Example: Production of the pbar

- 1954: Operation of Bevatron, first proton synchrotron for 6.2GeV, production of the anti-porton by Chamberlain and Segrè

$$p + p \quad \mapsto \quad p + p + p + \overline{p}$$

$$\tfrac{1}{c^2} E_{\rm cm}^2 = 2(\frac{E_1 E_2}{c^2} + p_{z1} p_{z2}) + (m_{01} c)^2 + (m_{02} c)^2$$

$$(4 m_{p0} c)^2 < \tfrac{1}{c^2} E_{\rm cm}^2 = 2 \frac{E_1 m_{p0}}{c^2} + (m_{p0} c)^2 + (m_{p0} c)^2$$

$$7 m_{p0} c^2 < E_1$$

$$K_1 = E_1 - m_0 c^2 > 6 m_{p0} c^2 = 5.628\,\text{GeV}$$

NP 1959
Emilio Gino Segrè
Italy 1905 – USA 1989

NP 1959
Owen Chamberlain
USA 1920 - 2006

Example: c-cbar states

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- 1974: Observation of $c-\bar{c}$ resonances (J/Ψ) at Ecm = 3095MeV at the e^+/e^- collider SPEAR

$$\frac{1}{c^2}E_{\mathrm{cm}}^2 = 2\left(\frac{E_1E_2}{c^2} + p_{z1}p_{z2}\right) + (m_{01}c)^2 + (m_{02}c)^2$$

$$E_1 = E_2 \quad \Rightarrow \quad E_{\mathrm{cm}}^2 = 4E^2$$

Energy per beam: $K = E - m_0c = 1547\mathrm{MeV}$

Beam energy needed for an equivalent fixed target experiment: $\frac{E_{cm}^2}{c^2} = 2[Em + (mc)^2]$

$$K = E - m_{0e}c^2 = \frac{E_{cm}^2}{2m_{0e}c^2} - 2m_{0e}c^2 = 9.4\mathrm{TeV}$$

NP 1976
Burton Richter
USA 1931 -

NP 1976
Samuel CC Ting
USA 1936 -

Rings for Synchrotron Radiation

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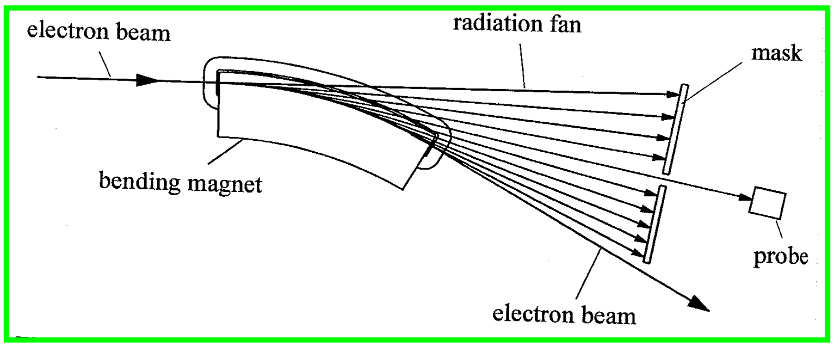
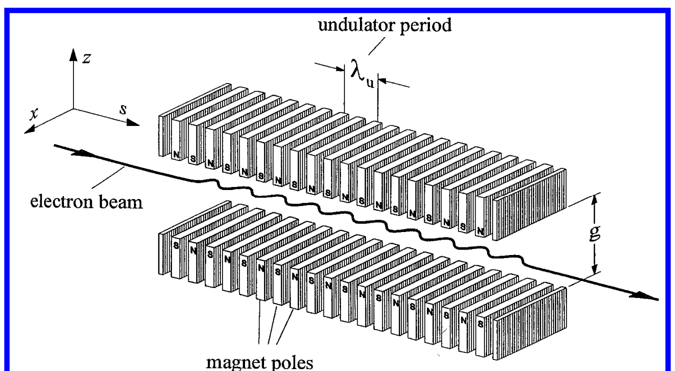
- 1947: First detection of synchrotron light at General Electrics.
- 1952: First accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1968: TANTALOS, first dedicated storage ring for synchrotron radiation

