November 9th, 2010, JLab PEPPo Collaboration Meeting

Considerations for the Future Positron Capture Experiments

Yujong Kim

Department of Physics & Idaho Accelerator Center

Idaho State University, Pocatello, ID 83209, USA

Thomas Jefferson National Accelerator Facility

Newport News, VA 23606, USA

yjkim@isu.edu, http://www.isu.edu/~yjkim

ISU-JLAB-2010-009

Outline

- Acknowledgements
- Required Positron Beams for CEBAF
- Electron Beam Energies (10 MeV or 126 MeV)
- Characteristics of Positron Beams generated by 10 MeV Electron Beams
  - Large Angle, Large Energy Spread, and Long Bunch Length
- Quadrupole Triplet or Solenoid for Initial Positron Capture
- Performance of Solenoid Based Initial Positron Capture
- Optional Chicane, Bunch Compressor, and Energy Compression System.
- Possible Layouts for Future Positron Capture Experiments - Temporary
- Plans for Capture Experiments at Idaho State University
- Summary

Acknowledgements

Yujong Kim gives his sincere thanks to

Dr. J. Grames, Dr. A. Freyberger, Dr. S. Golge, Dr. M. Poelker, Dr. H. Areti, Dr. A. Hutton of Jefferson Laboratory.

Prof. T. Forest, Prof. A. Hunt, Prof. D. Wells, Prof. D. Dale of Idaho State University.

In addition to my former supervisors who had worked for position sources (Dr. K. Floettmann of DESY and Dr. H. Braun of PSI).

for their encouragements and valuable discussions.

Required Positron Beams for CEBAF

- At the CEBAF injection point, e^+ beams should have following parameters:

- geometrical emittance $\leq$ 5 μm
- normalized emittance $\leq$ 665 μm @ 68 MeV
- absolute energy spread $\leq$ 1 MeV ($\sigma_\delta \leq$ 14.7% @ 68 MeV)
- energy at the end of injector ~ 68 MeV
- beam current $\geq$ 50 nA (100 nA ?)
- bunch length $\leq$ 2 ps
- duty factor = 100%
- frequency = 1.497 GHz (or sub-harmonic)

A. Freyberger, JPOS2009

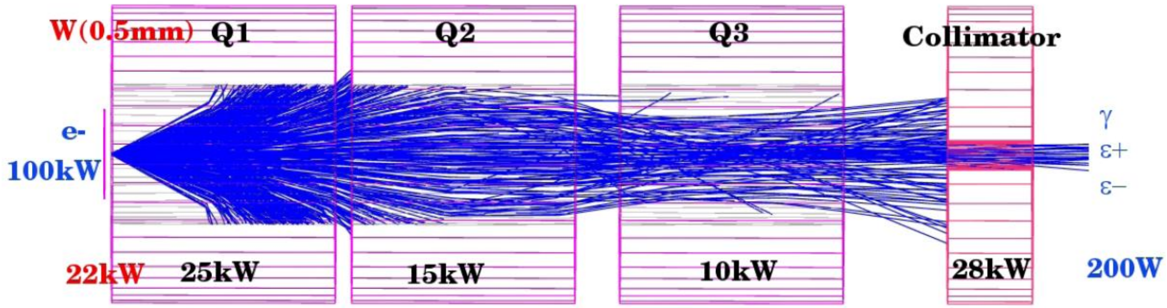
Electron Beam Energy for Experiments

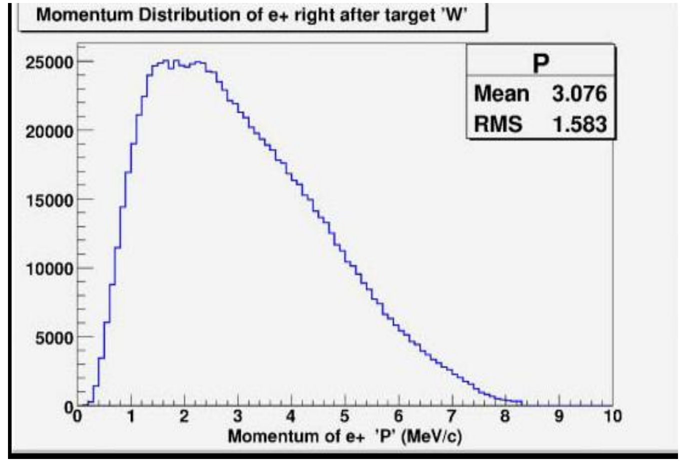
It seems that we may get a sufficient positron current (~ 100 nA) by shooting 10 mA, 120 MeV (or 1 mA, 1 GeV) electron beams on the tungsten target. But if we consider a much higher radiation, much higher power deposition on the target, much higher energy spread after the target, it will be better for us to choose the lower energies.

If we choose low energy electron beams (10 mA, 10 MeV), the angular divergence becomes higher and the positron current becomes lower. But after considering available accelerators at IAC and JLab, it will be better for us to choose 10 MeV for the future positron capture experiments. 10 MeV electron beams will be also helpful to relax the heat power deposition at the W target.

10 mA, 10 MeV e⁻ based Positron Beam Source

S. Golge *et. al.*, Proc. PAC2007 issue : high angular divergence and low positron current

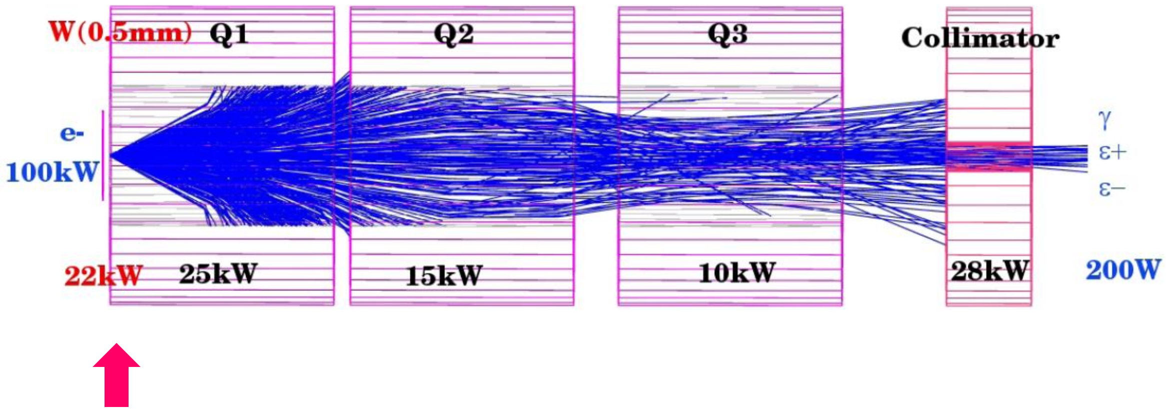


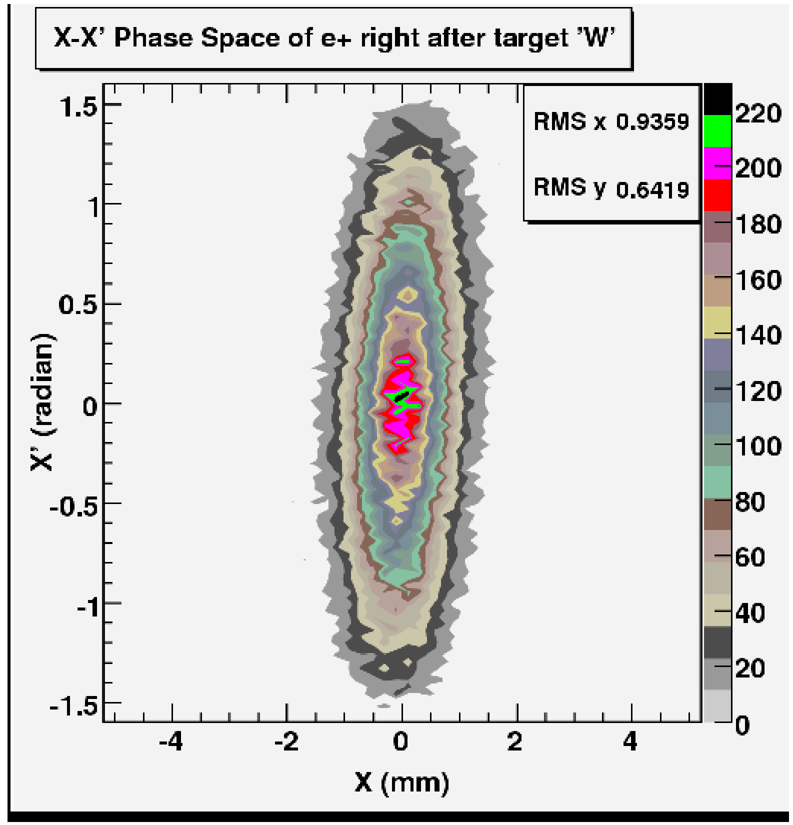


electron average current : 10 mA
electron energy = 10 MeV
electron geometrical emittance < 1 μm @ 10 MeV (?)
target = tungsten (W) with a thickness of 500 μm
power deposition on target : 20% of electron beam power = 0.2× 10 mA × 10 MV = 20 kW
positron yield = 6×10^{-4} (e+/e-) @ 3.076 MeV, 500 μm thick W target
positron geometrical emittanc after the target ≥ 200 μm (?)
positron mean energy = 3.076 MeV
positron rms relative energy spread = (1.583/3.076)×100 = 52%
positron current within CEBAF admittance ~ 20 nA
issue : high angular divergence, high energy spread, and low positron current

10 mA, 10 MeV e^- based Positron Beam Source

S. Golge *et. al.*, Proc. PAC2007





Positron Beams @ Right after W target

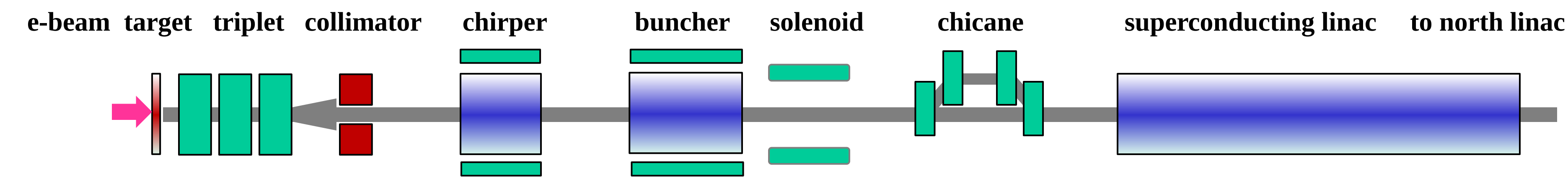
- rms beam size (σ_x) ~ 0.9359 mm
- rms angle ($\sigma_{x'}$) ~ 0.6419 radian
- rms relative energy spread σ_δ ~ 51.4%

For this study, in addition, we assumed followings:

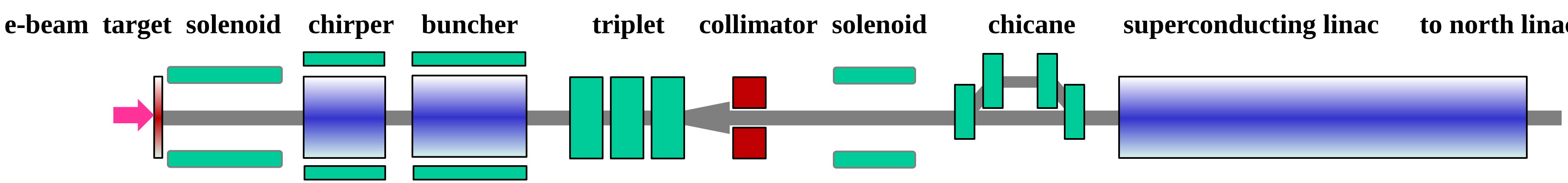
- positron normalized rms emittance ~ 602 μm
- positron bunch length ~ 2000 ps (FW), or 333 ps (rms) = 99.9 mm for 1 ps (rms) long e-
- Twiss parameters after target ($\alpha_{x,y}$ ~ -5.92, $\beta_{x,y}$ ~ 0.00876 m)

Triplet or Solenoid for Initial Positron Capture

It seems that solenoid has more operational freedom (quarter wave transformer and symmetric focusing) and have more bigger acceptance with a wider aperture to capture positron beams right after tungsten target. But we may test both quadrupole triplet and solenoid for the initial positron capture experiments.



Triplet based Initial Positron Capture*



Solenoid based Initial Positron Capture*

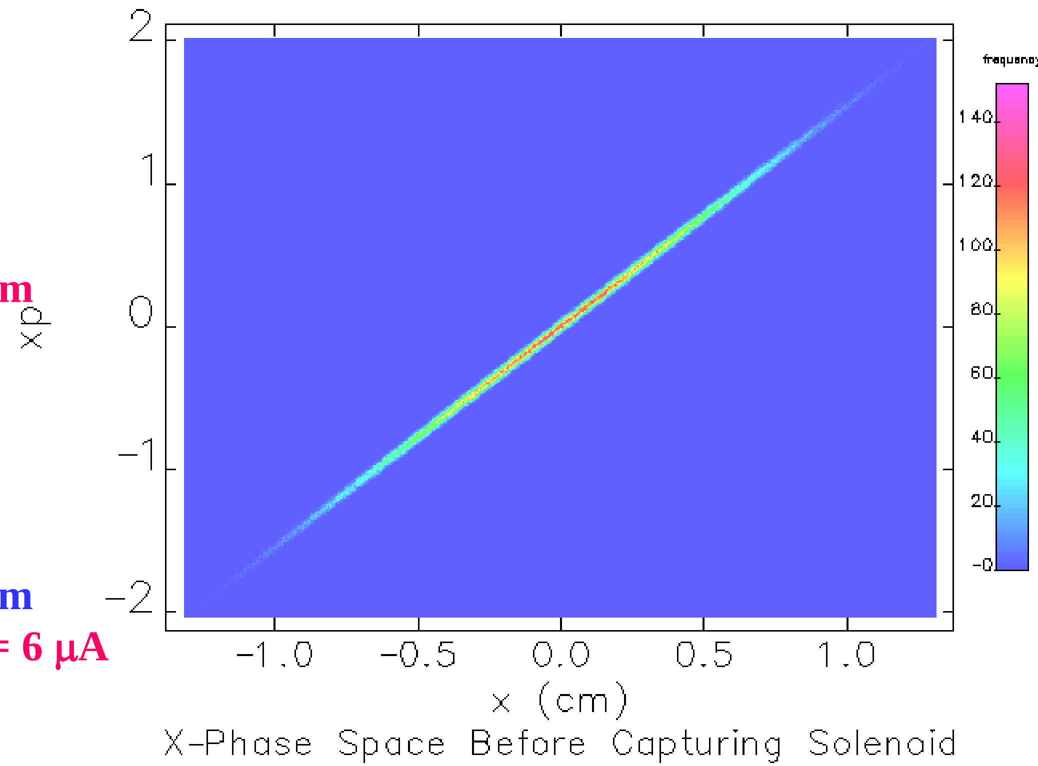
* note that these are not fixed layouts.

