FAIR Antiproton Source-Design Considerations

- Requirements and Promises (CDR 2001 and FBTR 2006)
- FAIR Accelerator Complex for pbar Beams
- Topology near Antiproton Source & Antiproton Separator
- Physics of Antiproton Production
  - Invariant Inclusive Production Cross Section
  - Double Differential Laboratory Cross Section and Production Density
  - Yield Dependence on
    - Proton energy
    - pbar Momentum
    - pbar Emission Angle
    - Target Material
- Technical Concept (FBTR), see Talk by Peter Sievers
- Potential for Future Upgrades at FAIR?

Requirements and Promises FBTR and CDR

Internal target experiments at HESR

Average Luminosity	$\mathcal{L}_{max} = 1.4\times10^{32}$ (CDR: 2×10^{32}) $cm^{-2}\,s^{-1}$
Consumption rate for pbar → p	$R_{cons.} = 1.4\times10^{7}$ (CDR: 2×10^{7}) s^{-1}

Primary proton beam from SIS100

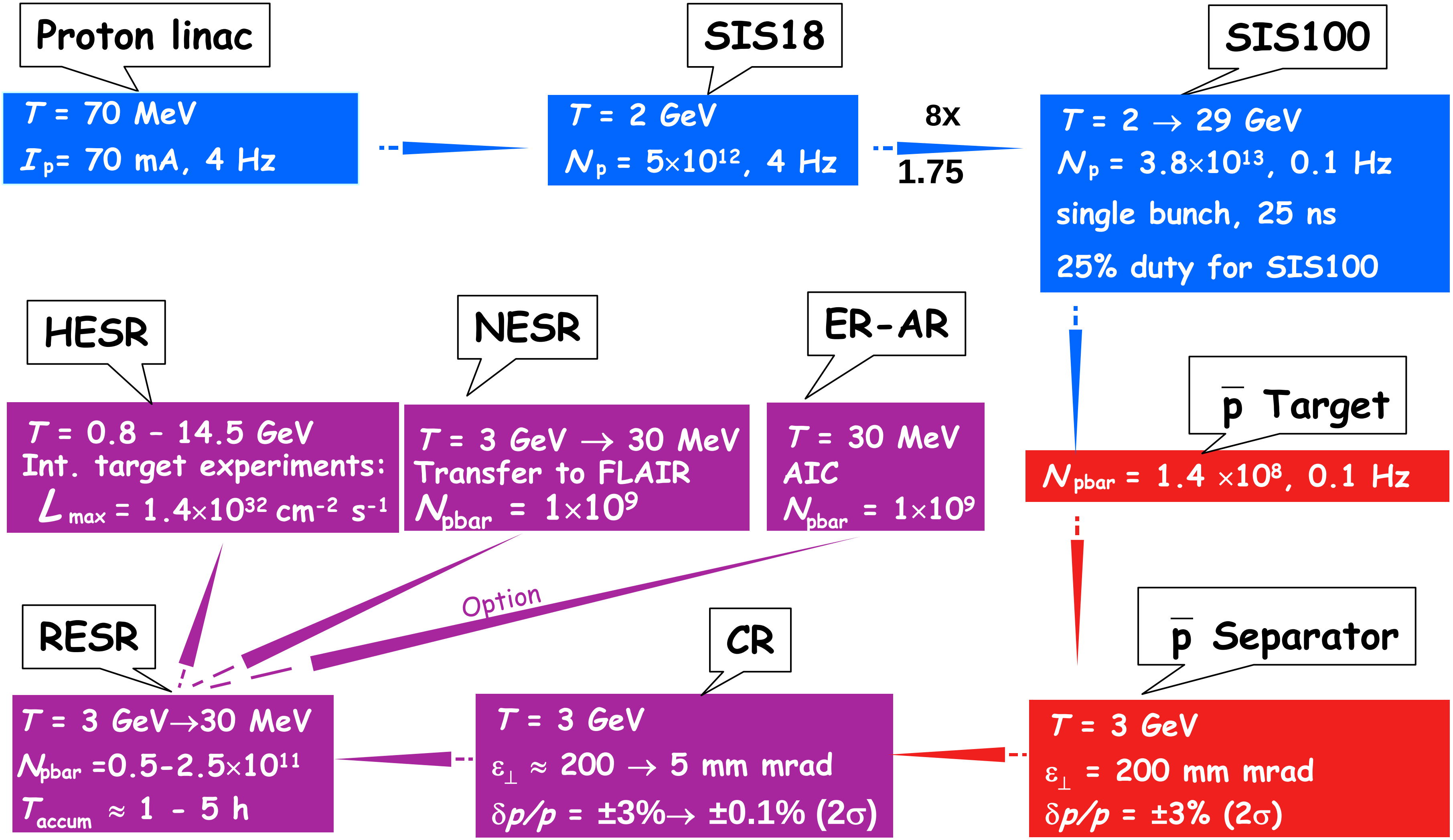
Kinetic energy	29 GeV
Cycle time SIS100	3s (CDR 2 s)
Protons per bunch	3.8×10^{13} (CDR: 2.8×10^{13})
Transverse beam emittances	5 (h) / 3 (v) mm mrad (2σ)
Momentum spread	$\delta p/p = \pm0.7$ % (2σ)
Bunch length	25 ns
Repetition rate	0.1 Hz (CDR: 0.2Hz)

Phase space acceptance of Collector Ring CR

Transverse acceptance	$A_{x,y} = 200$ mm mrad
Momentum acceptance	$\Delta p/p = \pm3$ %
Cooling & stacking time	10 s (CDR: 5 s)

FAIR Accelerator Complex for pbar Beams

(FBTR 2006)



Proton linac

T = 70 MeV

I_p = 70 mA, 4 Hz

SIS18

T = 2 GeV

N_p = 5×10^{12}, 4 Hz

8x

1.75

SIS100

T = 2 → 29 GeV

N_p = 3.8×10^{13}, 0.1 Hz

single bunch, 25 ns

25% duty for SIS100

$\bar{p}$ Target

N_{pbar} = 1.4 $\times10^{8}$, 0.1 Hz

$\bar{p}$ Separator

T = 3 GeV

$\varepsilon_\perp$ = 200 mm mrad

$\delta p/p$ = ±3% (2σ)

CR

T = 3 GeV

$\varepsilon_\perp \approx 200 \rightarrow 5$ mm mrad

$\delta p/p$ = ±3%→ ±0.1% (2σ)

RESR

T = 3 GeV→30 MeV

N_{pbar} =$0.5-2.5\times10^{11}$

$T_{accum} \approx 1 - 5$ h

Option

HESR

T = 0.8 – 14.5 GeV

Int. target experiments:

L_{max} = 1.4×10^{32} cm^{-2} s^{-1}

NESR

T = 3 GeV → 30 MeV

Transfer to FLAIR

N_{pbar} = 1×10^{9}

ER-AR

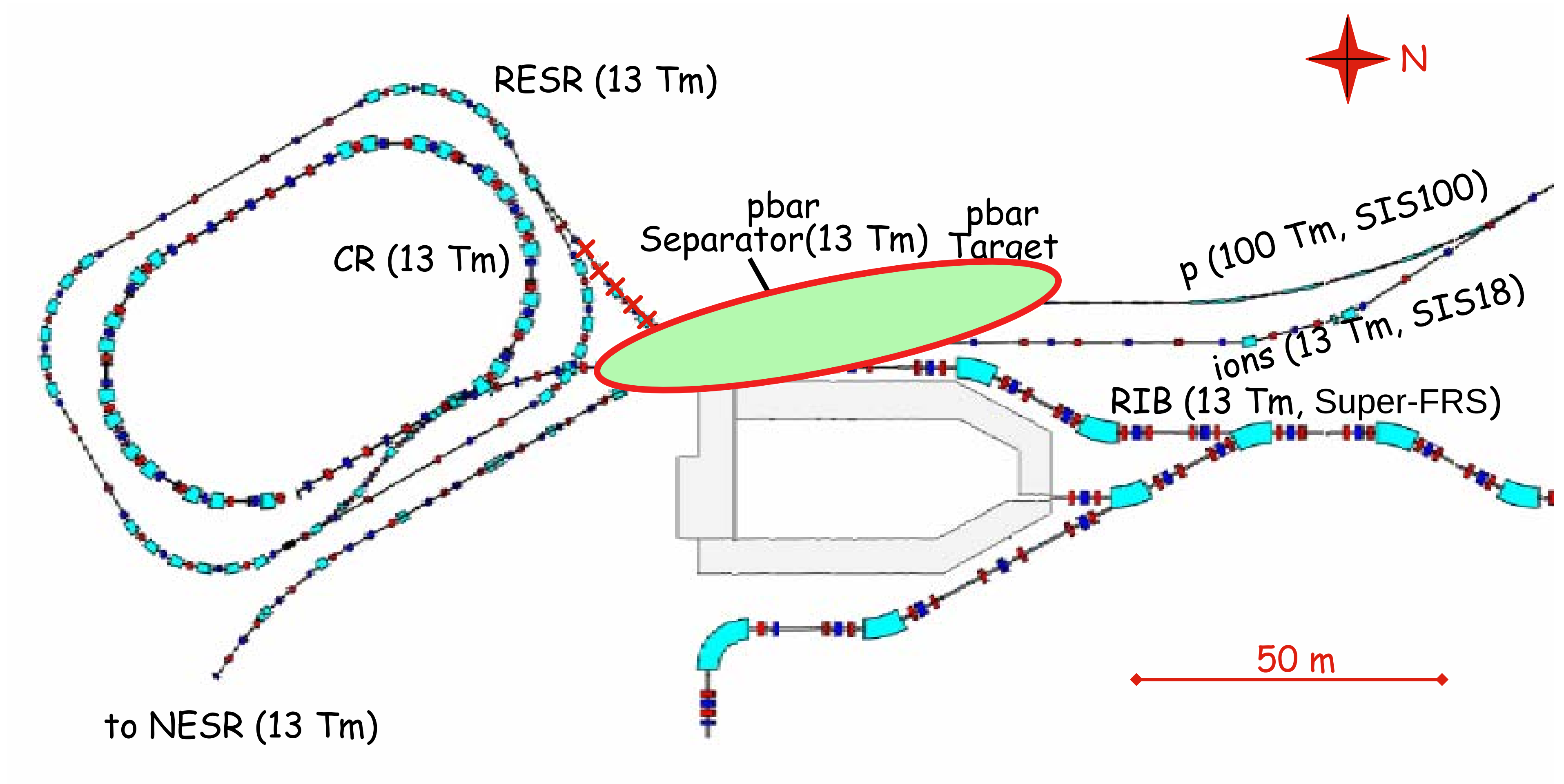
T = 30 MeV

AIC

N_{pbar} = 1×10^{9}

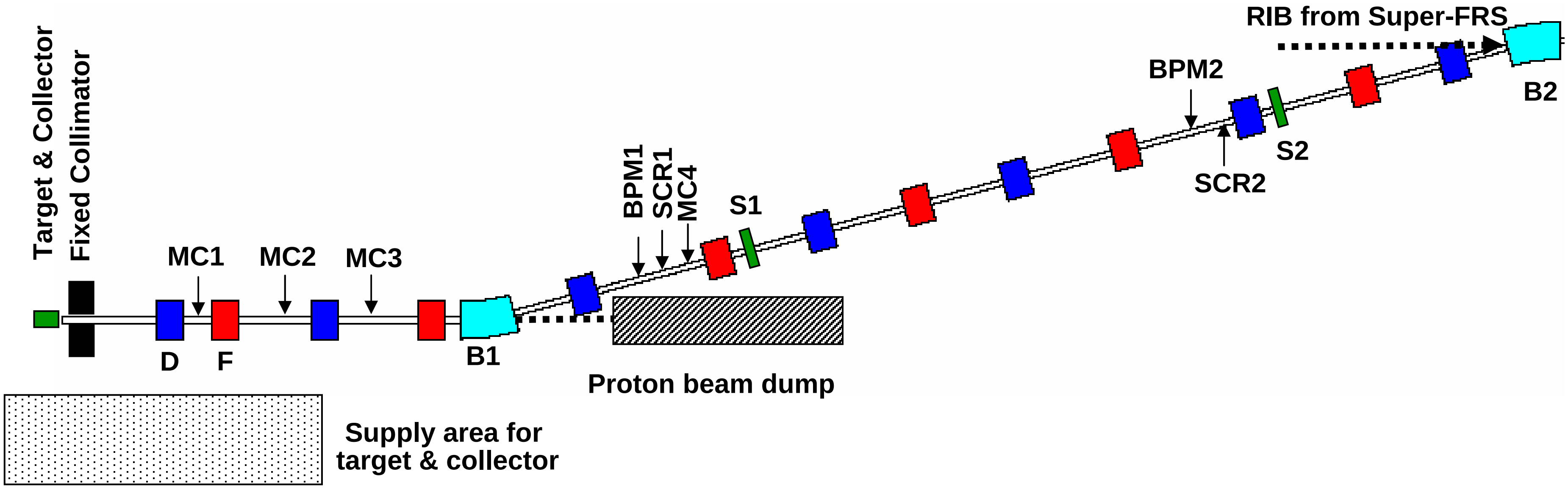
Topology near Antiproton Source

(Status 2005, new layout by S. Ratschow underway)



