 2600 bunches of e+s in 1 m sec.
  - Heat load is a serious problem.
  - It requires a challenging rotation target (100 m/s).

    (spreads 2600 bunches in 100 mm length)

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- **300 Hz Scheme w/ liq. lead target (alternative)**
  - It creates 2600 bunches of e+s in 63 m sec. (stretching)
  - Heat load is not a problem.
  - It requires a window between liq. lead and acc.
  - Does the window (material BN) survive under shock wave?

300 Hz scheme

e+ generation in 63 m sec (cf. undulator : in 1 m sec)

How?

- Total Number of bunches: 2640
- Divide into 20 triplets
  (1 Triplet = 3 Mini-Trains)
- Each triplet contains 132 bunches
- 2640 = 20 x 132
- 300 Hz creation of triplets
  triplet to triplet time space = 3.3 m sec
- Create 20 triplets : 63 m sec

⇨ **Stretching in time**

Conventional e+ Source for ILC

Normal Conducting Drive and Booster Linacs in 300 Hz operation

e+ creation

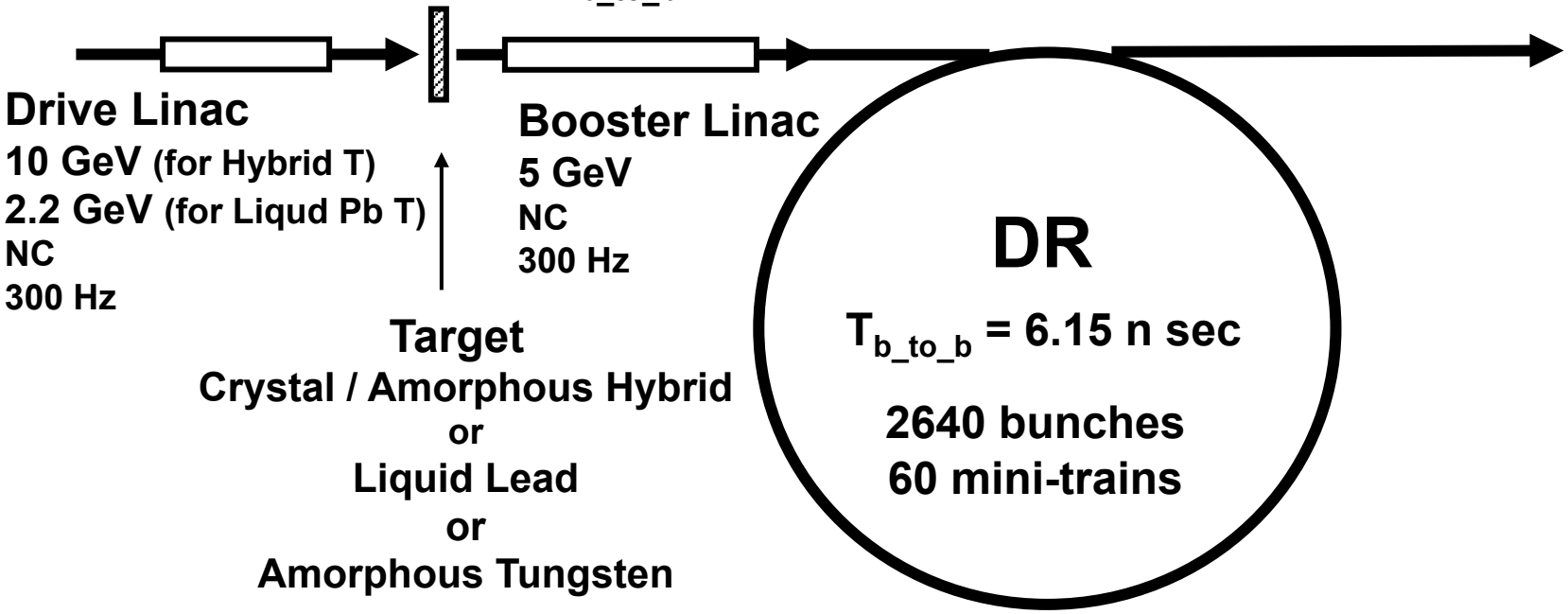
20 triplets, rep. = 300 Hz

- triplet = 3 mini-trains with gaps
- 44 bunches/mini-train, $T_{b\_to\_b}$ = 6.15 n sec

go to main linac

2640 bunches/train, rep. = 5 Hz

- $T_{b\_to\_b}$ = 369 n sec



Time remaining for damping = 137 m sec

We create 2640 bunches
in 63 m sec

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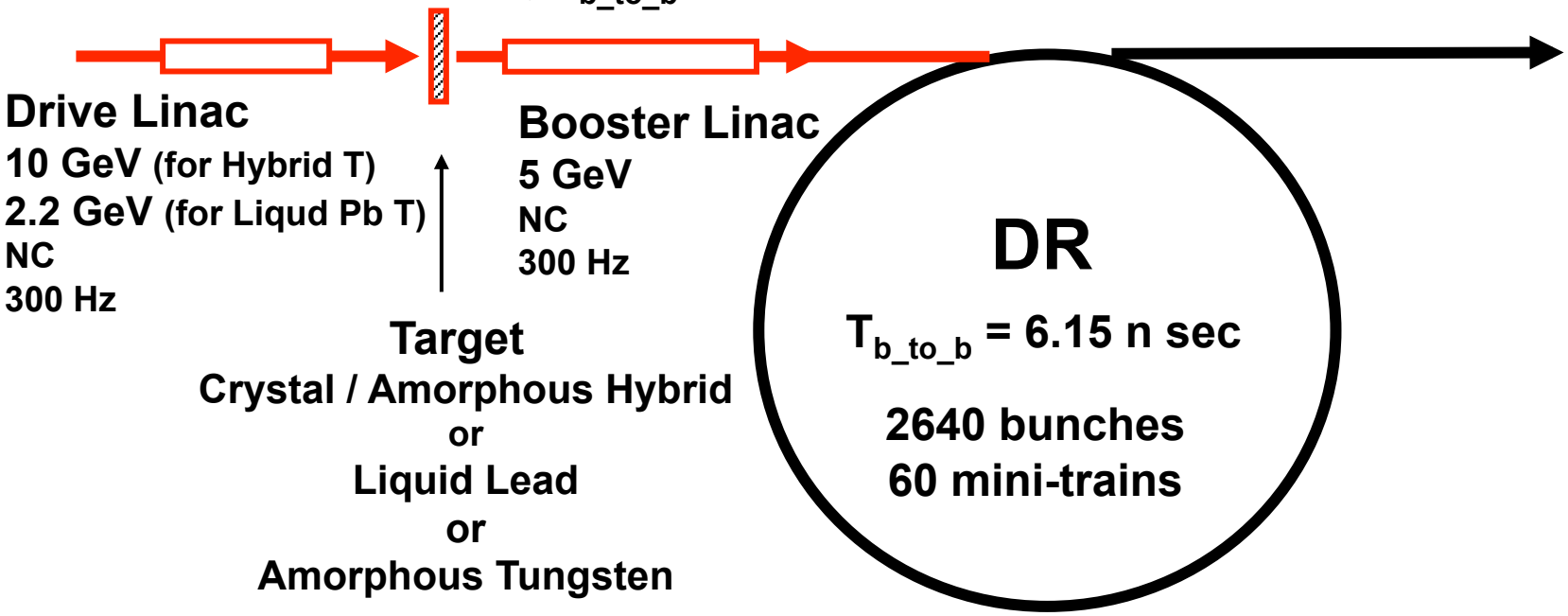

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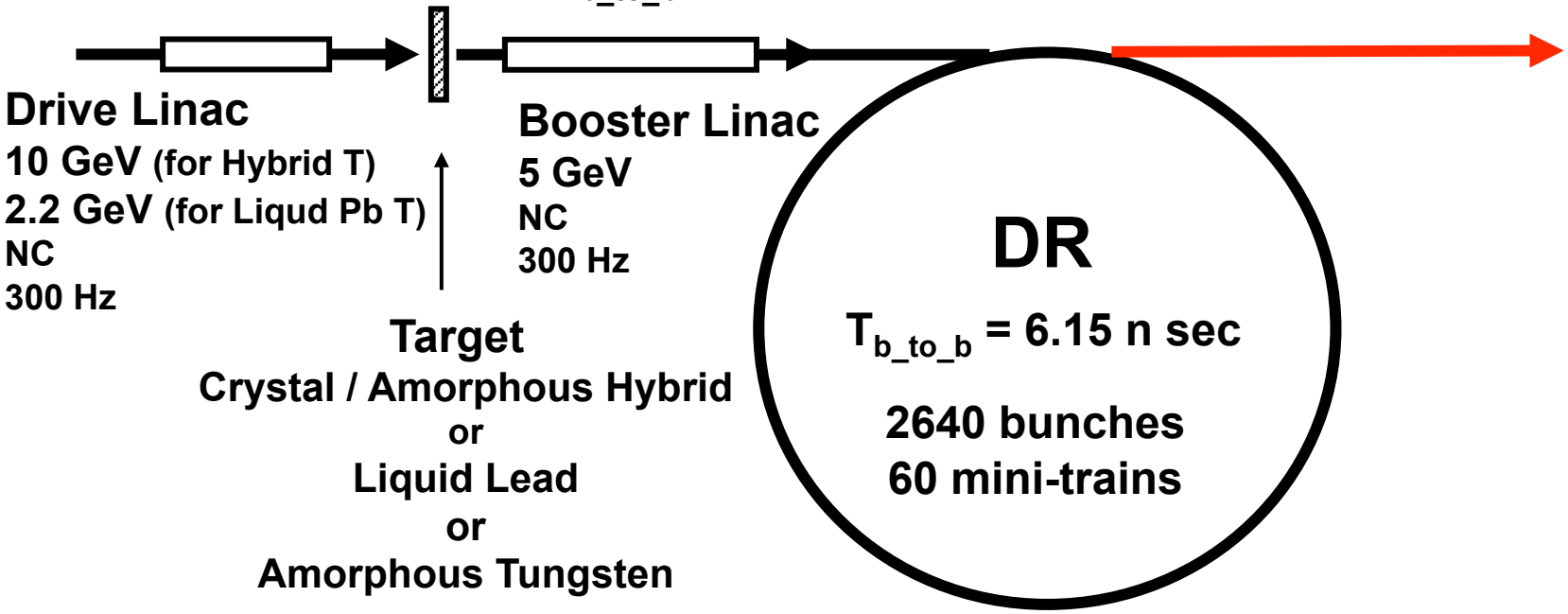

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300 Hz scheme

- **Stretching in time**

300 Hz scheme

- Stretching in time

- The Same as Warm colliders

  NLC 120 Hz
  GLC 150 Hz
  CLIC 50 Hz

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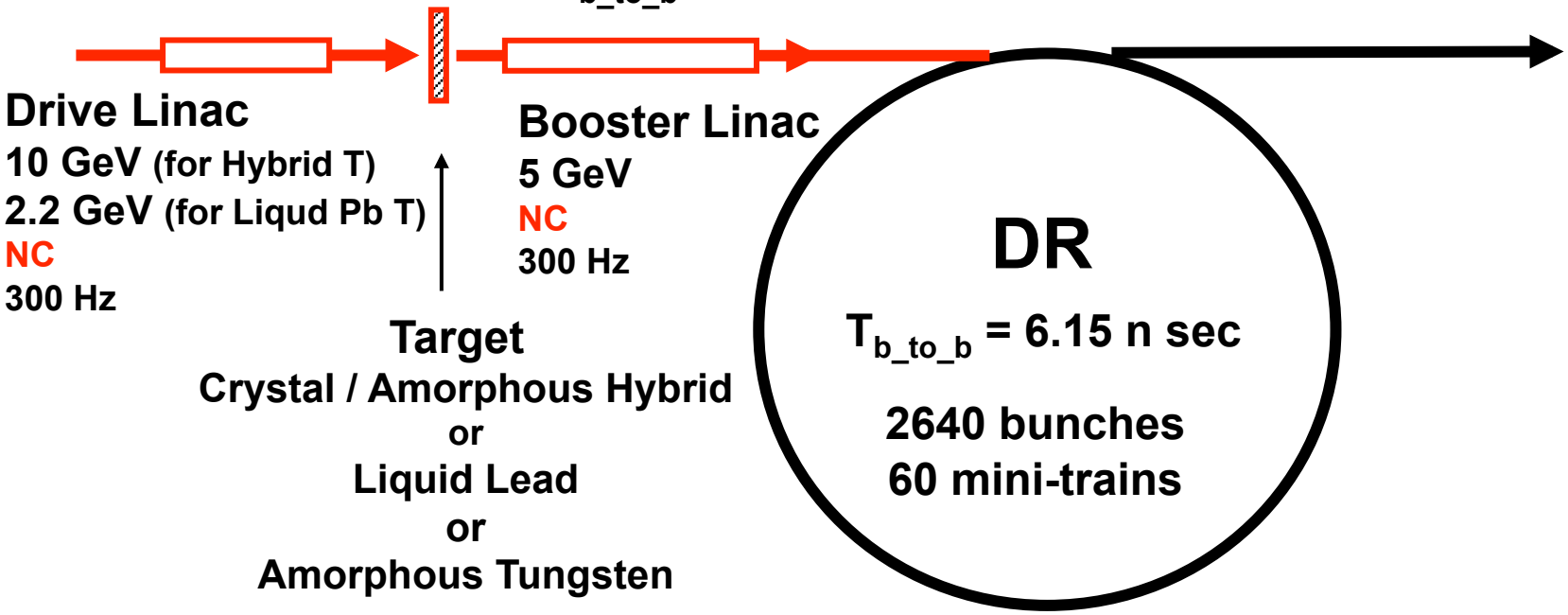

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Employs 3-4 targets
Thermal Shockwave

300 Hz scheme

- Stretching in time

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  NLC 120 Hz
  GLC 150 Hz
  CLIC 50 Hz

  ← Employs 3-4 targets
  Thermal Shockwave

- We try to employ single target.