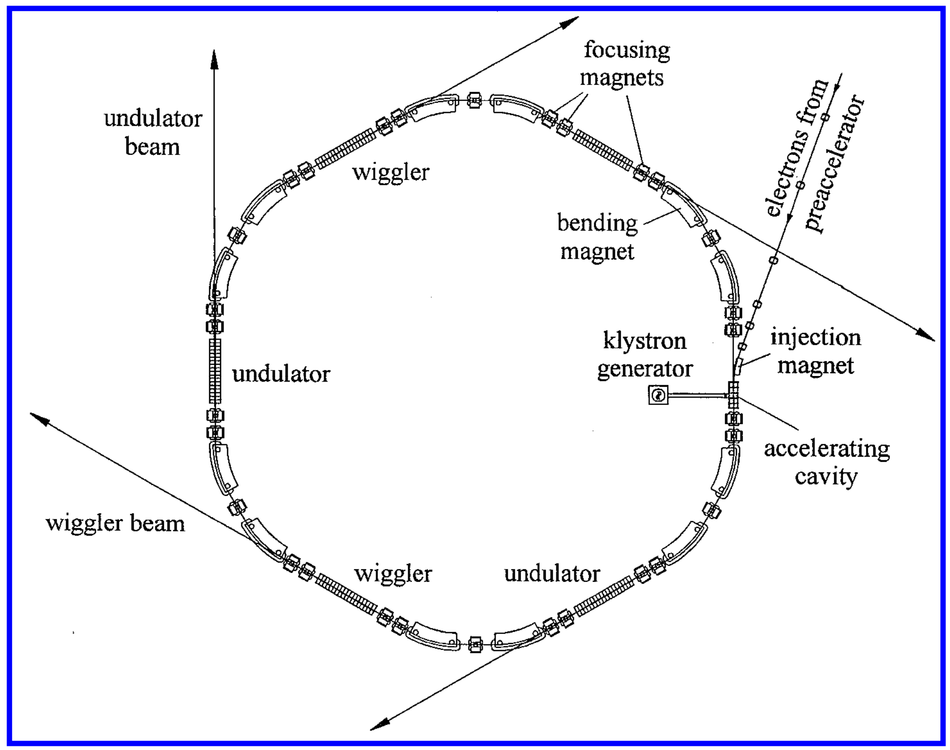
Dale Corson
Cornell's 8th president
USA 1914 –

3 Generations of Light Sources

- 1st Genergation (1970s): Many HEP rings are parasitically used for X-ray production
- 2nd Generation (1980s): Many dedicated X-ray sources (light sources)
- 3rd Generation (1990s): Several rings with dedicated radiation devices (wigglers and undulators)
- Today (4th Generation): Construction of Free Electron Lasers (FELs) driven by LINACs







