8. Muons and neutrinos

- Muon colliders and neutrino factories
  - Motivation
  - Schematic of a muon/neutrino facility
  - Radioactive ion beams
  - Long baseline neutrino experiments
- Muon accelerator challenges
  - Proton drivers
  - High power targets
  - Pion capture
  - Phase rotation
  - Muon cooling by ionization
  - Muon acceleration
- Spallation neutron sources

ICFA Beam Dynamics Newsletter No.55,
Muon collider and neutrino factory, Aug. 2011,
http://icfa-usa.jlab.org/archive/newsletter.shtml

- Outlook: new accelerating techniques

Motivation

Muon collider

- Muon = “heavy electron” : $m_\mu = 207\ m_e$, τ =2.2 us
- Synchrotron radiation loss $P \sim \gamma^4$ ⇨ only 10^{-9} of electrons

⇒ TeV *lepton* collisions in <u>compact</u> *circular* collider

  - $E_{cm} \approx 1.5...4$ TeV → Circumference $C < 10$ km
  - Multiple collisions (1.5 TeV muon ($\gamma \approx 14000$) makes 1000 turns in 10 km ring!)
- **Alternatives**
  - ***hadron*** (p–p) circular collider **LHC**: $E_{cm} = 14$ TeV, $C = 27$ km
  - lepton (e^+–e^-) ***linear*** collider **CLIC**: $E_{cm} = 3$ TeV, $L = 48$ km

Neutrino factory

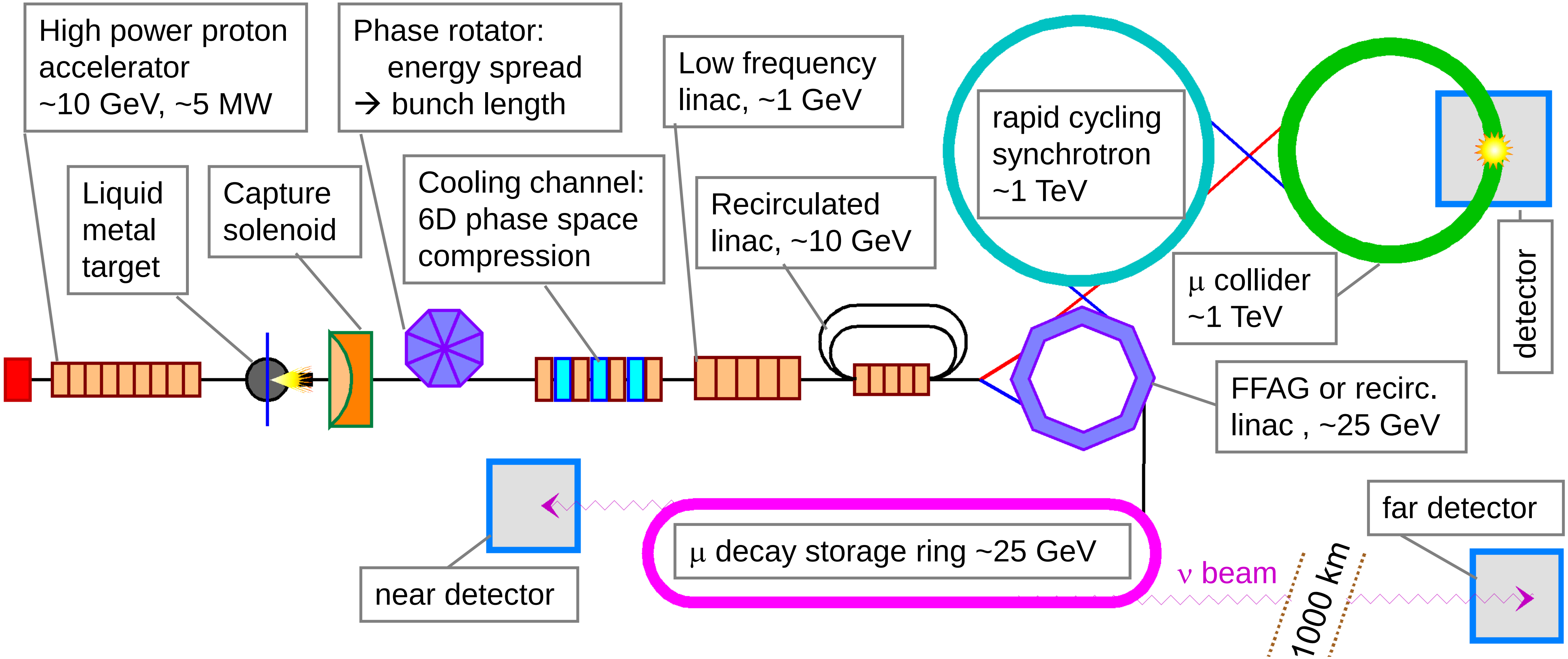
- Long ($L > 1000$ km) baseline experiments (e.g. **CNGS**)
  - neutrino flavour mixing: probability $\propto L$
- High energy neutrino beams (cross section $\propto$ energy)

⇒ Neutrino factory & muon collider = one facility.

Schematic of a μ/ν facility

Muon and neutrino production:

- proton beam on target: $p \rightarrow \pi^+, \pi^-, \pi^o....$
- muons from pion decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu \;,\quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- neutrinos from muon decay: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \;,\quad \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$



Radioactive ion storage ring

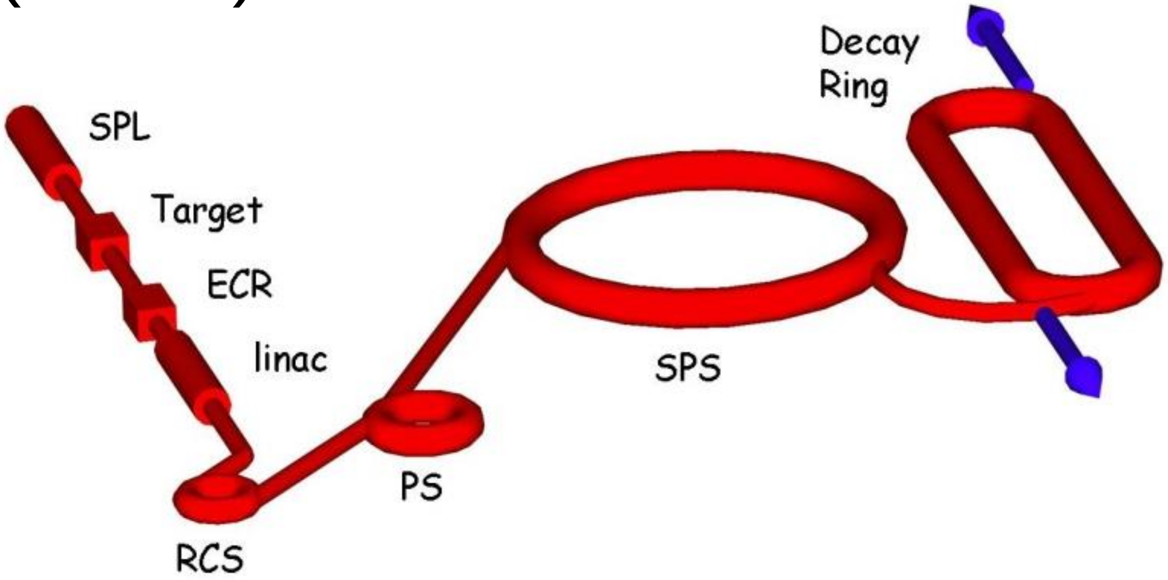
Alternative neutrino production:

Neutrinos from beta decay, e.g.

$$ {}^{6}_{2}\mathrm{He} \rightarrow {}^{6}_{3}\mathrm{Li} + e^{-} + \overline{\nu}_e \;,\quad {}^{18}_{10}\mathrm{Ne} \rightarrow {}^{18}_{9}\mathrm{F} + e^{+} + \nu_e $$

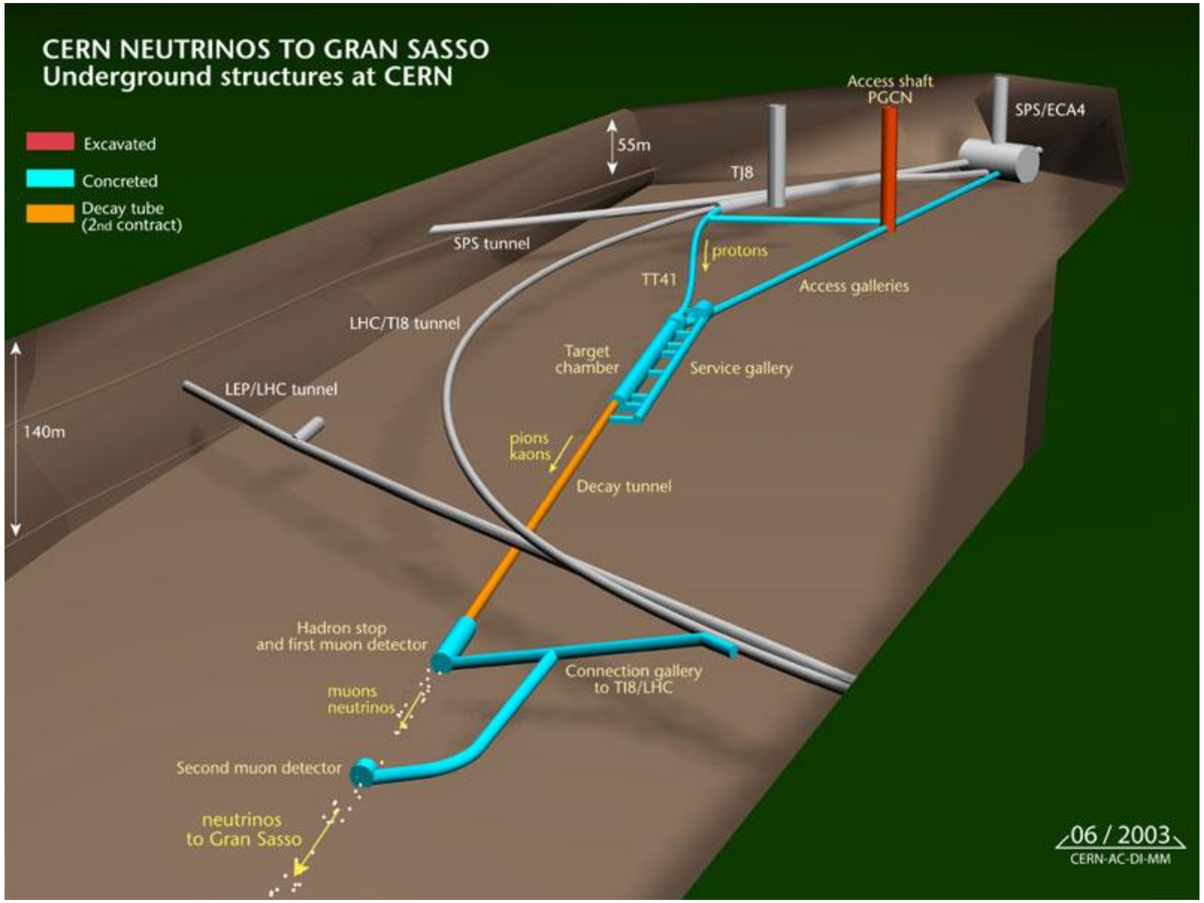
EURISOL collaboration – **BetaBeam** project

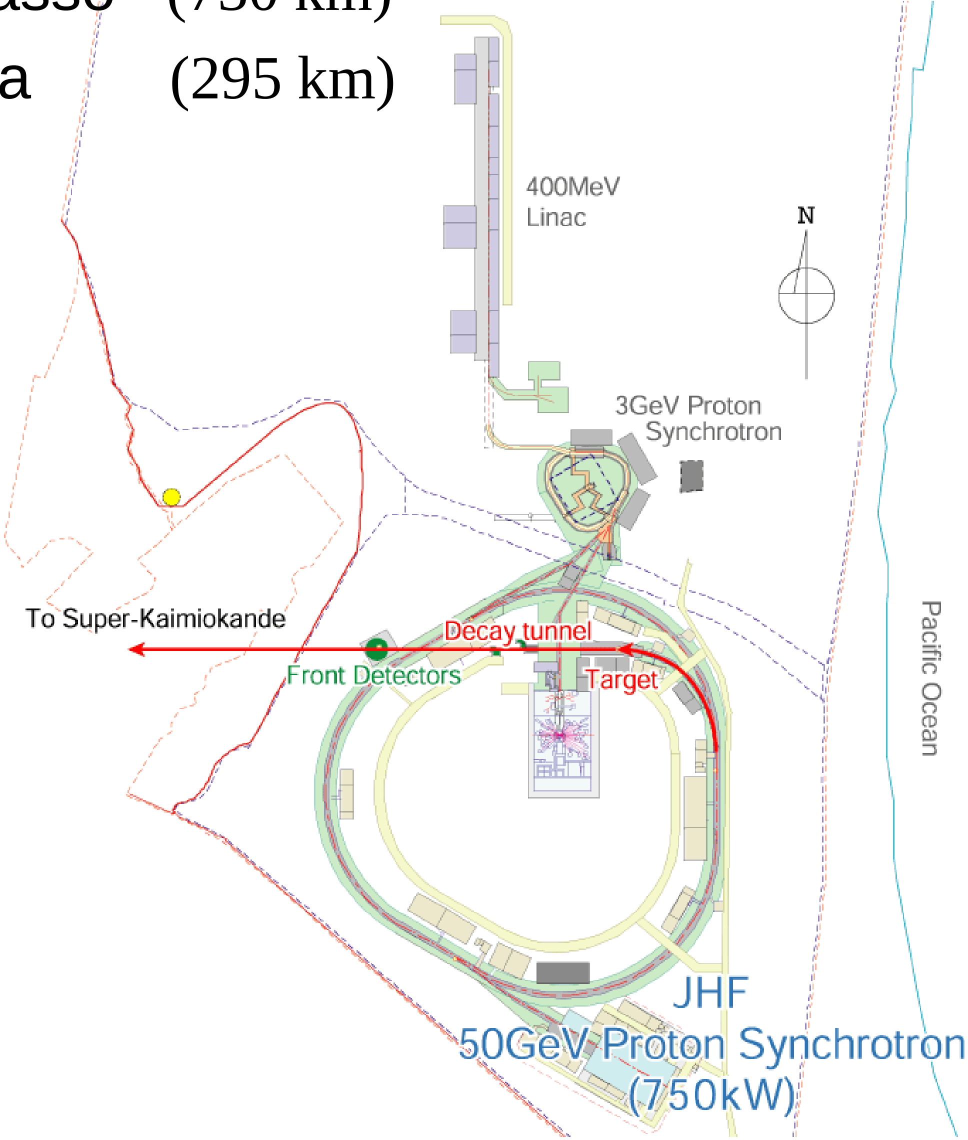
- using existing machines (CERN)
- medium life time $(\sim 1\ \mathrm{s})$
  light noble gas ions
  - compromise of neutrino flux and transport losses
  - light nuclei: higher γ
  - noble gas: low reactivity