  Crystal / Amorphous Hybrid ← Takahashi's talk
  or
  Liquid Lead ← My talk
  or
  Amorphous Tungsten ← Takahashi's talk
  Truly Conventional

Conventional e+ Source for ILC

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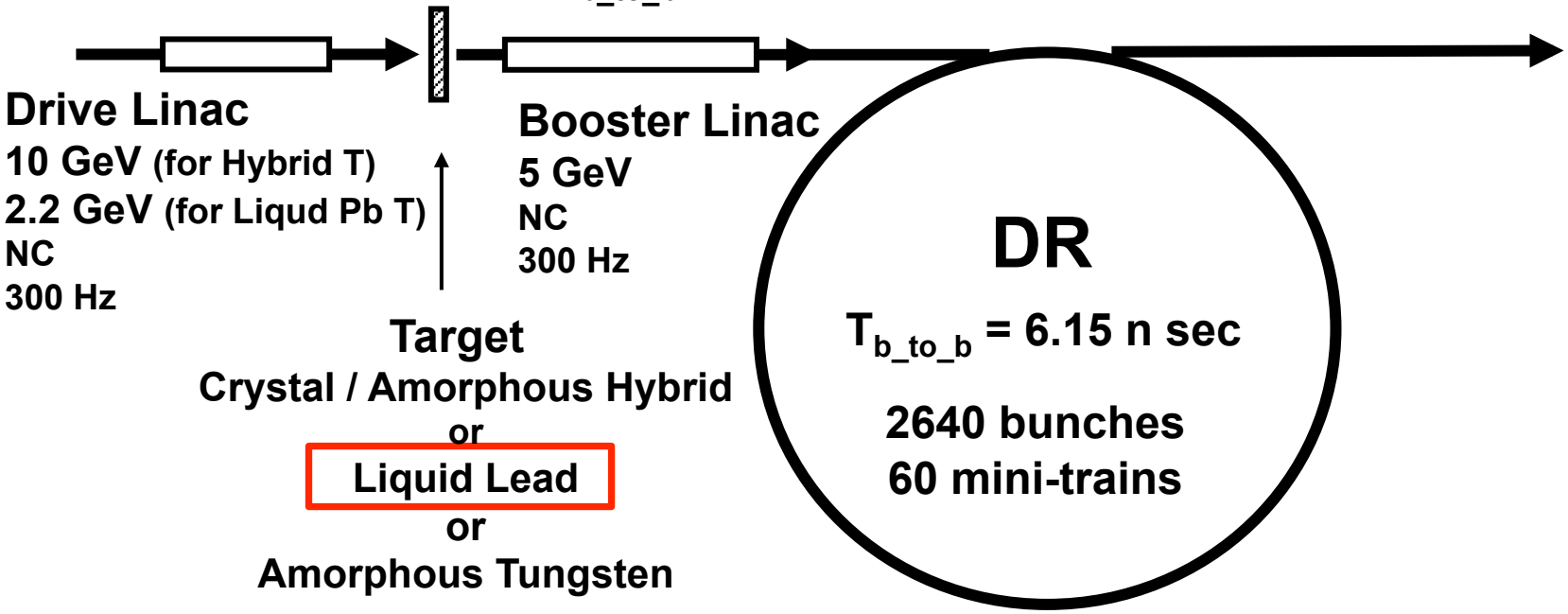

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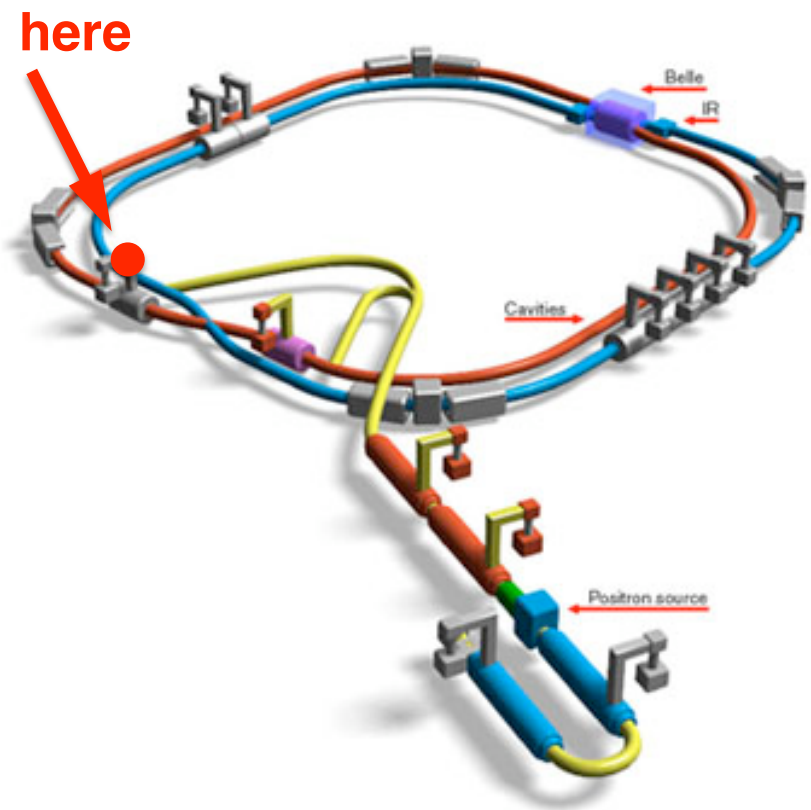
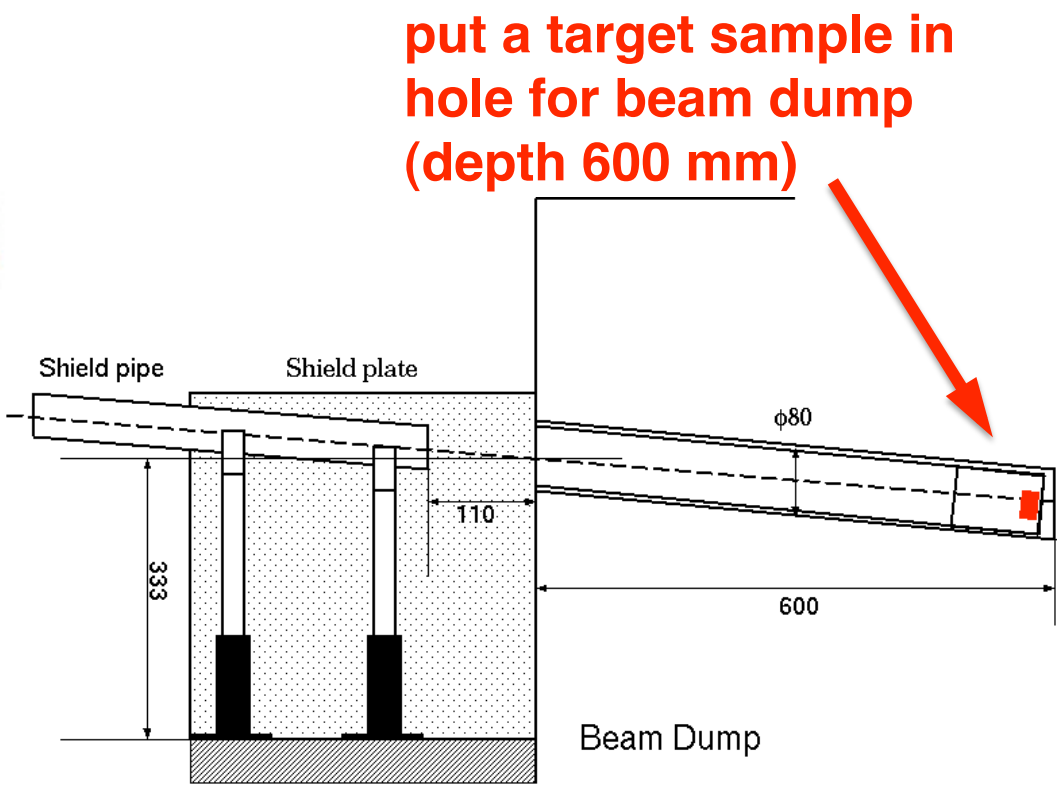
R/D of Liq. Pb Target

Shockwave on BN window

Test at KEKB ring

Liq. Pb Window Test at KEB





- KEKB-HER: 8GeV, 10nC (Max), up to 1600 bunches (1600mA)
- The beam is deflected by the abort kicker as shown when it is dumped.

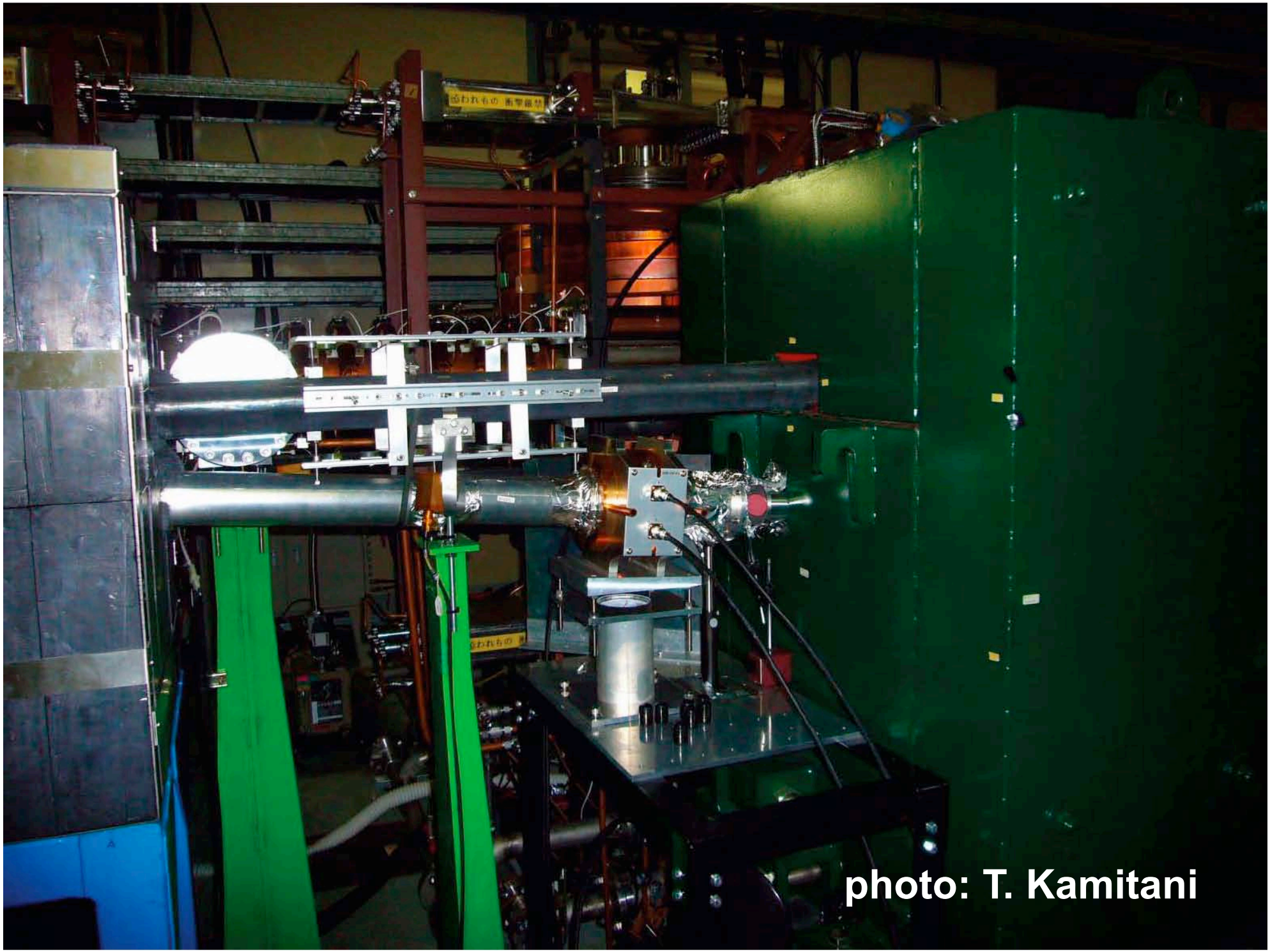


photo: T. Kamitani

Choice of Target Sample

1. Liquid Pb Target

   Best, but not possible.
   No space to install liquid Pb target
   in KEKB ring

2. Stack BN and soild Pb

   Melting point of Pb is too low to perform
   safe experiment. Failed in last year.

3. Stack BN and X(metal)

   X: We choose Tungsten (W).

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Peak Energy Deposit Density of 300 Hz w/Liq Pb

PEDD(300 Hz Lig. Pb) = 96 J/g (GEANT4 simulation)

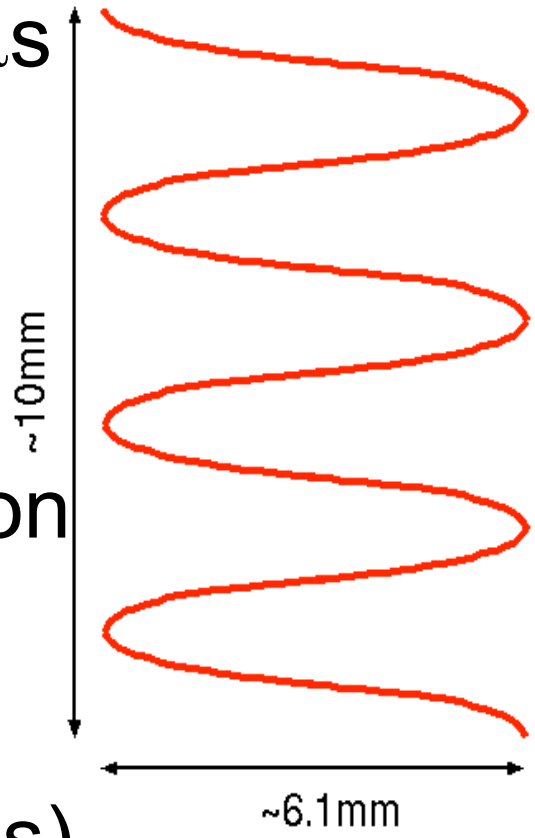
How to reproduce it in KEKB ring?

