

*Undulator-based and Crystal-based Gamma Radiation Sources for Positron Generation*

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# Conventional positron sources

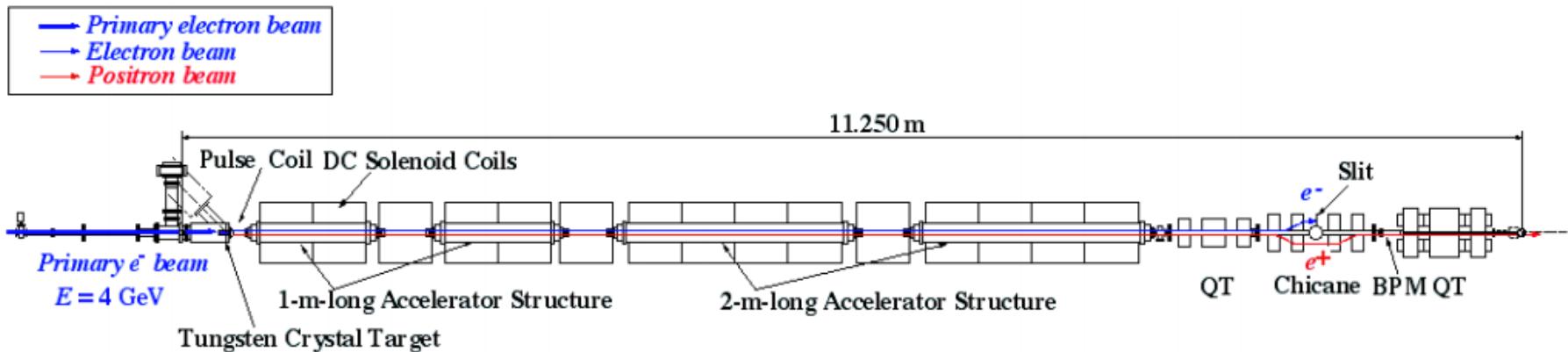
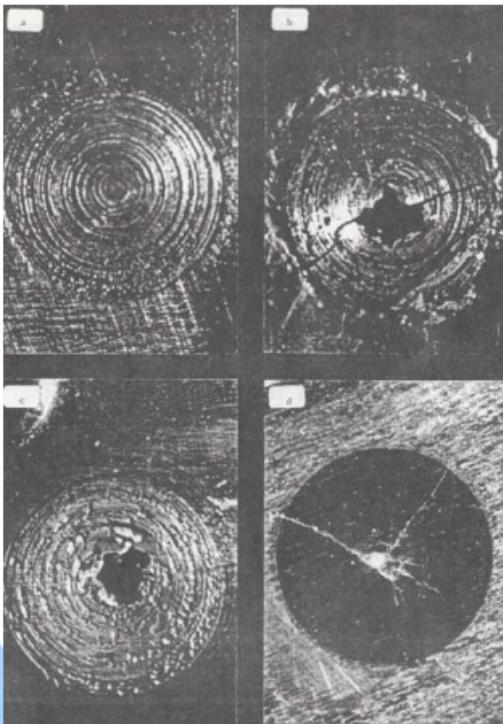


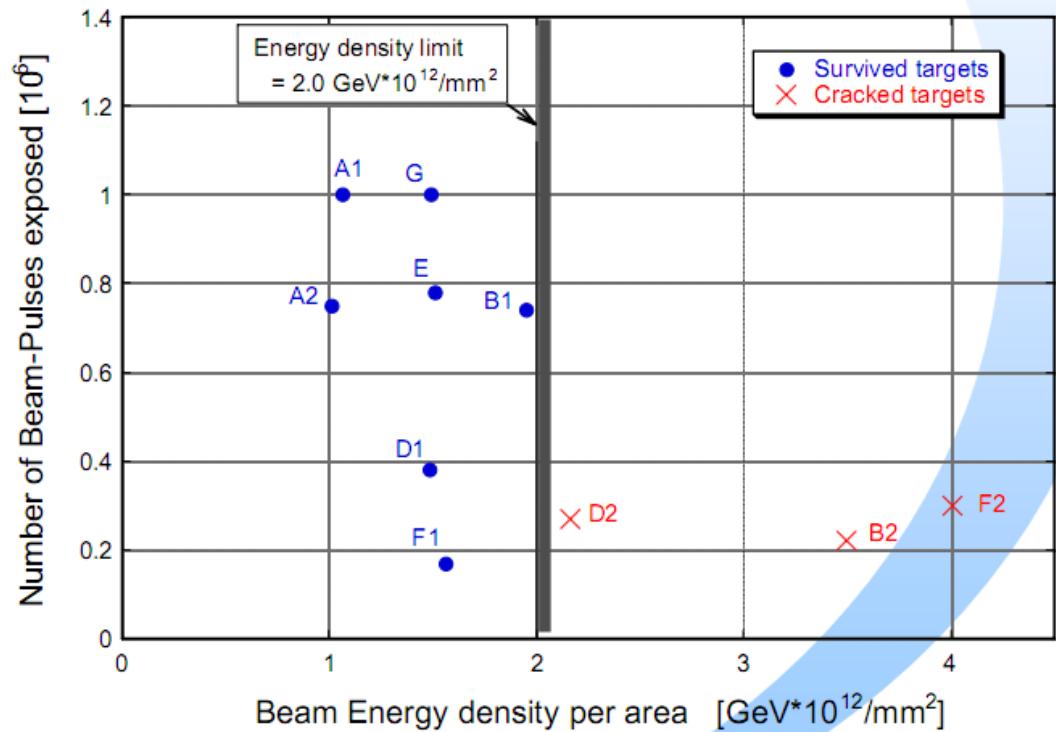
FIG. 1. (Color) Layout of the positron source at the KEKB injector linac. QT, quadrupole triplet.

Positrons are generated from showers produced by an initial electron beam in amorphous target with thickness  $\sim L_0$  ( $L_0$  – radiation length).  
Target thermal damage is the key problem.