Performance of Positron Capture with Solenoid

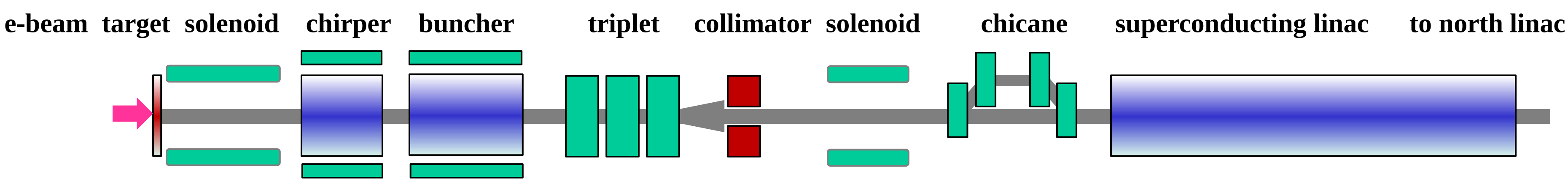
ELEGANT code simulations to check capturing performance of a solenoid. Tracking & scanning region: from right after a tungsten target to right before a chirper with following conditions:

Positron Beams @ Right after W target

- rms beam size (σ_x) ~ 0.9359 mm
- rms angle ($\sigma_{x'}$) ~ 0.6419 radian
- rms relative energy spread σ_δ ~ 51.4%
- positron normalized rms emittance ~ 602 μm
- rms positron bunch length = 99.9 mm
- $\alpha_{x,y}$ ~ -5.92
- $\beta_{x,y}$ ~ 0.00876 m
- pure solenoid length ~ 4 cm
- inner diameter of beampipe = 36.1 mm
- distance between target and solenoid = 5 mm
- positron single bunch charge = 12 fC, → I = 6 μA



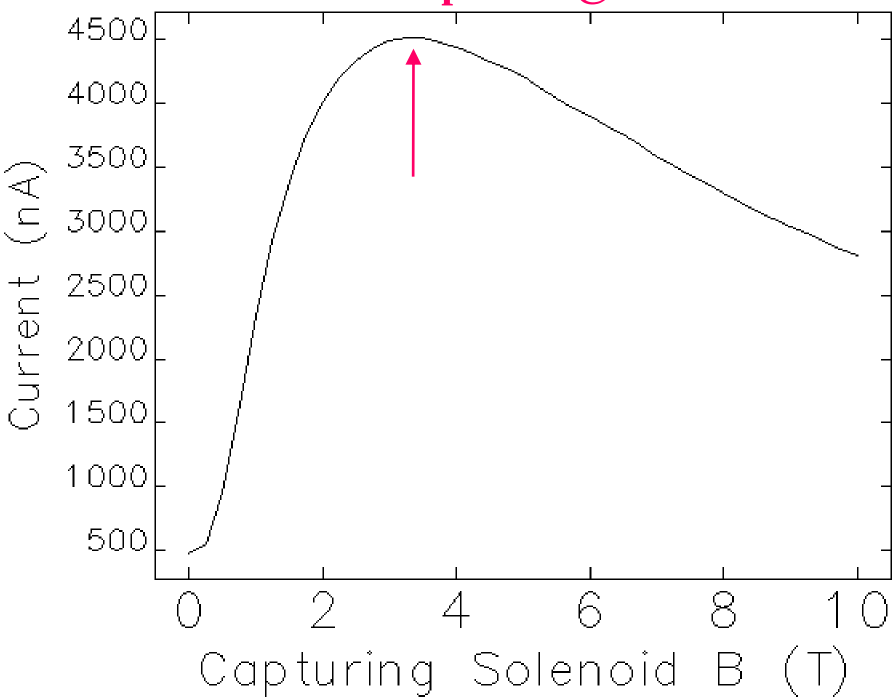
X-Phase Space Before Capturing Solenoid



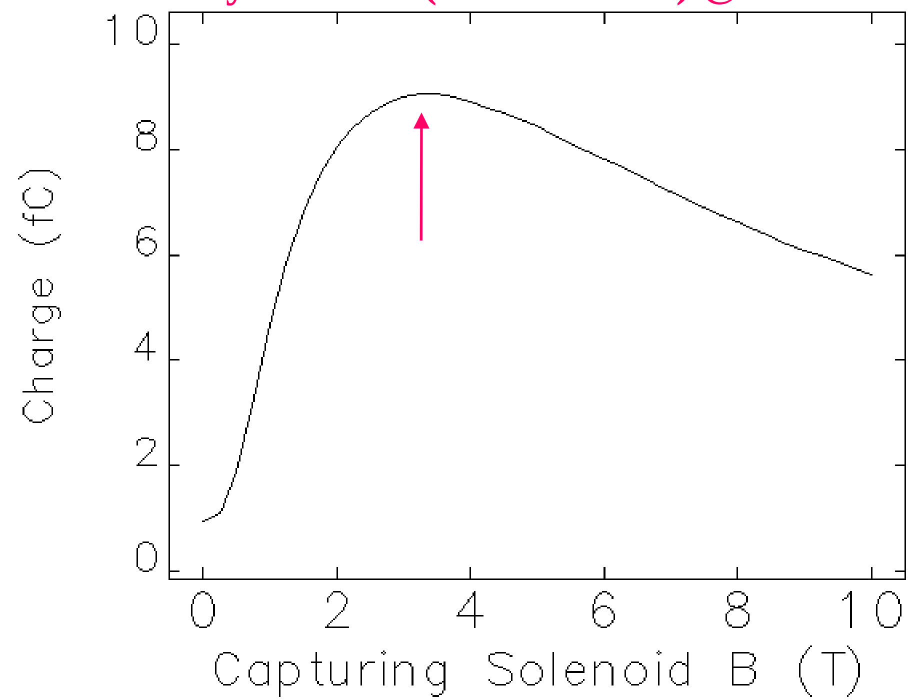
Performance of Positron Capture with Solenoid

ELEGANT code simulation on solenoid field scanning (0 - 10 T) to check capturing efficiency.

4500 nA captured @ *B* ~ 3.5 T



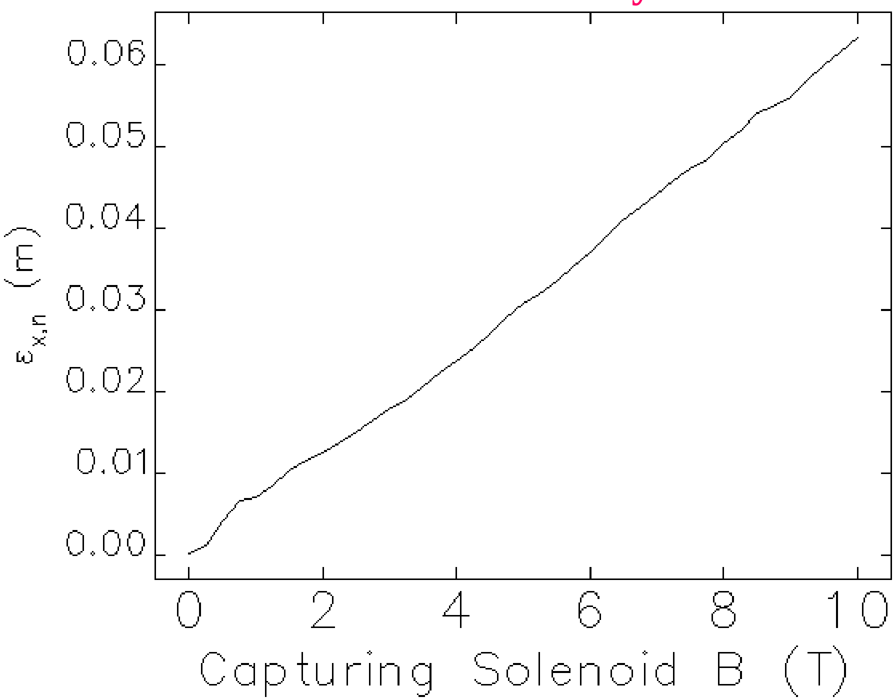
only 3 fC loss (12 fC → 9 fC) @ *B* ~ 3.5 T



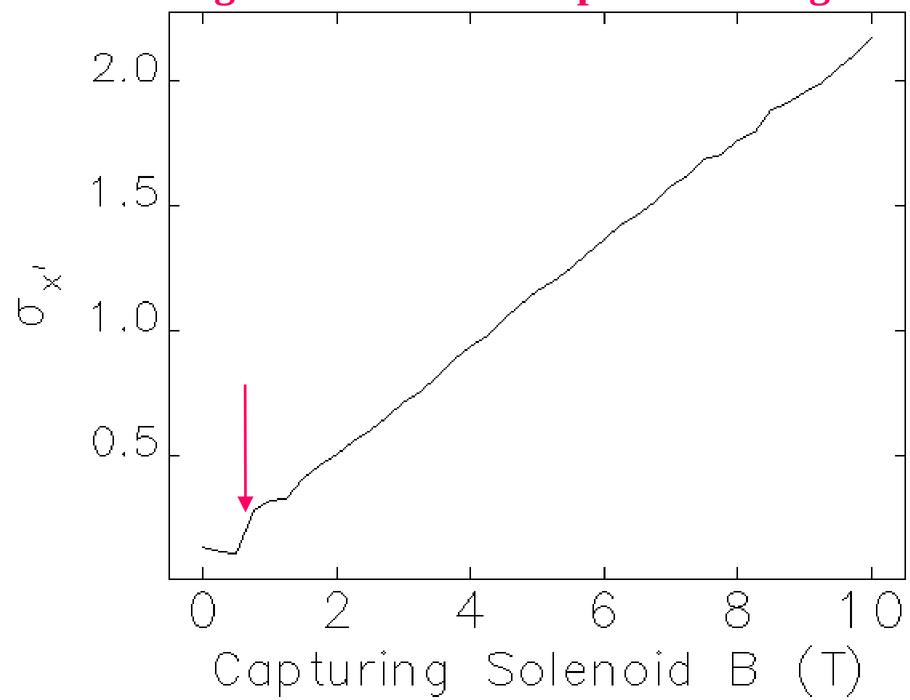
Performance of Positron Capture with Solenoid

ELEGANT code simulation on solenoid field scanning (0 - 10 T) to check capturing efficiency.

emittance is continuously increased.



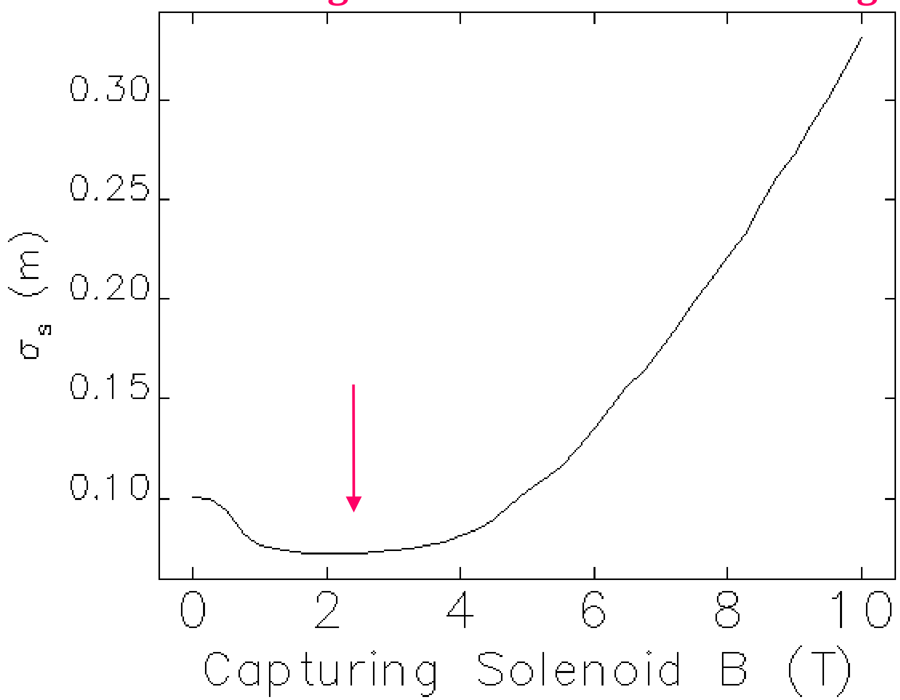
angle is increased except a low *B* region



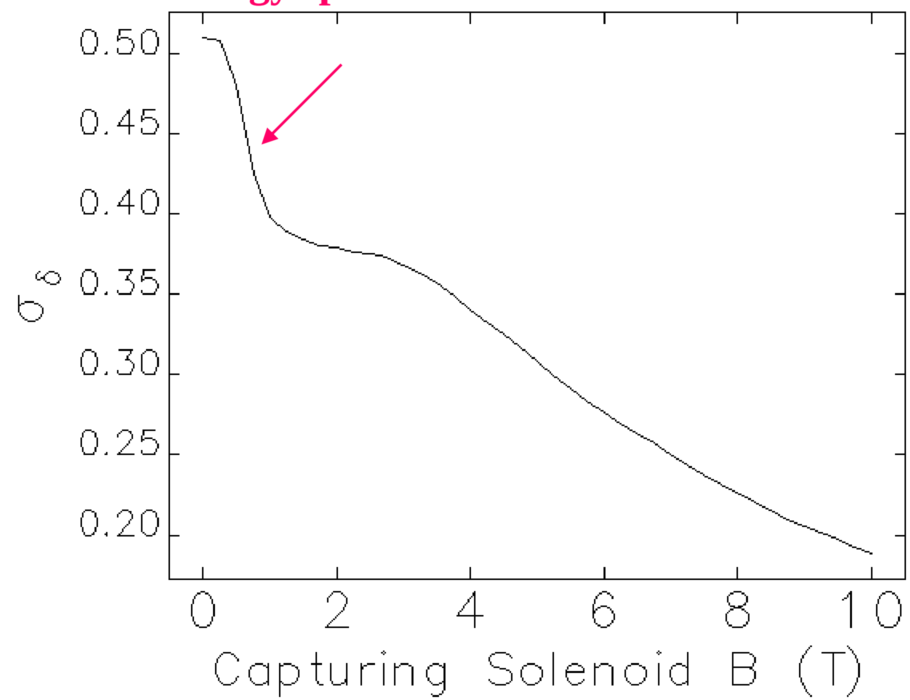
Performance of Positron Capture with Solenoid

ELEGANT code simulation on solenoid field scanning (0 - 10 T) to check capturing efficiency.

bunch length is decreased at a low *B* region



energy spread is decreased at *B* ~ 0.085 T

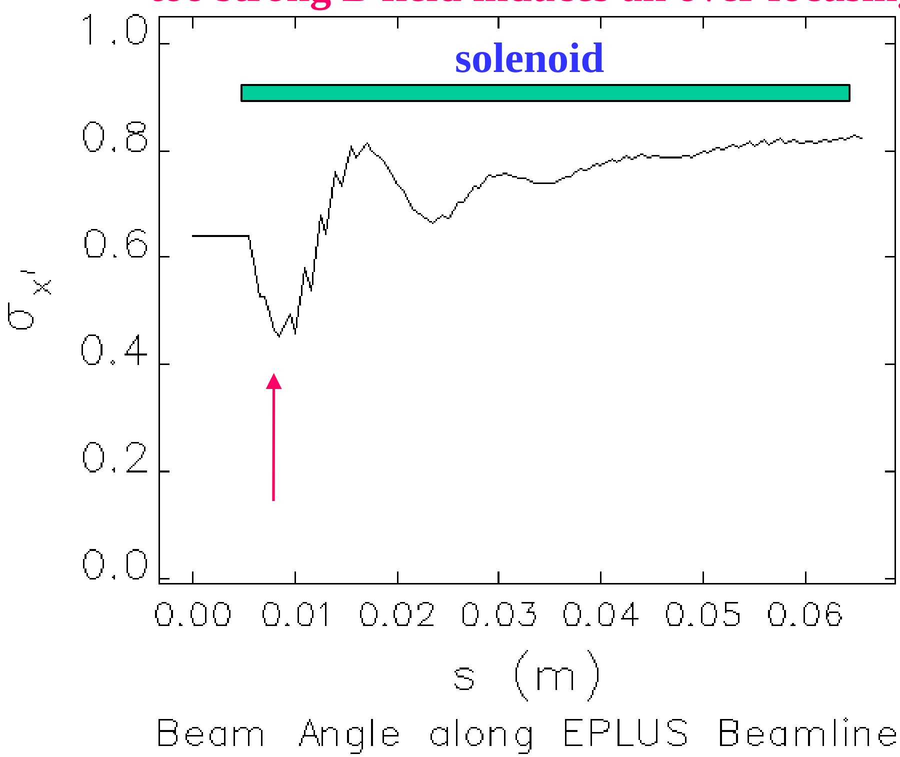


Let's check two special points (*B* ~ 3.5 T & *B* ~ 0.085 T) by ELEGANT tracking.

