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Thoughts on proton drivers for a muon facility

Shinji Machida
UKRI/STFC Rutherford Appleton Laboratory

20 May 2021
1st Muon Community Meeting

Two main subjects

Beam power:	a few MW
Short bunch:	a few ns

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Two main subjects

Beam power:	a few MW
Short bunch:	a few ns

Beam power

proven?

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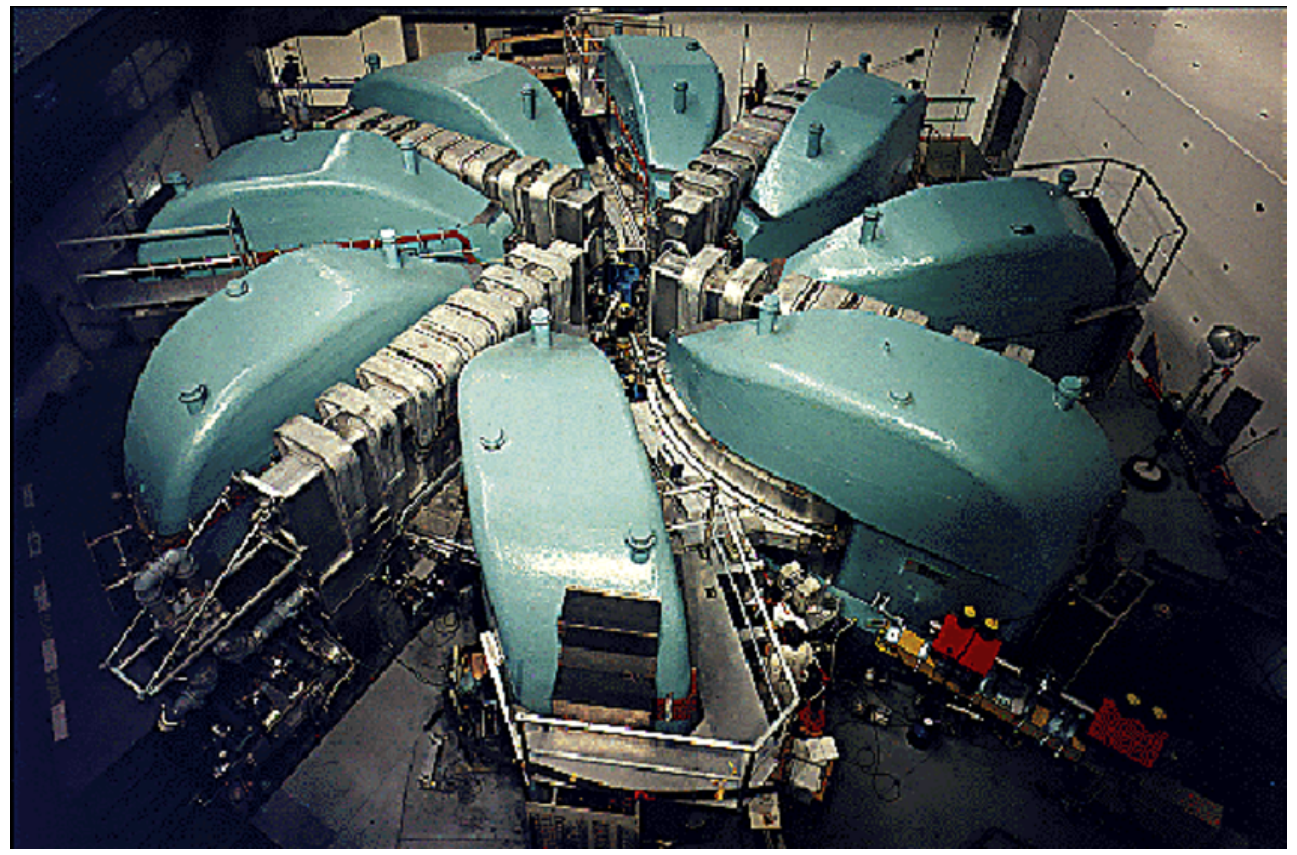
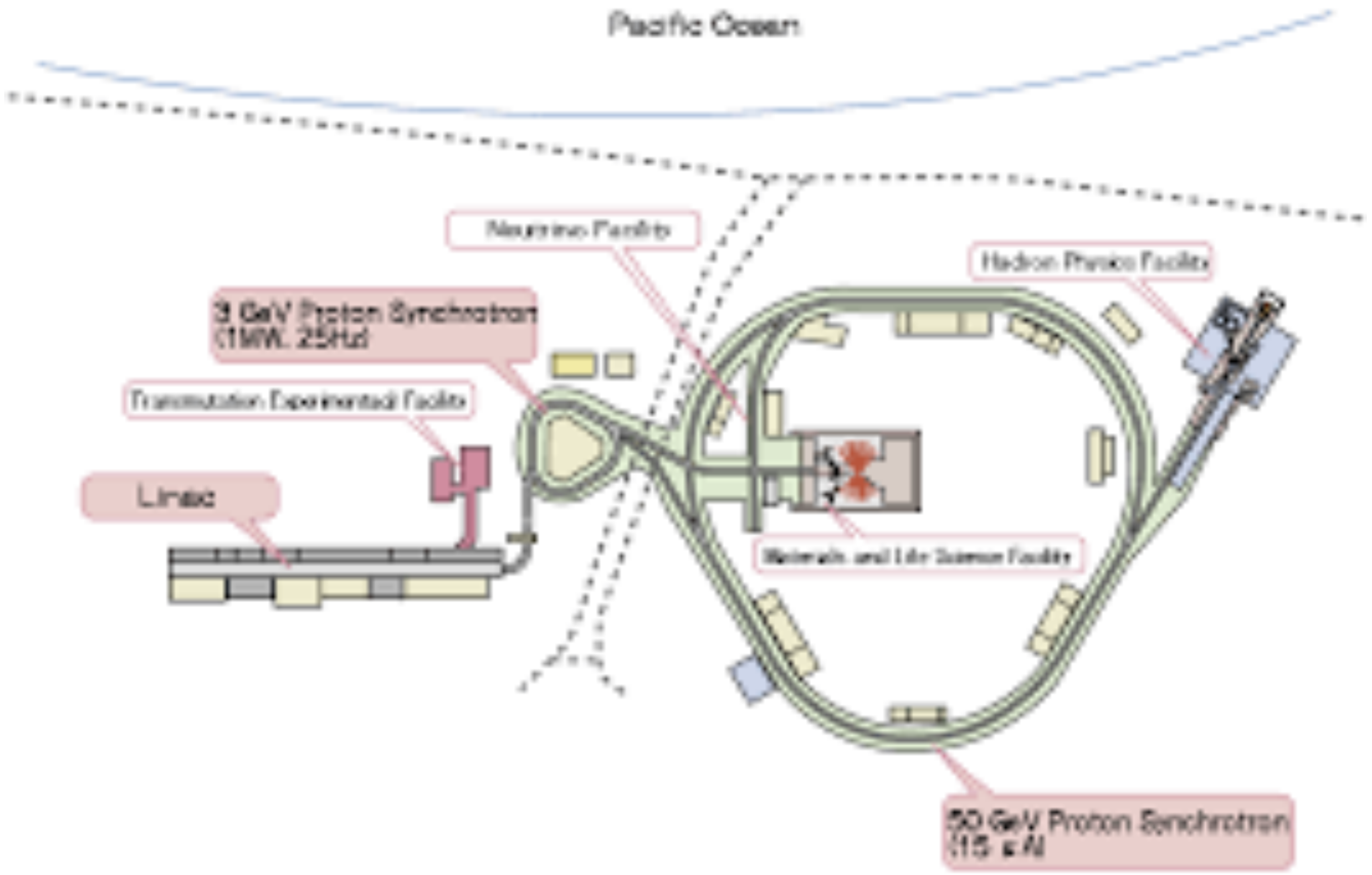
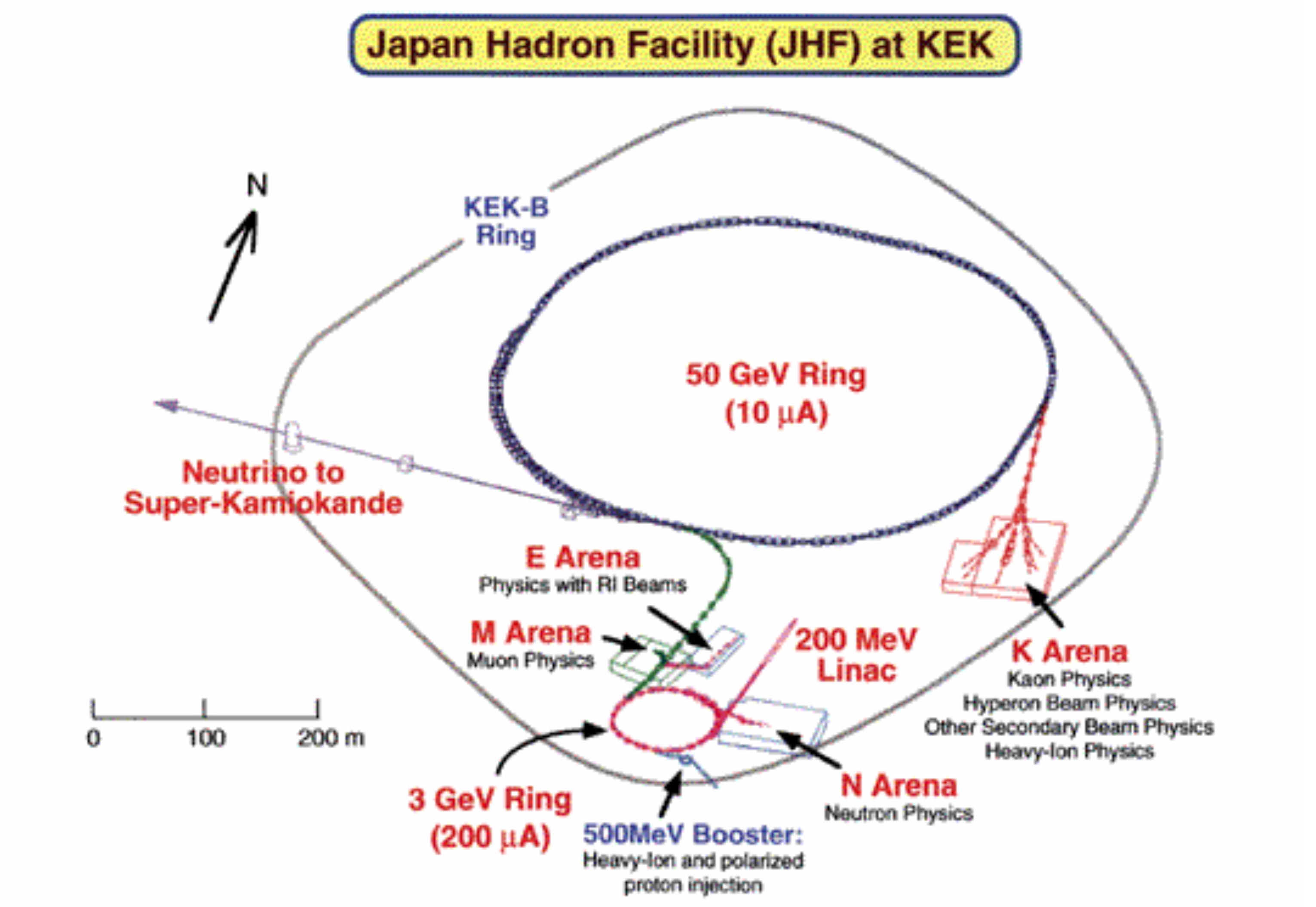
- We think we know how to design and operate a MW class proton accelerator.
  - Cyclotron: PSI
  - Full energy linac and accumulator ring: SNS, (ESS)
  - Rapid cycling synchrotron: ISIS, J-PARC