Parameters : 300 Hz Scheme w/Lig Pb Target

- Eb = 3.5 GeV, 5.9 nC/bunch
- 132 bunches hit target in 0.8 micro sec at almost the same point of the target.
- Liq Pb Flow Speed = 4 m/s
  Liq Pb runs 13 mm before the next pulse (132 bunches) hit target.
  We ignore hit of the next pulse.
- Beam Size : Sigma = 2 mm
- Target Thickness = 4 X0

KEKB Beam Condition

- 10nC, up to ~1600 bunches, 10μs
- Bunch-by-bunch impossible
- Unable to change beam size (~1mm rms?)
- Swept by kicker (protect extraction window) --> sinusoidal motion.
- Moves 7μ ~ 45μ/bunch on target (0.9mm ~ 6mm over 132 bunches)



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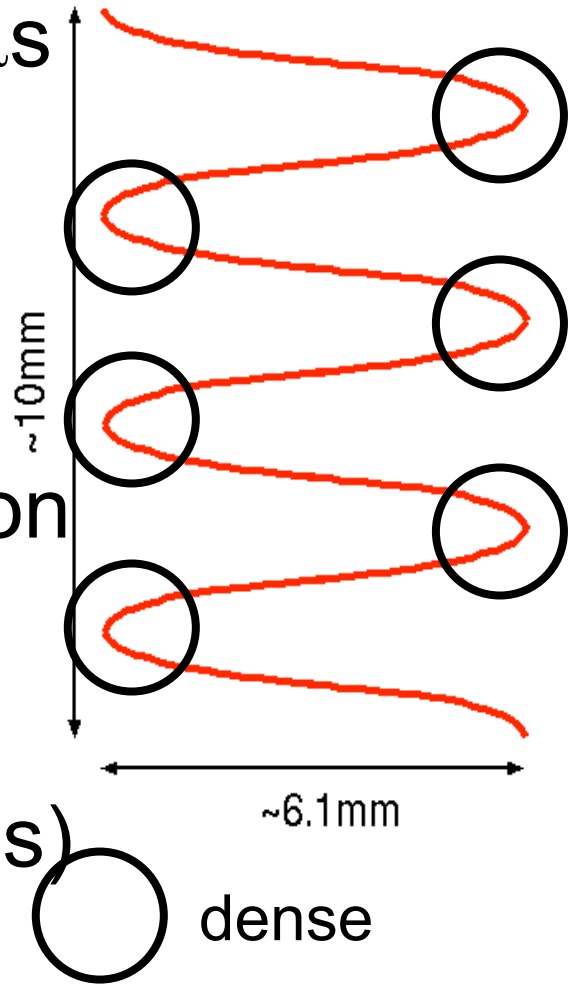
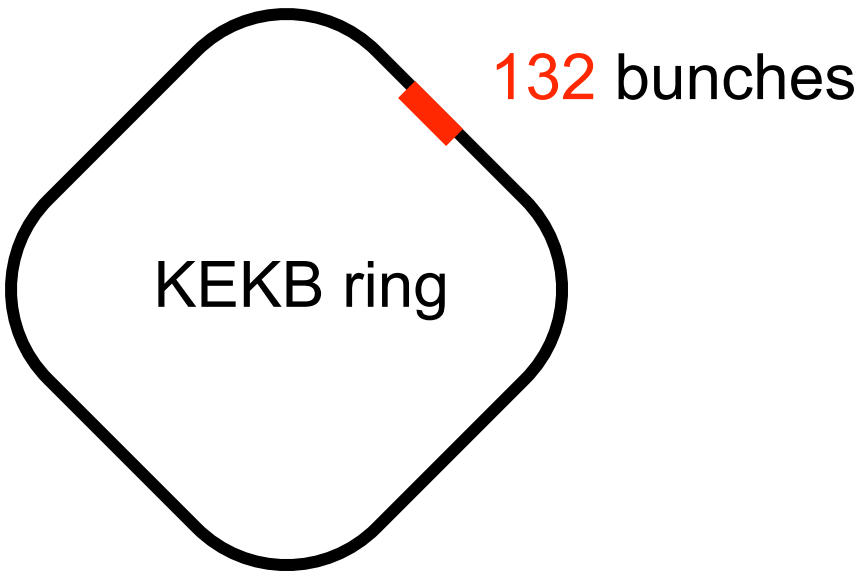
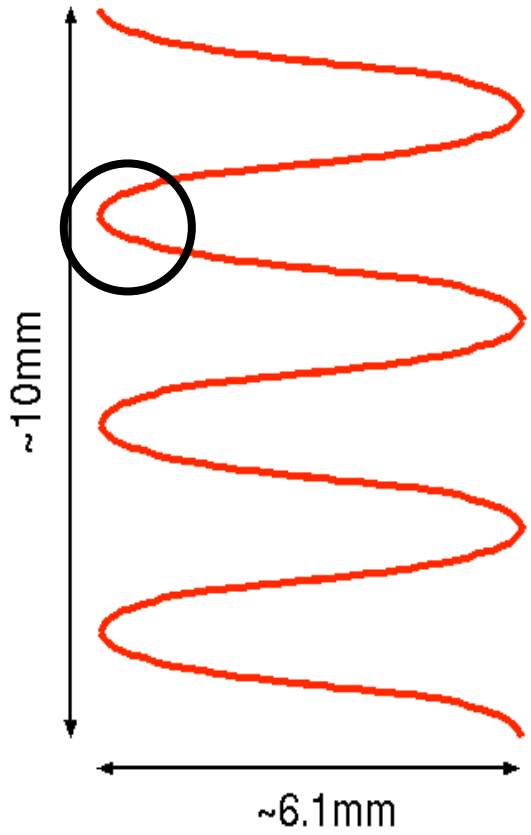


KEKB Beam Condition (Fill Pattern)

- We planned to fill 132 bunches in a part of KEKB ring which correspond one crest of sinusoidal motion of the extracted beam.





KEKB experimental condition

- Eb = 8GeV
- Beam Size: Sigma =1.17mm
- Fill only 132 bunches in a part of KEKB ring which correspond one crest of sinusoidal motion of the extracted beam.
- Bunch Charge : adjustable (Max 10 nC)
- Target Thickness = 4 X0

(1) Calculate "Bunch Charge" which gives 96 J/g

(2) Calculate "Temperature of W at Highest point"

(3) Calculate "Pressure" on the BN window.

Temperature Rise : ΔT

$$\Delta T = \frac{\Delta E}{c_v}$$

ΔE : Energy Deposit
Cv : Specific Heat Capacity (at Constant Volume)

	W
Melting Point (K)	3695
Radiation Length (mm)	3.5
Charge/b (nC) for 96 J/g (132 in Ring)	1.24
Temp at Max. Point (K)	1020

- Tungsten (W) has very large margin. -> Safe

Pressure Rise (Linear Approximation)

$$\Delta P = \frac{K\beta}{c_v}\Delta E$$

ΔE : Energy Deposit
Cv : Specific Heat Cap.
β : Vol. Thermal Exp. Coeffi.
K : Bulk Modulus

- Pressure on the window ~ $(\beta \times K) / C_V$

		W	Liq. Pb
Atomic Number		74	82
V. T. Exp. Coef. (10^{-6} K^{-1})	β	13.5	112
Bulk Modulus (GPa)	K	310	33.3
Specific Heat (J g^{-1} K^{-1})	C_V	0.132	0.146
$(\beta \times K) / C_V$		31700	25500

Pressure at ΔE = 96 J/g

	W	Liq. Pb
ΔP(GPa)	3.1	2.3

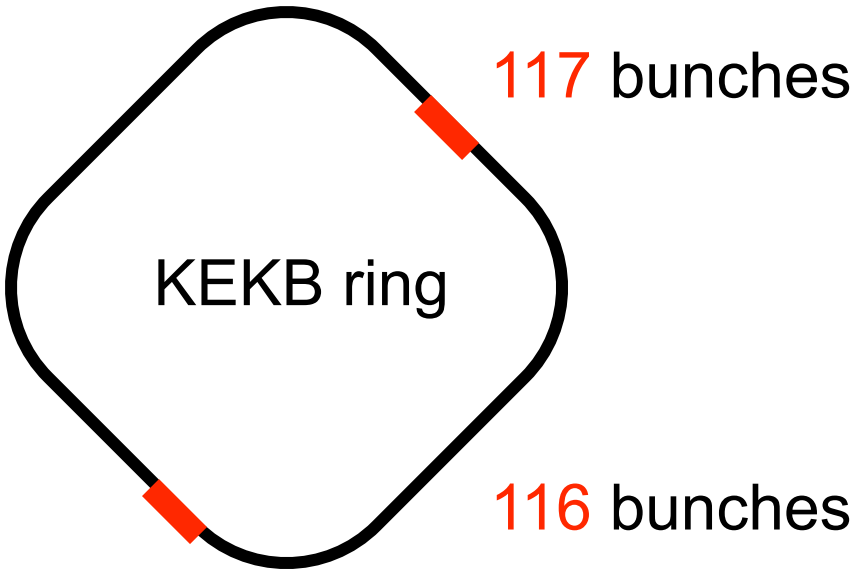
Pressure of W
~ Pressure of Liq. Pb

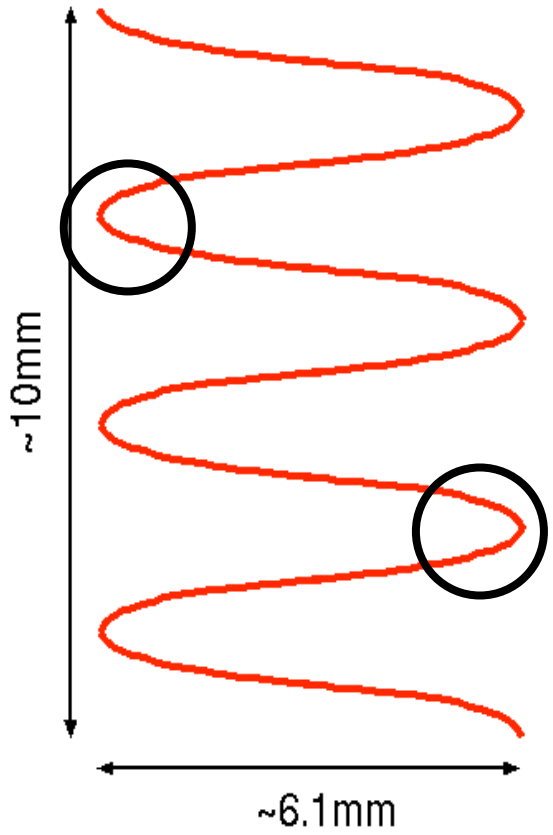
Evaluation

Experiment using KEKB ring and BN-W stack is;
Safe and reproduce pressure on BN window.

KEKB Beam Condition (Fill Pattern)

- Actually, we successed to fill 116 bunches and 117 bunches at two parts in the KEKB ring.





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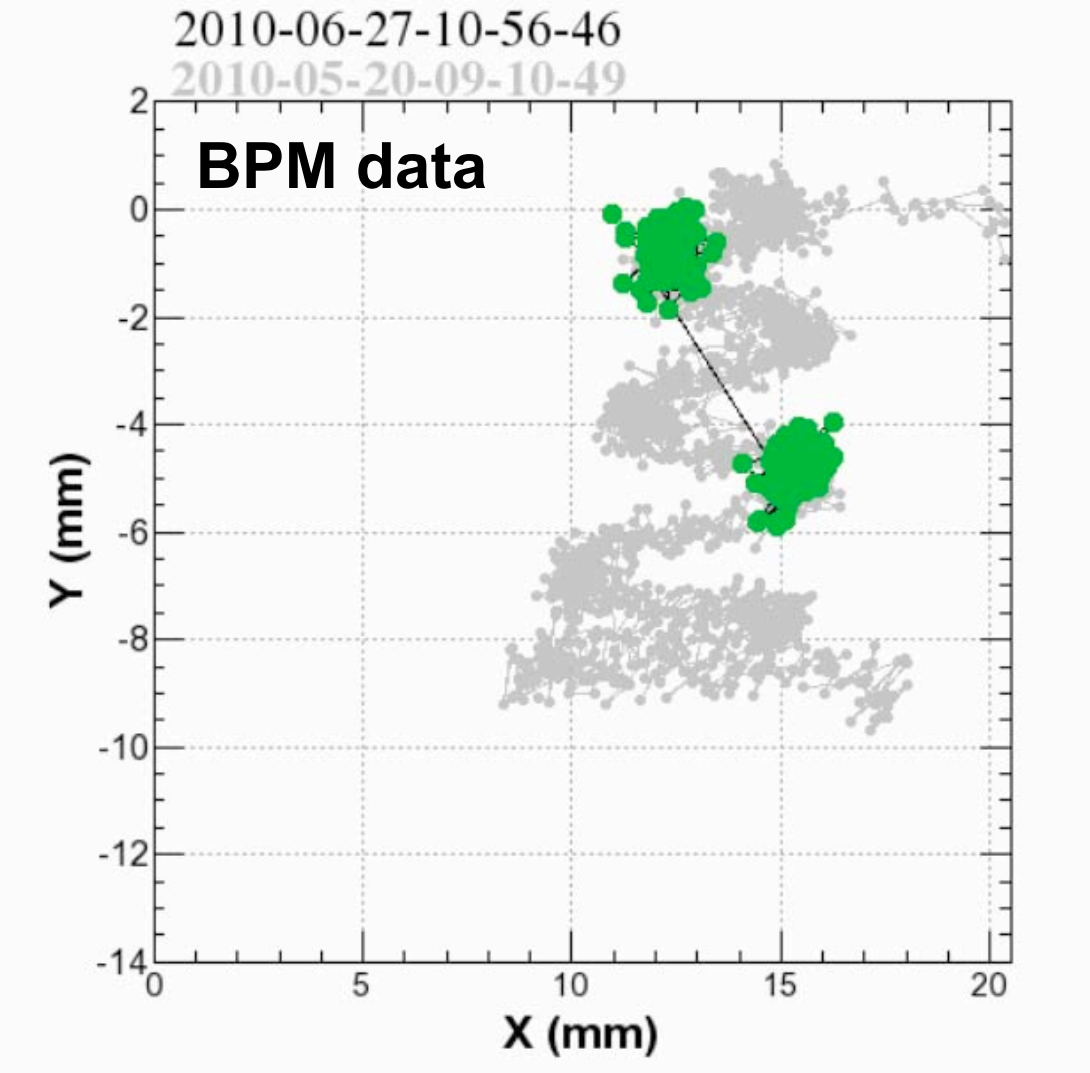
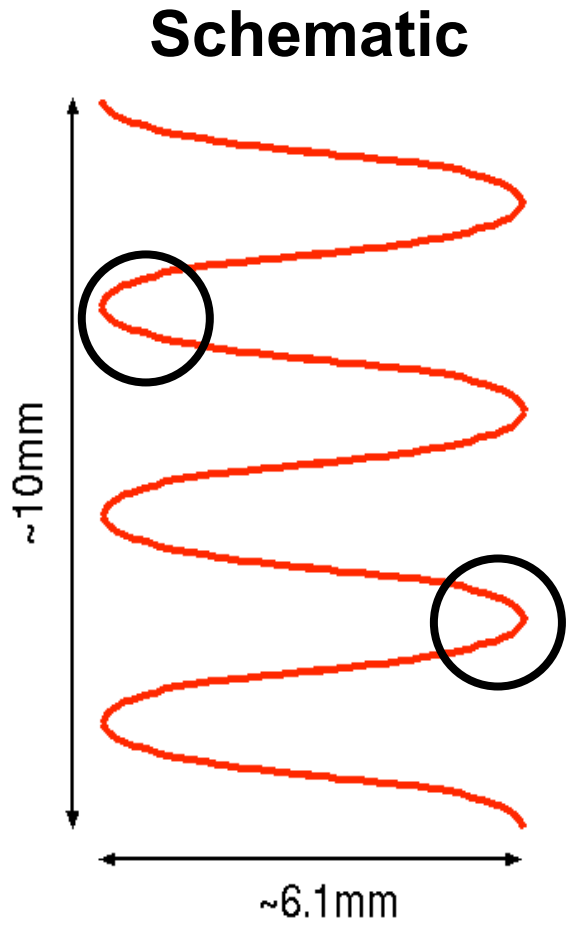




