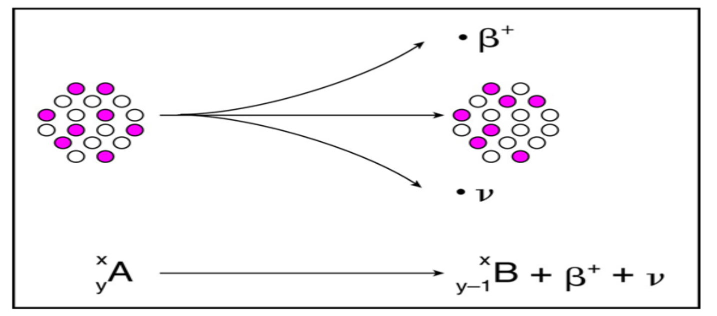
POSITRONS SOURCES

THE PHYSICAL PROCESSES

1^{ST} NUCLEAR B⁺ DECAY

- The β^+ radioactivity concerns atoms with an excess of protons. The transformation is represented hereafter:
- $_{y}^{x}A \quad => \; _{y-1}^{x}B \; + \beta^+ \; + \nu$
- Where a proton is exchanged with a neutron giving a positron and a neutrino. The new atom has a higher ratio[Number n/Number p]
- For instance: $_{11}^{22}Na => \; _{10}^{22}Ne + \beta^+ \; + \gamma + \nu$



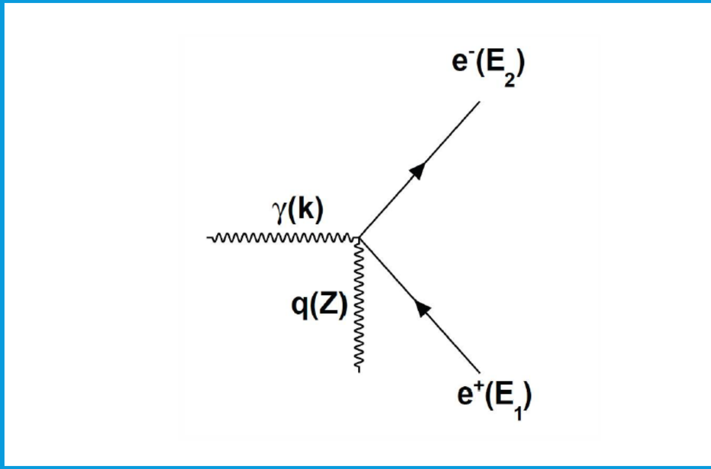
POSITRONS WITH B+ DECAY

- The positrons produced by radioisotope decay are polarized but being emitted isotropically and with a broad energy distribution.
- Electron-positron accelerators are requiring high intensities of positrons; for instance about 10^{12} e^+/s and even more and in a small solid angle.
- The intensity provided by radioactive sources may be 4 to 5 orders of magnitude lower.
- BNL reactor using ^{64}Cu, it exhibited in a total solid angle of 4π sterad , about $10^{12} e^+/s$ and with an energy spread of 200 keV. So, we have much less in a solid angle corresponding to a cone of 10 degrees, what it is currently accepted in positron machines.

PAIR CREATION - THE PHYSICAL PROCESSES

-

- Charged particles impinging on targets loose energy by radiation and collision on the atoms . The energy lost by radiation – Bremsstrahlung - is distributed among photons which interact mainly with the nucleus Coulomb field and undergo materialization with e+e- pair creation.
- The energy lost by collision is used in atom excitation and secondary emission leading to ionization; this energy is dissipated in the target and leads to heating.



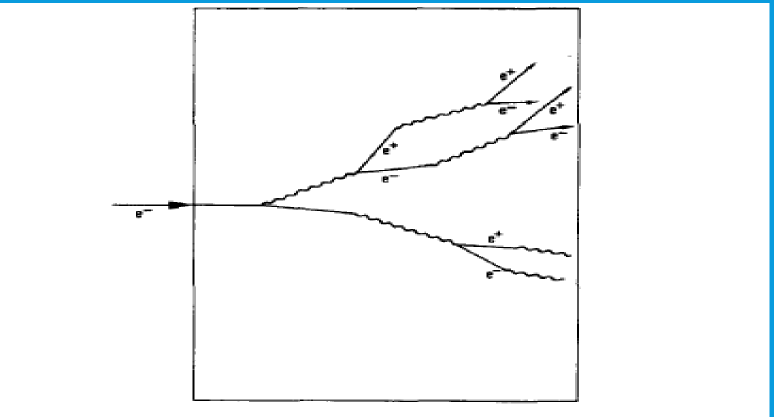


Fig. 1 Electron generated cascade shower

POSITRON SOURCES FOR POSITRON ELECTRON COLLIDERS

- The created photons may also interact with the electrons by elastic collision (Compton effect); cross-section decreases as photon energy increases. At energies above 10 MeV, for lead, it becomes very weak.
- Other processes as multiple scattering which affects the positron angular distribution and, hence, the positron emittance must be taken into account.
- As the created pairs contribute to ionization in the target, energy is deposited and heating is of concern.
- For the sake of simplicity in the introduction to the shower development, we shall emphasize on bremsstrahlung and pair creation.

ELECTROMAGNETIC SHOWER: A SIMPLE APPROACH

- The positron yield is determined by the pair production cross-section (Heitler):

$$\sigma_{pair} \sim \frac{28\alpha Z^2 r_0^2}{9} \, ln \frac{183}{\sqrt[3]{Z}}$$

Where α is the fine structure constant (1/137), Z, the atomic number, r_o the classical electron radius.

The mean free path (distance between events) for pair production is:

$$l_{pair} = 1/[N\sigma_{pair}]$$

Where N is the number of atoms per unit volume

The decrease of intensity of a beam of primary photons creating pairs is, then:

.
$$\frac{dn}{n} = -\frac{dx}{l_{pair}}$$

Giving the exponential decrease: $n = n_o e^{-x/lpair}$;

comparison with the radiation length $l_{rad} = \frac{1}{4Z^2 \alpha r_0^2 ln(\frac{183}{\sqrt[3]{Z}})}$

leads to the relation: $l_{rad} = (7/9) l_{pair}$.

Then $n = n_o e^{-(7x/9\ lrad)}$

METHODS FOR SHOWER ANALYSIS ANALYTICAL APPROACH (SEE B.ROSSI)

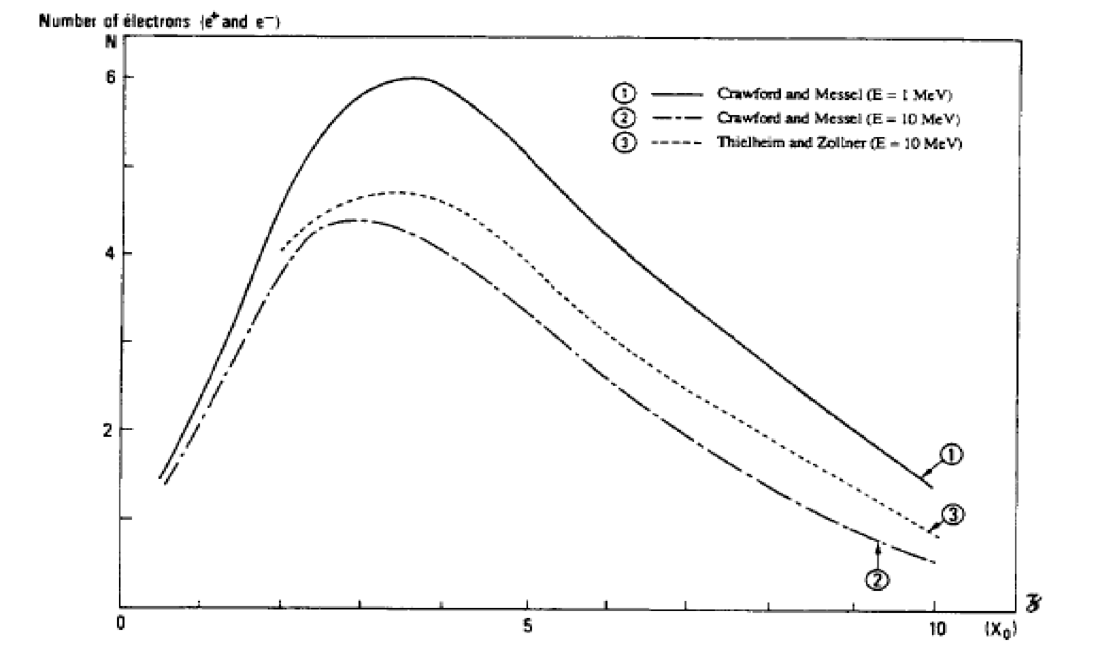
- Considering the so-called Approximation B where bremsstrahlung and pair production are taken into account and where the ionization losses are taken at a constant rate, we can get for the position of the shower maximum:
- $$T_{max} \approx \left[ln\left(\frac{E_0}{\varepsilon_0}\right) - 1 \right]$$
- Where Eo is the incident electron energy and e_o the material critical energy (when radiation losses and ionization losses are equal). For W, e_0= 8 MeV
- The number of created pairs at shower maximum is given by:

$$N_{max} \approx \frac{E_0}{\varepsilon_0}\left[\frac{0{,}31}{\sqrt{ln\left(\frac{E_0}{\varepsilon_0}\right) - 0{,}37}}\right]$$

These quantities corresponding to impinging electrons on the target are essential for the description of the transition curve which represents the number of created pairs along the target thickness

ELECTROMAGNETIC SHOWER: TRANSITION CURVE

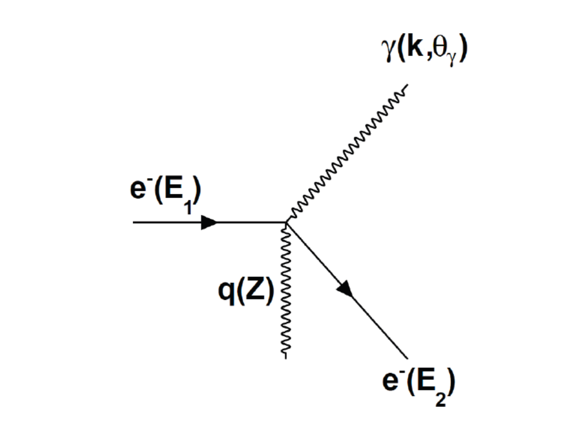
- Transition curves for 1 GeV incident electron in lead: 2 cut-off energies are considered: 1 and 10 MeV.



- 2 steps
- 1) Emission of a gamma photon by bremsstrahlung
- 2) Conversion of the gamma photon in a positron electron pair

BREMSSTRAHLUNG

- Cross section
- Furry Sommerfeld Maue
- Approx E_1, E_2, k>>1 (in electron mass)
- $u = |\vec{u}| = p_{inc}\theta_\gamma < \frac{1}{E_1}$



α= fine structure constant, r_e = classical electron radius

$$\frac{d^2\sigma}{dk\,d\xi} = 2\alpha Z^2 r_e^2 \frac{1}{k\,E_1^2}\left[(E_1^2+E_2^2)(3+2\Gamma) - 2E_1E_2(1+4u^2\xi^2\Gamma)\right]$$

$$\Gamma = \mathcal{F}\left(\frac{\delta}{\xi}\right) - \ln(\delta) - 2 - f(Z)\,.$$

$$f(Z) = a^2\sum_{n=1}^{\infty}\frac{1}{n(n^2+a^2)} \qquad a = \alpha Z,$$

Screening effects taken into account by $F\left(\frac{\delta}{\xi}\right)$ with $\xi = \frac{1}{1+u^2}\pi r^2$ *and* $\delta = \frac{k}{2E_1E_2}$

Angle and energy parameters

BORN APPROXIMATION

$$\mathcal{F}\left(\frac{\delta}{\xi}\right) = \int_{(\delta/\xi)}^{\infty} \left([1 - F(q)]^2 - 1\right) \frac{q^2 - (\delta^2/\xi^2)}{q^3}\, dq$$

$F(q)$ = Form factor and
q = momentum transferred to the nucleus

In the Thomas Fermi model

$$\frac{1 - F(q)}{q^2} = \sum_{i=1}^{3} \frac{\alpha_i}{\beta_i^2 + q^2}$$

$\beta_i = (Z^{1/3}/121) b_i$

$b_1 = 6.0,\ b_2 = 1.2,\ b_3 = 0.3.$

After integration

$$\mathcal{F}\left(\frac{\delta}{\xi}\right) = -\frac{1}{2}\sum_{i=1}^{3} \alpha_i^2 \ln(1 + B_i) + \sum_{i=1}^{3}\sum_{j=1}^{3} \alpha_i \alpha_j \left[\frac{1 + B_j}{B_i - B_j} \ln(1 + B_j) + \frac{1}{2}\right]$$

