Feasibility Study for a Biomedical Research Facility at CERN

PARTNER Meeting

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Contents:

Need for Basic and Applied RB Research:

Radiobiological Research is needed

- Protons and Carbon ions in **clinical use**
  - superior dose distribution should give better clinical outcomes, but so far **limited evidence** for clinical superiority
  - **other ions** (He, Li, B, O) could offer **ballistic advantages** compared to Protons and **less fragmentation** compared to Carbon ions
- **incoherent** sets of data (radiobiological and clinical) with very **different experimental conditions**
- **new dosimetry and imaging** modalities needed

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- **incoherent** sets of data (radiobiological and clinical) with very **different experimental conditions**
- **new dosimetry and imaging** modalities and instruments need to be developed to bring ion beam therapy to its full potential

Lack of Beamtime

European facilities providing **ion beams with energies** $> 50\,\mathrm{MeV/n}$

- **nuclear physics laboratories**
  - GANIL (FR), INFN LNS (IT), KVI/AGOR (NL)
  - GSI (DE), ITEP (RU), JINR (RU)

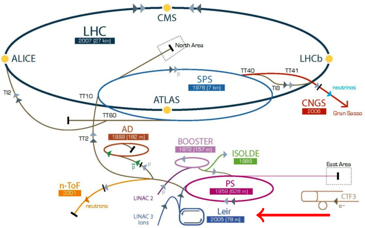
► **limited time availability**

- **ion beam therapy centres**
  - HIT (DE), CNAO (IT)
  - soon MedAustron (AT)

► only **limited range of ions, priority given to clinical use**

Action from *Physics for Health in Europe* workshop 2010:

A ***biomedical research facility****, supported* ***by a consortium of laboratories****, to be made available* ***at CERN*** *to the international scientific community. The facility will provide* ***particle beams of different types and energies*** *to external users interested in radiobiology and detector development*



- **LEIR** (Low Energy Ion Ring) part of injection chain for LHC ion programme
- **not used all the time**
- energy range ∼ **ion beam therapy energies**
- **ancillary space** for experiments and laboratories

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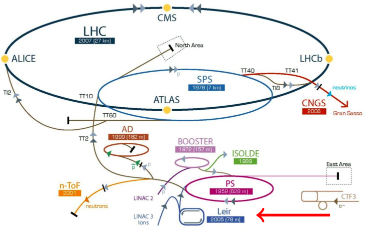

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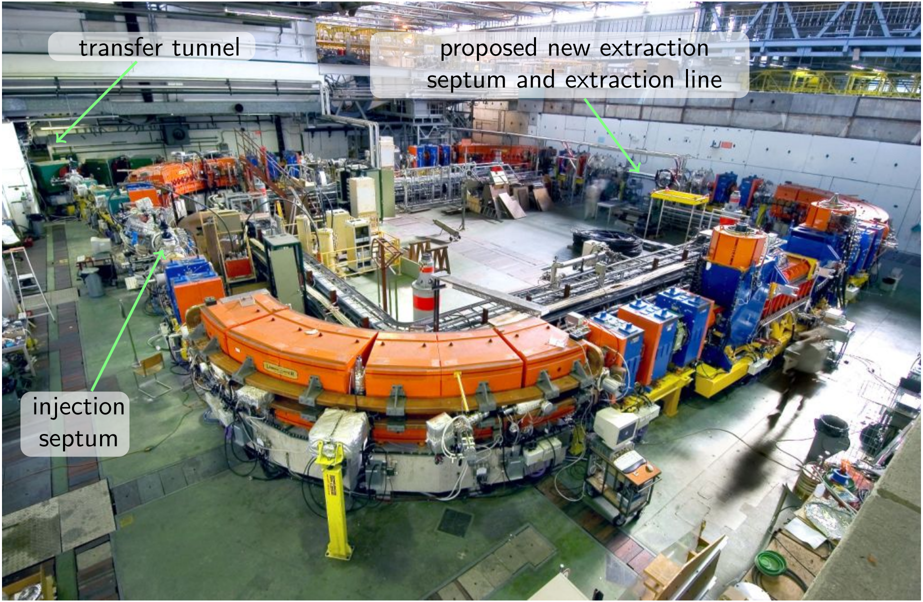
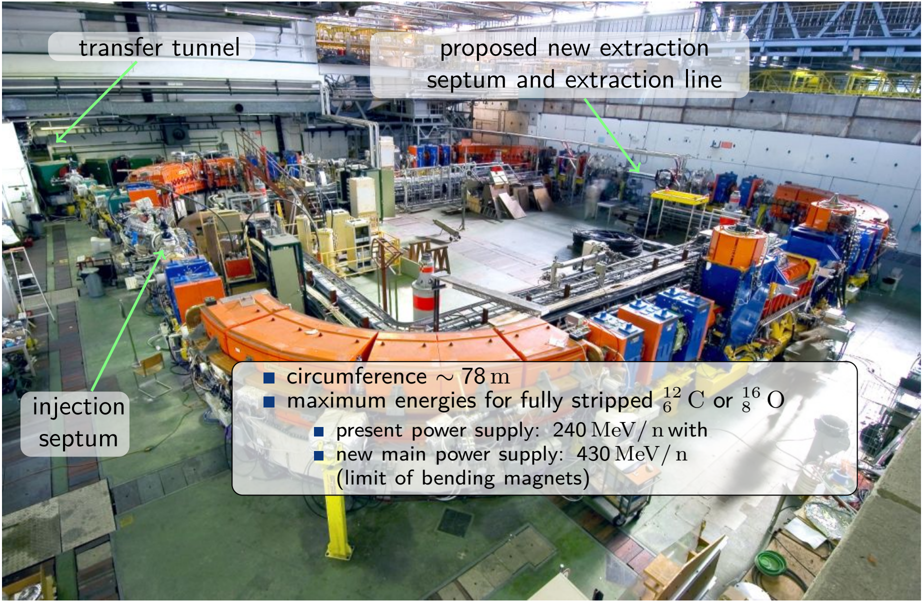
Strong Interest from Community