116 bunches and 117 bunches

KEKB Beam Condition (Actually Achieved)

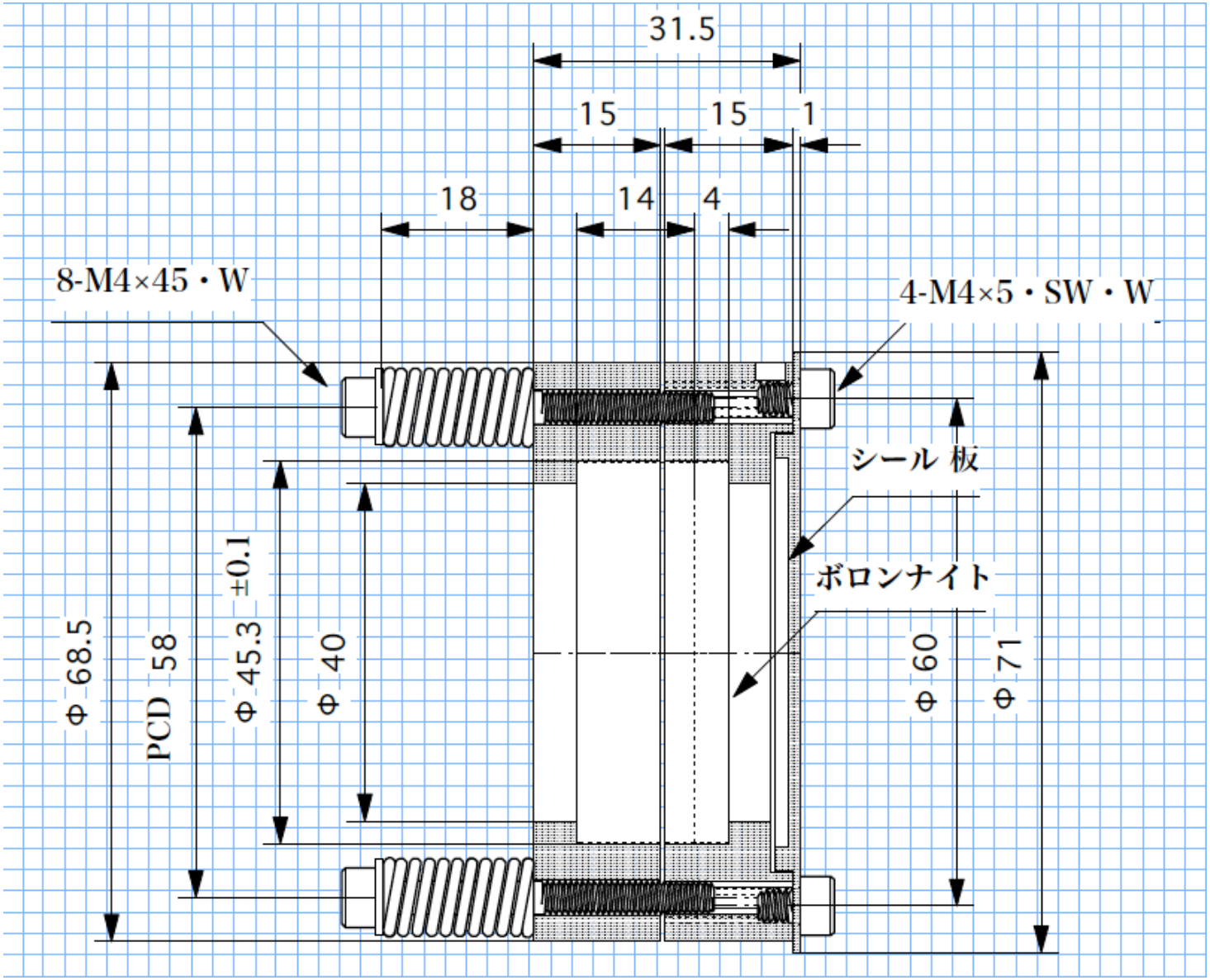
	Planed	Actually Achieved
Number of Bunches	132	116.5
Charge/Bunch	1.24 nC	1.4 nC
Expected PEDD	96 J/g	96 J/g

x 2 spots

PEDD: Peak Energy Deposit Density

The 2 spots were well separated spatially, so not affected each other.

Target Sample



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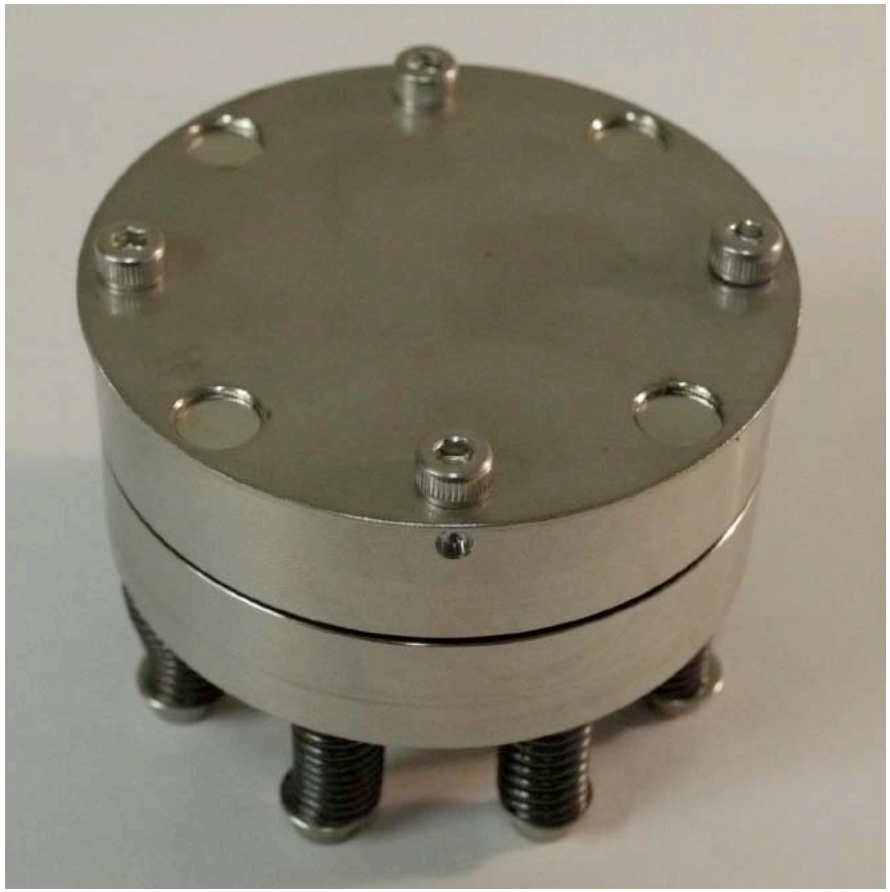
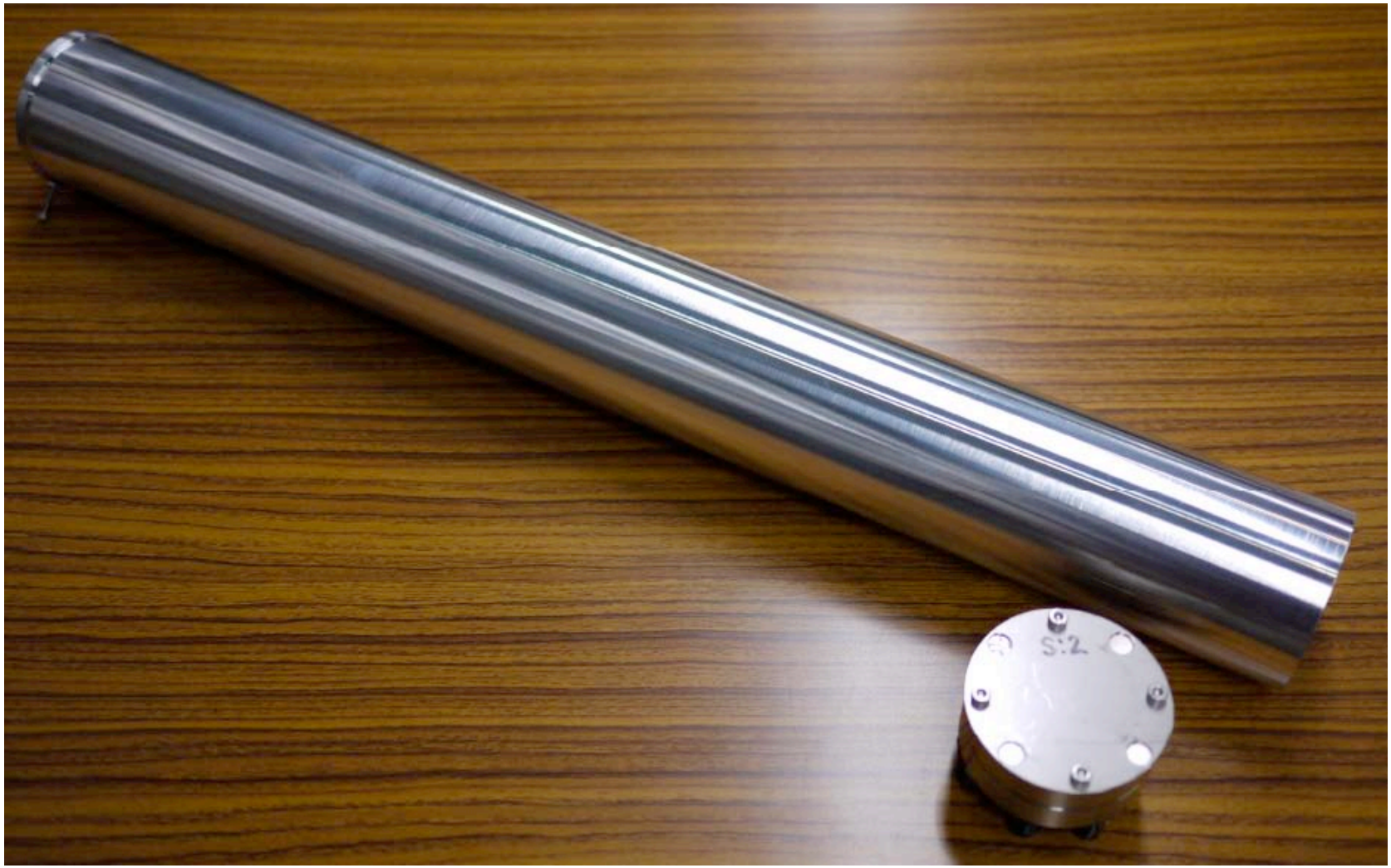
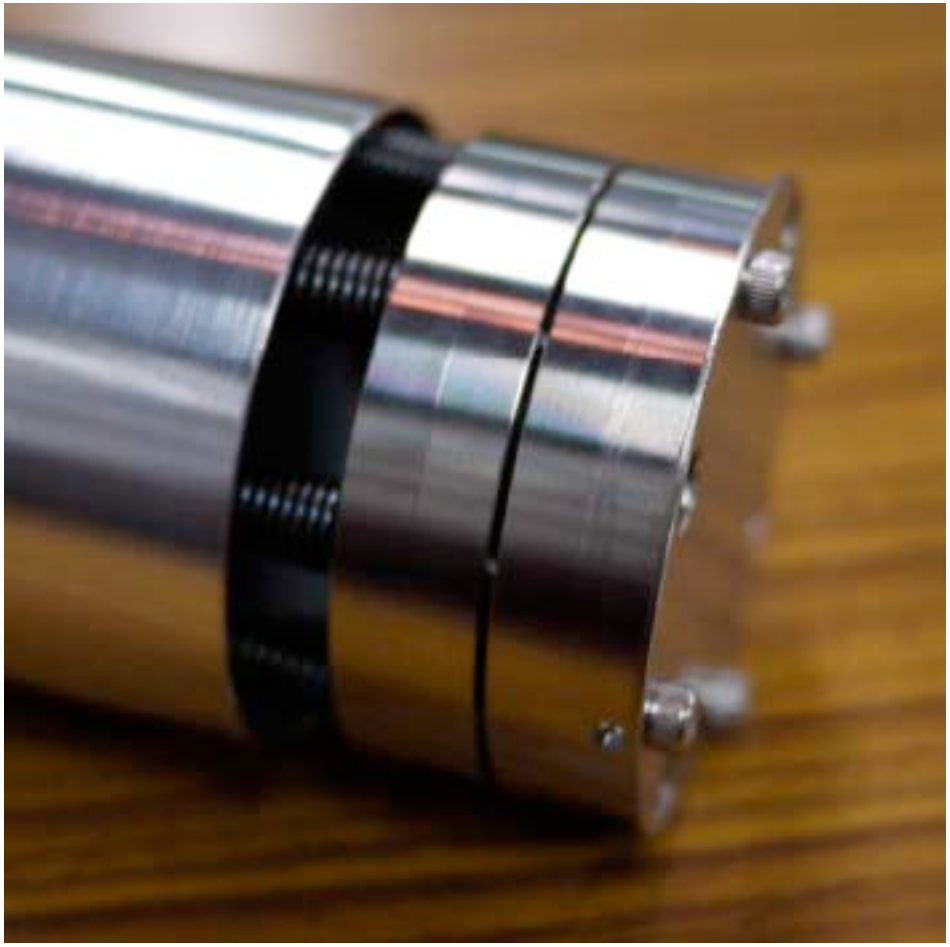