Accelerators of the World

CHESS & LEPP

Sorted by Location

Europe

AGOR	Accelerateur Groningen-ORsay, KVI Groningen, Netherlands
ANKA	Ångströmquelle Karlsruhe, Karlsruhe, Germany (Forschungsgruppe Synchrotronstrahlung (FGS))
ASTRID	Aarhus Storage Ring in Denmark, ISA, Aarhus, Denmark
BESSY	Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung, Germany (BESSY I status, BESSY II status)
BINP	Budker Institute for Nuclear Physics, Novosibirsk, Russian Federation (VEPP-2M collider, VEPP-4M collider (status))
CERN	Centre Europeen de Recherche Nucleaire, Geneva, Suisse (LEP & SPS Status, LHC, CLIC, PS-Division, SL-Division)
COSY	Cooler Synchrotron, IKP, FZ Jülich, Germany (COSY Status)
CYCLONE	Cyclotron of Louvain la Neuve, Louvain-la-Neuve, Belgium
DELTA	Dortmund Electron Test Accelerator, U of Dortmund, Germany (DELTA Status)
DESY	Deutsches Elektronen Synchrotron, Hamburg, Germany (HERA, PETRA and DORIS status, TESLA)
ELBE	ELectron source with high Brilliance and low Emittance, FZ Rossendorf, Germany
ELETTRA	Trieste, Italy (ELETTRA status)
ELSA	Electron Stretcher Accelerator, Bonn University, Germany (ELSA status)
ESRF	European Synchrotron Radiation Facility, Grenoble, France (ESRF status)
GANIL	Grand Accélérateur National d'Ions Lourds, Caen, France
GSI	Gesellschaft für Schwerionenforschung, Darmstadt, Germany
IHEP	Institute for High Energy Physics, Protvino, Moscow region, Russian Federation
INFN	Istituto Nazionale di Fisica Nucleare, Italy, LNF - Laboratori Nazionali di Frascati (DAFNE, other accelerators), LNL - Laboratori Nazionali di Legnaro (Tandem, CN Van de Graaff, AN 2000 Van de Graaff), LNS - Laboratori Nazionali del Sud, Catania, (Superconducting Collider & Van de Graaff Tandem)
ISIS	Rutherford Appleton Laboratory, Oxford, U.K. (ISIS Status)
ISL	IonenStrahlLabor am HMI, Berlin, Germany
JINR	Joint Institute for Nuclear Research, Dubna, Russian Federation (U-200, U-400, U-400M, Storage Ring, LHE Synchrophasotron / Nuclotron)
JYFL	Jyväskylän Yliopiston Fysiikan Laitos, Jyväskylä, Finland
KTH	Kungl Tekniska Högskola (Royal Institute of Technology), Stockholm, Sweden (Alfén Lab electron accelerators)

Accelerators of the World

CHESS & LEPP

LMU/TUM	Accelerator of LMU and TU Muenchen, Munich, Germany
LURE	Laboratoire pour l'Utilisation du Rayonnement Electromagnétique, Orsay, France (DCI, Super-ACO status, CLIO)
MAMI	Mainzer Microtron, Mainz U, Germany
MAX-Lab	Lund University, Sweden
MSL	Manne Siegbahn Laboratory, Stockholm, Sweden (CRYRING)
NIKHEF	Nationaal Instituut voor Kernfysica en Hoge-Energie Fysica, Amsterdam, Netherlands (AmPS *closed!*)
PSI	Paul Scherrer Institut, Villigen, Switzerland (PSI status, SLS *under construction*)
S-DALINAC	Darmstadt University of Technology, Germany (S-DALINAC status)
SRS	Synchrotron Radiation Source, Daresbury Laboratory, Daresbury, U.K. (SRS Status)
TSL	The Svedberg Laboratory, Uppsala University, Sweden (CELSIUS)
TSR	Heavy-Ion Test Storage Ring, Heidelberg, Germany