$B_i = (\beta_i \xi/\delta)^2$

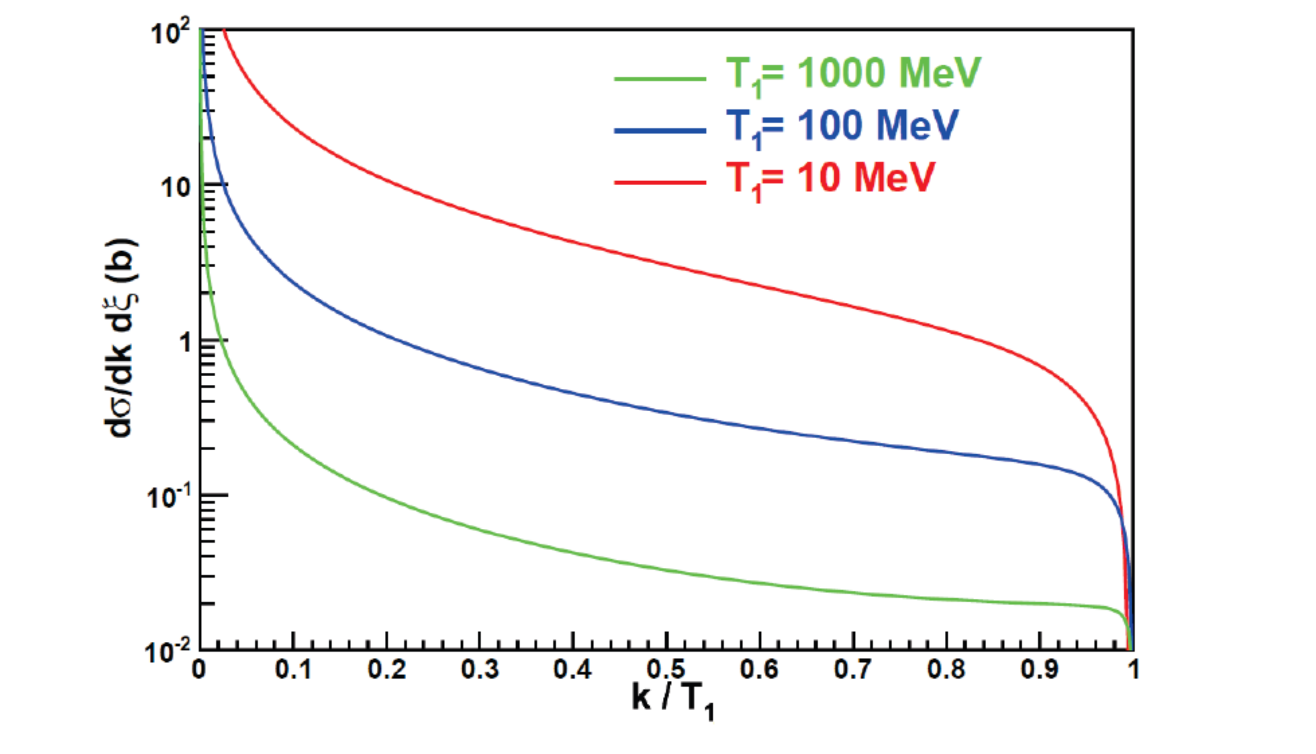
$\alpha_1 = 0.1,$

$\alpha_2 = 0.55,\ \alpha_3 = 0.35$

Screening is minimized for large δ values and maximised for $\frac{\beta_i \xi}{\delta} \gg 1$ … . .in this case it is Possible to approximate

$$\mathcal{F}\left(\frac{\delta}{\xi}\right) = \ln\left(\frac{111\, Z^{-1/3} \xi}{\delta}\right)$$

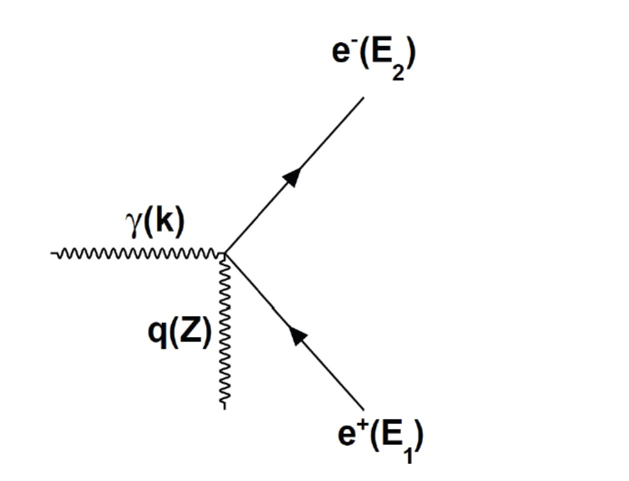
W NUCLEUS



T1= 1000 MeV
T1= 100 MeV
T1= 10 MeV
dσ/dκ dξ (b)
k / T1
10^2
10
1
10^-1
10^-2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

PAIR CREATION

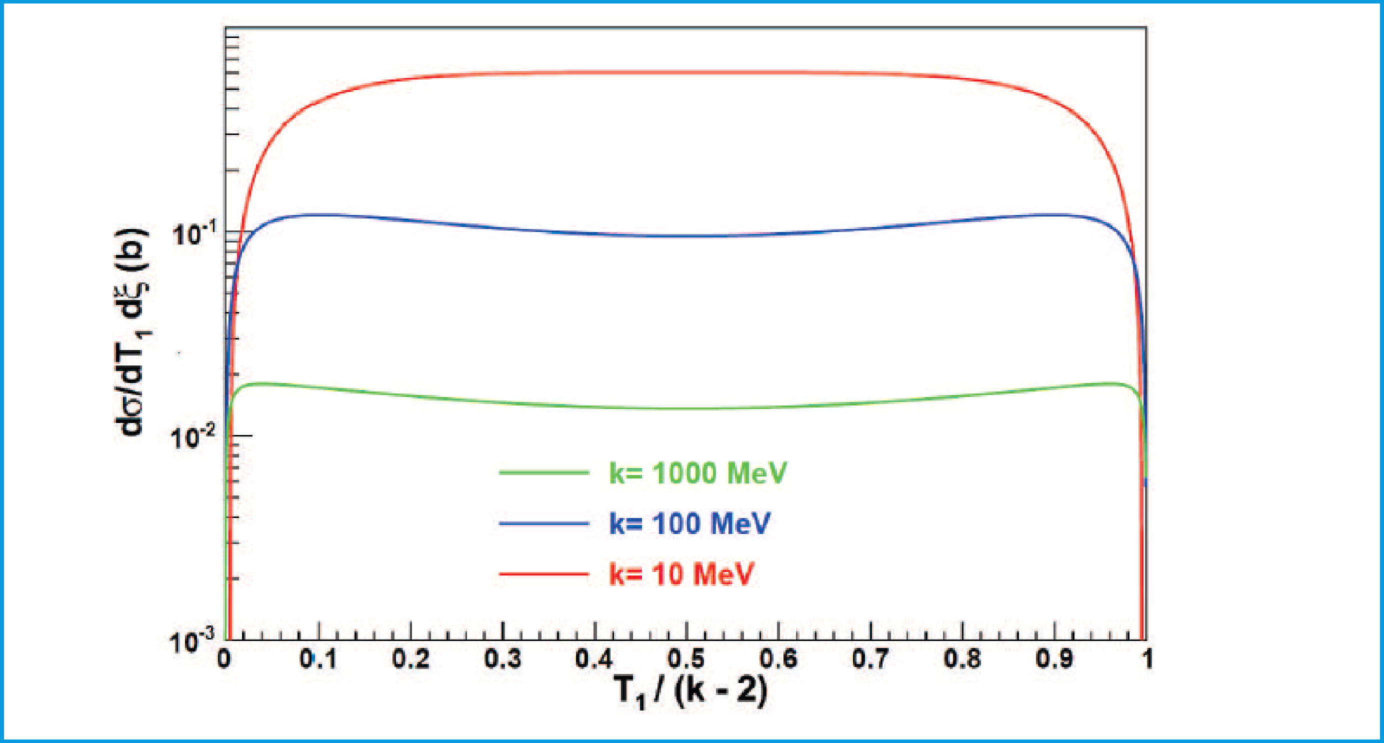
Respect bremsstrahlung E_2->-E_2
From energy conservation -> $E_1 = k + E_2$ for Brem and
$k= E_1+E_2$ for pair



$$\frac{d^2\sigma}{dE_1 d\xi} = 2\alpha Z^2 r_e^2 \frac{1}{k^3}\left[(E_1^2+E_2^2)(3+2\Gamma)+2E_1E_2(1+4u^2\xi^2\Gamma)\right]$$

$$\frac{d^2\sigma}{dk d\xi} = 2\alpha Z^2 r_e^2 \frac{1}{k\,E_1^2}\left[(E_1^2+E_2^2)(3+2\Gamma)-2E_1E_2(1+4u^2\xi^2\Gamma)\right]$$

W FOR FIXED EMISSION ANGLE



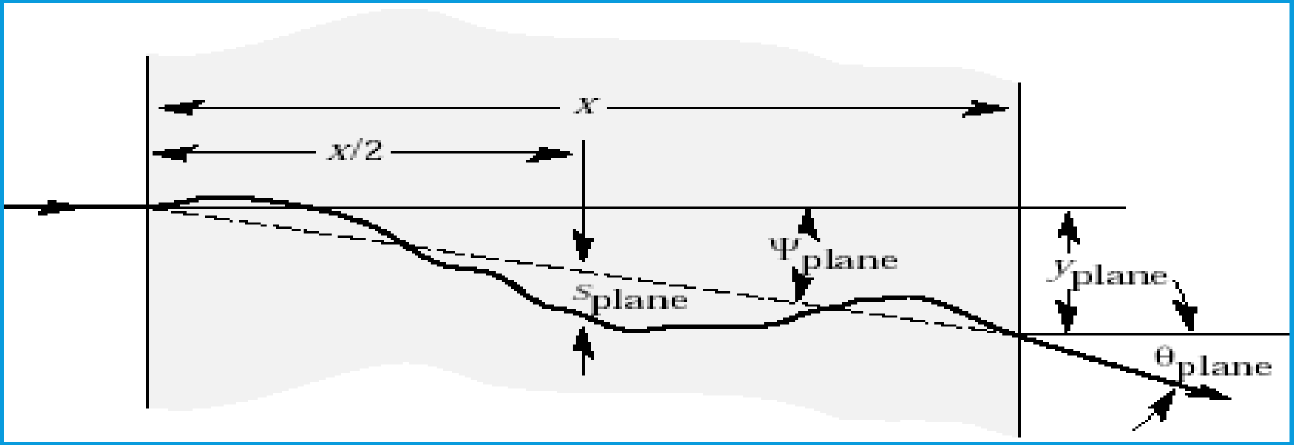
MULTIPLE SCATTERING AND EMITTANCE

distribution of scattering angles after a distance x through a material of radiation length Xo is approximately gaussian:

$$\frac{dP}{d\vartheta} = \frac{1}{\theta\sqrt{2\pi}} e^{\frac{-\vartheta^2}{2\theta^2}}$$

With θ rms angle of scattering given by: $\theta \sim \frac{14}{pc}\sqrt{\frac{x}{l_{rad}}}$

Lateral view of particle trajectory



ELECTROMAGNETIC SHOWERS: M-C SIMULATION

- The analytical approach presented above does not give a precise estimation of the positron beam characteristics. High Z materials are often used for the target in order to improve the pair creation. Multiple scattering becomes important and the particle trajectory in the target is, then, complicated. Longitudinal development and lateral spread of the particle trajectory cannot be separated. Moreover, the energy deposition in the target being inhomogeneous induces severe thermal gradients which may lead to target destruction. So, a precise Monte Carlo simulation taking into account the different processes in the target is mandatory.
- What can be obtained from the simulations: e+ yield, e+ phase space, energy deposited energy in the target.

OTHER POSSIBLE PHOTONS SOURCES

A MAGNETIC UNDULATOR AS A RADIATOR

- A planar undulator may be used to avoid putting a thick solid target in an intense beam (cf. TESLA project)

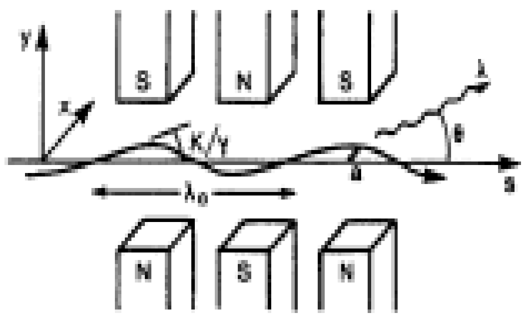
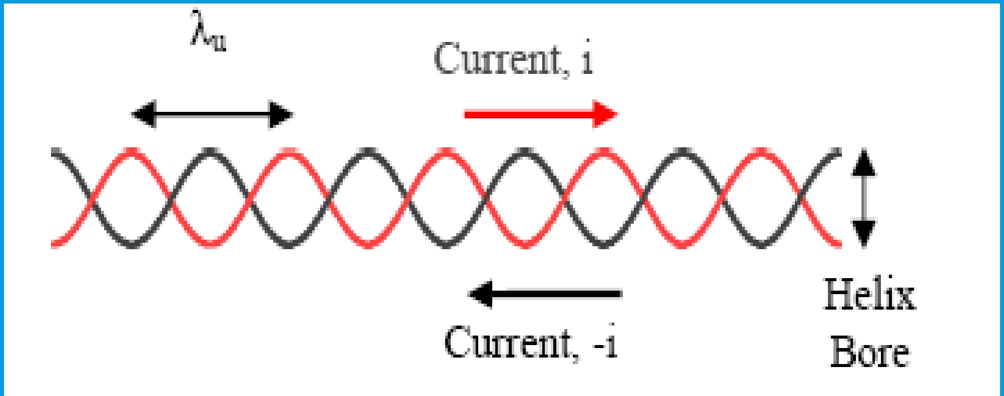


Fig. 2 Schematic of planar undulator and coordinate system

- An helical undulator providing circularly polarized photons to produce polarized positrons in a thin amorphous target [ILC baseline project]

- THE HELICAL UNDULATOR



A SC helical undulator is made of two SC wires wound around a tube with currents flowing in opposite directions. The undulator period and the electron orbit period are the same: λ_u. Synchrotron radiation, circularly polarized is emitted in a conical angle $\theta \sim 1/\gamma$ around the e- direction of motion.