Long baseline neutrino experiments

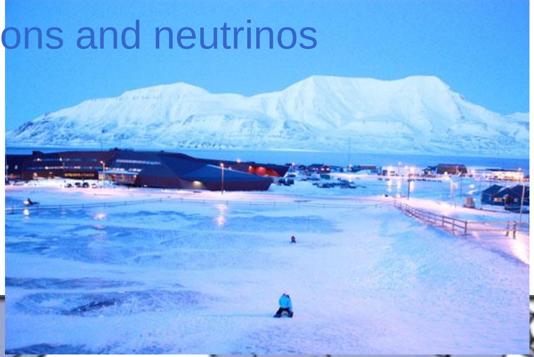
- In operation
  - **CNGS** CERN (SPS) ⇒ Gran Sasso (730 km)
  - **T2K** Tokai (J-PARC) ⇒ Kamioka (295 km)

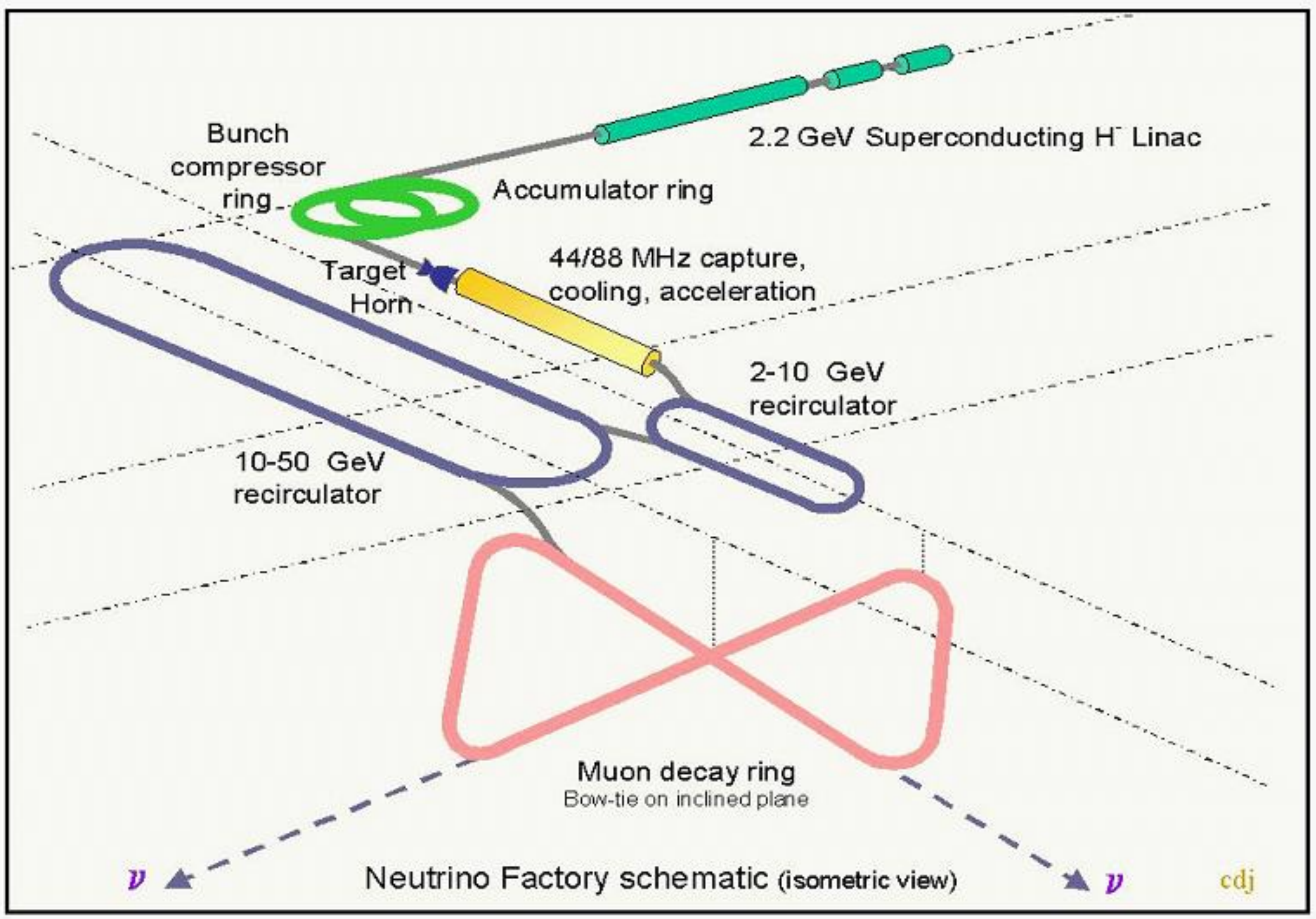




Multiple neutrino beams

- Neutrino beam apex towards detectors at different distances
- Projects at
  JAERI, CERN, BNL, FNAL, RAL





Neutrino Factory schematic (isometric view)

Muon accelerator challenges

- **multi-MW proton drivers*** → cyclotrons and linacs
- **multi-MW targets*** (π/μ production) → liquid metal jet
- **pion/muon capture** → magnetic horn, multi-Tesla solenoids
- **phase rotation** (de-bunching) → drift & buncher or FFAG
- **muon cooling** (compression of 6d-phase space) → ionization cooling channels
- **muon acceleration** (very fast acceleration) →
  - recirculated linacs (RLA)
  - rapid cycling synchrotrons (RCS)
  - fixed field alternating gradient cyclotrons (FFAG)

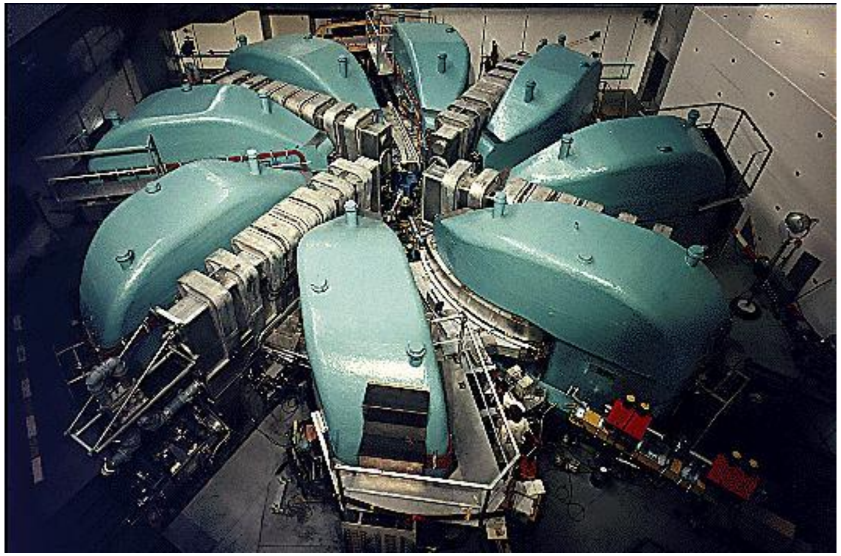
---

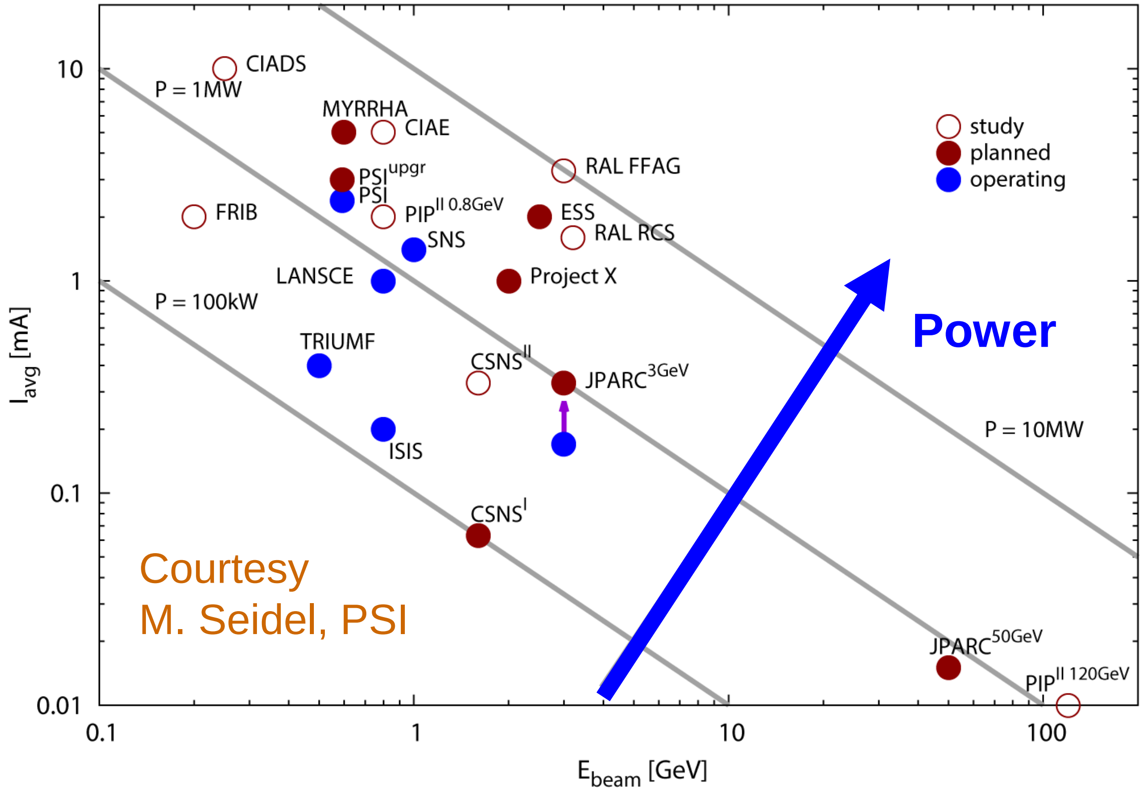
*common interest with spallation neutron sources for materials research and energy production

Megawatt proton drivers

Cyclotrons

PSI **HIPA**: $P = 1.4$ MW
(operational)



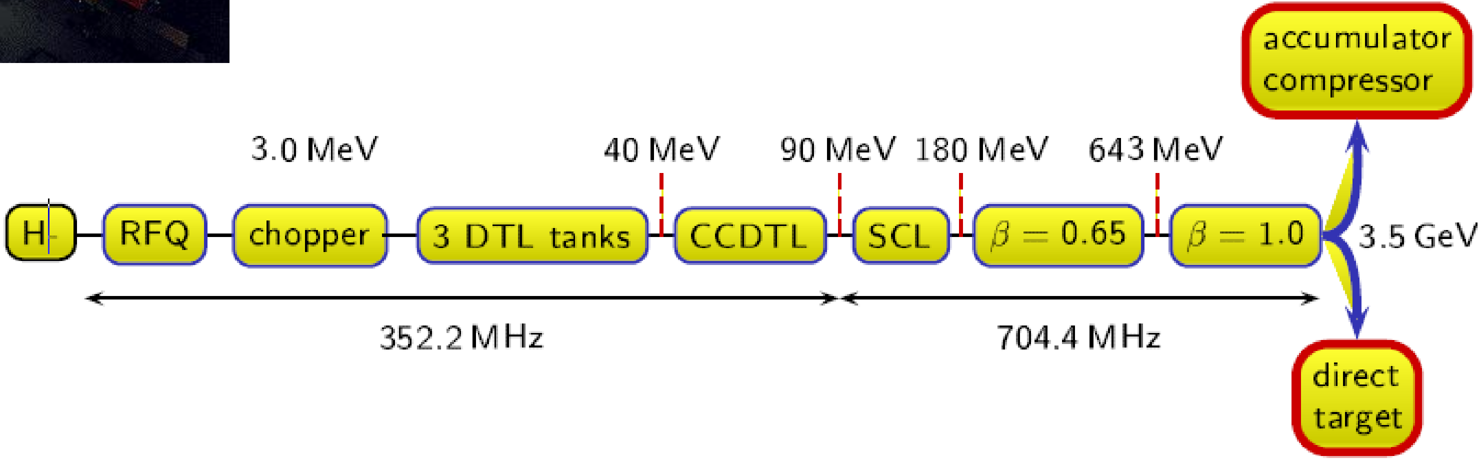


Courtesy
M. Seidel, PSI

Linacs

CERN **SPL**

$P = 4..5$ MW



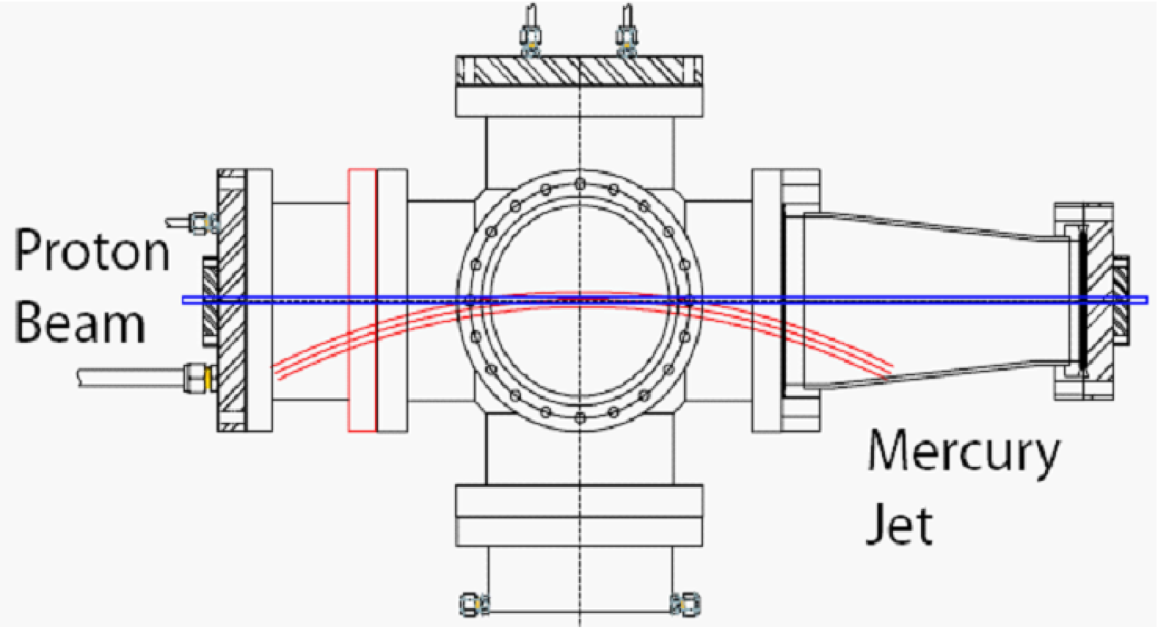
Megawatt targets

Challenge: thermal stress (MW in small volume) and nuclear activation

⇦ PSI rotating graphite wheel target for pion production: ≈ 100kW, operating temperature 1700ºC, lifetime ~1 year

PSI **MegaPie** liquid metal (Pb/Bi) ⇨ target for **SINQ** neutron source (1 MW)