North America

88" Cycl.	88-Inch Cyclotron, Lawrence Berkeley Laboratory (LBL), Berkeley, CA
ALS	Advanced Light Source, Lawrence Berkeley Laboratory (LBL), Berkeley, CA (ALS Status)
ANL	Argonne National Laboratory, Chicago, IL (Advanced Photon Source APS [status], Intense Pulsed Neutron Source IPNS [status], Argonne Tandem Linac Accelerator System ATLAS)
BNL	Brookhaven National Laboratory, Upton, NY (AGS, ATF, NSLS, RHIC)
CAMD	Center for Advanced Microstructures and Devices
CHESS	Cornell High Energy Synchrotron Source, Cornell University, Ithaca, NY
CLS	Canadian Light Source, U of Saskatchewan, Saskatoon, Canada
CESR	Cornell Electron-positron Storage Ring, Cornell University, Ithaca, NY (CESR Status)
FNAL	Fermi National Accelerator Laboratory , Batavia, IL (Tevatron)
IAC	Idaho accelerator center, Pocatello, Idaho
IUCF	Indiana University Cyclotron Facility, Bloomington, Indiana
JLab	aka TJNAF, Thomas Jefferson National Accelerator Facility (formerly known as CEBAF), Newport News, VA
LAC	Louisiana Accelerator Center, U of Louisiana at Lafayette, Louisiana
LANL	Los Alamos National Laboratory
MIT-Bates	Bates Linear Accelerator Center, Massachusetts Institute of Technology (MIT)
NSCL	National Superconducting Cyclotron Laboratory, Michigan State University
ORNL	Oak Ridge National Laboratory (EN Tandem Accelerator), Oak Ridge, Tennessee
SBSL	Stony Brook Superconducting Linac, State University of New York (SUNY)
SLAC	Stanford Linear Accelerator Center (Linac, NLC - Next Linear Collider, PEP - Positron Electron Project (finished), PEP-II - asymmetric B Factory (in commissioning), SLC - SLAC Linear electron positron Collider, SPEAR - Stanford Positron Electron Asymmetric Ring (actually SPEAR-II, see SSRL), SSRL - Stanford Synchrotron Radiation Laboratory)
SNS	Spallation Neutron Source, Oak Ridge, Tennessee
SRC	Synchrotron Radiation Center, U of Wisconsin - Madison (Aladdin Status)

SURF II	Synchrotron Ultraviolet Radiation Facility, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland
TASCC	Tandem Accelerator Superconducting Cyclotron (Canada) *(closed!)*
TRIUMF	TRI-University Meson Facility / National Meson Research Facility, Vancouver, BC (Canada)

South America

LNLS	Laboratorio Nacional de Luz Sincrotron, Campinas SP, Brazil
TANDAR	Tandem Accelerator, Buenos Aires, Argentina

Asia

BEPC	Beijing Electron-Positron Collider, Beijing, China
KEK	National Laboratory for High Energy Physics ("Koh-Ene-Ken"), Tsukuba, Japan (KEK-B, PF, JLC)
NSC	Nuclear Science Centre, New Delhi, India (15 UD Pelletron Accelerator)
PLS	Pohang Light Source, Pohang, Korea
RIKEN	Institute of Physical and Chemical Research ("Rikagaku Kenkyusho"), Hirosawa, Wako, Japan
SESAME	Synchrotron-light for Experimental Science and Applications in the Middle East, Jordan (under construction)
SPring-8	Super Photon ring - 8 GeV, Japan
SRRC	Synchrotron Radiation Research Center, Hsinchu, Taiwan (SRRC Status)
UVSOR	Ultraviolet Synchrotron Orbital Radiation Facility, Japan
VECC	Variable Energy Cyclotron, Calcutta, India

Africa

NAC	National Accelerator Centre, Cape Town, South Africa

Sorted by Accelerator Type

Electrons

Stretcher Ring/Continuous Beam facilities

ELSA (Bonn U), JLab, MAMI (Mainz U), MAX-Lab, MIT-Bates, PSR (SAL), S-DALINAC (TH Darmstadt), SLAC

Accelerators of the World

CHESS & LEPP

Synchrotron Light Sources

ANKA (FZK), ALS (LBL), APS (ANL), ASTRID (ISA), BESSY, CAMD (LSU), CHESS (Cornell Wilson Lab), CLS (U of Saskatchewan), DELTA (U of Dortmund), ELBE (FZ Rossendorf), Elettra, ELSA (Bonn U), ESRF, HASYLAB (DESY), LURE, MAX-Lab, LNLS, NSLS (BNL), PF (KEK), UVSOR (IMS), PLS, S-DALINAC (TH Darmstadt), SESAME, SLS (PSI), SPEAR (SSRL, SLAC), SPring-8, SRC (U of Wisconsin), SRRC, SRS (Daresbury), SURF II (NIST)