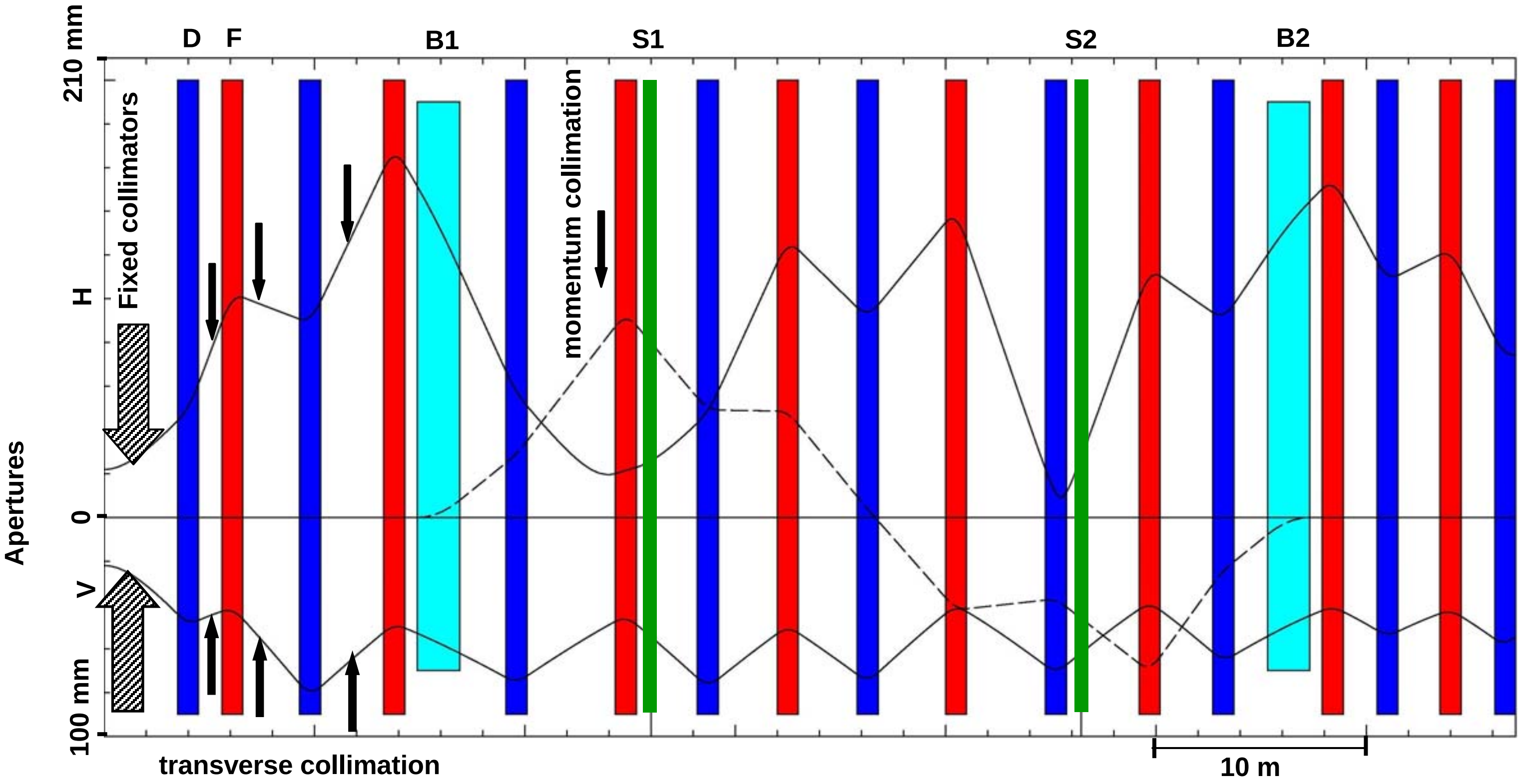
Magnetic Separator Layout

Sebatian Ratschow, GSI,2005



Magnetic Separator Layout

(Sebastian Ratschow, GSI, old design, 2005)



Physics of Antiproton Production

Usual description:

Lorentz invariant inclusive cross section:

$$\underset{\text{c.m.s.}}{E^* \frac{\mathrm{d}^3 \sigma^*_{\bar{\mathrm{p}}}}{\mathrm{d}(p^*)^3}} = \underset{\text{lab.s.}}{E \frac{\mathrm{d}^3 \sigma_{\bar{\mathrm{p}}}}{\mathrm{d}\, p^3}} = \mathrm{f}\,(p_\perp, x_\mathrm{R}, s)$$

$p^*_\perp = p_\perp = p\,\theta$ $\quad$ [transverse antiproton momentum]

$s = \left(E^*_\mathrm{tot}\right)^2 = 2m_\mathrm{p}\, c^2 (m_\mathrm{p}\, c^2 + E_\mathrm{p})$ $\quad$ $\left[E^*_\mathrm{tot} = \text{total c.m. energy}, E_\mathrm{p} = \text{primary proton energy}\right]$

$x_\mathrm{R} = E^* / E^*_\mathrm{max}$ $\quad$ $\left[\text{radial scaling variable, } E^* = \text{pbar energy in c.m.s.}\right]$

$E^*_\mathrm{max} = (s - 8m_\mathrm{p}^2\, c^4)/(2E^*_\mathrm{tot})$ $\quad$ [maximum possible c.m. energy of pbar]

Empirical pbar Invariant Production Cross Section

Latest publication with best fit to all available experimental results, especially at lower proton energies down to a few GeV : R.P. Duperray et al., Phys. Rev. **D 68**, 094017 (2003) :

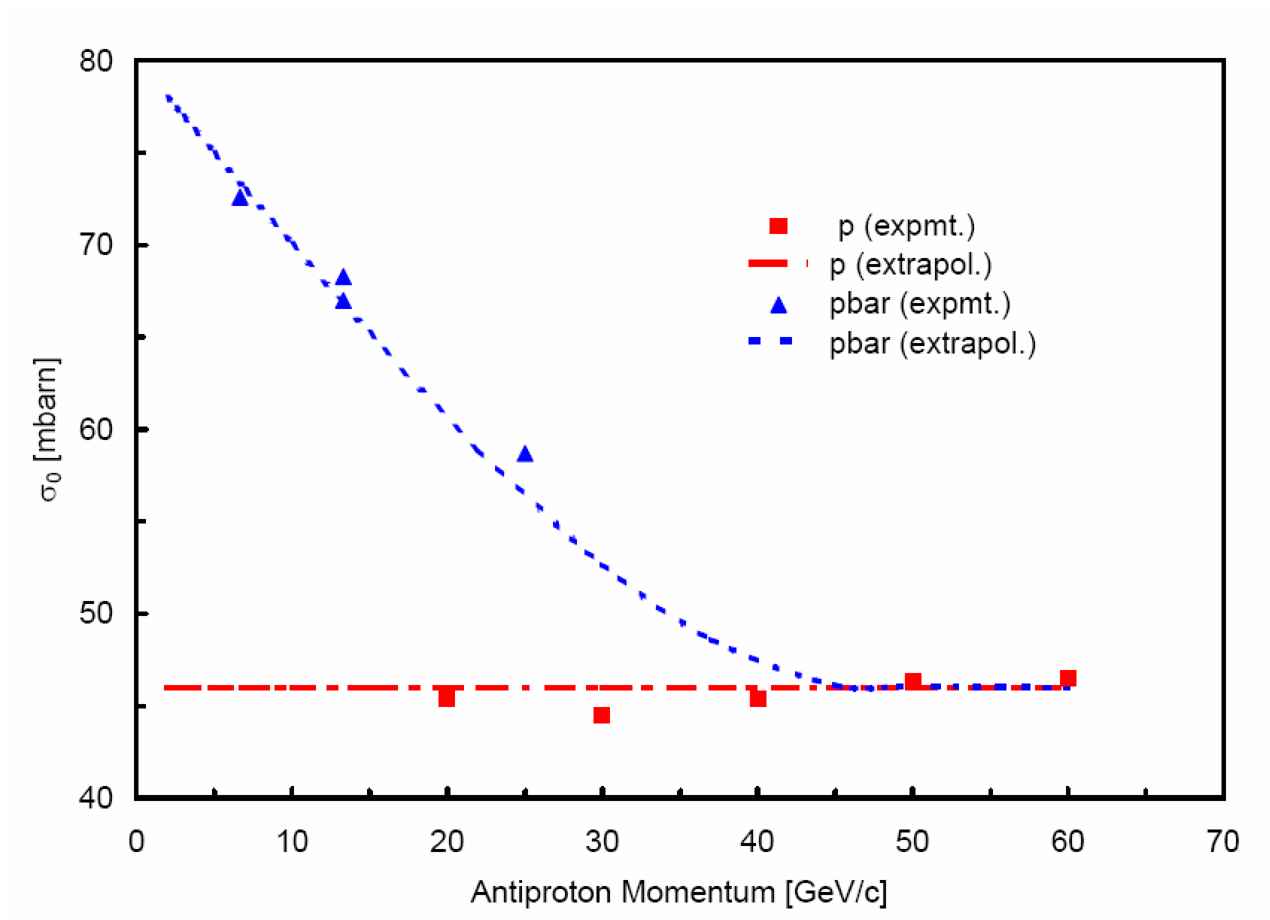
$$E^* \frac{\mathrm{d}^3 \sigma^*_{\bar{\mathrm{p}}}}{\mathrm{d}\left(p^*\right)^3} = \sigma_{\mathrm{abs}}\, A^{C_1\, p_\perp \ln(\sqrt{s}/C_2)}\, (1 - x_{\mathrm{R}})^{C_3 \ln(\sqrt{s})}\; e^{-C_4 x_{\mathrm{R}}} \times \left(C_5 \left(\sqrt{s}\right)^{C_6} e^{-C_7 p_\perp} + C_8 \left(\sqrt{s}\right)^{C_9} e^{-C_{10} p_\perp^2} \right)$$

$$\sigma_{\mathrm{abs}} = \sigma^*_{\mathrm{abs}} = \text{total inelastic c.s. (absorption c.s.)}$$

Parameter	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Value	0.167	10.28	2.27	3.707	0.0092	0.4812	3.36	0.06394	-0.1824	2.4850

Older formulae:
C. Hojvat and A. Van Ginneken , *Calculation of Antiproton Yields for the Fermilab Antiproton Source*, Nucl. Instr. Meth. **206**, 67 (1983)
A.N. Kalinovski, M.V. Mokhov, et al., *Passage of High Energy Particles through Matter*, AIP, New York, 1989, Chap. 3 (1989) applied in MARS-Code

Total Absorption Cross Section



Experiments by Denisov et al. (1973):