- success of recent brainstorming meeting with potential users: **over 200 participants**
- **proposal paper** to *European Strategy for Particle Physics Open Symposium* (10-12 September, Krakow)

LEIR


transfer tunnel
proposed new extraction septum and extraction line
injection septum

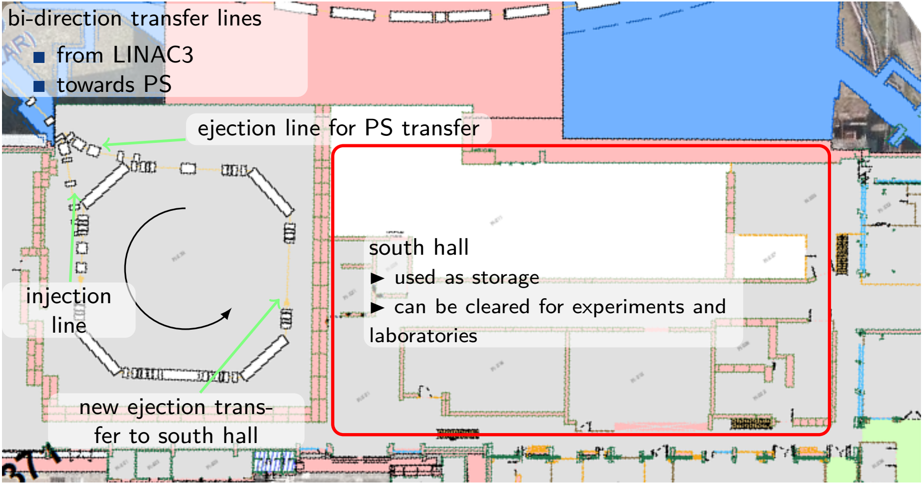
LEIR



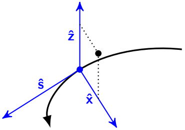
- circumference $\sim 78\,\mathrm{m}$
- maximum energies for fully stripped ${}^{12}_{6}\mathrm{C}$ or ${}^{16}_{8}\mathrm{O}$
  - present power supply: $240\,\mathrm{MeV/n}$ with
  - new main power supply: $430\,\mathrm{MeV/n}$ (limit of bending magnets)

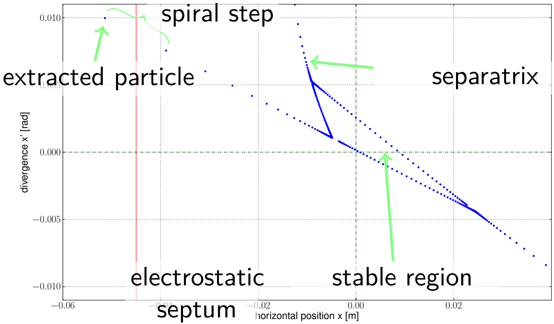
- **new ion source** and modifications in preacceleration chain to deliver **light ions**
- **transferlines** to experiments
- **infrastructure for experiments** required