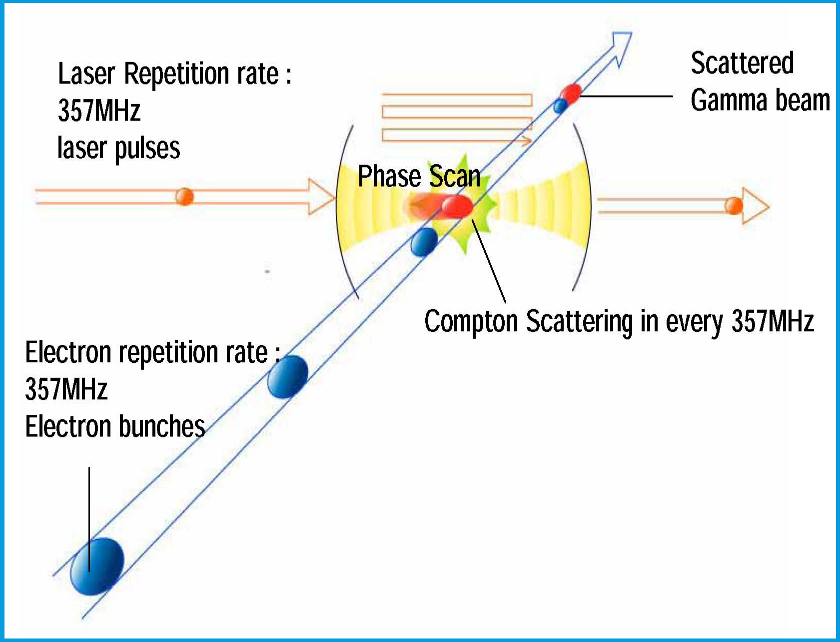
THE HELICAL UNDULATOR

- * Radiation wavelength: the radiation emitted in an helical undulator of period l_u and field B by electrons of relative energy g, is given by:
- $\lambda = (\lambda_u/2\gamma^2)(1 + K^2)$ (first harmonic, on axis)
- where $K = eB\lambda_u/(2\pi mc)$ is the undulator deflection parameter.
- In order to get γ's with enough energy (~30 MeV) to produce e- e+ pairs in a target , we need electrons having more than 150 GeV as we are dealing with periods λ_u of ~1 cm. The bore aperture is ~4-5 mm.
- * Number of photons : the number of photons is proportional to the number N of periods.

COMPTON BACKSCATTERING: USE OF OPTICAL CAVITY

- In order to improve the available laser power at the Compton interaction point, an optical cavity (FP) is used.

The figure shows how with a F-P Cavity and a high repetition rate, it is possible to enhance the number of e-beam-laser collisions

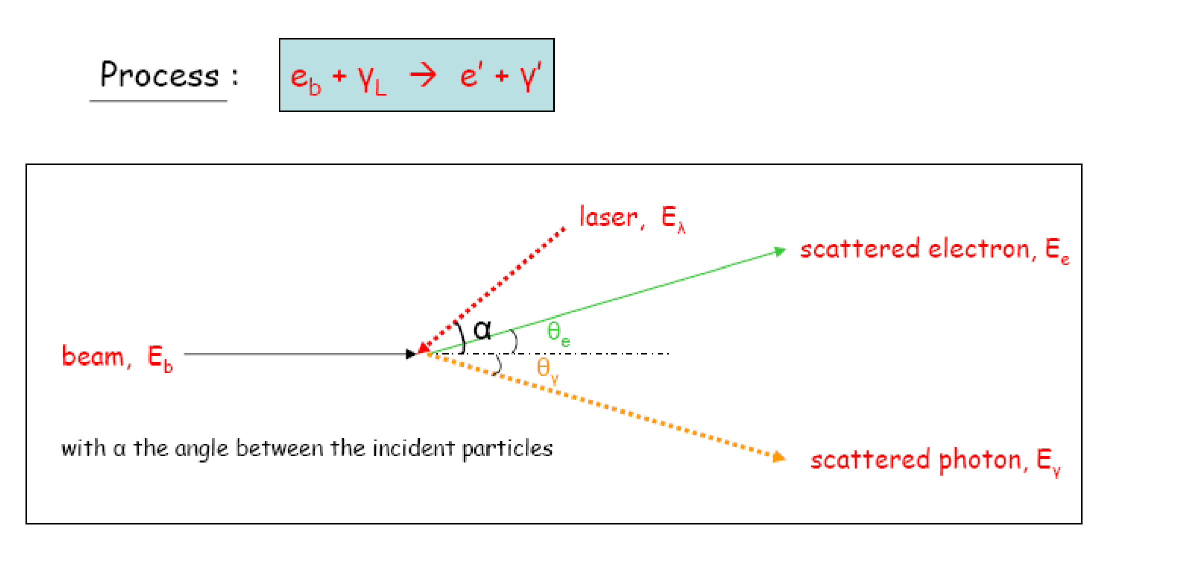


COMPTON BACKSCATTERING

The scattered γ: $\lambda = \lambda_{laser}/2\gamma^2(1 + \cos\theta_\gamma)$

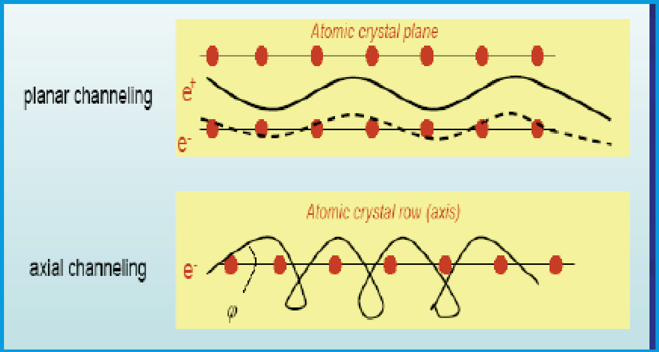
COMPTON BACKSCATTERING

The backscattered photon has an energy >> $(h\nu)_{laser}$: with Eb ~ 1 GeV, E_γ ~20 MeV
These γ can create e+e- pairs in a target. If $(h\nu)$ circularly polarized, γ also.



CHANNELING

- PHOTONS FROM CHANNELING IN ORIENTED CRYSTALS
- The average potentials in the neighbourhood of crystal atoms when an incident electron penetrates the crystal at glancing incidence to the rows/planes makes the electron "trapped" in the potentials and it radiates quite intensively (Kumakhov). The radiation becomes much more intense than ordinary bremsstrahlung at energies > 1 GeV, for W. Channeled electrons are then a powerful source of photons.
-

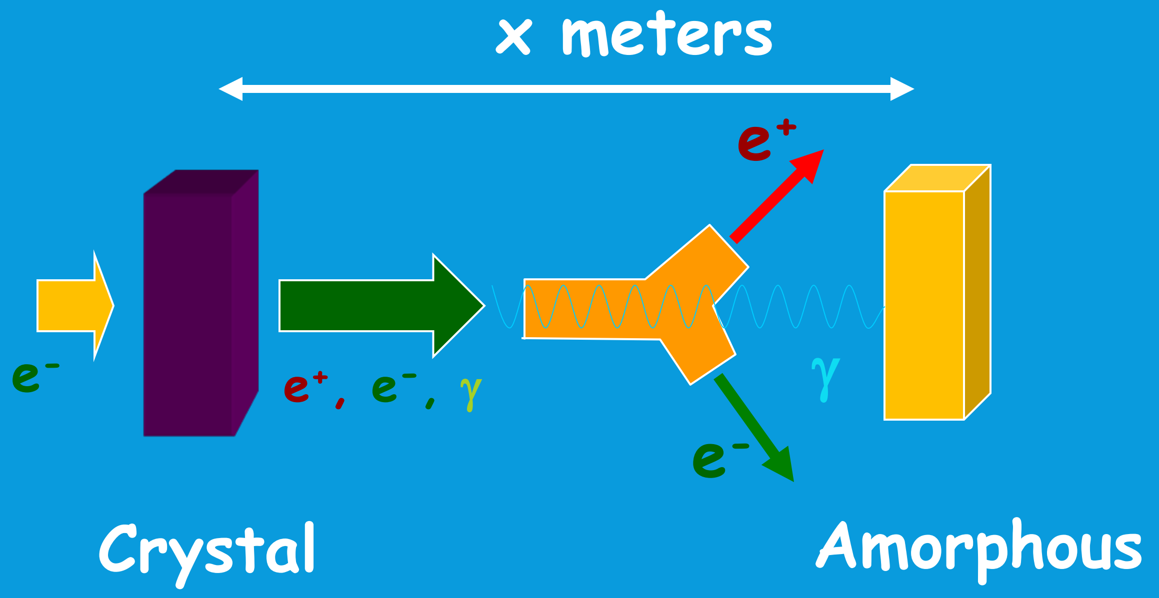


CHANNELING

- AXIAL CHANNELING OF RELATIVISTIC ELECTRONS
- Axial potentials are generally 5 to 10 times stronger than planar potentials. Moreover, the radiated energy is proportional to the square of the channeling field; that explains why axial channeling is preferred for γ-radiation in a positron source.
- In the case of W, one of the most used crystal for this purpose, the potential depth is of 1 kV at normal temperature.
- Provided the angle of incidence of the e- on the atomic rows is smaller than the Lindhard critical angle,
- $\Psi_c=[2U/E]^{1/2}$,
- where U is the potential depth and E, the electron energy, the e- will develop a rosette motion and as in a magnetic wiggler, will radiate. The frequency of the radiated photon is approximately,
- $\omega = 2\gamma^2 \Delta E_T$
- Where γ is the Lorentz factor and ΔE_T is the transverse energy loss between channeled states. Typically, ΔE_T is of some eV and for 1 GeV e- beam, we can obtain 40 MeV photons, which represents an interesting energy to produce e+e- pairs

HYBRID SOURCE

- THE CRYSTAL AS A "CONVENTIONAL" SOURCE



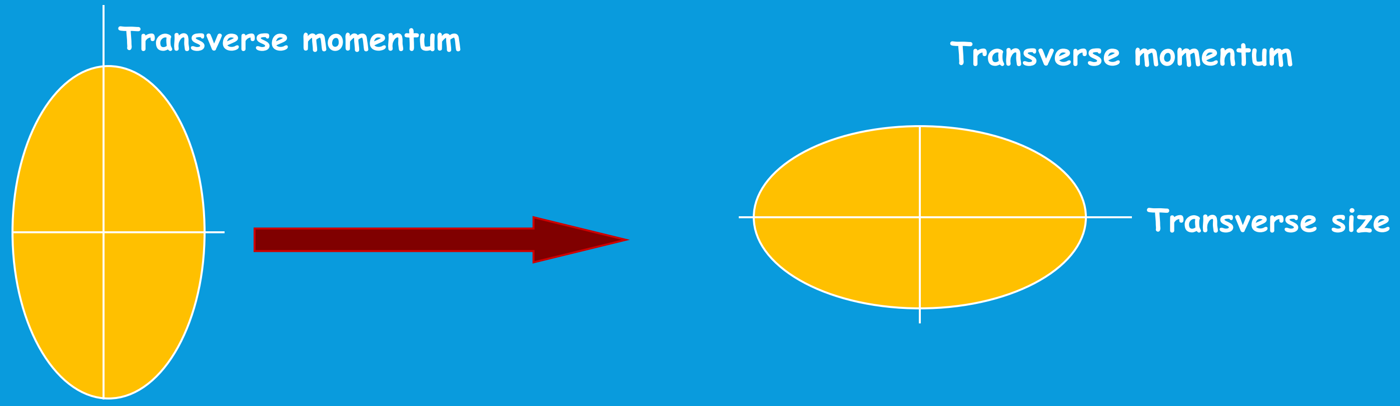
Only the photons are impinging on the amorphous converter

HOW TO CREATE A POSITRON BEAM?

- SECOND PART:
- # CAPTURE AND ACCELERATION OF POSITRONS

CAPTURE AND ACCELERATION OF POSITRONS

- THE MATCHING SYSTEM
- The matching system (transverse phase space) transforms the e+ emittance at target output { large transverse momentum, small dimensions} in an emittance with different shape {small transverse momentum, large dimensions} easier to transport in the accelerator channel.



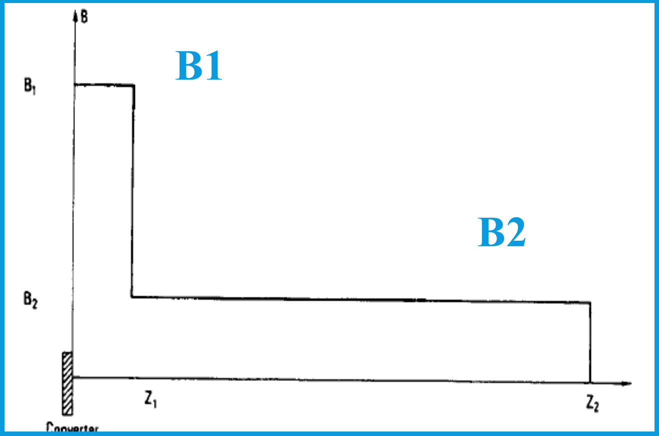
MATCHING SYSTEMS

- AXIAL MAGNETIC FIELD SYSTEMS (SOLENOIDS)
- Two main kinds of solenoidal fields are used: the QWT (Quarter Wavelength Transformer) and the AMD (adiabatic Matching Device)

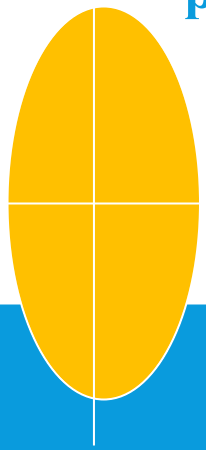
QWT

The QWT

- Made of a short lens with high magnetic field and a long solenoidal magnetic field.
- The emittance is rotated by $\pi/2$ in the phase space. This effect is due to the stepping field, introducing a B_r component.



QWT



- MAIN FEATURES OF A QWT (Immersed target)

- * Acceptance on the target plane

The semi-axes are: $x_0 = \frac{B_2}{B_1} a$ and

$$P_{\perp} = \frac{1}{2} q B_1 a \left[1 + \frac{B_2}{B_1}\right] \Rightarrow in\ \frac{MeV}{c} \Rightarrow \frac{1}{2} 300\ B_1 a \left[1 + \frac{B_2}{B_1}\right]$$ B [T] a [m]

where B1 and B2 are the field values and a, the iris radius

* Momentum acceptance

- It is a narrow band system; typically,

3-4 MeV FWHM for B1 = 2T and B2 =0.3 T and an iris radius of ~1 cm

ADIABATIC MATCHING DEVICE (AMD)

- This magnetic lens system has a magnetic field tapering slowly from a maximum value (B_0) to a minimum value (B_s) on a length L. From the maximum to the minimum values, the field varies adiabatically keeping constant the adiabatic invariant $\int \sum p_i dq_i = \frac{\pi p_\perp^2}{qB}$
- Such system has a large momentum acceptance, provided the parameter of smallness $\varepsilon = \frac{P}{qB^2}\frac{dB}{dz}$ be small enough (<<1).