# *Experiment of positron target at SLAC*



20 GeV, 16nC electron beam on W75Re25  
The damage of the positron target  
In the various beam  
(S. Ecklund, SLAC-CN-128, 1981)



Target damage depends on thermal energy density caused by the beam

T. Kamitani (modified by T.Mimashi)

# *To avoid damage of Positron Target*

## Material

- A high heat capacity
- A low coefficient of thermal expansion
- A high ratio of yield strength
- A Large material yield stress

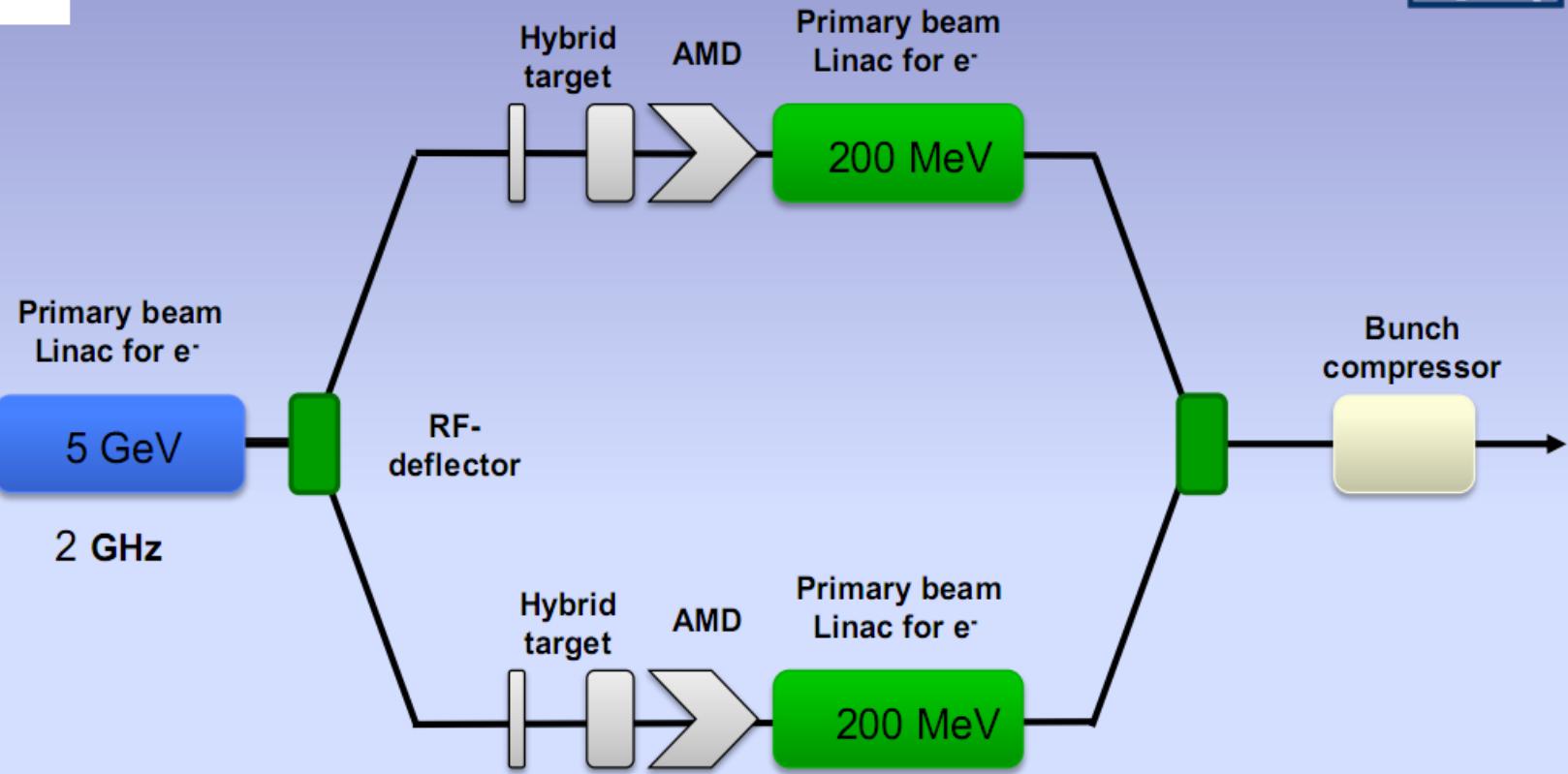
## Multi Target System

Rotate Target to avoid individual pulses imping on the same spot

Undulator - based scheme

Crystal - based scheme

# Multi - target positron source

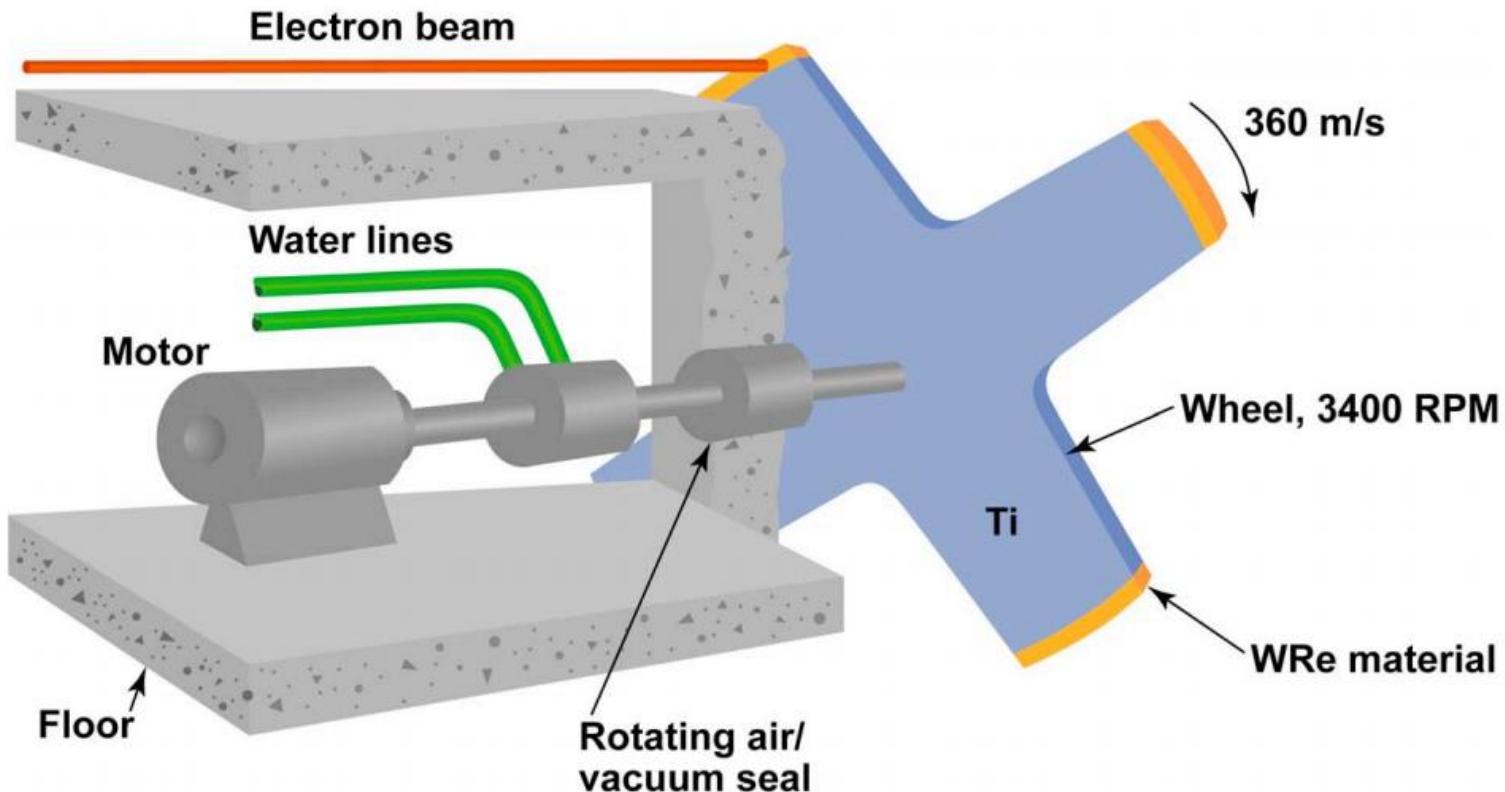