PSI



SNS



J-PARC

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Beam power

bunch intensity, not average power

- All high power proton driver operates at >10 Hz.
- A proton driver for a muon collider at 5 Hz.
  - **Intensity per bunch increases by a factor or one order of magnitude.**
  - Beam loss should be the same or lower.
  - Even ESSnuSB AR avoids the challenge by splitting into 4 batches to realise 5 MW with 14 Hz.

Shift from 10^{14} to 10^{15}

	2 MW	4 MW
3 GeV	0.833×10^{15}	1.67×10^{15}
4 GeV	0.625×10^{15}	1.25×10^{15}
5 GeV	0.5×10^{15}	1×10^{15}

- Challenge of a proton driver for muon collider is equivalent to a neutron spallation source of 10 MW-ish.

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Choice

extrapolation of present technology

- Cyclotron needs an accumulator ring to create a short bunch.
  - **Injection is a challenge.** KAON project at TRIUMF in 1980s proposed a similar scheme.

- Rapid cycling synchrotron has a **bottleneck at injection energy**.
  - Need more than one order of magnitude greater particles than J-PARC RCS.

- Full energy (superconducting) linac and accumulator ring seems to be **only feasible option.**
  - A bit more challenge of ESSnuSB accumulator ring.

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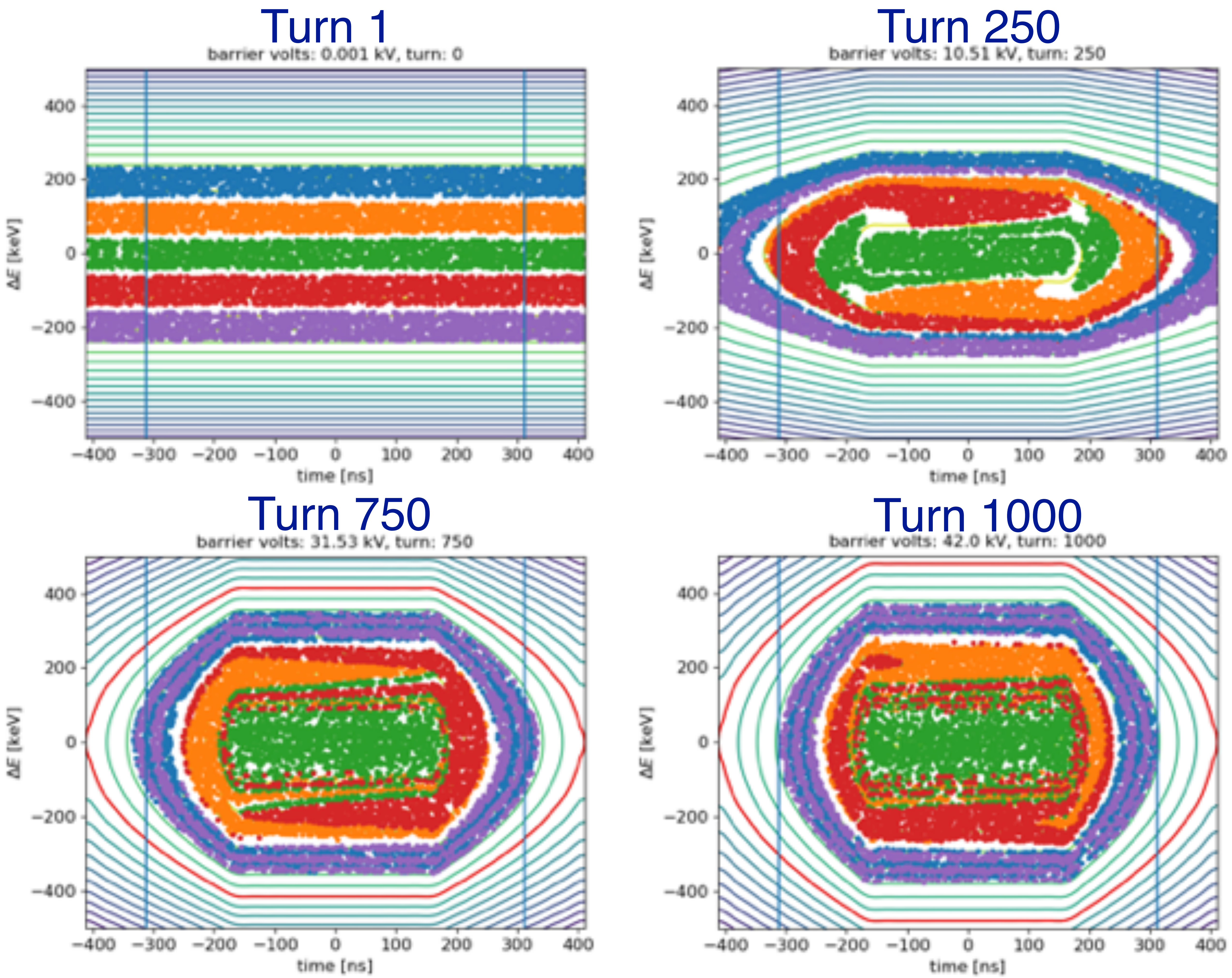
Choice

something different

Fixed-Field Alternating-Gradient Accelerator (FFA)

- Operate accelerator at 50 Hz to reduce bunch intensity at injection energy.
- Stack beams 10 times at extraction energy to reduce rep rate for the target at 5 Hz.
- Capture by a barrier bucket for extraction.



Courtesy of D. Kelliher, STFC/RAL

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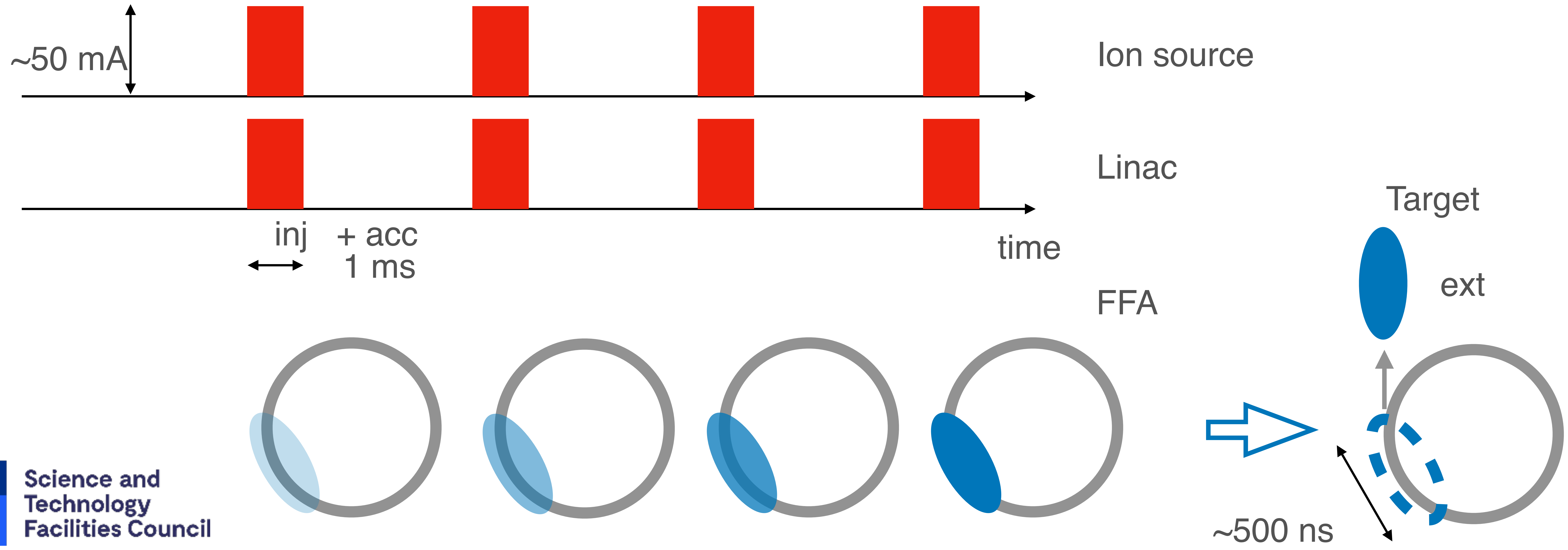
Similar request in neutron community