Other

Alfén Lab (KTH), IAC

Protons

88" Cyclotron (LBL), CELSIUS (TSL), COSY (FZ Jülich), IPNS (ANL), ISL (HMI), ISIS, IUCF, LHC (CERN), NAC, PS (CERN), PSI, SPS (CERN)

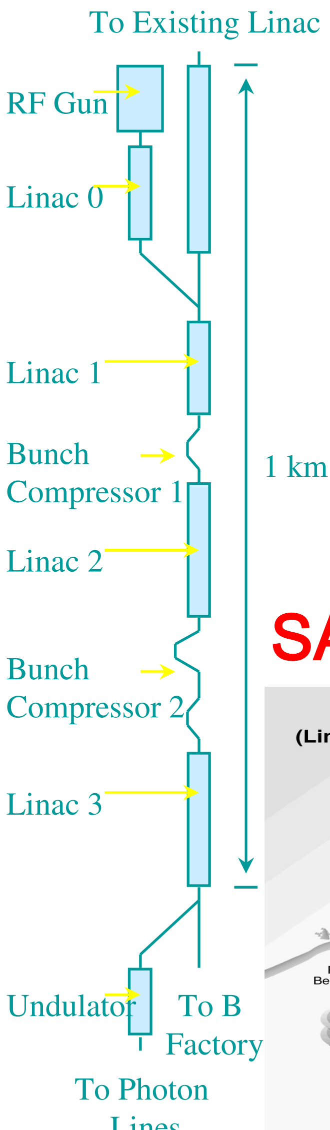
Light and Heavy Ions

88" Cyclotron (LBL), AGOR, ASTRID (ISA), ATLAS (ANL), CELSIUS (TSL), CRYRING (MSL), CYCLONE, EN Tandem (ORNL), GANIL, GSI, ISL (HMI), IUCF, JYFL, LAC, LHC (CERN), LHE Synchrophasotron / Nuclotron (JINR), LMU/TUM, LNL (INFN), LNS (INFN), NAC, NSC, PSI, RHIC (BNL), SBSL, SNS, SPS (CERN), TANDAR, TSR, U-200 / U-400 / U-400M / Storage Ring (JINR), VECC

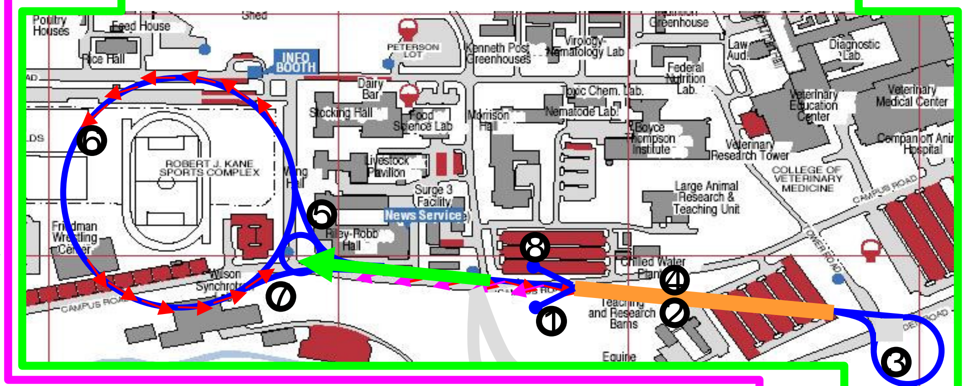
Collider

BEPC, CESR, DAFNE (LNF), HERA (DESY), LEP (CERN), LHC (CERN), PEP / PEP-II (SLAC), SLC (SLAC), KEK-B (KEK), TESLA (DESY), Tevatron (FNAL), VEPP-2M, VEPP-4M (BINP)