AMD: 200 mm long, 20 mm radius, 6 T field

Target Parameters Crystal		
Material	Tungsten	W
Thickness (radiation length)	0.4	$\chi_0$
Thickness (length)	1.40	mm
Energy deposited	~1	kW

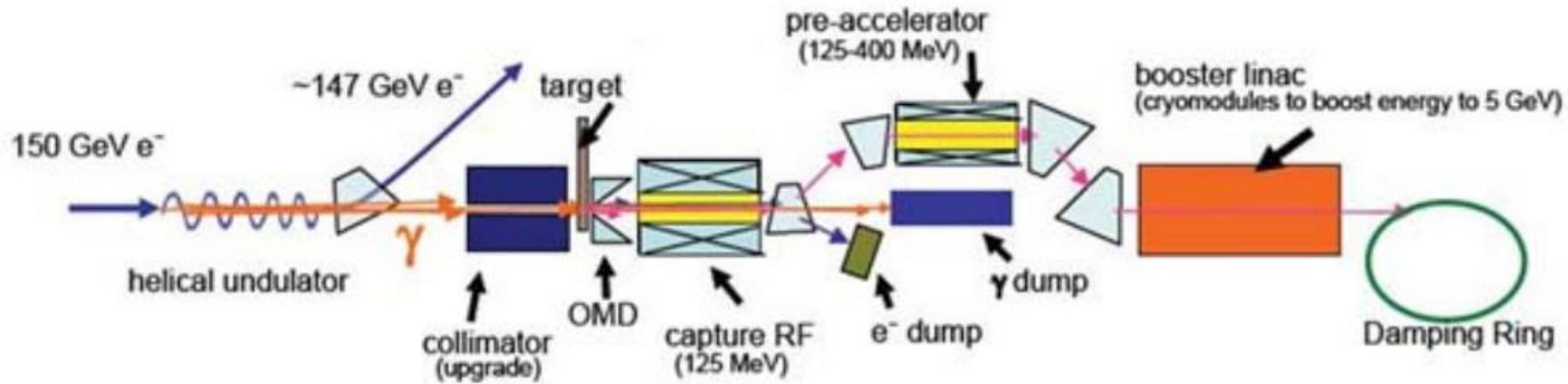
Target Parameters Amorphous		
Material	Tungsten	W
Thickness (Radiation length)	3	$\chi_0$
Thickness (length)	10	mm
PEDD	30	J/g
Distance to the crystal	2	m

## Conventional source target system layout



## Undulator – based scheme:

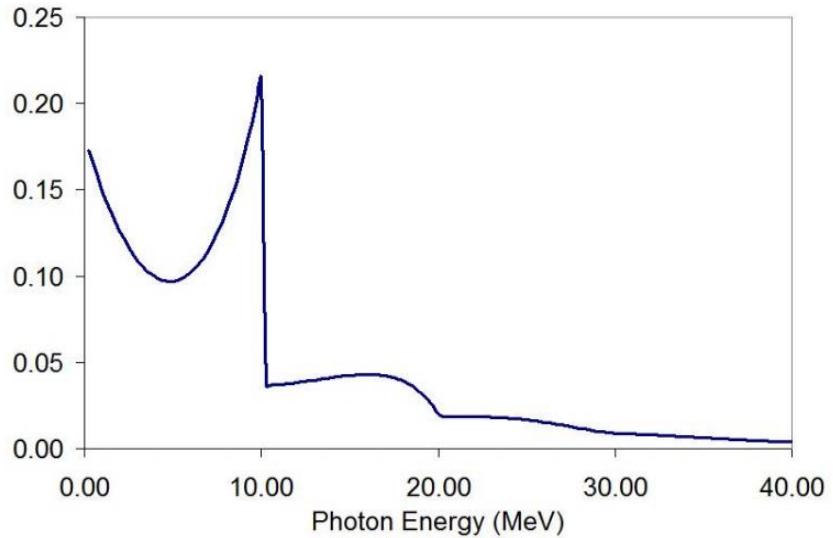
- long undulator ( $\sim 100$  m);
- electron energy ( $> 100$  GeV);
- mean photon energy ( $< 20$  MeV);
- amorphous converter ( $\sim 0.5 L_0$ ).