high peak brightness

- Short pulse neutron users demands high peak brightness with low rep rate.
    - ISIS (50 Hz), SNS (60 Hz), J-PARC (25 Hz): It is rather high at present.

- ISIS-II, ideally at 10 Hz delivering 1.25 MW at 1.2 GeV.
    - Plan is to operate a FFA at 100 Hz and extract the 10 stacked beams at 10 Hz.



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Two main subjects

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Beam power:	a few MW
Short bunch:	a few ns

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Short bunch

issues with bunch rotation

- Short bunch means large momentum spread.
  - Chromaticity correction is necessary.
  - Higher order momentum compaction factor distorts bunch shape.

$$\frac{\Delta\omega}{\omega_0} = -\left(\eta_0 + \eta_1\delta + \eta_2\delta^2 + \ldots\right)\delta$$

$$\eta_0 = \left(\alpha_0 - \frac{1}{\gamma_0^2}\right) \qquad \eta_1 = \frac{3\beta_0^2}{2\gamma_0^2} + \alpha_1 - \alpha_0\eta_0$$

$$\eta_2 = -\frac{\beta_0^2\left(5\beta_0^2 - 1\right)}{2\gamma_0^2} + \alpha_2 - 2\alpha_0\alpha_1 + \frac{\alpha_1}{\gamma_0^2} + \alpha_0^2\eta_0 - \frac{3\beta_0^2\alpha_0}{2\gamma_0^2}$$

$$R = R_0\left(1 + \alpha_0\delta + \alpha_1\delta^2 + \ldots\right)$$

Table: compaction of η_1

	$\alpha_i = 0$	$\alpha_i \neq 0$
3 GeV	0.080	~0.5
4 GeV	0.052	~0.5
5 GeV	0.037	~0.5
	Kinematic term only	Kinematic and path length terms

- Nonlinear magnets controls chromaticity and higher order momentum compaction factor at the same time, e.g. C.R. Prior and G.H. Rees at NuFact2000.

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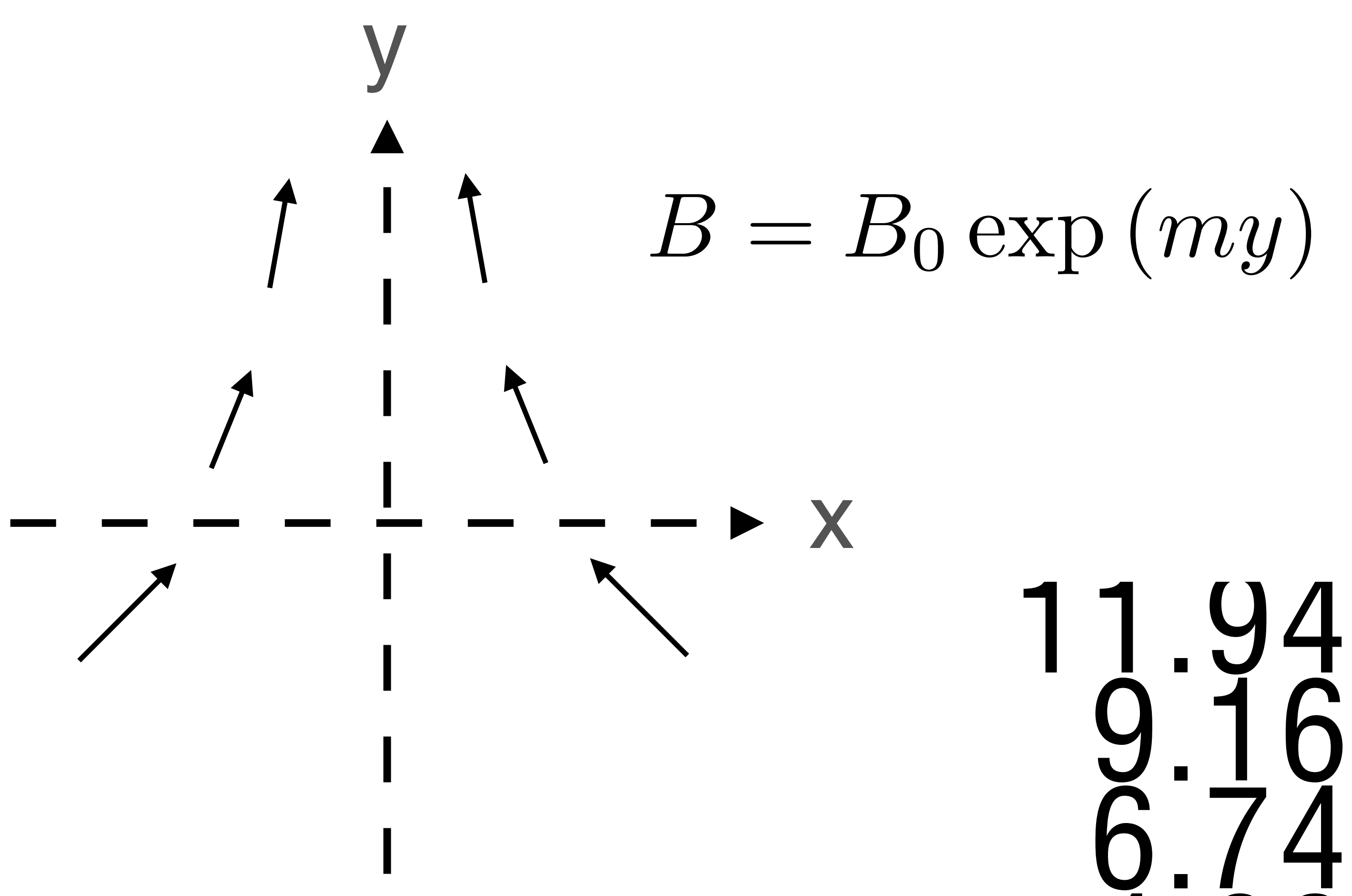
Short bunch