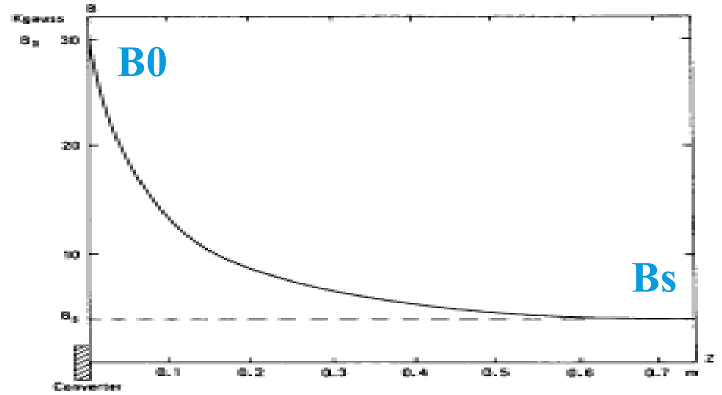
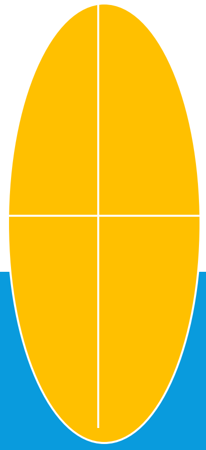


Fig. 17 Field profile of the adiabatic device

MAIN FEATURES OF THE AMD



- **Acceptance on the target plane**
- For a target *inside* the field (immersed target), the

Semi-axes are: $p_{\perp} = q\sqrt{B_0 B_s}a$ and $x_0 = \sqrt{\frac{B_s}{B_0}}a$

Momentum acceptance

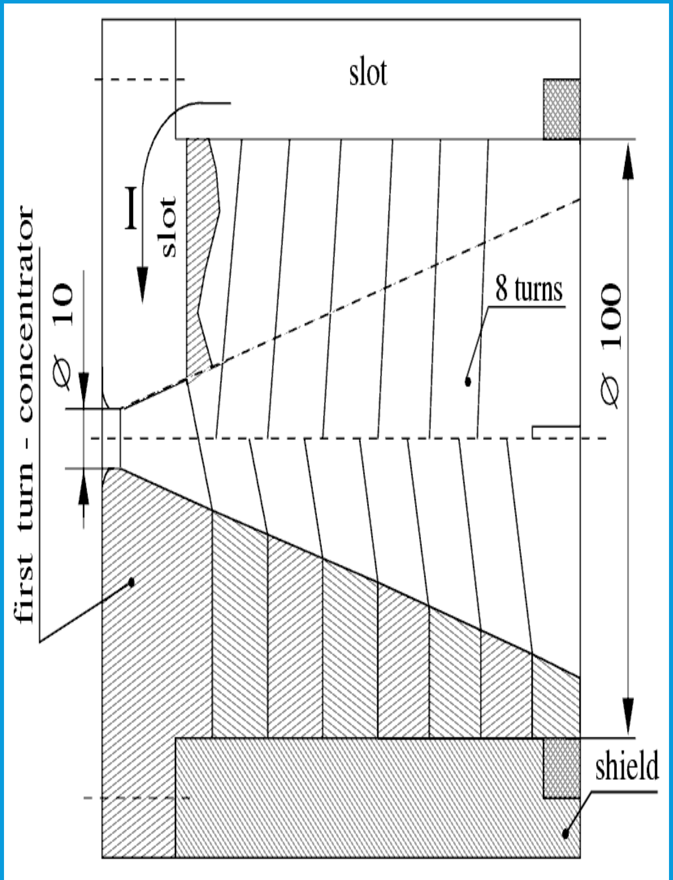
- It is rather large and limited on the higher part of the spectrum by the adiabatic constraint,

$$\varepsilon = \frac{P}{qB^2}\frac{dB}{dz} \ll 1$$

Typically ΔP ~20 MeV/c for B_0~5-6 Tesla, a=2cm and B_s~0.5 Tesla

THE AMD

- The device is using a **Flux Concentrator**
- It is a pulsed coil having a conical shape
- The aperture at the target is rather small and enlarges after; typically, the initial aperture is of some mm diameter and the final of some cm. The field on the axis is inversely proportional to the cross-sectional area.



AZIMUTHAL MAGNETIC FIELD SYTEMS

- 2-1 MATCHING SYSTEMS
- An azimuthal magnetic field created by a longitudinal current of radius Ro circulating in the same direction of theparticles provides a strong focusing.

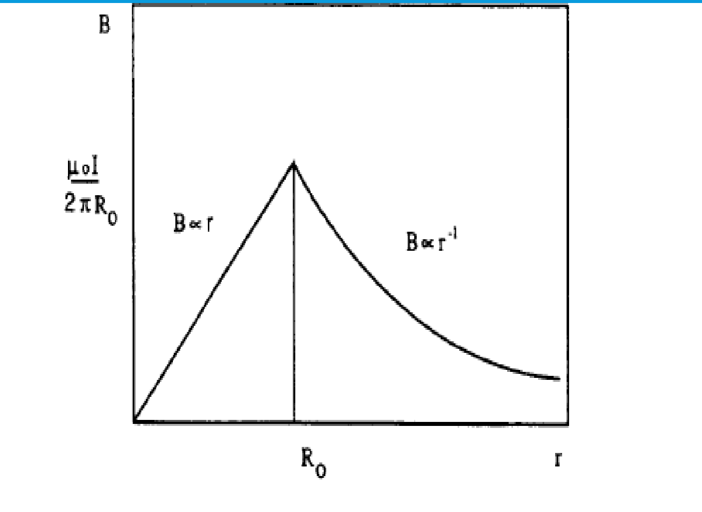
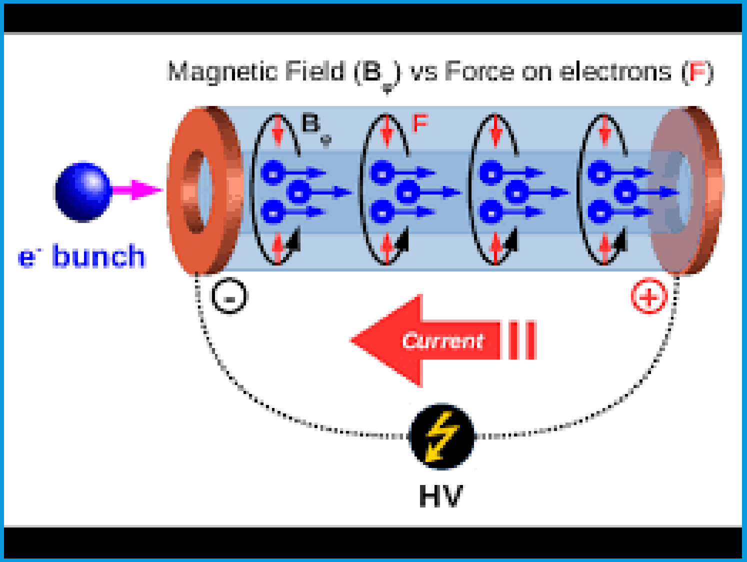


Fig. 19 Sketch of the azimuthal magnetic field

- The field is given by :
- $B = \frac{\mu_0 I}{2\pi R_0^2} r$ for r < Ro
- $B = \frac{\mu_0 I}{2\pi r} r$ for r > Ro
- Such field focuses one of the particles and defocuses the other.

AZIMUTHAL MAGNETIC FIELD: PLASMA LENS

- The conductor is a column of ionized gas.
- A high intensity pulsed current, created with a discharge circuit and flowing through the ionized gas (Argon) produces an imploding plasma column. The e+ moving through the plasma when the "pinch' is reached, are strongly focused .On the figure, the plasma lens {Brookhaven-Columbia}. Simila devices have been studied at CERN for antiproton focusing [B.Autin et al.]



AZIMUTHAL MAGNETIC FIELD: LITHIUM LENS

- The lens is made of a cylindrical lithium conductor traversed by a uniform current distribution. The Lithium is placed into a thin wall Titanium cylinder.

First proposal was issued from BINP-Novosibirsk [G.Silvestrov]. A sketch of the lens proposed in 1997 is given. A variant with liquid lithium has also been studied. The lens acts as a QWT.

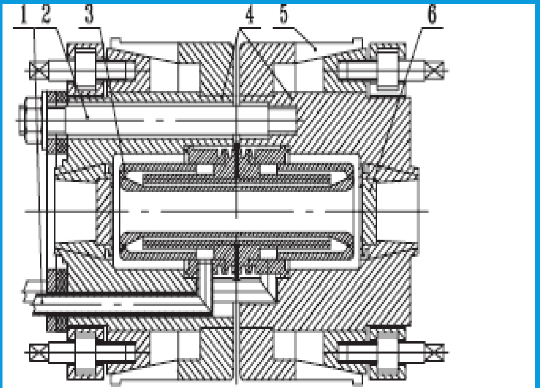


Fig. 1. BINP solid lithium lens with elastic shell.

1 – water supply; 2 – retaining bolts; 3 – titanium body of the lens; 4 – steel body of the lens; 5 – collecting contact; 6 – beryllium windows.

THE ACCELERATION

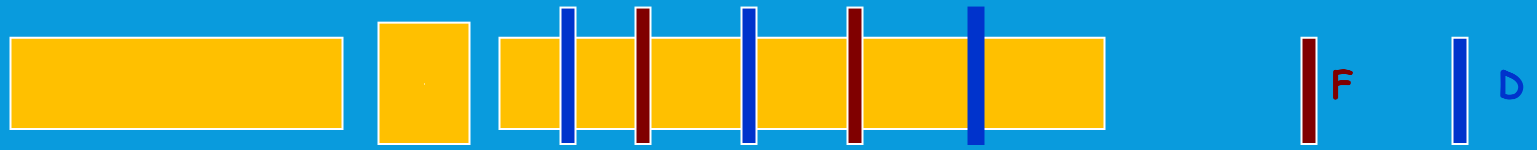
- 2-2The kind of acceleration just after the target is important:
- * for the longitudinal phase space: for bunch length and relative energy spread
- * for the transverse phase space: the accelerator iris aperture is an important element of the geometrical acceptance. Moreover, a strong accelerating field damp the beam divergence and, hence, the beam emittance.
- => in order to have a large acceptance, L-Band accelerating sections (with f_o= 1.3 Ghz) are preferred to S-Band sections (f_o=3 Ghz)

BEAM PHASE SPACE OPTIMIZATION

- Transverse and Longitudinal post capture shaping

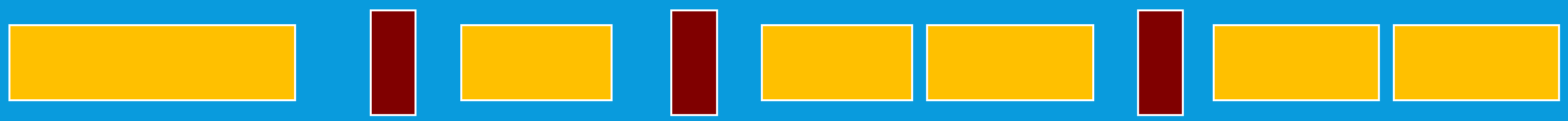
- The positron emittance being large, it must be reduced before injection in the main linac; that is the task of the Damping Ring. This injection requires a good matching to the DR acceptance. Two conditions:
- 1/ Transverse emittance preservation; that means matching all along the accelerator prior to the DR. We can consider 2 cases:

* Normal conducting accelerating cavities => use of FODO



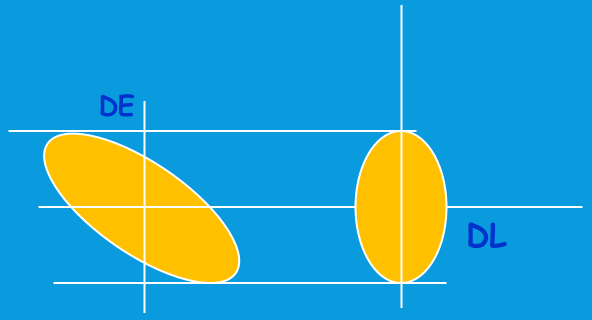
The matching device (doublet) transforms the circular beam shape into elliptical for a better transmission in the FODO system

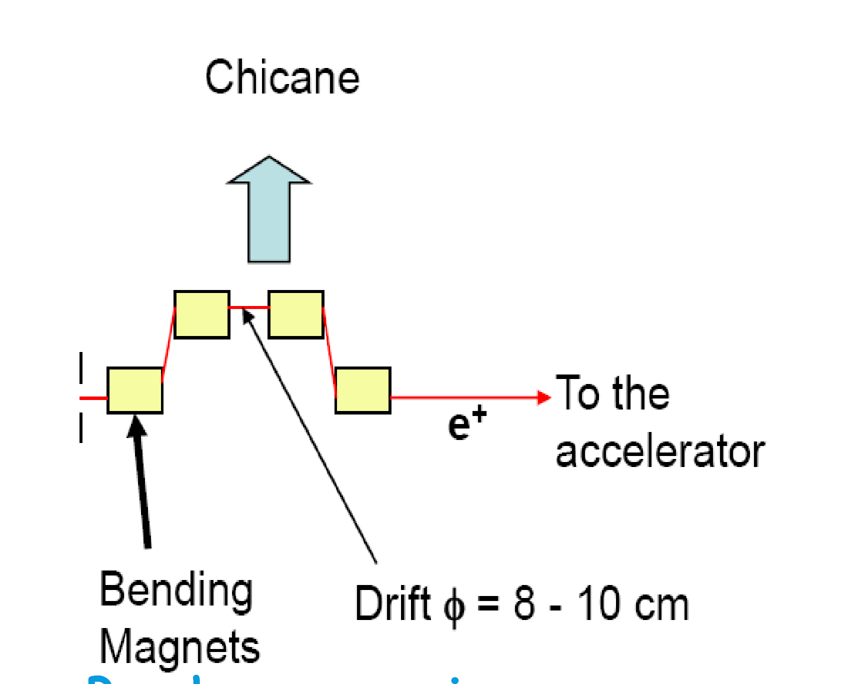
- * Superconducting cavities: use of triplet system between cavities



The triplets are put between the accelerating sections with an increasing geometrical periodicity, due to γ increase.
If the section with solenoid is a normal temperature section,
the other sections are superconducting.