Target Sample with the pipe



Target Sample installed in the pipe



Irradiation : Day 1
27-June-2010

Experiment: 27-June-2010

Experiment: 27-June-2010

Irradiations on 3 Samples

Charge Index	nC/bunch	Current(mA) (116+117 bunches)	# Sample
0.5	0.7	17.4	S:1
1	1.4	32.9	S:2
2	2.8	65.7	S:3

Charge Index =**1** ⟷ PEDD=**96** J/g (1.24 nC x 132 bunches)

(1.4 nC x 117 bunches)

Irradiation : Day 2
28-June-2010

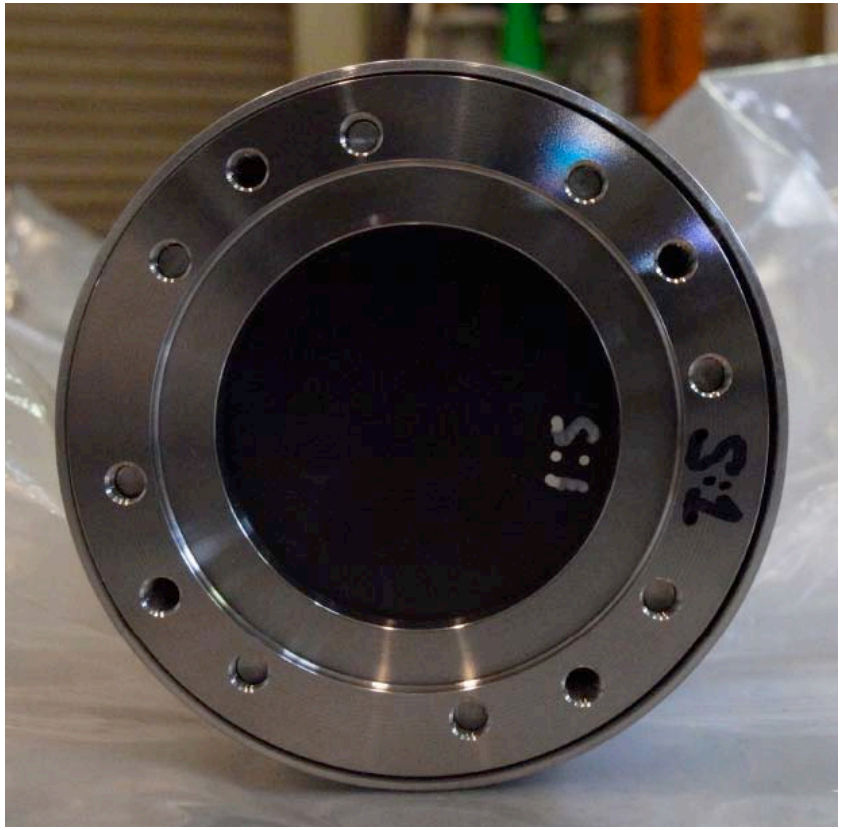
Check radiation level of Irradiated Samples (irradiated on the previous day) with opining the rids of the pipes

Sample	Charge Index	Radiation Level
S:1	c=0.5	2.6 μS/h
S:2	c=1	5.9 μS/h
S:3	c=2	13.6 μS/h

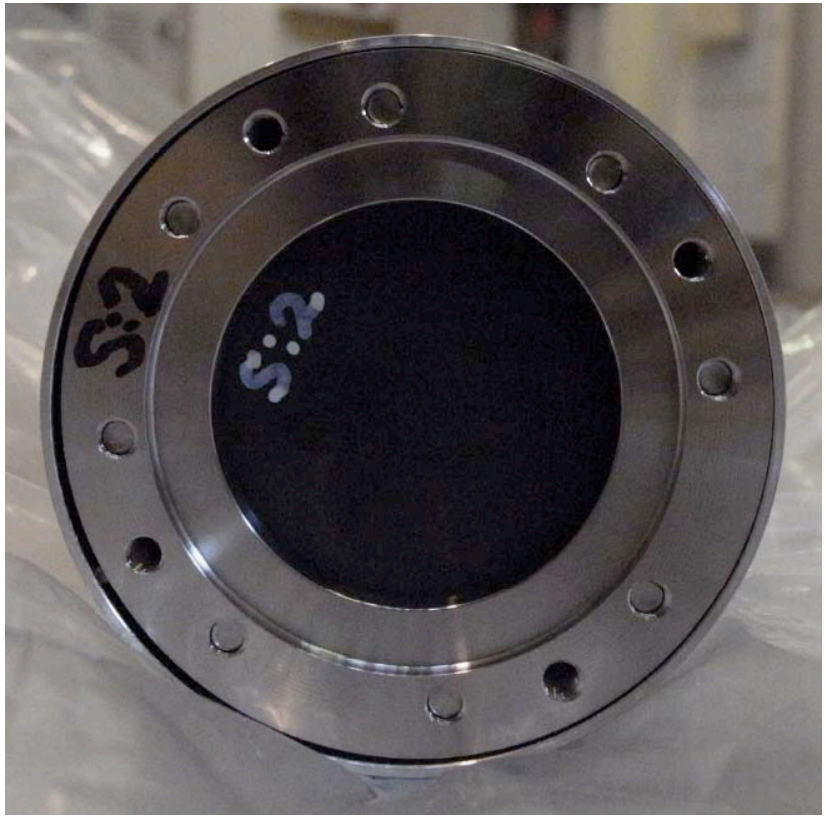
photo: N. Iida

Look Samples Irradiated on 27/June

S:1 (c=0.5)



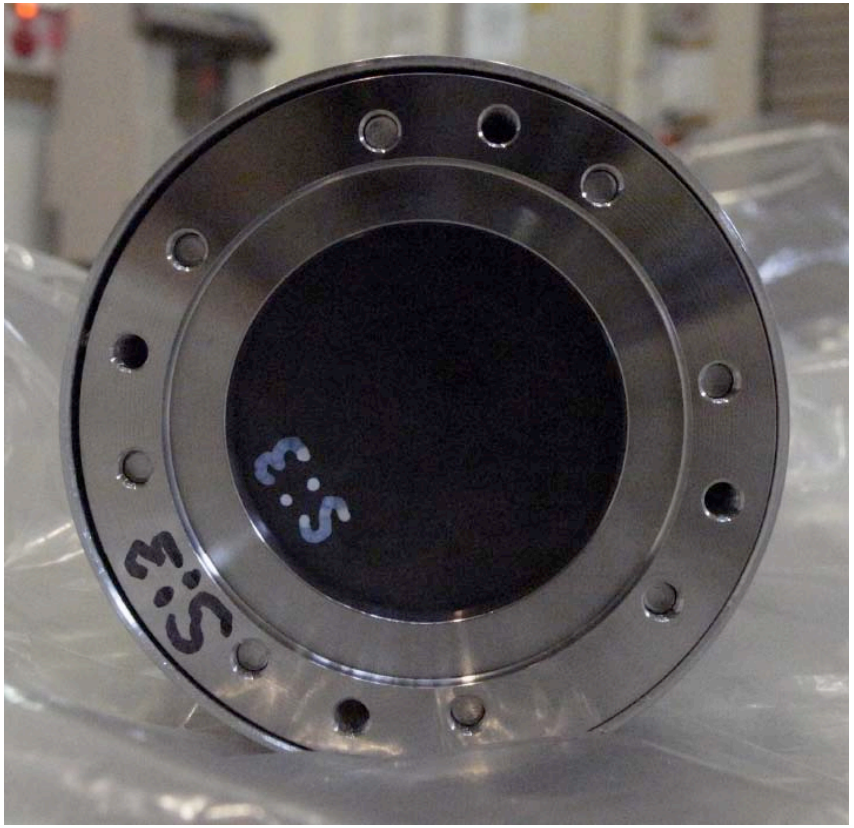
S:2 (c=1)



No obvious damage, defect, or crack was observed.

Look Samples Irradiated on 27/June

S:3 (c=2)



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Multiple Irradiation to the same Sample
28-June-2010

Multiple Irradiation to the same Sample
28-June-2010

Make 4 irradiations on to the same sample (S:0).

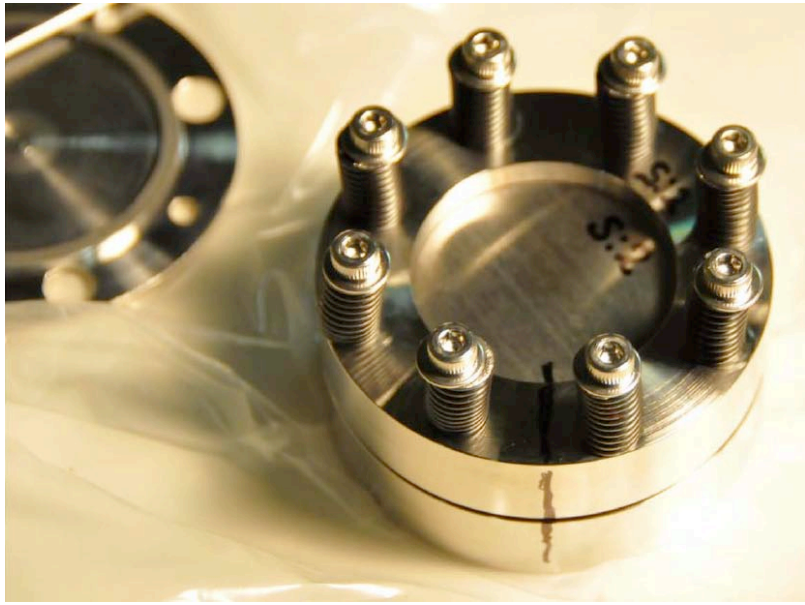
Condition of each irradiation

Charge Index	nC/bunch	Current(mA) (116+117 bunches)	# Sample
1	1.4	33	S:0

x 4

Disassembling
&
Observation
26-August-2010

S:2 (c=1)



S:2 (c=1)

W

BN

2 spots (reduced brilliance) were observed by eyes.
We can see them in photo.

2 very faint spots (slightly reduced brilliance) were observed by eyes.
We can NOT see them in photo.

No damage, defect, or crack was observed.

S:3 (c=2)

W

2 spots (reduced brilliance) were observed by eyes.
We can see them in photo.

BN

2 spots (reduced brilliance) were observed by eyes.
We can see them in photo.

No damage, defect, or crack was observed.

S:1 (c=0.5)

W

BN

2 very very faint spots (slightly reduced brilliance) were observed by eyes.
We barely see them in photo.

No spots were observed even by eyes.

No damage, defect, or crack was observed.

S:0 ((c=1) x 4 irradiations)

W

No spots were observed even by eyes.

BN

No spots were observed even by eyes.

No damage, defect, or crack was observed.