$\sigma_{abs}= \ \sigma_{abs} A^{\alpha}$

Protons

$\alpha \approx 0.694$,

σ_0=const≈46 mbarn

Antiprotons

$\alpha \approx 0.634$

below 50 GeV/c

$\sigma_0 \approx 80 - p + 1.82 \times 10^{-5} p^{3.5}$

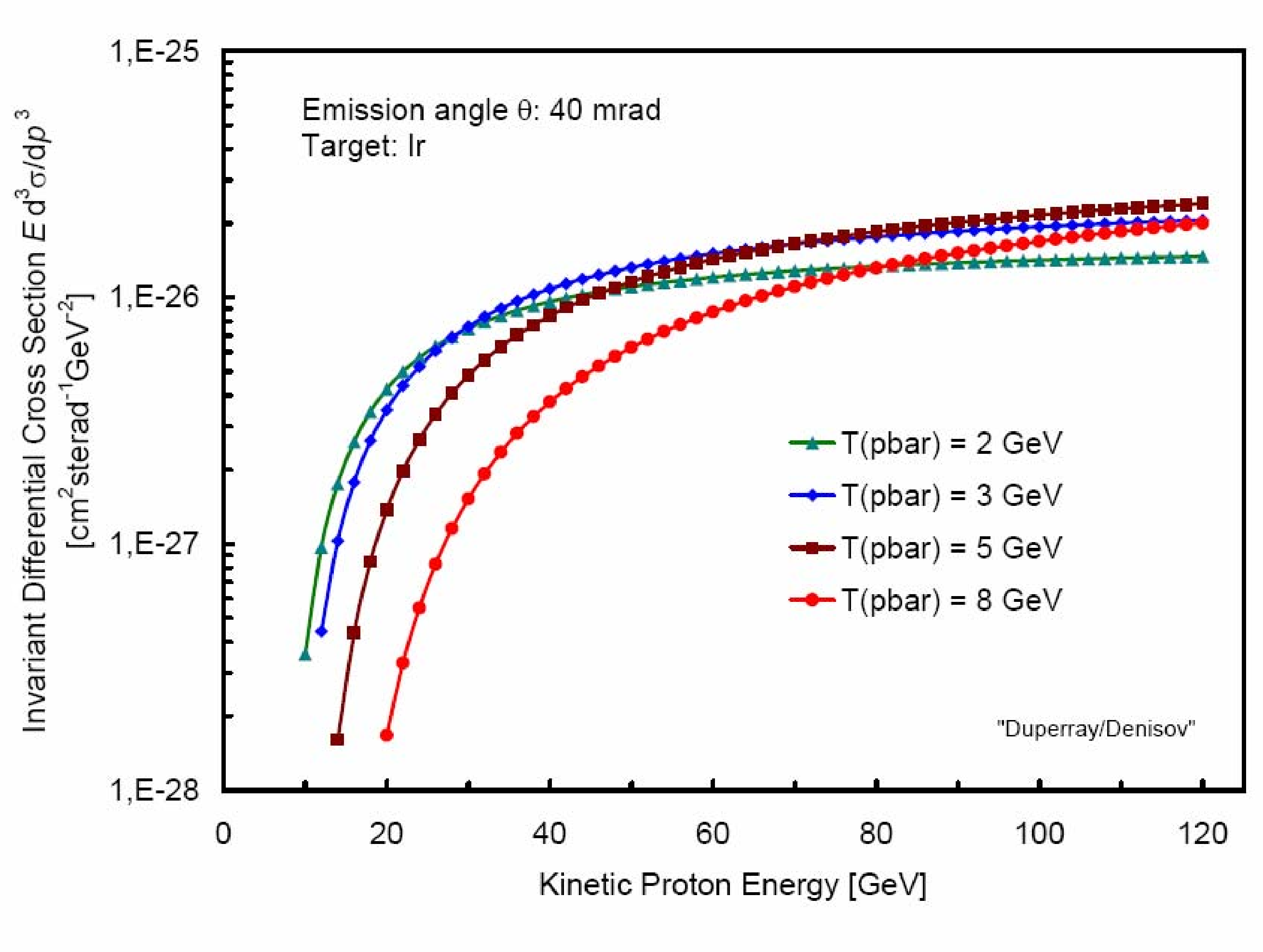
above 50 GeV/c

σ_0≈const≈46 mbarn

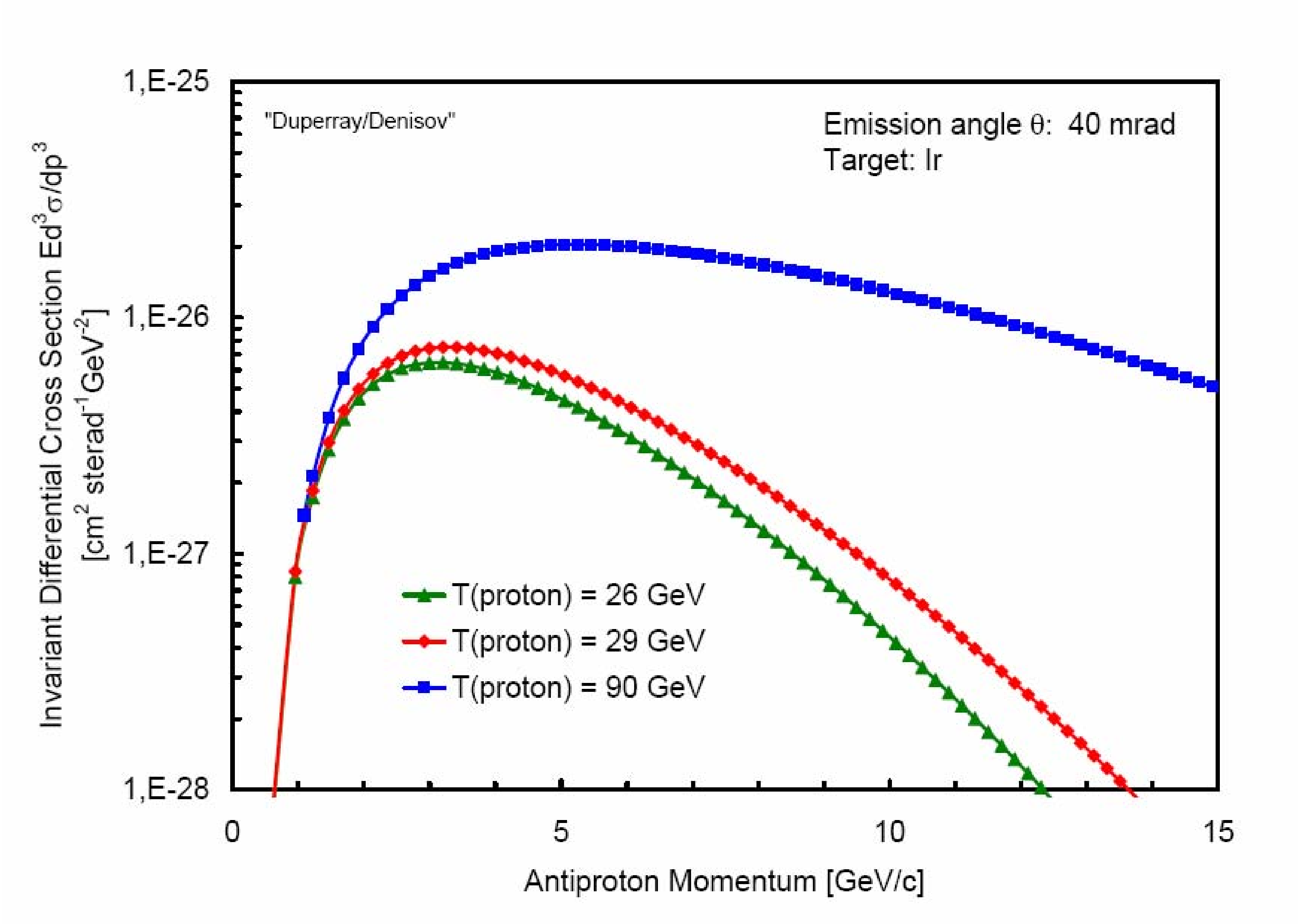
S.P. Denisov et al., *Absorption Cross Sections for Pions, Kaons, Protons and Antiprotons on Complex Nuclei in the 6 to 60 GeV/c Momentum Range*, Nucl. Phys. **B 61**, 62 (1973)

See also: J.R. Letaw et al., Astropart. J. Suppl. Ser. **51**, 271 (1983)

Lorentz Invariant Production C.S. vs. Proton Energy



Lorentz Invariant Production C.S. vs. pbar Momentum



Laboratory Production Cross Section and Yield

Double differential production cross section in the laboratory system:

$$\boxed{\underset{\text{c.m.s.}}{E^* \frac{d^3 \sigma^*_{\bar{p}}}{(d p^*)^3}} = \underset{\text{lab. system}}{E \frac{d^2 \sigma_{\bar{p}}}{p^2 \, d p \, d\Omega}} \qquad \text{or} \qquad \frac{d^2 \sigma_{\bar{p}}}{d p \, d\Omega} = \frac{p^2}{E} \left(E^* \frac{d^3 \sigma^*_{\bar{p}}}{(d p^*)^3} \right)}$$

because $d p_x \, d p_y = p^2 \, d x' \, d y' = p^2 \, d\Omega$

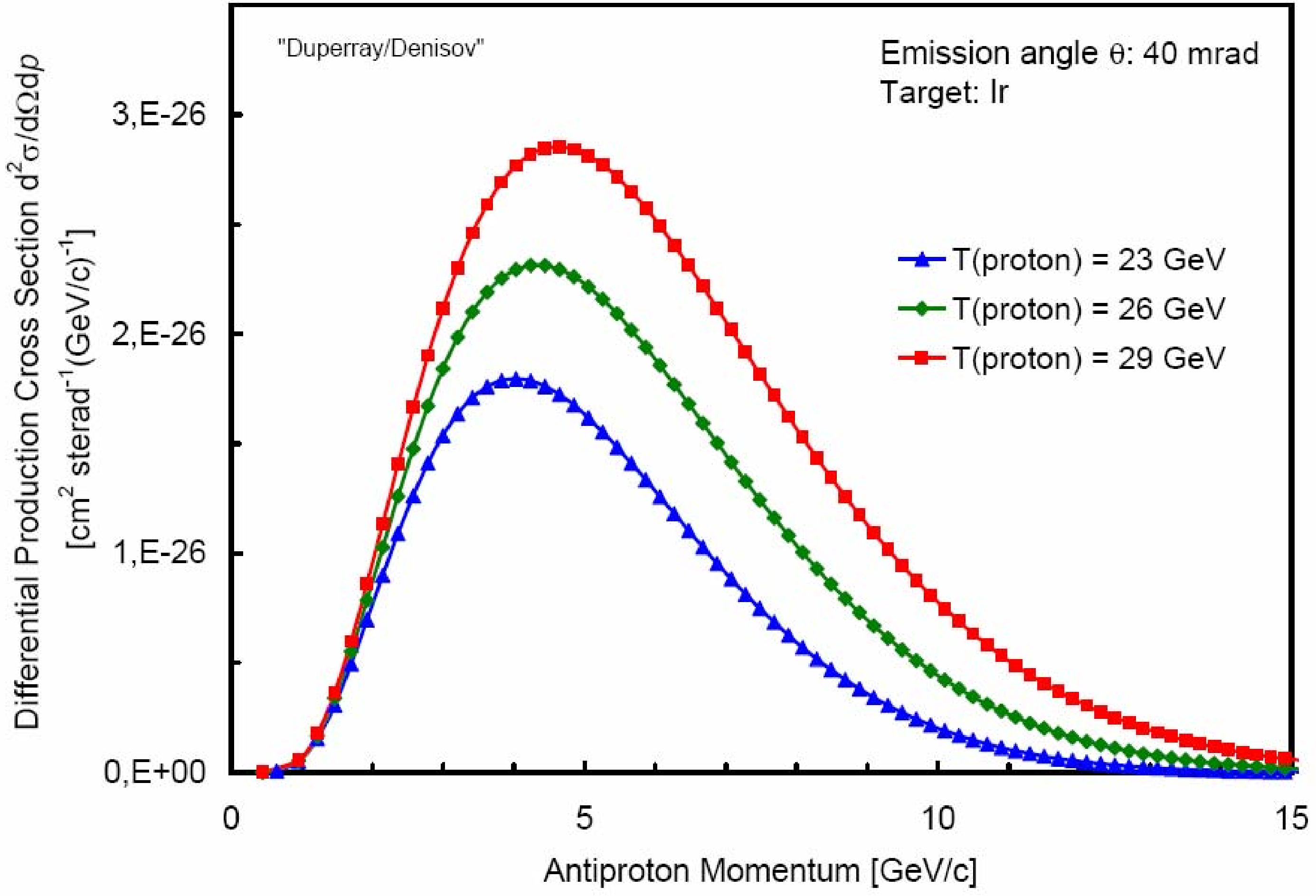
Double differential yield per primary proton:

$$\boxed{\frac{d^2 N_{\bar{p}}}{d p \, d\Omega} = \frac{1}{\sigma_{abs}(p)} \frac{d^2 \sigma_{\bar{p}}}{d p \, d\Omega}}$$

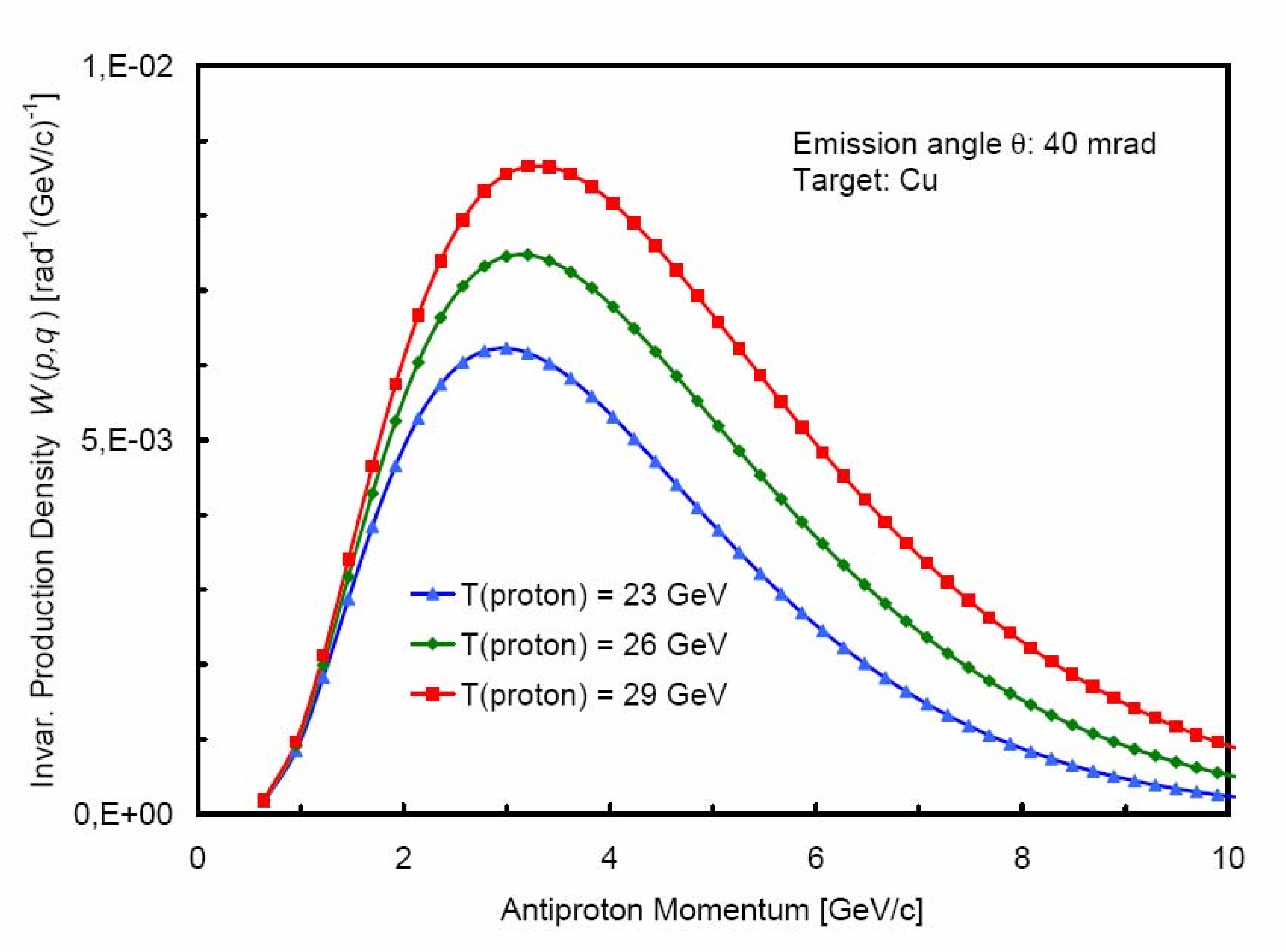
Definition of invariant production density:

$$\boxed{W(p,\theta) = \frac{2E}{p^2} \frac{d^2 N_{\bar{p}}}{d p \, d\Omega}}$$

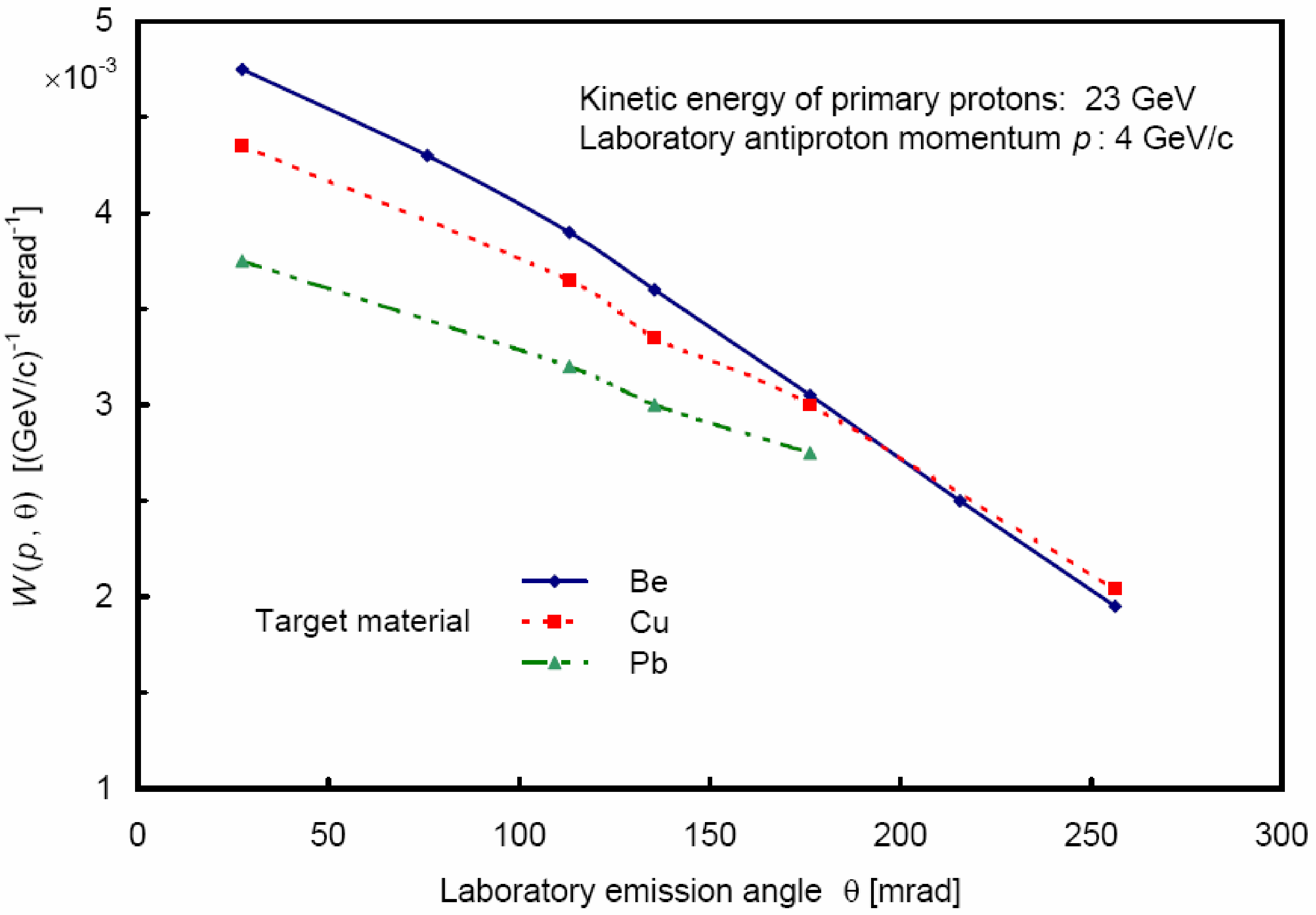
Production C.S. in Laboratory System



Invariant production Density



Dependence on Emission Angle



Integration over Momentum and Angular Acceptance

$$k = \int_{-\Delta p}^{+\Delta p} \int_{\Omega=0}^{\Omega_{\max}} \frac{\mathrm{d}^2 N_{\bar{\mathrm{p}}}}{\mathrm{d}\,p\,\mathrm{d}\Omega} \mathrm{d}\,p\,\mathrm{d}\Omega \approx 2p\frac{\Delta p}{p} \;\pi\left(\theta_{\max}\right)^2 \left|\frac{\mathrm{d}^2 N_{\bar{\mathrm{p}}}}{\mathrm{d}\,p\,\mathrm{d}\Omega}\right|_{\Delta p=0,\, 2\theta_{\max}/3}$$