⇩ BNL design for liquid metal jet target



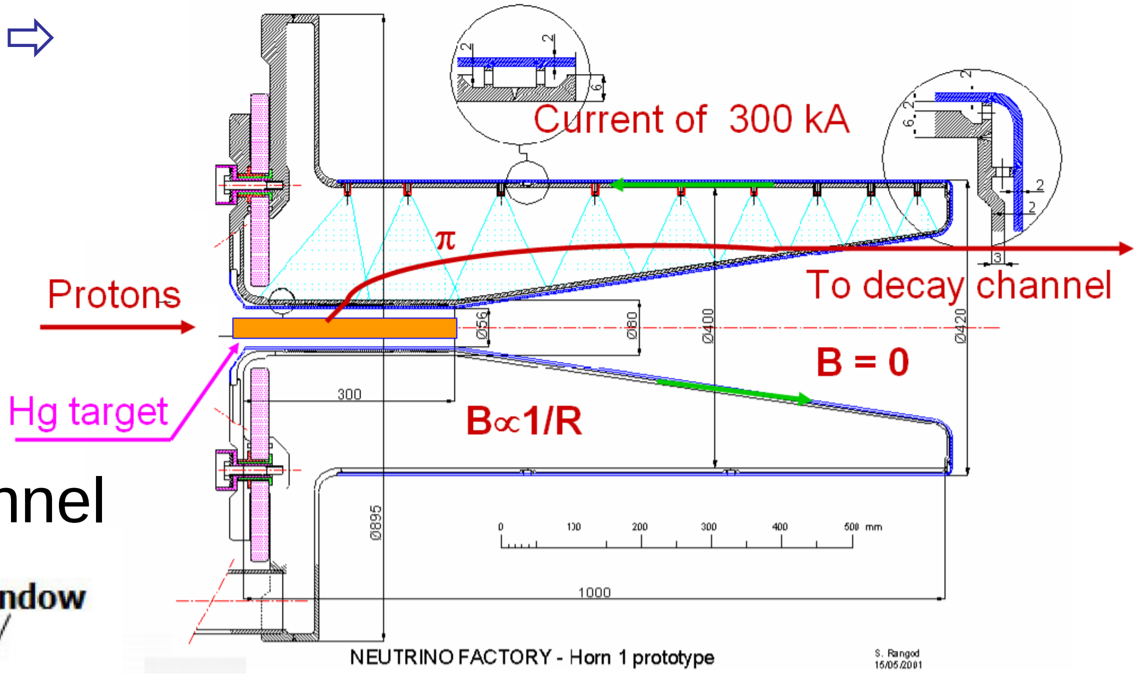
Pion capture

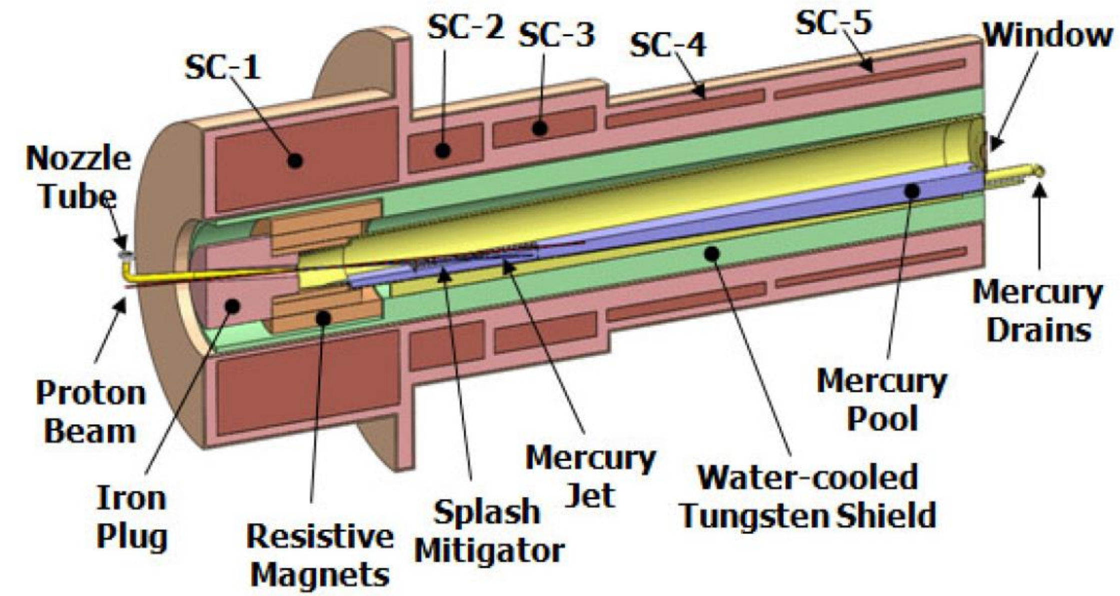
Challenge: focus divergent beam with wide energy spectrum

CERN **CNGS** magnetic horn ⇘ ⇨

CERN **MERIT** experiment ⇩

- ◆ mercury jet target
- ◆ 24 GeV proton beam
- ◆ 20 T pulsed copper coil
- ◆ superconducting solenoid channel





K.T.McDonald et al., THE MERIT HIGH-POWER TARGET EXPERIMENT AT THE CERN PS, IPAC-10

Energy → phase rotation

Drift space (after target & capture):

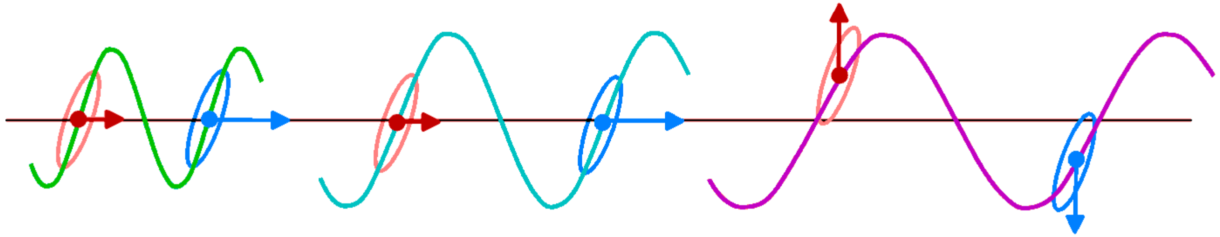
- ◆ pion → muon decay
- ◆ ballistic *de*-bunching

Muon beam longitudinal phase space:

- ◆ large momentum spread (0...500 MeV/c)
- ◆ long bunch (100 m)
- ◆ nonlinear shape

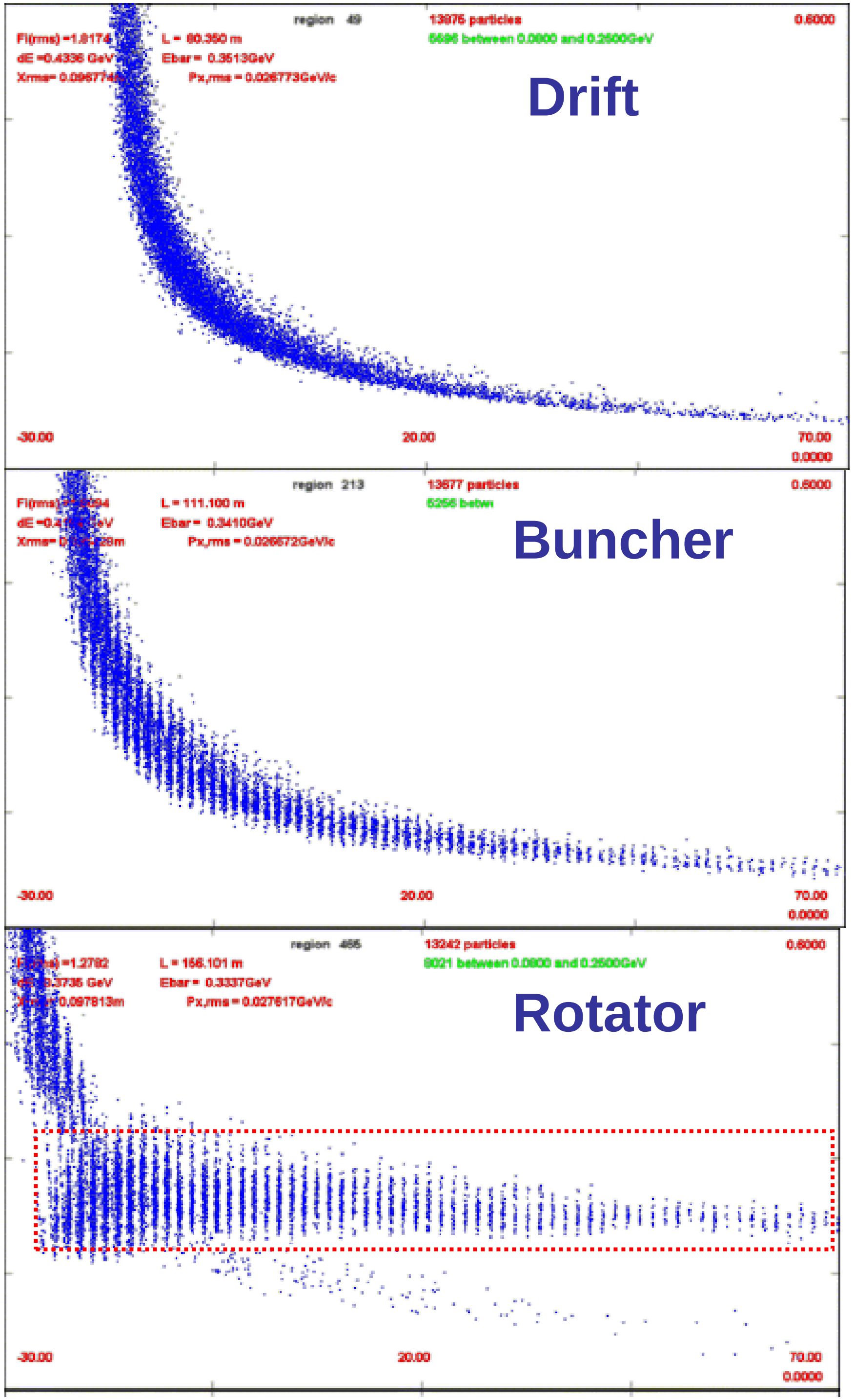
→ not acceptable by RF

Buncher & Rotator: series of RF cavities
with staggered frequencies



⇒ 40 bunches, 201 MHz, p=232 ± 23 MeV/c

from: D. Neuffer et al., *Muon capture in the front end of the IDS neutrino factory*, IPAC-2010



Ionization cooling

Electrons: radiation cooling

- decrease of total momentum due to radiation
- increase of p_s only by acceleration ⇒ damping of transverse momenta

but: increase of momentum spread due to stochastic photon emission

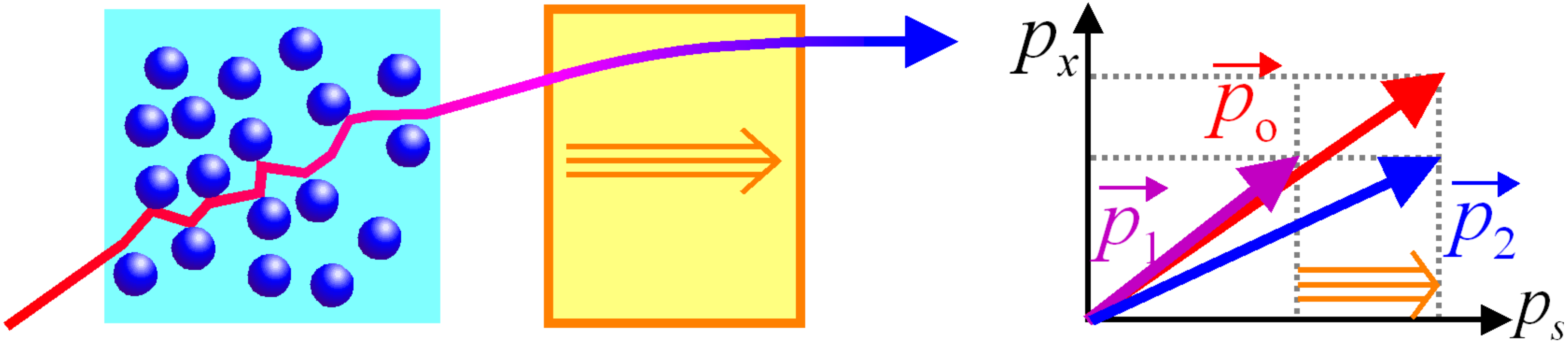
⇒ focus in bending magnets.

Muons: ionization cooling = friction

- decrease of total momentum due to multiple ionization of atoms
- increase of p_s only by acceleration ⇒ damping of transverse momenta

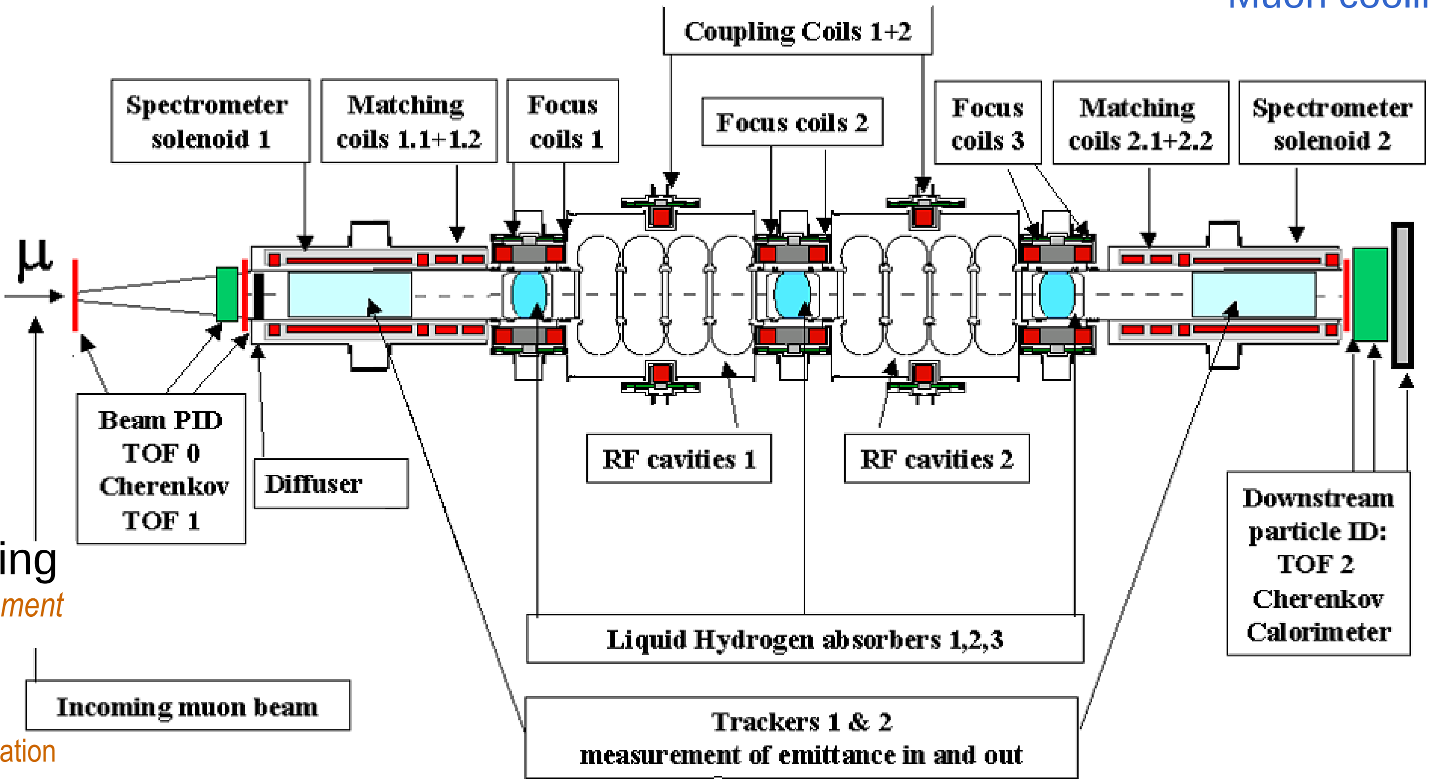
but: increase of momentum spread due to stochastic scattering events

⇒ focus in medium.