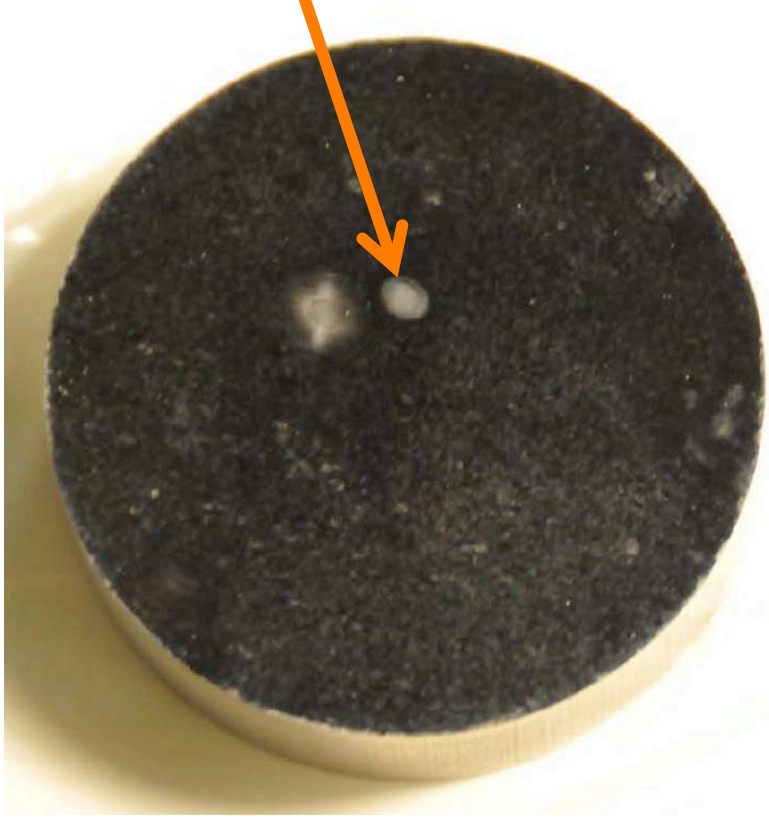
Observation
by "Microscope"

October-2010

S:3 (c=2)

look by "microscope"

W



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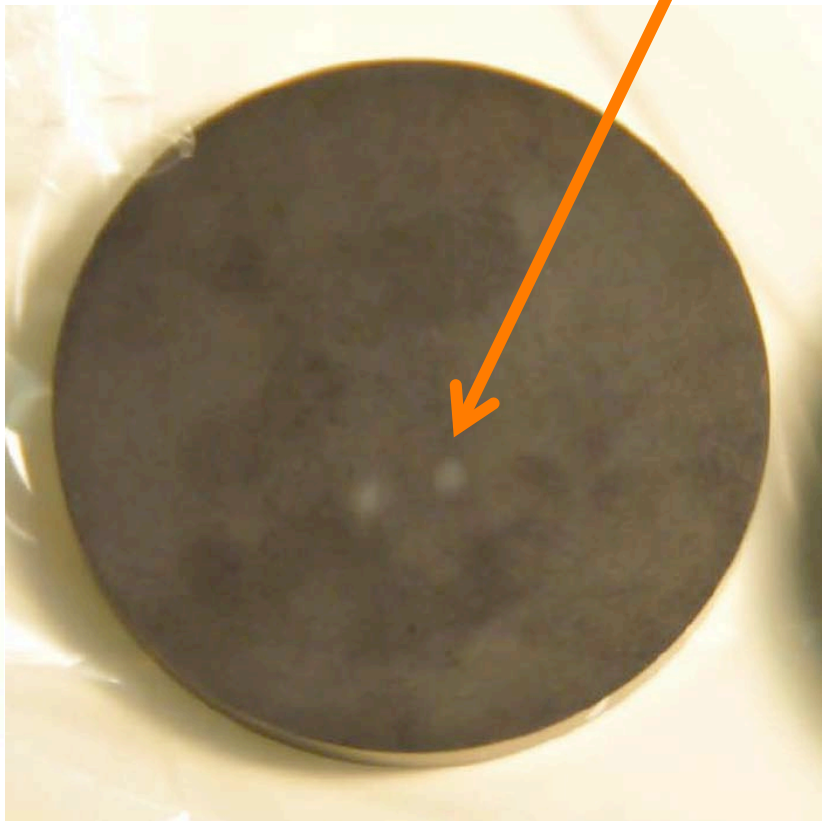

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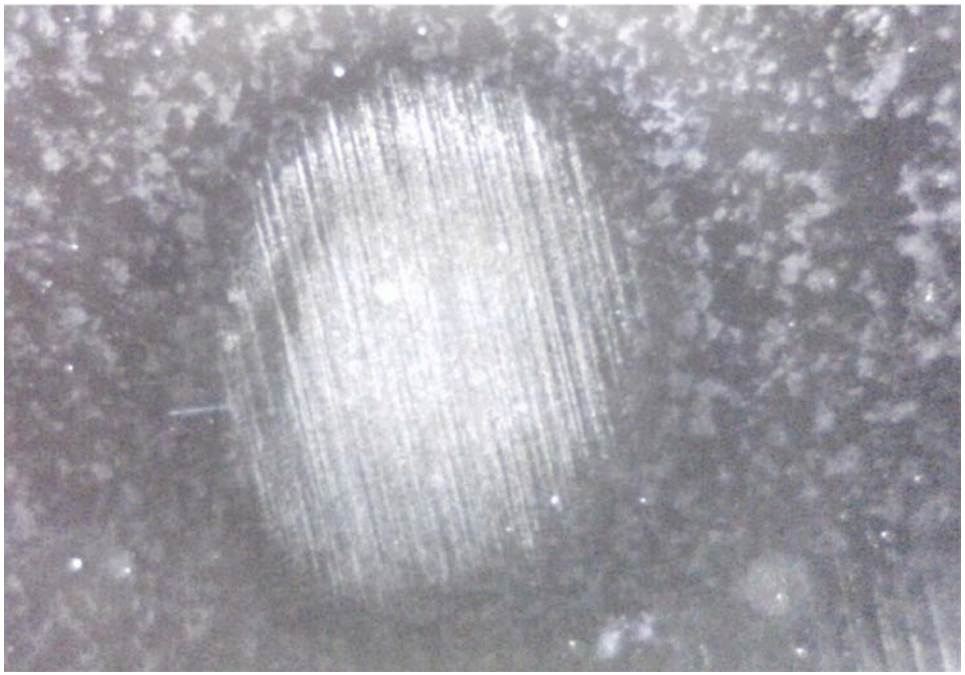
S:3 (c=2)

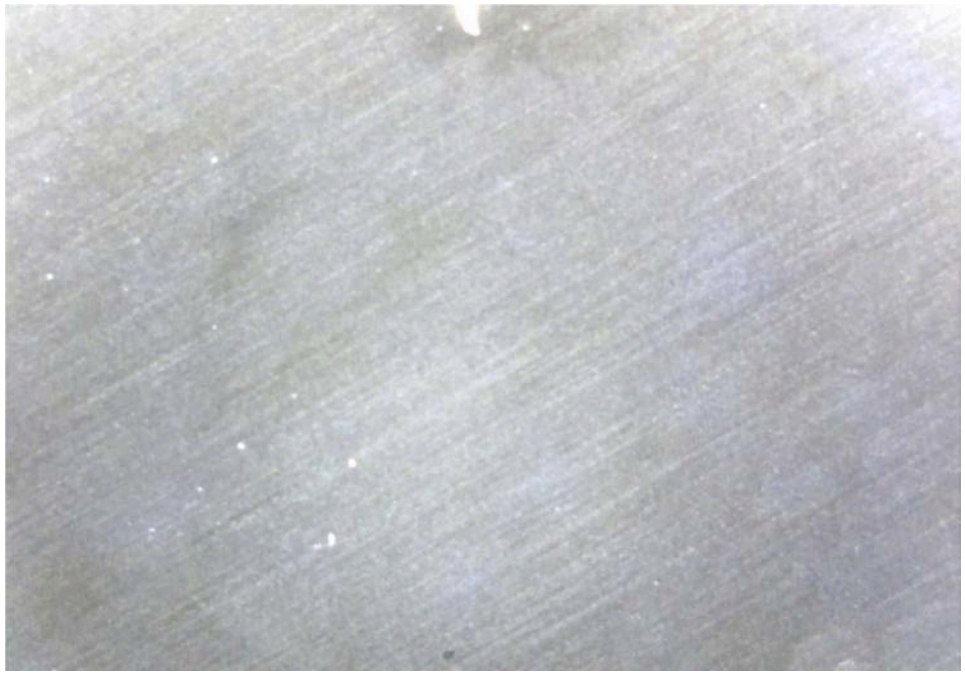
W



look by "microscope"

BN

this white object is a pointer



look by "microscope"

No damage, defect, or crack was observed.

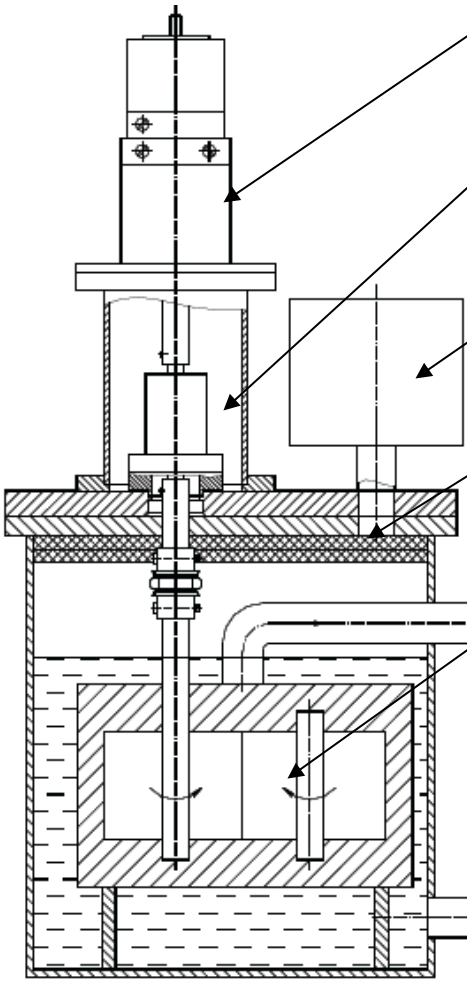
Liq. Pb target R/D

Test at ATF Linac

Prototype of Liquid Lead Positron Production Target

Logachev-san et al, BINP

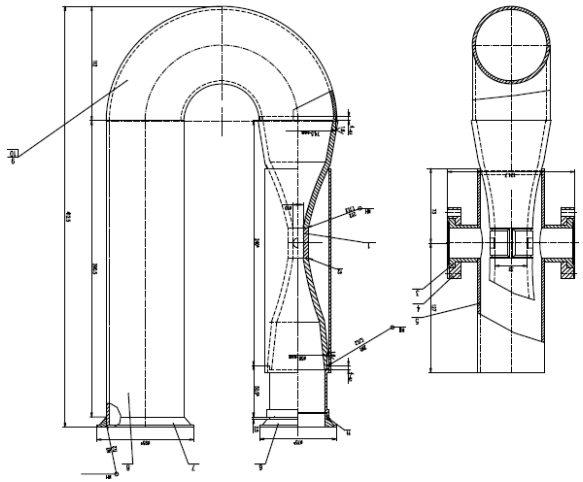
Operation experience 20000 h



Window thickness 4mm
BN disks for windows
Diameter 12mm

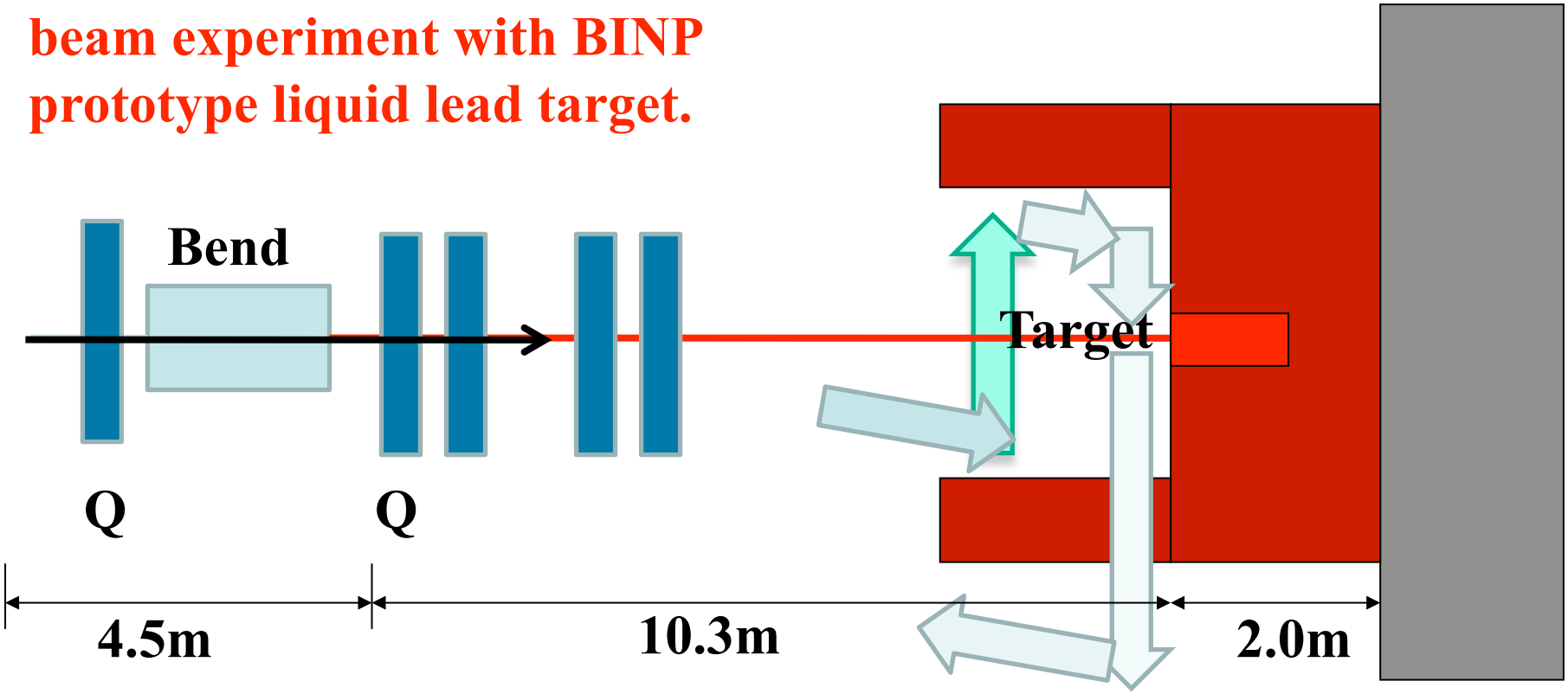
Liquid lead target test

at ATF Linac End



Liquid lead 300℃

We kek decided to do the beam experiment with BINP prototype liquid lead target.



Status and Schedule

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- **Two engineers, M. F. Blinov san and V. Golikov san, came ATF, made discussion with KEK people, and checked the area where the prototype will be installed.**

Liquid Pb Target at ATF

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- Two engineers, M. F. Blinov san and V. Golikov san, came ATF, made discussion with KEK people, and checked the area where the prototype will be installed.

Plan

- Originally, we planed installation in summer 2010. But delayed.
- Install in winter 2010-2011, or summer 2011?

Summary

Summary

- Two Issues on Target
  - Heat Load (by beam): Time Scale ~ 1 m sec.
  - Thermal shock wave: Time scale ~ sub micro sec.