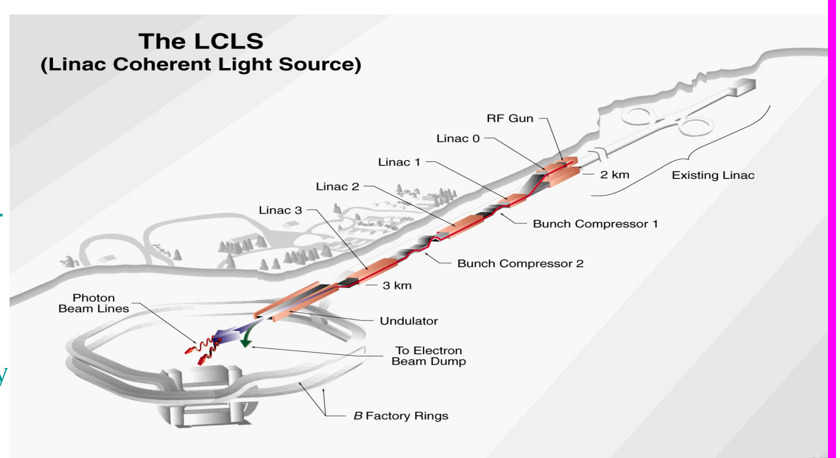
The Future



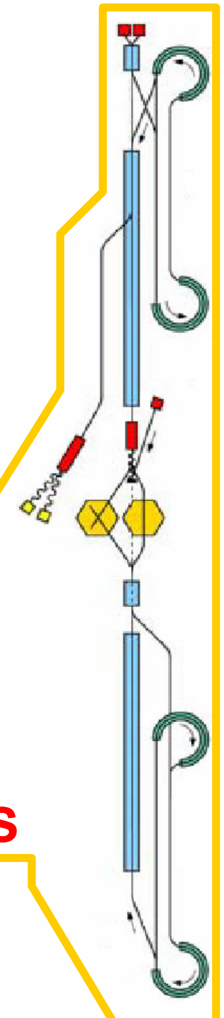
Energy Recovery Linacs



SASE Free Electron Lasers



Linear Colliders



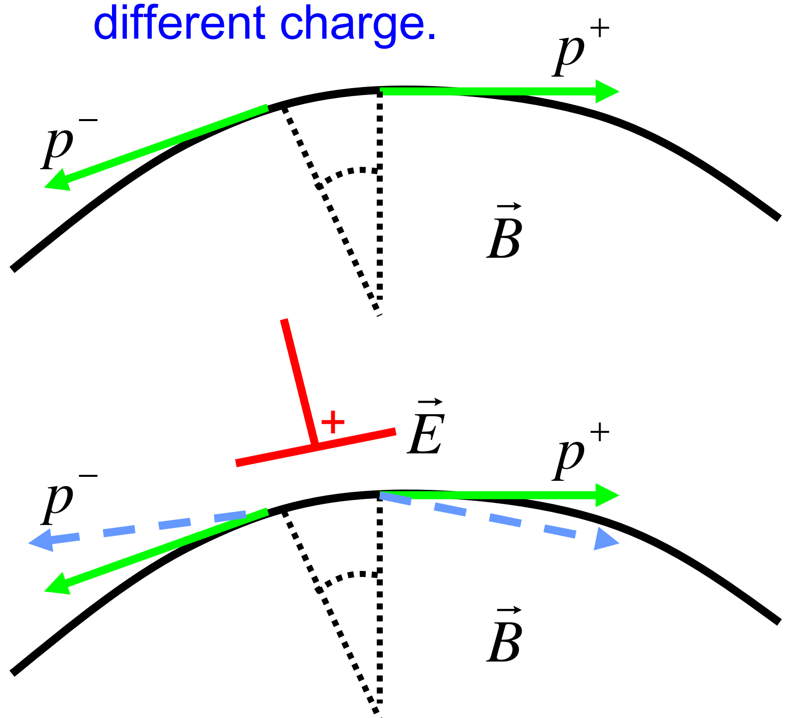
Macroscopic Fields in Accelerators

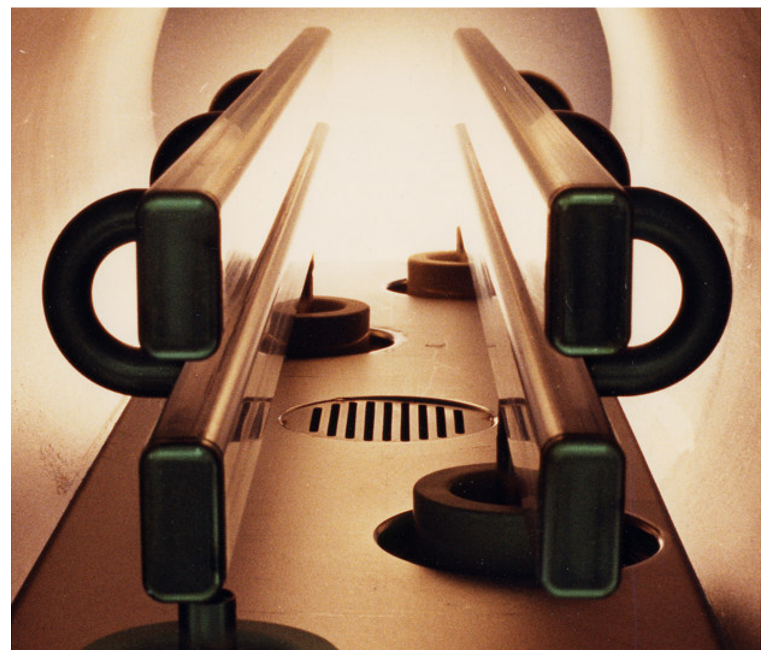
$$\frac{d}{dt}\vec{p} = q(\vec{E} + \vec{v} \times \vec{B})$$

E has a similar effect as v B.

For relativistic particles B = 1T has a similar effect as E = cB = 3 10^8 V/m , such an Electric field is beyond technical limits.

- Electric fields are only used for very low energies or
- For separating two counter rotating beams with different charge.