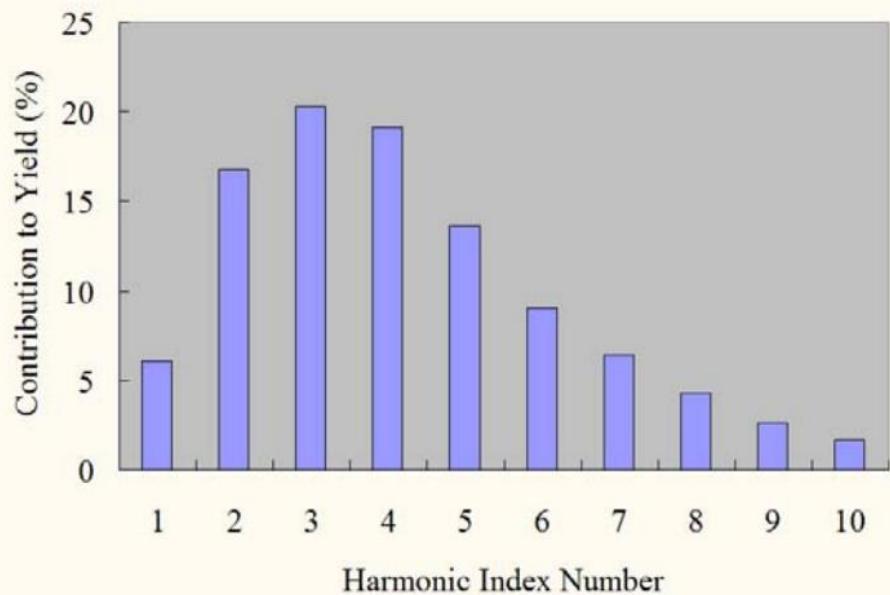
## Advantages:

- low energy deposition in converter;
- good positron emittance.

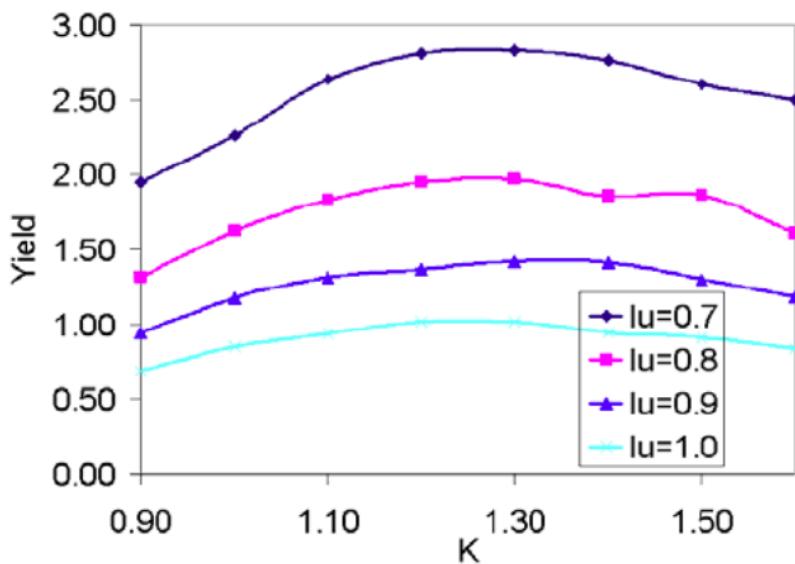
RDR, 150GeV



Photon number spectrum of RDR undulator with 150GeV drive.



Yield contribution from different harmonics of RDR undulator

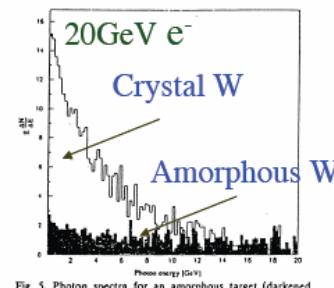
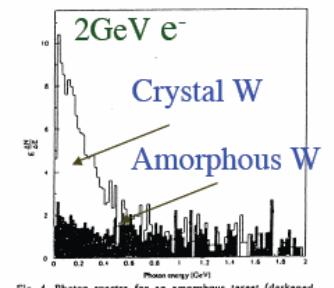
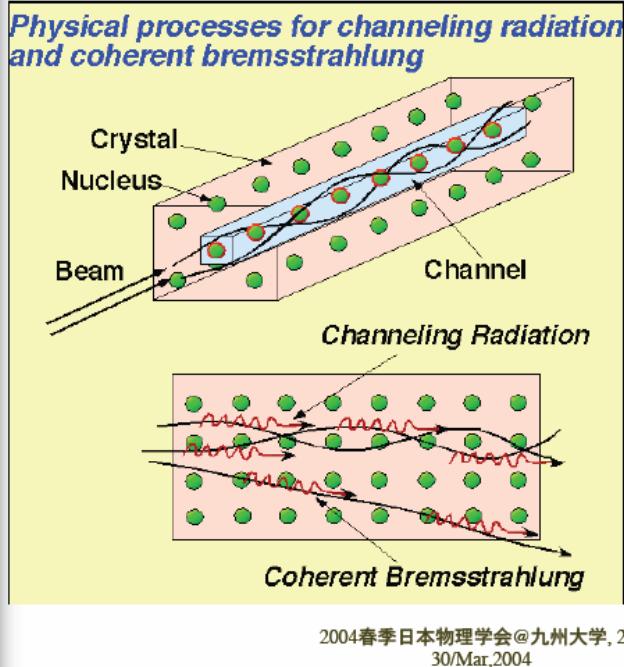


Yield of different high  $K$  short period undulator with 100 GeV driver beam energy.

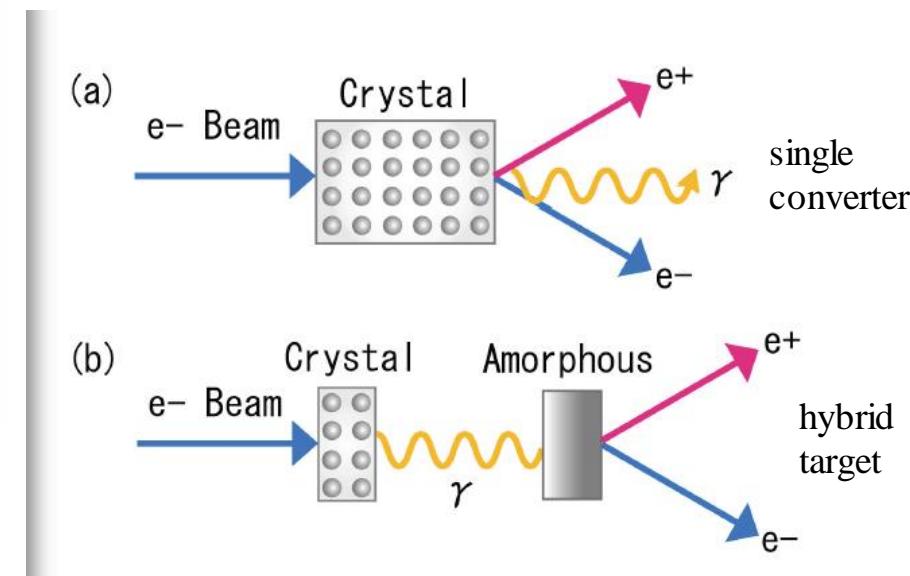
# Alternative approach to obtain intense photon source is using an oriented crystal target (“solid – state undulator”)