- **new ejection** towards south hall needed
  - **slow ejection** preferable for experiments
  - easier to implement than fast ejection



- **standard method** for **extracting particles over many turns** ($\sim 10^6$)
  - fine control of particle flux
- uses **third order resonance**
  - particle tune multiple of $\pi/3$
  - particles at same point in phasespace every 3rd turn
- **amplitude** of motion **builds up due to sextupole kicks**
- stable part of phasespace adopts **triangular** shape
- unstable **particles diverge along separatrices**

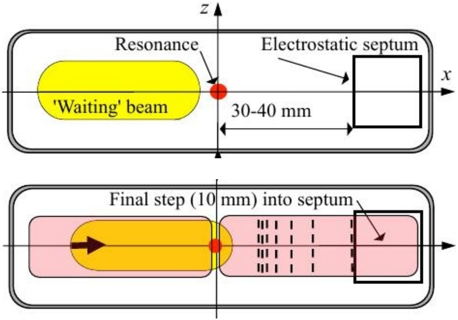




- 'stable beam' to be slowly **moved into resonance**

- **amplitude** of particles 'locked' in resonance **grows**
- particles enter **electrostatic septum**
  - ► **kick** onto extraction trajectory

- kick results in **separation** between circulating and extracted particles
  - ► **gap** for **magnetic septum**



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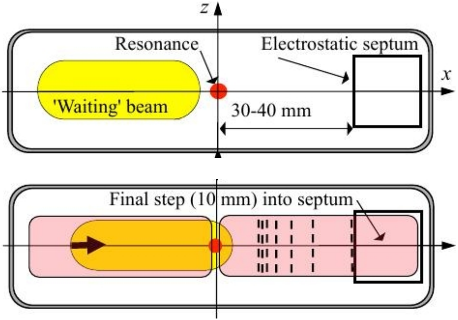

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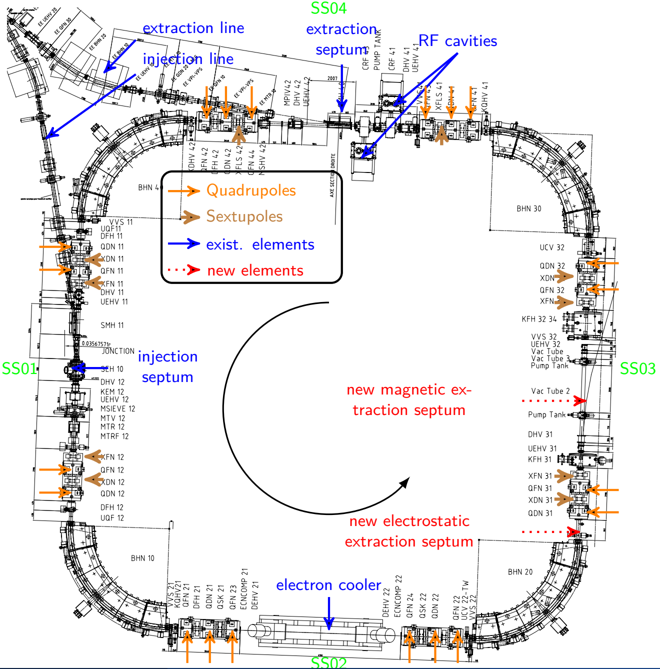
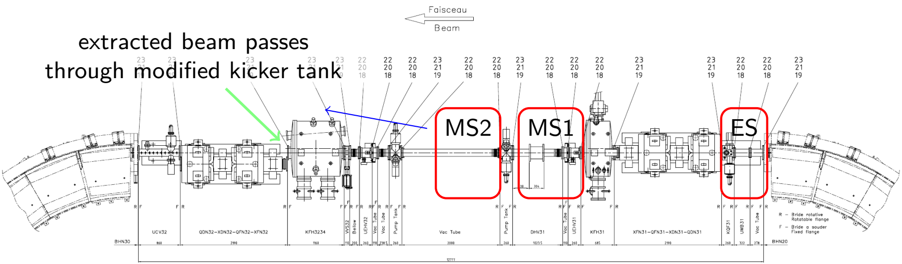
Studied feasibility of implementation in LEIR...