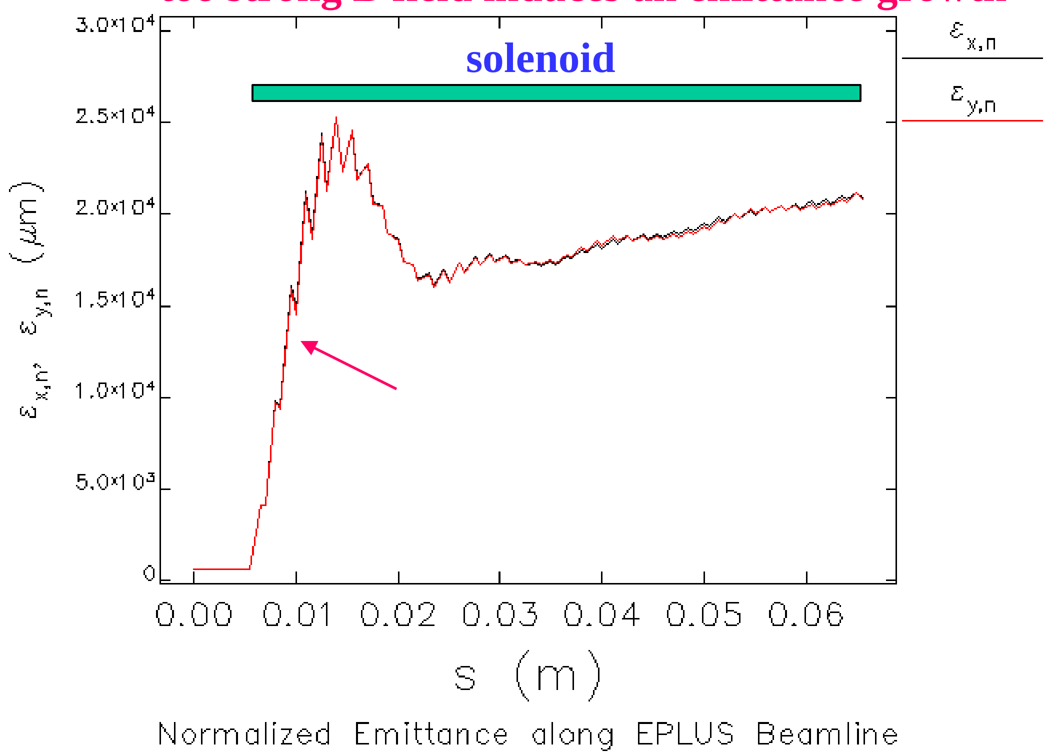
Performance of Positron Capture with Solenoid

ELEGANT code tracking with *B* = 0.35 T to check capturing efficiency.

too strong B field induces an over focusing



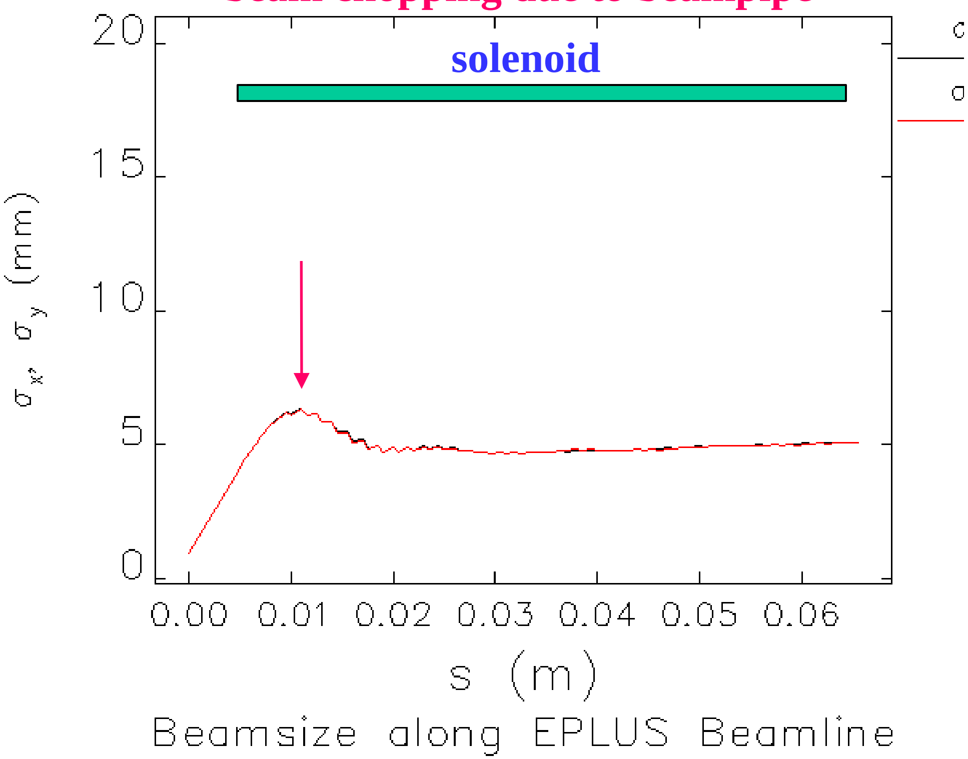
too strong B field induces an emittance growth



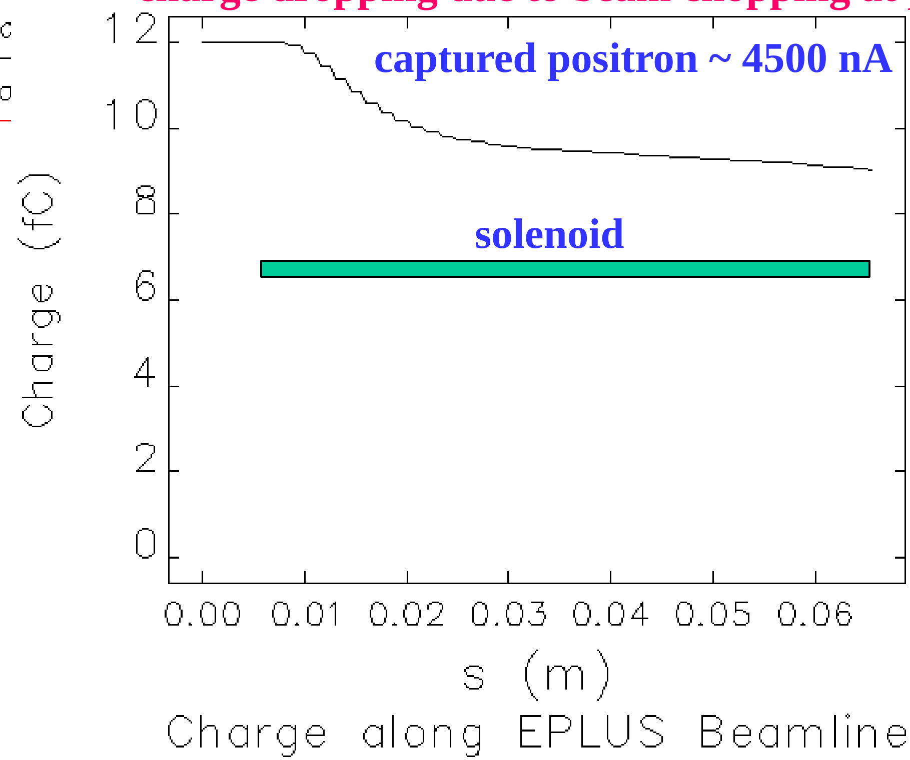
Performance of Positron Capture with Solenoid

ELEGANT code tracking with B = 0.35 T to check capturing efficiency.

beam chopping due to beampipe



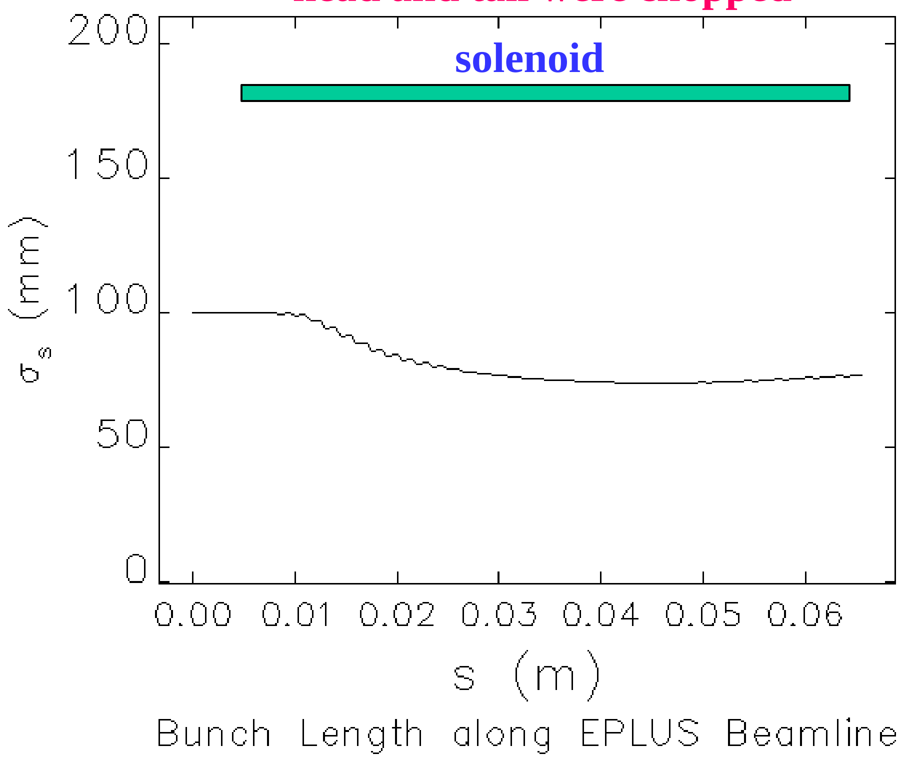
charge dropping due to beam chopping at pipe



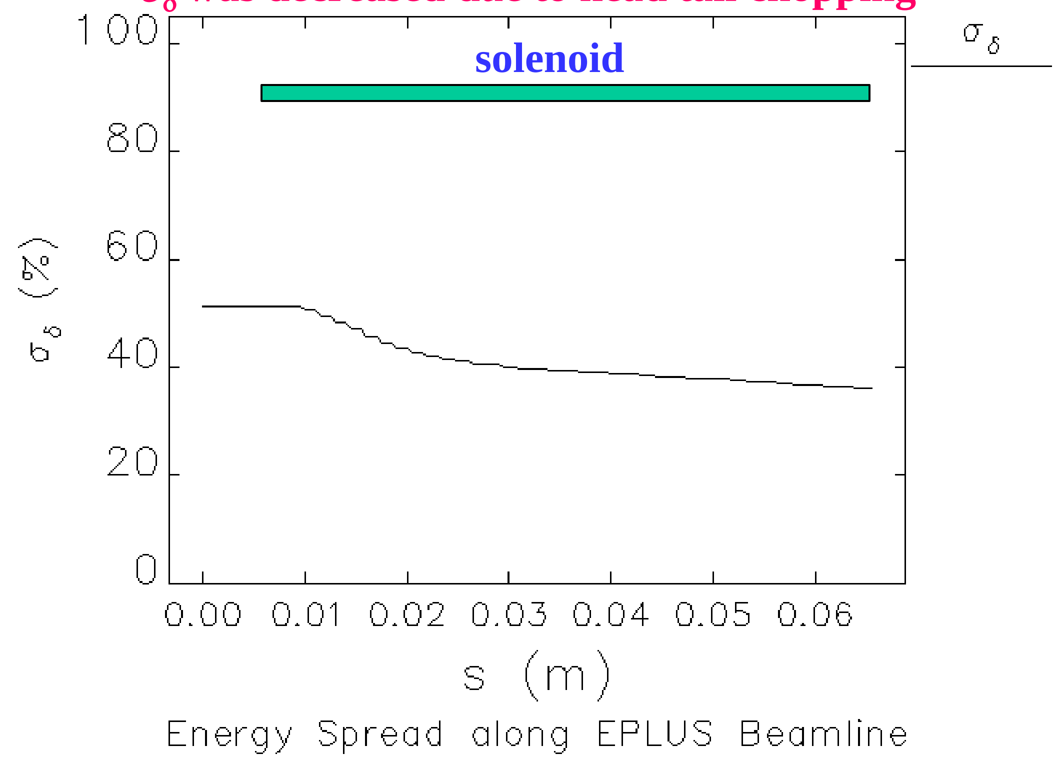
Performance of Positron Capture with Solenoid

ELEGANT code tracking with *B* = 0.35 T to check capturing efficiency.
→ *B* = 0.35 T gives a longitudinal chopping such as Quadrupole Triplet.