Two radiation mechanisms – channeling radiation and coherent bremsstrahlung (CBS):

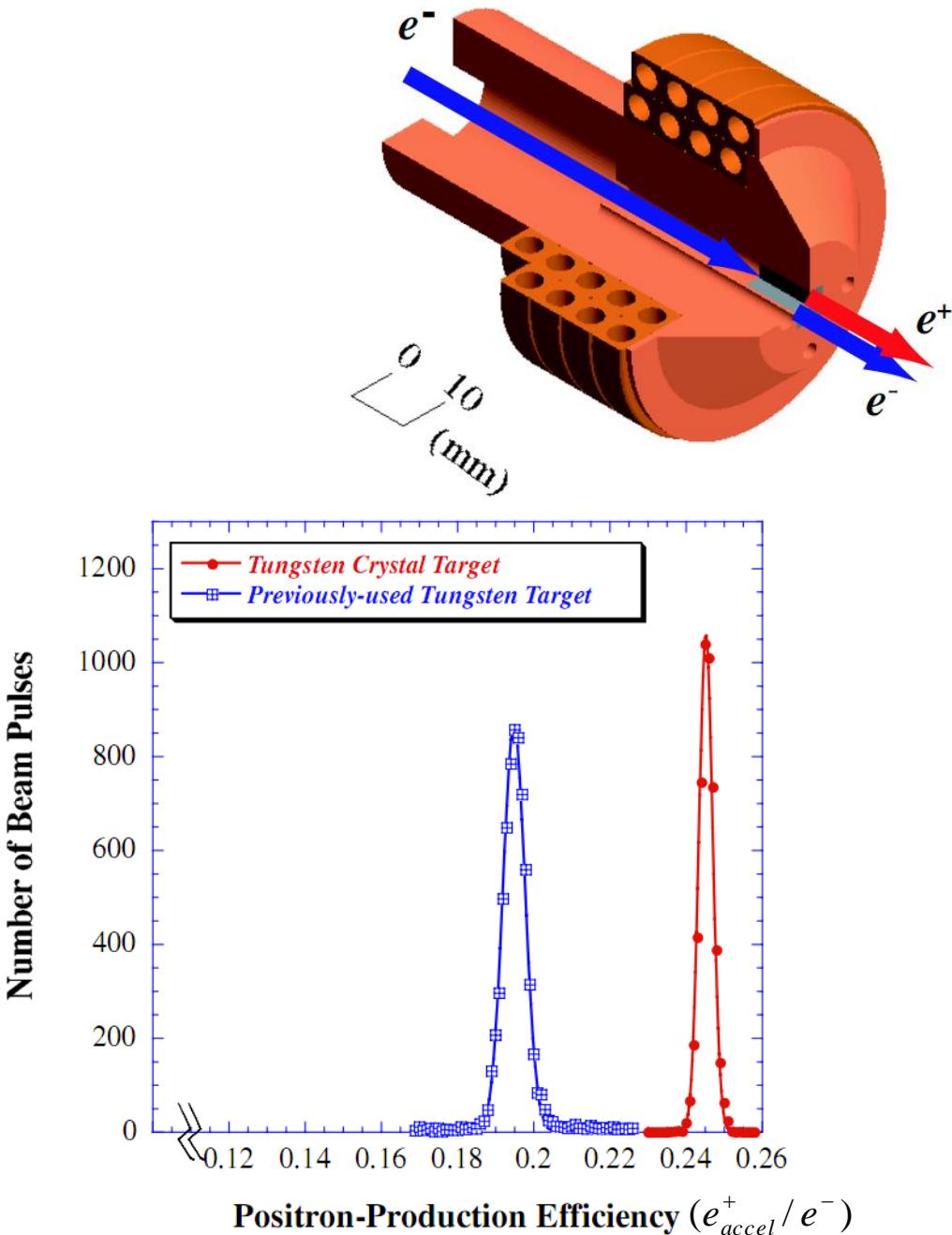
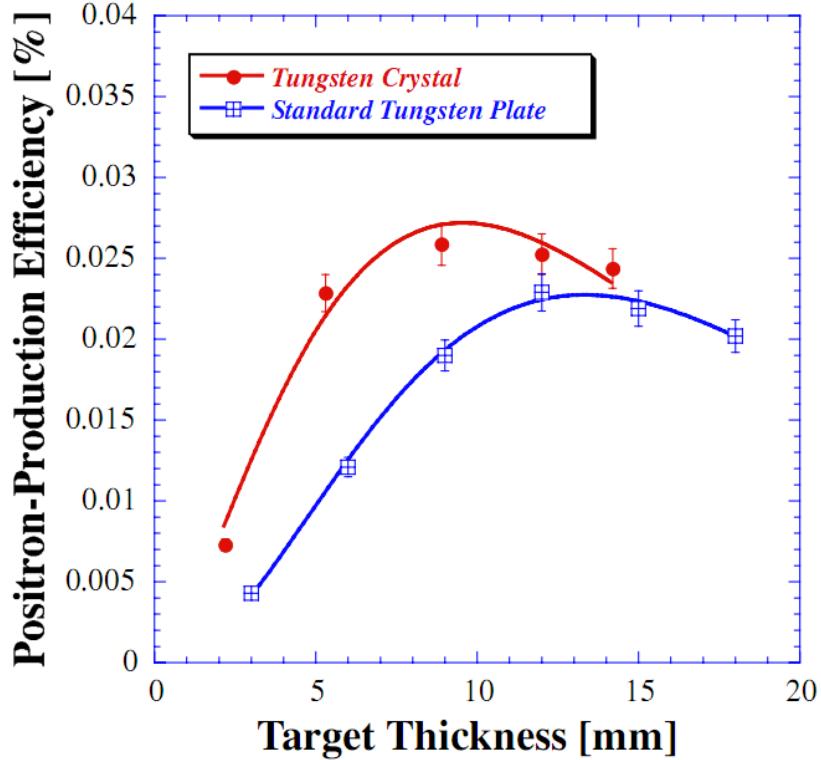
## Channeling Radiation & Coherent Bremsstrahlung Processes



There are two possible schemes:



# First application of a W crystal positron source at the KEK B factory



## The main spectral characteristics

Bremsstrahlung (BS): radiation losses in a target  $\Delta E_{\text{BS}} \approx (t/L_0)E_0$  ( $t \leq X_0$ ),  
 $t/L_0$  – target thickness (in units  $L_0$ ),  $E_0$  – electron energy.