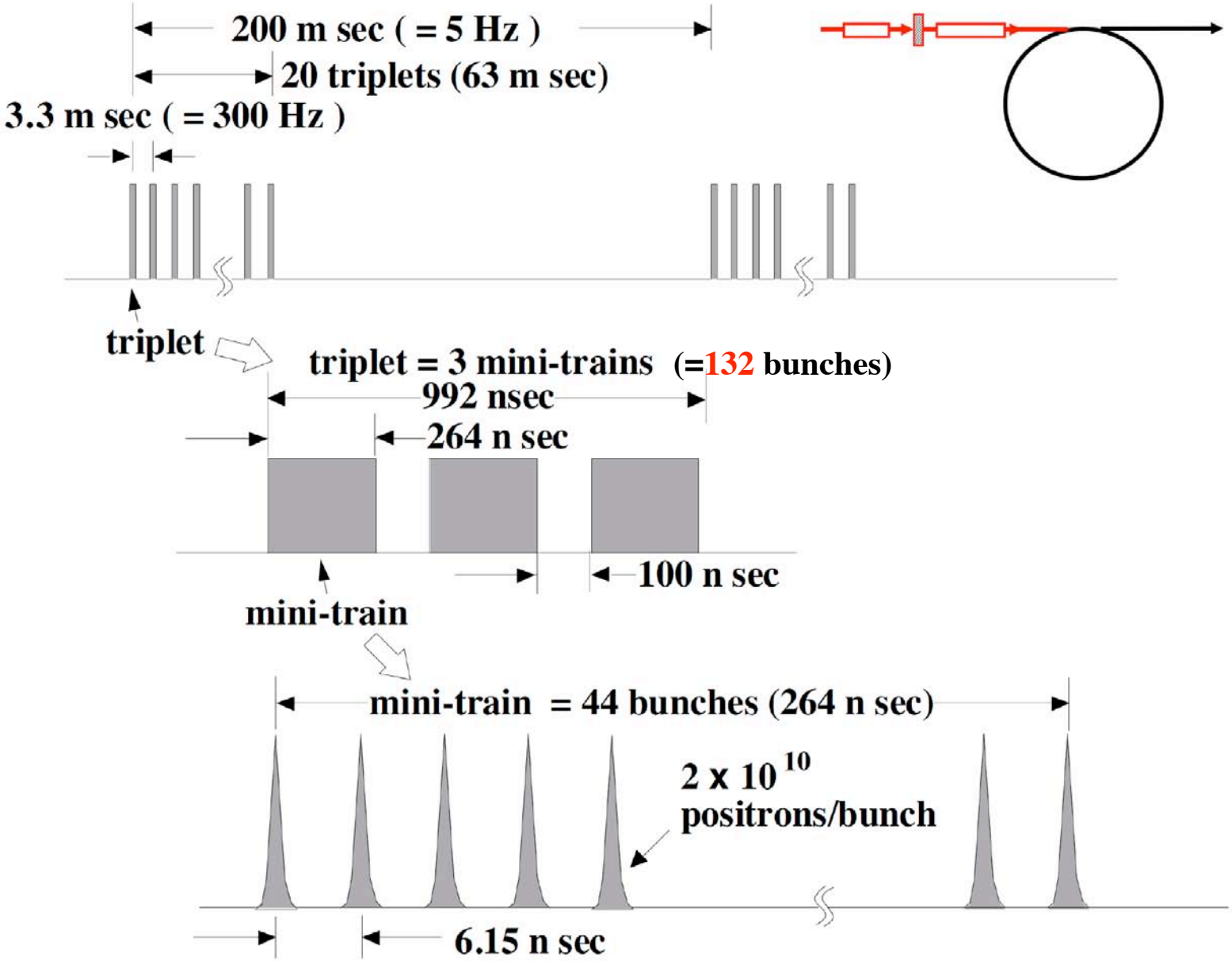
- 300 Hz Scheme w/ liq. lead target (alternative)
  - It requires a window between liq. lead and acc.
  - Does the BN window survive under shock wave?

- Thermal shockwave on BN window:
  - Tested at KEKB High Energy Ring
  - No damage, defect, or crack was observed up to twice bunch charge.

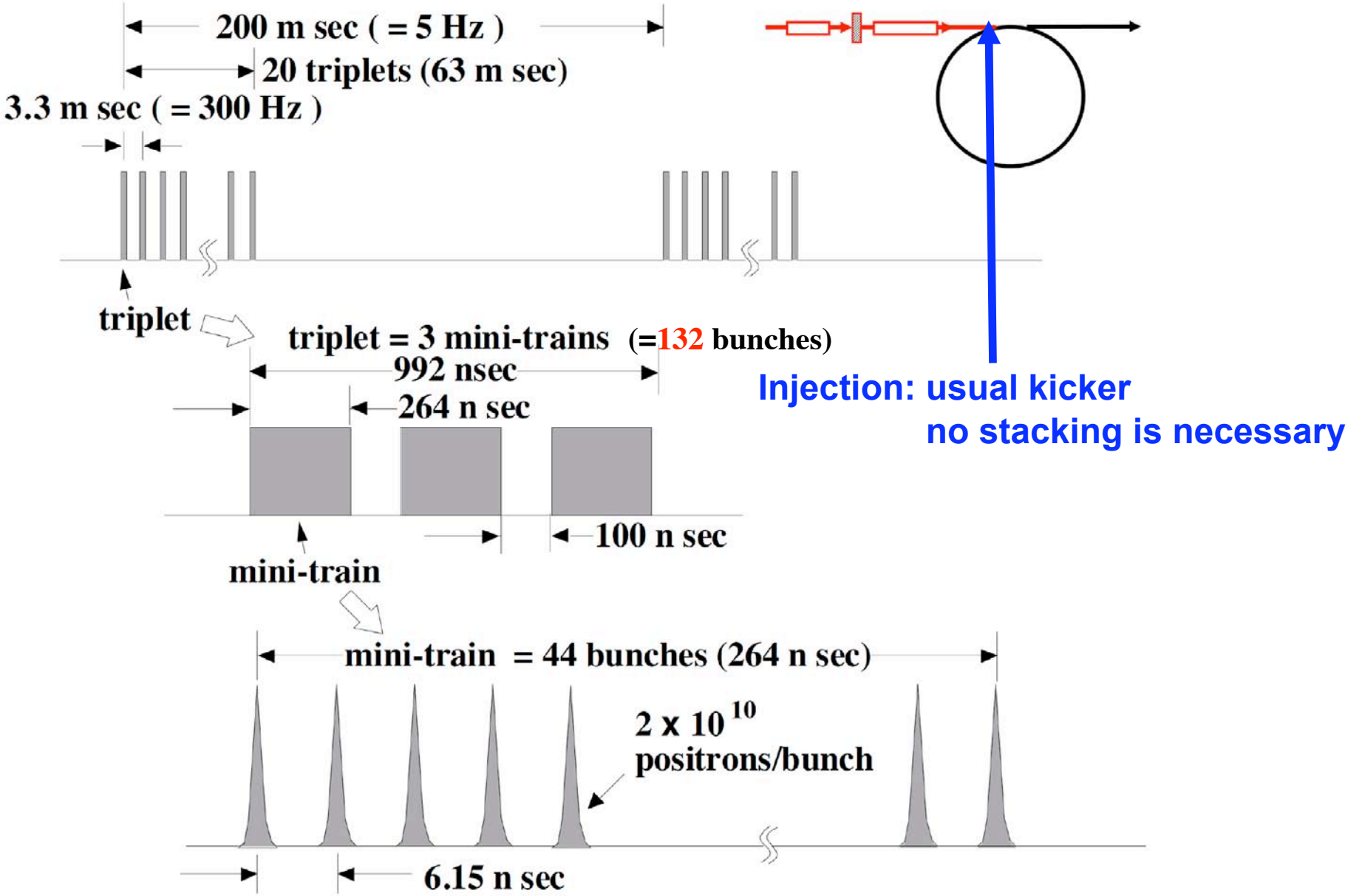
- Operation experience with beam:
  - Plan: Install Liq. Lead Target in ATF Linac

Backups

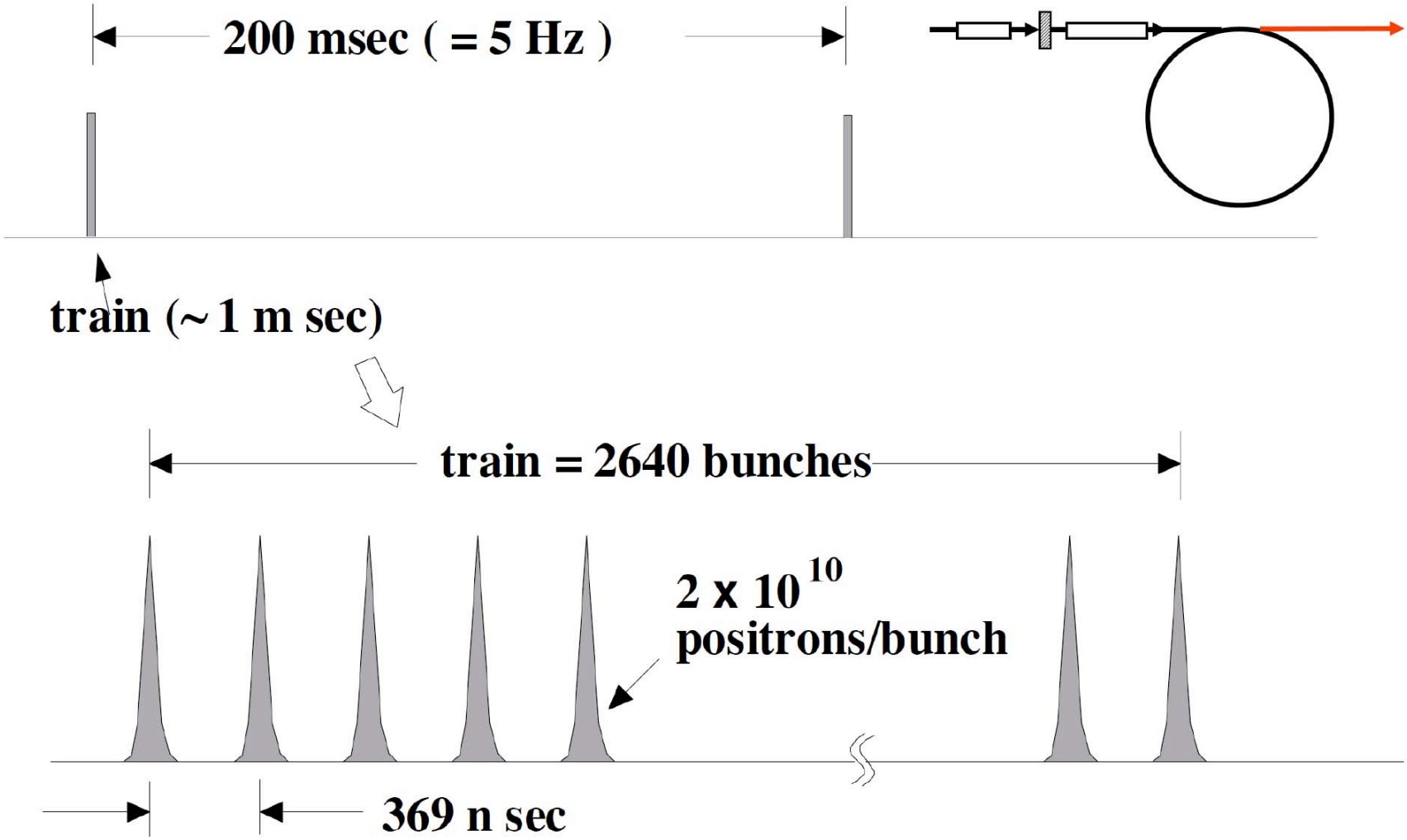
Beam before DR



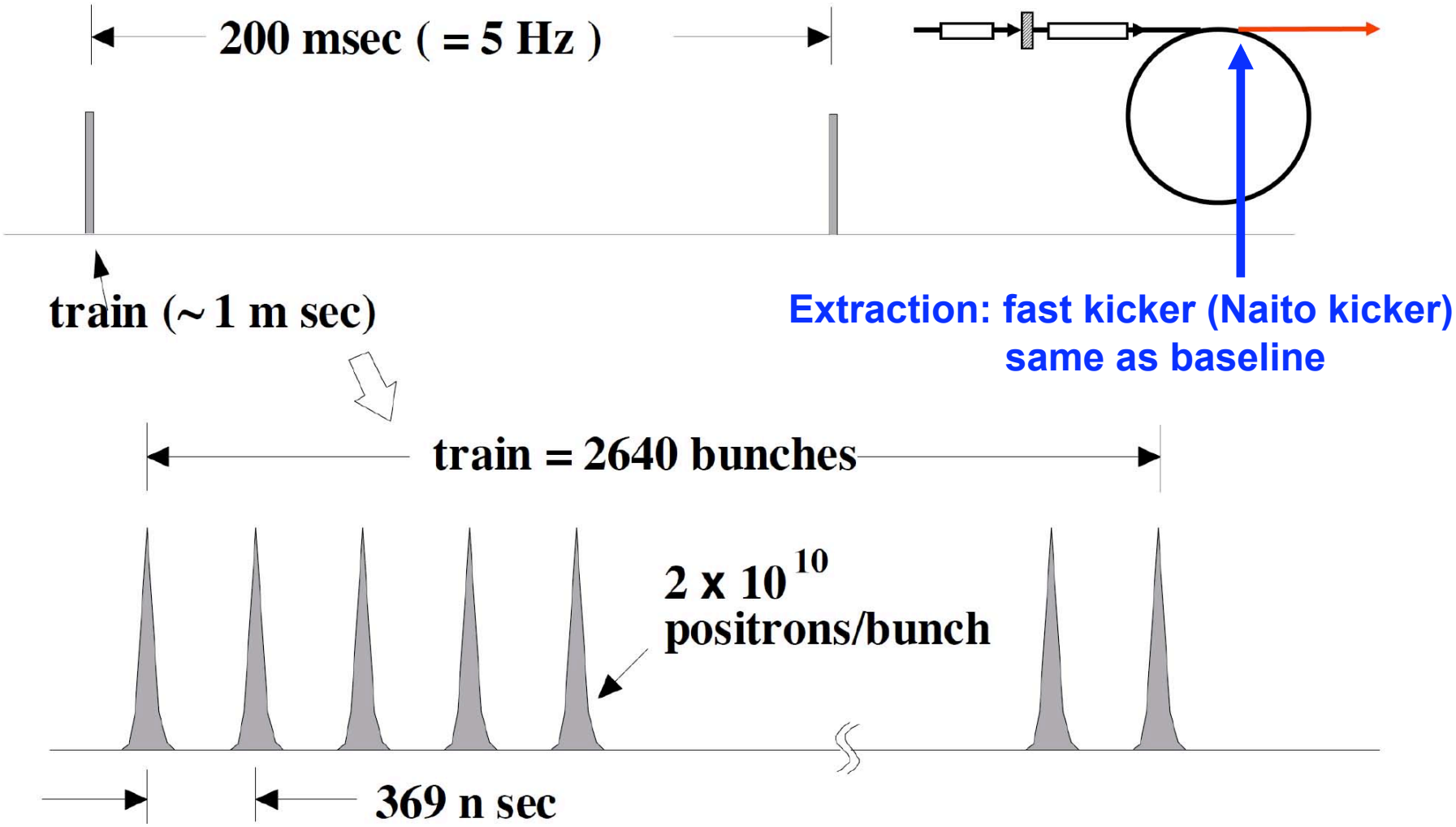
Beam before DR



Beam after DR



Beam after DR



Experiment using metals other than Pb
Is the experiment useful?