LONGITUDINAL PHASE SPACE OPTIMIZATION

- 2/ Following the requirements for stacking in the Damping Ring, the positron longitudinal phase space may be transformed before injection in the DR.
- 2-1/ Bunch compression: the bunch length may be reduced in a magnetic chicane
- 

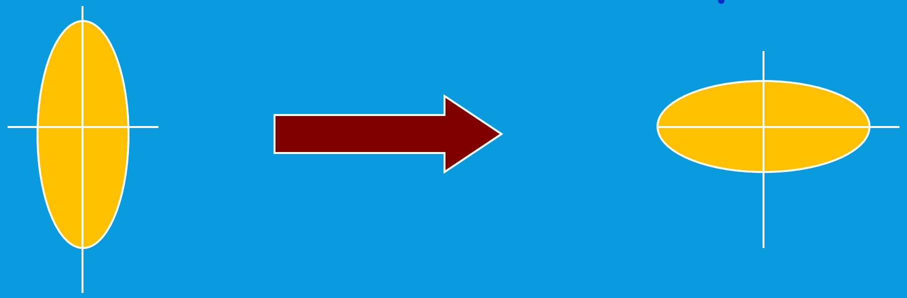


Bunch compression

POSITRON SOURCES FOR E+E- COLLIDERS: APPLICATION TO ILC AND CLIC

- **Energy compression:** many methods allow energy compression. As an illustration, we present that using an achromatic line associated to a debuncher. Schematically, the debuncher plays in the longitudinal phase space the same role as a lens in the transverse phase space with a "focusing"strength" a proportional to the electric field in the debuncher structure,
- $$M_D = \begin{vmatrix} 1 & 0 \\ -a & 1 \end{vmatrix}$$

The global effect is to rotate the ellipse in the phase space



POSITRON SOURCE PERFORMANCES

Table 1
Positron sources parameters.

Facility	**PEP-II**	**KEKB**	**DAFNE**	**BEPC**	**LIL**	**CESR**	**VEPP-5**
Research center	**SLAC**	**KEK**	**LNF**	**IHEP**	**CERN**	**Cornell**	**BINP**
Repetition frequency, Hz	120	50	50	12.5	100	60	50
Primary beam energy, GeV	33	3.7	0.19	0.14	0.2	0.15	0.27
Number of electrons per bunch	5×10^{10}	6×10^{10}	1.2×10^{10}	5.4×10^{9}	3×10^{9}	3×10^{10}	2×10^{10}
Target	W-25Re	W	W-25Re	W	W	W	Ta
Matching device	AMD	QWT	AMD	AMD	QWT	QWT	AMD
Matching device field, T	6	2	5	2.6	0.83	0.9	10
Field in solenoid, T	0.5	0.4	0.5	0.35	0.36	0.24	0.5
Capture section RF frequency	S-band	S-band	S-band	S-band	S-band	S-band	S-band
Positron yield, 1/GeV	0.054	0.023	0.053	0.014	0.0295	0.013	0.1
Positron output, 1/s	8×10^{12}	2×10^{11}	2×10^{10}	2.5×10^{8}	2.2×10^{10}	6.6×10^{10}	10^{11}

POLARIZED POSITRONS

Polarization in pair production is a stochastic process, the resulting positrons beams not polarized (unpolarised).

But we know that a certain 'polarization transfer' can happen from a polarized initial state to a polarized final state (for example in Compton backscattering the initial photon polarization state is transferred to the final)

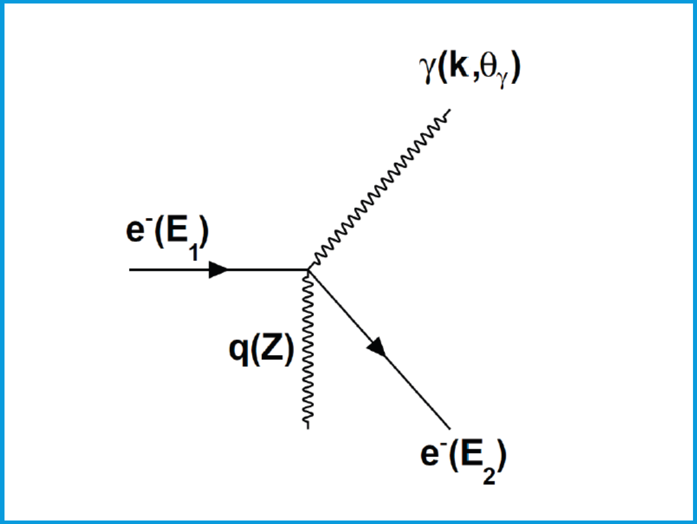
So to produce polarised positrons we should perform a two step process:

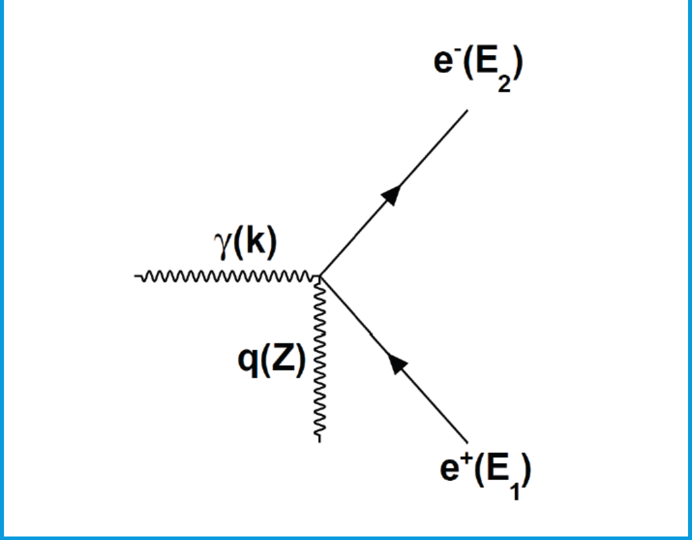
1) Provide polarised photons (Bremsstrahlung, Compton, Undulator)

2) Polarised photons in a target will produce polarised pairs

BREMSSTRAHLUNG

- Important since not only gives the cross section for the production of polarised photons by polarised electrons, but having the inversion of the Feynman diagram also the polarization transfer in a target (reciprocal processes) (E_2->-E_2)

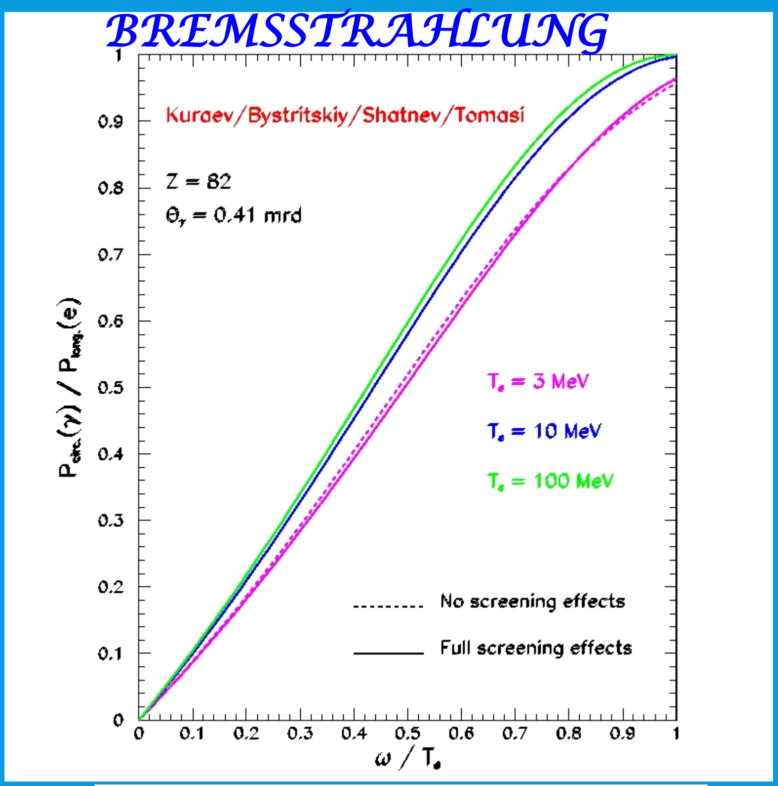




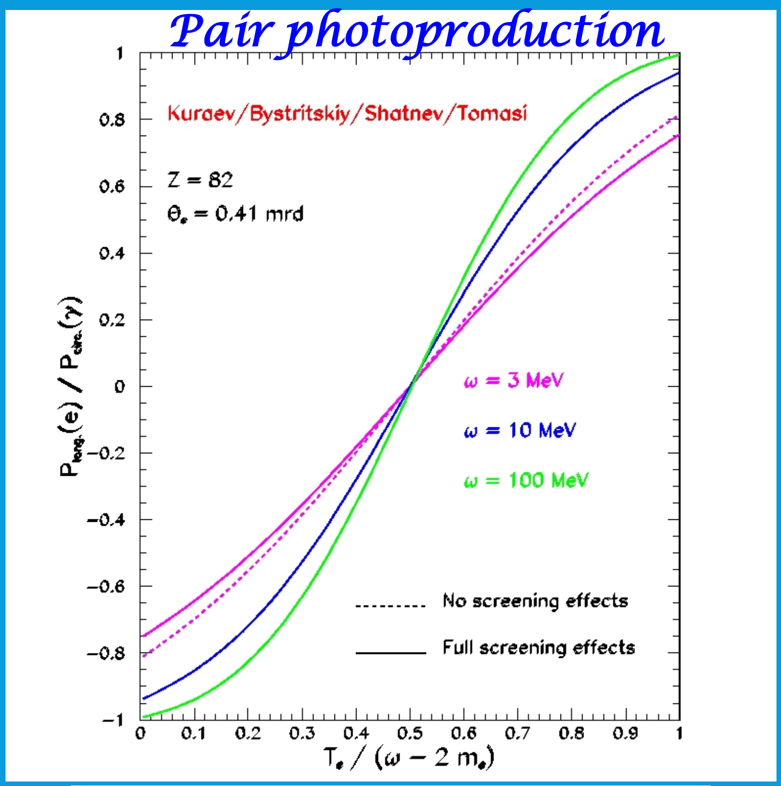
BREMSSTRAHLUNG AND PHOTOPRODUCTION

H. Olsen, L. Maximon, PR 114 (1959) 887 E.A. Kuraev, Y.M. Bystritskiy, M. Shatnev, E. Tomasi-Gustafsson, PRC 81 (2010) 055208

- **Very complex formulas…bremsstrahlung and pair creation processes predict very efficient polarization transfers.**

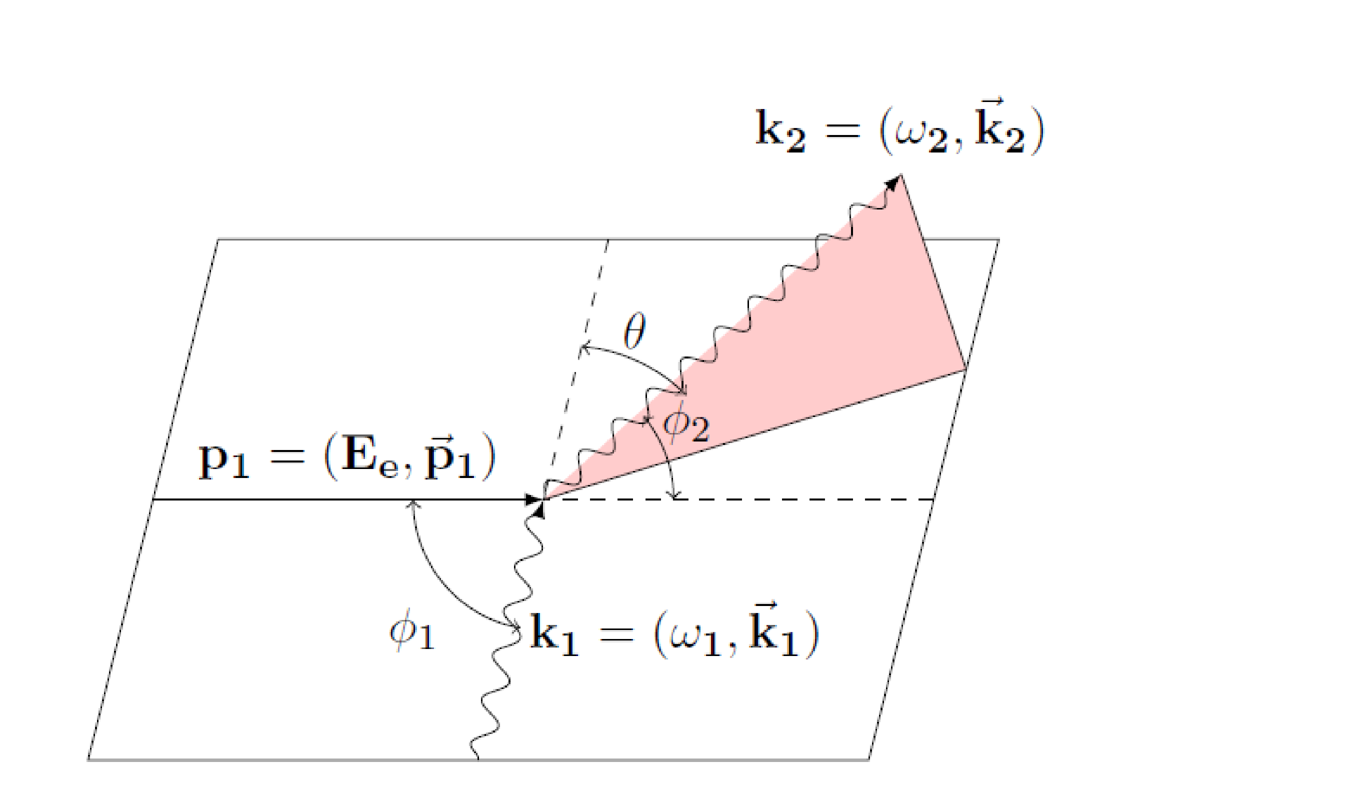


$$e^-(p) + T(P) \to \gamma(k,e) + e^-(p') + T(P'),$$



$$\gamma(k,e) + T(P) \to e^+(q_+) + e^-(q_-) + T(P'),$$

COMPTON SCATTERING



COMPTON SCATTERING AND UNDULATOR -CIRCULAR POLARIZED PHOTONS

σ_0= unpolarised cross section

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{dy} = \frac{2\sigma_0}{x_1\sigma_c}\left(\frac{1}{1-y} + 1 - y - 4r(1-r) + 2\lambda_e P_c r x_1(1-2r)(2-y)\right)$$