vertical excursion FFA

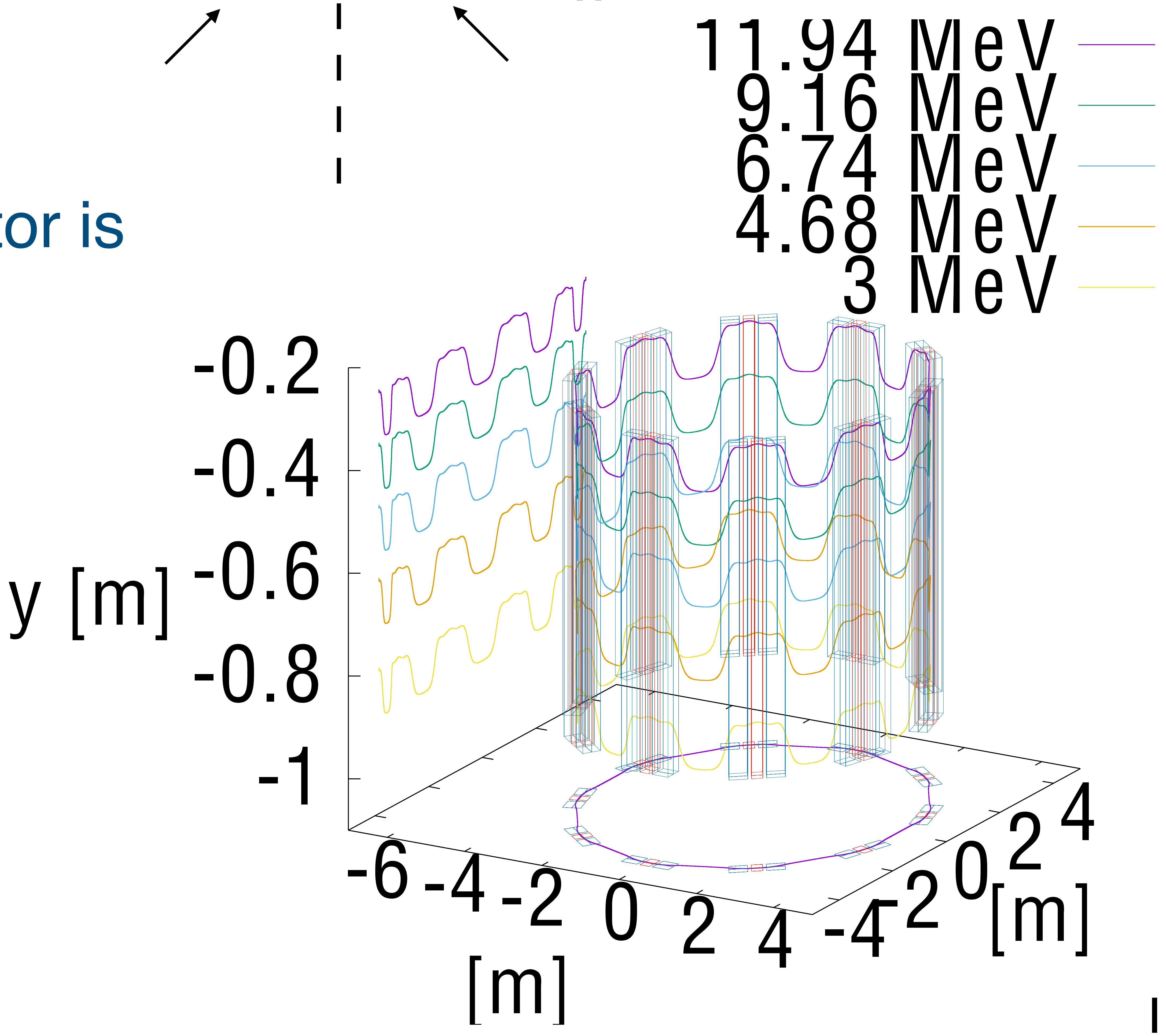
- Orbit moves vertically.
- It is like a "circular linac".



- All order of chromaticity is zero.
- All order of the momentum compaction factor is zero.