The mean photon energy for BS:  $\langle E_{\text{BS}} \rangle \approx \Delta E_{\text{BS}} / \langle N_{\text{BS}} \rangle$ ,  
 $\langle N_{\text{BS}} \rangle$  - mean number of emitted BS photons per electron

$$\langle N_{\text{BS}} \rangle \approx \frac{t}{L_0} \int_{\gamma_0 \omega_p}^{E_0} \frac{d\hbar\omega}{\hbar\omega} \approx \frac{t}{L_0} \ln \frac{mc^2}{\omega_p} \approx 10 \frac{t}{L_0}$$

$$\gamma_0 = E_0/mc^2, \hbar\omega_p - \text{plasmon energy}$$

For targets from W  $\omega_p = 70 \text{ eV}$   $\langle E_{\gamma\text{BS}} \rangle \sim 0.1 E_0$ ;

For  $E_0 = 1 \text{ GeV}$   $\langle E_{\gamma\text{BS}} \rangle \sim 100 \text{ MeV}$

# Channeling radiation (ChR)

$$\frac{\langle E_{\gamma ChR} \rangle}{E_0} \approx \frac{2\gamma_0^{1/2} \sqrt{\frac{V_0}{mc^2}} \frac{\lambda_e}{a_s}}{1 + \frac{1}{2} \frac{\gamma V_0}{mc^2}},$$

$V_0$  – potential of axis,

$a_s$  – screening radius,

$\lambda$  – electron compton wavelength.

For  $<111>$  axis of Si target and  $E_0 \sim 1$  GeV  $\langle E_{\gamma ChR} \rangle \sim 15$  MeV

For  $<111>$  W  $\langle E_{\gamma ChR} \rangle \sim 40$  MeV

## Coherent bremsstrahlung (CBS)

$$\frac{\langle E_{\gamma CBS} \rangle}{E_0 - \langle E_{\gamma CBS} \rangle} \sim \frac{\pi \gamma_0 \theta}{d}$$

$\theta$  – orientation angle  $\left( \theta \geq \theta_L = \sqrt{\frac{V_0}{\gamma m c^2}} \right)$ ,

$d$  – interplanar distance.

For a thick monocrystalline target  $\theta \sim \bar{\theta}_{ms}$ ,  $\bar{\theta}_{ms} \approx \frac{21}{E_0} \sqrt{\frac{t}{2L_0}}$

For  $t = 10$  mm, Si  $<111>$ ,  $E \sim 1$  GeV

$\langle E_{\gamma CBS} \rangle \sim 50$  MeV

# Radiation losses in a crystalline target

$$\Delta E = \Delta E_{BS} + \Delta E_{cry}$$

	diamond <100> t=10 mm	Silicon <111> t= 10 mm	tungsten <110> t=1.2 mm
$\Delta E_{cr} / \Delta E_{BS}$	$\sim 2,5$	$\sim 1,8$	$\sim 1,5$

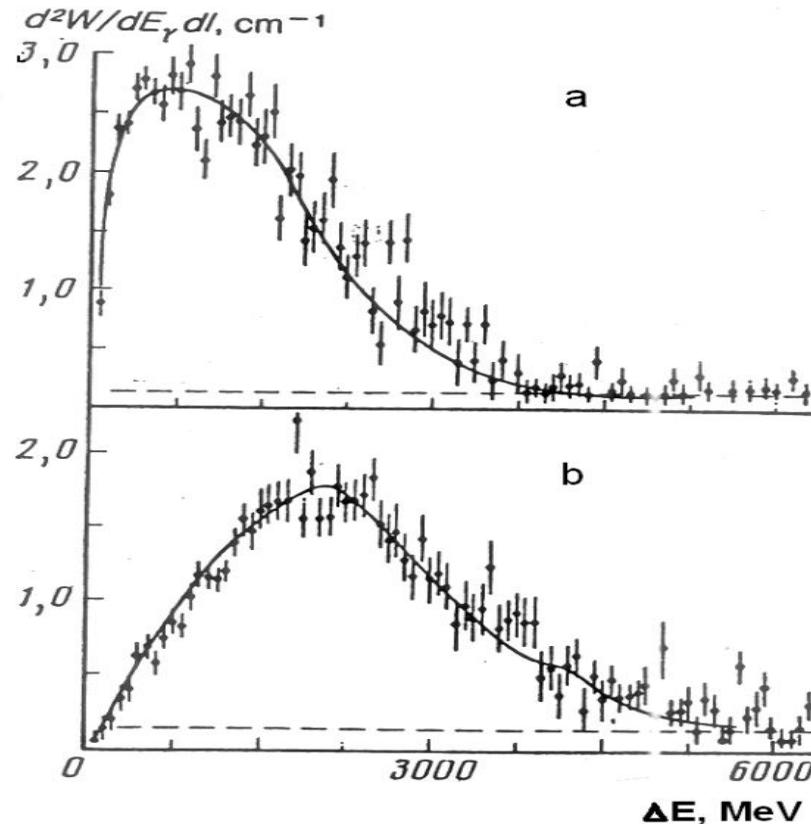
$$\langle N_{cry} \rangle \sim \frac{\Delta E_{cry}}{\langle E_{\gamma CBS} \rangle} >> \langle N_{BS} \rangle$$

# Photon multiplicity

More real estimation and simulation of a mean photon number (photon multiplicity) from oriented thick crystalline target is a very difficult task.

There are much more troubles to measure such a characteristic in an experiment.

In the experiment [M.D. Bavizhev et al. Sov. Phys. JETP, V.68 (1998) 803] authors had measured energy losses from  $e^-$  with  $E_0 = 10$  GeV for Si  $<111>$  targets with thickness  $t = 0.8$  mm and 3.0 mm.