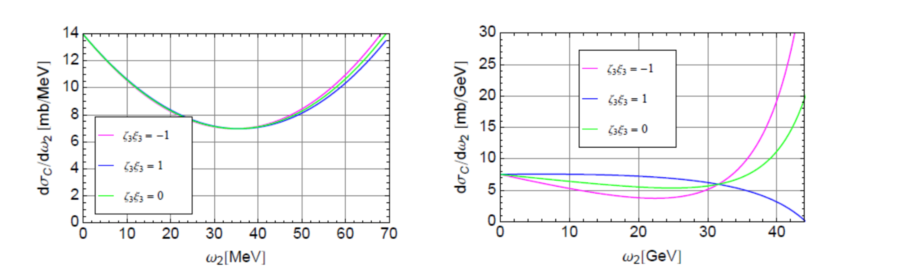
Electron helicity (λ_e) Photon polarization (P_c)

$$x_1 = \frac{s - m_e^2}{m_e^2} = 2\gamma\frac{\omega_1}{m_e}(1 - \beta\cos\phi_1)$$

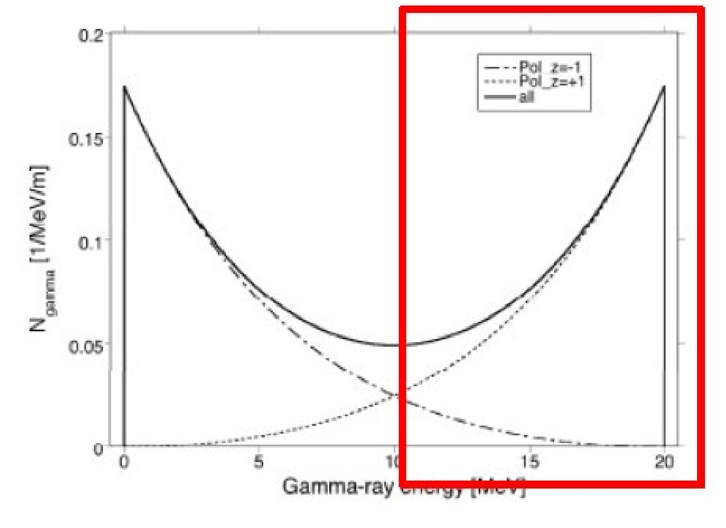
$$y = \frac{\omega_2}{E_e} \le y_m = \frac{x_1}{x_1+1}$$

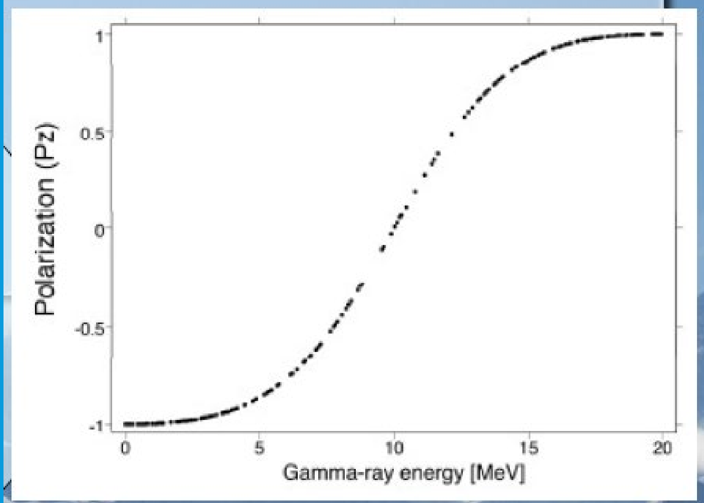
$$r = \frac{y}{x_1(1-y)} \le 1.$$

$$\xi_{3f} = \frac{\left(2\lambda_e r x_1\left(1 + (1-y)(1-2r)^2\right) + P_c(1-2r)\left(\frac{1}{1-y} + 1 - y\right)\right)}{\left(\frac{1}{1-y} + 1 - y - 4r(1-r) + 2\lambda_e P_c r x_1(1-2r)(2-y)\right)},$$



(a) (b)





HELICAL UNDULATOR

$$\frac{dN_\gamma}{dE_\gamma}\left[\frac{1}{\mathrm{m\ MeV}}\right] = \frac{10^6 e^3}{4\pi\epsilon_0 c^2\hbar}\frac{K^2}{\gamma^2}\sum_{n=1}^{\infty}\left(J_n'^2(x_n) + \left(\frac{\alpha_n}{K} - \frac{n}{x_n}\right)^2 J_n^2(x_n)\right)\Theta(\alpha_n^2)$$

$$\alpha_n^2 = n\frac{E_{1c}(1+K^2)}{E_\gamma} - 1 - K^2,$$

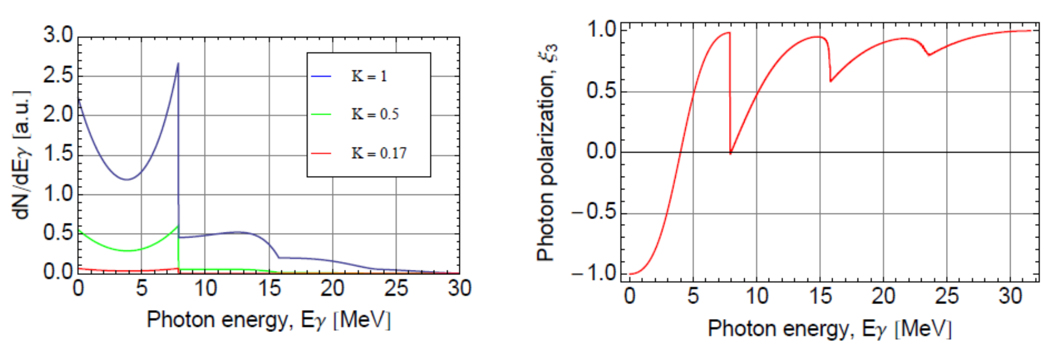
$$E_{c1} = \frac{2\gamma^2 hc/\lambda_u}{1+K^2+2\gamma\lambda_C/\lambda_u},$$

$$x_n = 2K\frac{E_\gamma}{E_{1c}(1+K^2)}\alpha_n,$$

K= Undulator strength parameter
J_n= Bessel function nth order
E_{1c}= Energy cut off first harmonic
Θ=Heaveside function

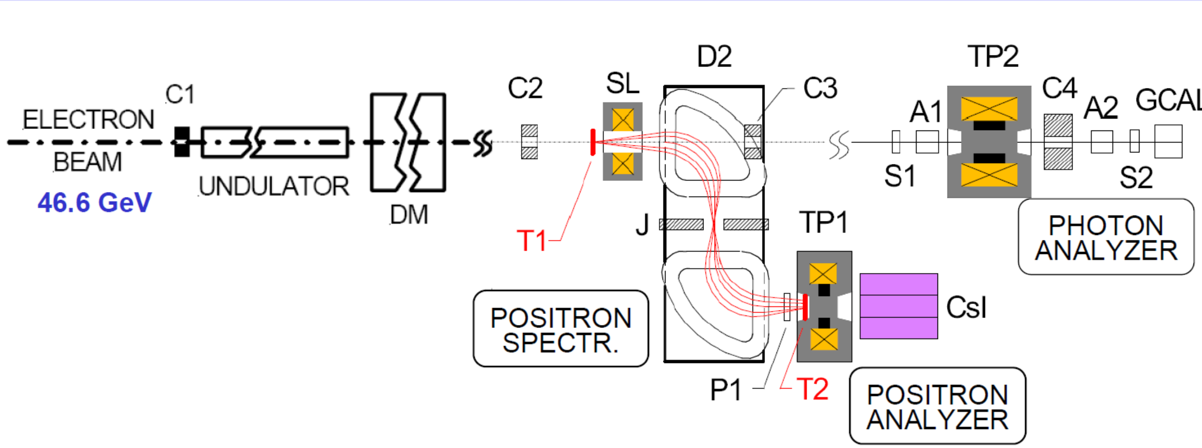
1st harmonic (dominating) expressions:

Spectrum:	Angular Distribution:	Polarization:
$\frac{dN_\gamma}{ds} = 4\pi\alpha M\frac{K^2}{1+K^2}\cdot\frac{1}{2}(1-2s+2s^2)$ $s = \omega_0/\omega_0^{max}$	$\theta = \frac{1}{\gamma}\sqrt{(1+K^2)(1-s)/s}$	$P_\gamma = \frac{2s-1}{1-2s+2s^2}$



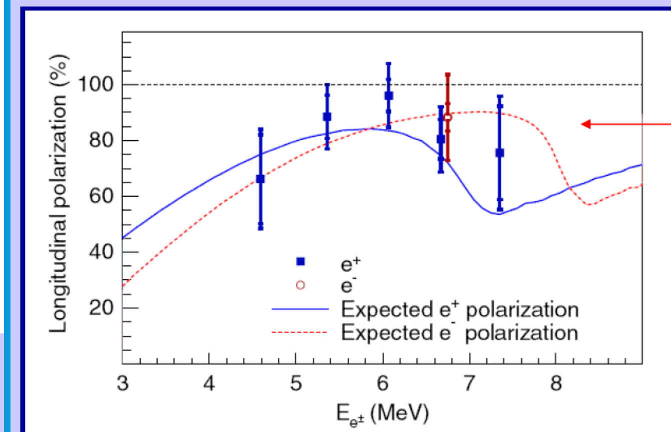
E166 SLAC

E166 experimental setup

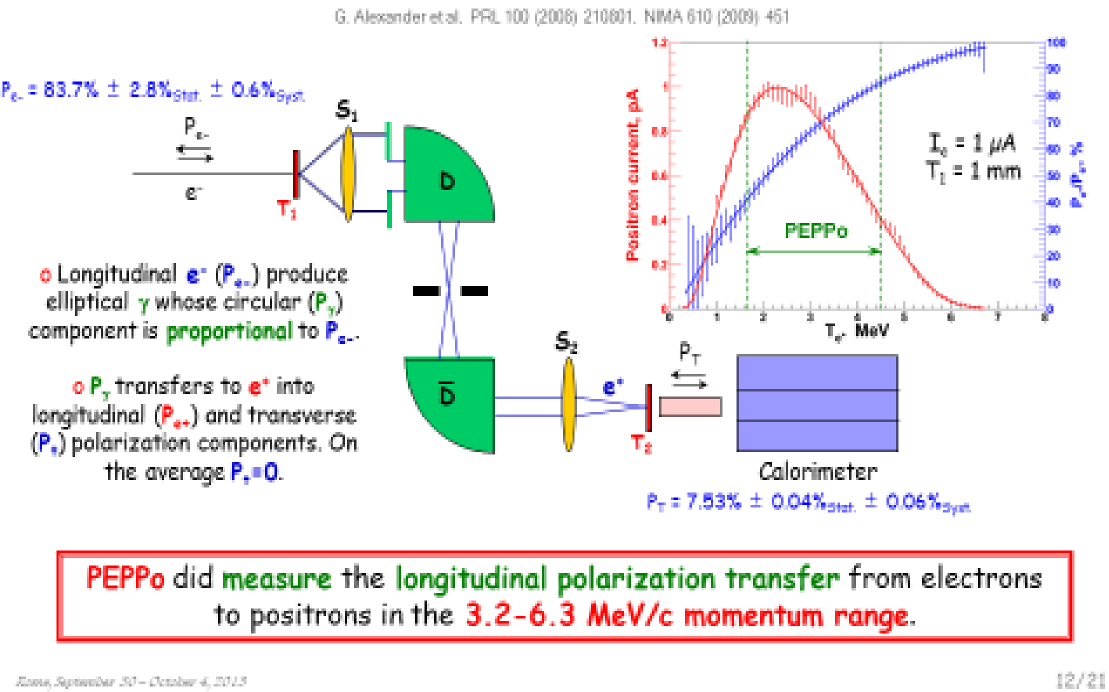


DM:	**electron beam dump magnets**
T1:	**$\gamma \rightarrow$ e+ prod. target (0.2 X_0 W)**
T2:	**e+ $\rightarrow \gamma$ reconv. target (0.5 X_0 W)**
P1:	**e+ flux monitor (Silicon)**
CsI:	**CsI calorimeter**
SL:	**solenoid lens**
J:	**movable jaws**