⇩

- **Bunch rotation in a linear regime.**



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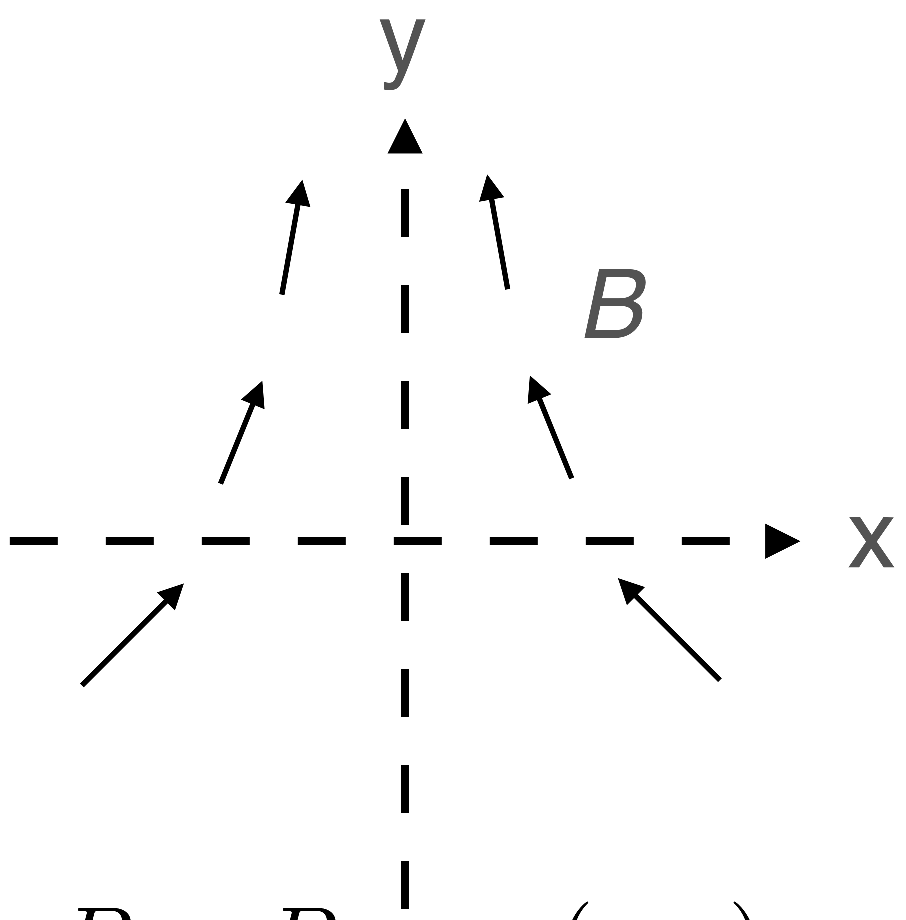
Short bunch

vFFA lattice as AR without acceleration

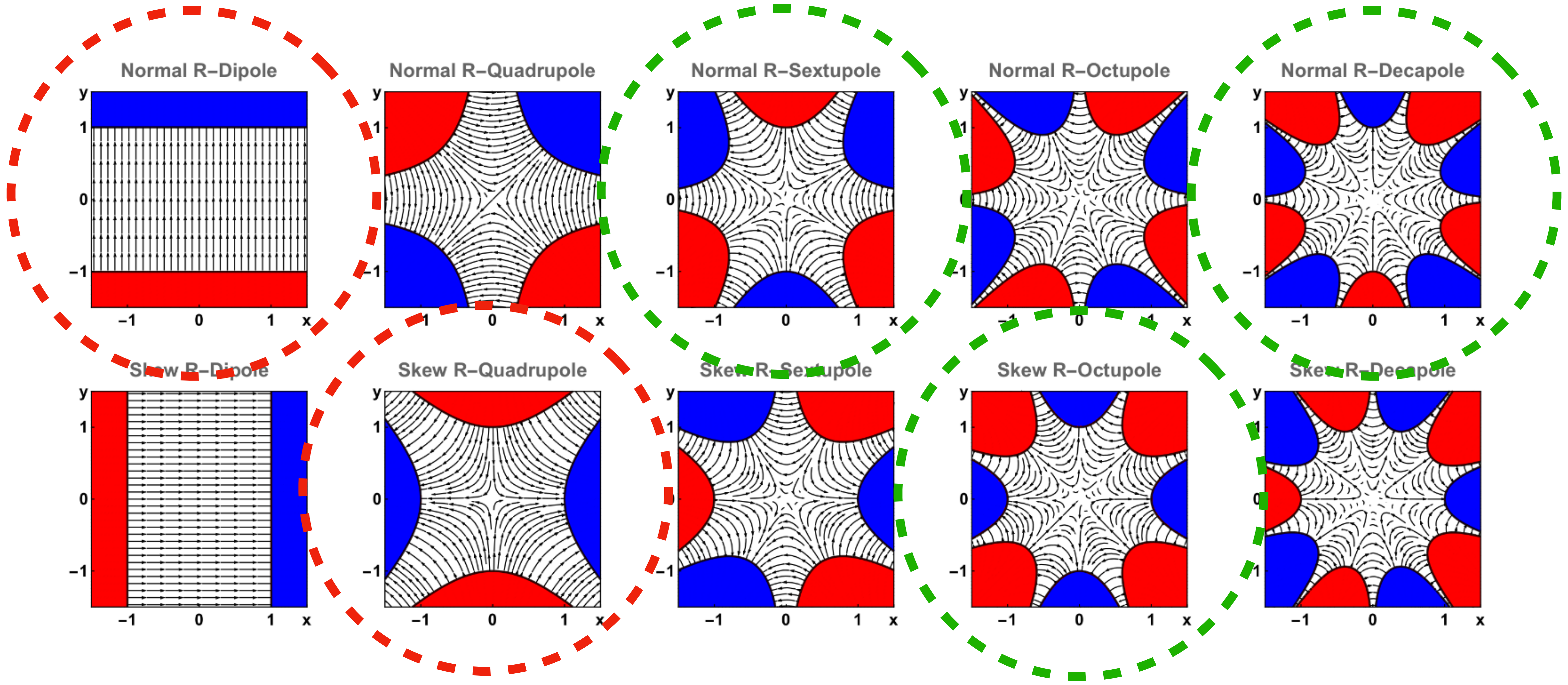
- Combination of a few low order multipole can create vFFA like optics as AR lattice.

$$\frac{B_y}{B_0} = \exp(my)\cos(mx) \approx 1 + my + \frac{m^2}{2!}\left(y^2 - x^2\right) + \frac{m^3}{3!}\left(y^3 - 3x^2y\right) \quad + \dots$$

Normal Dipole **Skew** Quad **Normal** Sext **Skew** Oct



$$B = B_0 \exp(my)$$



Summary

- Both beam power and short pulse are still challenges.
- FFAs add unique features to both challenges
  - Reduce bunch intensity keeping low rep rate.
  - Provide a linear momentum dependence to minimise bunch distortion.

… and another couple of slides.