- positioning of septa in lattice
- magnet settings for extraction
- aperture limitations

Elements in LEIR



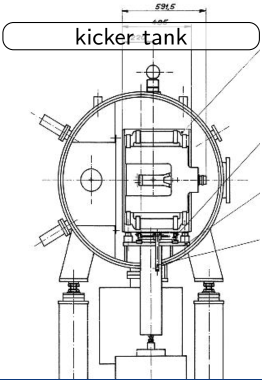


Critical point is ES:

- very limited space
- field strength limited by vacuum requirements for Pb

Septa	Electrostatic	Magnetic
Physical length	86 cm	120 cm
Effective length	66 cm	100 cm
Septum thickness	0.1 mm	10 mm
Field Strength	7 MV/m	0.5 T
Kick	3.4 mrad	80 mrad

($400\,\mathrm{MeV/n}$, $Q/A = 0.5$)

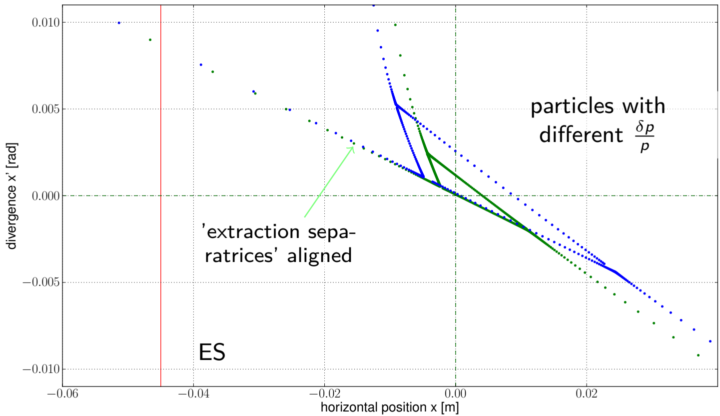


Sextupole Settings for Resonance Excitation

Sextupoles tuned to

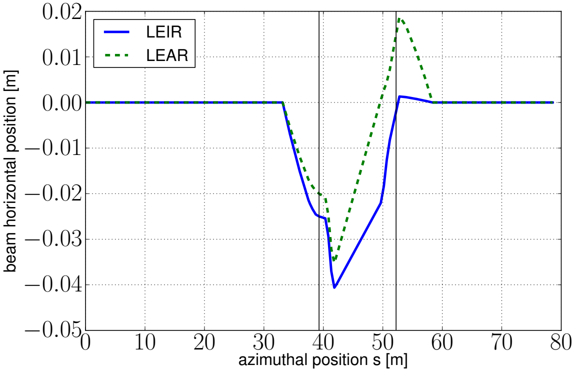
- **excite 3rd order resonance** for spiral step $\sim 10\,\mathrm{mm}$
- **adjust chromaticity** for Hardt condition
  - ► alignment of separatrices for off-momentum particles

Integrated Sextupole strength [T/m] ($B\rho = 4.8\,\mathrm{Tm}$)	LEIR-like	LEAR-like
F-family SS10/30	-3.8	-6.2
D-family SS10/30	3	5.9
sextupole 1 in SS40	-9	-6.0
sextupole 2 in SS40	-0.90	20.0

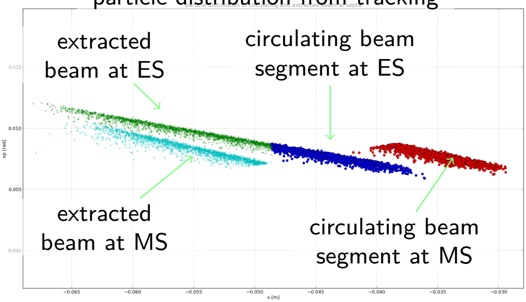


Aperture Considerations

- Pb **operation for LHC not to be perturbed**
  i.e. machine aperture not be reduced by new electrostatic and magnetic septum
- **horizontal position** of septa:
  - $\sim -45\,\mathrm{mm}$ for **electrostatic septum**
  - $\sim -55\,\mathrm{mm}$ for first **magnetic septum**
- **local orbit bump** required around septa to **avoid loss of particles on separatrices** at other elements