MICE
Muon Ionization Cooling Experiment

Layout ⇨



μ

Coupling Coils 1+2

Spectrometer solenoid 1

Matching coils 1.1+1.2

Focus coils 1

Focus coils 2

Focus coils 3

Matching coils 2.1+2.2

Spectrometer solenoid 2

Beam PID
TOF 0
Cherenkov
TOF 1

Diffuser

RF cavities 1

RF cavities 2

Downstream particle ID:
TOF 2
Cherenkov
Calorimeter

Liquid Hydrogen absorbers 1,2,3

Incoming muon beam

Trackers 1 & 2
measurement of emittance in and out

⇩ Simulations of emittance damping

Ref.: M. Appollonio & J. H. Cobb, *Emittance measurement in MICE,* J. Phys. Conf. Ser. 110(2008)122001

Muon preparation ⇨

Picture taken from K. Long, Presentation at MICE collaboration meeting 47, 2017

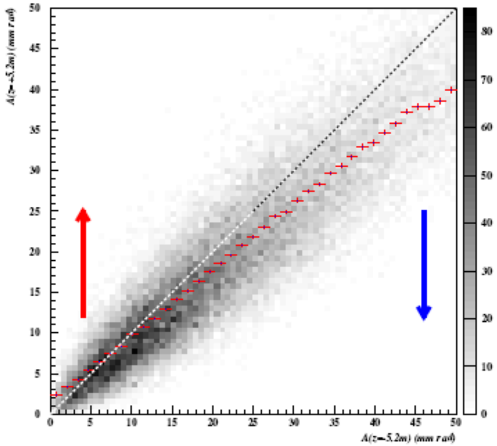


Figure 1. *Cooling of an $\epsilon_N^T = 6$ mm rad beam. Scatter plot: amplitudes evaluated after the channel (downstream tracker) versus the one computed in the first tracker.*

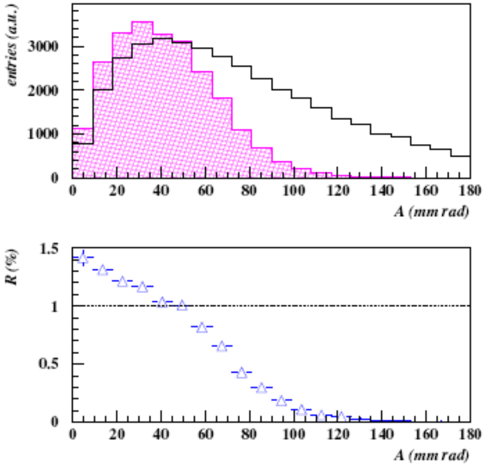
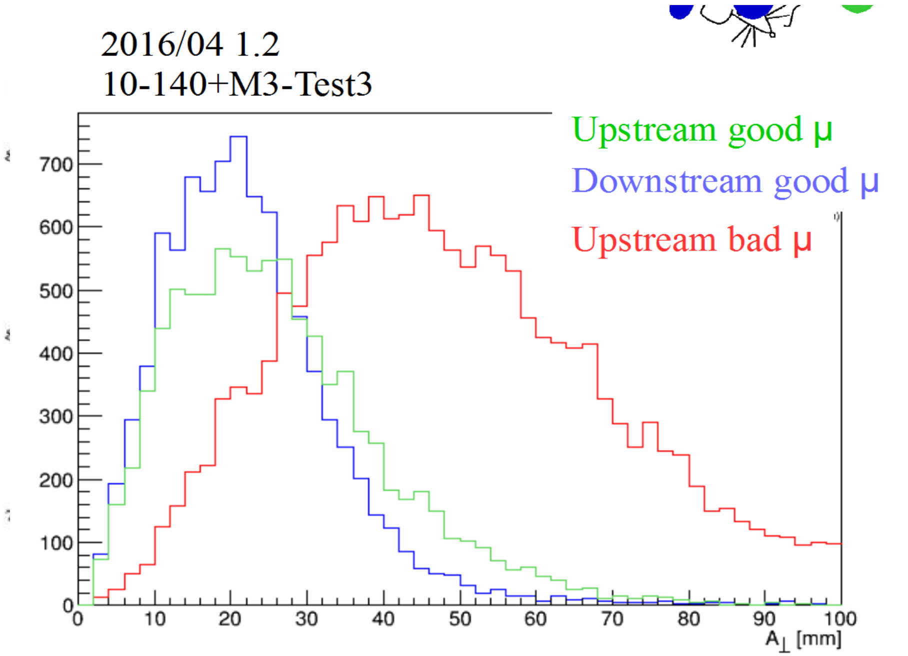
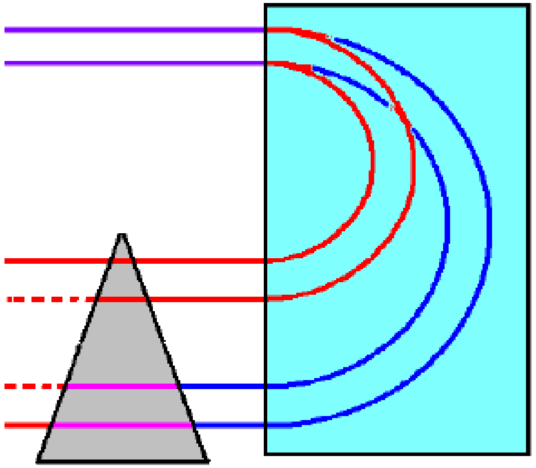


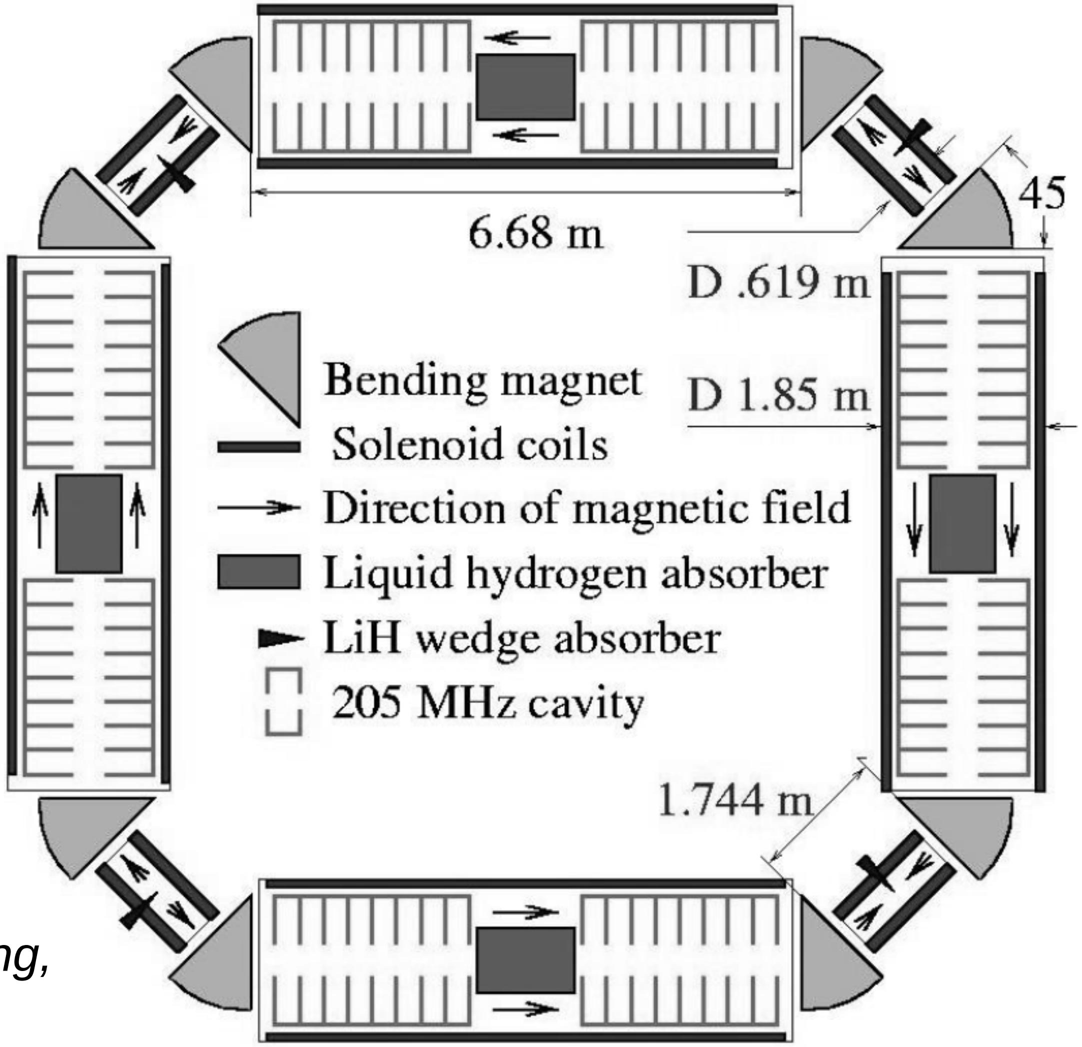
Figure 2. *(top) amplitude distributions before (solid line) and after (hatched histogram) the cooling channel ($\epsilon_N^T = 20$ mm rad). (bottom) ratio of the above histograms.*



6D-cooling

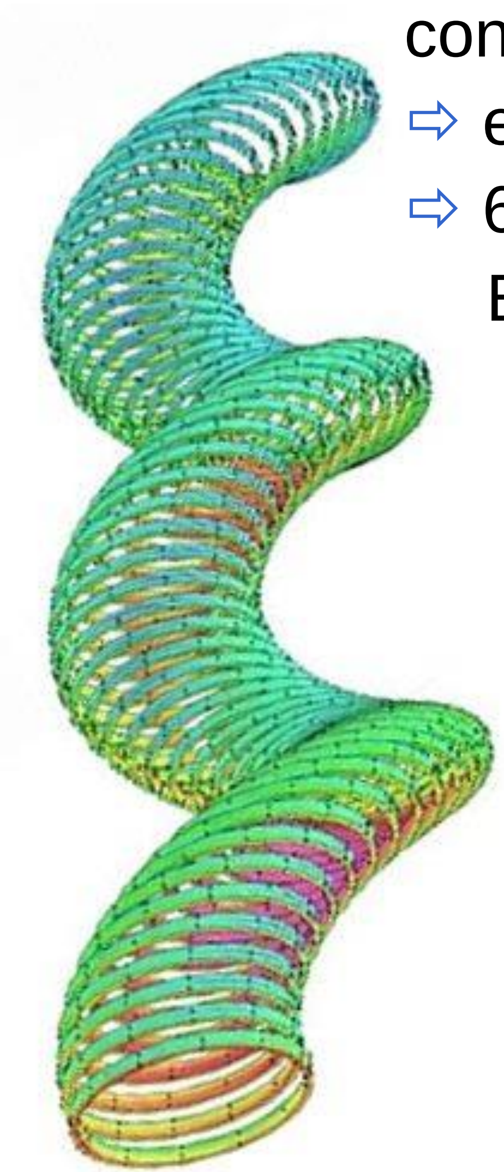
- Ionization cooling: transverse emittance reduction but increase of momentum spread
- Longitudinal cooling
  by dispersion: $\Delta p \rightarrow x$





- Muon cooling ring,
  e.g. **TETRA**
  Ref.: . Kahn et al., *TETRA muon cooling ring,*
  AIP Conf. Proc. Volume 721, pp. 387-390 (2004).

Helical cooling channels



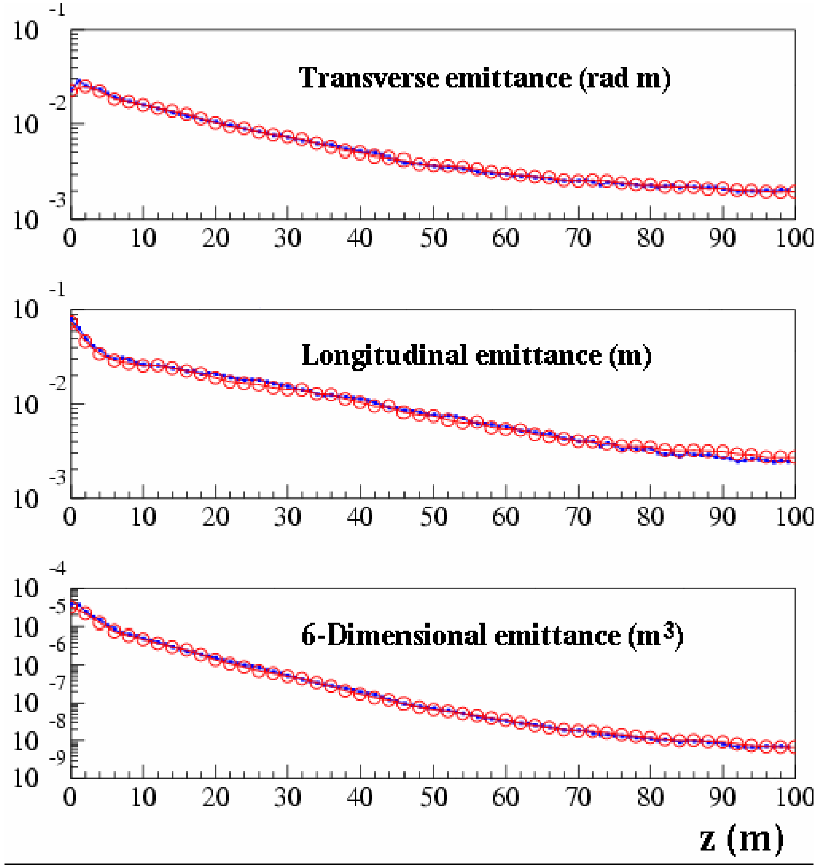
continuous focusing and dispersion along helical path

⇨ exchange transverse ↔ longitudinal

⇨ 6-D phase space cooling

Emittances as function of length

↓



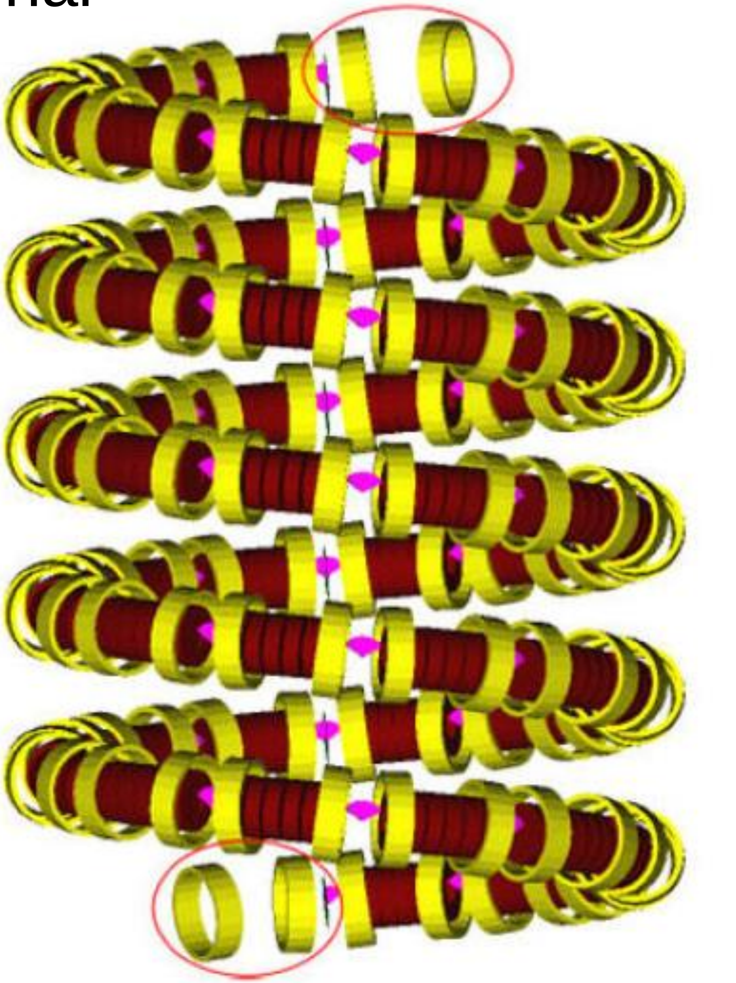


Figure 3: Schematic of the Guggenheim Cooling Channel. The RF cavities are in red, the solenoids in yellow and the LH_2 wedge-absorbers in pink.