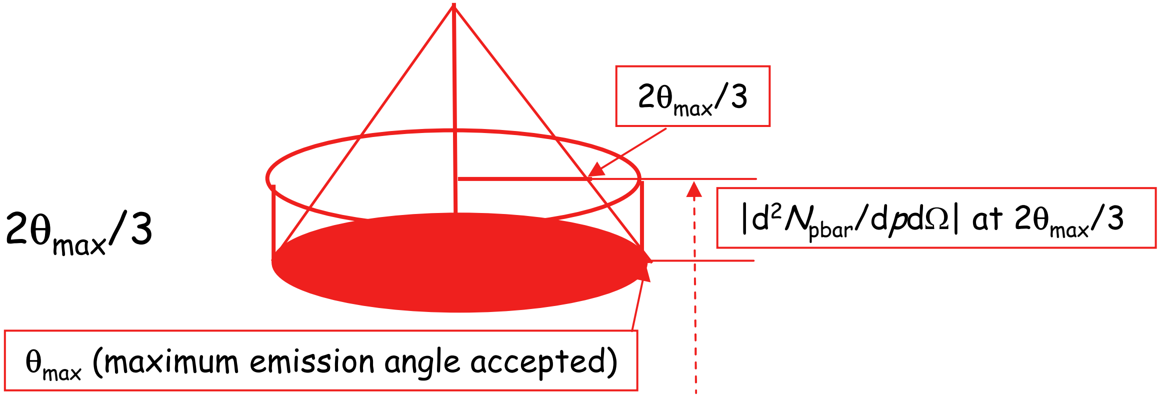
Because of the almost linear decrease of the yield with increasing emission angle we can apply the volume formula for a cone

$V = \pi r^2 h/3$

with

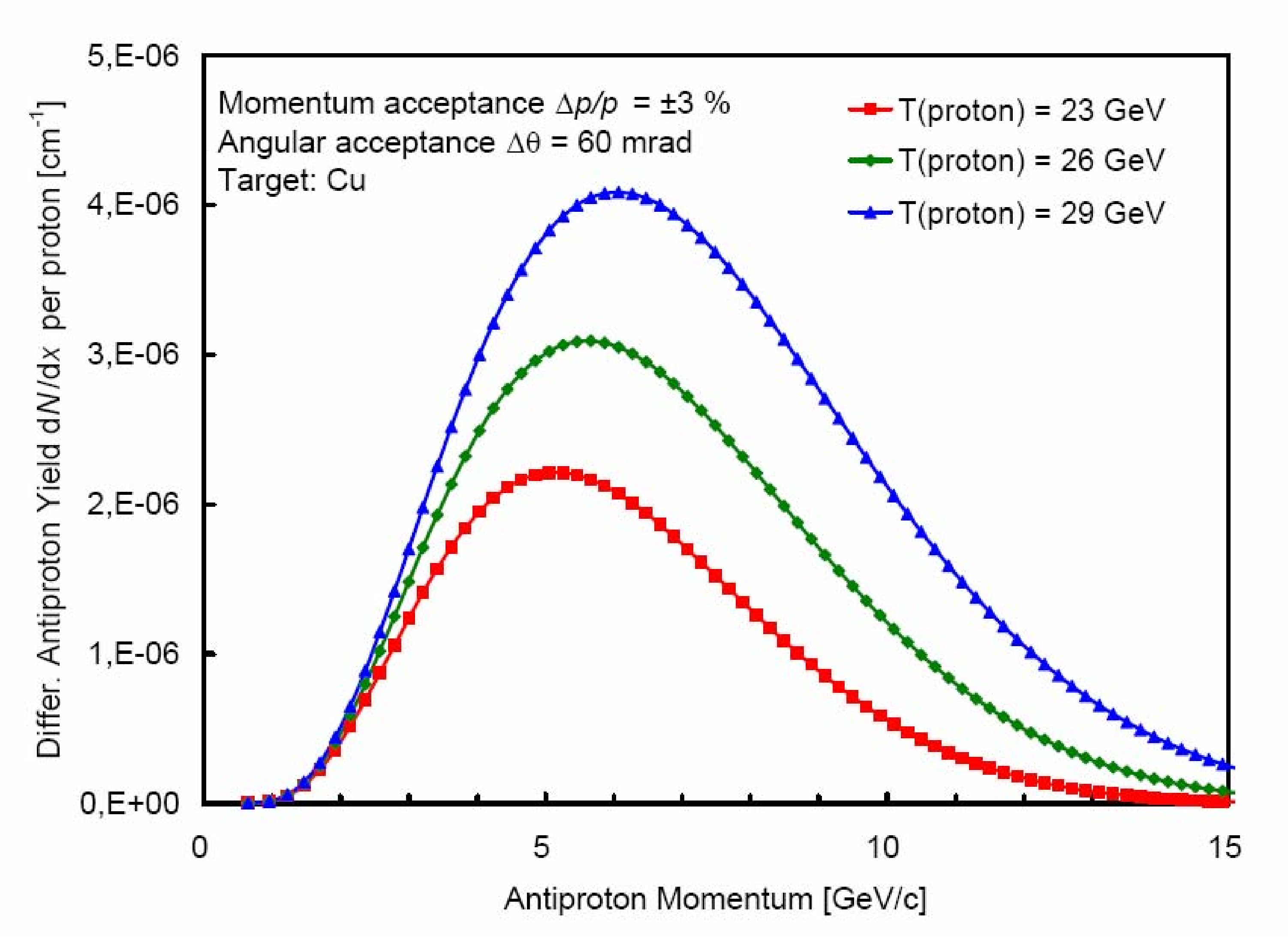
$r = \theta_{max}$ and

$h/3 = |d^2N_{pbar}/dp d\Omega|$ at $\Delta p=0, 2\theta_{max}/3$

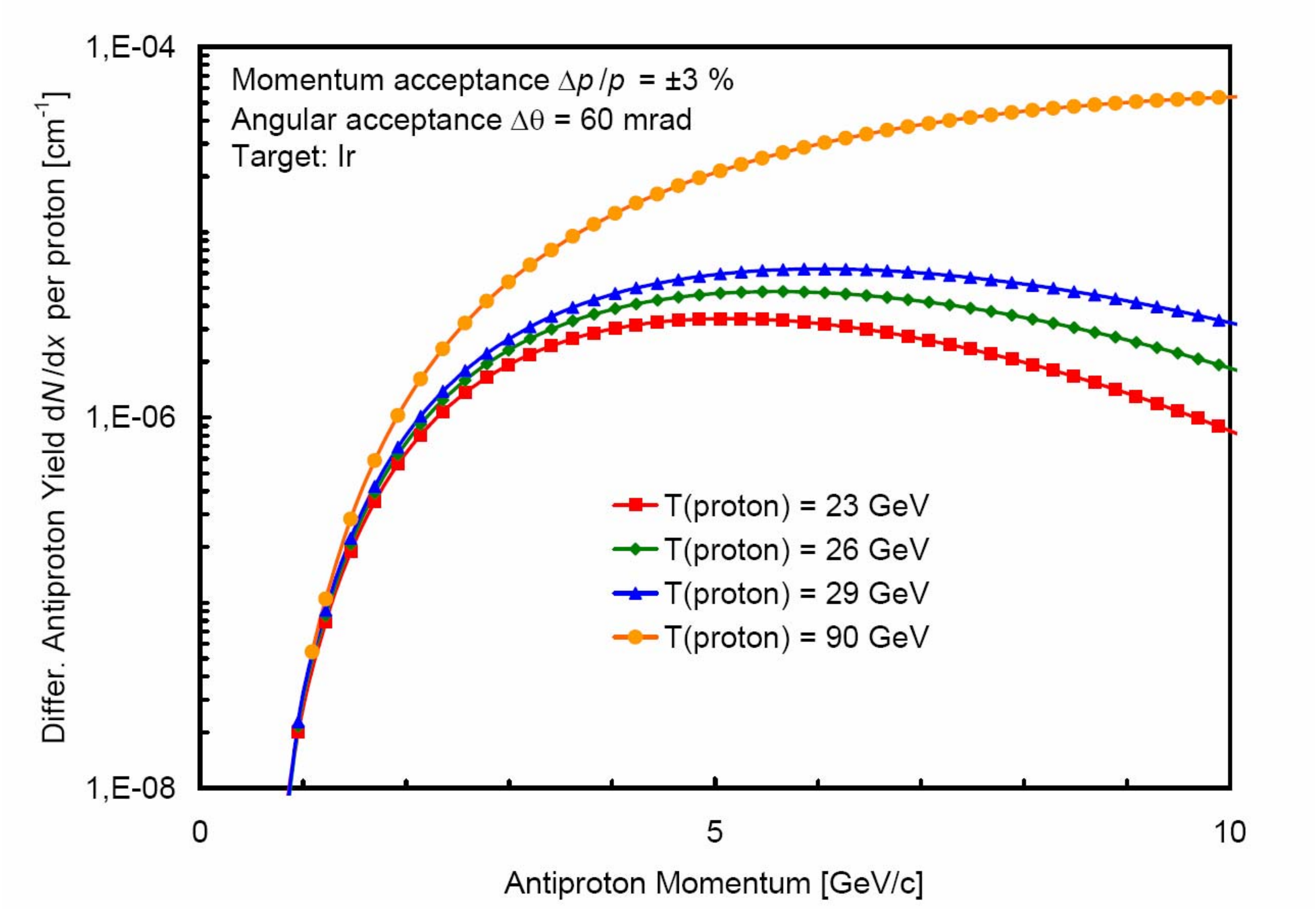


The variation of $d^2N_{pbar}/dp\, d\Omega$ over the momentum acceptance of ±3% is very small. Therefore, we can apply the value at $\Delta p=0$, 2θmax/3.

Differential Antiproton Yield



Differential pbar Yield for Diff. Proton Energies



Differential Equation for Yield vs. Target Length

$$\boxed{\frac{\mathrm{d}\,N_{\bar{\mathrm{p}}}(x)}{\mathrm{d}\,x} = k\,\frac{N_{\mathrm{p}}(x)}{\lambda_{\mathrm{p}}} - \frac{N_{\bar{\mathrm{p}}}(x)}{\lambda_{\bar{\mathrm{p}}}}}$$

with the interaction lengths

$$\lambda_{\mathrm{p}} = \frac{A}{L\,\rho\,\sigma_{\mathrm{abs}}(\mathrm{p})} \qquad \text{for protons}$$

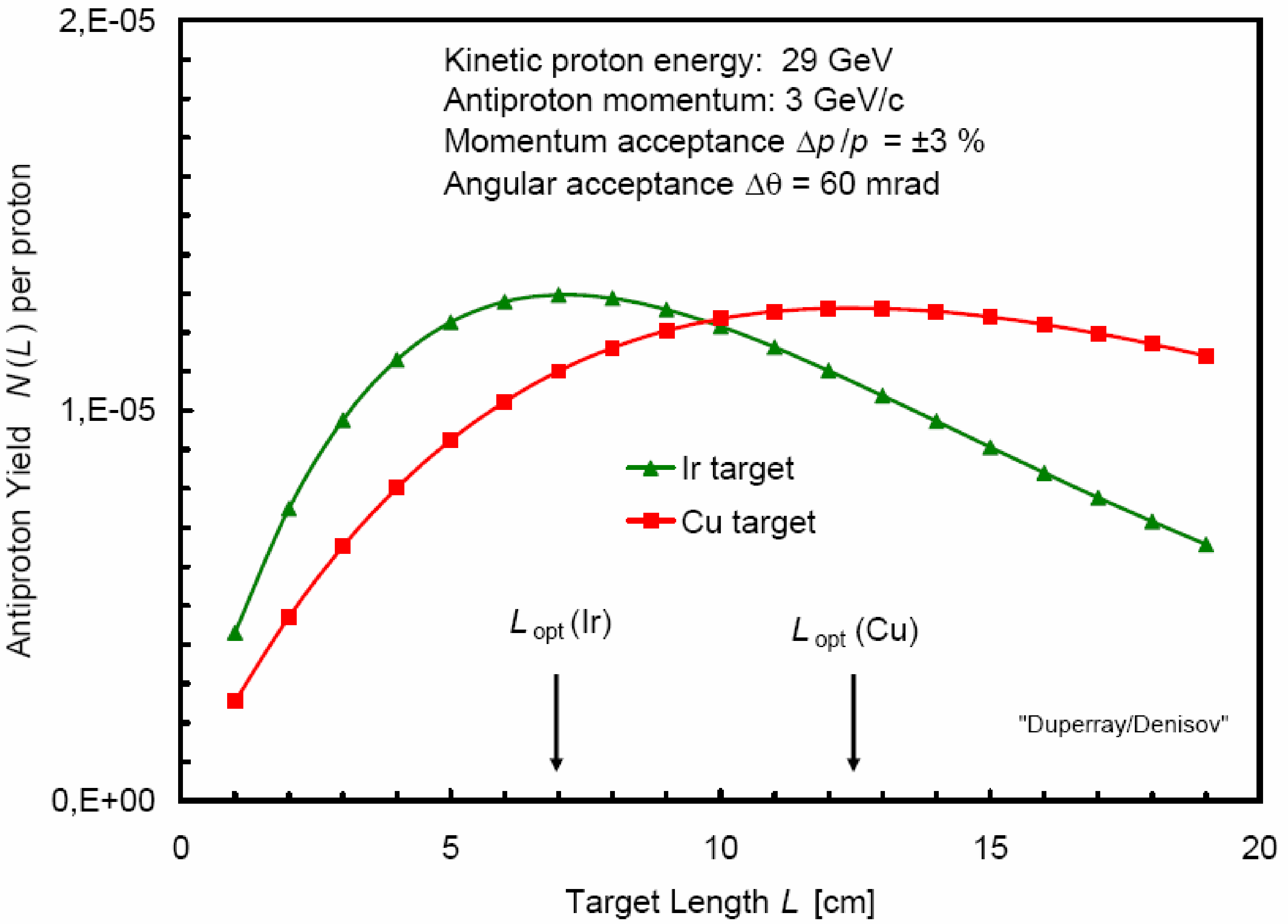
$$\lambda_{\bar{\mathrm{p}}} = \frac{A}{L\,\rho\,\sigma_{\mathrm{abs}}(\bar{\mathrm{p}})} \qquad \text{for antiprotons (anihilation)}$$