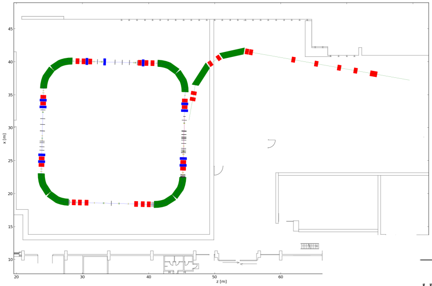


particle distribution from tracking



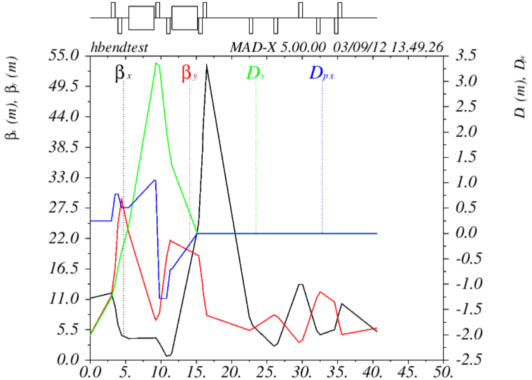
separation between extracted and circulating beam determines position and kind of second septum

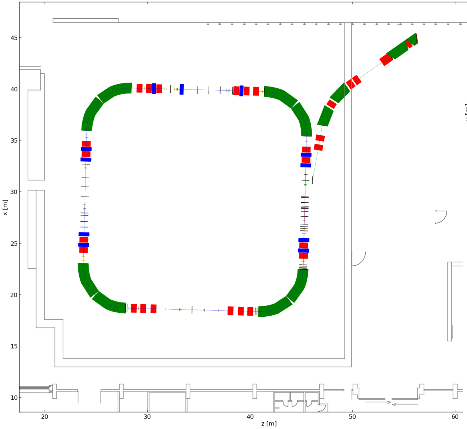
- **start parameters** for transferlines:
  - vertical phasespace: as in lattice
  - horizontal phasespace:
    'bar of charge': D, D' given by momentum dependency of spiral step, ϵ, β from fitting extracted distribution
  - first quadrupole $\sim 3\,\mathrm{m}$ downstream of kicker tank
- **design parameters** for transferlines:
  - horizontal beamline up to 430 $\mathrm{MeV/\,n}$
  - vertical beamline up to 75 $\mathrm{MeV/\,n}$
  - $> 5 \times 5\,\mathrm{cm}^2$ field size,
  - field non-uniformities $< \pm 5\%$

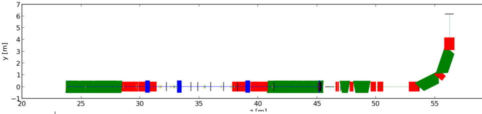


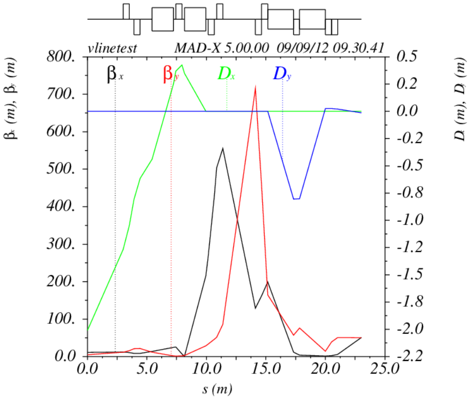
- first **broadbeam** (by scattering or non-linear magnetic effects), later upgrade for scanning
- **bending magnet**:
  430 MeV / n , $\approx 90^\circ$
  ► $\rho \approx 4.2$ m, $l \approx 6.55$ m

- **matching constraints**:
  $D = 0$, $D' = 0$ at end of beamline









- **Bending magnet**:
  75 MeV / n , 90°
  - $\rho \approx 1.6\,\mathrm{m}$, $l \approx 2.5\,\mathrm{m}$
- **vertical space limited** to $\approx 8\,\mathrm{m}$
- **matching constraints**:
  $D_{x,y} = 0$, $D'_{x,y} = 0$ at end of beamline

Summary and Outlook

Status of studies for the implementation of a biomedical facility at CERN

- re-implementation of a **slow extraction well advanced**
  - sextupole settings to adjust chromaticity and extraction resonance
  - orbit bump at new extraction septa to keep acceptance for ion accumulation
- design of experimental **beam lines in initial stage**
- further studies:
  - options for low energy front-end (2nd Linac3 source or other solution) under study
  - radioprotection study in initial stage

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Outlook

- **sextupole and dipole strengths** to be verified
- discuss and refine **septa parameter** with hardware experts, modification of the kicker (for fast ejection) tank
- **line design** and discussions with hardware experts (magnets, vacuum, etc.)
- continuation of **radio protection studies** with updated input based on first transfer line design

► get clear picture of the **conceptual design** by the end of the year

► estimate resources needed: material and manpower, possible timescales

Supervision by:

CERN: Manjit Dosanjh, Christian Carli

PTCRi: Ken Peach

Further THANKS to:

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... and to you!