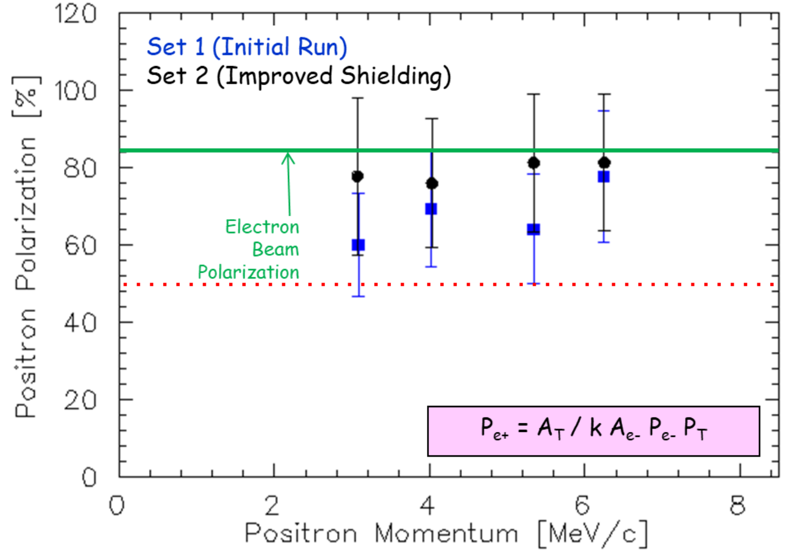
C1 – C4:	**photon collimation**
A1, A2:	**aerogel detectors**
S1, S2:	**silicon detectors**
GCAL:	**Si/W-calorimeter**



PEPPO JLAB



G. Alexander et al. PRL 100 (2008) 210801. NIMA 610 (2009) 451
P_{e-} = 83.7% ± 2.8%$_{Stat.}$ ± 0.6%$_{Syst.}$
S_1
P_{e-}
e^-
T_1
D
D̄
S_2
e^+
T_2
P_T
Calorimeter
P_T = 7.53% ± 0.04%$_{Stat.}$ ± 0.06%$_{Syst.}$
o Longitudinal e^- (P_{e-}) produce elliptical γ whose circular (P_γ) component is proportional to P_{e-}.
o P_γ transfers to e^+ into longitudinal (P_{e+}) and transverse ($P_\perp$) polarization components. On the average $P_\perp$=0.
Positron current, μA
T_{e^+}, MeV
P_{e^+}/P_{e^-} %
I_0 = 1 μA
T_1 = 1 mm
PEPPo
PEPPo did measure the longitudinal polarization transfer from electrons to positrons in the 3.2-6.3 MeV/c momentum range.
Rome, September 30 – October 4, 2013
12/21

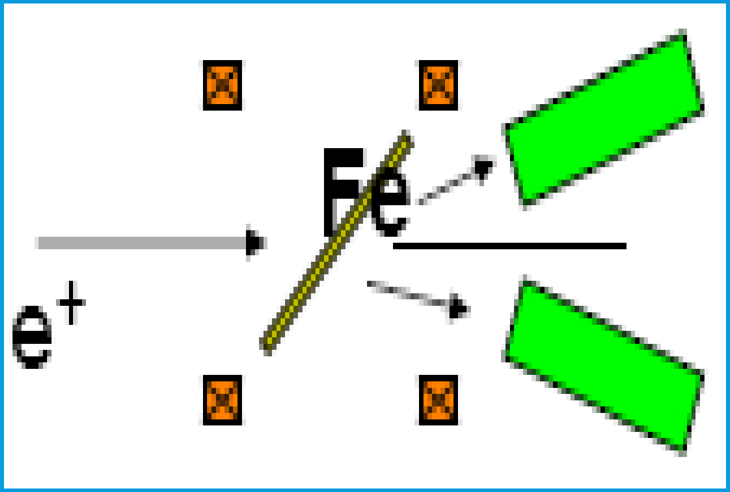


Set 1 (Initial Run)
Set 2 (Improved Shielding)
Electron Beam Polarization
$P_{e+} = A_T / k\, A_{e-}\, P_{e-}\, P_T$
Positron Polarization [%]
Positron Momentum [MeV/c]

POLARIZATION

- POLARIZATION CONTROL : the rate of longitudinal polarization of the positrons must be measured. One interesting possibility studied by S.Riemann et al (DESY-Zeuthen) is to do the measurement at relative low energy (200-400 MeV) using Bhabha Scattering. The measurement of scattered e+ as well as of e- allows polarization determination. However, it would be more interesting to select the scattered e- to suppress the background due to bremsstrahlung

Both e+ and e-(target) are polarized Pol(e-)~7% in Fe. Angular distribution of scattered e- , depending on polarization, is measured for two magnetization states of the target; asymmetry is of some %. For P^+=0.6 and P^-=0.07, maximum asymmetry is ~0.03. The needed angular aperture is < 10 degrees, for E+=400 MeV.



ANTIPROTONS (AND OTHERS)

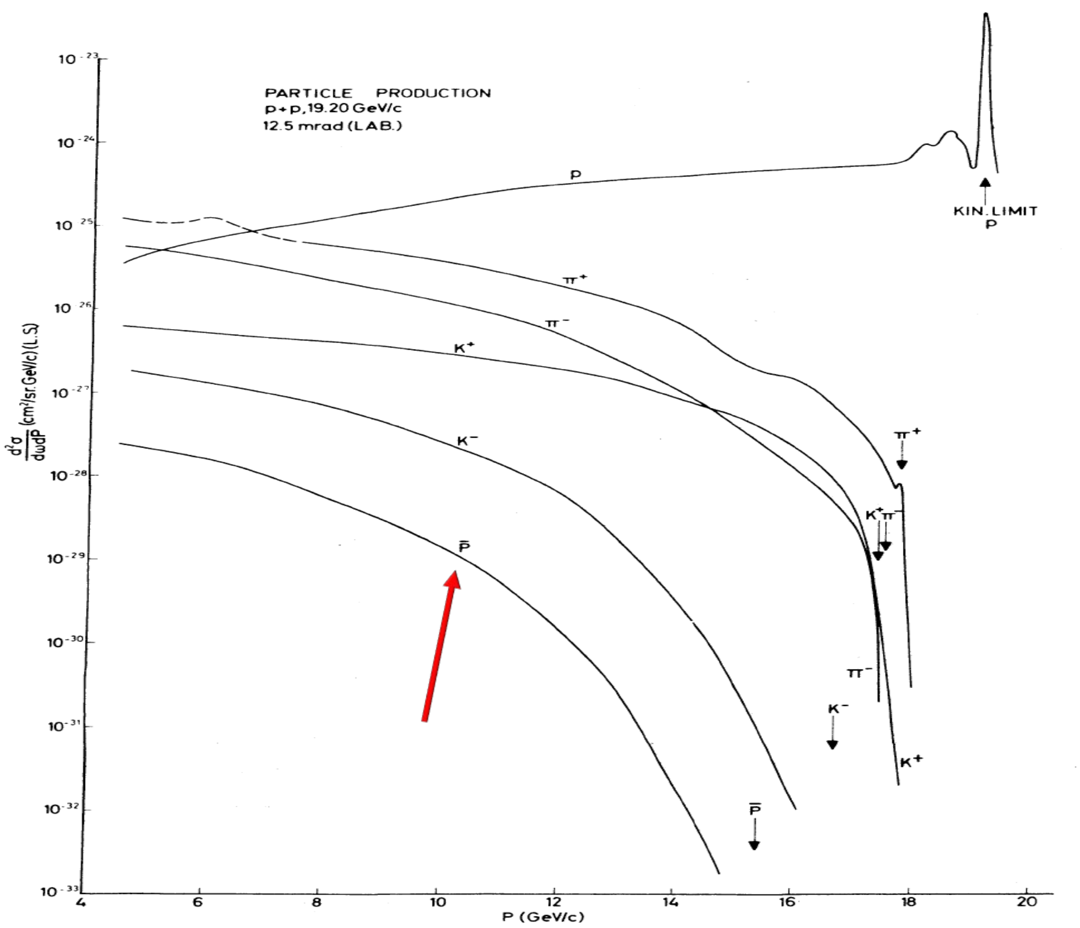
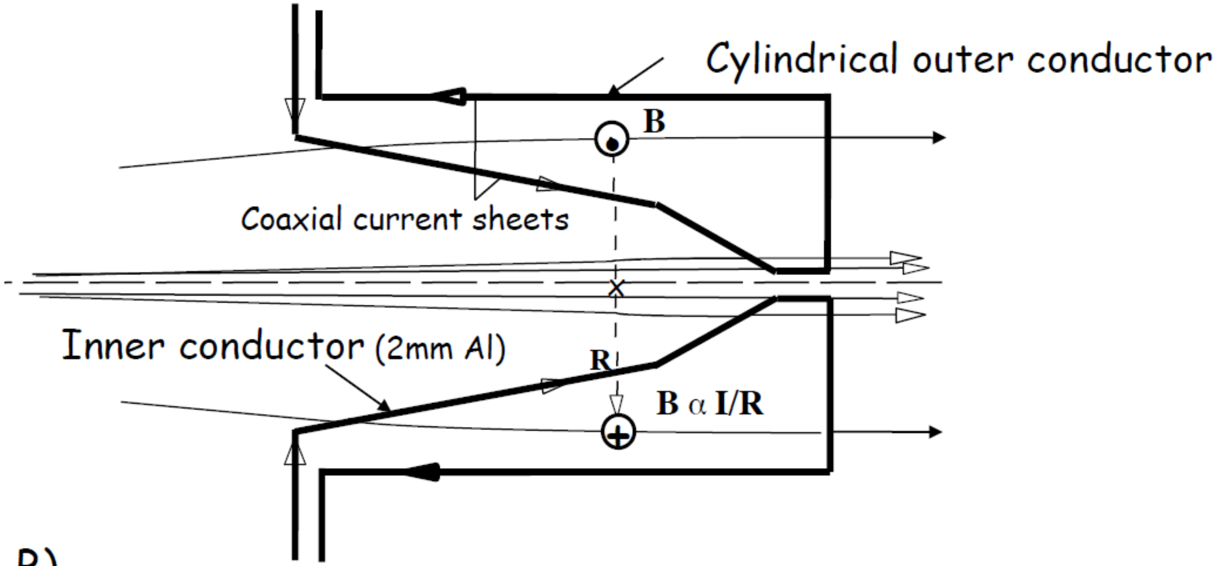


Figure 5: Particle Production by pp Interactions at 19.2 GeV/c

HORN - ANTIPROTON COLLECTION

- **Horns**: focusing element downstream the primary target to capture the charged secondaries (**π**,signle-sign) and focus them towards the experiment where they decay producing **μ**, and then **ν**
- **Pros:** uniform field, focusing on all planes, can be combined to make final beam optics
- **Cons:** high-current, pulsed, radiation and thermal load in the inner conductor, end window

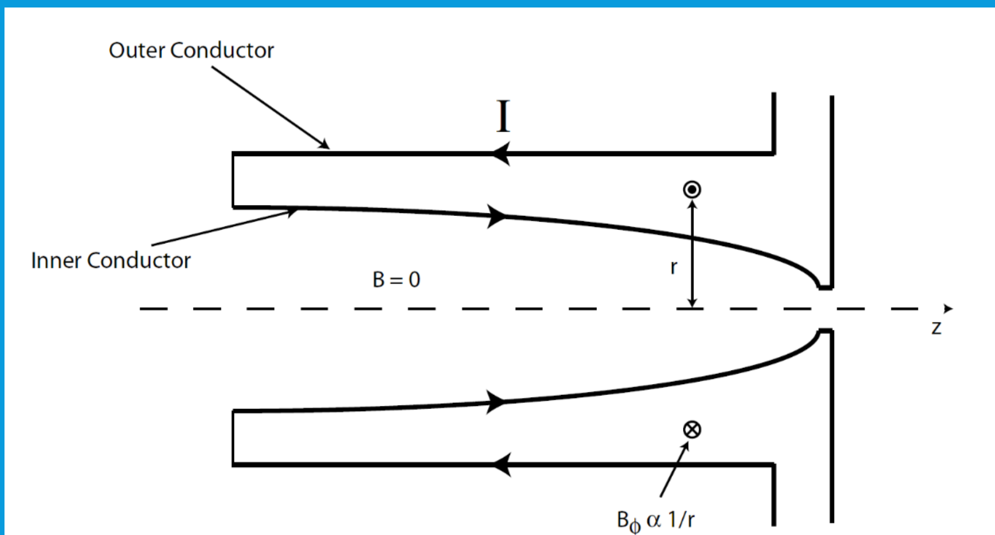


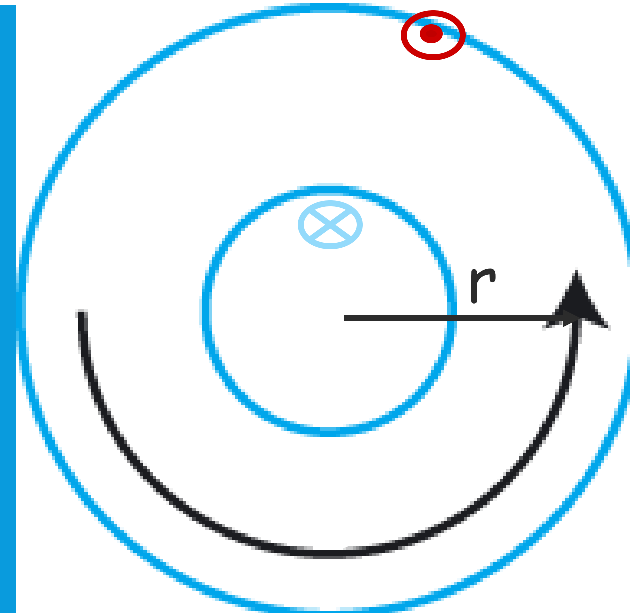
$F = q\,(v \wedge B)$

$B = \mu_0\, I / 2\pi R$

CNGS → I=150 kA, R =15.4 mm B = 1.95 Tesla

MAGNETIC HORN





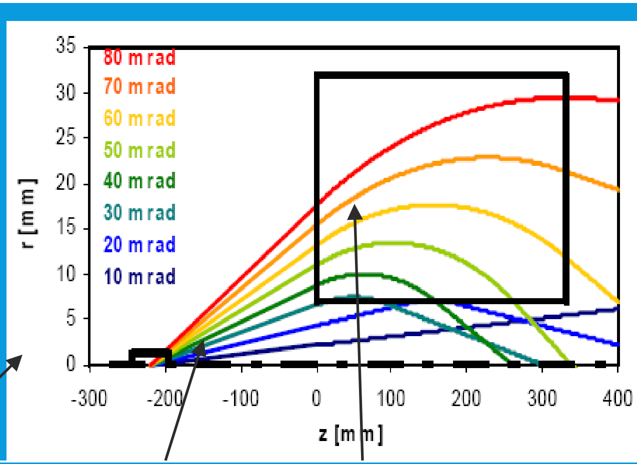
Magnetic volume according to the Ampere law:

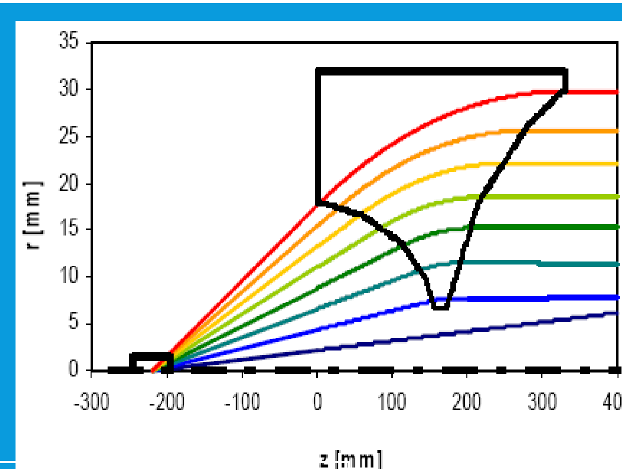
$$\oint B \cdot dl = 2\pi r B = \mu_0 I$$

$$B = \frac{\mu_0 I}{2\pi r}$$

⊗ Current OUT

⊙ Current IN

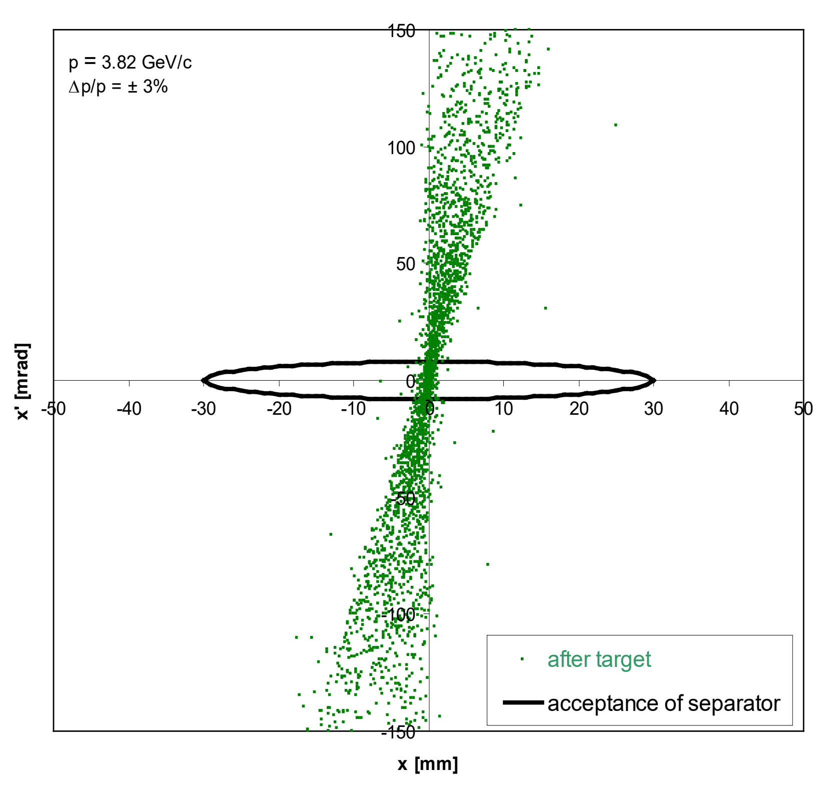


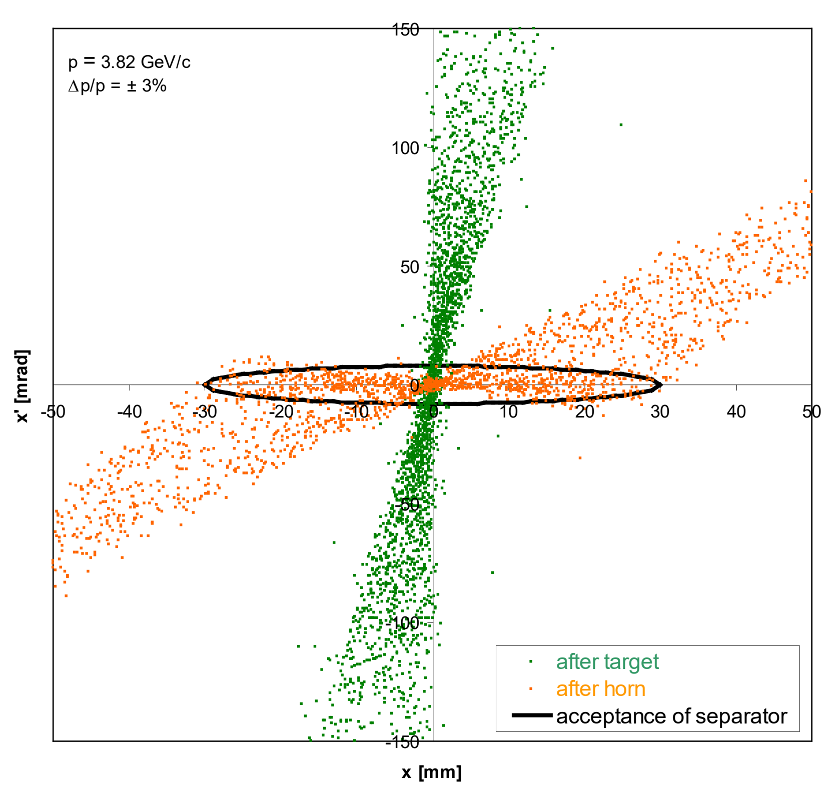


target beam axis magnetic field area

CERN ACOL Horn, I = 400 kA

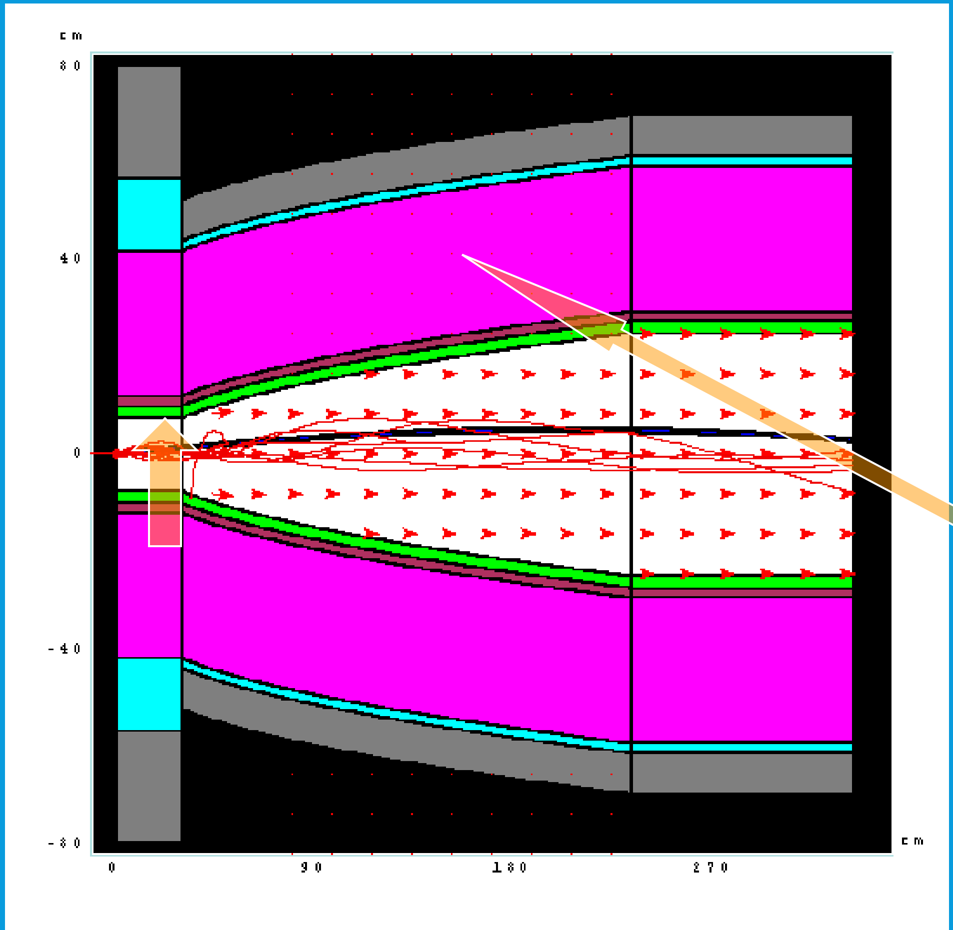
HORN PHASE SPACE ROTATION





US-NUFACT: THE PBAR AMD

Capture B=20 T Φ = 15 cm, L=30 cm



•Focusing:
Tapered field 20 T → 1.25 T

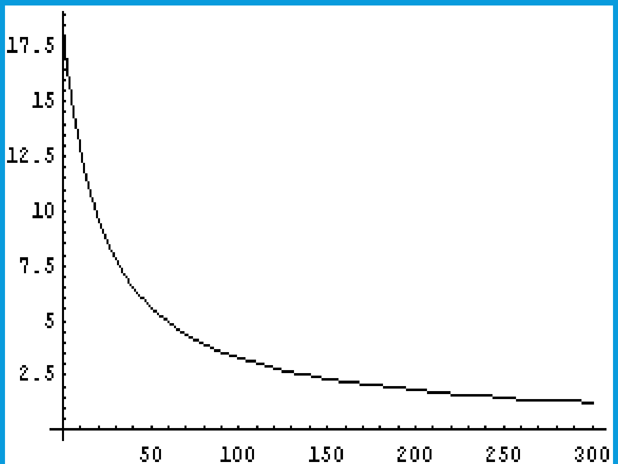
$$B_z(z) = \frac{B_0}{1 + \alpha * z}$$

$$B\rho^2 = const$$

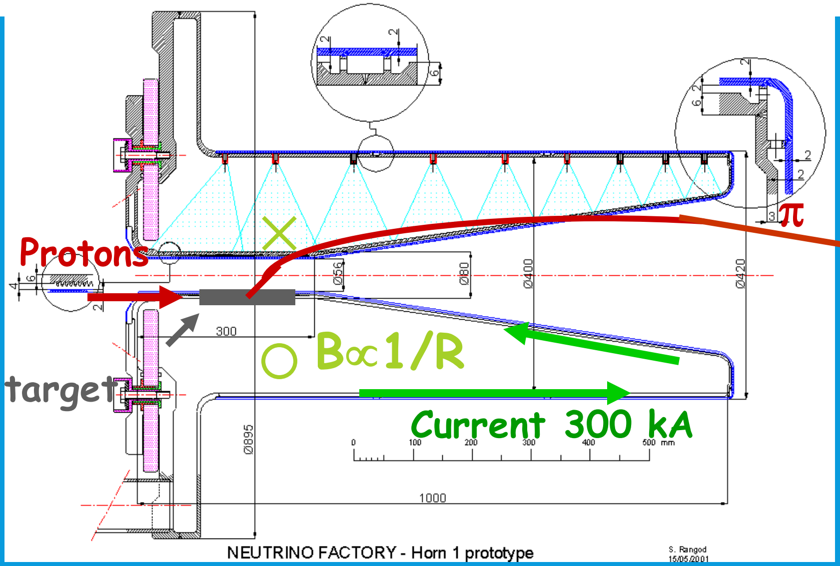
•Magnetic flux conservation

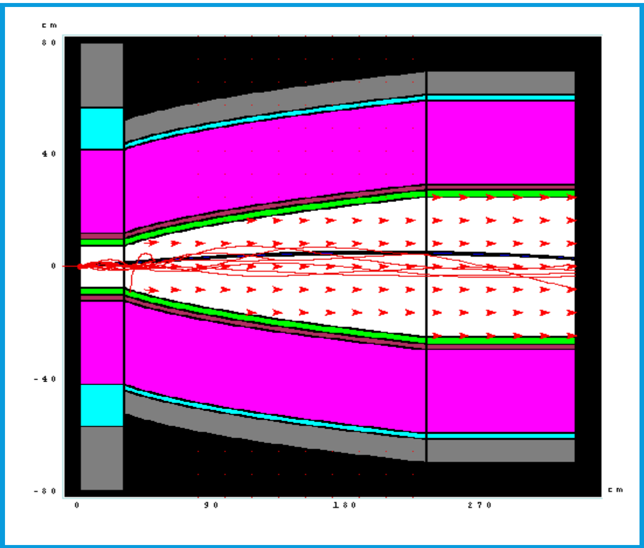
$$\frac{B}{p_{\perp}2} = const$$

•Angular momentum conservation



FOCUSING OPTIONS





- B=0 T at target
- Focuses only one charge state, which is required for super-beam
- highly restricted space

- B = 20 T at target
- Adiabatic focusing channel
- Two charges collected can be separated by RF