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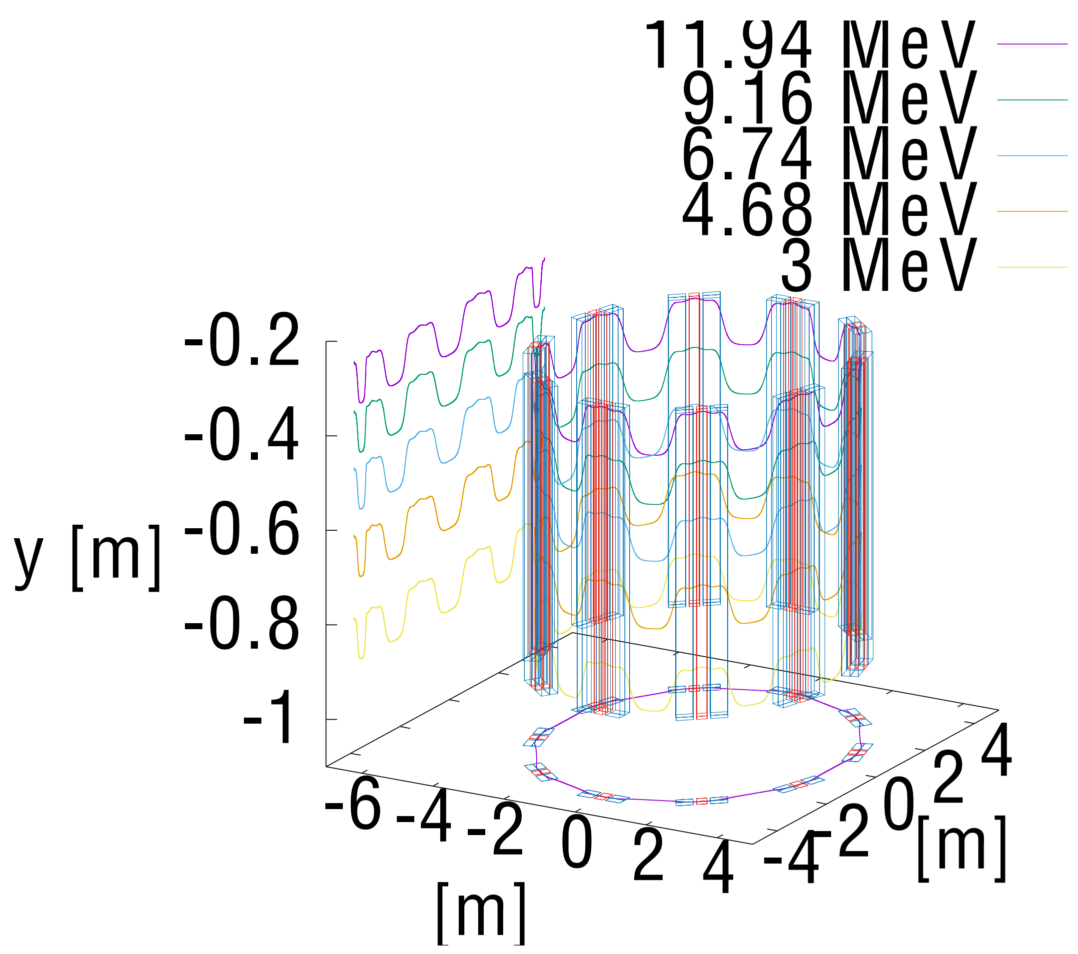
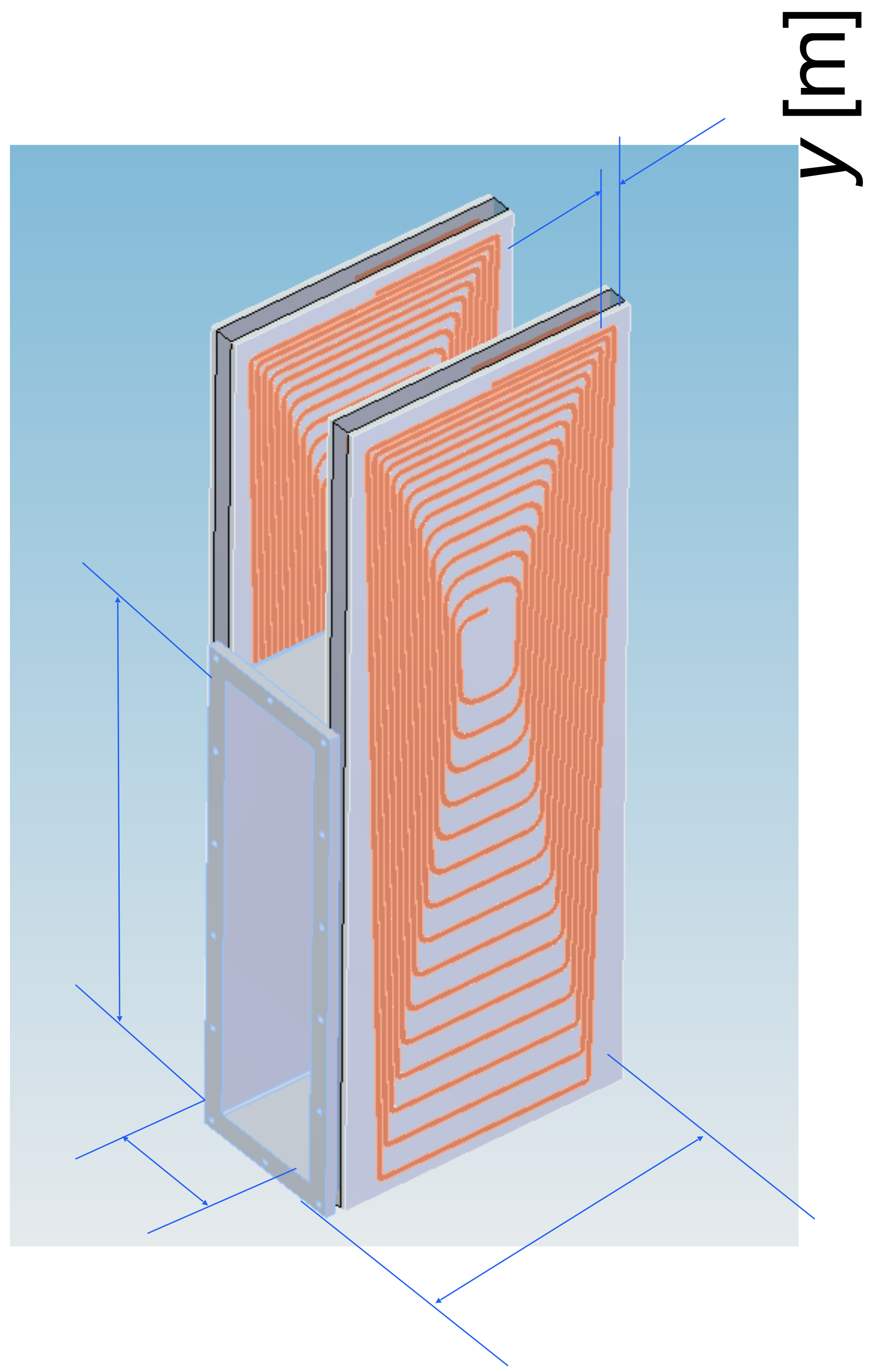
R&D at STFC/RAL