head and tail were chopped

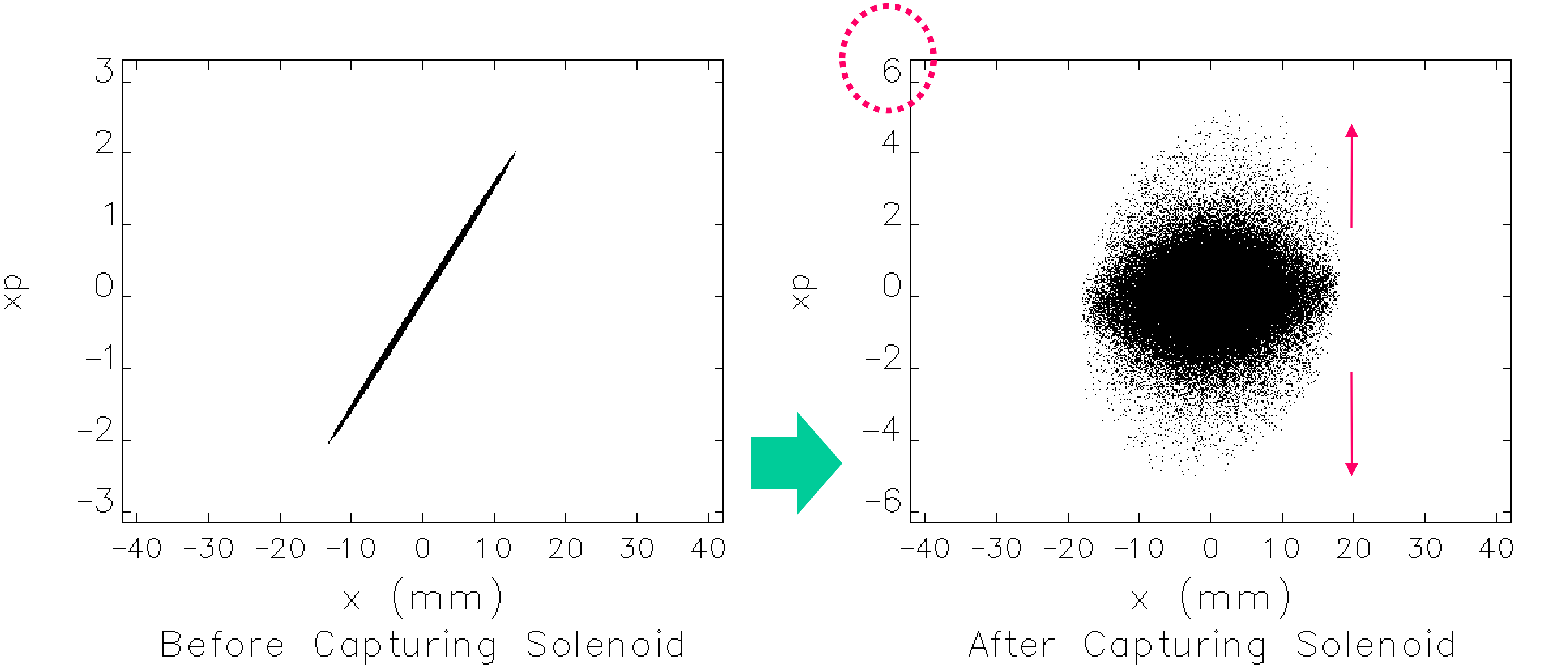


σ_δ was decreased due to head tail chopping



Performance of Positron Capture with Solenoid

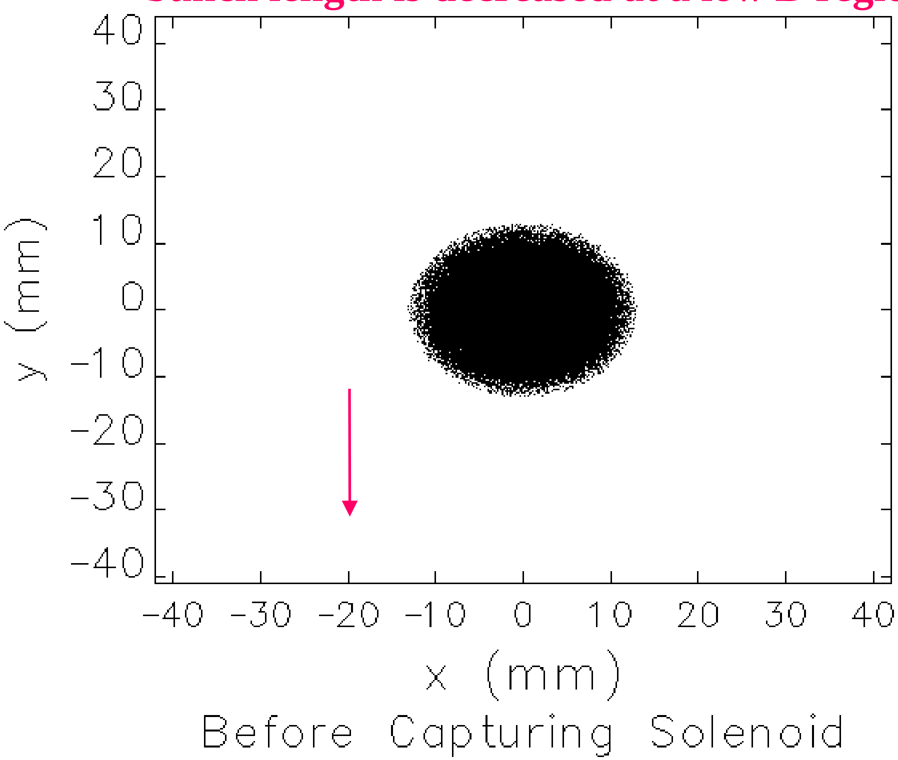
ELEGANT code tracking with B = 0.35 T to check capturing efficiency.
Over-focusing gives a big angle growth after the solenoid!
This can be a problem due to too strong overfocusing at the downstream of the solenoid. This is similar to quadruple triplet case.



Performance of Positron Capture with Solenoid

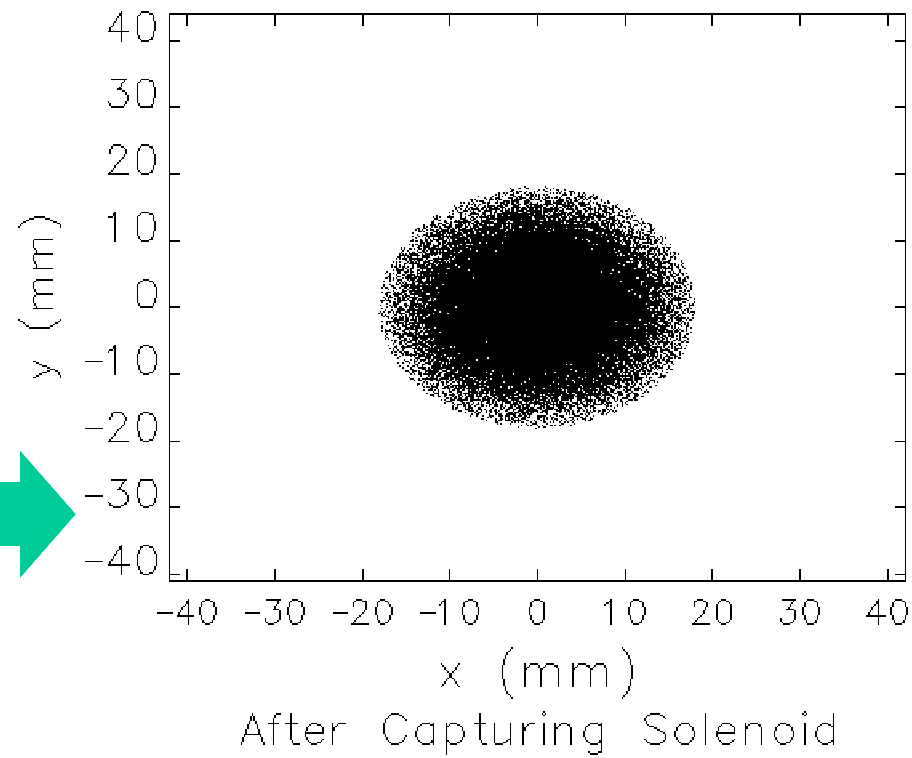
ELEGANT code tracking with *B* = 0.35 T to check capturing efficiency.

bunch length is decreased at a low *B* region



beam diameter = 36.1 mm = beampipe ID

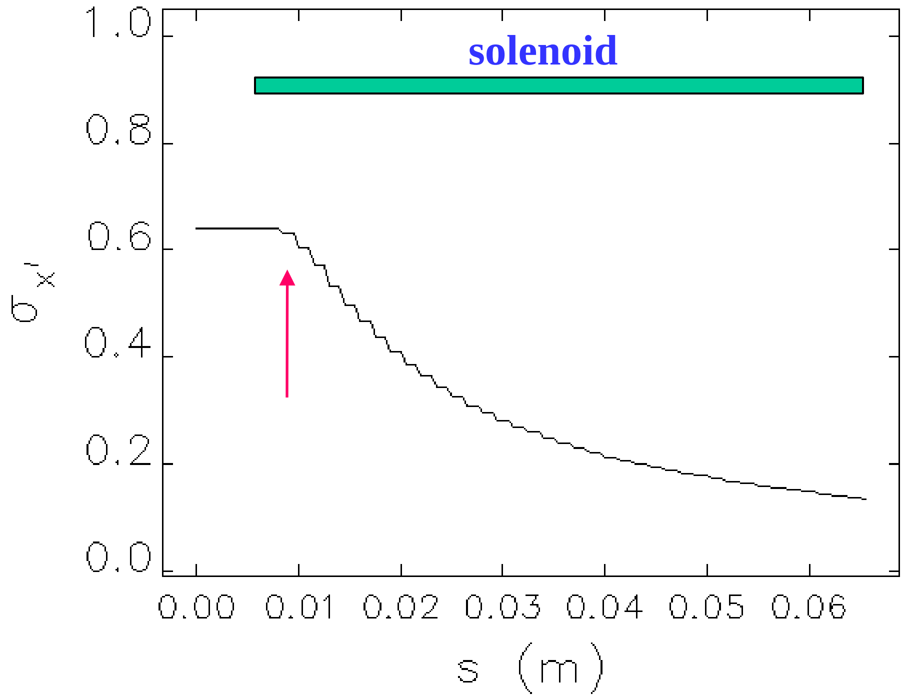
but non-uniform beam



Performance of Positron Capture with Solenoid

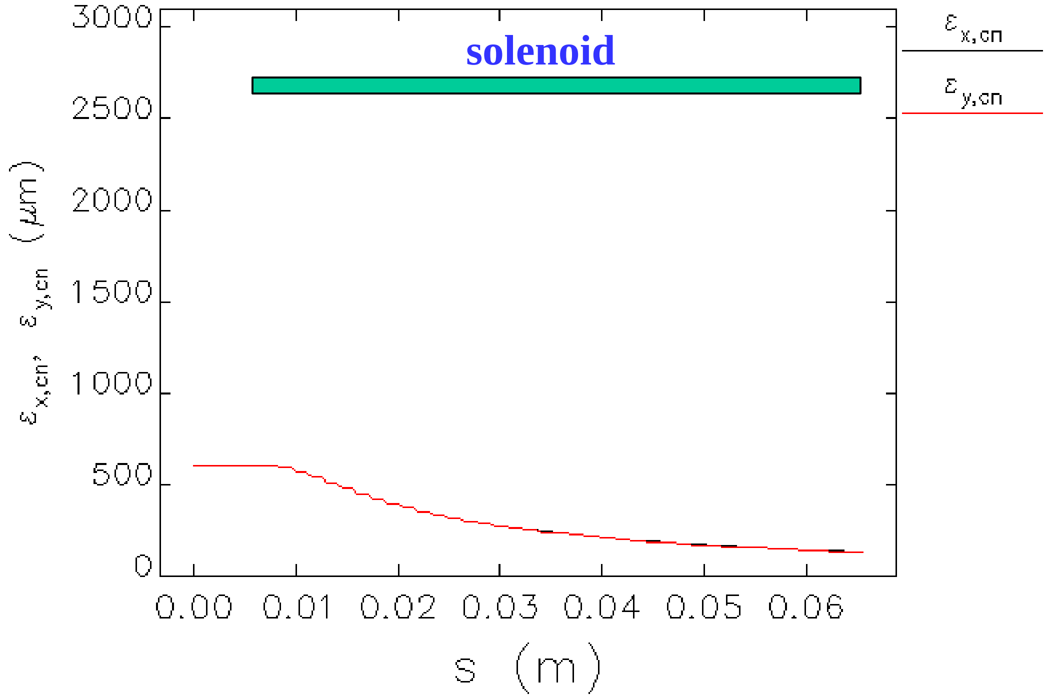
ELEGANT code tracking with B = 0.085 T to check capturing efficiency.
B = 0.085 T gives a continuous transverse chopping, which is a good balance between beam divergence and solenoid focusing.

proper focusing gives a continuous angle decreasing due to beam transverse chopping



Beam Angle along EPLUS Beamline

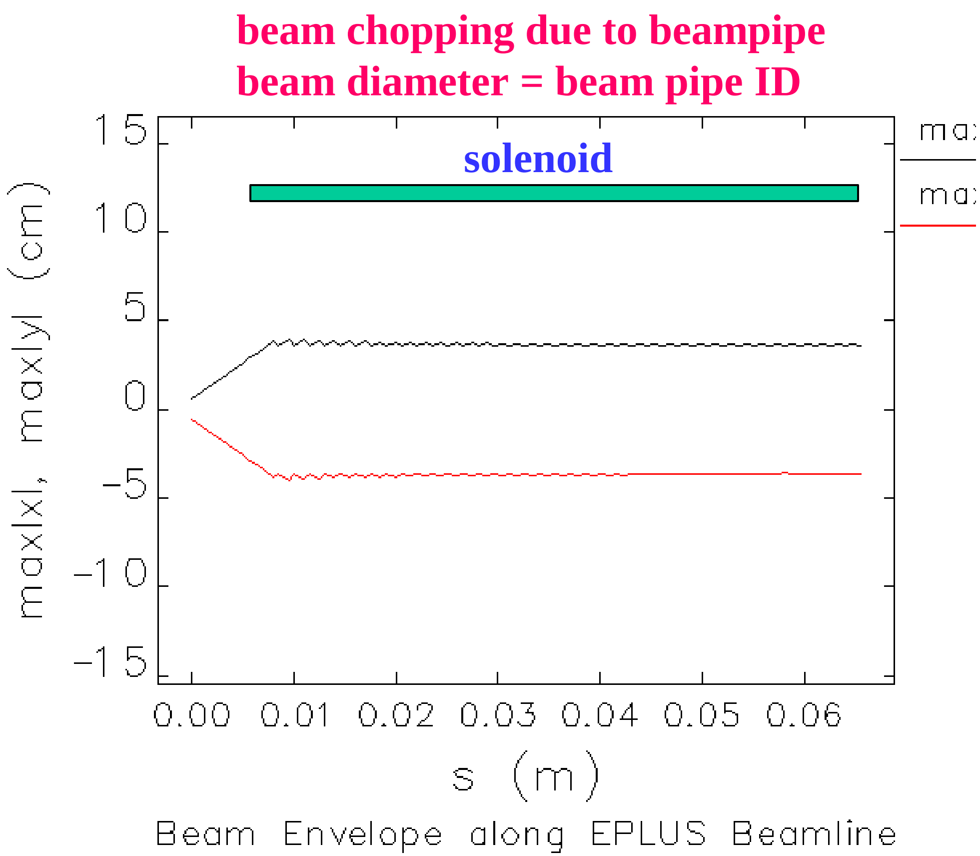
proper B field gives a continuous emittance damping due to beam transverse chopping

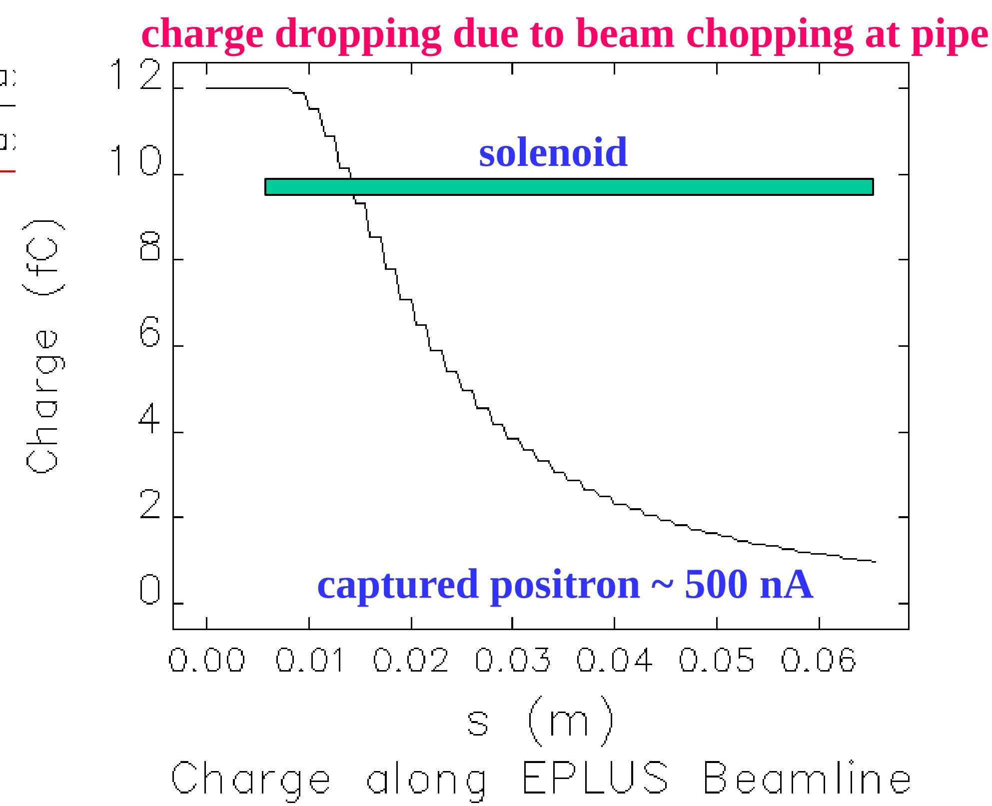


Normalized Emittance along EPLUS Beamline

Performance of Positron Capture with Solenoid

ELEGANT code tracking with B = 0.085 T to check capturing efficiency.