From Monte-Carlo simulations they have obtained

$$0.8 \text{ mm } \langle N_{\text{cry}} \rangle = 1.8 \text{ ph}/e^-$$

$$3.0 \text{ mm } \langle N_{\text{cry}} \rangle = 5.4 \text{ ph}/e^-$$

The model of Baier et al.  $\langle N \rangle = 24 \text{ ph}/e^-$

The contribution from BS process is much less:

$$0.8 \text{ mm } \langle N_{\text{BS}} \rangle \approx 0.9 \cdot 10^{-3} \text{ ph}/e^-$$

$$3.0 \text{ mm } \langle N_{\text{BS}} \rangle \approx 3.2 \cdot 10^{-3} \text{ ph}/e^-$$

For a photon multiplicity  $\langle N \rangle \gg 1$  this value can be estimated [A. Kolchuzhkin, A. Potylitsyn NIMB 173 (2001) 126] from energy losses

$$\langle N \rangle \approx \langle Q \rangle^2 / \sigma^2, \quad \langle E_\gamma \rangle \approx \Delta E / \langle N \rangle,$$

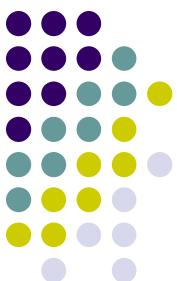
where  $\langle Q \rangle$  is the mean value of radiation losses,  $\sigma$  is distribution variance,  $\Delta E$  – total energy losses.

From such an estimation for 3 mm Si target:

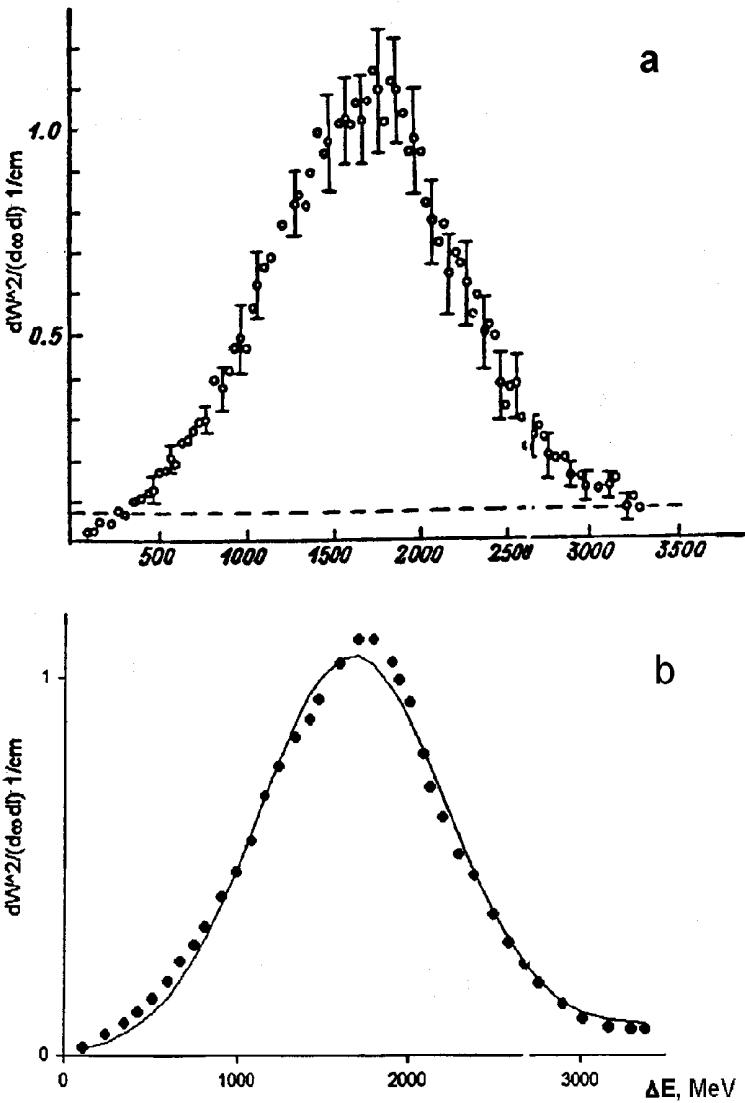
$$\langle Q \rangle = 2.3 \text{ GeV}, \quad \sigma \approx 1.1 \text{ GeV}, \quad \Delta E \approx 800 \text{ MeV} (\sim 0.08 E_0),$$

$$\langle N \rangle \approx 4 \text{ ph/e}^-, \quad \langle E_{cry} \rangle \approx 200 \text{ MeV}.$$

# Diamond target



Let's remember experiment [R. Avakian, A.E. Avetisyan, R.A. Asatryan et al., Sov. Tech. Phys. Lett., V.14 (1988) 395]



a

$E_0 = 4.5 \text{ GeV}$   
diamond  $t=10 \text{ mm}$  ( $t/L_0=0.08$ )

Fit:  $\langle Q \rangle = 1660 \text{ MeV}$

$\sigma = 536 \text{ MeV}$

$\Delta E = 1300 \text{ MeV} (\sim 0.3E_0)$

The estimation of multiplicity:

$\langle N_{cry} \rangle \approx 10 \text{ ph/e}^-$

$\langle E_\gamma \rangle \approx 130 \text{ MeV}$

One can expect a multiplicity  $\langle N_{cry} \rangle > 10 \text{ ph/e}^-$  for Si target with thickness  $\sim 20 \text{ mm}$  and  $E_0 \sim 10 \text{ GeV}$ .

# Positron yield

Estimation of positron yield from a converter with thickness  $t/L_0$ .