Solution:

$$\boxed{N_{\bar{\mathrm{p}}}(x) = k\,\frac{\lambda_{\bar{\mathrm{p}}}}{\lambda_{\mathrm{p}} - \lambda_{\bar{\mathrm{p}}}}\,\mathrm{e}^{-\frac{x}{\lambda_{\mathrm{p}}}}\left(1 - \mathrm{e}^{x\frac{\lambda_{\mathrm{p}}-\lambda_{\bar{\mathrm{p}}}}{\lambda_{\mathrm{p}}\lambda_{\bar{\mathrm{p}}}}}\right) \quad \text{for } \lambda_{\bar{\mathrm{p}}} \neq \lambda_{\mathrm{p}}}$$

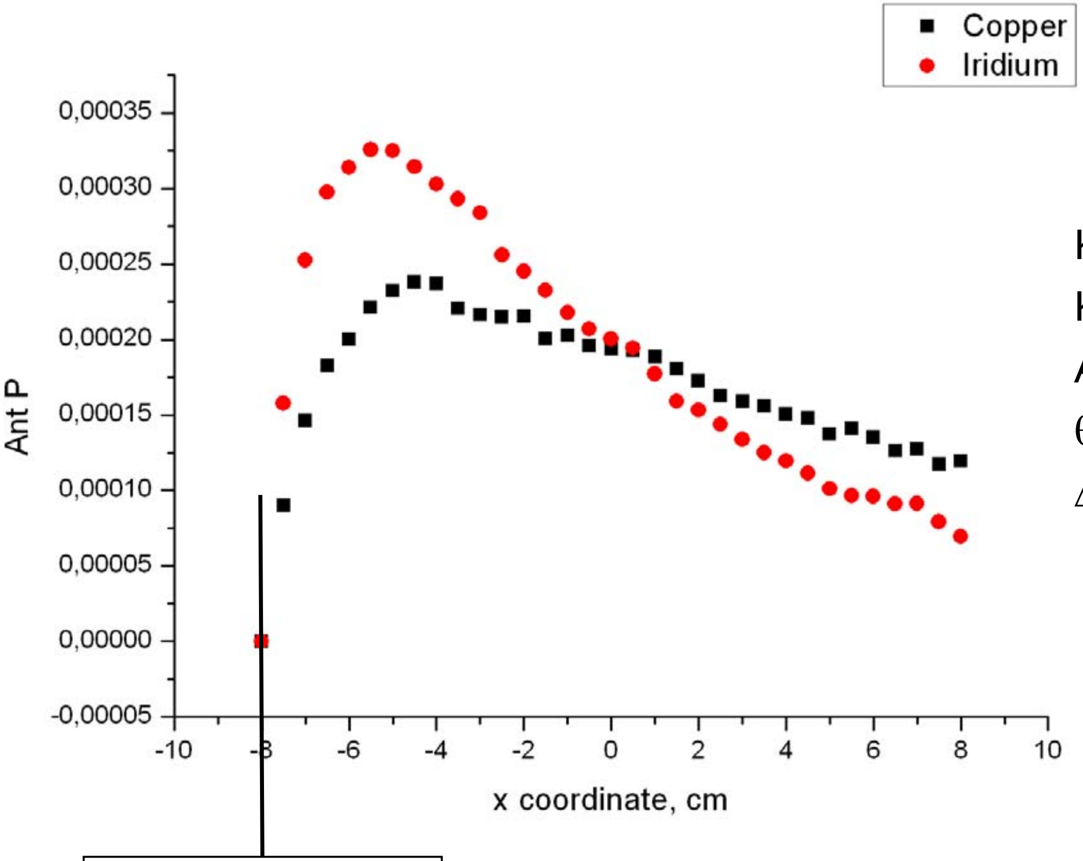
$$\boxed{N_{\bar{\mathrm{p}}}(x) = k\,\frac{x}{\lambda_{\mathrm{p}}}\,\mathrm{e}^{-\frac{x}{\lambda_{\mathrm{p}}}} \quad \text{for } \lambda_{\bar{\mathrm{p}}} = \lambda_{\mathrm{p}}}$$

Antiproton Yield in Cu and Ir



Antiproton Yield in Cu and Ir by FLUKA

(by A.B. Plotnikov Nov. 2006)



target entrance

Kin. energy of protons: 29 GeV

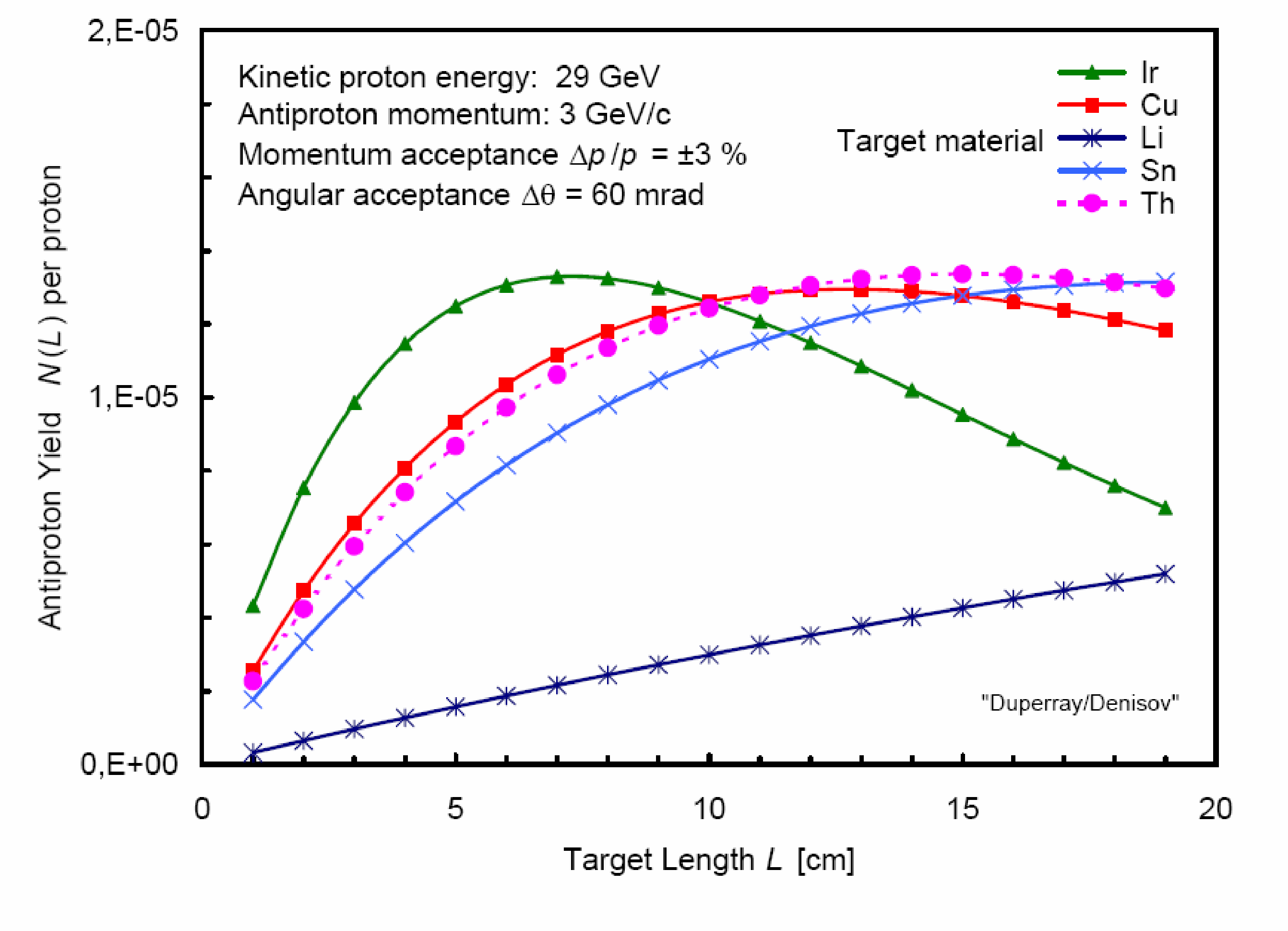
Kin. energy of pbars: 3 GeV

Acceptance:

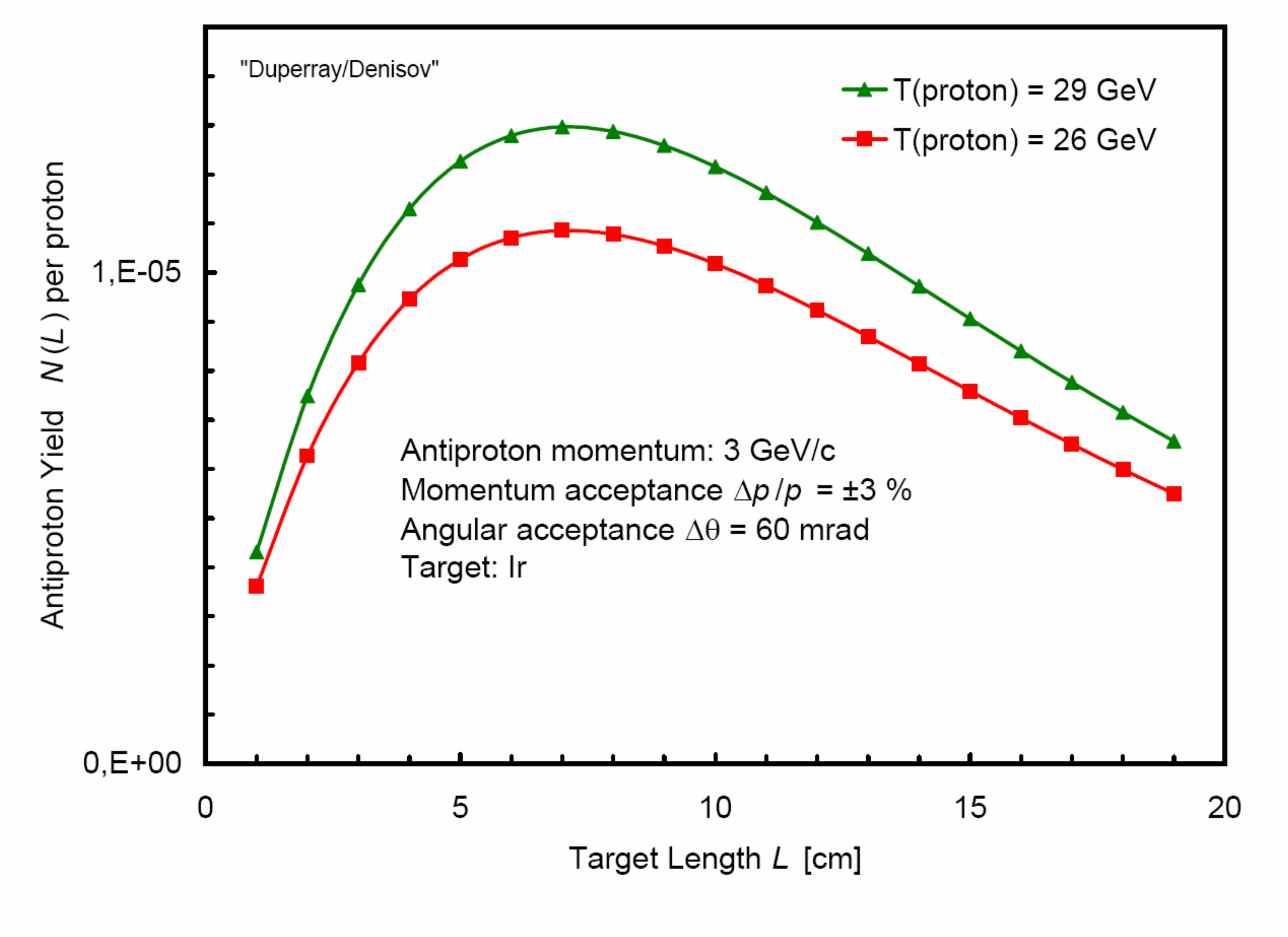
θ=100 mrad

$\Delta p/p$=6%

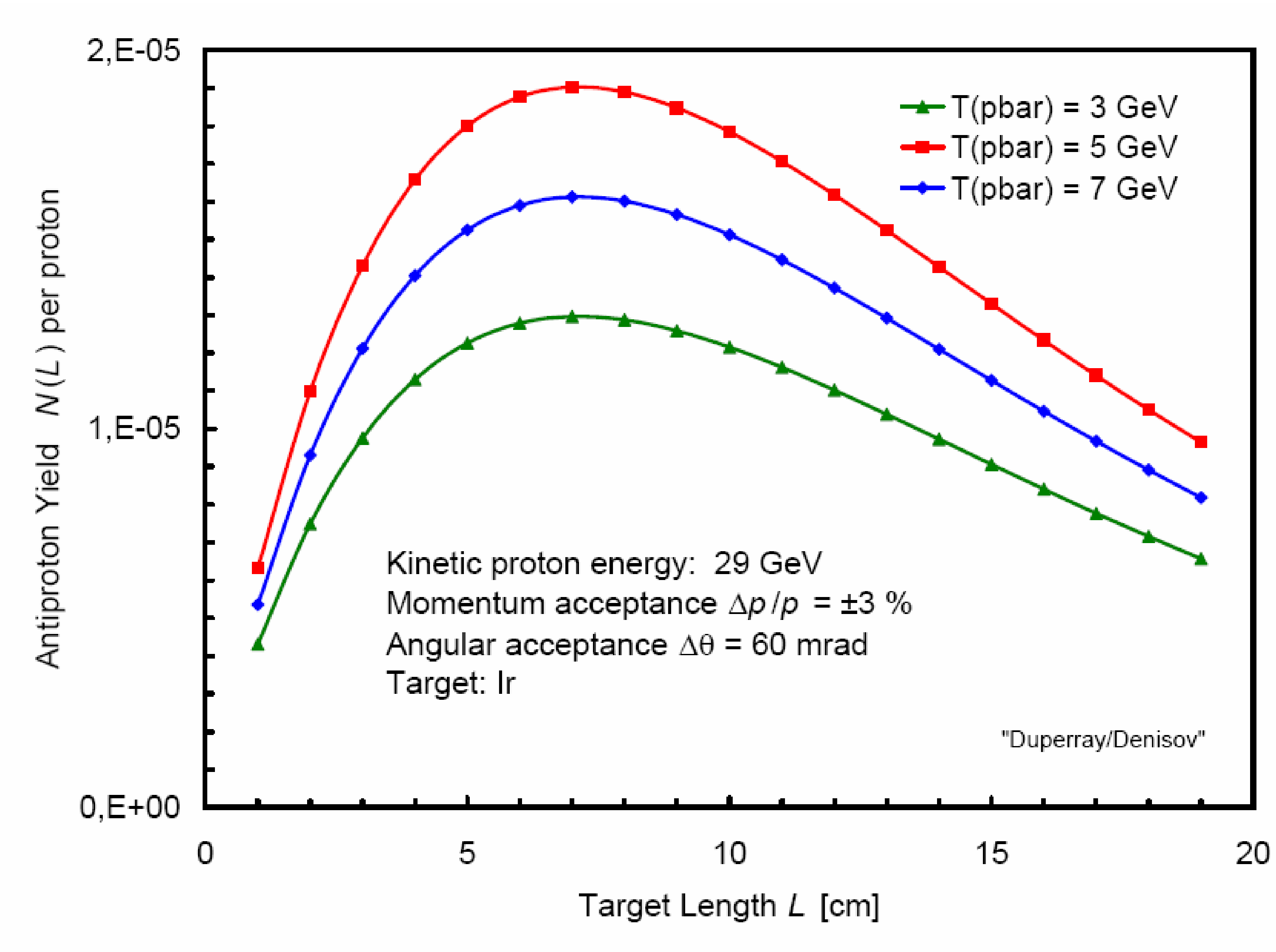
Antiproton Yield in Various Targets



Antiproton Yield at Different Proton Energies

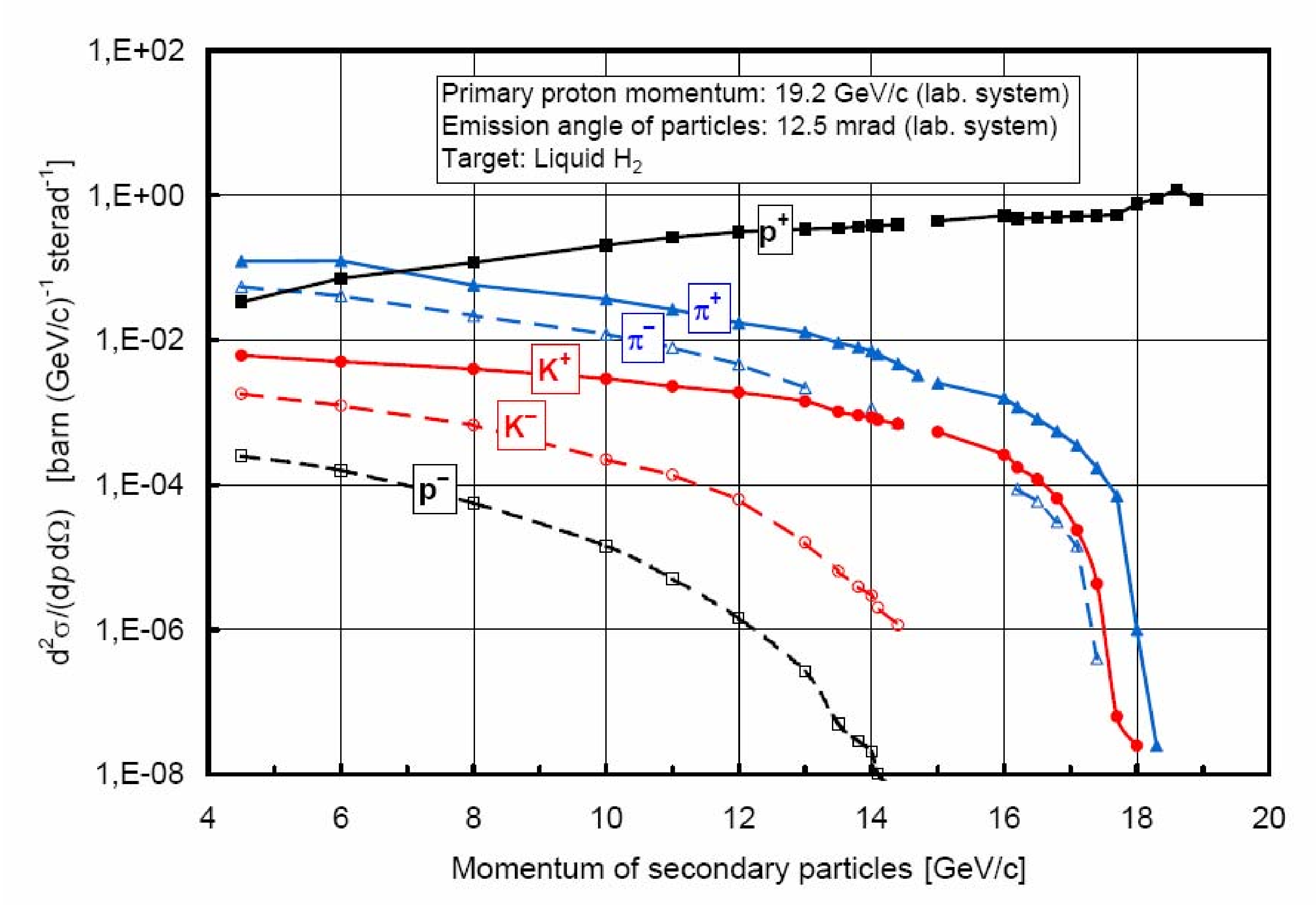


Antiproton Yield at Different pbar Momenta



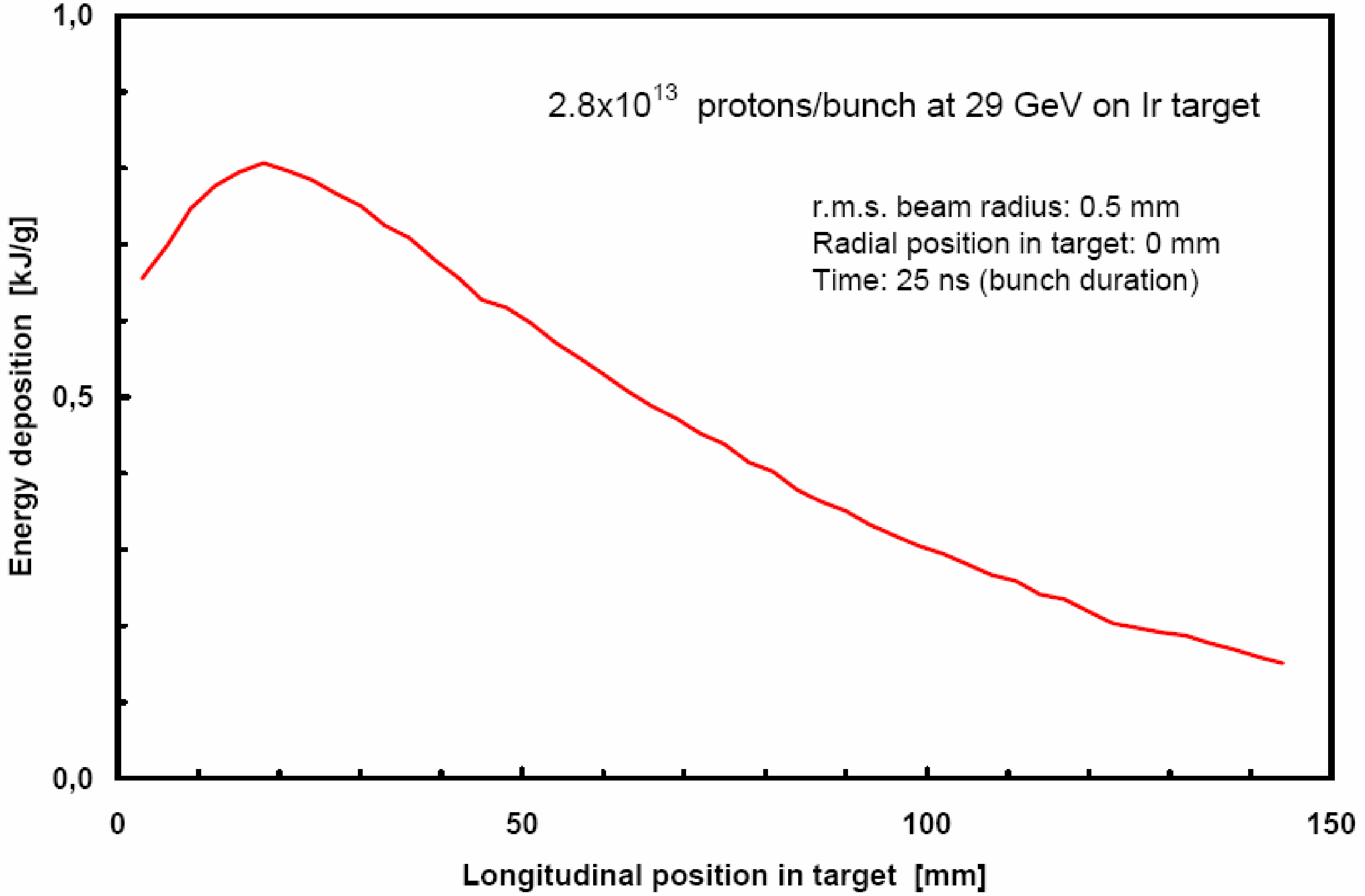
Meson Spectrum from p→p Collisions

(Allaby et al., 1970)



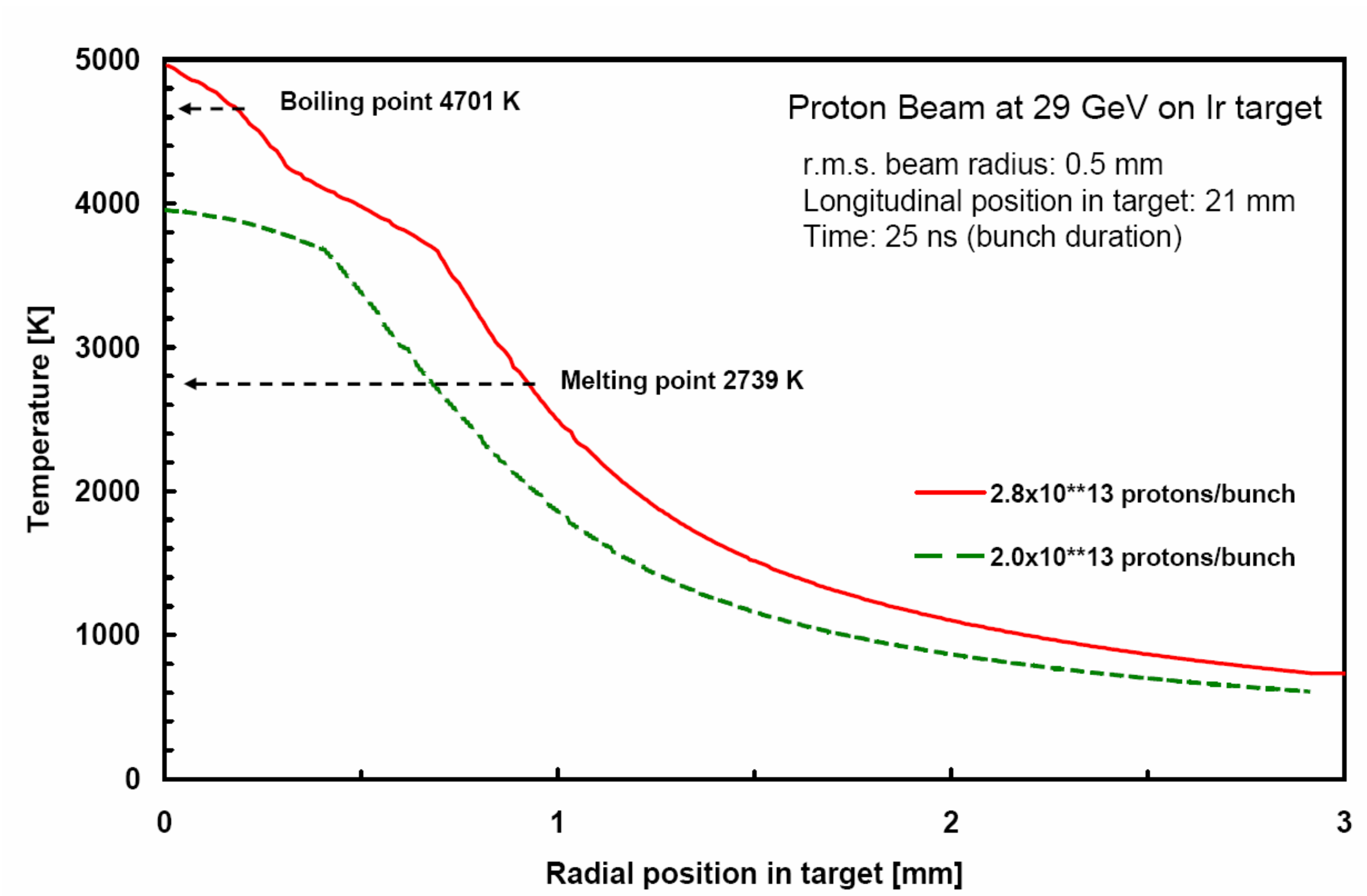
Energy Deposition in Ir Target

(by N. Tahir, Aug. 2006, from FLUKA-Output)