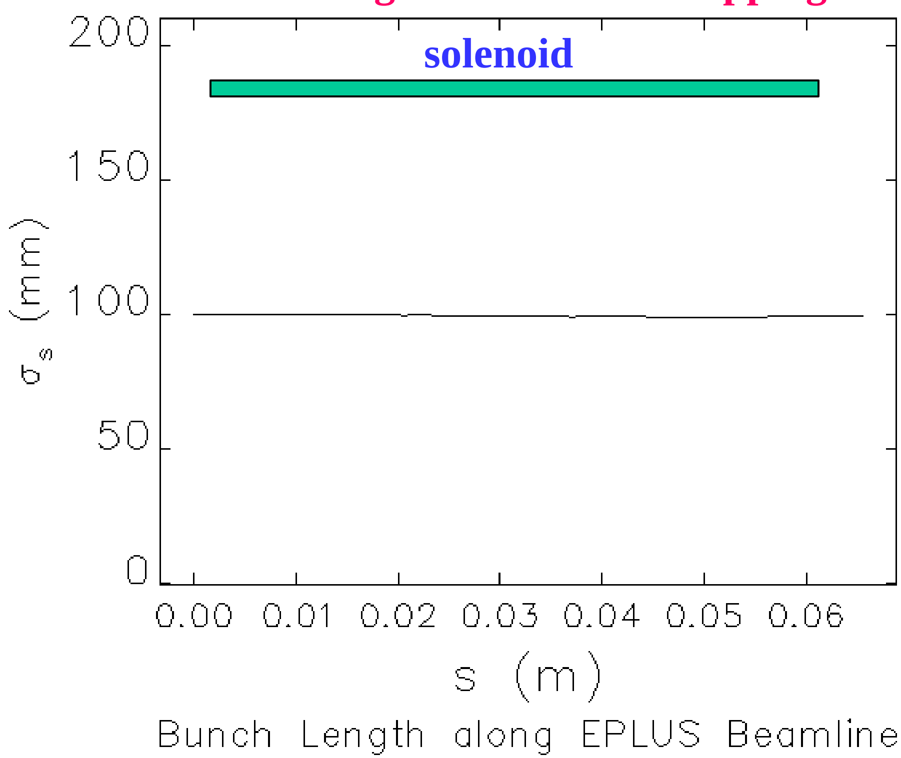




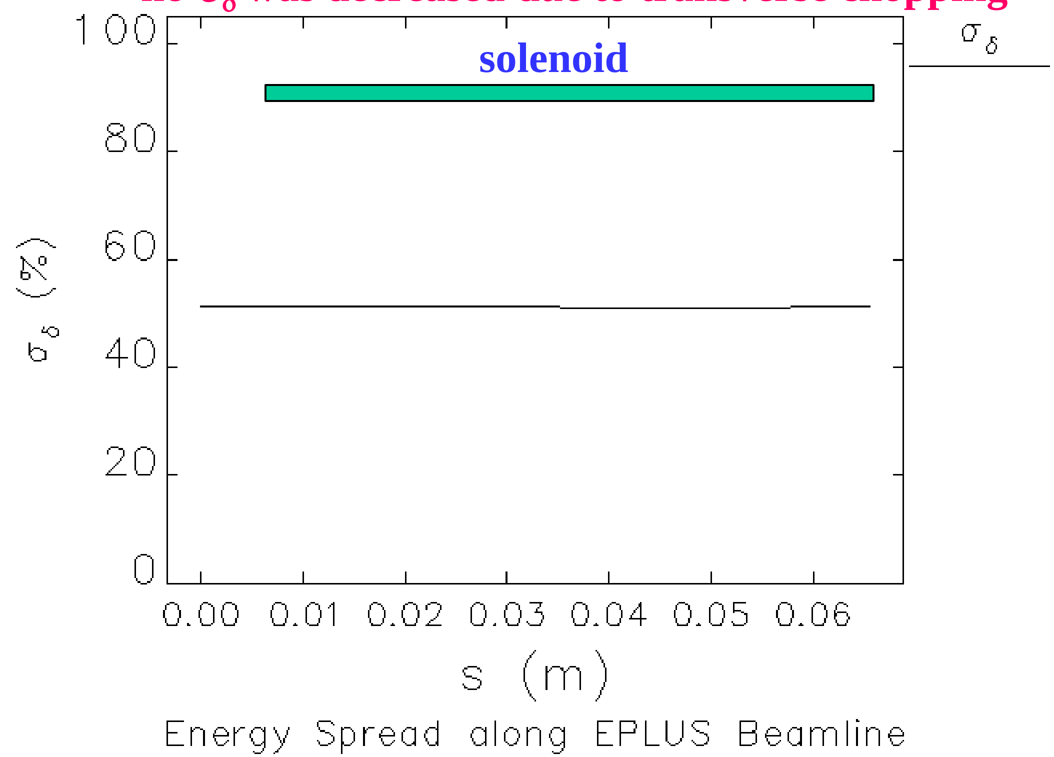
Performance of Positron Capture with Solenoid

ELEGANT code tracking with *B* = 0.085 T to check capturing efficiency.
→ *B* = 0.085 T gives only transverse beam chopping.
Good chirper and buncher are needed at the downstream!

no longitudinal beam chopping

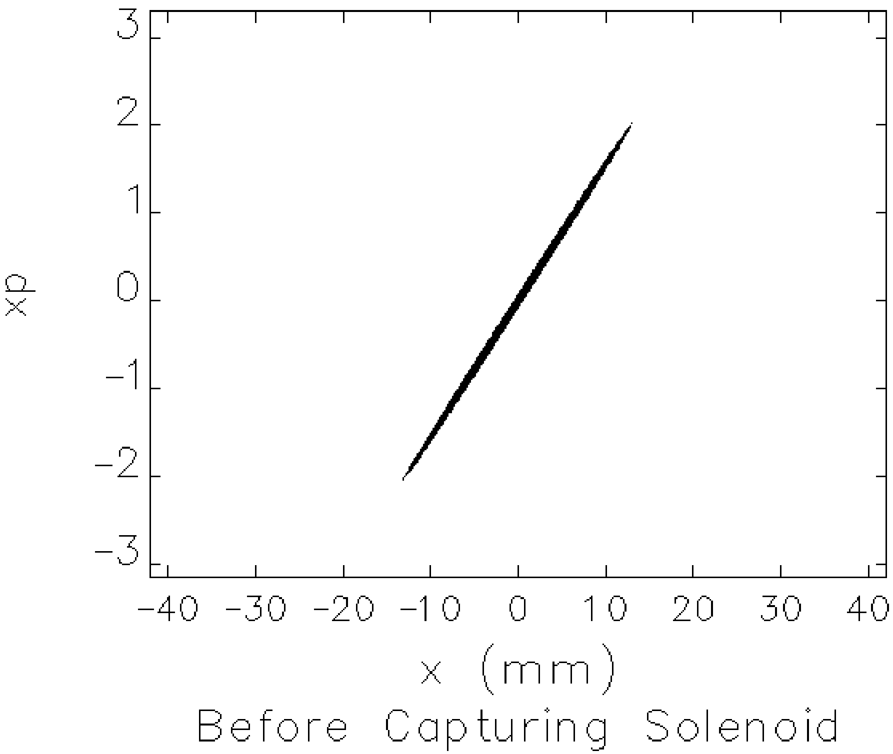


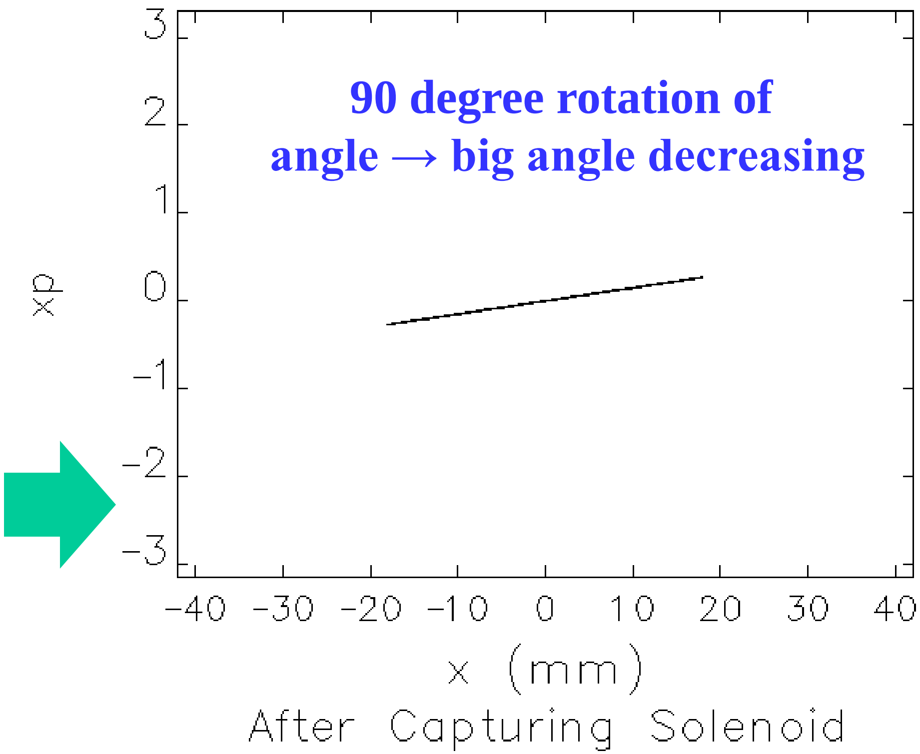
no σ_δ was decreased due to transverse chopping



Performance of Positron Capture with Solenoid

ELEGANT code tracking with B = 0.085 T to check capturing efficiency.
Proper-focusing gives a 90 degree angle rotation (quarter wave transformer)!
This can be helpful at the downstream to control emittance.

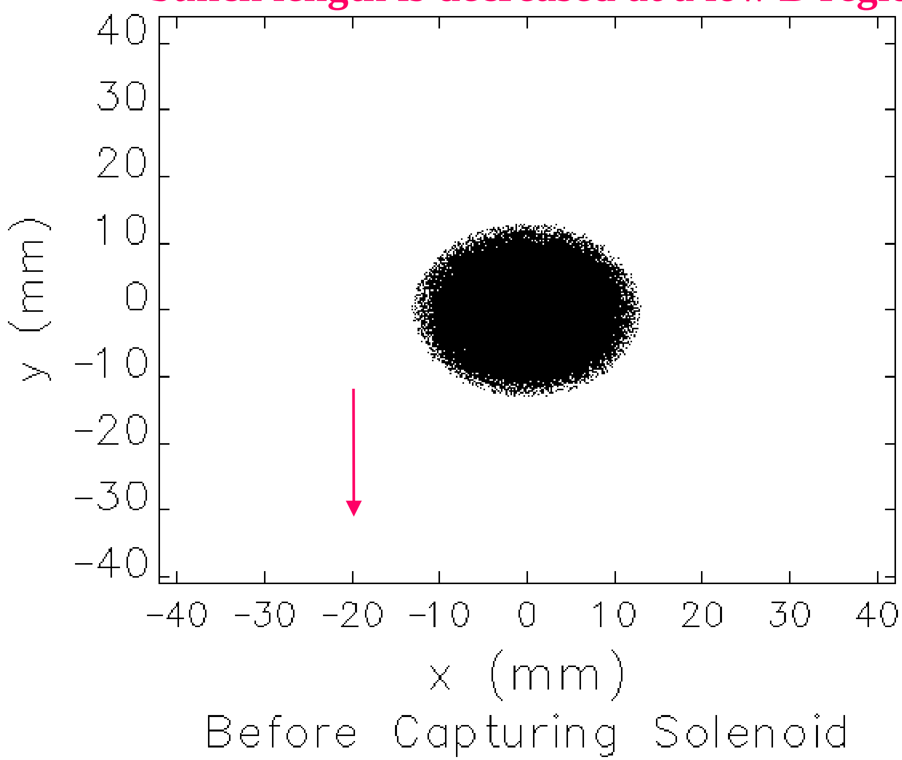




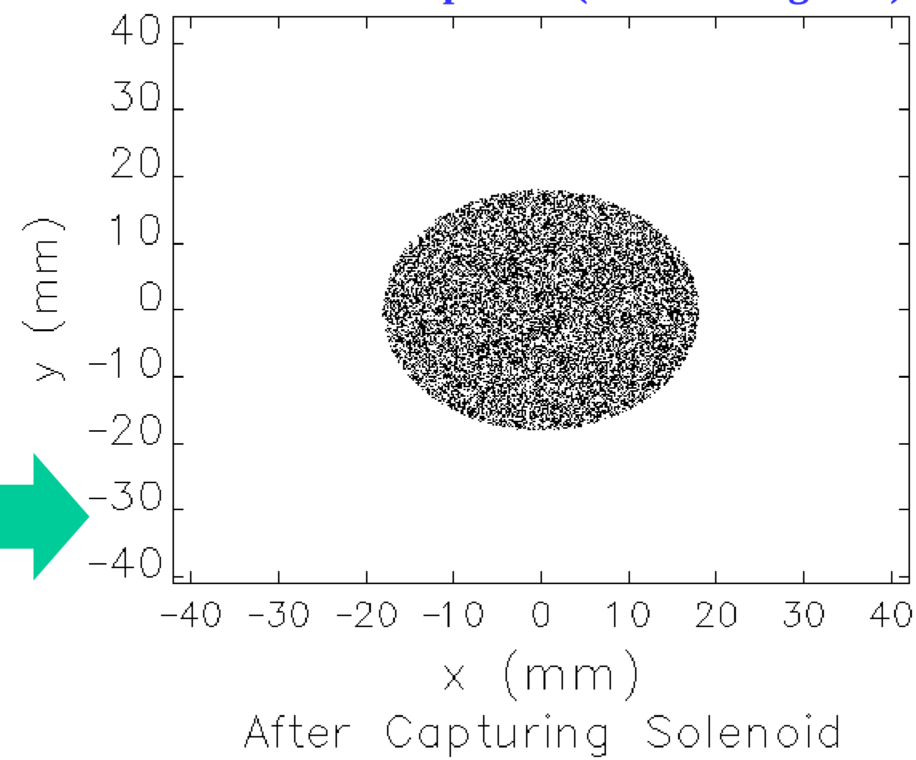
Performance of Positron Capture with Solenoid

ELEGANT code tracking with B = 0.085 T to check capturing efficiency.