Figures taken from Yonehara et al., PAC'05, p.3212 and Bross et al., Proc.COOL-2009

Muon acceleration

Acceleration has to be very fast!

Decay path length = $\gamma\tau \times \beta c = \beta\gamma \times 660\ \text{m} = p\ [\text{GeV/c}] \times 6.3\ \text{km}$

⇒ high accelerating gradients and compact machine (high bending fields)

- Linac
- RLA (Recirculating Linac Accelerator)
  - compact: “dog bone” recirculation tracks

    Figure from G.M.Wang et al., *Multi-pass arc lattice design for recirculating linac muon accelerators*, PAC-2009

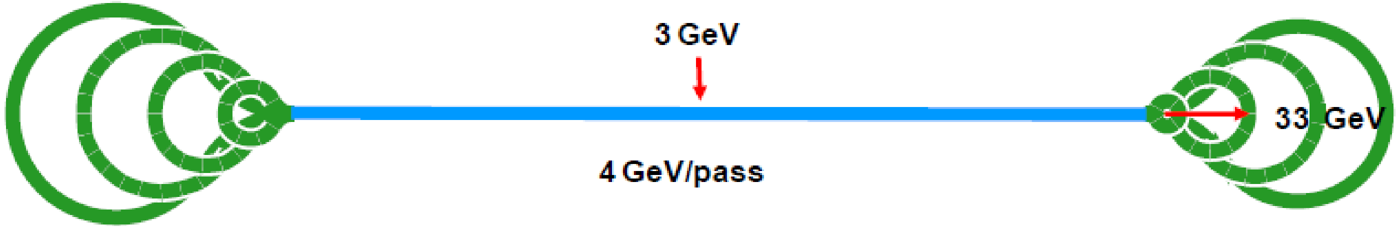
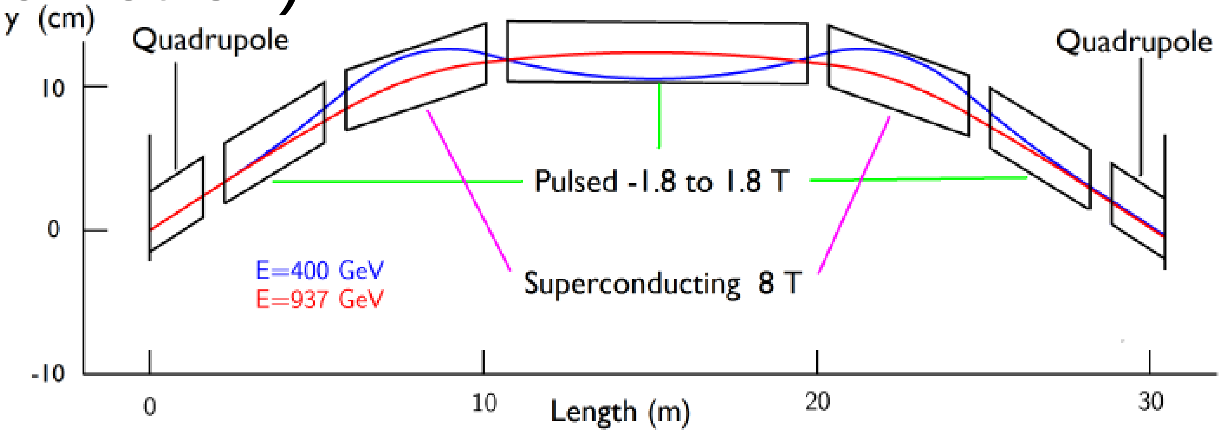


Figure 1: Layout of an 8-pass ‘Dogbone’ RLA with the top-to-injected energy ratio of 11.

- RCS (Rapid Cycling Synchrotron)
  - compact:
    s.c. magnets (8 T)
  - fast:
    pulsed n.c. magnets
    (–1.8 ⇨ +1.8 T)



FFAG (Fixed Field Alternating Gradient cyclotron)

Machine	Field	Radius	Frequency	Tunes Q(E)
Synchrotron & betatron	variable	fixed	fixed	constant
Microtron & cyclotron	fixed	variable	fixed	~constant
FFAG (scaling)	fixed	variable	variable	constant
FFAG (non scaling)	fixed	variable	fixed	variable

FFAG: + fast acceleration + large momentum aperture ⇨ *muons!*

Scaling FFAG:

- ◆ fast acceleration
- ◆ avoid resonance crossing
- ⇨ tunes, betas etc. constant on ramp
- ⇨ wide orbit range
- ⇨ complicated magnet design

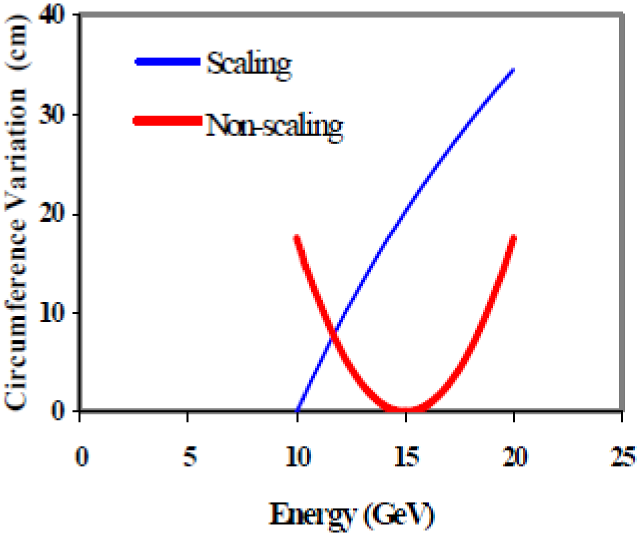


Figure 5: Scaling and non-scaling FFAG orbit patterns (above), and circumference variation with energy (below).

Non-scaling FFAG

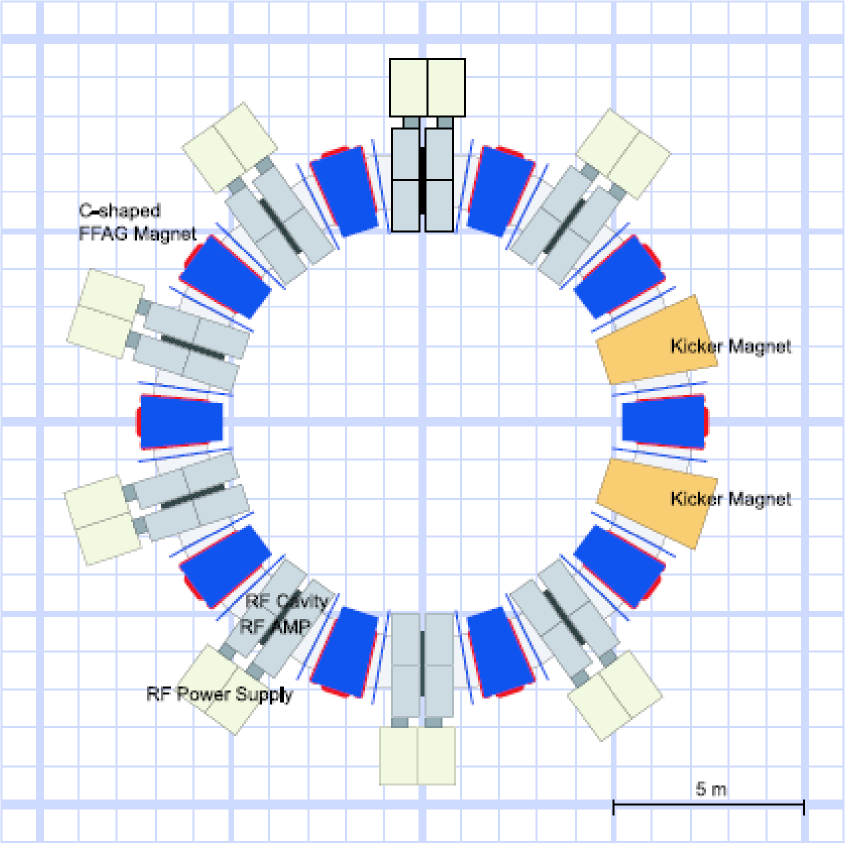
- ◆ even faster acceleration: few turns only
- ⇨ ignore resonances
- ⇨ keep RF constant
- ⇨ asynchronous acceleration (no bucket!)
- ⇨ stability ?

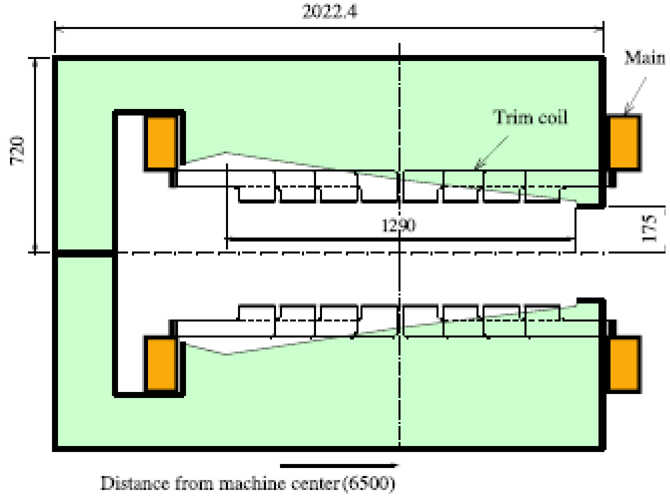
Ref. M. Craddock, Proc. PAC'05, p.261

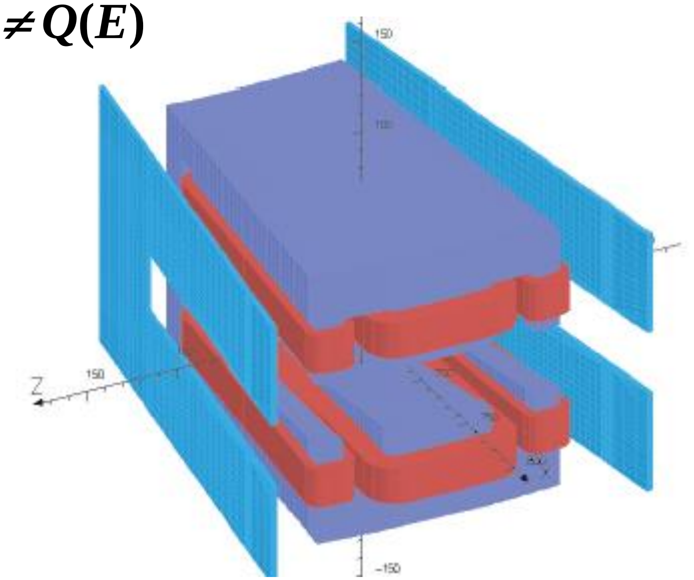
PRISM (Phase Rotated Intense Slow Muon beam) FFAG for muon phase rotation

phase rotation = 90º rotation in $(\Delta E, \Delta s)$ space to reduce energy spread on expense of bunch length

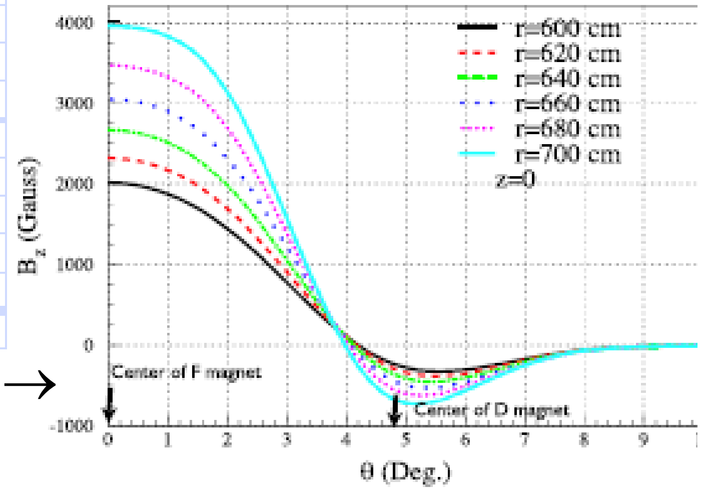
Challenging magnet design: wide aperture and achromatic, i.e. $Q \neq Q(E)$