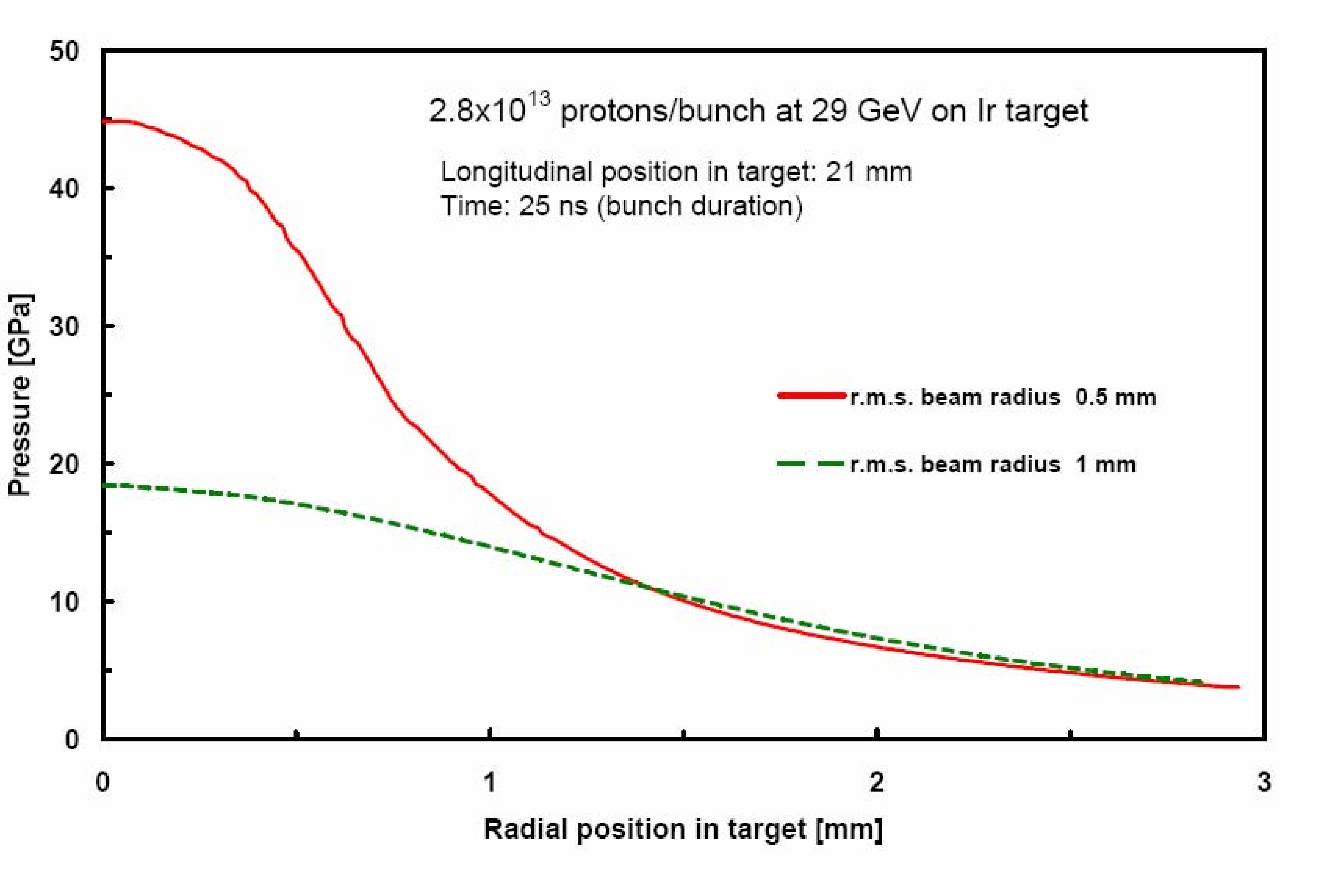
Temperature in Ir Target

(by N. Tahir, Aug. 2006, from FLUKA-Output)

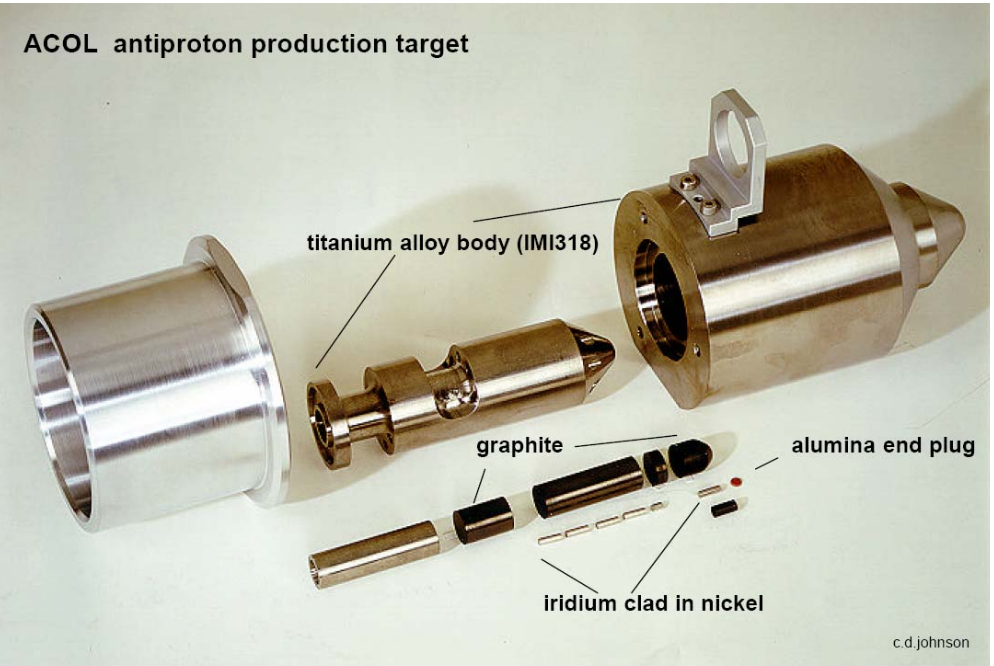


Pressure in Ir Target

(by N. Tahir, Aug. 2006, from FLUKA-Output)



Production Target : ACOL-Target for FAIR?



<u>Proposed</u>:

ACOL target for FAIR up to 50% p-intensity

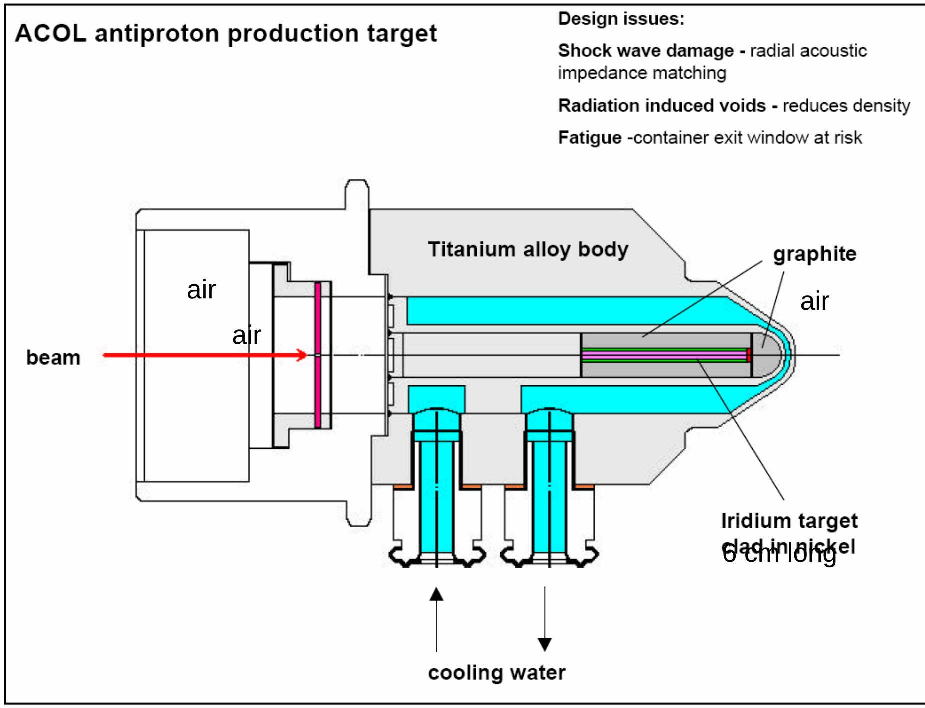
<u>Arguments</u>:

Should withstand beam period of 2-3 months

Simple construction

Not too expensive

Easy exchange (coolant connections only)



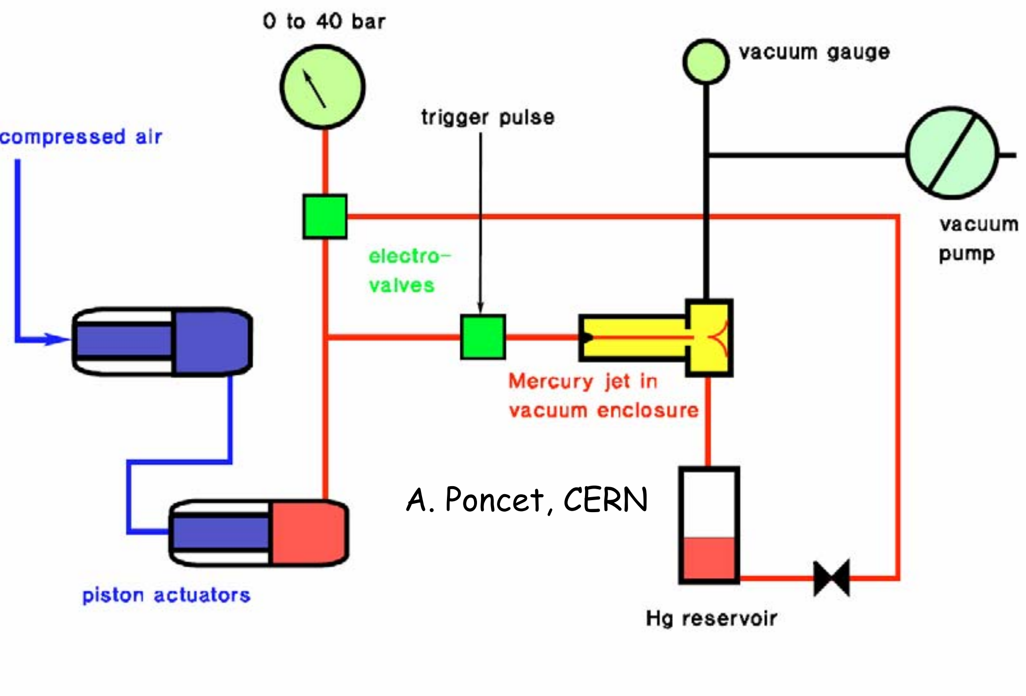
Design issues:

Shock wave damage - radial acoustic impedance matching

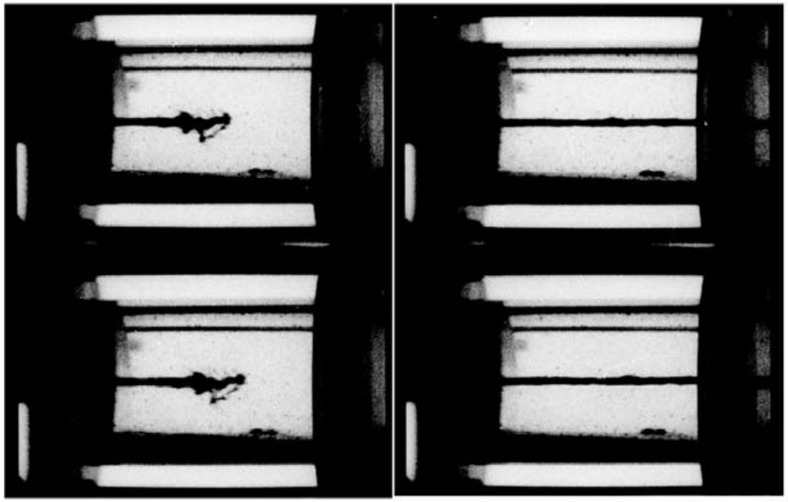
Radiation induced voids - reduces density

Fatigue -container exit window at risk

Production Target Upgrade: Liquid Metal Target?



Schematic diagram of the mercury jet target – laboratory test



High-speed photographs of mercury jet target for CERN-PS-AA (laboratory tests)

4,000 frames per second, Jet speed: 20 ms-1, diameter: 3 mm, Reynold's Number:>100,000

A. Poncet

Proposed

Liquid metal target for FAIR up to 100% p-intensity

Expectations

Should withstand beam periods up to 6 months

Constant target thickness

In situ cleaning from radio-active species possible

Combined function target/collection lens? (CERN)

Liquid target R&D

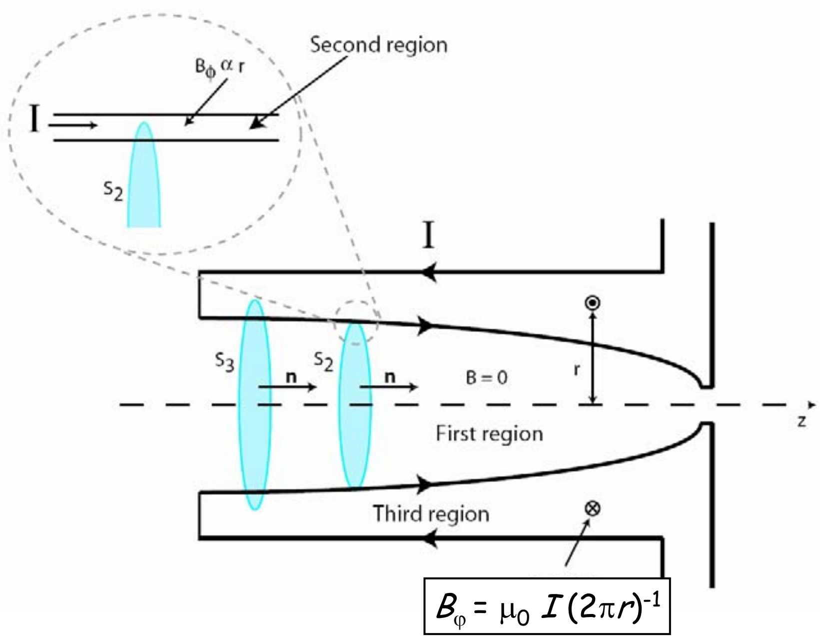
Li	SNS, ANL, FZK
Hg	CERN
Pb-Bi	BINP/Novosibirsk

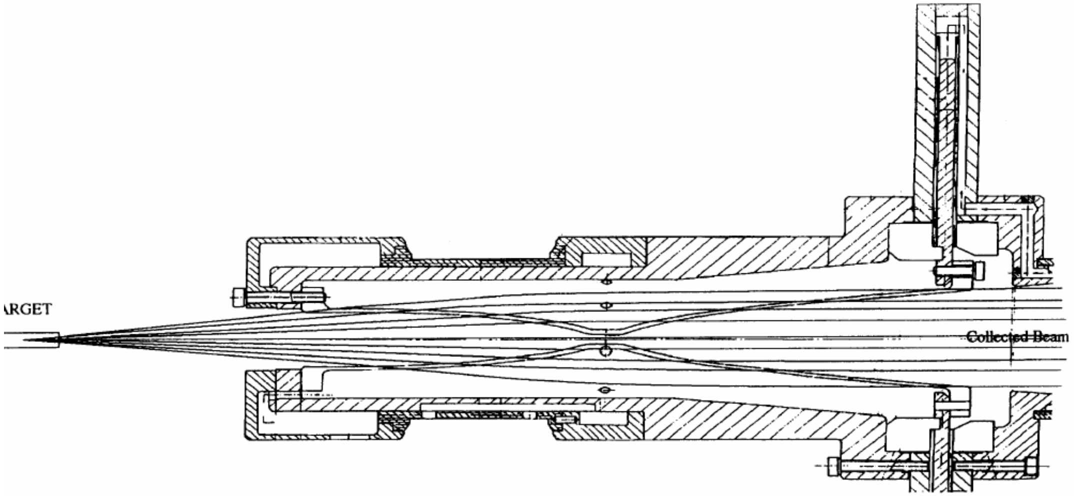
Cost estimate for Hg-target: 160 000 €

Investment for 2 units recommended

R&D necessary!