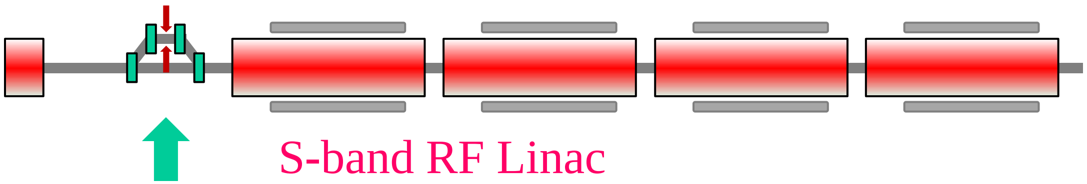
bunch length is decreased at a low B region



beam diameter = 36.1 mm = beampipe ID
uniform beam profile (weak divergence)

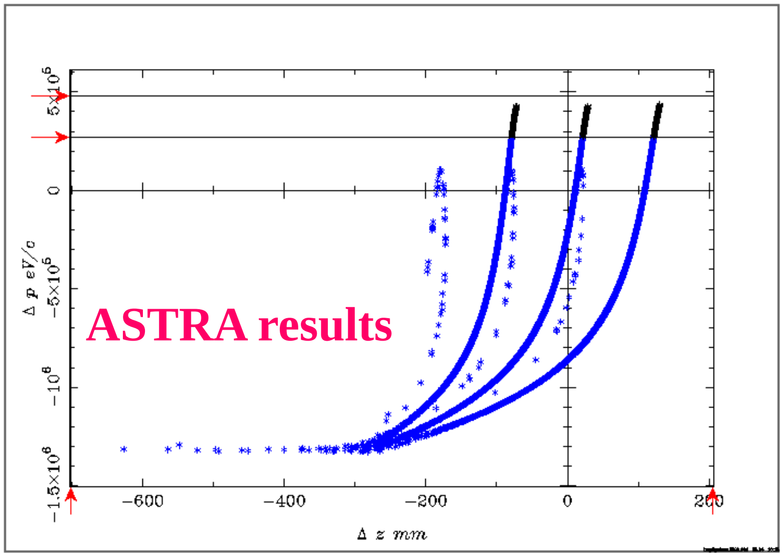


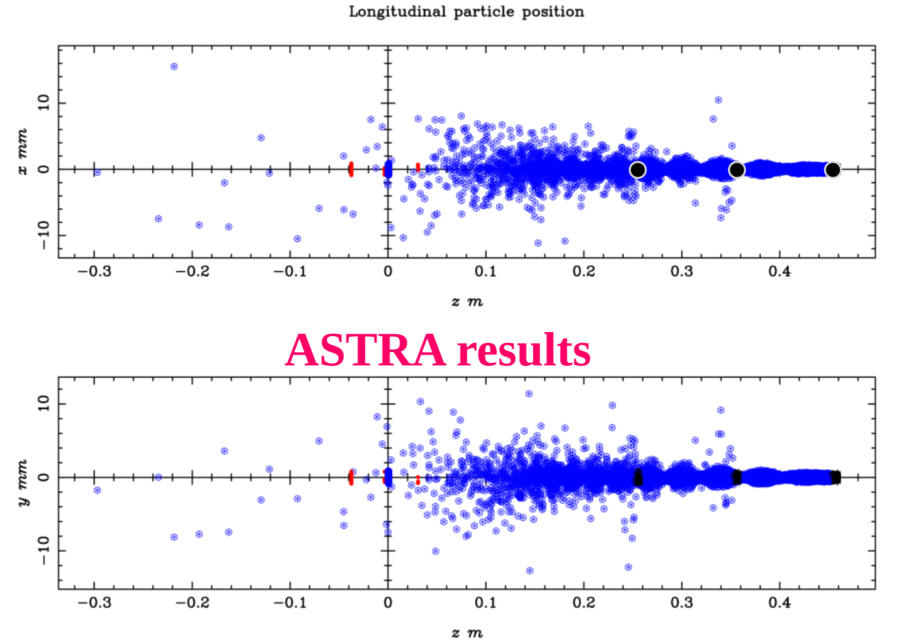
σ_δ and σ_z Damping in ALPHA Phase-II Linac



blue = collimated electrons

black = remain alive electrons





<u>Before Collimation</u>

$\sigma_{x,y}$ ~ 0.6521 mm

σ_z ~ 90.59 mm

averaged total energy ~ 1.373 MeV

rms energy Spread ~ 26.9%

Q ~ 218 pC

normalized transverse emittance ~ 4.97 μm

<u>After Collimation at Chicane</u>

$\sigma_{x,y}$ ~ 0.3595 mm

σ_z ~ 0.3593 mm

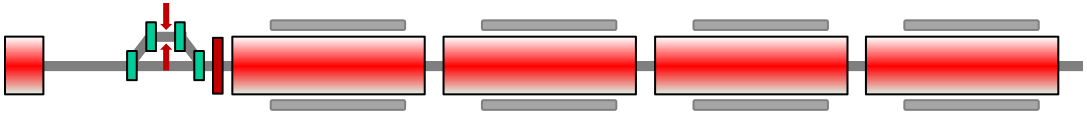
averaged total energy ~ 1.756 MeV

rms energy spread ~ 3.3%

Q ~ 90 pC (30 pC per bunch)

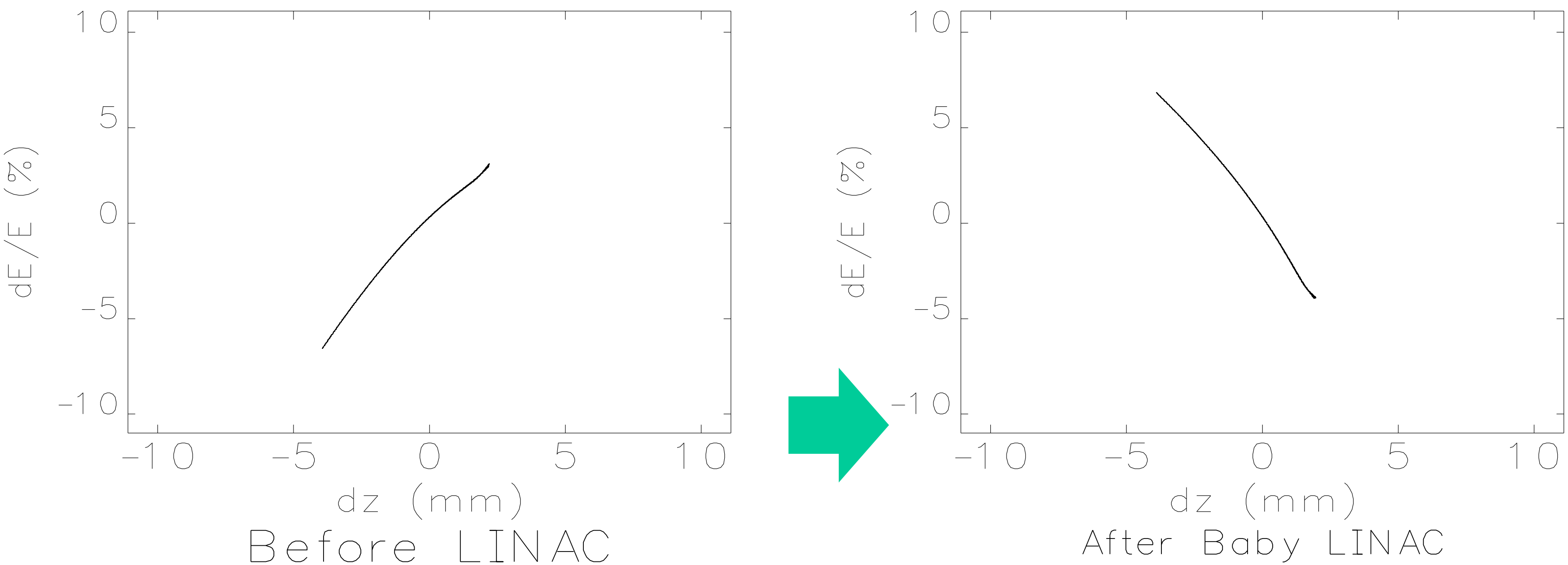
normalized transverse emittance ~ 0.602 μm

ELEGANT Results on ALPHA Phase-II Linac



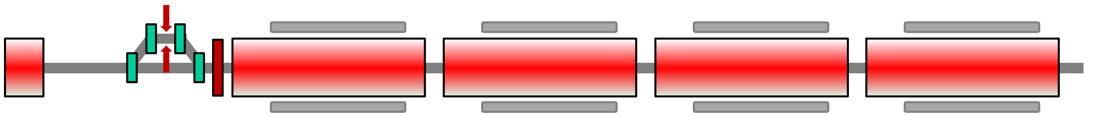
RF phase @ baby lianc = -100 deg, others RF phase = -1.3 deg
gradient for all linacs = 6.87 MV/m

adding a three-cell (10 cm) S-band Baby linac after collimator solves the problem



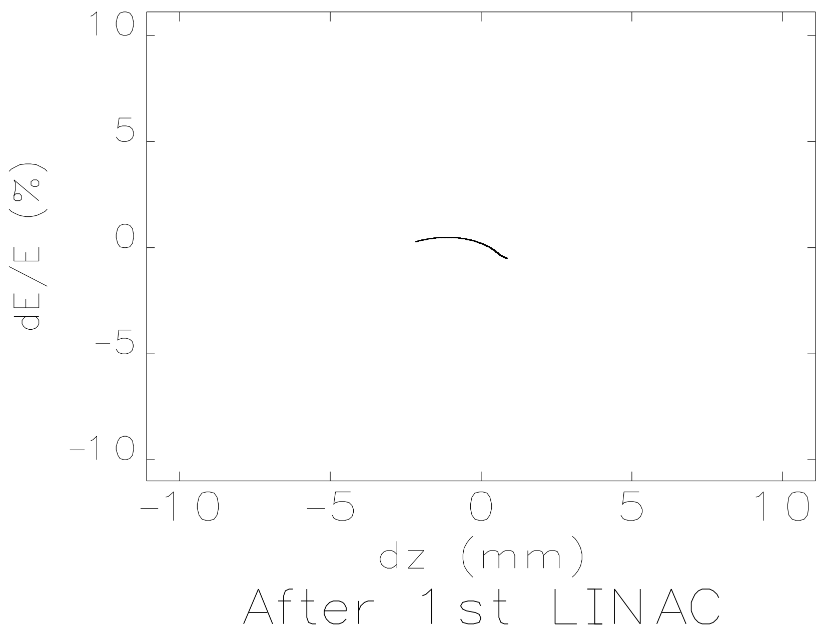
chirp can be reversed by adding a baby linac in front of the first linac!

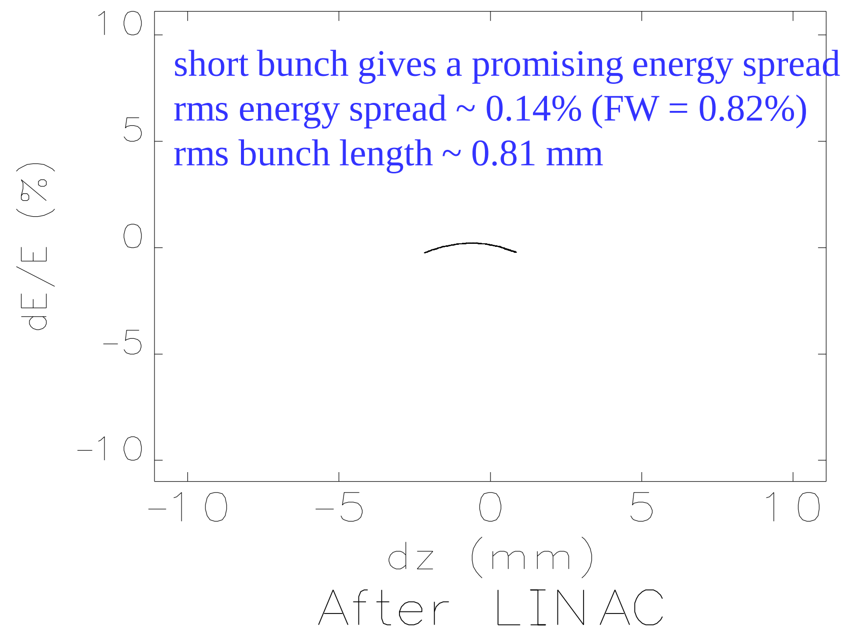
ELEGANT Results on ALPHA Phase-II Linac



RF phase @ baby lianc = -100 deg, others RF phase = -1.3 deg
gradient for all linacs = 6.87 MV/m

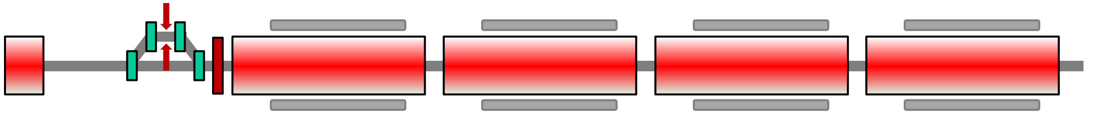
adding a three-cell (10 cm) S-band Baby linac after collimator solves the problem





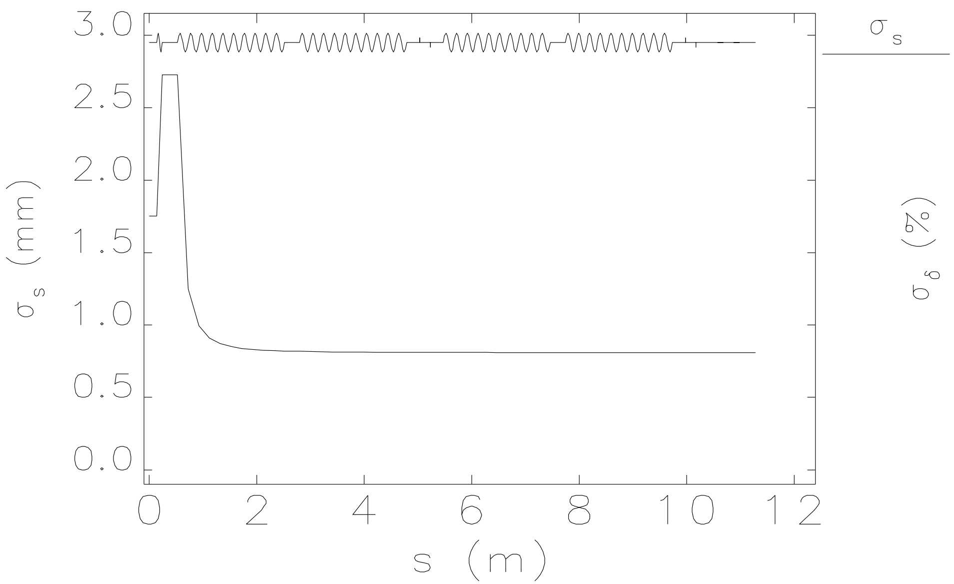
chirp can be reversed by adding a baby linac in front of the first linac!