Electrostatic separators at CESR

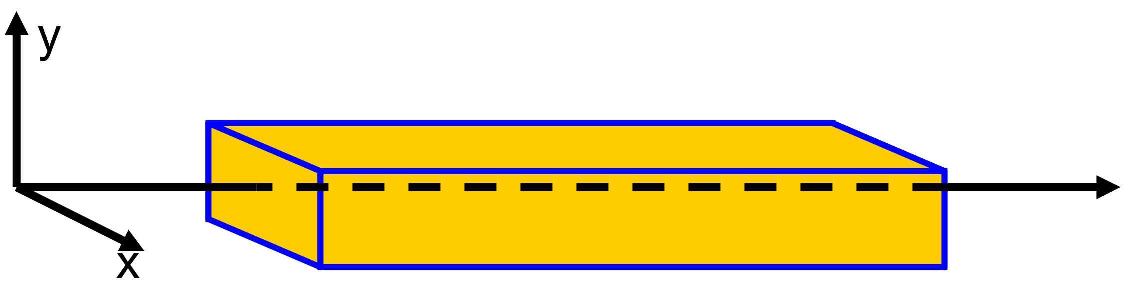
Magnetic Fields in Accelerators

CHESS & LEPP

Static magnetic fileds: $\partial_t \vec{B} = 0\,;\quad \vec{E} = 0$ Charge free space: $\vec{j} = 0$

$$\vec{\nabla}\times\vec{B} = \mu_0(\vec{j} + \varepsilon_0 \partial_t \vec{E}) = 0 \quad\Rightarrow\quad \vec{B} = -\vec{\nabla}\,\psi(\vec{r})$$

$$\vec{\nabla}\cdot\vec{B} = 0 \quad\Rightarrow\quad \vec{\nabla}^2 \psi(\vec{r}) = 0$$



(x=0,y=0) is the beam's design curve

For finite fields on the design curve,
Ψ can be power expanded in x and y:

$$\psi(x,y,z) = \sum_{n,m=0}^{\infty} b_{nm}(z)\, x^n y^m$$