Collector: Magnetic Horn and (or?) Li-Lens





Proposed

Bi-conical ACOL-horn for FAIR (assembly drawing)

Operational parameters

Horn current	400 kA
Rise time	15 μs
Acceptance angle for pbars	82 mrad
Manufacturing costs per unit:	30 000 €

5 units recommended

(R. Maccaferri, CERN, private communication, July 2005)

Proposed upgrade for 100% proton intensity:

3cm ∅ Li-lens with 1 MA pulser

Operational parameters

Current	1 MA
Rise time	1 ms
Acceptance angle for pbars	95 mrad
Manufacturing costs per lens:	80 000 €

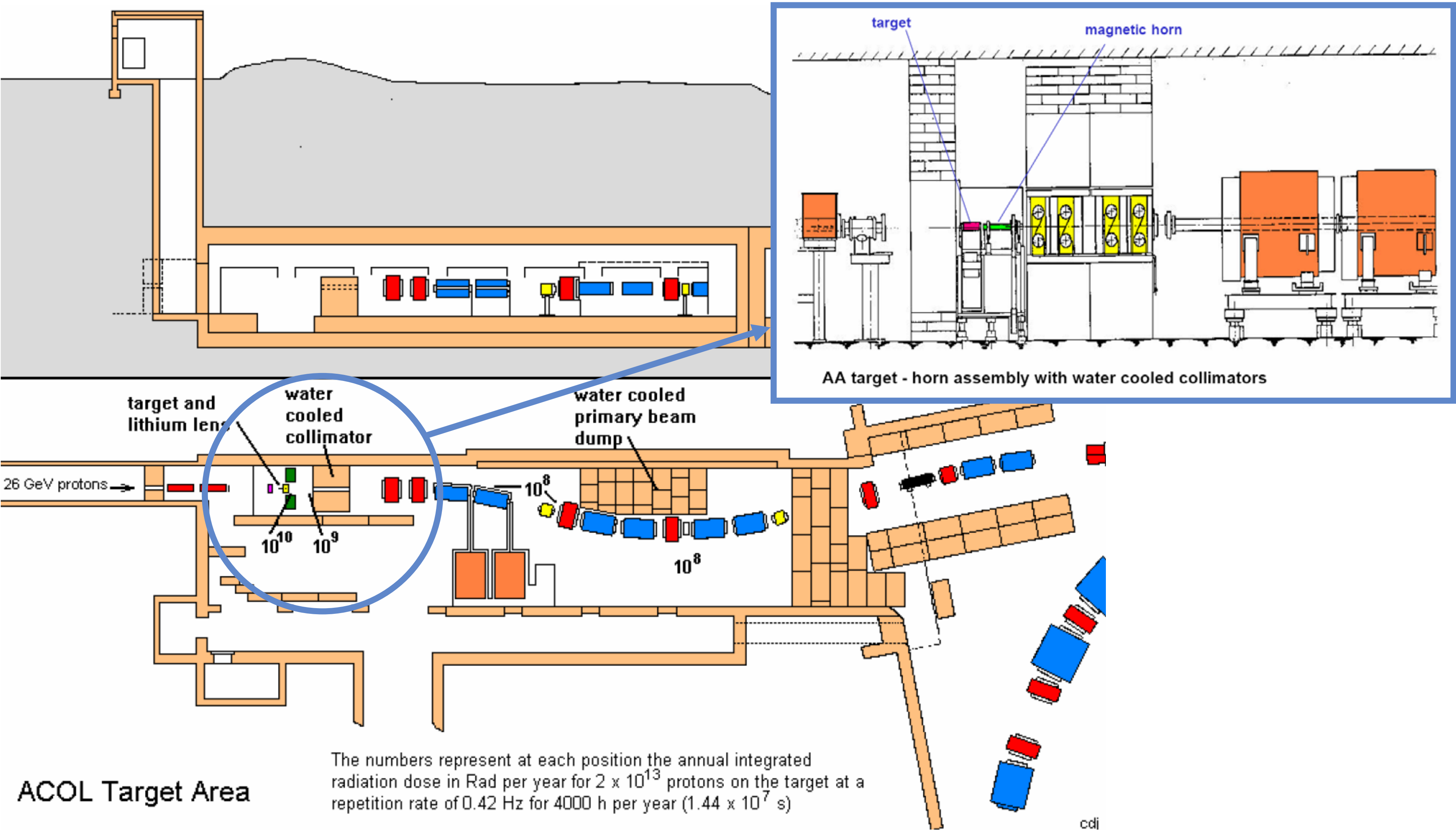
5 spare lenses recommended

(P. Sievers, CERN, private communication, July 2005)

1 MA pulser & transformer:	300 000 €

My own estimate!

Antiproton Source at CERN – Example for FAIR?



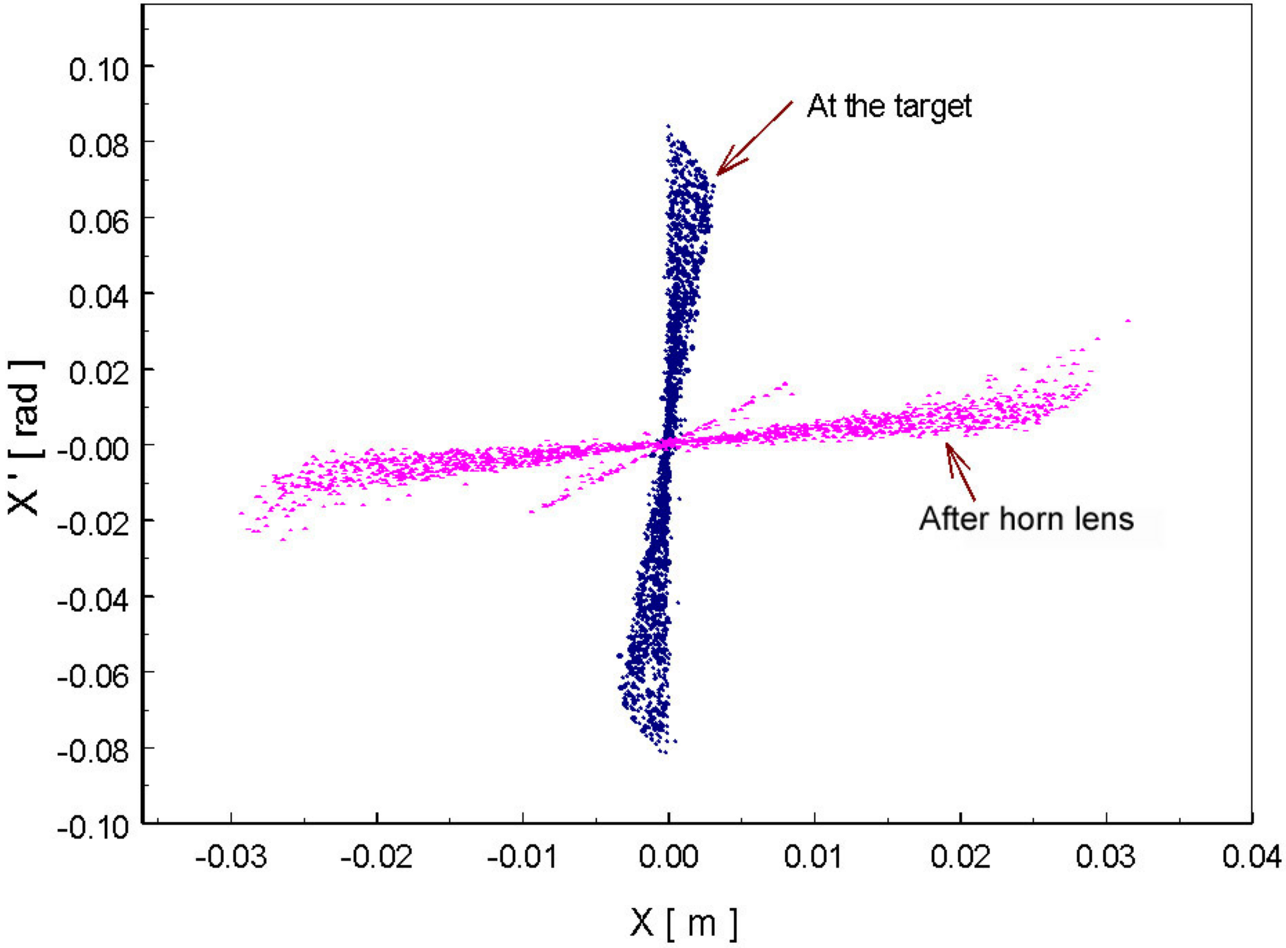
AA target - horn assembly with water cooled collimators

ACOL Target Area

The numbers represent at each position the annual integrated radiation dose in Rad per year for 2 x 10^{13} protons on the target at a repetition rate of 0.42 Hz for 4000 h per year (1.44 x 10^{7} s)

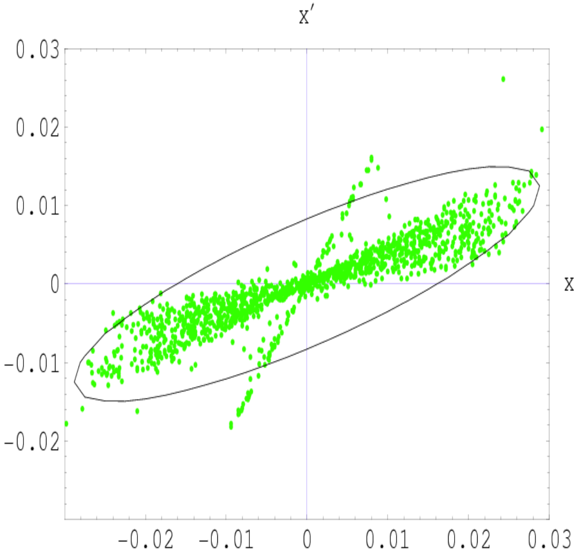
Distribution over Transverse Phase Planes

(MARS simulation by P. Shatunov, 2005)

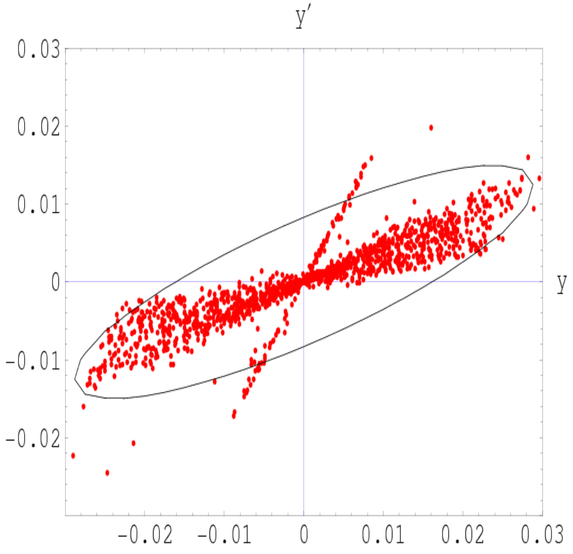


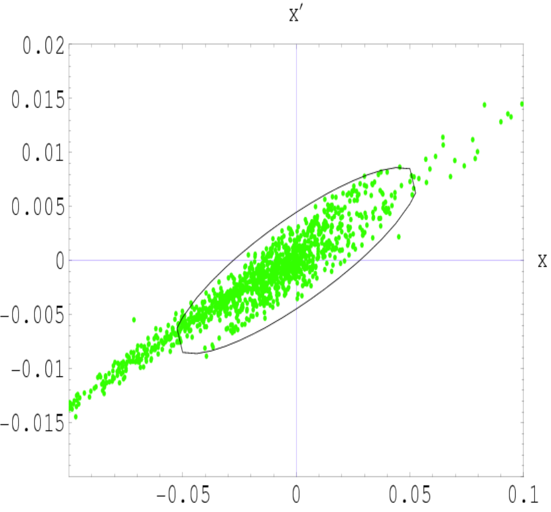
Transverse Matching to pbar Separator and CR

(by P. Shatunov, 2005)

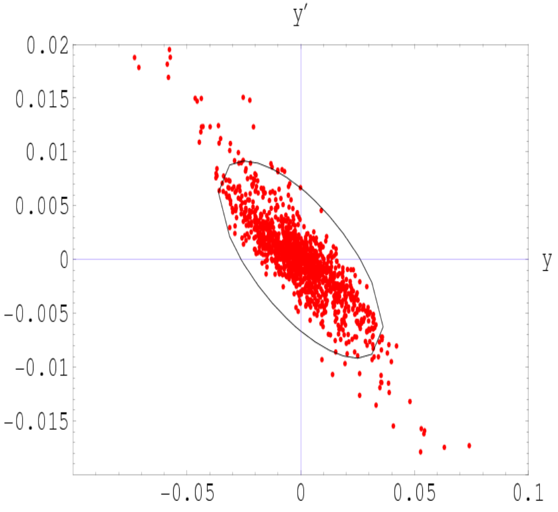


Separator
entrance





CR
injection



Potential for pbar Upgrades at FAIR

- Proton Linac
  - Later upgrade not possible (New linac for 200 MeV, 140 mA, costs about 60 M€)
- SIS18/SIS100
  - 1×10^{13} instead of 5×10^{12} per SIS18-cycle would reduce the cycle time for SIS100 from 3 s to 2 s. The space charge limit at 2 GeV is about 4×10^{13} !
- pbar Source
  - Optimization of target and collector (e.g. 10 T/cm Li-lense): up to 50%.
- pbar Separator
  - Careful corrections of chromaticity and other higher order effects: about 20%.
- CR
  - Upgrade of stochastic pre-cooling for the reduction of the cooling time by a factor of 3 should be possible. Probable costs about 5 M€.
- RESR
  - Stochastic accumulation in the RESR would have to be be upgraded accordingly. Probable costs about 10 M€.

Summary

We see potential for later upgrades of the pbar production rate at FAIR by up to a factor of 5 compared to that given in the FBTR, i. e. from 1.4×10^{7} s^{-1} to 7×10^{7} s^{-1}!

Probable costs 15 M€.

How this possible production upgrade can be transformed to a corresponding luminosity upgrade in HESR will not least depend on the technical design of this ring.