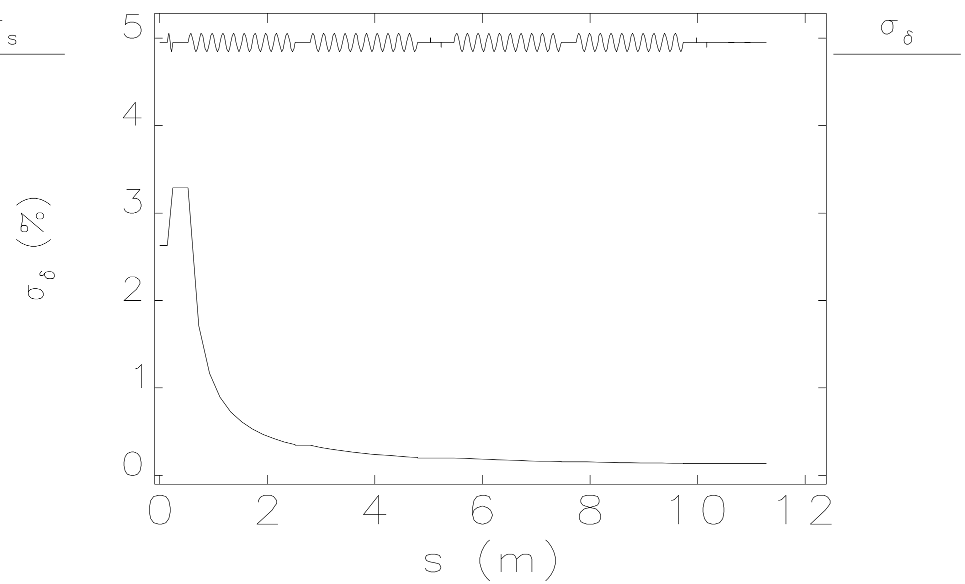
ELEGANT Results on ALPHA Phase-II Linac



RF phase @ baby lianc = -100 deg, others RF phase = -1.3 deg
gradient for all linacs = 6.87 MV/m

adding a three-cell (10 cm) S-band Baby linac after collimator solves the problem



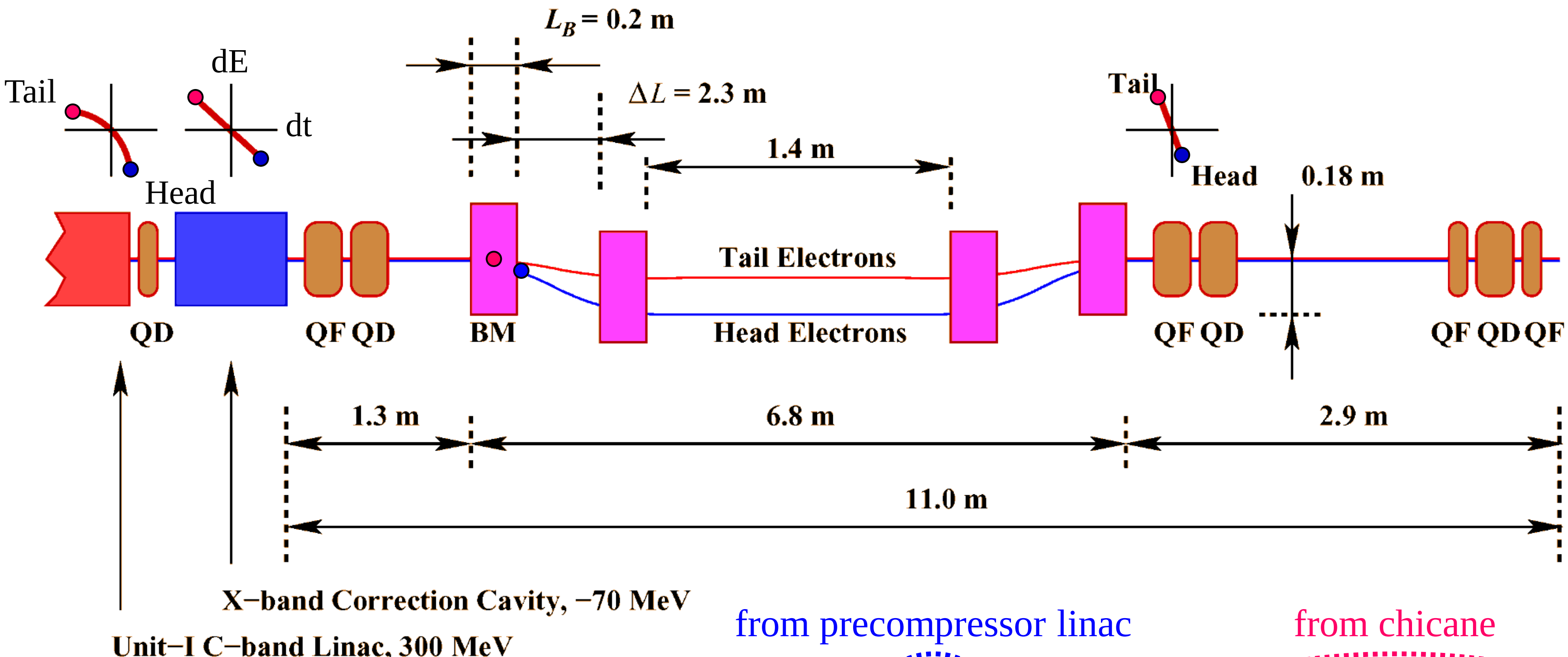


energy ~ 55 MeV, *Q* = 30 pC
rms energy spread ~ 0.14% (FW = 0.82%)
rms bunch length ~ 0.81 mm (2.7 ps)
peak current ~ 11 A
slice normalized emittance ~ 0.65 μm
projected normalized emittance < 1.0 μm

Optional - Bunch Compressor (BC)

Bunch Compressor Layout for SCSS Project - Y. Kim et al, NIMA 528 (2004) 421

XFELs & SuperB use Higher Harmonic Cavity for Effective Bunch Compression



from precompressor linac

from chicane

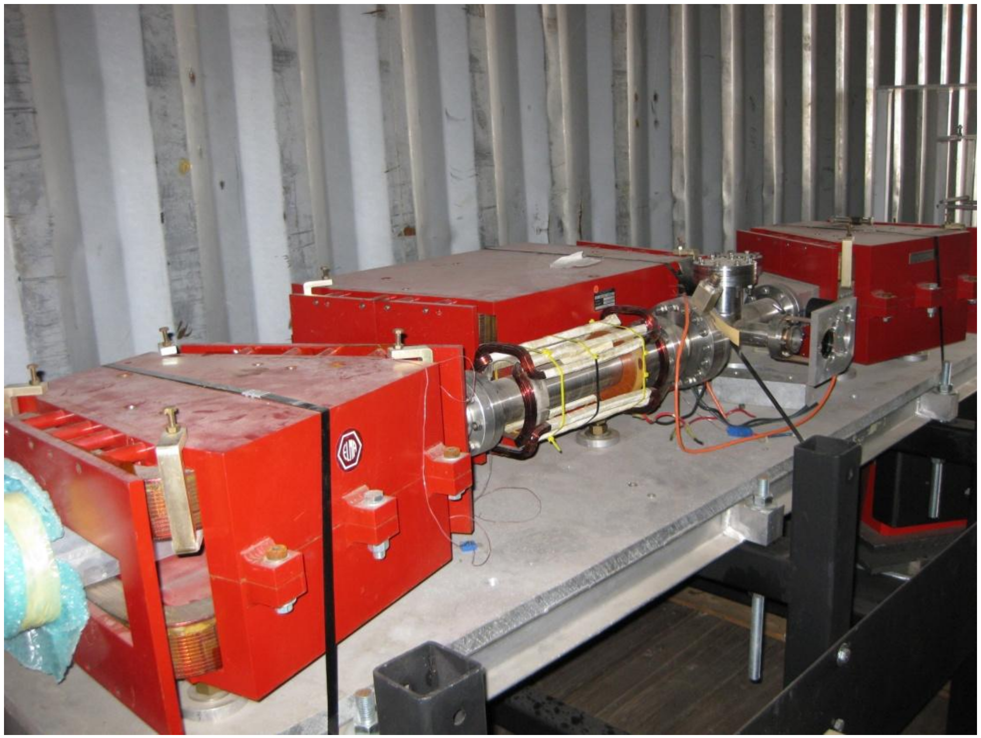
$$dz_f = dz_i + R_{56}(dE/E)_i + T_{566}(dE/E)_i^2 + O((dE/E)_i^3)$$

$$R_{56} \approx 2\theta_B^2\left(\Delta L + \frac{2}{3}L_B\right)$$

where $T_{566} = -\frac{3}{2}R_{56}$ for the rectangular bend chicane.

Optional Chicanes in the IAC Stockroom

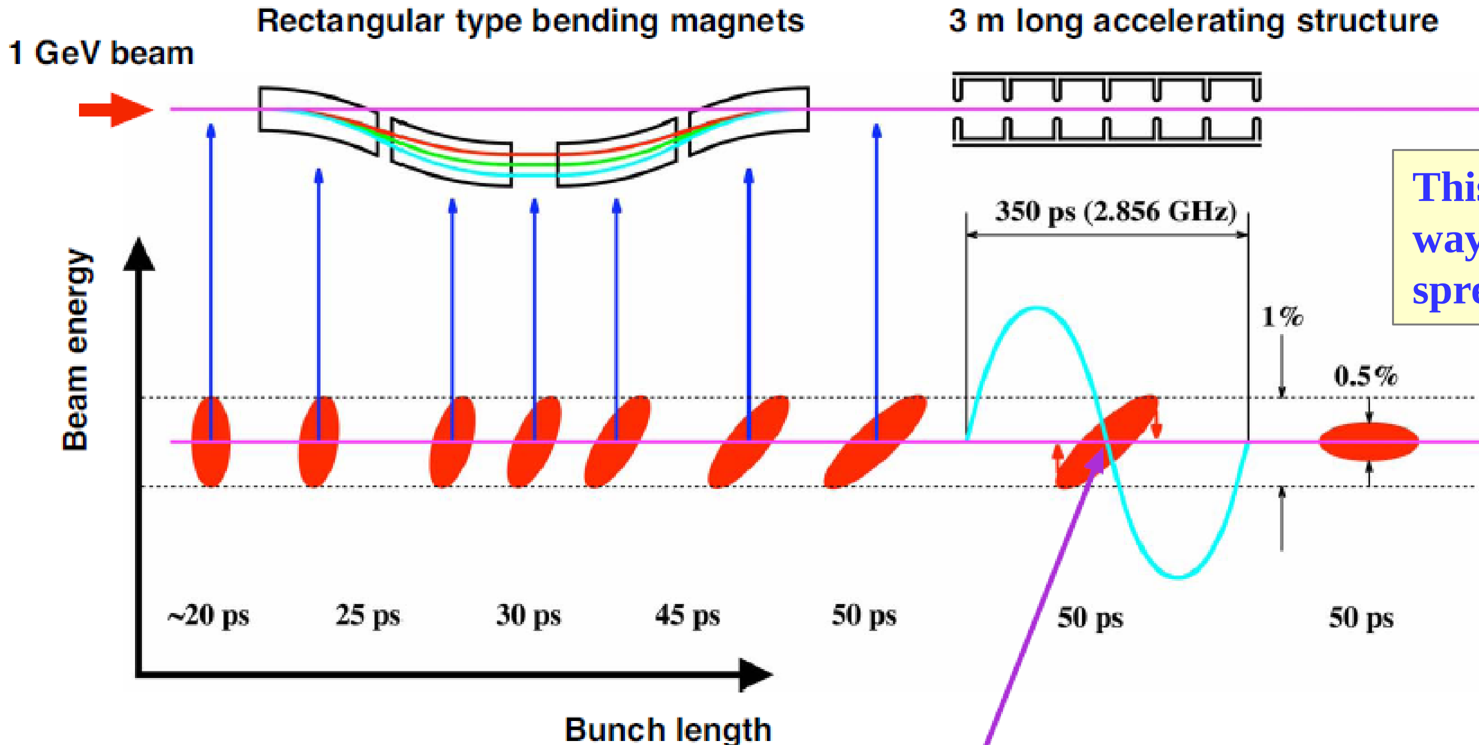
IAC has three chicanes in Stockrooms to reduce bunch length or energy spread compression.



One chicane with 30/60/30 deg dipoles
→ we can build a strong bunch compressor!

Two chicanes with four 7 deg dipoles
→ we can build two weak bunch compressors!

Optional - Energy Compression System (ECS)

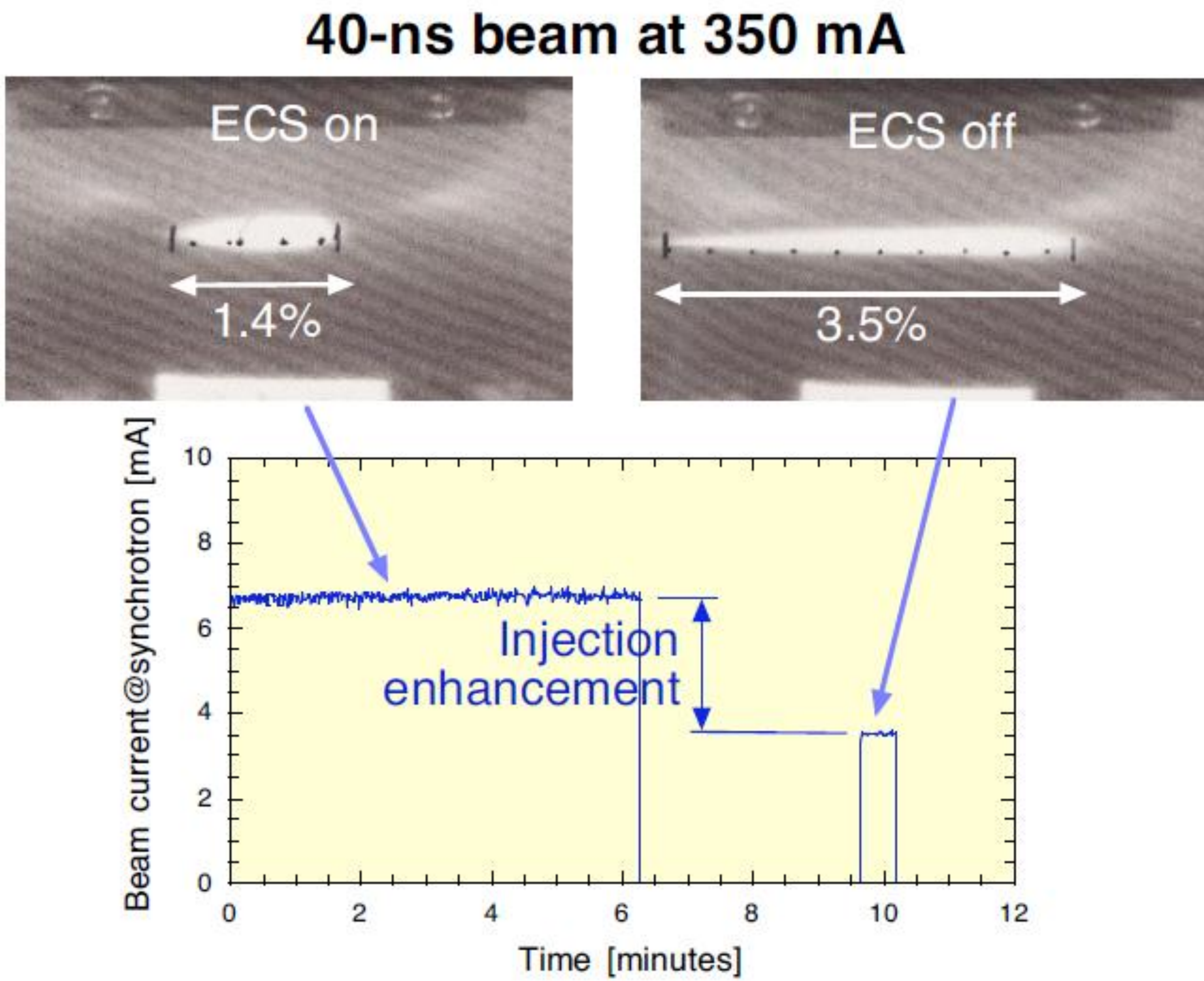


This ECS is an optional way to reduce energy spread from linac.

- Chicane expands bunch length along with beam energy.
- ECS compresses beam energy spread and variation.
- ECS requires RF phase stability

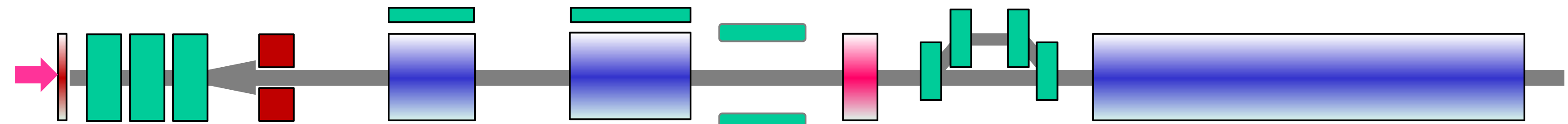
Energy Spread Reduction → Good for Injection
Pre-debunching → Good for Crane Users
Small Chicane + One Linac Structure are Needed

Energy Compression System @ SPring-8 Linac



ECS reduced energy spread by 2.5 times and improved injection rate!