vFFA prototype of 12 MeV proton acc

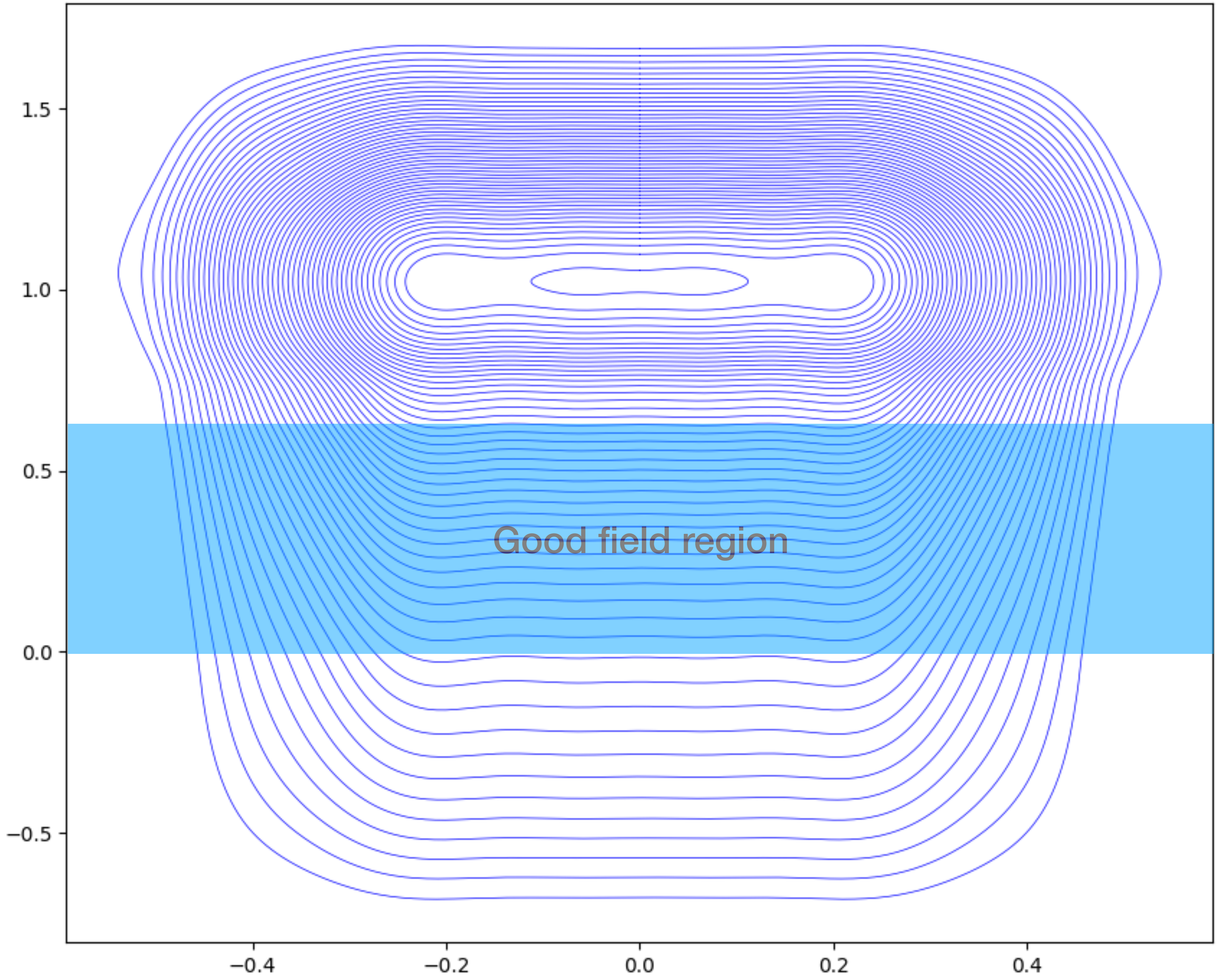
Prototype magnet parameters:

- 1 m-long magnet
- 0.6 m vertical good field region
- 22 cm full gap size
- 50 turns of coils
- 4.7 mm minimum spacing (centre coil to centre coil)





Coil dominated magnet (superconducting)



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FFA as sustainable option

energy efficient operation

- Energy efficient operation is one of the key consideration in the future accelerator facility.
  - Type of accelerators: cyclotron, synchrotron, etc.
  - Technology: superconducting magnet, permanent magnet, etc.

- Cyclotron is the most energy efficient accelerator: ~20% from grid power to beam power.
- Superconducting linac has good efficiency.

- FFA option
  - Cyclotron cannot go beyond 1 GeV, but FFA can with similar components.
  - Superconducting magnets as the main lattice components enhance efficiency.
  - FFA needs injector unlike cyclotron, but it will be superconducting linac.

*Workshop at PSI, 2016

	PSI cyclotron*	ISIS-II FFA	SNS linac*	J-PARC linac+RCS*
Beam energy	0.59 GeV	1.2 GeV	1.0 GeV	3.0 GeV
Beam power	1.3 MW	1.25 MW	1.4 MW	1.0 MW
Power consumptio	6.9 MW		16.2 MW	25.2 MW
(Beam power) / (Grid power)	19%	20~10%	9%	4%

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R&D proposal

- **Proton driver design based on FFA (vFFA) concept**
  - Achieving required bunch intensity and creating ~ns short bunch are still big challenges, that has not been demonstrated in any accelerator facilities.
  - FFAs, in particular vertical excursion FFAs (vFFAs), has two unique features. One is a possible use of the beam stacking at the extraction energy which is possible due to huge momentum acceptance. With this, bunch intensity becomes an issue only at extraction. The other is zero momentum compaction factors for all the orders. This minimises distortion of a short bunch when a bunch rotation scheme is employed.
  - As an alternative, an accumulator ring could be designed using vFFA optics only with lower order multipoles, which makes it almost free from all the momentum compaction factor.
  - R&D aims for the completion of conceptual design in 2025.

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Thank you for your attention

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