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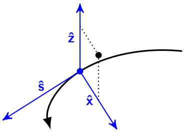
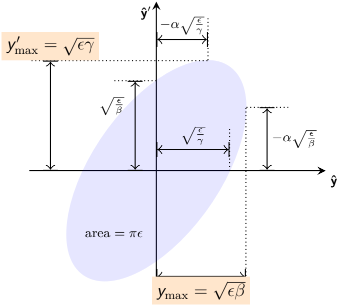
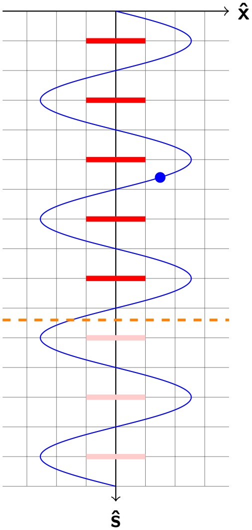
extra slides...

- motion of particles with charge q and velocity $\mathbf{v}$ in electromagnetic fields $\mathbf{E}$ and $\mathbf{B}$
  ▶ **Lorentz force**:
$$\mathbf{F}_{\mathrm{L}} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$
- **accelerator lattice**:
  sequence of elements for beam manipulation, diagnostics, etc.,
  aligned along **reference orbit** (trajectory of particle with design momentum $p = p_0$)
- from equilibrium condition of Lorentz and Centripetal forces:
  ▶ **magnetic rigidity** $B\rho$ of beam
$$B\rho = \frac{p}{q}$$
- curvilinear righthanded
  coordinate system ($\hat{\mathbf{x}}$, $\hat{\mathbf{z}}$, $\hat{\mathbf{s}}$):
  - $\hat{\mathbf{s}}$: distance along reference orbit
  - $\hat{\mathbf{x}}$ and $\hat{\mathbf{z}}$:
    horizontal and vertical
    component of displacement from
    reference orbit

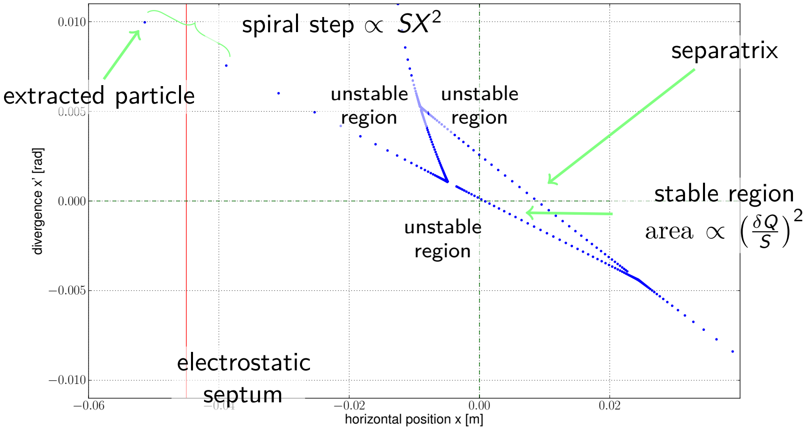


- alternating focusing / defocusing by **quadrupole magnets**
  ► oscillatory motion in transverse coordinates ($\hat{\mathbf{x}}$, $\hat{\mathbf{z}}$) along $\hat{\mathbf{s}}$ (**betatron oscillation**)
- **tune** Q: number of betatron oscillations $[2\pi]$ per turn
- **divergence** $x' = \frac{\partial x}{\partial s}$
- **phase space coordinates** $(x(s), x'(s), z(s), z'(s), p(s))$
- **stable particle motion**:
  ellipse in phase space with **emittance** ϵ