Possible Layout-I for Positron Capture Experiments



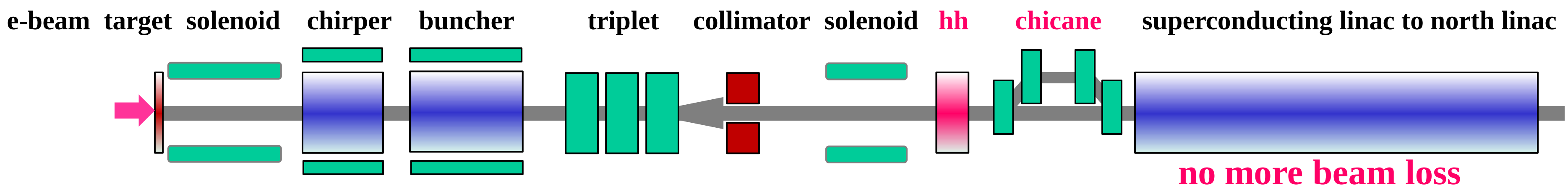
	chirper	buncher	hh	linac
gradient :	≤ 7.5 MV/m	≤ 7.5 MV/m	7.5 MV/m	≤ 12.5 MV/m
active length :	~ 0.4 m	~ 0.8 m	~ 0.2 m	~ 5.6 m (module with 7 cell 8 cavities)
frequency :	748.5 MHz	748.5 MHz	1497 MHz	1497 MHz

note that all parameters & layout are temporary.

beam type :	e^-	e^+	e^+	e^+	e^+	e^+
beam energy :	10 MeV	3.0 MeV	3.0 MeV	5.0 MeV	5.0 MeV	70 MeV
rms e-spread :	30 keV	1.6 MeV	1.0 MeV	1.0 MeV	1.0 MeV	1.0 MeV
geo-emittance :	0.03 μm	≥ 100 μm	≤ 100 μm	≤ 100 μm	≤ 10 μm	≤ 5 μm
rms bunch length :	0.2 ps	170 ps	100 ps	10 ps	10 ps	2 ps
average current :	10 mA		≥ 50 nA	≥ 50 nA	≥ 50 nA	≥ 50 nA

- ☐ QM Triplet + collimator : positron focusing + energy collimation
- ☐ chirper : 748.5 MHz NC cavity to cover a long bunch for energy chirp
- ☐ buncher : 748.5 MHz NC cavities for acceleration + bunching
- ☐ 0.3 m long solenoid : max 5 T DC solenoid for emittance compensation
- ☐ optional higher harmonic (hh) cavity + chicane for BC, ECS, and collimation
- ☐ booster : new JLab cryo-module for acceleration + energy spread damping

Possible Layout-II for Positron Capture Experiments



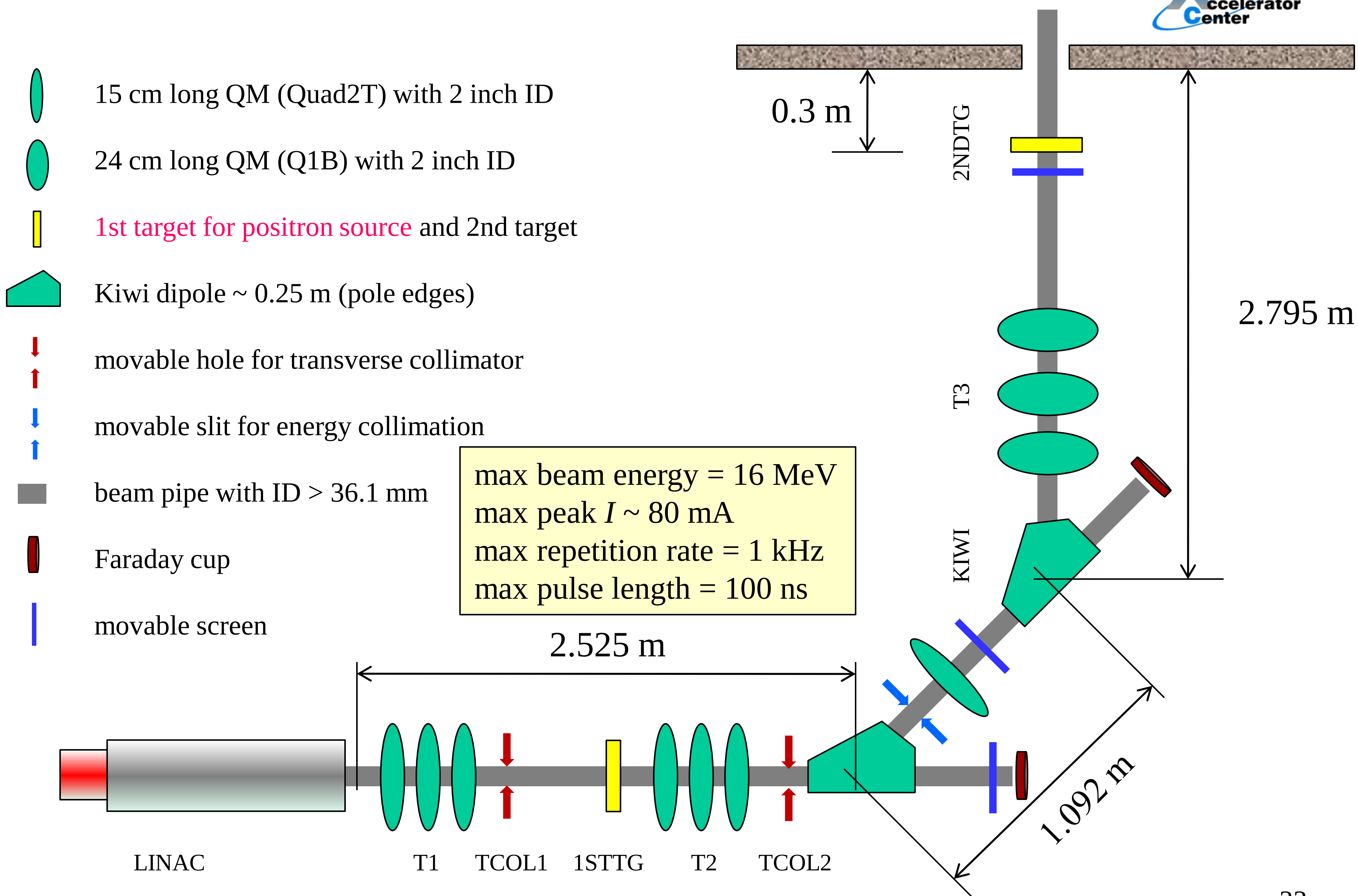
	chirper	buncher	hh	superconducting linac
gradient :	≤ 7.5 MV/m	≤ 7.5 MV/m	7.5 MV/m	≤ 12.5 MV/m
active length :	~ 0.4 m	~ 0.8 m	~ 0.2 m	~ 5.6 m (module with 7 cell 8 cavities)
frequency :	748.5 MH	748.5 MHz	1497 MHz	1497 MHz

note that all parameters & layout are temporary.

beam type :	e^-	e^+	e^+	e^+	e^+	e^+
beam energy :	10 MeV	3.0 MeV	5.0 MeV	5.0 MeV	5.0 MeV	70 MeV
rms e-spread :	30 keV	1.6 MeV	1.6 MeV	1.0 MeV	1.0 MeV	1.0 MeV
geo-emittance :	0.03 μm	≥ 100 μm	≥ 100 μm	≤ 100 μm	≤ 10 μm	≤ 5 μm
rms bunch length :	0.2 ps	170 ps	20 ps	10 ps	10 ps	2 ps
average current :	10 mA				≥ 50 nA	≥ 50 nA

- ☐ 0.3 m long solenoid : max 5 T DC solenoid for focusing of positrons
- ☐ chirper : 748.5 MHz NC cavity to cover a long bunch for energy chirp
- ☐ buncher : 748.5 MHz NC cavities for acceleration + bunching
- ☐ QM Triplet + collimator : positron focusing + energy collimation
- ☐ 0.3 m long solenoid : max 0.5 T DC solenoid for emittance compensation
- ☐ optional higher harmonic (hh) cavity + chicane for BC, ECS, and collimation
- ☐ booster : new JLab cryo-module for acceleration + energy spread damping

Layout of New HRRL Beamline @ IAC/ISU



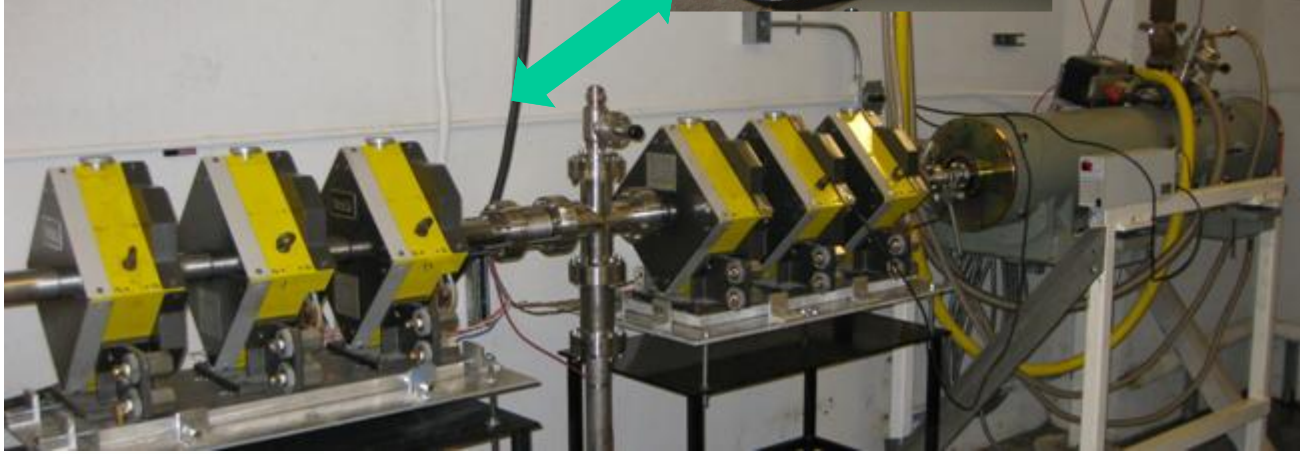
Current Status of HRRL Beamline @ IAC/ISU

Idaho Accelerator Center

Main components are almost installed.

Diagnostics will be installed in early 2011.

Capture efficiency with a solenoid or a quadrupole triplet will be tested in 2011-2012.



max beam energy = 16 MeV
max peak I ~ 80 mA
max repetition rate = 1 kHz
max pulse length = 100 ns

Summary

Due to a much higher heat power deposition on the target, much higher energy spread of emitted positron beams, a higher energy electron beams (10 mA, 120 MeV or 1 mA, 1 GeV) are somewhat difficult for us to generate high brightness CW positron source for CEBAF.

If we choose low energy electron beams, the neutron activation on components will be ignorable. Therefore, there are some advantages if we choose low energy electron beams (10 mA, 10 MeV).

It seems that a solenoid has more operational freedom and effective to capture positron beams initially. We need more optimization of solenoid field shape. At the IAC of ISU, we will check performance of solenoid and quadrupole triplet.

By performing experimental cross-checking, we may find a much better solution on the CW positron source for the CEBAF in the near future.

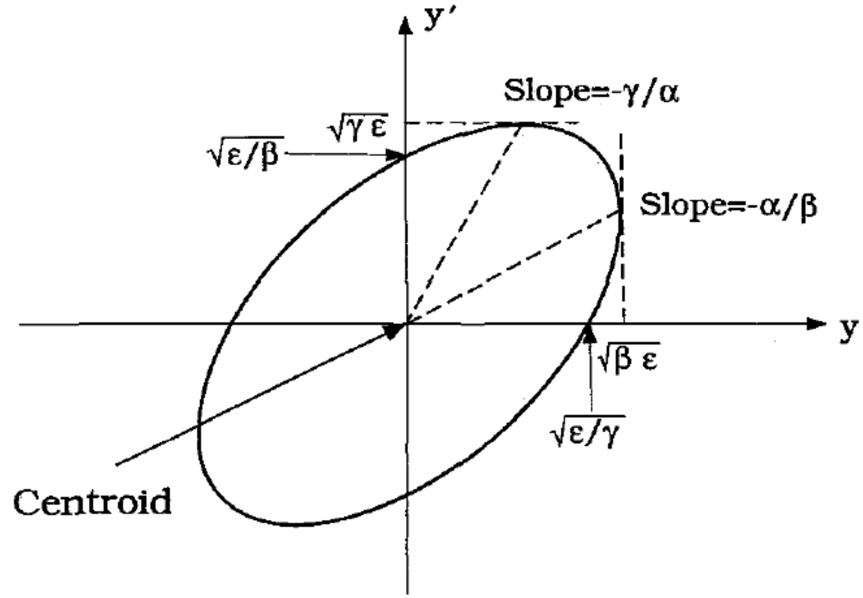
Suggested layouts are not fixed yet. We need more time to finalize the layout. If energy spread is big (or bunch length is big), we may consider chicane type, bunch compressor and energy compression system.

Appendix - Beam Phase Space Ellipse

max divergence (angle) and amplitude of betatron oscillation:

$$\sigma_y(s)=\sqrt{\varepsilon_y(s)\beta_y(s)},\quad \sigma_{y'}(s)=\sqrt{\varepsilon_y(s)\gamma_y(s)}$$

$$\gamma=\frac{1+\alpha^2}{\beta},\quad \text{or}\quad \beta\gamma-\alpha^2=1.$$



Appendix - Magnets in Accelerator

Typically, magnets in accelerator supply transverse or longitudinal magnetic fields.

From the Lorentz force, magnets are used to change of the direction of motion of a particle; $\vec{F} = q\vec{v} \times \vec{B}$ **. Example, bending magnet.**

Magnets with transverse fields (ex, dipole, quadrupole) are backbone of accelerator and beam transport system, and magnets with longitudinal fields (ex, solenoid) can be used to detect colliding beams in colliders or to focus beams in a low energy (ex, gun).

$$B[\mathrm{T}] = \mu n I = k\mu_0 n I = 4\pi \times 10^{-7} k\left(\frac{N}{L}\right) I$$

magnetic field of Solenoid B **[T], where**

μ **: permeability in material =** $k\mu_0$

N **: number of turns**

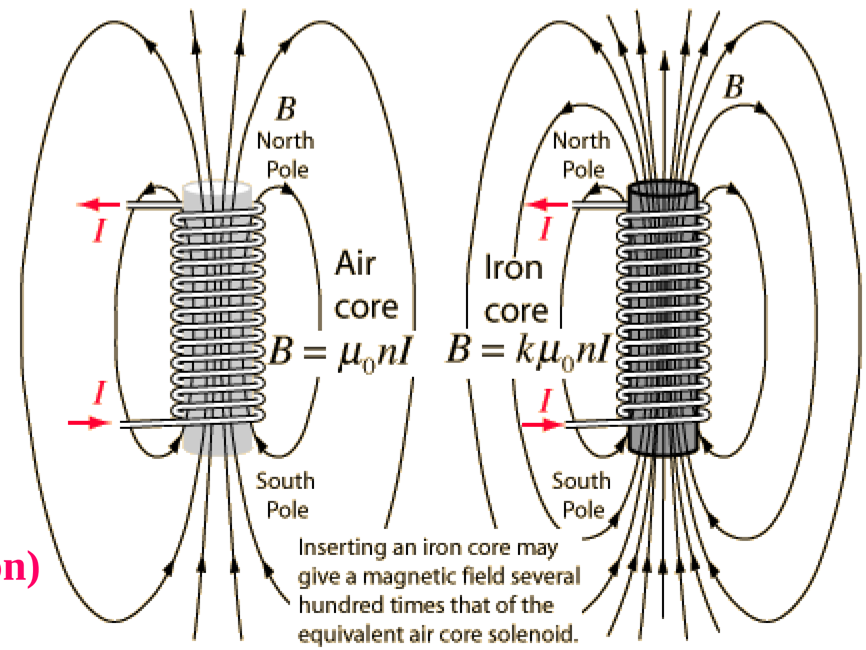
L **: length of solenoid [m]**

I **: current [A]**

k **: relative permeability**

~ 200 for magnetic iron

~ 20000 for μ-metal for magnetic shielding (75% nickel, 2% chromium, 5% copper, 18% iron)



http://hyperphysics.phy-astr.gsu.edu