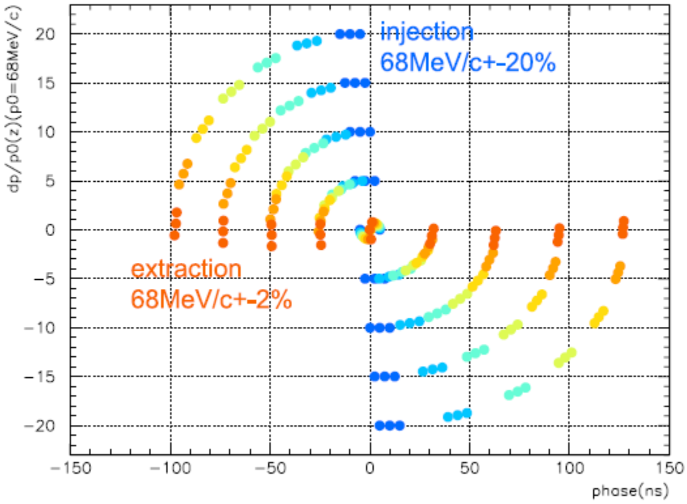






magnet field profiles →

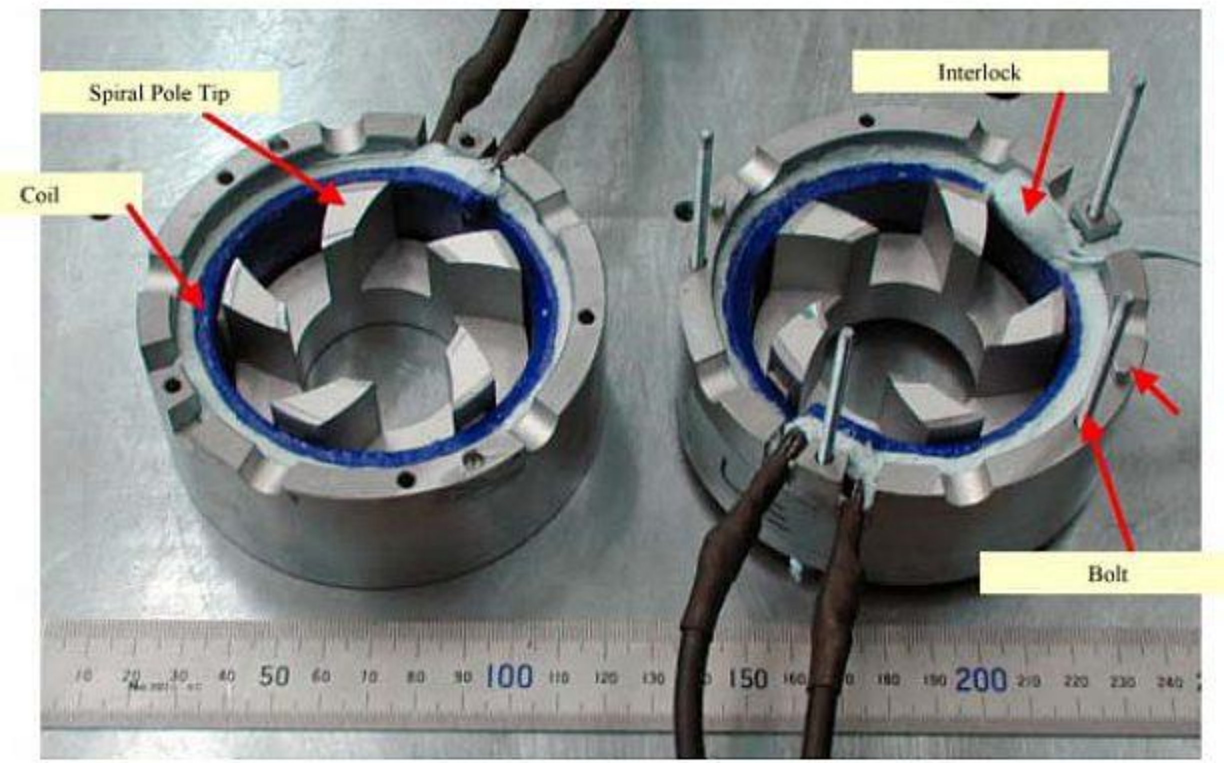




phase space motion

Ref.: A. Sato et al., *R&D status of the high-intense monochromatic low-energy muon source: PRISM,* IPAC-06

Scaling FFAGs



150 MeV proton
FFAG at KEK

↓

↑

LAPTOP

1 MeV electron FFAG for industrial and medical applications (∅ **10 cm** !)

Non-scaling FFAG

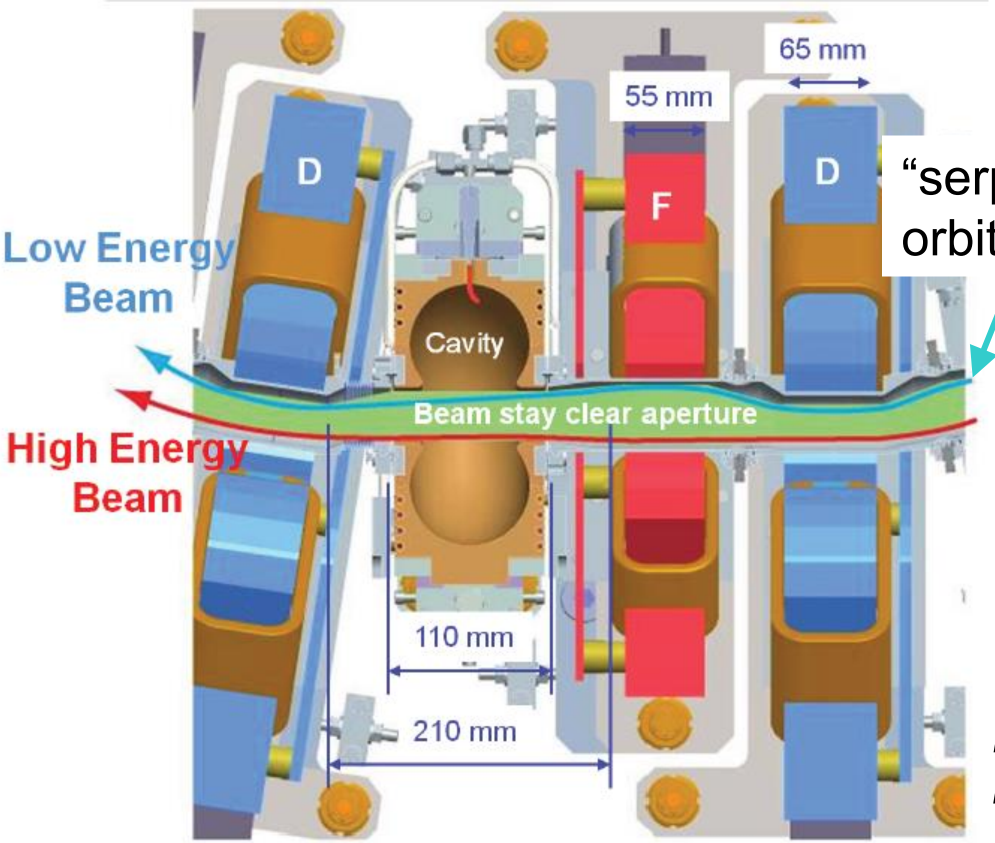
Prototype **EMMA** (Electron Model for Muon Accelerator)

Cockcroft Institute, Daresbury UK.

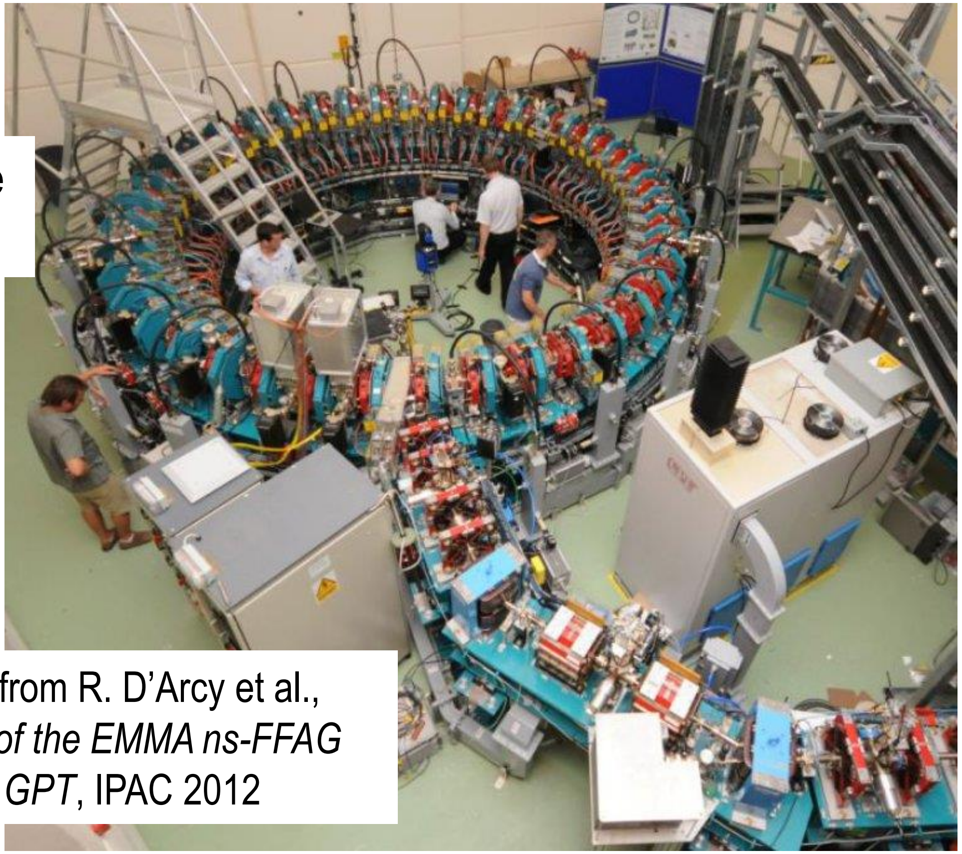
Ref.: R. Edgecock et al., *EMMA – the world's first non-scaling FFAG*, EPAC 2008

In operation (2011): electron acceleration 10 → 18 [20] MeV

Future plans: proton FFAG 10→20 GeV in 16 turns

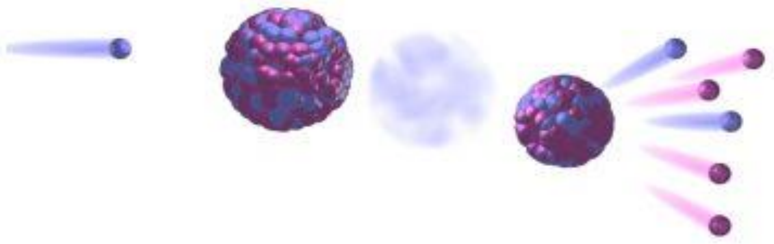


"serpentine orbit"



⇦ Figure from R. D'Arcy et al., *Modeling of the EMMA ns-FFAG ring using GPT*, IPAC 2012

Spallation neutron sources



Spallation: high energy proton excites nucleus
→ emission of several neutrons and protons.

Normalized yield neutrons/proton as function of incident proton energy →

Ref.: A. Letourneau et al., Neutron production in bombardments of thin and thick W, Hg, Pb targets by 0.4, 0.8, 1.2, 1.8 and 2.5 GeV protons, Nucl. Instr. and Meth. in Phys. Res. B 170 (2000) 299-322

⇨ requires **GeV**-proton beam of **MW** power

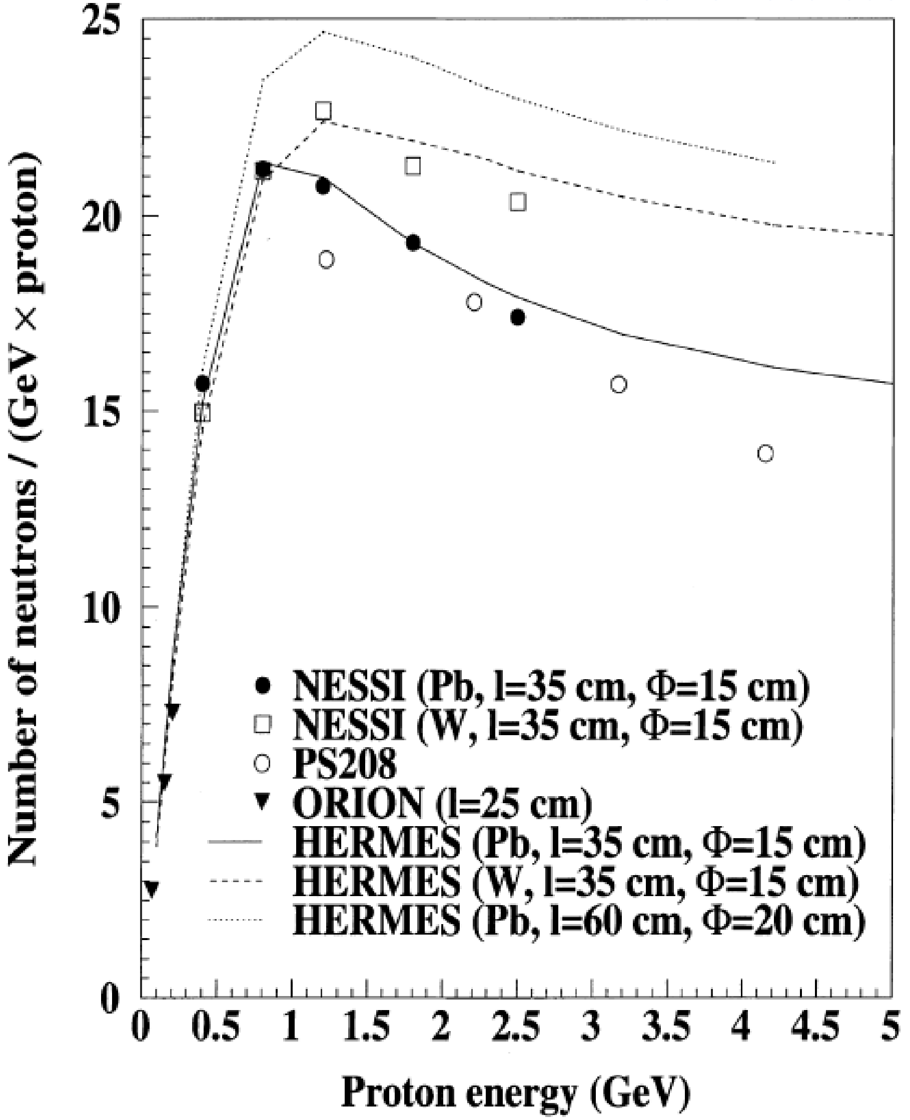
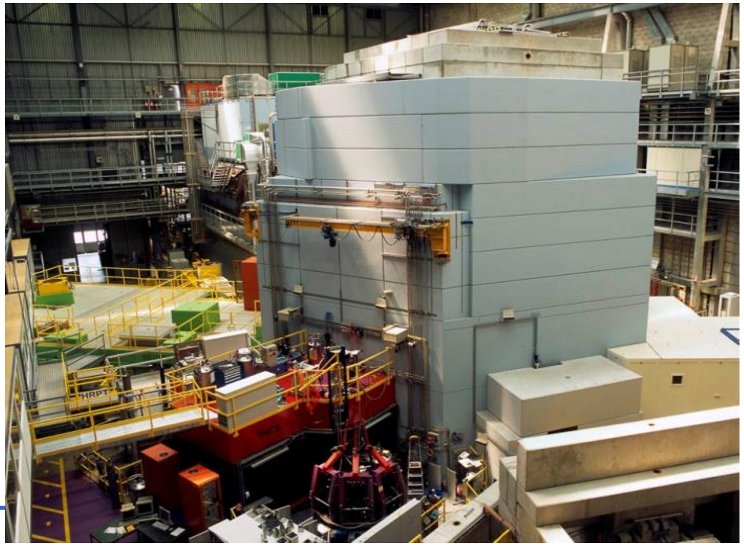


Fig. 16. Average neutron multiplicity (fully corrected) per unit energy (expressed in GeV) and per incident proton as a function of beam energy. Previously published data at high (PS208) [10]) and low energy (ORION [12]), respectively, have been added up to the present (NESSI) data. Statistical errors are within the symbol sizes. The solid, dashed and dotted curves are the results of HERMES simulations for Pb: 35 × 15 cm, Pb: 60 × 20 cm and W: 35 × 15 cm targets, respectively.