The simplest case for photon spectrum – “flat” one:

$$\frac{dN_\gamma}{E_\gamma} = \begin{cases} < N_\gamma > / E_{\gamma \max}, & E_\gamma < E_{\gamma \max} \\ 0, & E_\gamma > E_{\gamma \max} \end{cases}$$

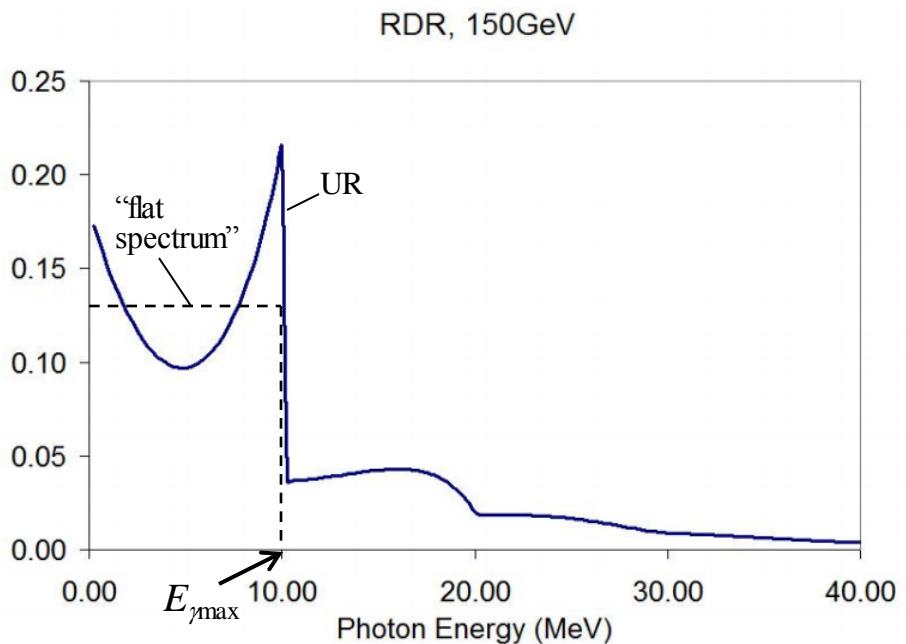
$< N_\gamma >$  is a multiplicity.

Radiation losses:

$$\Delta E = \int_0^{E_{\gamma \max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma =$$

$$= < N_\gamma > \frac{E_{\gamma \max}}{2} =$$

$$= < N_\gamma > \overline{E_\gamma},$$



Photon number spectrum of UR from 150 GeV  $e^-$  beam

A positron spectrum produced by photon with energy  $E_\gamma$  in the converter with thickness  $t$  [A.P. Potylitsyn NIMA 398 (1997) 395]

$$\frac{dN_+(E_\gamma)}{d\varepsilon_+} = \begin{cases} 0.14 \frac{t}{L_0} \frac{\ln(E_\gamma/mc^2) - 1.19}{E_\gamma}, & E_\gamma < \frac{2}{\rho} mc^2 \\ 0.14 \frac{t}{L_0} \frac{\ln(1/\rho) - 0.5}{E_\gamma}, & E_\gamma > \frac{2}{\rho} mc^2 \end{cases}$$

$\rho$  - screening parameter.

After convolution with “flat” photon spectrum

$$(*) \quad \frac{dN_+}{d\varepsilon_+} = 0.14 \frac{t}{L_0} \frac{\langle N_\gamma \rangle}{E_{\gamma \max}} \ln\left(\frac{E_{\gamma \max}}{\varepsilon_+}\right) \cdot \left[ \frac{1}{2} \ln\left(\frac{\varepsilon_+ E_{\gamma \max}}{m^2 c^4}\right) - 1.2 \right]$$

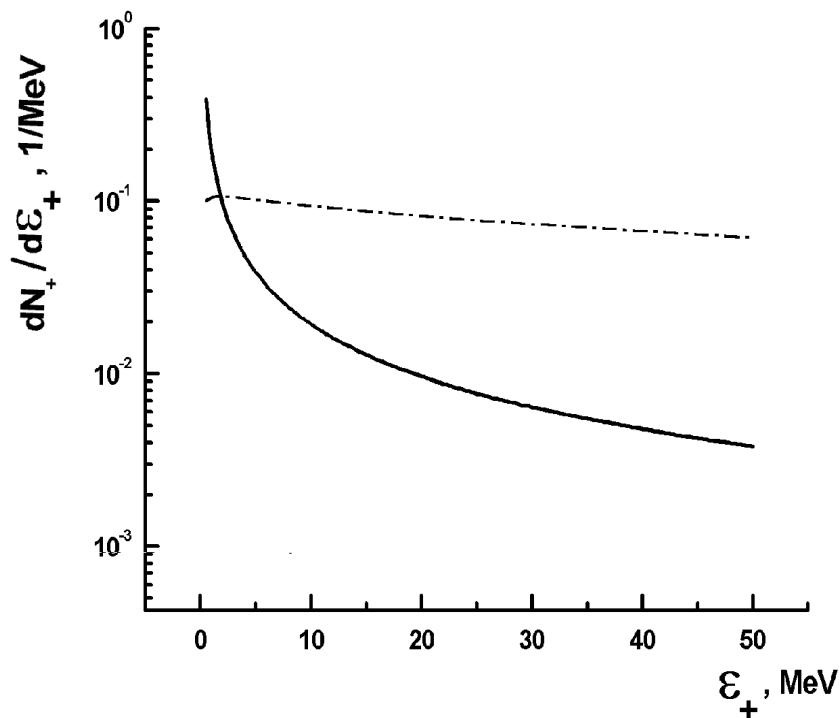
For  $\langle N_\gamma \rangle = 2 \text{ ph/e}^-$ ,  $t=L_0$ ,  $E_{\gamma \max} = 21 \text{ MeV}$  estimation (\*) gives

$$dN_+/d\varepsilon_+ = 0.02 \text{ for } \varepsilon_+ = 10 \text{ MeV.}$$

Flottmann’s estimation [K.Flotmann. Preprint DESY 93-161, Nov.1993] for exact UR spectrum for the same parameters:

$$dN_+/d\varepsilon_+ = 0.021$$

# Positron yield from thick oriented diamond converter ( $t_{\text{Di}} = 20 \text{ mm}$ )



$t = L_0$ ,  $\langle N_\gamma \rangle = 14$ ,  $E_0 = 10 \text{ GeV}$ ,  $\Delta E = 5 \text{ GeV}$ ,  $\langle E_\gamma \rangle \approx 360 \text{ MeV}$ .

Positron yield  $\Delta N_+ = 2 \text{ e}^+/\text{e}^-$  for  $5 \text{ MeV} \leq \varepsilon_+ \leq 25 \text{ MeV}$

85% are generated by photons, 15% are generated by electrons

# Summary

- Oriented crystal converter can provide efficiency  
 $> 1 \text{ e}^+/\text{e}^-$ ;
- Hybrid scheme (light crystal (Diamond, Si) →
  - photon source, amorphous tungsten ( $0.5 L_0$ ) –
  - positron converter);
- Detailed simulation of photon multiplicity from thick crystalline target ( $t \sim 0.3 \div 0.5 L_0$ ) is needed.