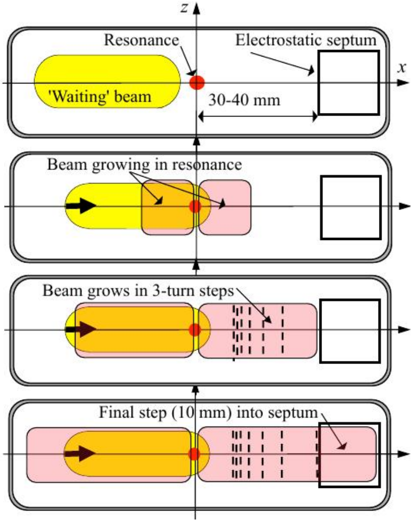
- **slow extraction** over many turns ($\sim 10^6$)
- **resonance**: Q multiple of π, here **1/3 integer resonance** $Q = n \cdot 1/3$
  - particles at same point in phase space every 3rd turn
  - periodic sampling of perturbations ▶ emittance growth
- 3rd order resonance excited by **sextupole magnet**



for slow extraction for medical synchrotrons see for example:
Badano, Benedikt, Bryant, Crescenti, Holy, Maier, Pullia, et al.: **Proton-Ion Medical Machine Study (PIMMS)**, 2000.
http://cdsweb.cern.ch/record/385378

Resonant Slow Extraction (continued)

slow extraction requires **'stable beam'** to be slowly **moved into resonance**



from Phil Bryant's presentation on Synchrotrons at PARTNER course *Accelerators and Gantries*, March 2012, CERN

options for driving particles into resonance

- shift of tune
- longitudinal excitation
- transverse excitation

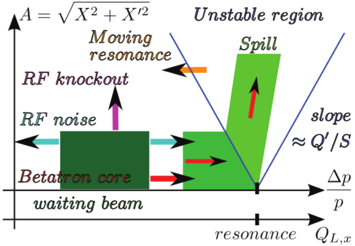
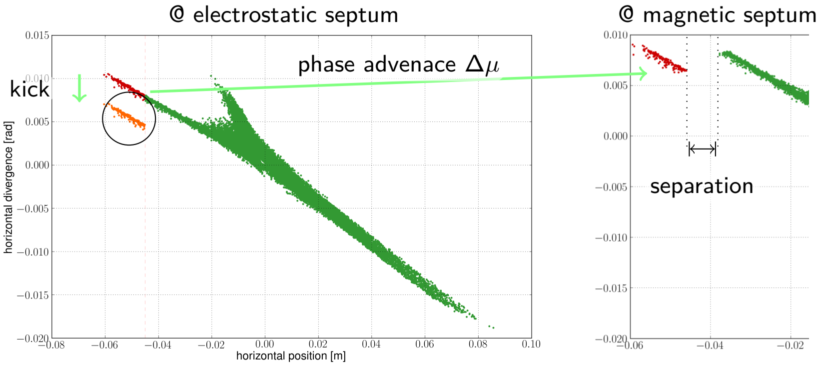


Figure 1: Steinbach diagram showing the various different driving mechanisms: a) betatron core (red), b) RF knock-out (magenta), c) RF noise (cyan) and d) lattice tune adjustment (orange). The spill is indicated for case a and c.

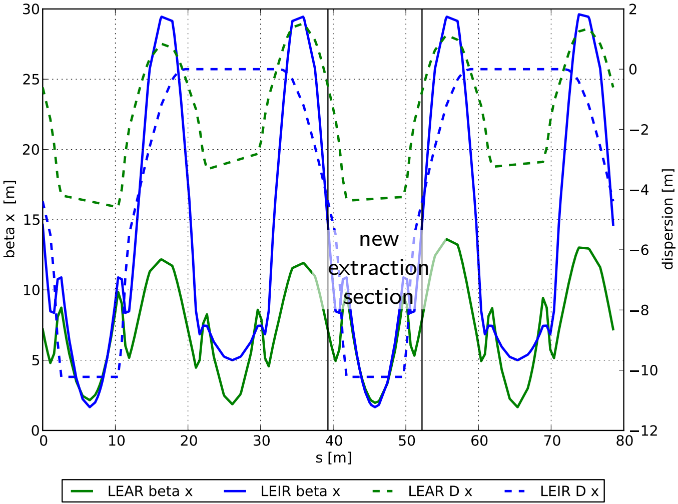
G. Feldbauer, M. Benedikt, U. Dorda:
Simulations of various driving mechanisms for the 3rd order resonant extraction from the MedAustron medical synchrotron, IPAC 2011, San Sebastián

Resonant Slow Extraction (continued)

- extracted beam segment at electrostatic septum
- **kick** given by electrostatic septum translates into **separation** for magnetic septum



configuration	Q_{H}	Q_{V}	$Q'_{\mathrm{H,nat}}$	$Q'_{\mathrm{V,nat}}$	$\beta_{x,\mathrm{max}}$	$\beta_{y,\mathrm{max}}$	$d_{x,\mathrm{max}}$	$d'_{x,\mathrm{max}}$
LEAR	7/3	2.73	-3.17	-7.46	12.82	22.16	-4,10	-2.23
LEIR	5/3	2.72	-3.49	-4.54	29.62	21.17	-10.22	-4.46