EM shower :

deposit energy in very short time
We ignore movement of each part of material.
Temperature and pressure rise, but density stay constant.

After EM shower, each part of material starts moving (sound in material).

Temperature Rise : ΔT

$$\Delta T = \frac{\Delta E}{c_v}$$

ΔE : Energy Deposit
Cv : Specific Heat Capacity (at Constant Volume)

Pressure Rise (Linear Approximation)

$$\Delta P = \left(\frac{\partial P}{\partial T}\right)_v \Delta T$$

$$= -\left(\frac{\partial P}{\partial V}\right)_T \left(\frac{\partial V}{\partial T}\right)_P \frac{\Delta E}{c_v}$$

$$= \frac{K}{V}\beta V \frac{\Delta E}{c_v}$$

$$= \frac{K\beta}{c_v}\Delta E$$

ΔE : Energy Deposit
Cv : Specific Heat Cap.
β : Vol. Thermal Exp. Coeffi.
K : Bulk Modulus

Pressure Rise (Linear Approximation)

$$\Delta P = \frac{K\beta}{c_v}\Delta E$$

ΔE : Energy Deposit
Cv : Specific Heat Cap.
β : Vol. Thermal Exp. Coeffi.
K : Bulk Modulus

If the energy deposit is same,

Pressure rise (force on BN window)
∝ (K x β) /Cv

Comparison of Metals

		Ti	Fe	Cu	W	Pb	Liq. Pb
Atomic Number		22	26	29	74	82	82
Density(g/cm^3)		4.51	7.87	8.92	19.3	11.3	10.7
V. T. Exp. Coef. (10^{-6} K^{-1})	β	26	35.4	50	13.5	86.7	112
Bulk Modulus (GPa)	K	108	111	138	310	45.8	33.3
Specific Heat (J g^{-1} K^{-1})	C_V	0.52	0.44	0.38	0.132	0.129	0.146
β x K		2808	3929	6900	4185	3971	3730
(β x K) / C_V		5400	8930	18160	31700	30800	25500
β / C_V		50	80	130	100	670	770

＜Comparison of Metals＞

		Ti	Fe	Cu	W	Pb	Liq. Pb
V. T. Exp. Coef. (10^{-6} K^{-1})	β	26	35.4	50	13.5	86.7	112
Bulk Modulus (GPa)	K	108	111	138	310	45.8	33.3
Specific Heat (J g^{-1} K^{-1})	C_V	0.52	0.44	0.38	0.132	0.129	0.146
$(\beta \times K) / C_V$		5400	8930	18160	31700	30800	25500

＜Evaluation＞

- Pressure on the window ~ $(\beta \times K) / C_V$
- Pressure of W and Cu ~ Pressure of Liq. Pb
  W／LiqPb ~ 1.3、 Cu／LiqPb ～0.7。
- Ti and Fe give too small pressure.

Pressure at ΔE = 96 J/g

	Cu	W	Liq. Pb
ΔP(GPa)	1.5	3.1	2.3

Summary Table

	Ti	Fe	Cu	W	Pb	Liq. Pb
Atomic Number	22	26	29	74	82	
Density (g/cm^3)	4.51	7.87	8.92	19.3	11.3	
Melting Point (K)	1941	1808	1358	3695	601	
Boiling Point (K)	3560	3023	2840	5828	2022	
Vol. Thermal Expansion Coeffi. (10^{-6} K^{-1}) β	26	35.4	50	13.5	86.7	112
Bulk Modulus (GPa) K	108	111	138	310	45.8	33.3
Specific Heat Capacity (const. V) ($J g^{-1} K^{-1}$) C_V	0.52	0.44	0.38	0.132	0.129	0.146
β x K	2808	3929	6900	4185	3971	3730
(β x K) / C_V	5400	8930	18160	31700	30800	25500
Radiation Length (mm)	35.6	17.5	14.3	3.5	5.6	
(a-1) Charge/b (nC) for 96 J/g (10 μs)	0.33	0.72	0.89	0.60	0.63	
(a-2) Temp at Max. Point (K)	458	472	534	1020	826	
(b-1) Charge/b (nC) for 96 J/g (132bunces)	3.41	3.22	2.82	1.24	1.7	
(b-2) Temp at Max. Point (K)	1920	1070	1040	1790	1850	

Plan of Experiment

1. We will use material (metal) which melting point is higher than that of lead.
2. We consider several metals.
3. According to the simulation, tungsten (W), copper (Cu), and iron (Fe) are good in a view point of safety.
4. In the view point of the emulation of the liquid lead target, a simple analytic model tell as W and Cu are good.
5. We choose W, because we have experiences to use W.

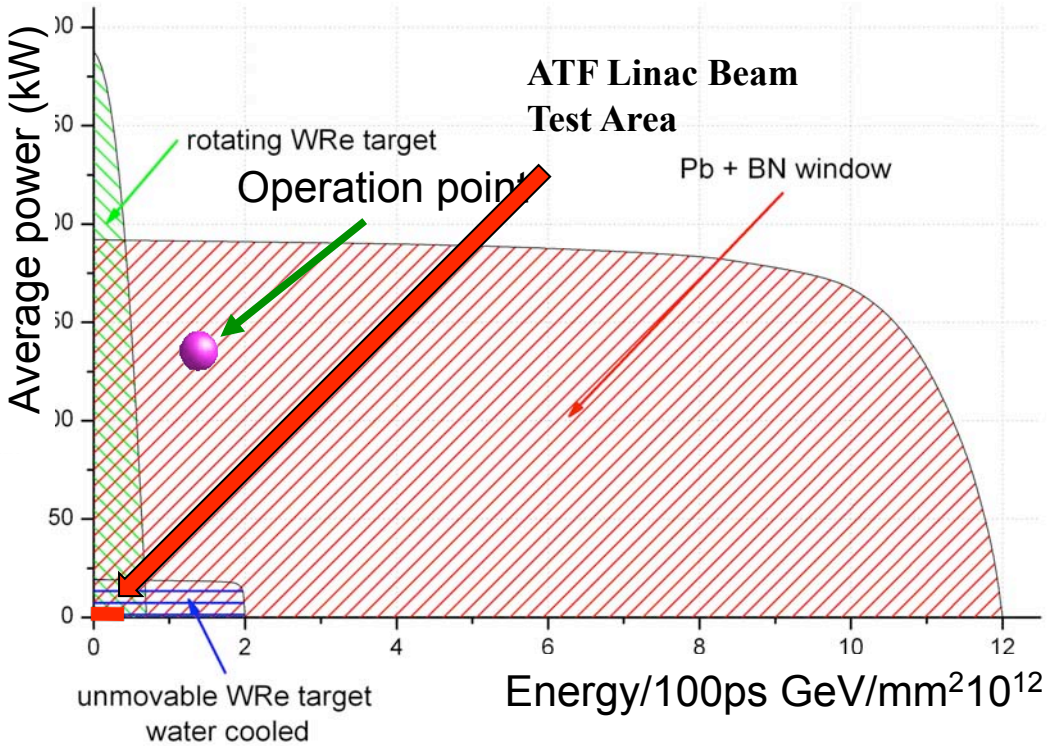
ATF Linac Beam Parameters

β function tuning range : 0.1m to 10m
Bunch structure : 1 to 20 bunches/train
Bunch charge : 0.5 to 2.0 x 10^{10} electrons/bunch
Beam energy : 1.3GeV
Repetition rate : 0.7 to 6.25Hz
Usual normalized emittance : less than 10πmmmrad
Beam size : 0.2 to 2.0mm

Energy density on target
0.006 to 48 x 10^{10} GeV/mm^2
Power deposit on target
0.004 to 300 x 10^{10} GeV/mm^2 s
Acceptable beam rep. rate?

Liquid Pb-Sn Target

- Liquid Pb target + BN window is very strong against high peak power, but less average power.
- Pulsed operation (e.g. 100 bunches with 6.2ns spacing, 0.6μs, 150Hz) moderates thermal effects.
- In the pulse operation, capture efficiency is higher and incident electron can be fewer.



P. Logachov et al. in APAC2007

Experiment: 27-June-2010

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photo: N. Iida

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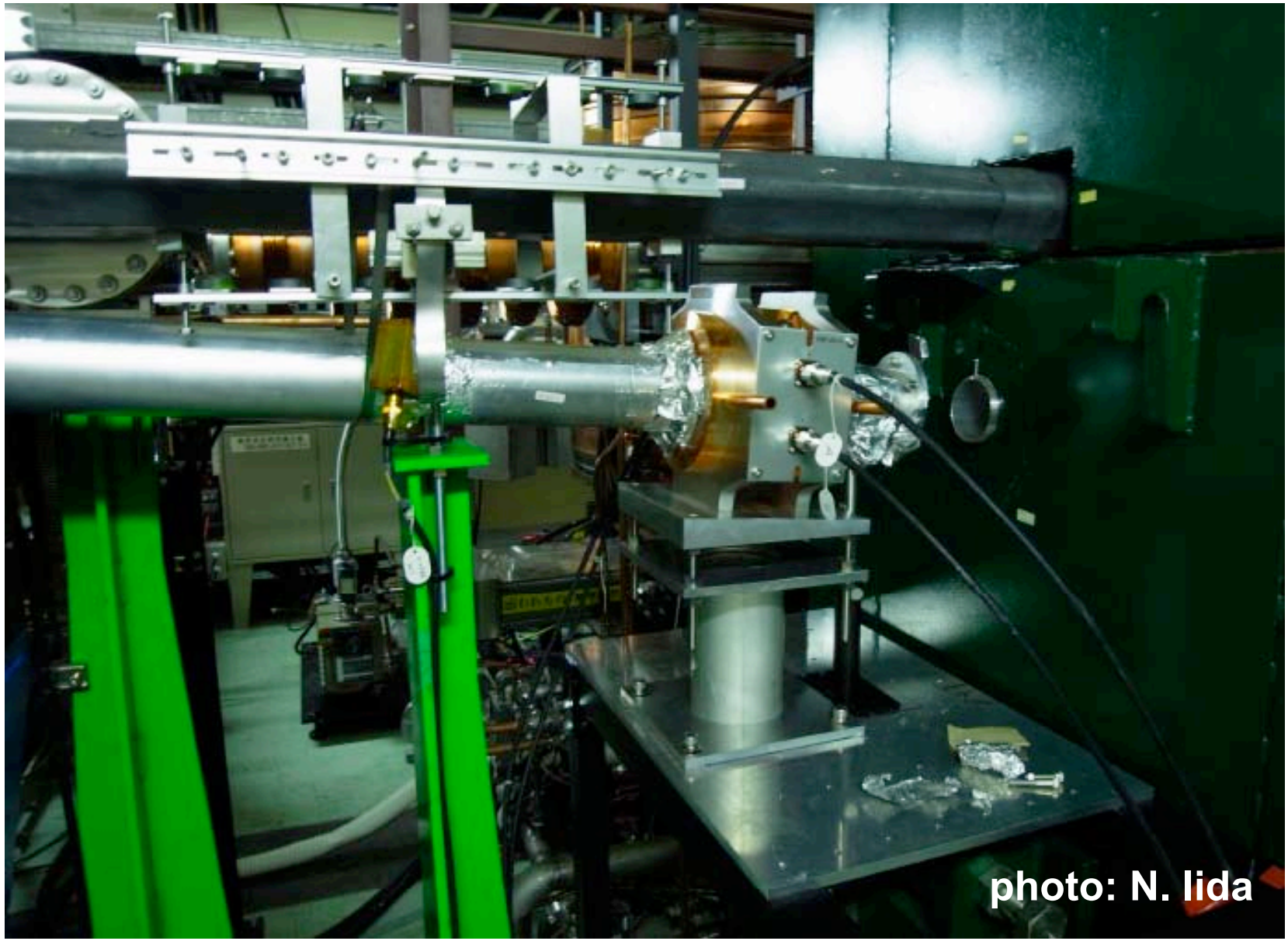
Experiment: 27-June-2010



Experiment: 27-June-2010

photo: N. Iida

Liquid Pb Target at ATF

Liquid Pb Target at ATF

Liquid Lead Target R/D

Three Activities

- **Heat Load (reported at TILC09):**
  - **By beam**
    - **Simulation (ANL) : done --> no problem (no report today)**
  - **By eddy current**
    - **Simulation (CI) : done --> no problem (no report today)**

- **Thermal shockwave on BN window:**
  - **Test at KEKB High Energy Ring (today's report)**
  - **Simulation is in preparation (no report today)**

- **Operation experience with beam:**
  - **Install Liq. Lead Target in ATF Linac (today's report)**