SINQ

Spallation neutron source at PSI for **materials research** (includes **MEGAPIE** liquid metal target)



SNS and ESS

Spallation
Neutron Source
Oakridge, USA

Power: 1.4 MW
1 GeV protons
n.c linac → 200 MeV
s.c. linac → 1 GeV
liquid Hg target
start of operation 2006
budget 1.4 G$

☜SNS liquid Hg target

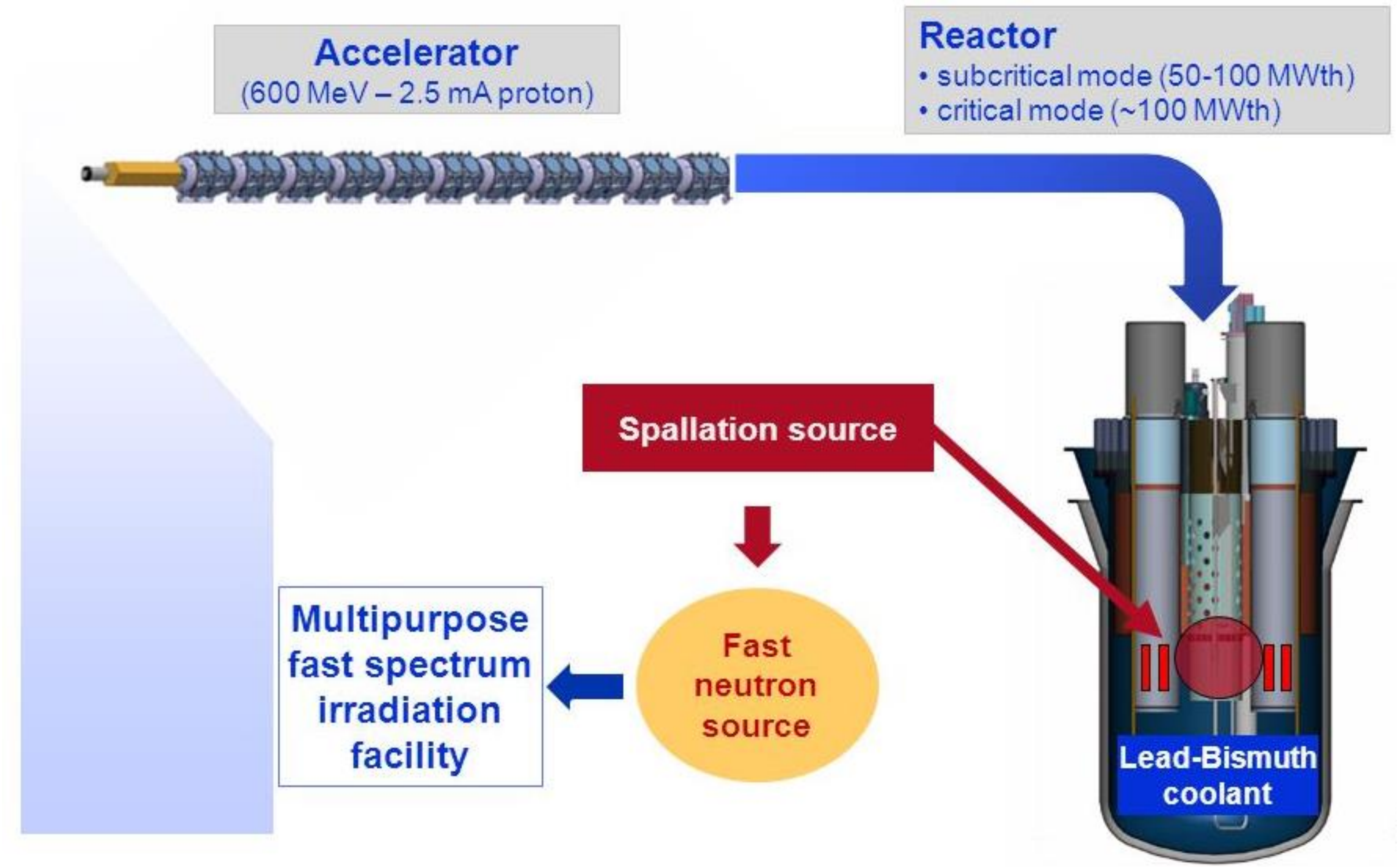
☜ESS artist's view

European
Spallation Source
Lund, Sweden
18 partner countries
Power 5.0 MW
1 GeV protons
n.c linac → 400 MeV
s.c. linac → 1 GeV
liquid Hg or Pb target
start of project 1993
decision on site 2009
start of operation 2019
fully operational 2025
budget 1.5 G€

MYRRHA

Multi-purpose hYbrid Research Reactor for High-tech Applications

- from spallation neutron source to accelerator driven nuclear reactor



H. A. Abderrahim, MYRRHA, SCK.CEN 2012

ADS: accelerator driven “system”

= accelerator driven nuclear fission reactor

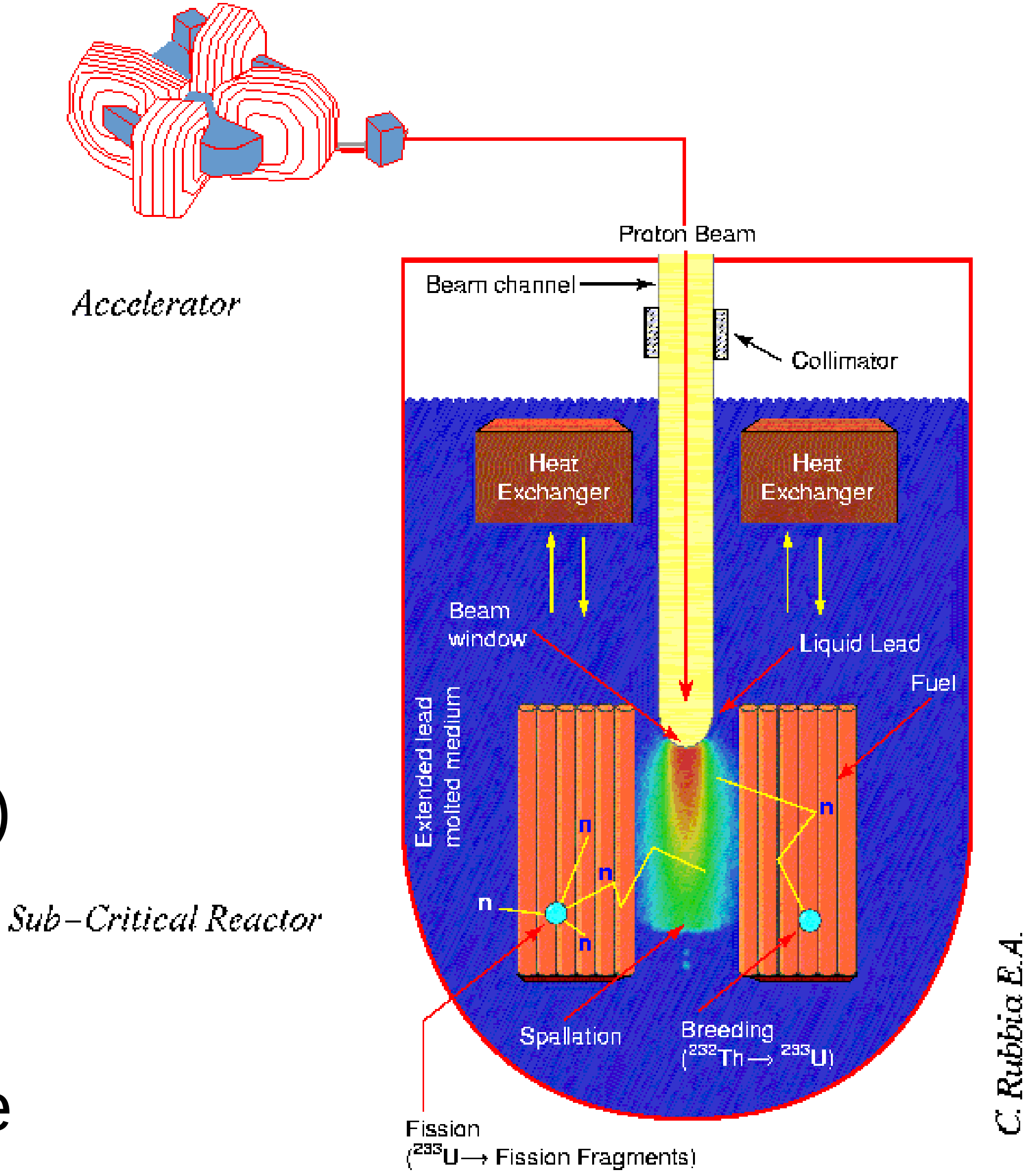
= spallation neutron source

Synergy with muon accelerators

- multi-MW proton accelerator
- multi-MW liquid metal target

ADS advantages (promises)

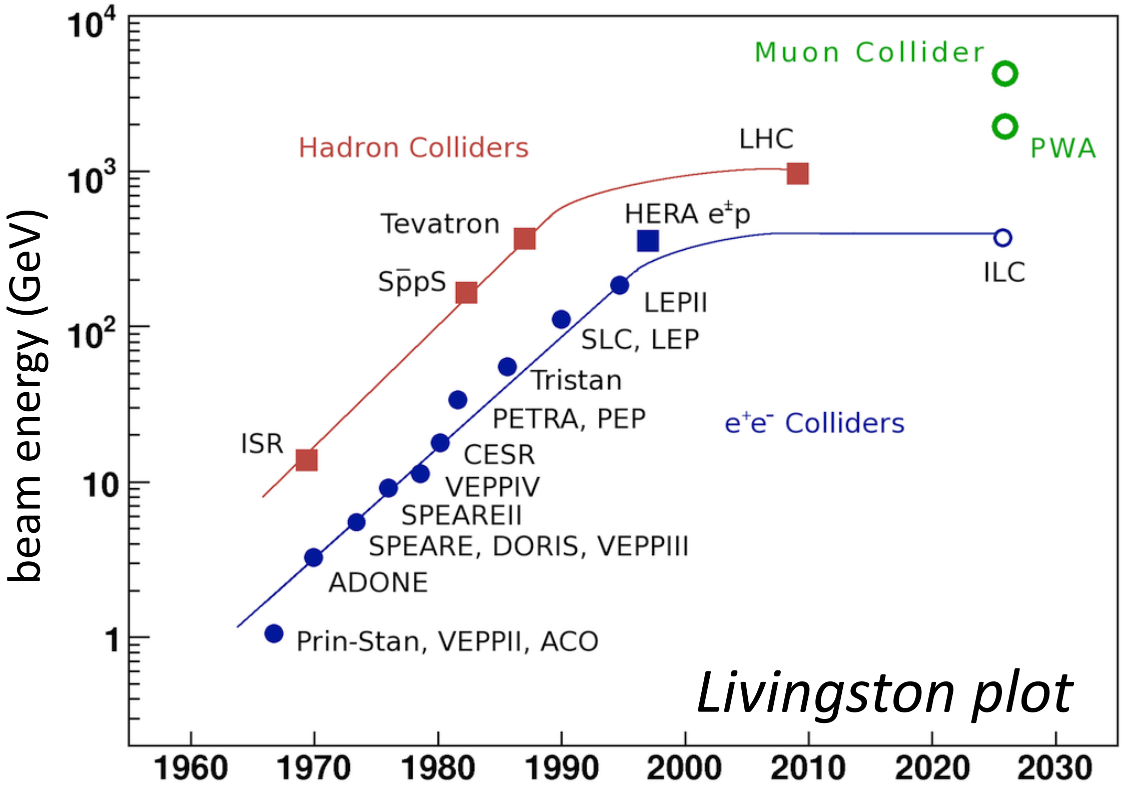
- sub-critical: inherent safety
- nuclear waste incineration
- little transuranic production (^{239}Pu)
- reduced risk of proliferation
- fuel breeding: $^{232}\mathrm{Th} \rightarrow {}^{233}\mathrm{U}$
- more tolerant to bad maintenance



C. Rubbia E.A.

Outlook: new accelerating techniques

- Electrostatic accelerators: < 10 MV
- RF accelerator (linac) gradient: ≤ 100 MV/m
  - get 10 MeV in < 1 m
  - periodicity: basically, maximum energy is unlimited, but...
    ⇨ Particle physics: > 10 km for > 1 TeV ⇨ **ILC, CLIC**
- Compact machines of higher energy
  - muon collider
  - new accelerating techniques, e.g. plasma wakefield accelerator (PWA):
    ⇨ 10..100 GV/m