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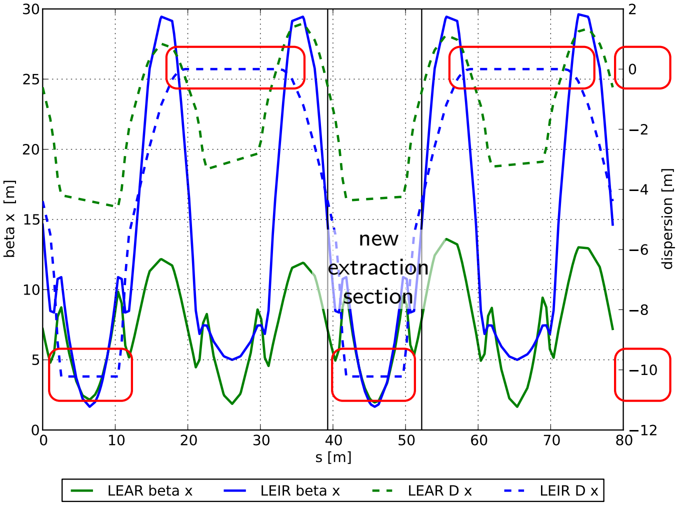

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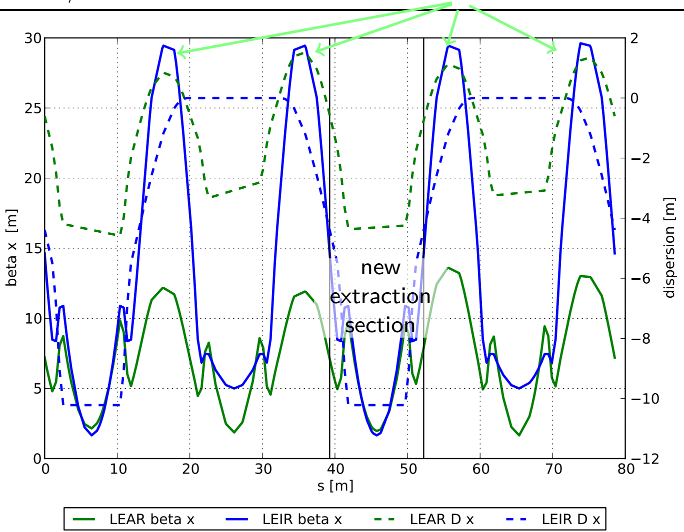

three options are discussed to provide LEIR with light ions

- Option1:
  new front end for Linac3 New source, new LEBT, new RFQ, switch yard to join into the MEBT of Linac3
    - Advantage: re-use of present equipment
    - Disadvantage: very limited space in Linac3 available, heavy ion operation should not be disturbed (maintain transmission of the MEBT), RFQ production takes some time, installation and commissioning only possible if Linac3 is not running for heavy ion physics ▶ many years from now before the first beam will be available
- Option 2:
  new linac – Linac5
    - Advantage: independent of Linac3 operation, machine well adapted to light ion operation
    - Disadvantage: RFQ production will also delay the whole schedule in this case
- Option 3:
  cyclotron
    - Advantage: probably of-the-shelf solution available
    - Disadvantage: no cyclotron specialists at CERN Man power, budget and schedule requests of the three options have to be compared to select the option which allows the earliest possible beam for the users

Option 1 has been studied using *Pantechnik Supernanogan* source

- at LINAC3 final energy ($4.2\,\mathrm{MeV}/\,\mathrm{n}$) neutron production may occur for light ions

- Ion species and intensities per cycle (2.4 or 3.6 s)
  - based on Linac3 source proposal (7.5 keV/n at RFQ entrance and injection of 5 efficient turns in LEIR, no cooling)
  - He: LEIR limitation lower than Linac3 limit $\approx 8.5 \cdot 10^{10}$ ions

species	C	N	O	Ne
intensity $[10^9]$	1.4	0.4	1.1	0.25

- Outcome of brainstorming meeting with experiments in June: Protons are very important
- production not trivial: H2+ or H3+ from Linac3 and stripping (low magnetic fields in LEIR) or Protons at 50 MeV from Linac2 or Linac4?
- Proposal: Acceleration and extraction of H2+ in LEIR – stripped to protons in line