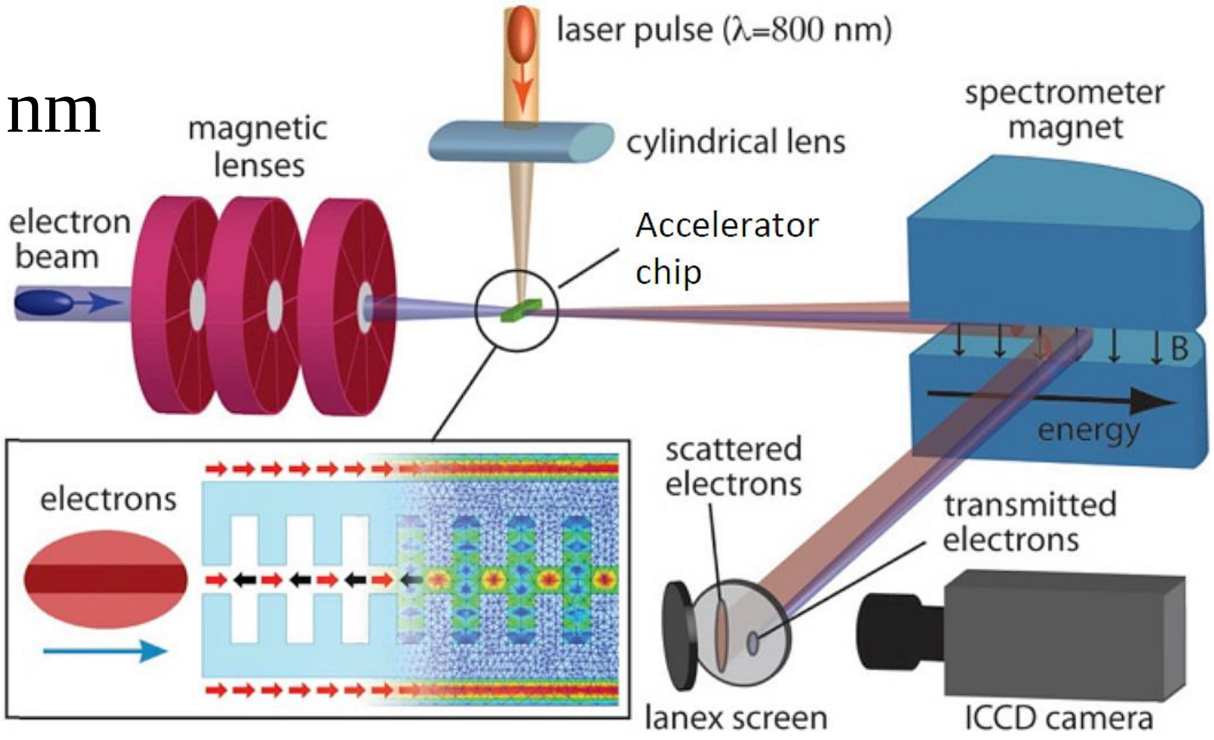


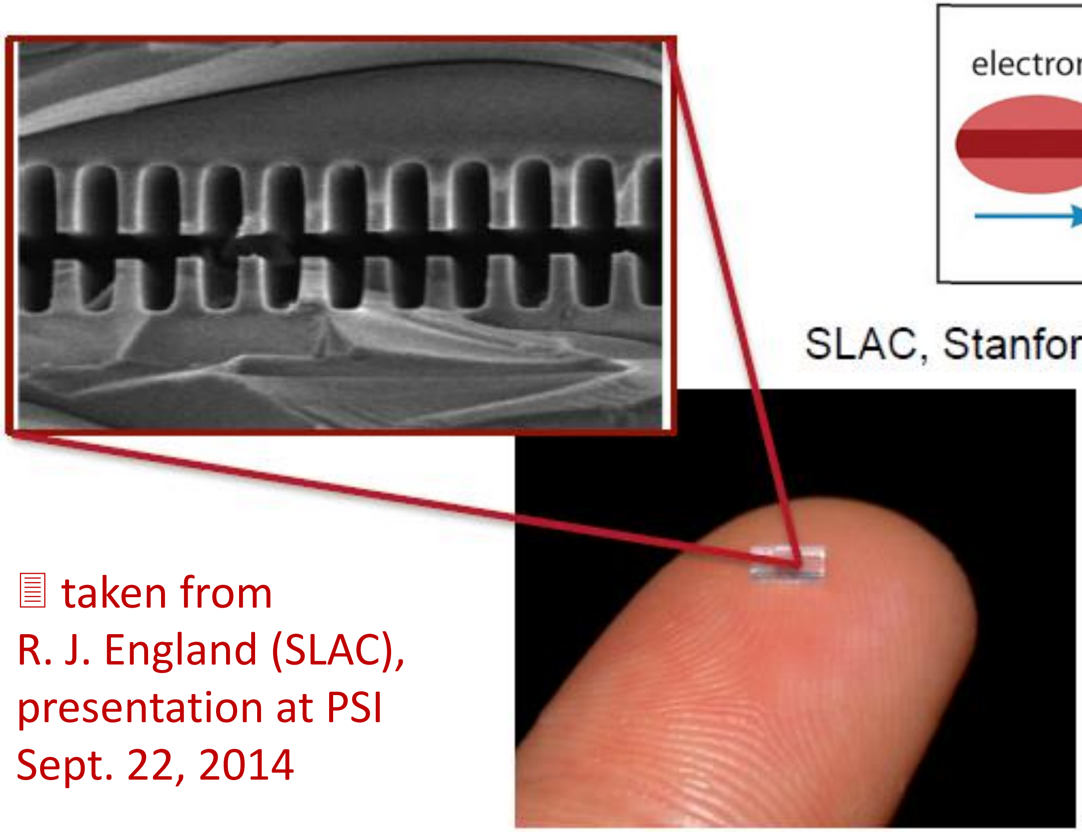
Dielectric laser acceleration

"Accelerator on a chip"

Linac microstructure, $\lambda \sim 800$ nm driven by high power laser

Gradients up to 700 MV/m ✓
up to 10 GV/m possible ?





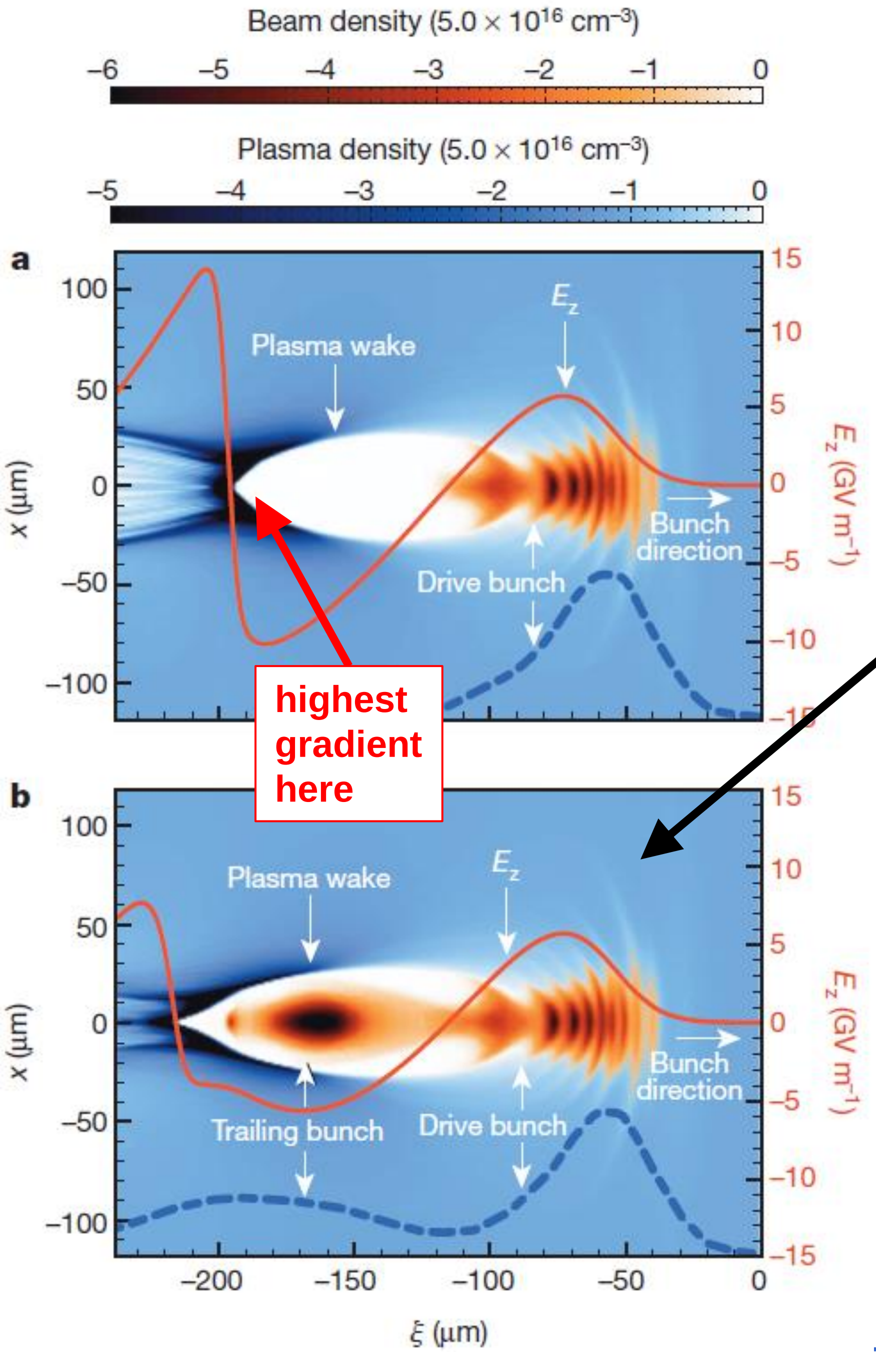
SLAC, Stanford

taken from
R. J. England (SLAC),
presentation at PSI
Sept. 22, 2014

Micro accelerator on chips

- Linacs
- Beam position monitors
- Undulator magnets
- etc.

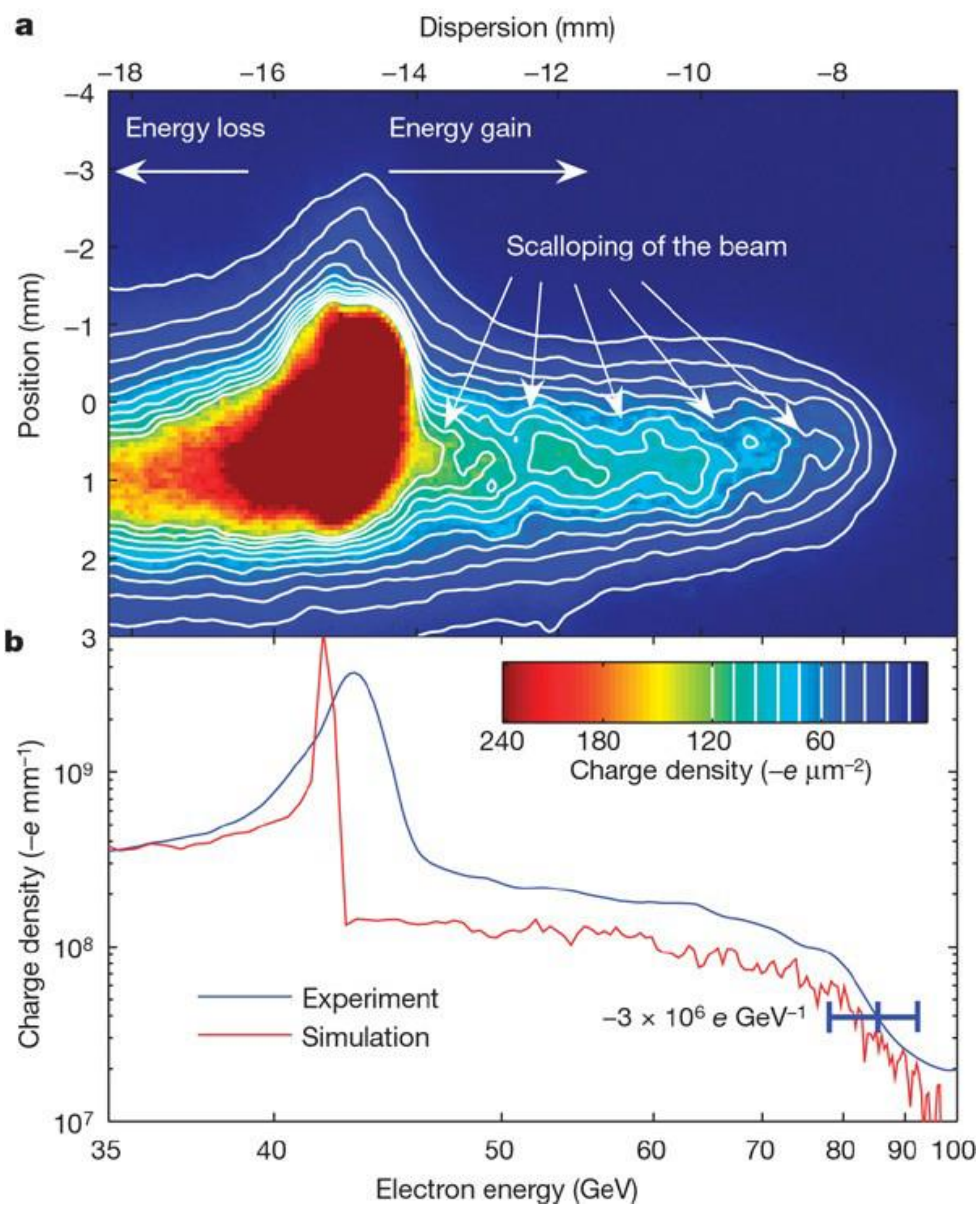
Plasma wakefield acceleration



highest gradient here

- Wakefield in plasma generated by laser pulse or by particle beam
- ΔE = 42 GeV in 85 cm (49 GV/m), but little charge

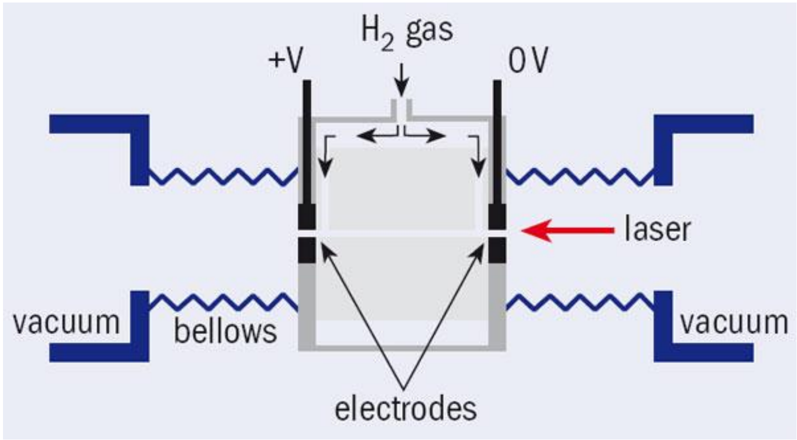
  figure next slide ⇨
- Drive bunch and trailing bunch:
  - substantial charge (75 pC)
  - small energy spread (<2%)
  - Gradient 4.4 GV /m (>> RF linac)
  - up to 30% energy transfer efficiency drive bunch ⇨ trailing bunch
- **FACET** at SLAC
  - I. Blumenfeld et al., Nature 445, 741 (2007)
  - M. Litos et al., Nature 515, 92 (2014)

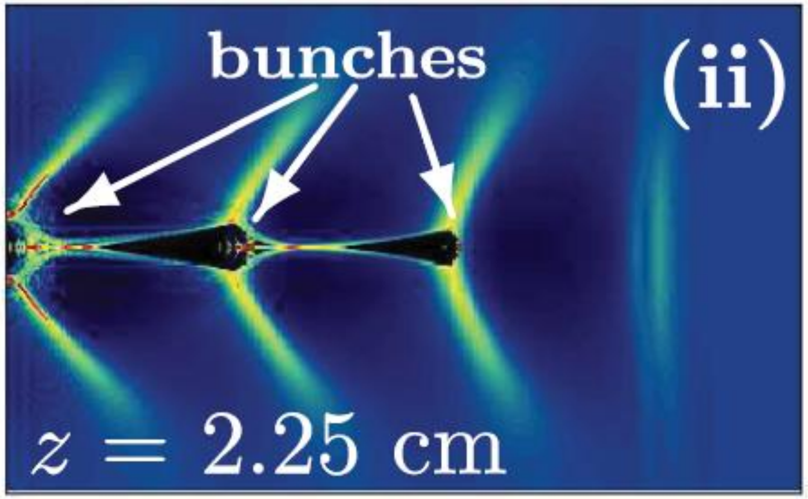


SLAC proof of principle 2007

I. Blumenfeld et al., Nature 445, 741 (2007)

Laser plasma wakefield





LBNL experiment

- 300 TW laser 50 fs pulse
- 4.2 GeV in 9 cm (47 GV/m)

W. P. Leemans et al., PRL 113, 245002 (2014)

LHC status and plans

- June 2017 $\mathcal{L} = 1.58 \cdot 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (Design: $1 \cdot 10^{34}$)
- Accelerator availability due to failures 62%
  - for comparison: SLS 97.6 % (2005-2016)
- Beam collisions: 20% of available time

LHC is rather an experiment than a user facility

- 2019-20 shutdown: injector overhaul
  - PS proton synchrotron injector in operation since 1959!
- 2020-23 run at $\mathcal{L} \rightarrow 2 \cdot 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- 2024-26 high luminosity upgrade $\mathcal{L} \rightarrow 5 \cdot 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
  - crossing angle 500 mrad: avoid parasitic collisions
  - new interaction regions (wide aperture quadrupoles 12 T peak field)
  - crab-cavities for head-on collision of crossing bunches
- Operation schedule until 2037

O. Brüning (CERN), presentation at PSI, Oct. 5, 2015